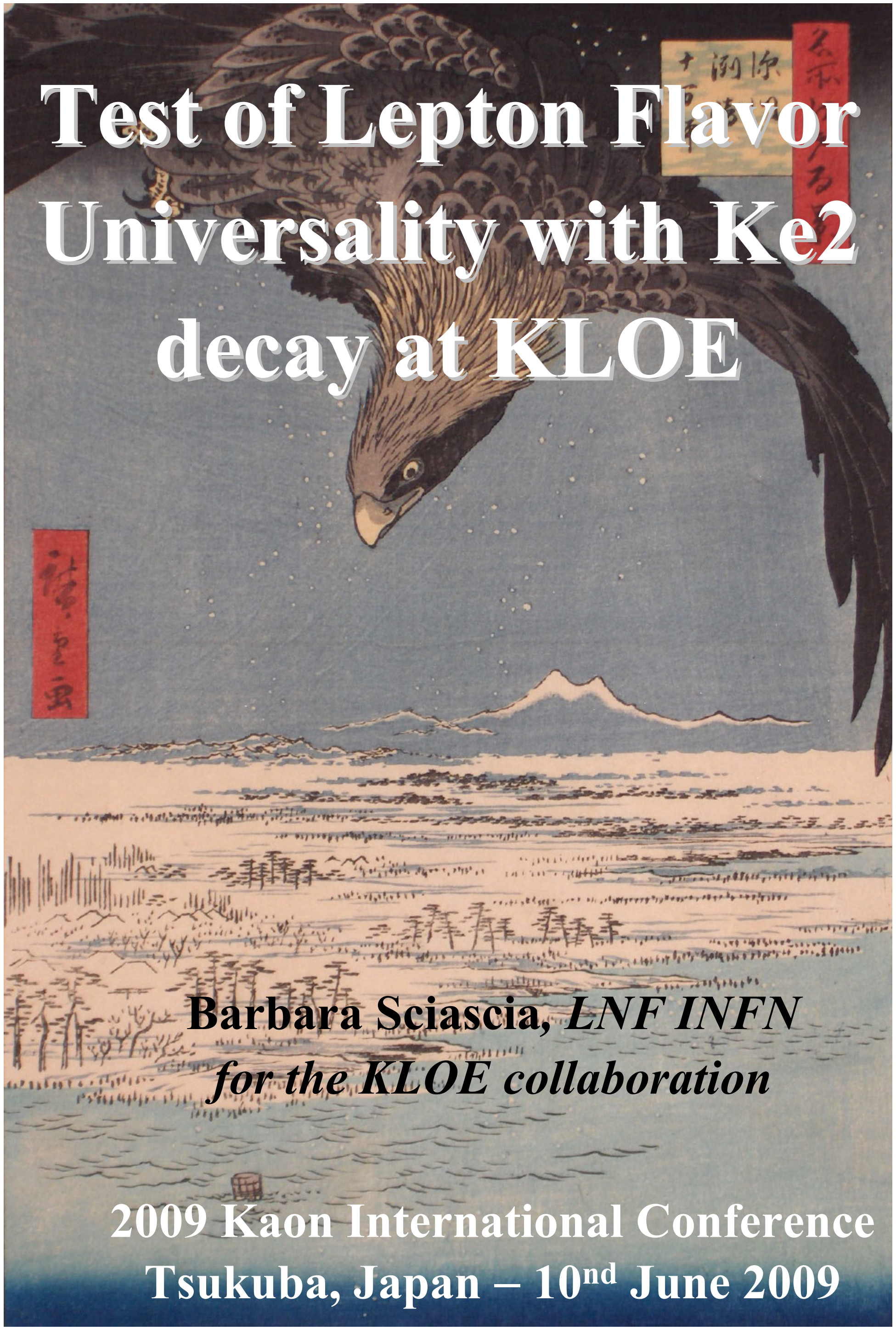


Test of Lepton Flavor Universality with Ke2 decay at KLOE

Barbara Sciascia, *LNF INFN*

for the KLOE collaboration

2009 Kaon International Conference

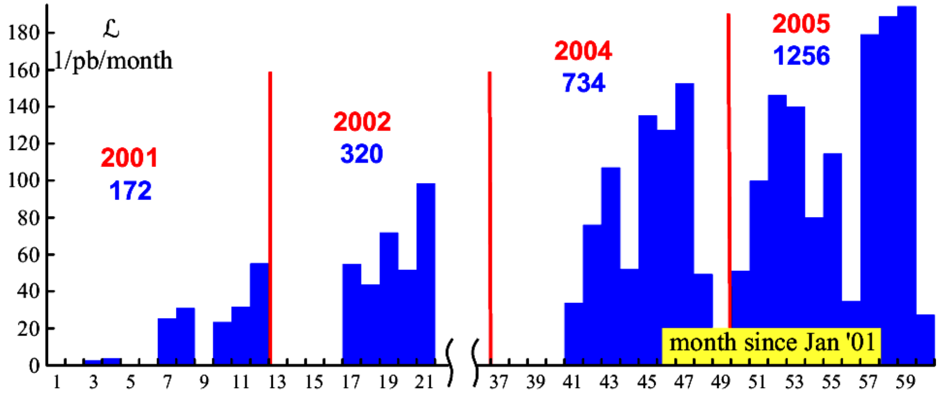
Tsukuba, Japan – 10nd June 2009

Measurement of $R_K=\Gamma(Ke2)/\Gamma(K\mu2)$

Introduction: R_K in and beyond SM.

Measurement of $R_K=\Gamma(Ke2(\gamma))/\Gamma(K\mu2(\gamma))$ at KLOE.

- Based on 2.2 fb^{-1} of data collected at e^+e^- collider DaΦne.
- BR($\phi\to K^+K^-$) ~ 0.49, yielding 3×10^9 K^+K^- pairs, ~50,000 Ke2 decays in FV

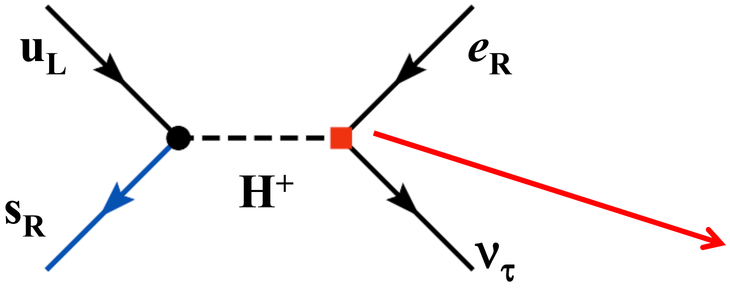


- Signal selection; analysis basic principle
- Background rejection
- Ke2 event counting; with systematics
- Reconstruction efficiencies
- Results on R_K.

NP potential of $R_K = \Gamma(K^{\pm}_{e2})/\Gamma(K^{\pm}_{\mu2})$

- SM prediction with 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): **R_K=2.477(1)×10^{-5}** [*Cirigliano Rosell arXiv:0707:4464*].

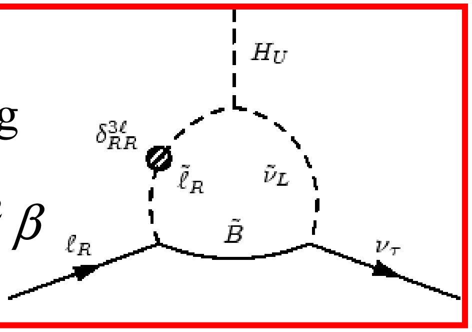
- Helicity suppression can boost NP [*Masiero-Paradisi-Petronzio PRD74(2006)011701*].



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

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

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



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

LFV can give **O(1%) deviation from SM (Δ_R^{31}~5×10^{-4}, tanβ ~40, m_H ~ 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**.

Entering the precision realm for R_K

Main actors (experiments) in the challenge to push down precision on R_K:

NA48/2: **preliminary** result with 2003 data: **$R_K = 2.416(43)_{stat}(24)_{syst} 10^{-5}$**, from **~4000 Ke2** candidates (2% accuracy)
NA48/2: **preliminary** result with 2004 data: **$R_K = 2.455(45)_{stat}(41)_{syst} 10^{-5}$**, from **~4000 Ke2** candidates from special minimum bias run (3% accuracy)

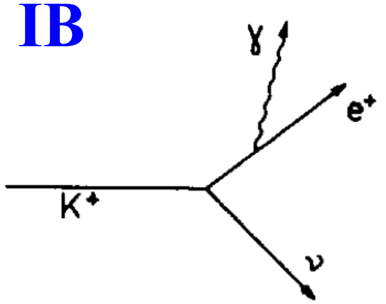
KLOE: **preliminary** result with 2001-2005 data: **$R_K = 2.55(5)_{stat}(5)_{syst} 10^{-5}$**, from **~8000 Ke2** candidates (3% accuracy), perspectives to reach 1% error after analysis completion.

NA62 (ex NA48): **collected ~150,000 Ke2** events in dedicated 2007 run, aims to breaking the 1% precision wall, possibly reaching <~0.5%

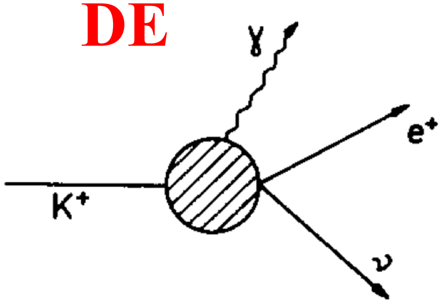
Ke2(γ): signal definition

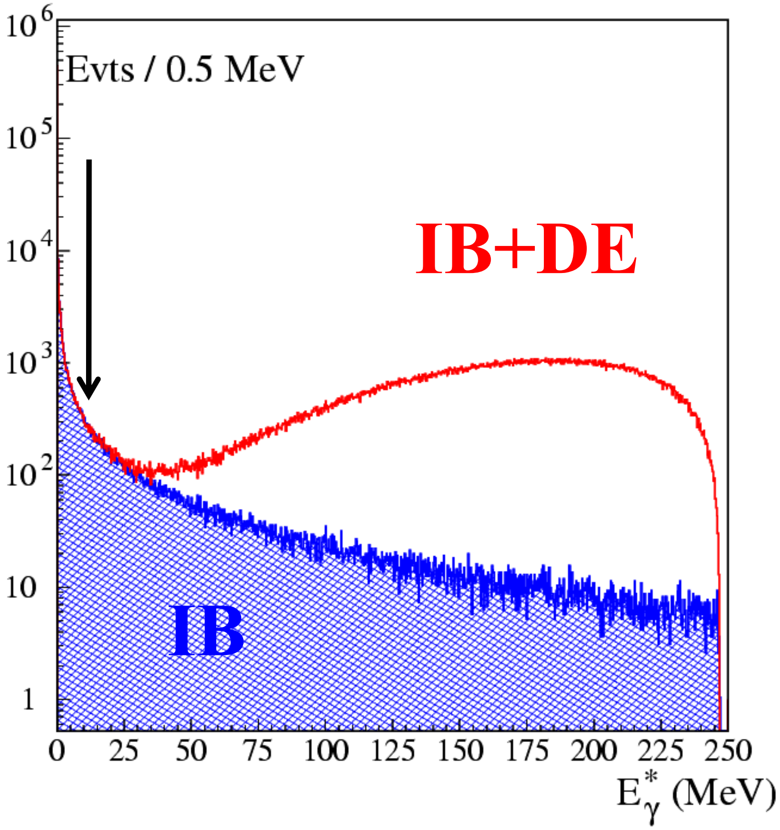
SM prediction is defined to be inclusive of **IB** (ignoring **DE** contributions).

IB



DE





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 ($O(\alpha)$+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

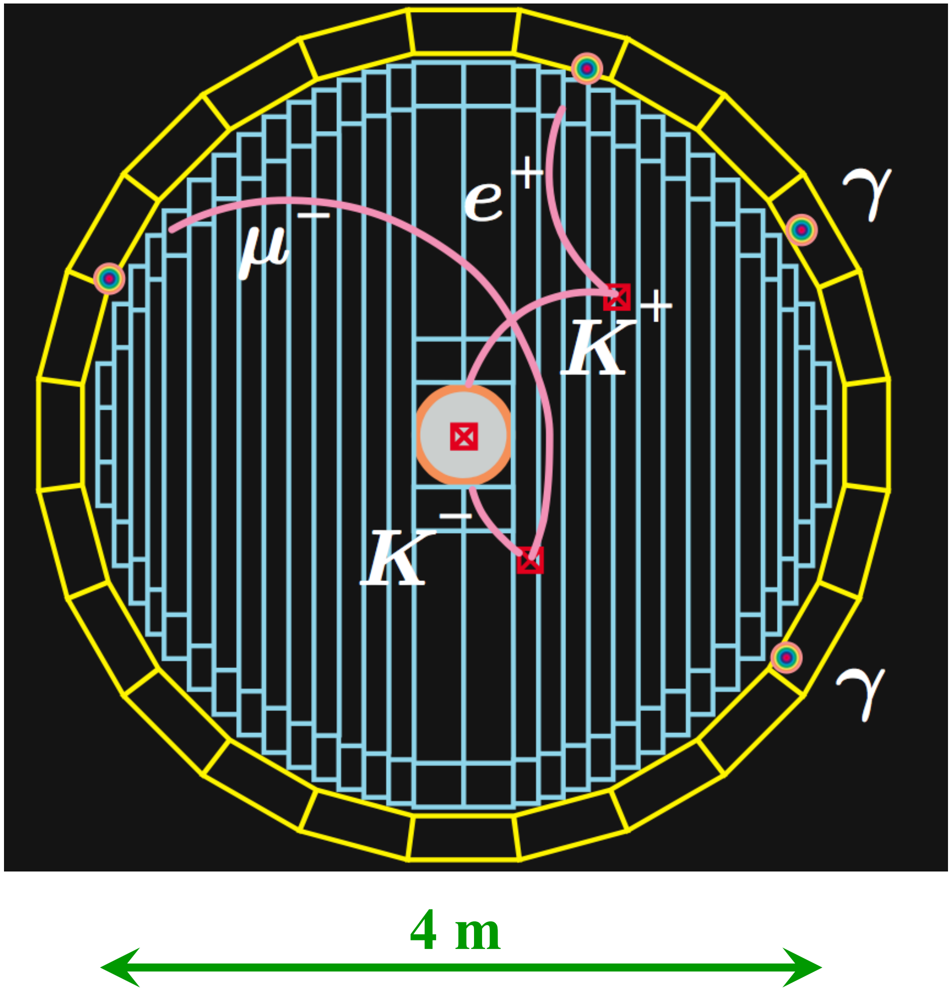
$\lambda \sim 90$ cm (56% of $K^\pm$ decay in DC).

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

Constraints from ϕ 2-body decay.

Particle ID with kinematics and ToF.

Tagging provides unbiased control samples for efficiency measurement.



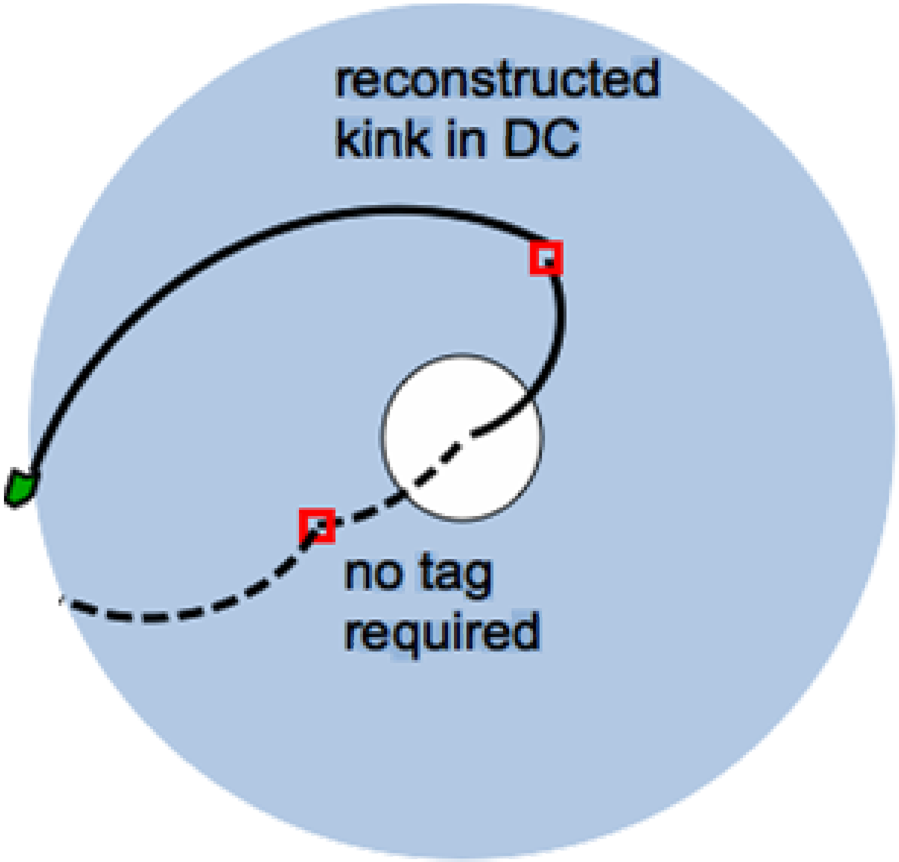
Analysis basic principles

$$R_K = \frac{N_{Ke2}}{N_{K\mu2}} \left[\frac{\varepsilon^{\mathrm{REC}}_{K\mu2}}{\varepsilon^{\mathrm{REC}}_{Ke2}} C^{\mathrm{TRG}} C^{\mathrm{REC}} \right] \frac{1}{\epsilon^{\mathrm{IB}}}$$

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%.



reconstructed kink in DC

no tag required

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

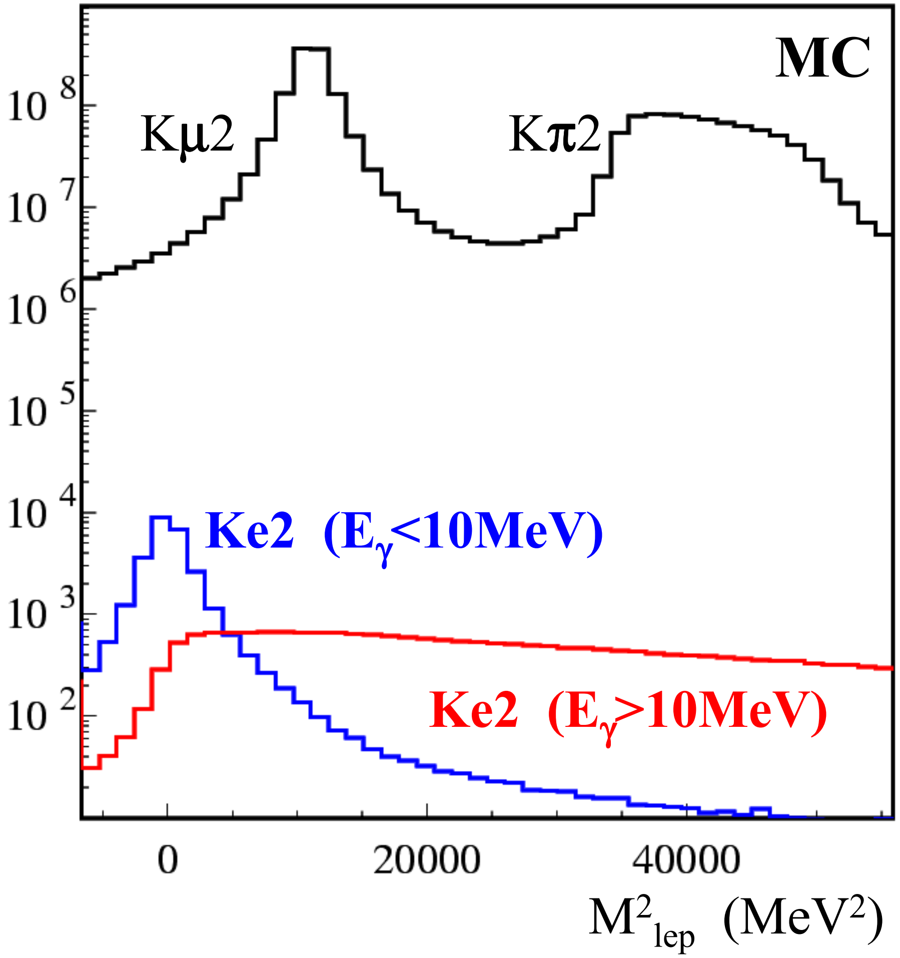
→ gain ×4 **of statistics**

Analysis basic principles

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

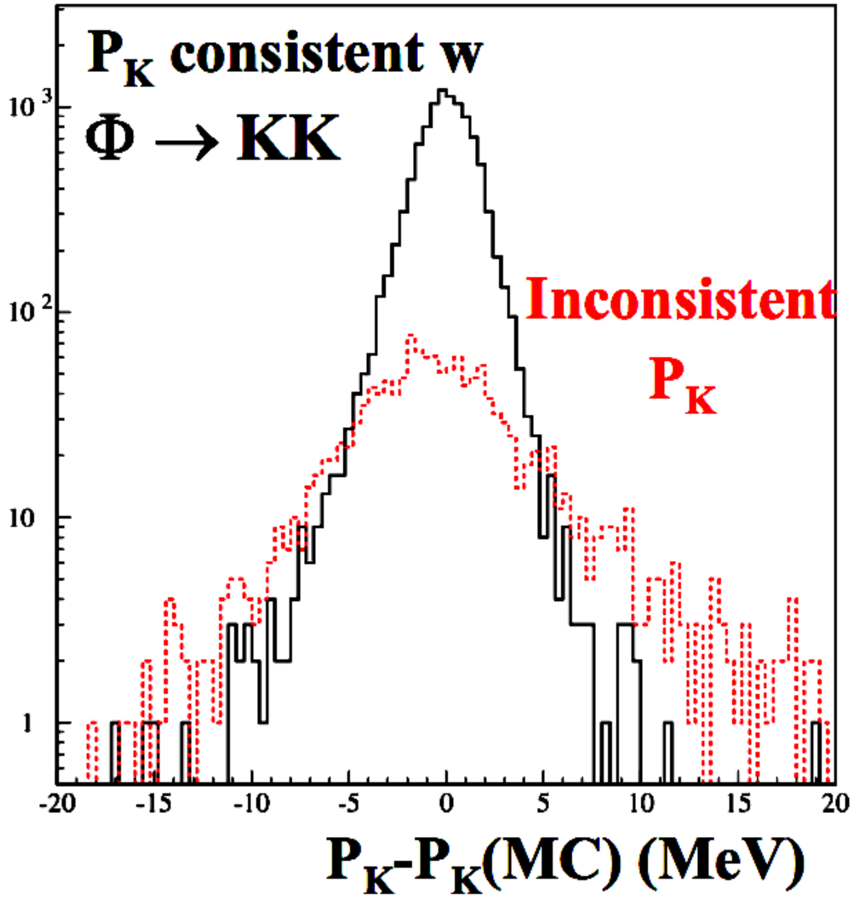
$$\mathbf{M^2_{lep} = (E_K - p_{miss})^2 - p^2_{lep}.}$$

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: Kμ2 events with bad p_K, p_{lep}, or decay vertex position reconstruction



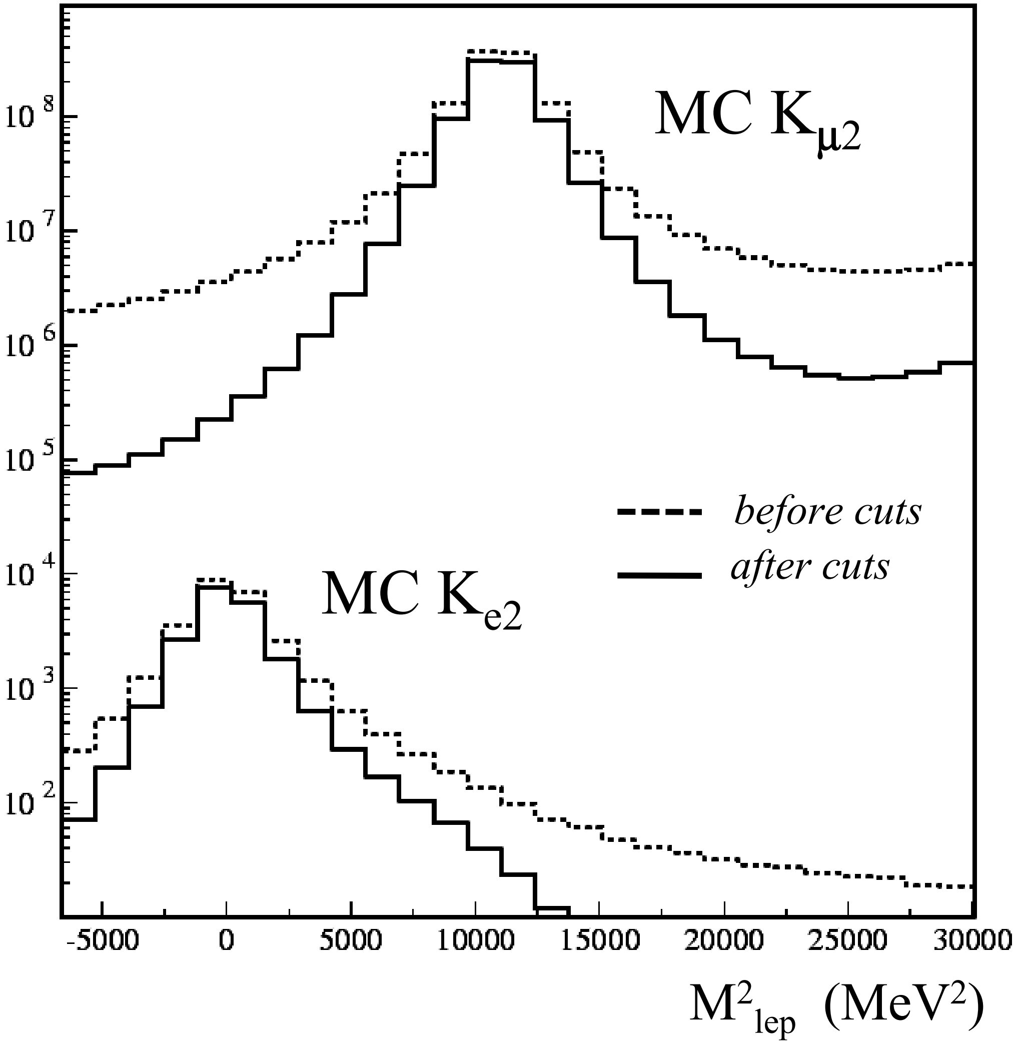
- require good quality vertex and secondary track (χ^2cut);

- 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).



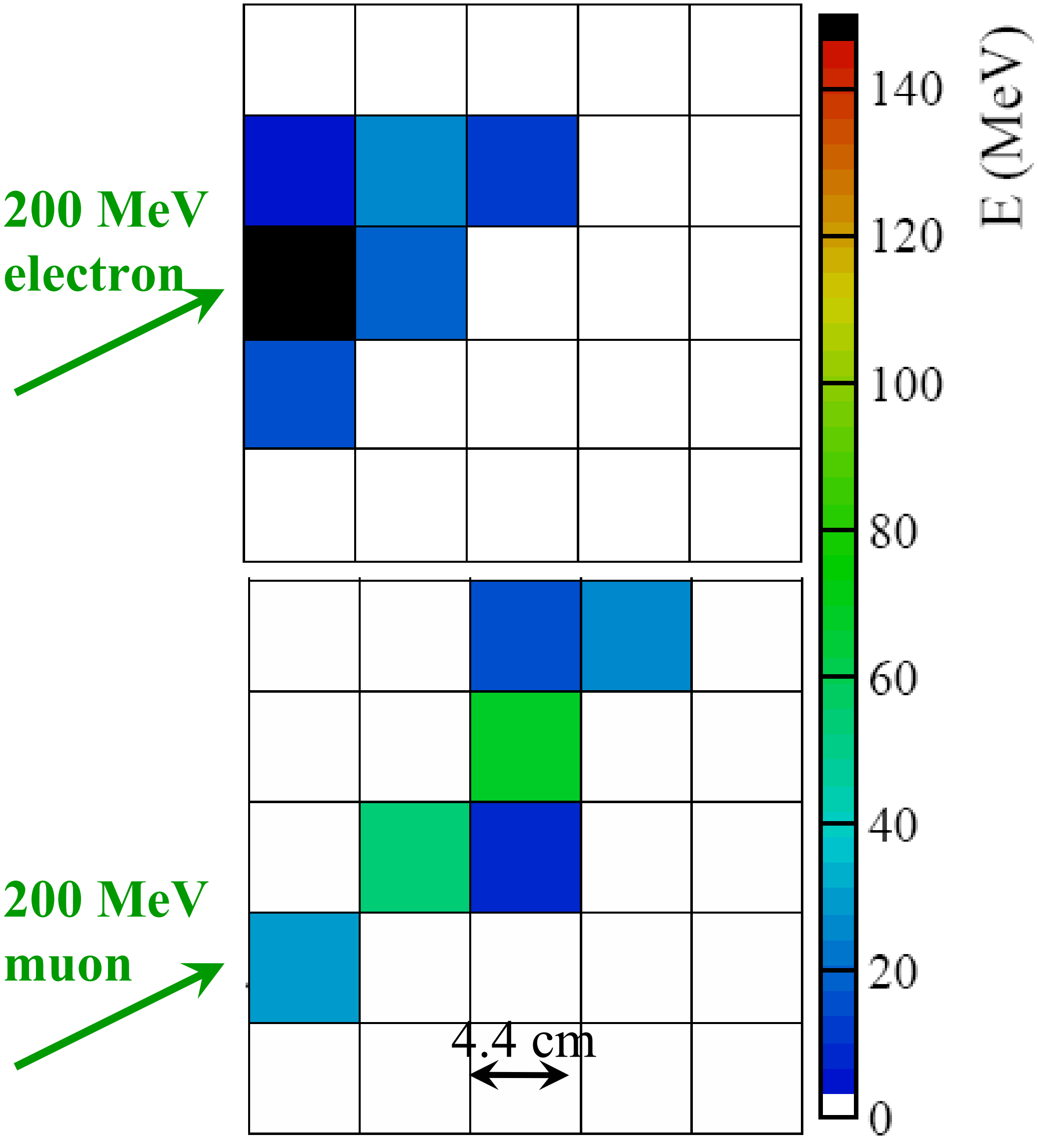
Background rejection (PID)

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.

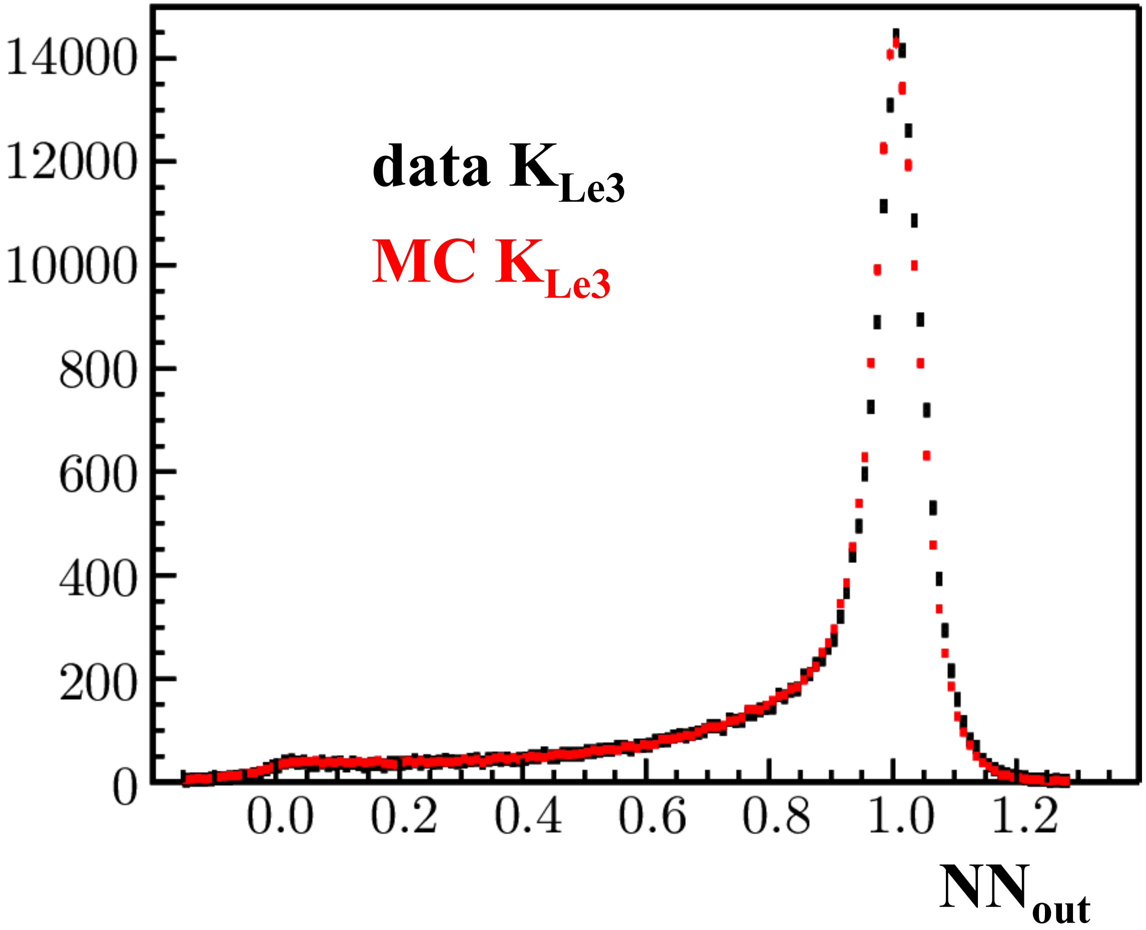
3) Combine all information in a neural network (NN).



Background rejection (PID)

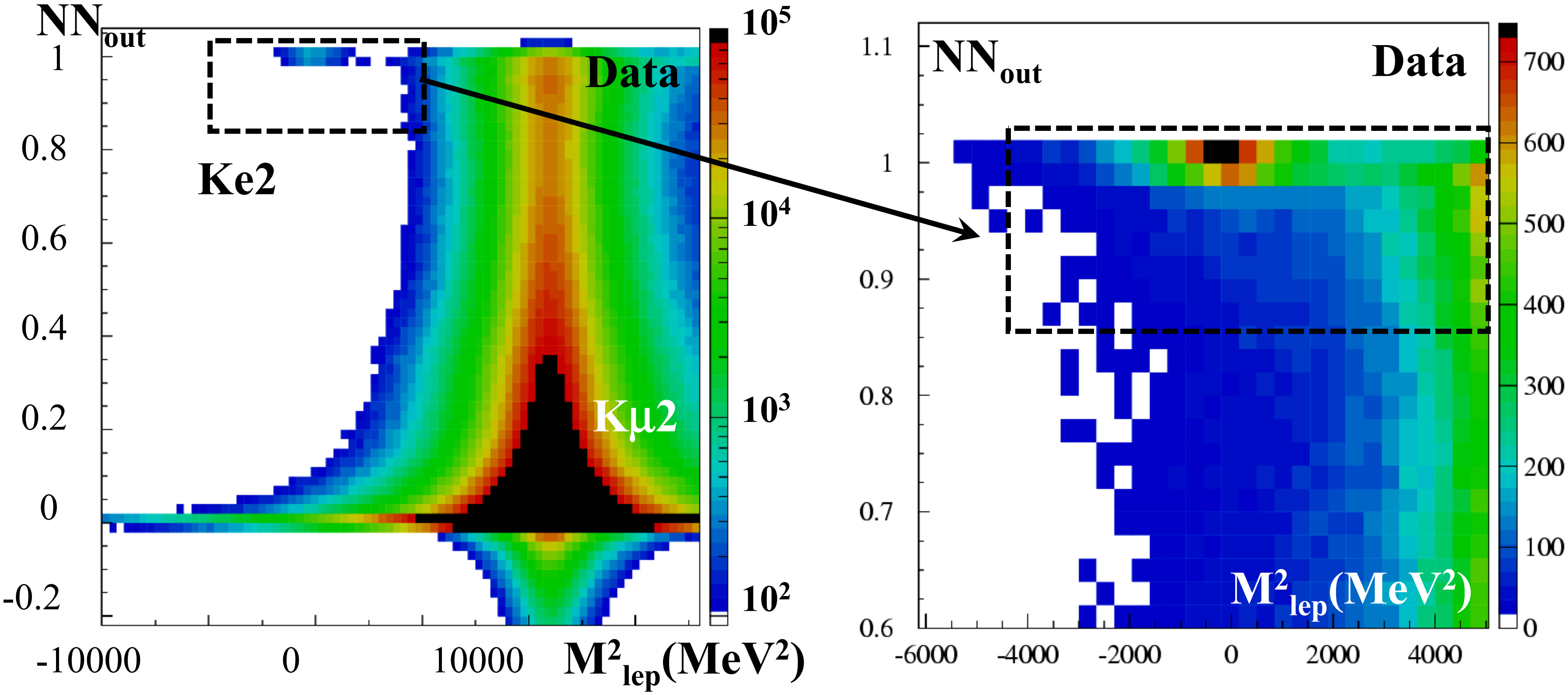
- Use a pure sample of K_Le3 to correct cell response in MC.

- K_Le3 anf Kμ2 for NN training.



Background rejection (PID)

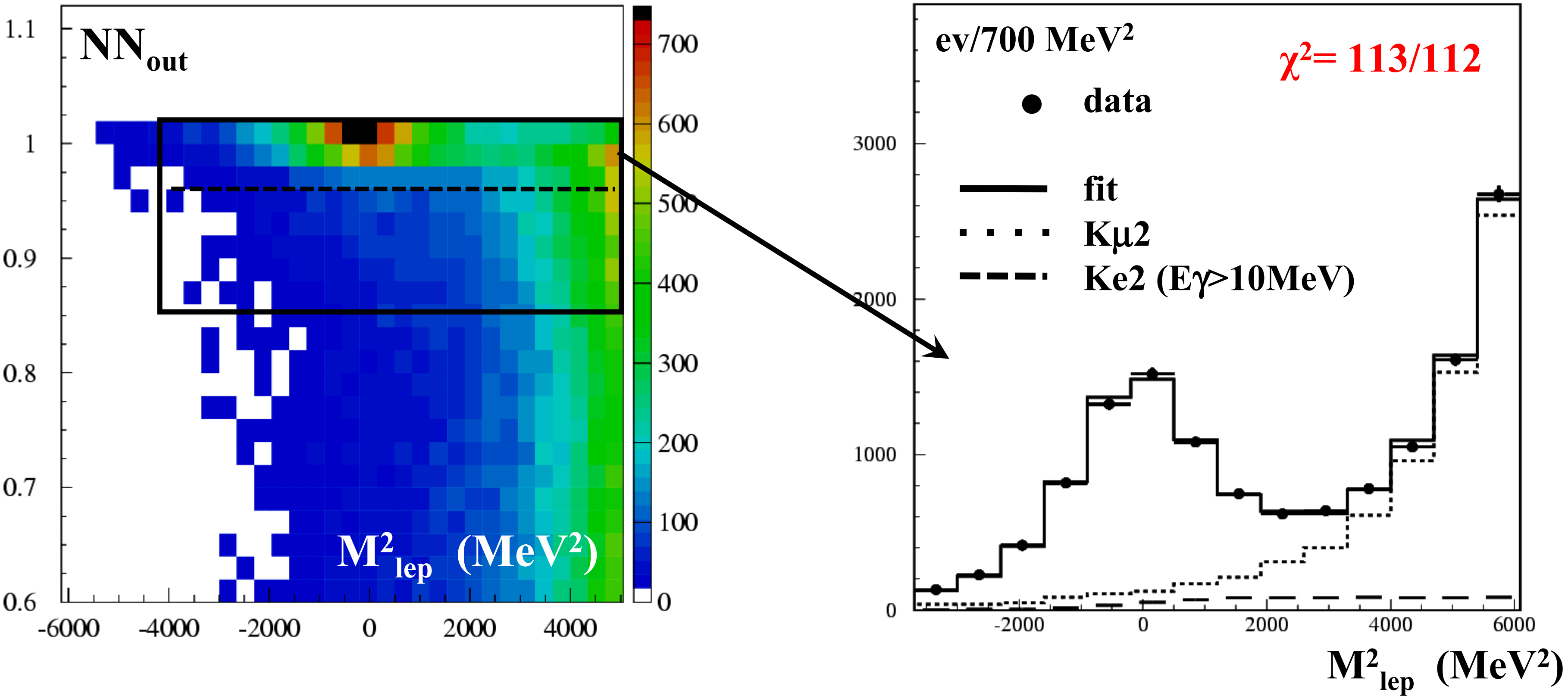
Select a region with good S/B ratio in the $M^2_{lep} - NN_{out}$ plane



after selection: ε~30% (~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 **$0.86<NN_{out}<1.02$**

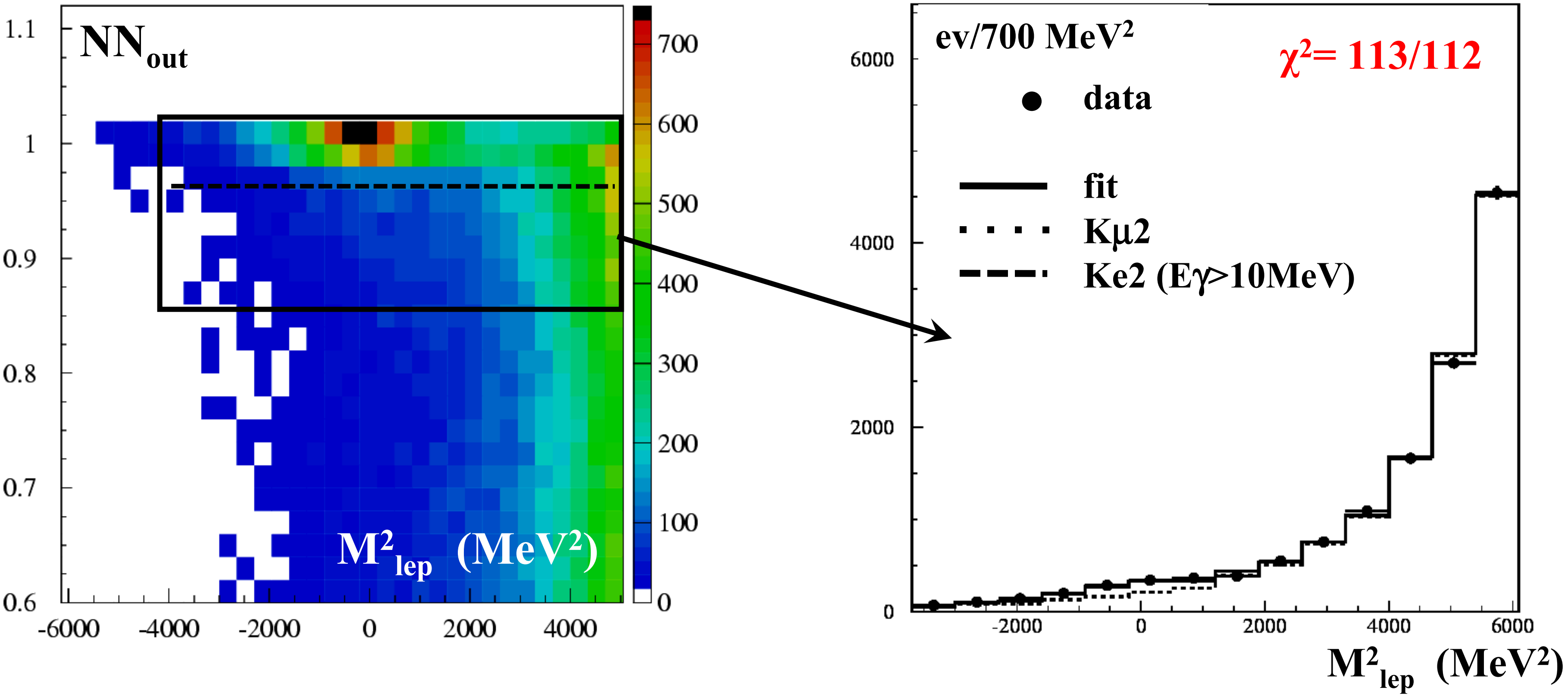


We count **7060 (102) Ke2+** **6750 (101) Ke2–** **(σ_{STAT}=1%, 0.85% from Ke2)**

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 **$0.86<NN_{out}<1.02$**

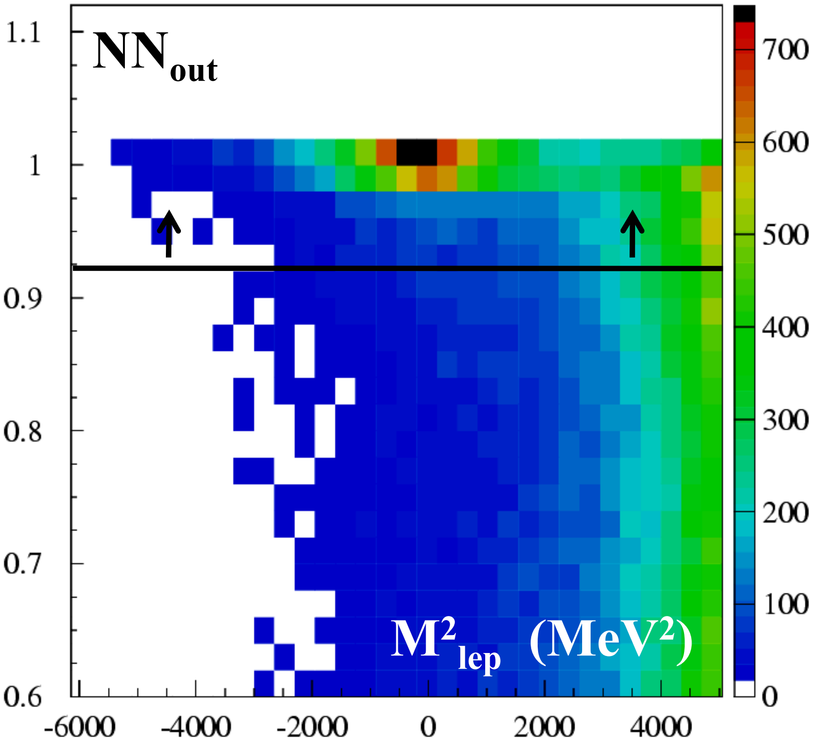
Ke2+ fit; M^2_{lep} proj for $NN_{out}<0.96$

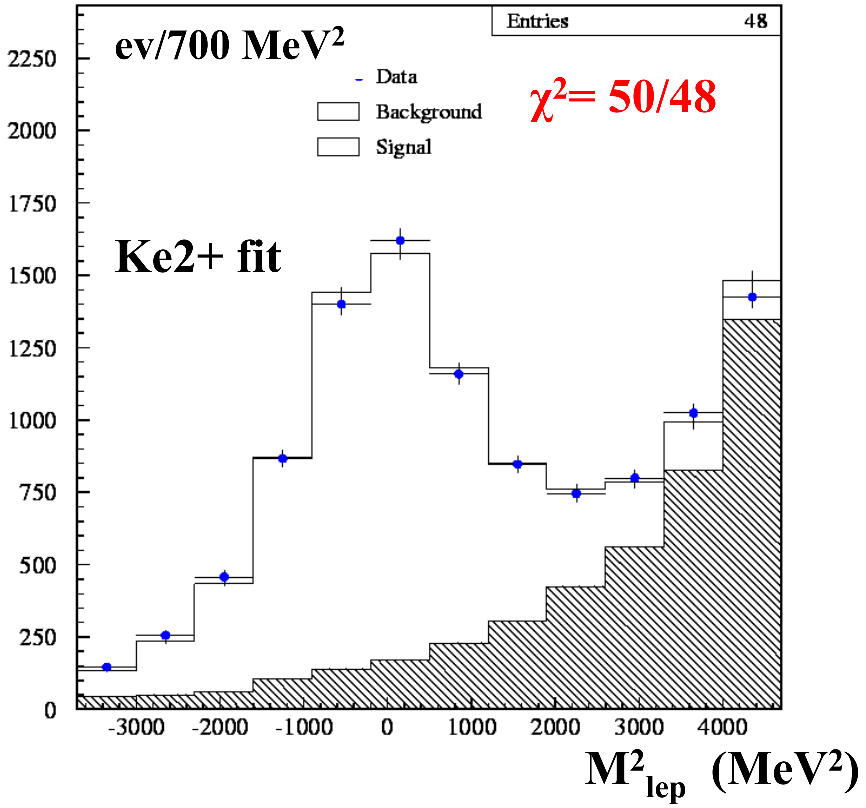


We count **7060 (102) Ke2+** **6750 (101) Ke2–** **(σ_{STAT}=1%, 0.85% from Ke2)**

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.

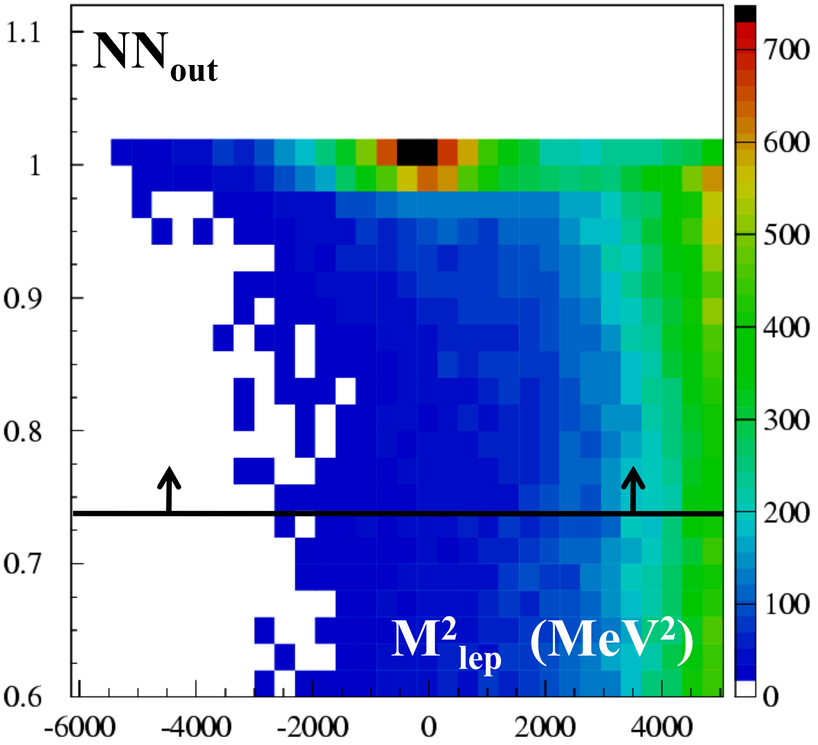


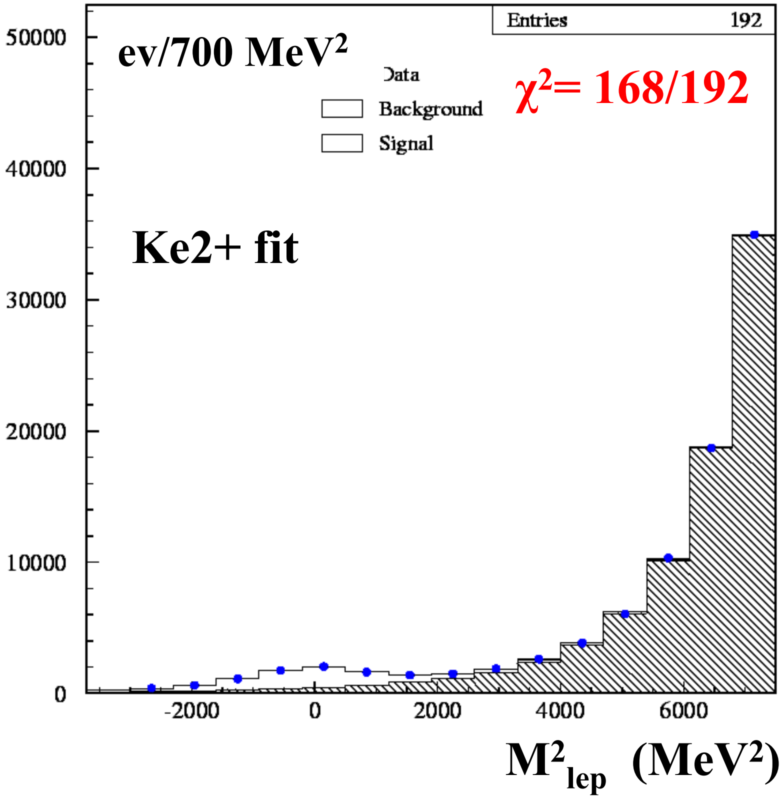


minimal bkg with: $-4000 < M^2_{lep} < 4650$ and $0.94 < NN_{out} < 1.02$

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 $0.78 < NN_{out} < 1.02$

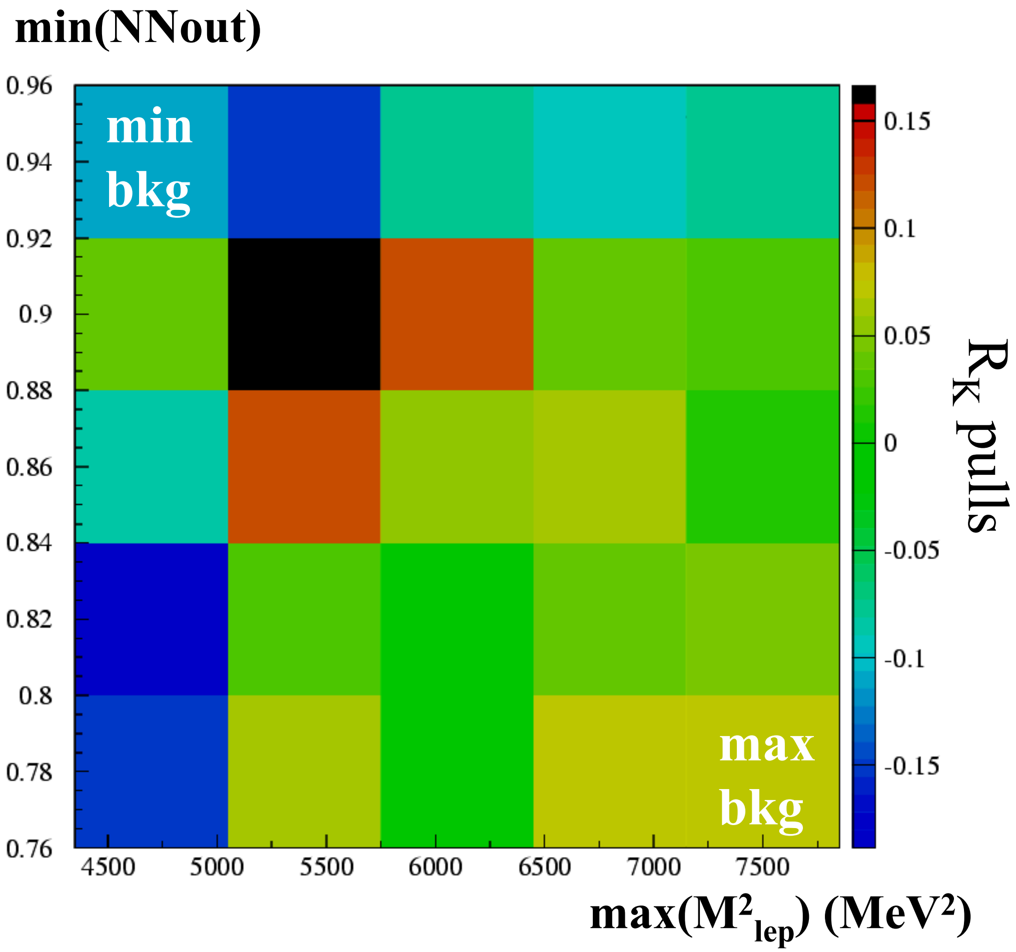
K_{e2} event counting: systematics

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

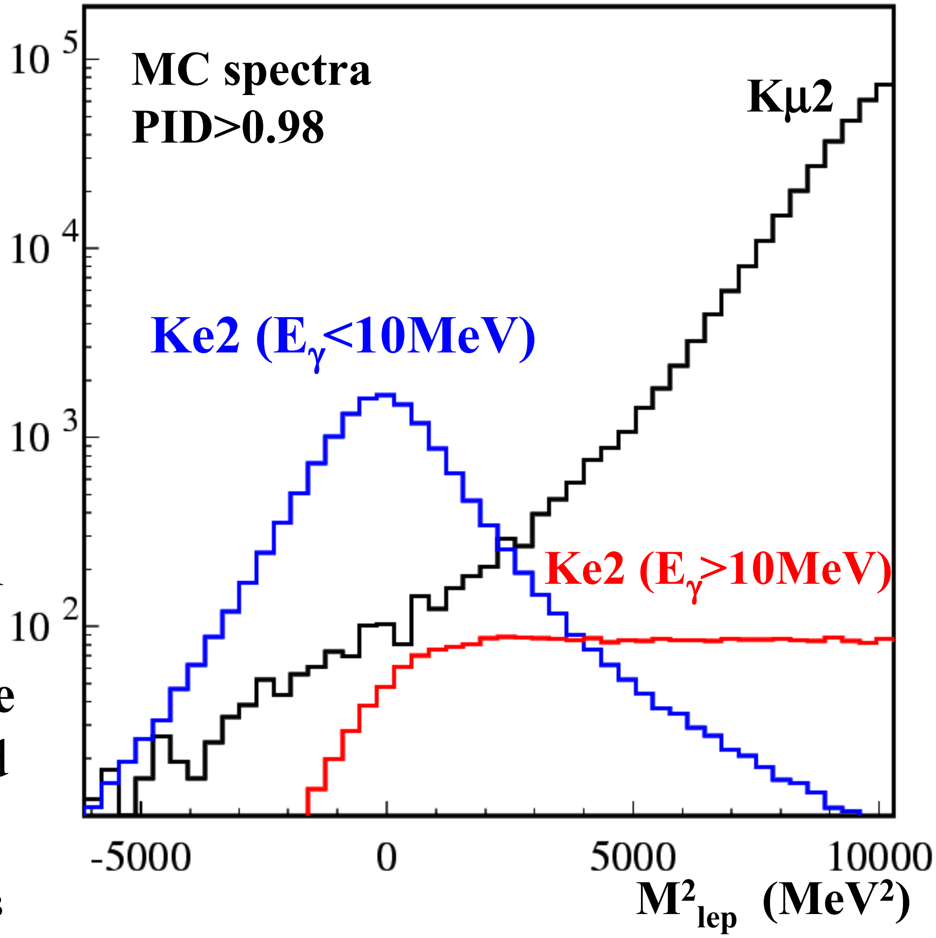
- Analysis inclusive of photons in the final state. In our fi region we expect:

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

- 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** (see Moulson talk):

- **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}**



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 $K^+\mu2$ 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: $\varepsilon(Ke2)/\varepsilon(K\mu2) = 0.946\pm0.007$

Control samples for tracking efficiencies

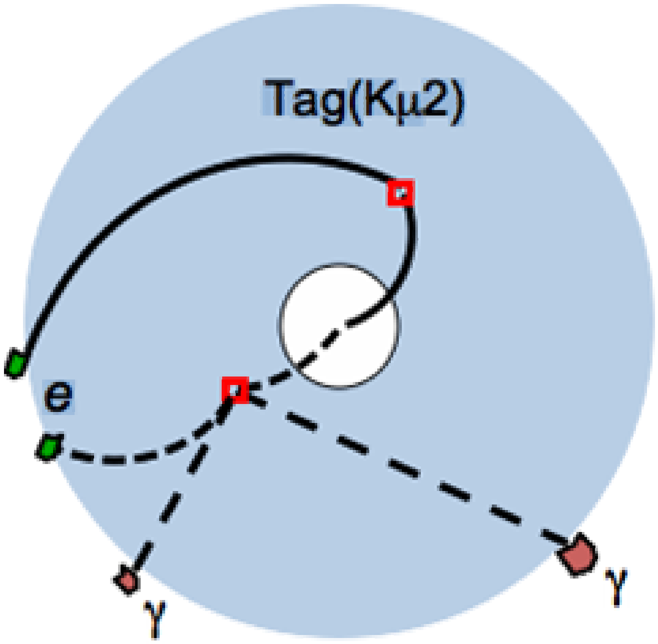
Just an example: selection of K^+e3 control sample to measure tracking efficiency for electrons

0) Tagging decay ($K\mu2$ or $K\pi2$);

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

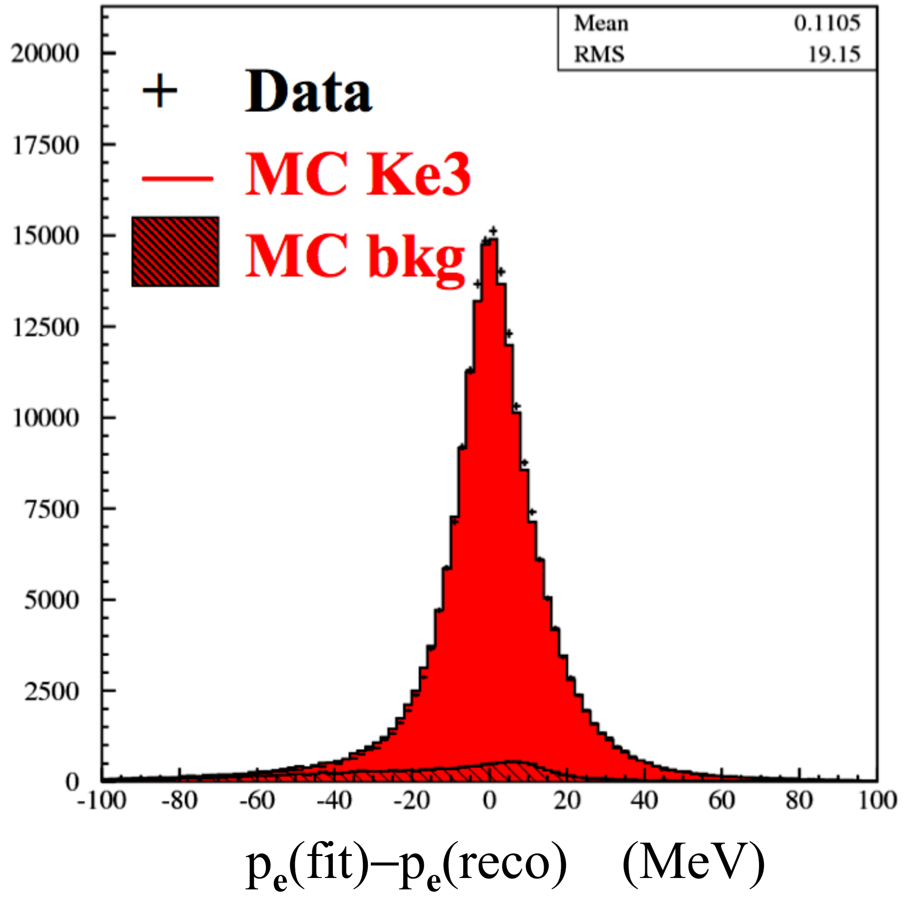
2) Using a ToF technique a $\pi^0 \rightarrow \gamma\gamma$ decay vertex is reconstructed along the K decay path;

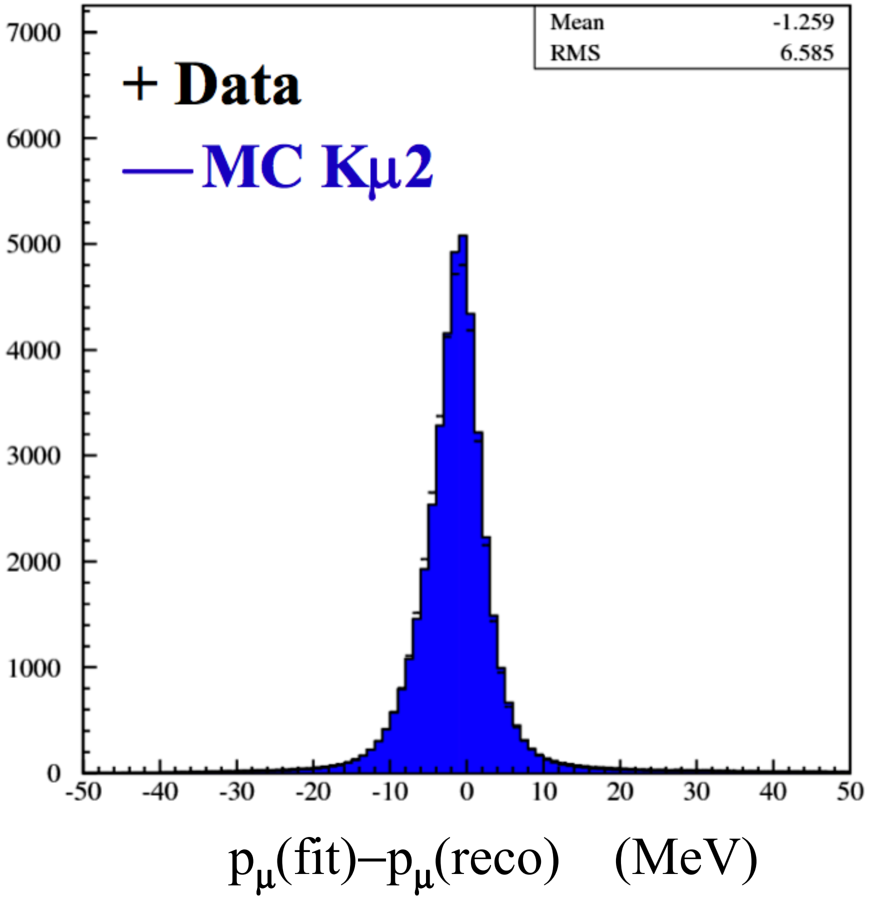
3) Require an electron cluster: p_e estimated from a kinematic fit with constraints on E/p, ToF, cluster position, and $E_{miss} - P_{miss}$.



Evaluate the K + electron kink reconstruction efficiency

Control samples for tracking efficiencies





- For electron tracks obtain a resolution σ~19 MeV

- With a similar method, get σ~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 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

- 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:

$R_K = (2.45\pm0.11)\times10^{-5}$

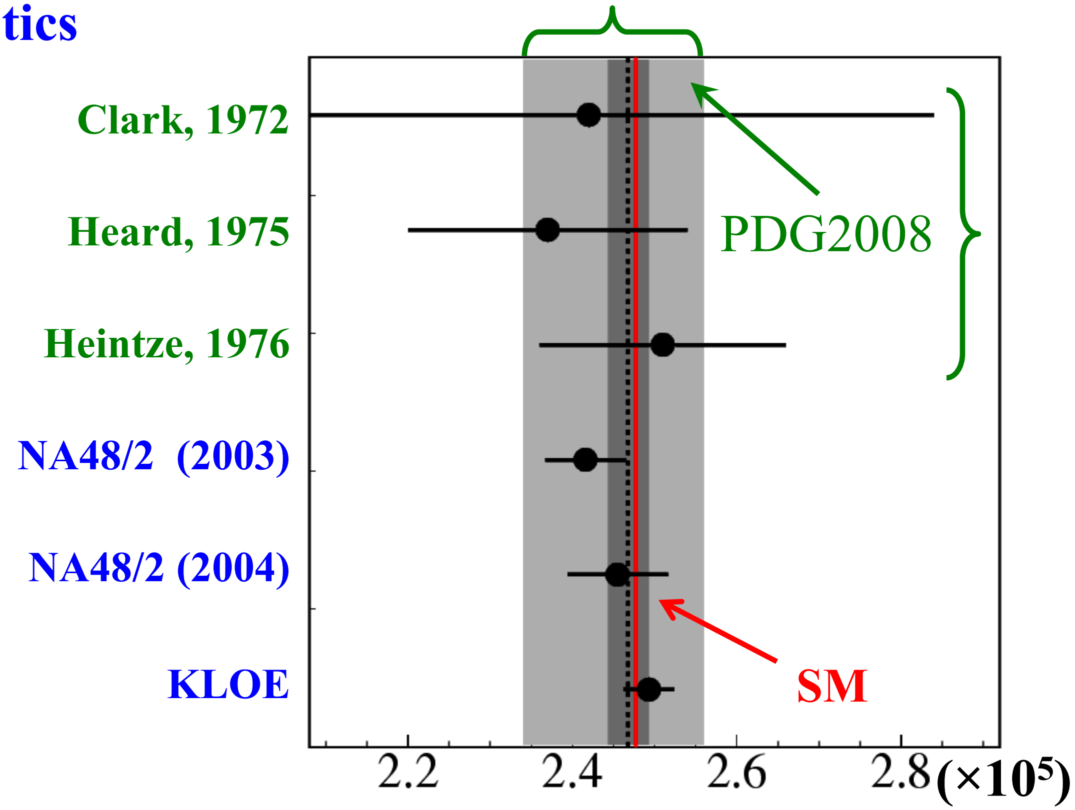
4.5% accuracy

New world average:

$R_K = (2.468\pm0.025)\times10^{-5}$

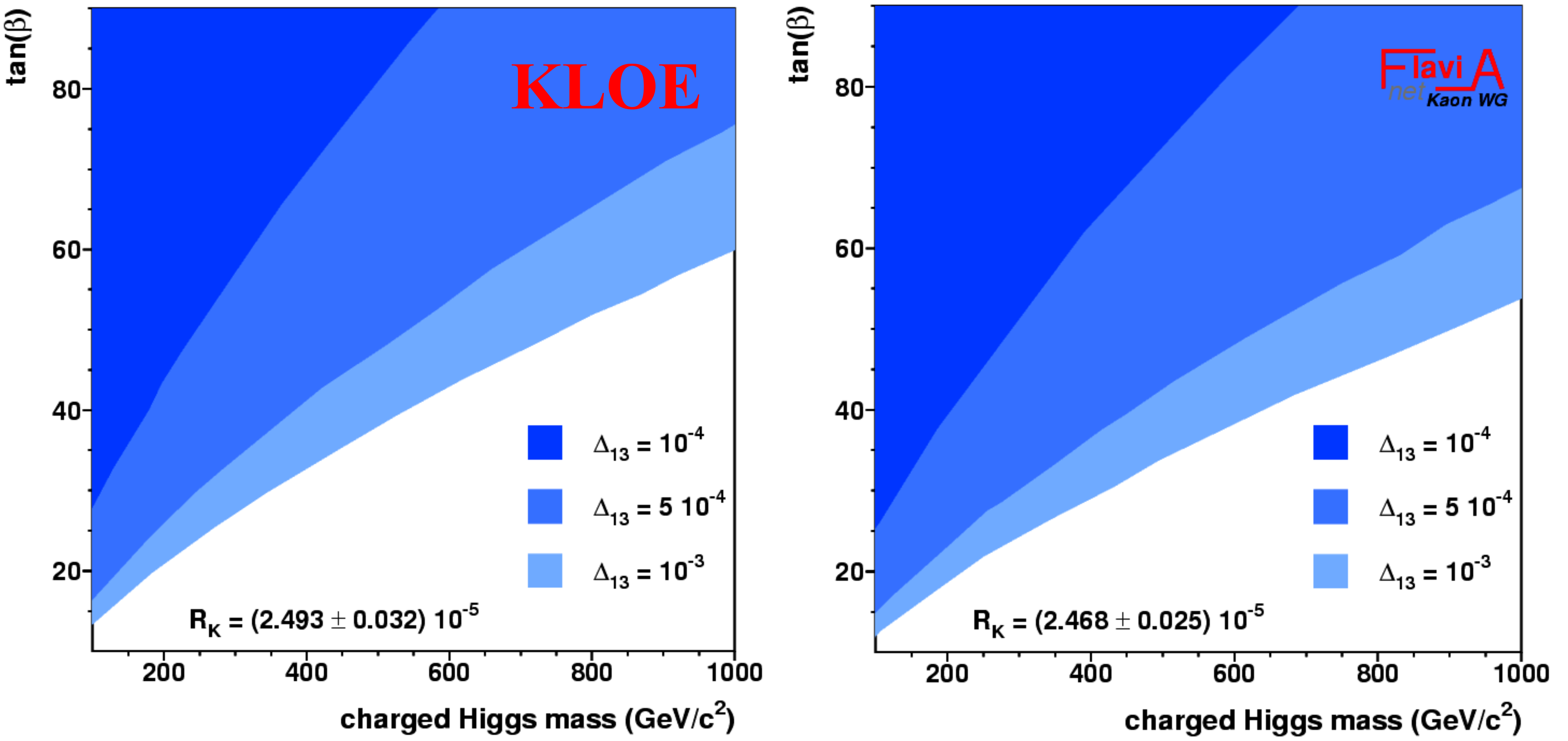
1% accuracy

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



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, $\Delta_{13} = 10^{-3}$, 5×10^{-4}, 10^{-4}



Conclusions

- 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
- 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.

Additional information

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

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

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

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

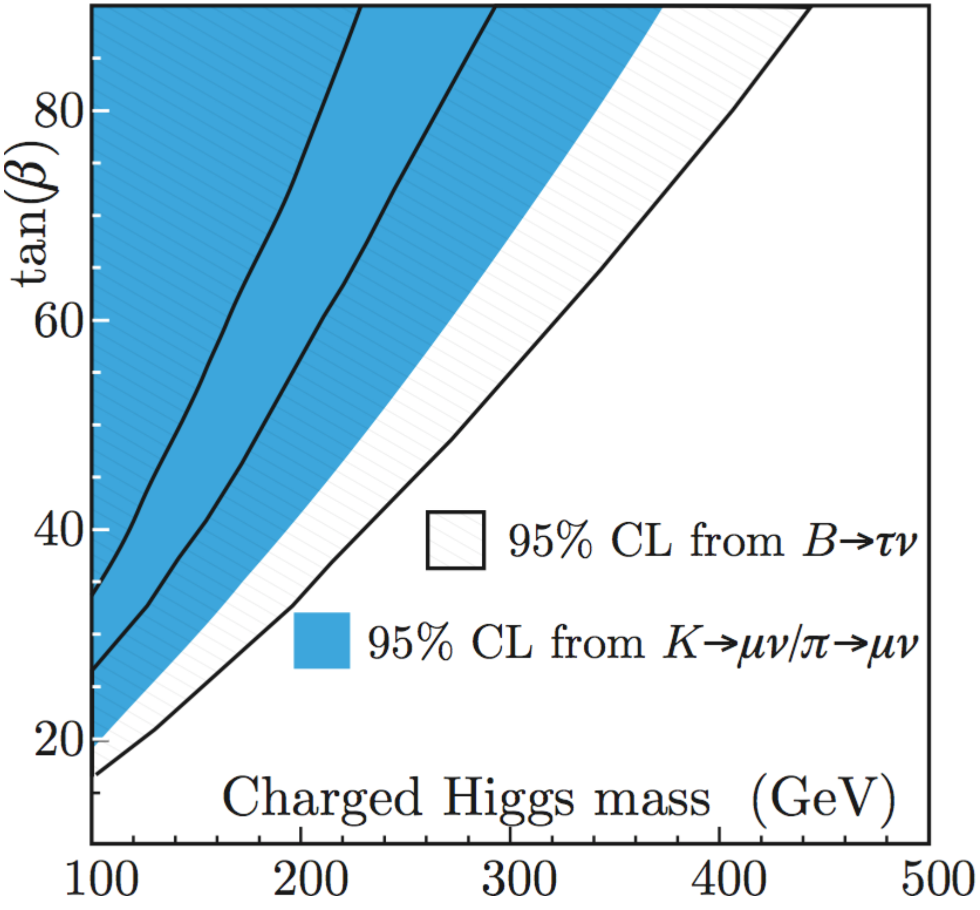
[Hou, Isidori-Paradisi]

R_{l23} =1 in SM

we find

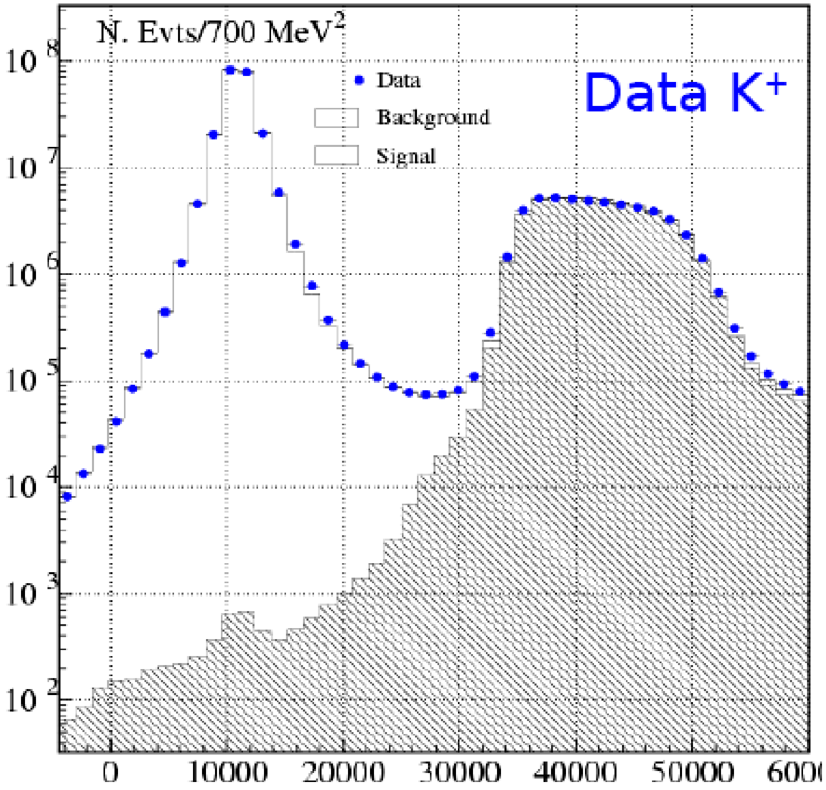
$R_{l23} = 1.008 \pm 0.008$

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

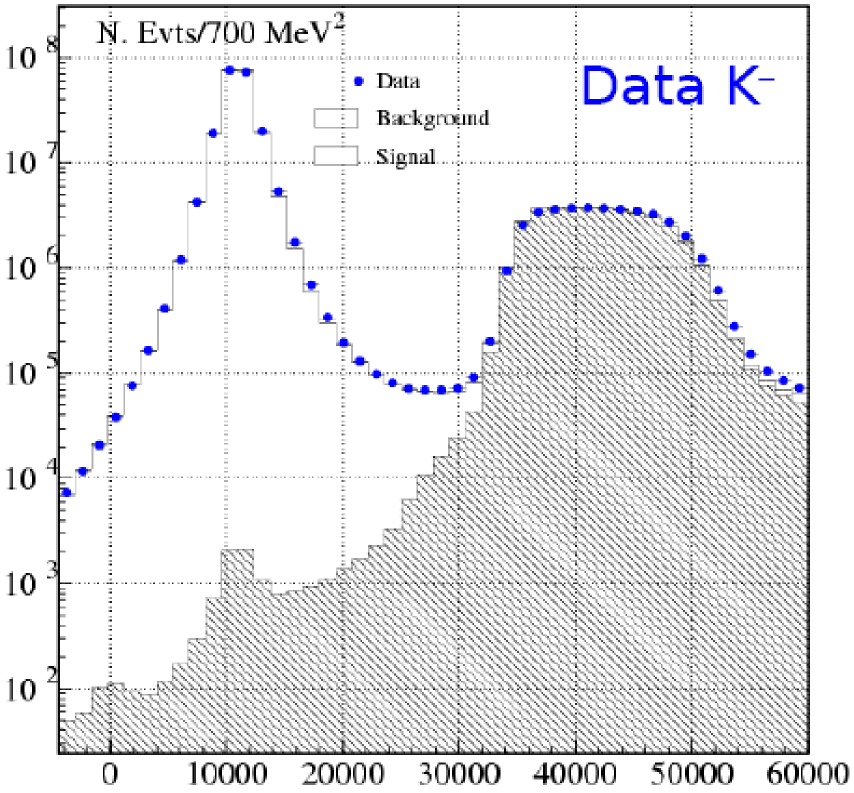


From direct searches (LEP), M_{H+}> 80 GeV, tanβ > 2

Kμ2 event counting



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

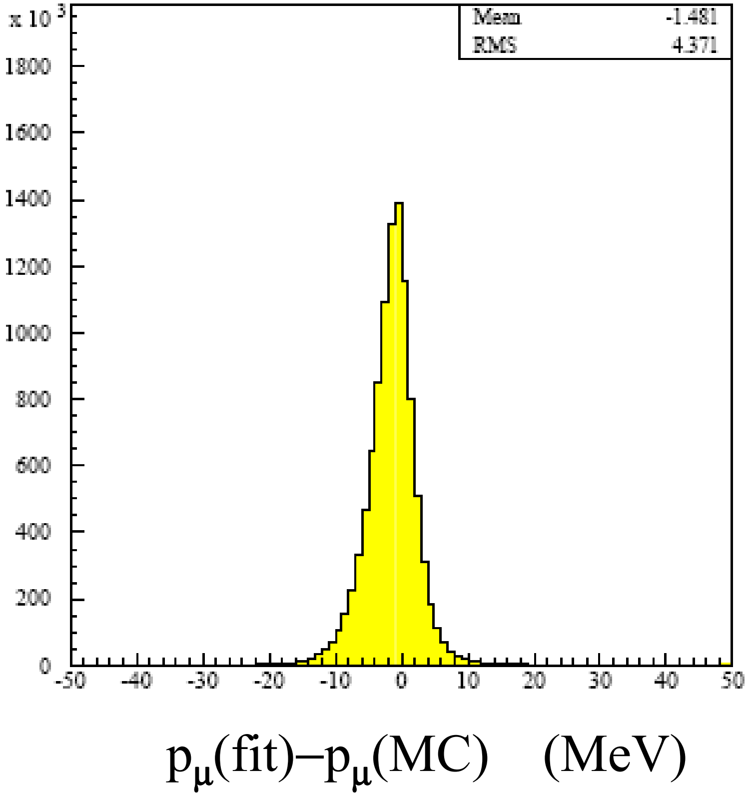


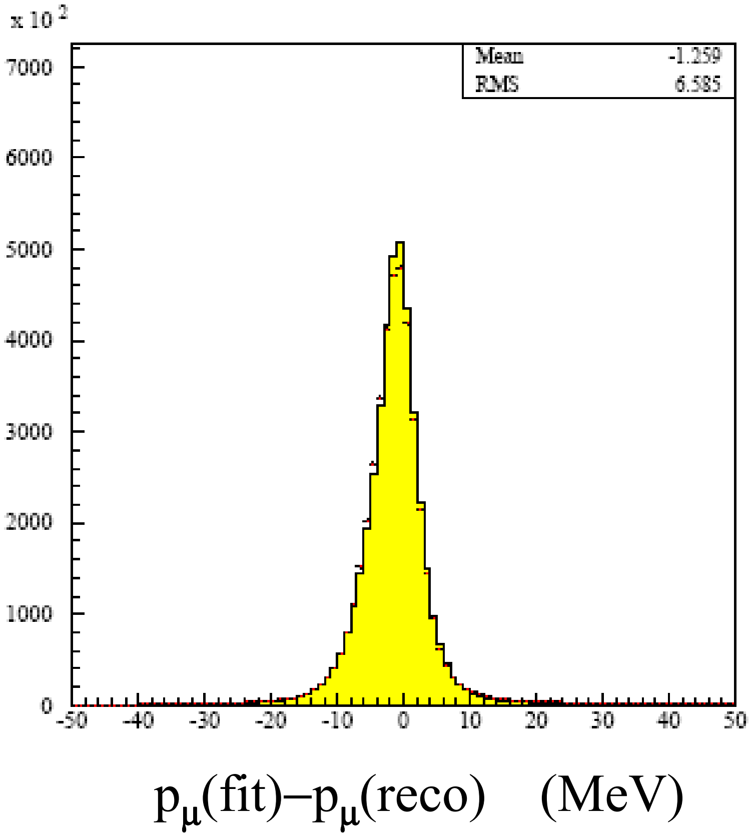
M^2_{lep} (MeV^2)

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

Background under the peak <0.1%, from MC

Tracking efficiency





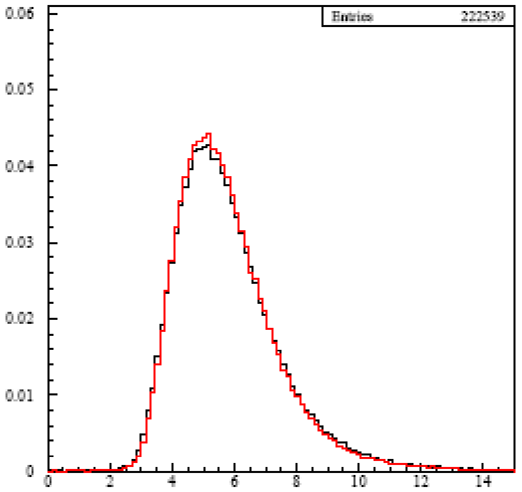
NN details

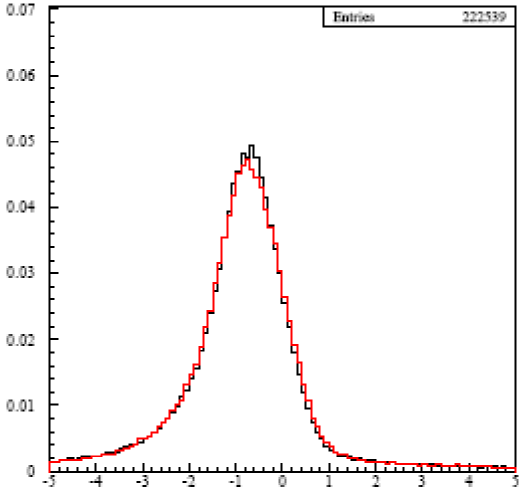
1) E/P;
2) 1st momentum of the distribution of the longitudinal energy path deposition (cluster centroid depth) evaluated at cell level;
3) the 3td momentum of the longitudinal energy path deposistion (skewness);
4,5) asymmetry of energy lost in first two innermost (outermost) planes;
6) RMS of energy 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

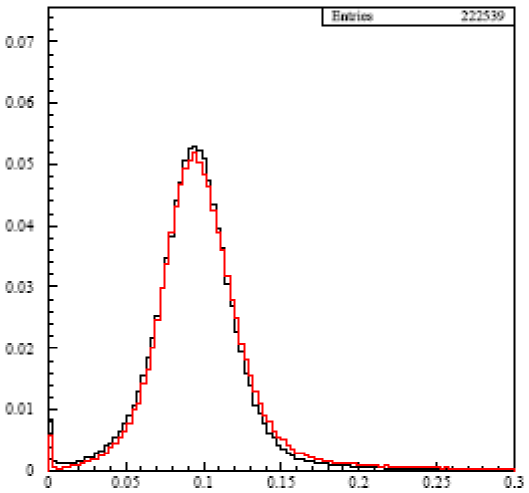


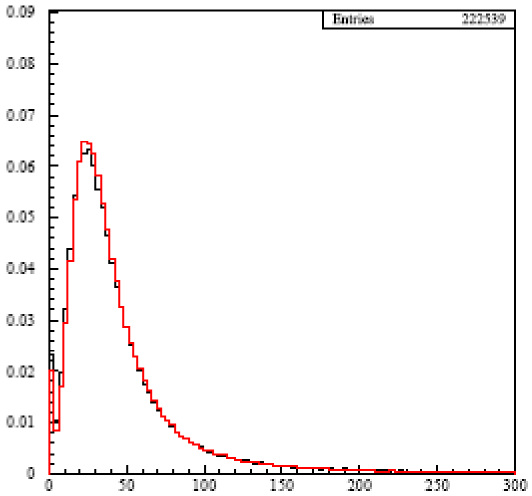


Asymmetry of energy lost in first two innermost planes

Data and **MC**

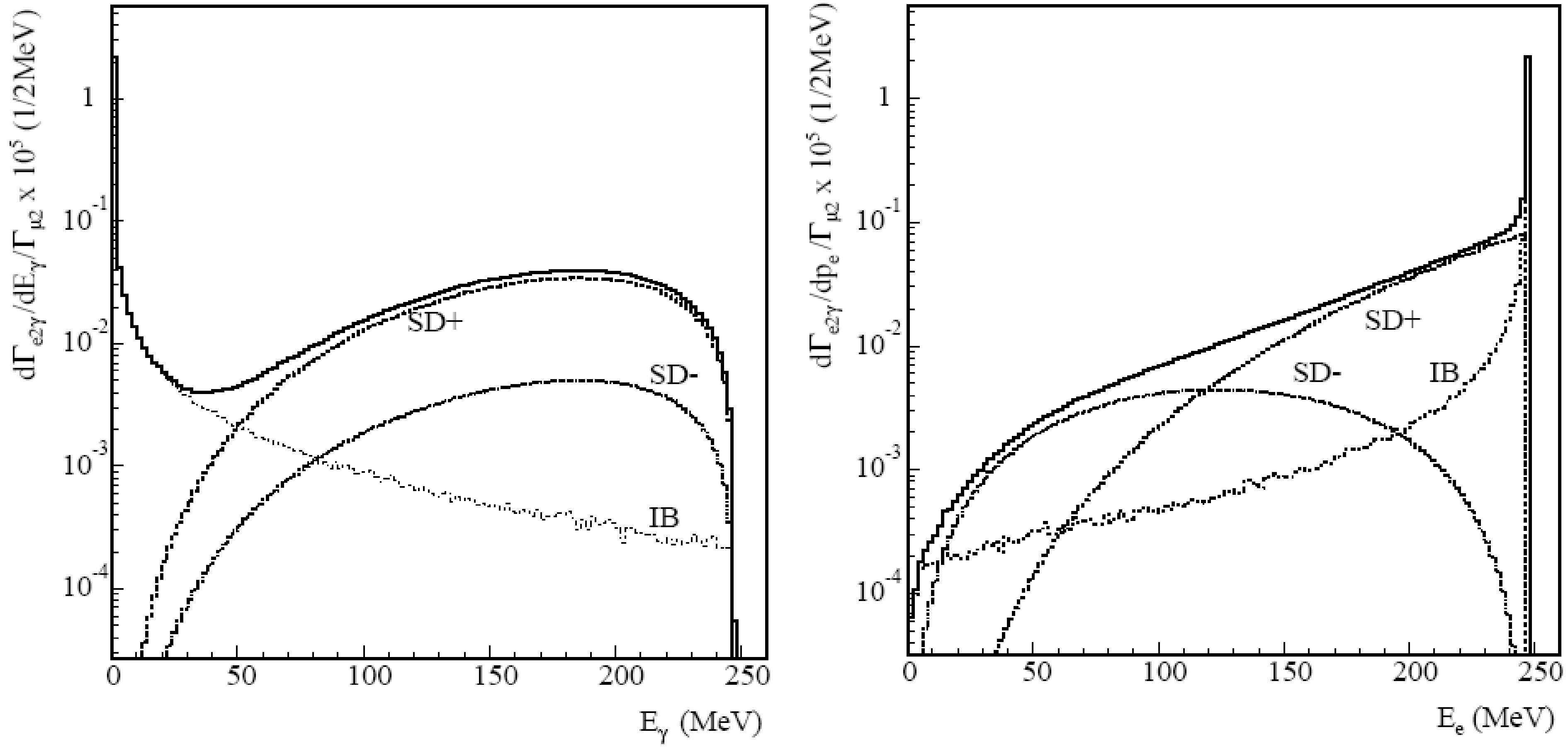
dE/dx





$E_{INT}(x)$ 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

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

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 –

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

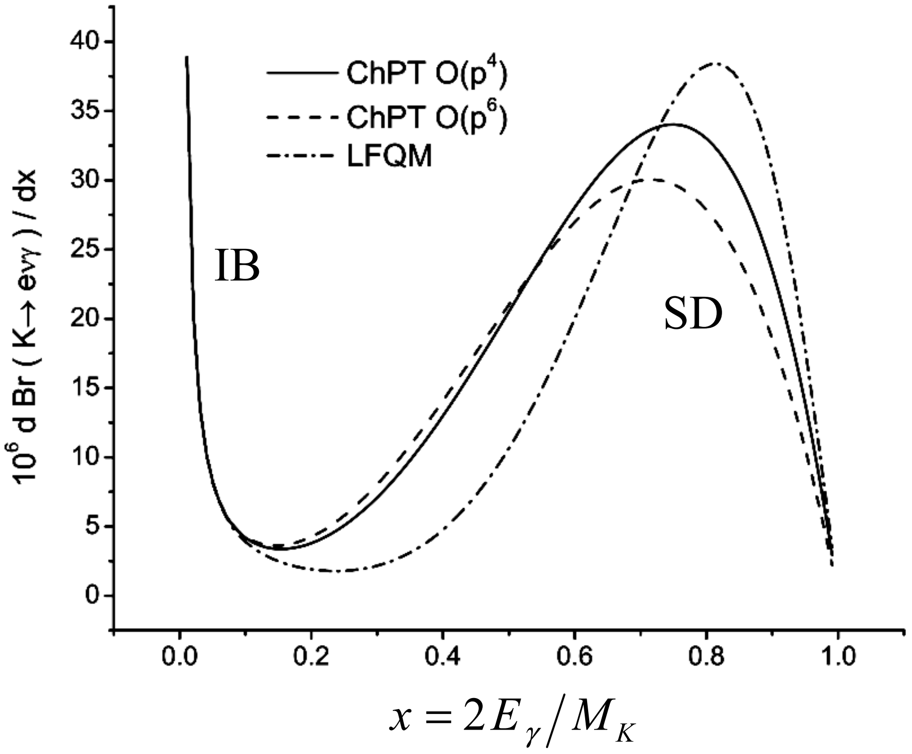
2) ChPT at O(p^6):

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

$f_A \approx 0.034$

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

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



from Phys. Rev. D77 (2008) 014004

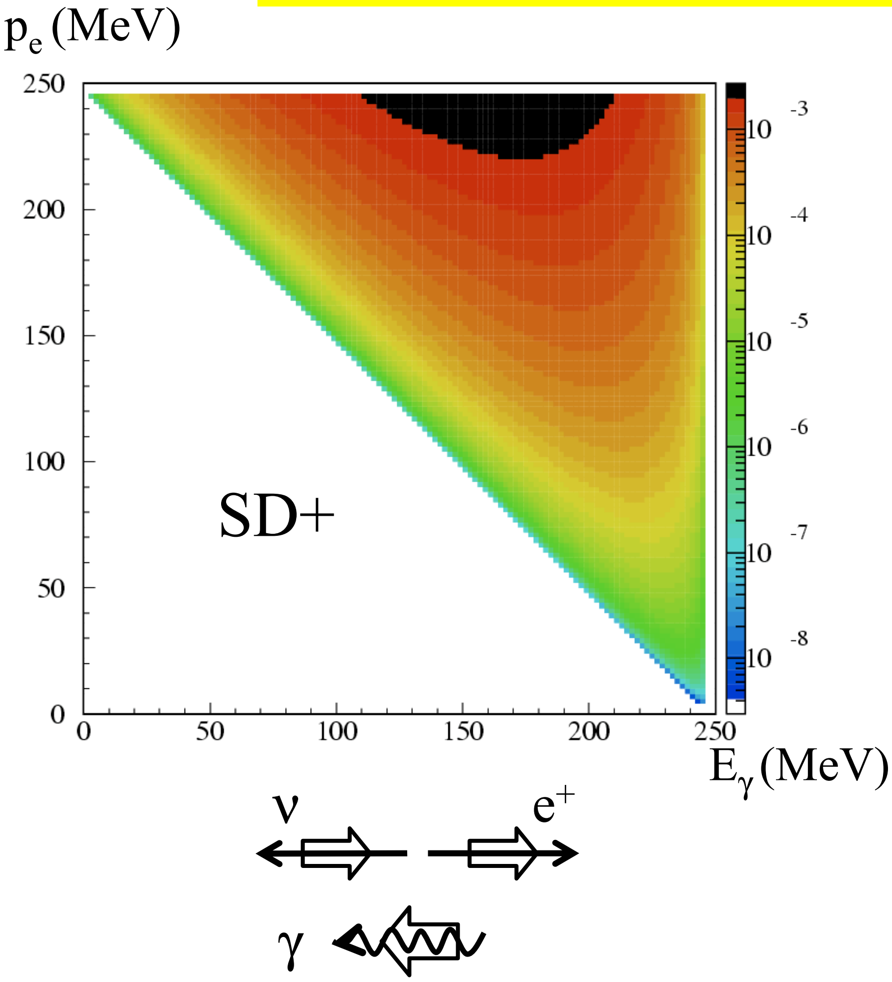
3) LFQM:

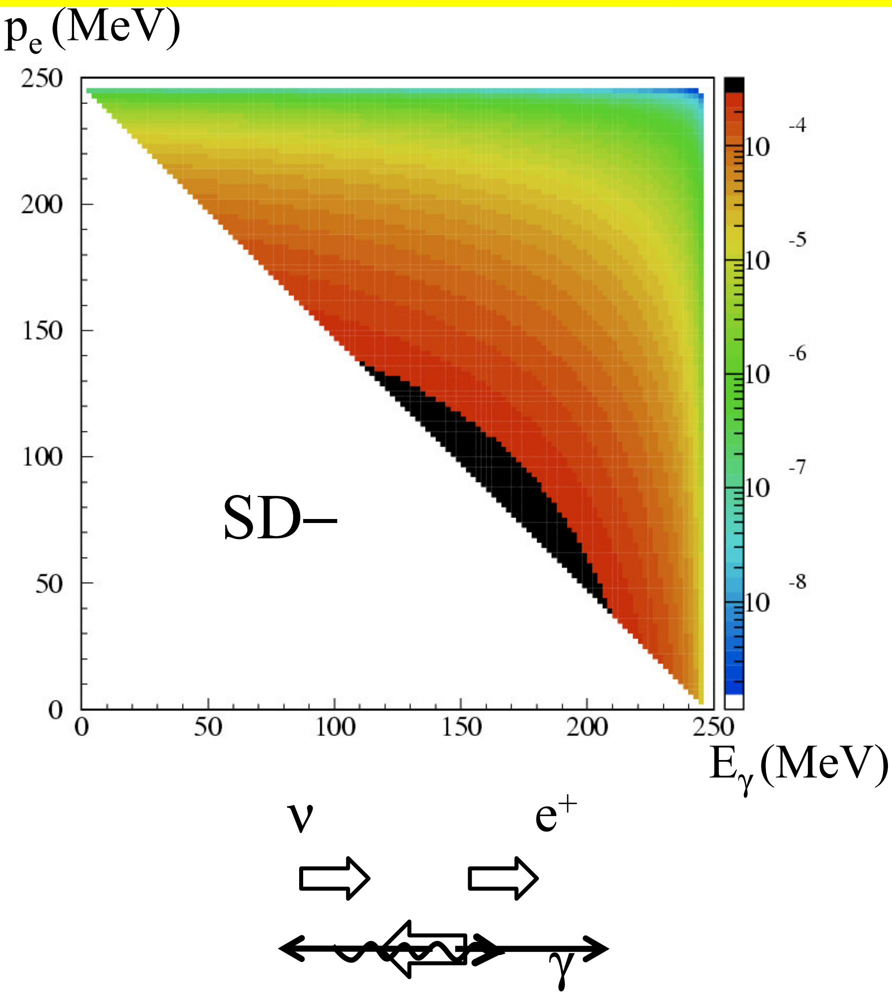
non trivial x dependence

$f_V = f_A = 0$ at x=0

Chen, Geng, Lih 08

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