KLOE measurement of $Ke2/K\mu2$ and $K\to e\nu\gamma$

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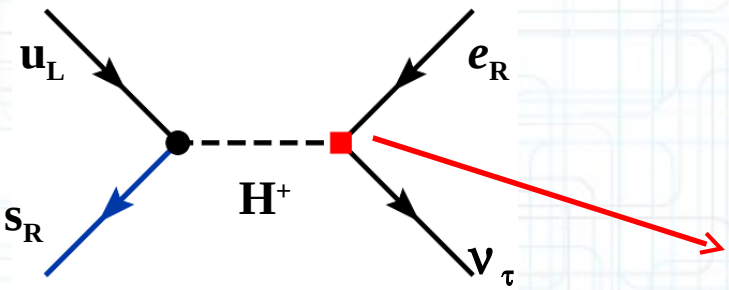
NP potential of $R_K=\Gamma(Ke2)/\Gamma(K\mu 2)$

- SM prediction with 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): **$R_K=2.477(1)\times10^{-5}$** [*Cirigliano Rosell arXiv:0707:4464*].

- Helicity suppression can boost NP [*Masiero-Paradisi-Petronzio PRD74(2006)011701*].

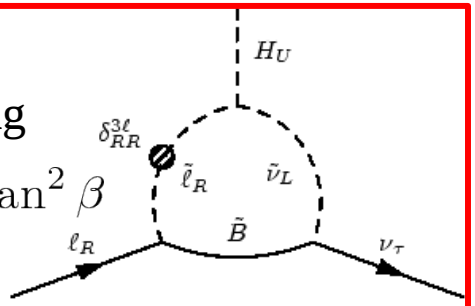


$$R_K^{\rm LFV} \approx \frac{\Gamma(K\to e\nu_e)+\Gamma(K\to e\nu_\tau)}{\Gamma(K\to \mu\nu_\mu)}$$

$$R_K^{\rm LFV} \approx R_K^{\rm SM}\left(1+\frac{m_K^4}{m_H^4}\frac{m_\tau^4}{m_e^4}|\Delta_R^{31}|^2\tan^6\beta\right)$$

LFV from loop generates an effective $eH^+\nu_\tau$ coupling

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

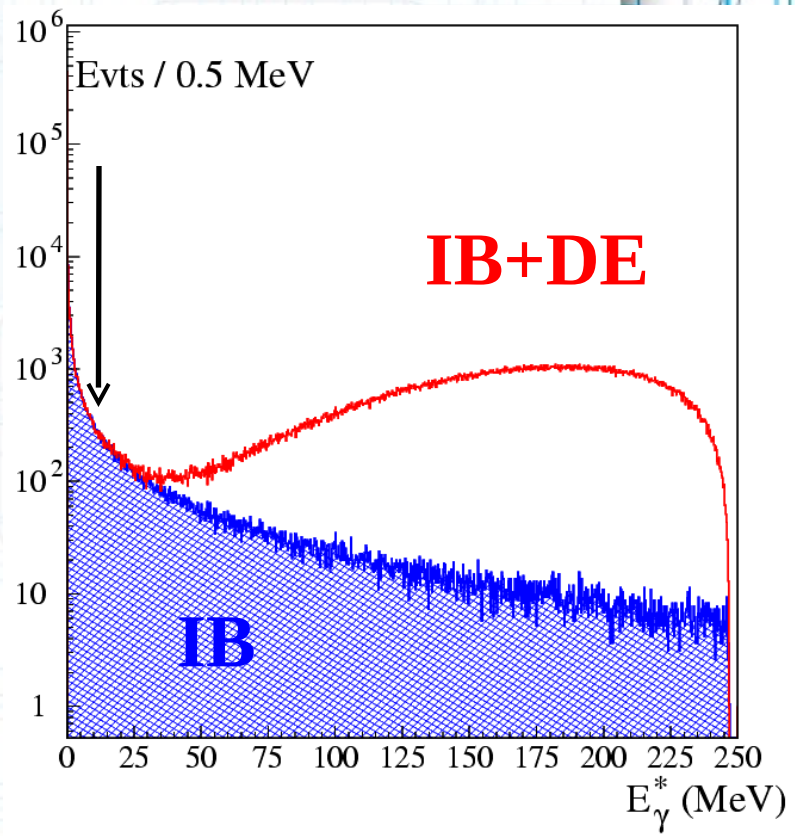


LFV can give **O(1%) deviation from SM ($\Delta_R^{31}\sim 5\times10^{-4}$, tanβ ~ 40, $m_H\sim$ 500 GeV)**

- Exp. accuracy on R_K (before KLOE and NA62 results) at 5% level.
- New measurements of R_K can be very interesting, **if error at 1% level or better**.

Ke2(γ): signal definition

SM prediction is defined to be inclusive of **IB** (ignoring **DE** contributions).



From theory (ChPT) expect **DE ~ IB** for Ke2, but experimental knowledge is poor: **δDE/DE~ 15%**

- **Define as "signal" events with E_γ<10 MeV**.
- Evaluating **IB** spectrum (O(α)+resummation of leading logs) obtain a 0.0625(5) correction for the IB tail.
- Under 10 MeV, the **DE** contribution is expected to be negligible.

Charged kaon at KLOE

ϕ decay at rest provides pure kaon beams of know momentum

$p_K \sim$ 100 MeV

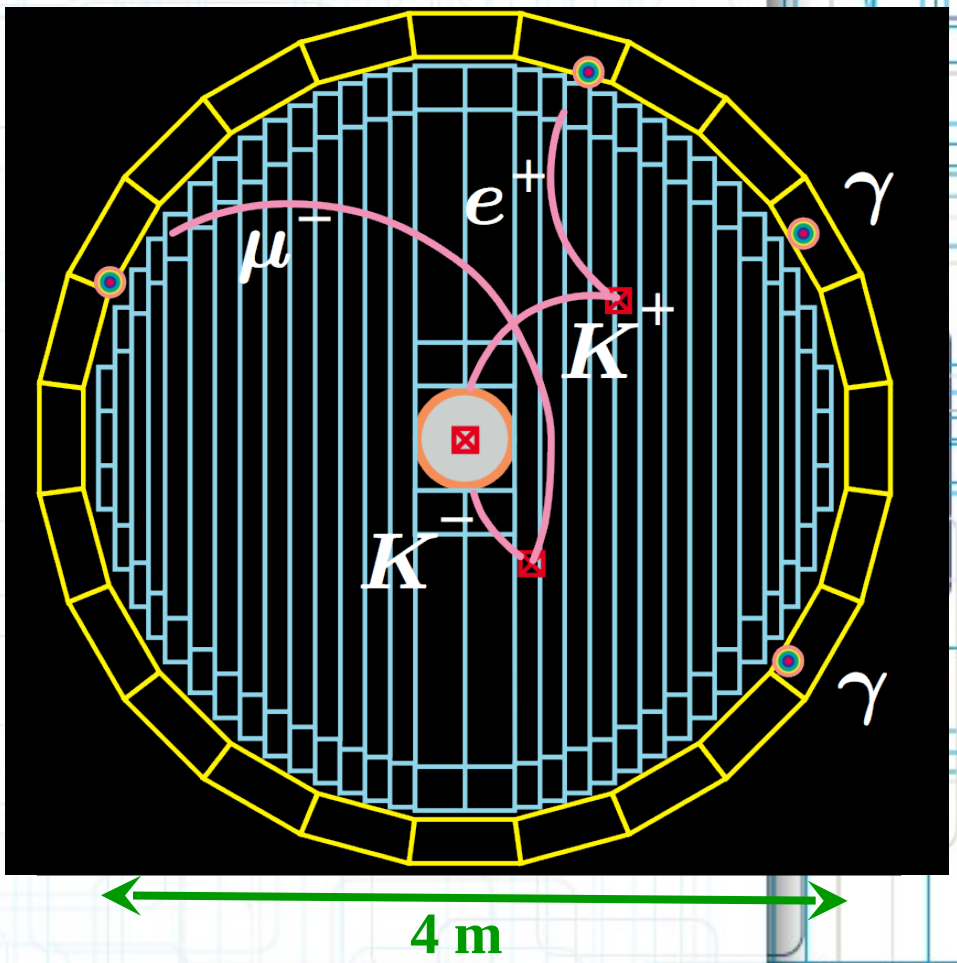
$\lambda \sim$ 90 cm (56% of $K^{\pm}$ decay in DC).

Kaon momentum measured (event by event) with 1 MeV resolution in DC.

Constraints from ϕ 2-body decay.

Particle ID with kinematics, energy deposition and ToF.

Tagging provides unbiased control samples for efficiency measurement.



Analysis basic principles

$$R_K = \frac{N_{Ke2}}{N_{K\mu 2}} \left[\frac{\varepsilon^{\mathrm{REC}}_{K\mu 2}}{\varepsilon^{\mathrm{REC}}_{Ke2}} C^{\mathrm{TRG}} C^{\mathrm{REC}} \right] \frac{1}{\epsilon^{\mathrm{IB}}}$$

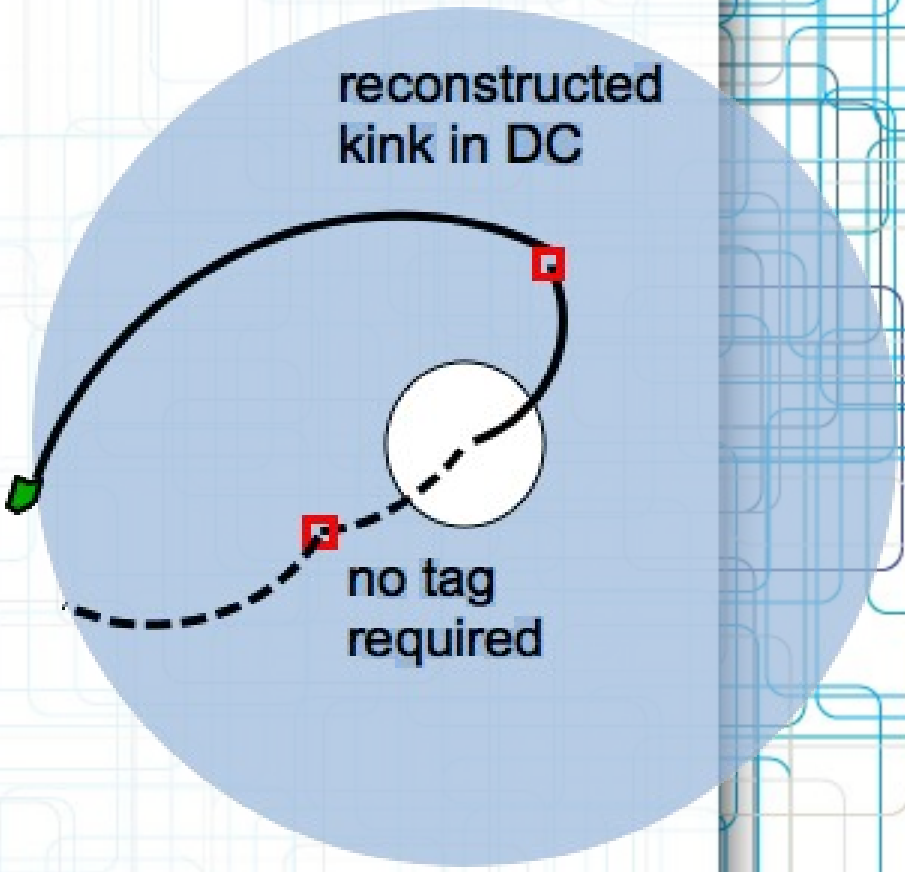
1) Select kinks in DC (~ fiducial volume)

- K track from IP
- secondary with p_{lep}>180 MeV

for decays occurring in the FV;
the reconstruction efficiency is ~ 51%.

2) No tag required on the opposite "hemisphere" (as we usually do!)

→gain **×4 of statistics**

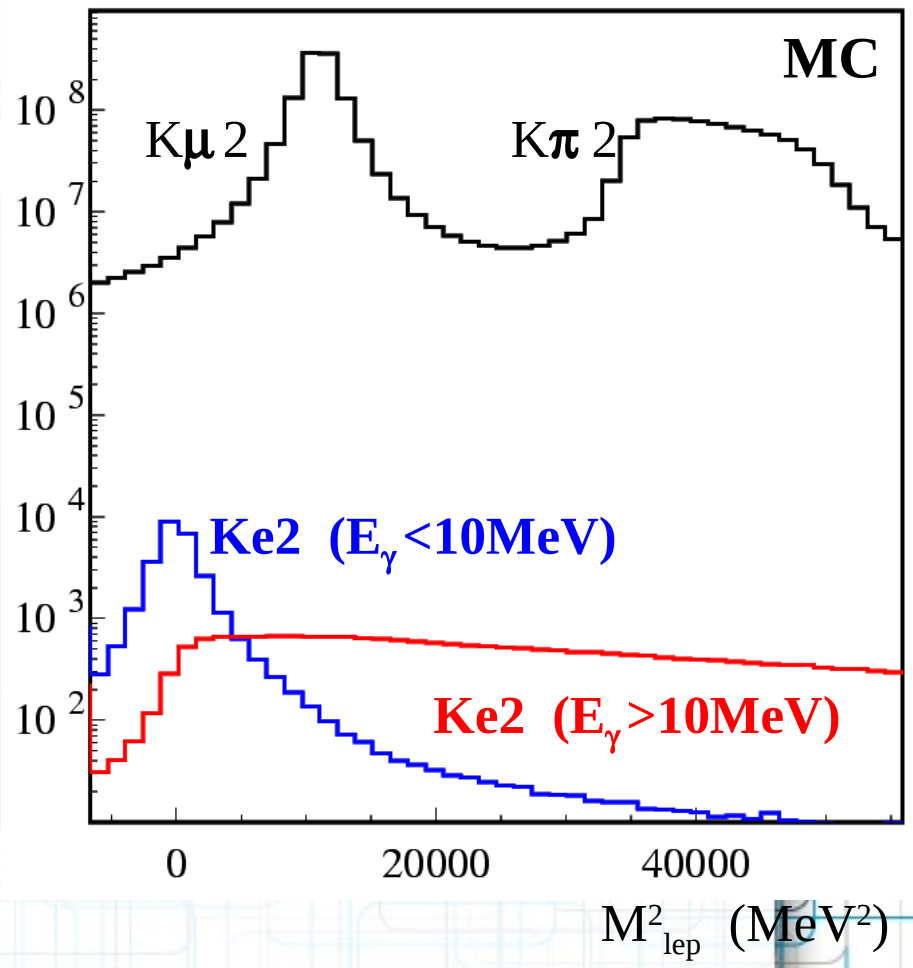


Analysis basic principles

3) Exploit tracking of K and secondary: assuming $m_\nu=0$ get M^2_{lep}:

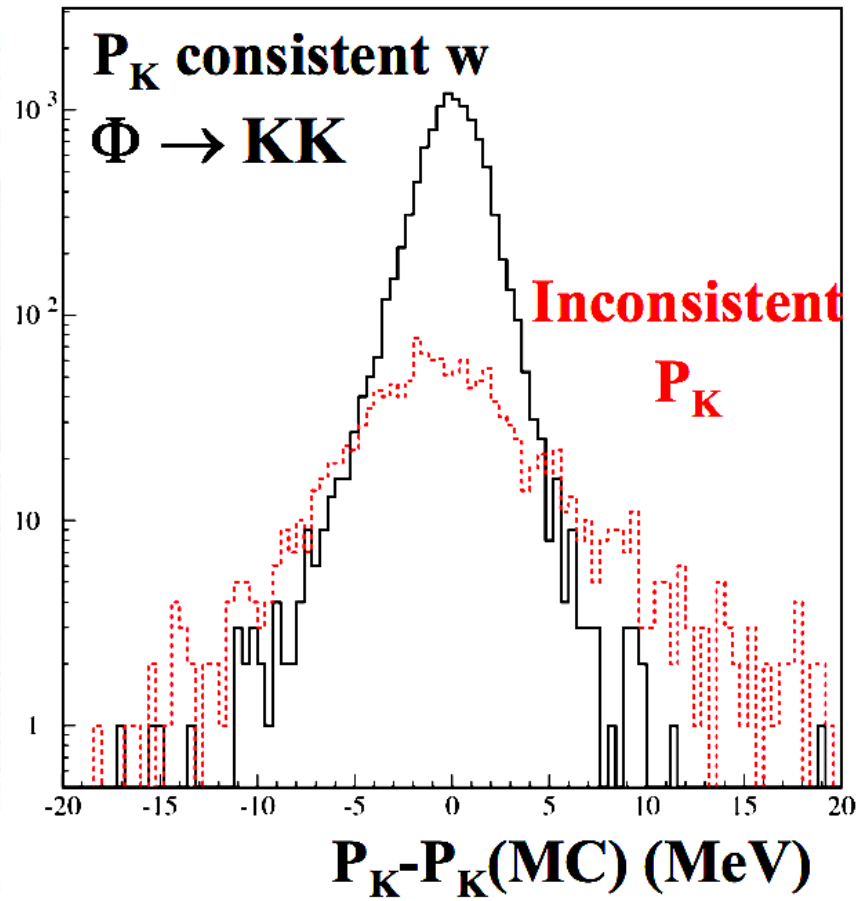
$$M^2_{lep} = (E_K - p_{miss})^2 - p^2_{lep}.$$

Around $M^2_{lep}=0$ we get **S/B ~ 10^{-3}**, mainly due to tails on the momentum resolution of Kμ2 events.



Background rejection (track quality)

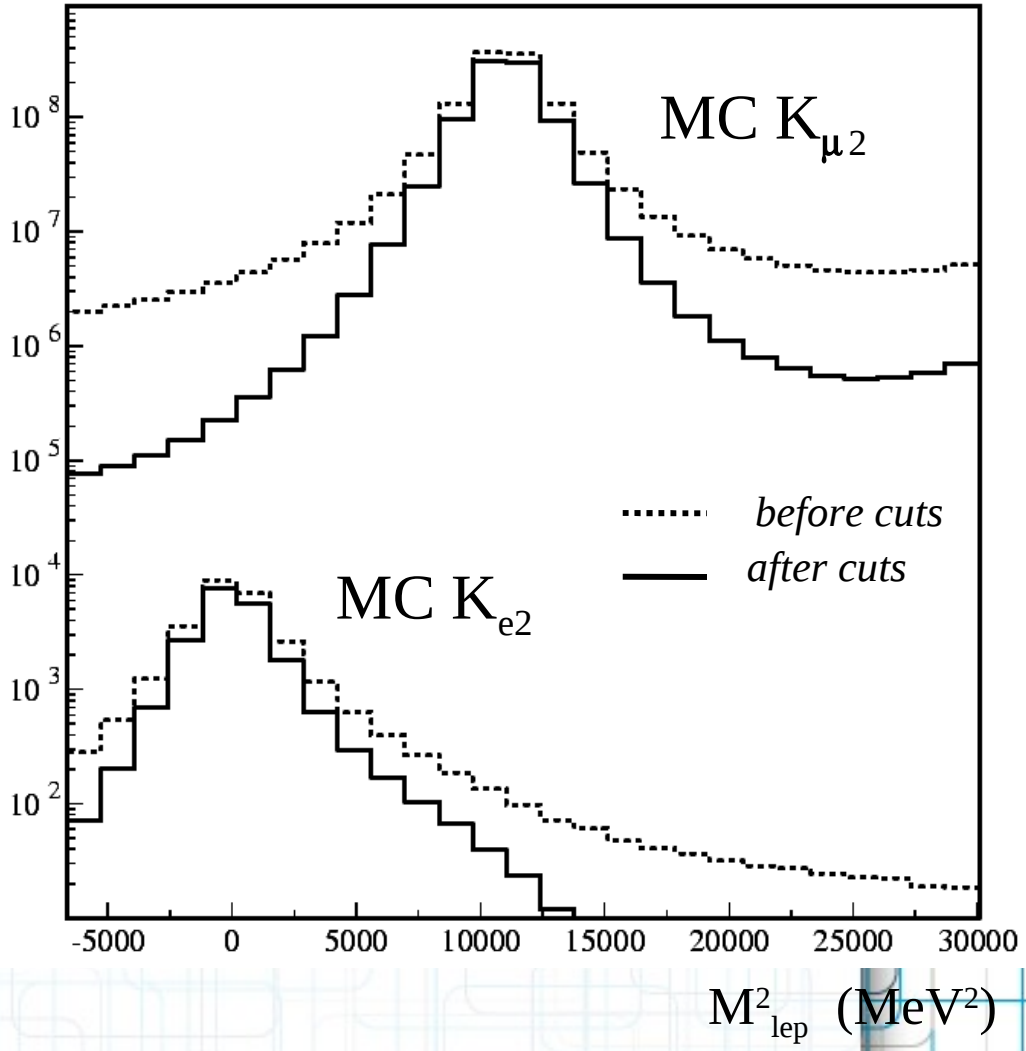
Background composition: $K\mu 2$ events with bad p_K, p_{lep}, or decay vertex position reconstruction



- require good quality vertex and secondary track (χ^2cut);
- reduce $K_{\mu 2}$ tails cutting on the error on M^2_{lep} expected from track parameters;
- quality cuts for K: the kinematic of $\phi \rightarrow K^+K^-$ 2-body decay allows redundant p_K determinartion.

Background rejection (track quality)

- after cuts, we accept ~ 35% of decays in the FV
- most of Ke2 events lost have bad resolution
- **S/B ~ 1/20**, not enough!
- require the lepton track to be extrapolable to the calorimeter surface and to be associated to an energy release (cluster).



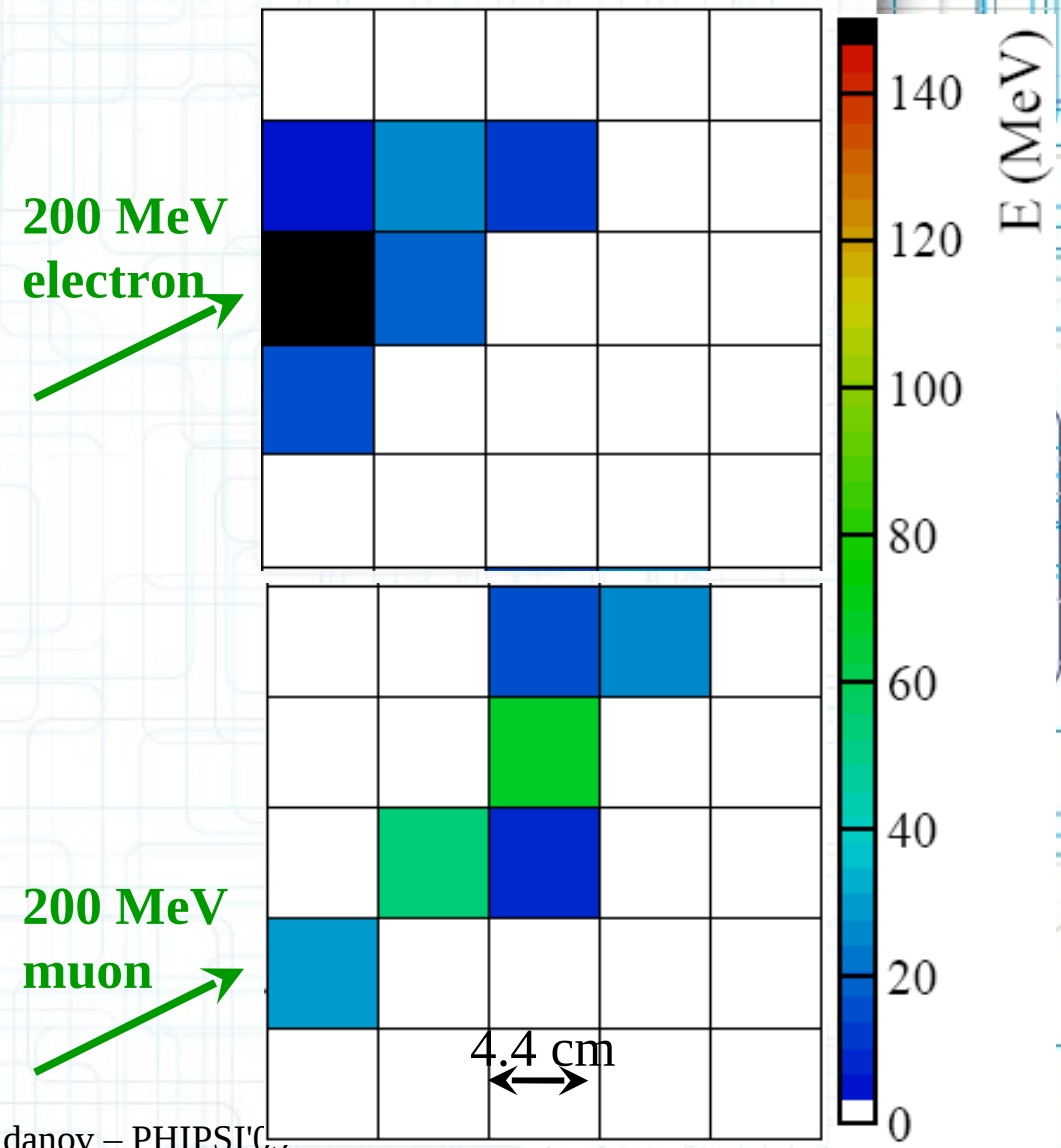
Background rejection (PID)

1) Particle ID exploits EMC granularity (energy deposits into 5 layers in depth):

the energy distribution and the position along the shower axis of all cells associated to the cluster allow for e/μ PID (define 11 descriptive variables).

2) Add E/p and ToF.

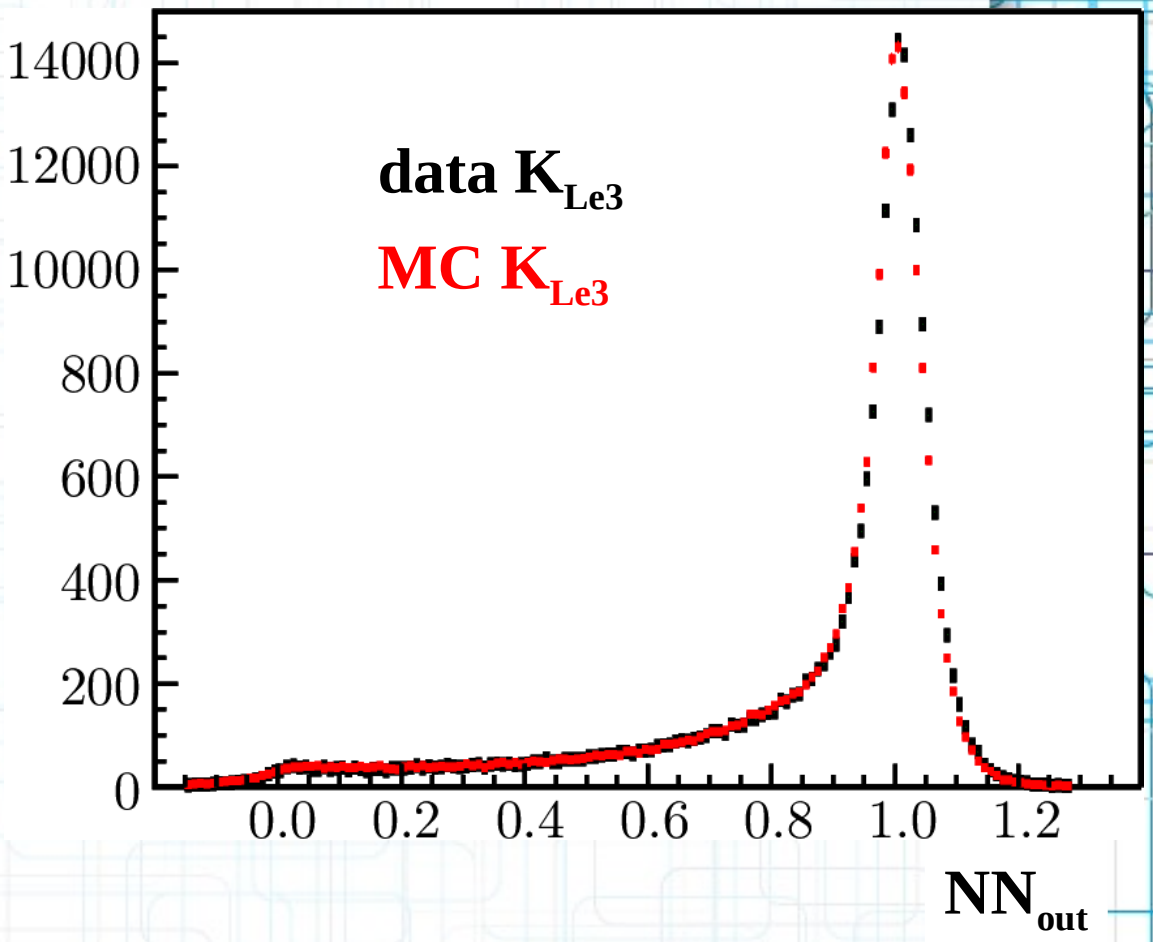
3) Combine all information in a neural network (NN).



Background rejection (PID)

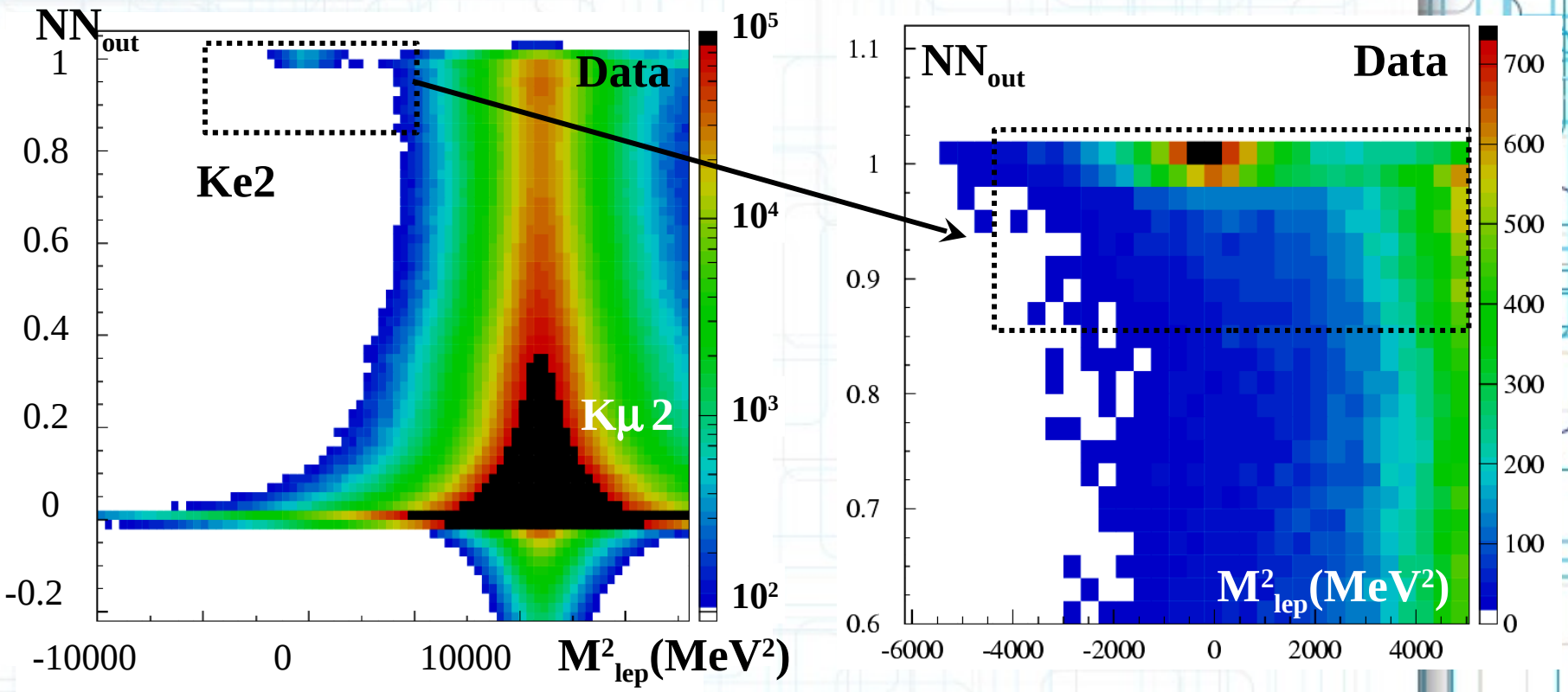
- Use a pure sample of $K_L e3$ to correct cell response in MC.

- $K_L e3$ anf $K\mu 2$ for NN training.



Background rejection (PID)

Select a region with good S/B ratio in the M^2_{lep} – NN_{out} plane

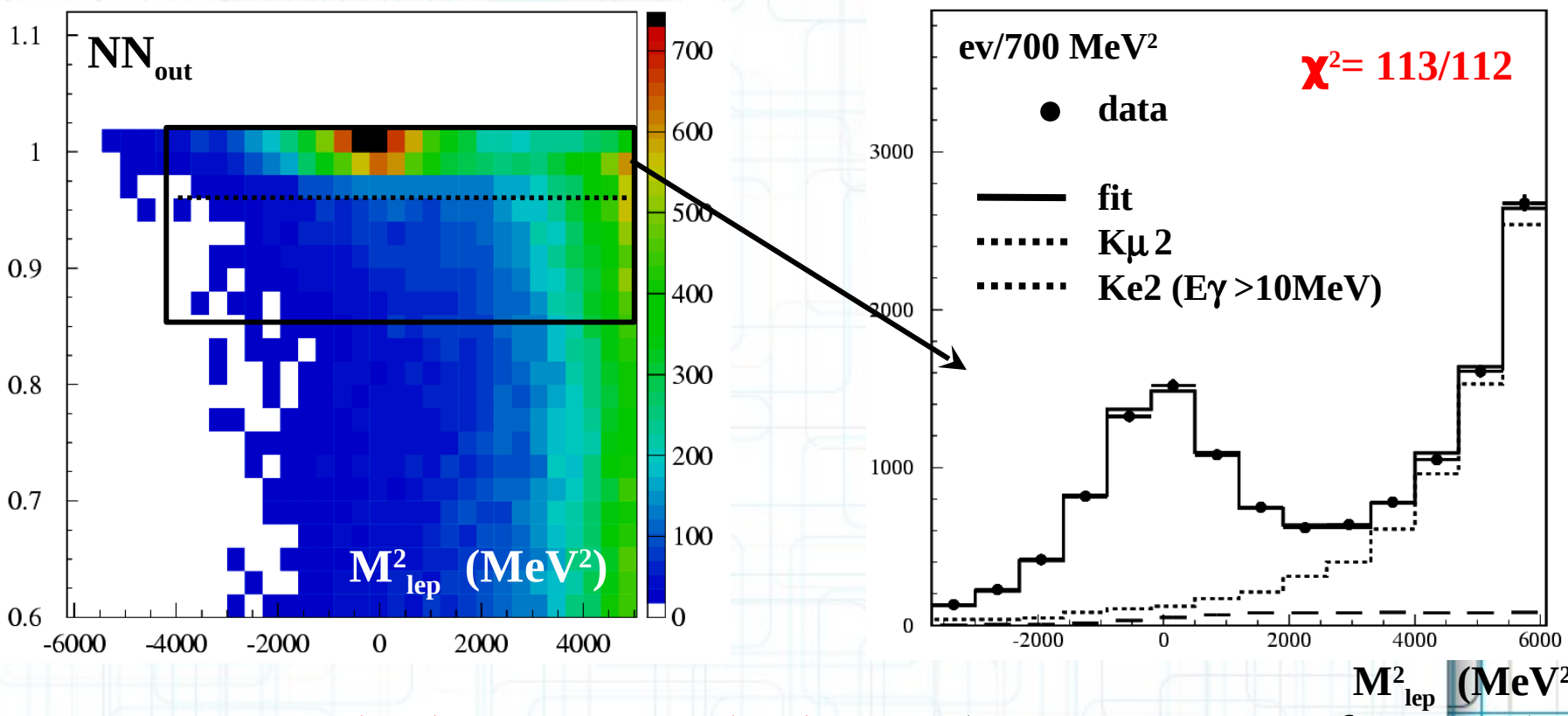


after selection: $\varepsilon \sim 30\%$ ($\sim 15{,}000\ K_{e2}$) **S/B ~ 5**

K_{e2} event counting

Two-dimensional binned likelihood fit in the M^2_{lep}–NN_{out} plane in the region **$-4000<M^2_{lep}<6100$** and **$0.86<NN_{out}<1.02$**

Ke2+ fit; M^2_{lep} proj for $NN_{out}>0.96$

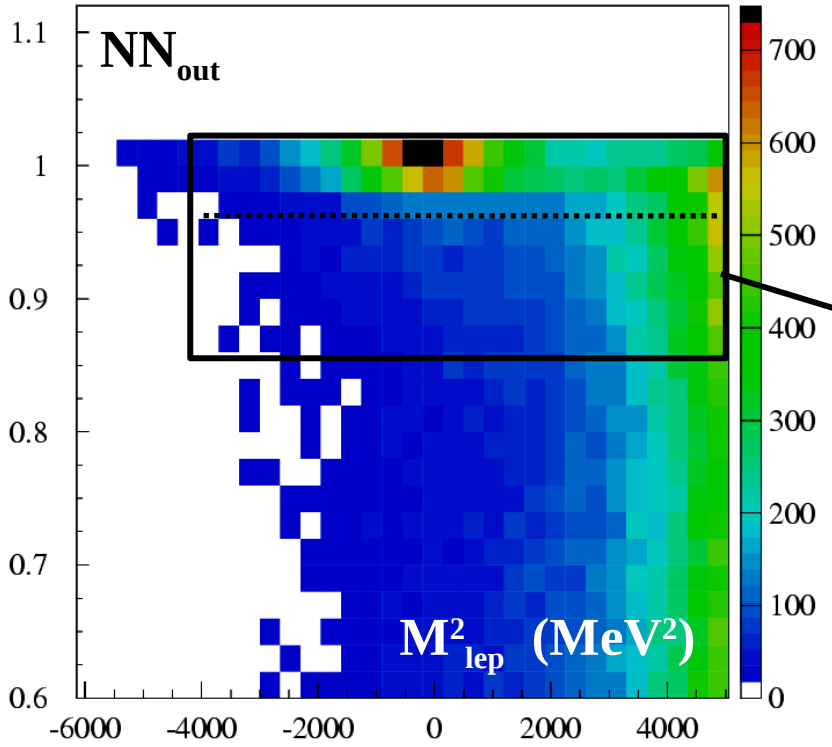


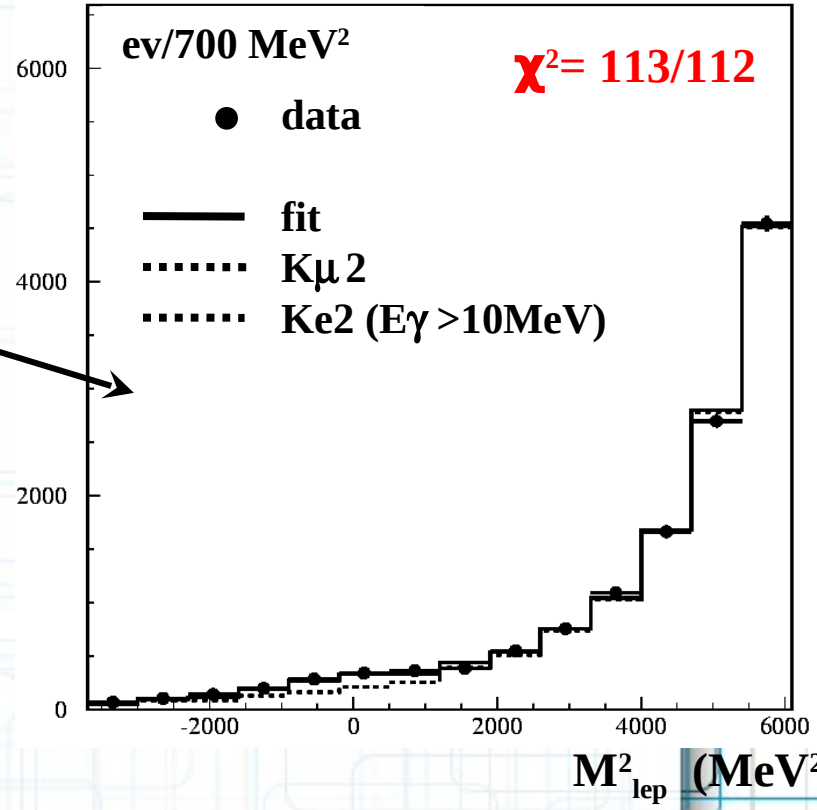
We count **7060 (102) Ke2+** **6750 (101) Ke2–** **(σ_{STAT}=1%, 0.85% from Ke2)**

K_{e2} event counting

Two-dimensional binned likelihood fit in the M^2_{lep}–NN_{out} plane in the region **$-4000<M^2_{lep}<6100$** and **$0.86<NN_{out}<1.02$**

Ke2+ fit; M^2_{lep} proj for $NN_{out}<0.96$

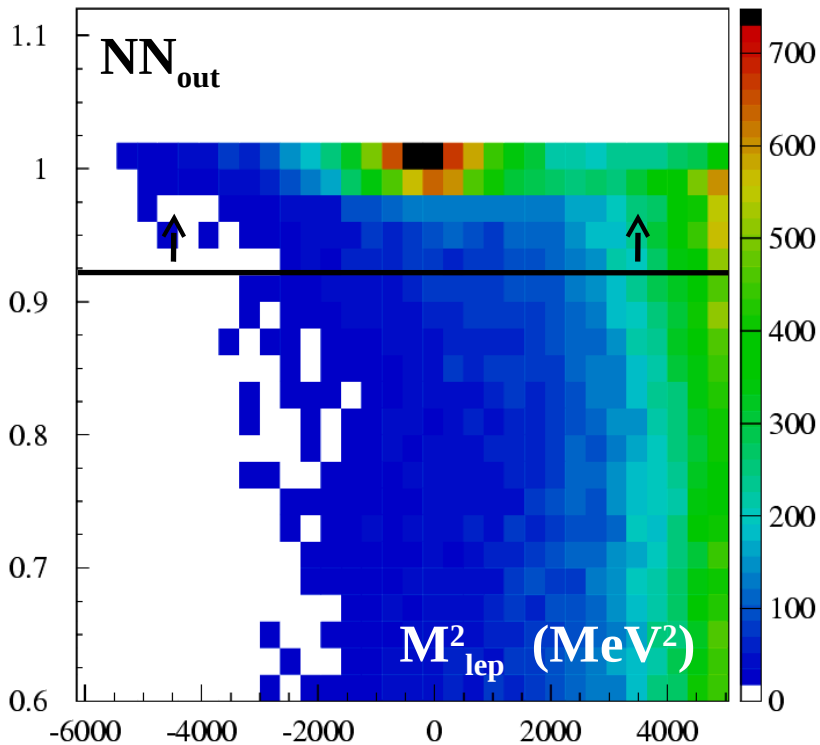


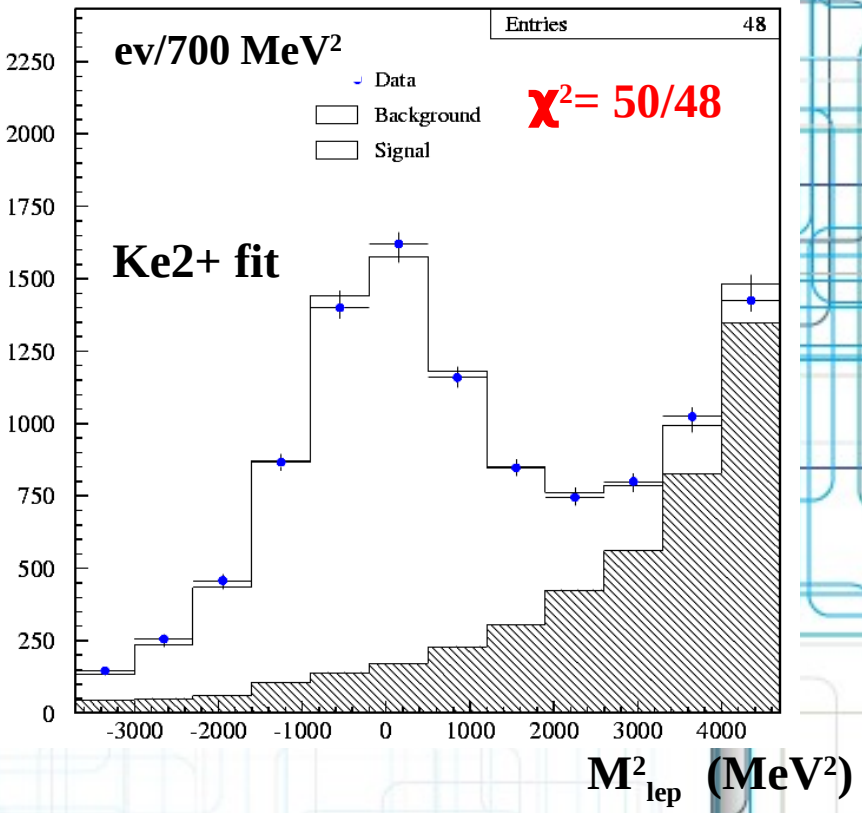


We count **7060 (102) Ke2+** **6750 (101) Ke2–** **(σ_{STAT}=1%, 0.85% from Ke2)**

K_{e2} event counting: systematics

Repeat fit with different values of **max(M^2_{lep})** and **min(NN_{out})**: vary significantly (×20) bkg contamination + lever arm.

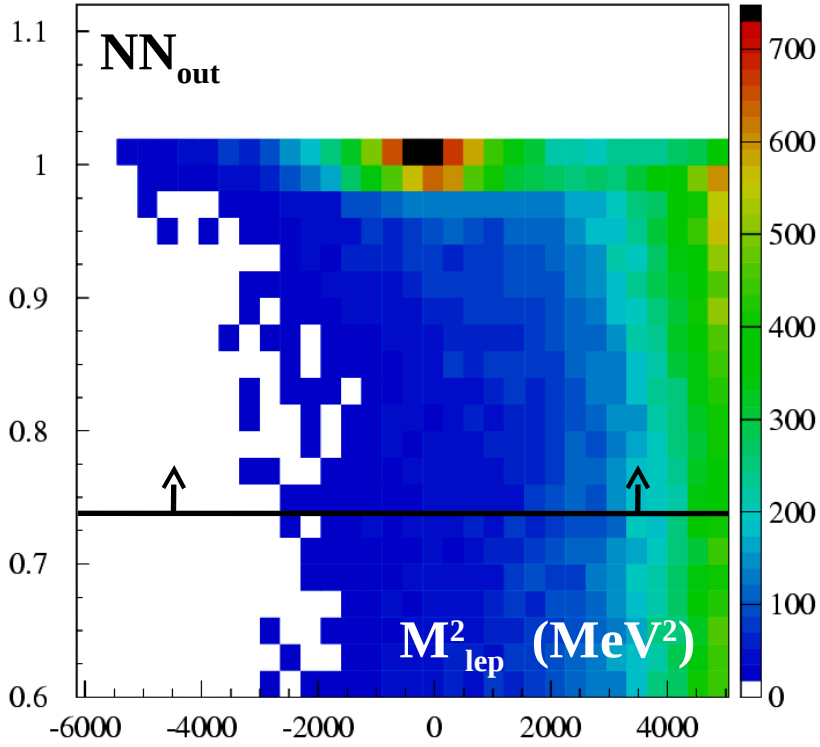


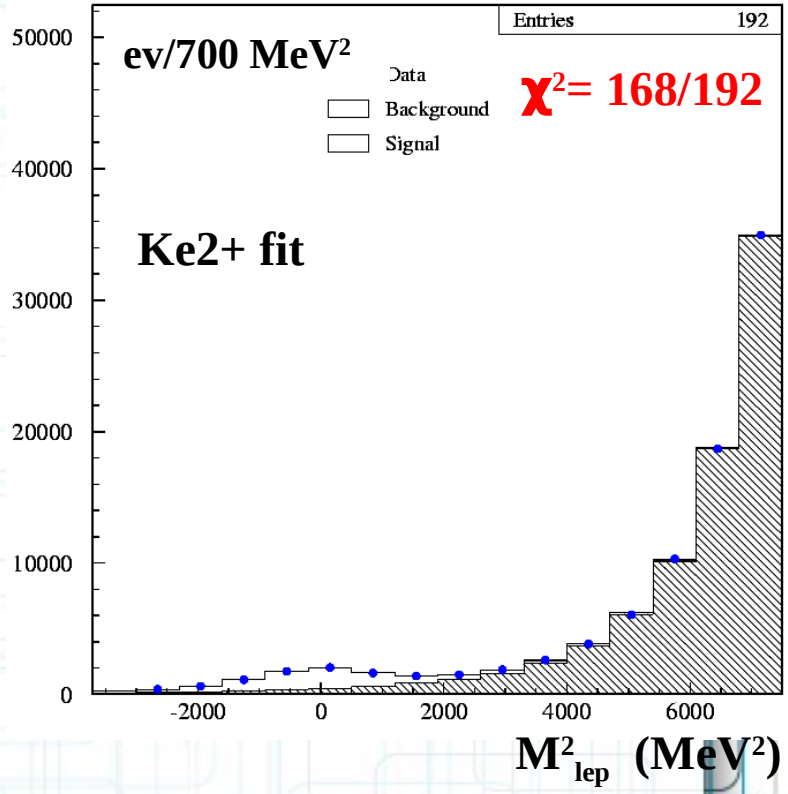


minimal bkg with: $-4000 < M^2_{lep} < 4650$ and $0.94 < NN_{out} < 1.02$

K_{e2} event counting: systematics

Repeat fit with different values of **max(M^2_{lep})** and **min(NN_{out})**: vary significantly (×20) bkg contamination + lever arm.





maximum bkg with: $-4000 < M^2_{lep} < 7500$ and $0.78 < NN_{out} < 1.02$

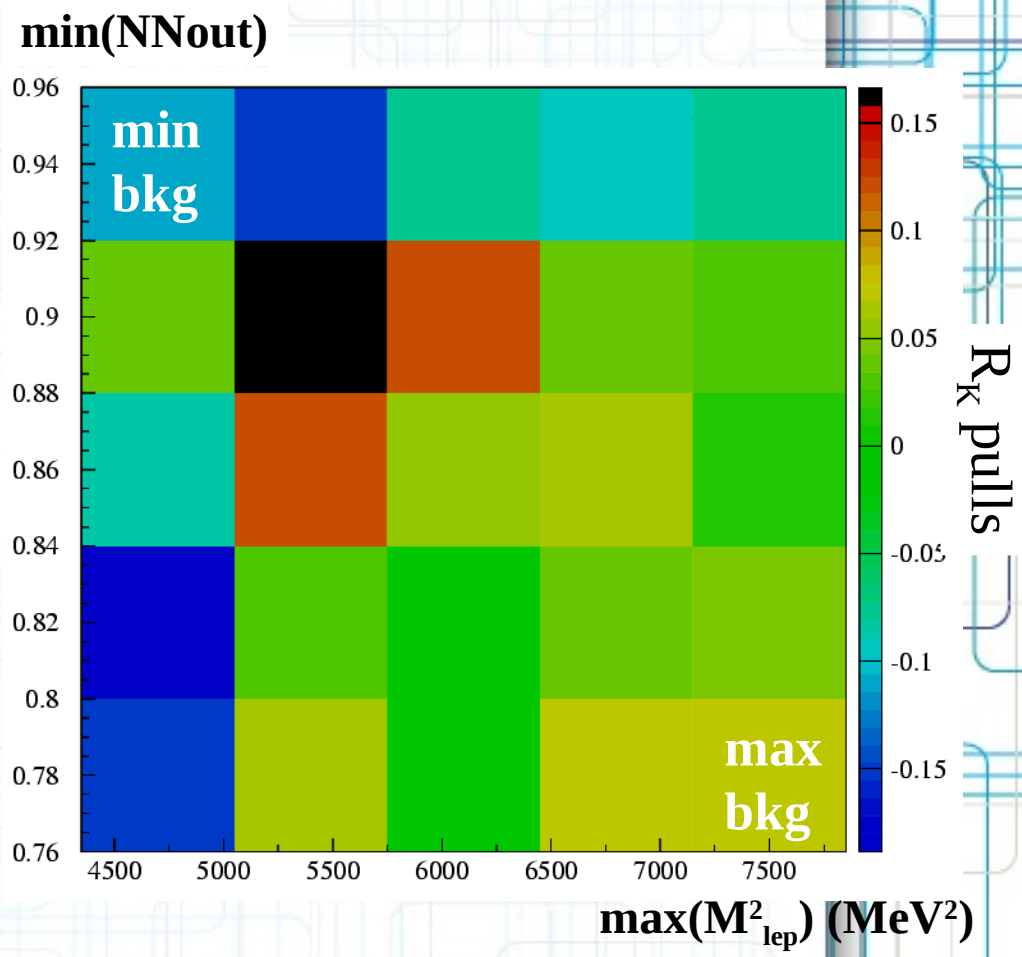
K_{e2} event counting: systematics

We change by a factor of 20 the amount of bkg falling in the fit region by moving

- min(NNout)
- max(M^2_{lep}).

Signal counts change by 15%.

From the pulls of the R_K measurements **we evaluated a 0.3% systematic error**.



Ke2 fit: radiative corrections

- Analysis is inclusive of photons in the final state. In our fit region we expect:

$$\frac{\text{Ke2 } (E_\gamma > 10\text{MeV})}{\text{Ke2}(E_\gamma < 10\text{MeV})} \sim 10\%$$

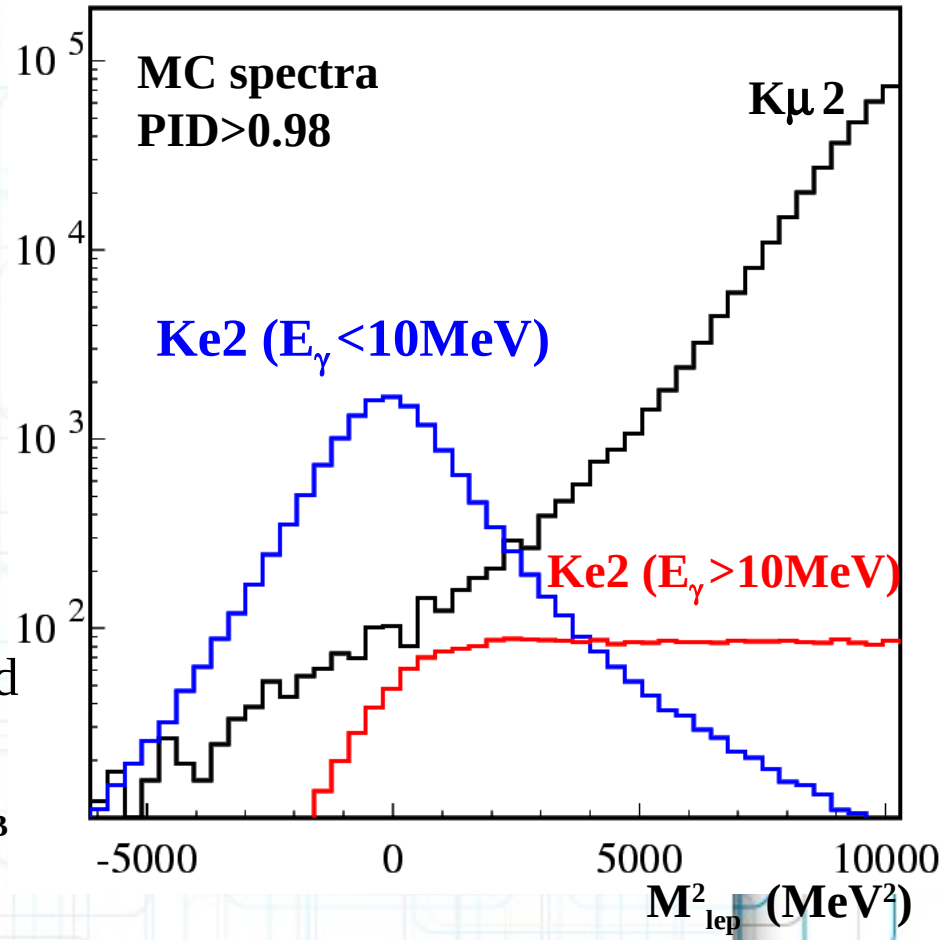
- Repeat fit by varying Ke2 (E_γ>10 MeV) by 15% (DE uncertainty) get 0.5% error.

We performed a **dedicated study of the Ke2γ differential decay rate**:

- E_γ spectrum measured for the first time

- confirm DE content of our MC, evaluated with ChPT O(p^4), within ~ 4% accuracy

- obtain 0.2% systematic error on $Ke2_{IB}$

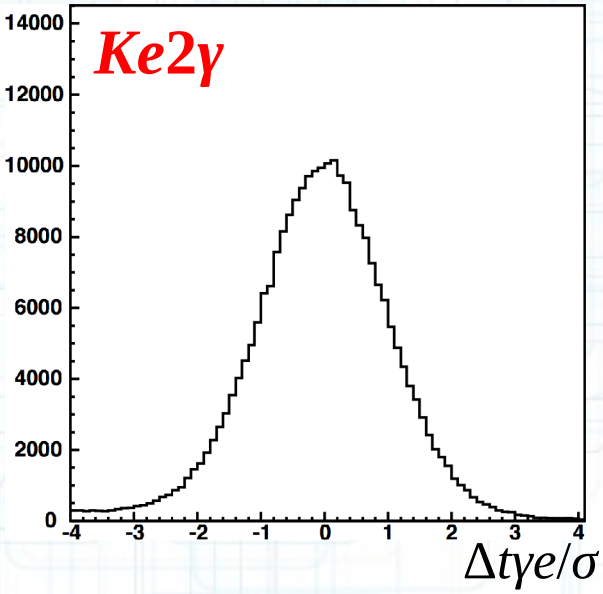


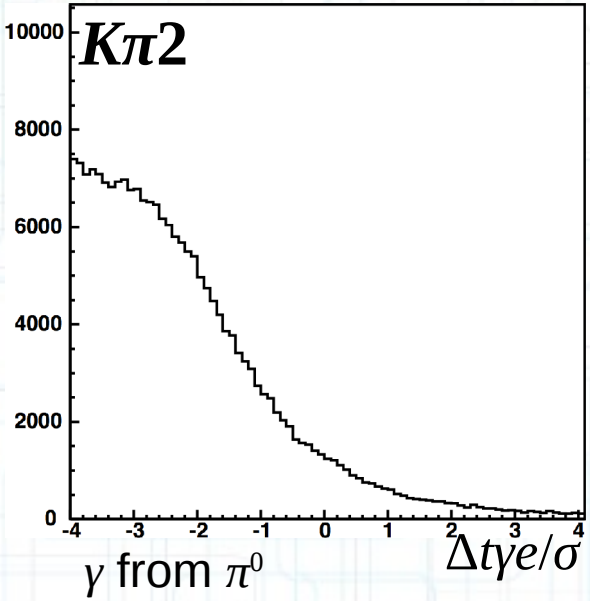
Ke2γ selection

To select Ke2γ events additional selection criteria were applied:

- Harder cut on NN output to reject Kμ2 with accidental γ
- Explicit detection of γ with E>20 MeV
- Time for γ and *e* in EMC must be compatible:

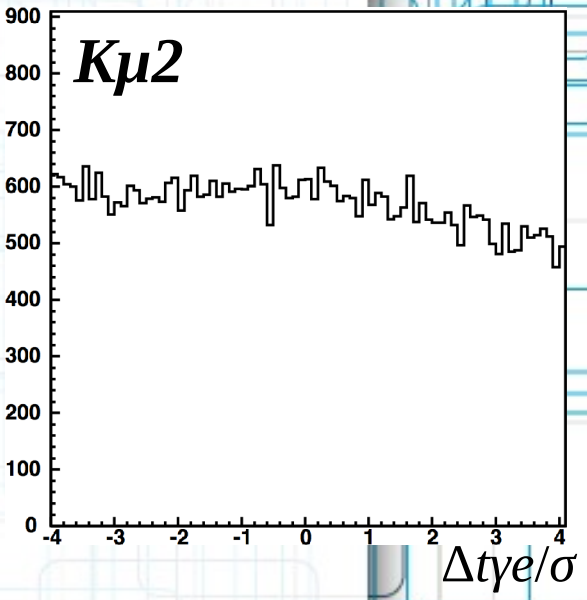
$$|\Delta t_{\gamma e}| = |(t_\gamma - L_\gamma/c) - (t_e - L_e/c)| \leq 2\sigma$$





γ from π^0

$\beta(\pi+) \approx 0.8$, not 1



Accidentals flat in time

Ke2γ selection

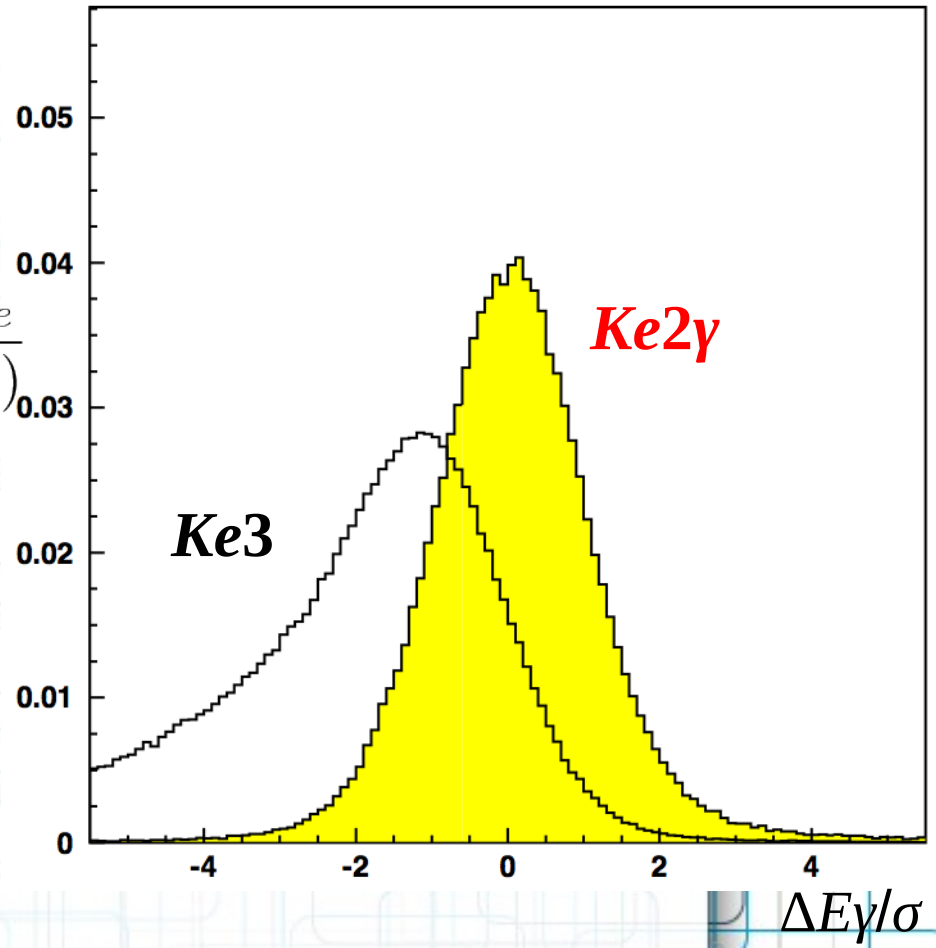
Difference between measured and expected γ energy can be useful in bkg/signal separation:

$$E_\gamma^{\rm lab} = \frac{m_K^2 + m_e^2 - 2E_K E_e + 2p_K \cdot p_e}{2(E_K - E_e - p_K \cdot n_\gamma + p_e \cdot n_\gamma)}$$

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

$$\sigma_E^{\rm EMC} \approx 30 \text{ MeV}$$

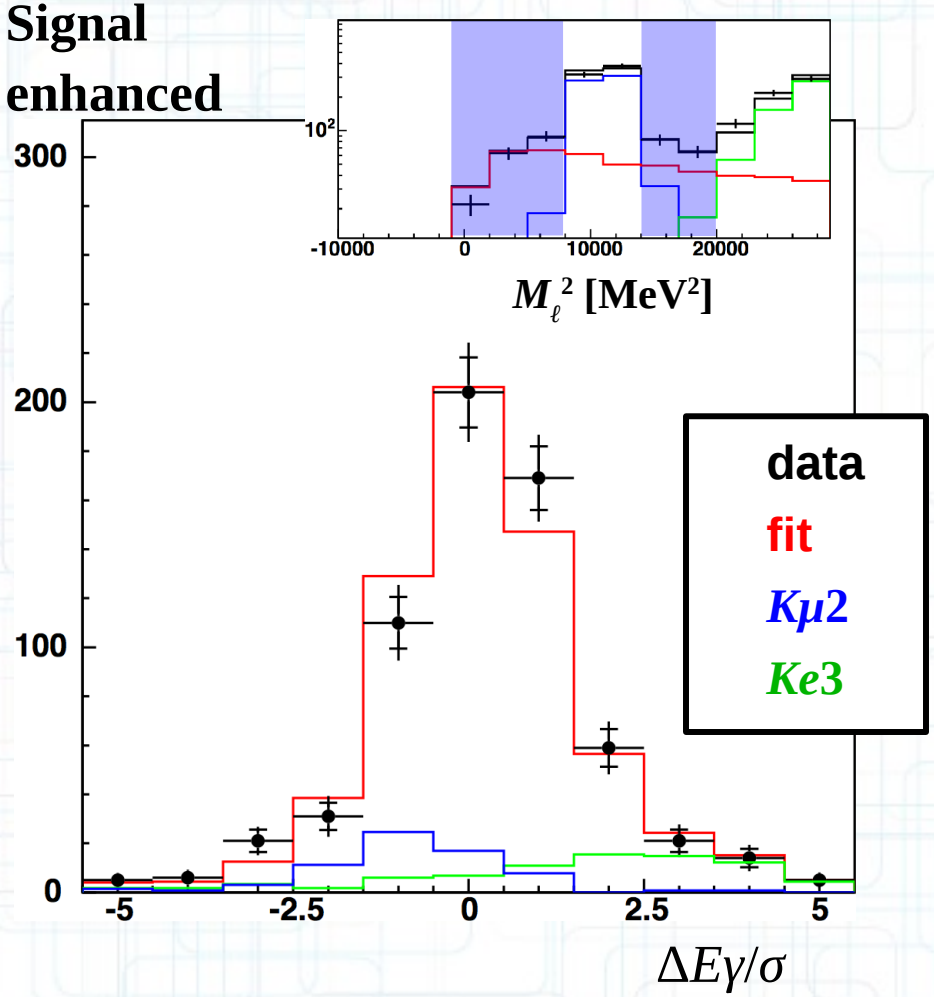
Perform 2-dimensional fit binned likelihood fit M_l^2, $\Delta E_\gamma/\sigma$ in 5 bins of E_γ^*



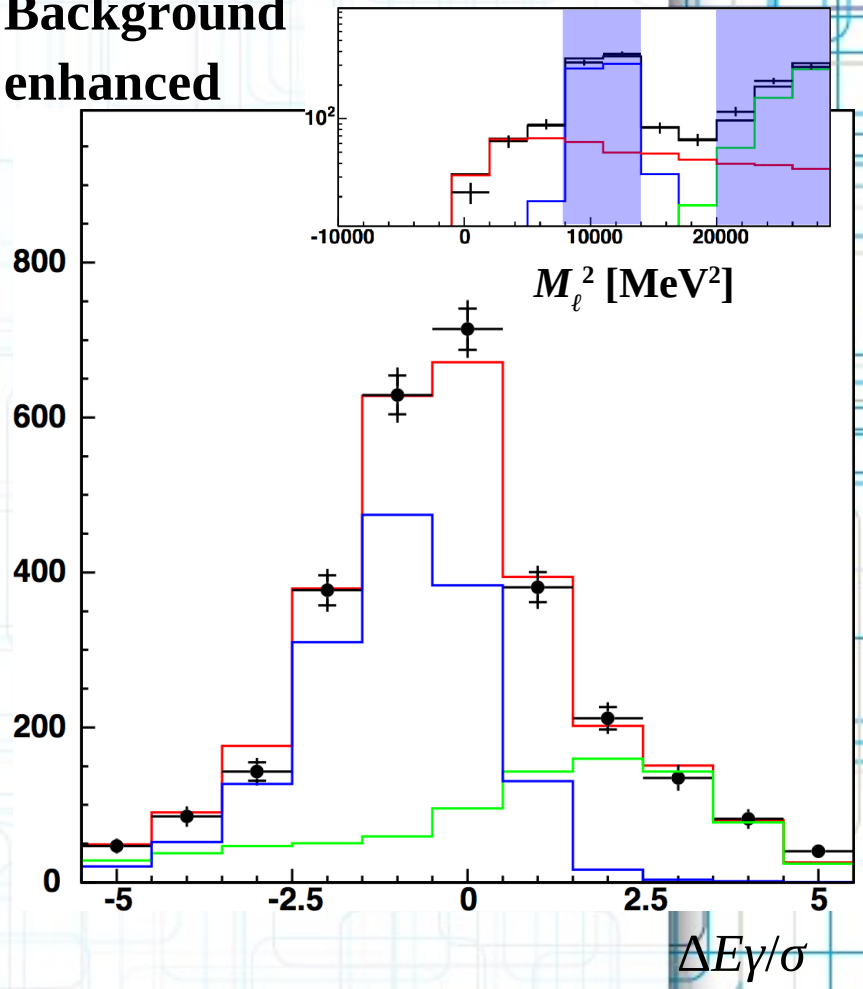
Ke2γ fit result

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

Signal enhanced



Background enhanced



Ke2γ spectrum

We measure $\frac{1}{\Gamma(K_{\mu 2})}\frac{d\Gamma_{SD+}(K_{e2\gamma})}{dE_\gamma}$, where "SD+" means:

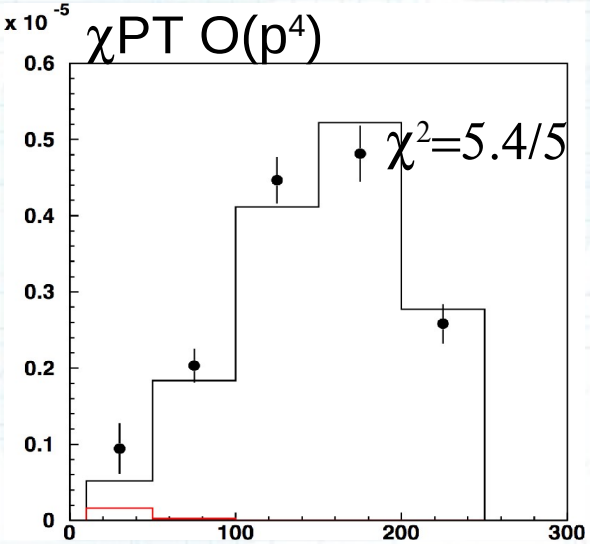
$$E^*_\gamma > 10\ \mathrm{MeV},\ \cos\theta^*_{e\gamma} < 0.9,\ p^*_e > 200\ \mathrm{MeV}/c$$

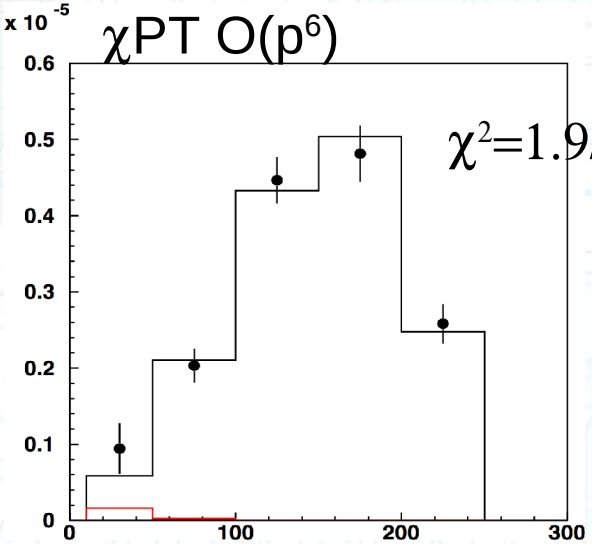
$N_{SD+}(Ke2\gamma) = 1378 \pm 63 \Rightarrow \Gamma_{SD+}(Ke2\gamma)/\Gamma(K\mu 2) = 1.484(66)_{stat}(16)_{syst}\times 10^{-5}$,

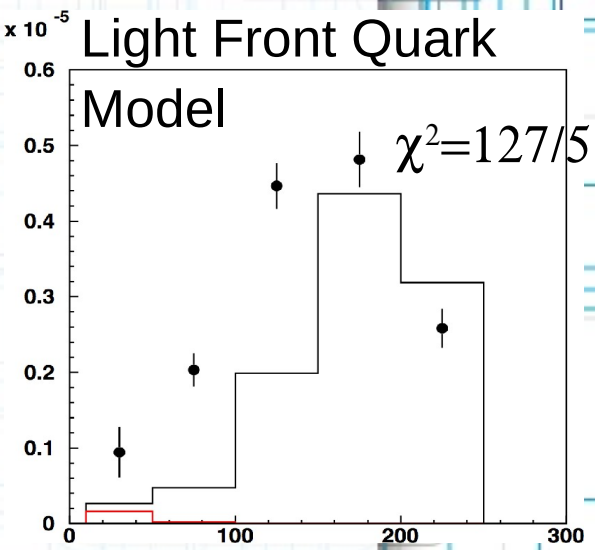
which is in agreement with χPT $O(p^4)$ prediction

1.447×10^{-5} [Bijnens, Ecker, Gasser '93]

KLOE MC was validated to within 4.6% ⇒ systematic error on R_K is 0.2%







Reconstruction efficiencies

The ratio of Ke2 to Kμ2 efficiencies is evaluated with MC and corrected using data control samples

1) **kink reconstruction (tracking):** K^+e3 and $K^+\mu 2$ data control samples selected using the tagging and additional criteria based on EMC information only (next slide)

2) **cluster efficiency (*e*, μ):** K_L control samples, selected with tagging and kinematic criteria based on DC information only

3) **trigger**: exploit the OR combination of EMC and DC triggers (almost uncorrelated); downscaled samples are used to measure efficiencies for cosmic-ray and machine background vetoes

We obtain: ε(Ke2)/ε(Kμ2) = 0.946±0.007

Control samples for tracking efficiencies

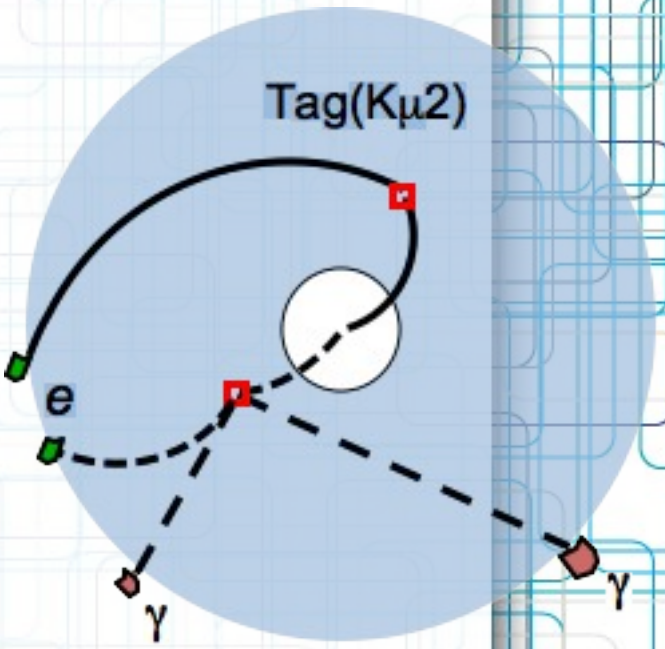
Just an example: selection of K^+e3 control sample to measure tracking efficiency for electrons

0) Tagging decay ($K\mu 2$ or $K\pi 2$);

1) Tagging decay ($K\mu 2$ or $K\pi 2$): reconstruction of the opposite charge kaon flight path;

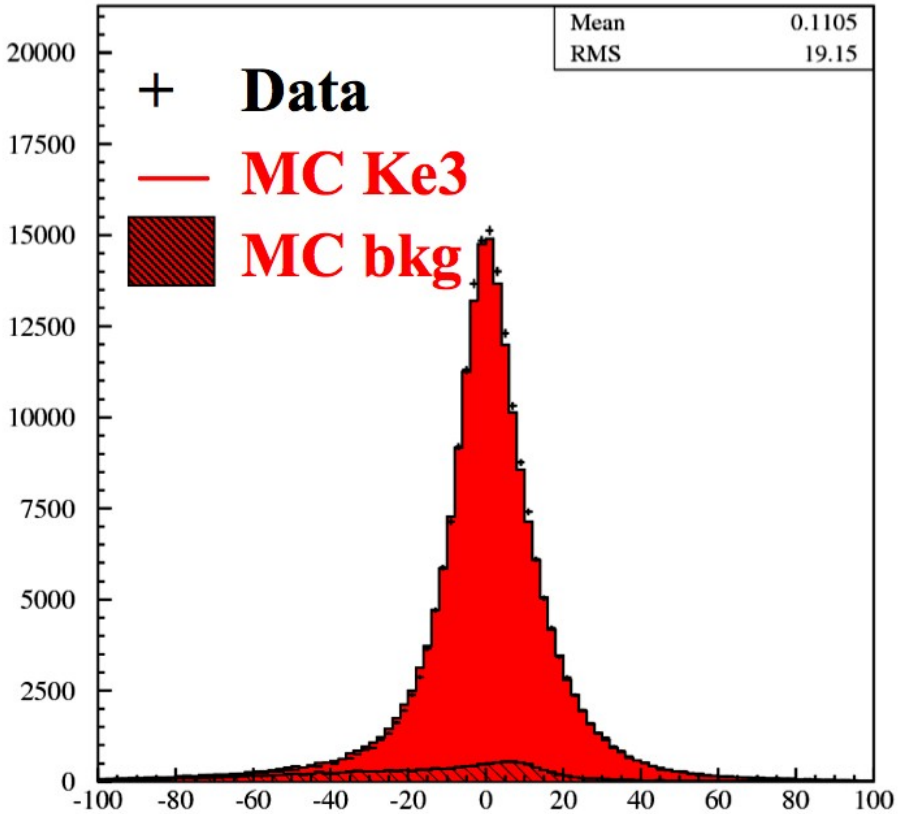
2) Using a ToF technique a $\pi^0 \rightarrow \gamma\gamma$ decay vertex is reconstructed along the K decay path;

3) Require an electron cluster: p_e estimated from a kinematic fit with constraints on E/p, ToF, cluster position, and $E_{miss} - P_{miss}$.

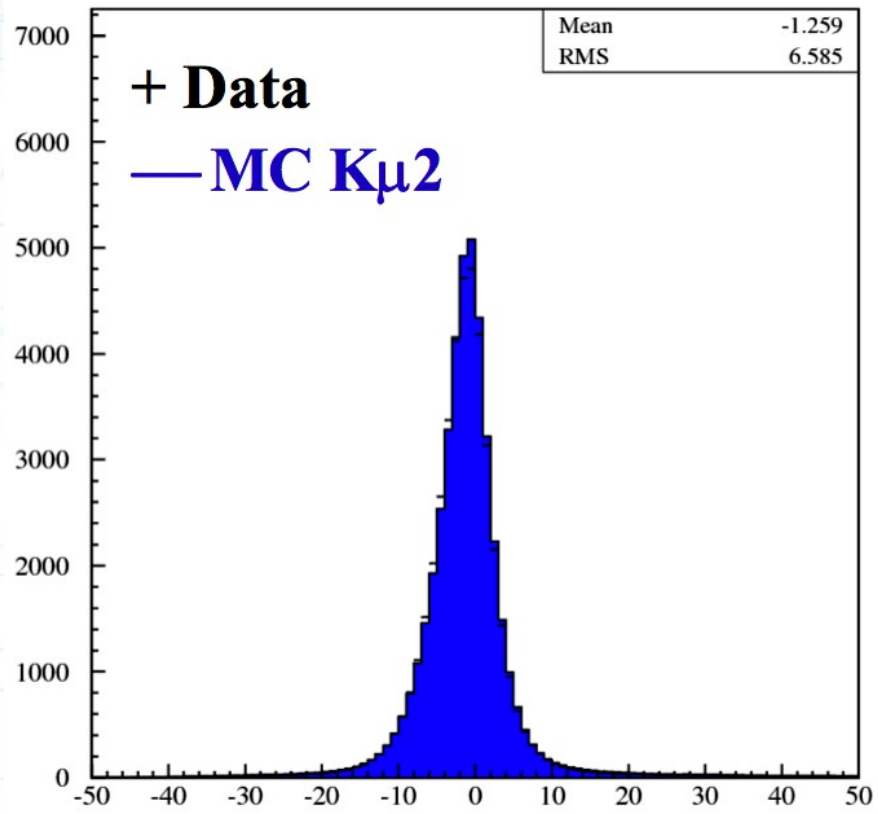


Evaluate the K + electron kink reconstruction efficiency

Control samples for tracking efficiencies



$p_e(\text{fit})-p_e(\text{reco})$ (MeV)



$p_\mu(\text{fit})-p_\mu(\text{reco})$ (MeV)

- For electron tracks obtain a resolution $\sigma \sim 19$ MeV
- With a similar method, get $\sigma \sim 7$ MeV for muon tracks

Systematics and checks

Cross-check on efficiencies: use same algorithms to measure $R_{l3} = \Gamma(Ke3)/\Gamma(K\mu 3)$

$R_{l3} = 1.507 \pm 0.005$ for K^+

$R_{l3} = 1.510 \pm 0.006$ for K^-

SM expectation (FlaviaNet)

$R_{l3} = 1.506 \pm 0.003$

Summary of systematics:

Tracking	**0.6%**	K^+ control samples
Trigger	**0.4%**	downscaled events
syst on Ke2 counts	**0.3%**	fit stability
Ke2γ DE component	**0.2%**	measurement on data
Clustering for e, μ	**0.2%**	K_L control samples

Total Syst **0.8%**

(0.6% from statistics of control samples)

R_K: KLOE result

$R_K = (2.493 \pm 0.025 \pm 0.019)\times10^{-5}$

Total error:

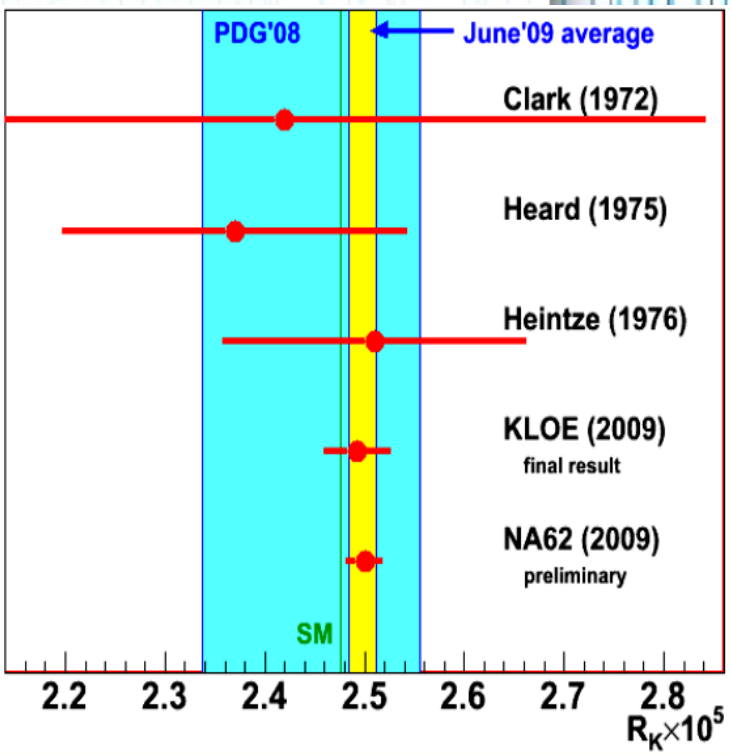
1.3% = 1.0%$_{stat}$ + 0.8%$_{syst}$

0.9% from 14k Ke2 + bkg subtraction

dominated by statistics

Accepted for publication on EPJC

- The result does not depend upon the kaon charge: K^+: 2.496(37) vs K^-: 2.490(38) (uncorrelated errors only)
- Agrees with SM prediction



PDG 2008:

$R_K = (2.45\pm 0.11)\times10^{-5}$

4.5% accuracy

NA62 preliminary result:

$R_K=(2.500 \pm 0.012 \pm 0.011)\times10^{-5}$

World average with NA62 result:

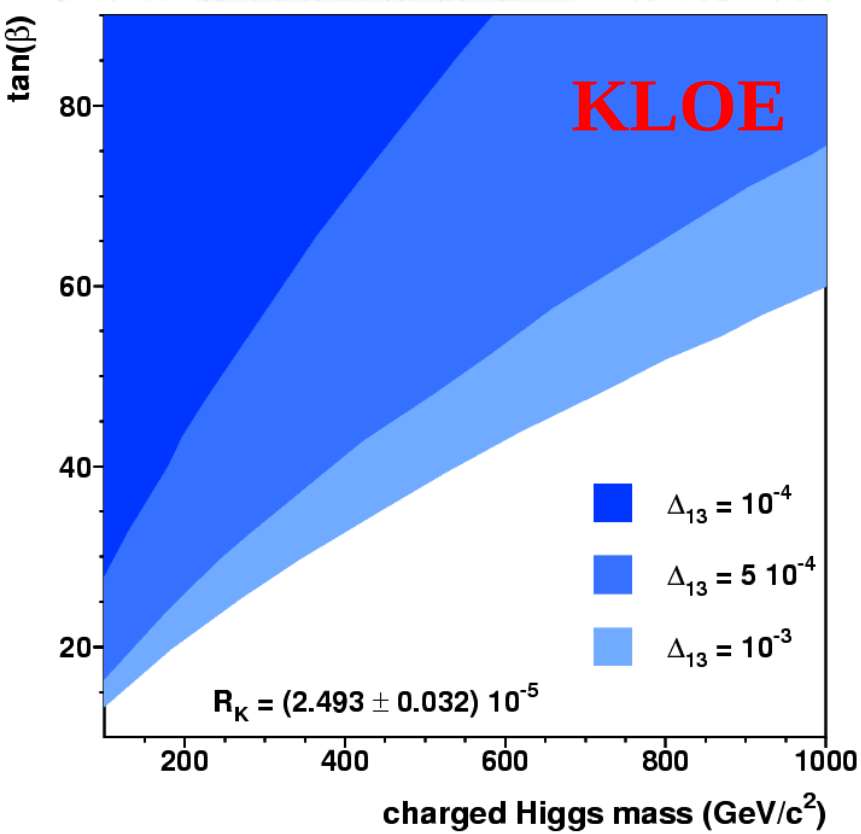
$R_K = (2.498\pm 0.014)\times10^{-5}$

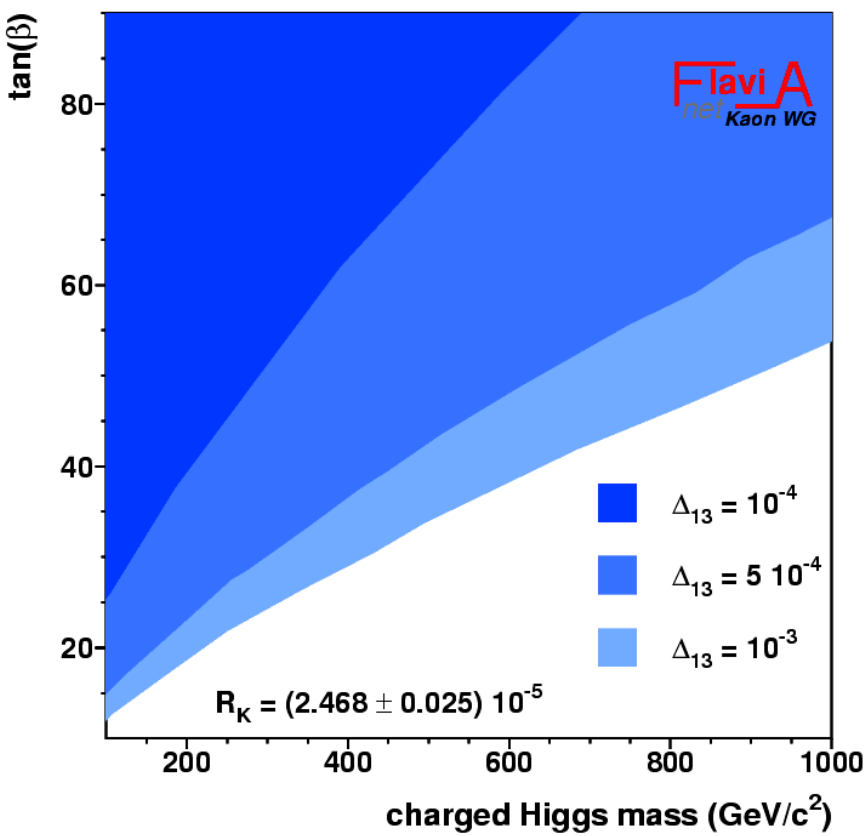
0.56% accuracy

$R_K^{SM} = 2.477(1) \times10^{-5}$

R_K : sensitivity to new physics

Sensitivity shown as 95% CL excluded regions in the tanβ–M_H plane, for different values of the LFV effective coupling, $\Delta_{13} = 10^{-3}, 5\times10^{-4}, 10^{-4}$





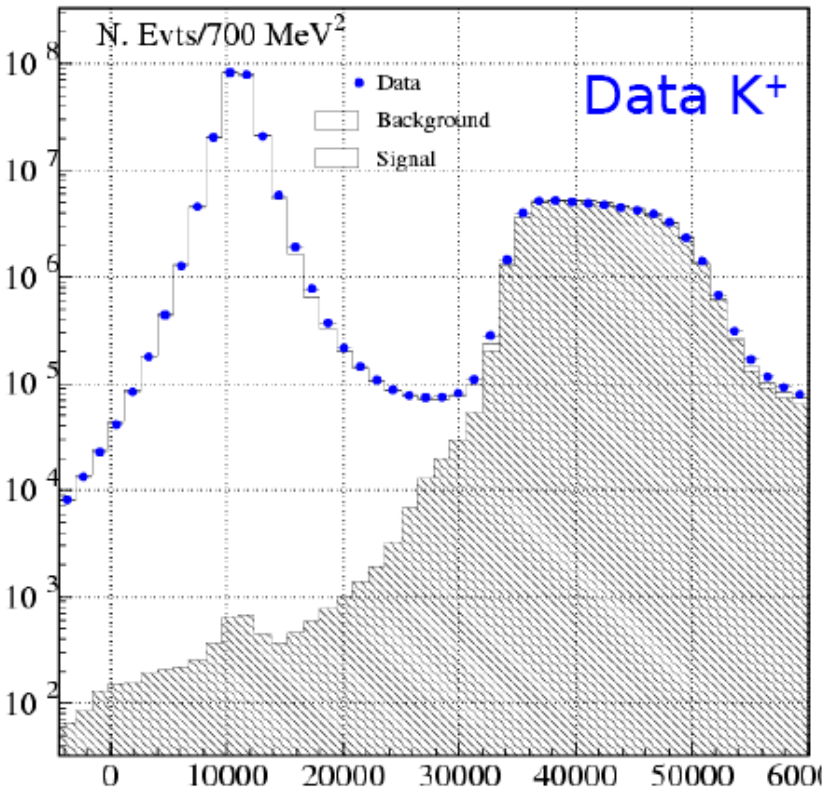
Conclusion

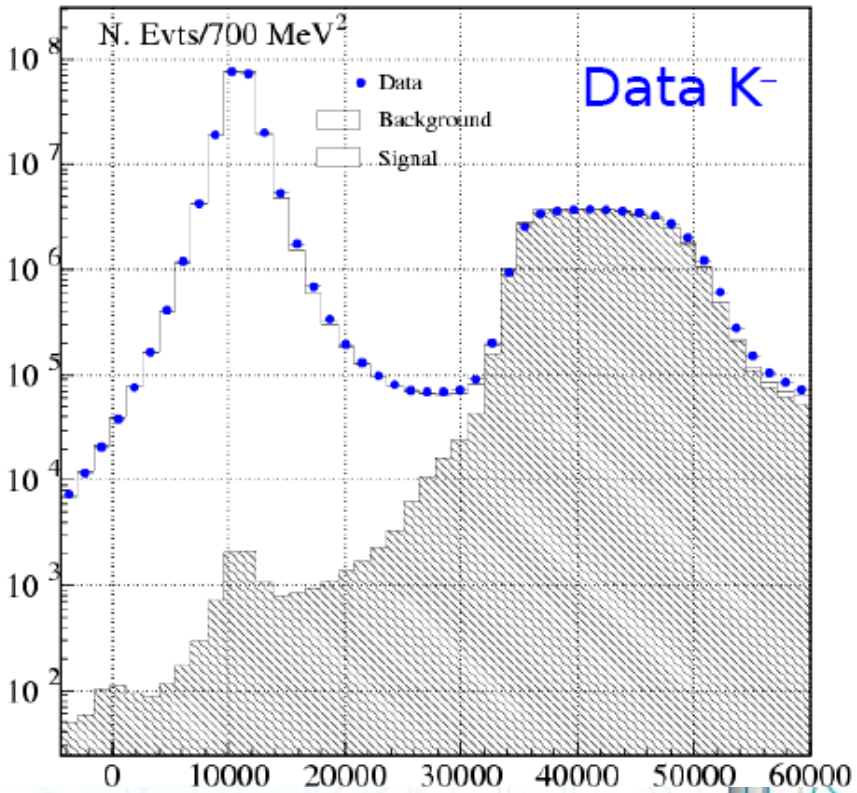
- Using 2.2 fb^{-1} of data acquired at the ϕ peak, KLOE measured:

$$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$$

- This results confirms the SM prediction within the 1.3% accuracy
- Systematic error from DE model of KLOE MC on R_K is 0.2%
- E_γ spectrum measured for the first time
- The error is dominated by the counting and the control samples statistics.
- Can contribute to set constraints on the parameter space of MSSM with LFV.

Kμ2 event counting



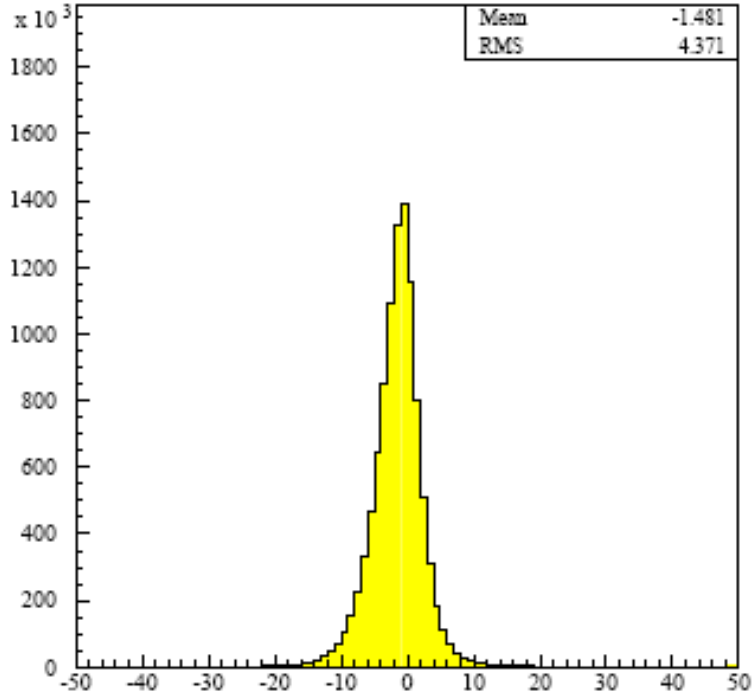


M^2_{lep} (MeV^2) M^2_{lep} (MeV^2)

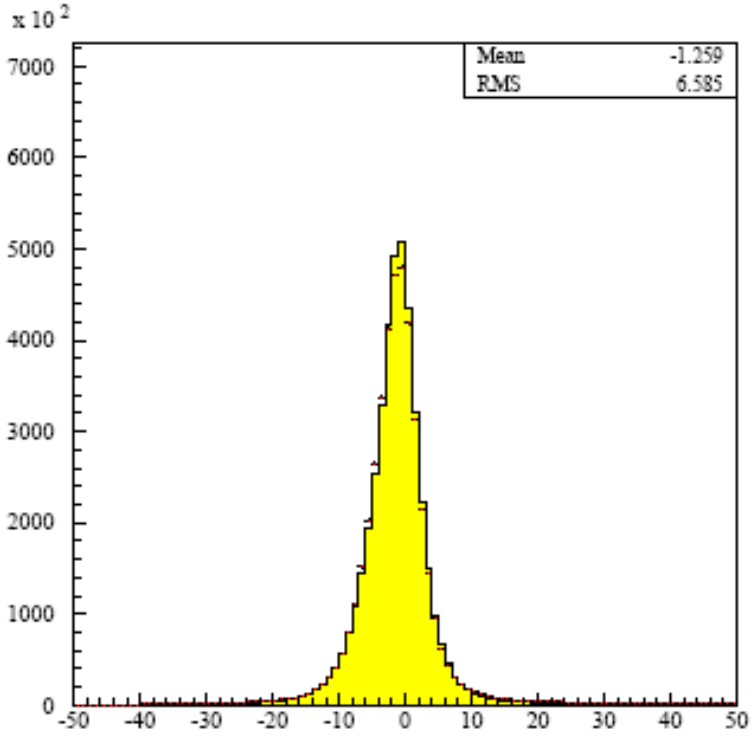
Fit to M^2_{lept} distribution: 300 million Kμ2 events per charge

Background under the peak <0.1%, from MC

Tracking efficiency



$p_\mu(fit)-p_\mu(MC)$ (MeV)



$p_\mu(fit)-p_\mu(reco)$ (MeV)

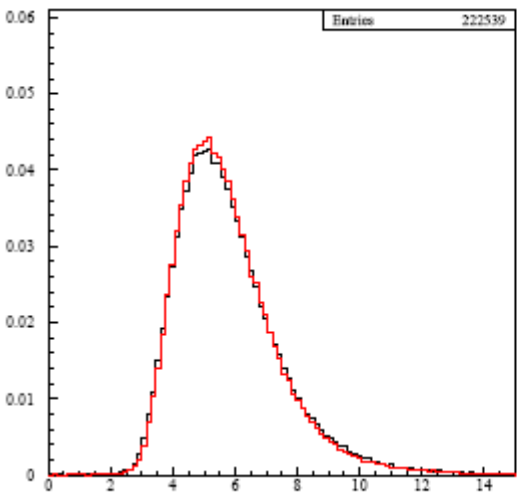
NN details

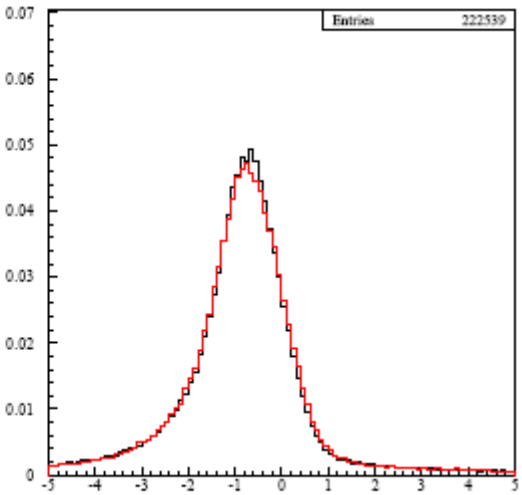
1) E/P;
2) 1st momentum of the distribution of the longitudinal energy path deposition (cluster centroid depth) evaluated at cell level;
3) the 3td momentum of the longitudinal energy path deposistion (skewness);
4,5) asymmetry of energy lost in first two innermost (outermost) planes;
6) RMS of energy plane distribution;
7) energy lost in the 1st plane;
8) number of the plane with larges energy deposition;
9) largest energy deposition in a single plane;
10) slope of the E_int(x) energy distribution;
11) curvature of the E_int(x) energy distribution;
12) de/dx i.e. value of E_int(x)/x|x<15 cm

Additional separation using ToF information: difference δT of the time measured in the EMC with that expected from the DC measurements in electron mass hypothesis has been included in the final version of the NN: 12-25-20-1 becomes 13-25-20-1

NN input distributions: some example

Cluster centroid depth

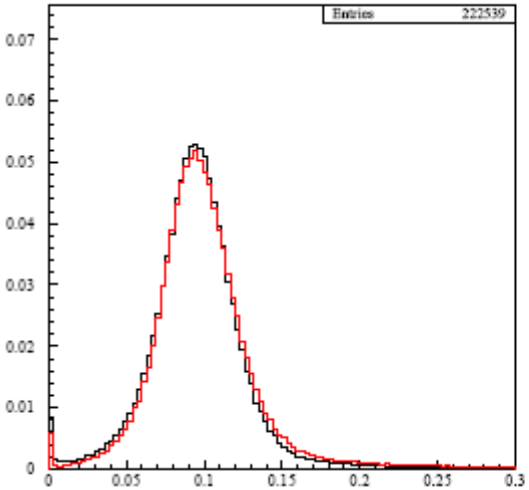


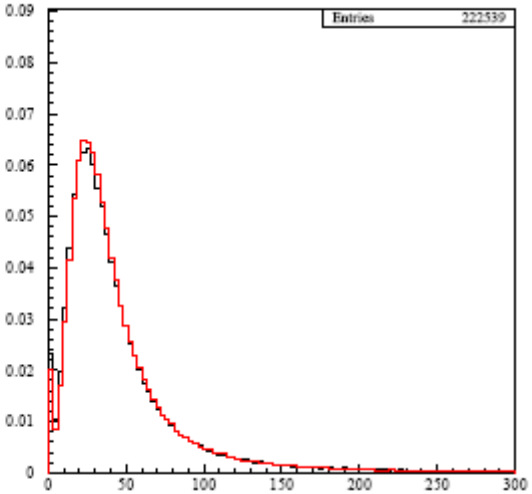


Asymmetry of energy lost in first two innermost planes

Data and **MC**

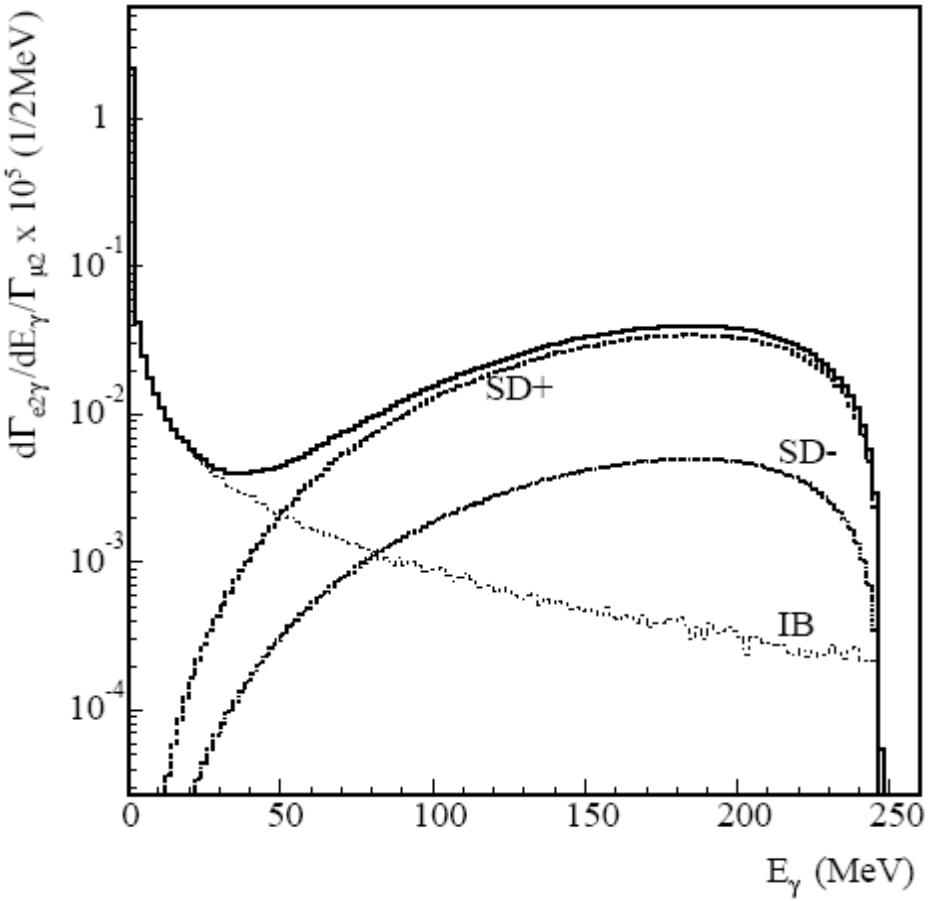
dE/dx

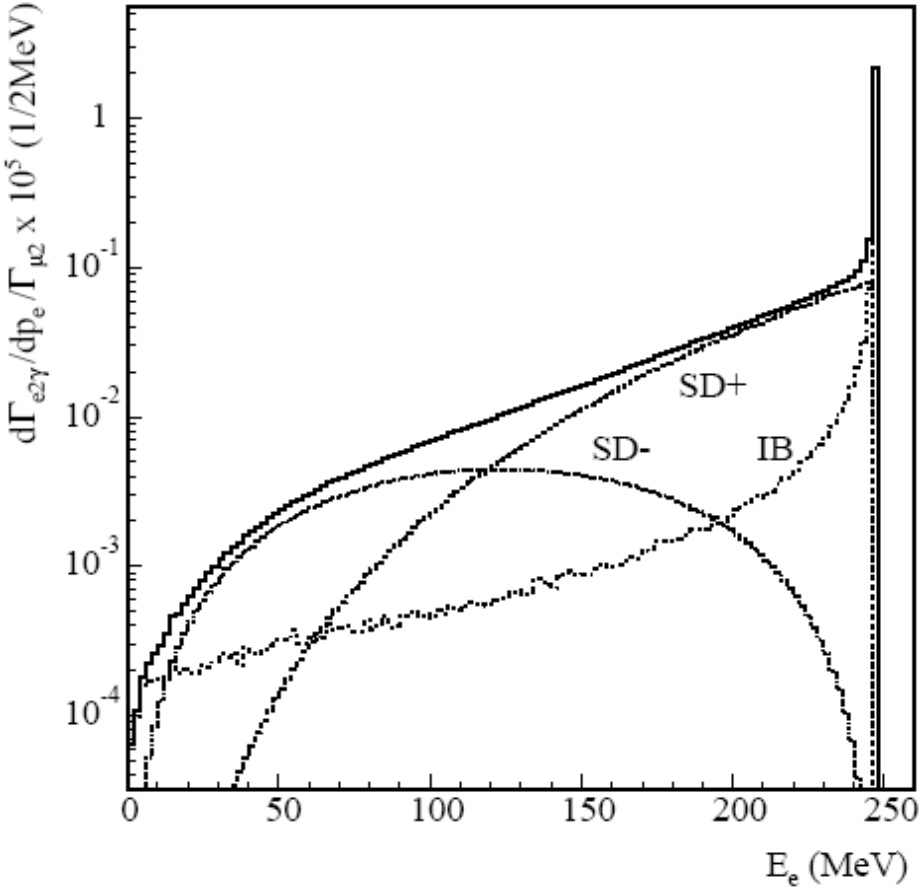




$E_{INT}(x)$ slope

Distributions for Ke2γ decay





For Ke2γ generator, the IB component is described with χ_{PT} at $O(e^2p^2)$ including resummation of leading logaritms, while DE component is described with χ_{PT} at $O(e^2p^4)$.

Ke2γ process

Dalitz density

$$\frac{d\Gamma(Ke2\gamma)}{dxdy} = \rho_{\rm IB}(x,y) + \rho_{\rm DE}(x,y) + \rho_{\rm INT}(x,y)$$

helicity suppressed

negligible

$$x = 2E_\gamma/M_K, \;\; y = 2E_e/M_K$$

E_γ, E_e in the K rest frame

Structure Dependent

$$\rho_{\rm DE}(x,y) = \frac{G_F^2|V_{us}|^2\alpha}{64\pi^2} M_K^5 \left((f_V+f_A)^2 f_{\rm SD+}(x,y) + (f_V-f_A)^2 f_{\rm SD-}(x,y)\right)$$

f_V, f_A : effective vector and axial couplings

SD+ = V+A : γ polarization +

SD−= V−A : γ polarization −

Ke2γ : theory predictions

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

$f_V \approx 0.0945$

$f_A \approx 0.0425$

no dependence on photon energy

Bijnens, Ecker, Gasser 93

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

$f_V \approx 0.082(1+\lambda(1-x))$

$f_A \approx 0.034$

V linear x dependence ($\lambda \approx 0.4$)

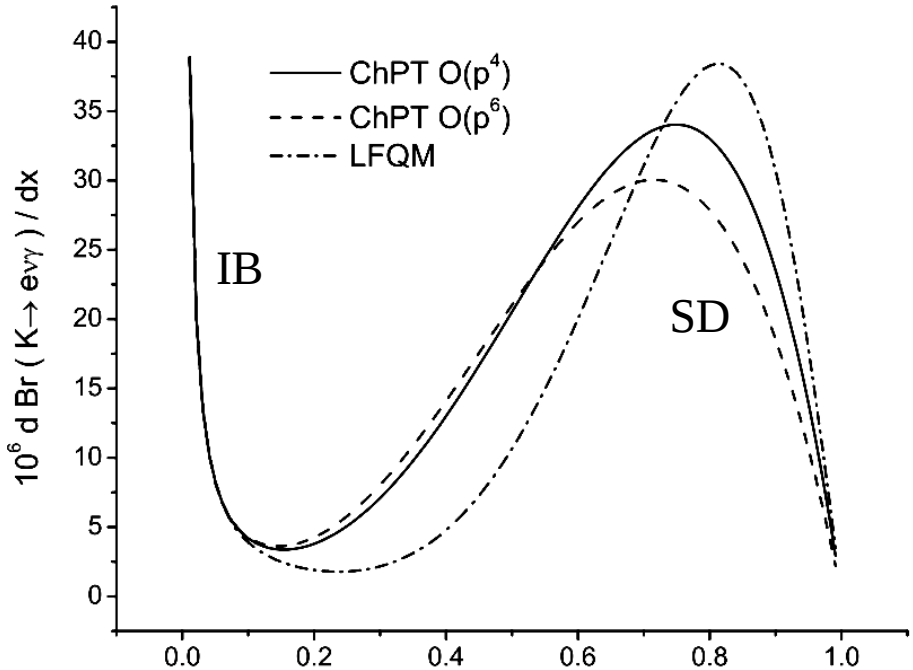
Ametller, Bijnens, Bramon, Cornet 93
Geng, Ho, Wu 04
Chen, Geng, Lih 08

3) LFQM:

non trivial x dependence

$f_V = f_A = 0$ at $x=0$

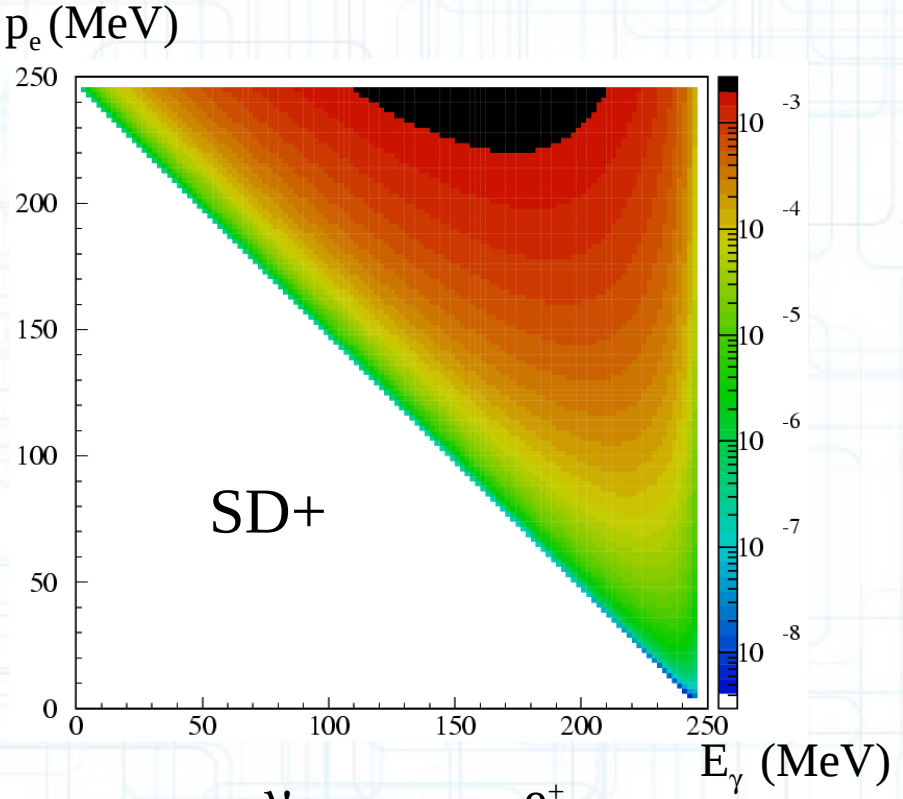
Chen, Geng, Lih 08

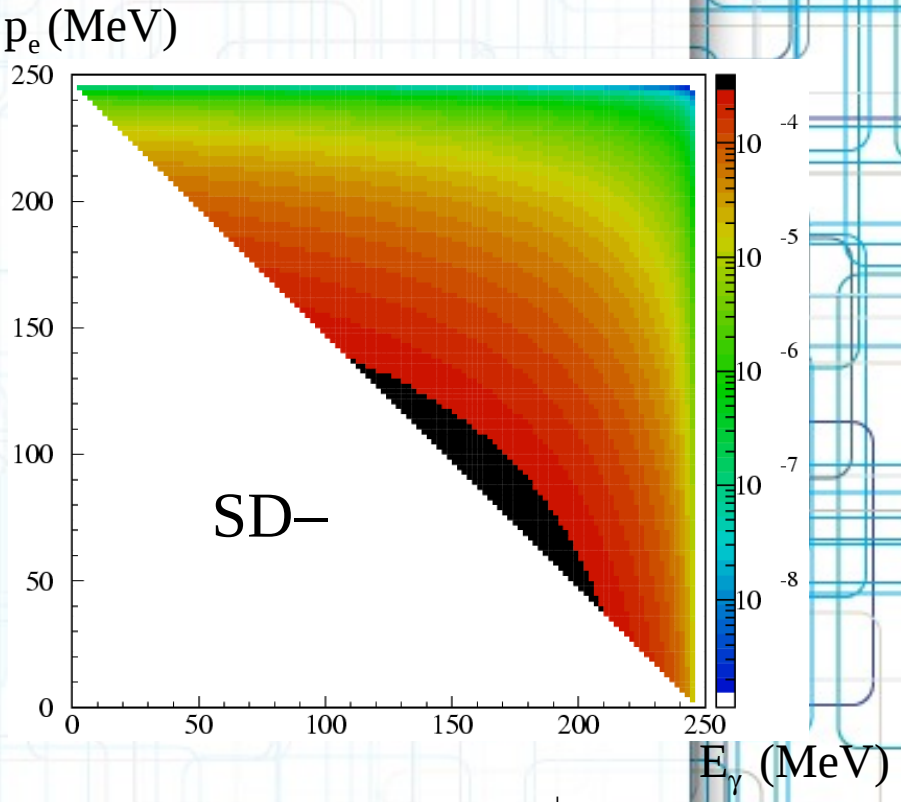


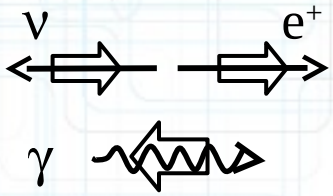
$x = 2E_\gamma / M_K$

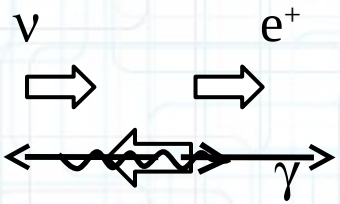
from Phys. Rev. D77 (2008) 014004

Dalitz plots for SD+ and SD–







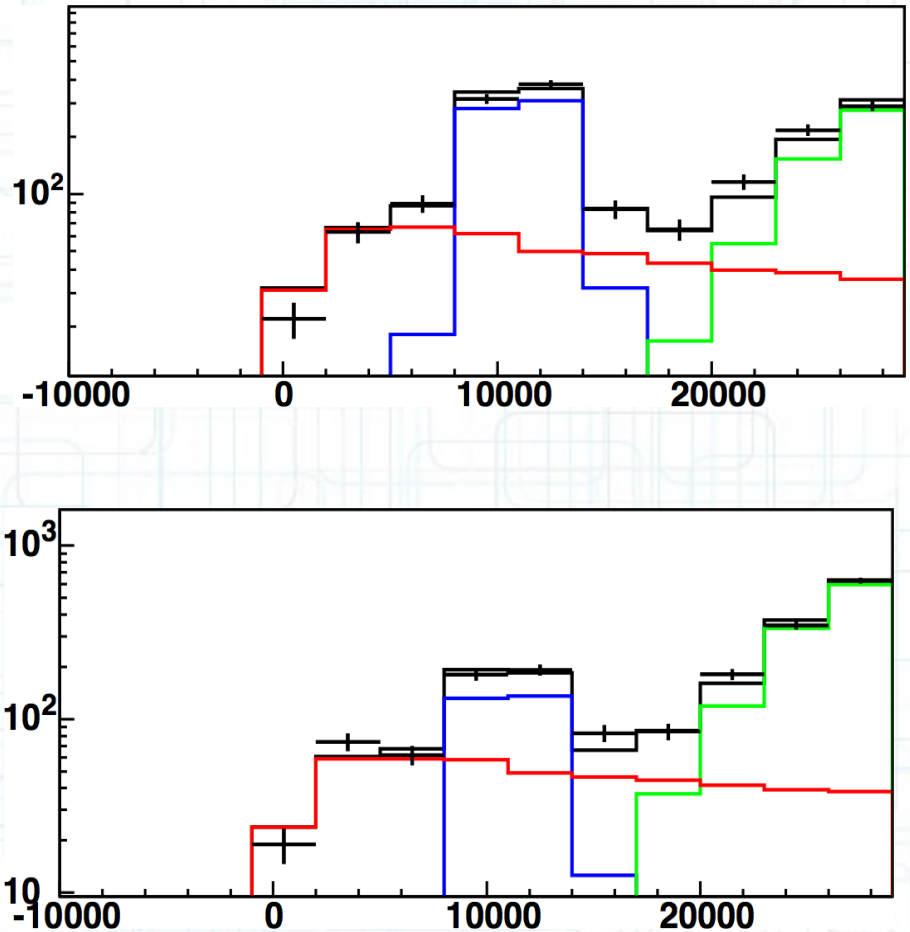


electron peaks at 250 MeV,
e-γ antiparallel

electron peaks at 100 MeV: **very bad**,
since Ke3 endpoint is 230 MeV

$Ke2\gamma$ fit results

Projections on $M\ell 2$ axis for 2 most populated $E\gamma^*$ bins



data
fit
$Ke2\gamma$
$K\mu 2$
$Ke3$

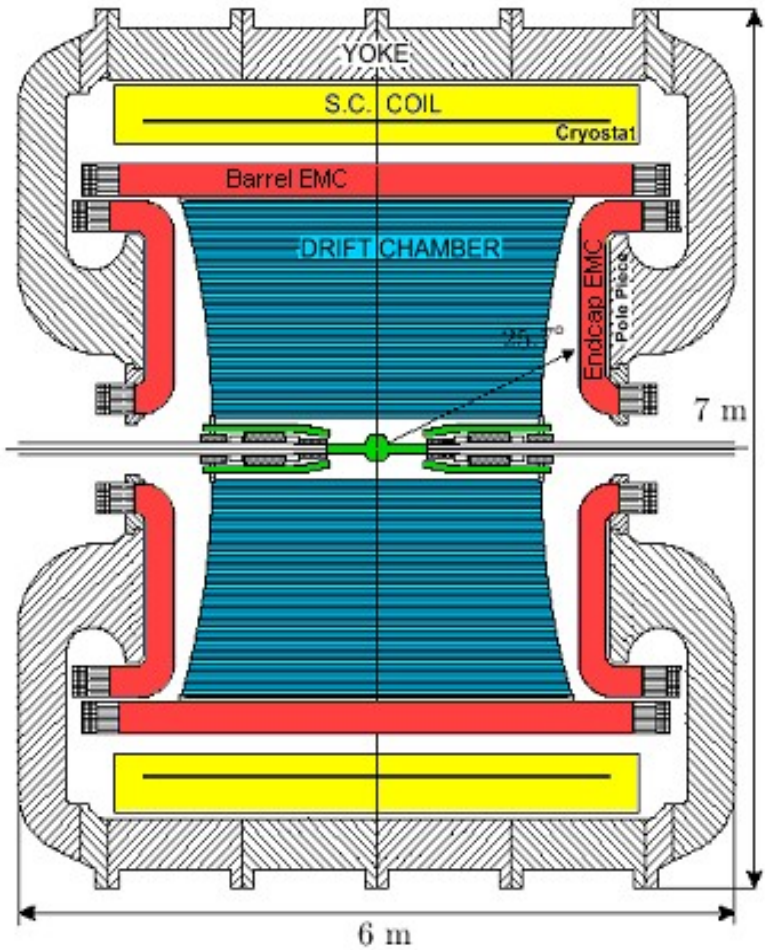
$150 < E\gamma < 250$ MeV

$N_{Ke2\gamma} = 4631 \pm 38$

$\chi^2/ndf = 170/166$

$M\ell 2$ [MeV^2]

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% iC_4H_{10}, composite frame, 12582 stereo sense wires

Electromagnetic calorimeter

Lead/scintillating fibers

4880 PMTs

Superconducting coil (5 m bore)

B = 0.52 T ($B\,dl$ = 2 T·m)