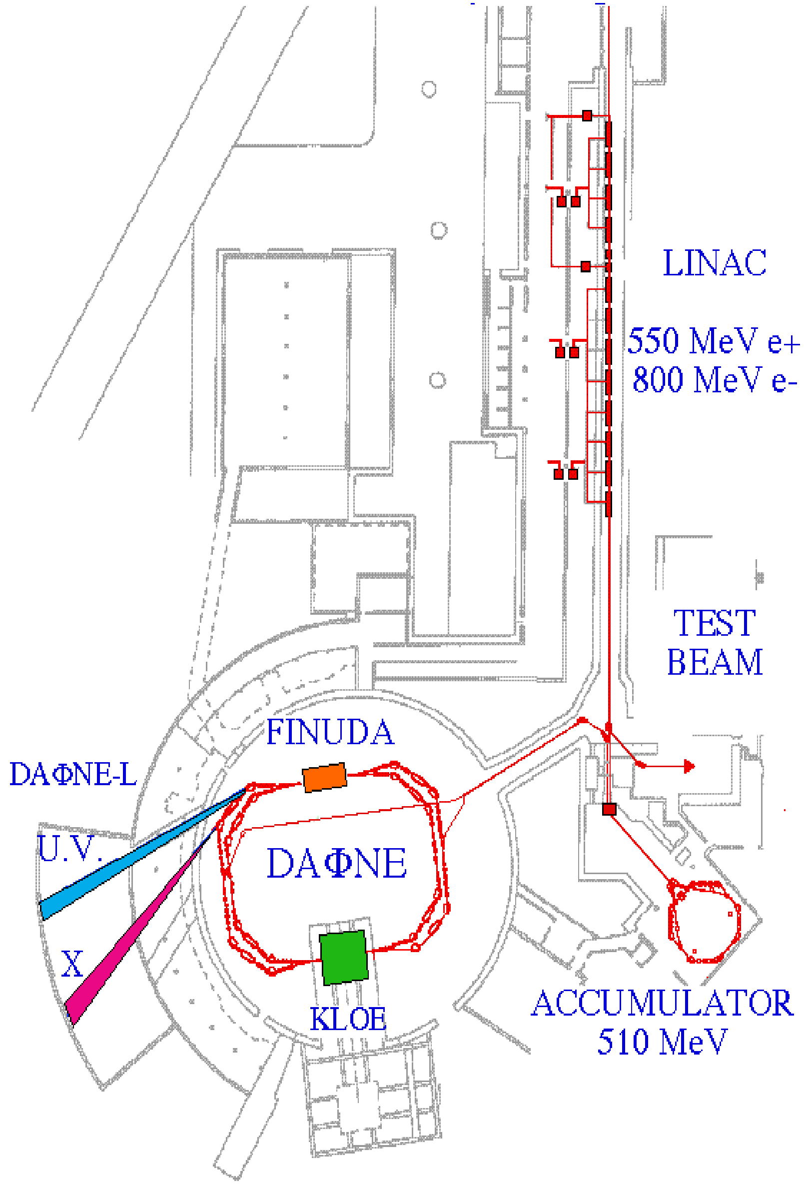
K_S lifetime and Ke2g from KLOE

Mario Antonelli
LNF, INFN

beach 2010

June 2010 Perugia

DAΦNE e^+e^- collider at LNF



- **$\sqrt{s}$ ~ 1019.46 MeV = m_ϕ**
  - σ_ϕ ~ 3.1 μb at peak
  - crossing angle ~ 12.5 mrad
- **today, L_{peak} = 4.5×10^{32} $cm^{-2}s^{-1}$**

Kaon physics at KLOE

The ϕ decay at rest provides ***monochromatic***

and ***pure*** beam of kaons

$K^+ \; K_S \longleftarrow \phi \longrightarrow K_L \; K^-$

$$\frac{1}{\sqrt{2}}\left(|K_L, p\rangle|K_S, -p\rangle - |K_L, -p\rangle|K_S, p\rangle\right)$$

ϕ decay mode	BR
K^+K^-	49.1%
K_SK_L	34.1%

$\Rightarrow$ K_S beam unique!!

$\Rightarrow$ kaon momentum is measured with 1 MeV resolution

K^+K^-: p^* = 127 MeV/c; $\lambda_\pm$ = 95 cm

$K_S K_L$: p^* = 110 MeV/c; λ_S = 6 mm; λ_L = 3.4 m

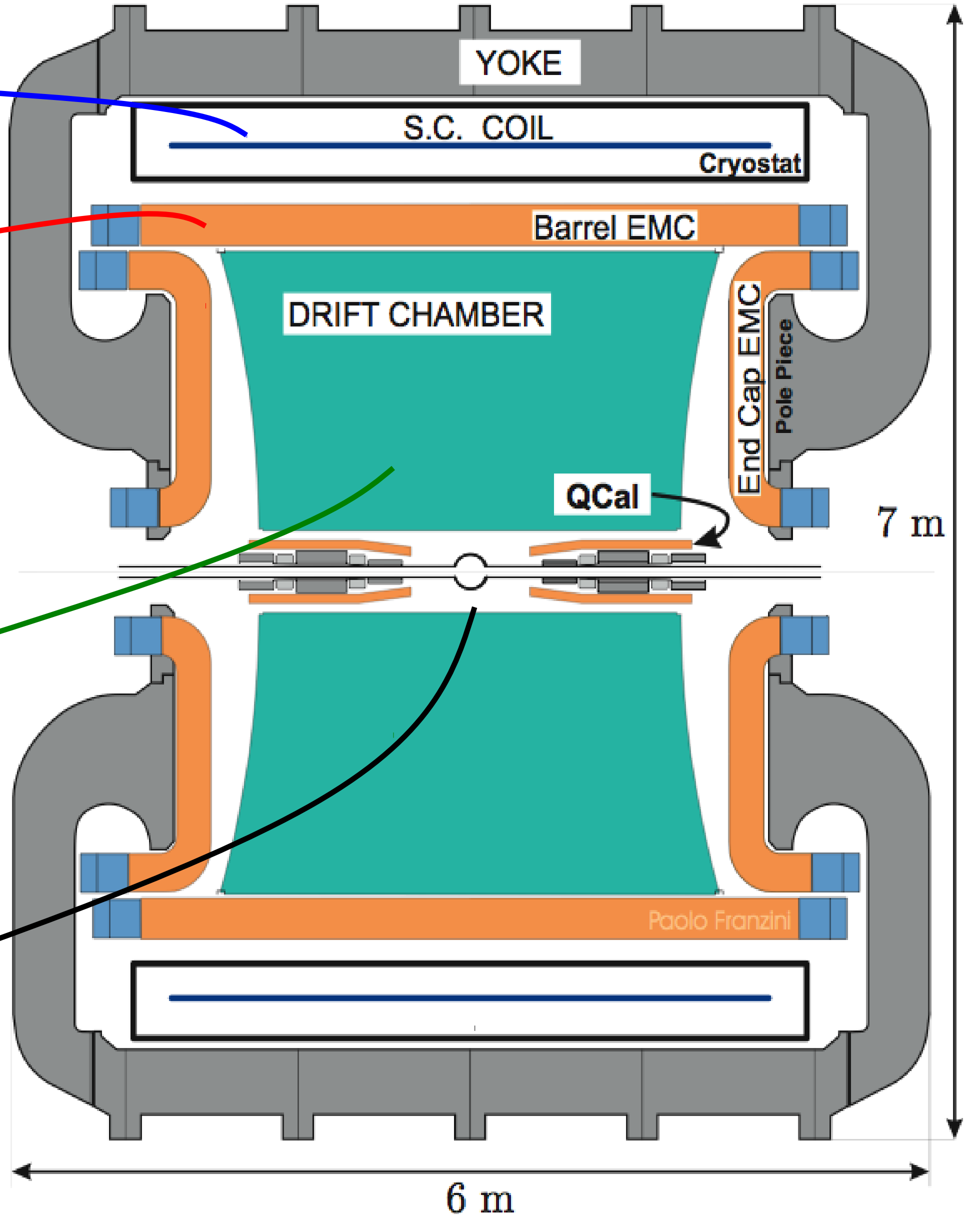
The KLOE Experiment

Magnet
SC coil, B = 0.6 T

EM Calorimeter
Pb-scint fiber
4880 PMs, 2440 cells

Drift chamber
12582 sense wires
52140 tot wires
Carbon fiber walls

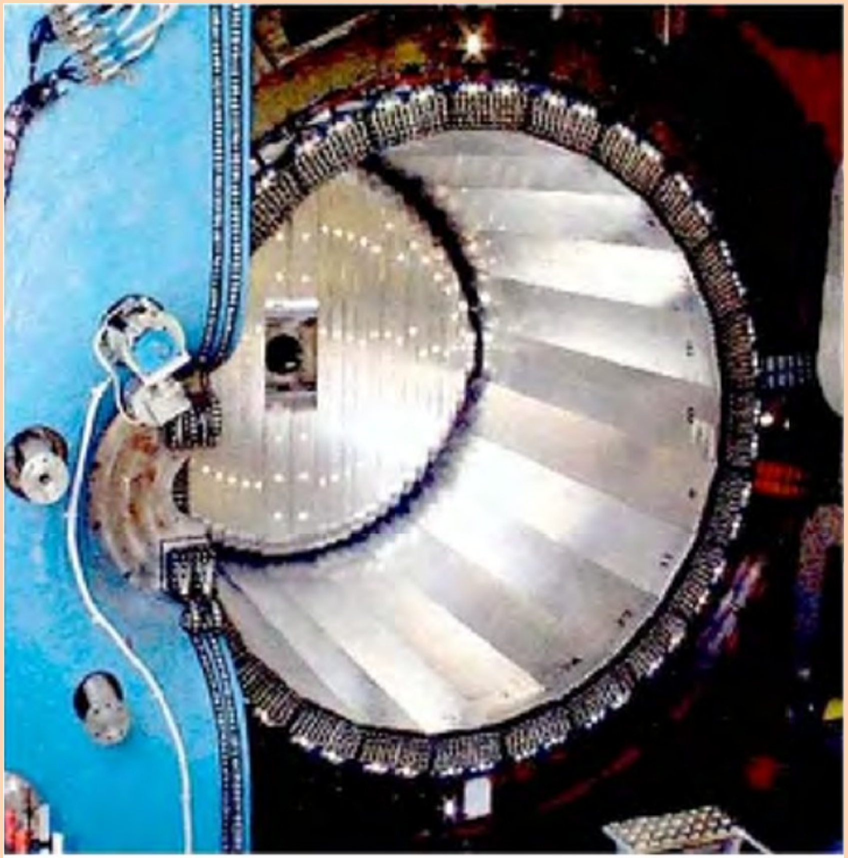
Al-Be beam pipe
r = 10 cm, 0.5 cm thick



Detector performances

$$\sigma_E/E = 5.7/\sqrt{E(GeV)}$$

$$\sigma_t = 54/\sqrt{E(GeV)} \oplus 140ps$$



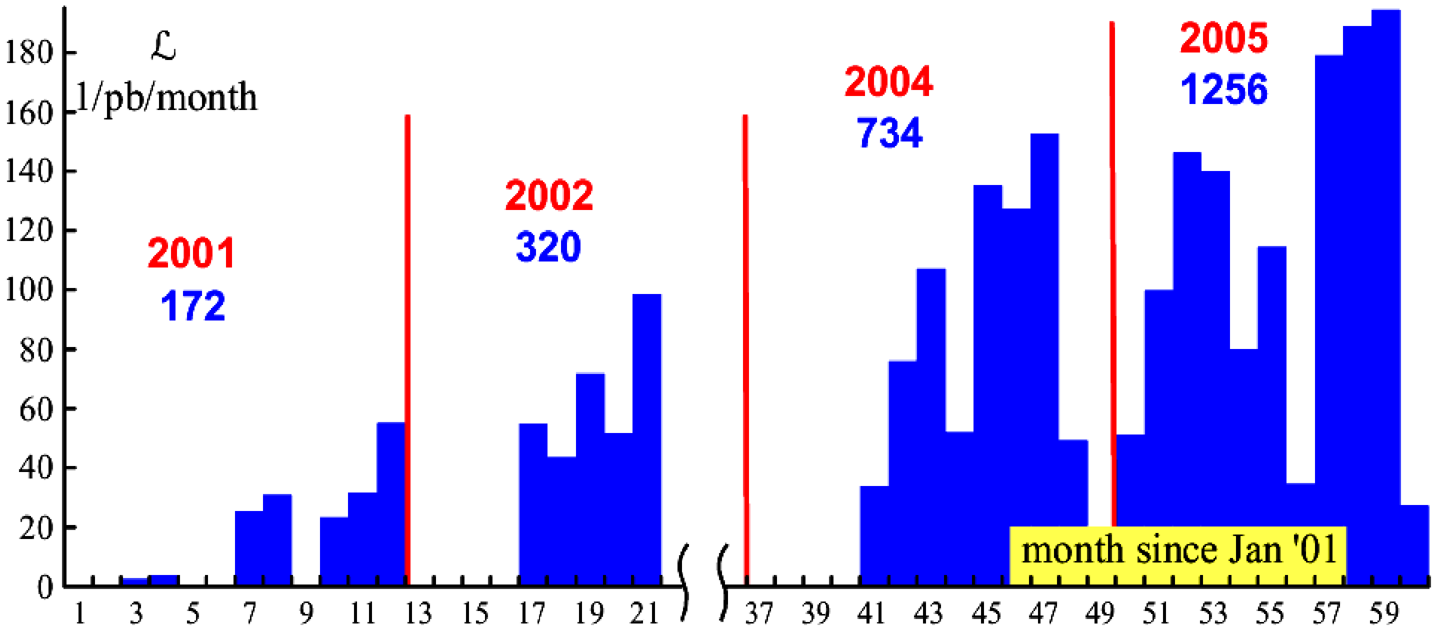
EM Calorimeter

Drift Chamber

$$\sigma(p_\perp)/p_\perp = 4‰, \sigma(m_{K_S}) \leq 1 MeV$$

$$\sigma_{x,y} = 150\ mm\ ; \sigma_z = 2\ mm$$

Summary of KLOE data taking



$\int L = 2.2\ fb^{-1}$

at ϕ peak

yielding 3×10^9 K^+K^- and 2×10^9 $K_S K_L$ pairs

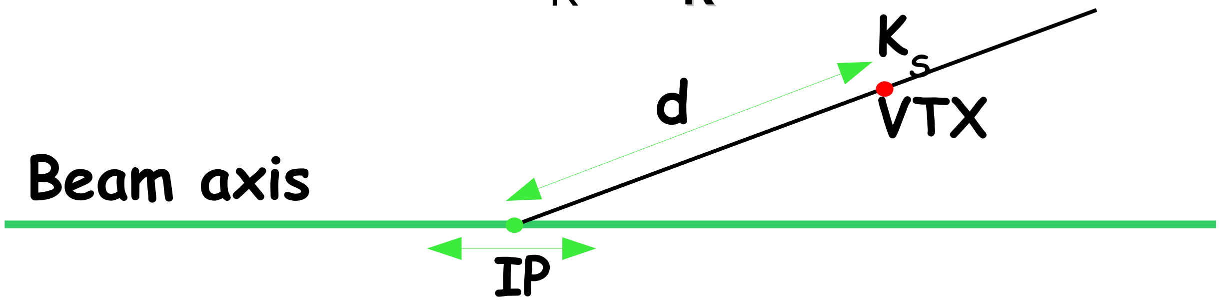
K_S lifetime

Introduction

Fit to proper time distribution of

$K_S \rightarrow \pi^+\pi^-$

$$t^* = d/\beta\gamma c = \mathbf{d}M_K/c\mathbf{p}_K$$



Needs for $O(10^{-4})$* measurement:

$O(10^7)$ $K_S \rightarrow \pi^+\pi^-$, not a problem with the KLOE data set, 0.4 fb^{-1} (2004)

Calibration of K_S momentum at 10^{-4}: determination from $\sqrt{s}$ and kinematic

Decay length ~ resolution: improve resolution as much as possible

Calibration of decay point: use redundant K_S momentum determination

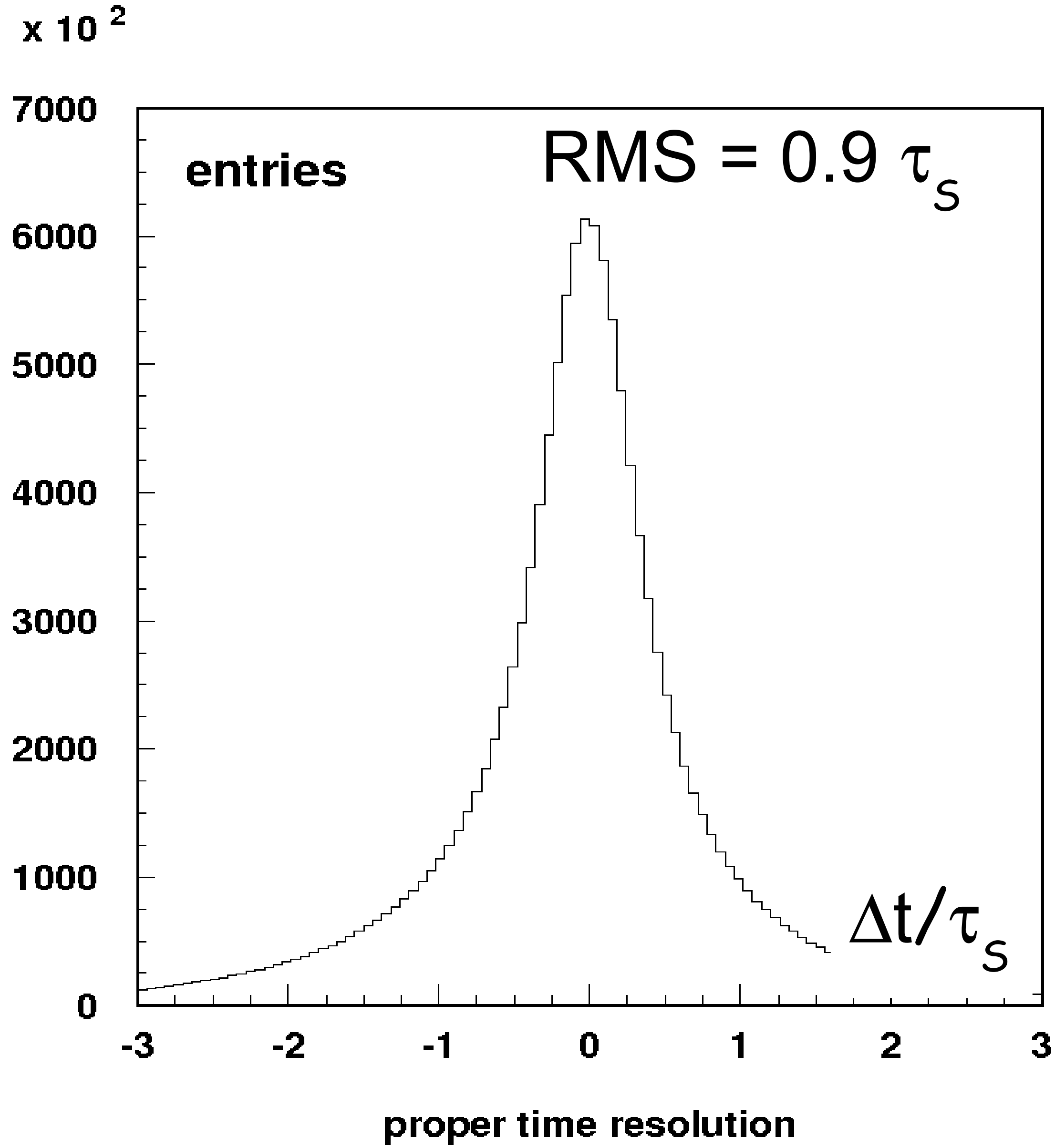
Resolution from negative tail of proper time distribution

* ~ accuracy of WA (NA48 + KTeV)

SELECTION

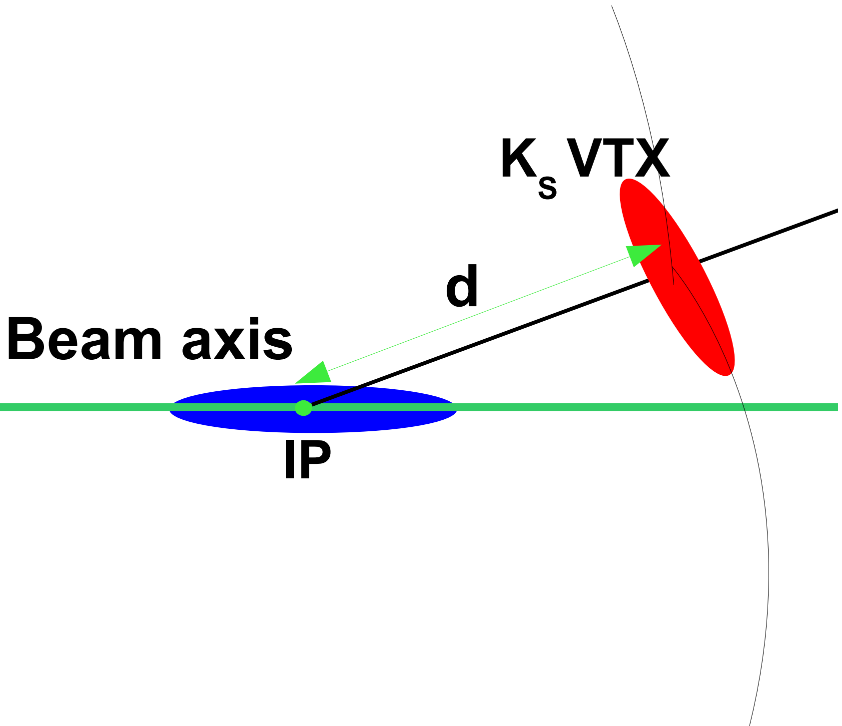
- 2 tracks from ~ IP
- standard cut on invariant mass (10 MeV)

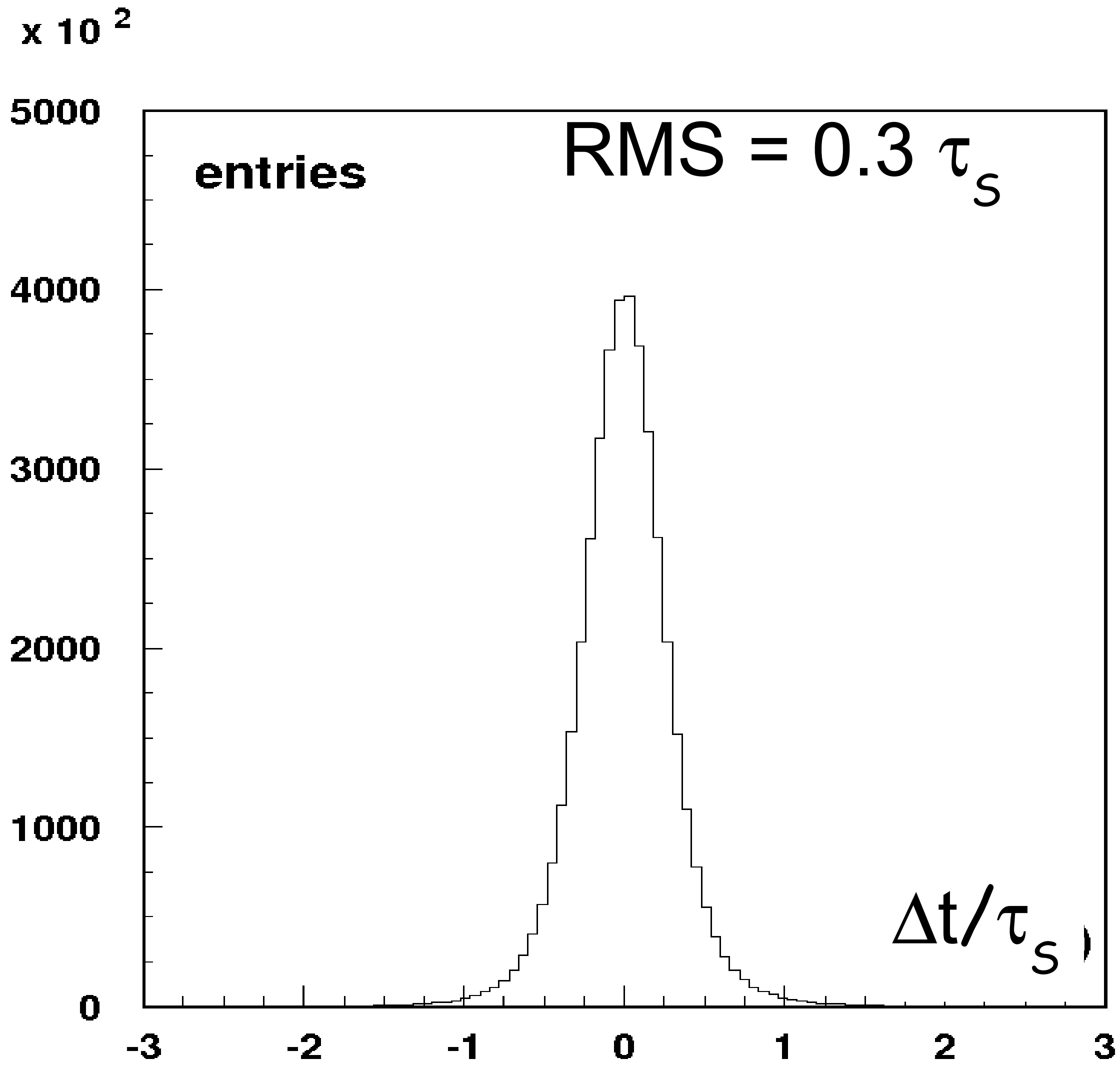
Very bad resolution!



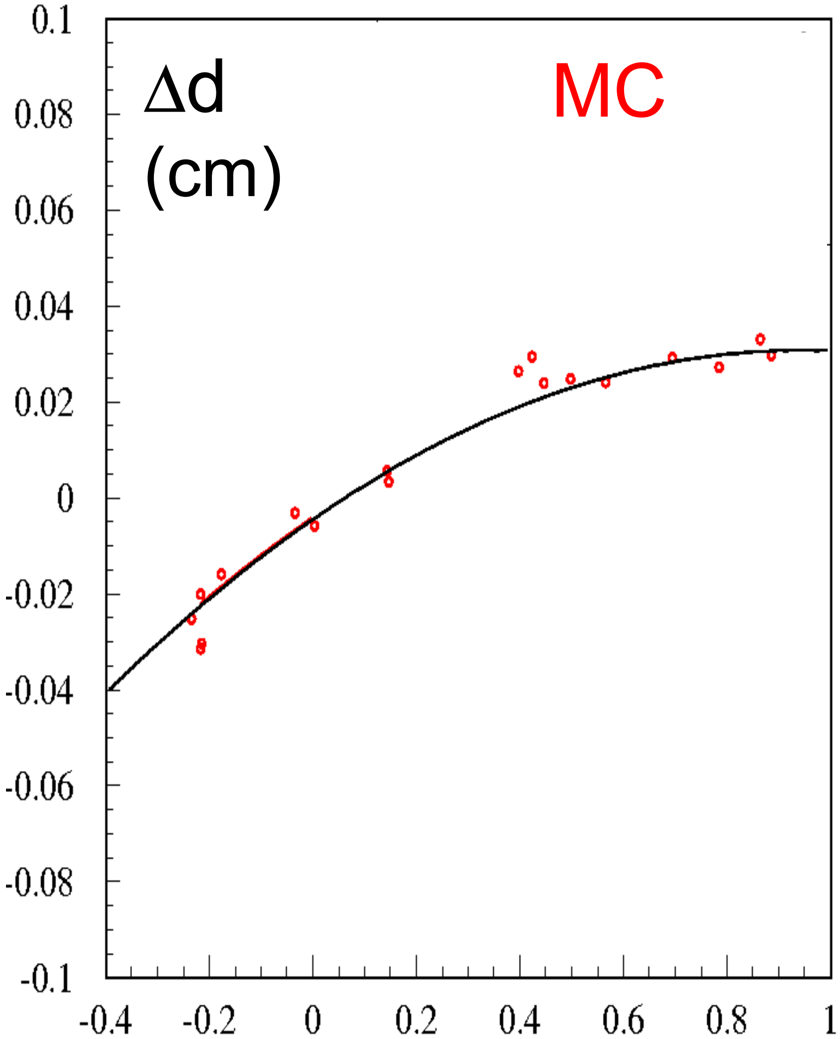
SELECTION

- use events with:
  well measured tracks
  passing topological cuts
- additional improvement
  with geometrical fit

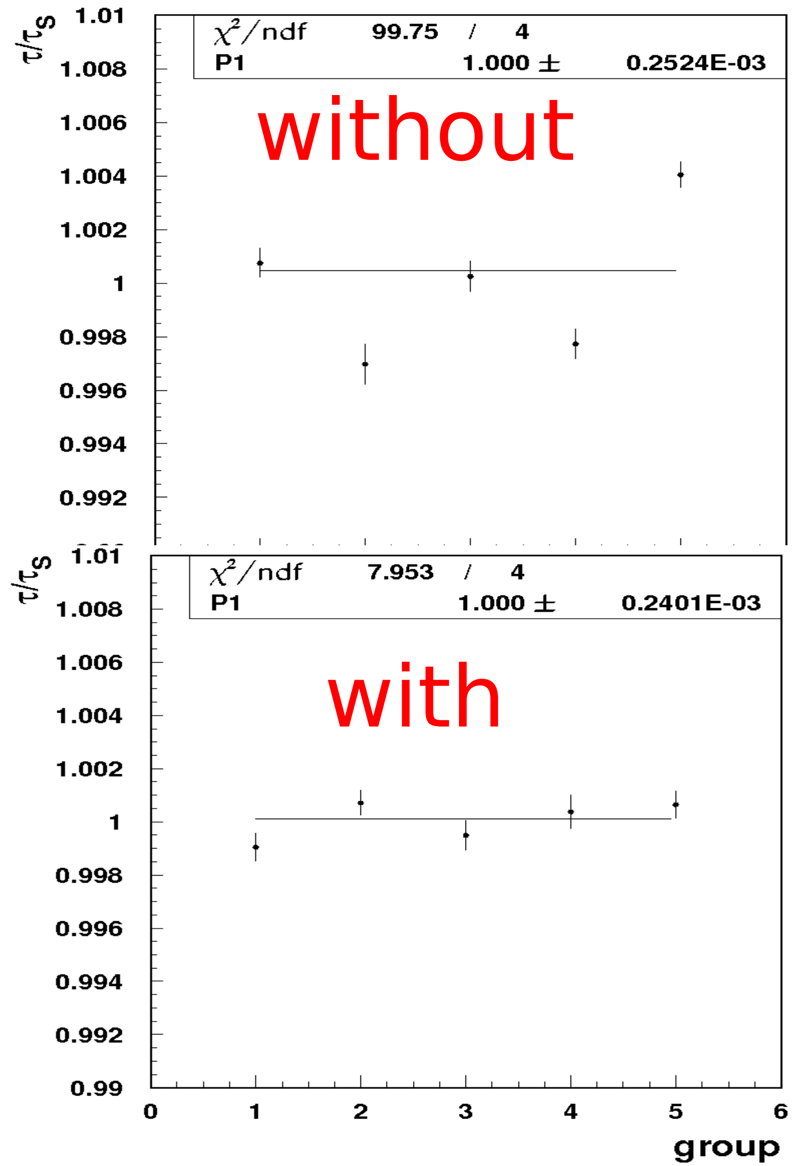




decay length & momentum calibration



$p_{\pi\pi}$ $-p_{K\ MCtrue}$ (MeV)



Decay point correction using 2nd determination of kaon momenta

FIT METHOD

Detector divided in : 18x10 $[\phi_K, \cos\theta_K]$ $(-0.5<\cos\theta_K< 0.5)$

Account for resolution dependence

Check result stability

Fit range : 15 bins from -1 to +6.5 (τ_S)

Fit parameters:

$$\tau, \sigma_1(\phi,\theta), \sigma_2(\phi,\theta), \alpha(\phi,\theta), \delta(\phi,\theta)$$

Resolution: $R = \alpha g_1 + (1-\alpha) g_2$

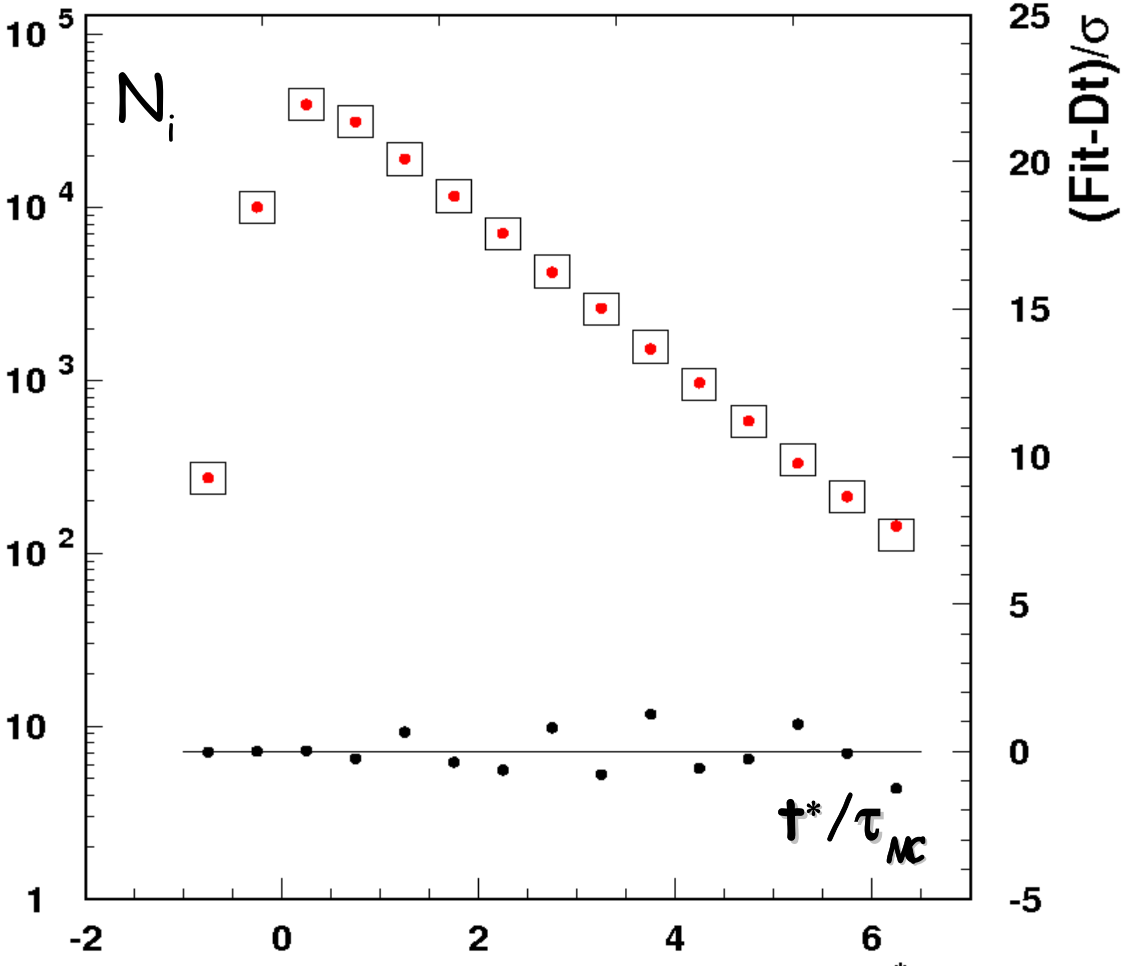
- Fit function derived from :

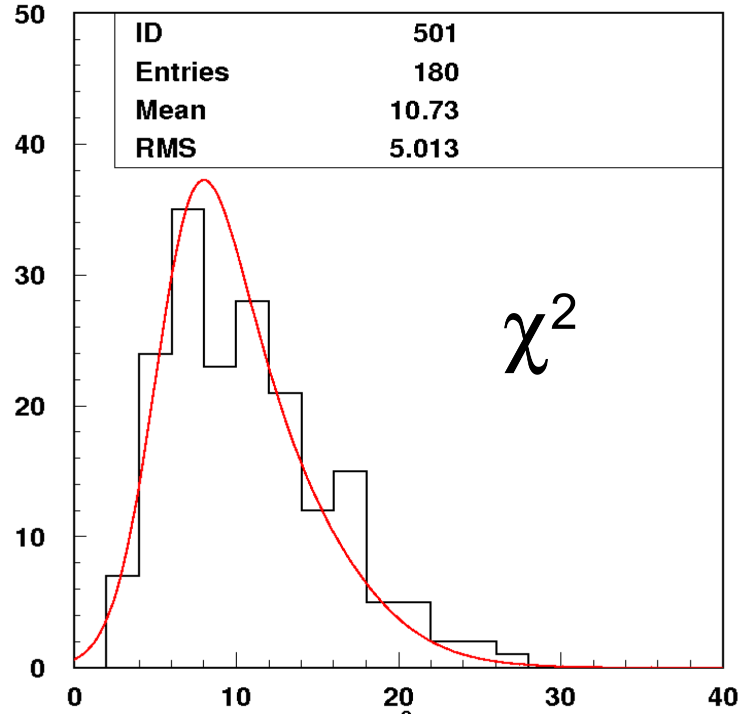
$$f(t) = A \int_{-\infty}^{\infty} \theta(x) \frac{1}{\tau} \exp(x/\tau)\, \varepsilon(x)\, g(t+\delta-x)\, dx$$

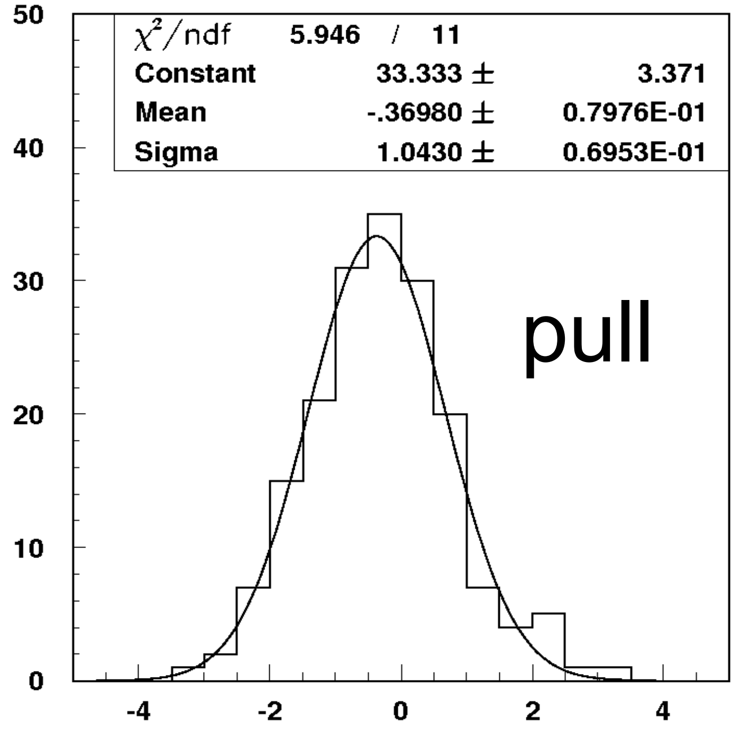
- We perform 180 fits → weighted average

FIT results

Fit example







Systematics

- Fit stability: study results with different fit ranges (+-2 τ_s)

  fractional uncertainty 13×10^{-5}

- Decay length calibration

  uncertainty on residual calibration

  study result stability by changing selection cuts affecting d resolution and calibration (+/- 60% in ε)

  fractional uncertainty 27×10^{-5}

  comparable results form knowledge of momentum calibration + dp vs Δd correlation from MC ($\sim 3 \times 10^{-4}$)

Systematics

- kaon momentum calibration and kaon mass

  use momentum from boost with the appropriate kaon mass(KLOE determination) reduce detector zone momentum calibration effects (impact on result stability) pk~ $\sqrt{ebeam^2-mk^2}$

  Residual effects:

  absolute P scale + knowledge of ISR effects

  Fractional uncertainty 37×10^{-5}

  knowlege of kaon mass

  Fractional uncertainty 4×10^{-5}

- Knowledge of efficiency variation:

  very uniform efficiency over 10's of τs:

  check result with exactly uniform efficiency

  Fractional uncertainty 5×10^{-5}

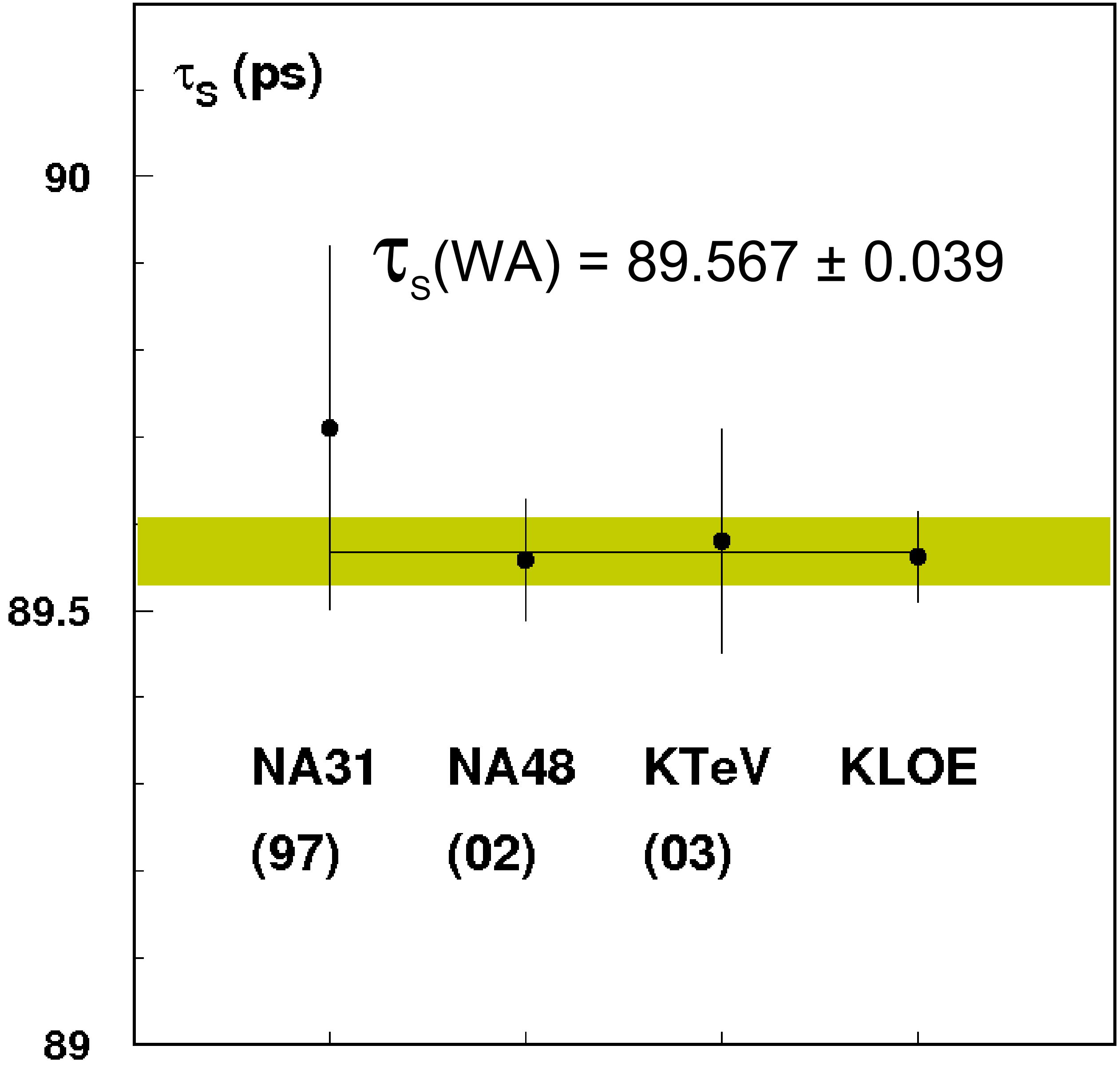
- additional checks, result stability verified over data taking period, detector region, decay topology ...

Result

Source	value (ps)
- fit range :	0.012
- d calibration:	0.024
- pk calibration:	0.033
- Kaon mass :	0.004
- efficiency :	0.005
---------------	--------------
Total	0.043

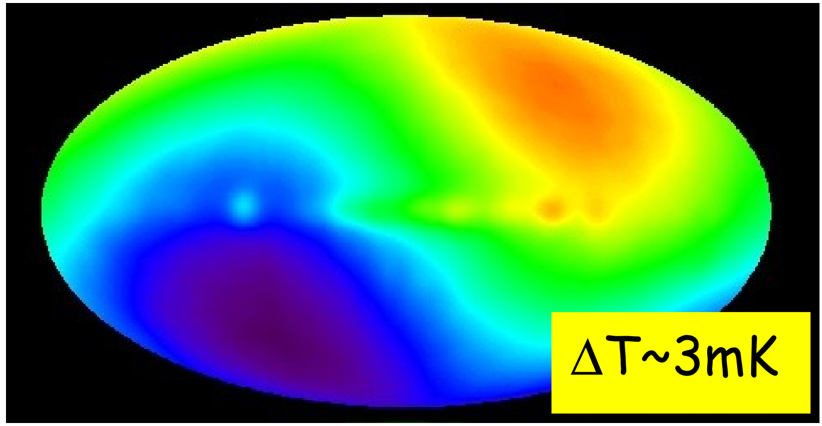
$$\tau_S = (89.562 \pm 0.029_{stat} \pm 0.043_{syst}) \text{ ps}$$

Results on the market and WA



isotropy of K_S lifetime measurement!?

- The CMB dipole anisotropy, if interpreted as a Doppler effect, is due to Local Group motion (~570 km/s) in the direction (l,b) = (263.86º, 48.24º)



- A test of the isotropy of K_S lifetime measurement is done by comparing the result parallel and antiparallel w.r.t. an assigned direction

$$A = \frac{\tau_S^{up} - \tau_S^{down}}{\tau_S^{up} + \tau_S^{down}}$$

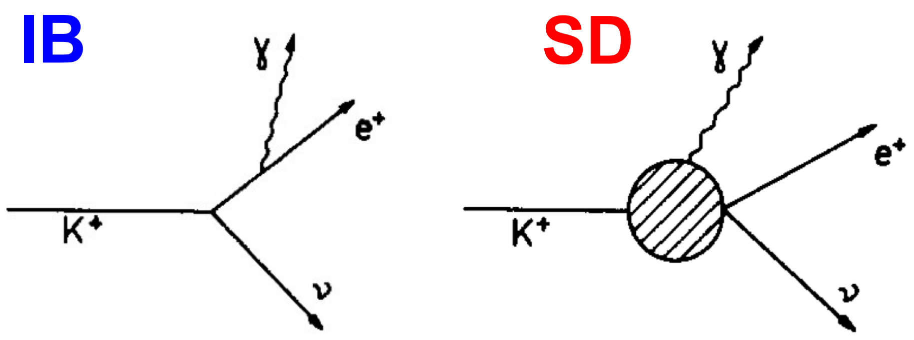
- retain decay events with $p_{K,GC}$ within a 30º cone around:

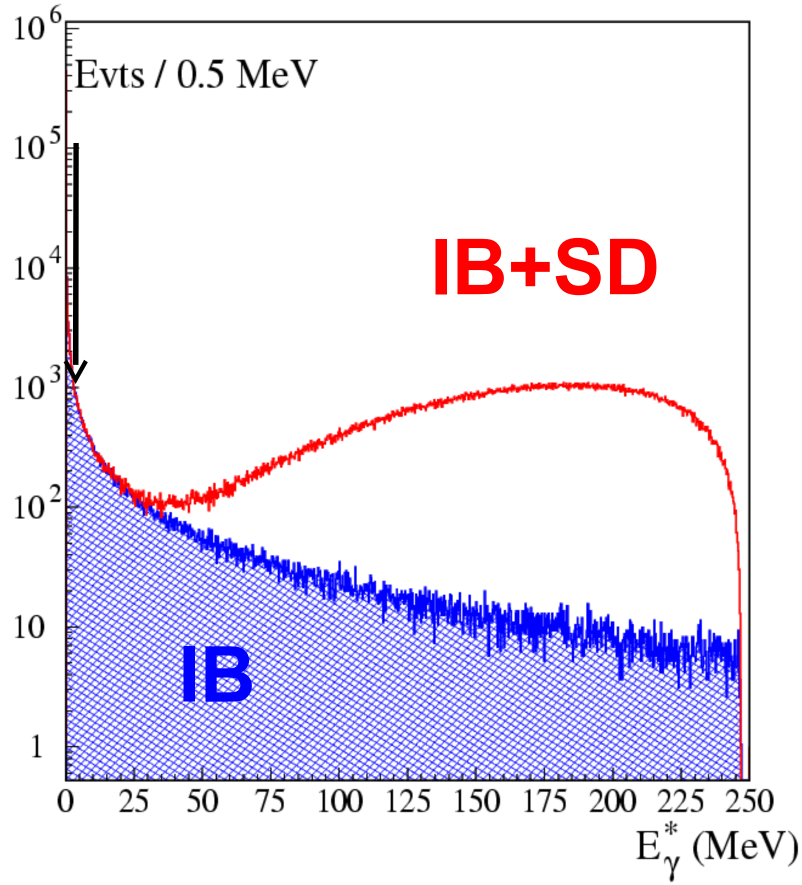
(263.86º, 48.24º)	(**CMB**)	A = -0.0002± 0.0010 ± 0.0003
(173.86º, 0º)		A = 0.0002± 0.0009 ± 0.0004
(263.86º, −41.76º)		A = 0.0000± 0.0008 ± 0.0003

Ke2γ

Ke2(γ): introduction

SM prediction made in terms of **IB** process only: unobservable!





From theory (ChPT) expect **SD** ≈ **IB** for Ke2, but experimental knowledge is poor

δSD/SD≈15%

1) **Consider as "signal" events with E_γ<10 MeV (SD negligible)**
2) **Correct for IB tail, 0.0625(5)**

Analysis basic principles

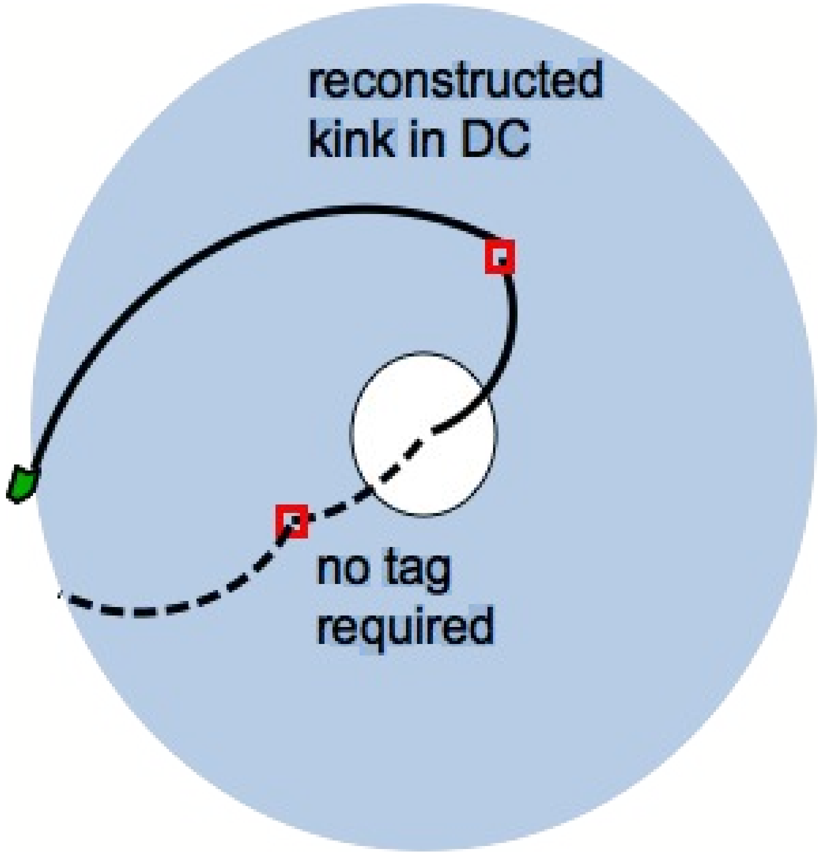
1) Select kinks in DC (≈ fiducial volume)

- 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

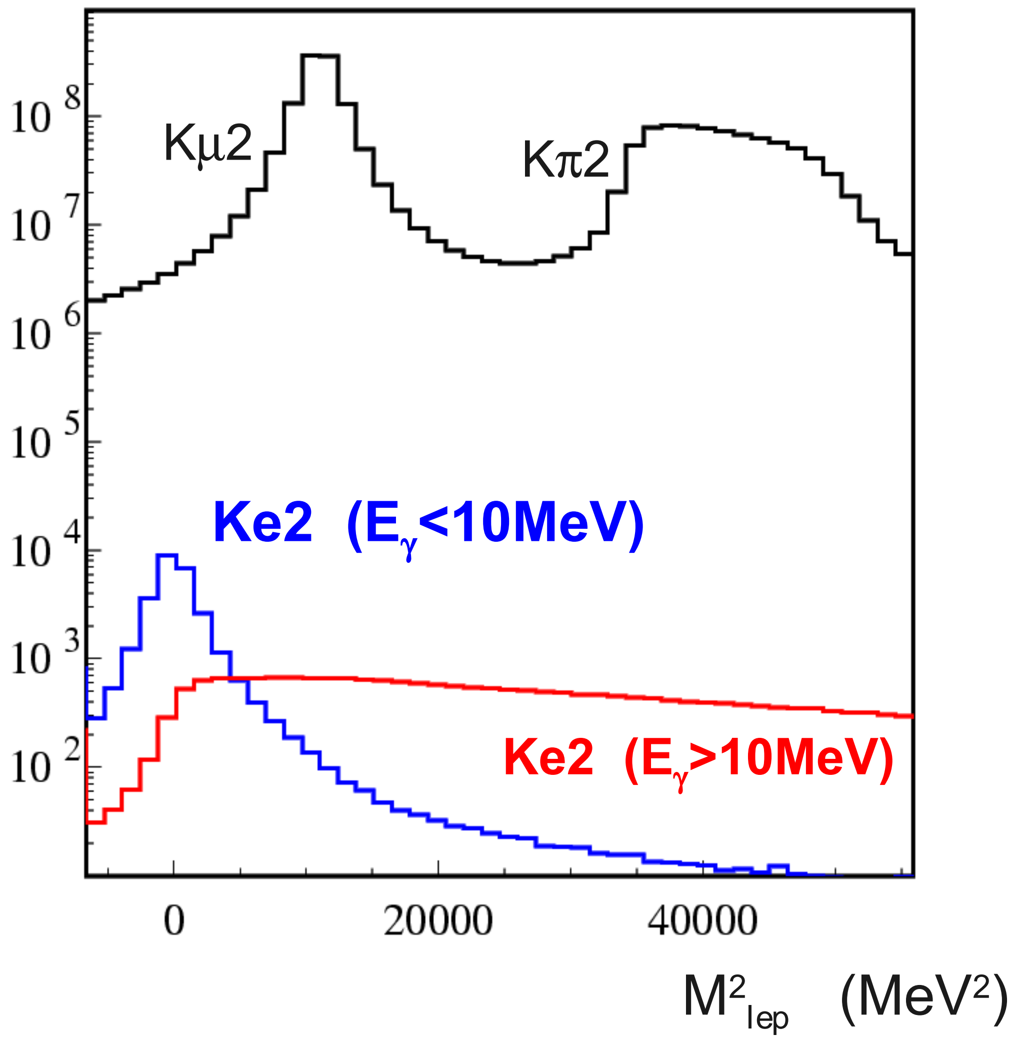


Analysis basic principles

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}



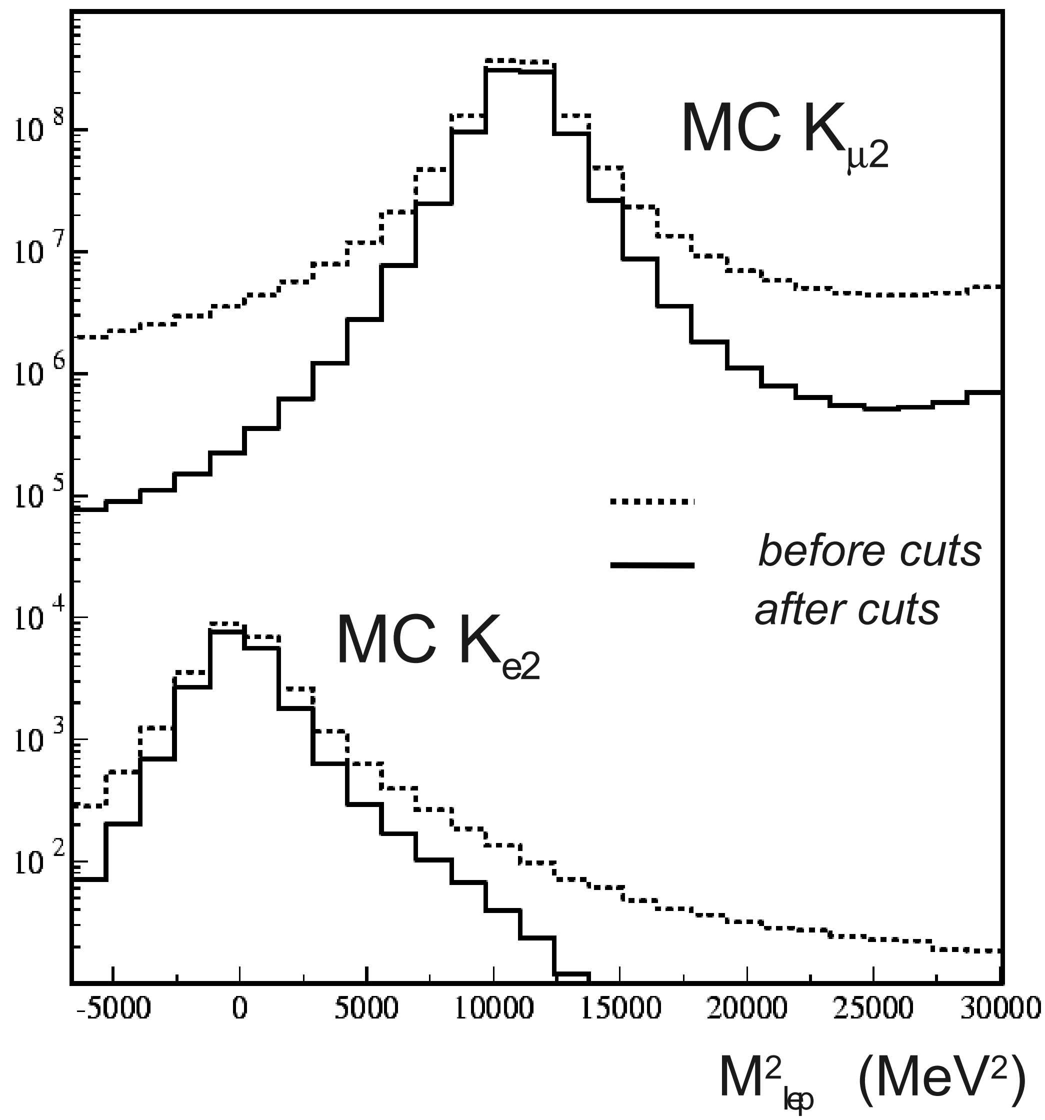
Background rejection (track quality)

we accept ≈35% of decays in the FV

most of Ke2 events lost have bad resolution

S/B = 1/20

not enough!

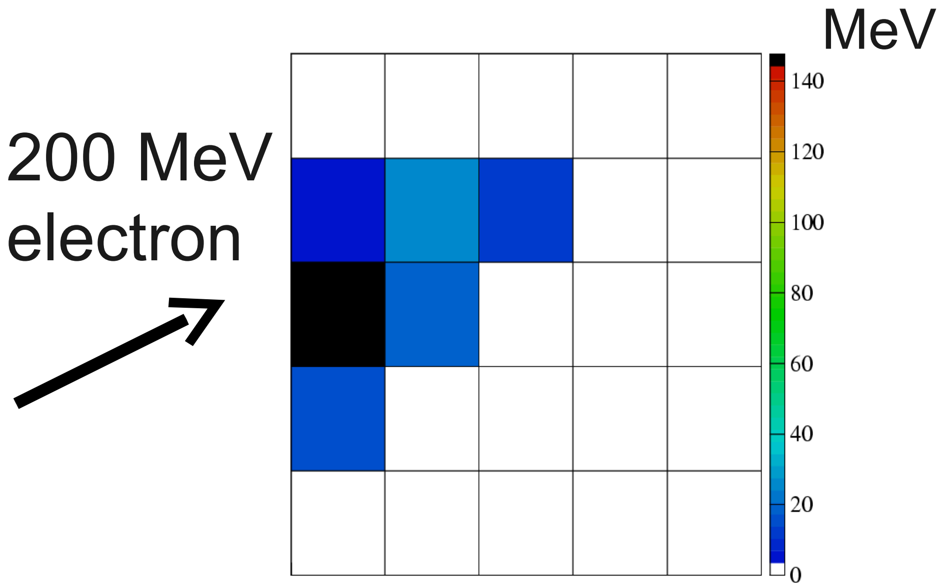


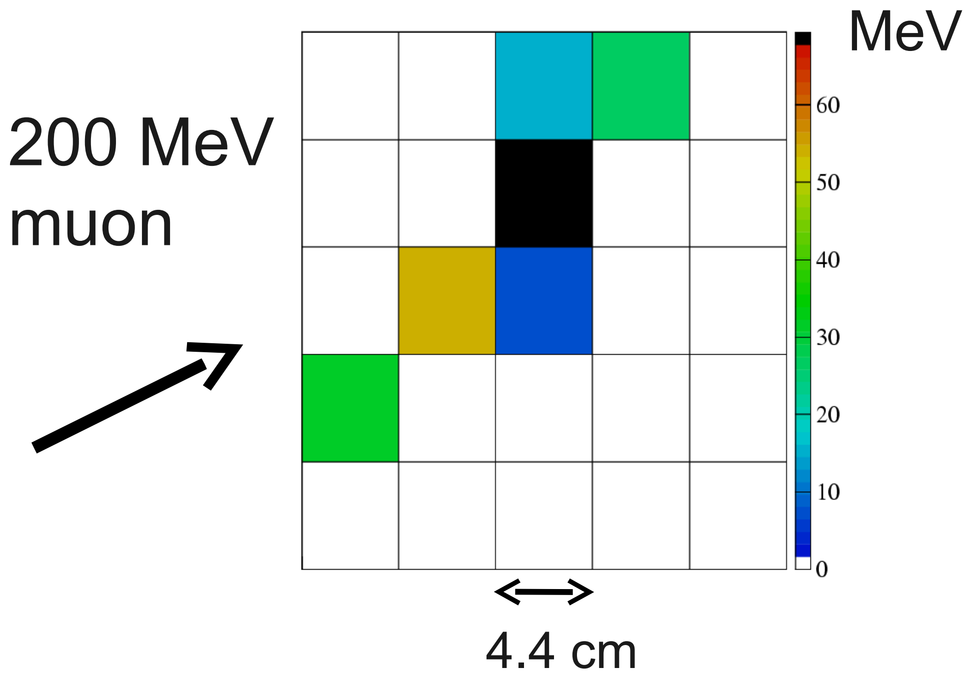
Background rejection (PID)

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

- cluster depth
- RMS of plane energies
- asymmetry of first (last) two energy releases
- skewness of cell-depth distribution
- E1, Emax, Nmax
- $\Delta E/\Delta x$

2) Add E/P and TOF

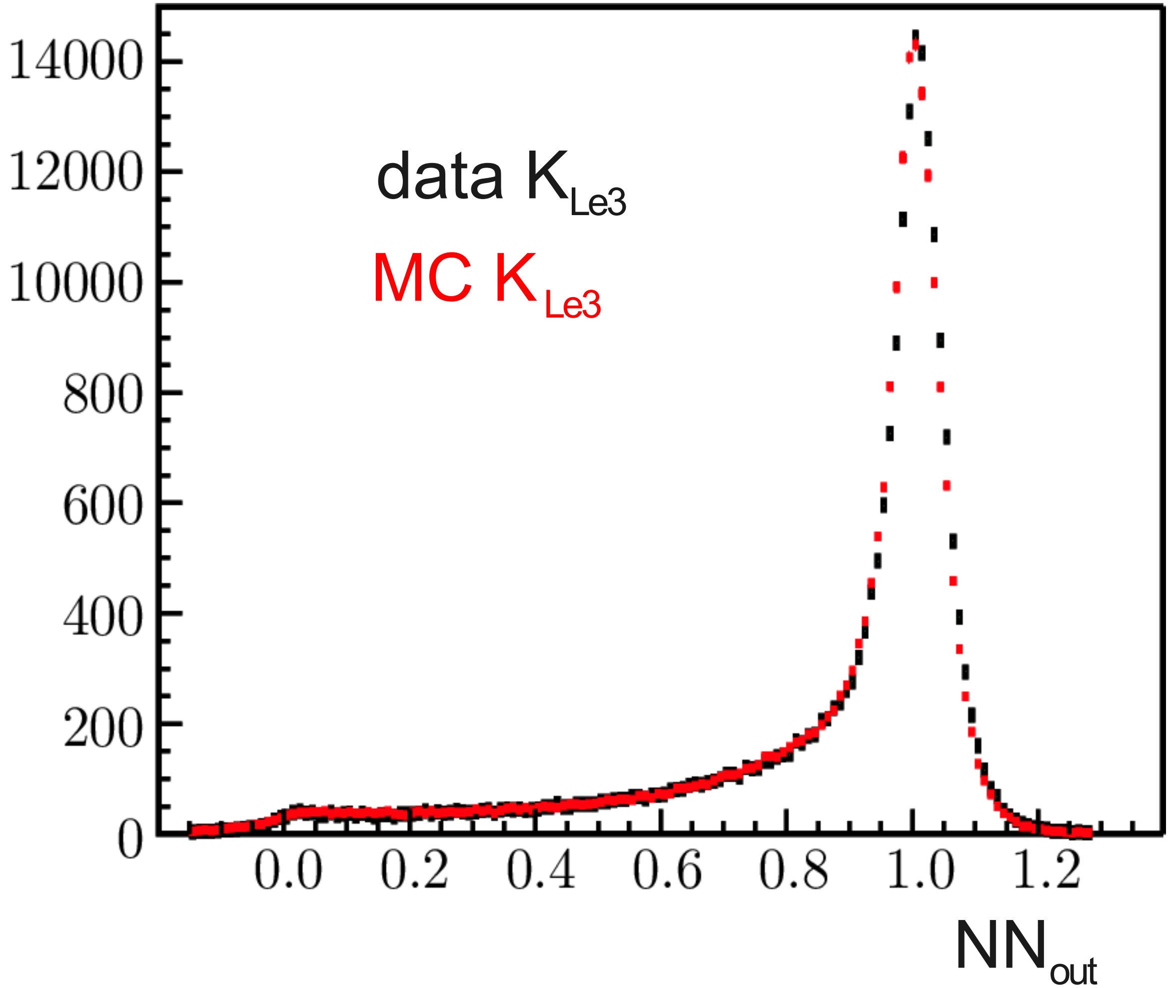




Background rejection (PID)

Combine PID variables using a NN

Use a pure sample of K_{Le3} to correct cell response in MC and for NN training



Ke2 fit: radiative corrections

The analysis above is inclusive of photons in the final state

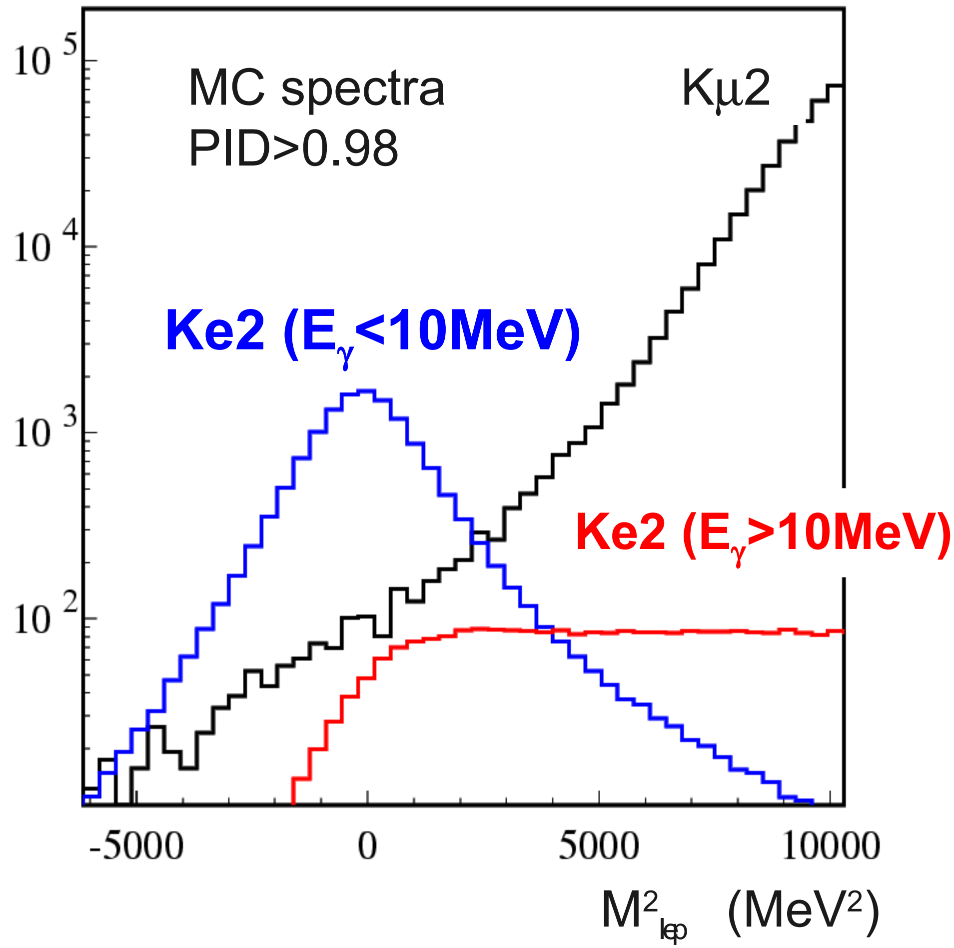
- in our fit region we expect

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

- repeat fit by varying

  Ke2 (E_γ>10MeV)

  by 15% (SD uncertainty):
  get **0.5%** error…**too large**



- Need a dedicated study of the **Ke2 (E_γ>10MeV)** component

Ke2γ process

Dalitz density

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

helicity suppressed *negligible*

$x=2E_g/M_K \quad y=2E_e/M_K$

E_γ, E_e in the K rest frame

Structure Dependent

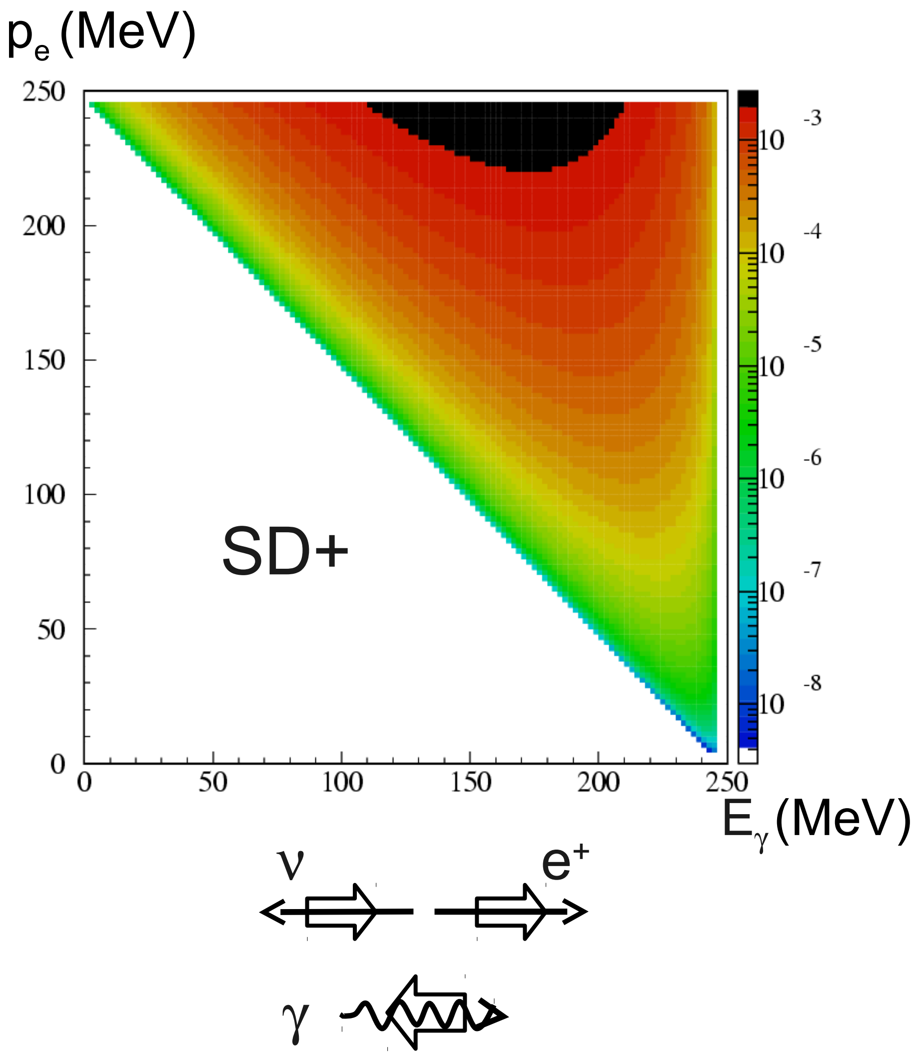
$$\rho_{SD}(x,y)=\frac{G_F^2|V_{us}|^2\alpha}{64p^2}M_K^5\left((f_V+f_A)^2 f_{SD+}(x,y)+(f_V-f_A)^2 f_{SD-}(x,y)\right)$$

f_V, f_A : effective vector and axial couplings

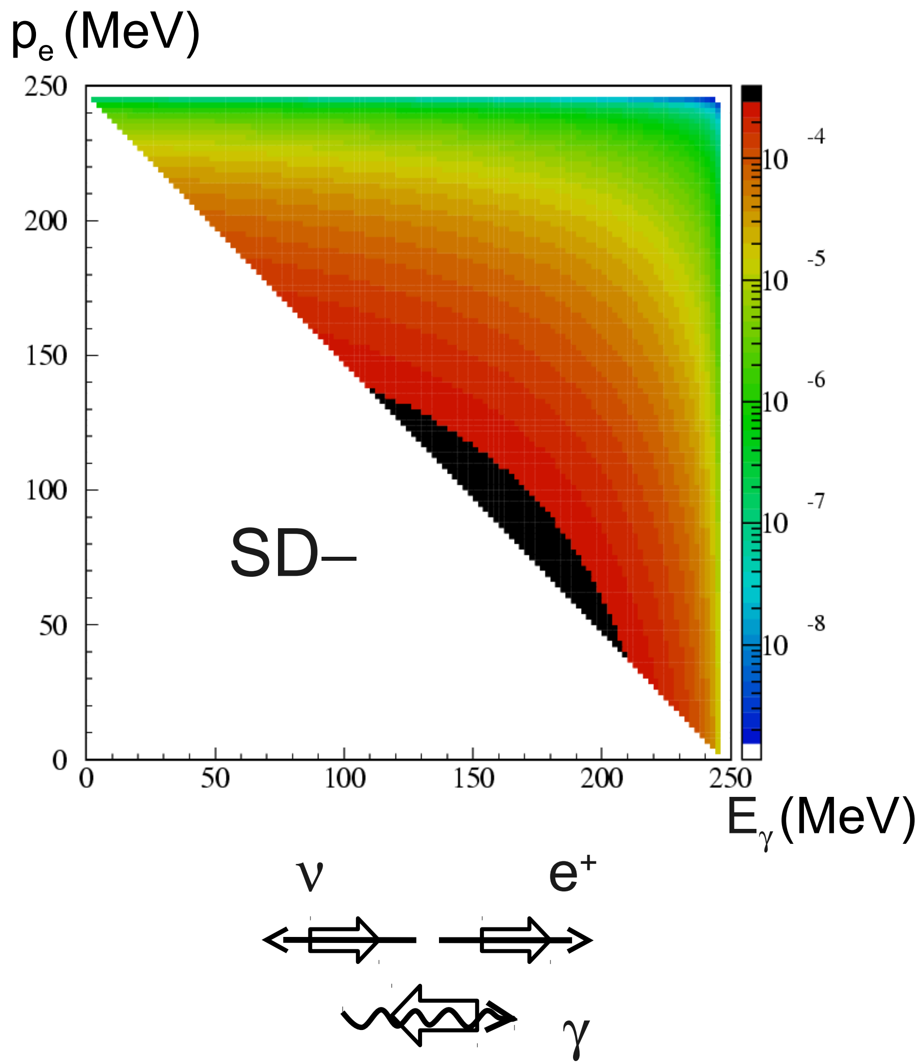
SD+ = V+A : γ polarization +

SD− = V−A : γ polarization −

Dalitz plots for SD+ and SD–



electron peaks at 250 MeV,
e-γ antiparallel



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

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 ($\lambda \approx 0.4$)

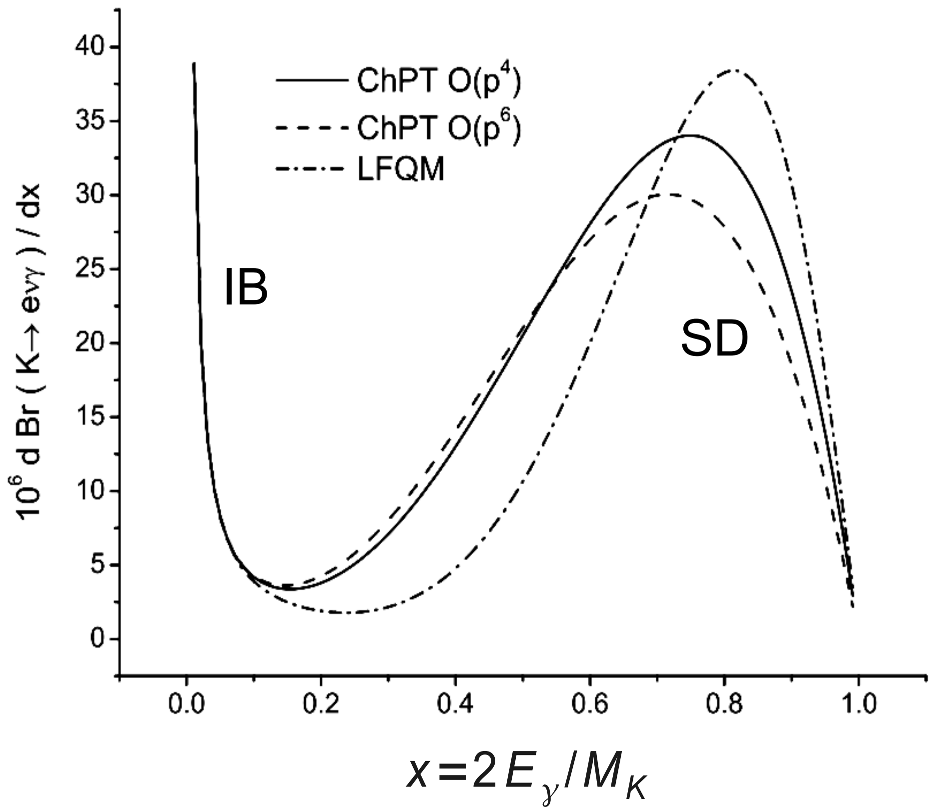
Ametller, Bijnens, Bramon, Cornet 93
Geng, Ho, Wu 04
Chen, Geng, Lih 08

3) LFQM:

non trivial x dependence

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

Chen, Geng, Lih 08



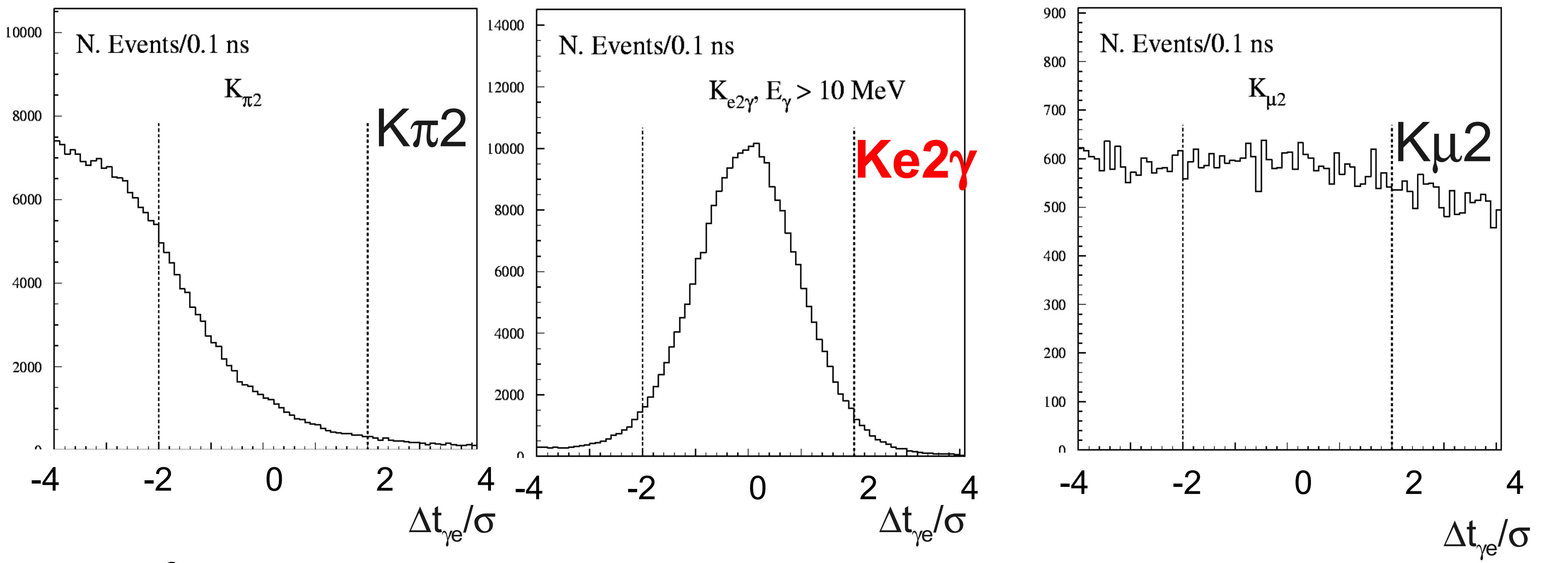
from Phys. Rev. D77 (2008) 014004

Ke2γ selection: photon detection

- A photon is required with energy E_γ^{calo} > 20 MeV to reject bkg
(we loose $Ke2_{IB}$, too)
- Time of arrival compatible with that of the event (electron):

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

(r = distance from K decay vtx)



γ from π^0
$\beta(\pi^+) \approx 0.8$ instead of 1

Fake γ from accidental bkg

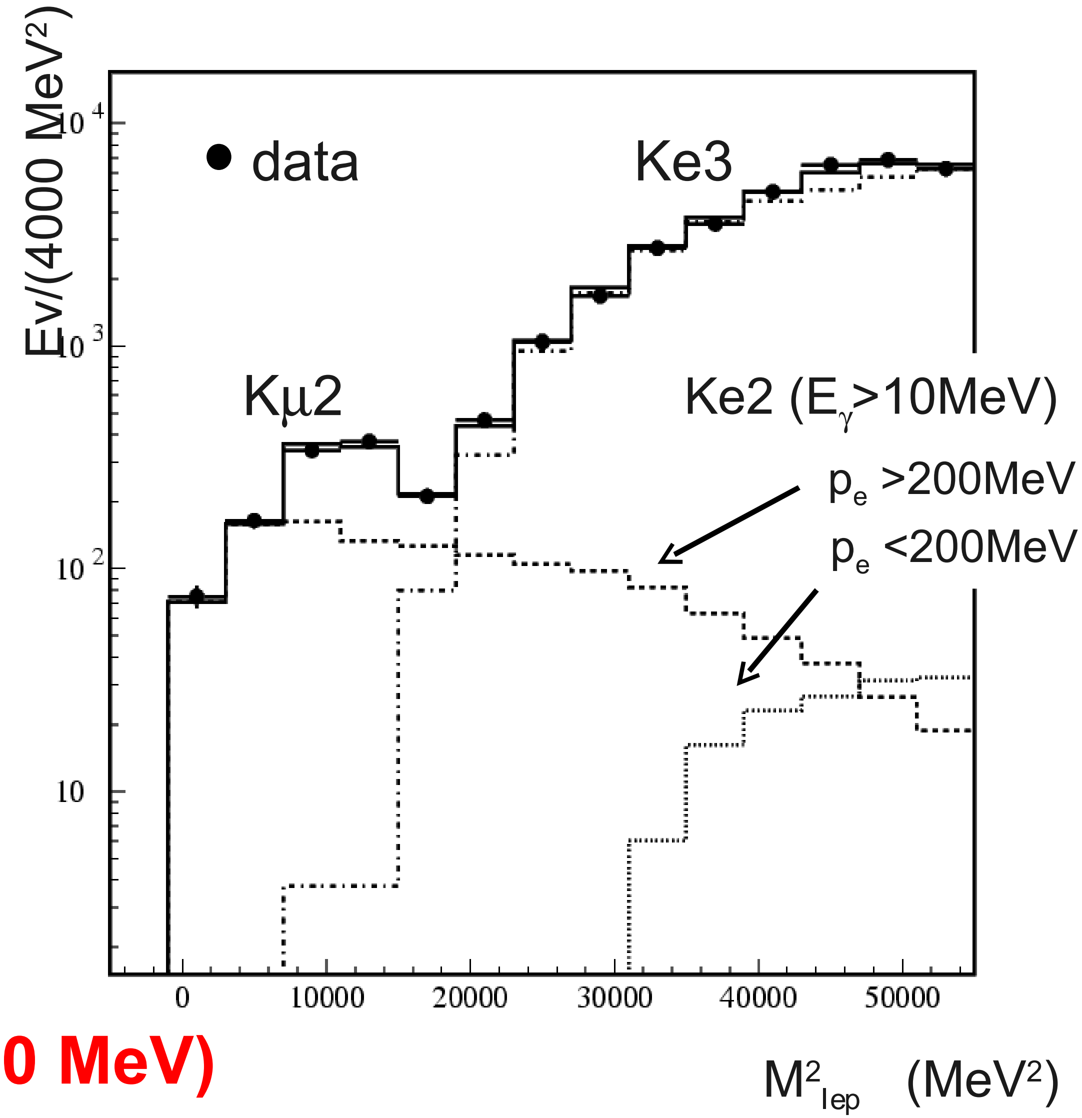
Ke2γ selection

After photon detection bkg is dominated by

- Kμ2 in the low M^2_{lep} region
- Ke3 for M^2_{lep} > 20000

No sensitivity for Ke2γ with p_e<200 MeV (SD– amplitude)

We measure
Ke2γ (Eγ>10 MeV, p_e<200 MeV)
→ SD+ amplitude



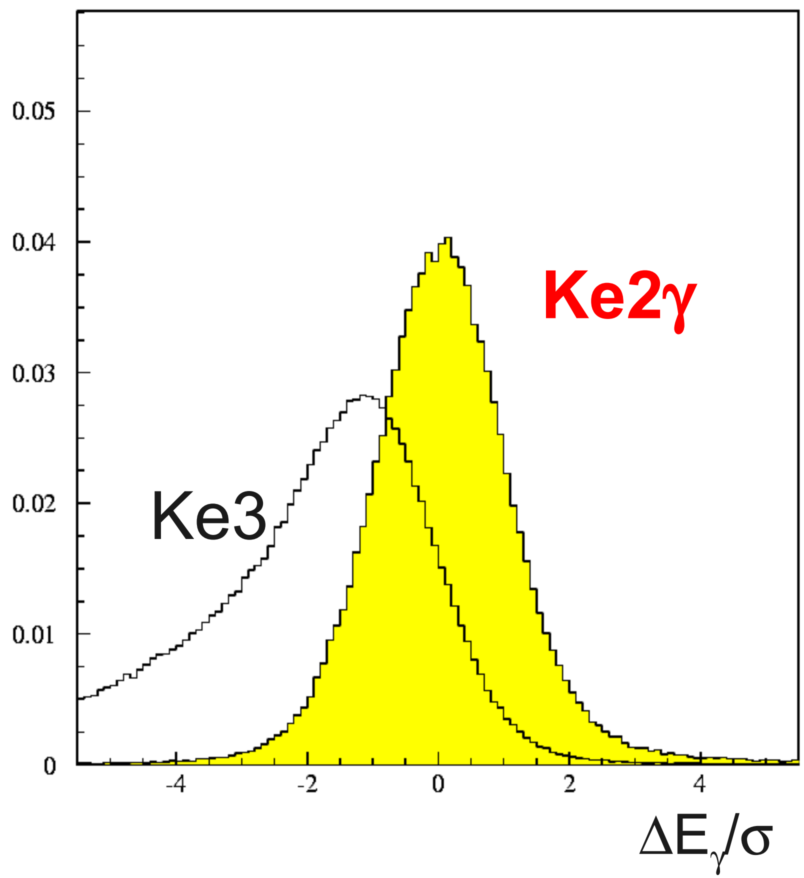
Ke2γ selection: photon matching

1) best evaluation of E_γ^{lab} from the kinematics of Ke2γ, using measured p_K, p_e and photon direction n_γ

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

⇨ **12 MeV resolution**

($\sigma_{calo} \approx 30$ MeV)



2) $\Delta E_\gamma = E_\gamma^{lab} - E_\gamma^{calo}$ is also useful as a discriminating variable against background

Ke2γ event counting

- Two-dimensional binned likelihood fit in the

  $M^2_{lep} - \Delta E_\gamma/\sigma$ plane

5 bins of E_γ (from E_γ^{lab} pass in K rest frame):

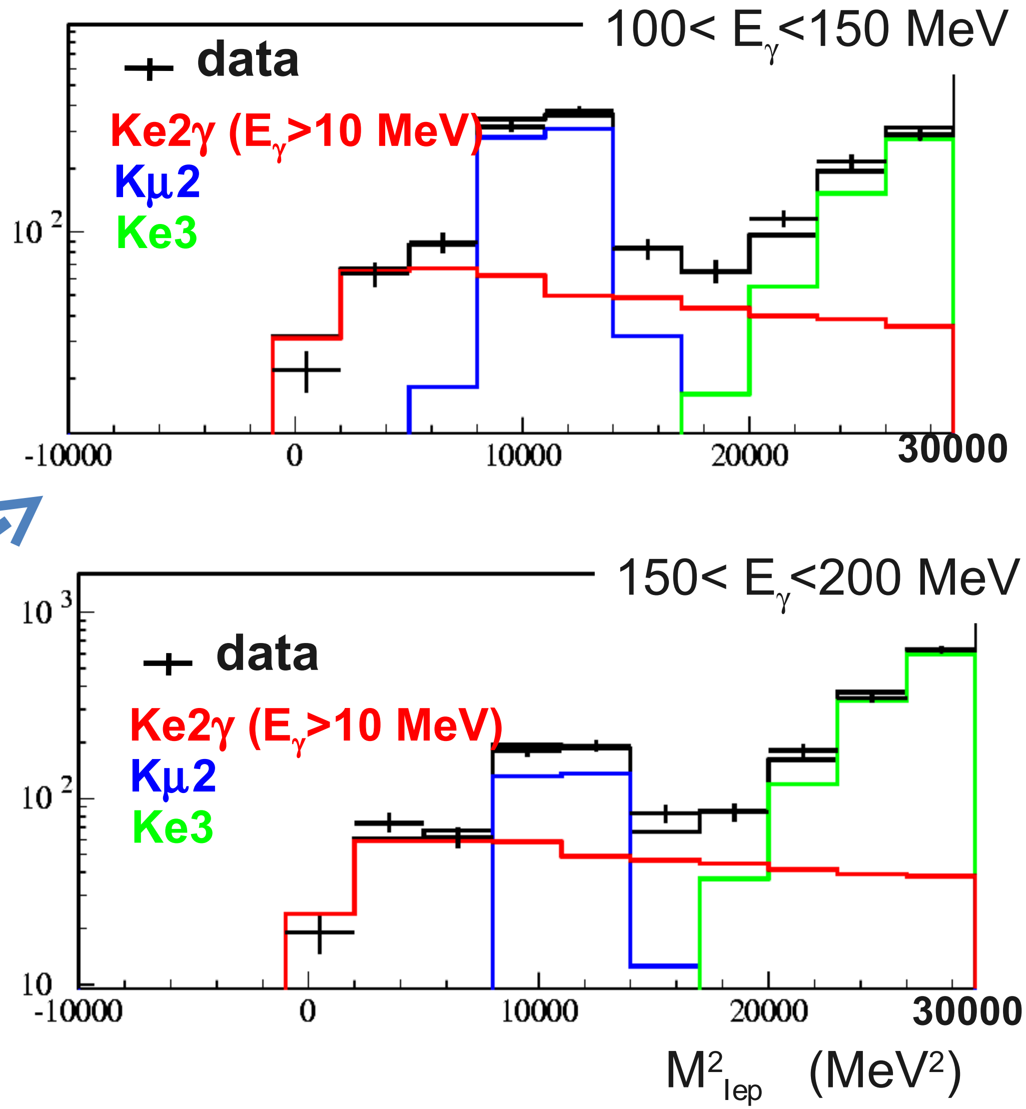
(10, 50) (50,100) (100,150) (150,200) (200,250)

- Most populated bins

  $100 < E_\gamma < 150$ MeV: N = 463 ± 32, $\chi^2 = 87/106$

  $150 < E_\gamma < 200$ MeV: N = 494 ± 38, $\chi^2 = 100/106$

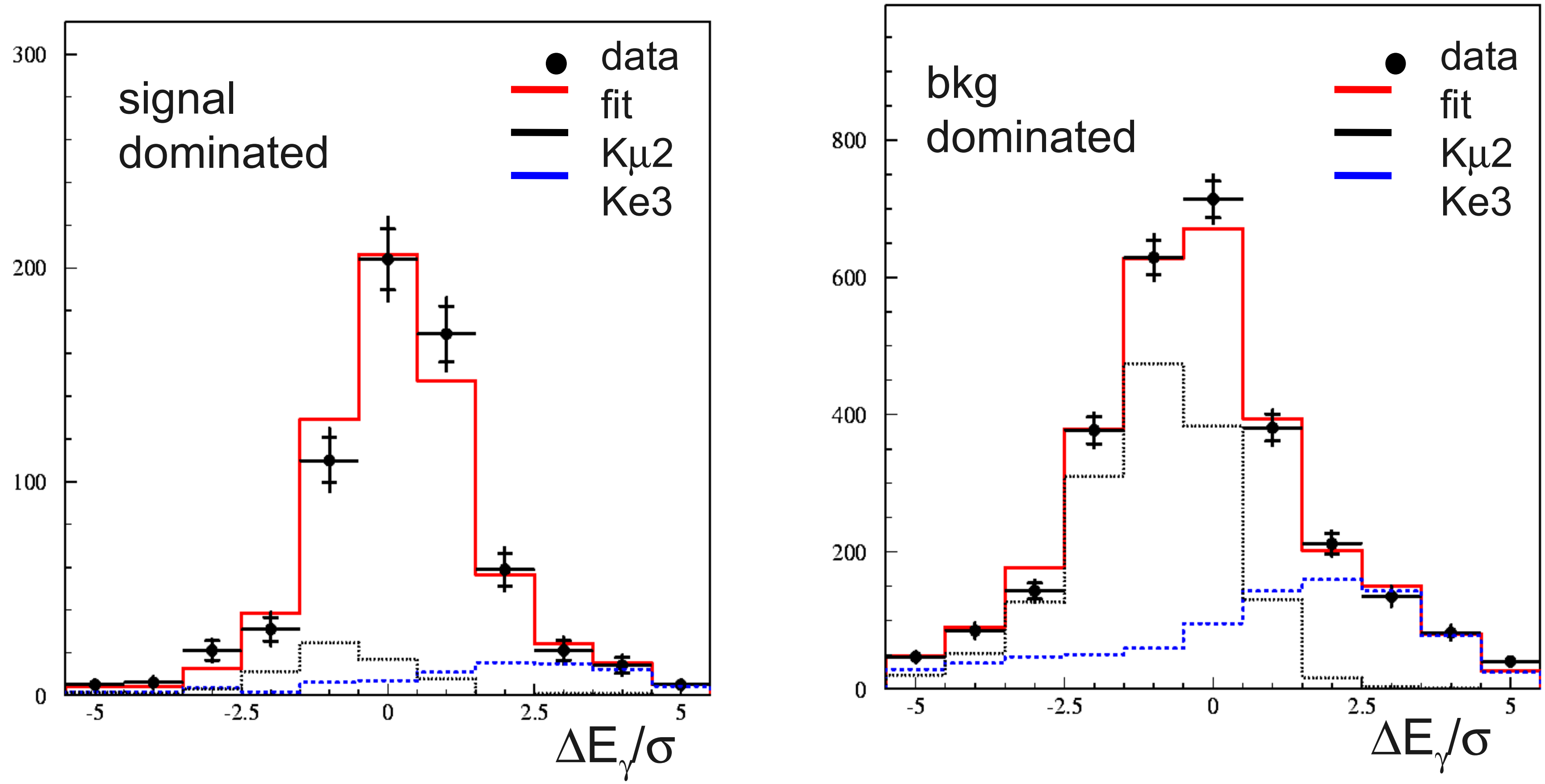
Fit projections on M^2_{lep} axis



Ke2γ event counting

Fit projections on $\Delta E_\gamma/\sigma$ (all E_γ bins together)

according to M^2_{lep}, we show separately regions dominated by signal and bkg



In total, we count Ne2γ = 1484 ± 63

Ke2γ spectrum vs ChPT O(p⁴)

We measure:

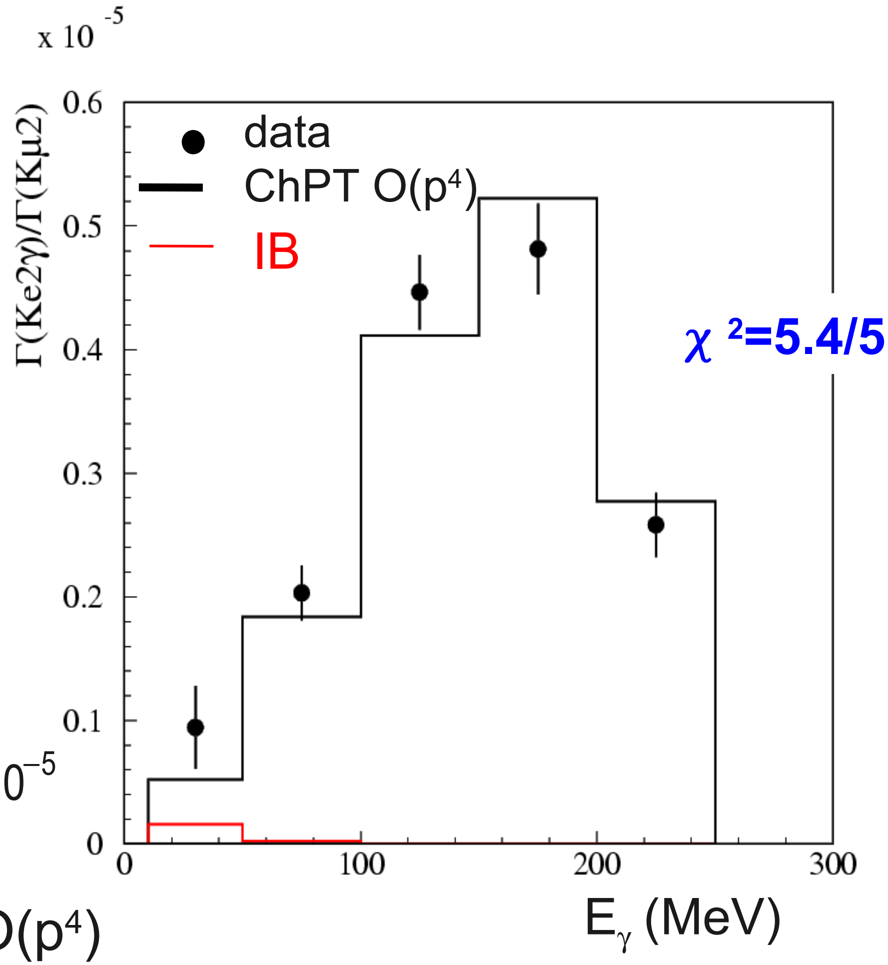
$$\frac{1}{\Gamma(K_{\mu 2})}\frac{d\Gamma(K_{e2}, E_\gamma > 10MeV, p_e^{\text{¿}} > 200MeV)}{dE_\gamma}$$

Data are **compared** with ChPT O(p⁴) calculation

Integrating we obtain:

$$\frac{\Gamma(K_{e2}, E_\gamma > 10MeV, p_e^{\text{¿}} > 200MeV)}{G(K_{\mu 2})} = 1.483(68)\,x10^{-5}$$

in agreement with 1.447×10^{-5} of ChPT O(p⁴)



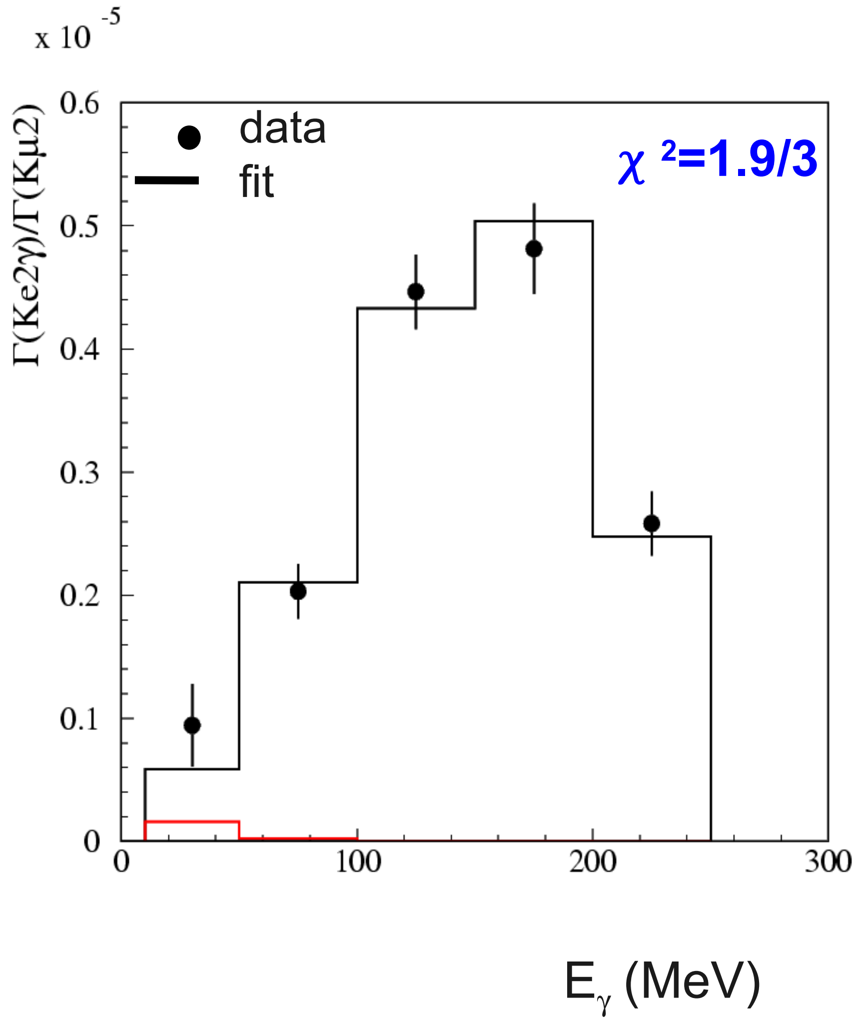
This confirm the SD content of our MC, evaluated with ChPT O(p⁴), within an accuracy of 4.6% and allows a 0.2% systematic error on $Ke2_{IB}$ to be assessed

Ke2γ spectrum: fit to ChPT $O(p^6)$

- We **fit** our data to extract $\mathbf{f_V+f_A}$ (SD+), allowing for a slope of the vector ff

$$f_V = \mathbf{f_{V0}}\ (1+\lambda\ (1-x))$$

- Since we are not sensitive to the SD– amplitude (acceptance≈2%) we keep f_V-f_A fixed to the ChPT $O(p^6)$ prediction



We obtain:

$$\mathbf{f_{V0}+f_A = (0.125 \pm 0.007)}$$

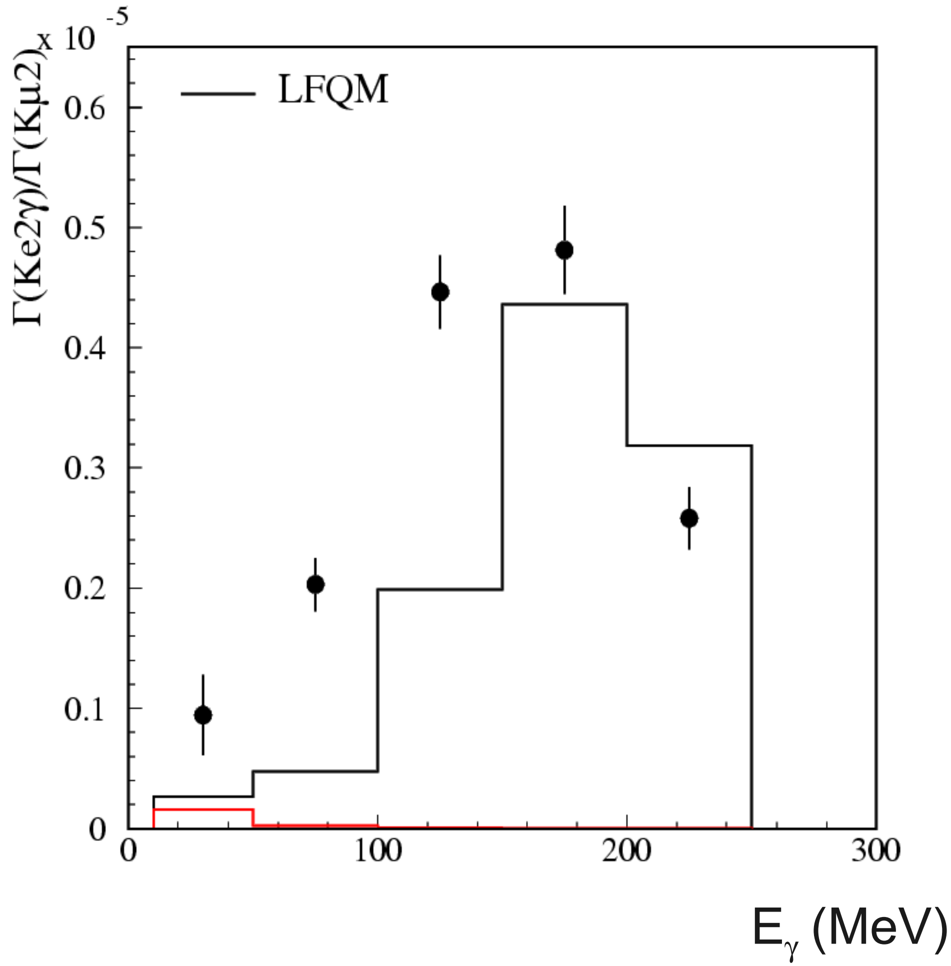
$$\mathbf{\lambda\ = 0.38 \pm 0.21}$$

Compare to ChPT $O(p^6)$: $f_{V0}+f_A \approx 0.116$, $\lambda \approx 0.4$

Phys. Rev. D77 (2008) 014004

Ke2γ spectrum vs LFQM

The spectrum predicted by the Light Front Quark Model is excluded by our data, χ^2=127/5



CONCLUSION

We have performed the most accurate measurement of
The K_s lifetime:

$$\tau_S = (89.562 \pm 0.029_{stat} \pm 0.043_{syst})\ \mathrm{ps}$$

.. and a funny test of isotropy (the most accurate with lifetime to my knowledge)

We also presented today the first measurement of the decay spectrum in a region dominated by SD

$$\frac{1}{\Gamma(K_{\mu 2})} \frac{d\Gamma(K_{e2}, E_\gamma > 10 MeV, p_e^{¿} > 200 MeV)}{dE_\gamma}$$

Results are in good agreement with expectations from ChPT

Reconstruction efficiencies

We use MC, with corrections from data control samples

1) **kink reconstruction (tracking):** K^+e3 and $K^+\mu2$ data control samples selected with tagging and additional criteria based on EMC info's only (next slide)

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

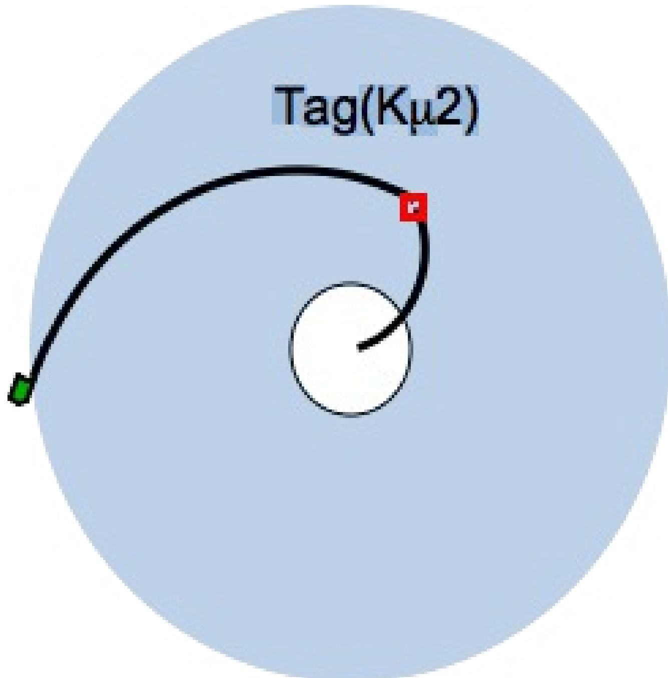
we obtain:

$$\varepsilon(Ke2)/\varepsilon(K\mu2) = 0.946 \pm 0.007$$

Control samples for tracking efficiencies

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

0) Tagging decay (Kμ2 or Kπ2) coming from IP



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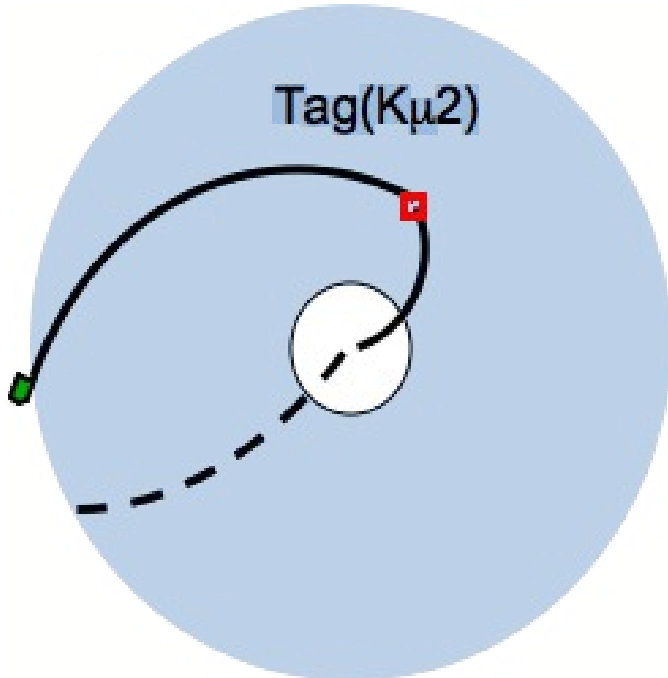
reconstruction of the opposite charge kaon flight path



Control samples for tracking efficiencies

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

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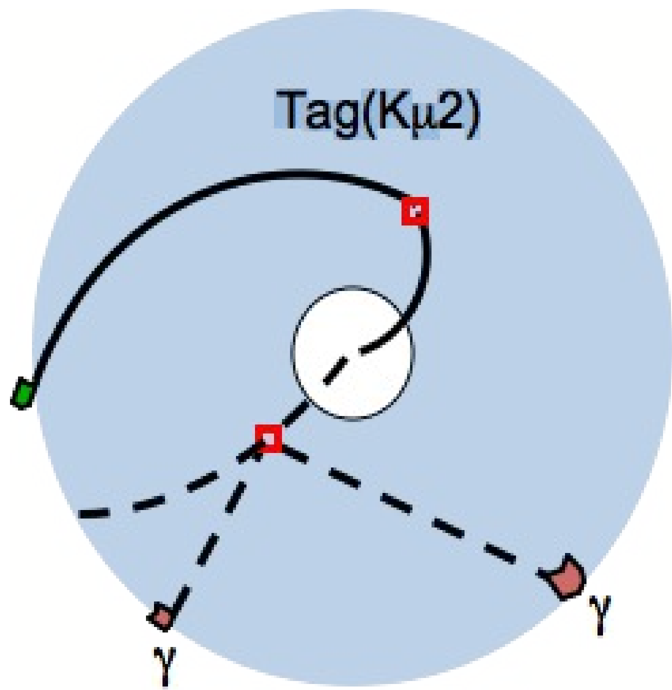
2) A $\pi^0 \to \gamma\gamma$ decay vertex is reconstructed along the K decay path, using TOF



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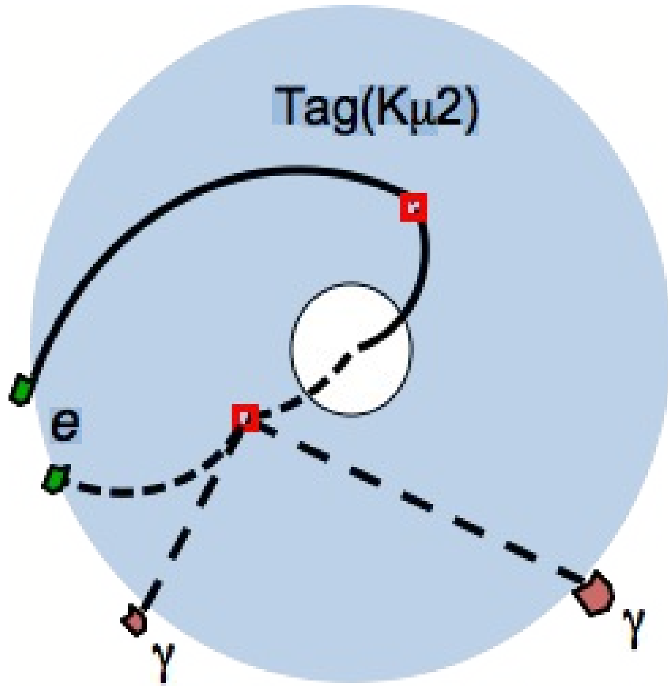
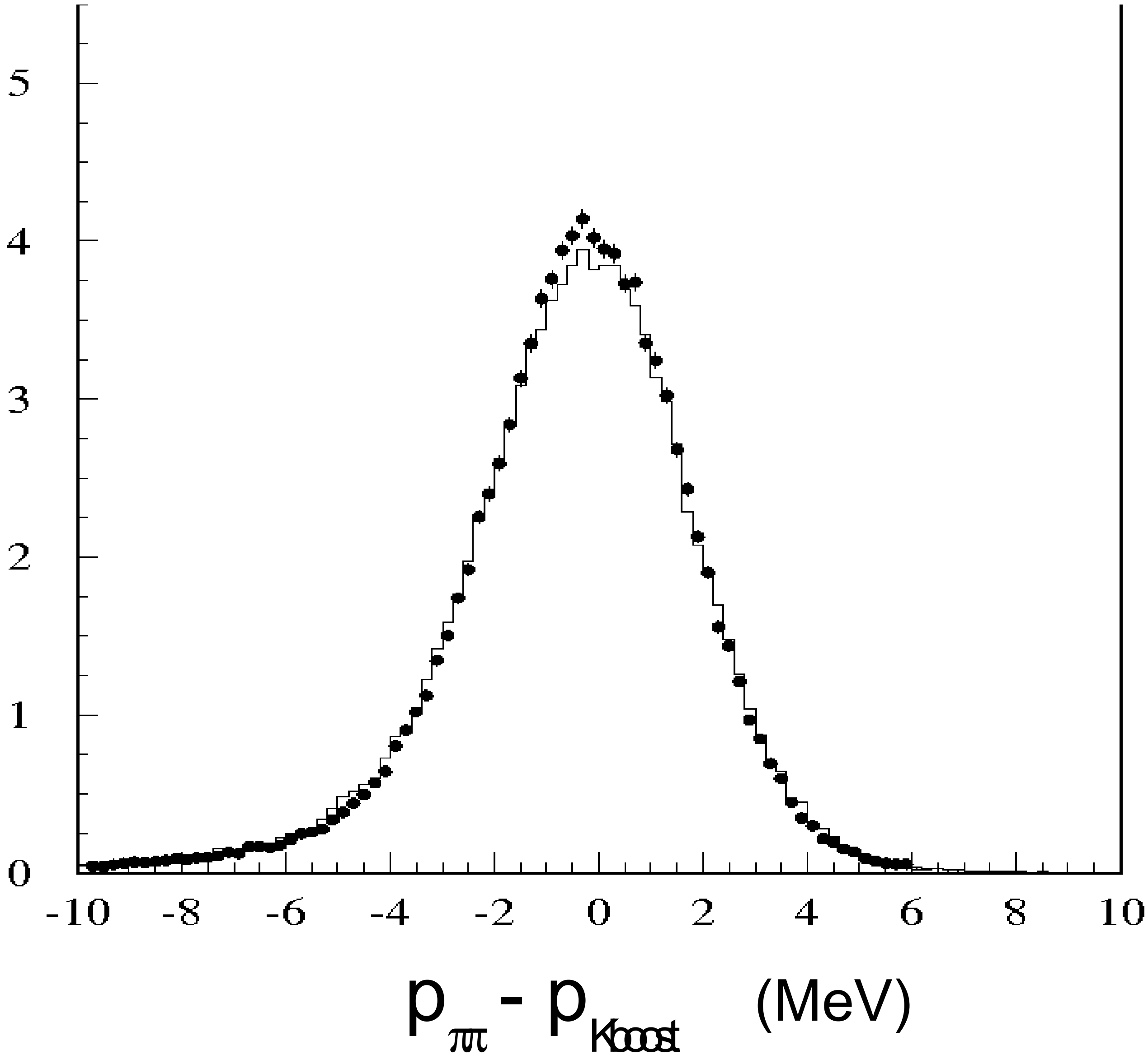


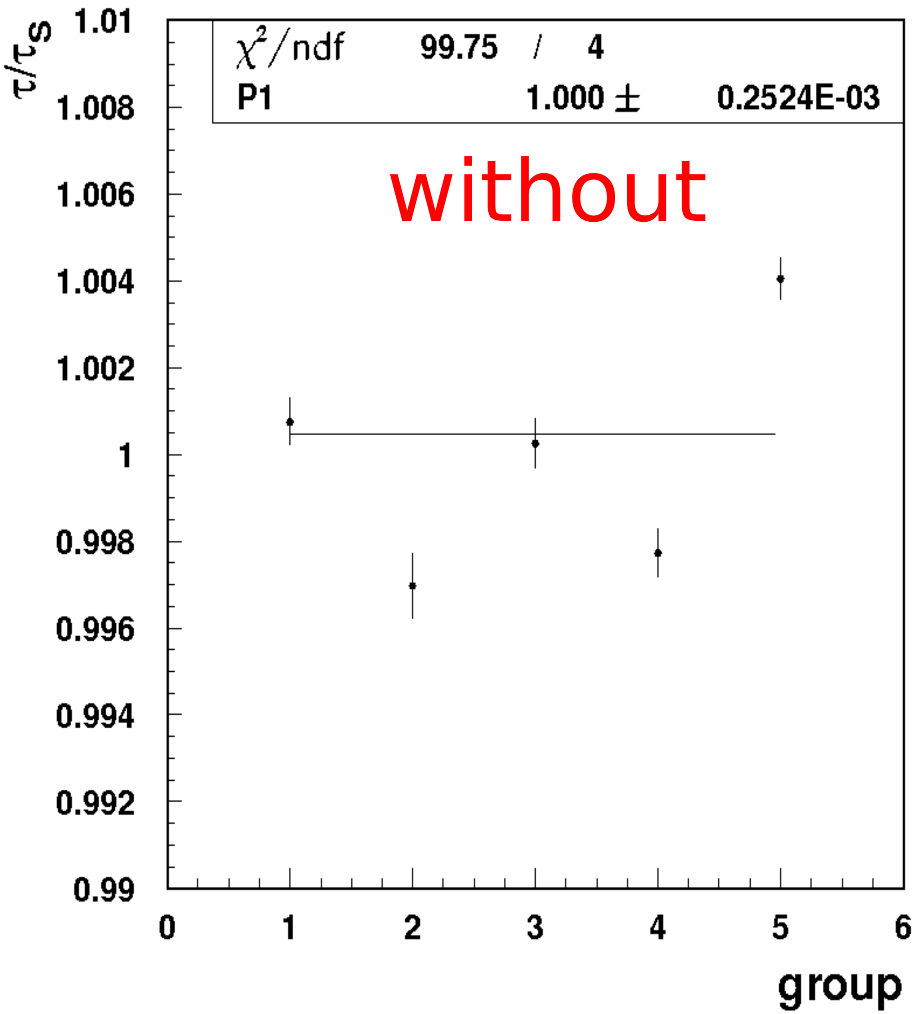
3) Electron cluster required; p_e estimated from a kinematic fit with constraints on E/p, TOF, r_e and $E_{miss} - P_{miss}$

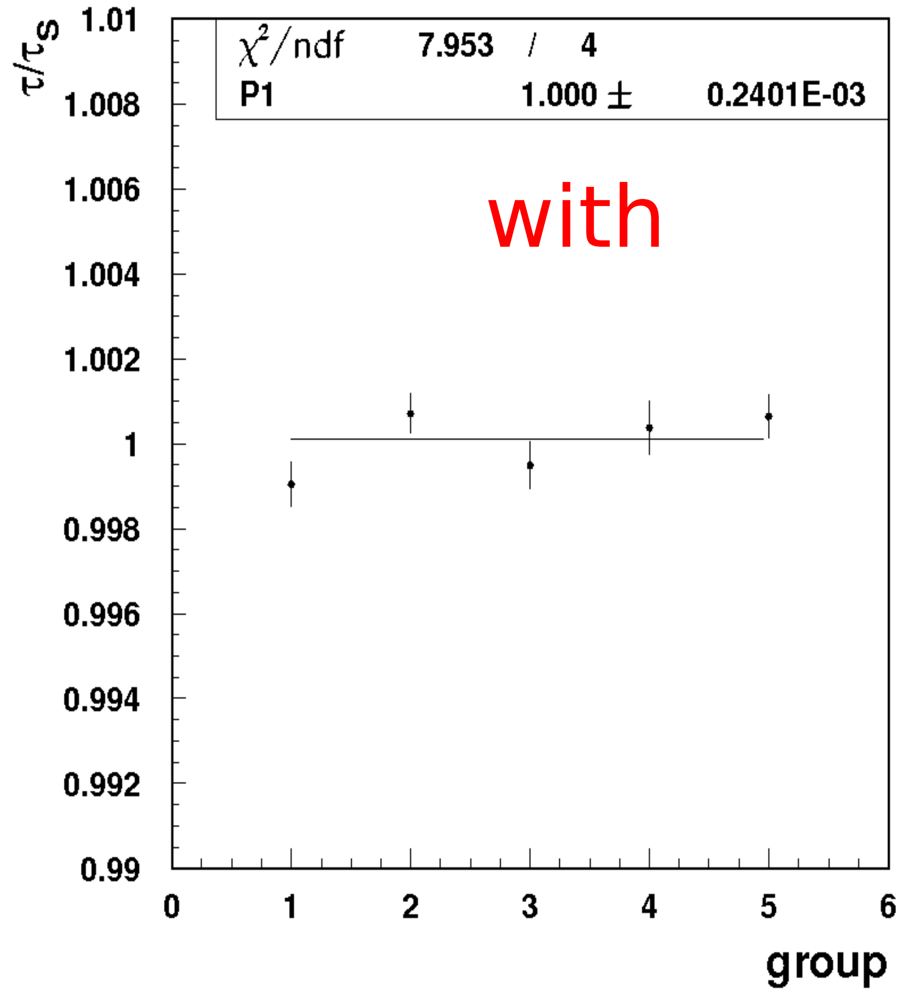
➡ We evaluate the K + electron kink reconstruction efficiency

Decay point correction using 2nd determination of kaon momenta

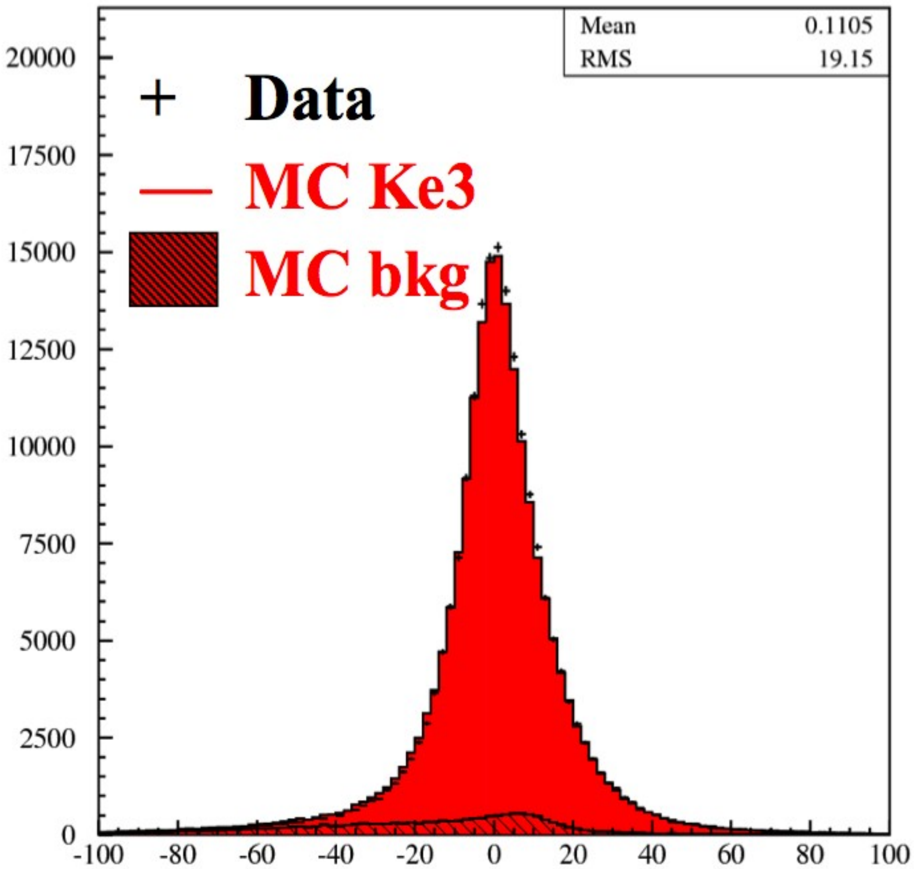


Stability with/out corrections

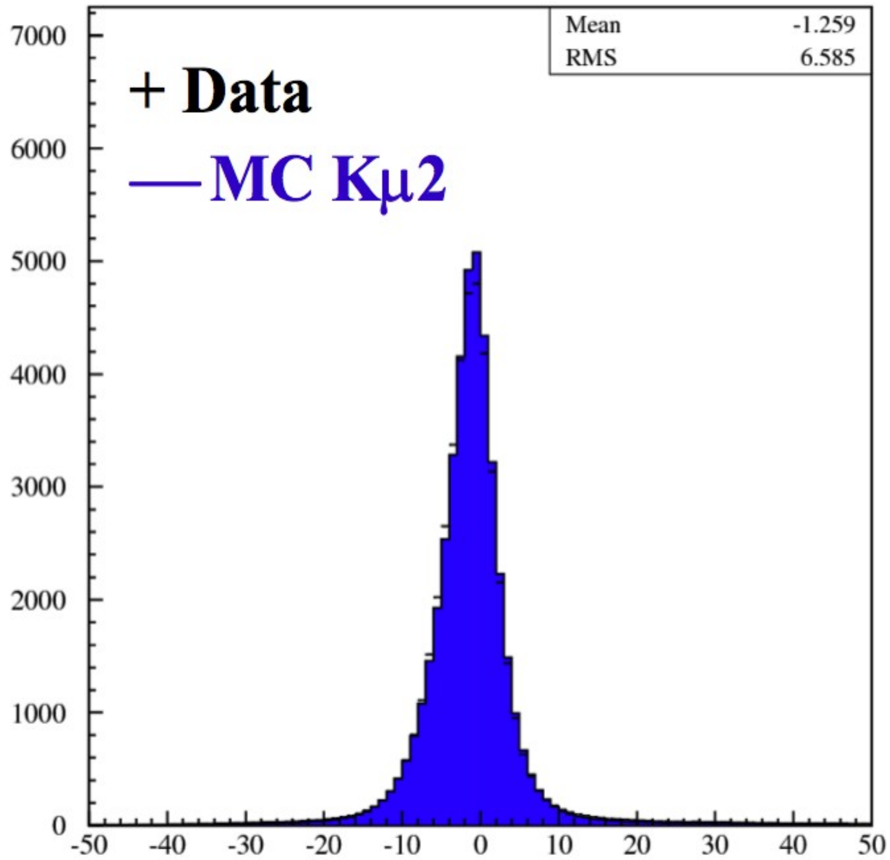




Control samples for tracking efficiencies



p_e(fit)-p_e(reco) (MeV)



p_μ(fit)-p_μ(reco) (MeV)

$\sigma \approx 19$ MeV

with a similar method, we get $\sigma \approx 7$ MeV for muon tracks

Systematics and checks

Cross-check on efficiencies: use same algorithms to measure $R_{l3} = \Gamma(Ke3)/\Gamma(K\mu3)$

$R_{l3} = 1.507 \pm 0.005$ 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 SD component	**0.2%**	measurement on data
Clustering for e, μ		

Total Syst **0.8%**

0.6% from statistics of control samples

R_K : KLOE result

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

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

0.9% from 14k Ke2 + bkg subtraction

dominated by statistics

- The result does not depend upon the kaon charge:

  K^+: 2.496(37) vs K^+: 2.490(38) uncorrelated errors only

- Our measurement agrees with SM prediction,

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

R_K : world average

PDG 2008:

$R_K = (2.45 \pm 0.11) \times 10^{-5}$

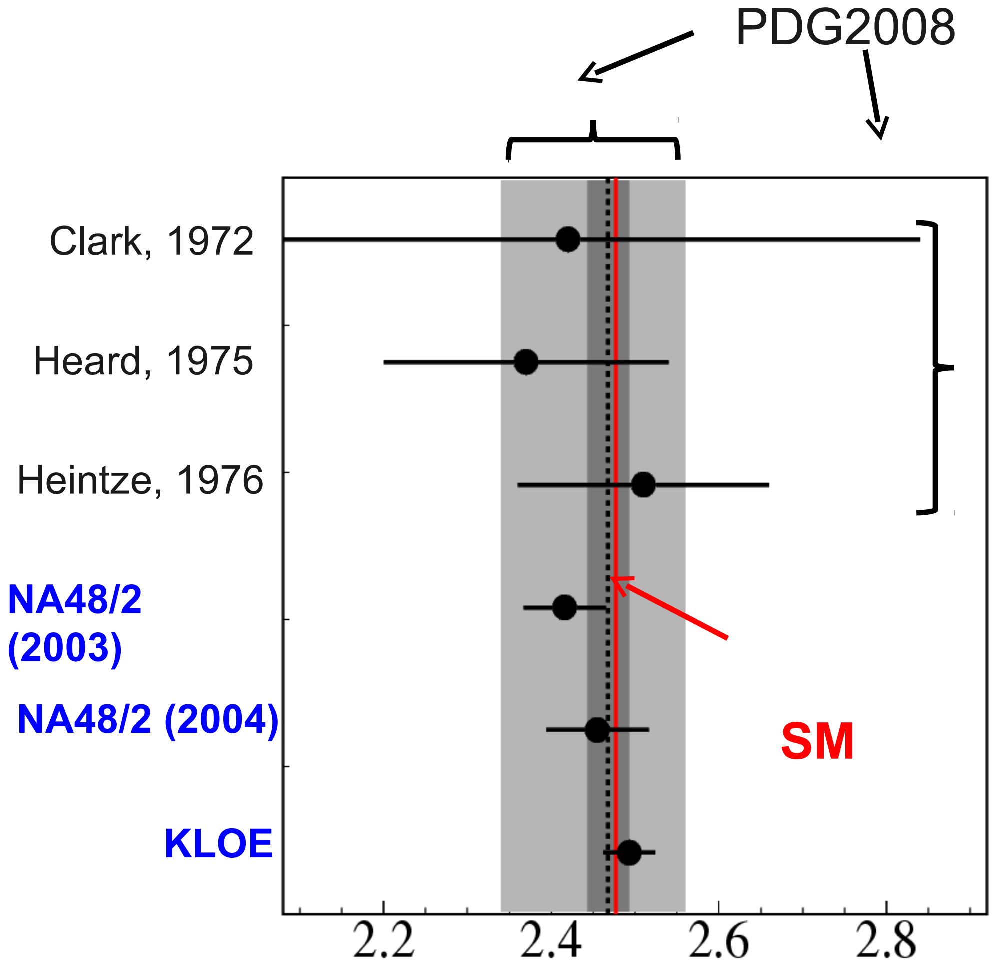
4.5% accuracy

New world average:

$\mathbf{R_K = (2.468 \pm 0.025) \times 10^{-5}}$

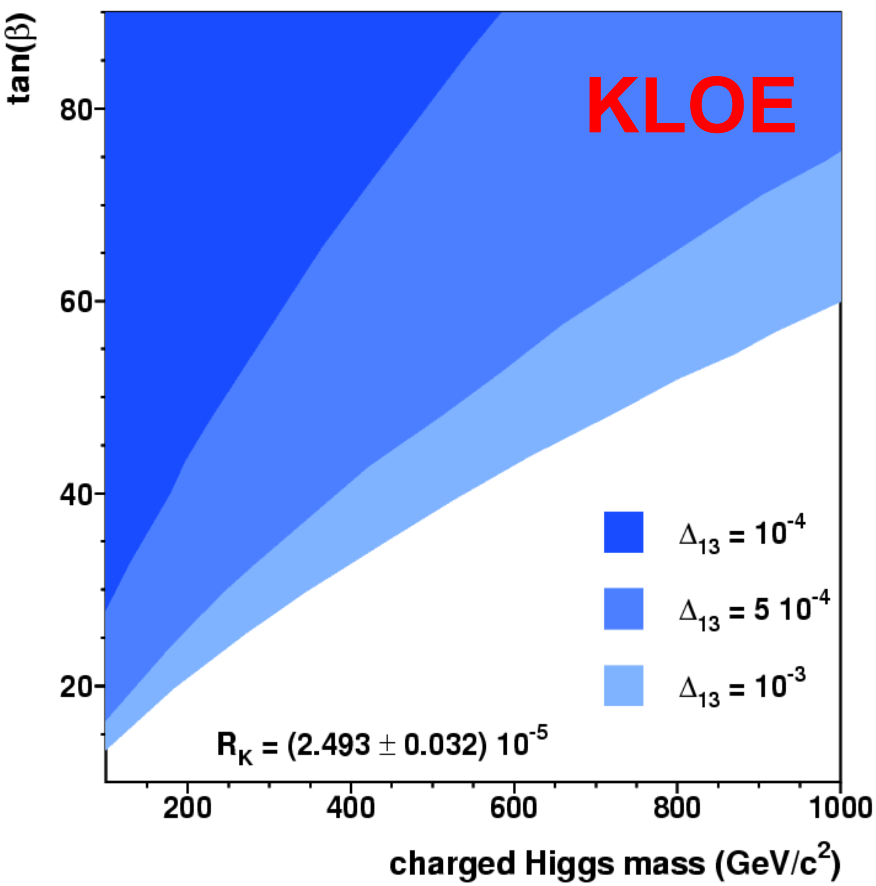
1% accuracy

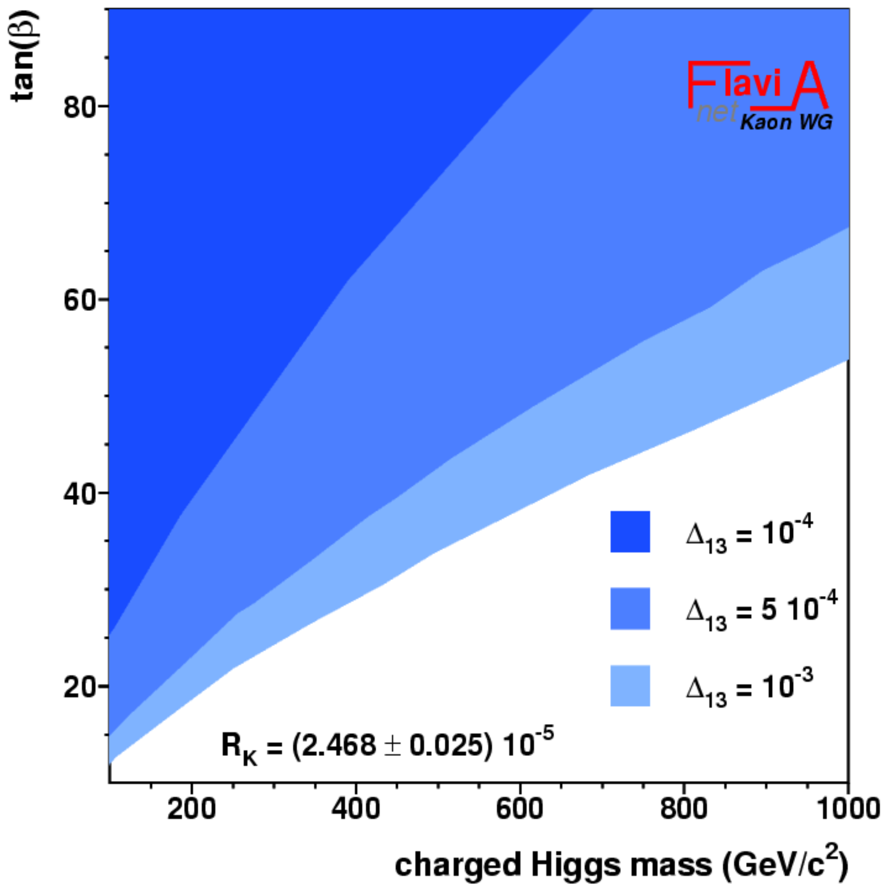
$\mathbf{R_K^{SM} = 2.477(1) \times 10^{-5}}$



R_K : sensitivity to new physics

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





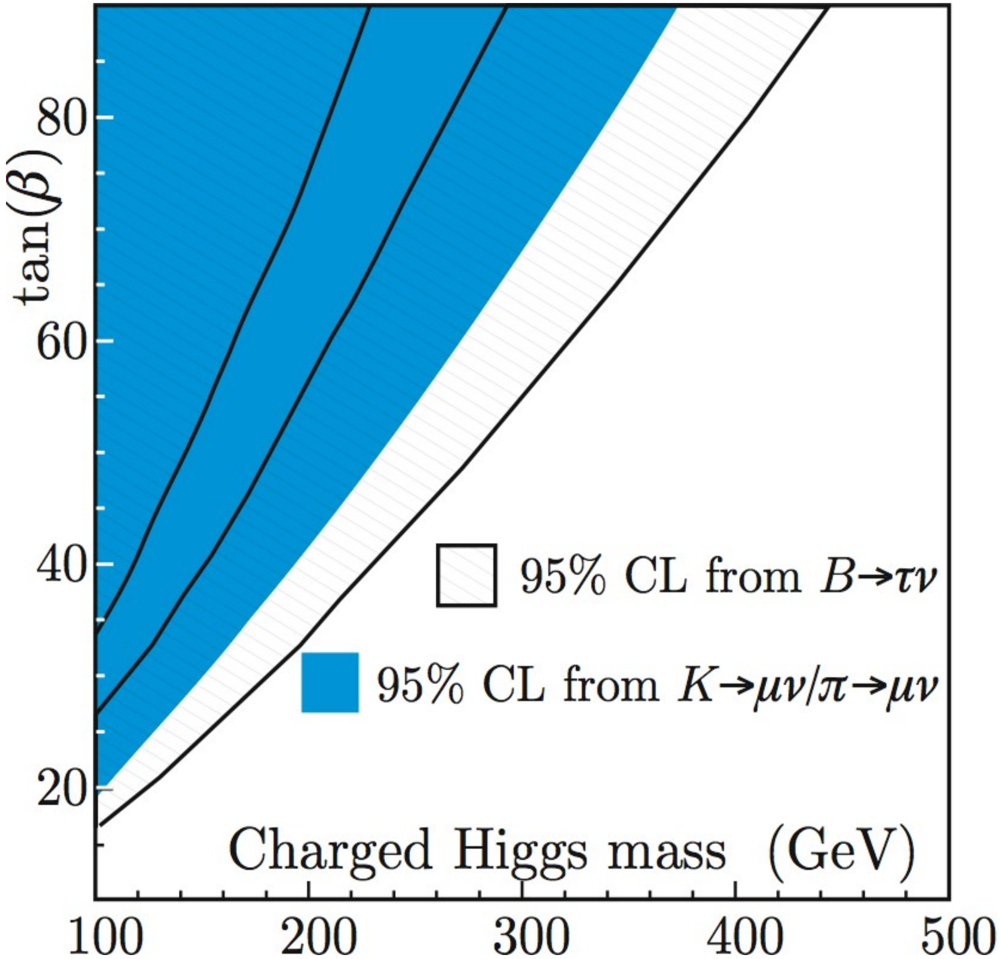
$K_{\mu 2}$: sensitivity to new physics

Scalar currents, e.g. due to Higgs exchange, affect $K \to \mu\nu$ width

$$R_{l23} = \left| \frac{V_{us}(K_{m2})}{V_{us}(K_{l3})} \cdot \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(p_{m2})} \right|$$

$$= \left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \left(1 - \frac{m^2_{p^+}}{m^2_{K^+}}\right) \frac{\tan^2\beta}{1 - e_0 \tan\beta} \right|$$

[Hou, Isidori-Paradisi]



R_{l23} =1 in SM

we find

R_{l23} = 1.008 ± 0.008

limited by lattice uncertainty on $f_+(0)$ and f_K/f_π

From direct searches (LEP), M_{H^+} > 80 GeV, $\tan\beta > 2$