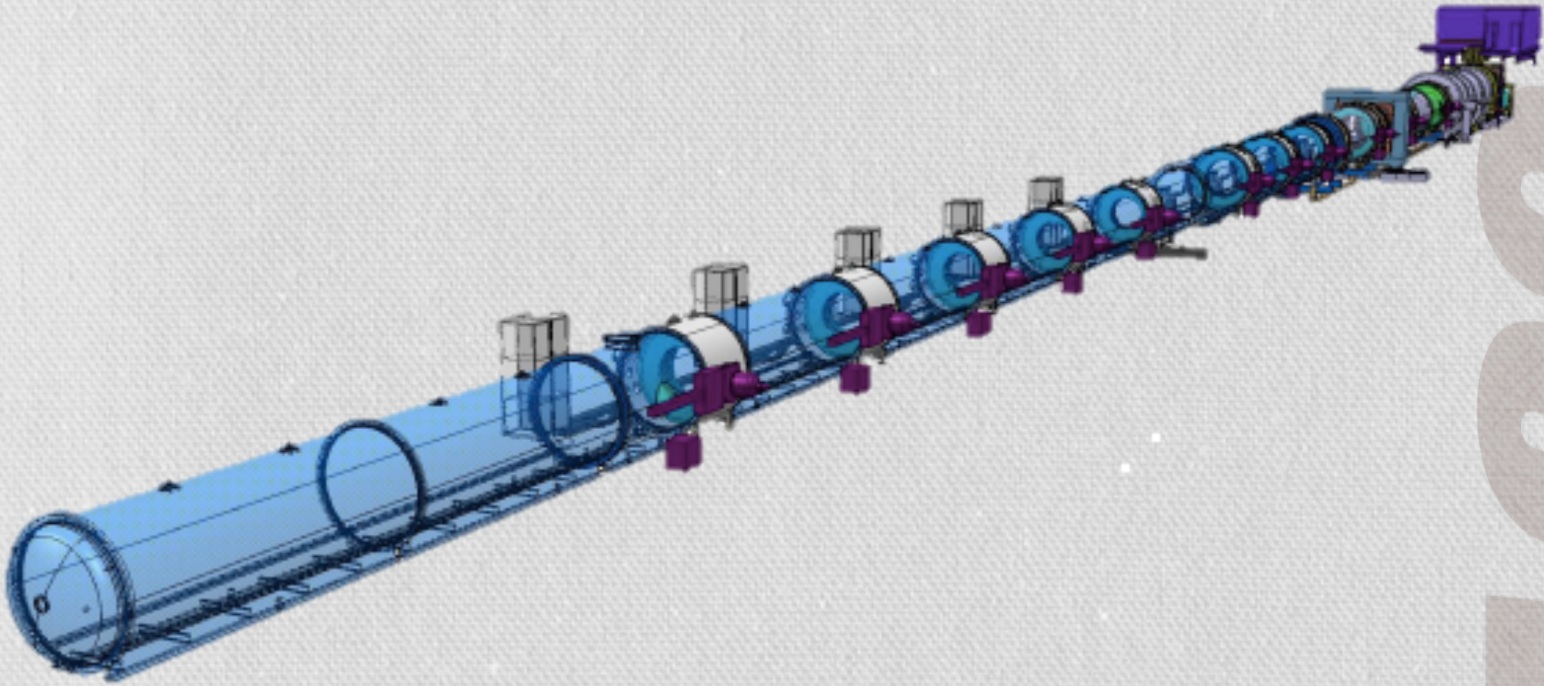
The NA62 experiment at CERN and the measurement of the ultra-rare decay $K^{+} \rightarrow \pi^{+} \nu \nu$

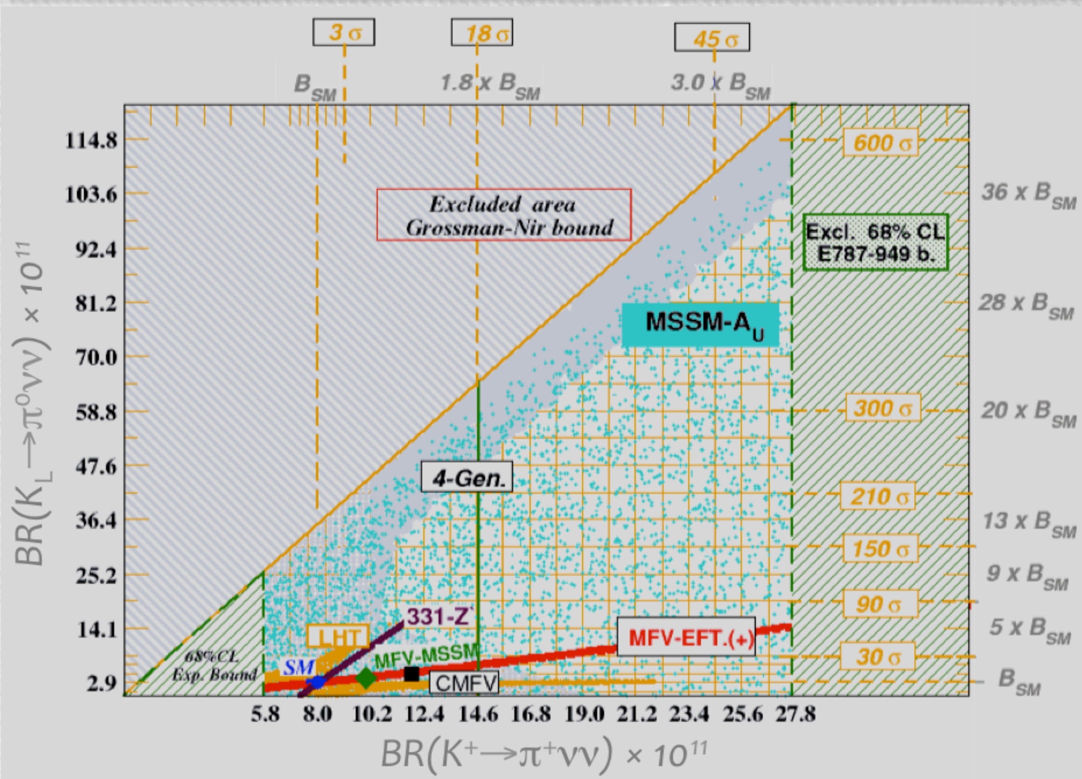


A.Antonelli(INFN-LNF)

on behalf of the NA62 Collaboration

Interest of $K^+ \to \pi^+ \nu\nu$ decay

- FCNC process, forbidden at tree level in the SM
- Ultra-rare, but promising opportunity to test SM, BR calculable with few ~10% precision
  - small-distance contribution dominates, hadronic contribution related to BR ($K \to \pi e \nu$)
- Very sensitive to physics beyond the SM: possible enhancement/suppression of BR by > ~30%
- In the SM, allows determination of V_{td} at 7% level, with no need of QCD input



A NP signal for both $K \to \pi\nu\nu$ modes might allow identification of a specific **NP** model: SUSY, MSSM with or without new CP violation or Flavour violation sources, extra-dimensions, etc.

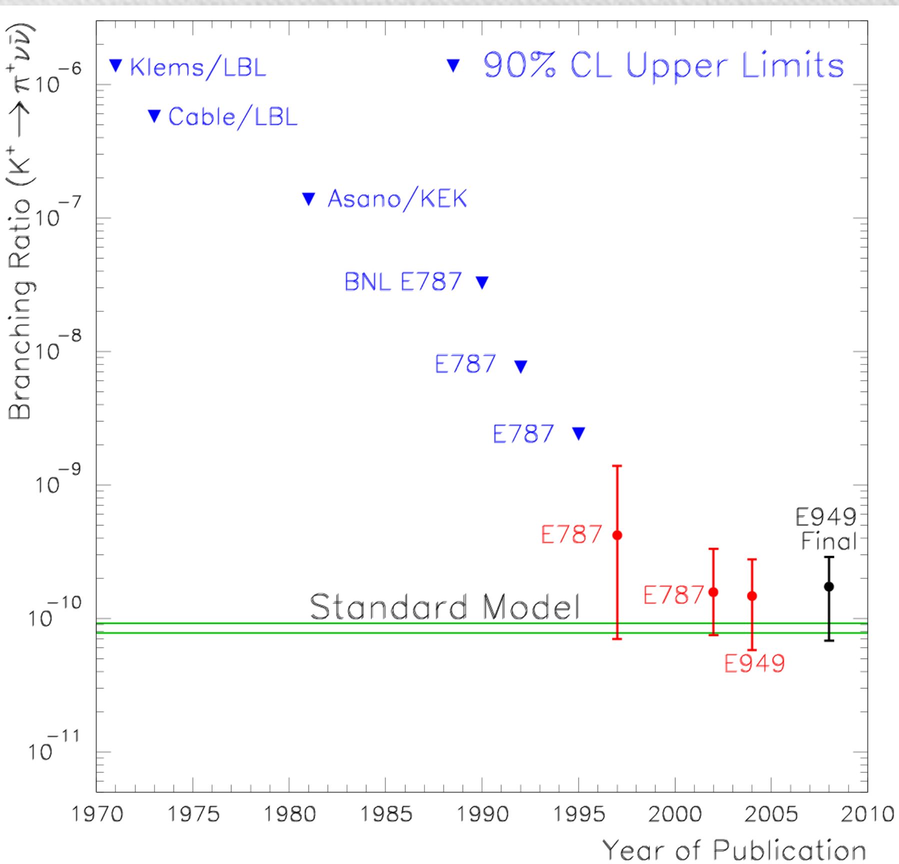
Theoretical and experimental status

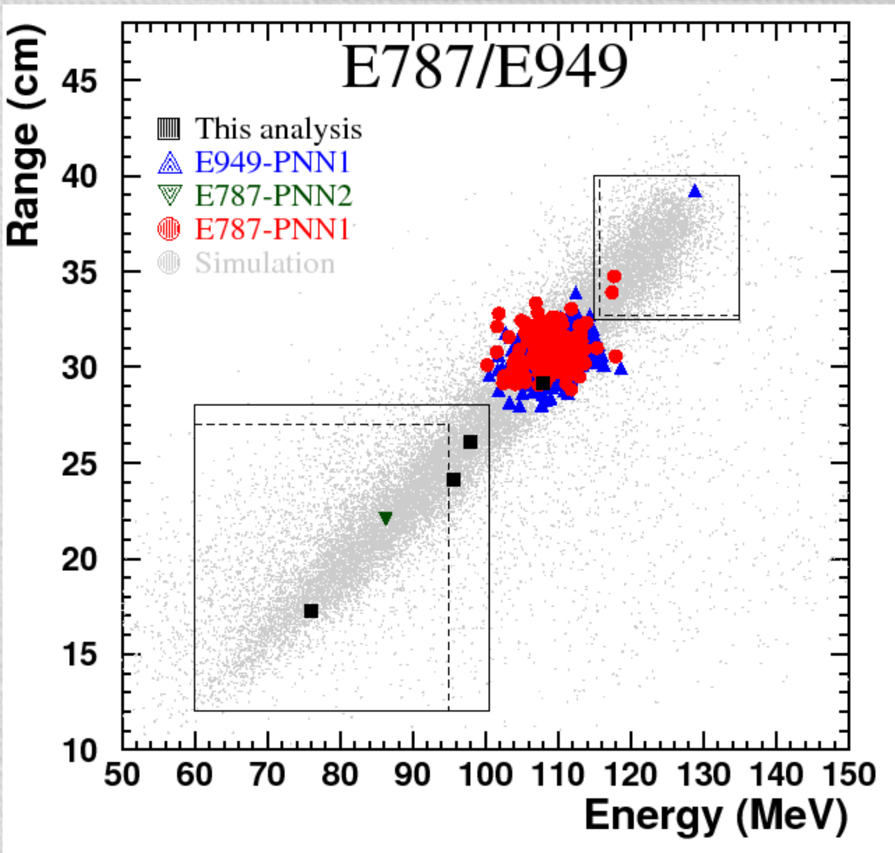
SM expectation: $BR(K^+\to\pi^+\nu\nu)=(8.22\pm0.75)10^{-11}$
9% total uncertainty, best known FCNC process

$$B_{\text{SM}}(K^+\to\pi^+\nu\bar\nu)=\frac{\tau_{K^+}M^5_{K^+}}{32\pi^3}(1+\Delta_{\text{EM}})\left|f_+^{K^+\pi^+}(0)\right|^2\mathcal{I}_\nu^+\left|\frac{G_F\alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W}Y\right|^2$$

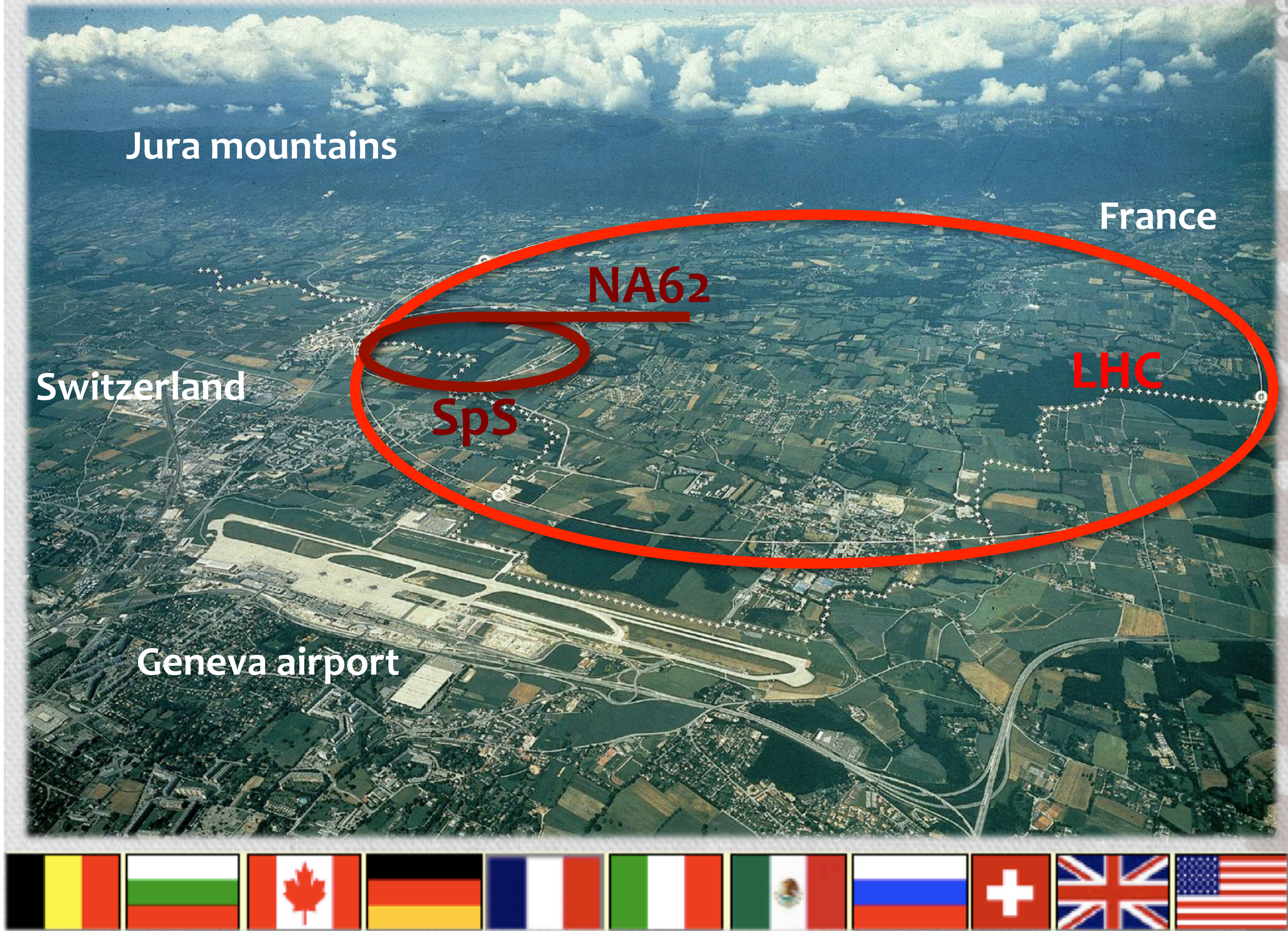
$$Y=V^*_{td}V_{ts}X(x_t)+V^*_{cd}V_{cs}\left[X(x_c)+|V_{us}|^4\delta P_{c,u}\right]$$

Experimental status, 7 candidates by E787/ E949: $BR(K^+\to\pi^+\nu\nu)$ $=(1.73\pm1.1)\times10^{-10}$
Uncertainty still far from theory error





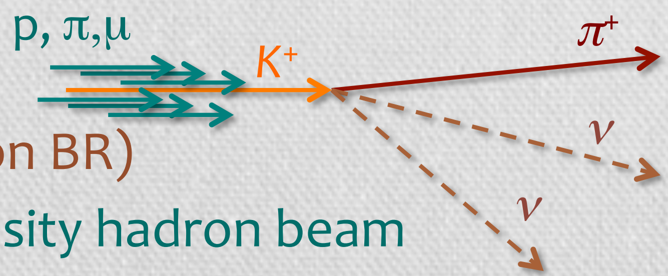
NA62 @ CERN SpS North Area



NA62 collaboration:

Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

NA62 a challenging experiment



- Collect ≈100 $\pi^+\nu\nu$ events in 2 years (10% precision on BR)
- Need ≈10^{13} K^+ decays: use un-separated high-intensity hadron beam
- 800 MHz beam of which only 50MHz (6%) are Kaons , *p*=75 GeV/c

Very small branching ratio

- *~ 1×10^{-10}*

Weak experimental signature

- *Only a pion in the final state*
- Cannot reconstruct K mass

Huge Backgrounds

- *61% $K^+ \longrightarrow \mu^+\nu$ decay*
- *21% $K^+ \longrightarrow \pi^+\pi^0$ decay*
- *5% $K^+ \longrightarrow \pi^+\pi^+\pi^-$ decay*

Need rejection factors for BG up to 10^{11} 10^{12} to get S/BG>10

Kinematical Rejection

- *K 4-momentum*
- π 4-momentum
- Kaon tag with ~100ps time resolution

BG rejection needed ~ 10^4

Vetoes for extra particles

- *Veto photons from π^0 decays*
- Veto μ from beam halo and K decays
- Need to cover huge range of energies
- Need to cover all angles <50 mrad
- Need ~1 ns time resolution

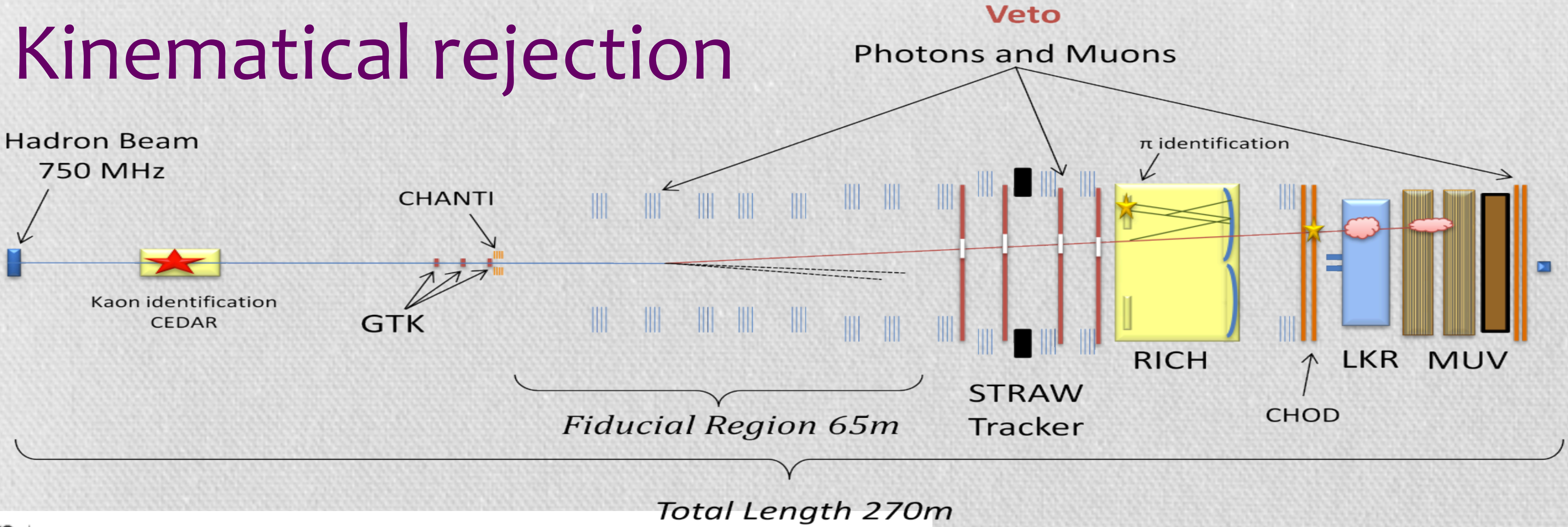
BG rejection needed ~ 10^4 γ ~ 10^5 μ

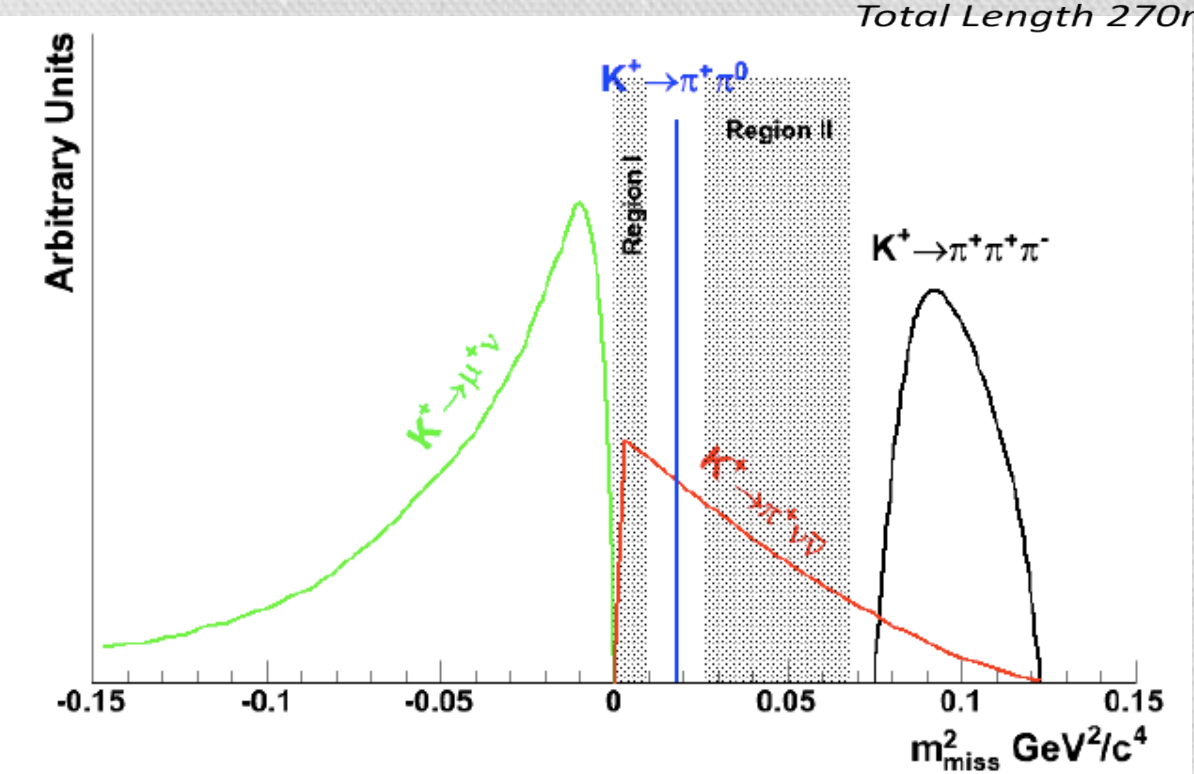
Particle ID

- Positively identify π^+
- Separate π, μ, e
- required up to 35 GeV
- Time resolution ~ 100 ps

BG rejection needed ~ 10^3

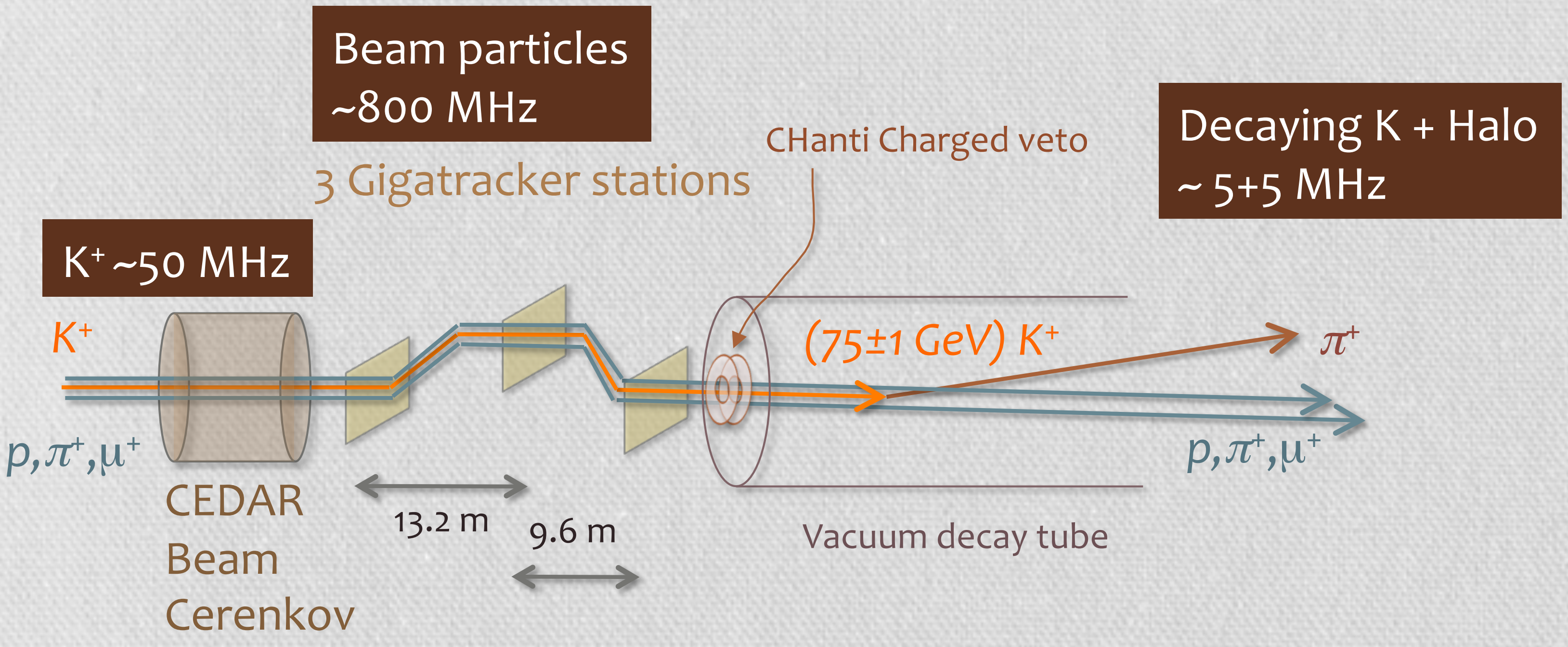
Kinematical rejection





Missing mass computed in the hypothesis that the daughter particle is a pion

K beam, and K beam spectrometer (P_K)



Cedar

- Thr cherenkov detector
- H2 @ 3.86 bar
- Tag K^+ with 99% purity
- Operate @ 50MHz
- 100γ / Kaon
- Time resolution 100ps

GigaTracker

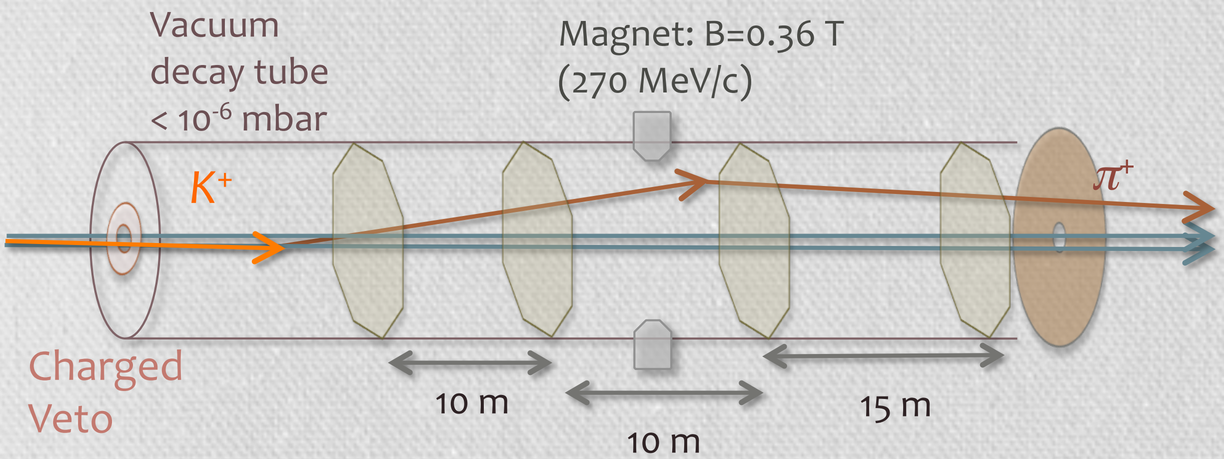
- 3 Silicon pixel 300 μm×300 μm
- 61×27 mm² active area, 54K pixels
- $< 3\times0.5\%\ X_0$ with > 99% efficiency
- Kaon momentum mesurement:
  - $\sigma_p/p \approx 0.2\%$
  - $\sigma_\theta \approx 16$ μrad
  - $\sigma_t < 200$ ps/station

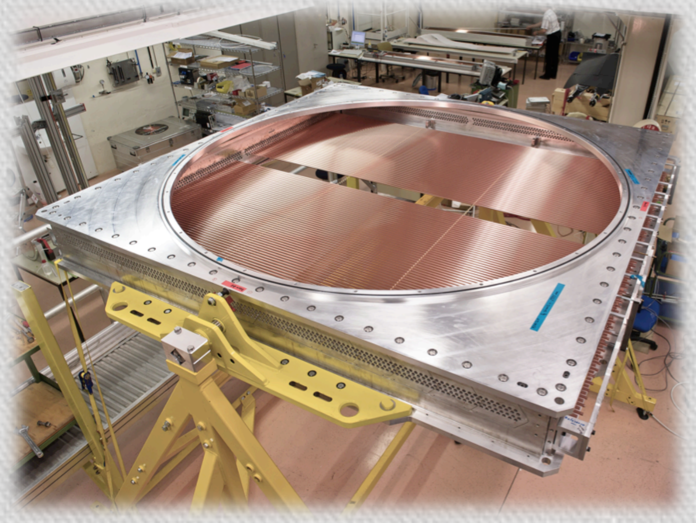
CHanti

Veto: 2MHz μ halo + inelastic interactions

- extruded scint. bars
- WLS fiber + SiPM's
- ≈ 10 ph.el. / MIP
- $\sigma_t < 2$ ns

Straw tracker spectrometer (P_{track})





4 straw tracker stations in vacuum

- Very good p resolution: $\sigma_p/p < 1\%$
- Angular resolution: $\sigma_\theta < 60$ μrad
- Material budget: $< 4\times0.5\%\ X_0$
- High efficiency: > 99% hit efficiency
- High rate: 0.5 MHz in hottest area

- 4 views/station (u-v, x-y)
- 2.1 m diameter acceptance
- 12 cm beam hole
- Track angle: ±3°
- $\sigma < 130$ μm per view
- 1800 straw tubes per station:
  - 30 μm Au-plated wire
  - 100 μm straw straightness
  - Ar(70%)/CO_2(30%)

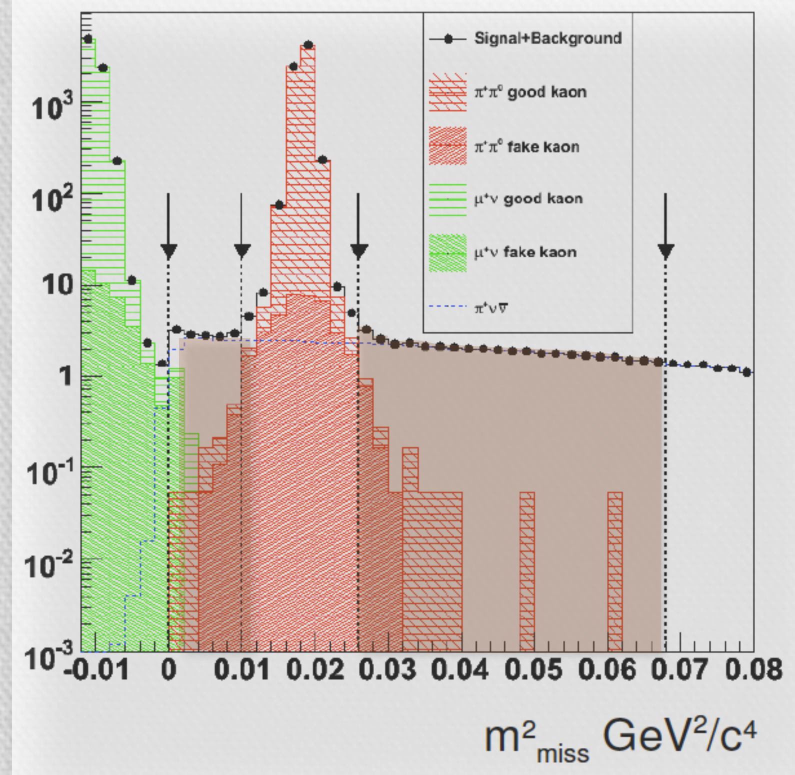
Kinematical rejection MC performance

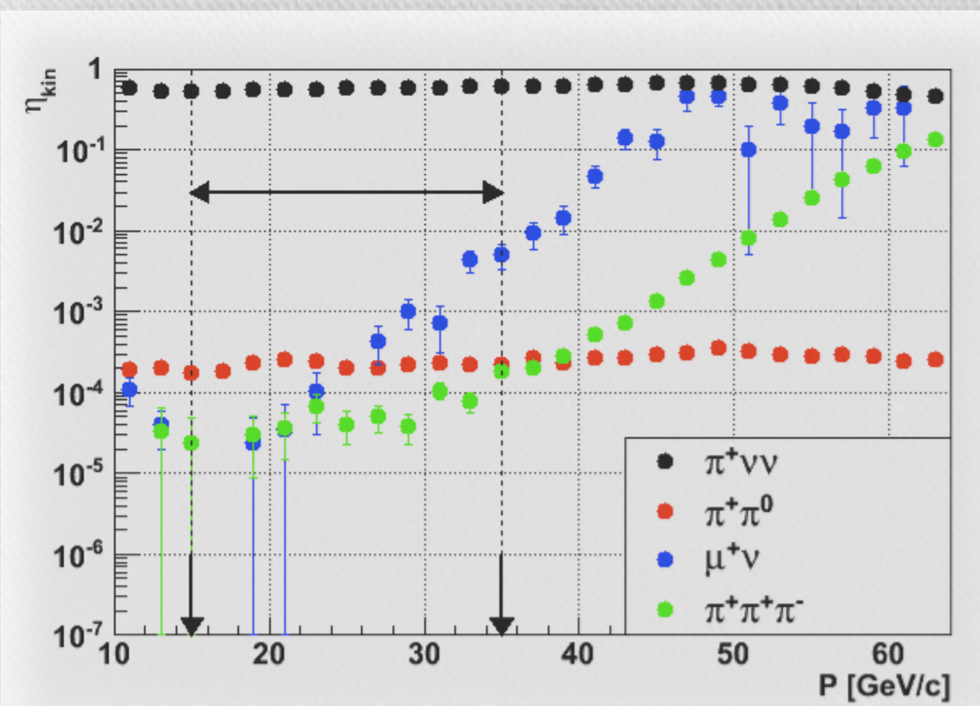
Main backgrounds sources:

- $K^+ \to \mu^+\nu$ (63%), $K^+ \to \pi^+\pi^0$ (21%) + beam halo and particle interactions

Sources of inefficiency:

- Multiple scattering, non gaussian tails
- $K\pi$ mis-match by Giga-tracker

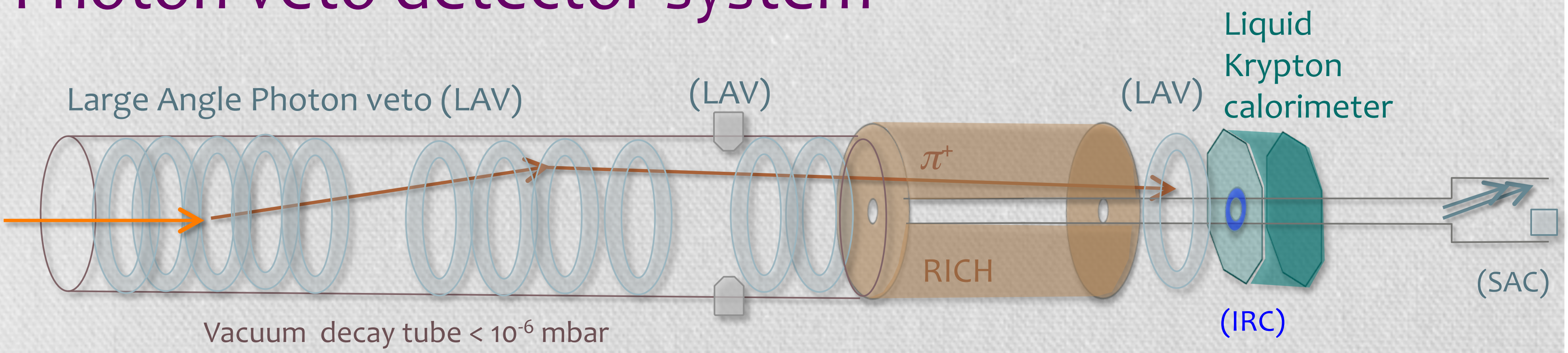




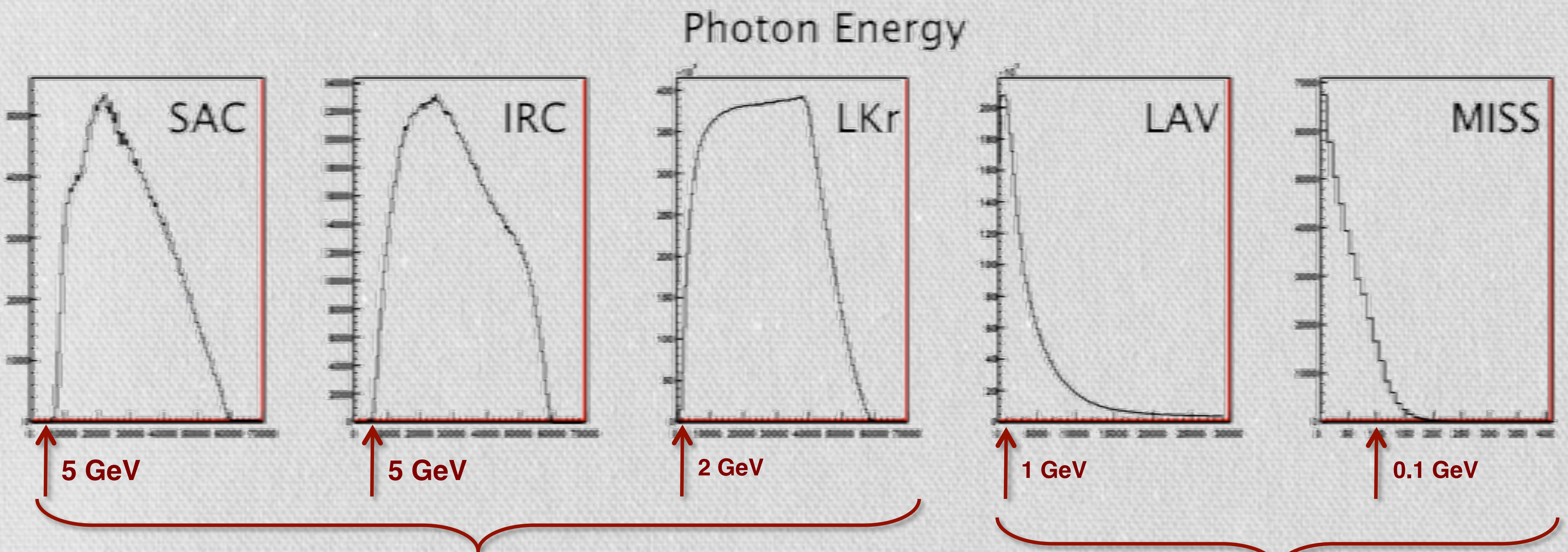
rejection power 10^4

$\pi^+\pi^0$, $\mu^+\nu$, 3π

Photon veto detector system



4 different types of detectors: LAV, LKr calorimeter, Intermediate ring calorimeter (IRC) and small angle calorimeter (SAC)

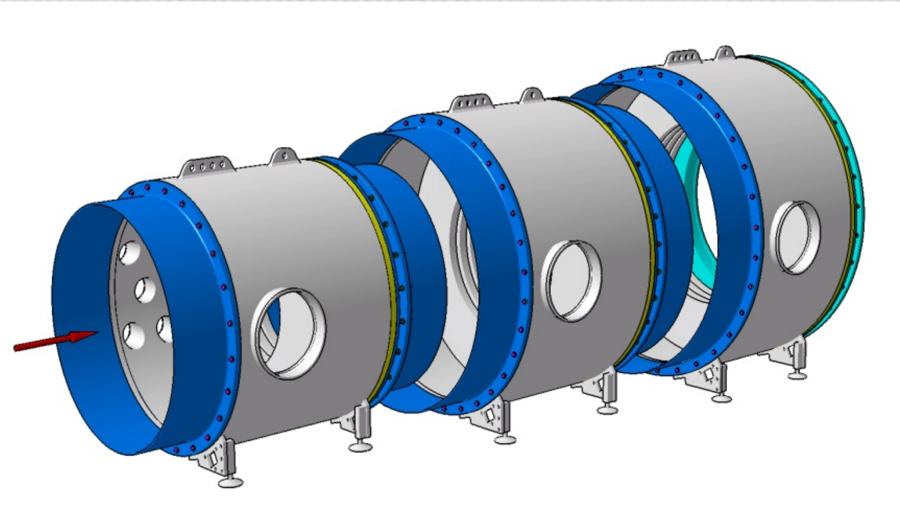


≈ 10^{-5} γ detection inefficiency

≈ 10^{-4} inefficiency E_γ > 200 MeV

Photon vetoes (LAV)

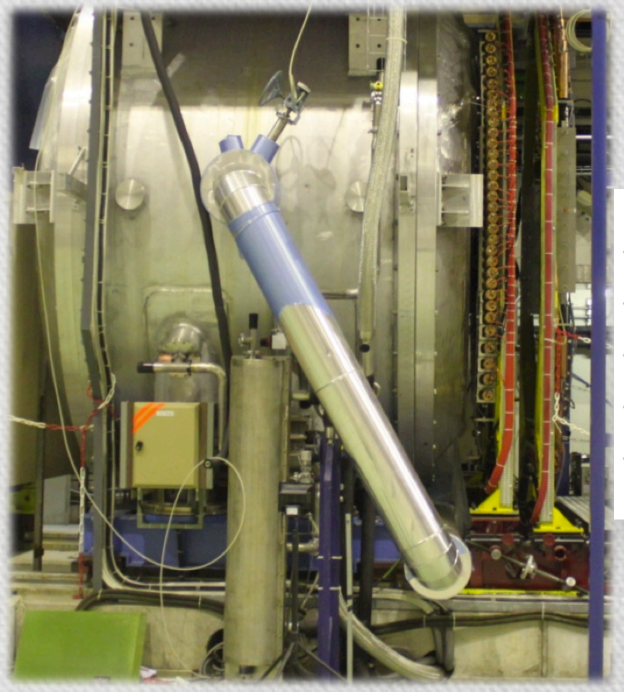
- **12 stations** along the decay tube
- 2500 lead glass blocks, re-used from **OPAL** electromagnetic calorimeter
- 11/12 stations operate in **vacuum**
- Cover 8 to 50 mrad



- **3** different ring sizes, **5 staggered layers** of blocks, for a total of ≈20 X_0
- **8/12 completed** stations In about 2 years
- Custom **time-over-threshold** electronics (double threshold, down to ≈1/5 MIP)
- $\sigma_E/E \approx 9\%/\sqrt{E[GeV]}$
- $\sigma_t \approx 210$ ps/$\sqrt{E[GeV]}$

Other photon veto detectors

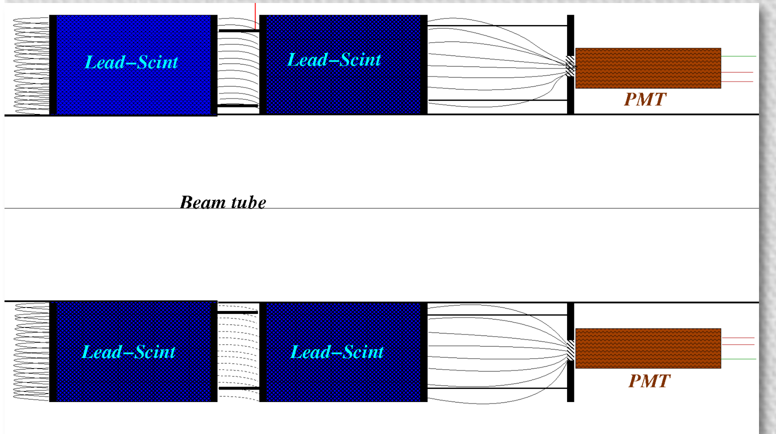
LKr calorimeter



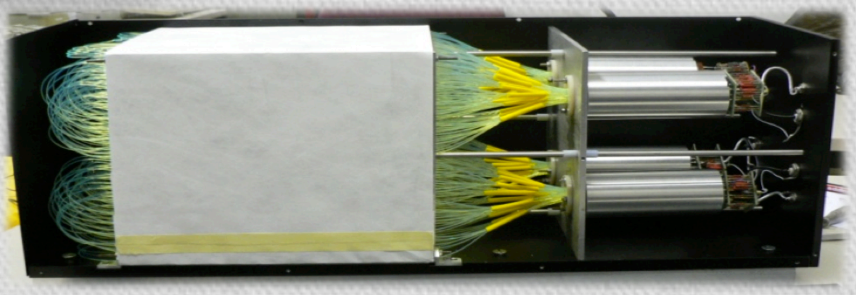
Reused NA48 Liquid Krypton calorimeter.
Cover angles <8mrad
Efficiency measured in a dedicated data taking

Energy	Inefficiency
$2 < E_\gamma < 3.5$ GeV	$(5.8 \pm 1.3)\times10^{-4}$
$3.5 < E_\gamma < 5$ GeV	$(1.6 \pm 0.4)\times10^{-4}$
$5 < E_\gamma < 7.5$ GeV	$(2.8 \pm 1.6)\times10^{-5}$
$7.5 < E_\gamma < 10$ GeV	$<2\times10^{-5}$
$E_\gamma > 10$ GeV	$<1\times10^{-5}$

Intermediate Ring Calorimeter

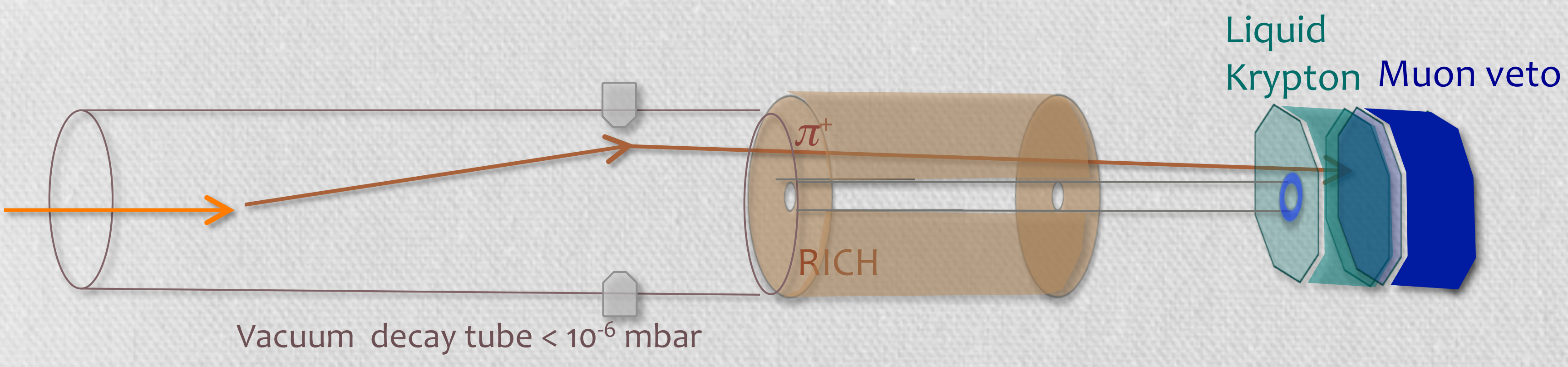


Small Angle Calorimeter



Shashlyk technology
Detects photons in the beam pipe
Measured inefficiency $3\text{x}10^{-5}$

Particle ID detectors

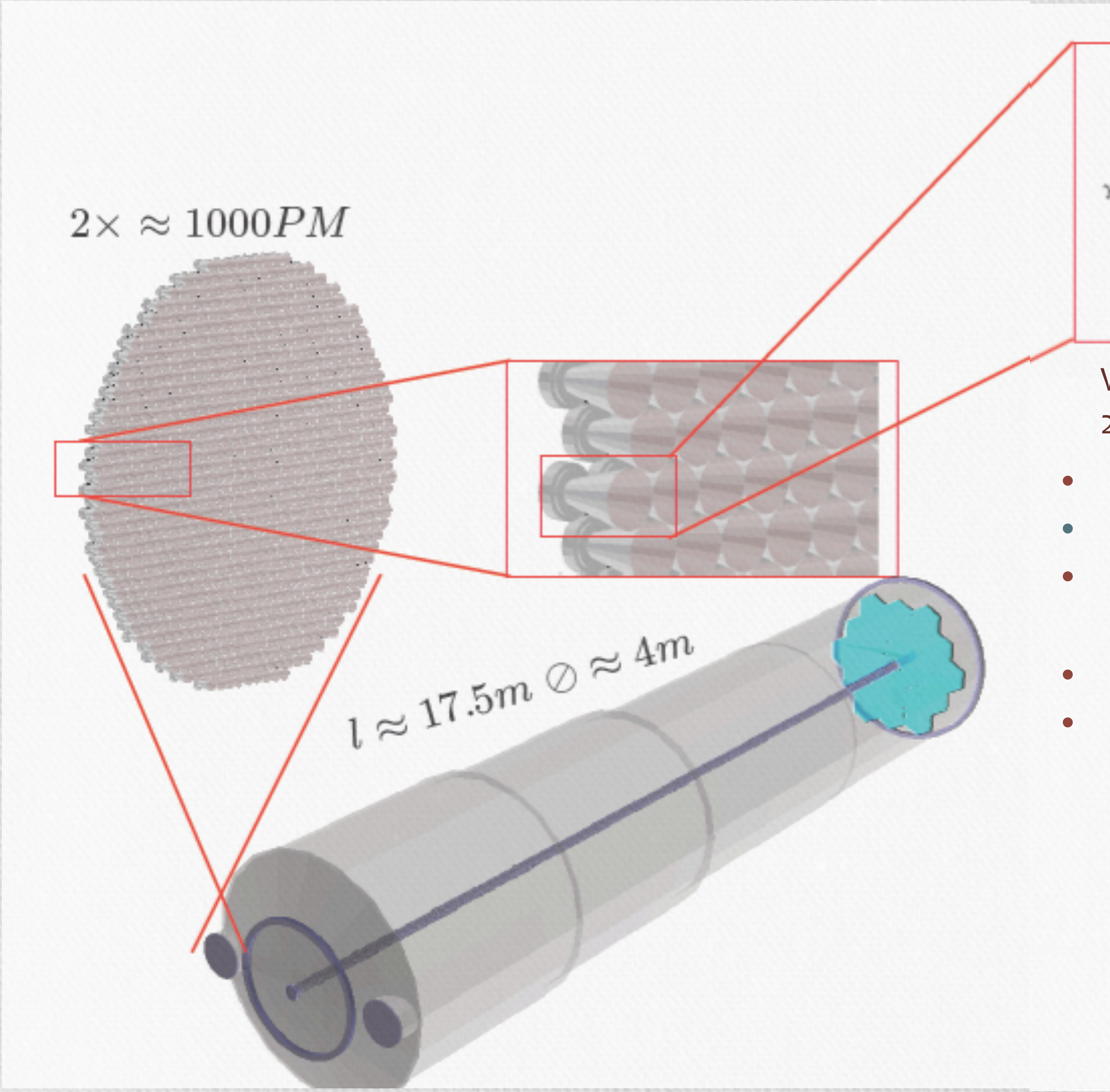


For 1-track sample, need to precisely identify the track as a pion

Three detectors involved:

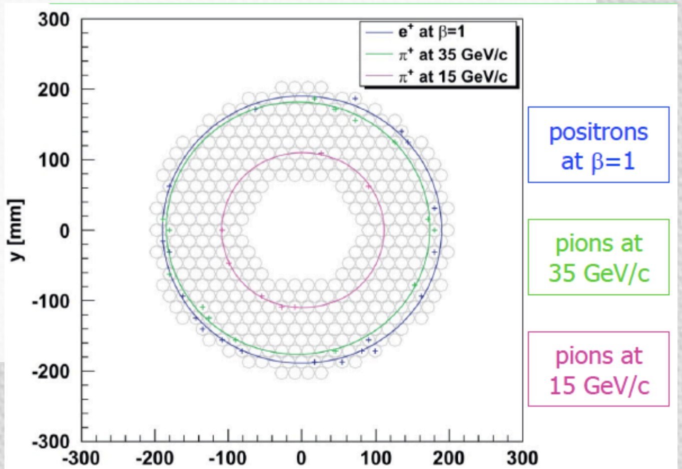
- The Ringing Image Cherenkov detector
  - Identifies π from μ and electrons
  - Keep the muon contamination below 1% in the 1-track sample up to 35 GeV
- The LKr calorimeter:
  - Allows rejections of e's from semi-leptonic K decays by using the E/p ratio
- The Muon Veto
  - Rejects muon from Kμ2 decay from within the 1-track event sample
  - Required inefficiency ~10^{-5}

The NA62 RICH detector



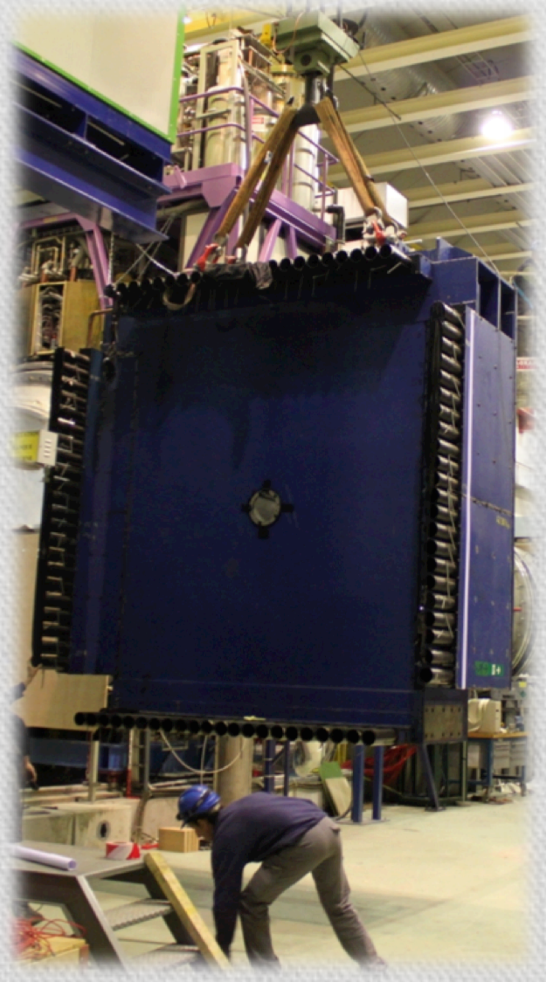
Winston cones+quartz window
2000 Hamamatsu R-7400-U03 PMT

- Neon p=1 atm (5% X_0)
- 20 mirror segments (20% X_0)
- μ contamination <1% between 15 and 35 GeV/c
- Use in Level-0 trigger
- σ_t < 100 ps



Typical data events with fitted rings

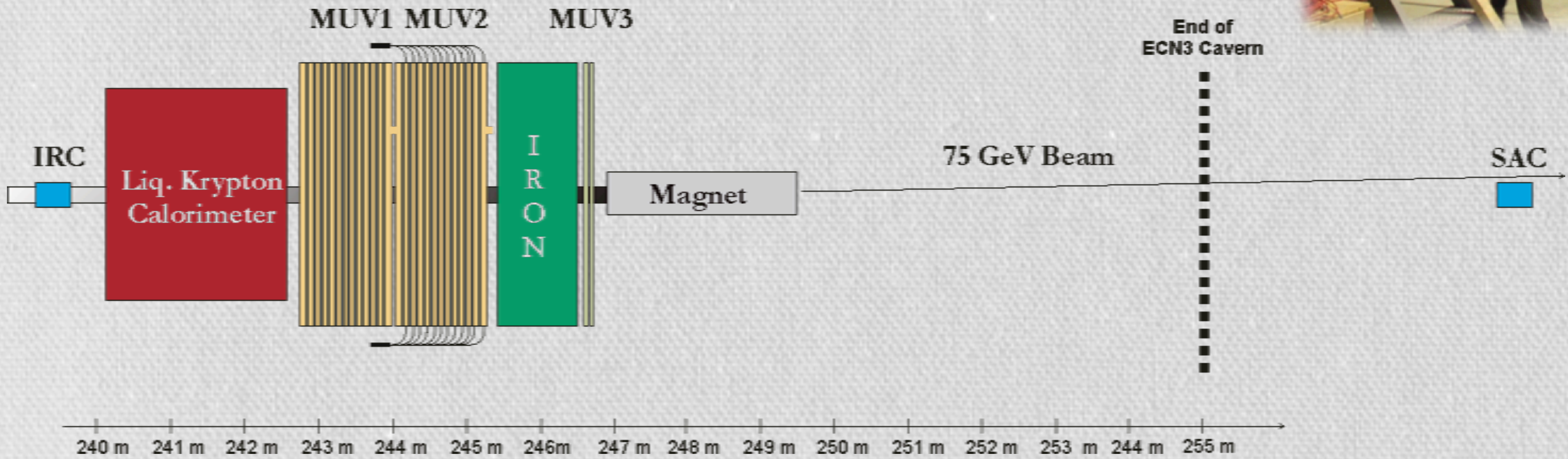
Muon veto stations



3 muon veto sections:

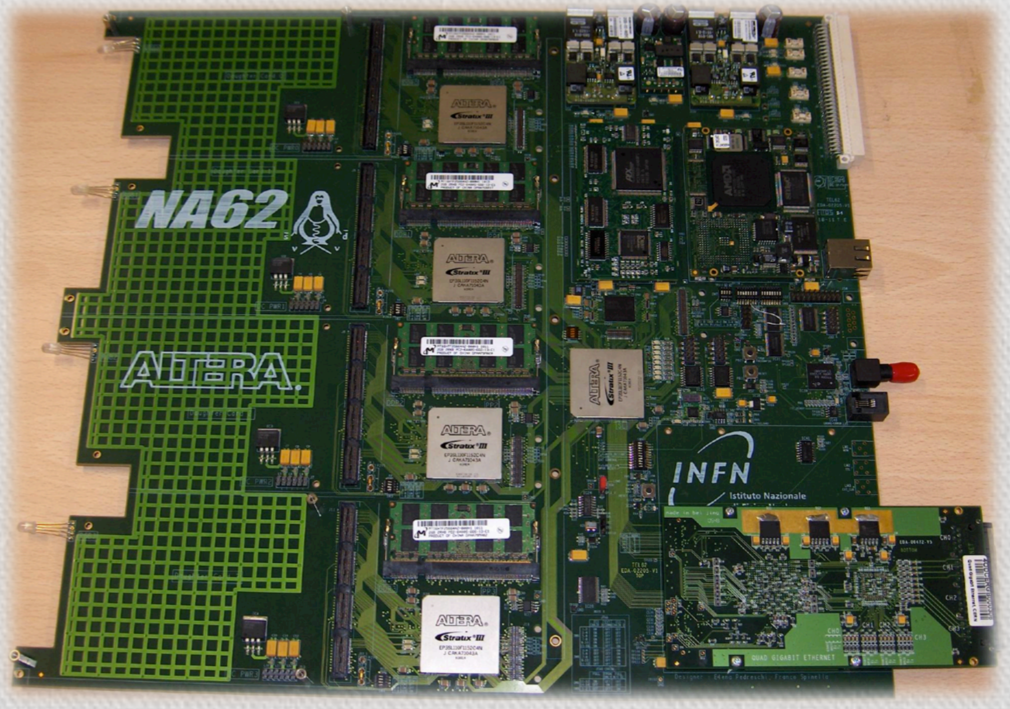
Partially by re-using hadron calorimeter from NA48

- **MUV1:**
  - 24 planes (iron/scintillator+WLS)
  - 6 cm strips (x-y)
  - 13 ph.el./MIP
- **MUV2:**
  - 22 planes (iron+scintillator)
- **MUV3:**
  - **Fast trigger signals**
  - Scintillator pads with direct readout of light in an (air) black box, to suppress reflections and Cerenkov



NA62 common DAQ

- Try to use **common** TDAQ board
  - (**TEL62,** based on LHCb TELL1)
  - **HPTDC** mezzanine card
- Custom solutions for **Liquid Krypton** and **Gigatracker** (too much data!)

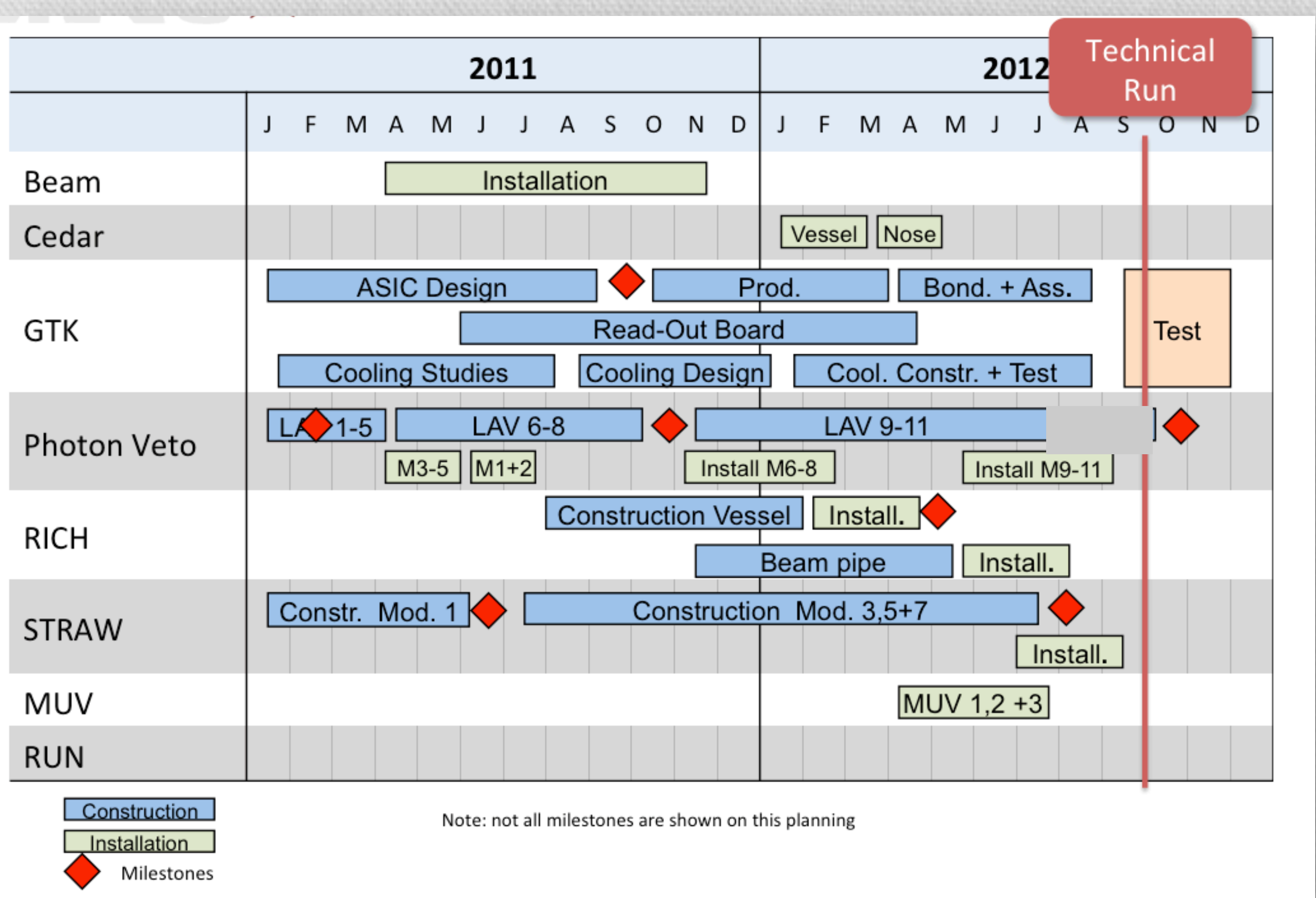


- **High data bandwidth (≈5 GB/s)**
- **No zero suppression (for candidate events)**

NA62 Trigger

- High trigger efficiency (>95%)
- Low random veto (<1%)
- Fully digital after Front-Ent profit of TEL62
- **Level-0** implemented in **hardware, 10 MHz → 1 MHz**
  - e.g. CHOD,RICH minimum multiplicity, Muon veto, LKr , Large angle veto
- **Level-1,** reconstruction at the level of full **sub-detector** (→ **100 KHz**)
- **Level-2** (on full event, → **few KHz**) implemented in **software**
  - e.g. vertex out of fiducial volume

Construction schedule



$K \rightarrow \pi\nu\nu$ sensitivity summary

Expt	Primary beam	Intensity (ppp)	SM evts/yr	Start date + run yrs	Total SM evts
NA62	**SPS 450 GeV**	3×10^{12}	**55**	**2014+2**	**110**
FNAL $K^{\pm}$	Project X 8 GeV	2×10^{14}	250	2018+5	1250
ORKA	Tevatron up <150 GeV	5×10^{13}	120	2018+5	600
E14	**JPARC-I 30 GeV**	$\mathbf{2 \times 10^{14}}$	**1-2**	**2013+3?**	**3-7**
E14	JPARC-II 30 GeV	3×10^{14}	30	2020+3?	100
FNAL K_L	Booster 8 GeV	2×10^{13}	30	2016+2	60
FNAL K_L	Project X 8 GeV	2×10^{14}	300	2018+5	1500

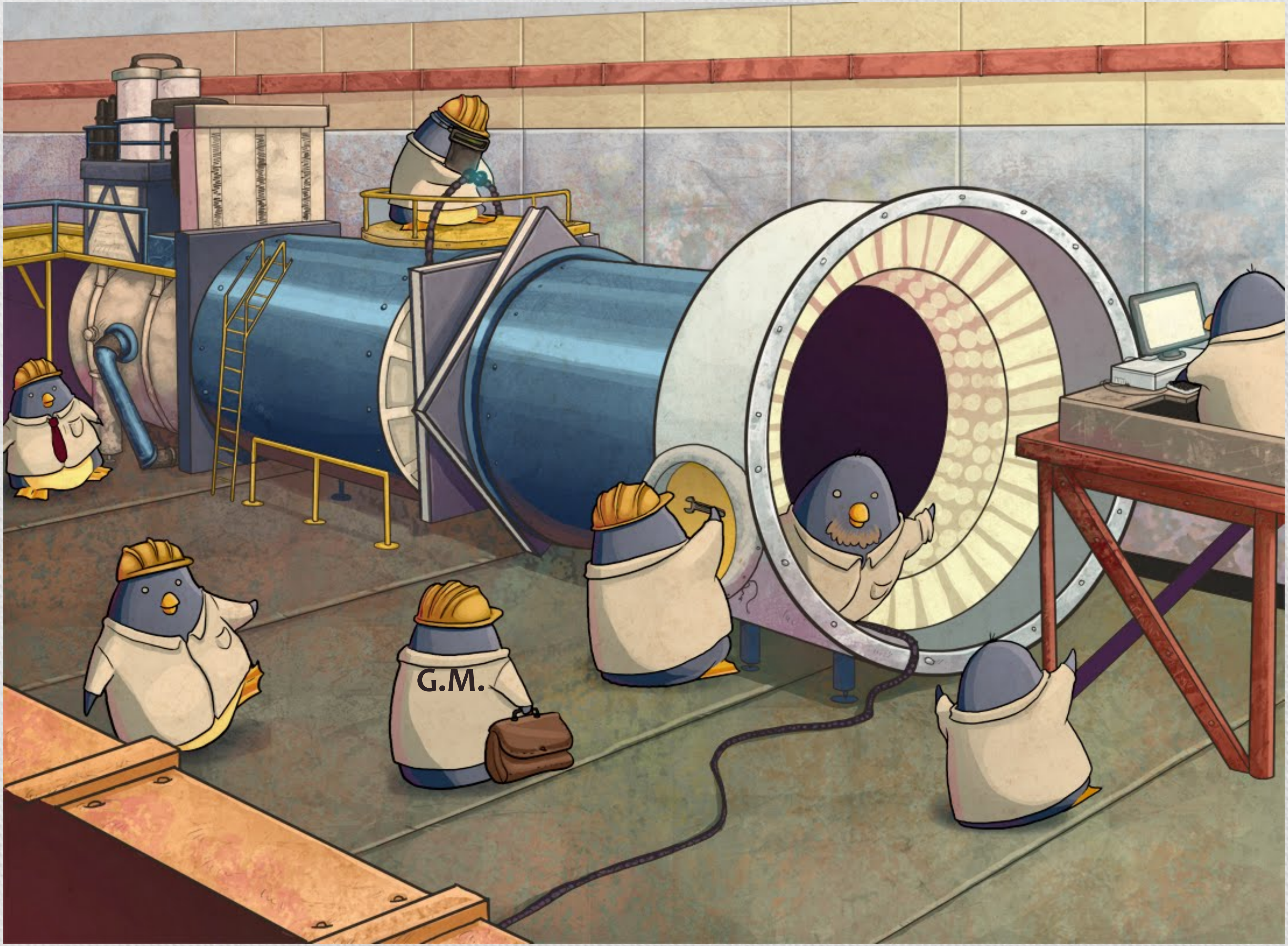
All dates/estimates are speculative, some are more speculative than others

Conclusions

- Flavor *physics is a powerful probe for test of SM at high energy*
- *$K^+ \to \pi^+ \nu\nu$* **very clean** mode; sensitivity to New Physics also at high energy scales: **complementary** to direct searches at LHC

- NA62 detectors have been carefully designed and validated (R&D, tests, Monte Carlo)
- **Construction** is proceeding steadily

- … and **getting ready to run**:
  - **Technical run** already at the end of year **2012** (without Gigatracker)
  - **Physics run** planned at SPS restart after long shutdown (**2014**)


G.M.

SPARE SLIDES

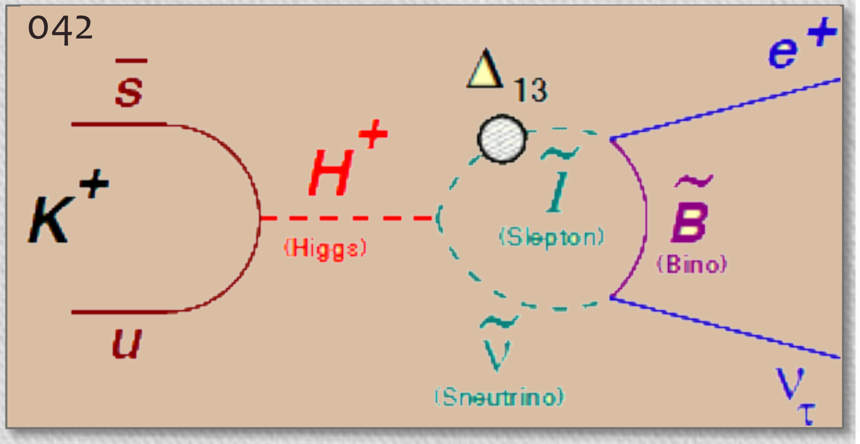
R_K beyond the SM 1 loop

2 Higgs Doublet Models – one-loop level

Dominant contribution to ΔR_K: $H^{\pm}$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement experimentally accessible

PRD 74 (2006) 011701, JHEP 0811 (2008) 042



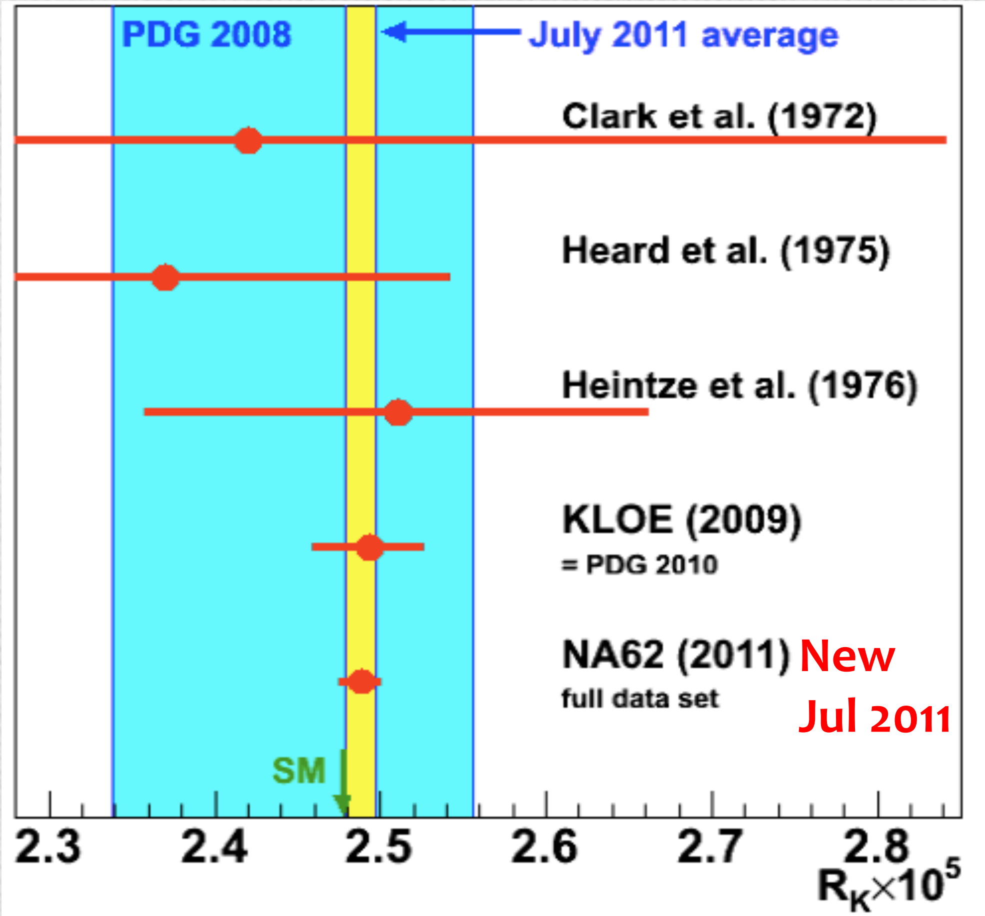
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

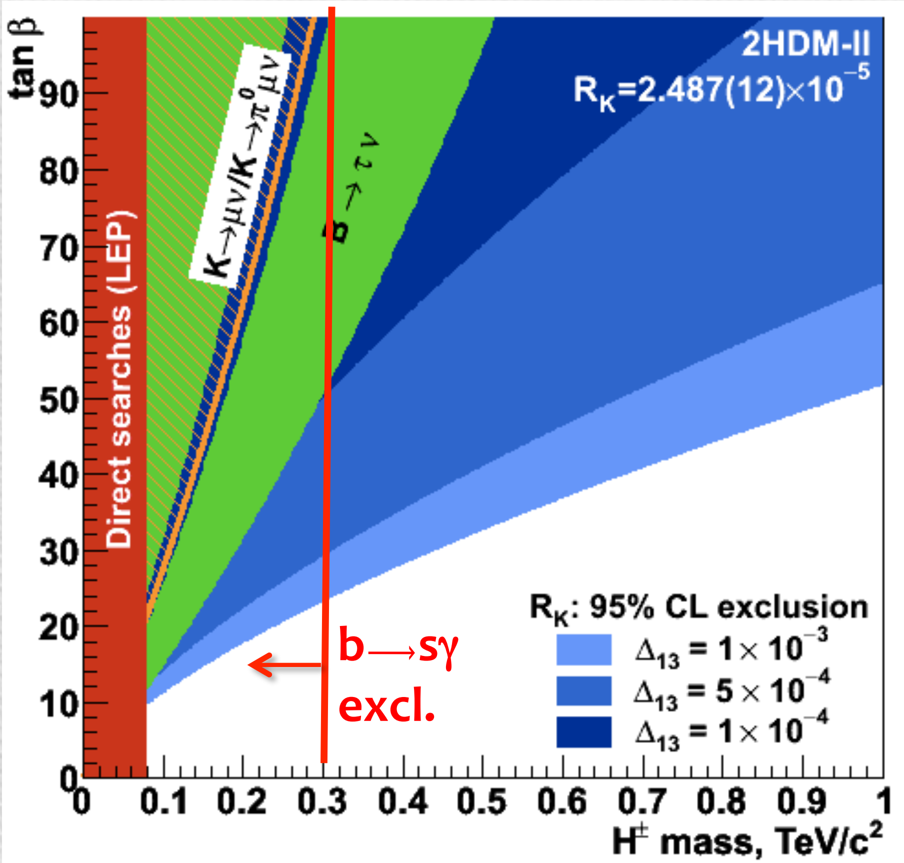
3 unknown parameters: $M_{H\pm}$, Δ_{13}, $\tan\beta$

Effect in large $\tan\beta$ regime with a massive $H^{\pm}$ ($\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c²) lead to $R_K^{MSSM} = R_K^{SM}(1+0.01)$ ~1% is measurable!

$$R_K = \frac{N(K_{e2})-N_B(K_{e2})}{N(K_{\mu2})-N_B(K_{\mu2})}\cdot\frac{A(K_{\mu2})\varepsilon(K_{\mu2})f_\mu}{A(K_{e2})\varepsilon(K_{e2})f_e}\cdot\frac{1}{f_{LKr}}$$

NA62 R_K and the Higgs





R_K can be used to exclude the presence of $H^{\pm}$ in a wide range of $M_{H\pm}$

	$\delta R_K \times 10^5$	Precision
NA62 R_K final	2.488±0.010	0.4%
Theory	2.477±0.001	0.04%

Even for tiny values of the LFV slepton mixing Δ_{13}, sensitivity to $H^{\pm}$ in $R_K=K_{e2}/K_{\mu 2}$ is better than in $B \rightarrow \tau\nu$

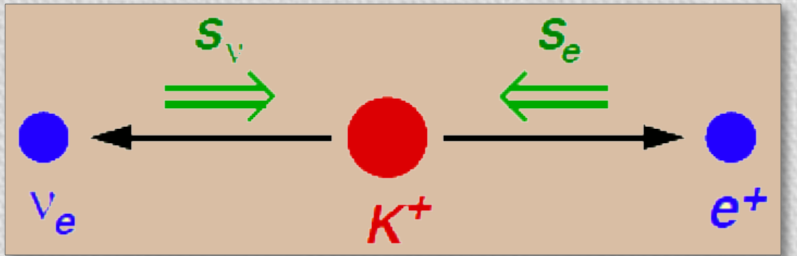
$R_K=\Gamma(K_{e2})/\Gamma(K_{\mu2})$ in the SM

Sensitive to lepton flavor violation and its SM expectation:

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

Few % due to: K->eν(γ) IB process

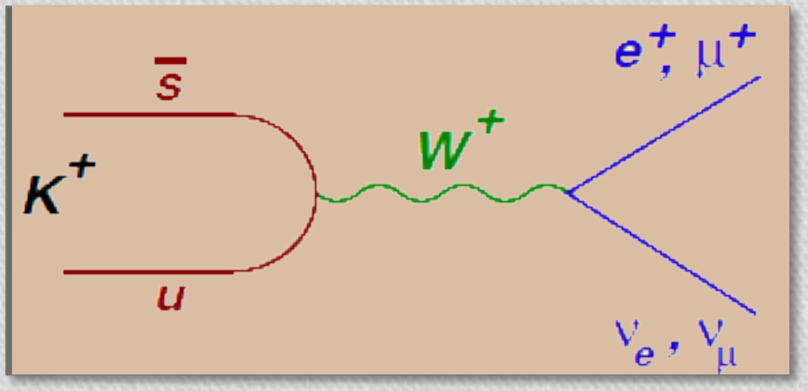
Helicty suppression factor ~10^{-5}



☑ SM prediction: excellent sub-permille accuracy due to cancellation of hadronic uncertainties.

☑ Measurements of R_K and R_π have long been considered as tests of lepton universality.

☑ Recently understood: helicity suppression of R_K might enhance sensitivity to non-SM



Theoretical expect. (Phys. Lett. 99 (2007) 231801):

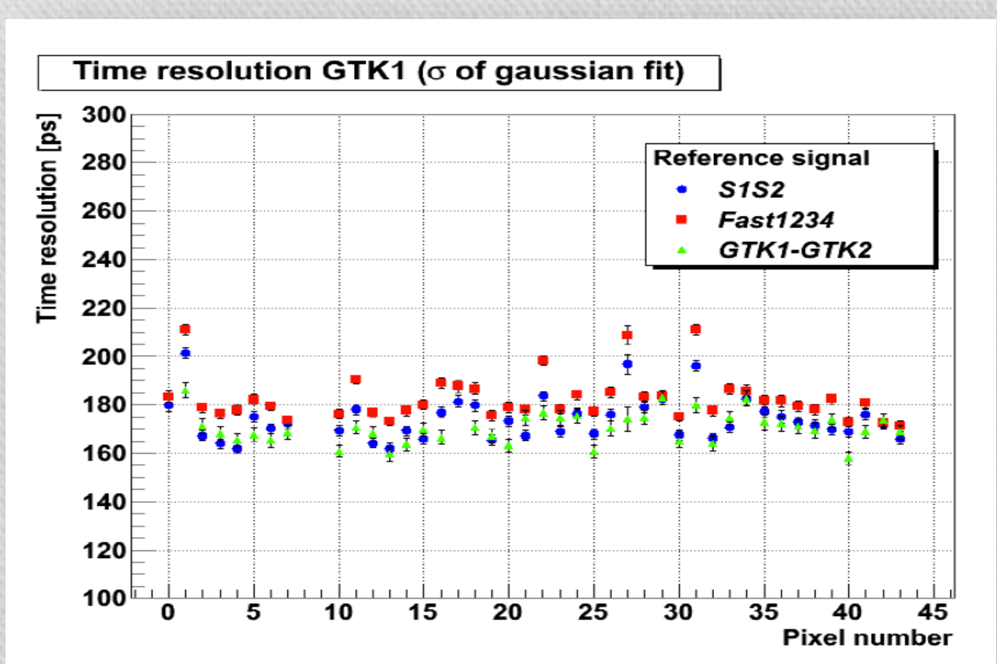
$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ (0.04% precision!)

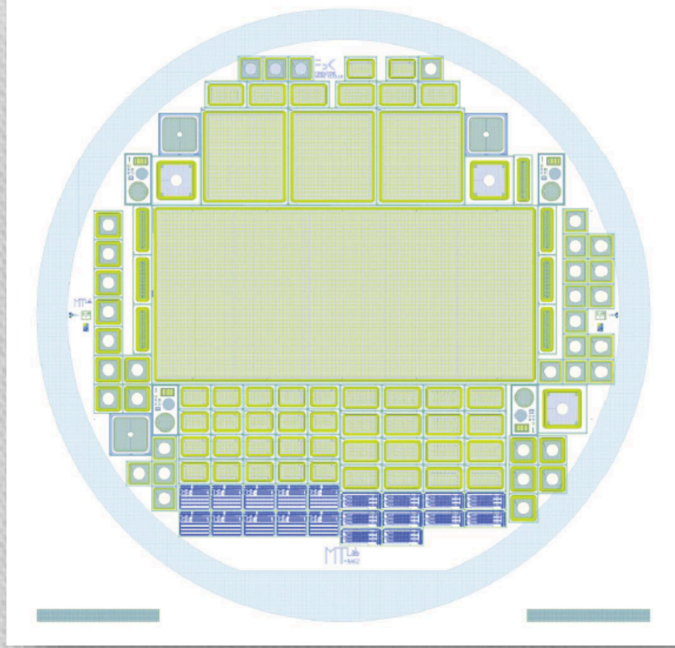
$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

Schedule

- Beam line: full system will be installed in 2011.
- Beam Dump: completion expected in 2011.
- Vacuum tank and vacuum system: full system should be available; some pumping units could be staged (depending on number of installed Straw modules).
- CEDAR: full system should be available.
- GTK: the final pixel detectors will not yet be available; possibility to use prototype sensors in the Technical Run.
- LAV: plan to install 10 (or 9) LAV modules. LAV12 will not be ready. If LAV10 is not ready we would install the empty vessel to complete the vacuum tank.
- STRAW: possibility to complete 3 or 4 (out of 8) chamber modules. Chambers 1, 2 and 4 could be equipped with one (instead of two) modules each. The missing modules will be replaced by empty module frames.
- RICH: plan to install the RICH vessel in Spring 2012, including the central beam pipe.
- LKR: the calorimeter will still be read out by the existing electronics (CPD/SLM) but prototypes of the final electronics (CREAM) will be tested.
- CHOD: use the existing NA48 CHOD with prototype read-out.
- MUV: full system.

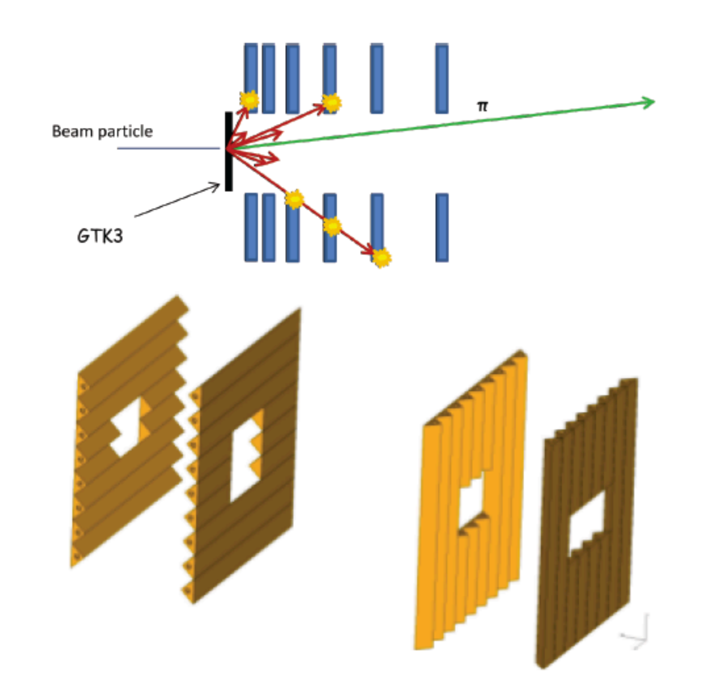
Gigatracker: the silicon pixel beam detector





Charged veto (CHANTI)

Veto:
2 MHz muon halo
+ inelastic interactions

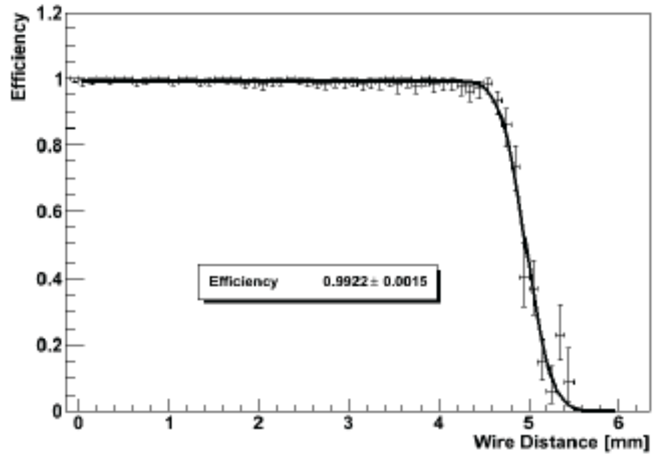


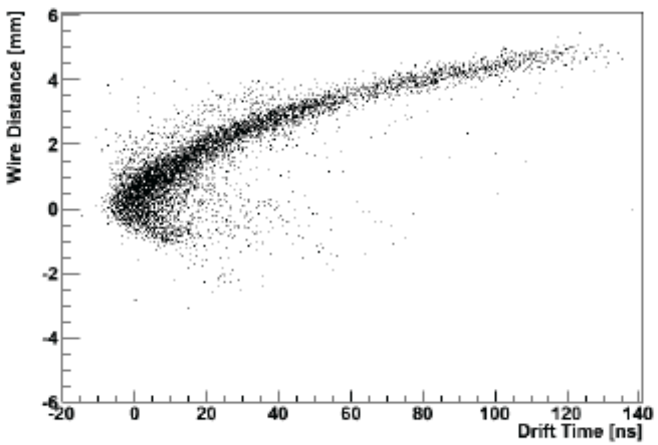
- Triangular shape extruded scintillator bars
- WLS fibers readout + SiPM's
- ≈ 10 ph.el. / MIP
- $\sigma_t < 2$ ns

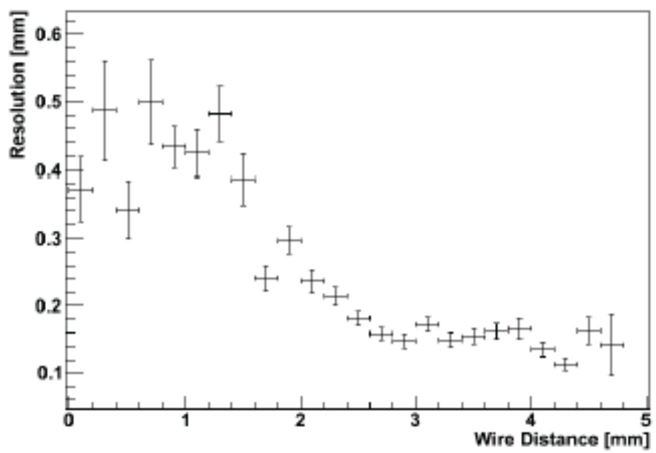
Straw tracker prototype

Straws prototype test:

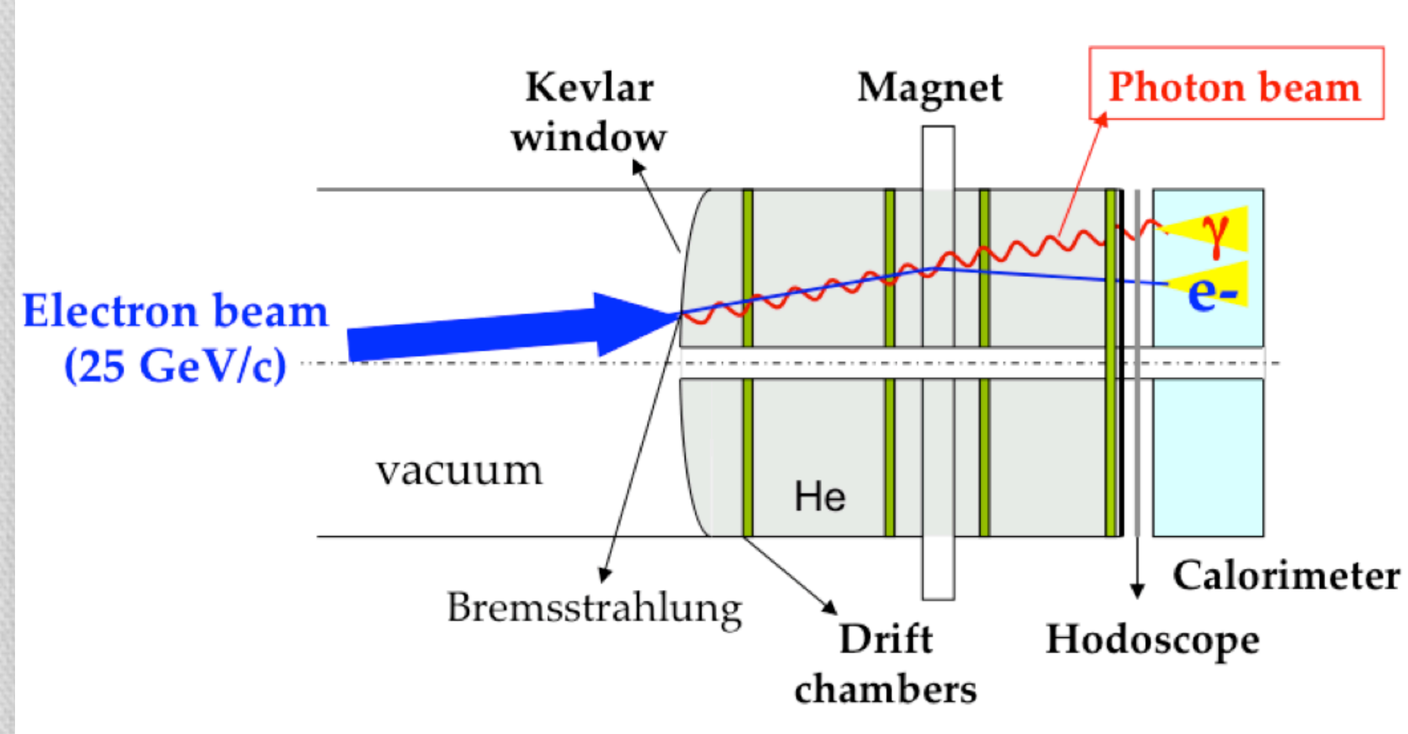
- 64 straws
- Final mechanics
- Vacuum vessel
- CARIOCA readout electronics
- Pion beam, 120 GeV/c





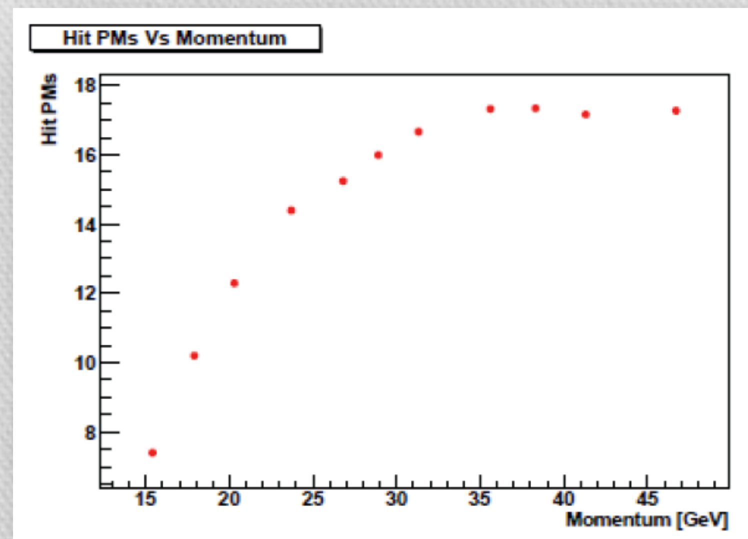


Liquid Krypton efficiency

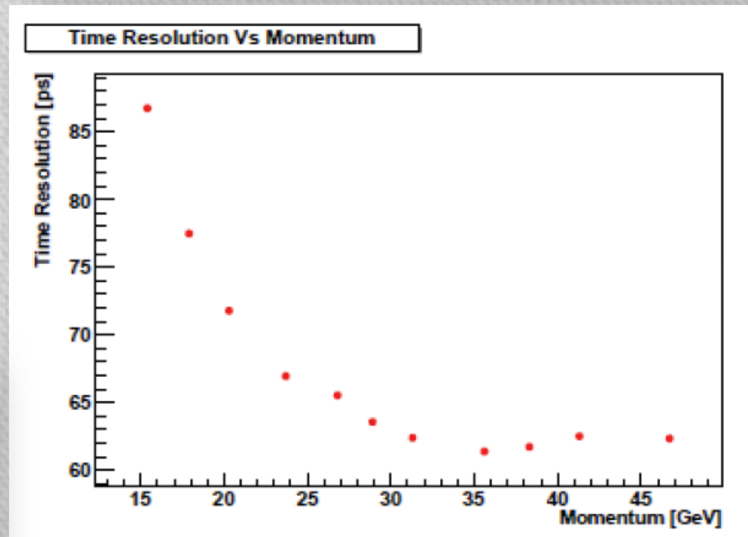


Energy	Inefficiency
$2 < E_\gamma < 3.5$ GeV	$(5.8 \pm 1.3)\times10^{-4}$
$3.5 < E_\gamma < 5$ GeV	$(1.6 \pm 0.4)\times10^{-4}$
$5 < E_\gamma < 7.5$ GeV	$(2.8 \pm 1.6)\times10^{-5}$
$7.5 < E_\gamma < 10$ GeV	$<2\times10^{-5}$
$E_\gamma > 10$ GeV	$<1\times10^{-5}$

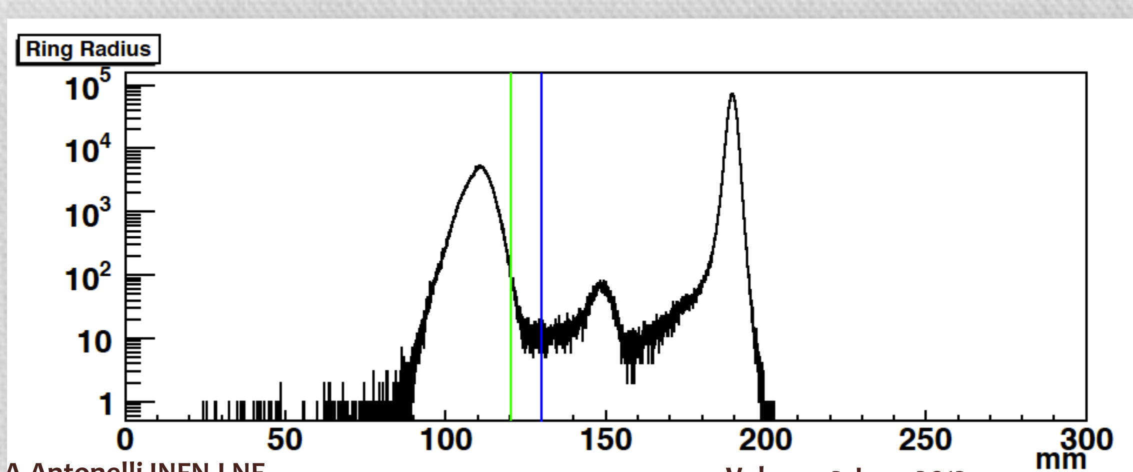
RICH performance



Number of hits vs. momentum



Time resolution vs. momentum



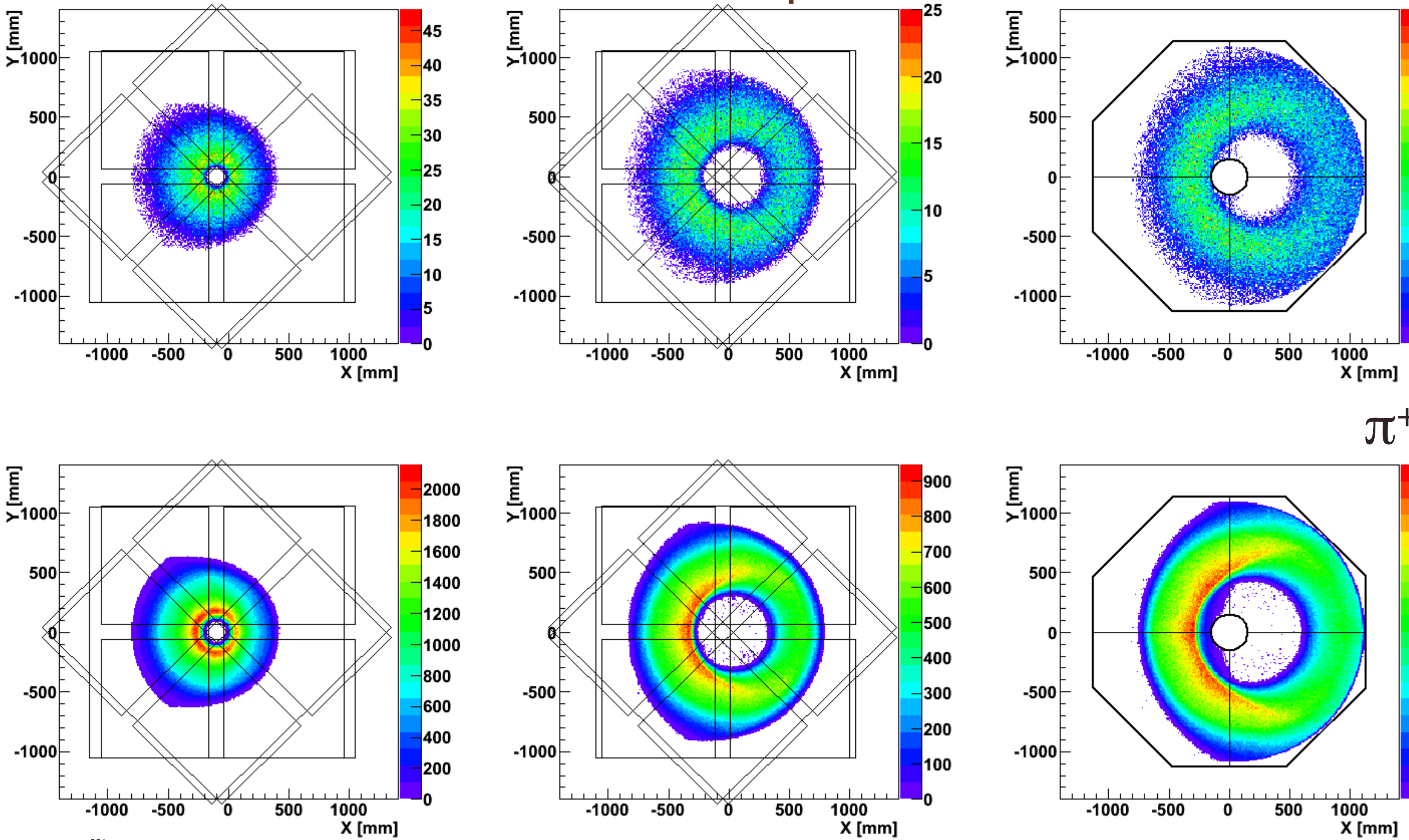
Monte Carlo: event selection

Cut on reconstructed momentum: $15 < P_{track} < 35$ GeV/c

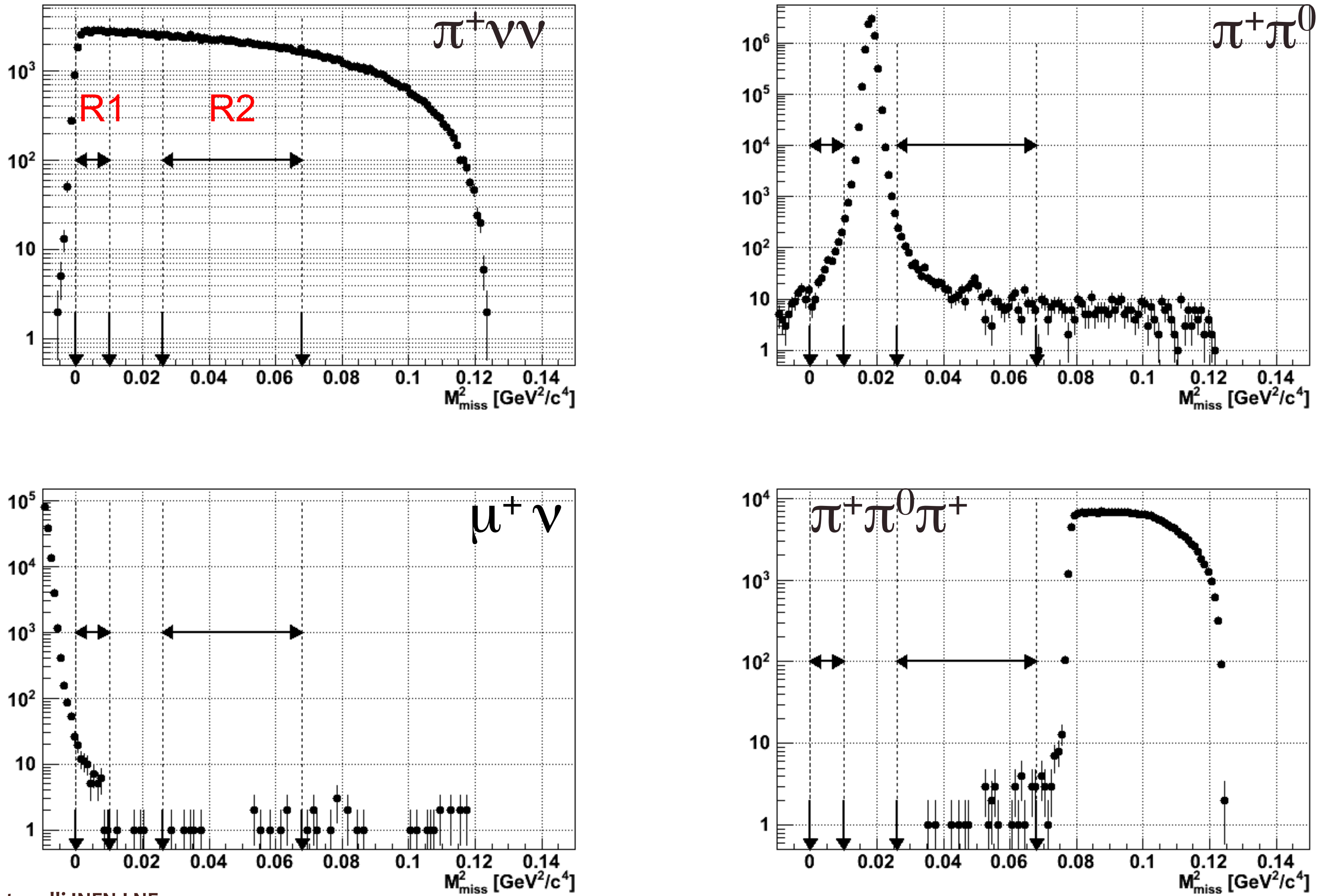
STRAW 1 | STRAW 4 | LKr

$\pi\nu\nu$

$\pi^+\pi^0$

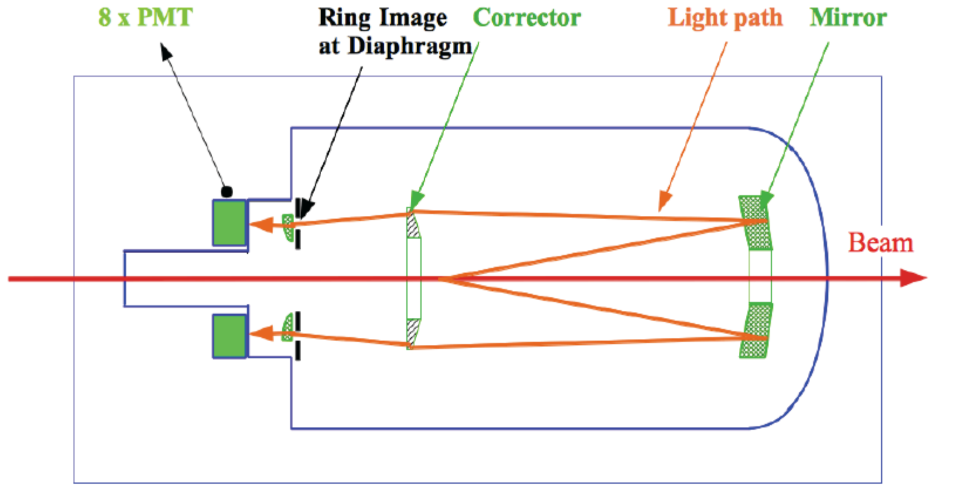


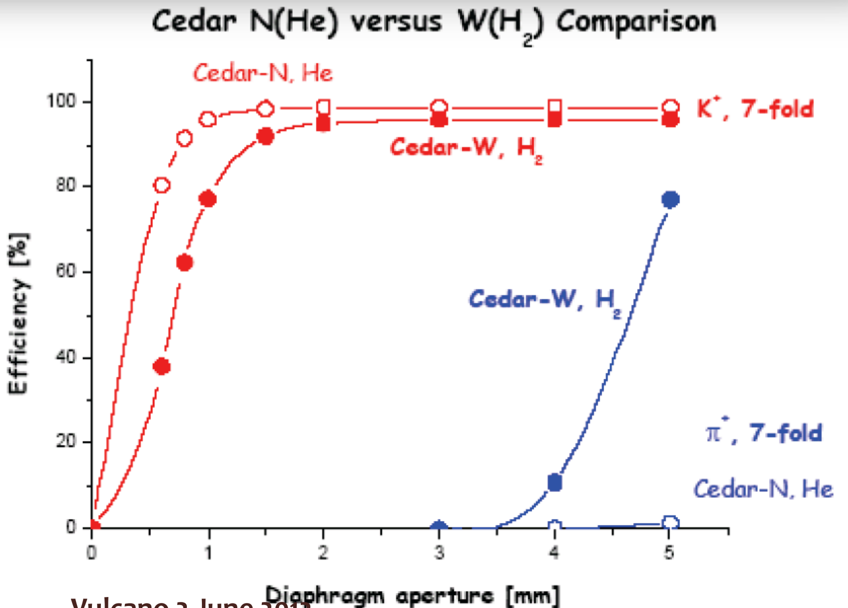
Monte Carlo: cut on m^2_{miss}



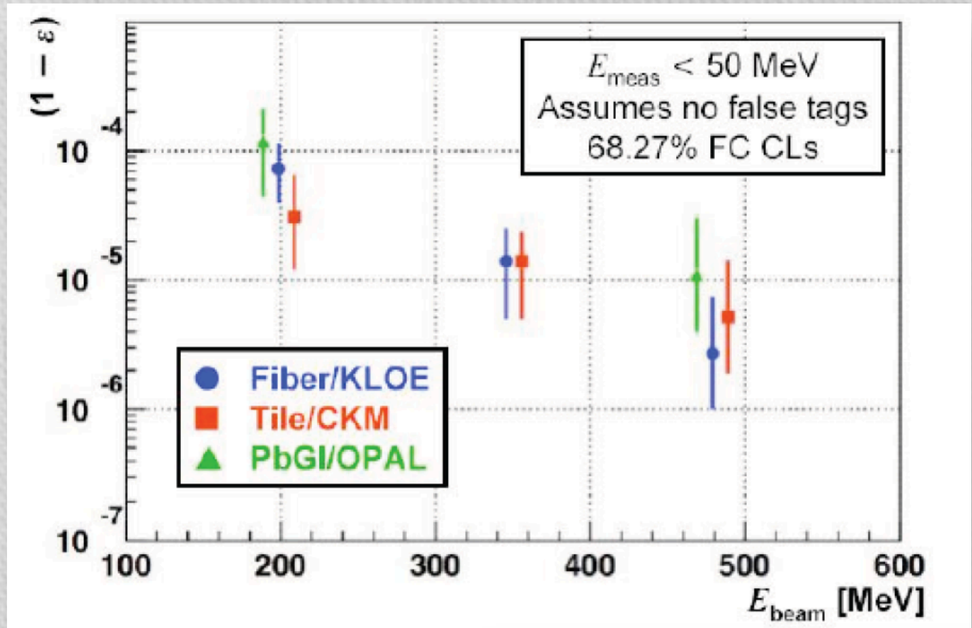
Kaon tagger: differential Cerenkov

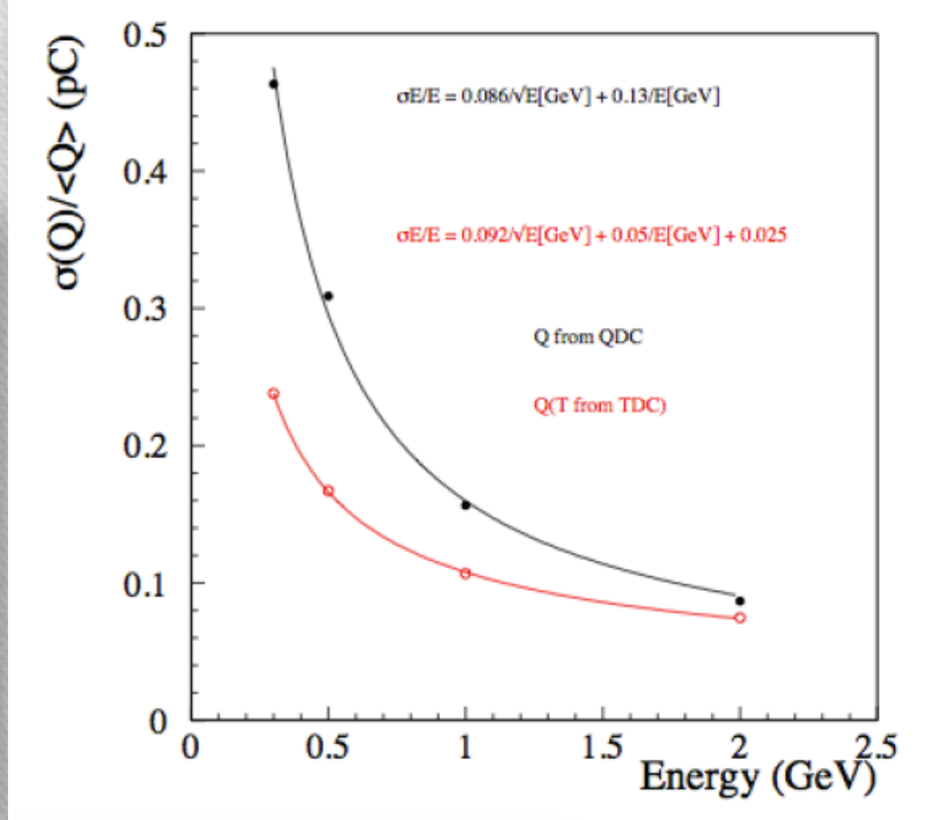
- H_2 @ 3.86 bar
- 100 photons/K
- K @ 50MHz
- $\approx$ 250 PMs
- 3MHz/PM
- $\sigma_t < 100$ps

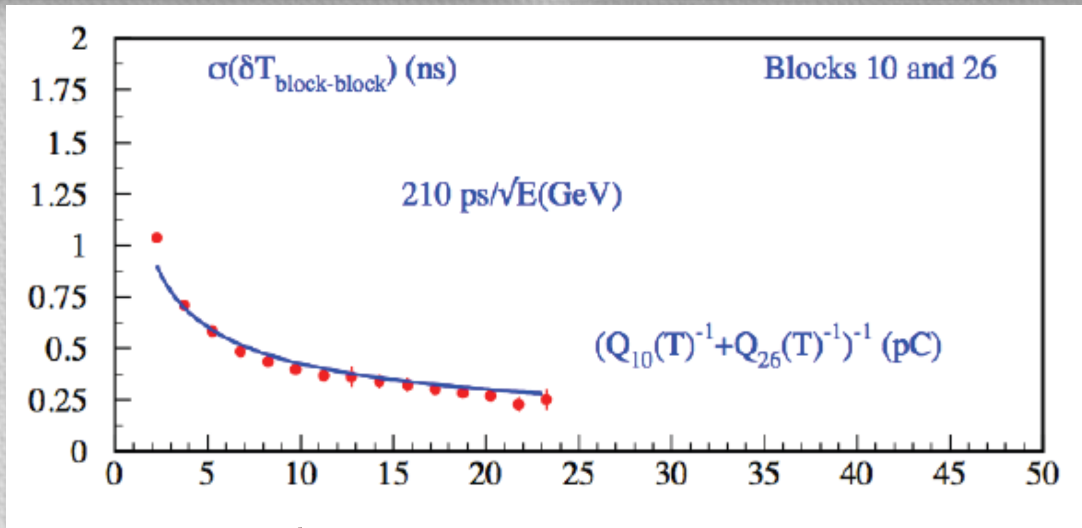




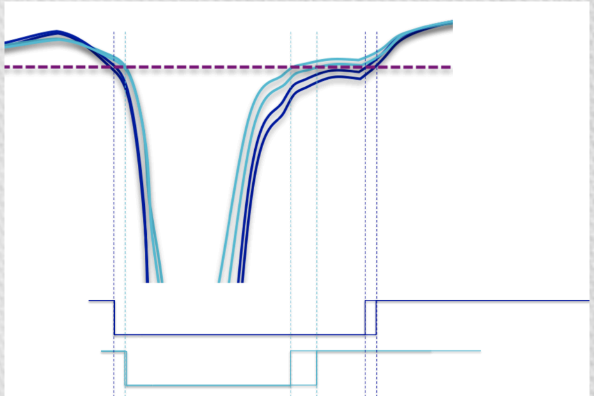
LAV performance



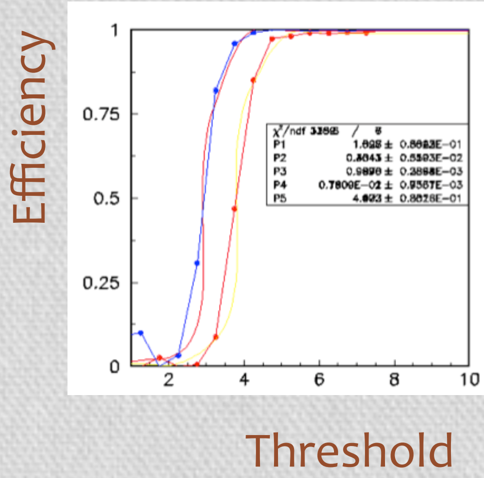




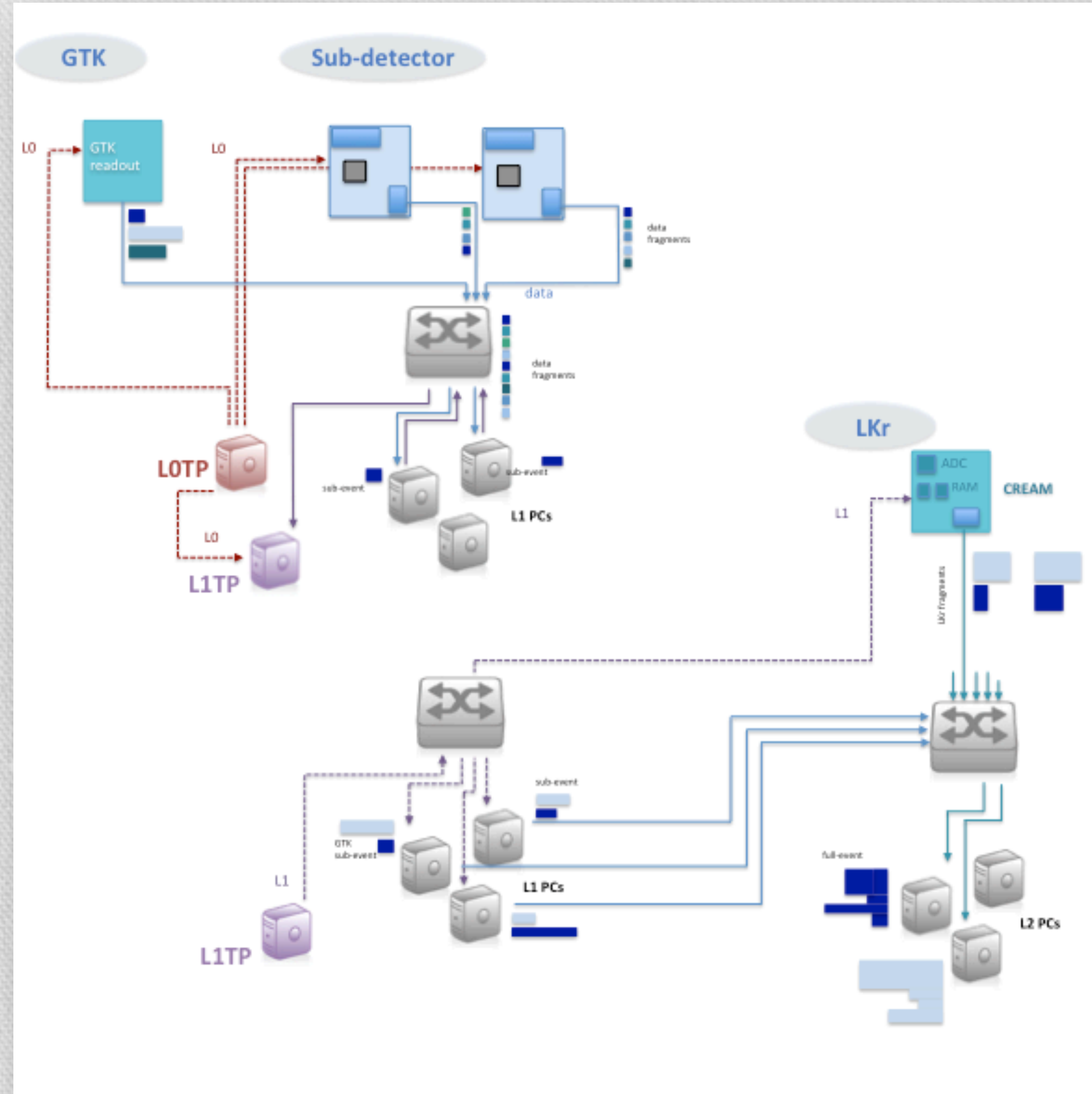
LAV readout electronics



Time-over-threshold discriminator:
dual threshold



Data flow

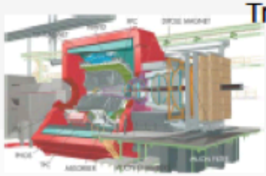
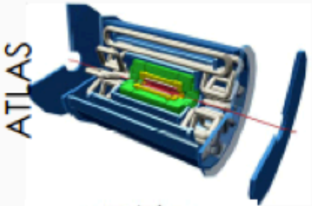
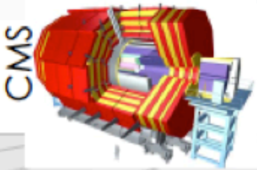
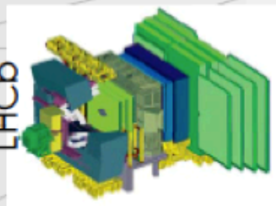
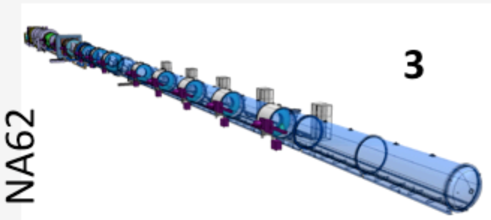

GTK
Sub-detector
L0
GTK readout
L0
data fragments
data
data fragments
L0TP
sub-event
sub-event
L1 PCs
L0
L1TP
LKr
ADC
RAM
CREAM
L1
LKr fragments
sub-event
GTK sub-event
L1
L1 PCs
full-event
L2 PCs
L1TP

L0 trigger rates

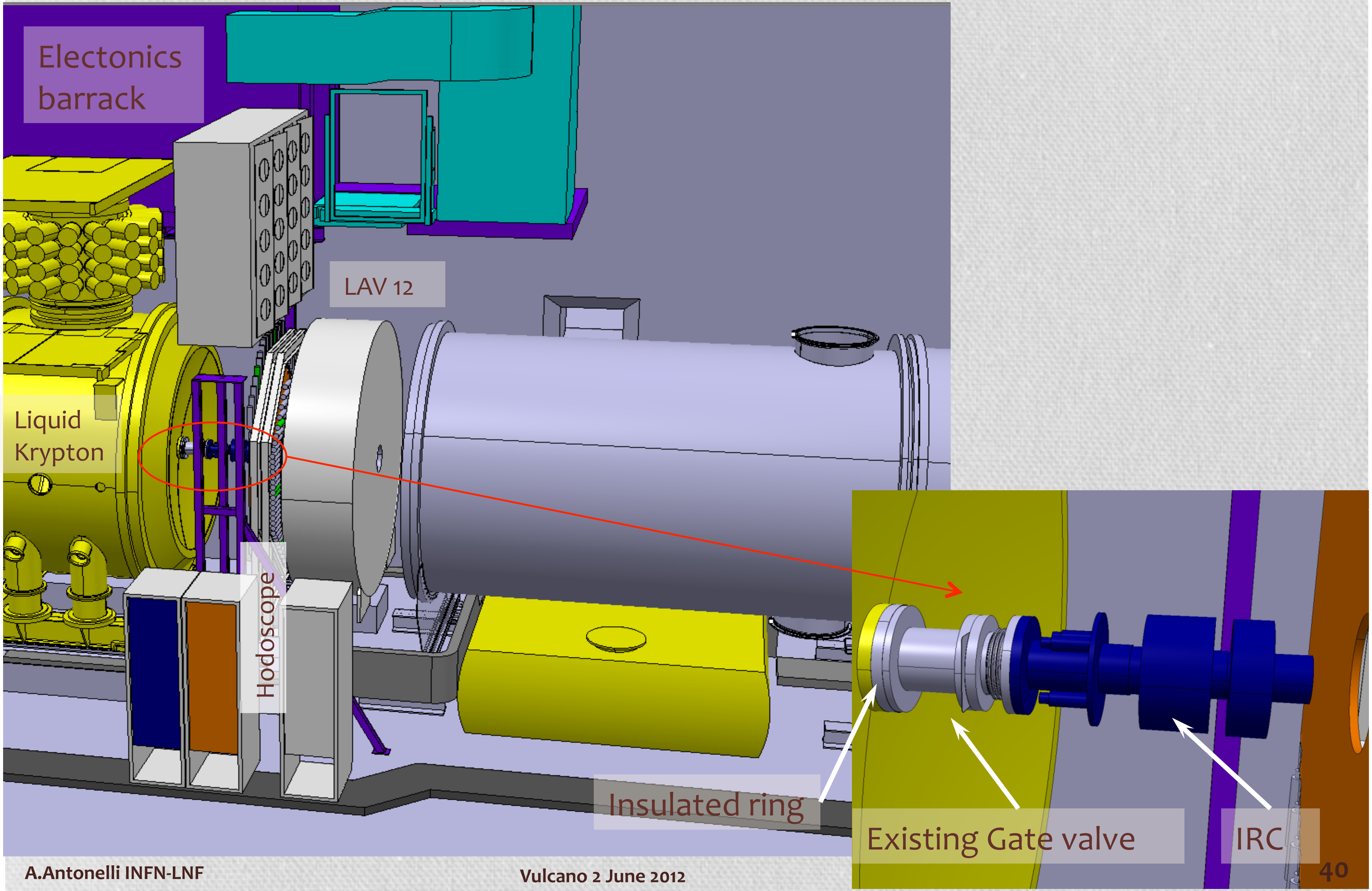
gradually add signals on top of the previous →

	kHz	CHOD	* RICH	* MUV3	* LKR	* LAV_12	* LAV_ALL
$\pi\pi^0$	**1859**	1255	1128	1078	200	134	85
$\mu\nu$	5719	3786	3376	1	1	1	1
$\pi\pi\pi$	503	393	379	315	89	89	89
$\pi\pi^0\pi^0$	158	105	97	90	3	1	0
$\pi^0 e\nu$	456	265	243	243	41	28	20
$\pi^0\mu\nu$	301	195	178	1	1	0	0
TOT	8998	**5999**	**5400**	**1727**	**334**	**254**	**196**
$\pi\nu\nu$ (P,Z cuts) eff. %		93	82	77	75	75	75

Data volume

	No.Levels Trigger	Level-0,1,2 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	HLT Out MB/s (Event/s)
ALICE 	4	Pb-Pb 500 p-p 10^3	$5\text{x}10^7$ $2\text{x}10^6$	25	1250 (10^2) 200 (10^2)
ATLAS 	3	LV-1 10^5 LV-2 $3\text{x}10^3$	$1.5\text{x}10^6$	4.5	300 ($2\text{x}10^2$)
CMS 	2	LV-1 10^5	10^6	100	~1000 (10^2)
LHCb 	2	LV-0 10^6	$3.5\text{x}10^4$	35	70 ($2\text{x}10^3$)
NA62 	3	LV-0 10^6 LV-1 10^5 LV-2 $1.5\text{x}10^4$	$3\text{x}10^4$	30	150 ($5\text{x}10^3$)

IRC


Electonics barrack
LAV 12
Liquid Krypton
Hodoscope
Insulated ring
Existing Gate valve
IRC

New beam dump