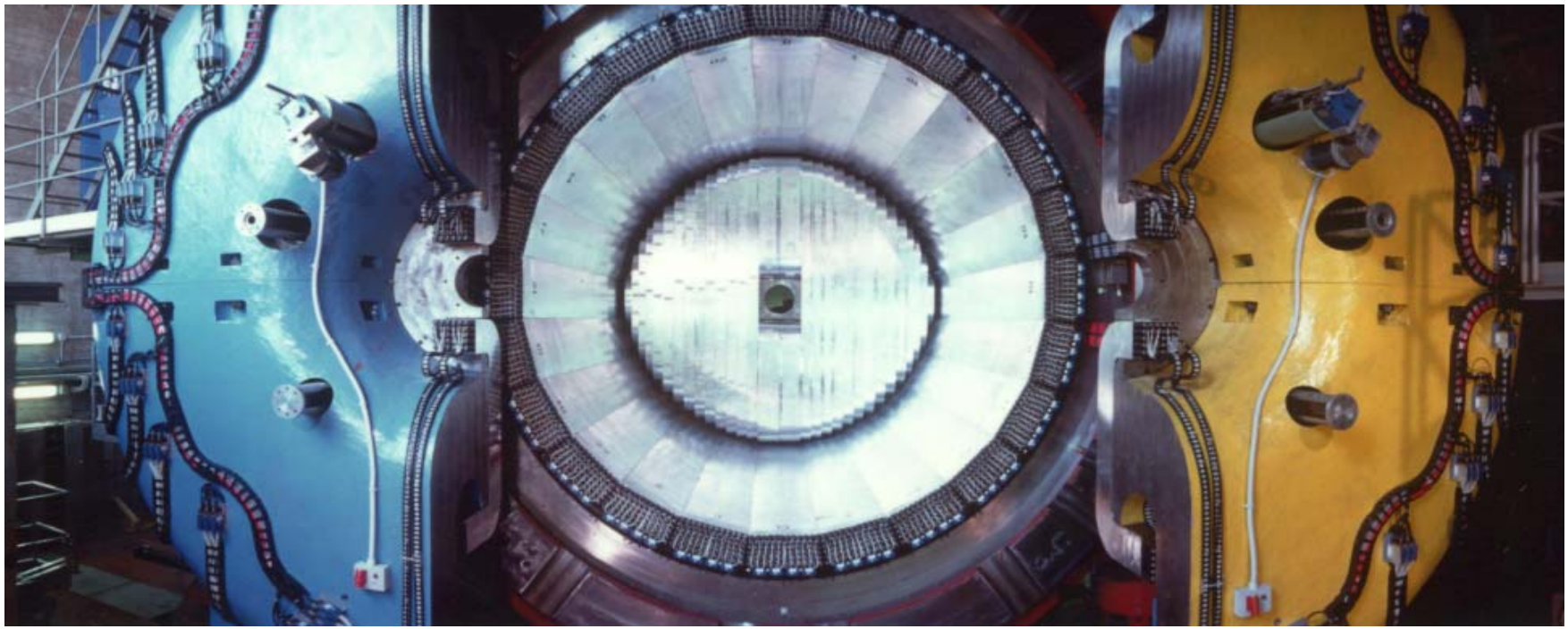
Highlights from the KLOE experiment @ DAΦNE



S.Miscetti, LNF INFN

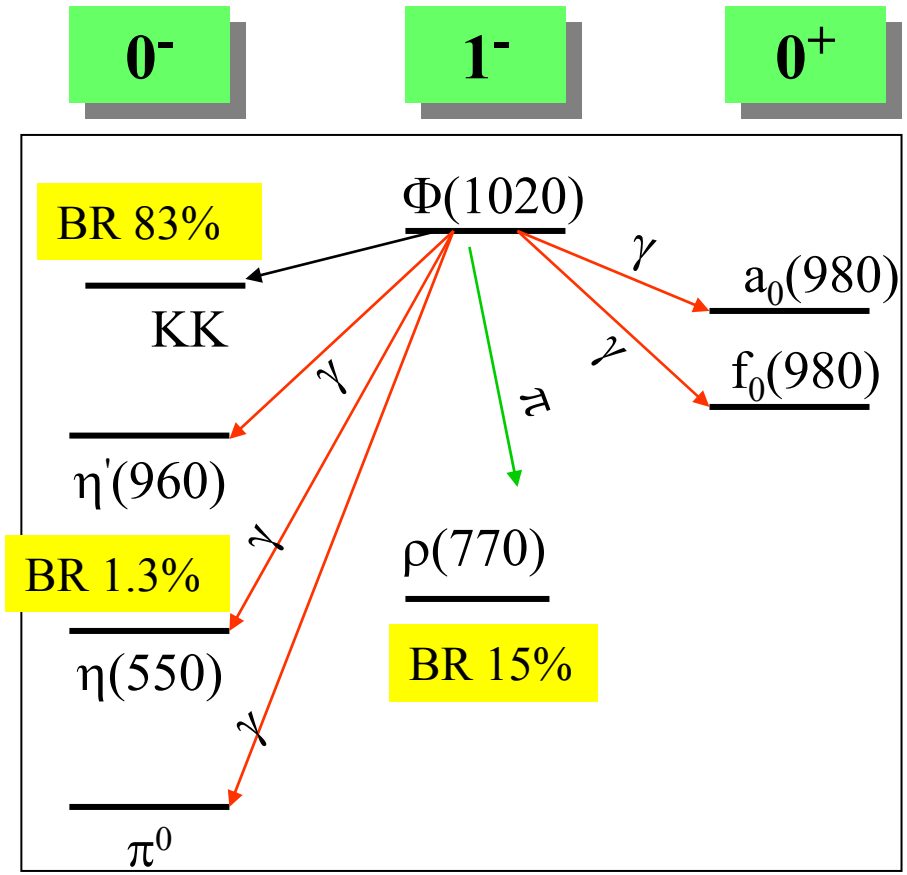
For the KLOE collaboration

Electroweak Interactions and Unified Theories, Moriond 04

LaThuile 21-28 March 2004

KLOE Physics program

A Φ-factory is a collider e^+e^- running at $\sqrt{s} = M_\Phi$



Main focus on KAON physics:

- CP double ratio/interferometry
- CPT Asym in semileptonic K_S, K_L decays
- V_{us}, K form factors
- BR of $K_{S,L}$, $K^\pm$
- Rare $K_{S,L}$ decays ($K_L \to \gamma\gamma$, $K_S \to 3\pi^0$, $\gamma\gamma$, $\pi^+\pi^-\pi^0$ ..)

Non Kaon Physics

- Radiative Φ decays
- $\pi\pi\gamma$ final state
- $\rho\pi$ final states

Continuum physics

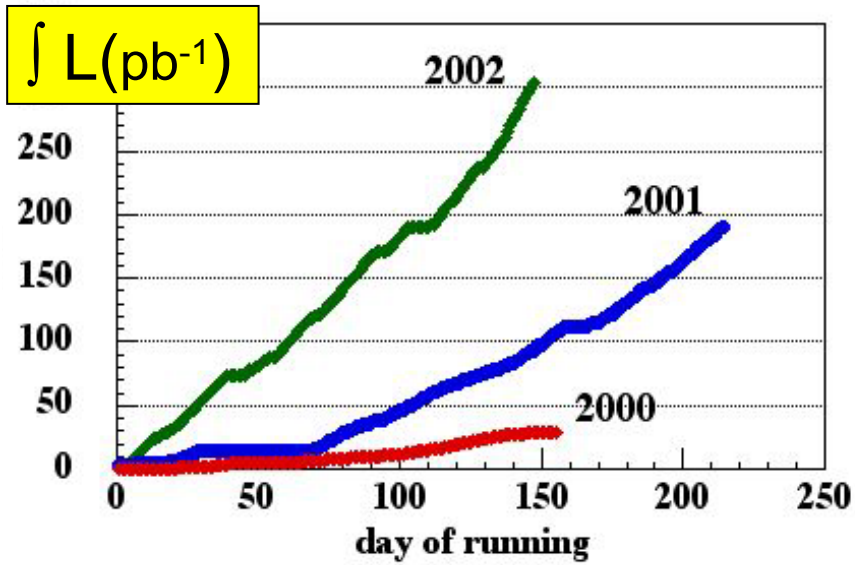
- σ(had)

DAΦNE status and plans

- e^+e^- collider @ $\sqrt{s}$ = 1020 MeV
- 2 IP (KLOE – DEAR/Finuda)
- Separate e^+, e^- rings
  to minimize beam-beam interactions
- Crossing angle: 12.5 mrad
- Injection during data-taking

DAΦNE Parameters	Design	2002 (KLOE)
N bunches	120+120	51+51
Lifetime (mins)	120	40
Bunch current(mA)	40	20
L_{bunch} ($cm^{-2}s^{-1}$)	$4.4 \cdot 10^{30}$	$1.5 \cdot 10^{30}$
L_{peak} ($cm^{-2}s^{-1}$)	$5.3 \cdot 10^{32}$	$0.8 \cdot 10^{32}$

2003 Finuda/IR



Standard analysis sample:
450 pb^{-1} from 2001-2002

2004 goal

- $L_{peak} = 2 \cdot 10^{32}\ cm^{-2}s^{-1}$
- L_{int} / day = 10 pb^{-1}
- L_{int} / year = 2 fb^{-1}

Characteristics of a Φ factory

- The KK pairs in the final state have the same Φ quantum numbers i.e. are produced in a pure $J^{PC} = 1^{--}$ stat

$K_S\ (K^+) \longleftarrow \Phi \longrightarrow K_L\ (K^-)$ purity $\approx 10^{-10}$

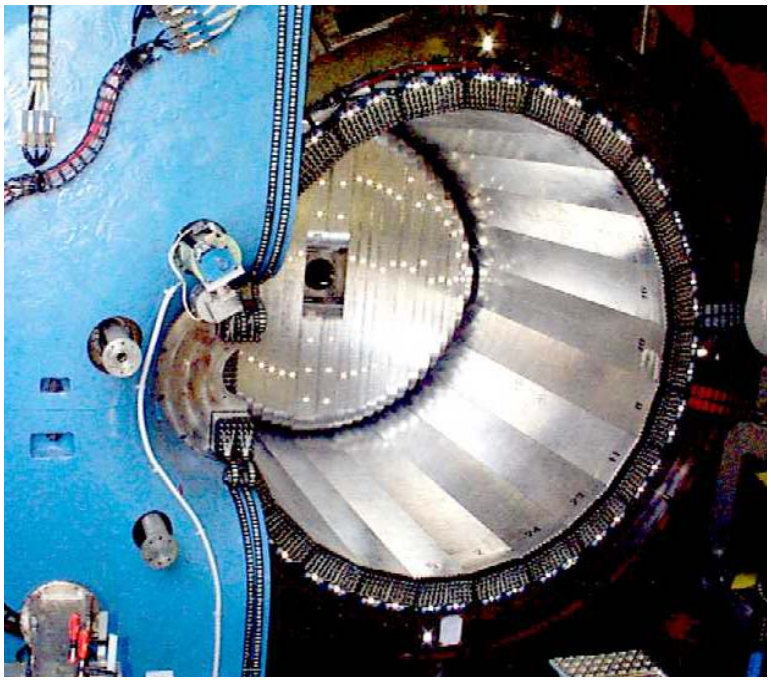
$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L,\mathbf{p}\rangle|K_S,-\mathbf{p}\rangle - |K_L,-\mathbf{p}\rangle|K_S,\mathbf{p}\rangle\right)$$

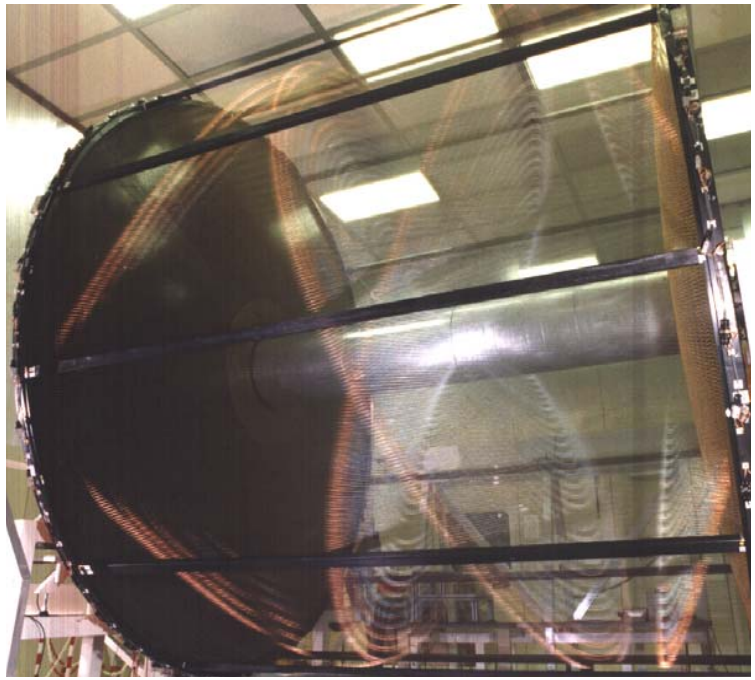
- **Tagging:** observation of $K_{S,L}$ signals presence of $K_{L,S}$
  - precision measurement of absolute BR's
  - interference measurements of $K_S K_L$ system

$p_{L,S}$ = 110 MeV λ_S **= 6 mm Ks decays near interaction point**

$\beta_{L,S}$ = 0.22 λ_L **= 3.4 m** Large detector to keep reasonable acceptance for K_L decays (~0.5 λ_L)

The KLOE experiment





$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$

$\sigma_T = 54$ ps $/ \sqrt{E(GeV)} \oplus 50$ ps

- PID capabilities mostly from TOF

$\sigma_L(\gamma\gamma) \sim 1.5$ cm (p^0 from $K_L \rightarrow \pi^+\pi^-\pi^0$)

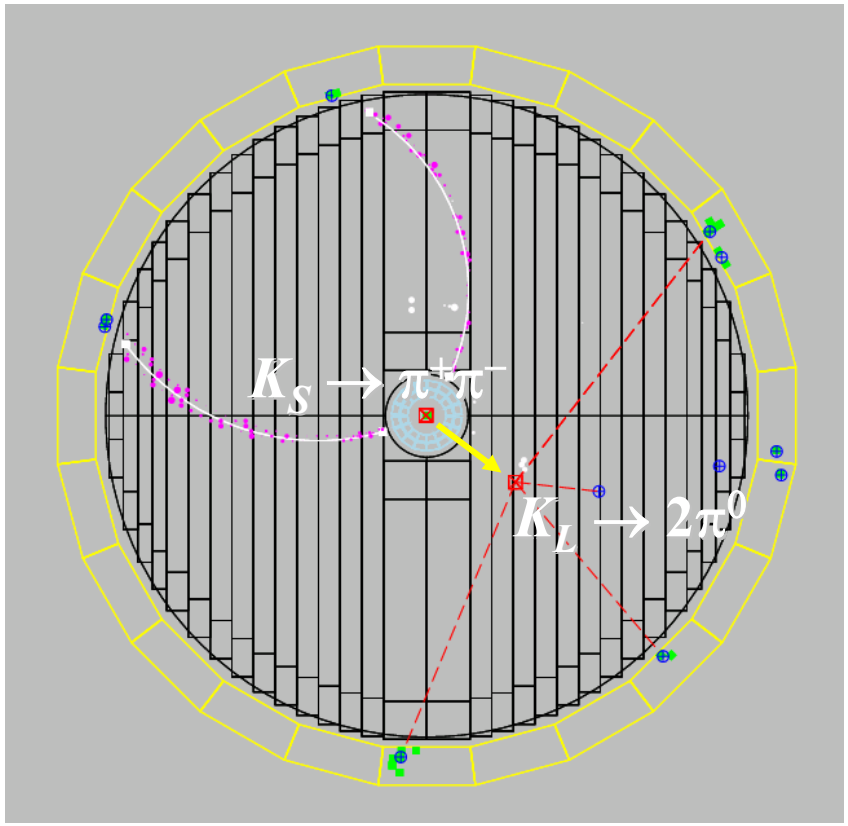
4m-∅, 3.75m-length, all-stereo

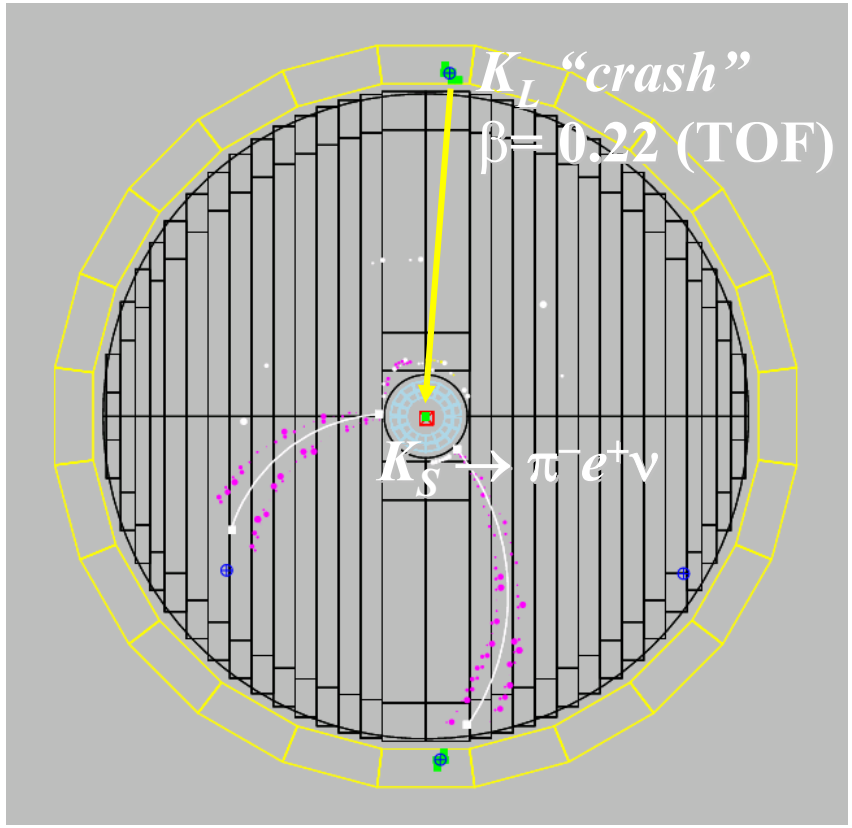
σ_p/p = **0.4 %** (tracks with $\theta > 45°$)

$\sigma_x^{hit} = 150\ \mu m$ **(xy), 2 mm (z)**

$\sigma_x^{vertex} \sim 1$ **mm**

Tagging of K_S K_L beams





K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP

ε ~ 70% (mainly geometrical)

K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 1 MeV

K_S tagged by K_L interaction in EmC

ε ~ 30% (largely geometrical)

K_S angular resolution: ~ 1° (0.3° in ϕ)

K_S momentum resolution: ~ 1 MeV

$K_S \to 3\pi^0$: test of CP and CPT

Observation of $K_S \to 3\pi^0$ signals CP violation in mixing and/or decay:

SM prediction: $\Gamma_S = \Gamma_L |\eta|^2$, giving $BR(K_S \to 3\pi^0) = 1.9\ 10^{-9}$

Present published results: $BR(K_S \to 3\pi^0) < 1.4\ 10^{-5}$

Uncertainty on $K_S \to 3\pi^0$ amplitude limits precision of CPT test.

Unitarity: $(1 + i \tan\phi_{SW}) R_e\varepsilon - \Sigma_f A^*(K_S \to f)\, A(K_L \to f)/\Gamma_S = (-i + \tan\phi_{SW})\, \mathrm{Im}\, \delta$

$(\varepsilon_{S,L} = \varepsilon \pm \delta)$

A limit on $BR(K_S \to 3\pi^0)$ at 10^{-7} level translates into a 2.5-fold improvement on the accuracy of Im δ **(2 10^{-5}).**

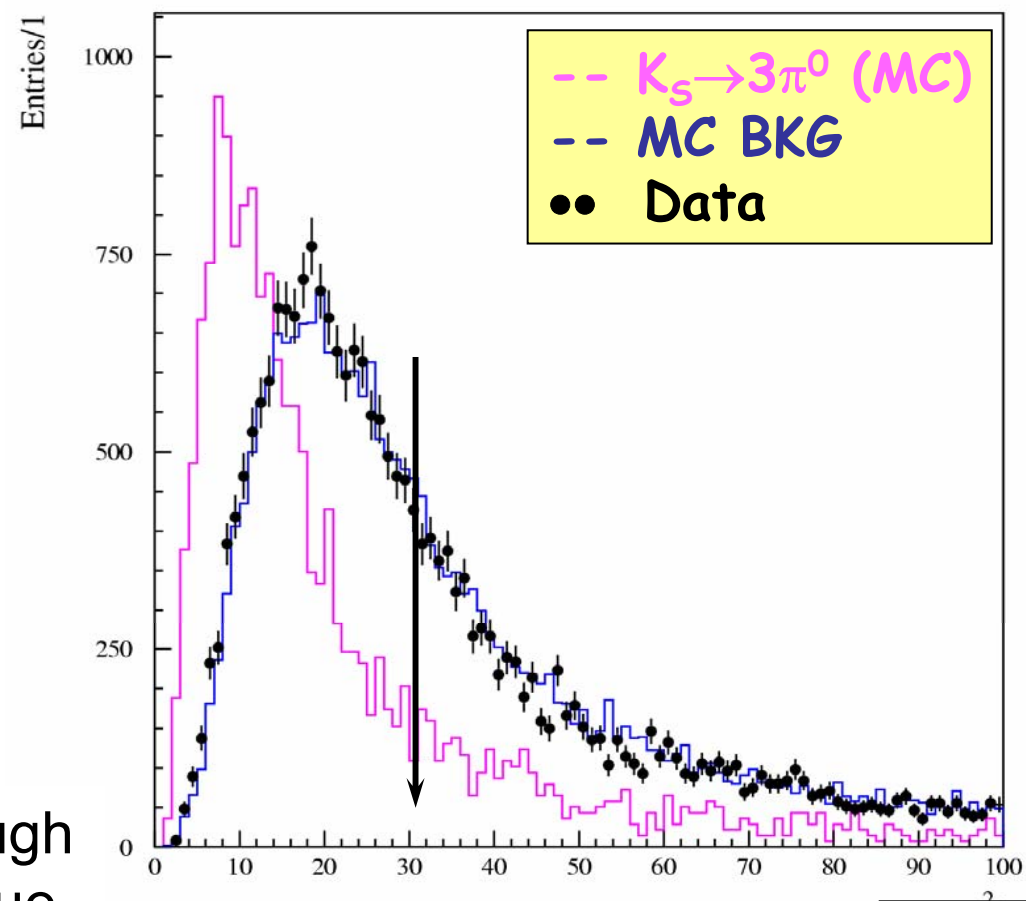
Assuming CPT invariance in the decay:

$$\frac{\delta(M_{K0} - M_{\overline{K0}})}{M_K} \sim 5\ 10^{-19} \qquad (M_K/M_{Planck} = 4\ 10^{-20})$$

$K_S \rightarrow 3\pi^0$ search: method

- ✓ K_S tagged by K_L *crash*
- ✓ 6 prompt γ's ($\beta_{clu} = 1$)
- ✓ no charged tracks from IP
- ✓ normalization with sample with 4 γ's (Ks $\rightarrow 2\pi^0$)
- ✓ Kinematic fit

- Impose K_S mass and K_L 4-momentum conservation, $\beta = 1$ for each γ
- Estimate E_γ, $\mathbf{r}_\gamma$, t_γ, $\sqrt{s}$, p_ϕ



χ^2_{Fit}

Rejection power of χ^2_{fit} not enough to eliminate main background due to **$K_S \rightarrow \pi^0\pi^0$ + 2 fake γ's**

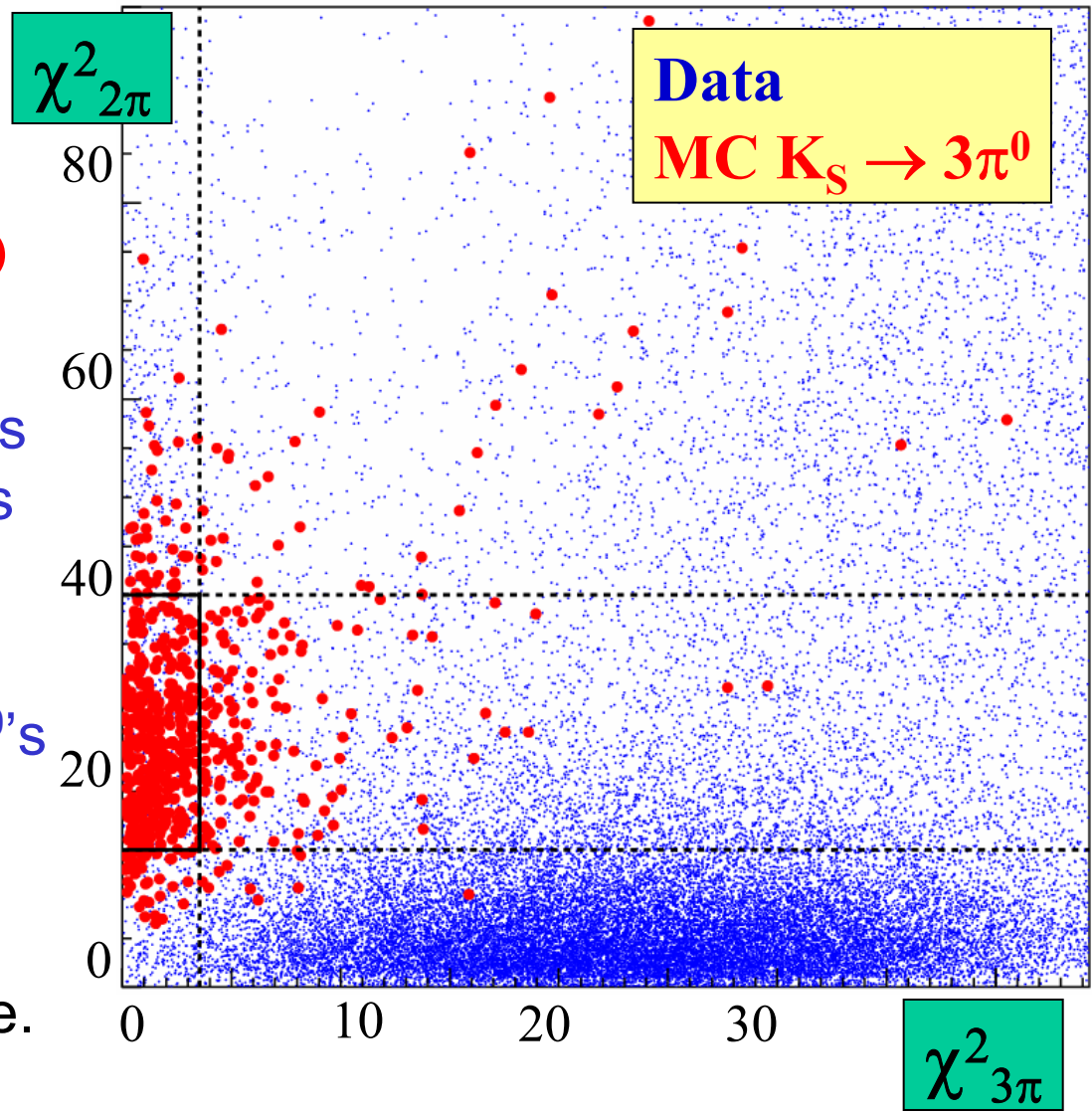
$K_S \to 3\pi^0$ search: $2\pi^0$ vs $3\pi^0$

Two pseudo-χ^2 built to discriminate between 2π vs 3π hypotheses

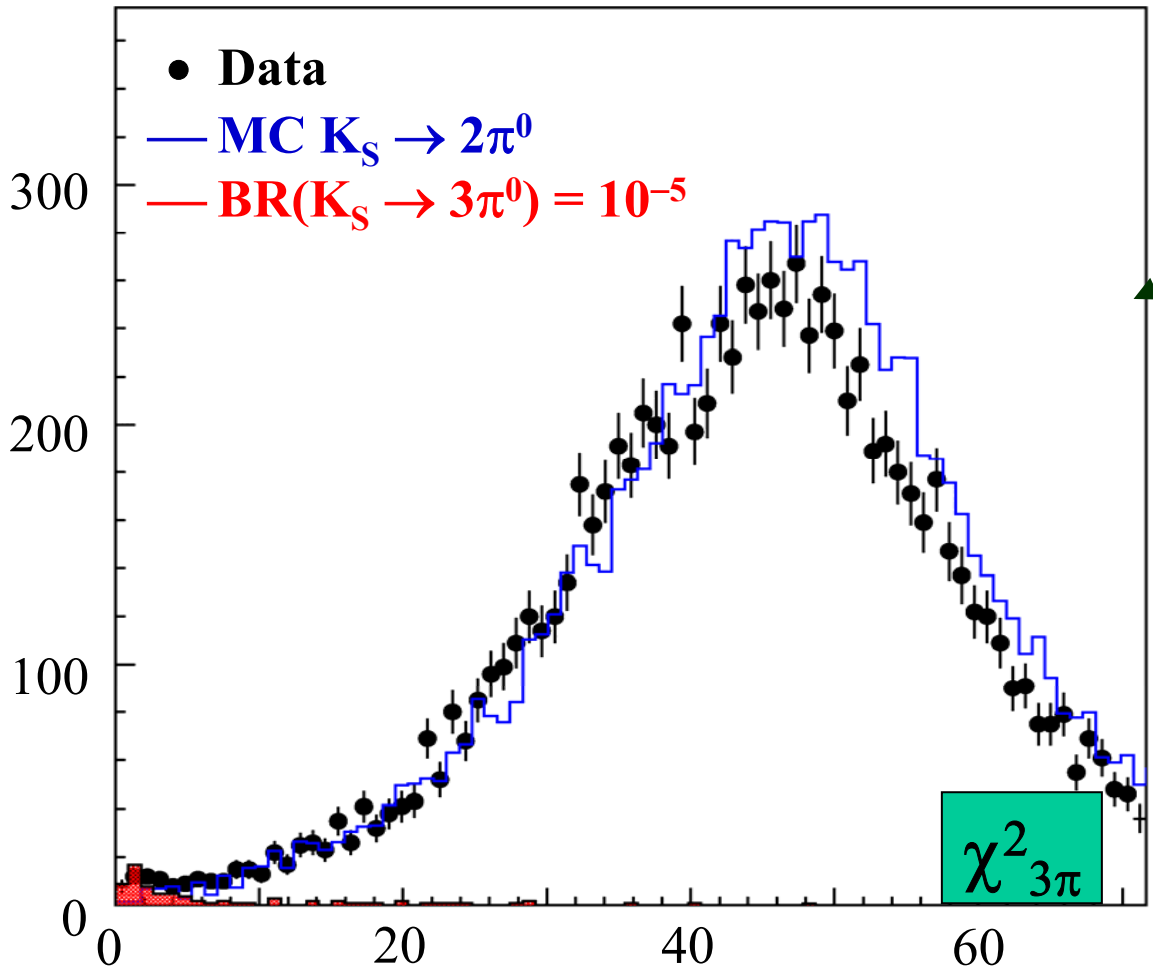
(BKG: $K_S \to \pi^0\pi^0$ + 2 fake γ's)

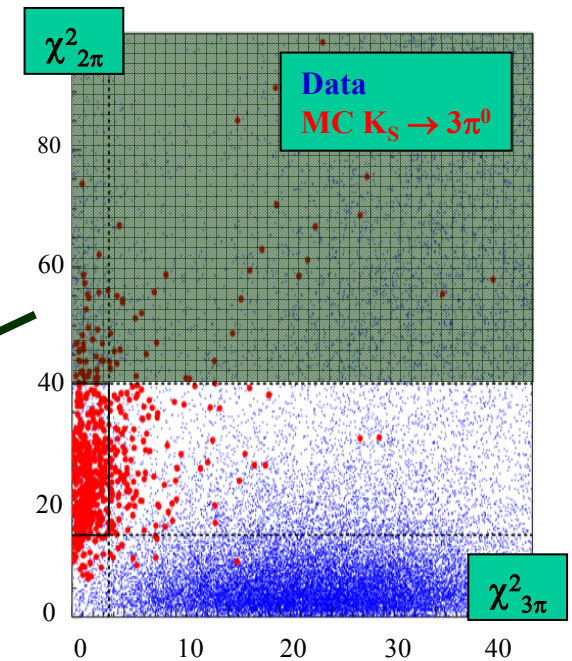
- $\chi^2_{3\pi}$ – pairing of 6 γ clusters with better π^0 mass estimates
- $\chi^2_{2\pi}$ – best pairing of 4 γ's out of 6: π^0 masses, $E(K_S)$, **P**(K_S), c.m. angle between π^0's

Initial Signal BOX definition obtained from analysis of 6-pb $^{-1}$ equivalent MC sample.



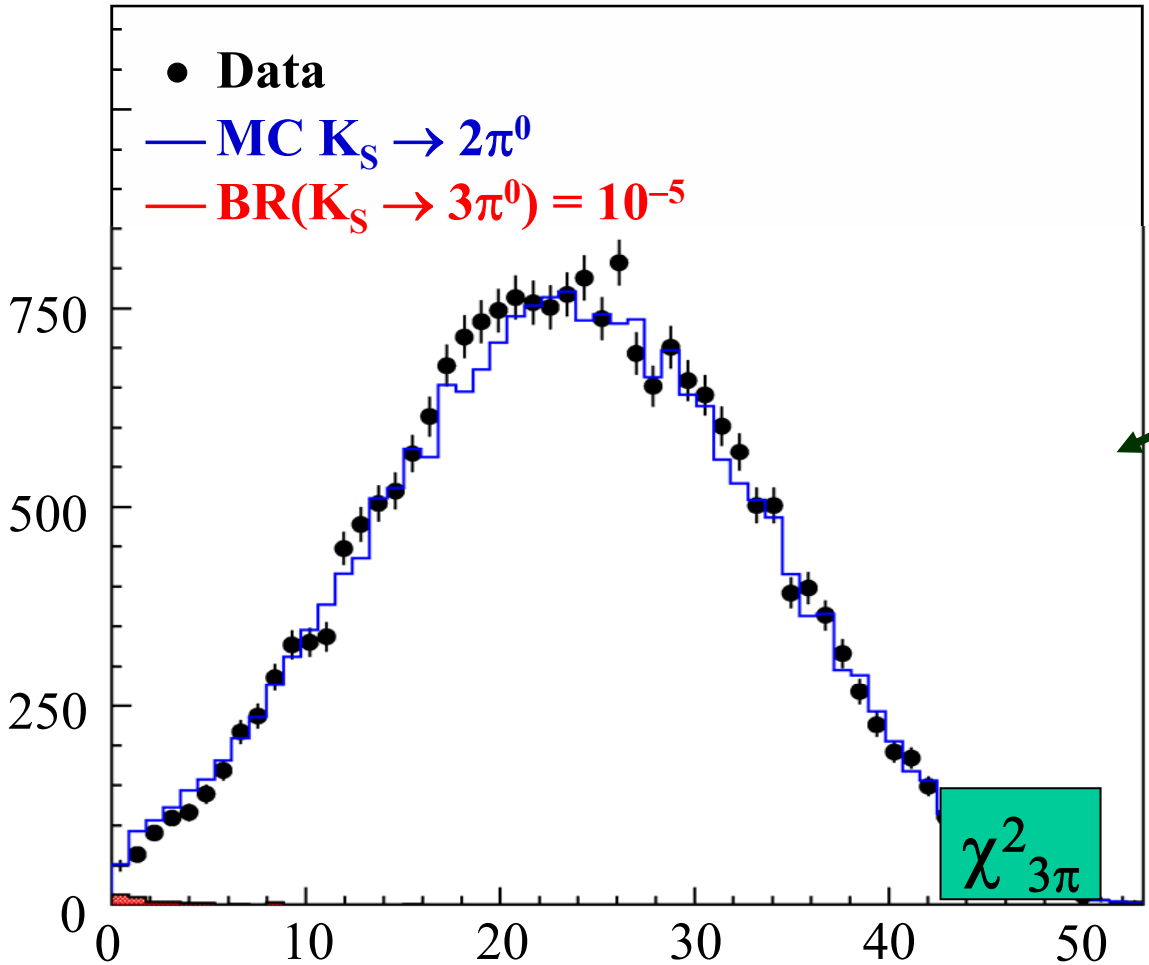
$K_S \rightarrow 3\pi^0$ search: $\chi_{2\pi}$, $\chi_{3\pi}$ sidebands

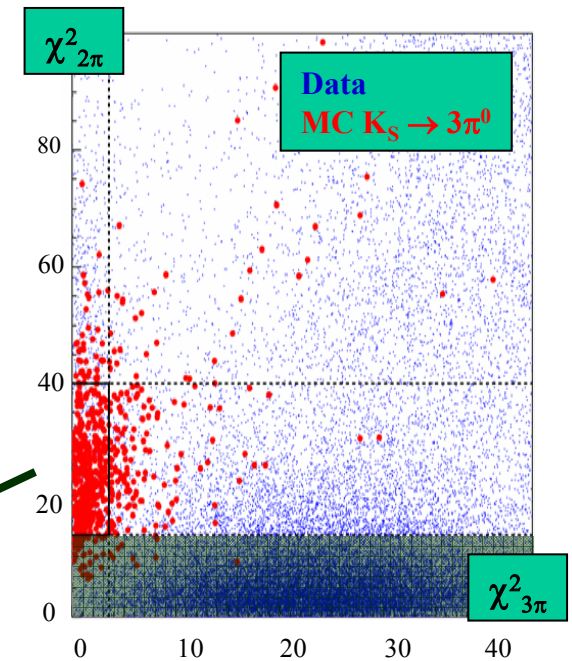




$K_S \rightarrow 3\pi^0$ decay switched on during MC production of 450 pb^{-1} equivalent data, with BR equal to the present upper limit

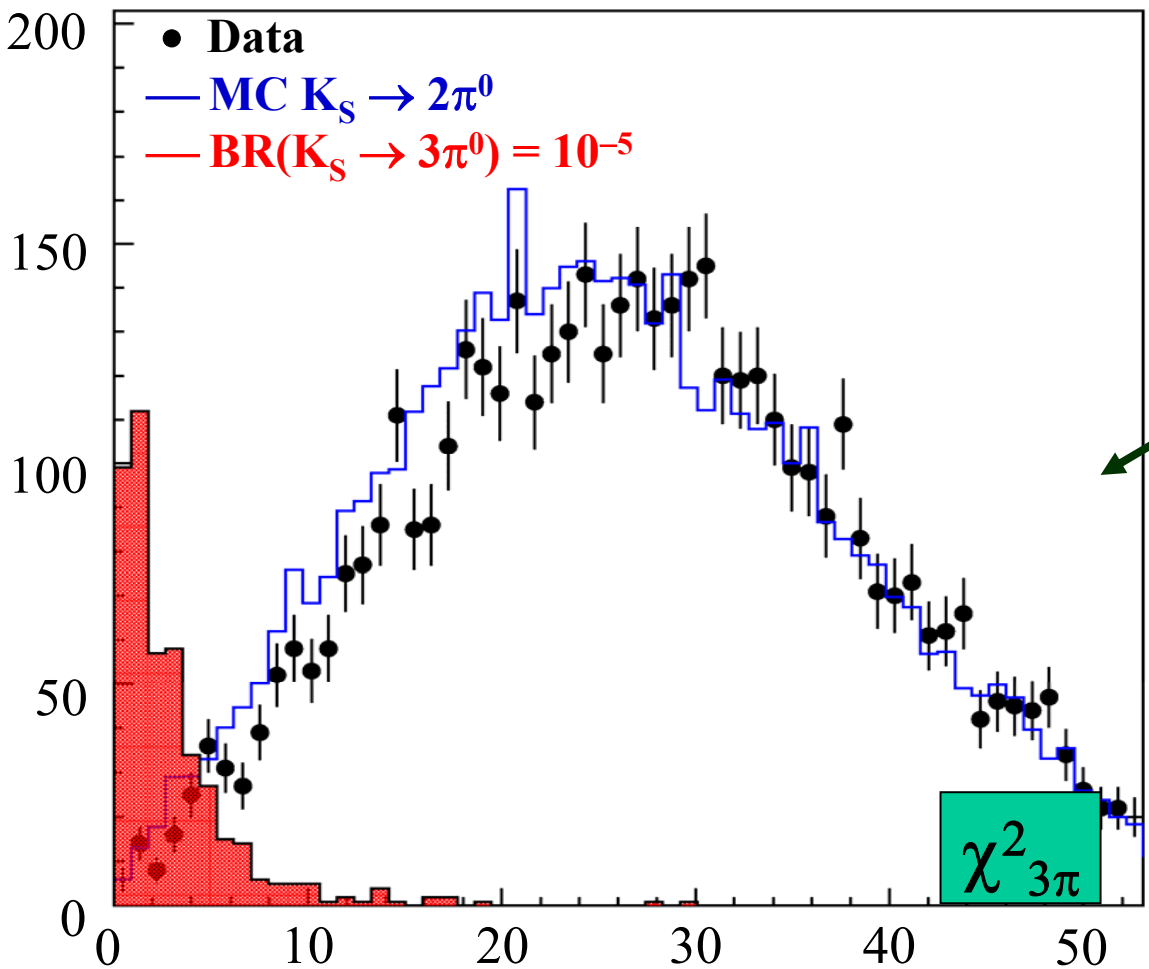
$K_S \rightarrow 3\pi^0$ search: $\chi_{2\pi}$, $\chi_{3\pi}$ sidebands

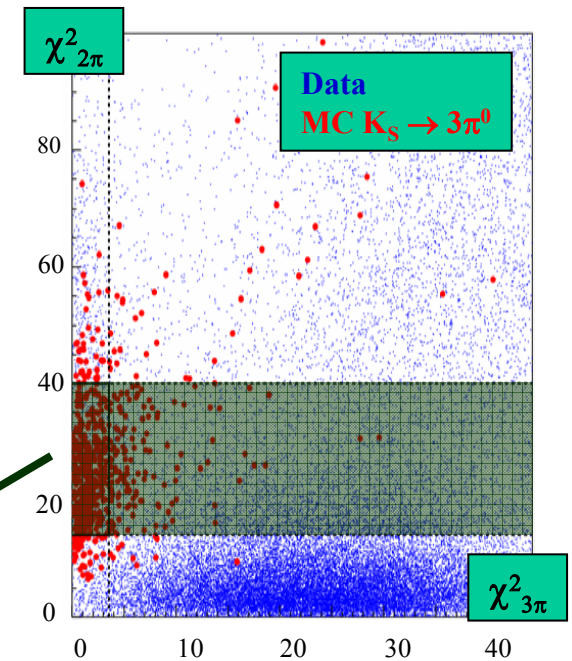




Absolute BKG normalization better than 10% in all control Boxes

$K_S \to 3\pi^0$: $\chi_{2\pi}, \chi_{3\pi}$ signal region





$K_s \to 3\pi^0$: preliminary result

UL optimized by varying in MC: Signal-Box definition, χ^2_{fit} and the residual K_s energy ($\Delta E = M_\Phi/2 - \Sigma E\gamma$). We find:

- **N(data) = 4 events** selected as signal, with efficiency $\varepsilon_{3\pi} = 22.6\%$
- **N(bkg) = 3 ±1.4 (stat.) ± 0.2 (sys.)** bkg events expected from MC.

Folding the proper BKG uncertainty we get: **$N_{3\pi} < 5.8$ @ 90% CL**

Normalize to $K_S \to 2\pi^0$ counts in same data set (**38×10^6**, $\varepsilon_{3\pi} = 92\%$)

Kloe preliminary

$$BR(K_S \to \pi^0\pi^0\pi^0) = \frac{N_{3\pi} / \varepsilon_{3\pi}}{N_{2\pi} / \varepsilon_{2\pi}} BR(K_S \to \pi^0\pi^0) < 2.1\ 10^{-7},$$

This translates to: $$|\eta_{000}| = \left| \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \right| < 2.4\ 10^{-2}$$

$K_S \to \pi e \nu$ decay: Physics issues

- ✓ Sensitivity to CPT violating effects through charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \nu)}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \nu)}$$

If CPT holds, $A_S = A_L$ $\to A_S \neq A_L$ signals CPT violation in mixing and/or decay with $\Delta S \neq \Delta Q$

- ✓ Sensitivity to CP violation in K^0-K^0 mixing:

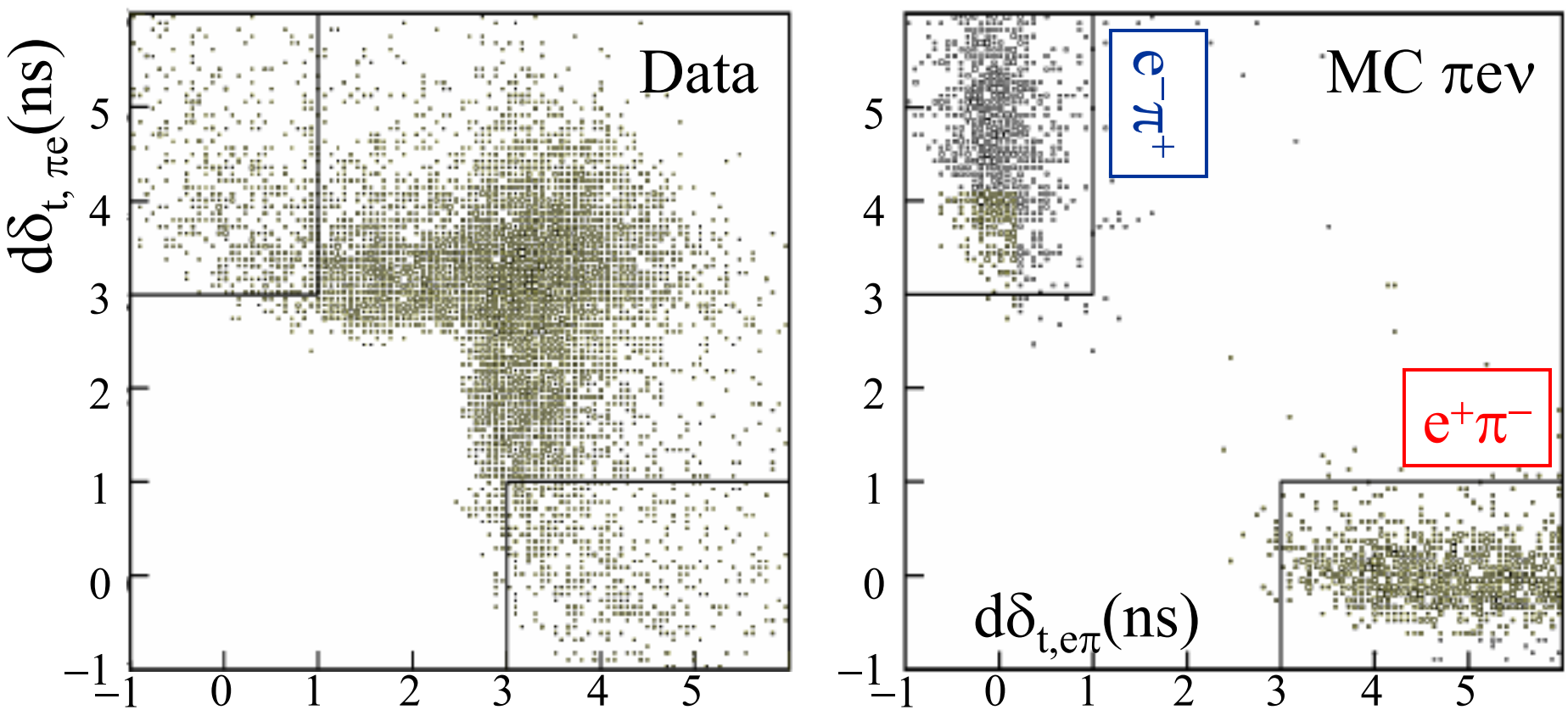
$A_S = 2R\varepsilon$ (CPT symmetry assumed)

A_S never measured before

- ✓ Can extract $|V_{us}|$ via measurement of $BR(K_S \to \pi e \nu)$

$K_S \to \pi e \nu$ decay: analysis path

- K_S tagged by K_L crash + 2 tracks from IP
- Main bkg from $K_S \to \pi\pi(\gamma)$, kinematic rejection: $M_{\pi\pi}$ < 490 MeV
- TOF Pid: compare π–e expected flight times, reject $\pi\pi$,$\pi\mu$ bkg



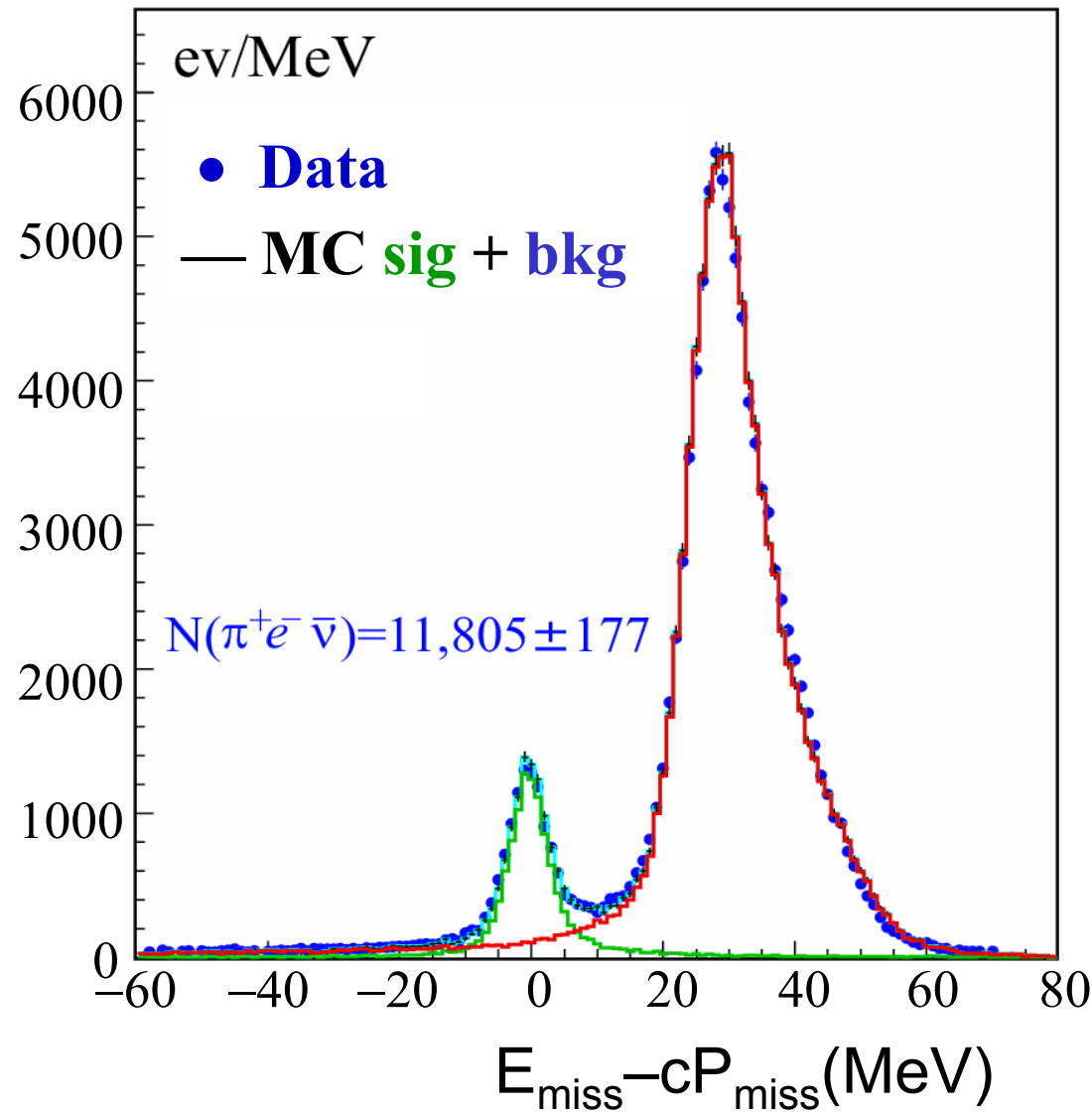
$K_S \to \pi e \nu$ decay: events counting

Kinematic closure: obtain K_S momentum $\mathbf{P_K}$ from K_L and test for presence of neutrino:

$$E_{miss} = \sqrt{M_K^2 + P_K^2} - E_\pi - E_e$$

$$P_{miss} = |\mathbf{P_K} - \mathbf{P_\pi} - \mathbf{P_e}|$$

Determine number of signal counts by fitting data to a linear combination of MC spectra for signal and BKG



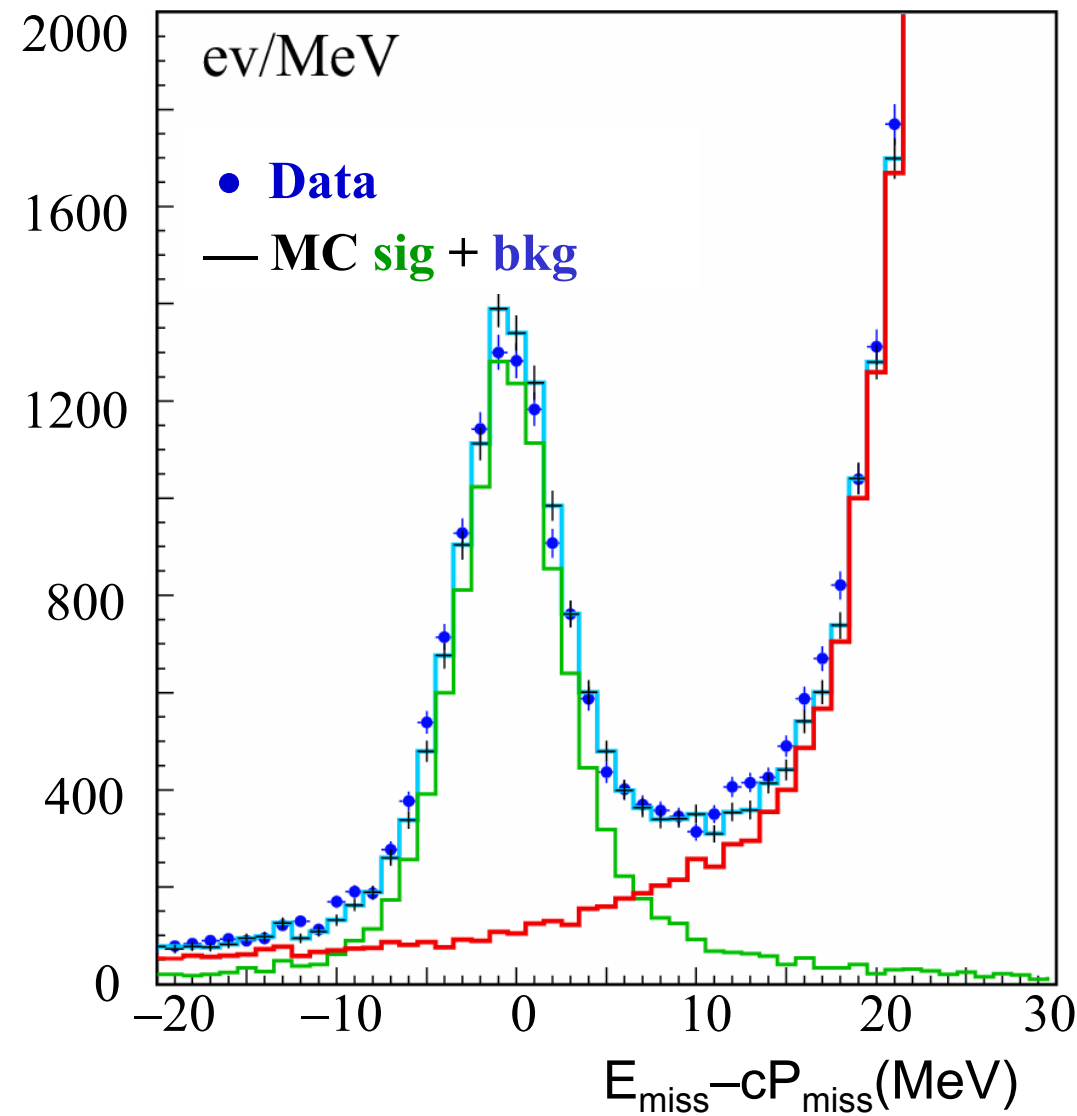
$K_S \to \pi e \nu$ decay: events counting ..

✓ Signal spectrum clearly sensitive to the presence of a photon in the final state

✓ Radiative effects included through an IR-finite treatment in MC (no energy cutoff)

Rate normalized to $K_S \to \pi\pi(\gamma)$ counts in the same data set

Use PDG03 for $BR(K_S \to \pi\pi(\gamma))$
KLOE dominated



$K_S \to \pi e \nu$ decay: BR and A_S

Correct for charge-dependent efficiencies, mainly due to TOF, extracted from data control sample ($K_L \to \pi e \nu$ with a vertex close to IP): $\varepsilon \approx 20\%$ given the K_L crash tag

$BR(K_S \to \pi^- e^+ \nu) = (3.54 \pm 0.05_{stat} \pm 0.05_{syst})\ 10^{-4}$

$BR(K_S \to \pi^+ e^- \nu) = (3.54 \pm 0.05_{stat} \pm 0.04_{syst})\ 10^{-4}$

KLOE preliminary
Evaluation of the systematics near completion

$$\mathbf{BR(K_S \to \pi e \nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst})\ 10^{-4}}$$

Published result: $(6.91 \pm 0.34_{stat} \pm 0.15_{syst})\ 10^{-4}$, KLOE '02

$\mathbf{A_S = (-2 \pm 9_{stat} \pm 6_{syst})\ 10^{-3}}$ (Never measured before)

$A_L = (3.322 \pm 0.058 \pm 0.047)\ 10^{-3}$ [KTeV 2002]

$A_L = (3.317 \pm 0.070 \pm 0.072)\ 10^{-3}$ [NA48 2003]

CKM unitarity test : V_{us}

Most precise test of CKM Unitarity comes, at present, from 1st row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$$

Can test if $\Delta = 0$ at few 10^{-3} (PDG02 $\Delta = 0.0042 \pm 0.0019$)

- super-allowed $0^+ \rightarrow 0^+$ Fermi transitions and n β – decays: $2|V_{ud}|\delta V_{ud} = 0.0015$
- semileptonic Kaon decays (PDG 2002 fit): $2|V_{us}|\delta V_{us} = 0.0011$

To extract $|V_{us}|$ from K^0_{e3} decays, have to include EM effects:

$$\Gamma(K^0 \rightarrow \pi e \nu(\gamma)) \propto |V_{us}\, f_+^{K0\pi-}(0)|^2 I(\lambda_t)\,(1 + \Delta I(\lambda_t,\alpha))\,(1 + \delta_{EM})$$

Relative uncertainty:

$$\frac{\delta|V_{us}|}{|V_{us}|} = 0.5\,\frac{\delta\Gamma}{\Gamma} \oplus 0.05\,\frac{\delta\lambda_t}{\lambda_t} \oplus \frac{\delta f_+^{K0\pi-}(0)}{f_+^{K0\pi-}(0)}$$

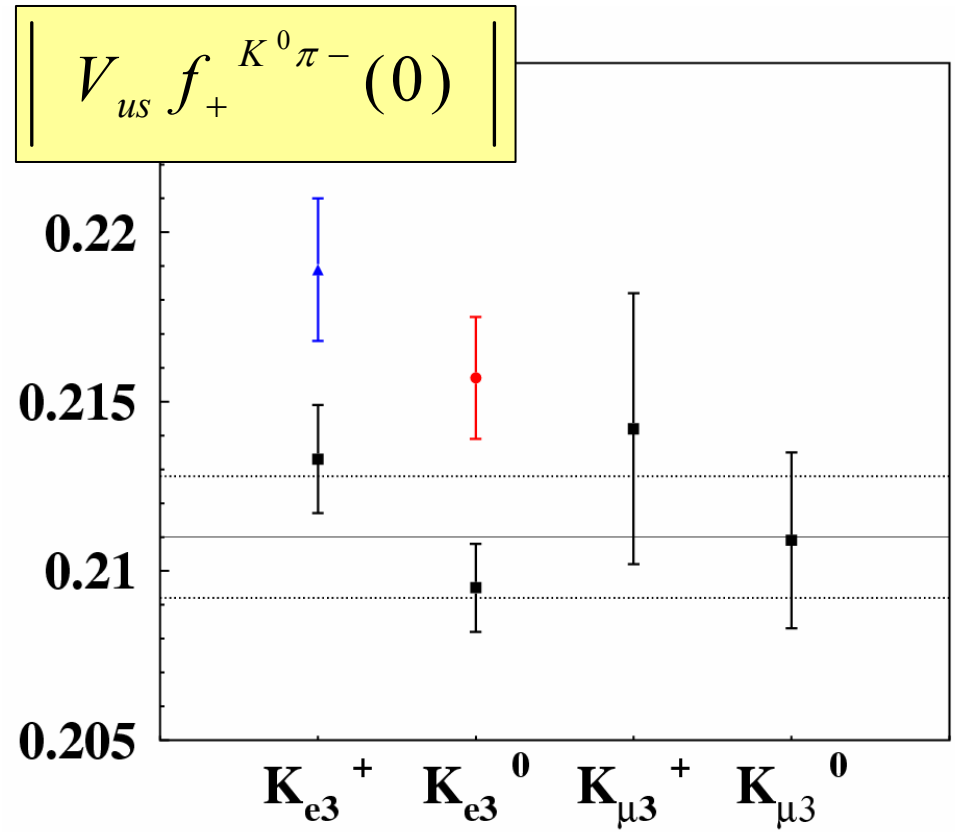
$$0.5\% \oplus 0.3\% \oplus 1\%$$

$K_s \to \pi e \nu$ decay: $V_{us} f_+^{K\pi}(0)$

Compare our K_s measurement of $| V_{us} f_+^{K0\pi-(0)} |$ with existing numbers on PDG 02:

- fit result for $\Gamma(K^+ \to \pi^0 e^+ \nu)$
- fit result for $\Gamma(K_L \to \pi^- e^+ \nu)$,
- fit result for $\Gamma(K^+ \to \pi^0 \mu^+ \nu)$
- fit result for $\Gamma(K_L \to \pi^- \mu^+ \nu)$,

and $\Gamma(K^+ \to \pi^0 e^+ \nu)$ from E865 experiment



CKM wg prescription

Our preliminary result shows better agreement with latest K^+ data, and a appreciable deviation from old measurements

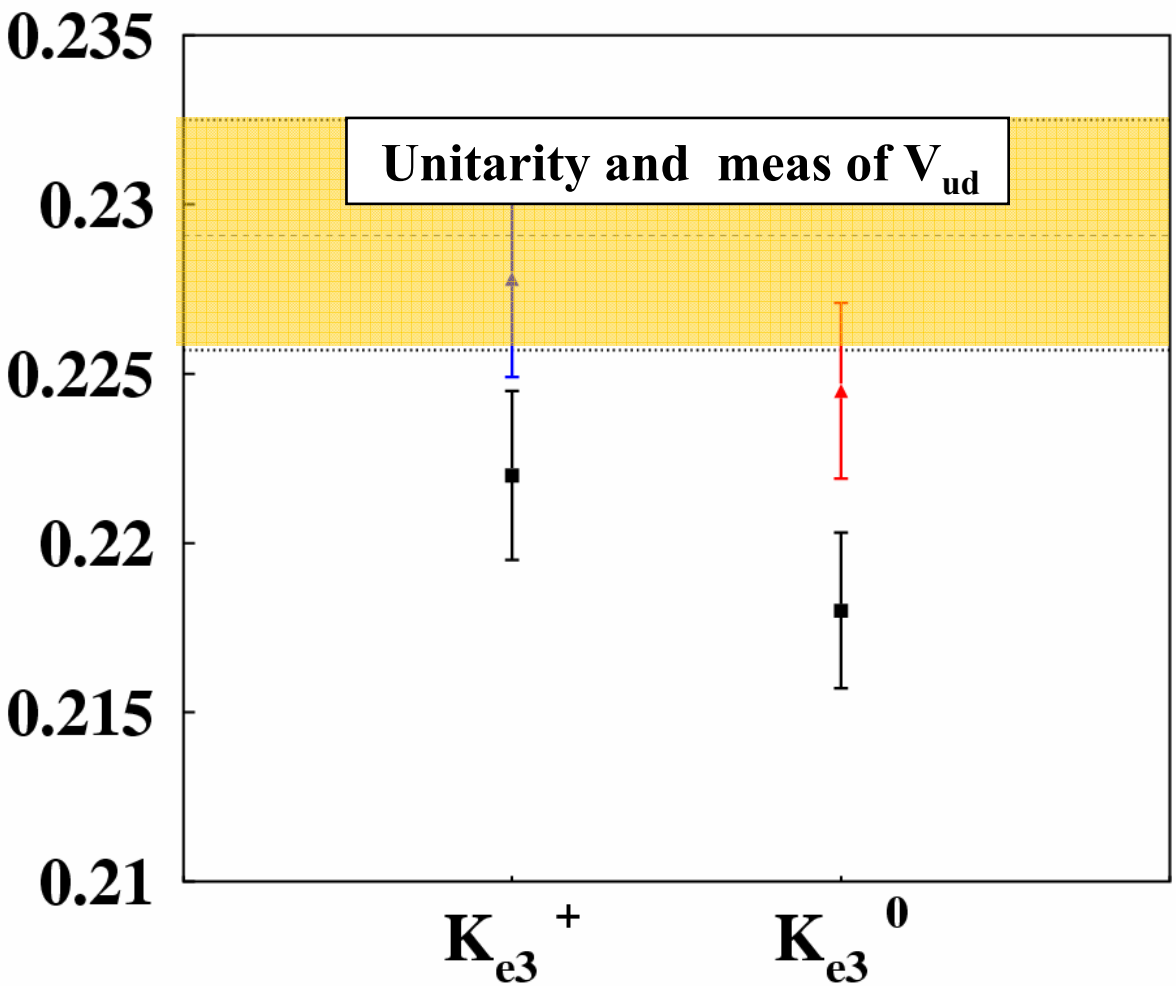
$K_s \to \pi e \nu$ decay: V_{us} determination

PDG02, CKMwg use

$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

From **Leutwyler, Roos**
Z.Phys. C 25 1984

- p^4 contr. in χPT



Knowledge of K_L BR's

Knowledge of 4 main K_L BR's at present dominated by 3 measurements:

- $\dfrac{\Gamma(K_L \to \pi^0\pi^0\pi^0)}{\Gamma(K_L \to \pi e \nu)}$ and $\dfrac{\Gamma(K_L \to \pi^0\pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)}$, with ~2% relative uncertainty [NA31]

- $R_{\mu/e} = \dfrac{\Gamma(K_L \to \pi \mu \nu)}{\Gamma(K_L \to \pi e \nu)} = 0.702 \pm 0.011$ [Argonne HBC 1980]

3-σ discrepancy (~**4%**) between measurement and expectation for $R_{\mu/e}$:

- $R_{\mu/e} = 0.671 \pm 0.002$, direct measurement for K^+, from KEK-E246 01
- $R_{\mu/e}$ calculable from the slopes λ_+ and λ_0 of vector and scalar f.factors:

$$\begin{cases} 0.670 \pm 0.002, & \text{if } \lambda_0 = 0.0183 \pm 0.0013, \text{ from ISTRA+ 2003} \\ 0.668 \pm 0.006, & \text{if } \lambda_0 = 0.017 \pm 0.004, \text{ from one-loop } \chi\text{Pt} \end{cases}$$

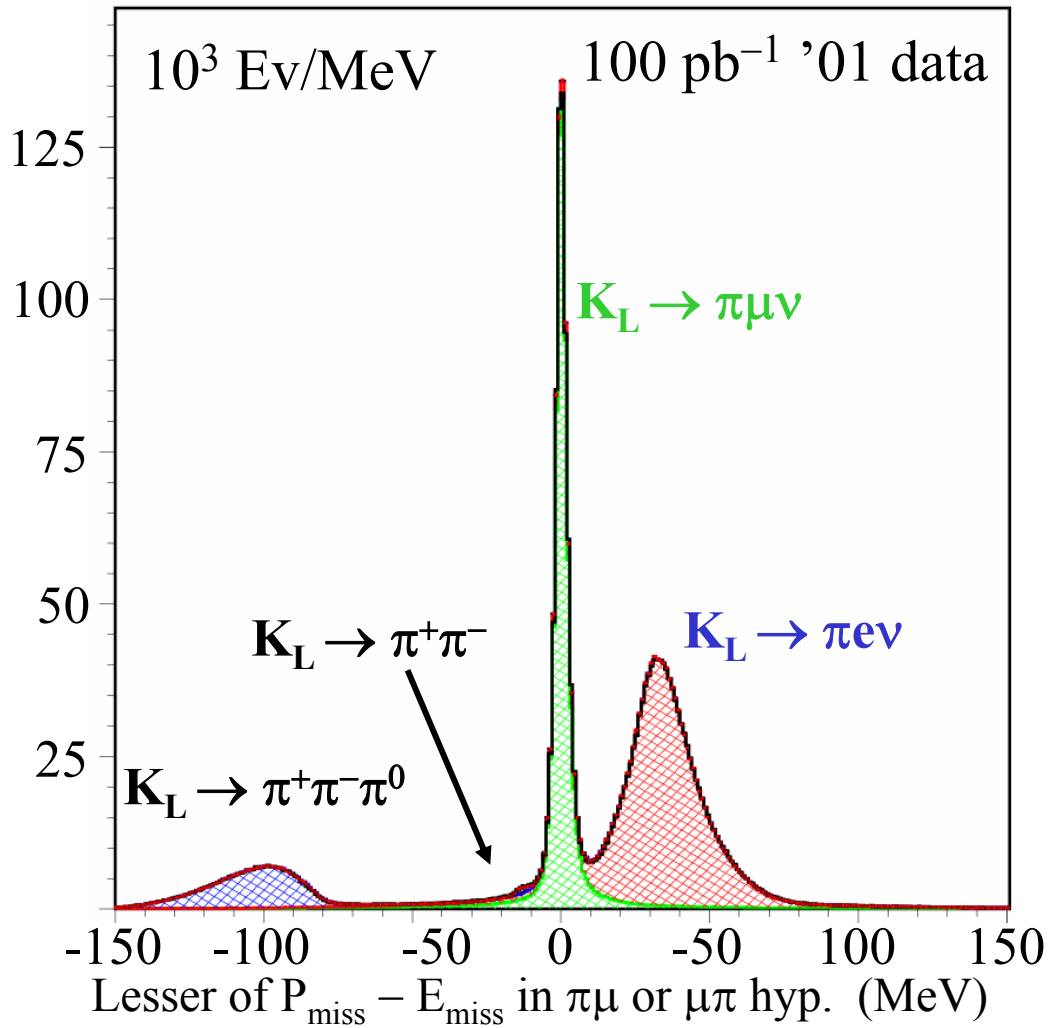
Status of K_L BR's measurement

Have to precisely measure **absolute** branching ratios, with rel. accuracy < 1%

- K_L beam tagged by identification of $K_S \rightarrow \pi^+\pi^-$
- K_L decay vertex in a given fiducial volume in DC
- Kinematic identification using reconstructed momenta

In progress:

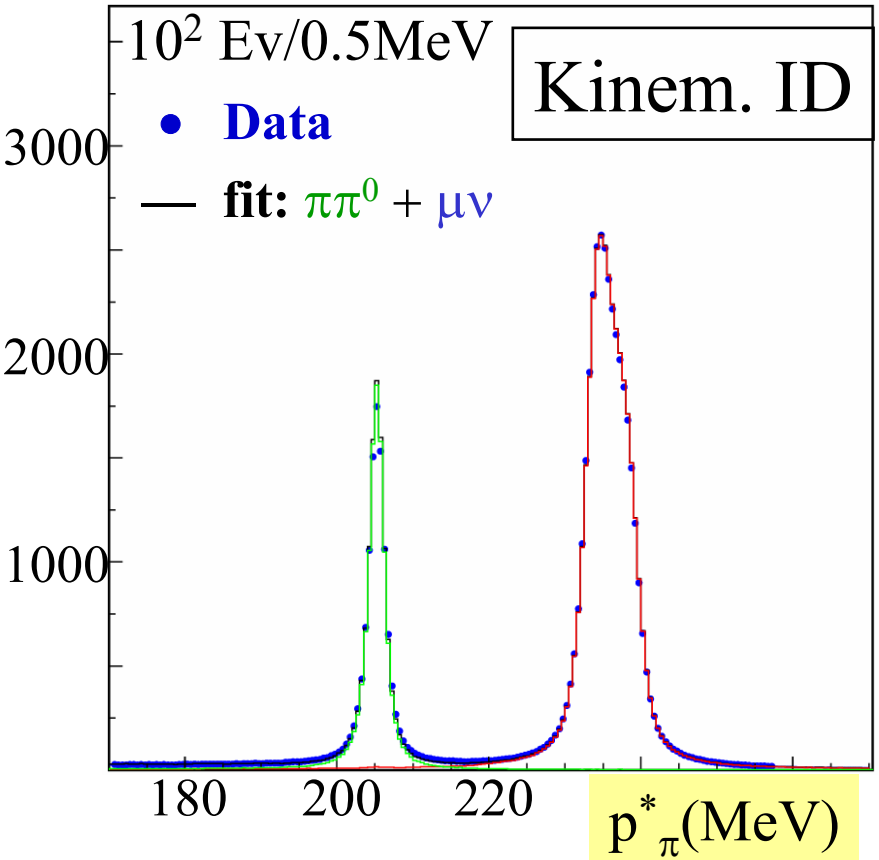
- new detailed MC with radiation and $\pi-\mu$ response
- Selection efficiency
- Tagging efficiency

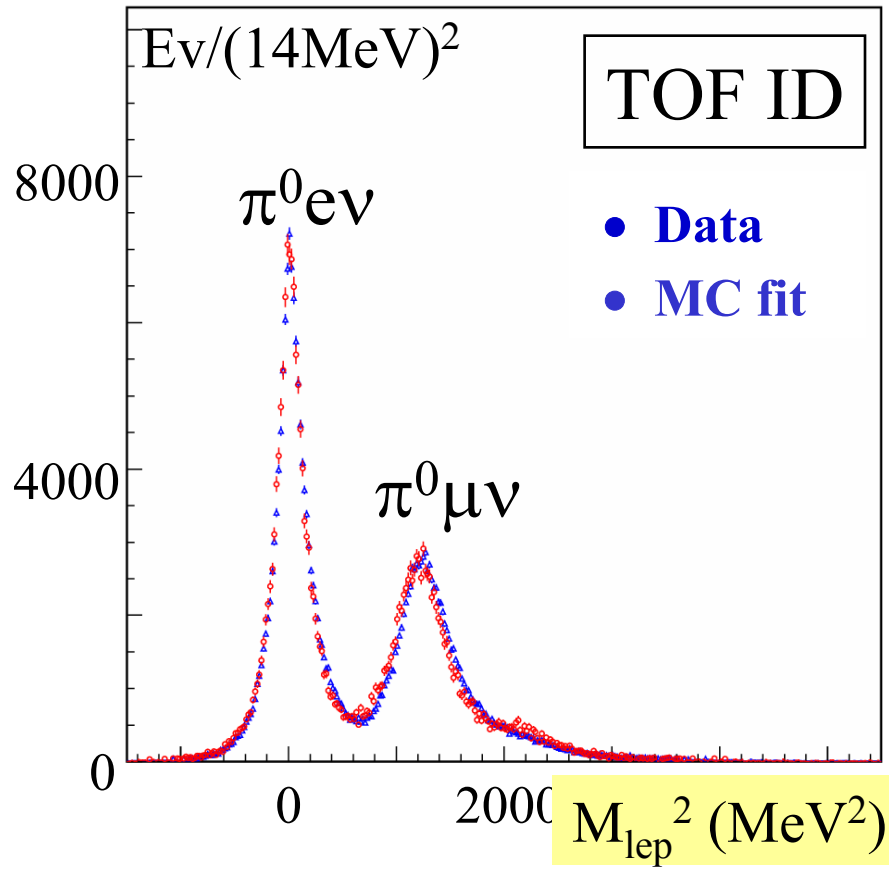


$K^{\pm}$ decays: analysis status

Dedicated reconstruction for $K^{\pm}$ tracks applied, all data re-processed

Measurement of absolute BR's: K^+ beam tagged from $K^- \rightarrow \pi^-\pi^0, \mu^-\nu$





Working on: efficiency estimates, bias from requiring tagging decay

a_μ- SM prediction vs experiment

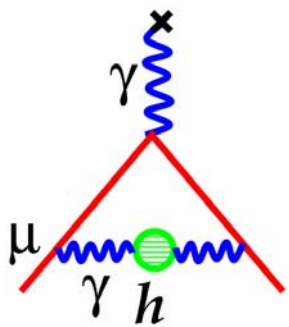
Updated measurement from E821@BNL, averaging results for μ^+ and μ^-:

$$a_\mu = (11\ 659\ 208 \pm 6)\ 10^{-10}$$

Contributions to the SM prediction: (10^{-10} units)

$$\begin{cases} a_\mu(\text{QED}), & 11\ 658\ 470.4 \pm 0.3 \\ a_\mu(\text{weak}), & 15.4 \pm 0.2 \\ a_\mu(\text{hadronic}), & \sim 700 \end{cases}$$

Uncertainty on lowest-order hadronic vacuum polarization dominates



Hadronic correction to the γ propagator not calculable by p-QCD for low M_{γ^*}

a_μ- SM prediction vs experiment

Dispersion integral relates a_μ^{had}(vac-pol) to $\sigma(e^+e^- \to$ hadrons)

$$a_\mu^{\text{had,lo}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to\text{hadr}}(s)K(s)\mathrm{d}s$$

Process $e^+e^- \to \pi^+\pi^-$ @ $\sqrt{s}$ < 1 GeV contributes 66% to a_μ^{had}

So far, estimates of a_μ^{had} from:

- measuring $\sigma(e^+e^- \to \pi^+\pi^-)$ vs $\sqrt{s}$ at an e^+e^- collider, varying the beam energy (CMD2, 0.9% rel. uncertainty)
- using the spectral function from $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ (LEP, CESR data)

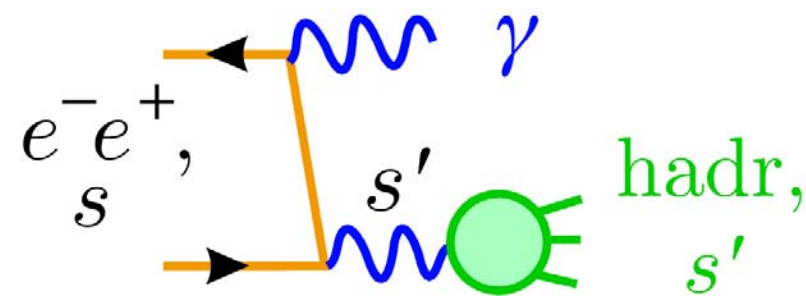
However, $a_\mu(e^+e^-) - a_\mu(\tau) \sim 20\ 10^{-10}$

$\sigma(e^+e^- \to \pi^+\pi^-)$ from $\pi^+\pi^-\gamma$ events

Measure $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ at fixed $\sqrt{s}$

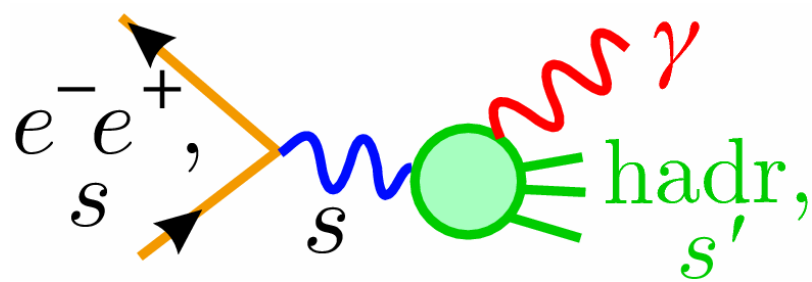
Exploit ISR to extract $\sigma(e^+e^- \to \pi^+\pi^-)$ for $\sqrt{s'}$ from $2m_\pi \to \sqrt{s}$

($s' = s - 2\,E_\gamma\,\sqrt{s}$)

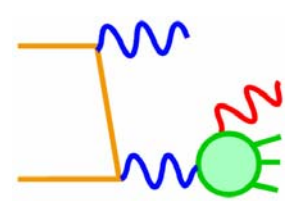


Have to watch out for hard FSR:

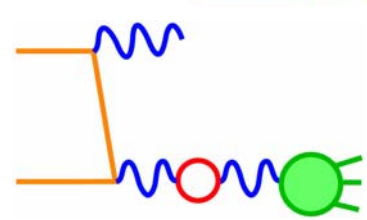
- Rate ~ same order as ISR signal
- FSR causes events with $M_{\gamma^*} = \sqrt{s}$ to be assigned to lower $\sqrt{s'}$ values



Have to properly include radiative corrections,



Must remove vacuum polarization,



Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$

- Two high-θ tracks from a vertex close to IP

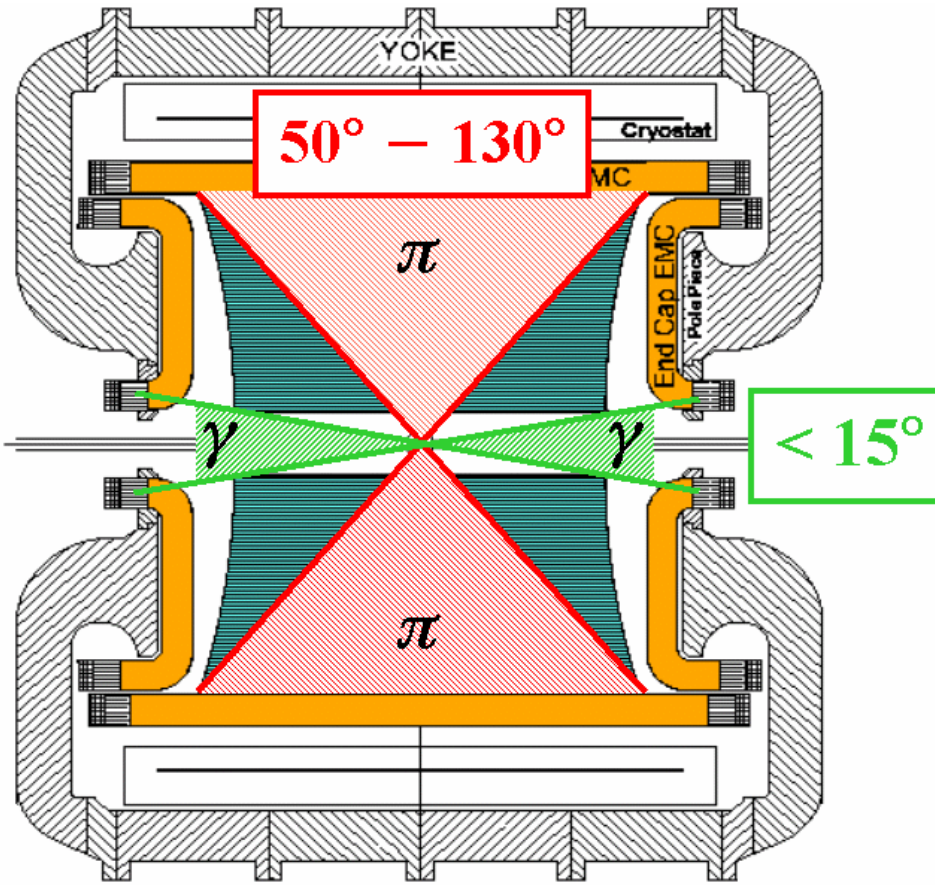
- Compute photon momentum, **without explicit γ detection:**

$p_\gamma = p_{e+} + p_{e-} - p_{\pi+} - p_{\pi-}$

- Select signal with a **small-θ photon**, to enhance ISR:

$d\sigma_{ISR}/d\Omega \sim 1/\sin^2\theta$

  - relative contribution of hard FSR below the % level over entire $M_{\pi\pi}$ spectrum
  - no acceptance for $M_{\pi\pi} < 600$ MeV
  - Reduce background



Residual background from $\pi^+\pi^-\pi^0$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$

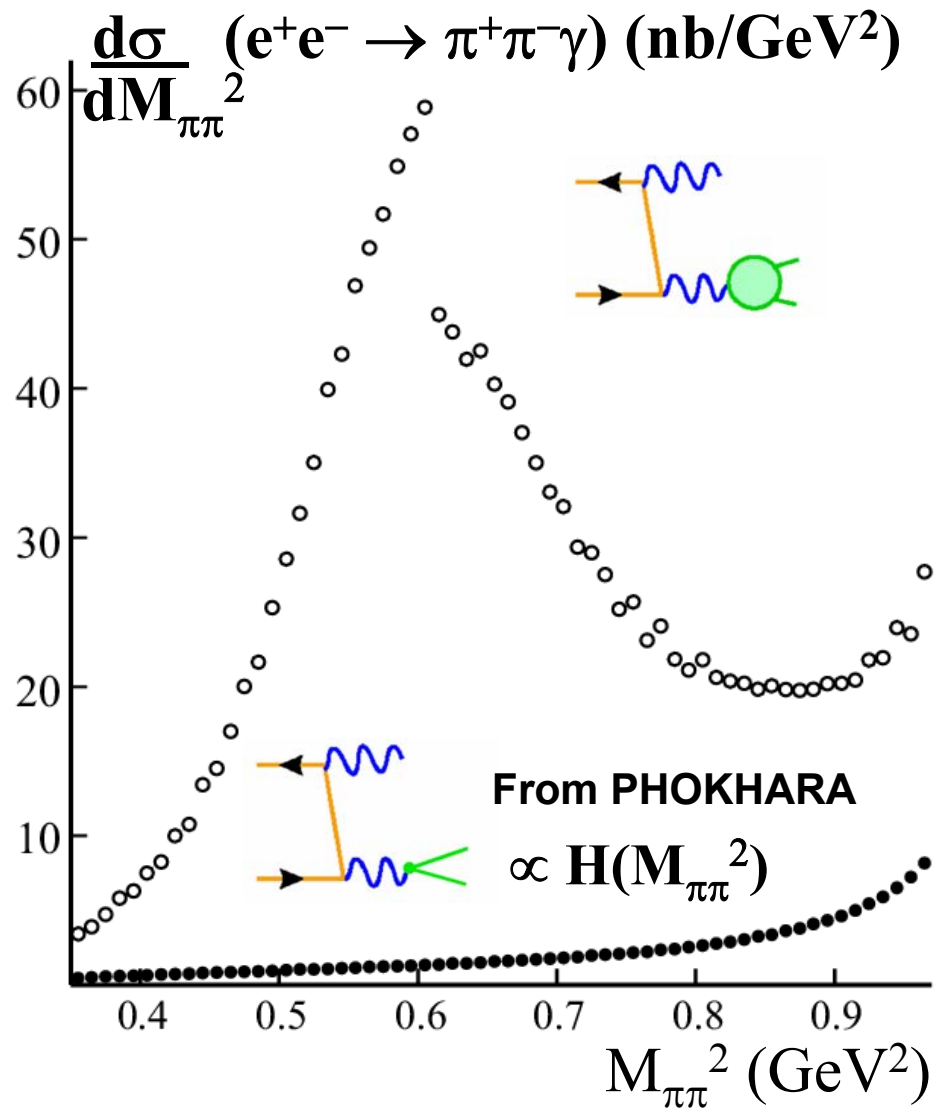
Preliminary result: $\sigma(\pi^+\pi^-\gamma)$

- Luminosity from $e^+e^-(\gamma)$ counts, $55° < \theta_e < 125°$, σ calculated at 0.5%, experimental accuracy 0.3%
- Experimental $M_{\pi\pi}^2$ resolution unfolded in all spectra shown

Radiator function $\mathbf{H(M_{\pi\pi}^2)}$, defined as:

$$\frac{d\sigma(\pi\pi\gamma, M_{\pi\pi}^2)}{dM_{\pi\pi}^2} = \mathbf{H(M_{\pi\pi}^2)}\ \sigma(\pi\pi, M_{\pi\pi}^2),$$

with inclusion of radiative effects, from QED MC calculation (PHOKHARA, Karlsuhe Theory Group, Kühn et al.)



Preliminary result : a_μ

Calculating the dispersion integral,

$$\sigma(e^+e^- \to \pi^+\pi^-) = \frac{\pi\,\alpha^2}{3M_{\pi\pi}^2}\,\beta^3\,|F_\pi(M_{\pi\pi})|^2$$

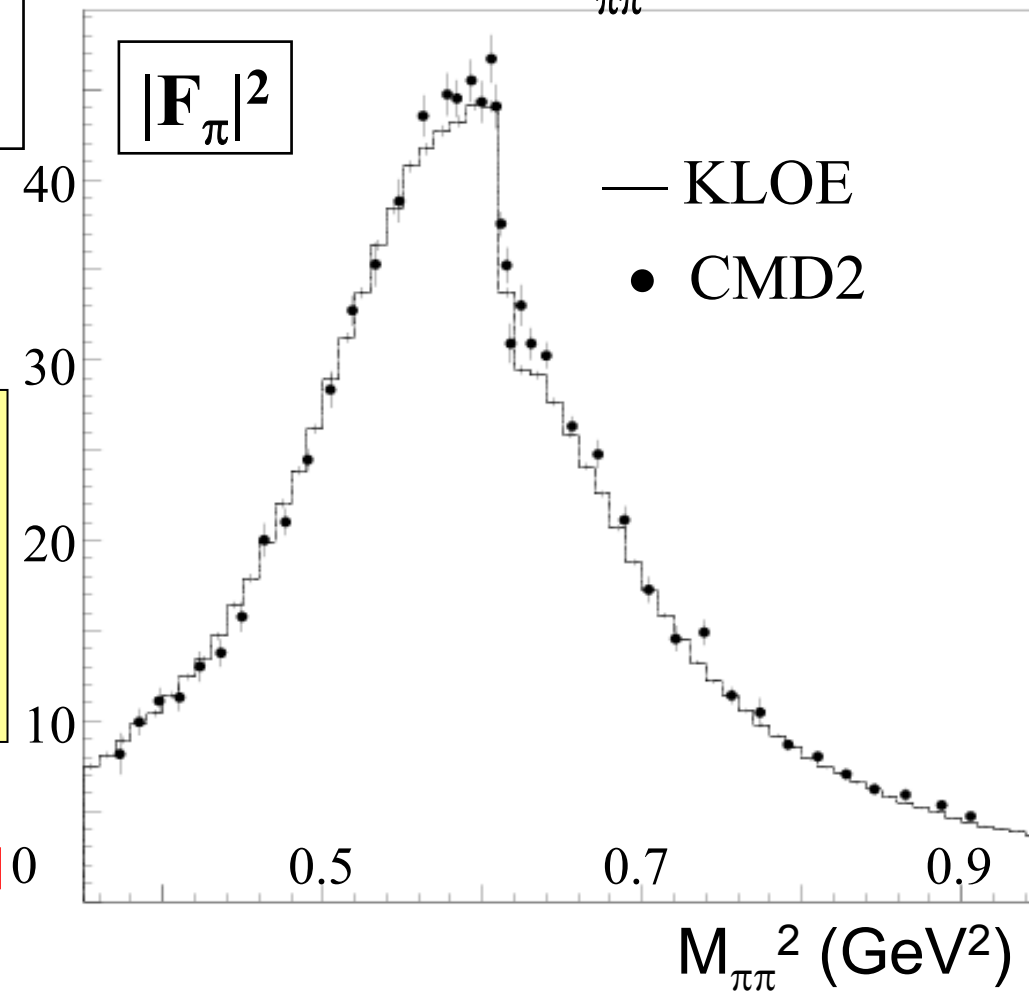
$a_\mu^{had\text{-}\pi\pi}$ $(0.35<M_{\pi\pi}^2<0.95\ GeV^2)$ =
$(389.2 \pm 0.8 \pm 4.7_{sys} \pm 3.9_{th})10^{-10}$

Comparison with CMD2:

$a_\mu^{had\text{-}\pi\pi}(0.37< M_{\pi\pi}^2< 0.93\ GeV^2)$:

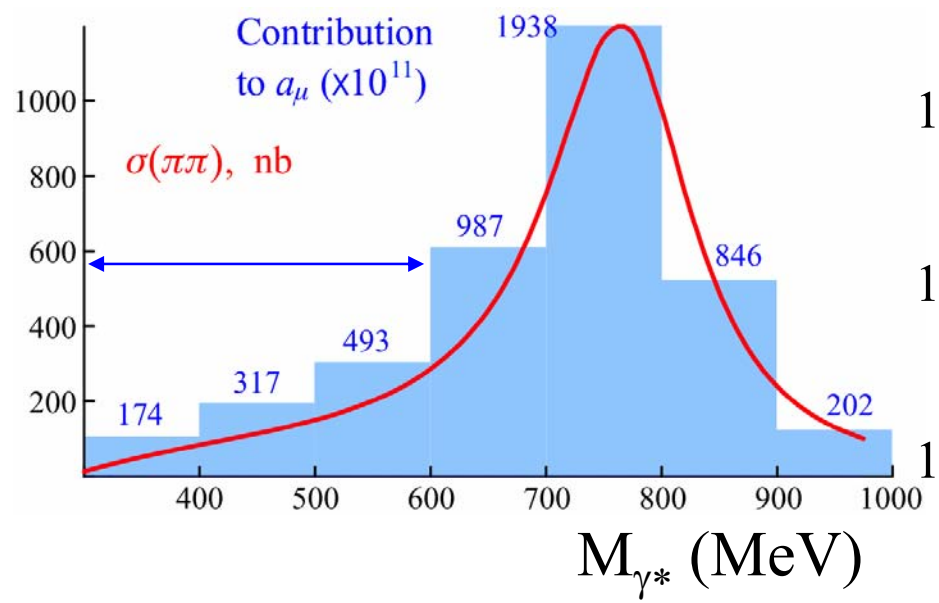
KLOE
$(376.5 \pm 0.8_{stat} \pm 5.9_{sys+th})\ 10^{-10}$
CMD2
$(378.6 \pm 2.7_{stat} \pm 2.3_{sys+th})\ 10^{-10}$

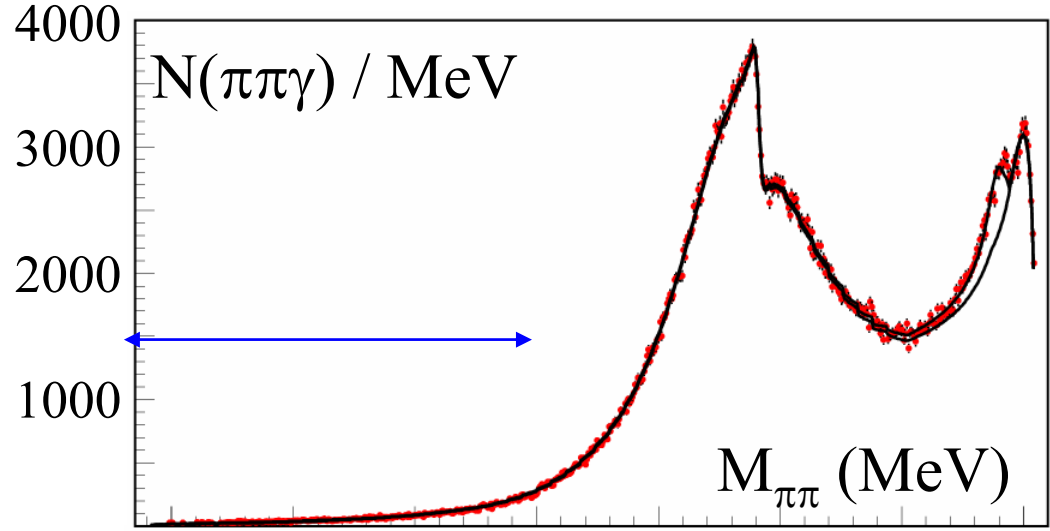
- **Measurements agree**
- **$e^+e^- - \tau$ discrepancy confirmed**

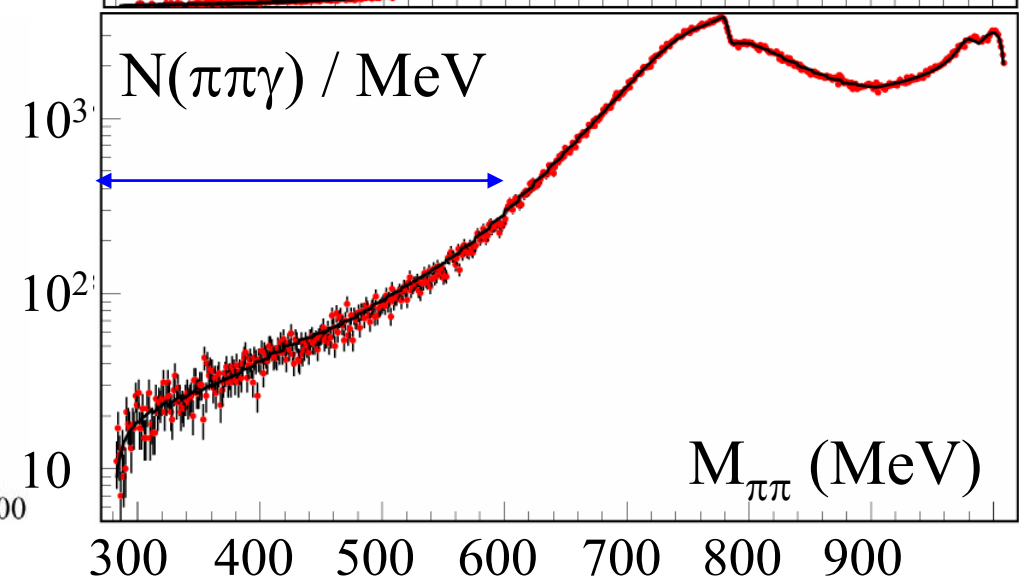


a_μ: prospects $\pi^+\pi^-\gamma$ at large angles

- ✓ Measure $\sigma(\pi\pi)$ in the region close to threshold, $M_{\pi\pi}$ < 600 MeV, responsible for ~20% of a_μ^{had}
- ✓ This region currently excluded by angular selection

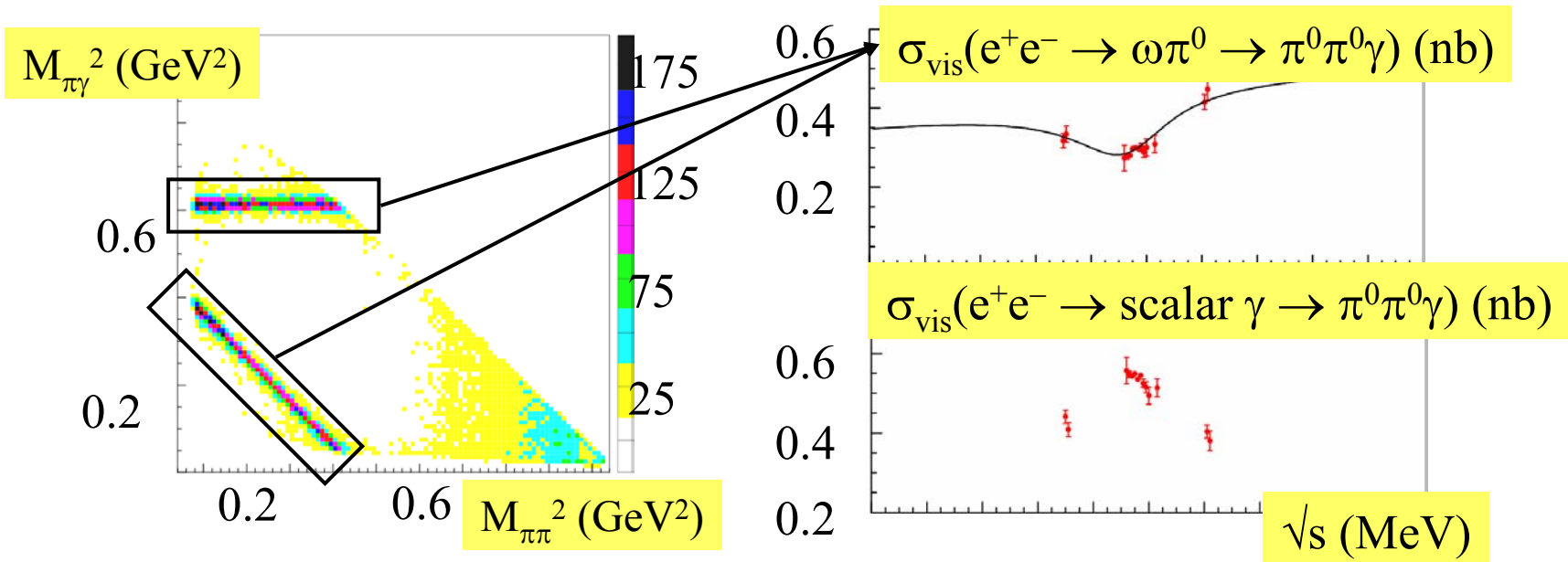






Other on-going analysis (I)

- $\pi^+\pi^-\gamma$ at large angle. Study interference pattern FSR and $\Phi \to f_0\gamma$ (first hints of an $f_0(980)$ signal)
- $\pi^0\pi^0\gamma$ high stat. sample for $\Phi \to f_0\gamma \to \pi^0\pi^0\gamma$
  - separate not resonant vs resonant contribution
  - fit Dalitz plot to study interference between $\Phi \to S\gamma$ and VDM production



Other on-going analysis (II)

- ~ 20 million η's produced

Search for forbidden η decays:

C violating: **$BR(\eta \to \gamma\gamma\gamma) < 1.7\ 10^{-5}$**, 90% CL, hep-ex/0402011

CP, P violating: $BR(\eta \to \pi^+\pi^-) < 9\ 10^{-6}$, 90% CL, in prog

preliminary

Precision studies of meson dynamics:

Dalitz plot analyses of $\eta \to 3\pi$, $\eta \to \pi^0\gamma\gamma$, and $\eta \to \pi^+\pi^-\gamma$

- **Pseudoscalar mixing angle measurements, $\phi \to \eta'\gamma$**

Analysis of $\pi^+\pi^-3\pi^0\gamma$ final states from decay chain $\eta' \to \eta\pi\pi$, $\eta \to 3\pi$

$$\mathbf{BR(\phi \to \eta'\gamma) = (6.04 \pm 0.10_{stat} \pm 0.36_{syst})10^{-5}}$$

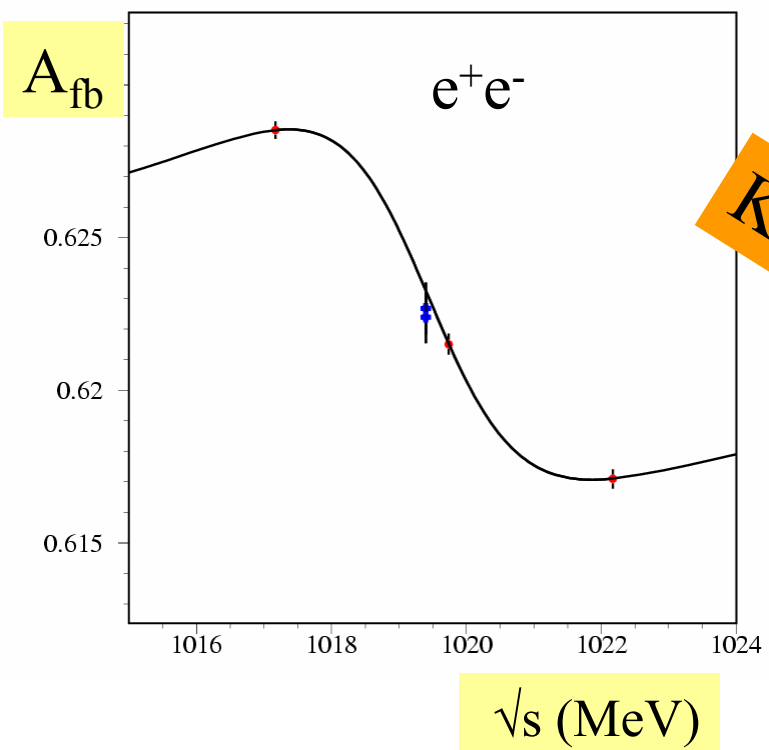
Kloe preliminary

- confirm previous KLOE result
- can extract mixing angle, uncertainty better than 1-degree

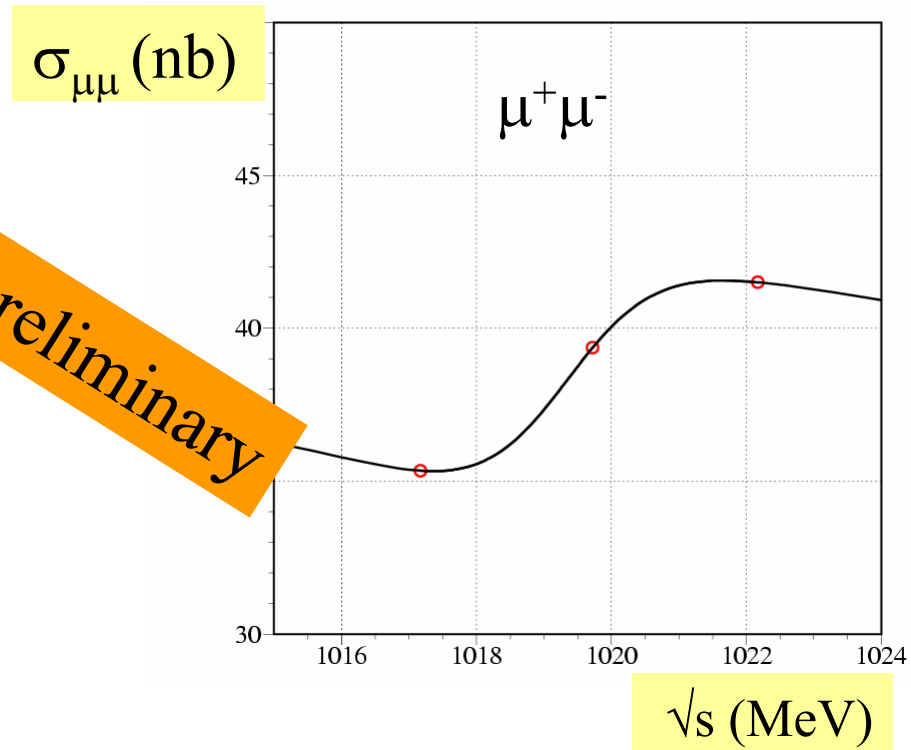
Other on-going analysis (III)

❑ Φ-meson properties:

- Combined line-shape fit in principal decay channels
- Measurement of $\Gamma(\phi \rightarrow e^+e^-)$ from FB asymmetry vs $\sqrt{s}$
- Measurement of $\Gamma(\phi \rightarrow \mu^+\mu^-)$ from $\sigma_{\mu\mu}$ vs $\sqrt{s}$



Kloe preliminary



Summary

KAON physics:

- Sensitivity to K_s BR's at the 10^{-7} level (preliminary UL for $K_S \to 3\pi^0$)
- Measurement of K_{e3} mode at the % level, 10^{-2} accuracy on A_S

Measurement of BR's for semileptonic K_L and K^+ decays in progress

- Huge statistics, uncertainty will be limited by systematics
- Will clarify situation concerning V_{us}

Non Kaon physics:

- Analysis of σ(had) at small angles almost completed (draft in preparation)

Measurement of **a_μ^{had} with 6 10^{-10}** total error, **$\sigma(e^+e^- \to \pi^+\pi^-)$ at 1.6%**

Large angles meas. in progress: a_μ^{had} contribution for $M_{\gamma*} < 600$ MeV

- A lot of measurement in progress on light scalar, pseudoscalar mesons and on determination of lineshape and Γ_{ll}