The Physics of KLOE

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OUTLINE

1. The ϕ–factory
   (a) $e^+e^-\to\phi$
   (b) $\phi\to K^0\overline{K^0}\to K_SK_L$
   (c) High luminosity
2. DAΦNE
3. KLOE
4. Kaons
5. S=0 mesons
6. Hadronic cross section

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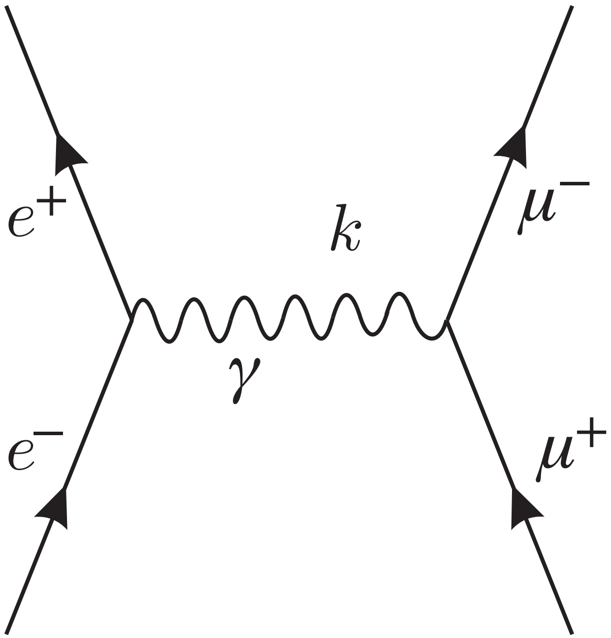
$\boxed{e^+e^- \to f\bar{f}}$

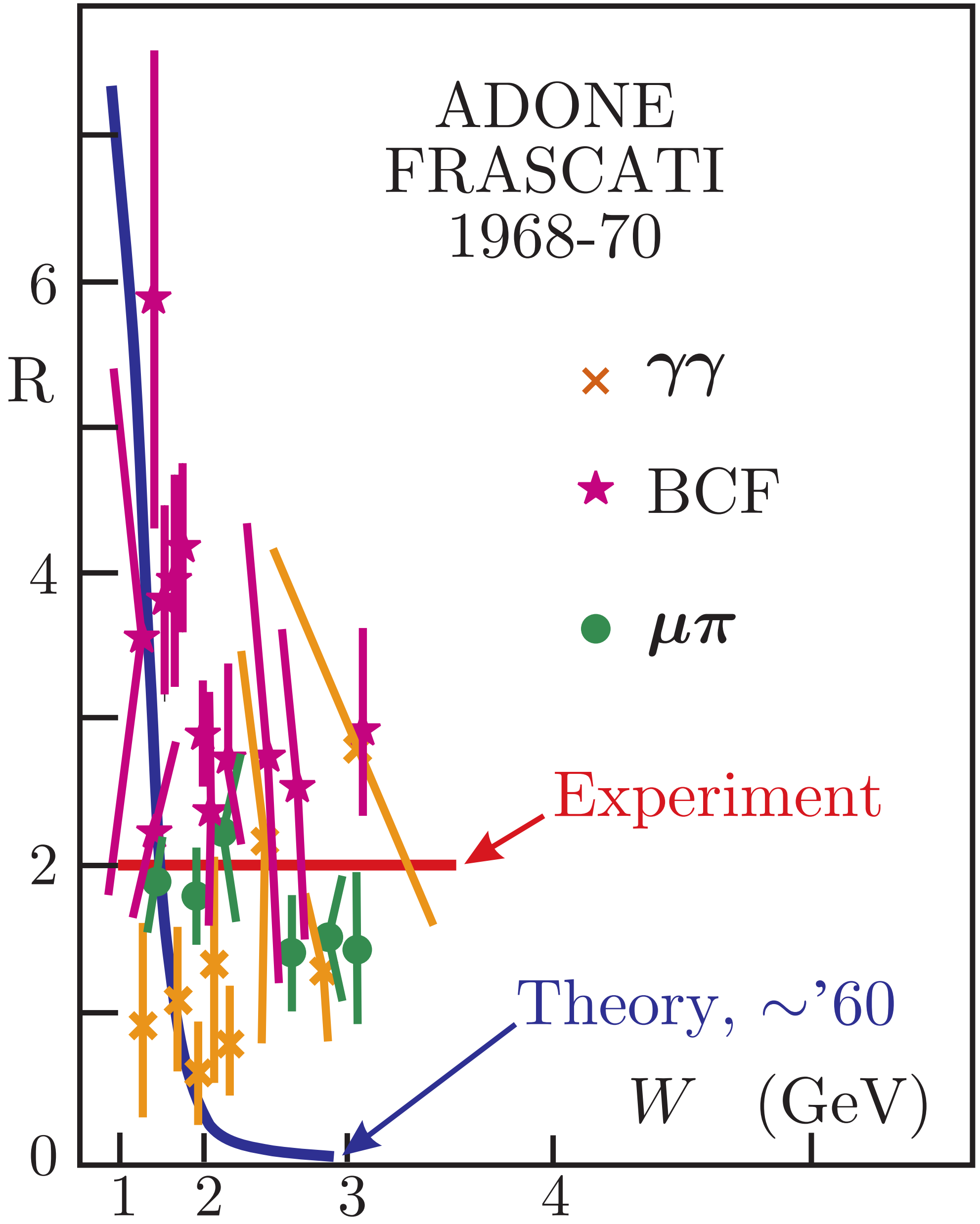


$e^+e^- \to \mu^+\mu^-$ Reference process

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}\,\frac{\beta_\mu(3-\beta_\mu^2)}{2}$$

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{86.854\ \text{nb}}{s/(1\ \text{GeV}^2)}$$

ADONE, 1968-70



$$\sigma(e^+e^- \to q\bar{q}) = Q_q^2 \times \sigma(e^+e^- \to \mu^+\mu^-)$$

$$\sigma(e^+e^- \to \text{hadrons}) = 3\sum_f Q_q^2 \times \sigma(e^+e^- \to \mu^+\mu^-)$$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 2$$

for $q = u,\ d,\ s$

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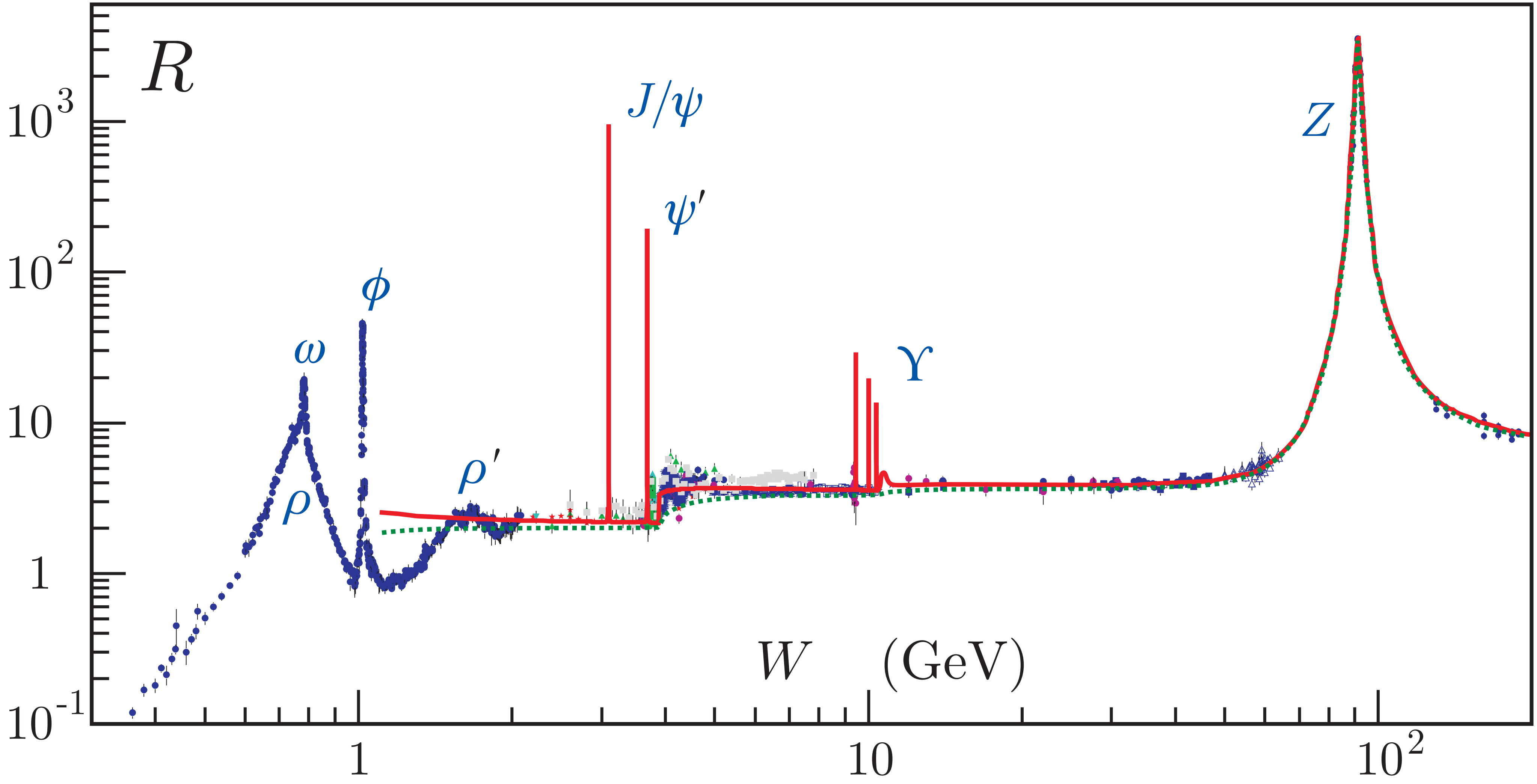
R



R
10^3
10^2
10
1
10^{-1}
J/ψ
ψ'
ϕ
ω
ρ
ρ'
Υ
Z
W (GeV)
1
10
10^2

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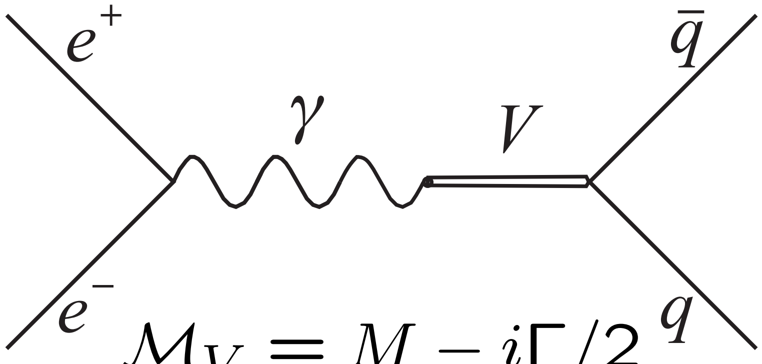
$e^+e^- \to \phi$ for W=1020 MeV



$$\mathcal{M}_V = M - i\Gamma/2$$

$$\sigma_{\text{res},(q\bar{q})} = \frac{12\pi}{s} \frac{\Gamma_{ee}\Gamma M^2}{(M^2-s)^2 + M^2\Gamma^2} = \frac{12\pi}{s} B_{ee} \frac{M^2\Gamma^2}{(M^2-s)^2 + M^2\Gamma^2}$$

ϕ: $s\bar{s}$, ${}^3S_1$ bound state with J^{PC}=1^{--}

$$\sigma(e^+e^- \to \phi) \sim \frac{12\pi}{s} B_{ee} = 0.011\ \text{GeV}^{-2} \sim 4000\text{nb}$$

σ(hadr)$\sim$(5/3)$\times$87$\sim$100 nb.

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ϕ–decays

Mode	BR, %
K^+K^-	49.2
$K^0\overline{K}^0$	33.8
$\pi^+\pi^-\pi^0$	15.5
$\eta\gamma$	1.3
$\pi^0\gamma$	0.1
other	$<$0.1

A charged kaon factory

A neutral kaon factory

An η factory

K_S and K_L decay lengths

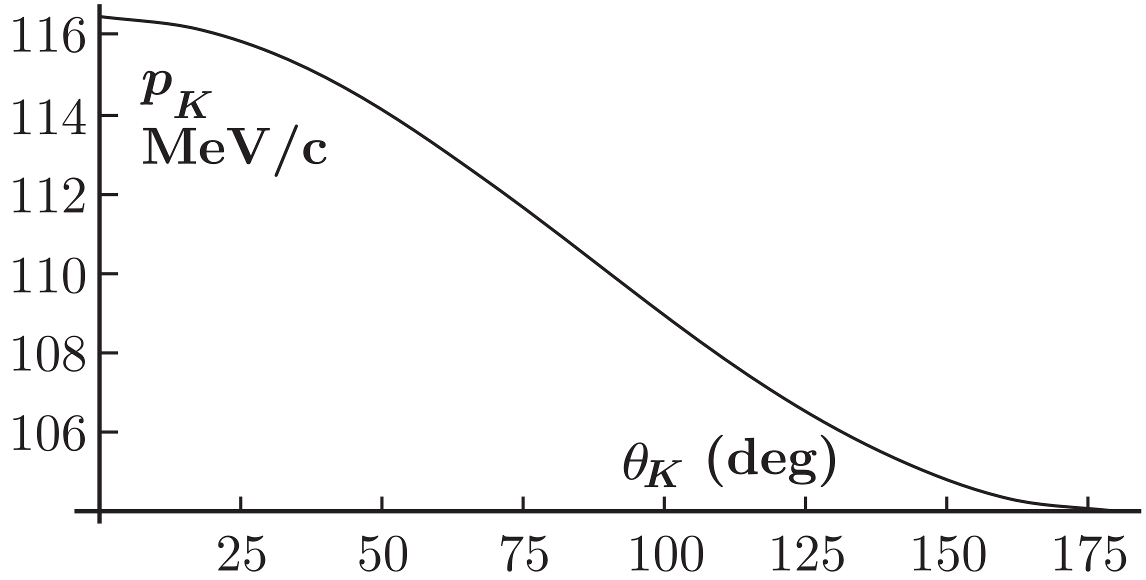
e^+e^- beams collide at 2π-25 mrad, p_ϕ=25 MeV/c

$\langle\gamma\beta c\tau_L\rangle = 3.4$ m

Drives detector size

$\langle\gamma\beta c\tau_S\rangle = 5.6$ mm

Drives IP surroundings



$$\langle\beta_{K^0}\rangle = 0.225$$

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$$\boxed{\phi \rightarrow K^0 \overline{K^0}}$$

$$|\,i\,\rangle = \frac{|\,K^0,\mathbf{p}\,\rangle|\,\overline{K^0},-\mathbf{p}\,\rangle - |\,\overline{K^0},\mathbf{p}\,\rangle|\,K^0,-\mathbf{p}\,\rangle}{\sqrt{2}}$$

$$|\,K_S\,\rangle \equiv p'|\,K^0\,\rangle + q'|\,\overline{K^0}\,\rangle \qquad |p'|^2 + |q'|^2 = 1$$

$$|\,K_L\,\rangle \equiv p|\,K^0\,\rangle - q|\,\overline{K^0}\,\rangle \qquad |p|^2 + |q|^2 = 1$$

$$|\,i\,\rangle = \frac{|\,K_S,\mathbf{p}\,\rangle|\,K_L,-\mathbf{p}\,\rangle - |\,K_L,\mathbf{p}\,\rangle|\,K_S,-\mathbf{p}\,\rangle}{\sqrt{2(qp'+q'p)}}$$

CPT invariance requires $p' = p$ and $q' = q$

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Pure Beams

1. Pure, K_L, K_S, K^0, $\overline{K}^0$ beams
2. Kaon interferometry

$$\frac{e^+e^- \to K_S K_S \text{ or } K_L K_L}{e^+e^- \to \phi \to K_S K_L} \sim \text{few} \times 10^{-10}$$

KLOE measured, $<10^{-8}$

Only way to get a true K_S beam

Unique opportunity to study:

K_S BR's to high accuracy

K_S Rare decays: K_S semileptonic... $K_S \to \pi^0\pi^0\pi^0$, ($K_S \to \pi^0 \nu\bar{\nu}$)

in addition to CP and CPT, the original mission of KLOE.

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Interference

$$I(f_1,f_2,t_1,t_2)=|\langle\, f_1|\,K_S\,\rangle|^2|\langle\, f_2|\,K_S\,\rangle|^2e^{-\Gamma_S\,t/2}\times$$
$$[|\eta_1|^2e^{\Gamma_S\Delta t/2}+|\eta_2|^2e^{-\Gamma_S\Delta t/2}-2|\eta_1||\eta_2|\cos(\Delta m\,t+\phi_1-\phi_2)]$$

$$I(f_1,\ f_2;\ \Delta t)=\frac{1}{2\Gamma}|\langle f_1|\,K_S\,\rangle\langle f_2|\,K_S\,\rangle|^2\times[|\eta_1|^2e^{-\Gamma_L\Delta t}+$$
$$|\eta_2|^2e^{-\Gamma_S\Delta t}-2|\eta_1||\eta_2|e^{-\Gamma\Delta t/2}\cos(\Delta m\Delta t+\phi_1-\phi_2)]$$

Measure ΔM, Γ, η_i – including phases.

$$\boxed{\eta_i=\frac{A(K_L\to i)}{A(K_S\to i)},\ \ \arg(\eta)=\phi}$$

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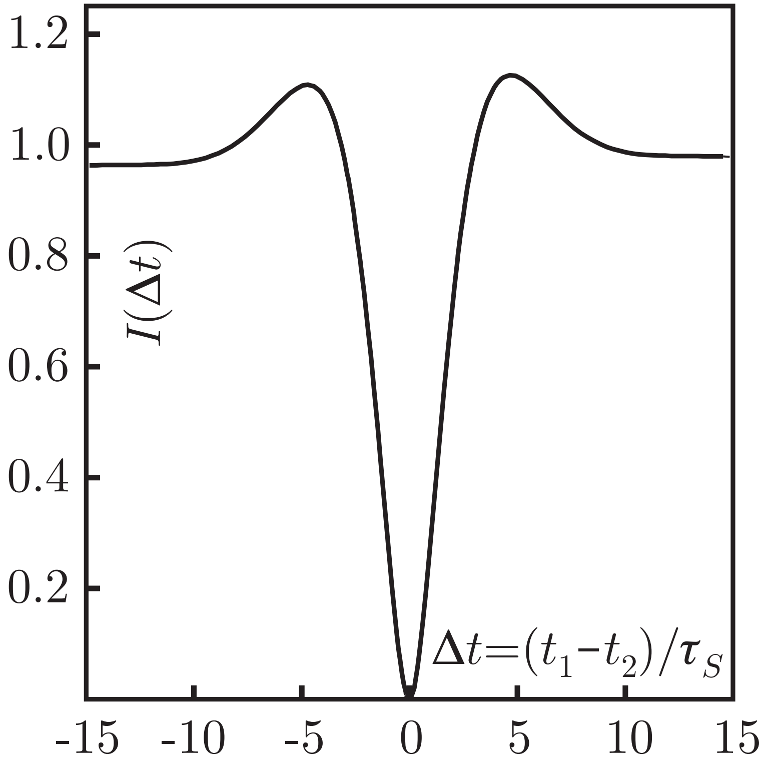
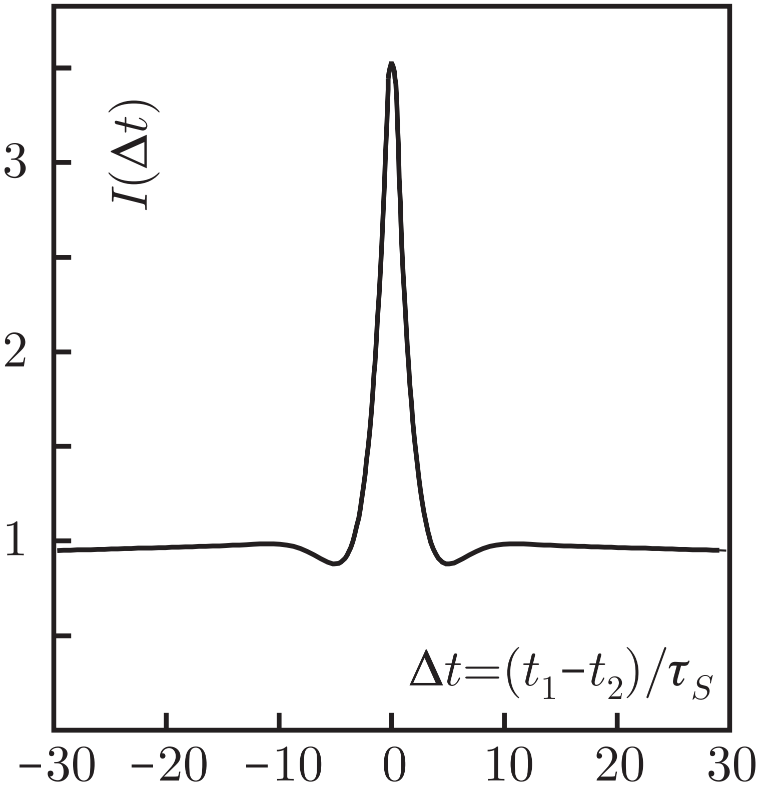
Interference examples

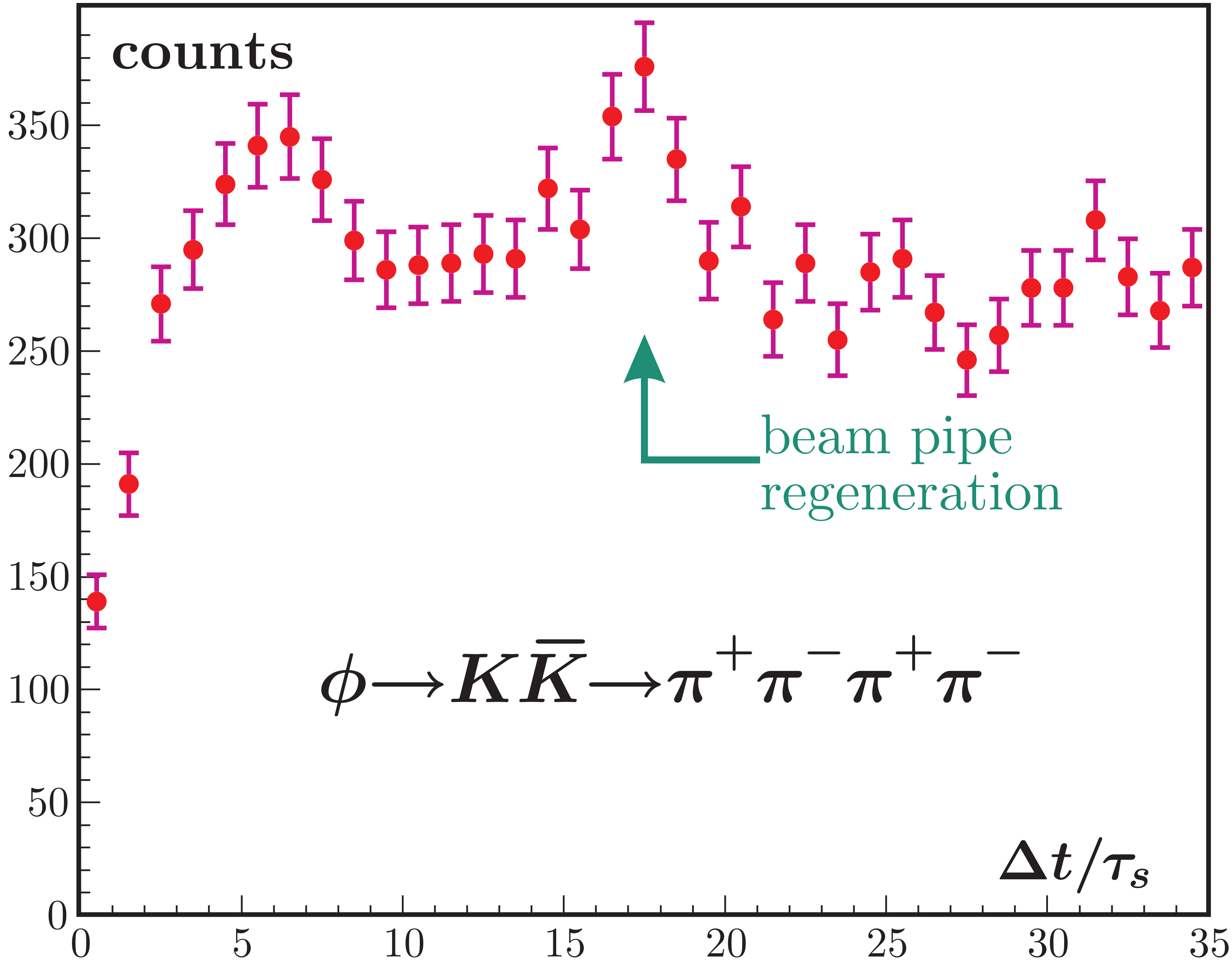




$f_{1,2} = \pi^+\pi^-$, $\pi^0\pi^0$
$\Re(\epsilon'/\epsilon)$, $\Im(\epsilon'/\epsilon)$

$f_{1,2} = \ell^-, \ell^+$
$\Re$ and $\Im$ of $A_{\ell\pm}$

First observation of coherence in neutral $K\bar{K}$ system



Luminosity

Event rate=$\mathcal{L} \times \sigma$

$$\mathcal{L} = f_c \, \frac{N_{e^+} \, N_{e^-}}{4 \, \pi \, \sigma_x \, \sigma_y}$$

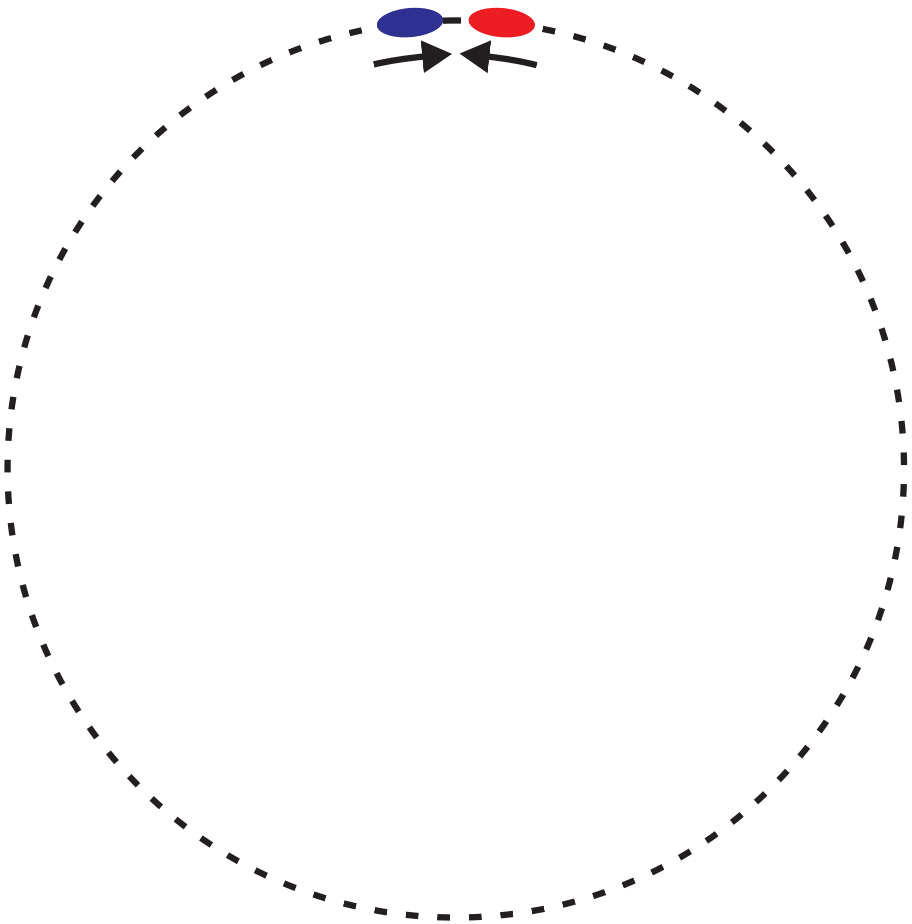
So, increase N, decrease bunch size!!

$\Rightarrow$ Instabilities blow up bunch size

Go to many bunches, same problem

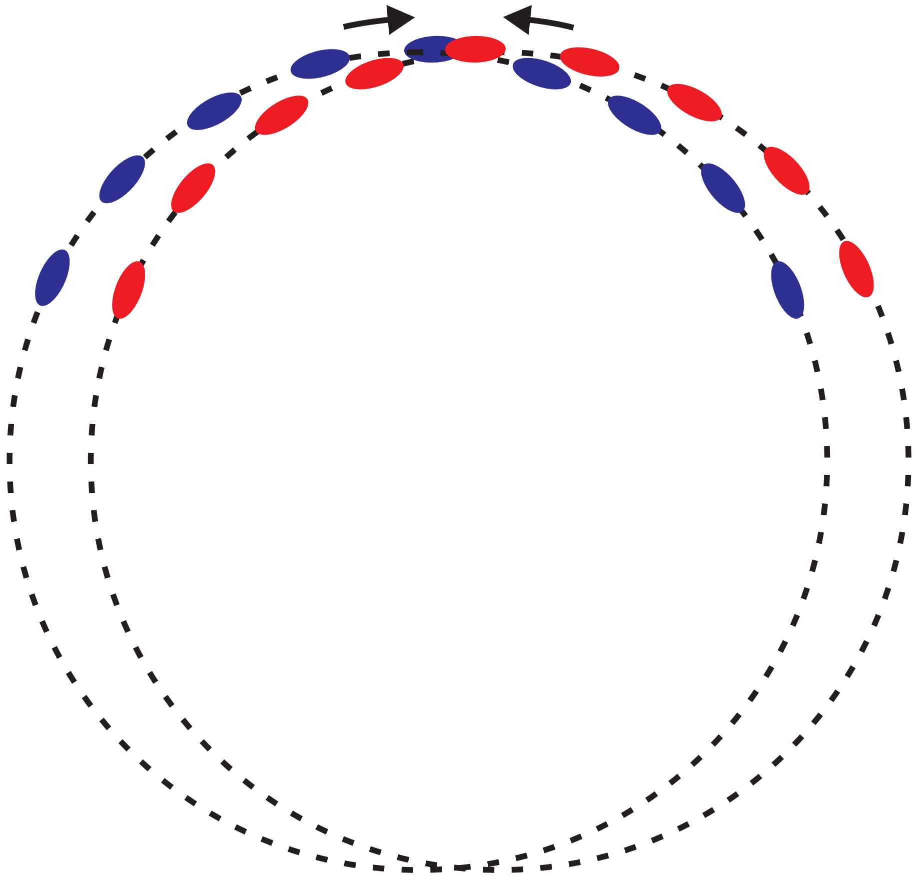
Many bunches in separated rings!!

High $\mathcal{L}$ colliders



1 ring collider

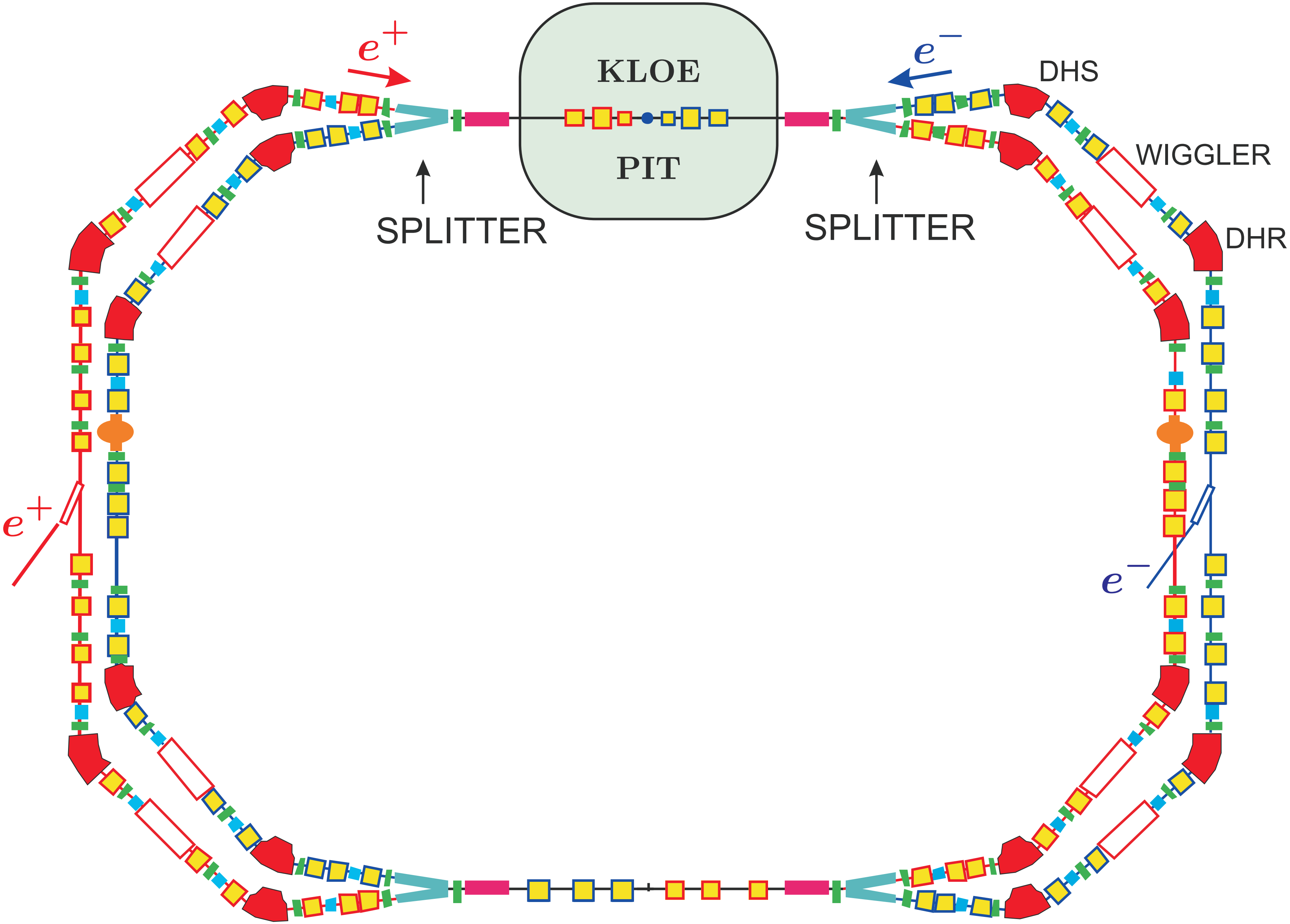
1+1 e^+e^- bunches



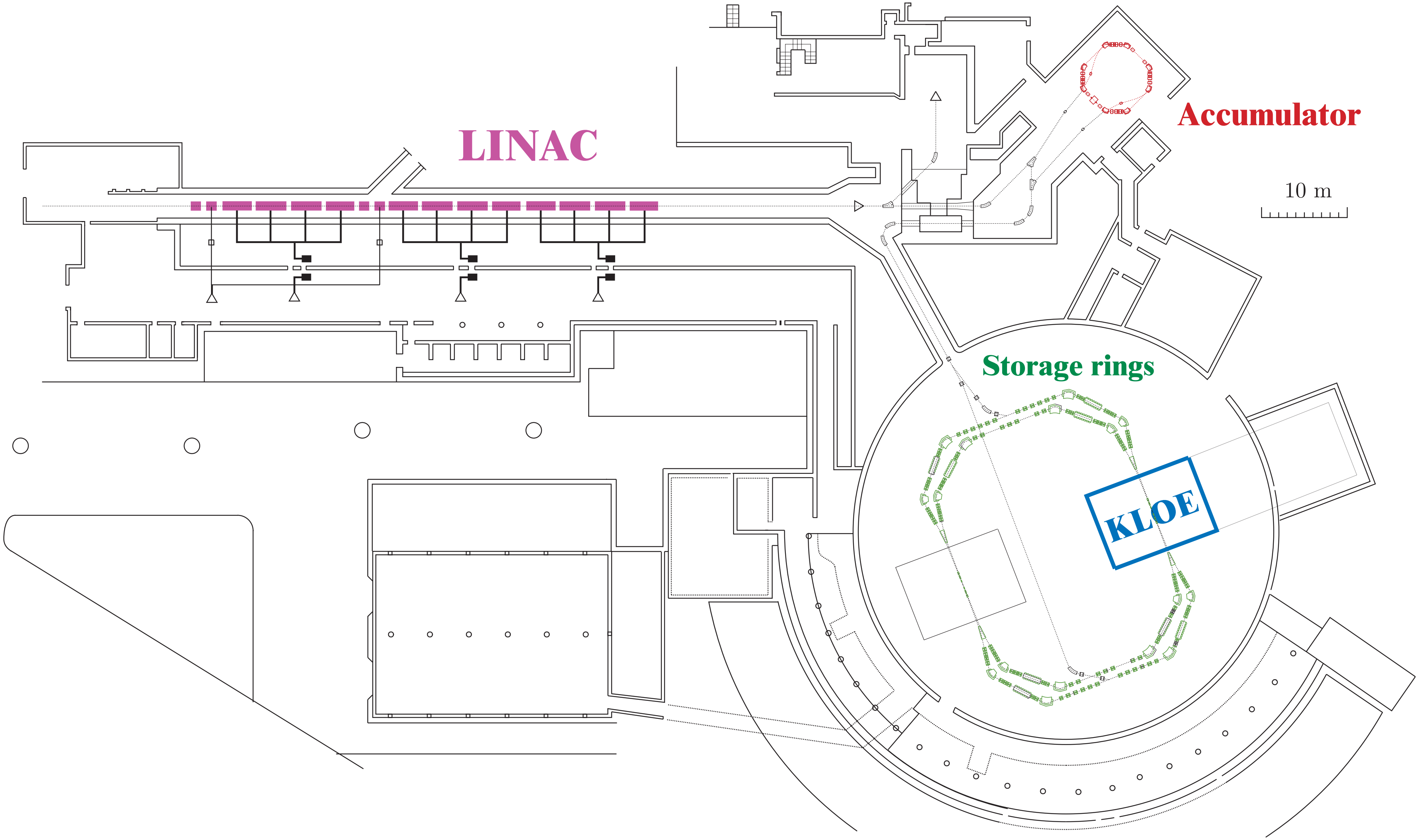
2 rings collider

N+N bunches, $\mathcal{L}$=N$\times\mathcal{L}_0$

DAΦNE RINGS



DAΦNE

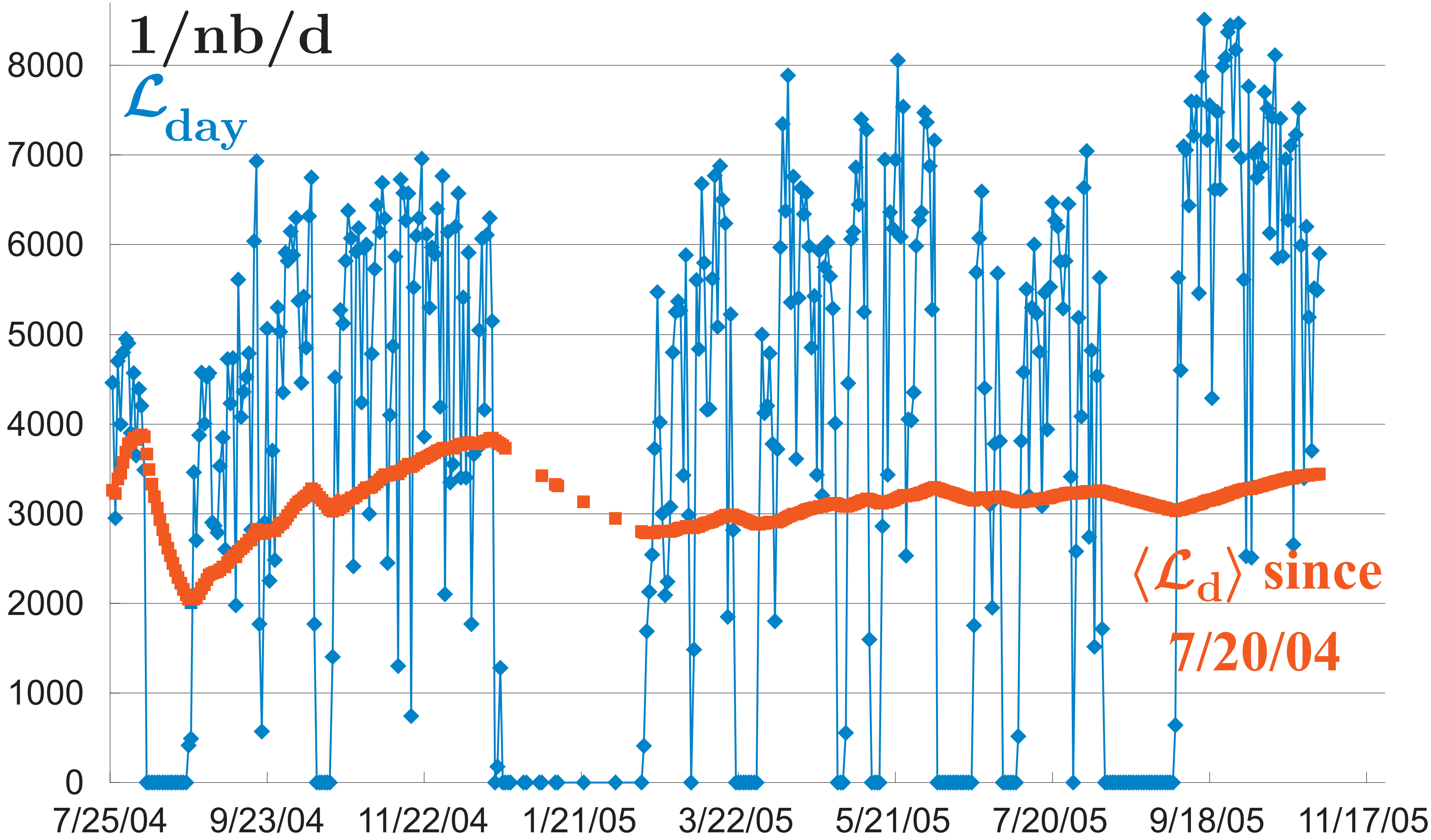


DAΦNE

Parameter	Design	Today
Bunches	120	100
Current (A)	5	1.2
$\mathcal{L}$ (μb^{-1} s^{-1})	5×10^{32}	1.4×10^{32}
Beam τ (h)	20	0.5
$\int_{1\mathrm{y}}\mathcal{L}\mathrm{d}t$ pb^{-1}	5000	1300

Crossing angle=12.5+12.5 mrad

DAΦNE



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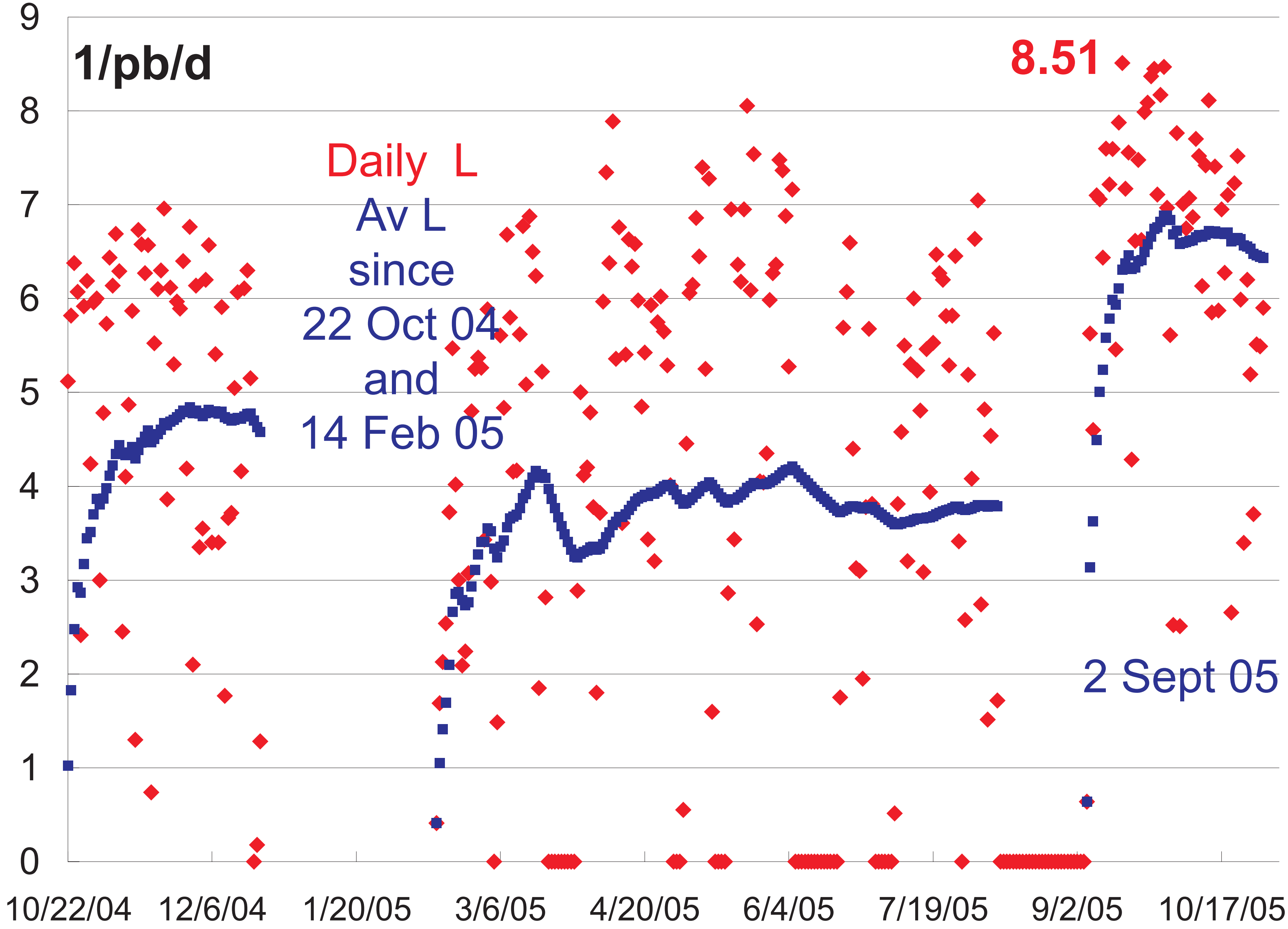
DAΦNE



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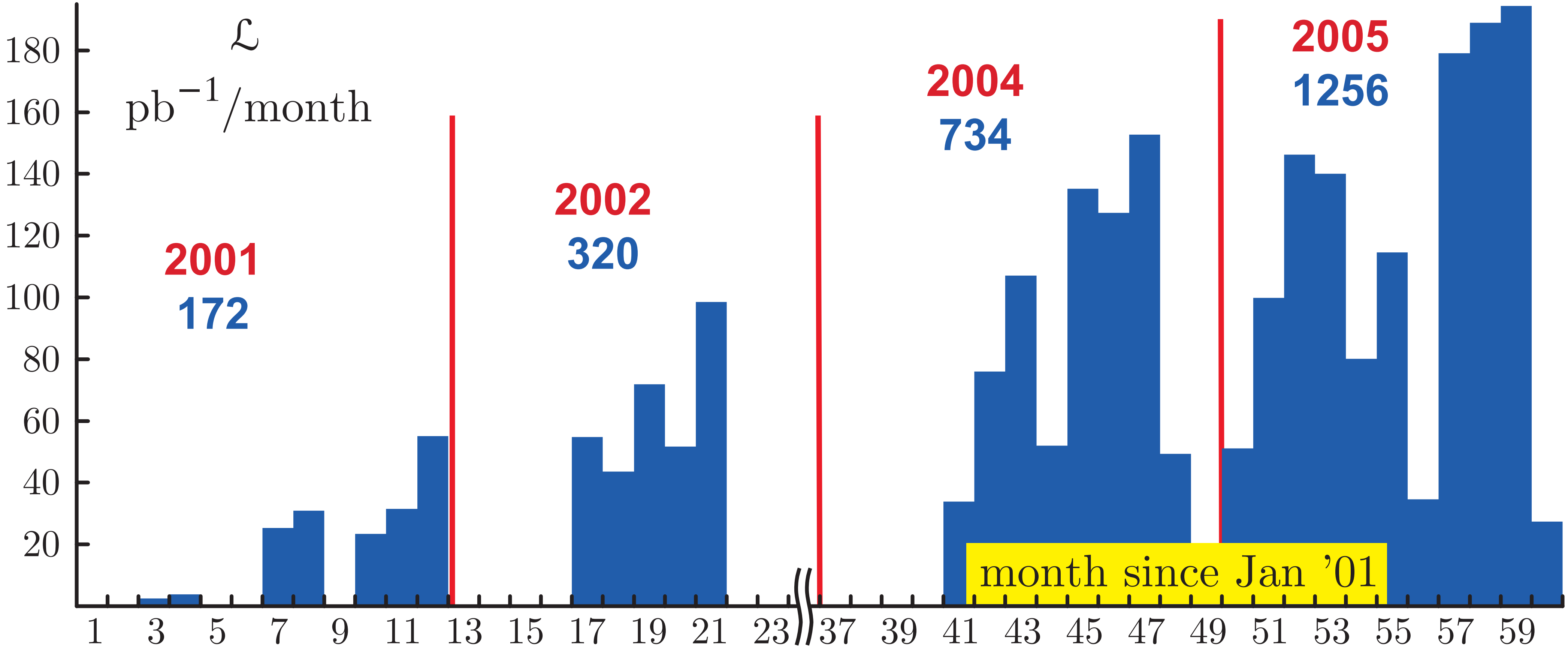
DAΦNE



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KLOE

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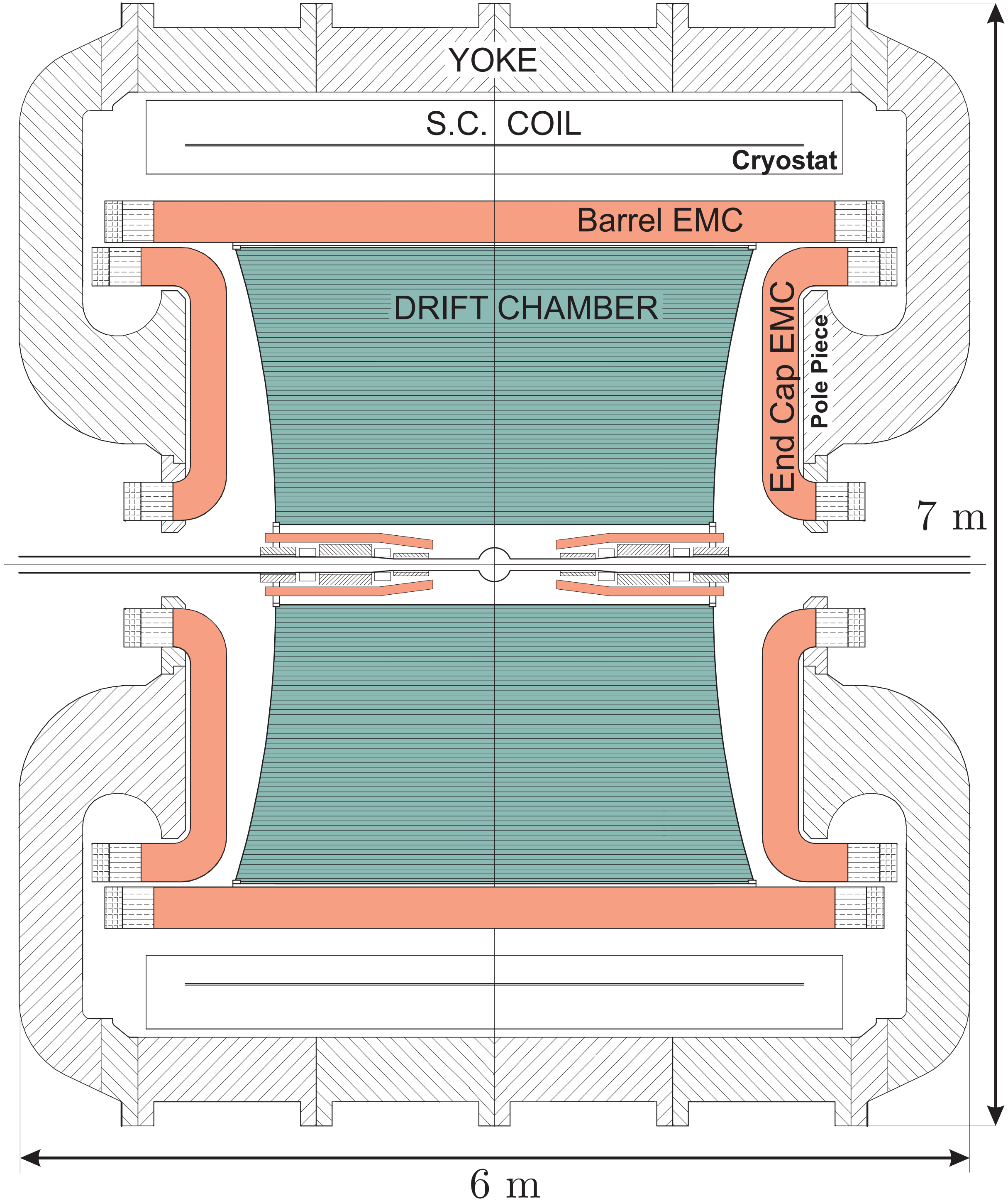
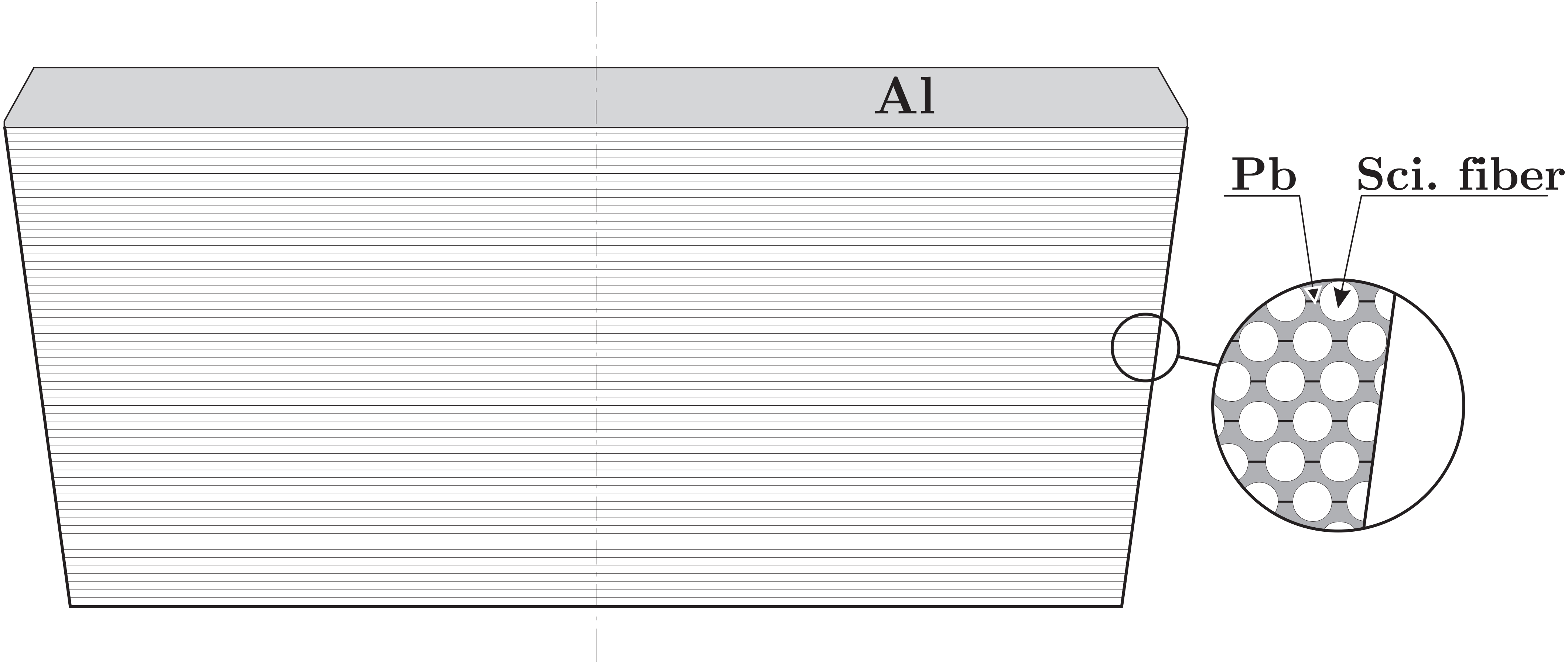

YOKE
S.C. COIL
Cryostat
Barrel EMC
DRIFT CHAMBER
End Cap EMC
Pole Piece
7 m
6 m

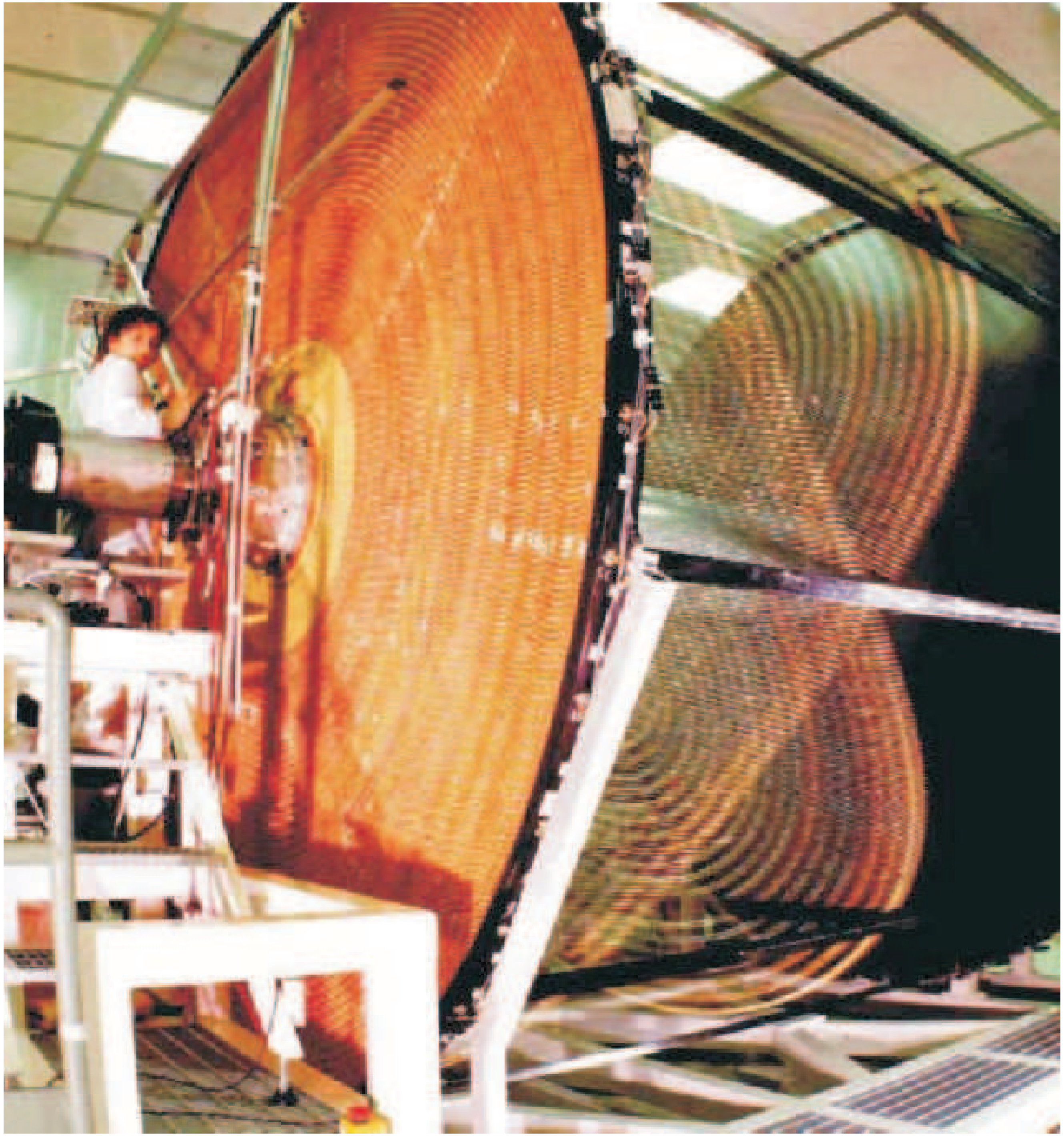
KLOE



200 fiber layers + 200 pb layers

430 cm long× 23 cm thick

Trapezoidal ×-section, bases 59 and 52 cm



52,000 wires - Al + W.

All C-fiber construction.

Spherical end-plates tensioned while stringing.

He + 10% iso-C_4H_{10}+ water 0.5%.

Wire tension measured electrostatically.

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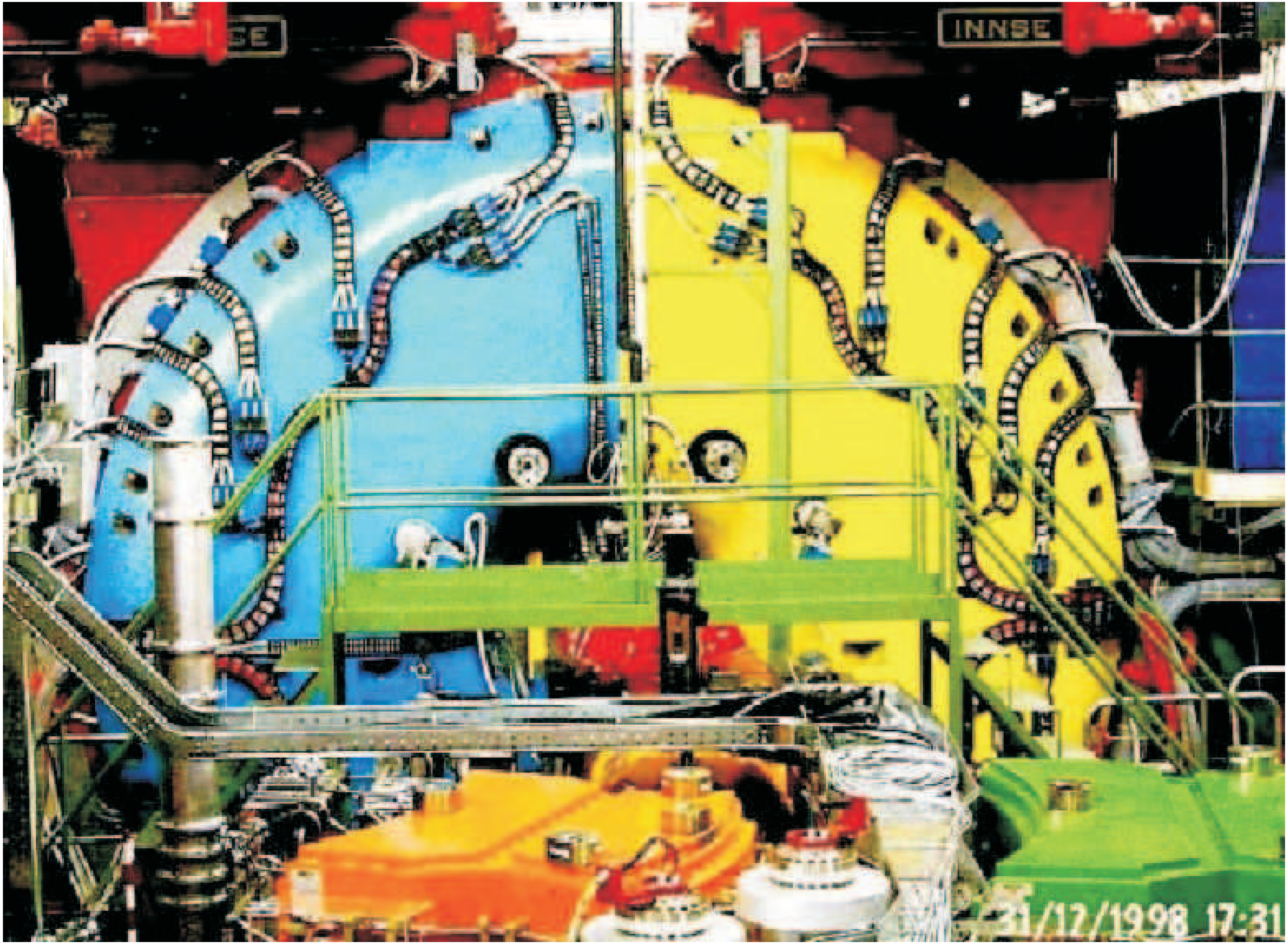

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KLOE

Calorimeter

Pb-scintillating fibers

$L \leq$4.5 m

Both ends read out

4880 pm tubes

$\sigma(E)/E$=5.7% at 1 GeV

$\sigma(t)$=70 ps at 1 GeV

$\sigma(x,y)$=1.2 cm

$\sigma(z)$=1.2 cm at 1 GeV

Provides trigger signals

Drift chamber

4 m dia., 3.5 m long

12,000 cells, 2×2, 3×3 cm^2

All stereo, variable

$\sigma(d)\sim$120 μm

B=6 kG

$\sigma(p_\perp)/p_\perp$=0.4 %, $\theta >$45°

d$E/$dx, 12-wire groups

Provides trigger signals

KLOE

Trigger

Single energy release in EMC

Dual thresholds

Combinatorial logic

Saturated hit counts in DC layers, fast and slow

Slow count can abort trigger

Bhabha trigger

Cosmic ray veto

Luminosity measurements

Calibration

EMC E: Cosmic rays

: $\gamma\gamma$

EMC t: Cosmic rays

: $\gamma\gamma$

DC $s-t$: Cosmic rays

: Bhabha

Momentum scale: M_K

Calibration from data, requires ~1 h (100 nb^{-1})

Feedback to DAΦNE, in real time

Luminosity

Machine energy

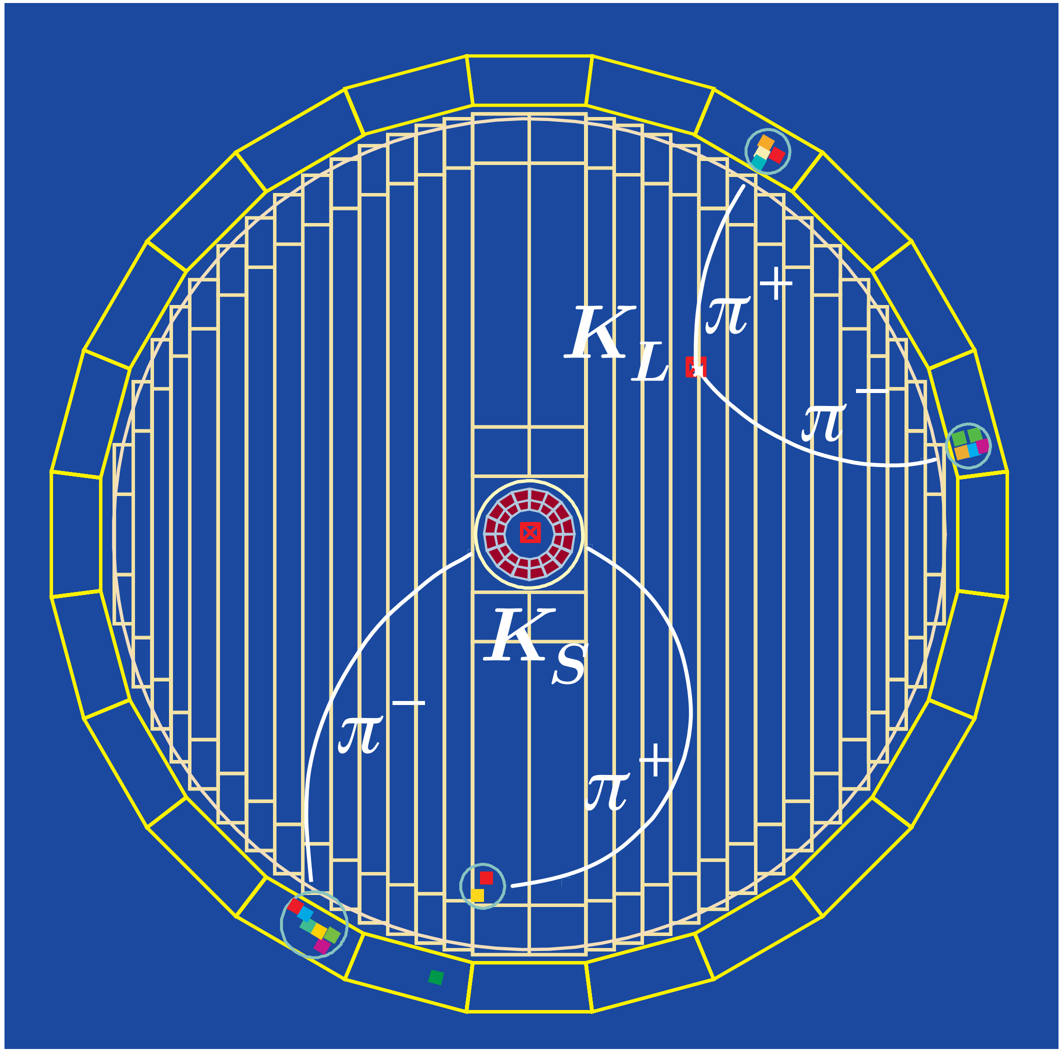
Beam x-ing position

X-ing angle

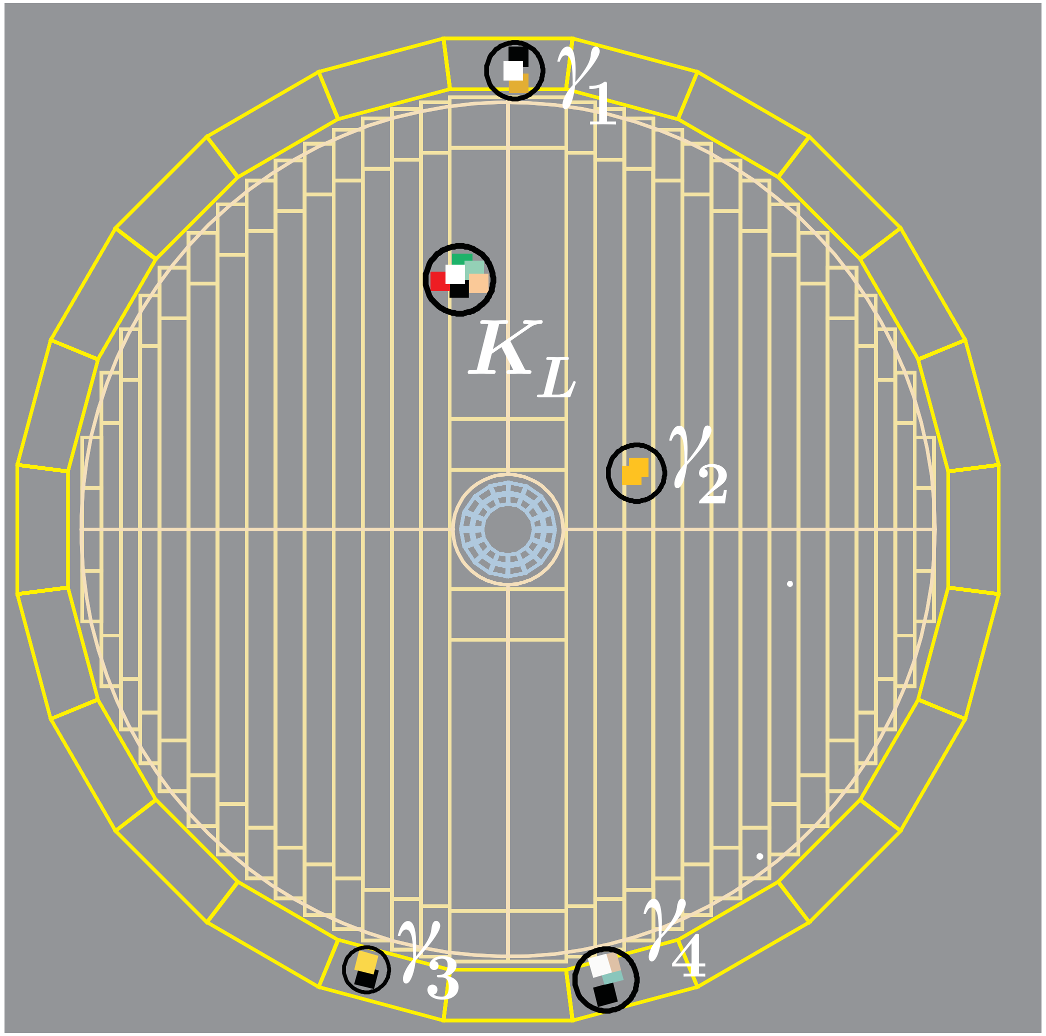
Beam size, except vertical

Background counts

The first events, April '99



$K_S \to \pi^+\pi^-$, $K_L \to \pi^+\pi^-$



$K_S \to \pi^0\pi^0$, K_L interacts in ECal

$\phi \to K_S K_L$ $\quad\quad$ $K_S \to \pi^+\pi^-$ or $K_S \to \pi^0\pi^0 \to 4\gamma$

Par	Val	Unit
E_K	510	MeV
p_K	110	MeV
β_K	0.2	–
γ_K	1.04	–
E_γ	15-300	MeV
p_π	100-300	MeV/c

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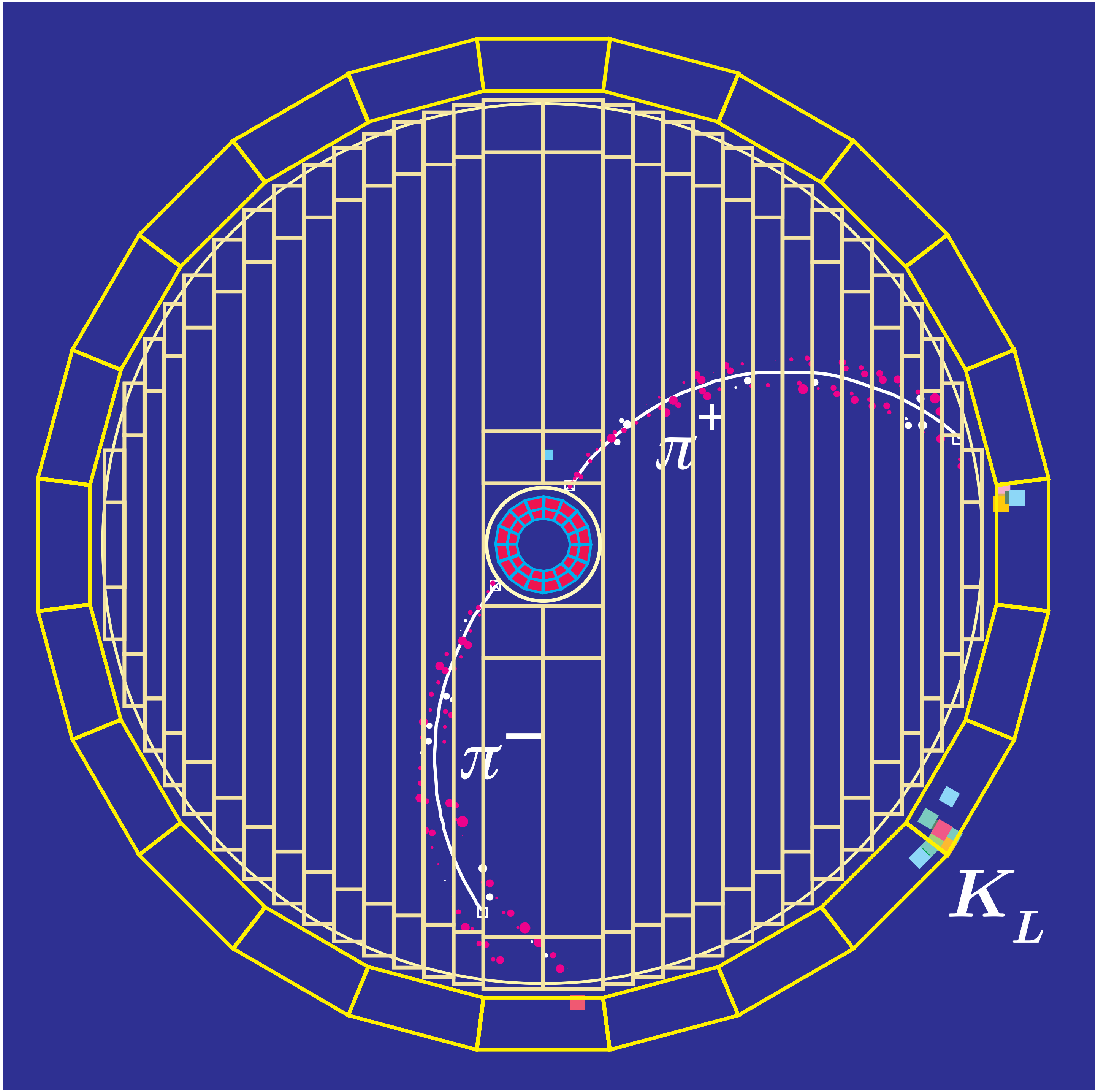
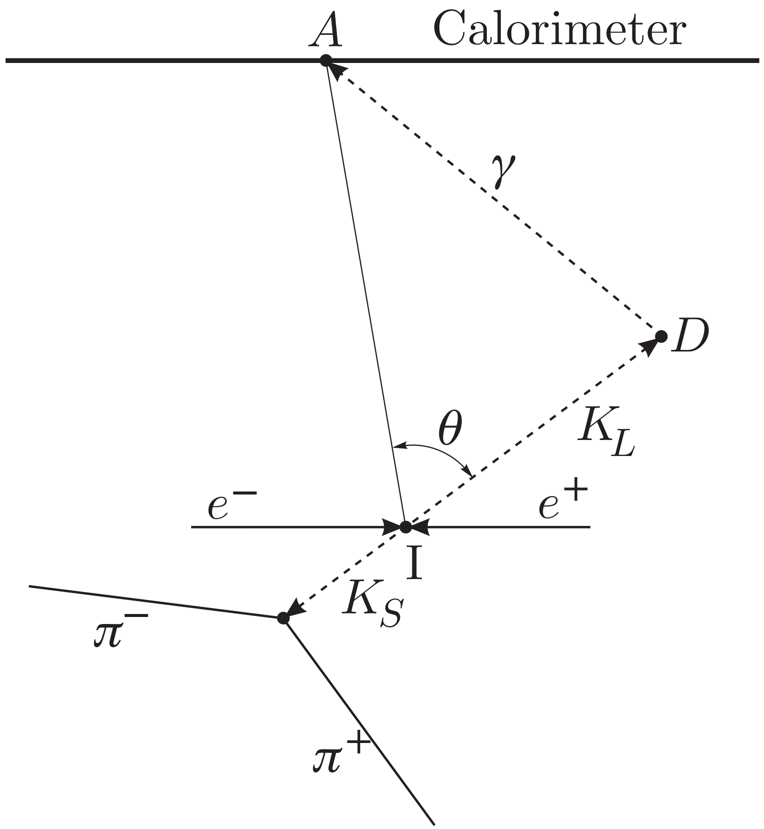


"K_L-crash"

Neutral particles in KLOE

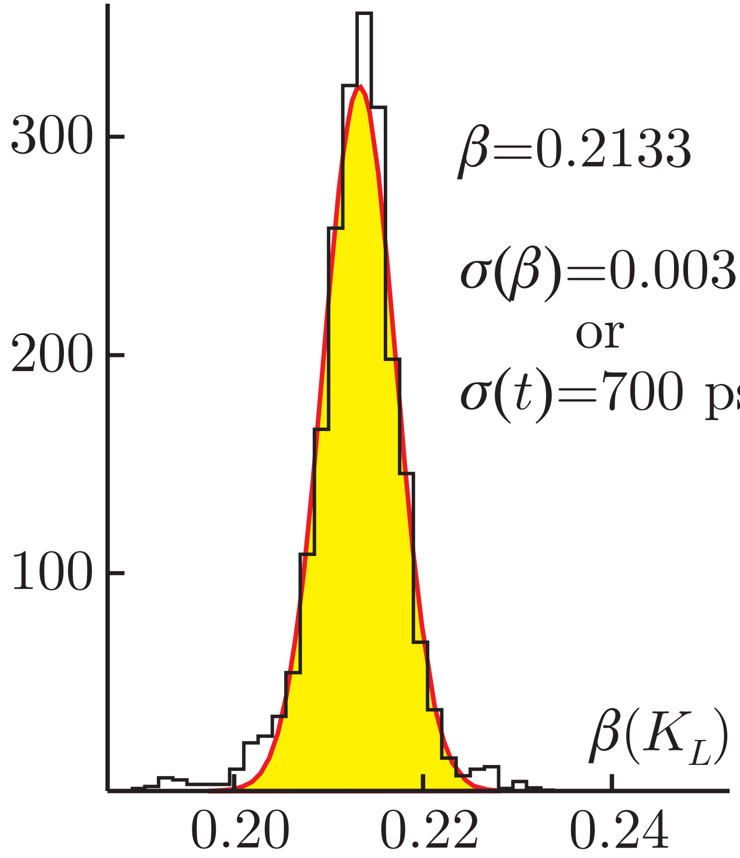
Locating $K^0 \to \gamma \ldots$ point



Find K_L decay point from $t(I \to A)$
and K_S direction

Identify "K_L-*crash*"

$\beta(K_L)$ in ϕ CM



δW(DAΦNE)=1 MeV
gives $\delta\beta$=0.004

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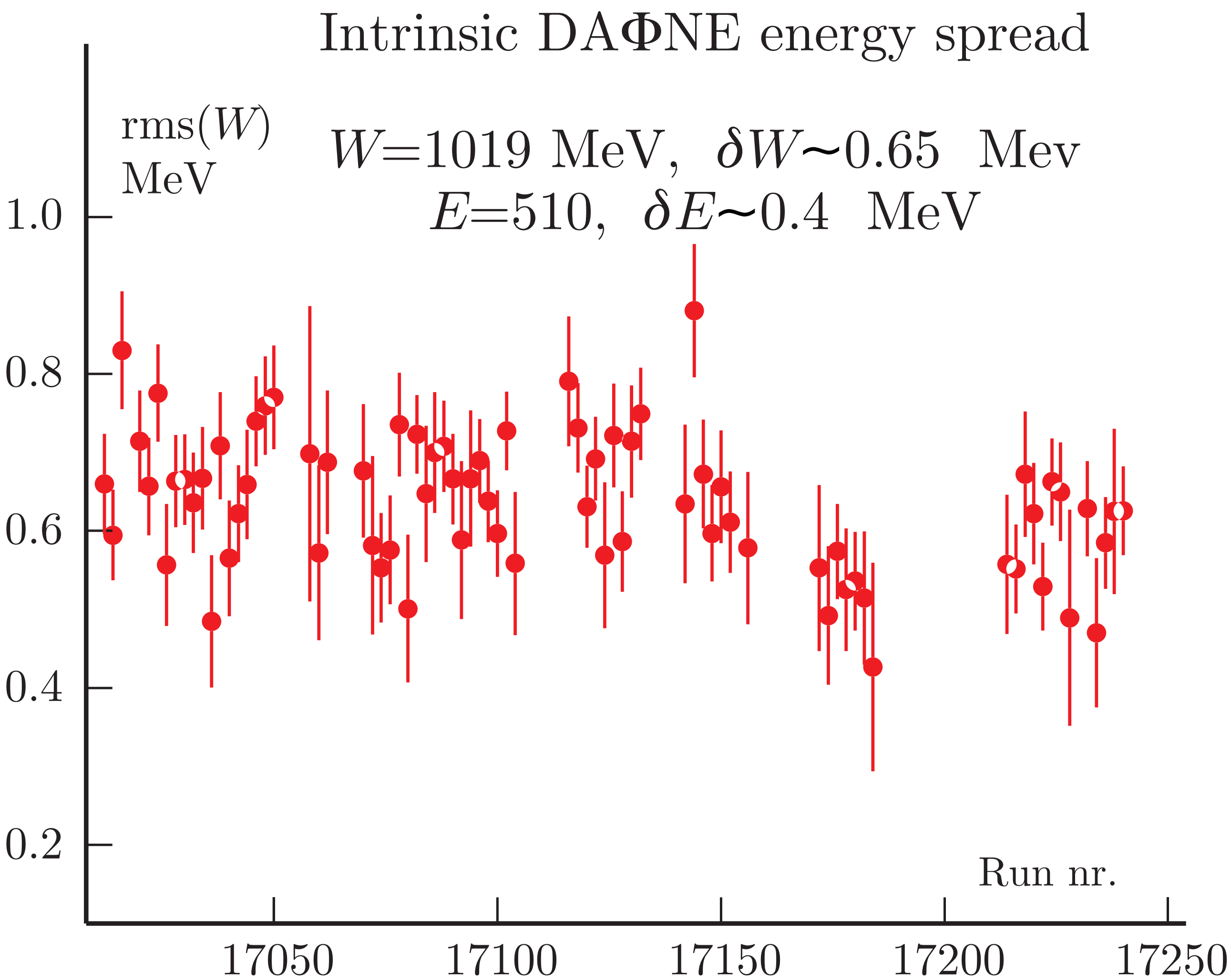
For events with $K_S \to \pi^+\pi^-$and K_L-crash we have two independent measurements of W: W_S and W_L. We take the difference and sum of the two value, $\Delta = W_S - W_L$ and $\Sigma = W_S + W_L$. The intrinsic machine energy spread cancels in Δ. The rms fluctuation of Δ is the KLOE energy resolution σ_E while for Σ the fluctuation is $\sqrt{\sigma_E^2 + \sigma_W^2}$, where σ_W is the DAΦNE intrinsic energy spread, $\sim\sqrt{2}\times\sigma_{\mathrm{B}}$ with σ_{B} the energy spread of the beams.

From the observed rms(Δ) and rms(Σ) we find σ_W.

DAΦNE Energy spread

Use $p(K_S)$ and $\beta(K_L)$, two independent values of w(DAΦNE)

From w_1+w_2, beam spread dependent and w_1-w_2 b. s. ind.:



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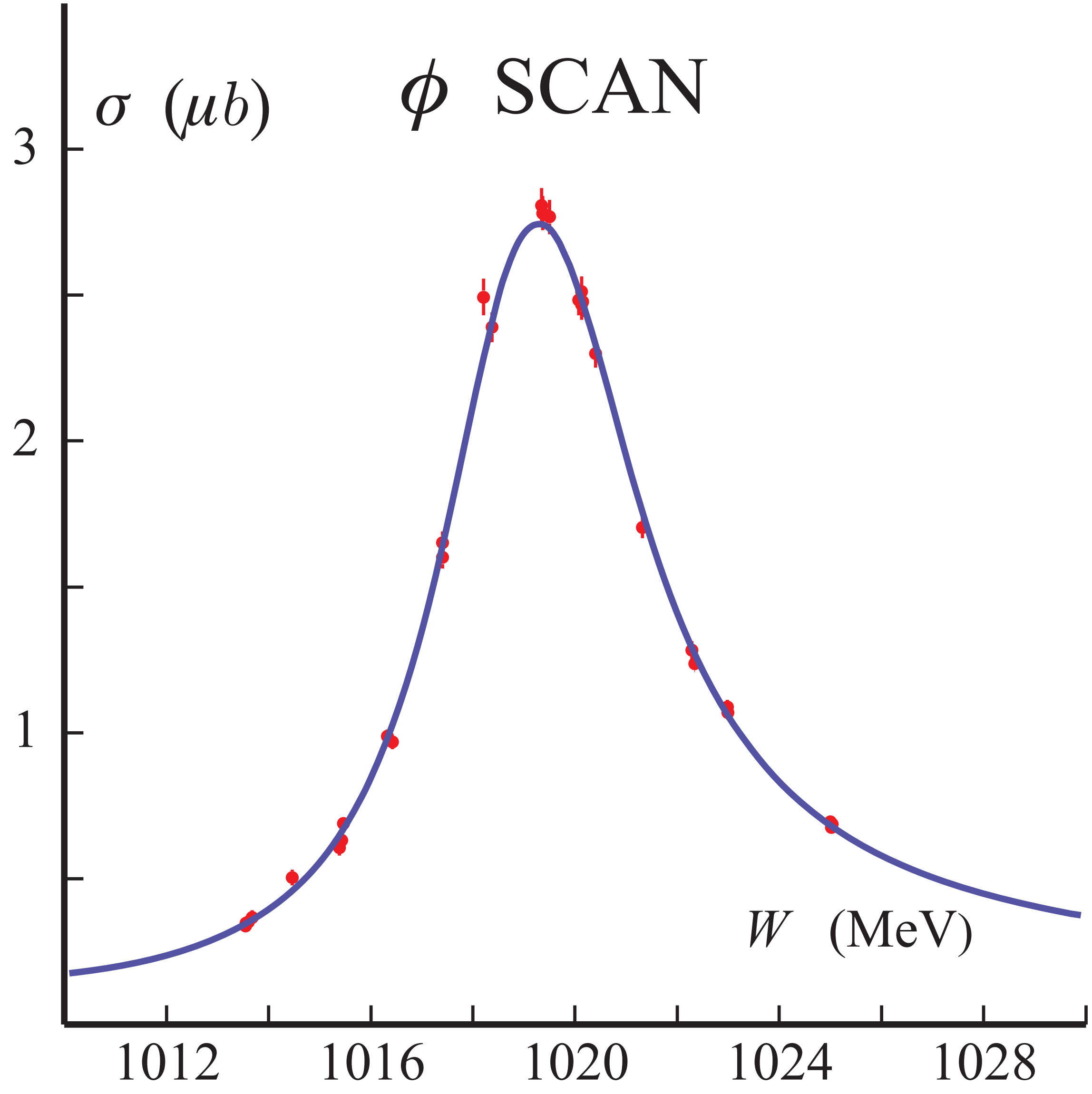
Absolute scale calibration



300,000 K_S events

$M = 1019.7$ MeV

$\delta M = 10$ keV

Calibrates scale by comparing with $g-2$ depolarization measurements

$M(\phi)$=1019.460$\pm$0.019 MeV (PDG)

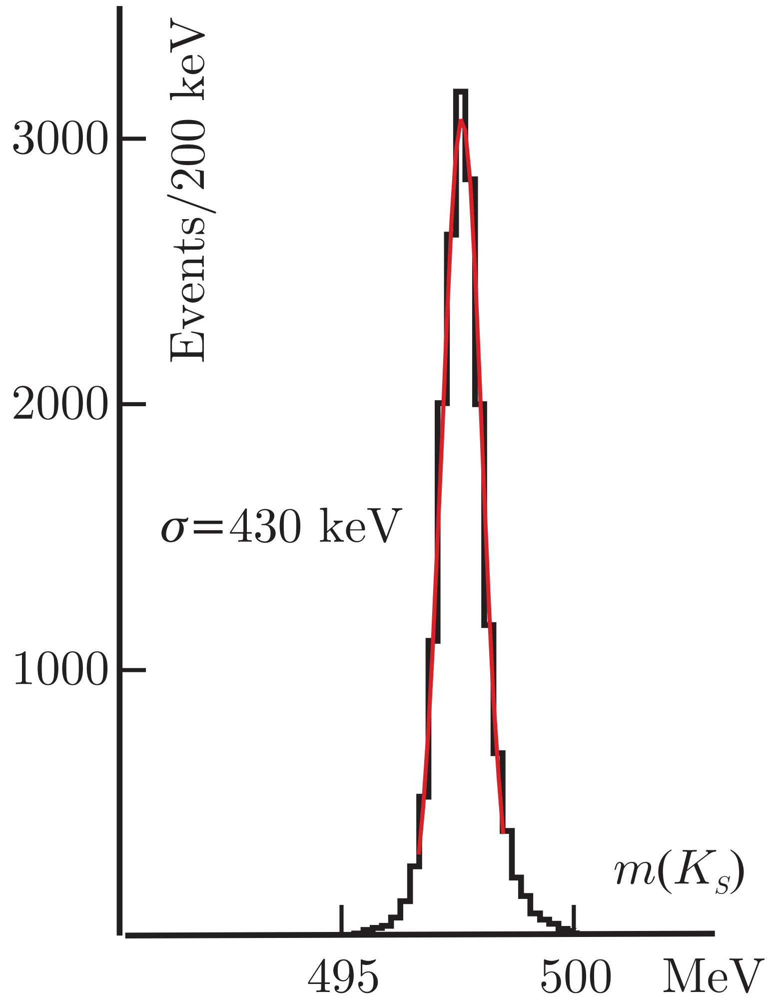
Rad corr, β^3...

Kinematics

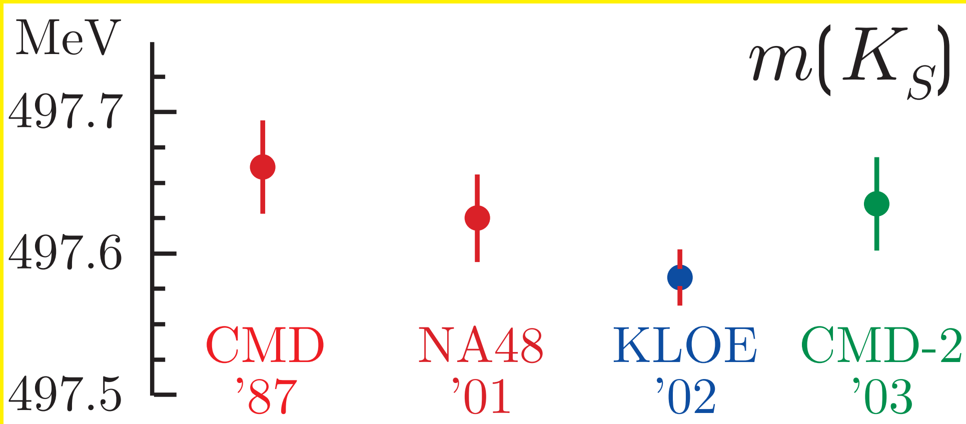
$$
\begin{array}{lll}
1 \quad - \quad E_K^2 = m_K^2 + p_K^2 & & \color{red}{\delta E_K} = \beta\delta p_K \\
2 \quad - \quad E_K = m_K \times \gamma & \Rightarrow & \color{blue}{\delta E_K} = E_K\beta\gamma^2\delta\beta_K \\
3 \quad - \quad m_K^2 = E_K^2 - (\vec{p}_{\pi^+} + \vec{p}_{\pi^-})^2 & & \color{green}{\delta m_K} \cong 2\beta\delta p_K
\end{array}
$$

1. With one event $p(K_S \to \pi^+\pi^-) \Rightarrow \delta W_{DA\Phi NE}$~0.4 MeV
2. With one event $\beta(K_L) \Rightarrow \delta W_{DA\Phi NE}$~0.8 MeV
3. With one event $m(K_S \to \pi^+\pi^-) \Rightarrow$ KLOE scale to 0.4%

$M(K_S)$



$$m(\phi) - 2m(K_S) = 26 \text{ MeV}$$
$$(1/2m(\phi))^2 \cong m^2(K_S) + p^2_{K_S}$$
$$\delta M_{KLOE} \sim 270 \text{ keV}$$
$$\delta M_{DA\Phi NE} \sim 220 \text{ keV}$$
$$\delta M_{RadCor} \sim 20 \text{ keV}$$



$$m(K_S) = 497.583 \pm 0.005 \pm 0.020 \text{ MeV}$$

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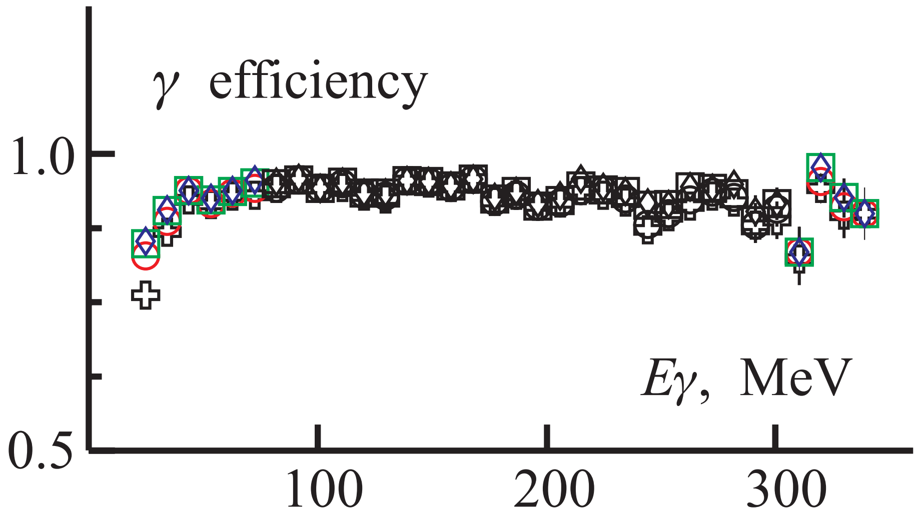
Who is right? QED rad corr are site dependent

Efficiencies

1. γ efficiency vs E, θ
2. Track efficiency
3. Vertex efficiency
4. Trigger efficiency

From $K_L \to \pi^+\pi^-\pi^0 \to \pi^+\pi^-\gamma\gamma$ find direction and momentum of one γ. Compare with cluster finding result. Adjust algorithm.



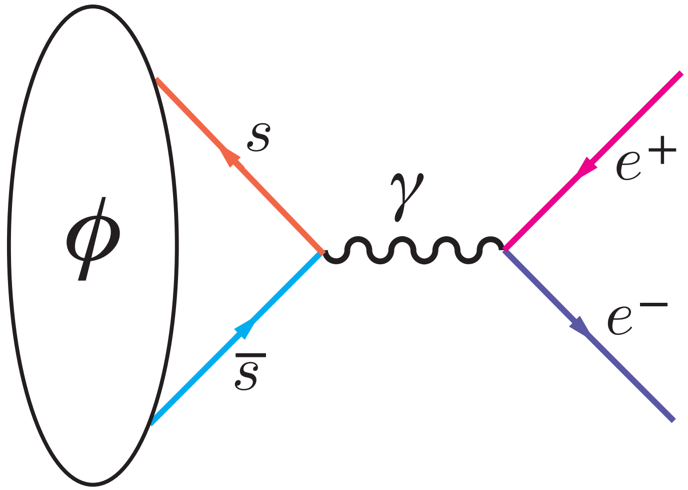
All done from data. MC cross checks/adjustments.

$\boxed{\Gamma_{ee}(\phi)}$

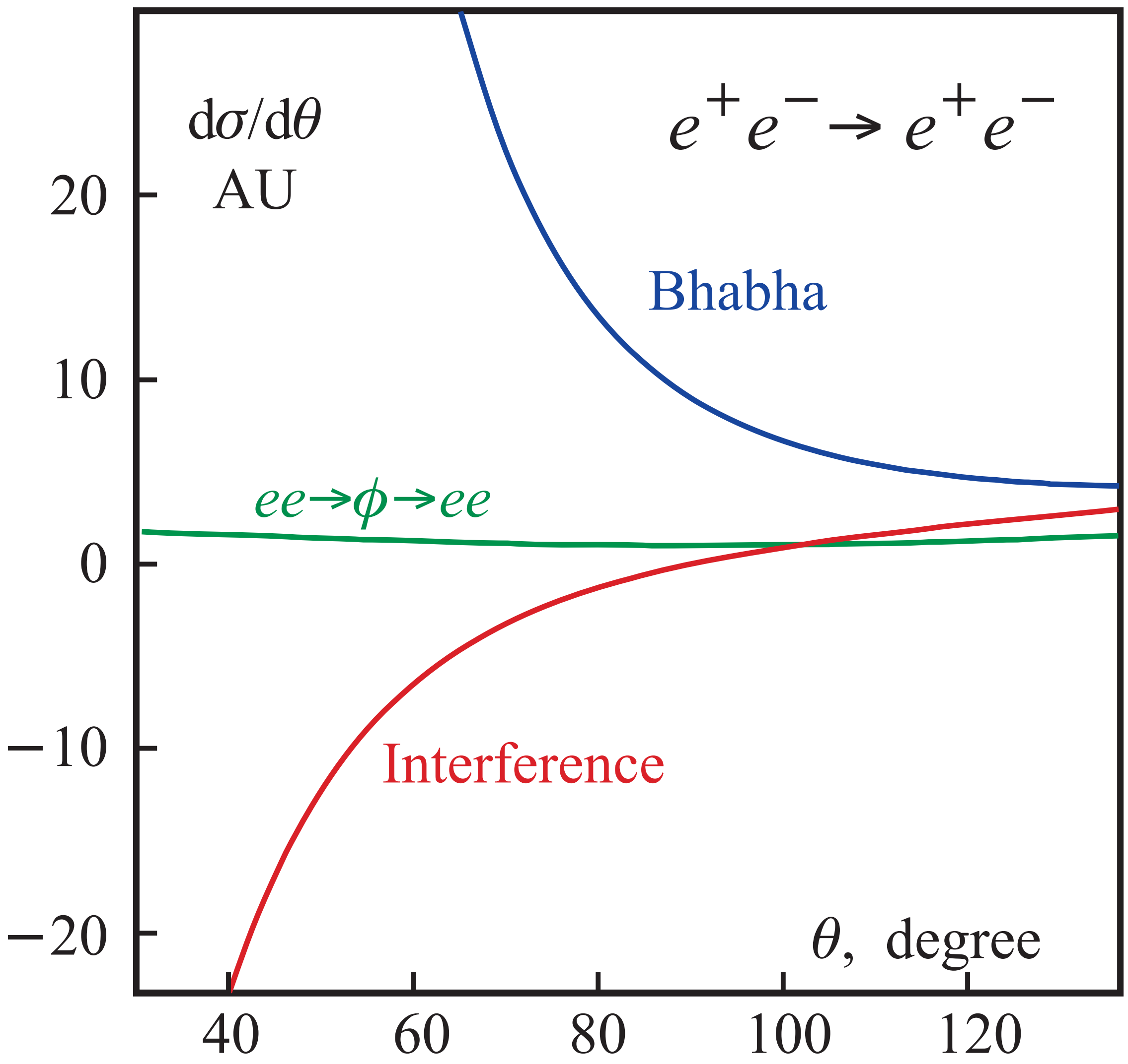
Directly connected to the vector meson wave function and quark charge.

"Weiskopf - Van Royen formula", 1967

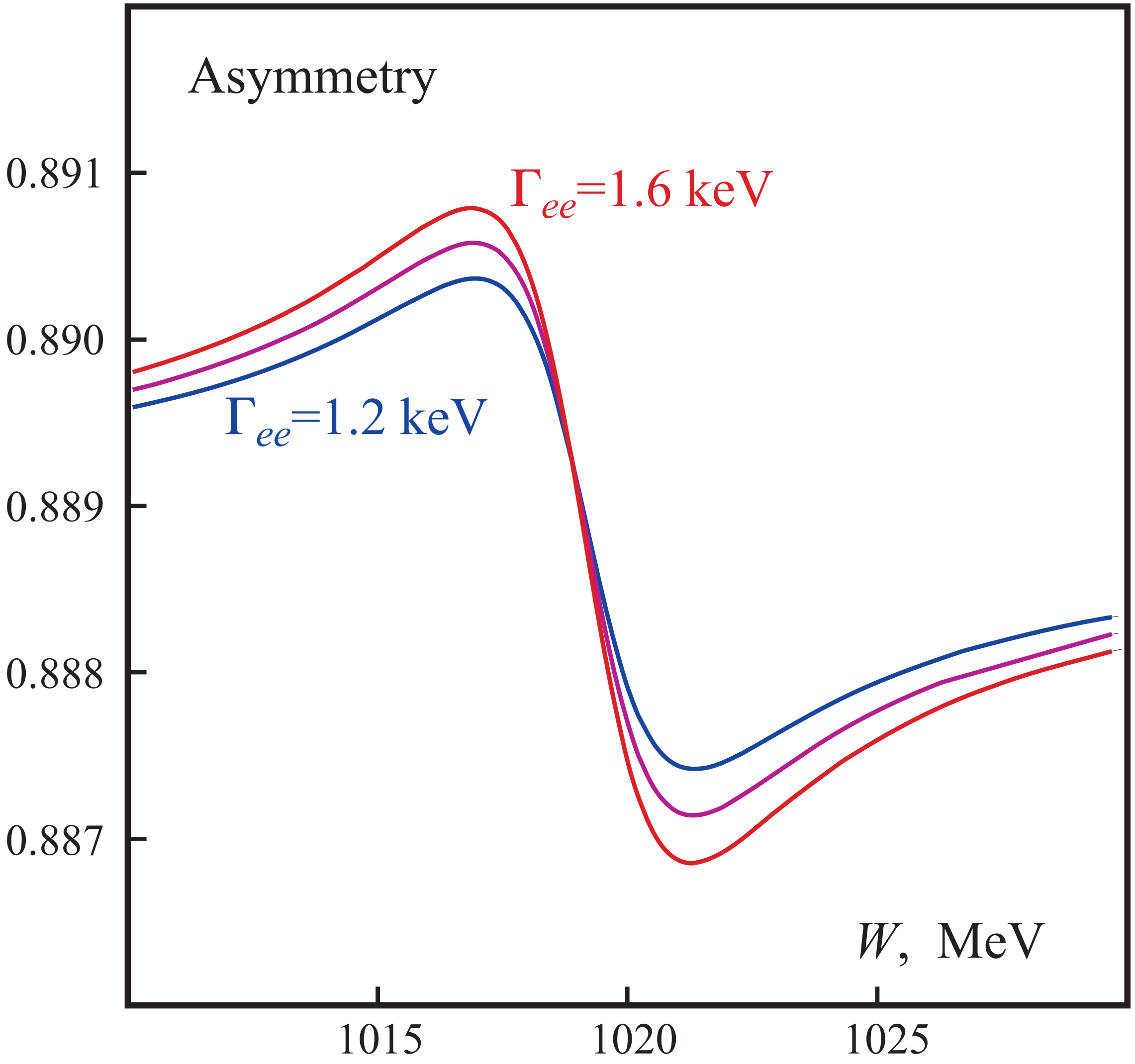
$$\Gamma_{ee} = \frac{16\alpha^2 q_s^2}{M^2} |\Psi(0)|^2 (1 - \frac{16\alpha_s}{3\pi} \ldots)$$



$$\boxed{e^+e^-\to e^+e^-}$$

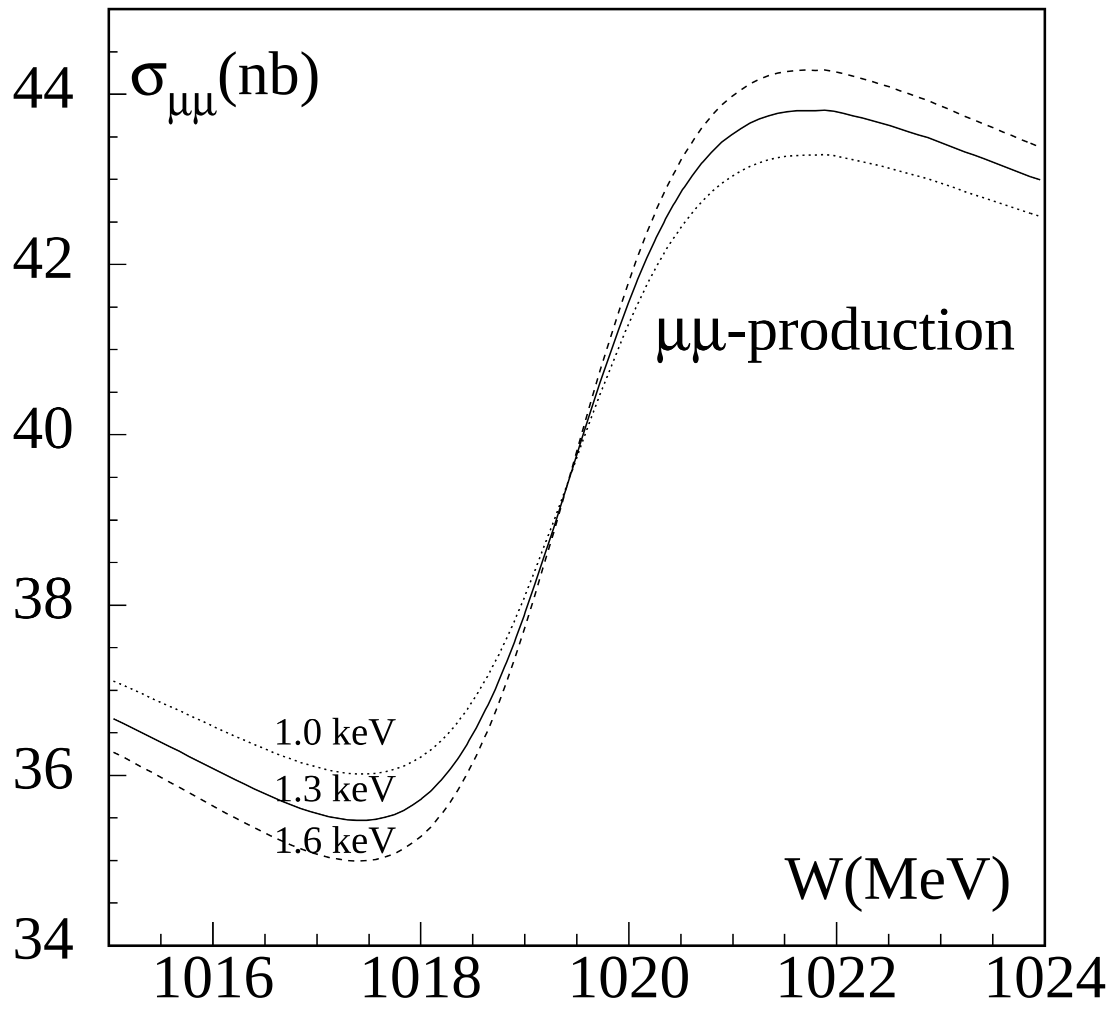


Asymmetry



Asymmetry
0.891
0.890
0.889
0.888
0.887
Γ_{ee}=1.6 keV
Γ_{ee}=1.2 keV
W, MeV
1015
1020
1025

$\boxed{e^+e^-\to\mu\mu}$



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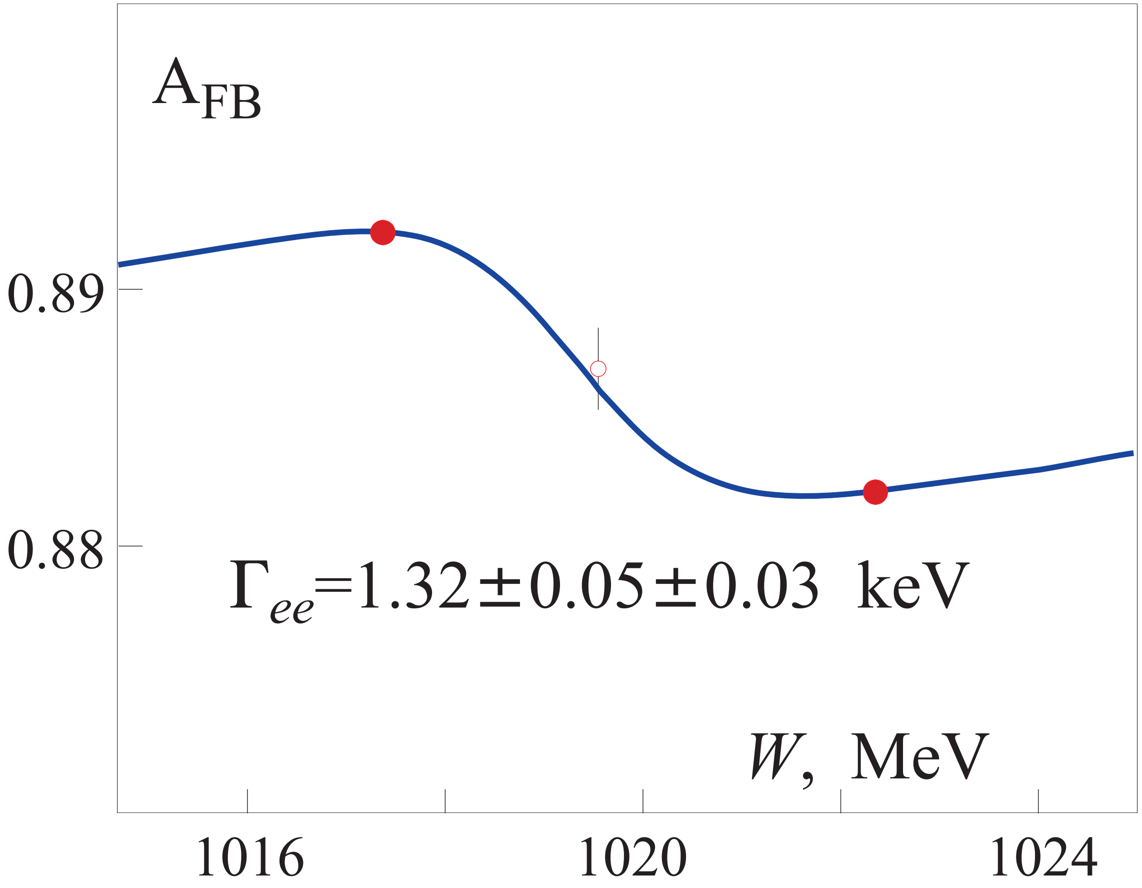
$\Gamma_{\ell\ell}(\phi)$



$$\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}} = 1.320 \pm 0.018 \pm 0.017$$

$$\Gamma_{\ell\ell}(\phi) = 1.320 \pm 0.023 \text{ keV}$$

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V_{us}

1. Flavor mixing, Cabibbo '63
   (a) Kaons were discovered 60 years ago.
   (b) Soon strangeness was introduced to explain, not really justify maybe, the slowness of the strangeness changing processes.
   (c) $|\Delta S|=1$ processes were recognized as weak processes, similar to nuclear β-decay, muon and pion decays.
   (d) By '59 it was clear that $|\Delta S|=1$ decays where about 20 times slower than $|\Delta S|=0$ decays.
   (e) In '63 Cabibbo introduced flavor mixing. In modern language the u-quark couples to $d\cos\theta + s\sin\theta$, a vector in $\{d,\, s\}$ space of unit length, $\sin\theta \sim 0.25$, from $K_{\mu 2}/\pi_{\mu 2}$.

This is usually referred to as unitarity and was invented in order not to introduce a new Fermi constant.

2. GIM, 1970

Two quark doublets

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}, \qquad J_\alpha = \bar{\mathbf{U}}\gamma_\alpha(1-\gamma_5)\mathbf{V}\mathbf{D}$$

$$\mathbf{U} = \begin{pmatrix} u \\ c \end{pmatrix},\ \mathbf{D} = \begin{pmatrix} d \\ s \end{pmatrix},\ \mathbf{V}\dagger\mathbf{V} = 1,\ \Rightarrow \mathbf{V} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

No FCNC. No $K^0 \to \mu\mu$. $M(K_L) - M(K_S) \sim \Gamma(K_S)$

3. KM

Three quark doublet, 3×3 unitary mixing matrix ⇒ 3 rotations plus one phase, $\not{C}\not{P}$ is allowed.

$$\mathbf{V}_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \cdots & & \\ \cdots & & V_{tb} \end{pmatrix}$$

Some $V's$ are complex; 6 "unitarity" triangles with same area and

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=|V_{ud}|^2+|V_{us}|^2+2\times10^{-5}=1$$

CUSB, 1983, $<4\times10^{-5}$

4. Measuring $|V_{us}|$

$$\Gamma(|\Delta S|=1 \text{ decay})\propto\overline{|\langle f|J_\alpha J^\alpha|i\rangle|^2}\propto G^2|V_{us}|^2$$

$$\langle\ell\nu|J_\alpha^\ell|0\rangle=\bar\ell\gamma_\alpha(1-\gamma_5)\nu$$

(a) Hadron are not pointlike, extra t dependence

(b) $SU(3)_{\text{flavor}}$ breaking

(c) Isospin breaking

(d) But, for $0^-\to0^-$ transitions, only vector part contributes and $SU(3)$ breaking appears only to second order. A&G

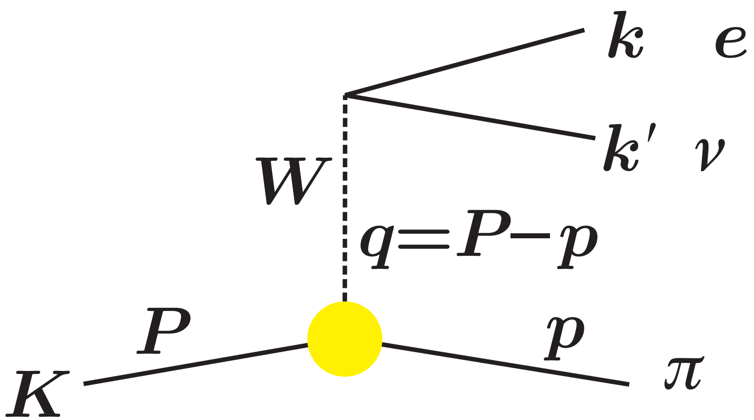
5. Best choice $K \to \pi\ell\nu$:

$$K_L \to \pi^{\pm}\ell^{\mp}\nu(\bar{\nu})$$
$$K_S \to \pi^{\pm}\ell^{\mp}\nu(\bar{\nu})$$
$$K^{\pm} \to \pi^{0}\ell^{\pm}\nu(\bar{\nu})$$

Ignoring $SU(3)$, $SU(2)$ breaking (and em corrections), from L-invariance $\Rightarrow$

$$\langle\pi|J_\alpha^{\text{hadr}}|K\rangle = c_i \times (f_+(t) \times (P+p)_\alpha + f_-(t) \times (P-p)_\alpha)$$

where P, p are the kaon and pion 4-momenta and $t=(P-p)^2$. c_i depends on the kaon, pion and J_α I-spin property and one must be careful with $K^{\pm}$ vs K_S, K_L.



Because of $SU(3)$ breaking, $f_{+,-}(0) \neq 1$. We shall use $f(t) = f(0)\times\tilde{f}(t)$ with $\tilde{f}(0)=1$.

this is tex

6. $f(0)$

   $f(0)$ computed from prime principles. L&R, 1984 gave $f(0)$=0.961±0.008. Lattice calculation of $f(0)$ are very promising and will soon give more precise answers. At the moment it is the outstanding obstacle to overcome in order to obtain an accurate measurement of $|V_{us}|$

7. From PDG 2004, BR($K_{\ell 3}$) $\to\sim$2.5%

   $|V_{us}|$=0.2196, $|V_{ud}|$=0.9734, $\sum<$1. Unitarity fails to $\sim 2\sigma$? BR's are not measured but come from fits to various ratios.

8. BR's Before getting into more details we recall that

   (a) Decay Width=Decay Rate=$\Gamma = 1/\tau$

   (b) Branching Ratio, BR$_i$=Γ_i/Γ

   (c) $\Gamma(K_i \to \pi\ell_j\nu)$=BR$(K_i \to \pi\ell_j\nu)/\tau_i$
       with $i = \pm$, L, S and $j = e,\ \mu$

(d) $\Gamma_{i,j} \propto G^2\,|V_{us}|^2\,M_i^5\,I_{i,j}\,C_i$. $I_{i,j}$ are phase space integrals.

9. Form Factors

   Knowledge of the form factors, mentioned above, is necessary for the calculation of the phase space integrals. Ignoring the FF leads to errors of as much as 10% on Γ or 5% on $|V_{us}|$.

10. Corrections

    Isospin corrections and radiative corrections must be obtained and finally we remain with one problem:

11. $f(0)$

Experiments must provide

Lifetimes   Branching Ratios   The form factor shape

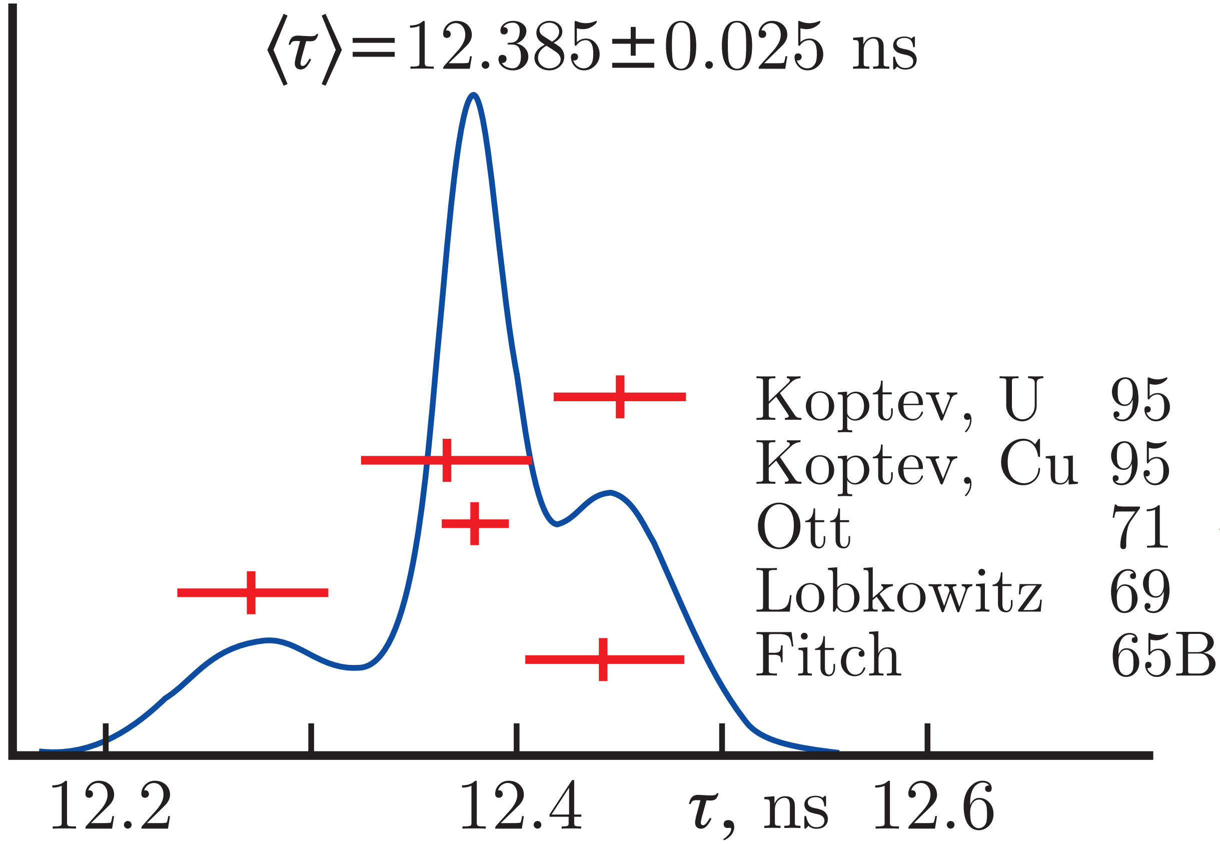
Charged particles τ

1. Monochromatic beam. Count decays vs path length $\Rightarrow$time. Fit decay curve. Beam count not necessary but available.
2. Bring particles to rest. Count decays vs elapsed time from stop. Fit decay curve. Beam count not necessary but available.
3. For known initial number N_0, count ΔN in interval Δt. $\Gamma = (1/N_0)(\Delta N/\Delta t)$

Method 3 never used in particle physics, see later.

Charged Kaons

Methods 1 and 2, but mostly 2



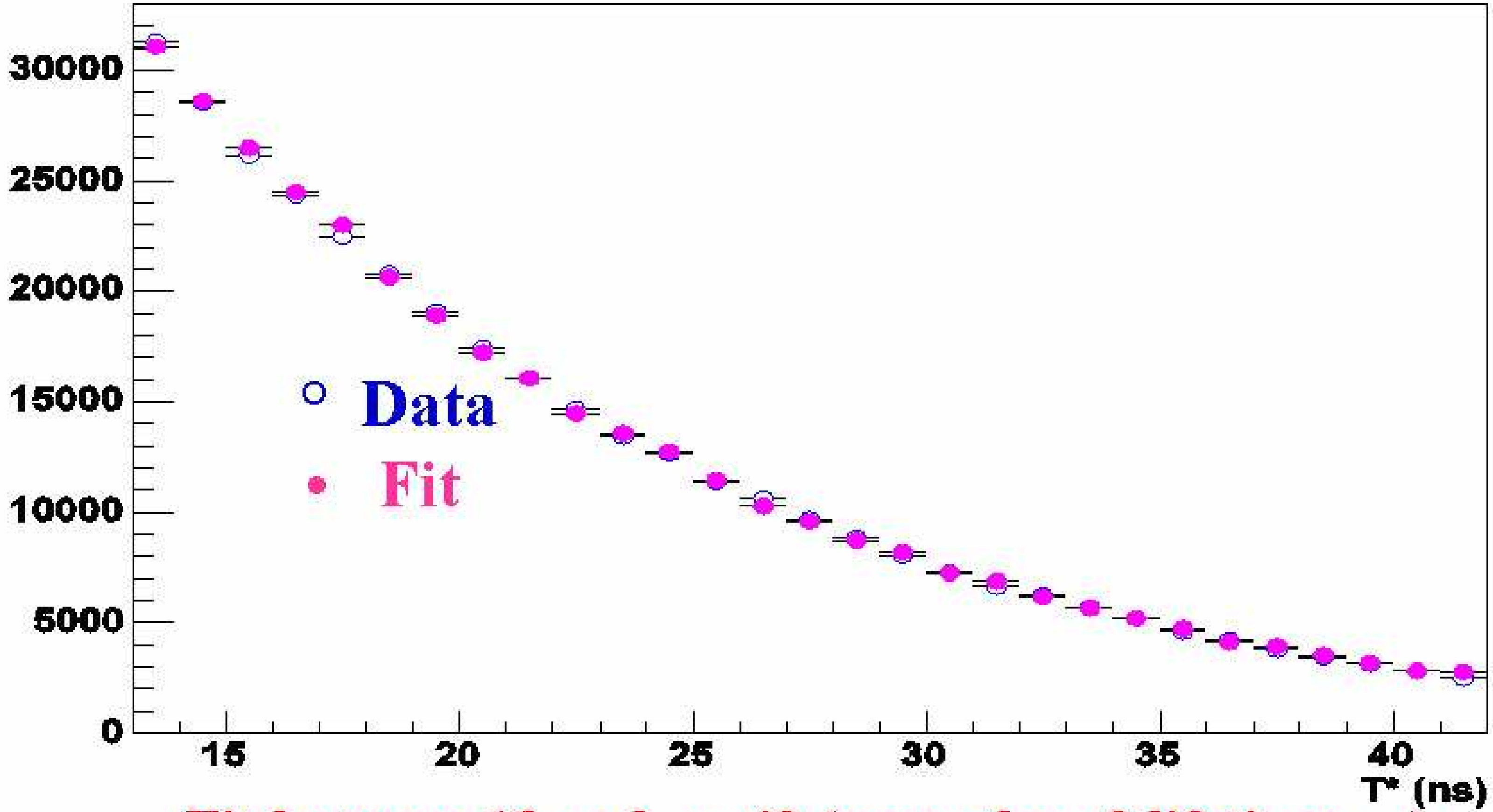
$\Leftarrow$ This error is wrong, too small by ∼2

$\delta\tau/\tau > 2 \times 10^{-3}$

WE ARE MEASURING IT, see next week

A preview

Data τ^+ measurement: largest fit window



Fit between 13 and ns 42 (more than 2 lifetimes...)

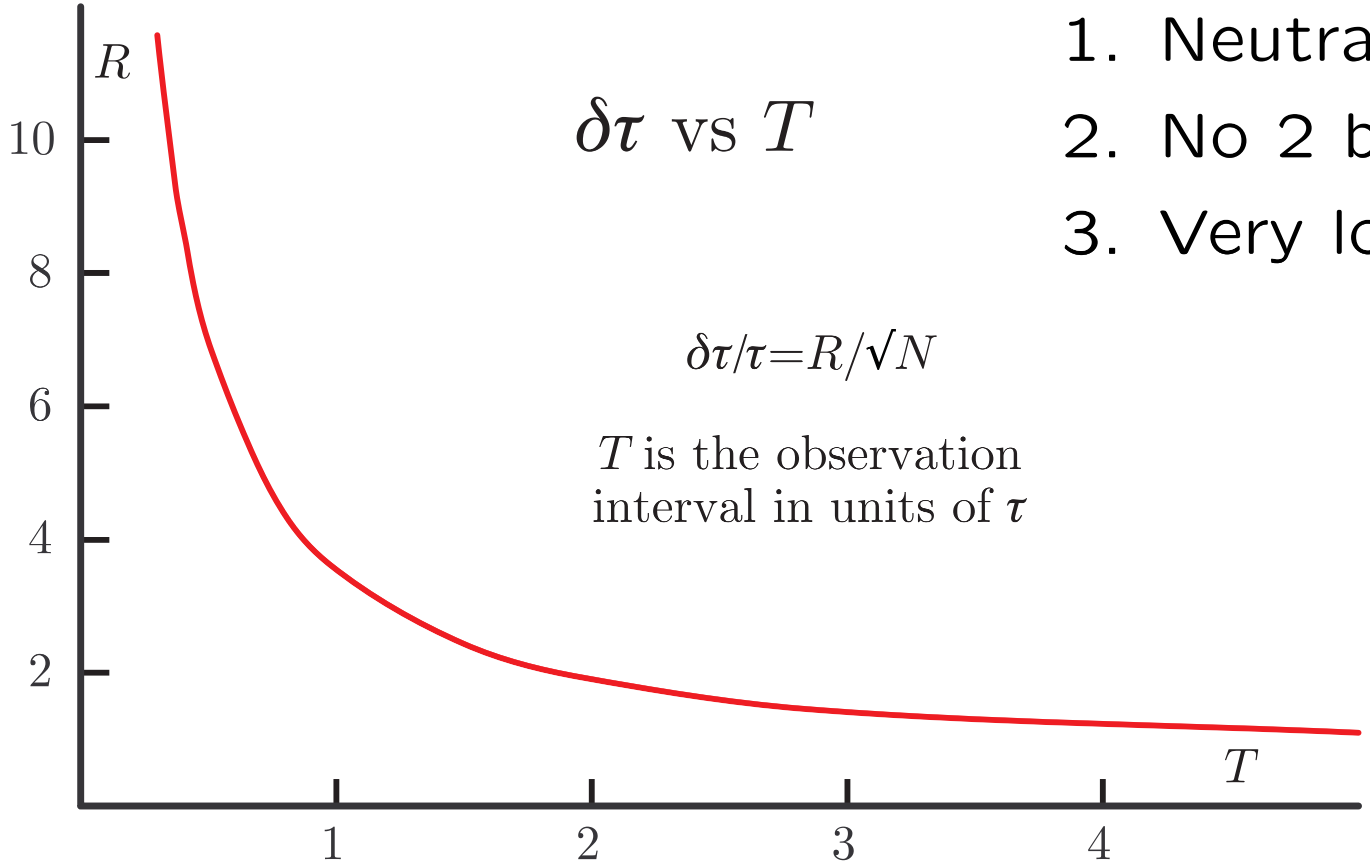
τ^{+}_{Data}=12.xxx ± 0.0xx ns χ^2/ndf = 25.7/28, $P\chi^2$ = 59.%

$$\boxed{K_S}$$

The value of τ and the copious, simple decay $K_S \to \pi^+\pi^-$ make it "easy" to precisely measure $\tau(K_S)$ by method 1. The "beam" is not monochromatic and its intensity is not known.

$$\tau(K_S) = 0.8953 \pm 0.0005; \ \delta\tau/\tau = 5.6 \times 10^{-4}$$

$\tau(K_L)$

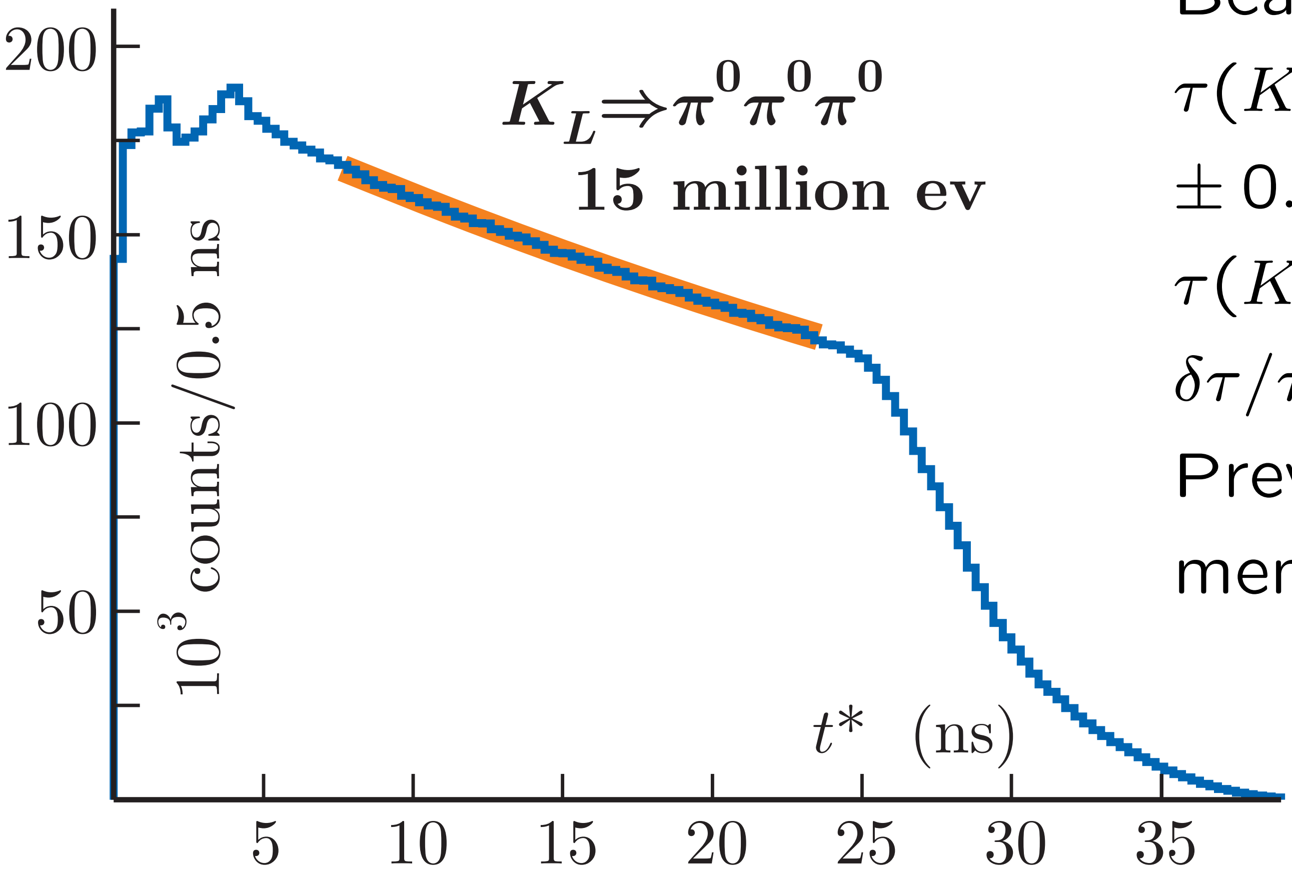


Hardest to measure because:

1. Neutral
2. No 2 body decay
3. Very long decay path

KLOE

Monochromatic $K_L$beam!!



Beam count not known.

$\tau(K_L) = 50.92 \pm 0.17$

$\pm\, 0.25$ or

$\tau(K_L) = 50.92 \pm 0.30$

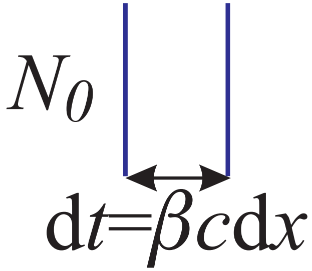
$\delta\tau/\tau{=}5.9 \times 10^{-3}$

Previous measurement: 8.5×10^{-3}

this is tex

Tagged K_L-beam at DAΦNE

Ideal case

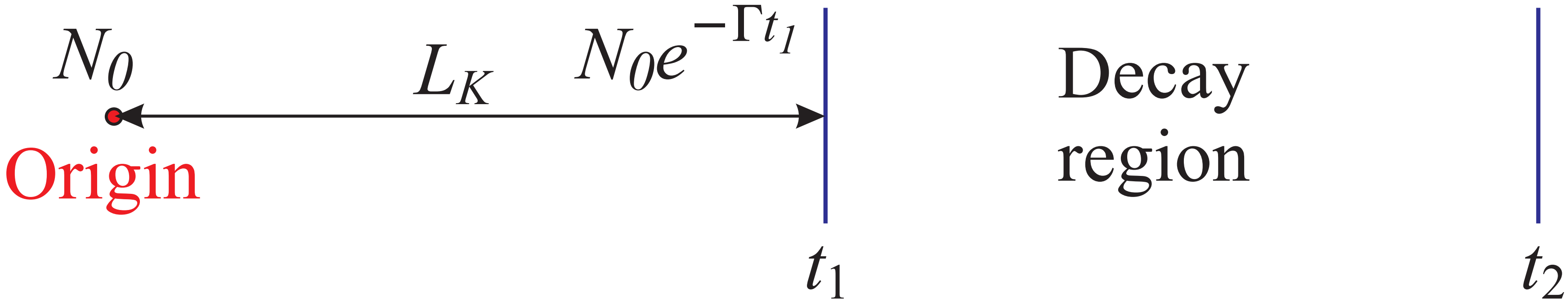


$$\Gamma_j = \frac{dN_j}{dt}\frac{1}{N_0}$$

Measure directly Γ_i, τ not necessary

$$\sum \text{all channels} \Rightarrow \Gamma = 1/\tau$$

Real life:



See later. . .

$\boxed{K_S \to \pi e \nu}$

K_S semileptonic decays. In SM

$$\Gamma(K_{S-\ell 3}) \equiv \Gamma(K_{L-\ell 3})$$
$$\mathcal{A}^\ell_L \equiv \mathcal{A}^\ell_S$$

$\mathcal{A}^\ell$ is the leptonic charge asymmetry

Independent of pseudo CVC, $SU(2)/SU(3)$ corrections, hadronic matrix elements...

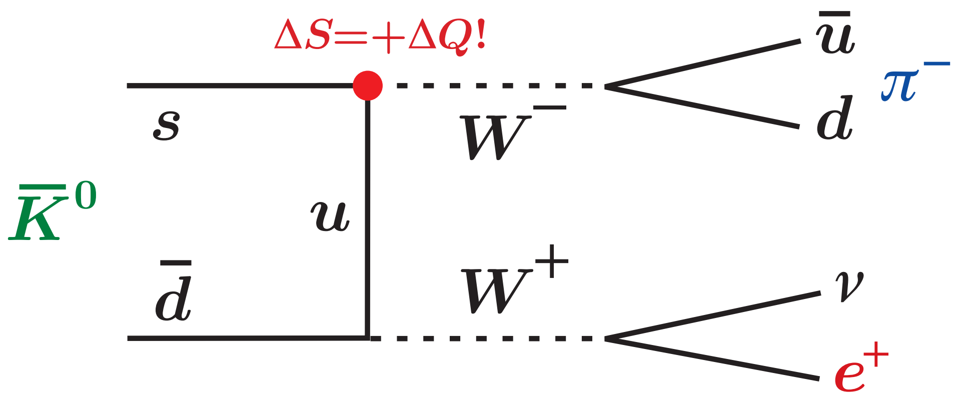
Only TCP and $\Delta S = \Delta Q$! More interesting than direct CP once it's been proved it's there. ...nobody can compute $\Re(\epsilon'/\epsilon)$, yet!

$\boxed{\Delta S = -\Delta Q?!}$

$\Gamma(K_S \to \pi^0 e\nu)$ and $\Delta S = \Delta Q$

Apparent $\Delta S = -\Delta Q$

No loops, no susy



$$x = \frac{A(\bar{K} \to \ell^+ \pi^- \nu)}{A(\bar{K} \to \ell^- \pi^+ \bar{\nu})} \sim Gm^2 \sim 10^{-6}$$

$$\text{NOT } x = \frac{A(\Delta S = -\Delta Q)}{A(\Delta S = \Delta Q)}$$

Exp: $x < 10^{-2}$ @90% CL (CPLEAR $\pm 6 \times 10^{-3}$)

$$\Re x = (1/4)\,(\Gamma_S^{s\ell}/\Gamma_L^{s\ell} - 1)$$

To improve on $\Re x$ by a factor 10, requires 3000 pb^{-1}.

$$\boxed{\mathcal{A}_S^\ell}$$

Leptonic charge asymmetry

$$\mathcal{A}_S^\ell - \mathcal{A}_S^\ell = 4\Re\delta, \quad \delta = \epsilon_S - \epsilon_L \neq 0 \Rightarrow \not{C}\not{P}\not{T}$$

There are 3 levels.

1. $\mathcal{A}_S^\ell$ is consistent with $2\Re\epsilon \sim 0.003$, 2 fb^{-1}.
2. Measure $\mathcal{A}_S^\ell$ to some significance (30%), 20 fb^{-1}.
3. Improve limits on $\delta = \epsilon_S - \epsilon_L$, requires 200 fb^{-1}. But. . .

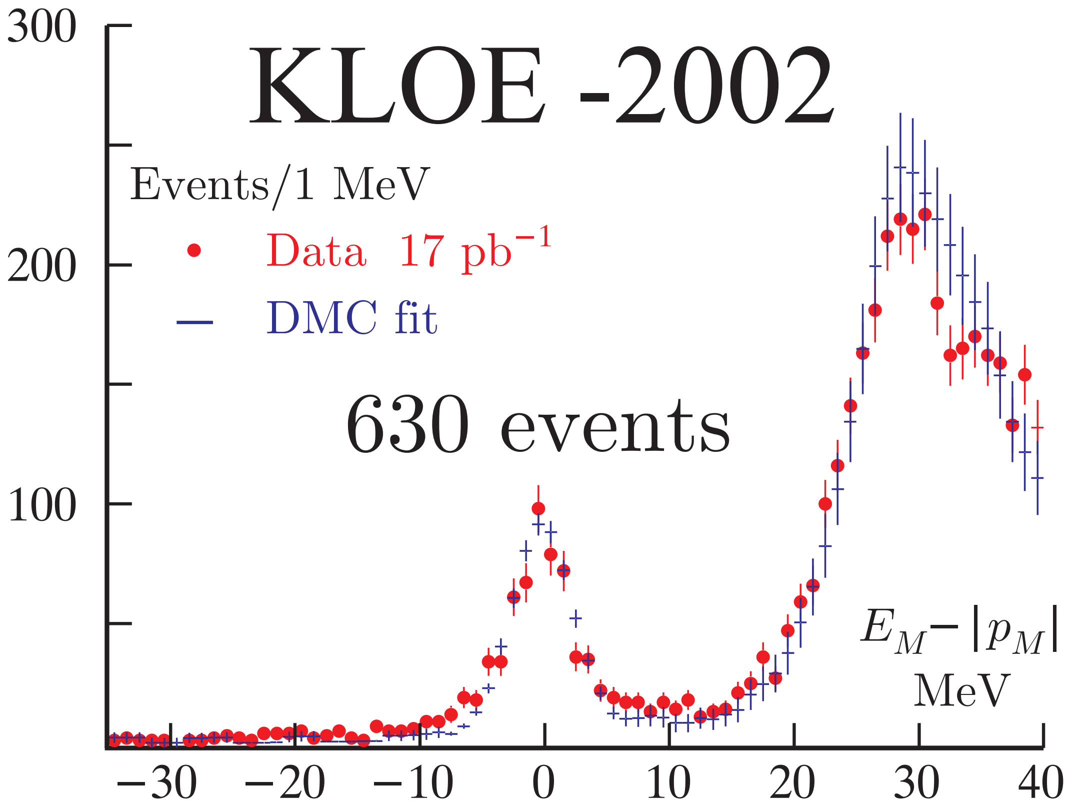
No. 3: the new DAΦNE?

The decay $K_S \to \pi^\pm e^\mp \nu(\bar{\nu})$ was not observed till the year 1999

this is tex

K_S semileptonic: $K_S \to \pi e \nu$ $\Gamma(K_L) \equiv \Gamma(K_S)$ $-$ *CPT*

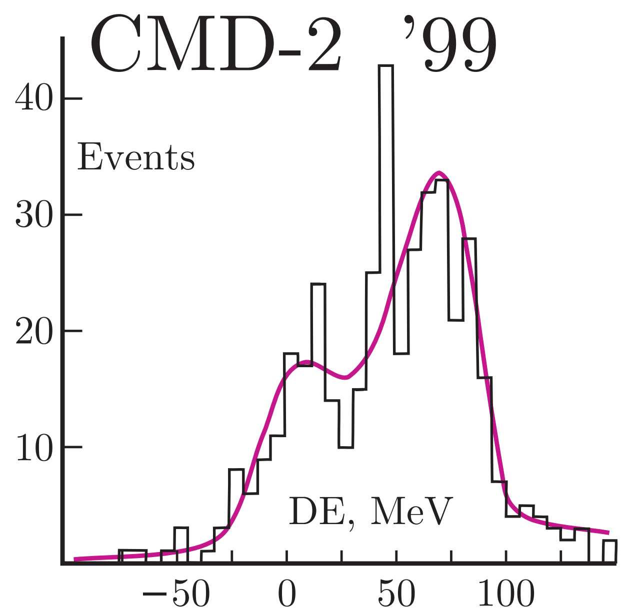
Begin with a "K-crash" as K_S-tag



Use only non spiralling tracks TOF for electron ID

Compare E_{miss} with $|p_{miss}|$

Almost complete rejection of $\pi^+\pi^-$ background



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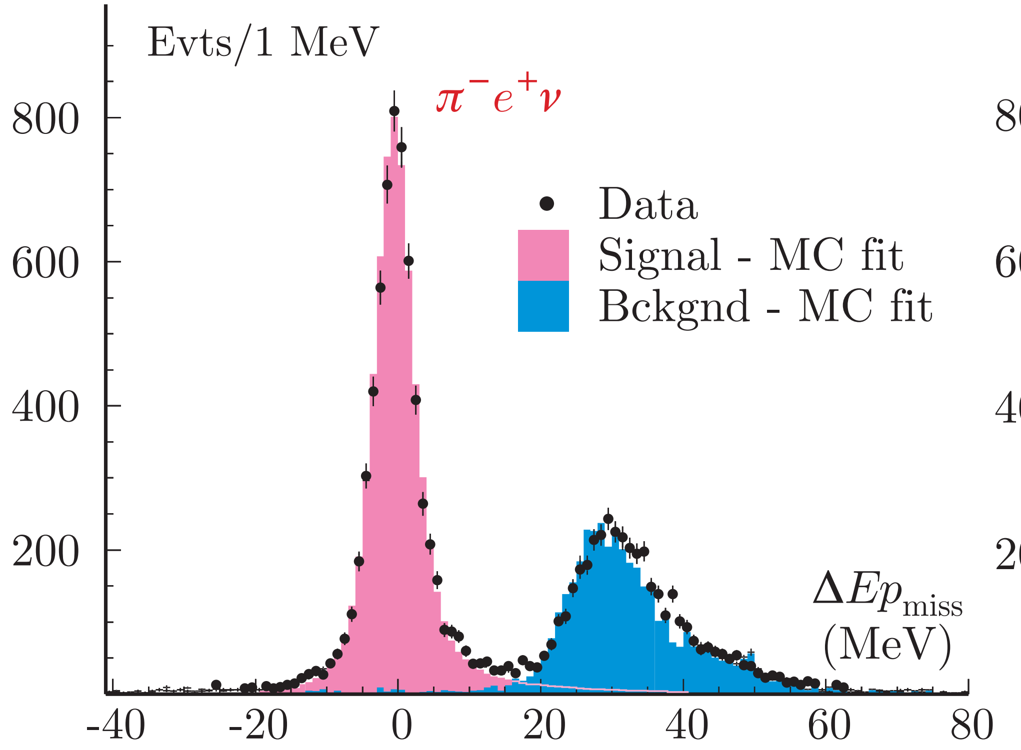
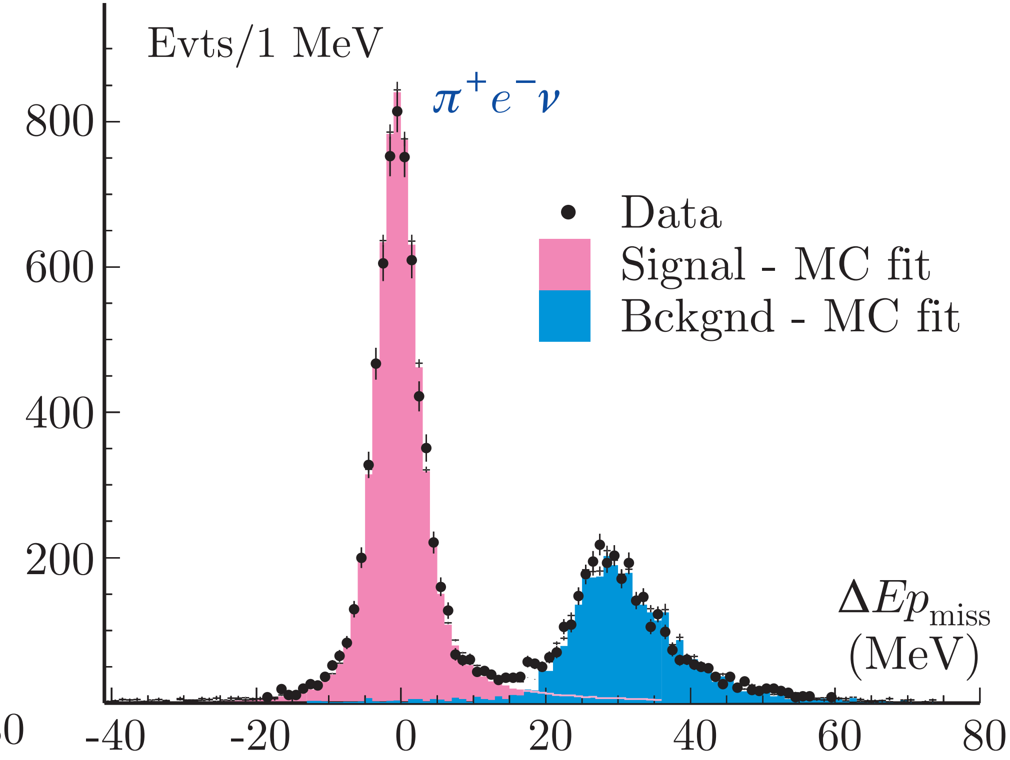
$K_S \to \pi e \nu$, 2005





We ask for two tracks reaching calorimeter, low eff!, ~22%

Overall efficiency: 21.8%

~13,000 signal events

$K_S \to \pi e \nu$

$$\text{KLOE}: \quad \text{BR}(K_S \to \pi^- e^+ \nu(\gamma)) = (3.528 \pm 0.062) \times 10^{-4}$$

$$\text{KLOE}: \quad \text{BR}(K_S \to \pi^- e^+ \nu(\gamma)) = (3.517 \pm 0.058) \times 10^{-4}$$

$$\text{KLOE}: \quad \text{BR}(K_S \to \pi^\pm e^+ \nu(\gamma)) = (7.046 \pm 0.091) \times 10^{-4}$$

$$\Gamma_{S,\ell 3} = \Gamma_{L,\ell 3}: \quad \text{BR}(K_S \to \pi^\pm e^\mp \nu) = (7.116 \pm 0.038) \times 10^{-4}$$

Essentially pure sample

Statistics $\sim$500$\times$Novosibirsk

We still have $\sim\times 5$ more data

this is tex

$K_S \to \pi e \nu$

The leptonic charge asymmetries $\mathcal{A}^{\ell}_{S,L}$:

$$\mathcal{A}^{\ell} \equiv \frac{N^+ - N^-}{N^+ + N^-} = 2\Re(\epsilon + x + \delta + y + x')\ ^{\dagger}$$

$$\begin{array}{rcl} \epsilon & \Leftarrow & \not{C}\not{P} \text{ in mixing} \\ x & \Leftarrow & \Delta S = -\Delta Q \\ \delta & \Leftarrow & \not{C}\not{P}\not{T} \text{ in mixing} \\ y & \Leftarrow & \text{“direct” } \not{C}\not{P}\not{T},\ \Delta S = \Delta Q \\ x' & \Leftarrow & \text{“direct” } \not{C}\not{P}\not{T},\ \Delta S = -\Delta Q \end{array}$$

Some terms cancel in $\mathcal{A}^{\ell}_S - \mathcal{A}^{\ell}_L$: measure δ

† Signs are symbolic, some change under $K_S \leftrightarrow K_L$.

$\boxed{\mathcal{A}_S^\ell}$

We find

$$\mathcal{A}_S = (1.5 \pm 9.6 \pm 2.9) \times 10^{-3}$$

Remember that $\mathcal{A}_S = \mathcal{A}_L = 2\Re\epsilon \sim 3 \times 10^{-3}$, OK for $\mathcal{A}_L$.

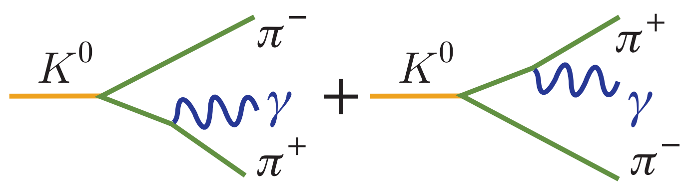
$\Delta S = \Delta Q$ is verified, $x_+ = (1.2 \pm 3.6) \times 10^{-3}$ improving by about $\times 2$ over CPLEAR.

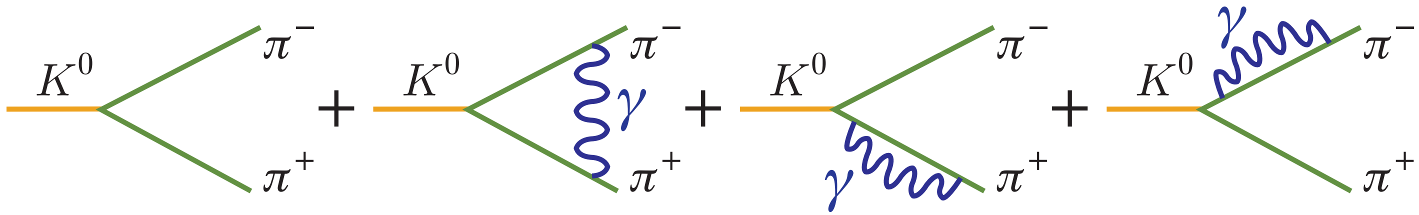
Even such a limited first result is of help in deriving consequences of unitarity. (BSR)

See later for $\delta = \epsilon_L - \epsilon_S$, etc.

Radiation must be included

BR($K\to f(\gamma)$) stand for BR($K\to f$ and $K\to f\gamma$, $0<\omega<\omega_{\text{max}}$)

Why? Take for example $K_S\to\pi^+\pi^-$. In the real world the em interaction gives $\Gamma_1 \propto \Big|$  $\Big|^2 \to\infty$ for $\omega\to 0$. Thus the decay $K\to\pi^+\pi^-$ is accompanied by an infinite number of events with an unobservable photon.

The infinity is however cancelled by an opposite sign contribution from $\Gamma_2 \propto \Big|$  $\Big|^2$.

$\Gamma_1+\Gamma_2$ is finite but contains a correction of $\mathcal{O}((\alpha/\pi)\ln(\omega_0/M))$.
ω_0 is finite and experiment dependent.

Radiation inclusive branching ratios

A sharp cut-off on the photon energy could insure a correct connection between theory and experiment. Since however inclusion or exclusion of photons does affect event acceptance in any experiment, it is far better to give results fully inclusive of radiation up to the kinematic limit. This requires correct accounting of radiation in the Monte Carlo detector simulation program.

In the KLOE MC program, Geanfi, radiation is included at the event generation level, event by event. In the following, even if not explicitly stated, BRs are totally inclusive of radiation.

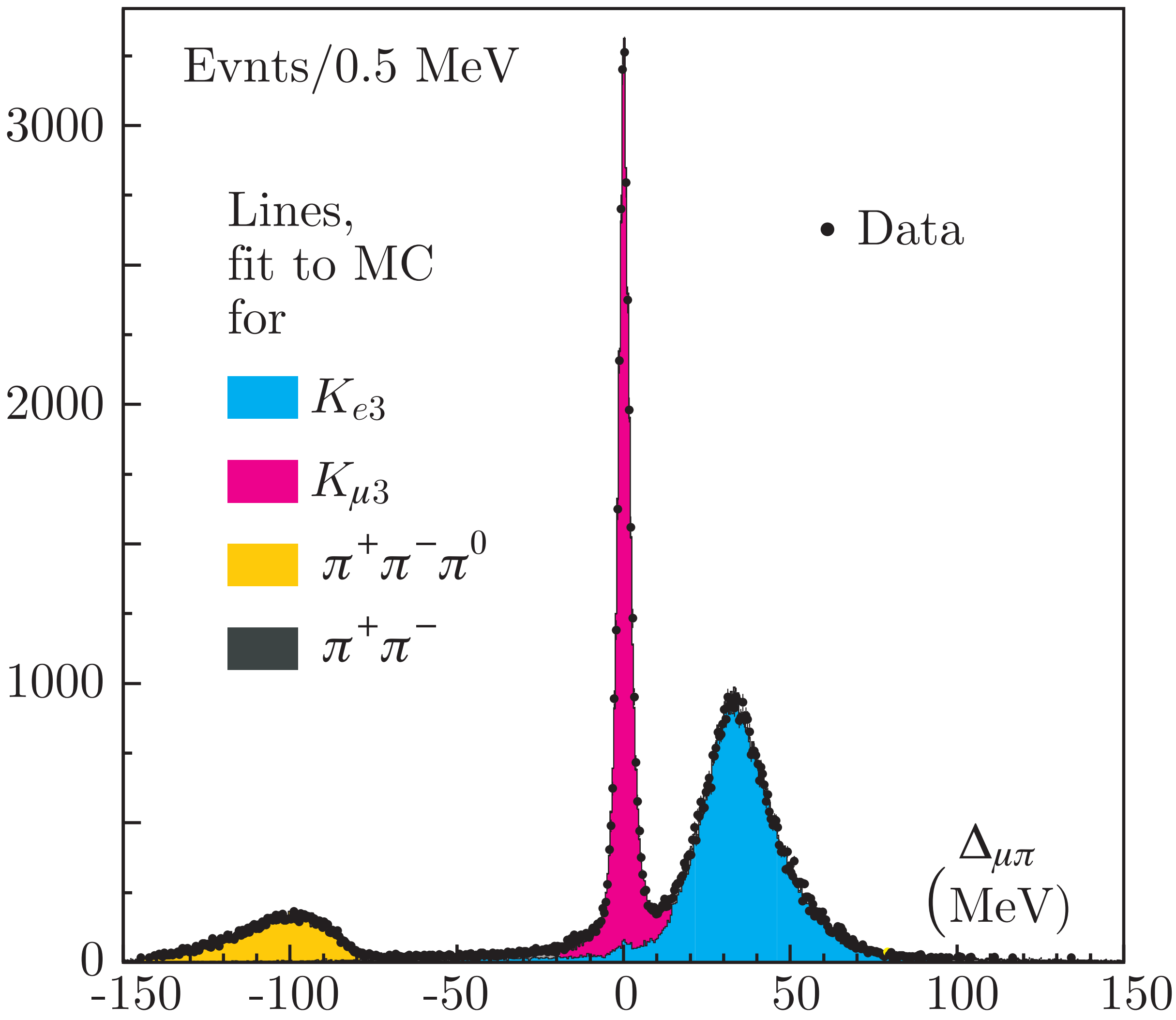
Dominant K_L decays

Ideally the tag signals the presence of a K_L, independently of its decay. One thus knows the total number of initial particles and needs only assign, event by event the K_L to the appropriate decay mode. In practice one needs determining the

1. "tag bias" for each decay mode, before trigger check (0.99 to 1.06)
2. detection efficiency for each mode.

In addition decays are accepted over a finite time interval and the identified number of decays depend on the lifetime. This in fact is a bonus, since, as noticed already, it allows measuring the lifetime, always thanks to the tag.

Dominant K_L decays

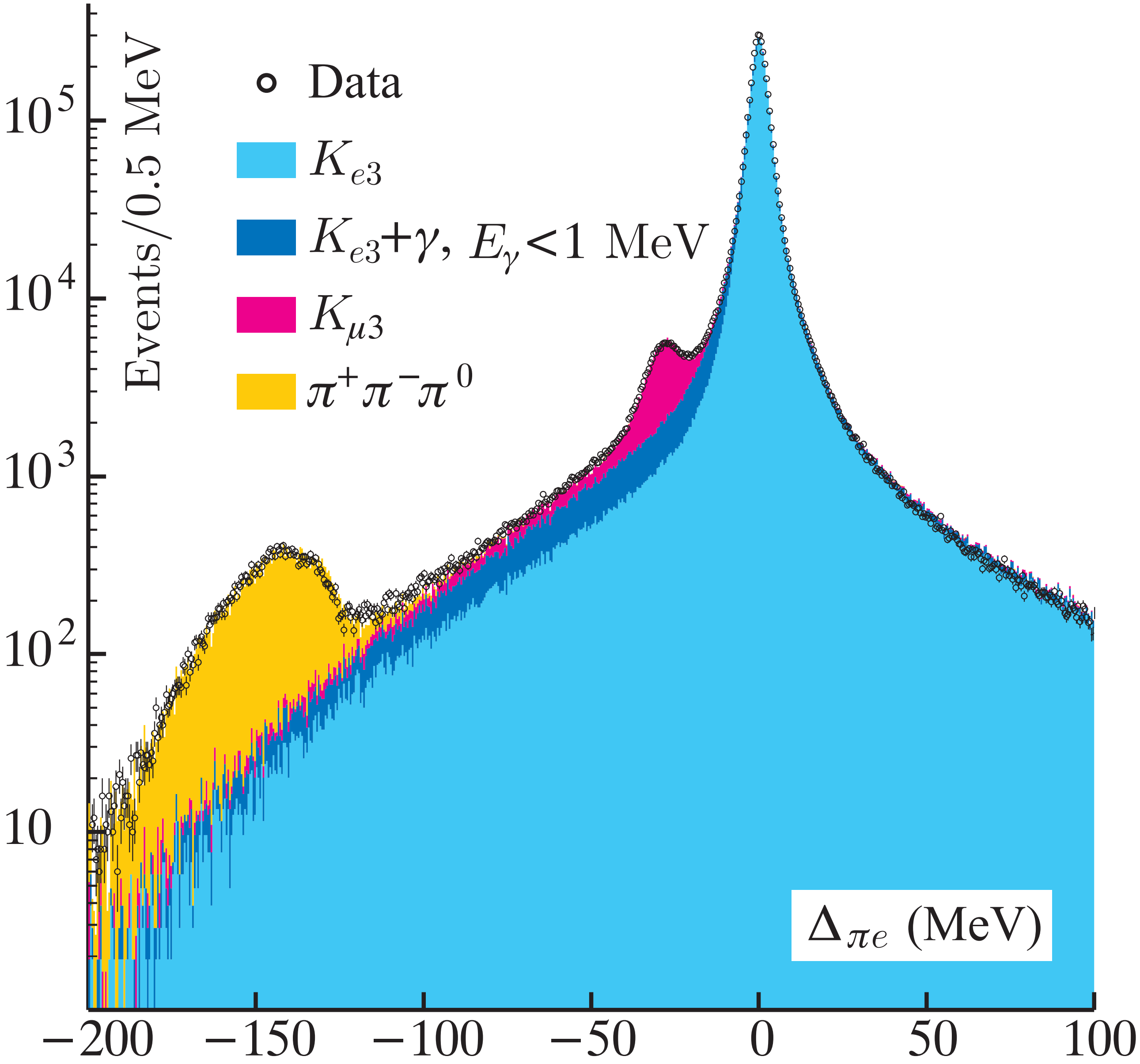


$\Delta_{\mu\pi}$ spectrum for 1 out of 14 data samples.

K_L production tagged by $K_S \to \pi^+\pi^-$. Must remove trigger dependence on decay of K_L, tag bias. The charged modes are distinguished using $\Delta_{\mu\pi} = \min[E_{\text{miss}} - |\mathbf{p}|_{\text{miss}}]$ assigning pion and muon masses to the two observed particles

this is tex

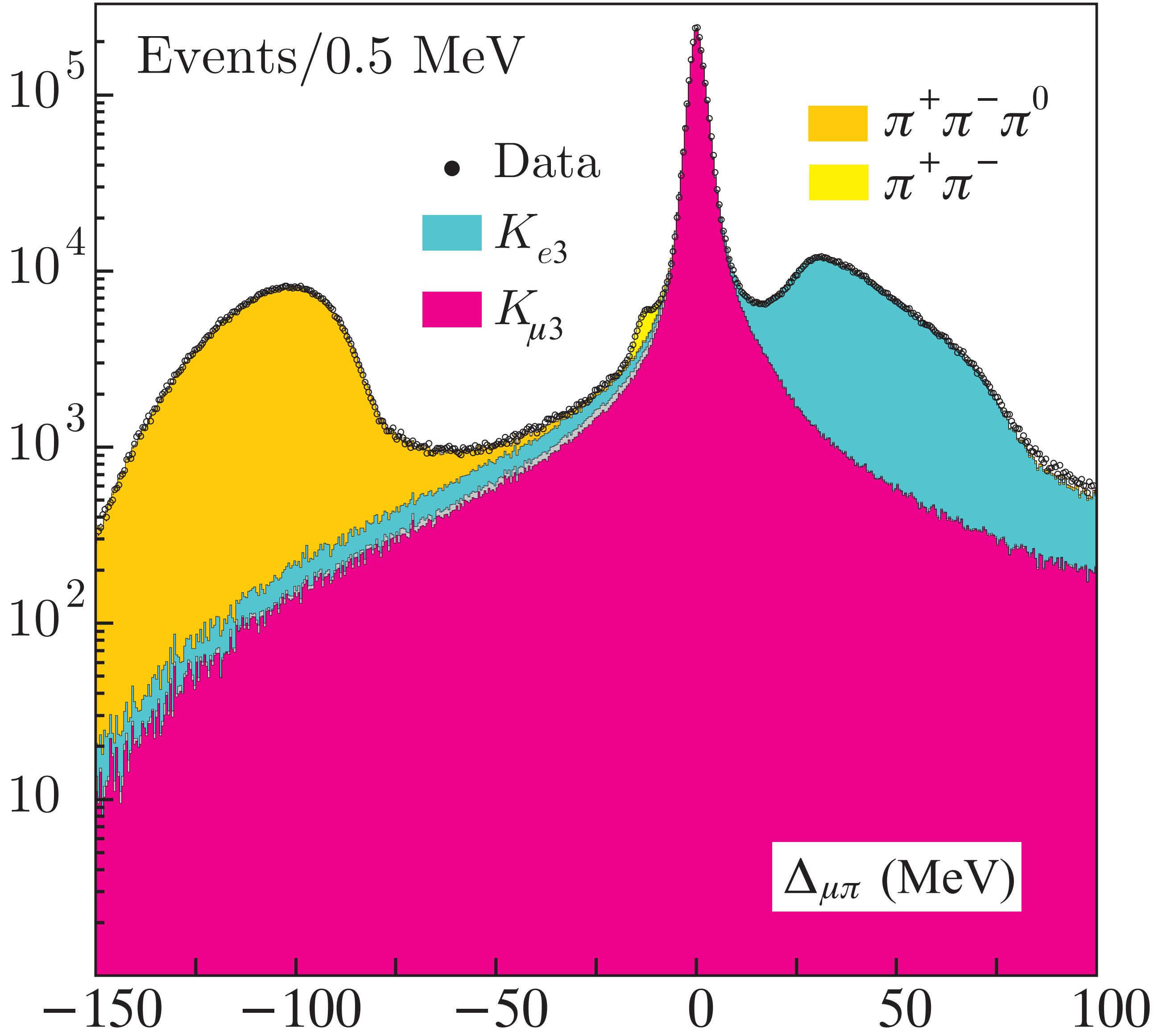
Dominant K_L decays



Comparisons with MC prediction of the $\Delta_{e\pi}$ distribution for events with a recognized electron. Electron ID is obtained from time of flight, momentum and track length.

All events.

Dominant K_L decays



Comparisons with MC prediction of the $\Delta_{\mu\pi}$ distribution for events with a recognized muon. Muon ID is obtained from the pattern of energy deposition in the calorimeter layers. All events.

Dominant K_L decays

We impose the constraint that the four modes on the side plus $K_L \to \pi^+\pi^-$, $K_L \to \pi^0\pi^0$ and $K_L \to 2\gamma$ equal the events counted by the tag. We thus obtain the BRs in the table and the $K_L$lifetime.

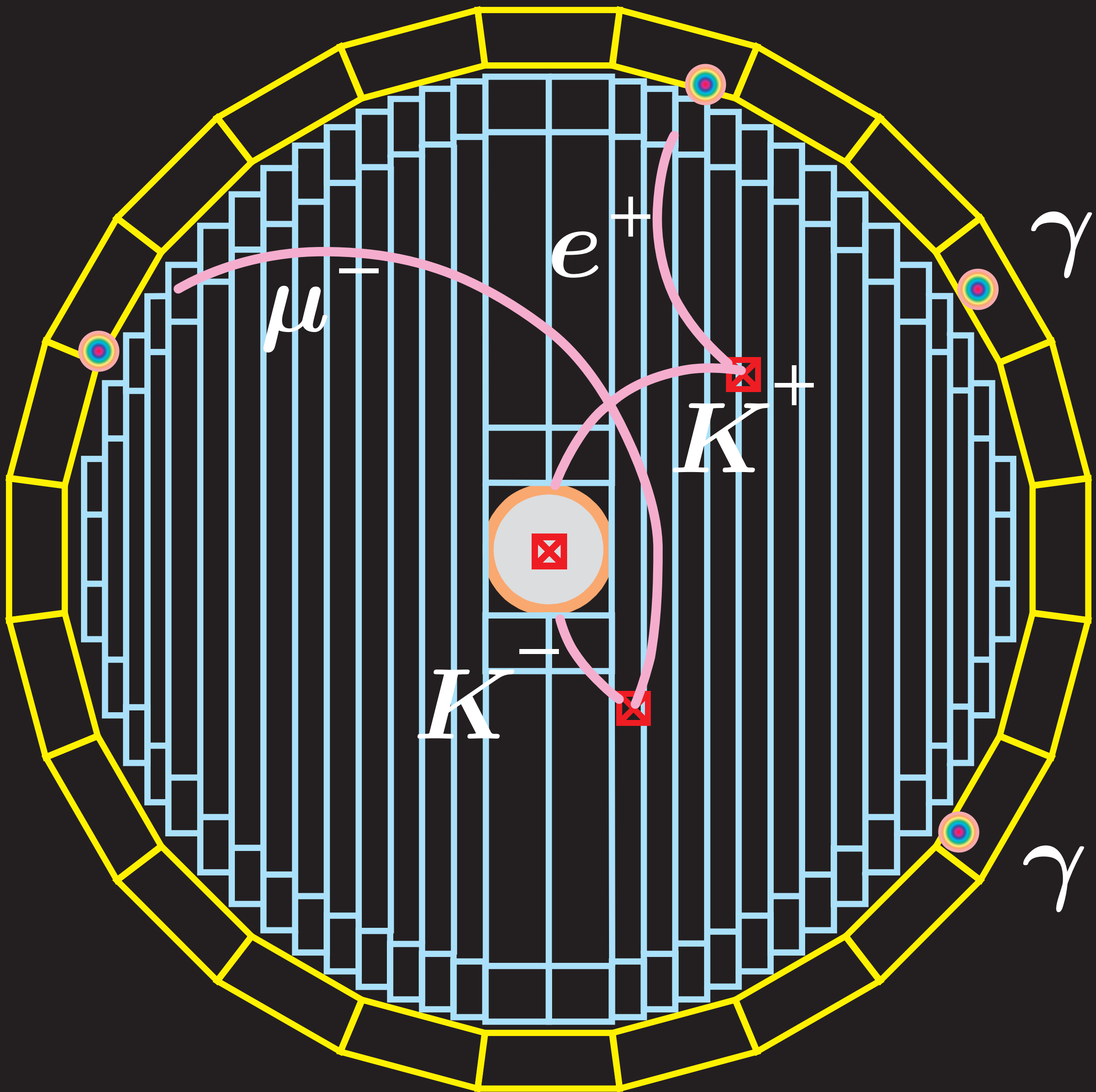
Mode	BR	δ stat	δ syst
$\pi^\pm e^\mp \nu(\gamma)$	0.4007	0.0006	0.0014
$\pi^\pm \mu^\mp \nu(\gamma)$	0.2698	0.0006	0.0014
$\pi^0\pi^0\pi^0$	0.1997	0.0005	0.0019
$\pi^+\pi^-\pi^0(\gamma)$	0.1263	0.0005	0.0011

$$\tau(K_L) = 50.72 \pm 0.17_{\text{stat}} \pm 0.33_{\text{syst}} \quad \text{ns}$$

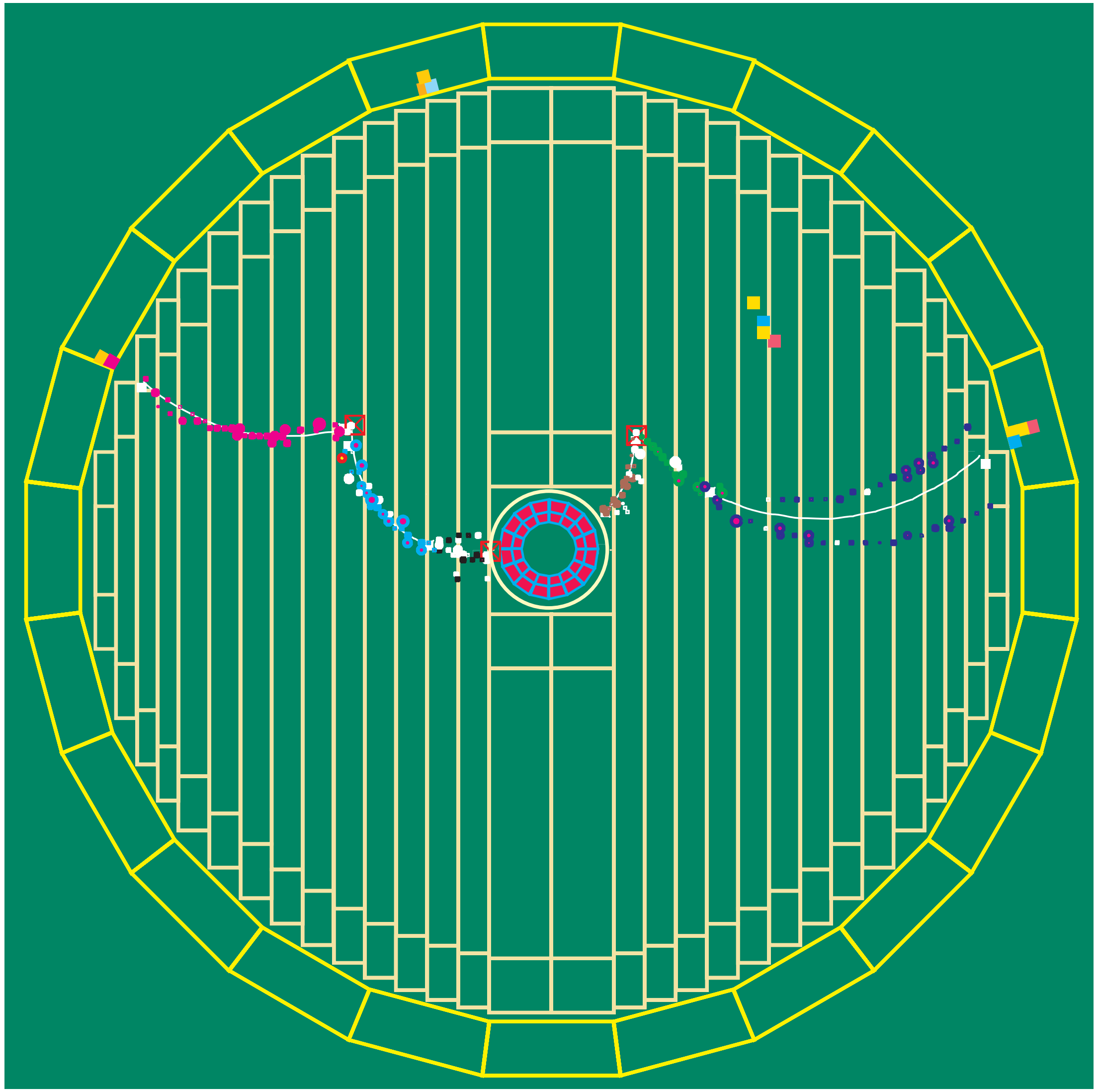
Combining with previous value:

$$\tau(K_L) = 50.84 \pm 0.23 \quad \text{ns}$$

$K^{\pm}_{\ell 3}$ decays

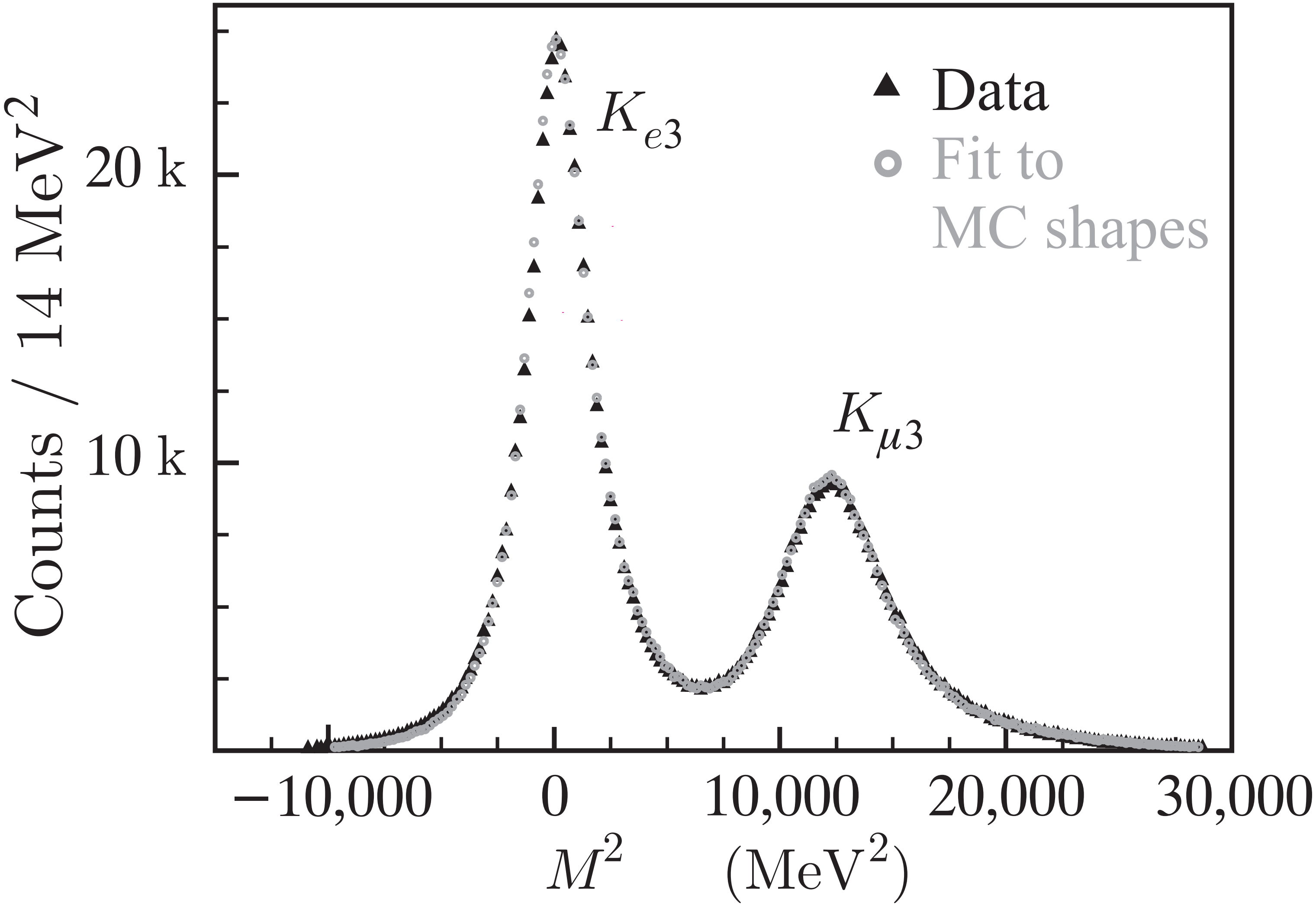


$K^{\pm}_{\ell 3}$ decays



Tag	–	Decay
$K^+ \to \mu^+\nu$	–	$K^- \to \pi^0 e^- \bar{\nu}$
$K^+ \to \pi^+\pi^0$	–	$K^- \to \pi^0 \mu^- \bar{\nu}$
$K^- \to \mu^-\bar{\nu}$	–	$K^+ \to \pi^0 e^+ \nu$
$K^- \to \pi^-\pi^0$	–	$K^+ \to \pi^0 \mu^+ \nu$

$K^{\pm}_{\ell 3}$ decays



Lepton mass from kinematics and TOF

BR's see later

V_{us} from $K_{\ell 3}$

$$\Gamma^i(K_j) = |V_{us}|^2 \frac{C_i^2\, G^2\, M^5}{768\pi^3} S_{\rm EW}\,(1+\delta_{i,\,\rm em}+\delta_{i,\,SU(2)})\,|f_+^{K^0}(0)|^2\, I_j^i$$

$i = K^0 \to \pi^\pm,\ K^\pm \to \pi^0;\quad C_i^2 = 1,\ 1/2$

$j = e3,\ \mu3.$ I_j^i are the appropriate phase space integrals.

$S_{\rm EW}$ and $\delta_{\rm em}$ are the short and long range em corrections.

$\delta_{SU(2)}$=I-spin breaking correction

$f_+^{K^0}(0)$ is the form factor normalization due to $SU(3)$ breaking.

$f_+^{K^0}(0) = 0.961 \pm 0.008$ (0.96–0.98) is the most uncertain factor.

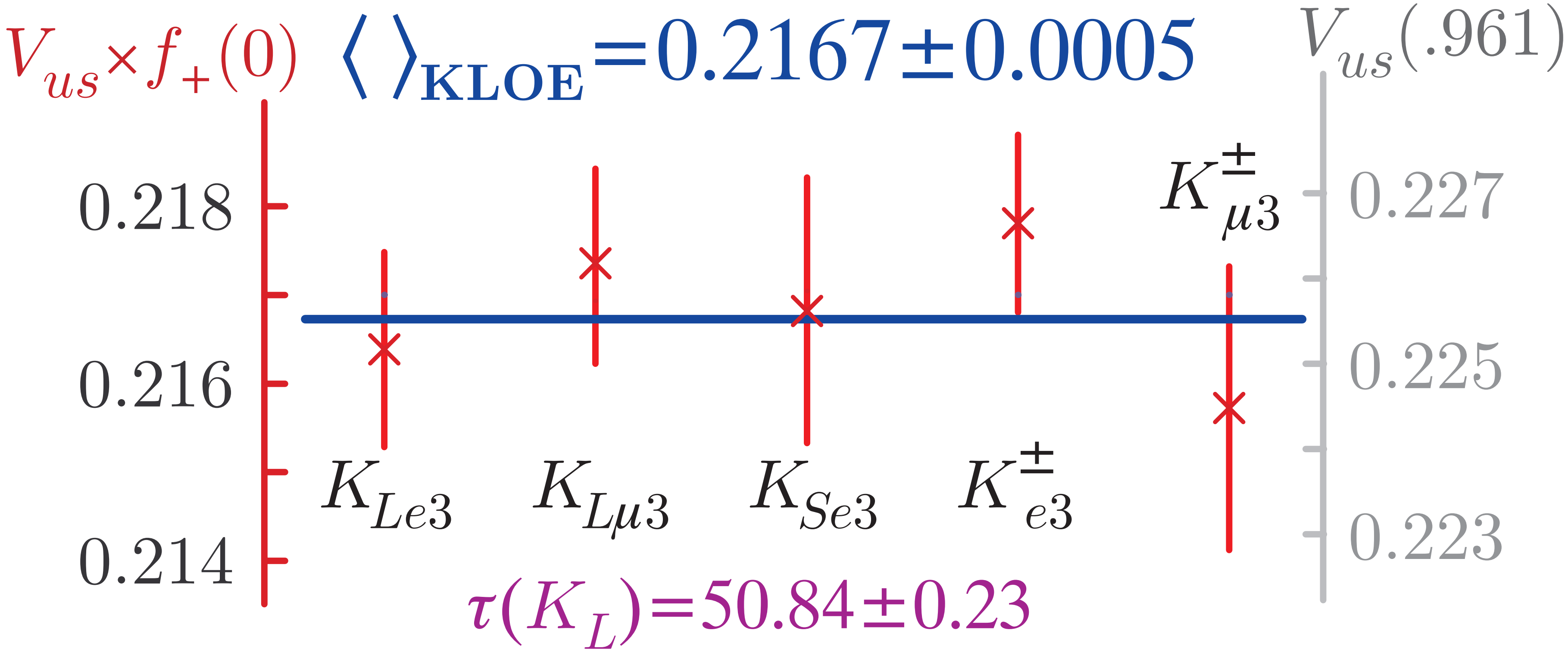
Lattice favors 0.96, recent χpt prefers 0.98.

$f_+^{K^0}(0)|V_{us}|$ from $K_{\ell 3}$

Decay	BR	τ, ns	Γ, μs^{-1}	$f_+^{K^0}(0)\,|V_{us}|$
$K_{L\,e3(\gamma)}$	0.4007(15)	50.84(23)*	7.88(4)	0.2164(6)
$K_{L\,\mu 3(\gamma)}$	0.2698(15)	50.84(23)*	5.307(32)	0.2173(8)
$K_{S\,e3(\gamma)}$	$7.05(9) \times 10^{-4}$	0.08958(6)	7.87(10)	0.2161(14)
$K^{\pm}_{e3(\gamma)}$	0.0505(5)	12.385(25)	4.08(4)	0.2178(13)
$K^{\pm}_{\mu 3(\gamma)}$	0.0331(5)	12.385(25)	2.67(4)	0.2157(16)

* KLOE

$|V_{us}|$ from KLOE data



$\chi^2/\text{ndf} = 2.34/4$, C.L. 67%

Covariance Matrix

Let $F(\mathbf{p},x)$ be a PDF, where $\mathbf{p}$ is some parameter vector, which we want to determine. x is a running variable, like t, for instance. Before doing an experiment, we would like to know which accuracy we can reach.

The inverse of the covariance matrix is given by:

$$(\mathbf{G}^{-1})_{ij} = -\frac{\partial^2 \ln L}{\partial p_i \partial p_j}$$

Therefore, for N events

$$\langle(\mathbf{G}^{-1})_{ij}\rangle = N \int \frac{1}{F}\frac{\partial F}{\partial p_i}\frac{\partial F}{\partial p_j}\,\mathrm{d}\upsilon$$

FF parameters, $Ke3$

Choices for the form factor in:

$$\langle\pi|J_\alpha^{\text{hadr}}|K\rangle =\propto \tilde{f}_+(t) \times (P+p)_\alpha$$

Trivial: $\tilde{f}_+(t) = 1 + \lambda'(t/m^2) + \lambda''(t^2/m^4)\ldots.$ But λ' and λ'' are 95% correlated, which means larger error, ~3x then for no t^2 term. The error matrix is

$$\mathbf{G} = \begin{pmatrix} \overline{\delta\lambda'_+{}^2} & \overline{\delta\lambda'_+\delta\lambda''_+} \\ \overline{\delta\lambda''_+\delta\lambda'_+} & \overline{\delta\lambda''_+{}^2} \end{pmatrix} = \frac{1}{N}\begin{pmatrix} 1.25^2 & -0.607 \\ -0.607 & 0.51^2 \end{pmatrix}$$

or, for 1,000,000 events,

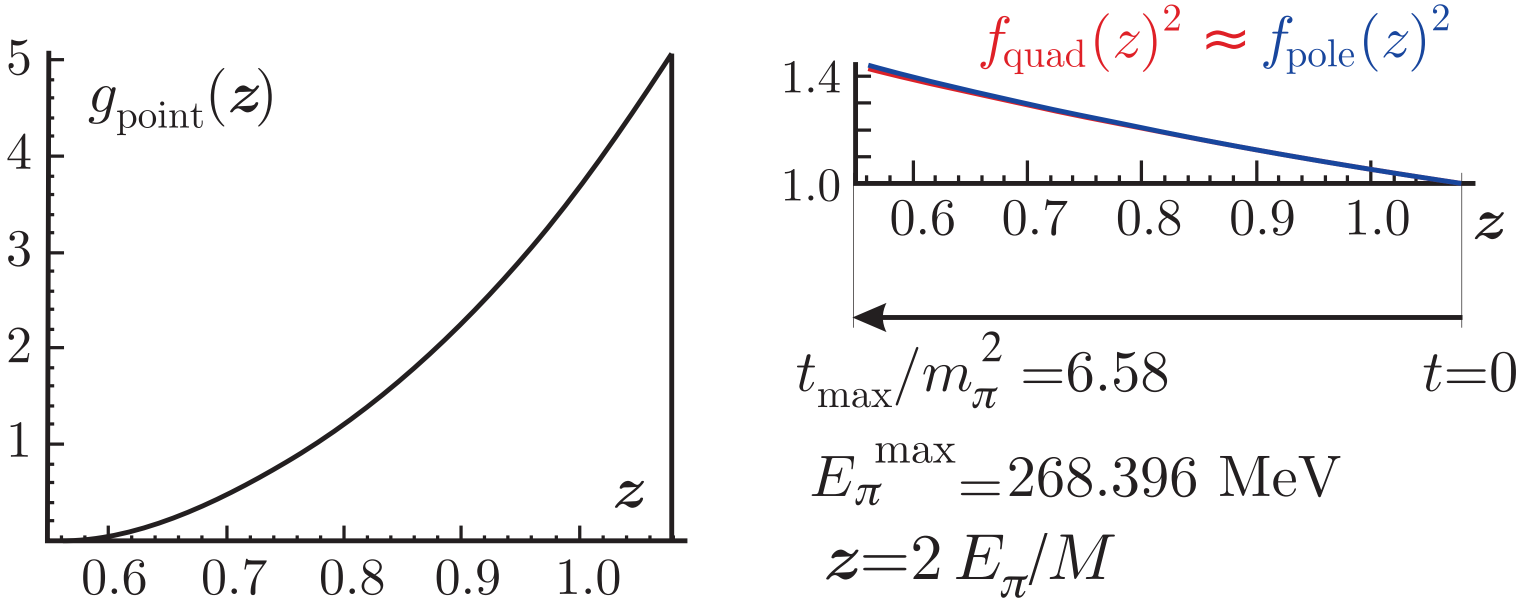
$$\delta\lambda' = 0.00125 \sim 5\%$$

$$\delta\lambda'' = 0.00051 \sim 40\%$$

this is tex

FF cntn'd

We use $z = 2E_\pi/M$, $2\sqrt{a} < z < 1 + a$, with $a = m^2/M^2$. Then $t/m^2 = (P-p)^2/m^2 = 1 + 1/a - z/a$, *i.e.* t/m^2 is max for $z = 2\sqrt{a}$ and $t/m^2{=}0$ for $z = 1 + a$. $\tilde{f}(t)$ multiplies the point like spectrum which vanishes at $z = 2\sqrt{a}$ where FF is largest.



A power expansion of $\tilde{f}(t)$ is truly an infelicitous choice. Another choice is $\tilde{f}(t) = M_V^2/(M_V^2 - t)$ *i.e.* a pole in the $\pi - K$ scattering amplitude. Only one parameter!

FF cntn'd

In real life, errors are larger, $\times 2$-$\times 3$, because of systematic uncertainties. Errors will also be enlarged by poor resolution and kinematics problems, *eg* two solutions.

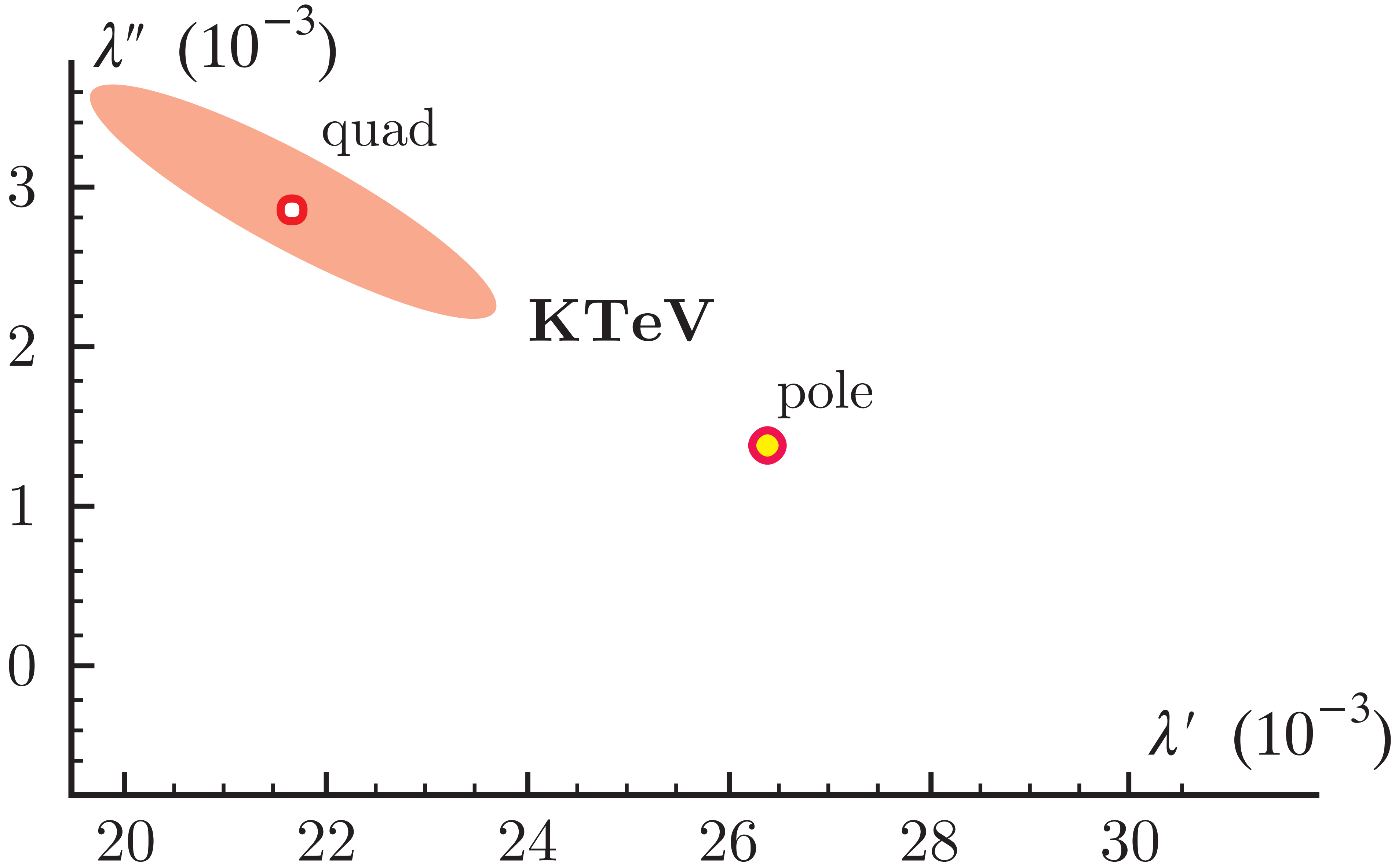
Fitting to a pole is much more robust against statistical fluctuation. Several authors justify the pole and experiment agrees. Still $>$100 million events are necessary to distinguish pole from power expansion, the difference however is very small. Note that:

$$\frac{M_V^2}{M_V^2 - t} = 1 + \frac{t}{M_V^2} + \frac{t^2}{M_V^4} \ldots$$

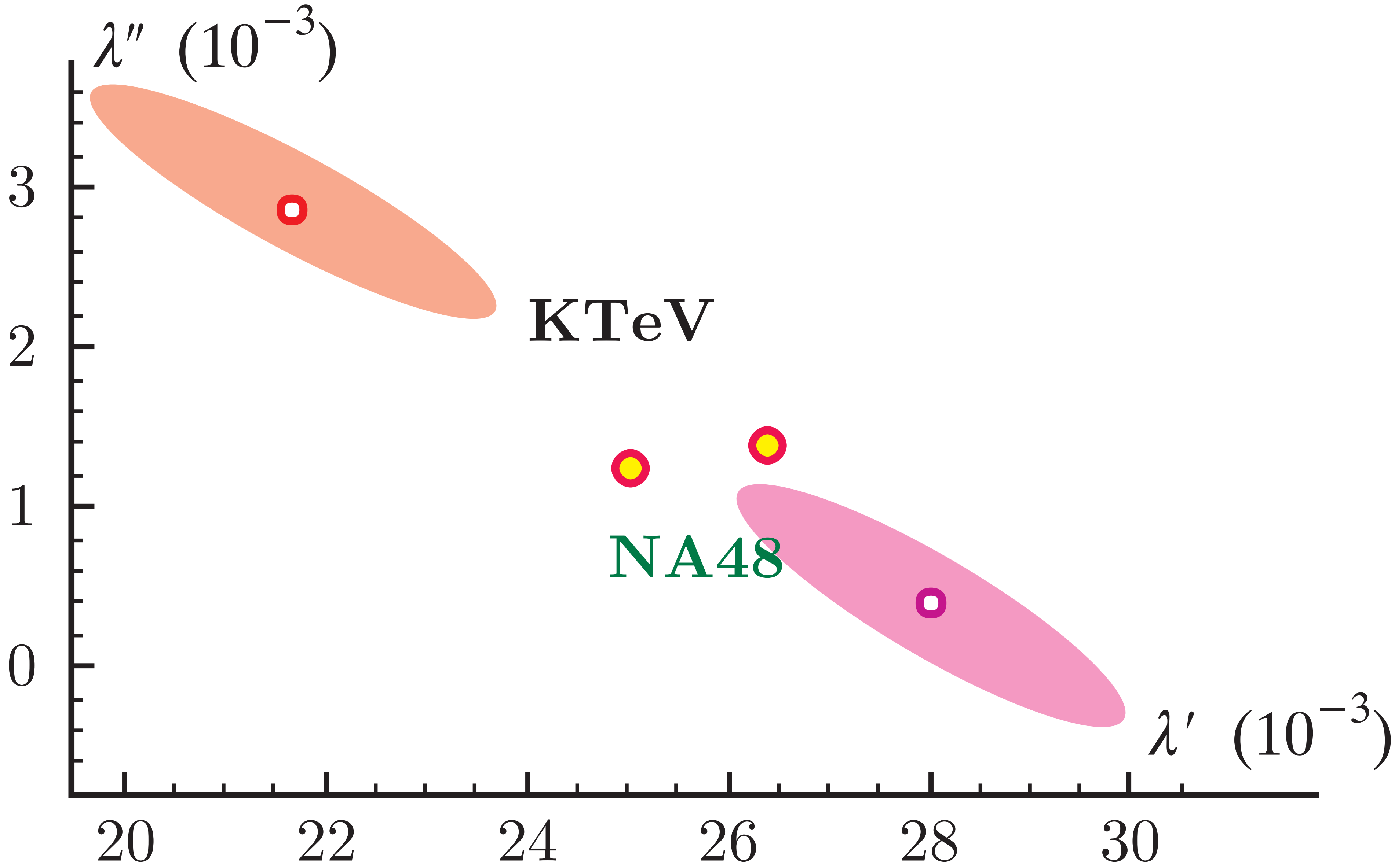
i.e.

$$\lambda' = \frac{m^2}{M_V^2}, \;\; \lambda'' = 2\,\lambda'^2$$

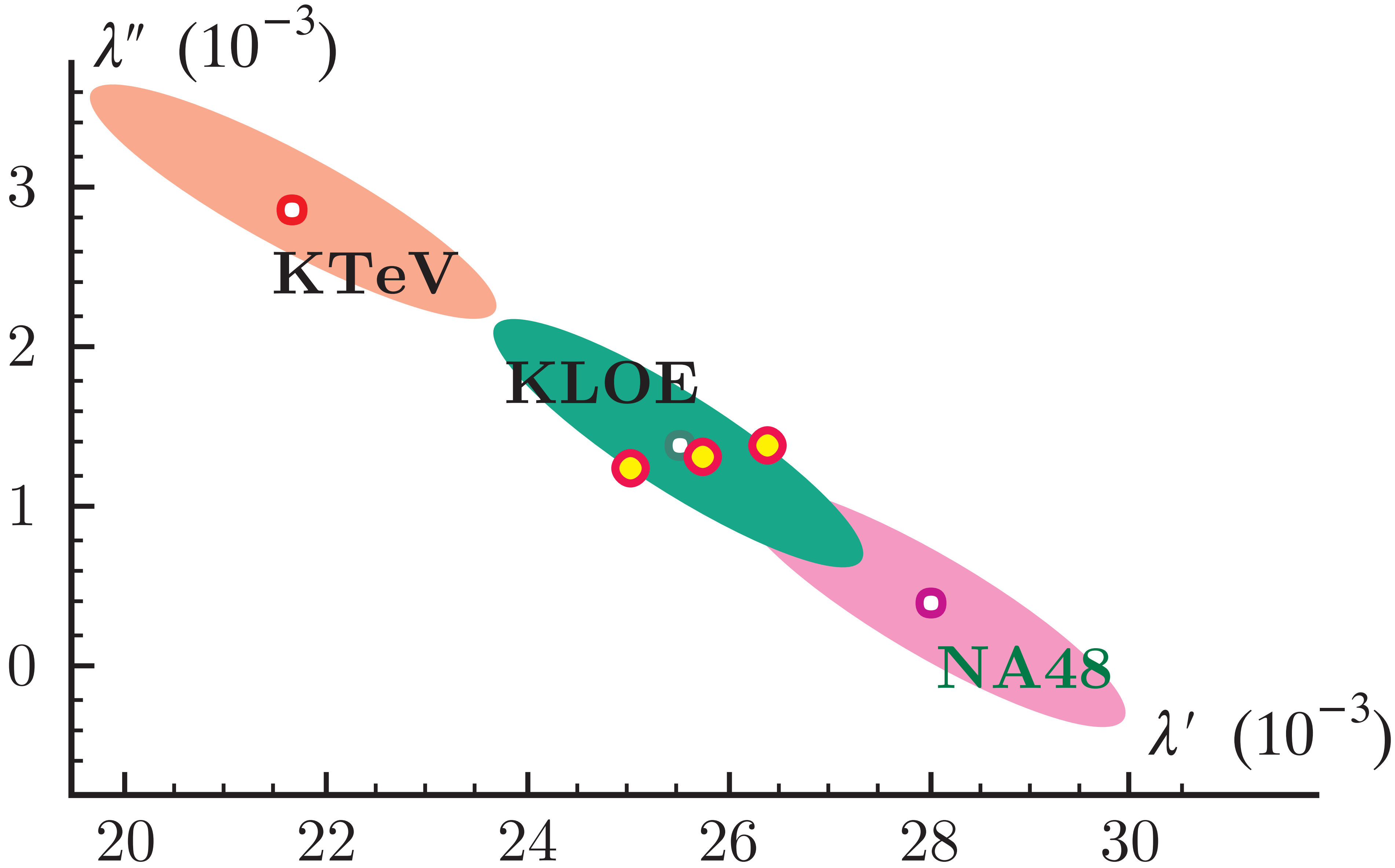
K_{e3}: λ' & λ''



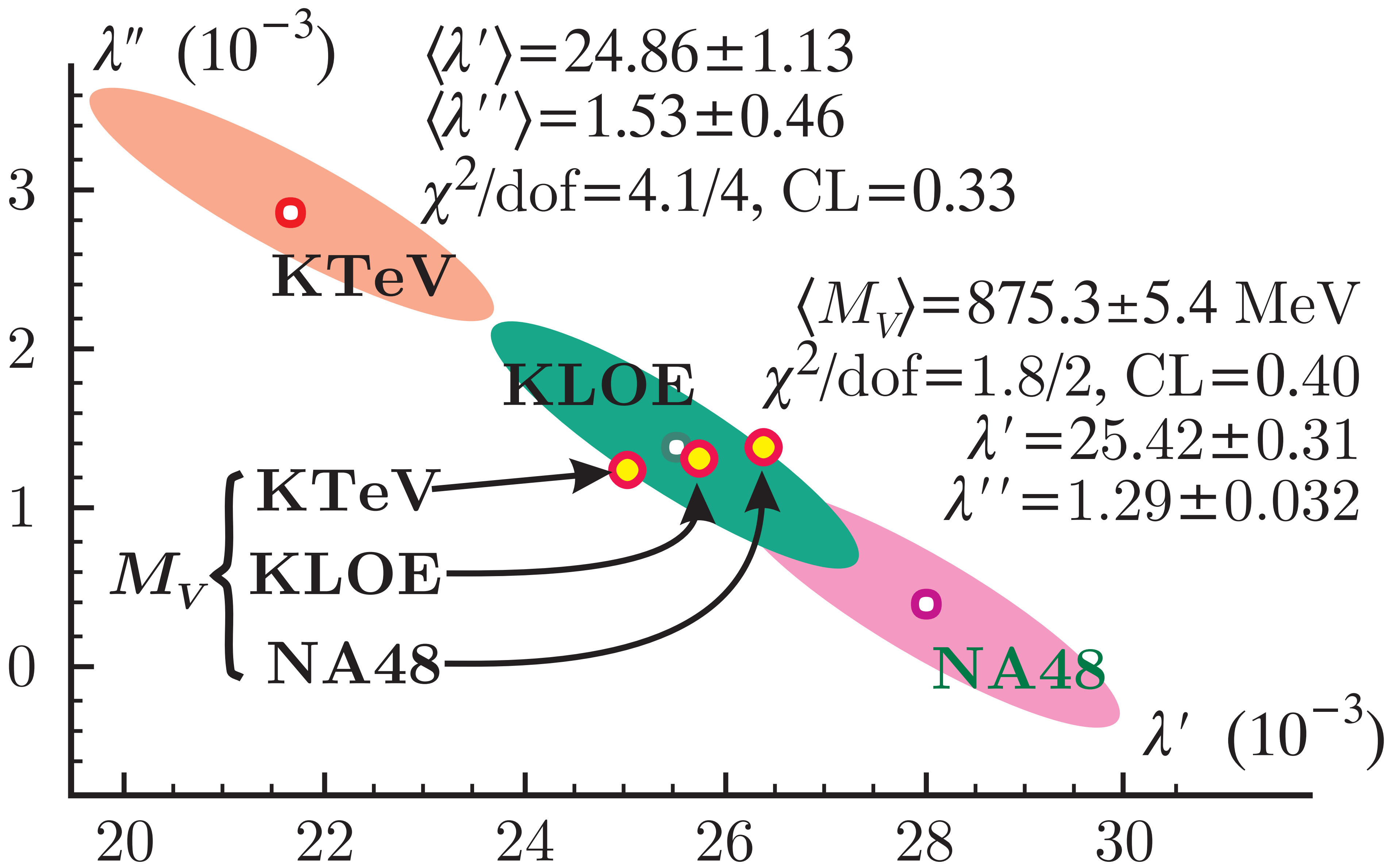
K_{e3}: λ' & λ''



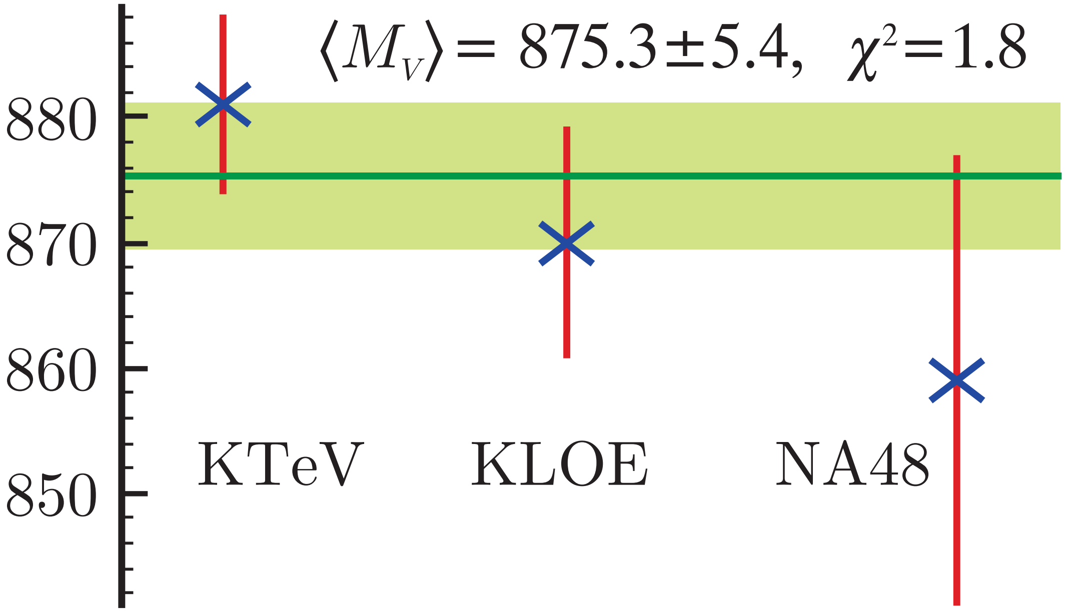
K_{e3}: λ' & λ''



K_{e3}: λ' & λ''



Pole fit, K_{e3}



CL for pole fit 41%

CL for quadratic FF fit 33%

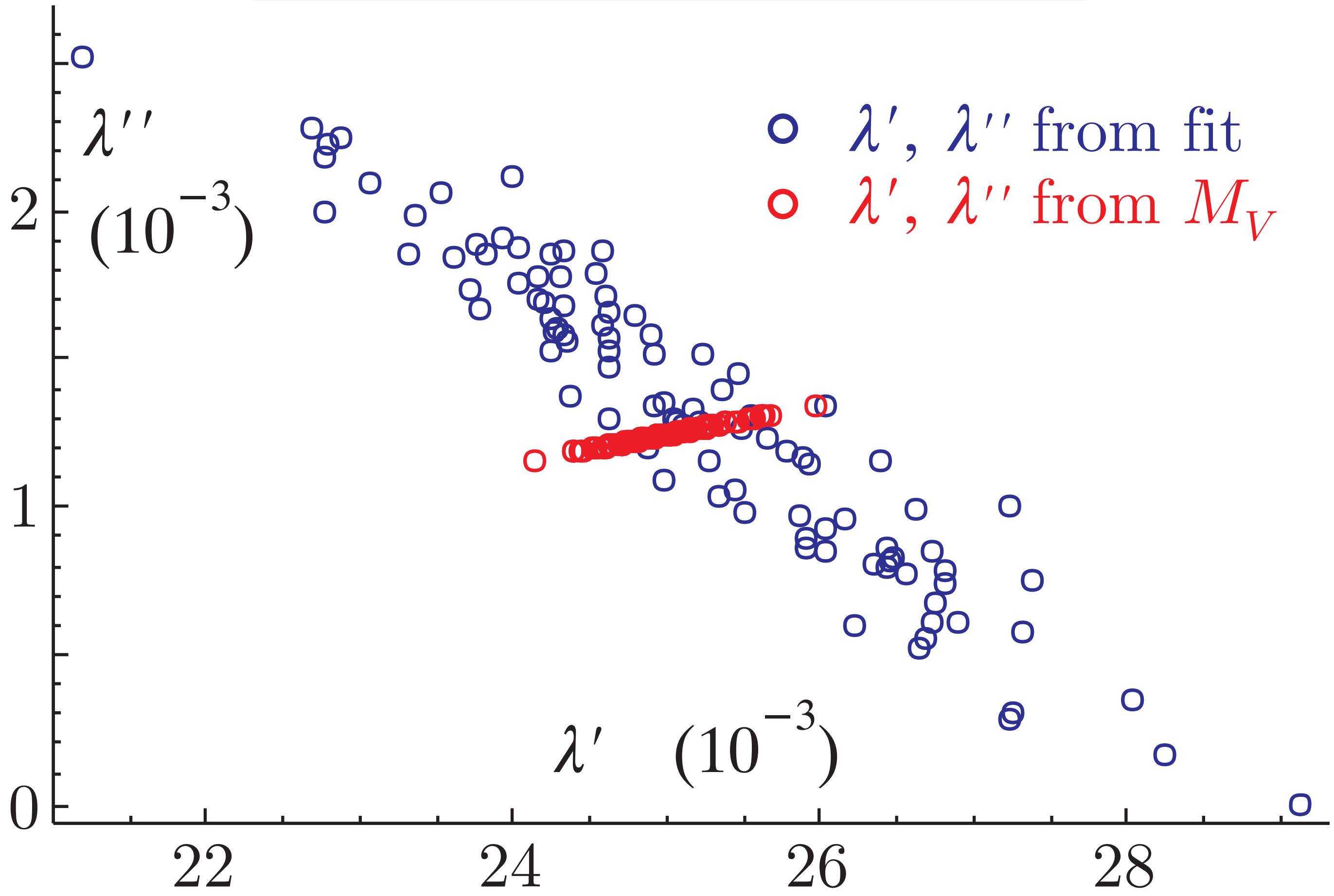
$\lambda'_{\text{pole}} - \lambda'_{\text{quad}} = 0.6 \pm 1.2$

$\lambda''_{\text{pole}} - \lambda''_{\text{quad}} = 0.24 \pm 0.46$

Pole and quad result OK for I_{e3}

$\times$100 statistics required to distinguish

FF parameters, K_{e3}



The -95% correlation between λ' and λ'' results in wild fluctuations while a pole fit is much more stable. 10^6 events.

FF parameters, $K_{\mu3}$

Everything is worse for $K_{\mu3}$, $E_\pi^{\rm max}$, 3 or 4 parameters. It will never be possible to experimentally determine λ_0'' as an independent parameter. The error matrix, for N events is:

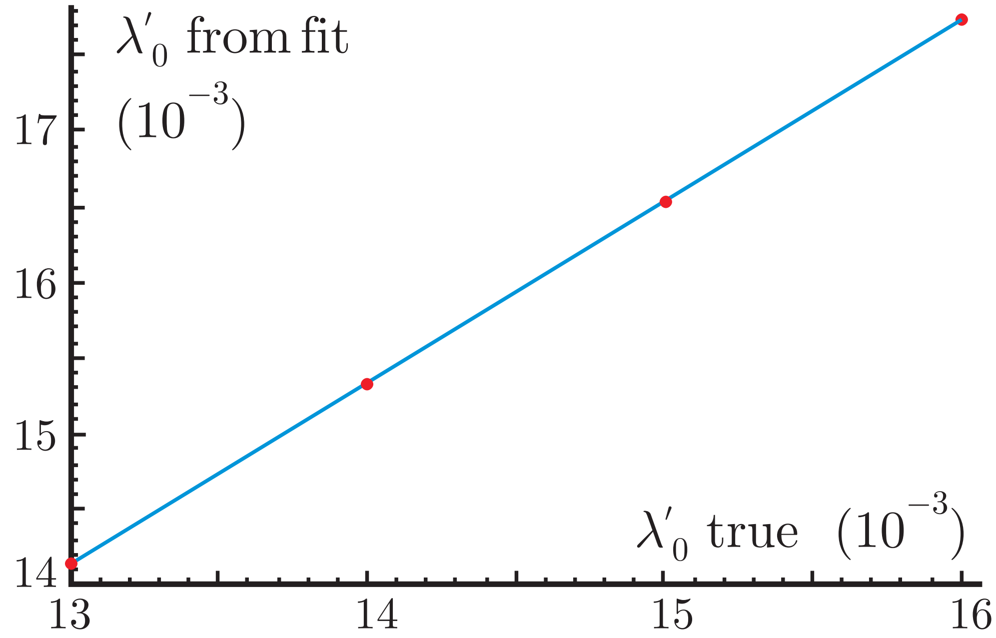
$$
\begin{array}{cc}
 & \begin{array}{cccc} \lambda_0' & \lambda_0'' & \lambda' & \lambda'' \end{array} \\
\mathbf{G} = \dfrac{1}{N} & \begin{pmatrix} 63.9^2 & -1200 & -923 & 197 \\ -1200 & 18.8^2 & 272 & -59 \\ -923 & 272 & 14.8^2 & -49 \\ 197 & -59 & -48 & 3.4^2 \end{pmatrix}
\end{array}
$$

In particular, for 1 million events, $\delta\lambda_0' = 0.064$, $\delta\lambda_0'' = 0.019$ and the correlation between λ_0' and λ_0'' is $\rho = -99.96\%$.

FF parameters, $K_{\mu 3}$

Assuming $\lambda_0' \sim 0.016$ and $\lambda_0'' \sim 2\lambda_0'^2 \sim 0.0005$, a fit to the pion spectrum from 1 million $K_{\mu 3}$ decay determines λ_0' and λ_0'' to an accuracy of $\pm$4,000% and $\pm$38,000%, respectively. 100 million events only get you $\pm$40% and 380%, still not a measurement.

Moreover, ignoring λ_0'' leads to a systematic shift of λ_0' if a quadratic term is present.



Error on λ_0' if $\lambda_0'' = 2\times\lambda_0'^2$.

$\lambda_0' \sim 0.016 \pm 0.002 \pm 0.002$, KLOE
$\lambda_0' = 13.1 \pm 1.4$, CL 10^{-6}

K_S-decays

$\pi^+\pi^-$, $\pi^0\pi^0$, 99.9%

$\Delta I = 1/2$

Chiral expansion parameters

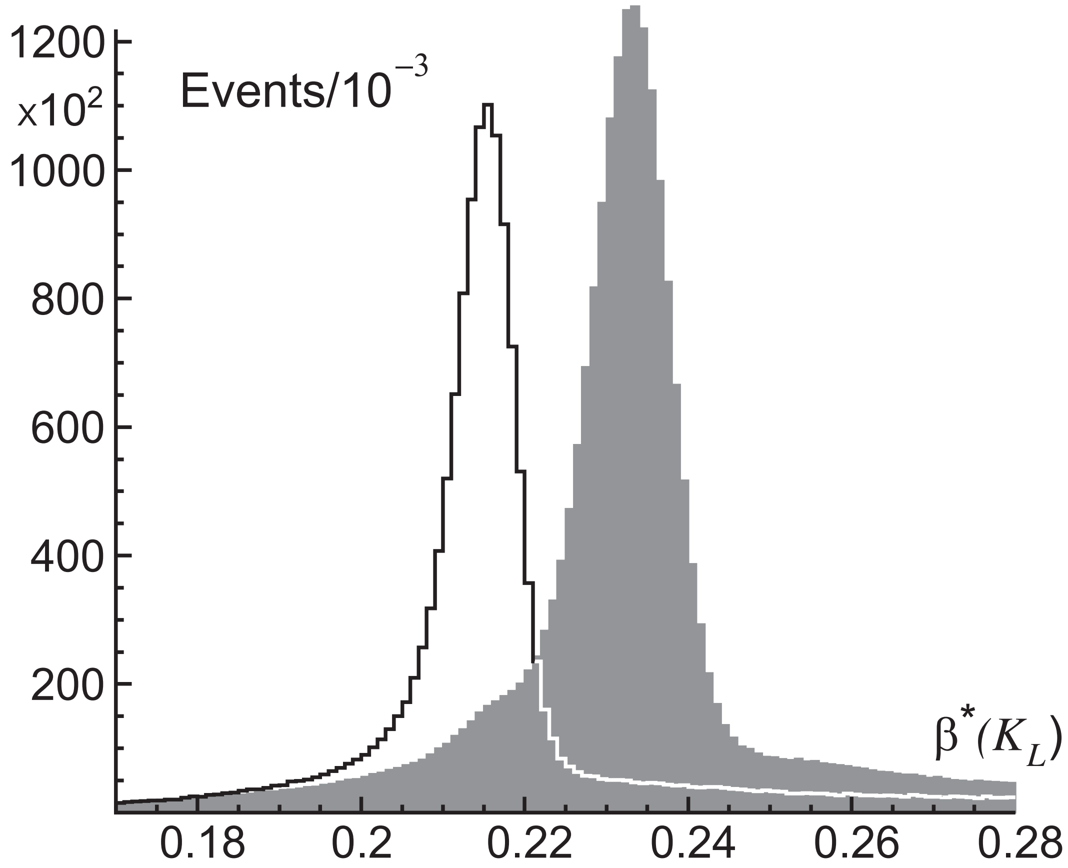
Calculation of $\Re(\epsilon'/\epsilon)$

BR's for K_S decays (and K_L)

$R = \Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_S \to \pi^0\pi^0)$, not well known

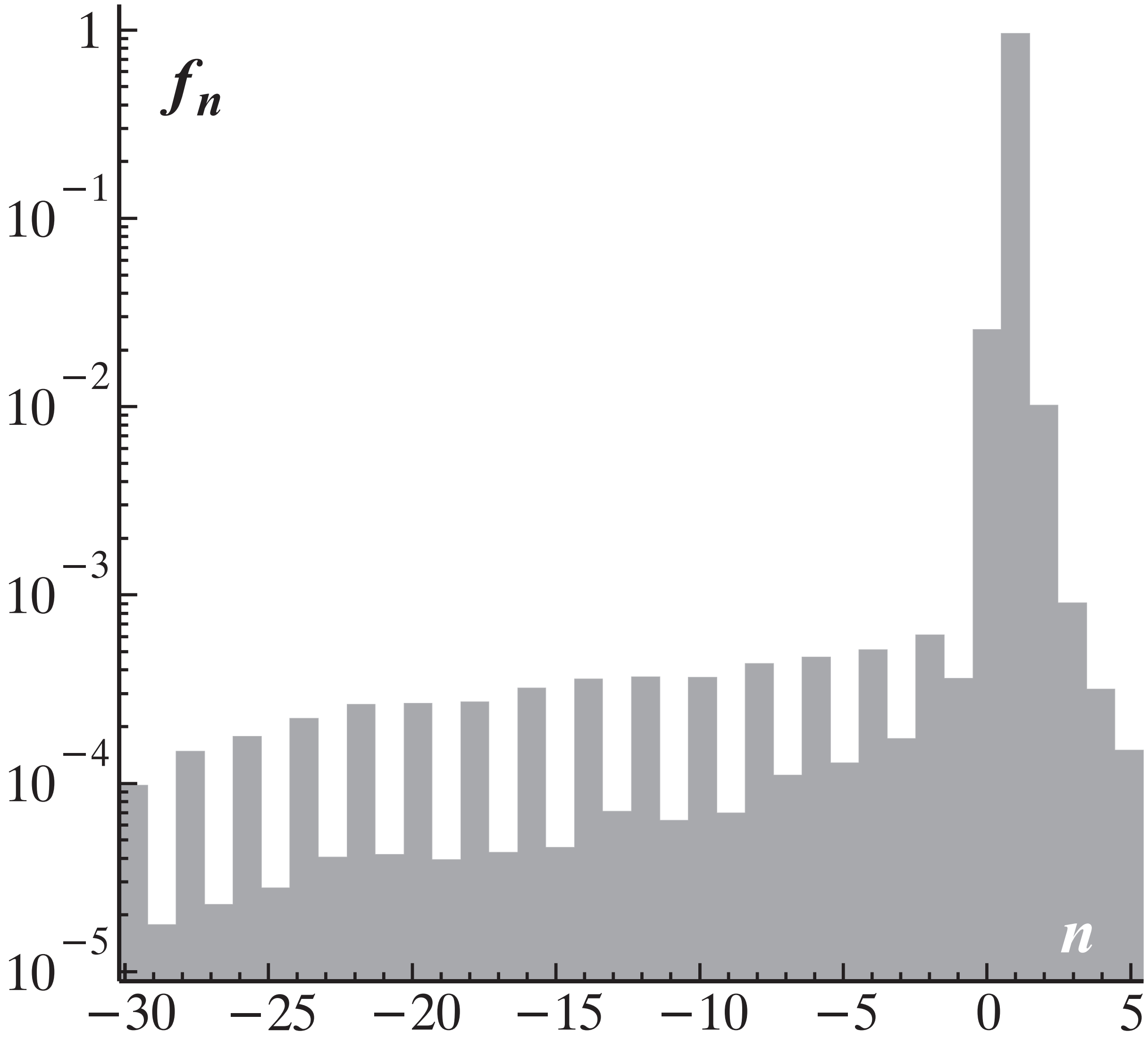
K_S decays

First level, crude K_S tag by K_L TOF



K_L interacting in the calorimeter give an ideal K_S tag, almost independent of K_S decay mode

Reconstructed crossing time



Corrected, largest systematic uncertainty

this is tex

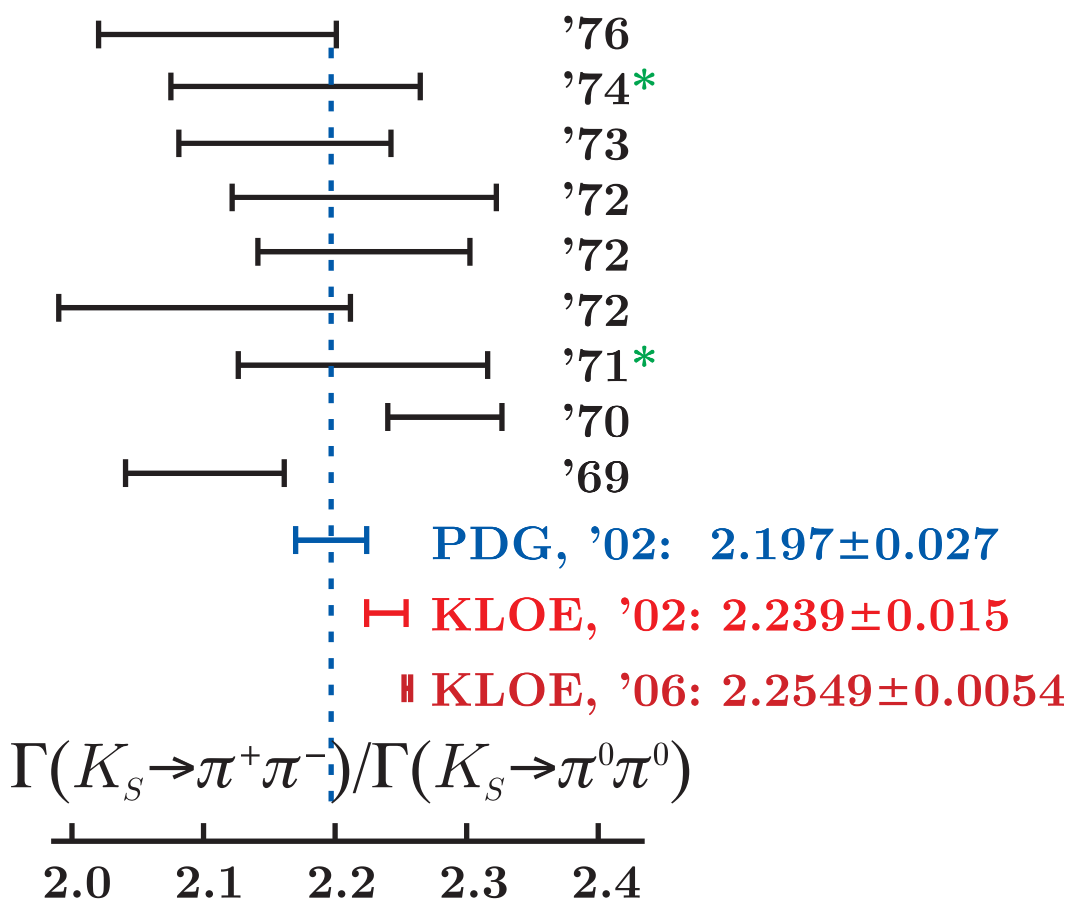
Trigger eff >96.5%

Overall accept. $\sim$57%

ALL FROM DATA $\Downarrow$

Systematic errors

Source	Error, %
T_0	0.2
Cluster count	0.06
Trigger	0.06
Cosmic-r. veto	0.045
Tagging	0.04
Total	0.225



$R = 2.2549 \pm 0.0018(\text{stat.}) \pm 0.0051(\text{syst.})$ with 2002 data

KLOE includes all $K_S \to \pi^+\pi^-\gamma$, others inc. unknown fraction.

$\Delta I = 1/2$ and $3/2$

$$\langle \pi^+\pi^- | K_1 \rangle = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$$\langle \pi^0\pi^0 | K_1 \rangle = \sqrt{\frac{1}{3}} A_0 e^{i\delta_0} - \sqrt{\frac{2}{3}} A_2 e^{i\delta_2}$$

$$\langle \pi^+\pi^0 | K^+ \rangle = \frac{1}{2}\sqrt{3} A_2 e^{i\delta_2}$$

$$\frac{\Gamma(K_1 \to \pi^+\pi^-)}{\Gamma(K_1 \to \pi^0\pi^0)} = \frac{\rho_\pm}{\rho_{00}} \left[2 + 6\sqrt{2} \frac{A_2}{A_0} \cos(\delta_2 - \delta_0) \right]$$

$$\frac{\Gamma(K^+ \to \pi^+\pi^0)}{\Gamma(K_1 \to 2\pi)} = \frac{3}{4} \left(\frac{A_2}{A_0} \right)^2$$

From old data:

$$A_2/A_0 = 0.045$$

$$\delta_0 - \delta_2 = 56.7^\circ \pm 3.8^\circ$$

inconsistent with

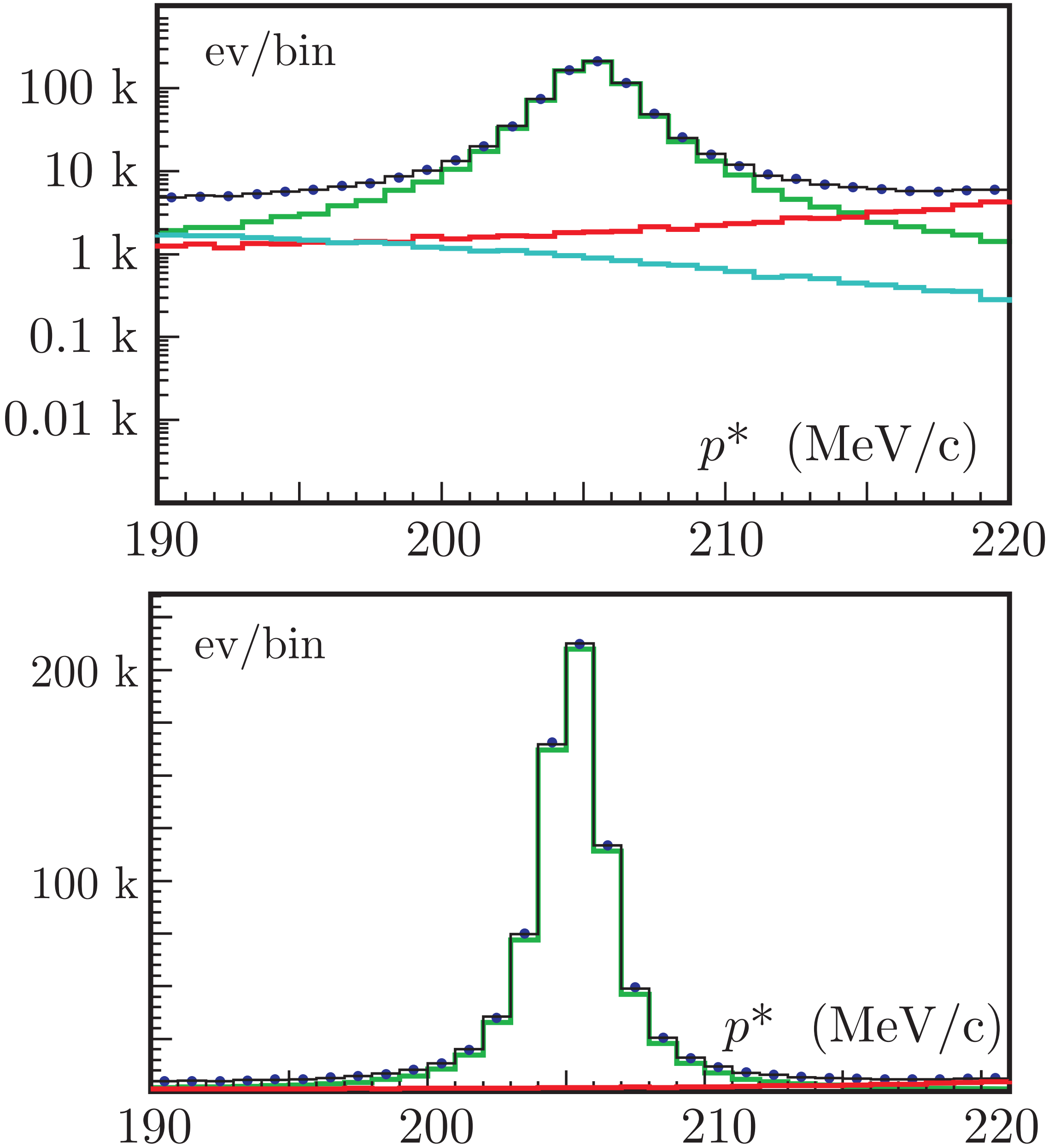
- measurement: $45.2^\circ \pm 1.3^\circ \pm 1.5^\circ$
- $\mathcal{O}(p^2)$ χpt value $45^\circ \pm 6^\circ$
- the phase of ϵ_K,

The '02 KLOE value gives

$$\delta_0 - \delta_2 = 48^\circ \pm 3^\circ$$

in much better agreement. Radiative correction must be included. $\Gamma(K^+ \to \pi^+\pi^0)$ needs remeasuring before seeing improvement from new $K_S \to \pi^+\pi^-, \pi^0\pi^0$. ALMOST DONE! See next week.

A preview



BR($K^+ \to \pi^+\pi^0(\gamma)$)=
(xx.xxx±0.06)%

KLOE measurements of K_S branching ratios

Decay mode	BR(mode)/BR($\pi^+\pi^-$)	BR(mode)
$\pi^+\pi^-(\gamma)$	—	(69.196±0.51)%
$\pi^0\pi^0$	$1/(2.2549 \pm 0.0054)$	(30.687±0.51)%
$\pi^-e^+\nu(\gamma)$	$5.099 \pm 0.091 \times 10^{-4}$	$3.528 \pm 0.063 \times 10^{-4}$
$\pi^+e^-\bar{\nu}(\gamma)$	$5.083 \pm 0.084 \times 10^{-4}$	$3.517 \pm 0.057 \times 10^{-4}$
$\pi e\nu(\gamma)$	$10.19 \pm 0.13 \times 10^{-4}$	$7.046 \pm 0.091 \times 10^{-4}$

$\boxed{K_{e4}}$

The decay $K \to \pi\pi e\nu$ offers a very clean way to study the dynamics of the $\pi - \pi$ interaction

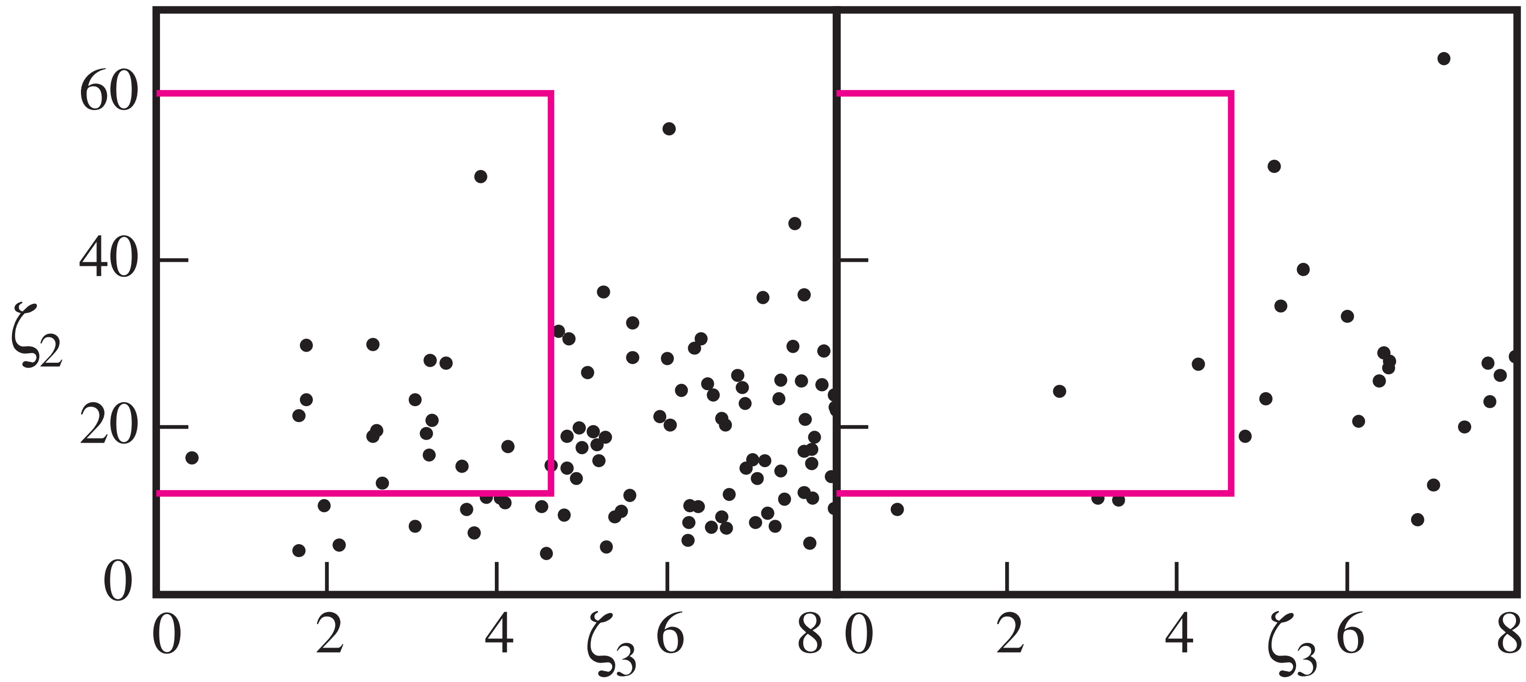
BR($K_{L}, e4$)$\sim 5 \times 10^{-5}$, BR($K^{\pm}_{e4}$)$\sim 2 \times 10^{-5}$. 10^4 decays needed.

Search begun.

$K_S \to \pi^0\pi^0\pi^0$

$BR_S = BR_L |\epsilon|^2 \tau_S/\tau_L$

$K_S \to \pi^0\pi^0\pi^0$ violates CP. $BR(K_S \to \pi^0\pi^0\pi^0) \cong 1.69 \times 10^{-9}$

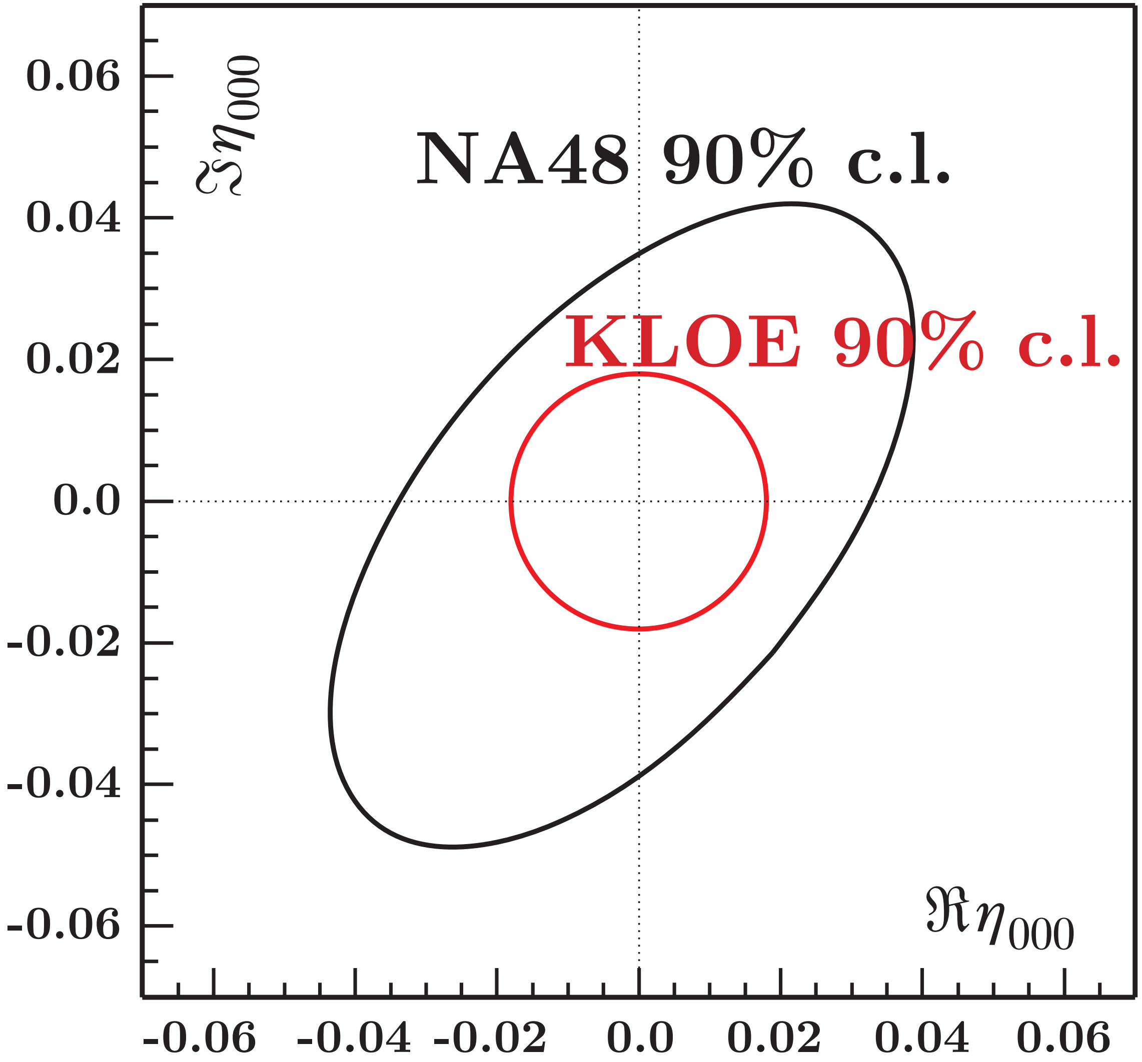


Expect 3±0.9 background events in box, find 2

$BR(K_S \to \pi^0\pi^0\pi^0 \leq 1.2 \times 10^{-7})$ @ 90% CL

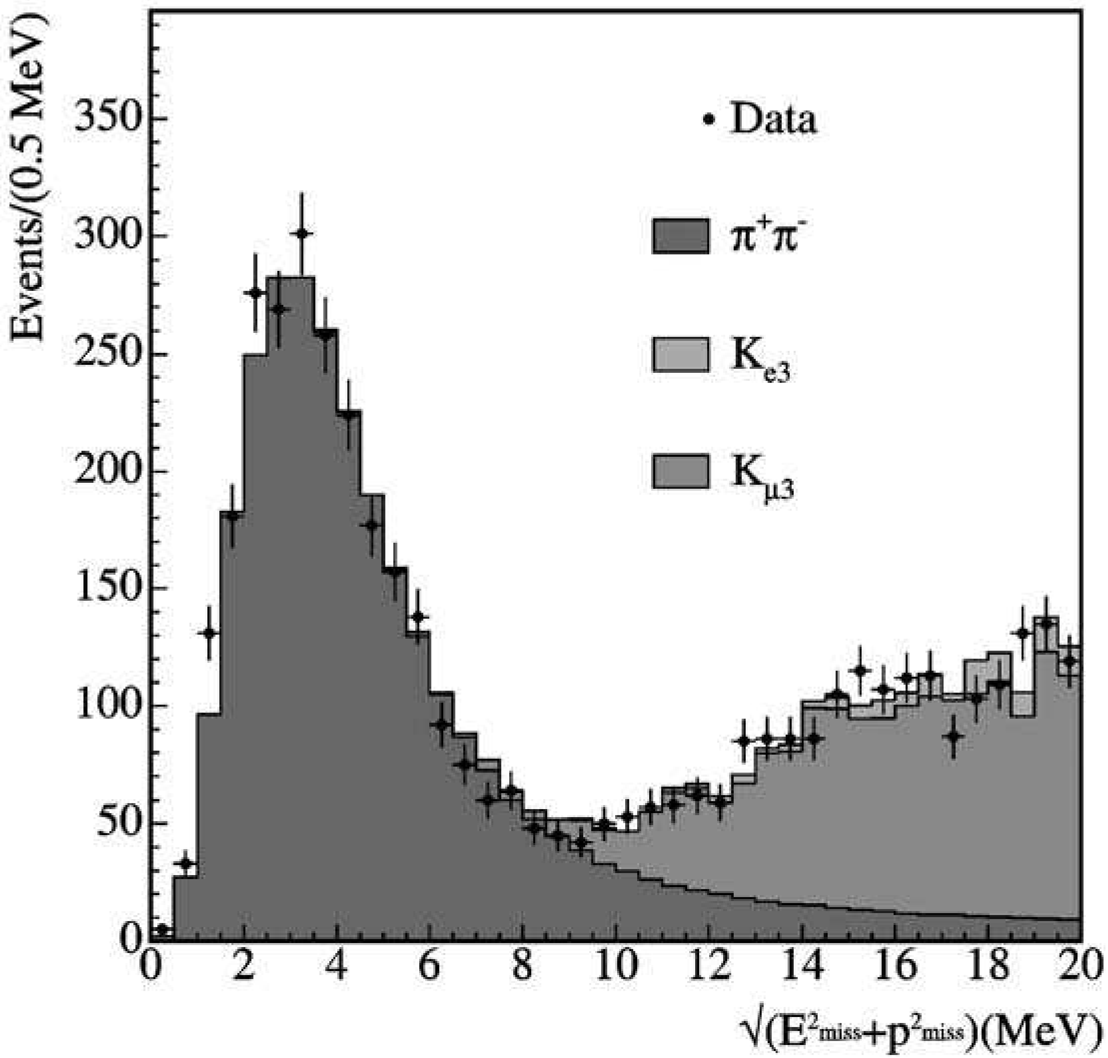
All data, improved analysis, 10^{-8} upper limit possible

$K_S \to \pi^0\pi^0\pi^0$



NA48 searches for a distortion in the $3\pi^0$ decay distribution of a K_L-K_S mixture, due to a possible $K_S \to \pi^0\pi^0\pi^0$. Interference terms sensitive to $\Re\eta_{000}$ and $\Im\eta_{000}$ appear in the distribution.

$K_L \to \pi^+\pi^-$



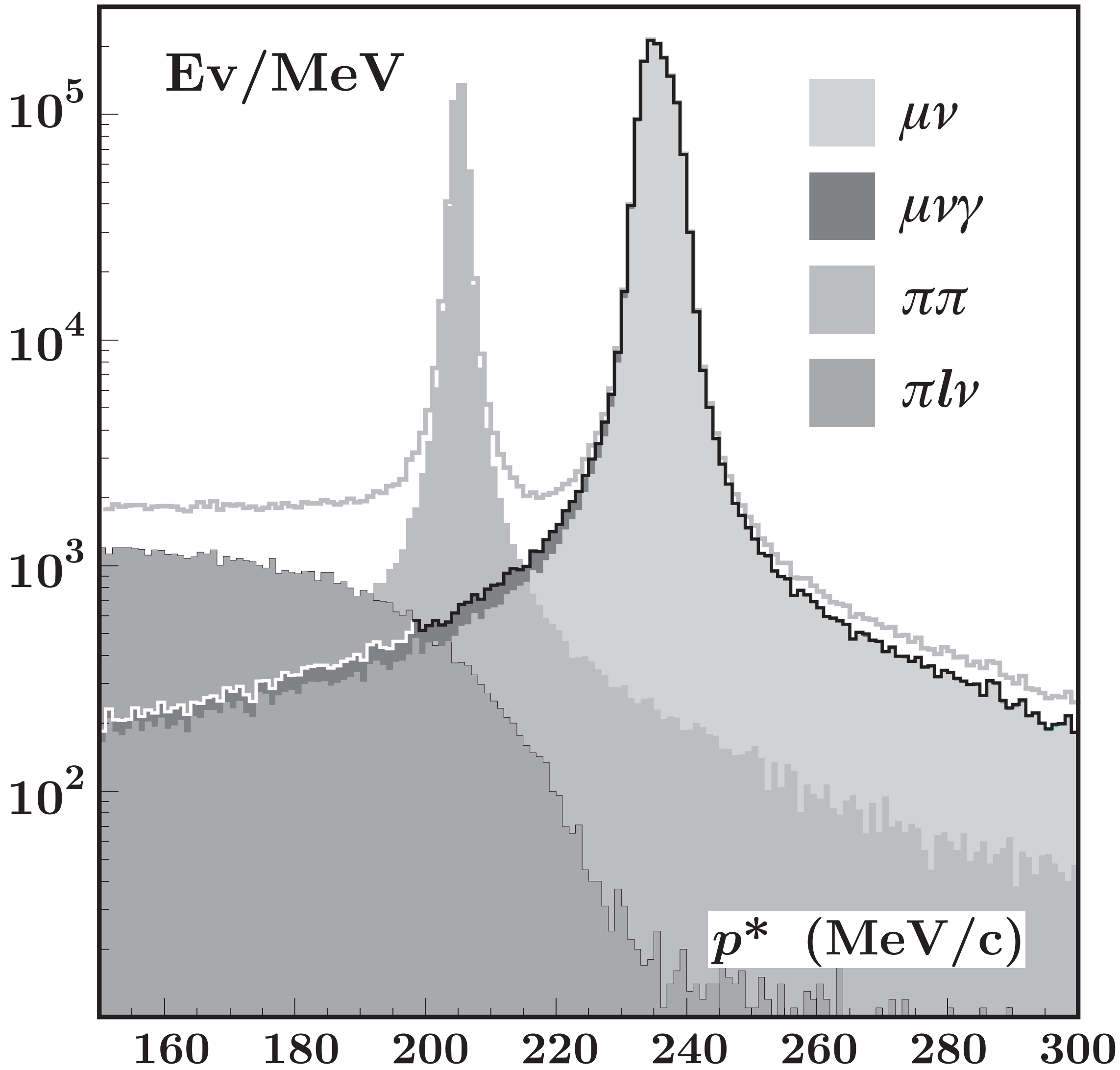
$\text{BR}=(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$

$|\eta_{+-}|=(2.219 \pm 0.013) \times 10^{-3}$

$|\epsilon|=(2.216 \pm 0.013) \times 10^{-3}$

$|\epsilon|_{\text{PDG}}=(2.284 \pm 0.014) \times 10^{-3}$

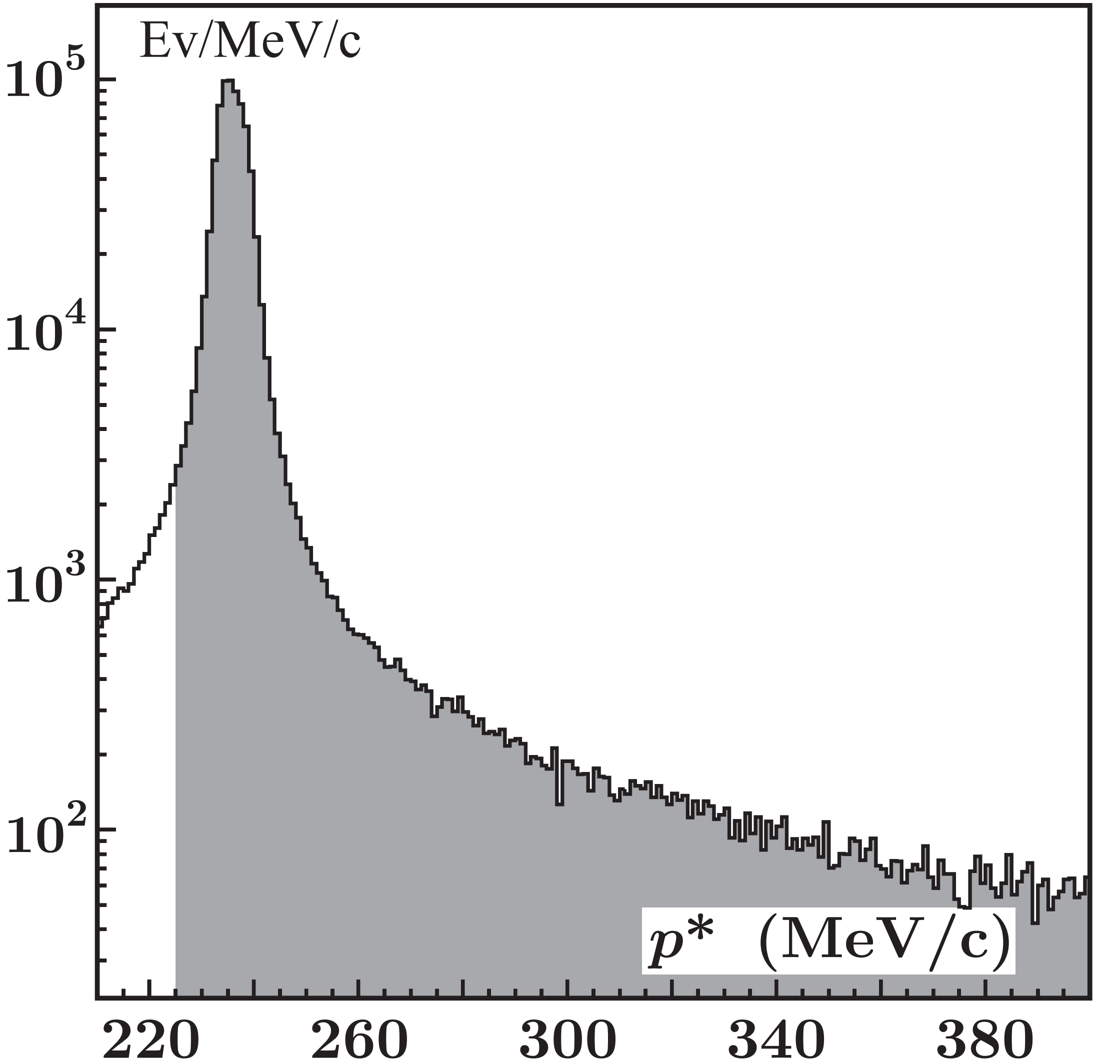
$K^+ \to \mu^+\nu(\gamma)$



Tag by detecting $K^- \to \mu^-(\pi^-)\bar{\nu}$.
Compute decay particle momentum in Kaon rest frame, assuming $K^+ \to \pi^+\nu$.
$K_{\pi 2}$ and $K_{\mu 2}$ signal are well separated.
Note radiative tail.

this
is
tex

$K^+ \to \mu^+\nu(\gamma)$



$K_{\mu 2}$ events are counted only in shaded area.
BR($K^+ \to \mu^+\nu(\gamma)$) =
0.6366±0.0009±0.0015.

V_{us} from $\Gamma(K \to \mu\nu)/\Gamma(\pi \to \mu\nu)$

Marciano, 2004

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K \left(1 - m_\mu^2/m_K^2\right)^2}{m_\pi \left(1 - m_\mu^2/m_\pi^2\right)^2} \times (0.9930 \pm 0.0035)$$

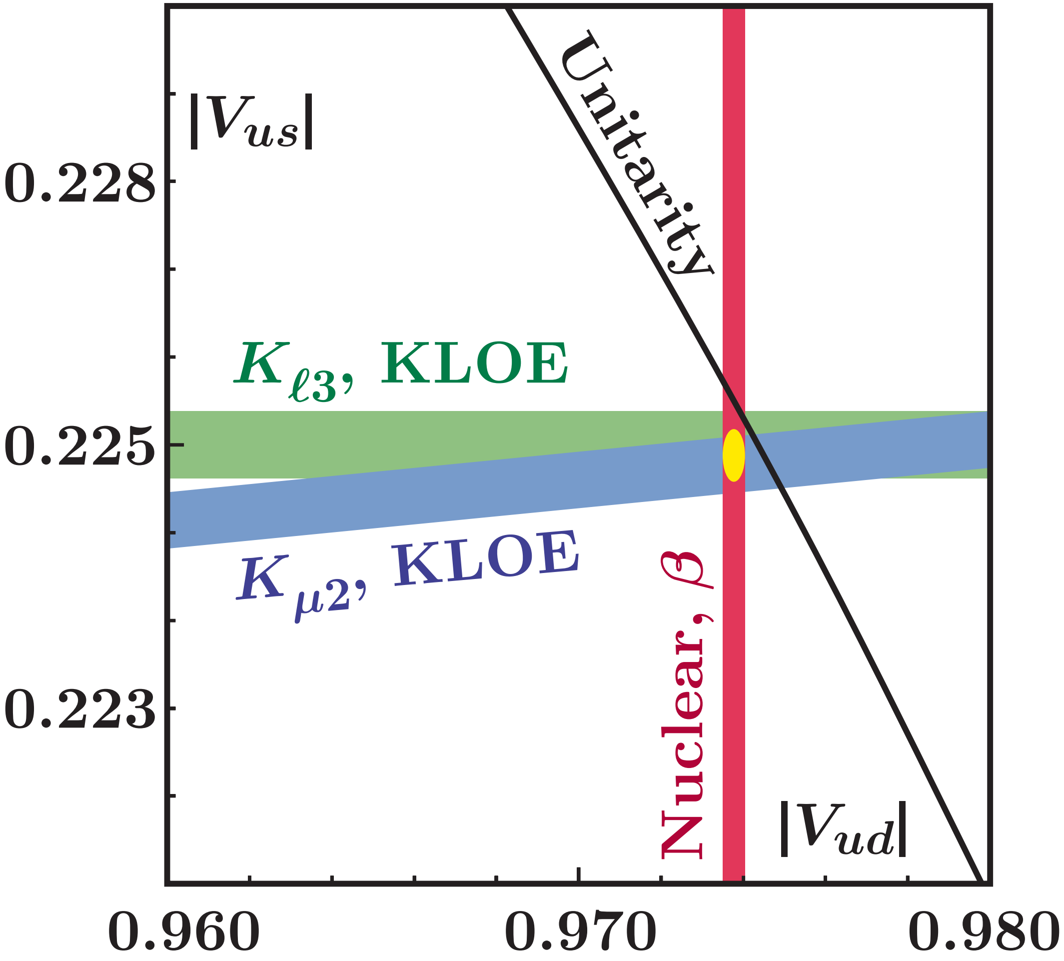
Rad. corr, Marciano.

From lattice,

$$\frac{f_K}{f_\pi} = 1.208(2)(^{+7}_{-14}),\ \text{MILC}$$

$$|V_{us}|/|V_{ud}| = 0.2286(^{+27}_{-15})$$

$|V_{us}|$ from $K_{\mu 2}$ and $K_{\ell 3}$



From $K_{\ell 3}$

$1\text{-}\sum_i |V_{ui}|^2 = 0.0011 \pm 0.0010$

From all K

$1\text{-}\sum_i |V_{ui}|^2 = 0.0012 \pm 0.0009$

$|V_{us}|$ and $|V_{ud}|$ errors contribute equally

$|V_{us}|$ error due to $f(0)$

Unitarity and CPT

Unitarity, through the so called Bell-Steinberger relation -BSR- relates possible CPT violation in the time evolution of the neutral kaon system, $M(K^0) \neq M(\overline{K}^0)$ and/or $\Gamma(K^0) \neq \Gamma(\overline{K}^0)$ to the observable $\not{C}\not{P}$ interference in K_S, K_L decays.

KLOE has performed three measurements which allows improved accuracy in the check of the possible $\not{C}\not{P}\not{T}$ inequalities above.

1. Our measurement of BR($K_L \rightarrow \pi^+\pi^-$) gives an improved determination of ϵ.
2. An improved limit on $K_S \rightarrow \pi^0\pi^0\pi^0$ improves the limit on $\Im\delta$.
3. The first measurement of $\mathcal{A}_S$, which allows for the first time to determine the contribution of the semileptonic channels, without invoking unitarity.

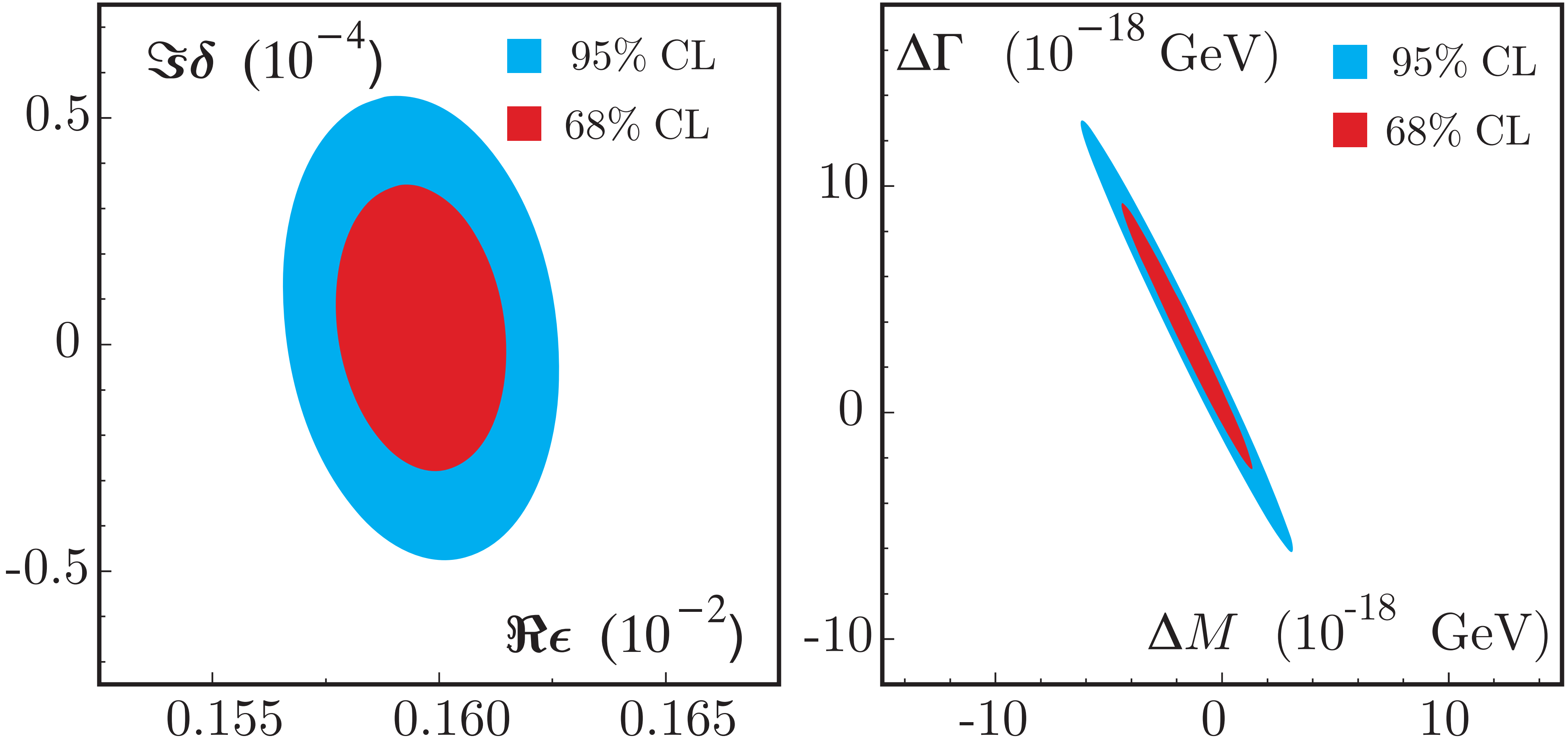
Definitions

Without assuming CPT-invariance, the eigenstates of the time evolution equation for neutral kaons are:

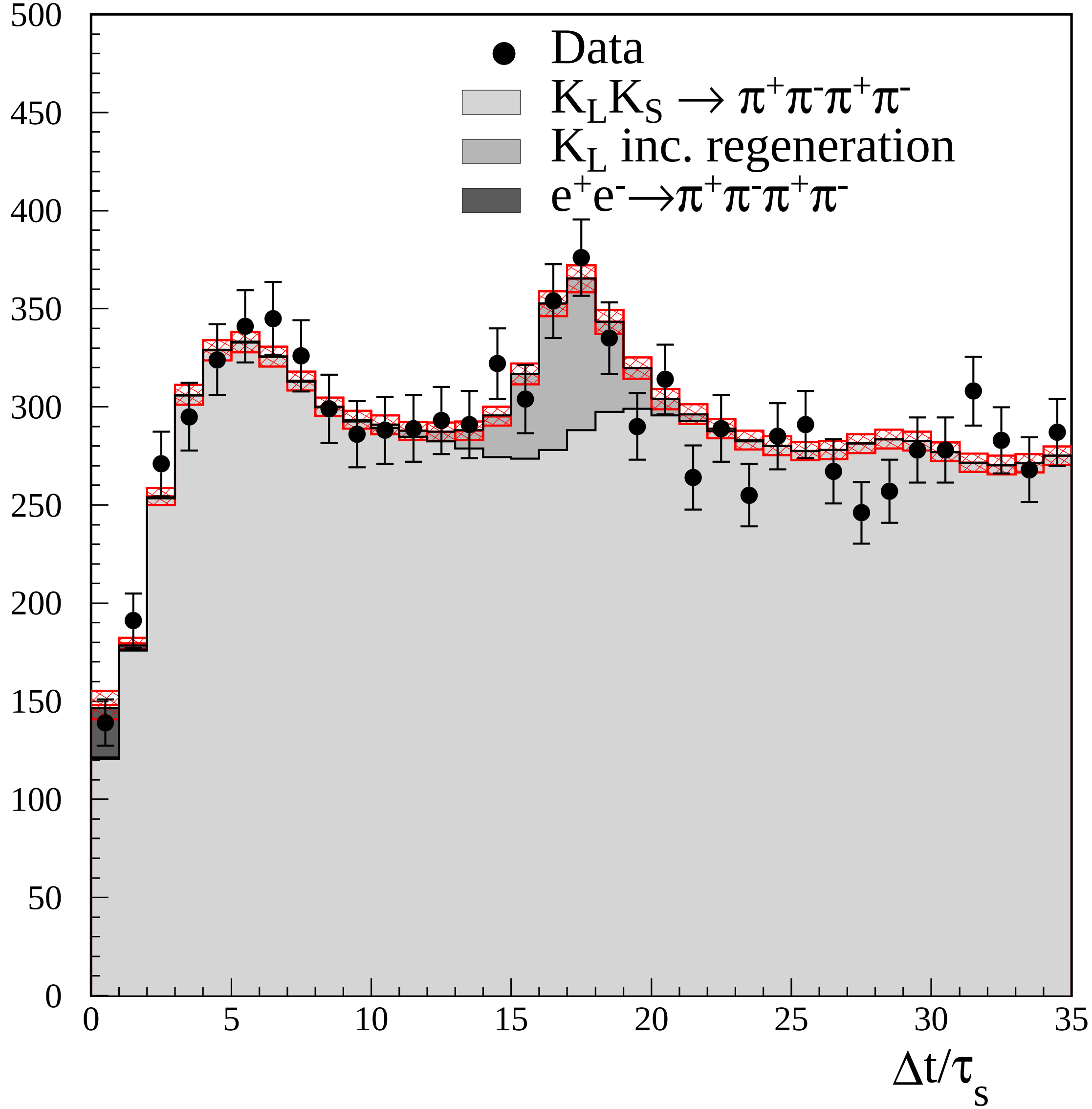
$$K_{S,\,L} = \frac{1}{\sqrt{2(1+|\epsilon_{S,L}|^2)}}\Big((1+\epsilon_{S,L})K^0 \pm (1-\epsilon_{S,L})\overline{K^0}\Big)$$

with $\epsilon_{S,L} = \epsilon \pm \delta$. CPT-invariance requires δ=0.

$\Re\epsilon$ and new $\Im\delta$, ΔM, ΔM limits



Q.M. & Coherence



The time difference distribution has a QM-interference terms:

$2|\eta_1||\eta_2|\cos(\Delta m\, t + \phi_1 - \phi_2)$

A study of the interference allows testing QM. Empirically we multiply the interference term by a factor $(1 - \zeta)$, and determine ζ from a fit to the distribution on the left.

Coherence test

The decay distribution intensity vs t_1, t_2 can be written both in the $K_{S,L}$ and K^0, $\overline{K}^0$ basis. Correspondingly one introduces two coherence loss parameters ζ_{00} and ζ_{SL}.

From the fit we find

$$\zeta_{LS} = 0.02 \pm 0.04$$
$$\zeta_{00} = (0.1 \pm 0.2) \times 10^{-5}$$

Recently, KEKB reported $\zeta_{00}^{B} \sim 0.03$ to be compared to the kaon value of 0.00002.

Other rare and semirare kaon decays

$K_L \to \gamma\gamma$ BR=$(5.89 \pm 0.11) \times 10^{-4}$

$K_S \to \gamma\gamma$ BR=$(2.27 \pm 0.13) \times 10^{-6}$

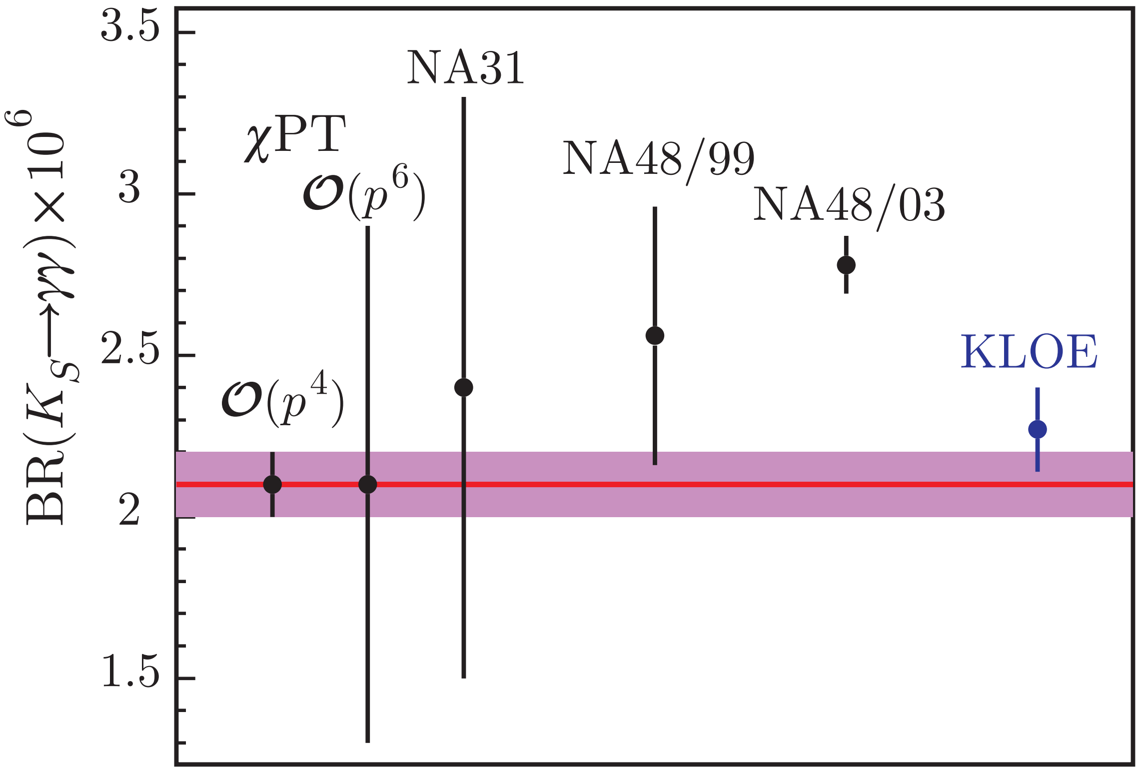
$K_L \to \pi e \nu \gamma^{\dagger}$ BR=$(3.6 \pm 0.12) \times 10^{-3}$

$K^{\pm} \to e^{\pm}\nu$ BR=wait next week

$K_S \to e^+ e^-$ BR=$< 2.1 \times 10^{-8}$ @ 90% CL

† $E_\gamma > 30$ MeV, $\theta_{\gamma-e} > 20^\circ$, $\langle X \rangle = -2.3 \pm 1.3 \pm 1.4$(DE term)

$K_S \to \gamma\gamma$



$K_L \to \gamma\gamma$ is CP allowed

$K_S \to \gamma\gamma$ violates CP to LO

$\mathcal{O}(p^6)$ χpt quite uncertain

$q\bar{q}$ spectroscopy

$2\,^3S_1$ ρ, ω, ϕ

$1\,^3P_J$ a_0, f_0, f_1, f'

$2\,^1S_0$ π, η

1500 Mev

Level diagram

$s\bar{s}$ contents

Gluon contents

Chiral expansion

a_0, f_0??
950 MeV

$1\,^3S_1$ ρ, ω, ϕ

$1\,^1S_0$ π, η

$J^{PC} =$ 0^{-+} 1^{--} $(0,1,2)^{++}$

$\boxed{\eta \text{ meson}}$

In KLOE, $\sim$100 million η-mesons have been produced. What can we do with it:

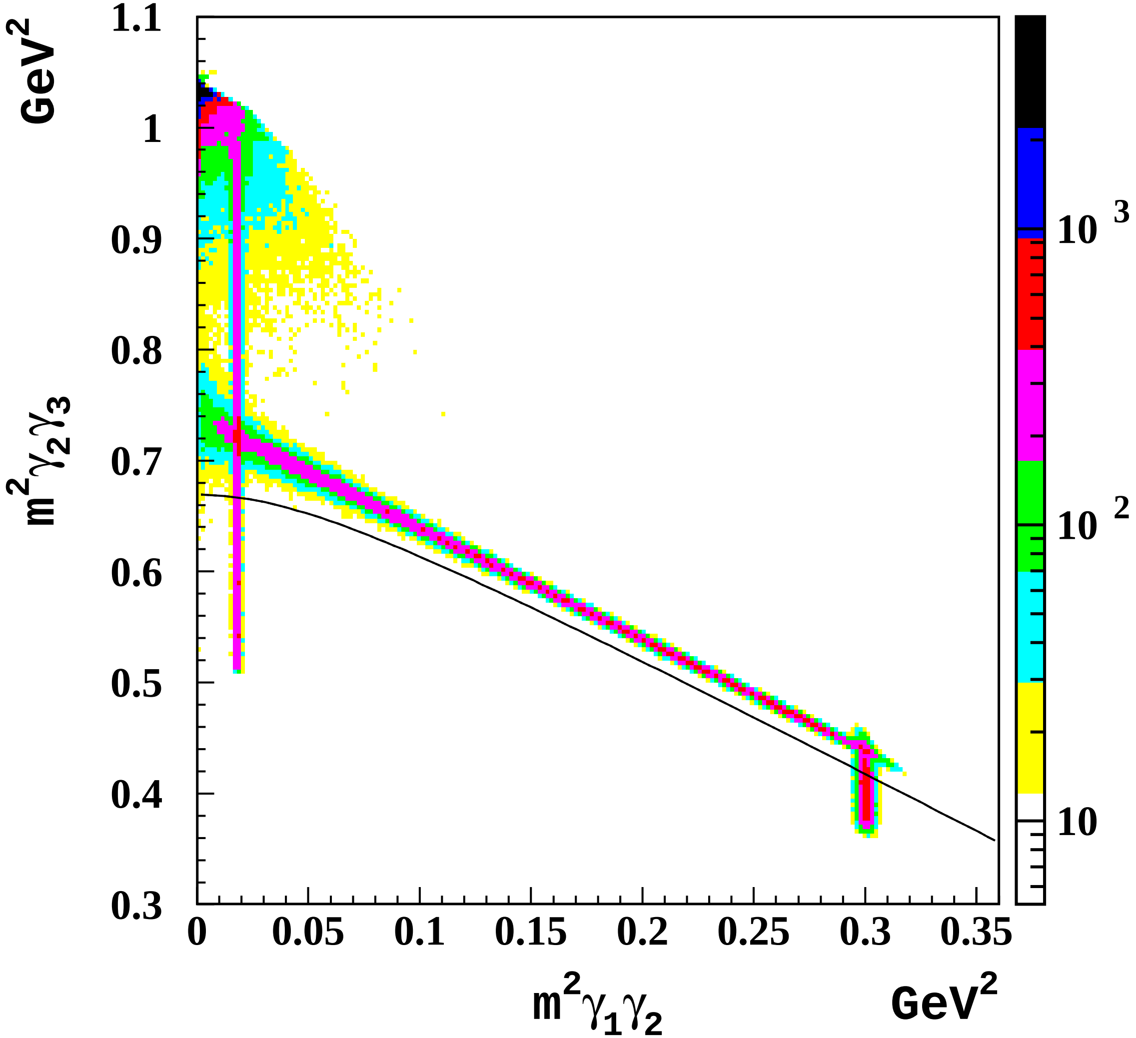
– mass

– decay dynamics

– C-invariance etc., tests

– forbidden modes

η mass

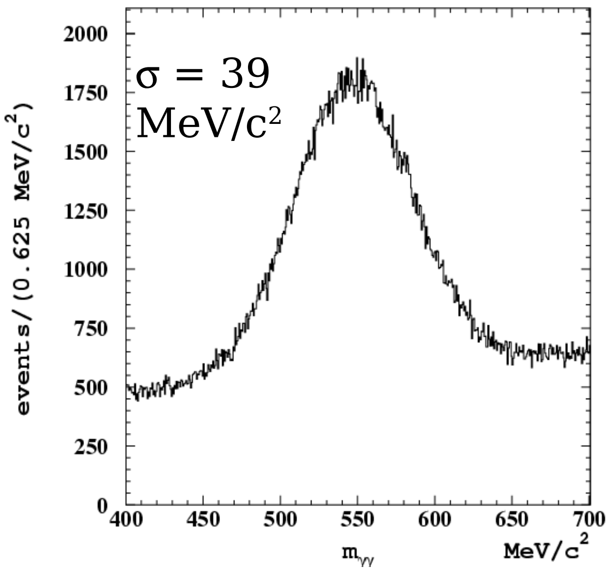


$\phi \to \gamma\eta \to \gamma_1\gamma_2\gamma_3$, 4-C fit ($\gamma$ angles enough) Photons are labelled so that $E_1 < E_2 < E_3$. Both the η-meson and the neutral pion are visible as vertical lines in $M(\gamma_1, \gamma_2)$. The η is also visible as a diagonal line. For $\phi \to \pi^0\gamma$, γ_3 is always the recoil γ.

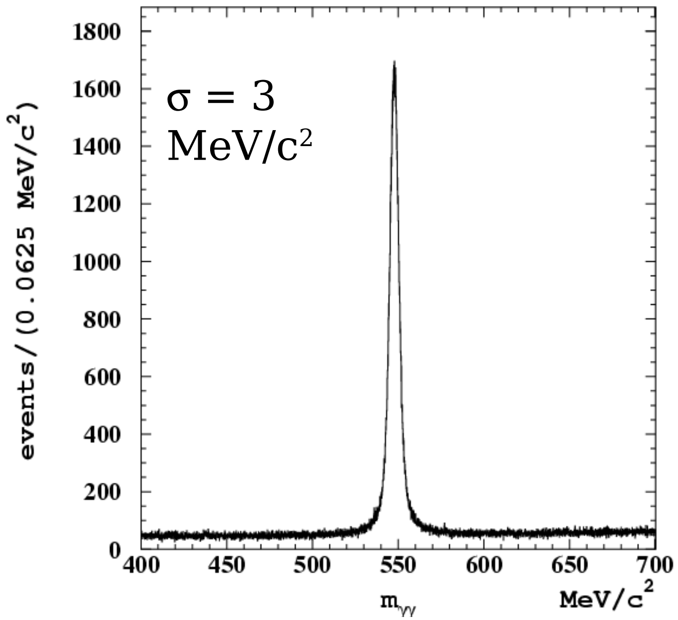
$$M(\eta) = 547.822 \pm 0.005 \pm 0.069$$

in agreement with NA48 but not with GEM

before kin. fit



after kin. fit

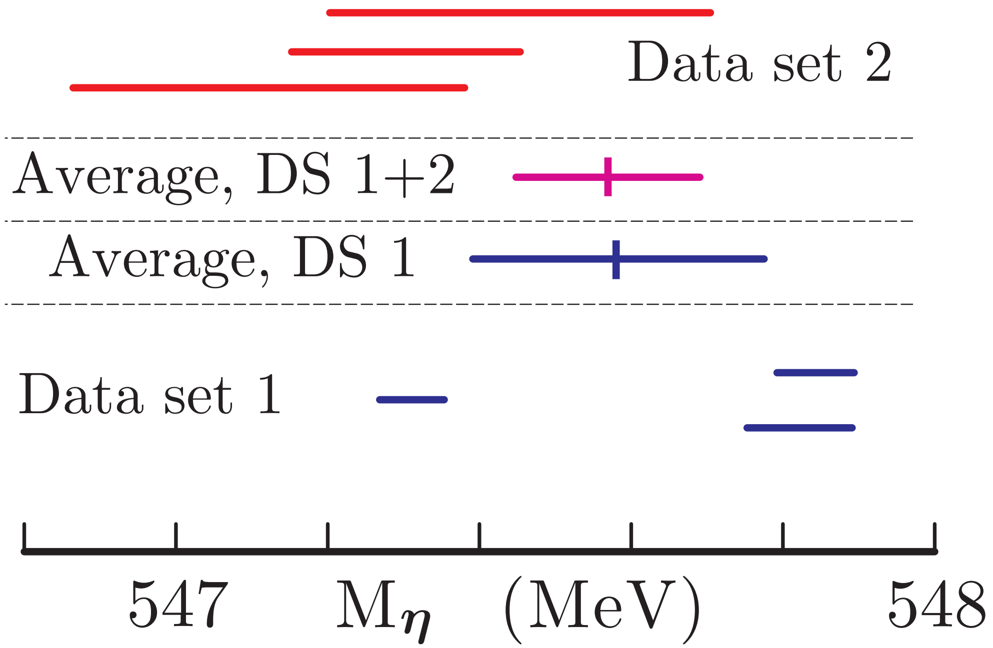


the kinematic fit squeeze the distribution because of the very good angular resolution.

5

Comparison

Experiment	Mass
GEM	547.311±0.043
NA48	547.843±0.051
KLOE	547.822±0.069



On the left is an illustration of how the PDG would treat the data. Note how throwing in three old measurements of no accuracy, decreases the error by ∼2 without changing the central value.

My average: $M(\eta)$=547.836±0.041, CL=80.6%

Forbidden η-decays

$$\eta \to \pi^+\pi^-,\ \pi^+\pi^-\gamma$$

violates both P and CP.

$$\mathrm{BR}(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5} \text{ at 90\% CL}$$

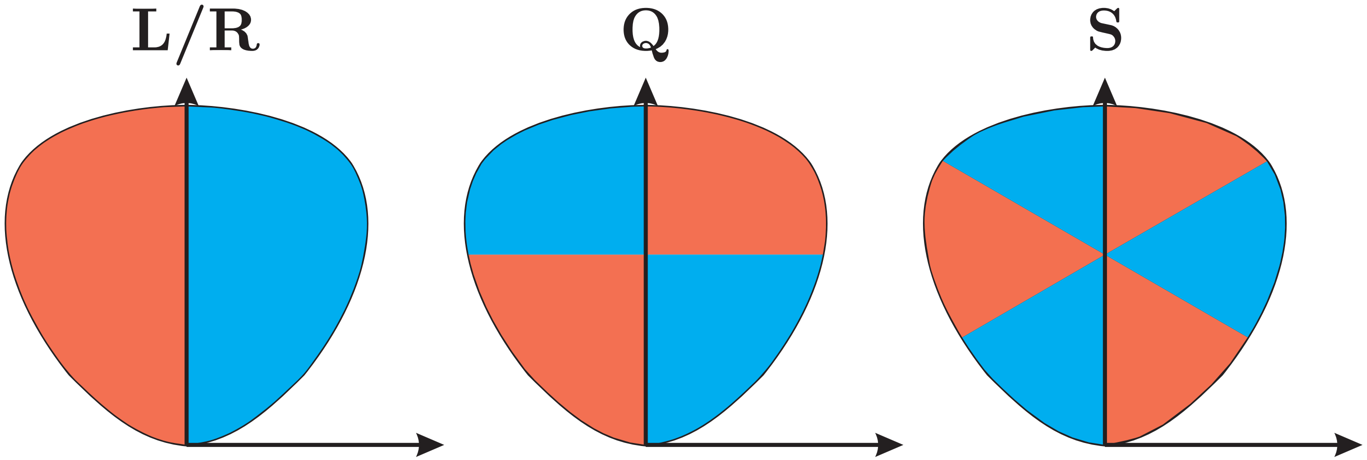
$$\eta \to \gamma\gamma\gamma$$

violates both CP.

$$\mathrm{BR}(\eta \to \gamma\gamma\gamma) \leq 1.6 \times 10^{-5} \text{ at 90\% CL}$$

Both limits are $\sim$30$\times$ more stringent than previously known.

Dalitz plot asymmetries in $\eta \to \pi^+\pi^-\pi^0$



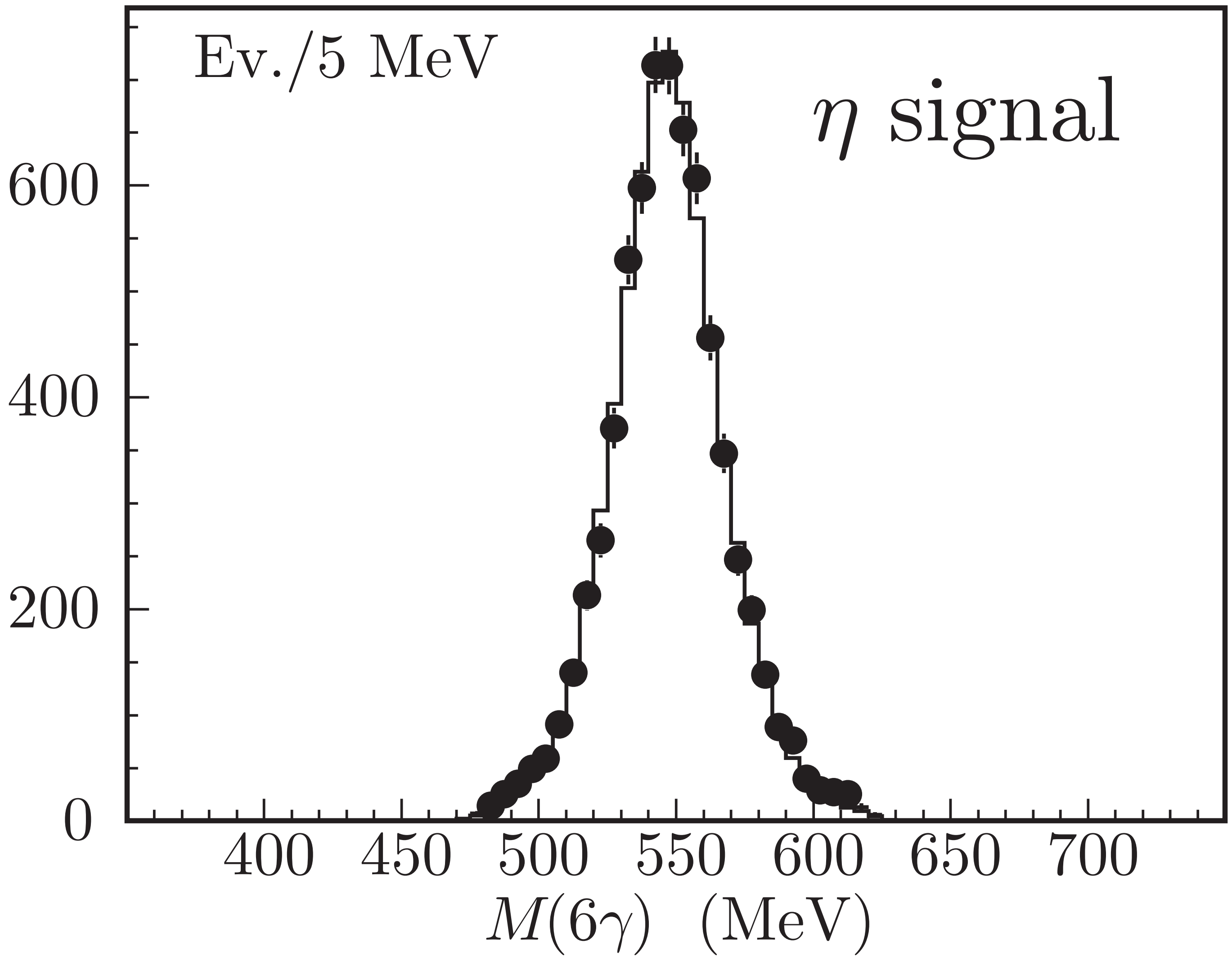
$I = 2$ $\quad\quad$ $I = 1$

Charge asymmetries: L/R: A_{LR}, Q: A_{Q}, S: A_{S}

All asymmetries consistent with zero at 10^{-3} level, $\mathcal{O}(10^6$ events)

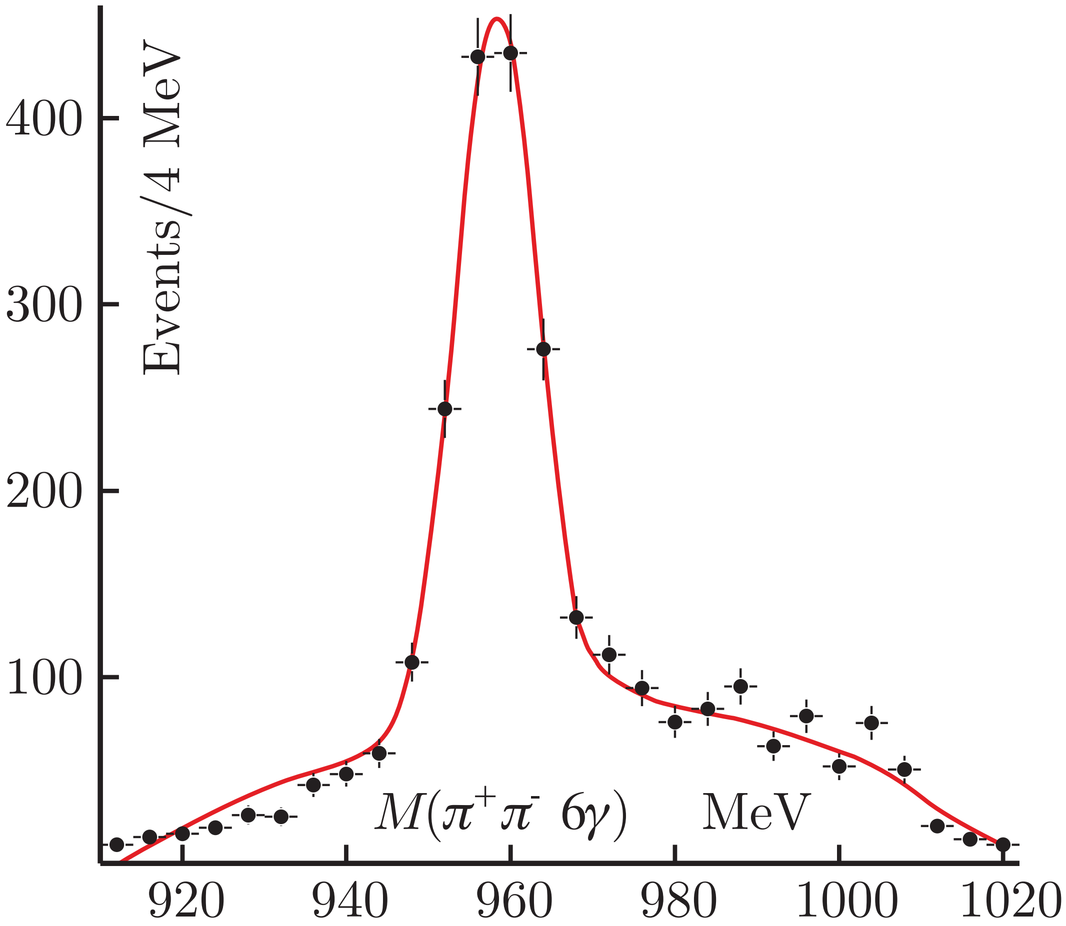
C-invariance OK.

$\boxed{\phi \to \gamma\eta,\ \gamma\eta'}$



$\phi \to \eta\gamma \to$
$\pi^0\pi^0\pi^0\gamma \to 7\gamma$

$\phi \to \eta' \gamma \to \eta \pi^0 \gamma \to \pi^+ \pi^- \, 7\gamma$



$\phi \to \eta' \gamma \to \pi^+ \pi^- \eta \gamma \to \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \gamma \to \pi^+ \pi^- \ 7\gamma$

$\phi \to \eta' \gamma \to \pi^0 \pi^0 \eta \gamma \to \pi^0 \pi^0 \pi^+ \pi^- \pi^0 \gamma \to \pi^+ \pi^- \ 7\gamma$

$R_\phi = (4.77 \pm 0.09 \pm 0.19) \times 10^{-3} \Rightarrow$

$\mathrm{BR}(\phi \to \eta' \gamma) = (6.2 \pm 0.11 \pm 0.25) \times 10^{-5}$

η and η' Mixing

In the quark-flavor basis mixing let

$$|\eta\rangle = \cos\phi\,|u\bar{u} + d\bar{d}\,\rangle/\sqrt{2} + \sin\phi|s\bar{s}\,\rangle$$
$$|\eta'\rangle = -\sin\phi\,|u\bar{u} + d\bar{d}\,\rangle/\sqrt{2} + \cos\phi|s\bar{s}\,\rangle$$

then

$$R_\phi = \frac{\text{BR}(\phi\to\eta'\gamma)}{\text{BR}(\phi\to\eta\gamma)} = \cot^2\phi_P\left(1-\frac{m_s}{\bar{m}}\,\frac{C_{NS}}{C_S}\,\frac{\tan\phi_V}{\sin 2\phi_P}\right)^2\left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

where corrections for $SU(3)$ breaking, wave function overlap and phase space are included. ϕ_V=3.4° is the mixing angle for vector mesons. We find

$$\phi_P = (41.4 \pm 0.3_{\text{stat}} \pm 0.7_{\text{sys}} \pm 0.6_{\text{th}})^\circ$$

In the singlet-octet basis: $\theta_P = \phi_P - \arctan\sqrt{2} = (-13.3 \pm 0.3_{\text{stat}} \pm 0.7_{\text{sys}} \pm 0.6_{\text{th}})^\circ$.

Is there gluonium in the η'

Bound gluon states, gluonium, could mix in the η':

$$|\eta'\rangle = X|q\bar{q}\rangle + Y|s\bar{s}\rangle + Z|G\rangle$$

Gluonium mixing means $Z \neq 0$ and $X^2 + Y^2 < 1$. Since gluonium does not couple to photons, the ratio R_ϕ above acquires an extra factor $\cos\phi_g = \sqrt{1 - Z^2}$. Combining with other ratios:

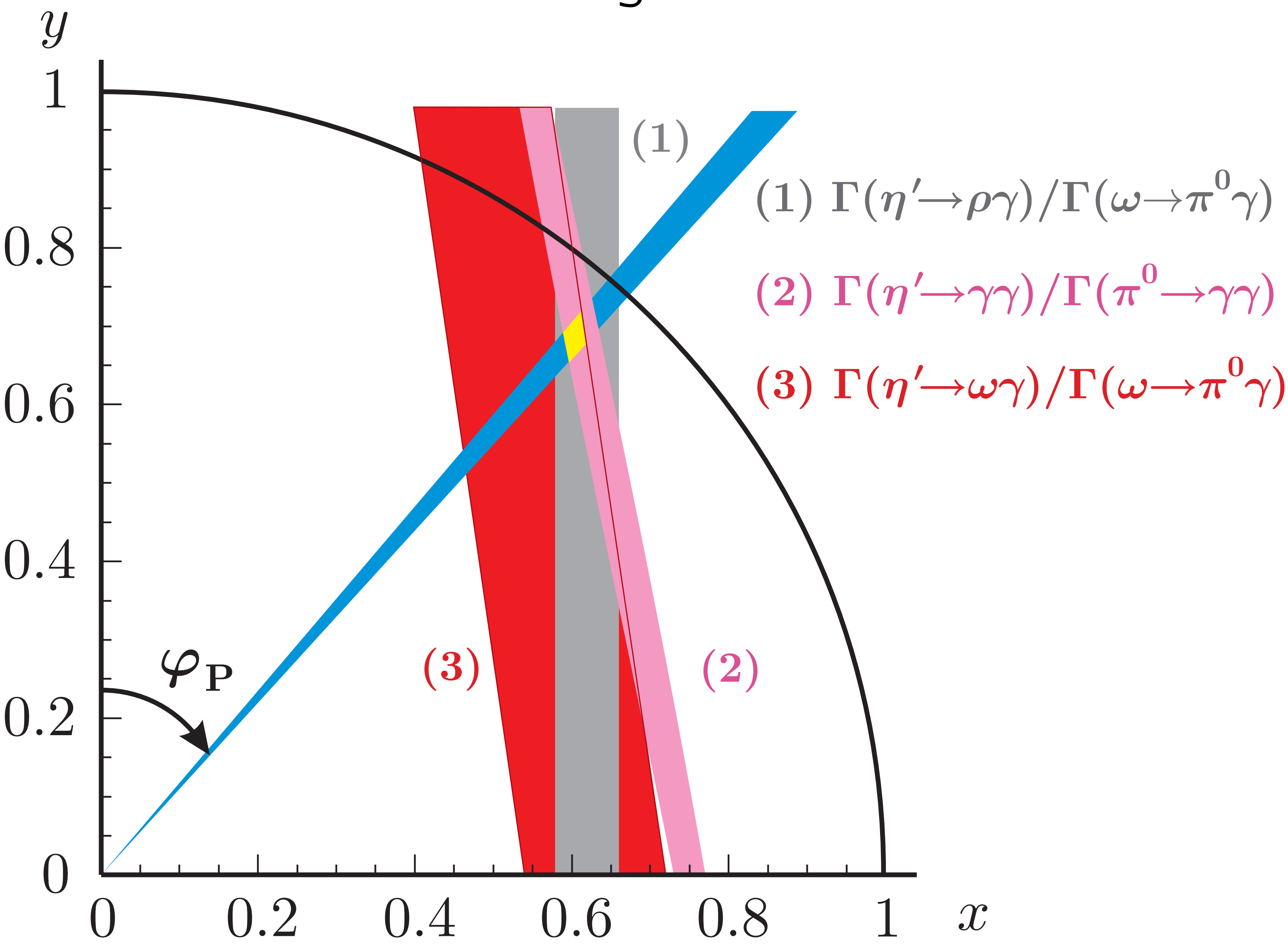
$$\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma) \quad (1)$$

$$\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma) \quad (2)$$

$$\Gamma(\eta' \to \omega\gamma)/\Gamma(\omega \to \pi^0\gamma) \quad (3)$$

we get the picture below

eta-glue-a



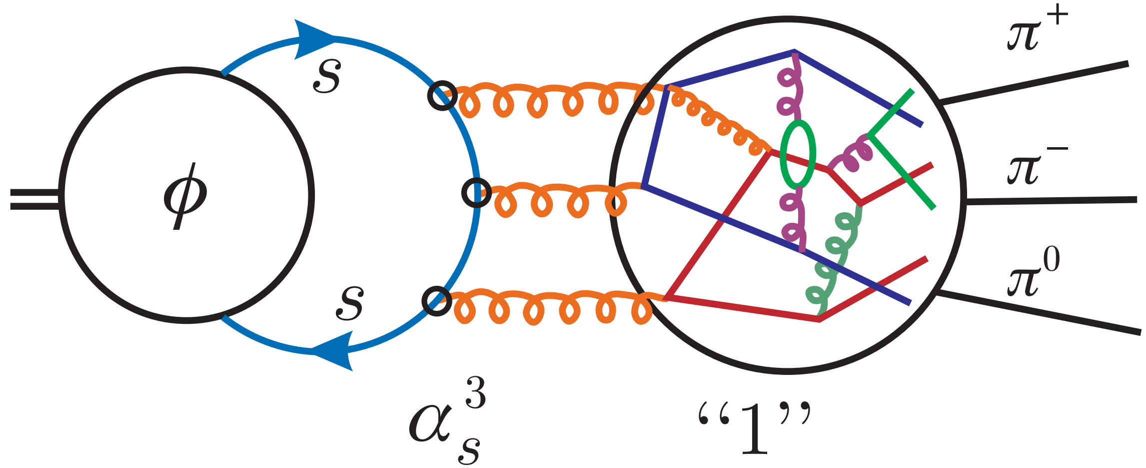
which seems to say that there is glue!

$\boxed{\phi \to \pi^+\pi^-\pi^0}$

BR($\phi \to ggg \to \pi^+\pi^-\pi^0$)=15.5%

(Origin of OZI-rule)

Dominated by $\rho\pi$

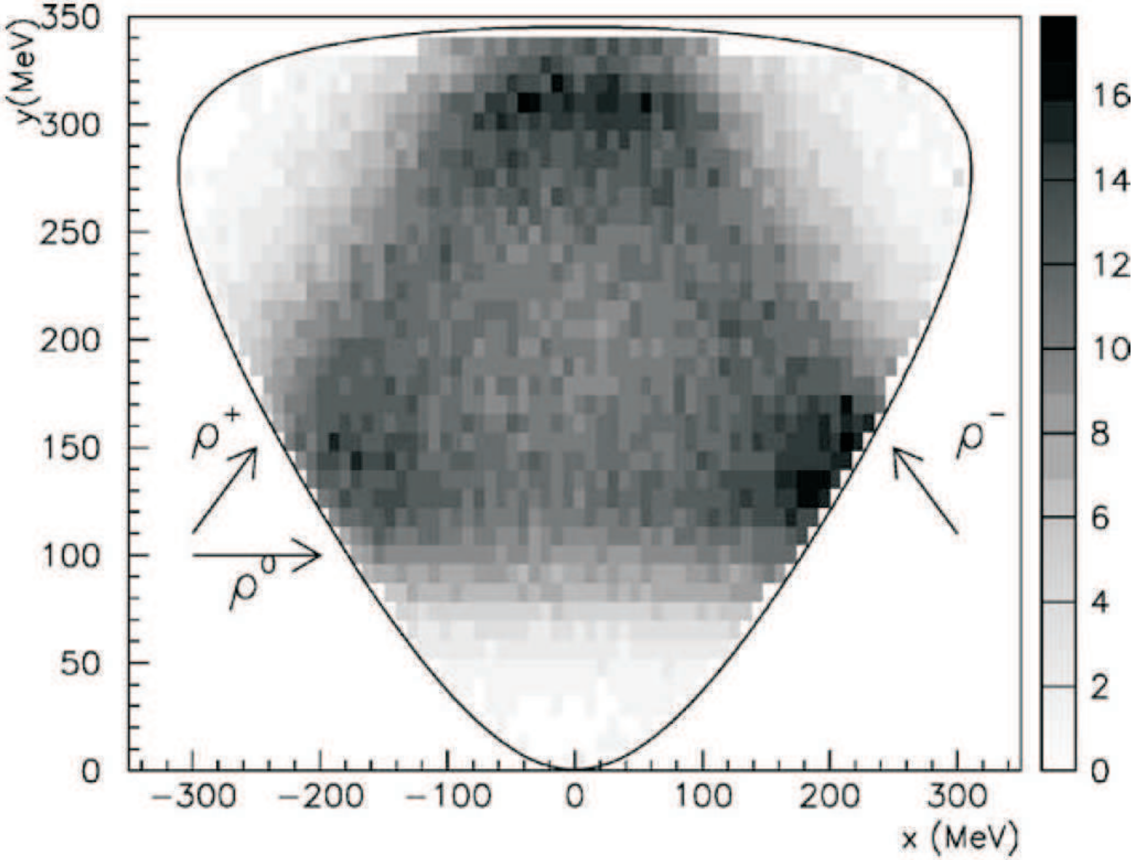


Large sample of $\rho^+,\ \rho^-,\ \rho^0$

Precise and consistent measurement of $M^{\pm,0}$, $\Gamma^{\pm,0}$

Relevant to $\delta a_{\mu,\text{"hadr"}}$

$\phi \to \pi^+\pi^-\pi^0 \to \rho^{\pm,0}\pi^{\mp,0}$



$\rho\pi/\mathrm{all} > 94\%$

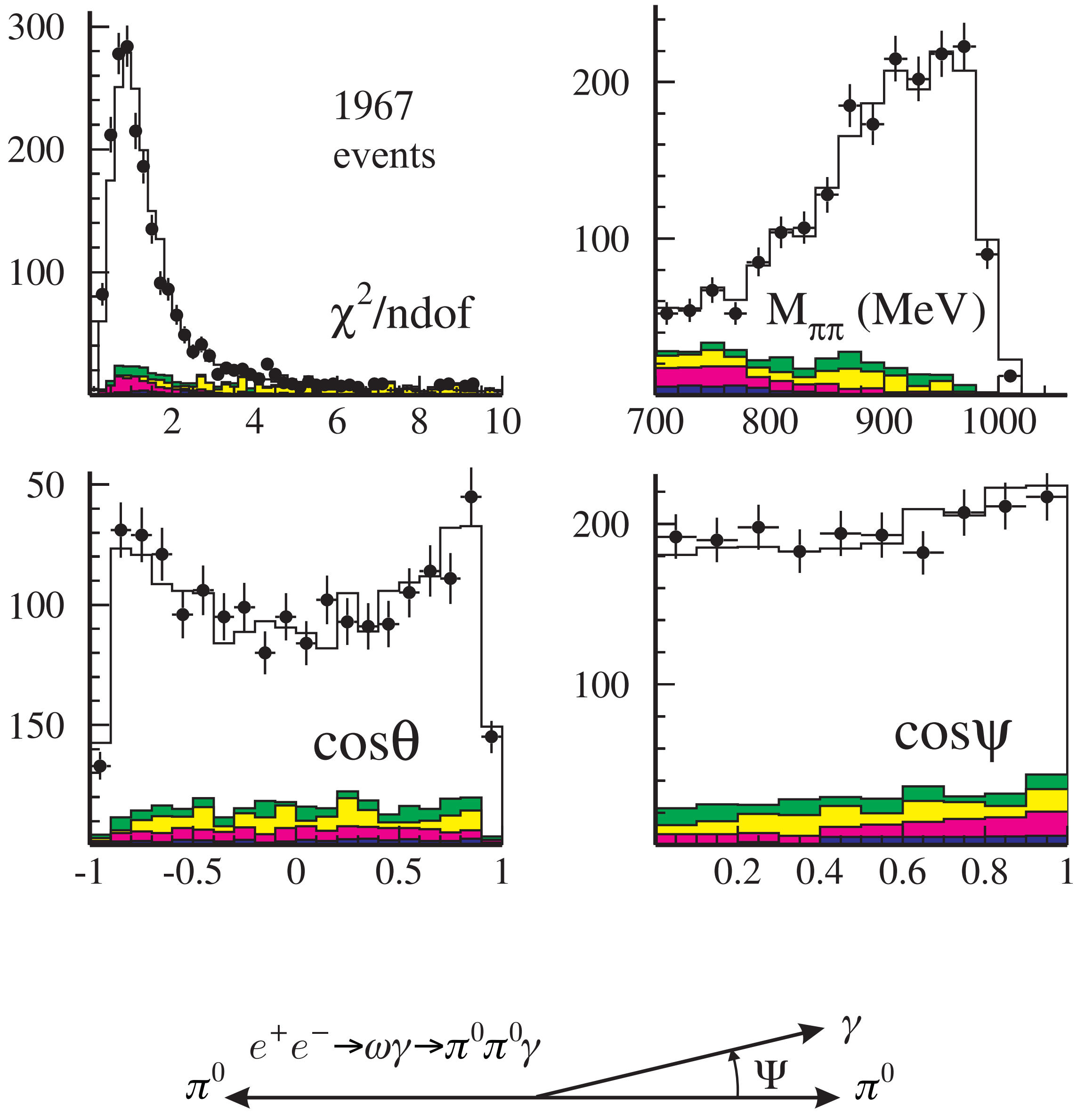
$\langle M(\rho)\rangle = 775.8 \pm 0.6$ MeV

$\langle \Gamma(\rho)\rangle = 143.9 \pm 1.7$ MeV

$M(\rho^0) - M(\rho^\pm) = 0.4 \pm 0.9$

$\Gamma(\rho^0) - \Gamma(\rho^\pm) = 3.6 \pm 2.1$

Scalars: f_0 and a_0



The scalars' puzzle

Wrong mass

What are they

$q\bar{q}$, gg

$q\bar{q}q\bar{q}$, $K\bar{K}\ldots$

Combination of the above?

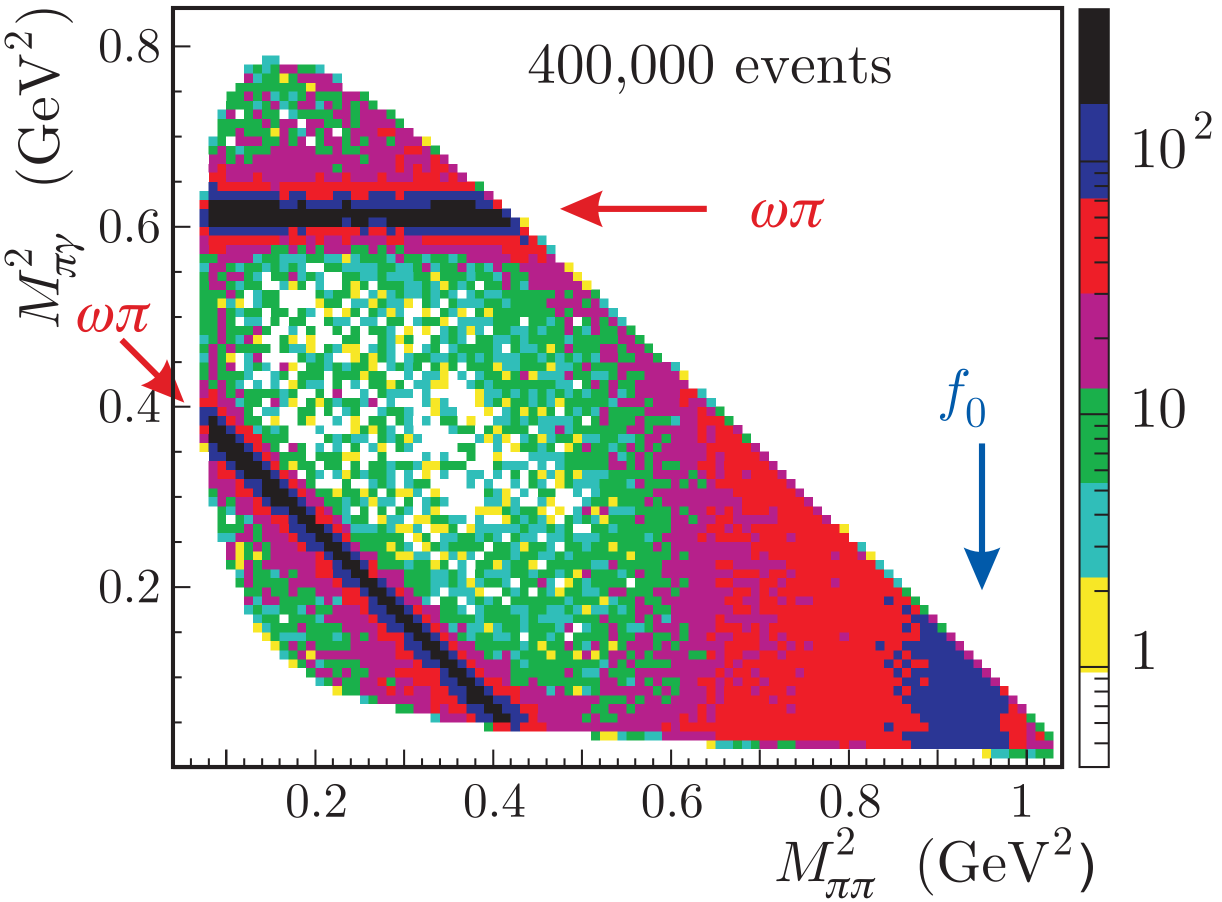
$I = 0, \quad f_0 \to \pi^0\pi^0$

$\phi \to f_0\gamma, \; f_0 \to 4\gamma$

$\phi \to 5\gamma$

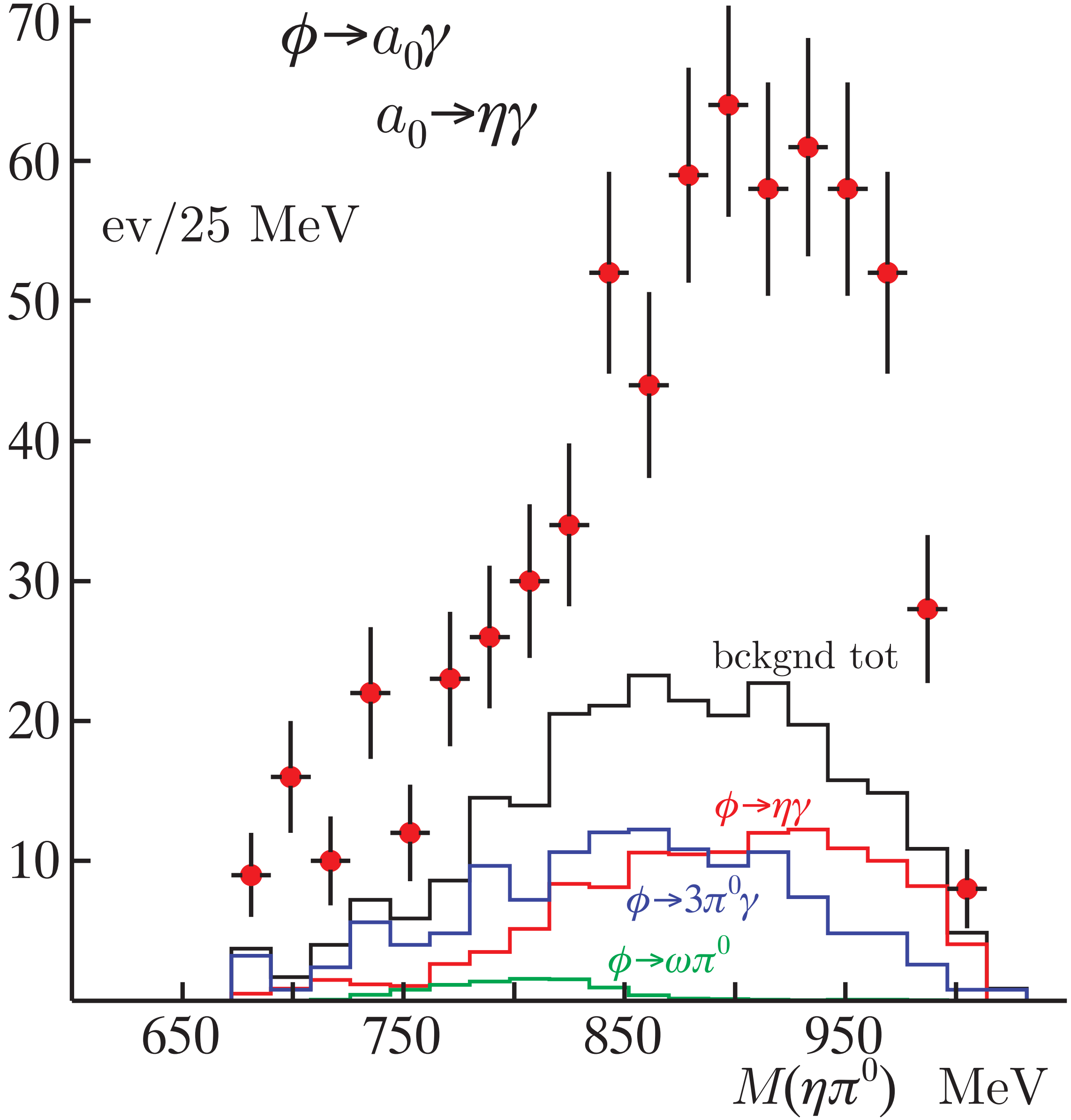
this is tex

Dalitz plot for $\phi \to \pi^0 \pi^0 \gamma$



The Dalitz plot density is fit in 2-D to $e^+e^- \to \phi \to \gamma f_0$ + $e^+e^- \to \omega\pi$ + 5 more channels to extract the f_0 signal. Amplitudes!

Scalars: a_0

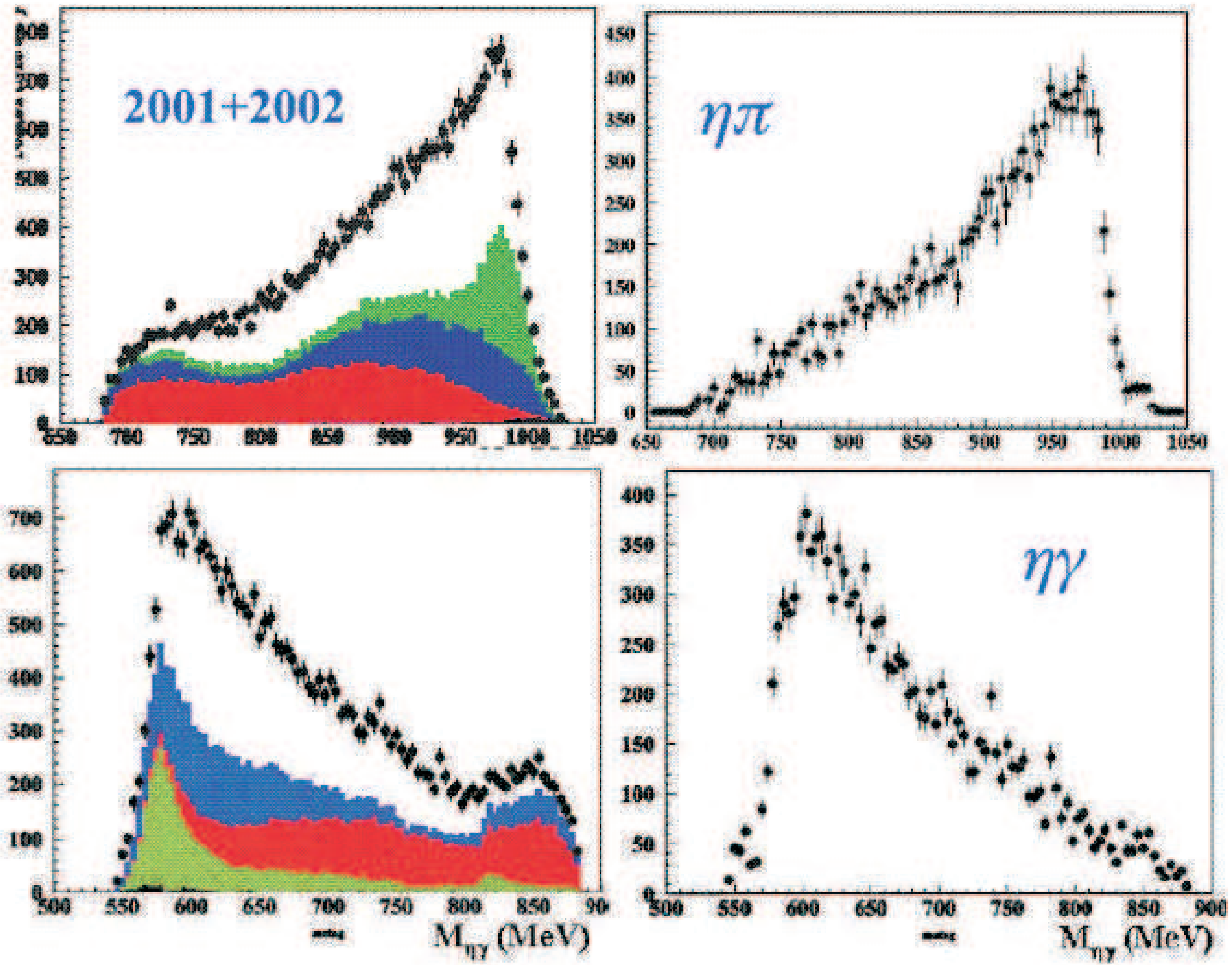


$I = 1, \quad a_0 \not\to \pi^0\pi^0$

$\phi \to a_0\gamma, \; a_0 \to \eta\pi^0$

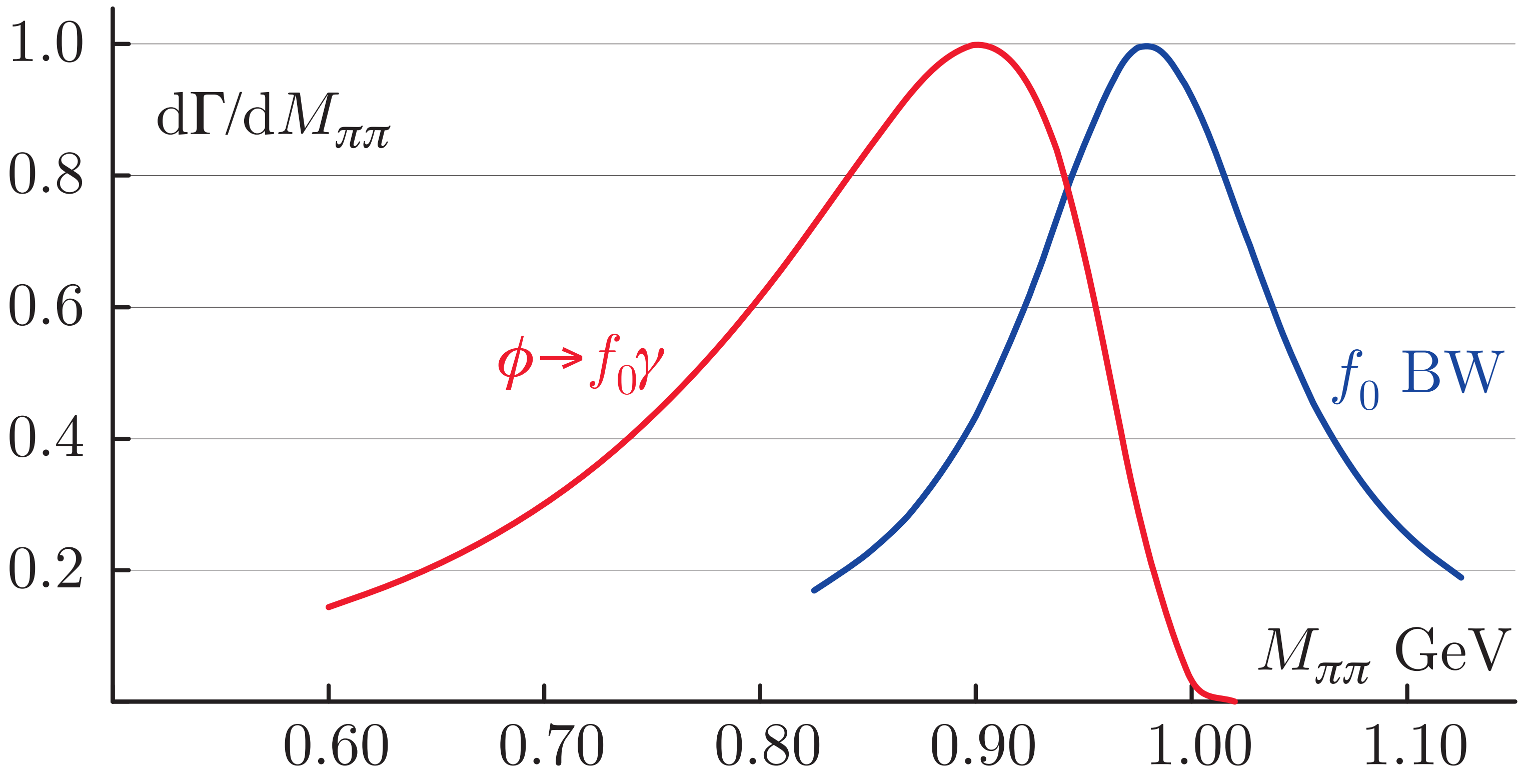
$\phi \to 5\gamma$

Dalitz plot projections



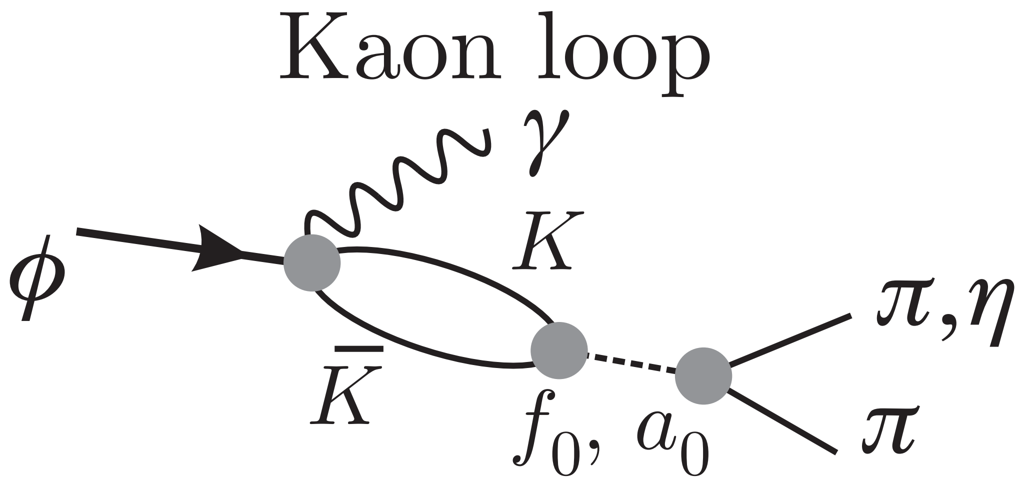
Backgrounds, colors as in previous data, subtracted in the right graphs

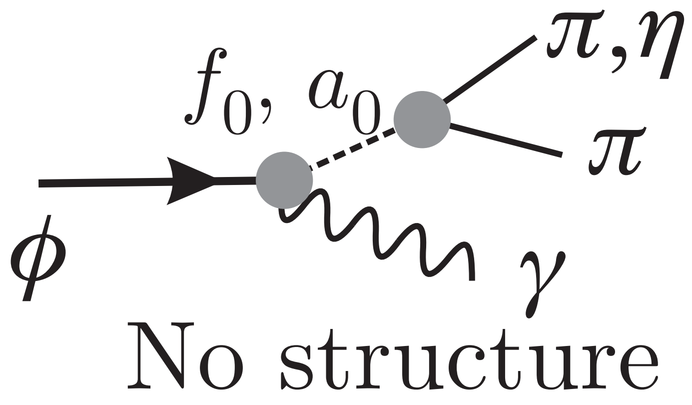
Signal shape



$$d\Gamma/dM_{\pi\pi} \propto \text{BW} \times k^3 \times \text{Overlap}$$

Models for scalars





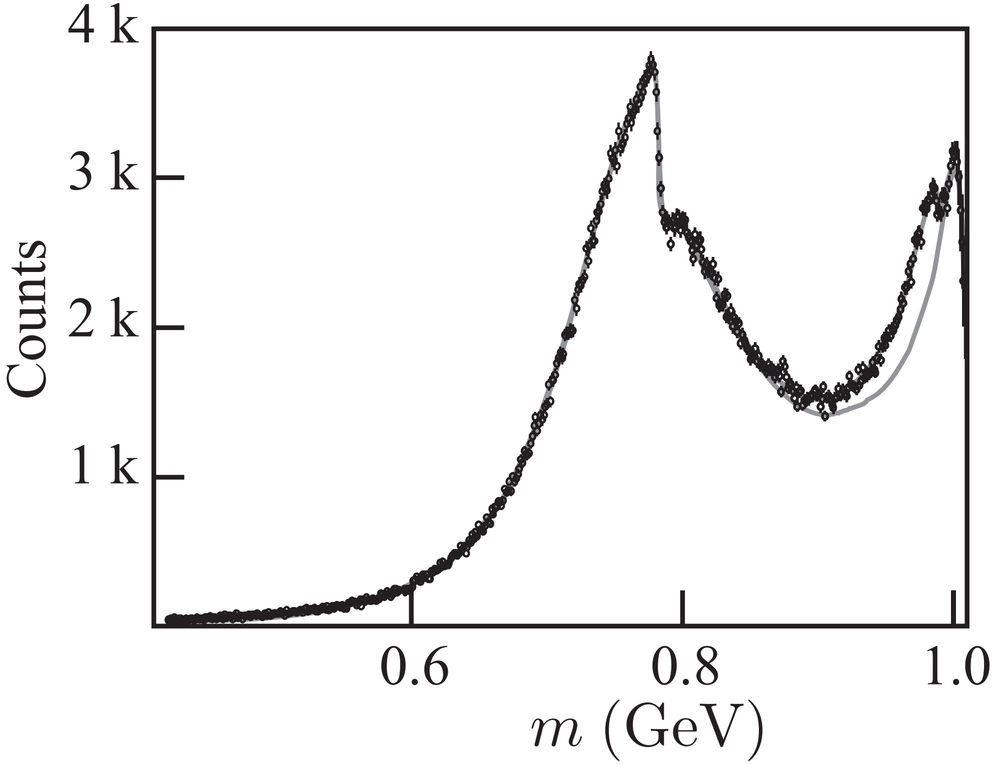
Needed to determine the couplings and the BR's.

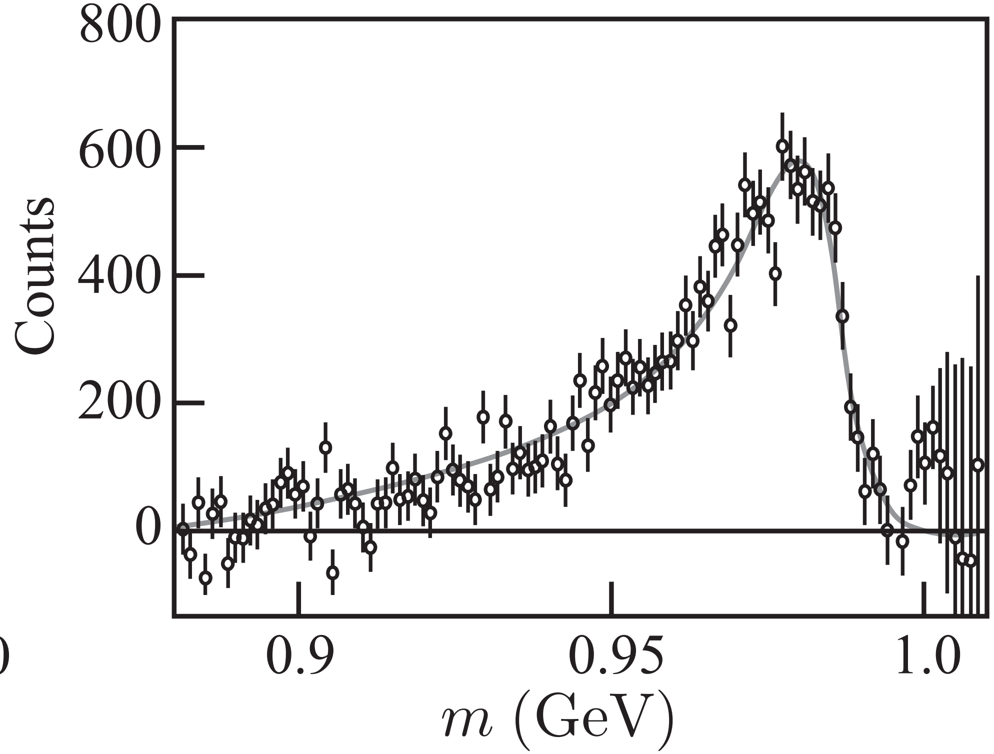
BR($\phi\to$scalar$+\gamma$, $\to\pi^0\pi^0\gamma$)$=(1.07\pm0.04\pm0.05$ (model)$)\times10^{-4}$

BR($\phi\to a_0+\gamma$)$=(7.xx\pm0.xx\pm0.05)\times10^{-5}$

Couplings still under study.

$$\boxed{e^+e^-\to\pi^+\pi^-\gamma}$$





$f_0 \to \pi^+\pi^-$ signal

$e^+e^- \to$hadrons

Why... $a_\mu = (g-2)/2 = \alpha/2\pi + \ldots$

$$a_{\mu,\text{“expt”}} = (116592080 \pm 63) \times 10^{-11}$$

$$a_{\mu,\text{“expt”}} - a_{\mu,\text{“theory”}} = (295 \pm 88) \times 10^{-11},$$

– with

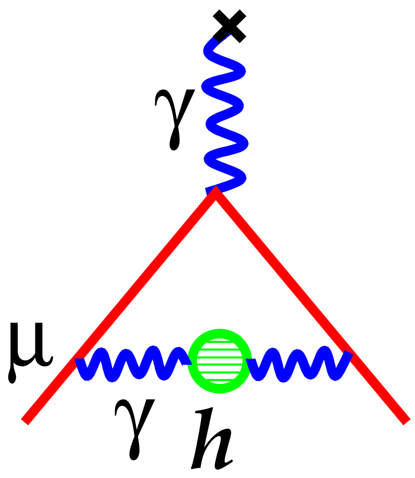
$$88 = 63\big]_{\text{Ex}} \oplus 61\big]_{\text{Th}}$$

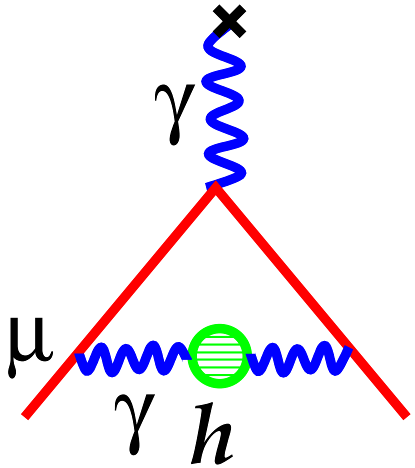
Should we get excited?

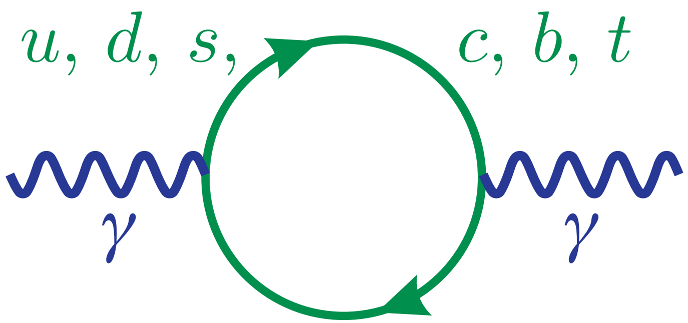
$$\delta a_{\mu,\text{“EW”}} = 150 \times 10^{-11} \quad \delta a_{\mu,\text{“L}\times\text{L”}} = (110 \pm 40) \times 10^{-11}$$

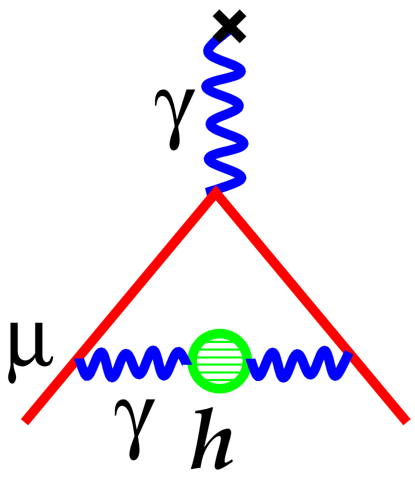
marginal... in view of LEP, M(top), $b \to s\gamma$, $\Re(\epsilon'/\epsilon)$, sin 2β

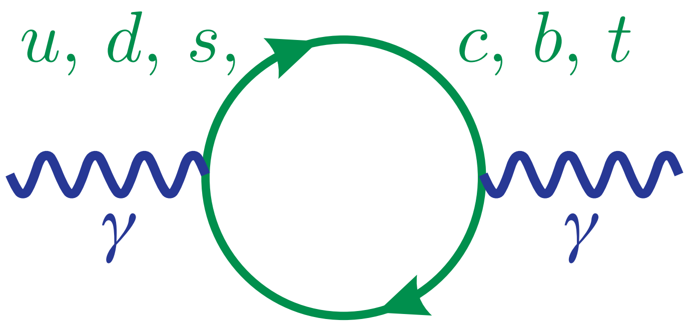
But think, if it were true. . .

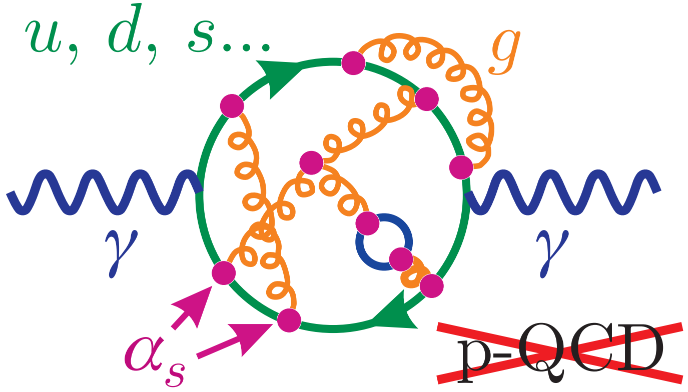

γ
μ
γ
h

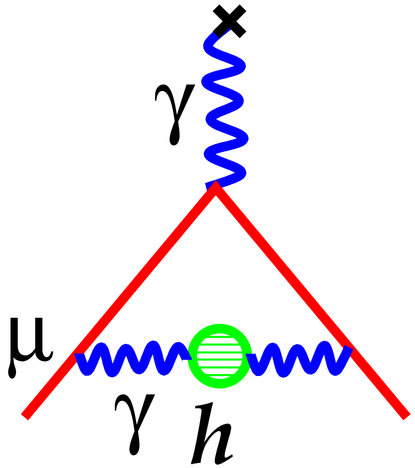

γ
μ
γ
h

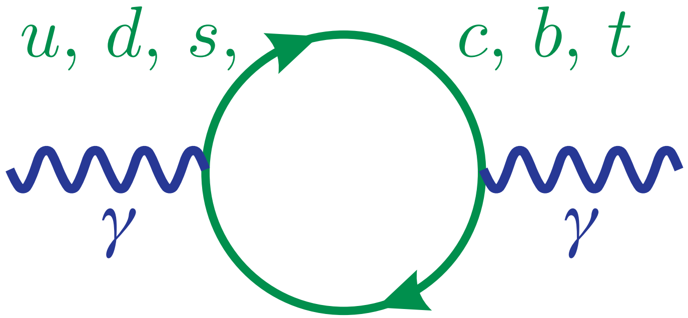

$u,\ d,\ s,$
$c,\ b,\ t$
γ
γ

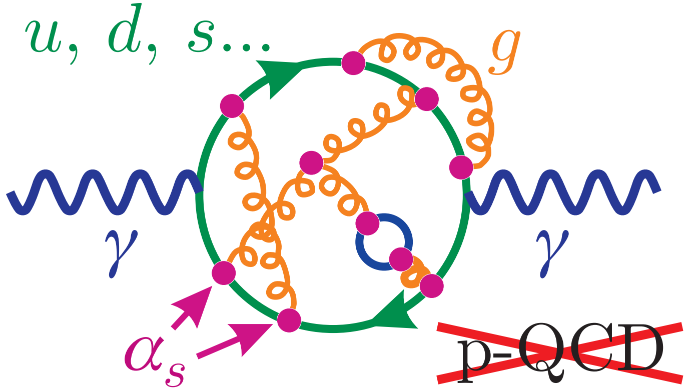

γ
μ
γ
h


u, d, s,
c, b, t
γ
γ

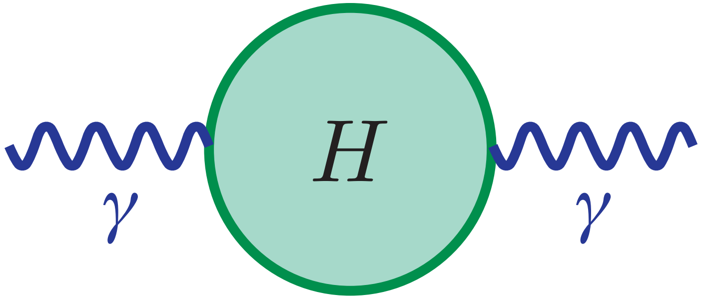

u, d, s...
g
γ
γ
α_s
~~p-QCD~~

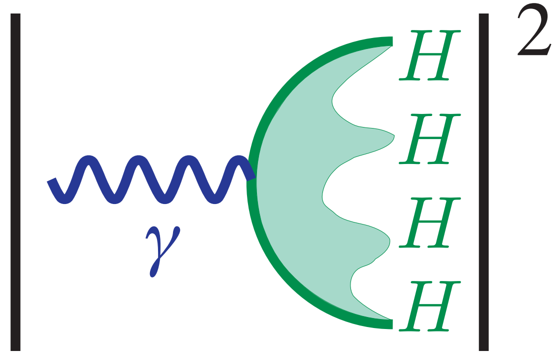






$\delta a_{\mu,\text{“had-1”}} \sim$ 6900 is not computed





$\Pi(k^2)$ $\sigma(s)$

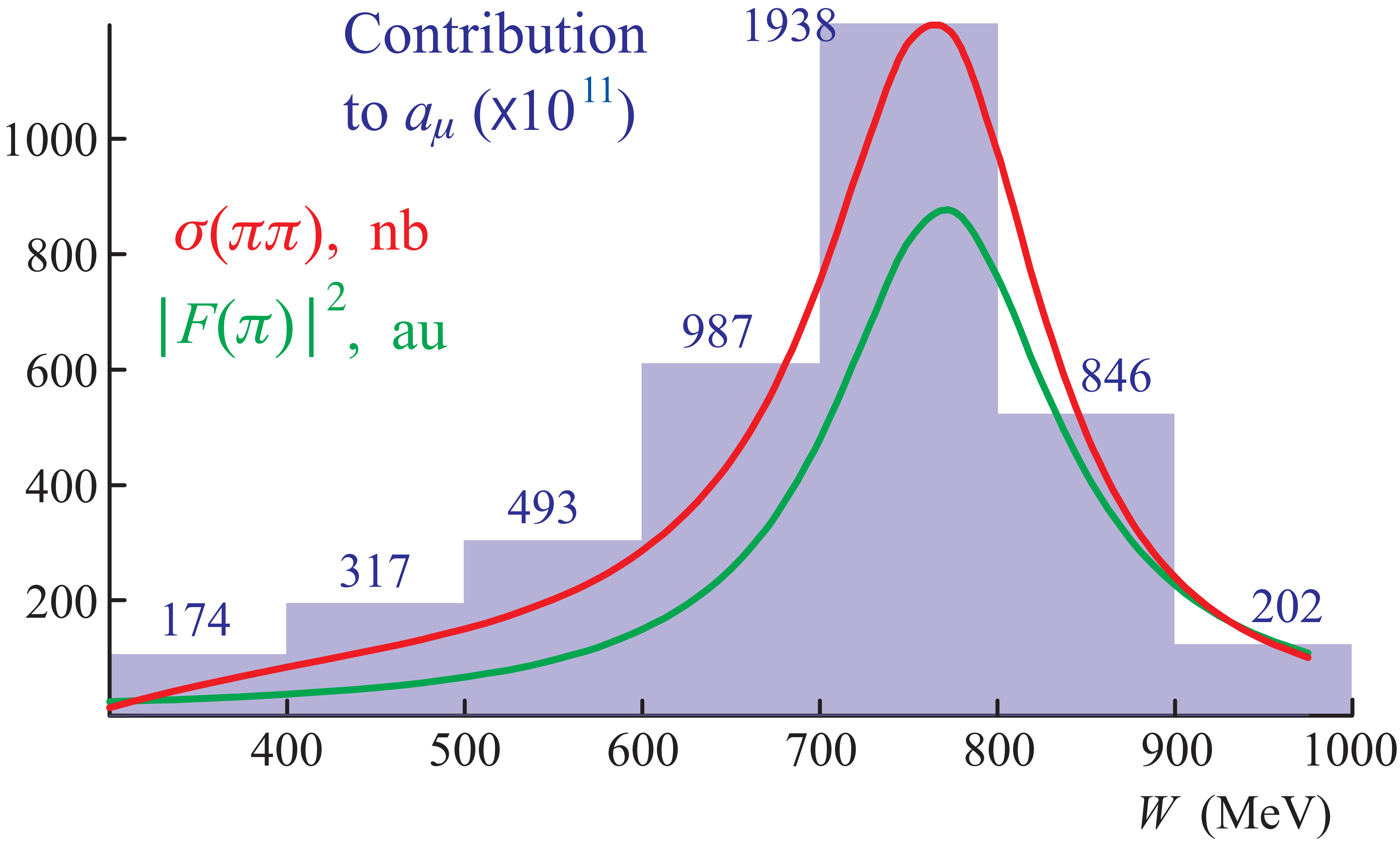
$$\Im\Pi(s)/\pi \quad = \quad s\sigma(e^+e^- \to \text{hadr})/(16\pi^3\alpha^2)$$

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

$K(s) \approx 1/s$, *i.e.* enhance low s. Some authors substitute:

$$\sigma_{e^+e^-\to\,\text{hadr}}(s) \Rightarrow \frac{4483.124}{4483.124}\frac{s}{s}\,\sigma_{\,\text{hadr}}(s) = \frac{R_{\,\text{hadr}}}{s\times 4483.124}.$$

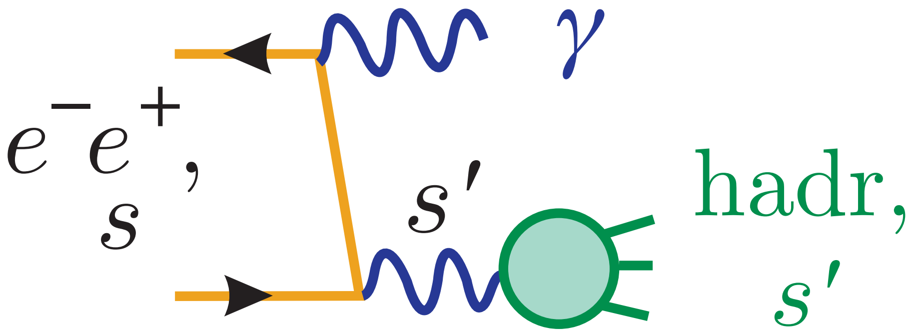
$1/(s\times 4483.124)$ $(=4\pi\,\alpha^2/3s)$ is the lowest order QED cross section for e^+e^- annihilation into massless muons.


Contribution
to a_μ (x10^{11})
$\sigma(\pi\pi)$, nb
$|F(\pi)|^2$, au
1938
987
846
493
317
174
202
1000
800
600
400
200
400
500
600
700
800
900
1000
W (MeV)

this
is
tex

Variable energy

Initial state radiation, gives us the possibility of measuring hadro-production for $2m_\pi < s' < s$, at fixed collider s.
To lowest order the **ISR ONLY** amplitude is $(W^2 = s)$:



from which

$$\frac{\mathrm{d}\sigma(\text{hadrons} + \gamma)}{\mathrm{d}s_\pi \mathrm{d}\cos\theta_\gamma} = \frac{\alpha}{\pi s}\,\sigma_{\text{hadr}}(s')\,\left[\frac{s^2 + s'^2}{s'(s-s')}\frac{1}{\sin^2\theta} - \frac{s-s'}{2s'}\right]$$

Binner, Kühn and Melnikov

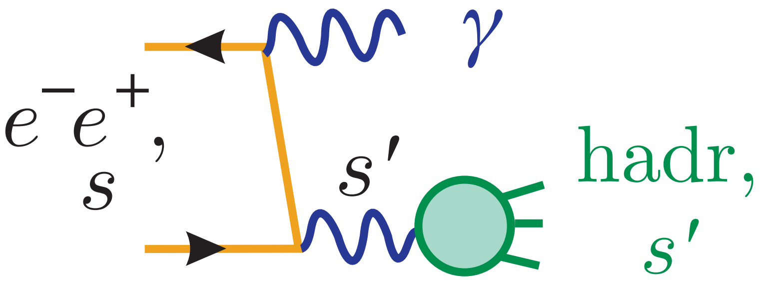
Example: hadr=$\pi^+\pi^-$, $s' = s_\pi = M^2_{\pi^+\pi^-}$.

$$\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi \mathrm{d}\cos\theta_\gamma} \sim \sigma(e^+e^- \to \pi^+\pi^-,\ s_\pi) \times \sigma(e^+e^- \to \gamma\gamma,\ s)$$

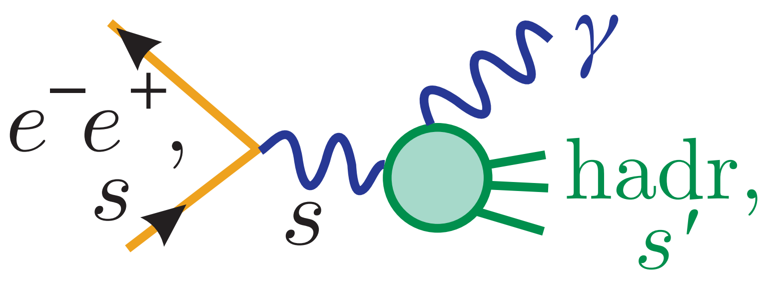
Advantages

1. Do not need to operate the collider at different energies
2. The overall energy scale, at least in a detector like KLOE is established at W=m$_\phi$ and applies to all values of M(hadr)
3. The luminosity is measured at fixed energy, for the entire data set, avoiding painful corrections

Disadvantages I.



$\boxed{\sim}$

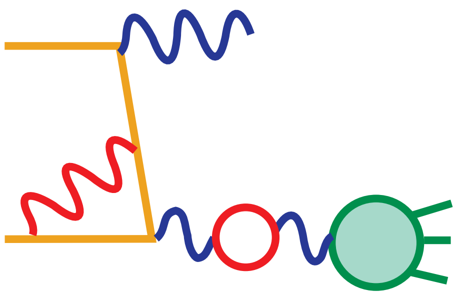


$s_\gamma = s'$ $\qquad$ $s_\gamma = s \neq s'$

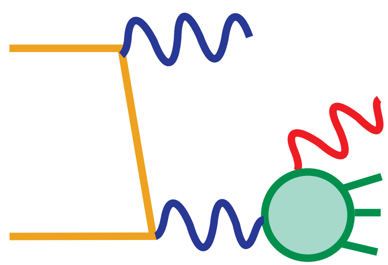
FS radiation is $\mathcal{O}(1)$ background to σ of interest!

Cannot distinguish two processes, need precise estimates.

Must also remove - correct for



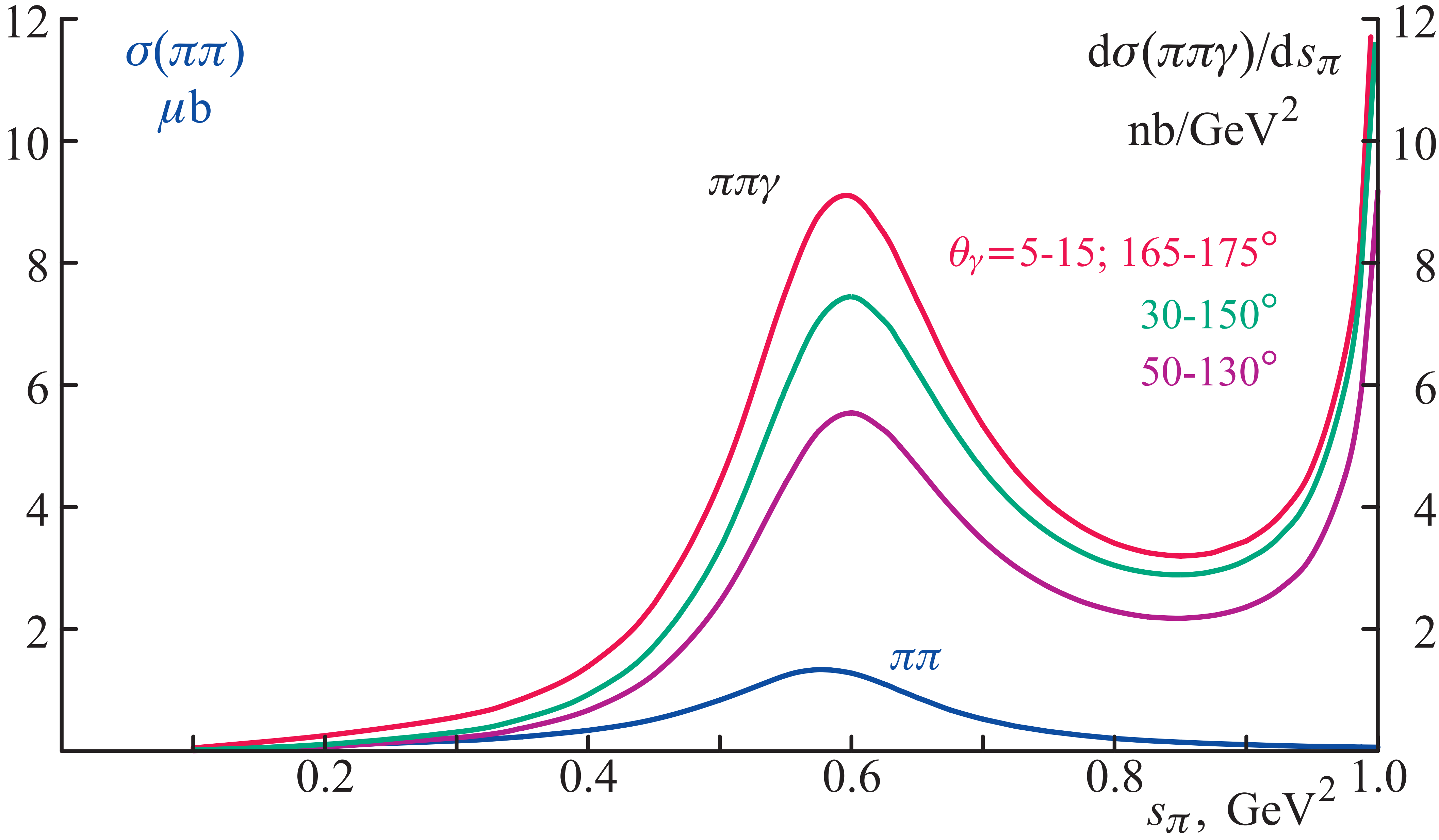
and properly retain



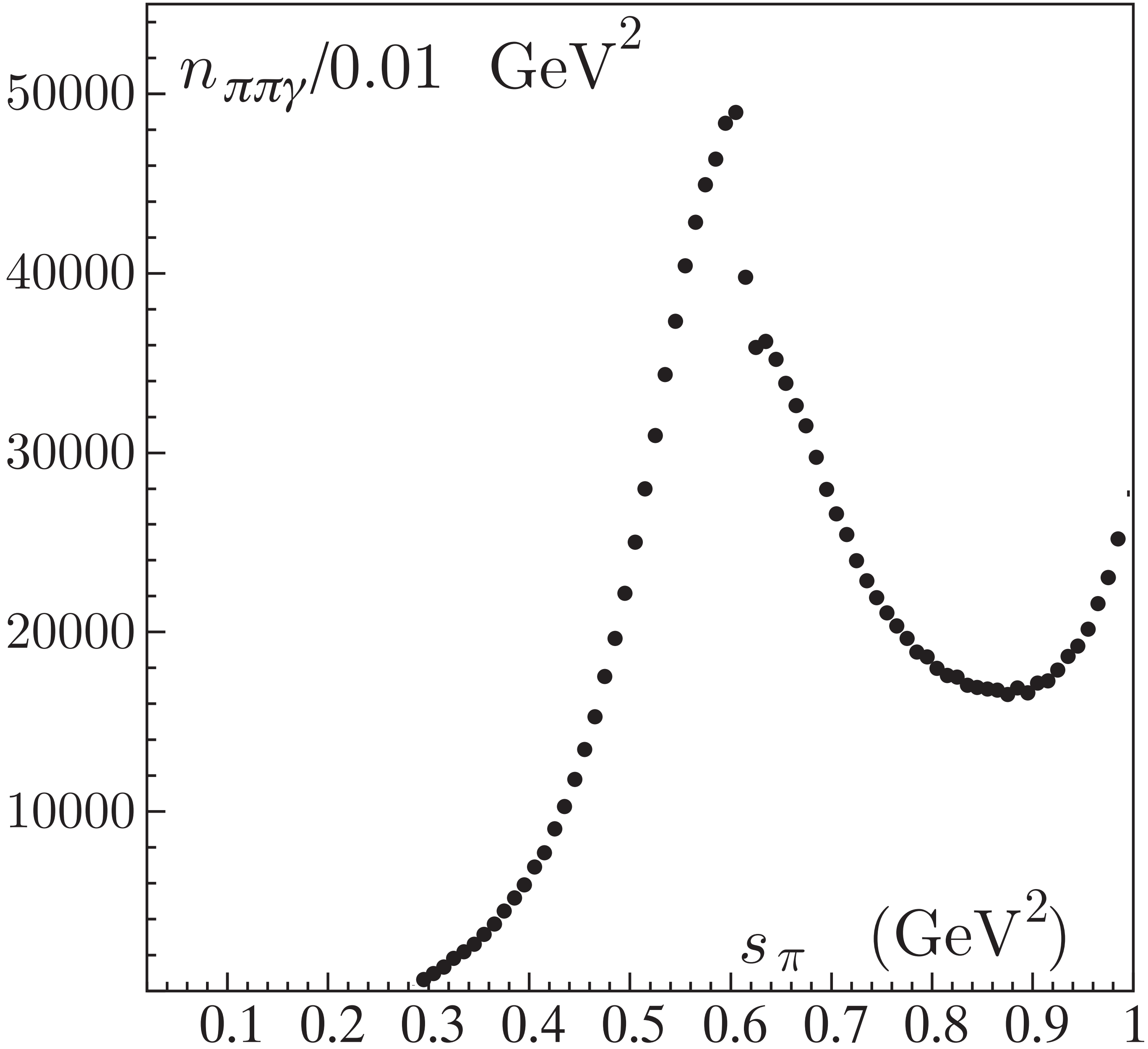
Disadvantages II.

One must perform an absolute measurement of a cross section which is only a tiny fraction of the total cross section

At KLOE, σ(Bhabha)$\sim$100 μb
σ(hadrons)$\sim$3 μb
$\sigma(\pi^+\pi^-\gamma)\sim$0.01 μb

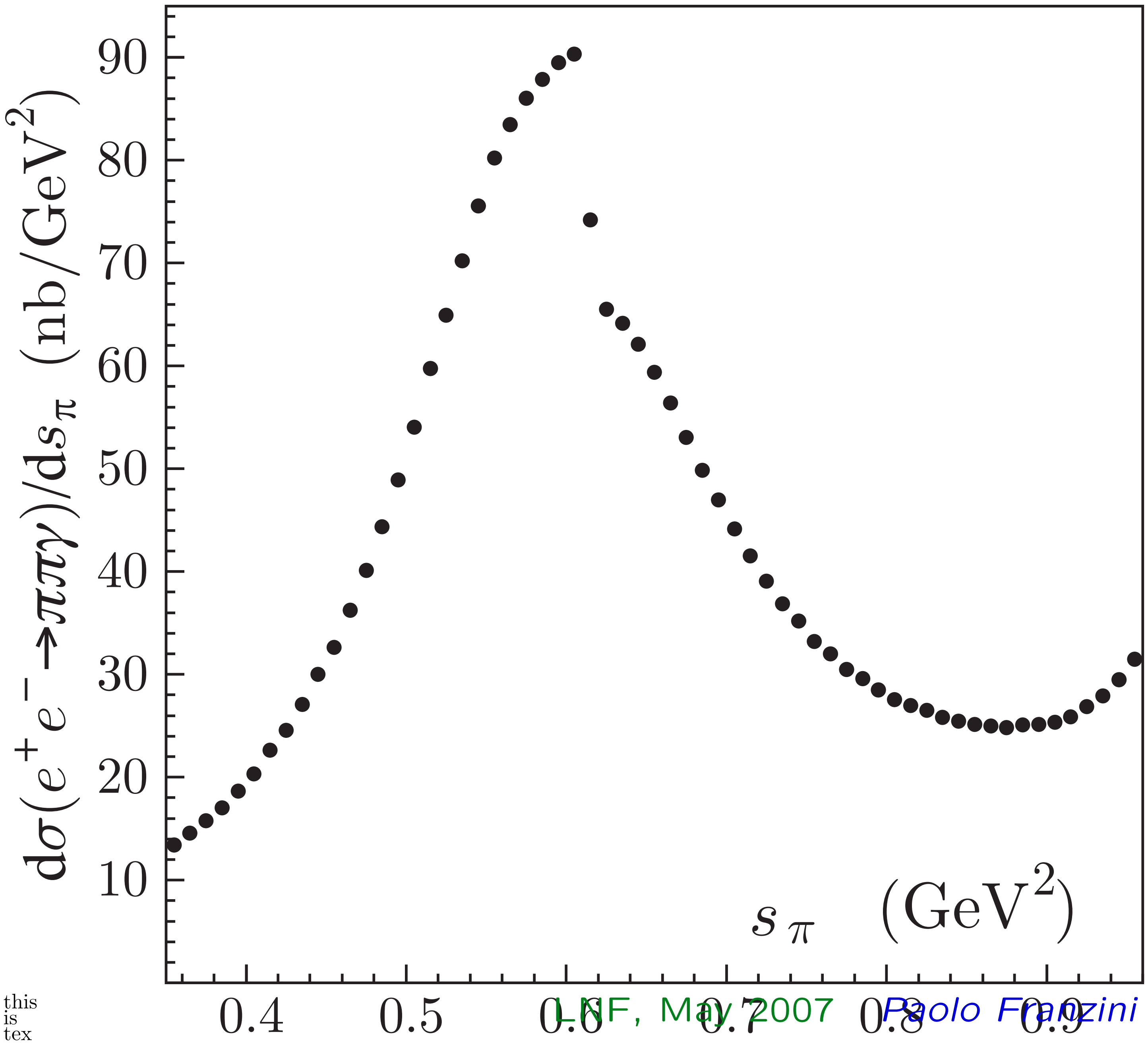

$\sigma(\pi\pi)$
μb
$d\sigma(\pi\pi\gamma)/ds_\pi$
nb/GeV^2
$\pi\pi\gamma$
θ_γ=5-15; 165-175°
30-150°
50-130°
$\pi\pi$
12
10
8
6
4
2
0.2
0.4
0.6
0.8
1.0
s_π, GeV^2

First results



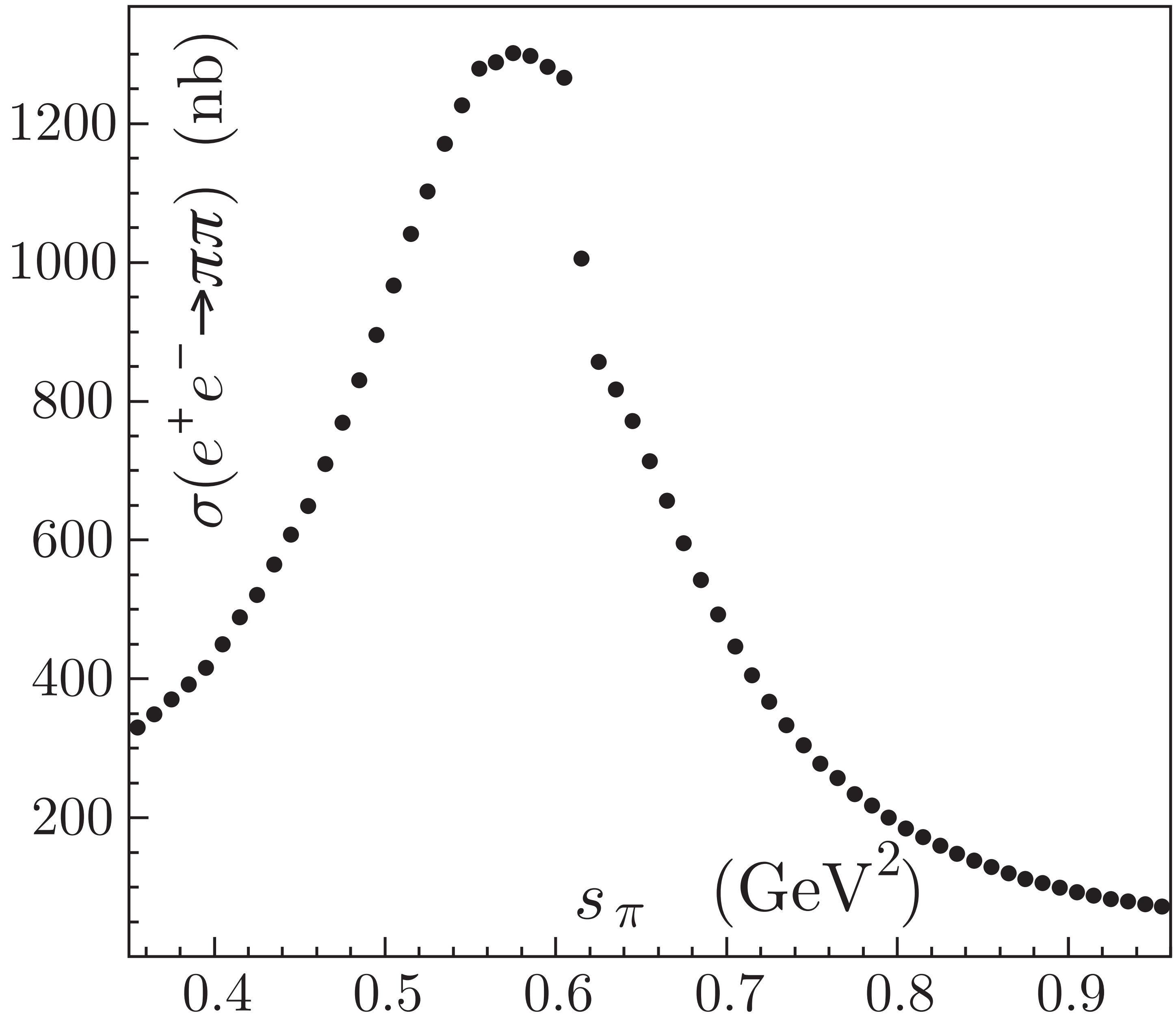
Use small angle unobserved photons. No low $M(\pi^+\pi^-)$ sensitivity. Minimal FSR corrections.

$e^+e^-\to\pi^+\pi^-\gamma$



Cross section obtained with data above and the measured Bhabha yield

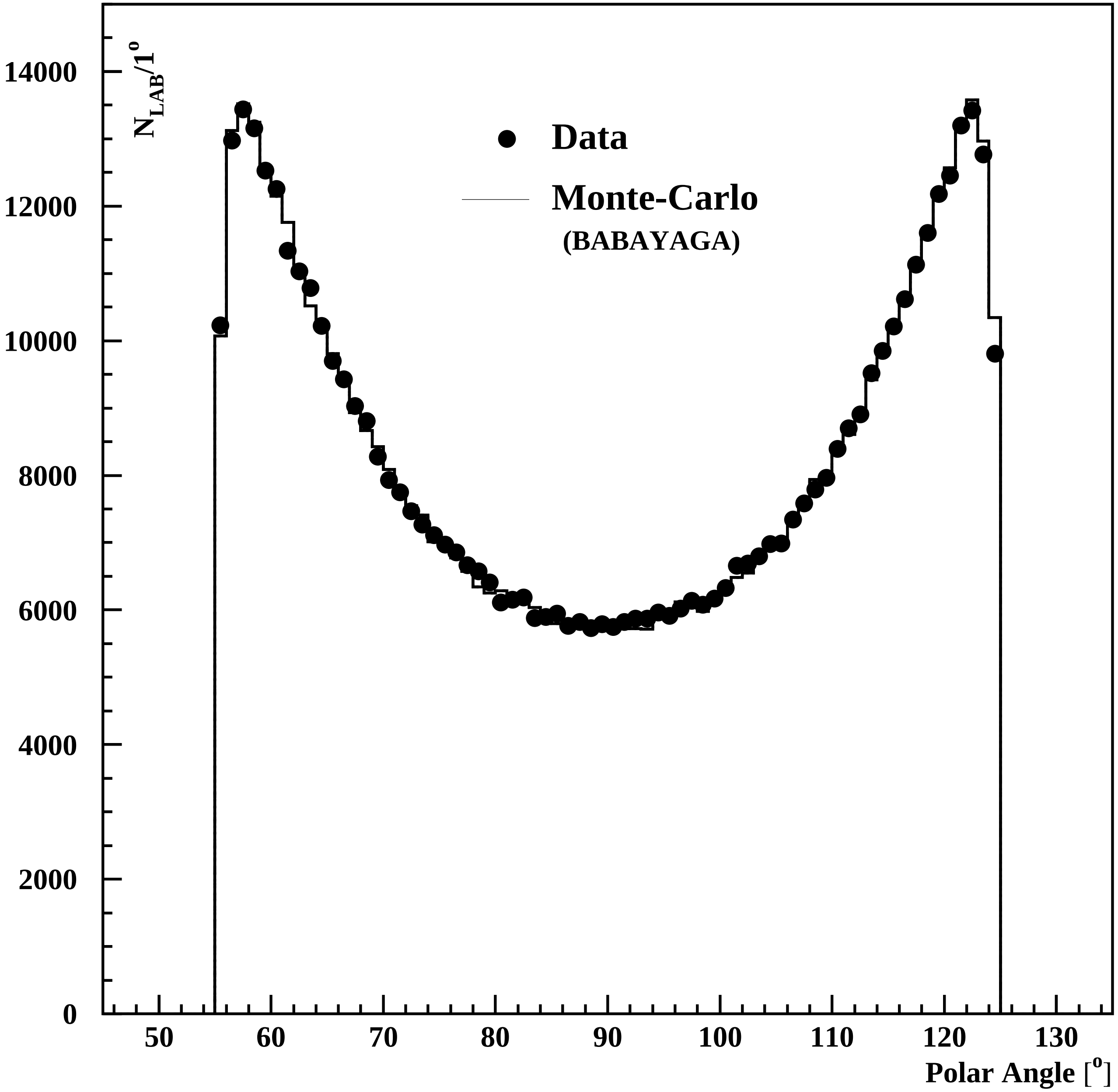
$e^+e^- \to \pi^+\pi^-$



Cross section for $e^+e^- \to \pi^+\pi^-$. Vacuum polarization and FSR correction must be applied for the computation of $\Delta^{\mathrm{H}} a_\mu$.

this is tex

$\mathcal{L}$ from Bhabha scattering



Comparison with MC expectation of the observed Bhabha angular distribution

$\boxed{a_\mu}$

$$a_\mu \propto \int \sigma(s_\pi) K(s_\pi) \mathrm{d}s_\pi$$

* our calculation, we use values w/o FSR and VP correc. (like us)

KLOE	PRELIMINARY
Δa_μ=3887±50	0.35< $M^2_{\pi\pi}$ <0.95 GeV^2
Δa_μ=3814±35	0.37< $M^2_{\pi\pi}$ <0.93 GeV^2
Δa_μ=2401±30	0.50< $M^2_{\pi\pi}$ <0.93 GeV^2
CMD-2	
Δa_μ=3767±30*	0.37< $M^2_{\pi\pi}$ <0.93 GeV^2
Δa_μ=2414±25*	0.50< $M^2_{\pi\pi}$ <0.93 GeV^2

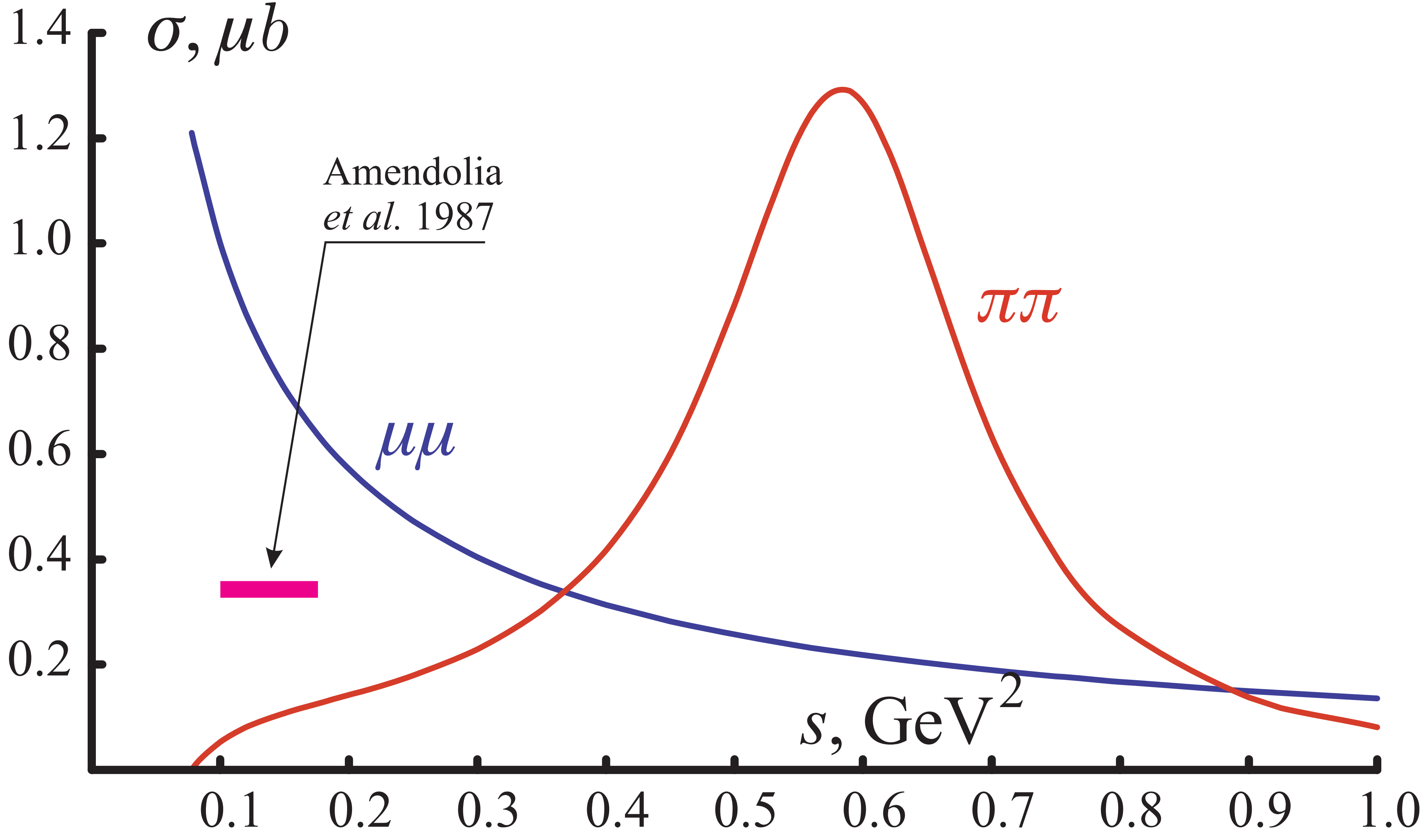
$\sim$0.5σ agreement with CMD-2

A direct measurement of R(had)

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \cong \frac{\sigma(e^+e^- \to \text{hadrons}\,\gamma)}{\sigma(e^+e^- \to \mu^+\mu^-\gamma)}$$

1. No need for independent $\mathcal{L}$ measurements.
2. Initial state radiation and vacuum polarization corrections cancel. FSR corrections needed
3. OK from threshold up, for $\pi^+\pi^-$. For $M(\pi\pi) < 600$ MeV, $\delta a_\mu \sim 1000 \times 10^{-11}$.

$\sigma(e^+e^-\to\pi^+\pi^-)$ and $\sigma(e^+e^-\to\mu^+\mu^-)$



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End Run

The next two years

Improve

1. BR(K)
2. $\tau(K_L, K^\pm)$
3. FF parameters
4. Masses
5. V_{us}
6. Rare decays
7. CPT limits
8. η studies
9. Understand scalars
10. $\sigma(e^+e^-\to\pi^+\pi^-)$

$\boxed{\textbf{The End}}$

KLOE is retired.

Major increase in DAΦNE $\mathcal{L}$? -2007-08.

KLOE might come back.

$\boxed{\textbf{2009?}}$

Lepton-quark Universality

$$K \to e\nu / K \to \mu\nu$$

$$CPT$$

???