Study of the $K^{\pm}$ to $\pi^{\pm} \pi^{0} e^{+} e^{-}$ decay with NA48/2 @ CERN

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on behalf of the NA48/2 Collaboration

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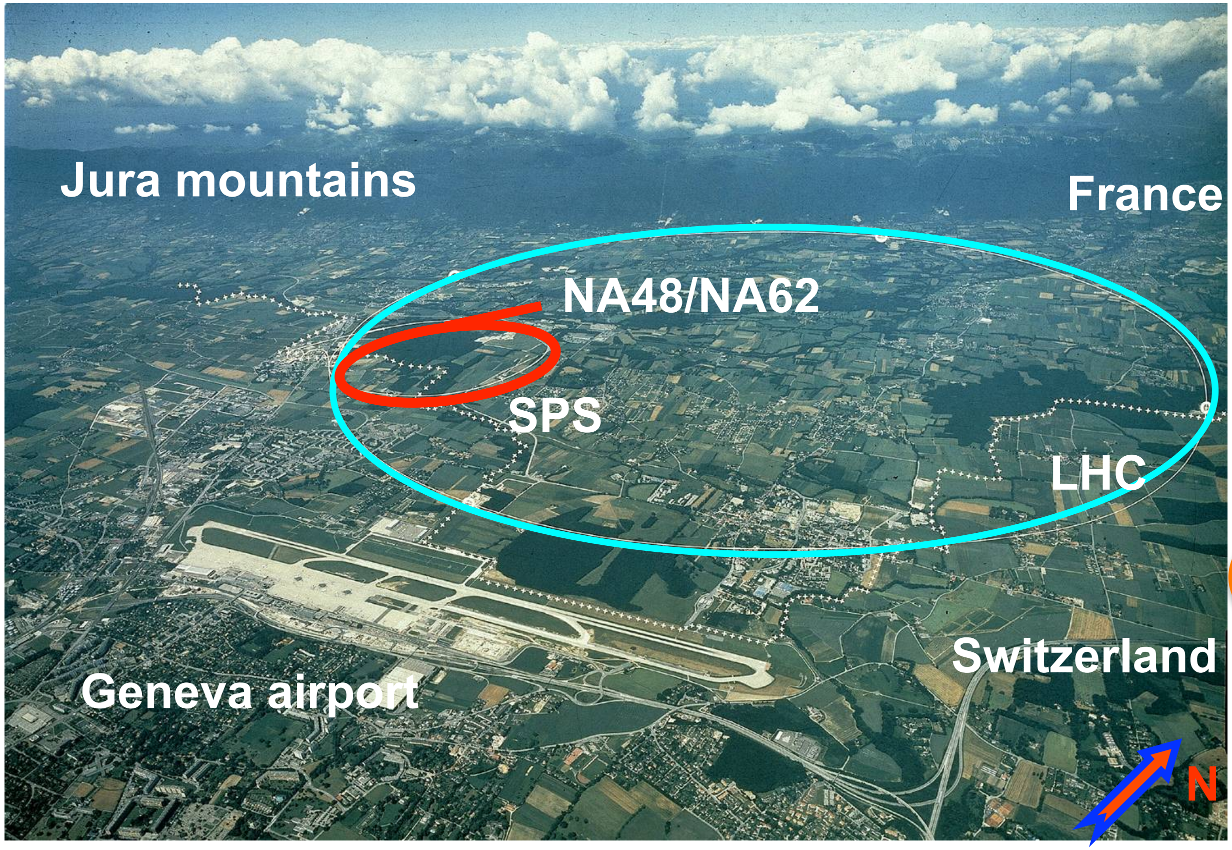
Outline

- NA48/2 description of experimental setup & detector performances…
  any need to repeat it ?
- ChPT and the $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} e^{+} e^{-}$ decay mode
- Selection and backgrounds
- Branching Ratio
- Summary/Prospects

Close to final !

The NA48/NA62 experiments at CERN-SPS



NA48 direct CPV ε'/ε	1997: $K_L + K_S$
	1998: $K_L + K_S$
	1999: $K_L + K_S$
	2000: K_L only
	2001: $K_L + K_S$
NA48/1	2002: K_S/hyperons
NA48/2	2003 $K^+ + K^-$ 2004 Ag(CPV)
NA62 (R_K)	2007 $K^+ + K^-$ 2008 R_K + tests
↓	2007 design & 2013 construction
NA62	2012 technical run 2013 long shutdown 2014 commissioning | & 2018 data taking

The NA48/2 collaboration:

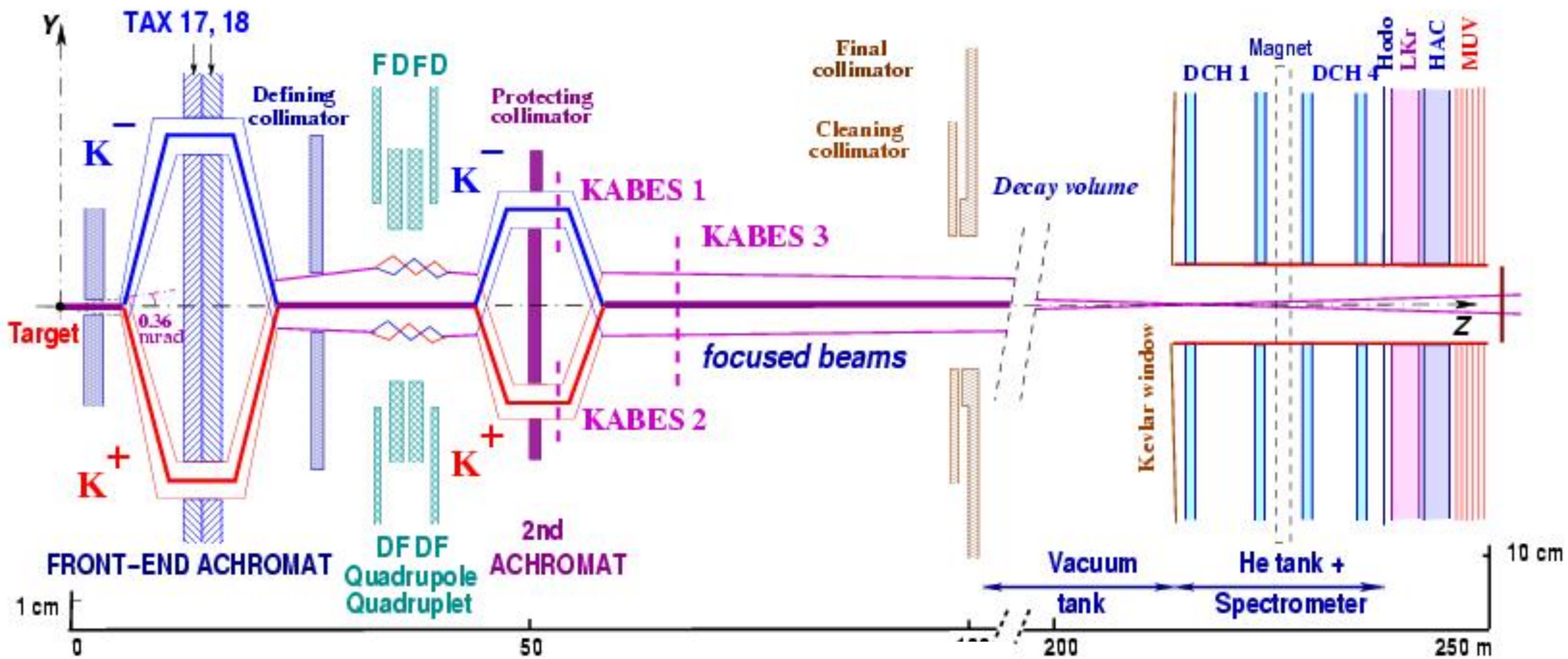
still analyzing > 10 years old valuable data !!

~100 physicists from 15 Institutes in 8 countries

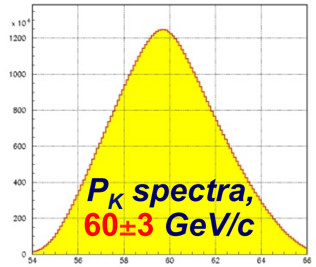
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze
Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

The NA48/2 experimental setup; Kaon beam

2003 + 2004 run: ~ 6 months, ~ 2 10^{11} $K^{\pm}$ decays in flight



Simultaneous K^+ and K^- beams: large charge symmetrization of experimental conditions



Beams coincide within ~1mm all along the 114m decay volume flux ratio K^+/K^- ~1.8

NA48/2 detector and performances

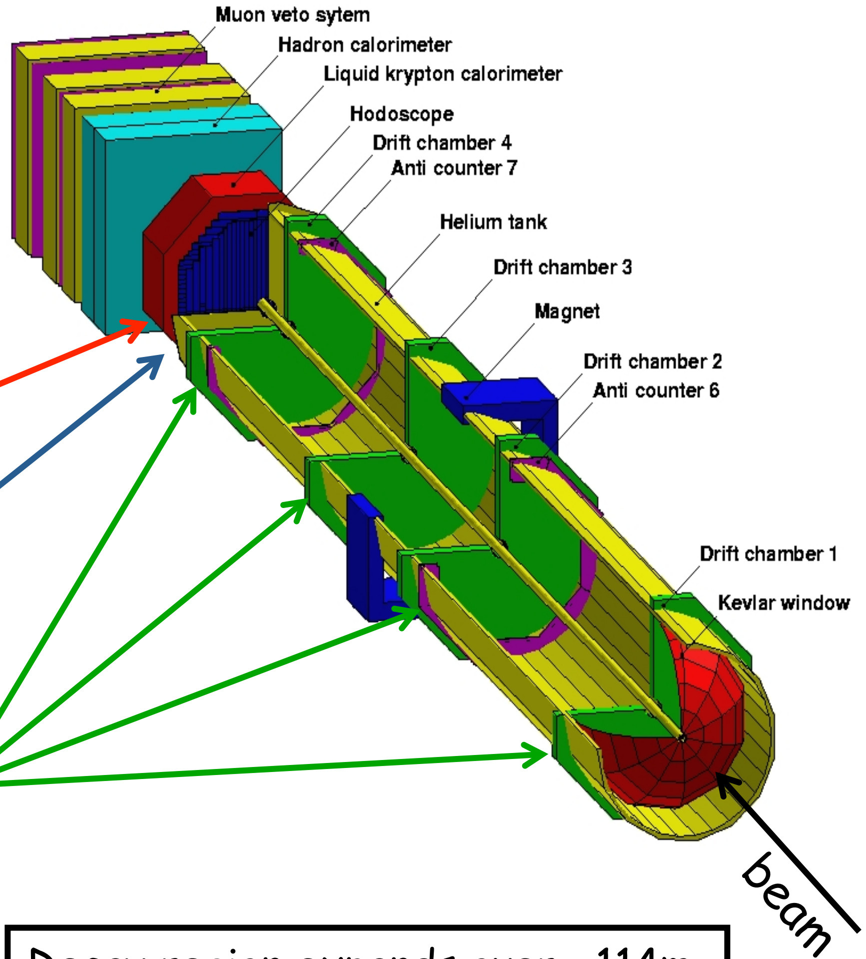
LKr electromagnetic calorimeter :
•quasi-homogenous and high granularity
•$\Delta E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)
$\sigma x = \sigma y \sim 1.5$ mm for E=10 GeV
•Very good resolution for neutrals ($\pi^0 \rightarrow \gamma\gamma$)
$\sigma(M\pi\pi^0\pi^0) = 1.4$ MeV/c^2

• E/p ratio can be used for e/π separation

Hodoscope for fast charged trigger

precise time resolution σt = 150 ps

Magnetic spectrometer :
- He tank to minimize multiple scattering
- 4 high-resolution DCH's + dipole magnet
- $\Delta p/p = (1.02 \oplus 0.044\ p)\%$ (p in GeV/c)
- Very good resolution for charged invariant masses: **$\sigma(M3\pi^{\pm}) = 1.7$ MeV/c^2**



Decay region expands over ~114m
Detector expands over ~50 m

Chiral Perturbation Theory and Kaon decays

- Kaon decays are a perfect laboratory to study ChPT (QCD at low energy)

  - see the many theory talks this week -

$K^{\pm} \rightarrow \pi^{\pm} l^{+} l^{-}$, $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$, $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \gamma$, $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \gamma^{*} \rightarrow \pi^{\pm} \pi^{0} e^{+} e^{-}$ and more..

πee PLB 677 (2009), $\pi\mu\mu$ PLB 697 (2011), $\pi\gamma\gamma$ PLB730 (2014), $\pi\pi^{0}\gamma$ EPJC 68 (2010)

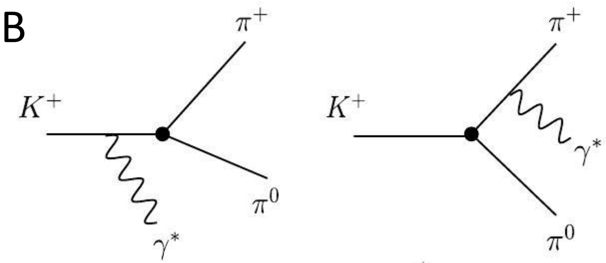
- What is so special about $\pi^{\pm} \pi^{0} e^{+} e^{-}$ decay ?

H.Pichl, EPJ C20 (2001) 371

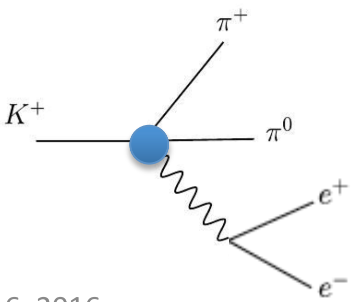
L. Cappiello, O. Catà, G. D'Ambrosio, D.Gao EPJ C72 (2012) 1872

$$\frac{d^3\Gamma}{dE^*_\gamma dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{E}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{M}}{dE^*_\gamma dT_c dq^2} + \frac{d^3\Gamma_{int}}{dE^*_\gamma dT_c dq^2}$$

IB



DE(M,E)



- Never observed so far: confirmation of BR magnitude from ChPT predictions ?
- If fine analysis possible (G.D'Ambriosio)

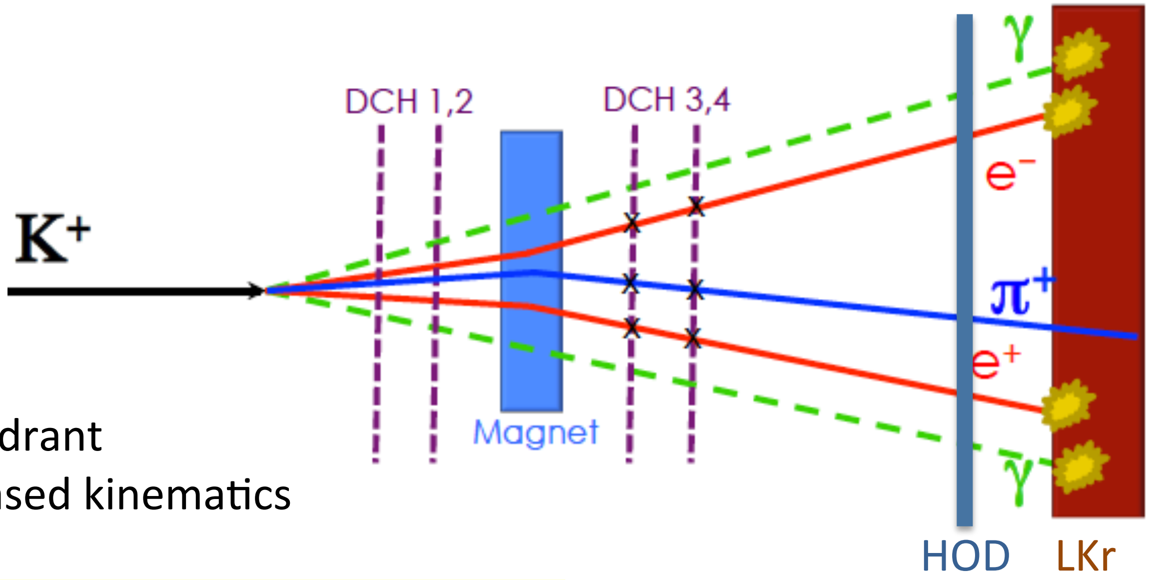
  > sign of interference term (IB,E)

  > Magnetic term through (IB,M) interference

  > Charge asymmetry as direct CP violation (M.Pospelov)

+.... > bump hunting in Mee spectrum

Event selection : signal and normalization



Trigger:
L1 : > 1 HOD quadrant
L2 : DCH track based kinematics

Signal: $\pi^\pm \pi^0 e^+ e^- = \pi^\pm \gamma \gamma e^+ e^-$

- Final state reconstructed from 3 charged track and 2 photons forming a π^0 pointing to the same decay vertex

- Closed kinematics with two constraints on $M_{\pi 0}$, M_K

- Differs from normalization by one extra γ

Normalization: $\pi^\pm \pi^0{}_D = \pi^\pm e^+ e^- \gamma$

- Final state reconstructed from 3 charged tracks and 1 photon forming, with 2 opposite sign tracks, a π^0 pointing to the same decay vertex
- Closed kinematics with two constraints on $M_{\pi 0D}$, M_K

- Very abundant: BR ($\pi\pi 0$) x BR ($\pi 0D$)
  20.66% x 1.174% = 2.425 10^{-3}

Event selection: signal, normalization and backgrounds

Signal: $\pi^{\pm}\ \gamma\ \gamma\ e^{+}\ e^{-}$

Normalization = $\pi^{\pm}\ e^{+}\ e^{-}\ \gamma$

Require 3 good quality tracks forming a vertex in the fiducial decay region

+ two good quality photon clusters (signal)

+ one good quality photon cluster (normalization)

- do not use PID from LKr information but only kinematics
- no more limitation from LKr geometrical acceptance for tracks

- Assign electron mass to the track with Q opposite to vertex charge
- For both (me, mπ) assignments to same charge tracks, compute reconstructed Mπ0 and Mkaon to be in a wide range and check kinematic correlation

$| M\pi0 - M_{PDG} | < 15$ MeV/c2

$| Mkaon - M_{PDG} | < 45$ MeV/c2

$| M\pi0 - 0.42\ mK + 73.2$ MeV/c2 $| < 6$ MeV/c2 (masses in Mev/c2)

Backgrounds

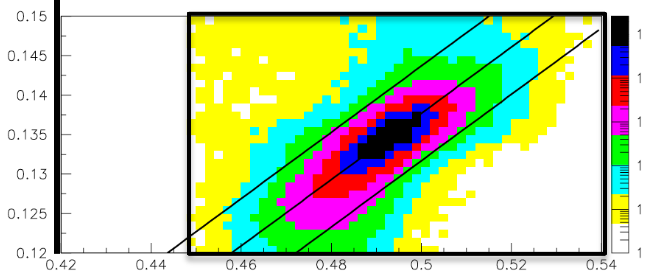
Normalisation MC K $\pi\pi^0D$

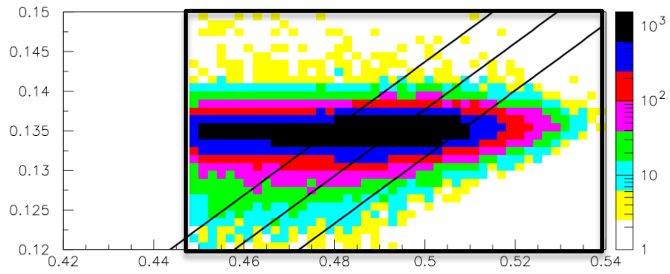
MC Kμ3D = $\mu\nu\ \pi^0D$

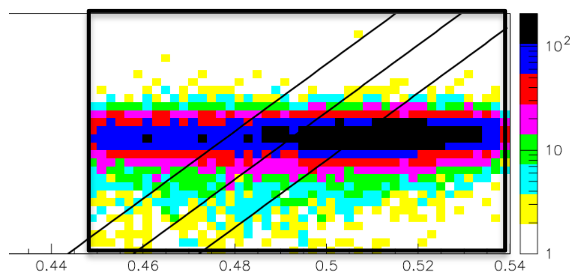
MC Ke3D = e$\nu\ \pi^0D$

genuine π^0D but μ or e taken as π

Mπ0D







mK

99.1% in the band

mK

54.6% in the band

mK

34.6% in the band

NB: Log colour scale !

Signal MC K $\pi\pi^0$ee

MC $\pi\pi^0D$

π e e $\gamma + \gamma$

low mπ0, high mK

(1 photon added)

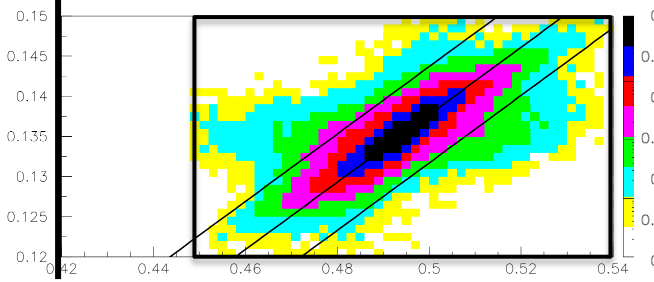
MC K$\pi\pi^0\pi^0D$

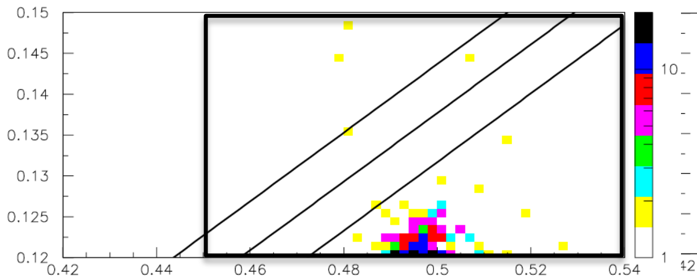
π e e γ γ (γ)

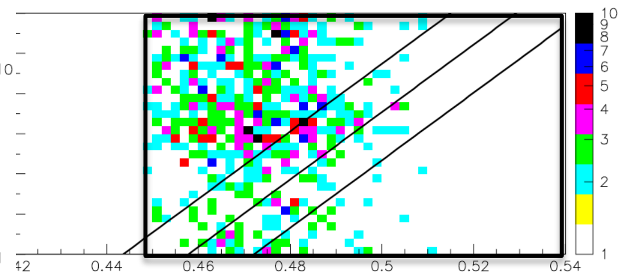
good/high mπ0 , low mK

(1 photon lost/fused)

Mπ0($\gamma\gamma$)







mK

96.5% in the band

mK

7.2% in the band

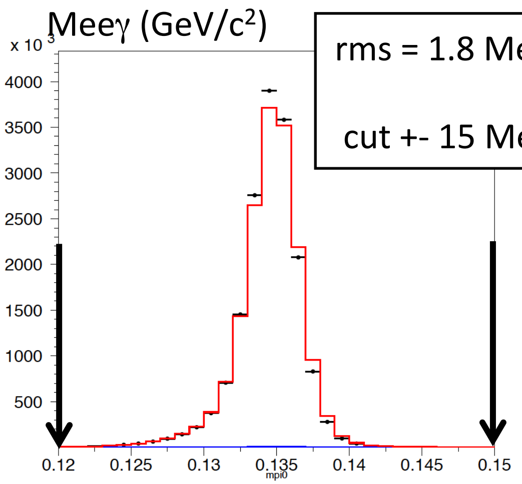
mK

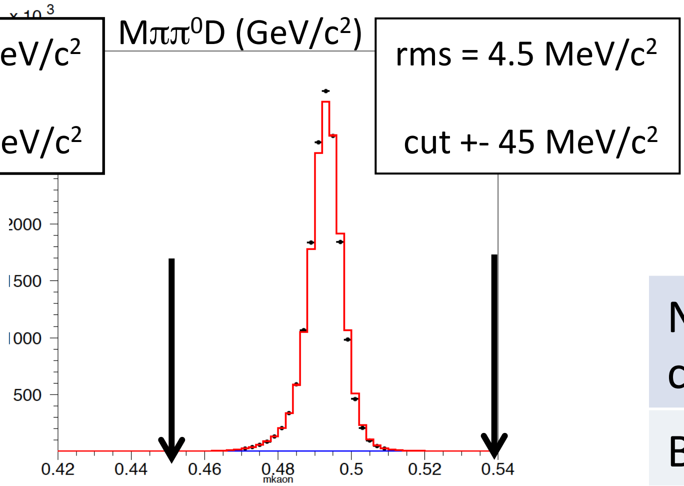
28.6% in the band

Normalization : large very pure sample

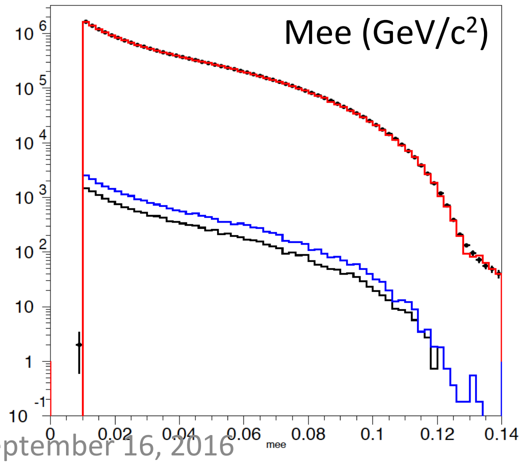
Normalisation K $\pi\pi^0$D :

- K $\pi\pi^0$ generator code including 1 real photon emission - Gatti EPJ C 45 (2006)
- π^0D decays including 1 extra photon emission - Husek, Kampf, Novotny PRD 92 (2015)
- also π^0D decays including extra photon(s) emission - Photos Was et al CPC 79 (1994)





Normalization candidates	16 774 613
Background	25 517
A (rad cor HKN)	4.083 (2) %
L1 efficiency	99.767(3) %
L2 efficiency	98.584(7) %



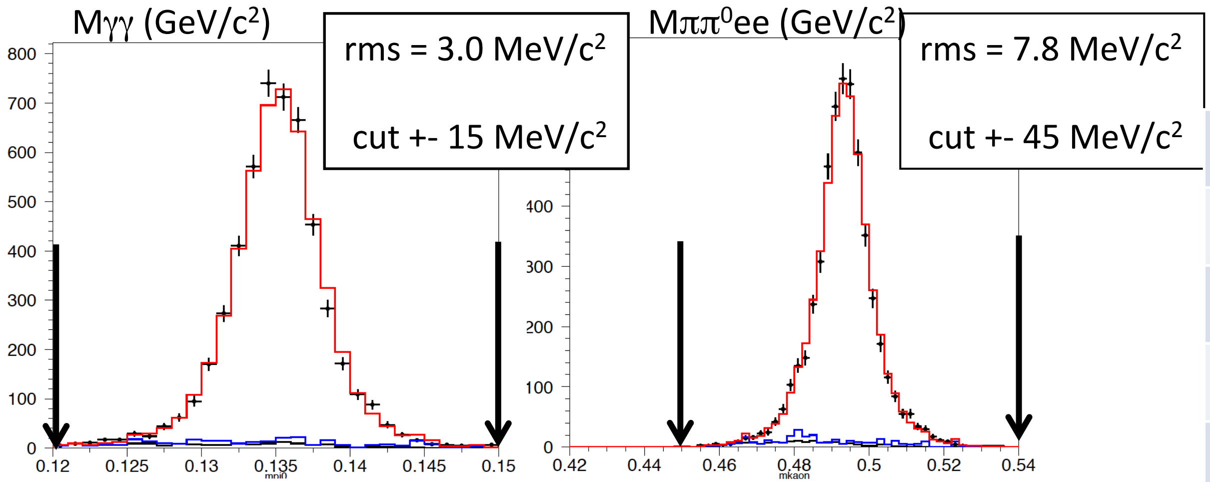
Kμ3 Bkg 15182 +- 173
Ke3 Bkg 10334 +- 140
B/(S+B) = 0.15%
MC + rad cor.

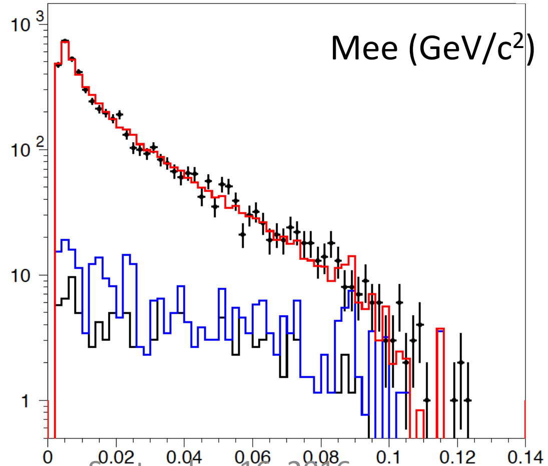
Mee> 10 MeV/c2, low sensitivity to rad.corr. modeling

Signal : small clean sample

Signal K ππ0 e e: dominated by

- IB, then DE (M) and INT(IB,E) : 4 independent generations (IB, M, INT>0 and INT <0) with different acceptances (A(M) and A(BE) ~ 3 x A(IB))
- Rad. cor. adding extra photon(s) emission using Photos





Signal candidates	5076
Background	289
A (rad cor) IB	0.650(1) %
A(rad cor) M	1.704(6) %
A(rad cor) INT>0	1.977(7) %
A(rad cor) INT <0	2.299(13) %
L1 efficiency	99.73(1) %
L2 efficiency	99.46(2) %

K3πD 159 +- 8
$K\pi\pi^0 D$ 130 +- 24
B/(S+B) = 5.4%
Signal IB +Photos

Mee> 3 MeV/c2 , dominated by bkg at large values

Branching ratio measurement and uncertainties

$BR = (Ns - Nbs)/(Nn - Nbn) \times (An/As) \times (\varepsilon L1n \times \varepsilon L2n)/(\varepsilon L1s \times \varepsilon L2s) \times BRn$

- What is As ? Define Aeff according to predicted fractions (IB/M) and (IB/BE) based on XE and XM measured in $\pi\pi^0\gamma$ by NA48/2 (EPJ C68 (2010) 75):

[A(IB) + 1/71 A(M) + 1/128 (0.732 INT>0 – 0.268 INT<0)] / (1 +1/71 +1/128)

Aeff = (0.666 +- 0.001) %

XE relative uncertainty ~30% , XM relative uncertainty ~5% translate to
δAeff/Aeff ~0.25% due to mixture composition

- Radiative corrections modeling ?
  An : compare HKN and Photos implementations
  Acceptances are close thanks to the Mee > 10 MeV/c2
  quote the statistical error on the difference as systematics ~0.30%
  As : compare Photos and no Photos Acceptances, quote 1/10 of full effect ~0.48%
  δAeff/Aeff ~0.56% combined due to rad cor modeling

Branching ratio measurement ingredients

Normalization candidates	16 774 613
Background	25 517
A (rad cor HKN)	4.083 (2) %
L1 efficiency	99.767(3) %
L2 efficiency	98.584(7) %

Signal candidates	5076
Background	289
A (rad cor) eff	0.666(1) %
L1 efficiency	99.73(1) %
L2 efficiency	99.46(2) %

Source	δBR/BR x 10^2	
Ns	1.40	stat 1.49
Nbs	0.51	
Nn	0.02	
Nbn	Negl.	
As	0.18	syst 1.03
An	0.05	
L1n x L2n	0.01	
L1s x L2s	0.04	
A (rad corr)	0.56 *	
A (fraction DE,INT)	0.25 *	
Trigger efficiency	0.80 *	
BR2π	0.39	ext 3.00
BRπ0D	2.98	

* = not final

Branching ratio measurement @ NA48/2

BR = $(4.22 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.13_{ext})\ 10^{-6}$

dominated by external error on BR(π0D)

In perfect agreement with

Theory : ChPT calculations EPJ C72 (2012) IB +DE + INT

BR (IB) = 4.19 10^{-6} no Rad Cor, No Isospin breaking Cor Total 4.29 10^{-6}

BR (IB) = 4.10 10^{-6} no Rad Cor, with Isospin breaking Cor** Total 4.19 10^{-6}

(** private communication from authors)

Summary

- NA48/2 has collected a clean sample of ~5000 $\pi\ \pi 0$ e+ e- decay candidates with ~5% background : first observation leading to a 3-4% BR measurement in perfect agreement with ChPT predictions.

Close to final !

- BR = $(4.22 \pm 0.08_{exp} \pm 0.13_{ext})\ 10^{-6}$
  uncertainty is dominated by external error
  experimental error is dominated by signal statistics

• discussion with theorists is most important for a correct and precise formulation of radiative and isospin breaking corrections

Prospects to collect more decays in the current NA62 run :

- requiring 3 tracks + large electromagnetic energy incompatible with $\pi\ \nu\nu$ trigger
- parasitic 3-track trigger downscaled by a large factor : no way to collect more data than in 2003-2004 with this trigger ($1.74\ 10^{11}$ charged kaon decays analyzed)
- could be studied in Run 3 after LS2 (after 2020) with dedicated trigger

Spares

What more ?

Measure BR(K+) and BR(K-) as independent quantities

Statistics is even more limited as K+/K- =~ 1.8 at production target

	K+	K-		K+	K-
Norm candidates	10776792	5997821	signal	3234	1842
Bkg	0.15%		Bkg	5%	
A (rad cor HKN)	4.087 (3) %	4.075 (4)%	Aeff	0.6687 (13) %	0.6605 (17) %
L1 efficiency	99.767(3) %		L1	99.73(1) %	
L2 efficiency	98.584(7) %		L2	99.46 (2) %	

BR(K+) = (4.17 +- 0.08) x 10^{-6} BR(K-) = (4.30 +-0.11) x 10^{-6}

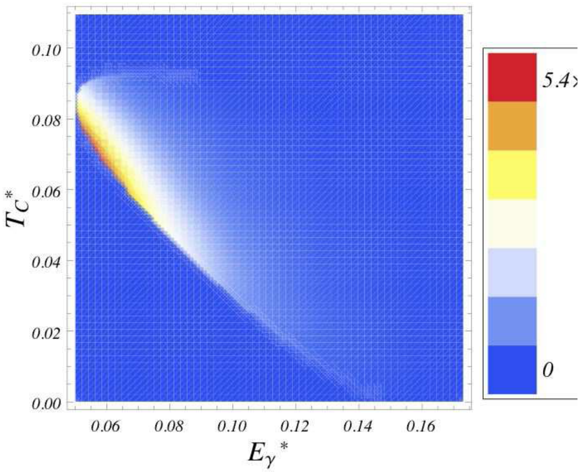
(BR(K+) - BR(K-)) / (BR(K+) + BR(K-)) = -0.015 +- 0.016
(stat errors only)

and more ?

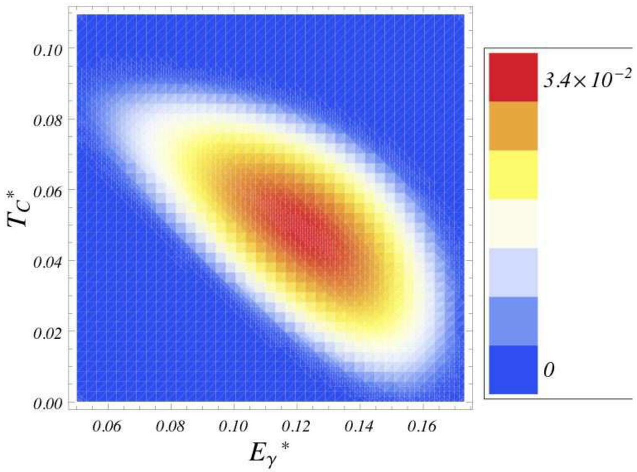
Cappiello et al. suggest to look at mee ~50 MeV/c2 where IB,DE, INT populate differently the (Eγ*,T*π) plane

INT<0

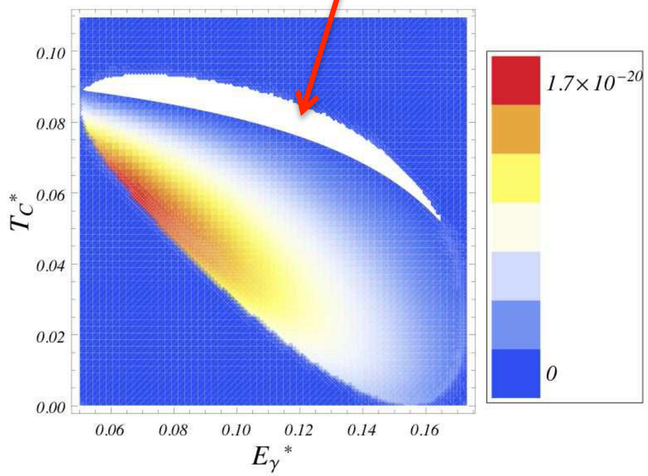
IB



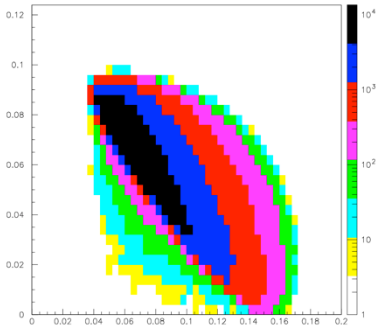
DE



INT

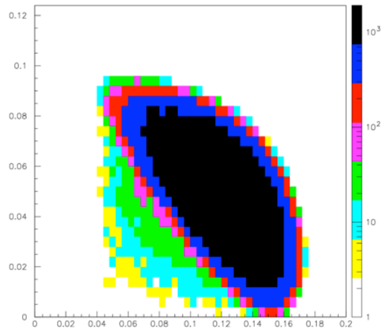


NA48 generated IB



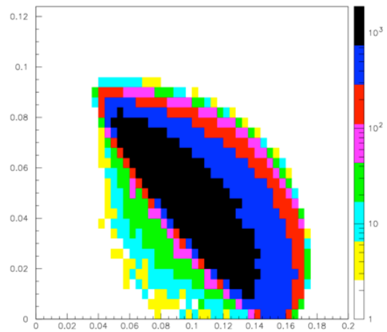
0. 0.20

DE



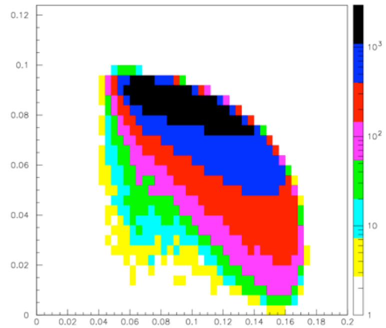
0. 0.20

INT>0



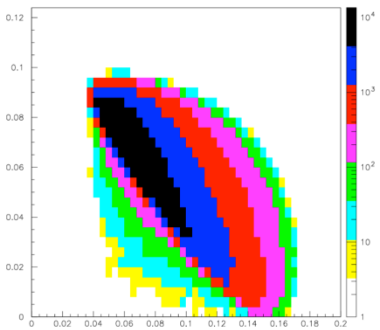
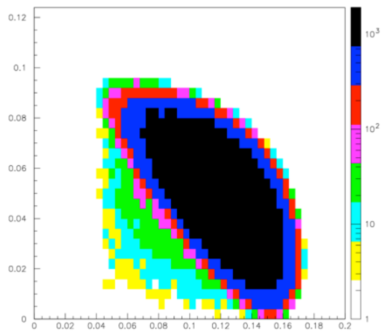
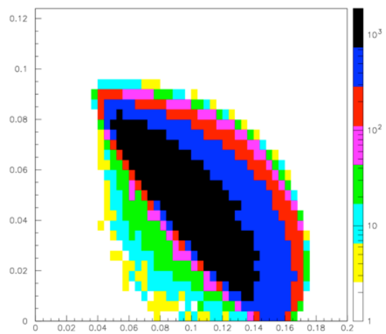
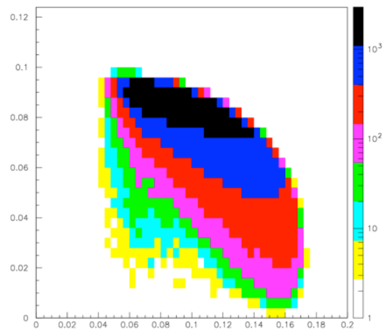
0. 0.20

INT <0

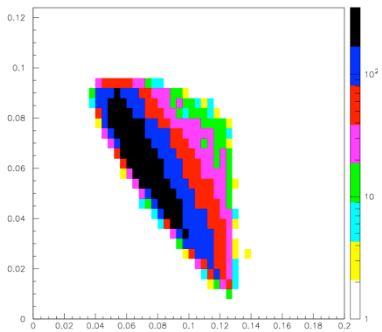
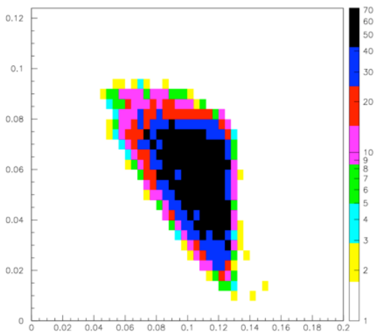
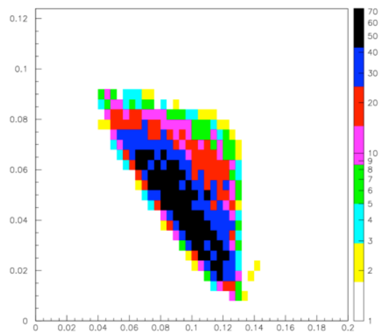
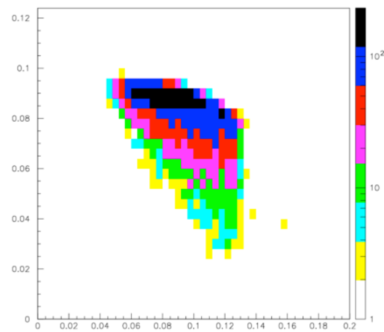


0. 0.20

NA48 generated IB | DE | INT>0 | INT <0

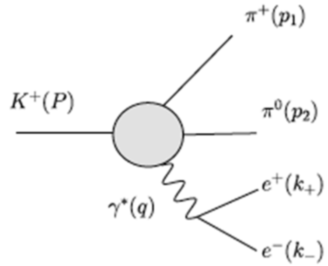
NA48 accepted IB 2.9% | DE 2.1% | INT>0 2.3% | INT <0 4.2%

After acceptance, we would need large statistics to disentangle the various contributions ....

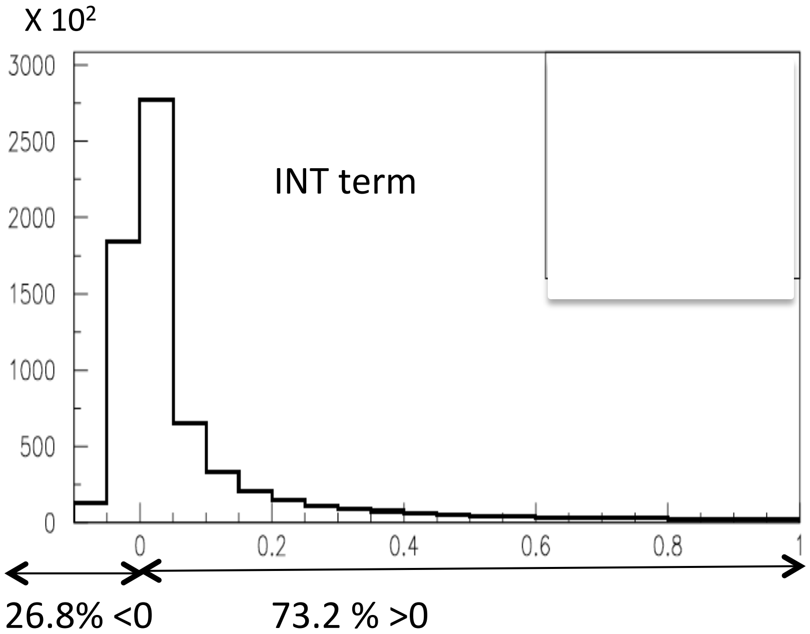
The INT term (Cappiello et al EPJ C72 (2012) 1872)

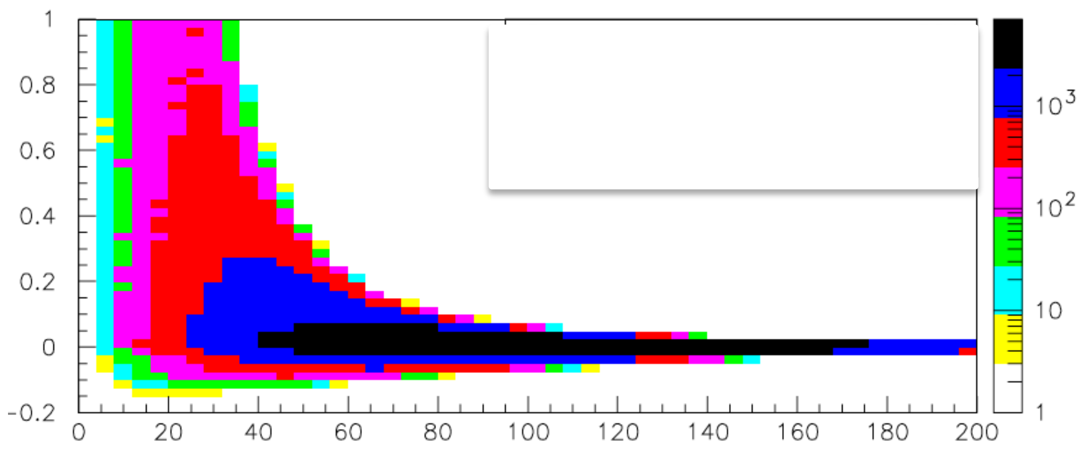
$$\frac{d^3\Gamma}{dE^*_\gamma dT^*_c dq^2} = \frac{d^3\Gamma_B}{dE^*_\gamma dT^*_c dq^2} + \frac{d^3\Gamma_E}{dE^*_\gamma dT^*_c dq^2} + \frac{d^3\Gamma_M}{dE^*_\gamma dT^*_c dq^2} + \frac{d^3\Gamma_{int}}{dE^*_\gamma dT^*_c dq^2},$$



Dominated by IB, DE mostly M (IB/M ~ 71) , INT mostly BE (IB/BE ~128)

Independent MC simulations of IB, DE and INT terms but ....





INT vs Mee (MeV/c2)

- INT<0 relative contribution increasing with Mee
- Two MC simulations, INTp according to INT if >0 , INTn according to –INT if <0
- Combined acceptance obtained as:

[A(IB) + 1/71 A(DE) + 1/128 (0.732 INTp – 0.268 INTn)] / (1 +1/71 +1/128)