QCD studies in NA48/NA62

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QCD@work, Lecce june 19, 2012

Outlook

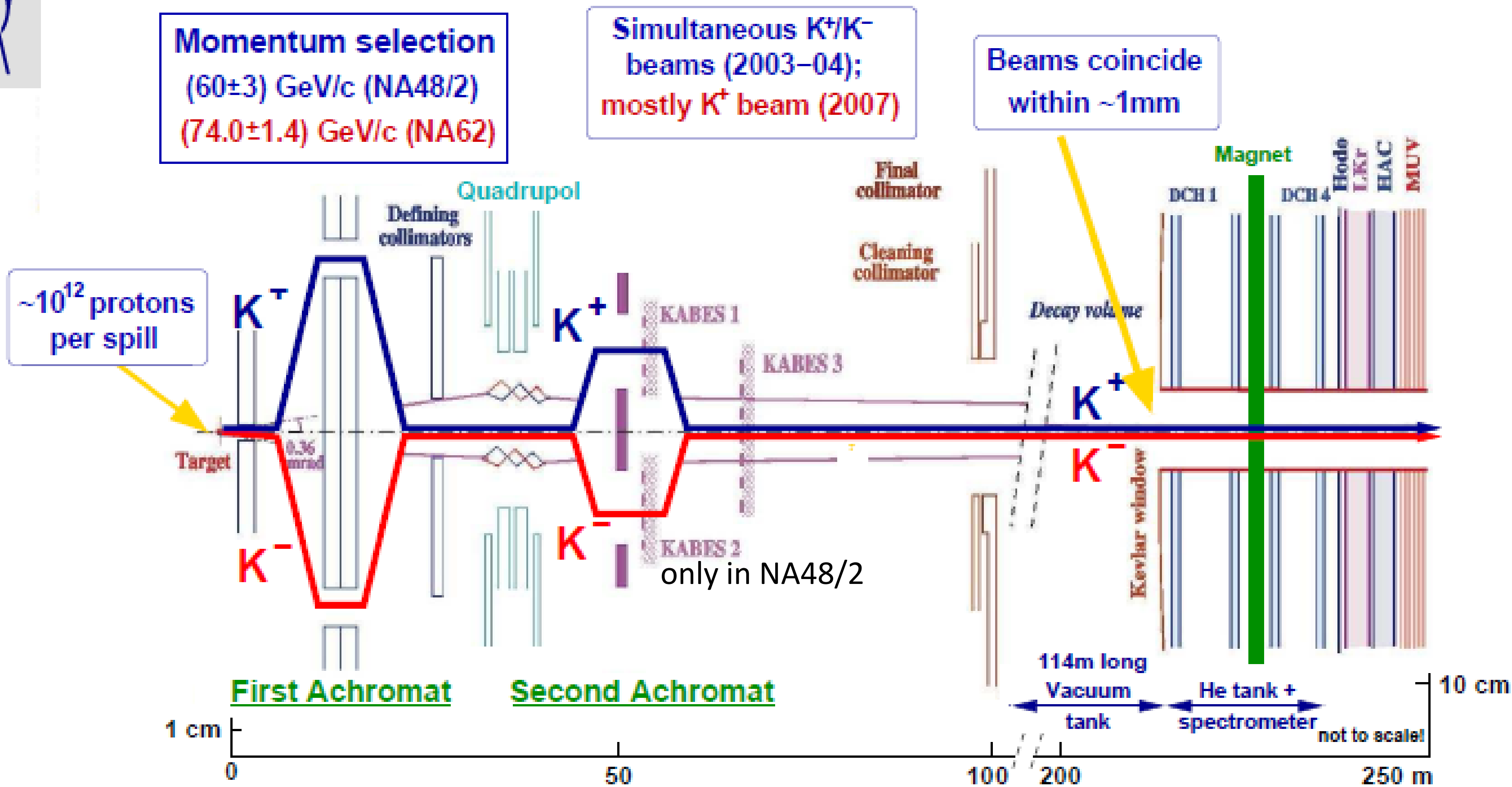
- NA48/2 – NA62: the CERN Kaon facility
- $K^{\pm} \to \pi^{\pm}\gamma\gamma$: BR and $\hat{c}$ parameter (NA48/2 – NA62) **NEW**
- $K^{\pm} \to e^{\pm}\nu\gamma$: preliminary distributions (NA62) **NEW**
- $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$: very preliminary analysis (NA48/2) **NEW**
- $K^{\pm} \to \pi^{0}l^{\pm}\nu$ (K_{l3}): Form Factors (NA48/2) **RECENT**
- $K^{\pm} \to \pi^{0}\pi^{0}e^{\pm}\nu$, $\pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4}): BR (NA48/2) **RECENT**
- Conclusions

NA48/NA62 at CERN

Ancestor: NA31

NA48	1997 ε'/ε run $K_L + K_S$
NA48	1998 ε'/ε run $K_L + K_S$
NA48	1999 ε'/ε run $K_L + K_S$; K_S Hi. Int
NA48	2000 K_L only; K_S High Intensity; *NO Spectrometer*
NA48	2001 ε'/ε run $K_L + K_S$; K_S High Int.
NA48/1	2002 K_S High Intensity
NA48/2	2003 $K^{\pm}$ High Intensity
NA48/2	2004 $K^{\pm}$ High Intensity
NA62 (R_K)	2007/08: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ runs
NA62	2007–2013: R&D; 2014: Start $K^+ \to \pi^+ \nu\bar{\nu}$

The NA48/2 and NA62(R_K) beam line



2.5×10^7 K/spill

K decays in the vacuum tank: 22% (18%)

Beam size: 4x4 mm^2, 10x10 μrad

NA48-NA62 detectors

Liquid Krypton Calorimeter:

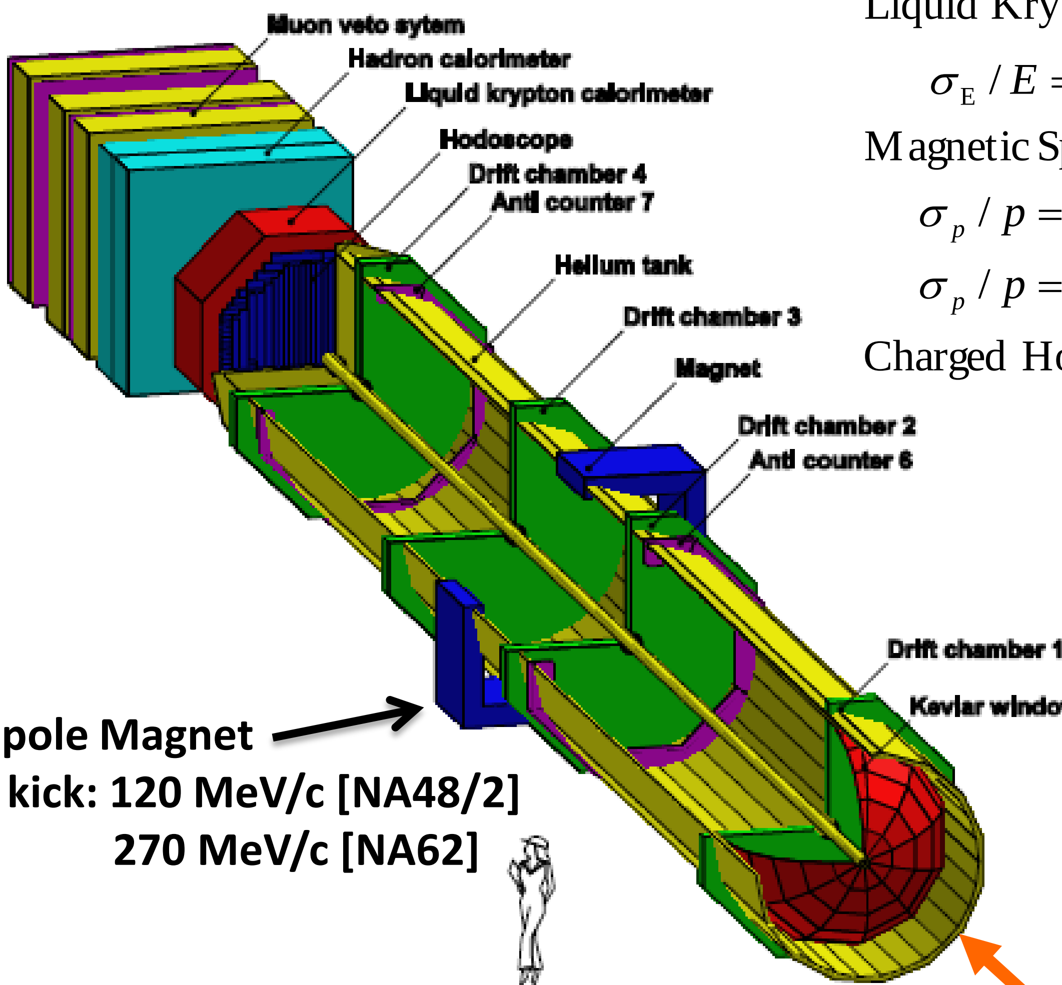
$$\sigma_E / E = 3.2\% / \sqrt{E} \oplus 9\% / E \oplus 0.42\% \quad [E \text{ in GeV}]$$

Magnetic Spectrometer (p in GeV/c):

$$\sigma_p / p = 1.00\% \oplus 0.044\% \times p \quad [\text{NA48/2}]$$

$$\sigma_p / p = 0.48\% \oplus 0.009\% \times p \quad [\text{NA62}]$$

Charged Hodoscope: $\sigma_t = 150$ ps

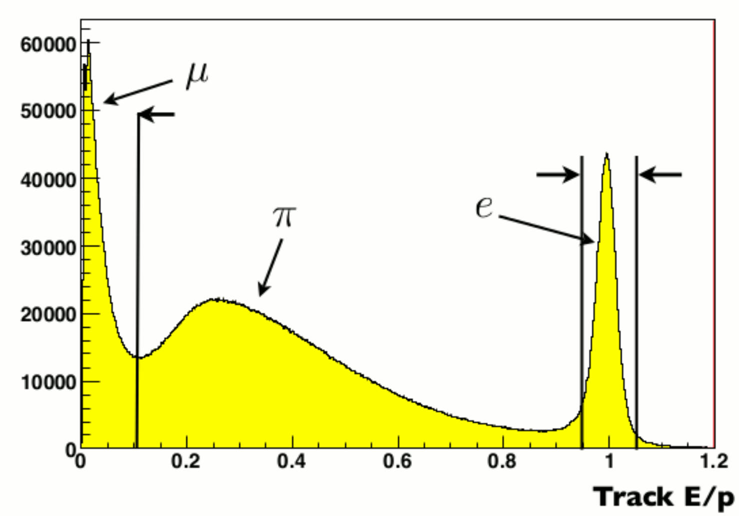


Dipole Magnet

P_t kick: 120 MeV/c [NA48/2]

270 MeV/c [NA62]

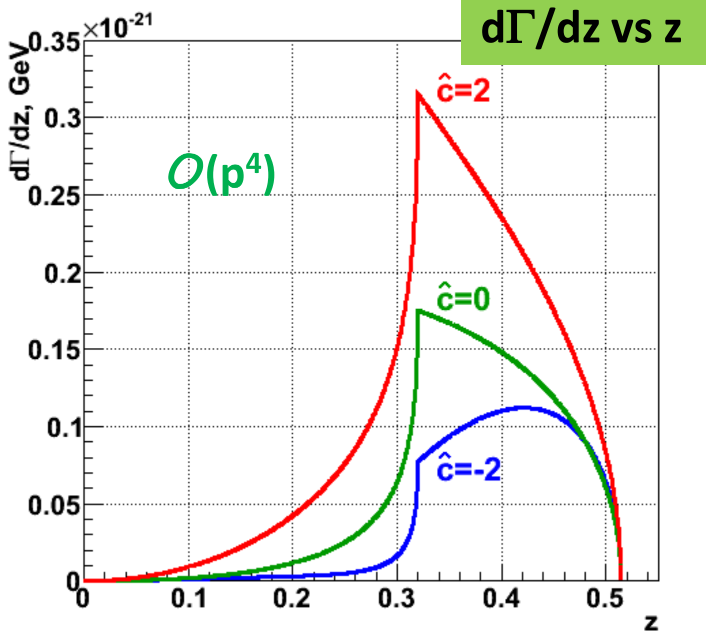
K^+



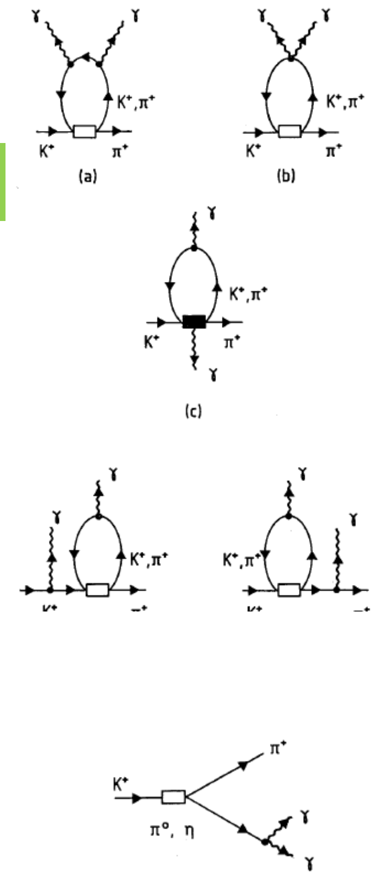
Theory

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

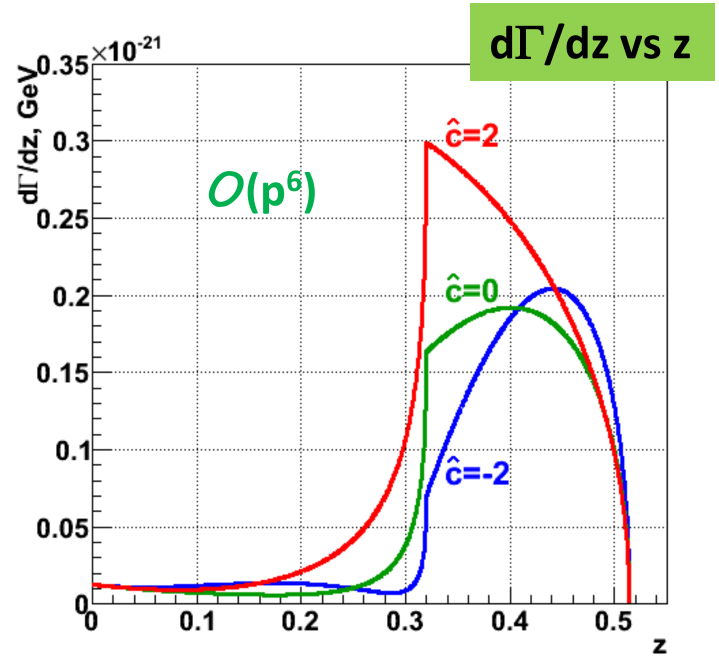
$\mathcal{O}(p^4)$: cusp at $\pi^+\pi^-$ threshold
$m_{\gamma\gamma}=2m_{\pi\pm}$ ($z=(m_{\gamma\gamma}/m_K)^2\approx0.32$)
[Ecker, Pich, de Rafael
NPB303(1988) 665]
Rate and Spectrum depend on
a single parameter $\hat{C}$



$z=(m_{\gamma\gamma}/m_K)^2$



$\mathcal{O}(p^6)$: Unitarity corrections
Increase BR at low z
Non-zero rate at $m_{\gamma\gamma}=0$
[D'Ambrosio, Portoles
PLB386(1996) 403]



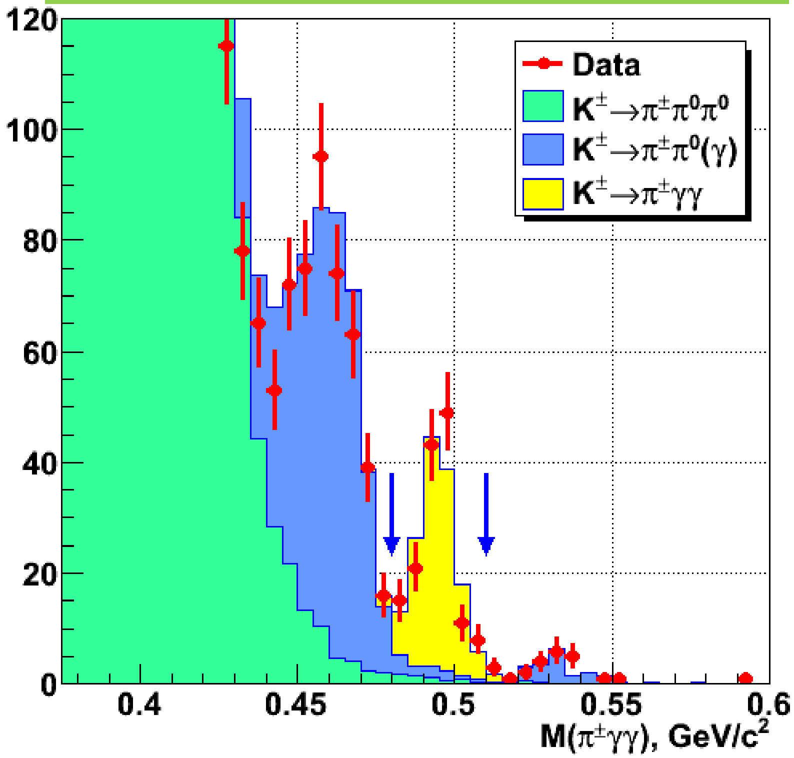
<u>BNL 787</u>: 31 candidates with 5 bkg events
BR = $(1.10\pm0.32)\times10^{-6}$ [PRL79 (1997) 4079]
$O(p^6)$ full kinematic range

$\pi\gamma\gamma$ invariant mass

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

Minimum bias trigger

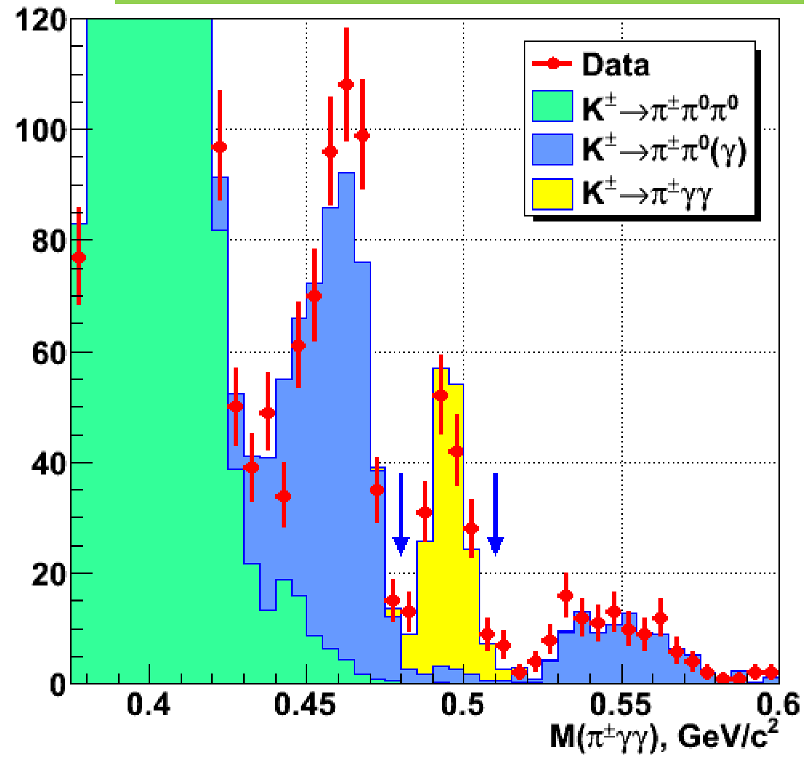
NA48/2 (2004): special run (3 days)



K_{pgg} candidates	147
$K_{2p(g)}$ background	11.0±0.8
K_{3p} background	5.9±0.7
K_{pgg} signal	130±12

downscaled trigger D≈20

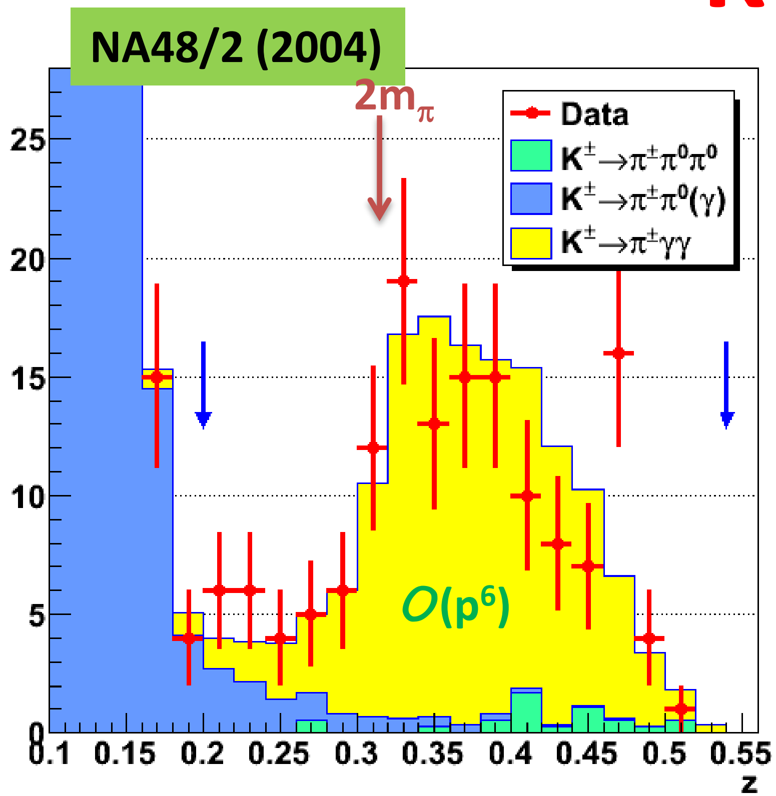
NA62 (2007): full run (3 months)



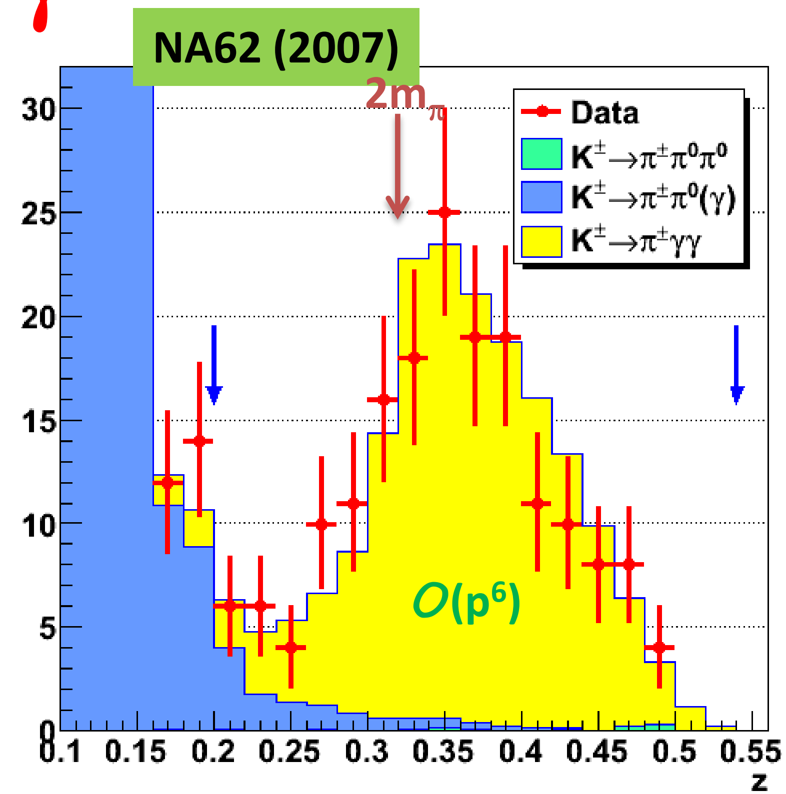
K_{pgg} candidates	175
$K_{2p(g)}$ background	11.1±1.0
K_{3p} background	1.3±0.3
K_{pgg} signal	163±13

z parameter distribution

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



$z=(m_{\gamma\gamma}/m_K)^2$



$K^+ \rightarrow \pi^+\pi^0$ peak is outside the plot ($m_{\gamma\gamma}$=135 MeV or z=0.075)

Signal region: z>0.2 or $m_{\gamma\gamma}$> 220 MeV/c^2 (blue arrows)

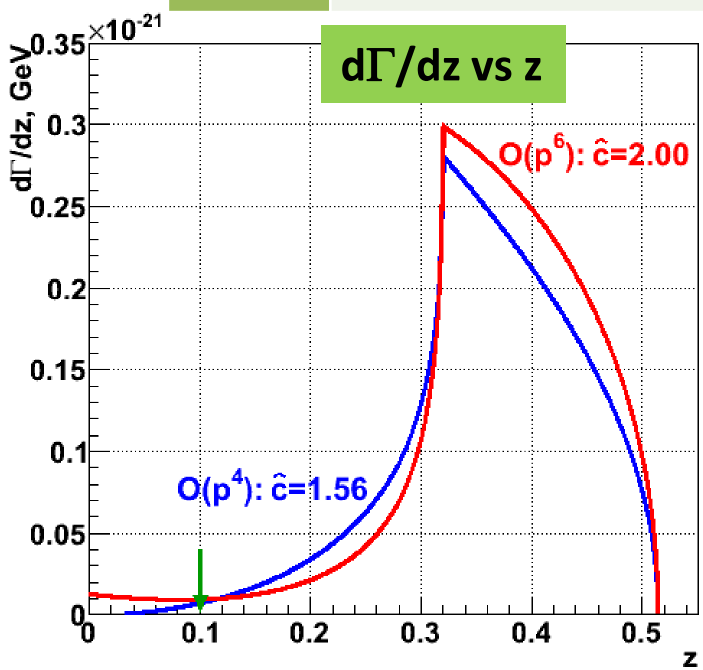
Cusp-like behaviour at $2m_\pi$

Preliminary Results

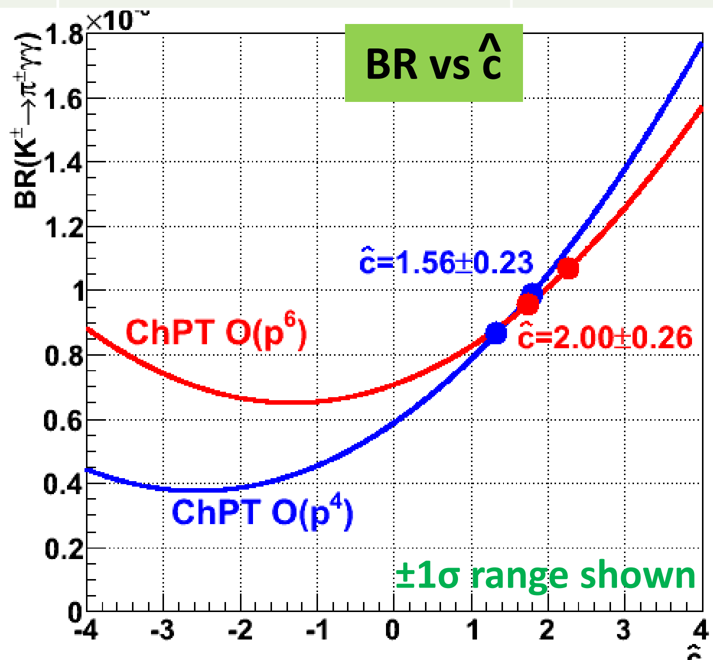
$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

Fully correlated systematic errors

$\hat{c}$ =	NA48/2(2004)	NA62(2007)	Combined
$O(p^4)$	$1.36 \pm 0.33_{stat} \pm 0.07_{syst}$ = 1.36±0.34	$1.71 \pm 0.29_{stat} \pm 0.06_{syst}$ = 1.71±0.30	$1.56 \pm 0.22_{stat} \pm 0.07_{syst}$ = 1.56±0.23
$O(p^6)$	$1.67 \pm 0.39_{stat} \pm 0.09_{syst}$ = 1.67±0.40	$2.21 \pm 0.31_{stat} \pm 0.08_{syst}$ = 2.21±0.32	$2.00 \pm 0.24_{stat} \pm 0.09_{syst}$ = 2.00±0.26

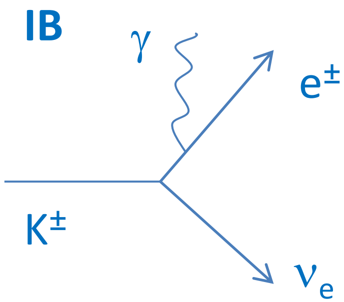


Not able to discriminate $O(p^4)$ from $O(p^6)$



BR = $(1.01 \pm 0.06) \times 10^{-6}$

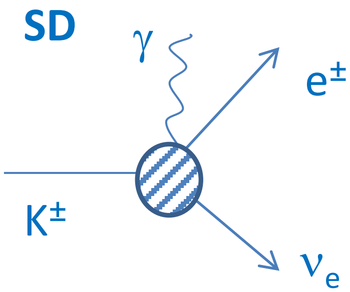
BR assuming $\mathcal{O}(p^6)$
Consistent with E787
but error: factor 5
improved!



Theory

$K^+ \rightarrow e^+\nu\gamma$ (SD^+)

SD^+: Structure Dependent
positive photon elicity



- Sensitive to Kaon structure, EW and hadronic interactions
- Form factors predicted by ChPT and by specific models
- Differential decay rate in term of vector and axial form factors:

$$\frac{d^2\Gamma(K^+ \rightarrow e^+\nu\gamma, SD^+)}{dxdy} = \frac{G_F^2 \sin^2\theta_c M_K^5 \alpha}{64\pi^2}(V+A)^2(1-x)(x+y-1)^2;$$

$$x = \frac{2E_\gamma^{CM}}{M_K}; \qquad y = \frac{2E_e^{CM}}{M_K};$$

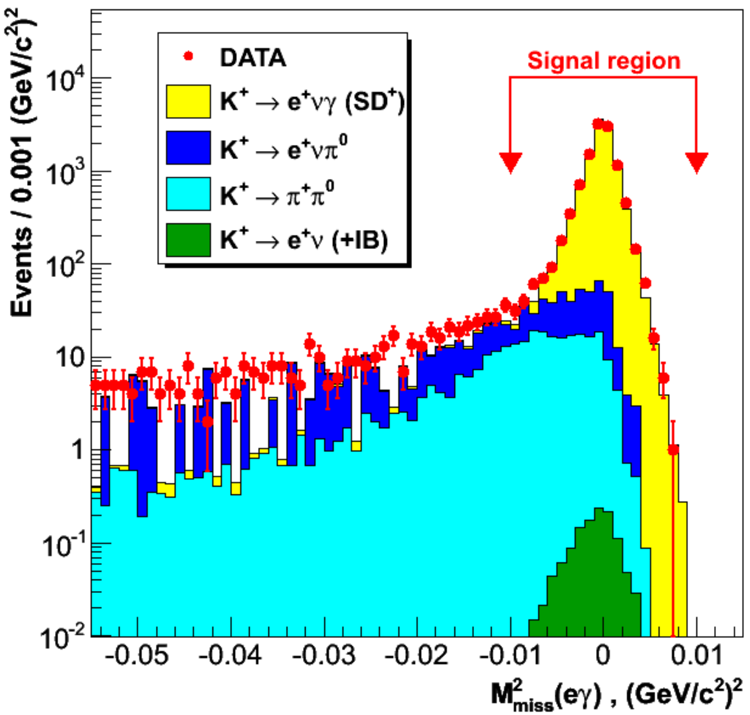
- PDG(2010): BR=$(9.4\pm0.4)\times10^{-6}$ [KLOE, 1484 events, $10<E_\gamma^*<250$ MeV, $p_e^*> 200$ MeV/c]

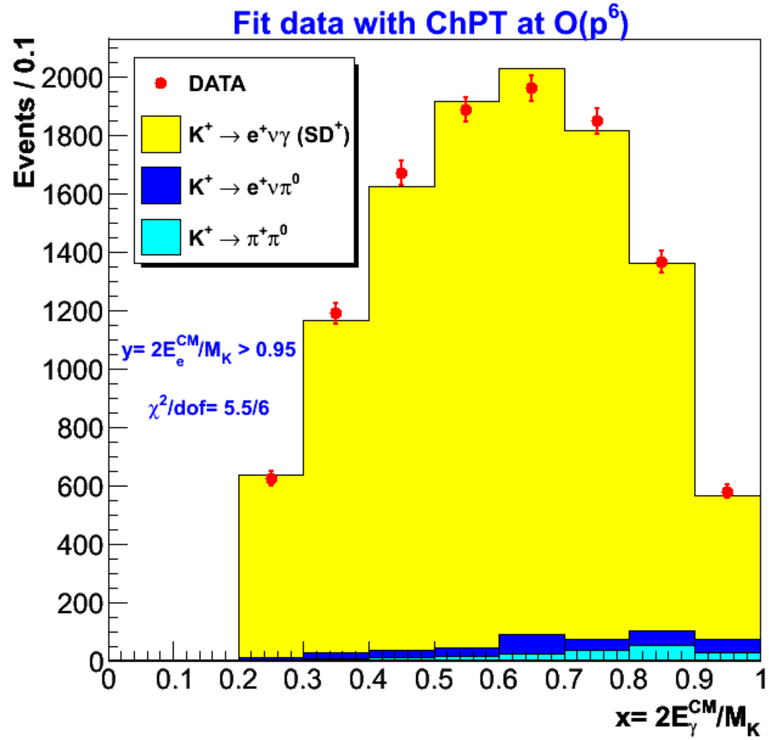
Bijnens, Ecker, Gasser, NPB 396 (1993) 81
Chen, Geng, Lih, PRD 77 (2008) 014004

Preliminary Results

$K^+ \to e^+\nu\gamma$ (SD^+)

NA62 partial (40%) data set: 2007





$\approx$10000 signal candidates (normalization mode $K^+ \to \pi^0 e^+ \nu$)

Signal acceptance $\approx$7%; Background $\approx$5%

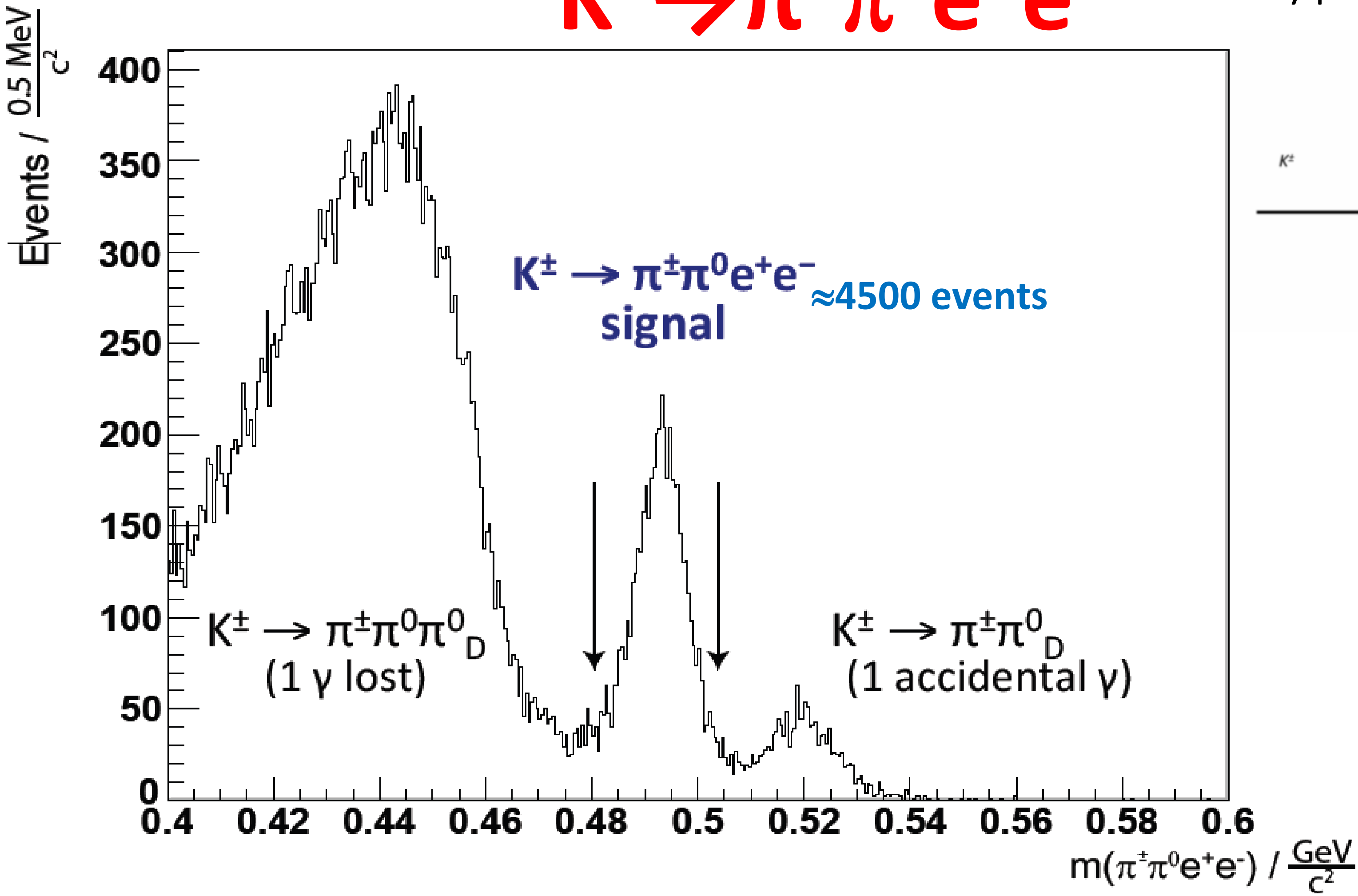
Systematics expected to be dominated by the background subtraction

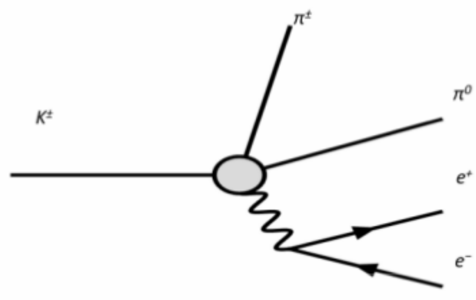
Only K^+ (most abundant sample) shown, final result with K^- too

First Observation

$K^\pm \to \pi^\pm \pi^0 e^+ e^-$

All NA48/2 data
Very preliminary results





Theory: H.Pichl, EPJ C20 (2001) 371 ; Cappiello, Catà, D'Ambrosio, Gao, EPJ C72 (2012) 1872
γ internal conversion in $\pi^\pm\pi^0\gamma$, depends on electric and magnetic FF
Sensitive to CPV and new physics….

$K^{\pm} \to \pi^0 l^{\pm} \nu (K_{l3})$

- K_{l3} decays are described by two form factors $f\pm(t)$ and the matrix element can be written as:

$$M = \frac{G_F}{2} V_{us} \left(f_+(t)(P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu \right)$$

- $t=q^2$ is the squared 4-momentum transfer to the l-ν system
- $f_-(t)$ can only be measured in $K_{\mu 3}$ decays ($m_e \ll m_K$)
- $f_+(t)$ is the vector form factor and $f_0(t)$ the scalar form factor

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

$$\bar{f}_+(t) \equiv \frac{f_+(t)}{f_+(0)}; \qquad \bar{f}_0(t) \equiv \frac{f_0(t)}{f_+(0)};$$

$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu (K_{l3})$

- Pole Parametrization: assume the exchange of vector and scalar resonances K* with spin-parity 1-/0+ and mass m_V/m_S. $f_+(t)$ can be described by K*(892), for $f_0(t)$ no obvious dominance is seen $$\bar{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t};$$
- Linear and quadratic parametrization: expansion in momentum transfer without a direct physical

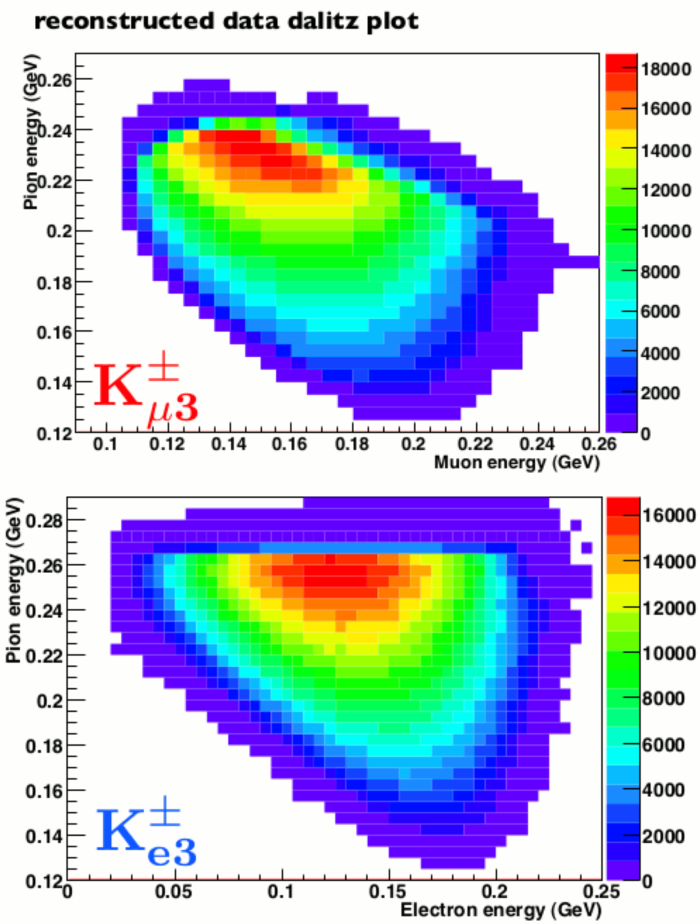
$$\bar{f}_{+,0}(t) = \left(1 + \lambda_{+,0} \frac{t}{m_\pi^2}\right) \qquad \text{Linear}$$

$$\bar{f}_{+,0}(t) = \left(1 + \lambda'_{+,0} \frac{t}{m_\pi^2} + \frac{1}{2} \lambda''_{+,0} \left(\frac{t}{m_\pi^2}\right)^2\right) \qquad \text{Quadratic}$$

Form Factors: Dalitz plots

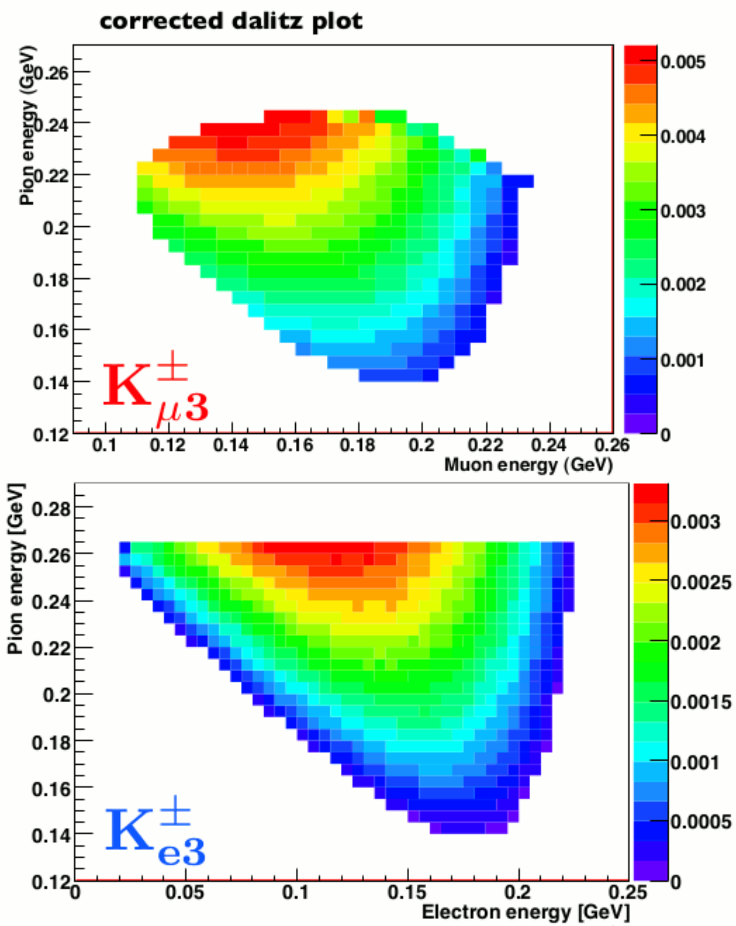
$K^{\pm} \to \pi^0 l^{\pm} \nu (K_{l3})$

Pion energy vs Lepton energy (CM)



Applied corrections:

- Background subtraction.
- Acceptance.
- Radiative corrections.

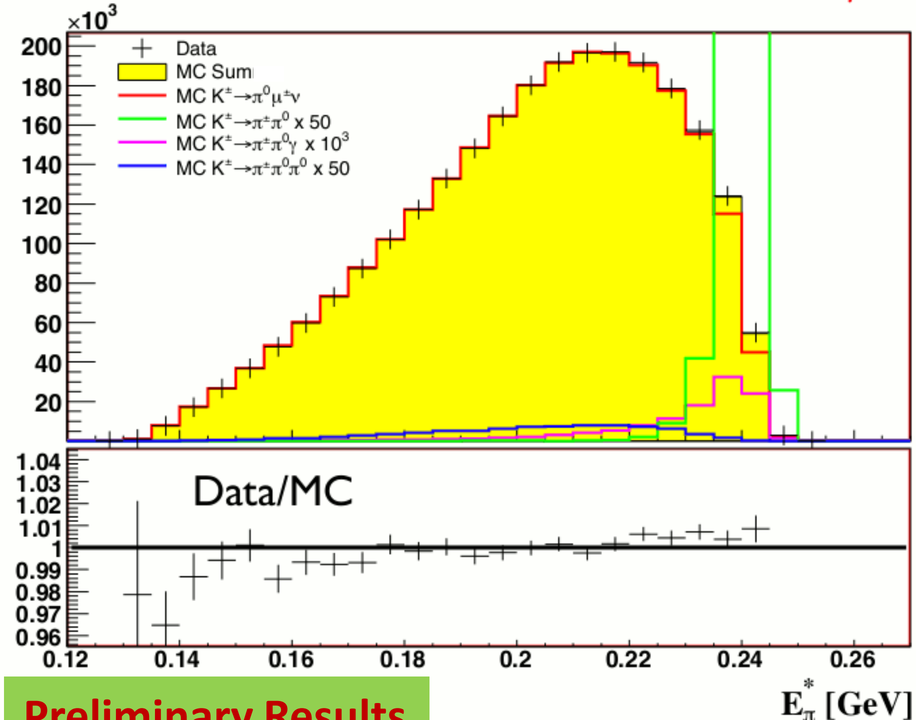


Form Factors: data-MC comparison

$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu (K_{l3})$

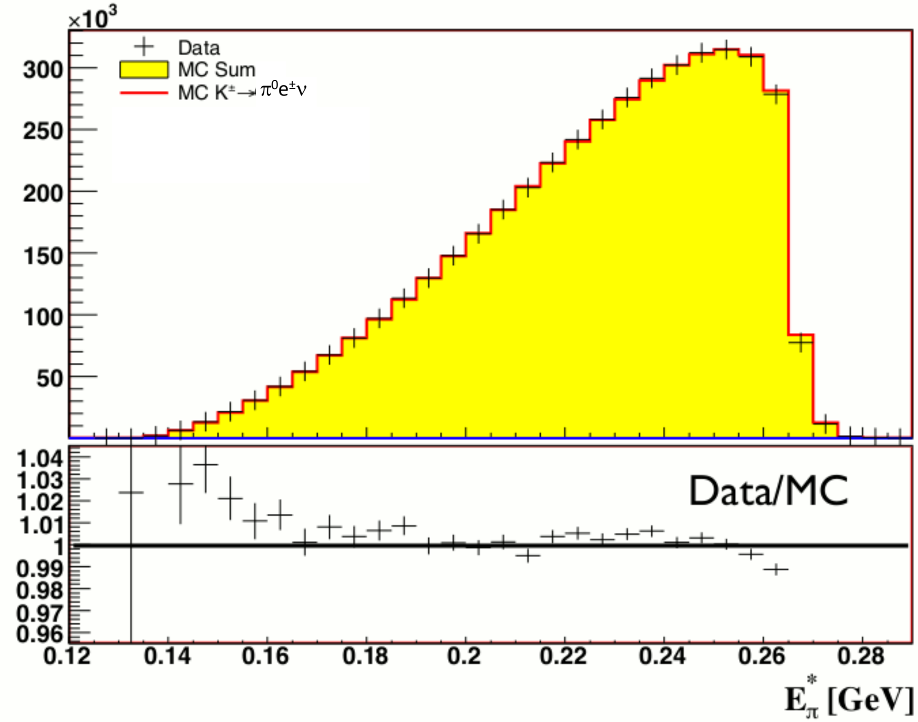
2.5×10^6 $K_{\mu3}$ events

- **Pion energy in the kaon rest frame: $K^{\pm}_{\mu3}$**



4.0×10^6 K_{e3} events

- **Pion energy in the kaon rest frame: $K^{\pm}_{e3}$**

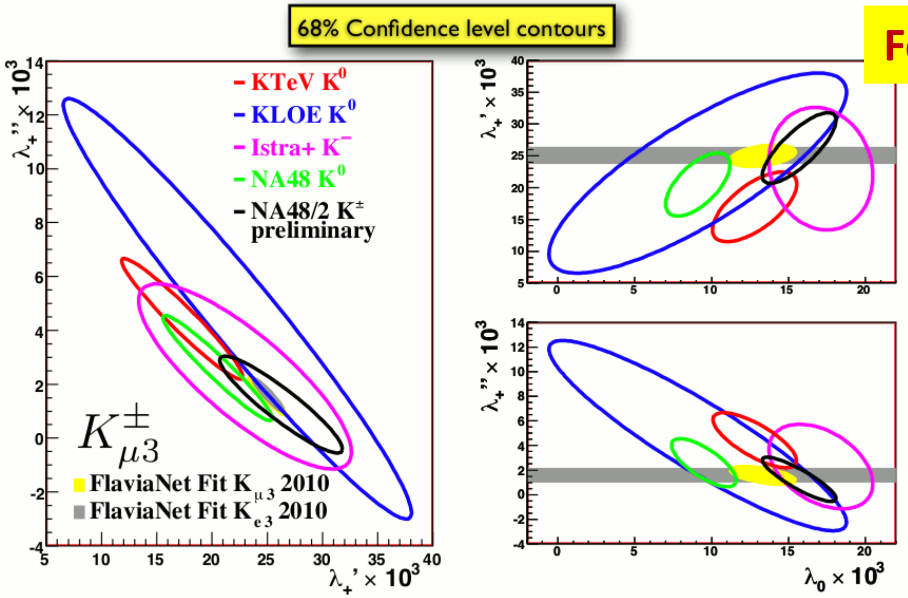


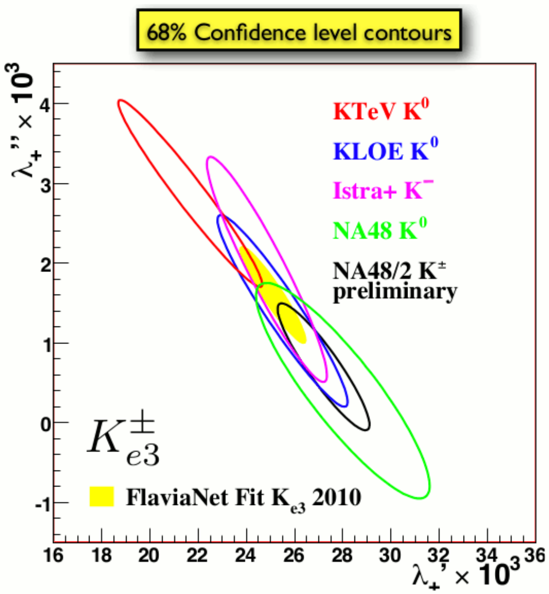
Preliminary Results

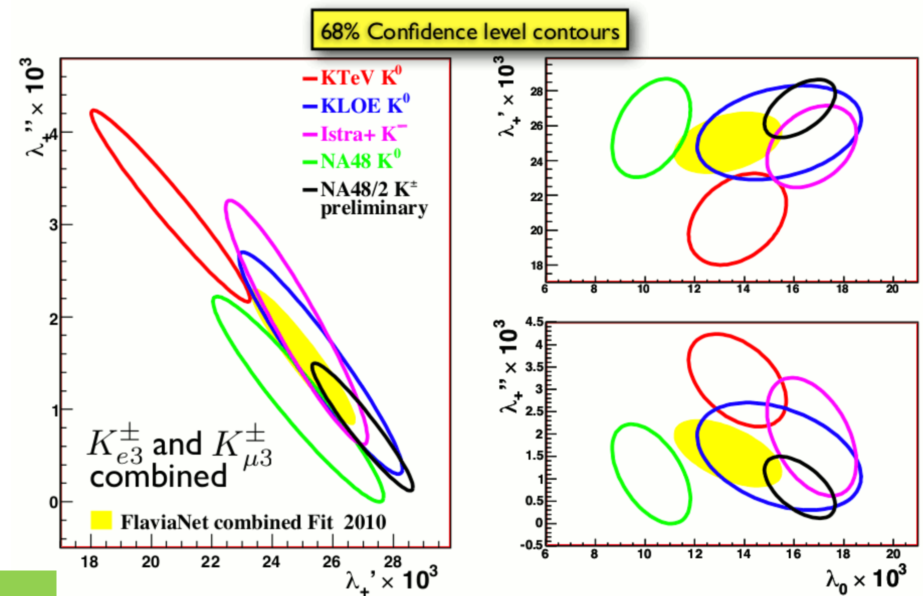
Quadratic $(\times10^{-3})$	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu3}$	$26.3 \pm 3.0_{\rm stat} \pm 2.2_{\rm syst}$	$1.2 \pm 1.1_{\rm stat} \pm 1.1_{\rm syst}$	$15.7 \pm 1.4_{\rm stat} \pm 1.0_{\rm syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{\rm stat} \pm 1.1_{\rm syst}$	$0.7 \pm 0.3_{\rm stat} \pm 0.4_{\rm syst}$	
Pole $(\mathrm{MeV/c^2})$	m_V		m_S
$K^{\pm}_{\mu3}$	$873 \pm 8_{\rm stat} \pm 9_{\rm syst}$		$1183 \pm 31_{\rm stat} \pm 16_{\rm syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{\rm stat} \pm 7_{\rm syst}$		

Form Factors: comparison with other experiments

K_{l3}







Preliminary Results

Quadratic $(\times 10^{-3})$	λ'_+	λ''_+	λ_0
$K^\pm_{\mu3} K^\pm_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole $(\mathrm{MeV/c^2})$	m_V		m_S
$K^\pm_{\mu3} K^\pm_{e3}$ combined	877 ± 6		1176 ± 31

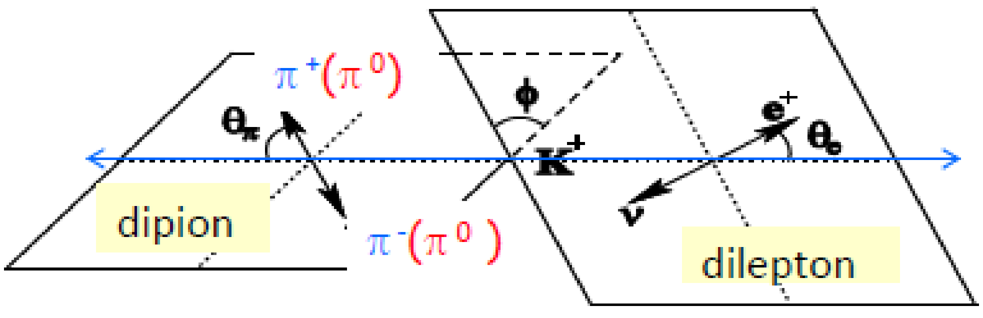
K_{e4}

- $K^{\pm} \rightarrow \pi^{+}\pi^{-}e^{\pm}\nu$ called $K_{e4}^{\pm}$ ("charged" mode)
- $K^{\pm} \rightarrow \pi^{0}\pi^{0}e^{\pm}\nu$ called K_{e4}^{00} ("neutral" mode)
- K_{e4} decays described by 5 kinematics variables [Cabibbo-Maksymowics PRB438(1965)349]:

➢ $S_{\pi}=M_{\pi\pi}^{2}$

➢ $S_{e}=M_{e\nu}^{2}$

➢ θ_{π}, θ_{e}, ϕ



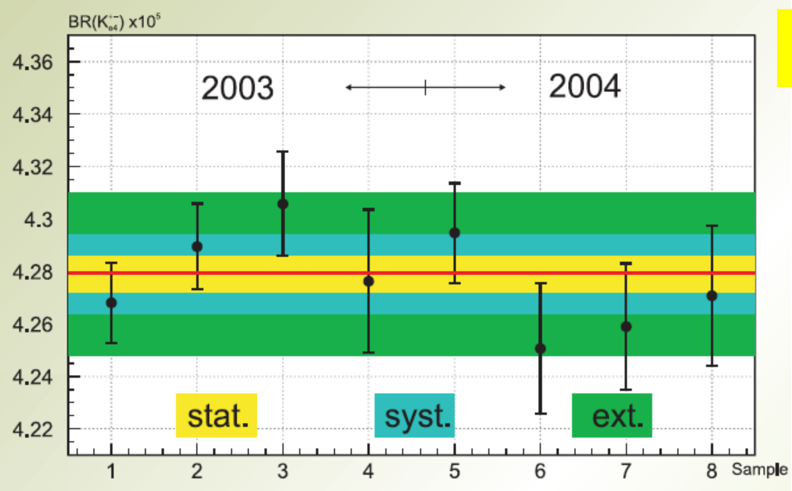
K_{e4}

- Ke4 hadronic current described by form factors
  → partial wave expansion [Pais-Treiman PR168(1968)1858],
  limited to S and P wave
- The transition amplitude depends on two axial (F,G) and one vector (H) complex form factors

➢ $F=F_s e^{i\delta_s}+F_p e^{i\delta_p}\cos\theta_\pi$

➢ $G=G_p e^{i\delta_p}$, $H=H_p e^{i\delta_p}$

- Measure F_s, F_p, G_p, H_p and $\delta=\delta_s-\delta_p$ and variation w.r.t. $q^2=(S_\pi/4m_{\pi+}^2)-1$ and S_e
- $F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e (S_e/4m_\pi^2) + \ldots;$ $F_p = f_p + f_p' + \ldots$
- $G_p = g_p + g_p' q^2 + \ldots;$ $H_p = h_p + h_p' q^2 + \ldots$
- In the "neutral" mode K_{e4}^{00} Bose-statistics reduces the form factors to the single F_s value
- $K_{e4}^{\pm}$ form factors studied by NA48/2 with 1.1 million decays and published in EPJ C70(2010)635



“charged” mode

PDG: $(4.09 \pm 0.10)\times 10^{-5}$

K_{e4}

$$BR(K^{\pm}_{e4}) = \frac{(N_s - N_b)}{N_n}\frac{A_n \varepsilon_n}{A_s \varepsilon_s} BR(K_{3\pi})$$

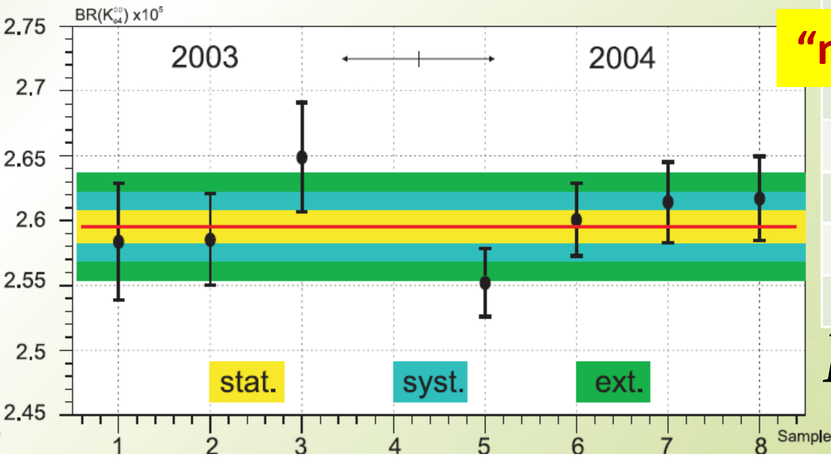
- Use 3 pions decays as normalization
- N_s, N_b, N_n : number of signal (1.11×10^6), background (0.95% of K_{e4}) and normalization (1.9×10^9) events
- A_n, A_s, ε_n, ε_s : signal and normalization acceptance (18.22% and 24.2%) and trigger efficiency (98.3% and 97.5%)
- $BR(K^{\pm}\rightarrow\pi^+\pi^-\pi^{\pm})$ = (5.59±0.04)%

Systematic Uncertainty	%
Acceptance and beam geom.	0.18
Muon vetoing	0.16
Accidental activity	0.15
Background	0.14
Particle ID	0.09
Radiative effects	0.08
Independent analysis	0.10

Preliminary Results

$$BR(K^{\pm(+)}_{e4}) = (4.277 \pm 0.009_{stat})\times 10^{-5};\ BR(K^{\pm(-)}_{e4}) = (4.279 \pm 0.012_{stat})\times 10^{-5}$$

$$BR(K^{\pm}_{e4}) = (4.279 \pm 0.004_{stat} \pm 0.016_{syst} \pm 0.031_{ext})\times 10^{-5}$$



“neutral” mode

$$\mathrm{PDG:}\left(2.2\pm0.4\right)\times10^{-5}$$

K_{e4}

$$BR(K^{00}_{e4}) = \frac{\left(N_s - N_b\right)}{N_n}\frac{A_n\varepsilon_n}{A_s\varepsilon_s}BR\left(K_{3\pi}\right)$$

- Use 3 pions decays as normalization
- N_s, N_b, N_n : number of signal (44909), background (1.3% of K_{e4}) and normalization (71×10^6) events
- A_n, A_s, ε_n, ε_s : signal and normalization acceptance (1.77% and 4.11%) and trigger efficiency (92% and 98%)
- $BR(K^\pm \to \pi^0\pi^0\pi^\pm) = (1.761\pm0.022)\%$

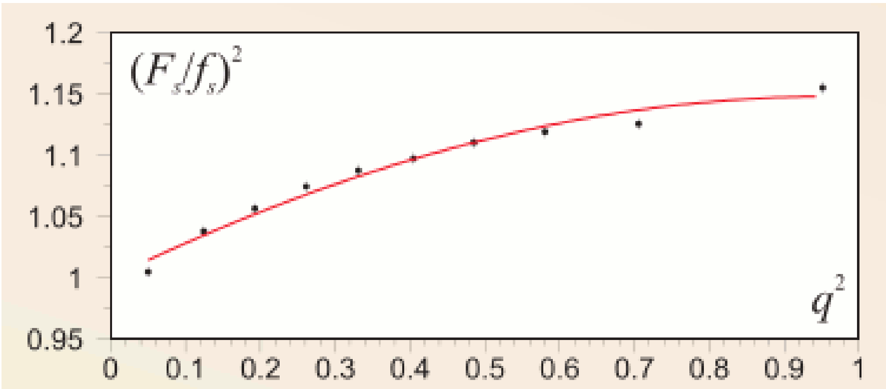
Systematic Uncertainty	%
Background	0.35
Simulation statistics	0.12
Form Factors dependence	0.20
Radiative effects	0.23
Trigger efficiency	0.80
Particle ID	0.10
Beam geometry	0.10

Preliminary Results

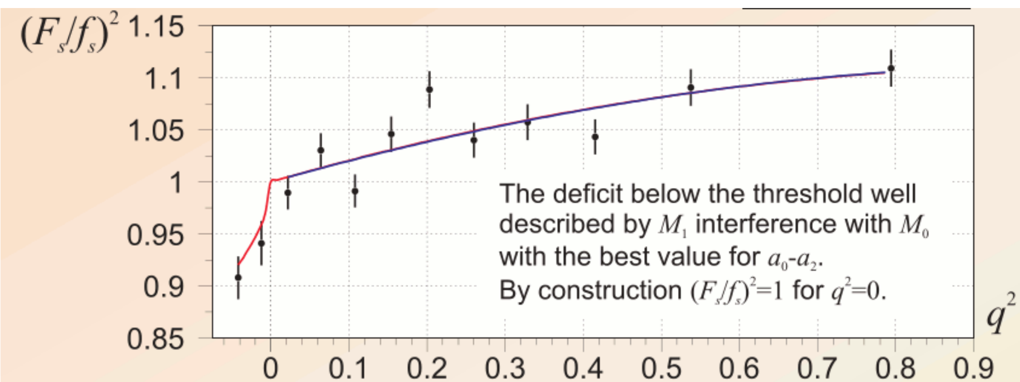
$$BR(K^{00}_{e4}) = \left(2.595\pm0.012_{stat}\pm0.024_{syst}\pm0.032_{ext}\right)\times10^{-5}$$

K_{e4}

relative form factor measurement as a function of $q^2=S_\pi/4(m_{\pi+})^2 - 1$



"<u>charged</u>" mode



"<u>neutral</u>" mode: includes one-loop theoretical prescription with negative Interference (charge exchange scattering $\pi^+\pi^- \rightarrow \pi^0\pi^0$, using known values for the $\pi\pi$ scattering lenghts)

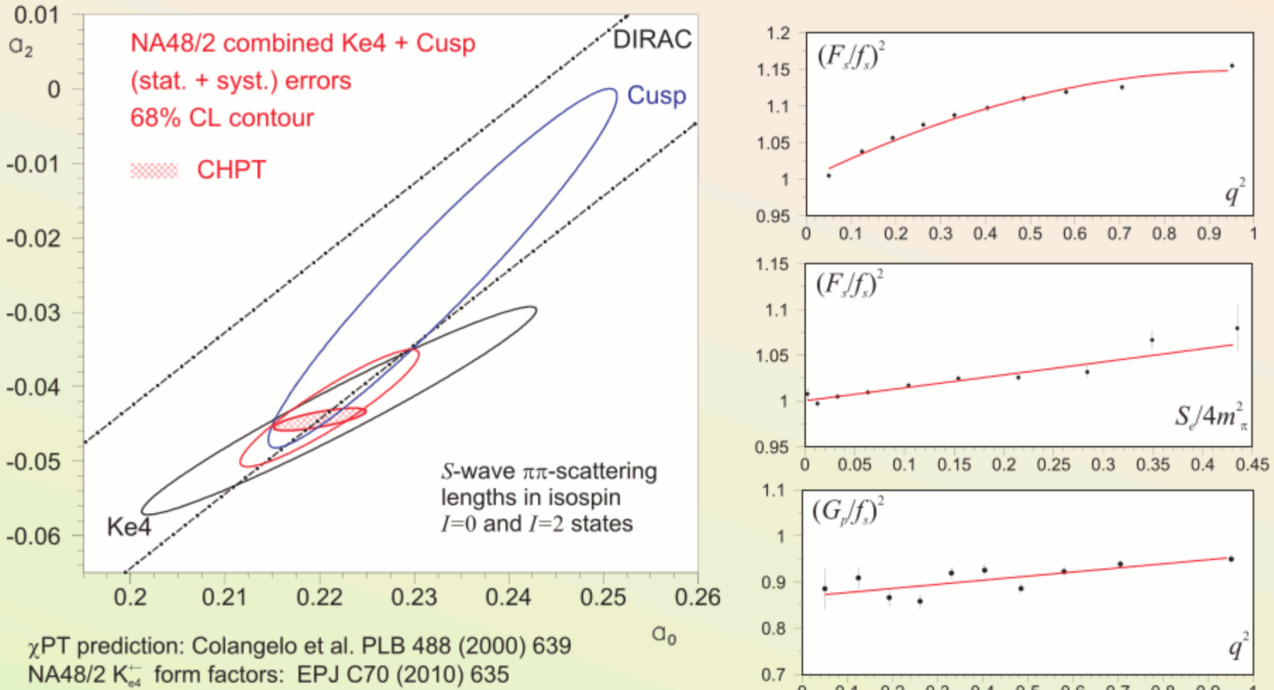
Conclusions

- Many items covered….
- Many more to come….
- NA62 ($K^+ \to \pi^+ \nu\nu$) to start data-taking in 2014

SPARES

K^{+-}_{e4} FORM FACTORS / FINAL

$$
\begin{aligned}
f'_s/f_s &= 0.152 \pm 0.007_{\rm stat} \pm 0.005_{\rm syst}\\
f''_s/f_s &= -0.073 \pm 0.007_{\rm stat} \pm 0.006_{\rm syst}\\
f'_e/f_s &= 0.068 \pm 0.006_{\rm stat} \pm 0.007_{\rm syst}\\
f_p/f_s &= -0.048 \pm 0.003_{\rm stat} \pm 0.004_{\rm syst}\\
g_p/f_s &= 0.868 \pm 0.010_{\rm stat} \pm 0.010_{\rm syst}\\
g'_p/f_s &= 0.089 \pm 0.017_{\rm stat} \pm 0.013_{\rm syst}\\
h_p/f_s &= -0.398 \pm 0.015_{\rm stat} \pm 0.008_{\rm syst}
\end{aligned}
$$



χPT prediction: Colangelo et al. PLB 488 (2000) 639
NA48/2 $K^{\pm}_{e4}$ form factors: EPJ C70 (2010) 635
DIRAC Pionium: CERN-PH-EP-2011-028
NA48/2 ππ-scattering lengths from $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$: EPJ C64 (2009) 589

M.Lenti