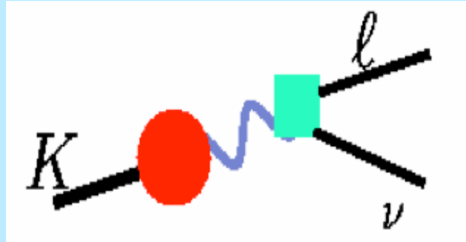


Test of lepton flavor violation with K_{e2} decay at KLOE

Matteo Palutan
INFN-LNF
(for the KLOE Collaboration)

CERN, May 25th 2009

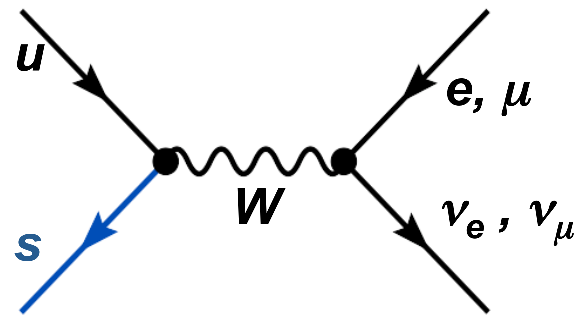
Measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

- Introduction
- K_{e2} events counting
- Study of direct emission in $K_{e2\gamma}$
- Results on R_K

Standard Model prediction for $R_K=\Gamma(K_{e2})/\Gamma(K_{\mu2})$

Reduced hadronic uncertainties in the ratio $K_{e2}/K_{\mu2}$ (no f_K)

$$R_K^{SM} = \frac{m_e^2}{m_\mu^2}\frac{\left(m_K^2 - m_e^2\right)^2}{\left(m_K^2 - m_\mu^2\right)^2}\left(1+\delta R_K^{rad}\right)$$



$$1+\delta R_K^{rad} = \left(0.9642 \pm 0.0004\right)$$ **IB only**

Finkemeier 97
Cirigliano-Rosell 07

$$R_K^{SM} = \left(2.477 \pm 0.0001\right)\times 10^{-5}$$ 0.04% uncertainty

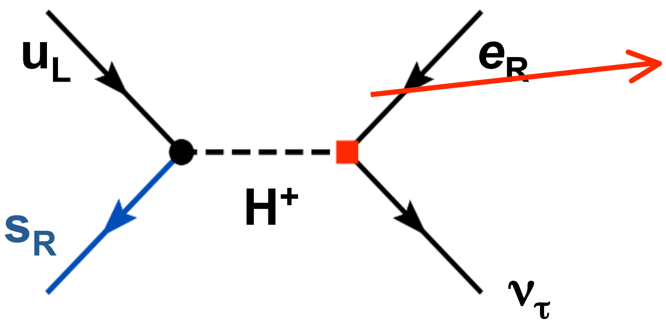
Strong helicity suppression of electron channel enhances sensitivity to physics beyond the SM

New Physics potential of R_K

In MSSM, LFV can give % deviations from SM

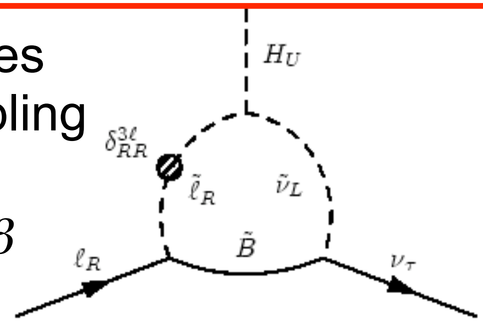
Masiero, Paradisi Petronzio 06

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \approx \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$



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

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



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

1 % effect if $\Delta_R^{31} \approx 5\times10^{-4}$, $\tan\beta \approx 40$, $m_H \approx 500$ GeV)

Entering the precision realm for R_K

PDG 2008 **$R_K = (2.45 \pm 0.11) \times 10^{-5}$** **4.5% accuracy**

three measurements from 70's

Main players in the challenge to push down precision on R_K

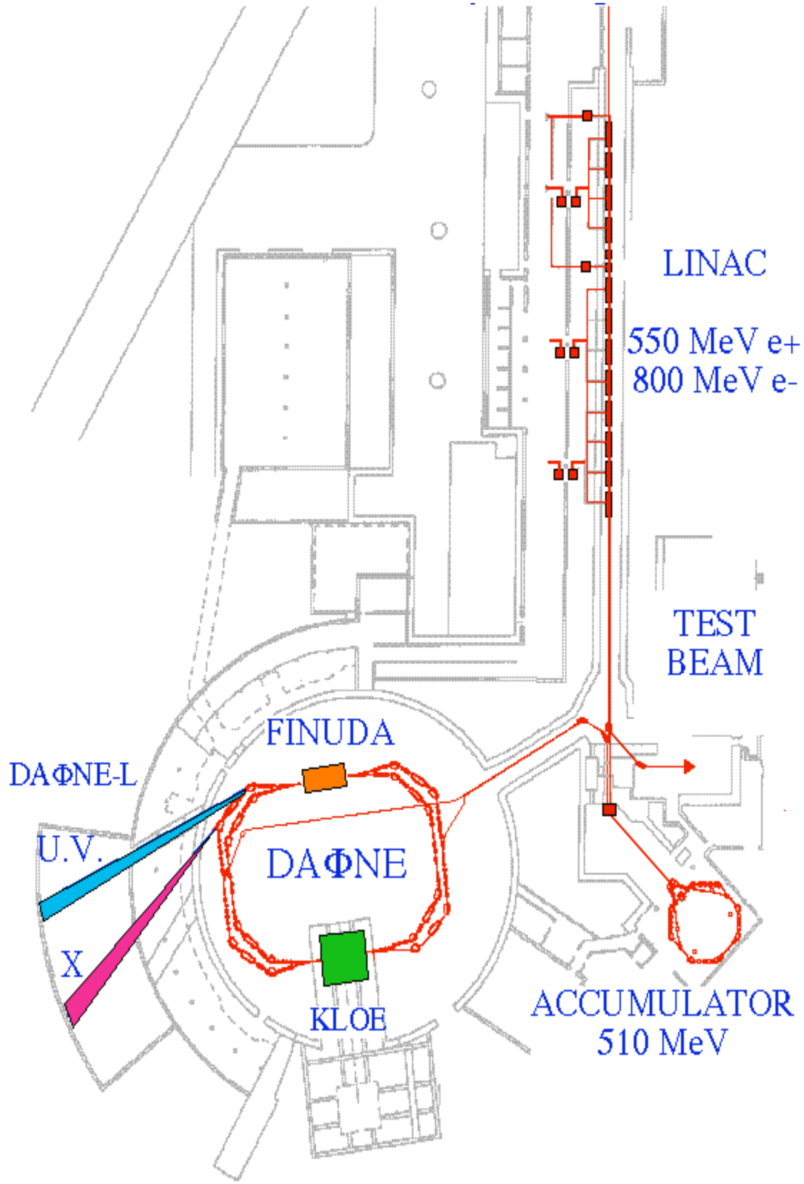
KLOE **preliminary** result with 2001-2004 data: **$R_K = 2.55(5)_{stat}(5)_{syst} \times 10^{-5}$**
from ≈ 8000 Ke2 candidates (**3% accuracy**)

NA48/2 **preliminary** result with 2003 data: **$R_K = 2.416(43)_{stat}(24)_{syst} \times 10^{-5}$**
from ≈ 4000 Ke2 candidates (**2% accuracy**)

preliminary result with 2004 data: **$R_K = 2.455(45)_{stat}(41)_{syst} \times 10^{-5}$**
from ≈ 4000 Ke2 candidates (**3% accuracy**)

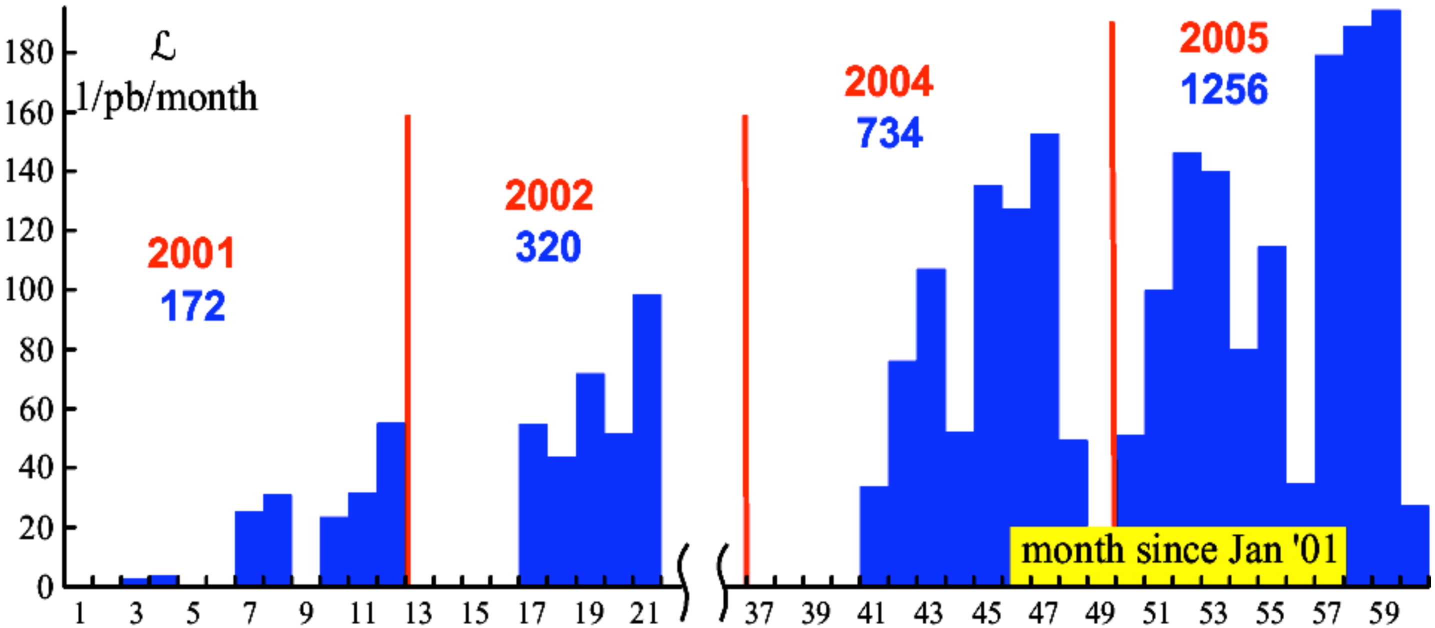
NA62 **≈ 150,000 Ke2 events collected in a dedicated 2007 run**
aims at ≈ 0.4%

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, $L_{peak} = 4.5\times10^{32}\ cm^{-2}s^{-1}$**

Summary of KLOE data taking



$\int L$ = 2.2 fb^{-1} at ϕ peak

$$BR(\phi \to K^+K^-) \approx 0.49$$ yielding 3×10^9 K^+K^- pairs

≈ 50,000 Ke2 decays in fiducial volume

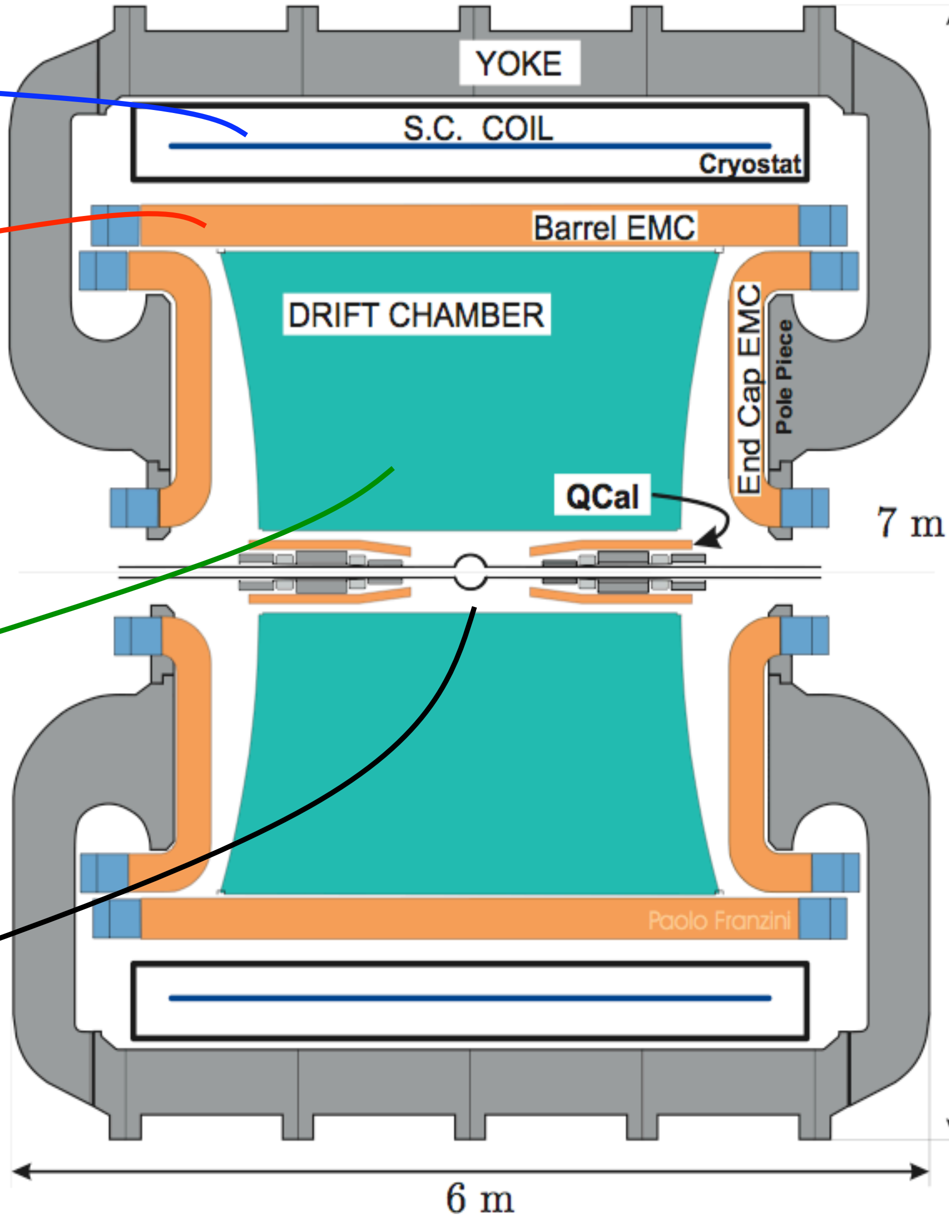
The KLOE experiment

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

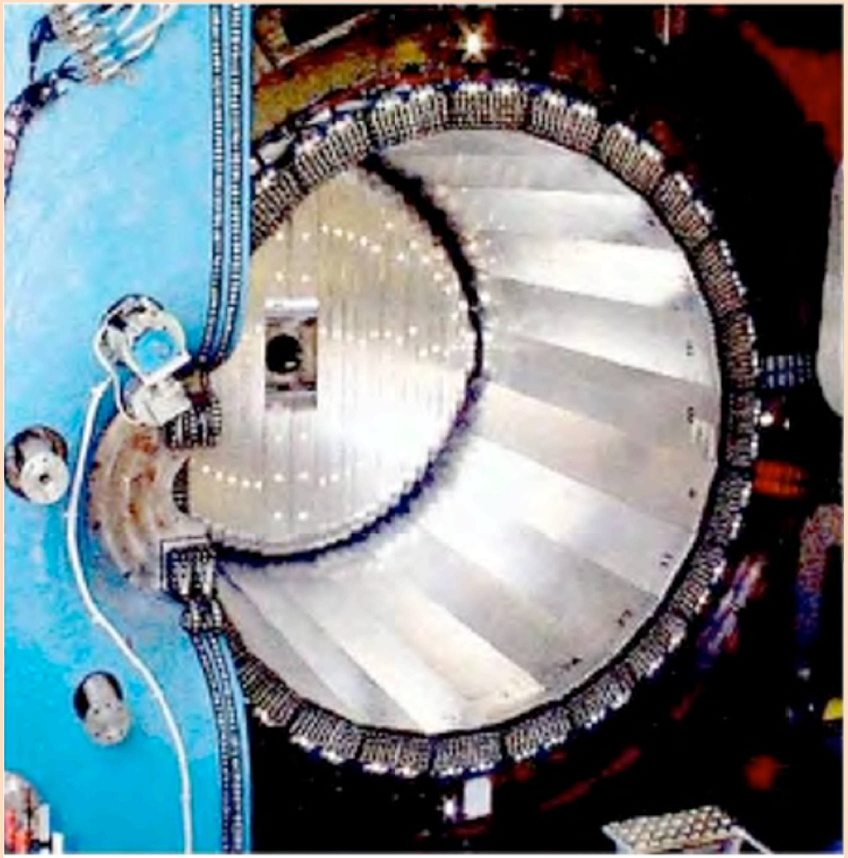
Al-Be beam pipe
r = 10 cm, 0.5 cm thick



Detector performances

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

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



EM Calorimeter

Drift Chamber

$$\sigma(p_\perp)/p_\perp = 0.4\%$$

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

Charged kaon beams

ϕ decay at rest provides almost ***pure*** kaon beams of known momentum

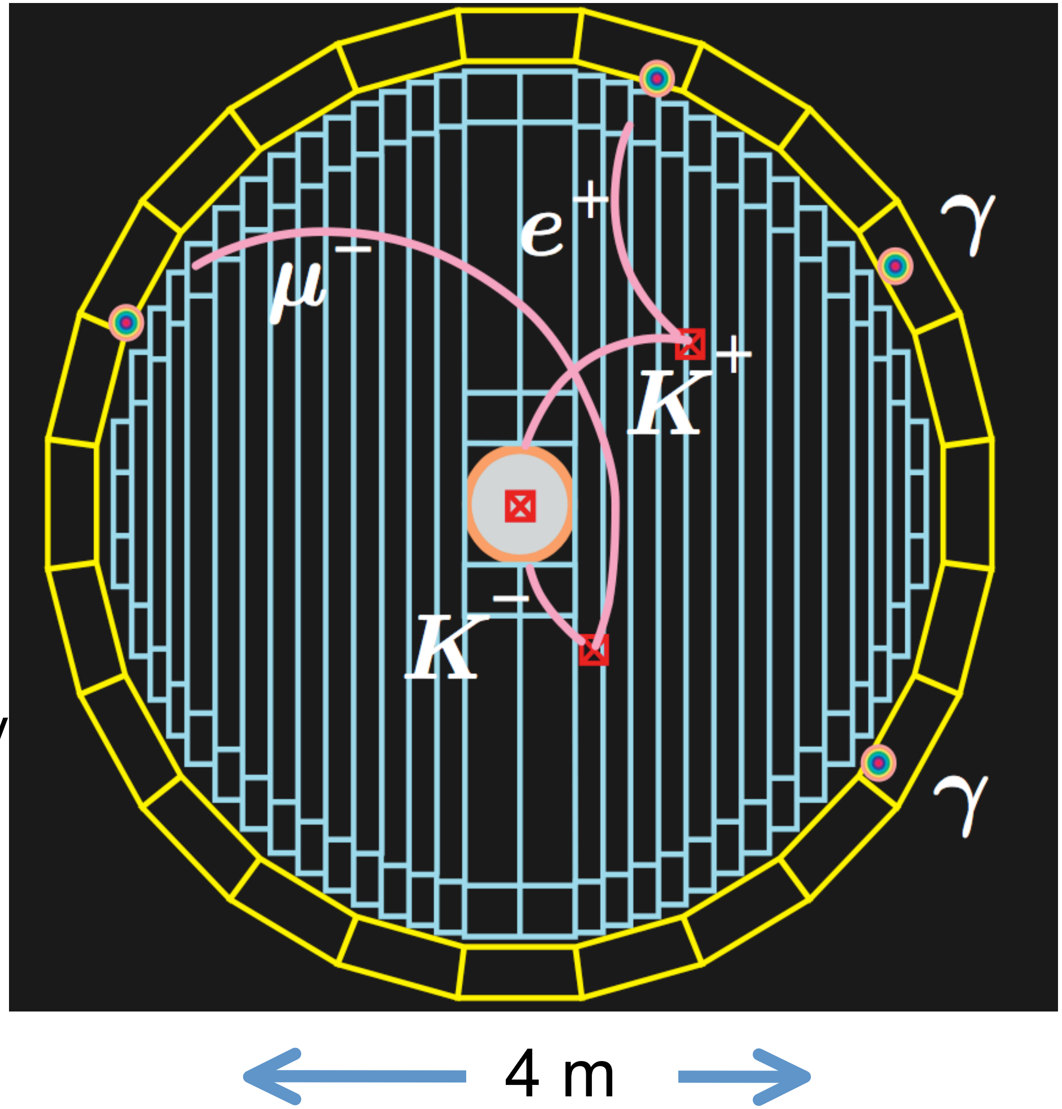
$p_K \approx 100$ MeV

$\lambda \approx 90$ cm

(56% of K^+ decay in DC)

Kaon momentum is measured with 1 MeV resolution in DC

- *Constraints* from ϕ 2-body decay
- *Particle ID* with kinematics and TOF
- *Tagging* provides unbiased control samples for efficiency measurement

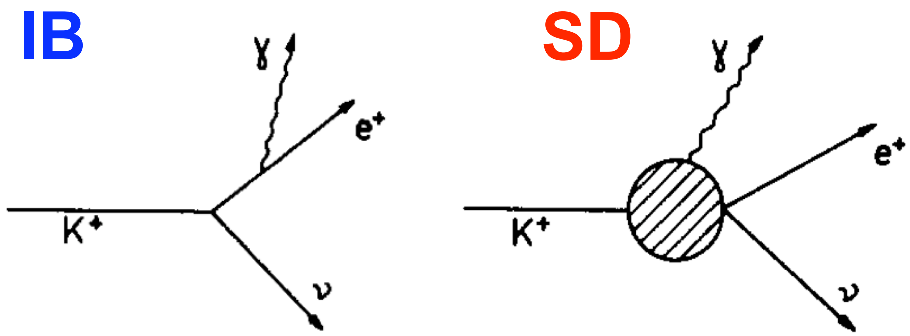


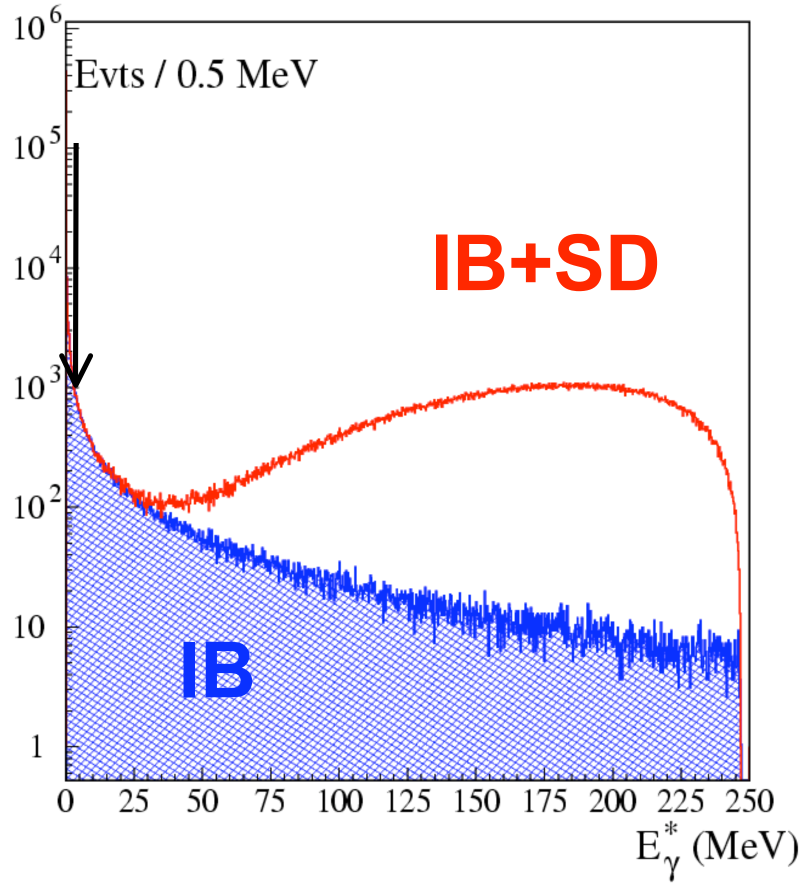
Measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$

- Introduction
- **K_{e2} events counting**
- Study of direct emission in $K_{e2\gamma}$
- Results on R_K

Ke2(γ): signal definition

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

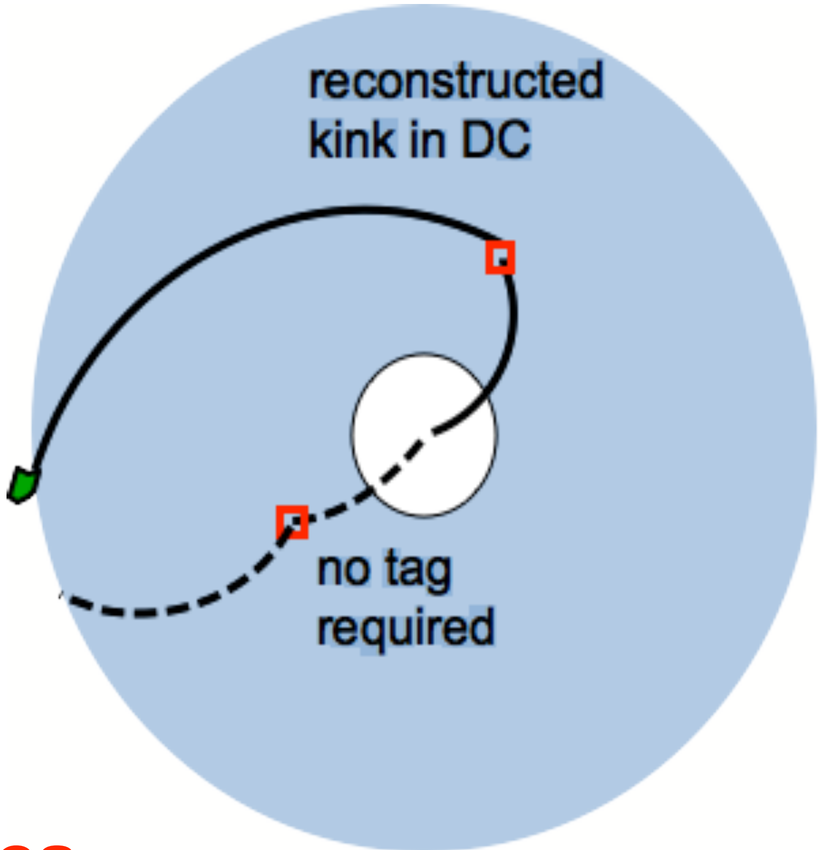
1) Select kinks in DC (≈ fiducial volume)

- 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

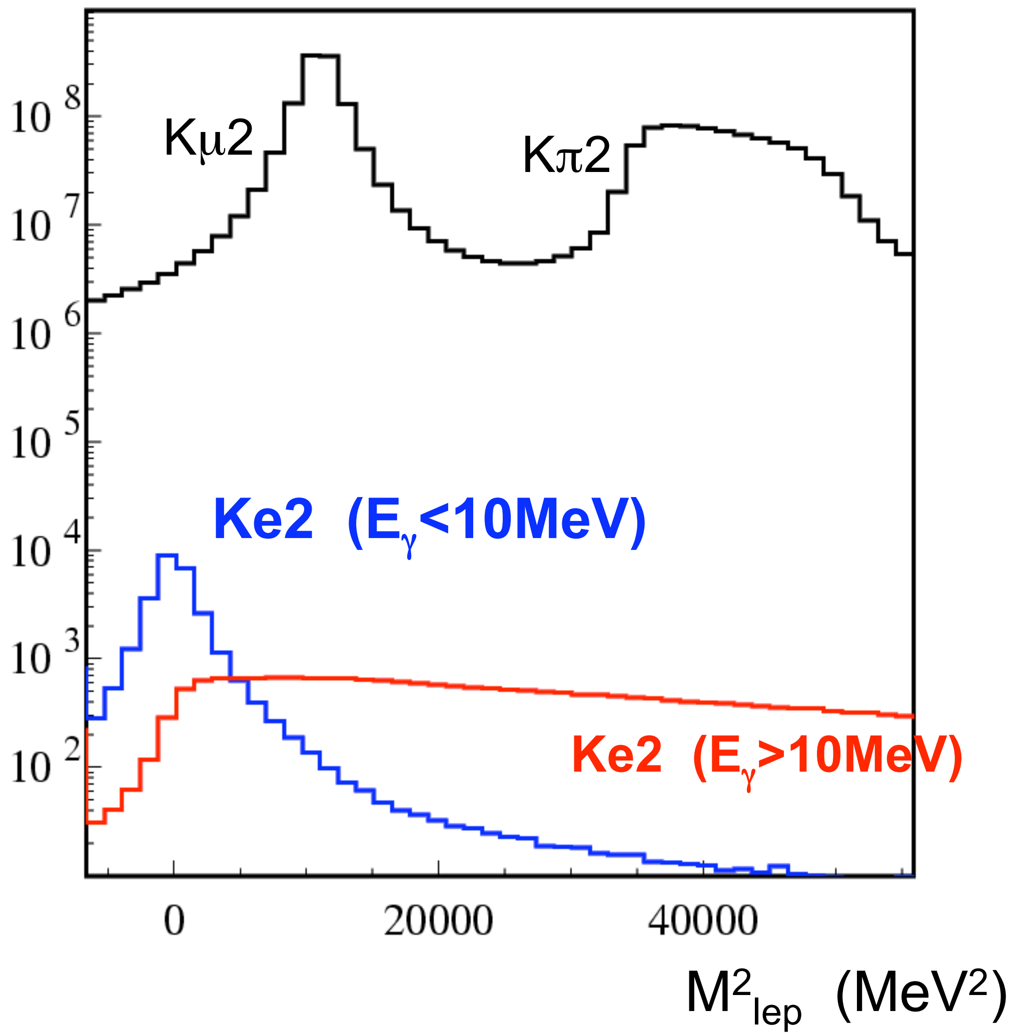


Analysis basic principles

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

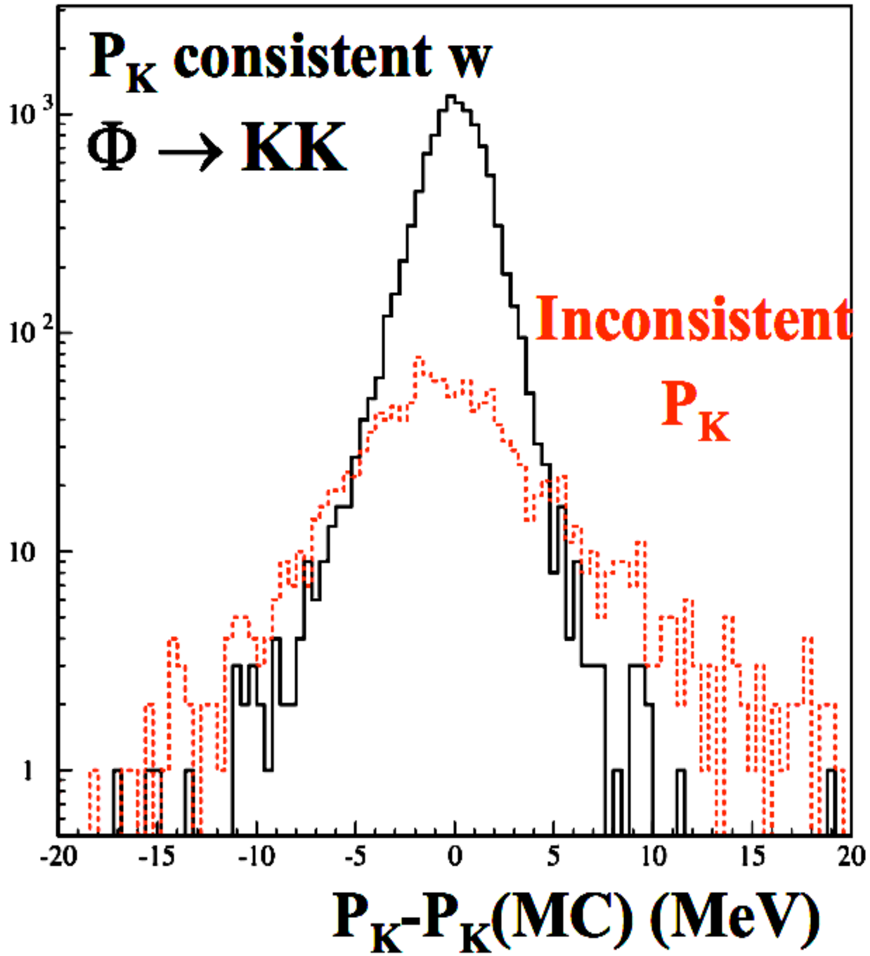
$$M^2_{lep} = \left(E_K - p_{miss}\right)^2 - p^2_{lep}$$

around M^2_{lep}=0 we get S/B = 10^{-3}



Background rejection (track quality)

Bkg composition: $K_{\mu 2}$ events with bad p_K, p_{lep} reconstruction



- quality cuts for K: exploit $\phi \to KK$ 2-body kinematics
- require good quality vertex and secondary track (χ^2 cut)
- reduce $K_{\mu 2}$ tails cutting on the expected error on M^2_{lep} (from track parameters)

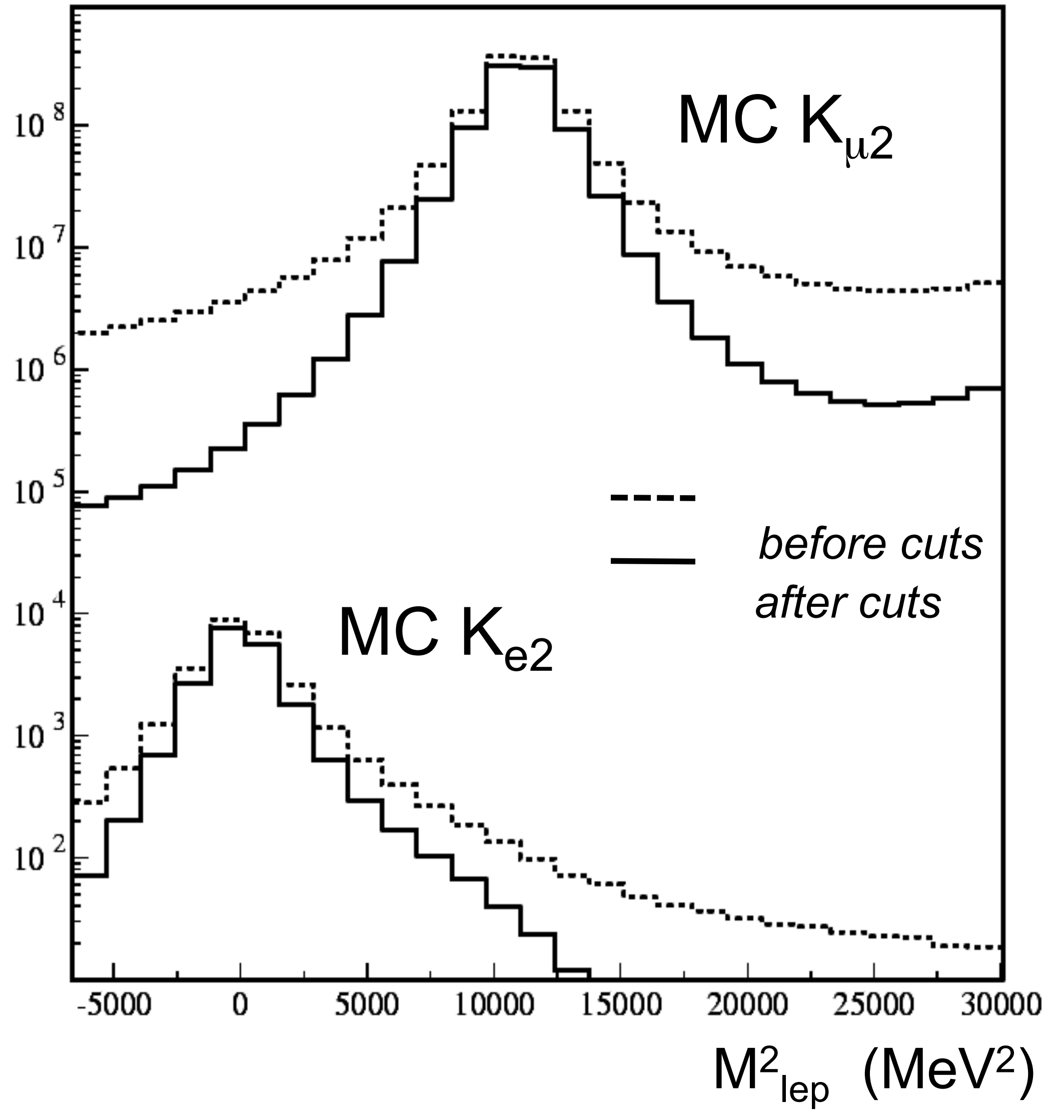
Background rejection (track quality)

after cuts, we accept ≈35% of decays in the FV

most of Ke2 events lost have bad resolution

S/B = 1/20

not enough!

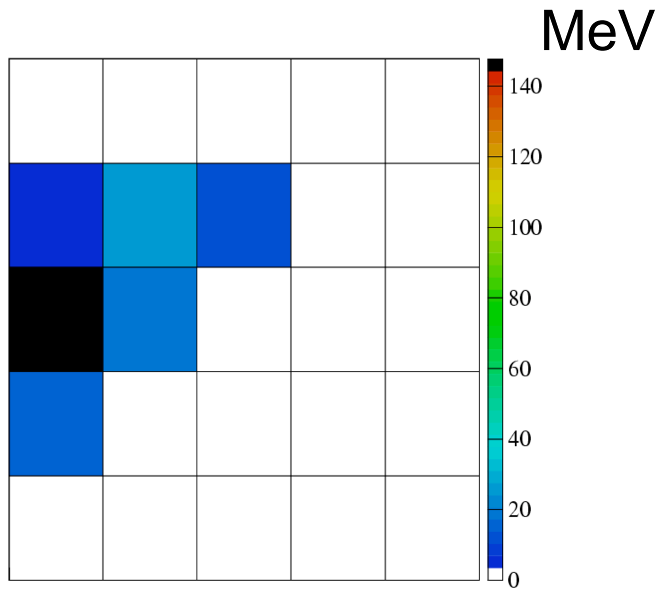


Background rejection (PID)

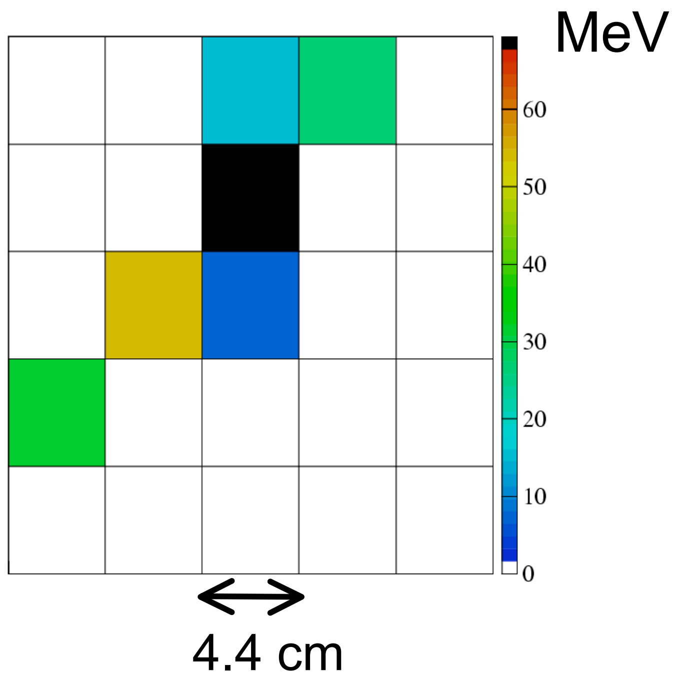
1) Particle ID exploits EMC granularity: energy deposits into 5 layers in depth

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

200 MeV electron



200 MeV muon

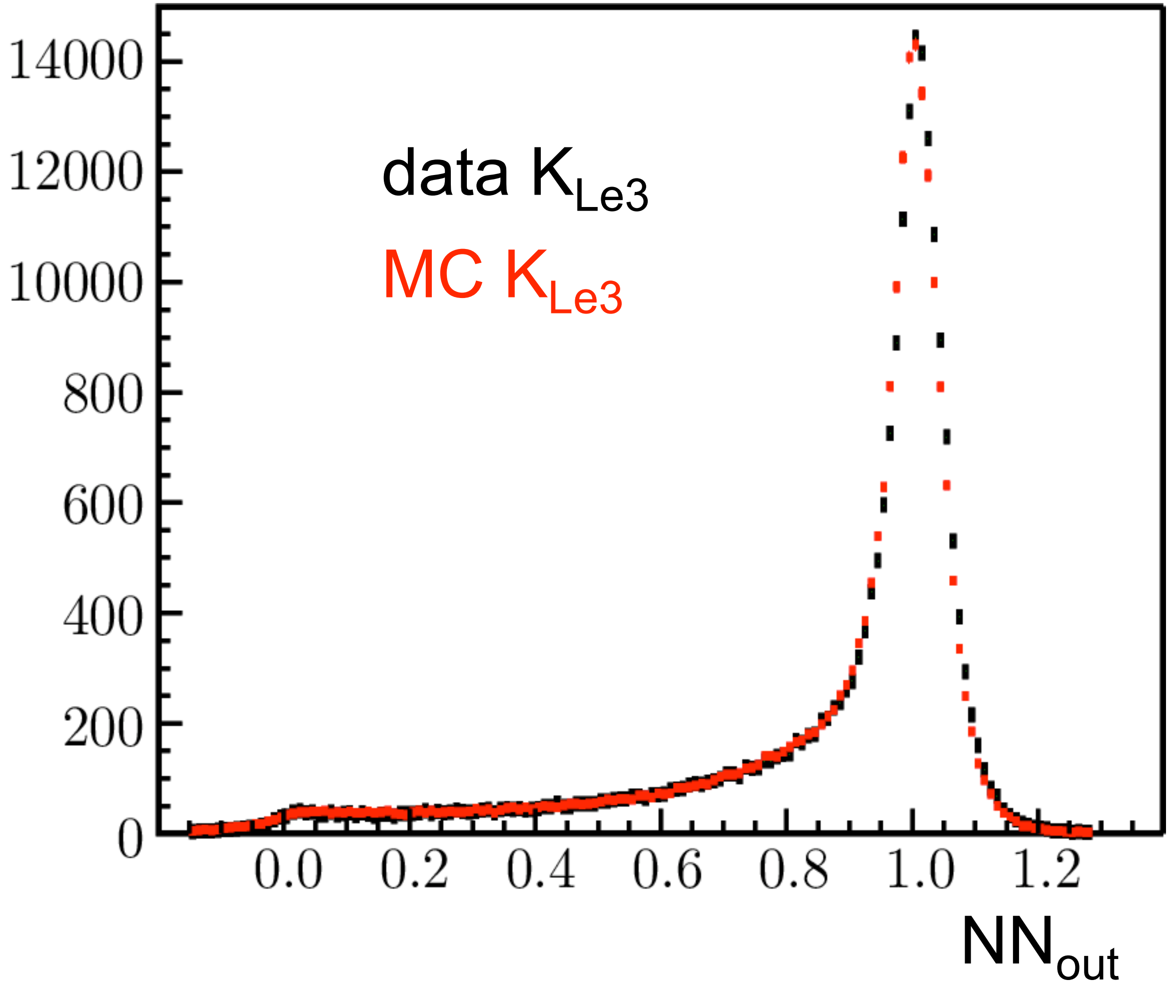


2) Add E/P and TOF

Background rejection (PID)

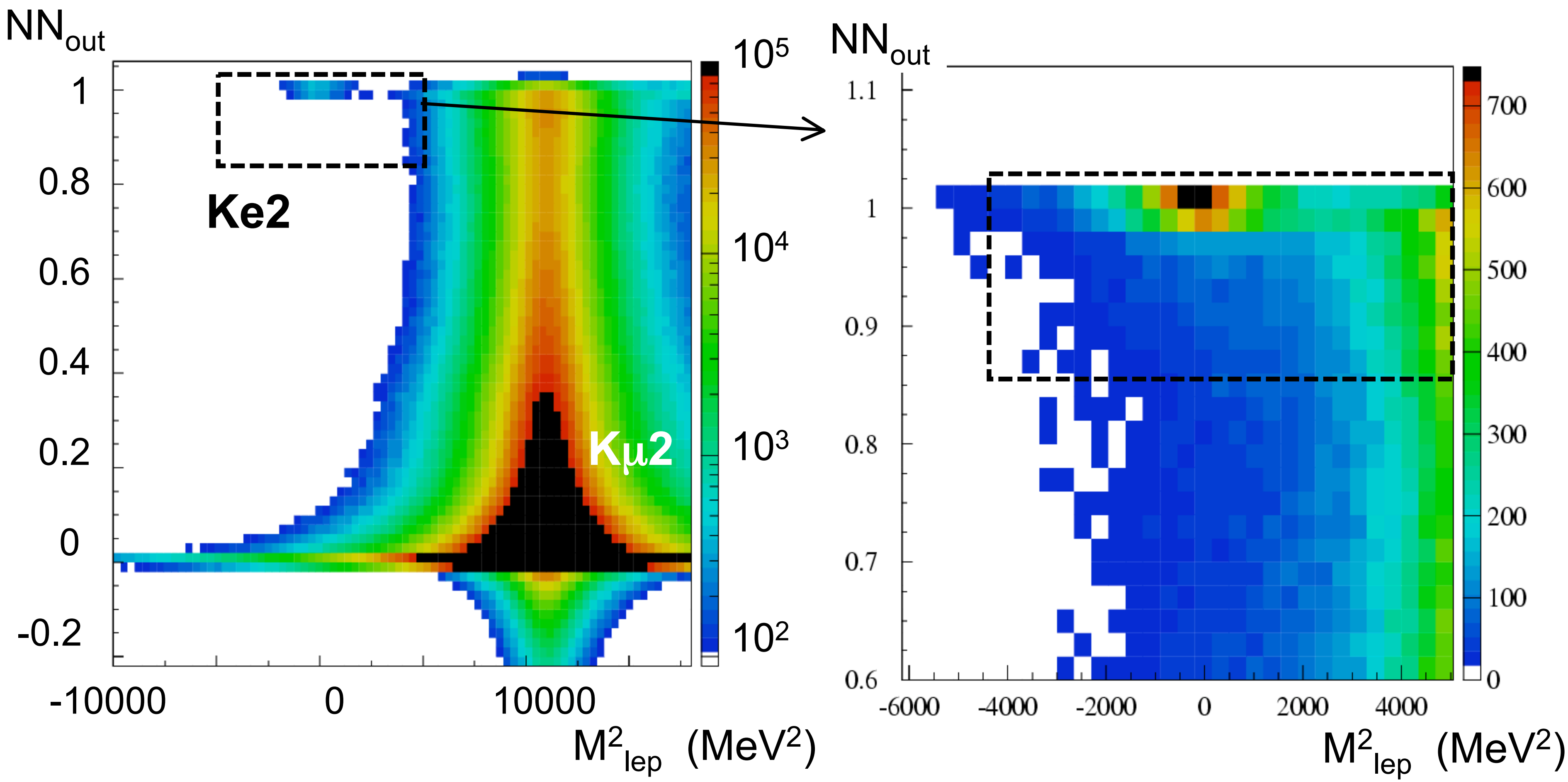
Combine PID variables using a NN

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



Background rejection (PID)

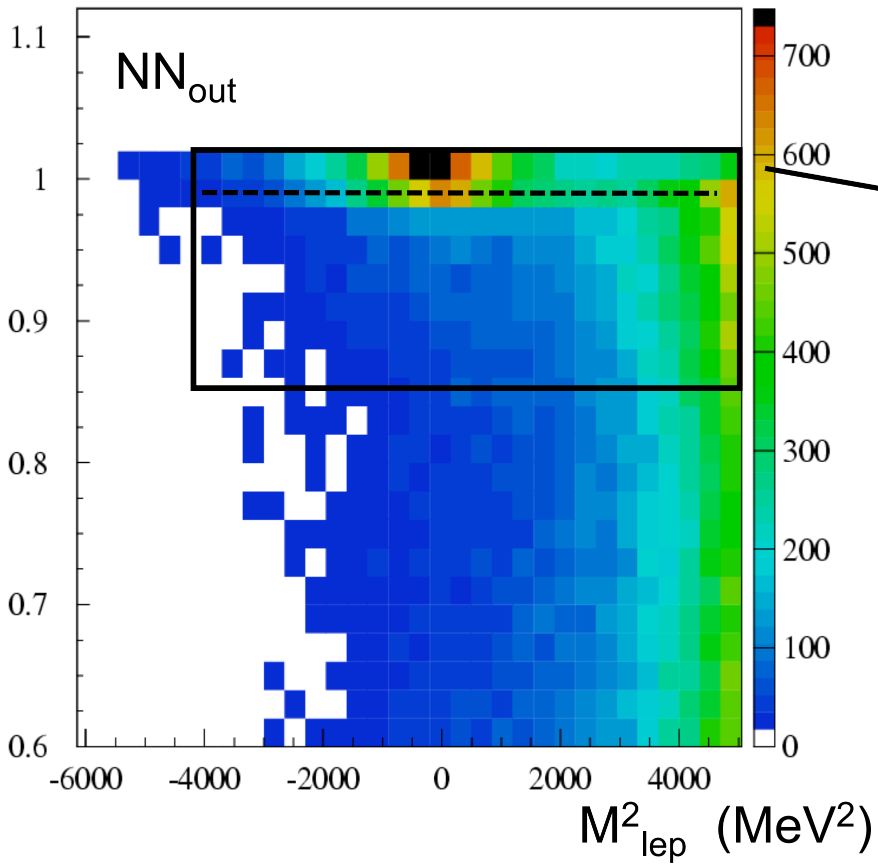
Select a region with good S/B ratio in the M^2_{lep} – NN_{out} plane



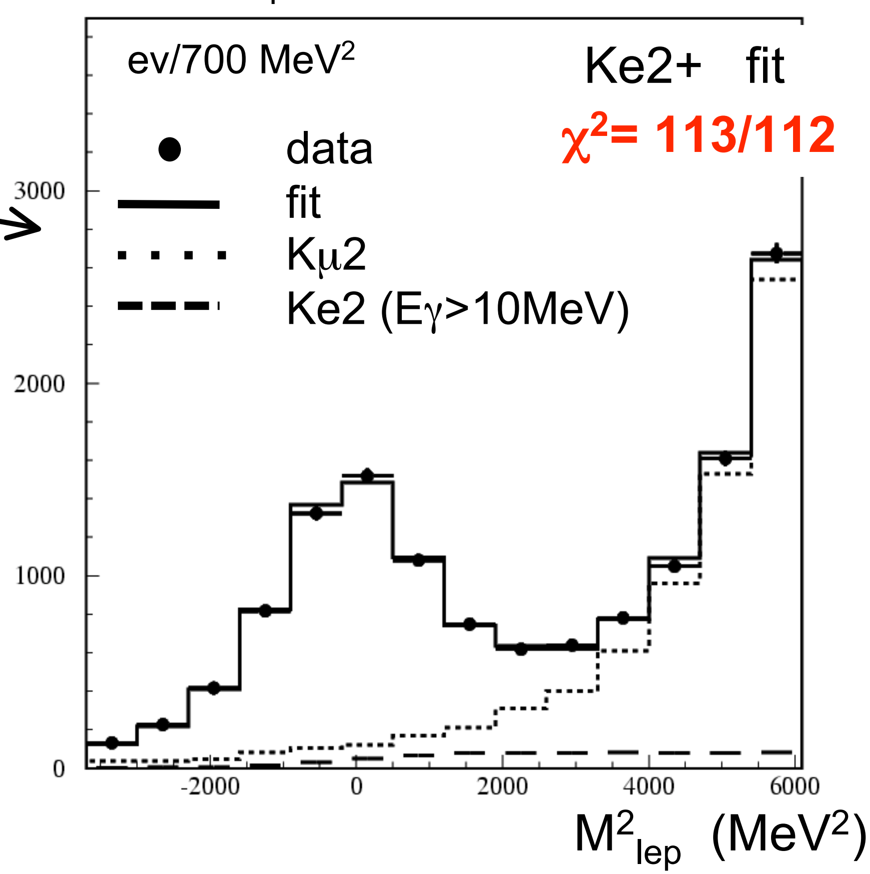
after selection: $\varepsilon = 30\%$ ($\approx$15k K_{e2}) S/B $\approx$ 5

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 $0.86 < NN_{out} < 1.02$



M^2_{lep} proj for NN_{out}>0.96

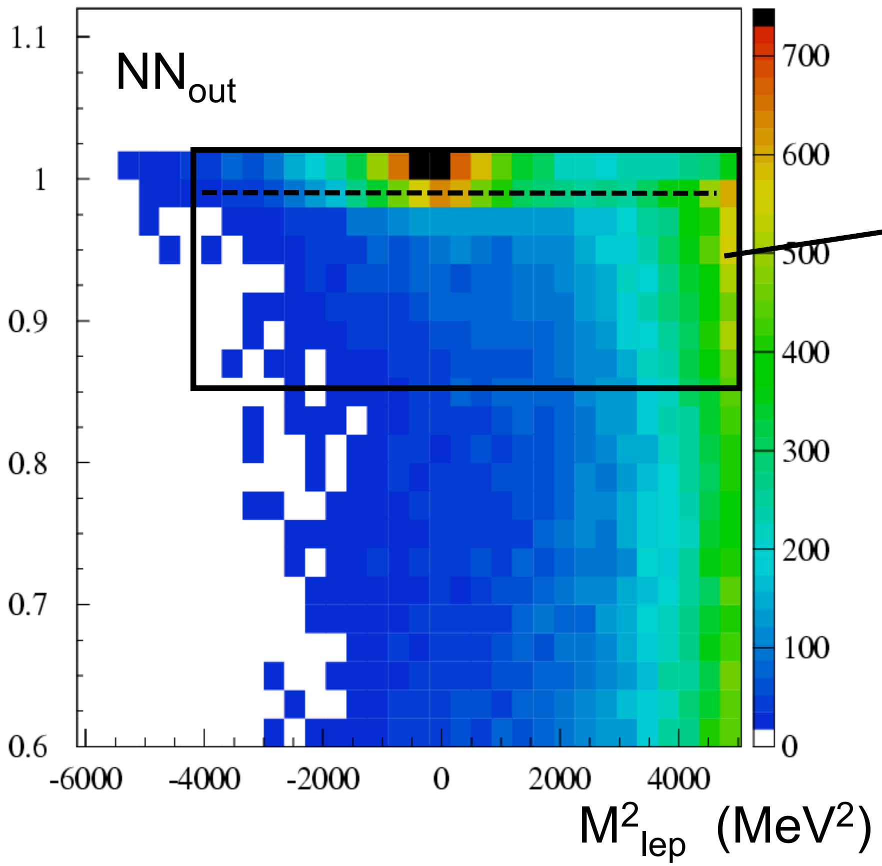


we count **7060 (102) Ke2+** **6750 (101) Ke2-** **σ_{stat}= 1%**

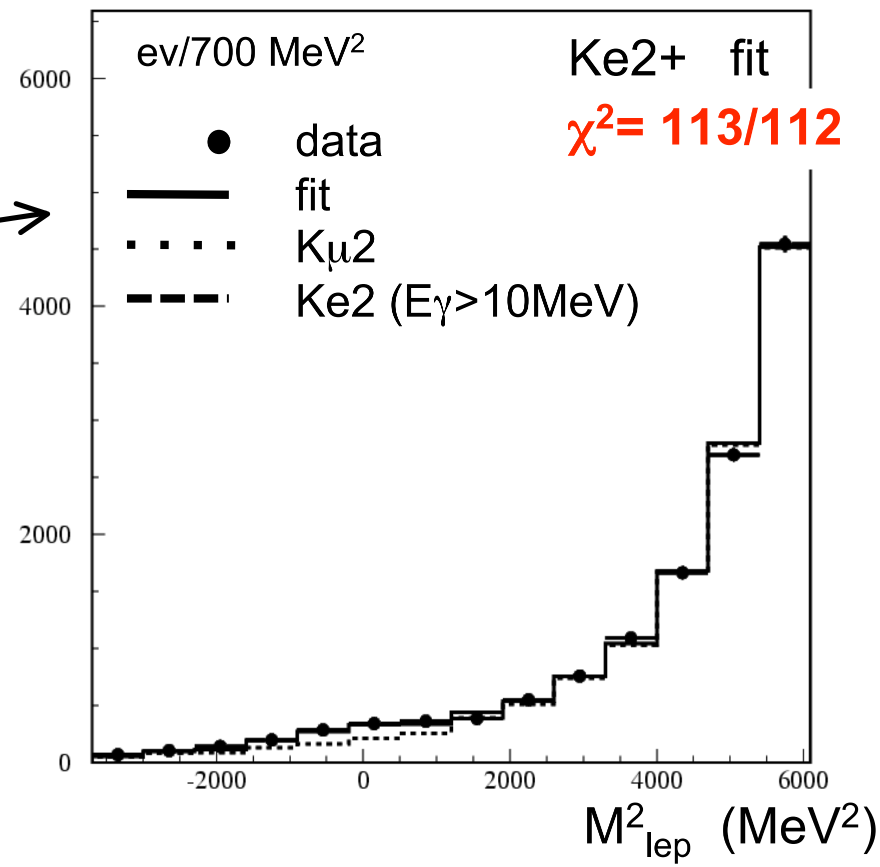
0.85% from Ke2

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 $0.86 < NN_{out} < 1.02$



M^2_{lep} proj for NN_{out} <0.96

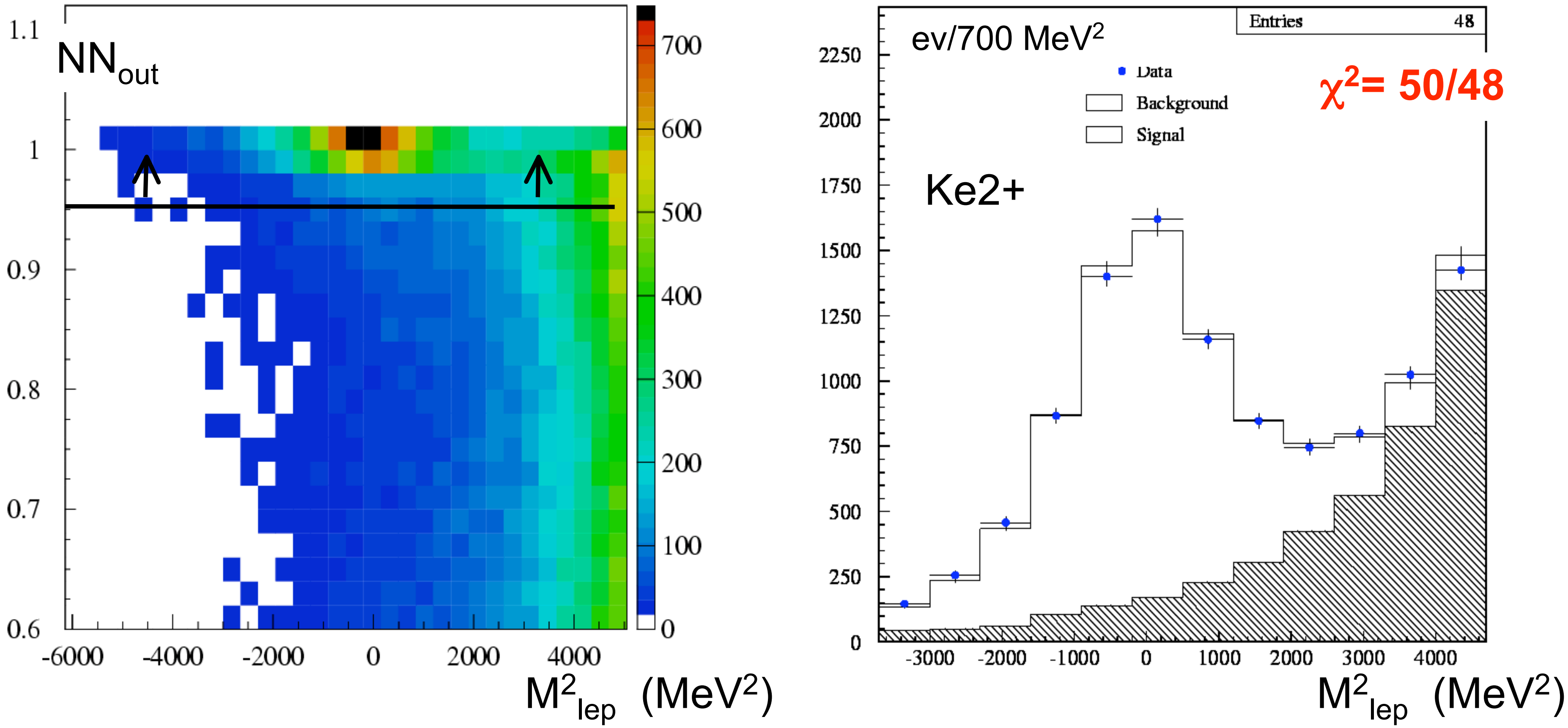


we count **7060 (102) Ke2+** **6750 (101) Ke2–** σ_{stat}**= 1%**

0.85% from Ke2

K_{e2} event counting: systematics

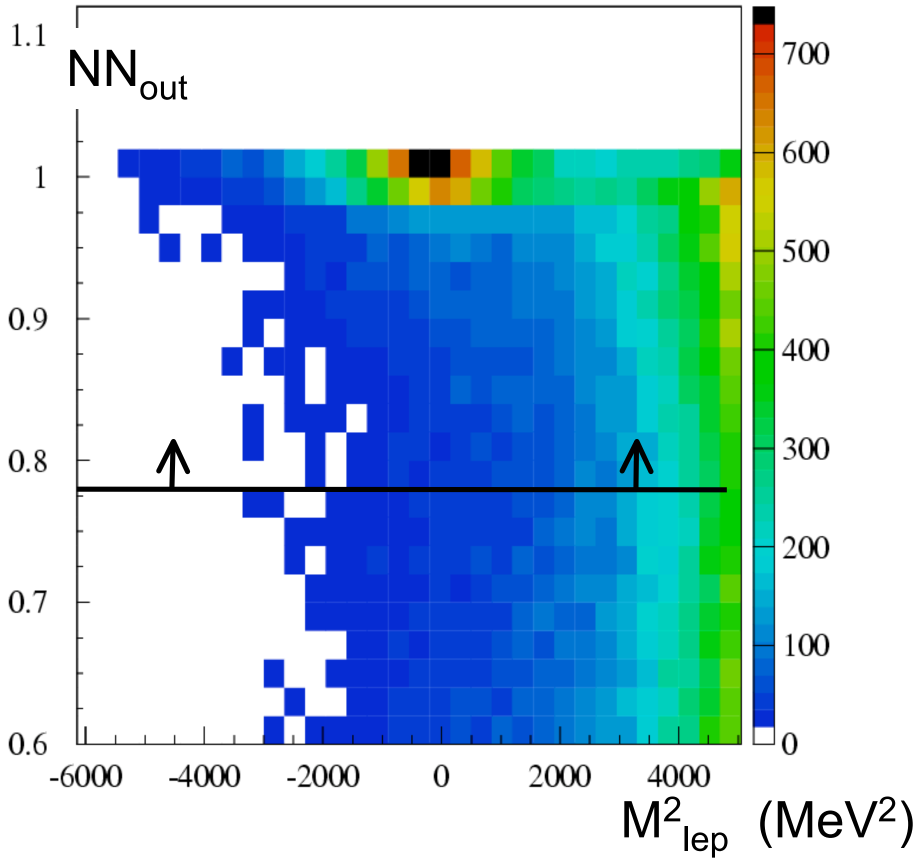
Repeat fit with different values of **max(M^2_{lep})** and **min(NN_{out})** : vary significantly (×20) bkg contamination + lever arm

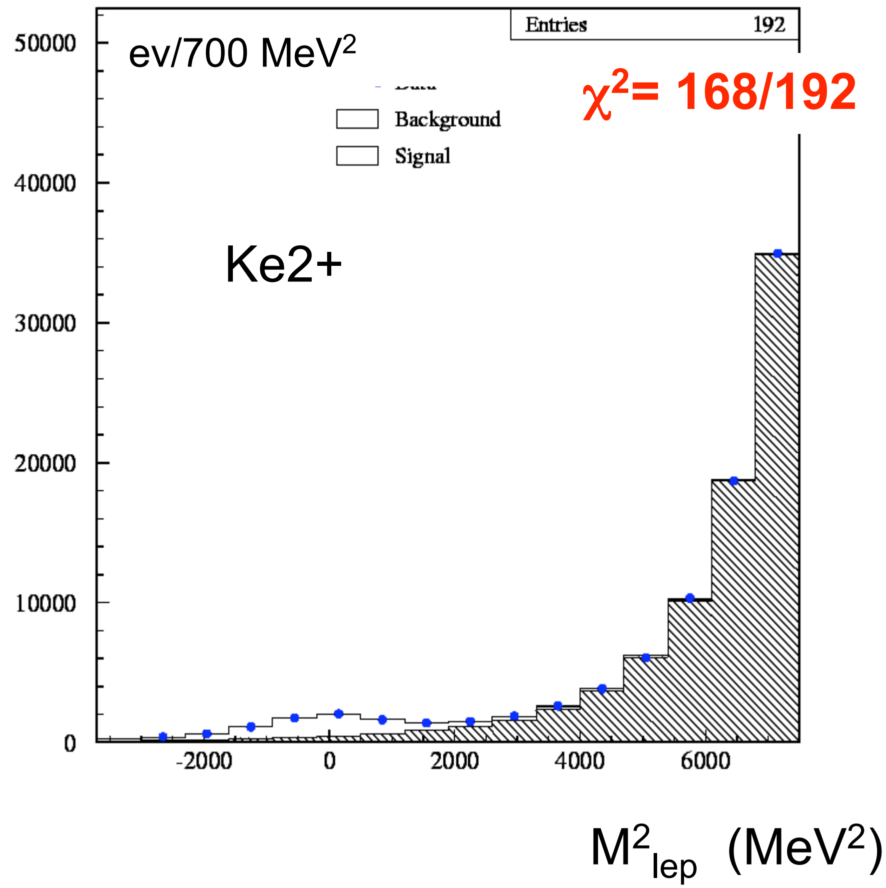


min bkg with: $-4000 < M^2_{lep} < 4650$ and $0.94 < NN_{out} < 1.02$

K_{e2} event counting: systematics

Repeat fit varying min(NN_{out}) and max(M^2_{lep}): vary significantly (×20) bkg contamination + lever arm





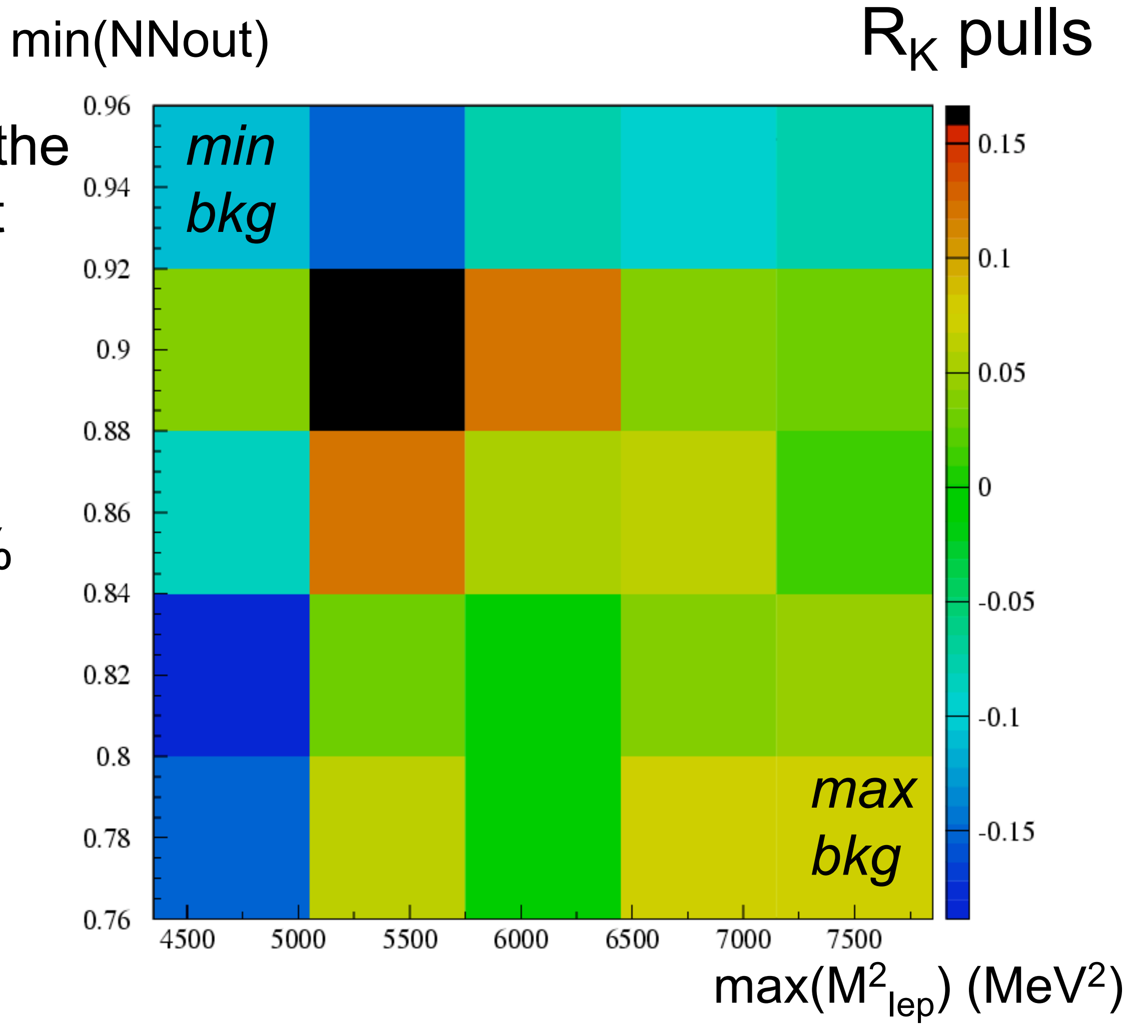
max bkg with: $-4000 < M^2_{lep} <$ 7500 and 0.78 $< NN_{out} < 1.02$

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 measurement we evaluate a 0.3% systematic error

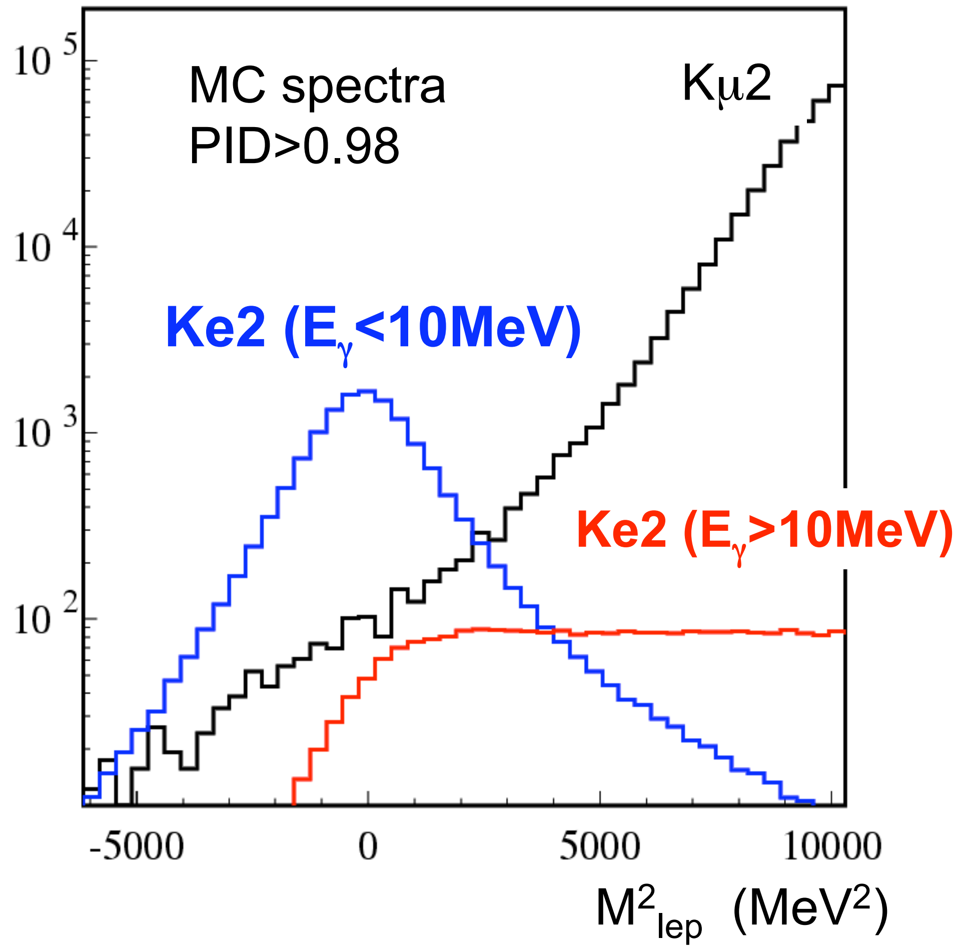


Ke2 fit: radiative corrections

The analysis above is inclusive of photons in the final state

- in our fit region we expect

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



- 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

Measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

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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*

$x = 2E_\gamma / M_K \quad y = 2E_e / M_K$

E_γ, E_e in the K rest frame

Structure Dependent

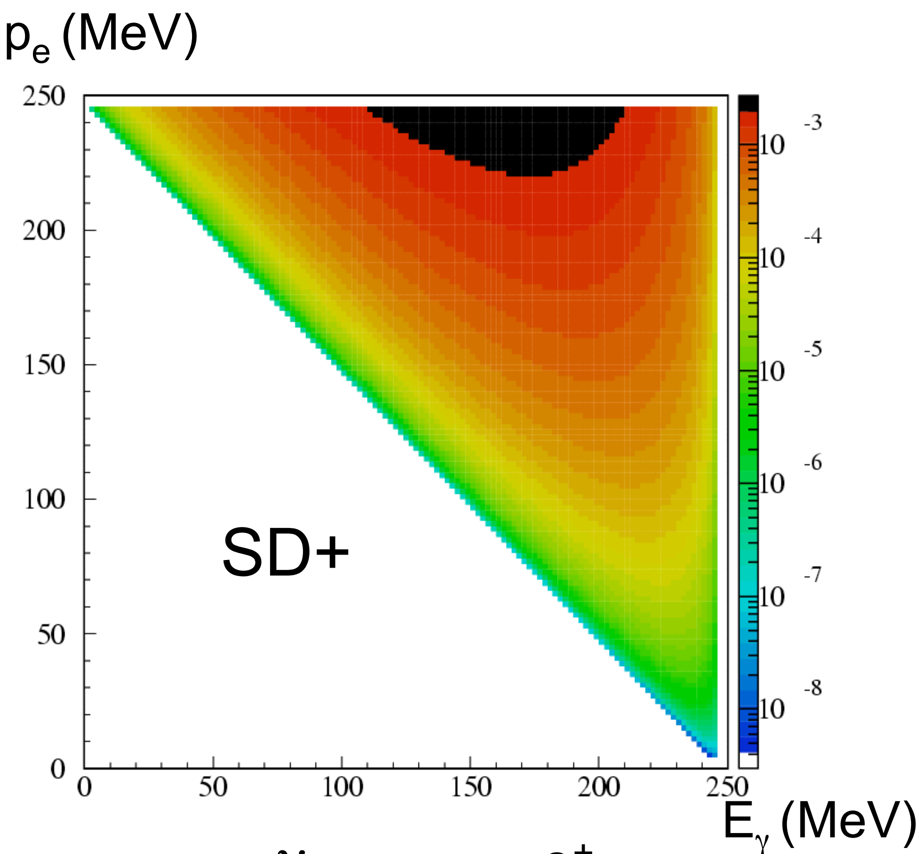
$$\rho_{SD}(x,y) = \frac{G_F^2 |V_{us}|^2 \alpha}{64\pi^2} M_K^5 \left((f_V + f_A)^2 f_{SD+}(x,y) + (f_V - f_A)^2 f_{SD-}(x,y) \right)$$

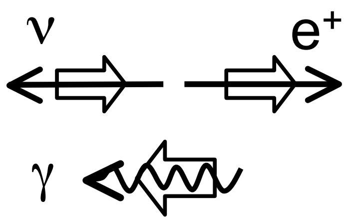
f_V , f_A : effective vector and axial couplings

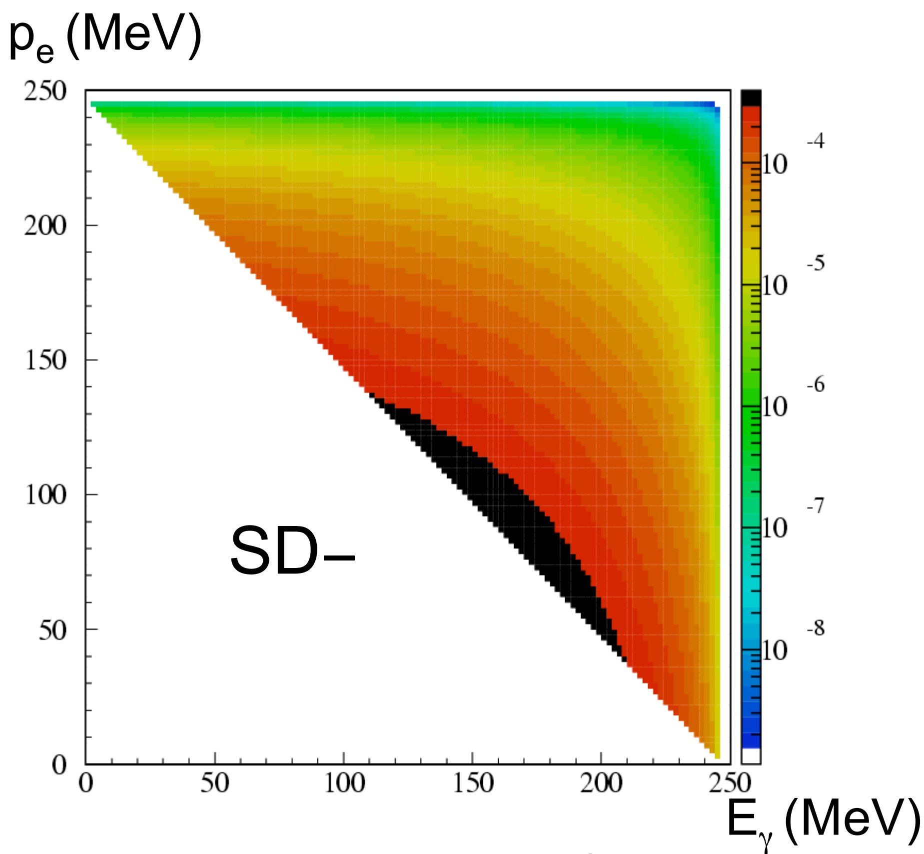
SD+ = V+A : γ polarization +

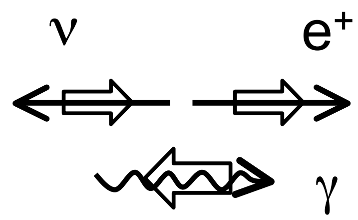
SD– = V–A : γ polarization –

Dalitz plots for SD+ and SD−









electron peaks at 250 MeV, e-γ antiparallel

electron peaks 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 ($\lambda \approx 0.4$)

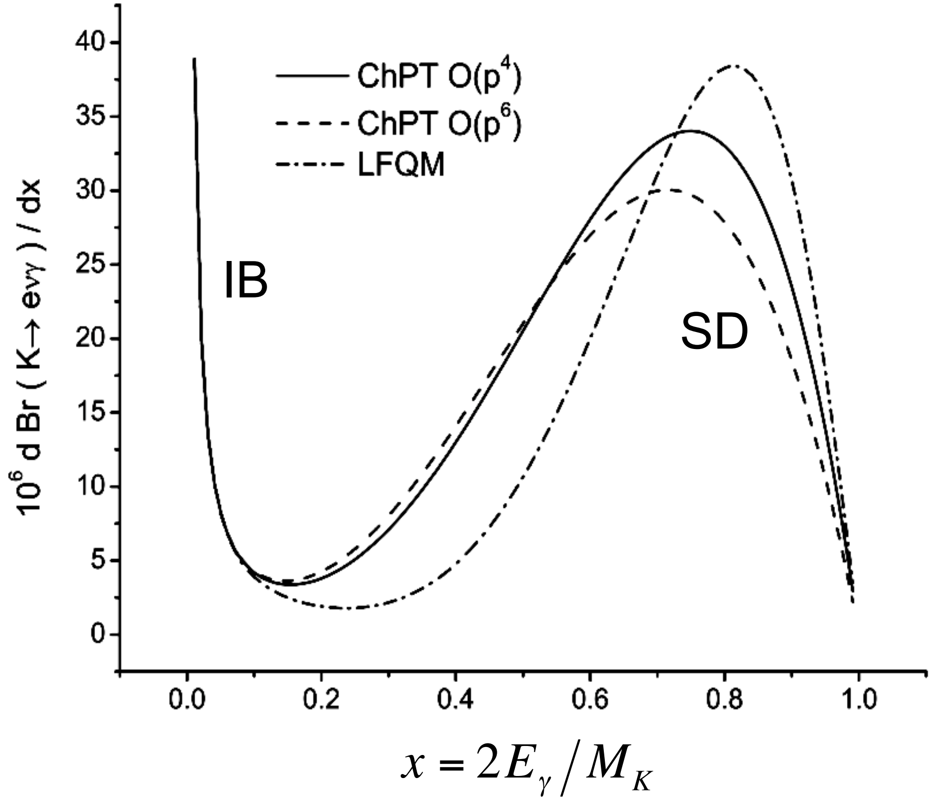
Ametller, Bijnens, Bramon, Cornet 93
Geng, Ho, Wu 04
Chen, Geng, Lih 08

3) LFQM:

non trivial x dependence

$f_V = f_A = 0$ at x=0

Chen, Geng, Lih 08



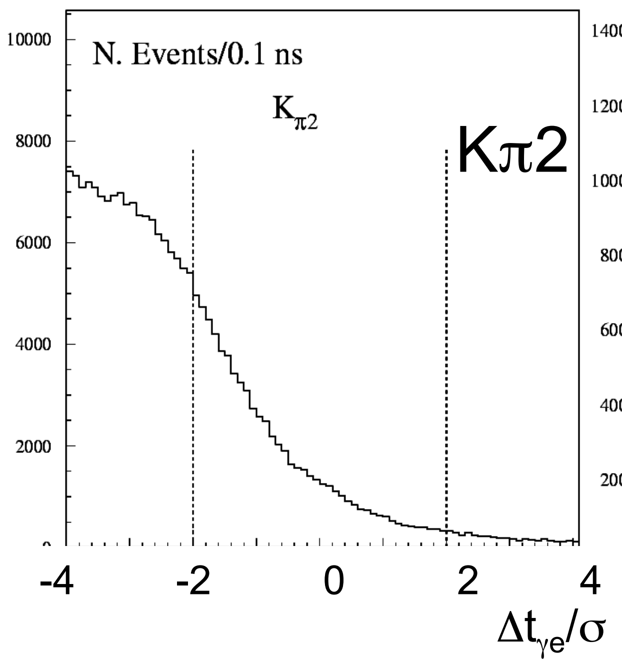
from Phys. Rev. D77 (2008) 014004

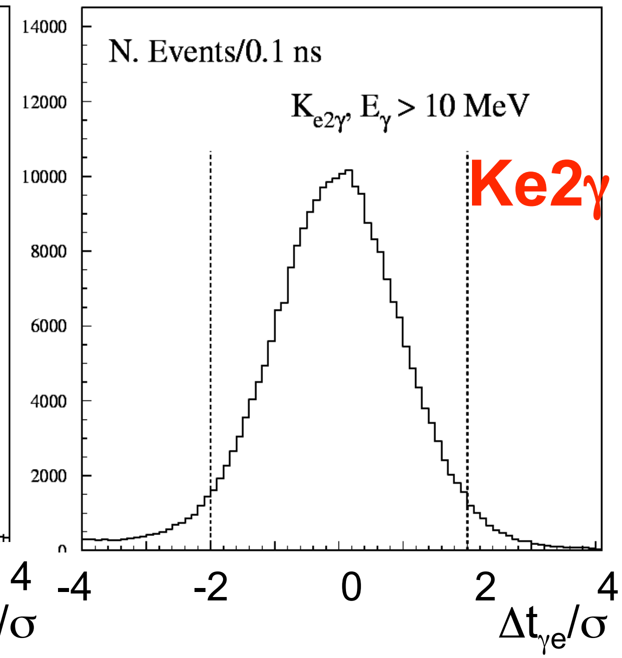
Ke2γ selection: photon detection

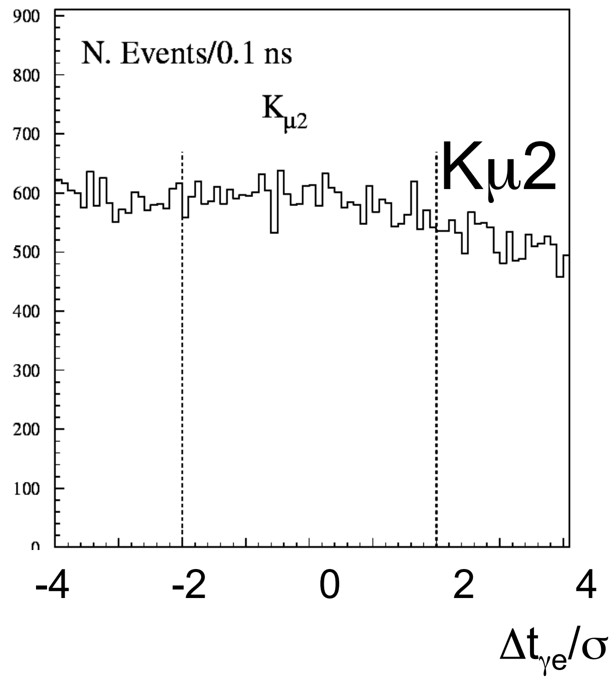
- A photon is required with energy $E_\gamma^{calo} > 20$ MeV to reject bkg (we loose $Ke2_{IB}$, too)
- Time of arrival compatible with that of the event (electron):

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

(r = distance from K decay vtx)







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

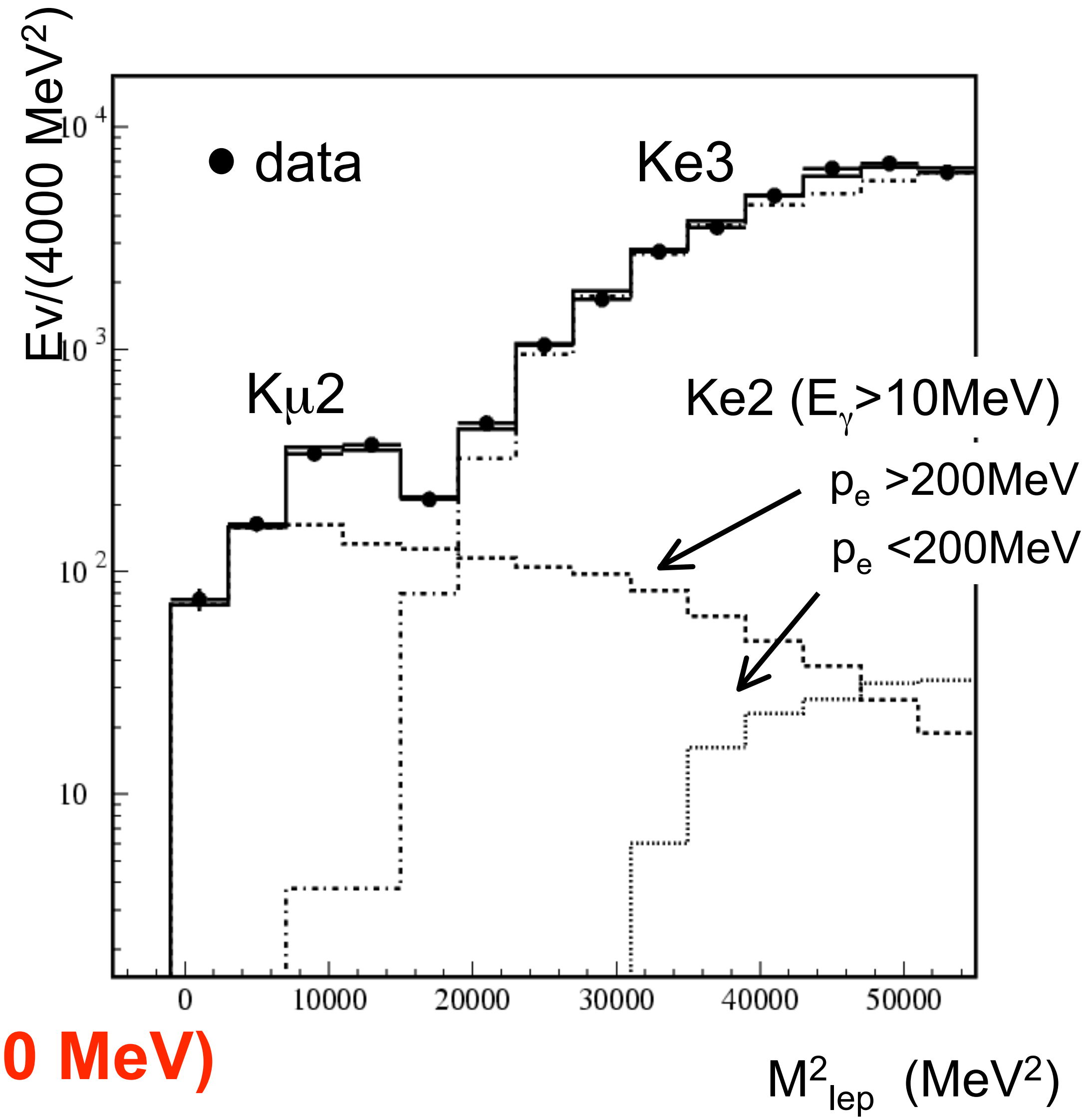
Fake γ from accidental bkg

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

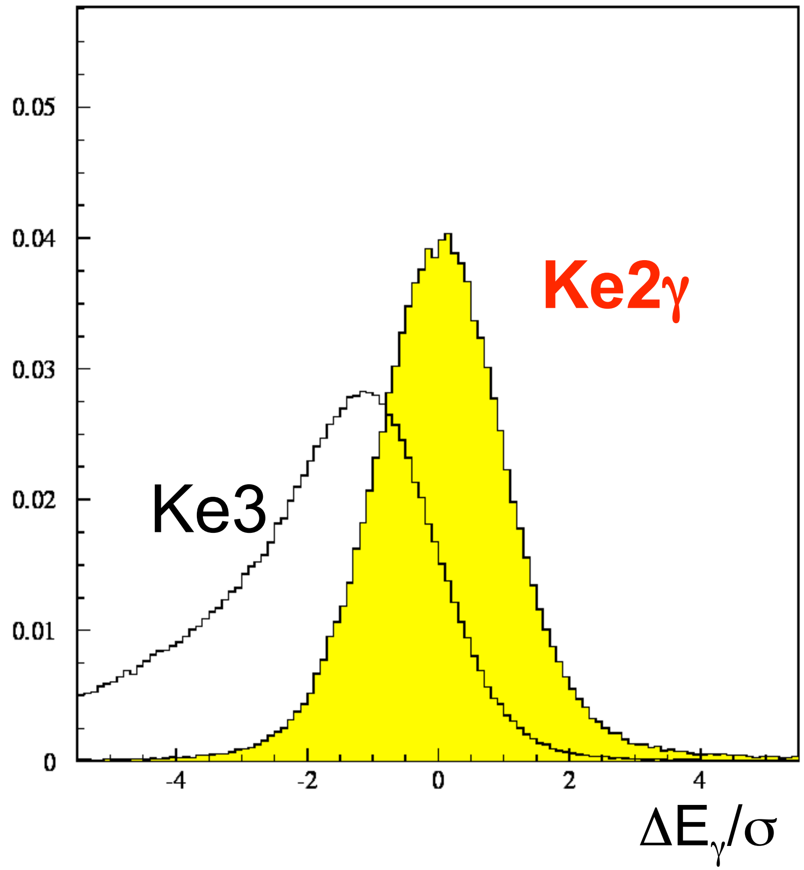
Ke2γ selection: photon matching

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):

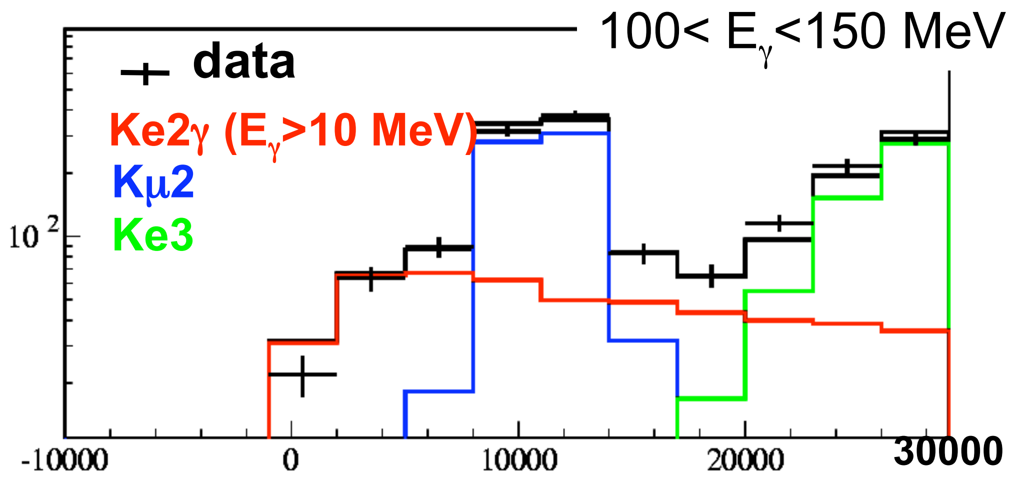
(10, 50) (50,100) (100,150) (150,200) (200,250)

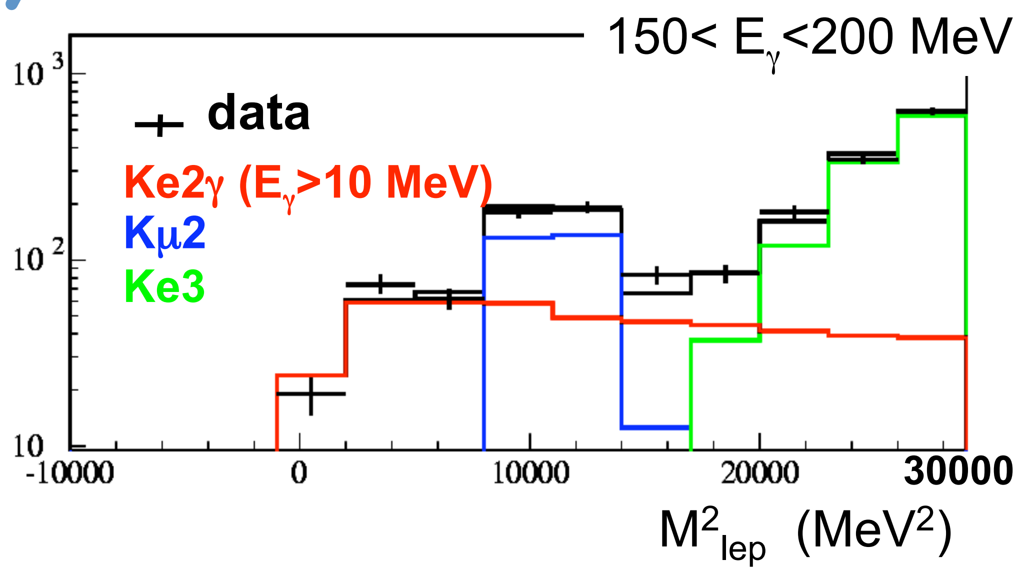
- Most populated bins

100< E_γ<150 MeV: N = 463 ± 32, χ^2 = 87/106

150< E_γ<200 MeV: N = 494 ± 38, χ^2 = 100/106

Fit projections on M^2_{lep} axis

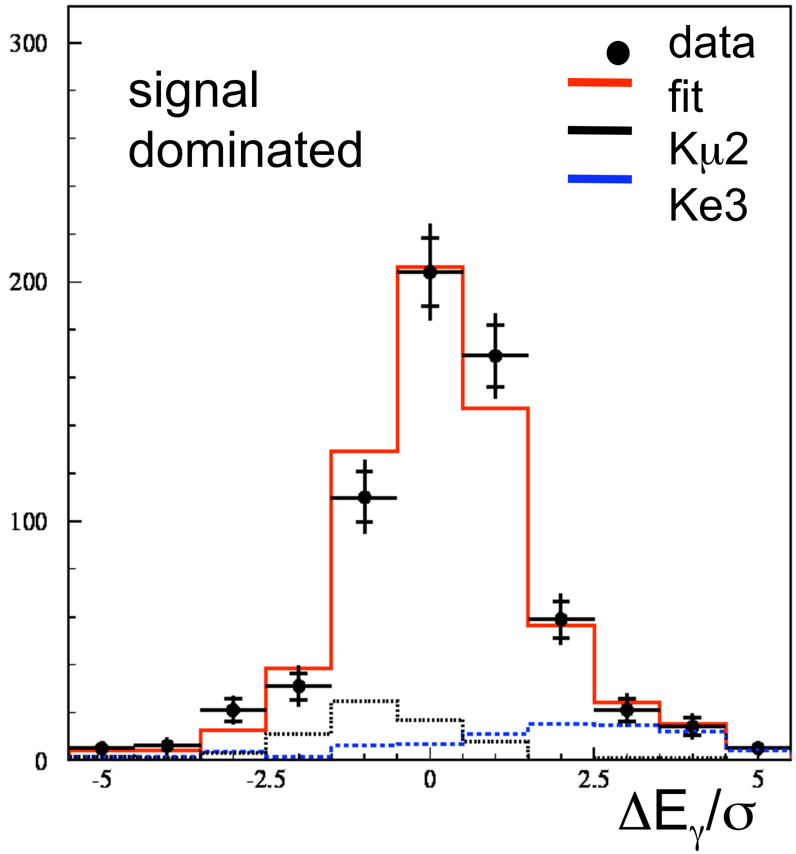


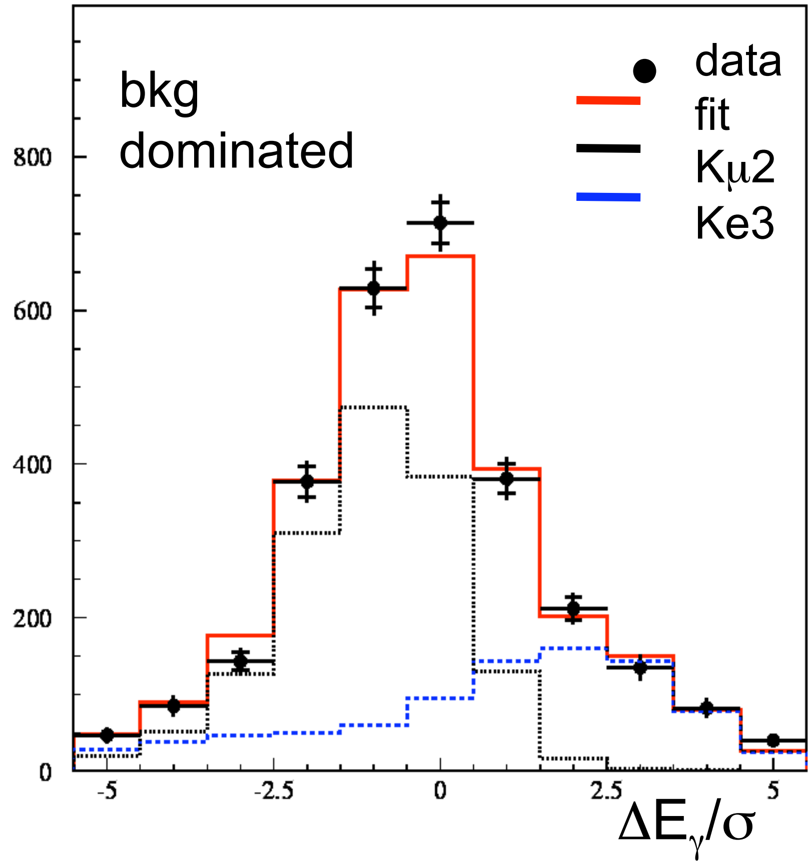


Ke2γ event counting

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(p^4)

We measure:

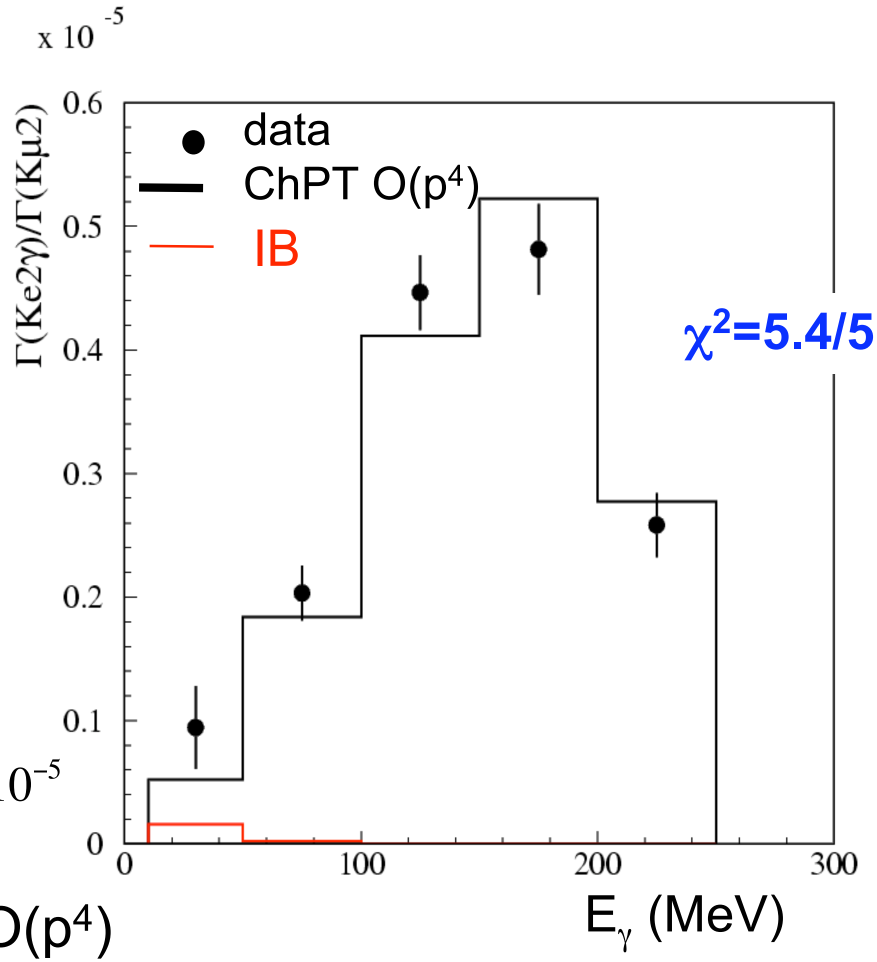
$$\frac{1}{\Gamma(K_{\mu 2})}\frac{d\Gamma(K_{e2},E_\gamma > 10MeV, p_e^* > 200MeV)}{dE_\gamma}$$

Data are **compared** with ChPT O(p^4) calculation

Integrating we obtain:

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

in agreement with 1.447×10^{-5} of ChPT O(p^4)



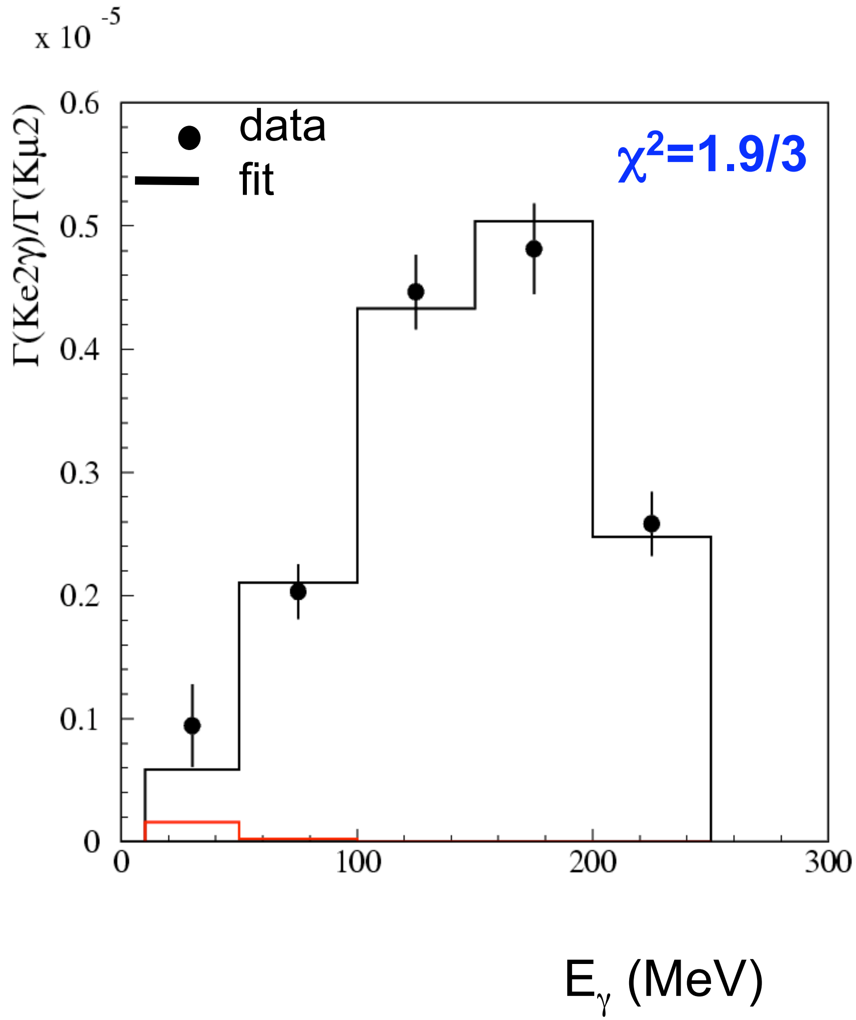
This confirm the SD content of our MC, evaluated with ChPT O(p^4), within an accuracy of 4.6% and allows a 0.2% systematic error on Ke2$_{IB}$ to be assessed

Ke2γ spectrum: fit to ChPT $O(p^6)$

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

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

- 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:

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

$$\lambda = 0.38 \pm 0.21$$

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

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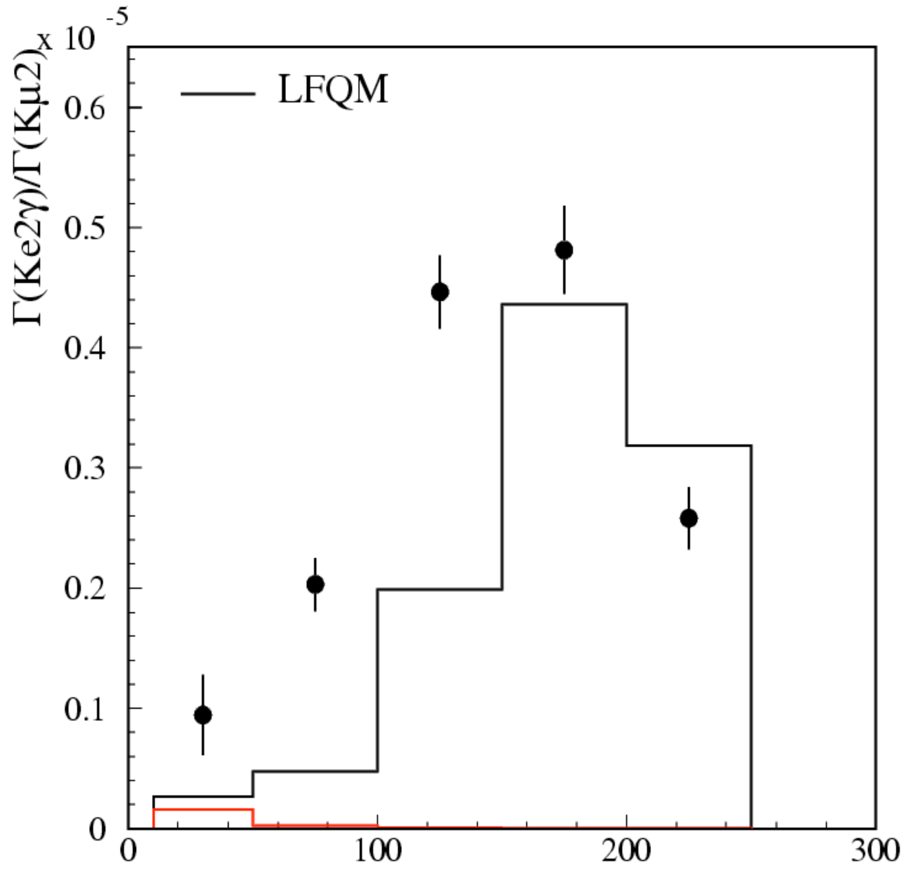
Ke2γ spectrum vs LFQM

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



E_γ (MeV)

Measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$

- Introduction
- K_{e2} events counting
- Study of direct emission in $K_{e2\gamma}$
- **Results on R_K**

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

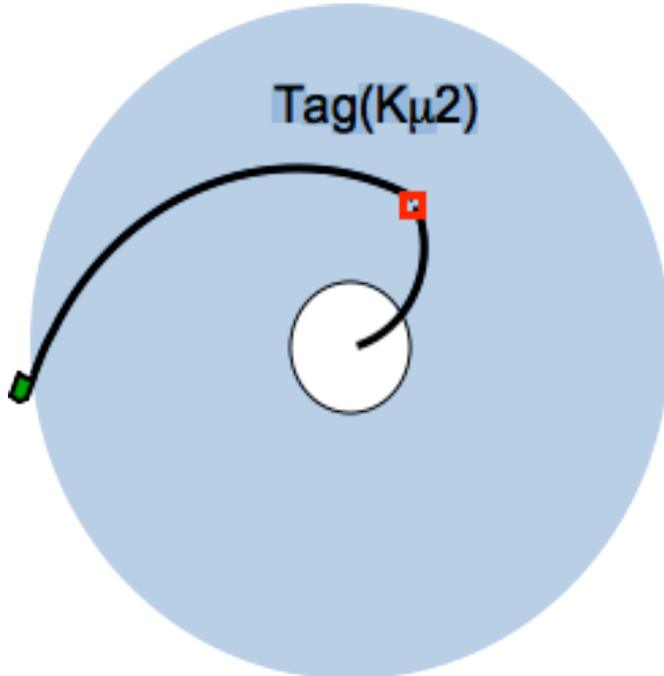
we obtain:

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

Control samples for tracking efficiencies

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

0) Tagging decay ($K\mu2$ or $K\pi2$) coming from IP

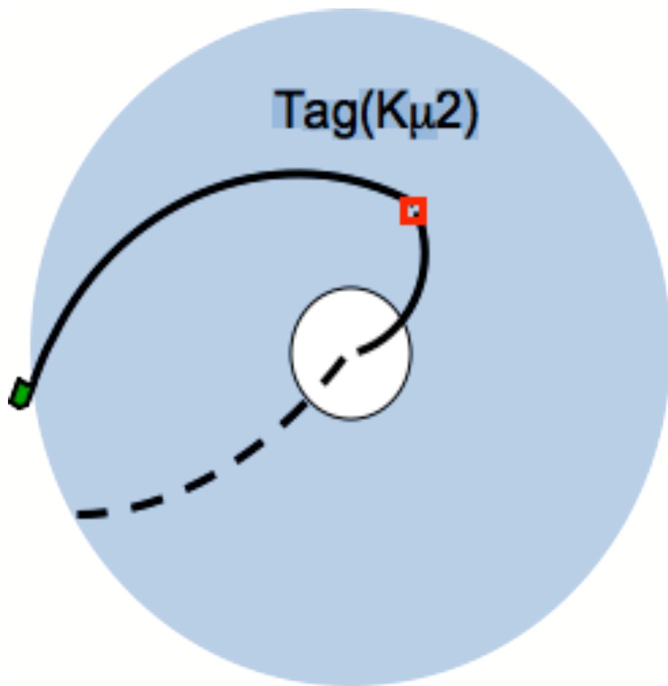


Control samples for tracking efficiencies

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

0) Tagging decay ($K\mu2$ or $K\pi2$) coming from IP

1) Tagging decay ($K\mu2$ or $K\pi2$):
reconstruction of the opposite charge kaon flight path



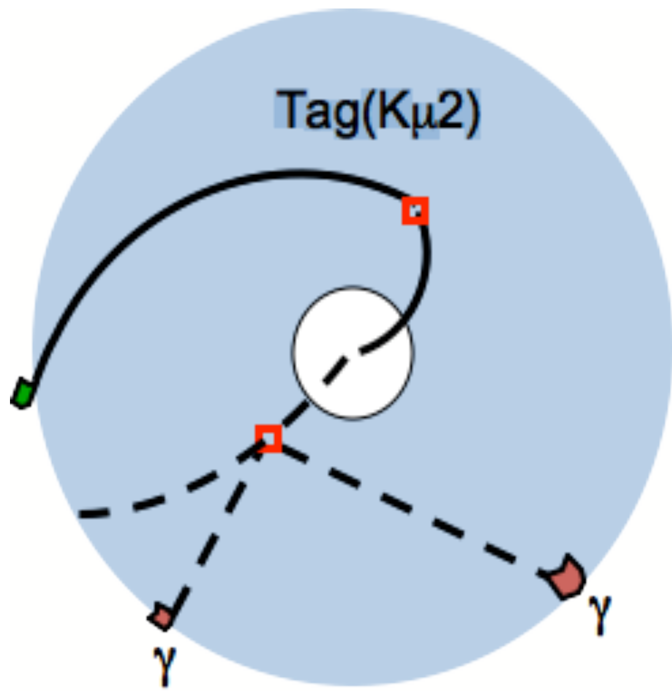
Control samples for tracking efficiencies

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

0) Tagging decay ($K\mu2$ or $K\pi2$) coming from IP

1) Tagging decay ($K\mu2$ or $K\pi2$): reconstruction of the opposite charge kaon flight path

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



Control samples for tracking efficiencies

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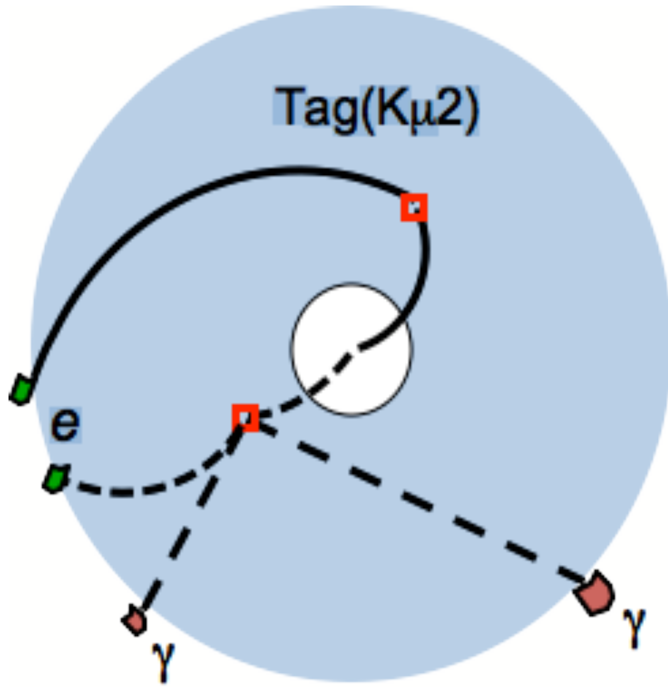
1) Tagging decay ($K\mu2$ or $K\pi2$): reconstruction of the opposite charge kaon flight path

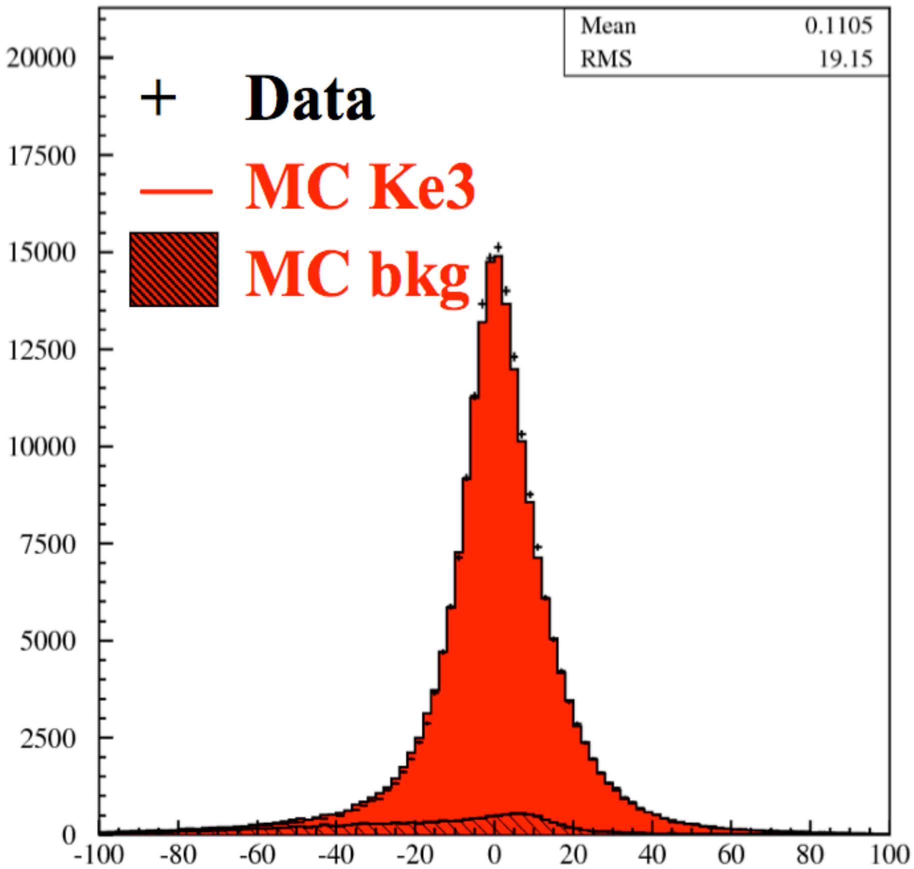
2) A $\pi^0 \to \gamma\gamma$ decay vertex is reconstructed along the K decay path, using TOF

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

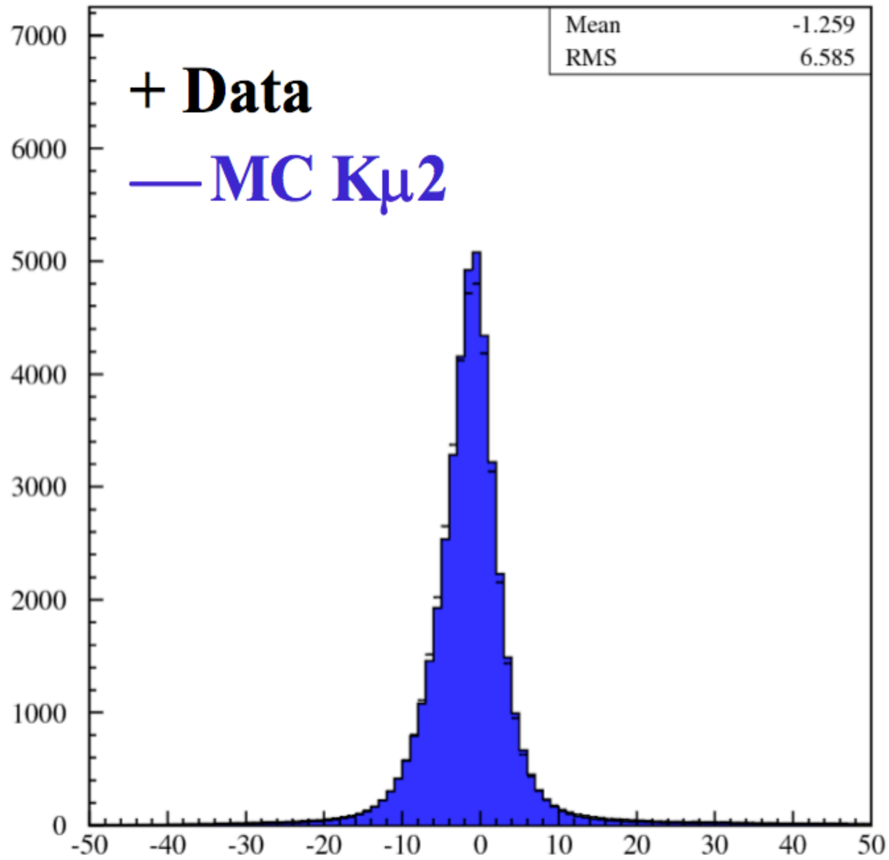


➡ We evaluate the K + electron kink reconstruction efficiency

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	**0.2%**	K_L control samples

Total Syst **0.8%**

0.6% from statistics of control samples

R_K : KLOE result

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

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:

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

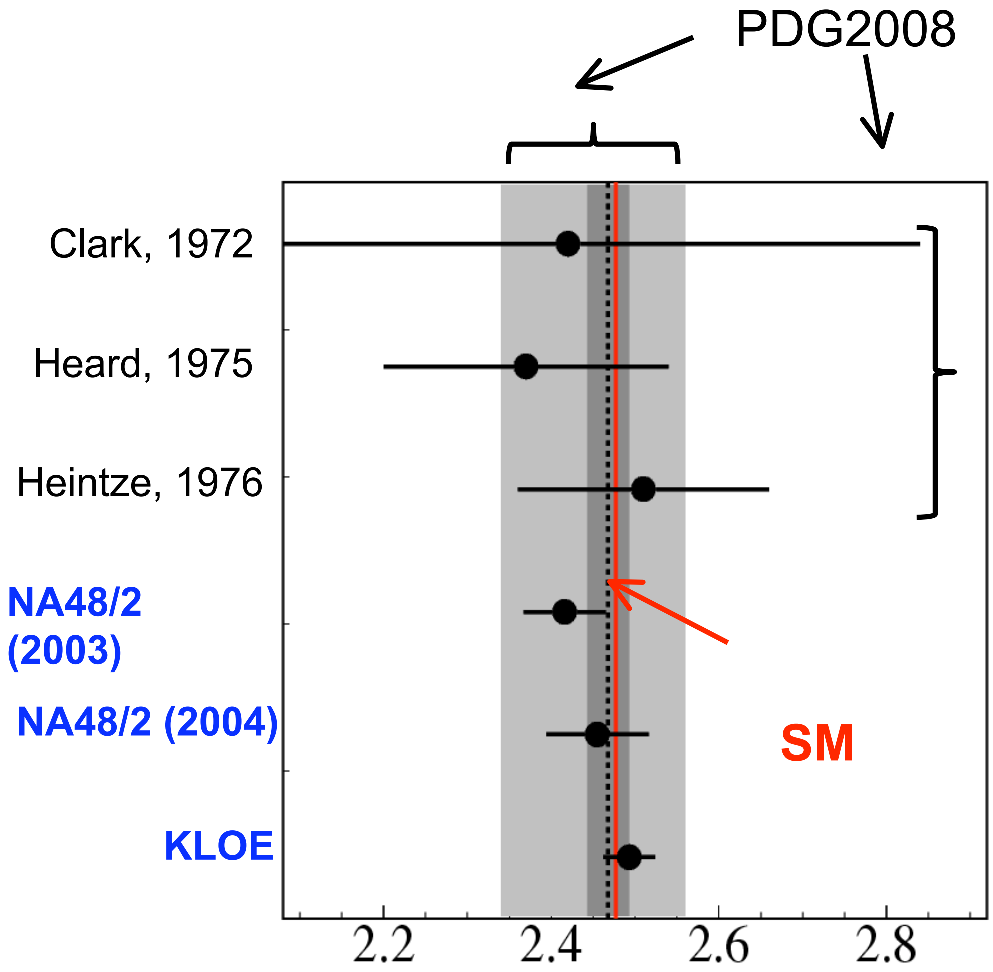
4.5% accuracy

New world average:

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

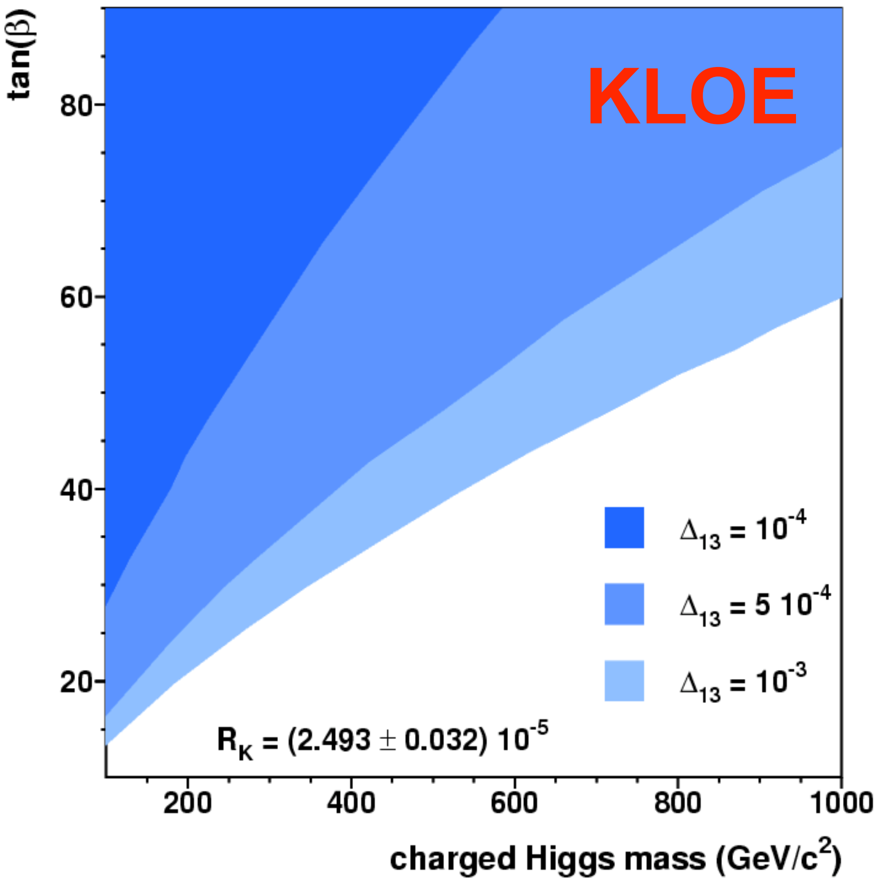
1% accuracy

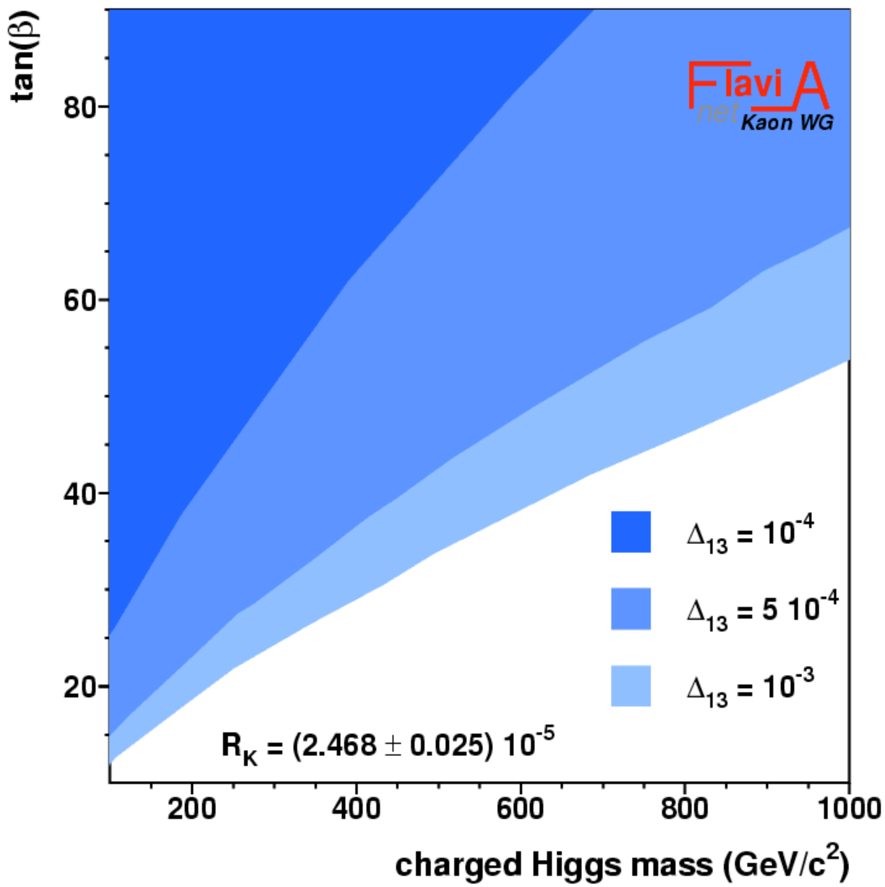
$R_K^{SM} = 2.477(1) \times 10^{-5}$



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}





Conclusions

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

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

This result confirms the SM prediction within the 1.3% accuracy, and can been used to set constraints on the parameter space of the MSSM with lepton flavor violation

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

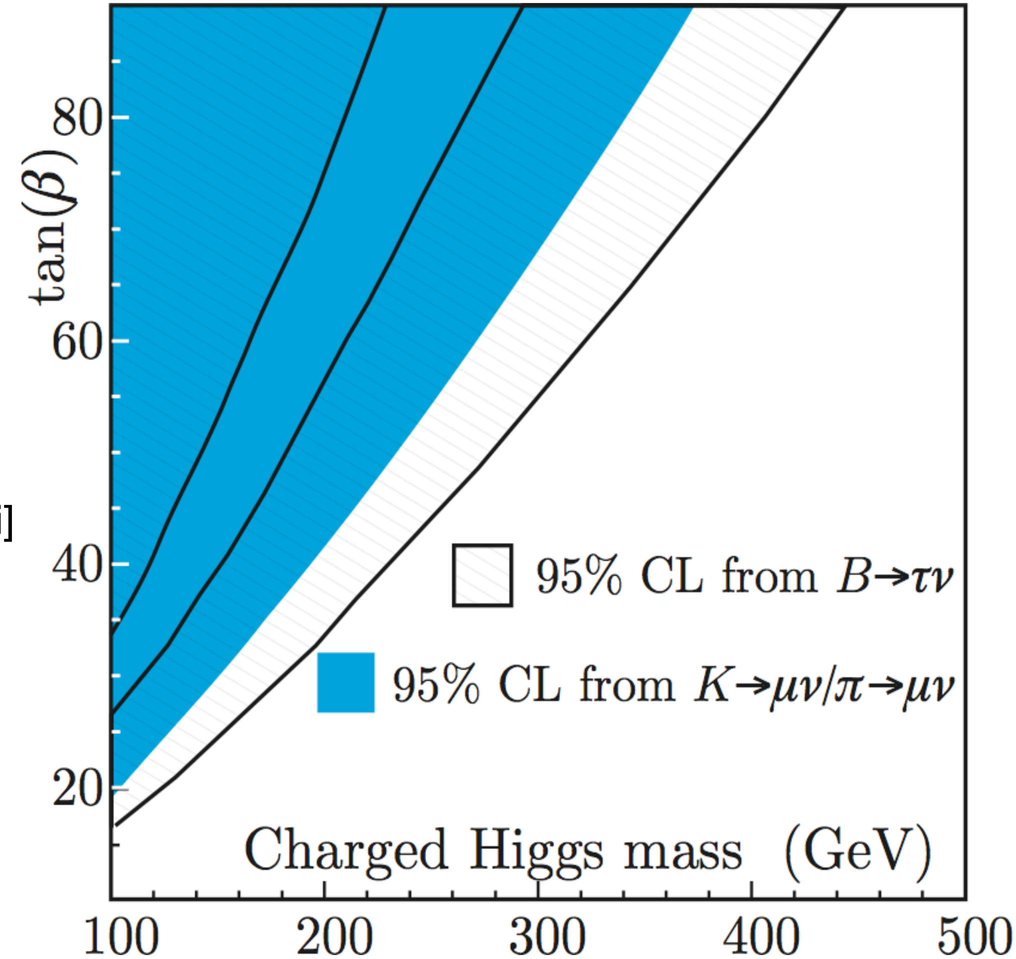
$K_{\mu 2}$: sensitivity to new physics

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

$$R_{l23} = \left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{l3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right|$$

$$= \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left(1 - \frac{m_{\pi^+}^2}{m_{K^+}^2}\right) \frac{\tan^2\beta}{1 - \varepsilon_0 \tan\beta} \right|$$

[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, $\tan\beta > 2$

KLOE measurement of kaon parameters

$K_{S\,e3}$	PLB 636 (2006) 173	***K_S BRs***
$K_S \to \pi\pi$	EPJC 48 (2006) 767	
$K_S \to \gamma\gamma$	JHEP 05(2008) 051	
K_L decay distribution (τ)	PLB 626 (2005) 15	***K_L BRs lifetime FFs***
K_L decays and lifetime	PLB 632 (2006) 43	
$K_L \to \pi^+\pi^-$	PLB 638 (2006) 140	
$K_L \to \gamma\gamma$	PLB 566(2003) 61	
K^0 mass	JHEP 12(2007)073	
$K_{Le3\gamma}$	EPJC 55 (2008) 539	
ff K_{Le3}	PLB 636 (2006) 166	
ff $K_{L\mu3}$	JHEP 12(2007)105	
$K^+_{\mu2}$	PLB 632 (2006) 76	***$K^\pm$ BRs lifetime***
K^+ lifetime	JHEP 01(2008)073	
K^+_{l3}	JHEP 02(2008)098	
$K^+_{\tau'}$	PLB 597 (2004) 139	
$K^+_{\pi2}$	PLB 666 (2008) 305	

KLOE V_{us} JHEP 04(2008)059