Recent KLOE results on radiative kaon decays

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KAON INTERNATIONAL CONFERENCE

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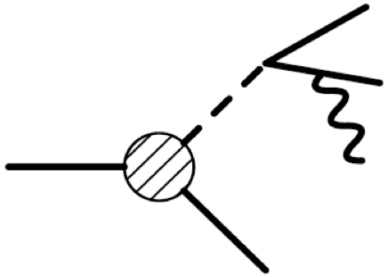
Radiative kaon decays

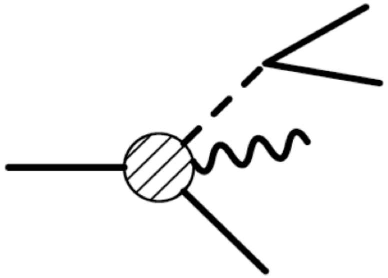
2 processes:



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:

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

Amplitudes are IR divergent at any fixed order in α

Physical amplitudes strongly peaked for $E_\gamma^* \to 0$ (or for $\theta_{\ell\gamma}^* \to 0$ 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

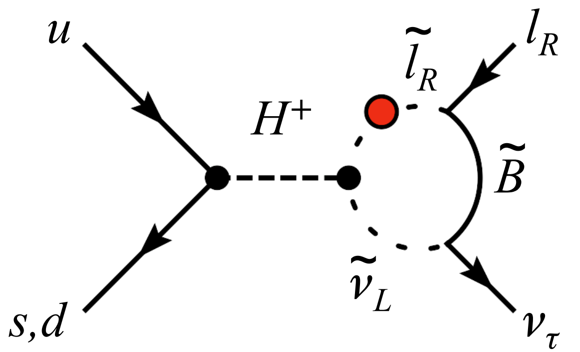
$$R_K \equiv \frac{\Gamma(K \to e\nu(\gamma_{\rm IB}))}{\Gamma(K \to \mu\nu(\gamma_{\rm IB}))}$$

Cirigiliano, Rosell '07

$R_K^{\rm SM}$ = 2.477(1) × 10^{-5}

MSSM with R parity

Masiero, Petronzio, Paradisi '06



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

~1% effect on R_K for:

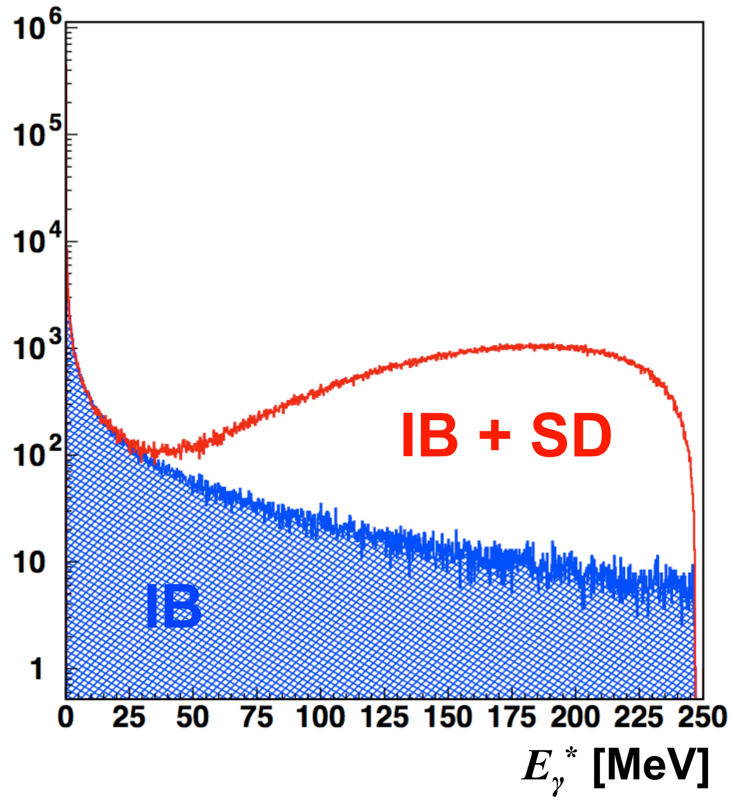
Δ_{13} ~ 5×10^{-4} tan β ~ 40 M_{H+} ~ 500 GeV

Definition of R_K inclusive of IB only

Helicity suppression: IB ~ SD

Experimental data is from '70s:

$\delta\Gamma$(SD)/Γ(SD) ≈ 15%



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

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

SD contribution to KLOE error reduced from 0.5% → 0.2%

$K_{e2\gamma}$ amplitudes

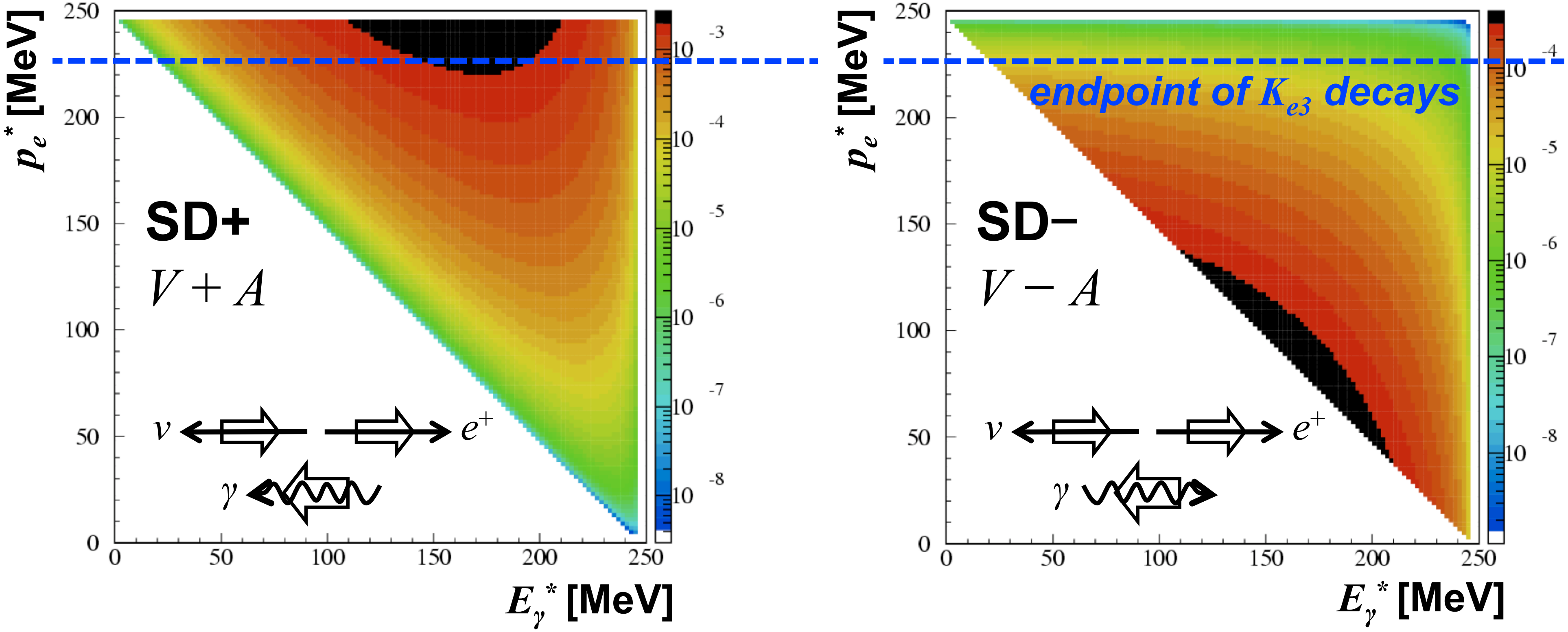
$$\frac{d\Gamma(K \to e\nu\gamma)}{dx\,dy} = \rho_{\text{IB}}(x,y) + \rho_{\text{SD}}(x,y) + \rho_{\text{INT}}(x,y)$$

negligible

$$x = 2E^*_\gamma / m_K \qquad y = 2E^*_e / m_K$$

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

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)**

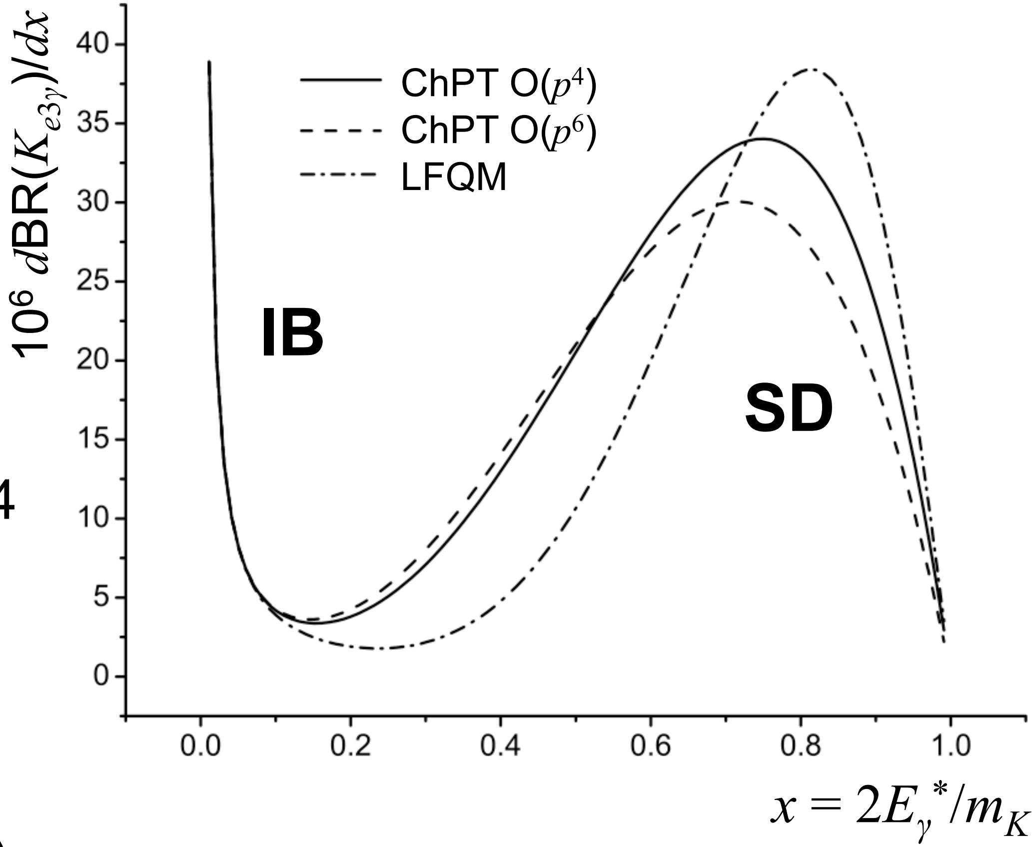
   Linear energy dependence for V
   $V \approx 0.082[1 + \lambda(1 - x)]$ with $\lambda \approx 0.4$
   $A \approx 0.034$

   Ametller, Bijnens, Bramon, Cornet '93
   Geng, Ho, Wu '04
   Chen, Geng, Lih '08

3. **Light Front Quark Model (LFQM)**

   Non-trivial x dependence
   $V = A = 0$ at $x = 0$ 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

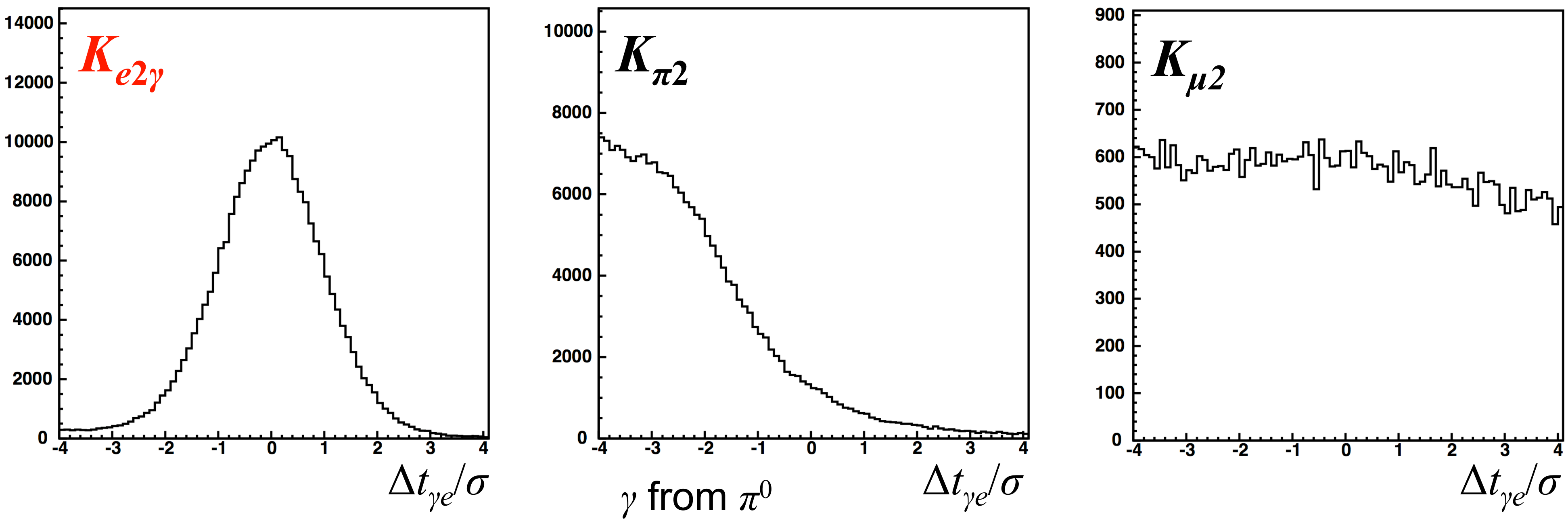
Make hard cut on neural-network output to reject $K_{\mu 2\gamma}$ with accidental photon

- Neural network uses EmC shower profile information, TOF

Require detection of γ with E^{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:

$K_{\mu 2}$ for M^2_ℓ < 20000 MeV²
K_{e3} for M^2_ℓ > 20000 MeV²

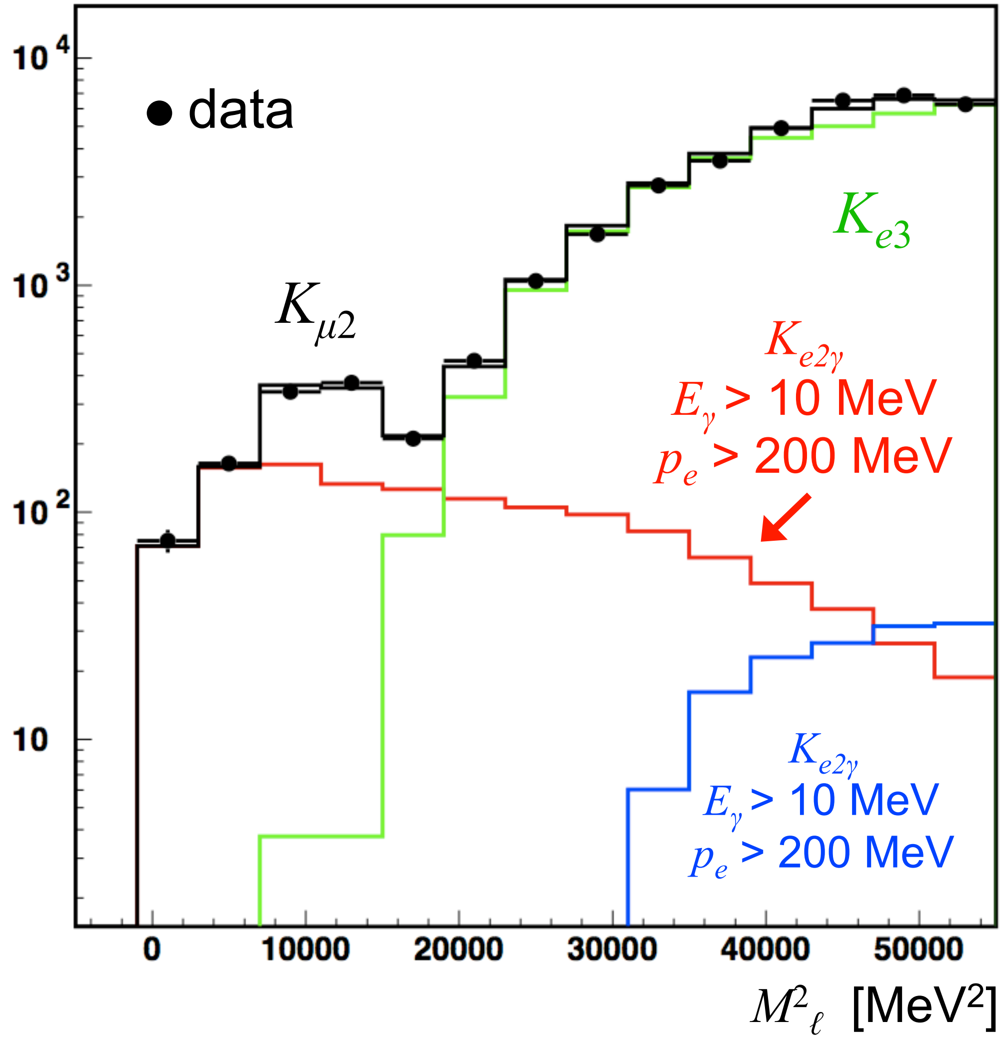
No sensitivity for $K_{e2\gamma}$ with p_e < 200 MeV (SD− amplitude)

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

E^*_γ > 10 MeV
$\cos\theta^*_{e\gamma}$ < 0.9
p^*_e > 200 MeV

This selection has:

Acceptance for SD+ events ~90%
SD− events ~2%
Residual IB events ~1%



$K_{e2\gamma}$ photon association

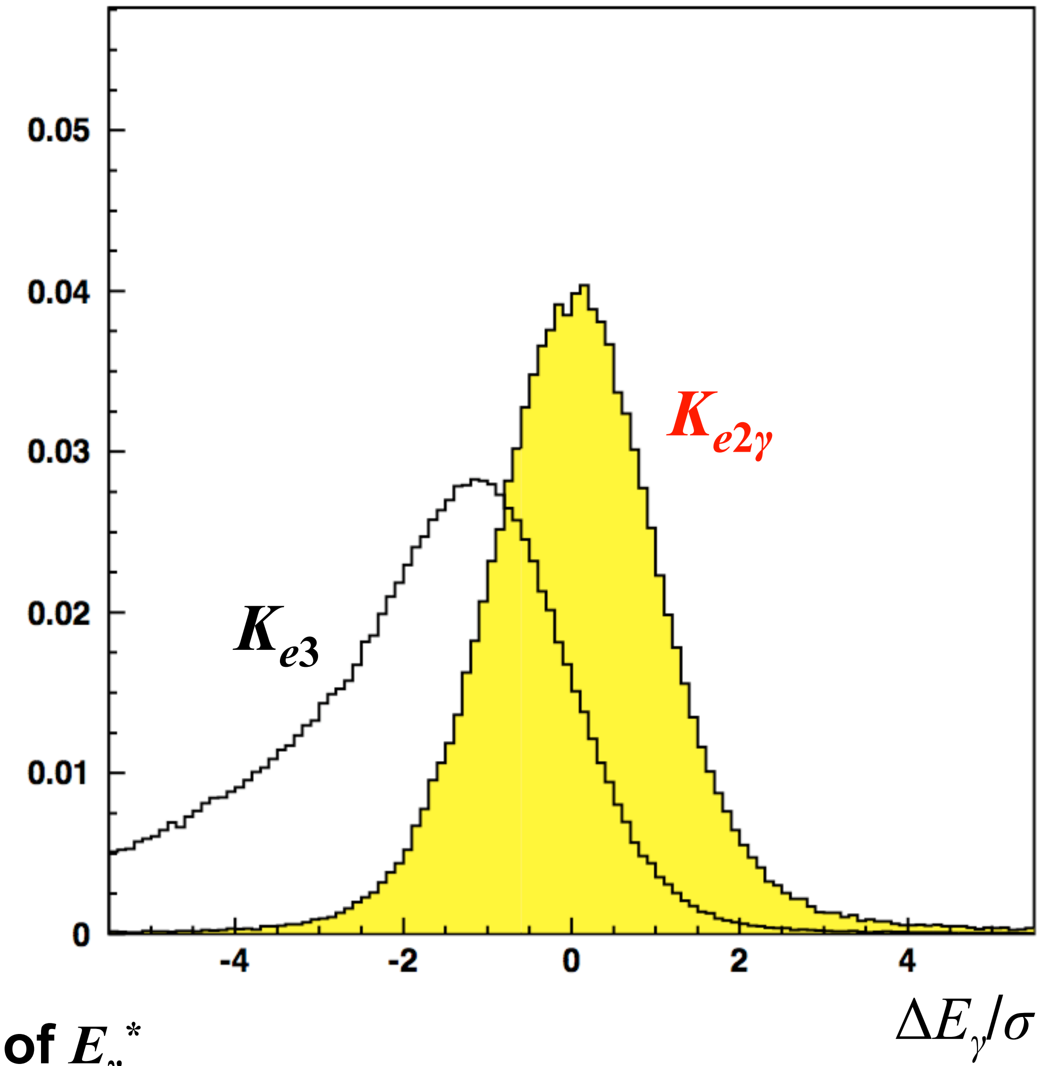
E_γ^{lab} can be evaluated from $K_{e2\gamma}$ kinematics, using measurements of:

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

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

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

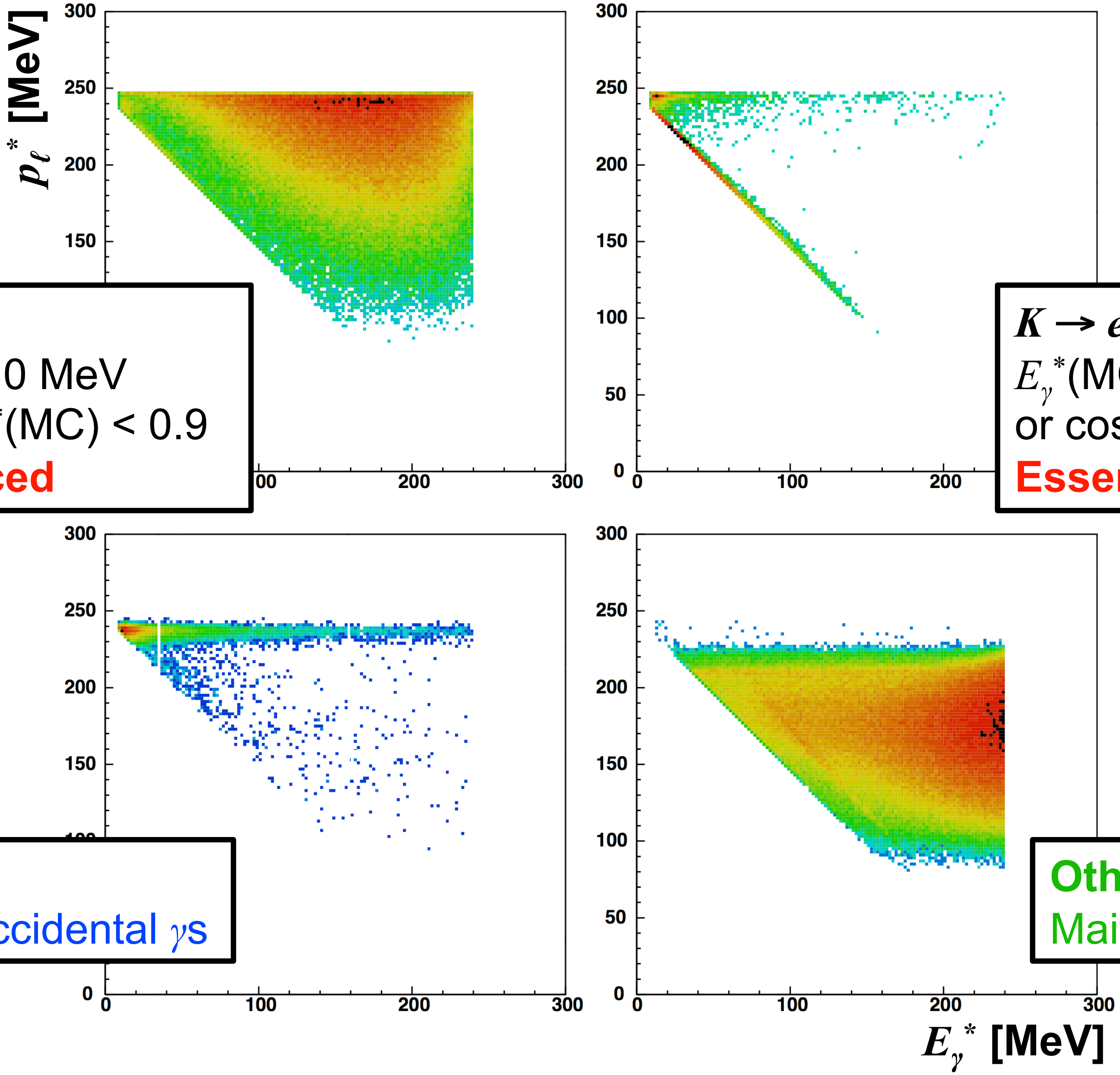
$\sigma_E^{\text{cal}} \approx$ **30 MeV**



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

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

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



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

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

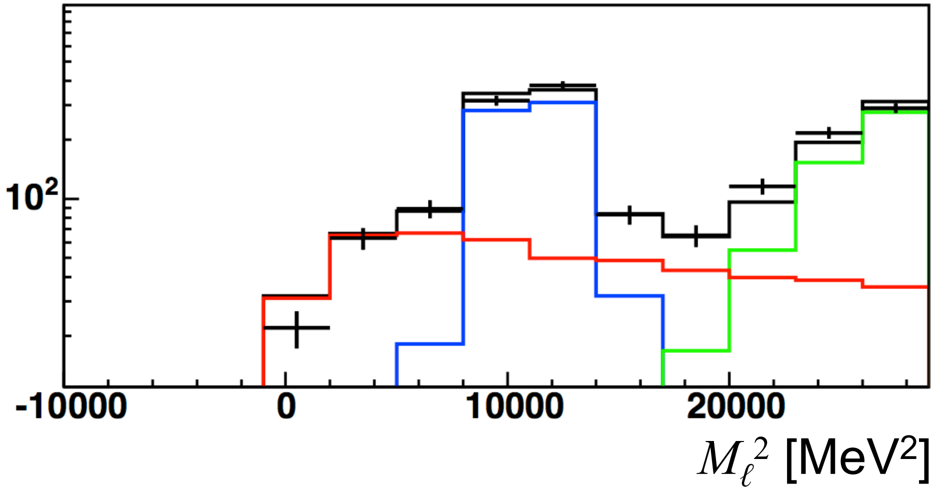
$K \to \mu\nu(\gamma)$
including accidental γs

Other background
Mainly K_{e3}

$K_{e2\gamma}$ fit results

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

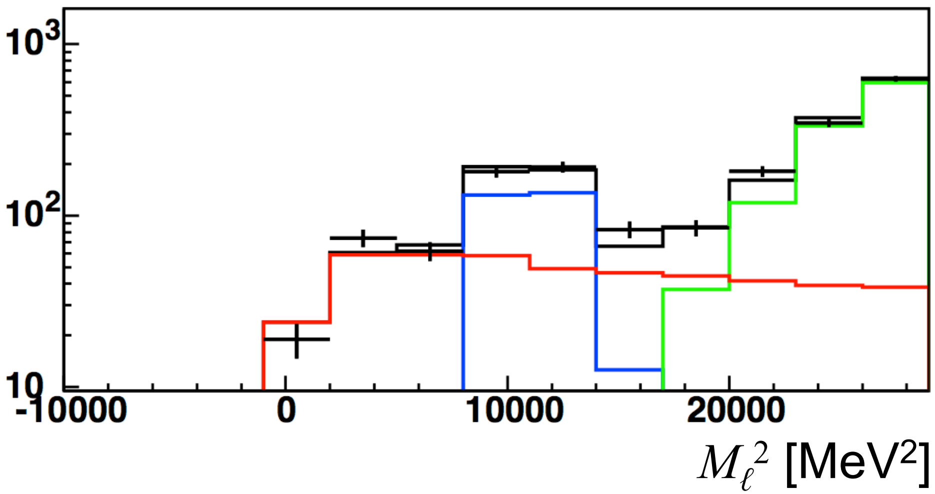
+	**data**
–	**fit**
–	$K_{e2\gamma}$
–	$K_{\mu2}$
–	K_{e3}



100 < E_γ < 150 MeV

$N_{e2\gamma}$ = 463 ± 32

χ^2/ndf = 87/106



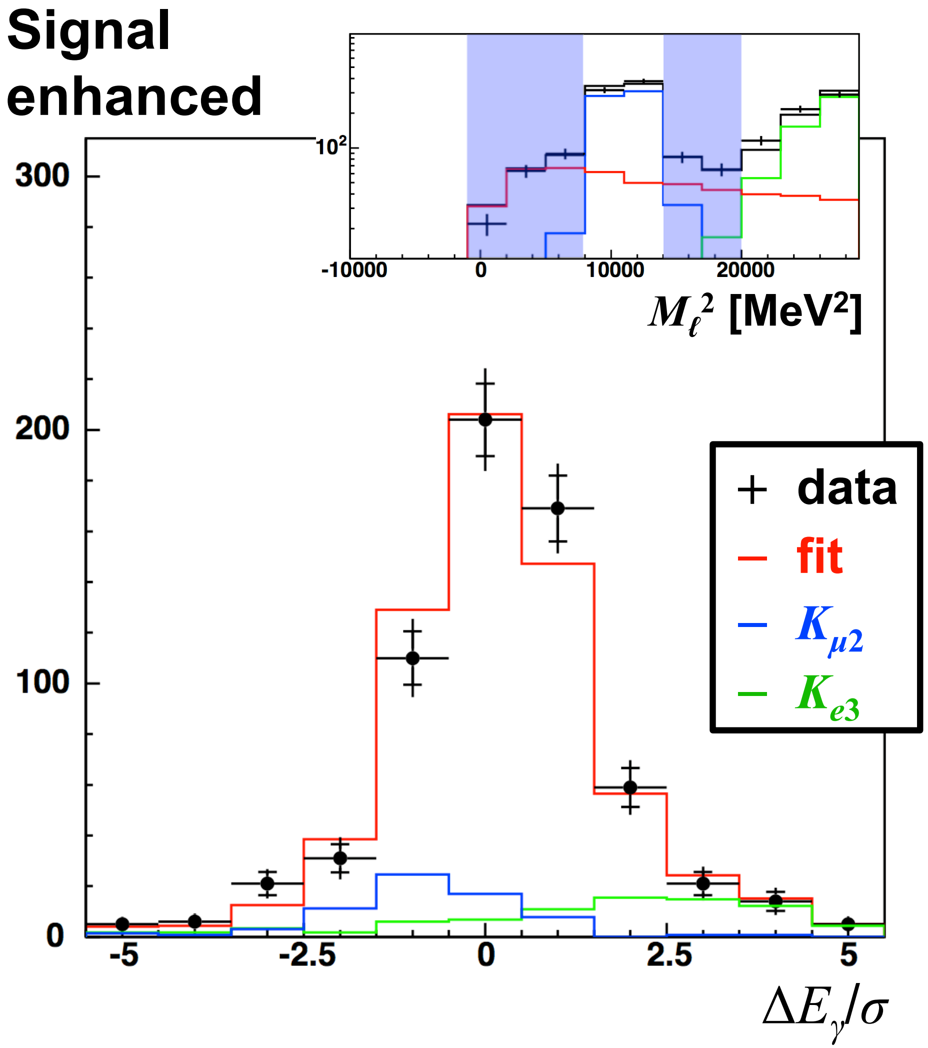
150 < E_γ < 200 MeV

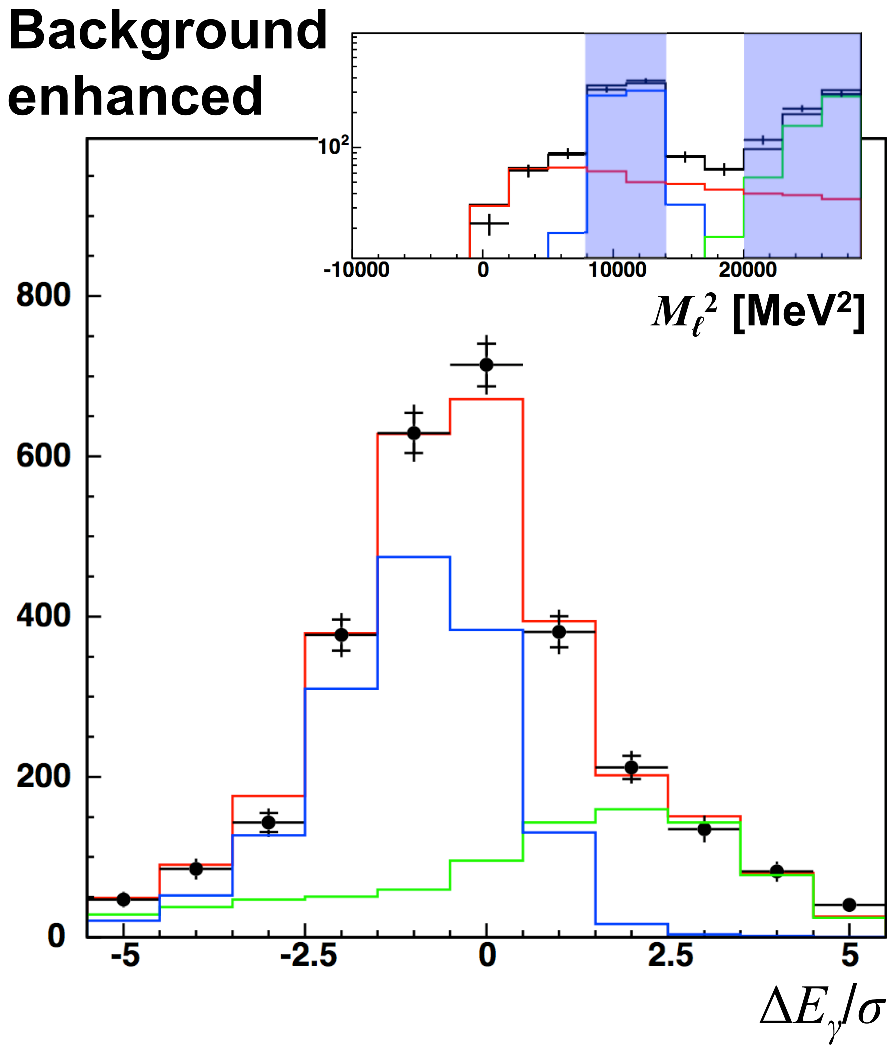
$N_{e2\gamma}$ = 494 ± 38

χ^2/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





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

We measure

$$\frac{1}{\Gamma(K_{\mu2(\gamma)})}\frac{d\Gamma_{\text{SD+}}(K_{e2\gamma})}{dE_\gamma}$$

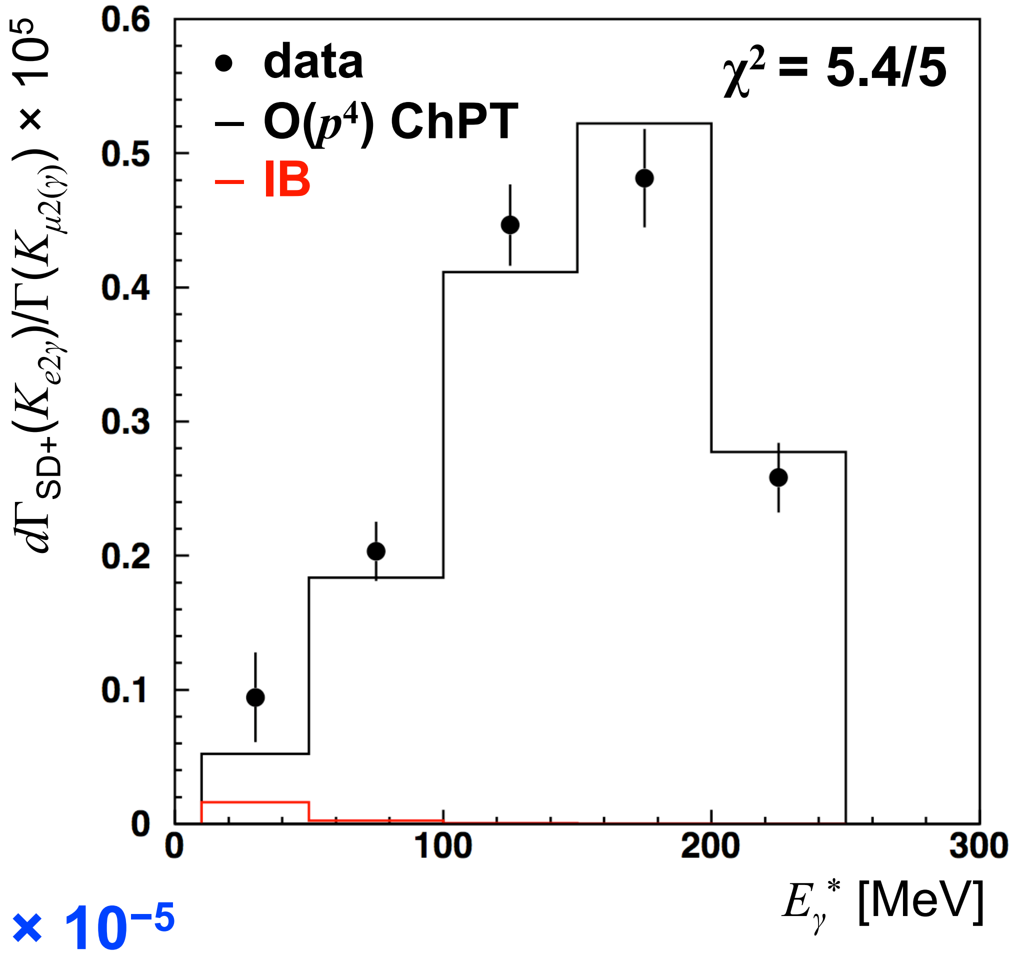
where “SD+” means:

$E_\gamma^* > 10$ MeV
$\cos\theta_{e\gamma}^* < 0.9$
$p_e^* > 200$ MeV

Summed over all bins in E_γ^*:

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

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



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 ~2%

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

Obtain:

$V_0 + A$ = 0.125 ± 0.007

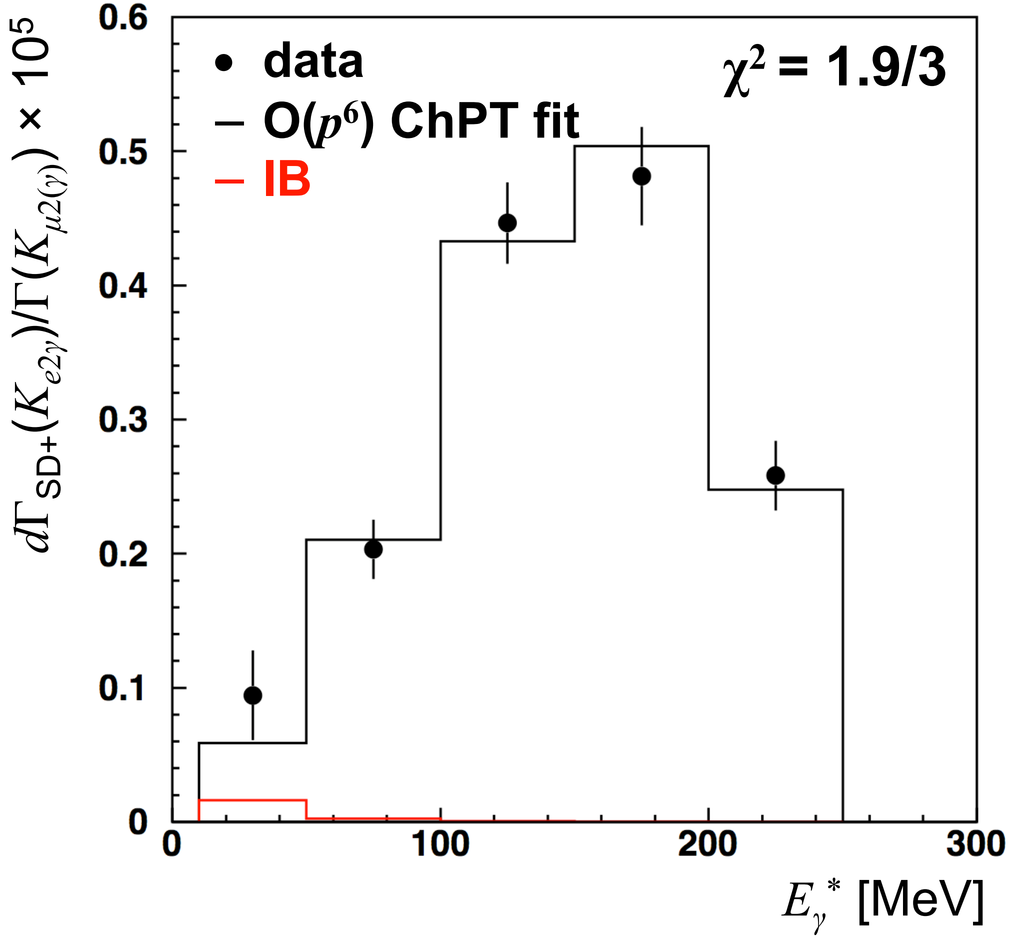
λ = 0.38 ± 0.21

Compare to ChPT O(p^6):

$V_0 + A \approx 0.116$

$\lambda \approx 0.4$

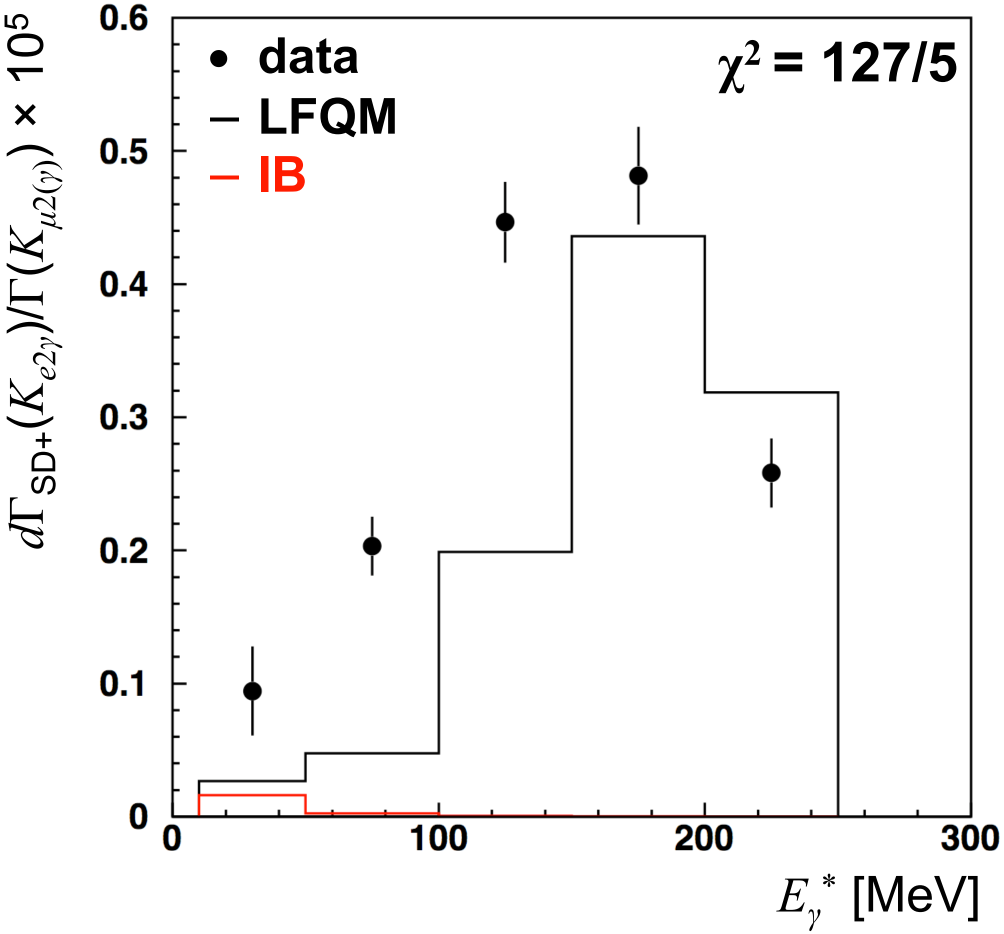
Chen, Geng, Lih '08



$K_{e2\gamma}$ 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 $K_L \to \pi e \nu \gamma$ ($K_{e3\gamma}$)

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

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

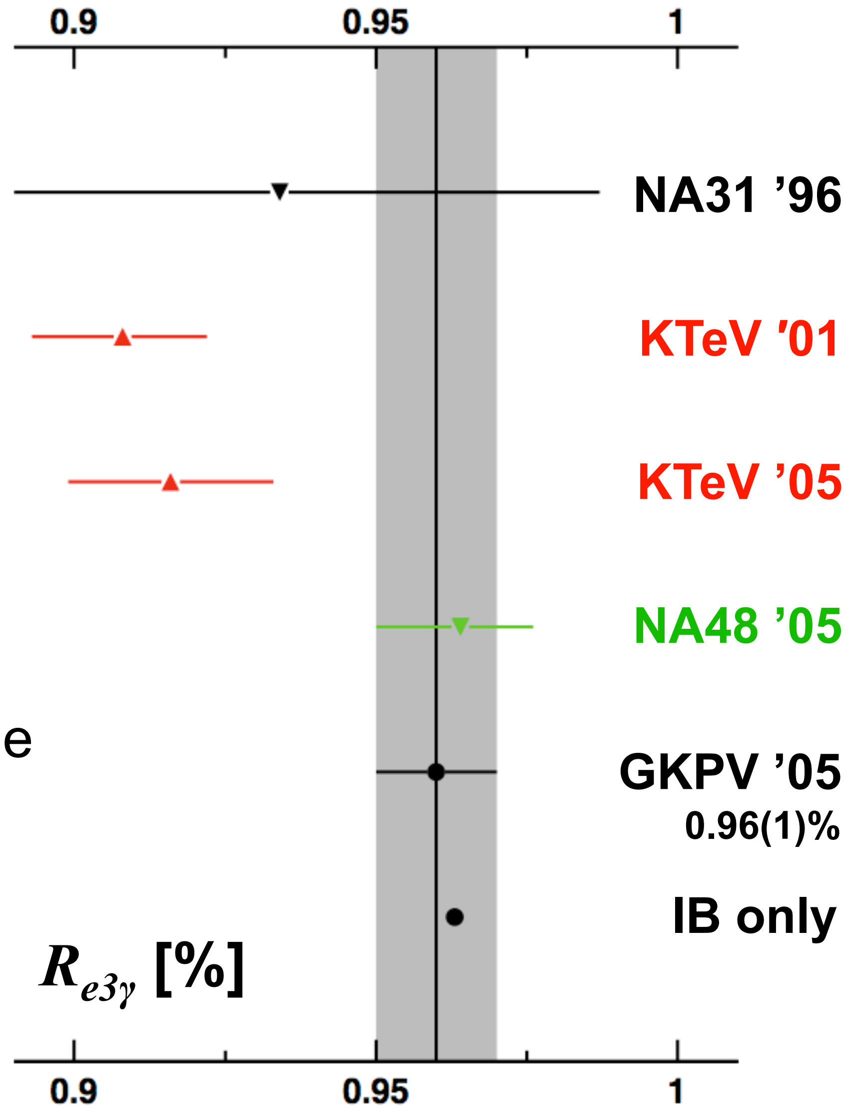
Reanalysis of previous data
Tighter cuts, 30% subsample

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

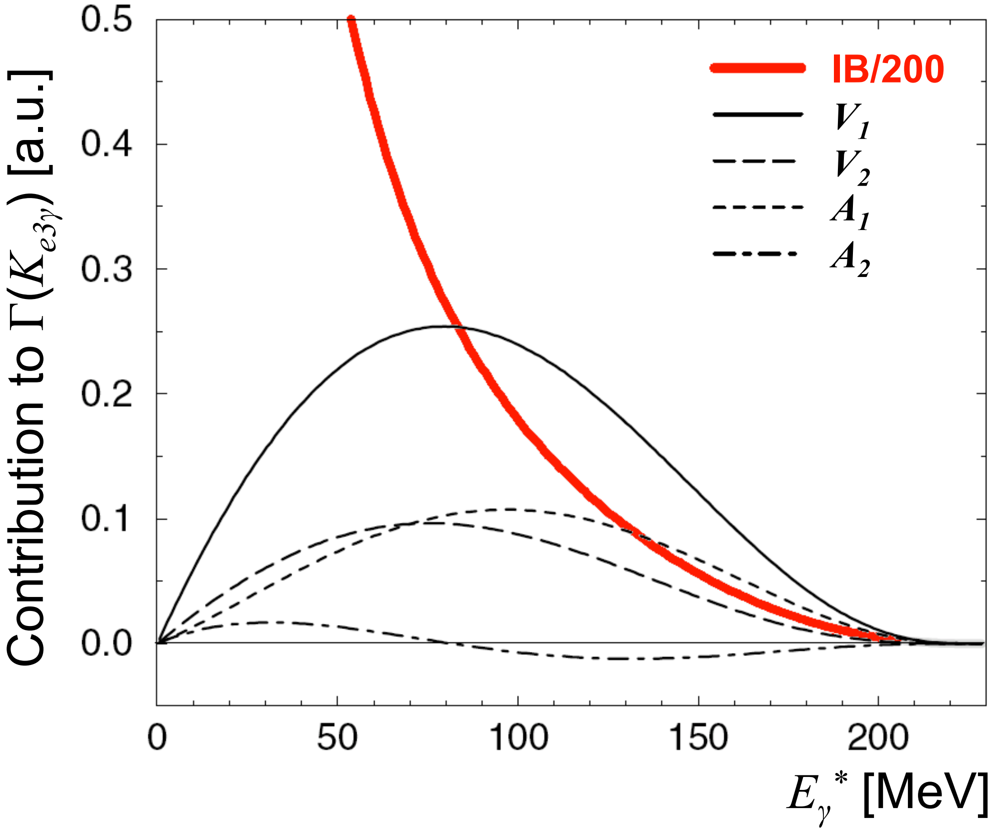
O(p^6) decomposition of photon spectrum:

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

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

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

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

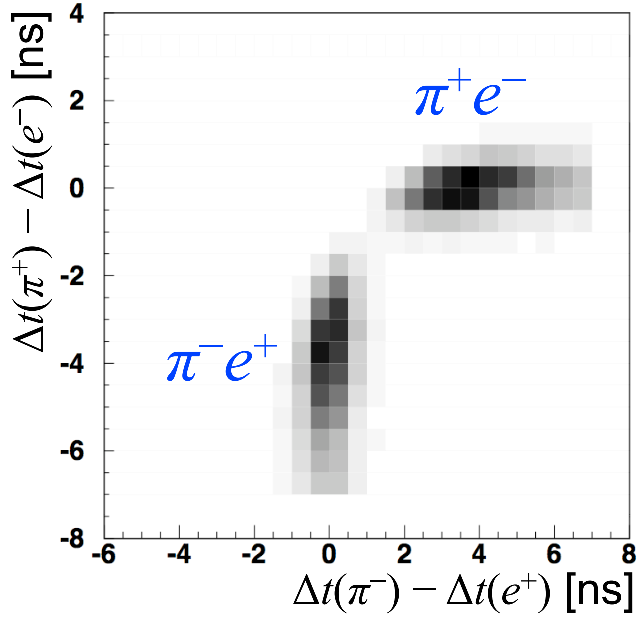


O(p^6) estimates (for V) and full calculations (for A) give $\langle X \rangle = -1.2 \pm 0.4$

Error from estimates of O(p^6) LECs

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

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



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

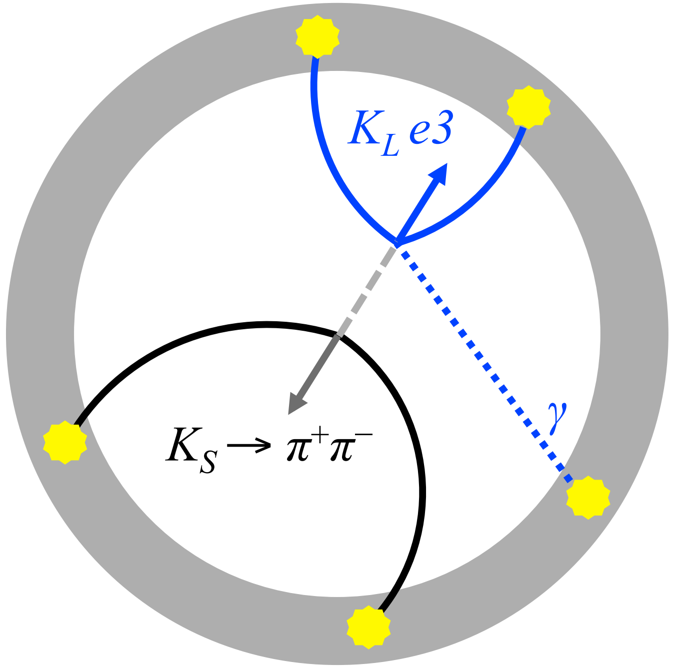
- 328 pb^{-1} of '01 + '02 data (same sample as for V_{us})
- K_L decay tagged by $K_S \to \pi^+\pi^-$
- Pos. and neg. tracks with vertex in fiducial volume
- Kinematic rejection for $K_{\mu 3}$ and $\pi^+\pi^-\pi^0$ decays (e.g. M_{miss})
- PID/charge assignment by TOF: $\Delta t_x = t_{\text{meas}}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

~ 3×10^6 $K_{e3(\gamma)}$ events, 0.7% background

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

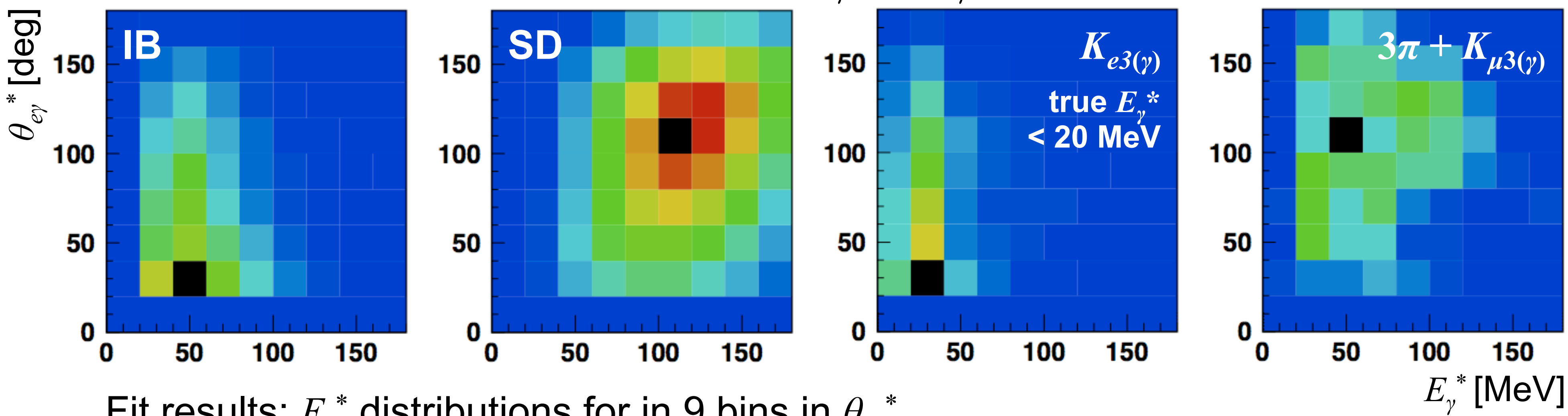
- Look for photon cluster with timing compatible with distance from track vertex
- Predict its energy from kinematics with $\sigma \approx 1$ MeV
- Cut on measured energy
- Refine using neural networks to reject $K_{\mu 3}$ and $\pi^+\pi^-\pi^0$ decays to ~1% level
- Use $\pi^+\pi^-\pi^0$ decays to check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

$$p^2_{\gamma 2} = 0 = (p_K - p_\pi - p_\pi - p_{\gamma 1})^2$$
$$p^2_\nu = 0 = (p_K - p_\pi - p_e - p_\gamma)^2$$

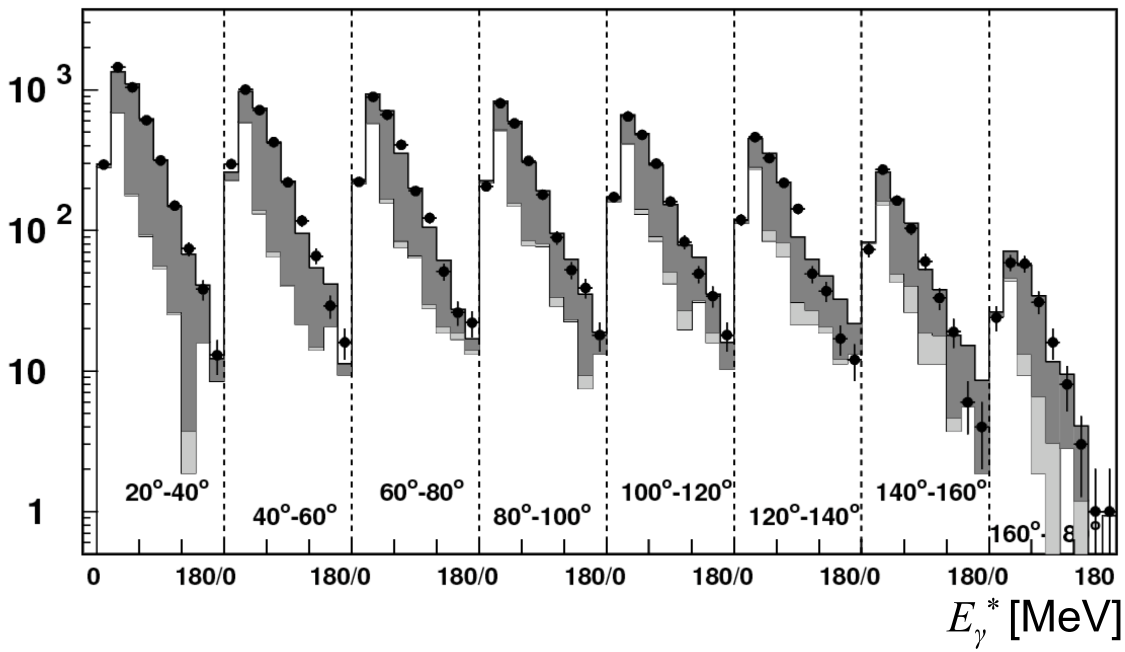


$K_{e3\gamma}$: Fit to $(E_\gamma^*, \theta_{\ell\gamma}^*)$ distribution

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
	$N_{\rm IB}$	**9083 ± 213**
	$N_{\rm SD}$	**−102 ± 59**
□	$N_{e3(\gamma)}$	6726 ± 194
▣	$N_{3\pi + \mu3(\gamma)}$	fixed

χ^2/ndf = 60/69 (P = 77%)

Destructive interference between IB and SD

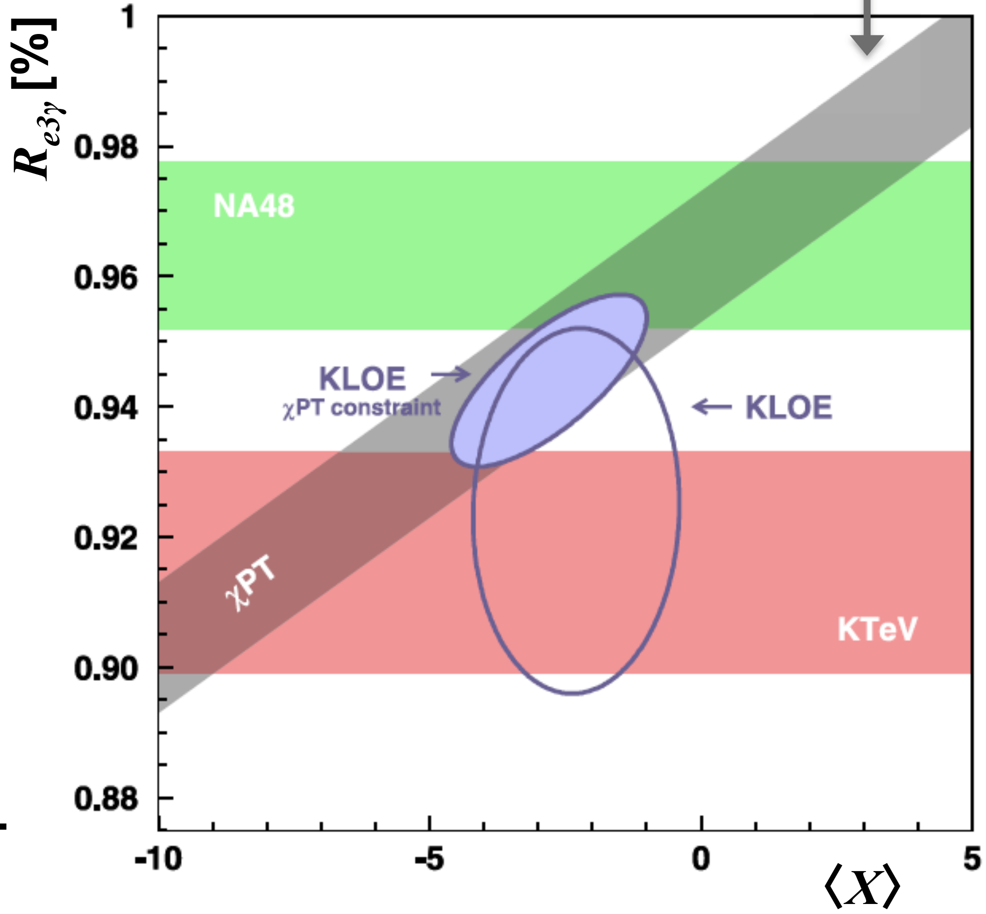
$K_{e3\gamma}$: Results for $R_{e3\gamma}$ and $\langle X \rangle$

KLOE
EPJC 55 (2008)

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

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

$K_{e2\gamma}$:

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

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

$K_{e3\gamma}$:

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

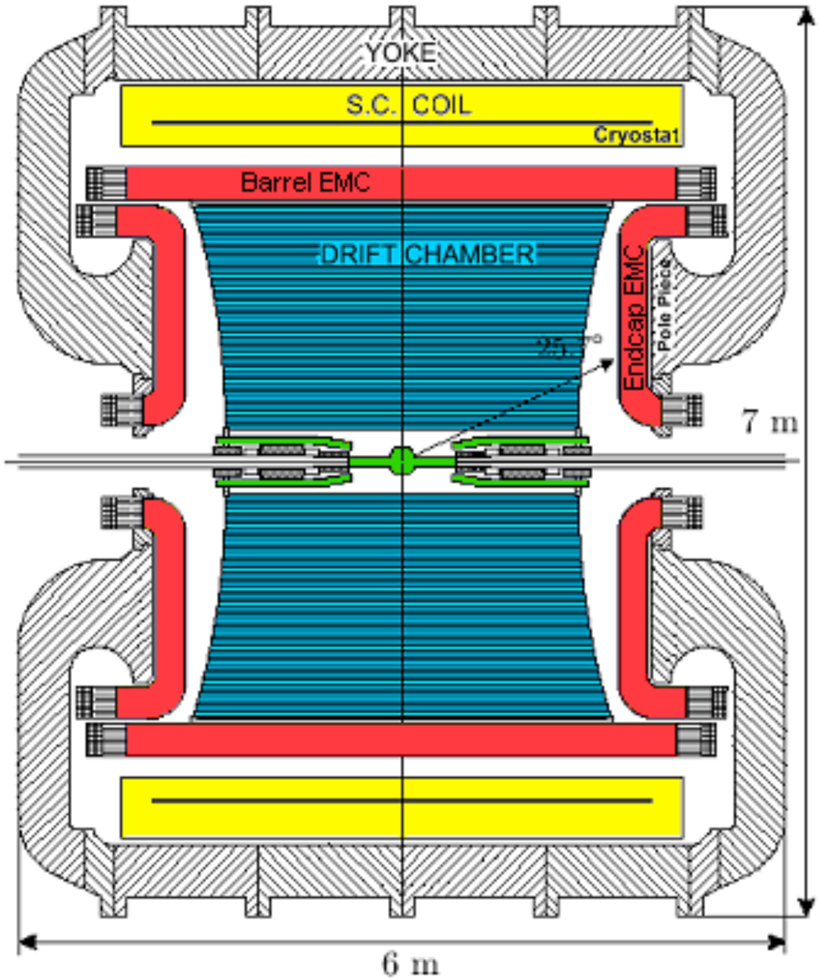
$$\langle X\rangle = -2.3 \pm 1.3_{\text{st}} \pm 1.4_{\text{sy}}$$

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

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 ∅ × 3.3 m)
90%He+10% IsoB, composite frame
12582 stereo sense wires

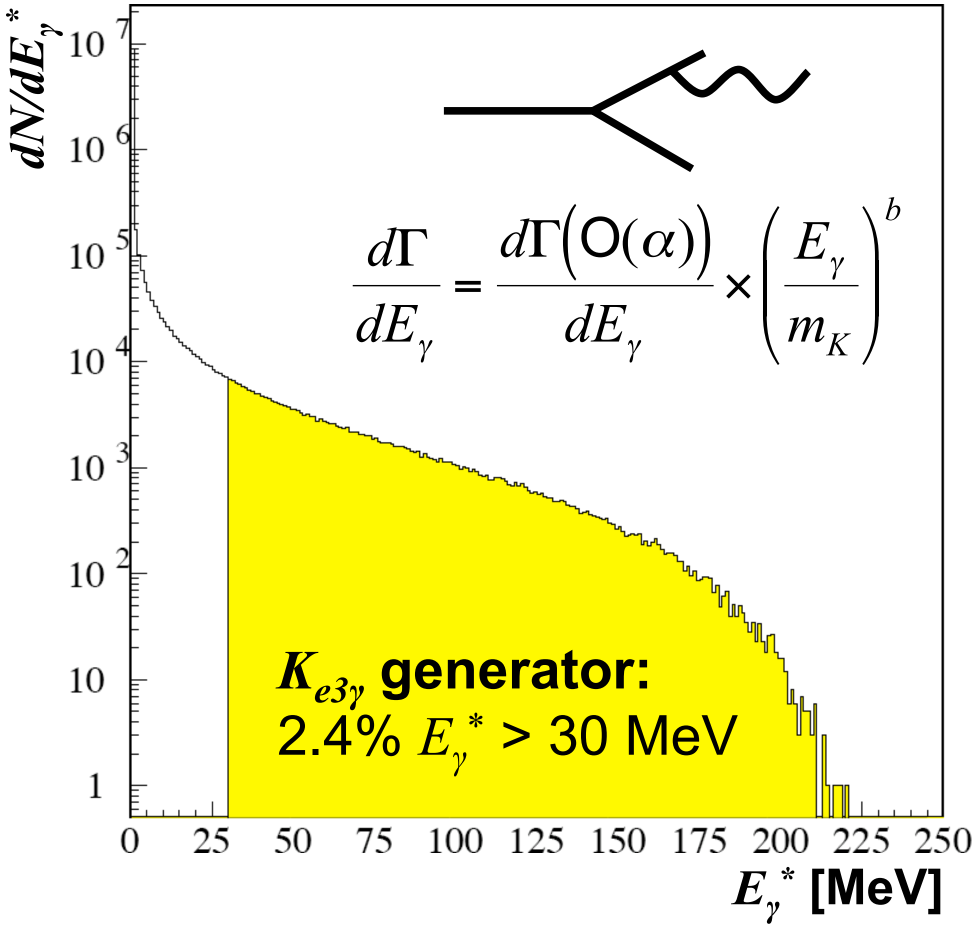
Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMTs

Superconducting coil (5 m bore)
$B = 0.52$ T ($\int B\,dl = 2$ T·m)

Generators for radiative kaon decays

KLOE generators for kaon decays include radiation with no cutoff energy

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



C. Gatti, EPJC 40 (2005)

$R_{e3\gamma}$ (E_γ > 30 MeV, $\theta_{e\gamma}$ > 20°)

KLOE generator	**0.93%**
Bijnens, Ecker, Gasser '93	**0.94%**
Gasser, Kubis, Paver, Verbeni '05	**0.96(1)%**

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 $K_{e3\gamma}$