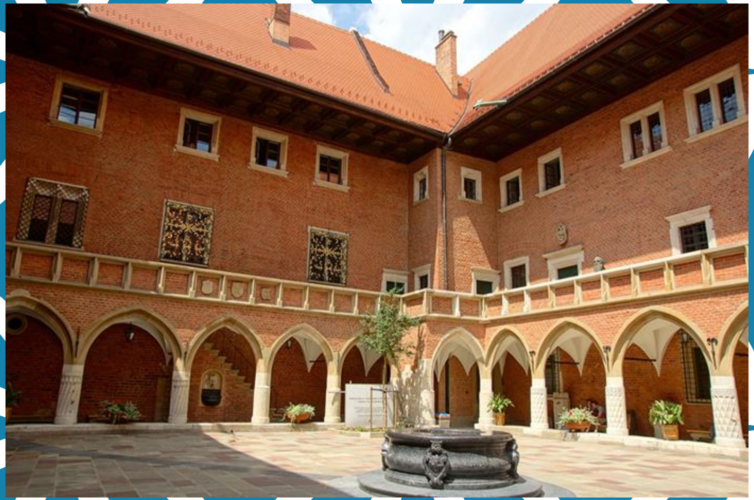


UNIVERSITAS IAGELLONICA CRACOVIENSIS

Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

June 7th - 13th, 2015

Kraków, Poland

DIRECT CP-VIOLATION AND RARE *K* DECAY PERSPECTIVES

Augusto Ceccucci / CERN

SETTING THE SCENE

Quark mixing and CP-Violation has been a very active area of investigation over the past decades

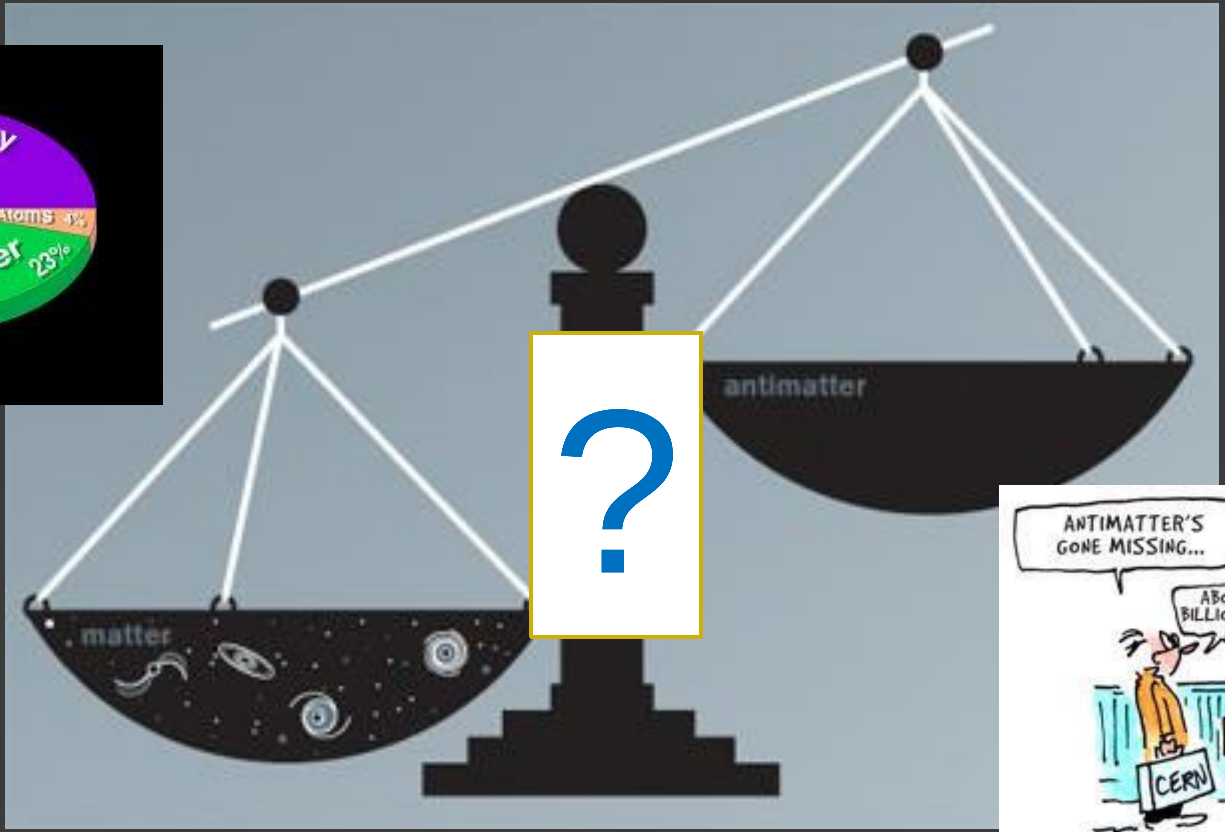
Owing to the last round of experiments in K and B mesons, our understanding is now completely compatible with the existence of "just" one phase in the Cabibbo-Kobayashi-Maskawa mixing matrix

The precision of the tests in the quark sector is improving thanks to the interplay of theory and experiments

Flavour transitions are so sensitive to short distance mechanisms that we need to press for quantitative tests of the Standard Model (SM)

Since the "directly" accessible energy frontier is limited (LHC for now) it is important to try explore the "zepto-universe", $O(10^{-21}$ m) "indirectly"

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

Types of CP-Violation

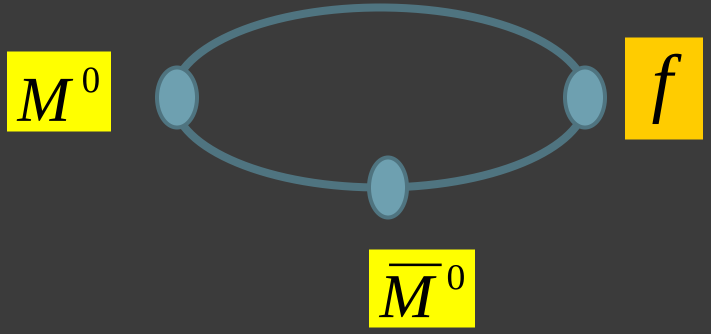
$$|M_L\rangle \propto p|M^0\rangle + q|\overline{M}^0\rangle$$
$$|M_H\rangle \propto p|M^0\rangle - q|\overline{M}^0\rangle$$

$\Delta F = 2$

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

$\Delta F = 1$

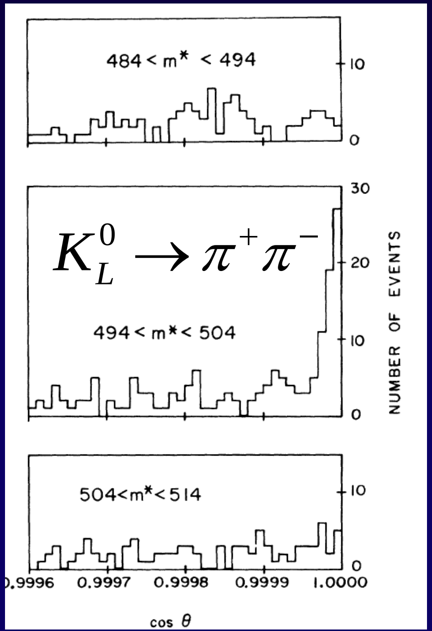
1. CP Violation in mixing $|q/p| \neq 1$ (indirect)
2. CP Violation in decays $|\overline{A}_{\bar{f}} / A_f| \neq 1$ (direct)
3. CP Violation in the interference



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

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

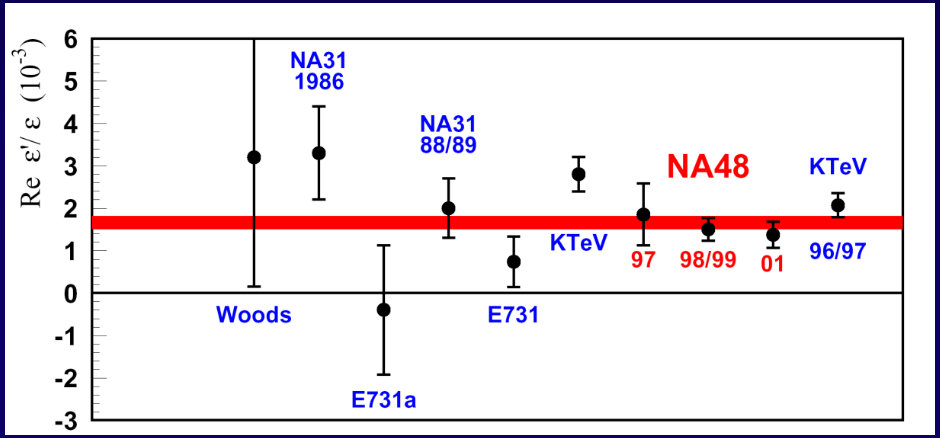
CP Violation



V.L.Fitch R.Turlay
J.W.Cronin J.H.Christenson
Phys. Rev. Lett. 13 (1964) 138.

Mixing

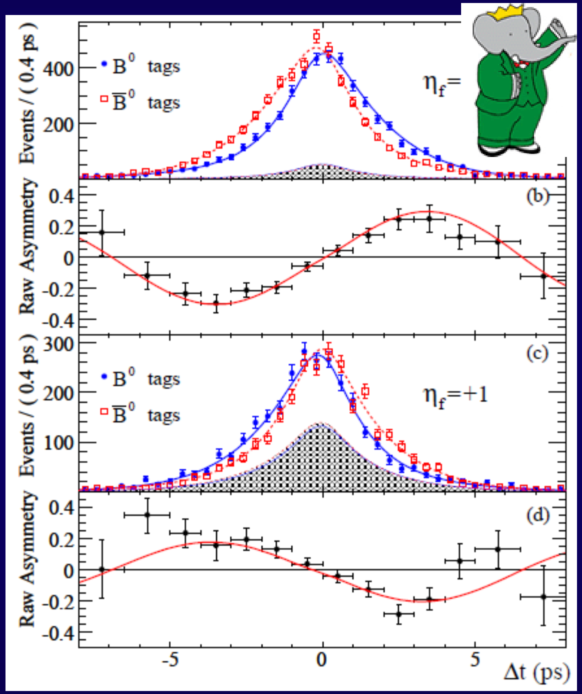
Re $\varepsilon'/\varepsilon = (1.68 \pm 0.14) \times 10^{-3}$



$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} \sim (5.5 \pm 0.5) \times 10^{-6}$$

Decay

BaBar + Belle:
sin 2 β =0.672 +/- 0.023



Interference

Quark masses and mixing

- The masses and mixings of quarks have a common origin in the standard model (SM): they arise from the Yukawa interactions with the Higgs condensate

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\,d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.}$$

- When ϕ acquires a VEV we get the masses of the quarks
- The diagonalization yields the physical states. As a result the charged currents couples to the physical quarks as:

$$\frac{-g}{\sqrt{2}}\left(\overline{u_L}, \overline{c_L}, \overline{t_L}\right)\gamma^\mu\, W^+_\mu\, V_{\text{CKM}}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.},$$

- V_{CKM} is a 3 x 3 complex matrix know as the Cabibbo, Kobayashi, Maskawa matrix

Cabibbo-Kobayashi-Maskawa (CKM) Quark Mixing

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

If V is unitary:

nxn real parameter
2n-1 unphysical pahses
n(n-1)/2 rotation angles
(n-1)(n-2)/2 complex phases

PDG 2014

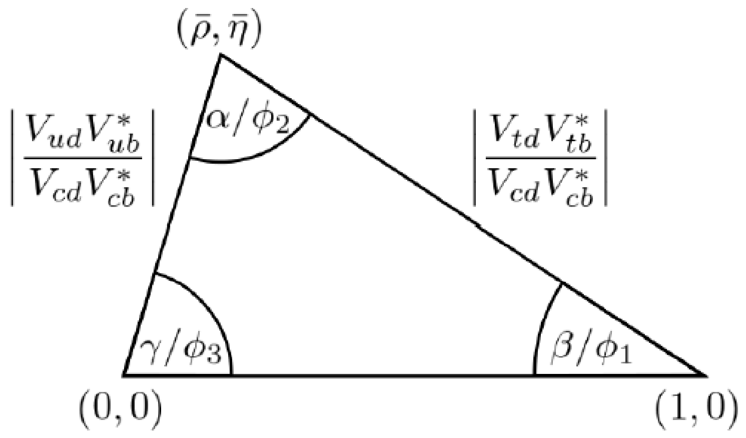
$\lvert V_{ud}\rvert = 0.97425 \pm 0.00022$	$0^+ \rightarrow 0^+$ super-allowed nuclear β decays
$\lvert V_{us}\rvert = 0.2253 \pm 0.0008$	Kaon semi-leptonic and leptonic decays
$\lvert V_{cd}\rvert = 0.225 \pm 0.008$	semi-leptonic D decays and neutrino/antineutrino
$\lvert V_{cs}\rvert = 0.986 \pm 0.016$	Average of semi-leptonic D and leptonic D_s decays
$\lvert V_{cb}\rvert = (41.1 \pm 1.3) \times 10^{-3}$	Combination of exclusive and inclusive B decays
$\lvert V_{ub}\rvert = (4.13 \pm 0.49) \times 10^{-3}$	Comb. of exclusive and inclusive charmless B decays*
$\lvert V_{tb}\rvert = 1.021 \pm 0.032$	Single top-quark production cross-section

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

*But tension inclusive and exclusive determinations

One (of the six) Unitarity Relations

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

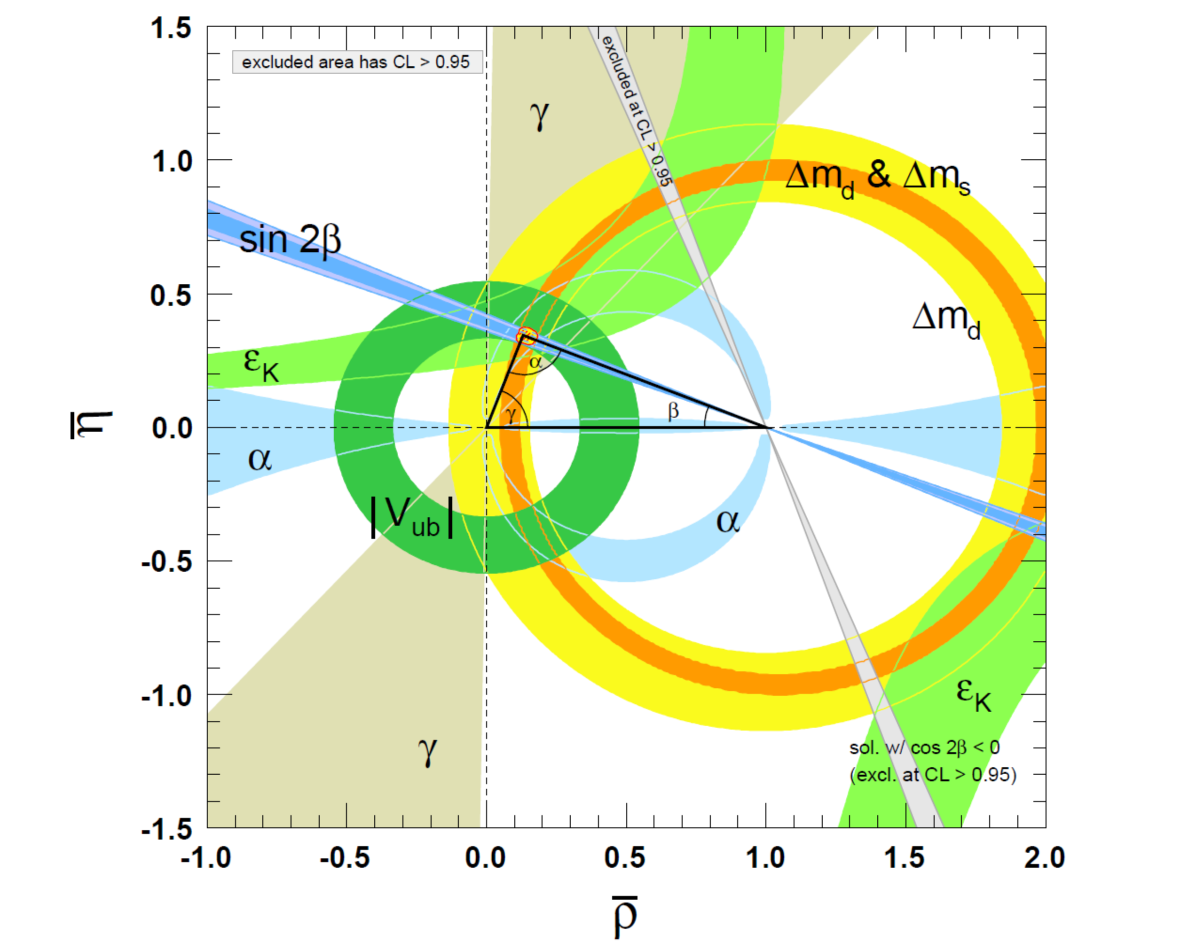


$$\beta=\phi_1=\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha=\phi_2=\arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma=\phi_3=\arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Constraints on the rho eta plane

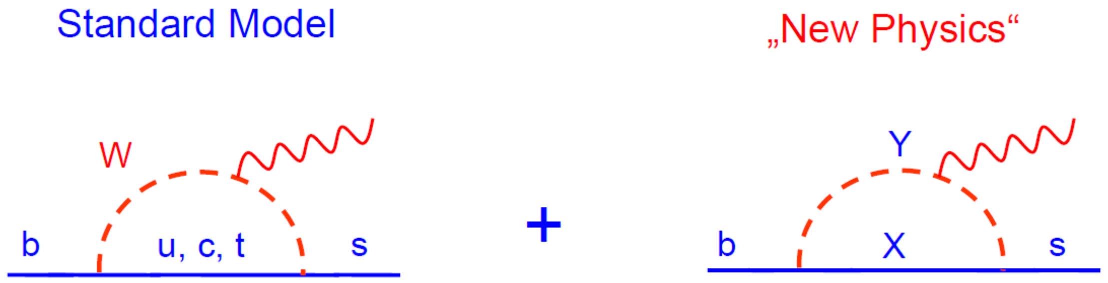


PDG 2014

The unique measure of CP-Violation in the SM is the area of the Unitarity Triangle (Jarlskog invariant J)

$$J = (2.96^{+0.20}_{-0.16}) \times 10^{-5}$$

PROMISE OF NEW PHYSICS IN LOOPS



$$\mathcal{A}_{SM} + \mathcal{A}_{NP}$$

$$A_{SM} + A_{NP} = K_{SM} \frac{\alpha_W}{4\pi} \frac{F_{CKM}}{M_W^2} + K_{NP} L \frac{F_{NP}}{\Lambda^2}$$

- L is a possible loop factor
- $K_{NP} \sim K_{SM}$
- F_{NP} is the NP Flavour coupling
- If $L > \alpha_W/4\pi$ and $F_{NP} > F_{SM}$ we can extract the NP scale Λ

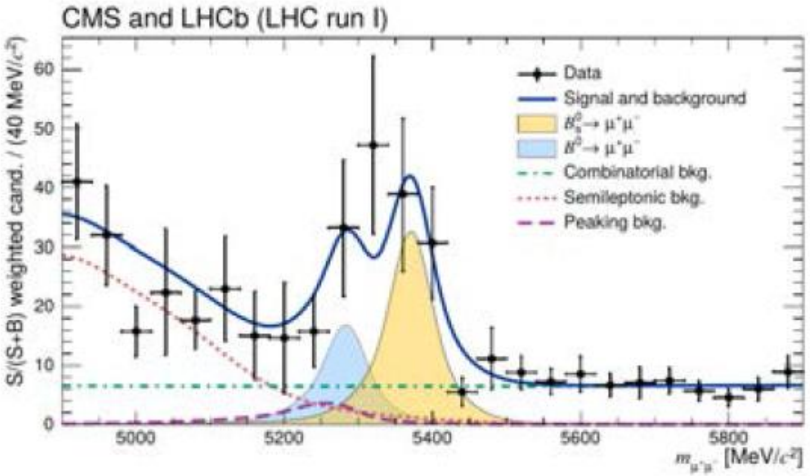
Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert_D$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d \to \psi K$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s \to \psi\phi$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

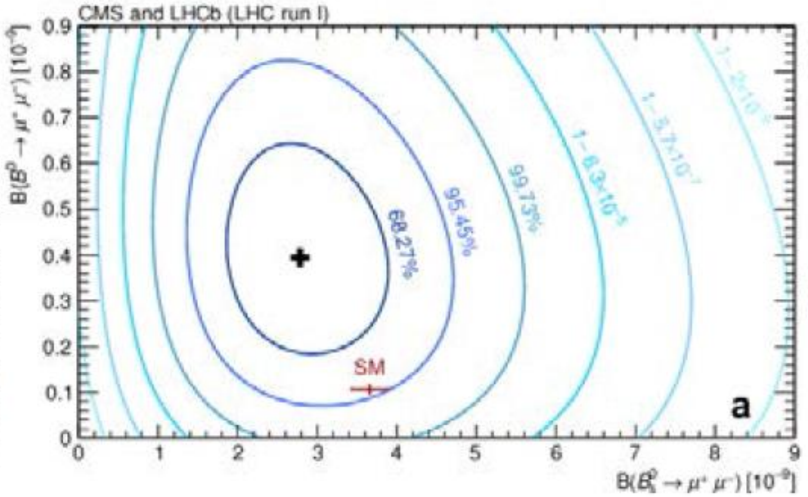
Isidori and Teubert, arXiv:1402.2844

B RARE DECAYS

- Few meson decays are particularly clean theoretically and so suppressed in the Standard Model that they provide a window to very short distance
- For B's I will just mention one example and the prospects for the next decades

The very rare decay $B_s^0 \to \mu^+\mu^-$

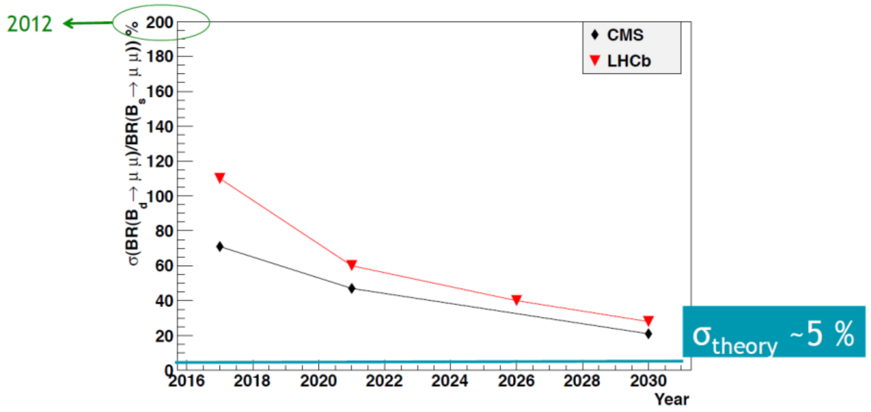




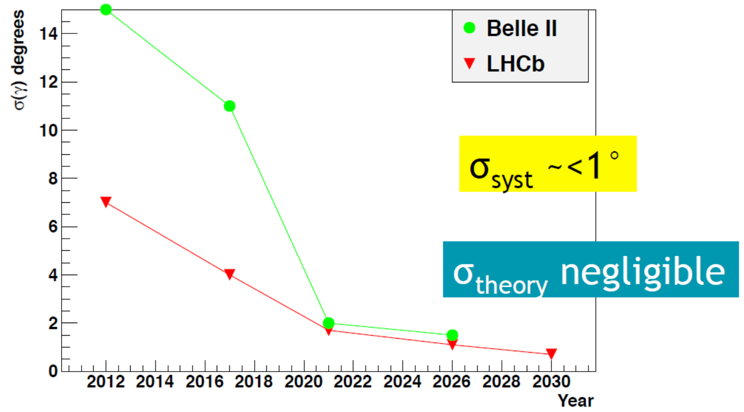
- Observation of $B_s^0 \to \mu^+\mu^-$ using combined CMS and LHCb dataset [arxiv:1411.4413], submitted to Nature
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.79^{+0.66+0.26}_{-0.60-0.19}) \times 10^{-9}$, 6.2σ sign. (7.6σ expected)
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.94^{+1.58+0.31}_{-1.41-0.24}) \times 10^{-10}$, 3.2σ sign. (0.8σ expected)
- SM predictions [Bobeth et al., PRL 112 (2014) 101801]
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$, compatible at 1.2σ
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$, compatible at 2.2σ

ECFA STUDY ON HEAVY FLAVOUR

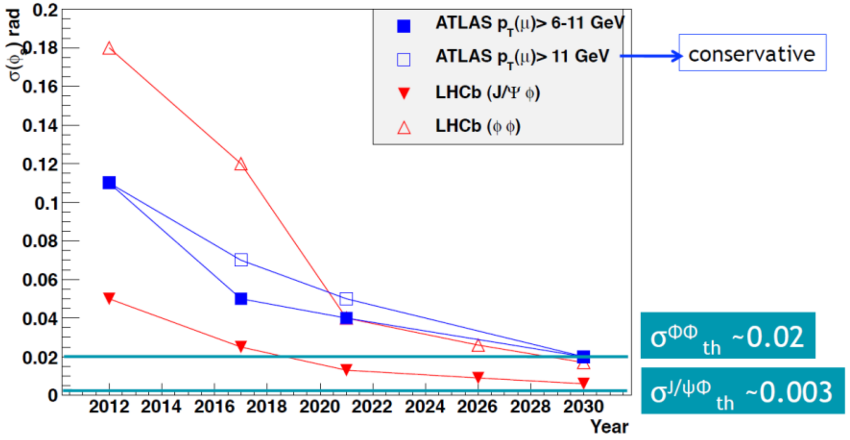
$BR(B_d \to \mu+\mu-)/BR(B_s \to \mu+\mu-)$



Expected precision on γ from tree decays

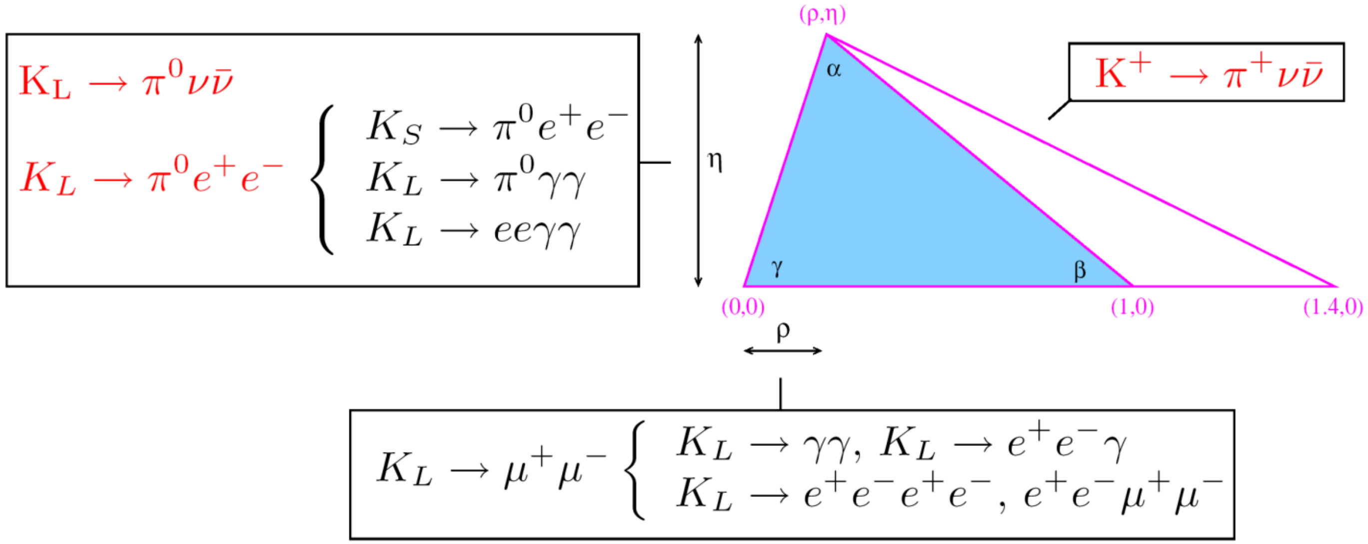


Expected precision on ϕ_s (rad)

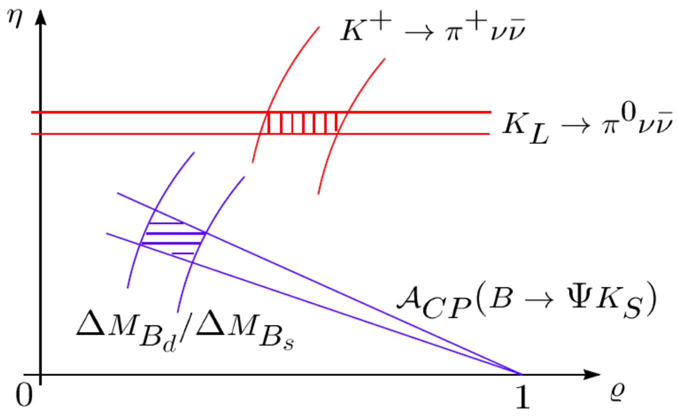


- 2025 appears to be the time for a good harvest
- A crossroad for B physics…

KAON RARE DECAYS



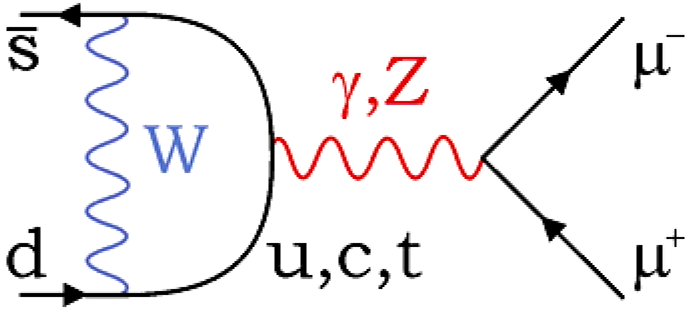
- K physics alone can fully constrain the CKM unitarity triangle.
- Comparison with B physics can provide description of NP flavour dynamics



$K^0_L \to \pi^0 e^+ e^-$ and $K^0_L \to \pi^0 \mu^+ \mu^-$

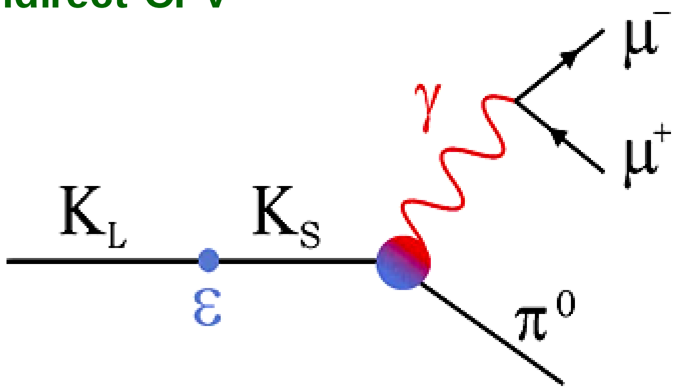
Study Direct CP-Violation

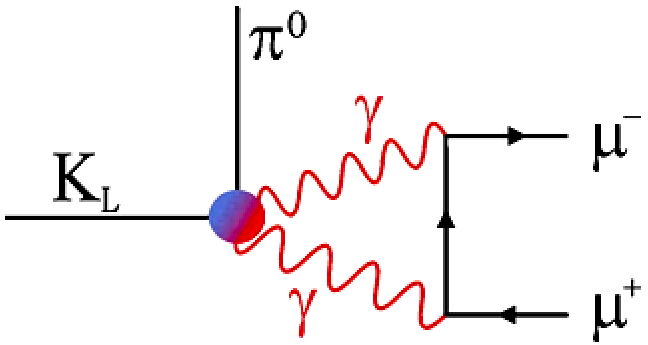
- NA48/1 has measured the Indirect CP-Violating Contribution for both modes
- S-L Constructive Interference preferred
- CP-Conserving Contributions are negligible



Direct CPV

Indirect CPV

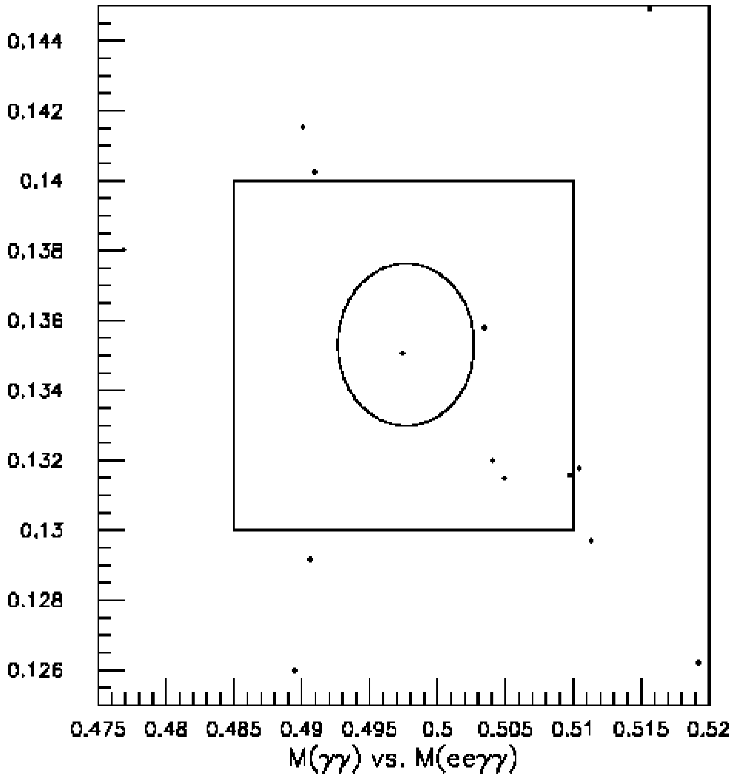




CPC

KTeV: $K_L \rightarrow \pi^0 ee$

1999 data



PRL93, 021805 (2004)

- One candidate in the signal box

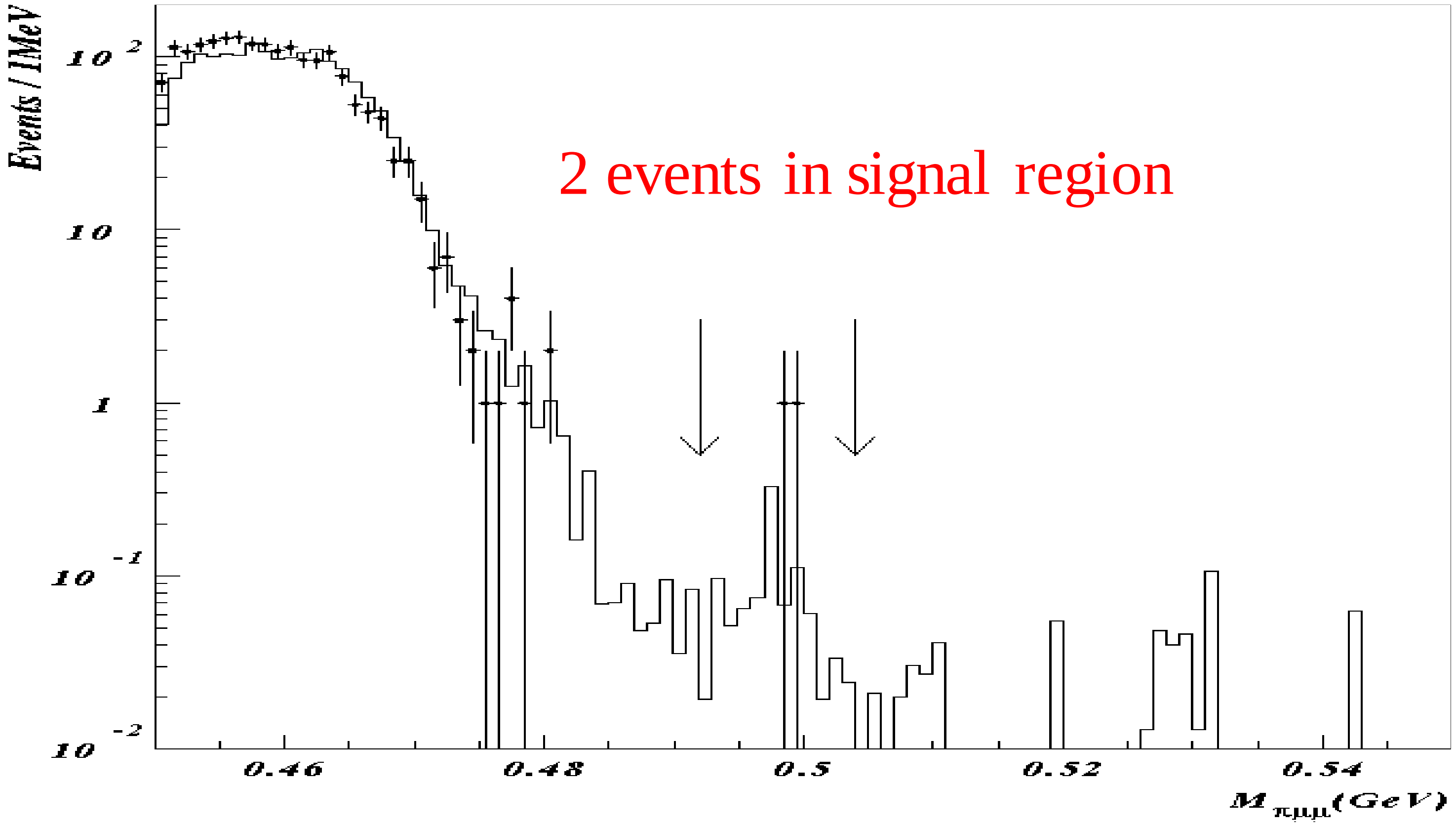
$BR(K_L \rightarrow \pi^0 ee) < 3.5 \times 10^{-10}$ @90%CL

- Combining 1997 and 1999:

$BR(K_L \rightarrow \pi^0 ee) < 2.8 \times 10^{-10}$ @90%CL

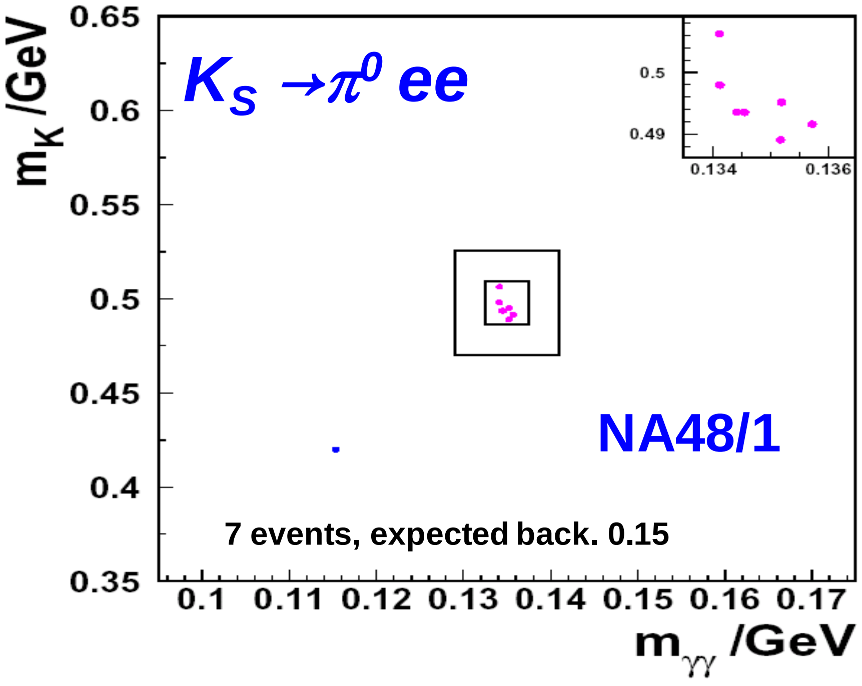
Expected Background 0.99 ± 0.35 events

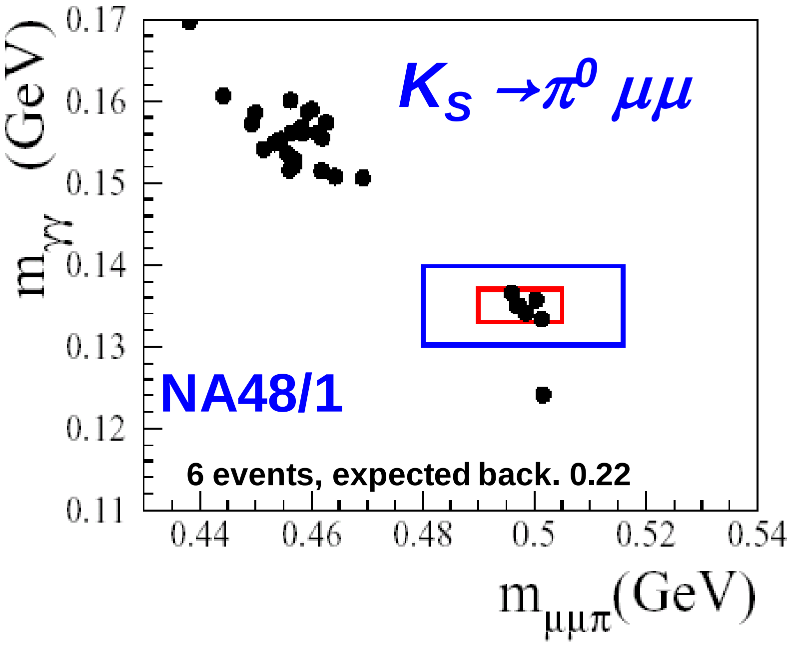
KTeV: $K^0_L \to \pi^0\mu\mu$



$BR(K^0_L \to \pi^0\mu\mu) < 3.8 \times 10^{-10}$ (90% C.L.) [PRL 86, 5425 (2001)]

$K^0_S \to \pi^0 e^+e^-$ and $K^0_S \to \pi^0 \mu^+\mu^-$





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

$|a_S| = 1.06^{+0.26}_{-0.21}\ (stat) \pm 0.07\ (syst)$
PLB 576 (2003)

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

$|a_S| = 1.55^{+0.38}_{-0.32}\ (stat) \pm 0.05\ (syst)$

PLB 599 (2004)

$K^0_L \to \pi^0 ee\ (\mu\mu)$: SM Branching Ratios

Thank to the NA48/1 measurements, the KL BR can now be predicted

(Isidori, Unterdorfer, Smith)

Constructive

$$B_{e^+e^-} = 3.7^{+1.1}_{-0.9} \times 10^{-11}$$

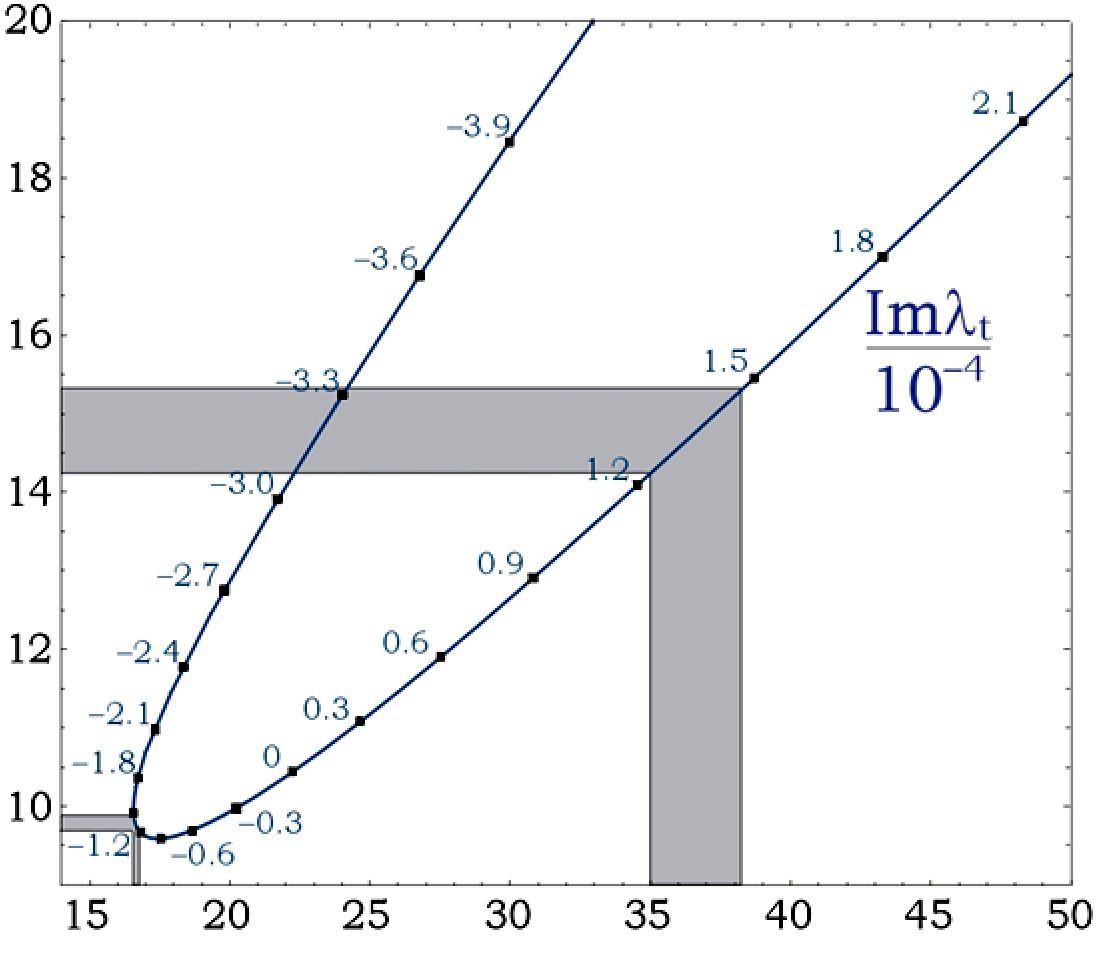
$$B_{\mu^+\mu^-} = 1.5^{+0.3}_{-0.3} \times 10^{-11}$$

now favored by two independent analyses*

Destructive

$$B_{e^+e^-} = 1.7^{+0.7}_{-0.6} \times 10^{-11}$$

$$B_{\mu^+\mu^-} = 1.0^{+0.2}_{-0.2} \times 10^{-11}$$



*G. Buchalla, G. D'Ambrosio, G. Isidori, Nucl.Phys.B672,387 (2003)

*S. Friot, D. Greynat, E. de Rafael, hep-ph/0404136

CP violating: $K_S \to \pi^0\pi^0\pi^0$
never observed so far !

SM $\Gamma(K_S\to 3\pi^0) = \Gamma(K_L\to 3\pi^0)\,|\eta_{000}|^2 \Rightarrow BR(K_S\to 3\pi^0) \sim 2\times10^{-9}$

KLOE/KLOE-2: Phys. Lett. B 723 (2013) 54

$$BR(K_S \to 3\pi^0) \leq 2.6 \times 10^{-8} \quad \text{at} \quad 90\% \quad \text{C.L.}$$

Factor of five better than previous results

$$\epsilon + \epsilon'_{000} = |\eta_{000}| = \left|\frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)}\right| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} \leq 0.0088 \quad \text{at} \quad 90\% \quad \text{C.L.}$$

Courtesy P. Moskal

KLOE-2 has a chance to observe K_S --> $\pi^0\pi^0\pi^0$ decay for the first time in the near future

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

HOLY GRAIL OF FLAVOUR PHYSICS?

- Why it is so special:

1. Apart from a small admixture (ε_K~2.228 10^{-3}), K^0_L is a CP eigenstate. Neglecting the CP-even state we can write:

$$< \pi^0 \nu\bar{\nu} | A | K^0 > \sim V_{td} V_{ts}^* X(x_t) + P_c(X) V_{cd} V_{cs}^*$$

$$< \pi^0 \nu\bar{\nu} | A | \bar{K}^0 > \sim V_{td}^* V_{ts} X(x_t) + P_c(X) V_{cd}^* V_{cs}$$

$$| K_L^0 > \sim \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

2. In taking the difference, the charm part (which is almost real) drops off and only the imaginary part of the top contribution remains!

$$< \pi^0 \nu\bar{\nu} | A | K_L^0 > \sim \mathrm{Im} V_{td} V_{ts}^* X(x_t)$$

3. The main experimental background ($K^0_L \to \pi^0 \pi^0$) is suppressed by CP conservation !
4. The very long life time of the K^0_L makes the interesting partial width “measurable” (Br~O(10^{-11}))

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

Formulas from A.J. Buras et al. RMP 80, 2008

$$Br(K_L^0 \to \pi^0 \nu \bar{\nu}) = \kappa_L \times \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

$$\kappa_L = (2.231 \pm 0.013) \times 10^{-10} \left[\frac{\lambda}{0.225} \right]^8$$

Numerical example:

$$\lambda_i = V_{id} V_{is}^{*}$$

$$\lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

$$\mathrm{Im}\, V_{td} V_{ts}^{*} = \sin \beta_K \, |V_{td} V_{ts}^{*}| \sim 1.29 \times 10^{-4}$$

$$X(x_t) \sim 1.44$$

$$Br(K_L^0 \to \pi^0 \nu \bar{\nu}) \sim 2.3 \times 10^{-11}$$

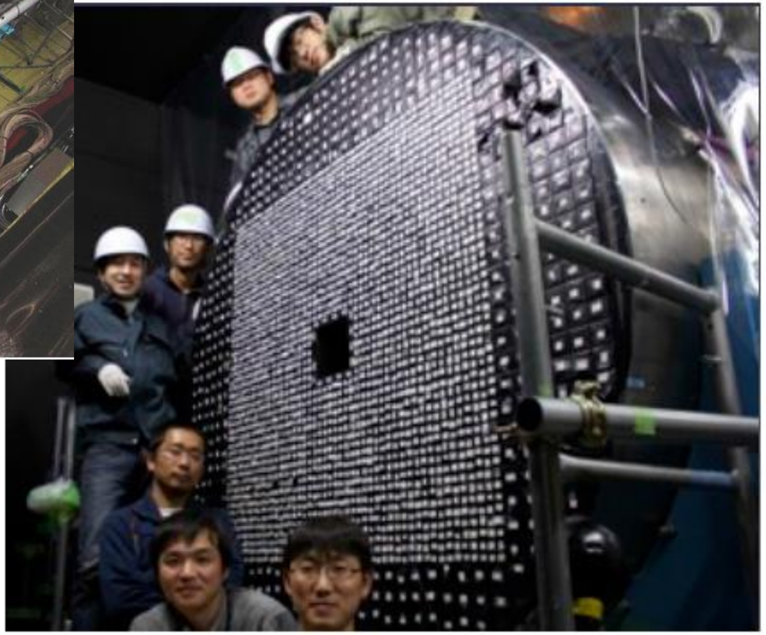
EXPERIMENT: BR<2.6 10^{-8} 90%CL (E391a - KEK)

NEXT EXPERIMENT: KOTO (E14, J-PARC)

KOTO - JPARC

Vacuum tank from E391a

Pure CsI recovered from
FNAL KTeV Experiment



Current SES based on 100 h run in 2013 (Preliminary): 1.29×10^{-8}

Expect "nominal" beam intensity in 2017

$Br(K^+ \to \pi^+ \nu\bar{\nu})$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1 + \Delta_{EM}) \times$$

$$\left[\left(\frac{\operatorname{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\operatorname{Re} \lambda_c}{\lambda} P_c(X) + \frac{\operatorname{Re} \lambda_t}{\lambda^5} \right)^2 \right]$$

$$\kappa_+ = (5.173 \pm 0.025) \times 10^{-11} \left[\frac{\lambda}{0.225} \right]^8$$

$$\lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

$$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \cdot \lambda^8$$

$$\lambda_i = V_{id} V_{is}^*$$

Formulas from A.J. Buras et al. RMP 80, 2008

$Br(K^+ \to \pi^+ \nu\bar{\nu})$ (MY NUMEROLOGY)

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) \propto 1.56 \times 10^{-4} \times$$

$$\left[|V_{td}V_{ts}^*|^2 \; X(x_t)^2 + 2\lambda^5 P_c(X)\,|V_{td}V_{ts}^*|\, X(x_t)\cos\beta_K + \lambda^{10} P_c(X)^2 \right] \approx$$

$$[\quad 4.40 \quad + \quad 3.68 \quad + \quad 0.87 \quad] \times 10^{-11} =$$

$$8.95 \times 10^{-11}$$

The charm- top-quark interference term is comparatively large

$$\cos\beta_K = \cos\beta - \beta_s \approx 0.94$$

For this set of values the m_c the parametric uncertainty is:
$\delta Br/Br \sim 0.68\ \delta P_c/P_c$

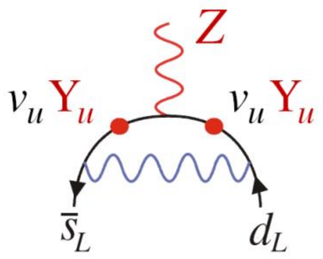
$$|V_{td}V_{ts}^*| \sim 3.69 \times 10^{-4} \quad \text{(PDG 2014)}$$

$$X(x_t) \sim 1.44 \quad \text{(Buras et al.)}$$

$$P_c(X) = 0.41 \pm 0.05 \quad \text{(Buras et al.)}$$

Kaon Rare Decays and NP [redacted]

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

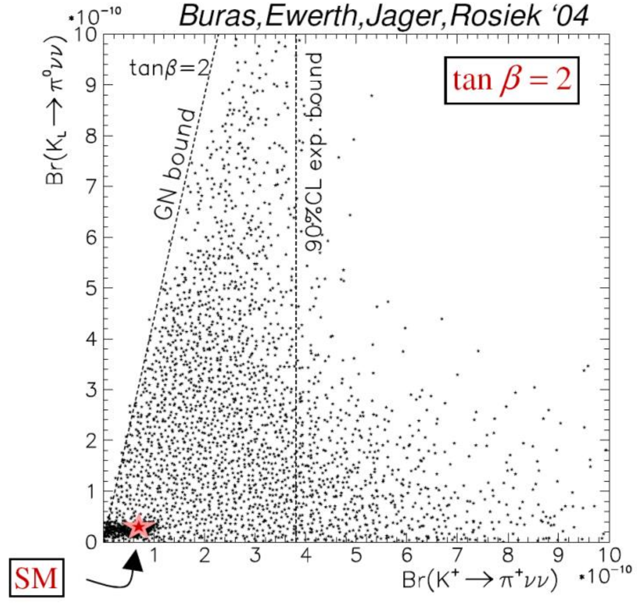


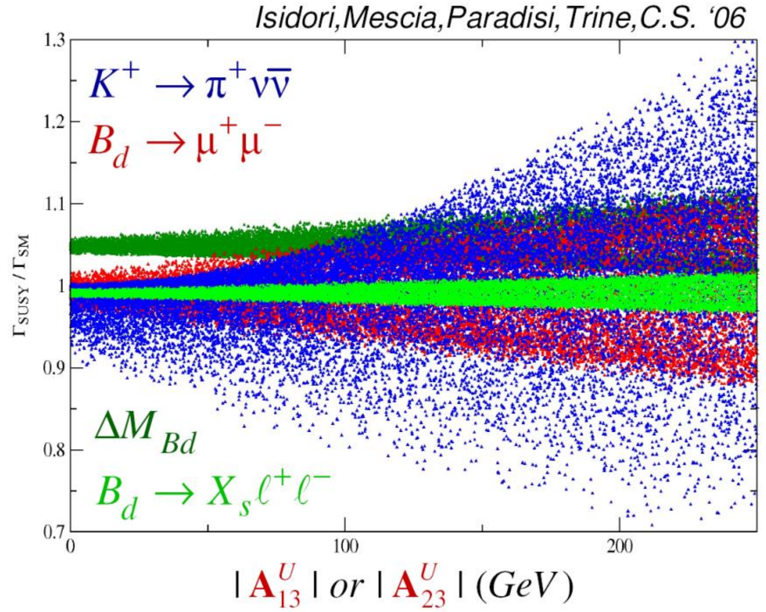
- $SU(2)_L$ breaking: $SM: v_u^2 \mathrm{Y}_u^{*32} \mathrm{Y}_u^{31} \sim m_t^2 V_{ts}^* V_{td}$

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

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

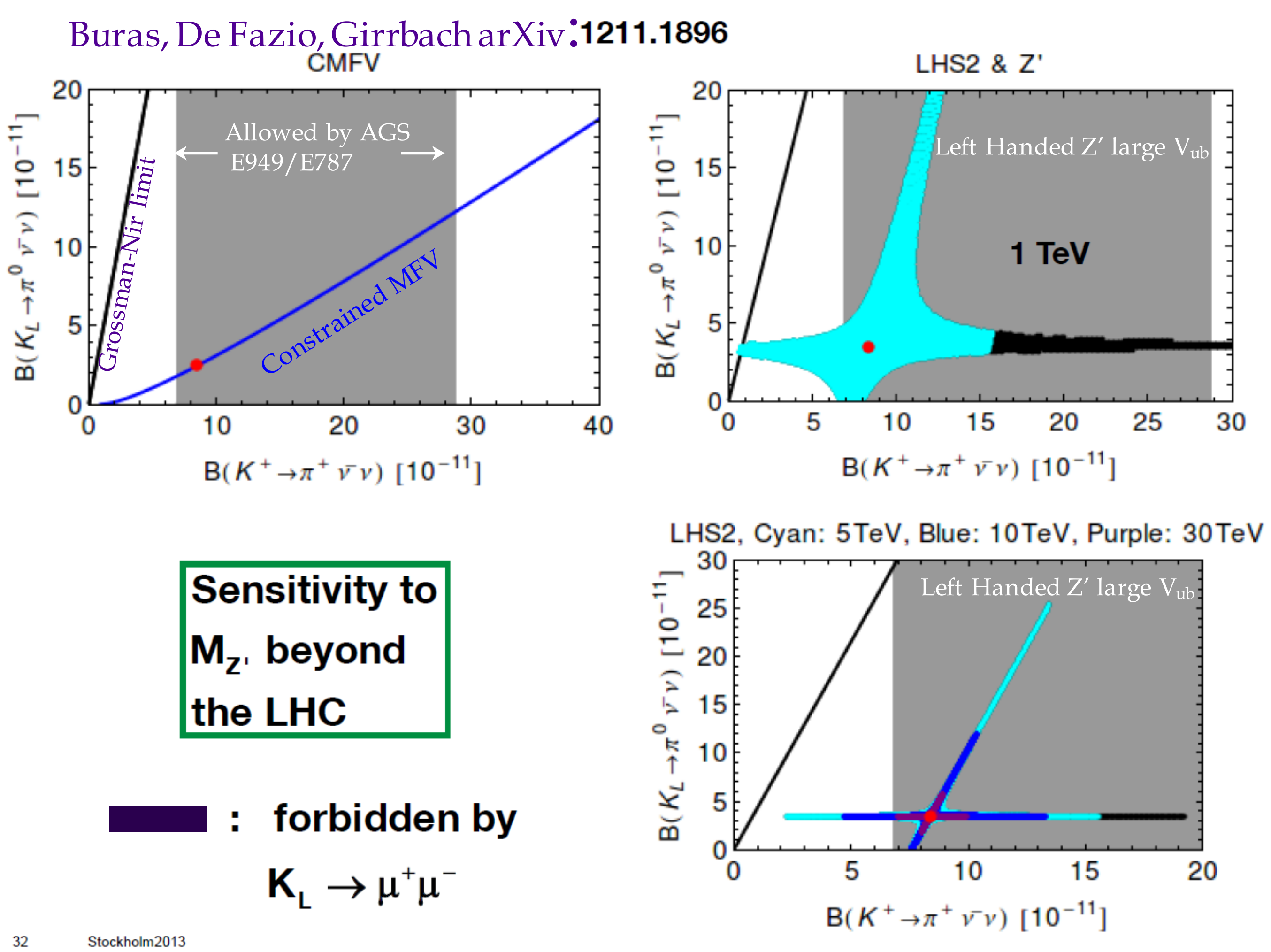
- Relatively slow decoupling (w.r.t. boxes or tree).





(courtesy by Christopher Smith)

Rare *K* decay sensitivity to flavor violating *Z'*



Sensitivity beyond direct searches

CHARGED K BEAMS

"Stopped"

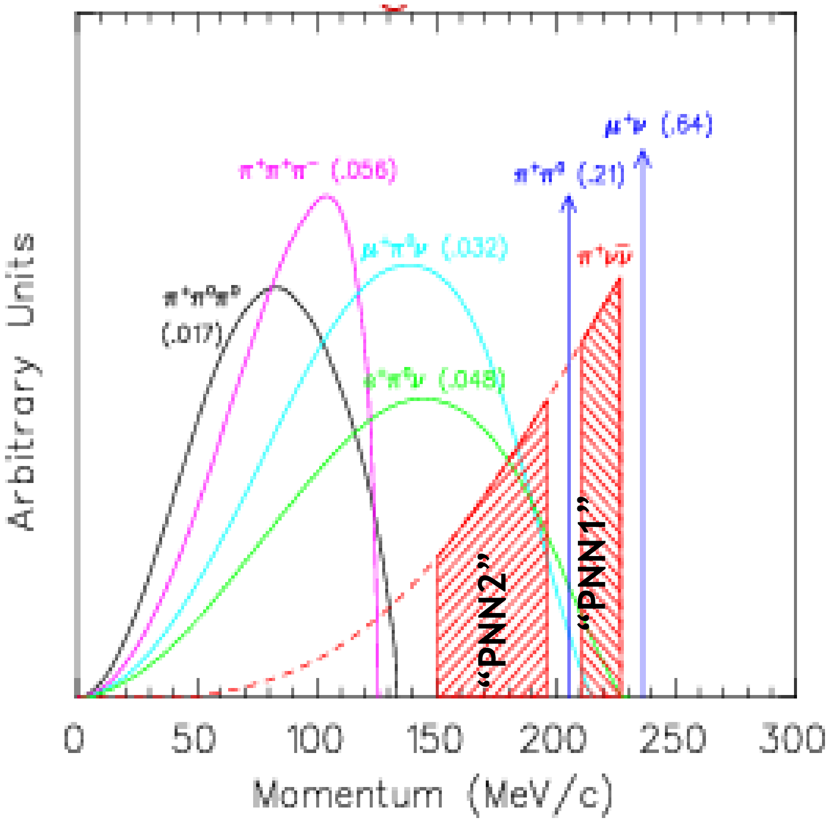
- Work in Kaon frame
- High Kaon purity (Electro-Magneto-static Separators)
- Compact Detectors

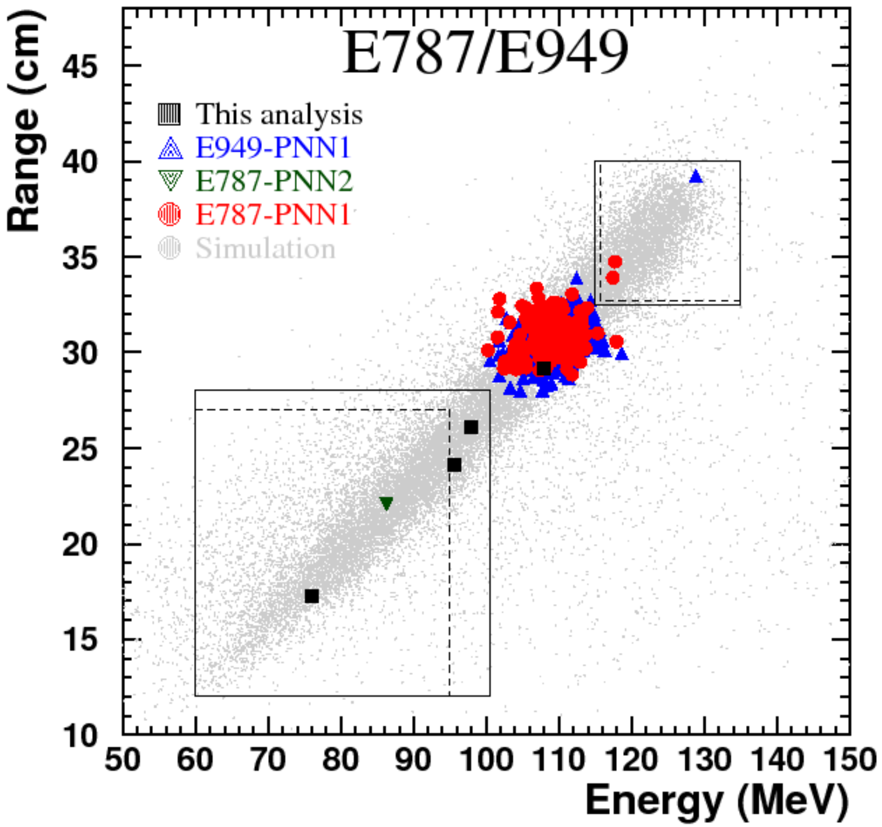
"In-Flight"

- Decays in vacuum (no scattering, no interactions)
- RF separated or Unseparated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped; Spark Chambers
	KEK	$<1.4 \times 10^{-7}$	Stopped; $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	AGS	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	Stopped; PPN1+PPN2
NA62	SPS		In-Flight; Unseparated

STATE OF THE ART: E787/E949 DECAYS AT REST



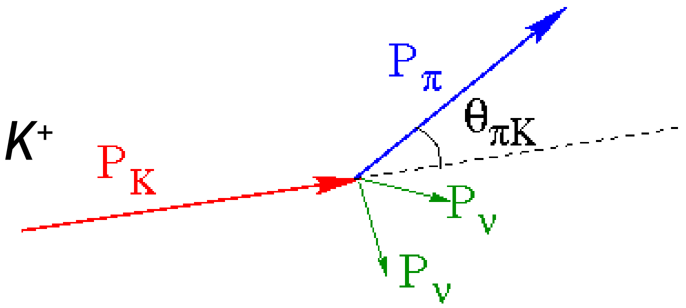


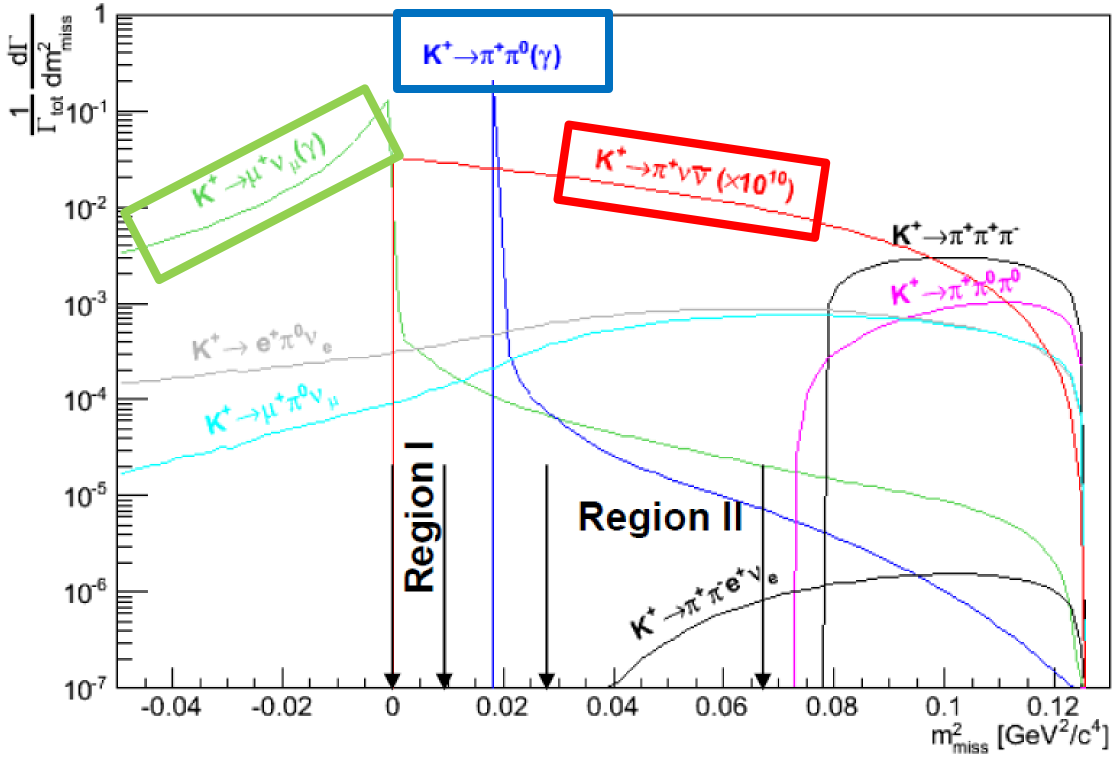
$$B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

PRL101, arXiv:0808.2459, AGS-E787/E949

NA62 IN-FLIGHT TECHNIQUE

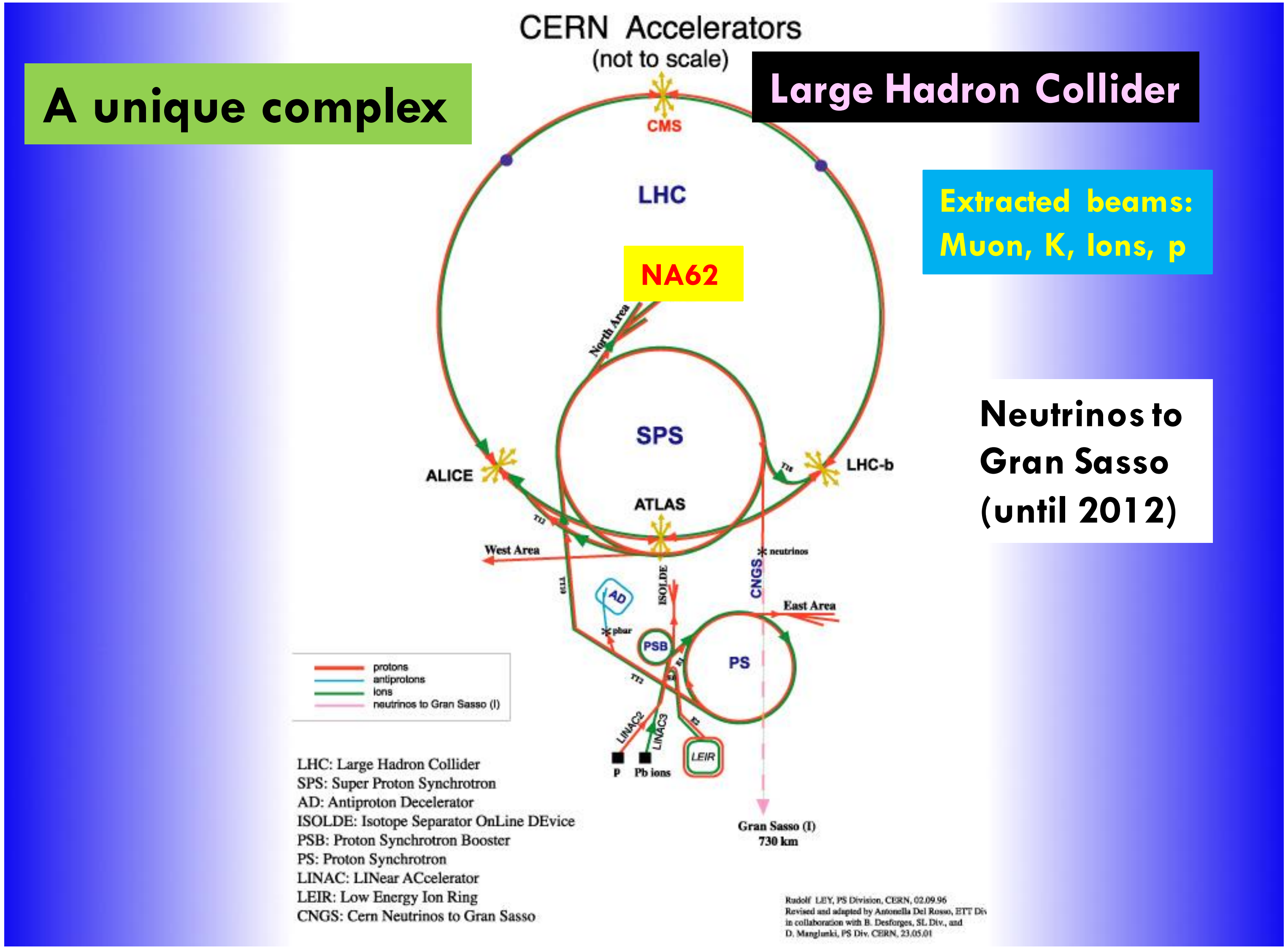
- Calorimetry to veto extra particles
- Very light trackers to reconstruct the K^+ and the π^+ momenta
- Full particle identification





$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

CERN ACCELERATORS



$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis Sensitivity (MC)

Decay	event/year
$K^+ \to \pi^+ \nu\nu$ [SM] (flux 4.5×10^{12})	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
$K^+ \to \pi^+ \pi^- e^+ \nu$ + other 3 tracks decays	< 1
$K^+ \to \pi^+ \pi^0 \gamma$(IB)	1.5
$K^+ \to \mu^+ \nu \gamma$(IB)	0.5
$K^+ \to \pi^0 e^+ (\mu^+) \nu$, others	negligible
Total background	< 10

CERN NA62 EXPERIMENT

- Picture taken just before beam in 2014
- Beam time 2015: June 22 – November 15

NA62 DETECTOR

View of ECN3

LAV 1-5 in TTC8

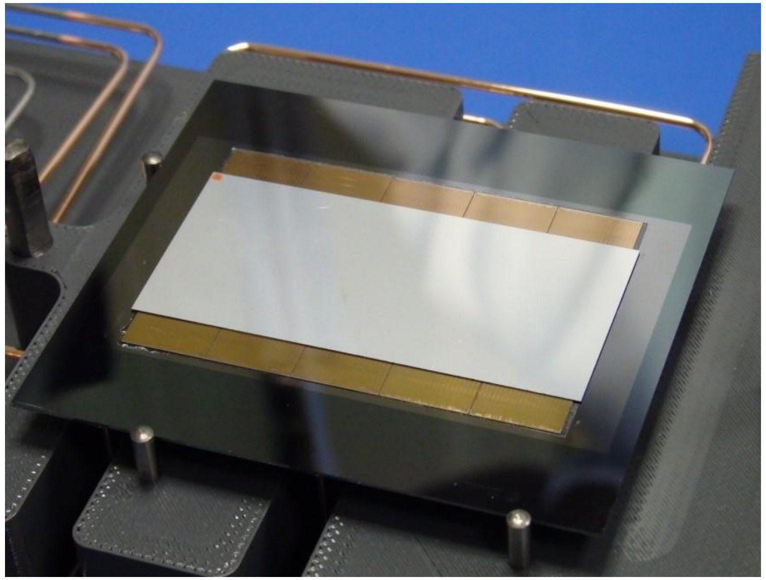
NA62 DETECTOR

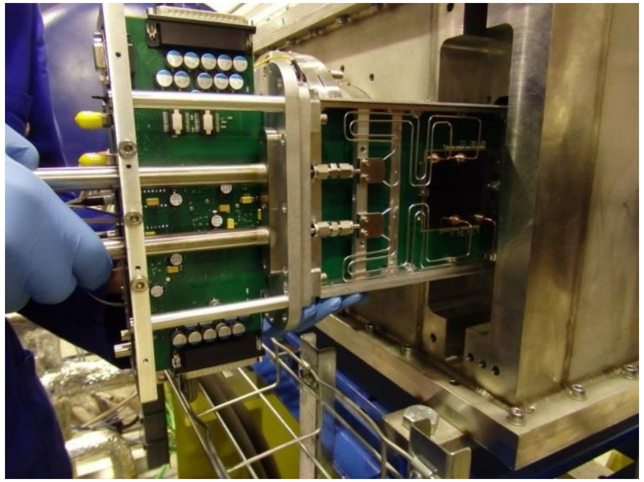
Straw3 - LAV10 - MNP33 - Straw2 - LAV9

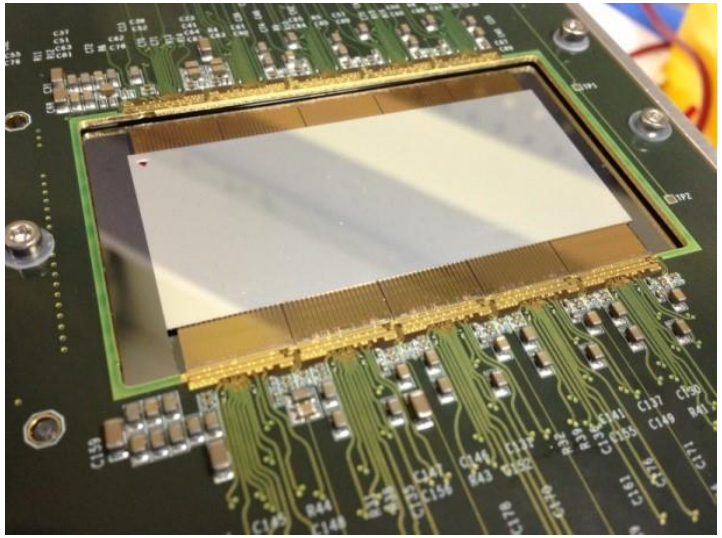
RICH Straw 4 and LAV11

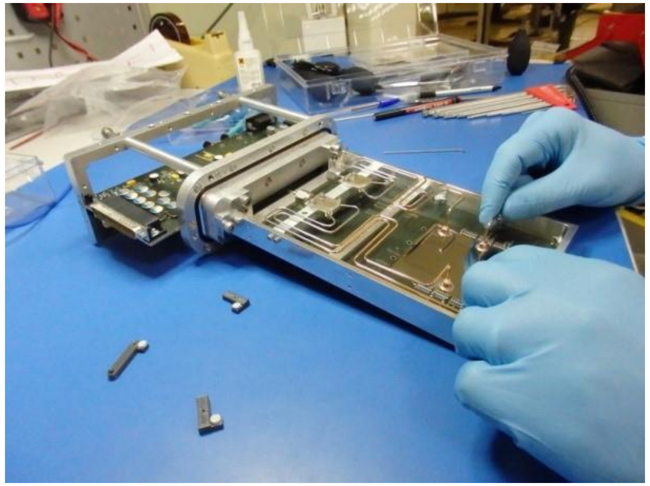
GIGATRACKER (GTK)

CERN (PH-DT, PH-ESE, PH-SME, EN,…)
Ferrara, Louvain-la-Neuve, Torino

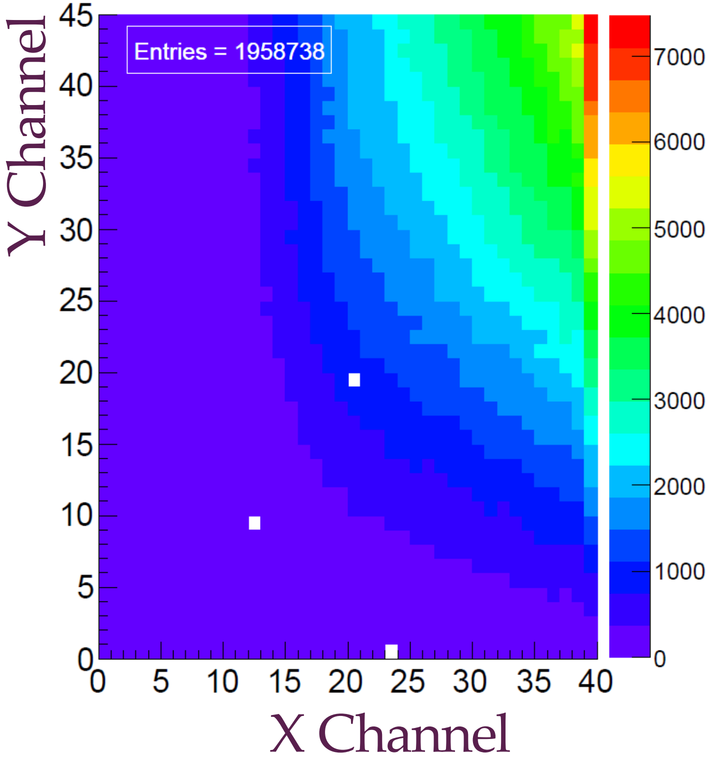




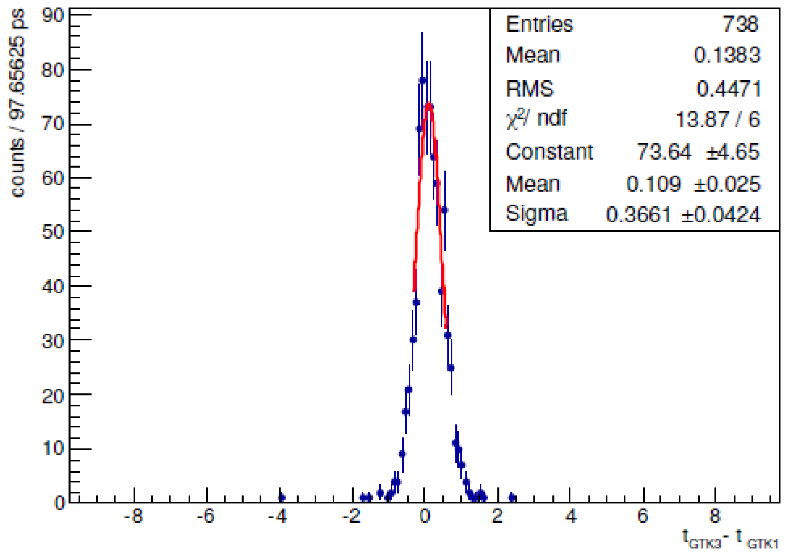




GIGATRACKER PERFORMANC



K12 Beam; Illumination of one GTK chip

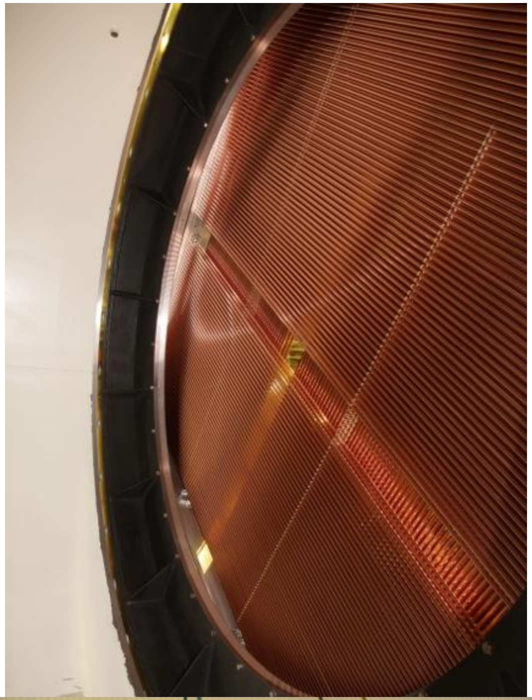


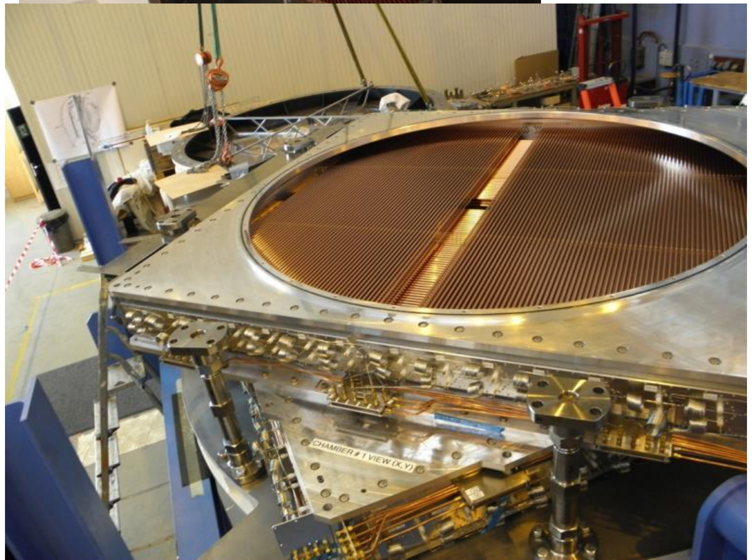
After ToT correction

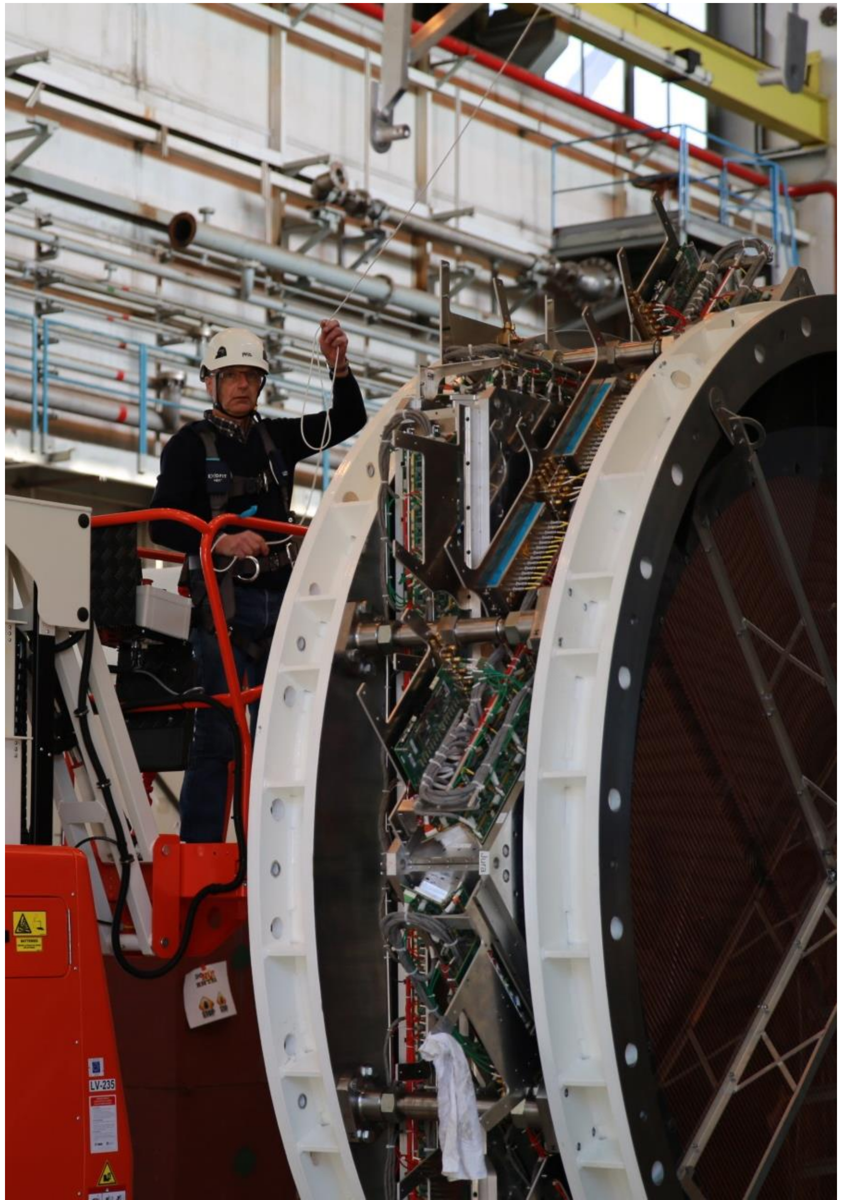
Time resolution~ 260 ps /station
In line with expectations for
HV= 200 V

NA62 STRAW TRACKER

CERN (PH-DT, PH-ESE,PH-SME) – JINR

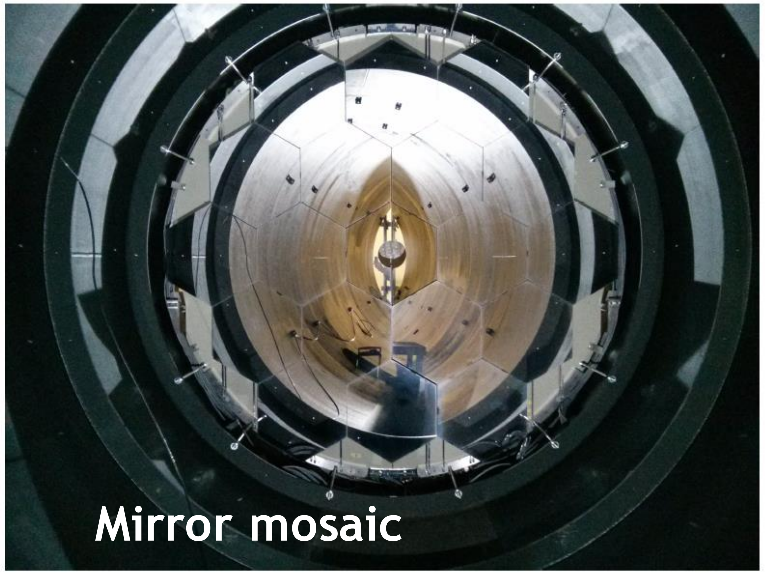


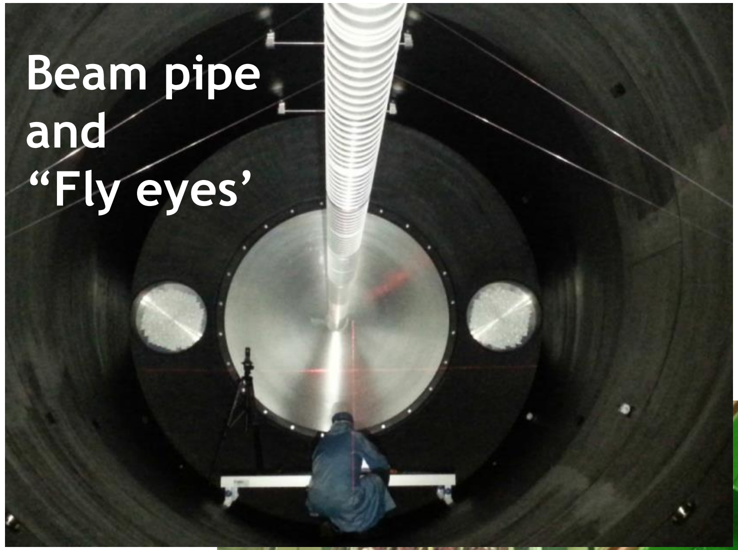


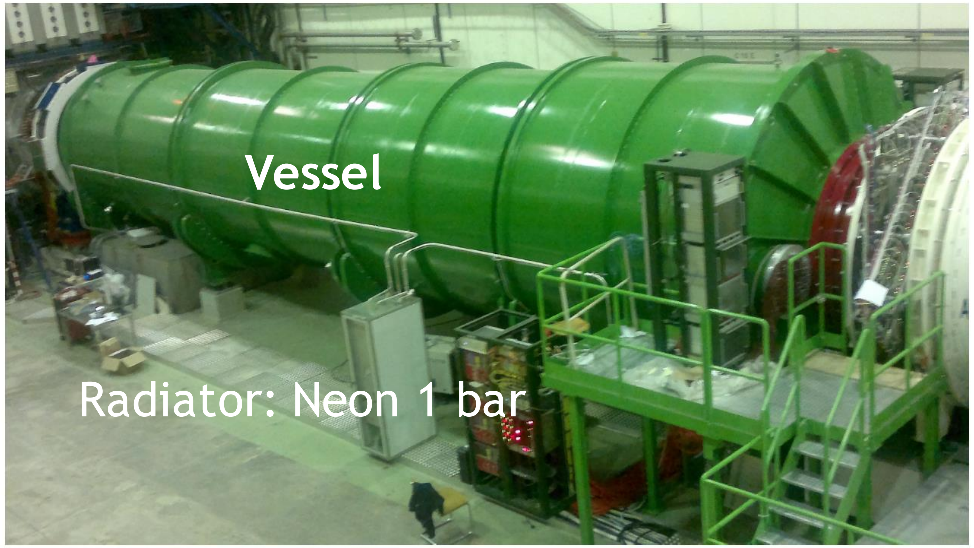


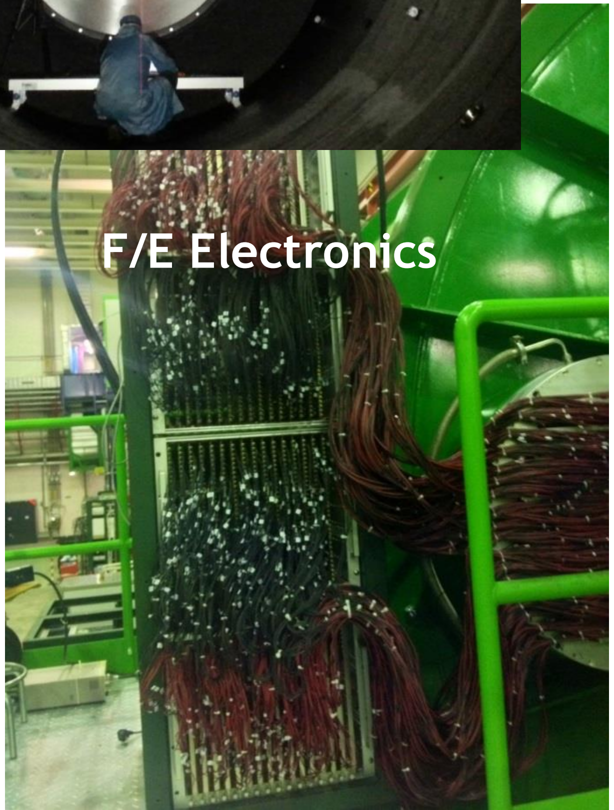
NA62 RICH

CERN (PH-DT,..), Firenze, Perugia

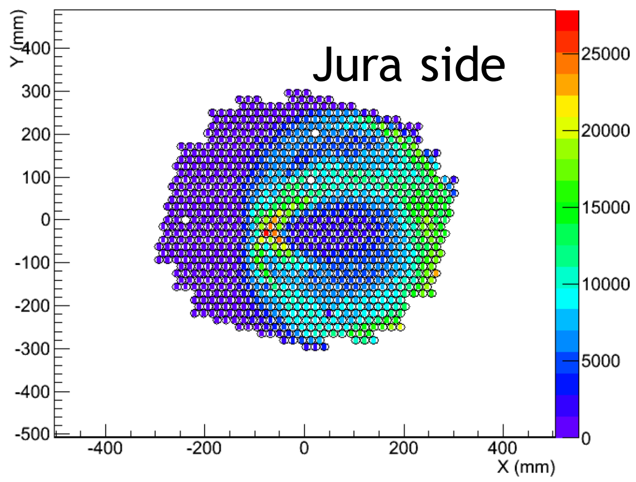


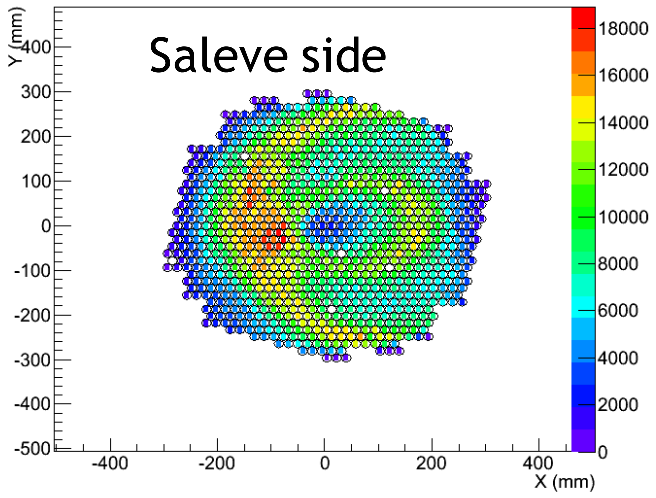


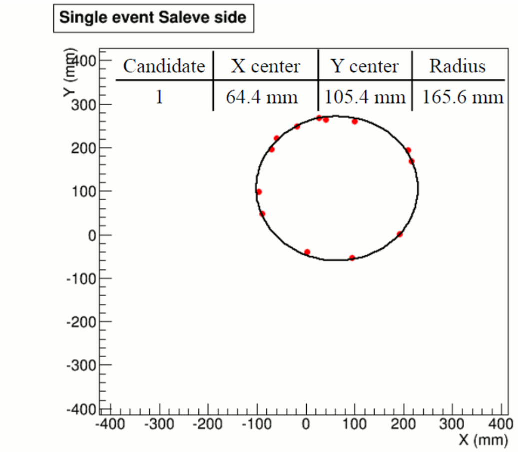


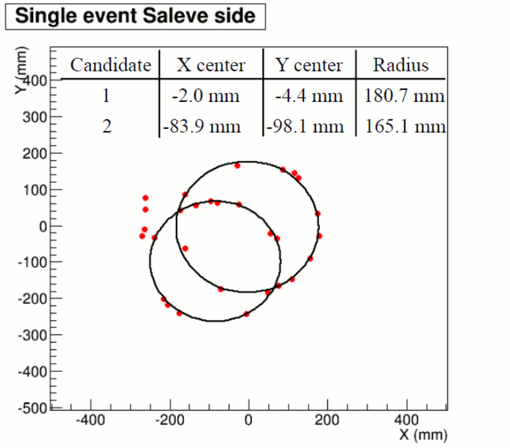


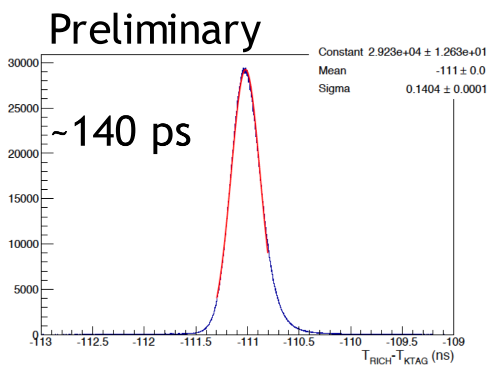
RICH DATA







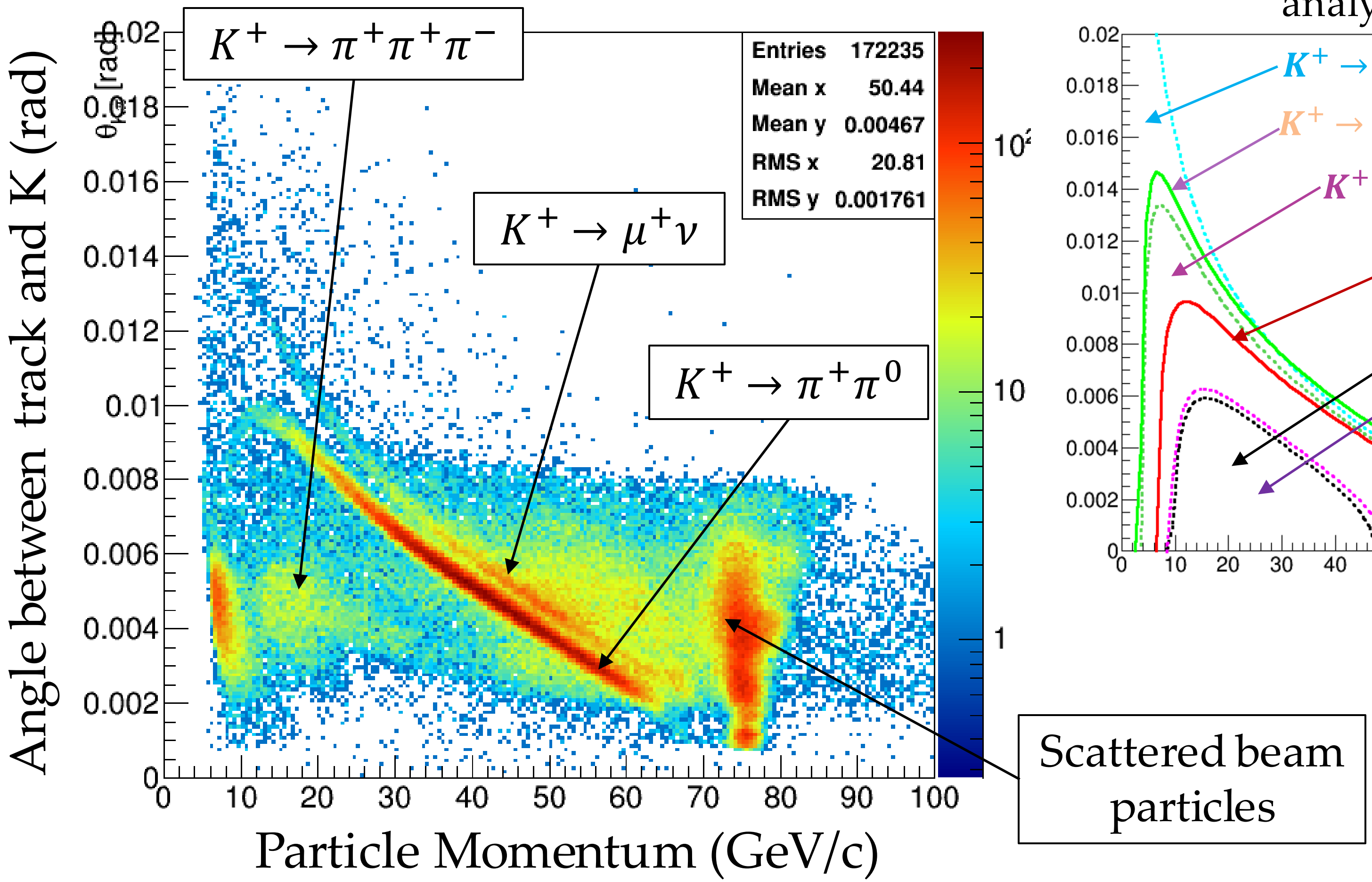


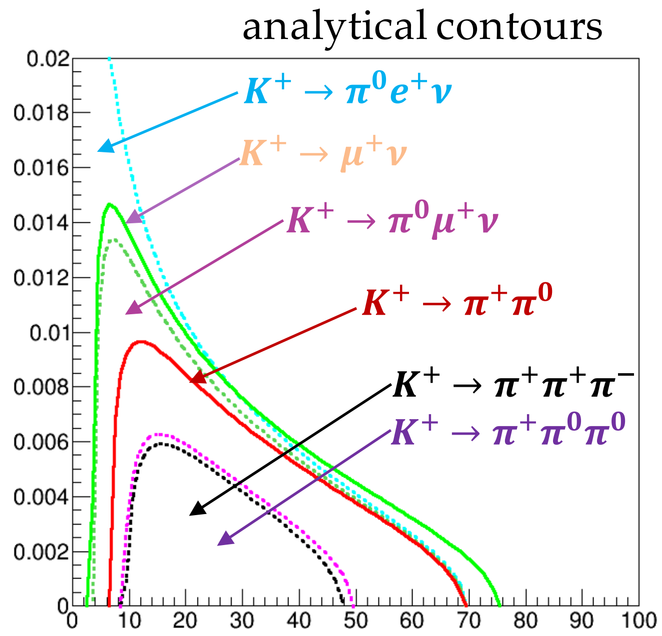


RICH-KTAG

2014 DATA QUALITY

- Events with only 1 track in the spectrometer reconstructed (within 40 ns)
- 10^2 muon rejection at trigger level



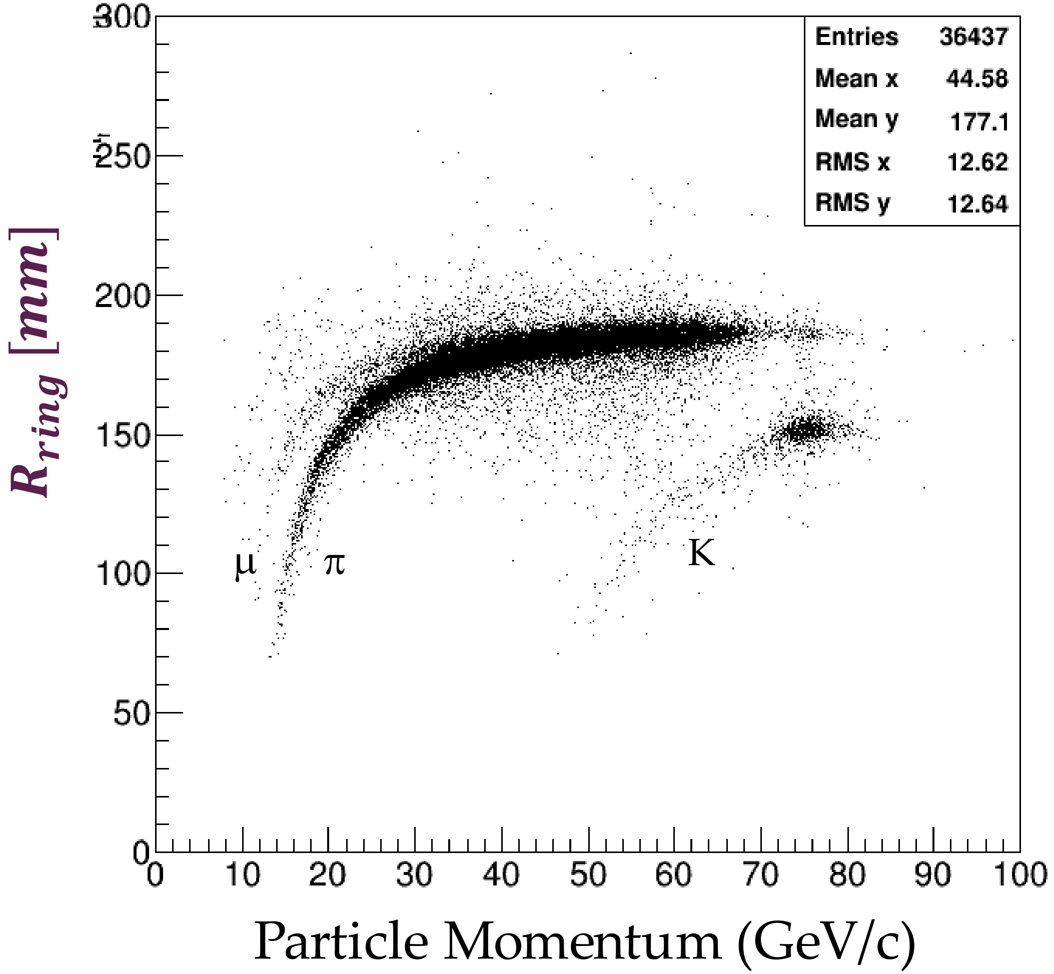


CERN-EP Seminar by Giuseppe Ruggiero, March 10, 2015:

https://indico.cern.ch/event/360237/

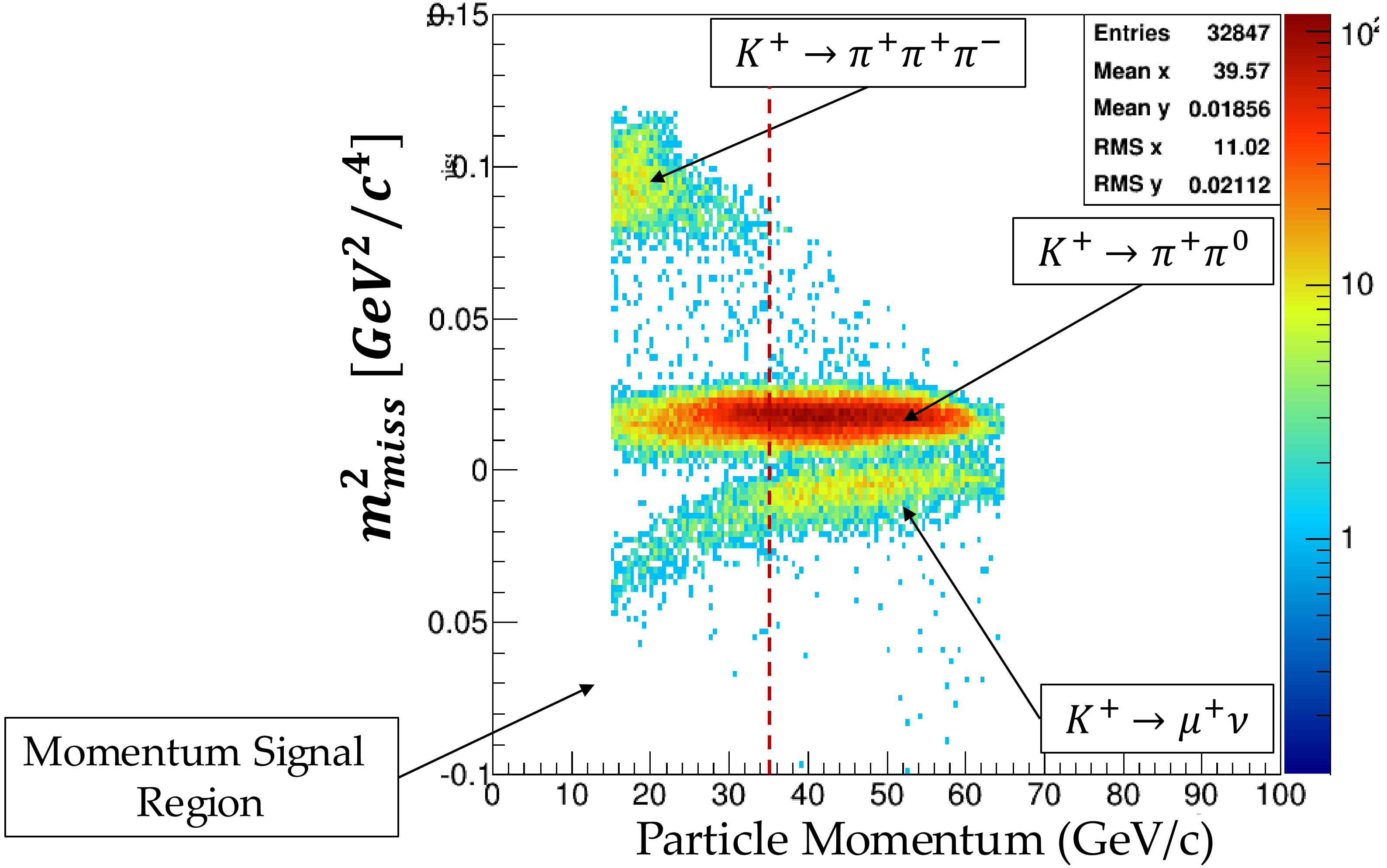
2014 DATA QUALITY

- Matching between track and RICH ring to study the particle content
- Positrons suppressed by the trigger



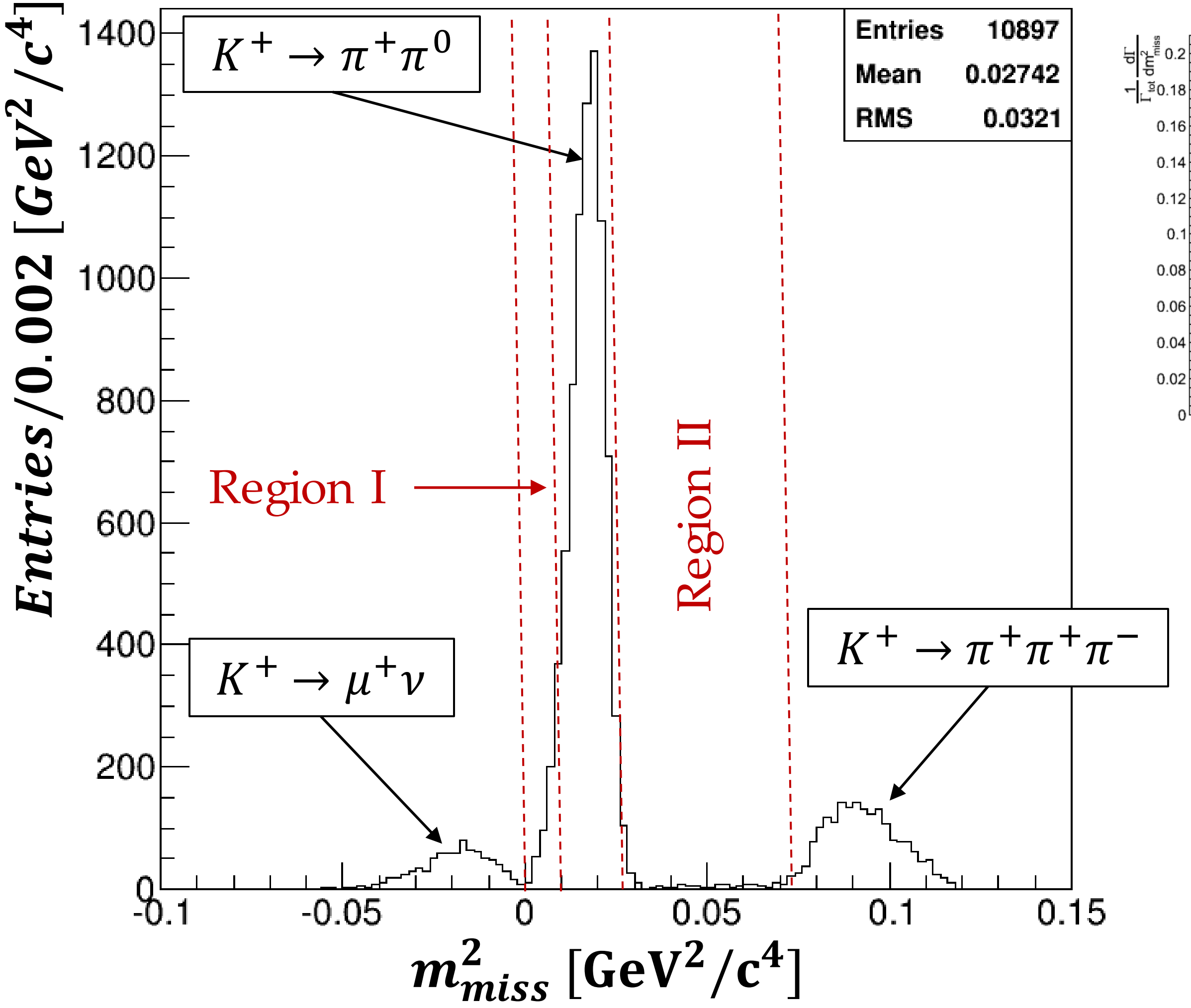
2014 DATA QUALITY

$$m_{miss}^2 = (P_K - P_{\pi^+})^2$$

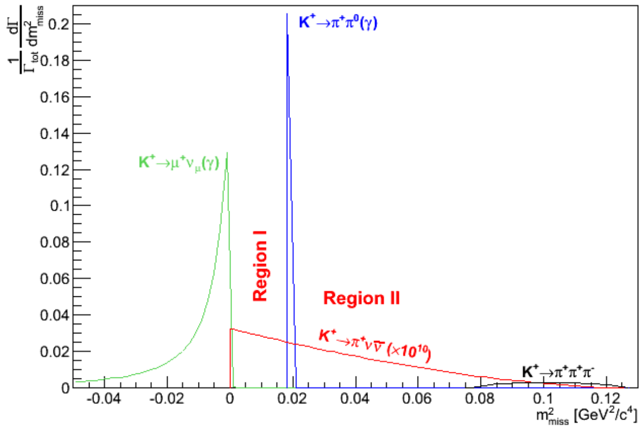


2014 DATA QUALITY

$P < 35\ GeV/c$



theoretical shapes



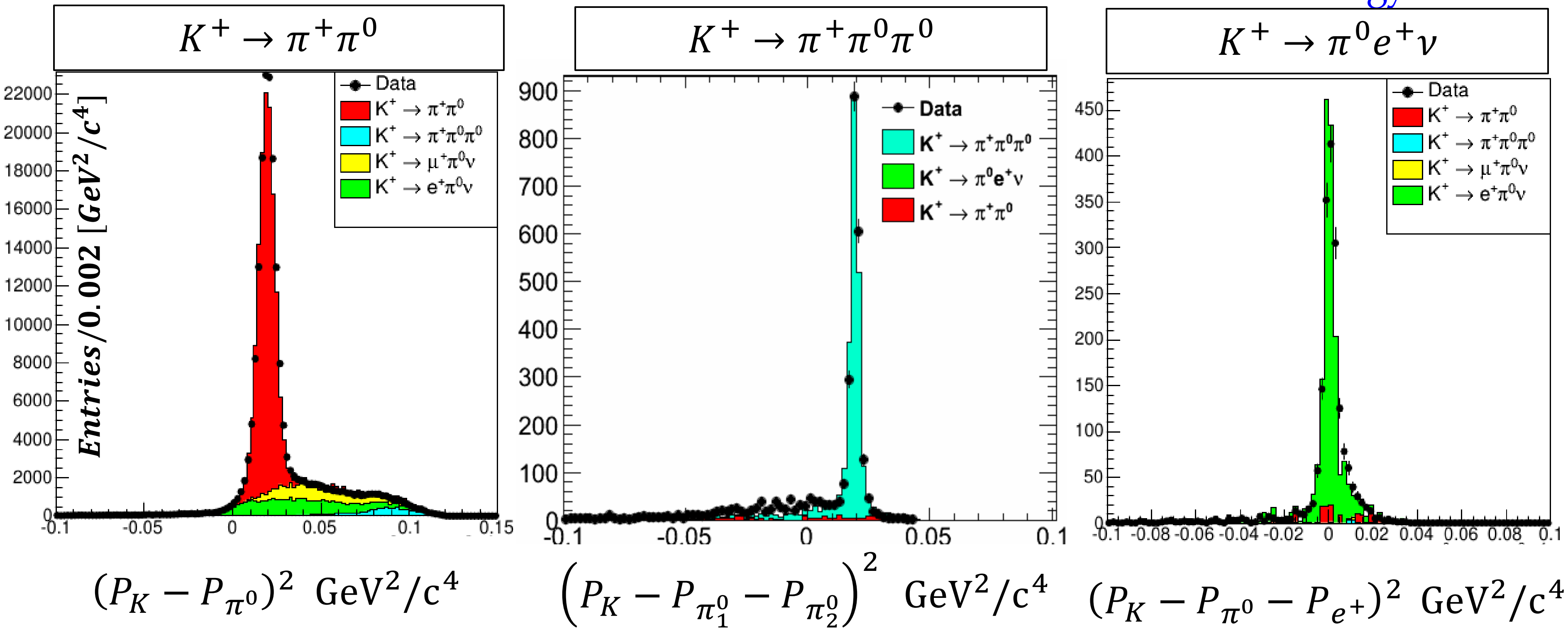
CONTROL SAMPLES

- Kaon decay modes reconstructed with the liquid Krypton calorimeter only (from minimum bias data)
- Useful to measure the kinematic suppression factor, particle ID efficiency ...

π^0 mass assumed

π^0 mass assumed

π^0 mass assumed and e^+ energy



Further NA62 K Physics Program

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9 \times 10^{-11}\ m_{X^0} = 0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h \to \nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350\ MeV$	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

SUMMARY

Fascinating adventure in between quark mixing, CP-Violation…

Number of fermion generations…

Quarks and Leptons…

High energy frontier…

Address fundamental question: How does the world work?

Rare *K* decays research offer a complementary way to see beyond SM with respect to high energy colliders

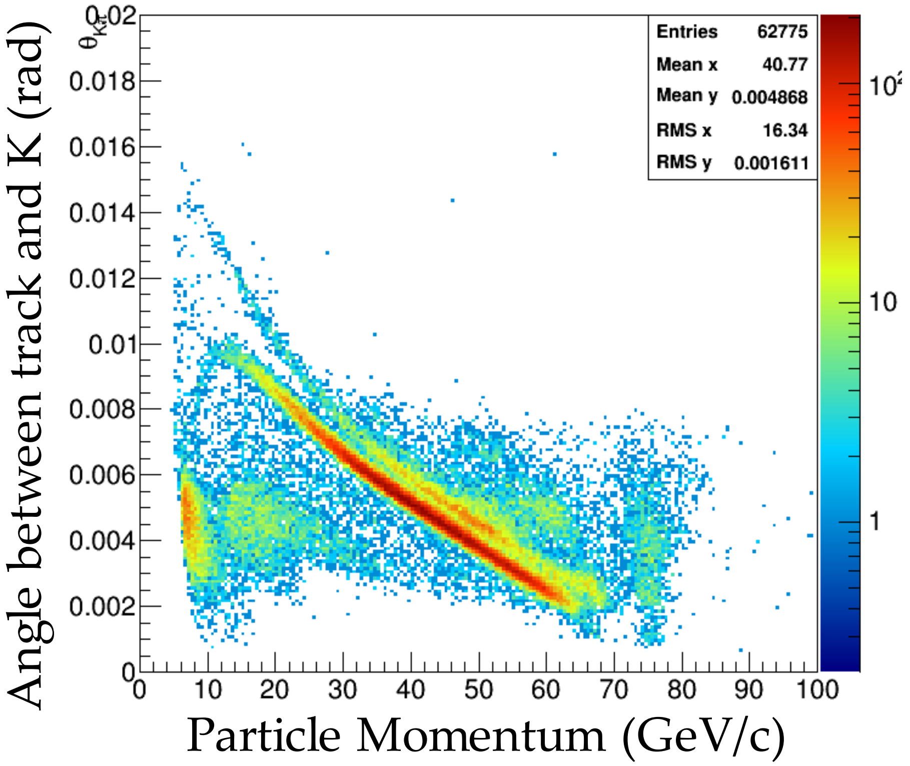
Ready to harvest un unprecedented amount of kaon decays…many questions are awaiting answers…

SPARE

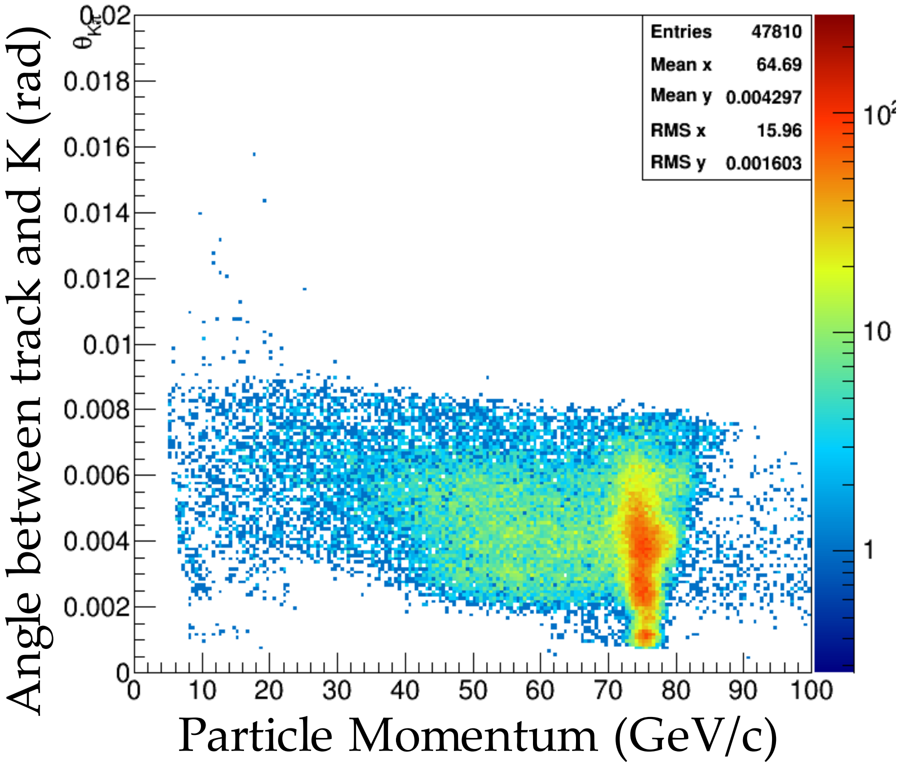
2014 DATA QUALITY

- Apply KTAG for kaon identification

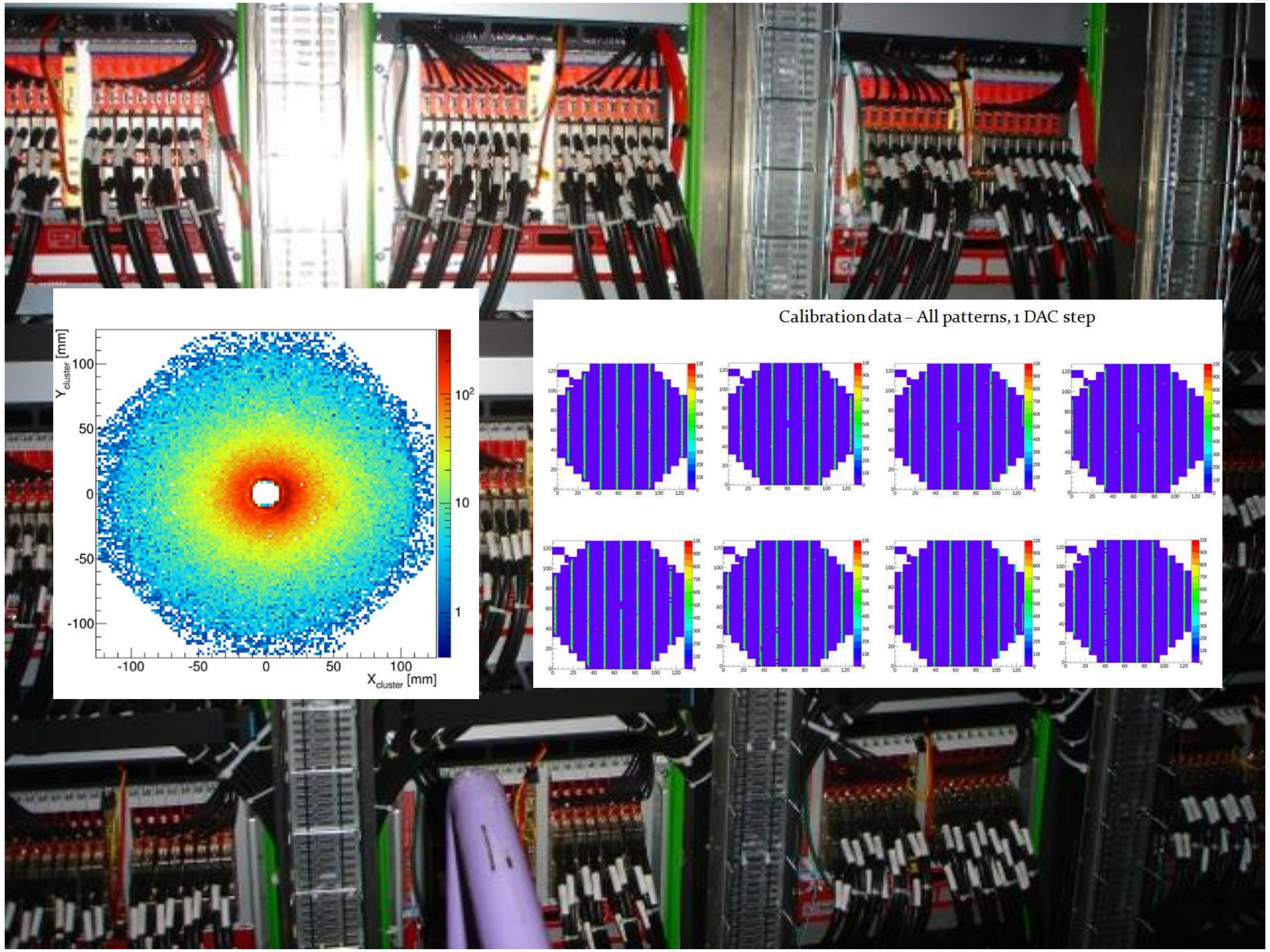
KTAG candidate



No KTAG candidate



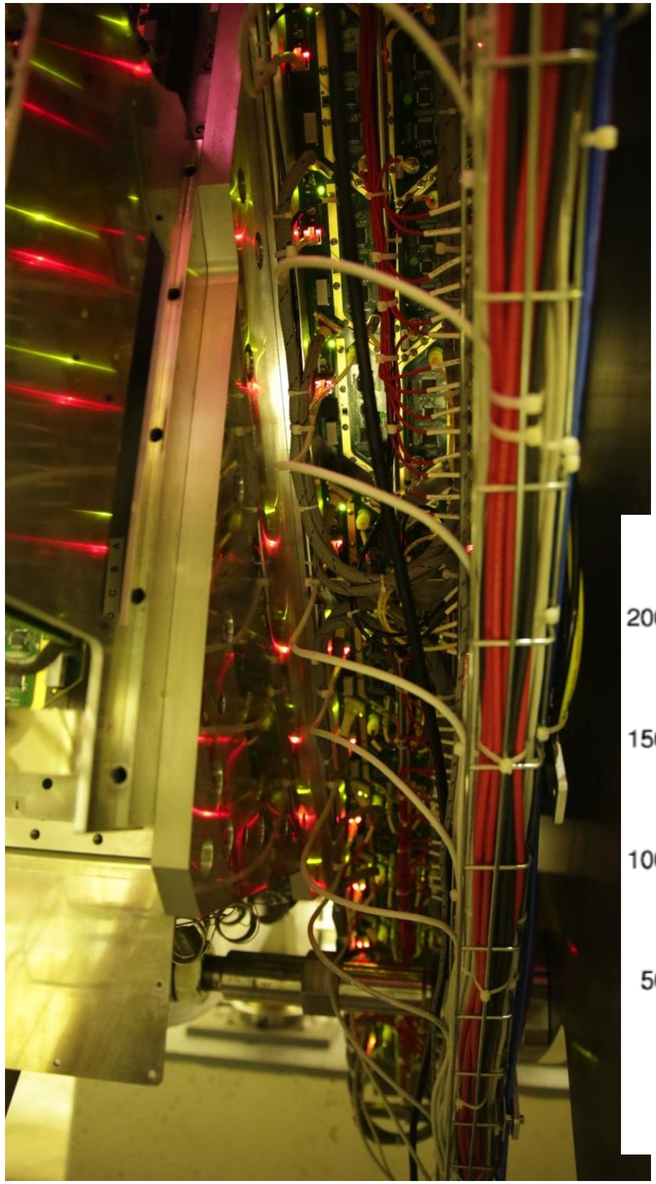
LIQUID KRYPTON READ OUT

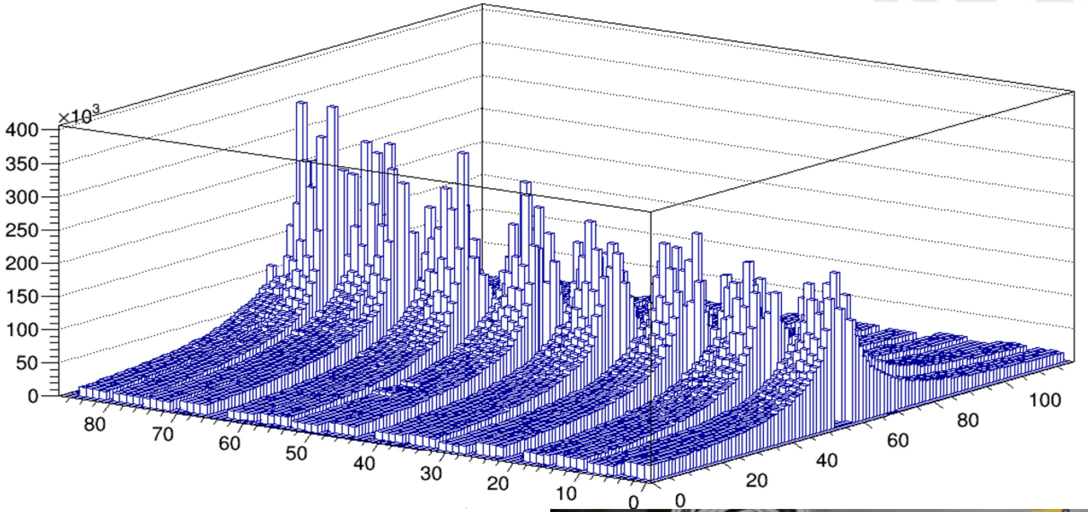


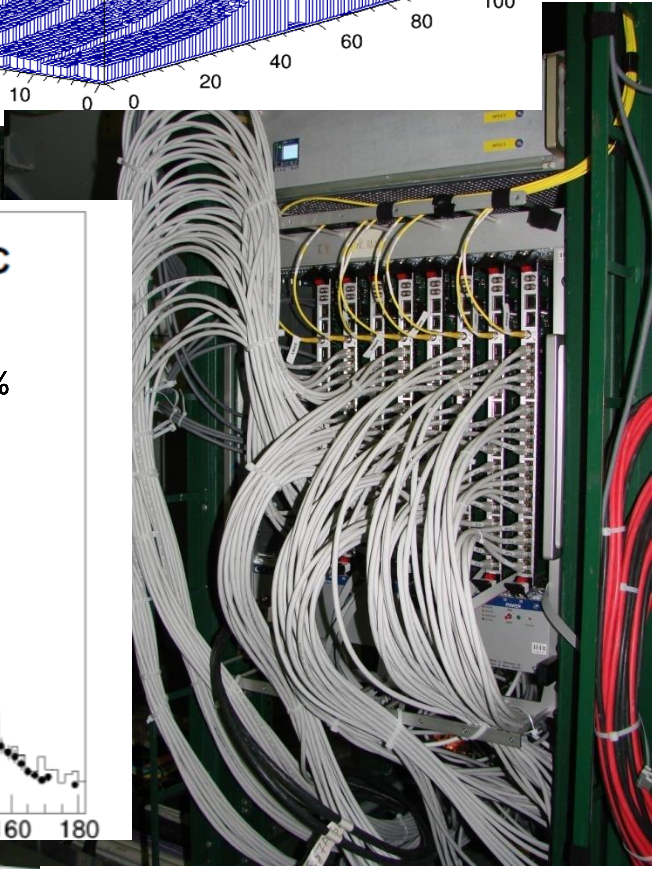
14 bit FADC, 40 Ms, 32 ch / module **432 modules, 28 VME crates**

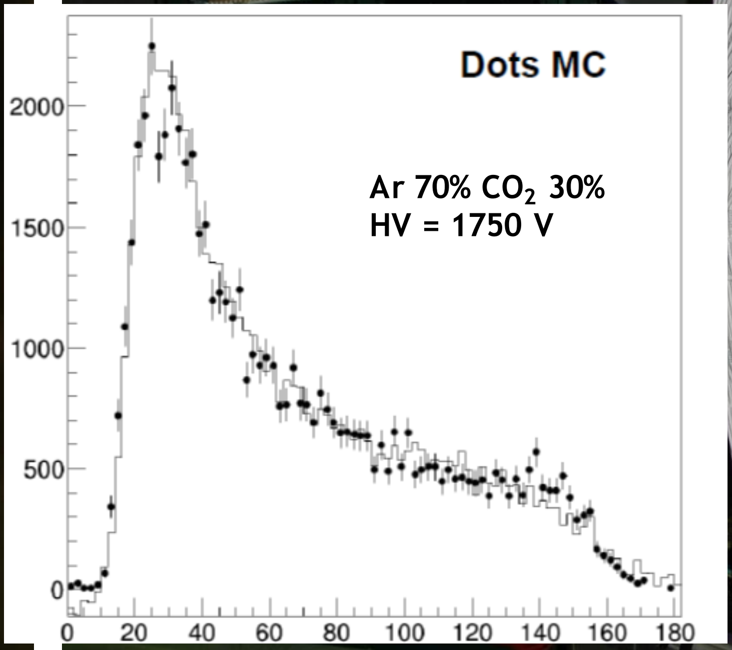
Specifications/Tender : CERN PH-ESE,PH-SME Manufacturer: CAEN (ITALY)

STRAW TRACKER

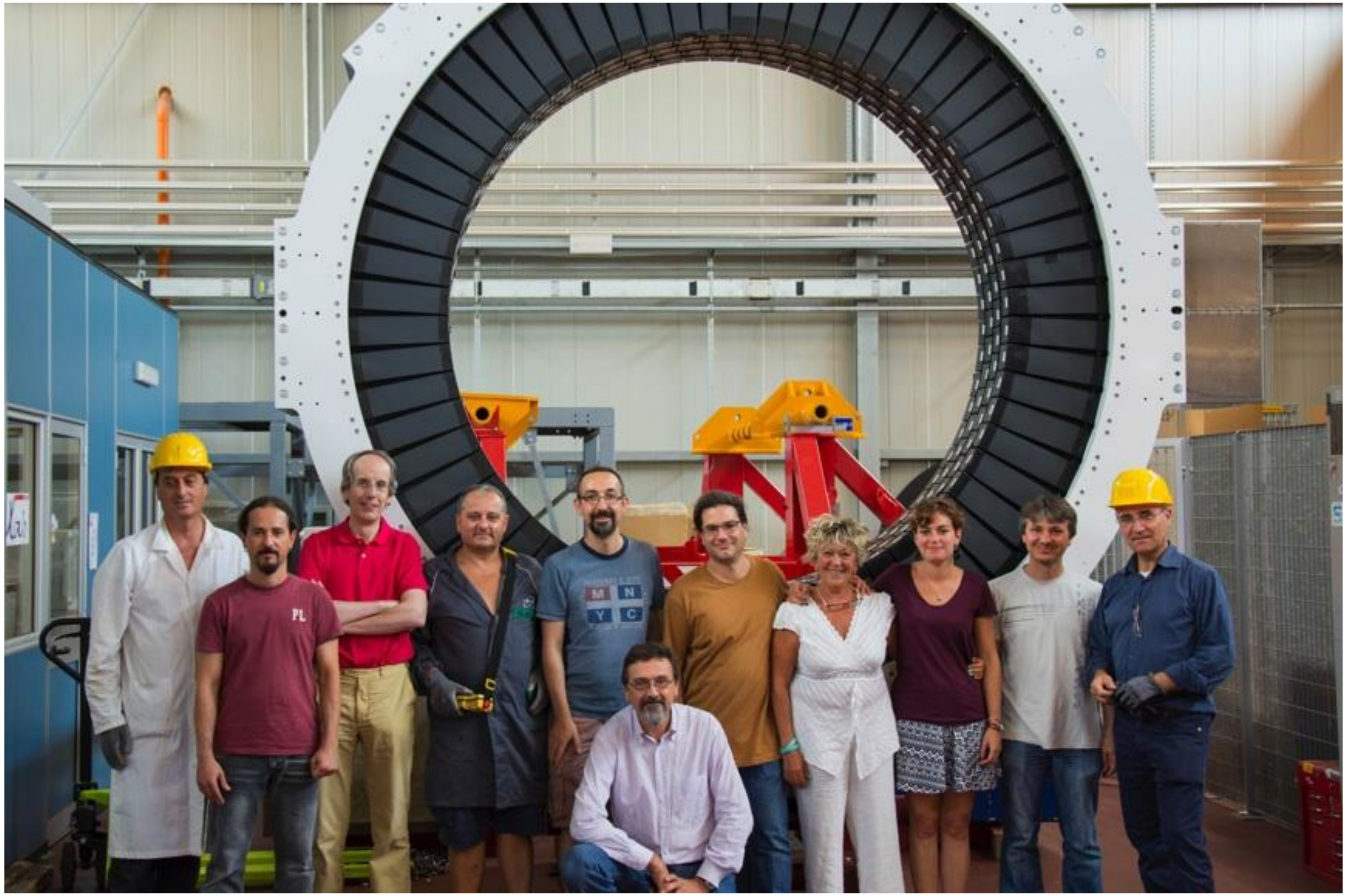








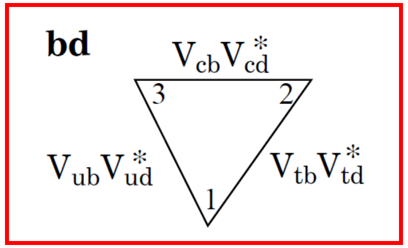
COMPLETION OF THE LAST LAV

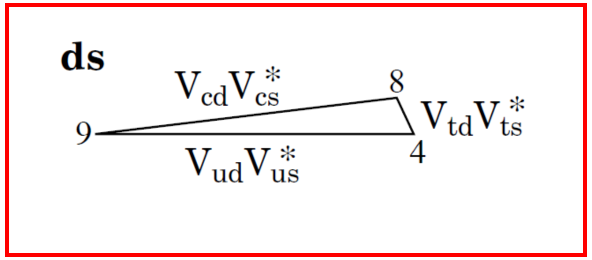


NA62 LAV: Frascati, Naples, Pisa & Rome 1 Collaboration

UNITARITY TRIANGLE FOR KAONS

- When the bd UT is used, the variables extracted from kaons are affected by an apparent parametric uncertainty due to V_{cb}





- The six UTs are all born equal (in the SM they have the same measure of CP-violation, the Jarlskog invariant J_{CP})

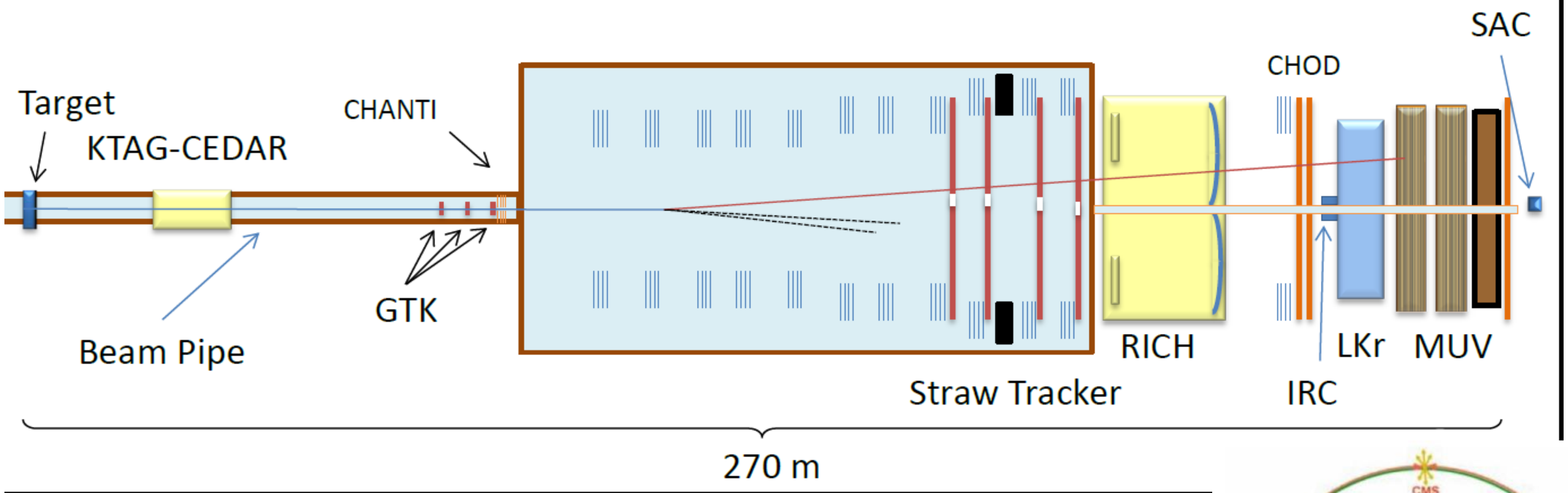
- A remarkable feature is that in the *ds* UT

$$J_{CP} = 5.6 * sqrt(BR(K_L \to \pi^0 \nu \nu))$$

This is a determination which is basically free from theoretical error (down to 1-2%)

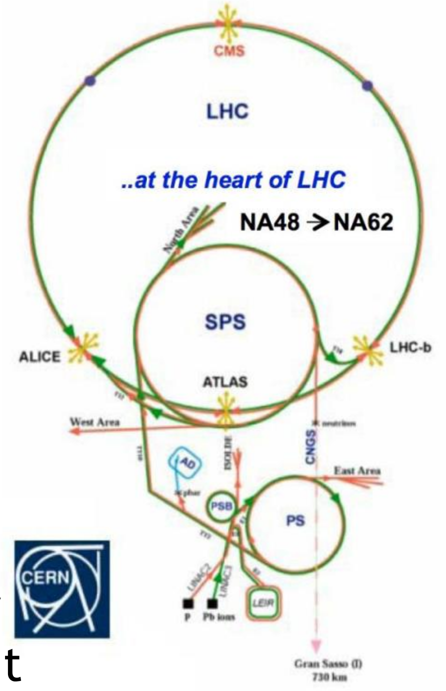
- It is to be compared with the current J_{CP} determination from the bd UT fit where the error ranges from 3% to 7% depending on the treatment of the errors

NA62 SCHEMATIC LAYOUT



10^{12} / s protons from SPS (400 GeV/c) on Be target (~1 λ)

750 MHz secondary beam: 75 GeV/c
- **Positive polarity**
- **Kaon fraction ~6%**
- **Δ p/p ~ 1%**
- **Useful kaon decays ~10% (5 MHz)**



NA62 is designed for a specific "silver bullet" measurement. This requires high beam rate, full PID, hermetic coverage, very light, high-rate tracking and state-of-the-art trigger and DAQ. It paves the way to a broad physics program

LARGE ANGLE VETOES

12 Electro-magnetic calorimeters
A1-A11 in Vacuum (including PMTs)
A12 in air
Lead Glass counters from the
LEP-OPAL ECAL (~2500 blocks)

All stations Installed

A Standard Model view of CP-Violation in Kaons

- Neutral Kaon Mixing (ππ, semi-leptonic)

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

$$|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$$

- Neutral Kaon Decays into ππ

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} \propto \mathrm{Im}(V_{td}V_{ts}^*)\left[P^{1/2} - P^{3/2}\right] e^{i(\phi_{\varepsilon'} - \varphi_{\varepsilon})}$$

PDG Average

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} = (1.68 \pm 0.14) \times 10^{-3}$$

Hierarchical Structure in powers of λ

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

λ = sine of the Cabibbo angle

Wolfenstein parameterization

From Global fit (PDG review, 2014):

Imposing SM constraint (3 generation unitarity):

$\lambda = 0.22535 \pm 0.00065$ $\quad$ $A = 0.811^{+0.022}_{-0.012}$

$\rho = 0.131^{+0.026}_{-0.013}$ $\quad$ $\eta = 0.345^{+0.013}_{-0.014}$

Some Constraints on the Unitarity Triangle

Process	CKM and other factors	Constraint
$b \rightarrow u$ / $b \rightarrow c$	$\lvert V_{ub}\rvert^2 / \lvert V_{cb}\rvert^2$	$\rho^2 + \eta^2$
Δm_{Bd}	$\lvert V_{td}\rvert^2 \ (f_{Bd}B_{Bd})^2$	$(1-\rho)^2 + \eta^2$
$\Delta m_{Bd} / \Delta m_{Bs}$	$\lvert V_{td} / V_{ts}\rvert^2 \ (f_{Bd}B_{Bd} / f_{Bs}B_{Bs})^2$	$(1-\rho)^2 + \eta^2$
ε_K	(see before)	$\eta(1-\rho)$
$B(K^0_L \rightarrow \pi^0 \nu \nu)$	$\lvert Im(V_{td} V^*_{ts})\rvert^2$	η^2