

Recent KLOE results on radiative kaon decays



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for the KLOE Collaboration**

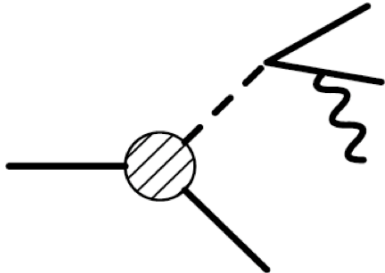
KAON INTERNATIONAL CONFERENCE

KAON09 TSUKUBA JAPAN 10 JUNE 2009

Radiative kaon decays



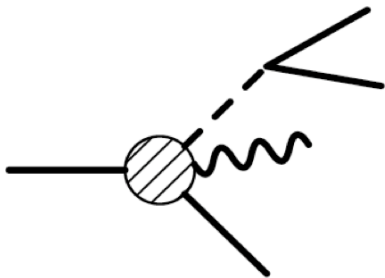
2 processes:



Internal Bremsstrahlung (IB)

Radiation from external charged particles

Completely determined by non-radiative amplitudes



Direct-emission (DE) or Structure-Dependent (SD)

Radiation from intermediate hadronic states

Theoretical approaches:

- Current algebra: Fearing et al. [FFS] '70
- Increasingly precise ChPT calculations

Observables:

$$R_{X\ell\gamma}(E_{\min}, \theta_{\min}) =$$

$$\frac{\text{BR}_{X\ell\gamma}(E_{\gamma}^* > E_{\min}, \theta_{\ell\gamma}^* > \theta_{\min})}{\text{BR}_{X\ell(\gamma)}}$$

Amplitudes are IR divergent at any fixed order in α

Physical amplitudes strongly peaked for $E_{\gamma}^* \rightarrow 0$ (or for $\theta_{\ell\gamma}^* \rightarrow 0$ if $m \approx 0$)

SD/(IB + SD) for $E_{\gamma}^* > E_{\min}, \theta_{\ell\gamma}^* > \theta_{\min}$

Separate by analysis of E_{γ}^* spectrum

K_{e2} and $K_{e2\gamma}$: Current status



$$R_K \equiv \frac{\Gamma(K \rightarrow e\nu(\gamma_{IB}))}{\Gamma(K \rightarrow \mu\nu(\gamma_{IB}))}$$

Cirigliano, Rosell '07

$$R_K^{\text{SM}} = 2.477(1) \times 10^{-5}$$

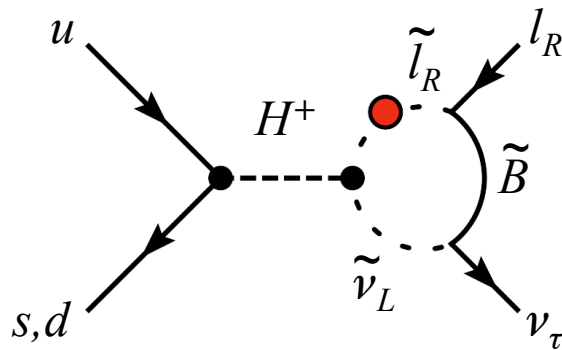
Definition of R_K inclusive of IB only

Helicity suppression: IB \sim SD

Experimental data is from '70s:

$$\delta\Gamma(\text{SD})/\Gamma(\text{SD}) \approx 15\%$$

MSSM with R parity



Masiero,
Petronzio,
Paradisi '06

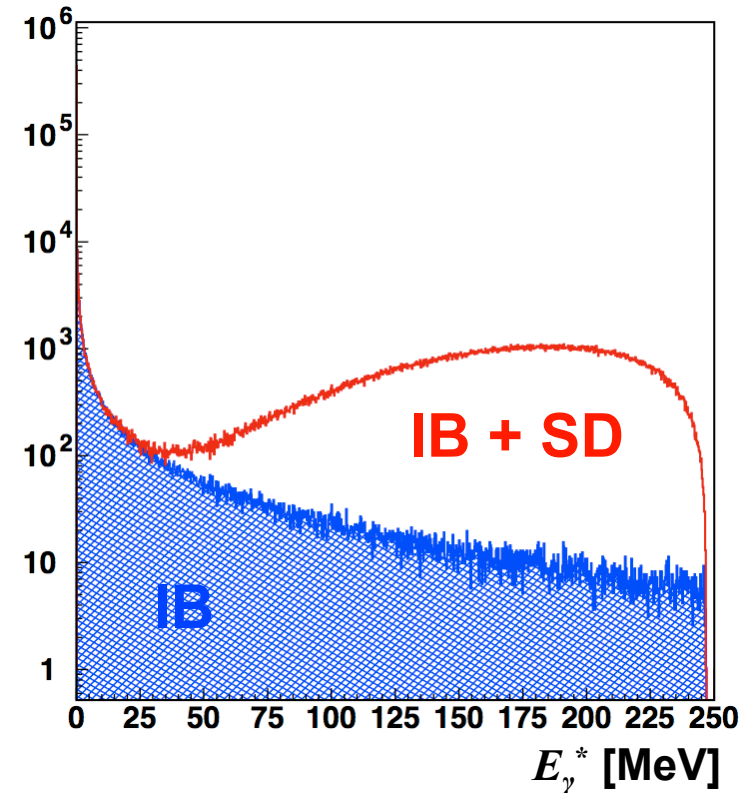
$$eH^\pm \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2 \beta$$

$\sim 1\%$ effect on R_K for:

$$\Delta_{13} \sim 5 \times 10^{-4} \quad \tan \beta \sim 40 \quad M_{H^\pm} \sim 500 \text{ GeV}$$

KLOE '09 final: $R_K = 2.493(31) \times 10^{-5}$

NA62 '09 prelim: $R_K = 2.500(16) \times 10^{-5}$



SD contribution to KLOE error
reduced from 0.5% \rightarrow 0.2%

$K_{e2\gamma}$ amplitudes



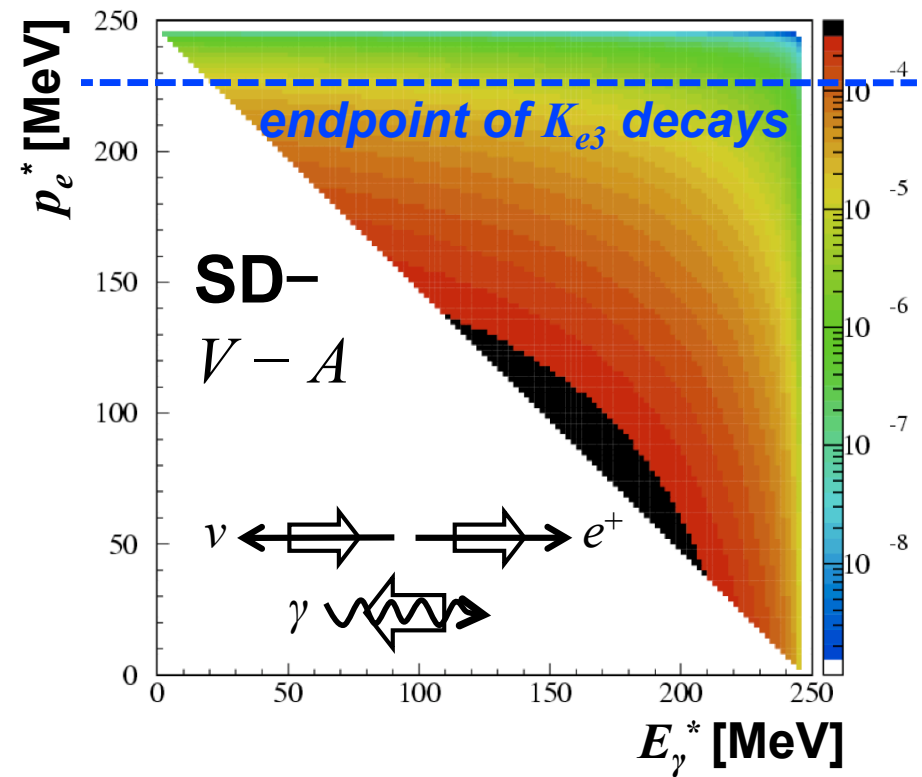
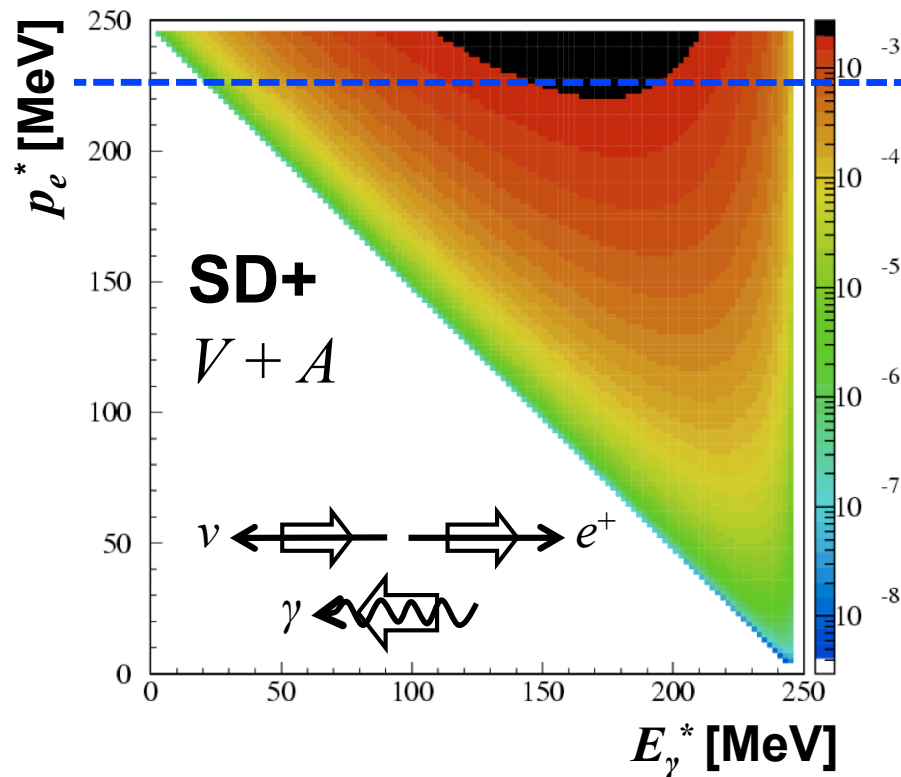
$$\frac{d\Gamma(K \rightarrow e\nu\gamma)}{dx dy} = \rho_{\text{IB}}(x, y) + \rho_{\text{SD}}(x, y) + \rho_{\text{INT}}(x, y) \quad \text{negligible}$$

$$x = 2E_\gamma^*/m_K$$

$$y = 2E_e^*/m_K$$

$$\rho_{\text{SD}}(x, y) = \frac{G_F^2 |V_{us}|^2 \alpha}{64\pi^2} m_K^5 \left((V + A)^2 f_{\text{SD}+}(x, y) + (V - A)^2 f_{\text{SD}-}(x, y) \right)$$

V, A : effective vector and axial couplings



$K_{e2\gamma}$: Theoretical predictions for SD



1. ChPT at $O(p^4)$

No dependence on γ energy

$$V \approx 0.0945$$

$$A \approx 0.0425$$

Bijnens, Ecker, Gasser '93

2. ChPT at $O(p^6)$

Linear energy dependence for V

$$V \approx 0.082[1 + \lambda(1 - x)] \text{ with } \lambda \approx 0.4$$

$$A \approx 0.034$$

Ametller, Bijnens, Bramon, Cornet '93

Geng, Ho, Wu '04

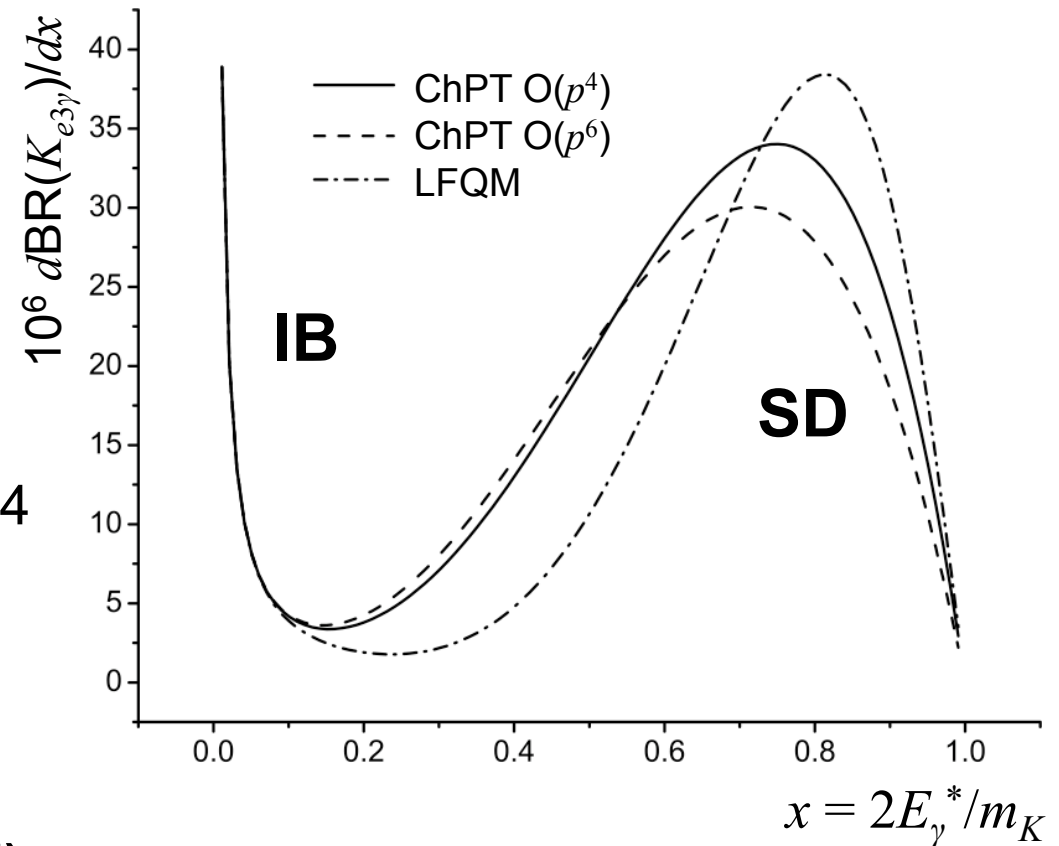
Chen, Geng, Lih '08

3. Light Front Quark Model (LFQM)

Non-trivial x dependence

$$V = A = 0 \text{ at } x = 0 \text{ or } t = t_{\max} = m_K^2$$

Chen, Geng, Lih '08



$K_{e2\gamma}$ event selection



Starting sample of $K_{e2(\gamma)}$ events same as for analysis of R_K

1-prong selection with tight track-quality cuts

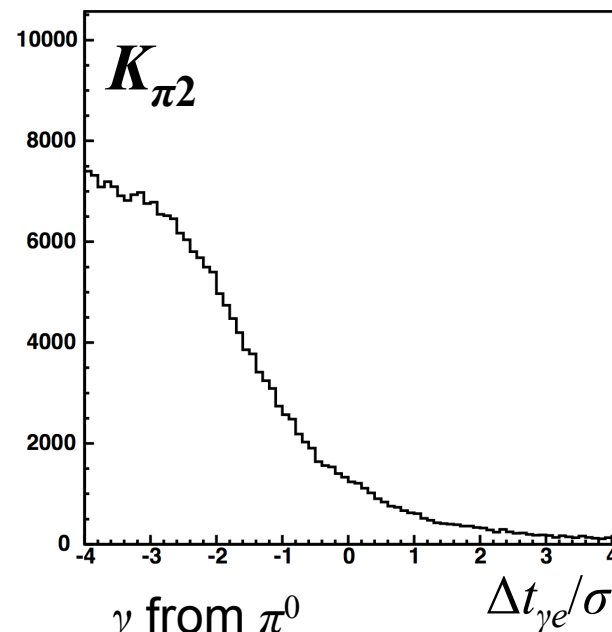
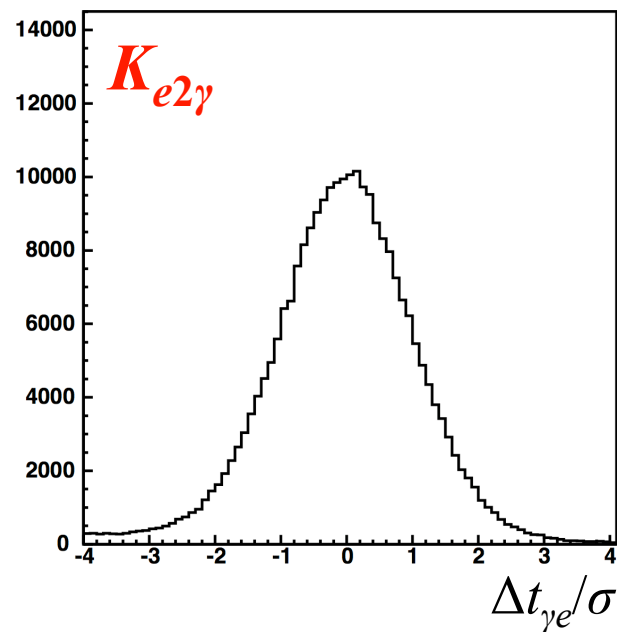
Make hard cut on neural-network output to reject $K_{\mu2\gamma}$ with accidental photon

Neural network uses EmC shower profile information, TOF

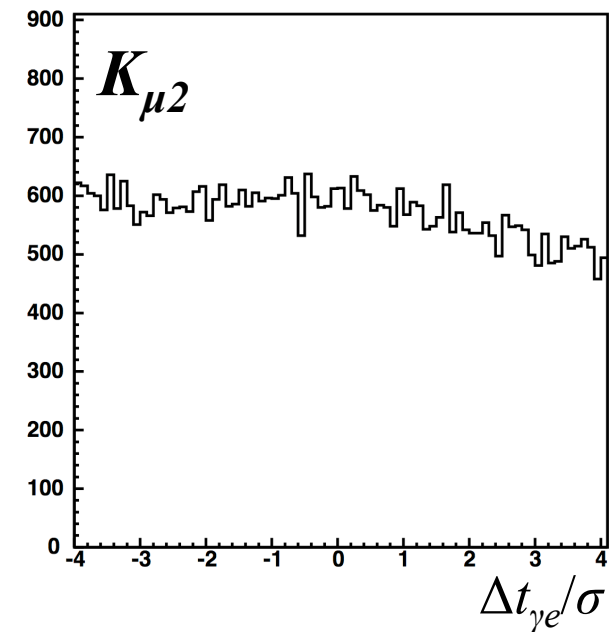
Require detection of γ with $E^{\text{cal}} > 20$ MeV to further reject accidentals/fragments

Cluster times for photon and electron must be compatible:

$$\Delta t_{\gamma e} = (t_{\gamma} - r_{\gamma}/c) - (t_e - L_e/c) < 2\sigma$$



γ from π^0
 $\beta(\pi^+) \approx 0.8$, not 1



Accidentals flat in time

$K_{e2\gamma}$ sample definition



Dominant backgrounds:

$$K_{\mu 2} \text{ for } M^2_\ell < 20000 \text{ MeV}^2$$

$$K_{e3} \text{ for } M^2_\ell > 20000 \text{ MeV}^2$$

No sensitivity for $K_{e2\gamma}$ with
 $p_e < 200 \text{ MeV}$ (SD- amplitude)

We measure $K_{e2\gamma}$ with:

$$E_\gamma^* > 10 \text{ MeV}$$

$$\cos \theta_{e\gamma}^* < 0.9$$

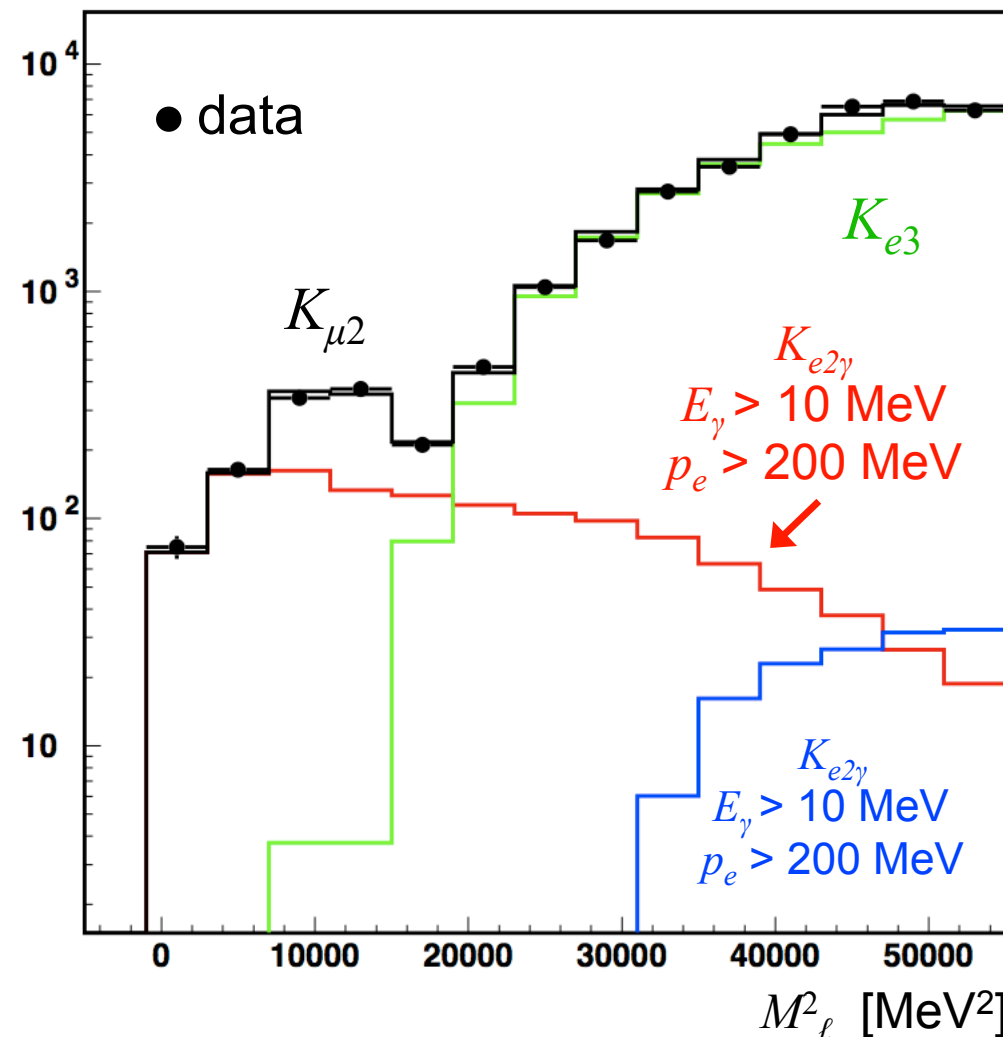
$$p_e^* > 200 \text{ MeV}$$

This selection has:

Acceptance for SD+ events $\sim 90\%$

SD- events $\sim 2\%$

Residual IB events $\sim 1\%$



$K_{e2\gamma}$ photon association



E_γ^{lab} can be evaluated from $K_{e2\gamma}$ kinematics, using measurements of:

- track momenta $\mathbf{p}_K, \mathbf{p}_e$
- photon direction \mathbf{n}_γ from cluster and vertex positions

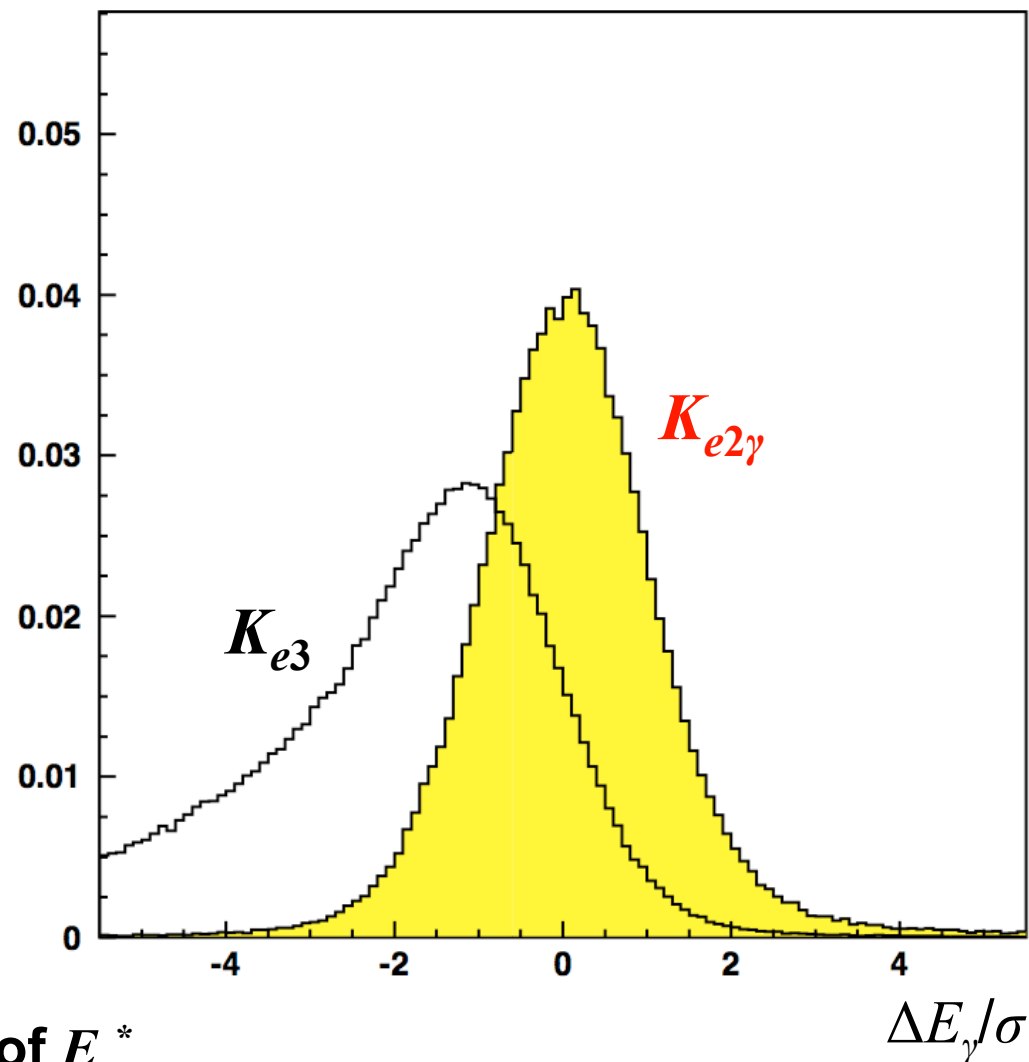
$$E_\gamma^{\text{lab}} = \frac{m_K^2 + m_e^2 - 2E_K E_e + 2\mathbf{p}_K \cdot \mathbf{p}_e}{2(E_K - E_e - \mathbf{p}_K \cdot \mathbf{n}_\gamma + \mathbf{p}_e \cdot \mathbf{n}_\gamma)}$$

$$\sigma_E^{\text{lab}} \approx 12 \text{ MeV}$$

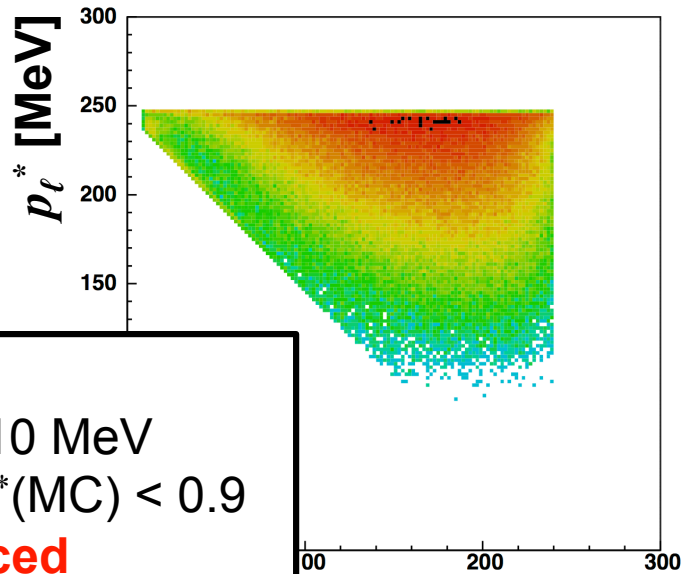
$$\sigma_E^{\text{cal}} \approx 30 \text{ MeV}$$

$\Delta E_\gamma = E_\gamma^{\text{lab}} - E_\gamma^{\text{cal}}$ useful for signal/background separation

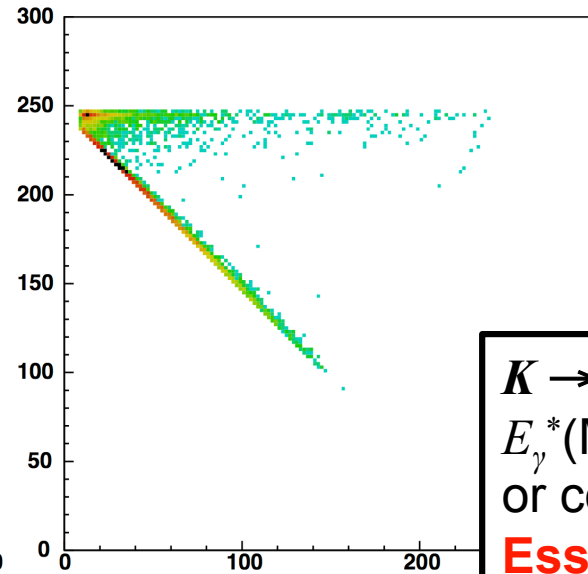
Perform 2-dimensional binned likelihood fit in $M_\ell^2, \Delta E_\gamma/\sigma$ in 5 bins of E_γ^*



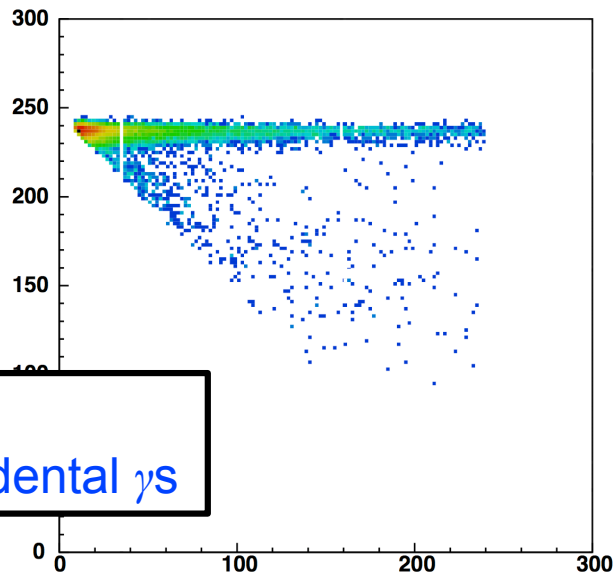
MC kinematics for samples in $K_{e2\gamma}$ fit



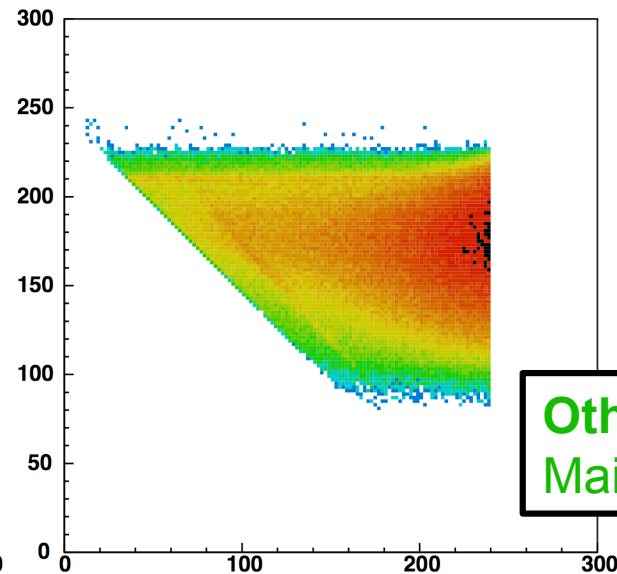
$K \rightarrow e\nu\gamma$
 $E_\gamma^*(MC) > 10$ MeV
 and $\cos \theta_{\gamma\ell}^*(MC) < 0.9$
SD enhanced



$K \rightarrow e\nu\gamma$
 $E_\gamma^*(MC) < 10$ MeV
 or $\cos \theta_{\gamma\ell}^*(MC) > 0.9$
Essentially all IB



$K \rightarrow \mu\nu(\gamma)$
 including accidental γ s



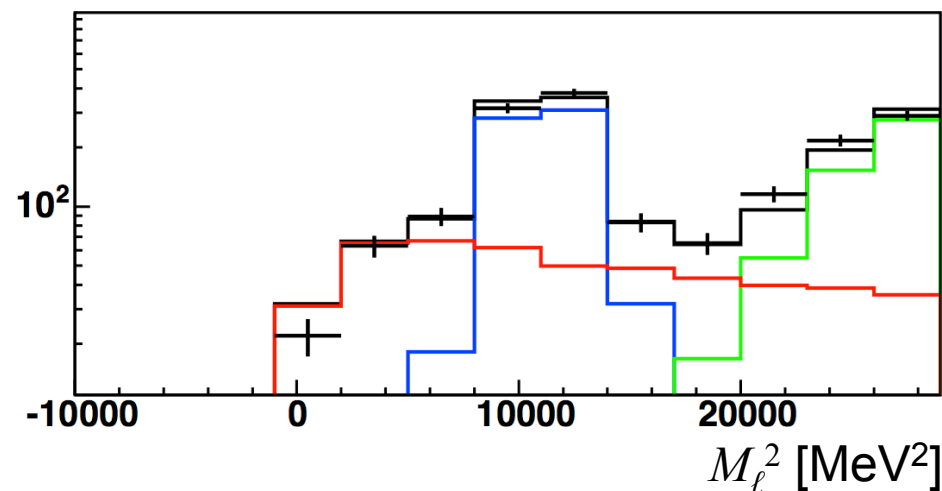
Other background
 Mainly K_{e3}

$E_\gamma^* [MeV]$

$K_{e2\gamma}$ fit results



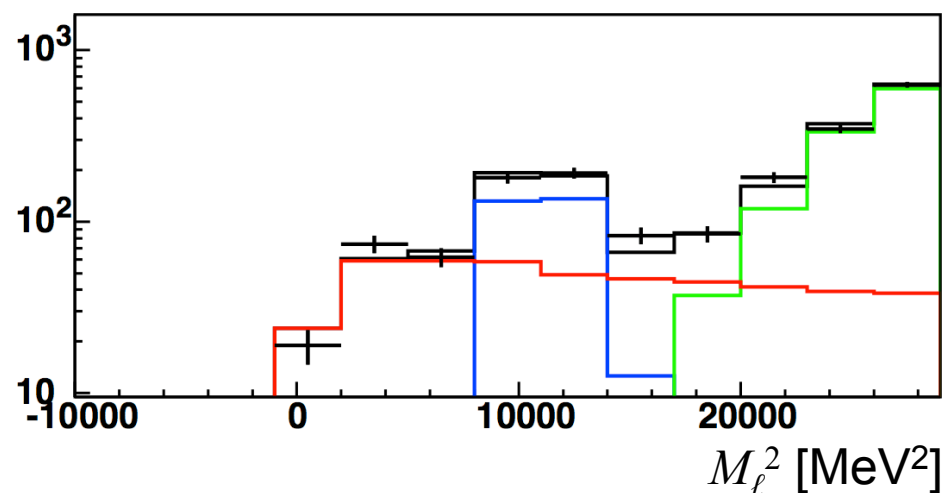
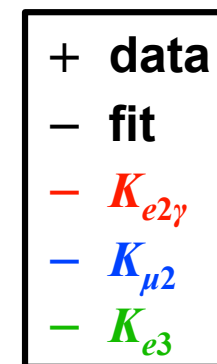
Projections on M_ℓ^2 axis for 2 most populated E_γ^* bins



$100 < E_\gamma < 150$ MeV

$$N_{e2\gamma} = 463 \pm 32$$

$$\chi^2/\text{ndf} = 87/106$$



$150 < E_\gamma < 200$ MeV

$$N_{e2\gamma} = 494 \pm 38$$

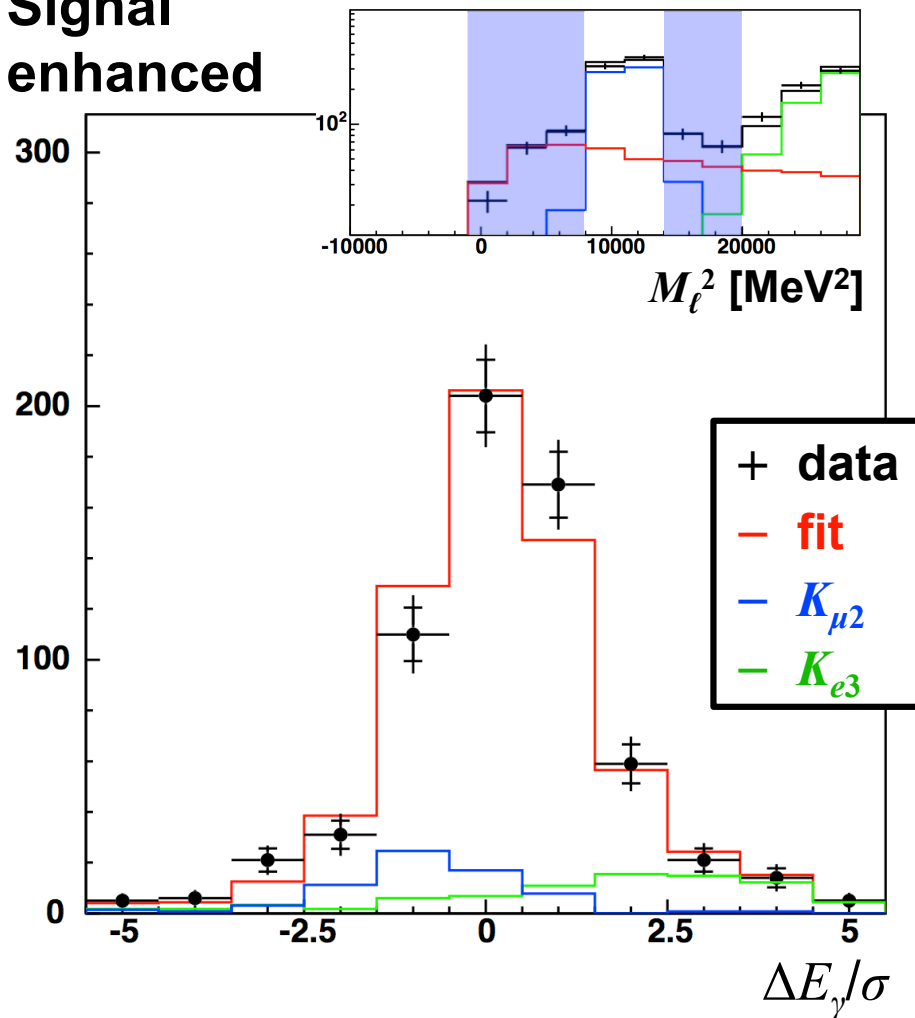
$$\chi^2/\text{ndf} = 100/106$$

$K_{e2\gamma}$ fit results

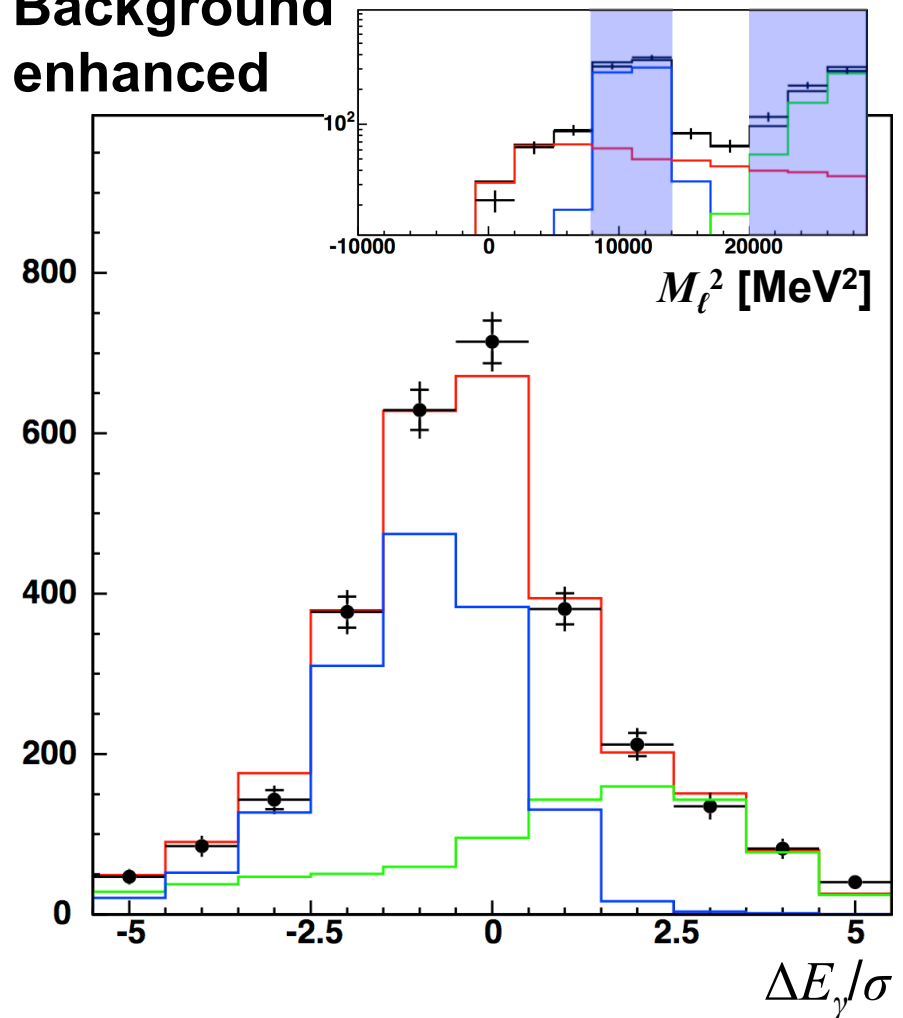


Projections on $\Delta E_\gamma/\sigma$ axis for all 5 E_γ^* bins, with cuts on M_ℓ^2

Signal enhanced



Background enhanced



$K_{e2\gamma}$ spectrum vs $O(p^4)$ ChPT



We measure

$$\frac{1}{\Gamma(K_{\mu 2(\gamma)})} \frac{d\Gamma_{SD+}(K_{e2\gamma})}{dE_\gamma}$$

where “SD+” means:

$$E_\gamma^* > 10 \text{ MeV}$$

$$\cos \theta_{e\gamma}^* < 0.9$$

$$p_e^* > 200 \text{ MeV}$$

Summed over all bins in E_γ^* :

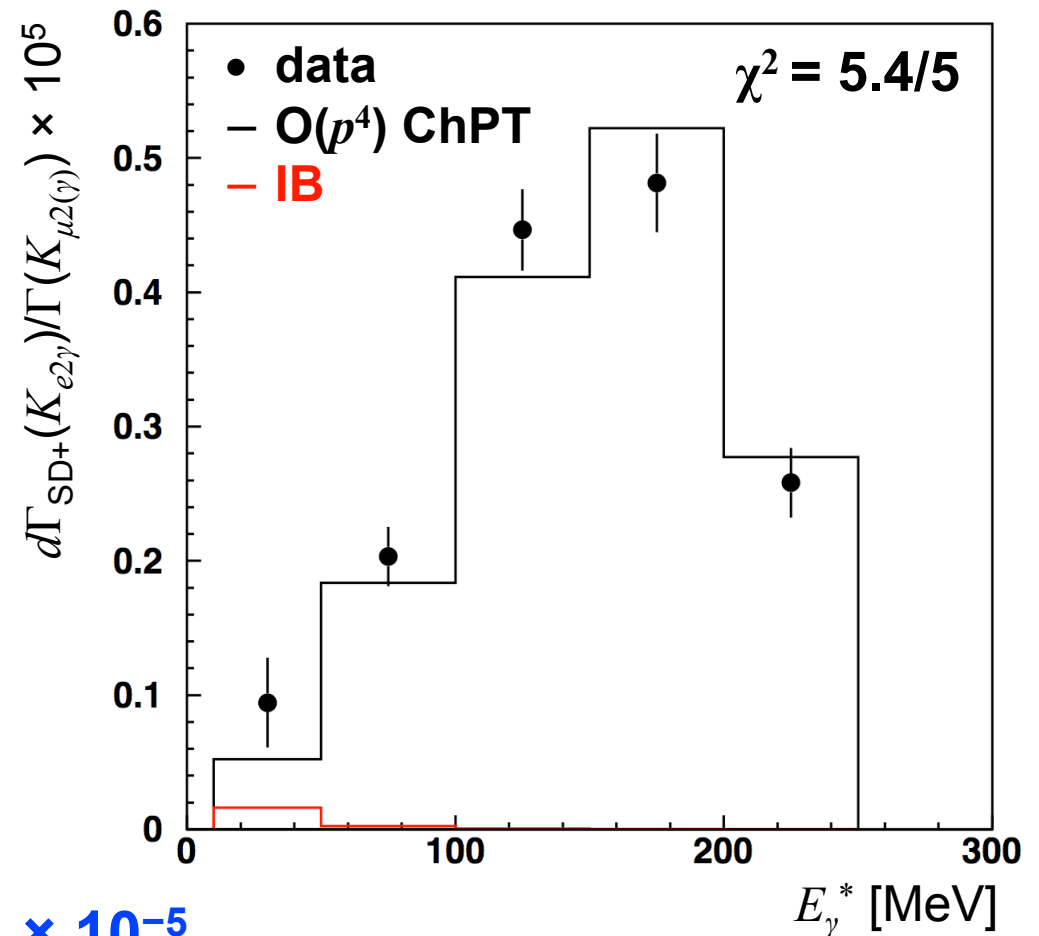
$$N_{SD+}(K_{e2\gamma}) = 1378 \pm 63$$

$$\frac{\Gamma_{SD+}(K_{e2\gamma})}{\Gamma(K_{\mu 2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$$

in agreement with ChPT $O(p^4)$ prediction, 1.447×10^{-5} [Bijnens, Ecker, Gasser '93]

KLOE MC implements $O(p^4)$ ChPT for SD – used in analysis of R_K

Validated to within 4.6% - systematic error on R_K from SD = 0.2%



$K_{e2\gamma}$ spectrum: fit to $O(p^6)$ ChPT



Fit data to extract $V + A$ for SD+

Get slope of vector form factor

$$V = V_0 [1 + \lambda(1 - x)]$$

Not sensitive to SD- amplitude

Acceptance $\sim 2\%$

Fix $V - A$ to $O(p^6)$ prediction

Obtain:

$$V_0 + A = 0.125 \pm 0.007$$

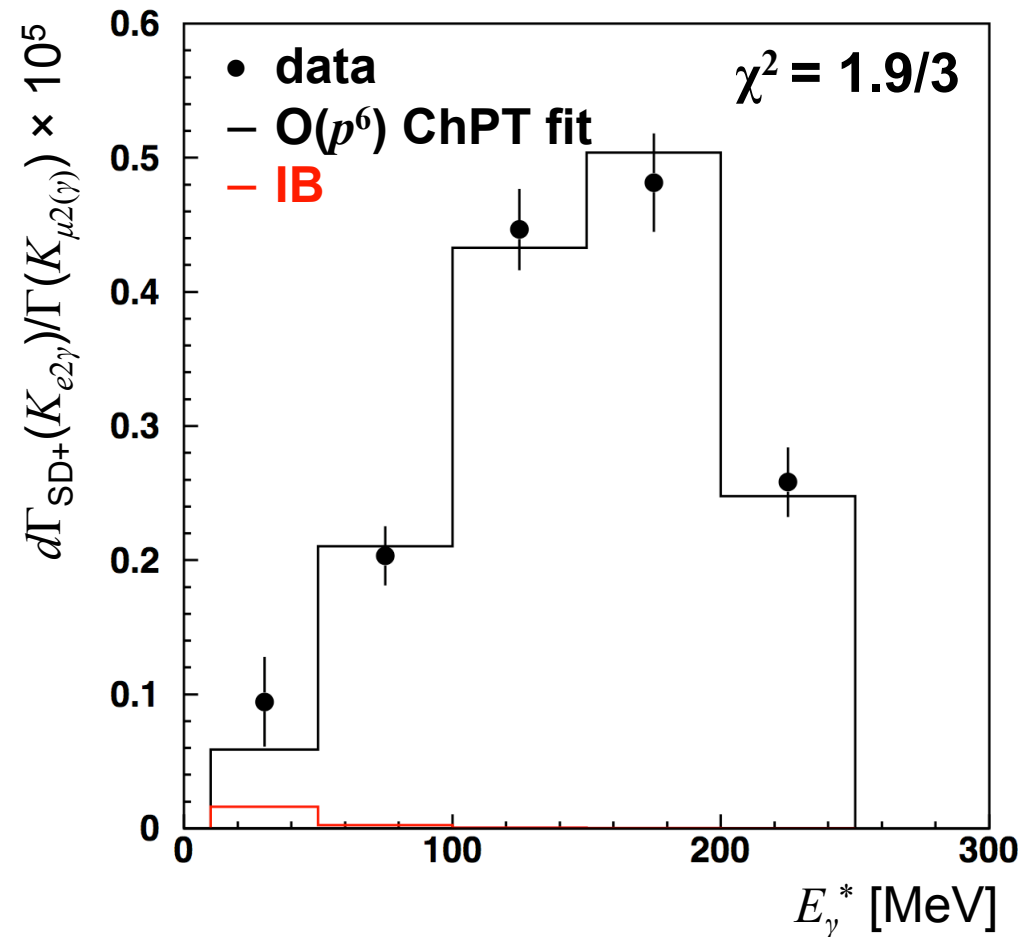
$$\lambda = 0.38 \pm 0.21$$

Compare to ChPT $O(p^6)$:

$$V_0 + A \approx 0.116$$

$$\lambda \approx 0.4$$

Chen, Geng, Lih '08

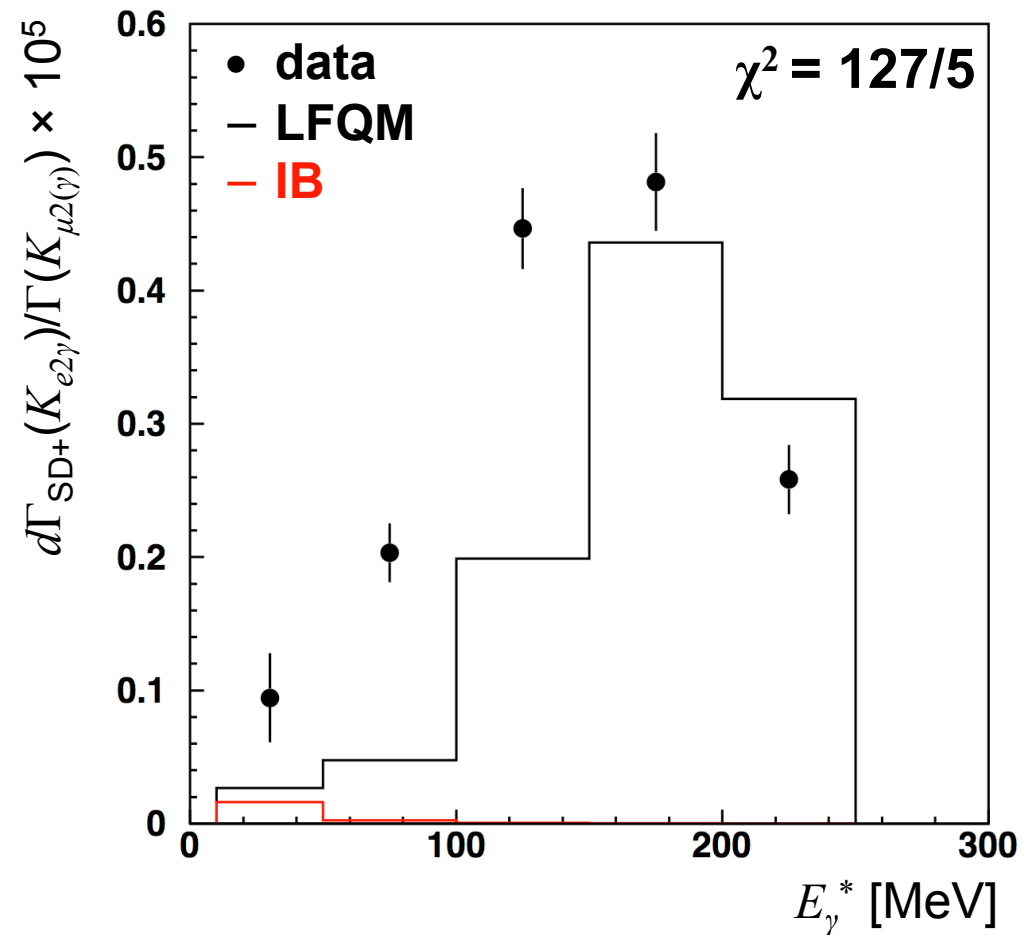


$K_{e2\gamma}$ spectrum vs LFQM



Light Front Quark Model
with parameters as in
Chen, Geng, Lih, '08

Excluded by our data
 $\chi^2 = 127/5$



Preexisting data on $K_L \rightarrow \pi e \nu \gamma$ ($K_{e3\gamma}$)



Most common observable: $R_{e3\gamma}(E_\gamma^* > 30 \text{ MeV}, \theta_{e\gamma}^* > 20^\circ)$

KTeV
PRD 64 (2001)

$R_{e3\gamma} = 0.908(8)^{(+13}_{-12)}\%$
15575 evts over 1% bkg

Attempt to study $d\Gamma/dE_\gamma^*$
Isolation of SD complicated
by use of cumbersome
theoretical framework

KTeV
PRD 71 (2005)

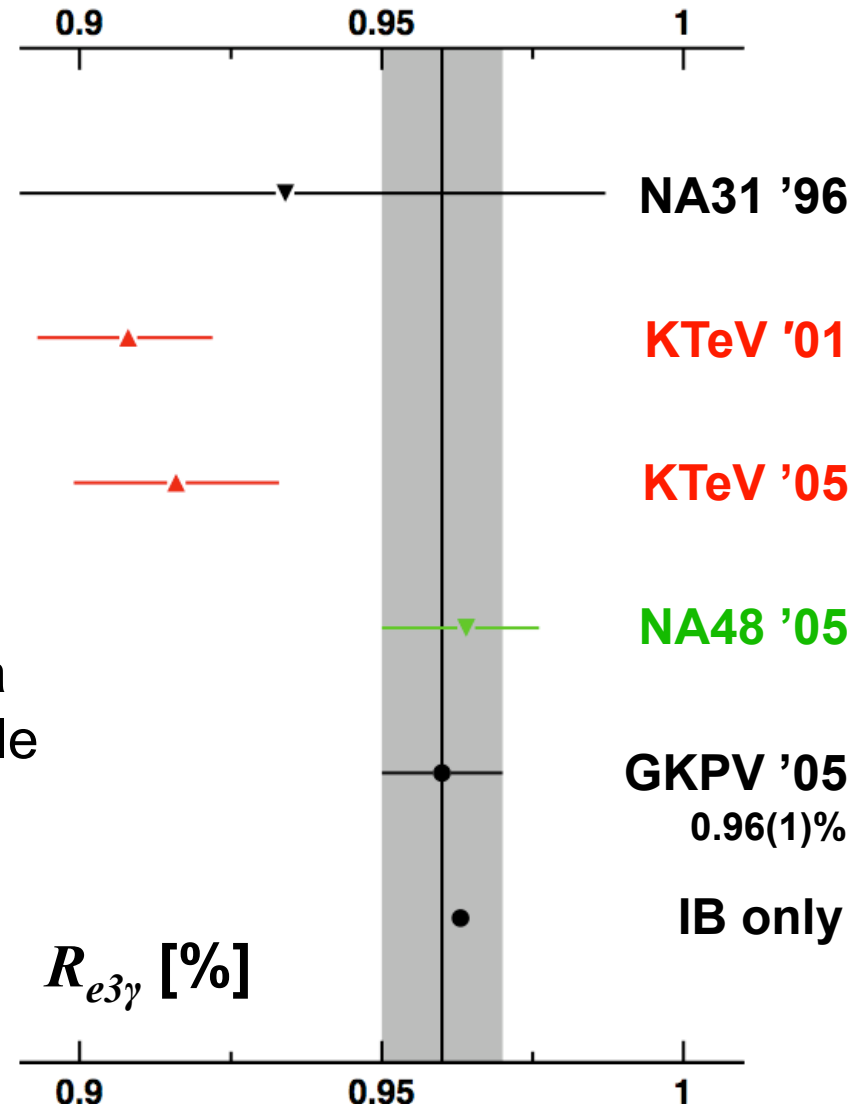
$R_{e3\gamma} = 0.916(17)\%$
4309 evts over 1% bkg

Reanalysis of previous data
Tighter cuts, 30% subsample
No attempt to isolate SD

NA48
PLB 605 (2005)

$R_{e3\gamma} = 0.964(8)^{(+11}_{-9)}\%$
18977 evts over 7% bkg

No attempt to isolate SD



$K_{e3\gamma}$ theory status



Gasser, Kubis, Paver, Verbeni [GKPV] '05

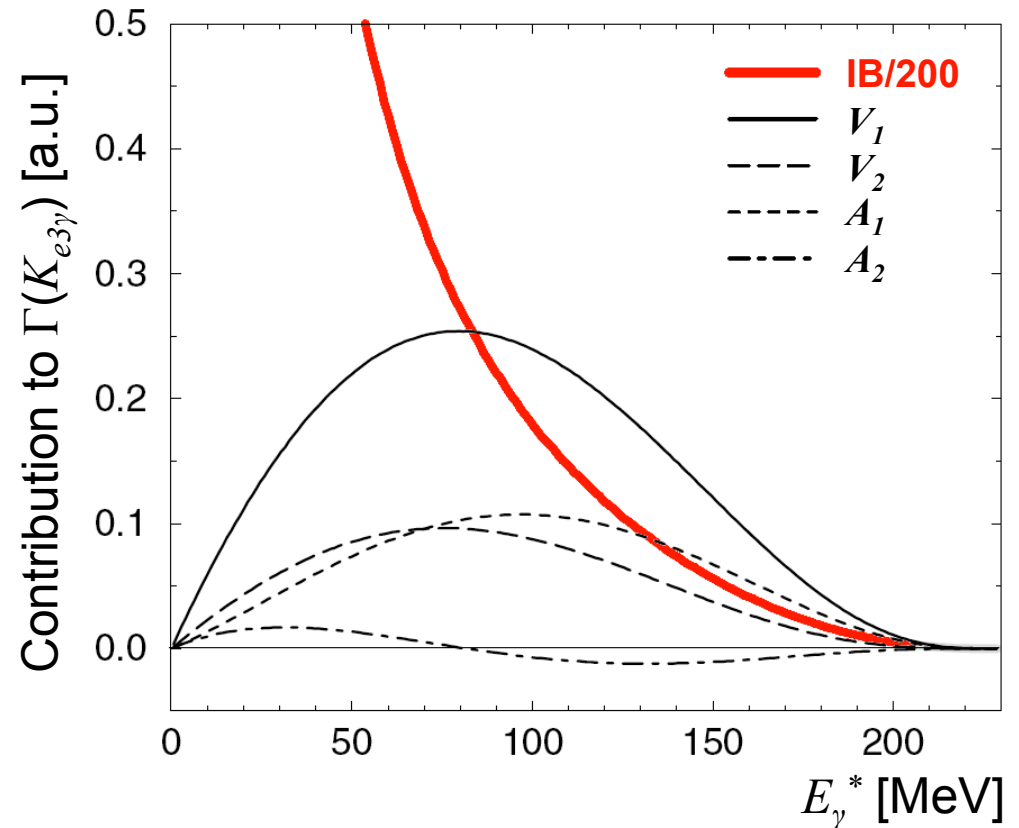
$O(p^6)$ decomposition of photon spectrum:

$$\frac{d\Gamma}{dE_\gamma^*} = \frac{d\Gamma_{\text{IB}}}{dE_\gamma^*} + \sum_{i=1,4} V_i \frac{d\Gamma_{V_i}}{dE_\gamma^*} + A_i \frac{d\Gamma_{A_i}}{dE_\gamma^*}$$

V_1, V_2, A_1 amplitudes dominant, have similar dependence on E_γ^*

$$\frac{d\Gamma}{dE_\gamma^*} = \frac{d\Gamma_{\text{IB}}}{dE_\gamma^*} + \langle X \rangle f(E_\gamma^*)$$

$$\langle X \rangle \approx \langle V_1 \rangle + 0.4\langle V_2 \rangle + 0.4\langle A_1 \rangle$$



$O(p^6)$ estimates (for V) and full calculations (for A) give $\langle X \rangle = -1.2 \pm 0.4$

Error from estimates of $O(p^6)$ LECs

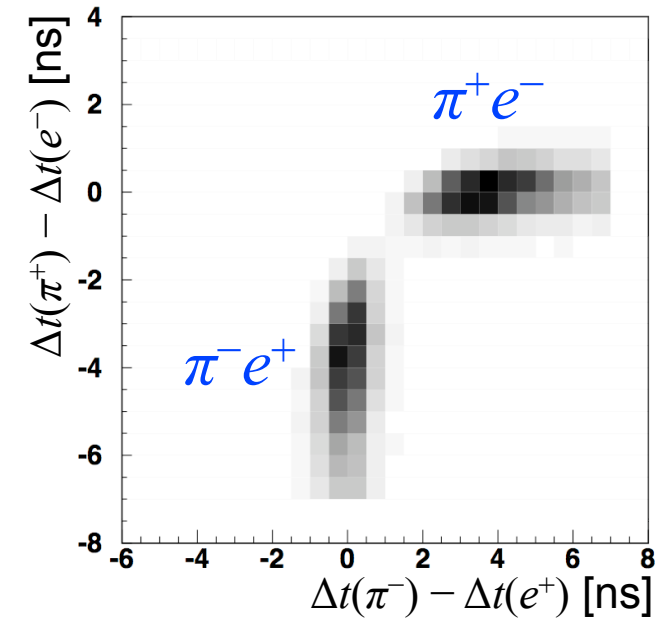
$$\text{Also have } R_{e3\gamma} = (0.963 + 0.006\langle X \rangle \pm 0.010)\%$$

$K_{e3\gamma}$ at KLOE: Event selection



Inclusive sample ($K_{e3(\gamma)}$)

- 328 pb⁻¹ of '01 + '02 data (same sample as for V_{us})
 - K_L decay tagged by $K_S \rightarrow \pi^+\pi^-$
 - Pos. and neg. tracks with vertex in fiducial volume
 - Kinematic rejection for $K_{\mu 3}$ and $\pi^+\pi^-\pi^0$ decays (e.g. M_{miss})
 - PID/charge assignment by TOF: $\Delta t_x = t_{\text{meas}} - t_{\text{pred}}(m_x)$
- $\sim 3 \times 10^6$ $K_{e3(\gamma)}$ events, 0.7% background

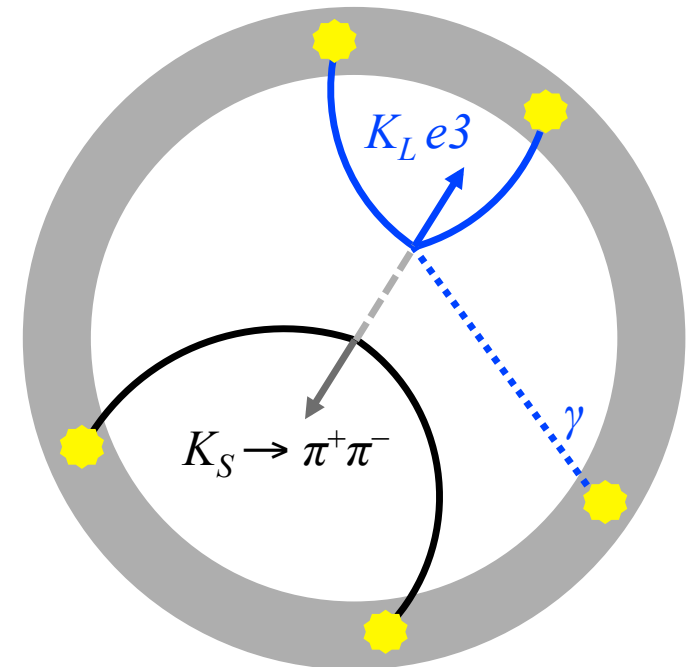


Radiative sample ($K_{e3\gamma}$)

- Look for photon cluster with timing compatible with distance from track vertex
- Predict its energy from kinematics with $\sigma \approx 1$ MeV
- Cut on measured energy
- Refine using neural networks to reject $K_{\mu 3}$ and $\pi^+\pi^-\pi^0$ decays to $\sim 1\%$ level
- Use $\pi^+\pi^-\pi^0$ decays to check photon reconstruction:

$$p_{\gamma 2}^2 = 0 = (p_K - p_{\pi^+} - p_{\pi^-} - p_{\gamma 1})^2$$

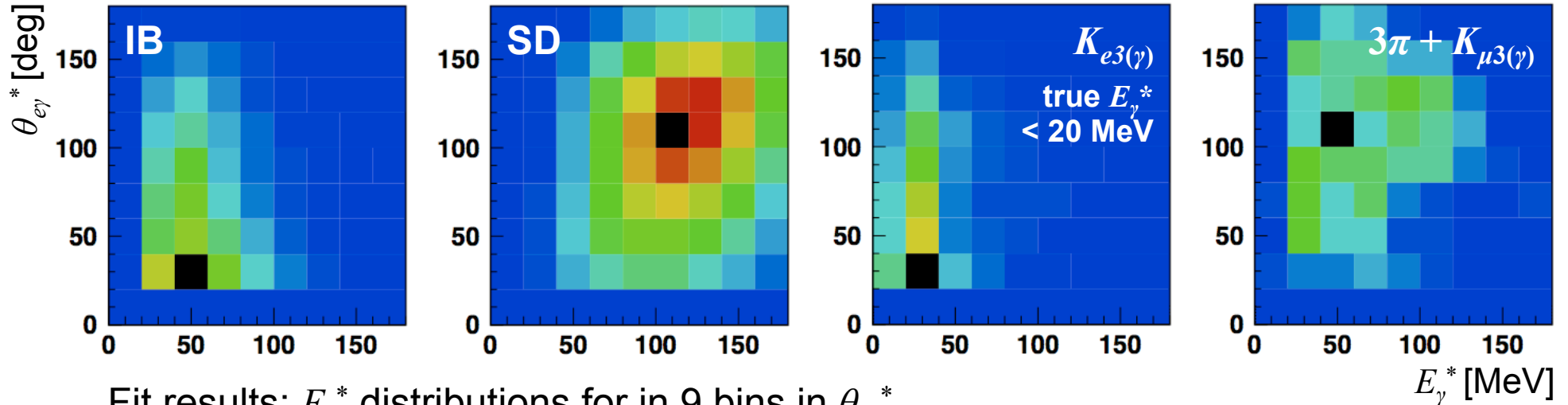
$$p_v^2 = 0 = (p_K - p_{\pi^+} - p_e - p_{\gamma})^2$$



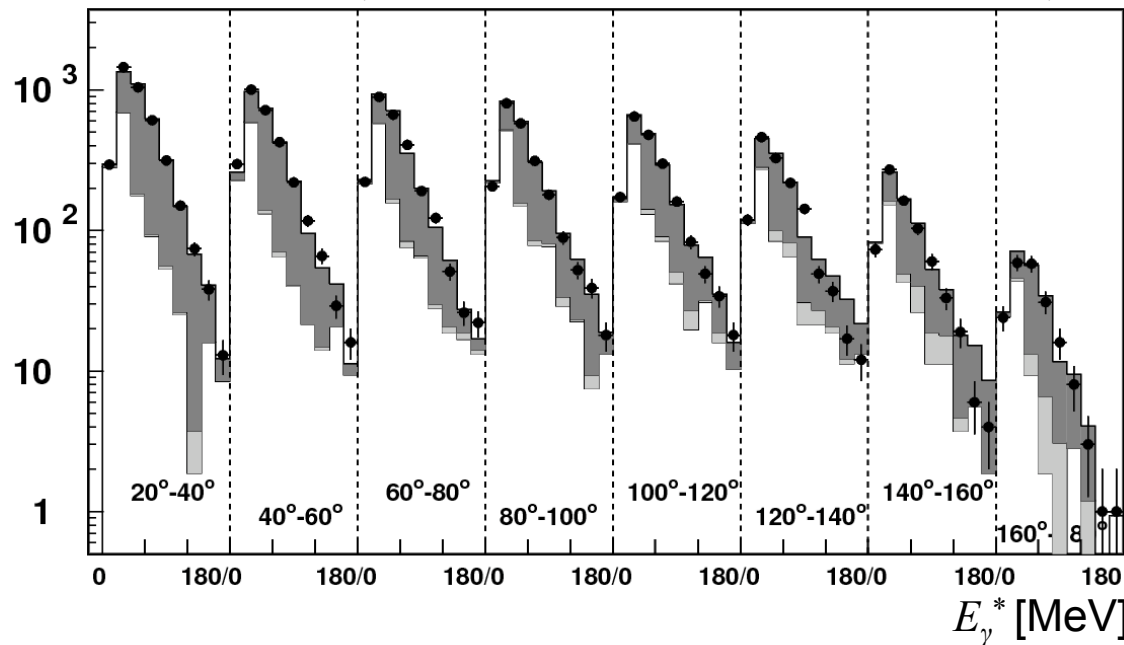
$K_{e3\gamma}$: Fit to $(E_\gamma^*, \theta_{\ell\gamma}^*)$ distribution



Monte Carlo distributions in 9×9 bins in $\theta_{e\gamma}^*$ vs. E_γ^* for:



Fit results: E_γ^* distributions for in 9 bins in $\theta_{e\gamma}^*$



■ $N_{e3\gamma}$	8981 ± 206
□ N_{IB}	9083 ± 213
□ N_{SD}	-102 ± 59
□ $N_{e3(\gamma)}$	6726 ± 194
■ $N_{3\pi + \mu3(\gamma)}$	fixed

$\chi^2/\text{ndf} = 60/69$ ($P = 77\%$)

Destructive interference between IB and SD

$K_{e3\gamma}$: Results for $R_{e3\gamma}$ and $\langle X \rangle$



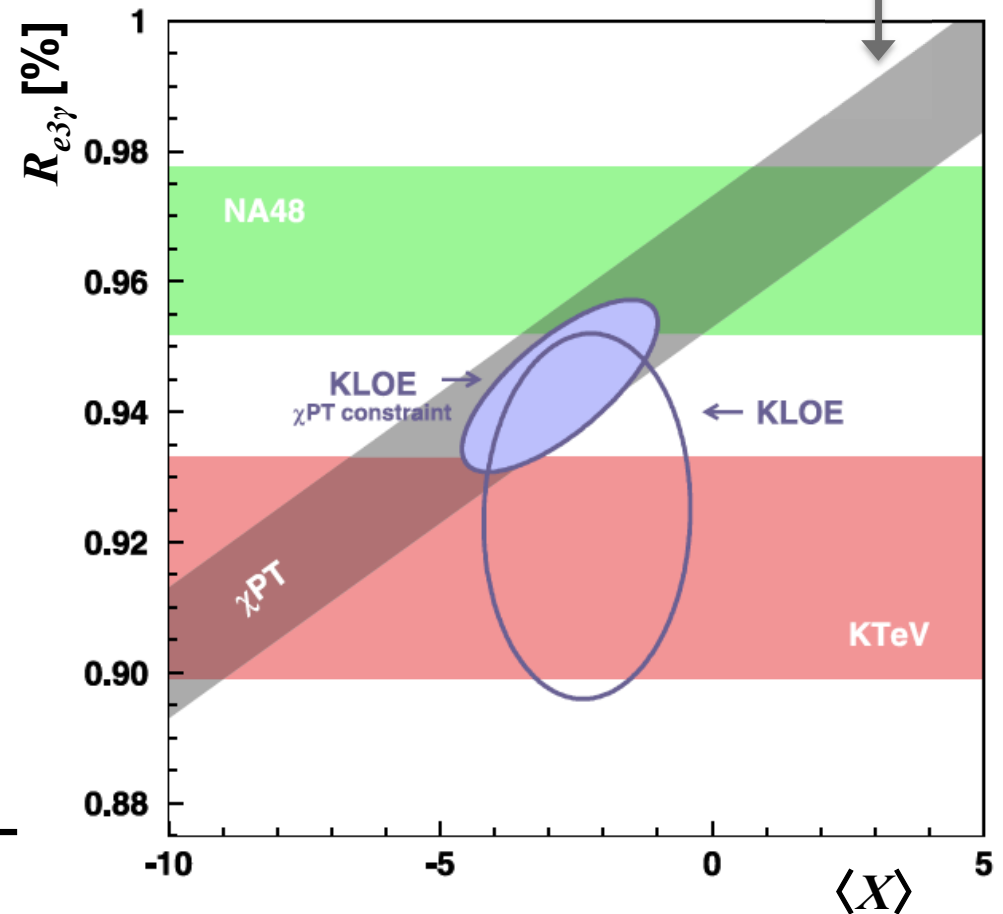
KLOE
EPJC 55 (2008)

$$R_{e3\gamma}(E_\gamma^* > 30 \text{ MeV}, \theta_{e\gamma}^* > 20^\circ) = 0.924(23)_{\text{st}}(16)_{\text{sy}} \%$$

$$\langle X \rangle = -2.3 \pm 1.3_{\text{st}} \pm 1.4_{\text{sy}}$$

Source	$\Delta R_{e3\gamma} \times 10^5$	$\Delta \langle X \rangle \times 10^5$
Tag & trigger	4.0	0.7
Tracking	1.5	0.8
Clustering	5.5	0.1
TOF cuts	1.3	0.5
p calibration	3.5	0.2
p resolution	7.2	0.4
Fiducial volume	3.0	0.5
Accidentals	5.2	0.4
γ association	2.9	0.3
Background	9.0	0.1
Total	15.5	1.4

ChPT constraint on KLOE result [GKPV '05]
 $R_{e3\gamma} = (0.963 + 0.006\langle X \rangle \pm 0.010)\%$



Summary



$K_{e2\gamma}$:

$$\frac{\Gamma_{SD+}(K_{e2\gamma})}{\Gamma(K_{\mu2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$$

Agreement with $O(p^4)$ ChPT used in KLOE MC gives systematic error on R_K from SD = 0.2%

Fits performed to determine vector form-factor parameters for comparison with ChPT at $O(p^6)$

LFQM ruled out

$K_{e3\gamma}$:

$$R_{e3\gamma}(E_\gamma^* > 30 \text{ MeV}, \theta_{e\gamma}^* > 20^\circ) = 0.924(23)_{st}(16)_{sy} \%$$
$$\langle X \rangle = -2.3 \pm 1.3_{st} \pm 1.4_{sy}$$

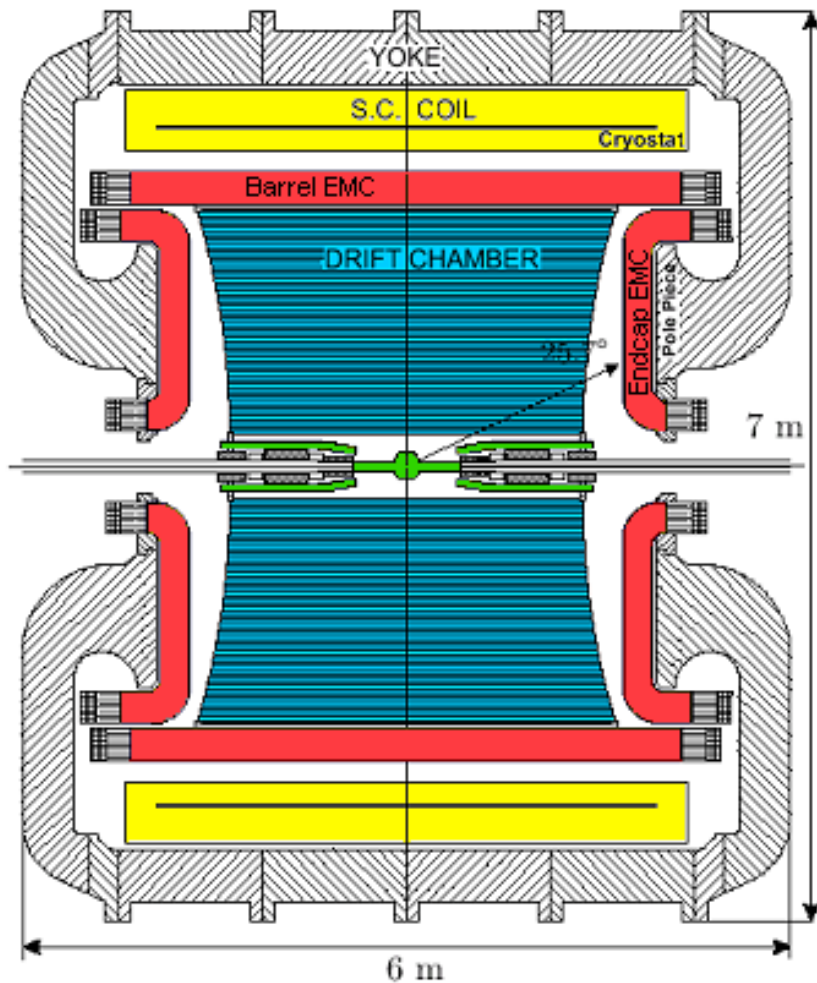
First complete study of $d\Gamma/dE_\gamma^*$ for $K_L \rightarrow \pi e \nu \gamma$

Measurement (esp. for $\langle X \rangle$) limited by statistics –
~7× more data available

Additional information



The KLOE experiment



Be beam pipe (0.5 mm thick)
Instrumented permanent magnet quadrupoles (32 PMTs)

Drift chamber (4 m \varnothing \times 3.3 m)
90%He+10% IsoB, composite frame
12582 stereo sense wires

Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMTs

Superconducting coil (5 m bore)
 $B = 0.52 \text{ T}$ ($\int B dl = 2 \text{ T}\cdot\text{m}$)

Generators for radiative kaon decays



KLOE generators for kaon decays include radiation with no cutoff energy

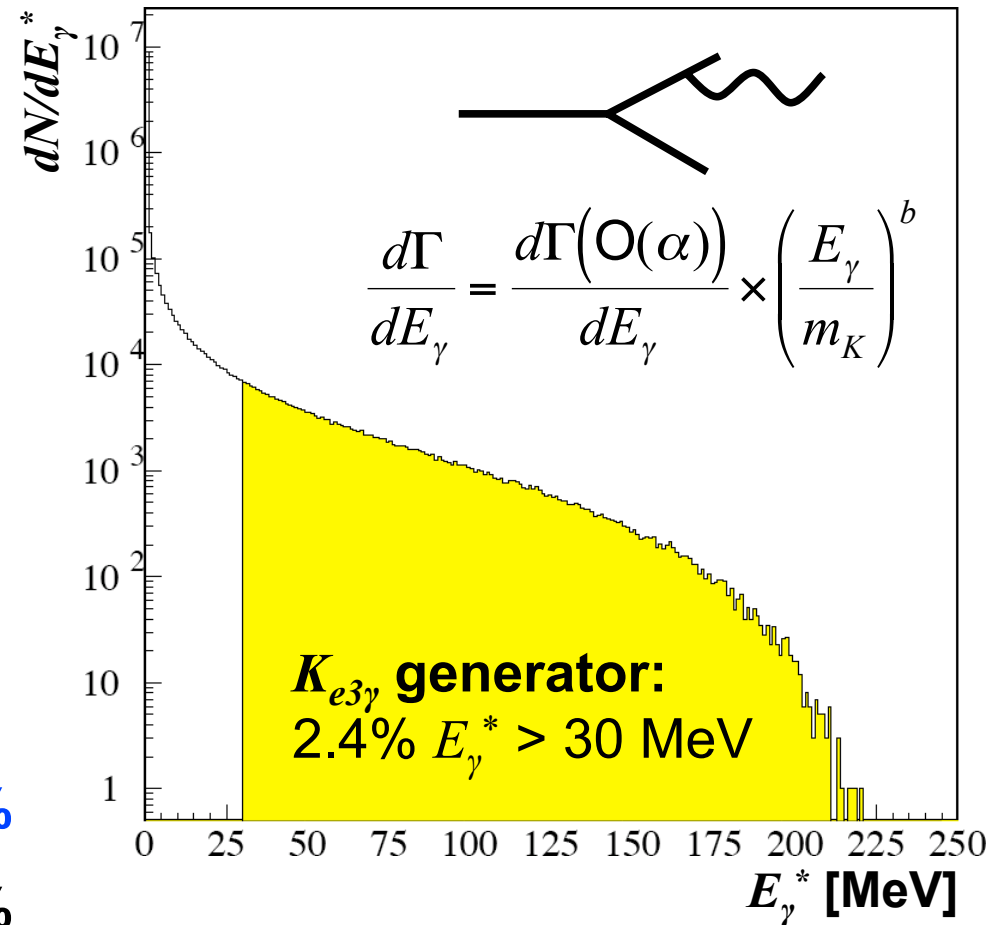
- Full $O(\alpha)$ amplitudes (real and virtual contributions) summed to all orders in α by exponentiation (soft-photon approximation)
- Carefully checked against all available data and calculations

$R_{e3\gamma}(E_\gamma > 30 \text{ MeV}, \theta_{e\gamma} > 20^\circ)$

KLOE generator **0.93%**

Bijnens, Ecker, Gasser '93 **0.94%**

Gasser, Kubis, Paver, Verbeni '05 **0.96(1)%**



C. Gatti, EPJC 40 (2005)

Accuracy of KLOE generator more than sufficient for inclusion of radiation in BR mmts.

Separate generator [GPKV '05] used to estimate $\langle X \rangle$ in study of $K_{e3\gamma}$