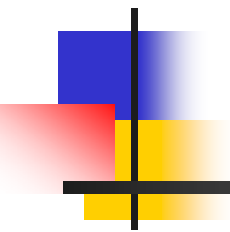


STUDY OF RADIATIVE DECAYS AND RELATED CHPT TESTS AT THE NA48/2 EXPERIMENT



Stefano Venditti

University of Pisa & INFN

On behalf of the NA48/2 collaboration

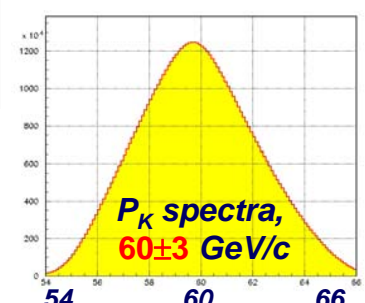
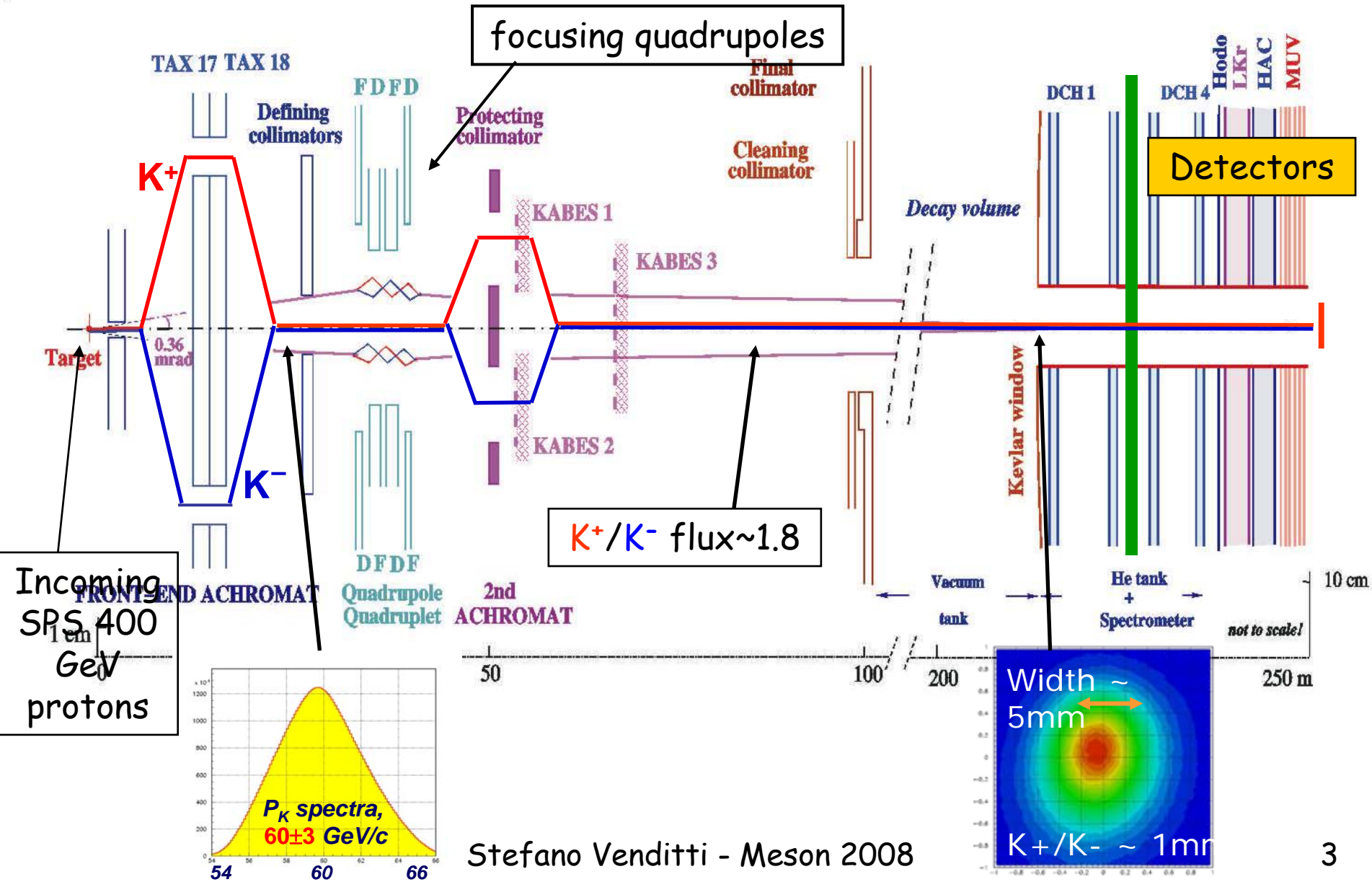
MESON 2008 - 06/06/2008 - Krakow



OUTLINE

- NA48/2 experiment: detectors and collected data;
- $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$: DE/INT part measurement;
- $K^\pm \rightarrow \pi^\pm \gamma \gamma$: BR measurement;
- $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$: first BR measurement ever, \hat{c} estimation;
- $K^\pm \rightarrow \pi^\pm e^+ e^-$: Model dependent and independent BR estimation, related parameters;
- Conclusions.

NA48/2 BEAM LINE



Stefano Venditti - Meson 2008



NA48/2 DETECTORS

- Spectrometer:

4 DCHs -> redundancy.

$$\sigma_p/p = 1.0\% + 0.044\% \times p(\text{GeV});$$

- Liquid Krypton EM calorimeter:

16000 cells -> high granularity.

$$\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%;$$

- Hodoscopes (charged, neutral):

Trigger, time measurement.

- Muon veto, Hadronic calo, Kabes, photon vetoes.

DATATAKING PERIODS:

2003: ~ 50 days

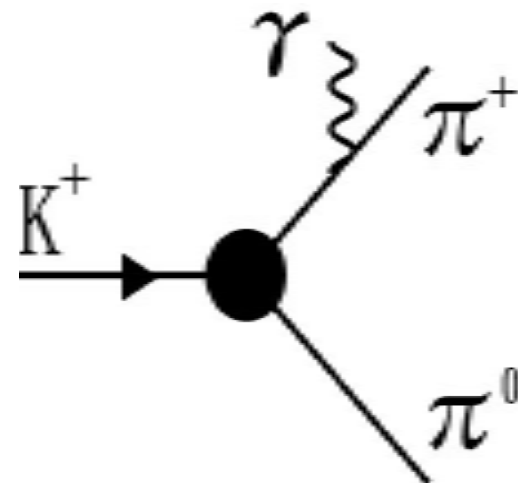
2004: ~ 60 days

~ $18 \cdot 10^9$ triggers collected

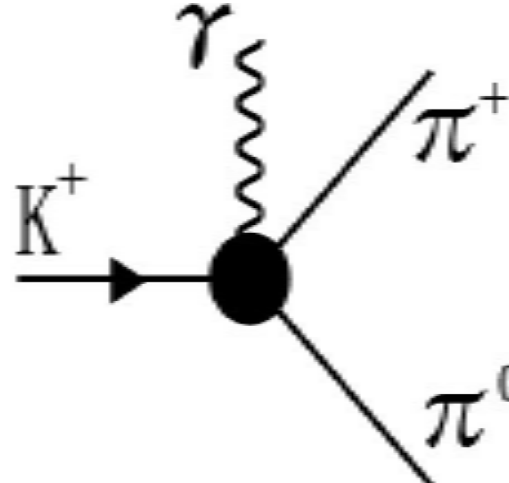
$$K^\pm \longrightarrow \pi^\pm \pi^0 \gamma$$

- 3 terms (pure IB and DE, INT) in the decay width, can be disentangled using W variable (and integrating over $T^* \pi$):

$$\frac{d\Gamma^\pm}{dW} \simeq \underbrace{\left(\frac{d\Gamma^\pm}{dW} \right)_{IB}}_{IB} \left[1 + \underbrace{2 \left(\frac{m_\pi}{m_K} \right)^2 W^2 |E| \cos((\delta_1 - \delta_0) \pm \phi)}_{INT} + \underbrace{\left(\frac{m_\pi}{m_K} \right)^4 W^4 (|E|^2 + |M|^2)}_{DE} \right]$$



IB



DE

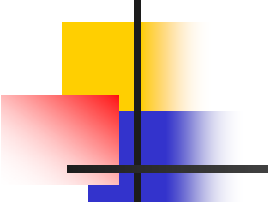
$$W^2 = \frac{(P_K \cdot P_\gamma) (P_\pi \cdot P_\gamma)}{(M_K M_\pi)}$$

($P = 4$ -momenta)

$T^* \pi =$ Pion CM kin. energy

$E =$ electric dipole

$M =$ magnetic dipole


$$K^{\pm} \longrightarrow \pi^{\pm} \pi^0 \gamma$$

- DE has magnetic (M) and electric (E) parts;
- DE magnetic part is due to chiral anomaly contribution (calculable) and direct contributions (non predictable);
- DE electric part is non predictable;
- DE electric part interferes with IB amplitude, giving INT amplitude.

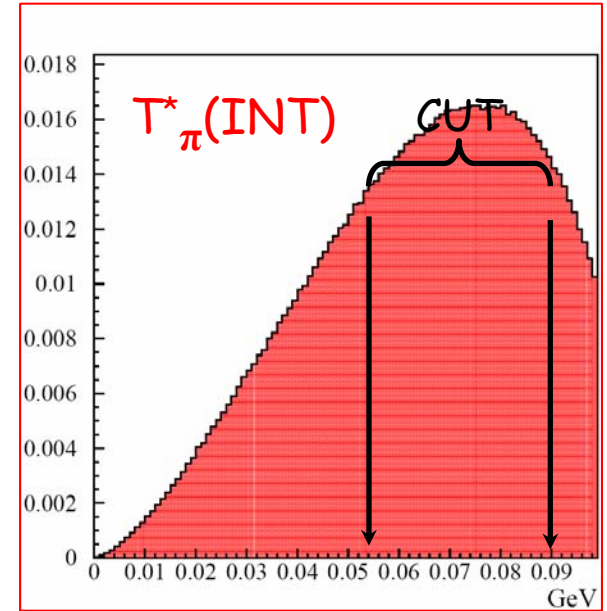
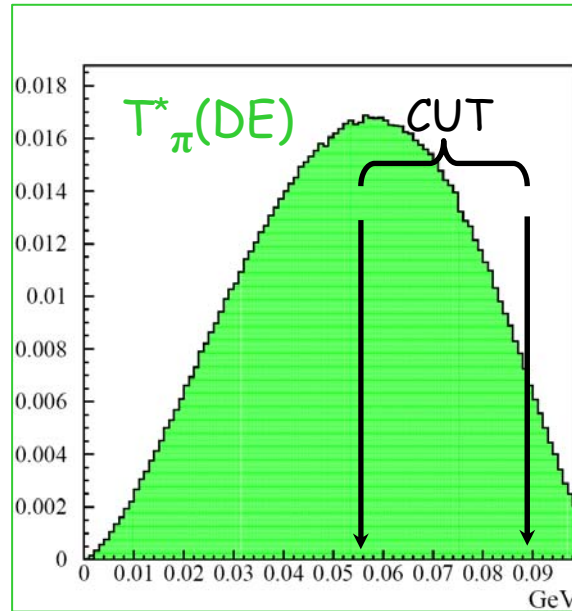
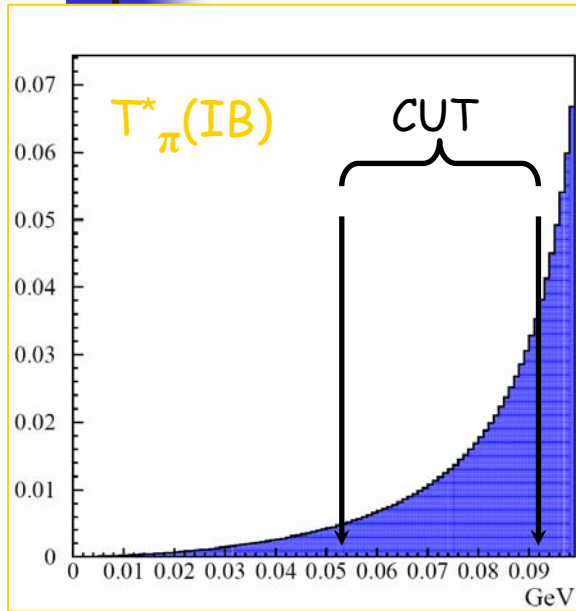
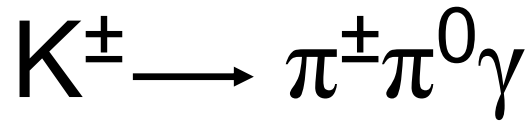
A measurement of DE and IB contributions allows to measure M and E

Current PDG values

IB term: $(2.75 \pm 0.15) \cdot 10^{-4}$ ($55 \text{ MeV} < T^* \pi < 90 \text{ MeV}$)

DE term: $(4.4 \pm 0.8) \cdot 10^{-6}$ ($55 \text{ MeV} < T^* \pi < 90 \text{ MeV}$)

INT term: not yet measured



- $55 \text{ MeV} < T^*_{\pi} < 90 \text{ MeV}$ cut used in previous analyses to reject BG (mostly $\pi^{\pm}\pi^0$ and $\pi^{\pm}\pi^0\pi^0$)
- However this cut excludes most of the DE events
- It was then decided to cut at $T^*_{\pi} < 80 \text{ MeV}$.

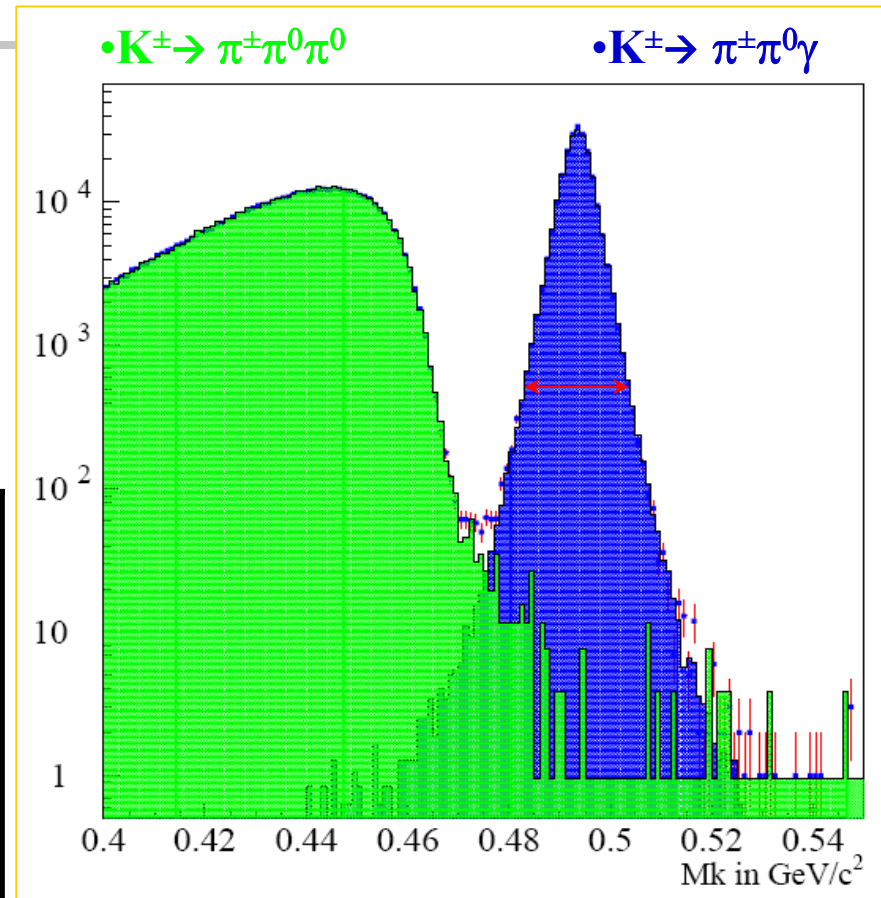
$$K^{\pm} \longrightarrow \pi^{\pm} \pi^0 \gamma$$

EVENT SELECTION

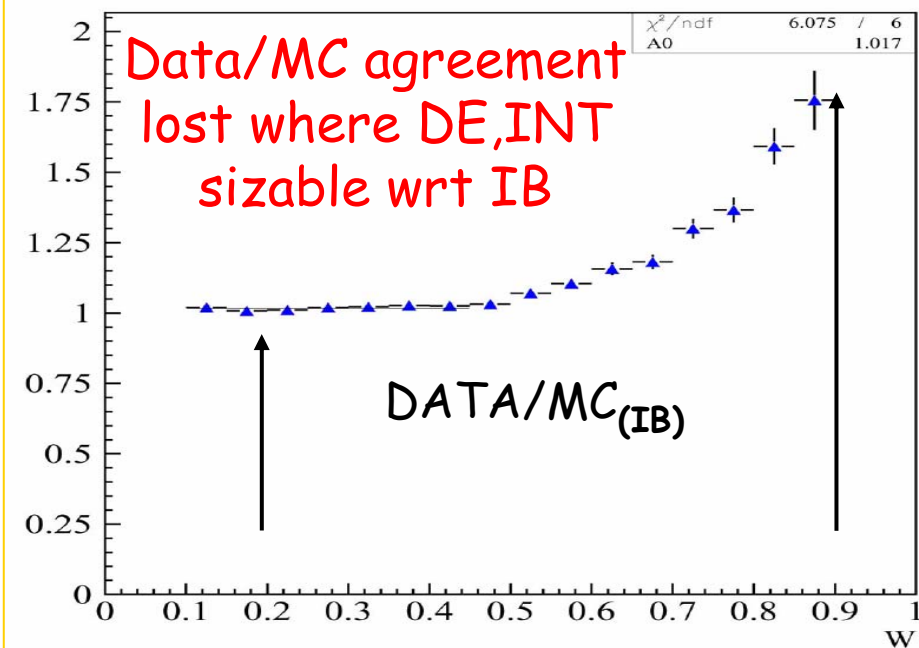
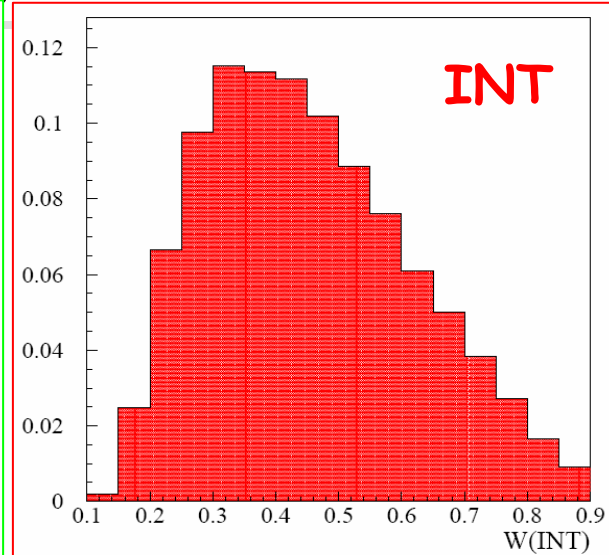
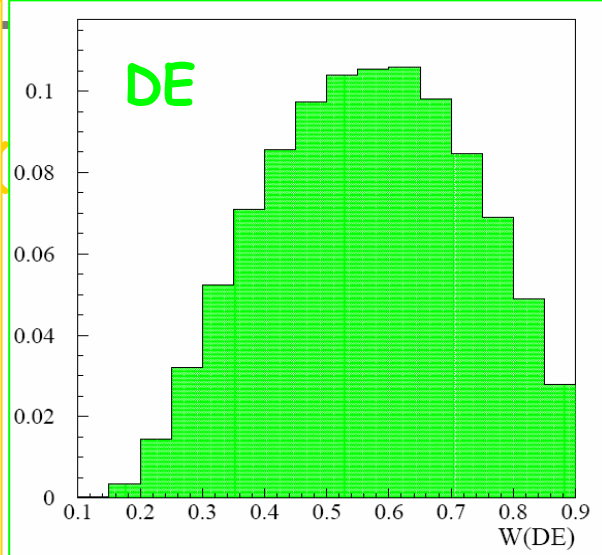
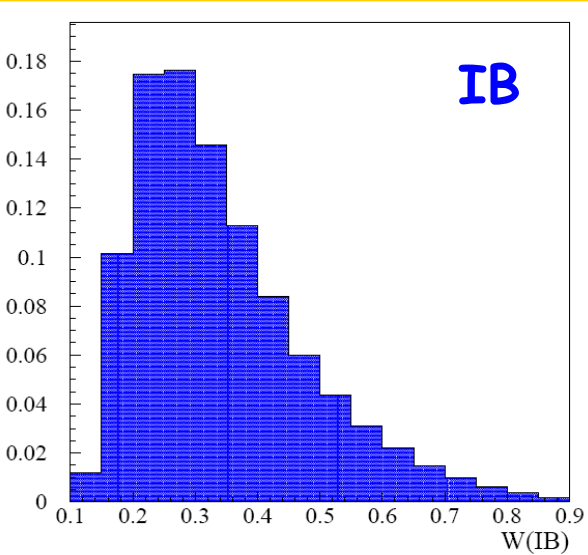
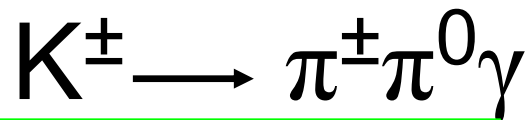
- At least 1 track and 3 clusters
- Acceptance and BG-rejection cuts (M_K , COG)

BG CHANNELS

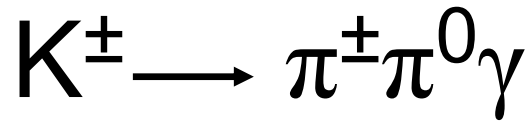
BG channel	BR	BG mechanism
$K^{\pm} \longrightarrow \pi^{\pm} \pi^0$	~21%	γ from accidental or hadr. shower
$K^{\pm} \longrightarrow \pi^{\pm} \pi^0 \pi^0$	~1.7%	missing or overlapping γ
$K^{\pm} \longrightarrow e^{\pm} \pi^0 \nu$	~5%	e mistagged as π , accidental γ
$K^{\pm} \longrightarrow \mu^{\pm} \pi^0 \nu$	~3.3%	μ mistagged as π , accidental γ



- Residual BG (due only to $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0$) less than 1% of DE
- mistagging probability (self BG) at % level



- IB, DE and INT MC sample produced separately
- Fit in $0.2 < W < 0.9$ region
- Looking for DE and IB weights (wrt IB) minimizing data/MC.

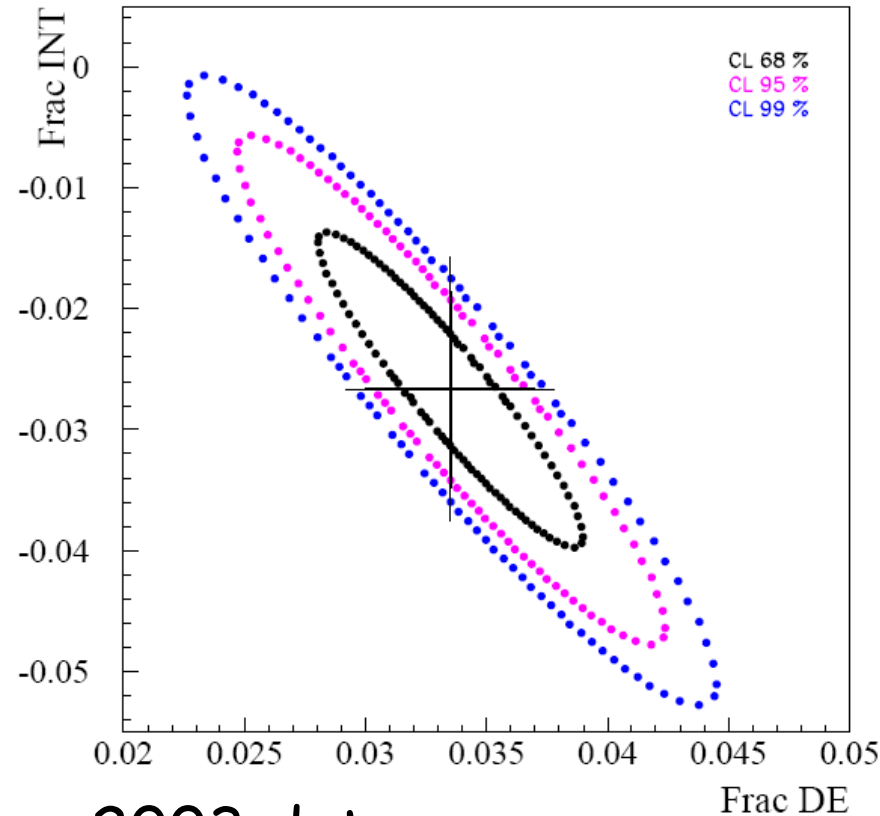


Fit function used:

$$W_{\text{DATA}} = (1-A-B) \cdot W_{\text{IB}} + A \cdot W_{\text{DE}} + B \cdot W_{\text{INT}}$$

with A, B free parameters

- A, B highly correlated ($\text{corr.} = -0.92$)
- systematics dominated by trigger efficiency
- $B \neq 0$: first evidence of INT term



Preliminary result on 2003 data:

$$\text{FRAC}_{\text{DE}}(0.2 < W < 0.9) = (3.35 \pm 0.35_{\text{stat.}} \pm 0.25_{\text{syst.}})\%$$

$$\text{FRAC}_{\text{INT}}(0.2 < W < 0.9) = (-2.67 \pm 0.81_{\text{stat.}} \pm 0.73_{\text{syst.}})\%$$

$$K^\pm \longrightarrow \pi^\pm \gamma \gamma$$

$$\frac{\partial^2 \Gamma}{\partial y \partial z} = \frac{m_{K^+}}{(8\pi)^3} \left[z^2 (|A + B|^2 + |C|^2) + \left(y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 (|B|^2 + |D|^2) \right]$$

$$y = \frac{P \cdot (q_1 - q_2)}{M_K^2} \quad z = \frac{(q_1 + q_2)^2}{M_K^2} = \frac{M_{\gamma\gamma}^2}{M_K^2}$$

P = pion 4-momentum
q_{1,2} = photon 4-momenta

(only Z is dynamically relevant) A, B, C, D depend on Z and on \hat{c} parameter

ChPT contributions to the amplitude:

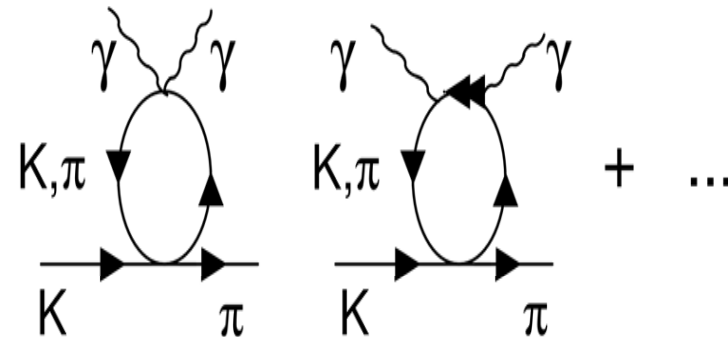
$O(p^4)$: $A(z, \hat{c})$ responsible for cusp at $m_{\gamma\gamma} = 2m_\pi$

$C \neq 0$ for WZW anomaly (poles and tadpoles)

$B = D = 0$

[D'Ambrosio, Portolés, PLB386 (1996) 403]

$O(p^6)$: unitarity corrections can increase BR by 30-40% (depending on \hat{c} value)

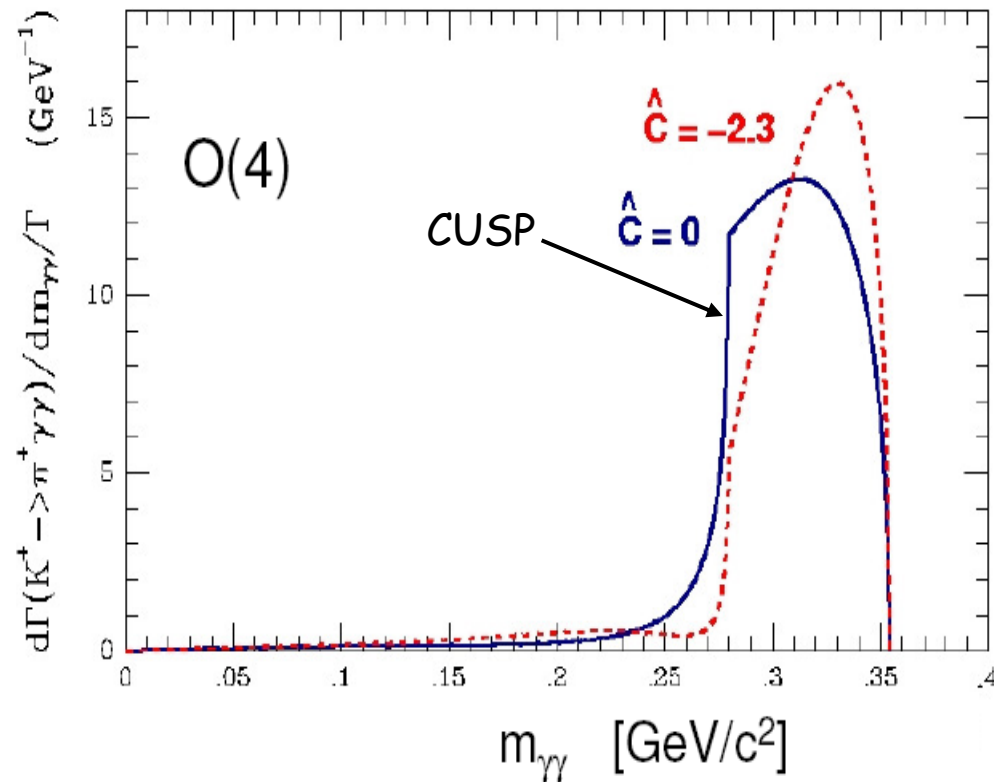
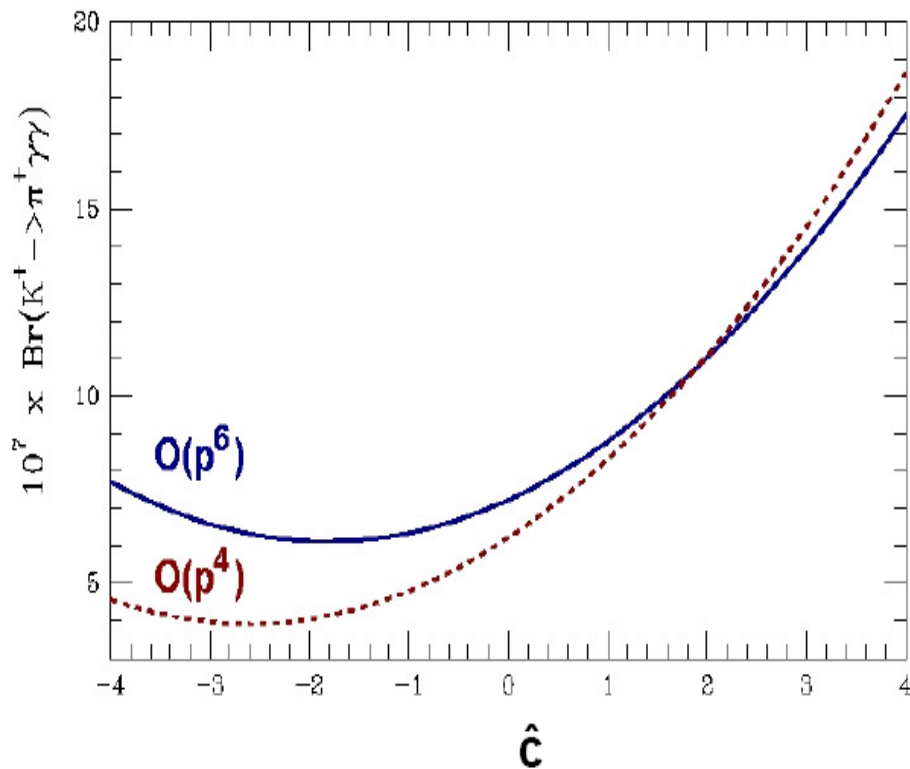


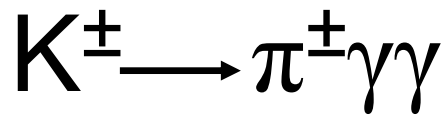
$$K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$$

BR \hat{c} dependence:

$$BR(K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma) = (5.26 + 1.64 \cdot \hat{c} + 0.32 \cdot \hat{c}^2 + 0.49) \times 10^{-7}$$

$$BR(K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma) \geq 4 \times 10^{-7}$$





Event selection:

- at least 1 π track, 2 clusters
- COG, CDA, chd vertex cuts
- $0 < M_{\gamma\gamma} < M_K - M_{\pi}$ (kinematic limit)

1164 events selected

- 20% of full datasample
- 40 times larger than total world sample
- 3% BG (mainly from $\pi^{\pm} \pi \gamma$)

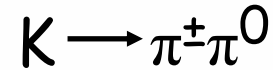
Actual measurement:

BNL E787(1991):

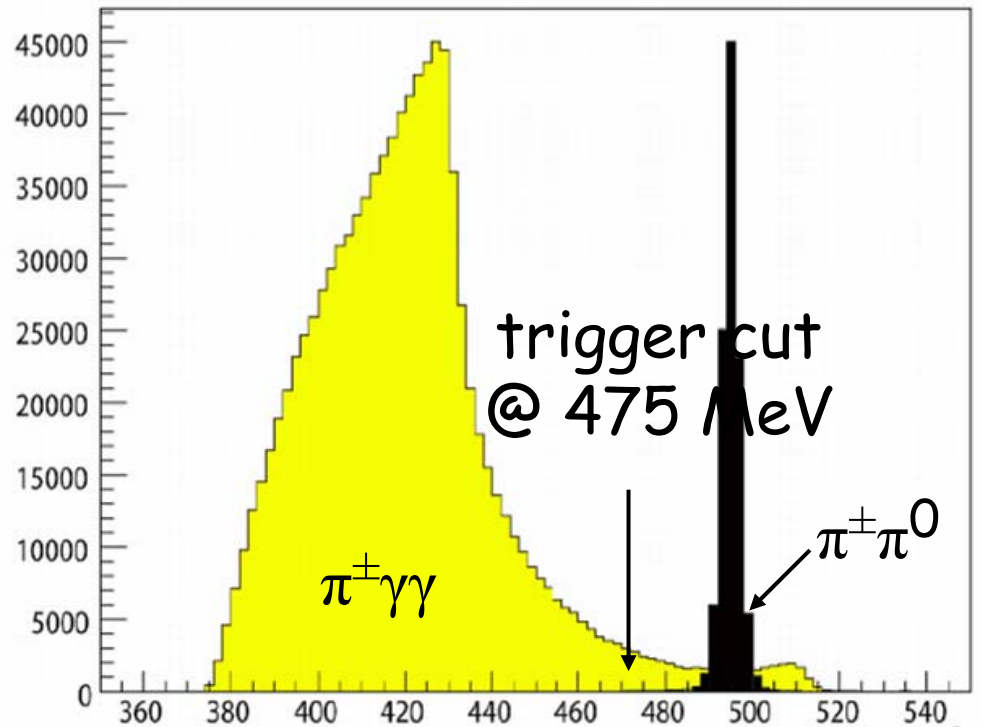
31 candidates, 5 BG events

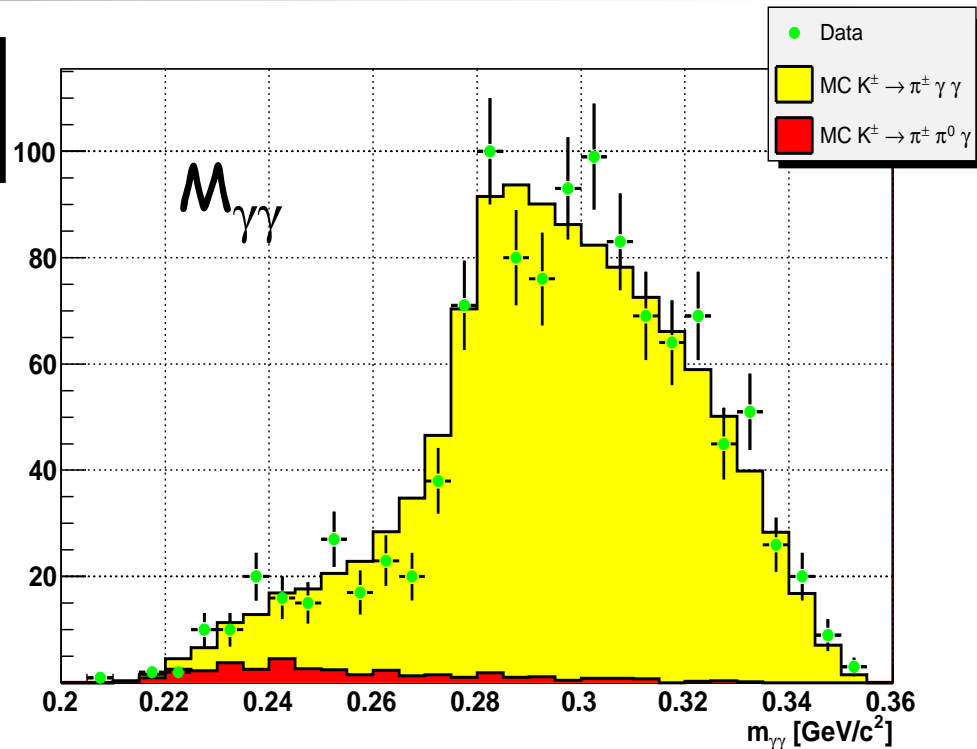
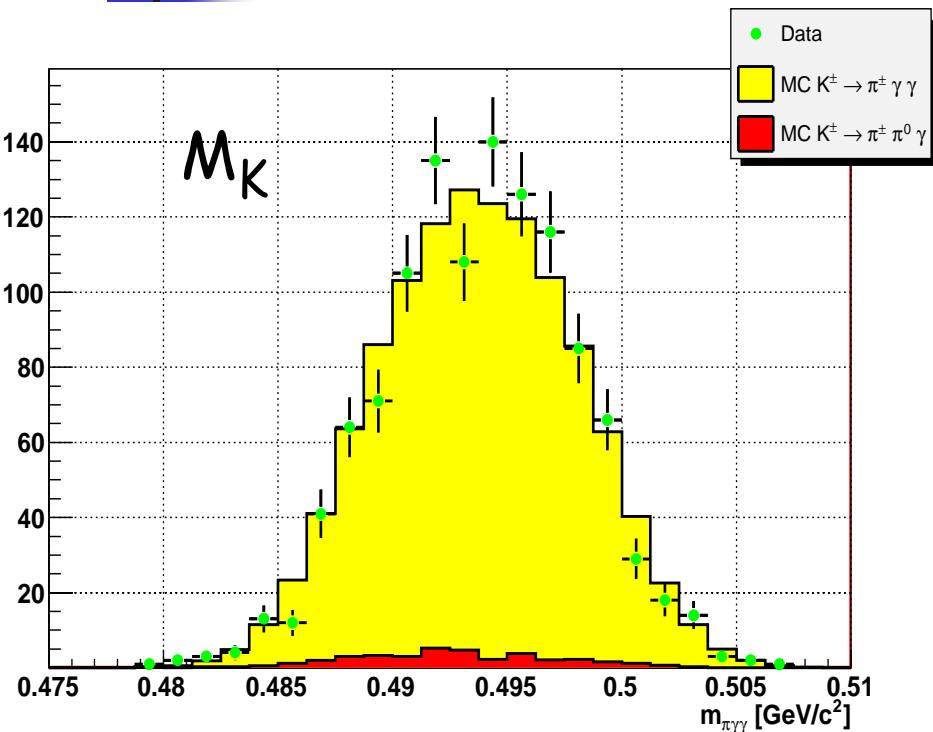
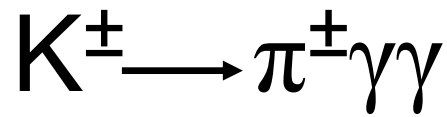
$BR = (1.10 \pm 0.32) \cdot 10^{-6}$

Normalization channel:



(~6M events selected)





BG mainly from $\pi^{\pm} \pi^0 \gamma$

Good agreement with $c=2$ generated MC sample

$$BR = (1.07 \pm 0.04_{\text{stat.}} \pm 0.08_{\text{syst.}}) \cdot 10^{-6}$$

PRELIMINARY

Future task: precise \hat{c} estimation

MAIN SYSTS:

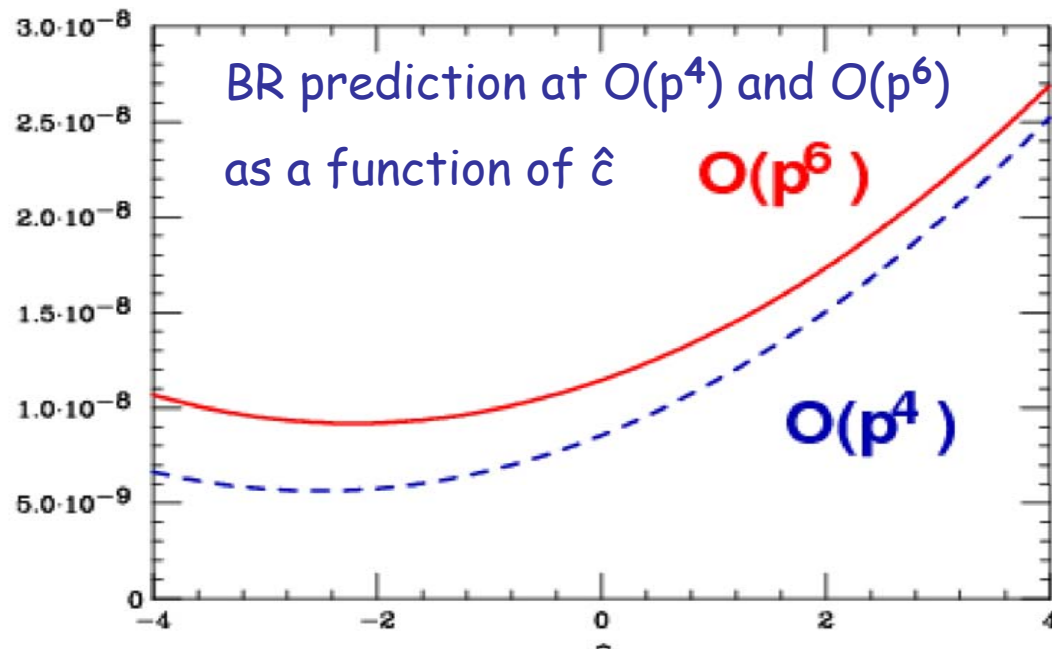
- pion-gamma cut
- Efficiency measurement

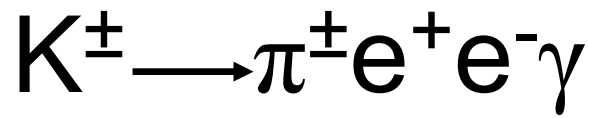
$$K^\pm \longrightarrow \pi^\pm e^+ e^- \gamma$$

- Theory is similar to $K^\pm \rightarrow \pi^\pm \gamma \gamma$ decay. Naively one expects $BR_{\pi e e \gamma} \sim BR_{\pi \gamma \gamma} \cdot 2\alpha \sim 1.6 \cdot 10^{-8}$.
- Theoretical expectation: $(0.9-1.6) \cdot 10^{-8}$ [Gabbiani, Phys. Rev. D 59]
- BR again depends on \hat{c} parameter (as in $K^\pm \rightarrow \pi^\pm \gamma \gamma$).
- Higher-order ($O(p^6)$) ChPT corrections increase the BR

GOALS:

- Model-independent BR measurement
- estimation of c from data
- use \hat{c} to compute model-dependent BR



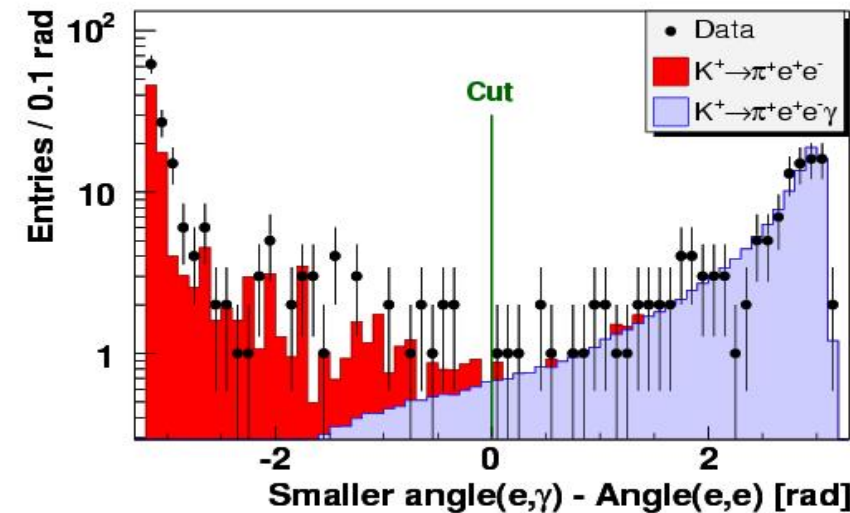


Event selection

- at least 3 tracks with $Q_{tot} = \pm 1$ and compatible decay vertex;
- at least 1 cluster not associated to track;
- $E/p > 0.94$ for e^\pm , < 0.8 for π^\pm
- $54 \text{ GeV} < E_{tot} < 66 \text{ GeV}$

BG suppression

- Many BG sources considered and evaluated with MC;
- $M_{ee\gamma} > 260 \text{ MeV}$ (low BG area);
- cut on $e-\gamma$ angle to reject $K^\pm \rightarrow \pi^\pm e^+ e^-$
- $480 \text{ MeV} < M_{\pi ee\gamma} < 505 \text{ MeV}$ (K mass)

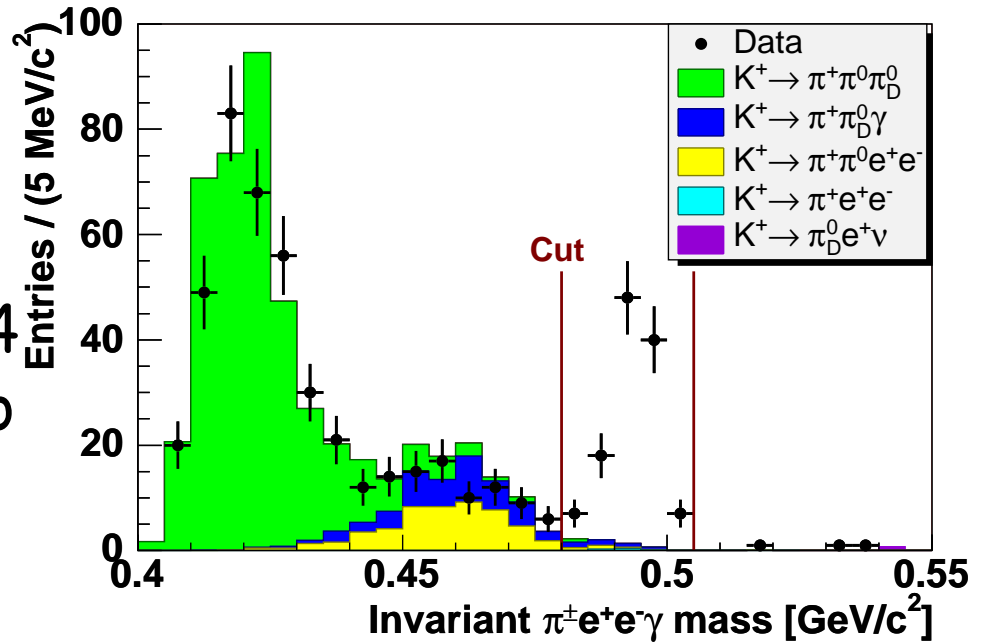
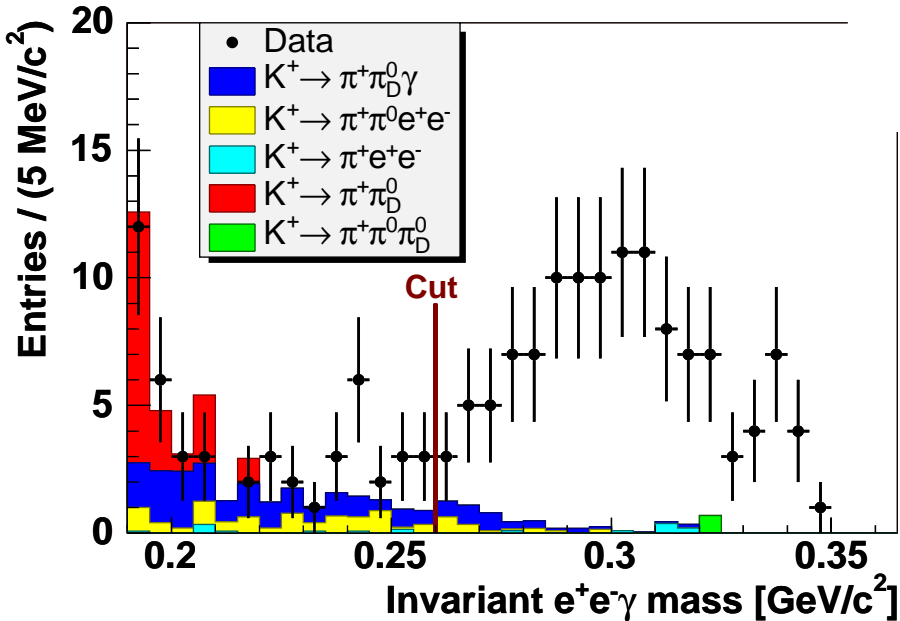


Background source	Branching ratio	Expected events
$K^\pm \rightarrow \pi^\pm \pi_D^0 \gamma$ (IB)	3.3×10^{-6}	3.1 ± 0.5
$K^\pm \rightarrow \pi^\pm \pi_D^0 \gamma$ (DE)	5.3×10^{-8}	0.12 ± 0.03
$K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ (IB)	$\sim 1.7 \times 10^{-6}$	1.6 ± 0.9
$K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ (DE)	$\sim 2.6 \times 10^{-8}$	0.02 ± 0.01
$K^\pm \rightarrow \pi^\pm e^+ e^-$	2.9×10^{-7}	0.8 ± 0.5
$K^\pm \rightarrow \pi^\pm \pi^0 \pi_D^0$	2.1×10^{-4}	0.7 ± 0.7
Accidentals	-	1.0 ± 1.0
Sum		7.3 ± 1.7

$$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-} \gamma$$

120 candidate events in accepted region, 7.3 ± 1.7 estimated BG events.

Normalized to $K^{\pm} \rightarrow \pi^{\pm} \pi^0$ (14 M events), PDG value used to compute absolute BR.



$\hat{c}=1.8$ for MC generation (same used in $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$ analysis)

FIRST OBSERVATION OF THIS DECAY

$K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$

- Model-independent BR in bins of $M_{ee\gamma}$ (5 MeV steps);
- Least squares fit on $M_{ee\gamma}$ to extract \hat{c}

$$BR_{MI} = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \cdot 10^{-8}$$

$$\hat{c} = 0.90 \pm 0.45 \quad (c = 1.8 \pm 0.6 \text{ in } K \rightarrow \pi \gamma \gamma)$$

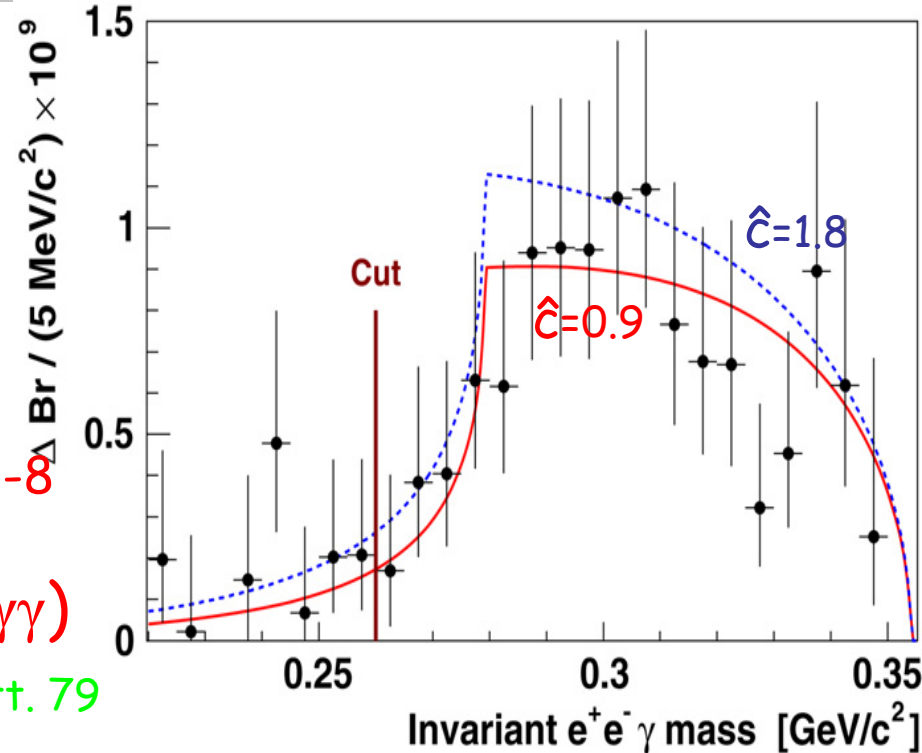
BNL E787, *Phys. Rev. Lett.* 79

Model-dependent ($c=0.9$) BR:

$$BR = (1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}}) \cdot 10^{-8}$$


Errors dominated by statistics

Paper published: *Phys. Lett. B* 659



MAIN SYSTS:

- BG subtraction
- Normalization
- MC statistics



$$K^\pm \longrightarrow \pi^\pm e^+ e^-$$

$$K^\pm \longrightarrow \pi^\pm \gamma^* \longrightarrow \pi^\pm e^+ e^- \quad \text{through suppressed FCNC.}$$

$$\frac{d\Gamma}{dz} = P(z) \cdot |W(z)|^2 \quad \left\{ \begin{array}{l} P(z) = \text{phase space factor} \\ z = \frac{M_{ee}^2}{M_K^2} \end{array} \right. \quad \begin{array}{l} \text{only 1 relevant variable,} \\ \text{second one integrated.} \end{array}$$

3 tested models for $W(z)$:

- polynomial: $G_F M_K^2 \cdot f_0 \cdot (1 + \delta z)$
- ChPT $O(p^6)$: $G_F M_K^2 \cdot (a_+ + b_+ z) + W_{\pi\pi}(z)$

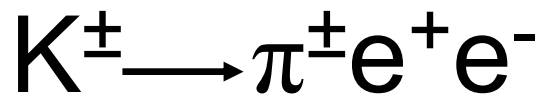
JHEP 8 (1998) 4

- Dubna ChPT: $W(M_a, M_\rho, z)$

hep-ph/0611175

GOALS

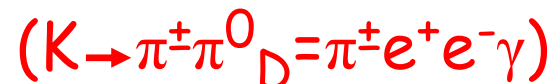
- Model independent BR in accepted kinematic range
- parameter and model-dependent BR estimations for the 3 models.



Selection cut: signal

- 3-track vertex;
- $E/p < 0.85$ (π^{\pm}), $E/p > 0.95$; (opposite sign electrons)
- $M_{ee} > 140$ MeV;
- Cut on kaon ($\pi^{\pm} e^{+} e^{-}$) mass, total and transverse momentum

Selection cut: normalization



- Selection of good γ
- Cut on kaon ($\pi^{\pm} e^{+} e^{-} \gamma$) mass

The use of a very similar channel cancels systematics (trigger, PID) in the BR ratio

BG subtraction: MC was used only to identify the BGs, BG estimation **DIRECTLY ON DATA** with same sign (SS) events.

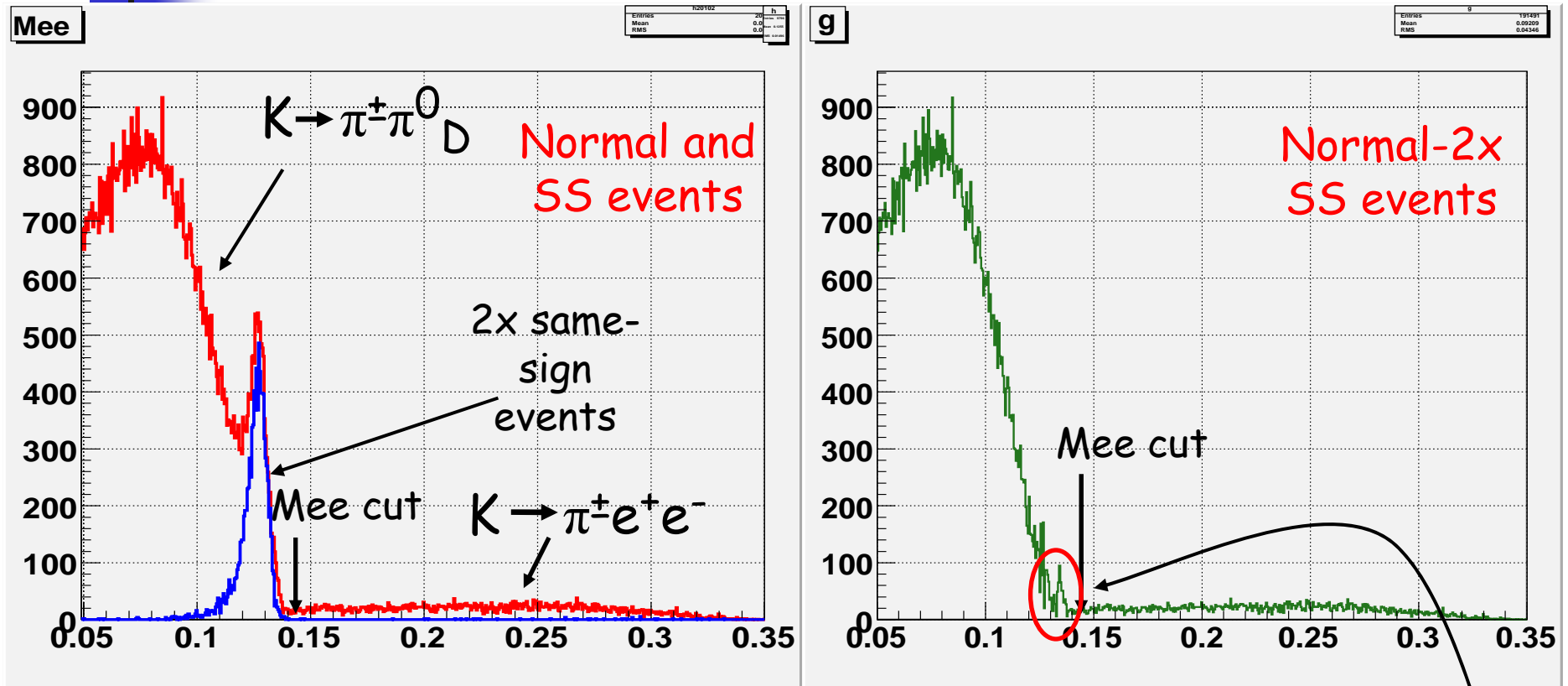
- $K^{\pm} \pi^{\pm} \pi^{0} \gamma$ with misid. e^{\pm} and π^{\pm}
 - $K^{\pm} e^{\pm} \nu \pi^{0} \gamma$ with misid. e^{\pm}
 - events with $e^{+} e^{-}$ pairs
- $$\left. \begin{array}{l} \frac{SS}{BG} = 1 \\ \frac{SS}{BG} = \frac{1}{2} \end{array} \right\}$$

SIGNAL CANDS: 7103

BG EVENTS: 56

BG/SIG. ~ 0.8%

$$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$$

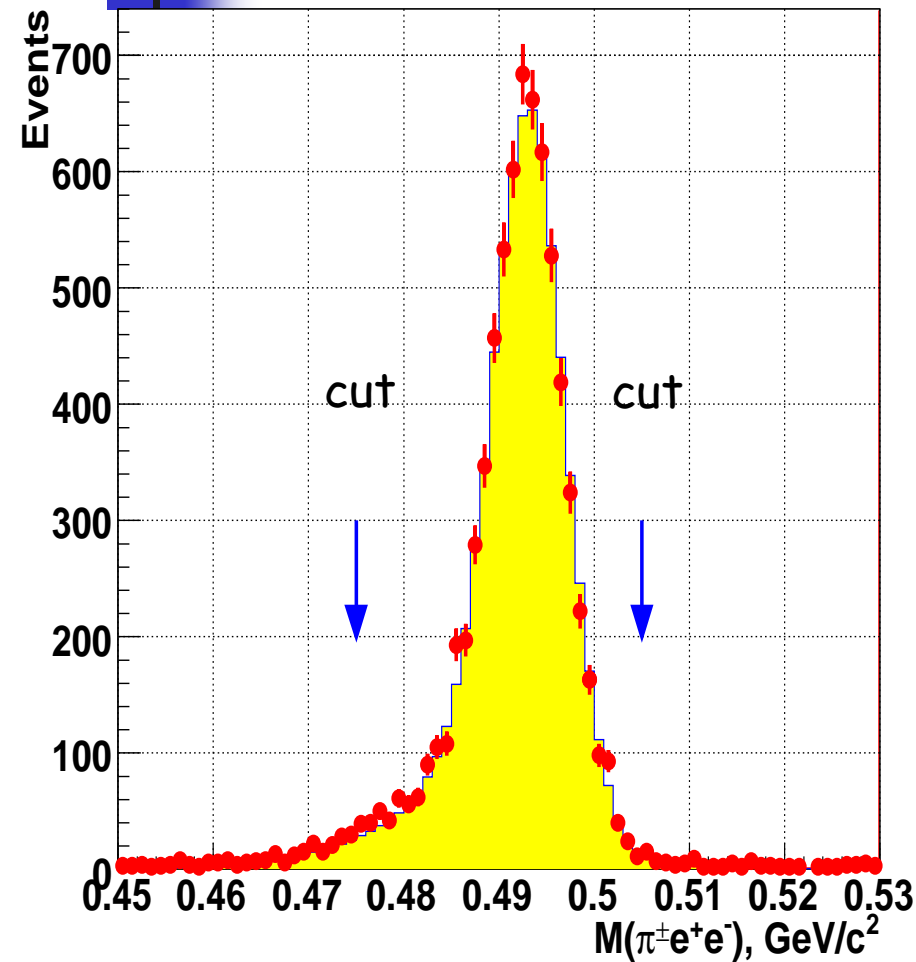


M_{ee} (all cuts applied except $M_{ee} > 140$ MeV)

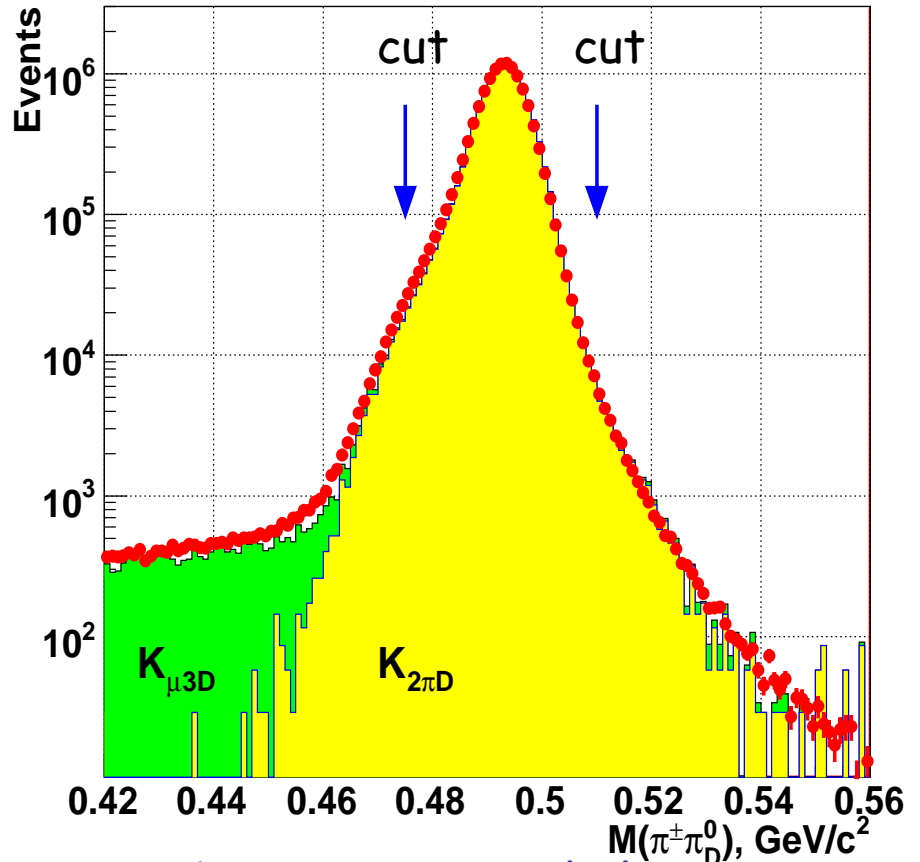
Region $M_{ee} < 140$ MeV dominated by BG

After BG subtraction $\pi^0 \rightarrow e^{+} e^{-}$ peak (~ 500 evts) can be seen

$$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$$



7103 candidates



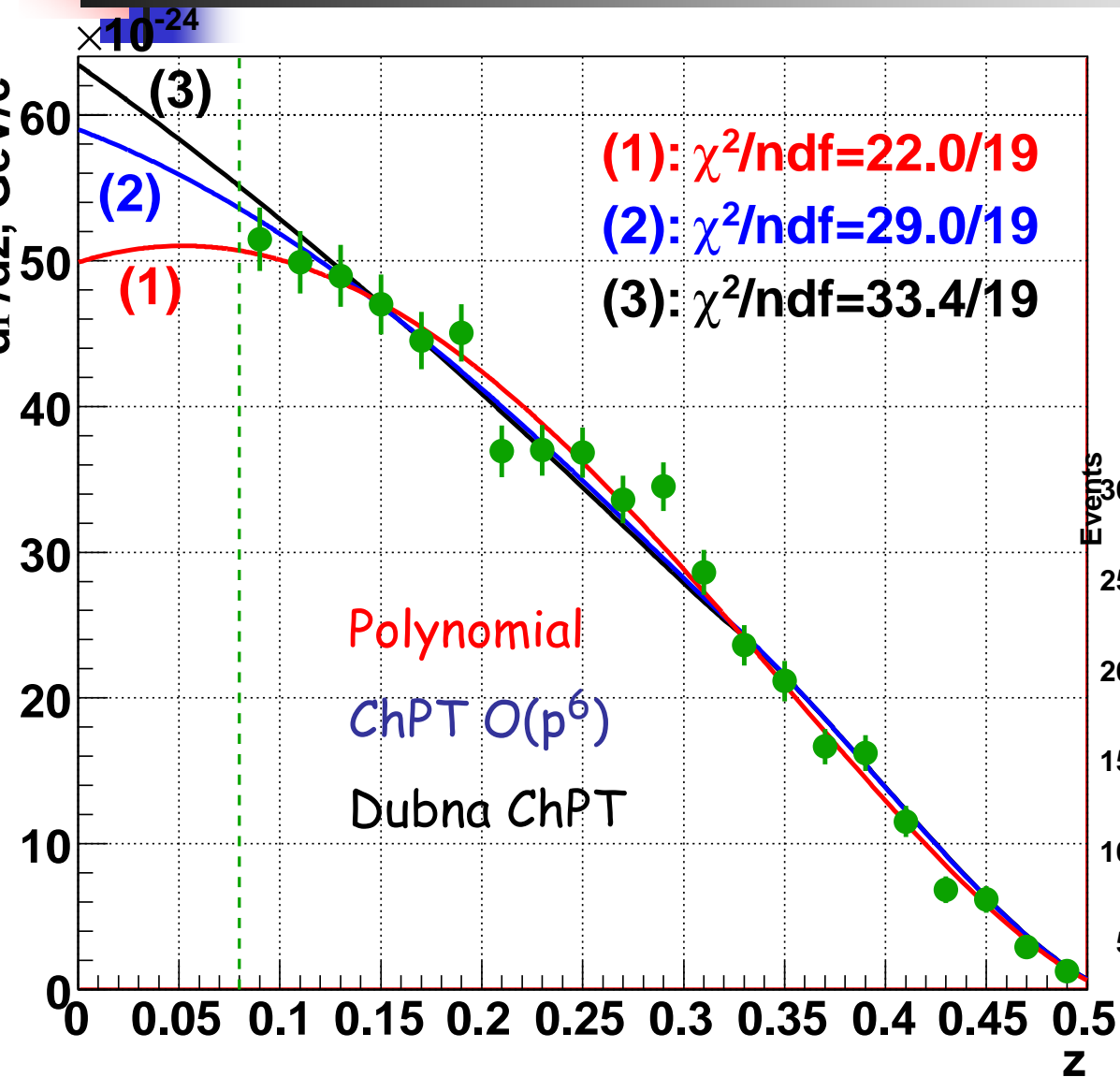
12.23 M candidates

BG/Signal $\sim 0.15\%$

($K^{\pm}\mu\nu\pi^0_D$ BG events subtracted with MC)

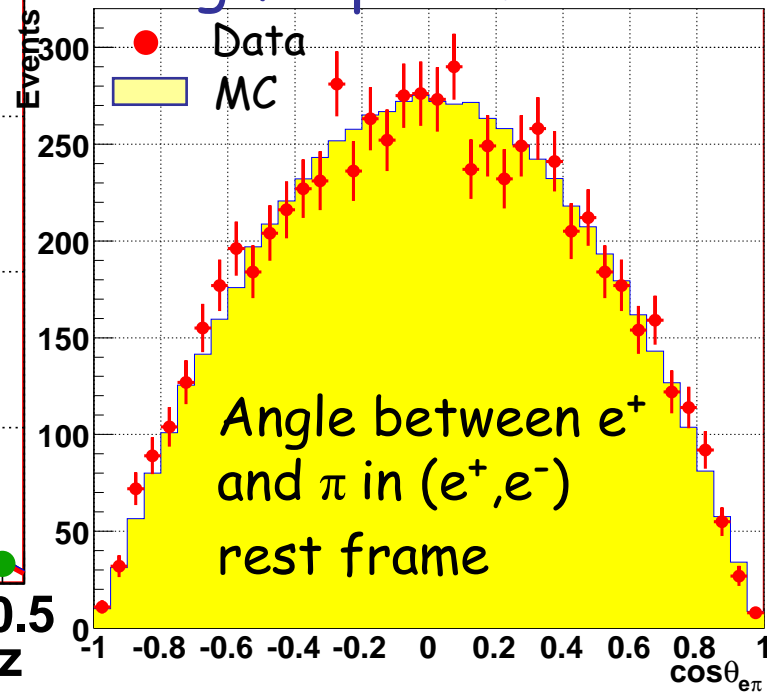
Kaon decay flux (2003+2004): $\Phi_K = 1.70 \times 10^{11}$ with $K^{\pm}\pi^{\pm}\pi^0$ PDG BR

$$K^\pm \rightarrow \pi^\pm e^+ e^-$$



All models reasonably agree with data.

- Model-independent BR integrating M_{ee} ;
- Model dependent BRs using fit parameters.



$K^\pm \rightarrow \pi^\pm e^+ e^-$

RESULTS

$$BR_{mi} \times 10^7 = 2.26 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.06_{\text{ext}} = 2.26 \pm 0.08$$

$$\delta = 2.35 \pm 0.15_{\text{stat}} \pm 0.09_{\text{syst}} = 2.35 \pm 0.18$$

$$f_0 = 0.532 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}} = 0.532 \pm 0.016$$

$$BR_1 \times 10^7 = 3.02 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.02 \pm 0.10$$

$$a_+ = -0.579 \pm 0.012_{\text{stat}} \pm 0.008_{\text{syst}} \pm 0.007_{\text{ext}} = -0.579 \pm 0.016$$

$$b_+ = -0.798 \pm 0.053_{\text{stat}} \pm 0.037_{\text{syst}} \pm 0.017_{\text{ext}} = -0.798 \pm 0.067$$

$$BR_2 \times 10^7 = 3.11 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.11 \pm 0.10$$

$$M_a = 0.965 \pm 0.028_{\text{stat}} \pm 0.018_{\text{syst}} \pm 0.002_{\text{ext}} = 0.965 \pm 0.033 \text{ GeV}$$

$$M_\rho = 0.711 \pm 0.010_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.002_{\text{ext}} = 0.711 \pm 0.013 \text{ GeV}$$

$$BR_3 \times 10^7 = 3.15 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} = 3.15 \pm 0.10$$

Including uncertainty due to the model dependence:

$$BR = (3.08 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.08_{\text{ext}} \pm 0.07_{\text{model}}) \times 10^{-7} = (3.08 \pm 0.12) \times 10^{-7}$$

CPV parameter (first measurement! correlated K^+/K^- uncertainties excluded):

$$\Delta(K^\pm_{\pi ee}) = (BR^+ - BR^-) / (BR^+ + BR^-) = (-2.1 \pm 1.5_{\text{stat}} \pm 0.3_{\text{syst}})\%$$



CONCLUSIONS

- First evidence of interaction term in $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ decay amplitude;
- Statistics on $K^\pm \rightarrow \pi^\pm \gamma \gamma$ improved wrt previous measurements by a factor 40;
- First observation of $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$, estimation of ChPT parameter \hat{c} ;
- Model-independent BR estimation in $K^\pm \rightarrow \pi^\pm e^+ e^-$ and test of various models.



SPARE SLIDES

$$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$$

Corrections & uncertainties

Parameter	Electron ID	Beam simulation	Radiative corrections	Background to $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$	Trigger inefficiency	Fitting procedure	External (PDG)
$BR_{mi} \times 10^7$	0.02	0.01	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0	0.06

Model (1): linear form-factor

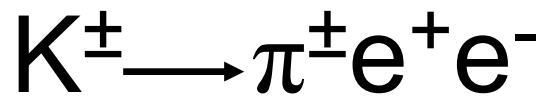
δ	0.01	0.04	0.05	-0.04 ± 0.04	-0.03 ± 0.03	0.03	0
f_0	0.001	0.006	0.004	$+0.002 \pm 0.002$	$+0.001 \pm 0.001$	0.003	0.007
$BR_1 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08

Model (2): ChPT form-factor [D'Ambrosio, Ecker, Isidori, Portoles, hep-ph/9808289]

a_+	0.001	0.005	0.004	-0.001 ± 0.001	-0.002 ± 0.002	0.004	0.007
b_+	0.009	0.015	0.022	$+0.017 \pm 0.017$	$+0.015 \pm 0.015$	0.010	0.017
$BR_2 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08

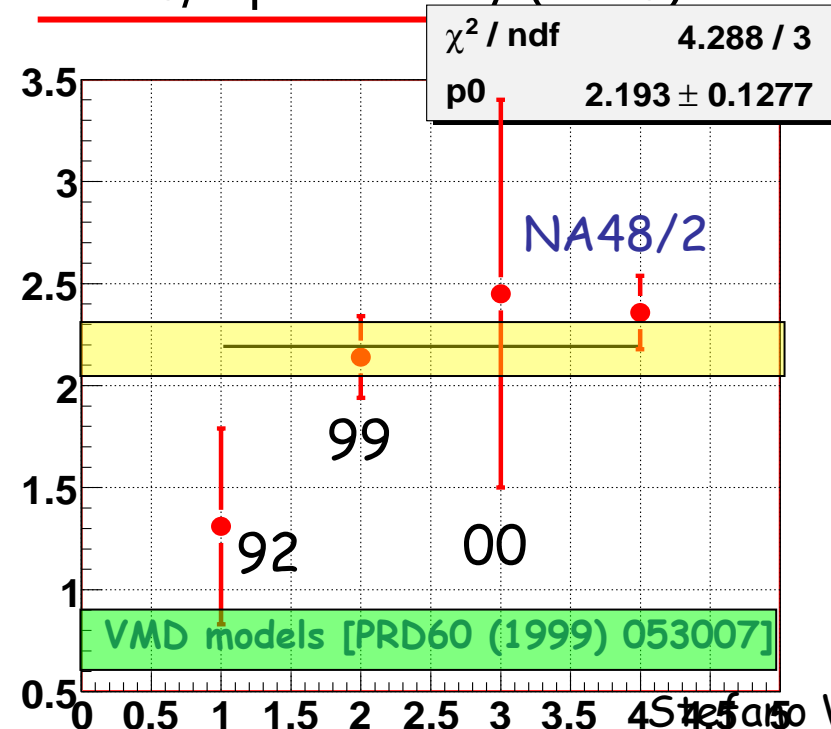
Model (3): Dubna ChPT [Pervushin et al., hep-ph/0611175]

M_a / GeV	0.004	0.009	0.009	$+0.008 \pm 0.008$	$+0.006 \pm 0.006$	0.006	0.002
M_p / GeV	0.002	0.003	0.004	$+0.003 \pm 0.003$	$+0.003 \pm 0.003$	0.002	0.002
$BR_3 \times 10^7$	0.02	0.02	0.01	-0.01 ± 0.01	-0.01 ± 0.01	0.02	0.08



δ (slope in polynomial model) comparison

Measurement	Process	Result
Alliegro et al., PRL 68 (1992) 278	$K^+ \rightarrow \pi^+ e^+ e^-$	1.31 ± 0.48
Appel et al. [E865], PRL 83 (1999) 4482	$K^+ \rightarrow \pi^+ e^+ e^-$	2.14 ± 0.20
Ma et al. [E865], PRL 84 (2000) 2580	$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	$2.45^{+1.30}_{-0.95}$
NA48/2 preliminary (2008)	$K^{\pm} \rightarrow \pi^{\pm} e^+ e^-$	2.35 ± 0.18



- NA48/2 measurement compatible with former results
- Difference wrt vector meson dominance models confirmed
- NA48/2 estimated values (f_0, a_+, b_+) in good agreement with BNL E865