RARE DECAYS

RAL, April 16, 2015

Prof. George E. Kalmus Fest

Particle Physics: from the bubble chamber to the LHC, and beyond

A. Ceccucci /CERN

SETTING THE SCENE

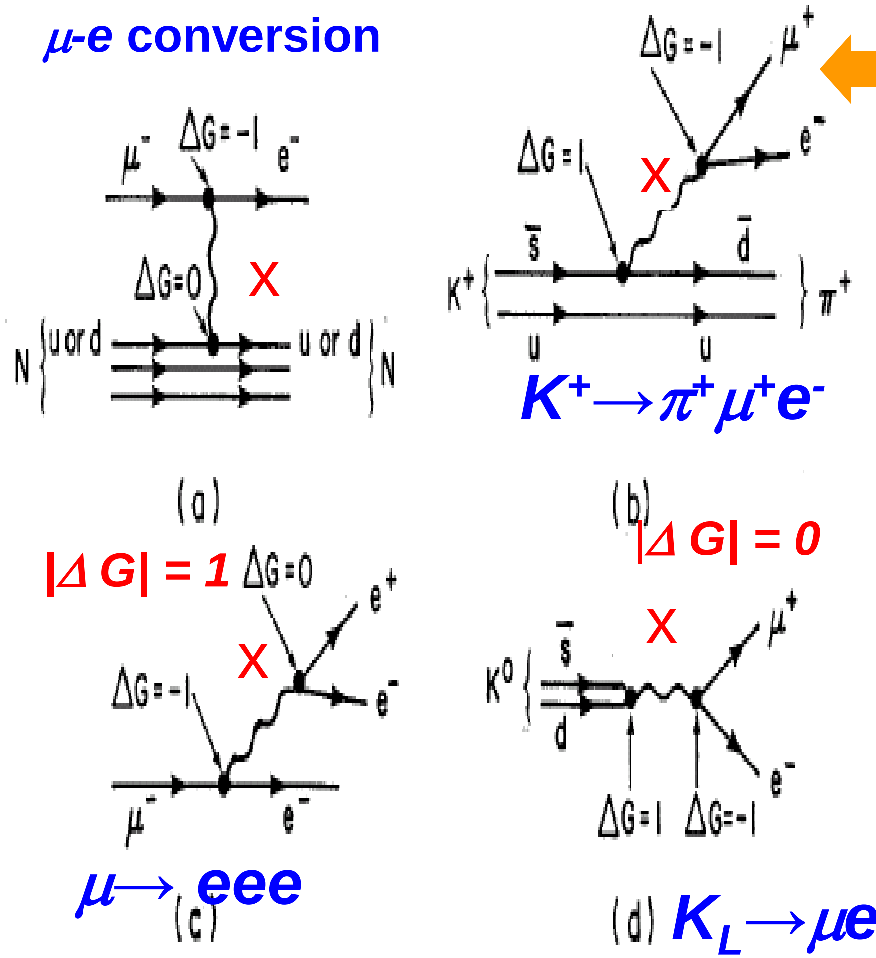
- Quark mixing and CP-Violation has been a very active area of investigation over the past decades
- Owing to the last round of experiments in K and B mesons, our understanding is now completely compatible with the existence of “just” one phase in the Cabibbo-Kobayashi-Maskawa mixing matrix
- The precision 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”

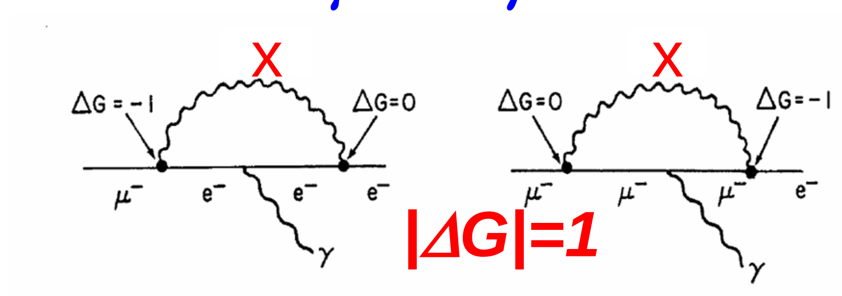
QUARKS AND LEPTONS

- FLAVOUR Encompasses quarks, charged and neutral leptons…
- But they are very different!
- Charged Lepton mixing is absent because of the quasi degeneracy of the neutrino masses
- For charged leptons the gauge base and the mass base are the same
- Neutrino mixing may or may not be irrelevant to charged lepton flavor violation
- In SM the weak charged current for leptons is diagonal. The "accidental" lepton flavour conservation is built to be conserved by construction

Puzzling replication of generations



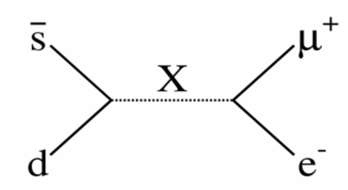
- Foreseen in many extensions of SM:
  - –Generation-Changing gauge interactions (Cahn, Harari (1980))
  - –Left-Right symmetry
  - –Technicolor
  - –Compositeness
  - –Super-symmetry



Lower bounds for generation-changing bosons ($g_X/g_W \sim 1$)

$$\frac{Br(K^+ \to \pi^+ \mu^+ e^-)}{Br(K^+ \to \pi^0 \mu^+ \nu)} = 16 \frac{1}{\sin^2 \vartheta_C} \left(\frac{g_X}{g_W} \right)^4 \left(\frac{M_W}{M_X} \right)^4$$

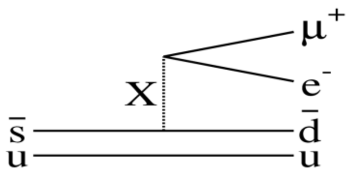
E871



$B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$

>150 TeV/c²

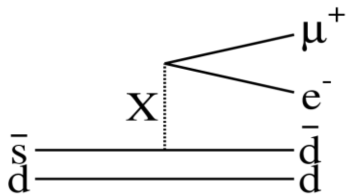
E865



$B(K^+ \to \pi^+ \mu^+ e^-) < 1.2 \times 10^{-11}$

>80 TeV/c²

KTeV



$B(K_L^0 \to \pi^0 \mu^+ e^-) < 3.2 \times 10^{-10}$

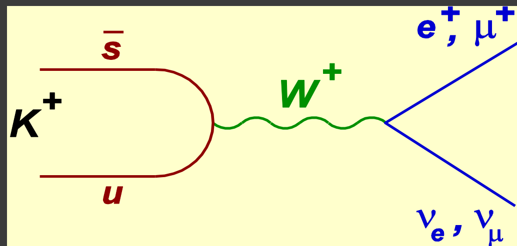
>37 TeV/c²

CHARGED LEPTON FLAVOUR VIOLATION: STATE OF THE ART AND EXPECTATIONS

Channel	Current limit (90%CL)	experiment	Future Expectation (SES)	When [my estimate]
μ --> e g	< 5.7 10^{-13}	MEG (PSI)		
		MEG-2 (PSI)	5 10^{-14}	2020
μ-->eee	<1 10^{-12}	SINDRUM (PSI)		
		Mu3e (PSI)	10^{-16}	2020
τ-->μ g	<4.4 10^{-8}	BABAR		
		BELLE II	2 10^{-9}	2023
μ – e conv	<7 10^{-13}	SINDRUM II (Au)		
		Mu2e / COMET	2 10^{-17}	2025

Related Topic: Lepton Universality $R_K = K_{e2}/K_{\mu 2}$

SM

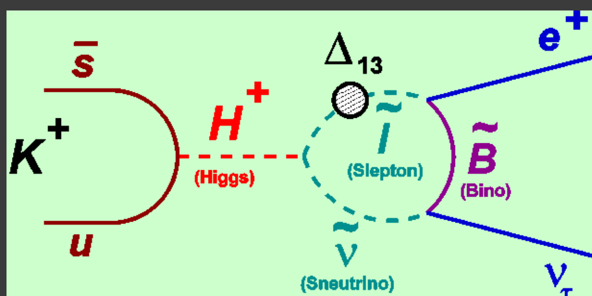


$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{rad.corr.})$$

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

Cirigliano & Rosell PRL 99 (2007) 231801

BSM, LFV



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

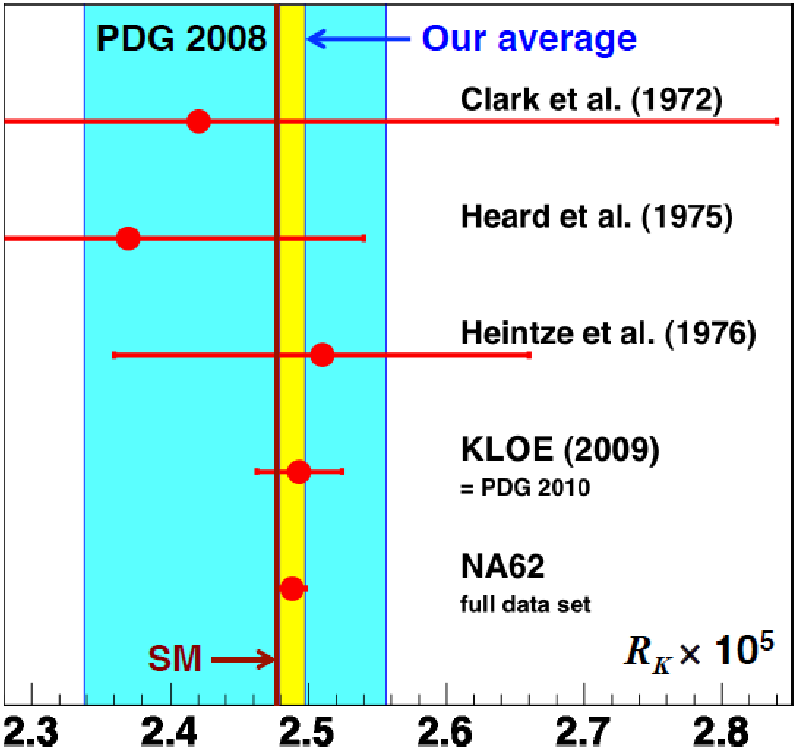
$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right) \left(\frac{m_\tau^2}{M_e^2}\right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

Example:

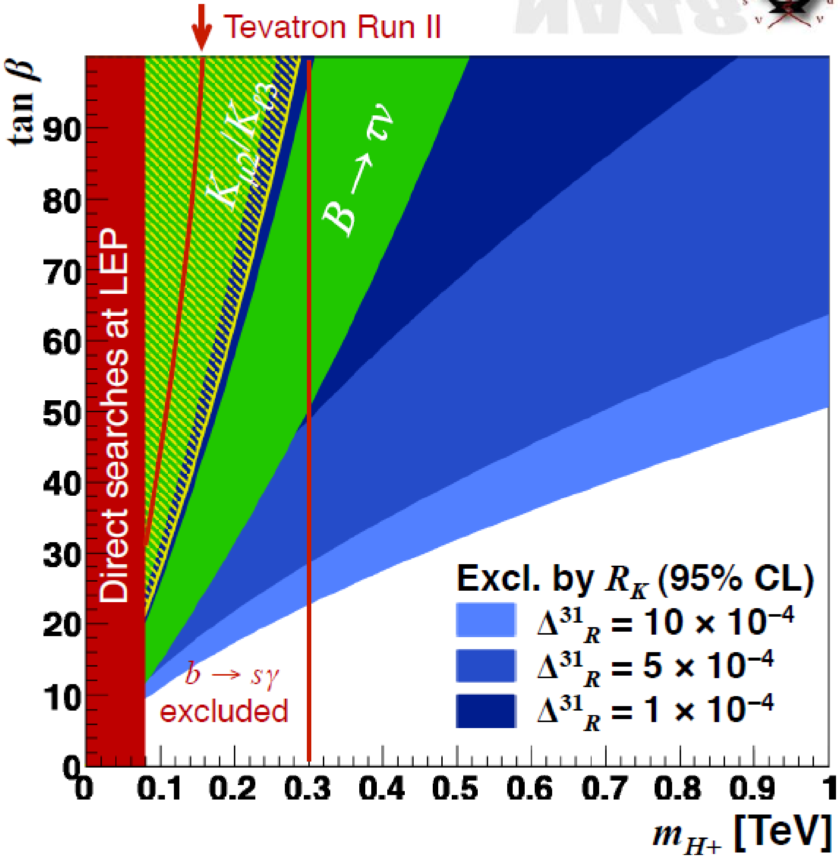
($\Delta_{13} = 5 \times 10^{-4}$, $\tan\beta = 40$, $M_H = 500$ GeV/c^2)

$R_K^{MSSM} = R_K^{SM}(1+0.013)$.

R_K: world average



Average	$R_K \times 10^5$	$\delta R_K/R_K$
PDG 2008	2.447±0.109	4.5%
Current	**2.488±0.009**	**0.4%**



MSSM with R parity

$$R_K^{\rm LFV} \approx R_K^{\rm SM}\left[1 + \frac{m_K^4}{m_H^4}\frac{m_\tau^2}{m_e^2}|\Delta_R^{31}|^2 \tan^6\beta\right]$$

PROMISE OF NEW PHYSICS IN LOOPS

Standard Model „New Physics“

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

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

- 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

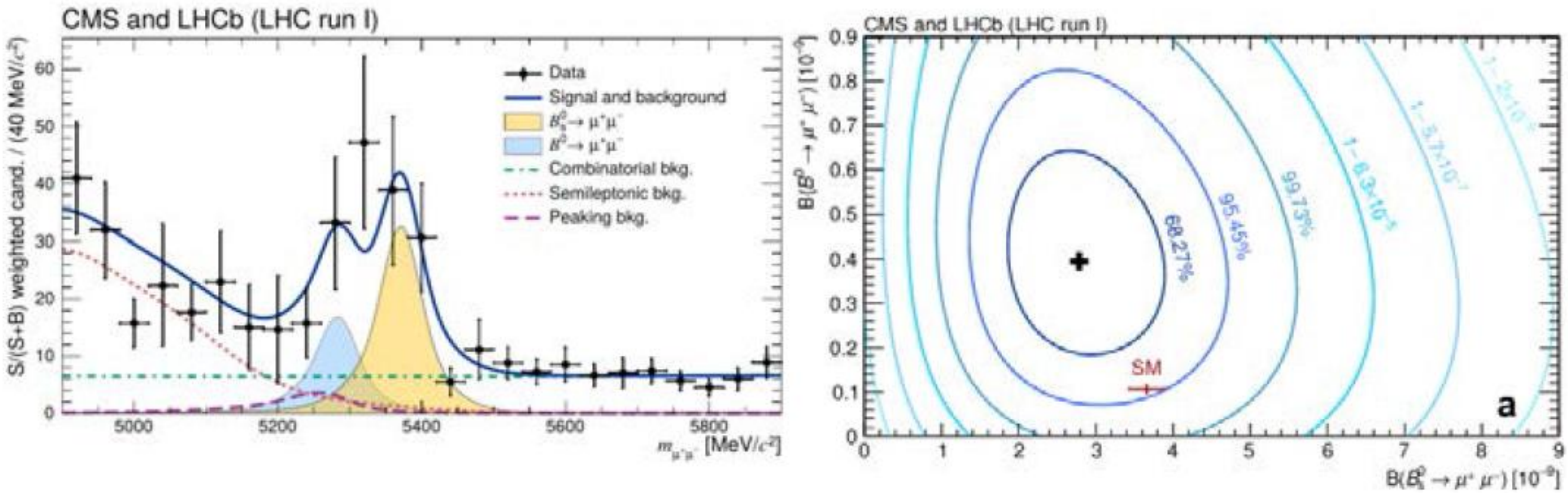
Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	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

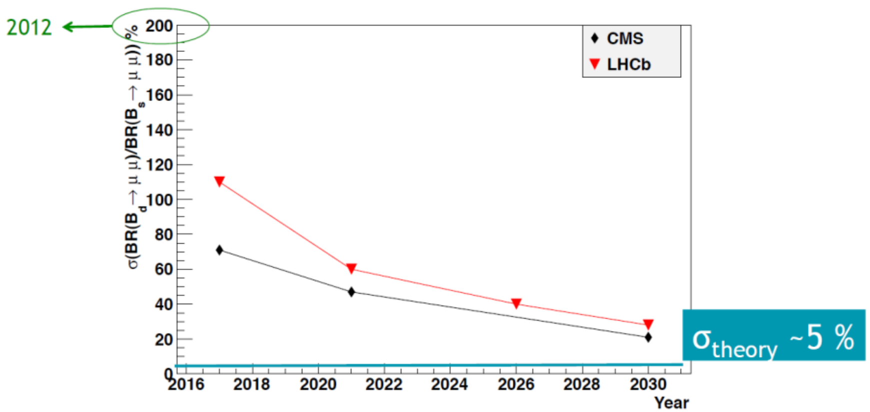
The very rare decay $B_s^0 \to \mu^+\mu^-$



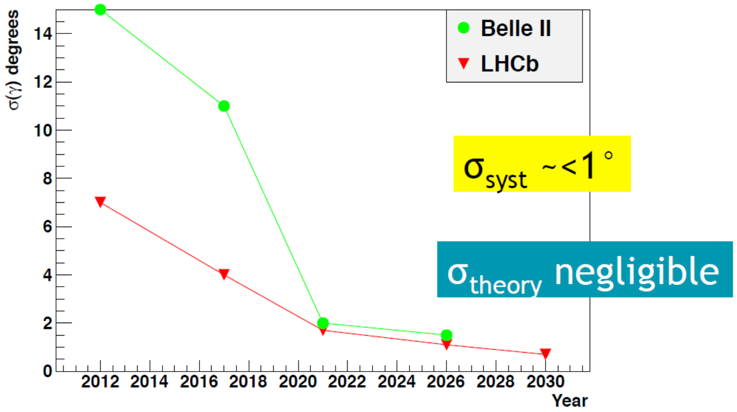
- Observation of $B_s^0 \to \mu^+\mu^-$ using combined CMS and LHCb dataset [arxiv:1411.4413], submitted to Nature
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.79^{+0.66+0.26}_{-0.60-0.19}) \times 10^{-9}$, 6.2σ sign. (7.6σ expected)
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.94^{+1.58+0.31}_{-1.41-0.24}) \times 10^{-10}$, 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

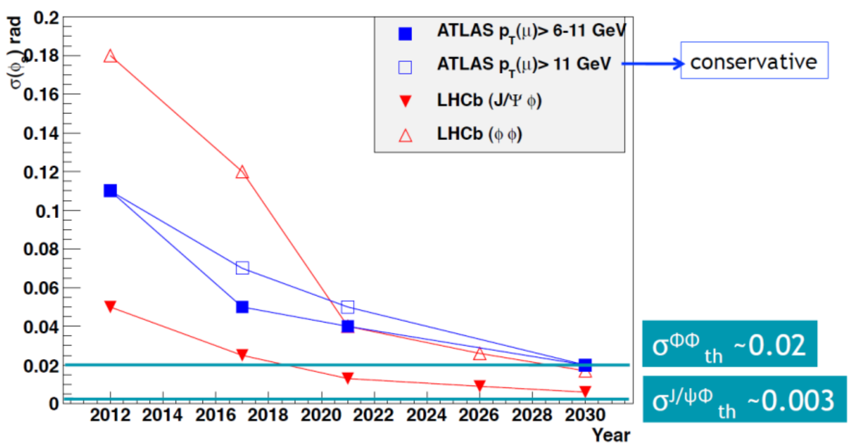
$BR(B_d \to \mu+\mu-)/BR(B_s \to \mu+\mu-)$



Expected precision on γ from tree decays

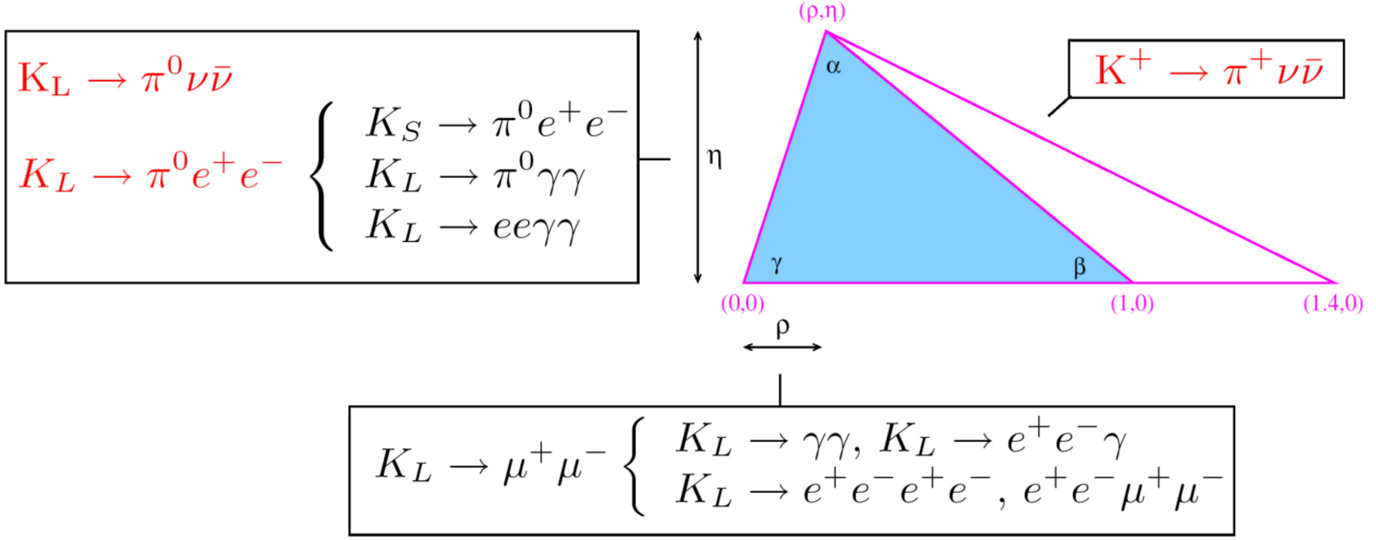


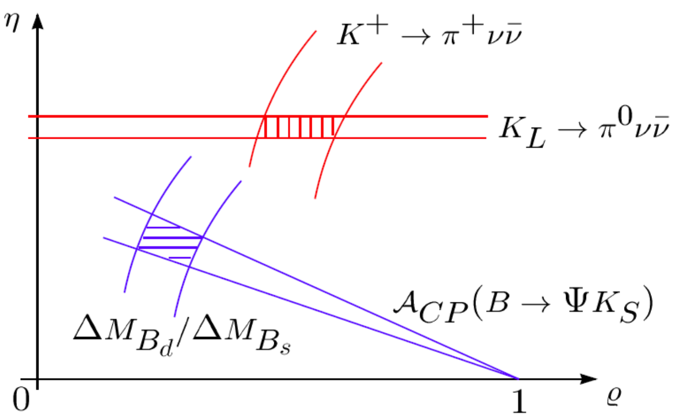
Expected precision on ϕ_s (rad)



- 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

KAON RARE DECAYS AT CERN

- Once the epsilon'/epsilon programme was well underway, at CERN we asked ourselves what could be done on rare kaon decays given our expertise and the SPS
- George came to CERN in 1998 to become Chairman of the SPC and he joined NA48 to explore the above mentioned possibility

CHAIRS OF THE CERN SPC

Terms of Office		
1954 - 1957 October	Prof. W. Heisenberg	Germany
1958 - 1960	Prof. E. Amaldi	Italy
1961 - 1963	Prof. C.F. Powell	United-Kingdom
1964 - 1966 June	Prof. L. Leprince-Ringuet	France
1966 - 1968 Oct.	Prof. G. Puppi	Italy
1968 - 1971	Prof. W. Gentner	Germany
1972 - 1974	Prof. A.G. Ekspong	Sweden
1975 - 1977	Prof. W. Paul	Germany
1978 - 1980	Dr G.H. Stafford	United-Kingdom
1981 - 1983	Prof. V.L. Telegdi	Switzerland
1984 - 1986	Prof. D.H. Perkins	United-Kingdom
1987 - 1989	Prof. I. Mannelli	Italy
1990- 1992	Prof. C.H. Llewelyn Smith	United-Kingdom
1993 - 1995	Prof. G.E. Wolf	Germany
1996 - 1998	Prof. J. Lefrançois	France
1999 - 2001	Prof. G.E. Kalmus	United-Kingdom
2002 - 2004	Prof. J. Feltesse	France
2005 - 2007	Prof. K. Peach	United-Kingdom
2008 - 2010	Prof. E. Fernandez	Spain
2011 - 2013	Prof. F. Zwirner	Italy
2014 -	Prof. T. Nakada	Switzerland

At the SPS Committee

GUESTS AT THE INAUGURAL SPS CEREMONY VISIT THE LAB

As it appears, George had been thinking about what to do with the SPS since a long time

FUTURE RARE DECAY SESSION

Thursday 11 Feb. 1999

Start 9.00

1.	Review actions from Dec. 98 NA 48RD W/S	George Kalmus	10'
2.	Competitiveness of a "Minimally" upgraded NA48 expt. for "one star" rare decays	George Kalmus	10'
3.	Other NA48RD items		
	a) More on K0L-->pi0e+e- b/g's	Victoria Martin	20'
	b) K0L-->pi0mu+mu- b/g's	Adrian Bevan/Matt Needham	15'
	c) Progress report on TRD	A. CATTA) Yuri Potrebennikov) Mauro Savrie)	15'
	d) Other contributions		15'
4.	COFFEE 10.25--10.45		
5.	K--->pi,nu,nubar at CERN		
	a) Physics and competition	George Kalmus	20'
	b) K0L--->pi0, nu, nubar Thoughts on feasibility	Bernard Peyaud	20'
	c) K+ --->pi+, nu, nubar Thoughts on feasibility	George Kalmus	15'
6.	Some comments on K+/- --->3pi asymmetry	George Kalmus	5'
7.	Discussion		15'

END 12.00

Above you see the names of some UK dream team students on NA48, here the others: R.S. Dosanjh, T.J. Gershon, E. Olaiya, R. Sacco

NA48 RD WORKSHOP

SUMMARY AND CONCLUSIONS FROM THE NA48 RARE DECAY WORKSHOP
30 NOV - 2 DEC 1998

George Kalmus

1.Aims of the Workshop :

a) To identify the physics case(s) for performing a rare decay search (primarily in K°_{L} decays) and estimate the sensitivity needed to achieve the goals.

b) To examine all the factors which might limit the ambitions identified in a). In particular to examine questions relating to the beam, triggering and signal extraction. Also to identify areas in the hardware which will need to be upgraded/replaced in order to achieve the maximum rate deliverable by an upgraded beam.

c) To involve and motivate a significant number of people in the definition and possible realisation of a competitive rare decay programme of intrinsic interest based on the present NA48 detector.

I believe that all these aims were met at some (useful) level. In particular I was gratified by the number of people who contributed to the workshop.

This was the first time we used videoconferencing in NA48….
There was a lot of “Hello, Hello, can you hear us….??”

MICHELIN STARS FOR KAONS

inrich gave the following Michelin ratings for the physics, and I am in broad
reement with him

* $K^\circ_L \rightarrow \pi^\circ \nu\nu$

is rate can be well calculated, the short distance (direct CP violating) amplitude
xpected to be >> than the long distance (indirect CP violating + CP conserving).

e B.R. is calculated to be $(3.1 \pm 1.3) \times 10^{-11}$ where the error is not theoretical but
minated by experimental input according to the standard model and

e value of η
Volfenstein representation of CKM triangle) can be directly determined from the
e.

$K^\circ_L \rightarrow \pi^\circ e+ e-$, $\pi^\circ \mu+ \mu-$

e decay has 3 components which in the standard model are (for $\pi^\circ e+ e-$)

Direct CP violating	B.R. = $(4.9 \pm 2.1) \times 10^{-12}$
Indirect CP violating	B.R. = $10^{-12} - 10^{-11}$
CP conserving	B.R. = few x 10^{-12}

(y understanding is that a) and b) are coherent and can interfere thus affecting the
e, but c) is not coherent with a) or b) and therefore there is no interference term.

e direct CP violating component is reasonably well calculated but the indirect
d CP conserving component are not, and require additional experimental
ormation e.g. $K^\circ_S \rightarrow \pi^\circ e+ e-$ for a better determination.

ver-the-less a measurement of this branching ratio would give information on
ect CP violating especially if combined with the measurement of $K^\circ_S \rightarrow \pi^\circ e+ e-$.
so, any B.R. substantially greater than 10^{-11} would be a clear indication of both
ect CP violation and new physics (e.g. SUSY).

Finally, there was a category of decays not discussed at the workshop and, therefore no "star" rating was given. These were the Lepton Family Violating (LFV) decays.

$K_L \rightarrow \gamma e \mu$
$\rightarrow \pi^\circ e \mu$
$\rightarrow e e e \mu$
$\rightarrow e \mu \mu \mu$
$\rightarrow e\pm\ e\pm\ \mu\pm\ \mu\pm$

I find it very difficult to give a star rating to these decays, since if one finds any of them then the rating is **** (only restaurant with this rating is in Stockholm!)

NA48 RD WORKSHOP

E) Signal Extraction and Simulation

Several channels were worked on , but the effort las largely concentrated, rightly, on the channel $K^\circ_L \to \pi^\circ$ e+ e- where two backgrounds were expected to be troublesome.

The conclusion reached was that for the decay $K^\circ_L \to \pi^\circ$ e+ e- there was an essentially irreducible background from the decay $K^\circ_L \to$ e+ e- $\gamma\gamma$. In the limit when the $\gamma\gamma$ invariant mass is that of a π° two decays are kinematically indistinguishable.

According to simulation, using cuts on the $\gamma\gamma$ invariant mass, that are already challenging, the rate of the b/g channel cannot be reduced to below about 10^{-10} and only this when the signal acceptance has been cut to 3 %.

It is very impotant that this result he checked independently.

At a level of a 10^{-11} SES for $K_L \to \pi^\circ$ e+ e- (which we might reach in 1 year operation at 3 % acceptance) we would expect 10 b/g events. This realistically limits our ability to measure the $K_L \to \pi^\circ$ e+ e- B.R. to $\lesssim 10^{-10}$.

Clearly a disappointment.

Work is continuing on $K_L \to \pi^\circ \mu^+ \mu^-$, although first indications are also not too hopeful for this decay.

And so we decided to focus on K_S first!

NA48/1 Status Report

Augusto Ceccucci/CERN

CERN-NA48/1: Cambridge, CERN, Chicago, Dubna, Edinburgh, Northwestern, Ferrara, Florence, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Turin, Warsaw, Wien

Collaboration Issues

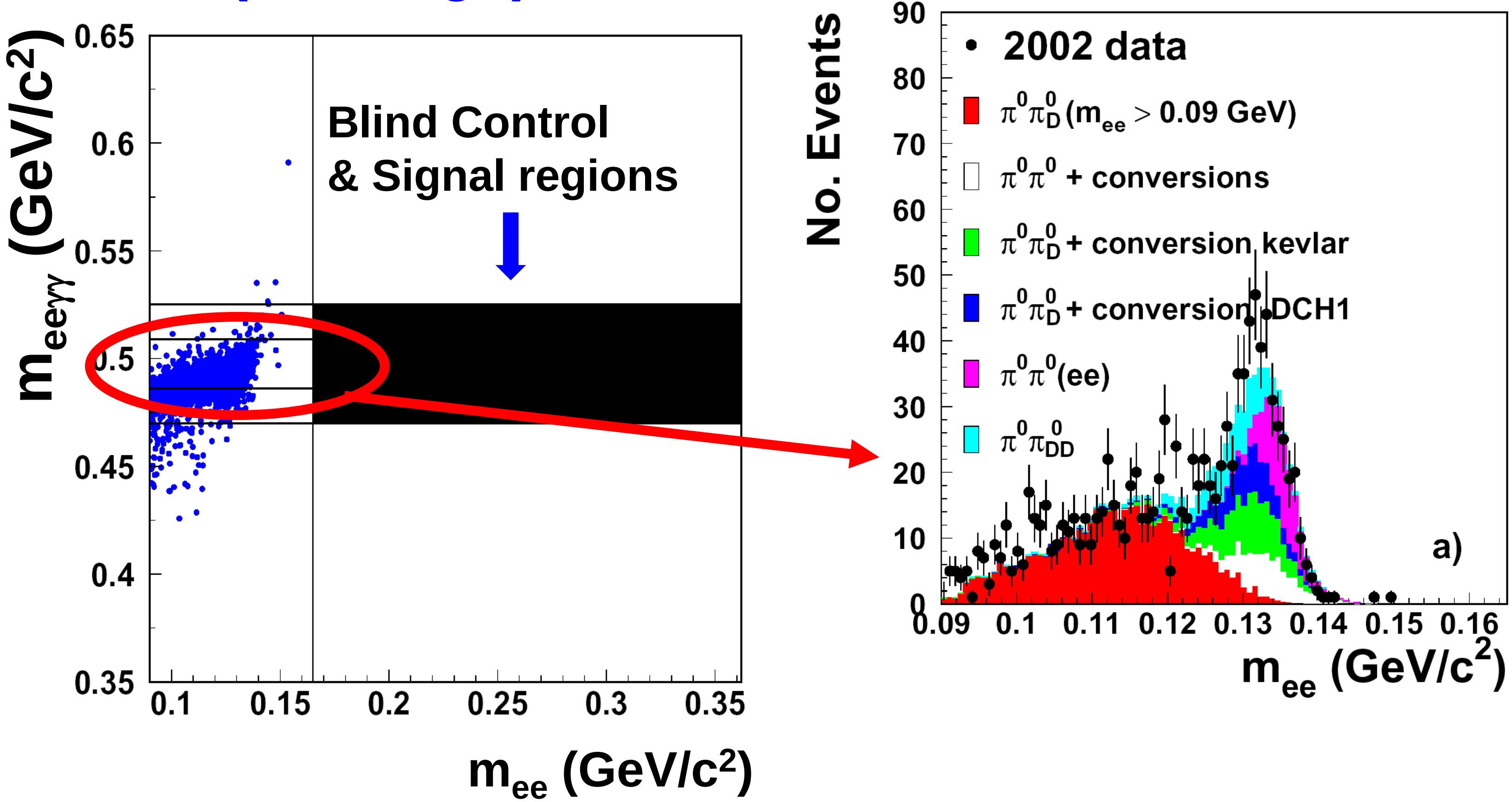
- **114 Scientific authors**
- **Monthly analysis meetings**
- **Insist on independent analyses**
- **12 PhD Students (either finished or quite advanced analyses)**
  - **Matthias Behler (Mainz)**
  - **Marco Clemencic (Torino)**
  - **Teresa Fonseca (Northwestern)**
  - **Guillaume Gouge (Saclay)**
  - **Andreas Hirstius (Mainz)**
  - **Ermanno Imbergamo (Perugia)**
  - **Venelin Kozhuharov (Dubna)**
  - **Peter Marouelli (Mainz)**
  - **Ulrich Moosbrugger (Mainz)**
  - **Mitesh Patel (Cambridge)**
  - **Mauro Piccini (Perugia)**
  - **Mark Slater (Cambridge)**

+ Several Master/Diploma theses

Analysis Co-ordinator
Cristina Lazzeroni

$K_S \to \pi^0 ee$

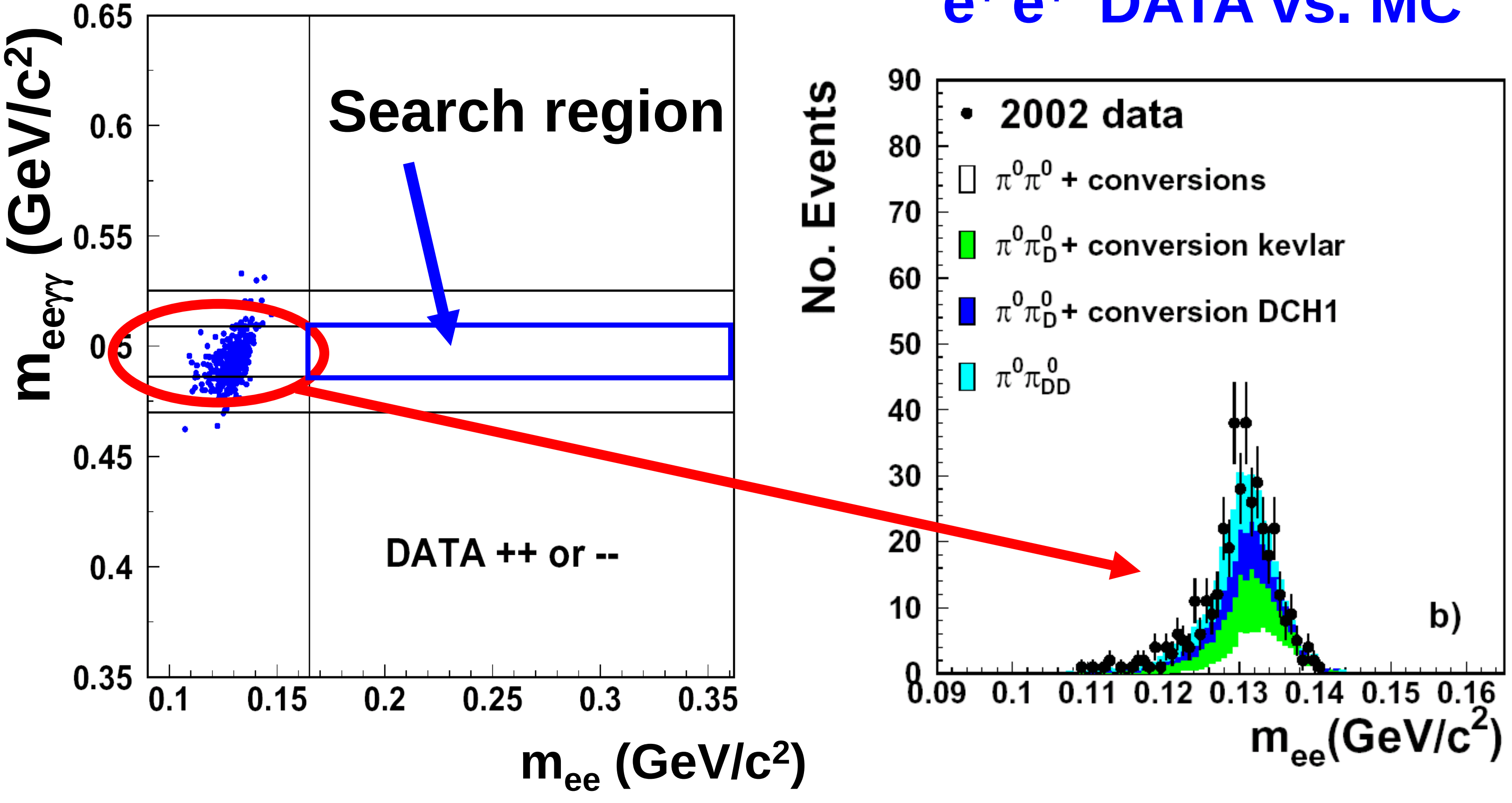
$e^{+-}e^{-+}$ (Odd Sign) DATA | **$e^{+-}e^{-+}$ DATA vs. MC**



$K_S \to \pi^0 ee$

$e^{+-}e^{+-}$ (Same Sign) DATA

$e^{+-}e^{+-}$ DATA vs. MC



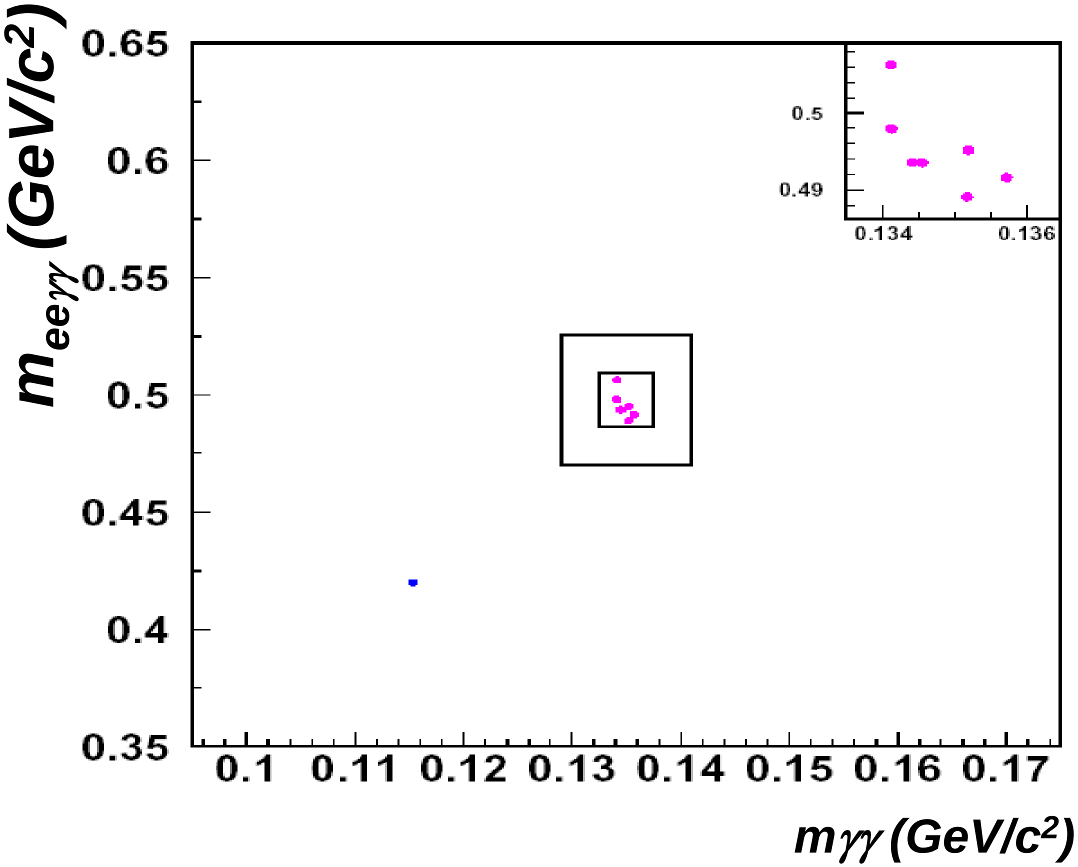
$K_S \to \pi^0 ee$

SUMMARY OF BACKGROUNDS:

Source	Control Region	Signal region
$K_S \to \pi^0_D \pi^0_D$	0.03	<0.01
$K_{L,S} \to ee\gamma\gamma$	0.11	0.08
$\pi e \nu + \pi^0 (\pi^0)$	0.19	0.07
Total	0.33	$0.15^{+0.10}_{-0.04}$

- Many other sources investigated and found to be negligible (e.g. neutral cascade decays)
- Blind analysis: Control and signal region remained masked until the study of the background was finished

$K_S \to \pi^0 ee$



- **7 candidates in the signal region**

- **0 in control region**
- **Background 0.15**

The probability that all 7 events are background is ~10^{-10}

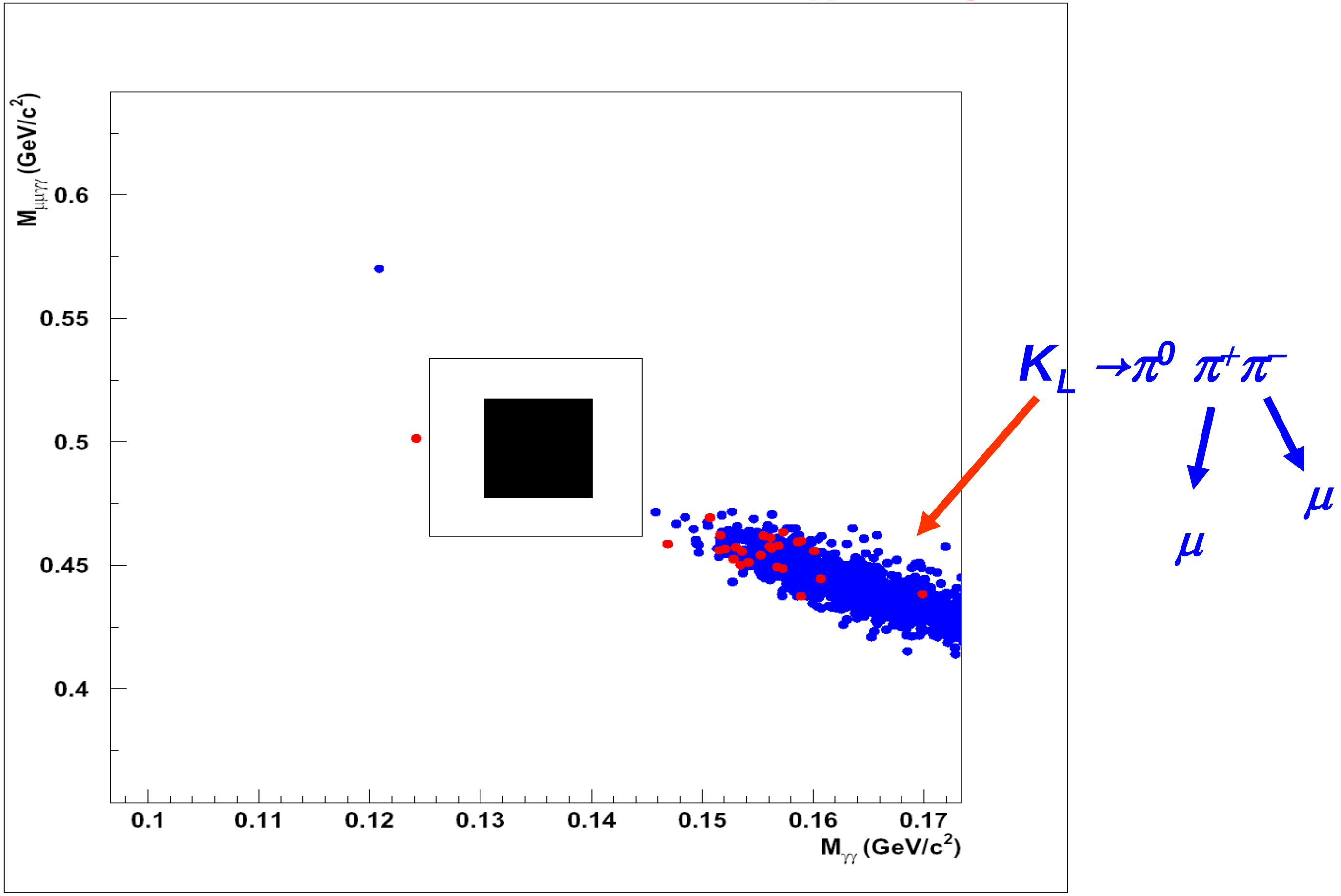
→ **First observation of $K_S \to \pi^0 ee$**

Backgrounds to $K_S \to \pi^0 \mu\mu$

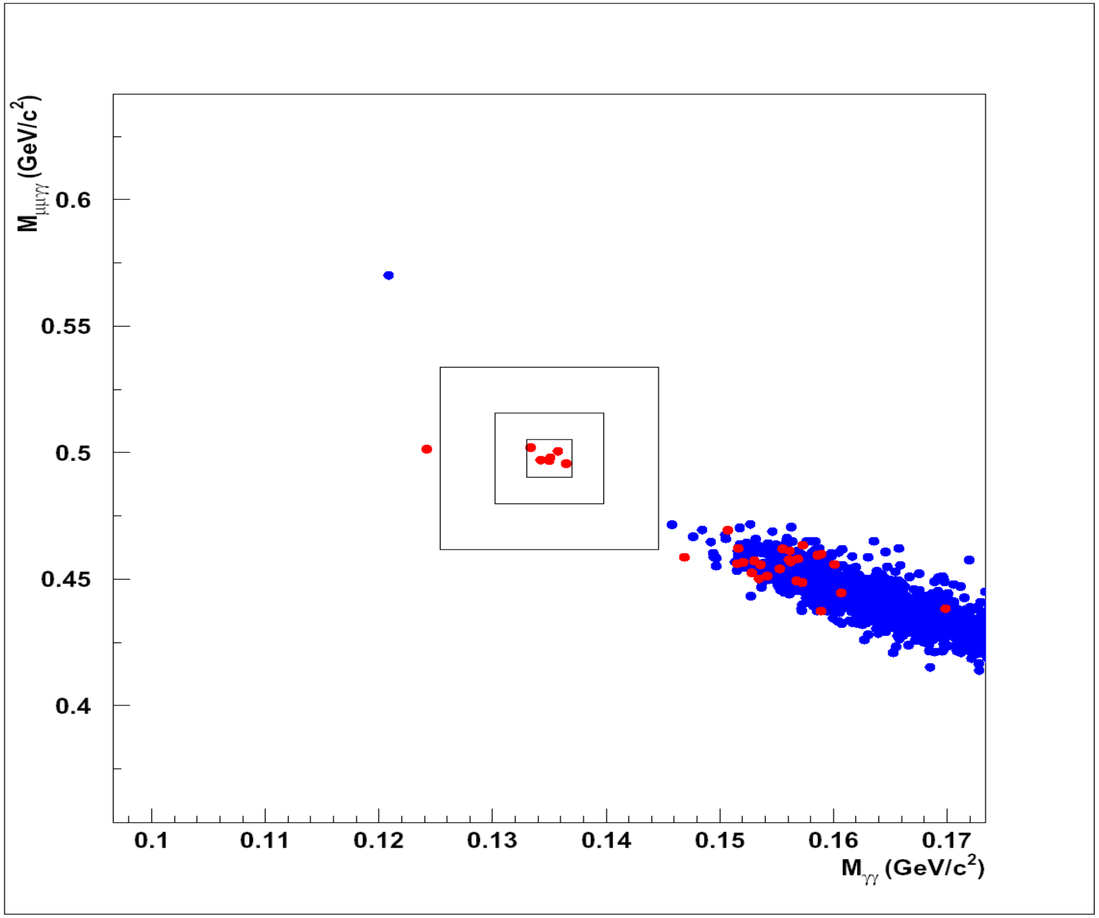
Source of Background	Expectation in signal region (# events)
$K_L \to \pi^+\pi^-\pi^0$	---
$K_{L,S} \to \mu^+\mu^-\gamma\gamma$	0.04
Neutral hyperons	---
Accidentals	0.20
In time background	---
Total	0.24

Ready to open box?

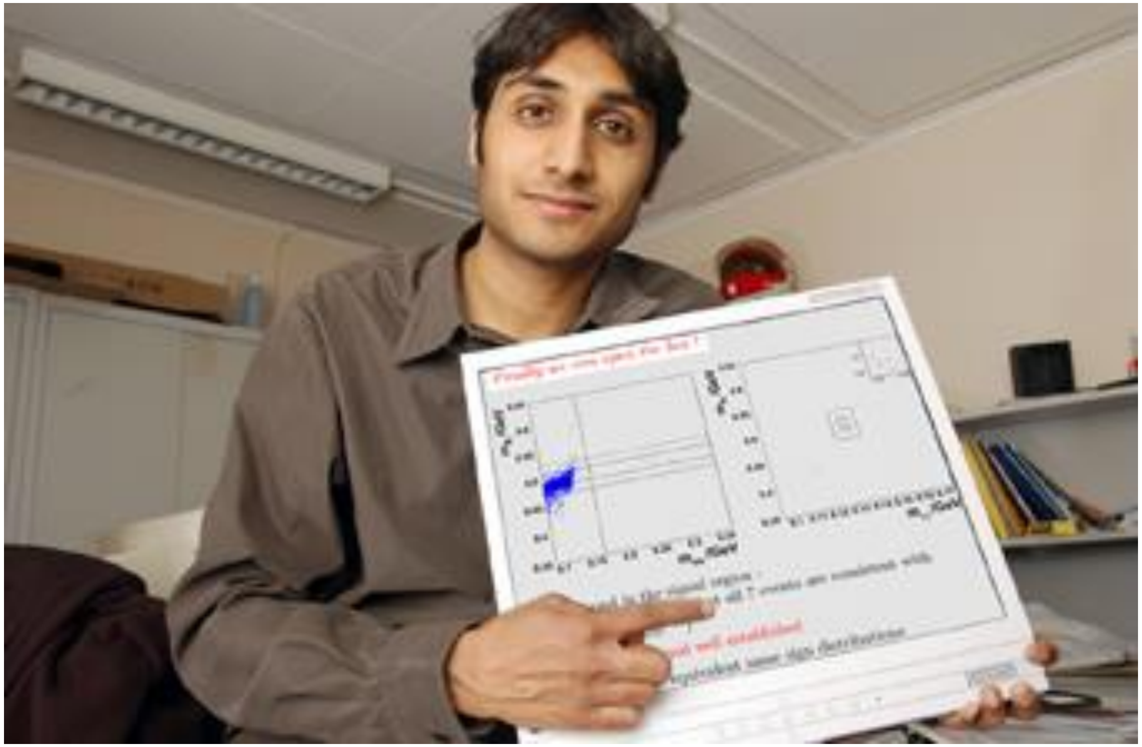
The red dots are the events passing $0 < \tau_K < 3\,\tau_S$



Six candidates!!



UNCOVERING THE VERY RARE
CERN BULLETIN 20/2004



“Physicists working on the NA48/1 experiment at CERN have made the first observation of the decay of the short –lived neutral kaon into a neutral pion and a muon- anti-muon pair. The decay, only recently presented at the winter conferences, occurs at a frequency of just a few parts per billion! Last year NA48/1 published the result of a decay into a pion and a positron electron pair. Together, for the first time, these two decays allow the prediction of the CP violation present in equivalent long-lived neutral kaon decays.”

KAON 99
CHICAGO

FUTURE CERN KAON PROGRAMME

GEORGE KALMUS
RAL

KAON99

1. PRESENTLY FORESEEN CERN PROGRAMME — FIG 1

2. DEVELOPMENT OF NA48 ? — FIG 2

K^0_L

- "RARE" DECAYS

  $K^0_L \longrightarrow \pi^0 e^+ e^-$

- "MEDIUM RARE" DECAYS

K^0_S + HYPERONS

$K^0_S \rightarrow \gamma\gamma$

$\rightarrow \pi^0 e^+ e^-$

$\rightarrow \pi^0 \gamma\gamma$

$\rightarrow \pi^0\pi^0\pi^0$??

K^+/K^-

$K^+/K^- \rightarrow 3\pi$ DALITZ PLOT ASYM.

$K^+ \rightarrow \pi^+\pi^- e^+ \nu$

3. BEYOND NA48

$K^0_L \rightarrow \pi^0 \nu\bar{\nu}$

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

28/5/99

	BEAM	P_p GeV/c	CYCLE SEC/SEC	PROTONS/PULSE ON TARGET	TOTAL DECAYS PER YEAR (120 DAYS, $\varepsilon = 0.5$) IN ACCEPTED P AND Z RANGE	SES (SINGLE EVENT SENSITIVITY) ASSUMING 10% ACCEPTANCE	ESTIMATED INSTANTANEOUS RATES IN DETECTOR COMPARED TO PRESENT NA48
1	K^0_L	450	2.5/14.4	1.5×10^{12}	6.7×10^{10}	1.5×10^{-10}	1
2	K^0_L	400	5.0/19.2	4×10^{12}	3.3×10^{11}	3×10^{-11}	3
3	K^0_L	400	5.0/19.2	1.2×10^{13}	1×10^{12}	10^{-11}	10
4	K^0_L	400	5.0/19.2	2.4×10^{13}	2×10^{12}	5×10^{-12}	20
5	K^0_S	450	2.5/14.4	3×10^{7}	8.7×10^{7}	1.2×10^{-7}	$\ll 1$
6	K^0_S	400	5.0/19.2	1×10^{10}	3.3×10^{10}	3×10^{-10}	< 3
7	$K^+ + K^-$	400	5.0/19.2	1×10^{12}	$(6.3 + 3.5) \times 10^{10}$	$(1.5 + 3) \times 10^{-10}$	2
8	K^0_L	400	5.0/19.2	1×10^{12}	8.3×10^{10}	1.2×10^{-10}	2

TABLE 1. SOME PARAMETERS OF POSSIBLE BEAMS THAT COULD BE INSTALLED IN THE PRESENT NA 48 BEAM LINE

(FOR SOME ADDITIONAL INFORMATION SEE "NOTES")

28/5/99

NOTES ON BEAMS

1. BEAM 1 AND BEAM 5 ARE THE TWO BEAMS CURRENTLY RUNNING SIMULTANEOUSLY FOR NA48. THE PROTONS USED FOR BEAM 5 ARE CHANNELLED TO THE K^0_S TARGET BY MEANS OF A BENT CRYSTAL.

2. BEAM 2 IS AN UPGRADE OF THE PRESENT K^0_L BEAM, IN WHICH THE K^0_S BEAM OPTION HAS BEEN REMOVED, THE V AND H ACCEPTANCES INCREASED AND THE PROTON INTENSITY INCREASED. THE PROTON MOMENTUM HAS BEEN REDUCED FROM 450 TO 400 GeV/c TO OBTAIN A HIGHER DUTY CYCLE. THIS WOULD REQUIRE MODEST MODIFICATIONS

3. BEAMS 3 AND 4 ARE SIMILAR TO BEAM 2 BUT WOULD REQUIRE CONSIDERABLE MODIFICATIONS TO HANDLE THE HIGHER PROTON FLUX ON TARGET

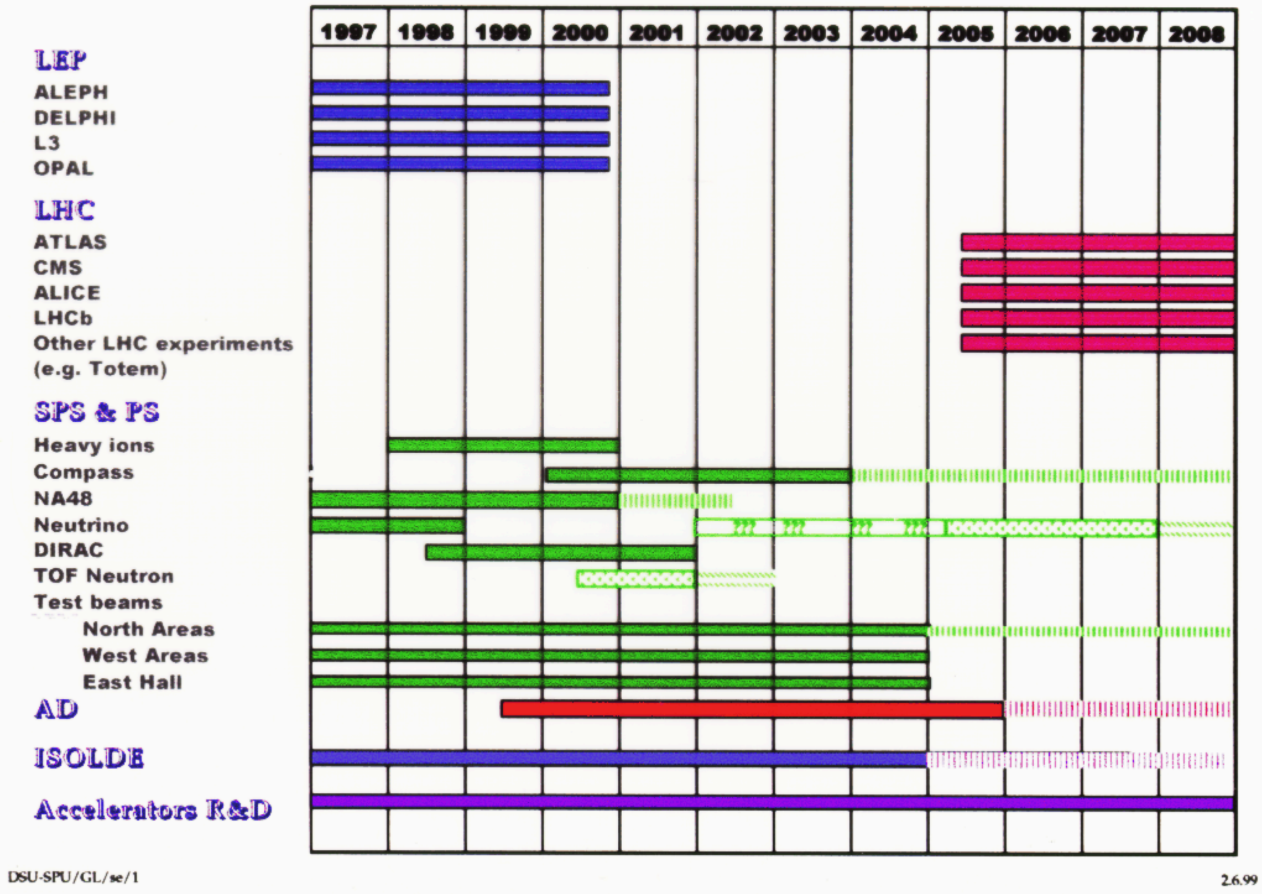
4. BEAM 6 IS A STAND ALONE K^0_S BEAM, THE BENT CRYSTAL BEING REPLACED BY A MAGNET

5. BEAM 7 IS A 60 ± 6 GeV/c K^+ AND K^- UNSEPARATED BEAM. THE 2 CHARGED BEAMS TRAVEL DOWN THE DECAY PIPE COINCIDENT IN BOTH TIME AND SPACE.

6. BEAM 8 IS A K^0_L BEAM WHICH CAN BE RUN SIMULTANEOUSLY WITH BEAM 7.

CERN PROGRAMME, CIRCA 1999

…no trace of kaon programme after mid 2002…



Presented by George at KAON99 at University of Chicago

YOU CAN READ GEORGE CONCLUSIONS PAPER IN THE PROCEEDINGS

Kaon Physics

Edited by
Jonathan L. Rosner
And Bruce D. Winstein

The University of Chicago Press
2001

Proceedings of Kaon 1999

57

Future CERN Kaon Program

George Kalmus

57.1 Introduction

The scientific program of CERN foreseen at present is summarized in fig. 57.1.

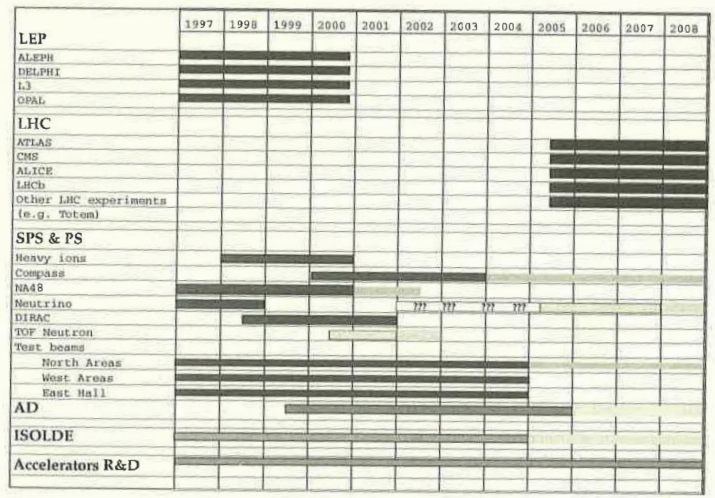


Figure 57.1: The scientific program of CERN.

It can be seen that NA48 continues through the year 2000. Beyond that, it might be extended to 2002 if a good enough scientific case can be made. NA48 is the only component of the CERN program containing a K decay element.

NA48 was designed primarily to measure ϵ'/ϵ, but it was foreseen that it would address various rare decay modes as well. Results from some of these have been presented by Wronka and Köpke at this conference.

	(GeV/c)	(sec/sec)	on target	per year (120 days, $\epsilon = 0.5$) in accepted P and Z range	(Single event sensitivity) assuming 10% acceptance	Estimated instantaneous rates in detector compared to present NA48
1 K_L^0	450	2.5/14.4	1.5×10^{12}	6.7×10^{10}	1.5×10^{-10}	1
2 K_L^0	400	5.0/19.2	4×10^{12}	3.3×10^{11}	3×10^{-11}	3
3 K_L^0	400	5.0/19.2	1.2×10^{13}	1×10^{12}	10^{-11}	10
4 K_L^0	400	5.0/19.2	2.4×10^{13}	2×10^{12}	5×10^{-12}	20
5 K_S^0	450	2.5/14.4	3×10^{7}	8.7×10^{7}	1.2×10^{-7}	$\ll 1$
6 K_S^0	400	5.0/19.2	1×10^{10}	3.3×10^{10}	3×10^{-10}	< 3
7 $K^+ + K^-$	400	5.0/19.2	1×10^{12}	$(6.3 + 3.5) \times 10^{10}$	$(1.5 + 3) \times 10^{-10}$	2
8 K_L^0	400	5.0/19.2	1×10^{12}	8.3×10^{10}	1.2×10^{-10}	2

Table 57.1: Some parameters of beams that could be installed in the present NA48 beam line (For additional information see 'Notes')

About a year ago a study started within the NA48 collaboration to determine whether the experiment and its beam could be modified in such a way as to allow very rare K_L^0 decay modes to be sought. (The guidelines were that changes to the present NA48 setup should neither be too costly nor take too much time or effort.) In particular the channel $K_L^0 \to \pi^0 e^+ e^-$ was targeted. The conclusion of this study was that it appeared to be possible, but not without some effort, to modify the experimental conditions so as to be able to reach a single-event sensitivity (SES) of $O(10^{-11})$ per running year in a typical channel.

This is a factor of about 30 lower than the present NA48 running conditions would allow, and is entering the interesting range for $K_L^0 \to \pi^0 e^+ e^-$, where the standard model branching ratio is expected to be $O(10^{-11})$. Recent studies [1, 2, 3], however, point out that the branching ratio for this channel might be enhanced to levels above 10^{-10}. A detailed study of backgrounds to this channel showed that the irreducible background due to $K_L^0 \to \gamma\gamma e^+ e^-$, as was pointed out by Greenlee [4], was at a level of 10^{-10} under the NA48 experimental conditions.

There is an ongoing study looking into less rare K_L^0 decay modes as well as K_S^0 modes and hyperon decays. A separate study is also being made into the feasibility of measuring the asymmetry in the Dalitz plot of K^+/K^- decays into 3 pions. A beam capable of transporting simultaneously K^+ and K^- down the present beam line has been designed.

Table 57.1 gives some of the parameters of beams that have been studied and would fit into the existing beam line without a major rebuild.

A decision by NA48 on which direction to follow after this year's running will be taken this autumn and presented to the SPS committee for approval.

There have also been some thoughts on the possibility of attacking the most interesting channels: $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$. However, the conclusion reached was that neither of these very challenging experiments could be seriously attempted without a completely new setup. My appraisal of the situation at CERN at present is that it would require the push from a sizeable community with considerable resources to launch such an ambitious program.

57.2 Notes on Beams

1) Beam 1 and beam 5 are the two beams currently running simultaneously for NA48. The protons used for beam 5 are channeled to the K_S^0 target by means of a bent crystal.

2) Beam 2 is an upgrade of the present K_L^0 beam, in which the K_S^0 beam option has been removed, the V and H acceptances have been increased, and the proton intensity has been increased. The proton momentum has been reduced from 450 to 400 GeV/c to obtain a higher duty cycle. This would require modest modifications.

3) Beams 3 and 4 are similar to beam 2 but would require considerable modifications to handle the higher proton flux on target.

4) Beam 6 is a stand-alone K_S^0 beam, the bent crystal being replaced by a magnet.

5) Beam 7 is a 60 ± 6 GeV/c K^+ and K^- unseparated beam. The 2 charged beams travel down the decay pipe coincident in both time and space.

6) Beam 8 is a K_L^0 beam that can be run simultaneously with beam 7.

References

[1] G. Colangelo and G. Isidori, JHEP **09**, 009 (1998).

[2] A.J. Buras and L. Silvestrini, Nucl. Phys. B **546**, 299 (1999).

[3] L. Silvestrini, TUM-HEP-350/99 (1999).

[4] H.B. Greenlee, 1990, Phys. Rev. D **42**, 3724 (1990).

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

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:

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

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

$$X(x_t) \sim 1.44$$

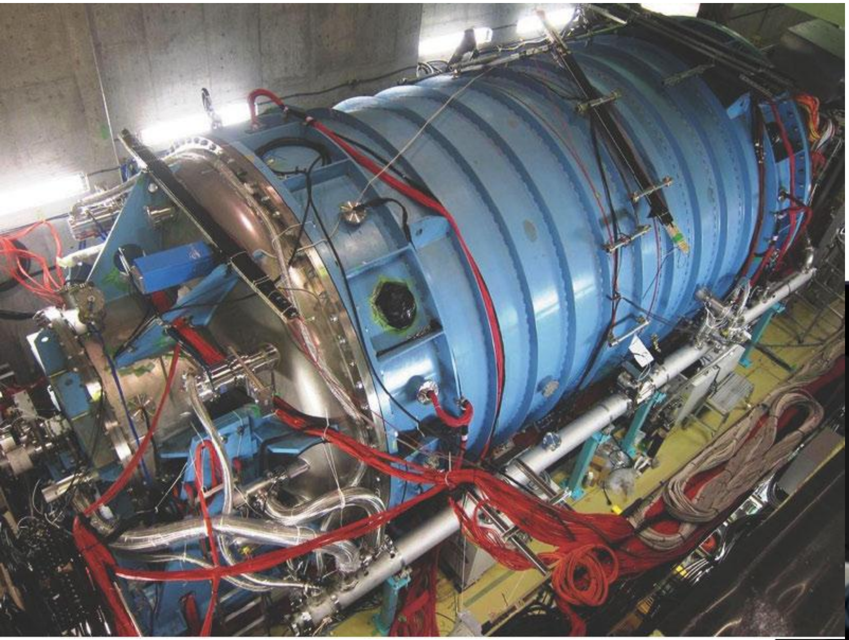
$$\lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

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

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

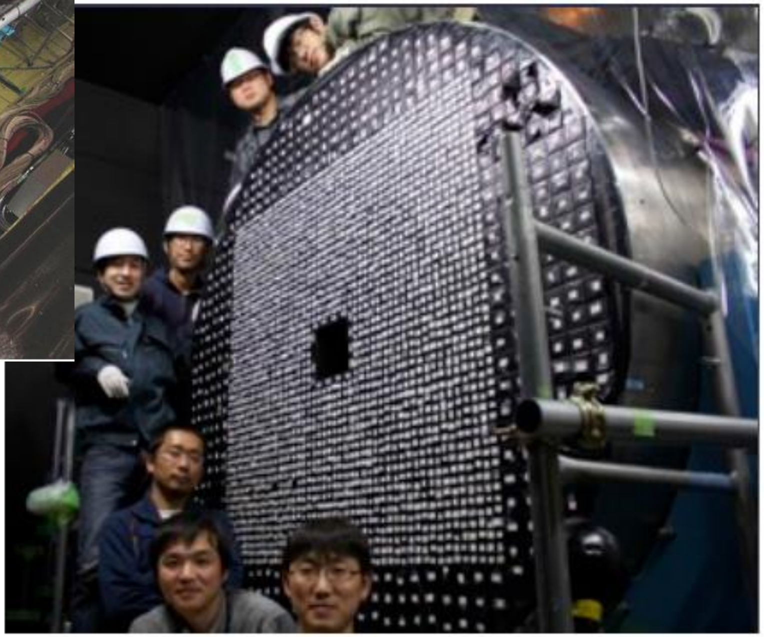
NEXT EXPERIMENT: KOTO (E14, J-PARC)

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

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

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

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

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

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

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

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

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:
$\delta Br/Br \sim 0.68\ \delta P_c/P_c$

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

$X(x_t) \sim 1.44$ (Buras et al.)

$P_c(X) = 0.41 \pm 0.05$ (Buras et al.)

CHARGED K BEAMS

"Stopped"

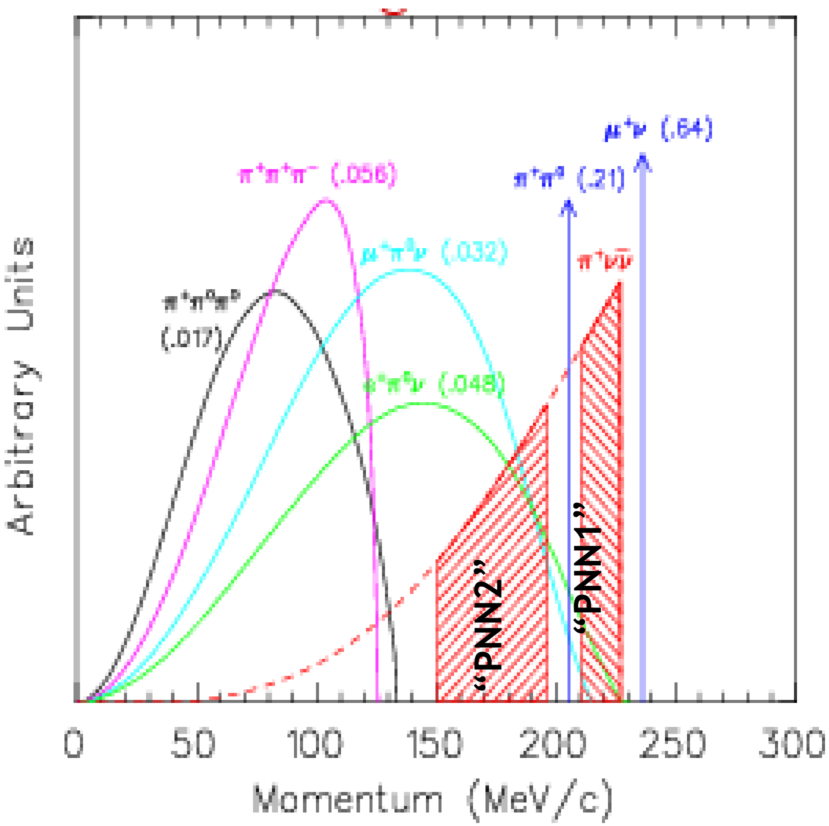
- Work in Kaon frame
- High Kaon purity (Electro-Magneto-static Separators)
- Compact Detectors

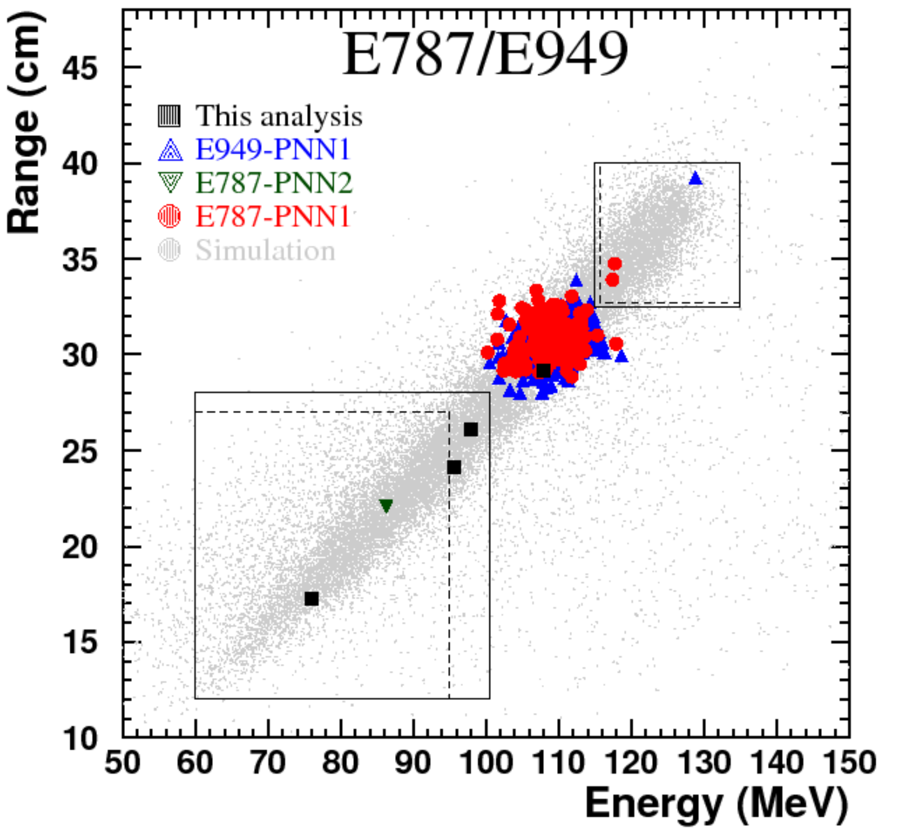
"In-Flight"

- 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

CERN-SPSC-2005-013
SPSC-P-326

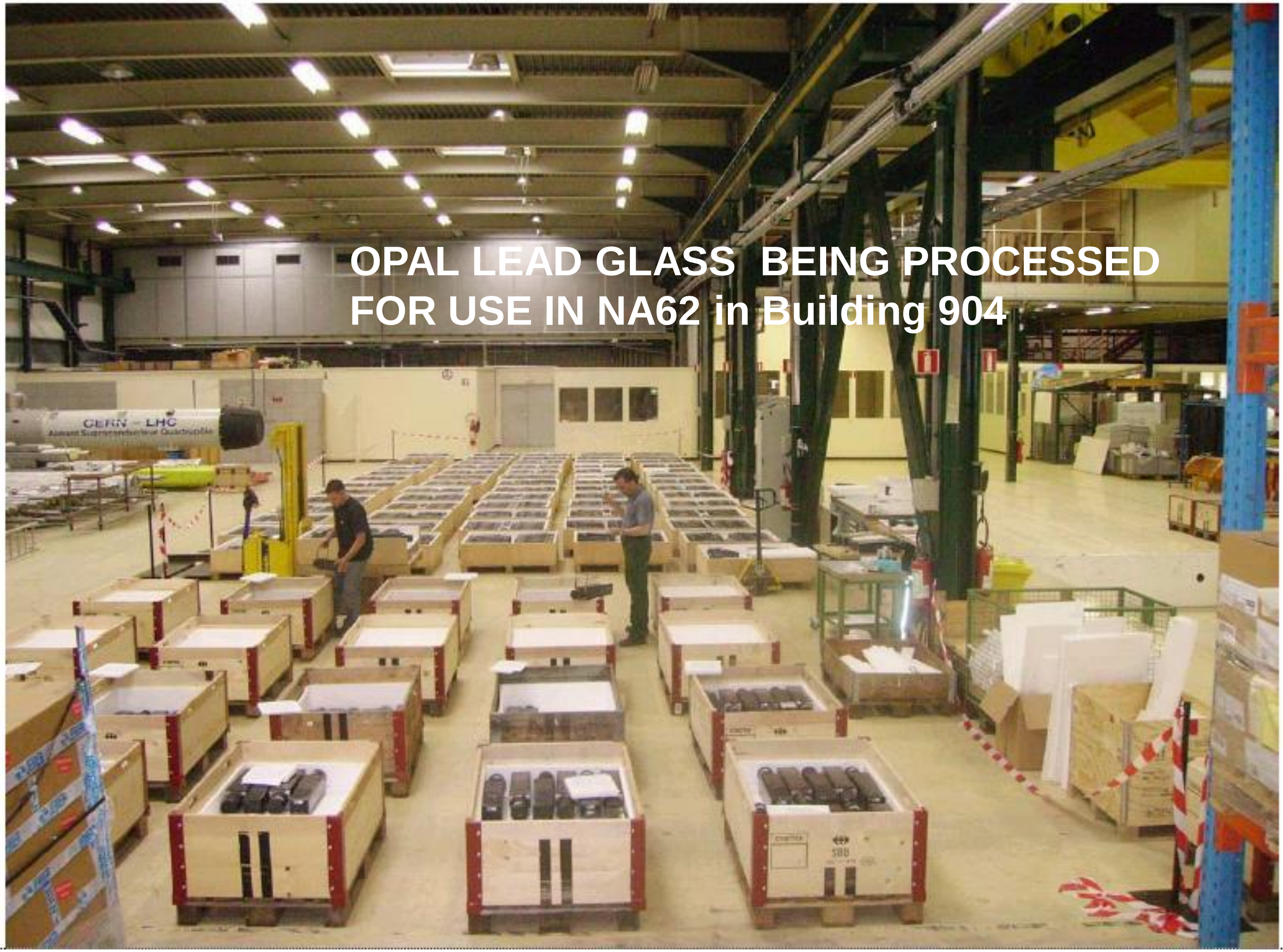
Proposal to Measure the Rare Decay $K^+ \to \pi^+ \nu \bar{\nu}$ at the CERN SPS

CERN, Dubna, Ferrara, Florence, Frascati,
Mainz, Merced, Moscow, Naples,
Perugia, Protvino, Pisa, Rome, Saclay,
San Luis Potosi, Sofia, Turin

A LOT OF HELP FROM GEORGE WAS NEEDED TO TURN THIS PROPOSAL INTO REALITY…

- Seminars in the UK…
- …after dinner scientific discussion at the Royal Society…
- And most of all…a phone call around Christmas 2006 when George kindly asked to look at CERN for some 3 inch phototubes to shield the Dark Matter detector in Daresbury from cosmic rays…
- …I asked Pippa Wells about the **OPAL** ones…
- …She pointed me towards Kawamoto-san….

Large Angle Photon Vetoes

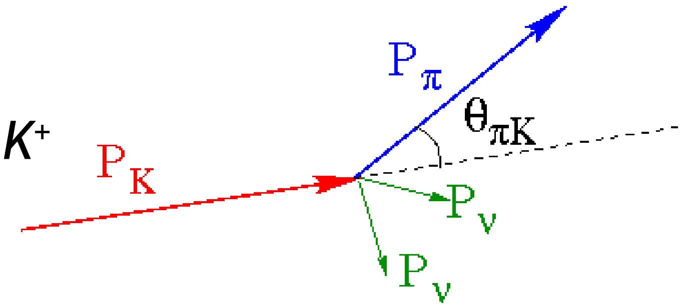


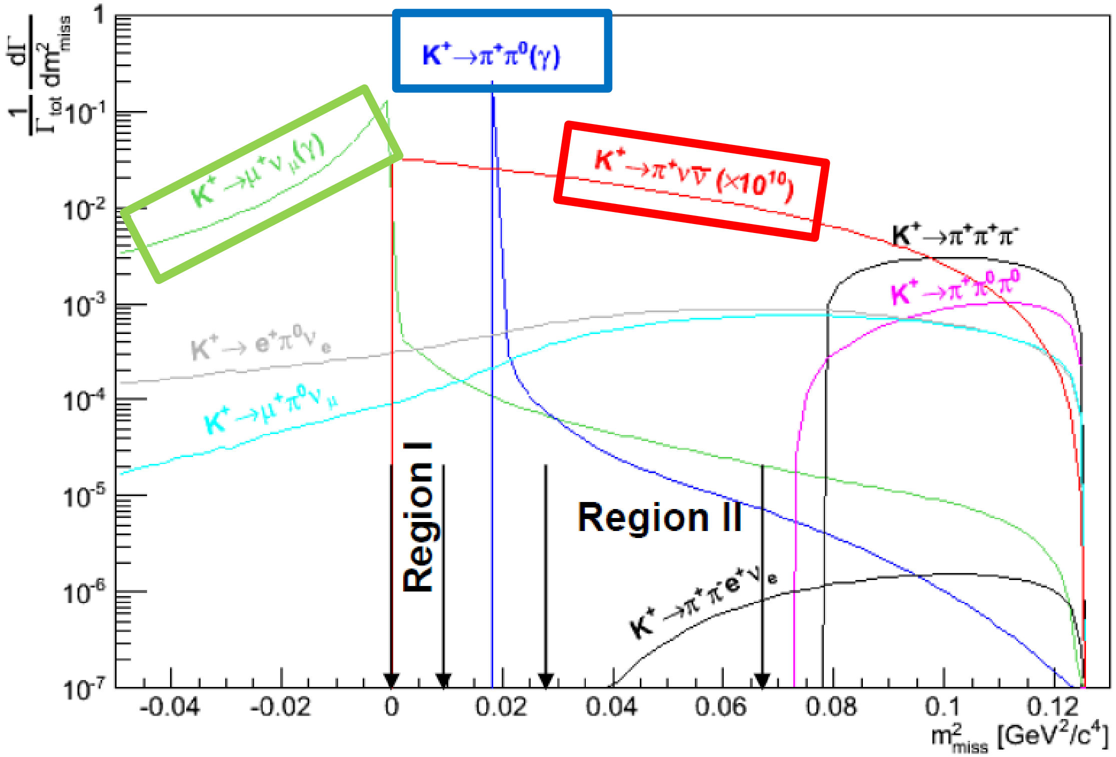
NA62 @ SPSC117 14/3/2015

235 Collaborators

NA62 IN-FLIGHT TECHNIQUE

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





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

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

NA62 EXPERIMENT IN ECN3

- Picture taken just before starting commissioning
- Beam time 2014: October 6 – December 15

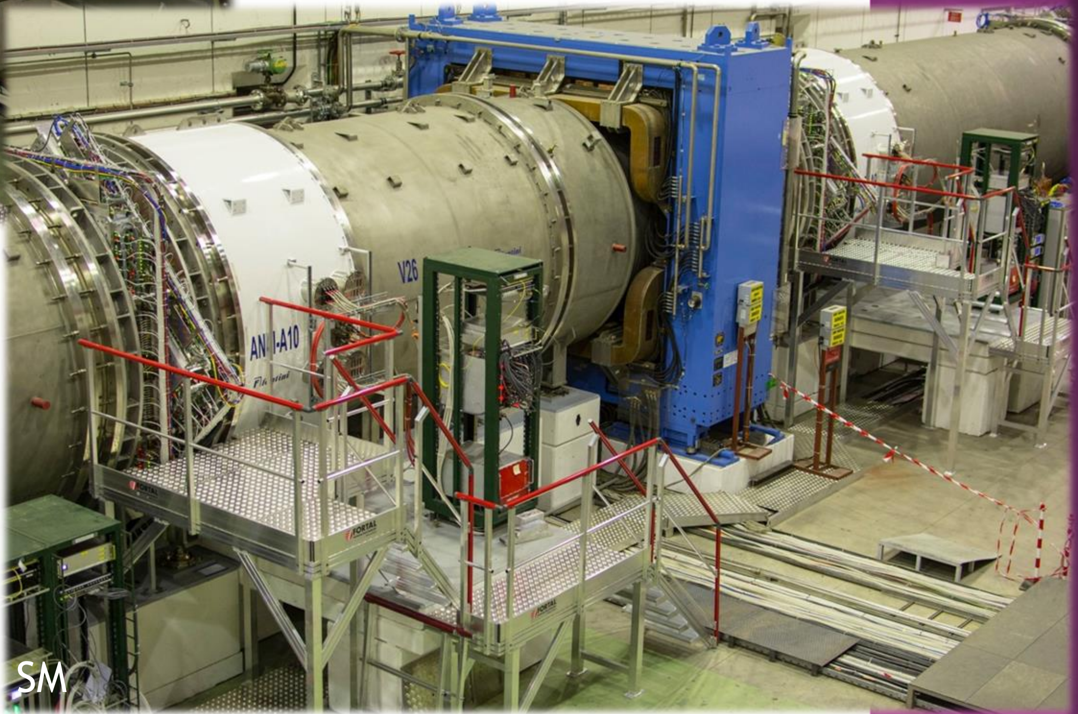
NA62 DETECTOR STATUS

View of ECN3

LAV 1-5 in TTC8

NA62 DETECTOR STATUS

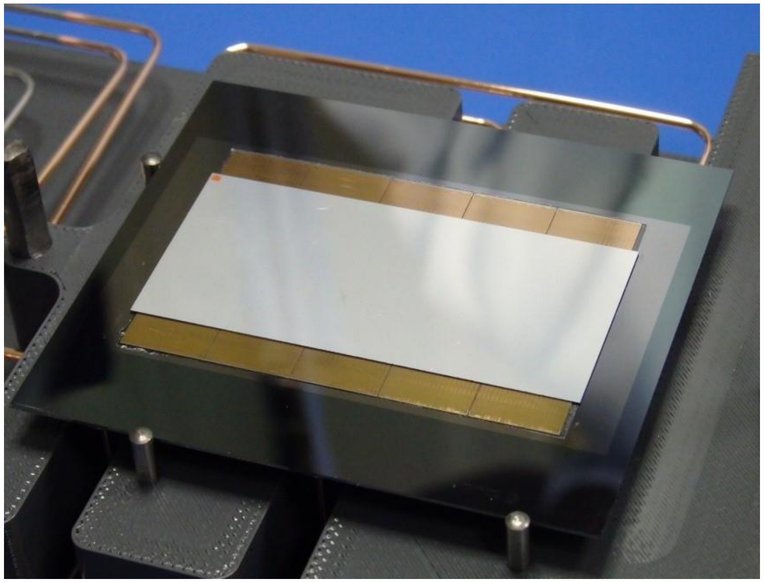
Straw3 - LAV10 - MNP33 - Straw2 - LAV9

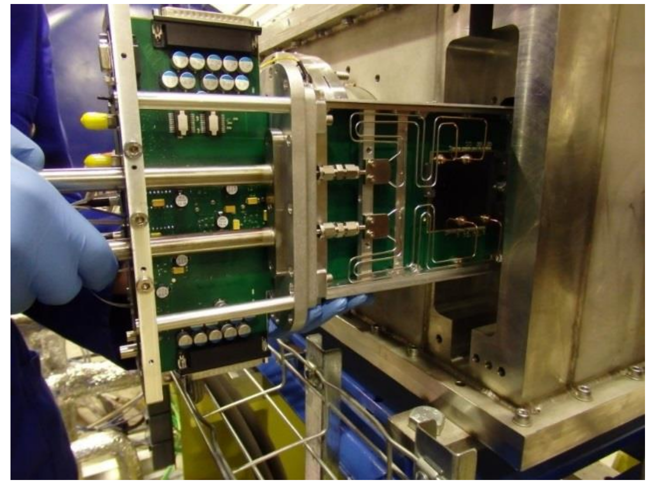


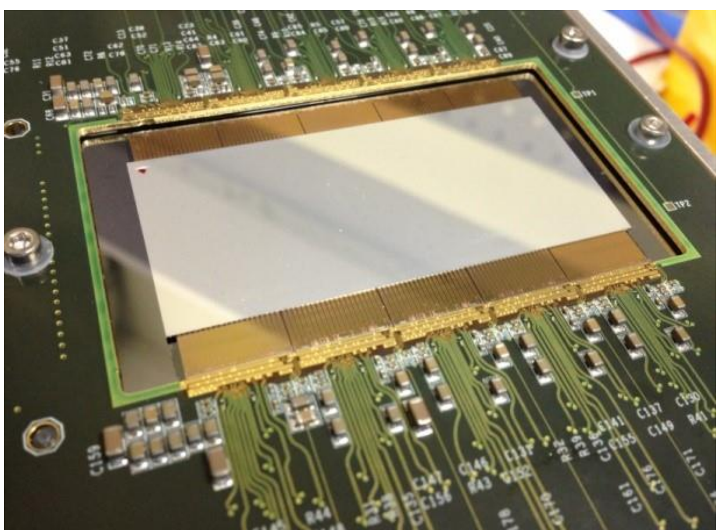
RICH Straw 4 and LAV11

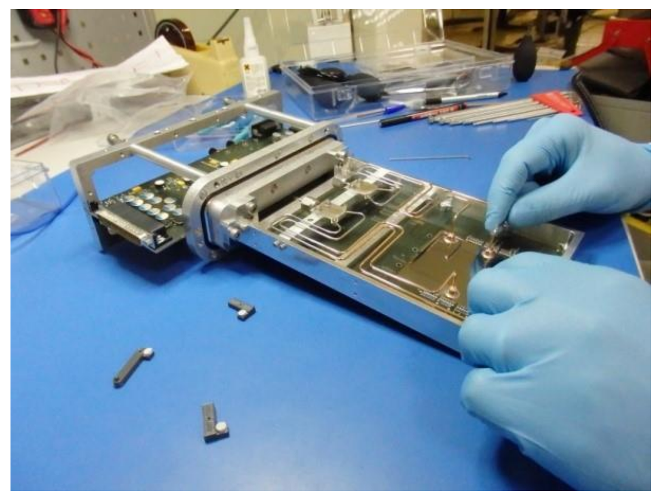
GIGATRACKER (GTK)

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

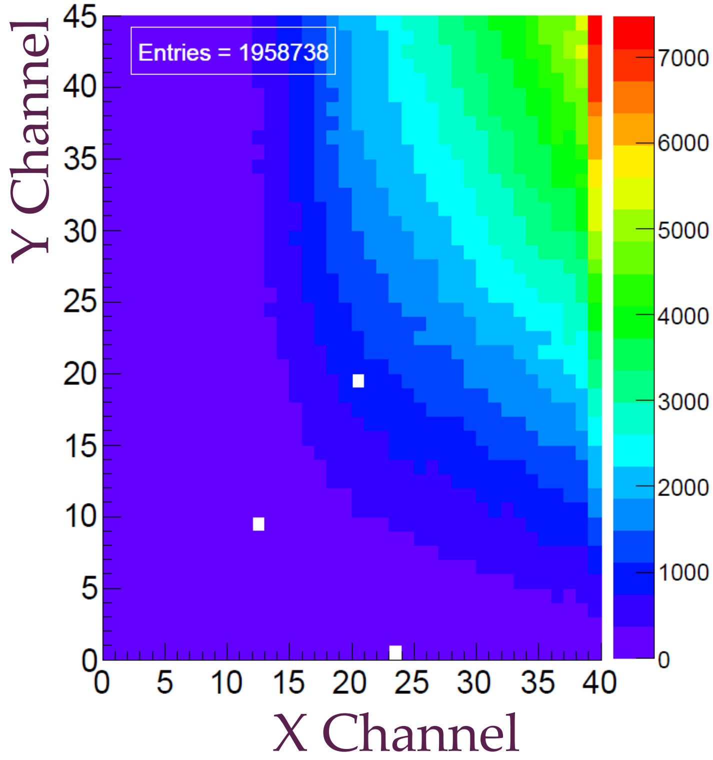


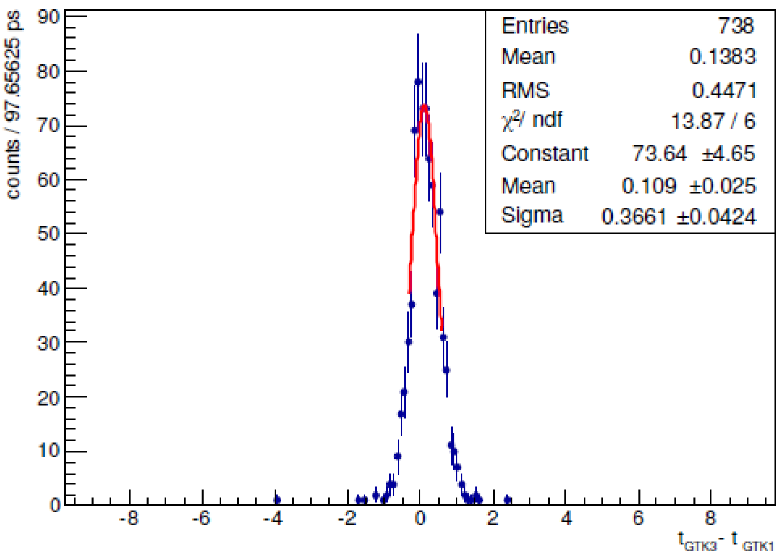






GIGATRACKER PERFORMANC





After ToT correction

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

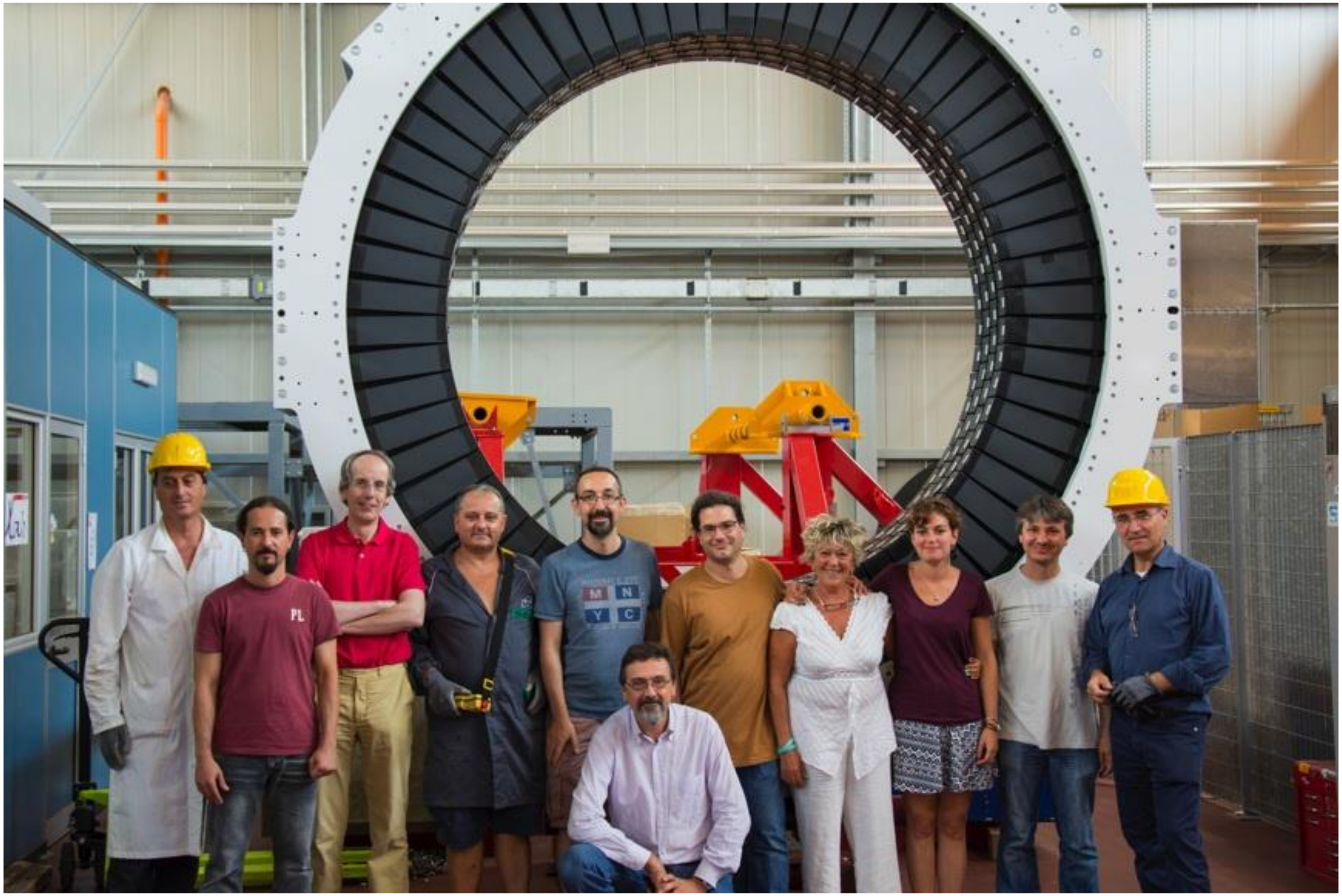
K12 Beam; Illumination of one GTK chip

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)

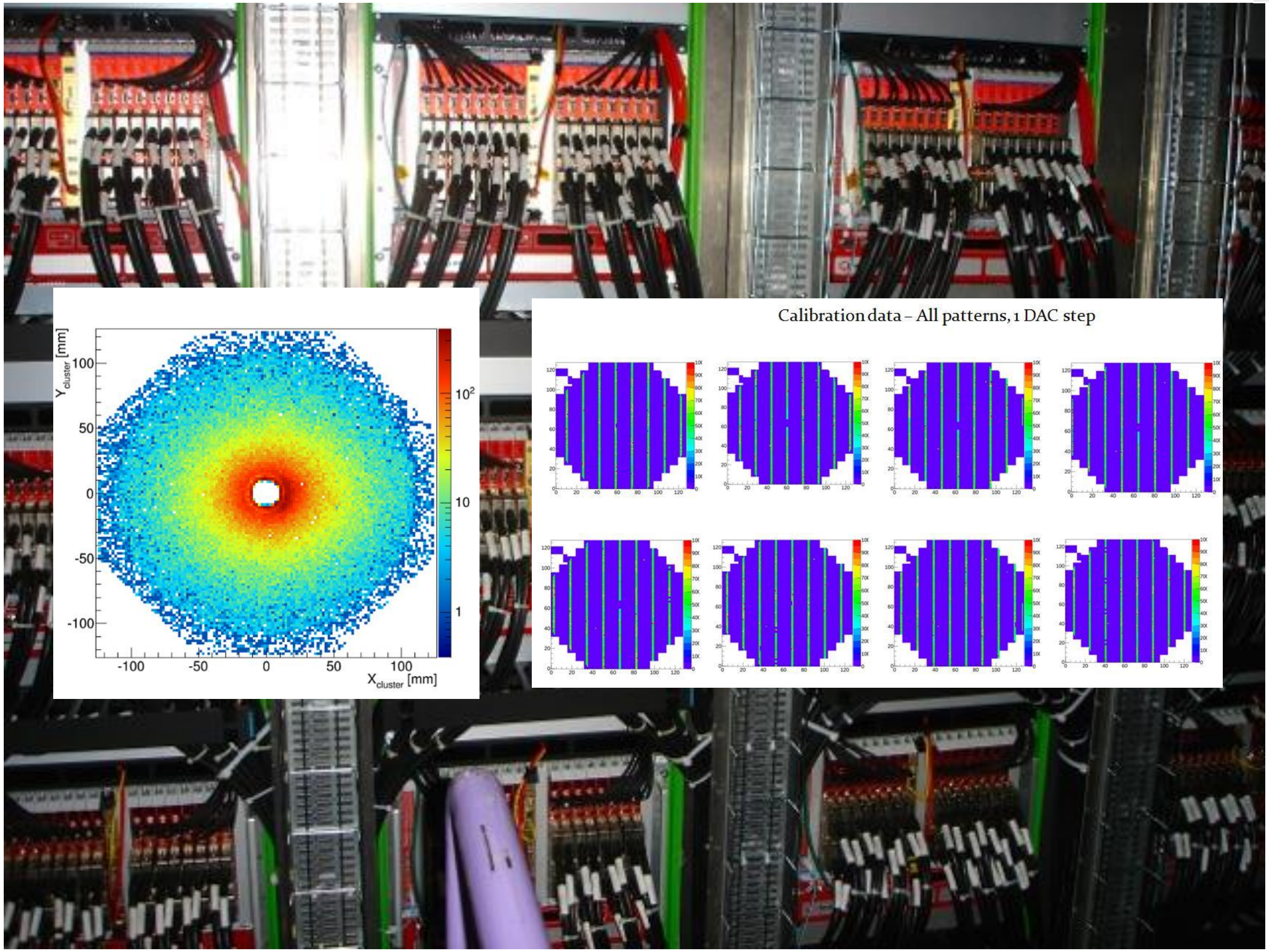
All stations Installed

COMPLETION OF THE LAST LAV



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

LIQUID KRYPTON READ OUT

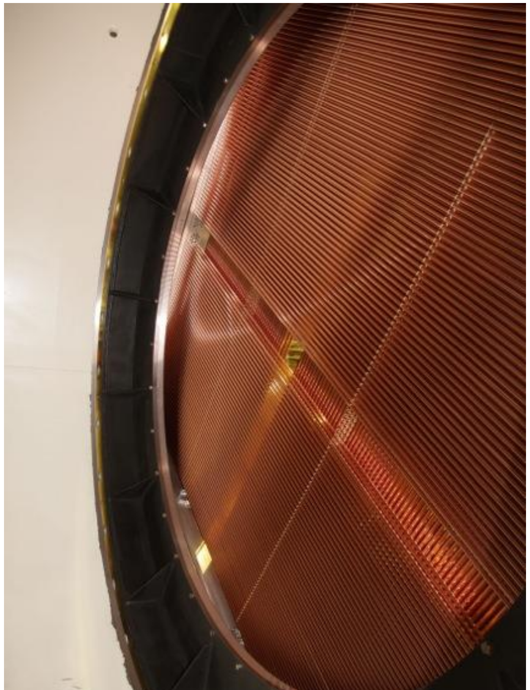


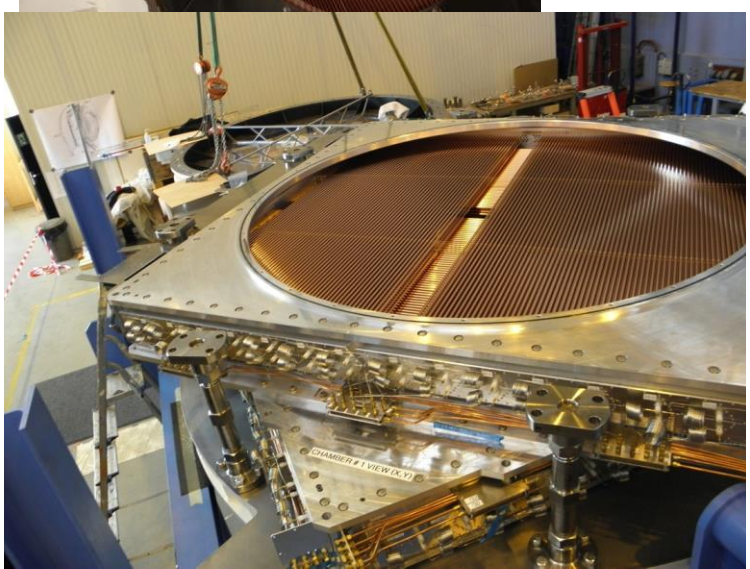
14 bit FADC, 40 Ms, 32 ch / module **432 modules, 28 VME crates**

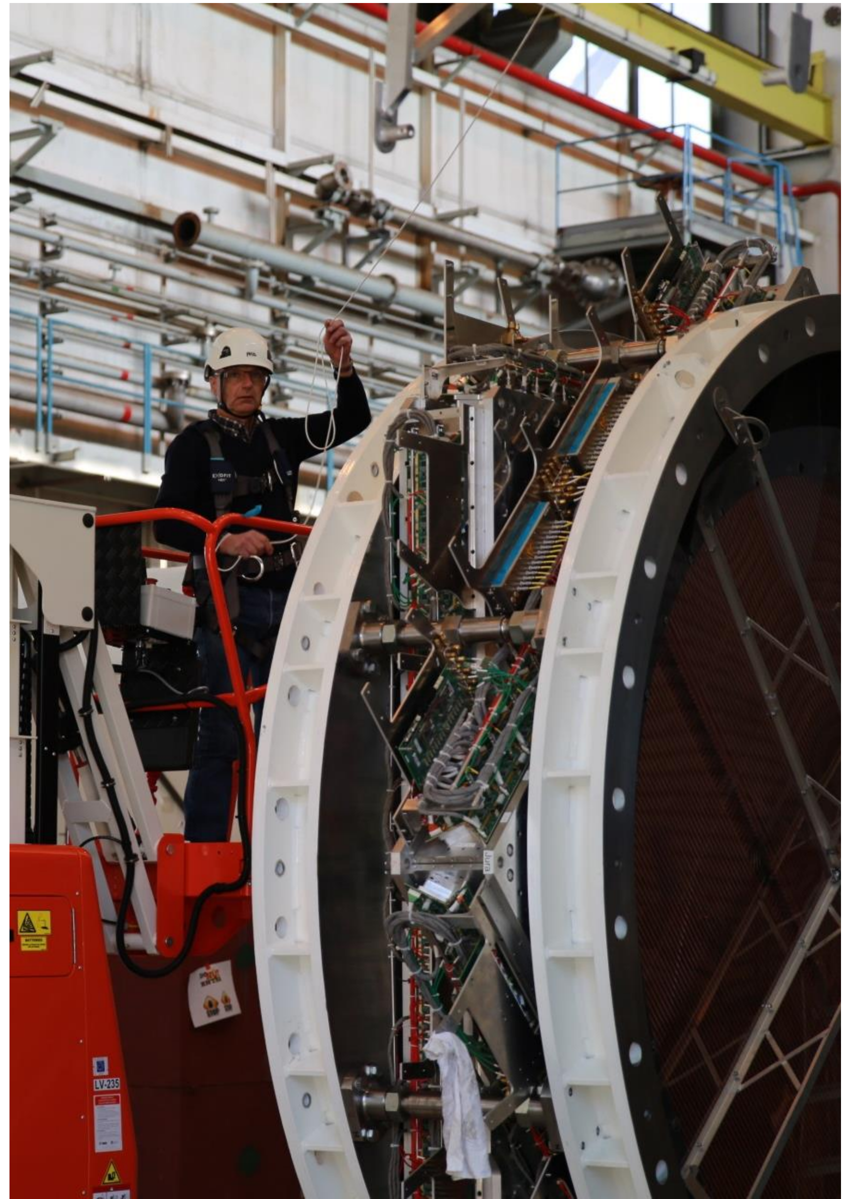
Specifications/Tender : CERN PH-ESE,PH-SME Manufacturer: CAEN (ITALY)

NA62 STRAW TRACKER

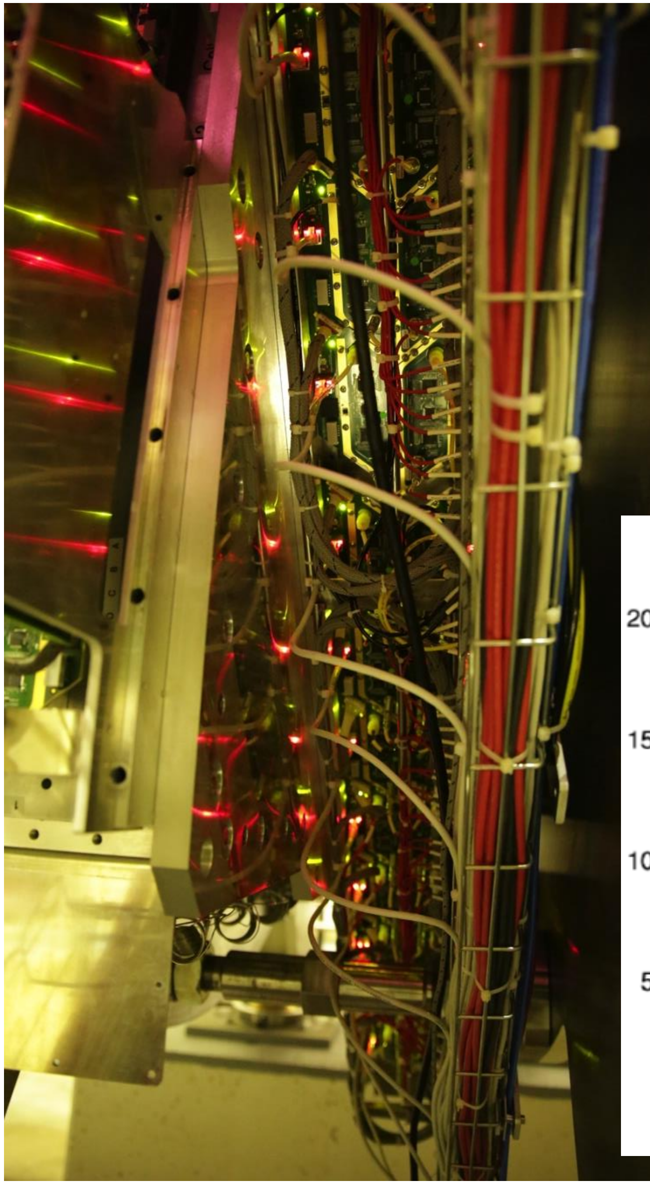
CERN (PH-DT, PH-ESE,PH-SME) – JINR

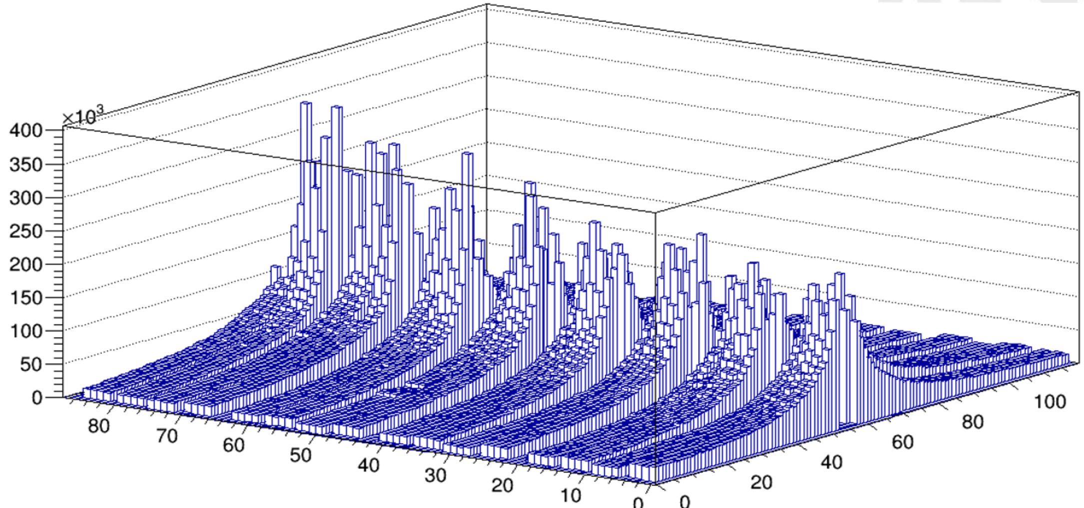


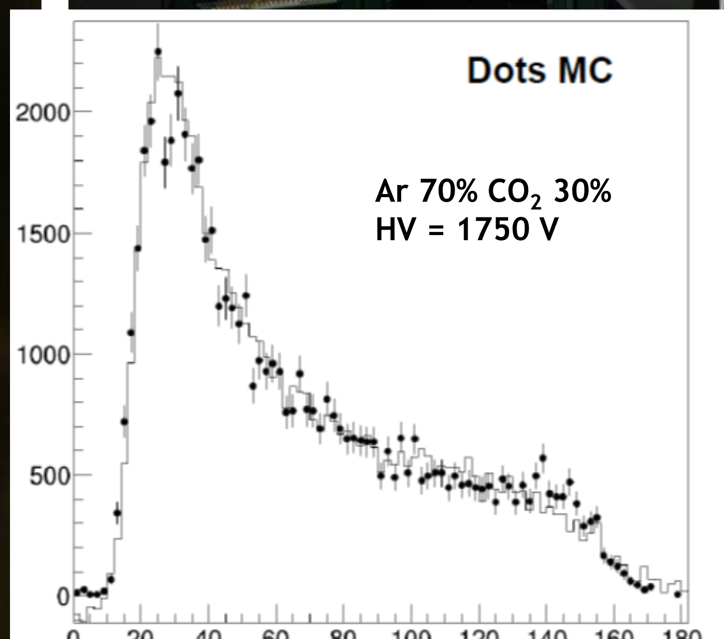


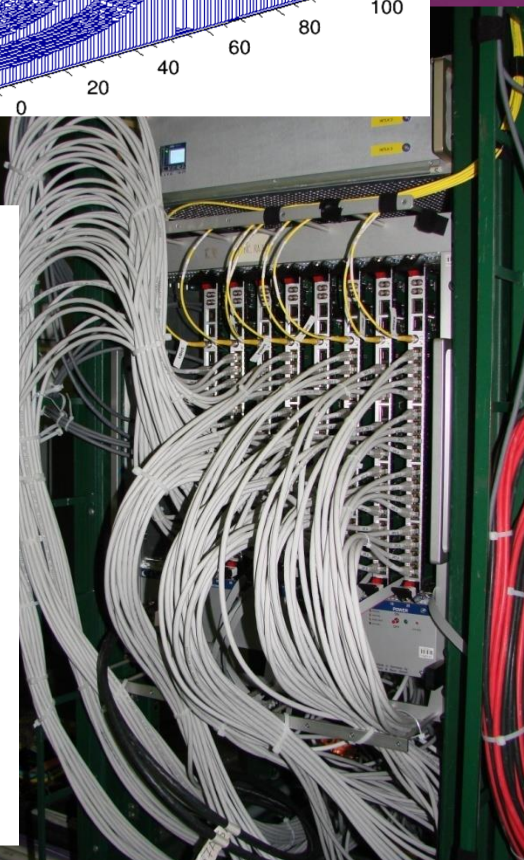


STRAW TRACKER



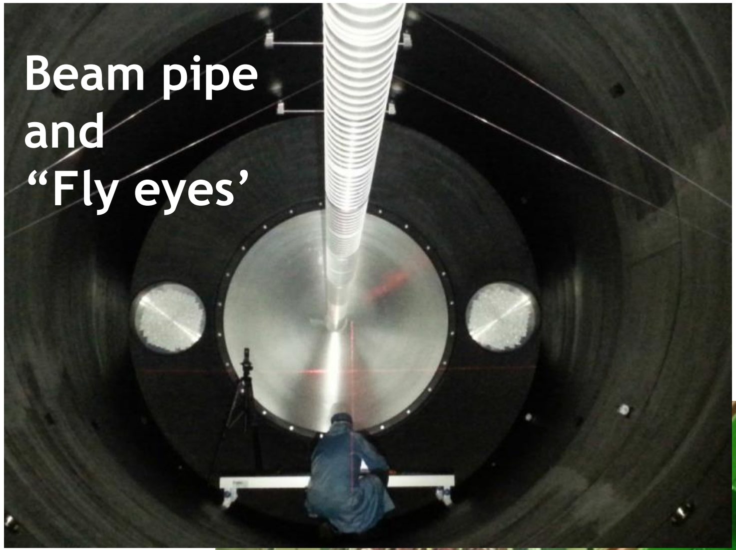


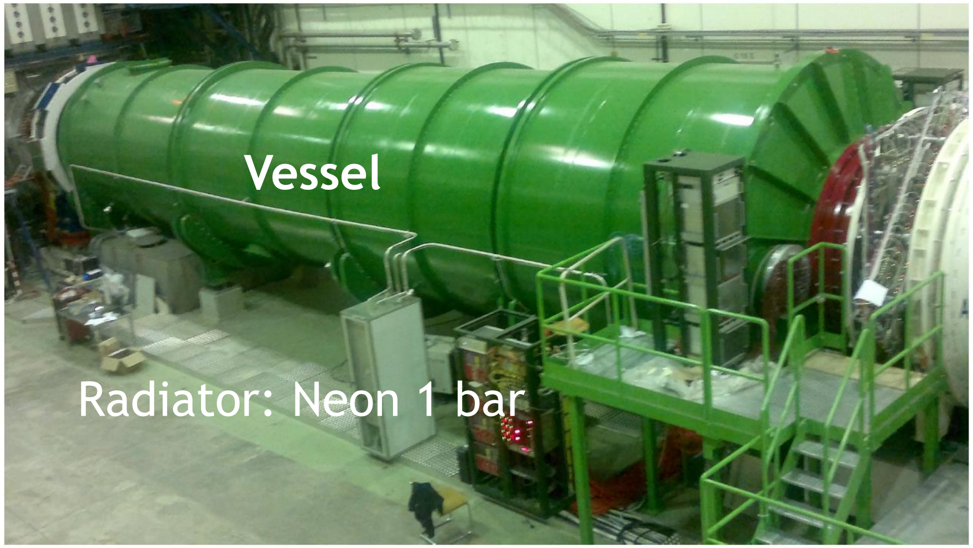


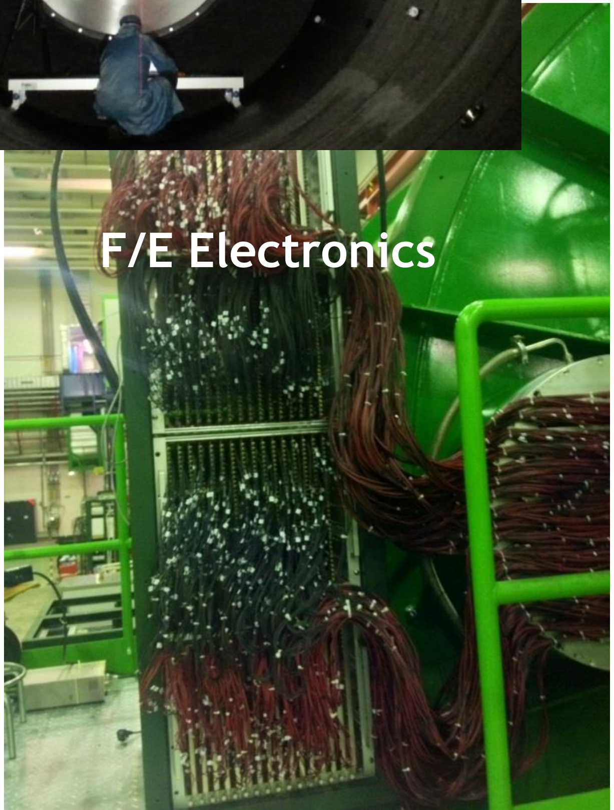


NA62 RICH

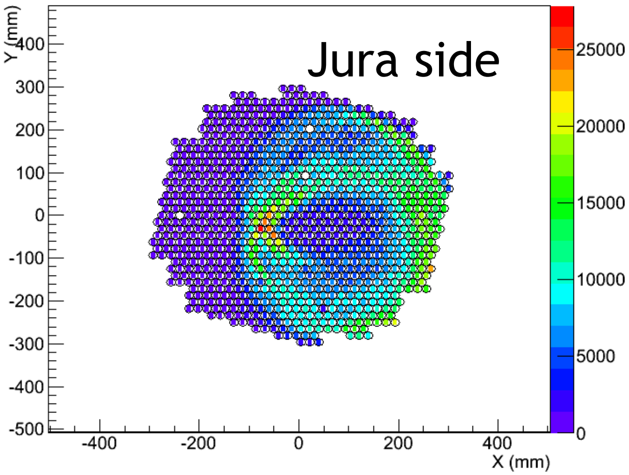
CERN (PH-DT,..), Firenze, Perugia

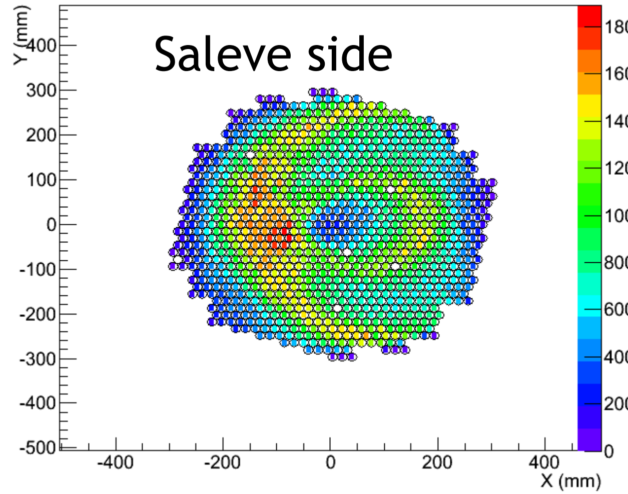


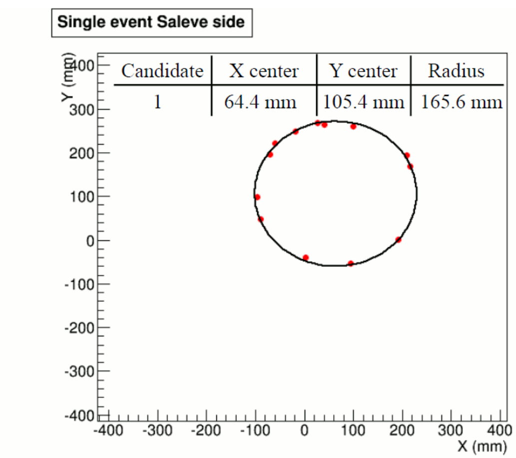


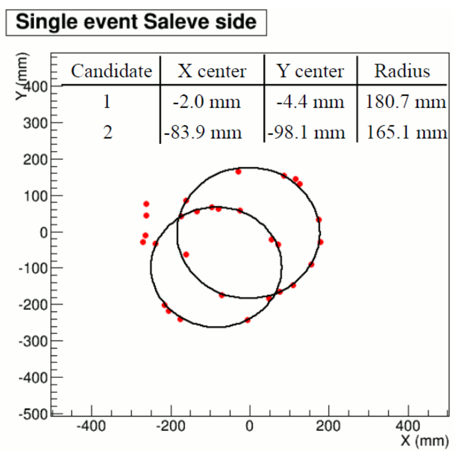


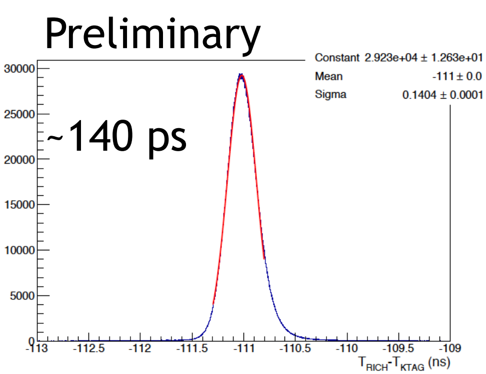
RICH DATA







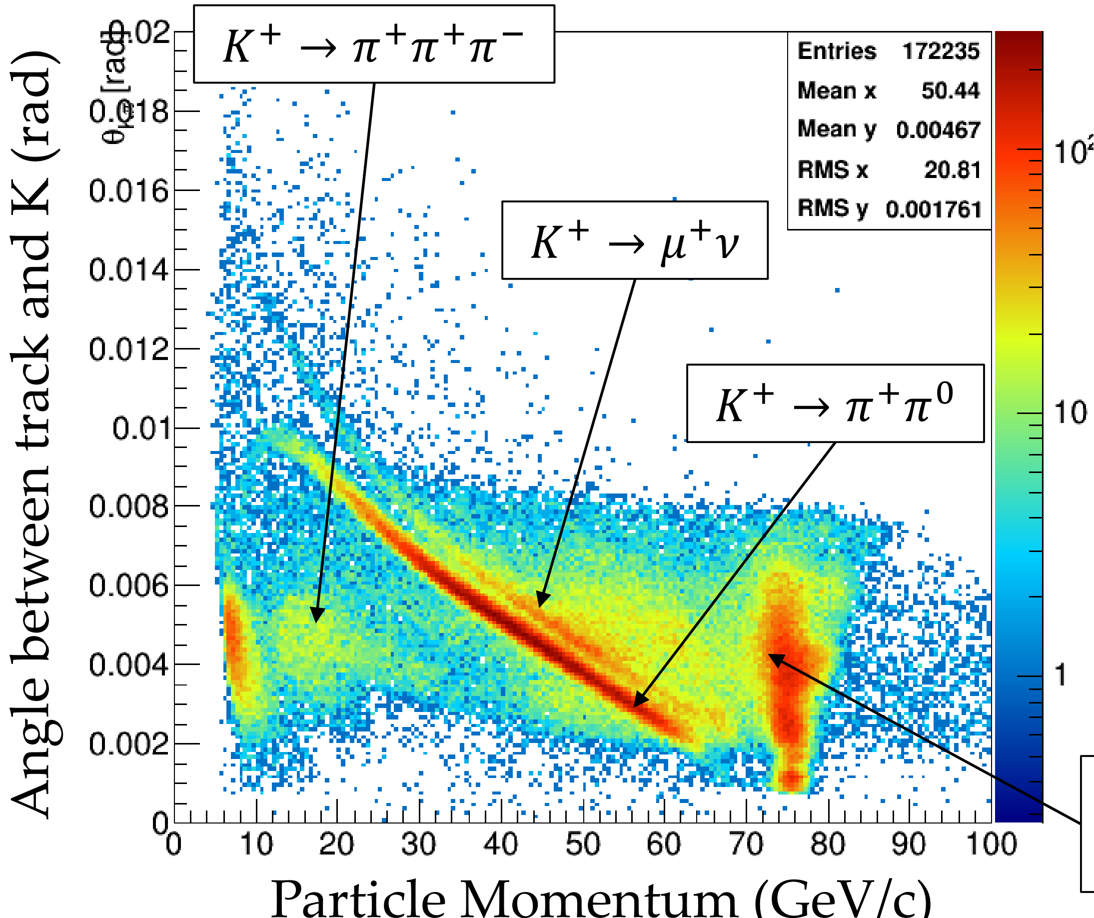


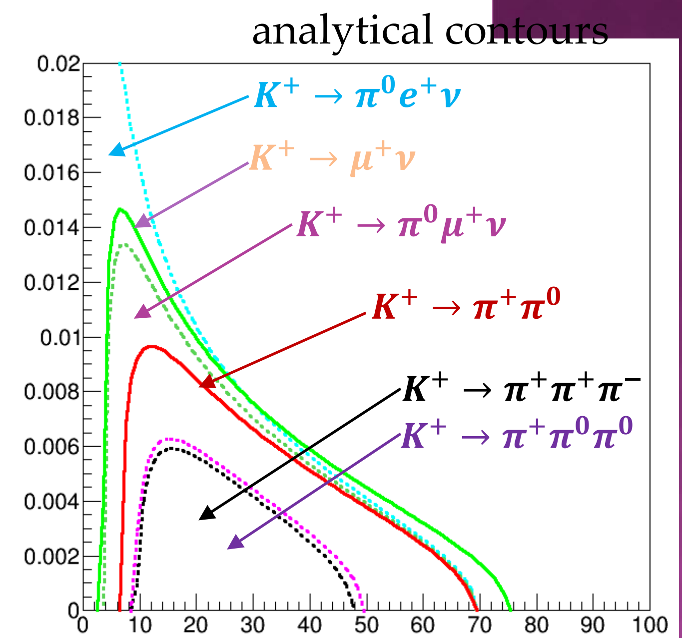


RICH-KTAG

2014 DATA QUALITY

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



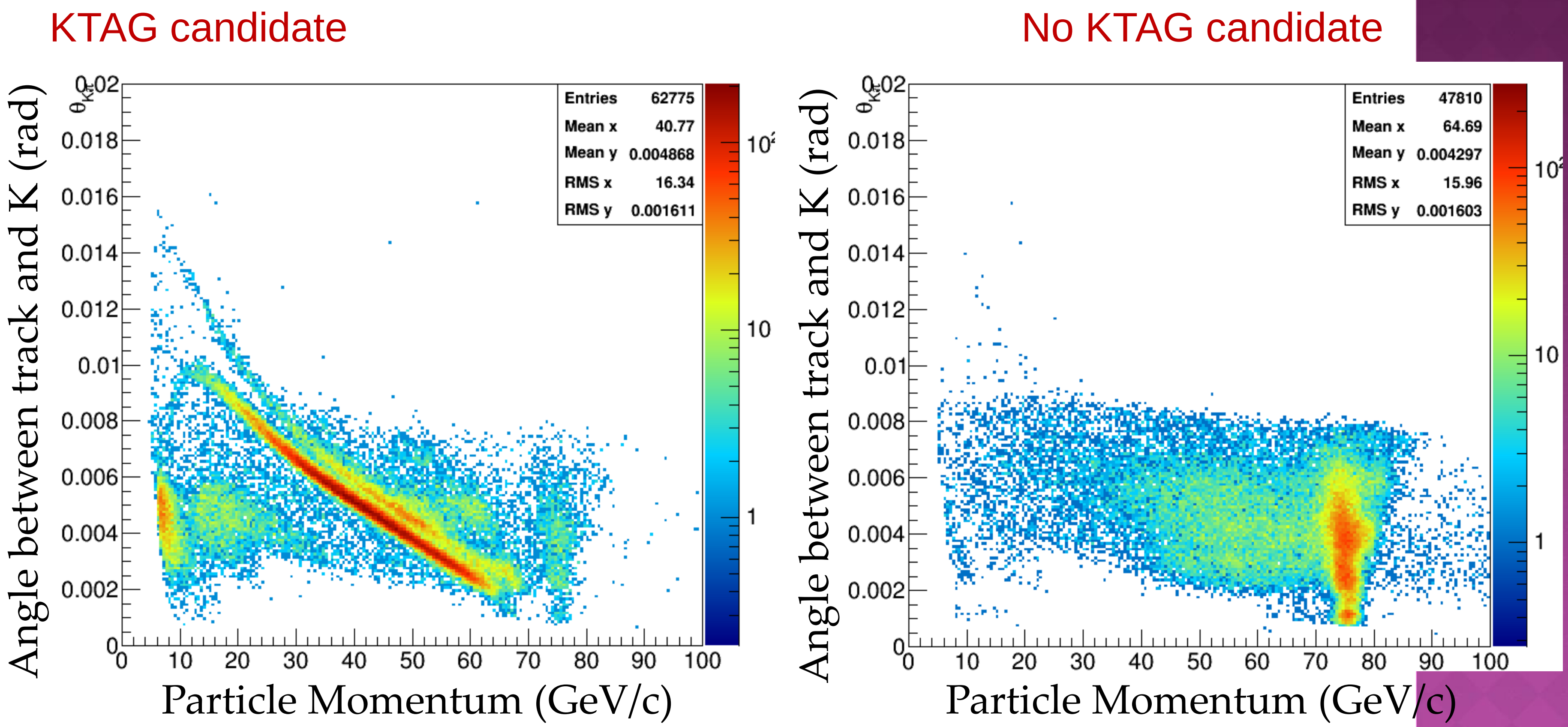


CERN-EP Seminar by Giuseppe Ruggiero, March 10, 2015:

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

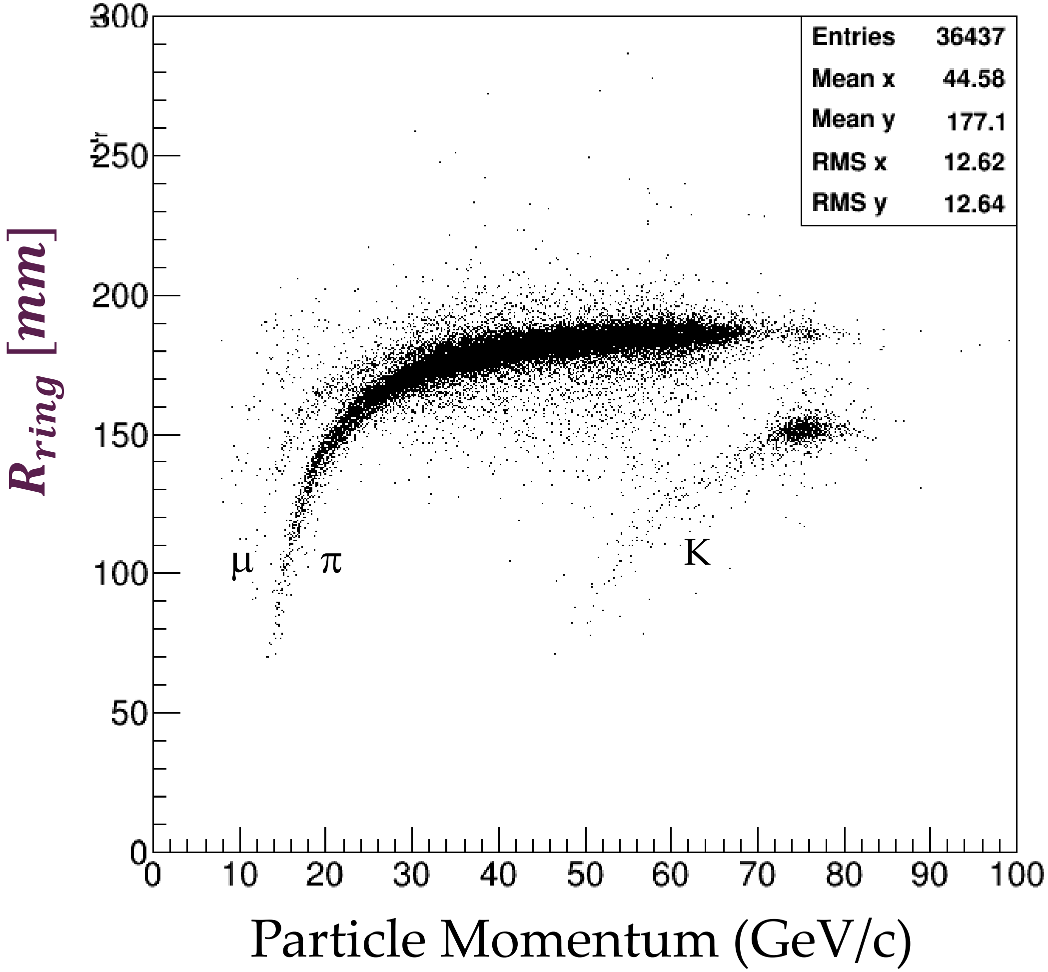
2014 DATA QUALITY

- Apply KTAG for kaon identification



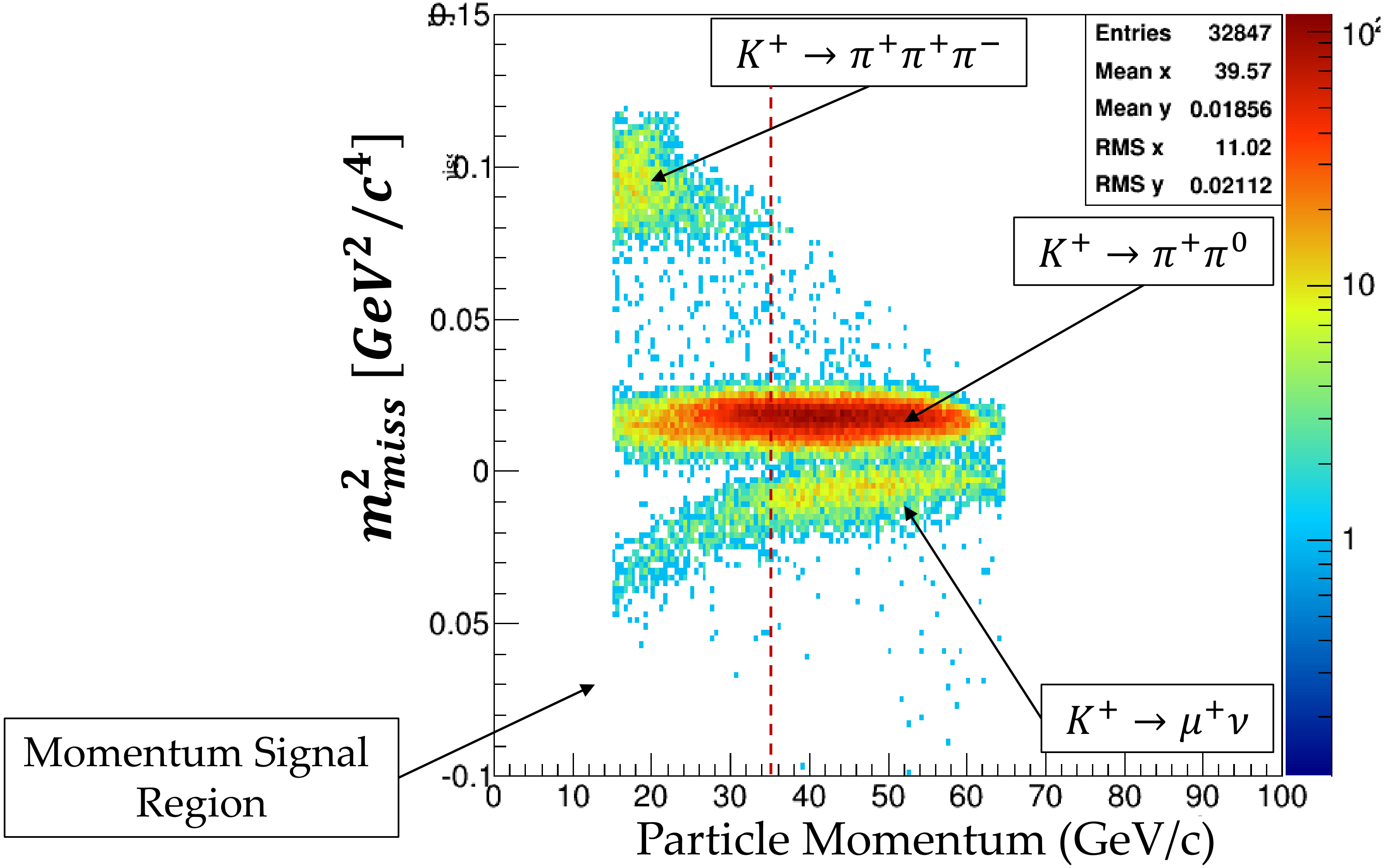
2014 DATA QUALITY

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



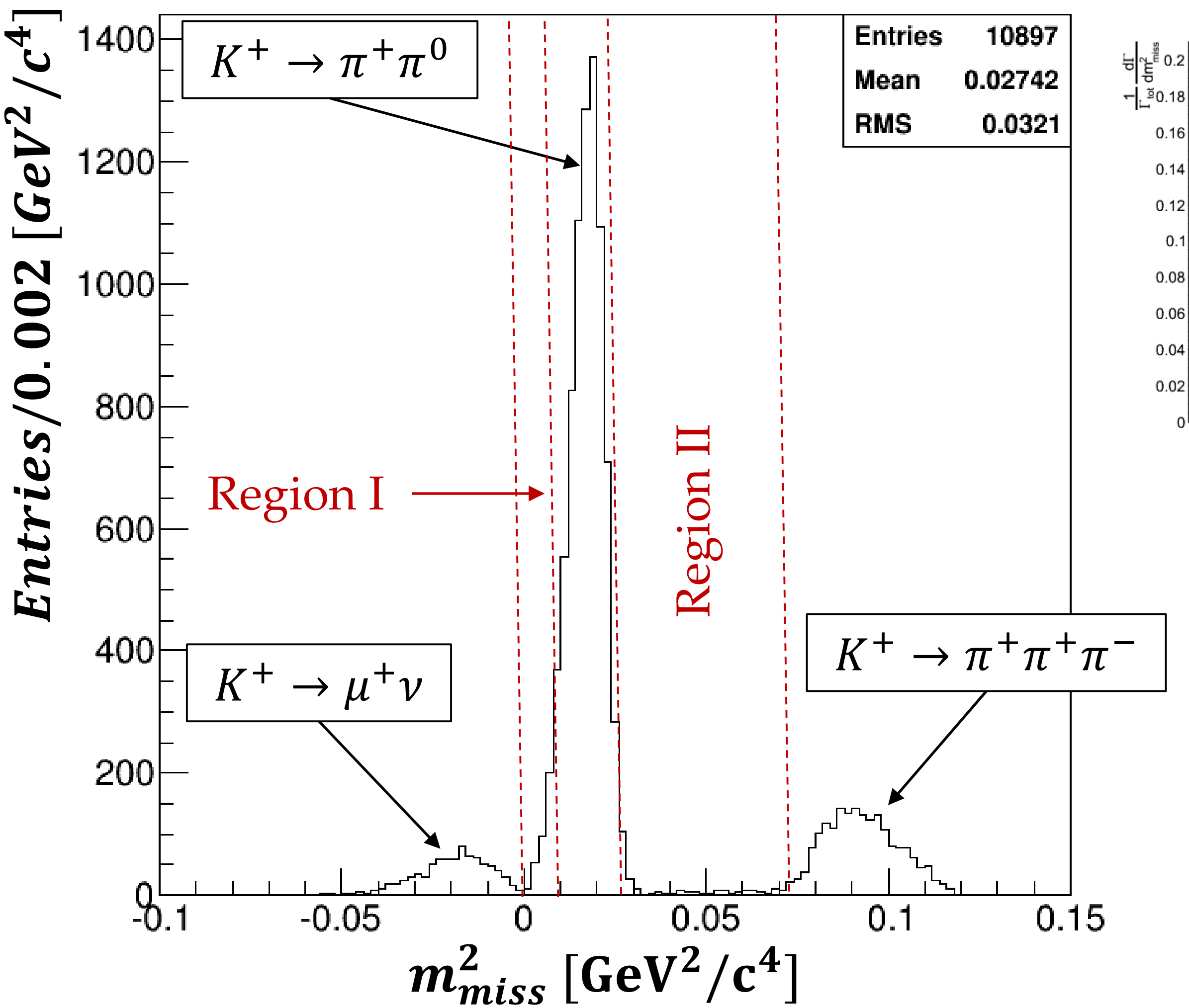
2014 DATA QUALITY

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

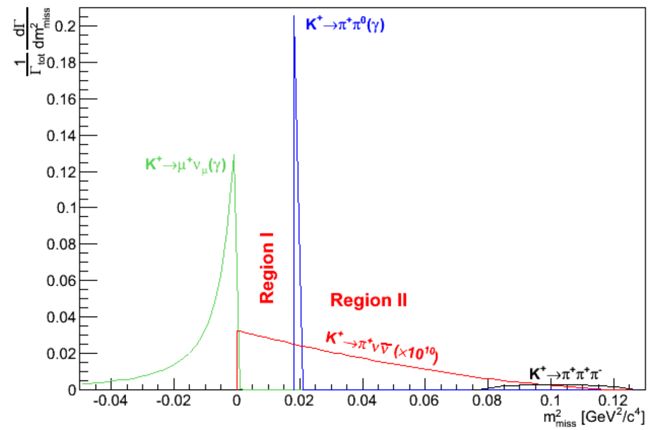


2014 DATA QUALITY

$P < 35\ GeV/c$



theoretical shapes

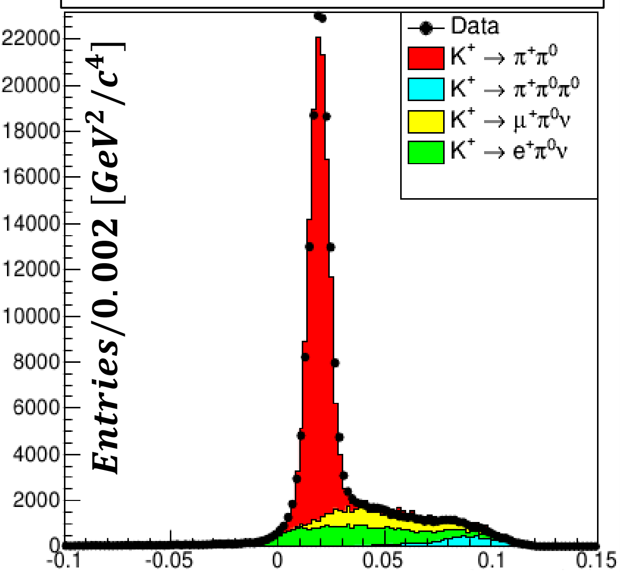


CONTROL SAMPLES

- 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

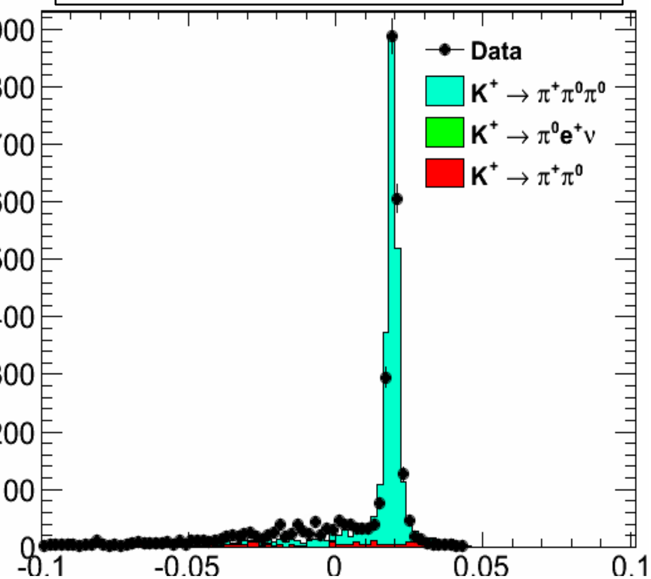
$K^+ \to \pi^+ \pi^0$



$(P_K - P_{\pi^0})^2\ \ \mathrm{GeV^2/c^4}$

π^0 mass assumed

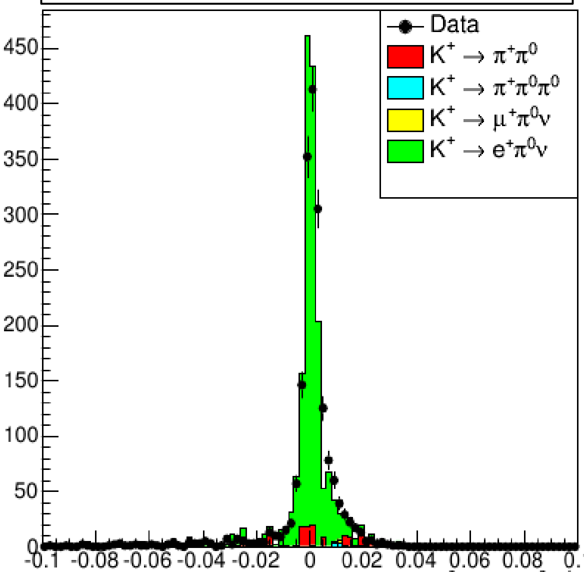
$K^+ \to \pi^+ \pi^0 \pi^0$



$\left(P_K - P_{\pi_1^0} - P_{\pi_2^0}\right)^2\ \ \mathrm{GeV^2/c^4}$

π^0 mass assumed and e^+ energy

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



$(P_K - P_{\pi^0} - P_{e^+})^2\ \ \mathrm{GeV^2/c^4}$

EXPECTED NA62 PROTON RUNNING FOR UPCOMING YEARS (NOT EVEN DRAFT)

2015 ~ 22 weeks

2016 ~30 weeks

2017 ~25 weeks

2018 <8 weeks (booster cooldown → LINAC4)

2019 LS2connection to LINAC4)

NA62 immediate goal: Accumulate and analyze $O(10^{13})$ good kaon decays before LS2

compatible with 10 y LHC plan shown at Moriond EW → next page

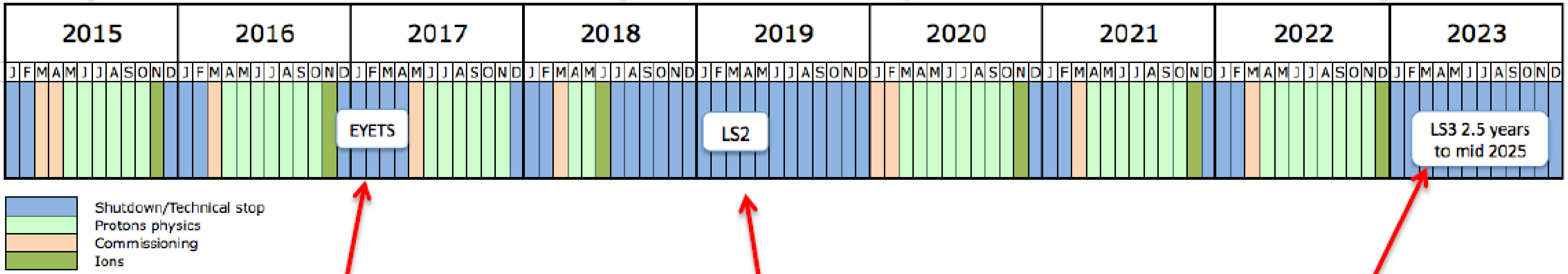
Mike Lamont
Moriond EW

10 year plan

- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7×10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV c.m. with peak luminosity of ~2×10^{34} cm^{-2} s^{-1}



EYETS 19 weeks
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

CERN-TH/2001-175
hep-ph/0107046
July 2001

George and I as co-authors of a CERN-TH preprint!

KAON PHYSICS WITH A HIGH-INTENSITY PROTON DRIVER

A. Belyaev [a], G. Buchalla [b] (convener), A. Ceccucci [b], M. Chizhov [b,c], G. D'Ambrosio [d], A. Dorokhov [e], J. Ellis [b], M. E. Gómez [f], T. Hurth [b], G. Isidori [b], G. Kalmus [g], S. Lola [b], K. Zuber [h]

7 SOME CONSIDERATIONS ON USING THE PROTON DRIVER OF A MUON STORAGE RING (MSR) AS A KAON FACTORY

G. Kalmus

7.1 Introduction

The purpose of this section is to explore the feasibility of using the proton driver of a possible MSR facility to produce kaon beams of intensity and characteristics that are not only competitive with those available elsewhere, but potentially even better.

Table 5: Comparison of proton intensities from existing, projected and proposed machines.

	Beam Energy (GeV)	Beam Current (μA)	Cycle Rate Hz	p/Pulse	p/sec
CERN PS	26	1.6	0.5	2×10^{13}	10^{13}
BNL AGS	24(30)	~ 5	0.3	10^{14}	3×10^{13}
FNAL MI (2002?)	120	1.6	0.33	3×10^{13}	10^{13}
JHF (2006/7?)	50	10	0.16	4×10^{14}	6×10^{13}
KEK	12	0.16	0.25	4×10^{12}	10^{12}
KAON (Defunct)	30	100	10	6×10^{13}	6×10^{14}
CERN MSR source (201N?)	24	160	15	7×10^{13}	10^{15}

Table 6 gives the characteristics of beams available at the Brookhaven AGS operating at 24 GeV [79].

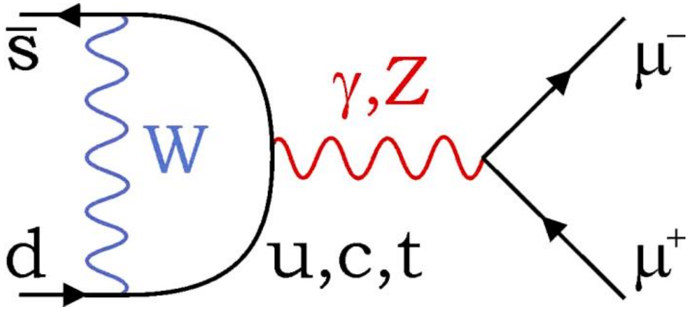
George also explored innovative options to make more kaons…

HAPPY BIRTHDAY PROF. KALMUS!!

- The rare decay program you identified at CERN 15 years ago is well under way…
- …it is now time for you to be back at CERN…
- …in order to launch a programme for the next 15 years!!!

SPARE

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

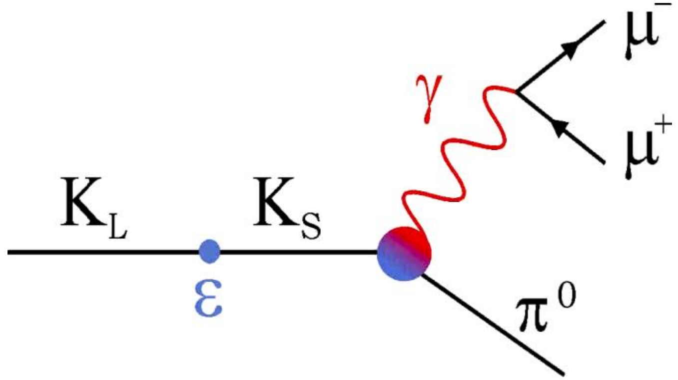


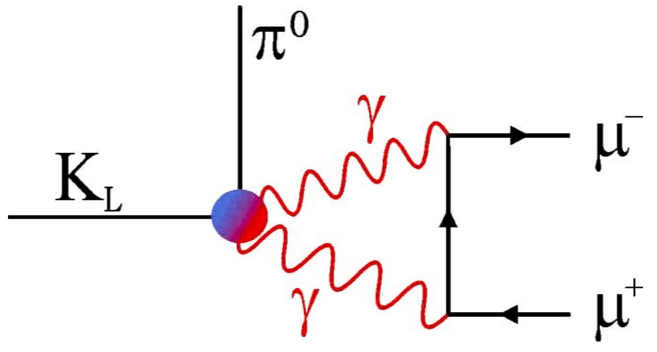
Direct CPV

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

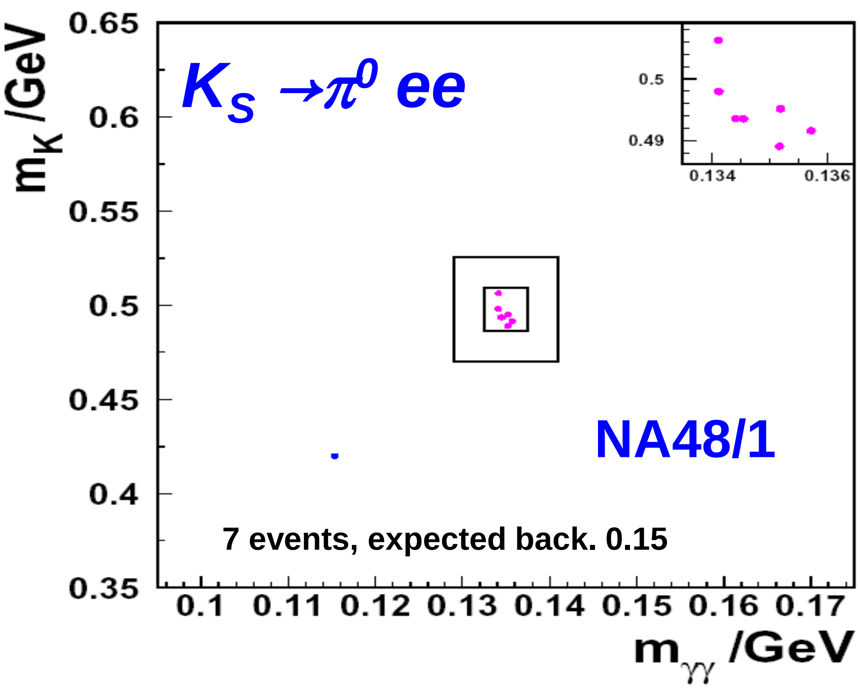
Indirect CPV

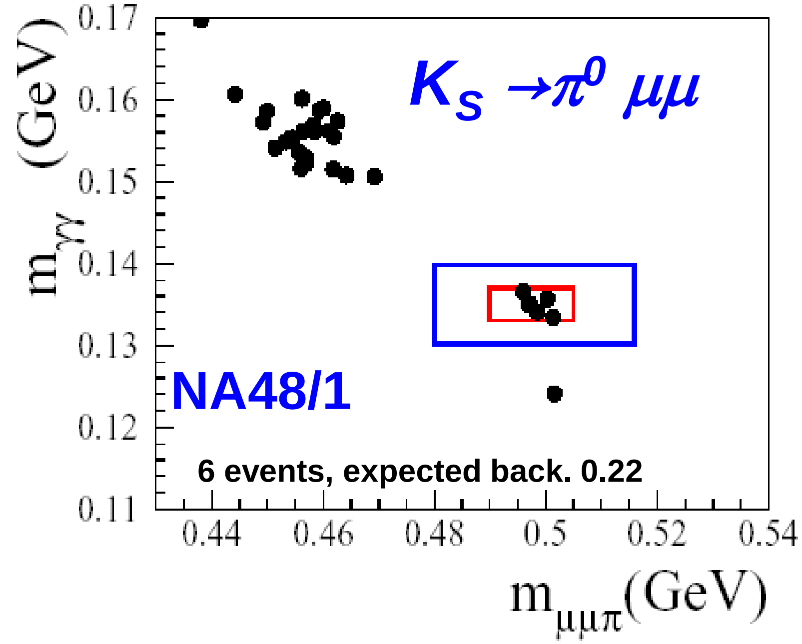




CPC

$K^0_S \to \pi^0 e^+e^-$ 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) ± 0.8(syst)

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

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

$|a_s|=1.55^{+0.38}_{-0.32}$ (stat) ± 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

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

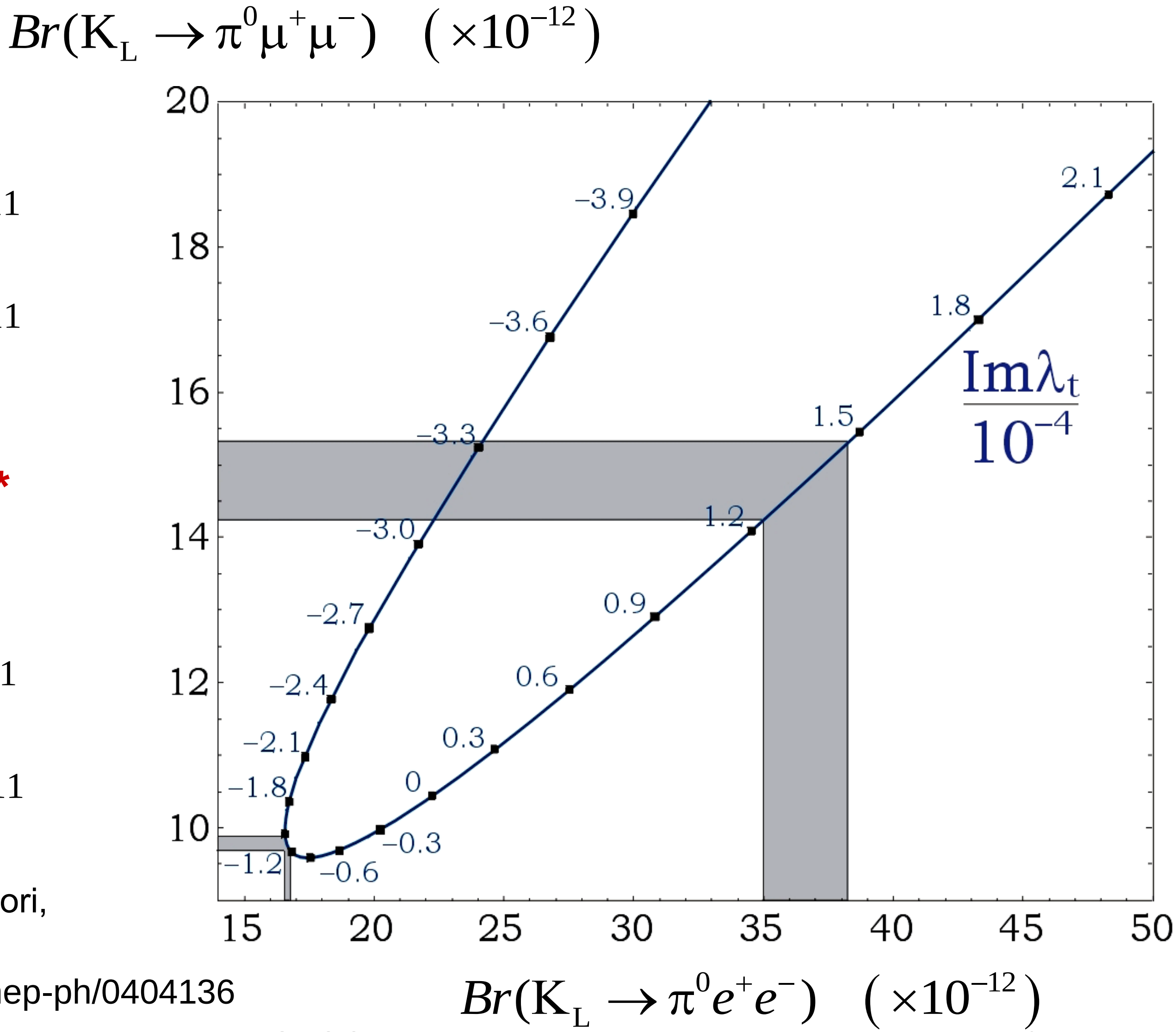
$$B_{\mu^+\mu^-} = 1.5^{+0.3}_{-0.3} \times 10^{-11}$$

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

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

Types of CP-Violation

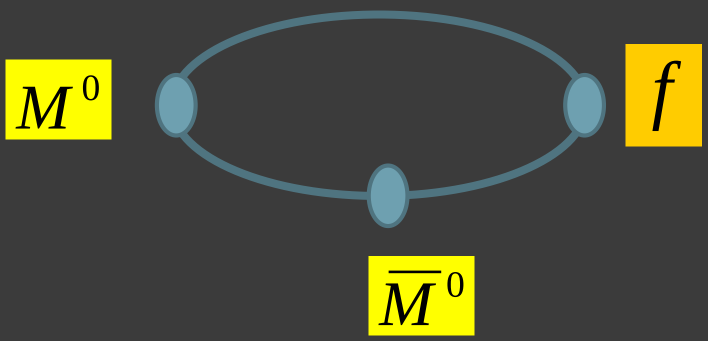
$$|M_L\rangle \propto p|M^0\rangle + q|\overline{M}^0\rangle$$
$$|M_H\rangle \propto p|M^0\rangle - q|\overline{M}^0\rangle$$

$\Delta F = 2$

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

$\Delta F = 1$

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

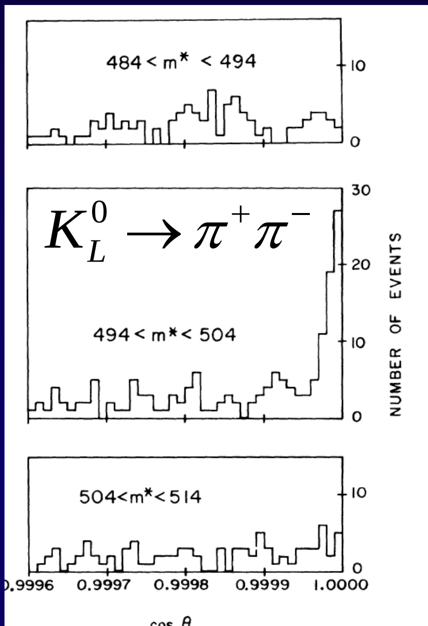


$$\mathrm{Im}\,\lambda_f \neq 0$$

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

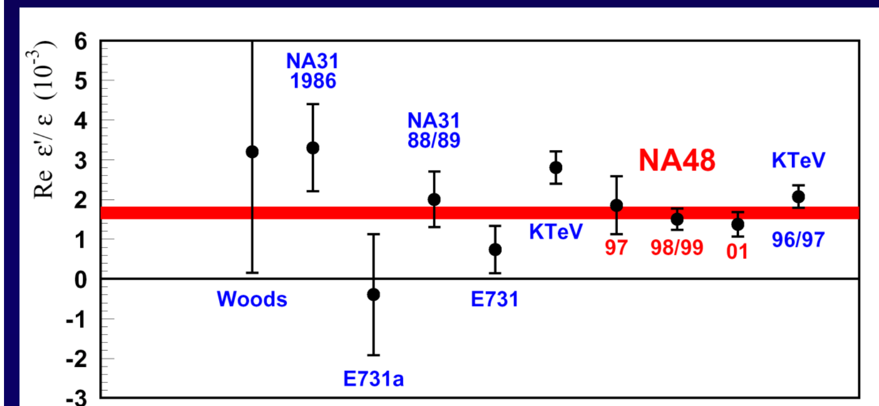
CP Violation

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

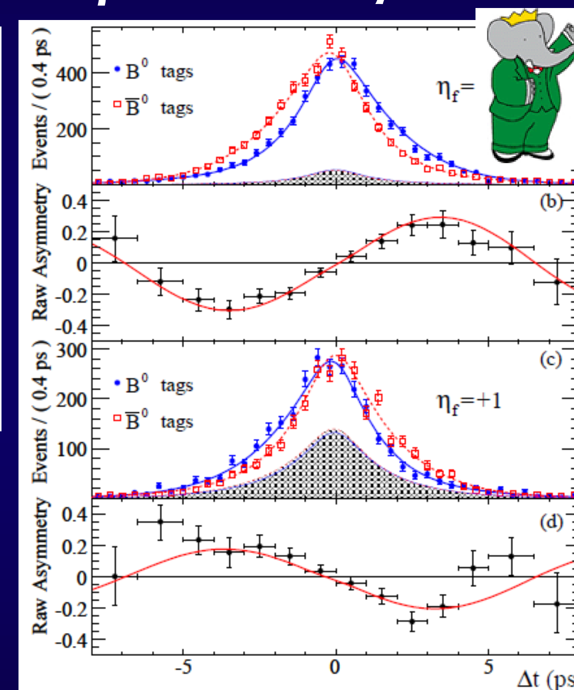


V.L.Fitch R.Turlay
J.W.Cronin J.H.Christenson
*Phys. Rev. Lett. 13 (**1964**) 138.*

Re ε′/ε=(1.68 ± 0.14) × 10^{-3}



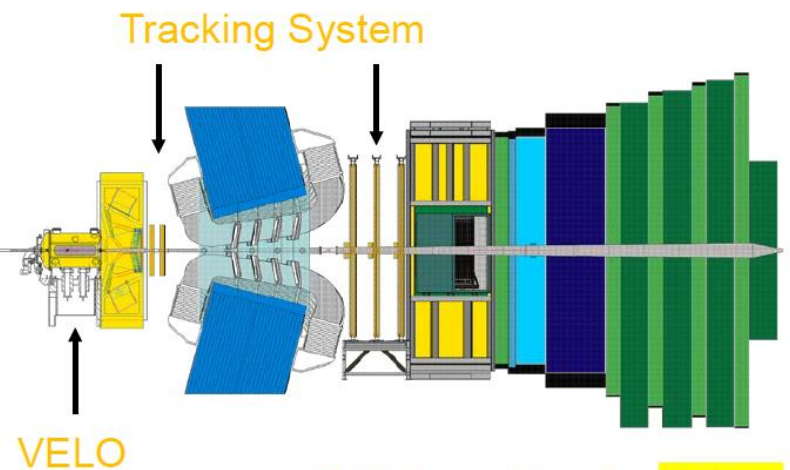
$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} \sim (5.5 \pm 0.5) \times 10^{-6}$$



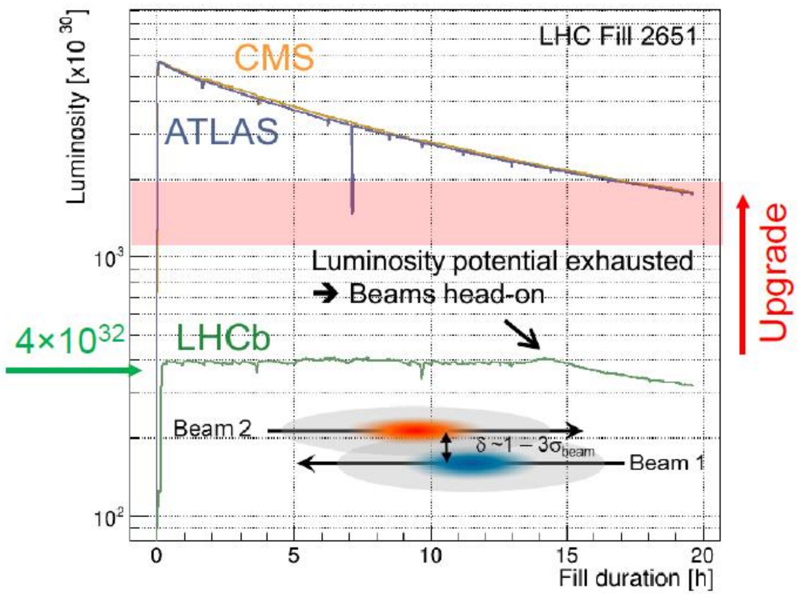
Mixing **Decay** **Interference**

Upgrade-Project

CERN-LHCC-2012-007



40 MHz readout for RICHs,
Calo, Muon System



LHCb Upgrade:
- Increased levelled luminosity
- Fully efficient software trigger
- Upgrade Vertex LOcator and Tracker

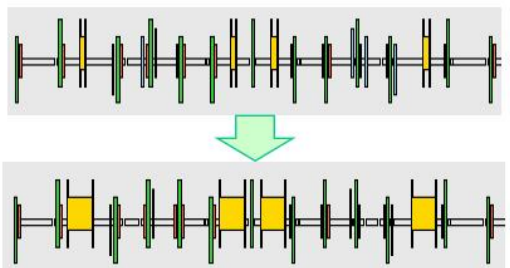
LHCB UPGRADE POTENTIAL

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\,K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Courtesy Ulrich Uwer

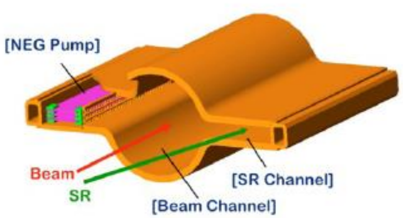
KEKB to SuperKEKB

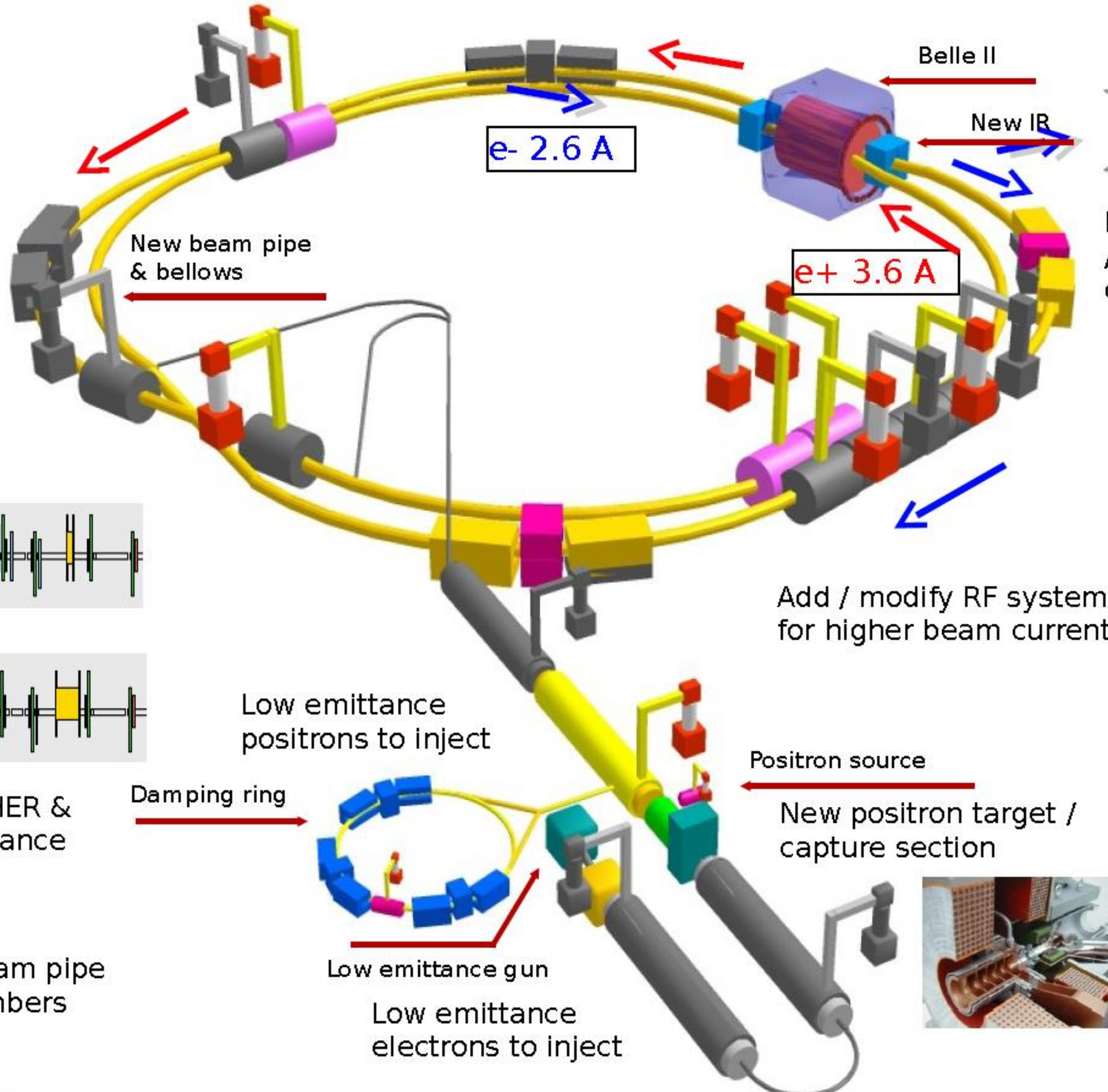
Replace short dipoles
with longer ones (LER)



Redesign the lattices of HER &
LER to squeeze the emittance

TiN-coated beam pipe
with antechambers



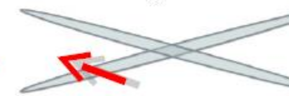


Low emittance
positrons to inject

Low emittance
electrons to inject

New positron target /
capture section

Colliding bunches



New superconduct
/permanent final fo
quads near the IP

Add / modify RF systems
for higher beam current

To obtain x40 higher luminosit

Examples of Belle II Expectation

Observable	SM theory	Current measurement (early 2013)	Belle II * ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.018
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.011
α from $B \to \pi\pi,\ \rho\rho$		$\pm 5.4°$	$\pm 1°$
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.035
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.07
$A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.005
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\gg 5\sigma$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 6\%$
$\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 30\%$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$ $(1 < q^2 < 6\,\mathrm{GeV}^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\mathrm{GeV}^2)$	$9\% \to 2\%$	11%	2.1%

Courtesy: Youngjoon Kwon @ Beauty2014
Snowmass (arXiv:1311.1076) + BPAC 2014 update(*)

$K_{L,S} \to \pi^0 ee\ (\mu\mu)$

- **Short Distance (Direct CP-Violation)**
  - **From Standard Model fit:** $Im\ \lambda_t = (1.36 \pm 0.12)\ 10^{-4}$
  - $B(K_L \to \pi^0 ee)_{CPV\text{-}dir} = (3.2 \pm 0.4) \times 10^{-12}$ **(hep-ph/0308008)**
- **Indirect CP-Violation**
  - $BR(K_L \to \pi^0\ ee)_{CPV\text{-}ind} \sim 1/330\ BR(K_S \to \pi^0\ ee)$

➡ **Essential to measure** $BR(K_S \to \pi^0\ ee)$

- **CP-Conserving contribution**
  - $BR_{CPC} < 3 \times 10^{-12}$ **(hep-ph/0308008)**
    - **They fix the 3 counter-terms from** $K_L \to \pi^0 \gamma\gamma$ **and** $K_S \to \gamma\gamma$

measured by NA48 and NA48/1

Main 2008 Activities

- Activities during the past year focused on engineering the solution to use the OPAL barrel Lead glass for a "All-in-vacuum design"
- In particular it was shown that
  - The blocks and photomultipliers can work in vacuum
  - The outgassing is tolerable
  - The design for installation in ECN3 is viable
- A major setback due to the floods in a storage area is being recovered
- Prototypes were beam tested
- The order for a full size ring was made (functional prototype)
- The Read-out electronics was defined

The flood

- In April, because of heavy rain, dirty water flooded the storage area in BB5
  - Half of the lead glass blocks were touched on part of their surface
- The CERN insurance is providing support for cleaning, recovery and validation of those blocks
  - There are about 1800 blocks to be recovered
  - The cleaning rate is 30/week
  - The blocks are cleaned, cabled and tested in a dark box with a LED pulser

OPAL Lead Glass Recovery Procedure

- ½ of blocks touched by flood water
- Some blocks (~9%) were broken by the thermal shock
- Other blocks require polishing

Careful recovery procedure underway to make sure that all the needed (2496 blocks) will be available

TATSUYA NAKADA'S DESPERATE FLAVOUR QUESTIONS

- My really desperate questions concerning the flavour are:
- **Why do we have "three" families?**
- **Why are the two mass matrices "as they are"?**

- I am not sure whether I will see the solution before I die (SUSY may answer many important questions, but not those).

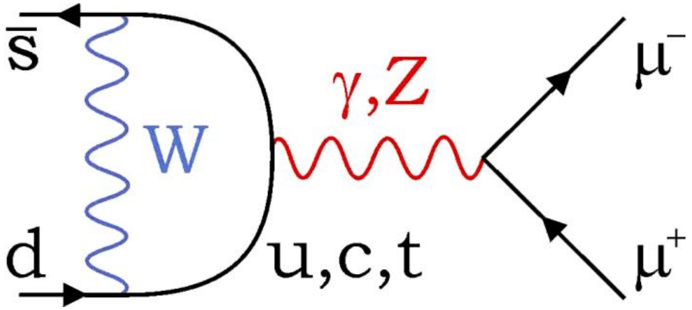
Tatsuya Nakada, Experimental Summary, Rencontres du Vietnam,
Quy Nhon (Vietnam) , July 27 - August 2, 2014

FLAVOUR IN A NUTSHELL

- Gauge invariance, renormalizability and particle content of the Standard Model (SM) imply the absence of the Flavour Changing Neutral Current (FCNC) transitions in the lepton sector and their strong suppression in the quark sector (absent at tree level).
- If the SM is just an effective theory up to a scale Λ, the SU(3)xSU(2)xU(1) invariance is not sufficient to protect the absence of FCNC from higher order operators suppressed by some power of Λ
- Consistency between the SM and the data implies that either Λ is huge or that dangerous interactions are absent because of symmetries of the new theory

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

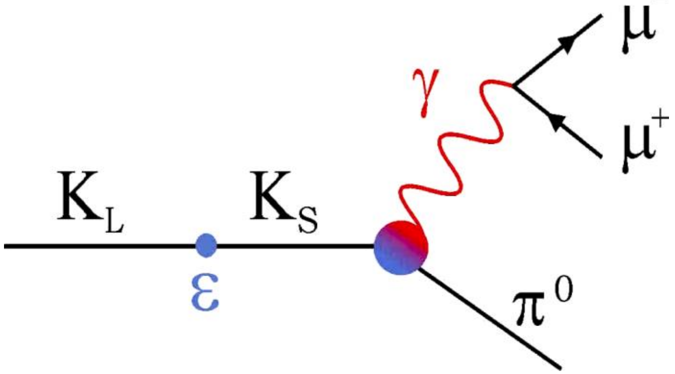
Study Direct CP-Violation

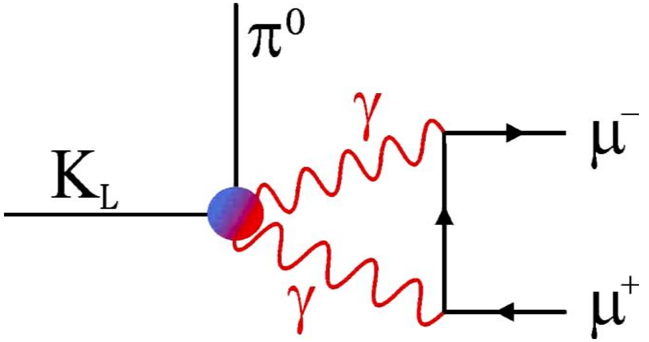


Direct CPV

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

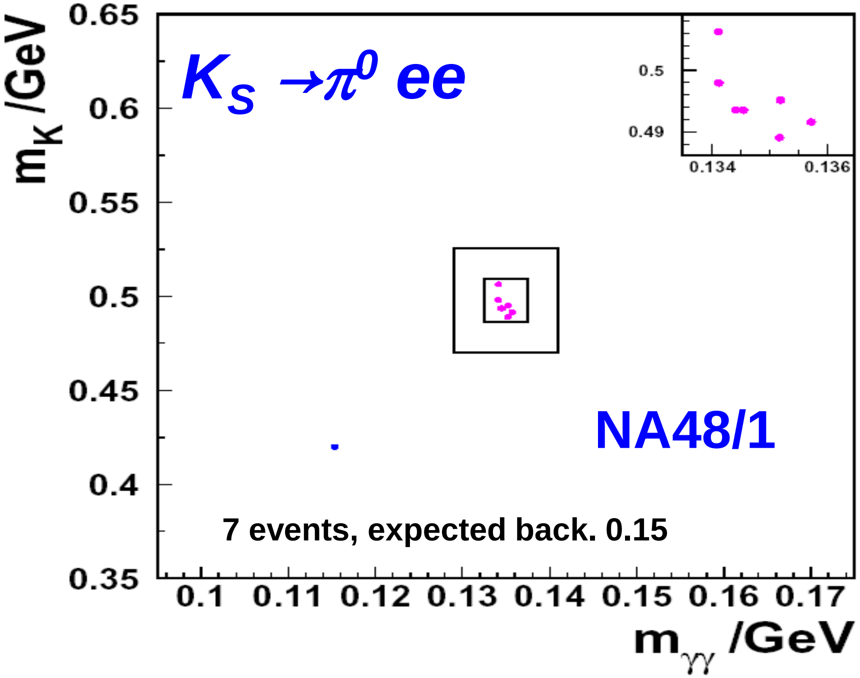
Indirect CPV

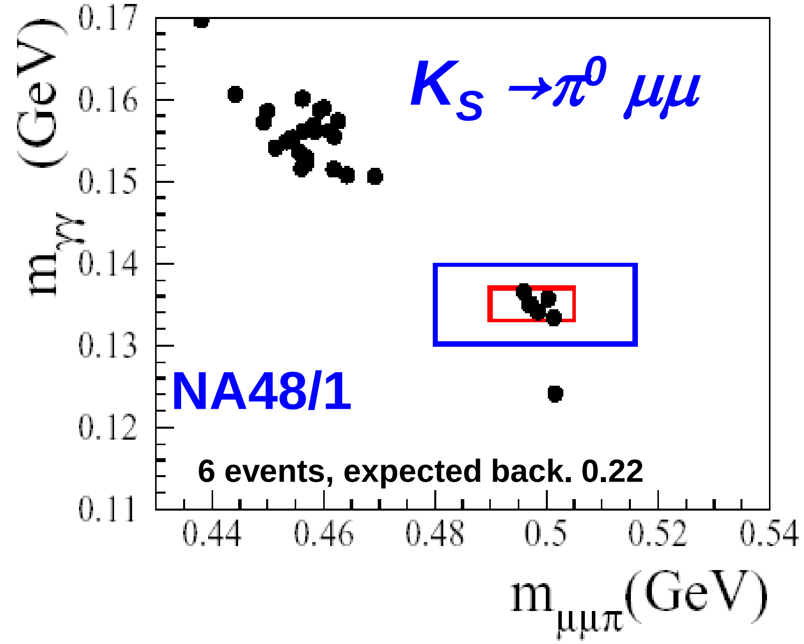




CPC

$K^0_S \to \pi^0 e^+e^-$ 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) ± 0.8(syst)

$|a_s| = 1.06^{+0.26}_{-0.21}$ (stat) ± 0.07 (syst)

PLB 576 (2003)

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

$|a_s| = 1.55^{+0.38}_{-0.32}$ (stat) ± 0.05 (syst)

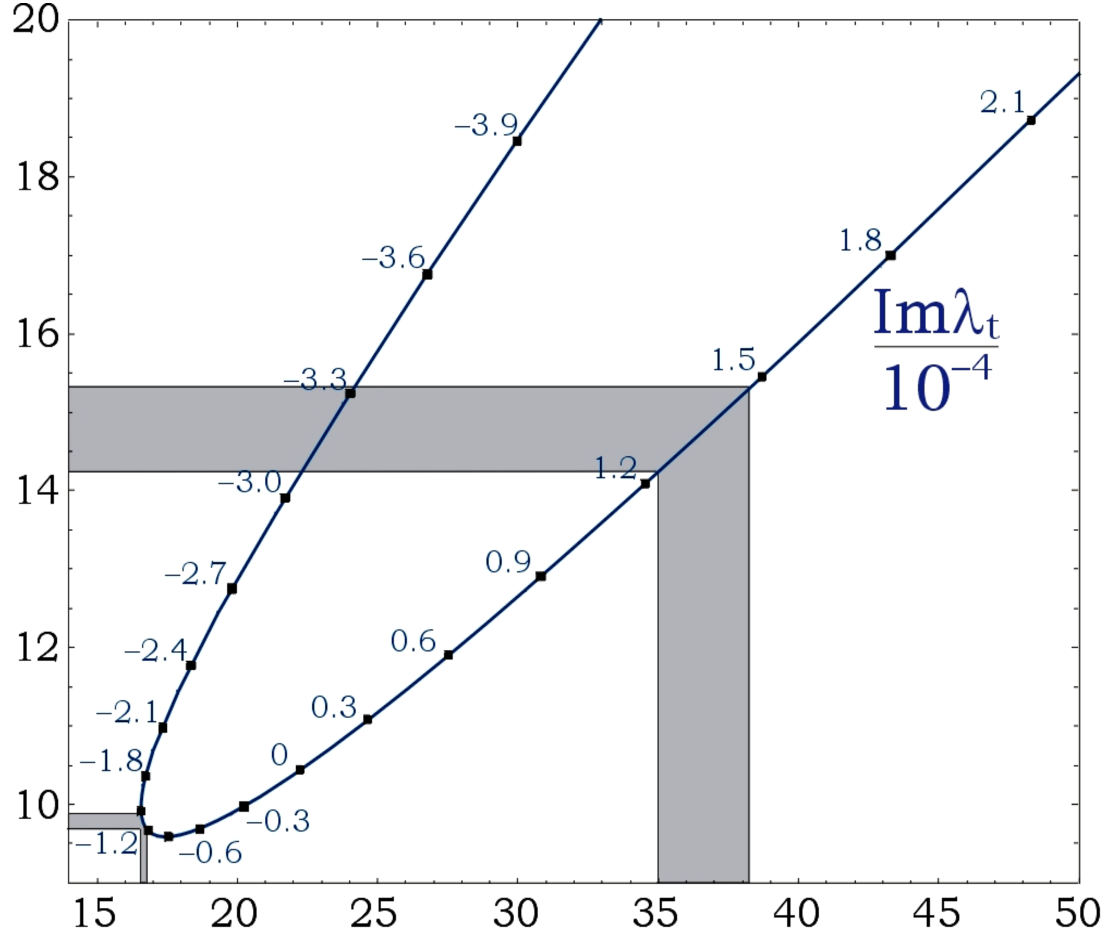
PLB 599 (2004)

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

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

(Isidori, Unterdorfer, Smith)

$$Br(K_L \to \pi^0 \mu^+ \mu^-) \quad (\times 10^{-12})$$



$$Br(K_L \to \pi^0 e^+ e^-) \quad (\times 10^{-12})$$

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

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

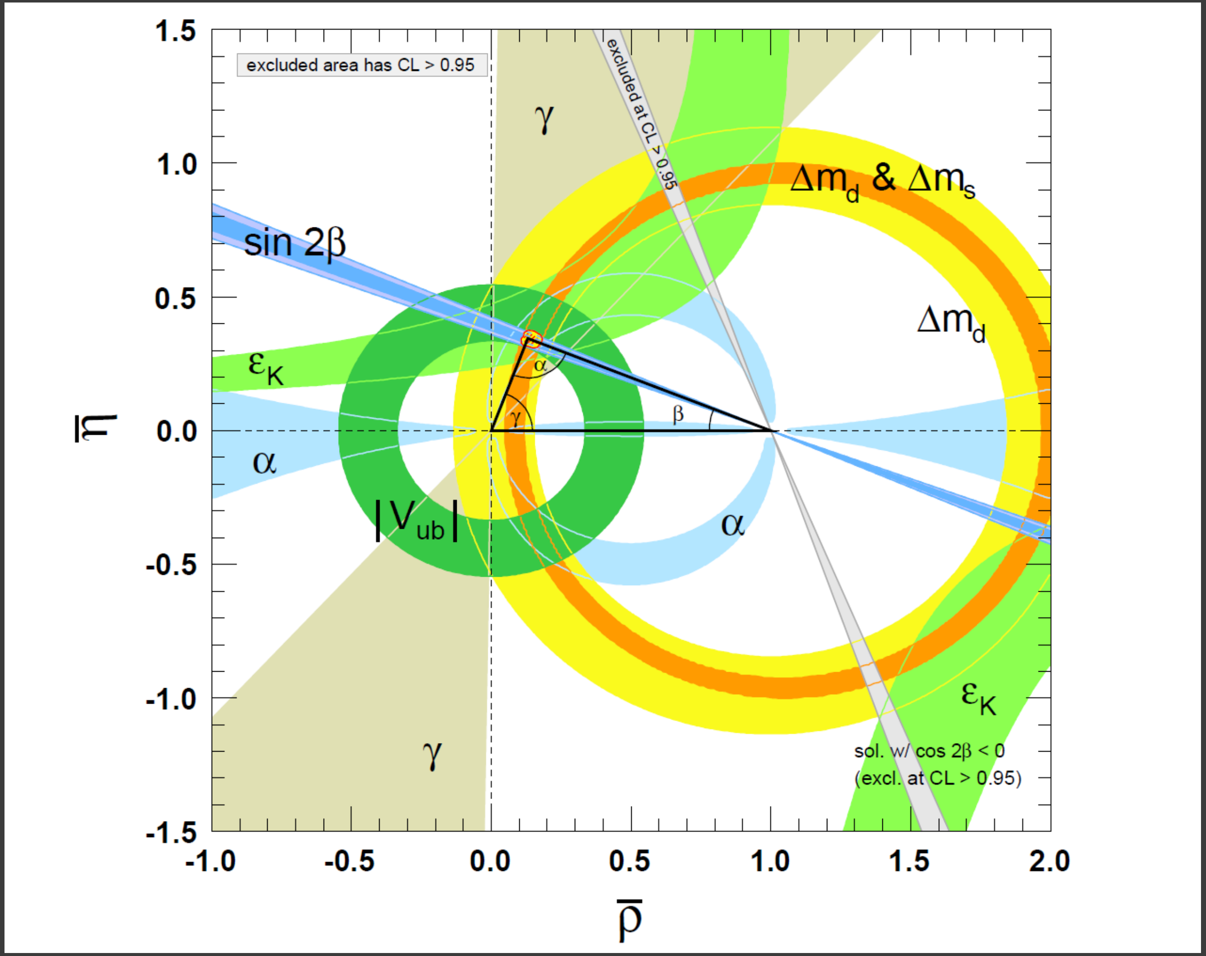
PDG 2014

$\lvert V_{ud}\rvert = 0.97425 \pm 0.00022$	$0^+ \rightarrow 0^+$ 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 (see later)

Constraints on the CKM triangle



PDG 2014

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

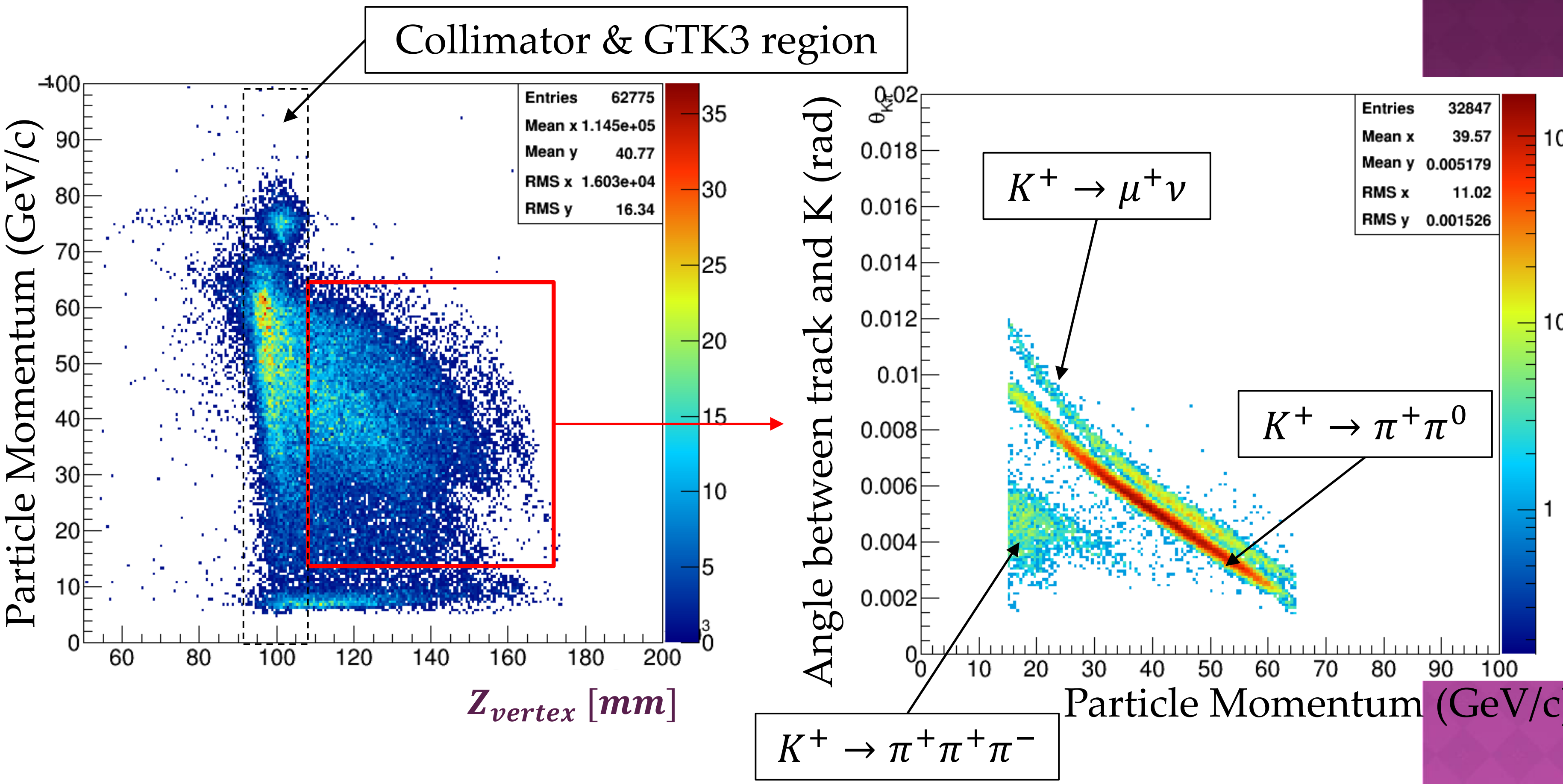
$$J = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$$

SEARCH FOR NEW PHYSICS

- Discoveries are almost always anticipated by arguments and indirect evidence:
  1. GIM: Charm@GeV
  2. Limits of Fermi theory: --> W,Z @ ~100 GeV
  3. CP-Violation--> 3rd generation of quarks
  4. Flavor, EW fit: m(top)~170 GeV
  5. EW fit: m(H) = 100 +/- 30 GeV
- Now the guidance from indirect evidence is lacking…we are left with arguments:
  - Hierarchy problem: NP close to EW scale
  - WIMP miracle: NP close to EW scale
  - Unification of gauge couplings
- So….while increasing the energy probed by direct searches, we need to seek for indirect evidence

2014 DATA QUALITY

- Use track origin to suppress the background from kaon interactions
- Decay vertex from the intersection between the track and the nominal K direction

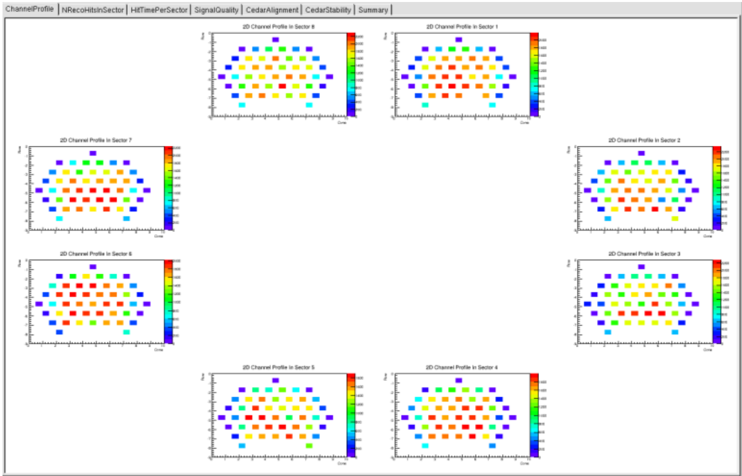


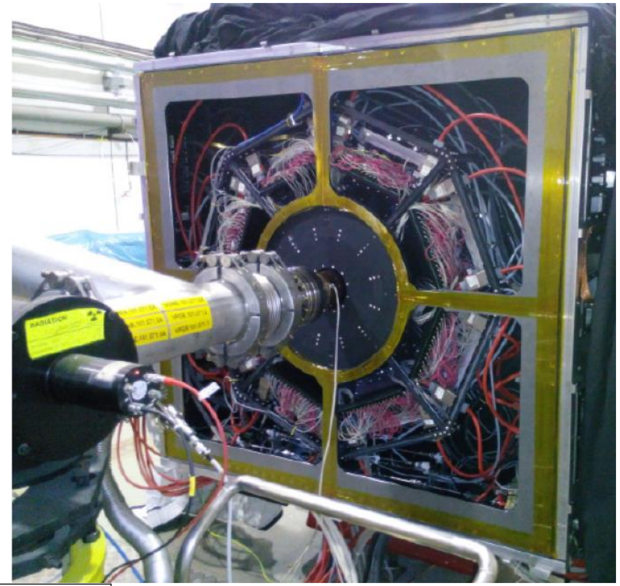
Search for $K_S \rightarrow \pi^0 \mu\mu$

- The considerations made before for $K_L \rightarrow \pi^0 ee$ apply also to $K_L \rightarrow \pi^0 \mu\mu$ but the CP-conserving contributions need more attention
- A measurement of $K_S \rightarrow \pi^0 \mu\mu$ is quite complementary to the $K_S \rightarrow \pi^0 ee$ one
  - Different backgrounds
  - Larger acceptance (no Dalitz background)
  - In principle one can relate $K_S \rightarrow \pi^0 \mu\mu$ and $K_S \rightarrow \pi^0 ee$ to extract the form factor (for example the a_S and b_S parameters)

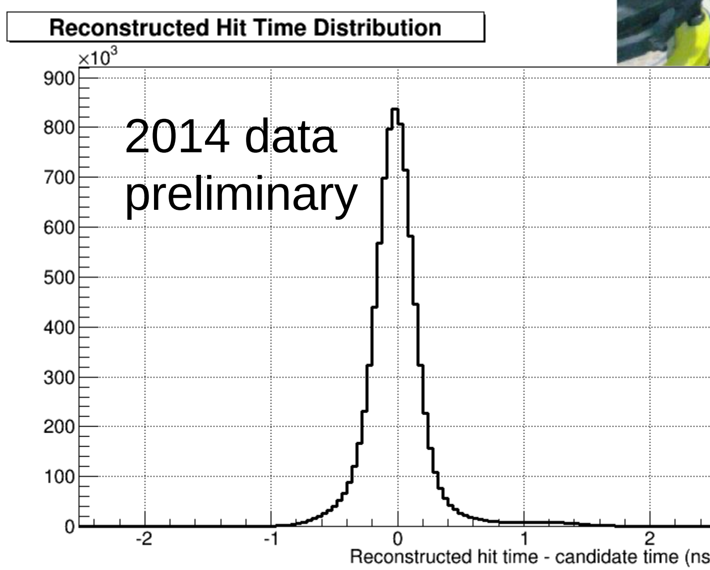
KTAG

Birmingham, Bristol, Liverpool





Kaon timing



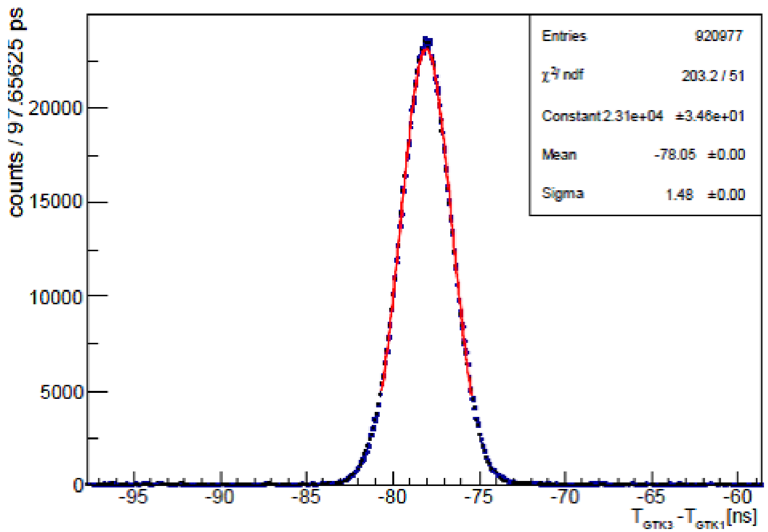
$\sigma_{PM}(t) \sim 280\ ps$

$\langle N_{PM} \rangle \sim 18$

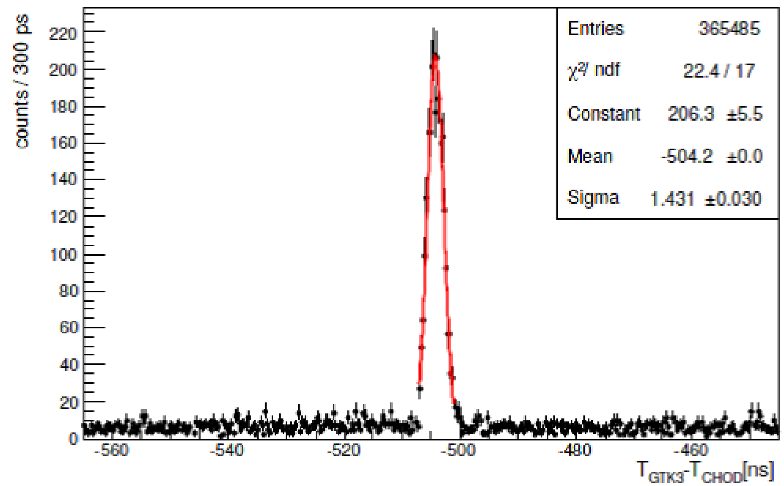
$\sigma_K(t) < 80\ ps$

Reconstructed hit time – candidate time [ns]

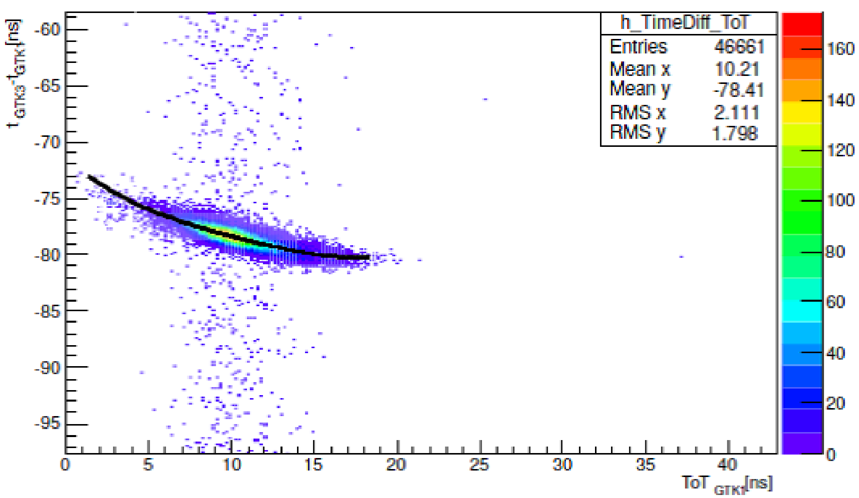
GTK analysis



GTK3 – GTK1 Before any correction



GTK3 – CHOD



GTK3-GTK1vs. ToT GTK1 (pixel 29,33)

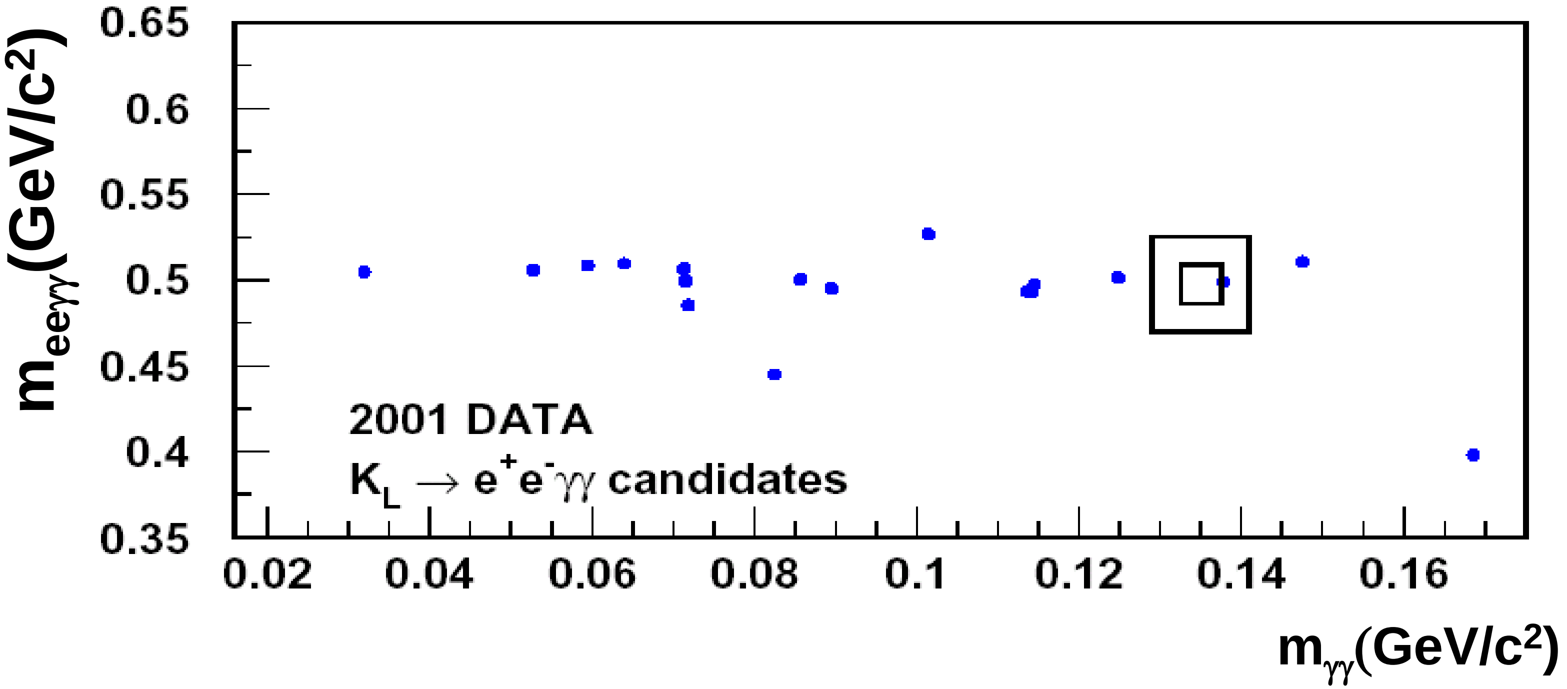
ToT is used to correct for
The slewing of the
signal

$K_S \to \pi^0 ee$

Background from $K_{L,S} \to ee\gamma\gamma$:

measured using NA48 K_L data from 2001

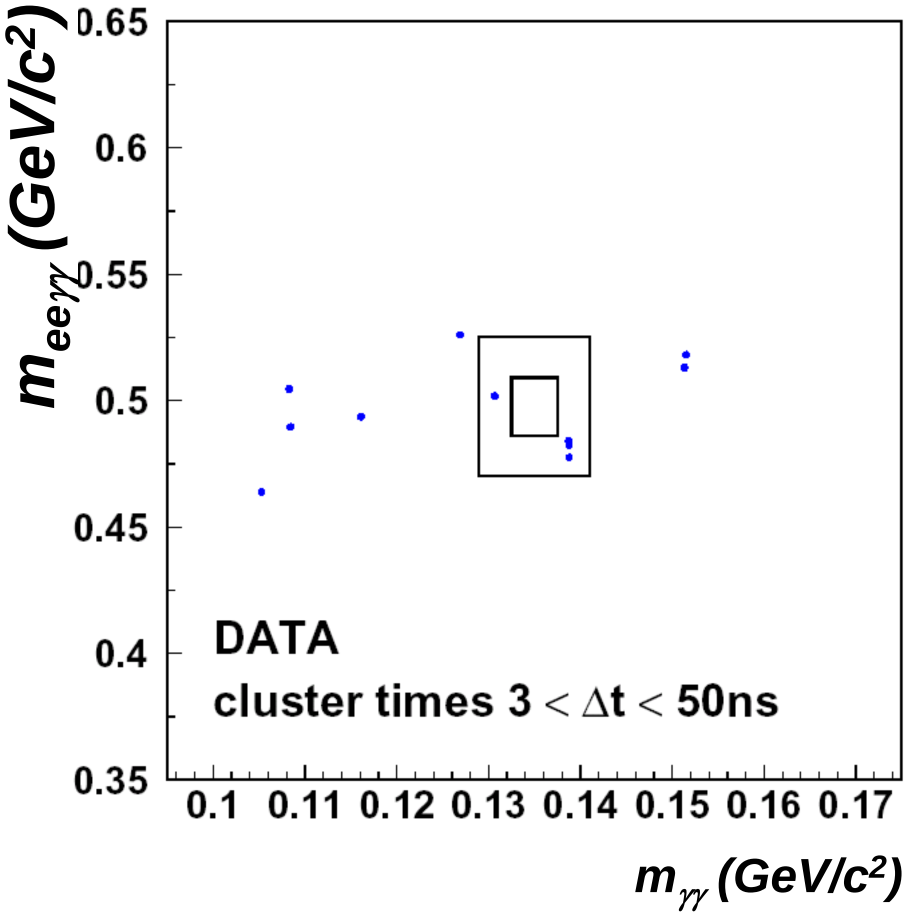
$N(K_L \to ee\gamma\gamma, 2001) \approx 10 \times N(K_{L,S} \to ee\gamma\gamma, 2002)$



$K_S \to \pi^0 ee$

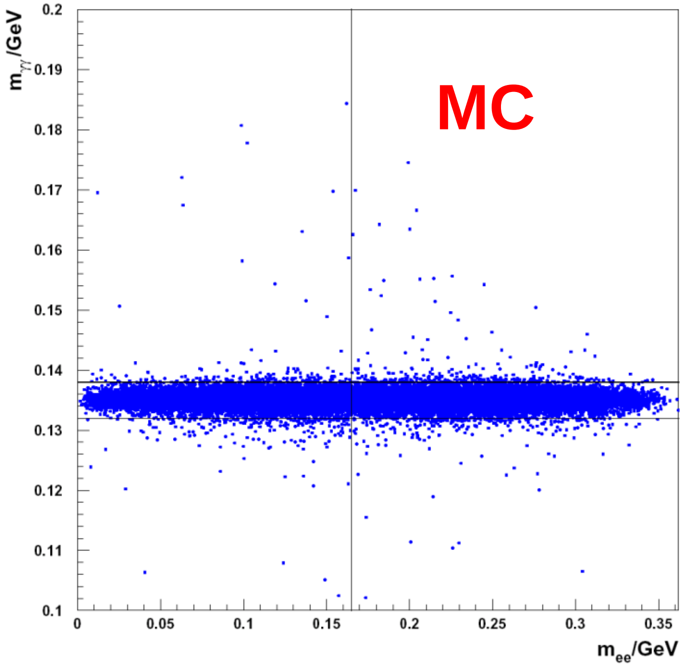
Accidental backgrounds

- **DC proton beam**
- **Read out window: ~ 200ns**
- **Use time side band to measure background from time-overlapping fragments from differ decays**
- **Major component:**
  - **$e\pi\nu + \pi^0(\pi^0)$**
  - **Confirmed relaxing E/P cuts**

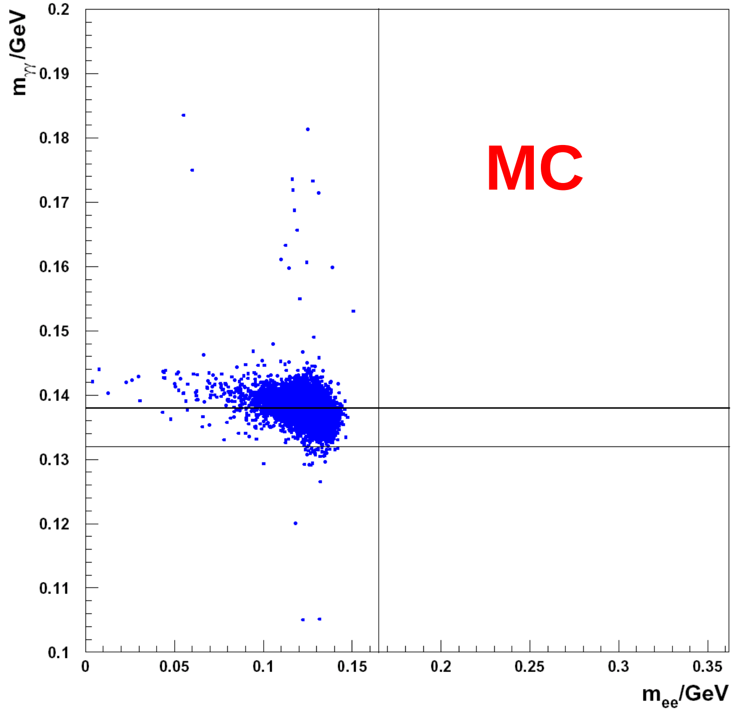


$K_S \rightarrow \pi^0\, ee$

$K_S \rightarrow \pi^0\, ee$



$K_S \rightarrow \pi^0\, \pi^0_D \rightarrow \gamma\gamma ee(\gamma)$



- **To reject the $K_S \rightarrow \pi^0\, \pi^0_D$ decays that may mimic $K_S \rightarrow \pi^0\, ee$ if a γ is lost, a cut $m_{ee}>0.165\ GeV/c^2$ is applied**

KOTO experiment

- Study of $K_L \to \pi^0 \nu \bar{\nu}$@J-PARC 30GeV Main Ring.
  - Successor to the E391a experiment
  - Goal is to observe few SM events.

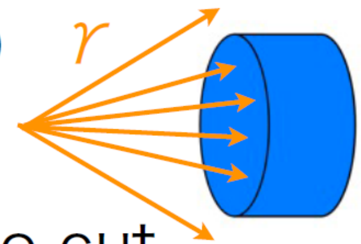
J-PARC

As presented by Koji Shiomi at CKM 2014 (Vienna)

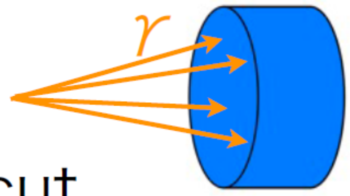
Veto detector performance

- 4 cluster samples

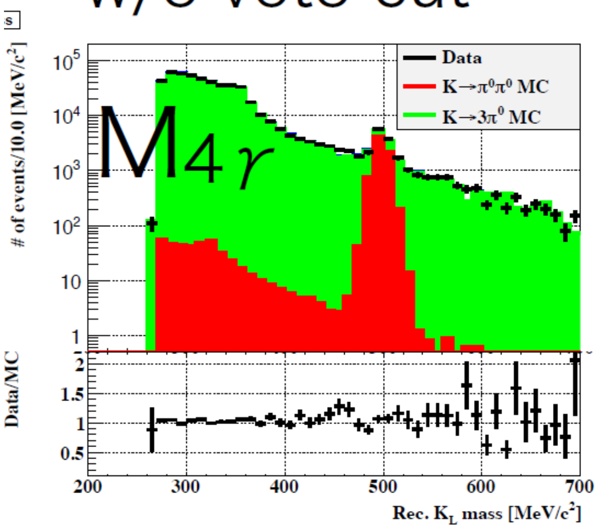
$BR(K_L \to 3\pi^0)$
$=20\%$



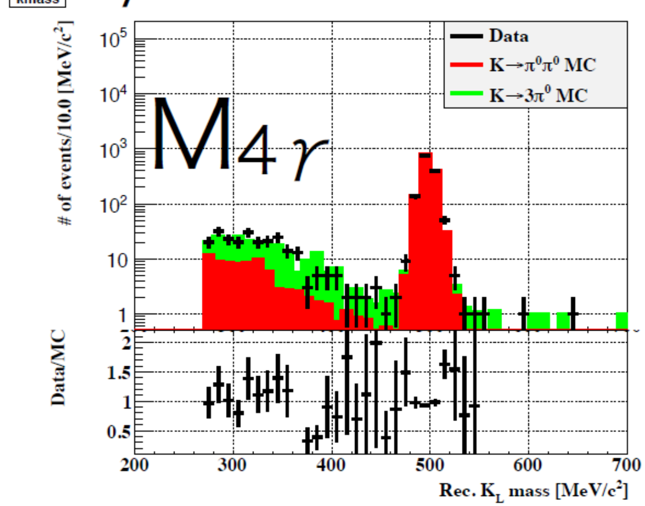
$BR(K_L \to 2\pi^0)$
$=8.6\times10^{-4}$



w/o veto cut



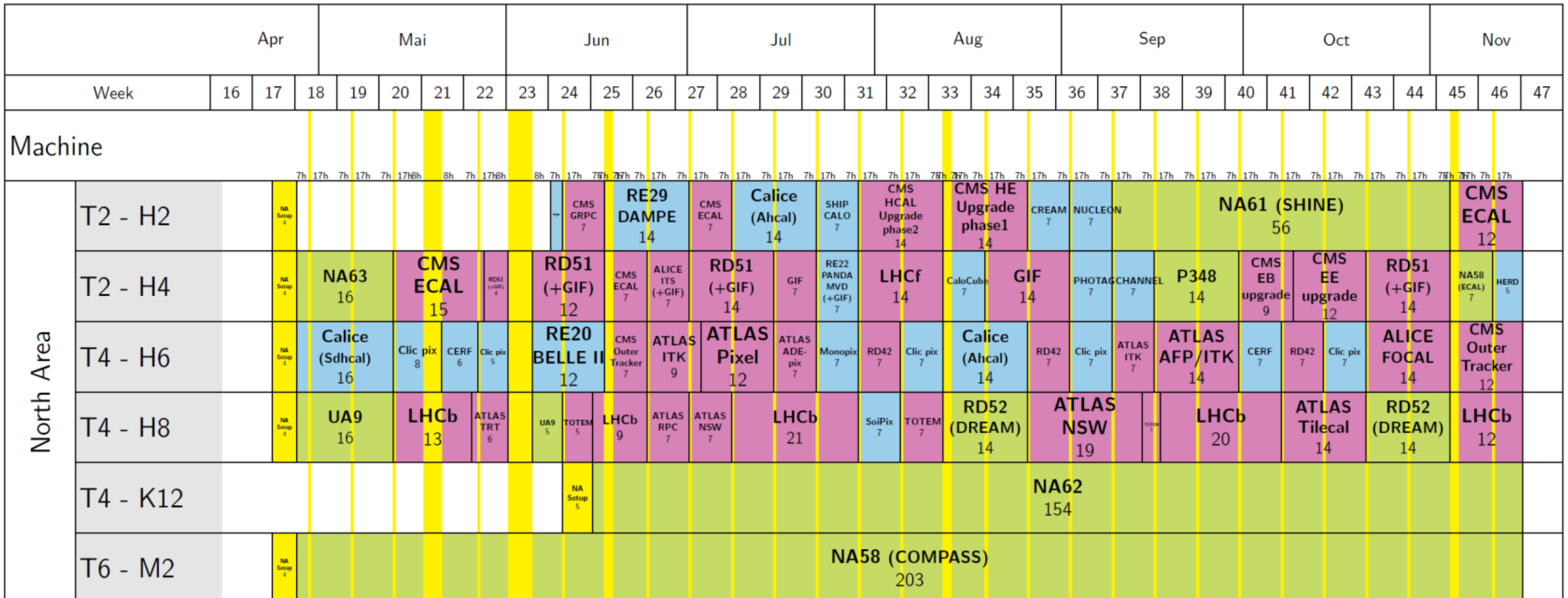
w/ veto cut



SPS user schedule for 2015

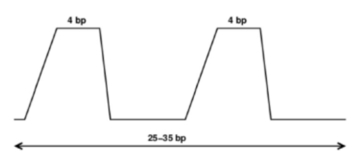
schedule issue date: 13-Mar-2015

Version: 1.03 LHC Exp. PS/SPS Exp. INT Exp. Other Exp.



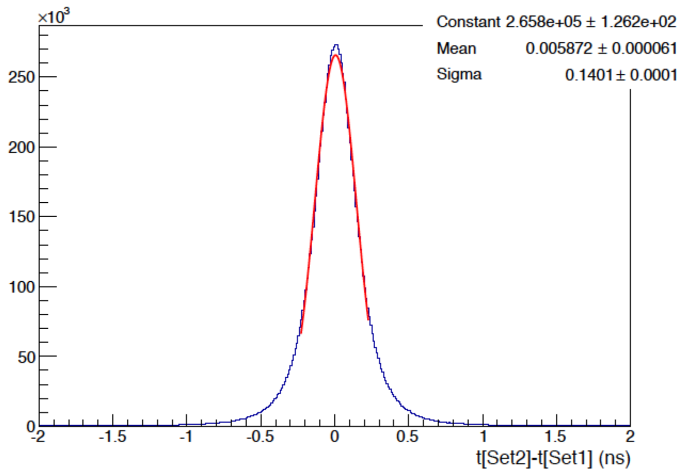
For further information contact the PS/SPS-Coordinator. Email: Sps.Coordinator@cern.ch, Tel: +41 76 487 3845.

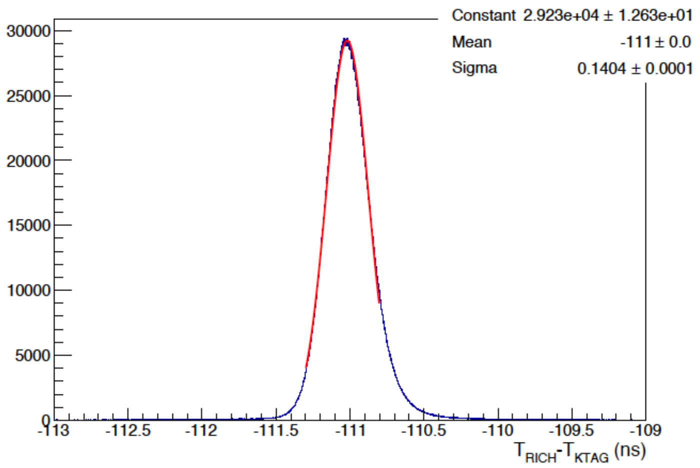
The latest version of the schedule are available here: http://sps-schedule.web.cern.ch/sps-schedule/
This schedule in synchronized with injector schedule v1.5
2 extractions with a 4.8s(4pb) flat top per supercycle.
No beam during Technical Stops (TS) and Machine Developments (MD)
NA62 startup schedule is very preliminary!!



RICH TIME RESOLUTION

For each event, average time of half of the hits – average time of the other half σ = 140 ps = 2 times the event time resolution

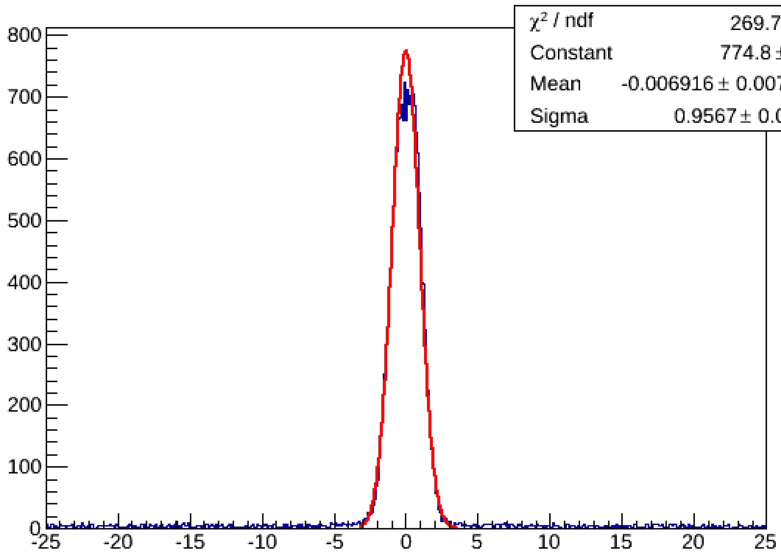


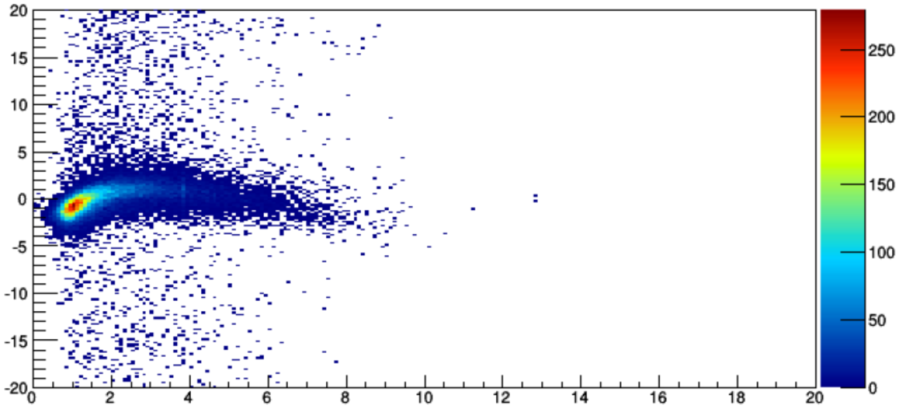


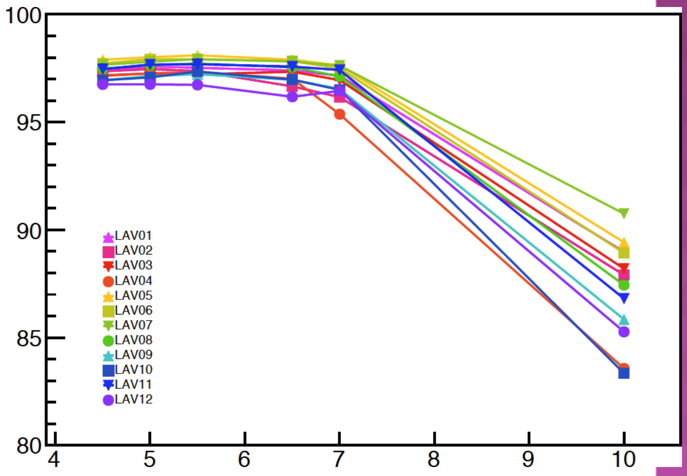
RICH event time resolution ~ 70 ps

LARGE ANGLE VETOES (LAV)

Frascati, Naples, Pisa, Rome I

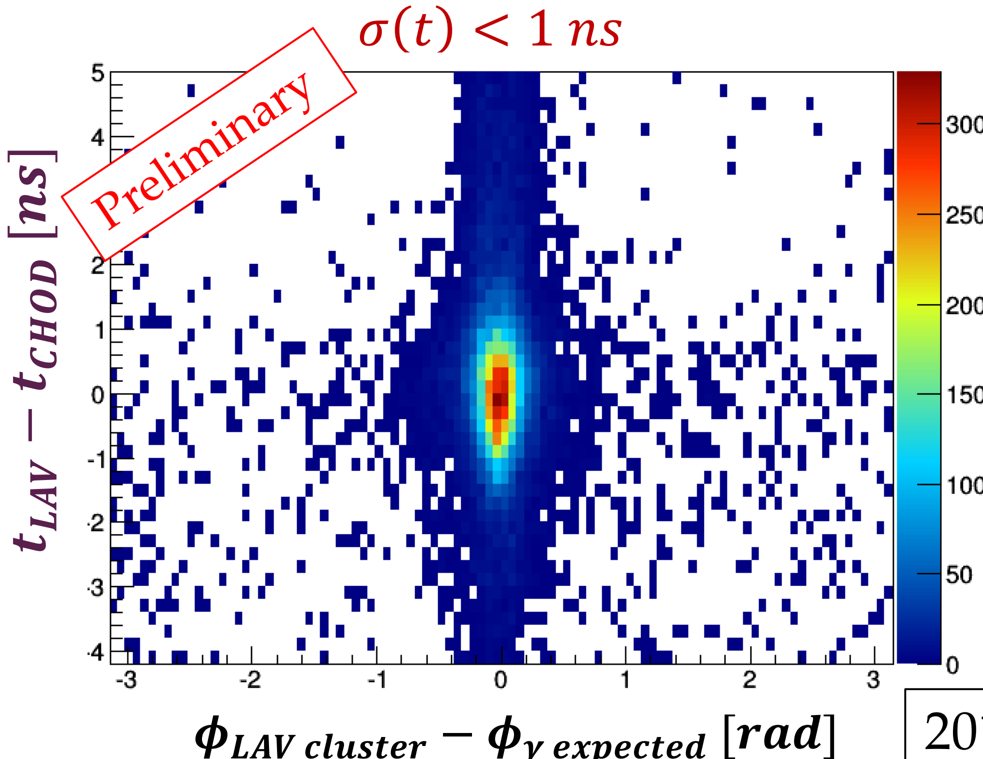




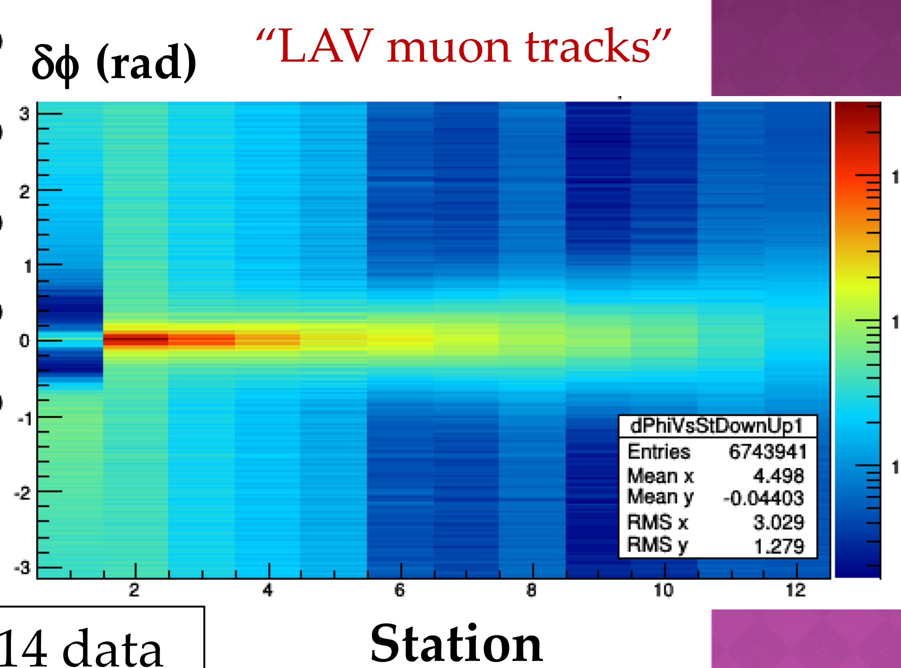


LAV SIGNALS

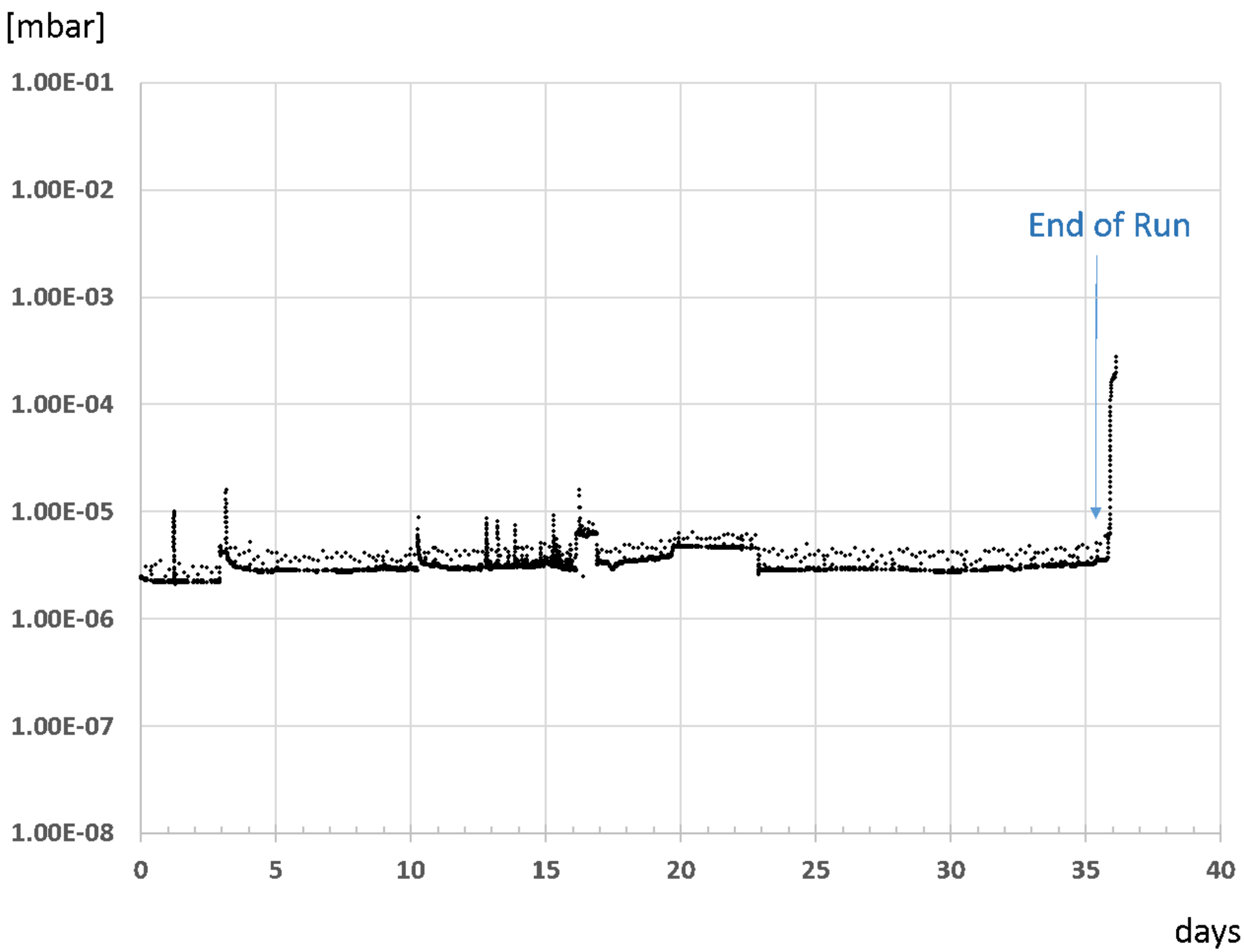
- Photons predicted in LAV match with reconstructed LAV clusters.
  - $K^+ \rightarrow \pi^+\pi^0$ reconstructed using straw spectrometer only.
  - 1 γ detected in the liquid Krypton calorimeter.
- LAVs' sensitive to muons



2014 data



VACUUM IN DECAY TANK



Very satisfactory performance

A. Buras list of Flavour Superstars

Superstars of 2011 – 2015 (Flavour Physics) $\rightarrow$ **2025**

$S_{\psi\varphi}$

$\not{C}\!\!\!\not{P}$ in $B_s^0 - \bar{B}_s^0$

$(B_s \rightarrow \varphi\varphi)$

$B_s \rightarrow \mu^+\mu^-$

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

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

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

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

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

γ from Tree Level Decays

$\mu \rightarrow e\gamma$

$\tau \rightarrow \mu\gamma$

$\tau \rightarrow e\gamma$

$\mu \rightarrow 3e$

$\tau \rightarrow 3$ leptons

ε'/ε *)

(Lattice)

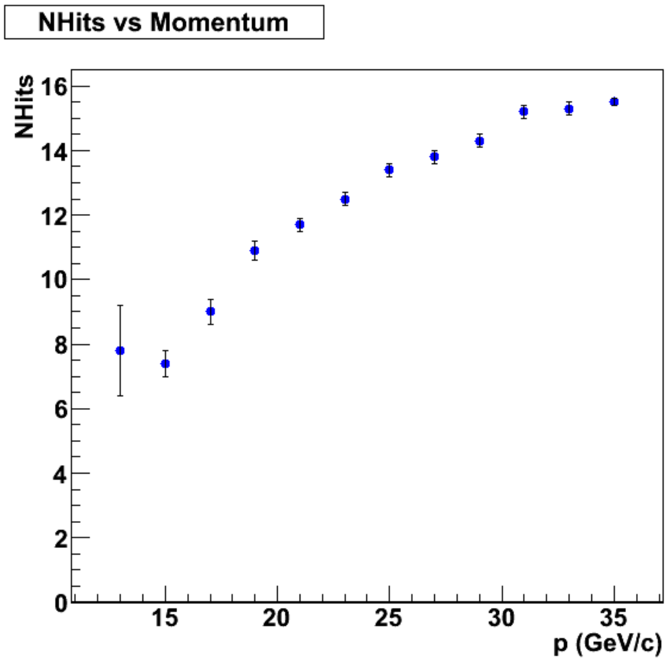
EDM´s

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

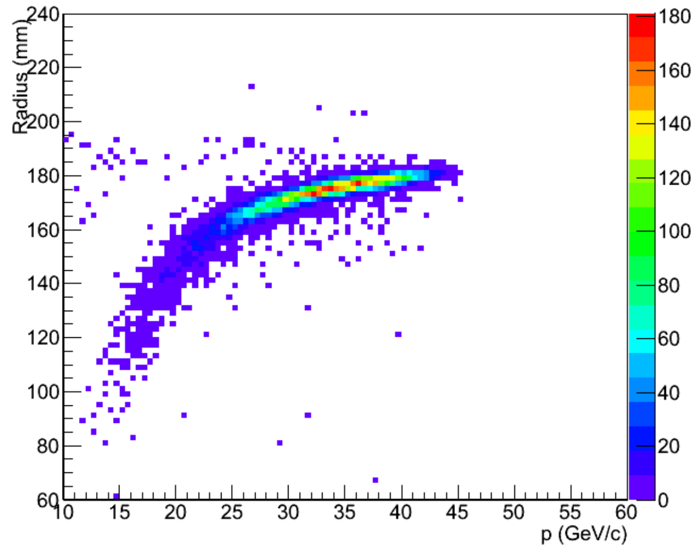
*) Direct $\not{C}\!\!\!\not{P}$ in $K_L \rightarrow \pi\pi$

37 Amsterdam0411

RICH PERFORMANCE



Number of hits per ring as a Function of particle momentum



Cherenkov ring radius vs. particle momentum for $\pi^{+}\pi^{0}$ events (w/o spectrometer information)