A new $K_S \rightarrow \pi\, e\, \nu$ branching fraction measurement from KLOE-2

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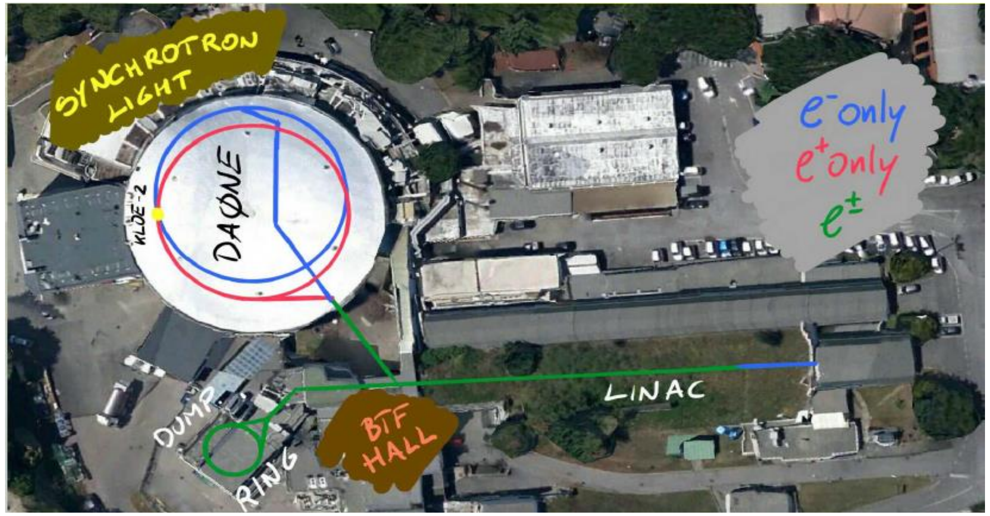
on behalf of the KLOE-2 Collaboration

International Conference of High Energy Physics, Bologna 6-13 july 2022

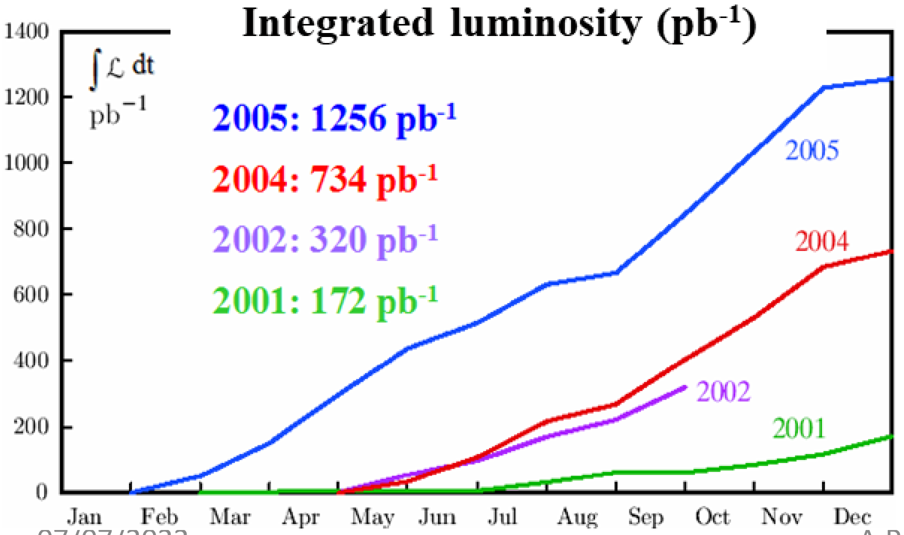
DAΦNE and KLOE

DAΦNE is a e+e- collider @ $\sqrt{s}$ = 1020 MeV,
located in Frascati National Laboratories.
Worked for KLOE (2000-2006): Max peak lumi: 1.5 10^{32} $cm^{-1}s^{-1}$
Best daily int. lumi: 8.5 pb^{-1}

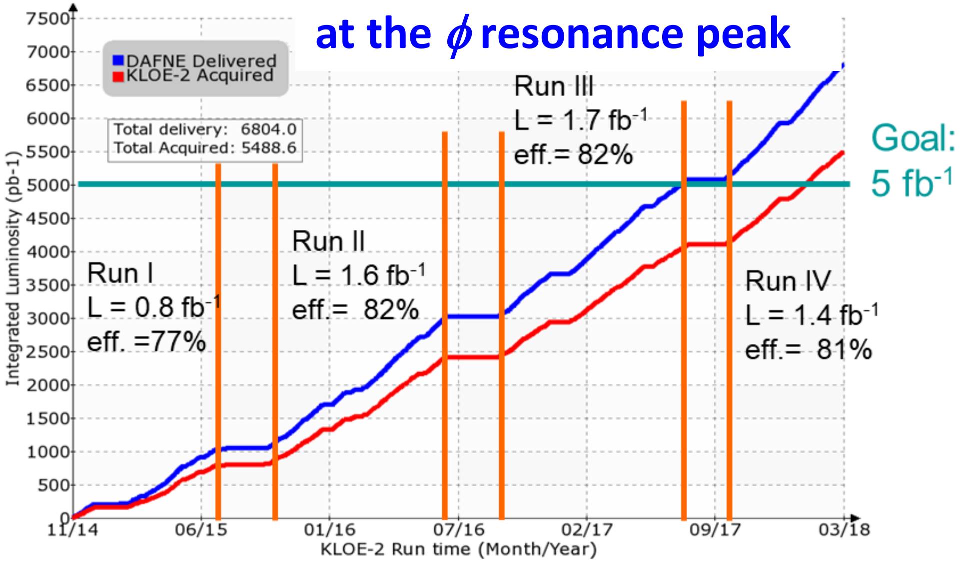
Upgraded in 2008 with crab-waist scheme
Worked for KLOE-2 (2014-2018): Max peak lumi: 2.4 10^{32} $cm^{-1}s^{-1}$
Best daily int. lumi: 11 pb^{-1}



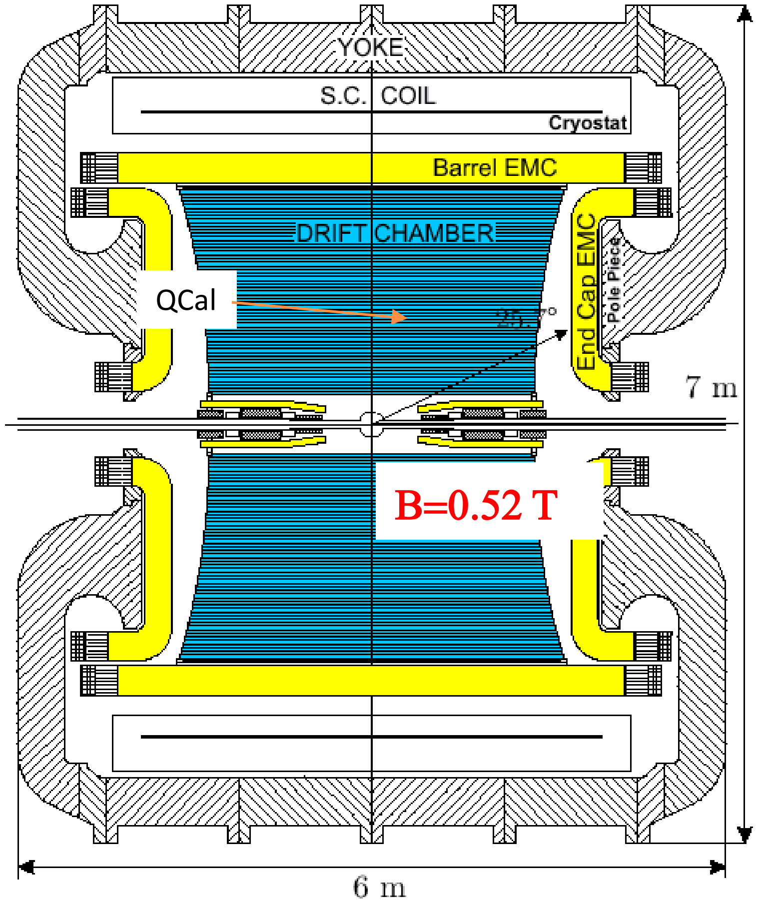
KLOE collected 2.5 fb^{-1} at the ϕ resonance peak and 250 pb^{-1} at $\sqrt{s}$ = 1000 MeV.



KLOE-2 collected 5.5 fb^{-1} at the ϕ resonance peak



The KLOE detector



Interaction region:
Instrument quadrupoles,
Al-Be spherical beam pipe

Large volume Drift Chamber
(13K cells, He gas mixt.) :

4m-∅, 3.75m-length, all-stereo

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

σ_x^{hit} = 150 μm (xy), 2 mm (z)

σ_x^{vertex} ~1 mm $\sigma_{M\pi\pi}$ ~ 1 MeV

Pb-SciFi Calorimeter
(barrel + endcap, 15 X_0 depth,
98% solid angle coverage) :

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

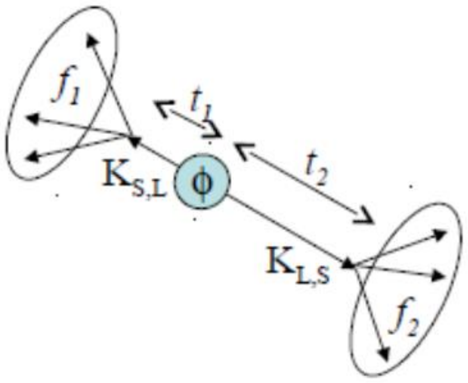
$\sigma_T = 54\ \text{ps} / \sqrt{E(\text{GeV})} \oplus 100\ \text{ps}$

- **PID capabilities mostly from TOF**

The ϕ-factory advantage

ϕ decays:	
K^+K^-	49.1%
K_LK_S	34.3%
$\rho\pi$	15.4%
$\eta\gamma$	1.3%

σ_ϕ~3 μb -> 10^6 neutral kaon pairs per pb^{-1}



- The final $K\bar{K}$ state has the same quantum numbers as the ϕ i.e. is a pure $J^{PC} = 1^{--}$ quantum state

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

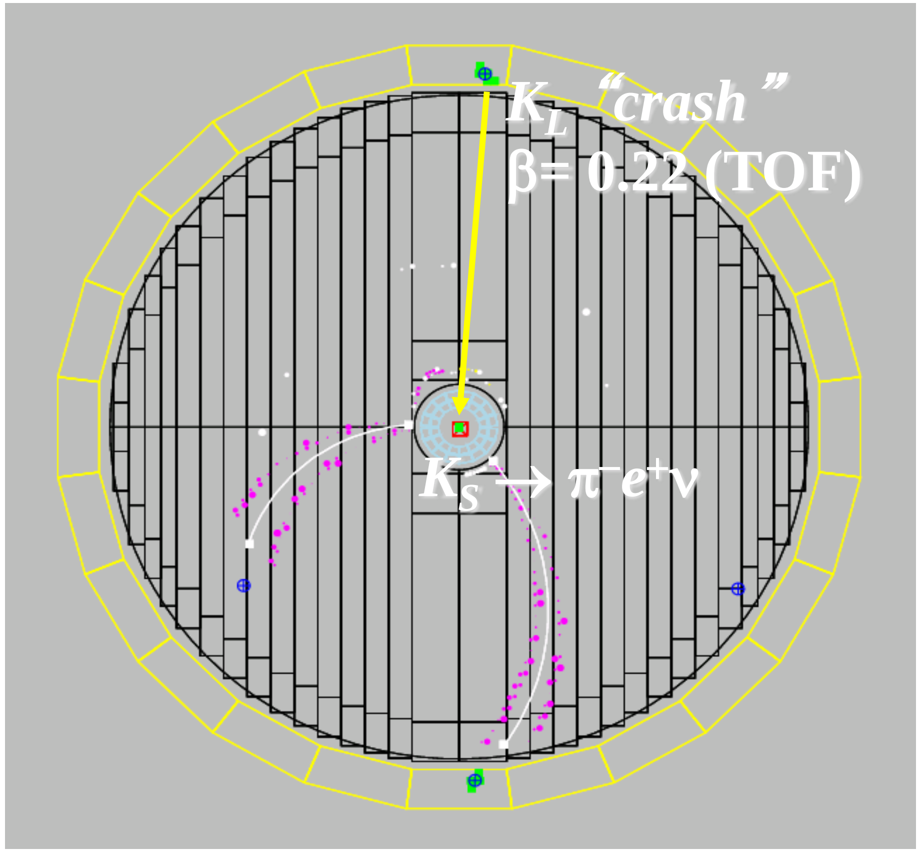
- $P_K=-P_{\bar{K}}$ ~110 MeV/c
- $\lambda(K_S)$ = 6 mm (τ = 90 ps), $\lambda(K_L)$ = 3.5 m (τ =51.7 ns)

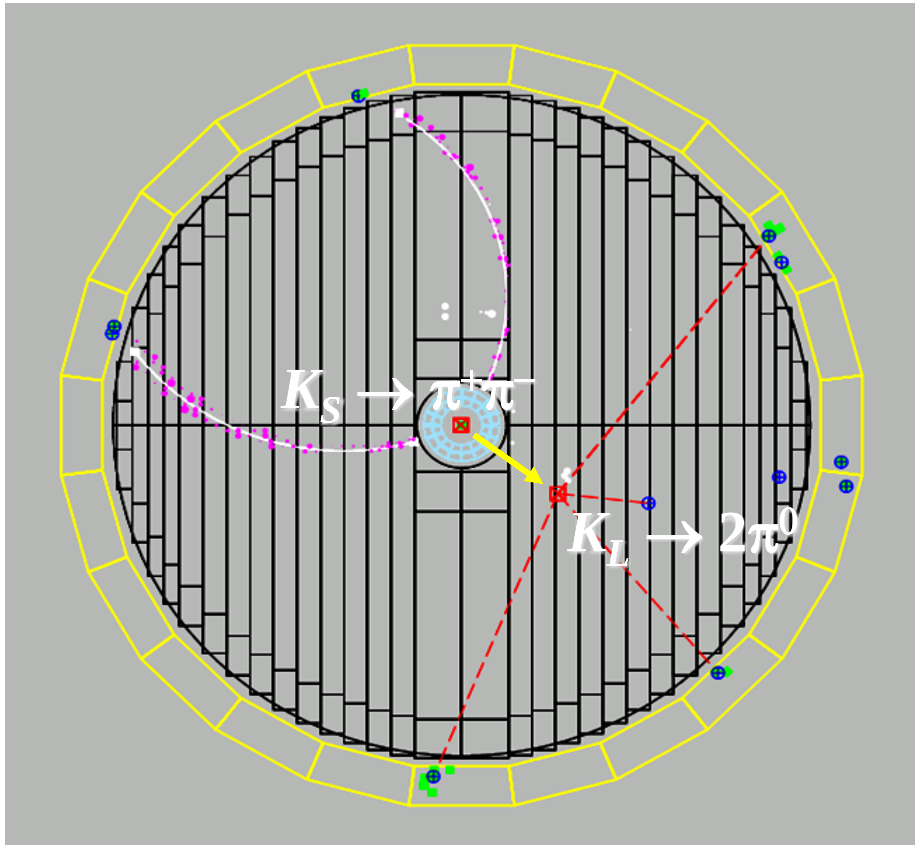
The presence of one kaon tags the other opposite one.
All K_S decay near the i.p.

KLOE has the unique capability of selecting pure KS and KL beams

Moreover: interference pattern and entanglement of K_S K_L state allows to study fundamental simmetries and quantum mechanics: see talk by E. Czerwinski at this Conference.

Neutral kaon tagging at KLOE





K_S tagged by K_L interaction in EmC

K_L velocity in ϕ rest frame $\beta^* = 0.218$

Efficiency ~ 30% (largely geometrical)

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

K_S momentum resolution: ~ 2 MeV

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: ~ 2 MeV

The KSe3 decay and the Cabibbo angle

In the SM :

$$\mathcal{B}(K_S \to \pi \ell \nu) = \frac{G^2(f_+(0)|V_{us}|)^2}{192\pi^3} \tau_S m_K^5 I_K^\ell S_{\mathrm{EW}} (1 + \delta_{\mathrm{EM}}^{K\ell})$$

The KSe3 determination of $|V_{us}|f_+(0)$ is the less accurate (apart from the recently measured and rarer KSμ3 mode Phys.Lett.B 804 (2020) 135378).

The presently available BR(KSe3) value is dominated by the KLOE measurement based on 0.4 fb^{-1} data sample:

$$\mathrm{BR}(K_S \to \pi e \nu) = (7.046 \pm 0.078 \pm 0.049) \times 10^{-4}$$

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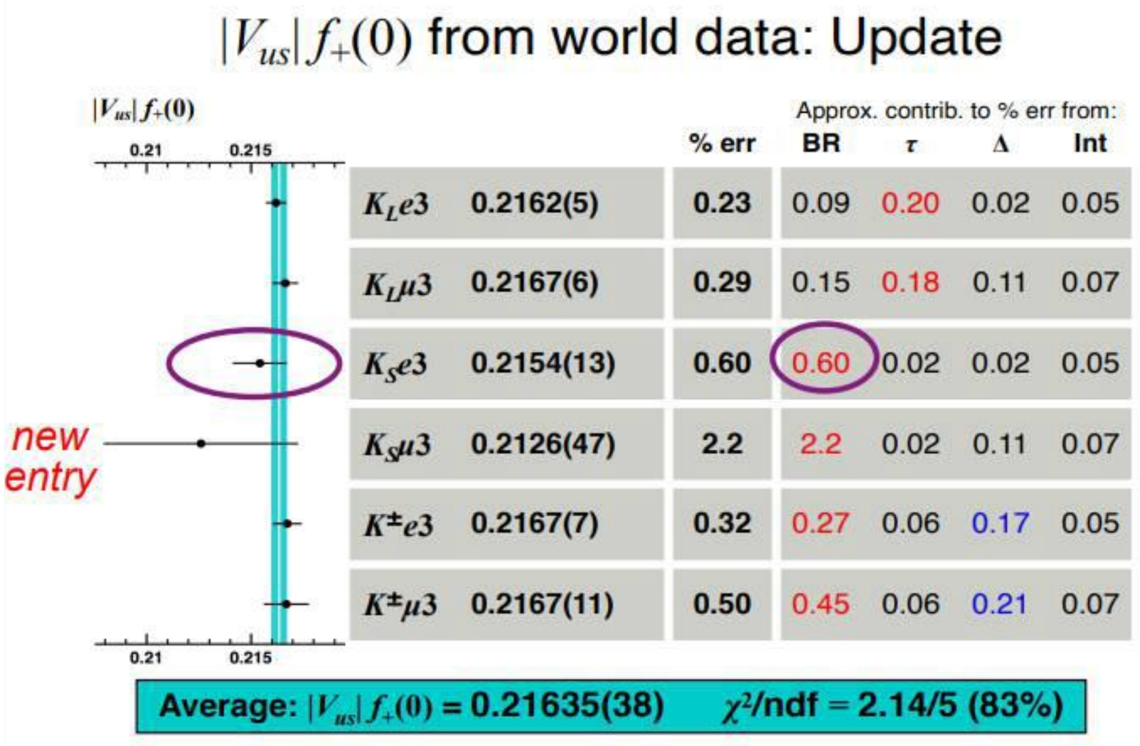
1.4% total uncertainty (1.1% stat ± 0.7% syst)



		% err	BR	τ	Δ	Int
$K_L e3$	0.2162(5)	0.23	0.09	0.20	0.02	0.05
$K_L \mu 3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
$K_S e3$	0.2154(13)	0.60	0.60	0.02	0.02	0.05
$K_S \mu 3$	0.2126(47)	2.2	2.2	0.02	0.11	0.07
$K^\pm e3$	0.2167(7)	0.32	0.27	0.06	0.17	0.05
$K^\pm \mu 3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

Average: $|V_{us}| f_+(0) = 0.21635(38)$ $\chi^2/\mathrm{ndf} = 2.14/5$ (83%)

M.Moulson and E.Passemar, CKM 2021

We present here a new measurement based on 1.63 fb^{-1} independent KLOE data sample.

What we measure

$$\mathcal{B}(K_S \to \pi e \nu) = \frac{N_{\pi e \nu}}{\epsilon_{\pi e \nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon \times \mathcal{B}(K_S \to \pi^+\pi^-)$$

$N_{\pi e \nu}$, $N_{\pi\pi}$: number of selected events for $K_S \to \pi e \nu$ and $K_S \to \pi^+\pi^-$

$\varepsilon_{\pi e \nu}$, $\varepsilon_{\pi\pi}$: selection efficiencies

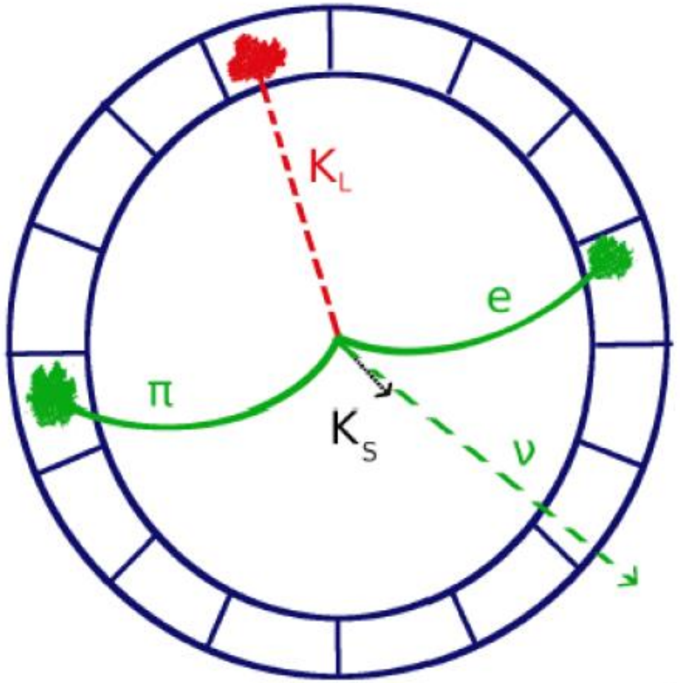
R_ε : ratio of common efficiencies for trigger, online filter, event classification and preselection

$BR(K_S \to \pi^+ \pi^-) = 0.69196 \pm 0.00051$ measured by KLOE **Eur. Phys. J. C 48 (2006) 767**

Preselection and normalization sample

K_L-crash:

- one neutral cluster with E > 100 MeV and polar angle $15^o < \theta < 165^o$
- velocity $0.17 < \beta^* < 0.28$ in the ϕ c.m.s. (in the lab: $\beta = r_{clu}/ct_{clu}$)



K_S side selection:

two charged tracks of opposite curvature forming a vertex inside the cylinder (ρ< 5 cm ; z < 10 cm)

The normalization sample of $K_S \to \pi^+ \pi^-$ decays is selected at this stage by requiring each of the two charged tracks momentum to be 140 MeV < p < 280 MeV. We obtain:

$$N_{\pi\pi} = (282.314 \pm 0.017) \times 10^6 \text{ events}$$

Efficiency 97.4% and purity 99.9% determined by simulation.

Sample composition after preselection

	n. events	Fraction (%)
Data	301 645 500	
MC	312 018 500	
$K_S \to \pi e \nu$	259 264	0.08
$K_S \to \pi^+\pi^-$	301 976 400	96.78
$\varphi \to K^+K^-$	9 565 465	3.07
$K_S \to \pi^0\pi^0$	30 353	0.01
$K_S \to \pi\mu\nu$	139 585	0.04
$K_S \to \pi^+\pi^-e^+e^-$	18 397	$6\ 10^{-3}$
$\varphi \to \pi^+\pi^-\pi^0$	24 153	$8\ 10^{-3}$
others	4 852	$2\ 10^{-3}$

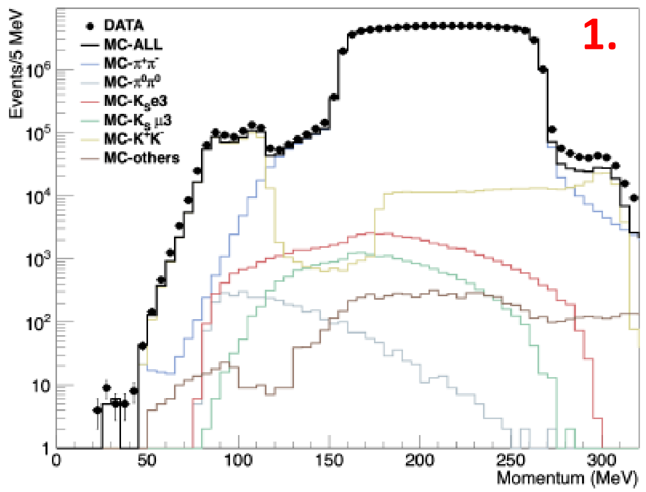
Signal selection is then performed in two steps based on uncorrelated information:

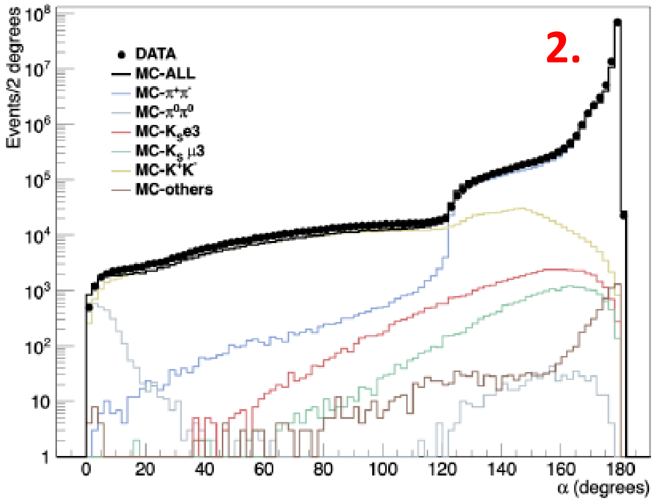
1) the event kinematics using only DC tracking variables

2) the time-of-flight measured with the calorimeter

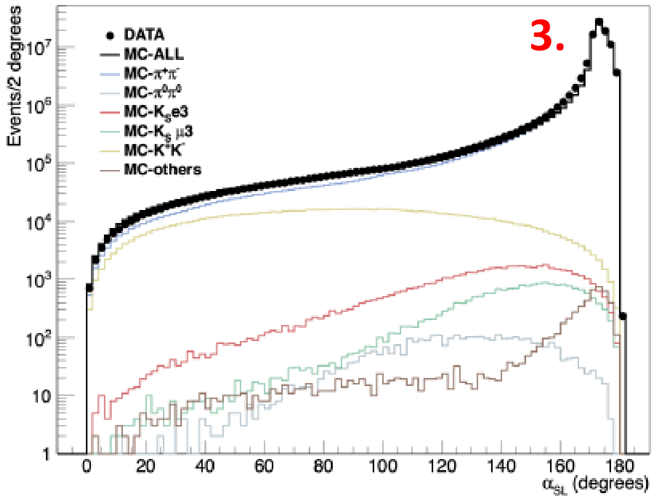
Multivariate selection based on tracking variables/1

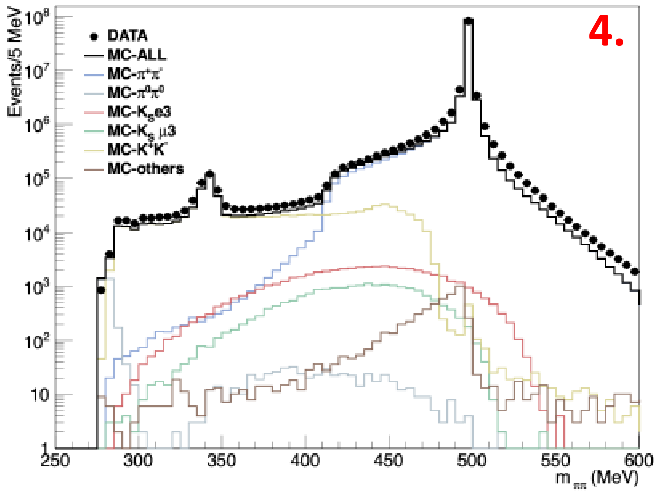
5 discriminating variables are selected. In the signal region they show satisfactory data-MC agreement

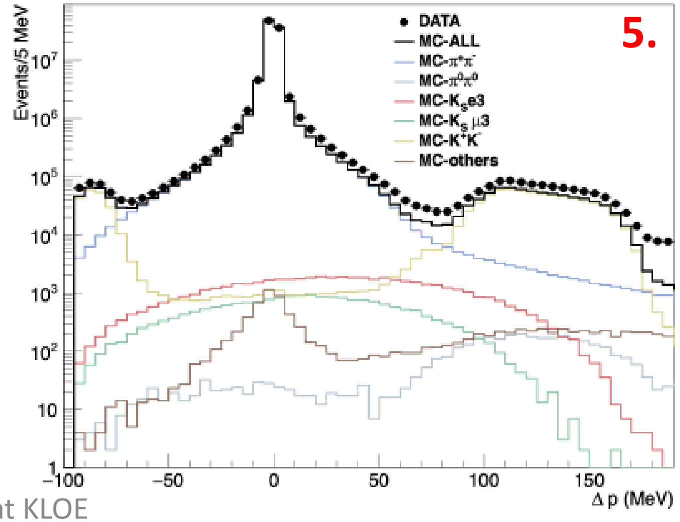




1. the tracks momenta: $\vec{p}_1, \vec{p}_2$
2. $\alpha_{1,2}$ angle formed by tracks momenta in the K_S reference system
3. α_{LS} angle between the total momentum and the K_L crash direction
4. Δp difference between total momentum and $|\vec{p}_{KS}|$ (determined from p_{KL} and p_ϕ)
5. $m_{\pi\pi}$ the 2 tracks invariant mass in 2 pion hypothesis







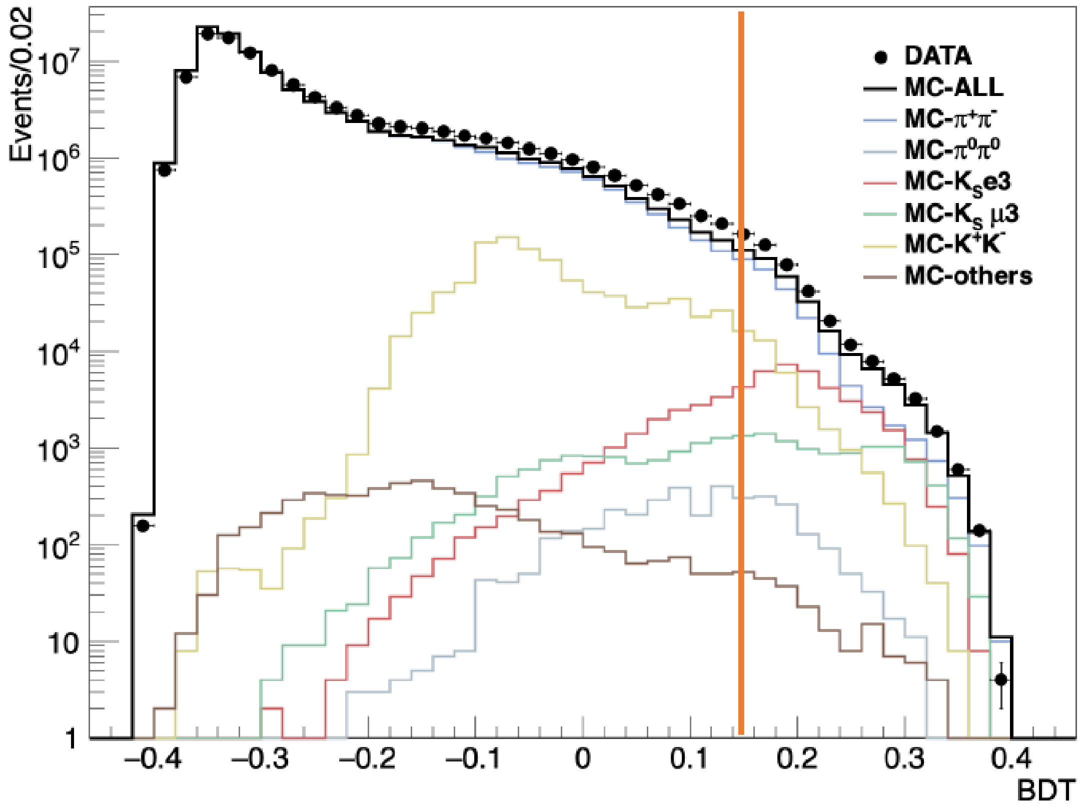
Multivariate selection based on tracking variables/2

BDT classifier trained on 5000 signal events and 50000 background simulated events

Tested on same size samples and run over the both full data and MC samples.

Events with BDT output > 0.15 are retained

to reduces main backgrounds from charged kaons and K_S-> $\pi\pi$



Time of flight selection/1

Track-to-cluster association (TCA) is required for both tracks:

clusters must have E_{clu} > 20 MeV, $\theta_{clu} > 15^{\circ}$, centroid within 30 cm of the track extrapolation.

For each track:

$$\delta t_i = t_{clu,i} - L_i/c\beta_i(m_i)$$

L_i track length, m_i mass hypothesis

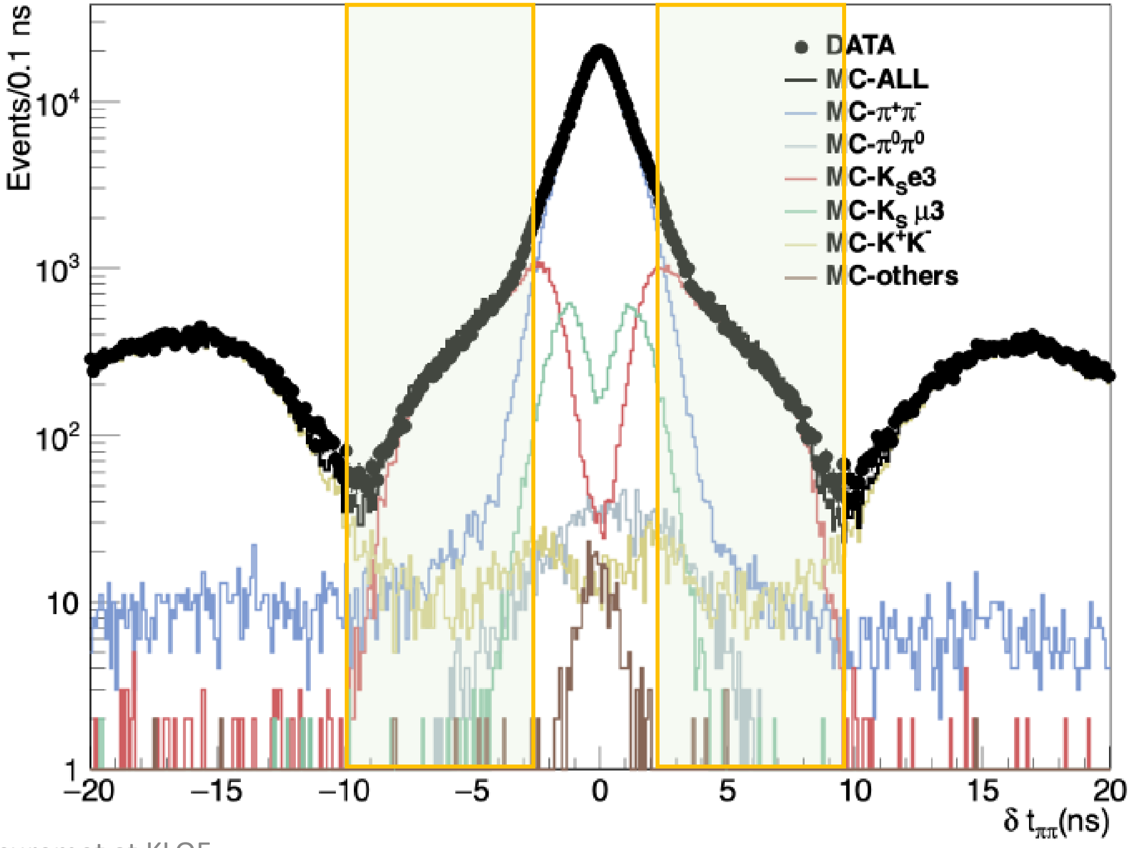
Correct mass hypothesis yields null δt_i

$\delta t = \delta t_1 - \delta t_2$ minimize event T_0 uncertainty

Test of the $\pi\pi$ hypothesis:

$$\delta t_{\pi\pi} = \delta t_{1,\pi} - \delta t_{2,\pi}$$

Selection applied: $2.5 \text{ ns} < |\delta t_{\pi\pi}| < 10 \text{ ns}$



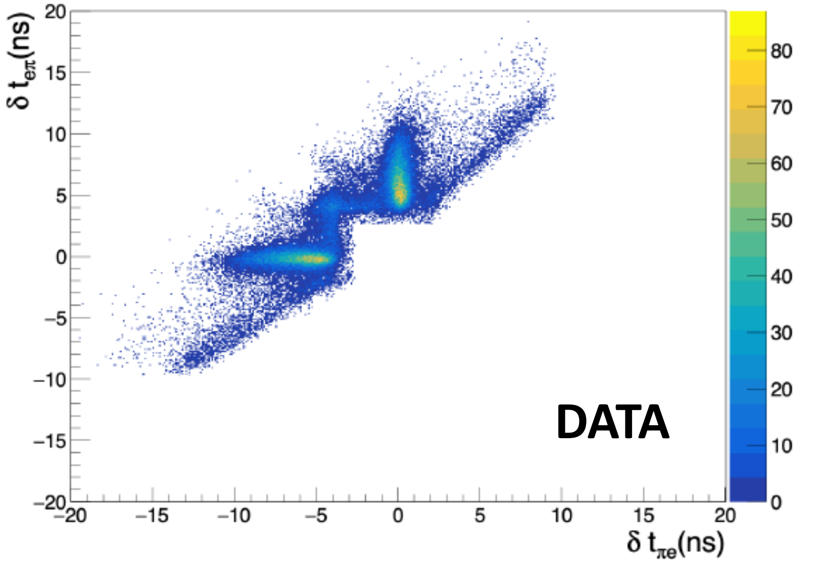
Time of flight selection/2

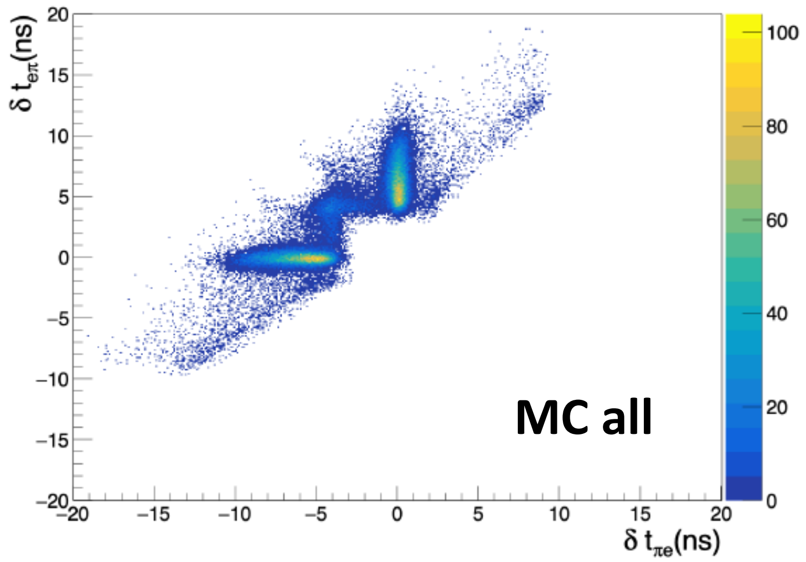
Test of πe vs $e\pi$ hypotheses:

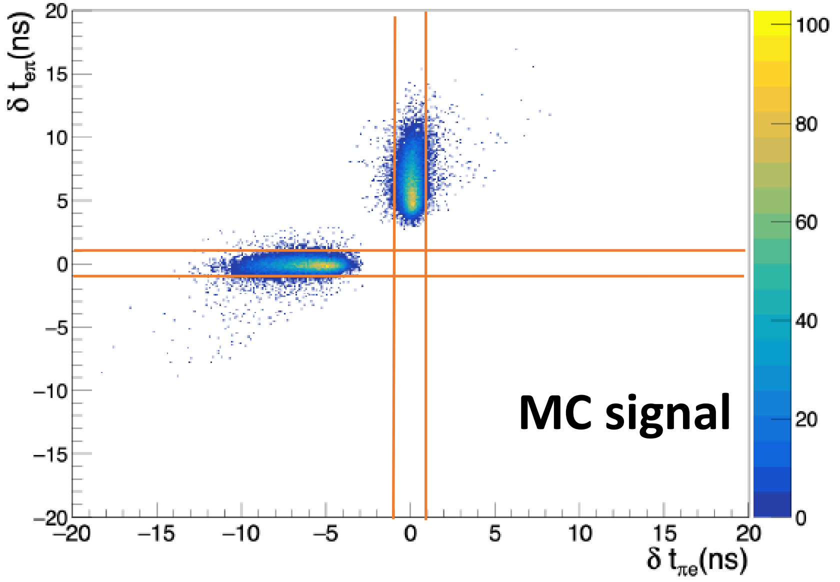
$$\delta t_{\pi e} = \delta t_{1,\pi} - \delta t_{2,e} \qquad \text{vs} \qquad \delta t_{e\pi} = \delta t_{1,e} - \delta t_{2,\pi} \qquad \text{(random track ordering)}$$

Lowest $|\delta t|$ is chosen as the correct hypothesis δt_e

$|\delta t_e| < 1$ ns is required







Signal extraction

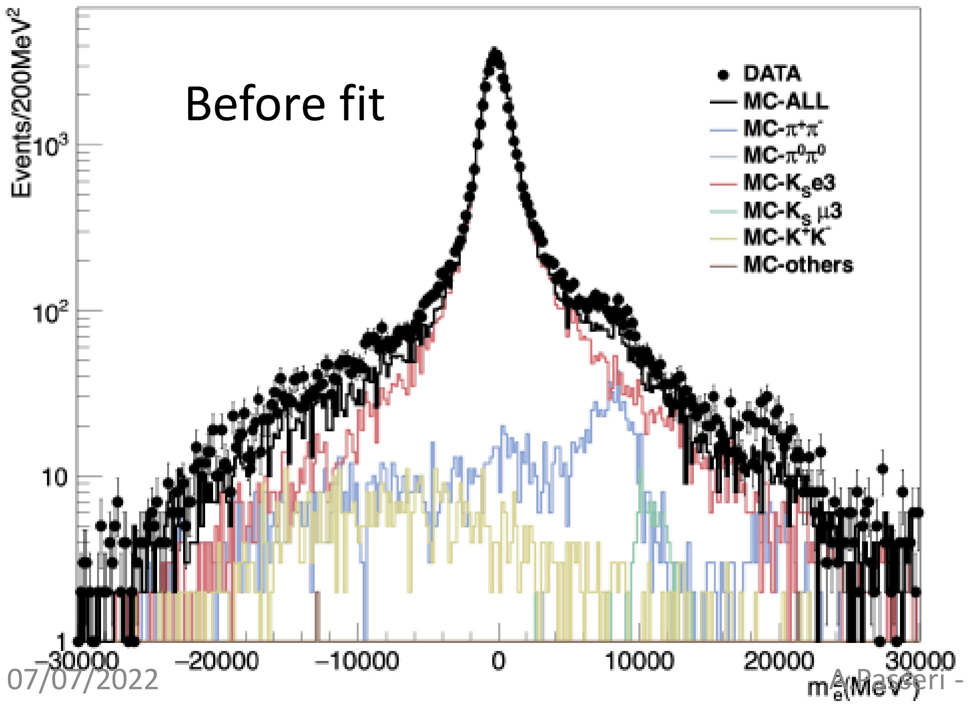
	n. events	Fraction (%)
Data	57577	
MC	56843	
$K_S \to \pi e \nu$	53559	94.22
$K_S \to \pi^+\pi^-$	2175	3.83
$\varphi \to K^+K^-$	903	1.59
$K_S \to \pi\mu\nu$	136	0.24
others	70	0.12

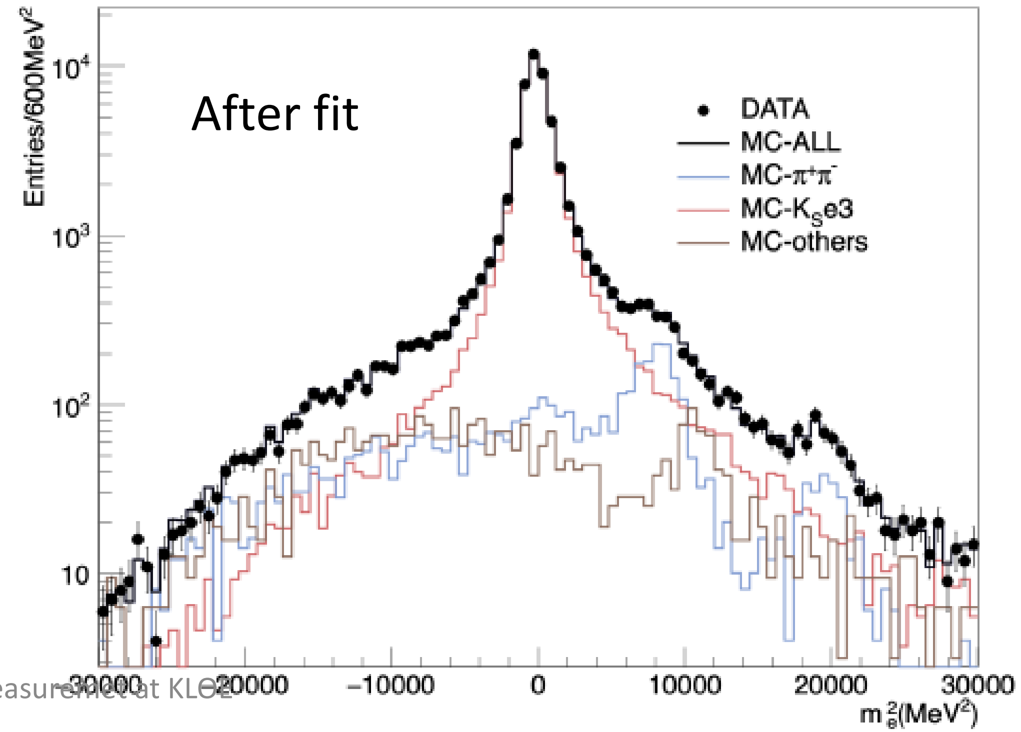
Selected sample is now signal dominated.
m_e^2 distribution is used to fit number of events:

$$m_e^2 = (E_{KS} - E_\pi - p_{miss})^2 - p_e^2 \qquad (E_{KS} \text{ and } p_{KS} \text{ from KL-crash})$$

Fit with 3 components ($\pi e \nu$, $\pi\pi$, others) yelds:

$$\boxed{N_{\pi e \nu} = 49647 \pm 316} \qquad \chi^2/\text{ndf} = 76/96$$





Evaluation of efficiencies

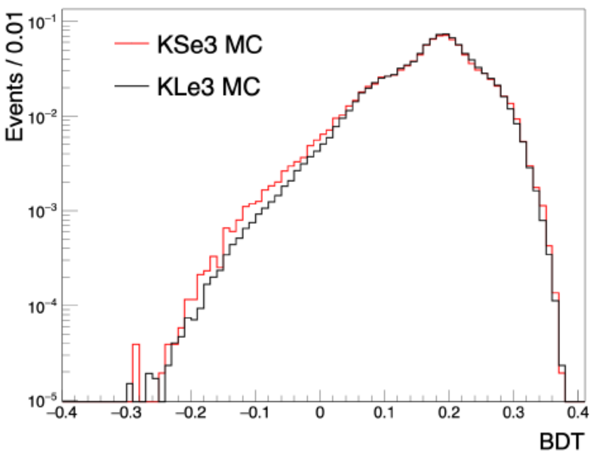
The KL -> π e ν control sample (CS) allows to determine efficiencies from data:

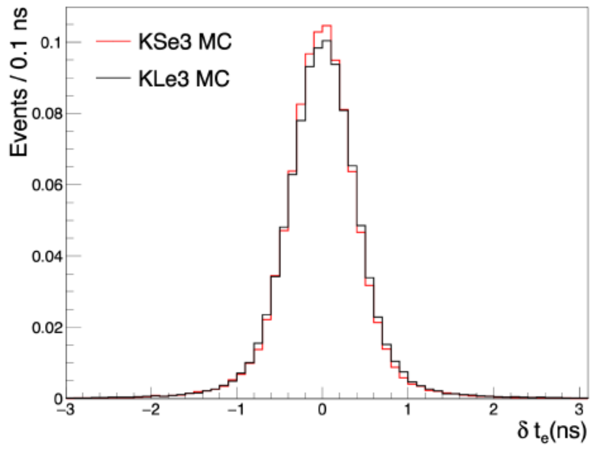
$$\epsilon_{\pi e\nu} = \epsilon_{\rm CS} \times \frac{\epsilon^{\rm MC}_{\pi e\nu}}{\epsilon^{\rm MC}_{\rm CS}}$$

CS Selected by K_S tag, requiring K_L decay radius in the range (1 cm, 5 cm). Missing mass cut discards $\pi^+\pi^-\pi^0$ component.

Two high purity (>95%) CS are built by cutting on TOF variables (for ε_{kine} evaluation) or kine variables (for ε_{tof} evaluation).

Good comparison of CS and signal samples observed in MC





We obtain:

Selection	Efficiency
Preselection (from MC)	0.9961 ± 0.0002
Kin. variables selection	0.9720 ± 0.0007
BDT selection	0.6534 ± 0.0013
TCA selection	0.4639 ± 0.0009
TOF selection	0.6605 ± 0.0012
Total	0.1938 ± 0.0006

The K_S-> $\pi^+\pi^-$ data sample sample is corrected for signal contamination after the momentum cut obtained by a dedicated CS. We then get:

$\varepsilon_{\pi\pi}$ = (96.657 ± 0.002) %

From simulation: R_ε = 1.1882 ± 0.0012

Systematic uncertainty

BDT cut is varied in the range (0.135,0.17) and good $N_{\pi e \nu}$ stability is observed. Spread is used as uncertainty.

TCA checked in CS. δt resolution checked to be identical in signal and control samples.

Lower $\delta t_{\pi\pi}$ cut varied in (2-3ns) range, $|\delta t_e|$ cut varied in (0.8-1.2 ns) range.

m_e^2 fit repeated varying range and bin width. Separate components for KSμ3 and $\phi \to K^+K^-$ backgrounds are tested.

Selection	$\delta\epsilon^{syst}_{\pi e\nu}$ [10^{-4}]	$\delta\epsilon^{syst}_{\pi^+\pi^-}$ [10^{-4}]
BDT selection	5.3	
TCA & TOF selection	6.0	
Fit parameters	3.0	
$K_S \to \pi^+\pi^-$ efficiency		8.8
Total	8.5	8.8

R_ε systematics evaluated by comparing data and MC for each of the included common selections

Result

$$N_{\pi e\nu} = 49647 \pm 316$$
$$N_{\pi\pi} = (282.314 \pm 0.017) \times 10^6$$
$$\epsilon_{\pi^+\pi^-} = (96.657 \pm 0.088)\%$$
$$\epsilon_{\pi e\nu} = (19.38 \pm 0.10)\%$$
$$R_\epsilon = 1.1882 \pm 0.0059$$

Including systematics

$$\mathcal{B}(K_S \to \pi e\nu) = \frac{N_{\pi e\nu}}{\epsilon_{\pi e\nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon \times \mathcal{B}(K_S \to \pi^+\pi^-)$$

$$\mathcal{B}(K_S \to \pi^+\pi^-) = 0.69196 \pm 0.00051$$

Measured by KLOE Eur.Phys. J. C **48** (2006) 767

New KLOE result:

$$\boxed{\mathcal{B}(K_S \to \pi e\nu) = (7.211 \pm 0.046_{\rm stat} \pm 0.052_{\rm syst}) \times 10^{-4} = (7.211 \pm 0.069) \times 10^{-4}}$$

Previous KLOE result: 0.4 fb^{-1} independent data sample. Phys.Lett. B **636** (2006) 173

$$\mathcal{B}(K_S \to \pi e\nu) = (7.046 \pm 0.076_{\rm stat} \pm 0.049_{\rm syst}) \times 10^{-4} = (7.046 \pm 0.091) \times 10^{-4}$$

Combination taking into account correlated systematics:

$$\boxed{\mathcal{B}(K_S \to \pi e\nu) = (7.153 \pm 0.037_{\rm stat} \pm 0.043_{\rm syst}) \times 10^{-4} = (7.153 \pm 0.057) \times 10^{-4}}$$

Conclusions

The KLOE experiment has performed a new measurement of the $K_S \to \pi e \nu$ branching ratio based on a 1.63 fb-1 data sample collected in 2004-05, with a < 1% overall uncertainty.

Combination with the previous KLOE measurement yields a new determination of BR($K_S \to \pi e \nu$) with 0.8% precision.

Using the SM formula $\mathcal{B}(K_S \to \pi \ell \nu) = \frac{G^2(f_+(0)|V_{us}|)^2}{192\pi^3} \tau_S m_K^5 I_K^\ell S_{\rm EW}(1+\delta_{\rm EM}^{K\ell})$

and taking the PDG values for τ_S and m_K and the most recent calculations of the other parameters (Phys.Rev.D 105, (2022) 013005) we obtain:

$$\boxed{f_+(0)|V_{us}| = 0.2170 \pm 0.0009}$$

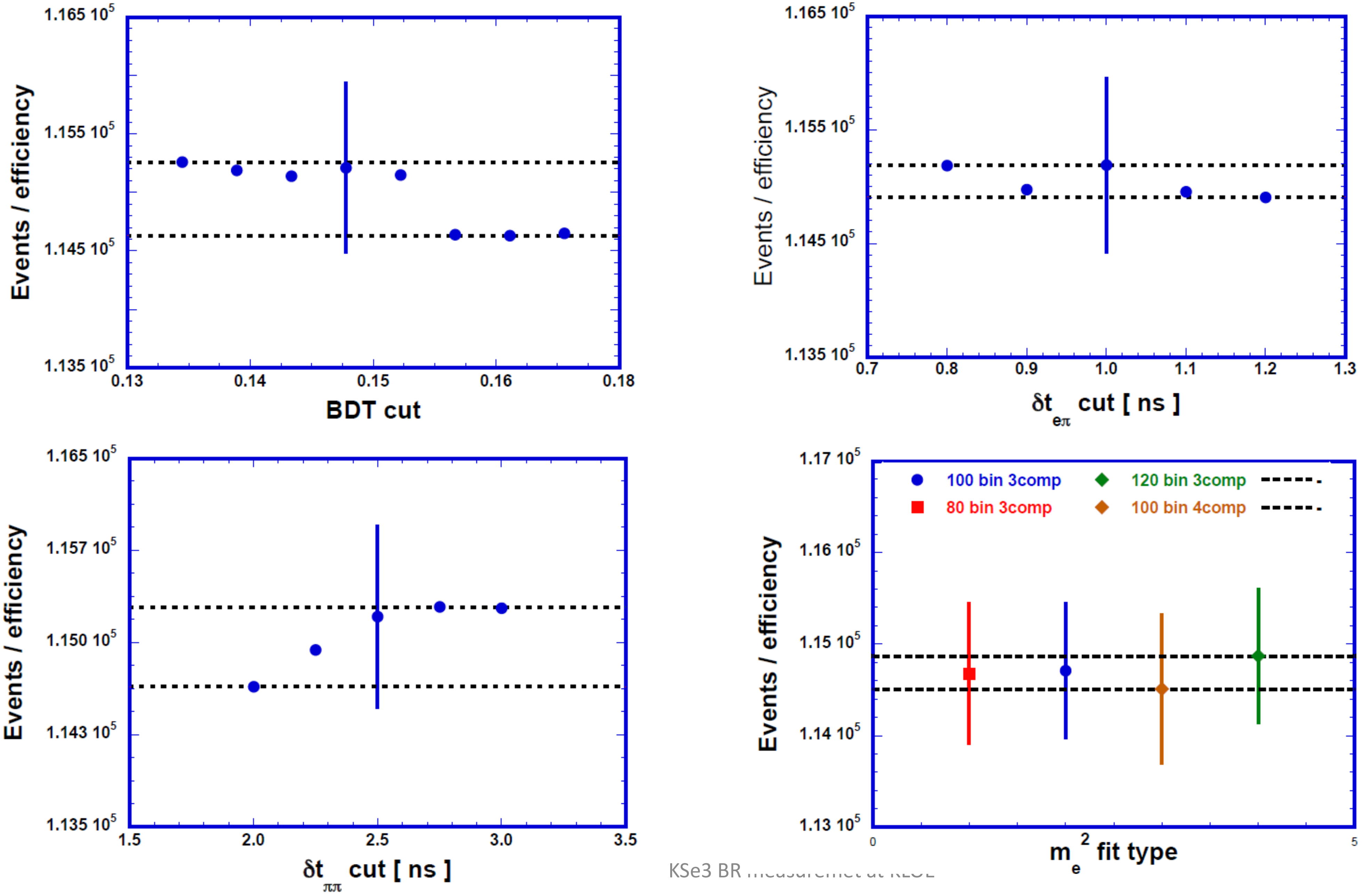
with a sizeable uncertainty reduction with respect to the previous BR(Kse3) measurement.

The sum of the four main K_S branching ratios measured by KLOE yields:

$$B_{\pi+\pi-} + B_{\pi 0 \pi 0} + B_{\pi e \nu} + B_{\pi \mu \nu} > 0.9983 \text{ @95\% CL}$$

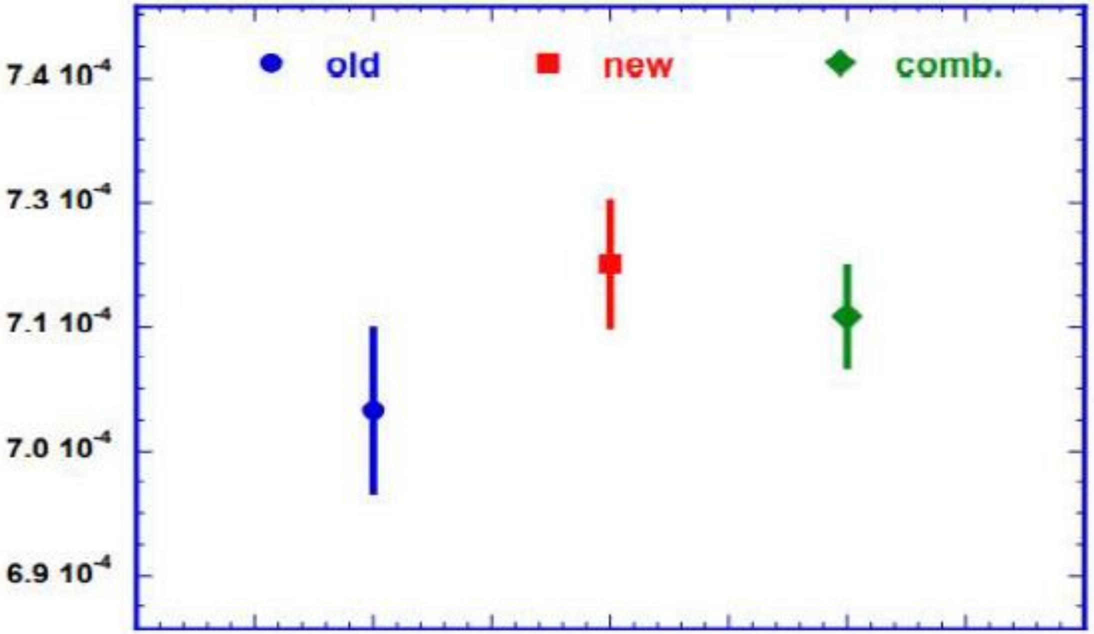
SPARES

Systematic uncertainties estimation



Combination of the 2 KLOE measurements of BR(KSe3)

	old stat $[10^{-3}]$	old syst $[10^{-3}]$	new stat $[10^{-3}]$	new syst $[10^{-3}]$
Trigger		0.9		0.1
Efficiencies		3.7		3.4
TOF		2.3		3.1
Ratio $\frac{\pi\pi}{\pi e \nu}$		5.1		5.0
Fit		6.2		1.5
$\mathcal{B}_{K_S \to \pi^+\pi^-}$		0.7		0.7
Total	9.1	9.2	6.4	7.0



The $f_+(0)|V_{us}|$ estimate from new BR(KSe3) is now more accurate than those from $K^\pm$ semileptonic decays