Measurement of the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ at the CERN SPS

Alive and Kicking*

* Fabio, thanks for the title

NA6.... what?

- Fixed target experiment @ CERN SPS (NA= North Area)

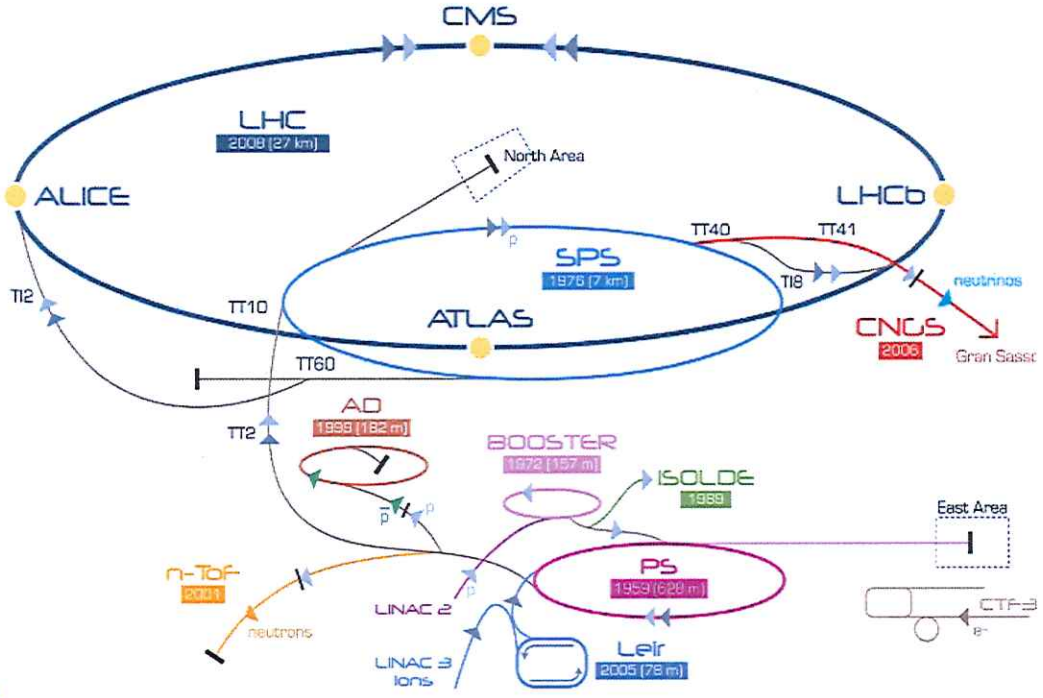
  400 GeV/c p on Be target ..... $1-3 \times 10^{12}$/s

  p = + 75 GeV/c (6% K^+) ..... $\sim 750 \times 10^6$/s

  K^+ decays ..... $\sim 5 \times 10^6$/s

- "Small" experiment

Institutes	32	(188)
Authors	234	(3582)
Participants	328	(5788)



- Data taking: 2015, 2016, 2017

KAONS: "old" lab for New Physics

$K \equiv$ flavor $\begin{cases} -\text{ CP violation discovery} & (1964) \\ -\text{ Direct CP violation} & (1999) \end{cases}$

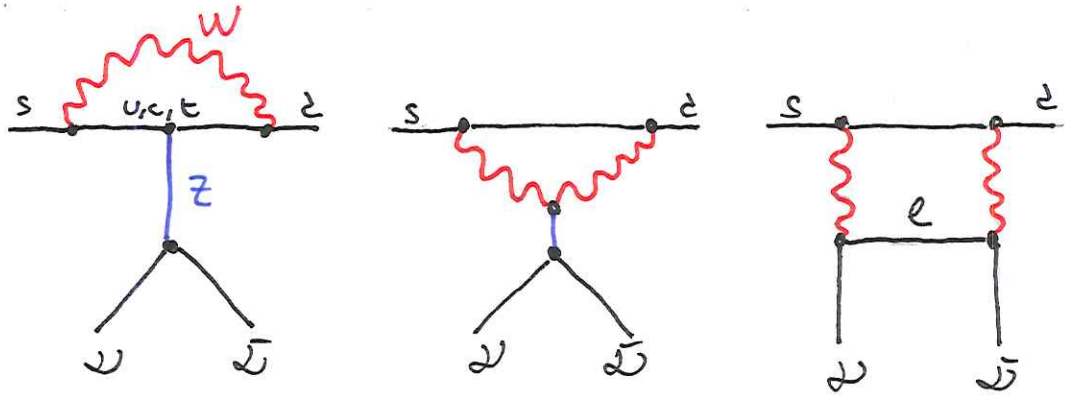
$K \equiv$ New Physics $\begin{cases} - K^+ \to \pi^+ \nu\bar{\nu} \\ - \text{LFV} \end{cases}$

Advantages of Kaons:

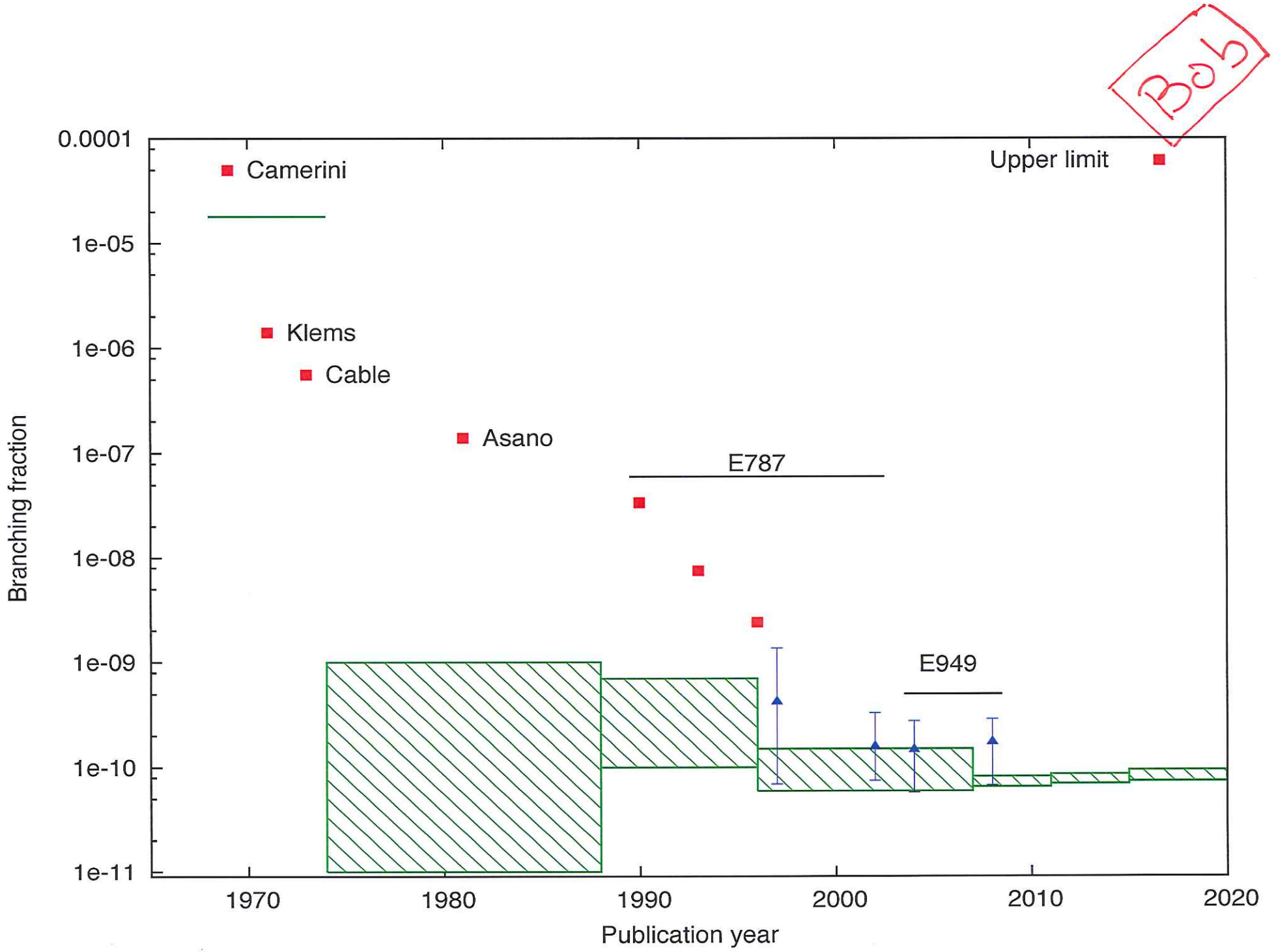
- Minimal flavor lab
- Well known decays
- Simple topologies
- Clean experimental signatures

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

- FCNC loop processes
- Short distance dominated
- Long distance effects taken from measurements



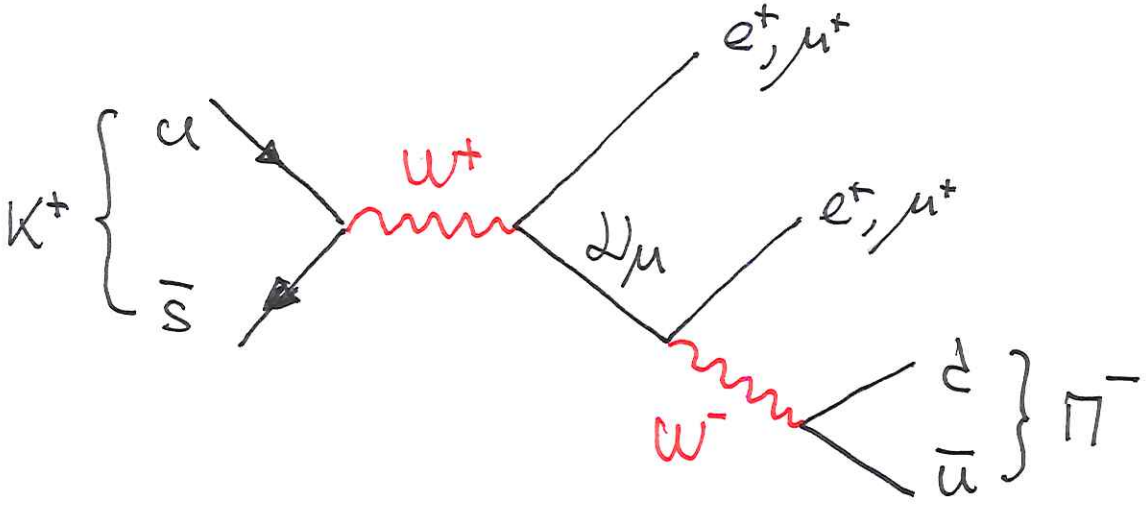
	Theory ($\times 10^{11}$)	Experiment ($\times 10^{11}$)
$K^+ \to \pi^+ \nu \bar{\nu}$	9.11 ± 0.72	$17.3^{+11.5}_{-10.5}$
$K^0 \to \pi^0 \nu \bar{\nu}$	3.00 ± 0.30	< 2600 (90% CL)


Bob
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
Branching fraction
Camerini
Klems
Cable
Asano
Upper limit
E787
E949
1970
1980
1990
2000
2010
2020
Publication year

LFV in Kaon decays

- 10^{13} K^+ decays → 10% acceptance → 10^{12} events
  - 10^{13} K^+ decays: largest sample of K^+ decays
  - 10^{12} events → single event sensitivities $\sim 10^{-12}$

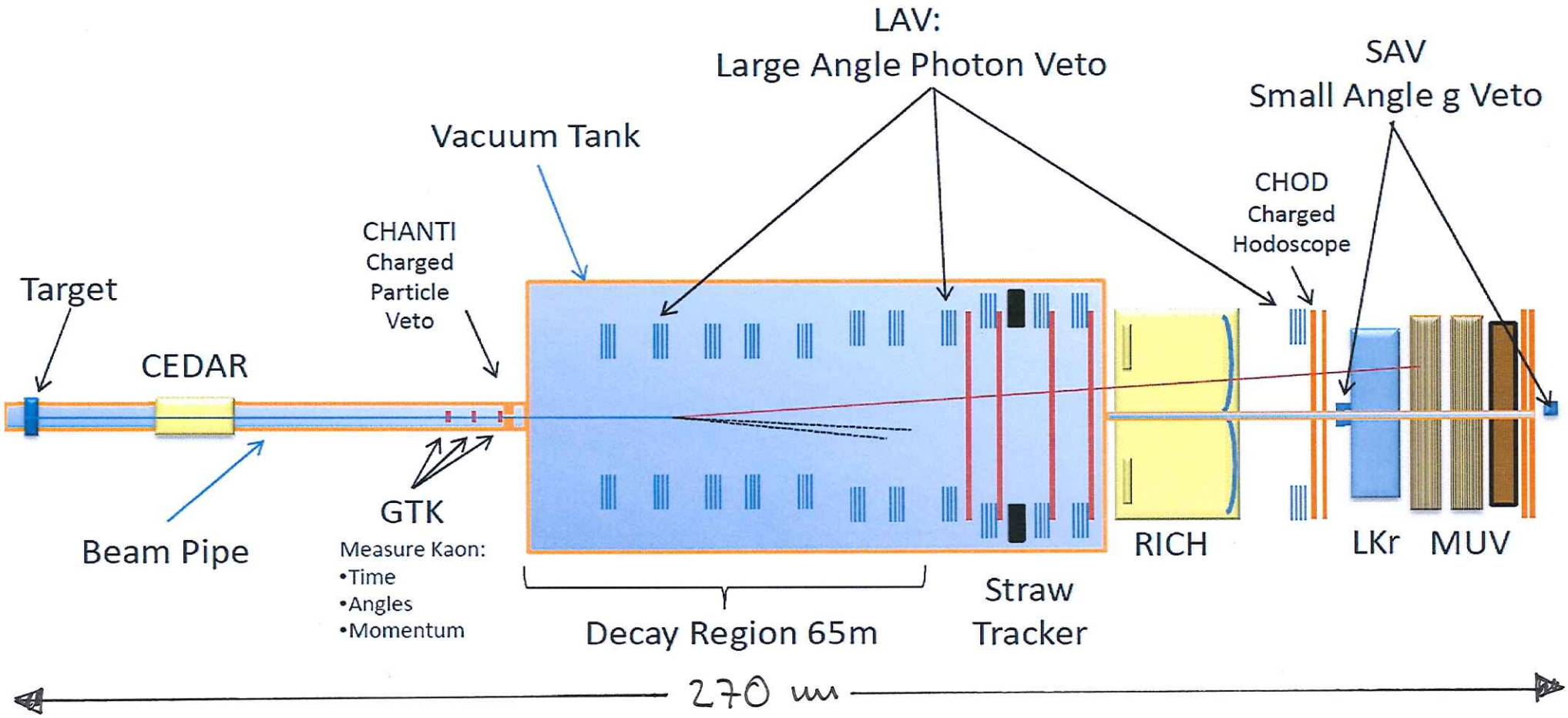
- $K^+ \to \pi \ell_1 \ell_2$ → Clean experimental signature



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)

NA62: Experimental setup

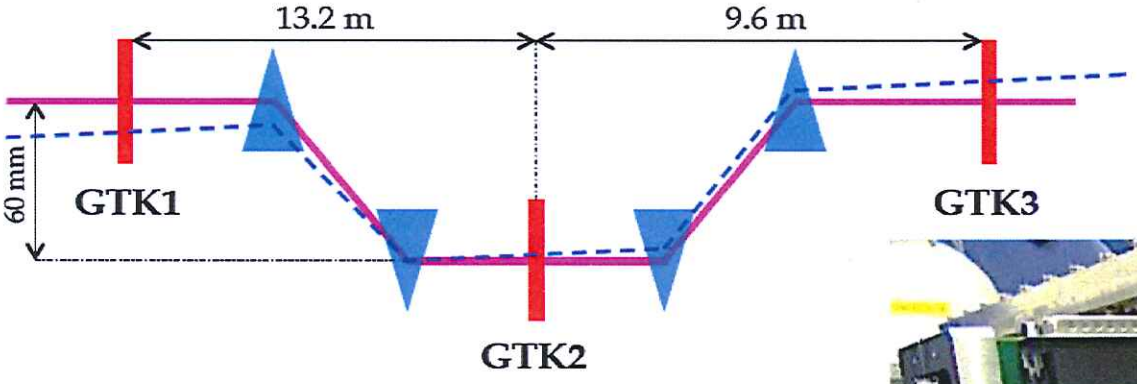
- Decay "in flight" technique
- High intensity beam
- Low mass tracking

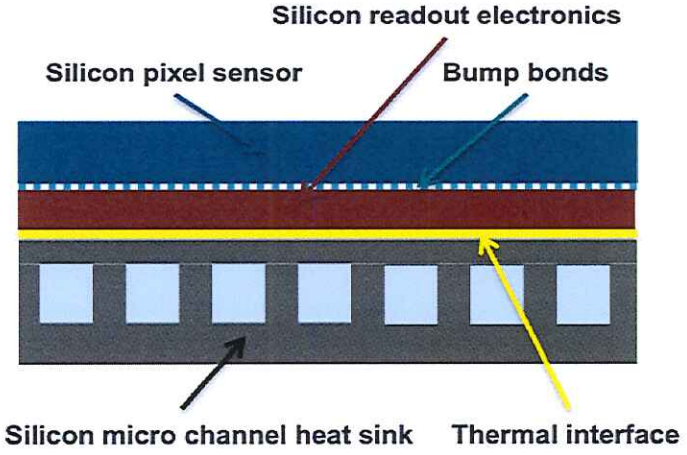



BRUNNHUBER
45/2,5 t

GTK

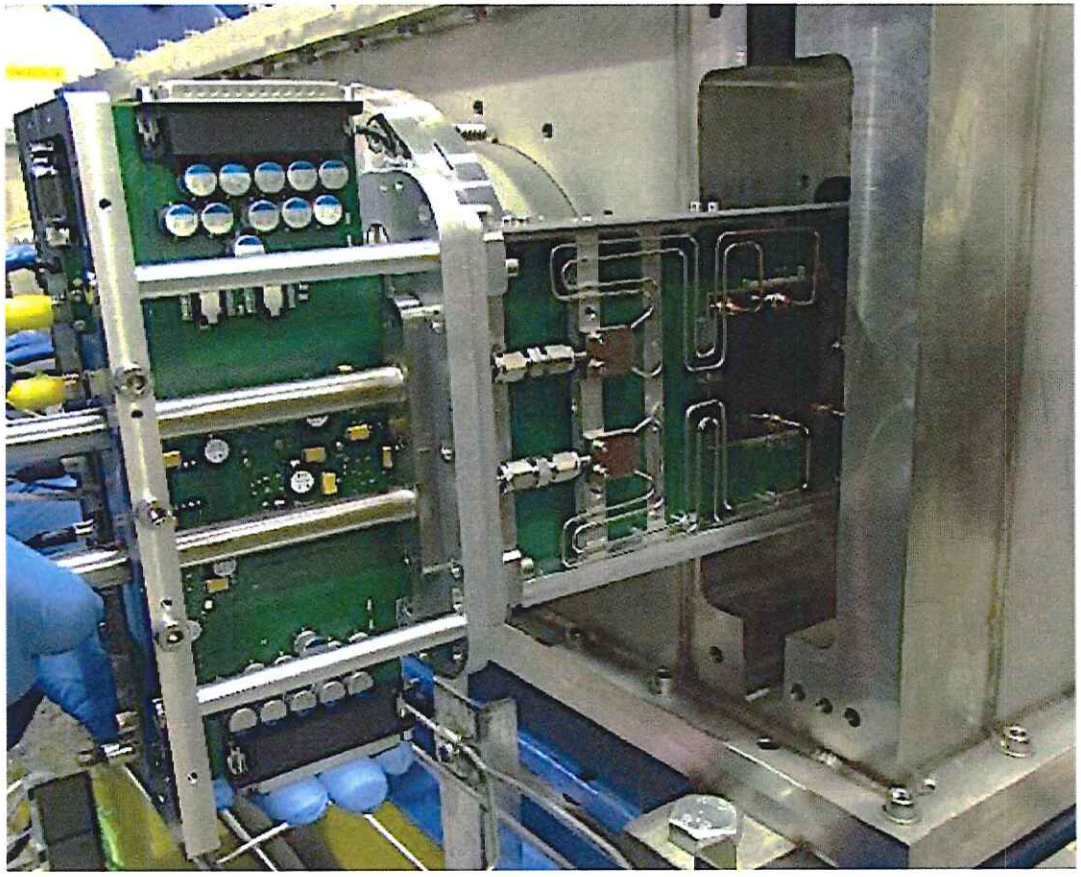
- 3 stations : 18000 pixels/station 300 μm × 300 μm
- Timing capabilities $\sigma_t \sim 200$ ps





CP3

- ROC design (Elena)
- Cooling system (Georg)
- Mechanics (Nicolas Sz)
- Simulation (Bob, Elisa)
- Reconstruction (Bob, Elisa)
- Performance analysis (Bob)

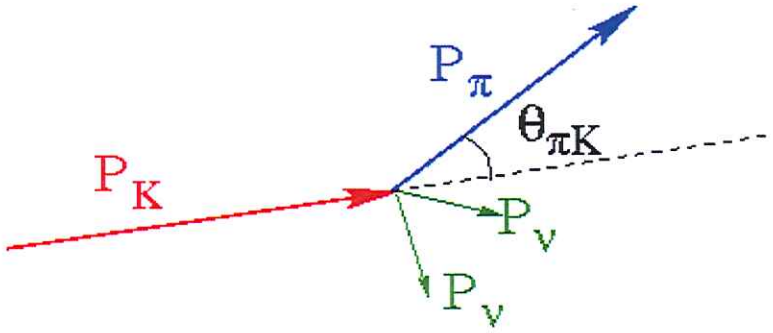


$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis strategy

Signal: single π^+ matching beam K^+

$O(10^{-11})$

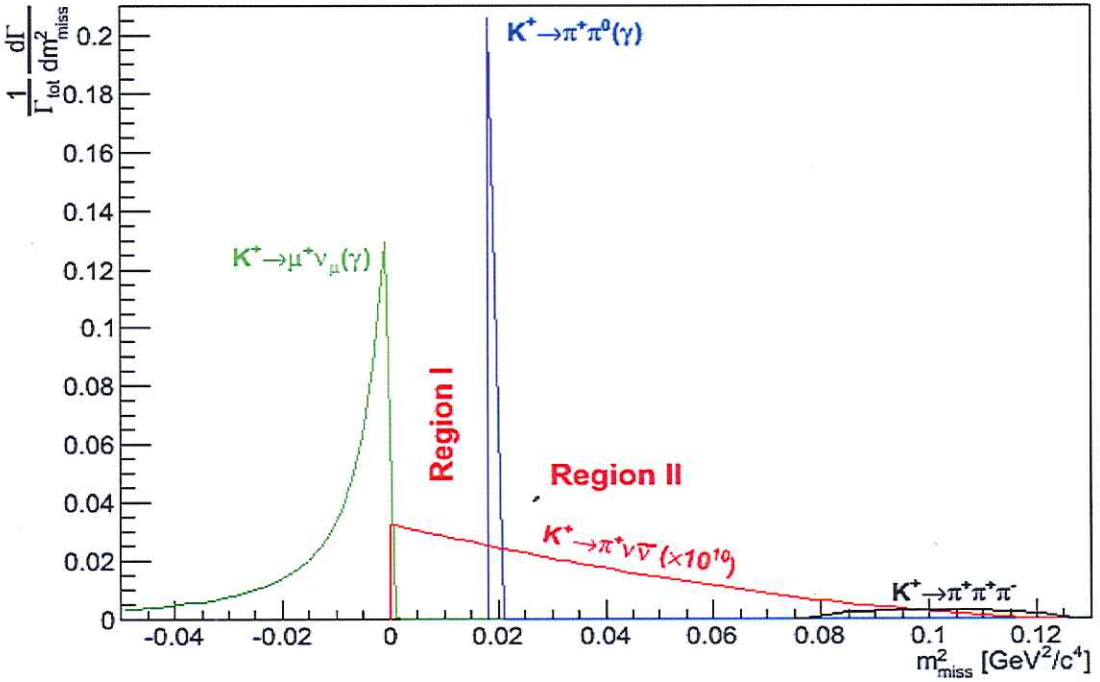
Background : $O(1)$

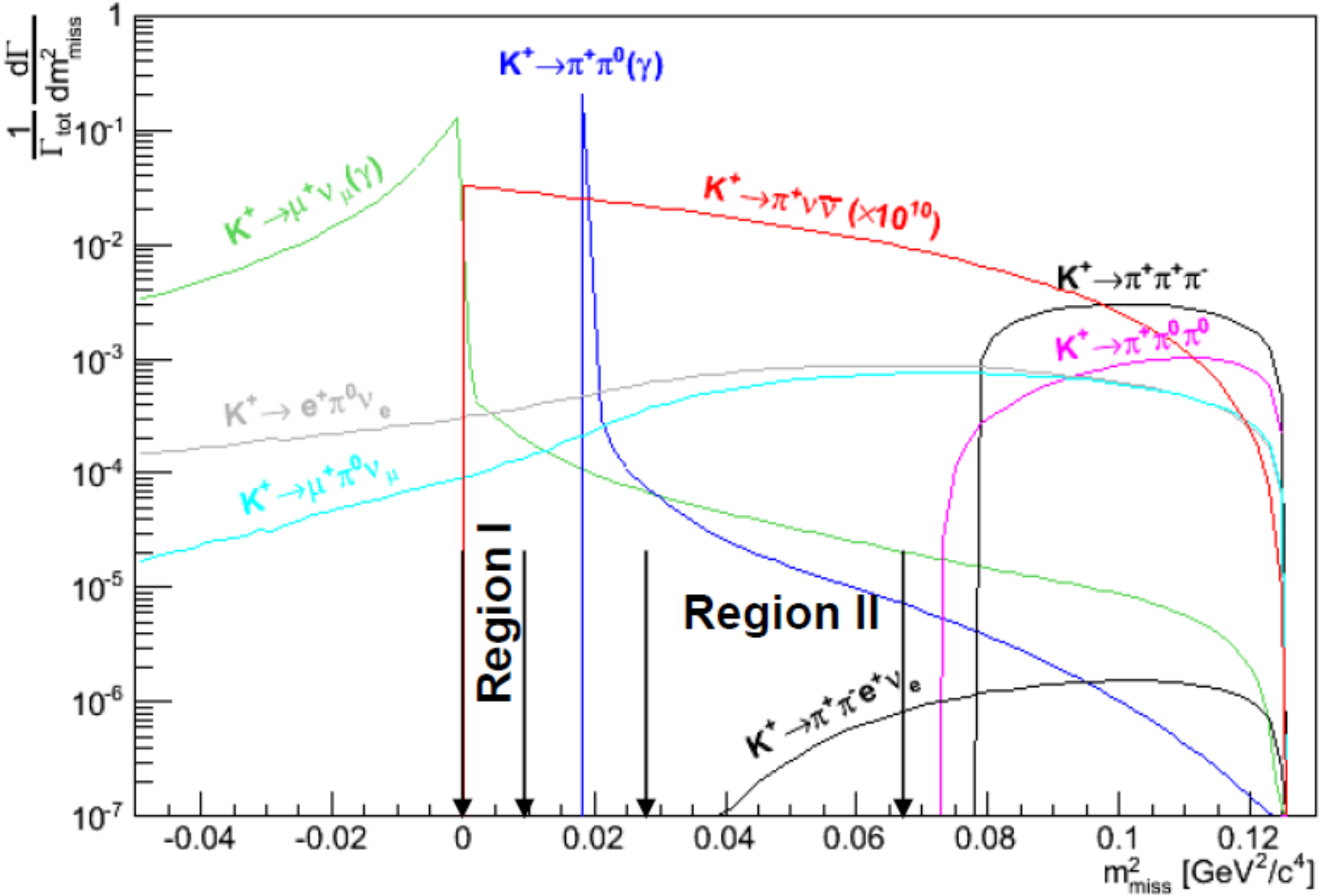


$$m^2_{miss} = (P_K - P_\pi)^2$$

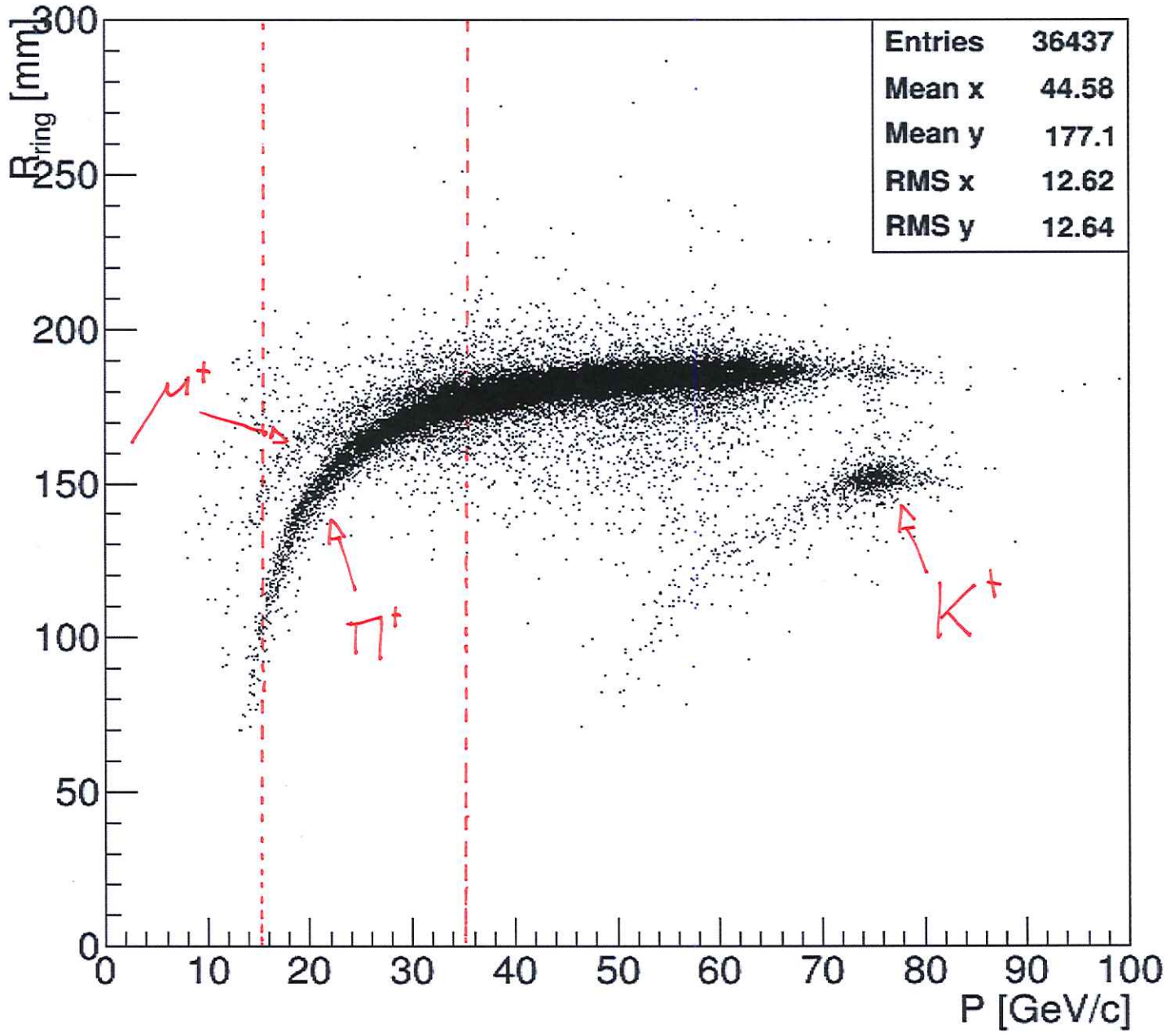
Background suppression:

1) Kinematics ..... $O(10^4 - 10^5)$
2) Timing ..... $O(10^2)$
3) Charge PID ..... $O(10^7)$
4) γ detection ..... $O(10^8)$




$\frac{1}{\Gamma_{tot}}\frac{d\Gamma}{dm^2_{miss}}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$K^+ \to \pi^+\pi^0(\gamma)$
$K^+ \to \mu^+\nu_\mu(\gamma)$
$K^+ \to \pi^+\nu\bar{\nu}$ ($\times 10^{10}$)
$K^+ \to \pi^+\pi^+\pi^-$
$K^+ \to \pi^+\pi^0\pi^0$
$K^+ \to e^+\pi^0\nu_e$
$K^+ \to \mu^+\pi^0\nu_\mu$
$K^+ \to \pi^+\pi^-e^+\nu_e$
Region I
Region II
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
m^2_{miss} [GeV^2/c^4]

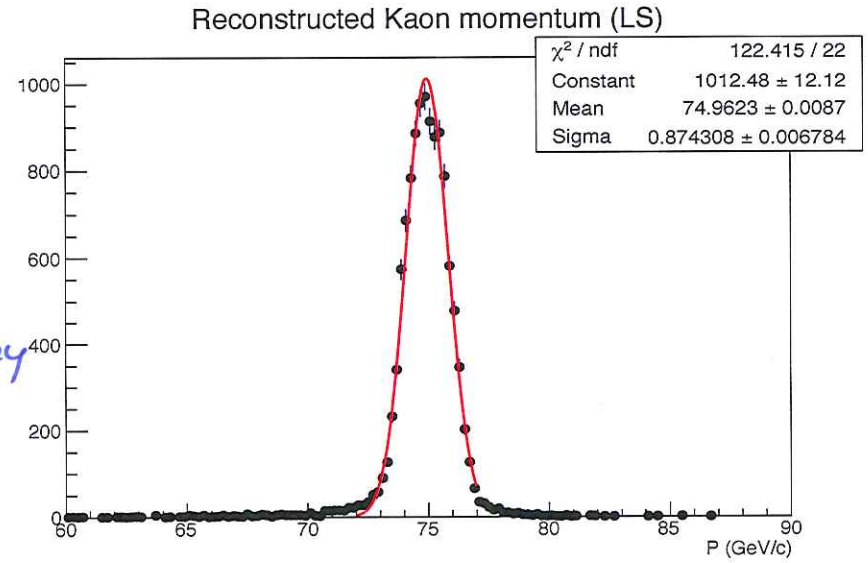
PID: RICH

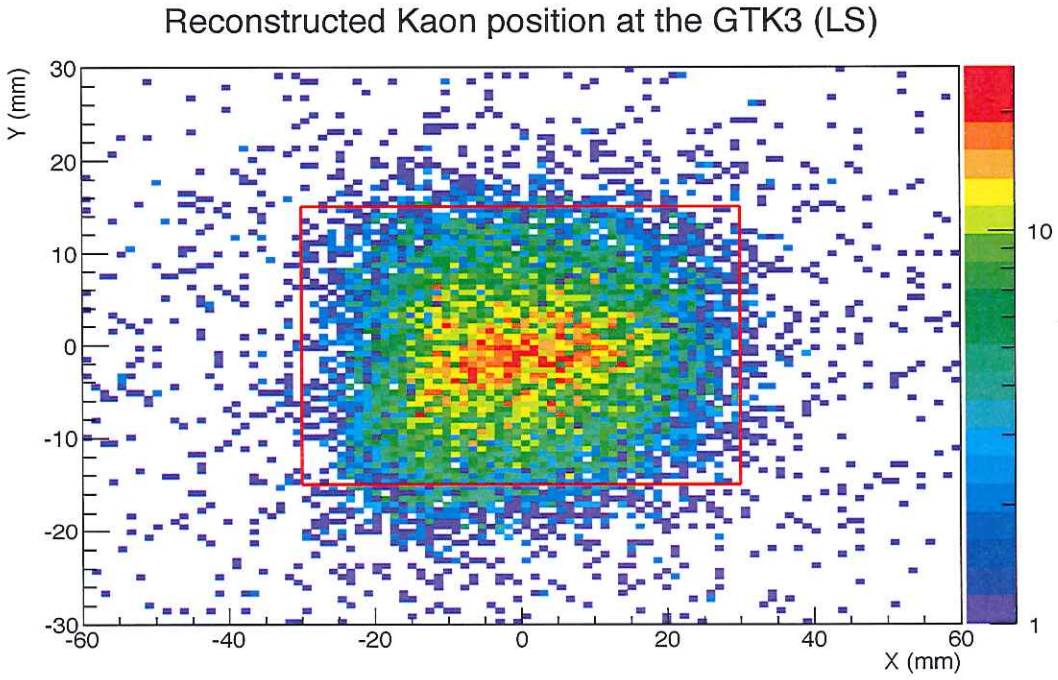

Entries 36437
Mean x 44.58
Mean y 177.1
RMS x 12.62
RMS y 12.64
R_{ring} [mm]
P [GeV/c]
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100
μ^+
π^+
K^+

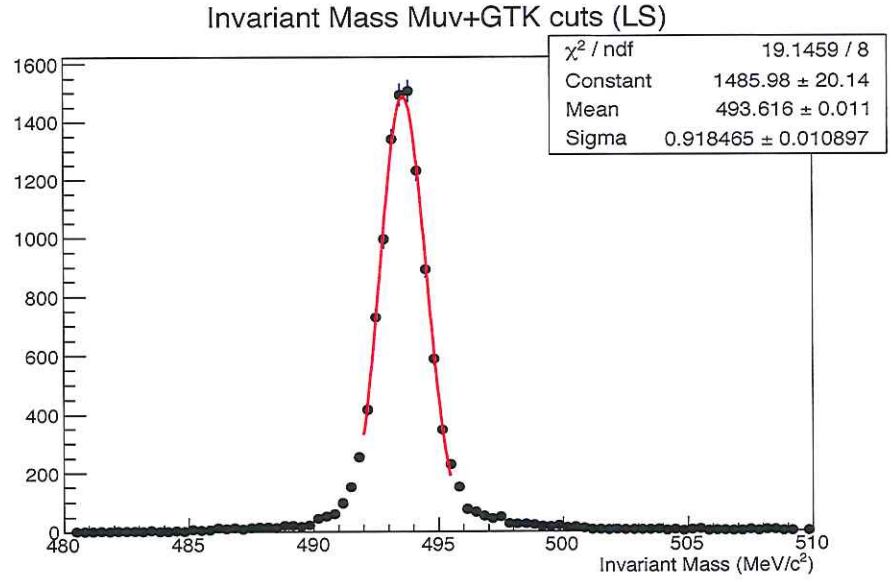
$K^+ \to \pi^+\pi^+\pi^-$: 2015 data

Planeu Elisa

- → K^+ info not available so far
- → Expected huge improvement once GTK info included
- → Essential decay
  - All BR measured wrt this decay
  - "Exercice" for LFV analysis

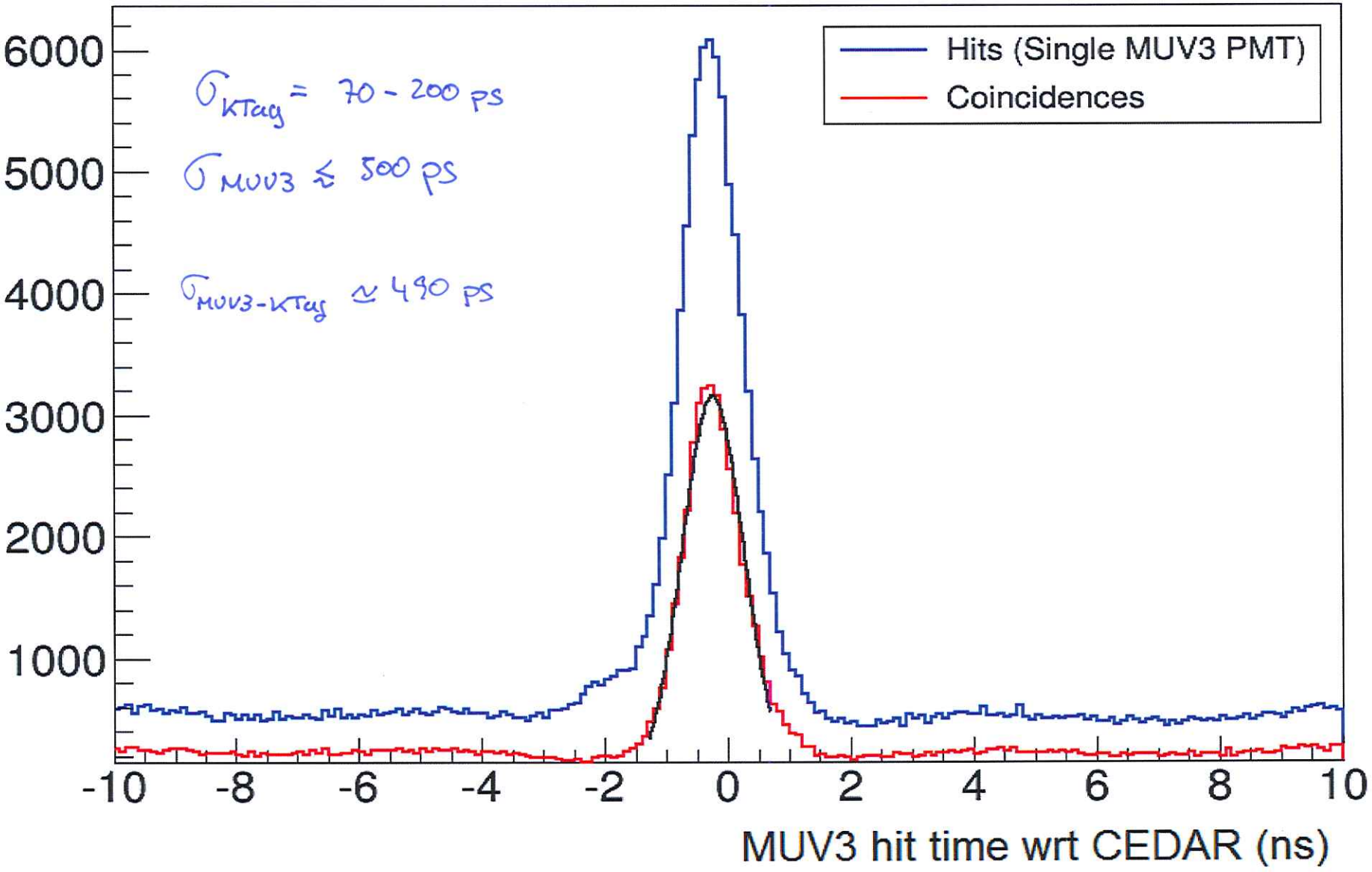






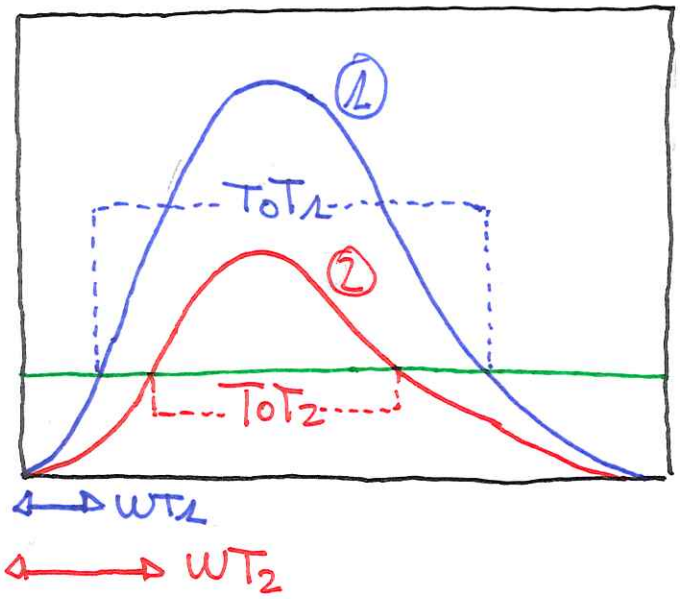
TIME RESOLUTION

Plamen



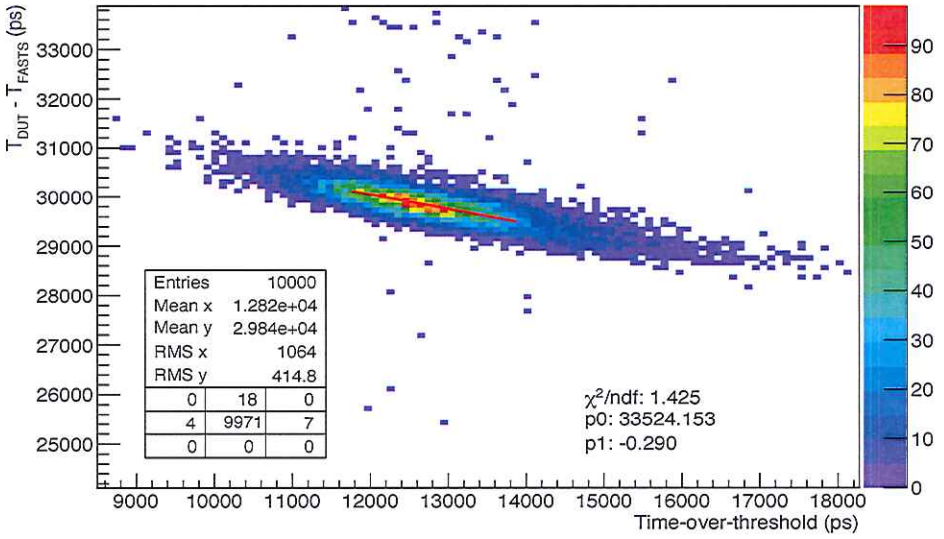
GTK: Time resolution

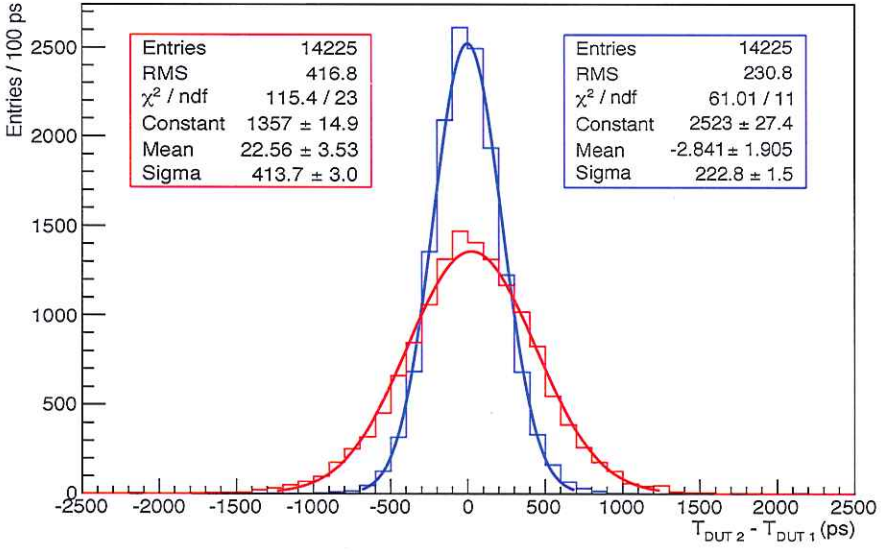
ToT ↑ → WT ↓

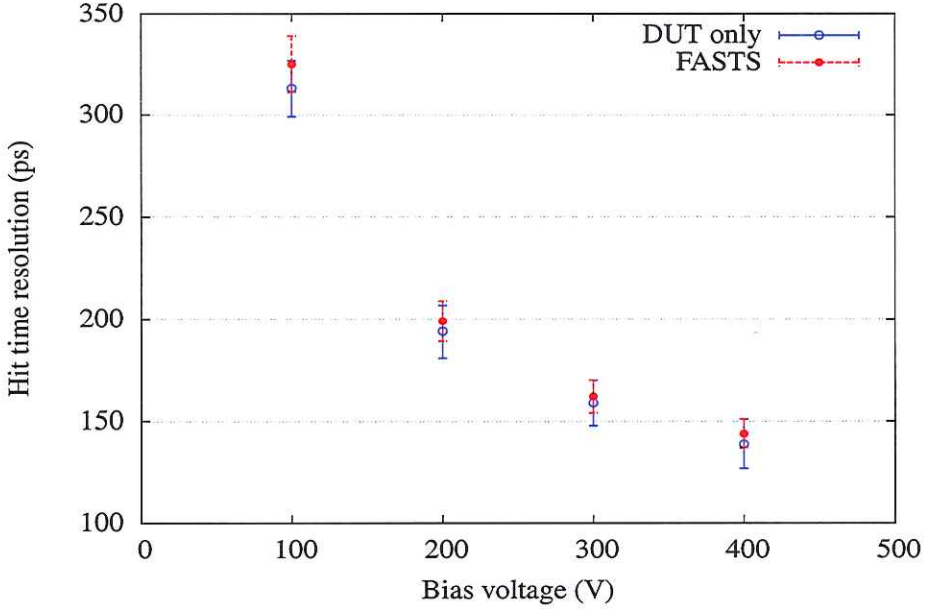


GTK demonstrator
- 1 column with 45 pixels
- Test @ PS

Bob







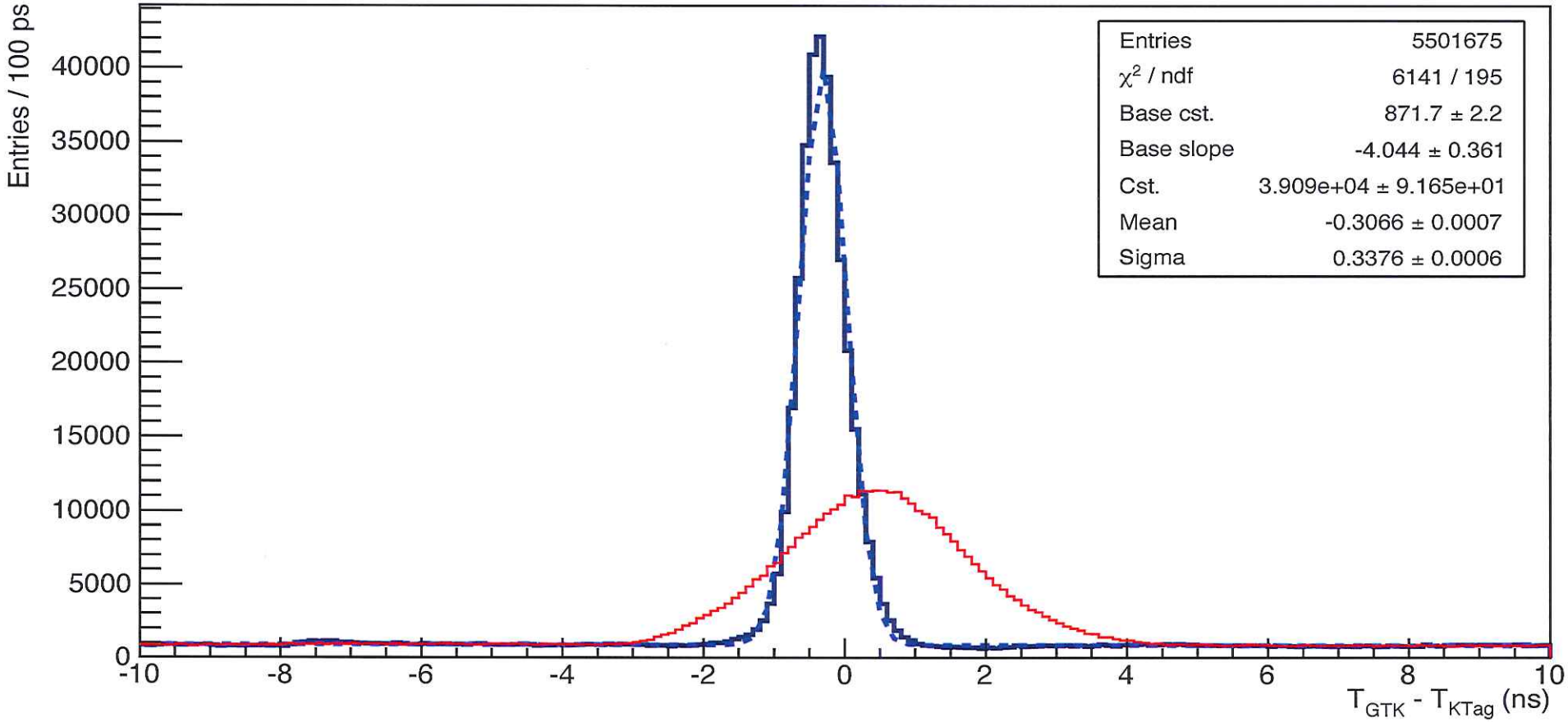
GTK: 2014 data

Bob

$V_{bias} \simeq 170V$

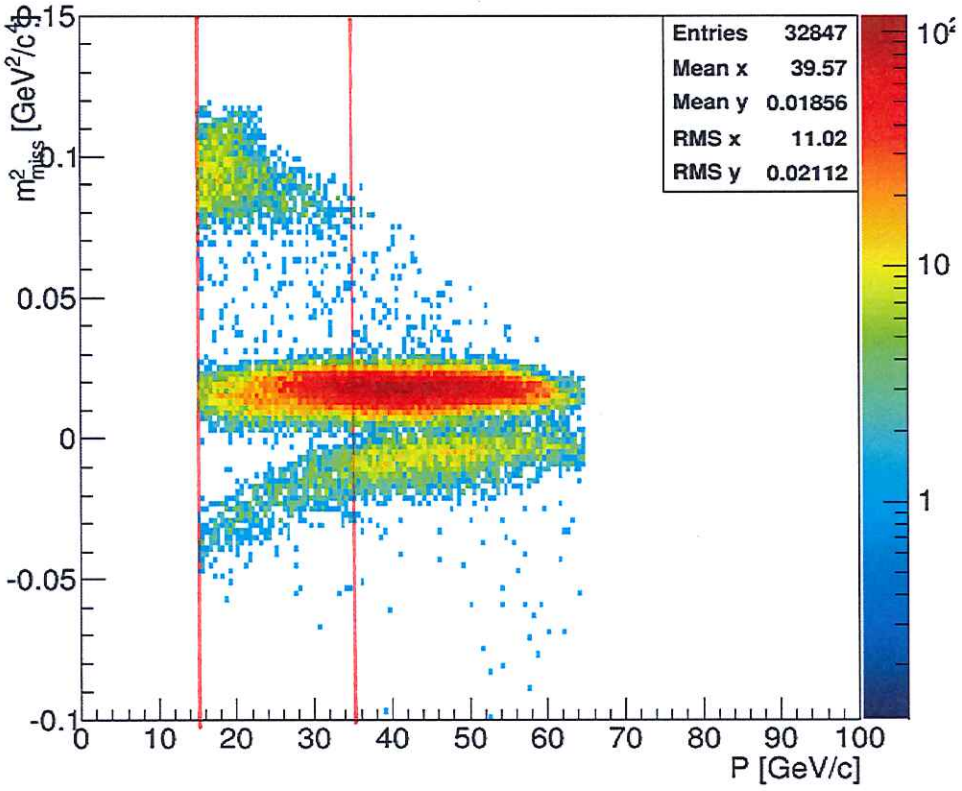
$\sigma_{KTag} \simeq 150\,ps$

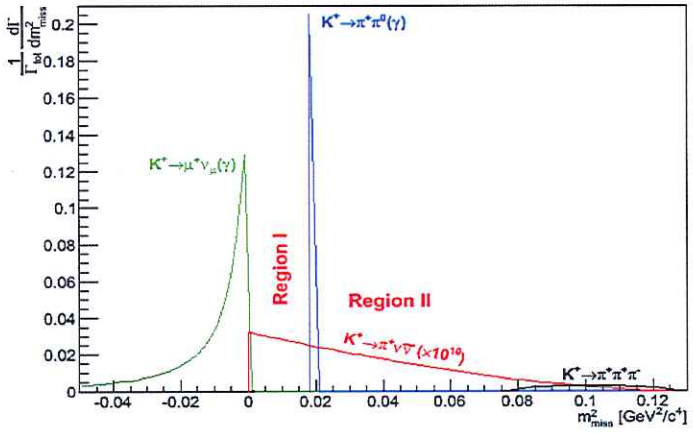
$\sigma_{GTK} \simeq 290\,ps \longrightarrow$ EXPECTED: $\sim 260\,ps$

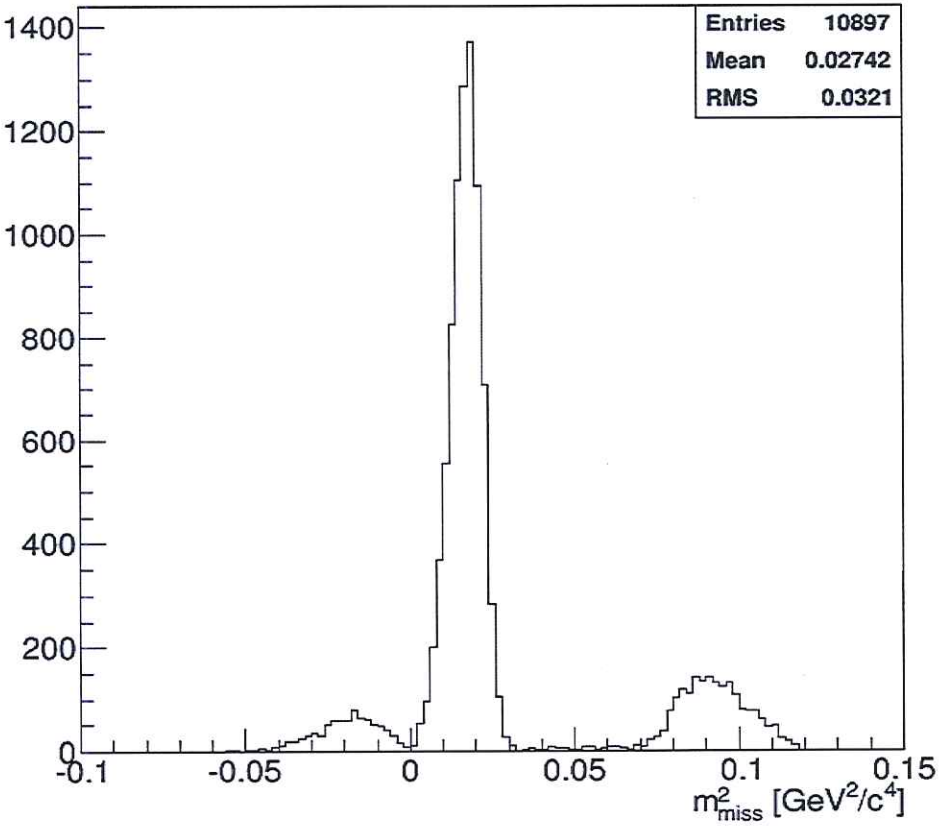


m^2_{miss}

⚠ No GTK



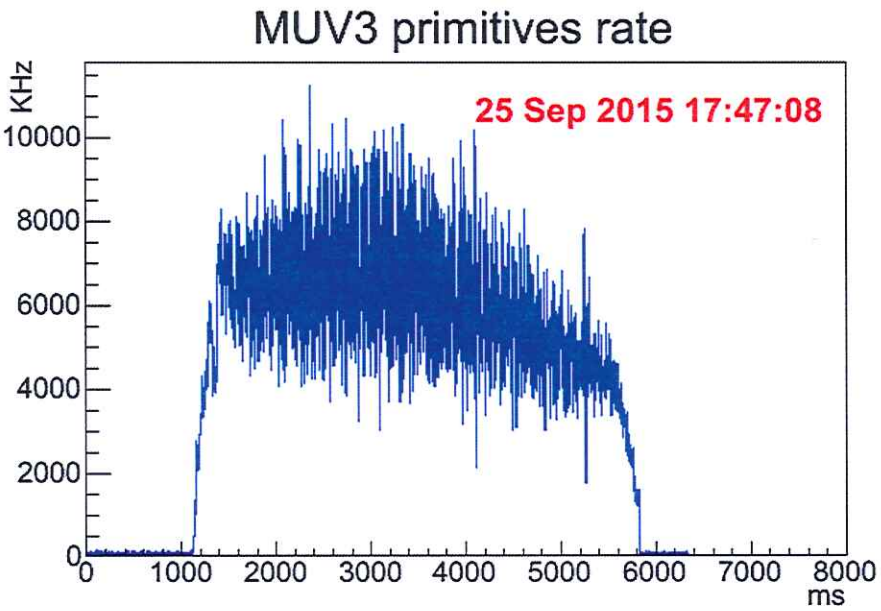


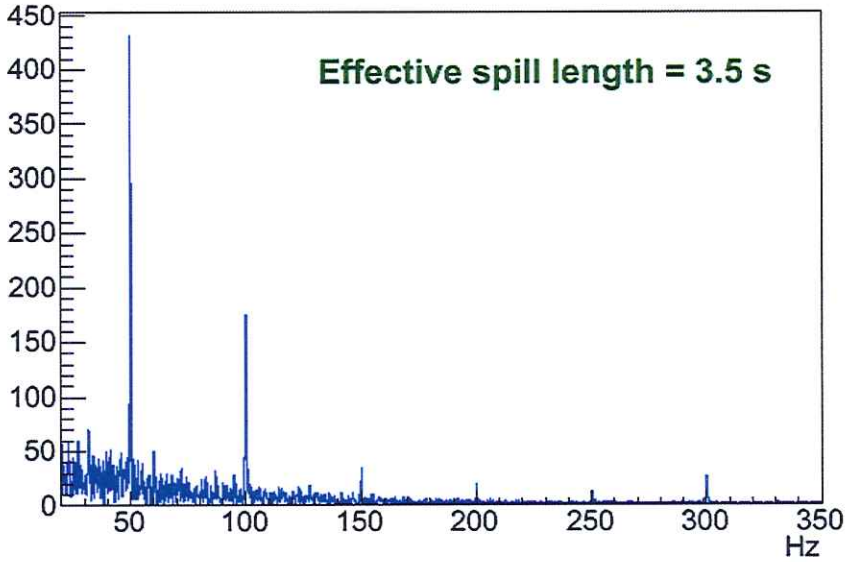


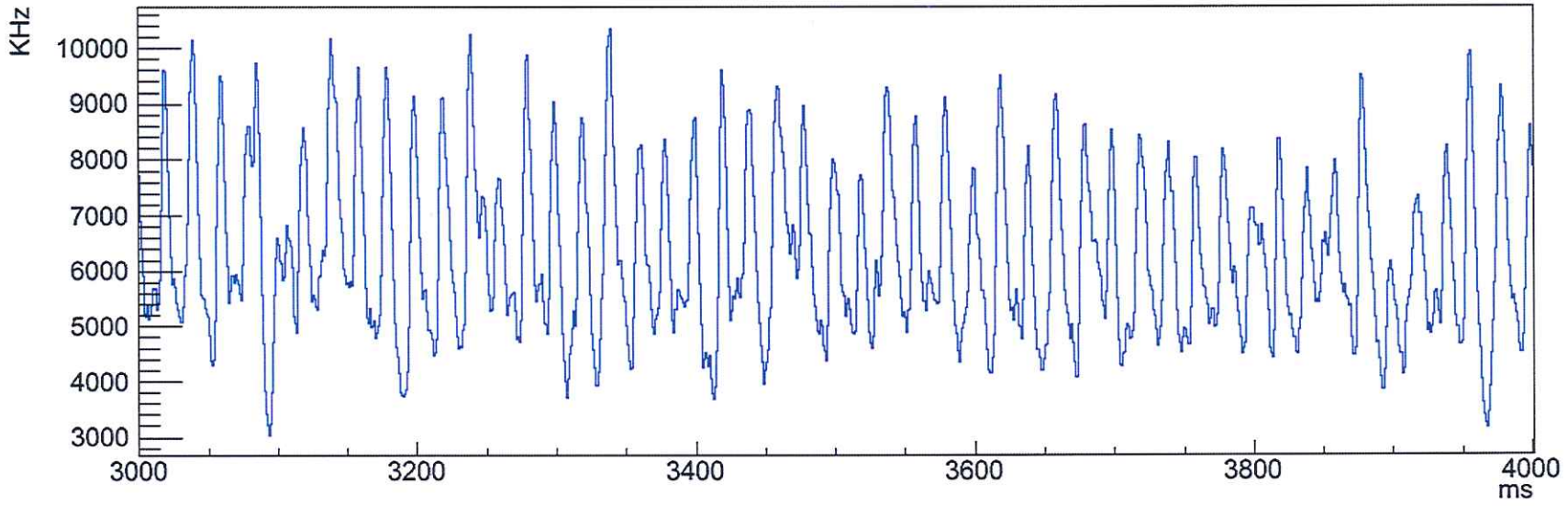
NA62: Challenges

- Detector performance → stability
- Time synchronization
  - ☆ Essential for event building
- Beam stability
  - ☆ Intensity → Rad hard issues !!
  - ☆ Time structure
  - ☆ LHC injection
- Instantaneous trigger rate
  - ☆ Completely asynchronous system
  - ☆ Some electronic components working "out" of specifications
- Man power....

Plamen


MUV3 primitives rate
25 Sep 2015 17:47:08
KHz
10000
8000
6000
4000
2000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
ms


FFT - MUV3
Effective spill length = 3.5 s
450
400
350
300
250
200
150
100
50
0
50
100
150
200
250
300
350
Hz


KHz
10000
9000
8000
7000
6000
5000
4000
3000
3000
3200
3400
3600
3800
4000
ms

NA62 screens

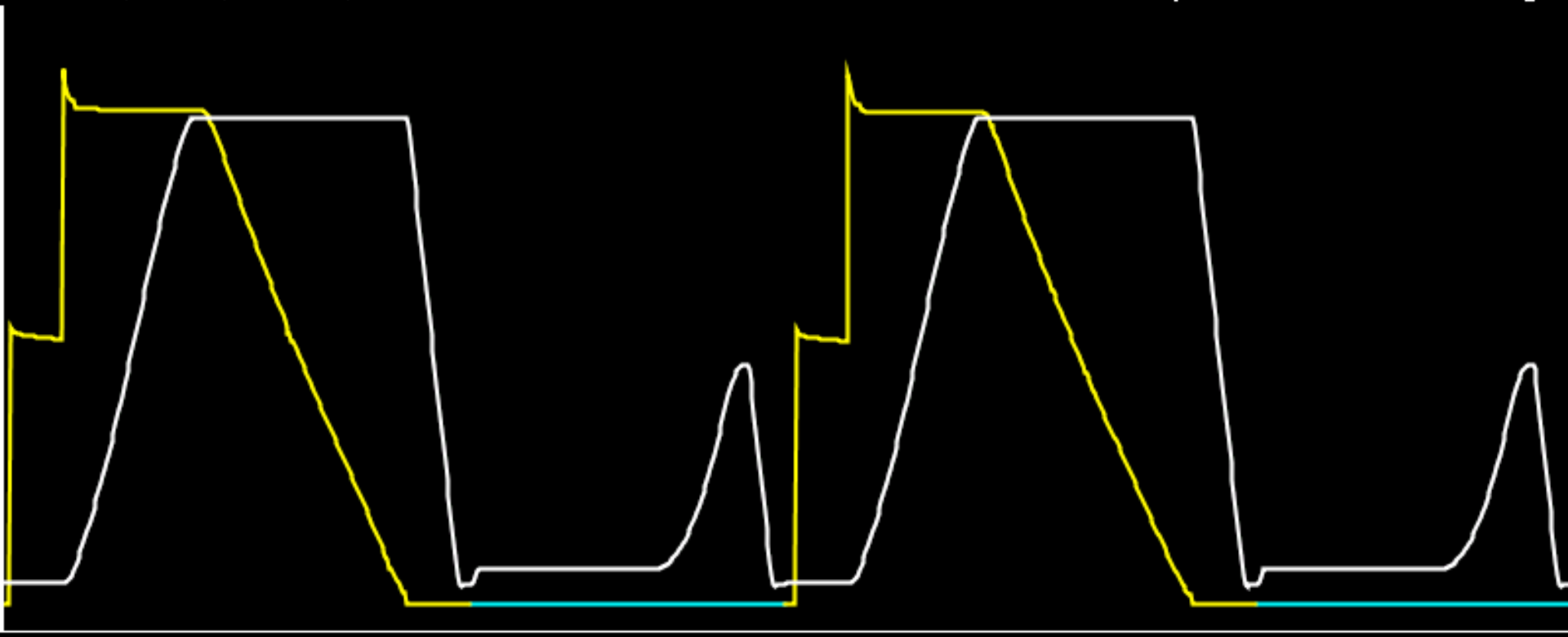
1) SPS "page 1"

2) Run Control

3) Triggers vs time

SPS-PAGE1 Current user: SFTPRO2 25-09-15 17:59:04

SC 47 (30BP, 36.0s) Last update: 7 seconds ago



Target	I/E11	MUL	%SYM	Experiment
T2	47.9	10	92 a	H2/H4
T4	43.9	7	94 a	H6/H8
T6	114.2	14	96 a	COMPASS
T10	12.7	0	11	NA62

Phone: 77500 or 70475

Comments (25-Sep-2015 16:25:43)

MD1 0.0 E8 0.0 E8

Trigger Flow

L0		65829	from L0TP				
L1	in	61527	out	61527	of which	2	SPECIAL
	LKr	in	61527	REQUESTED			
		out	55337	RECEIVED			
	L2	in	57069	out	57069	of which	1	SPECIAL
		Merger	in	57069	out	57068	

Primitives
Calibration
Synchro
Periodic
NIM

Run Infos

Run Type	Fw_301_MepFactor1
Start Time	2015.09.25 17:08:03.711
End Time	
Beam Type	
Shift crew	Hutchcroft & Lurkin
StartRun Comment	Restart run without straw. GTK is in.
EndRun Comment	
RunNumber	3572
Burst #	136
Burst State	

Primitives Count

Primitives

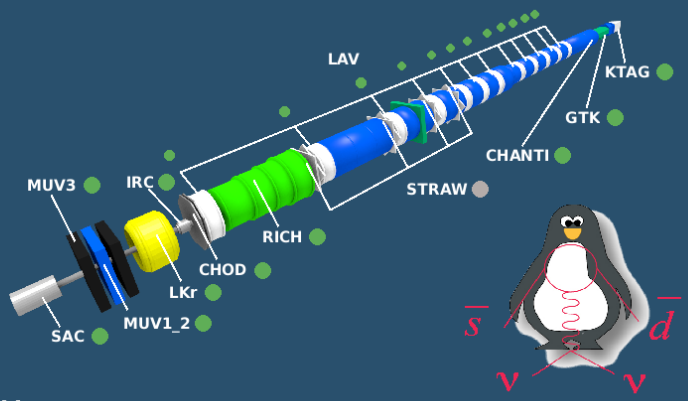
A Type	2.09e+07
B Type	3.20e+07
C Type	7.44e+06
D Type	2.67e+07
E Type	8.43e+06
F Type	1.89e+02
G Type	0.00e+00

Triggers

MASK0	0.00e+00	1000
MASK1	1.14e+07	200
MASK2	0.00e+00	10
MASK3	0.00e+00	100
MASK4	0.00e+00	100
MASK5	1.78e+07	2000
MASK6	0.00e+00	100
MASK7	0.00e+00	100

Exp. scalers

QX	2.46e+06
Q1-OR	6.49e+06
MUV1 OR MUV2	2.84e+06
MUV3	1.91e+07
NHOD	6.14e+06
IRC	4.30e+06
CHANTI	6.34e+06
ECN3_008	0.00e+00
ECN3_009	0.00e+00
ECN3_010	0.00e+00
ECN3_011	0.00e+00
ECN3_012	0.00e+00
ARGONION	7.08e+08



Clock

09/25/2015 05:48:51 PM

PCFarm

Per burst sum

Detector	MEPs/Producer	Lost prev. burst	Choke/Errors
CEDAR	58569	0	
GTK	58571	0	
CHANTI	58930	0	
LAV	58841	0	
RICH	58930	0	
CHOD	58931	0	
LKR	55337	405	
IRC_SAC	57843	0	
L0TP	58931	0	
MUV3	57843	0	

Data-Taking

Global TDAQ
PC Farm
Merger
Triggers

Beam Infos

Page1 comment

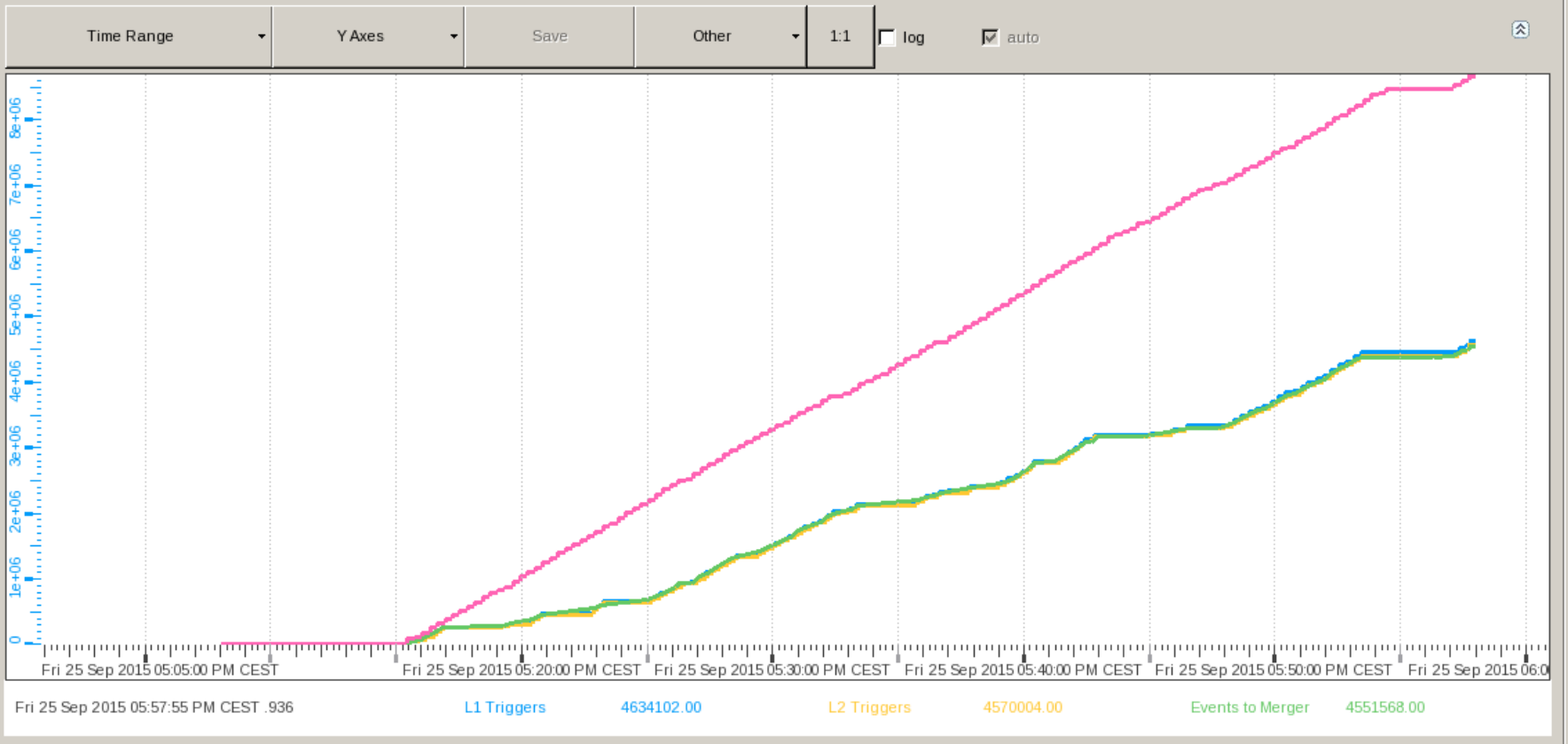
T10 Intensity [e^11]: 13.4274

T10 Symmetry: 0.1200

Merger

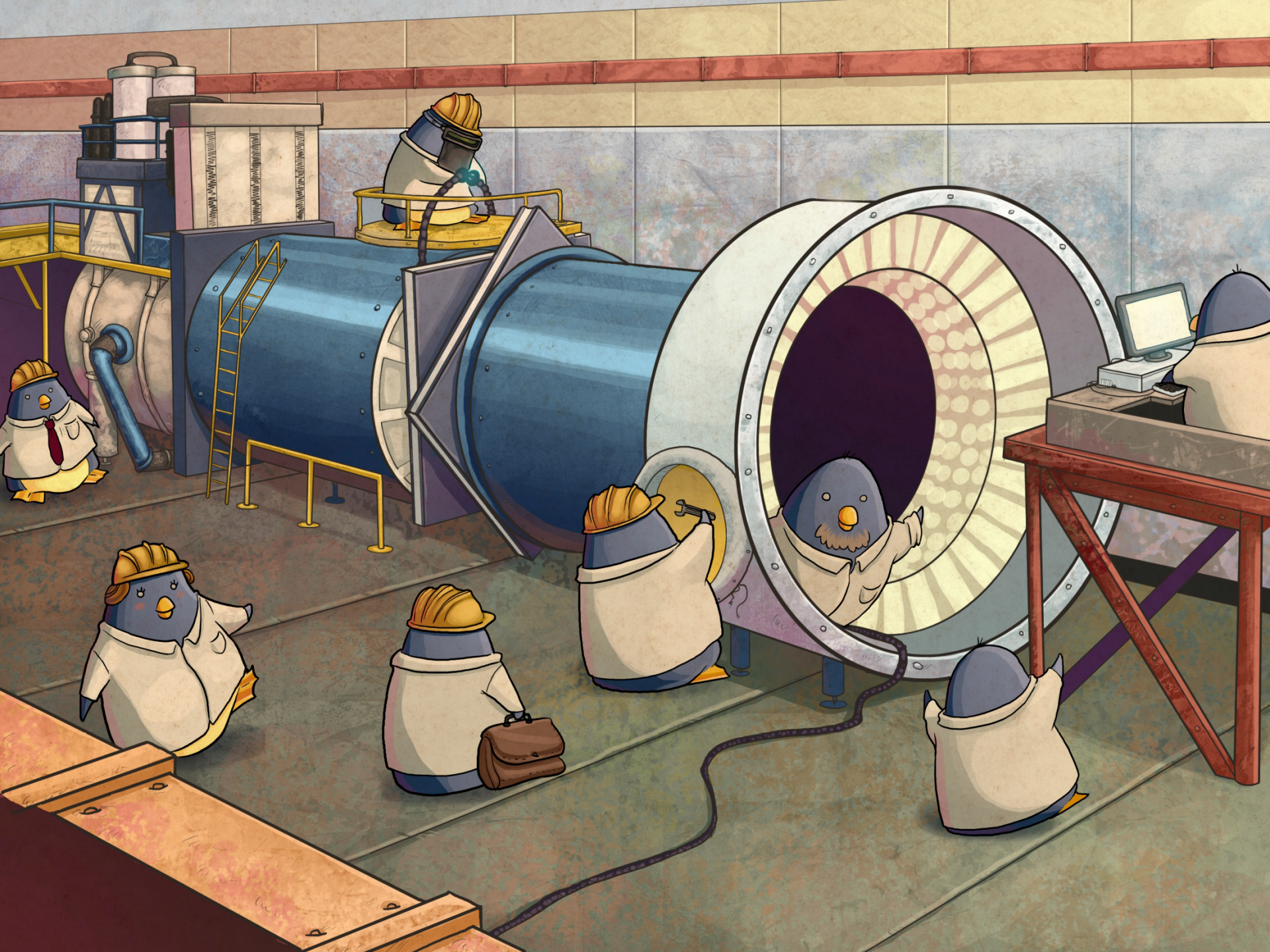
	Proc. Burst	# Events	Evts. Burst-1	Disk Space
Merger1	135	57590	57590	77%
Merger2	136	57068	11922	55%
Merger3	134	1	1	52%

NUMBER OF TRIGGERS VS. TIME



CONCLUSIONS

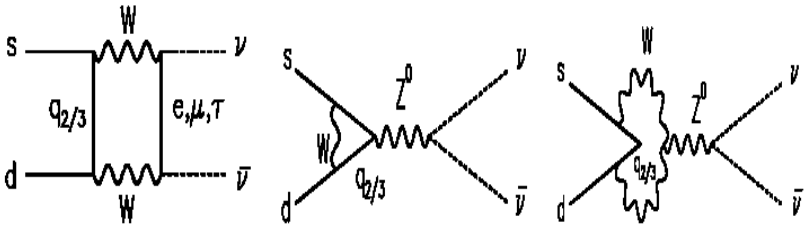
- Start up and commissioning longer than expected
  - ☆ 10/2014 → 10/2015 "Pilot run"
  - ☆ Stable conditions by the end of the month
  - ☆ All detector installed and operational
- Challenging measurements but...
  - ☆ Detector performances "better" than foreseen
  - ☆ Plenty of physics opportunities
- 1st $K^+ \to \pi^+ \nu\bar{\nu}$ by the end of 2015
  - ☆ SM sensitivity ~ 2 day @ full intensity



Backup

Theory in the Standard Model

- **FCNC loop processes**
- **SM precision surpasses any other FCNC process involving quarks**
- **Short distance dynamics dominated**



$\lambda = V_{us}$
$\lambda_c = V_{cs}^* V_{cd}$
$\lambda_t = V_{ts}^* V_{td}$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \cdot \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

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

Charm contribution

$$x(q) \equiv \frac{m_q^2}{m_W^2}$$

Top contribution

Theoretically clean, sensitive to new physics, almost unexplored

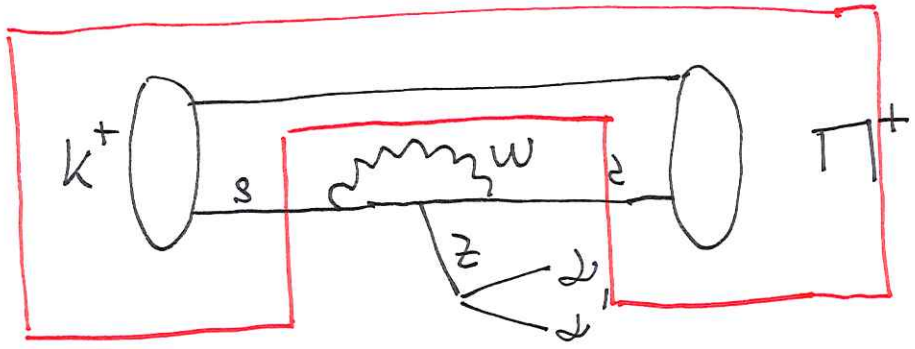
$$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \cdot \lambda^8$$

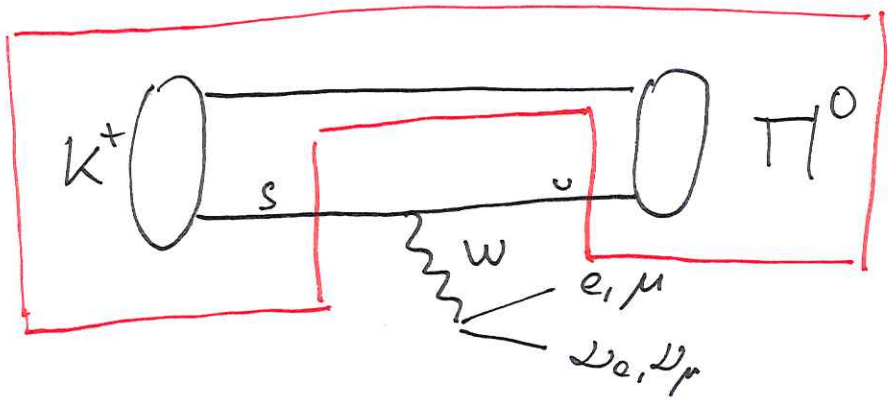
The Hadronic Matrix Element is measured and isospin rotated

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\nu$	9.11±0.72
$K_L \to \pi^0 \nu\nu$	3.00±0.30

[A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R.Knegjens, arXiv:1503.02693]

LONG DISTANCE: $K^+ \to \pi^+ \nu\bar{\nu}$ & $K^+ \to \pi^0 e^+ \nu$





New Physics Sensitivity

Z' gauge boson mediating FCNC at tree level

[A.J.Buras et al., JHEP 1302 (2013) 116

A.J.Buras et al. Eur. Phys. J. C74 (2014) 039]

Littlest Higgs with T-parity

[M. Blanke et al., Acta Phys. Polon. B 41 (2010) 657]

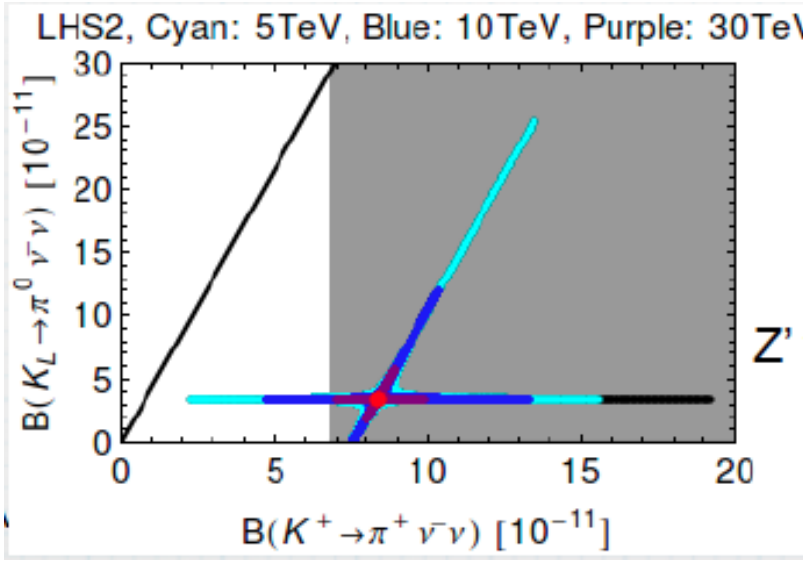
Custodial Randall-Sundrum

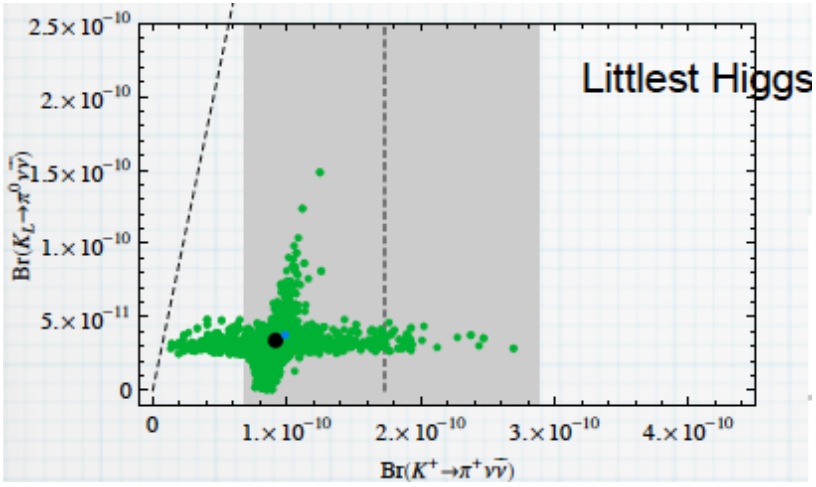
[M. Blanke et al., JHEP 0903 (2009) 108]

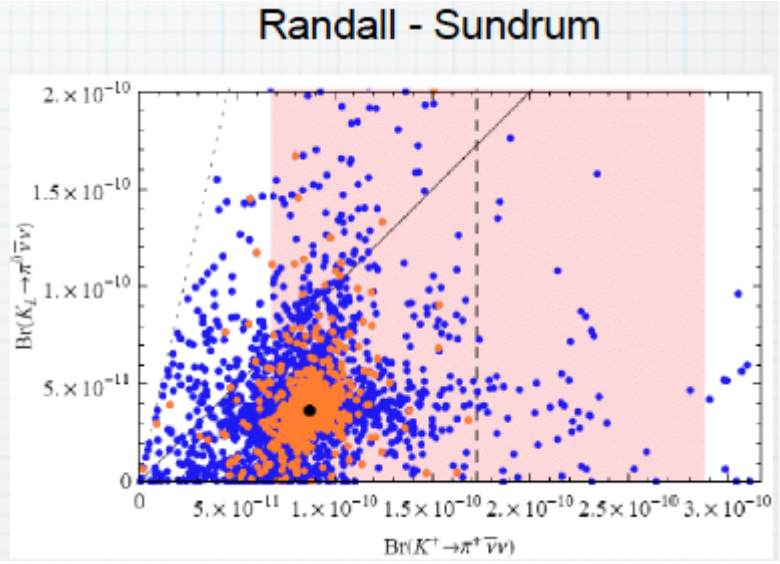
Best probe of MSSM non-MFV

(still not excluded by LHC)

[G. Isidori et al., JHEP 0608 (2006) 088]







TDCPix Wire Bonded to the Test Card