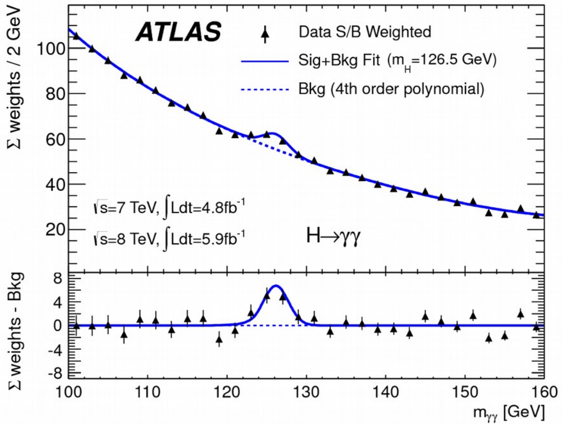
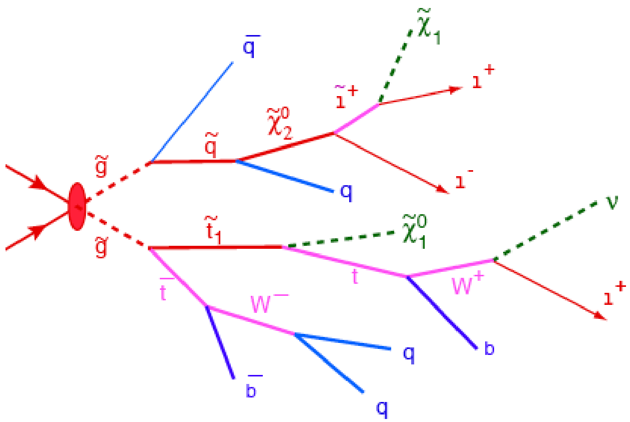
XVIII Frascati Spring School
"BRUNO TOUSCHEK"
in nuclear, subnuclear and astroparticle physics
LNF, May 9 - 13, 2016, Frascati (Italy)

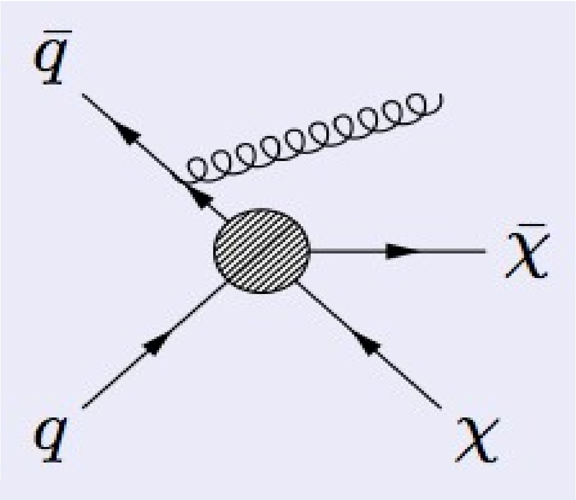
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Oliver Buchmueller, Imperial College London

SEARCHES FOR NEW PARTICLES AT THE LHC







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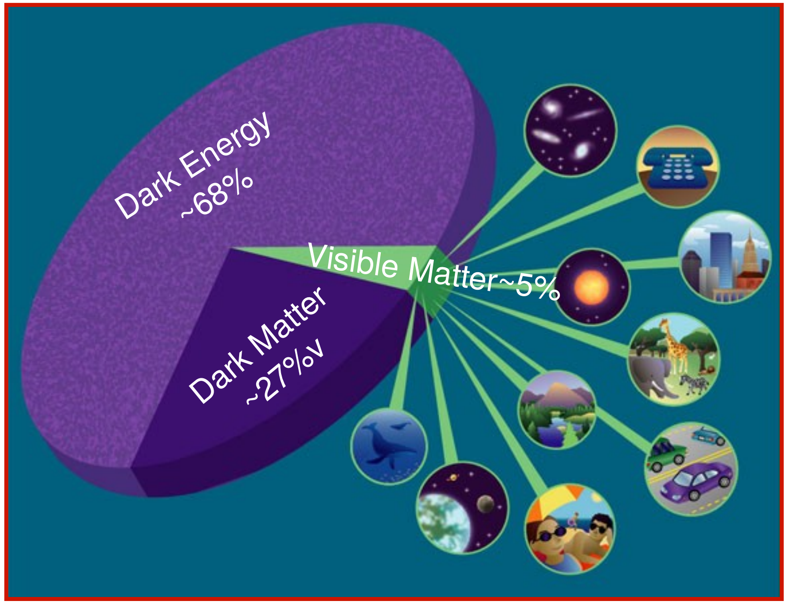
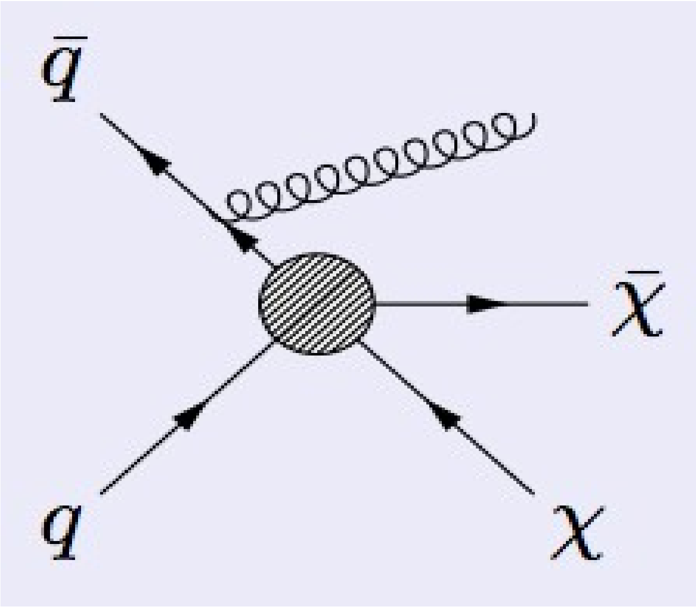
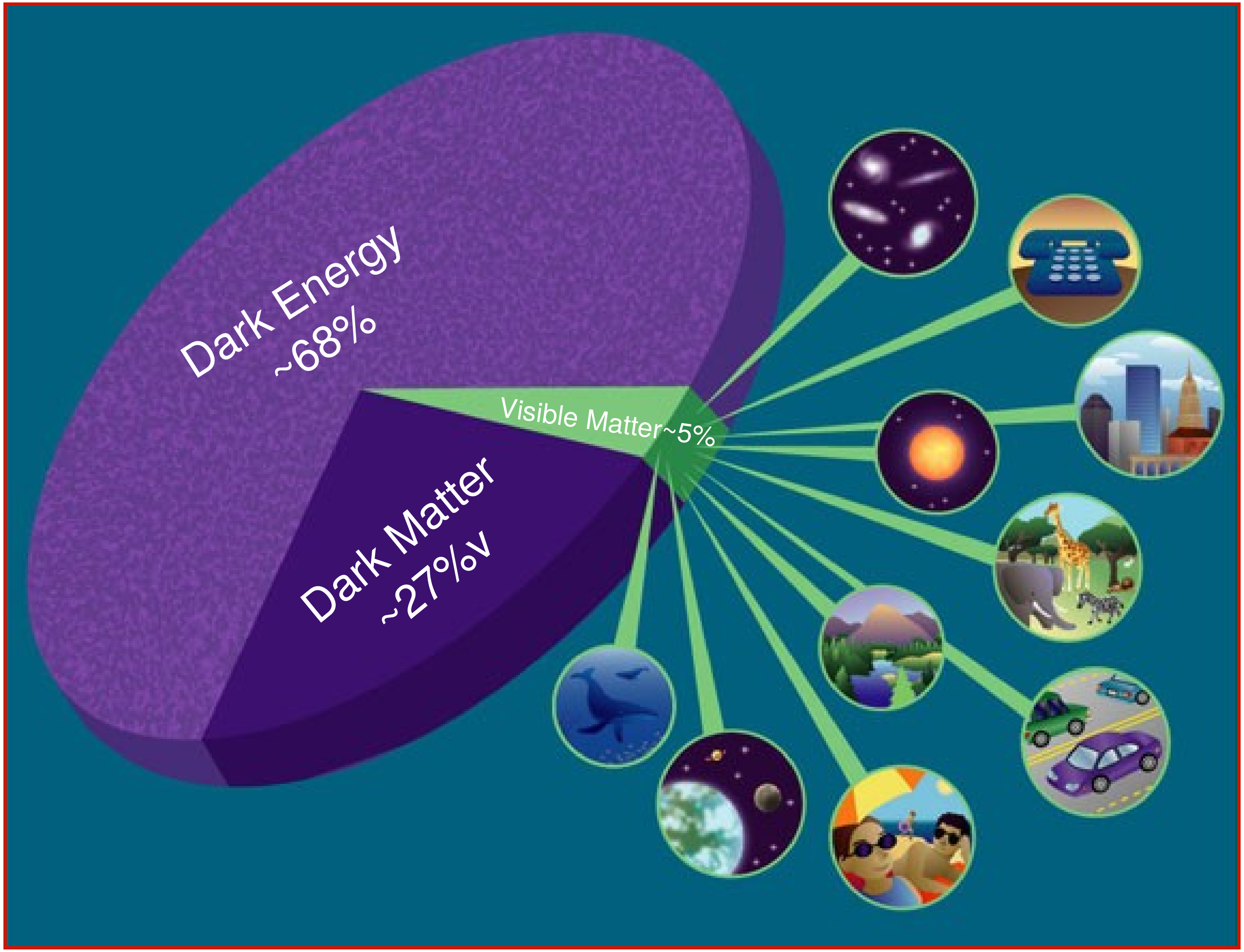
Oliver Buchmueller, Imperial College London

SEARCHES FOR DARK MATTER PRODUCTION AT THE COLLIDERS



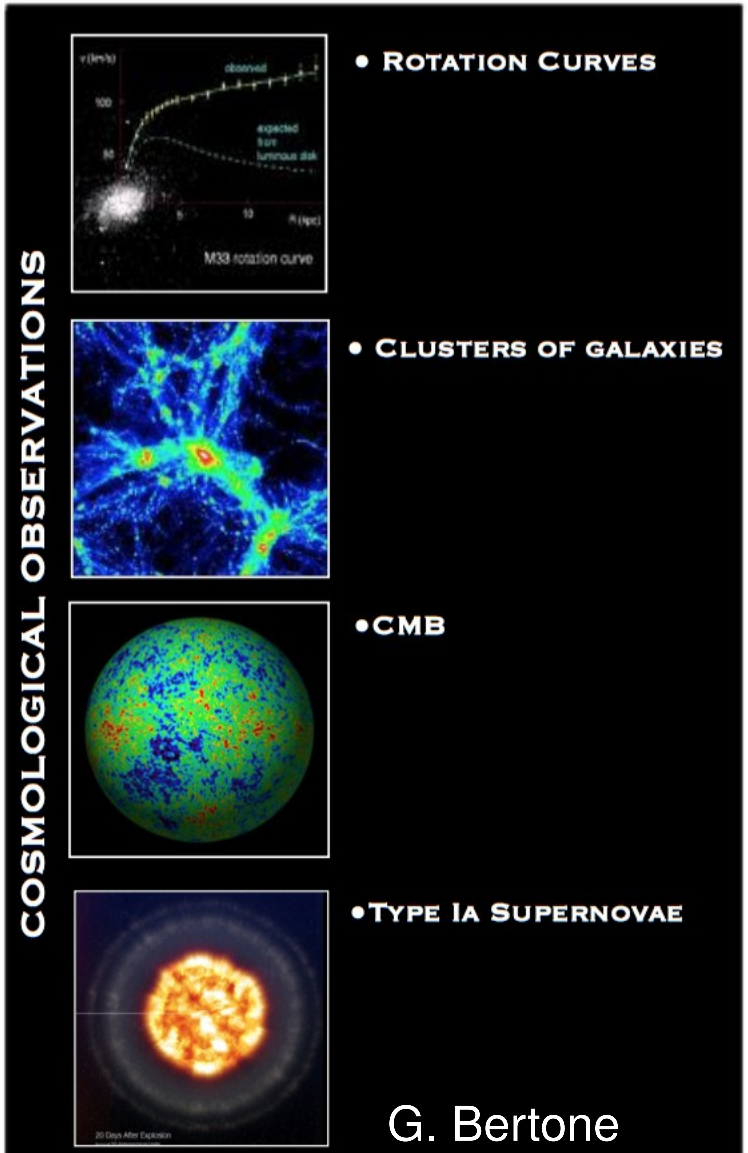


The Universe (as we know it today)

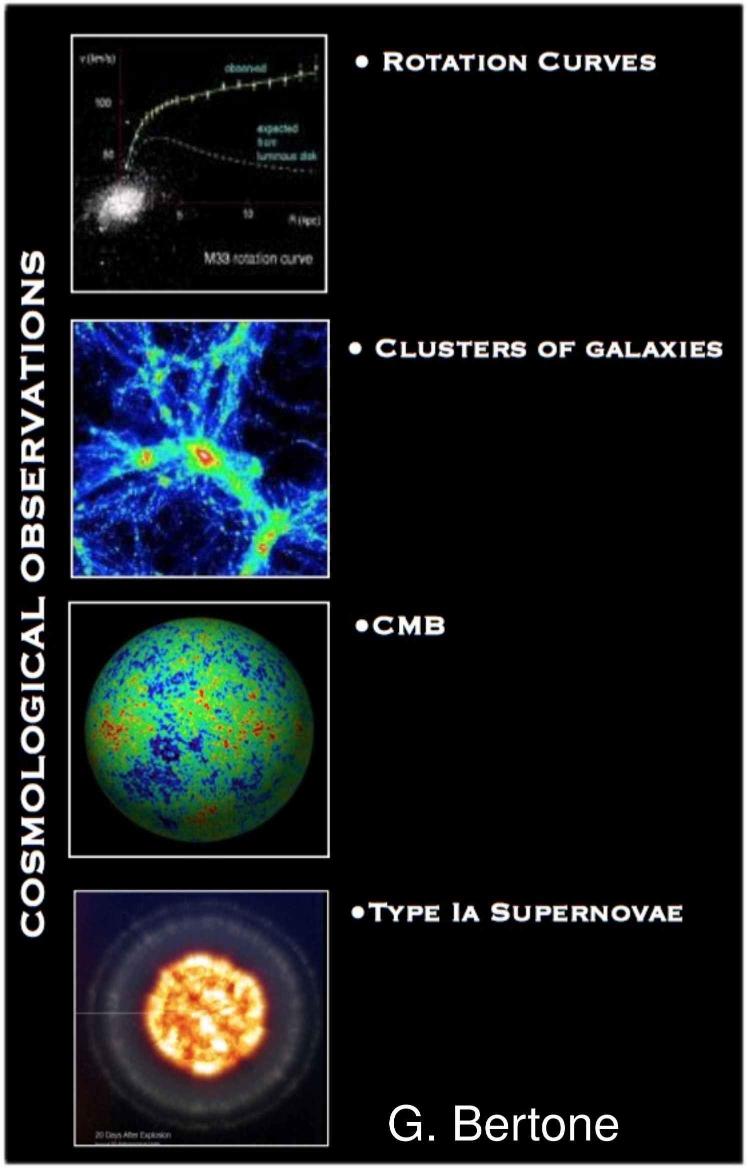


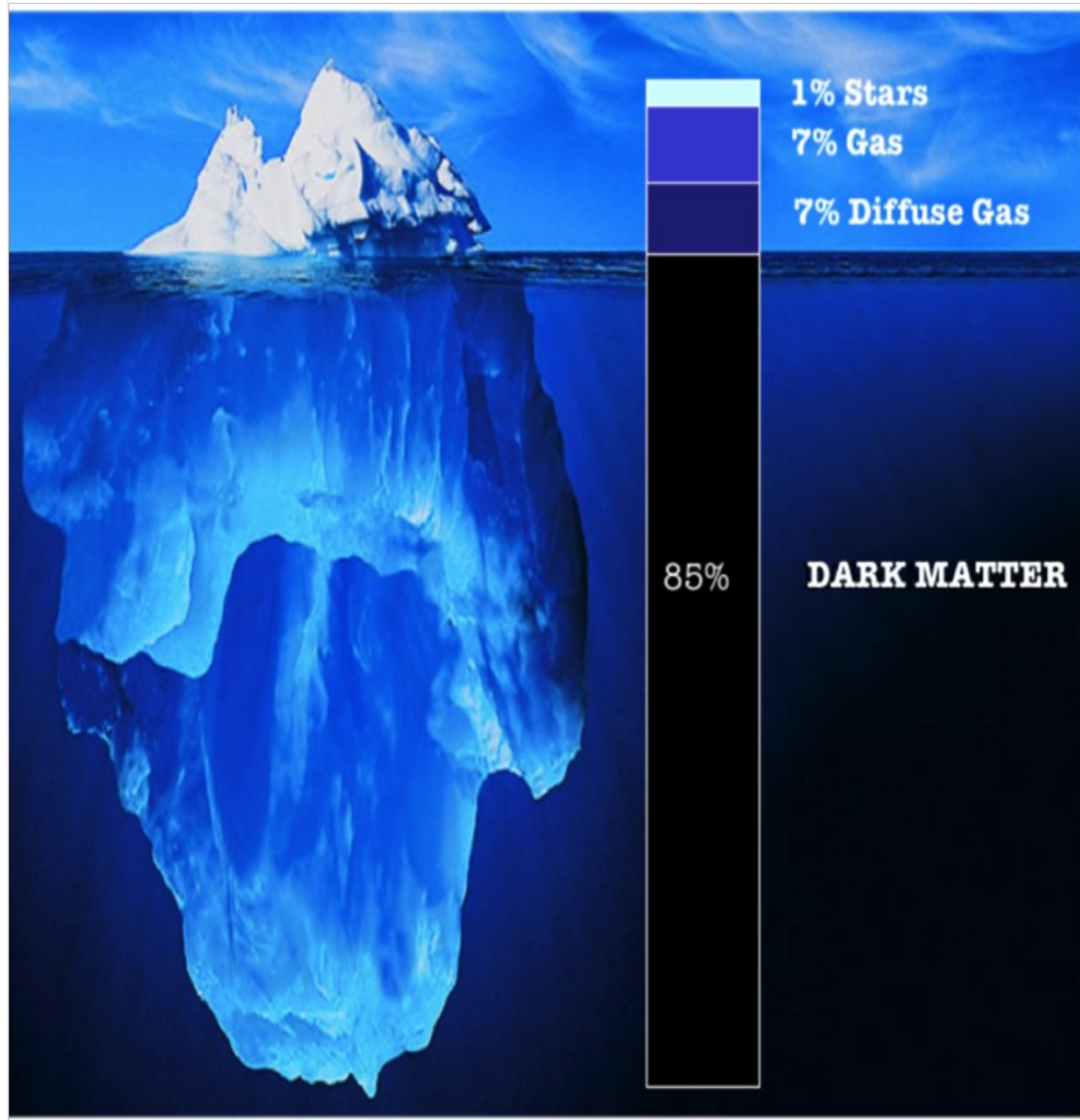
The Universe (as we know it today)

(Very Strong) Evidence for Dark Matter

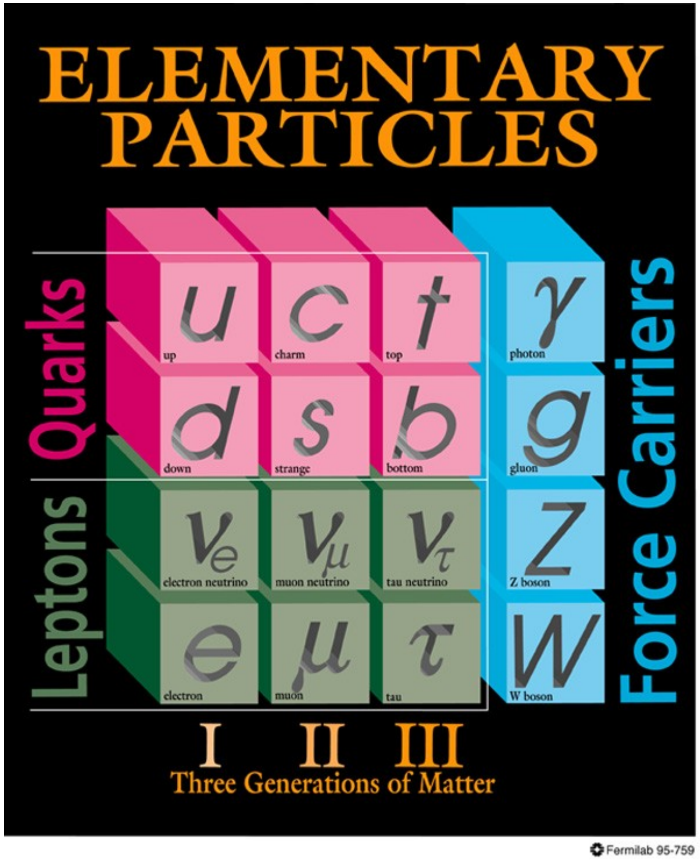


(Very Strong) Evidence for Dark Matter



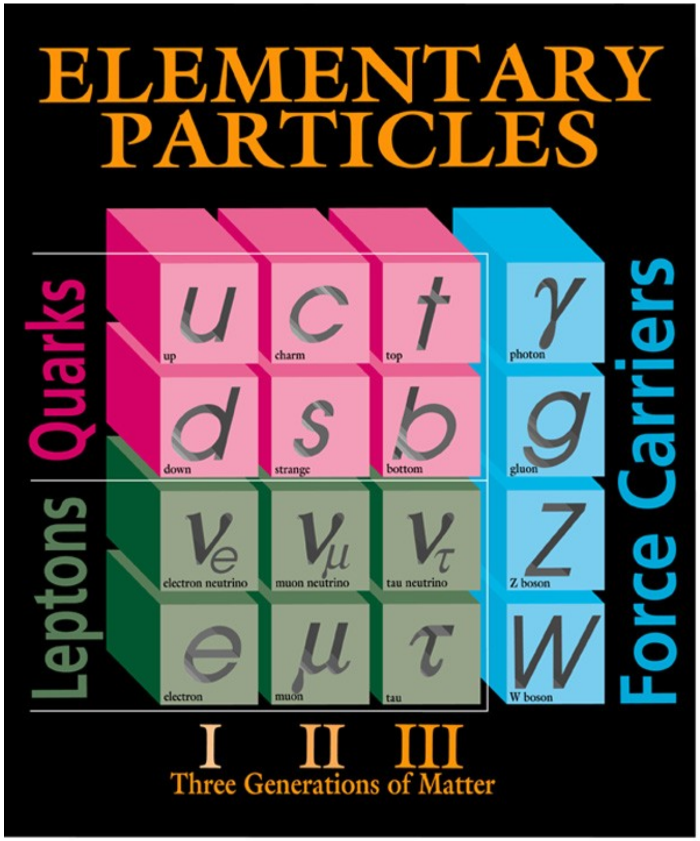


DARK MATTER – A Particle?!



Known DM properties

DARK MATTER – A Particle?!

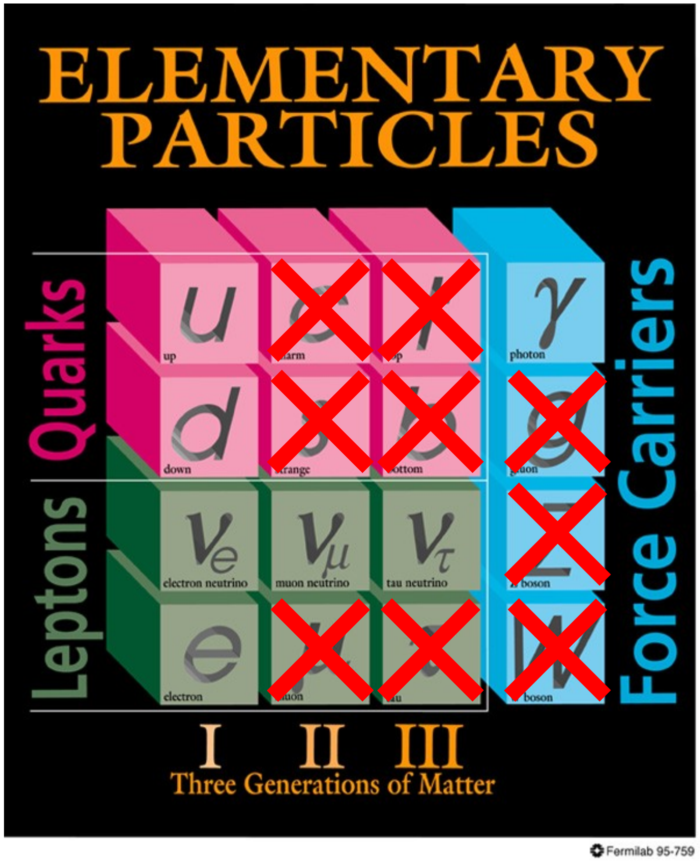


Fermilab 95-759

Known DM properties

- Gravitationally interacting

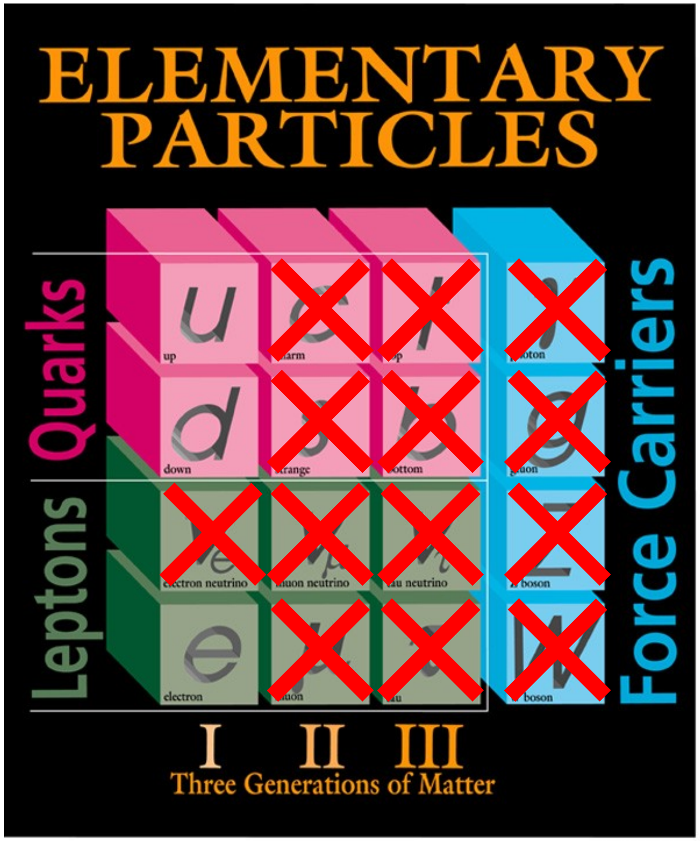
DARK MATTER – A Particle?!



Known DM properties

- Gravitationally interacting
- Not short-lived

DARK MATTER – A Particle?!

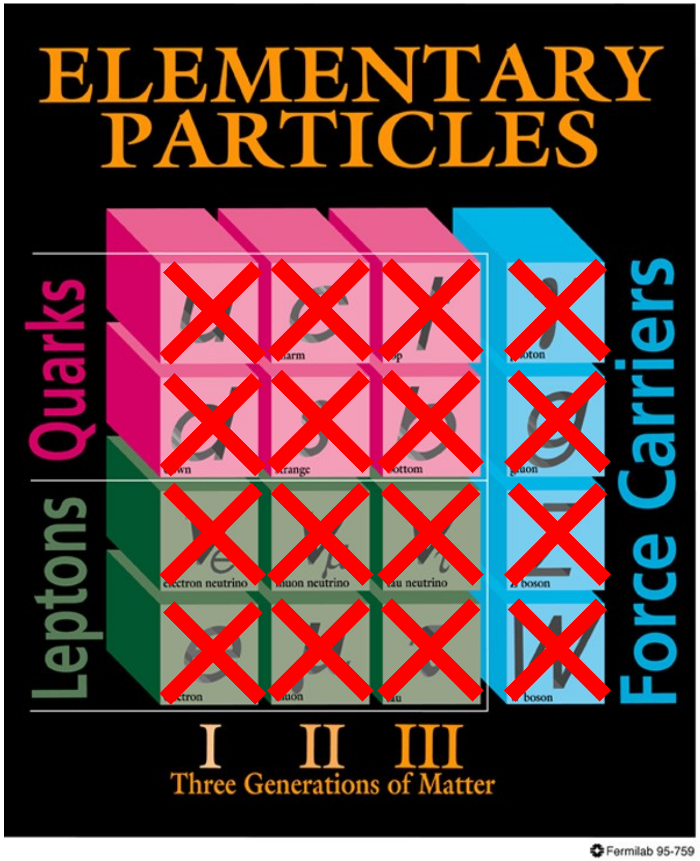


Fermilab 95-759

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot

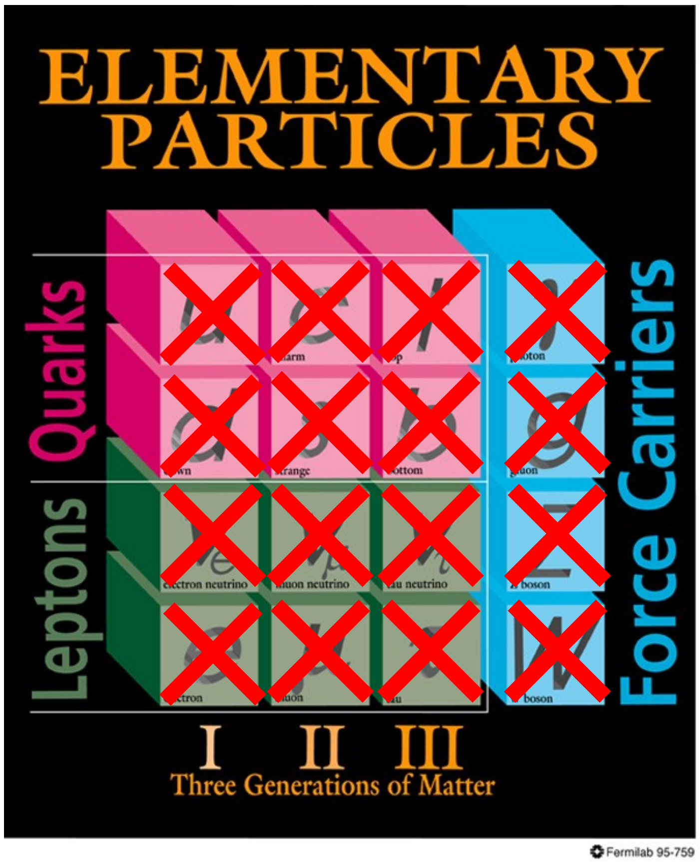
DARK MATTER – A Particle?!



Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

DARK MATTER – A Particle?!



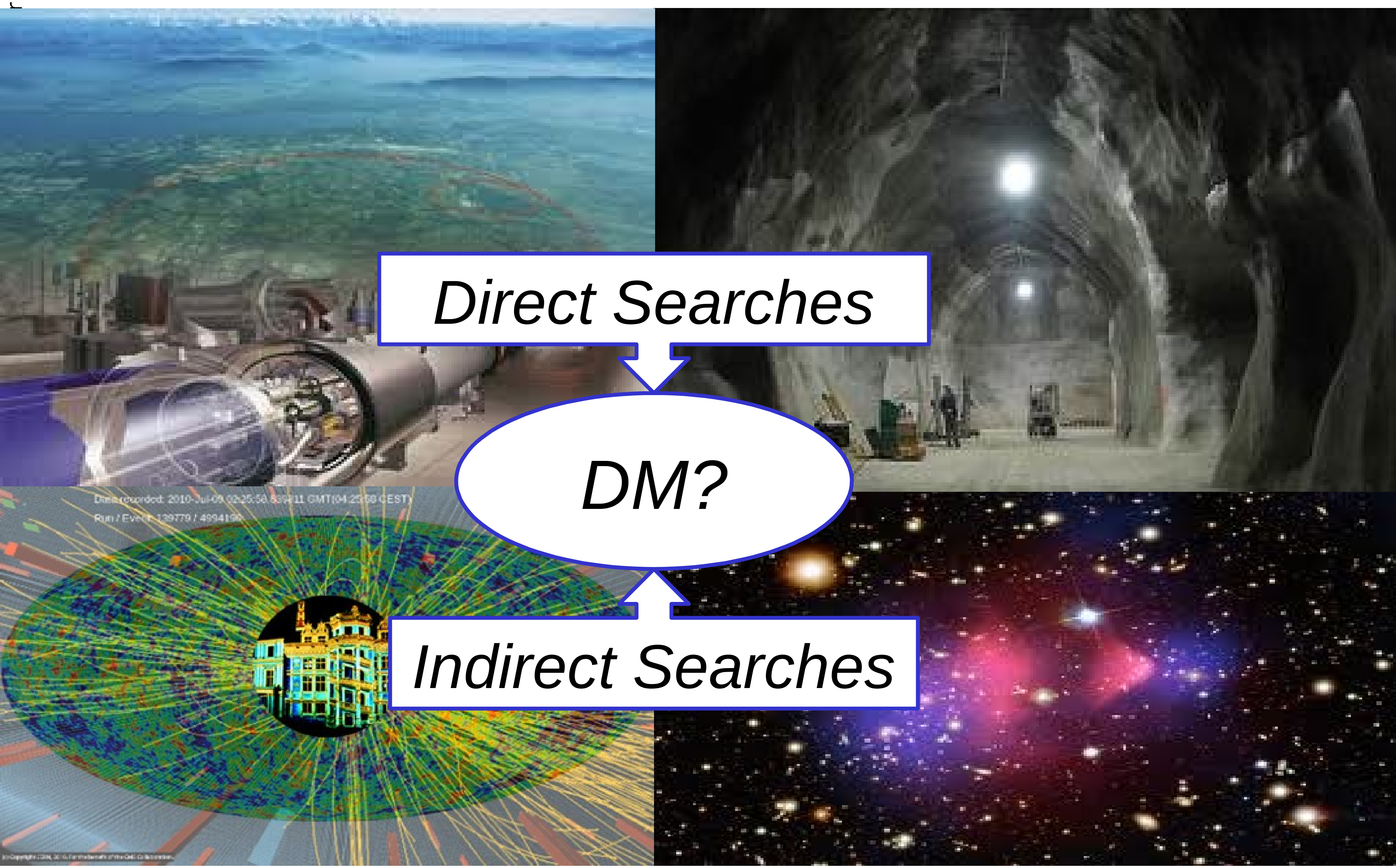
Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

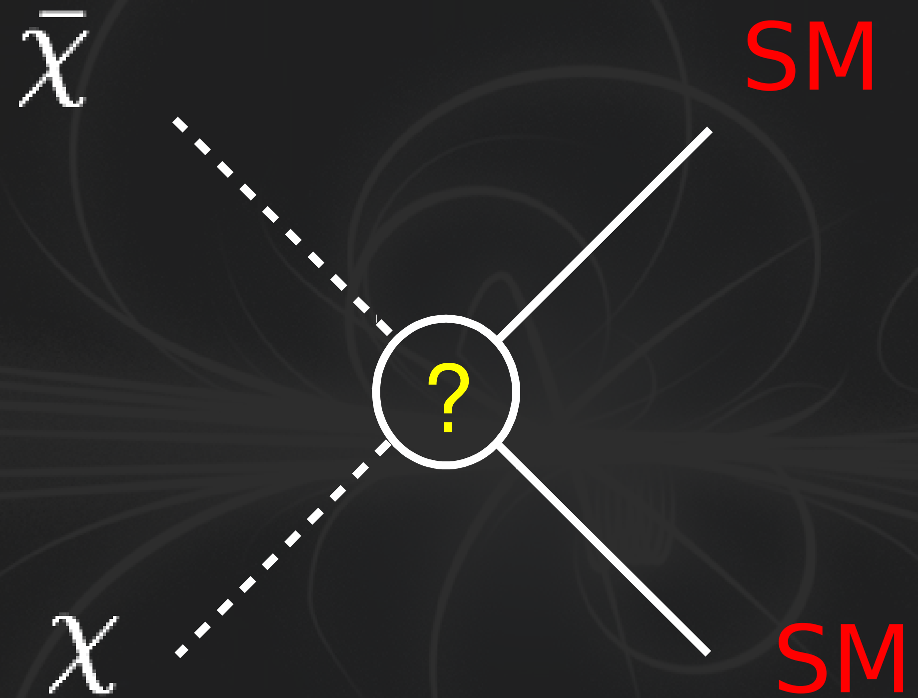
Clear evidence for a new particle(s)!

Imperial College London

Searches for Dark Matter (&SUSY)



How to Search for Dark Matter?

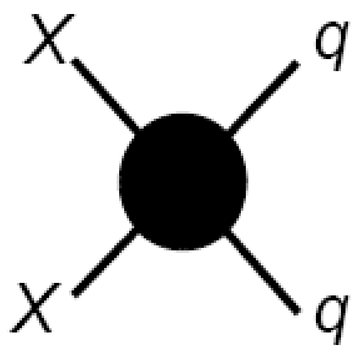


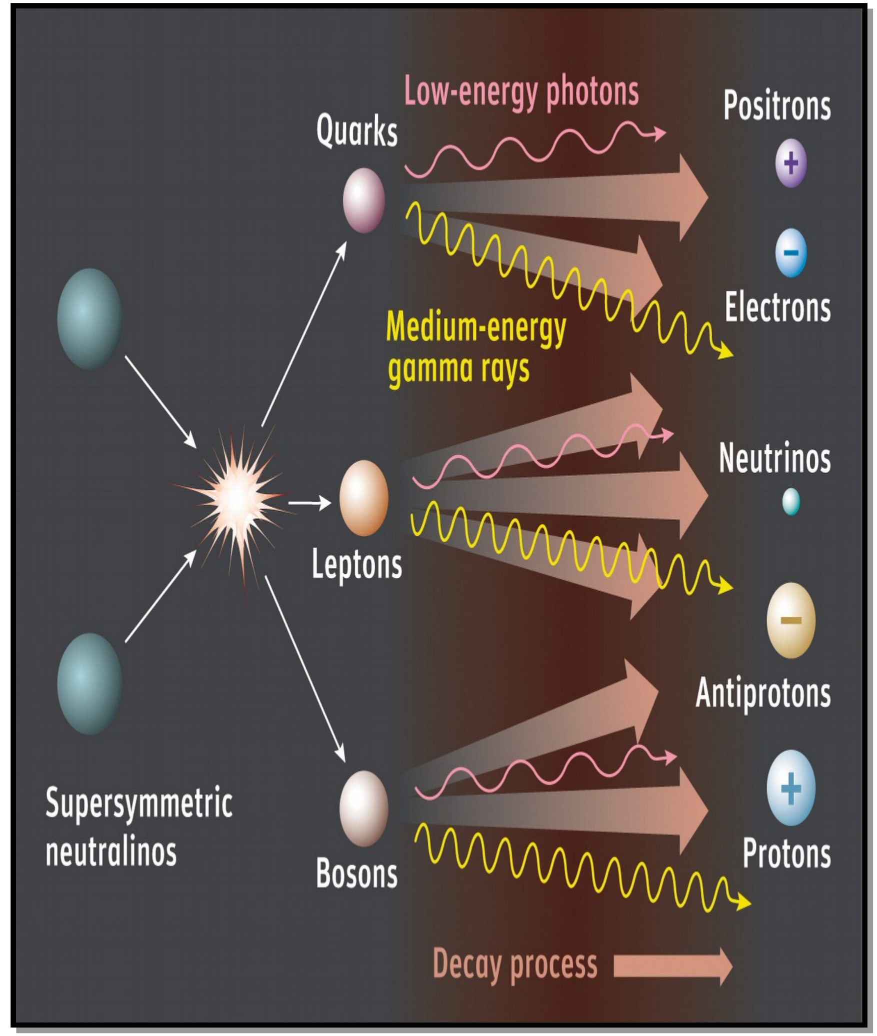
Searching for a particle means to interact with it using known particles in the detector or producing it

How to Search for Dark Matter?

INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons

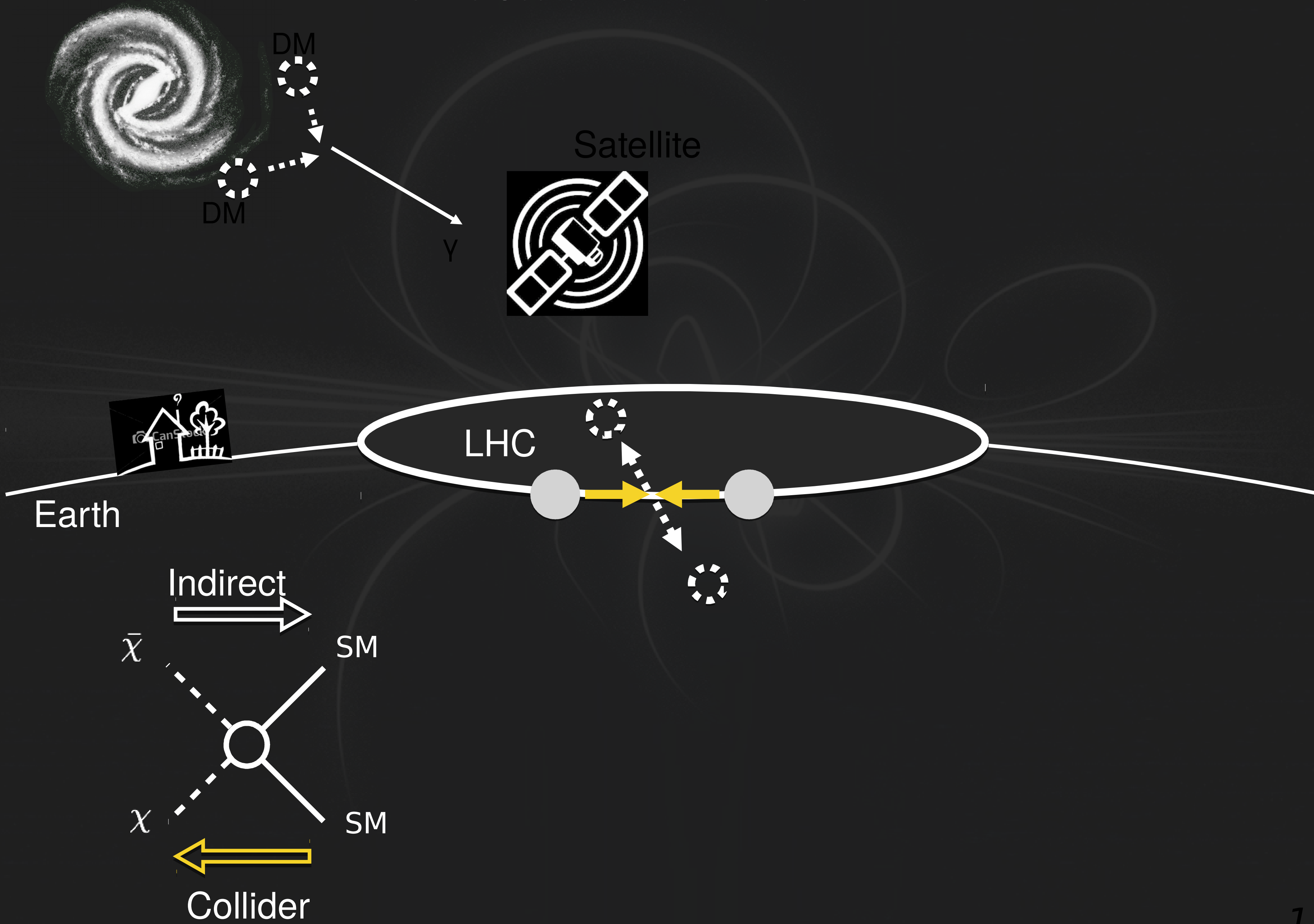




- The relic density provides a target annihilation cross section

$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ cm^3/s$

How to Search for Dark Matter?



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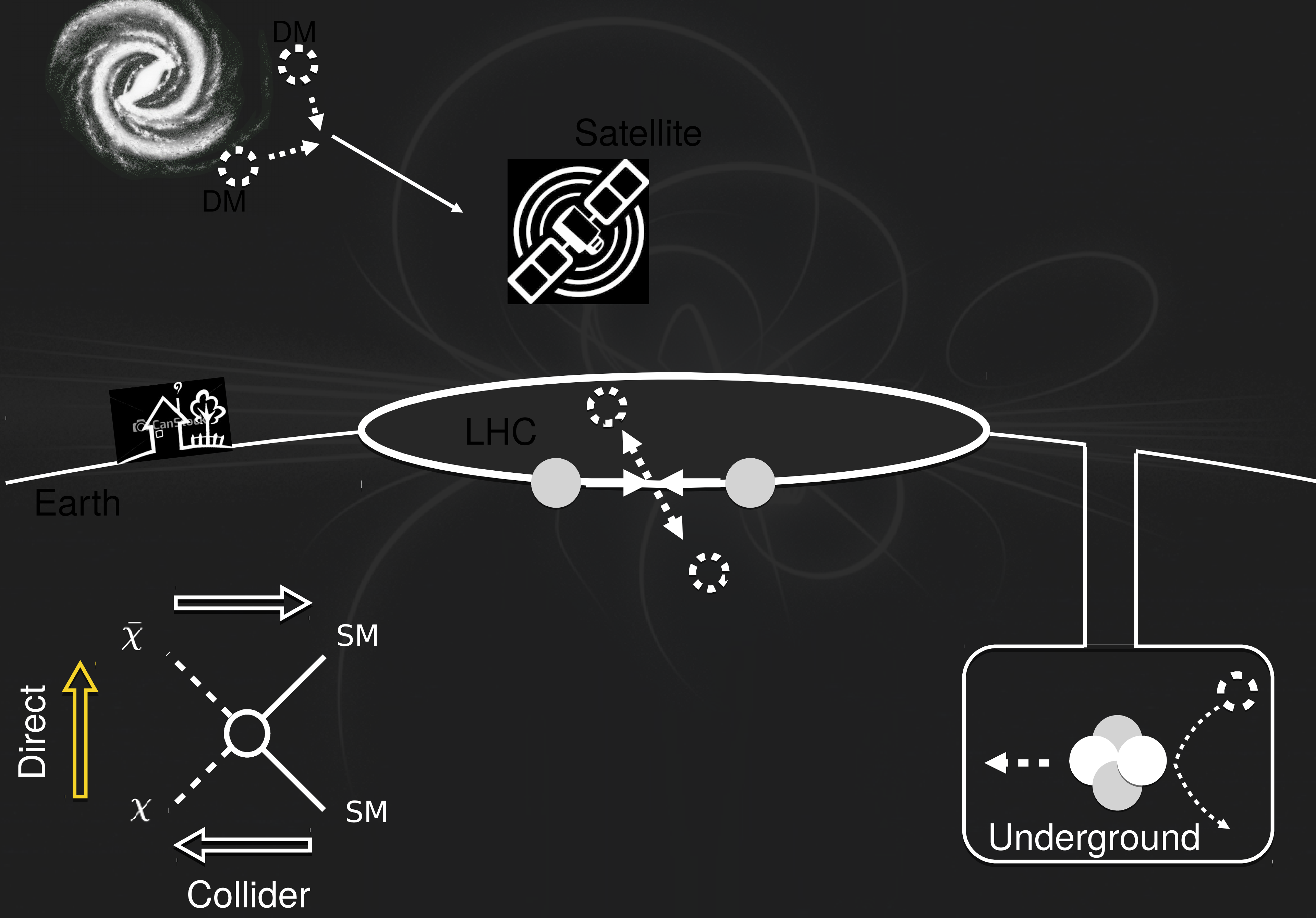


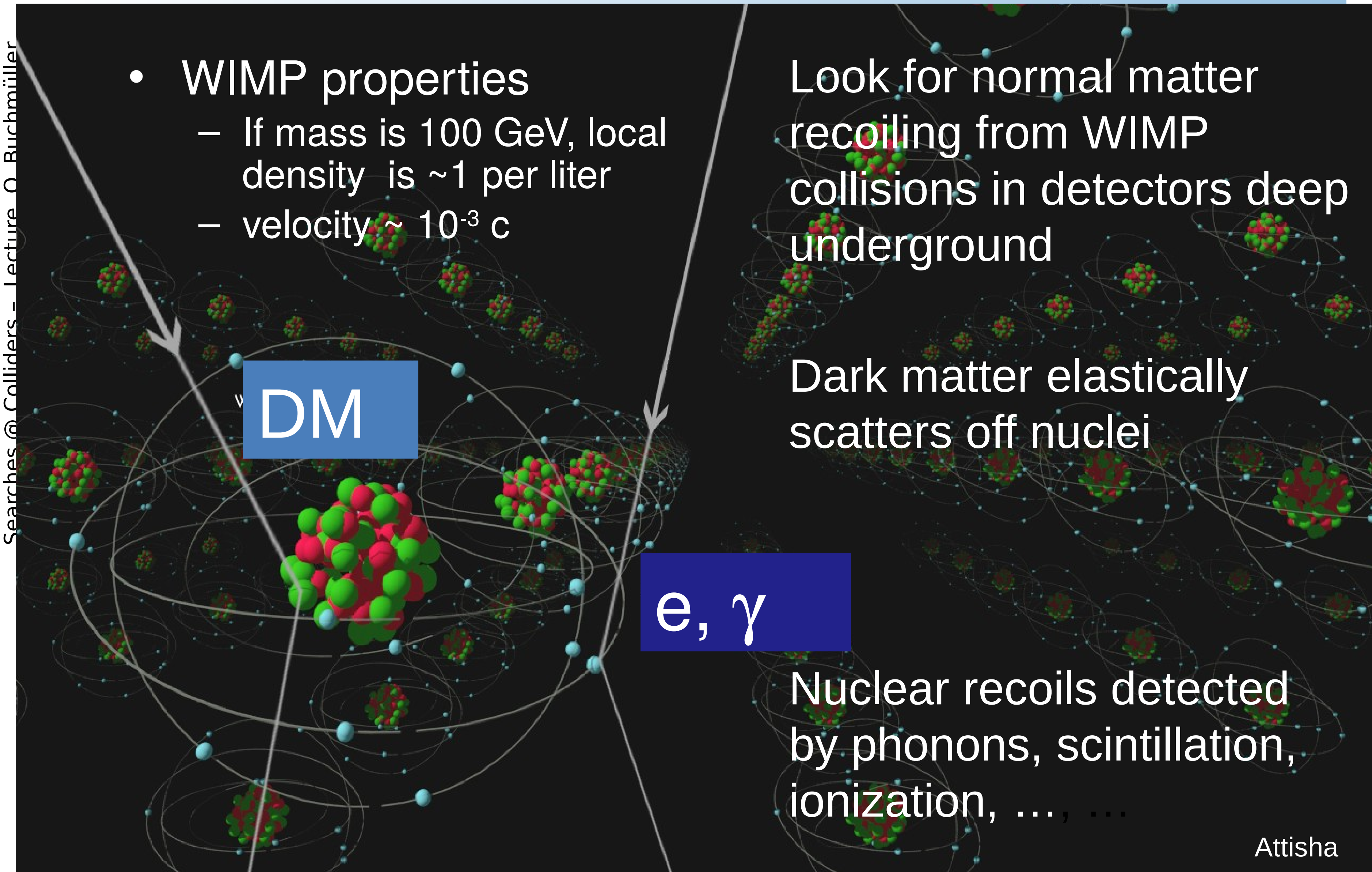
DIRECT DETECTION

- WIMP properties
  - If mass is 100 GeV, local density is ~1 per liter
  - velocity ~ 10^{-3} c

Look for normal matter recoiling from WIMP collisions in detectors deep underground

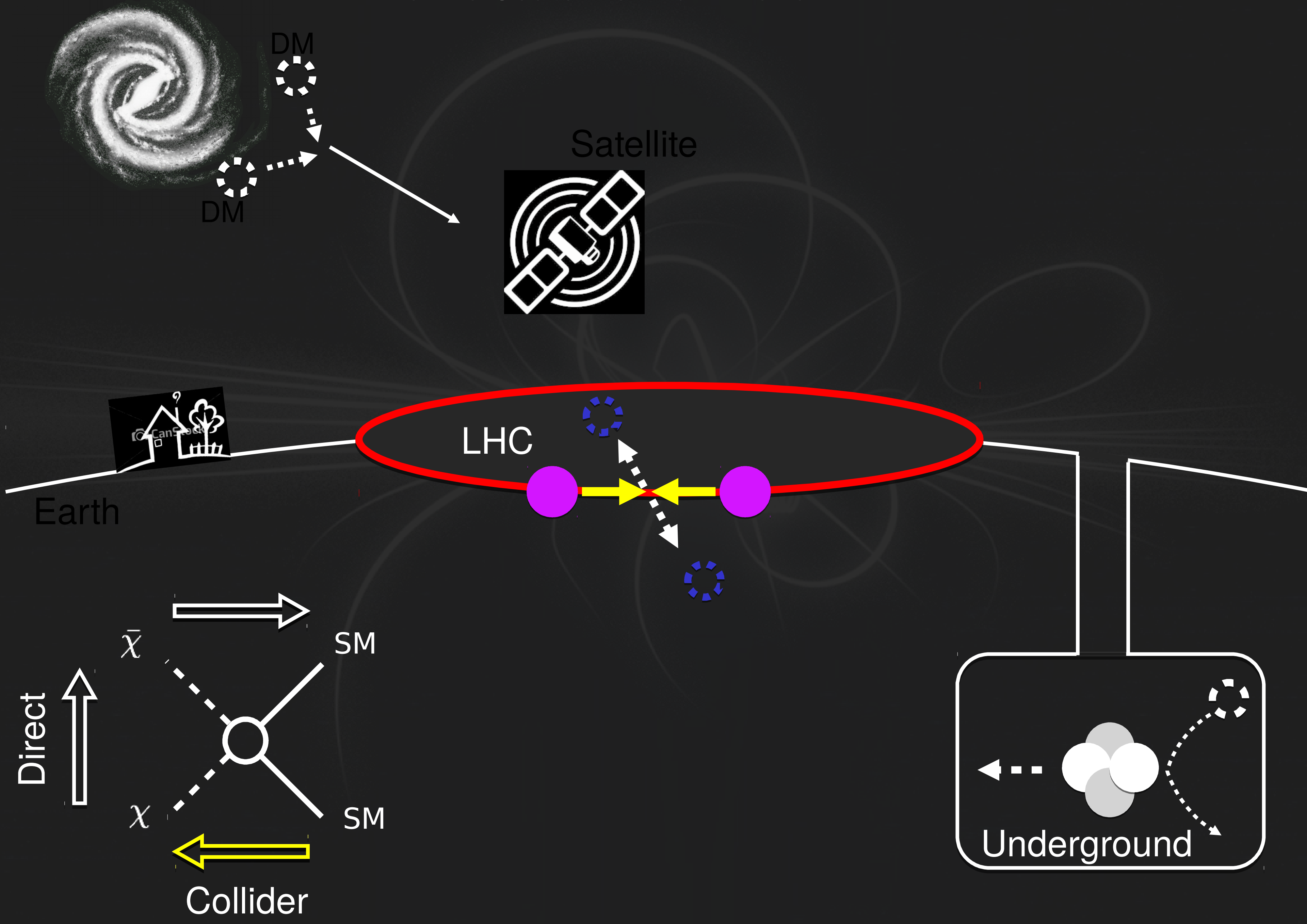
Dark matter elastically scatters off nuclei

Nuclear recoils detected by phonons, scintillation, ionization, …, …



Attisha

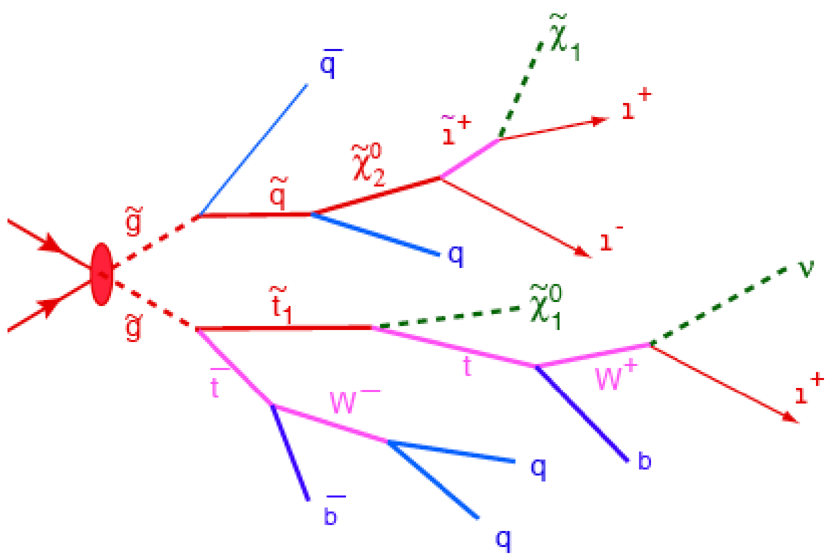
How to Search for Dark Matter?



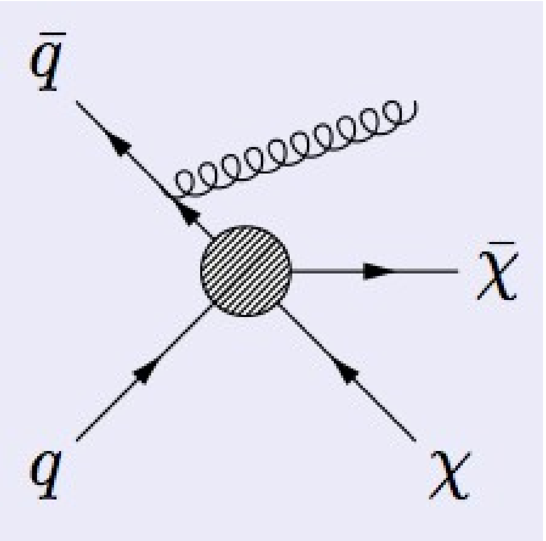
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



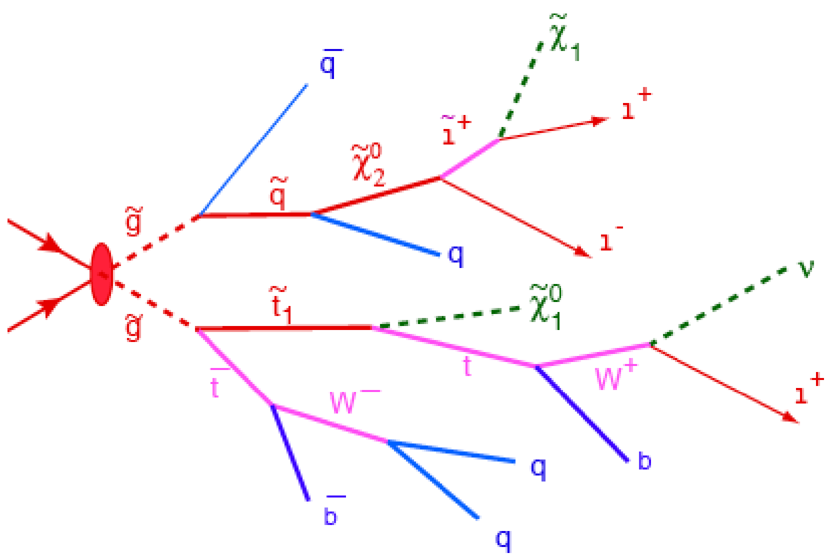
Example:
Effective Field Theory
Simplified models



Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY



Example:
Effective Field Theory
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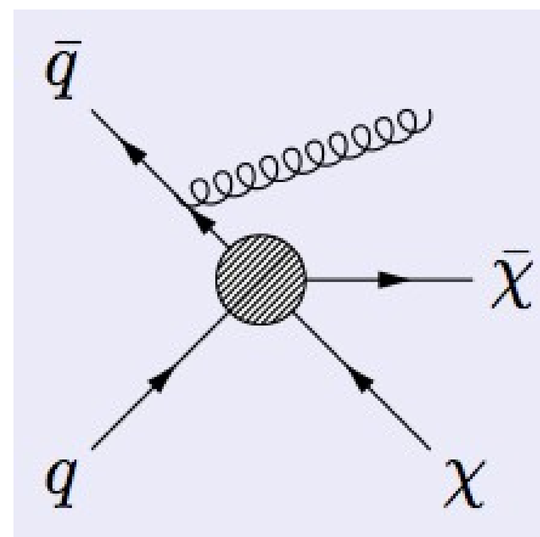
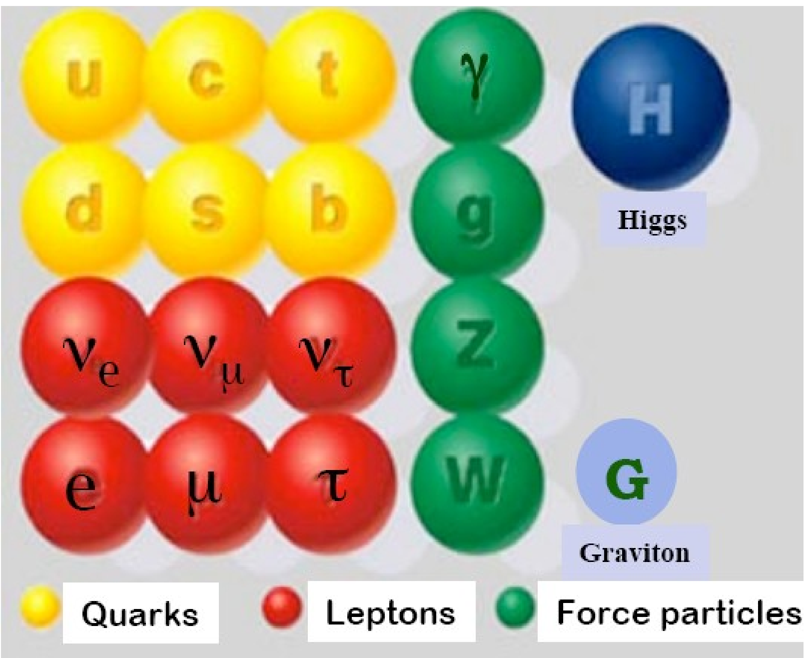


Supersymmetry

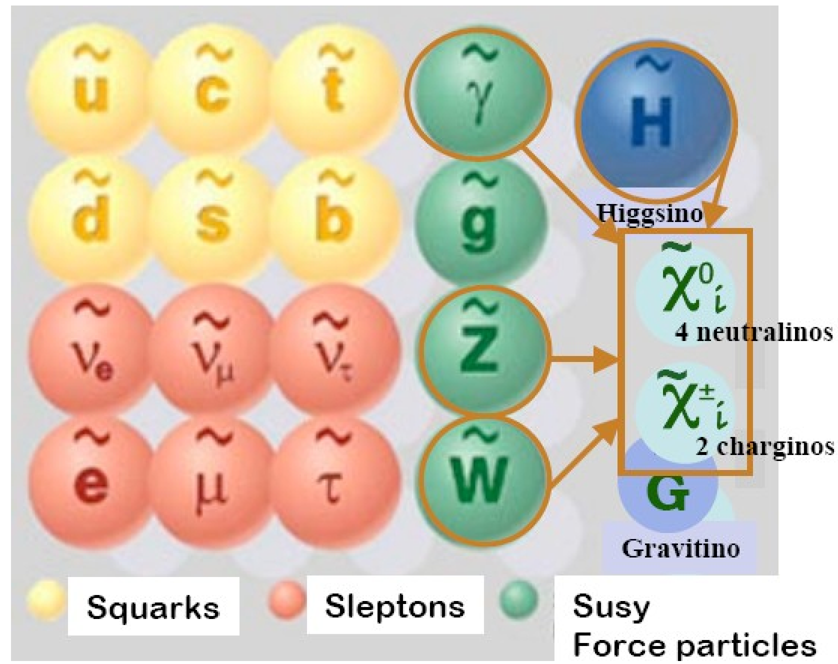
Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

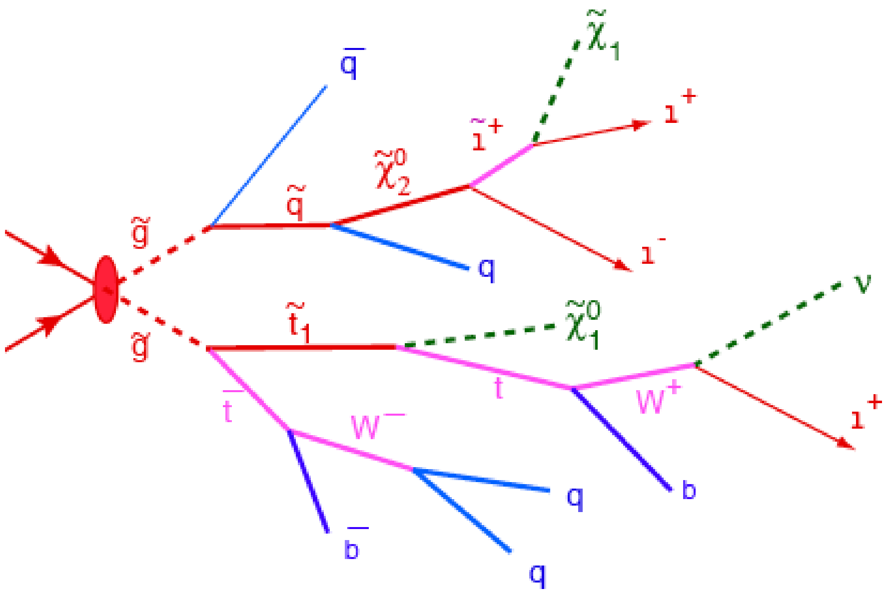
R-parity conservation:

- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

What do we call a "SUSY search"?

The definition is purely derived from the experimental signature. Therefore, a "SUSY search signature" is characterized by
Lots of missing energy, many jets, and possibly leptons in the final state

Slides from 2007



Missing Energy:
- *from LSP*

Multi-Jet:
- *from cascade decay (gaugino)*

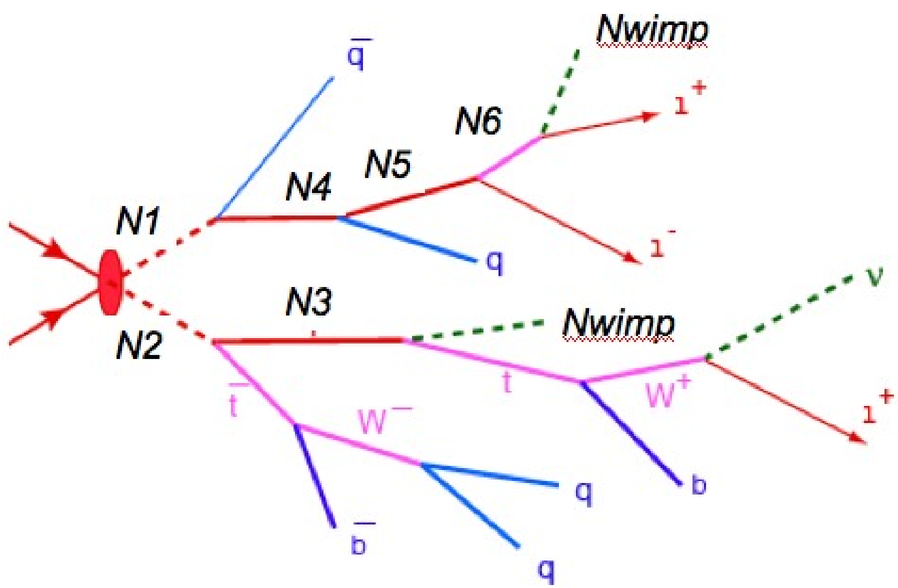
Multi-Leptons:
- *from decay of charginos/neutralios*

RP-Conserving SUSY is a very prominent example predicting this famous signature but …

What is its experimental signature?

… by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature

Slides from 2007



Missing Energy:

- *Nwimp - end of the cascade*

Multi-Jet:

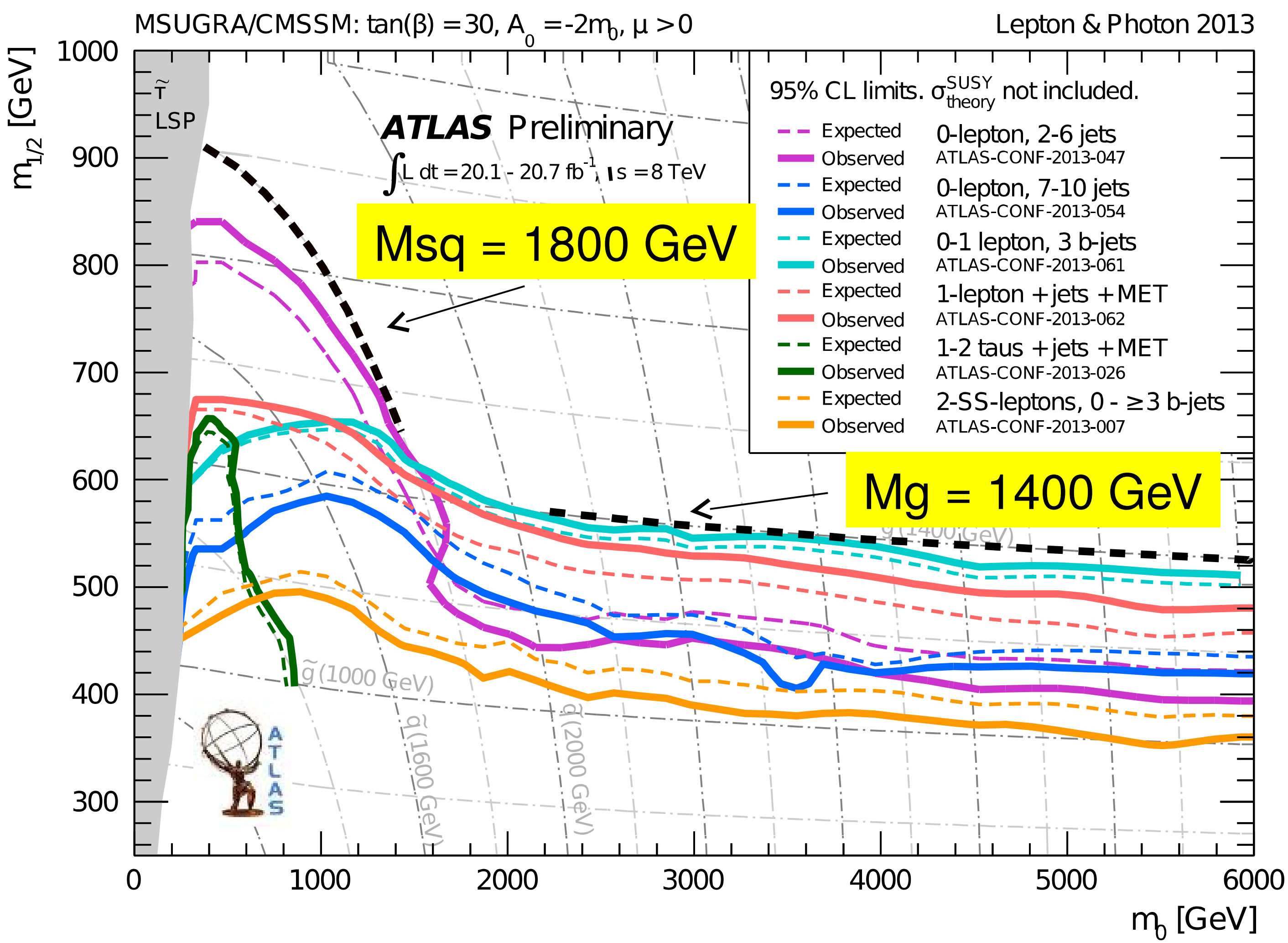
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

Multi-Leptons:

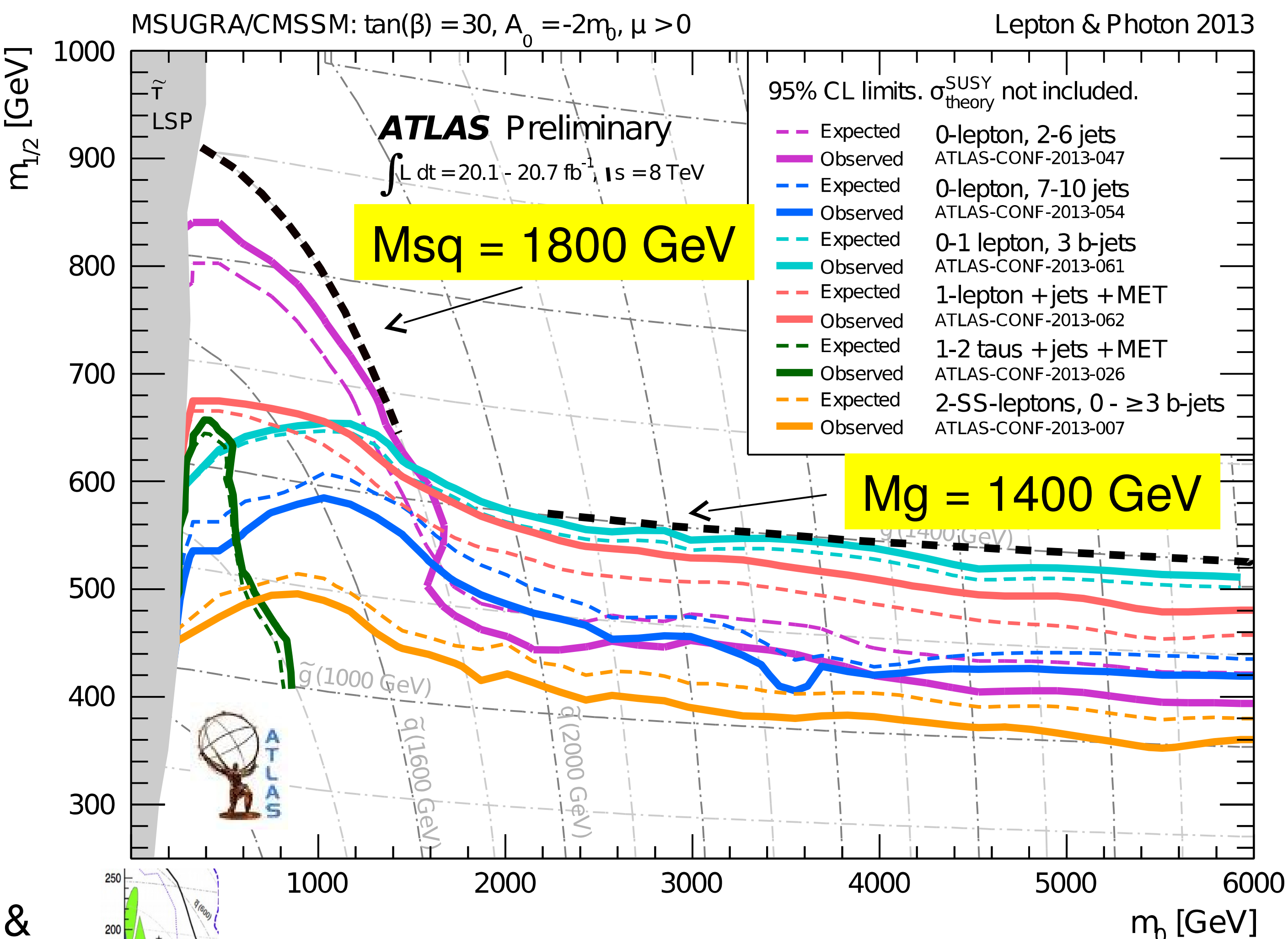
- *from decay of the N's*

Model examples are Extra dimensions, Little Higgs, Technicolour, etc but a more generic definition for this signature is as follows.

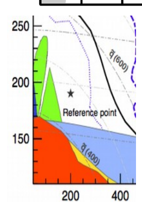
Inclusive SUSY Searches in 2013



Inclusive SUSY Searches in 2013



LEP & Tevatron



The LHC has pushed the mass scale in constraint SUSY models to a new level!

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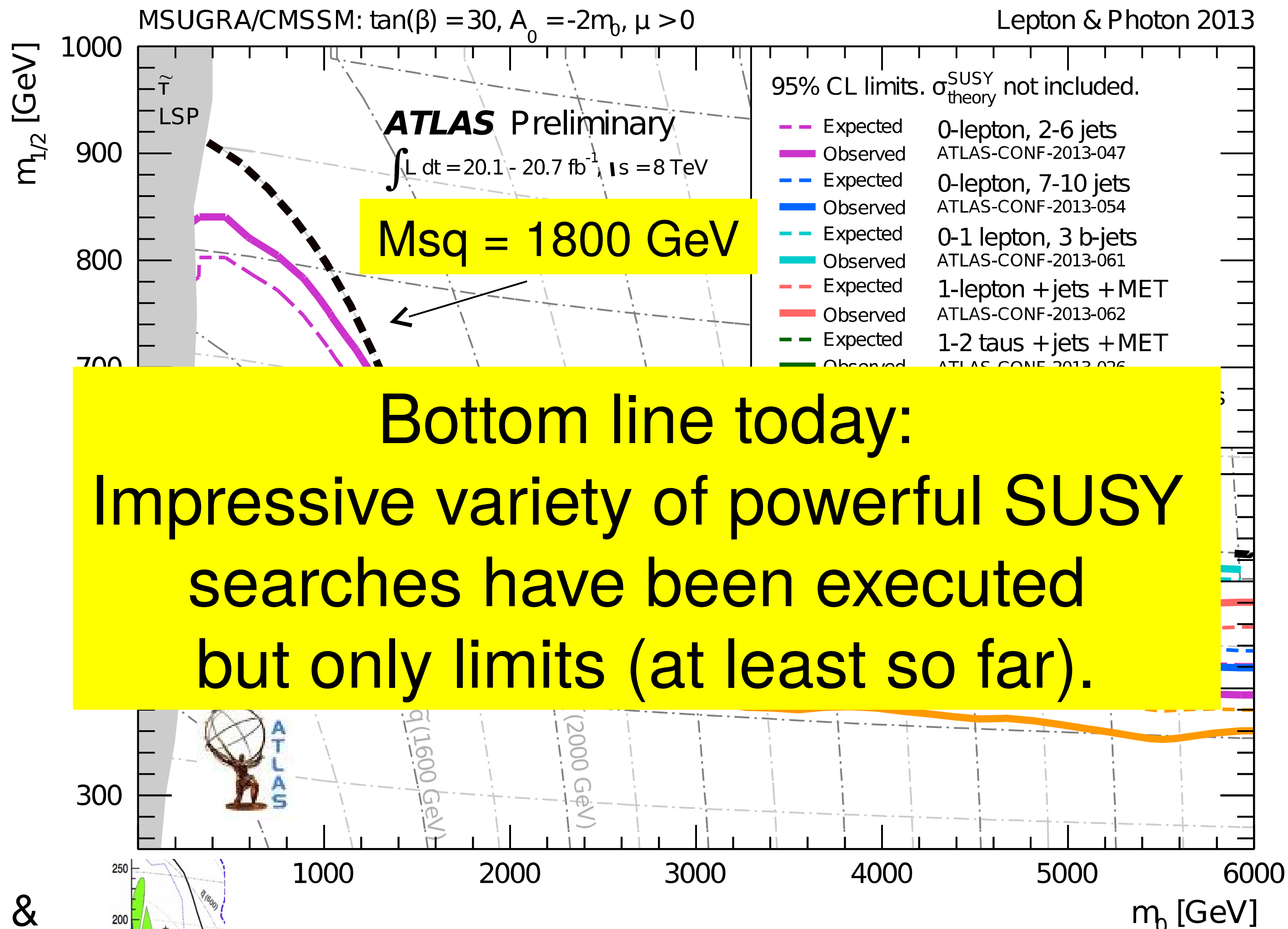
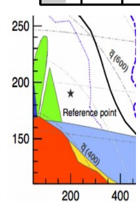


Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

LEP & Tevatron



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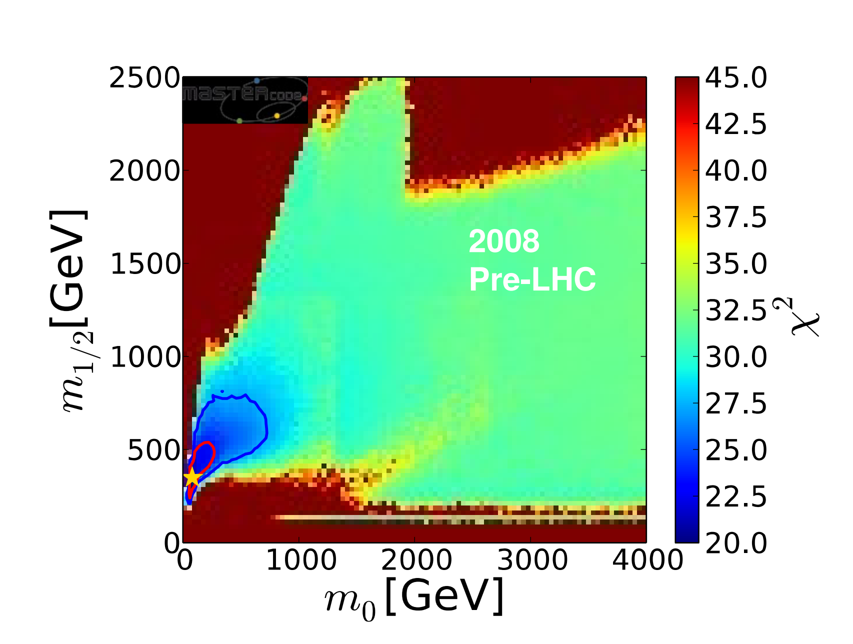
CMSSM: Evolution with time



X^2 increase from bluish to reddish

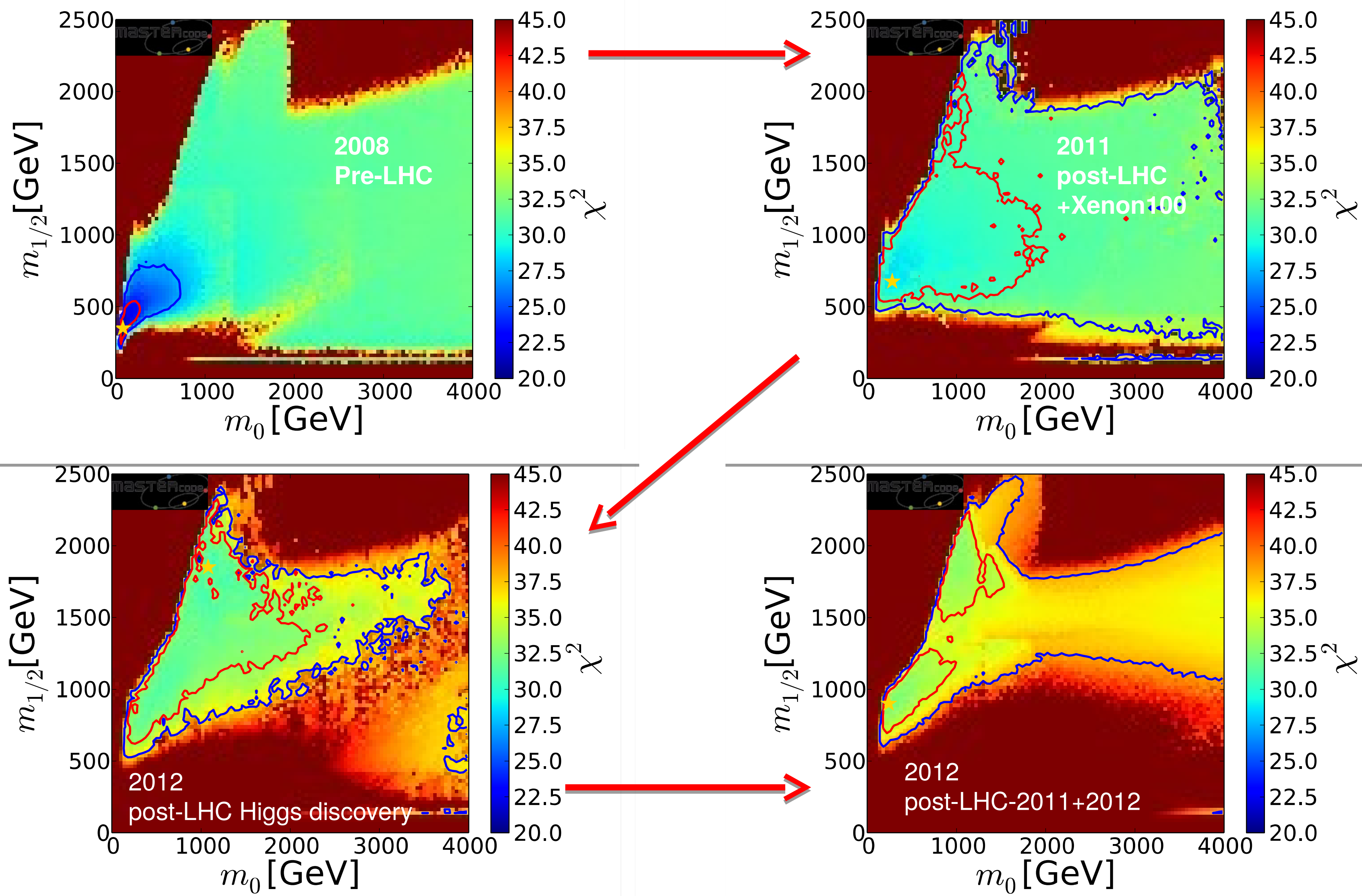
Source: http://mastercode.web.cern.ch/mastercode/

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
σ^0_{had} [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a_\mu^{EXP} - a_\mu^{SM}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4 [\pm 1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm 0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6 [\pm 0.01_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ_p^{SI}	[25]	$(m_{\chi^0_1}, \sigma_p^{SI})$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

Other "fitter" groups find very similar results: e.g.
SuperBayeS: **arXiv:1212.2636**
Fittino group: **arXiv:1204.4199**

CMSSM: Evolution with time



MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

$M_1,$

$M_2,$

$M_3,$

$m_{\tilde{q}12},$

$m_{\tilde{q}3},$

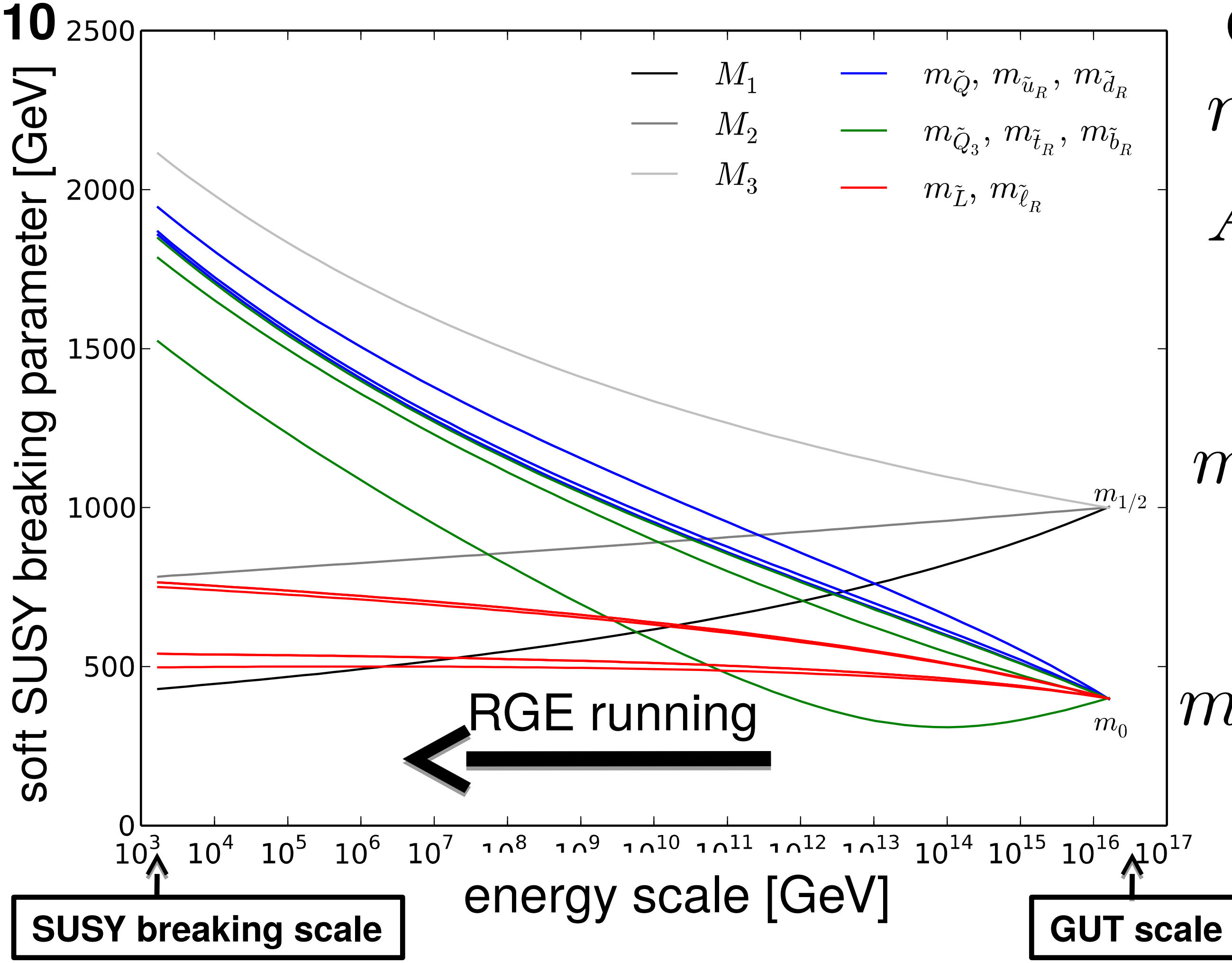
$m_{\tilde{\ell}},$

$A,$

$M_A,$

$\tan\beta$

μ



CMSSM

$m_0, \; m_{1/2},$

$A_0, \; \tan\beta$

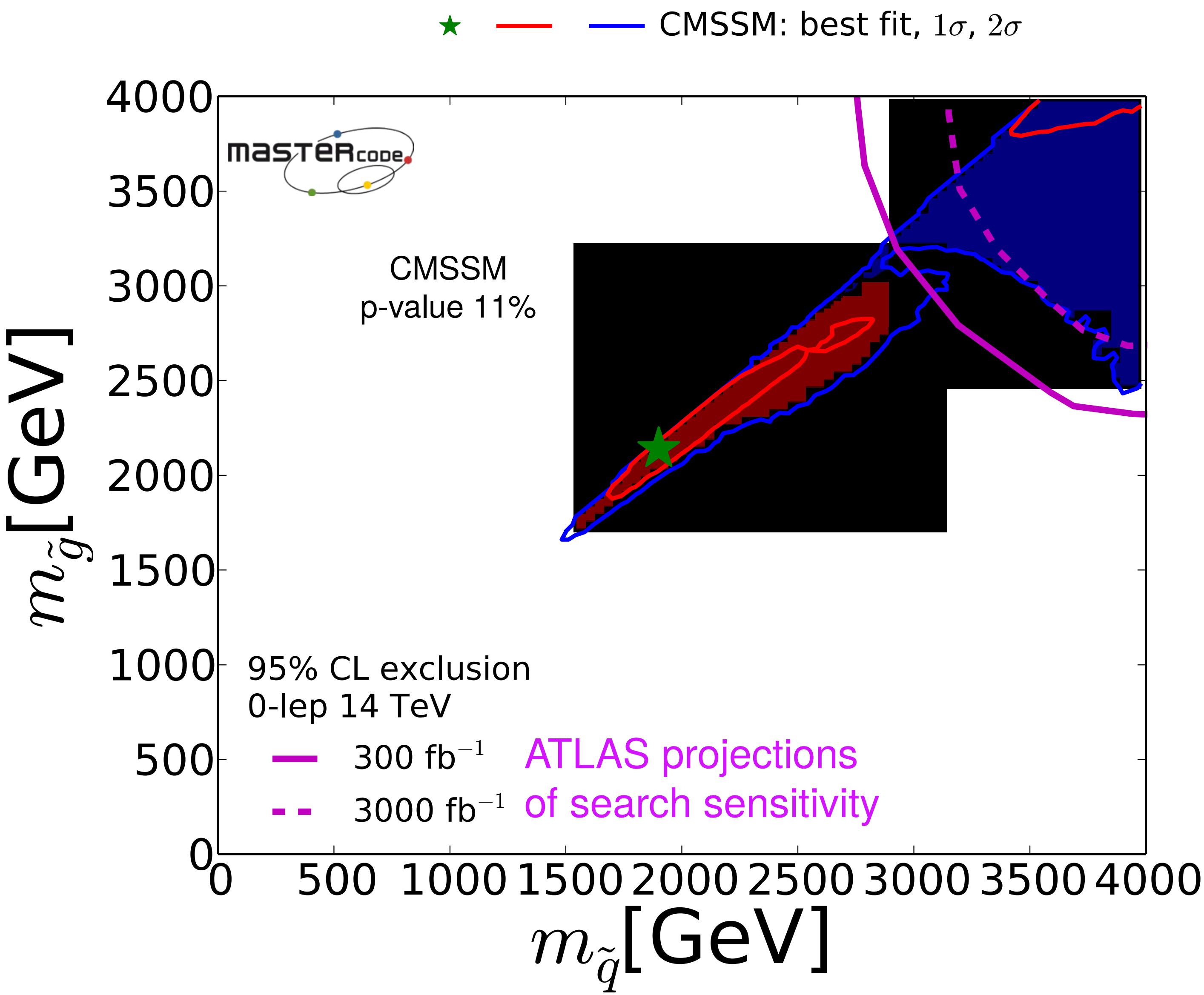
NUHM1

$m^2_{H_u} = m^2_{H_d}$

NUHM2

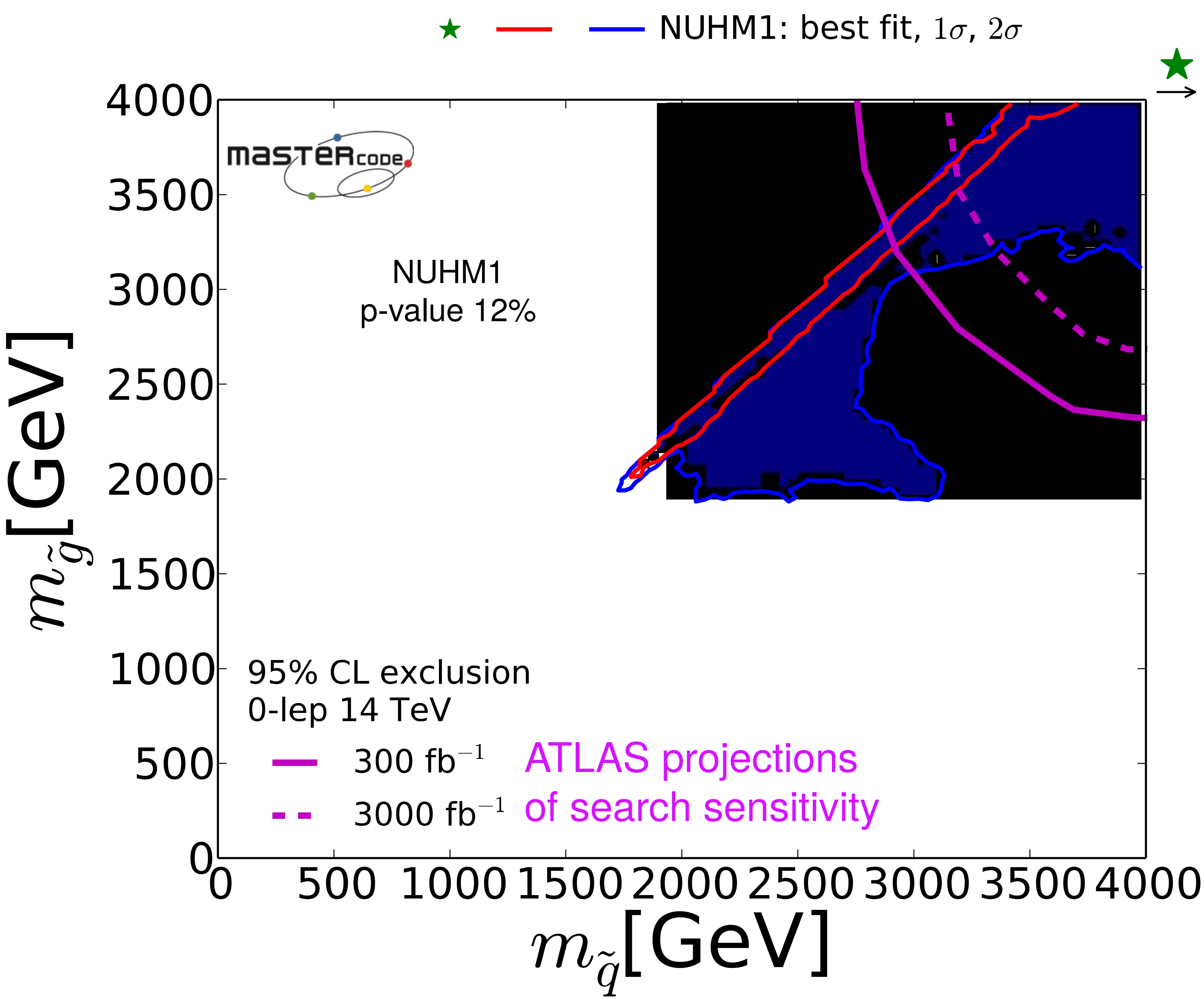
$m^2_{H_u} \neq m^2_{H_d}$

CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



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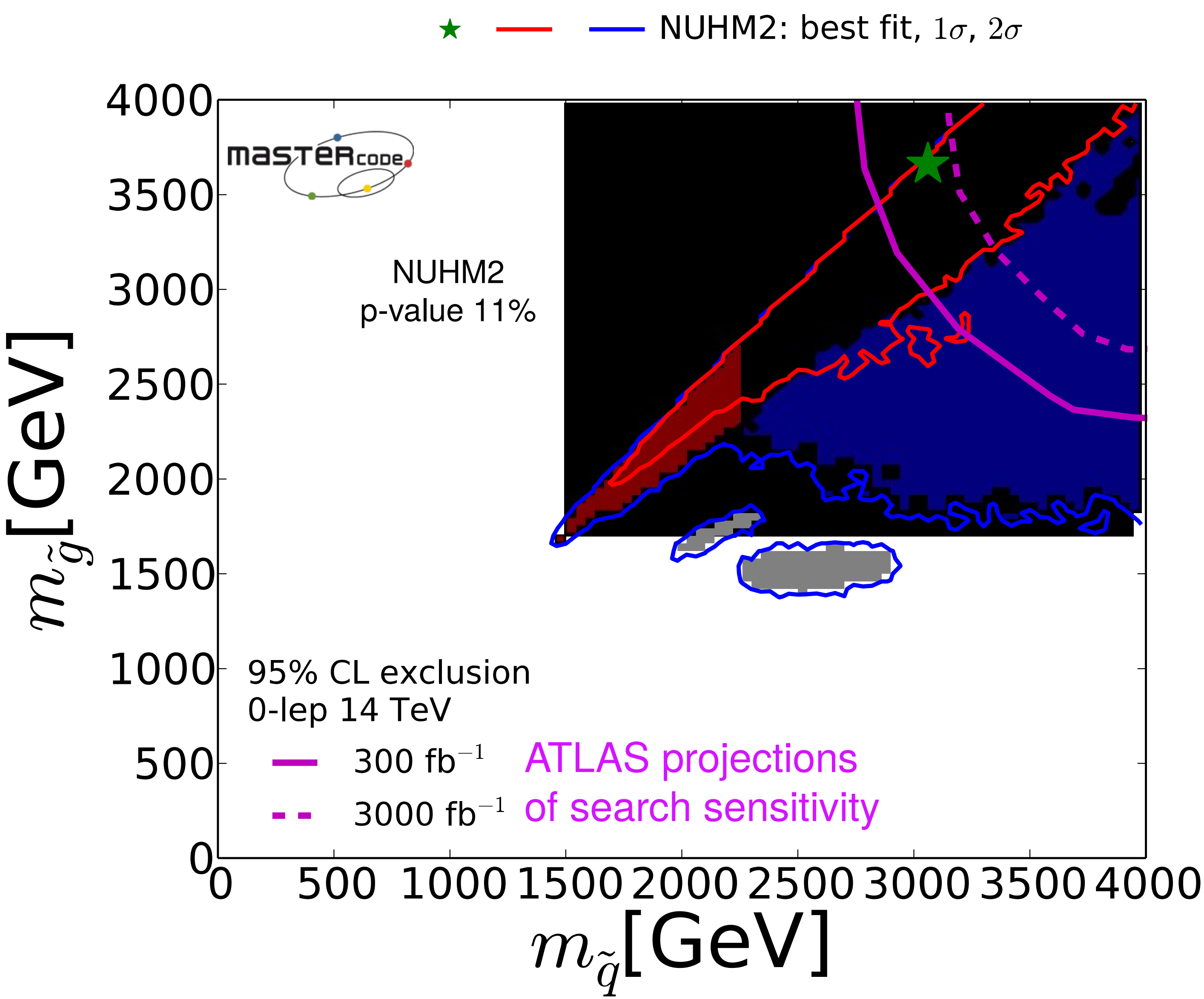
CMSSM Today: Mq-Mg Search plane



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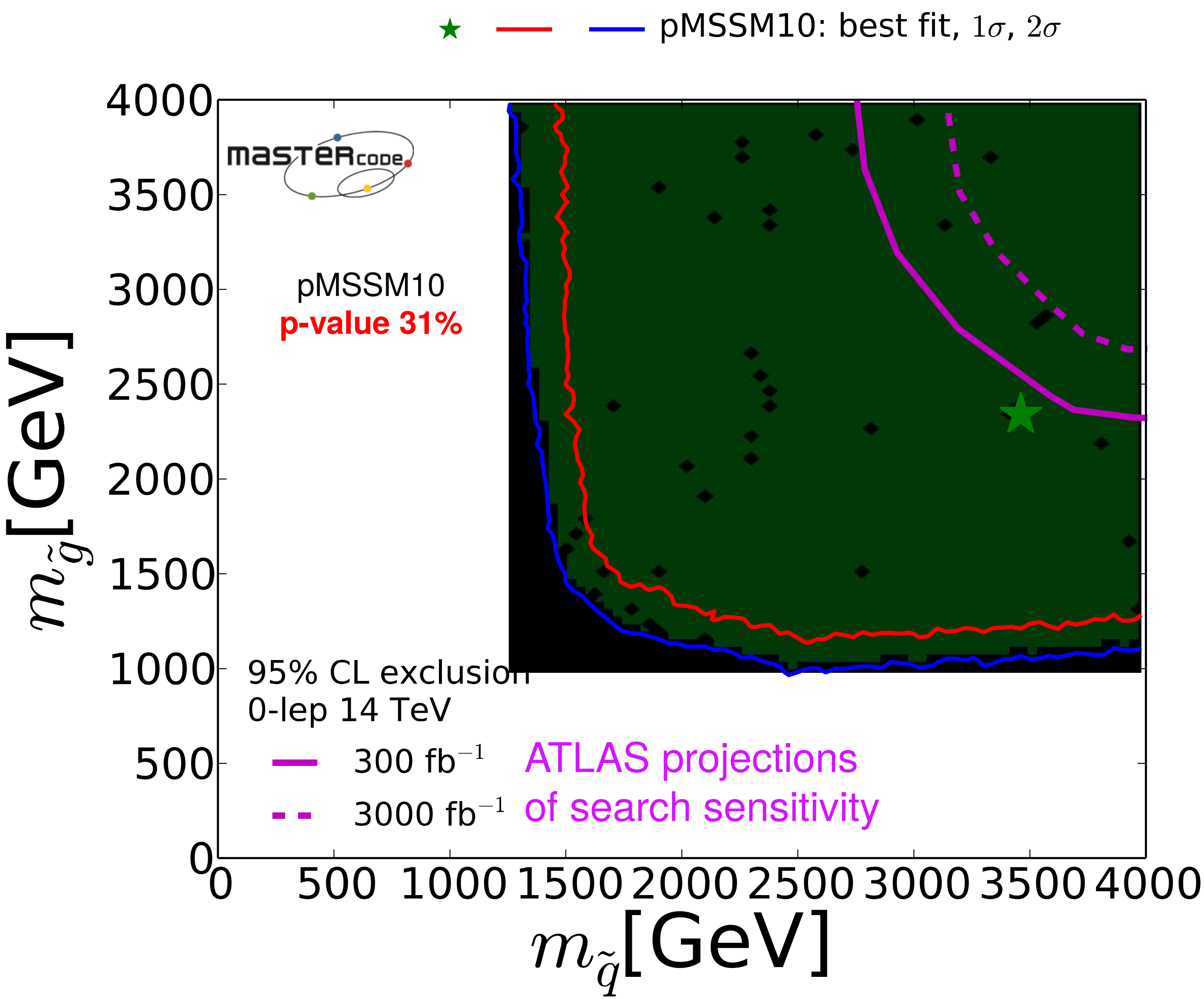
CMSSM Today: Mq-Mg Search plane



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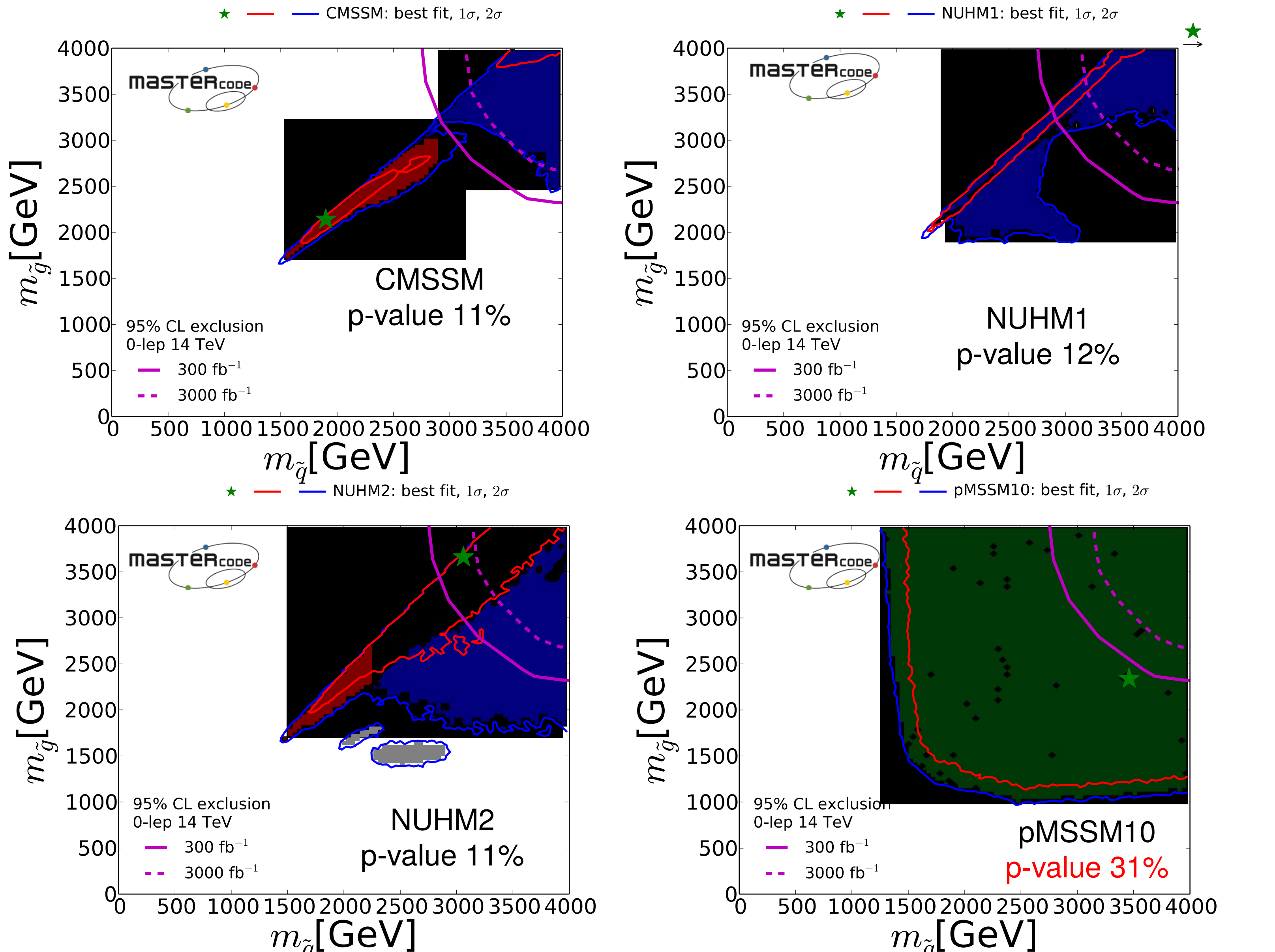
Models in Comparison in "Mq-Mg Search plane"



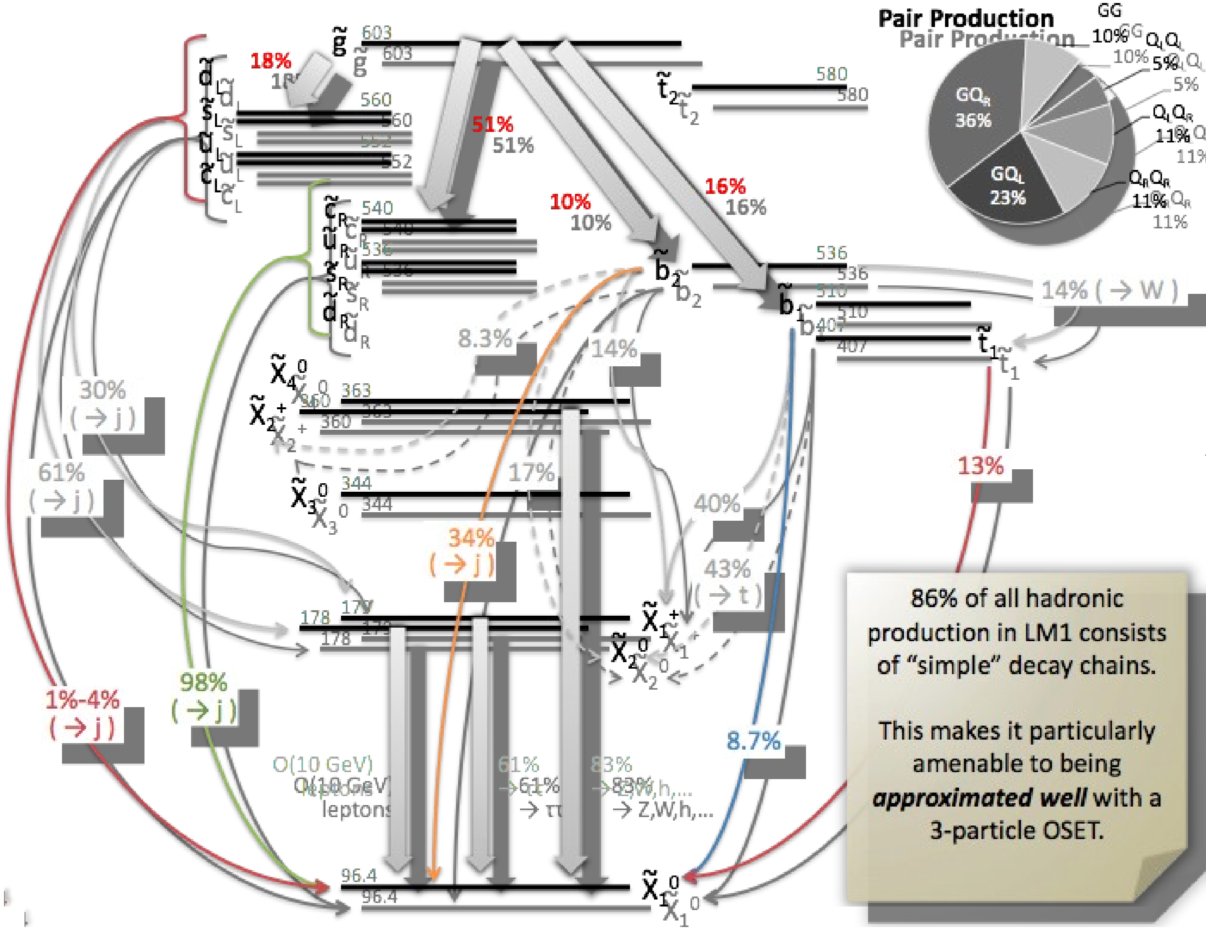
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

SUSY Status – post 7 TeV LHC data

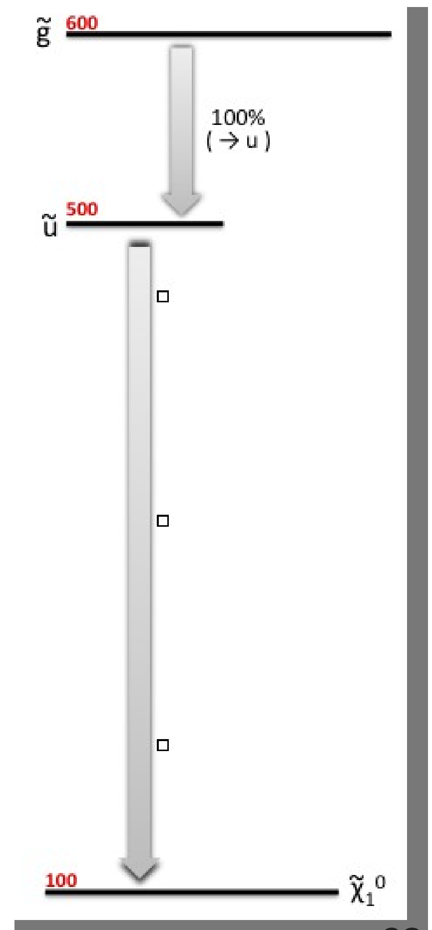
- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!
- Experiments need to define new benchmarks and to present the interpretation of their searches.
- A bottom-up approach, using so-called simplified models, was adopted but ATLAS and CMS as the primary vehicle to present SUSY searches!

Interpretation in Simplified Models

CMSSM



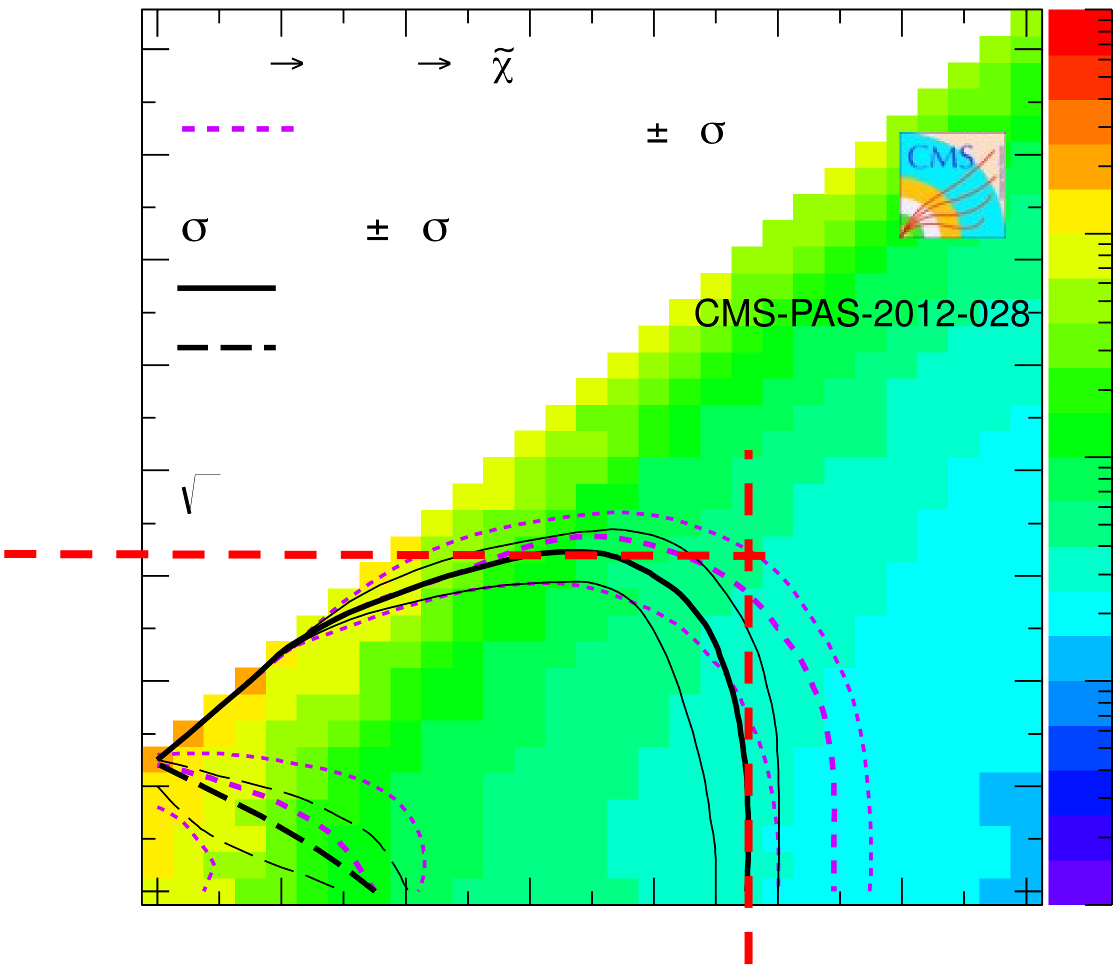
What the individual searches are sensitive to is much more simple…

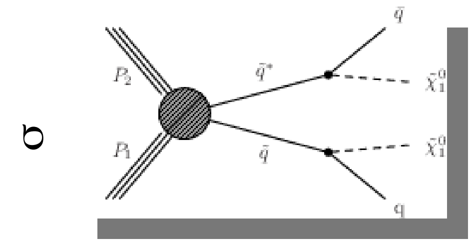


Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

SMS: a few interesting features

$m_{LSP}^{max} \approx$ 0.3 TeV : LSP mass above which there is NO limit anymore





$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$

$m_G^{max} \approx$ 0.8 TeV : Best limit in plane

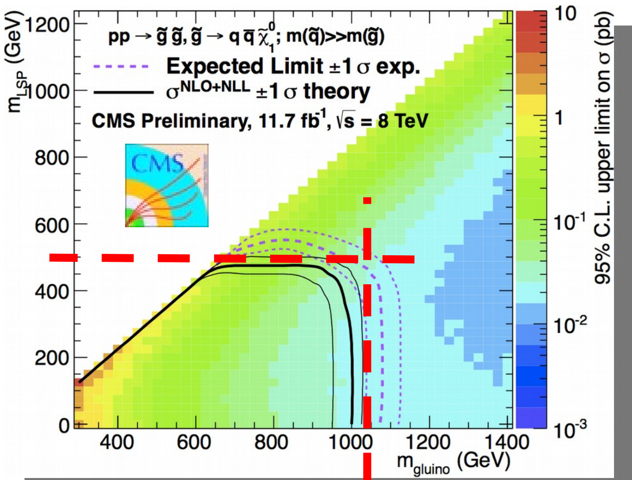
Assumes 100% BR for decay chain considered.

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
	all $m_{\tilde{g}}$	1300	-
Simplified model $\tilde{g}\tilde{g}$	$m_{\tilde{\chi}_1^0} = 0$	-	900
	$m_{\tilde{\chi}_1^0} > 300$	-	no limit
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900



This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

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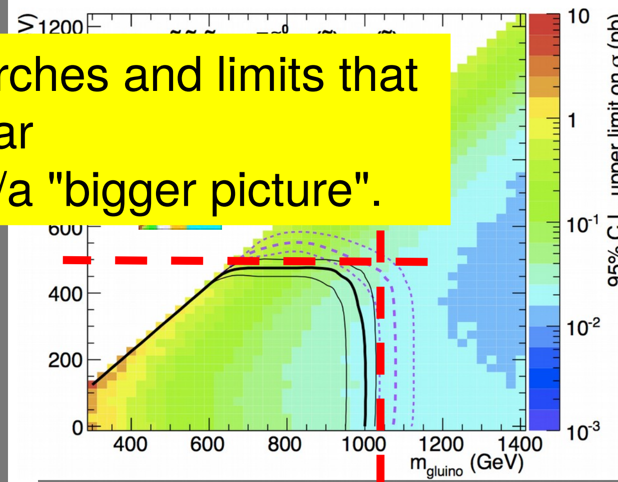
	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
CMSSM	all $m_{\tilde{q}}$ [illegible]		800
Simpli[illegible]	[illegible]	[illegible]	[illegible]
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900

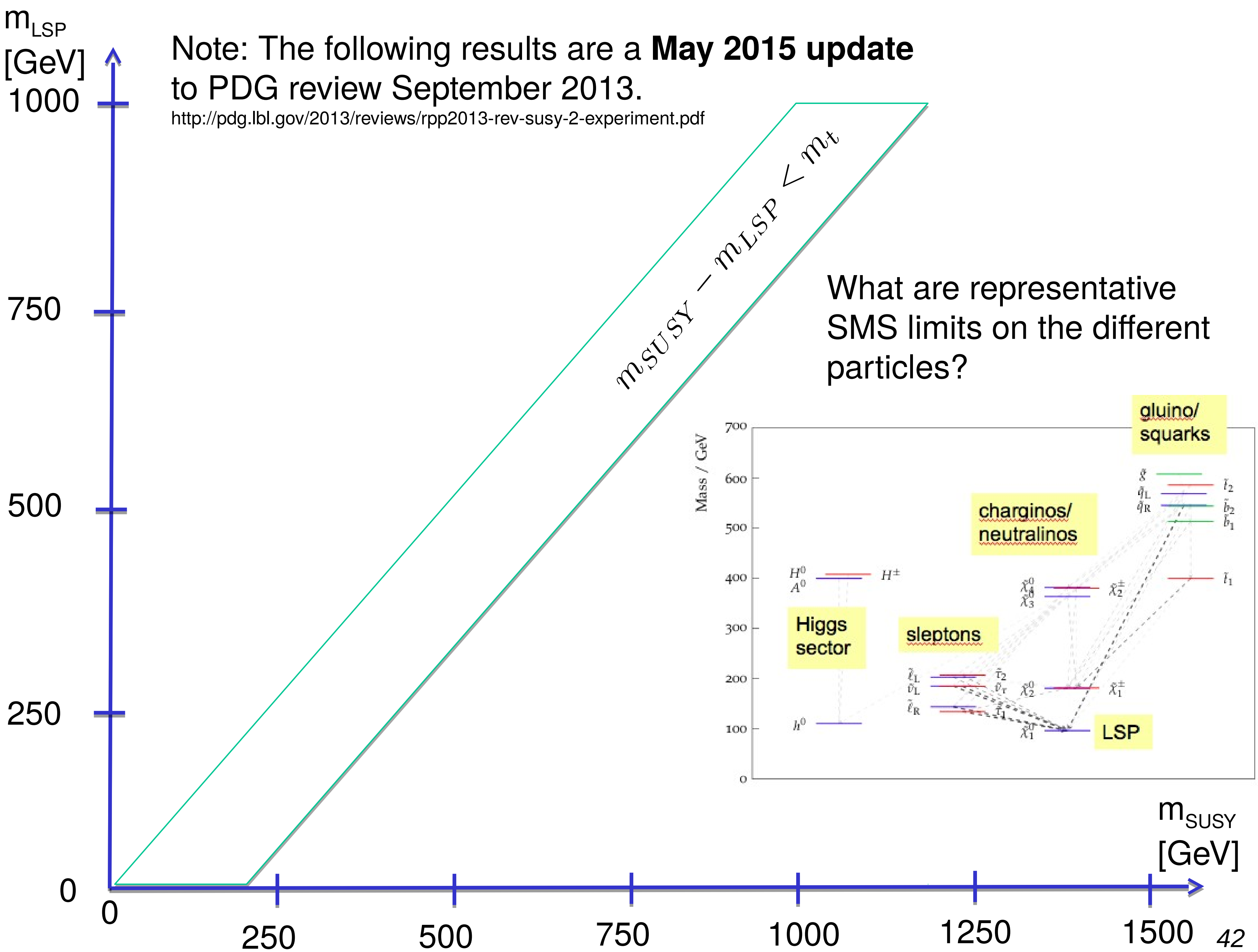
It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".



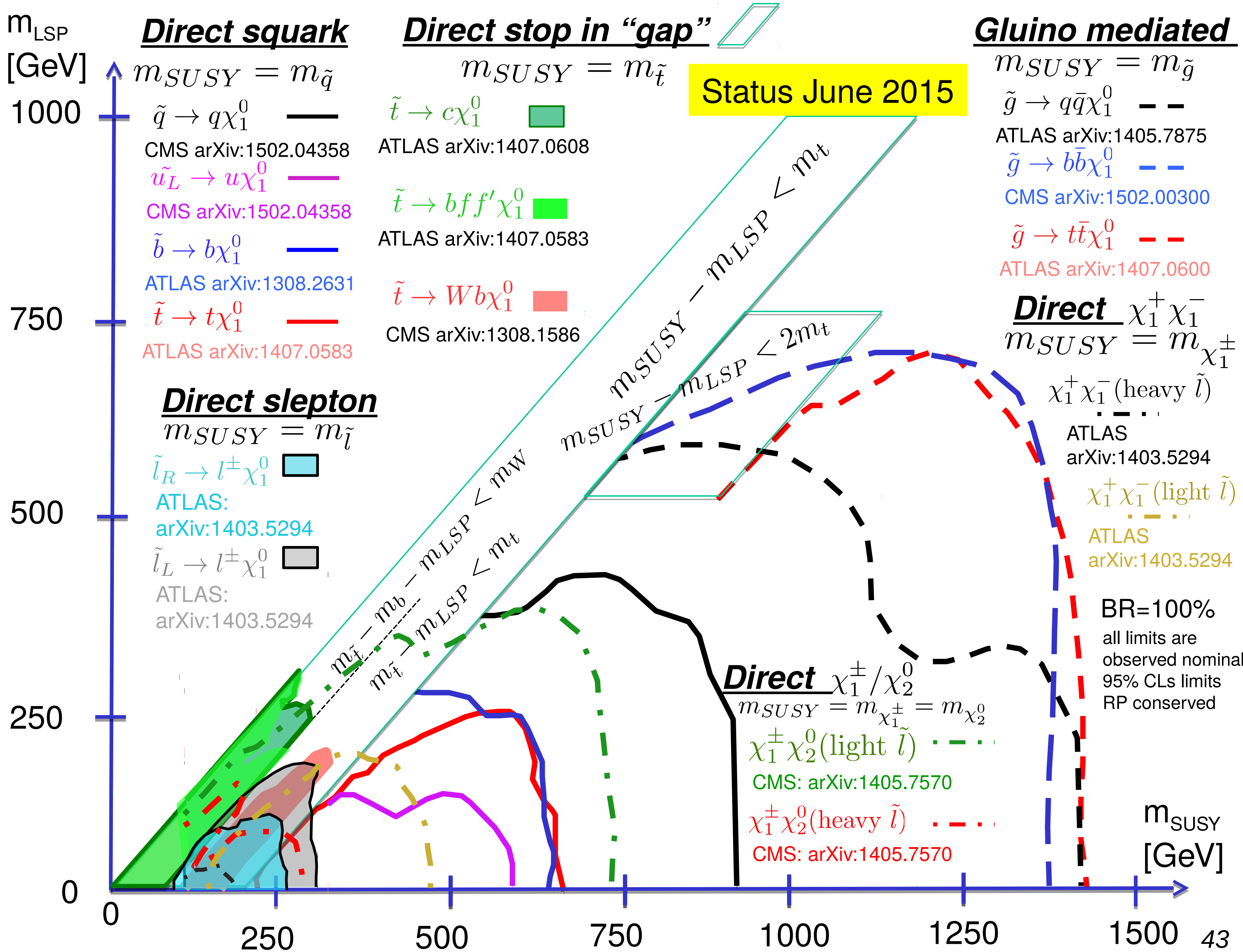
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

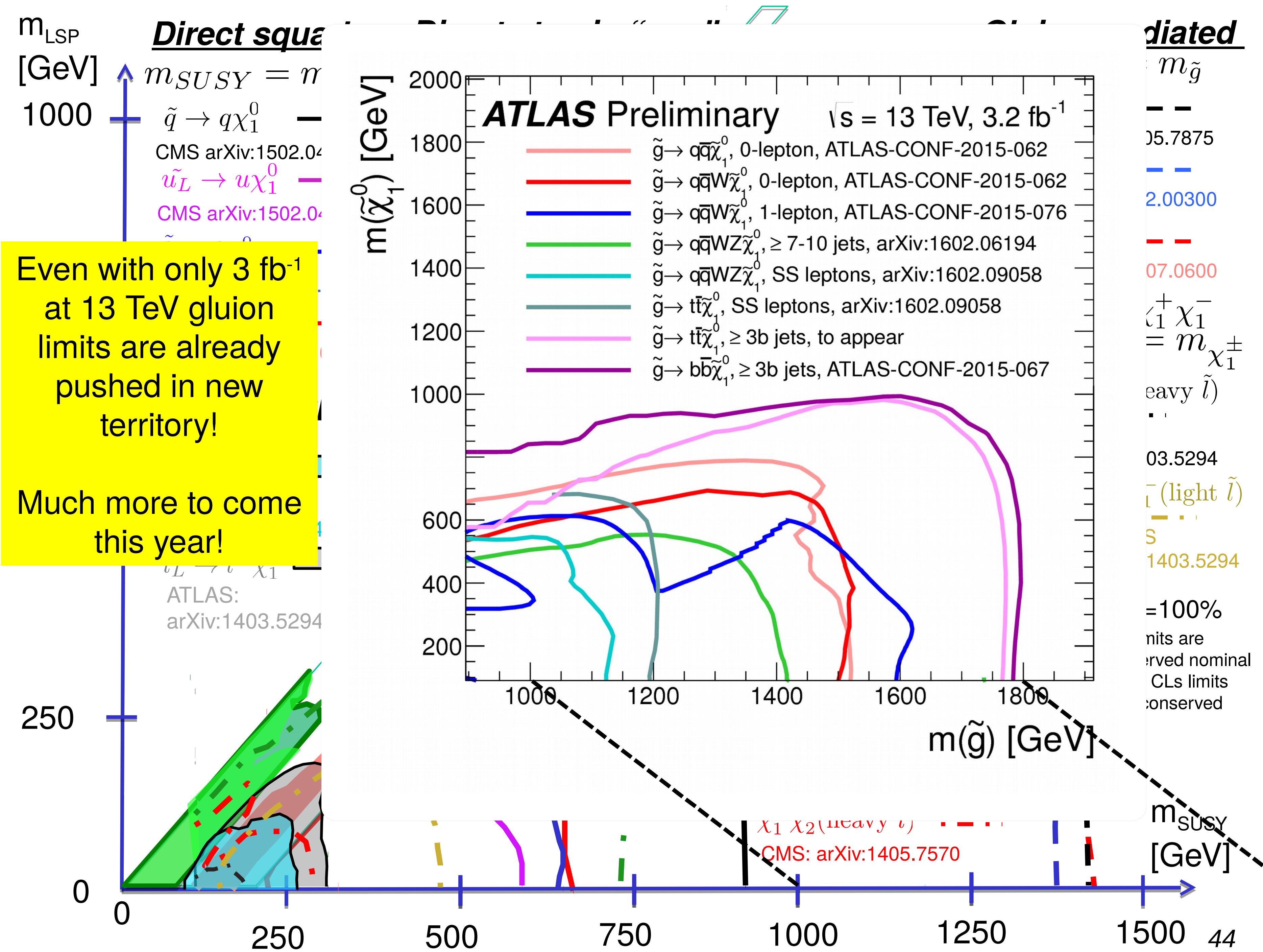
Note: The following results are a **May 2015 update** to PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

What are representative SMS limits on the different particles?



Searches @ Colliders - Lecture O. Buchmüller





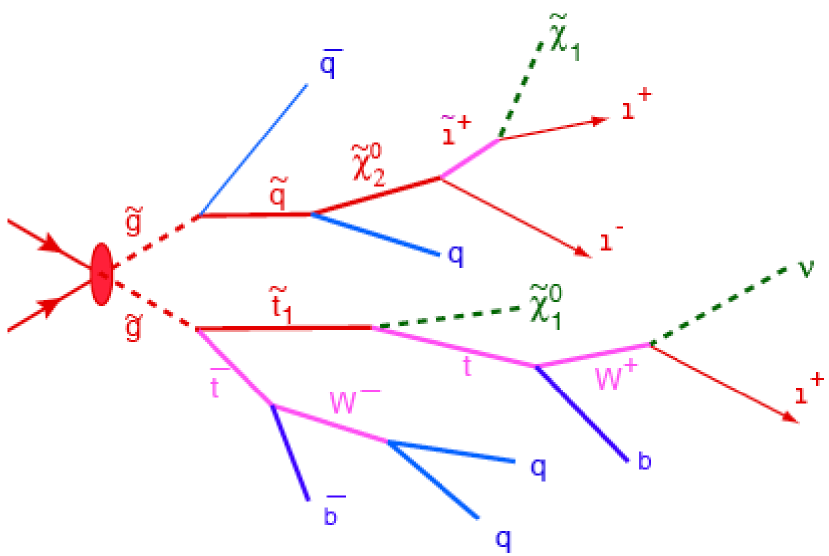
Even with only 3 fb⁻¹ at 13 TeV gluion limits are already pushed in new territory!

Much more to come this year!

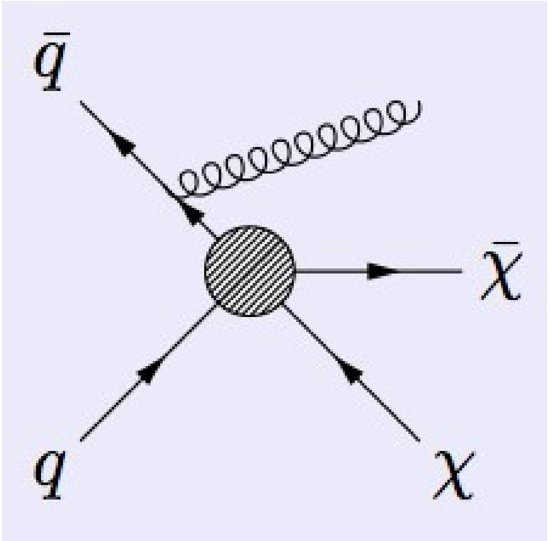
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY

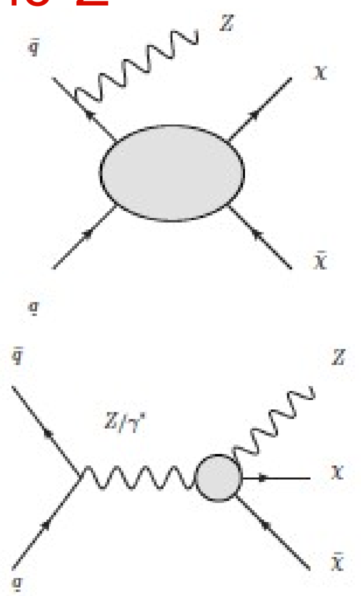


Example:
Effective Field Theory
Simplified models



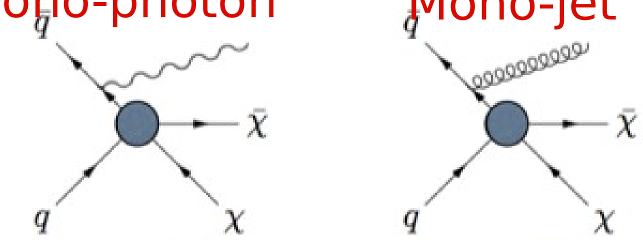
Mono-Mania (at the LHC)

Mono-Z

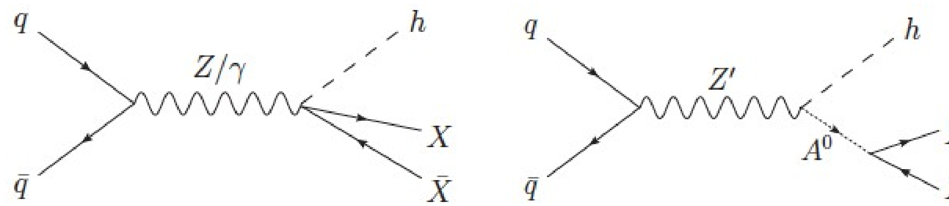


Mono-photon

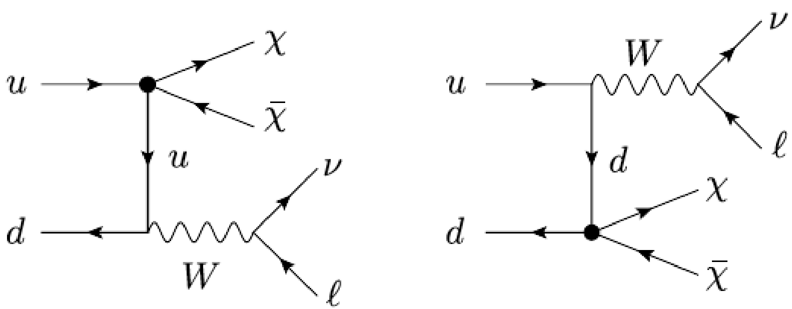
Mono-jet



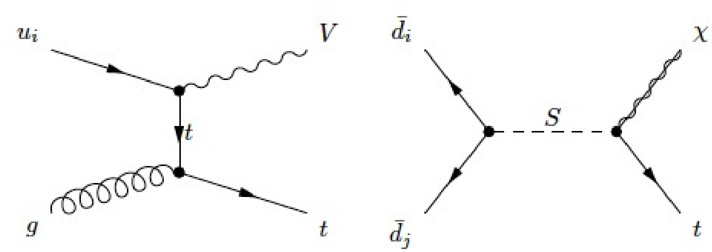
Mono-Higgs



Mono-W

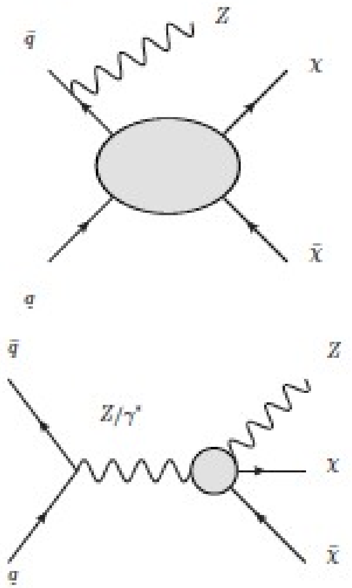


Mono-top



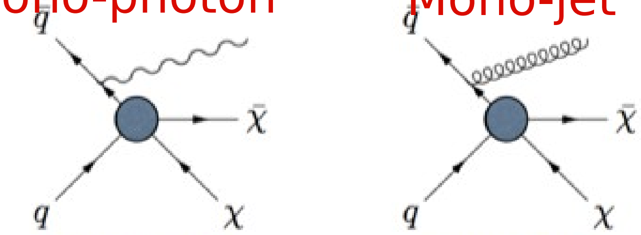
Mono-Mania (at the LHC)

Mono-Z



Mono-photon

Mono-jet



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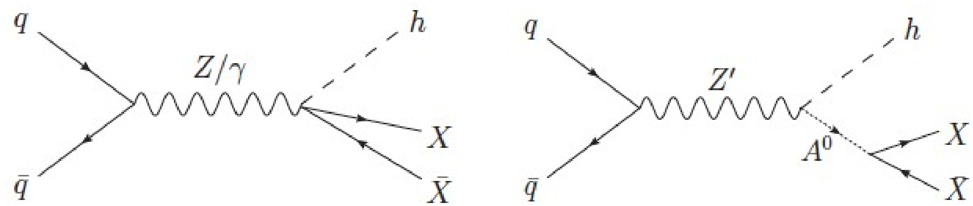
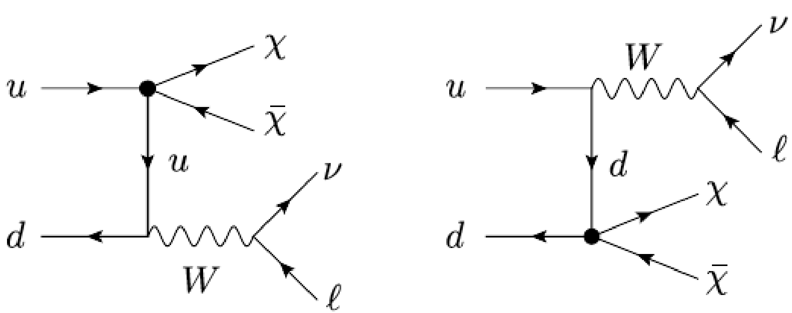
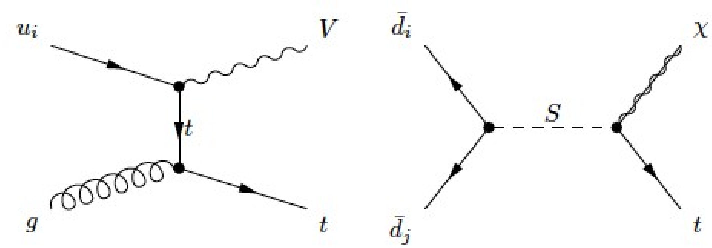


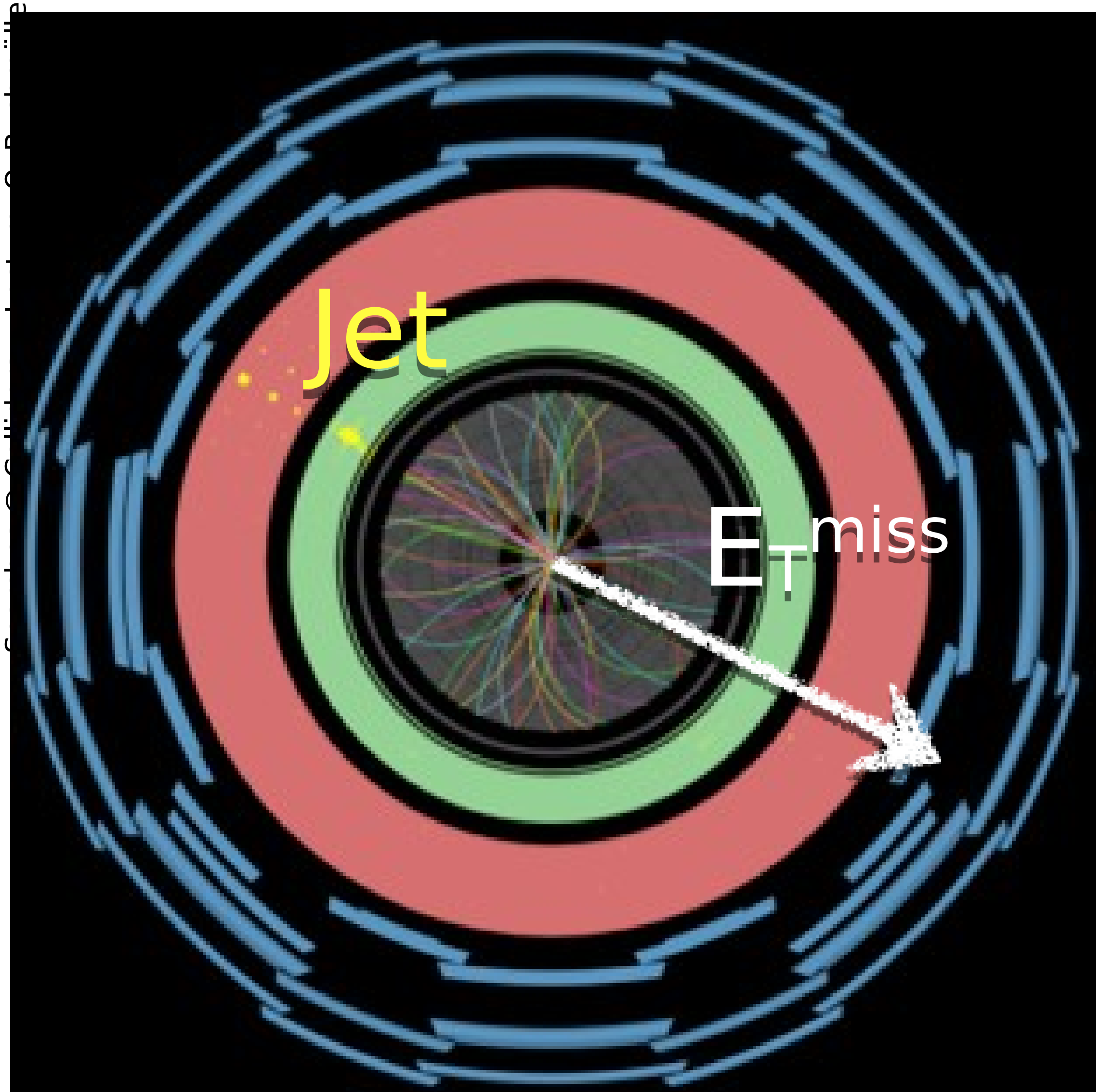
Mono-W



Mono-top



Mono-X searches at colliders



E_T^{miss} trigger

Example Monojet

(8 TeV, 20.3 fb-1)

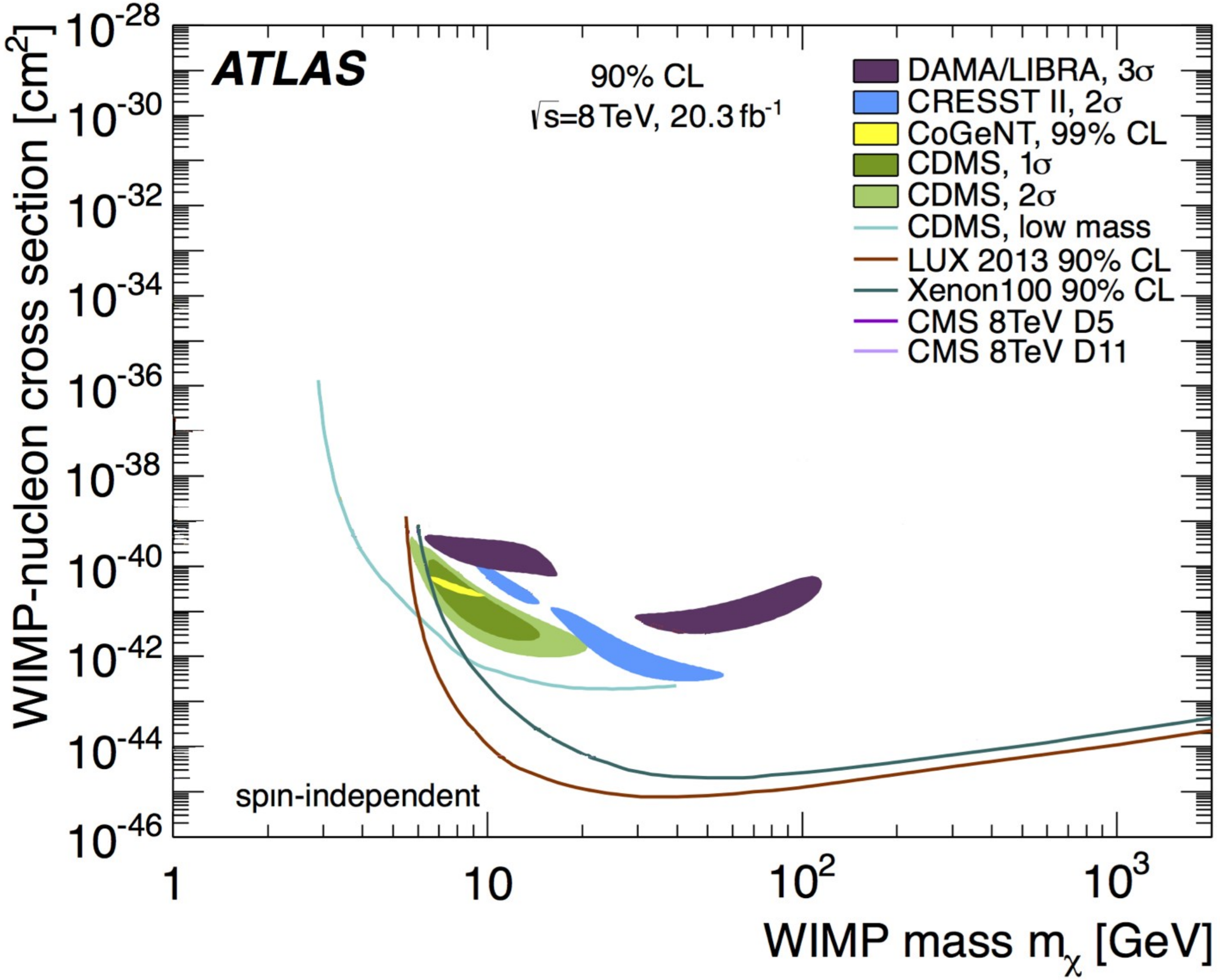
- E_T^{miss} , $p_T(j)$ > 150 - 900 GeV
- 1 or 2 jets (anti-k_T, R=0.4, p_T>30 GeV)
- $|\Delta\varphi(E_T^{miss}, j_2)| > 0.5$

Example Monophoton

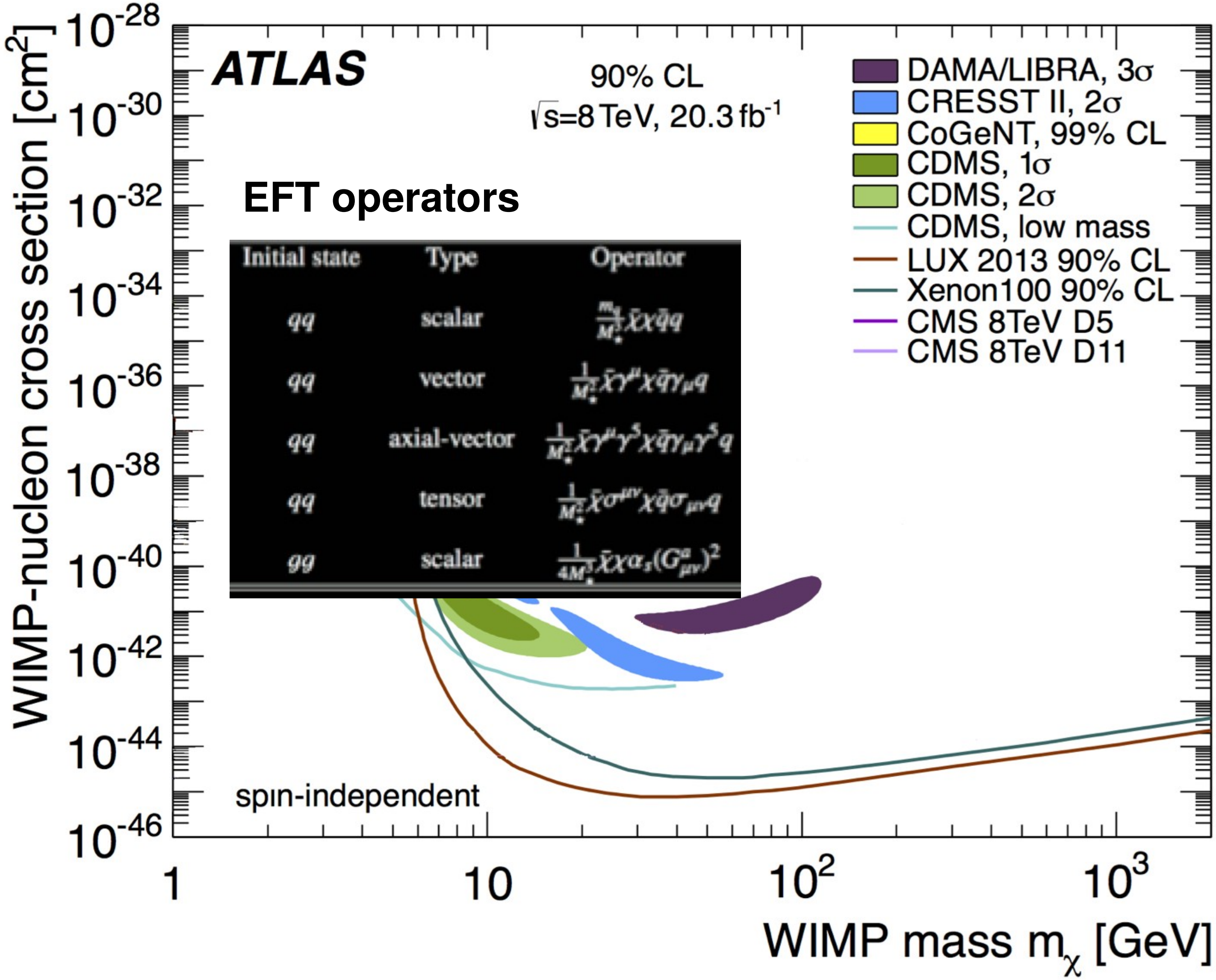
(8 TeV, 19.6 fb^{-1}):

- E_T^{miss} , $p_T(\gamma)$>140 GeV,
- N_{jet} < 2 (anti-k_T, R=0.5, p_T>30 GeV)
- $\Delta\varphi$ (γ, E_T^{miss}) >2,

ATLAS Mono-Jet: Comparison with Direct Detection



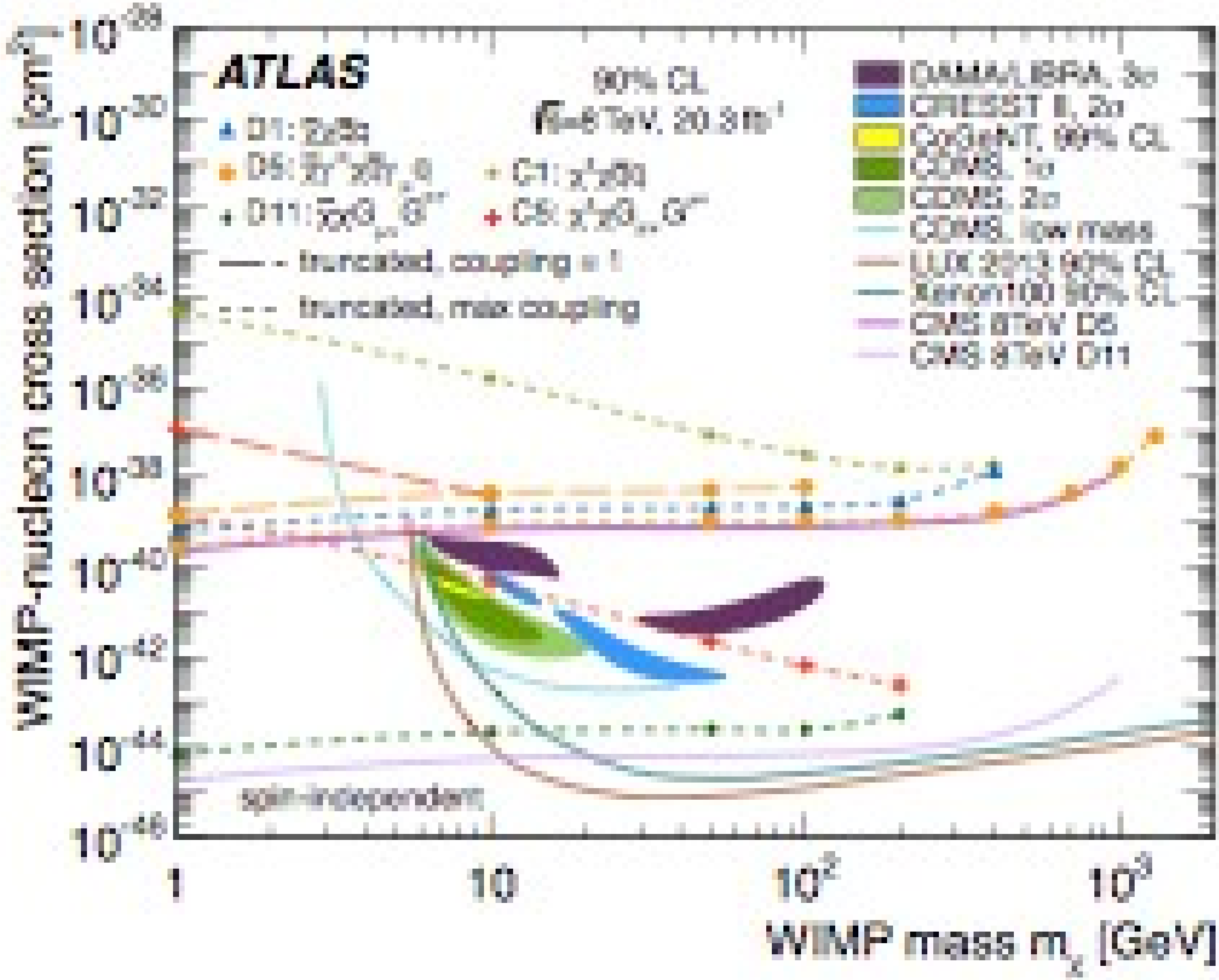
ATLAS Mono-Jet: Comparison with Direct Detection



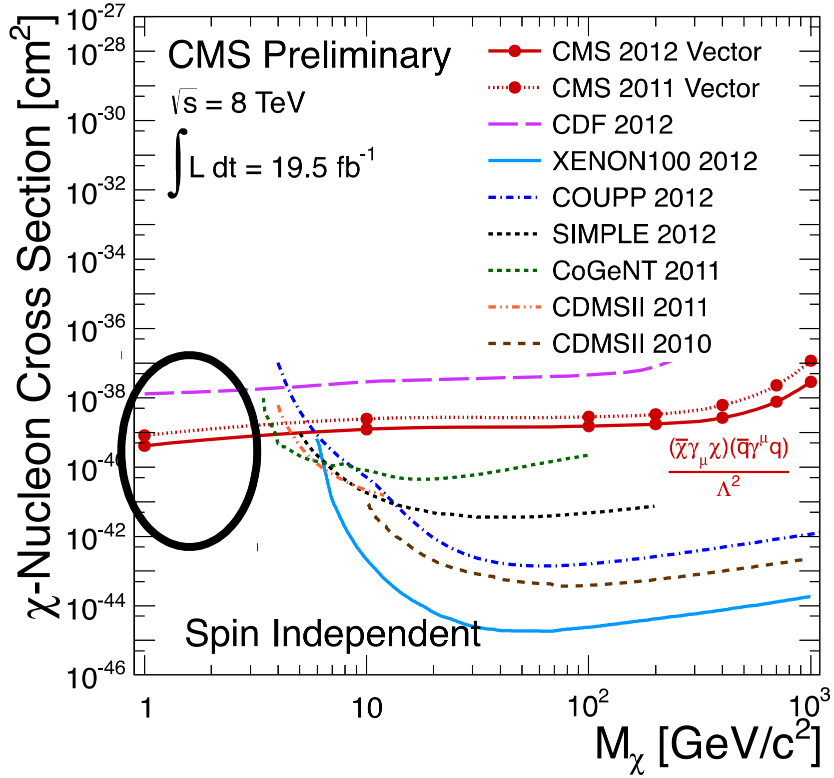
EFT operators

Initial state	Type	Operator
qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$
qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$
qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

ATLAS Mono-Jet: Comparison with Direct Detection



Mono-Jet analyses better than direct detection?!



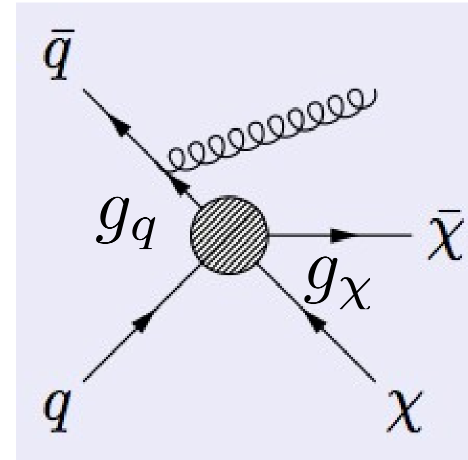
Claim [often made]:

For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu \chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel



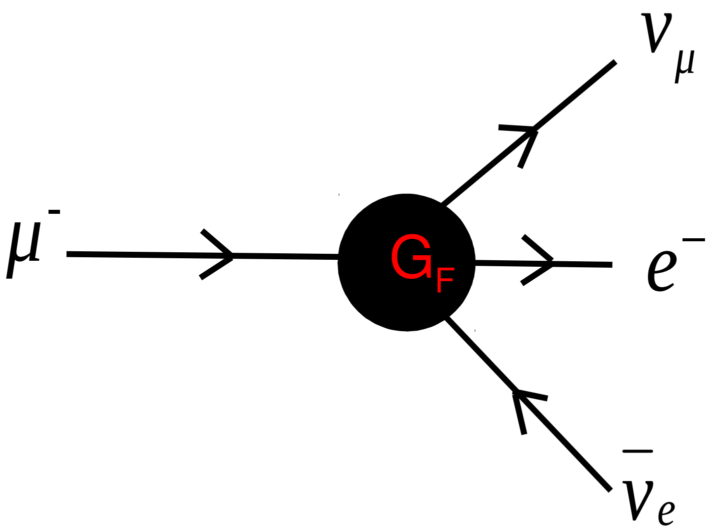
$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu \gamma_5 \chi)(\bar{q}\gamma_\mu \gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

Assumption of EFT

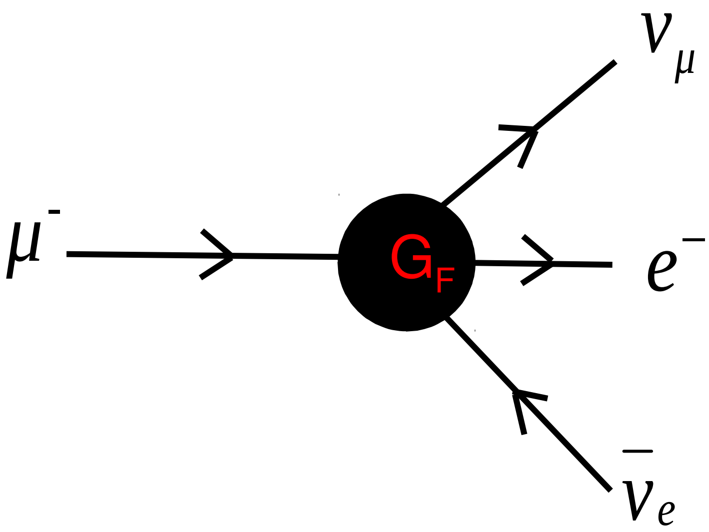
If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Fermi Interaction & Muon Decay



Fermi Interaction & Muon Decay



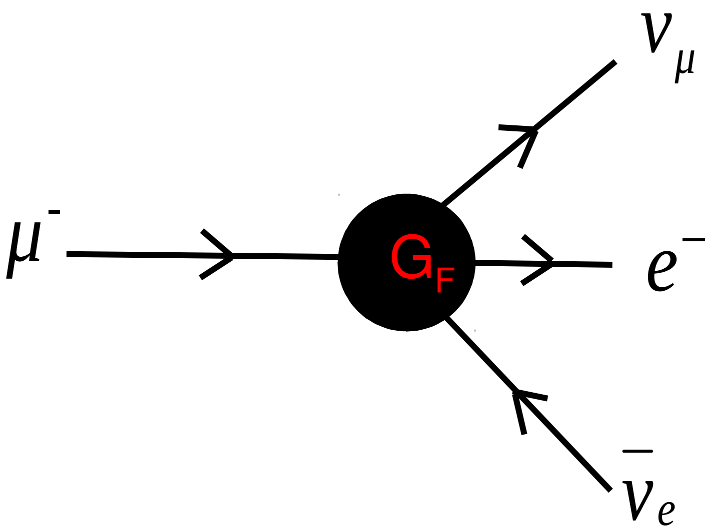
The Fermi 4-point interaction was able to explain well the beta-decay as well as the muon decay with one single interact strengths G_F (Fermi constant)

However, the cross-section grows as the square of the energy:

$$\sigma \propto G_F^2 E^2$$

making it invalid for higher energies!

Fermi Interaction & Muon Decay



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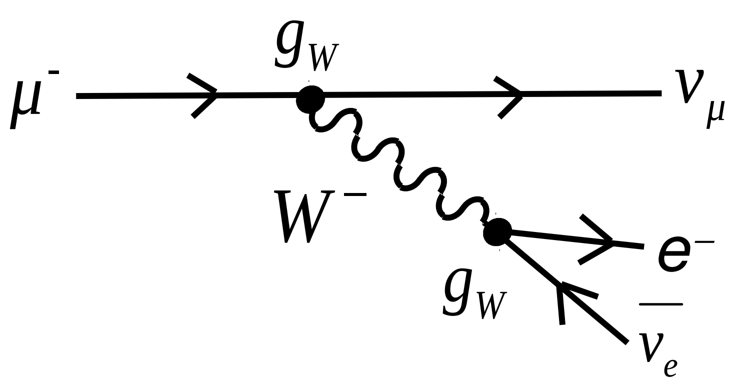


Solution:
Resolve the "blob" and replace the 4-point interaction with an ultraviolet complete theory!

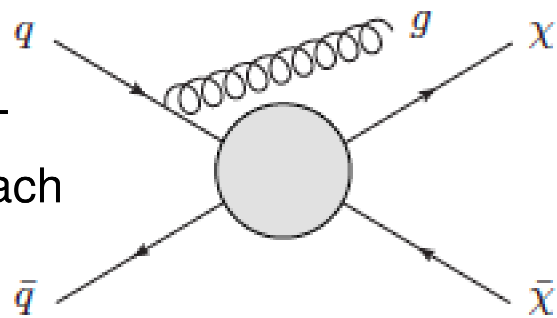
$$\sigma \propto G_F^2 M_W^2$$

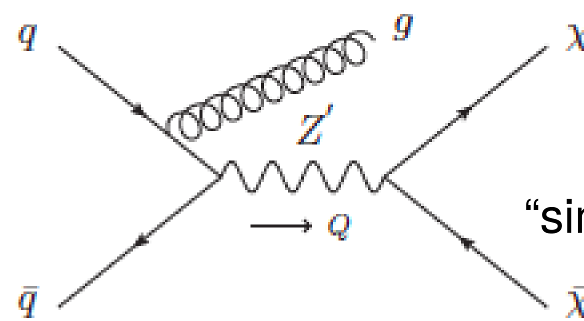
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- ➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

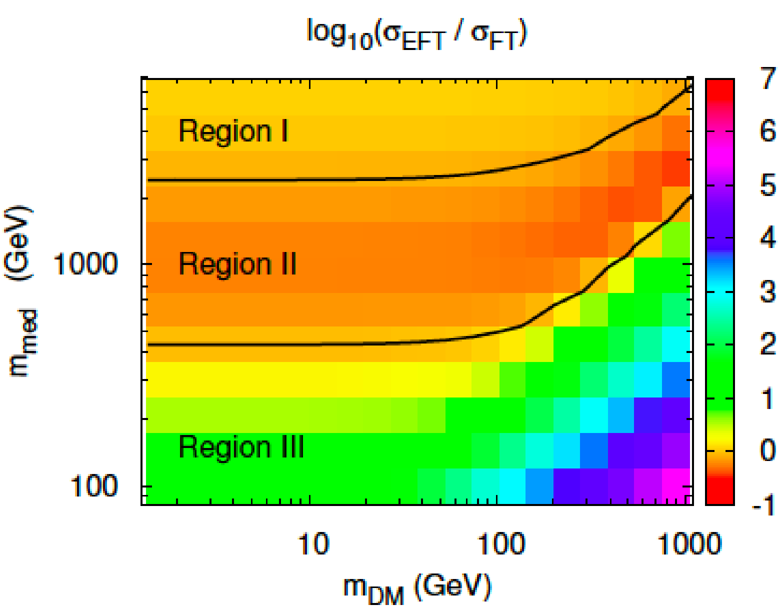
EFT
approach





FT
one diagram
“simplified model”

Use vector and axial-vector mediators (e.g. Z’) as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in $m_{med} – m_{DM}$ plane.
Three regions become visible:

Region I: EFT and FT agree better then 20%
- ➢ EFT is valid!

Region II: EFT yields significant weaker limits then FT
- ➢ EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT
- ➢ EFT limits are too aggressive!

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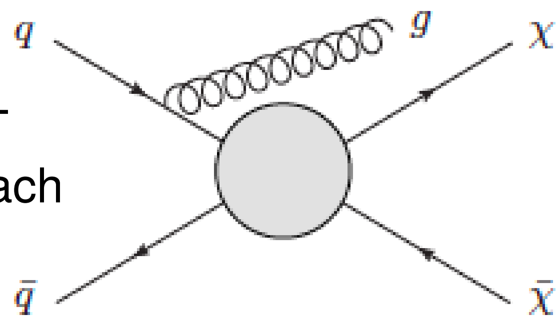
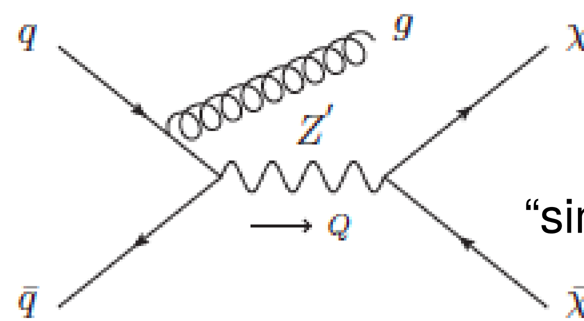
EFT approach





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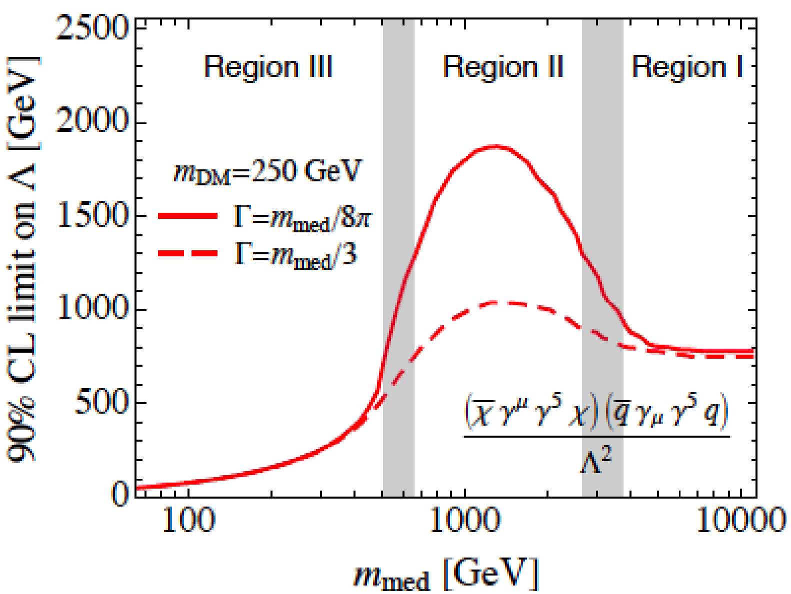


Three Regions as function of mediator mass:

Region I: Heavy m_{med}

➢ EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

➢ EFT limits are too conservative!

Region III: Low m_{med}

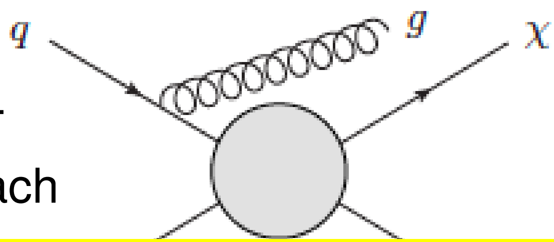
➢ EFT limits are too aggressive!

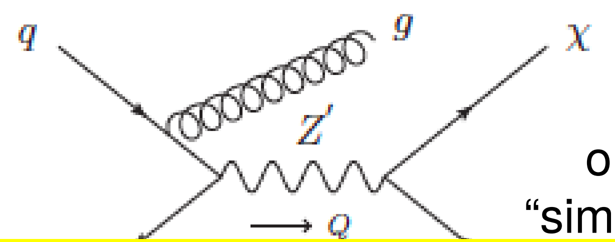
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach

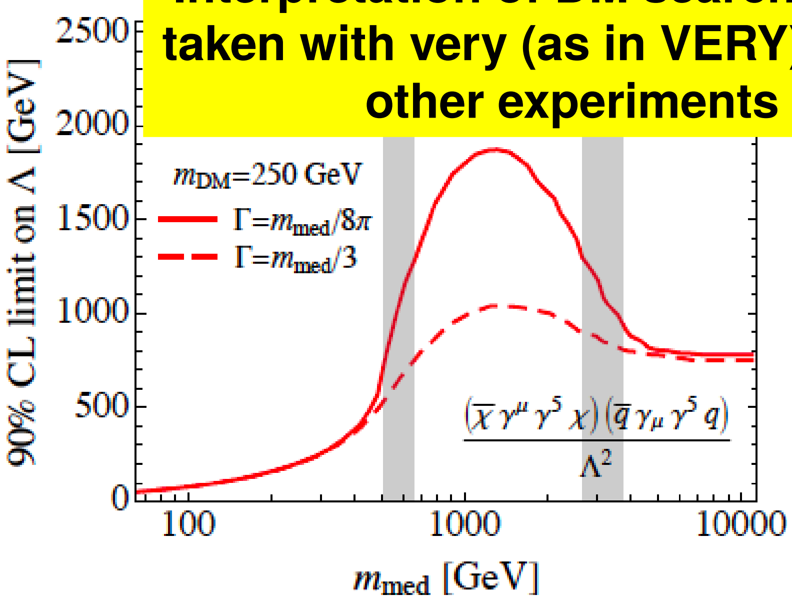




FT
one diagram
"simplified model"

Use v ... nclusion!

Conclusion:
The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!



Region I: Heavy m_{med}

- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

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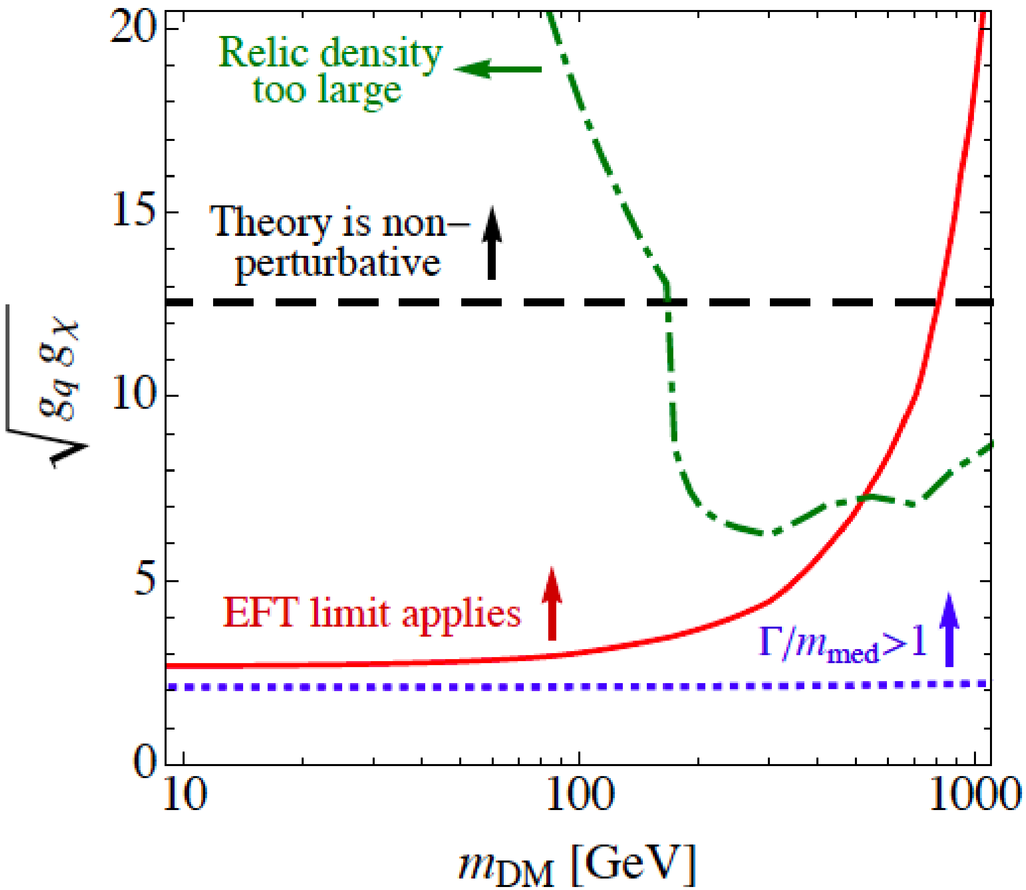
Region III: Low m_{med}

- EFT limits are too aggressive!

What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

* Coupling chose such that CMS EFT limit on Λ applies to FT

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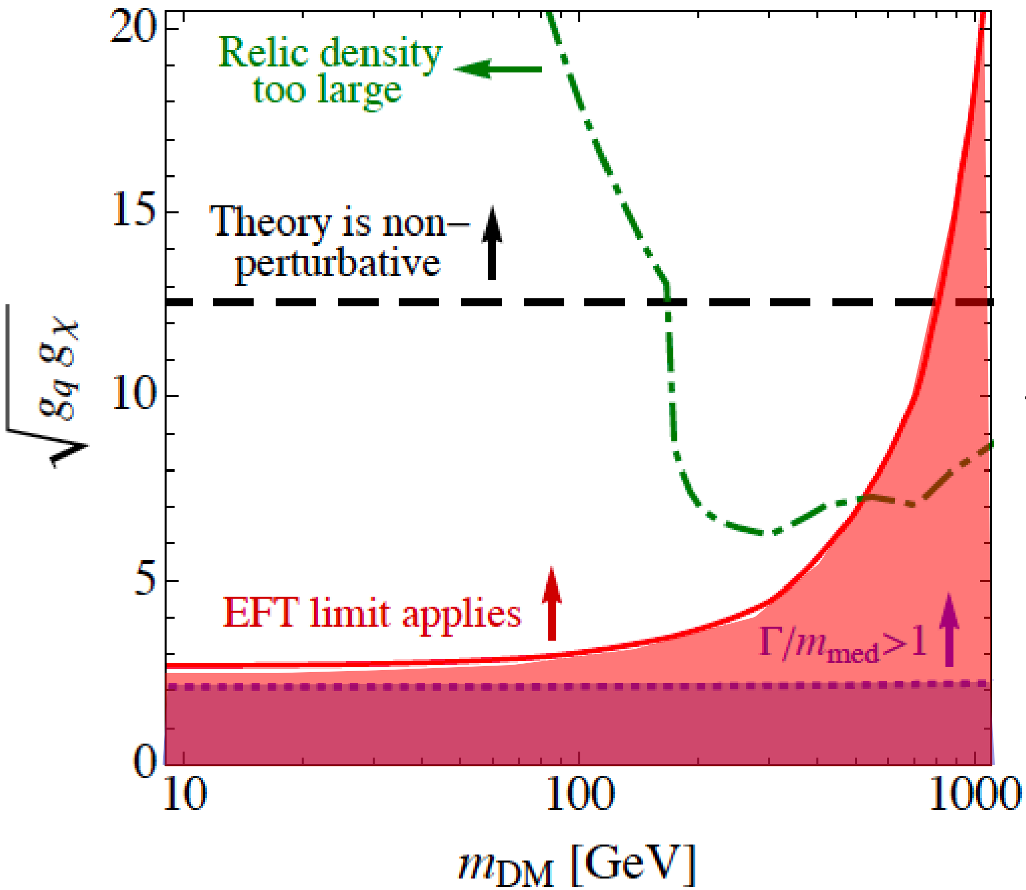
Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid

For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = m_{med}/\Lambda_{CMS}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better then 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on Λ applies to FT

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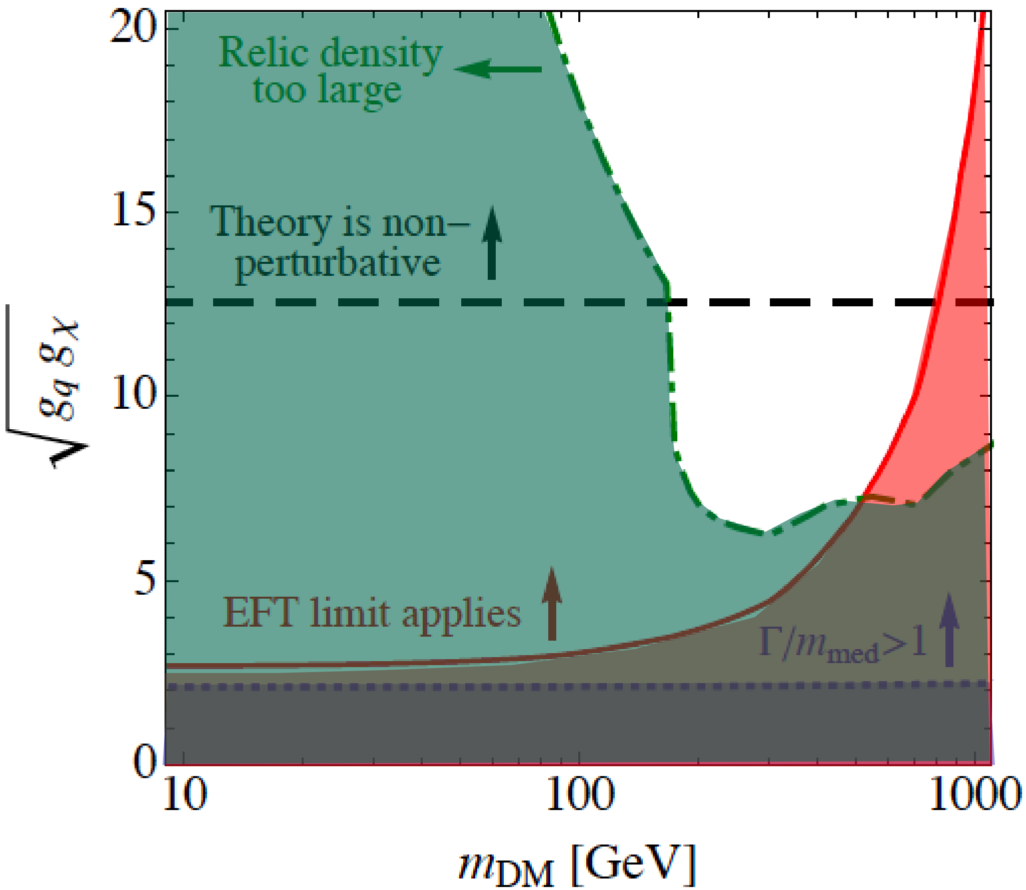
Model-dependences of EFT limits



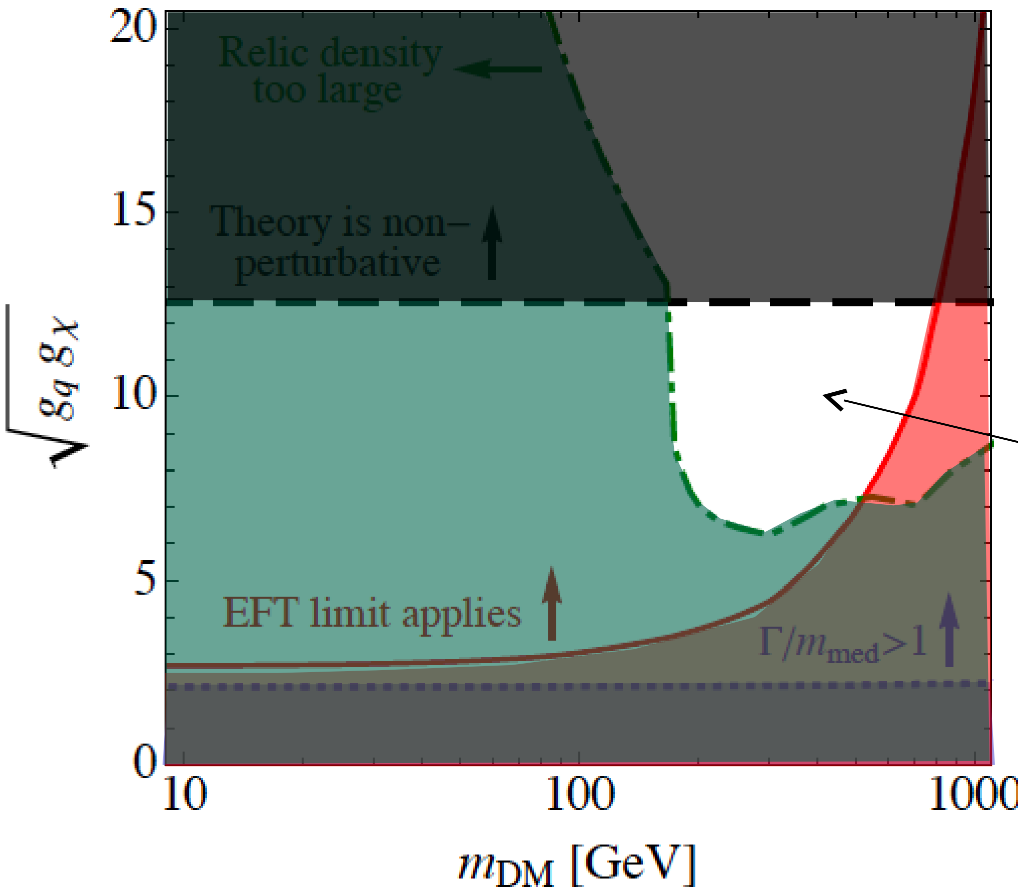
Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger then the observed value of $\Omega_{\chi\chi}h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)

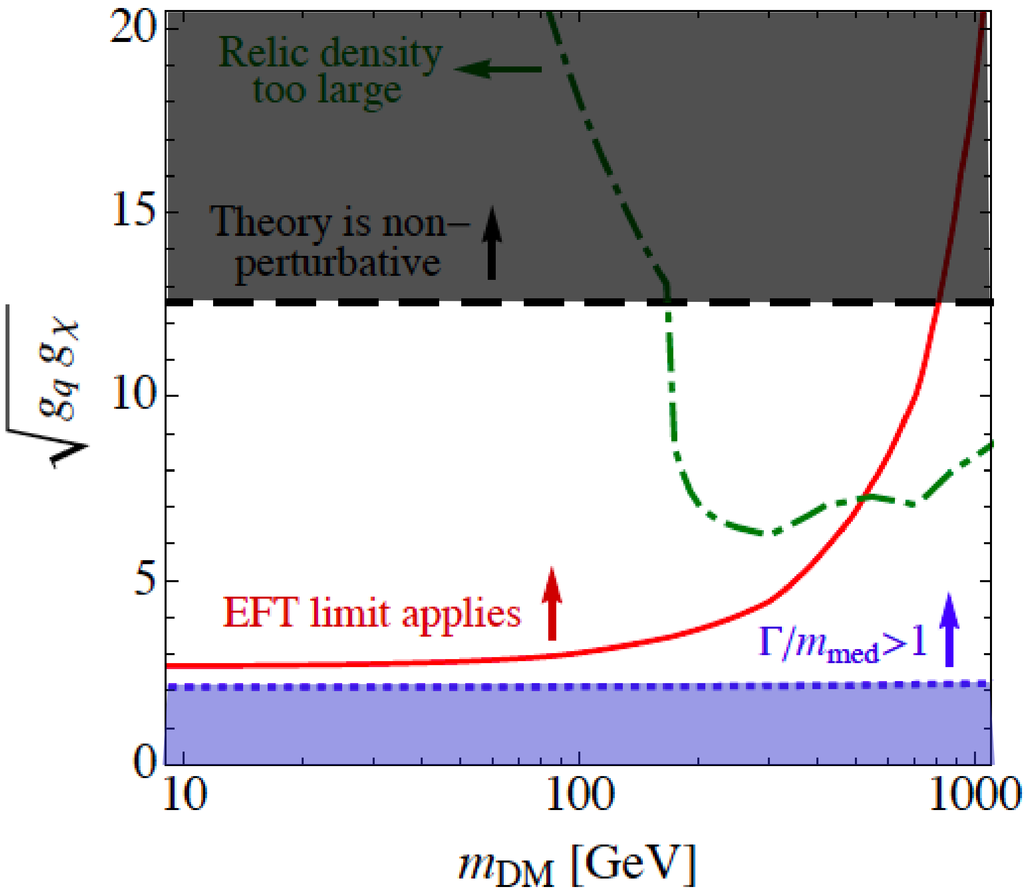
When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT is valid only IF the mass of the mediator is smaller than its width !

In the reaming part of the plot: $\sqrt{g_q g_\chi} > 2$

a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$!

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

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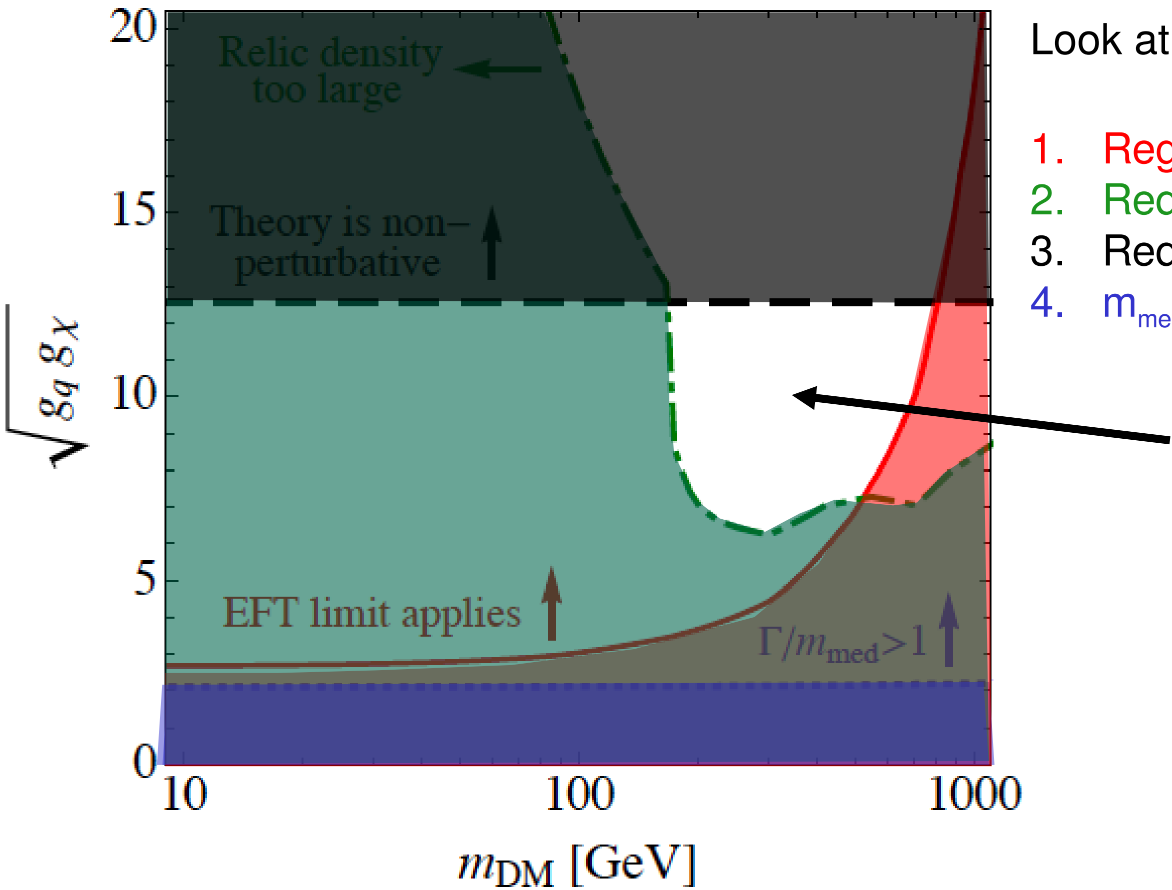
What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

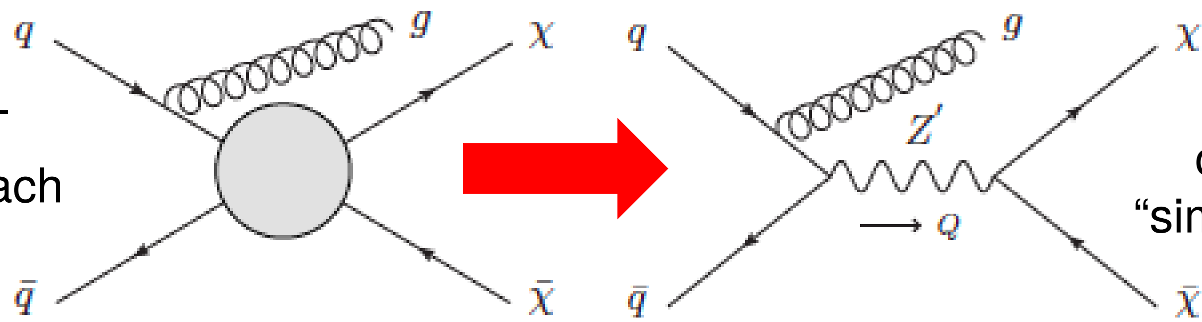
EFT limits of monojet searches are therefore highly model-depended!

Alternative Interpretation Ansatz: Simplified models

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach



FT
one diagram
“simplified model”

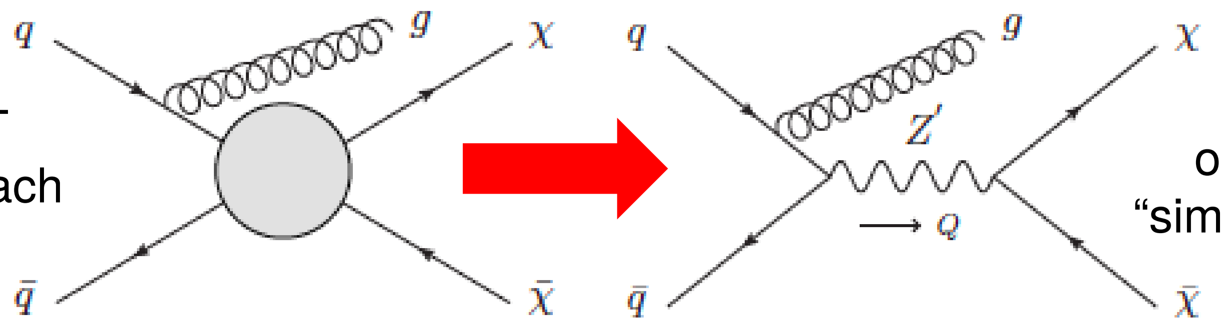
After three years of operation at the LHC the landscape for interpretation of searches has changed dramatically – new superior & modern approaches have replaced in many areas longstanding traditional ones
(e.g. SUSY searches)

Alternative Interpretation Ansatz: Simplified models

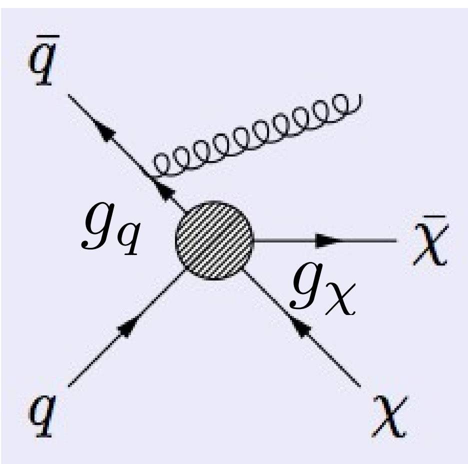
Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach



FT one diagram "simplified model"

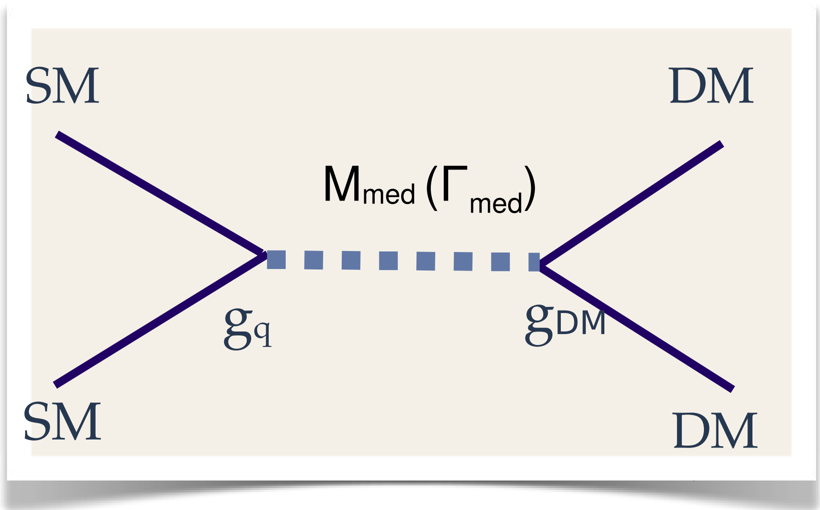


The problem is governed by five variables:

- Couplings g_q and g_χ
- Mediator mass m_{med} and mediator width Γ_{med}
- Dark matter candidate mass m_{DM}

Minimal Simplified Dark Matter Model

Based on work from :
OB, S. Malik, M.Dolan,C.McCabe arXiV:1407.8257



s-channel

Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

(Γ_{med} can also be free as long As Γ_{med}<M_{med})

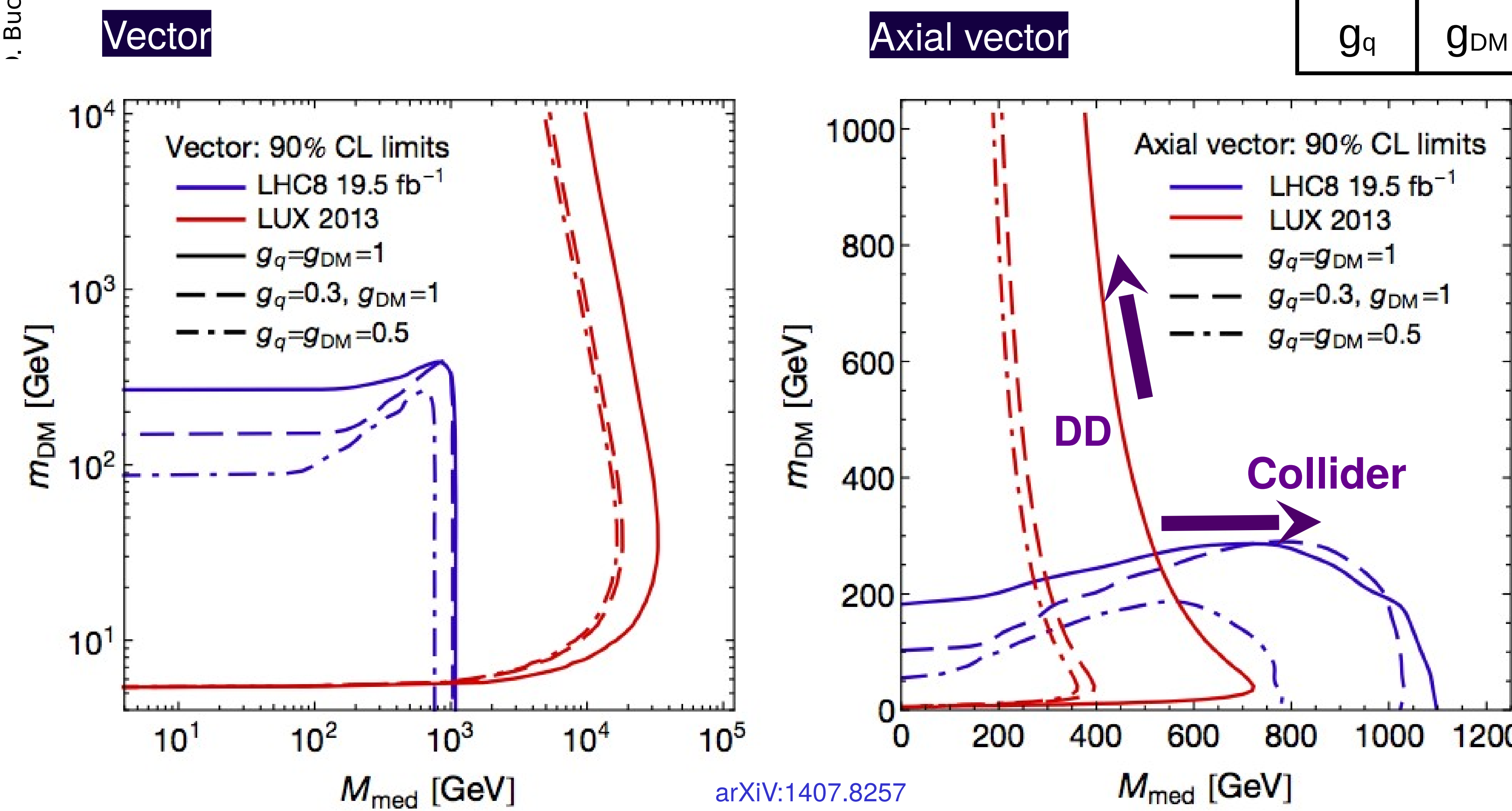
DM	
Dirac fermion	Scalar - real
Majoran a fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscal ar

Collider vs Direct Detection

O. Buchmüller

M_{DM}	M_{med}
g_q	g_{DM}



arXiV:1407.8257

Imperial College London

Scalar and Pseudoscalar

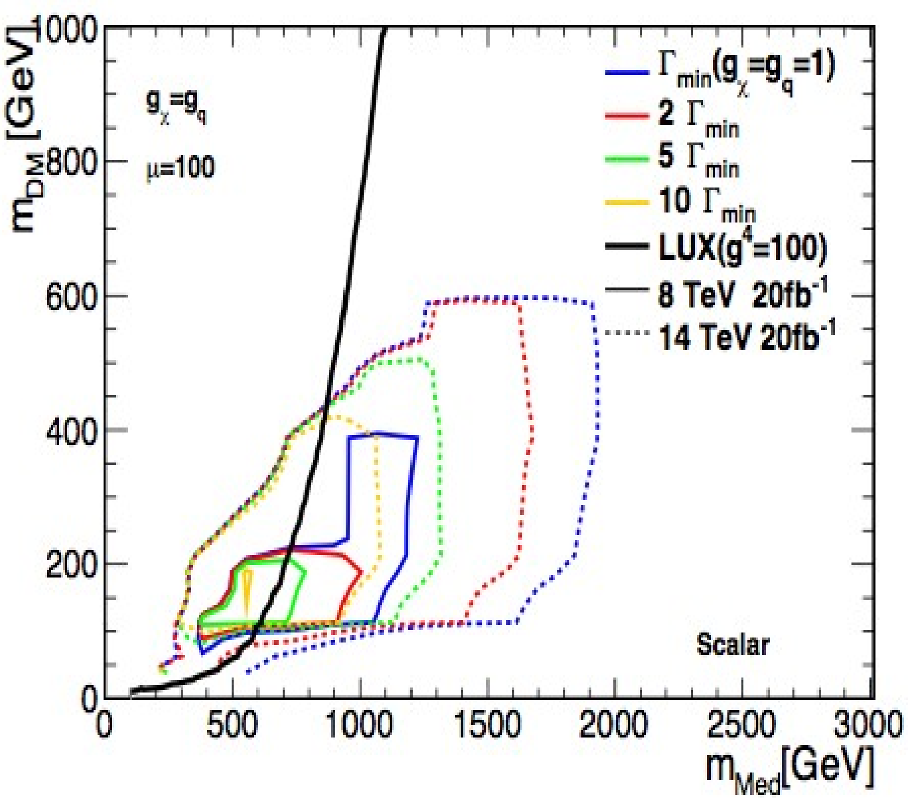
O. Buchmüller

Philip Harris, Valentin V. Khoze,
Michael Spannowsky, Ciaran Williams

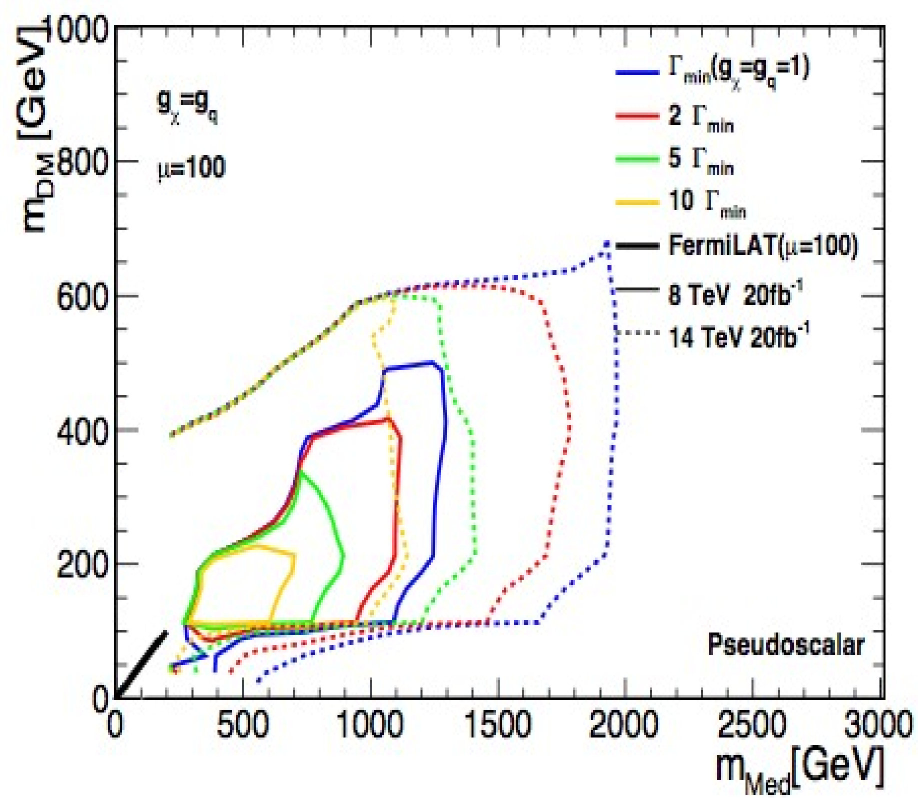
arXiv:1411.0535

See also Buckley et al
arXiv:1410.6497

Scalar



Pseudoscalar



7

Summary for most basic Mediator Interactions

… in a nutshell!

Basic Mediators	
Vector EWK like coupling (assumed equal to all leptons). *Besides very low DM masses DD wins clearly over collider!*	**Axial-vector** EWK like coupling (assumed equal to all leptons). *DD and collider are equal in overall sensitivity but probe different regions of parameter space!*
Scalar Yukawa like coupling on SM side (mass based on SM side) _ *DD and collider are equal in overall sensitivity but probe different regions of*	**Pseudoscalar** Yukawa like coupling on SM side (mass based on SM side) *No limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to*

NOW A BIT MORE FOR THE DM EXPERTS [OR THOSE WHO LIKE TO BECOME ONE ◀◀]

New LHC Dark Matter Working Group

This Working Group brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC.

More details can be found at this page:

http://lpcc.web.cern.ch/LPCC/index.php?page=dm_wg

and the mailing list is lhc-dmwg@cern.ch**.

Theory Representative: U. Haisch, M. Mangano

ATLAS Representative: A. Boveia, C. Doglioni

CMS Representative: O. Buchmueller, K. Hahn

**To join the WG mailing list, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

LHC DM WG: First Goal

The first goal of the LHC DM WG is to discuss and agree upon the presentation of collider searches for DM between ATLAS and CMS. Both LHC experiment and theory community will collaborate, in order to decide upon the best format for comparison between collider and non-collider results and on the usability of the material that is made public for the Winter conferences 2016.

LHC DM WG: First Goal

The first goal of the LHC DM WG is to discuss and agree upon the presentation of collider searches for DM between ATLAS and CMS. Both LHC experiment and theory community will collaborate, in order to decide upon the best format for comparison between collider and non-collider results and on the usability of the material that is made public for the Winter conferences 2016.

First meeting of the new LHC Dark Matter Working Group was devoted to this subject:

10-11 December 2015 CERN

https://indico.cern.ch/event/459037/

Recommendation Document

CERN-LPCC-2016-001

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

http://arxiv.org/pdf/1603.04156.pdf

Recommendation Document

CERN-LPCC-2016-001

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

A special acknowledgement for Felix Kahlhoefer, Christopher McCabe, and Tim Tait for their contributions as main editors with LHC DM WG conveners!

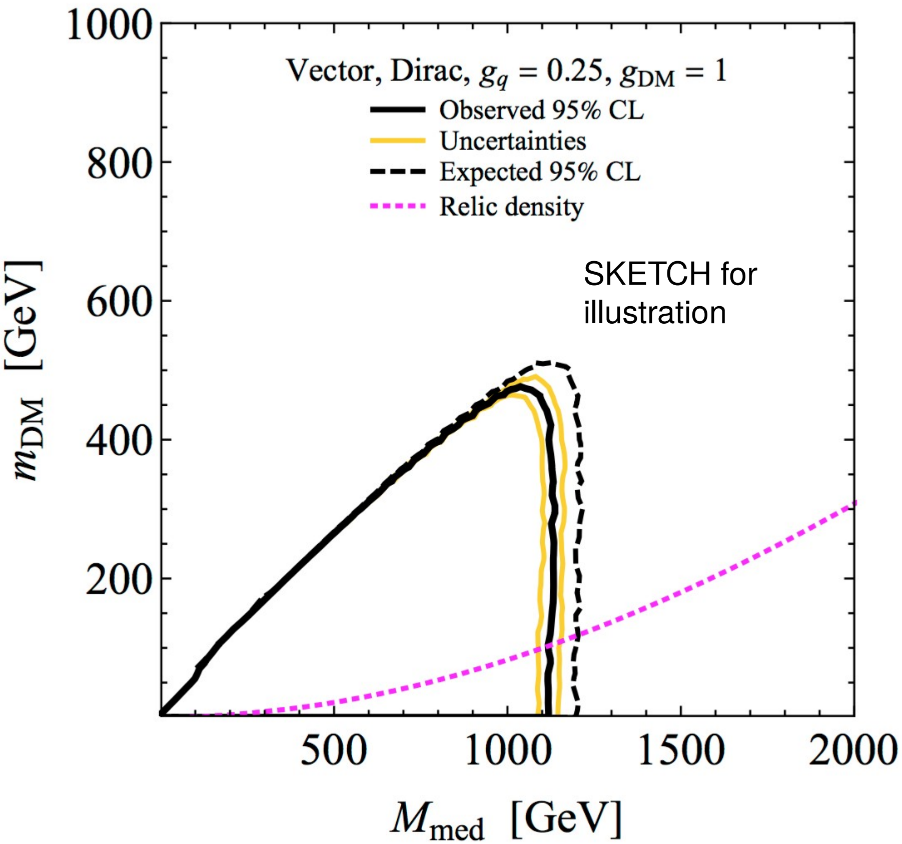
http://arxiv.org/pdf/1603.04156.pdf

Recommendation in a nutshell

- Primary focus on presentation of LHC results vis-a-vis DD/ID
- Recommend that LHC searches are presented as a ‘stand-alone” result in the appropriate variables of collider physics.
  - Main results should feature in the “mass-mass” plane [$M_{med} – M_{DM}$]
  - All important assumptions entering these results should be stated [on plot and in figure captions/accompanying documentation. The LHC WG recommendation contains examples for all primary issues.
- Recommend to compare LHC results with different experiments in their “language”.
  - Translation of “mass-mass” plane limits in $\sigma_{D/ID}$ - M_{DM} [direct detection experiment e.g. LUX] and $\sigma_{annihilation}$ - M_{DM} [indirect detection experiment e.g. Fermi-LAT] is well-defined.
  - This avoids manipulation of other experiments results and minimizes the caveats and assumptions entering. Yet, also here its critical to spell out all assumptions/caveats relevant. The LHC WG recommendation contains examples for all primary issues.

Mass-Mass plane [$M_{med} – M_{DM}$]

Main result of the interpretation of collider search in simplified model

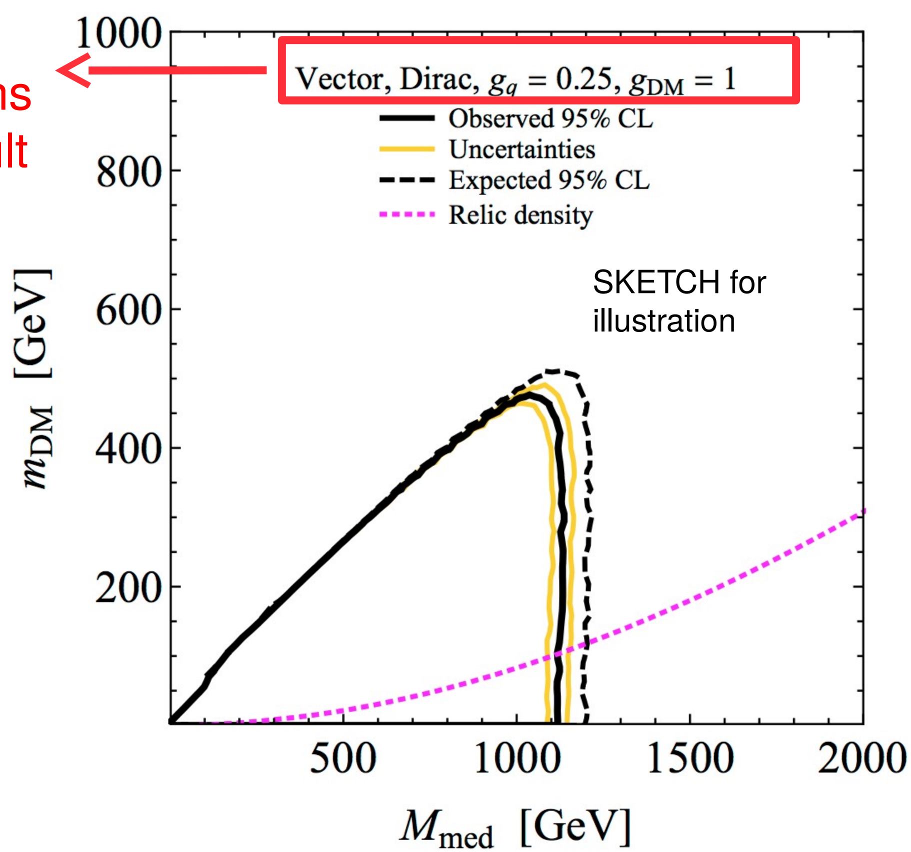


95% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings $g_q = 0.25$ and $g_{DM} = 1$. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate the scale uncertainties of the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard

Mass-Mass plane [$M_{med} – M_{DM}$]

Main result of the interpretation of collider search in simplified model

Clearly state
Main assumptions entering the result
- Mediator
- DM type
- Couplings



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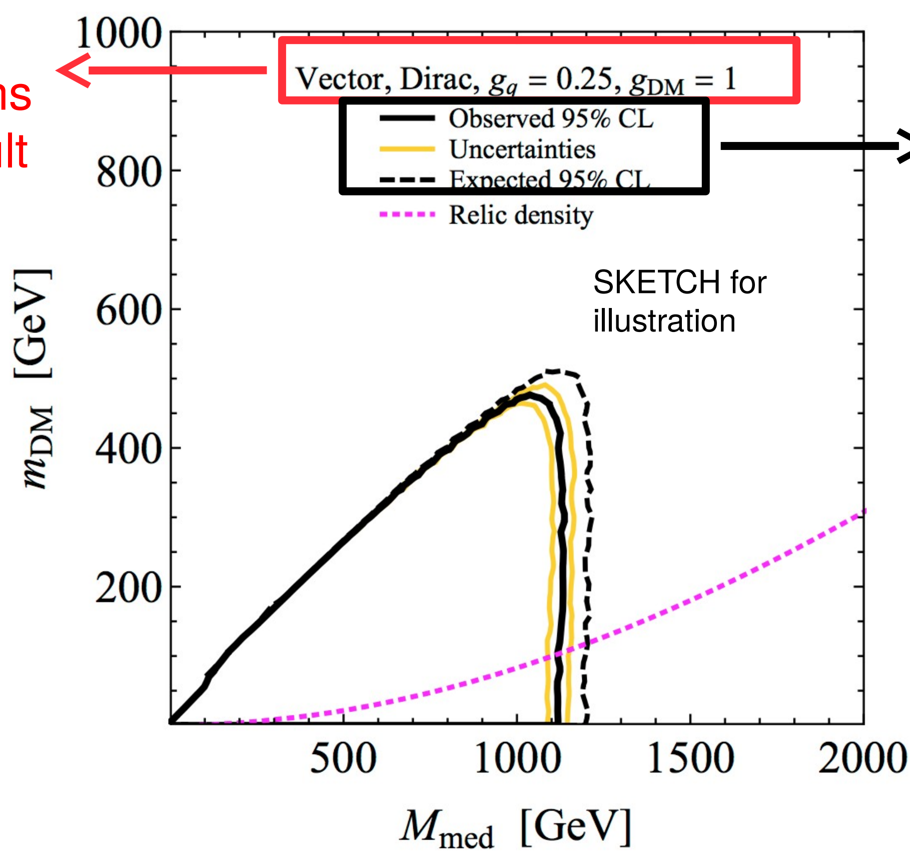

Usual "LHC limits"
For 95% CL [not 90%]

95% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings $g_q = 0.25$ and $g_{DM} = 1$. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate the scale uncertainties of the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard

Mass-Mass plane [M_{med} – M_{DM}]

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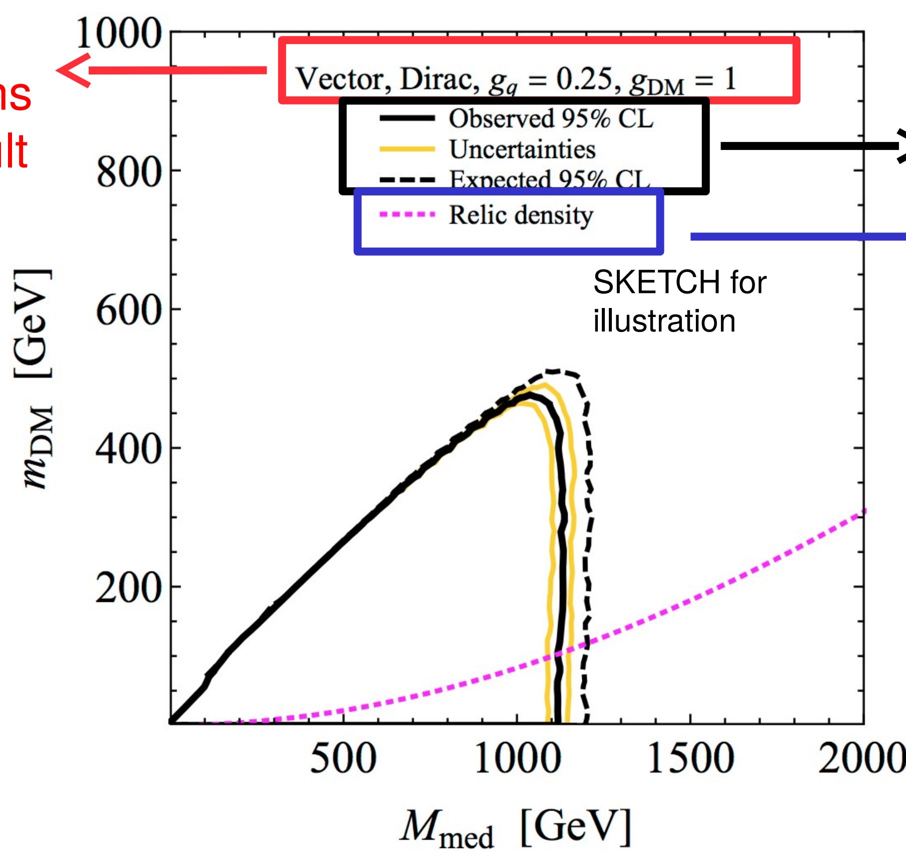

Usual "LHC limits"
For 95% CL [not 90%]

Indicate Relic density line but do not use it as "validity" requirement. Its FI only.
[more caveats and discussion are provided in the report]

95% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings $g_q = 0.25$ and $g_{DM} = 1$. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate the scale uncertainties of the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard

Mass-Mass plane [$M_{med} – M_{DM}$]

Main result of the interpretation of collider search in simplified model

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Main assumptions entering the result
- Mediator
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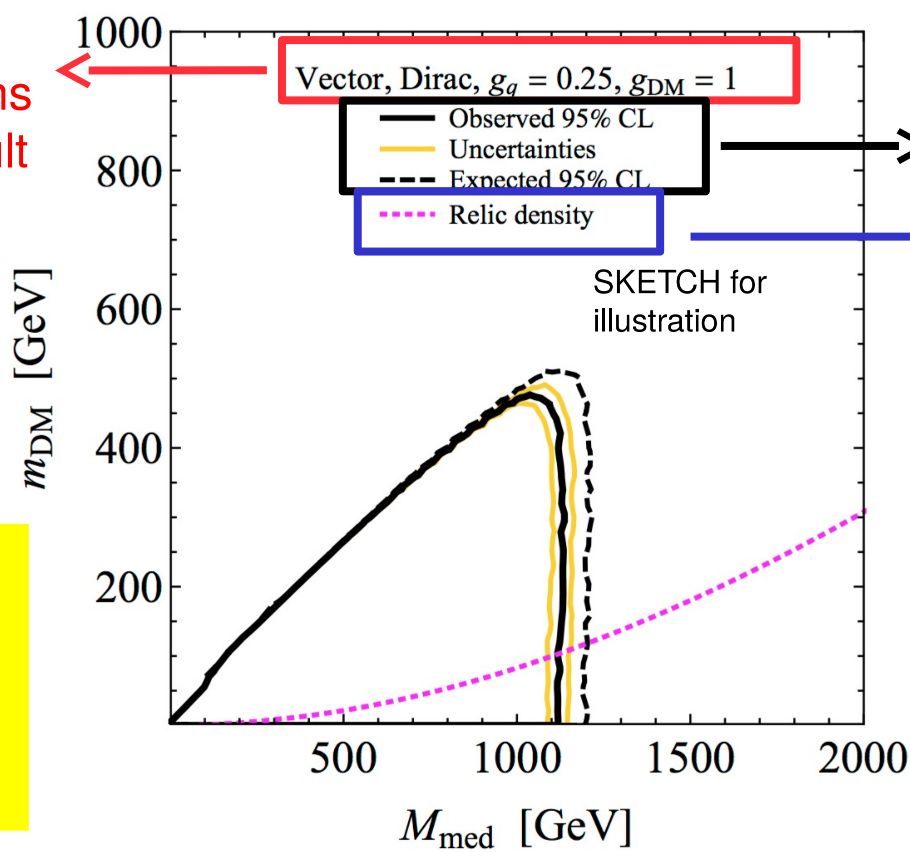

Usual "LHC limits"
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Indicate Relic density line but do not use it as "validity" requirement. Its FI only.
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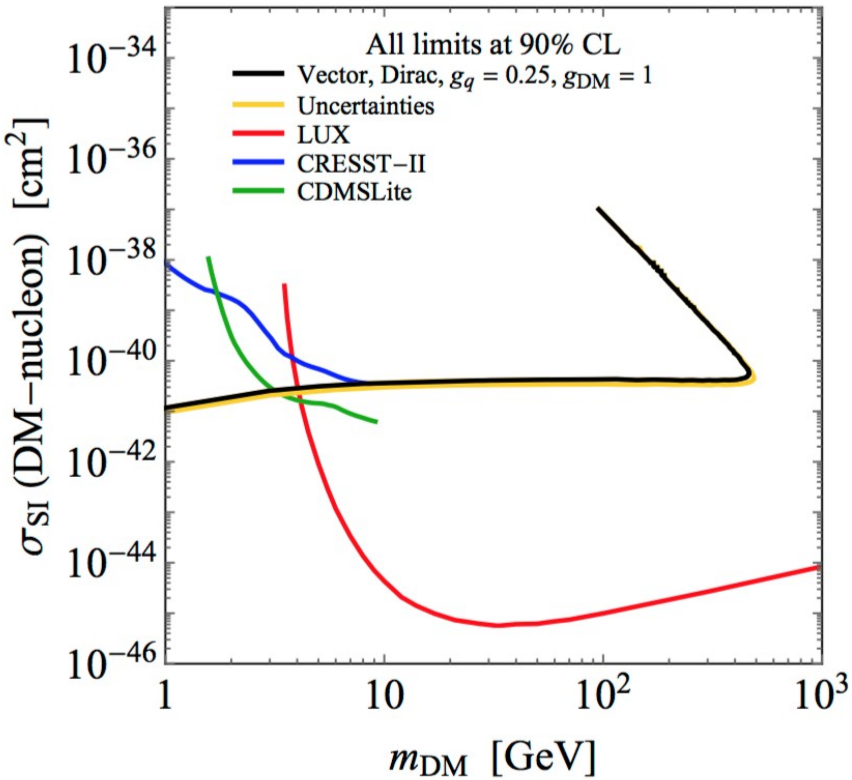
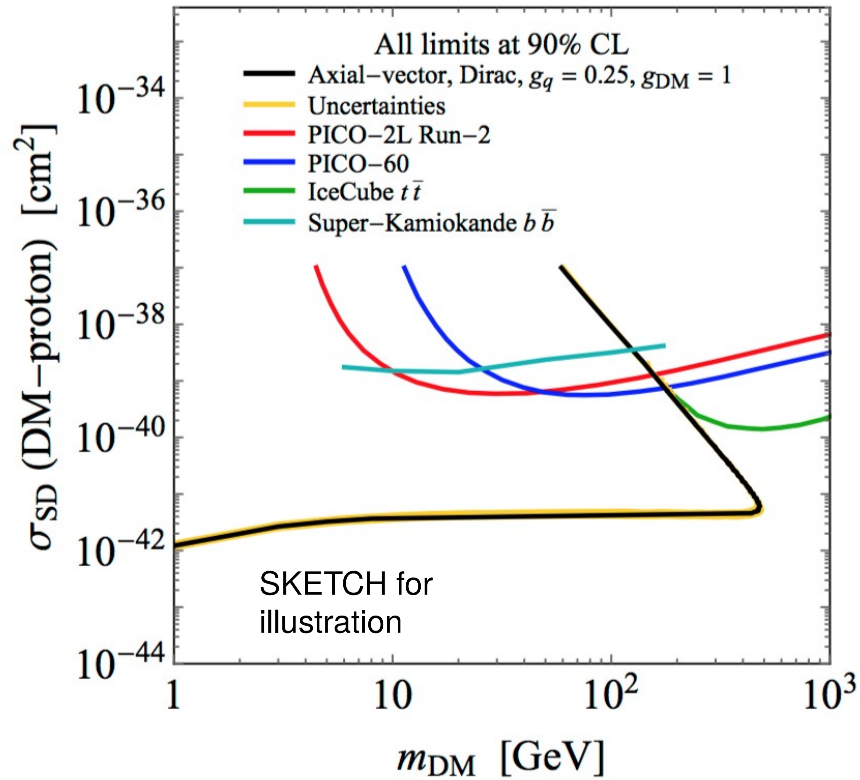
Much more discussion about assumptions entering are in the report

95% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings g_q = 0.25 and g_{DM} = 1. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate the scale uncertainties of the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard

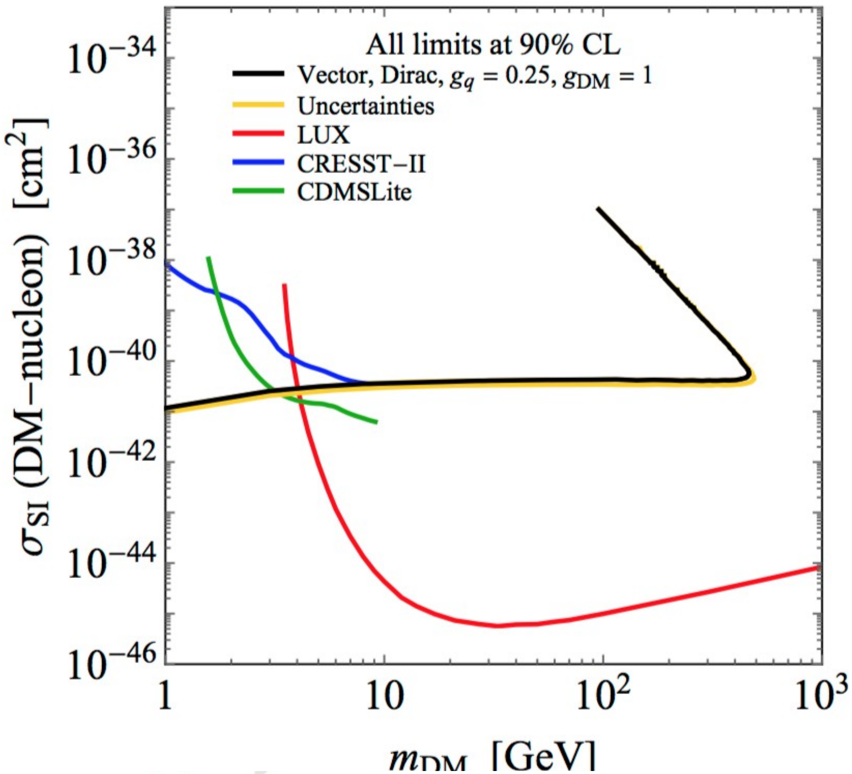
Comparison with Direct Detection

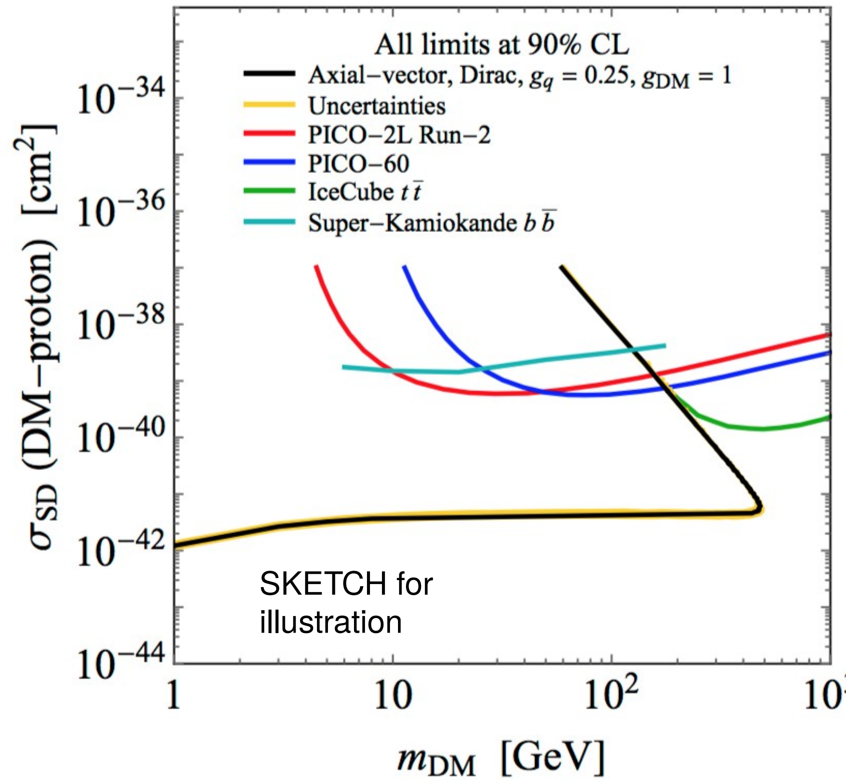




A comparison of collider results to the σ_{SI}-m_{DM} (a) and σ_{SD}-m_{DM} (b) planes. Unlike in the mass-mass plane, the limits are shown at 90% CL. The LHC contour in the spin-independent [spin-dependent] plane is for a vector [axial-vector] mediator, Dirac DM and couplings g_q = 0.25 and g_{DM} = 1. The LHC spin-independent exclusion contour is compared with the LUX, CDMSLite and CRESST-II limits, which are the most con- straining in the mass range shown. The spin-dependent exclusion contour constrains the DM-proton cross-section and is compared with limits from the PICO experiments. The shown collider results are intended for illustration only and are not based on real data.

Comparison with Direct Detection





Vector:

$$\sigma_{SI} = \frac{9\, g_q^2\, g_{DM}^2\, \mu_{n\chi}^2}{\pi M_{med}^4}$$

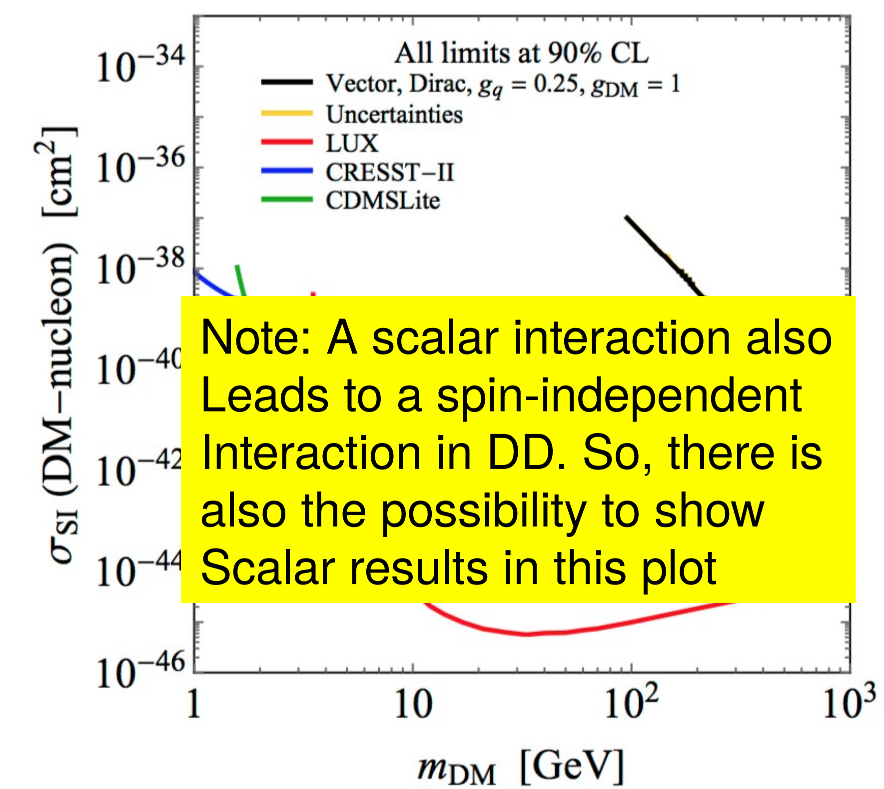
$$\approx 1.1 \times 10^{-39}\ \text{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \text{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \text{GeV}}\right)^2$$

Axial-Vector:

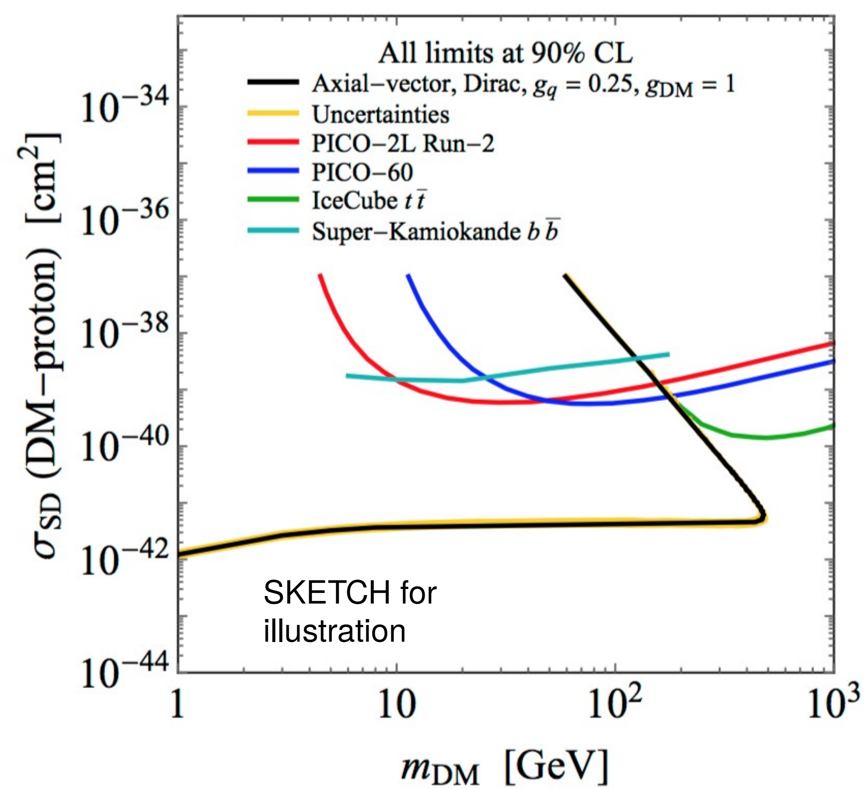
$$\sigma^{SD} \approx 3.8 \times 10^{-41}\ \text{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \text{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \text{GeV}}\right)^2$$

Provide simple formulas to perform the translation of the Mass-mass plane results into these planes. A full derivation of these formulas along with assumptions/caveat discussions is provided in the report.

Comparison with Direct Detection



Note: A scalar interaction also Leads to a spin-independent Interaction in DD. So, there is also the possibility to show Scalar results in this plot



Scalar:

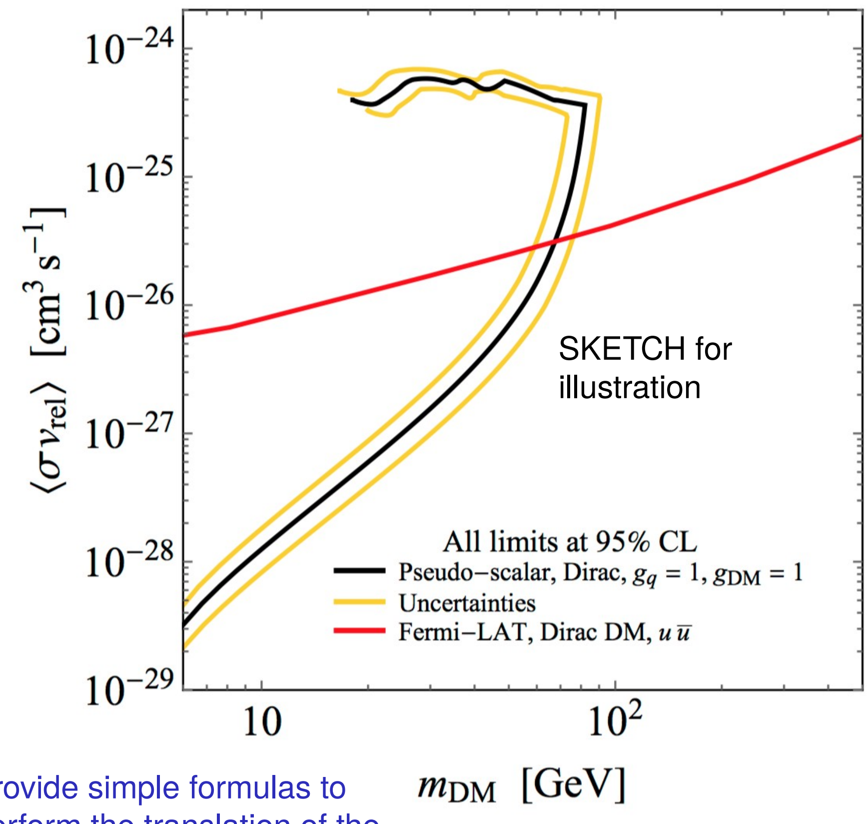
$$\sigma_{SI} \approx 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{125\ \mathrm{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

Axial-Vector:

$$\sigma^{SD} \approx 3.8 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

Provide simple formulas to perform the translation of the Mass-mass plane results into these planes. A full derivation of these formulas along with assumptions/caveat discussions is provided in the report.

Comparing with Indirect Detection



Due to additional velocity suppression DD experiments, Have partially know limits on Pseudo-Scalar (PS) mediators.

Hence for PS we compare with ID

Again; spelling out basic assumptions on the plot and accompanying documentation is strongly recommended.

Provide simple formulas to perform the translation of the Mass-mass plane results into these planes. A full derivation of these formulas along with assumptions/caveat discussions is provided in the report.

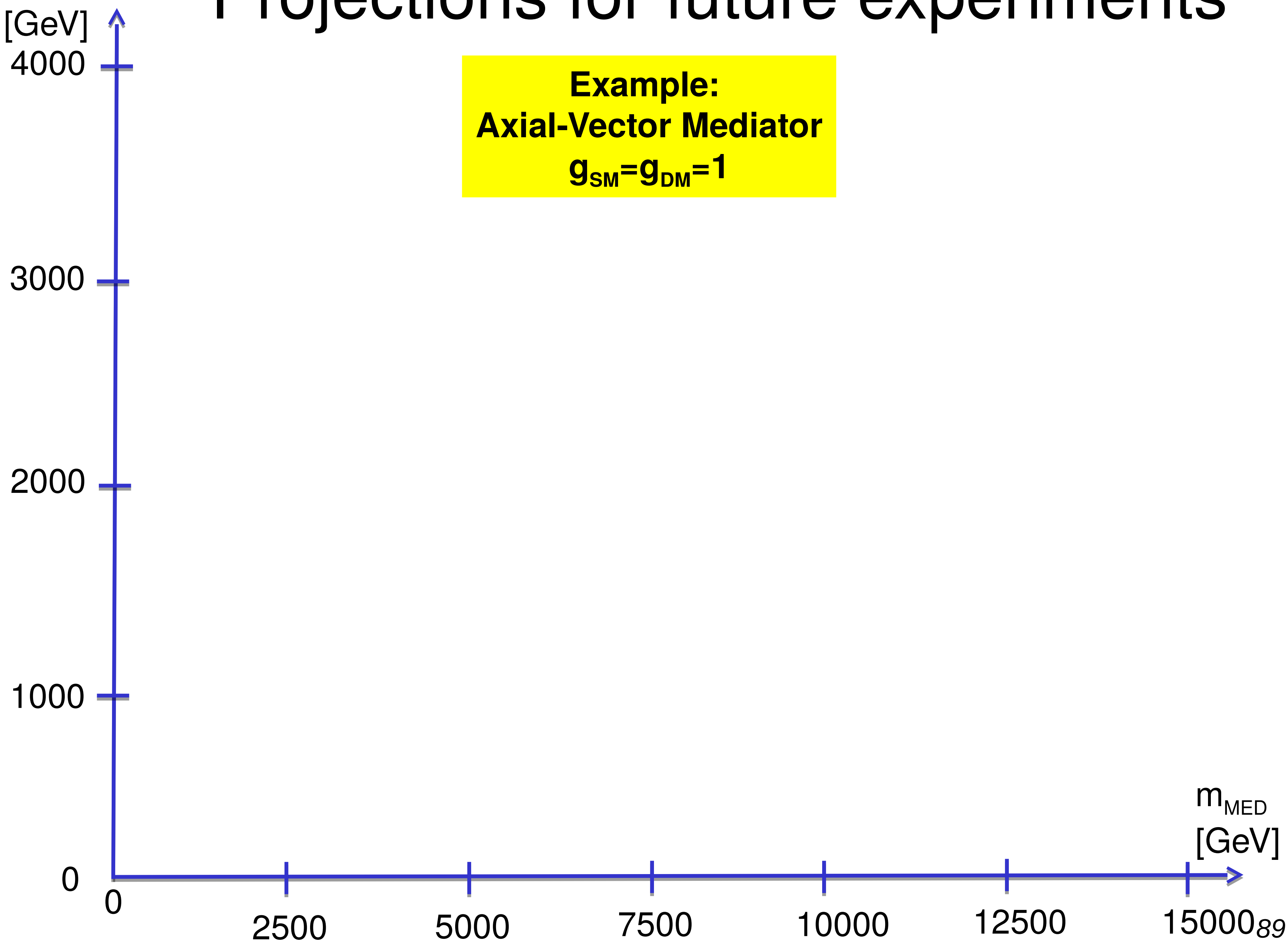
$$\langle \sigma v \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_{\rm DM}^2 \, g_q^2 \, m_{\rm DM}^2}{(M_{\rm med}^2 - 4 m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

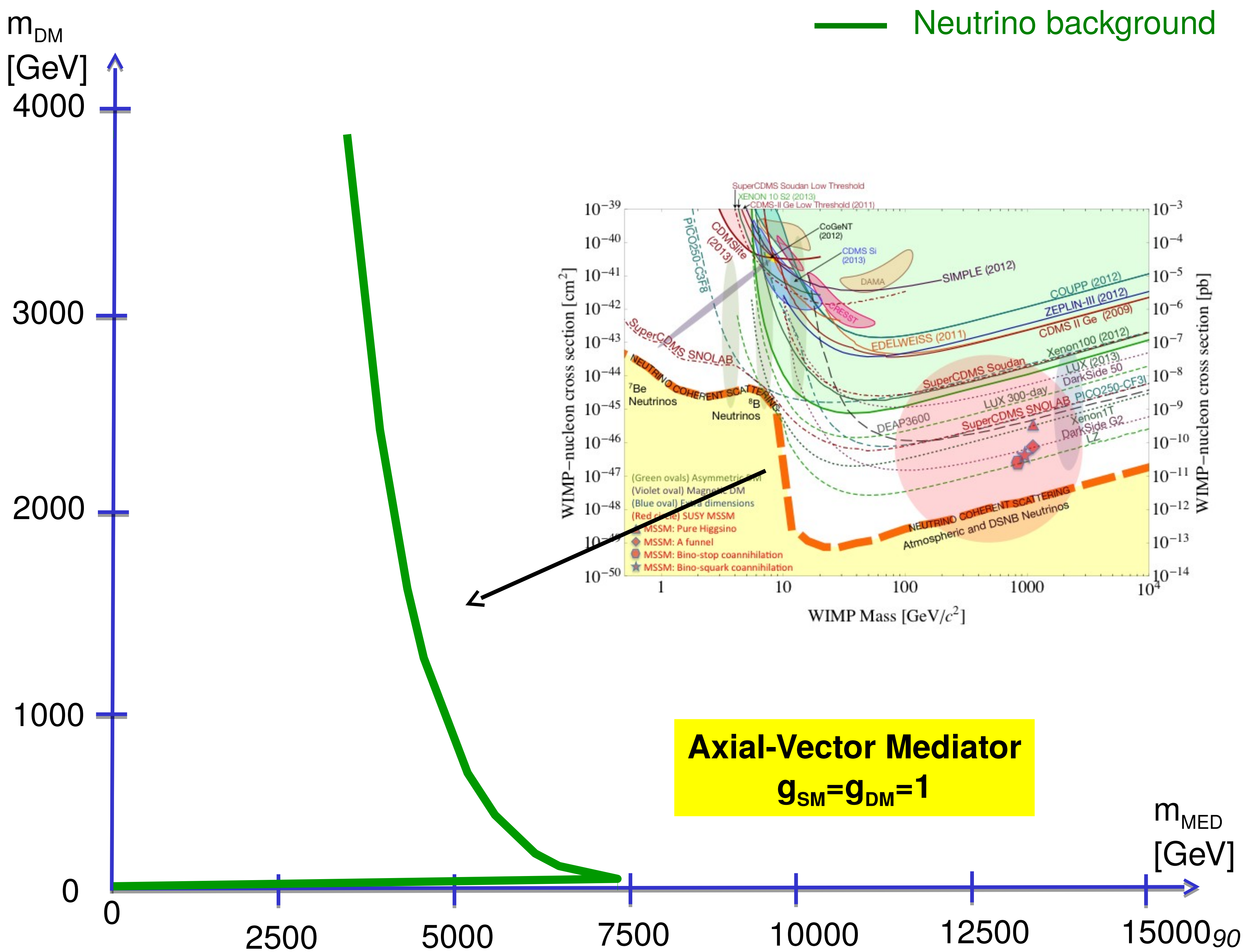
Summary

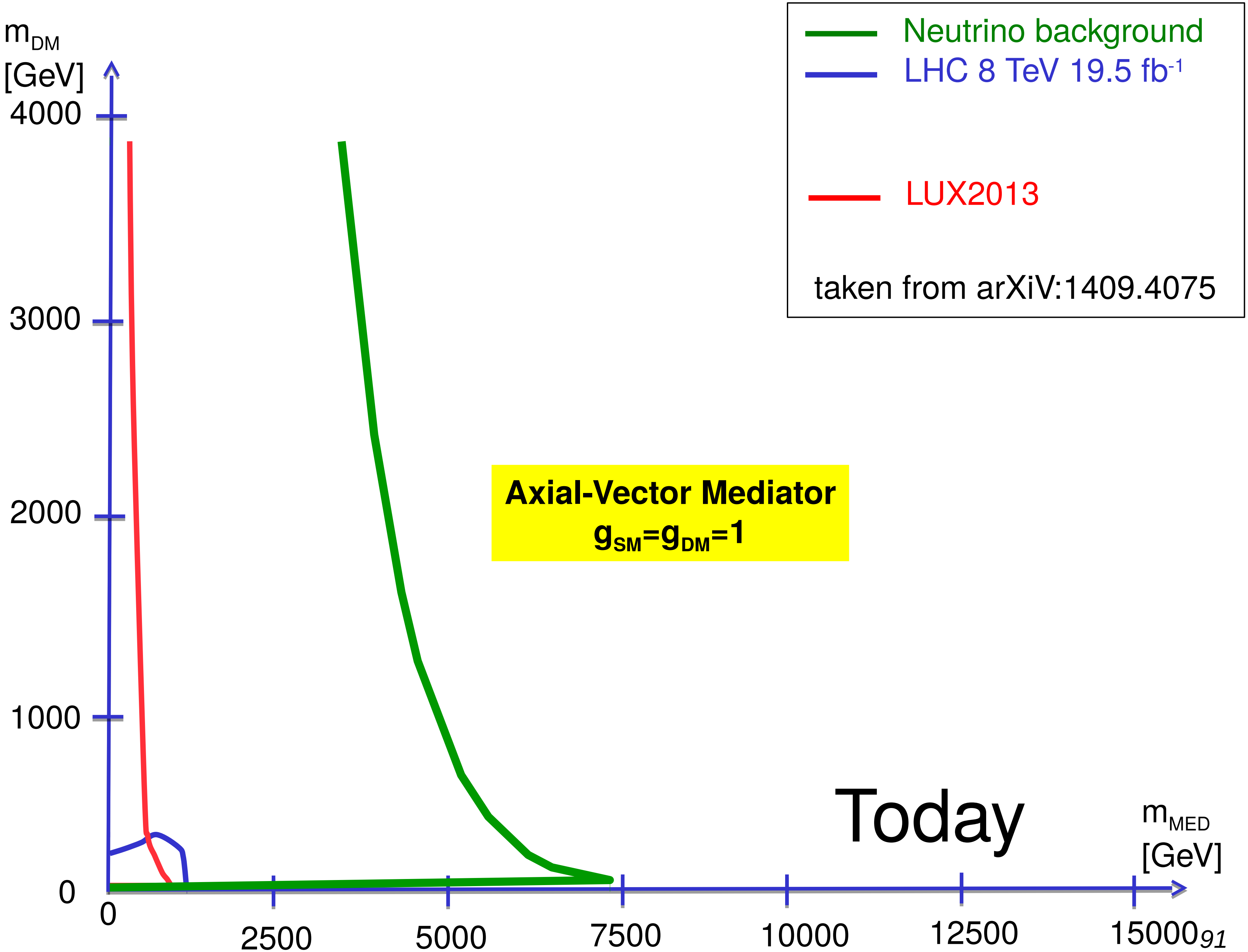
- Based on the WG workshop in December 2015 the LHC DM WG conveners in addition with interested and experienced theorists and experimentalists have put together a recommendation on how to present and compare collider DM searches using simplified models.
- The main purpose of the report is to establish a comprehensive summary of the wealth of available material accompanied with a hands-on description for the experiments on how to perform the presentations.
- A strong emphasis has been put on carefully outlining and discussing the assumptions and caveats coming along with this approach.
- This recommendation is by no means exhaustive and, as many other things in this developing field, will be subject to changes in the future – i.e. this is not cast in stone but it seems a very good starting base.

Projections for future experiments

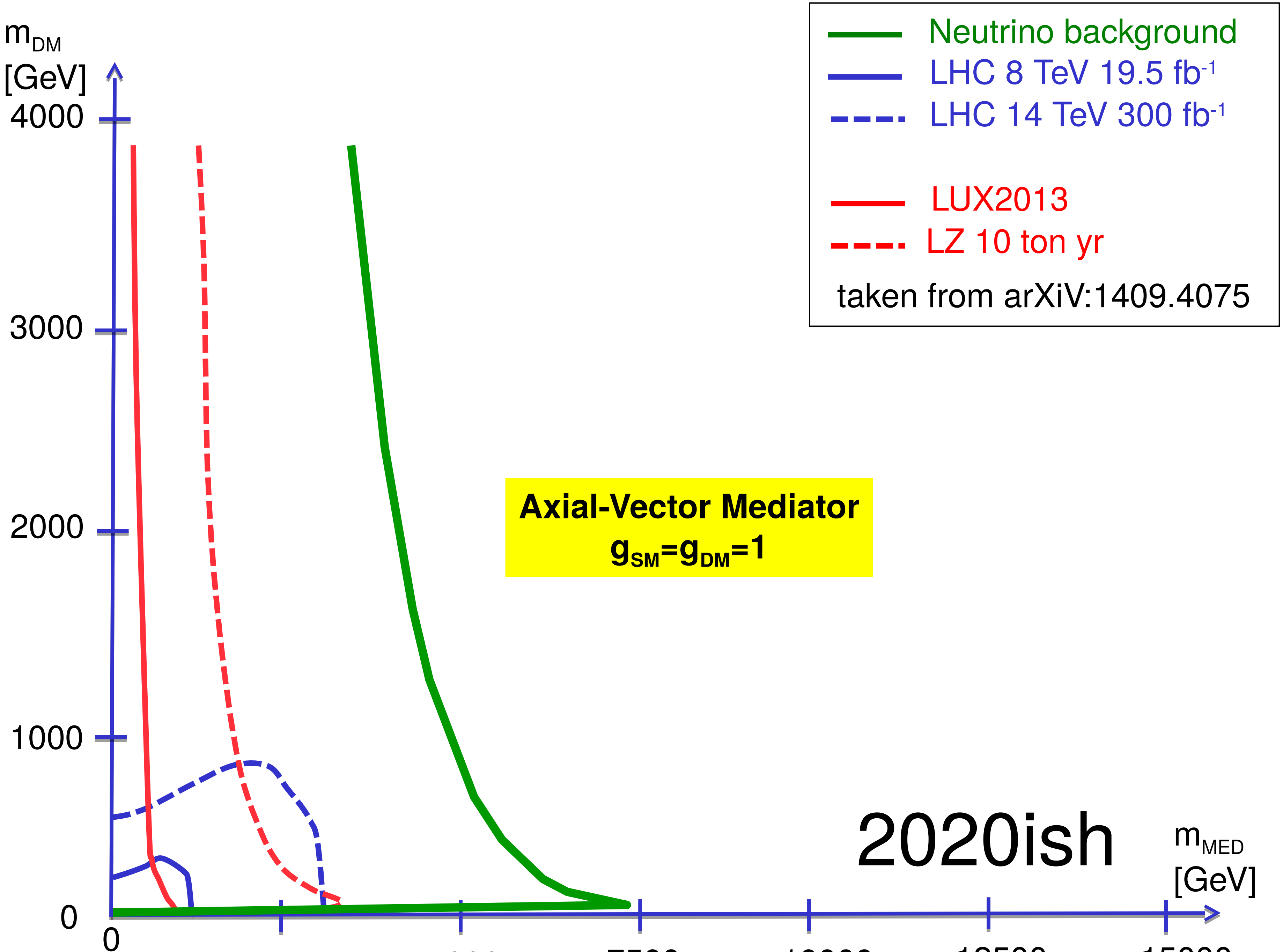
Example:
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$



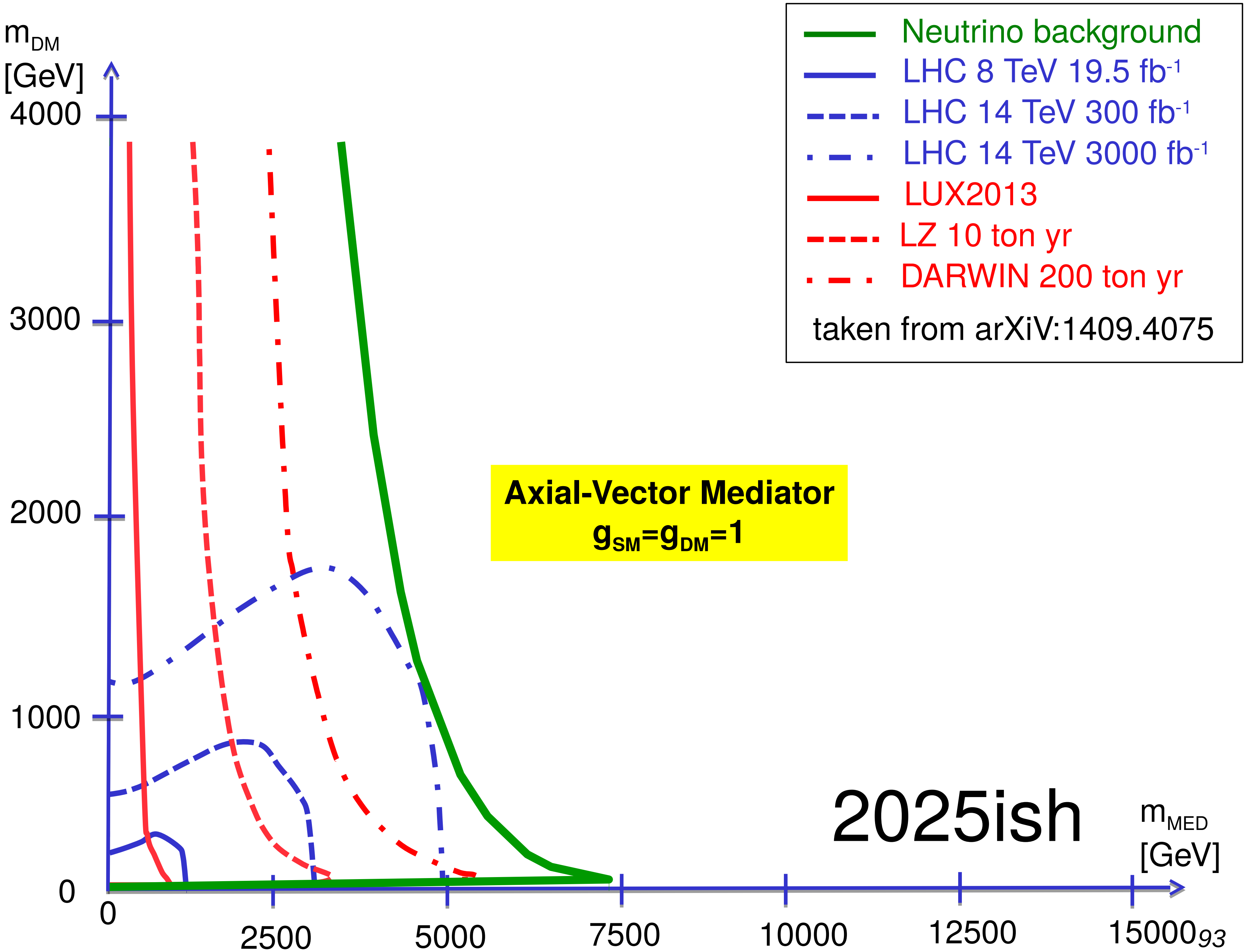

Neutrino background
m_{DM} [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
CDMSlite (2013)
PICO250-C3F8
SuperCDMS SNOLAB
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
PICO250-CF3I
LUX 300-day
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
DEAP3600
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation

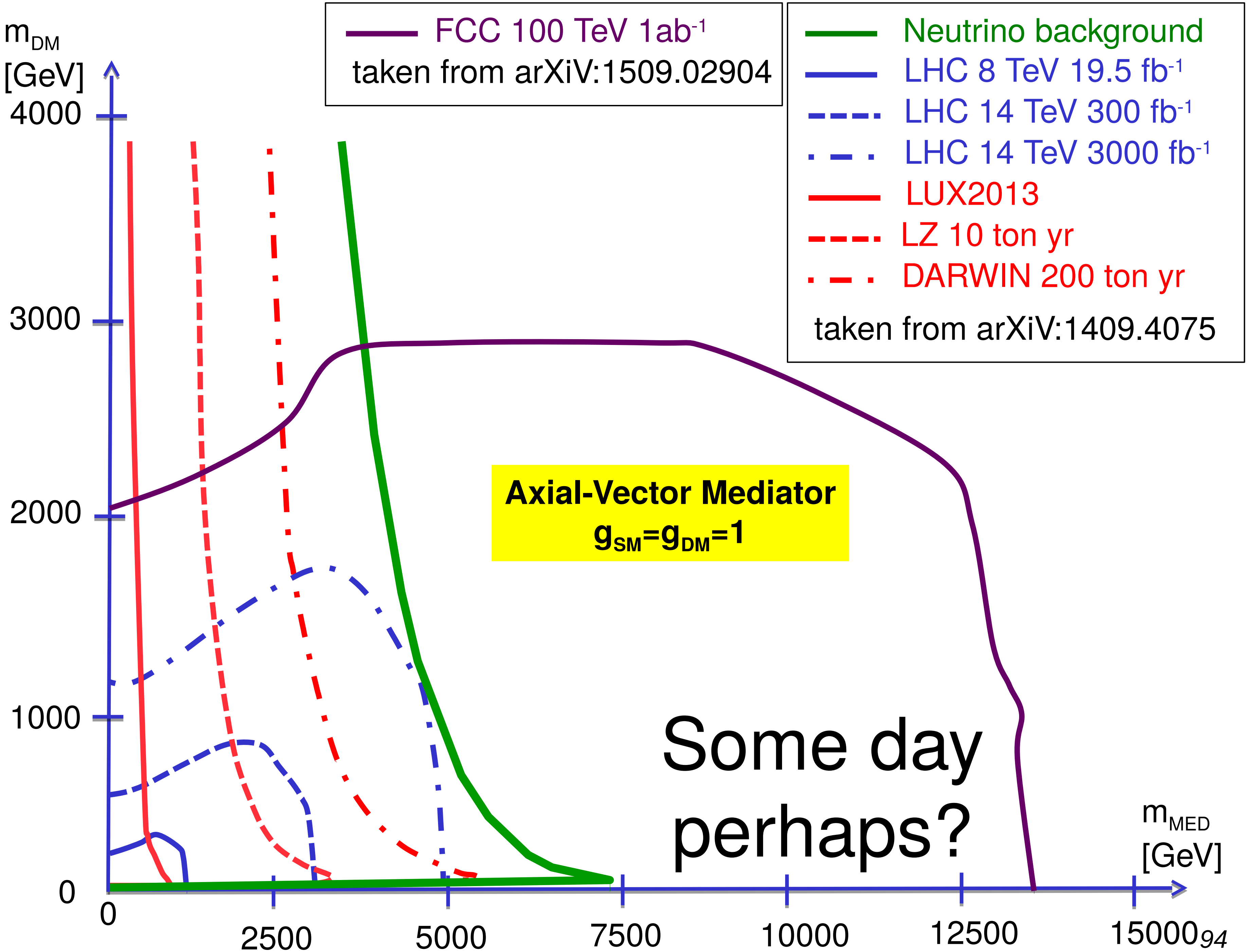


m_{DM} [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LUX2013
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Today

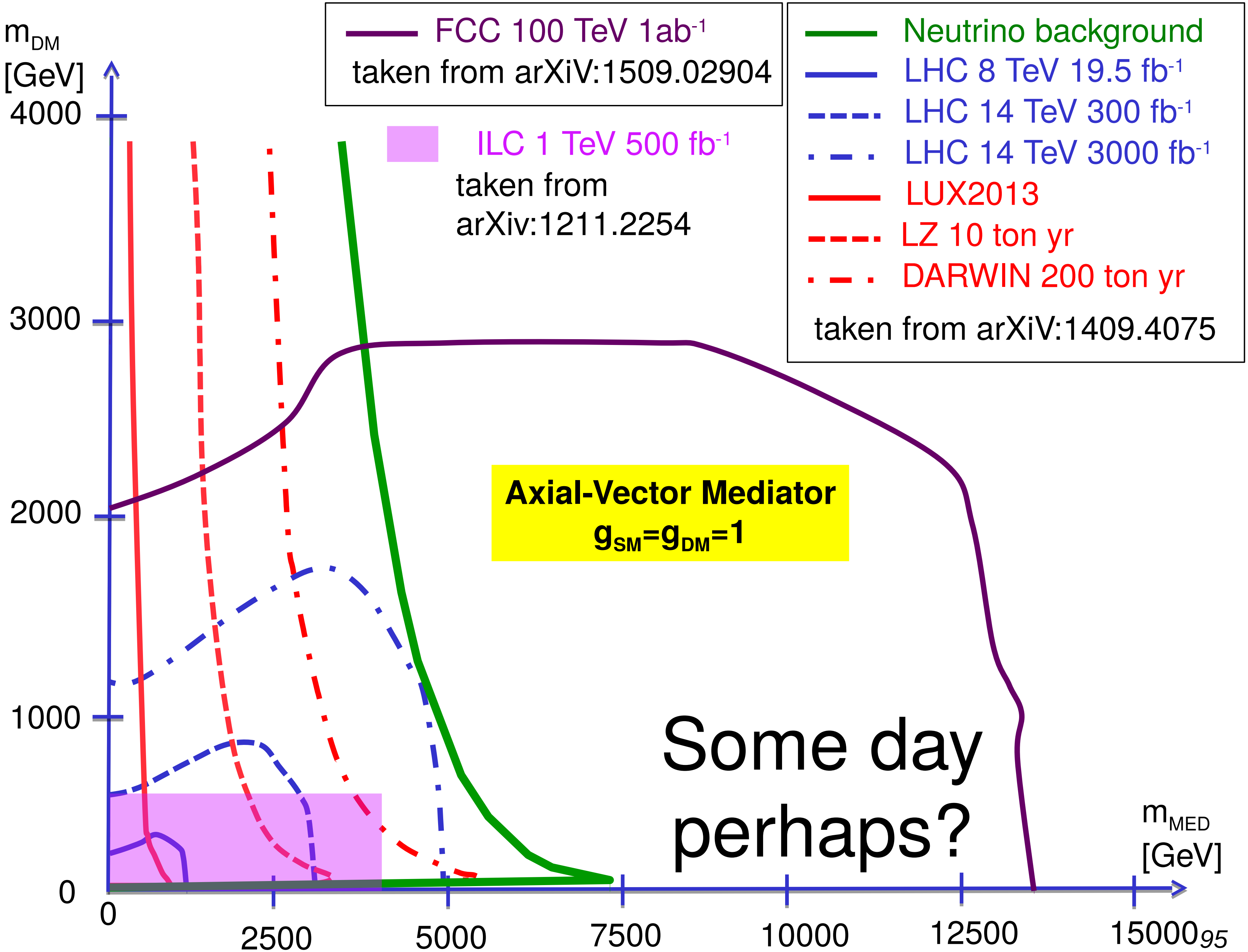


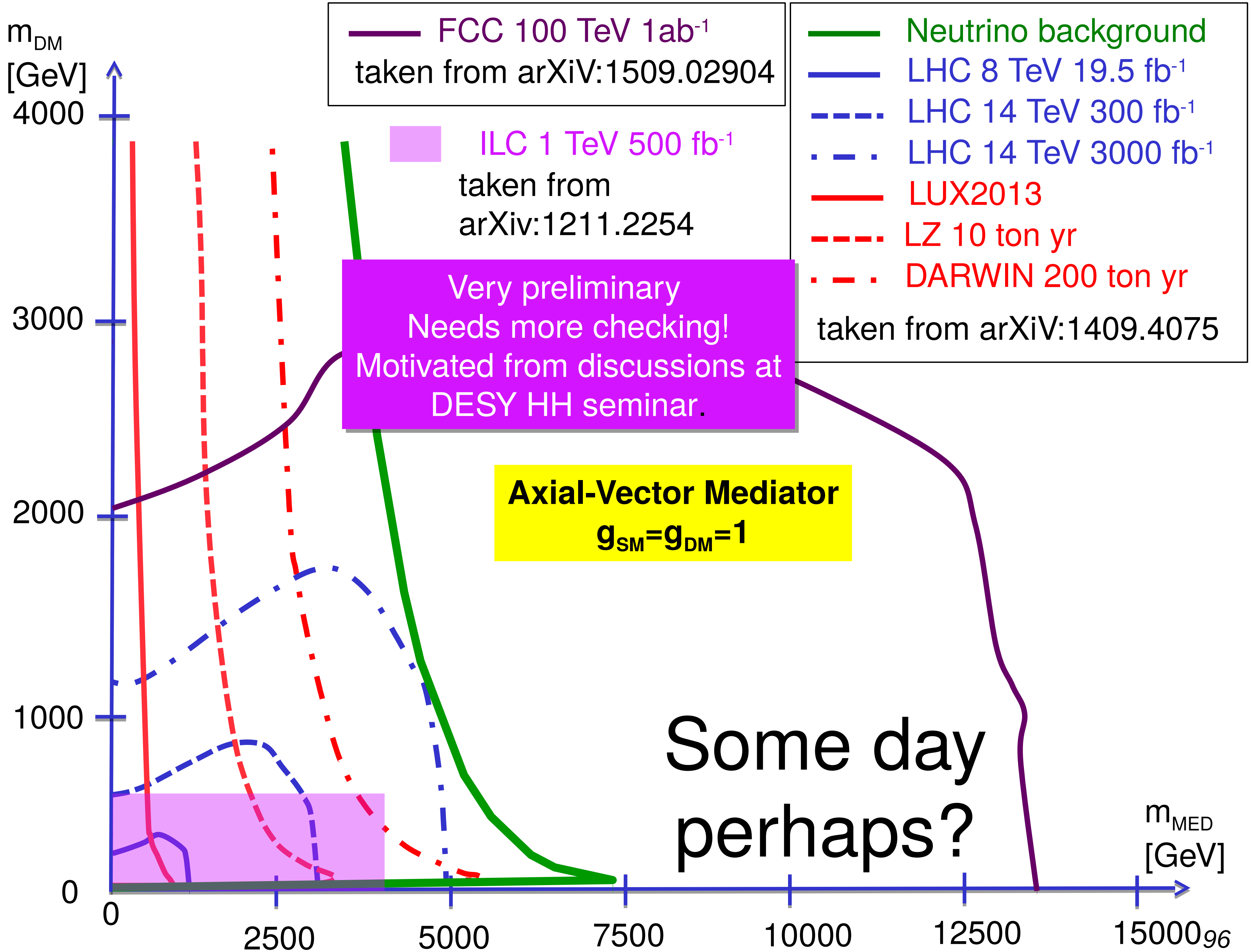
m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LUX2013
LZ 10 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
g_SM=g_DM=1
2020ish


m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
gSM=gDM=1
2025ish



FCC 100 TeV 1ab-1
taken from arXiV:1509.02904
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
mDM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
mMED [GeV]
Axial-Vector Mediator
gSM=gDM=1
Some day perhaps?


m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
FCC 100 TeV 1ab-1
taken from arXiV:1509.02904
ILC 1 TeV 500 fb-1
taken from arXiv:1211.2254
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
g_SM=g_DM=1
Some day perhaps?



m_{DM} [GeV]
4000
3000
2000
1000
0
FCC 100 TeV 1ab^{-1}
taken from arXiV:1509.02904
ILC 1 TeV 500 fb^{-1}
taken from arXiv:1211.2254
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LHC 14 TeV 3000 fb^{-1}
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Very preliminary
Needs more checking!
Motivated from discussions at
DESY HH seminar.
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Some day
perhaps?
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000

Outlook: 8 TeV vs 14 TeV

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

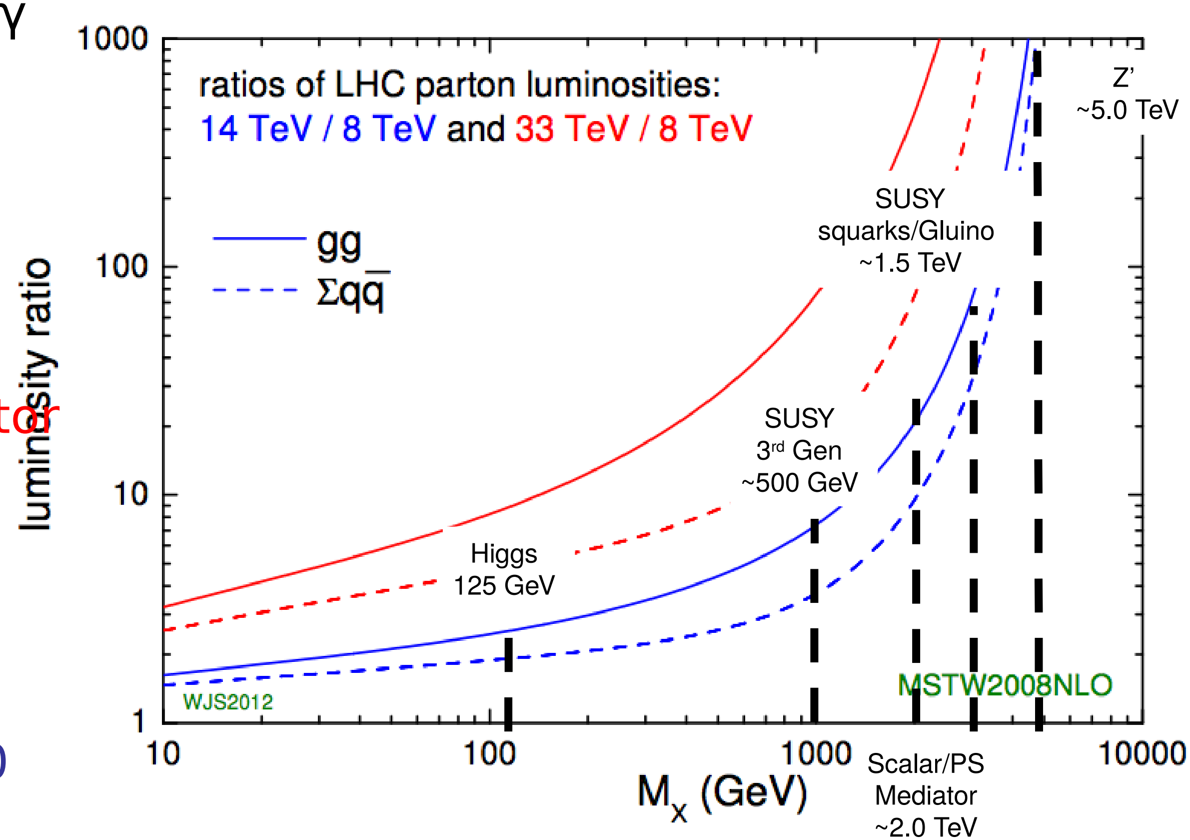
Higgs:
pp → H, H → WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

Scalar/Pseudoscalar Mediator
Mass scale ~ 2.0 TeV
gg: factor ~20

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

Vector/Axialvector a la Z' :
Mass scale ~ 5 TeV
qq: factor ~1000



Increase in energy will help a lot!

Summary

- *So far New Physics has not revealed itself!*
  - *Even by 2010 the LHC has enter new territory for New Physics searches and since pushed e.g. the (coloured) SUSY mass scale to the ~1 TeV scale*
  - *We were well prepared for an early discovery but we also knew that it could take more time and ingenuity before we can claim a discovery (if NP exist)*
- *The LHC experiments have established an impressive variety of very powerful direct searches for many different final states!*
  - *Based on these results we need to establish the "big picture" in order to understand if/where our search strategy might have weak spots or even holes!*
  - *This requires appropriate interpretations of the searches and a MEANIGFUL comparison with other experiments – important example DM searches!*

BACKUP

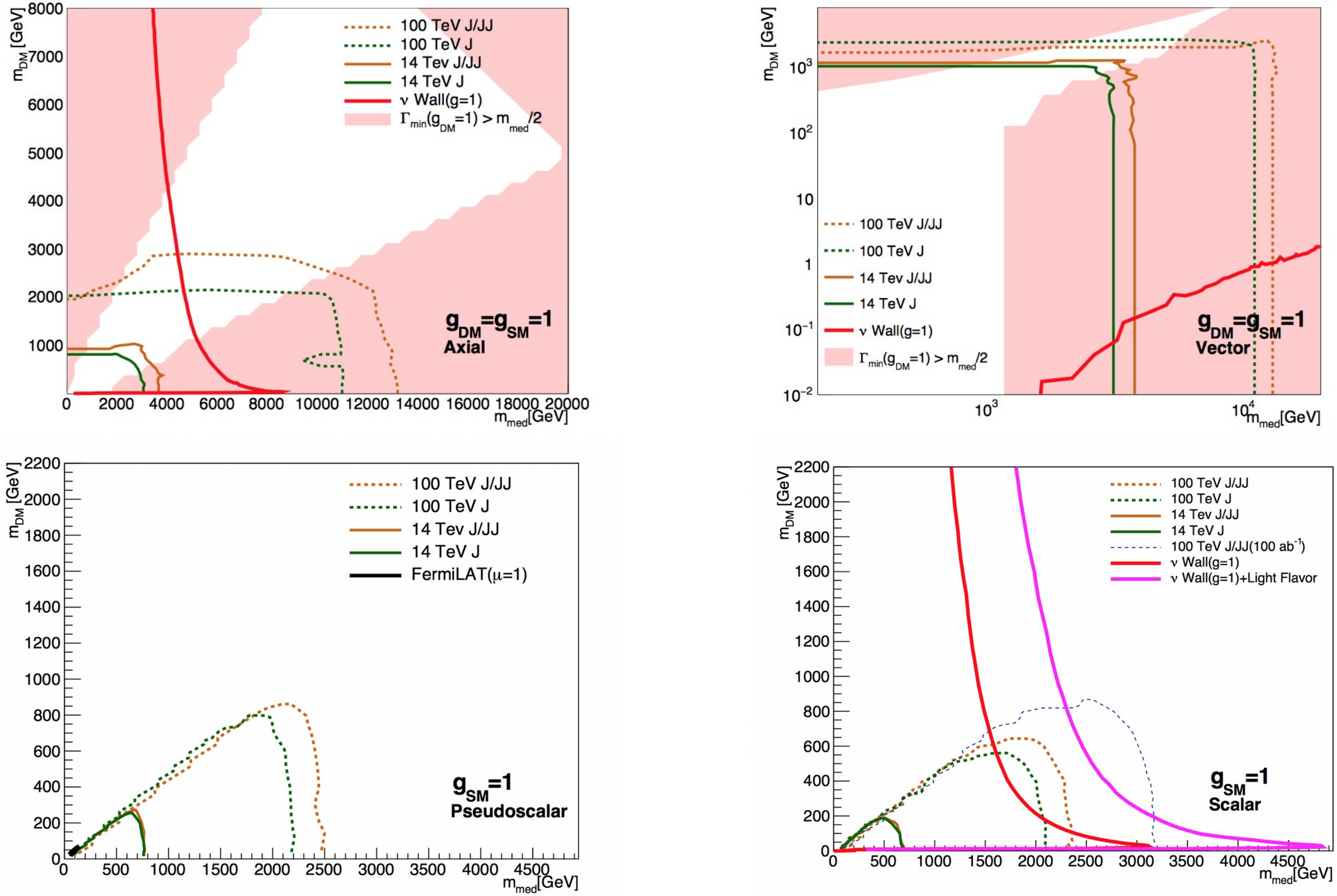
ATLAS & CMS public results

Most results presented in this talk (and many more) can be accessed via the public page of the ATLAS and CMS experiments:

ATLAS SUSY:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS SUSY
:https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

100 TeV Prediction from arXiv:1509.02904

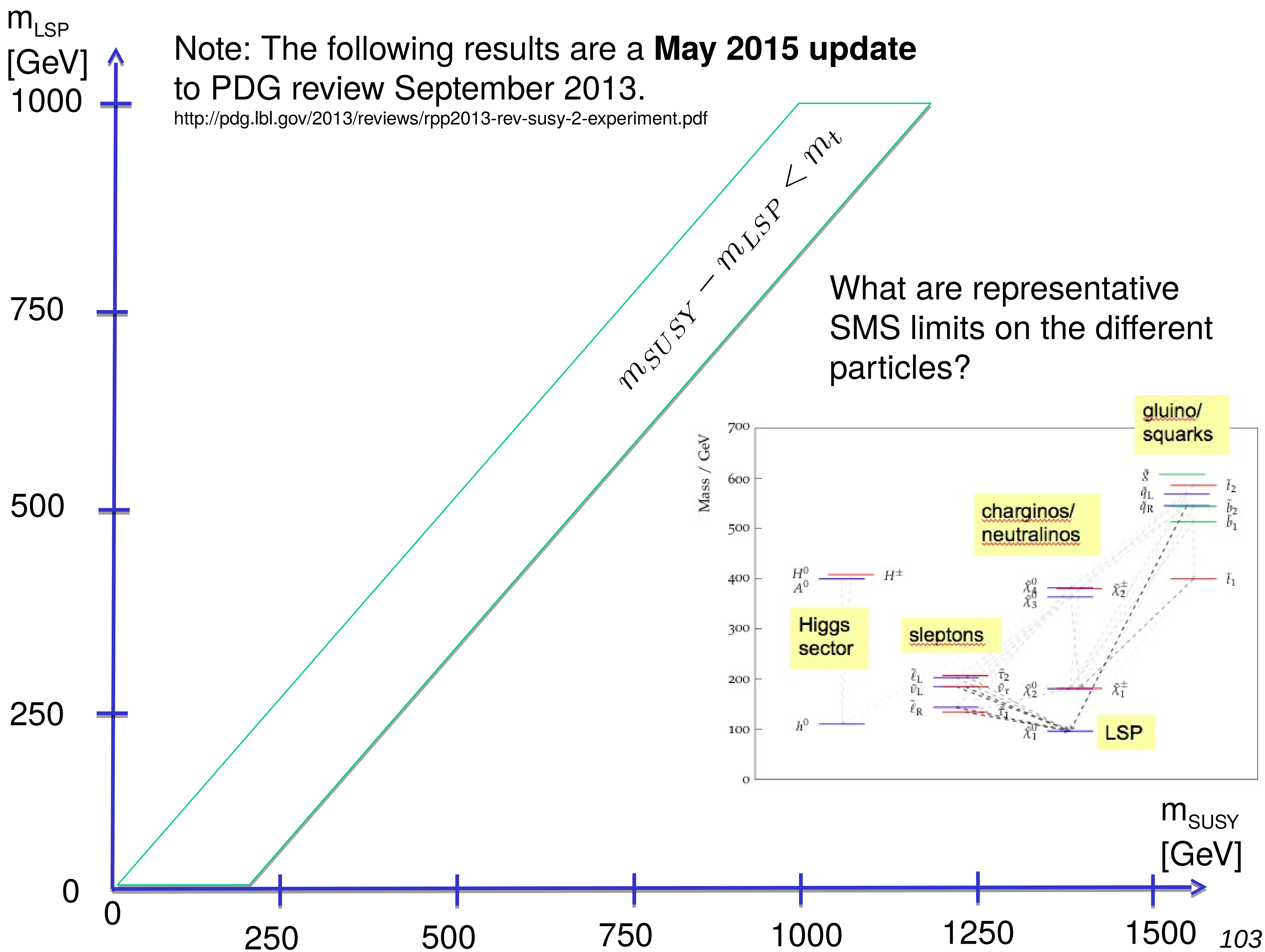


The full story

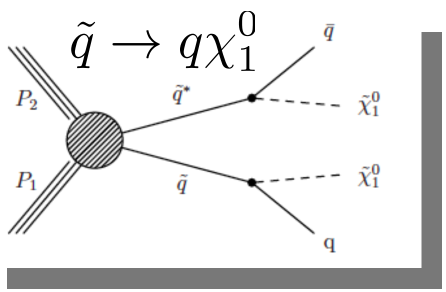
SUSY SUMMARY PLOT

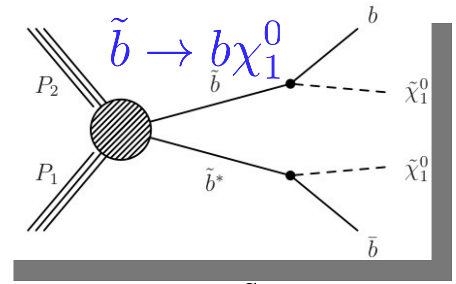
Note: The following results are a **May 2015 update** to PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

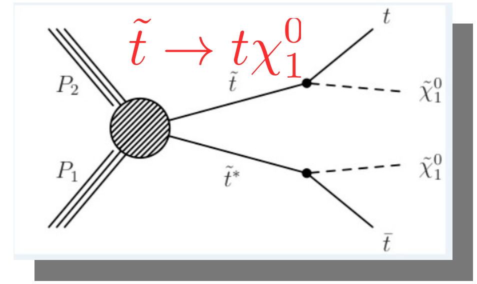
What are representative SMS limits on the different particles?

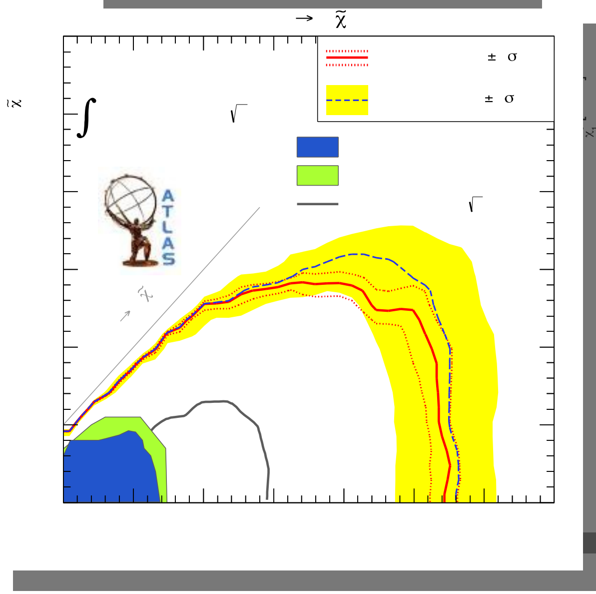


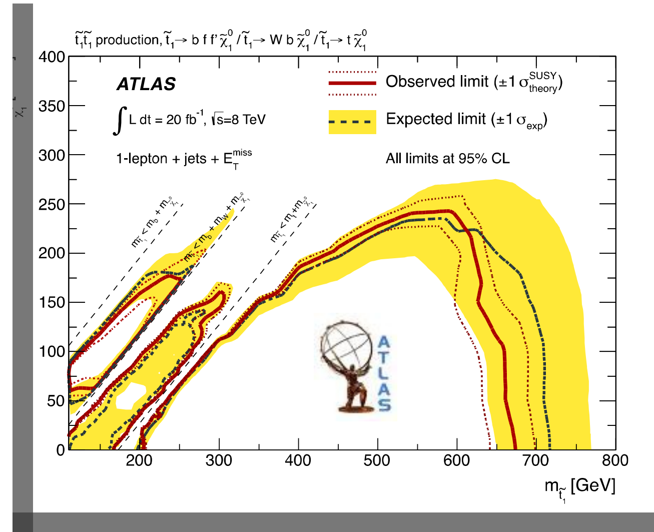
Direct squark production – chosen limits







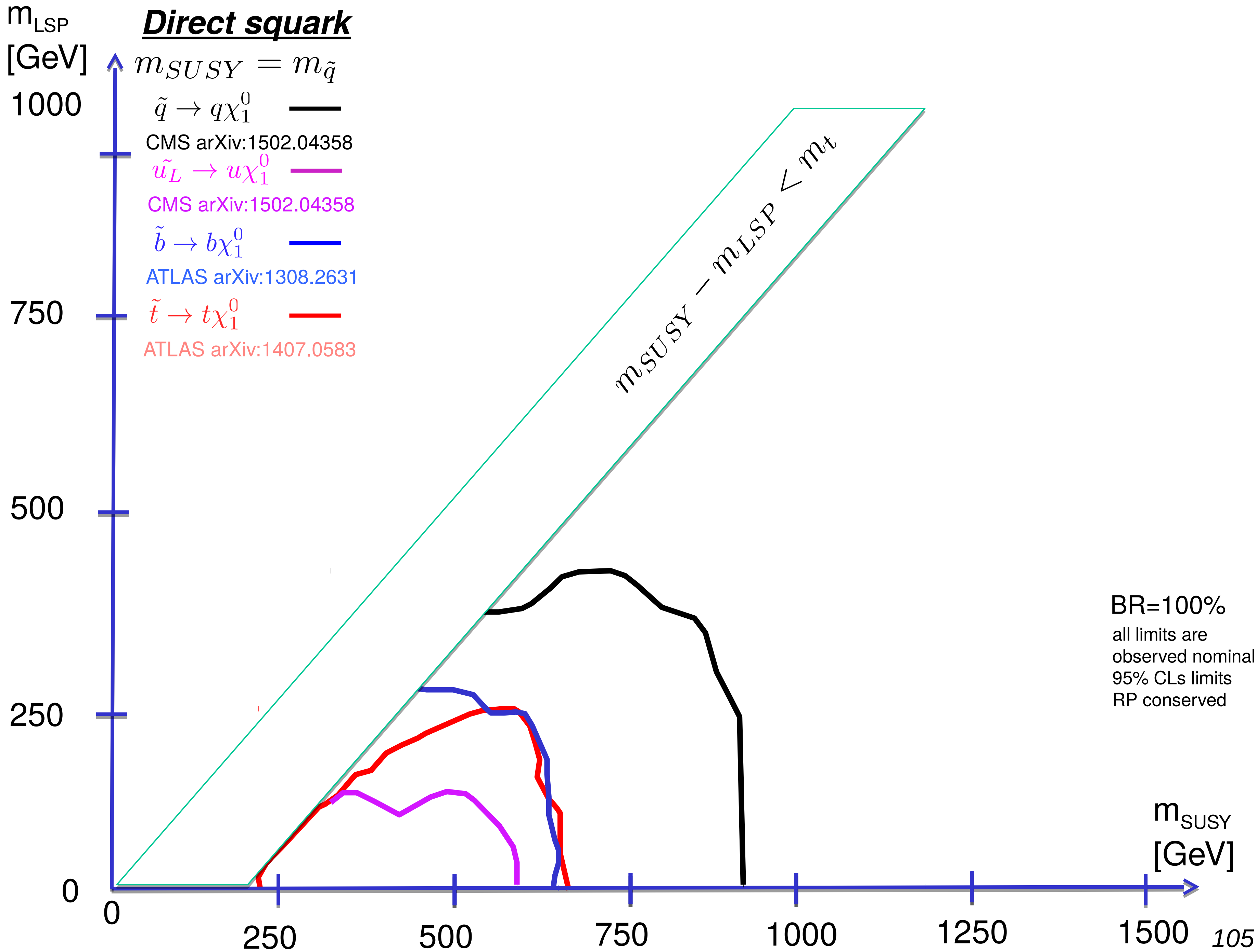




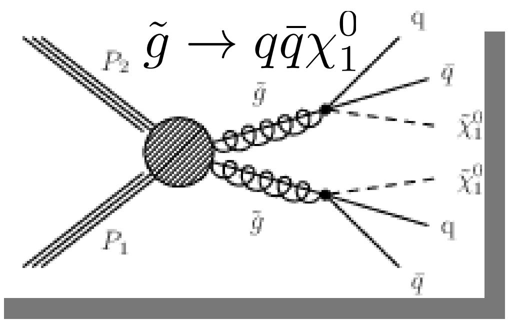
CMS arXiv:1502.04358
Signature: Jets + E_t^{miss} with M_{T2}
Limit assumes all 1st & 2nd gen squarks to be mass degenerate [or only one light squark]!

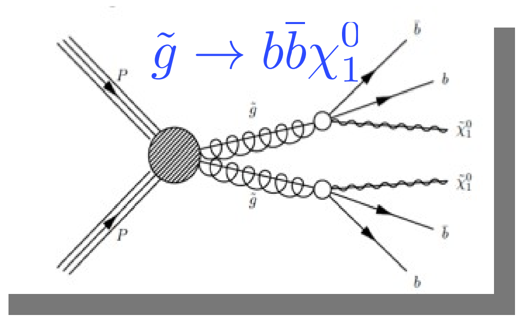
ATLAS arXiv:1308.2631
Signature: 2 b-jets + E_T^{mis}

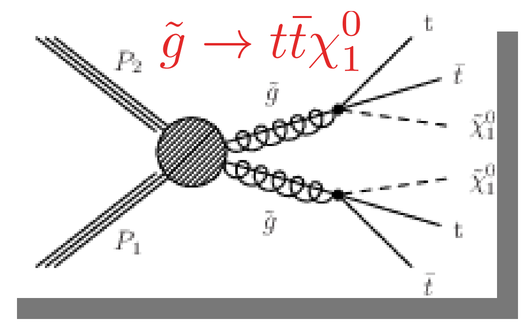
ATLAS arXiv:1407.0583
Signature: 1Lepton + jets + E_T^{mis}

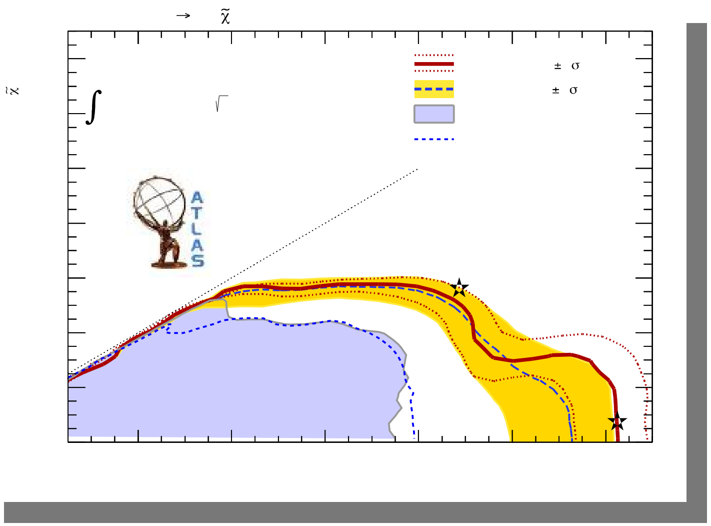

Direct squark
m_{LSP} [GeV]
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
$m_{SUSY} - m_{LSP} < m_t$
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

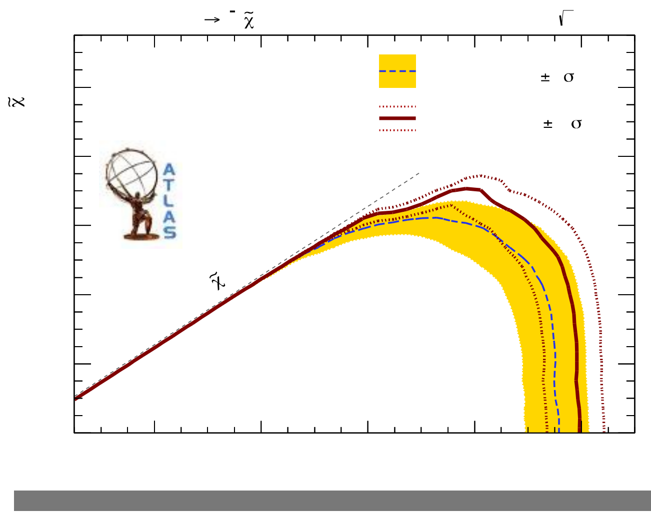
Gluino mediated squark production – limits chosen







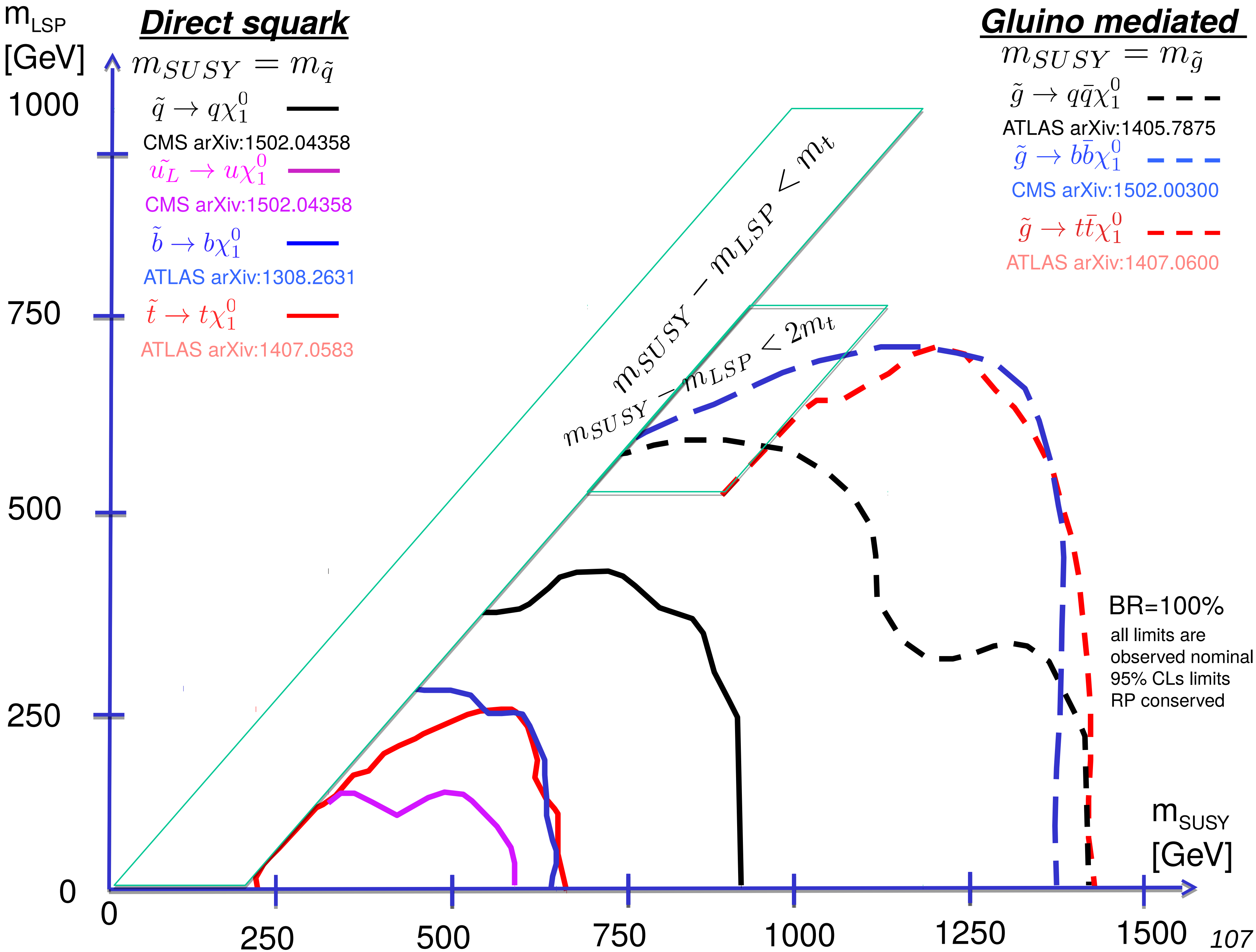




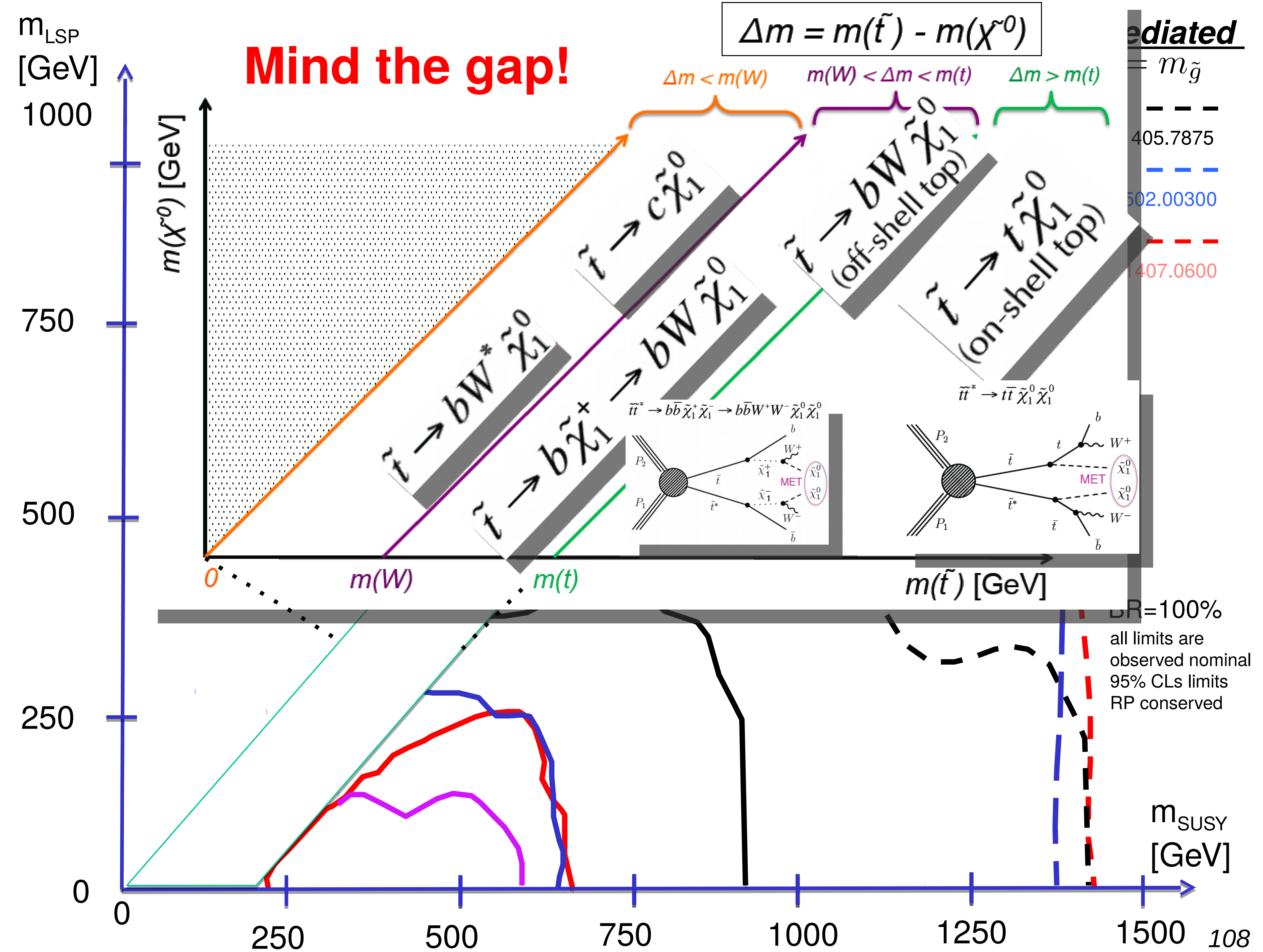
ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + E_t^{miss}

CMS arXiv:1502.00300
Signature: : 0L + Razor + b-tag

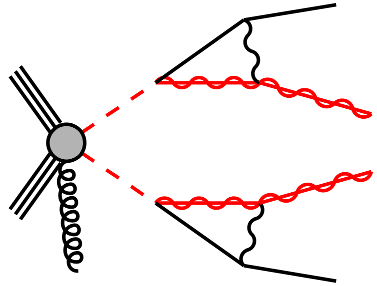
Signature: 0/1 Leptons + 3 b-tag + E_t^{mis}



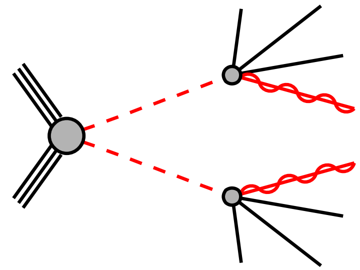
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
m_{LSP} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved


Mind the gap!
Δm = m(t̃) - m(χ̃⁰)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
m(χ⁰) [GeV]
m(t̃) [GeV]
0
m(W)
m(t)
t̃ → bW* χ̃₁⁰
t̃ → cχ̃₁⁰
t̃ → bχ̃₁⁺
t̃ → bW χ̃₁⁰
t̃ → bW χ̃₁⁰ (off-shell top)
t̃ → tχ̃₁⁰ (on-shell top)
MET
m_LSP [GeV]
m_SUSY [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
ediated
405.7875
502.00300
1407.0600
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

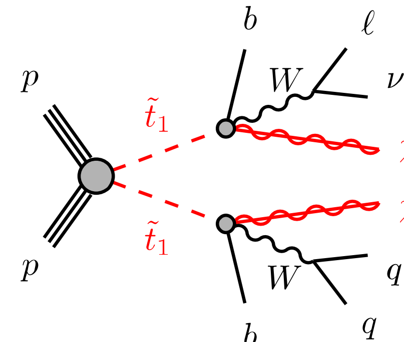
Compressed stop – mind the gap!



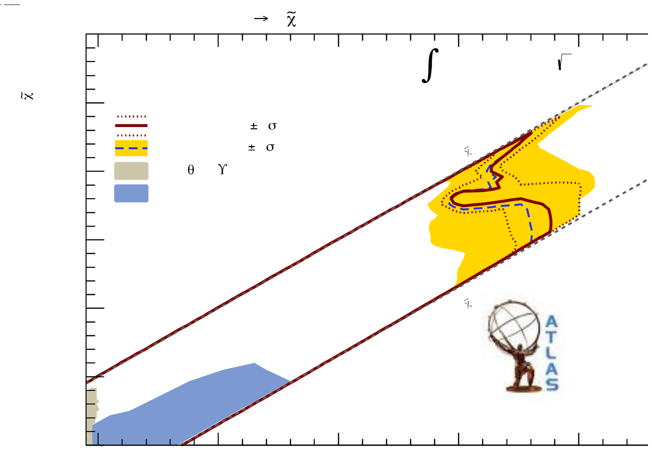
$\tilde{t} \to c\chi_1^0$

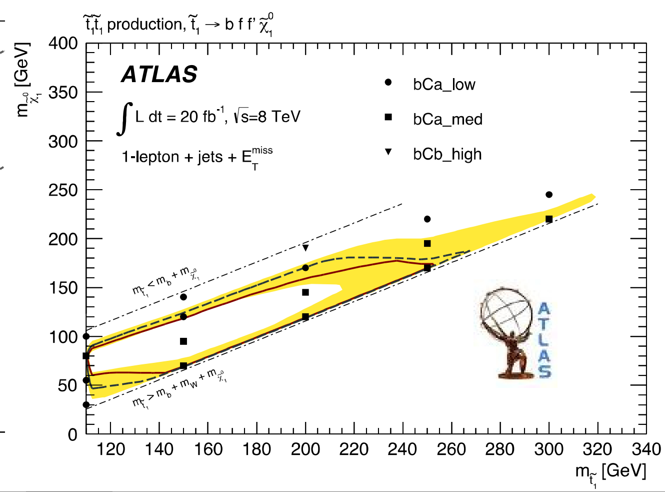


$\tilde{t} \to bff'\chi_1^0$



$\tilde{t} \to Wb\chi_1^0$

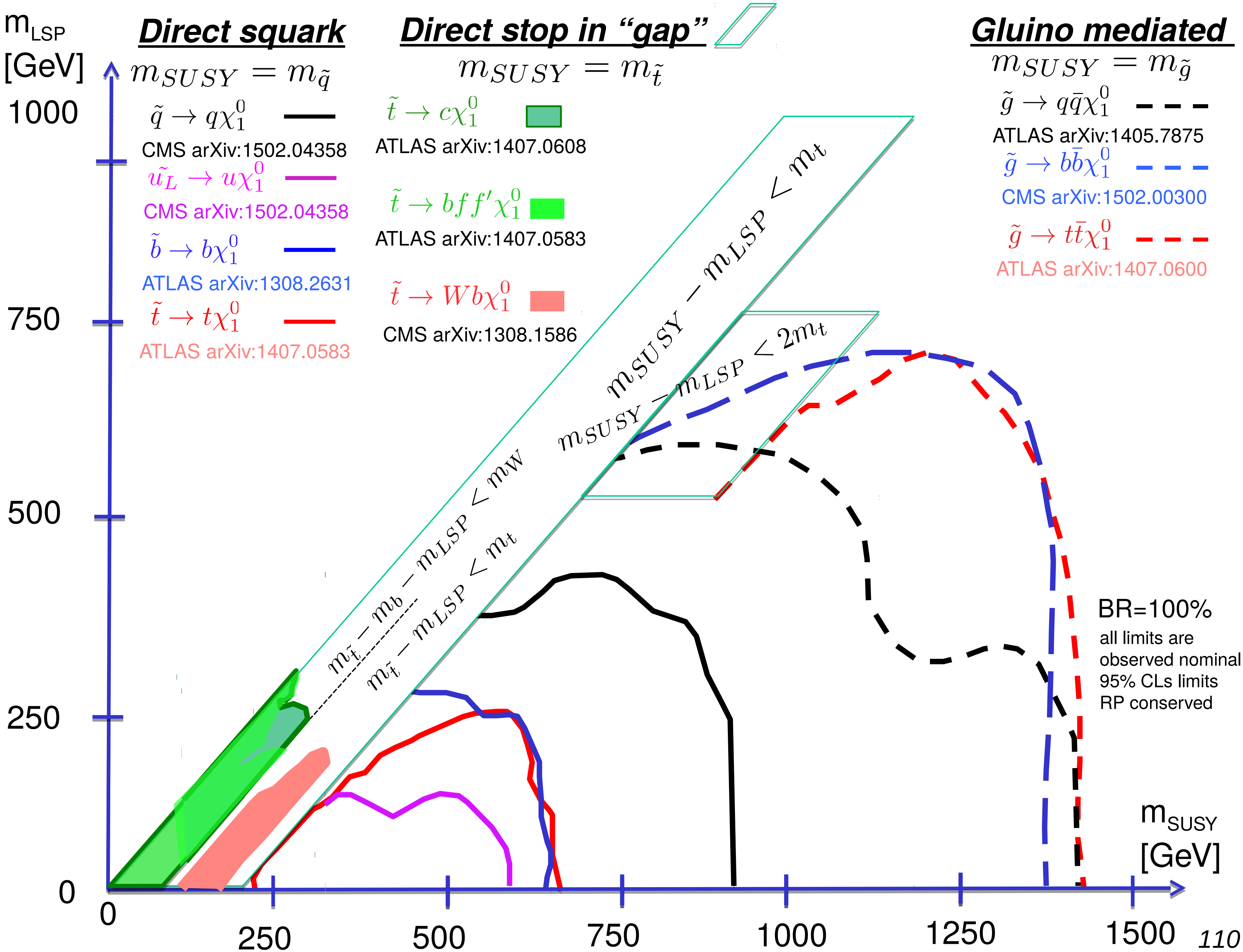




ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

ATLAS: arXiv:1407.0583
1L + E_t^{mis} & b-tag

CMS arXiv:1308.1586
1L + E_t^{mis} and BDT & b-tag

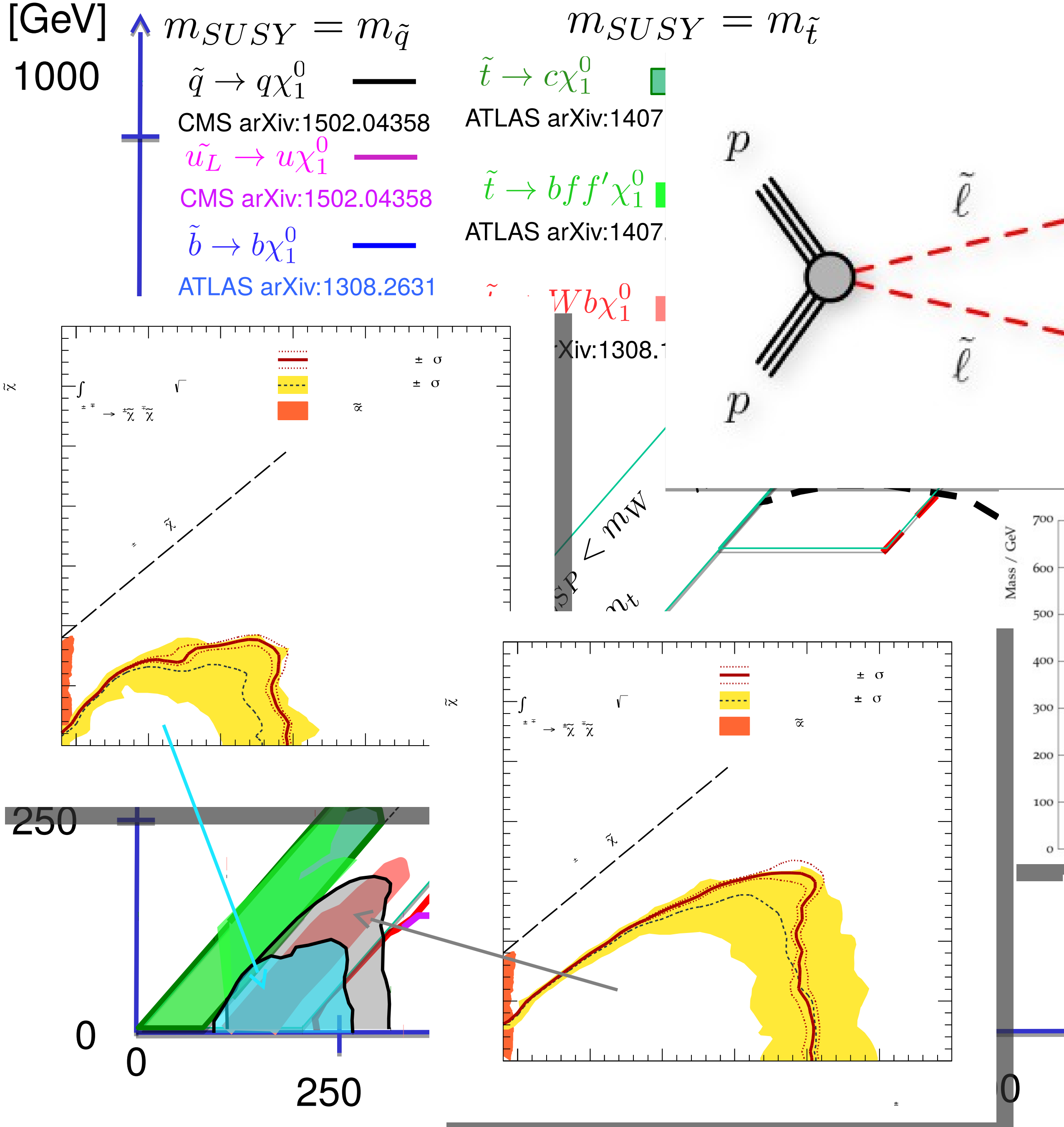

Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{LSP} [GeV]
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

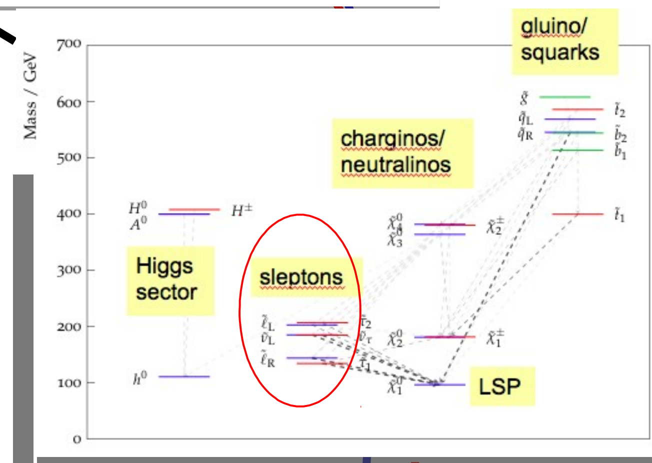
m_{LSP} [GeV]

Direct squark $m_{SUSY} = m_{\tilde{q}}$

Direct stop in “gap” $m_{SUSY} = m_{\tilde{t}}$

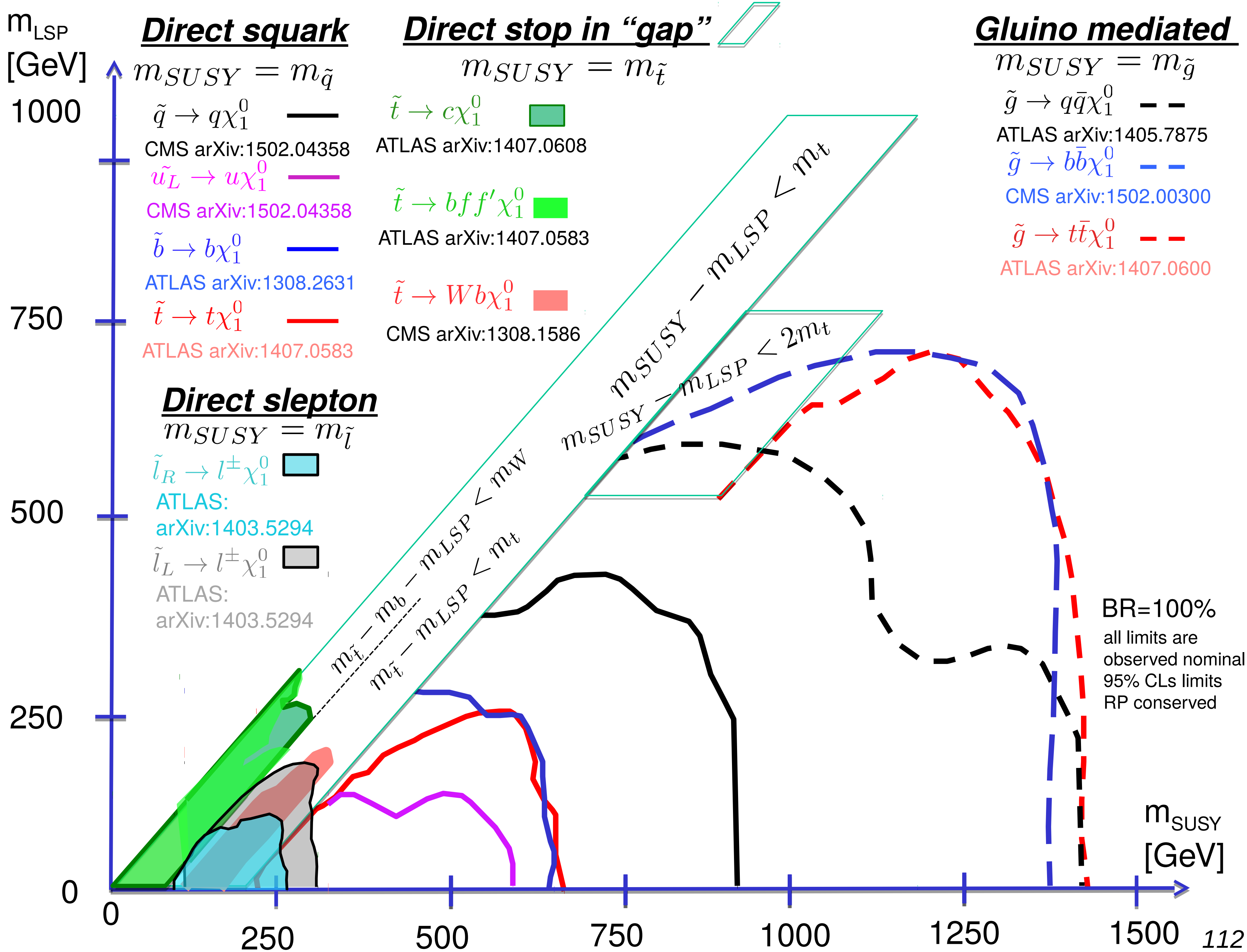
Gluino mediated $m_{SUSY} = m_{\tilde{g}}$





ATLAS arXiv:1403.5294

Signature
2 lepton + E_T^{miss}

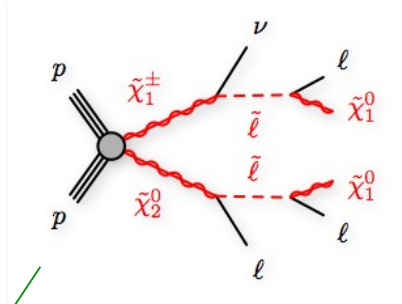


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

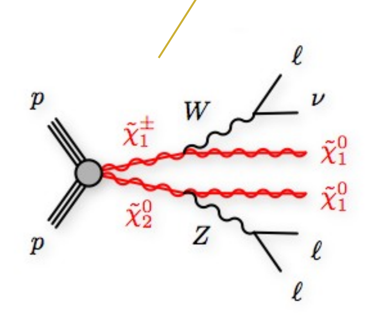
Searches @ Colliders - Lecture O. Buchmüller

Direct chargino/neutralino production

$X_2^0 X_1^{+-}$ production



CMS arXiv:1405.7570

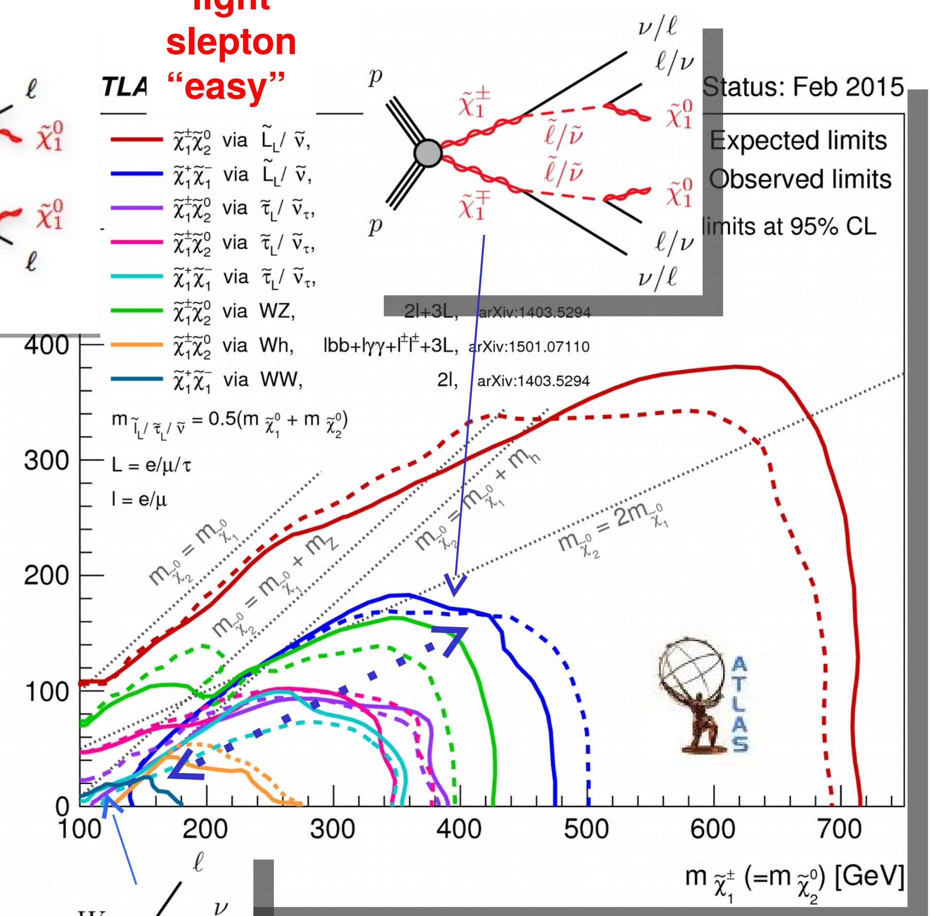


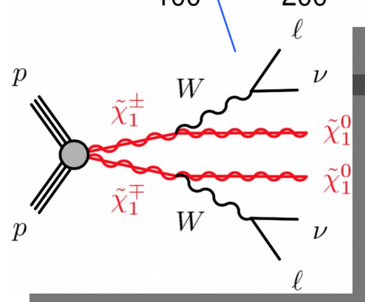
heavy slepton"hard(er)"

Add Z(l⁺l⁻)+2jets topology in bins of E_t^{miss} to increase sensitivity for "heavy" slepton case

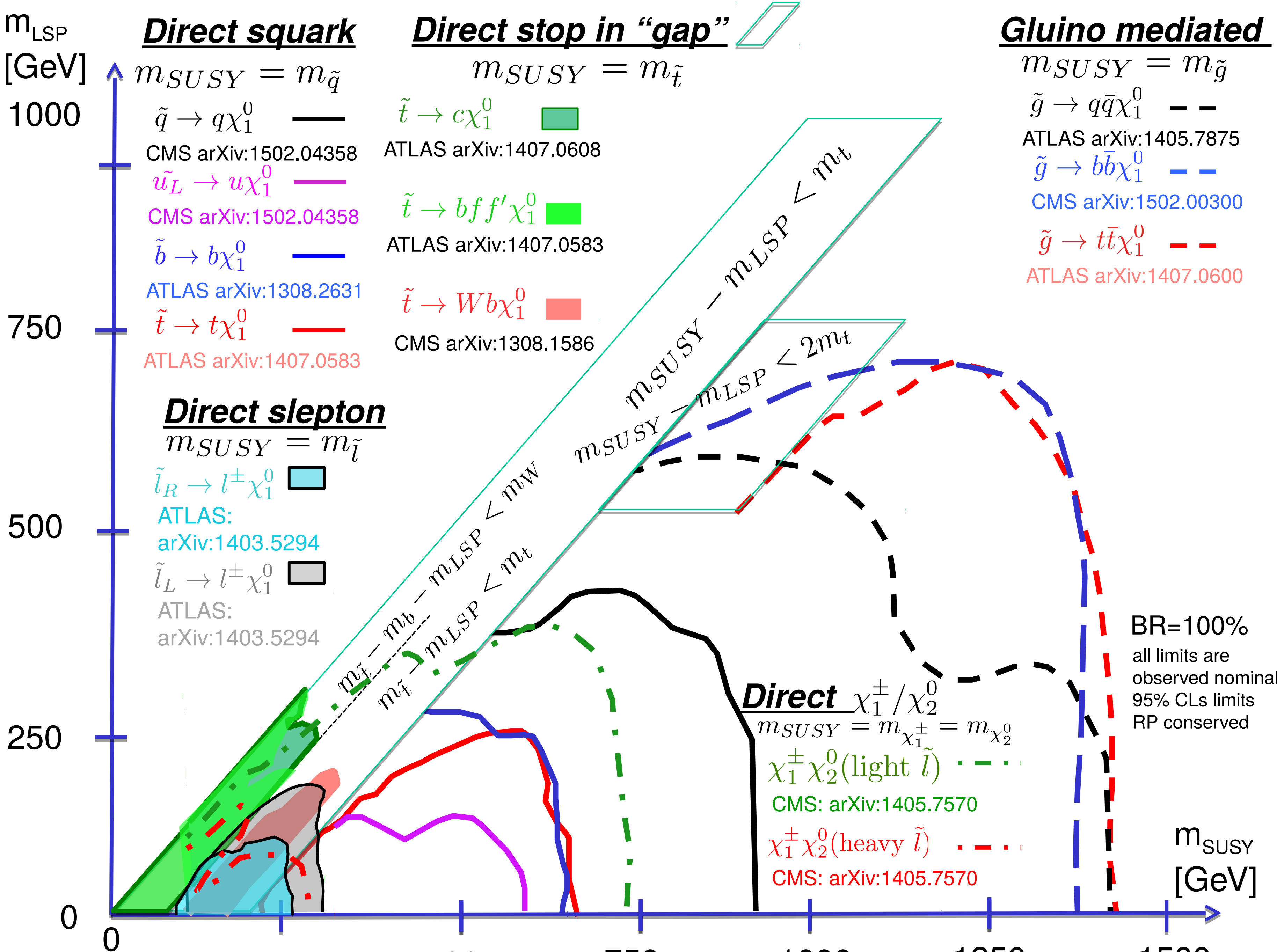
$X_1^+ X_1^-$ production

light slepton "easy"

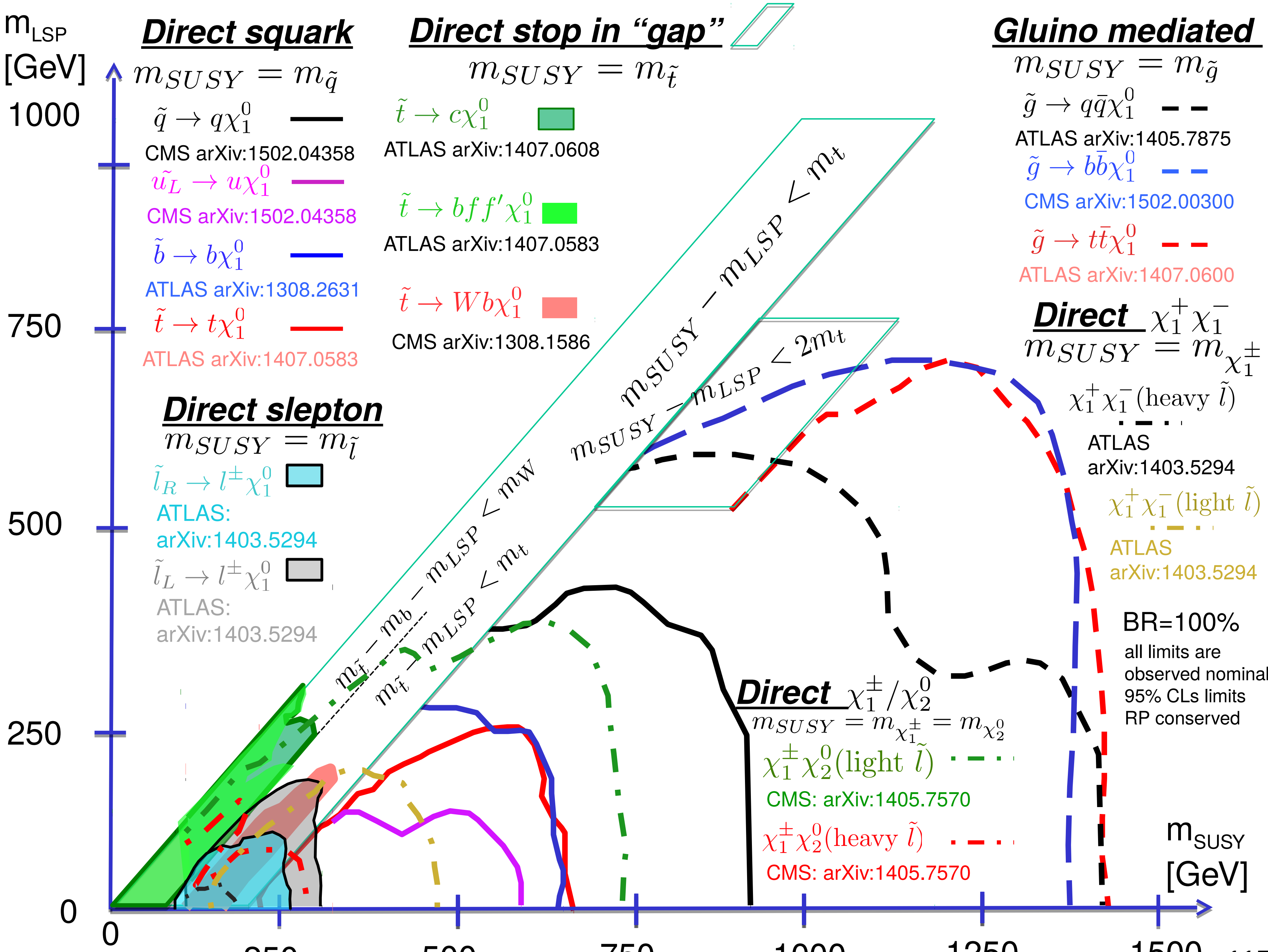




ATLAS arXiv:1403.5294



m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \rightarrow l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0(\text{light } \tilde{l})$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(\text{heavy } \tilde{l})$
CMS: arXiv:1405.7570
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
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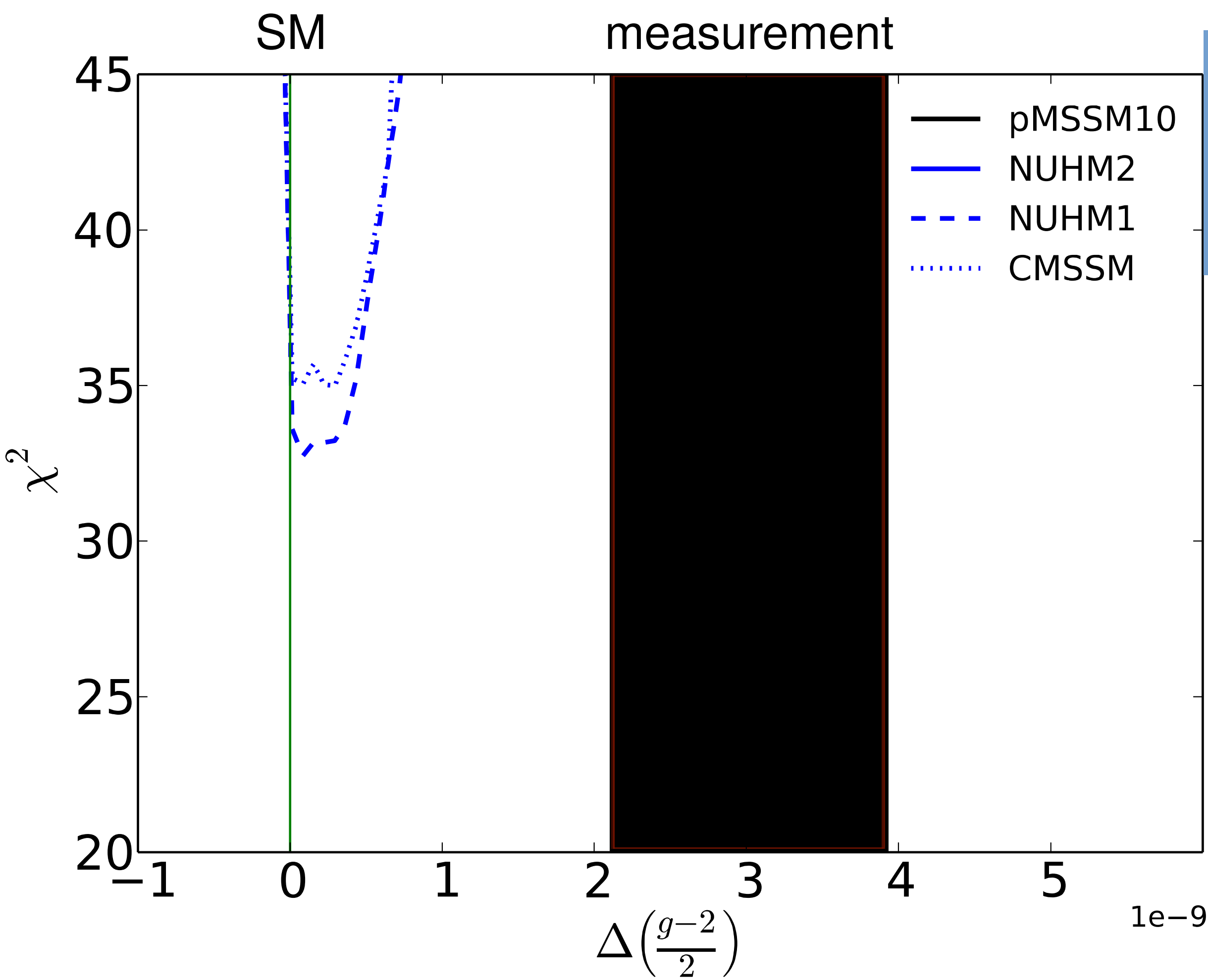
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-$(heavy $\tilde{l}$)
ATLAS arXiv:1403.5294
$\chi_1^+\chi_1^-$(light $\tilde{l}$)
ATLAS arXiv:1403.5294
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \rightarrow l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \rightarrow l^\pm\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^\pm\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500

MASTERCODE

Resolving tension (g-2) and LHC

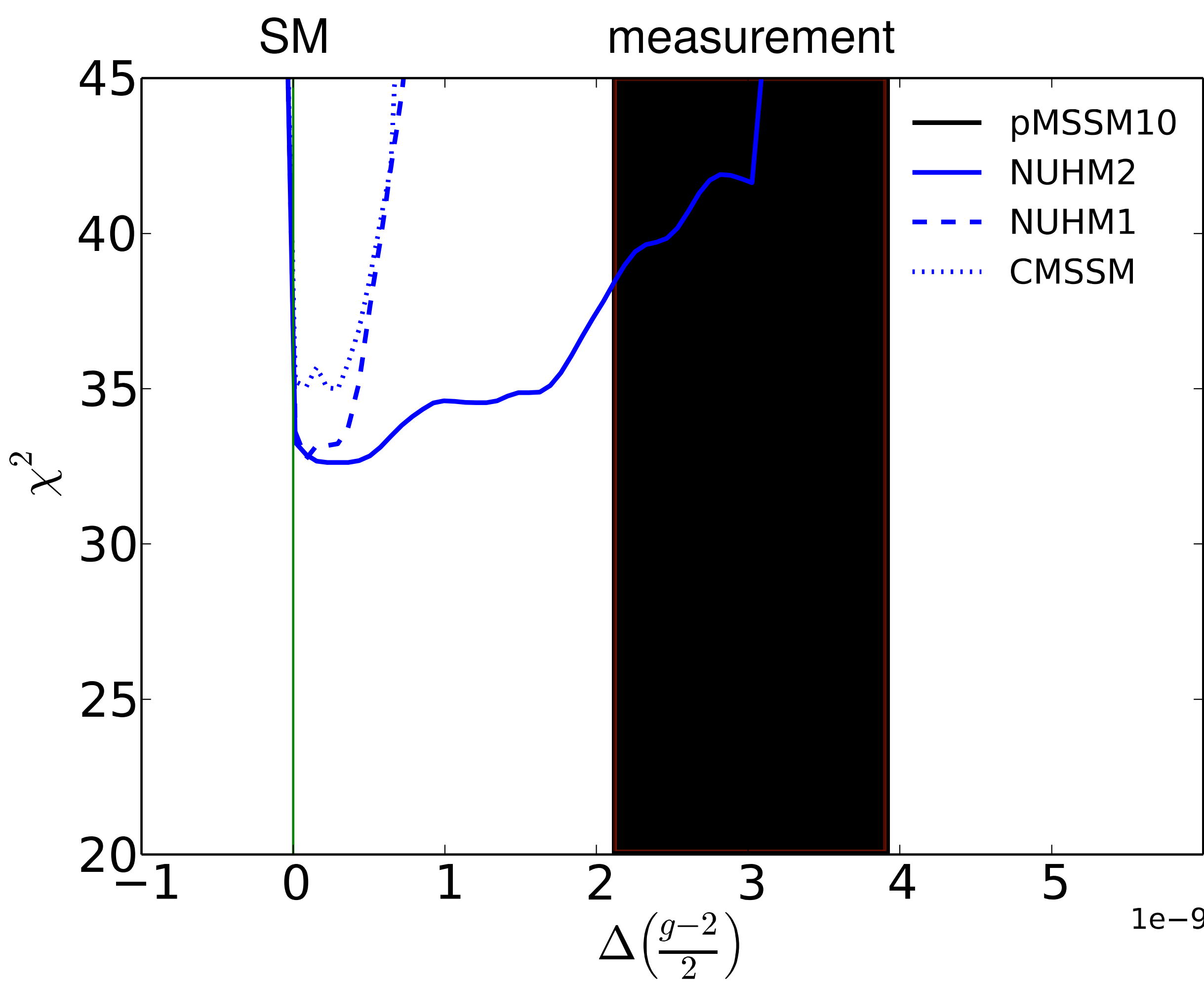


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

Can adding extra parameters resolve the tension between (g-2) and jets+MET constraints?

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC

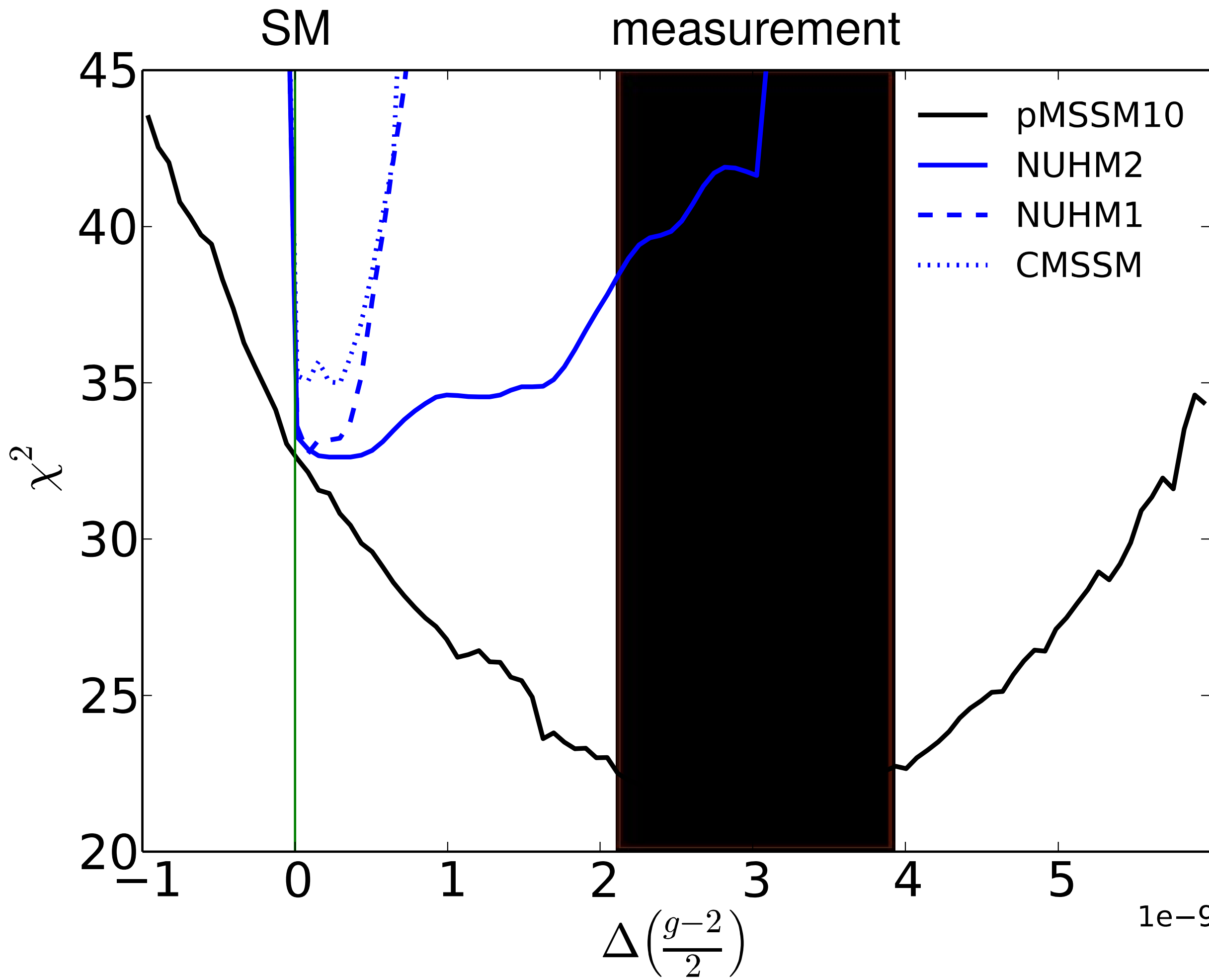


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

NUHM2 can get (g-2) right but only at the expense of M_h and jets + MET constraints.

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC

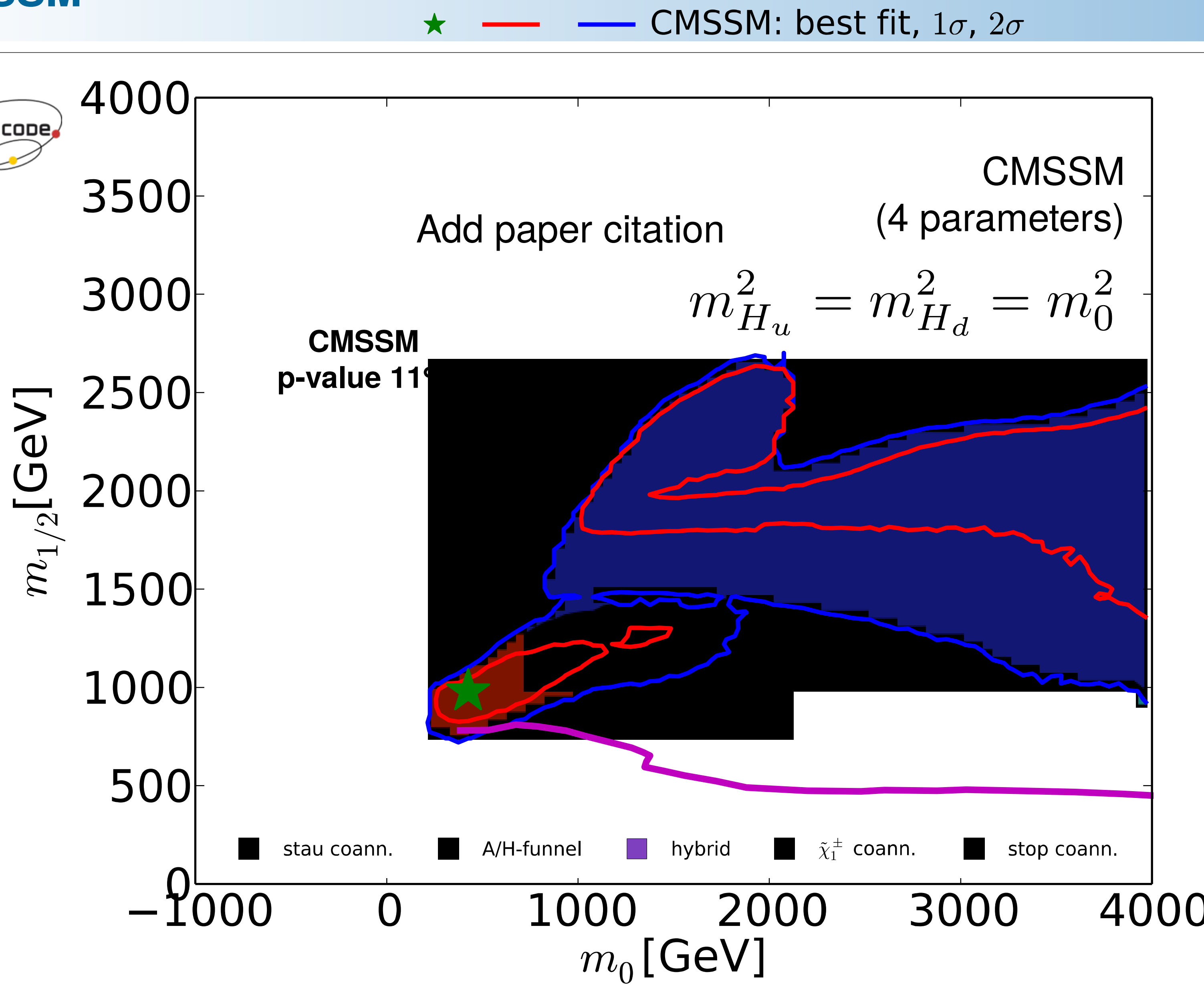


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

pMSSM10 resolves the tension between (g-2) and LHC constraints. This significantly improves the fit.

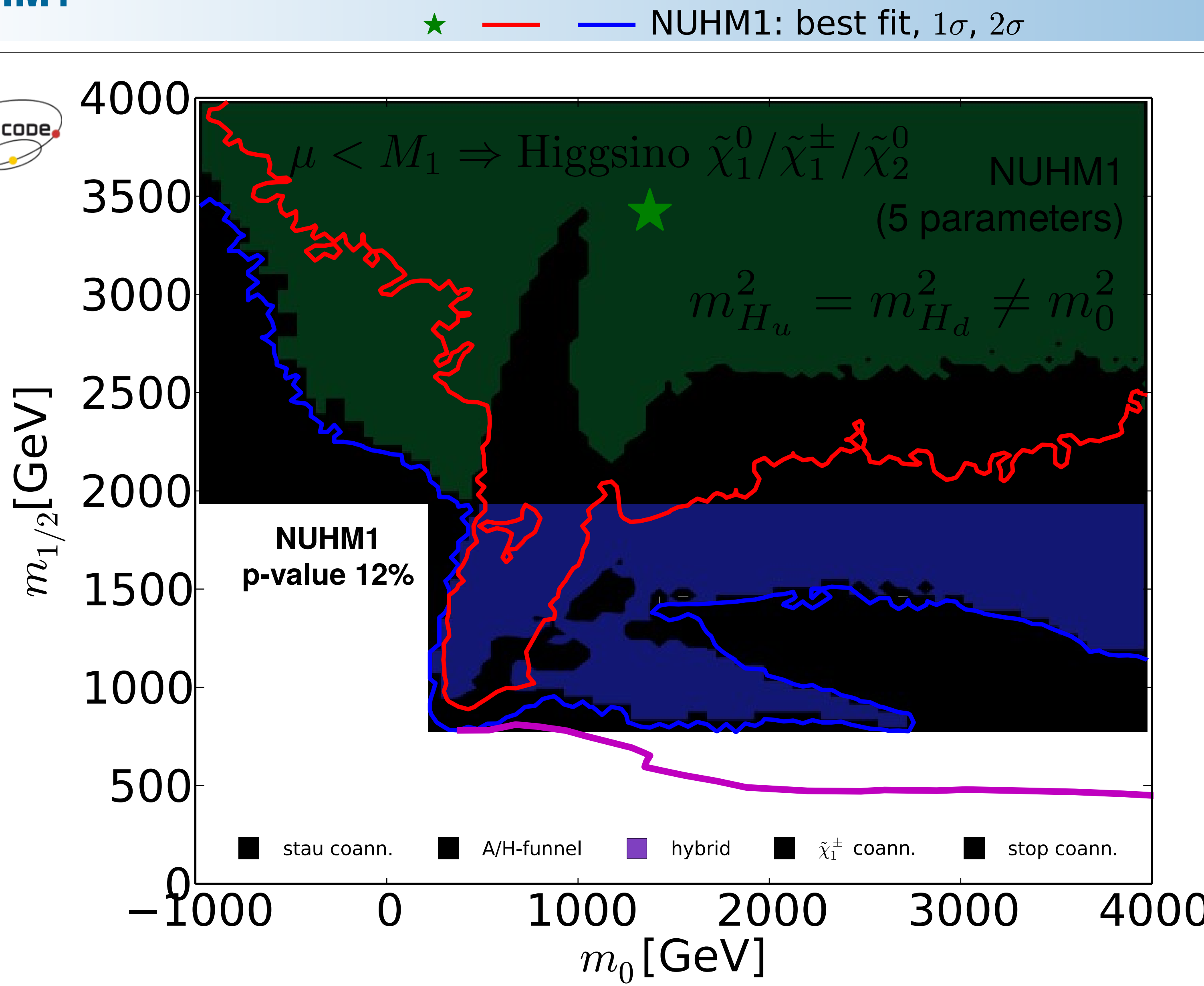
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM



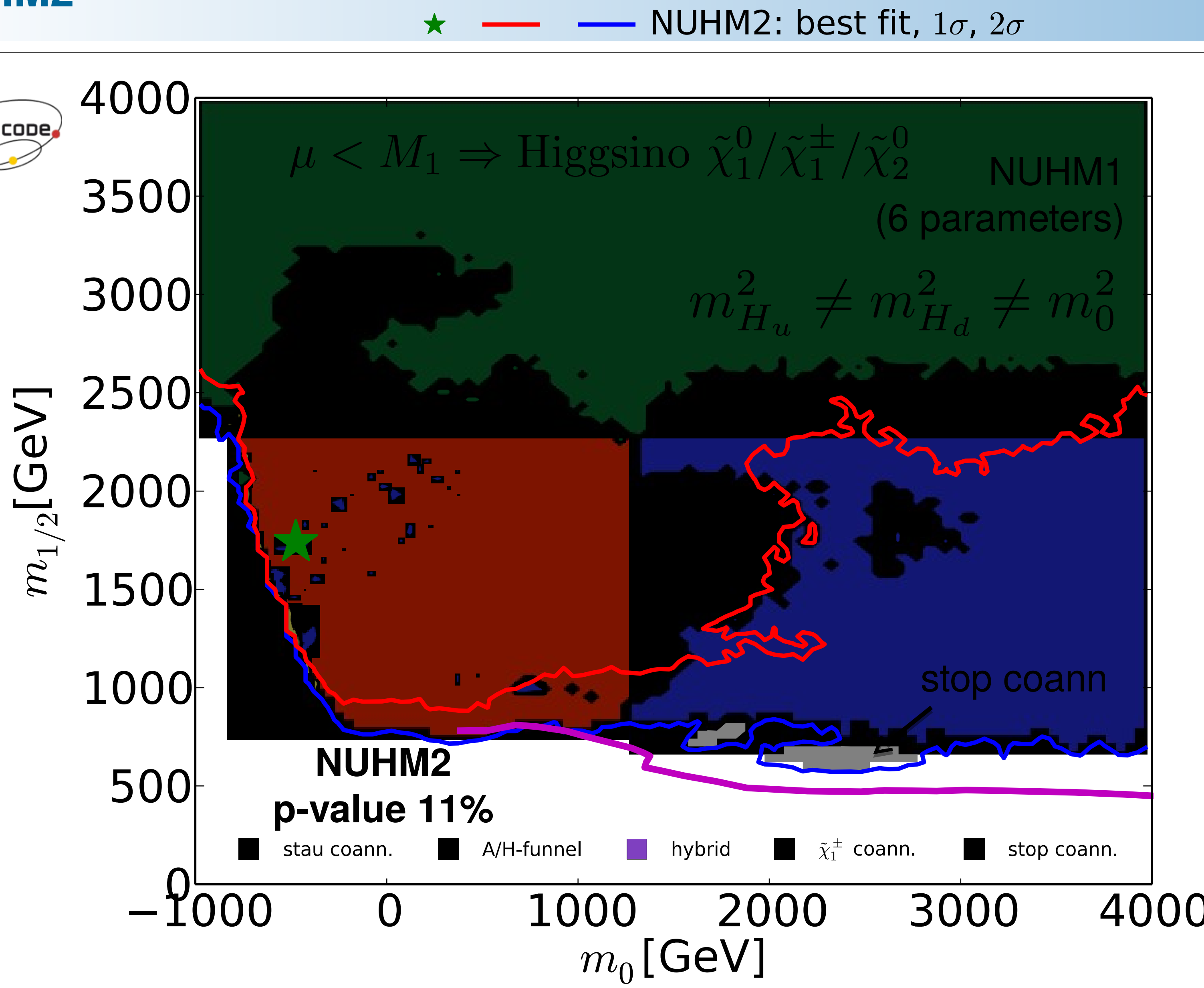
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

NUHM1



From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

NUHM2



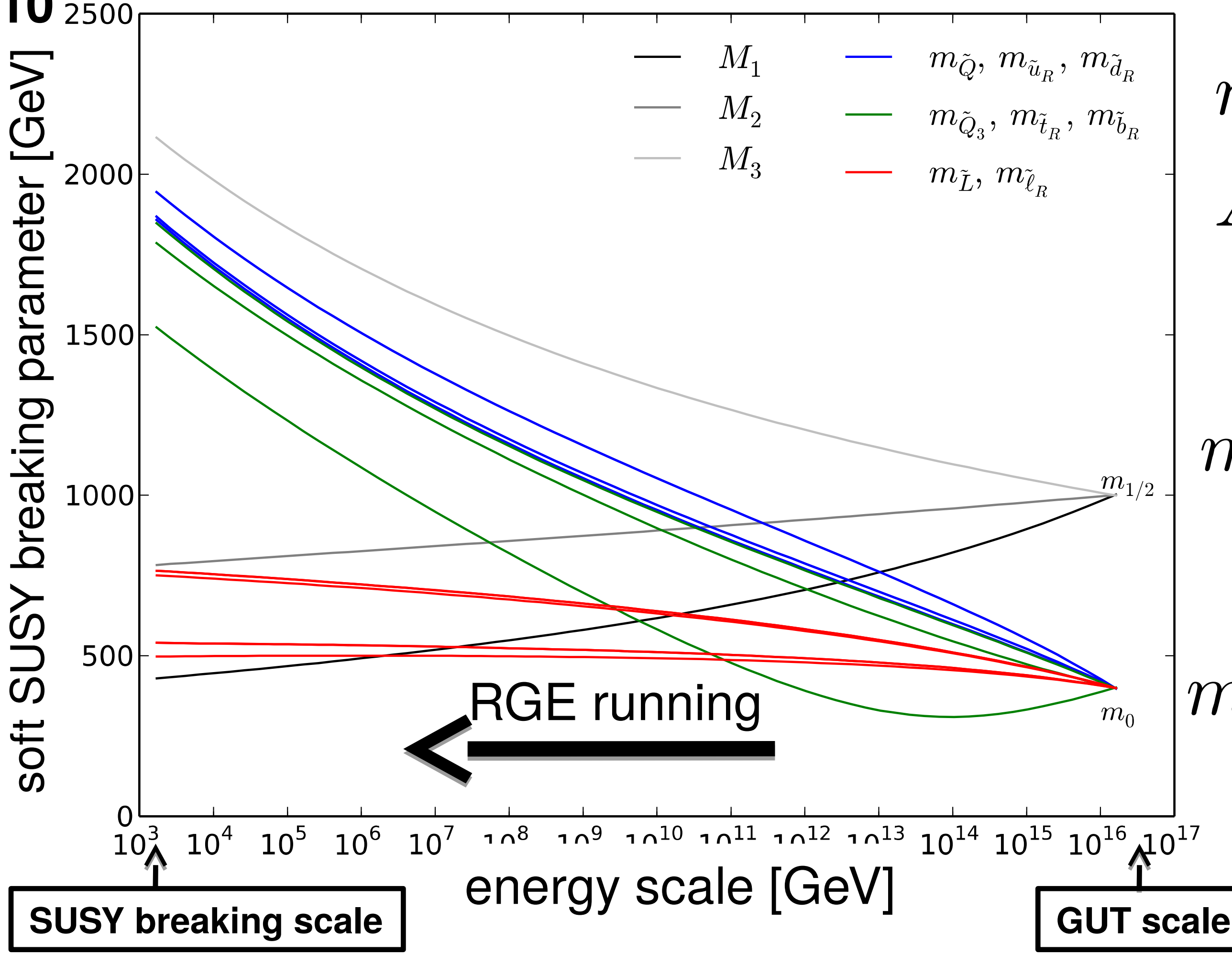
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

M_1, M_2, M_3, $m_{\tilde{q}12}$, $m_{\tilde{q}3}$, $m_{\tilde{\ell}}$, A, M_A, $\tan\beta$, μ



CMSSM

$m_0, \; m_{1/2}, \; A_0, \; \tan\beta$

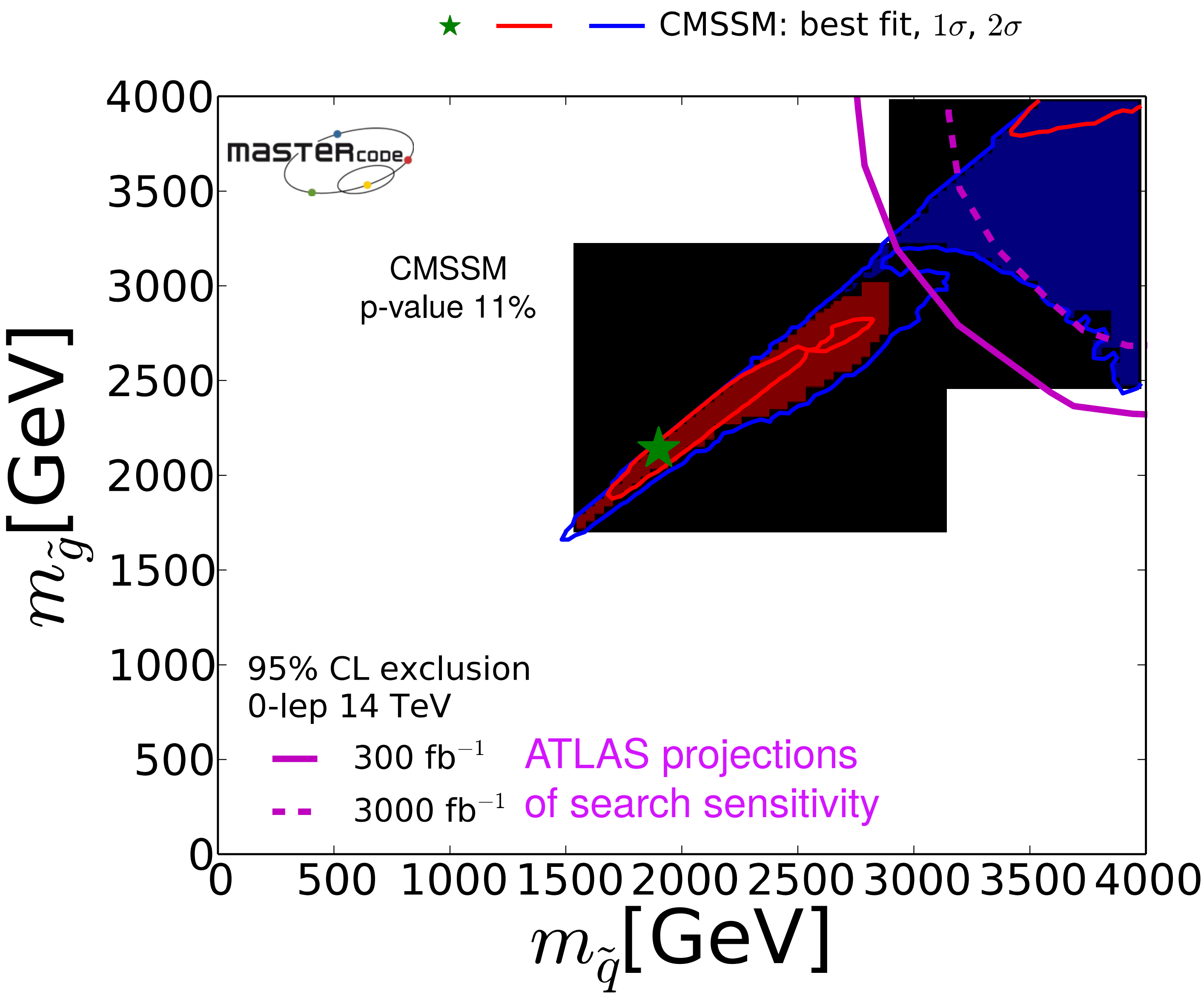
NUHM1

$$m^2_{H_u} = m^2_{H_d}$$

NUHM2

$$m^2_{H_u} \neq m^2_{H_d}$$

CMSSM Today: Mq-Mg Search plane



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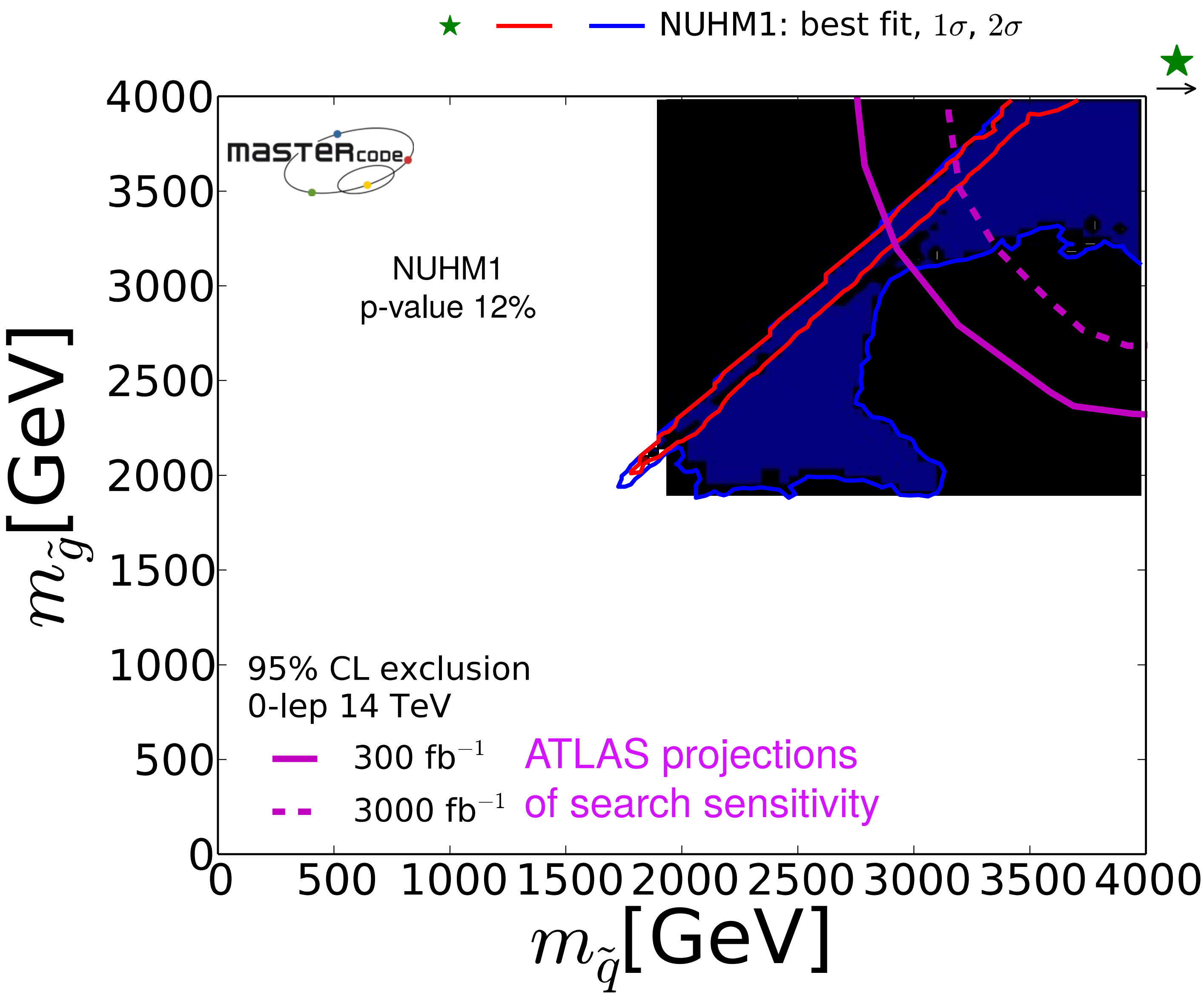
CMSSM Today: Mq-Mg Search plane



From MasterCode papers:
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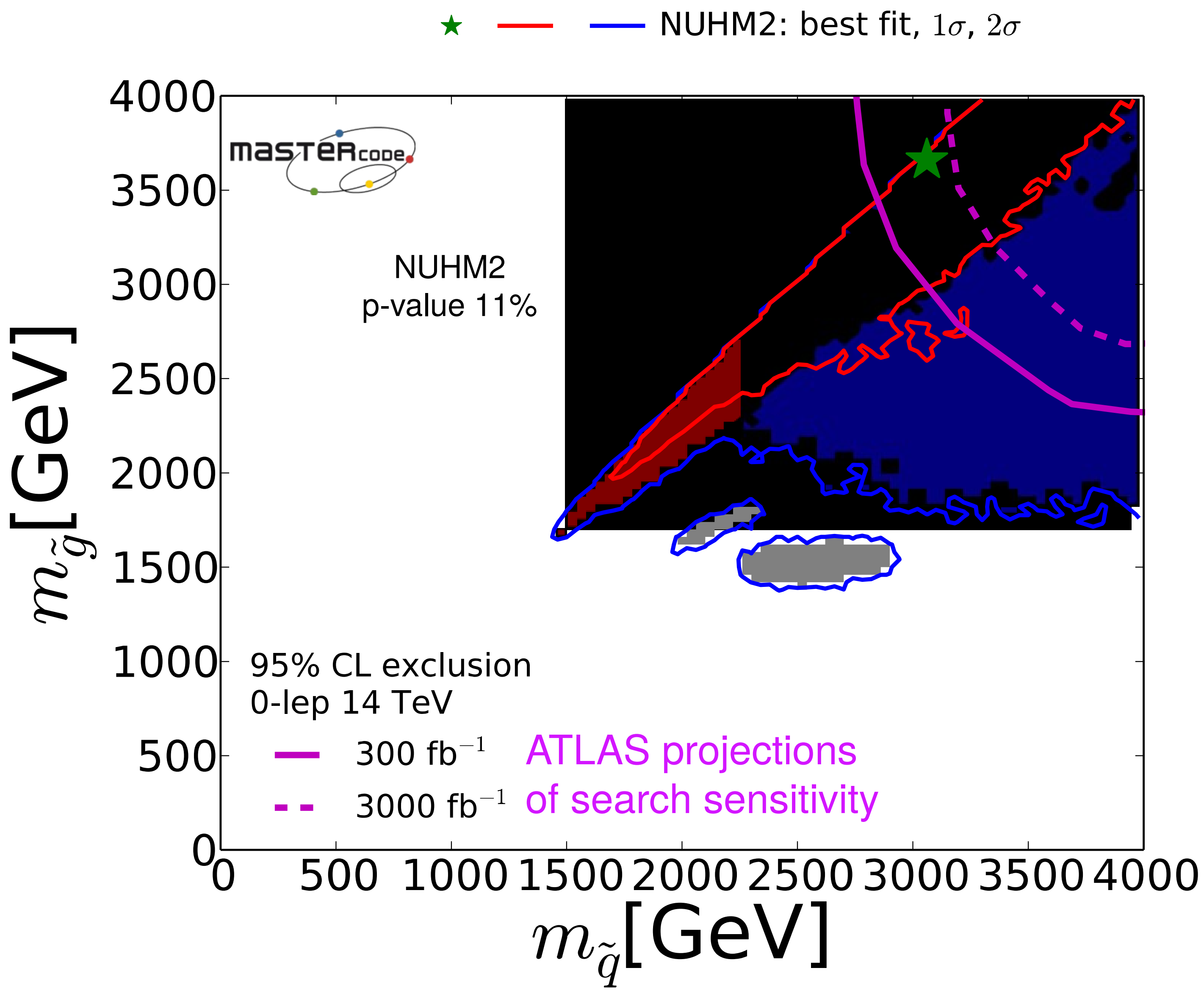
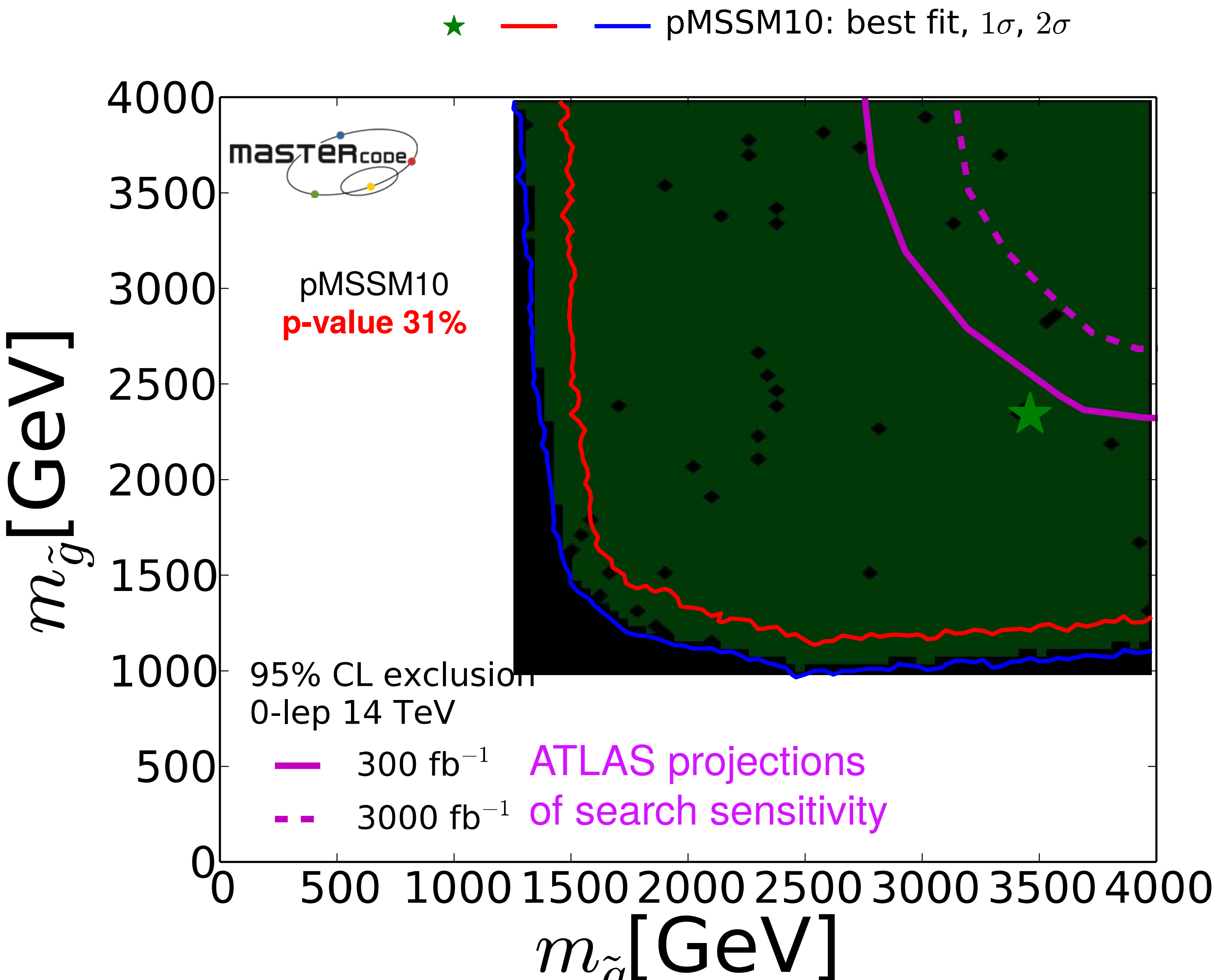
CMSSM Today: Mq-Mg Search plane



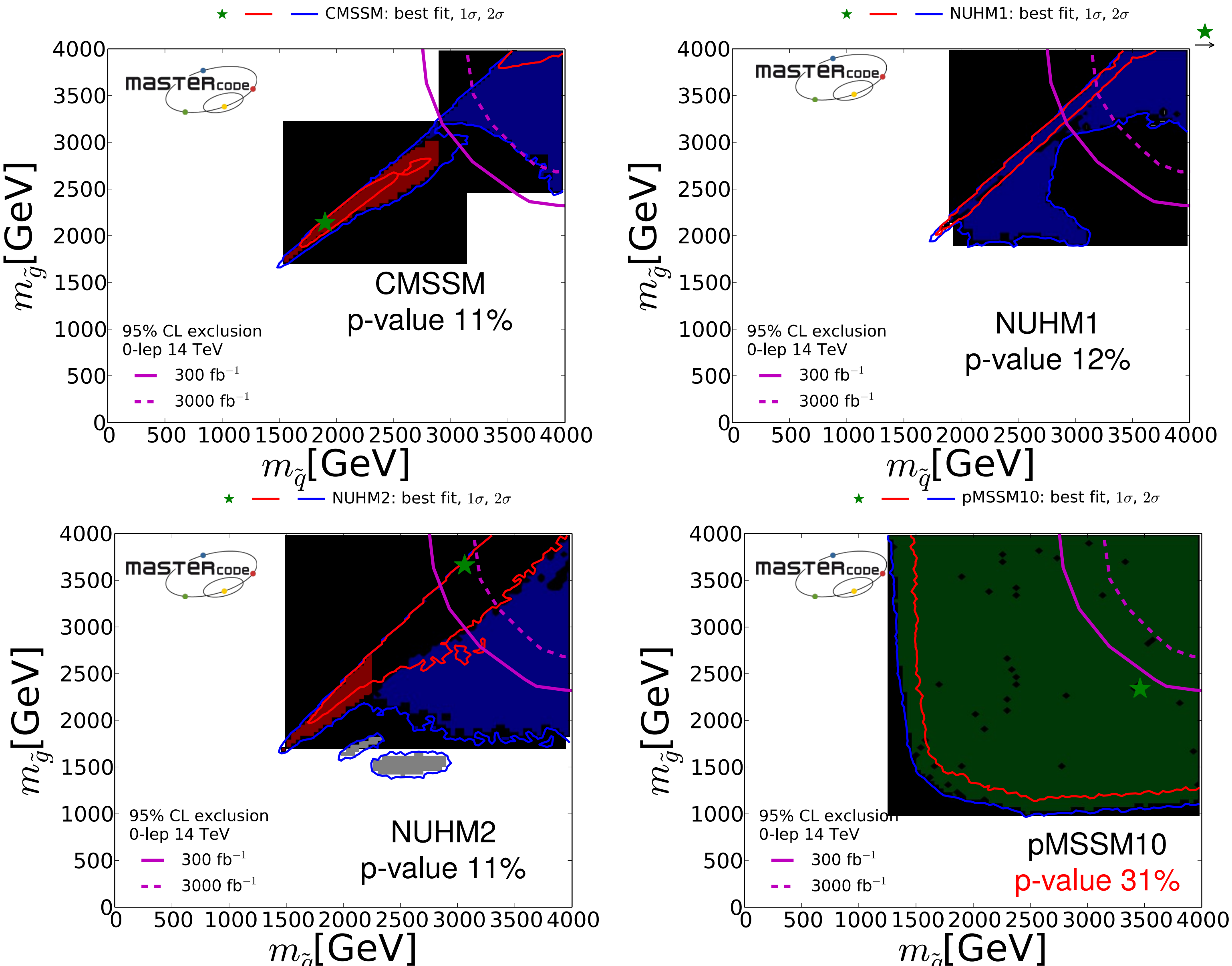
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



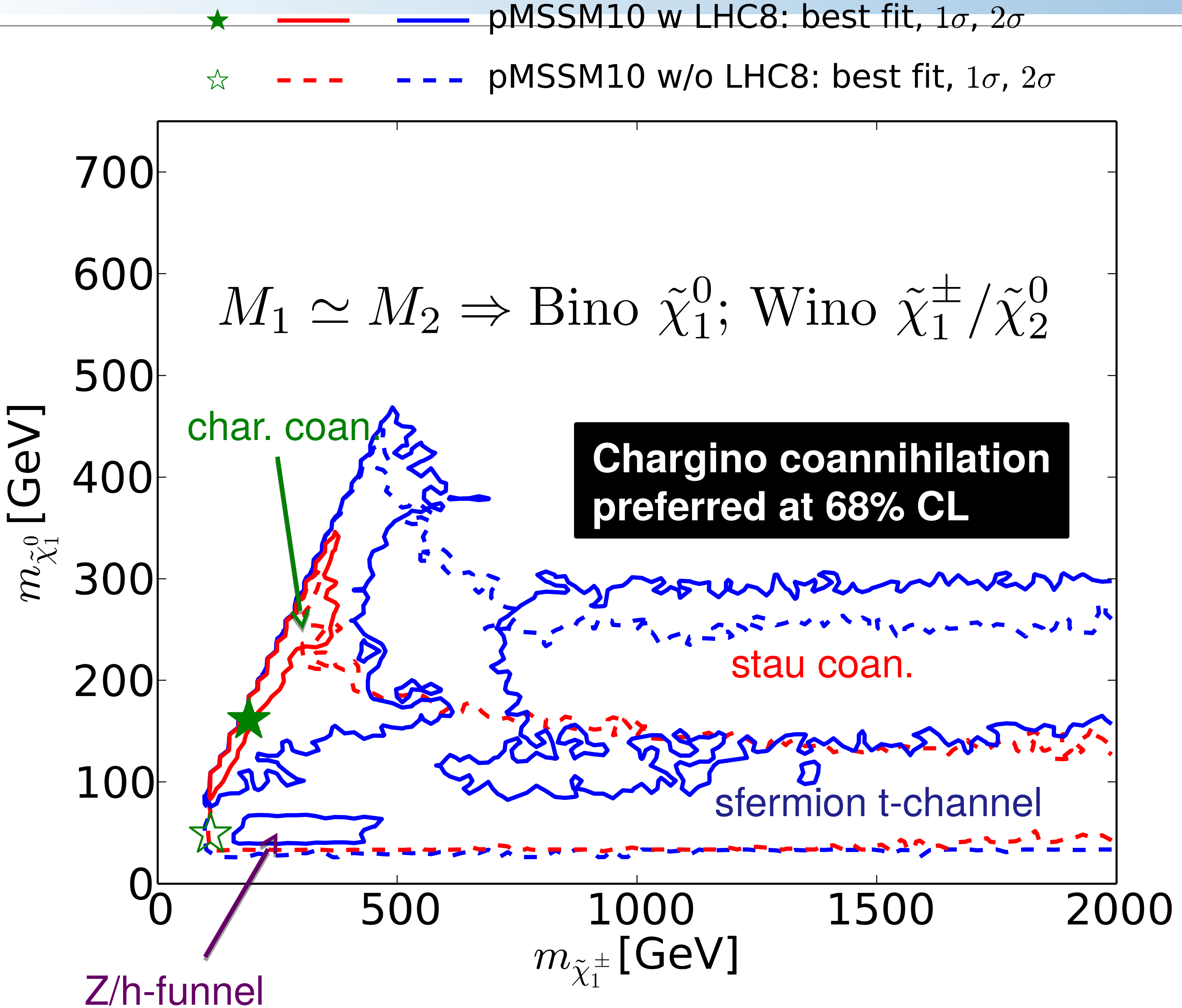
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in "Mq-Mg Search plane"

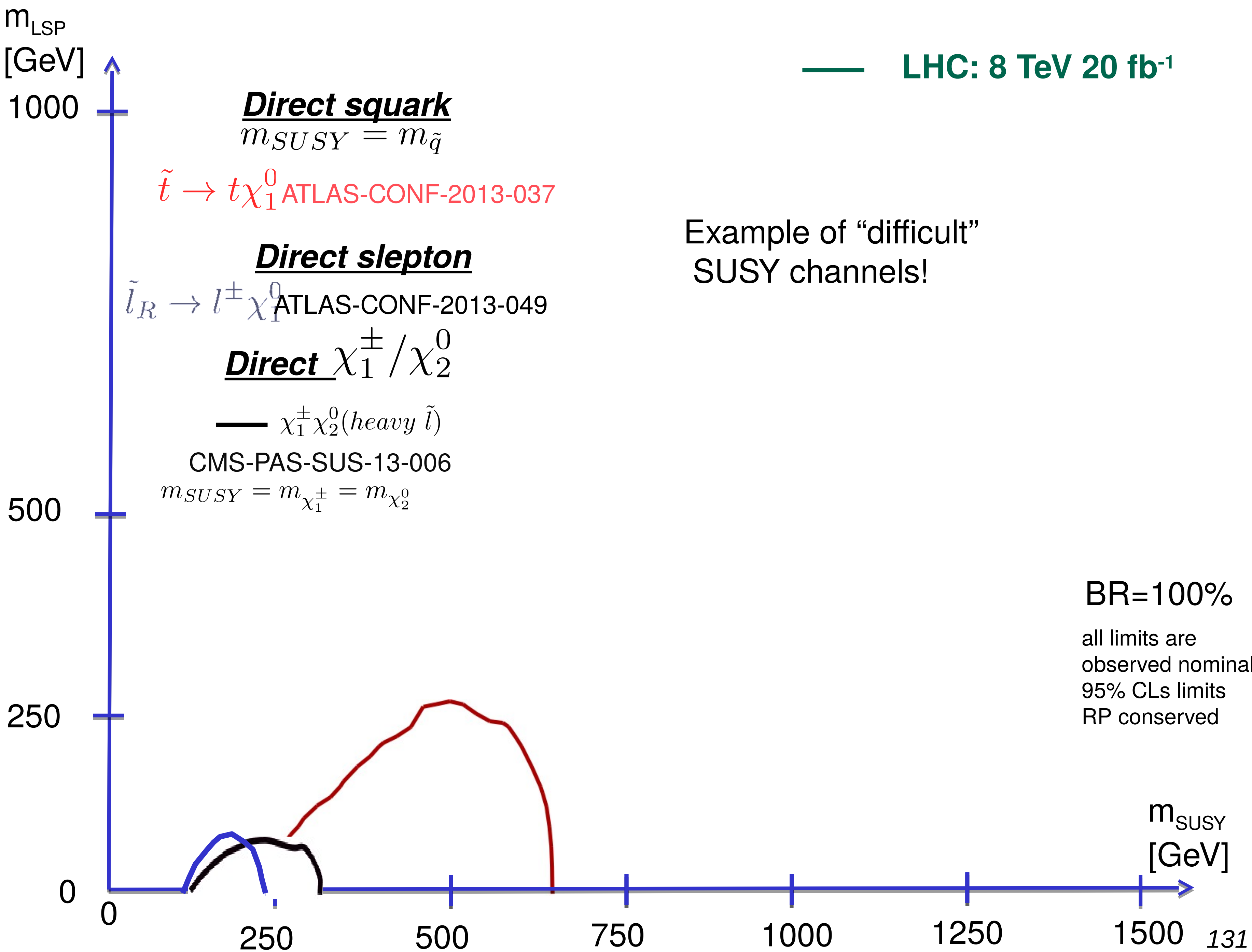


From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

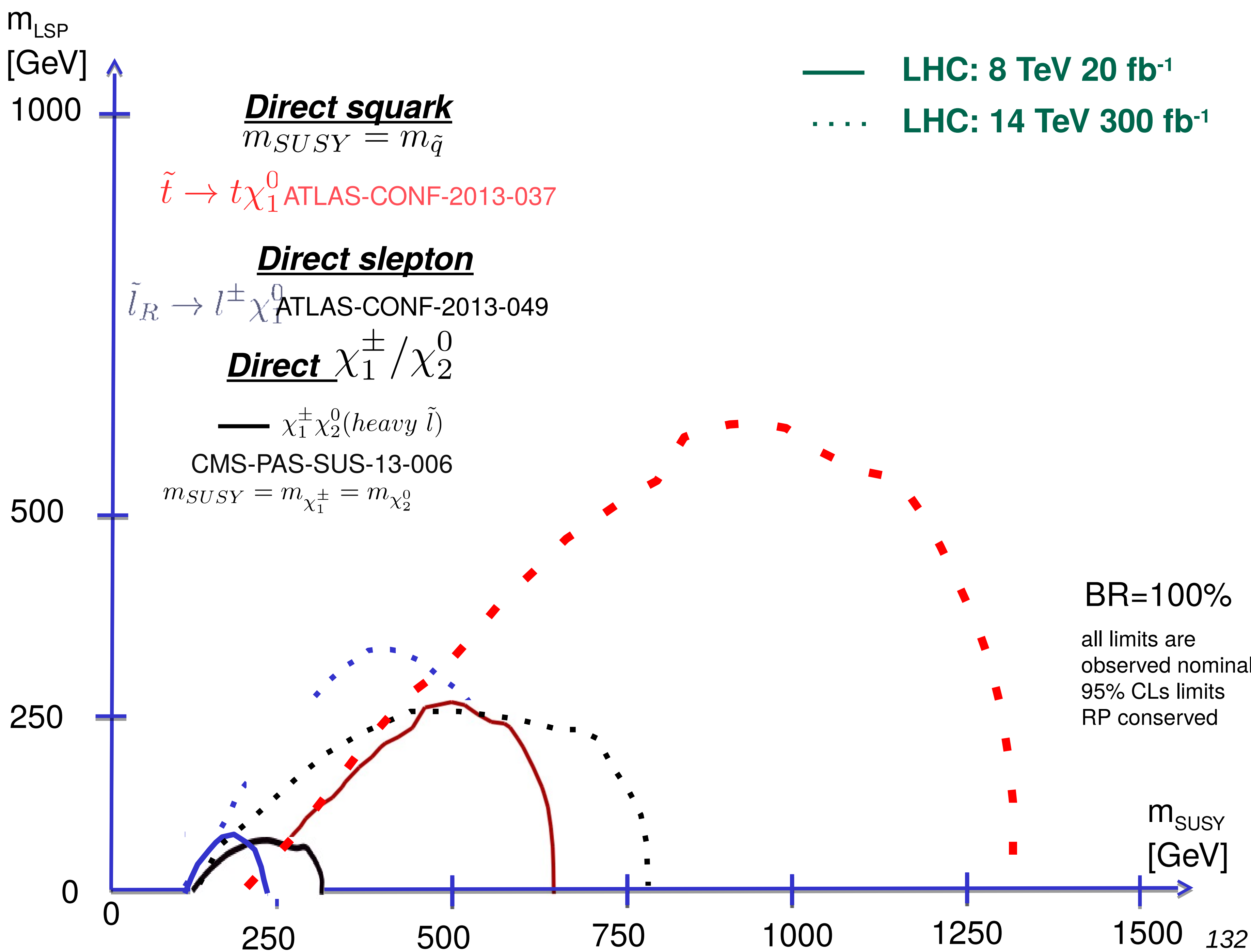
pMSSM10: parameter space



SUSY PROJECTION OF DIFFICULT CHANNELS



m_{LSP} [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
Example of "difficult" SUSY channels!
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



m_LSP [GeV]
1000
500
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LHC: 8 TeV 20 fb-1
LHC: 14 TeV 300 fb-1
Direct squark
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Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
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$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
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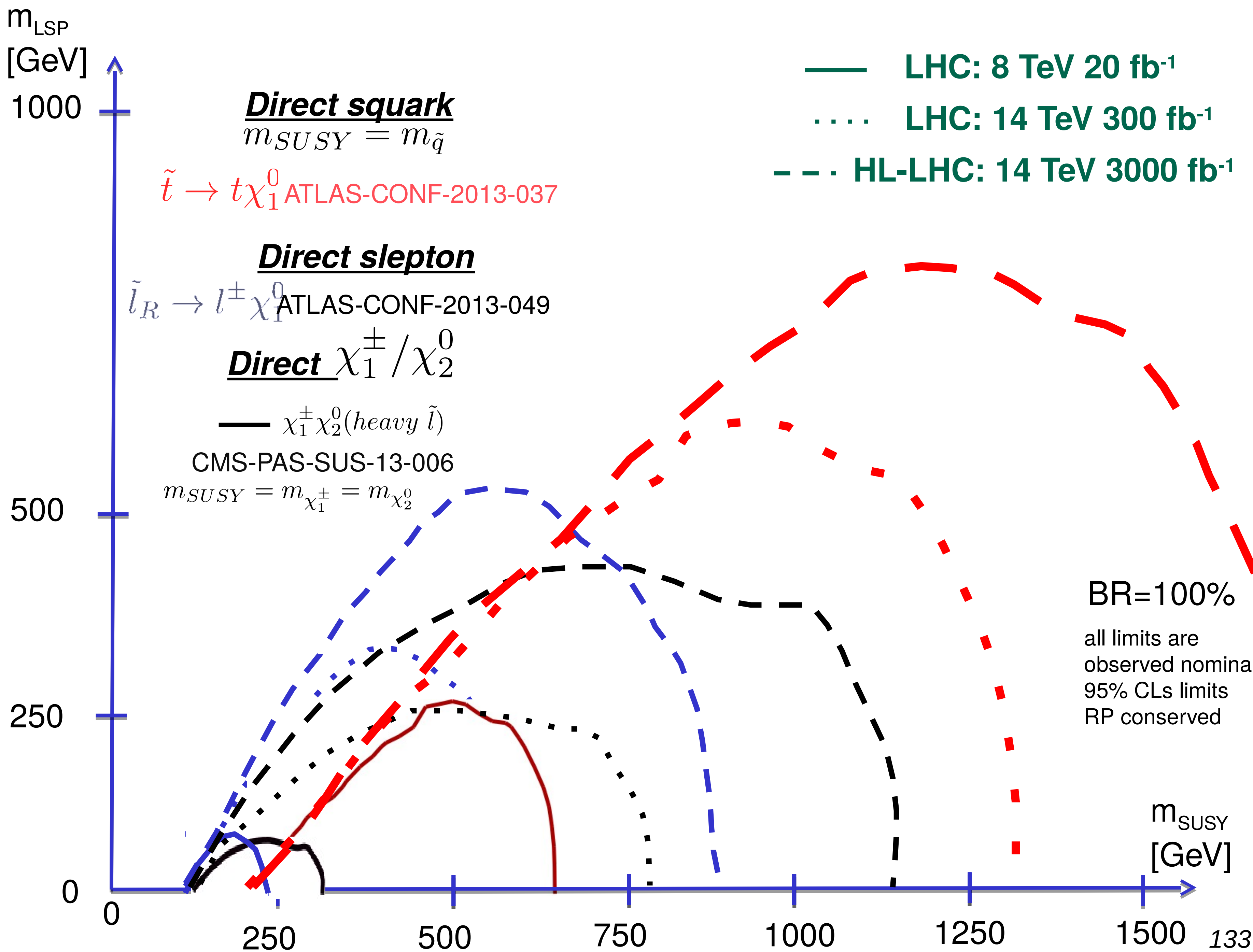
RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500


m_{LSP} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
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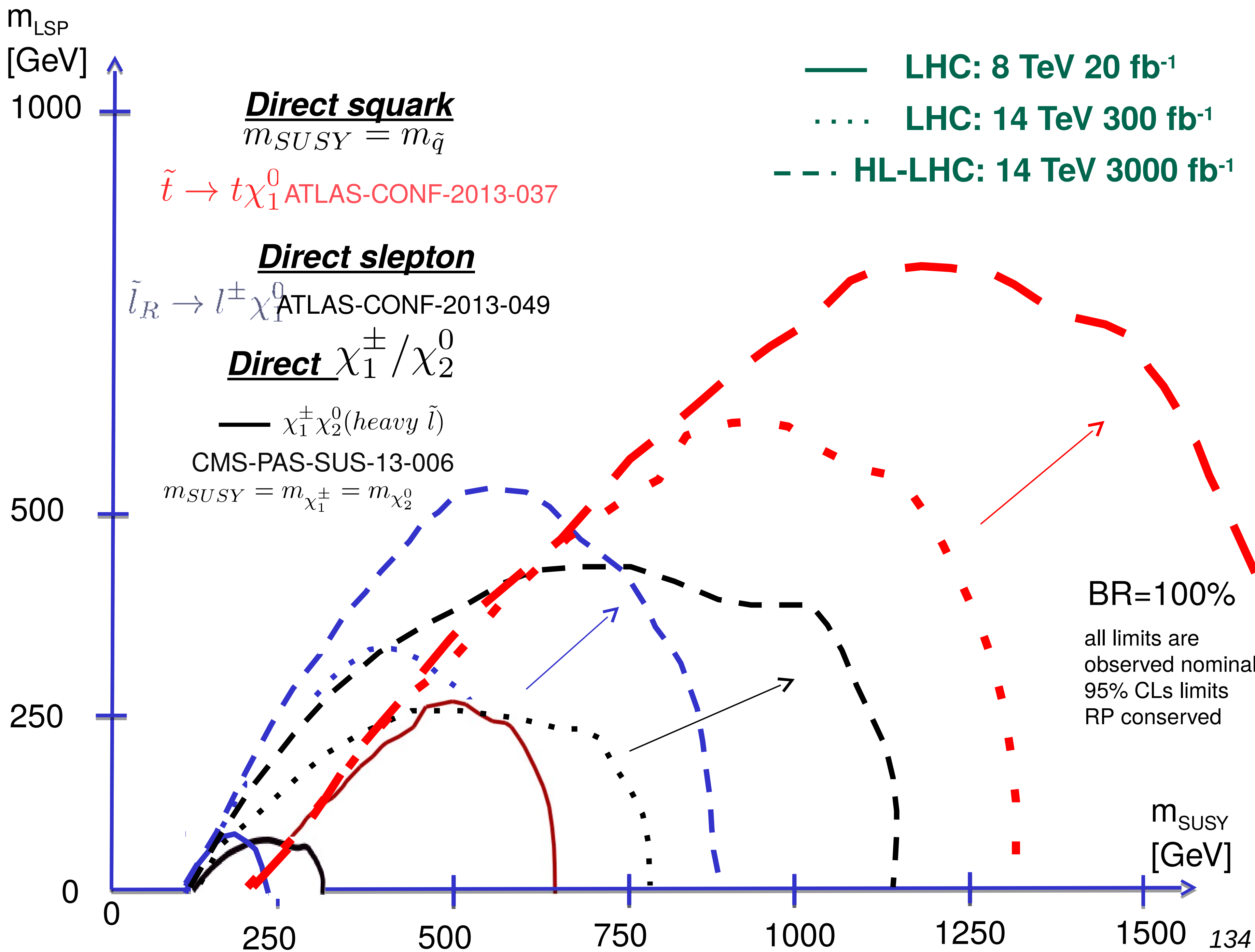
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved


m_LSP [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
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Direct $\chi_1^\pm/\chi_2^0$
$\chi_1^\pm\chi_2^0(heavy\ \tilde{l})$
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$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb-1
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m_SUSY [GeV]
0
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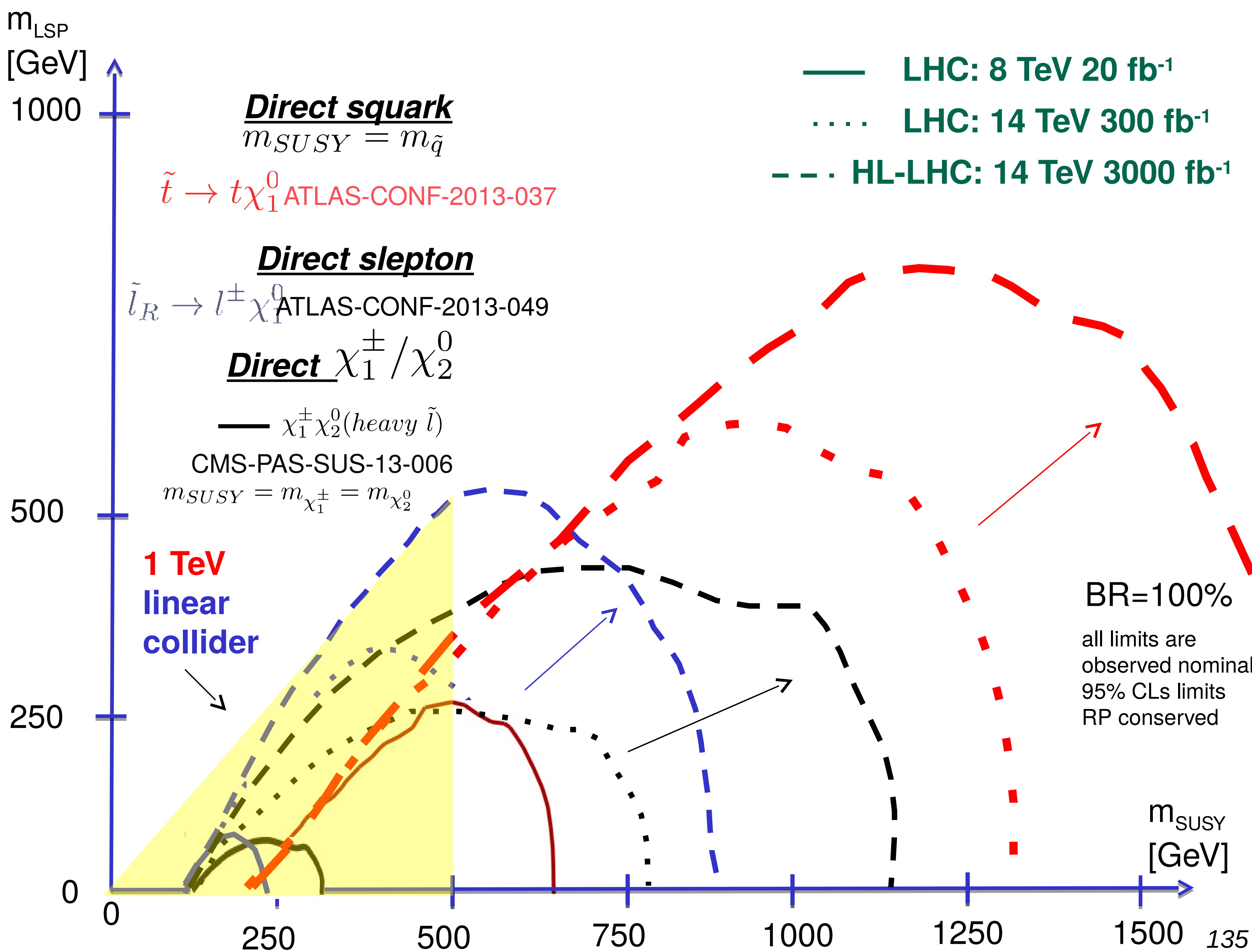
500
750
1000
1250
1500



m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
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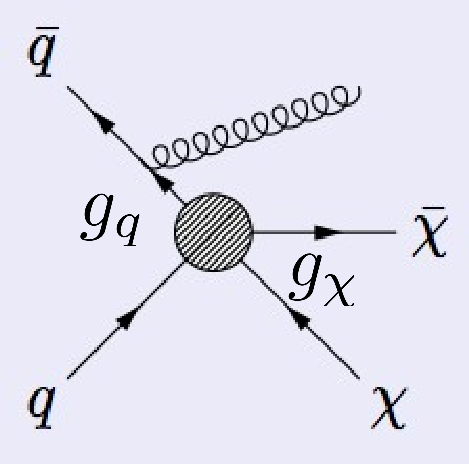
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb-1
LHC: 14 TeV 300 fb-1
HL-LHC: 14 TeV 3000 fb-1
1 TeV linear collider
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

EFT VALIDITY REGION ILLUSTRATED

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel



$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

Assumption of EFT

If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

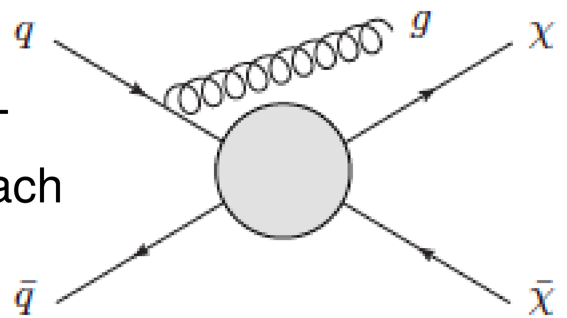
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

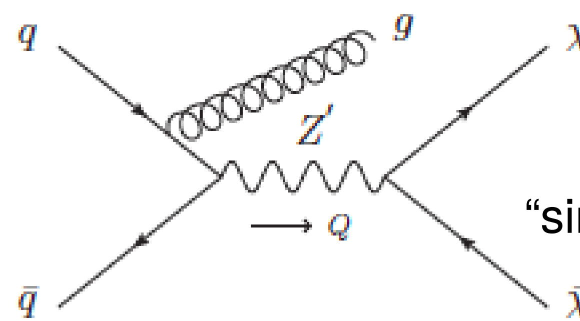
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

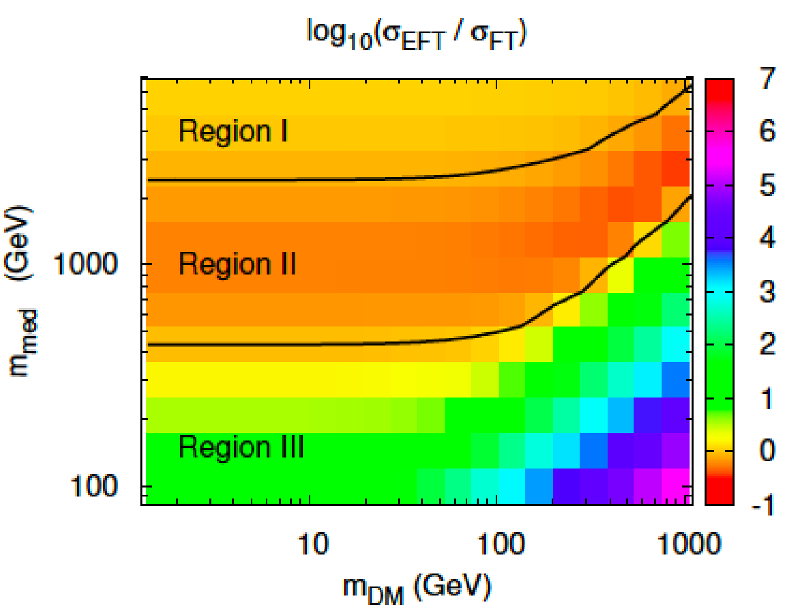
EFT approach





FT one diagram "simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in $m_{med} - m_{DM}$ plane. Three regions become visible:

Region I: EFT and FT agree better then 20%

- EFT is valid!

Region II: EFT yields significant weaker limits then FT

- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

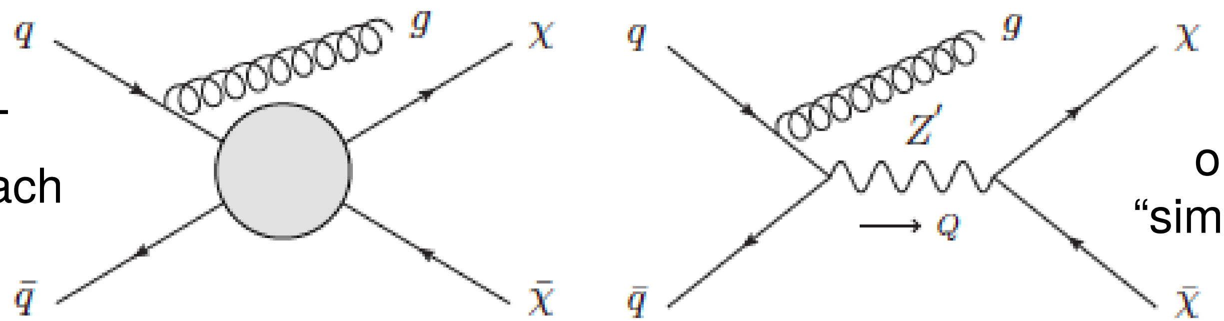
- EFT limits are too aggressive!

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

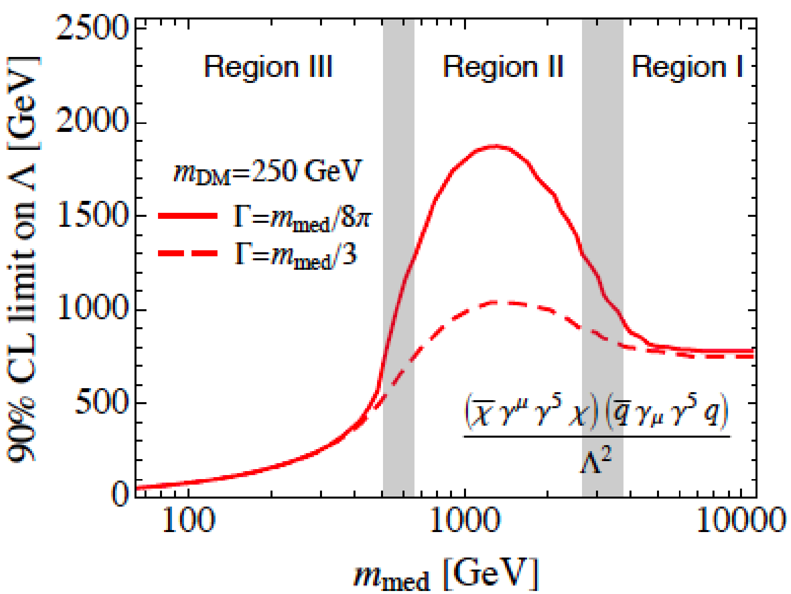
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach



FT one diagram "simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Three Regions as function of mediator mass:

Region I: Heavy m_{med}

- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

- EFT limits are too conservative!

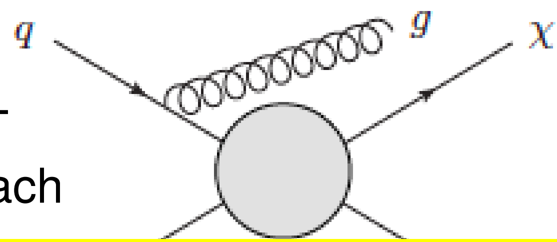
Region III: Low m_{med}

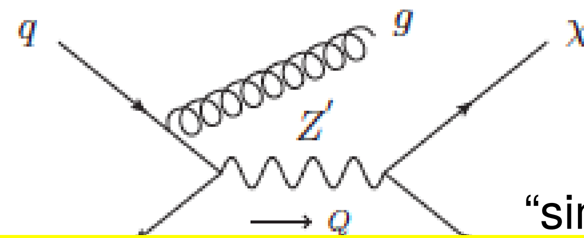
- EFT limits are too aggressive!

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach

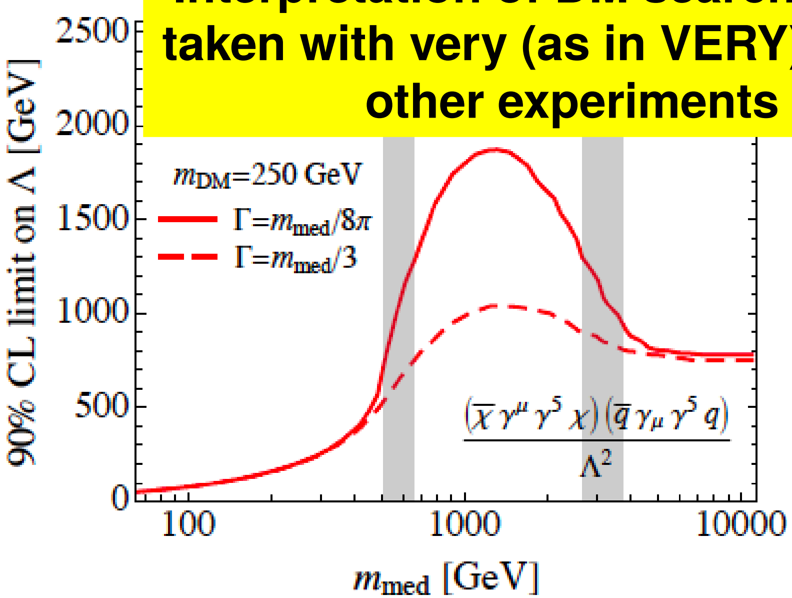




FT
one diagram
"simplified model"

Conclusion:
The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!

Use v … nclusion!

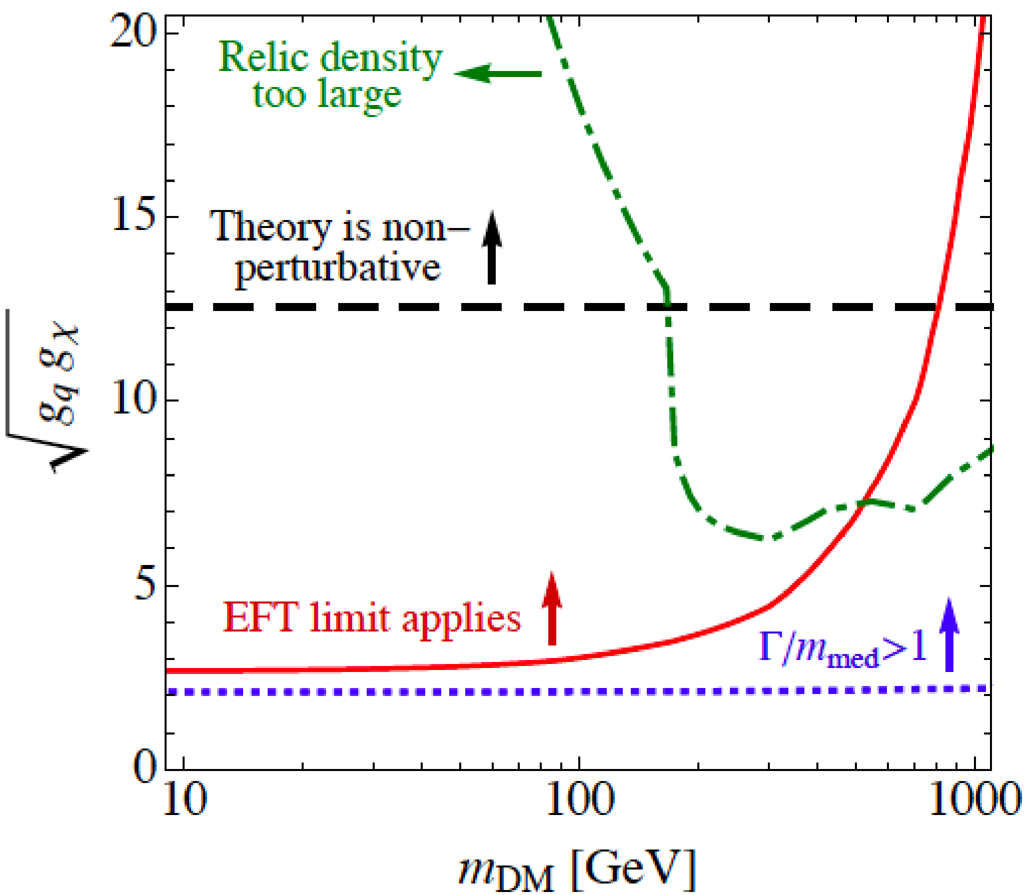


Region I: Heavy m_{med}
- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
- EFT limits are too conservative!

Region III: Low m_{med}
- EFT limits are too aggressive!

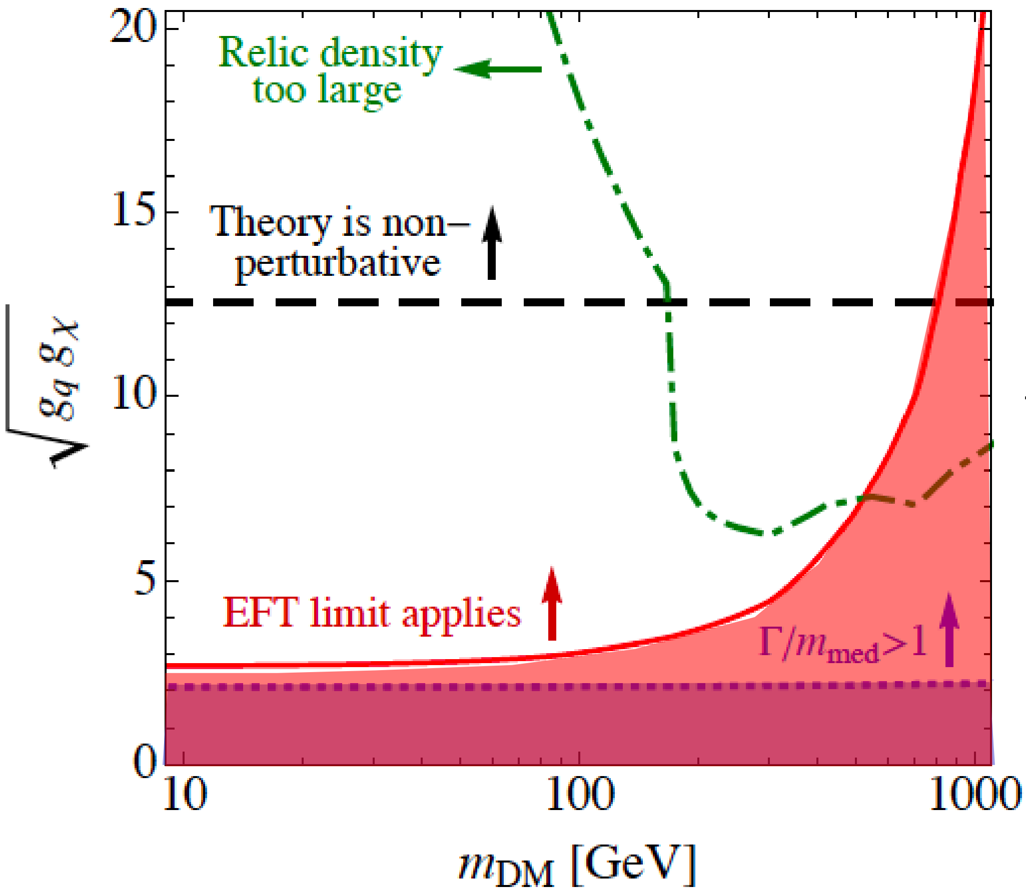
What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid

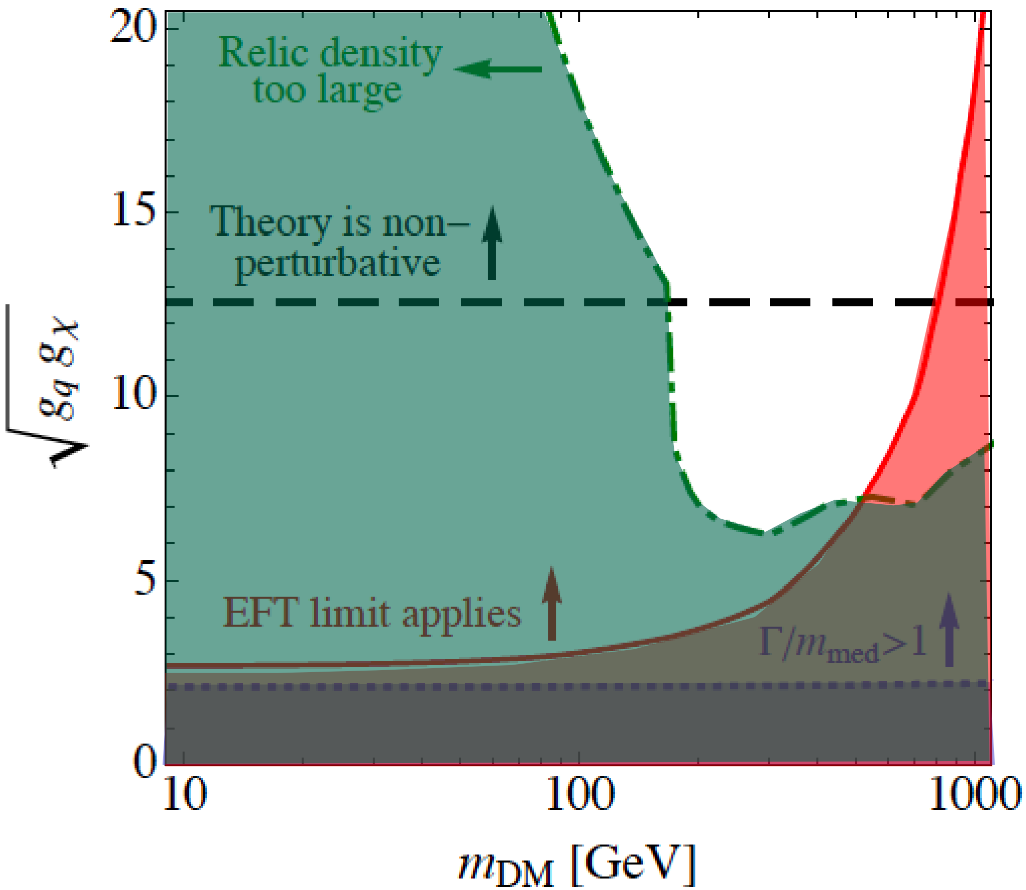
For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = m_{med}/\Lambda_{CMS}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better then 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



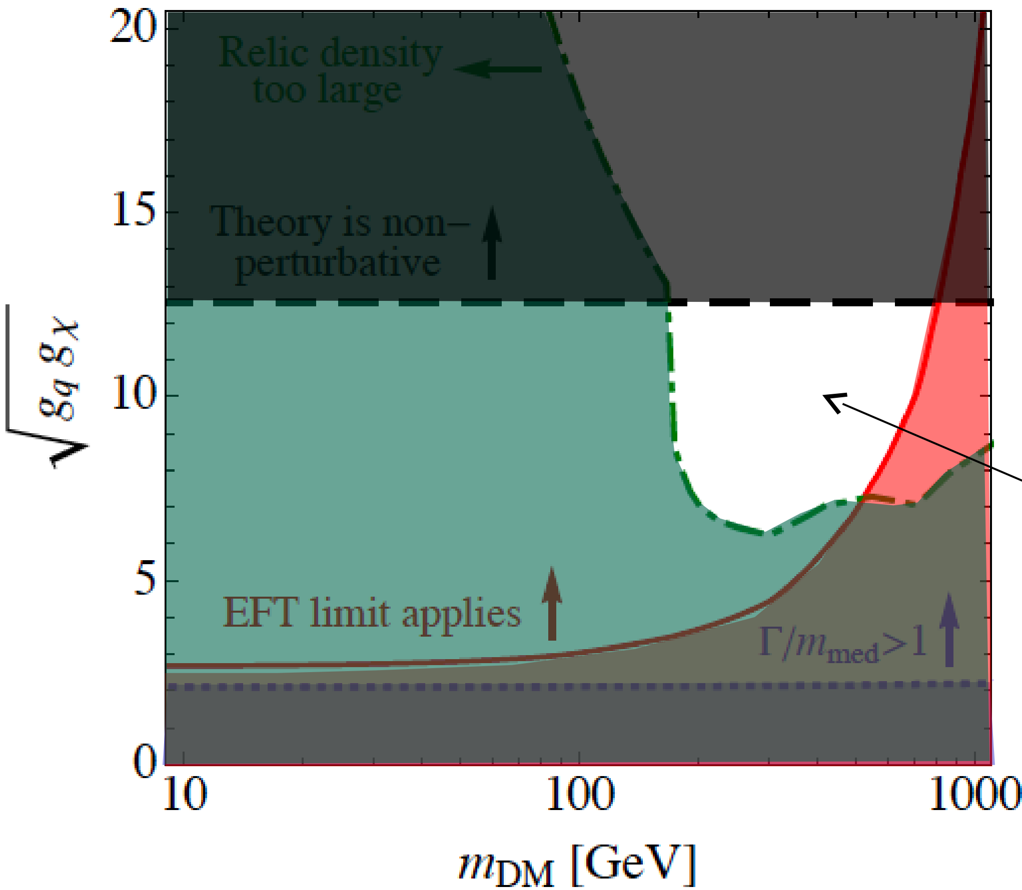
Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger then the observed value of $\Omega_{\chi\chi}h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Must require $m_{med} < \Gamma_{med}$
2. Region in which EFT is valid (20%)
3. Require compatibility with relic density
4. Require theory to be perturbative (<4π)

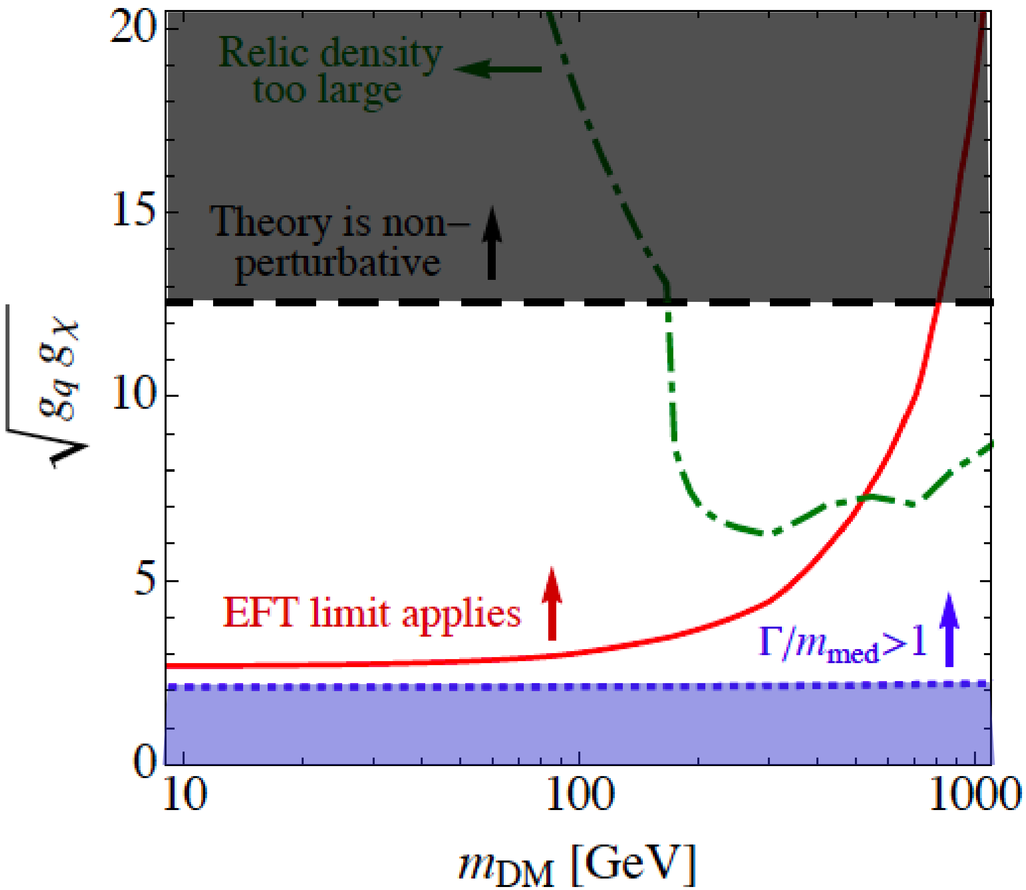
When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT
Is valid the mass of the mediator must be
Smaller than its width!

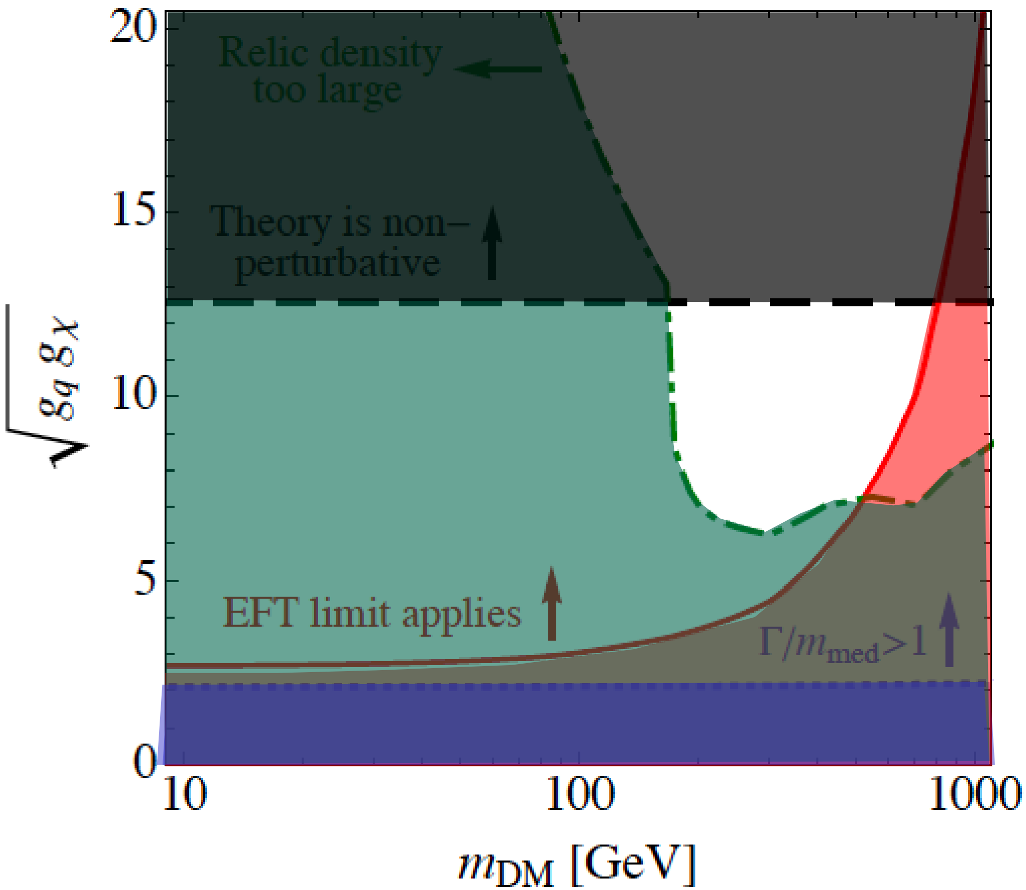
In the reaming part of the plot:

$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$!

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

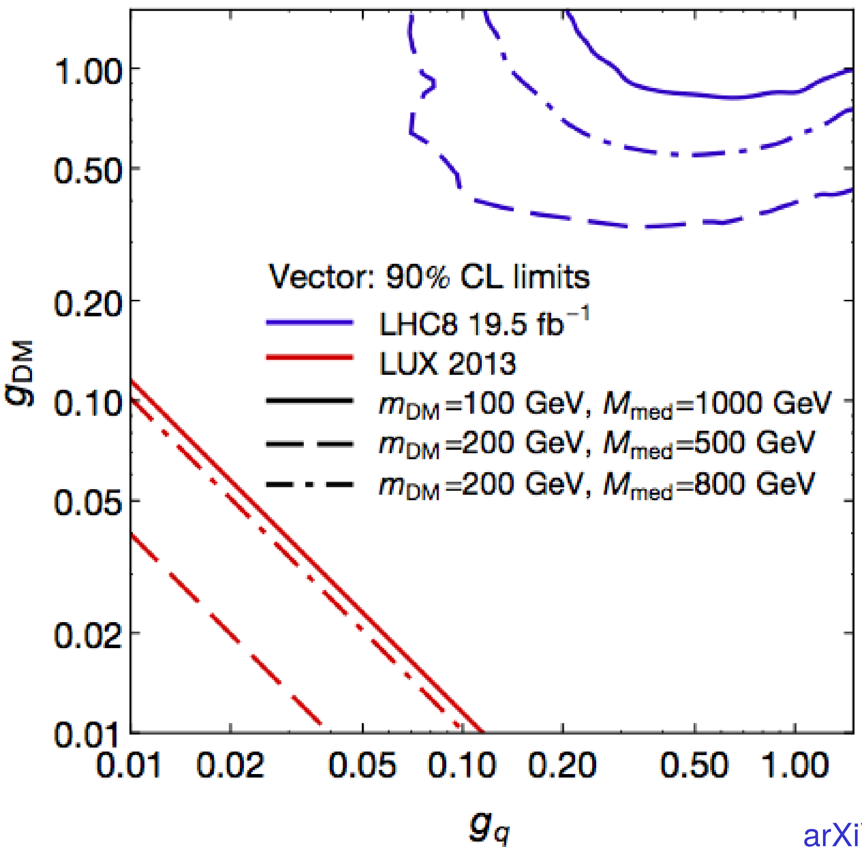
The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

EFT limits of monojet searches are therefore highly model-depended!

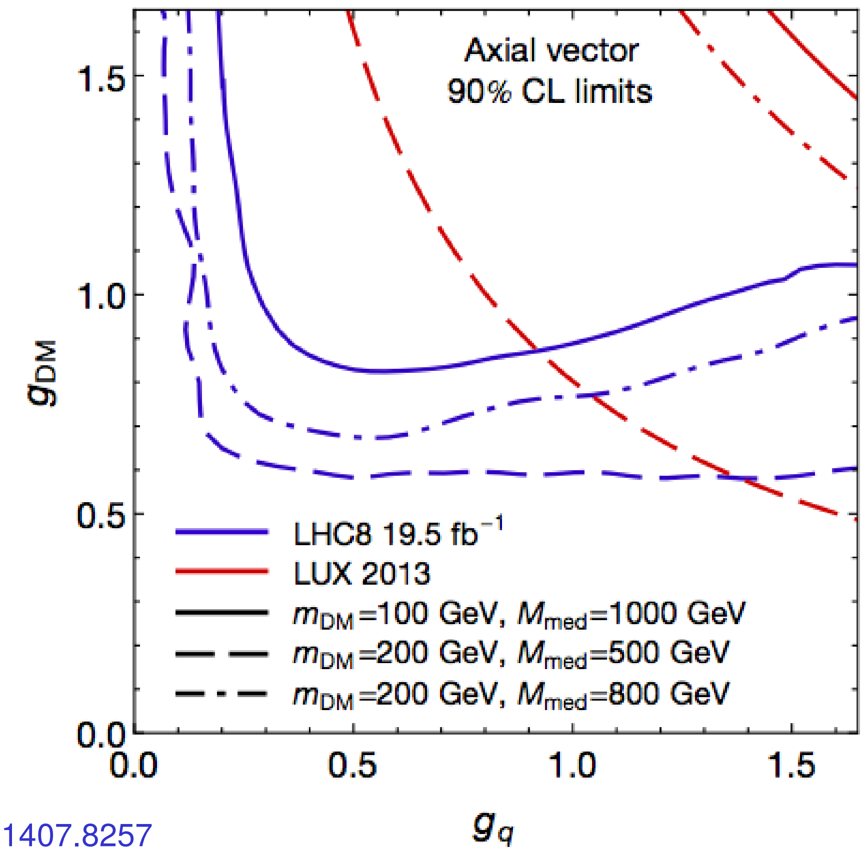
Collider vs Direct Detection

M_{DM}	M_{med}
g_q	g_{DM}

Vector



Axial vector

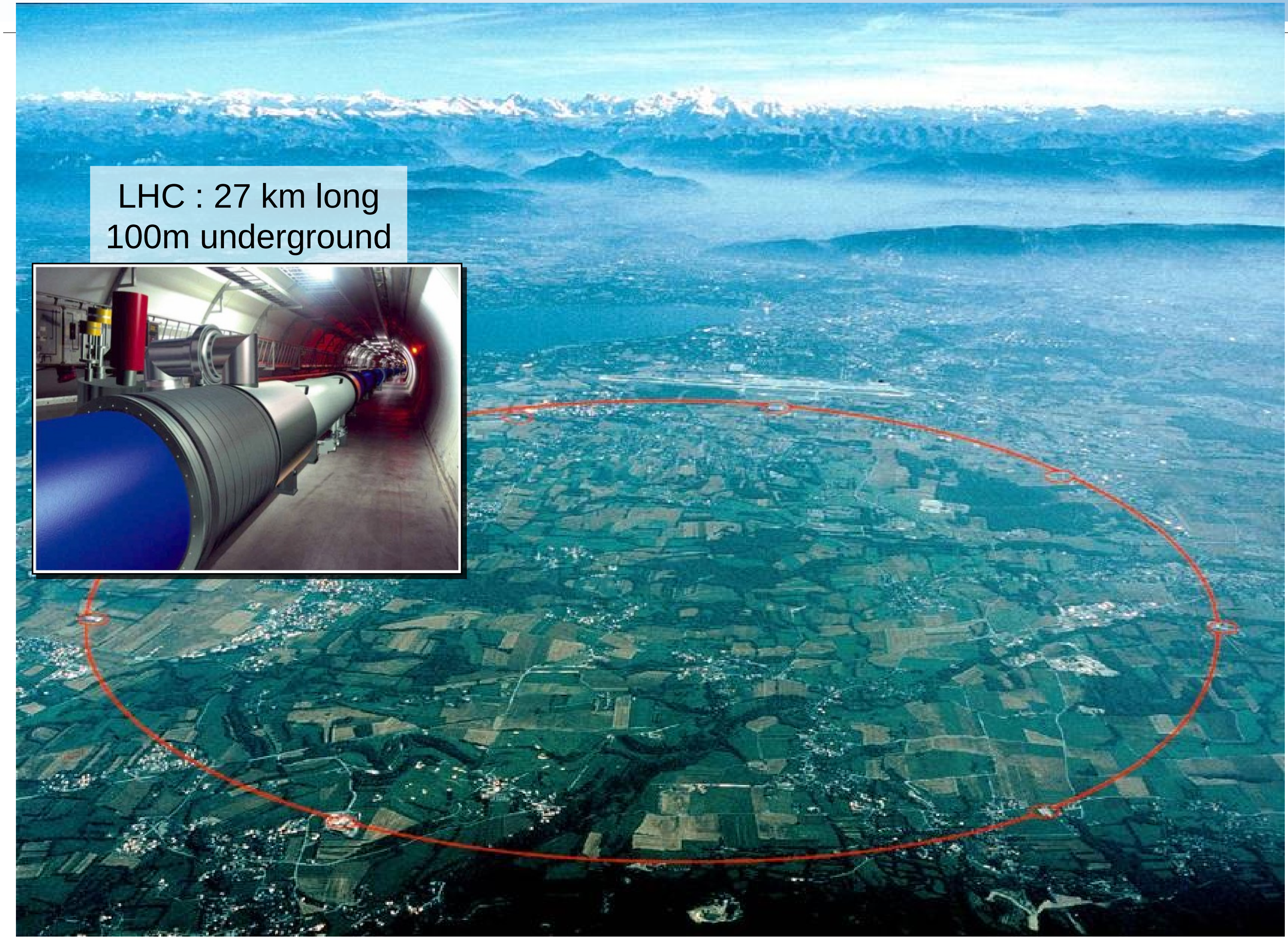


arXiV:1407.8257

LHC

The Large Hadron Collider at CERN

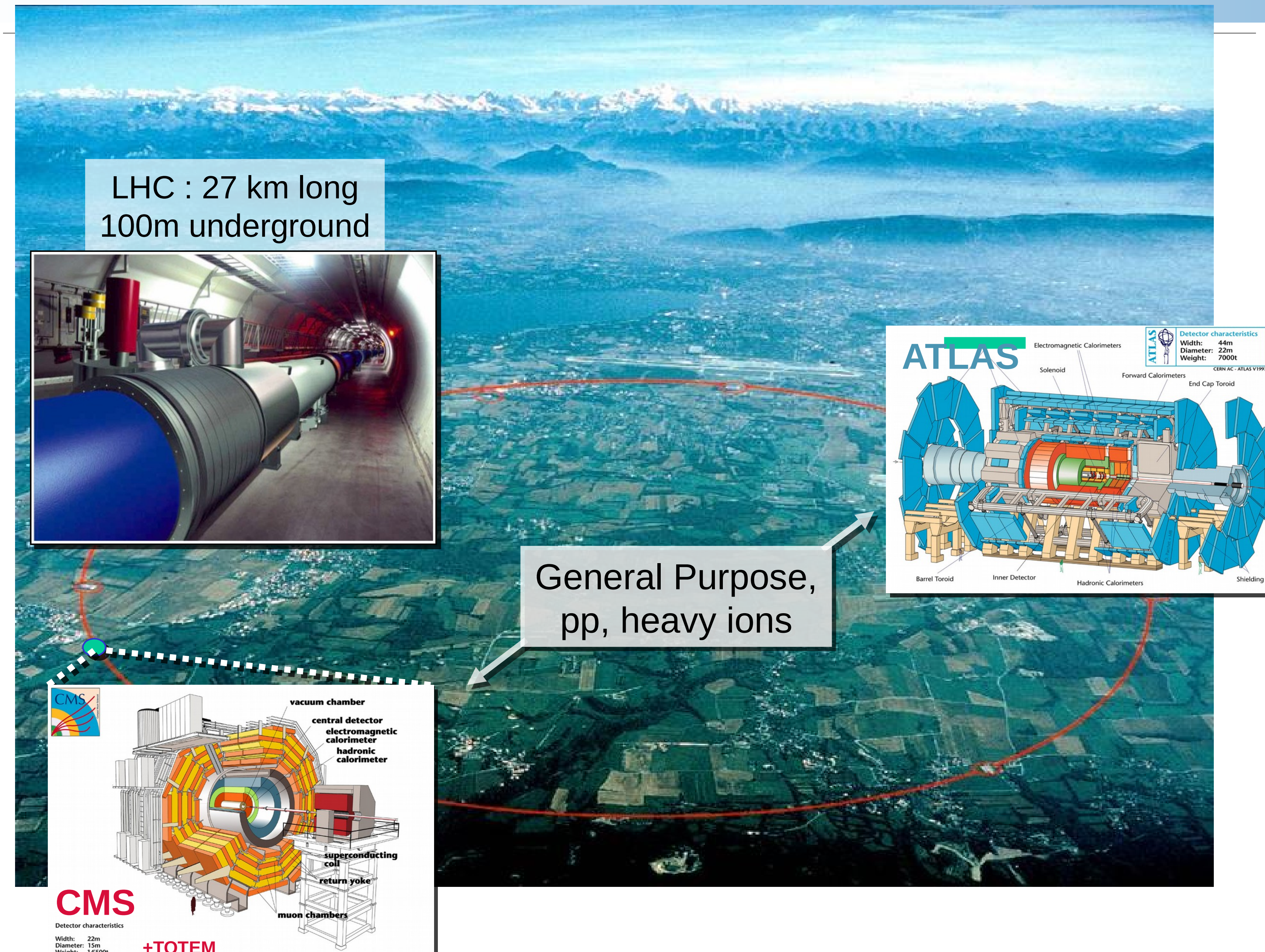
The Large Hadron Collider at CERN



The Large Hadron Collider at CERN

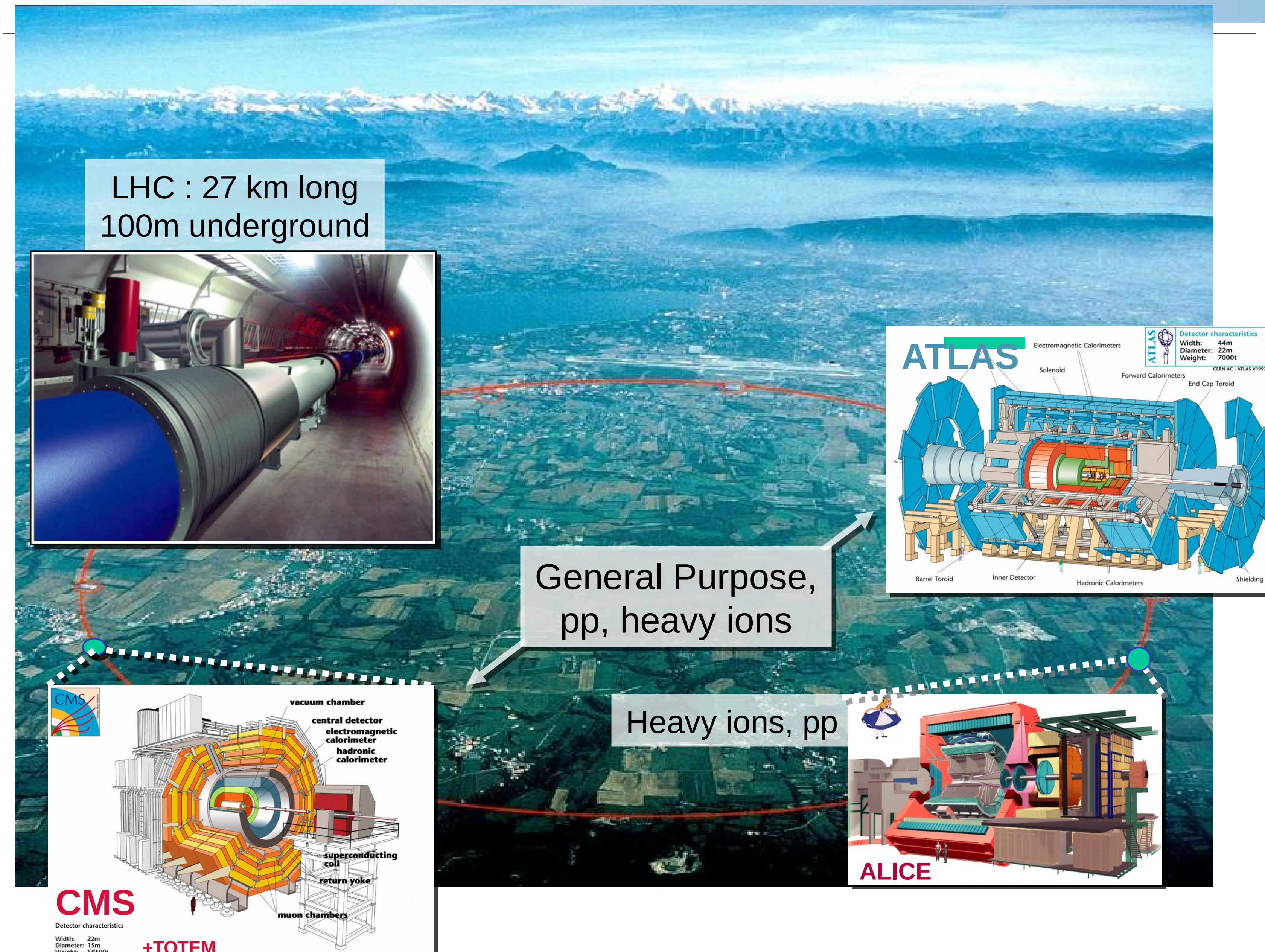
LHC : 27 km long
100m underground

General Purpose,
pp, heavy ions

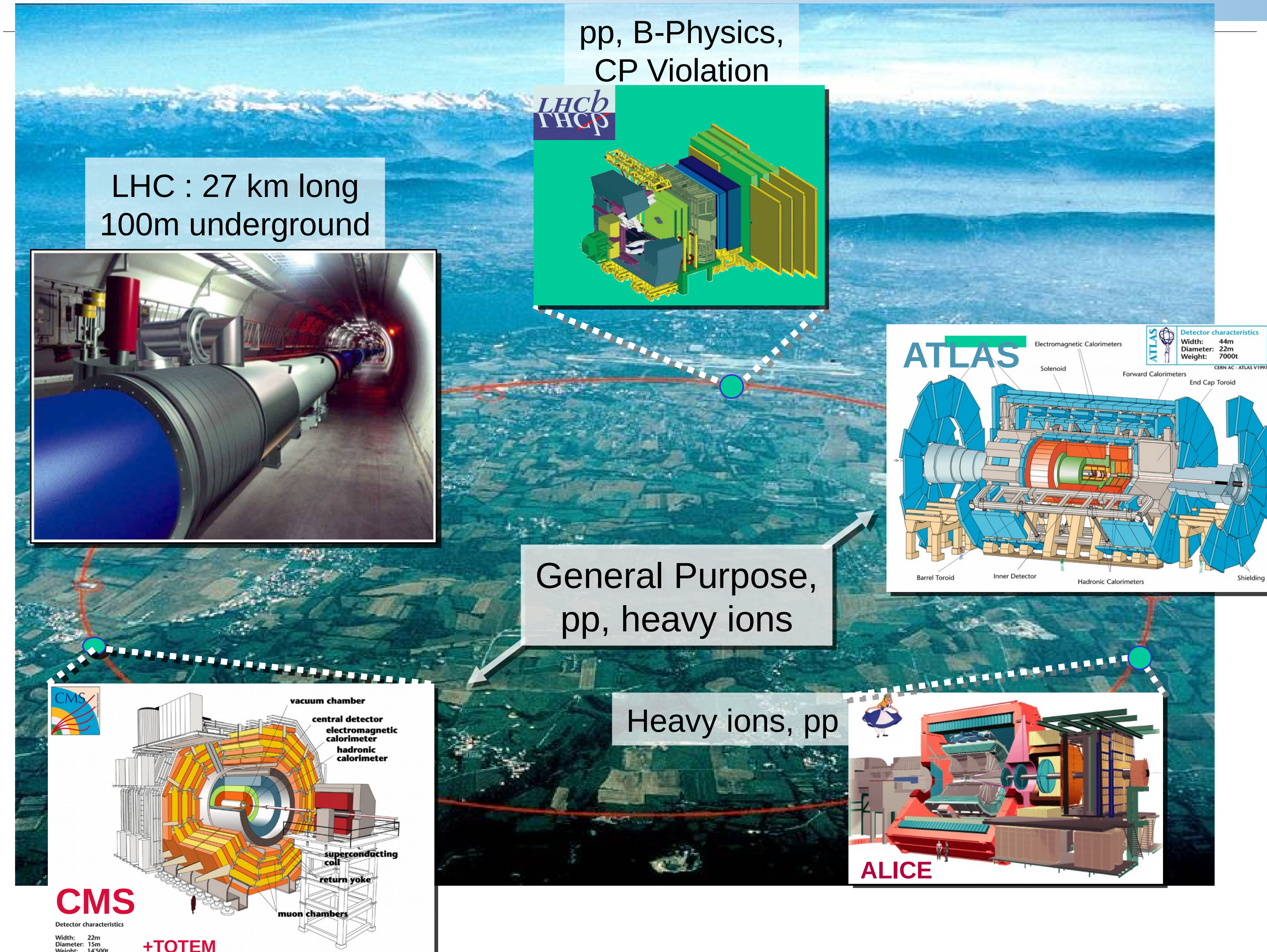


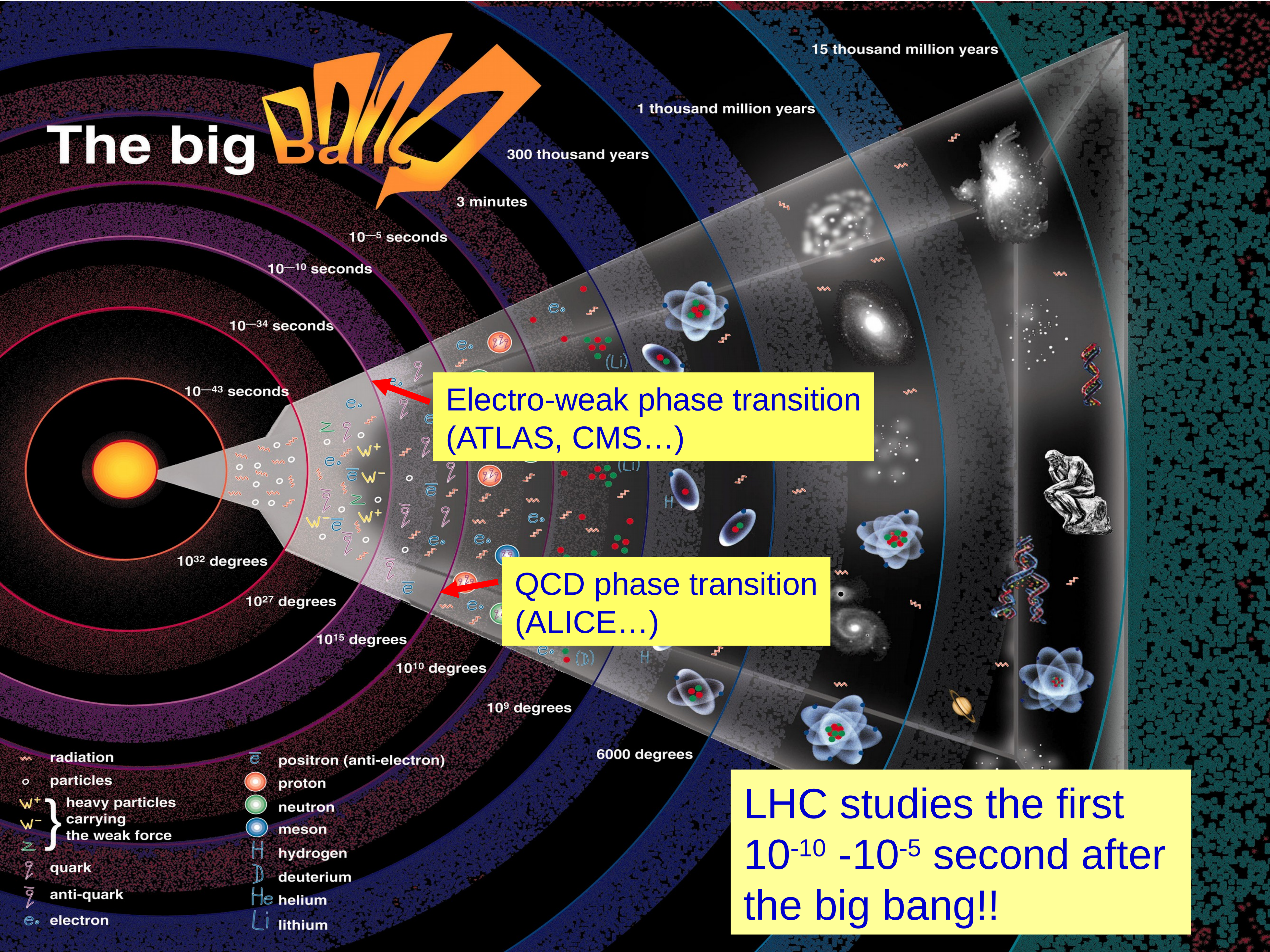
+TOTEM

The Large Hadron Collider at CERN



The Large Hadron Collider at CERN




The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
Electro-weak phase transition
(ATLAS, CMS…)
QCD phase transition
(ALICE…)
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
LHC studies the first
10-10 -10-5 second after
the big bang!!