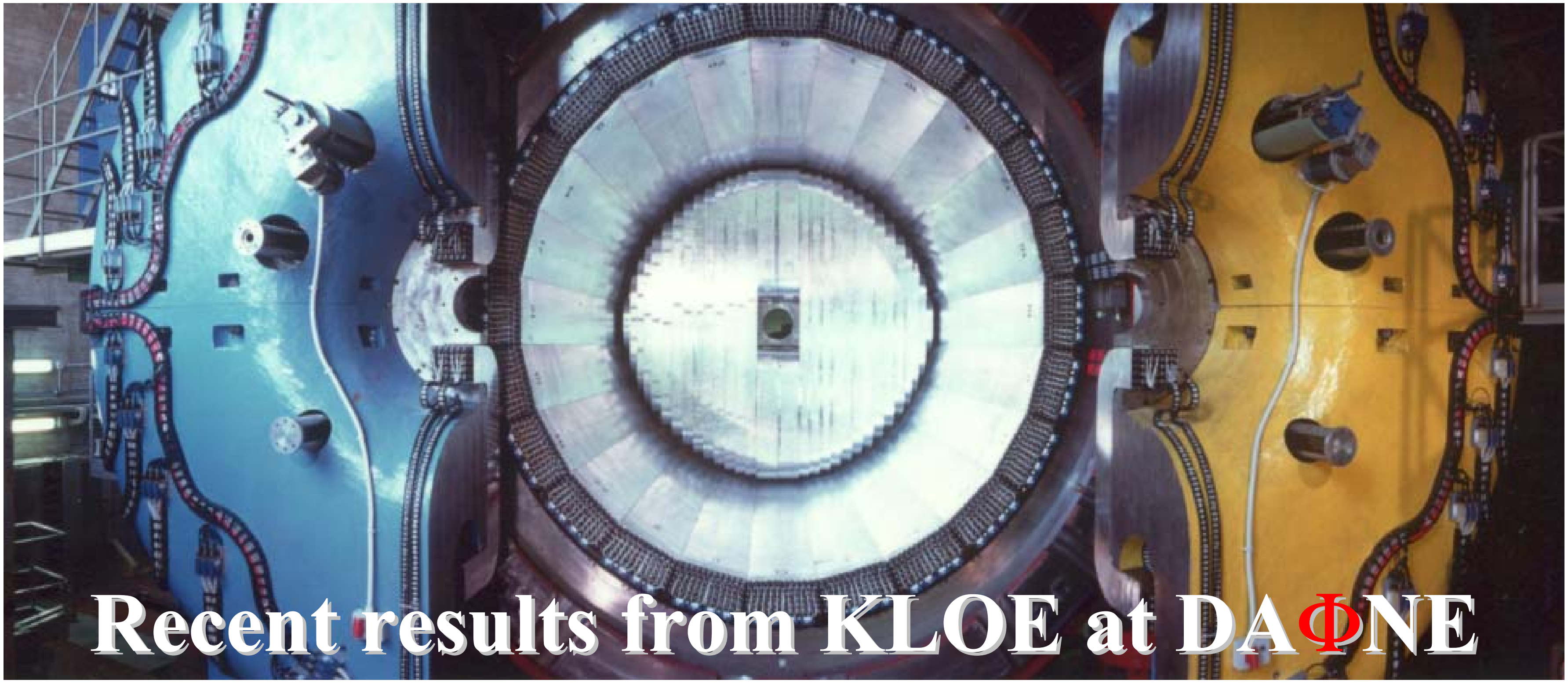


T. Spadaro, INFN/Frascati,
for the KLOE collaboration

Les rencontres de physique de la Vallée d'Aoste
La Thuile, 29th February – 6th March, 2004

KLOE physics

KLOE physics focus: tests of discrete symmetries: **C, CP, CPT**
Clean and absolute SM predictions

Kaon properties

$K_S K_L$ (K^+K^-) produced in pure $J^{PC} = 1^{--}$ state:

$$K_S, K^+ \longleftarrow \phi \longrightarrow K_L, K^-$$

Observation of $K_{S,L}$ signals presence of $K_{L,S}$

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

Allows precision measurement of absolute BR's

Allows interference measurements of $K_S K_L$ system

λ_S **= 6 mm:** K_S decays near interaction point

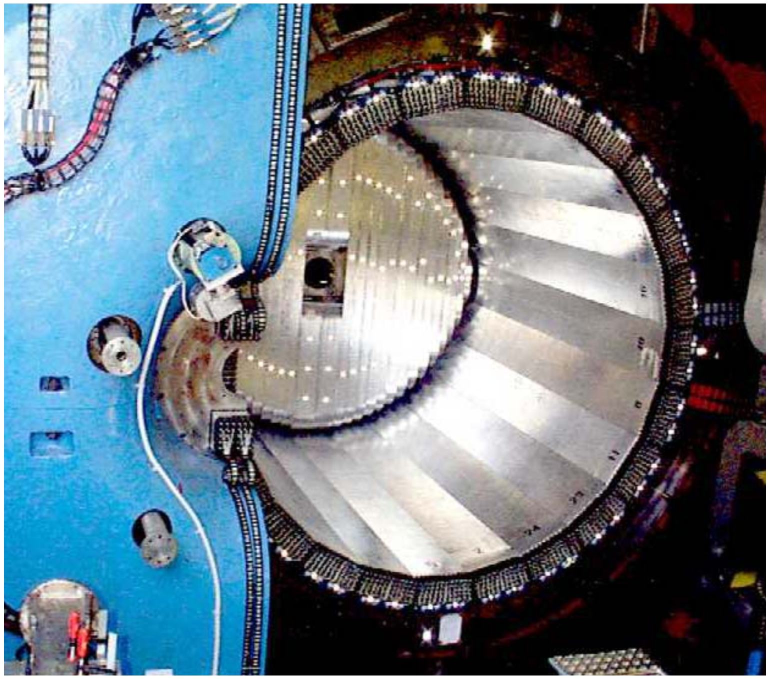
λ_L **= 3.4 m:** Appreciable acceptance for K_L ($\sim 0.5\lambda_L$)

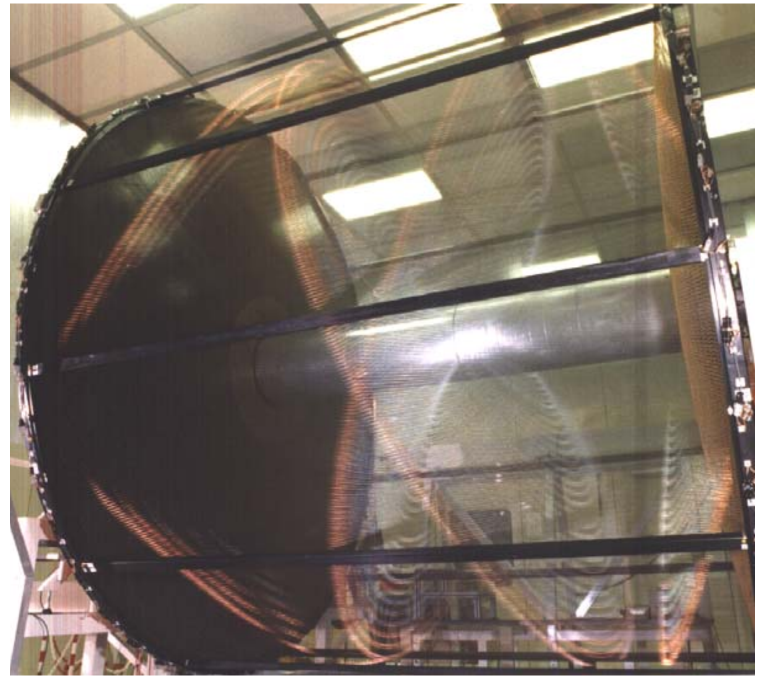
$\sigma(e^+e^- \to$ hadrons)

News on $\pi\pi\gamma$ analyses

News on analyses of η decays and ϕ meson properties

The KLOE experiment





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

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

(relative time between clusters) PID capabilities

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

4m–$\varnothing$, 3.75m–length, all-stereo

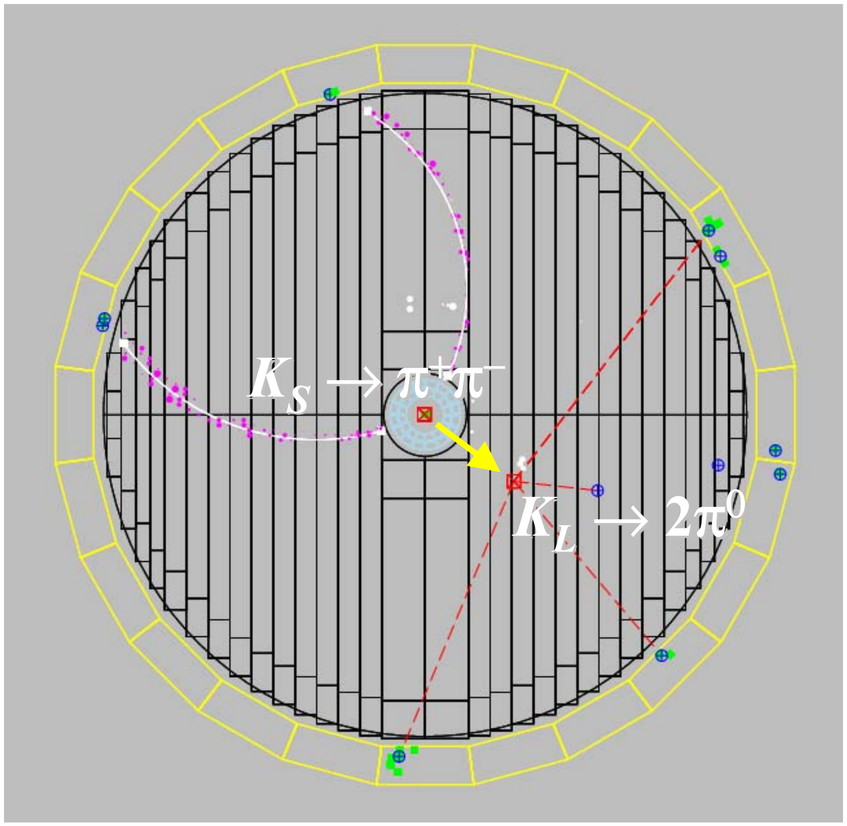
$\sigma_p/p = 0.4\ \%$ (tracks with $\theta > 45°$)

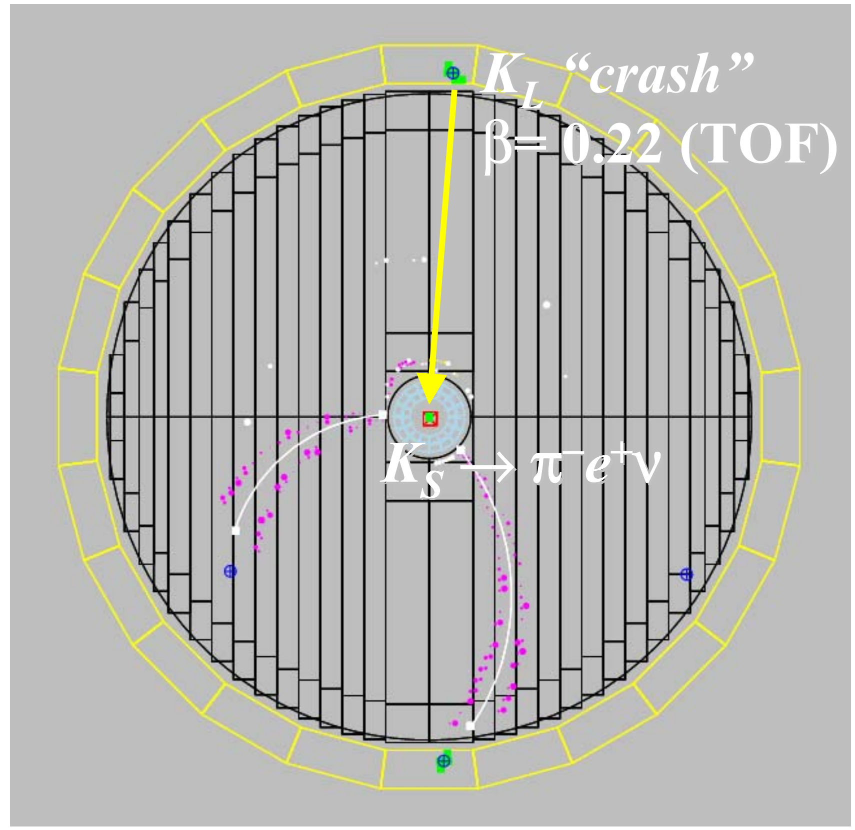
$\sigma_x^{hit} = 150\ \mu$m (xy), 2 mm (z)

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

Results presented in this talk from 2001-2002 data, $\int\mathcal{L} = 450$ pb^{-1}

Tagging of K_S and K_L "beams"





K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP
Efficiency ~ 70% (mainly geometrical)
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 1 MeV

K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 1 MeV

$K_S \rightarrow \pi^0\pi^0\pi^0$ – test of CP and CPT

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

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

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

Uncertainty on $K_S \rightarrow 3\pi^0$ amplitude limits precision of CPT test:

from unitarity

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

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

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

$$\frac{\delta(M_{K0} - M_{\overline{K0}})}{M_K} \sim 2\ 10^{-18} \rightarrow \frac{\delta(M_{K0} - M_{\overline{K0}})}{M_K} \sim 8\ 10^{-19} \qquad (M_K/M_{Planck} = 4\ 10^{-20})$$

Search for $K_S \rightarrow \pi^0 \pi^0 \pi^0$

Signal selection

K_S's tagged by means of K_{crash} identification

6 photons (neutral clusters, TOF consistent with $\beta = 1$)

No charged tracks from IP

Kinematic fit:

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

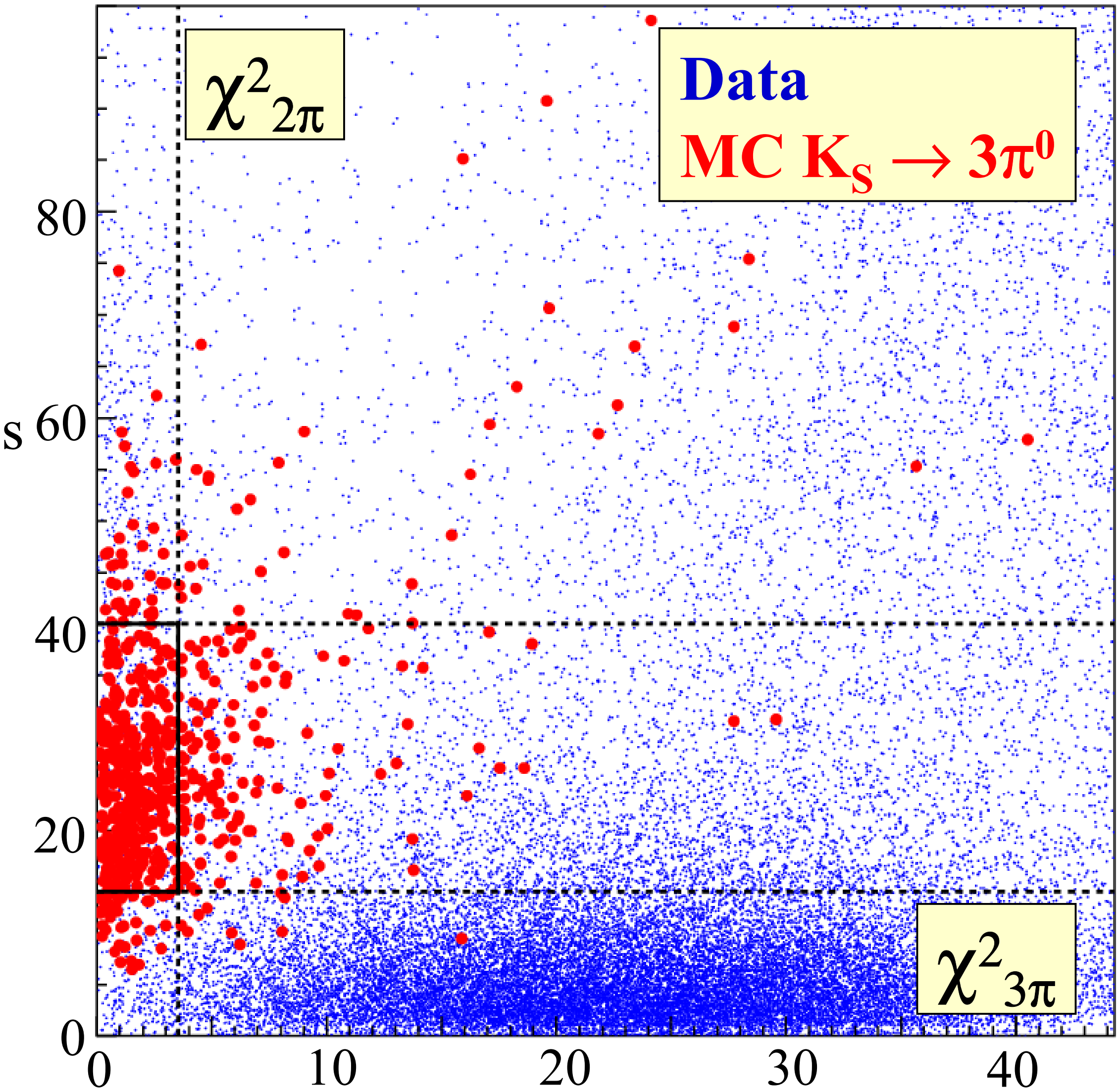
Rejection power of χ^2_{fit} not sufficient to eliminate main background due to $K_S \rightarrow \pi^0\pi^0$ + 2 fake γ's

Search for $K_S \to \pi^0\pi^0\pi^0$ – $2\pi^0$ vs $3\pi^0$

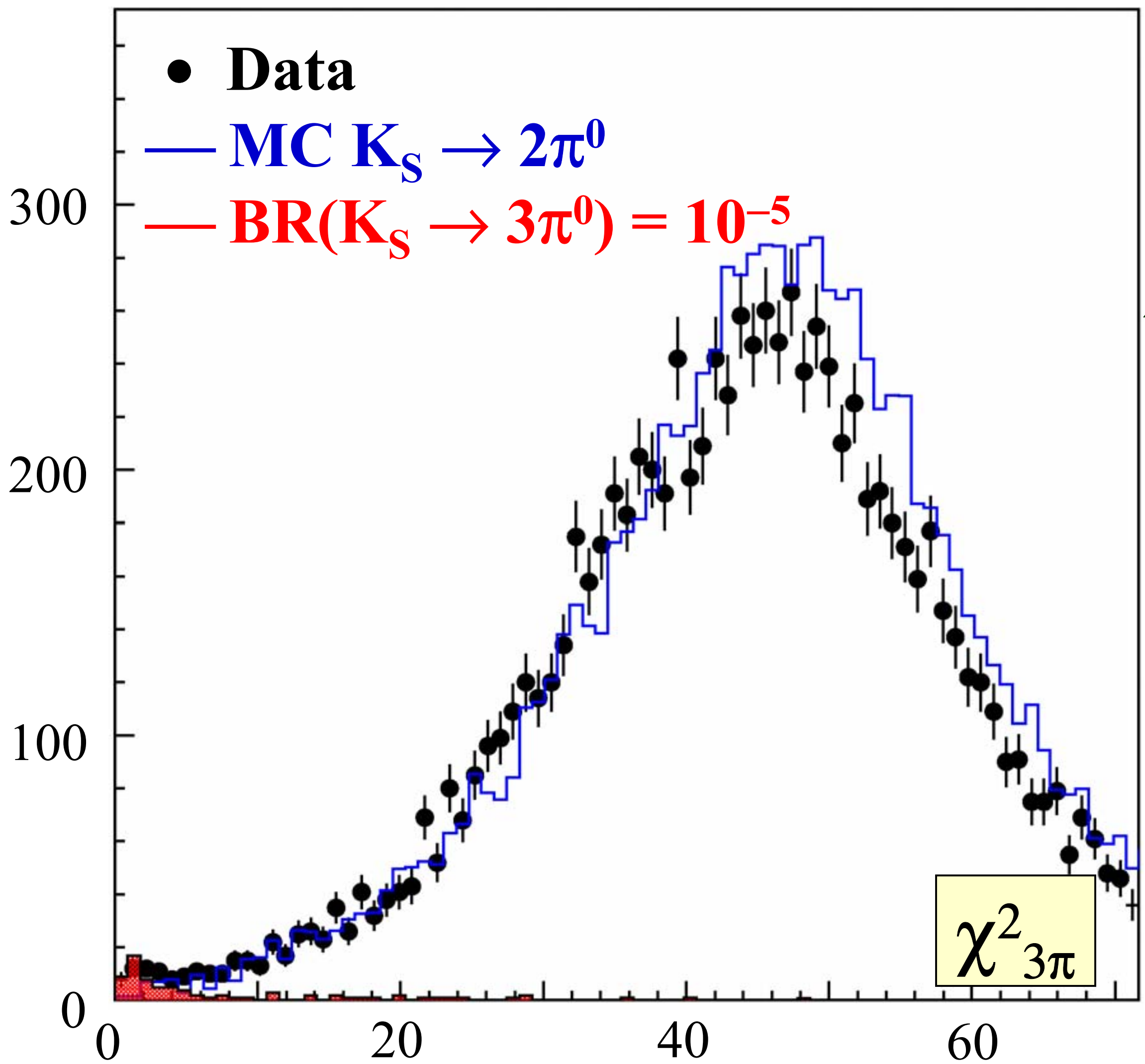
Main background from $K_S \to \pi^0\pi^0$ + 2 fake γ's:
Compare 3π vs 2π hypotheses:

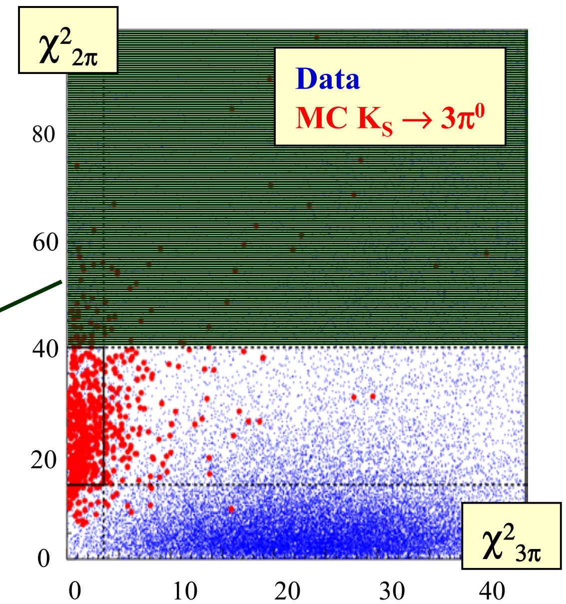
- $\chi^2_{3\pi}$ – pairing of 6γ clusters with better π^0 mass estimates
- $\chi^2_{2\pi}$ – pairing of 4γ's out of 6: π^0 masses, $E(K_S)$, $\mathbf{P}(K_S)$, c.m. angle between π^0's

Definition of the signal box obtained from analysis of 6-pb^{-1}-equivalent MC subsample



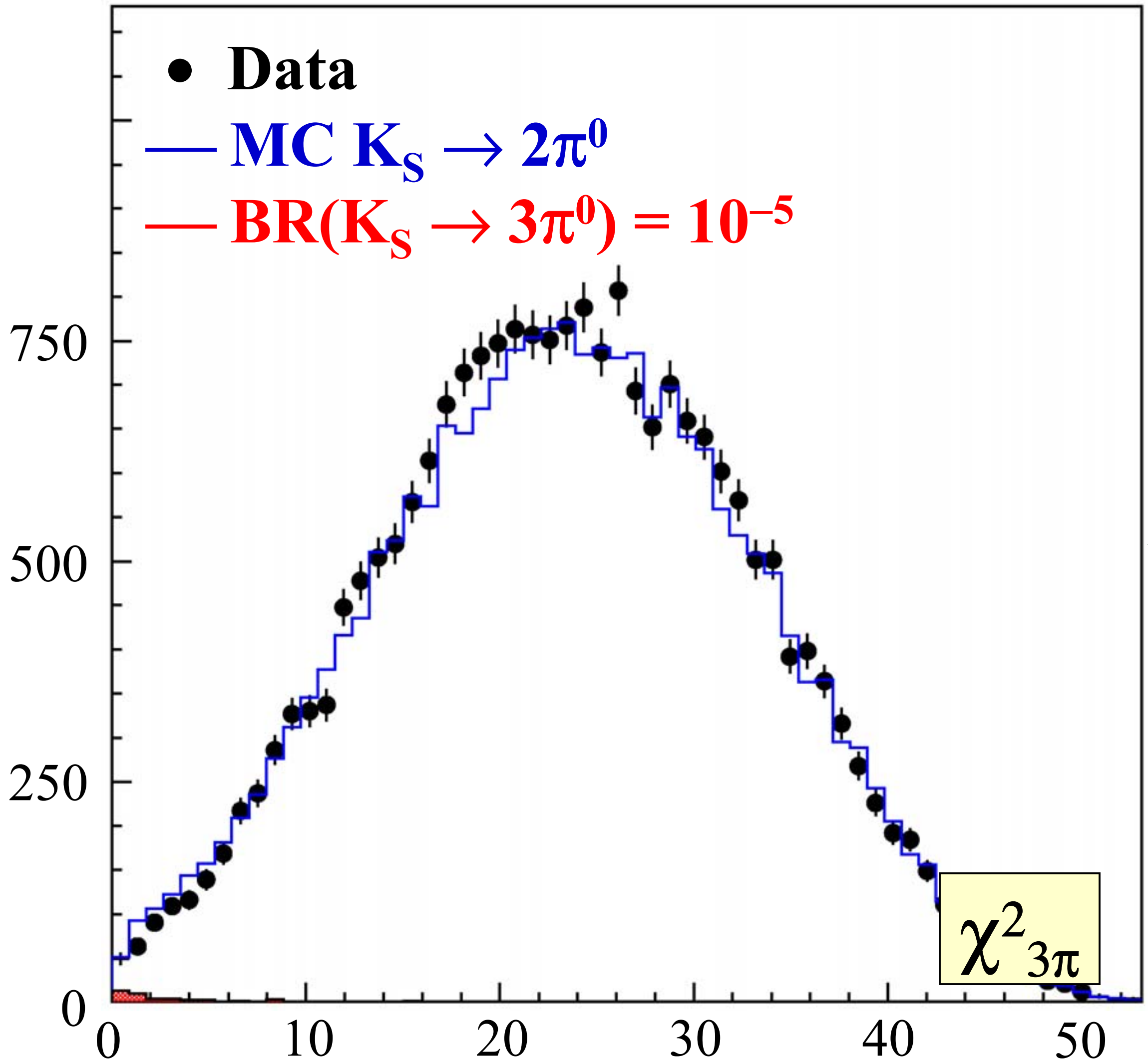
Search for $K_S \to \pi^0\pi^0\pi^0$ - sidebands

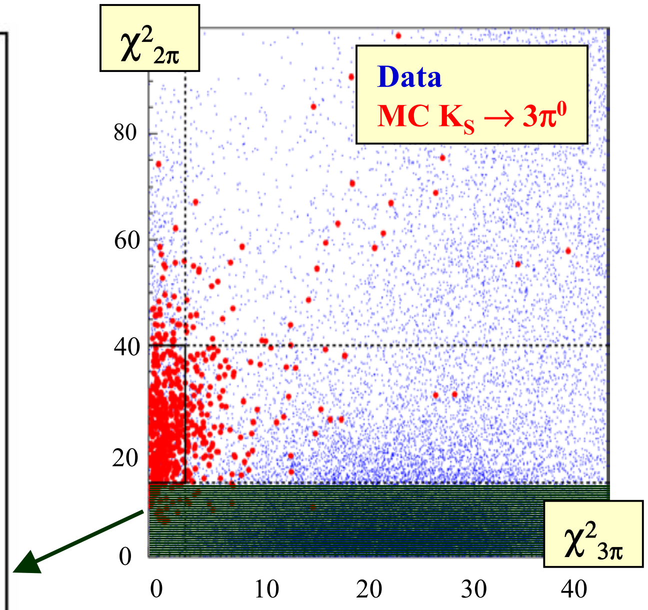




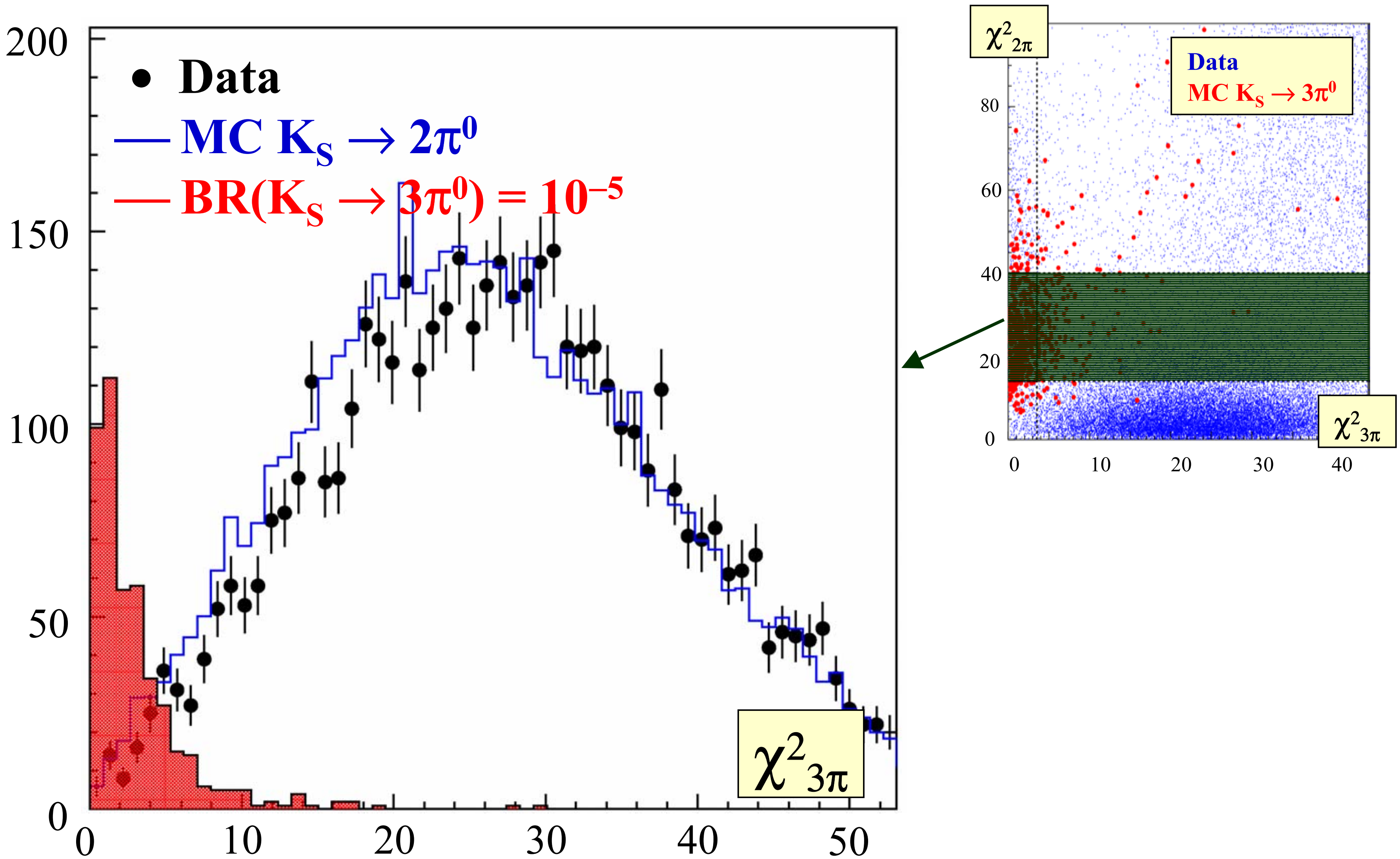
$K_S \to 3\pi^0$ decay switched on during MC production of 450 pb^{-1} equivalent data, with BR equal to the present upper limit

Search for $K_S \to \pi^0 \pi^0 \pi^0$ - sidebands





Search for $K_S \to \pi^0\pi^0\pi^0$ – signal region



$K_S \to \pi^0\pi^0\pi^0$ – Preliminary results

$\mathbf{N_{sel}(data) = 5}$ **events** selected as signal, with efficiency $\varepsilon_{3\pi} = 21\%$

$\mathbf{N_{sel}(bkg) = 3 \pm 1.3 \pm 0.2}$ bkg events expected from MC, use $N_{sel}(bkg) = 1.6$

Can state: $\mathbf{N_{3\pi} < 7.68}$ **with a 90% CL**

Normalize signal counts to $K_S \to \pi^0\pi^0$ count in the same data set:

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

Which translates into a limit on $|\eta_{000}| = \left| \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \right| < 3\ 10^{-2}$

$K_S \rightarrow \pi e \nu$ *decays – Physics issues*

Sensitivity to CPT violating effects through charge asymmetry:

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

If CPT holds, $A_S = A_L$

$A_S \neq A_L$ signals CPT violation in mixing and/or decay with $\Delta S \neq \Delta Q$

Sensitivity to CP violation in K^0-$\bar{K}^0$ mixing:

$A_S = 2\mathrm{Re}\,\varepsilon$ (CPT symmetry assumed)

A_S never measured before

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

Unitarity test of CKM matrix – V_{us}

Most precise test of unitarity possible at present comes 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}:

from super-allowed $0^+ \rightarrow 0^+$ Fermi transitions, n β-decays: $2|V_{ud}|\delta V_{ud} = 0.0015$

from 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:

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

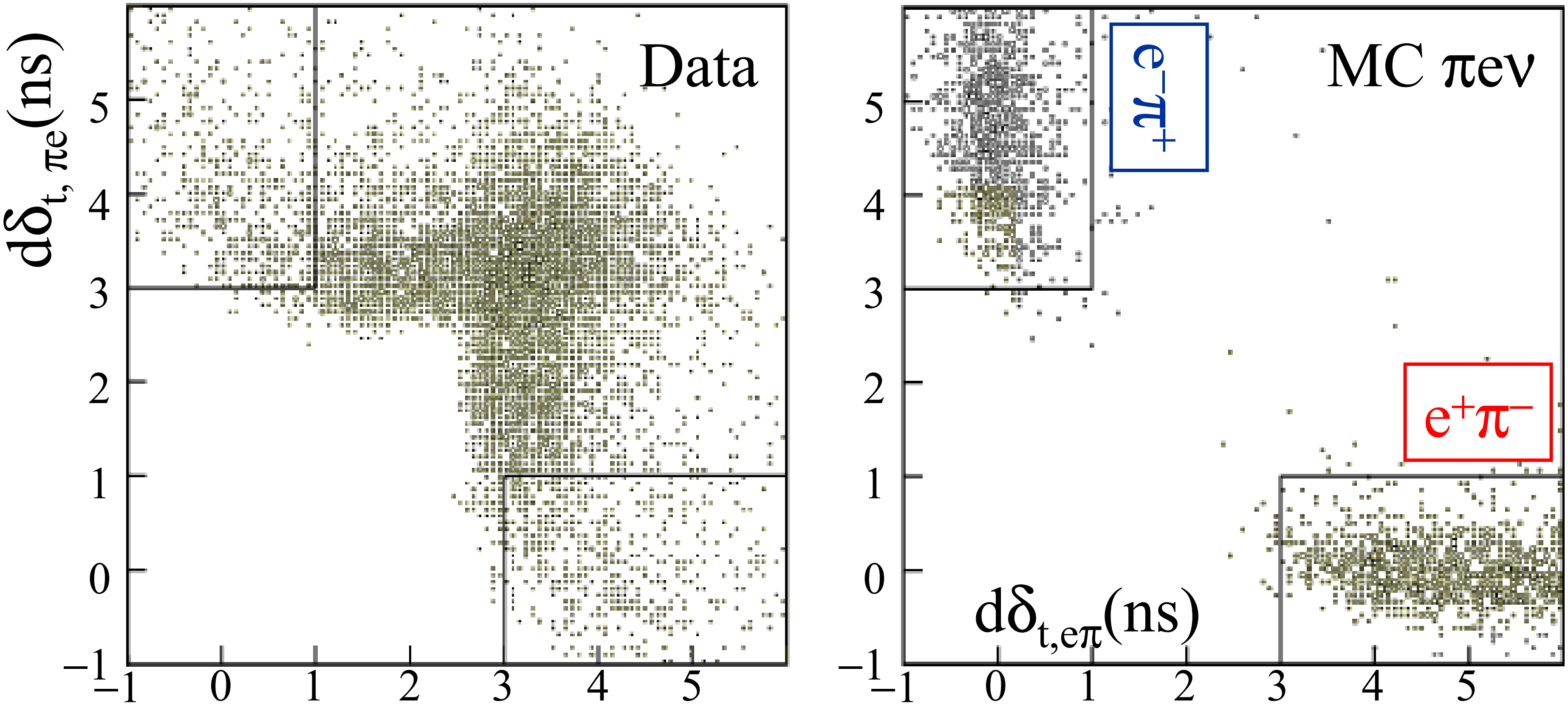
$$0.5\% \oplus 0.3\% \oplus 1\%$$

$K_S \to \pi e \nu$ decays – Analysis outline

Main background from $K_S \to \pi\pi(\gamma)$

Kinematic rejection: $M_{\pi\pi} < 490$ MeV

TOF identification: compare π-e expected flight times, reject ππ,πμ bkg



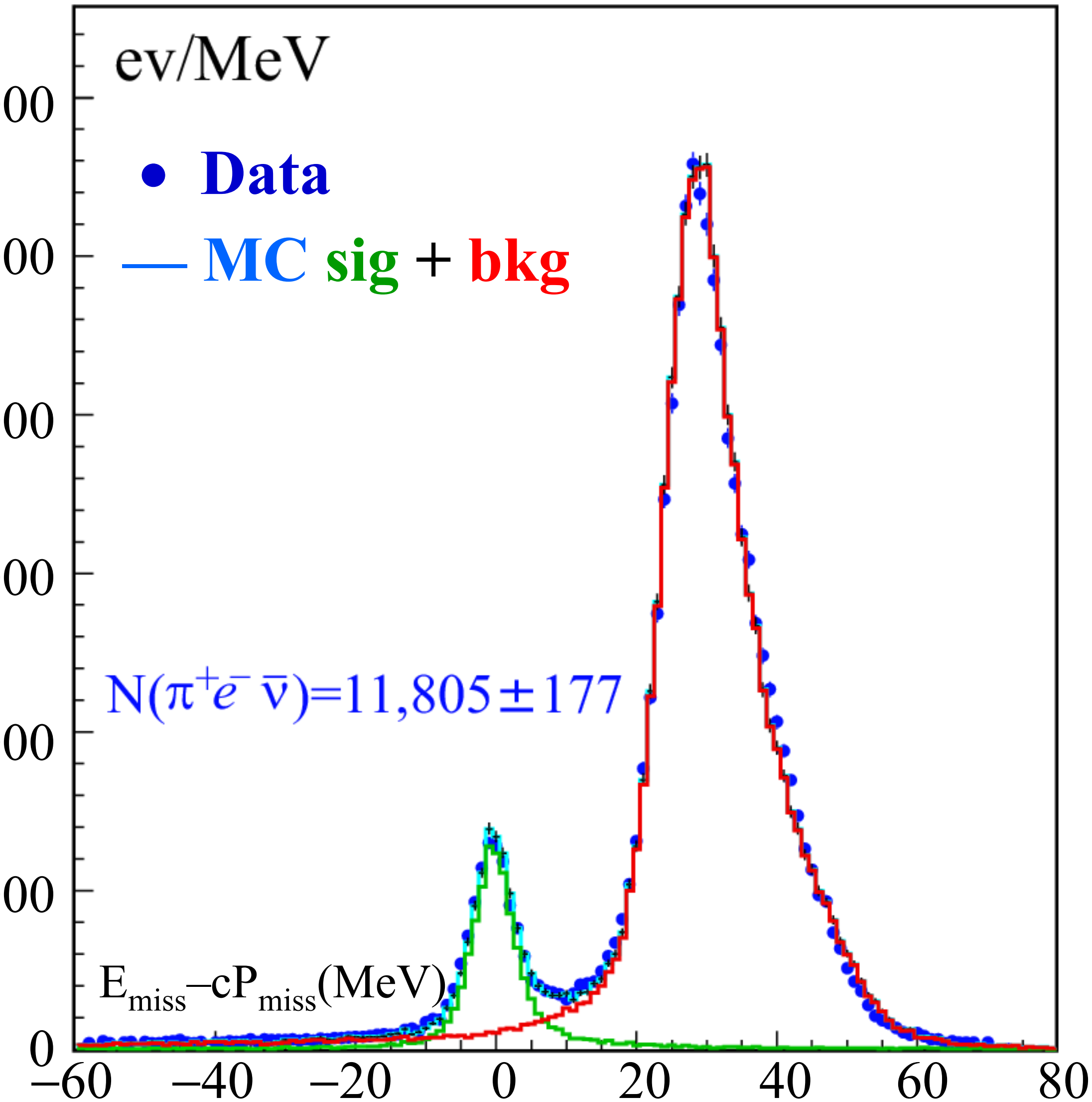
$K_S \to \pi e \nu$ decays – Analysis outline

Kinematic closure: use K_L to obtain K_S momentum $\mathbf{P_K}$ 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 background



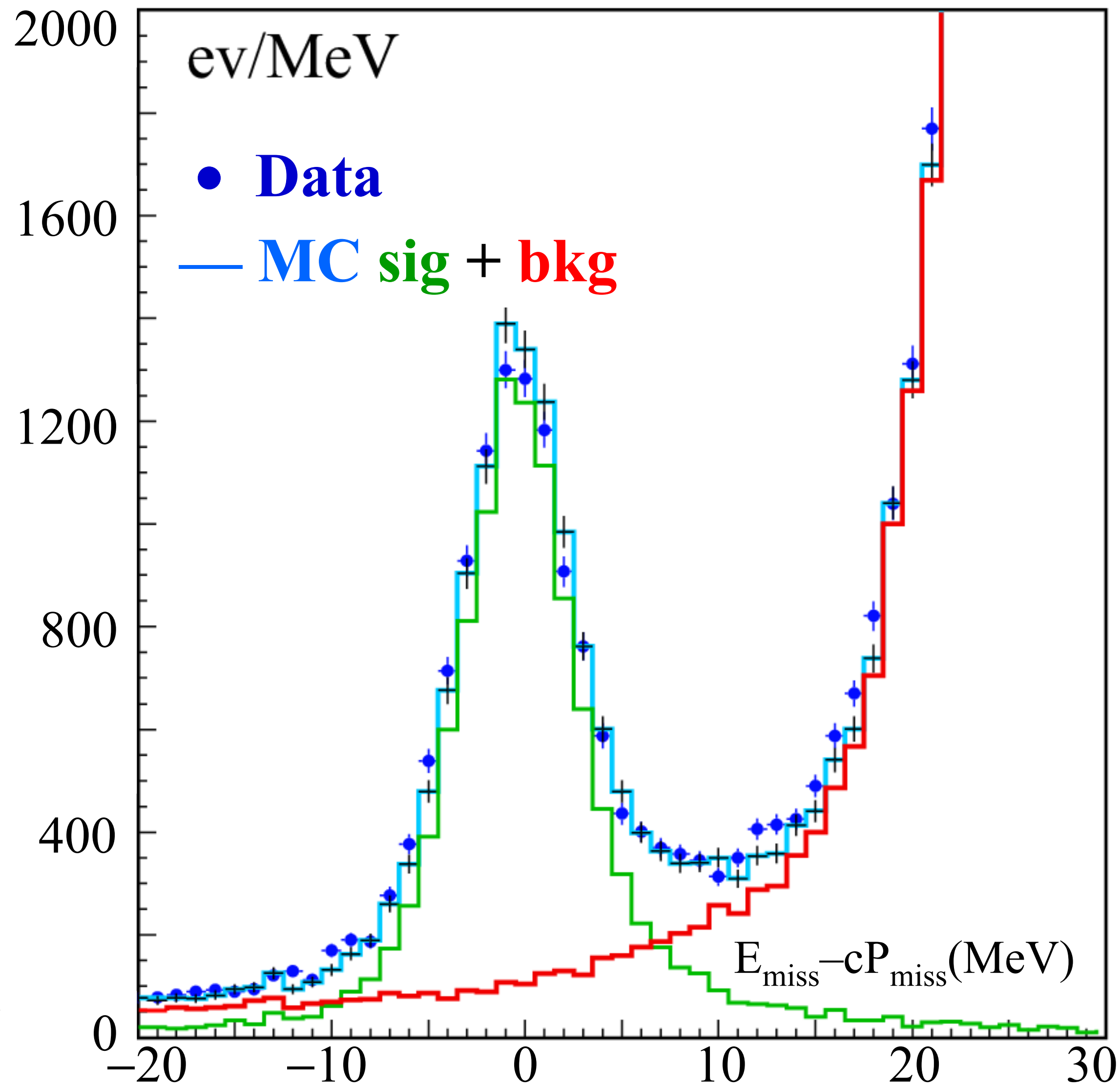
$K_S \to \pi e \nu$ decays – Analysis outline

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

Include radiative effects through an IR-finite treatment in MC (no energy cutoff)

Normalize signal counts to $K_S \to \pi\pi(\gamma)$ counts in the same data set

Use BR($K_S \to \pi\pi(\gamma)$) from previous KLOE measurement



$K_S \to \pi e \nu$ decays – Preliminary results

Correct for charge-dependent efficiencies, mostly extracted from data

$\varepsilon \approx 20\%$ given the tag

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

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

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

KLOE preliminary
Evaluation of the systematics near completion

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

Dependence of efficiencies on charge mainly due to TOF effects, estimated using data control sample of $K_L \to \pi e \nu$

$\mathbf{A_S = (-2 \pm 9_{stat} \pm 6_{syst})\ 10^{-3}}$

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

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

$K_S \to \pi e \nu$ decays – Preliminary results

$V_{us}(K_{S,e3}) = 0.2205 \pm 0.0029$

Compare with PDG 2002:

PDG fit result for $\Gamma(K^+ \to \pi^0 e^+ \nu)$

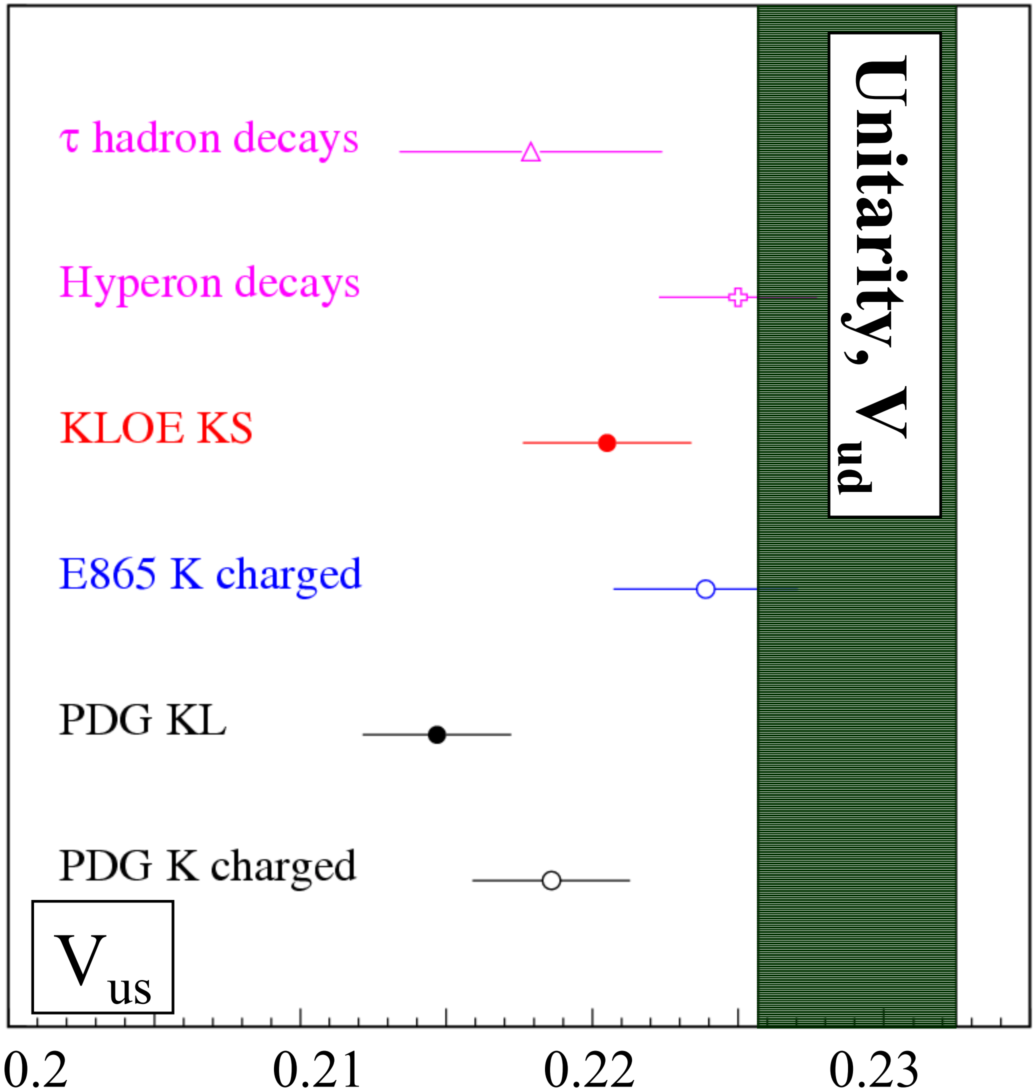
PDG fit result for $\Gamma(K_L \to \pi^- e^+ \nu)$,

and recent determinations of V_{us}, with error on Δ ranging from 0.0012 to 0.0016:

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

Re-analysis of semileptonic decays of Λ, Σ^-, $\Xi^{-,0}$

Estimate from spectral functions of hadronic τ decays, $\tau^- \to \nu_\tau X_{had}$



K_L decays – Present knowledge

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

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

$$R_{\mu/e} = \frac{\Gamma(K_L \to \pi\mu\nu)}{\Gamma(K_L \to \pi e \nu)} = 0.702 \pm 0.011$$
[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 2001

$R_{\mu/e}$ calculable from the slopes λ_+ and λ_0 of vector and scalar form factors:

0.670 ± 0.002, if $\lambda_0 = 0.0183 \pm 0.0013$, from ISTRA+ 2003

0.668 ± 0.006, if $\lambda_0 = 0.017 \pm 0.004$, from one-loop χPt

K_L decays – Status and objectives

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

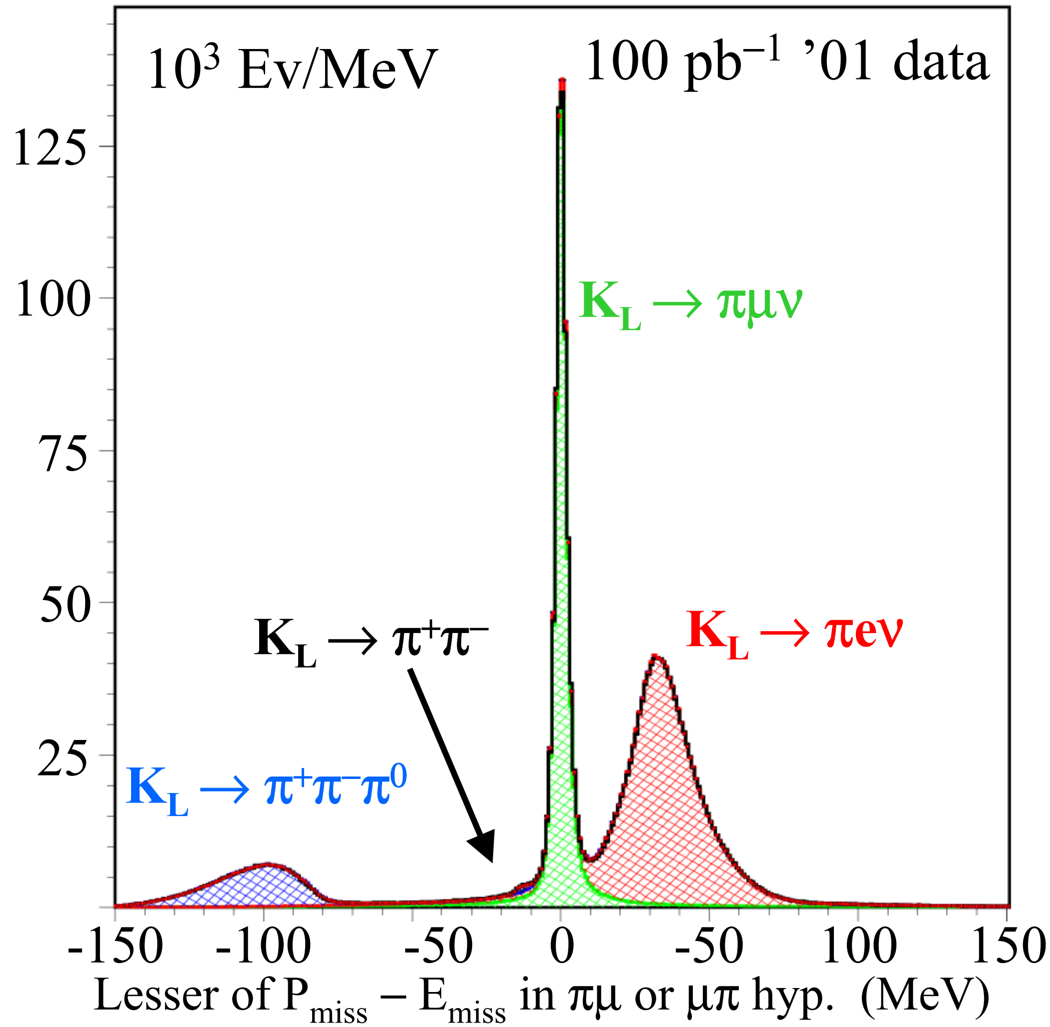
K_L beam tagged by identification of $K_S \to \pi^+\pi^-$

K_L decay vertex in a given fiducial volume in DC

Kinematic identification using reconstructed momenta

In progress (new detailed MC):

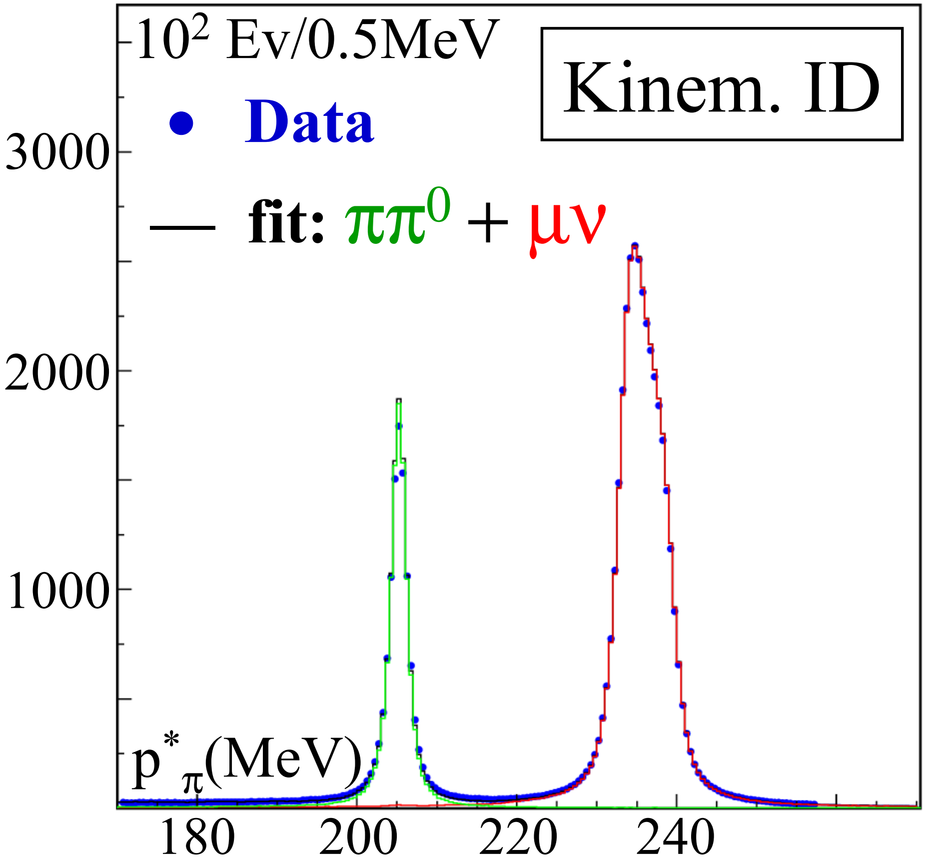
- Selection efficiency as a function of K_L vertex position and momenta of decay products

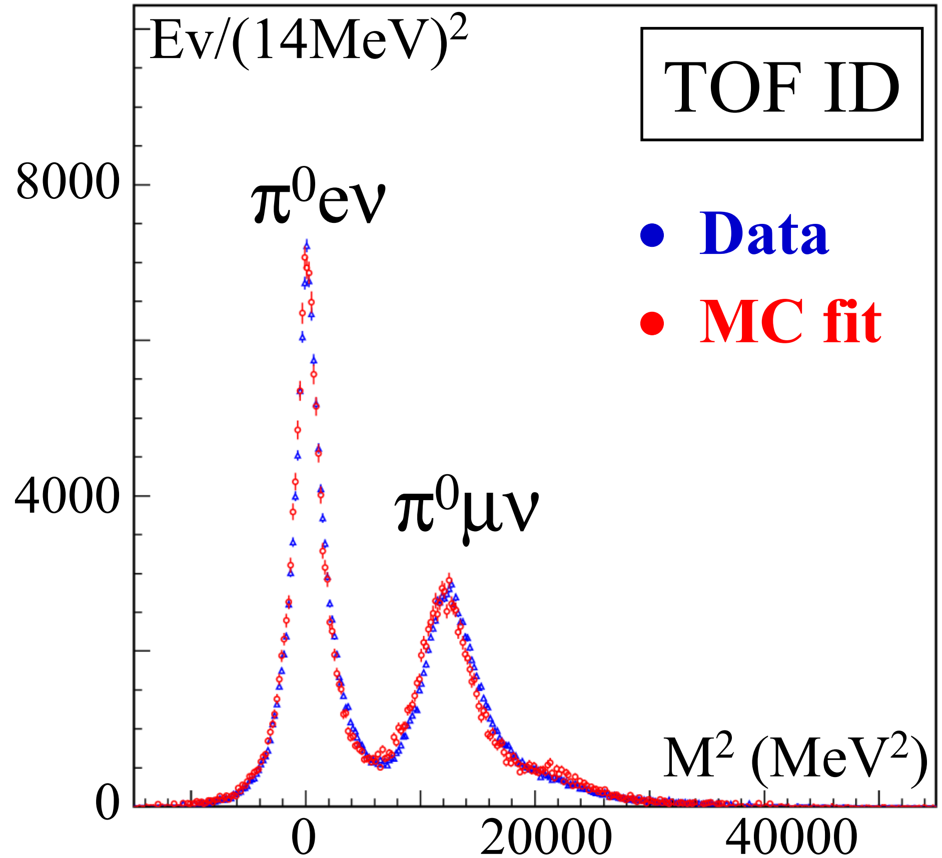


$K^{\pm}$ decays – Status and objectives

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

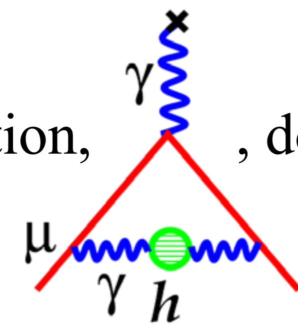
a_μ – SM prediction vs experiment

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)

a_μ(QED),	$11\ 658\ 470.4 \pm 0.3$
a_μ(weak),	15.4 ± 0.2
a_μ(hadronic),	~700

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 $\sigma(e^+e^- \rightarrow$ hadrons)

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

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

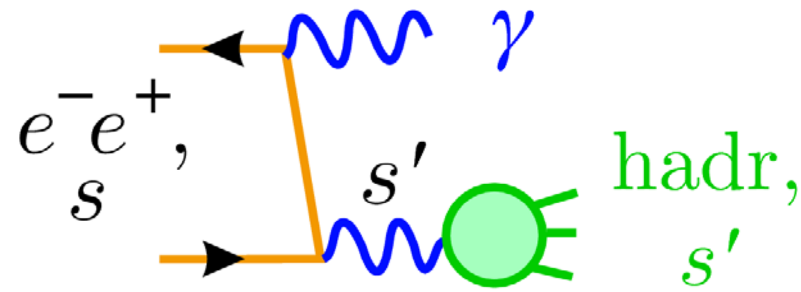
So far, estimates of a_μ^{had} from:

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

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

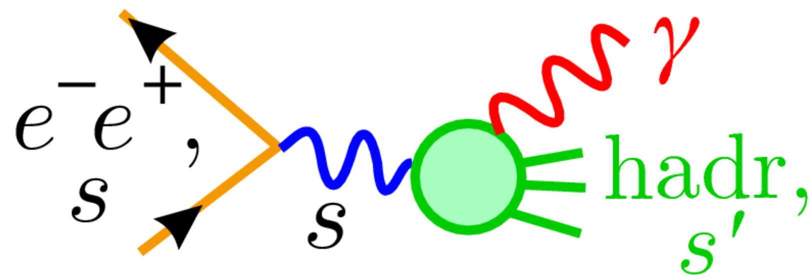
$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ from $\pi\pi\gamma$ events

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

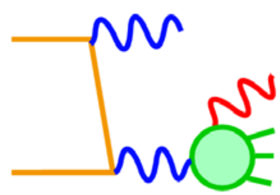


Have to watch out for hard FSR:

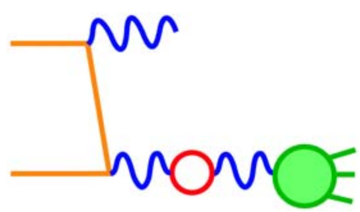
- Rate ~ same order as ISR signal
- FSR causes events with $M_{\gamma^*} = \sqrt{s}$ to be assigned to lower $\sqrt{s'}$ values



Have to properly include radiative corrections,

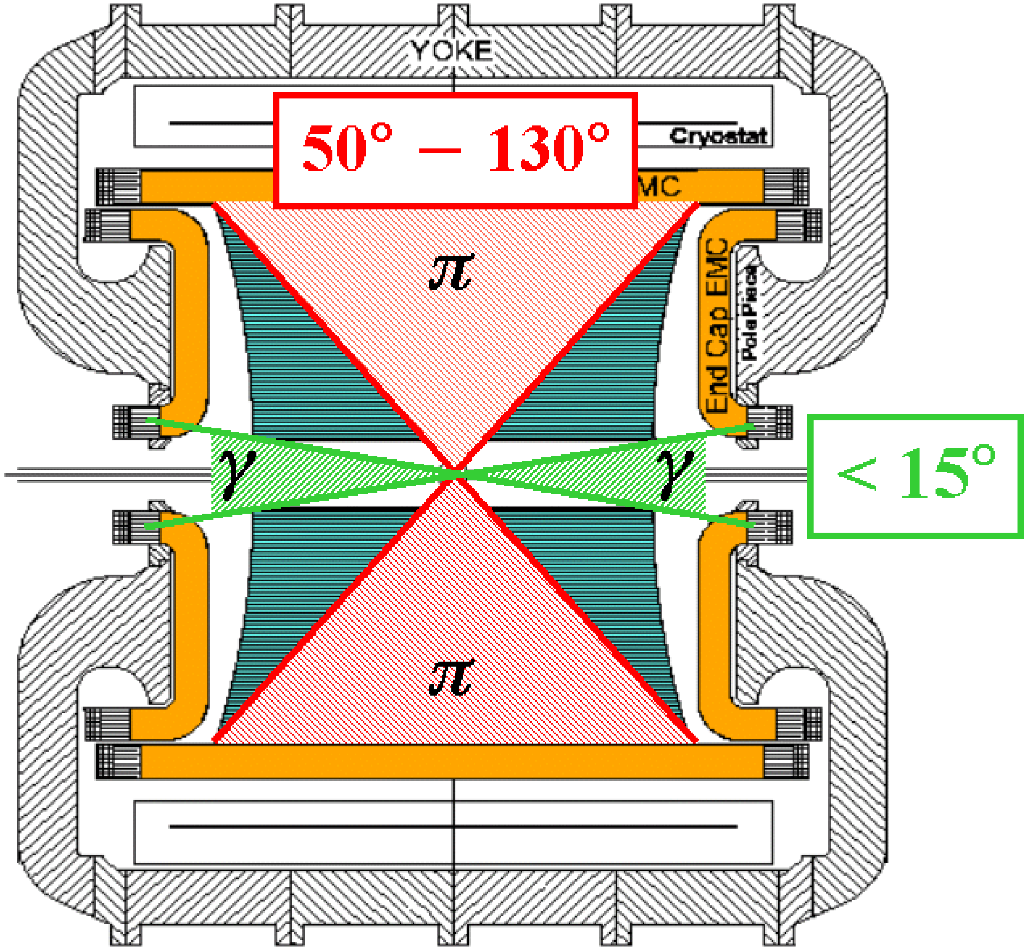


Must remove vacuum polarization,



Measurement of $\sigma_{\pi\pi\gamma}$ – Analysis scheme

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
- Lose events with $M_{\pi\pi} < 600$ MeV
- Reduce background

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

$\sigma(\pi\pi\gamma)$ – Preliminary result

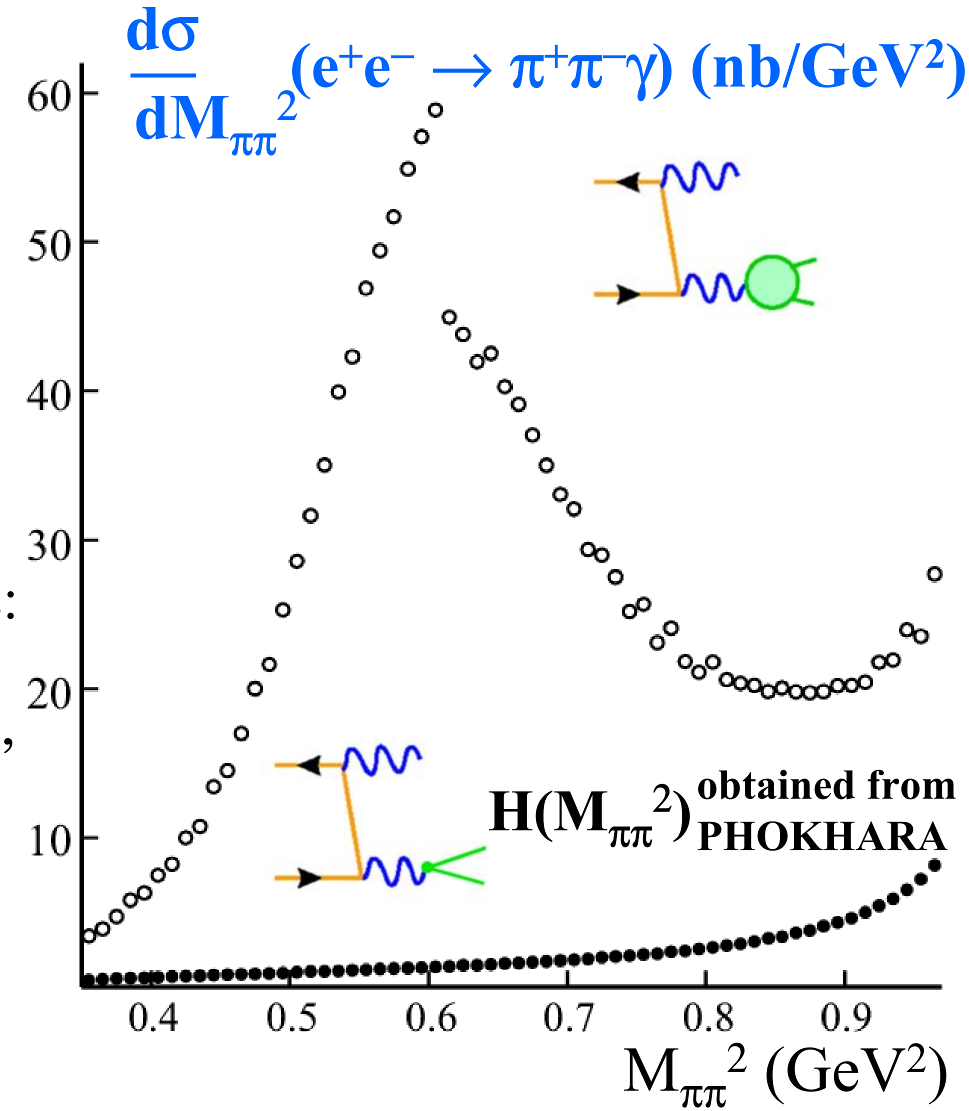
Luminosity from $e^+e^-(\gamma)$ counts, $55° < \theta_e < 125°$, σ calculated at 0.5%, experimental accuracy 0.3%

Experimental $M_{\pi\pi}^2$ resolution unfolded in all spectra shown

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

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

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



a_μ – Preliminary results

Calculating the dispersion integral,

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

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

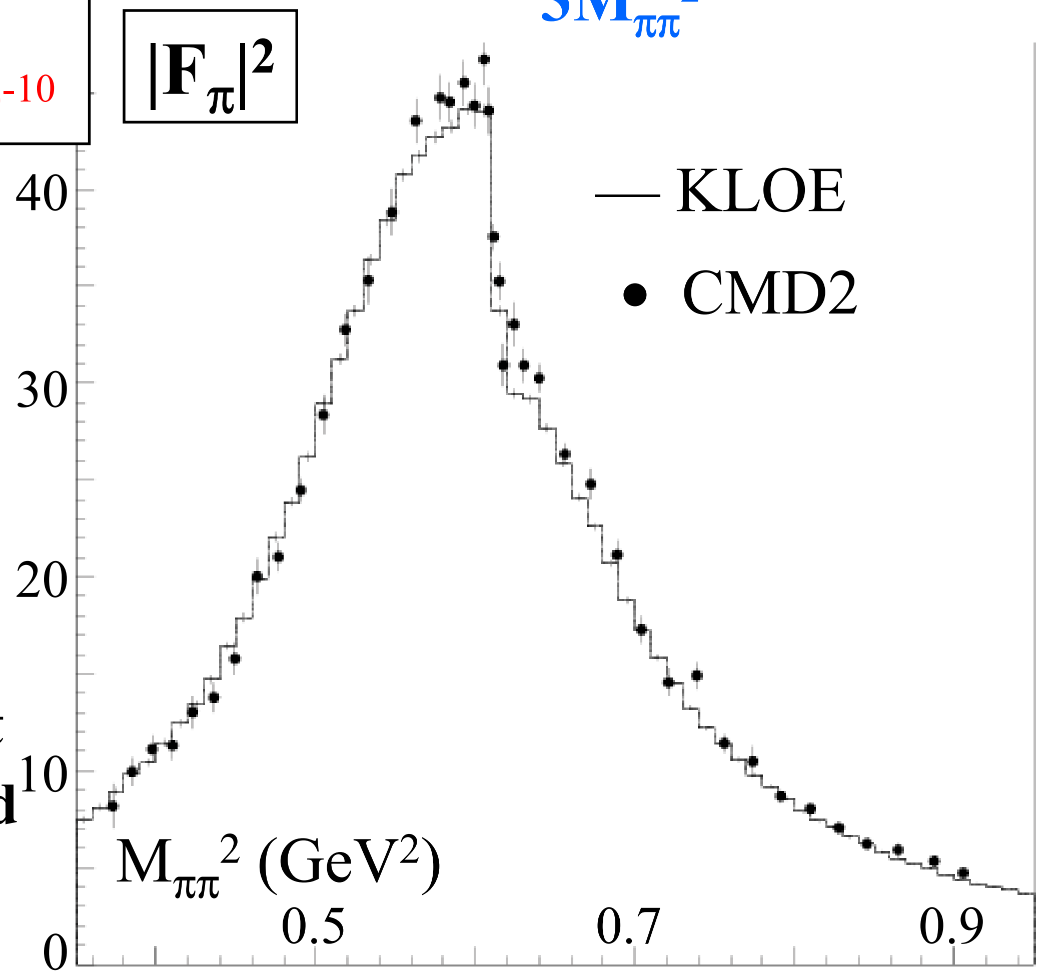
- Comparison with CMD2:

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

KLOE
$(376.5 \pm 0.8_{stat} \pm 5.9_{syst+theo})\ 10^{-10}$

CMD2
$(378.6 \pm 2.7_{stat} \pm 2.3_{syst+theo})\ 10^{-10}$

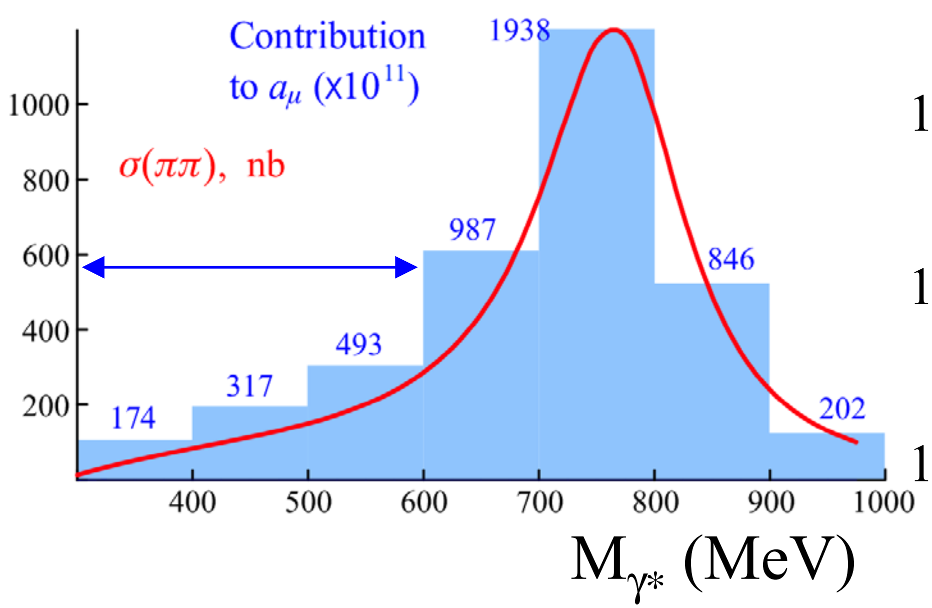
- **Measurements are in agreement**
- **$e^+e^- – \tau$ discrepancy is confirmed**

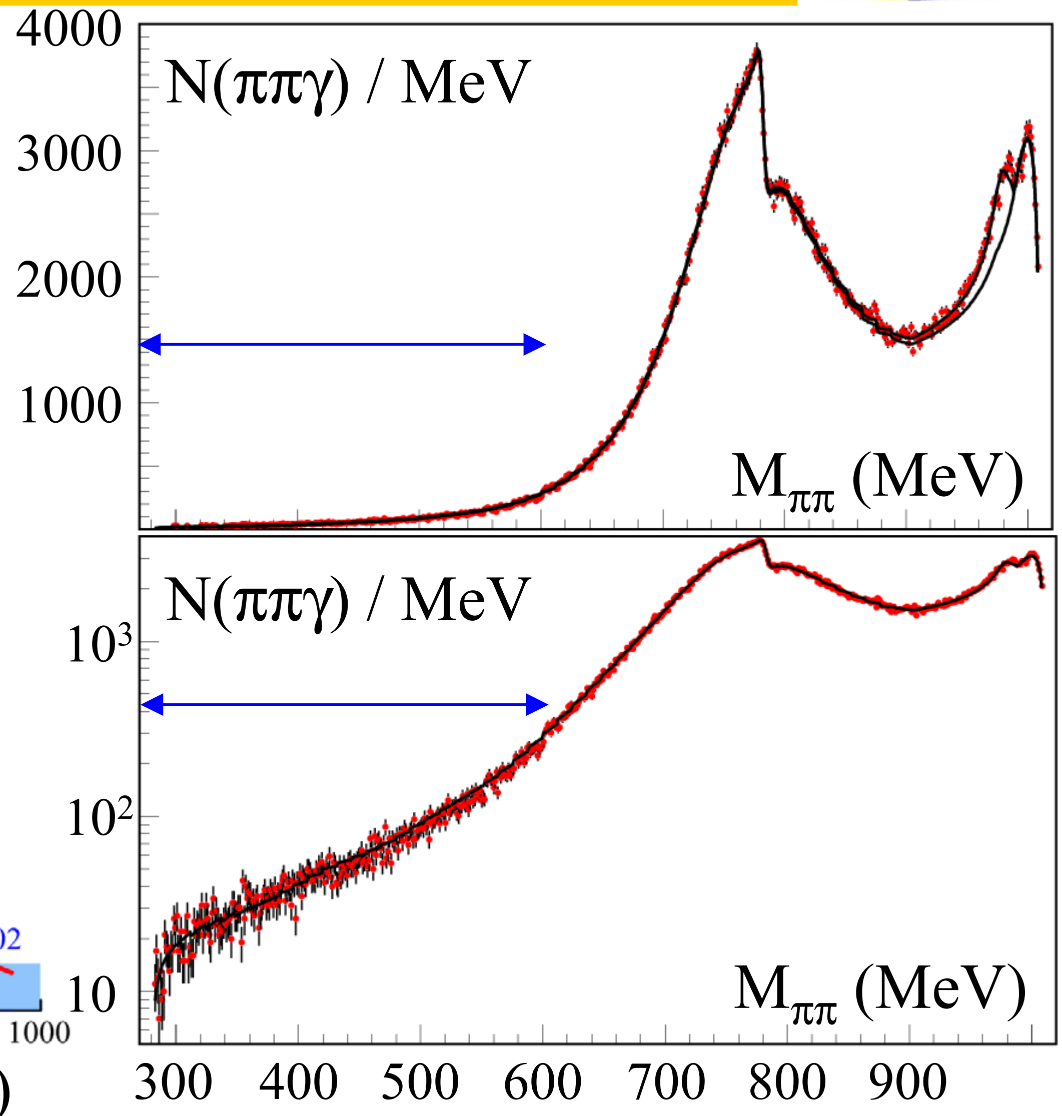


a_μ – *Prospects*

Measure σ(ππ) 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





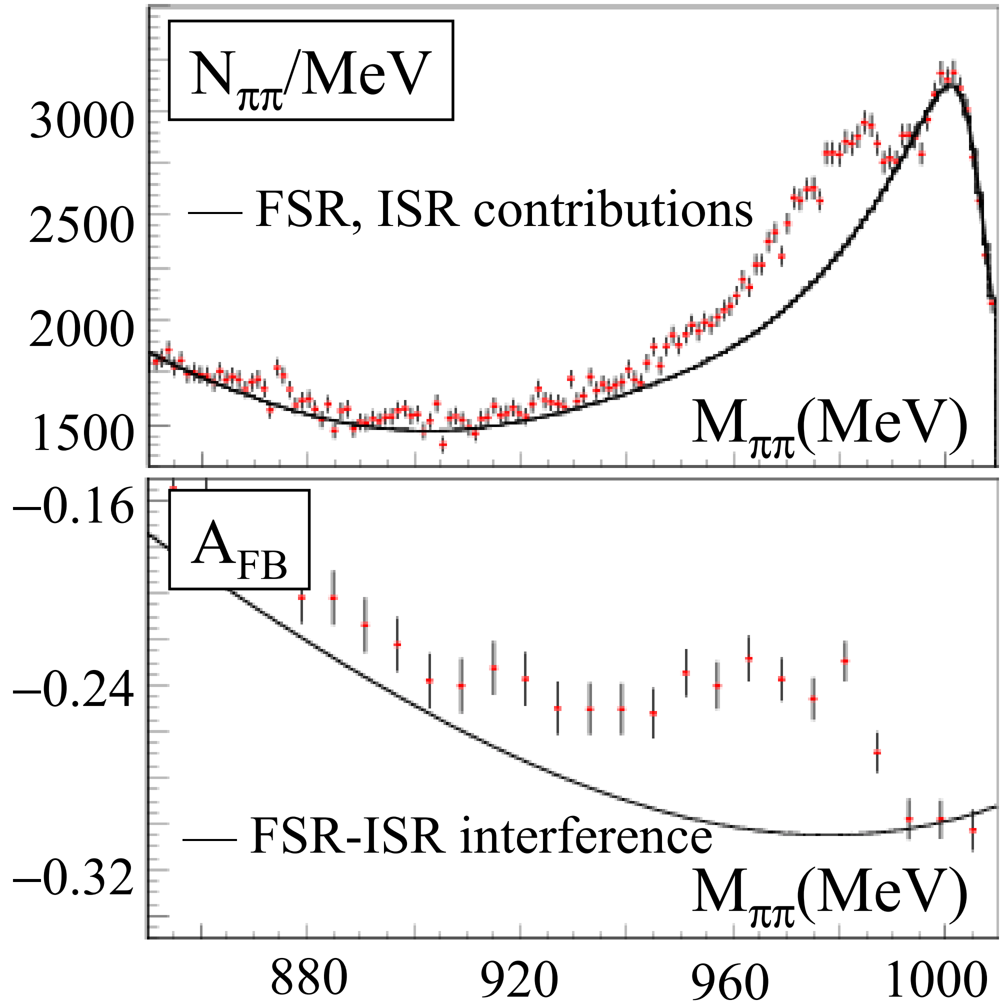
News on $\pi^+\pi^-\gamma$ analysis

Large-angle events, study of the decay $\phi \to \gamma f_0 \to \pi^+\pi^-\gamma$

$\pi^+\pi^-$ system C-odd in ISR events, C-even in FSR events and scalar decays

FB asymmetry measures ISR-FSR and ISR-scalar interference:

$$A_{FB} = \frac{N_{\pi+}(\theta > 90°) - N_{\pi+}(\theta < 90°)}{N_{\pi+}(\theta > 90°) + N_{\pi+}(\theta < 90°)}$$



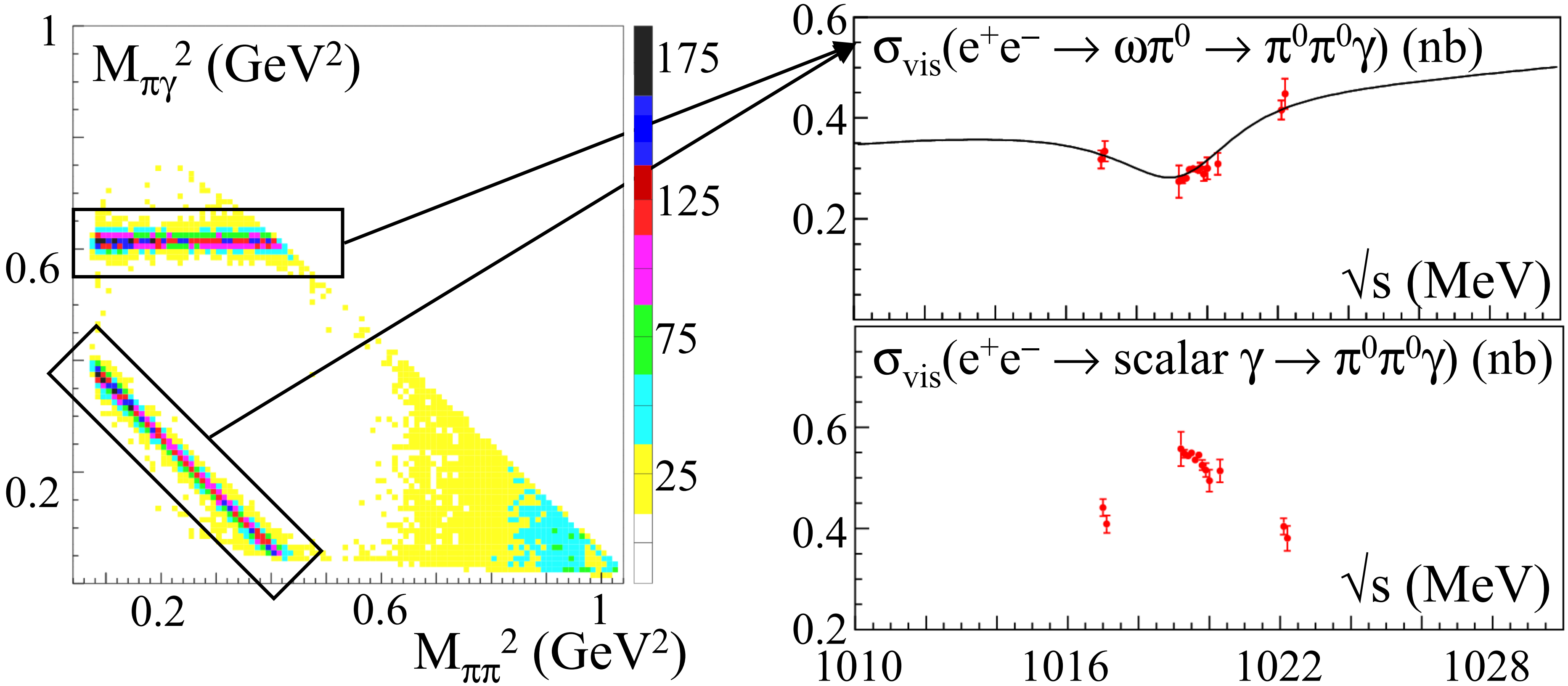
Preliminary evidence for an f_0 contribution

News on analysis of $\pi^0\pi^0\gamma$ final state

450 pb^{-1} allow for high statistical reach, ~30000 events assigned to scalar + γ

Dalitz plot analysis in progress: aims at extracting all possible contributions

- $e^+e^- \to \omega\pi^0$ interferes with ϕ-mediated production
- Line shape for non-ω-mediated final state shows resonant behavior



Outlook – Kaon physics

Present status - K_S:

Sensitivity to 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

Expect 2 fb^{-1} of integrated luminosity in 2004, would allow:

A_S with a total accuracy of $4\ 10^{-3}$, first test of SM prediction $A_S = 2\ \mathrm{Re}\ \varepsilon$

Sensitivity to $K_S \to 3\pi^0$ at 10^{-8} level

A measurement of $BR(K_S \to \pi^+\pi^-\pi^0)$ with 20% relative uncertainty

- First **direct** measurement
- Test of the χPt prediction, $BR(K_S \to \pi^+\pi^-\pi^0) = (2.4 \pm 0.7)\ 10^{-7}$

In progress:

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

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

Outlook – measurement of $\sigma(\pi\pi\gamma)$

Present status:

Analysis at small γ 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%

In progress:

Analysis at large γ angles, measure a_μ^{had} contribution for $M_{\gamma*} < 600$ MeV

Contribution of scalar-γ final states

- Forward-backward asymmetry
- Visible cross section

Normalization to $\mu^+\mu^-\gamma$ events, check of MC calculation

Other ongoing analyses

~ 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 (best world limit)

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

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, $\phi \to \eta'\gamma$ decays:

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

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

Can extract mixing angle, uncertainty at 1-degree level

ϕ-meson properties:

Combined line-shape fit in principal decay channels

Measurement of $\Gamma(\phi \to e^+e^-)$ and $\Gamma(\phi \to \mu^+\mu^-)$ from FB asymmetry vs $\sqrt{s}$