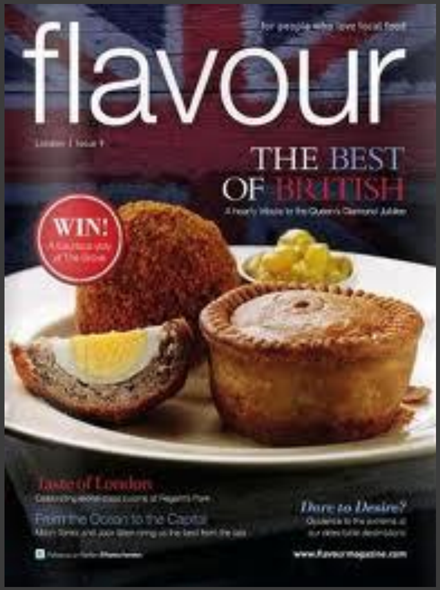


PHYSICS AT THE AD/PS/SPS

LECTURE 3: FLAVOUR AND NEUTRINOS

Augusto Ceccucci/CERN

RECONNU
SAVEUR
DE L'ANNÉE
monadia
Goûté par un jury
de consommateurs

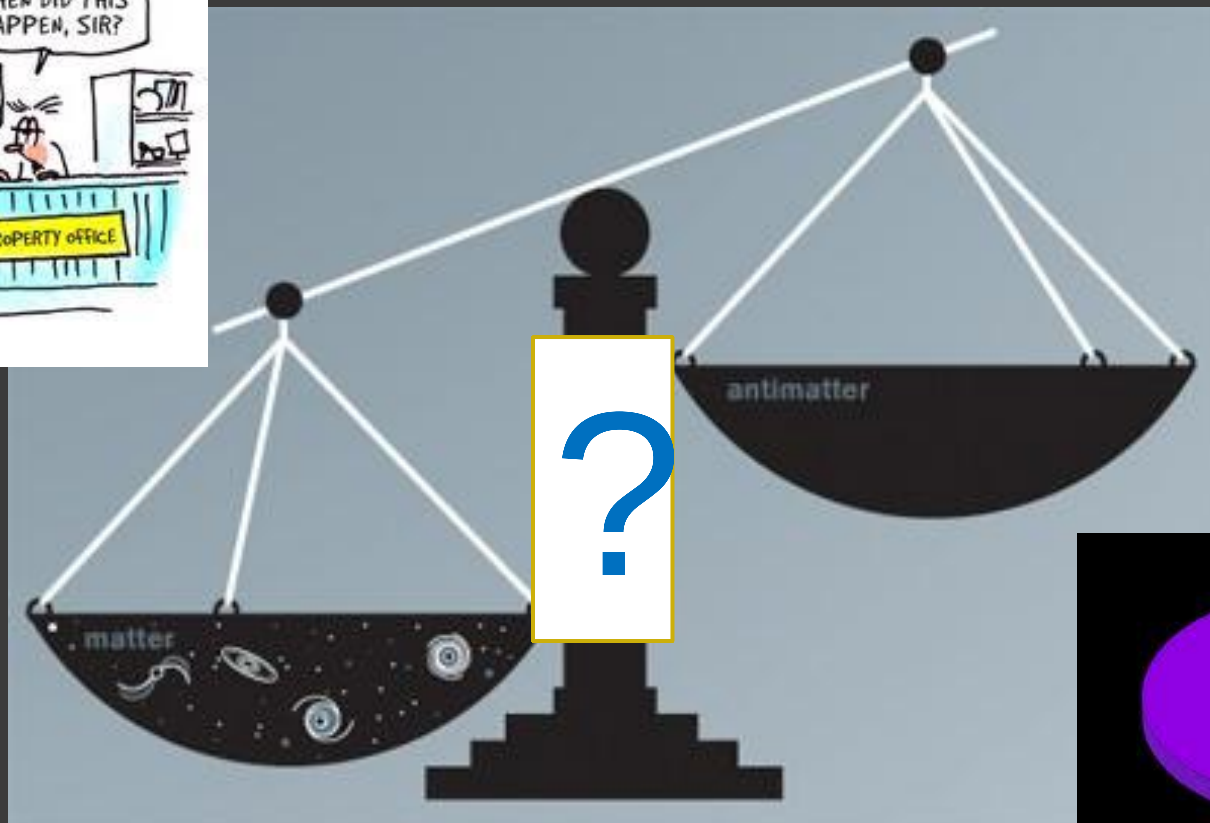
CERN Academic Lectures, June 21, 2012

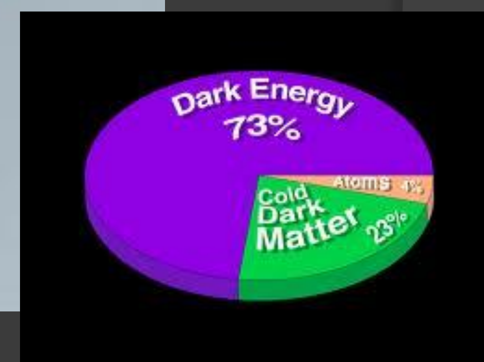
Outline

- Kaon Physics at the SPS (NA48, NA62)
  - CP-Violation & Quark Mixing
  - Lepton Universality
  - Strong Interaction at Low Energy
  - Rare Decays
- Neutrino Physics at the SPS
  - Long baseline neutrino experiments
    - CNGS1 OPERA
    - CNGS2 ICARUS

CP-VIOLATION AND QUARK MIXING

Baryon Asymmetry of the Universe (BAU)





n_{quark}-$n_{antiquark}$/n_{quark} (Proto Universe) ~n_{baryon}/n_{photon} (Today)~**5×10^{-10}**

Sakharov Conditions for BAU

Andrei Sakharov (1967)

To allow the development of an asymmetry between matter and anti-matter

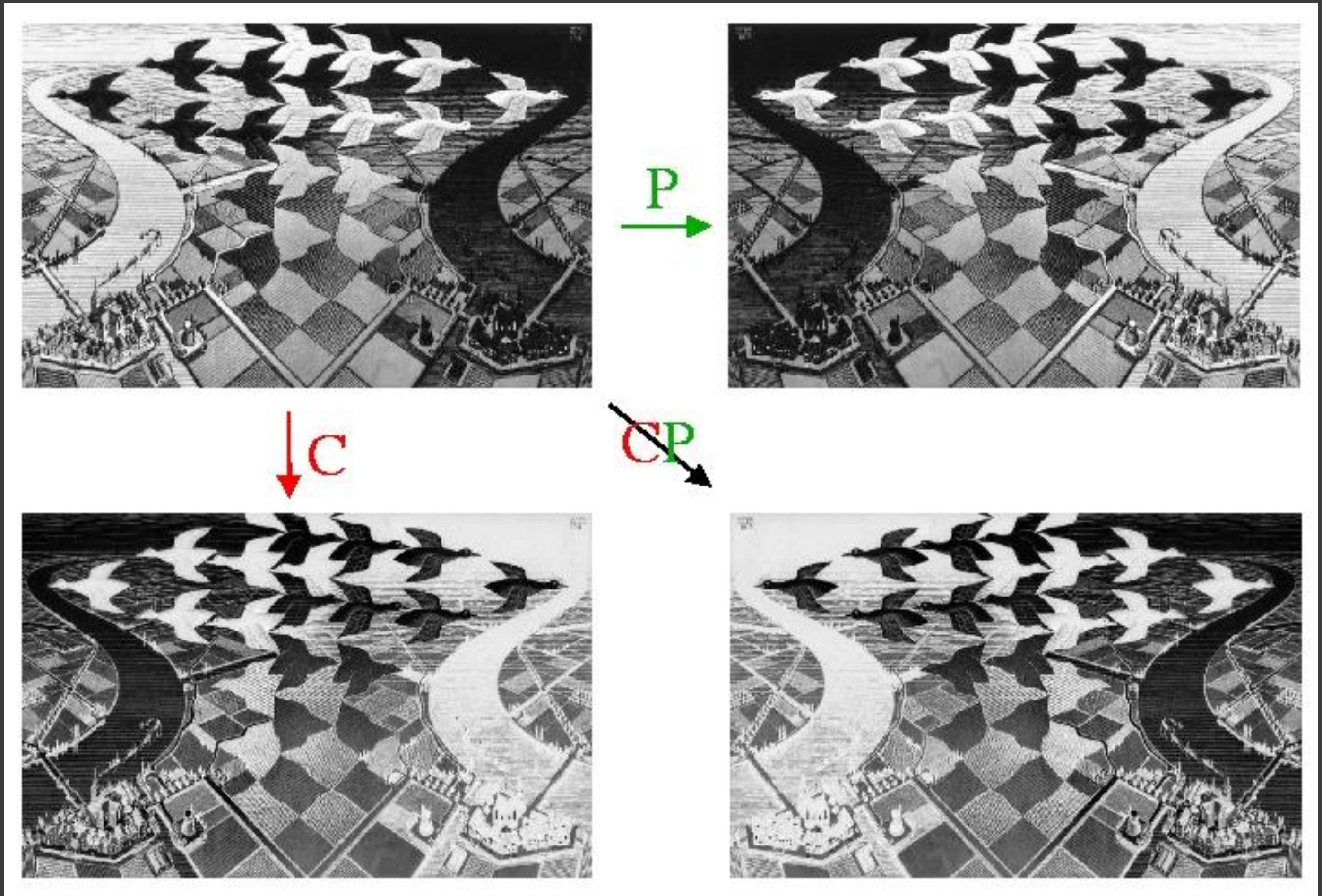
1. Violation of Baryonic Number

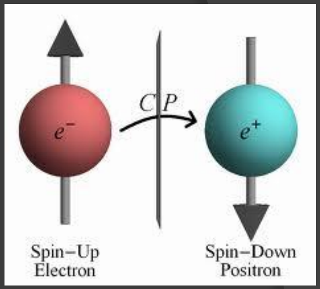
2. Thermodynamic Non-equilibrium

3. Violation of C & CP

Origin of BAU: Baryogenesis or Leptogenesis?

CP-Violation





When the top-left and the bottom-right Pictures are not exactly the same, we have CP-Violation

Da Gino Isidori:
http://scienzapertutti.lnf.infn.it/P1/schedaCP.html

Types of CP-Violation

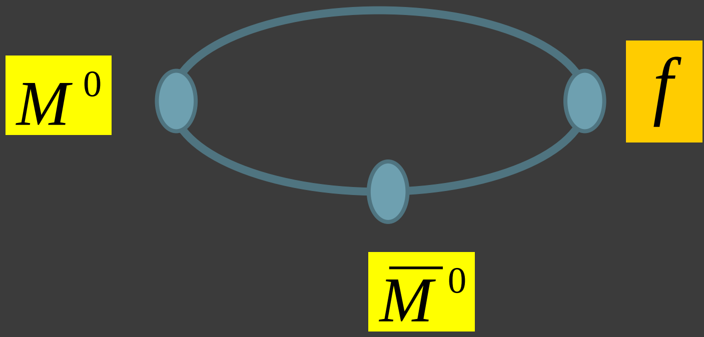
$$|M_L\rangle \propto p|M^0\rangle + q|\overline{M}^0\rangle$$
$$|M_H\rangle \propto p|M^0\rangle - q|\overline{M}^0\rangle$$

$\Delta F = 2$

$$A_f = \langle f|H|M\rangle, \quad \overline{A}_f = \langle f|H|\overline{M}\rangle$$
$$A_{\bar{f}} = \langle \bar{f}|H|M\rangle, \quad \overline{A}_{\bar{f}} = \langle \bar{f}|H|\overline{M}\rangle$$

$\Delta F = 1$

1. CP Violation in mixing $|q/p| \neq 1$ (indirect)
2. CP Violation in decays $|\overline{A}_{\bar{f}} / A_f| \neq 1$ (direct)
3. CP Violation in the interference

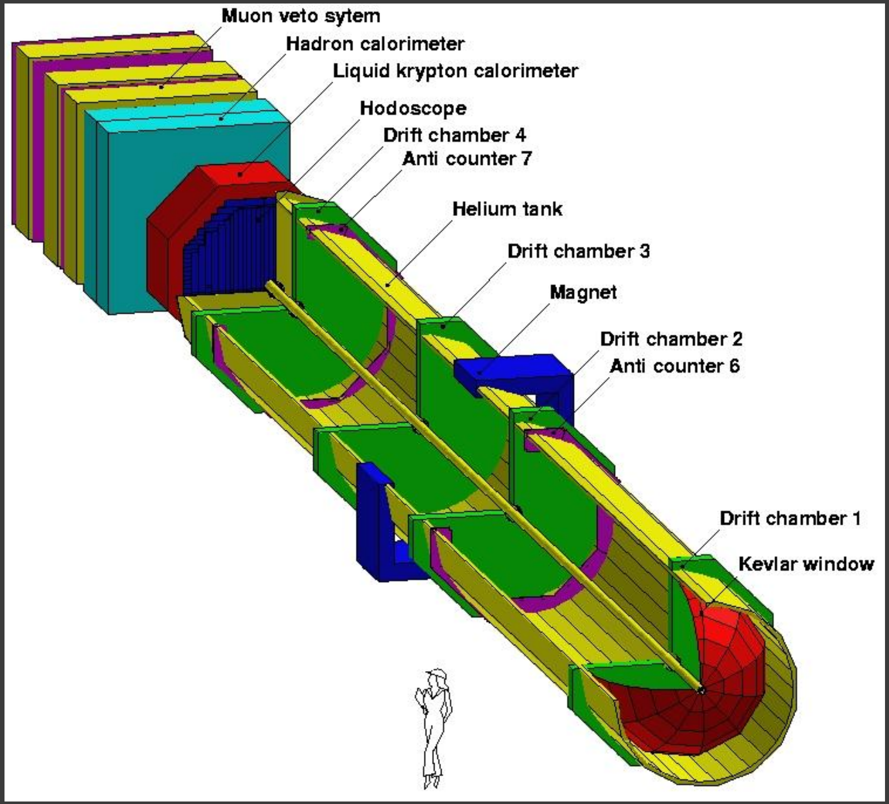


$$\mathrm{Im}\,\lambda_f \neq 0$$

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

The study of direct CP-violation in the two pion Decays of the neutral kaons **(ε'/ε)** was the main motivation to study kaon decays at the SPS

NA48/NA62 at CERN



NA48	1997: ε'/ε: K_L+K_S		
	1998: K_L+K_S		
	1999: K_L+K_S	K_S HI	
	2000: K_L only	K_S HI	
	2001: K_L+K_S	K_S HI	
NA48/1	2002: K_S/hyperons		
NA48/2	2003: K^+/K^-		
	2004: K^+/K^-		
NA62_RK	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests	
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests	
NA62	2012 Technical Run		
	2014- $K^+\to\pi^+\nu\bar{\nu}$ Data Taking		

Old Detector **New Collaboration**

New Detector
(more on this later…)

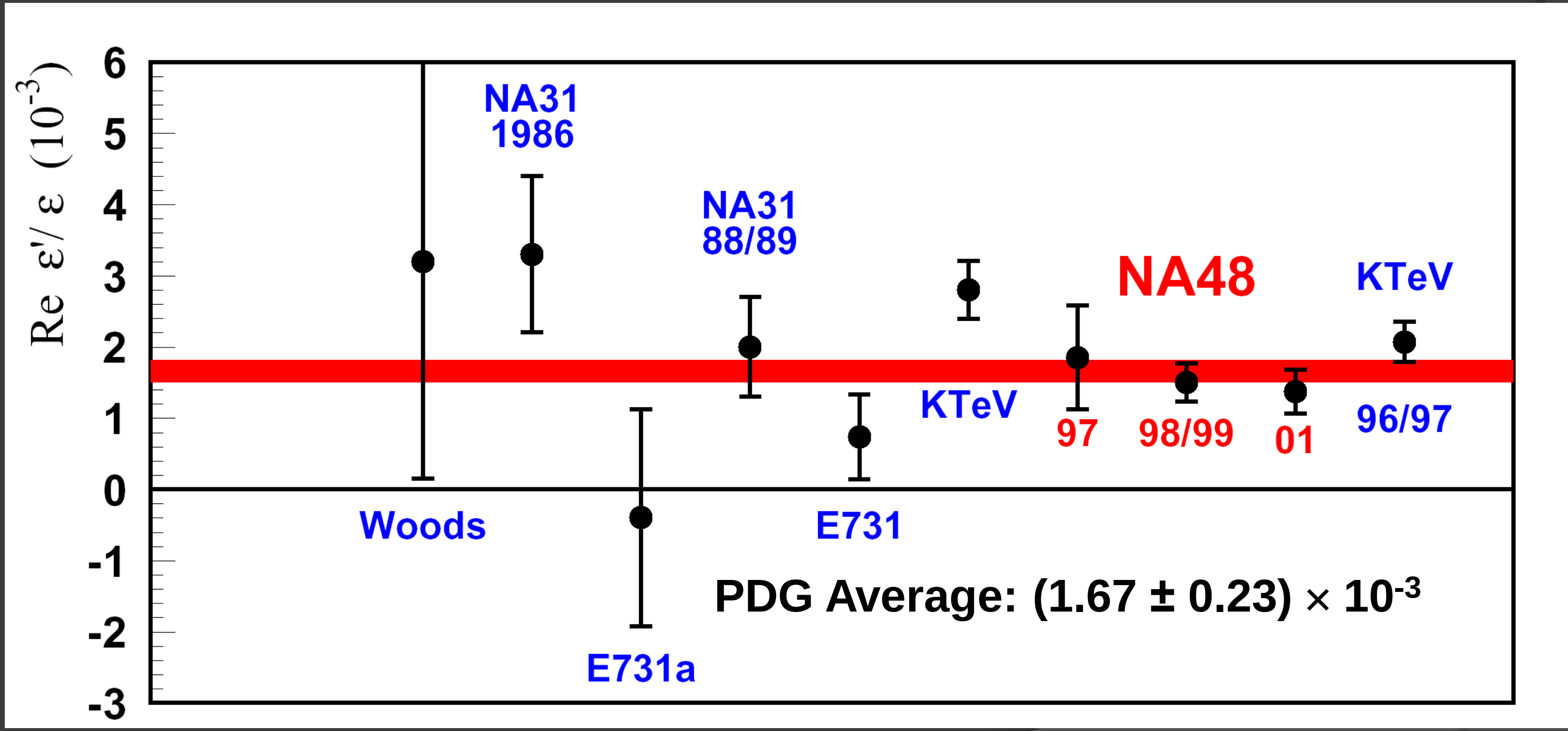
- Magnetic spectrometer (4 DCHs):
  - 4 views/DCH
  - $\Delta p/p = 0.48\% + 0.009\%{*}p$ [GeV/c]
- Liquid Krypton EM calorimeter (LKr)
  - High granularity, quasi-homogeneous;
  - $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV]
  - $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$mm (1.5mm@10GeV)

Re ε'/ε measurements versus time

$$R = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right)}{\Gamma\left(K_S \to \pi^0\pi^0\right)} / \frac{\Gamma\left(K_L \to \pi^+\pi^-\right)}{\Gamma\left(K_S \to \pi^+\pi^-\right)} \approx 1 - 6 \;\mathrm{Re}\,(\varepsilon'/\varepsilon)$$

Direct CP Violation

$$\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \to \pi^+\pi^-)$$



Crucial CERN Experiments: NA31 & NA48

Cabibbo-Kobayashi-Maskawa (CKM) Quark Mixing Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

With 3 generations CP violation is naturally introduced by an irreducible complex phase in the quark mixing matrix (Kobayashi & Maskawa, 1973)

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

(PDG 2012)

$\lvert V_{ud}\rvert = 0.97425 \pm 0.00022$	$0^+ \rightarrow 0^+$ super-allowed nuclear β decays
$\lvert V_{us}\rvert = 0.2252 \pm 0.0009$	**Kaon semi-leptonic and leptonic decays**
$\lvert V_{cd}\rvert = 0.230 \pm 0.011$	$2\mu/1\mu$ ratio in neutrino/antineutrino interactions
$\lvert V_{cs}\rvert = 1.006 \pm 0.023$	Average of semi-leptonic D and leptonic D_s decays
$\lvert V_{cb}\rvert = (40.9 \pm 1.1) \times 10^{-3}$	Combination of exclusive and inclusive B decays
$\lvert V_{ub}\rvert = (4.15 \pm 0.49) \times 10^{-3}$	Comb. of exclusive and inclusive charmless B decays
$\lvert V_{tb}\rvert = 0.89 \pm 0.07$	Single top-quark production cross-section

V_{td} & V_{ts} accessible from FCNC processes (loops)

CP-Violation in Kaons and CKM

- Neutral Kaon Mixing ($\pi\pi$, semi-leptonic)

$$|\varepsilon| = \frac{G_F^2 f_K^2 m_K m_W^2}{12\sqrt{2}\pi^2 \Delta m_K} \hat{B}_K \{\eta_1 S(x_c)\,\mathrm{Im}(V_{cs}V_{cd}^*)^2 + \eta_2 S(x_t)\,\mathrm{Im}(V_{ts}V_{td}^*)^2 + 2\eta_3 S(x_c, x_t)\,\mathrm{Im}(V_{cs}V_{cd}^* V_{ts}V_{td}^*)\}$$

$$|\varepsilon| = (2.233 \pm 0.015) \times 10^{-3}$$

- Neutral Kaon Decays into $\pi\pi$

PDG Average

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} \propto \mathrm{Im}(V_{td}V_{ts}^*)$$

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} = (1.67 \pm 0.23) \times 10^{-3}$$

Direct CP-Violation

V_{us} and universality

$$\frac{g}{\sqrt{2}} W_\alpha^+ \left(\overline{\mathbf{U}}_L \mathbf{V}_{\rm CKM} \gamma^\alpha \mathbf{D}_L + \overline{e}_L \gamma^\alpha \nu_{e\,L} + \overline{\mu}_L \gamma^\alpha \nu_{\mu\,L} + \overline{\tau}_L \gamma^\alpha \nu_{\tau\,L} \right) \; + \; \text{h.c.}$$

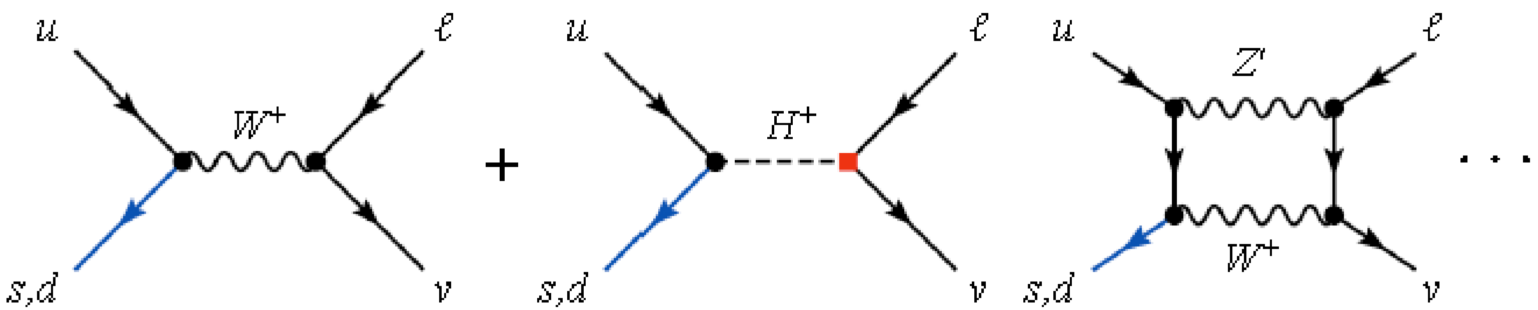
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Standard-model coupling of quarks and leptons to W

Universality: Is G_F from μ decay equal to G_F from π, K, nuclear β decay?

$$G_\mu^2 = (g_\mu g_e)^2 / M_W^4 \quad \stackrel{?}{=} \quad G_{\rm CKM}^2 = (g_q g_\ell)^2 \left(|V_{ud}|^2 + |V_{us}|^2\right) / M_W^4$$

Physics beyond the Standard Model can break gauge universality:



V_{us} from semileptonic decays

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\mathrm{EW}} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\mathrm{EM}}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

S_{EW} Universal SD EW correction (1.0232)

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios
- Kaon lifetimes

$I_{K\ell}(\{\lambda\}_{K\ell})$ Integral of form factor over phase space: λs parameterize evolution in t

- K_{e3}: Only λ_+ (or λ_+', λ_+'')
- $K_{\mu 3}$: Need λ_+ and λ_0

Inputs from theory:

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)

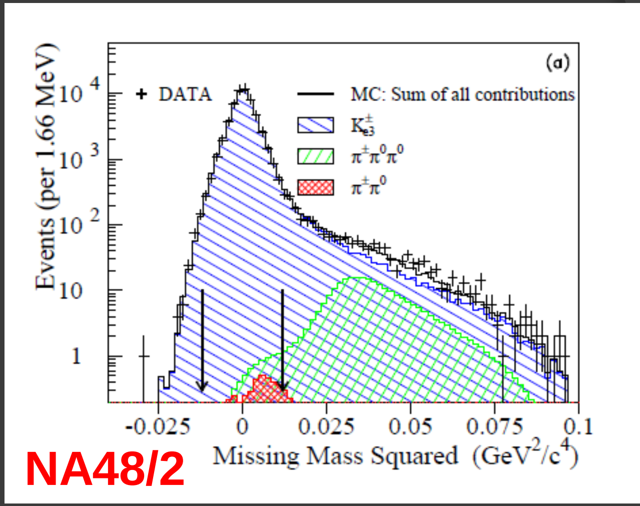
$\Delta_K^{SU(2)}$ Form-factor correction for $SU(2)$ breaking

$\Delta_{K\ell}^{\mathrm{EM}}$ Form-factor correction for long-distance EM effects

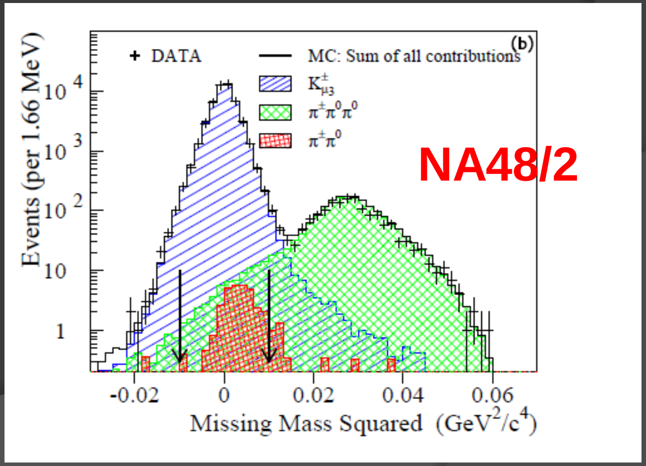
“Modern” V_{us} experimental input

Experiment	Measurement	Year
BNL865	BR($K^+ \to \pi^0{}_D e^+ \nu$)/BR($K^+ \to \pi^0{}_D X^+$)	2003
KTeV	$\tau(K_S)$	2003
	BR(K_{Le3}), BR($K_{L\mu3}$), $\lambda_+(K_{Le3})$, $\lambda_{+,0}(K_{L\mu3})$	2004
ISTRA+	$\lambda_+(K^-{}_{e3})$, $\lambda_{+,0}(K^-{}_{e3})$	2004
KLOE	$\tau(K_L)$	2005
	BR(K_{Le3}), BR($K_{L\mu3}$), BR(K_{Se3}), $\lambda_+(K_{Le3})$	2006
	$\lambda_{+,0}(K_{L\mu3})$	2007
	$\tau(K^\pm)$, BR(K_{Le3}), BR($K_{L\mu3}$)	2008
NA48	$\tau(K_S)$	2002
	BR(K_{Le3}/2 tracks), $\lambda_+(K_{Le3})$	2004
	BR(K_{Se3}/K_{Le3}), $\lambda_{+,0}(K_{L\mu3})$	2007
NA48/2	BR($K^+{}_{e3}/\pi^+\pi^0$), BR($K+{}_{\mu3}/\pi^+\pi^0$)	2007

$K^\pm \to \pi^0 e^\pm \nu$



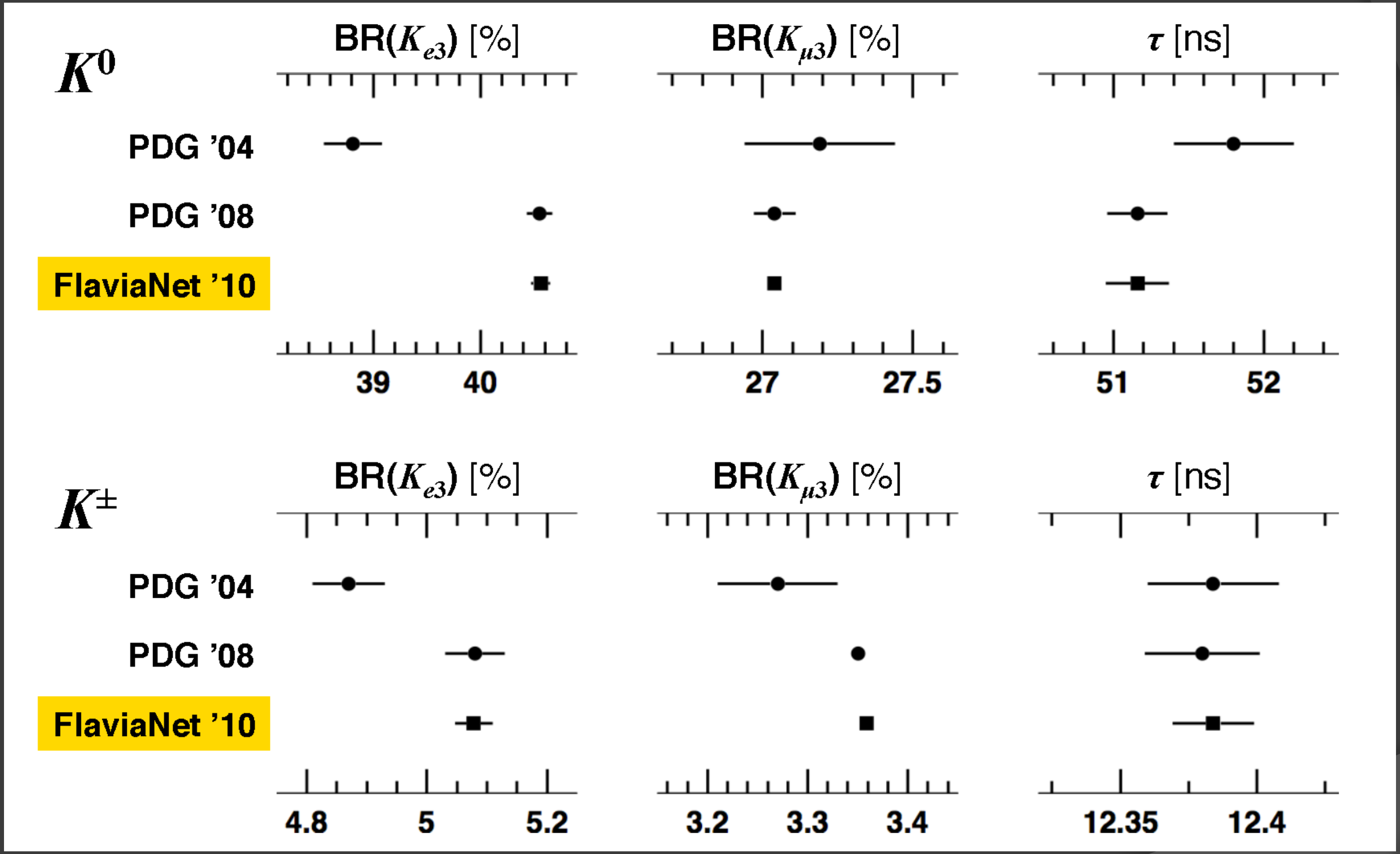
$K^\pm \to \pi^0 \mu^\pm \nu$



The experiments determine the product of
V_{us} $f_+(0)$ and $V_{us}f_K$

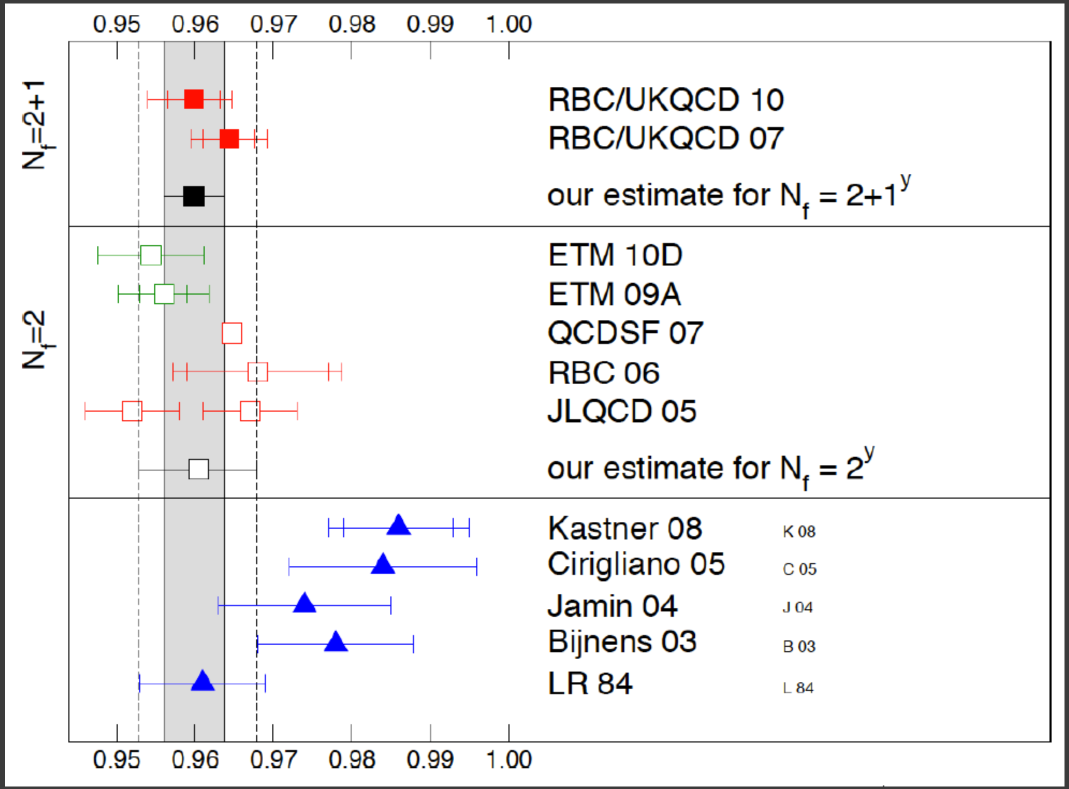
Precise theoretical calculations (lattice QCD and chiral perturbation theory) allow one to perform stringent tests. The theory works very well for kaons.

Evolution of Experimental Input…



"V_{us} Revolution" with experimental input changing ~ 5% in some cases….."

...and of the theoretical one $f_+(0)$



The LQCD calculations are Improving, for instance they go beyond “quenched” approximations ($N_f = 2$)

The **Cabibbo** angle can be precisely determined **(~0.4%)!**

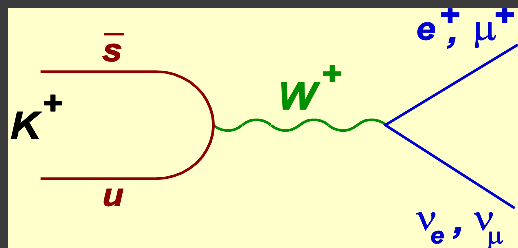
Unitarity test of CKM the first row (PDG 2012):

$$|V_{ud}|^2|+|V_{us}|^2+|V_{ub}|^2=0.9999 \pm 0.0006$$

LEPTON UNIVERSALITY

$R_K = K_{e2}/K_{\mu 2}$

SM

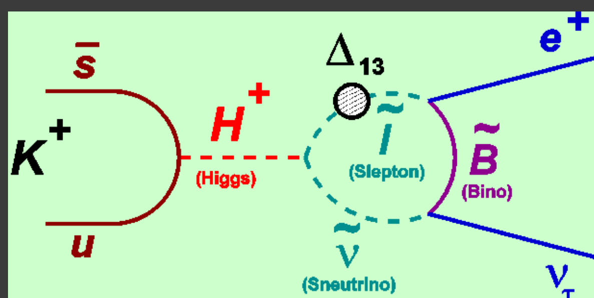


$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano & Rosell PRL 99 (2007) 231801

BSM, LFV



e.g. Masiero, Paradisi Petronzio
PRD 74 (2006) 011701,
JHEP 0811 (2008) 042

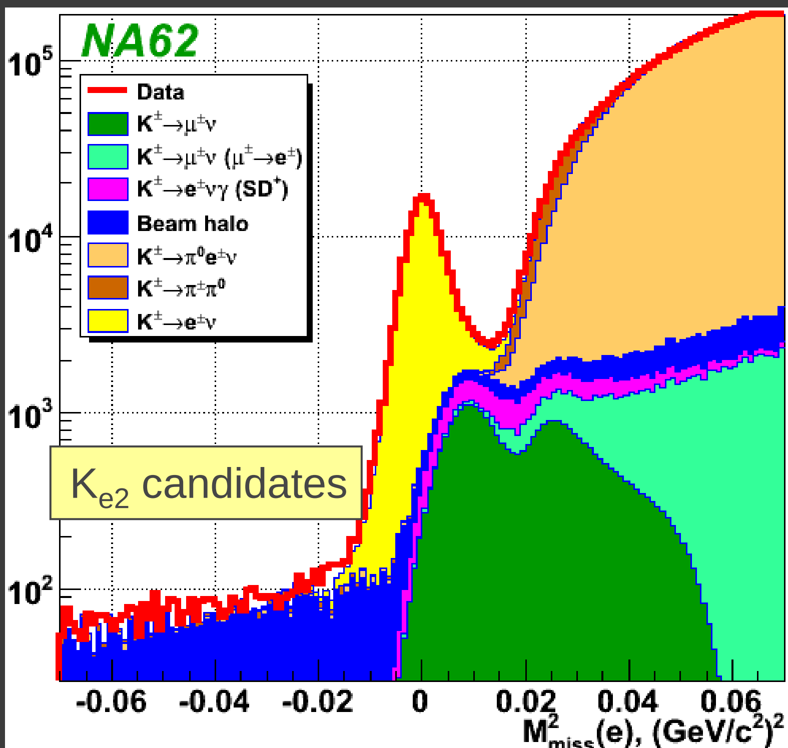
$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right) \left(\frac{m_\tau^2}{M_e^2}\right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

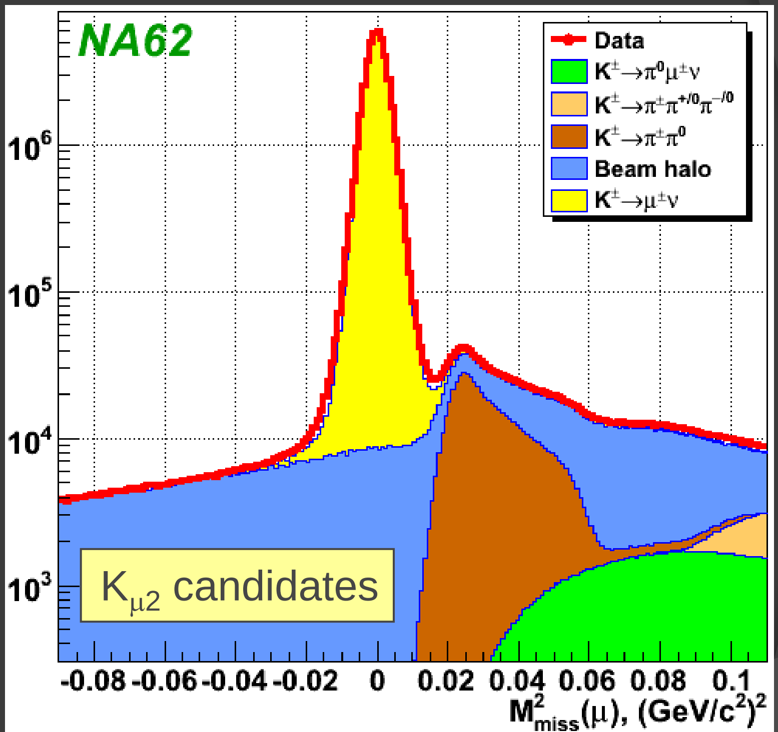
Leptonic decays of the pseudoscalar mesons are helicity Suppressed in the standard model

Example:
($\Delta_{13} = 5 \times 10^{-4}$, $\tan\beta = 40$, $M_H = 500$ GeV/c^2)
lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$.

NA62: $R_K = K_{e2}/K_{\mu2}$

Full data set





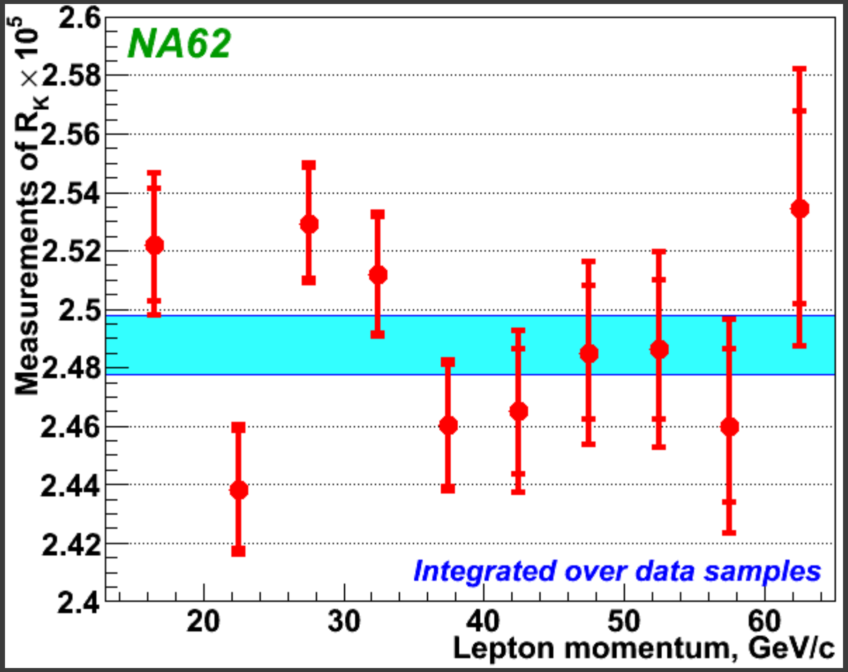
145,958 $K^{\pm} \to e^{\pm}\nu$ candidates.
Electron ID efficiency: (99.28±0.05)%.

NA62: R_K full data set

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

$R_K = (2.487 \pm 0.010) \times 10^{-5}$

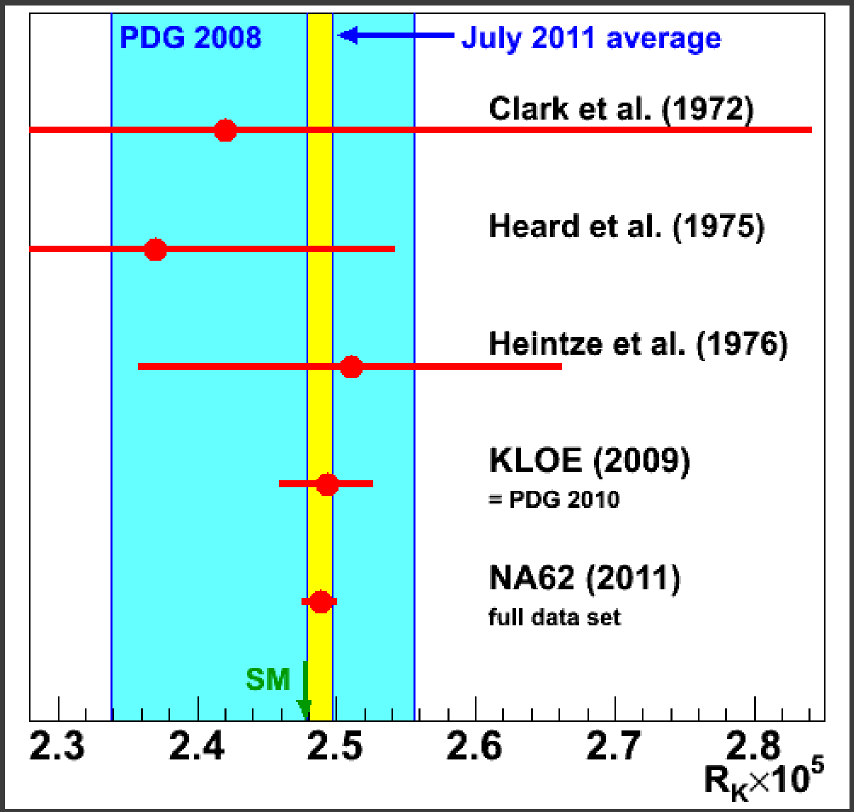
Published (40% sample)
CERN-PH-EP-2011-004,
arXiv:1101.4805,
PLB B698 (2011) 105

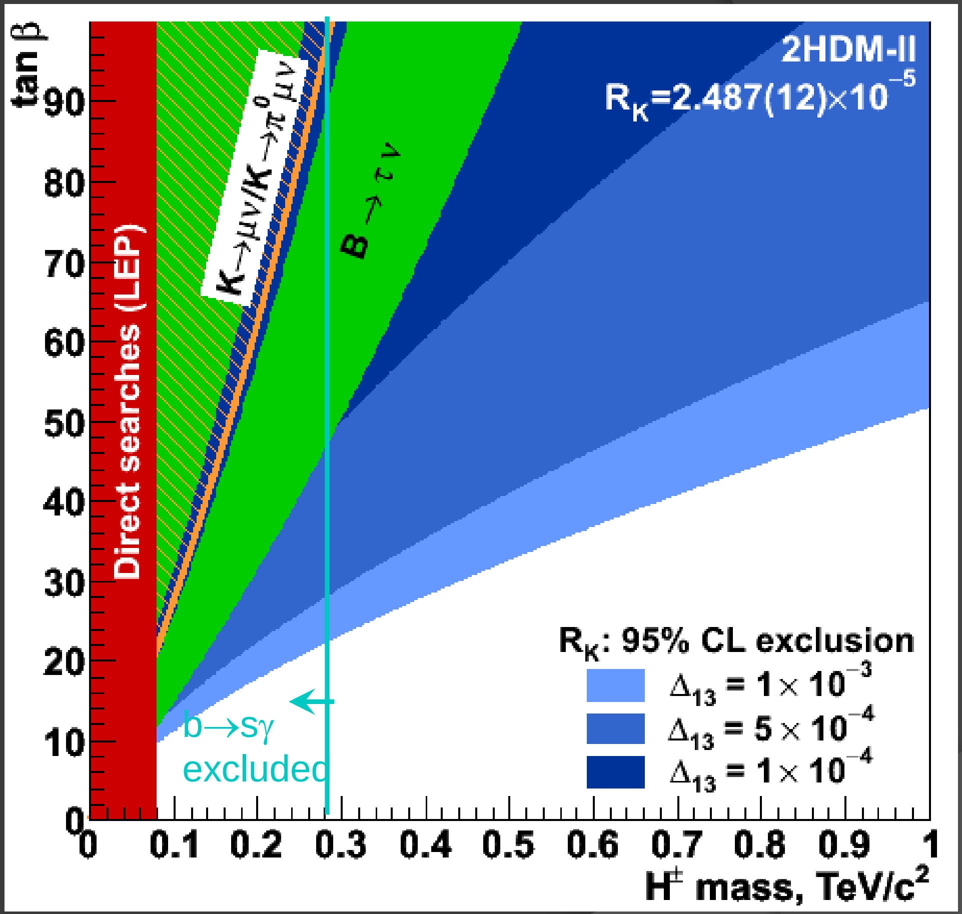


Errors in momentum bins are partially correlated

Background source	B/(S+B)
$K_{\mu 2}$	(5.64±0.20)%
$K_{\mu 2}$ ($\mu \to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD^+)	(2.60±0.11)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Muon halo	(2.11±0.09)%
Total	(10.95±0.27)%

R_K world average





World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
Today	2.488±0.009	0.4%

Other limits on 2HDM-II:
PRD 82 (2010) 073012
SM with 4 generations:
JHEP 1007 (2010) 006.

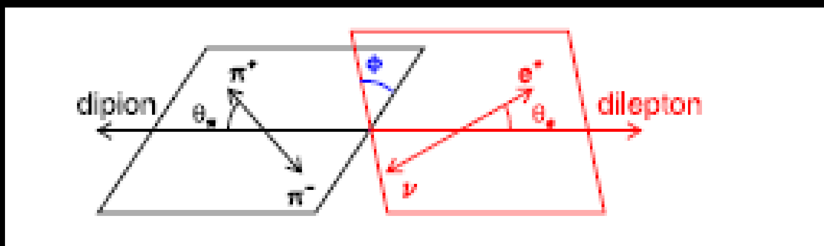
STRONG INTERACTION AT LOW ENERGY

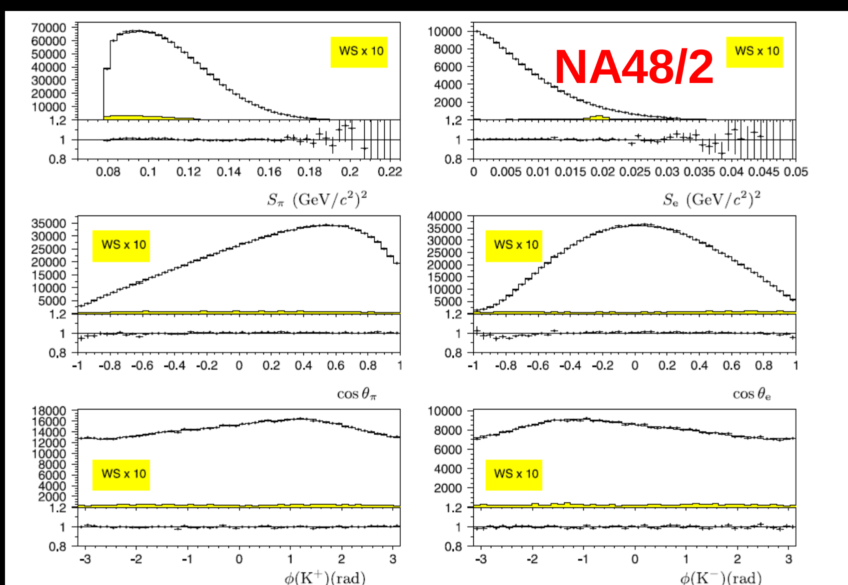
Strong Interaction at low energy

- At high energy the strong interactions are described by Quantum Chromo Dynamics (QCD)
- Below ~ 1 GeV, the strong coupling becomes large and the perturbative description is not possible
- An effective theory, Chiral Perturnation Theory (ChPT) allows to study the strong interaction at low energy in terms of momenta and light meson masses
- Kaons are a good laboratory to study the strong interactions at low energy ($\pi\,\pi$ scattering, radiative decays,…)

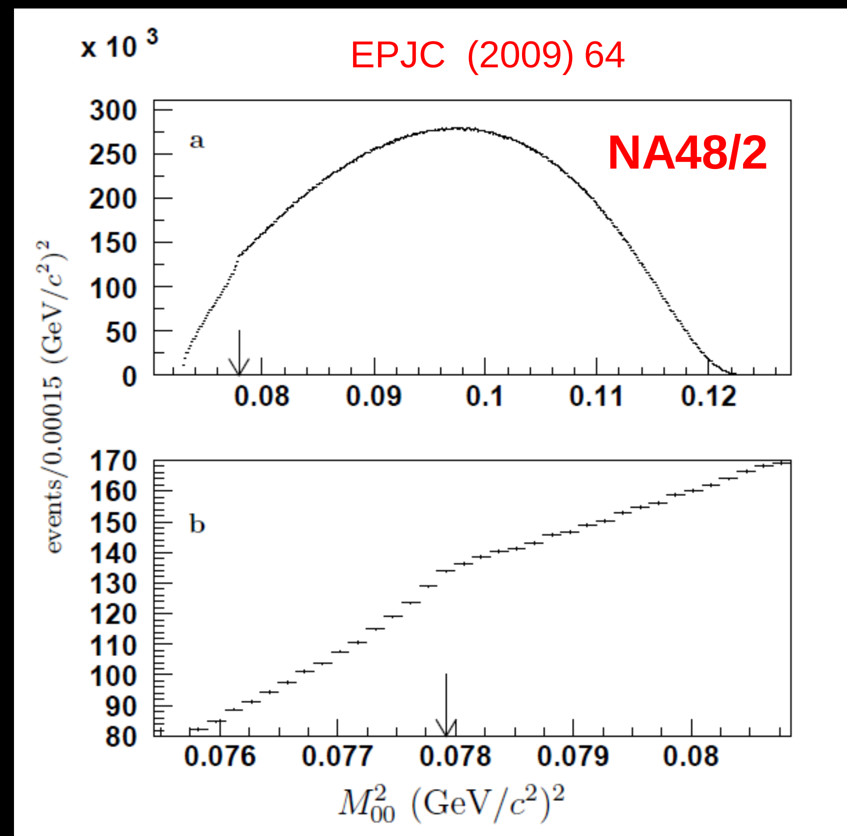
NA48/2: $K^{\pm}\rightarrow\pi^{+}\pi^{-}e^{\pm}\nu$ & cusp in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ cusp

$K^{\pm}\rightarrow\pi^{+}\pi^{-}e^{\pm}\nu$ (Ke4)





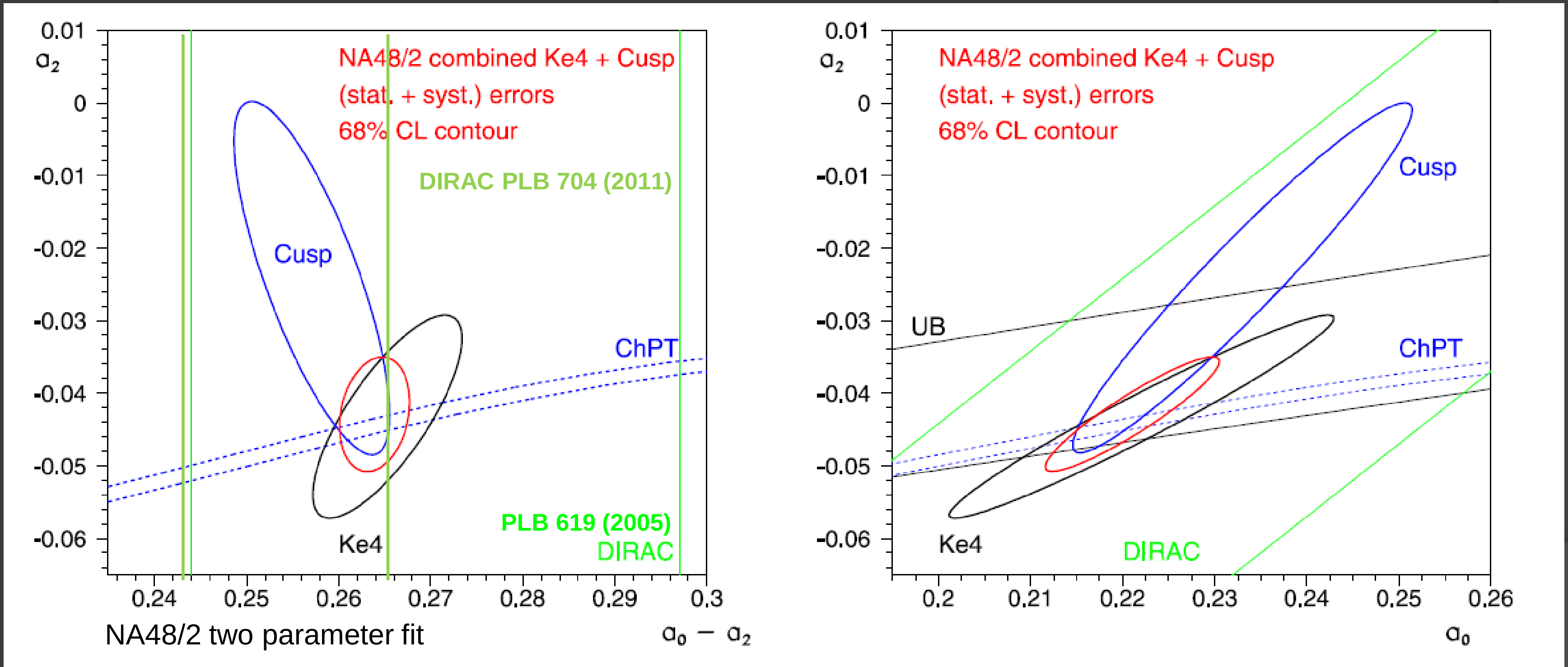
Cusp in $K^{\pm}\rightarrow\pi^{\pm}\pi^{o}\pi^{o}$ decays



Cusp-like structure at the $\pi^{+}\pi^{-}$ invariant mass threshold

ππ scattering length

NA48/2: EPJC (2010) 70



Consistent results on the scattering lengths obtained with completely independent techniques

RARE DECAYS

Looking for physics beyond the SM

- Direct searches: LHC energy frontier
- Indirect searches:

1. Improve meaurement precision of CKM elements
   - Compare measurements of the same quantities which may or may not be sensitive to new physics
   - Extract all CKM angles and sides in many different ways → inconsistencies would signal new physics
2. Study Flavour Changing Neutral Currents (FCNC) processes where the SM contributions are suppressed and precisely predictable → Rare Decays

A. Buras list of Flavour Superstars

Superstars of 2011 – 2015
(Flavour Physics)

$S_{\psi\varphi}$

$\not{CP}$ in $B_s^0 - \bar{B}_s^0$

$(B_s \to \varphi\varphi)$

$B_s \to \mu^+\mu^-$

$(B_d \to \mu^+\mu^-)$

$(B^+ \to \tau^+\nu_\tau)$

$K^+ \to \pi^+ \nu\bar{\nu}$

$(K_L \to \pi^0 \nu\bar{\nu})$

$(B_d \to K^* \mu^+\mu^-)$

γ
from Tree
Level
Decays

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to 3e$

$\tau \to 3$ leptons

ε'/ε *)

(Lattice)

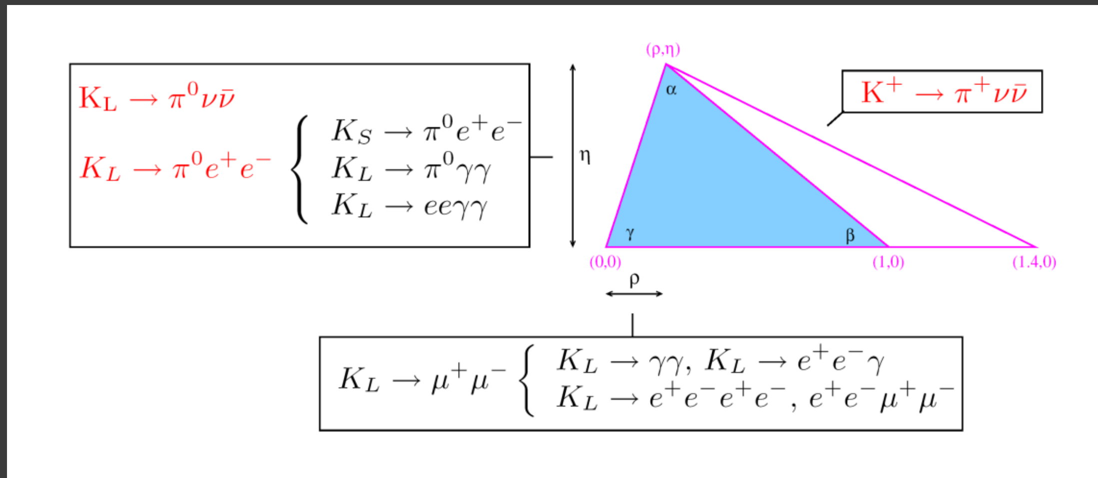
EDM´s

$(g\text{-}2)_\mu$

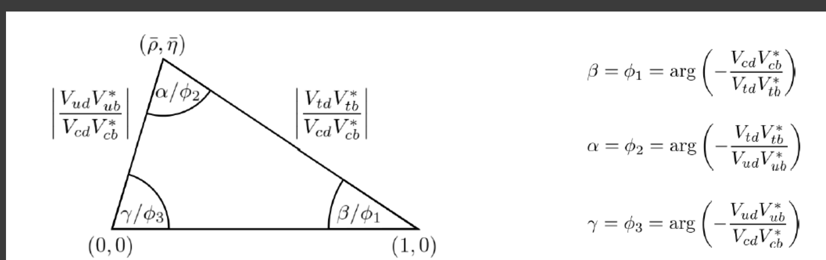
*) Direct $\not{CP}$ in $K_L \to \pi\pi$

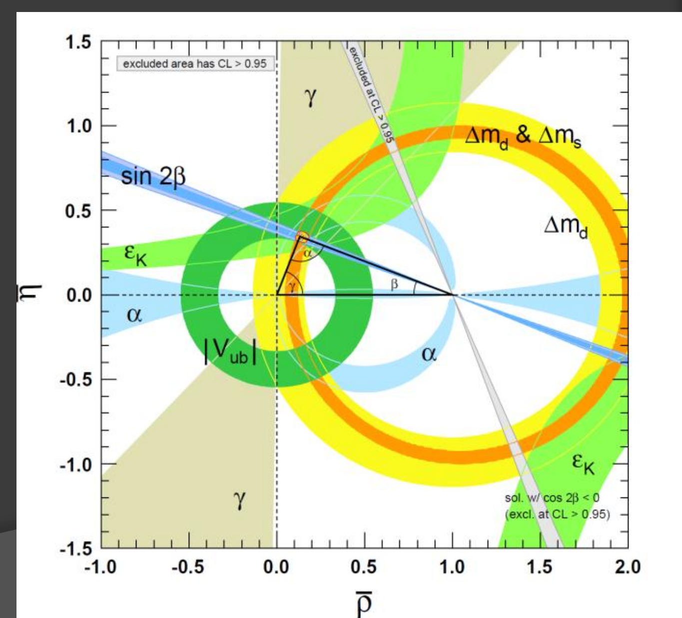
37 Amsterdam0411

Kaon Rare Decays & CKM



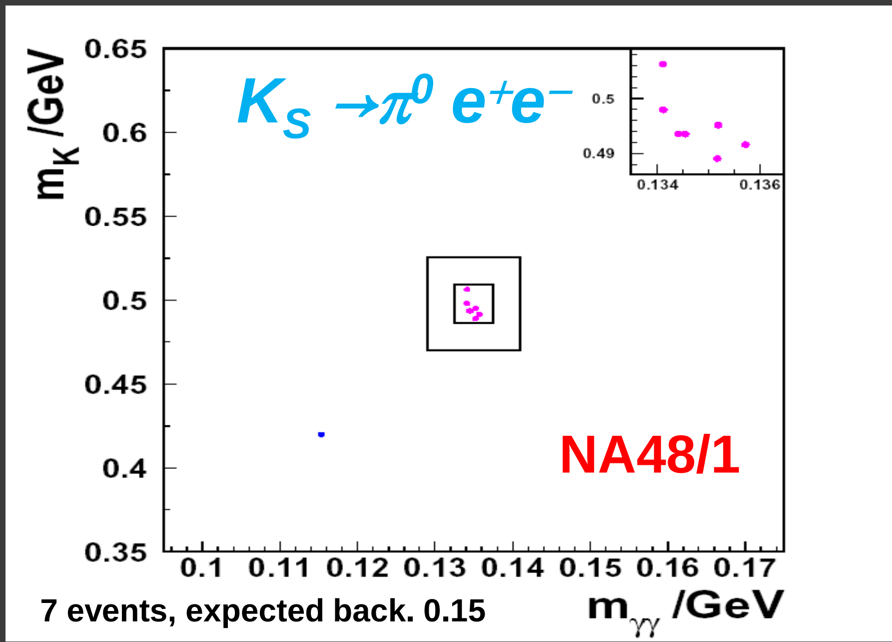
PDG 2012

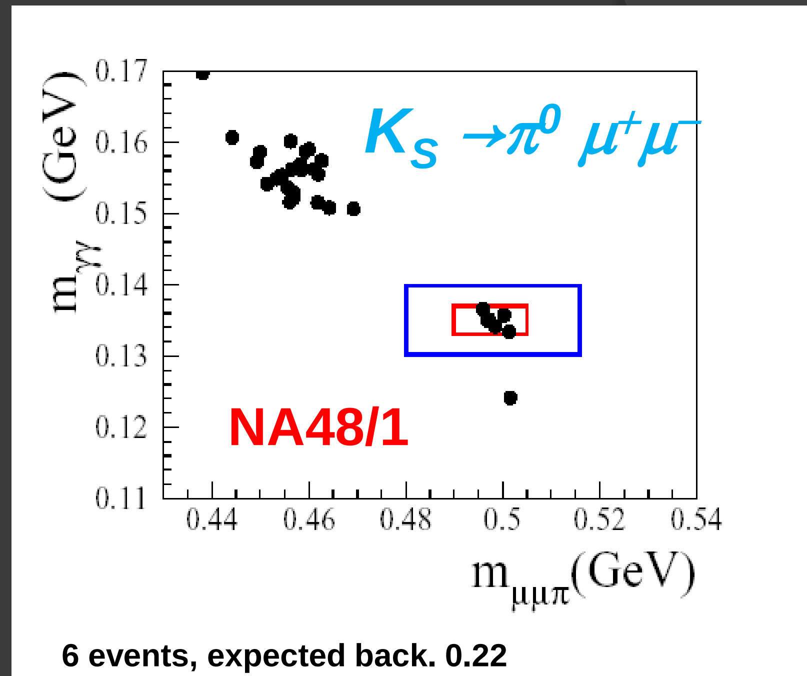




$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$$

NA48/1: $K^0_S \to \pi^0 e^+e^-$ and $K^0_S \to \pi^0 \mu^+\mu^-$





$BR(K_S \to \pi^0 ee) \times 10^{-9} =$
$5.8\,^{+2.8}_{-2.3}(stat) \pm 0.8(syst)$

PLB 576 (2003)

$BR(K_S \to \pi^0 \mu\mu) \times 10^{-9} =$
$2.9\,^{+1.4}_{-1.2}(stat) \pm 0.2(syst)$

PLB 599 (2004)

Blind analyses

Rare *K* Decays: Next Frontier

Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	0.85 ± 0.07 [1]	$1.73^{+1.15}_{-1.05}$ [2]
$K_L^0 \to \pi^0 \nu\bar{\nu}$	0.27 ± 0.04 [3]	< 260 (90% CL) [4]

[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
[2] AGS-E787/E949 PRL101, arXiv:0808.2459
[3] M. Gorbahn, arXiv:0909.2221
[4] KEK-E391a, arXiv:0911.4789v1

Remarkable stopped kaon experiment

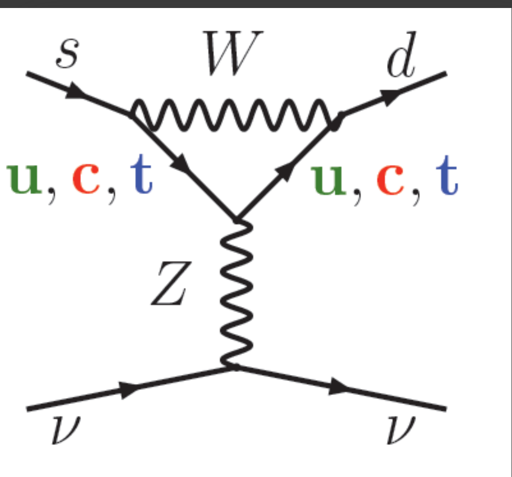
- Must bridge the existing gap between theory and experiment
- A measurement of BR($K^+ \to \pi^+ \nu \nu$) to 10 % determines V_{td} without input from Lattice QCD
- The strong suppression of the SM component ($<10^{-10}$) offers good sensitivity to NP

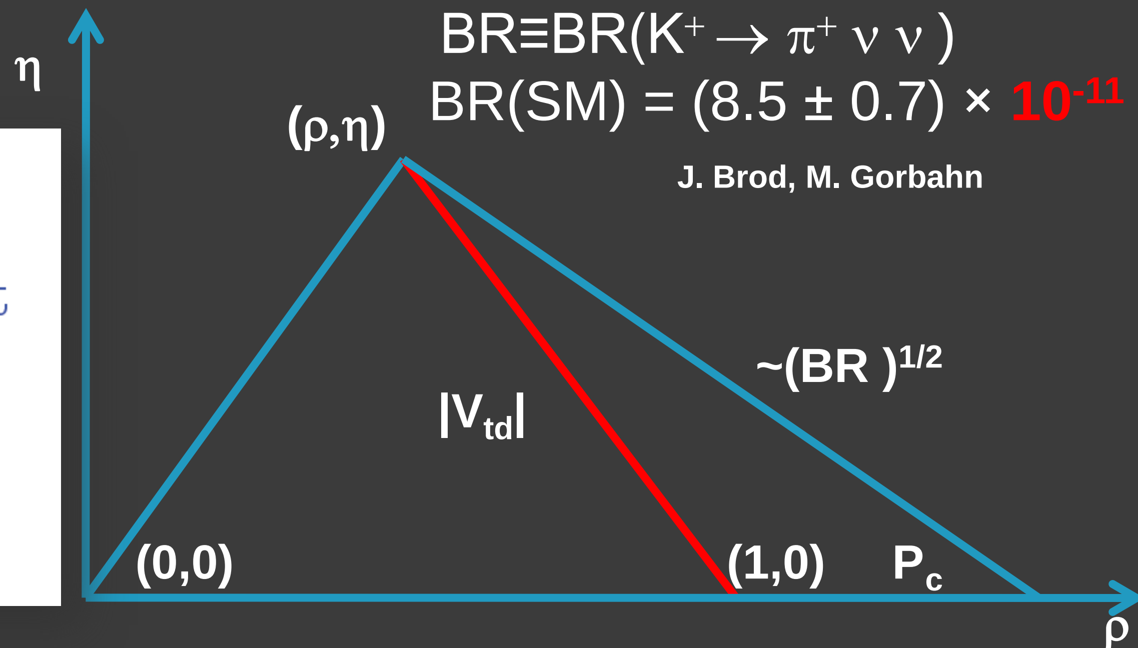
$K^+ \to \pi^+ \nu \bar{\nu}$ in SM

BR≡BR($K^+ \to \pi^+ \nu \bar{\nu}$)

BR(SM) = $(8.5 \pm 0.7) \times 10^{-11}$

J. Brod, M. Gorbahn





$\delta |V_{td}| / |V_{td}| \approx 0.4\, \delta P_c/P_c \oplus 0.7\, \delta BR/BR \oplus \delta |V_{cb}| / |V_{cb}|$

~2 % (mostly δm_c)

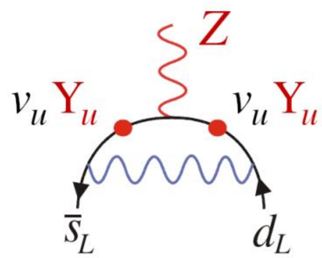
62 % BNL

7% aim of NA62 (2y)

3 %

Kaon Rare Decays and NP

C. The Z penguin (and its associated W box)



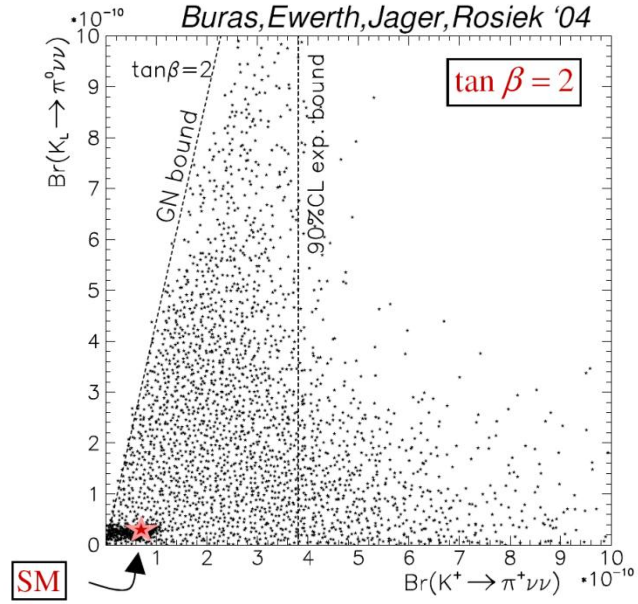
- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{*32} Y_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

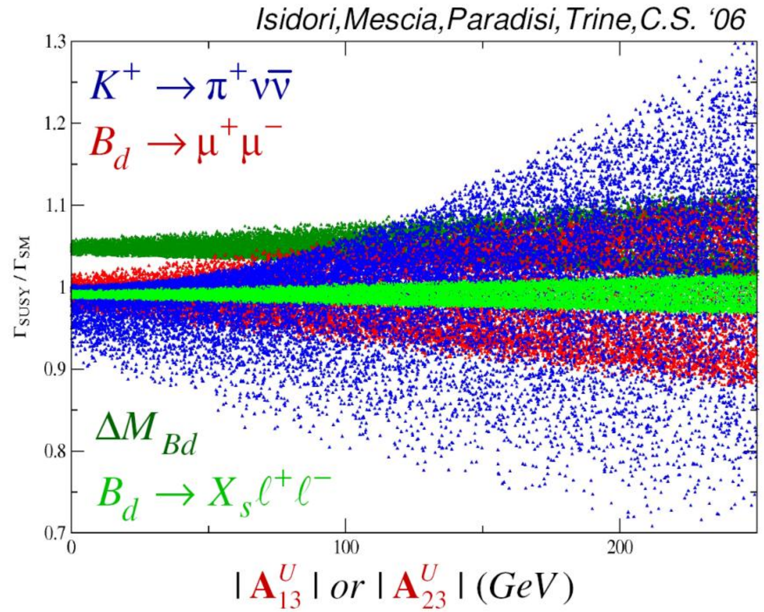
  $MSSM: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 \times O(1)$?

  $MFV: v_u^2 A_{\tilde{u}}^{*32} A_{\tilde{u}}^{31} \sim m_t^2 V_{ts}^* V_{td} \left|A_0 a_2^* - \cot\beta\mu\right|^2$.

- Relatively slow decoupling (w.r.t. boxes or tree).

(courtesy by Christopher Smith)



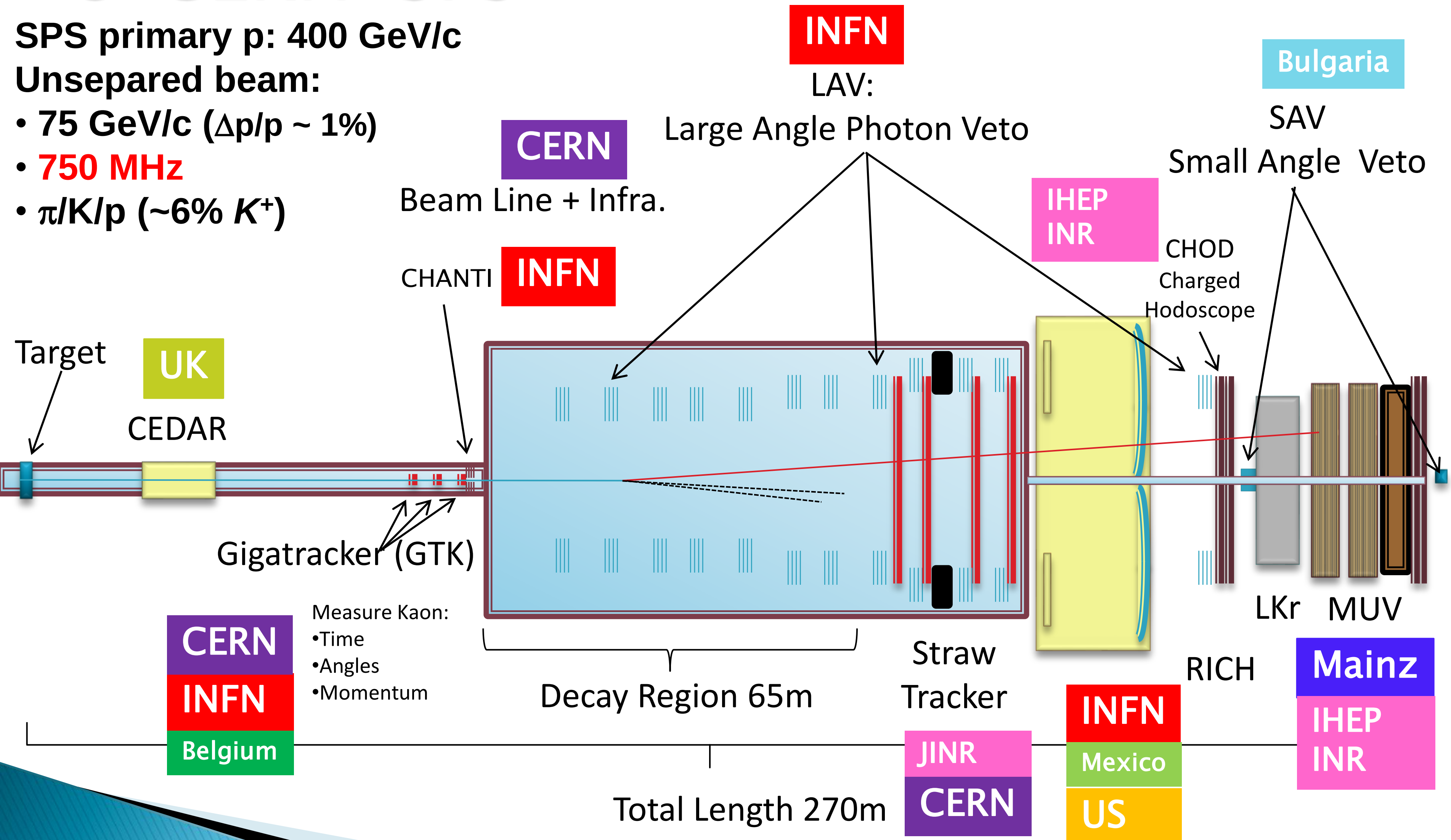


NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in–flight @ CERN–SPS

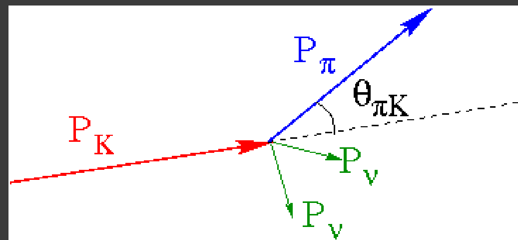
SPS primary p: 400 GeV/c

Unseparated beam:

- **75 GeV/c (Δp/p ~ 1%)**
- **750 MHz**
- **π/K/p (~6% K^+)**

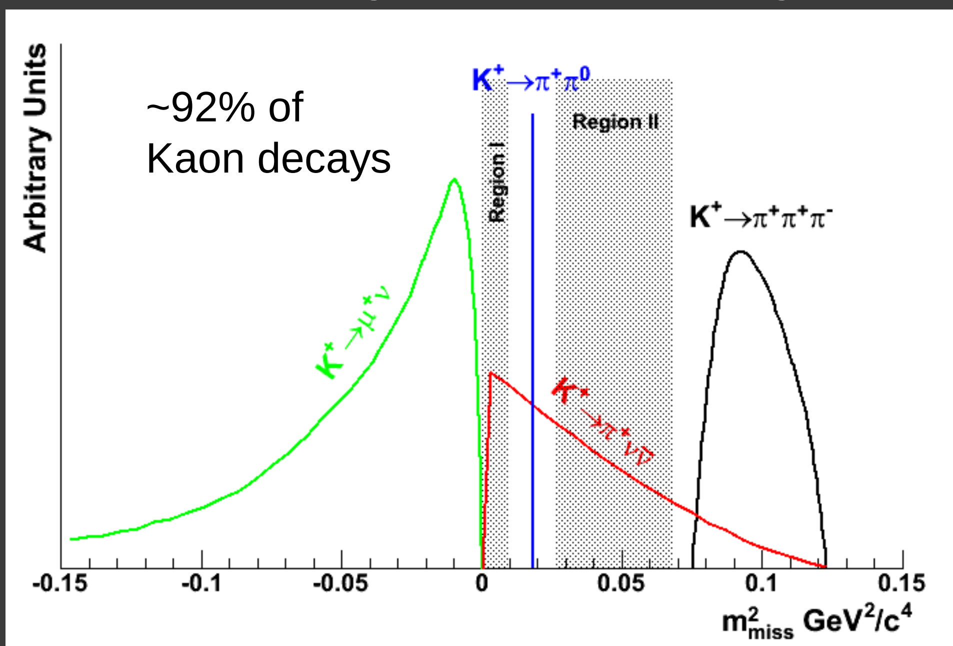


NA62 Technique: Decay in Flight

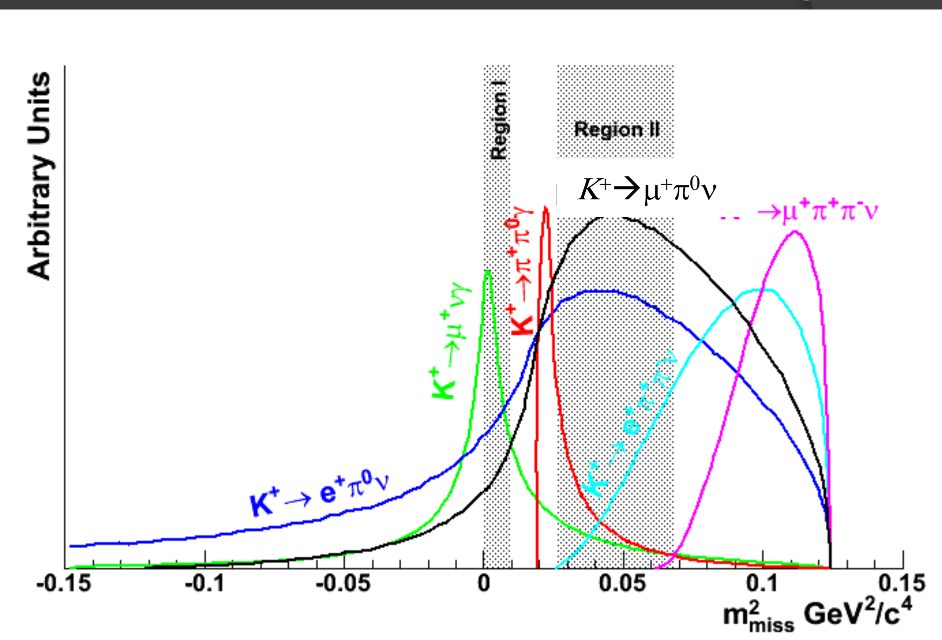


$$m^2_{miss} = (\tilde{p}_K - \tilde{p}_\pi)^2$$

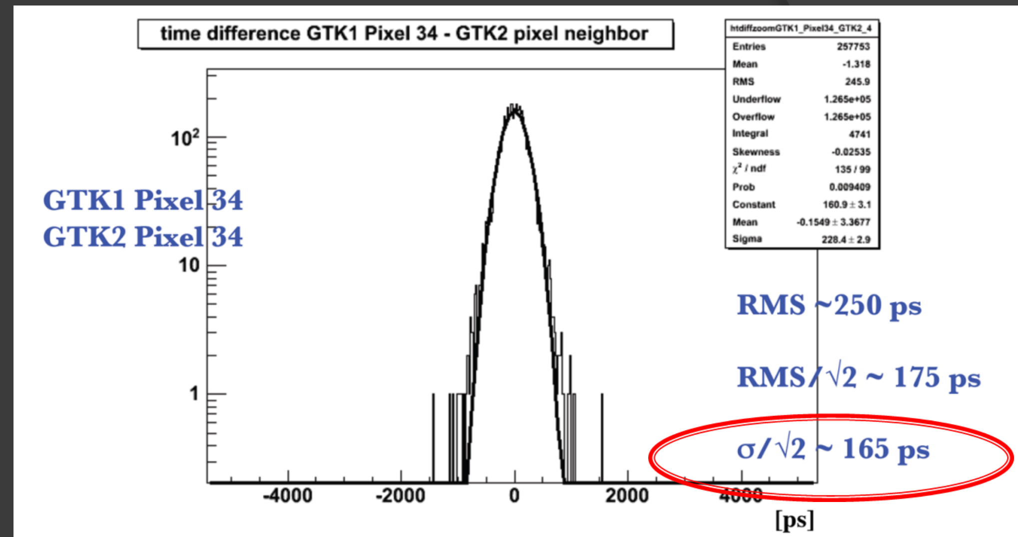
Kinematically Constraint Decays



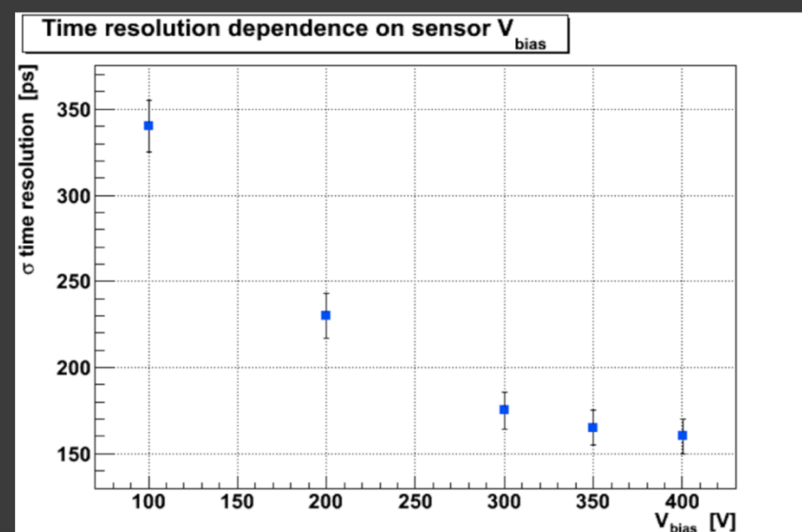
Unconstraint Decays



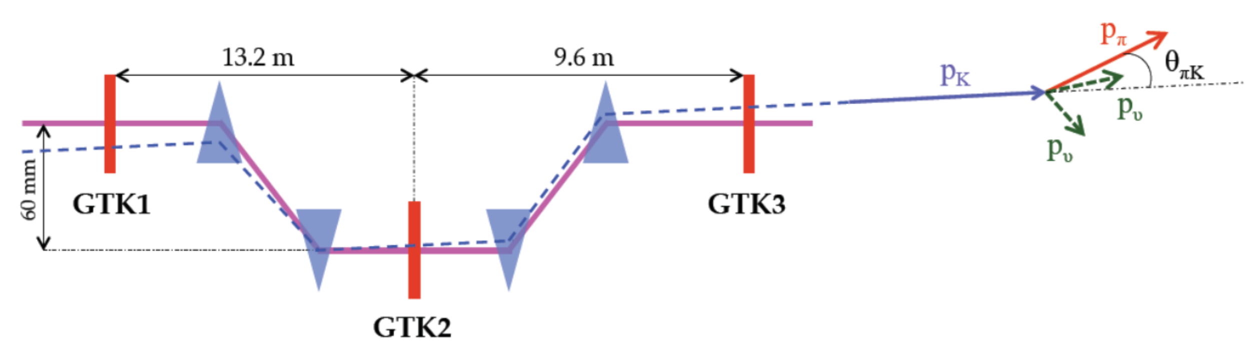
Gigatracker (GTK)

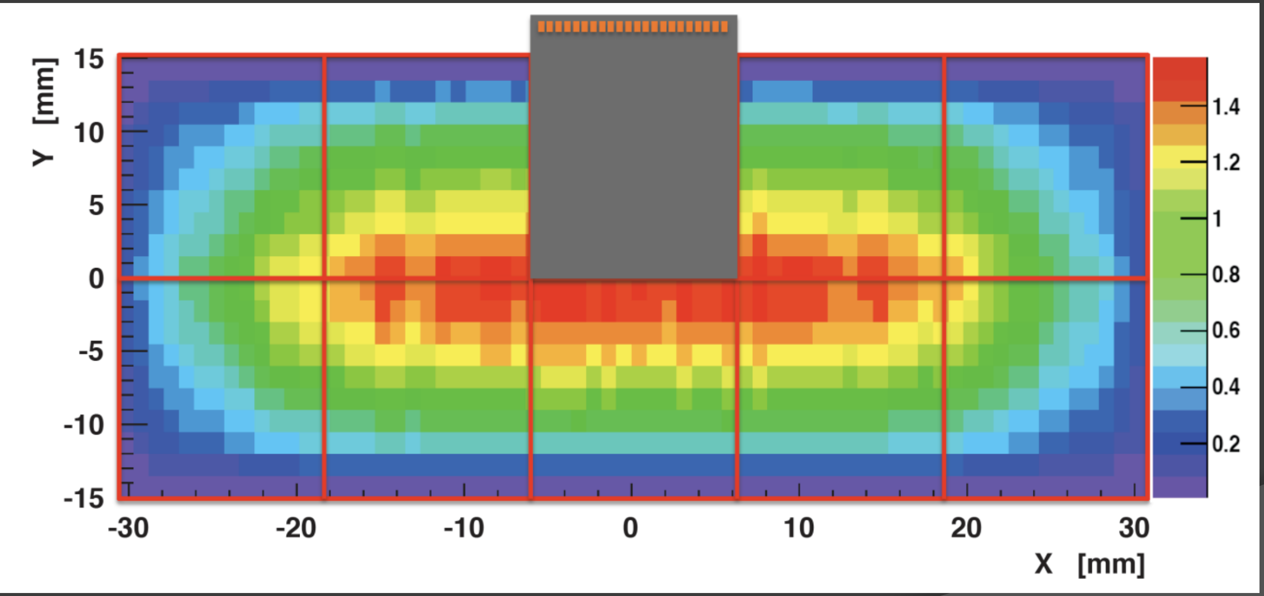


- Requirements:
  - Total rate: **~1 GHz /station** (hence the name!)
  - Time resolution:
    200 ps / station
  - Position resolution: pixel size 300 μm x 300 μm
  - Thickness : 0.5 % X_0 / station
  - Expected fluence: 2 x 10^{14} 1 MeV n_{eq} / year / cm^2
- Technology:
  - hybrid Si pixel
  - Flip-chip bonding
  - ASIC R/O chip 130 nm IBM CMOS with ToT front-end, DLL TDC
- Choice of sensor:
  - Planar Si 200 μm thick
  - Reverse Bias Voltage as high as possible (but at least 300 Volts)



GTK: Layout & Rate





MHz / mm ^{2}

NA62 Vetoes

- Photon vetoes to reject $K^+ \to \pi^+ \pi^0$

  P(K^+) = 75 GeV/c

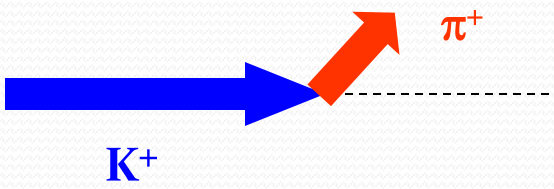
  Requiring P(π^+) < 35 GeV/c

  P(π^0) > 40 GeV/c → It can hardly be missed in the calorimeters

8 orders of magnitude π^0 suppression required

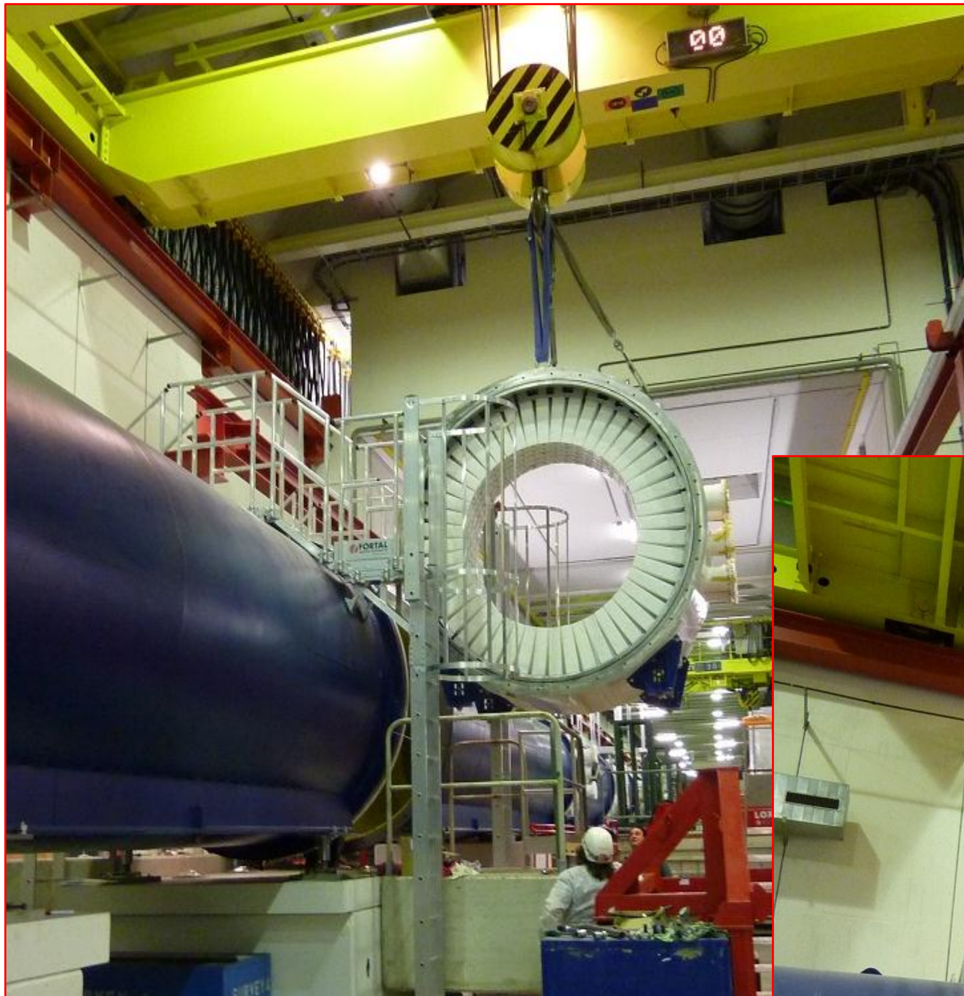
Signature:

- **Incoming high momentum K^+**
- **Outgoing low momentum π^+**



- Muon Veto to reject $K^+ \to \mu^+ \nu$

P326 NA62

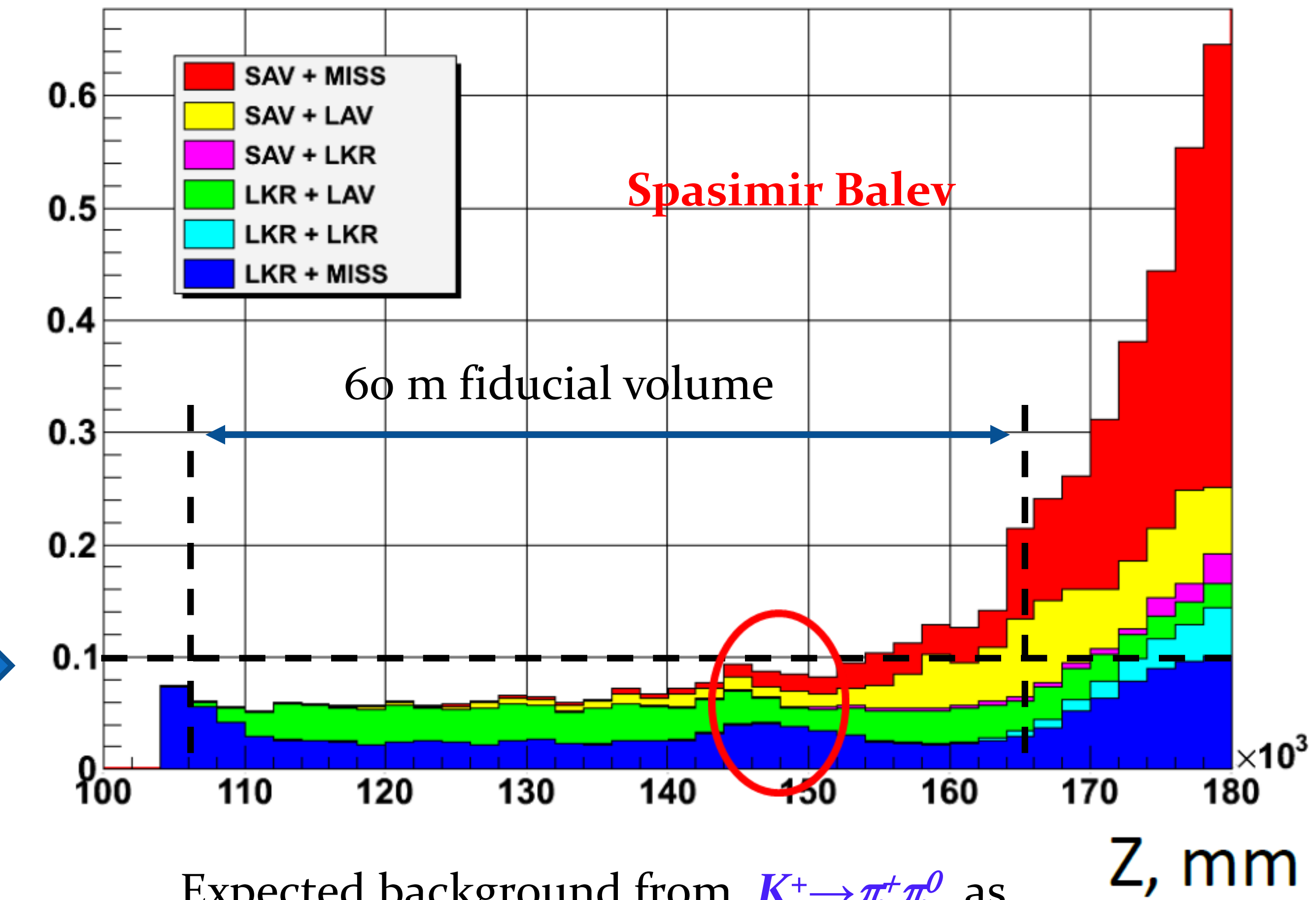


The NA62 A1-A8 LAV Stations all installed in ECN3

NA62 P326

NA62 photon vetoes: expected π^0 rejection ~ 5×10^{-8}

10%

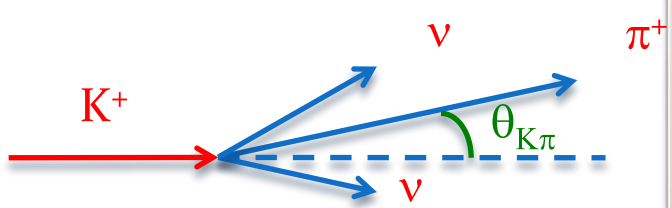


Expected background from $K^+\rightarrow\pi^+\pi^0$ as fraction of the $K^+\rightarrow\pi^+\nu\nu$ (SM) signal as a function of the kaon decay vertex

Straw Tracker in NA62

- There are two main performance requirements for secondary particles:

$$\frac{\Delta P}{P} \leq 1\%$$



$$\Delta\theta_{K\pi} \leq 60\ \mu rad$$

From this follow the main requirements on the straw detector:

◆ Spatial resolution ≤ 130 μm per coordinate and ≤ 80μm per space / point

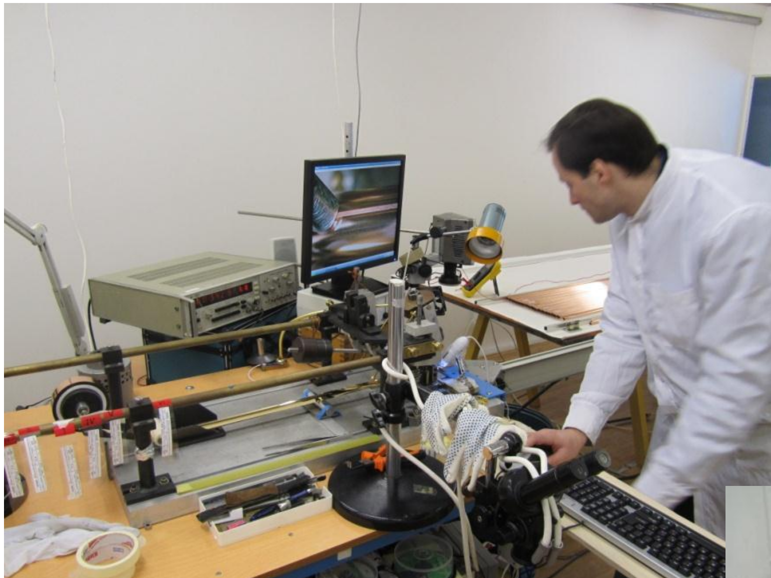
◆ ≤ 0.5% of a radiation length (X_o) for each chamber

◆ Installation inside the vacuum tank ($P < 10^{-5}$ mbar) with minimum gas load for the vacuum system *(~10^{-1} mbar* l/s)*

◆ For straws near the beam, operation in a high rate environment (up to 500kHz/Straw)

◆ Possible multiplicity veto for triggering

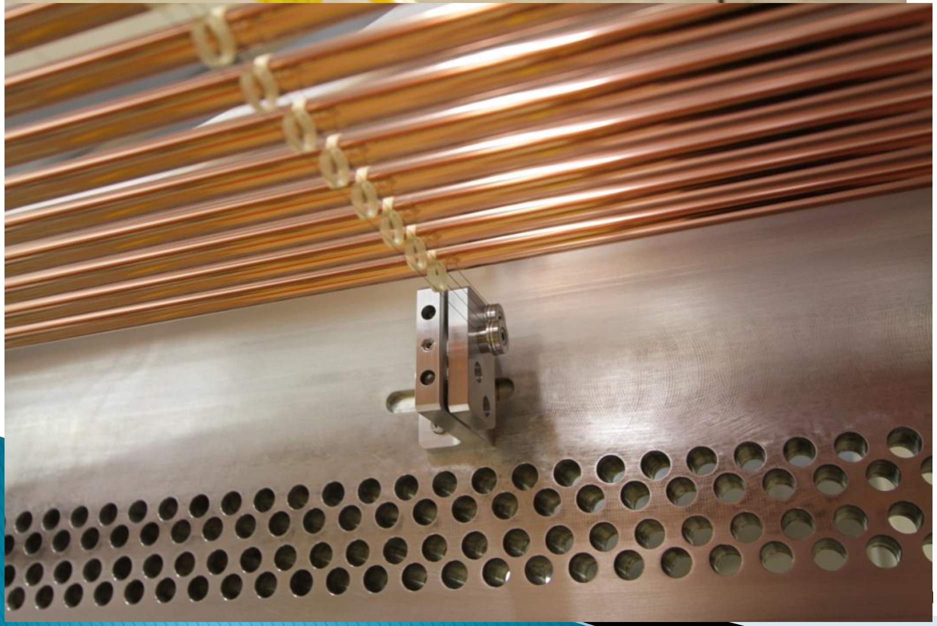
Straw production



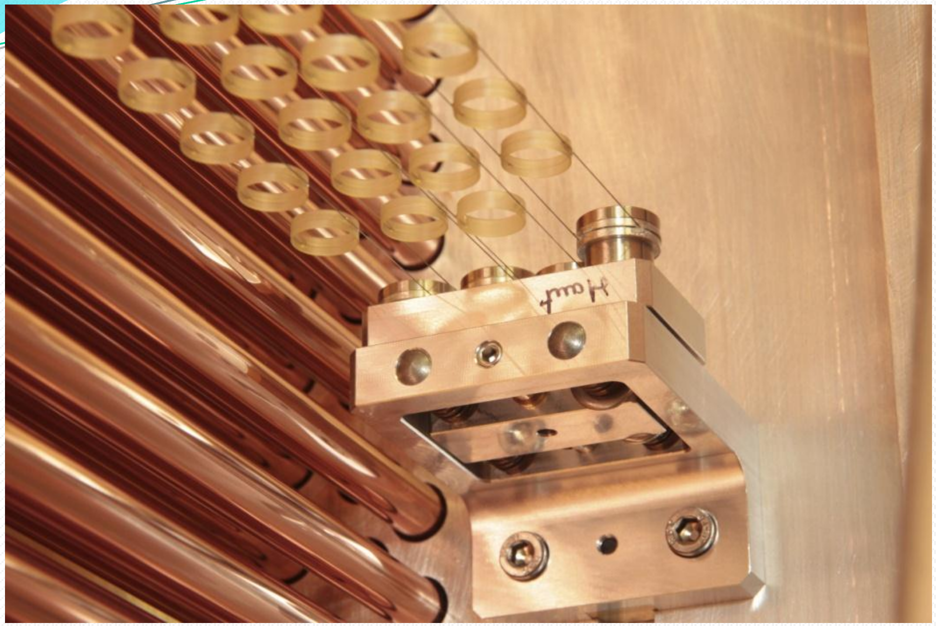
Straws are handled and transported under pressure

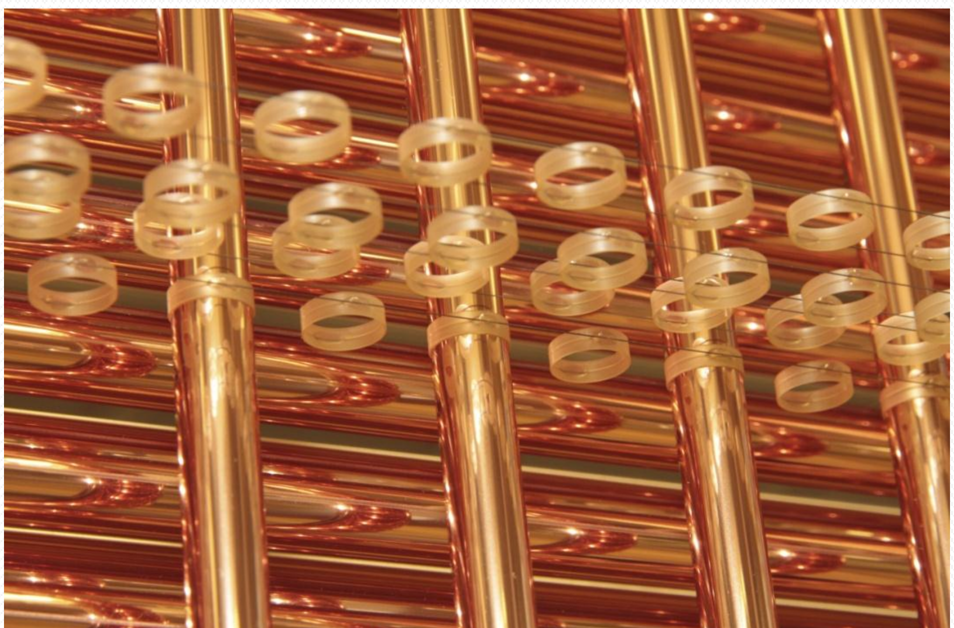
- PET 36 micron thick
- 9.9 mm diameter
- 50 nm copper
- 20 nm gold
- Ultrasound weld

Module assembly -straw insertion



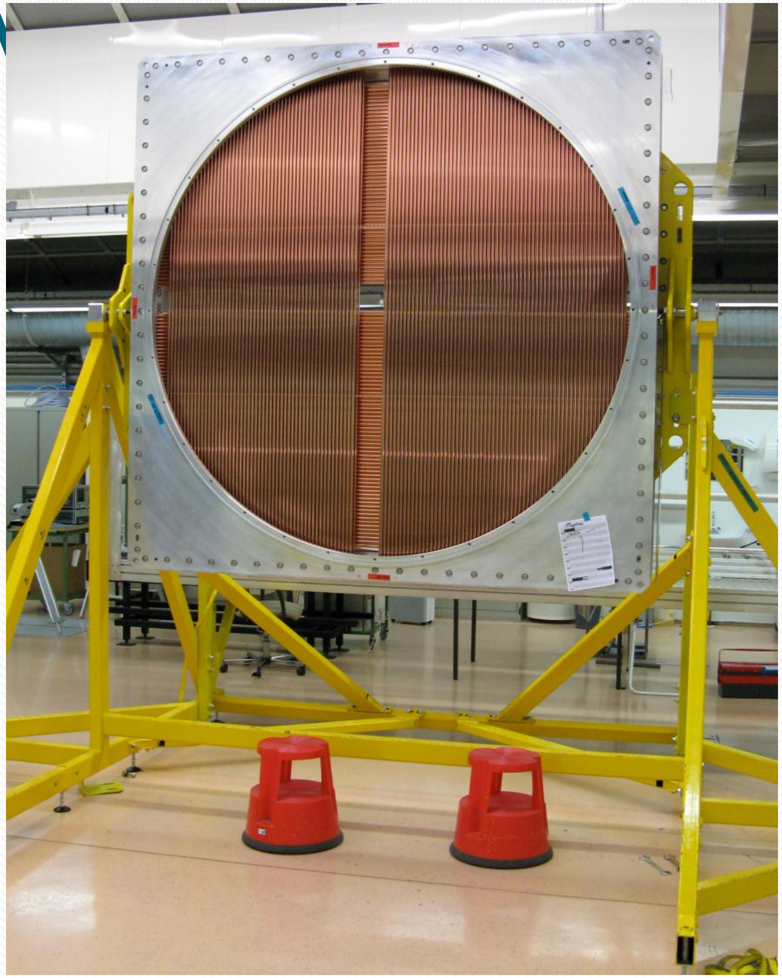
Spacers

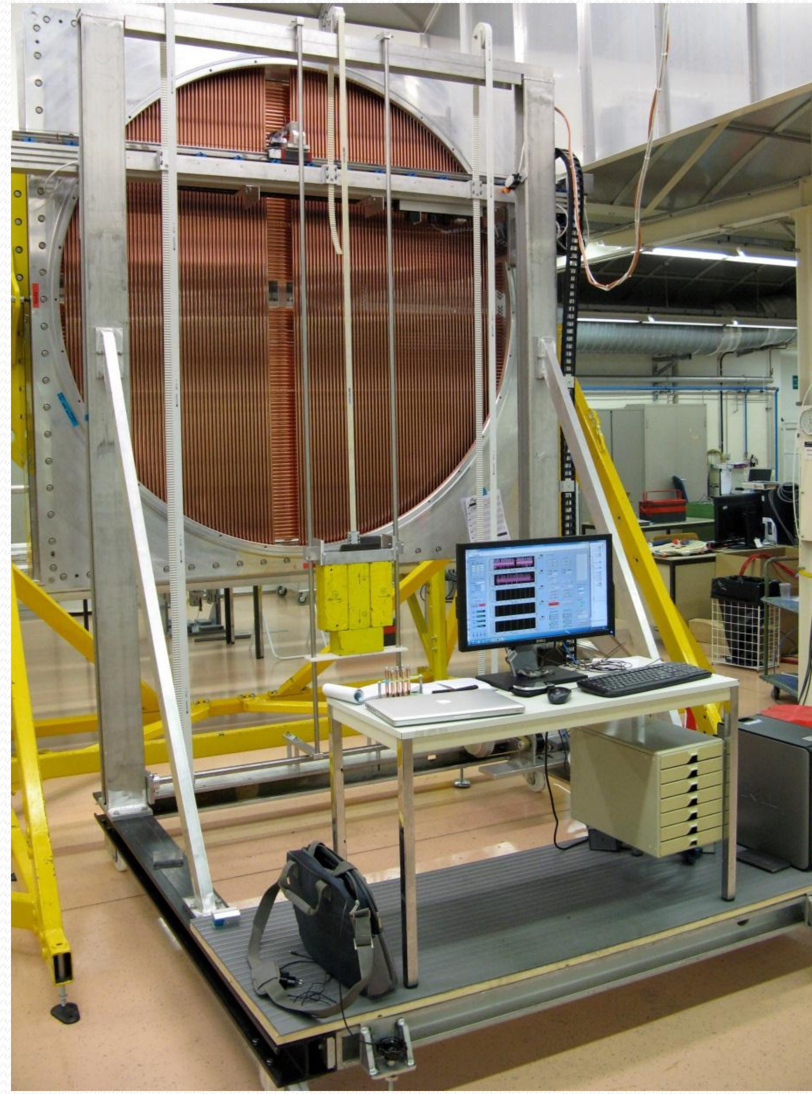




Straw Module

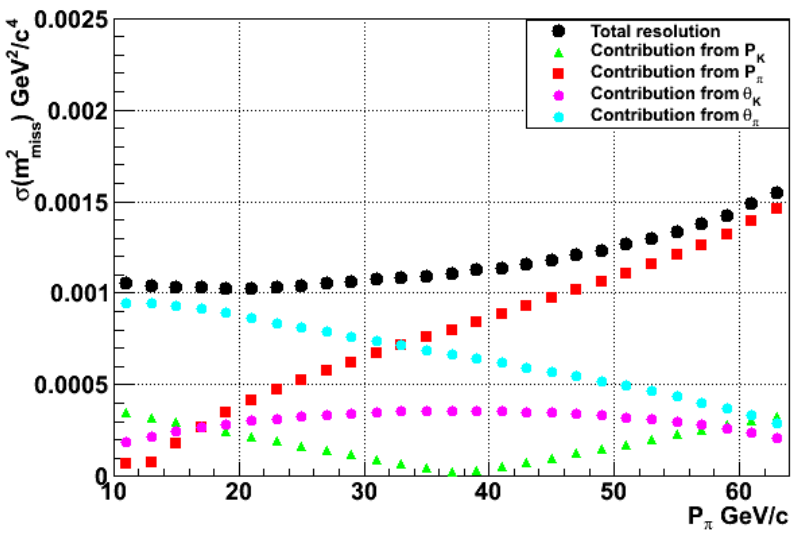
996 straws

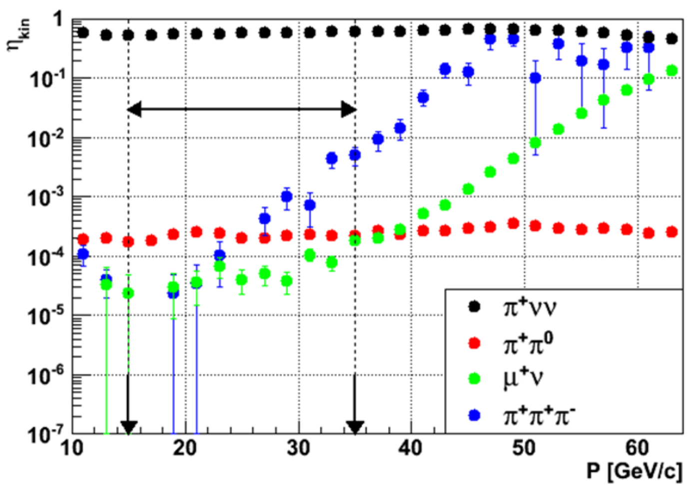




NA62 Spectrometer Reconstruction

Giuseppe Ruggiero





Missing Mass Resolution

Kinematic Rejection

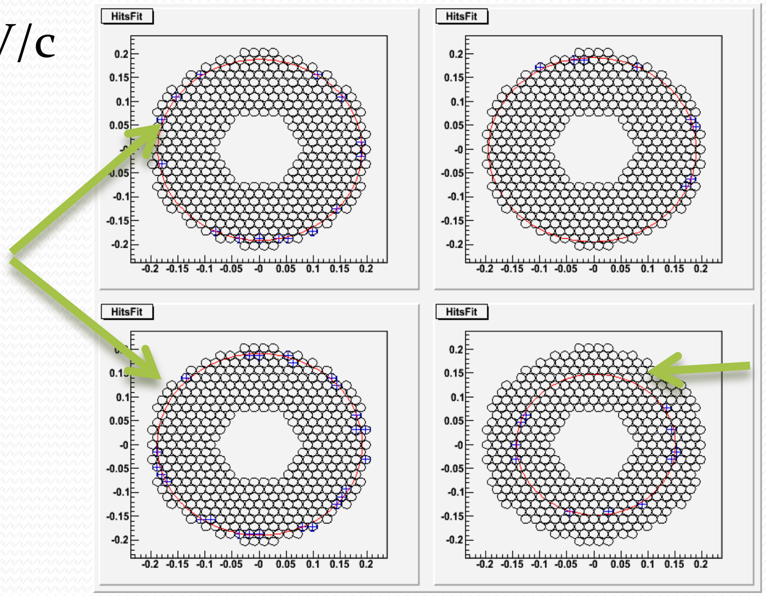
- The simulation includes:
- Multiple and Single large angle Coulomb scattering
- δ-rays
- Elastic and inelastic nuclear interactions
- Errors in the straw spectrometer pattern recognition

NA62 RICH

- $K_{\mu 2}$:largest BR: 63.4%
- Need ~10^{-12} rejection factor
- Kinematics (GTK +STRAW) : ~10^{-5}
- Muon Veto: ~10^{-5}
- Particle ID (RICH): ~10^{-2}

20 GeV/c

positrons

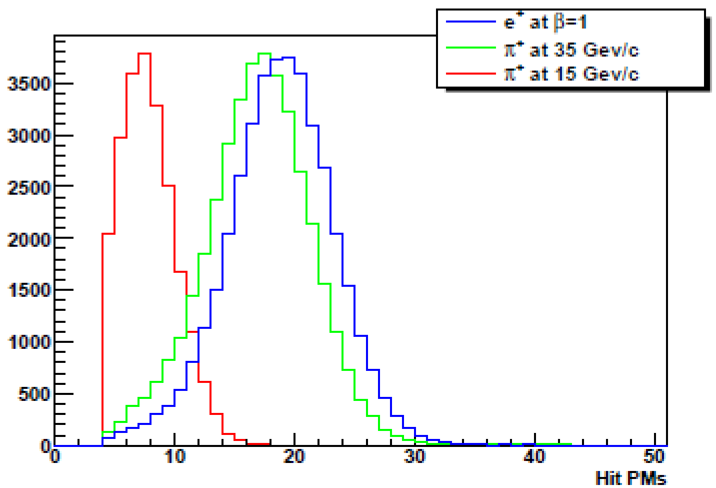


pion

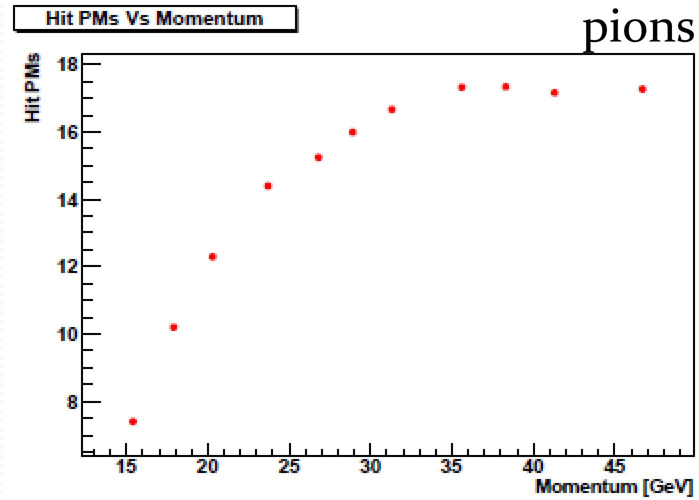
Rings in NA62 RICH prototype

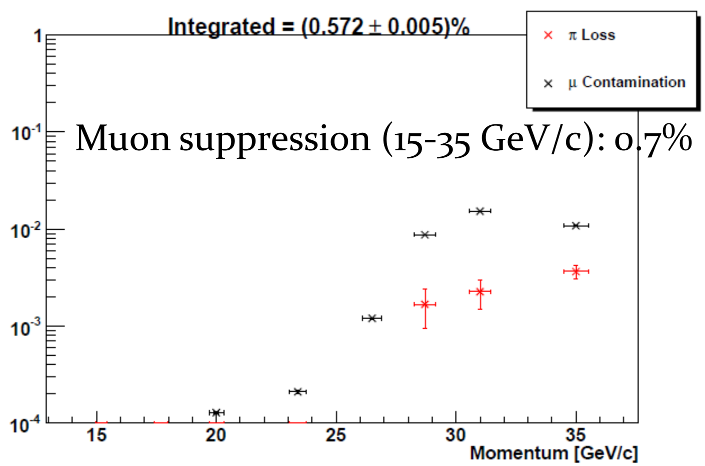
- Essential to match the pion track seen by the straw with track (kaon) seen by the beam spectrometer (rate: 800 MHz)
- To avoid a wrong match which spoils the kinematic suppression, the RICH must measure the pion time to 100 ps or better to connect to the kaon measured in the GTK
- Radiator: 17 m neon atmospheric pressure; spherical glass mirrors (17m focal length; ~ 2000 Hamamatsu PMT R7400U-03

RICH400: performance



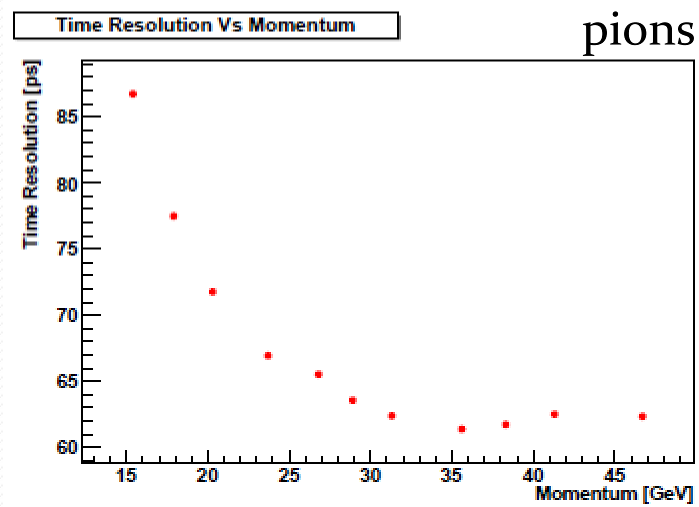
pions





Muon suppression (15-35 GeV/c): 0.7%

pions



B. Angelucci et al., NIM A621 (2010) 205-211

NA62 Sensitivity

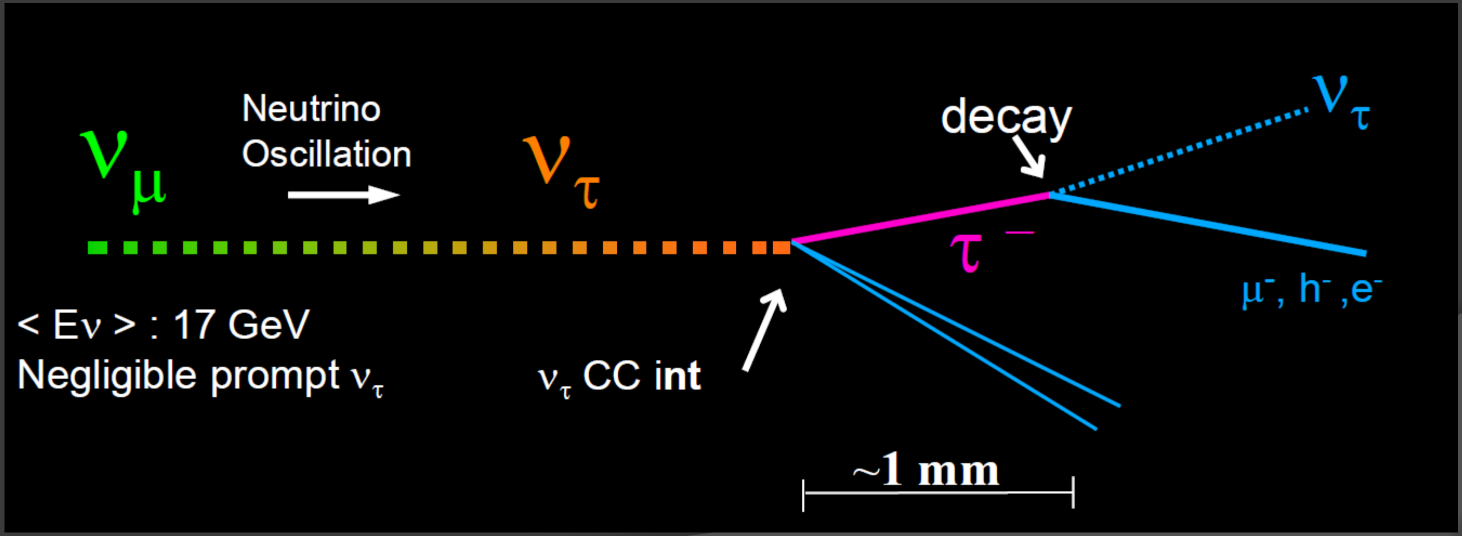
Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu\bar{\nu}$ *[flux = 4.8×10[12] decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ *[$\eta_{\pi 0}$ = 2×10[-8] (3.5×10[-8])]*	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+(\mu^+)\ \pi^0 \nu$, others	negligible
Expected background	≤13.5% (≤17%)

The ORKA proposal at FNAL plans to extend significantly the sensitivity of the BNL stopped kaon technique (4th generation experiment), while the KOTO experiment at J-PARC addresses $K^0_L \to \pi^0 \nu \bar{\nu}$ with a pencil beam

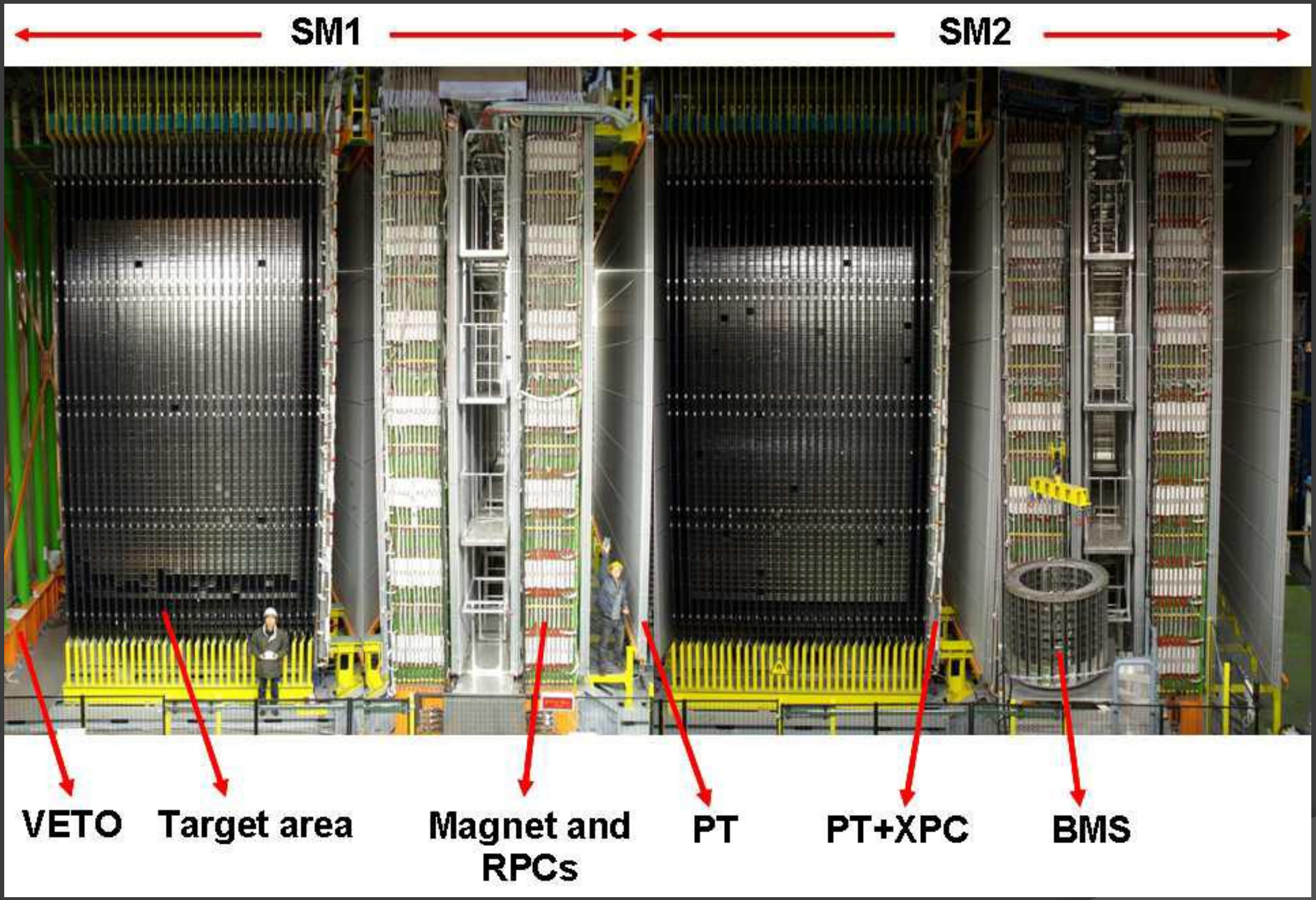
NEUTRINOS: CNGS1
OPERA

OPERA Experiment

- **Oscillation Project with Emulsion-tRacking Apparatus**
- Designed to make the first detection of neutrino oscillation in direct **appearance mode** through the study of $\nu_\mu \rightarrow \nu_\tau$.:
- OPERA is a hybrid detector consisting of emulsion/lead target complemented by electronic detectors
- It is placed in the high energy long-baseline CERN to LNGS beam (CNGS) 730 km away from the neutrino source
- The CNGS beam has enough energy to be above the τ threshold
- First ν_τ candidate event: Phys. Lett. B 691 (2010)



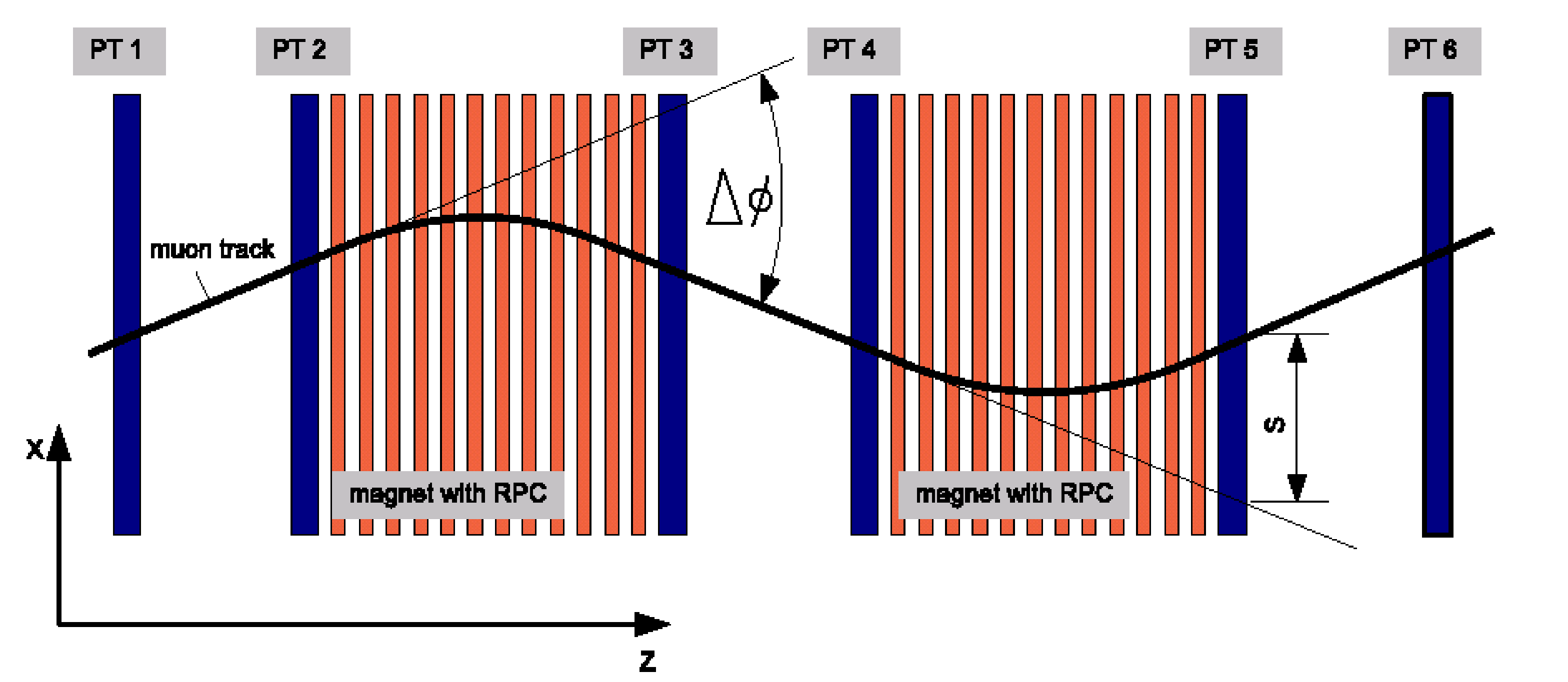
OPERA Detector



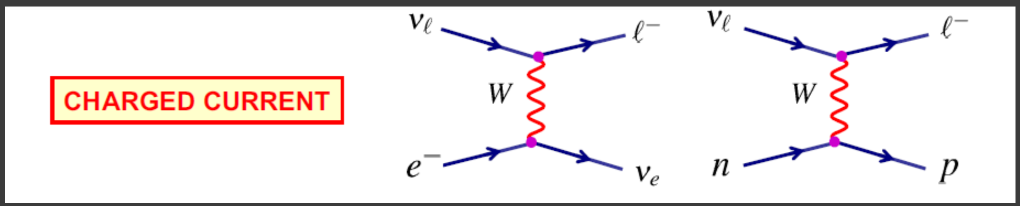
OPERA Muon Spectrometer

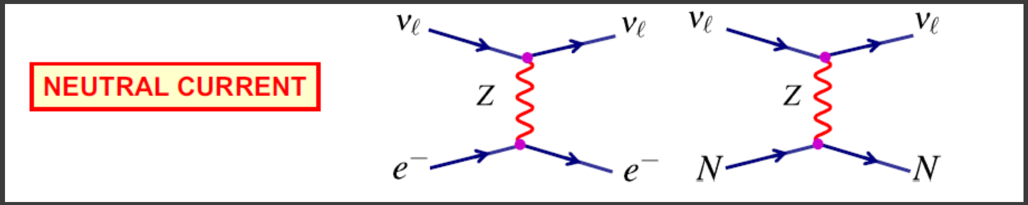
PT: Precision Tracker : drift tubes 8 x 8 m^2

Magnetised iron and RPC chambers

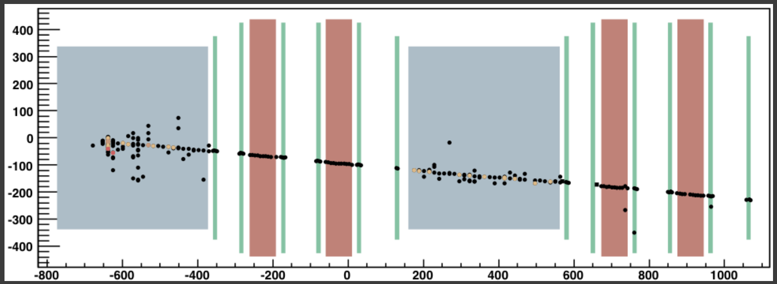


Neutrino interactions in OPERA

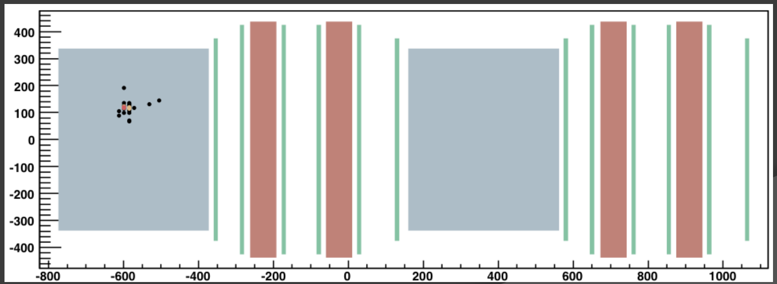




New J.Phys.13:053051,2011



Charged Current (CC) neutrino interaction



Neutral Current (NC) neutrino interaction

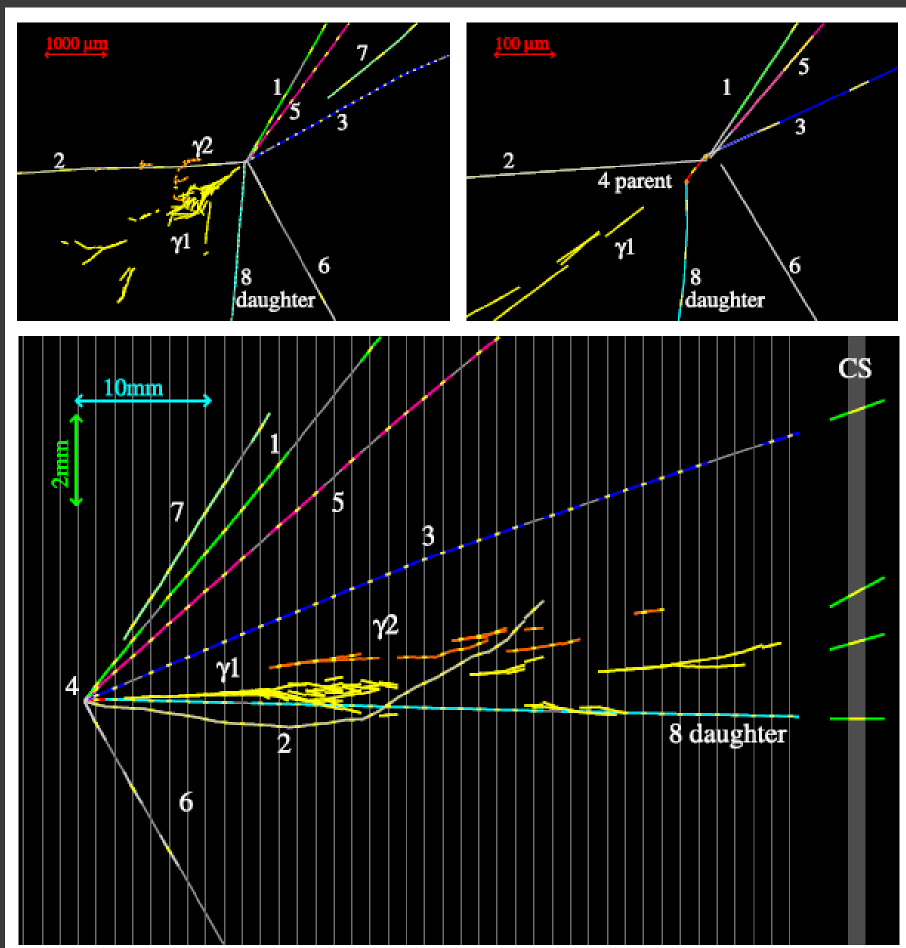
OPERA Emulsion Detector

Emulsion cloud chamber (ECC)
56 1mm thick lead plates
57 emulsion layers + changeable sheet

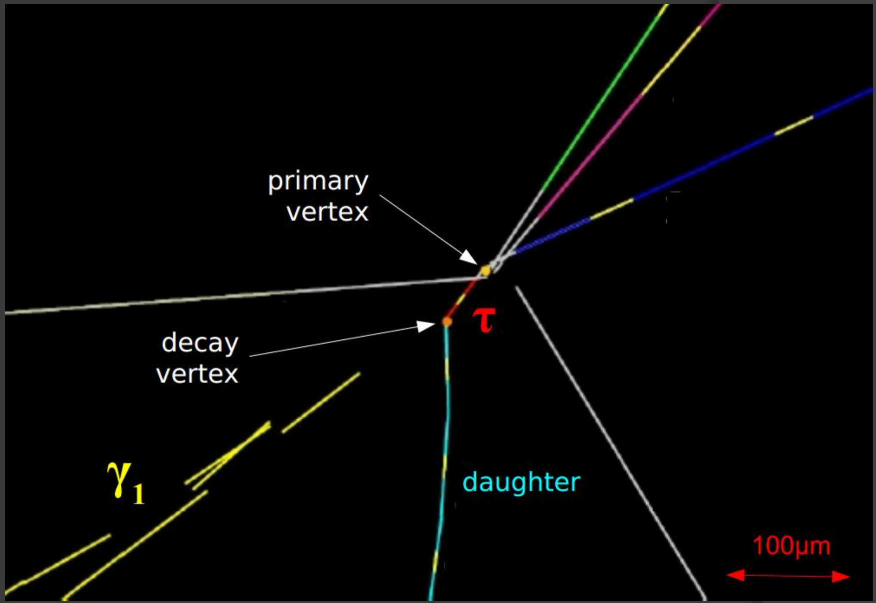
- Target: 2x625 tons of lead/emulsion
- Target Part: 31 walls (62 in total)
- 1 wall: brick wall + target tracker (TT)
- Automatic brick manipulation
- TT consists of horizontal and vertical strips with 2.6 x 2.6 cm^2 effective granularity
- TT provides a trigger for ν interactions

Brick piling station

Opera first τ Candidate

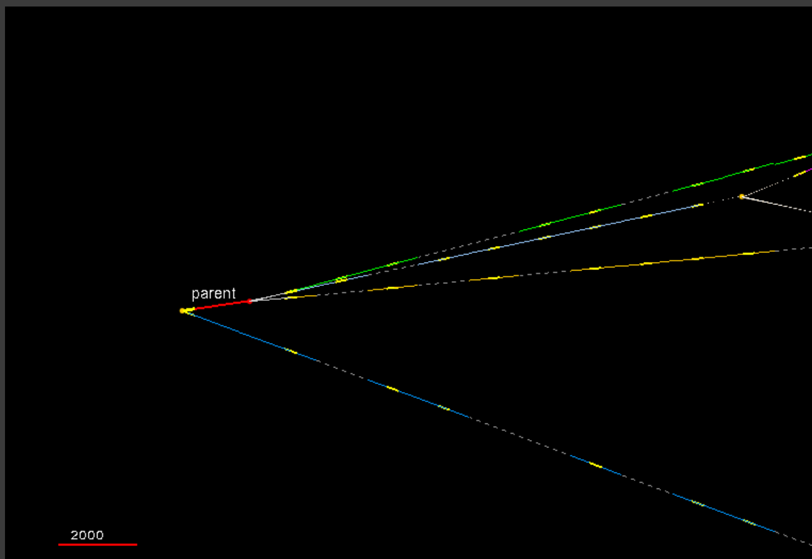


Phys. Lett. B 691 (2010)

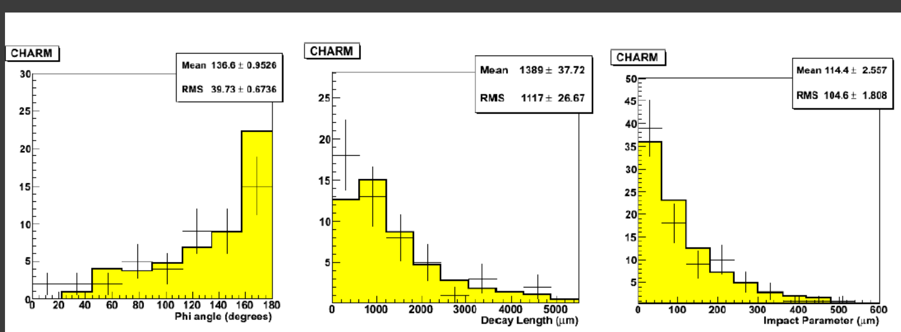


Variable	Cut-off	Value
Missing P_T at primary vertex (GeV/c)	<1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane (rad)	$> \pi/2$	3.01 ± 0.03
Kink angle (mrad)	>20	41 ± 2
Daughter momentum (GeV/c)	>2	12^{+6}_{-3}
Daughter P_T when γ-ray at the decay vertex (GeV/c)	>0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	<2 lead plates	1335 ± 35

Opera second τ Candidate



Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ Candidate Events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

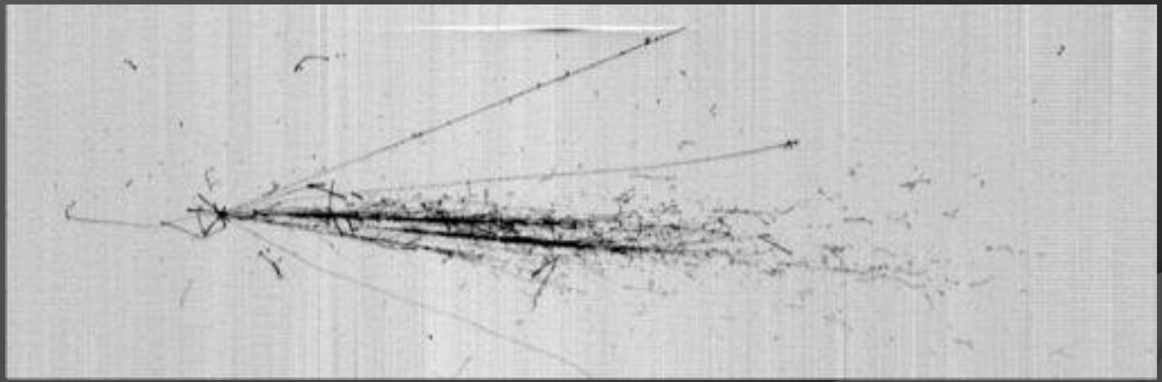


Phi angle Decay length Impact Parameter

Presented by M. Nakamura
@ Neutrino-2012, Kyoto

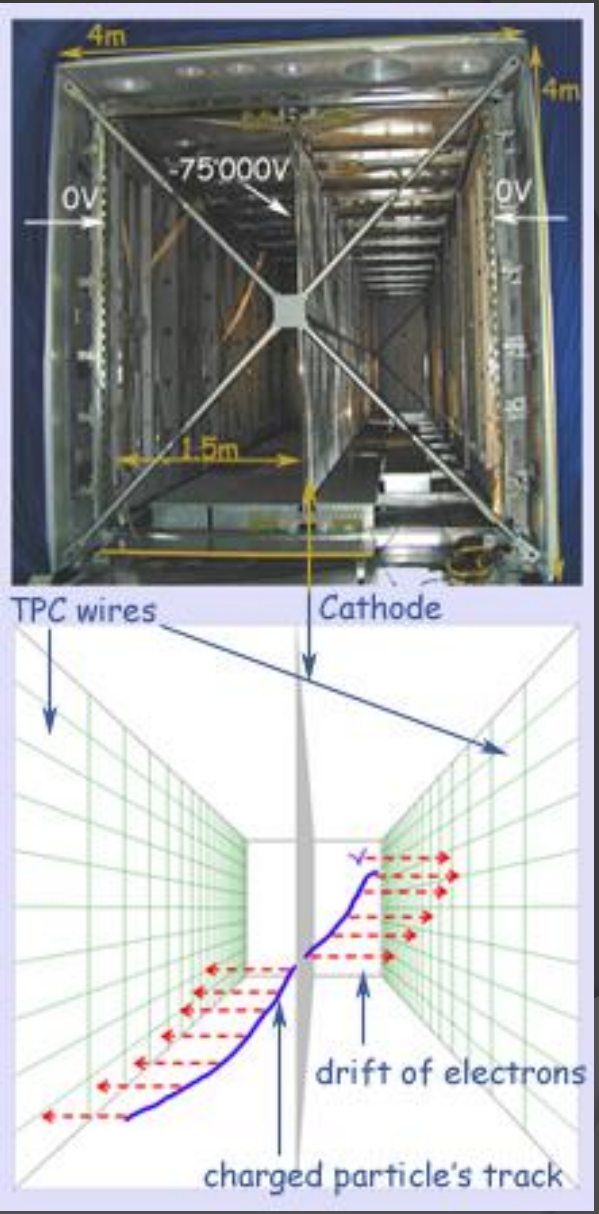
Charm Data/MC comparison

NEUTRINOS: CNGS2 ICARUS

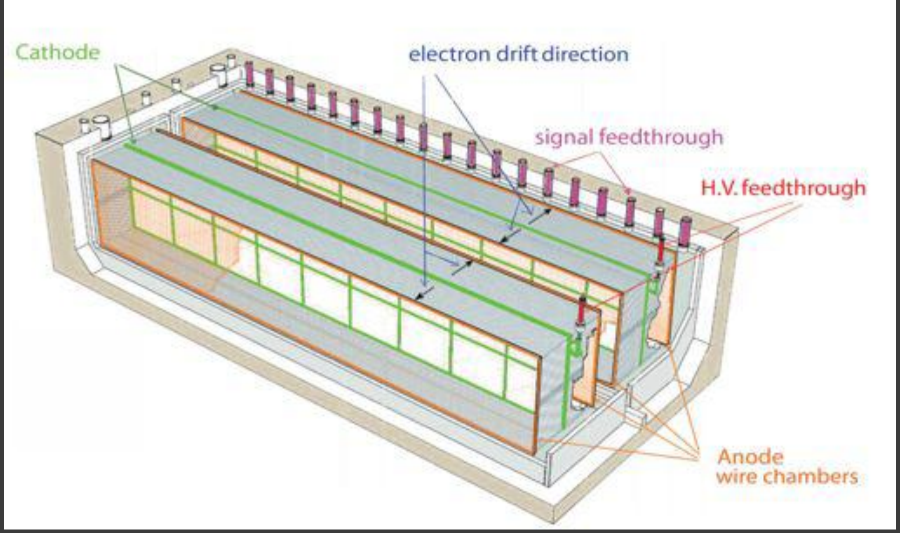


ICARUS Concept

- The Liquid Argon Time Projection Chamber: A New Concept For Neutrino Detector
C. Rubbia, CERN-EP/77-07 (1977)
- Innovative liquid argon time projection chamber, suitable for large volumes applications
- Spatial resolution comparable to that of bubble chambers bull fully electronic



ICARUS T600 Detector



Taking data in LNGS hall B

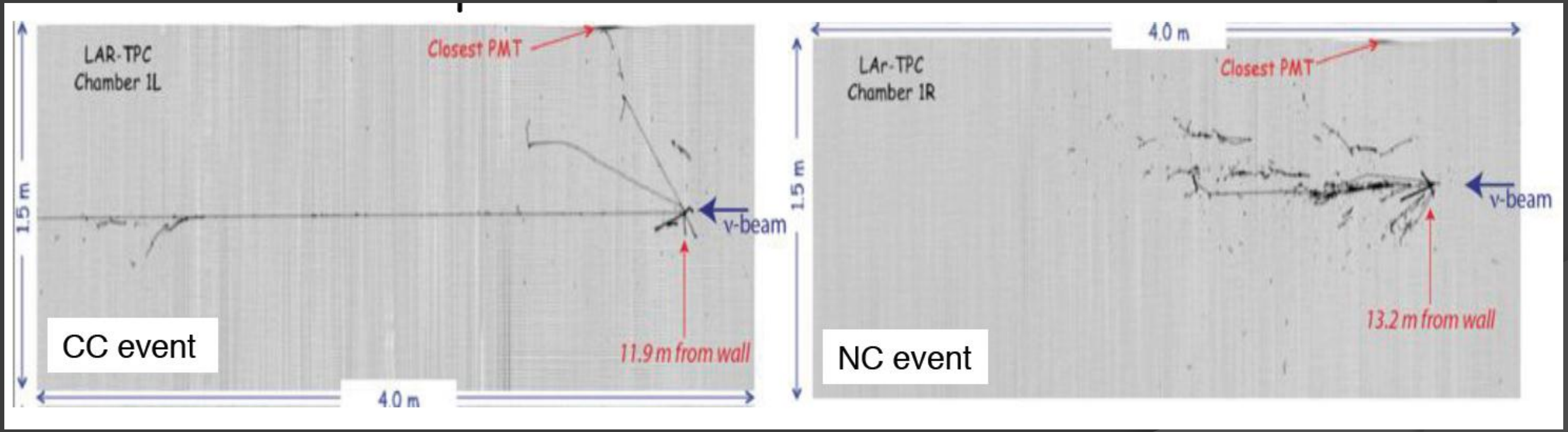
Two identical modules

- 3.6 x 3.9 x 19.6 ~ 275 m^3 each
- Liquid Ar active mass: ~ 476 t
- Drift length = 1.5 m (1 ms)
- HV = -75 kV E = 0.5 kV/cm
- v-drift = 1.55 mm/μs

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ~ 54000 wires, 3 mm pitch, 3!mm plane spacing
- 20+54 PMTs , 8” Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

ICARUS T600 physics potential

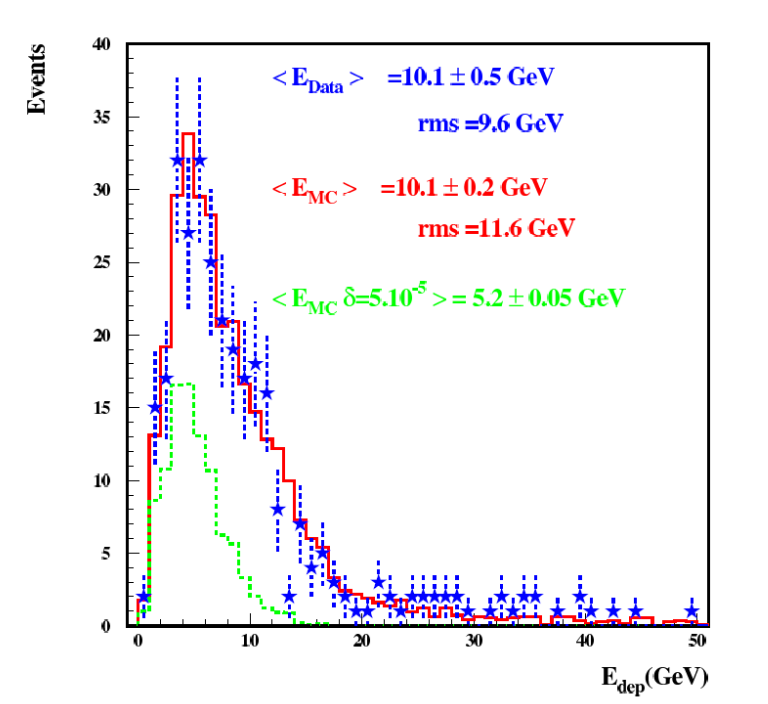
- For 10^{20} pot:
  - ~2800 CC events
  - ~900 NC events
  - $\nu_\mu \rightarrow \nu_\tau$
  - $\nu_\mu \rightarrow \nu_e$
  - Sterile neutrinos
  - …
- Self-triggered events
  - atmospheric ν CC interactions
  - Proton decay 3 10^{32} nucleons
  - …



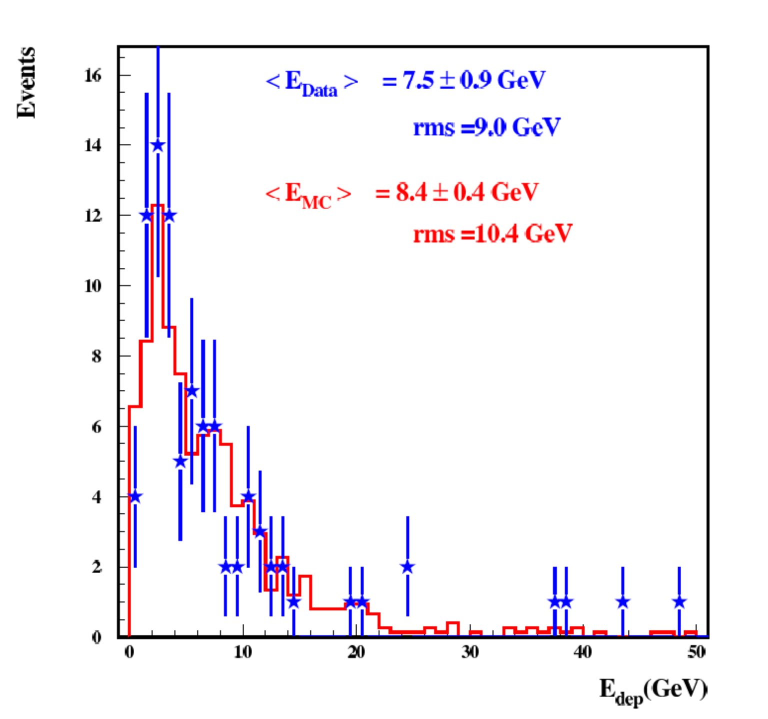
T600 is a milestone towards the realization of multikton Lar detectors

ICARUS Energy Reconstruction

M. Antonello et al. **Phys.Lett. B711 (2012) 270-275**
e-Print: **arXiv:1110.3763 [hep-ex]**

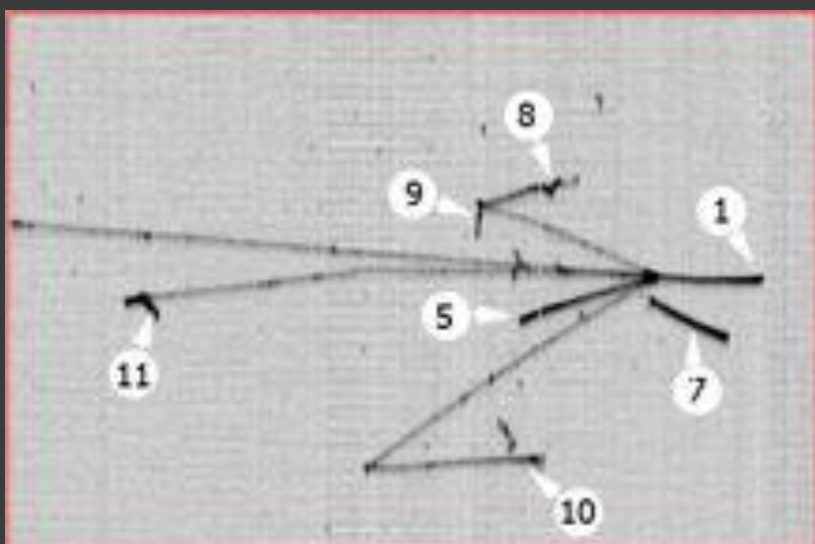


Deposited energy spectrum
For Charged Current (CC)
neutrino Interactions



Deposited energy spectrum
For Neutral Current (NC)
neutrino Interactions

ICARUS: Electronic Bubble Chamber



Shown at NEUTRINO-2012
In Kyoto by F. Pietropaolo

Track	E_{dep} [MeV]	range [cm]
1(p)	185±16	15
5(p)	192±16	20
7(p)	142±12	17
8(π)	94±8	12
9(p)	26±2	4
10(p)	141±12	23
11(p)	123±10	6

Flavour & Neutrinos at SPS: Summary

- Possible longer term evolution of this of the CERN programme:
  - Flavour: test the SM relation

$$(\sin 2\beta)_{K\to\pi\nu\bar{\nu}} = (\sin 2\beta)_{B\to J/\psi K_s}$$

    by studying very rare decays of both charged and neutral kaons
  - Neutrinos:
    - Long baseline experiments to address the neutrino mass hierarchy and CP violation in the leptonic sector
    - Short baseline experiments (e.g. P347) to clarify the situation of sterile neutrinos

Acknowledgements

- I have adapted material taken from the presentations of many of my colleagues in NA48/NA62 and public presentations made by the OPERA and ICARUS Collaborations
- These Collaborations deserve the credit
- I hope I succeeded to entice interest for the research programme that can be performed at the SPS
- The SPS is not just an injector: it has a unique physics programme with kaons, neutrinos, muons, ions and hadron beams
- I think that the overall CERN scientific programme is worth more than the sum of its single parts
- Thank you