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

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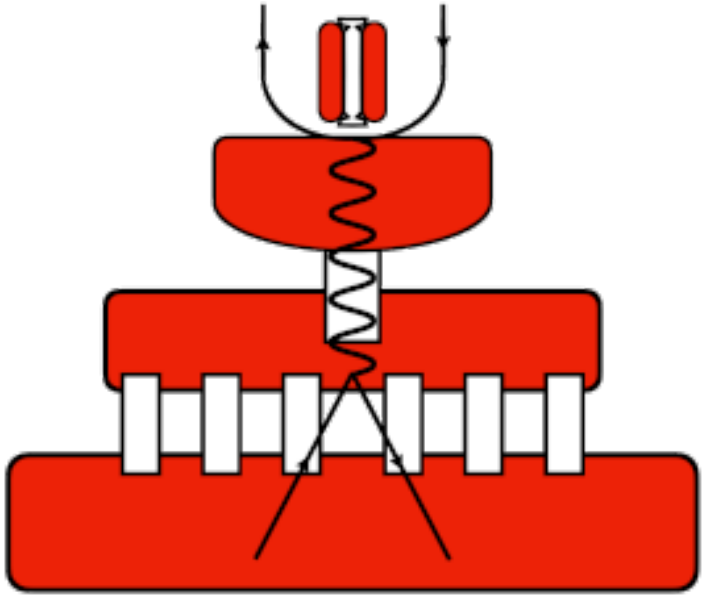
on behalf of the NA48/2 Collaboration



KAON2019

11th International Conference on Kaon Physics

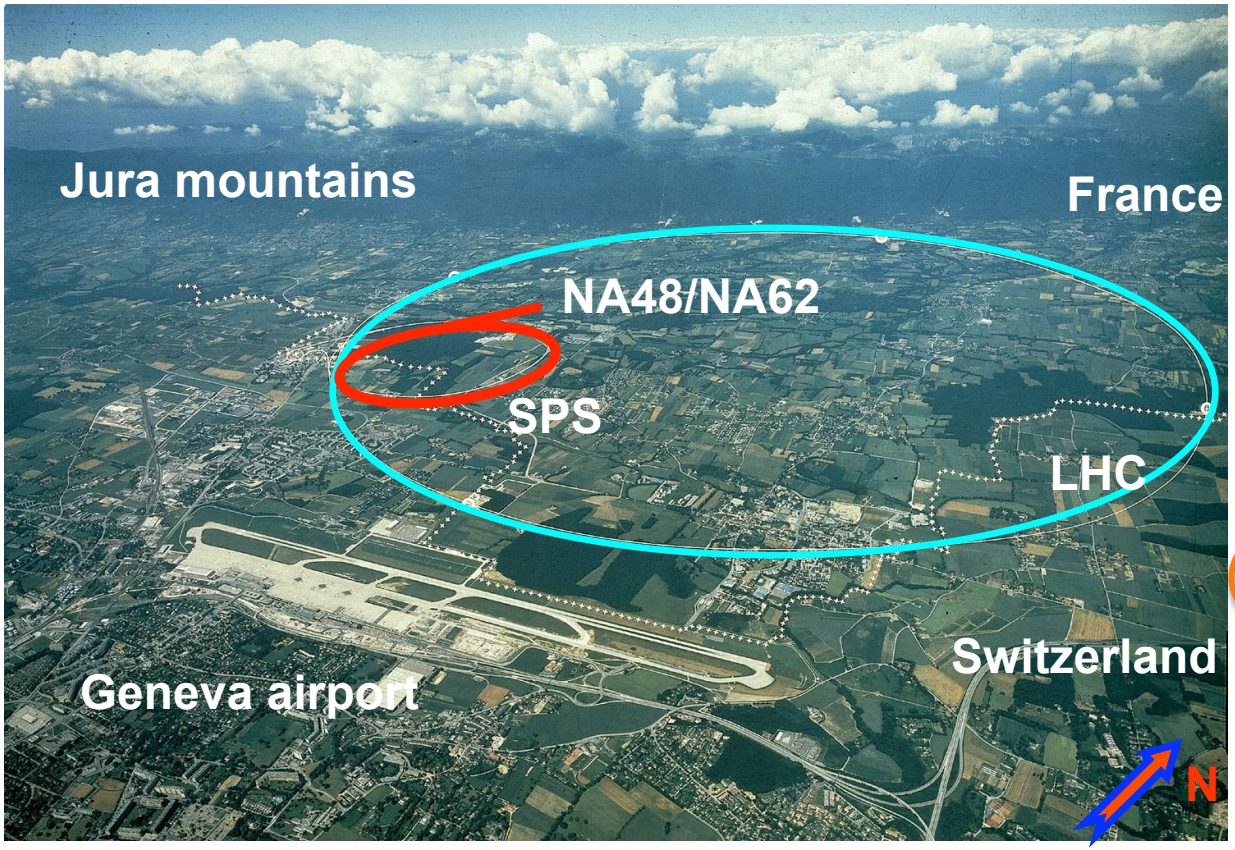
University of Perugia, Italy, September 10-13

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
- ChPT contribution
- Asymmetries
- Summary/Prospects

Recently Published
Phys. Lett. B 788 (2019) 552

The NA48/NA62 experiments at CERN-SPS



	1997: $K_L + K_s$
	1998: $K_L + K_s$
NA48 direct CPV ε'/ε	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:

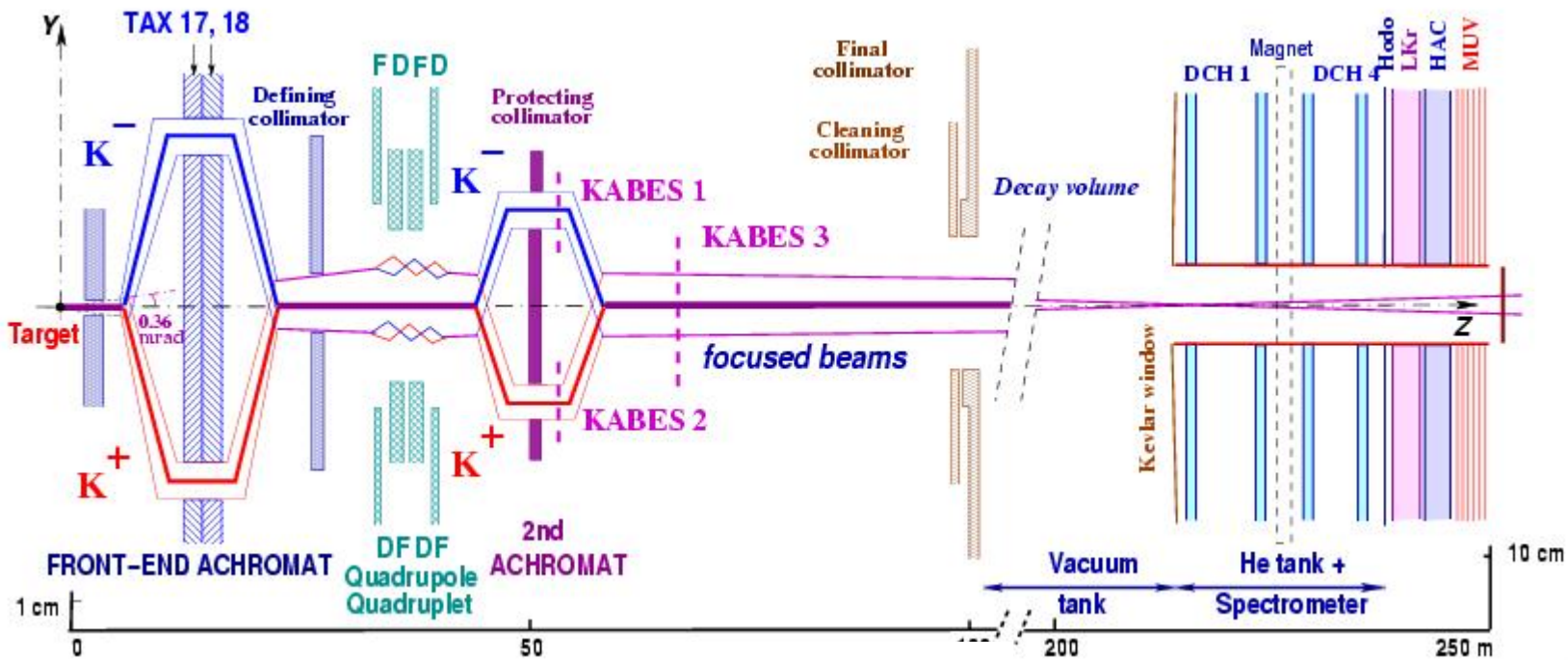
still analyzing > 15 years old valuable data !!

~100 physicists from 15 Institutes in 8 countries

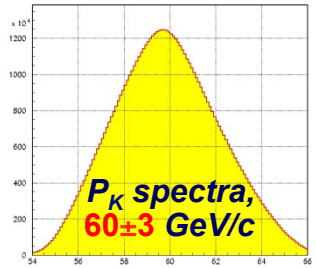
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze
Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

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 ($\pi^0 \rightarrow \gamma\gamma$)

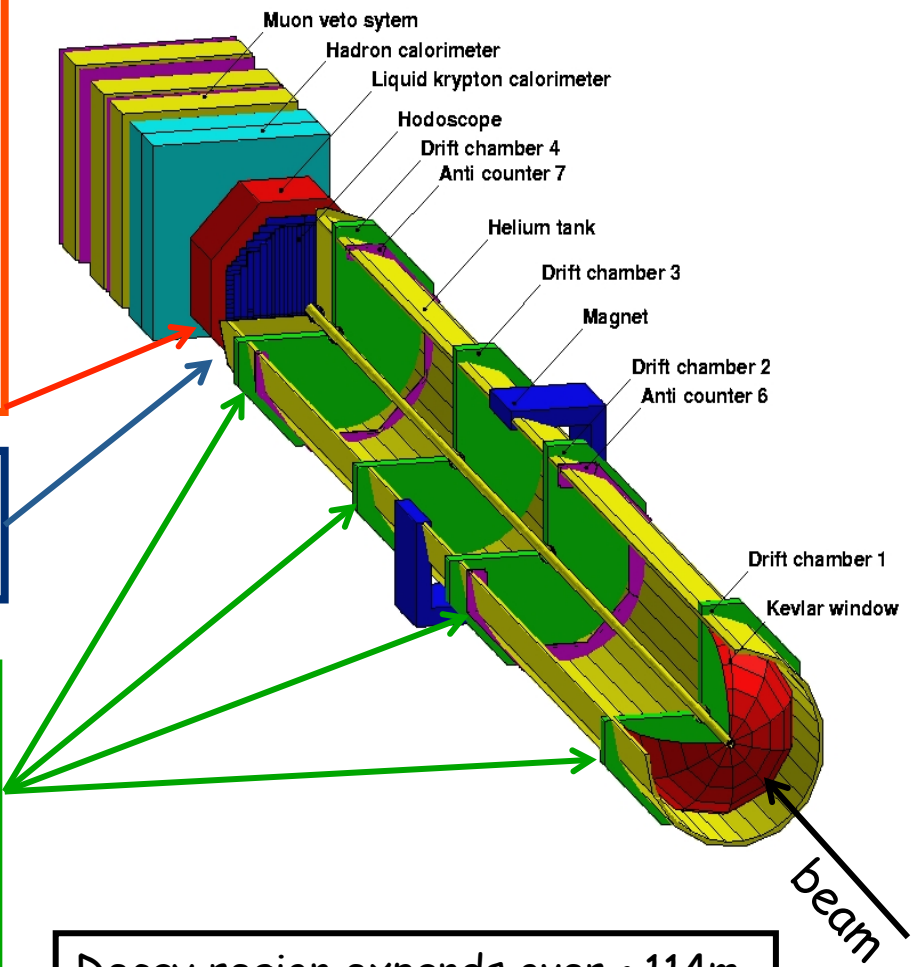
  $\sigma(M\pi\pi^0\pi^0) = 1.4$ MeV/c^2

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

Hodoscope for fast charged trigger

precise time resolution $\sigma_t = 150$ 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 theory talks this week-

$K^\pm \to \pi^\pm l^+ l^-$, $K^\pm \to \pi^\pm \gamma \gamma$, $K^\pm \to \pi^\pm \pi^0 \gamma$, $K^\pm \to \pi^\pm \pi^0 \gamma^* \to \pi^\pm \pi^0 e^+ e^-$ and many 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 ?

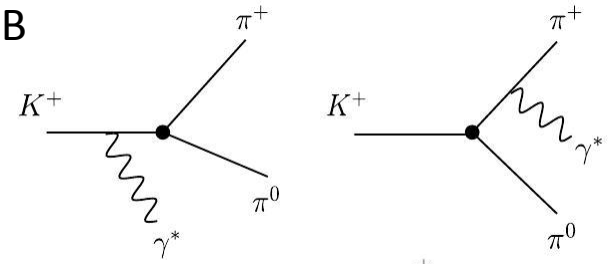
H.Pichl, EPJ C20 (2001) 371

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

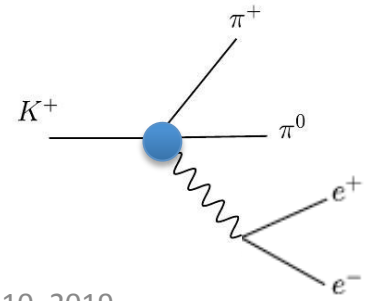
L. Cappiello, O. Catà, G.D'Ambrosio, EPJ C78 (2018) 265

$$\frac{d^3\Gamma}{dE_\gamma^* dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_E}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_M}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_{int}}{dE_\gamma^* dT_c dq^2}$$

IB



DE(M,E)



- Never observed so far: can BR magnitude confirm ChPT predictions of DE contribution ?

- If a fine analysis is possible:

  > sign of interference term (IB,E)

  > Magnetic term through (IB,M) interference

  > Charge asymmetry as direct CP violation

Event selection : signal and normalization

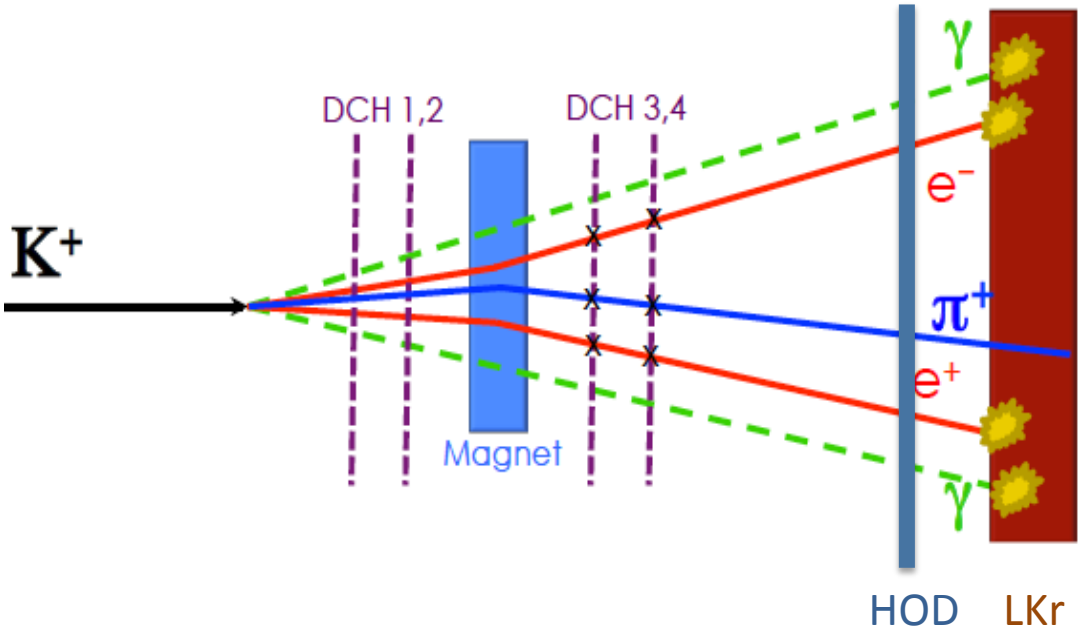
Normalization: $\pi^{\pm}\pi^{0}_{D} = \pi^{\pm} e^{+} e^{-} \gamma$
- Final state: 3 charged tracks and 1 photon forming, with 2 opposite sign tracks, a π^0 pointing to the same decay vertex
- Closed kinematics: constraints on $M_{\pi 0D}$, M_K
- Very abundant: BR ($\pi\pi^0$) x BR (π^0D)
  20.67% x 1.174% = 2.425 10^{-3}

Signal: $\pi^{\pm}\pi^{0} e^{+} e^{-} = \pi^{\pm} \gamma \gamma e^{+} e^{-}$
- Final state: 3 charged track and 2 photons forming a π^0 pointing to the same decay vertex. One more γ wrt norm mode
- Closed kinematics: constraints on $M_{\pi 0}$, M_K
- Subject to BR ($\pi^0\gamma\gamma$)=98.823%

Same Trigger chain:
L1 : > 1 HOD quadrant (out of 16)
L2 : DCH track based kinematics

Photons: E_{LKr} within [3,60 GeV]

Charged particles: no PID, but use kinematic constraint to maximize geometrical acceptance



Event selection: signal and normalization

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

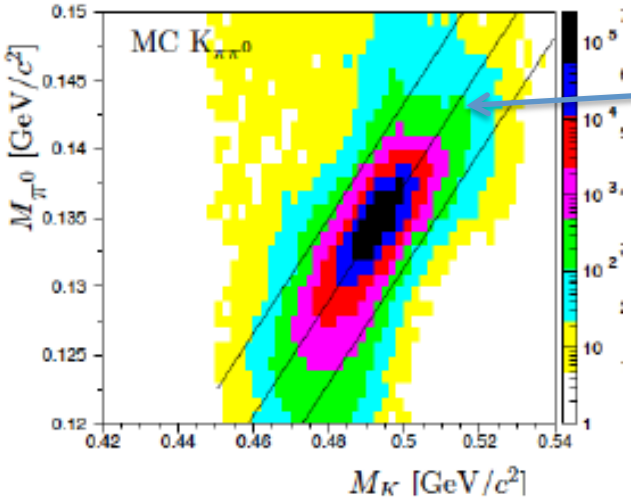
Require 3 good quality tracks forming a vertex in the fiducial decay region

+ two good quality photon clusters + one good quality photon cluster

- Assign electron mass to the track with Q opposite to vertex charge (K^{+} or K^{-})
- For both (m_e, m_π) assignments to same-charge tracks, compute reconstructed $M_{\pi 0}$ and M_K to be in a wide range and check kinematic correlation

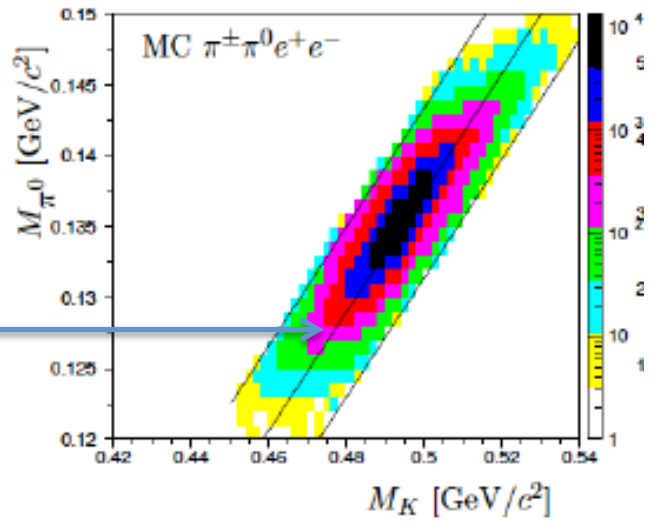
$| M_{\pi 0} - M_{PDG} | < 15$ MeV/c^2 $| M_K - M_{PDG} | < 45$ MeV/c^2

$| M_{\pi 0} - 0.42\ M_K + 73.2$ MeV/c^2 $| < 6$ MeV/c^2 (masses in MeV/c^2)



> 99% in the band

96.5 % in the band



Backgrounds

Normalization:

- Semileptonic Kl3D = Ke3D, Kmu3D

π^o_D is correctly reconstructed ($e^+e^-\gamma$)

π mass assigned to the e or mu track

Signal:

- $K\pi\pi^o\pi^oD$ with one photon lost/ merged: suppressed by $(M\pi\pi^o)^2 > 0.12$ GeV^2/c^4
- $K\pi\pi^oD$ with an extra photon:

suppressed by $|Mee\gamma - M\pi^o| > 7$ MeV/c^2

- Large simulated samples used to compute acceptances
- Contribution estimated from acceptances and BRs

- Resulting fractions:

Nbn / Nn = (0.106 ± 0.001)%

Kmu3D : 0.064%

Ke3D : 0.042%

- Resulting fractions:

Nbs / Ns = (4.9 ± 0.4)%

K3piD : 2.7%

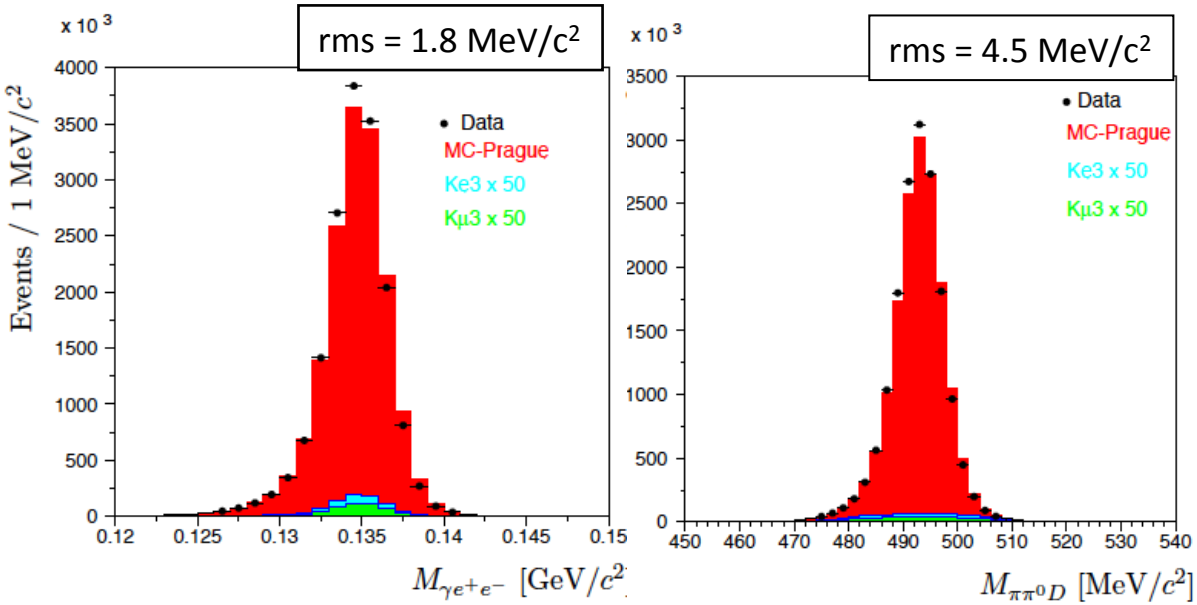
K2piD : 2.1 %

Ke3D : 0.1%

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)



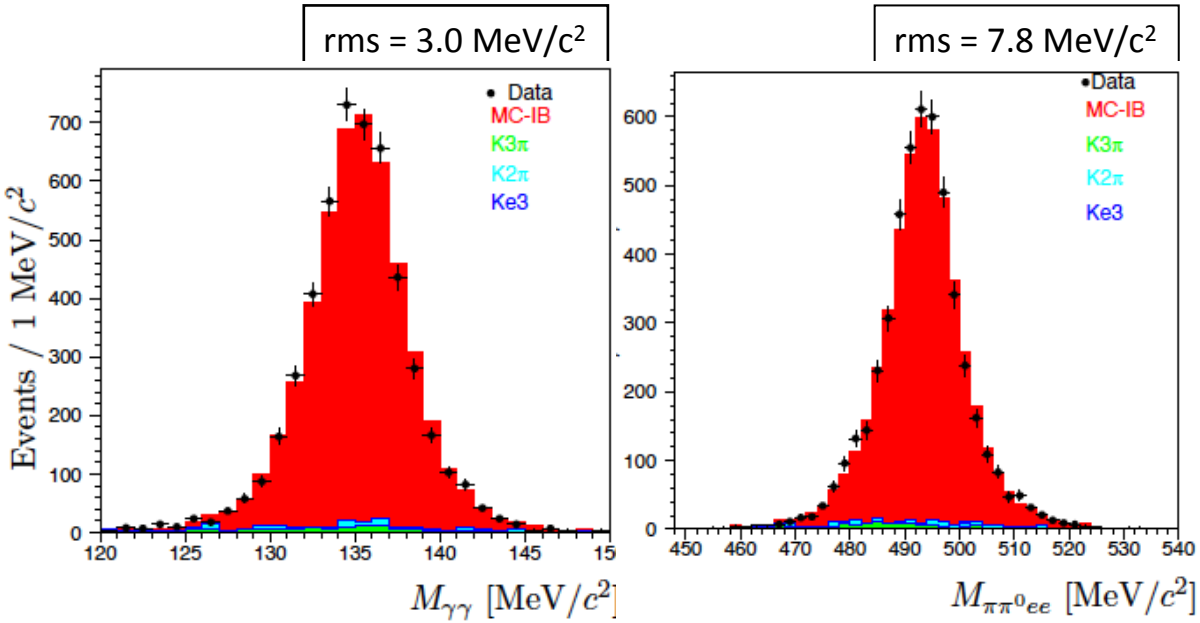
Normalization candidates	16 316 690 (4 039)
Background	17 292 (159)
A (rad cor HKN)	3.981 (2) %

B/(S+B) = 0.106%
Include HKN ("Prague") rad cor.

Signal : small clean sample

Signal K $\pi\pi^0$ee: dominated by

- IB (99%), then DE (M) (1.39%) and INT(IB,E) (0.39% negative) : independent generations (IB, M, INT(BE)) with different acceptances combined as Aeff according to relative contributions
- Rad. cor. adding extra photon(s) emission using Photos



Signal candidates	4919 (70)
Background	241 (20)
A (rad cor) IB	0.645(1) %
A(rad cor) eff	0.662(1) %

B/(S+B) = 4.9%
Include Photos rad cor

Branching ratio measurement ingredients

Normalization candidates	16 316 690 (4 039)
Background	17 292 (159)
A (rad cor HKN)	3.981 (2) %
L1 efficiency	99.767(3) %
L2 efficiency	98.495(6) %

Signal candidates	4919 (70)
Background	241 (20)
A(rad cor) eff	0.662(1) %
L1 efficiency	99.73(1) %
L2 efficiency	98.60(2) %

Source	$\delta BR/BR \times 10^2$	
Ns	1.426	stat 1.486
Nbs	0.416	
Nn	0.025	
Nbn	Negl.	
As (MC stat)	0.171	syst 0.777
An (MC stat)	0.051	
L1n x L2n (MC stat)	0.007	
L1s x L2s(MC stat)	0.023	
A (geometry control)	0.083	
A (time variation)	0.064	
Trigger efficiency	0.400	
Model dependence	0.285	
Radiative effects	0.490	
$BR\pi\pi^0$	0.87	external 2.971
$BR\pi^0D/BR\pi^0\gamma\gamma$	2.946	

Branching ratio measurement @ NA48/2

BR = $(4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6} = (4.237 \pm 0.145)\ 10^{-6}$

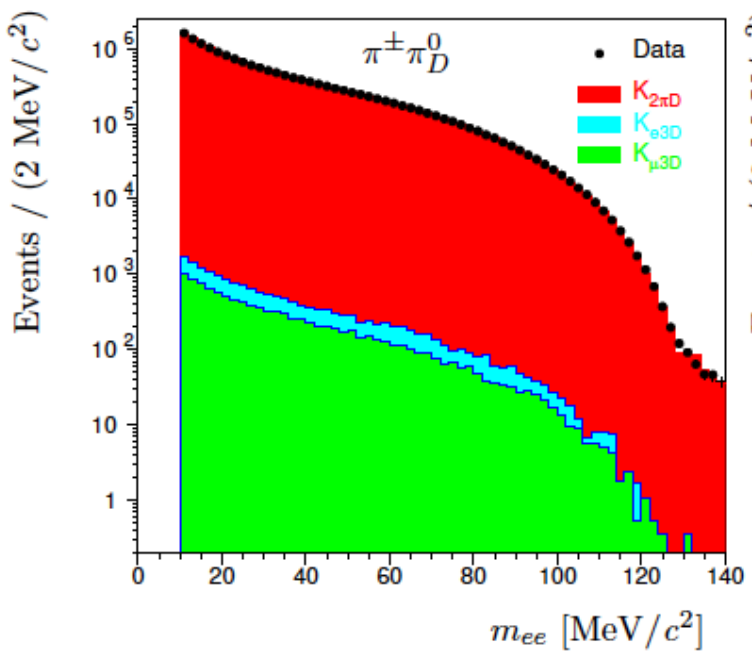
Currently dominated by external error on BR(π0D)

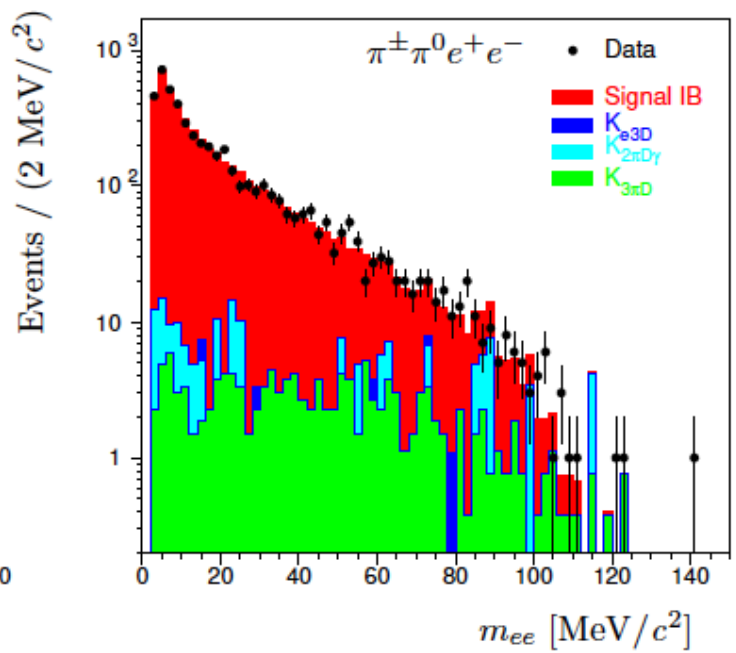
In perfect agreement with

ChPT calculations from EPJ C78 (2018), no Rad Cor, no Isospin breaking Cor

IB only	IB +DE + INT
$4.183\ 10^{-6}$	Total $4.229\ 10^{-6}$

Good data/MC agreement of the m_{ee} spectra over several orders of magnitude





Further studies

- Current BR measurement: ~3% precision
- Expected relative contribution of DE(M) term : ~ 1%
- Expected relative contribution of INT(BE) term : even smaller

No way to extract DE or INT contributions from the BR measurement BUT

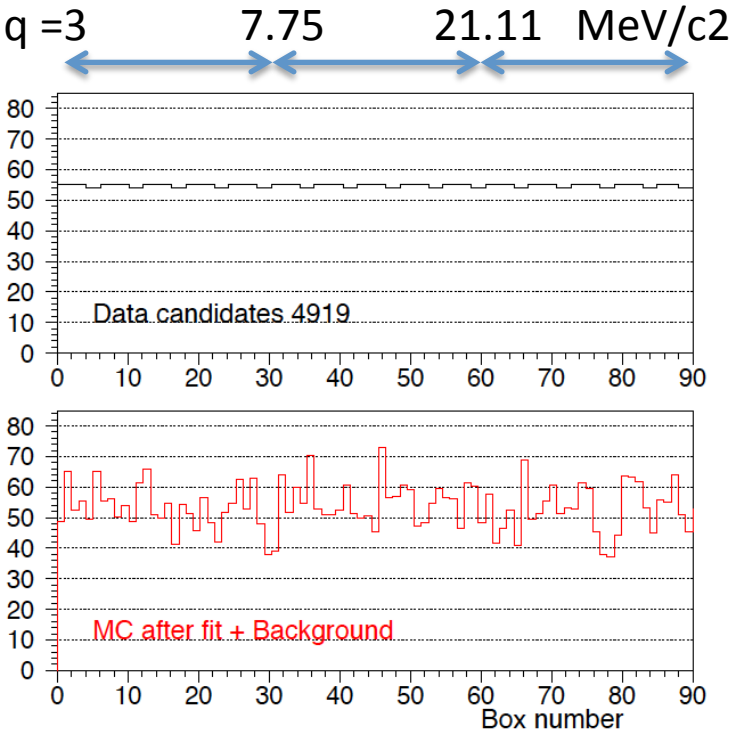
- Cappiello et al suggested to look at m_{ee}~50 MeV/c^2 where IB,DE, INT contributions populate differently the ($E\gamma^*$,$T^*\pi$) plane .
- Too few statistics, instead study the whole 3D-space (q^2, $E\gamma^*$,$T^*\pi$) in a grid of 3D-boxes of **equal data populations** (N1 bands in q^2,then N2 bands in $T^*\pi$, then N3 bands in $E\gamma^*$)
- Distribute simulated events and background over the same grid as the data.
- Minimize a χ^2 estimator to find *a* = DE/IB, *b* = INT/IB and *N* (overall norm)

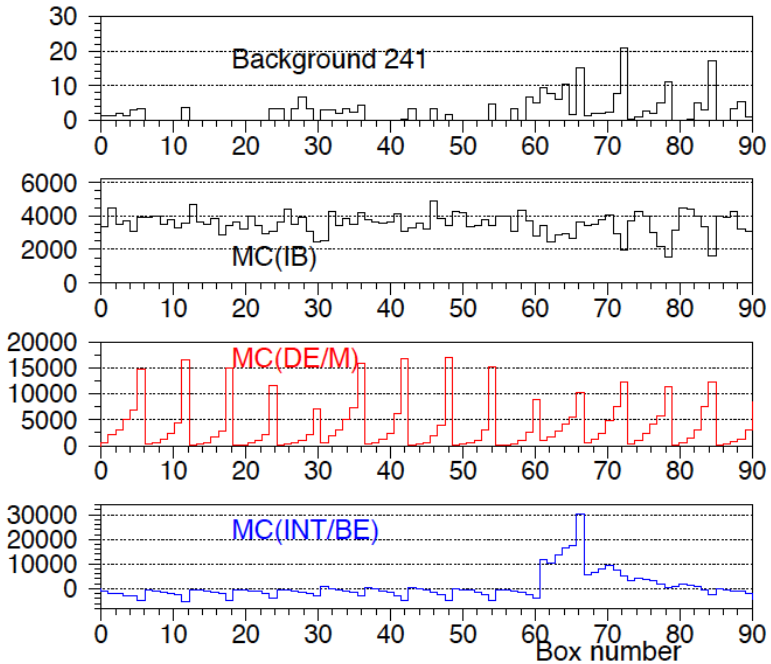
$$\chi^2 = \sum_{i=1}^{N1\times N2\times N3} (N_i - M_i)^2/(\delta N_i^2 + \delta M_i^2)$$

$$M_i = N \times (N_i^{\mathrm{IB}} + a \cdot N_i^{\mathrm{M}} + b \cdot N_i^{\mathrm{IB\text{-}E}}) + N_i^{Bkg}$$

In 3D-box i:
N_i (δN_i) = data events (error)
M_i (δM_i)= MC events (error)
N_i^{Bkg} = Bkg events

3D-kinematic space study (N1=3, N2=5, N3=6)





Fit result: χ^2 = 98.2/87, p-value = 19%

M/IB = 0.0114 ± 0.0043_{stat}

BE/IB = -0.0014 ± 0.0036_{stat}

ChPT predictions

M/IB = 0.0141 ± 0.0014_{ext}

BE/IB = -0.0039 ± 0.0028_{ext}

Good agreement but limited precision !

What else ? Asymmetries !

NA48/2 has accumulated K^+ and K^- decays concurrently allowing asymmetry studies with reduced systematics.
Measure BR(K+) and BR(K-) as independent quantities and evaluate:

$$A_{CP} = \frac{\Gamma(\pi^+\pi^0 e^+ e^-) - \Gamma(\pi^-\pi^0 e^+ e^-)}{\Gamma(\pi^+\pi^0 e^+ e^-) + \Gamma(\pi^-\pi^0 e^+ e^-)}$$

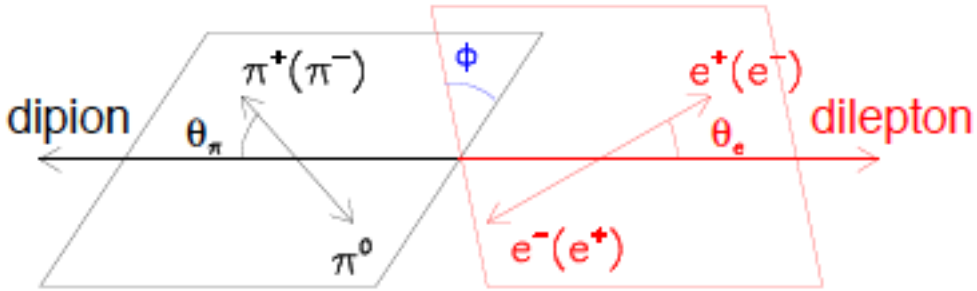
Statistics is even more limited as K^+/K^- ~ 1.8 at production target

$BR(K^+) = (4.151 \pm 0.078_{stat}) \times 10^{-6}$ $BR(K^-) = (4.394 \pm 0.108_{stat}) \times 10^{-6}$

$A_{CP} = -0.0284 \pm 0.0155_{stat}$ or single-sided UL $|A_{CP}| < 1.98 \times 10^{-2}$ at 90% CL

Other CP Asymmetries

Partial integration in the angular space allows to build other asymmetries:



$$\int_0^{2\pi} d\phi^* \equiv \left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi \text{ with } A_{CP}^{\phi^*} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+-K^-)}}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma_{(K^++K^-)}}{d\phi} d\phi},$$

$$\int_0^{2\pi} d\tilde{\phi} \equiv \left[\int_0^{\pi/2} + \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi \text{ with } A_{CP}^{\tilde{\phi}} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+-K^-)}}{d\phi} d\tilde{\phi}}{\int_0^{2\pi} \frac{d\Gamma_{(K^++K^-)}}{d\phi} d\phi}.$$

Asymmetries

Computing BR for K^+ and K^- in each Φ "sector" of the angular space:

A_{CP} (Φ*)= -0.0119 ± 0.0150_{stat} A_{CP} (Φ~)= 0.0058 ± 0.0150_{stat}

Both are consistent with 0 , giving single sided UL

$$|A_{CP}^{\phi}| < 1.9 \times 10^{-2} \text{ at } 90\% \text{ CL}$$

Another P-violating asymmetry can be defined for K^+ , K^- and combined if consistent

$$A_P^{(L)} = \frac{\int_0^{2\pi} \frac{d\Gamma}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma}{d\phi} d\phi} :$$

K^+ : $A_P^{(L)}$ = 0.0059 ± 0.0180 , K^- : $A_P^{(L)}$ = -0.0166 ± 0.0237 , $K^\pm$: $A_P^{(L)}$ = -0.0023 ± 0.0144

$$|A_P^{(L)}| < 1.8 \times 10^{-2} \text{ at } 90\% \text{ CL.}$$

Summary and prospects

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

  small sample but rich source of information

- BR = $(4.24 \pm 0.07_{exp} \pm 0.13_{ext}) \times 10^{-6}$

  total uncertainty dominated by external error

  experimental error dominated by signal statistics

  systematics could benefit from better consideration of radiative effects

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- First evaluation of the M contribution (1.1 ± 0.4)%, in agreement with ChPT prediction
- Several asymmetries investigated with single–sided UL of ~2% @ 90% CL

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 (2021-2023) with a dedicated trigger and the caveat that geometrical acceptance is lower than @NA48/2

Spares

Background estimate

$$N_{bn} = N_n \times A_{K_{l3}}/A_n \times \mathrm{BR}(K_{l3})/\mathrm{BR}(\mathrm{K}_{\pi\pi^0})$$

$A_{Kl3} \sim 10^{-4}$, $A_n \sim 4\ 10^{-2}$

$$K_{3\pi D} : N_{bs}/N_n = 2 \times A_{K_{3\pi D}}/A_n \cdot \mathrm{BR}(K_{3\pi}) \times \mathrm{BR}(\pi^0 \to \gamma\gamma)/BR(K_{\pi\pi^0}),$$

$$K_{2\pi D} : N_{bs}/N_n = A_{K_{2\pi D}}/A_n.$$

$A_{K3\pi D} \sim 2\ 10^{-6}$, $A_{K2\pi D} \sim 0.2\ 10^{-6}$

Acceptance

Aeff = [A(IB) + 1/71 A(DE) – 1/253 A(INT)]/[1 + 1/71 – 1/253]

INT(B-M) and INT(E-M) cancel in the angular integration
E term is order of magnitude smaller than M

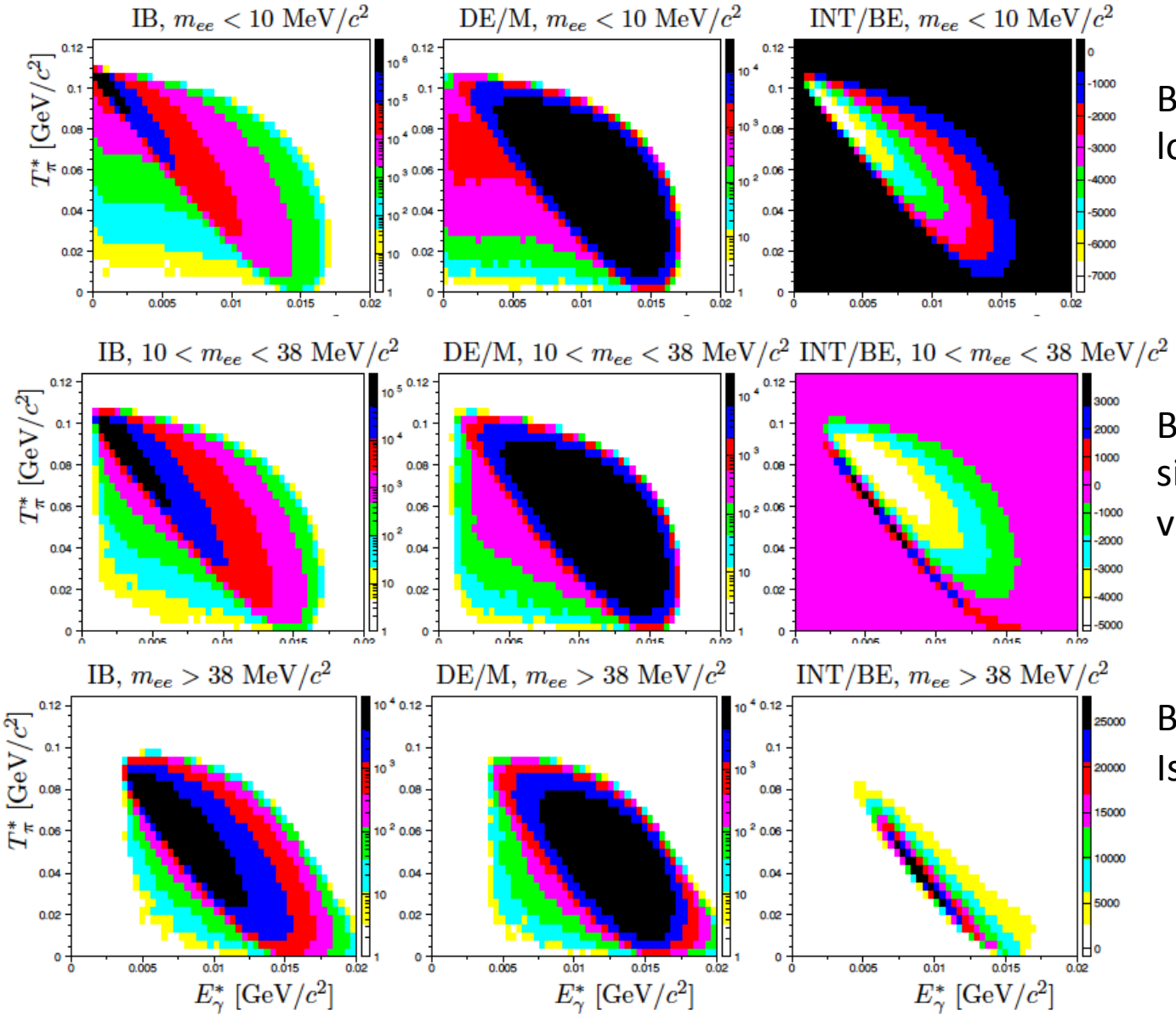
1/71 = (M/IB) predicted using $N_M^{(0)}$ = +0.0285(14)
-1/253 = (B-E/IB) predicted using $N_E^{(0)}$ = +0.0022(7) and "large" % $N_E^{(1,2)}$ values
$N_E^{(1)}$ = –0.0167(13), $N_E^{(2)}$ = +0.089(11),
L9 = 0.0069

$N_M^{(0)}$ comes from X_M = (254 ± 6 ± 6) GeV^{-4}
$N_E^{(0)}$ comes from X_E = (-24 ± 4 ± 4) GeV^{-4} , both from EPJ C68

A(IB) = (0.645 ± 0.001)%
A(DE) = (1.723 ± 0.003)%
A(INT>0) = (1.933 ±0.004)%
A(INT<0) = (1.805 ± 0.005)%
A(INT) = (0.288 ± 0.001)% (56% INT>0, 44% INT<0)

A_{eff} = (0.662 ± 0.001)%

3D-space: IB,DE, INT populate differently the (Eγ*,T*π) plane



BE contribution is <0 at low q^2 values

BE contribution changes sign with increasing q^2 values

BE contribution
Is >0 for large q^2 values

Asymmetries

$A_{CP} \approx \sin\delta \sin\Phi_E$

$A_{CP\Phi^*} \approx \cos\delta \sin\Phi_M$

$A_{CP\Phi^\sim} \approx \cos\delta \sin\Phi$

$A_P^{(L)} \approx N_M^{(0)} \sin\delta$

$\delta = \delta_1^1 - \delta_0^2$ Strong phase of the $\pi\pi^0$ system

Φ_E , Φ_M , Φ CP violating phase