Rare Kaon Decay Experiments

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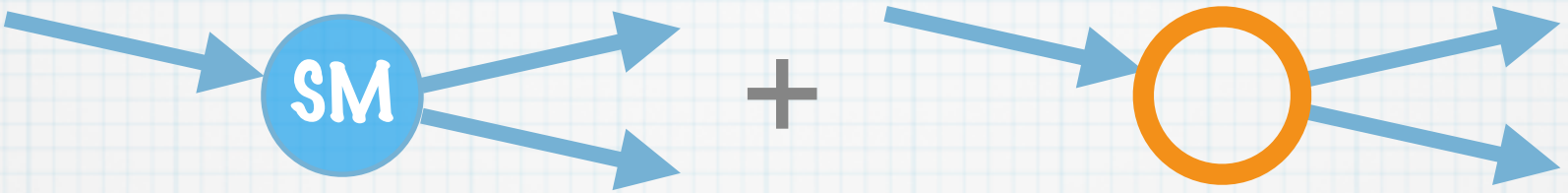
FPCP2016@Caltech

Kaons are sensitive probes to search for New Physics

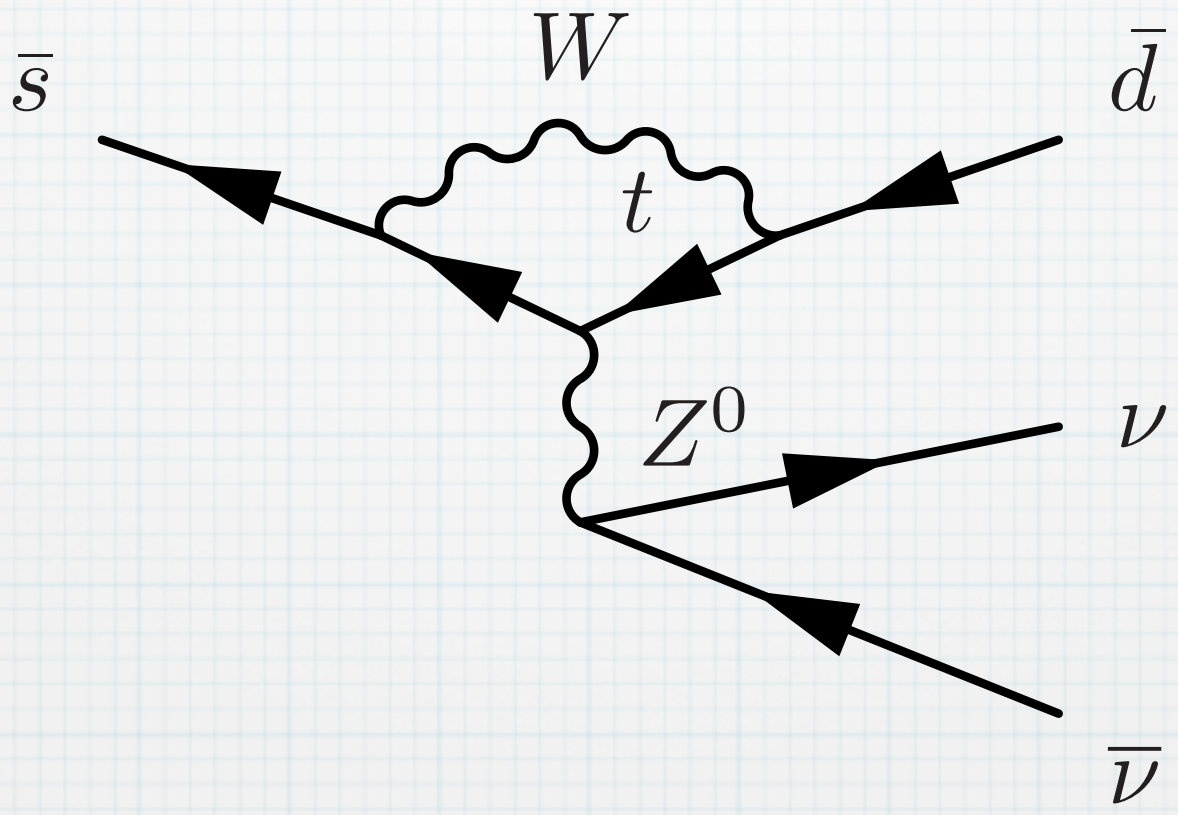
To search for New Physics

* Look for deviation from Standard Model

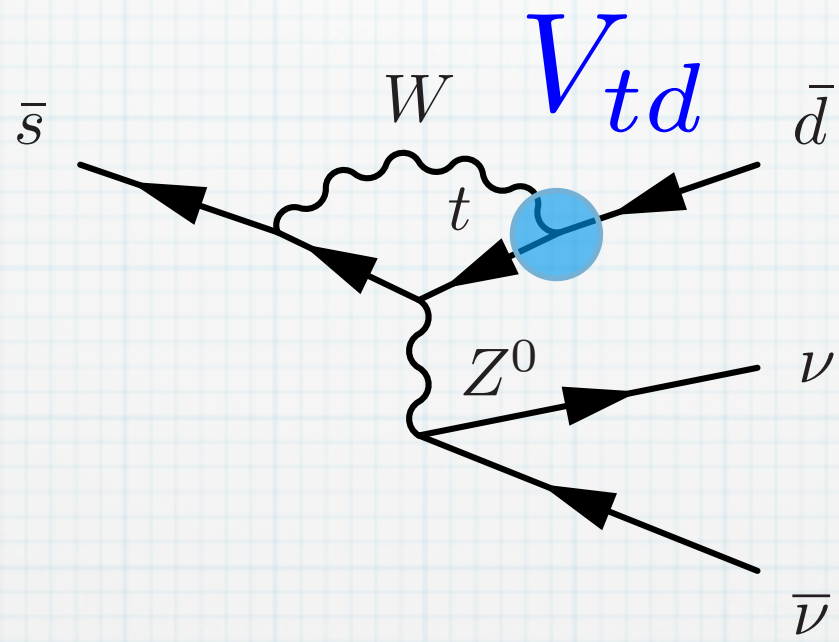


* Standard Model process should be
  * suppressed
  * well-known

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



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



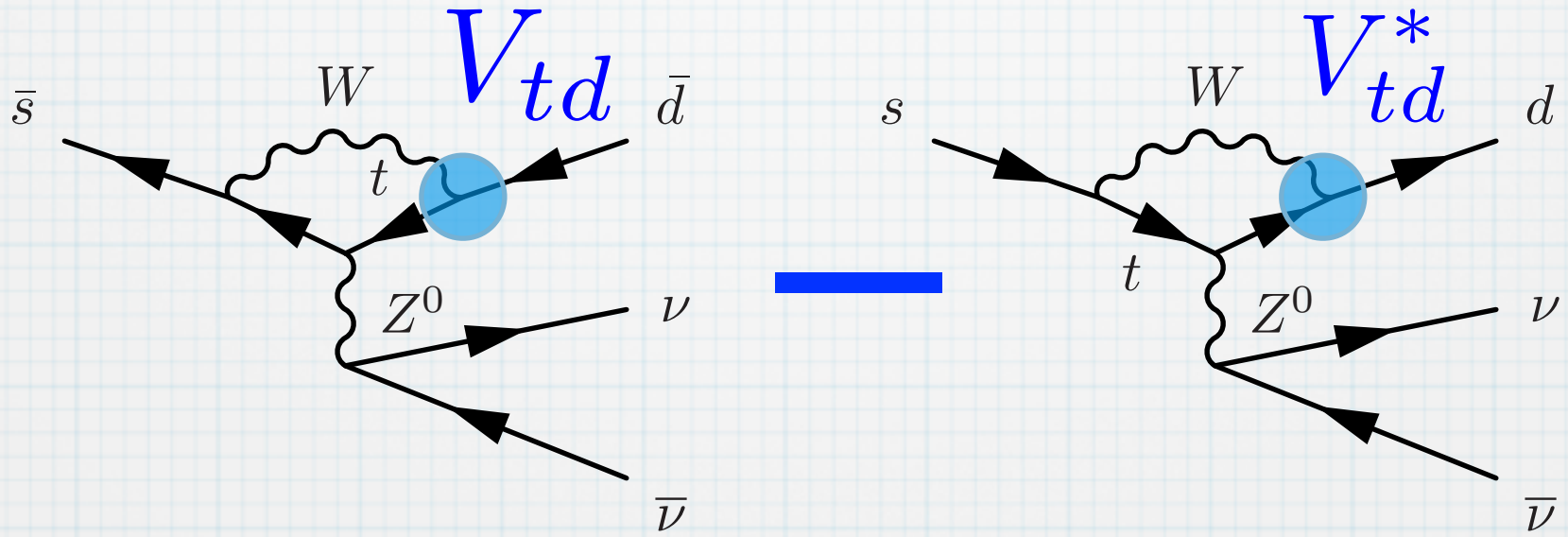
$$A(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{td}|$$

CP– CP+

$K_L \to \pi^0 \nu\overline{\nu}$

$$|K_L\rangle \simeq (|K^0\rangle - |\overline{K}^0\rangle)/\sqrt{2}$$

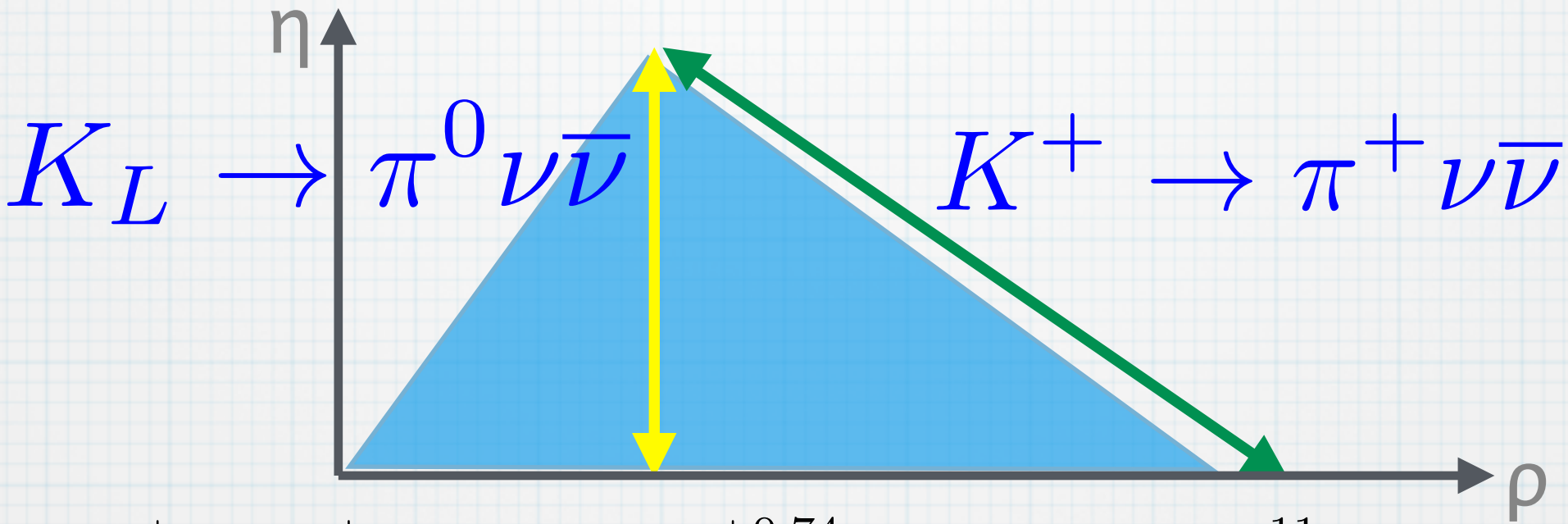
$$A(K_L \to \pi^0 \nu\overline{\nu}) \propto$$



$$A(K_L \to \pi^0 \nu\overline{\nu}) \propto V_{td} - V_{td}^*$$

$$\propto Im(V_{td})$$

Standard Model

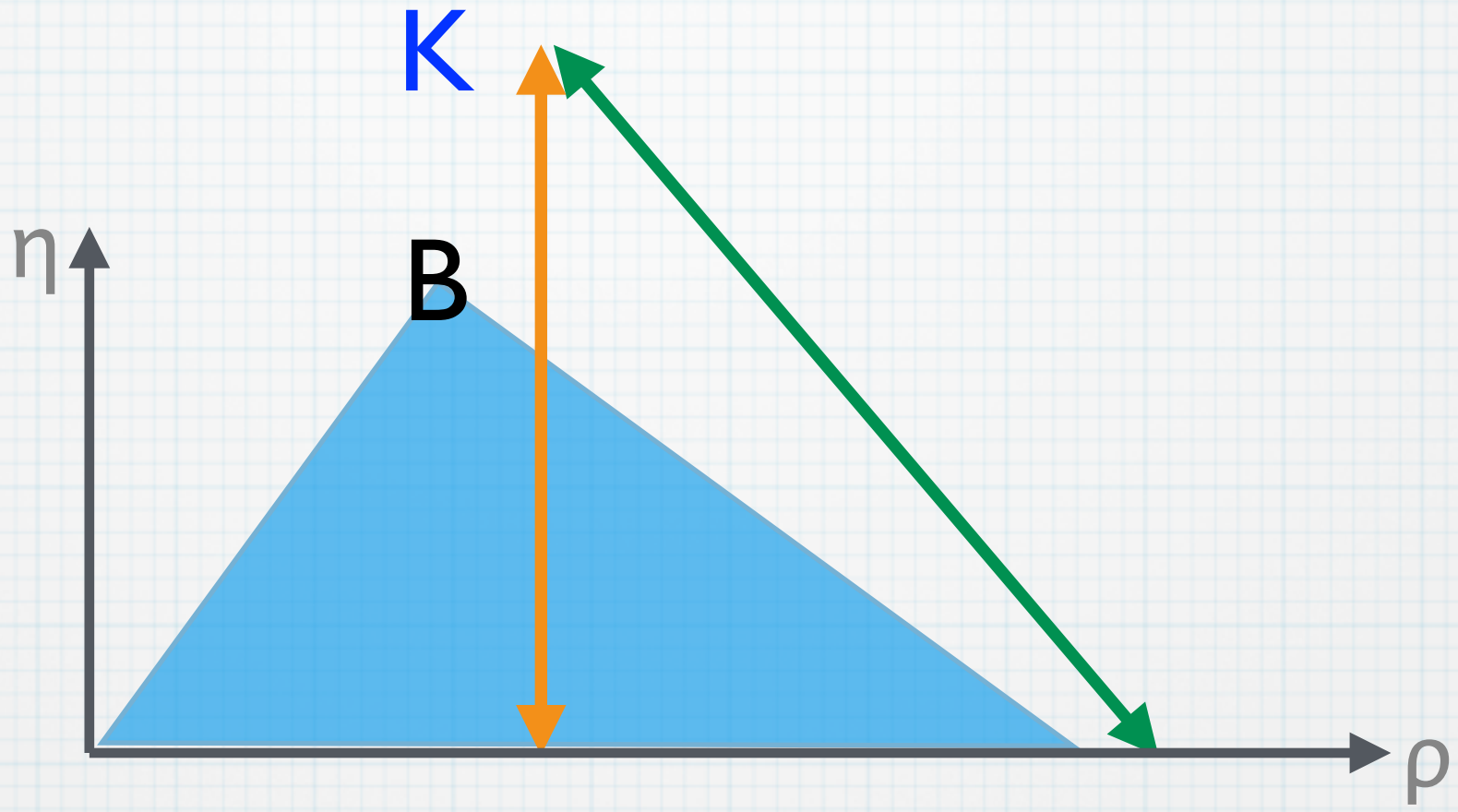


$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.22^{+0.74}_{-0.65} \pm 0.29) \times 10^{-11}$$
$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) = (2.57^{+0.38}_{-0.36} \pm 0.04) \times 10^{-11}$$

Brod et al., 1009.0947

- Small Standard Model "background"
- Small theoretical uncertainty

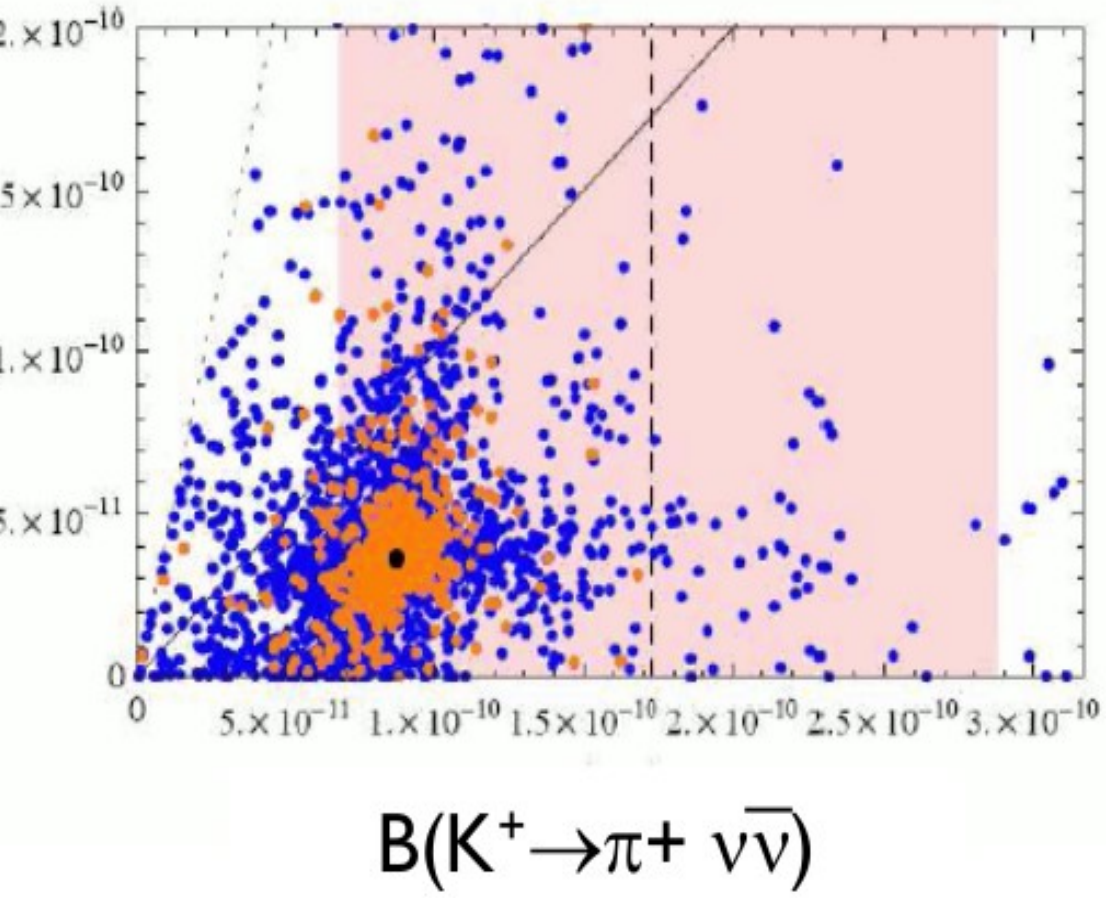
If K and B results do not agree



Sign of New Physics!

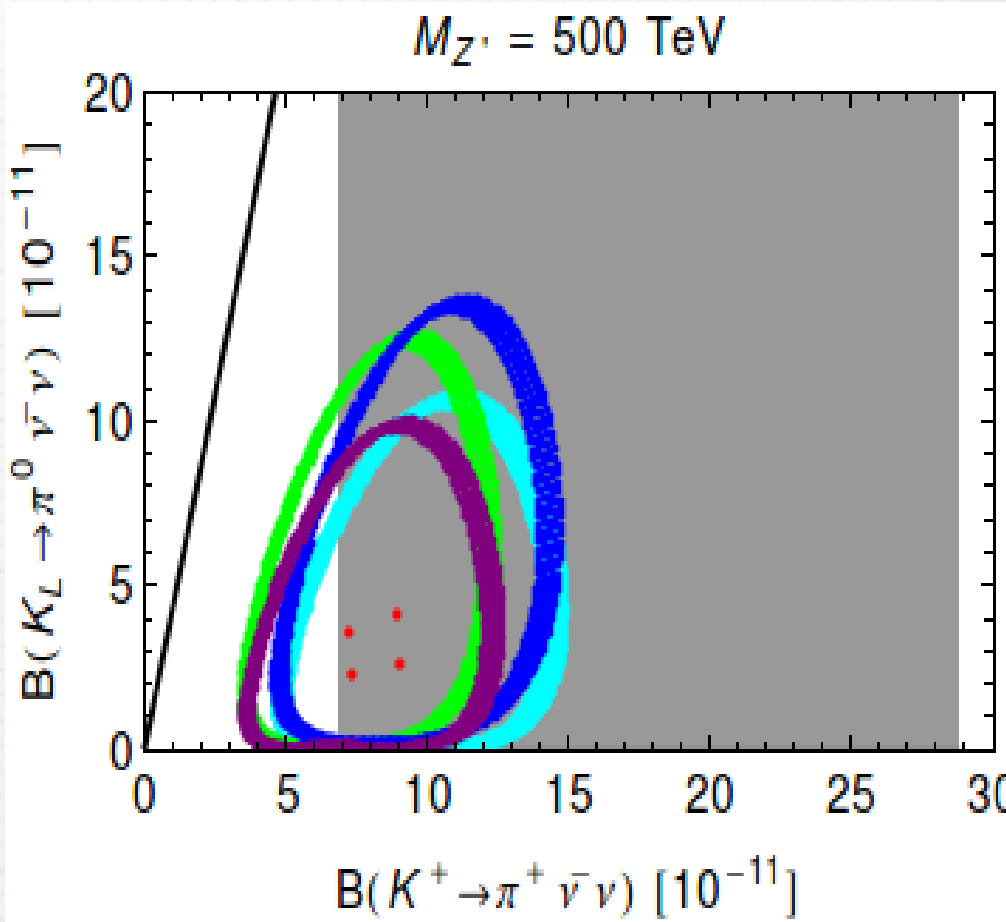
New Physics

Randall-Sundrum



Blanke et al., JHEP 0903, 108 (2009)

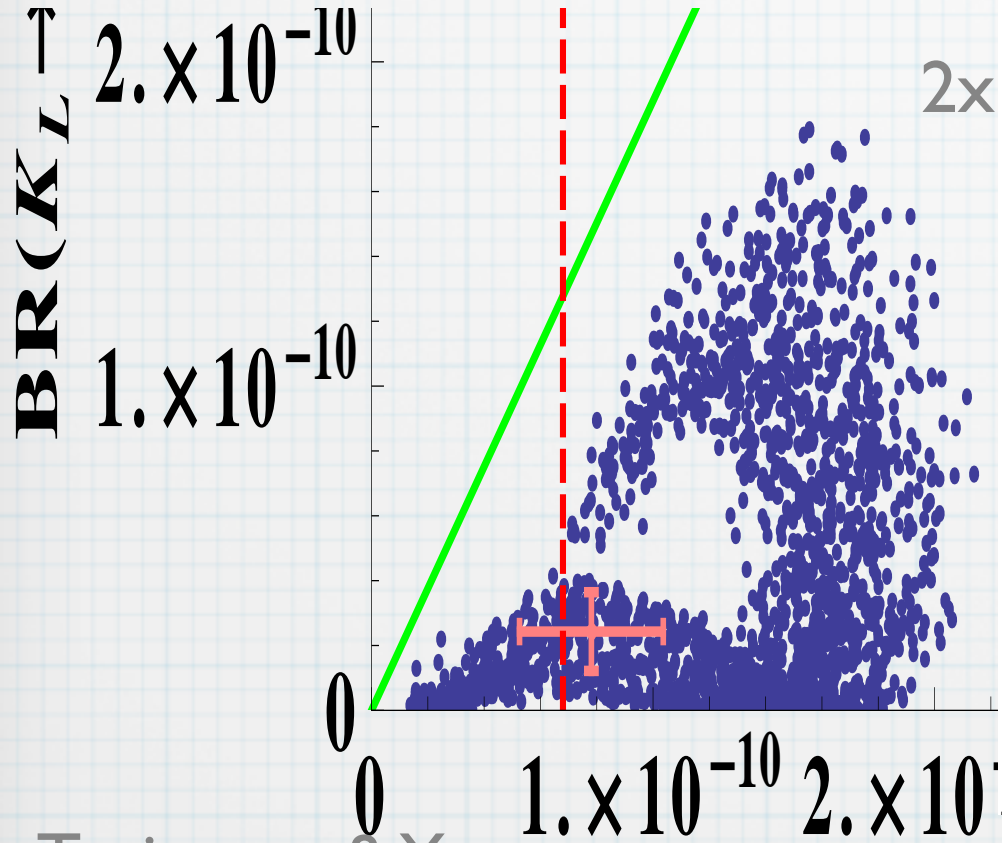
Z' contribution



Buras et al., 1408.0728

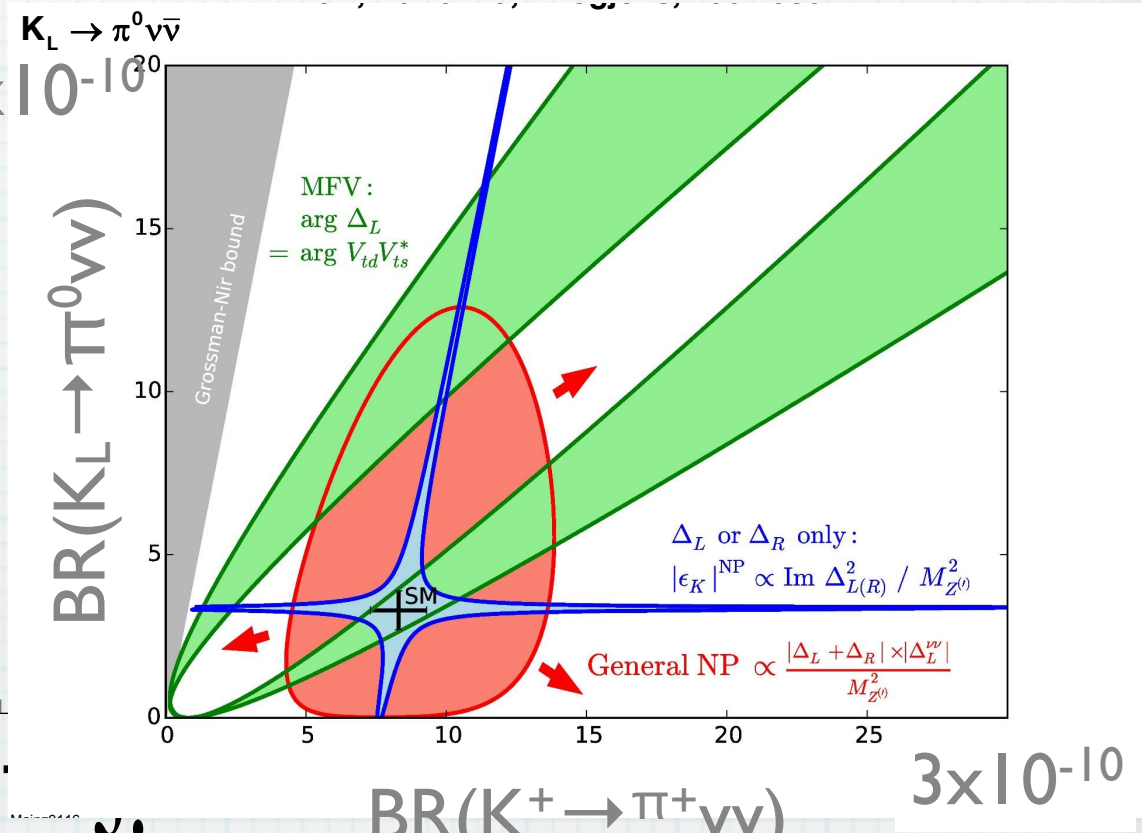
New Physics

SUSY@10TeV



Tanimoto & Yamamoto, 1503.06270

2x10-10



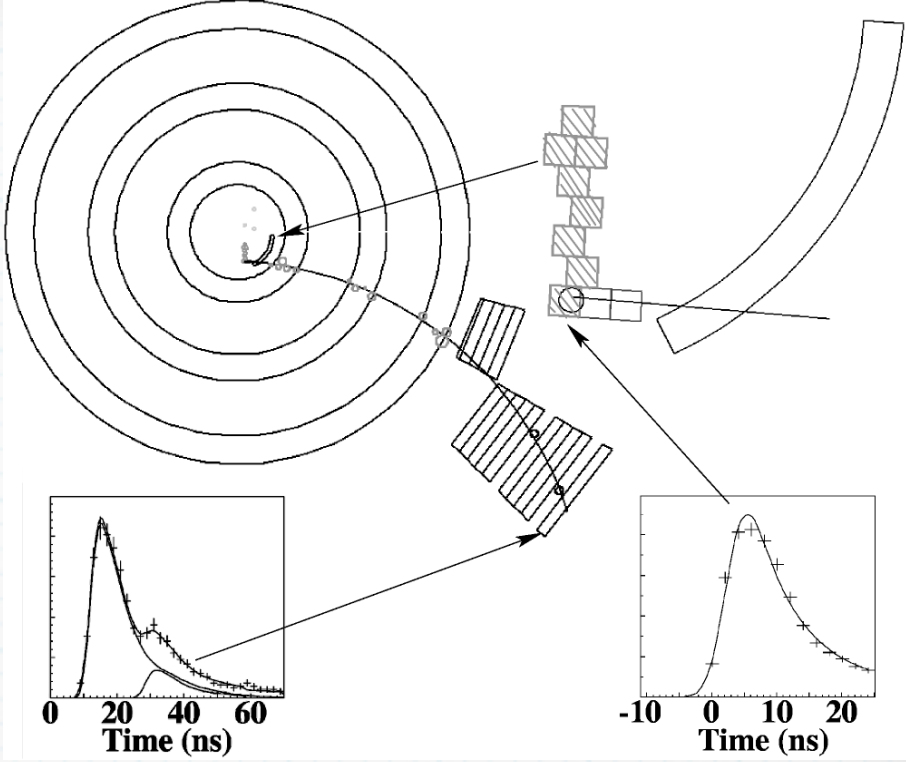
3x10-10

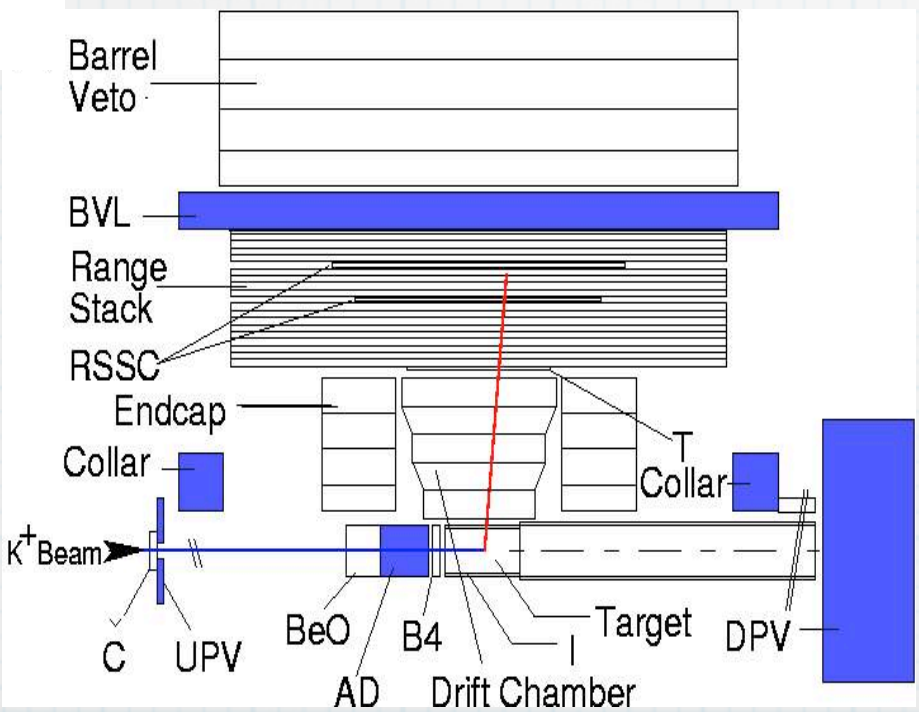
BR(K⁺ → π⁺νν)

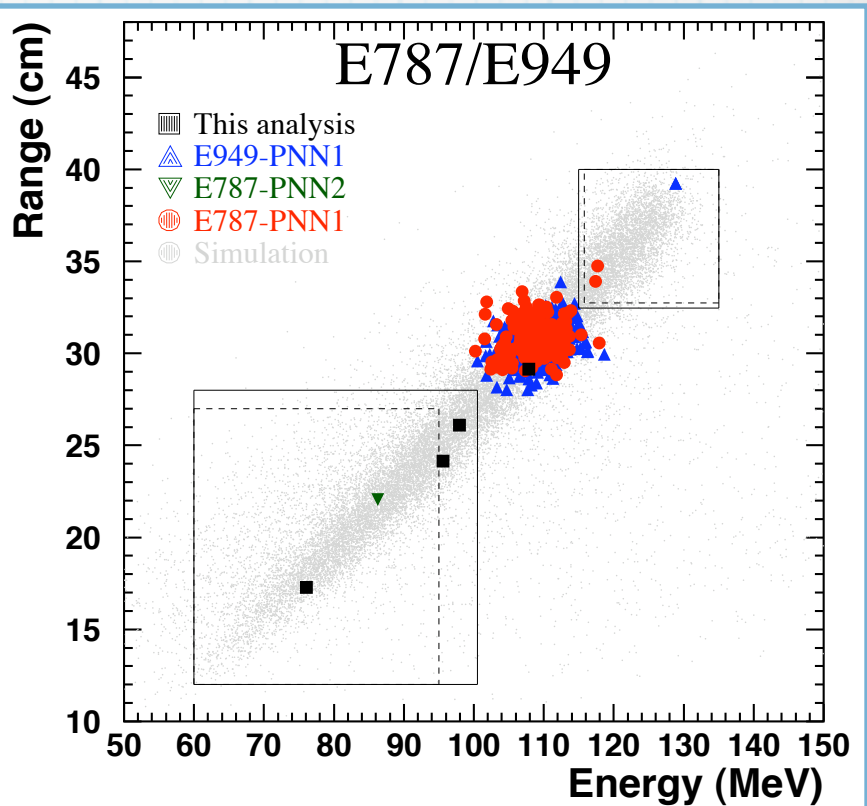
Buras et al, 1507.08762

K^+: E787+E949 Result

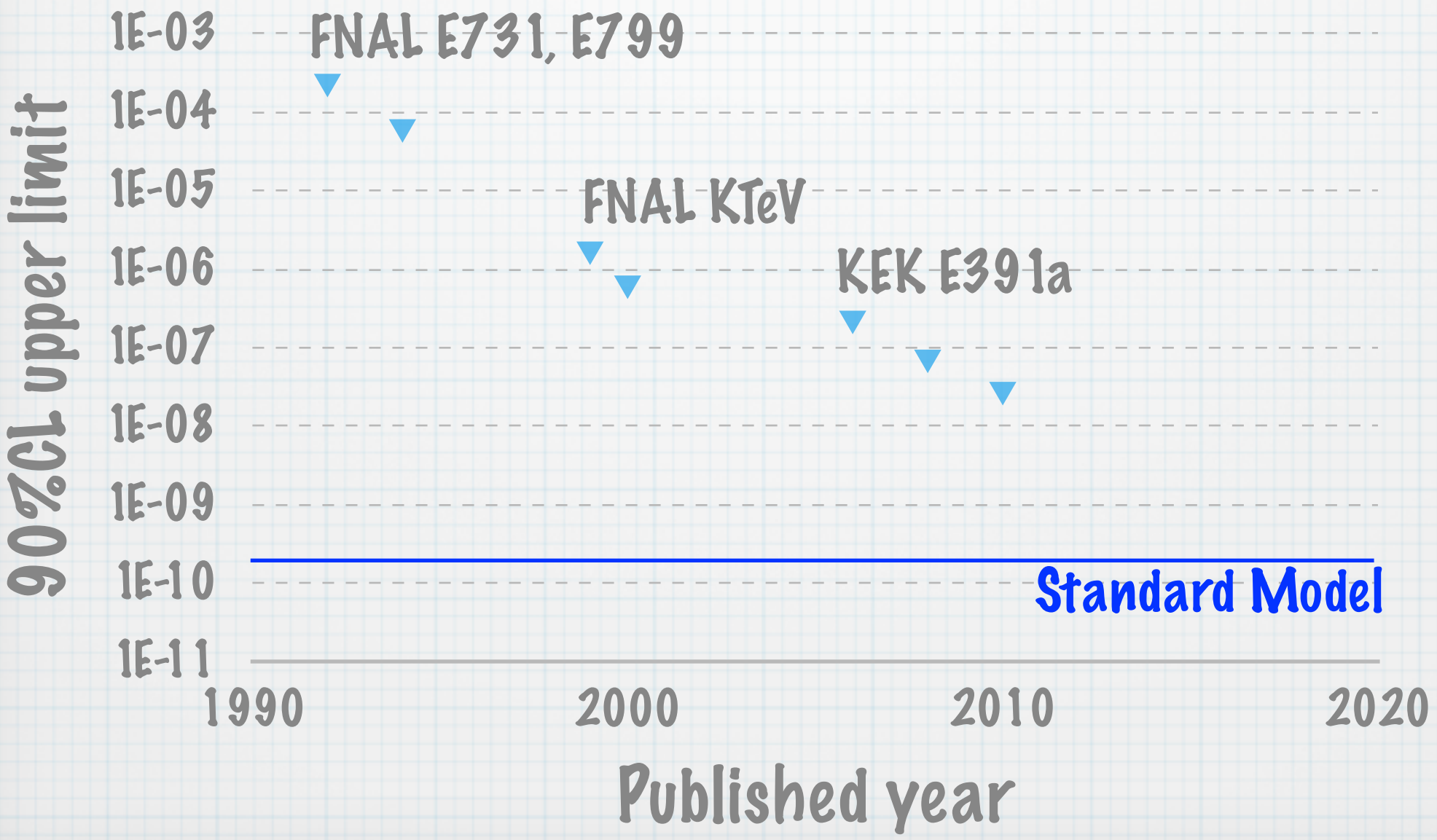
- Found 7 events
- $BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$
- PRD **79**, 092004 (2009)



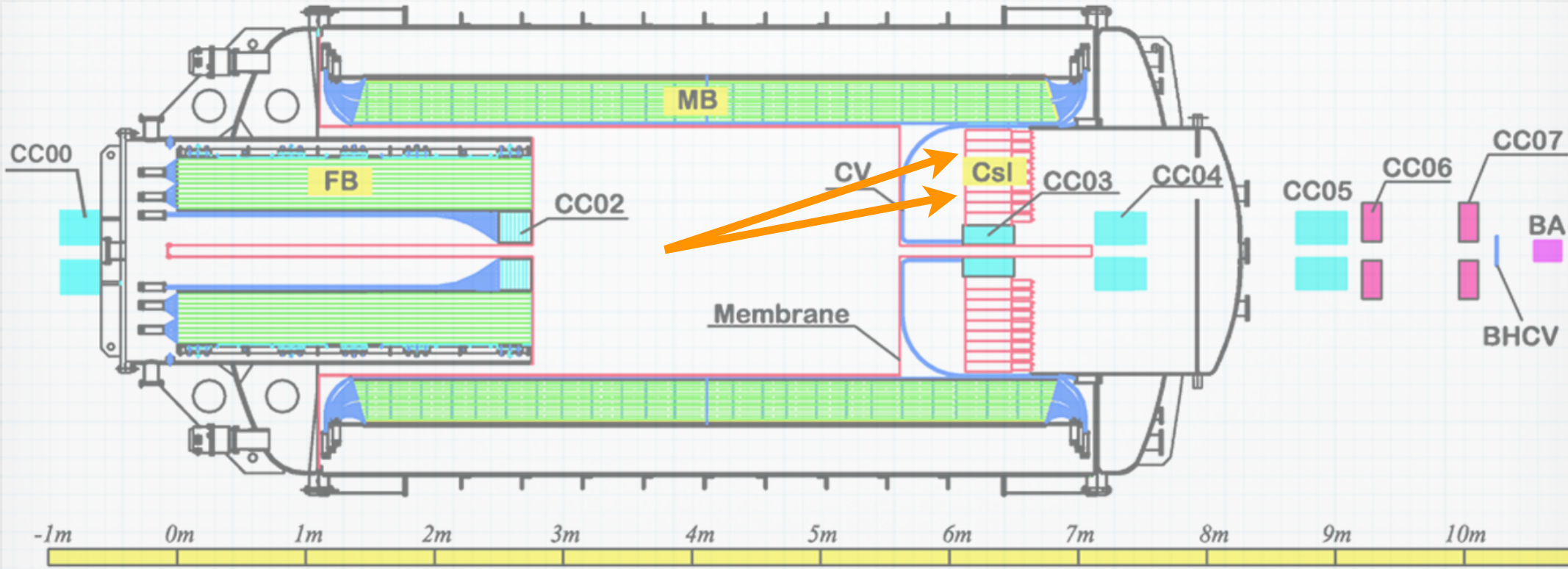




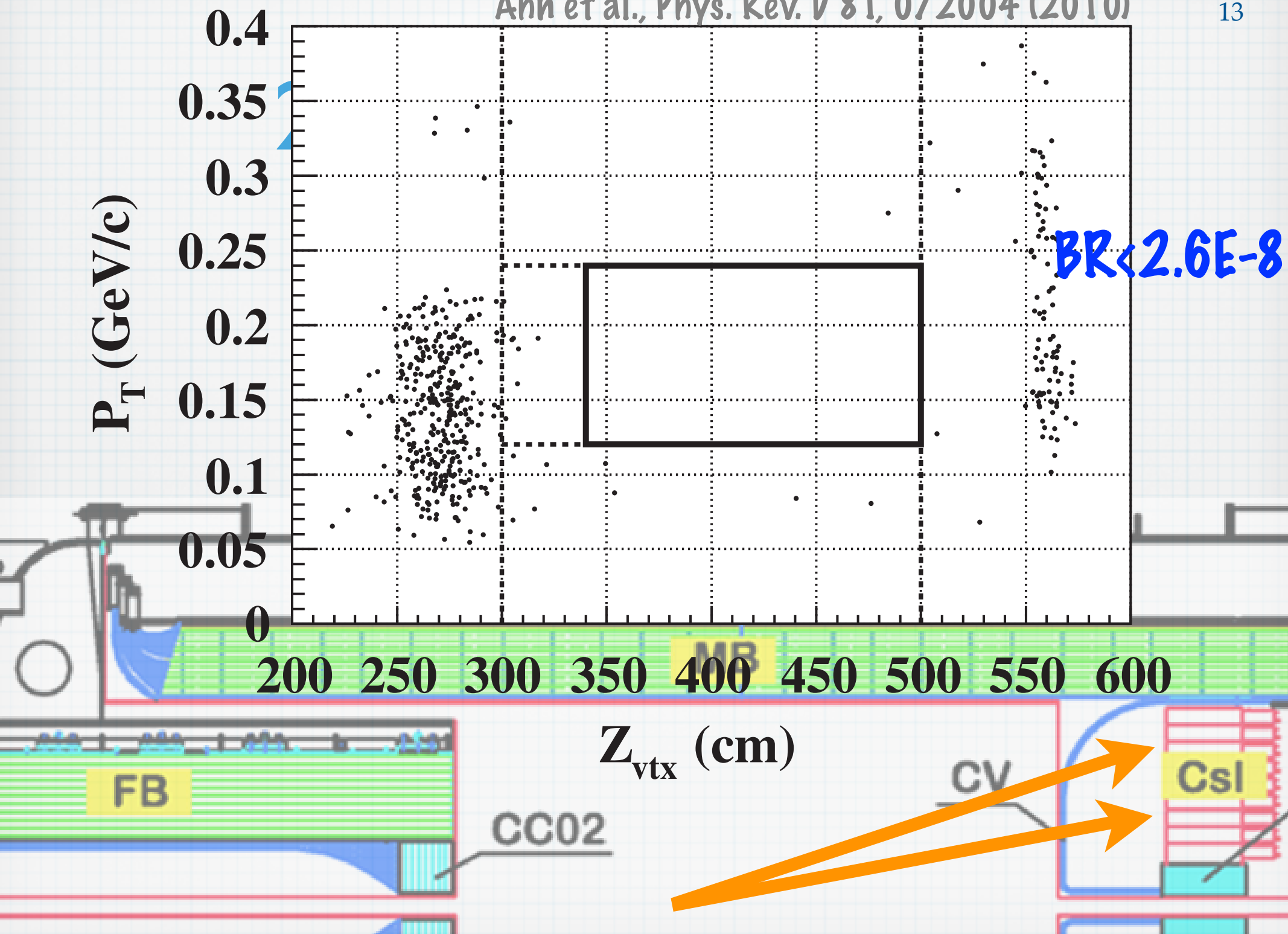
BR($K_L \to \pi^0 \nu\bar{\nu}$) limits

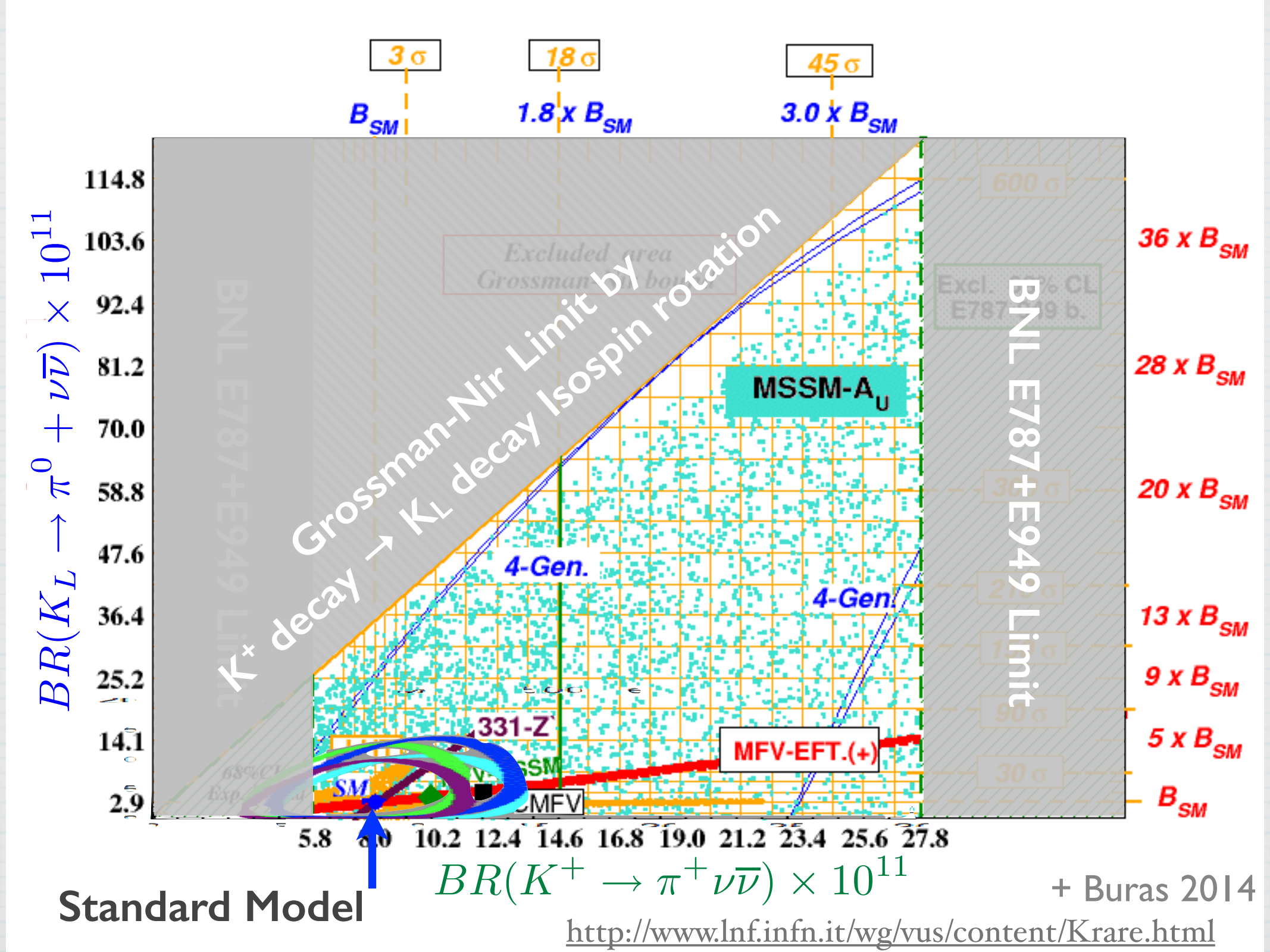


2004-2005: E391a



Ahn et al., Phys. Rev. D 81, 072004 (2010)

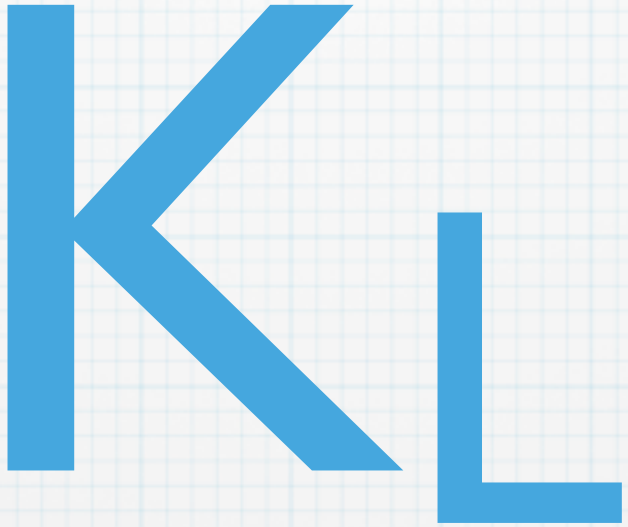




Standard Model

+ Buras 2014

http://www.lnf.infn.it/wg/vus/content/Krare.html


KL

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

J-PARC

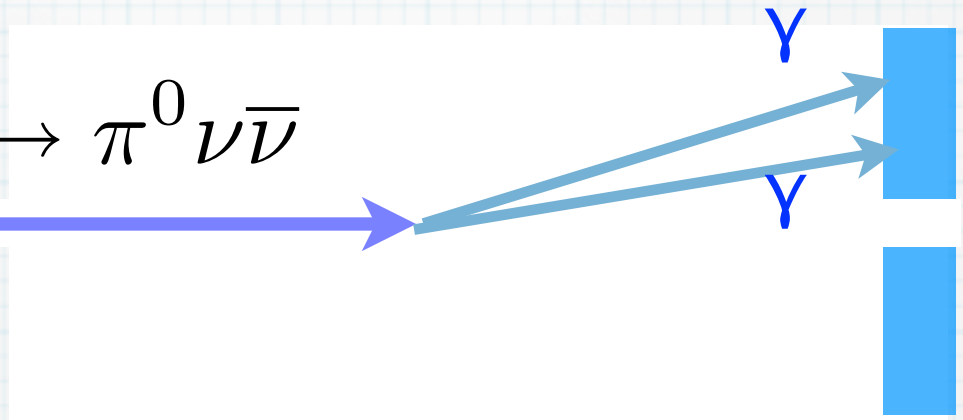
Arizona State, Chicago, Chonbuk, Jeju, KEK, Korea, Kyoto,
Michigan, NDA, NTU, Osaka, Okayama, Saga, Yamagata

J-PARC in Japan

Signal and Background

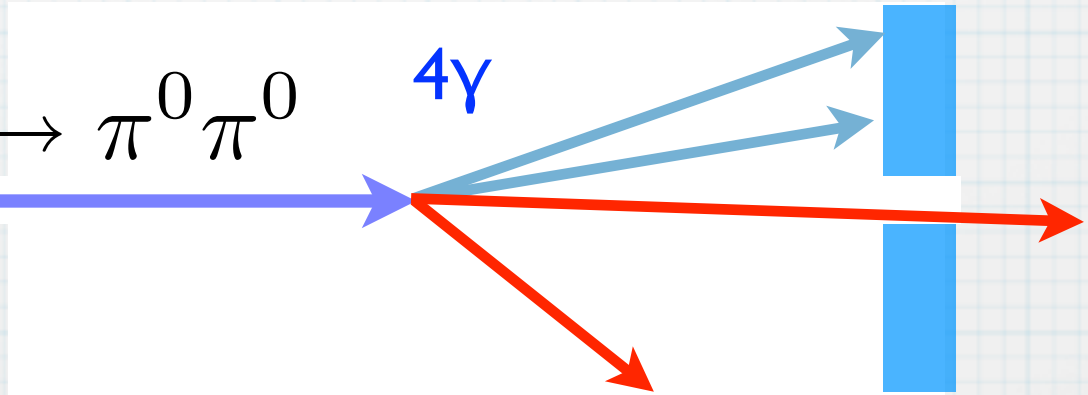
* Signal:

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



* Background

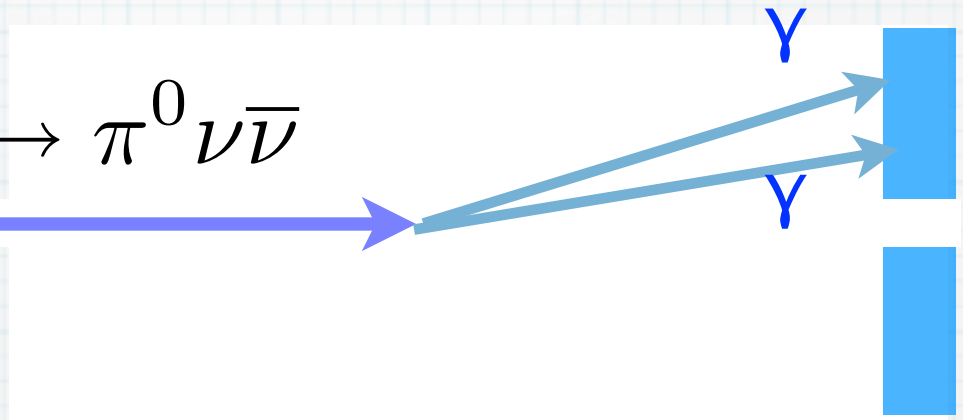
$$K_L \to \pi^0 \pi^0$$



Signal and Background

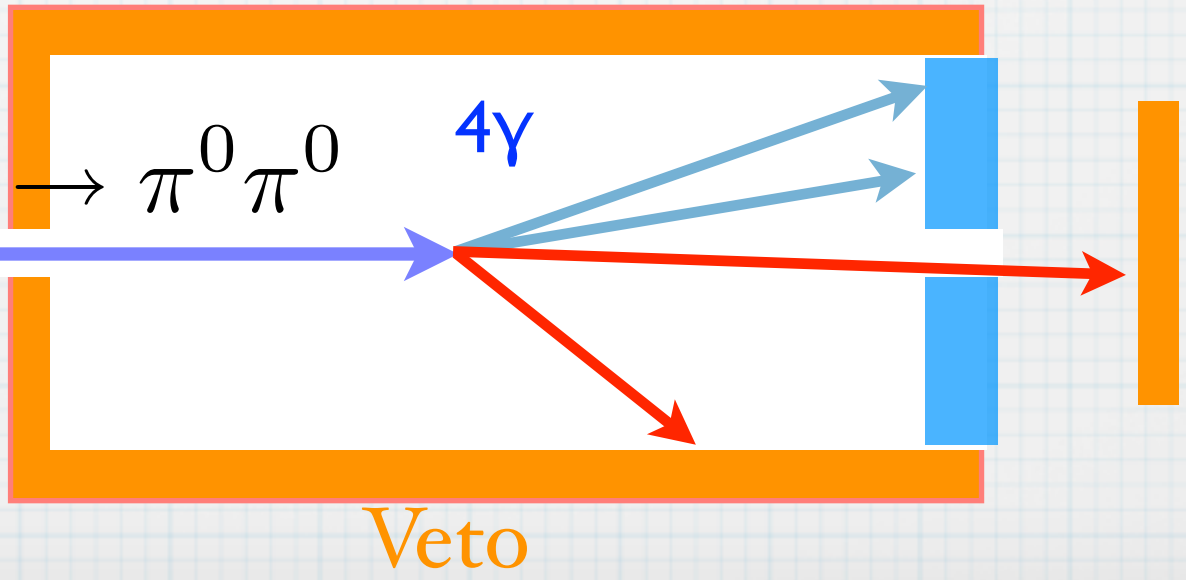
* Signal:

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



* Background

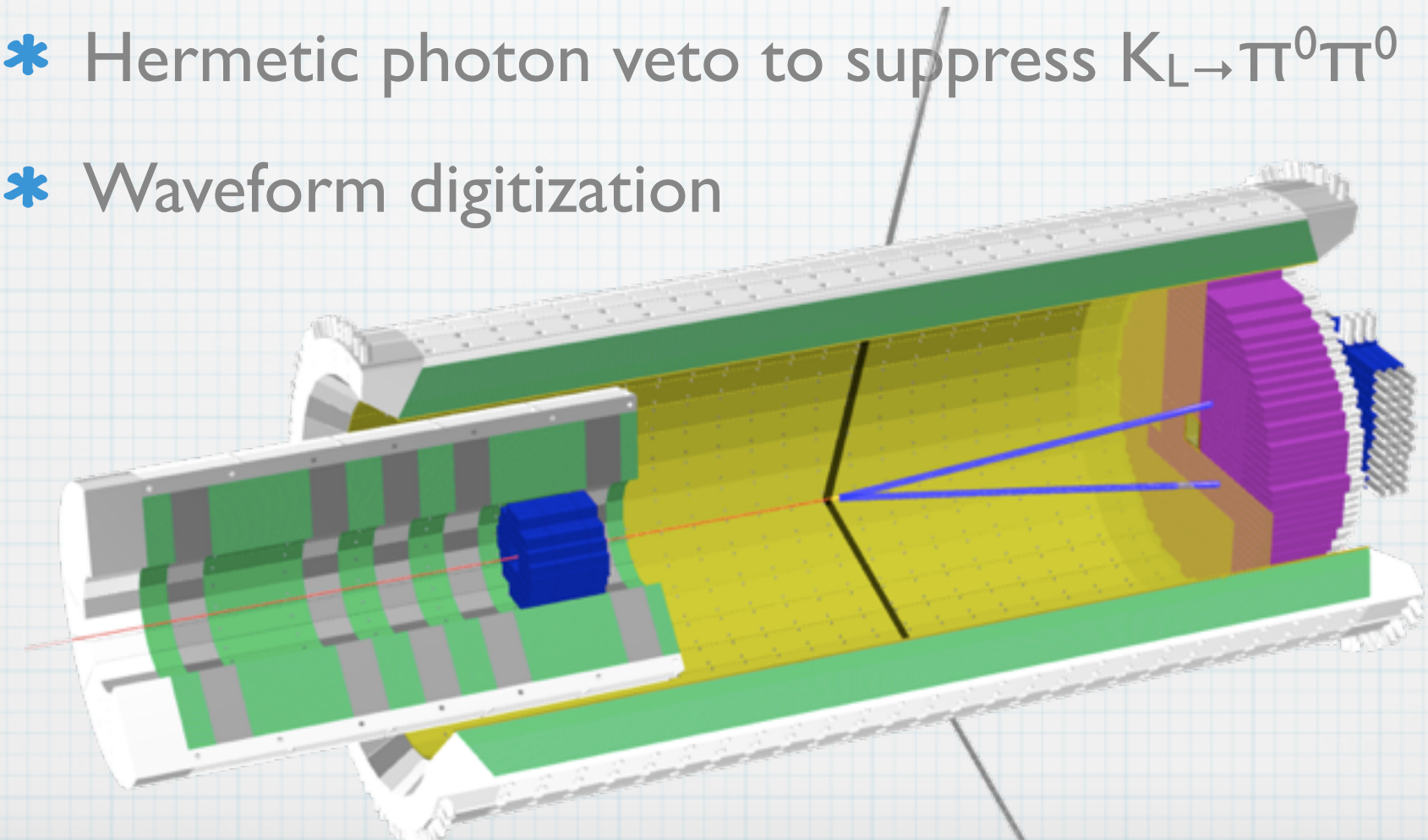
$K_L \to \pi^0 \pi^0$

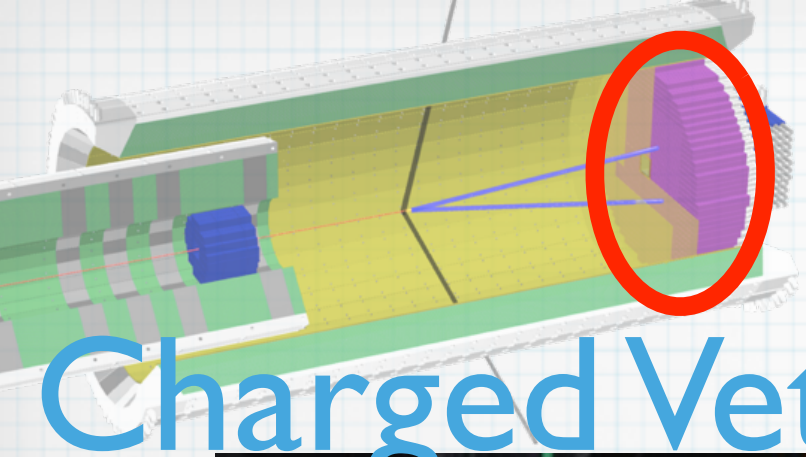


J-PARC KOTO

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

- CsI calorimeter from KTeV
- Hermetic photon veto to suppress $K_L \to \pi^0\pi^0$
- Waveform digitization

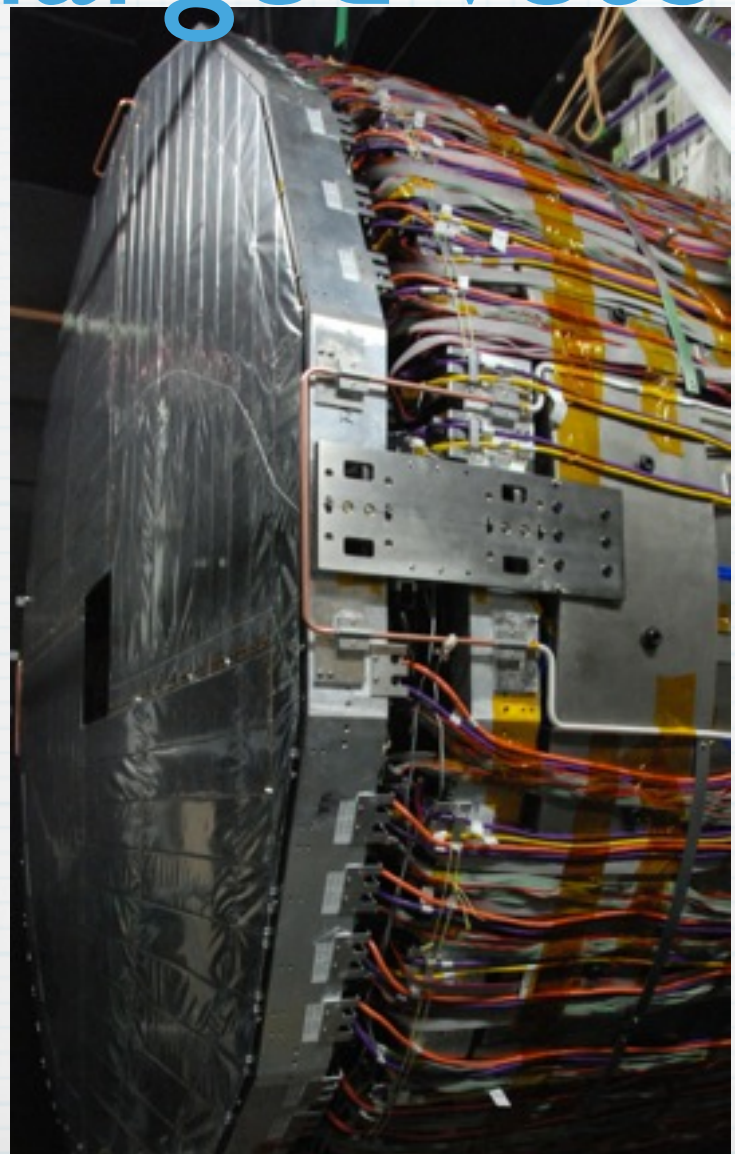




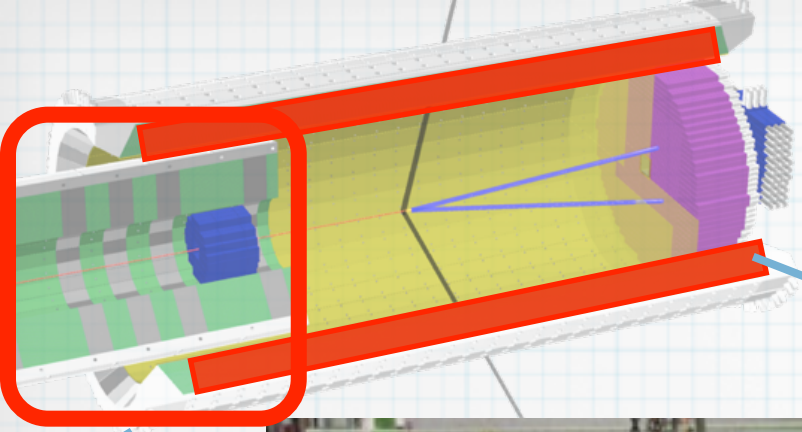
CsI Calorimeter

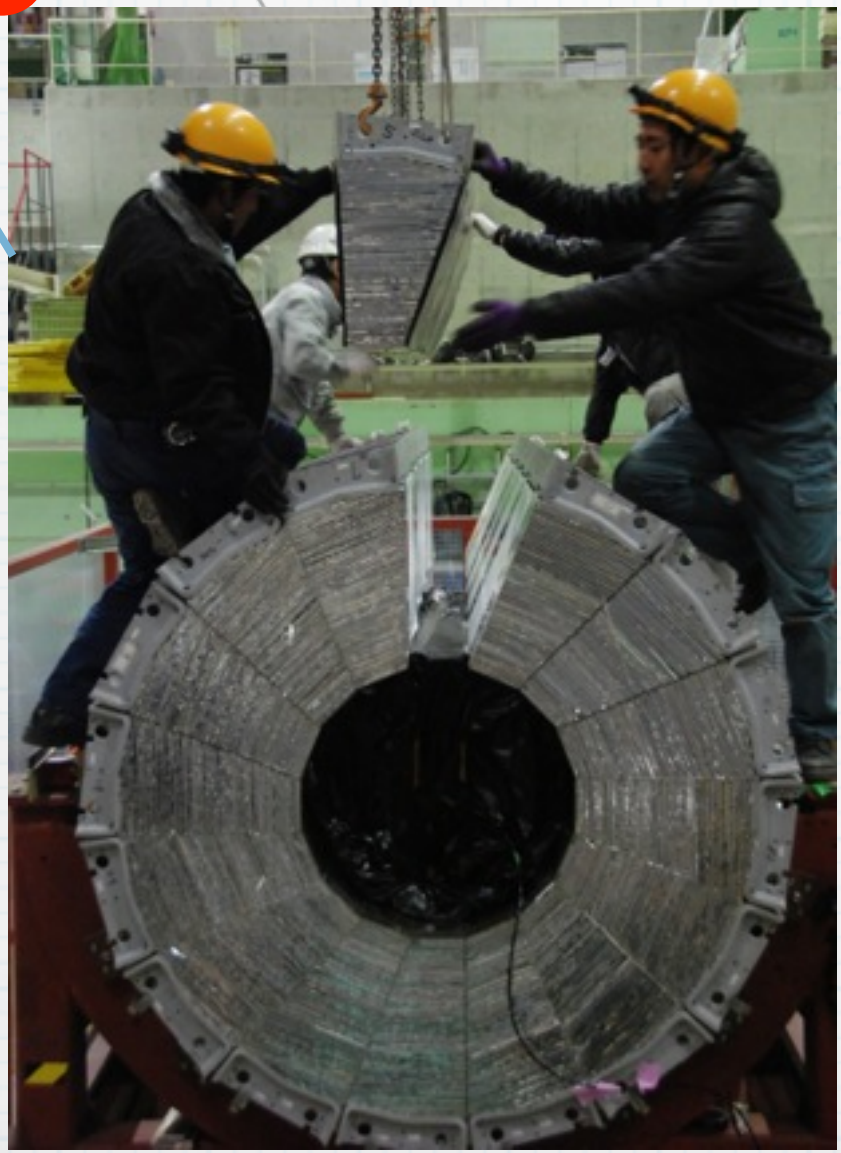
Charged Veto

Brought FNAL KTeV CsI

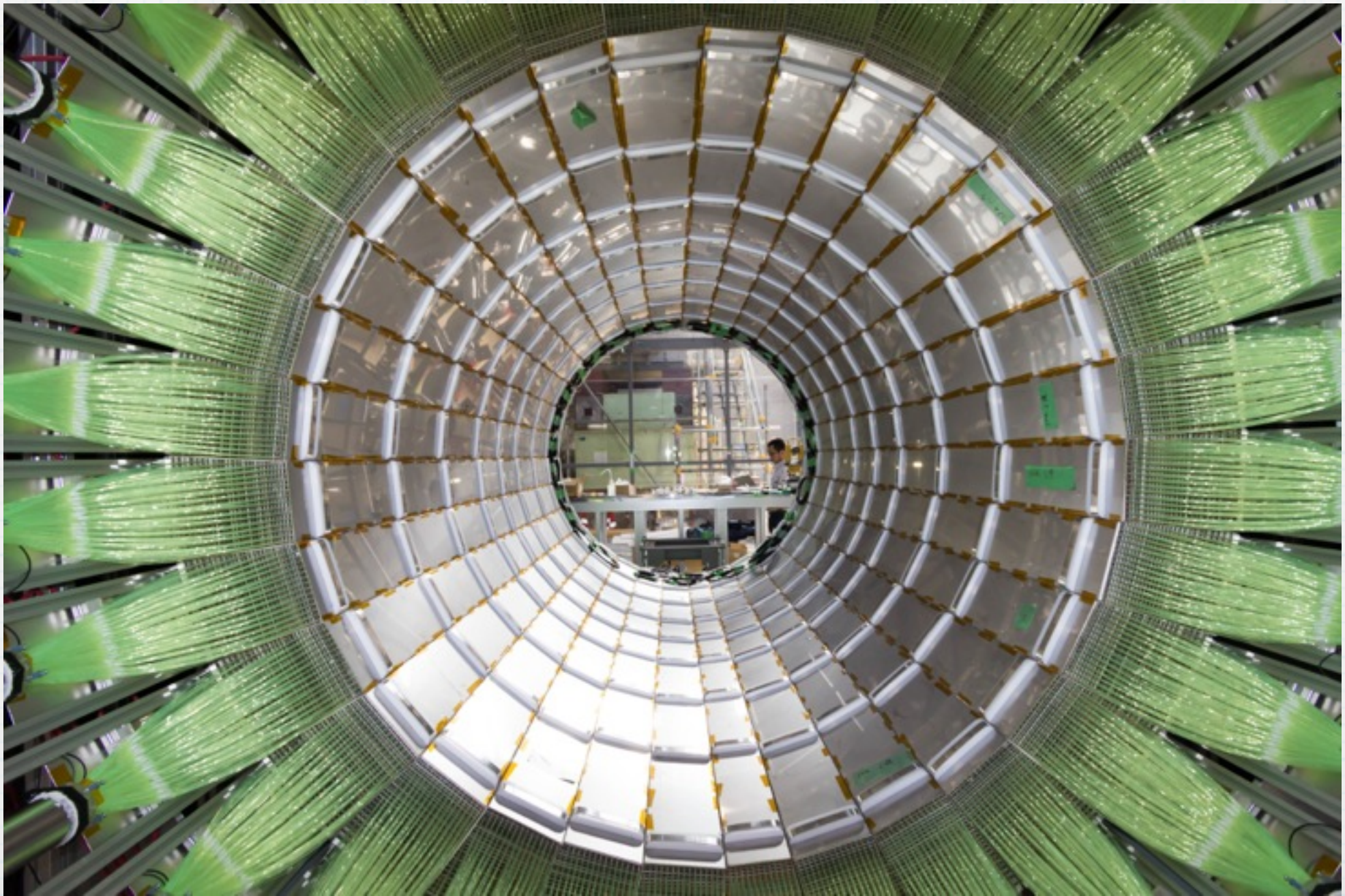


Main Barrel Photon Veto



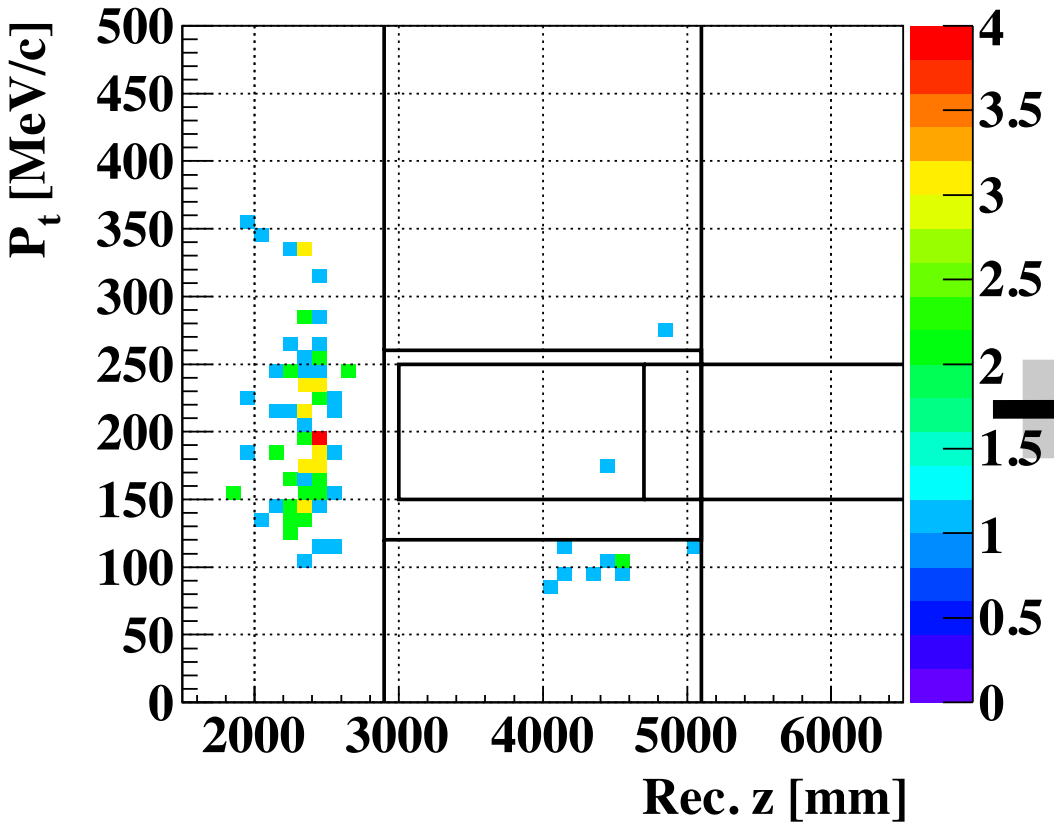


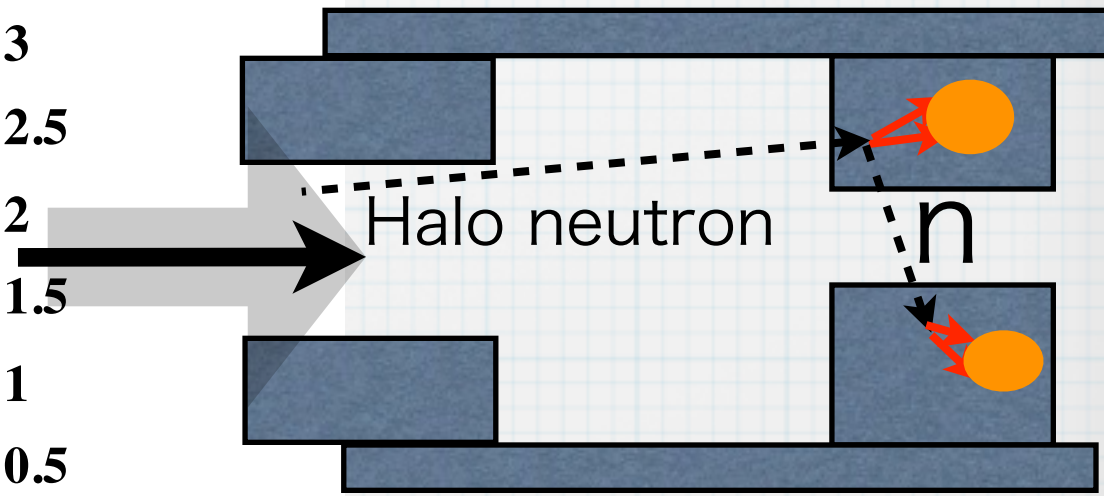
New additional γ veto



2013 Run

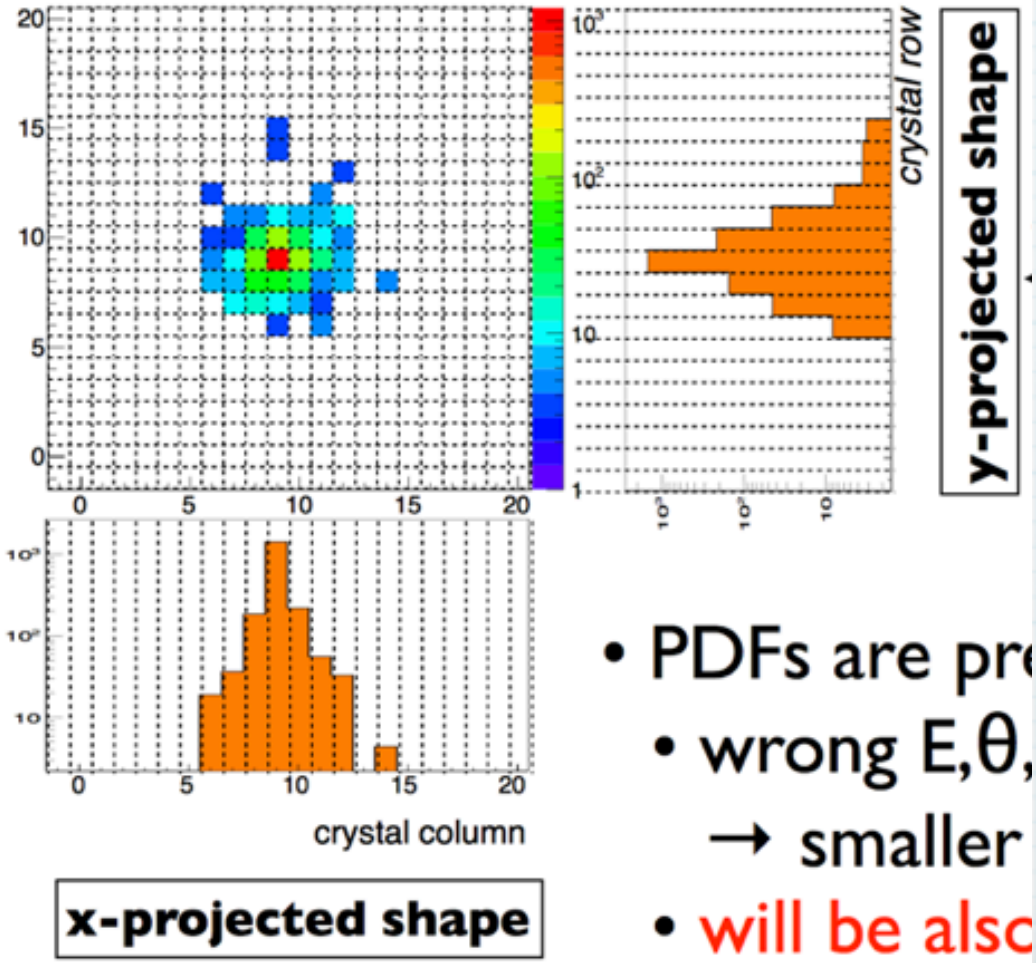
* Took data for 100 hours
* Sensitivity equivalent to E391a
* 1 background event by halo neutron interaction





Suppression of neutron background

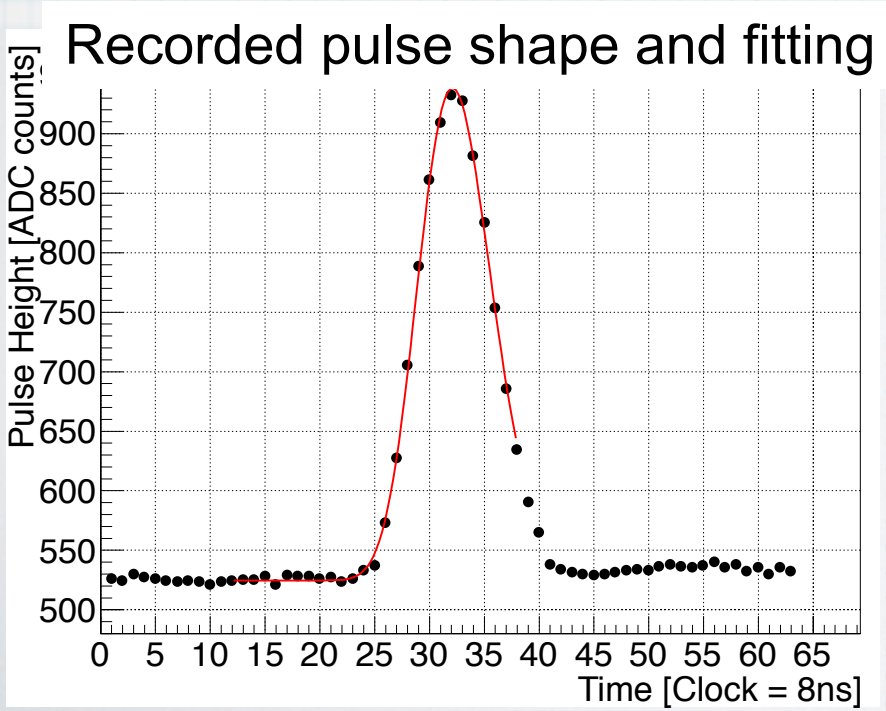
* x1/3 by shower shape



* x1/10 by pulse shape

$$A(t) = |A| \exp\left(-\frac{(t-t_0)^2}{2\sigma(t)^2}\right),$$

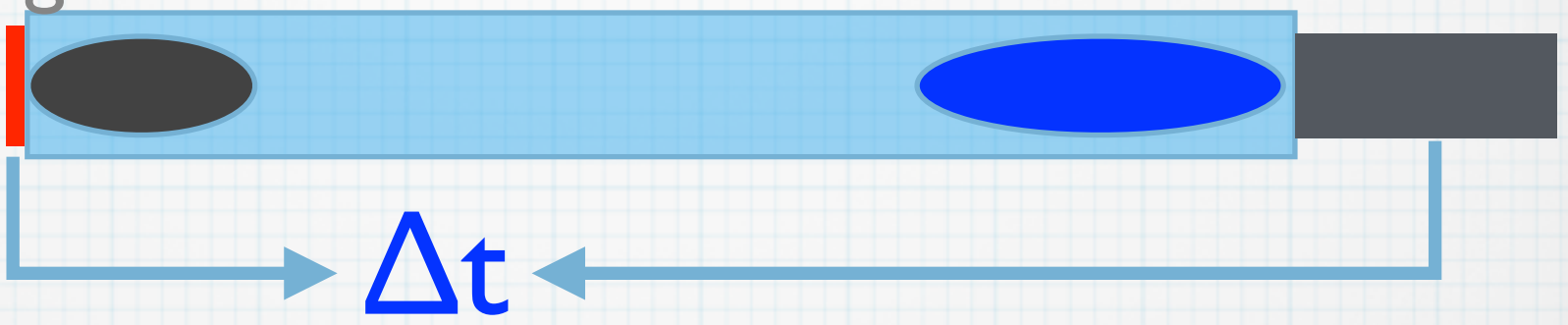
$$\sigma(t) = \sigma_0 + a(t - t_0)$$

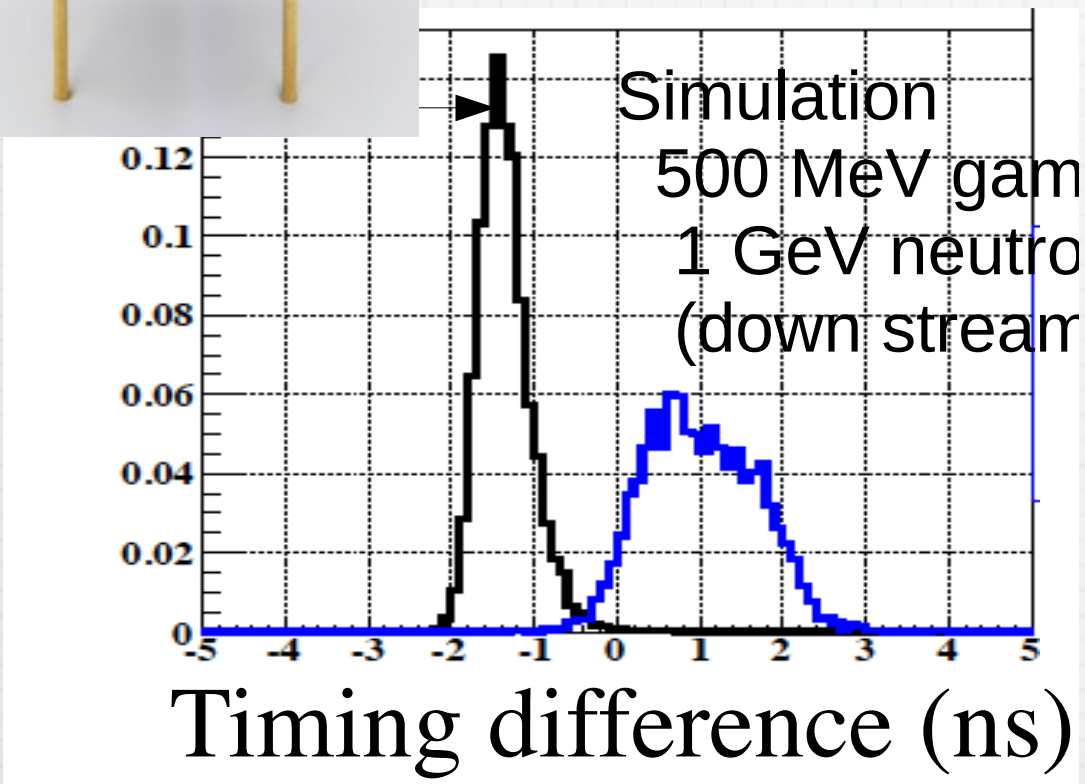


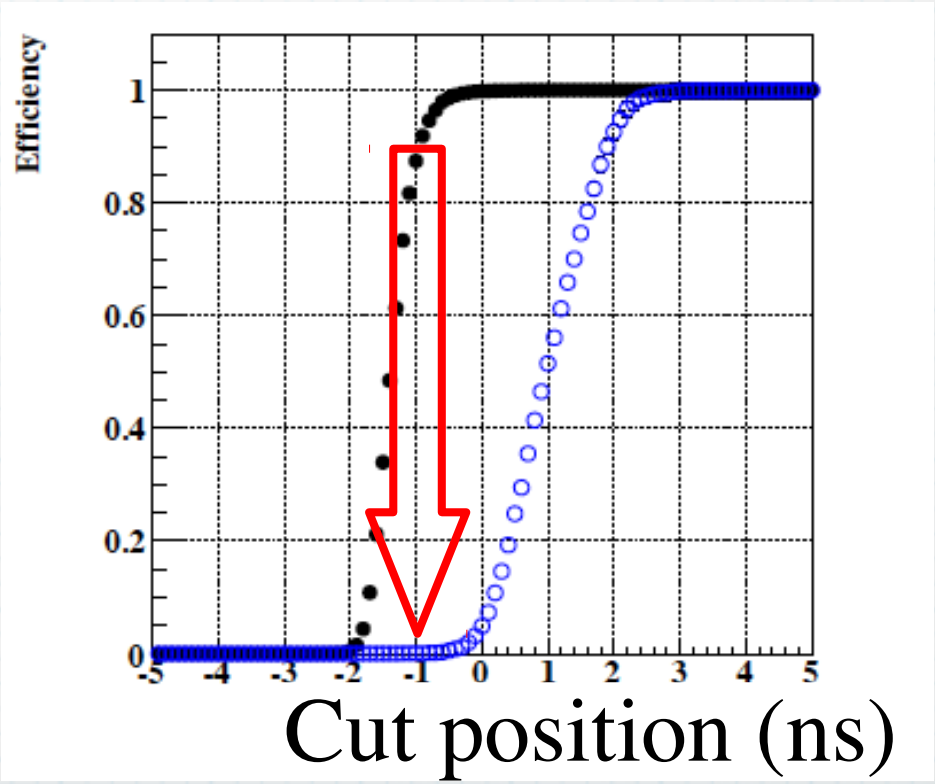
Neutron background

* x1/10 by shower depth

MPPC in front

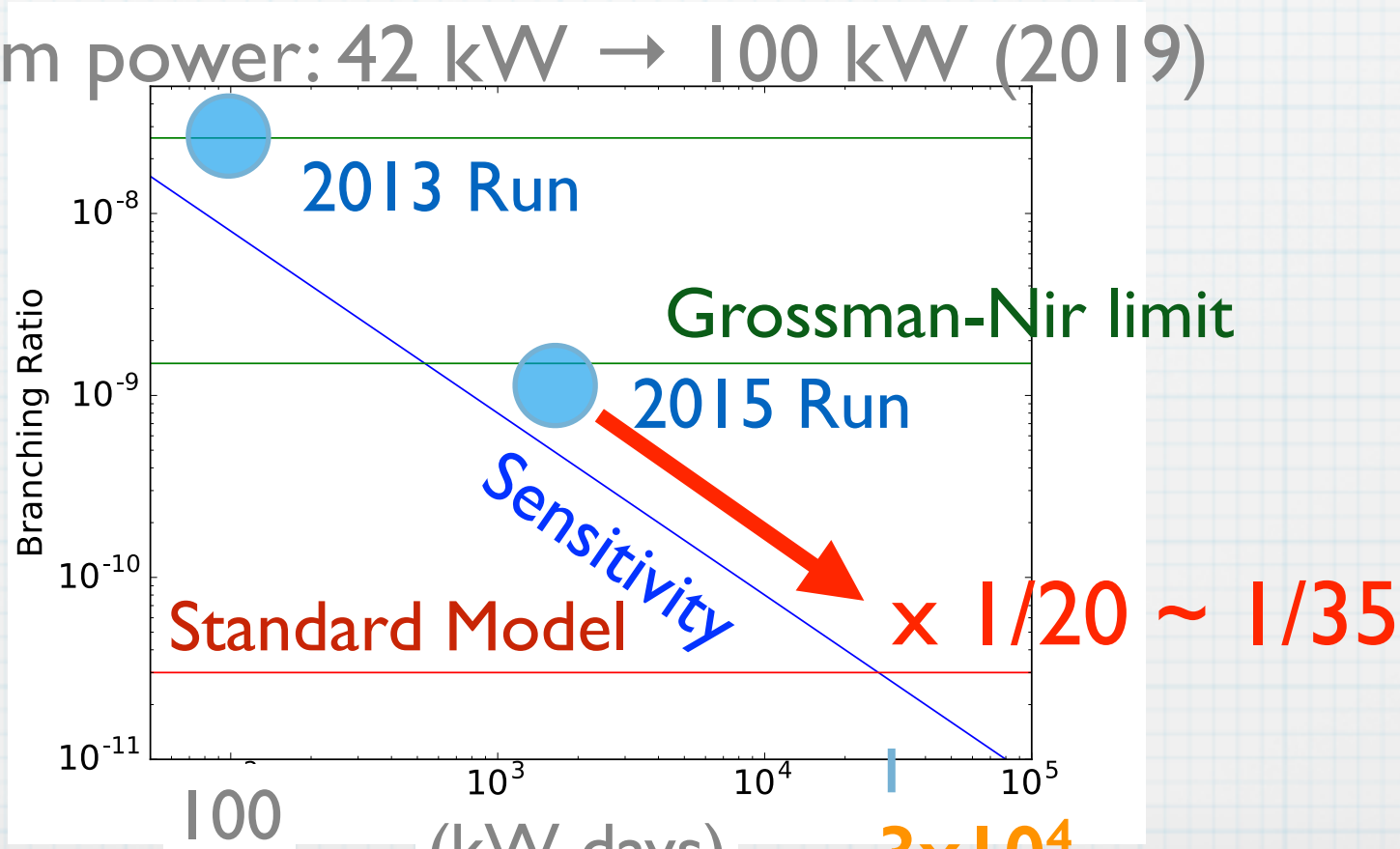


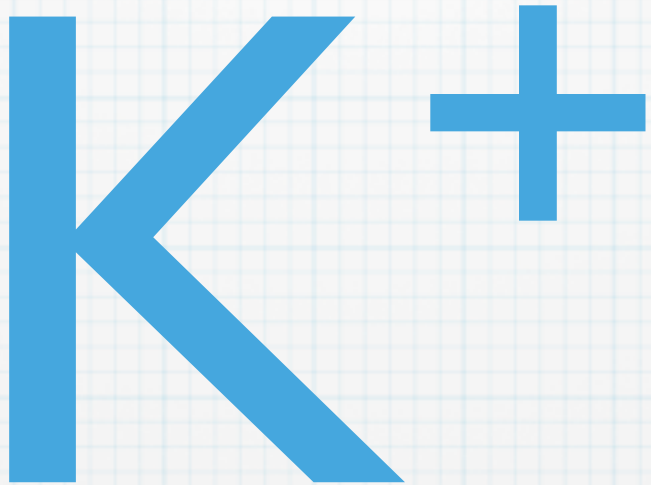




Prospect of KOTO

* 2015: Took x20 data than 2013 run
* 2016: Running now
* 2018: Add MPPCs on CsI calorimeter
* Beam power: 42 kW → 100 kW (2019)




K+

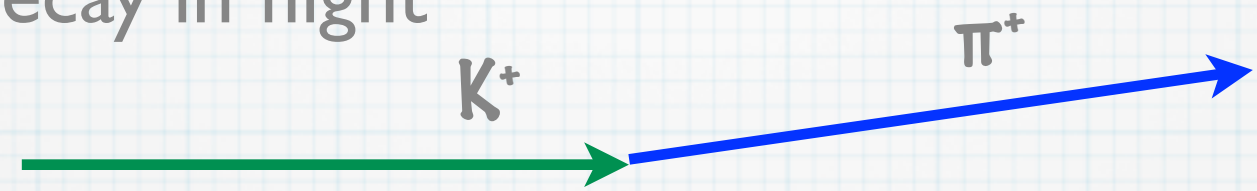
$$K^+ \to \pi^+ \nu\bar{\nu}$$

CERN

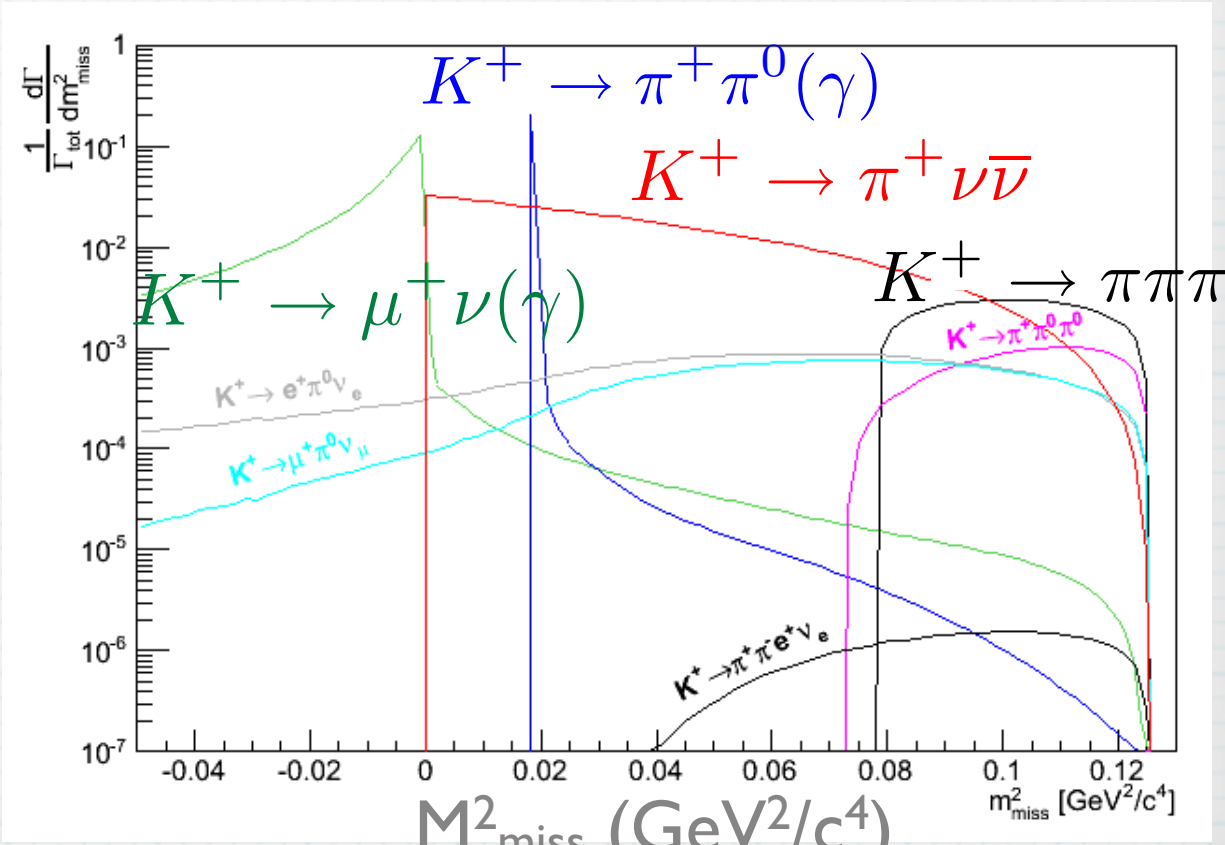
CERN NA62

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

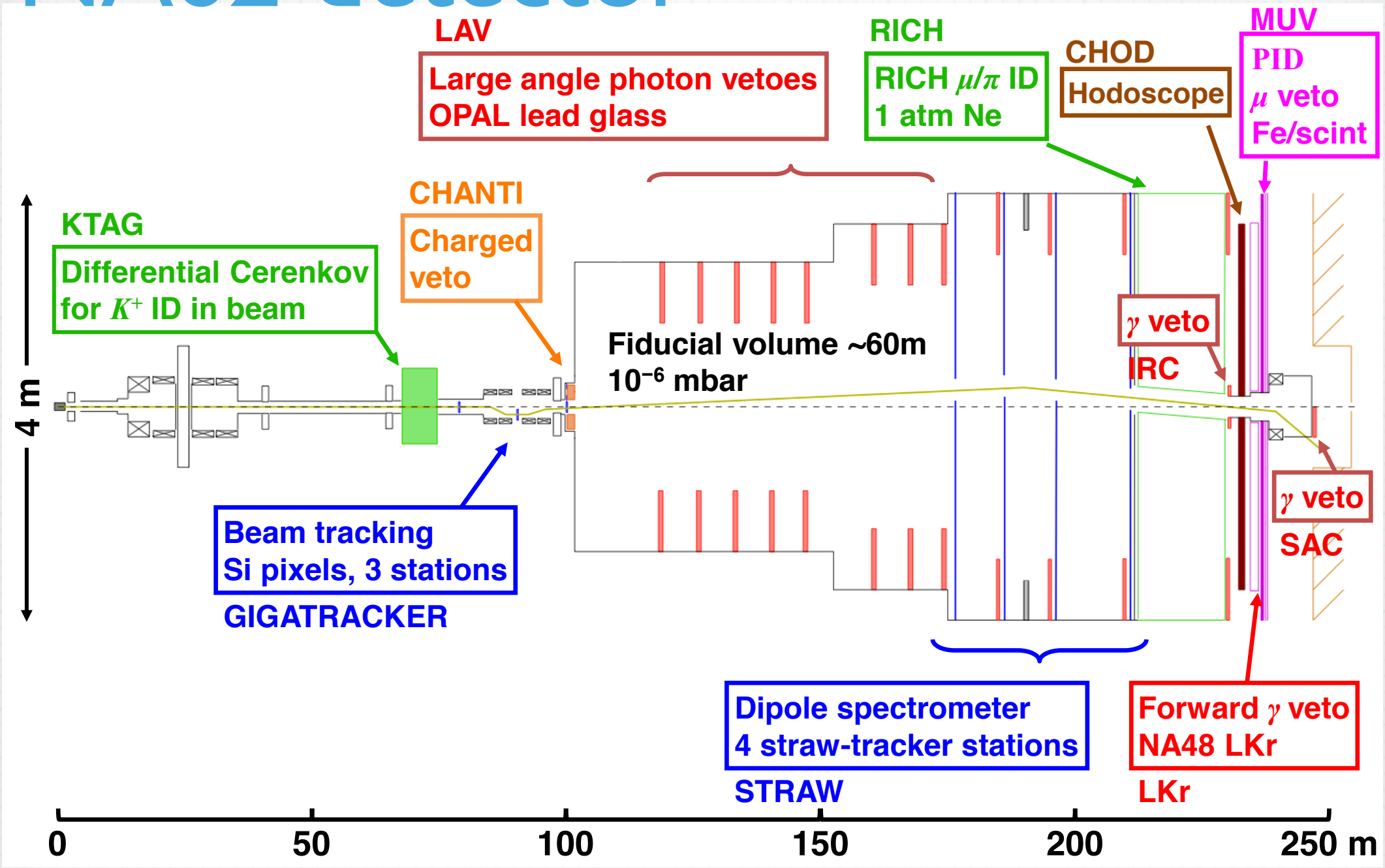
- Decay in flight



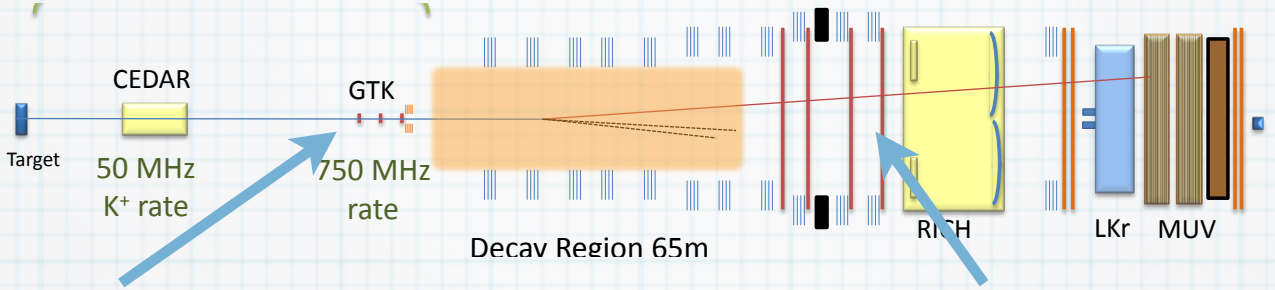
- Missing mass
- Good tracking
- Particle ID
- Photon Veto to suppress $K^+ \to \pi^+\pi^0$



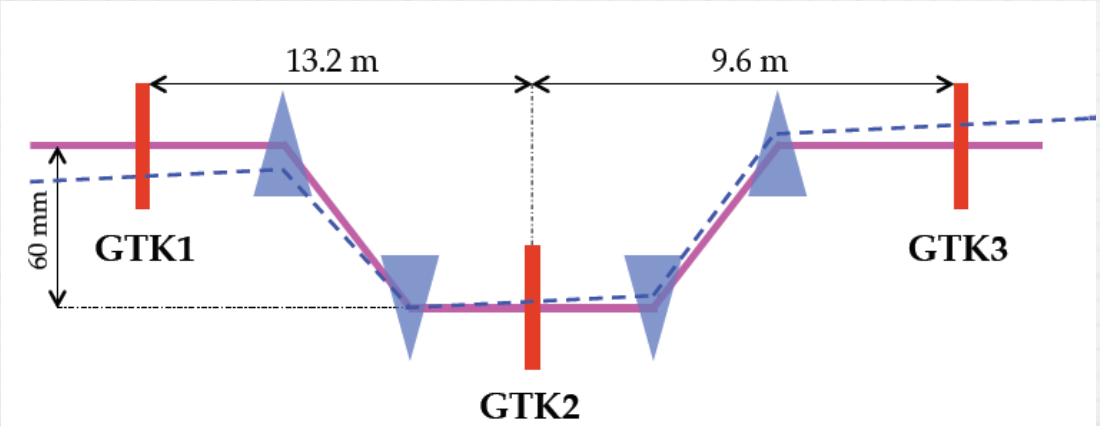
NA62 detector

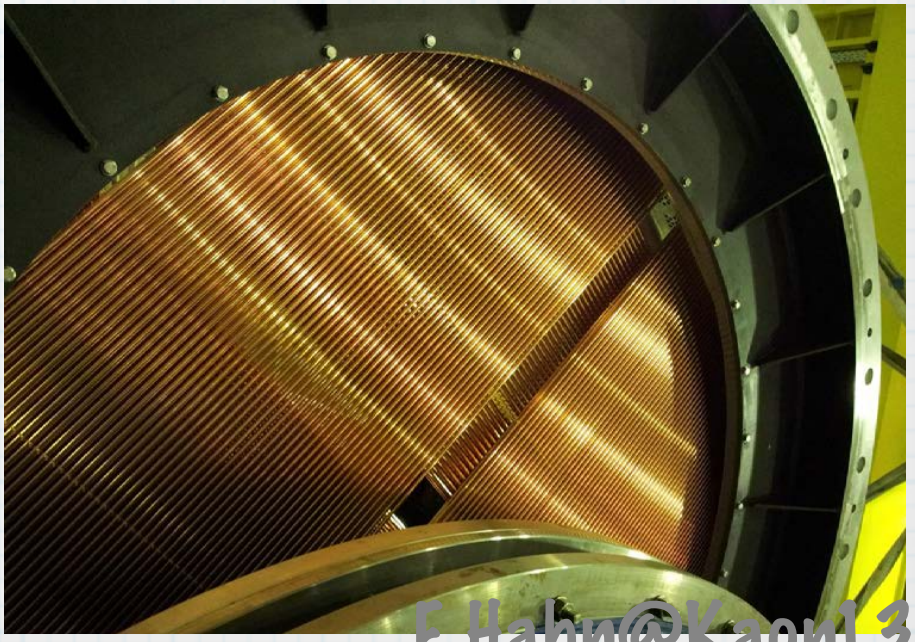


CERN NA62 trackers



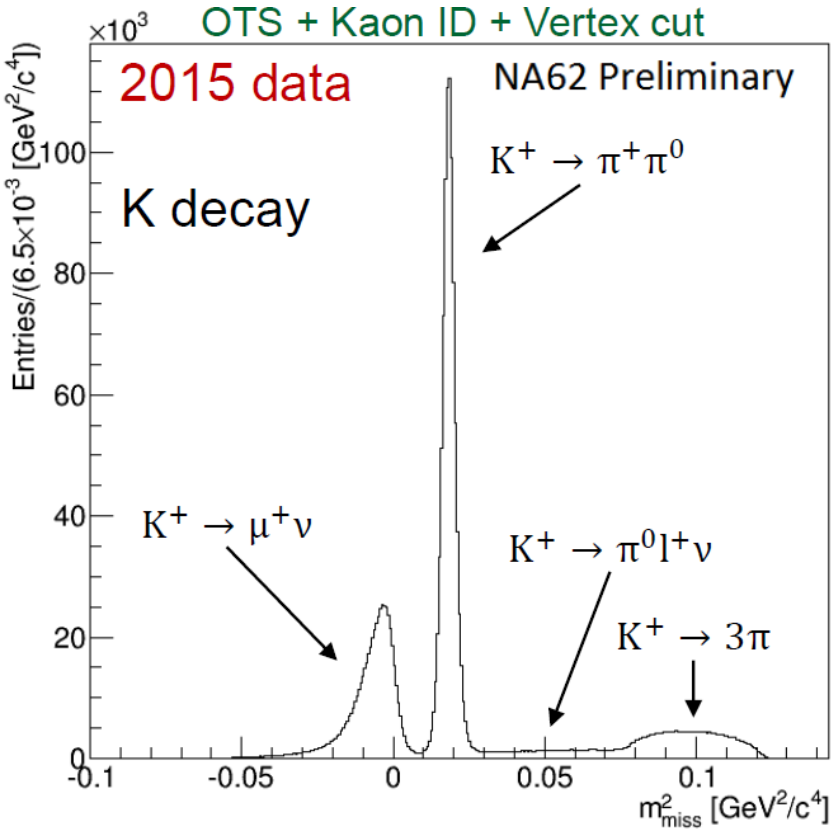
- For K^+
  - 300μm pixels
  - $\Delta\theta \sim 0.016$mrad
  - $\Delta t \sim 200$ps
- For π^+
  - straw tracker
  - $\Delta x \sim 140\mu$m

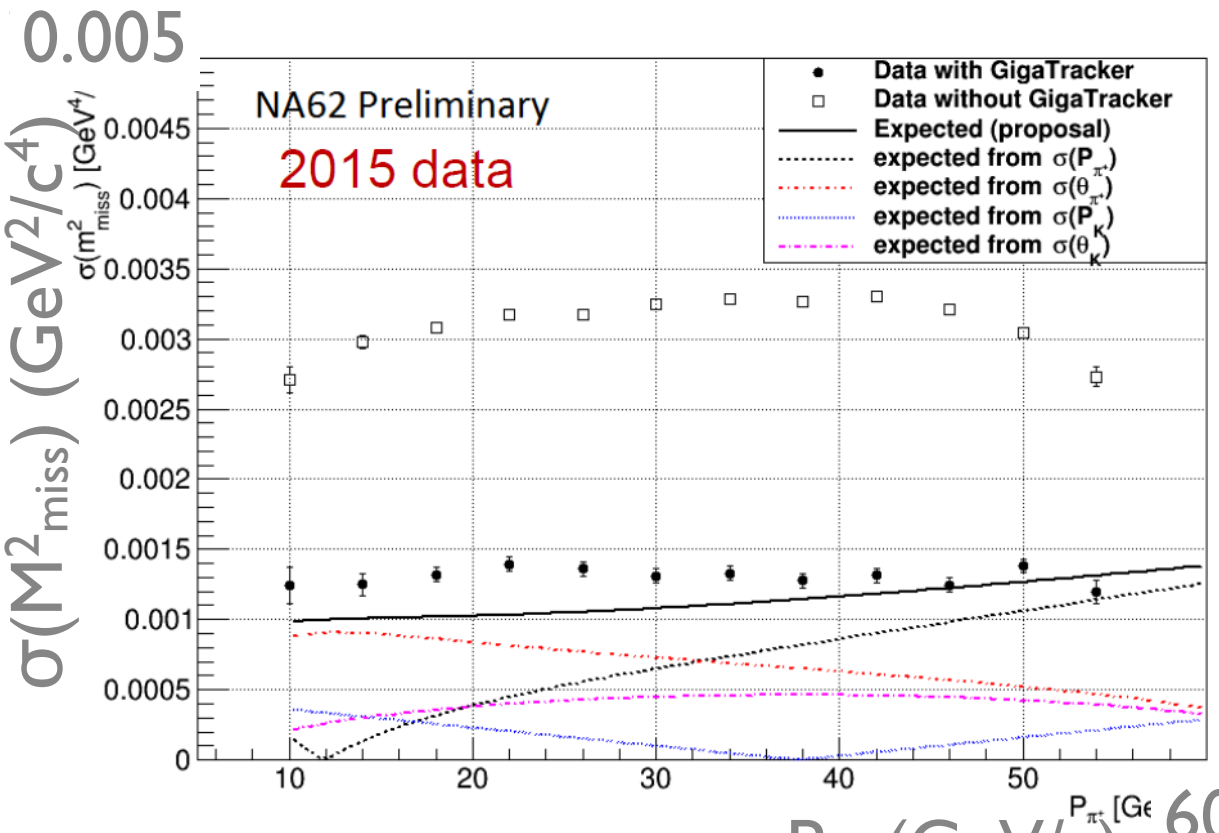




Missing Mass resolution

* Close to the design

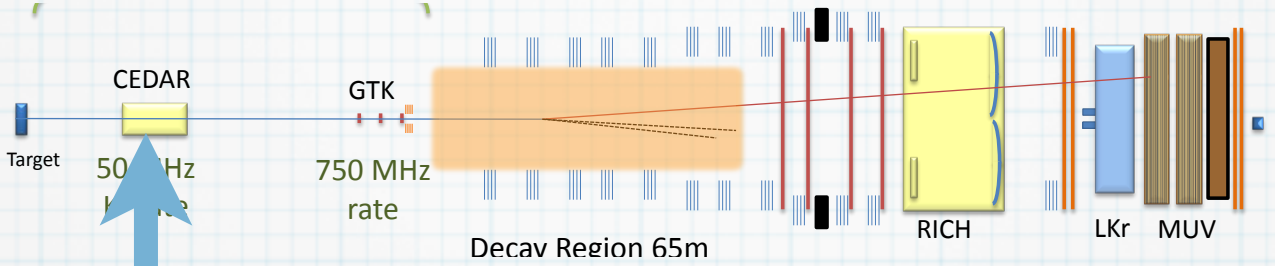


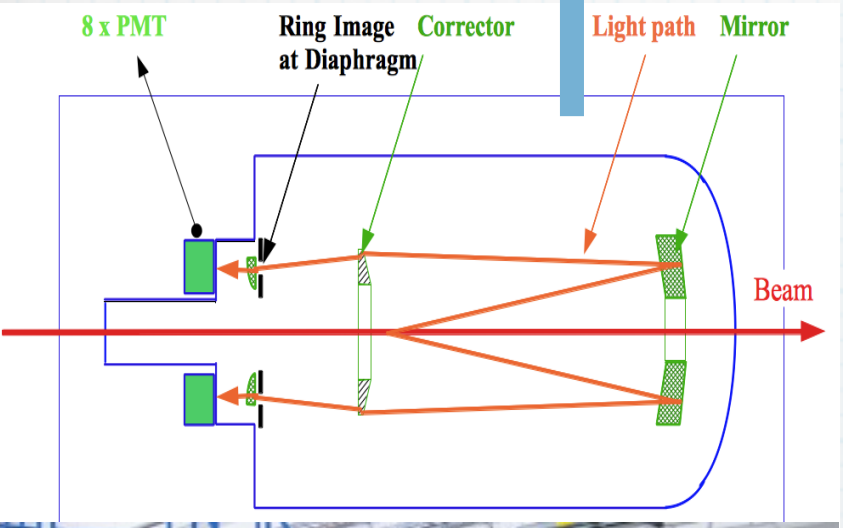


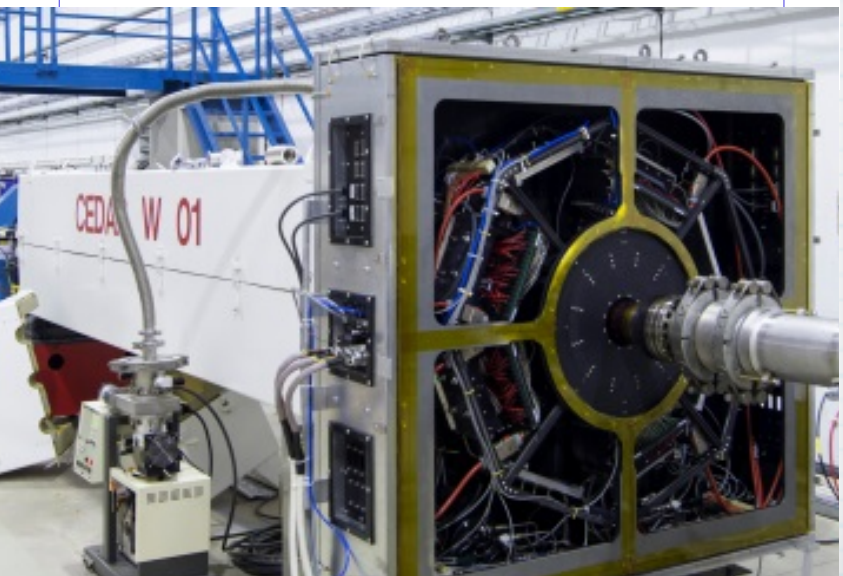
M$^2_{miss}$ (GeV^2/c^4)

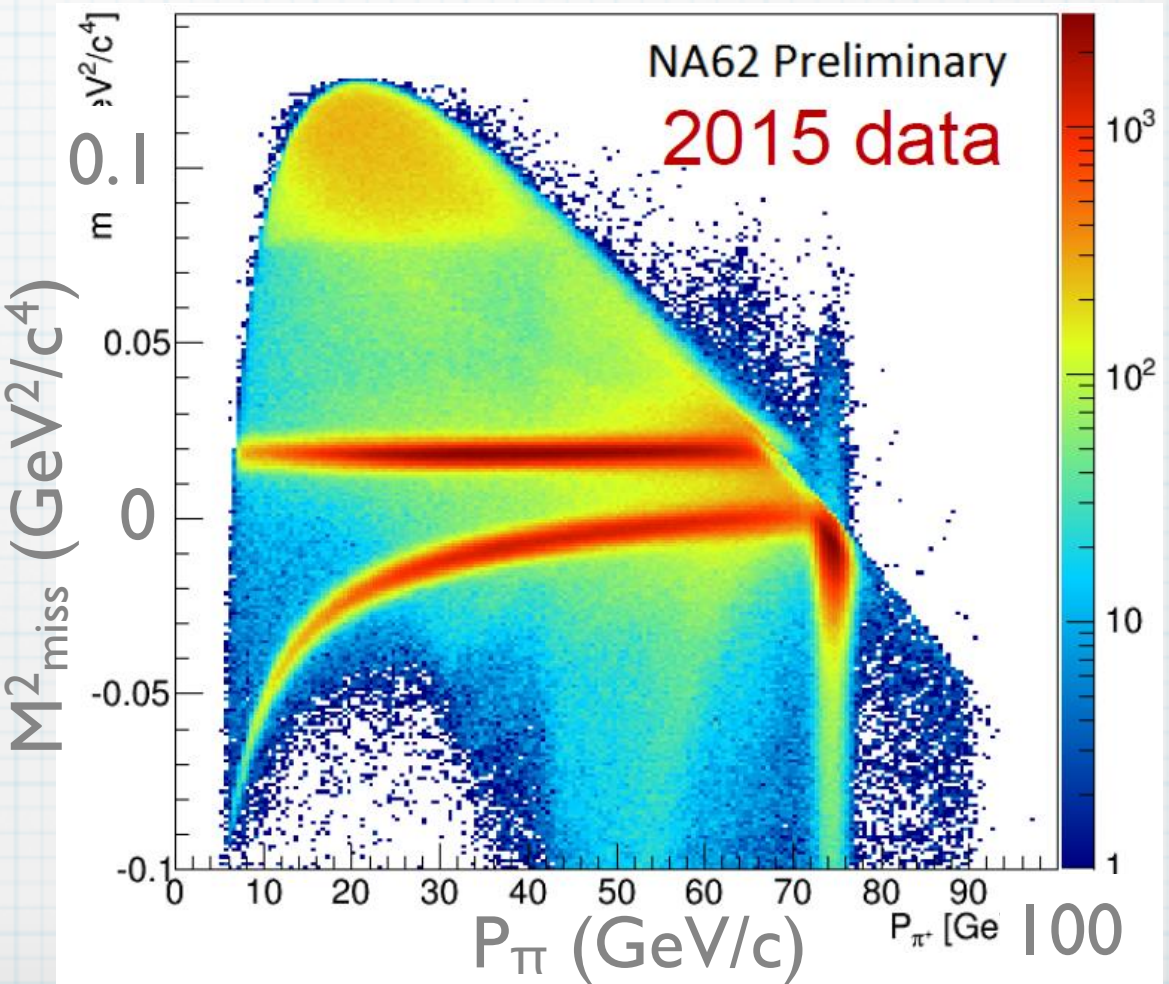
M. Mirra @HQL2016

CERN NA62 K^+ ID

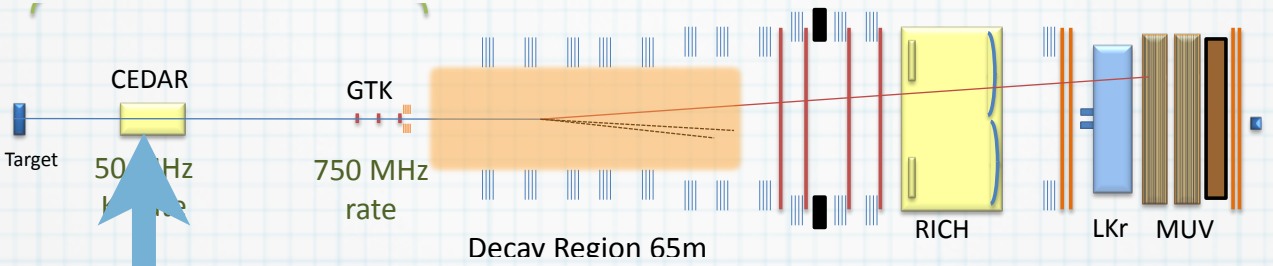


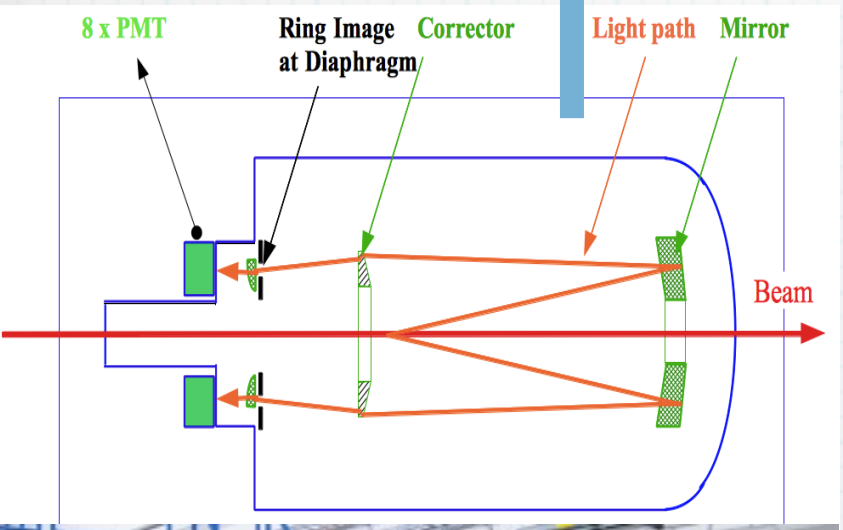


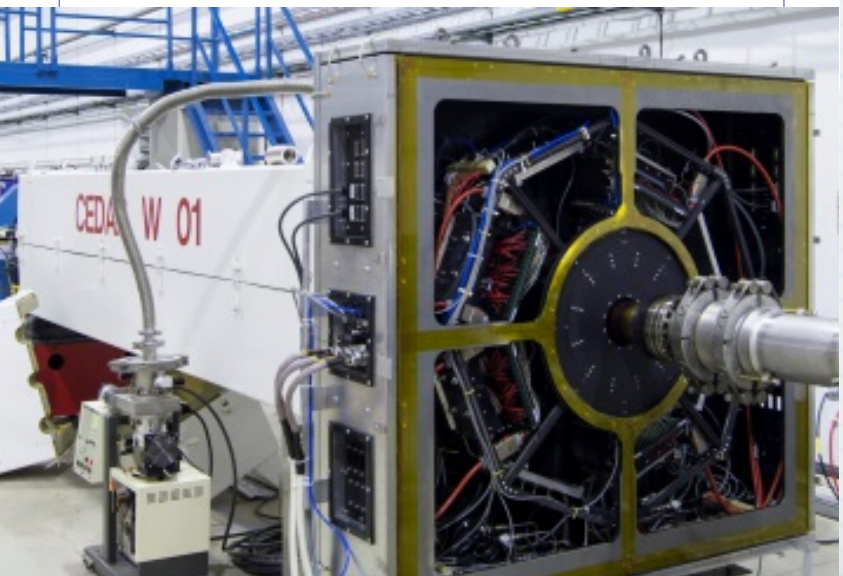


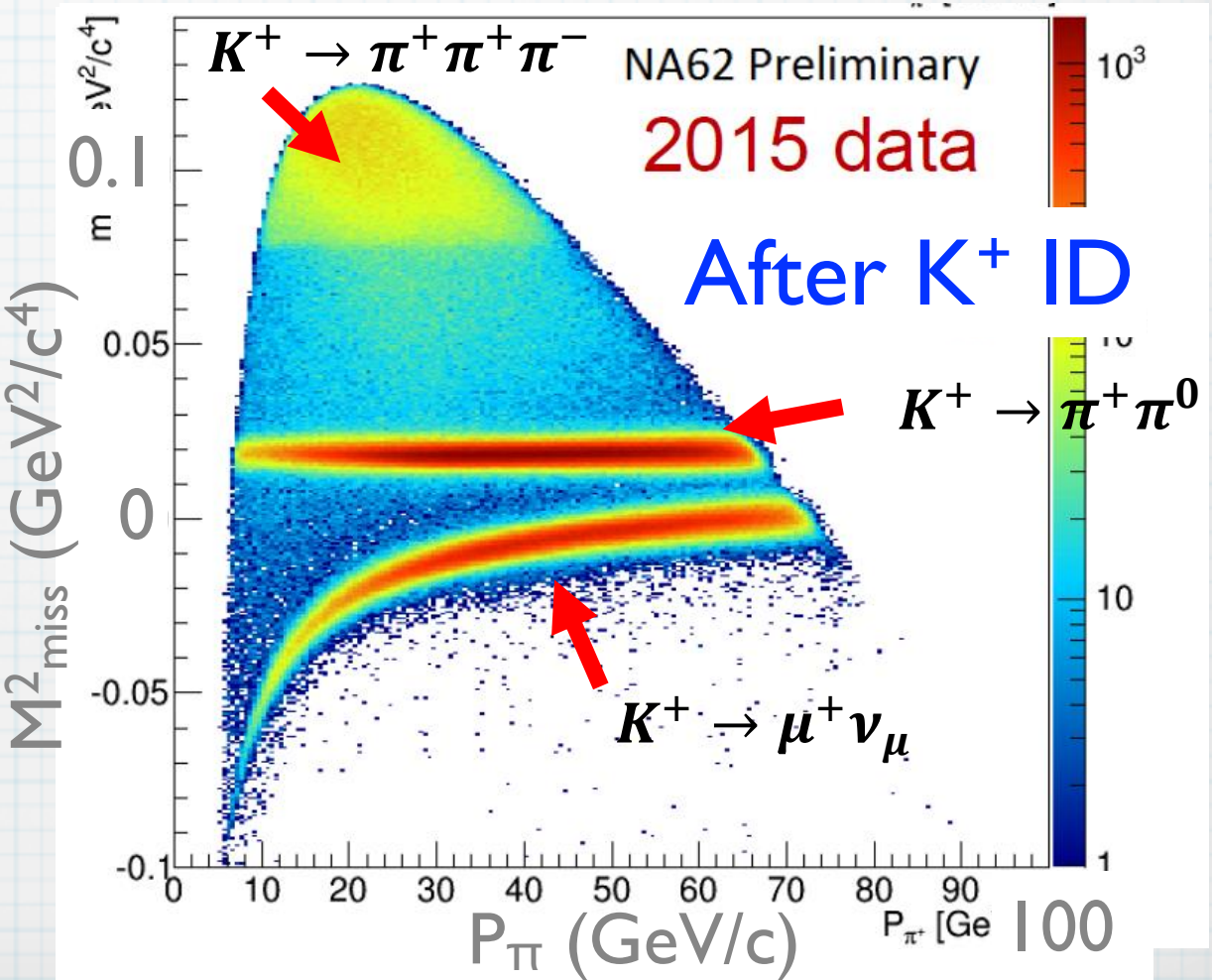


CERN NA62 K^+ ID

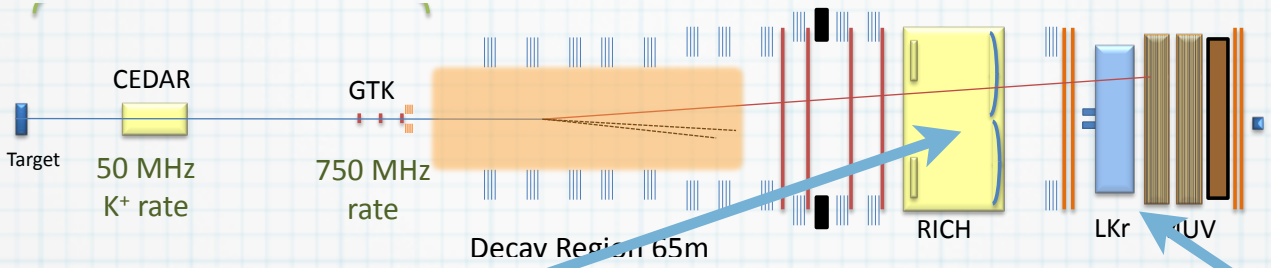


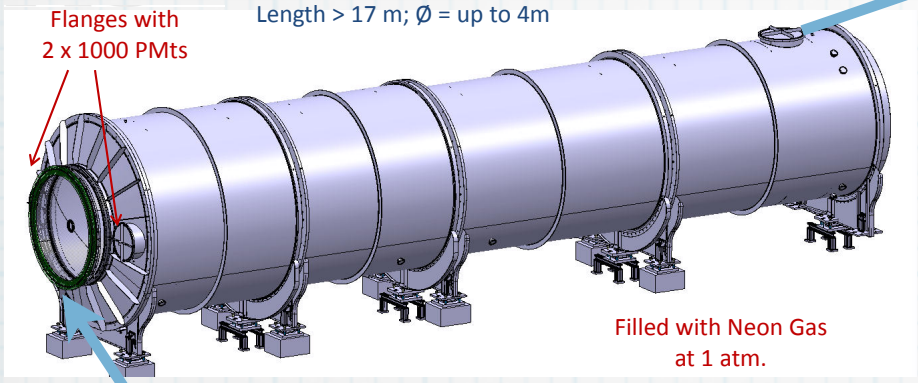




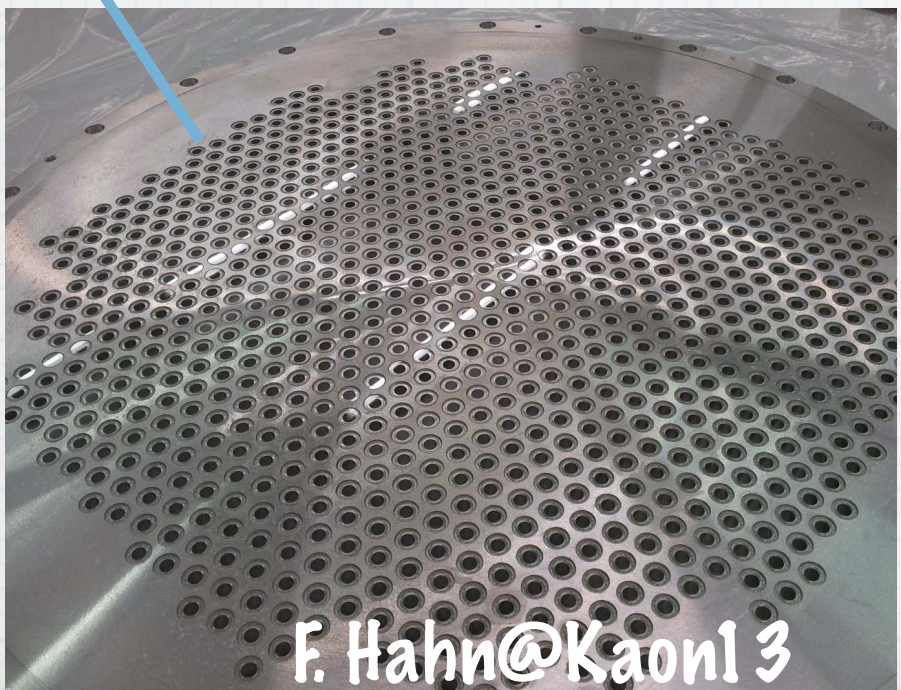


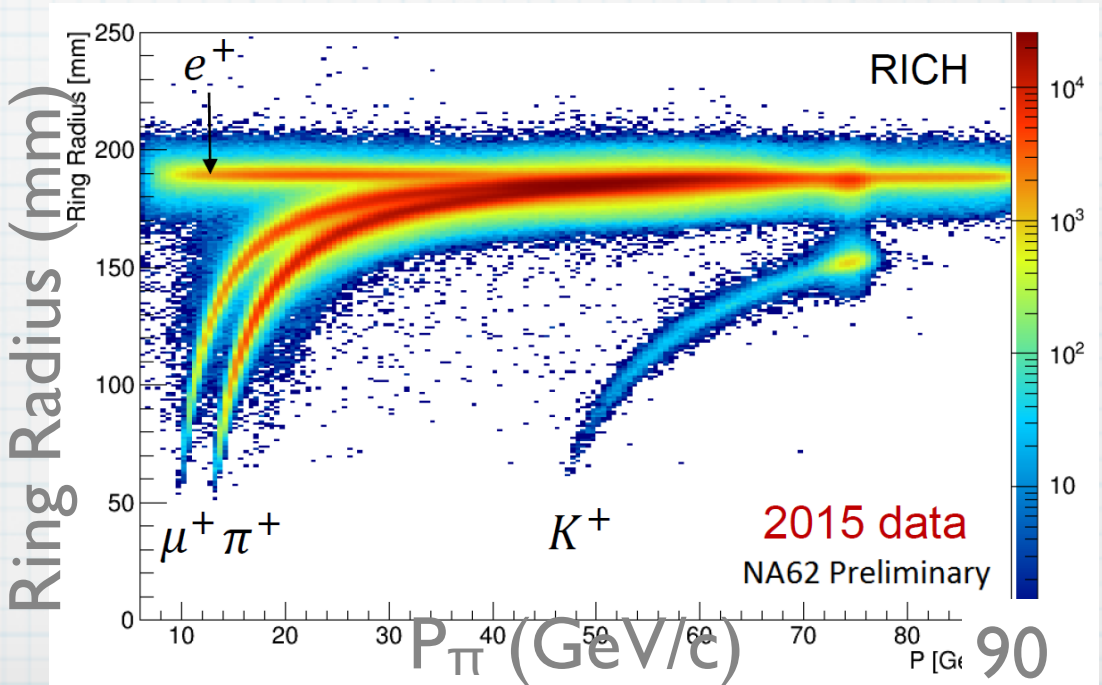
CERN NA62 π^+ ID



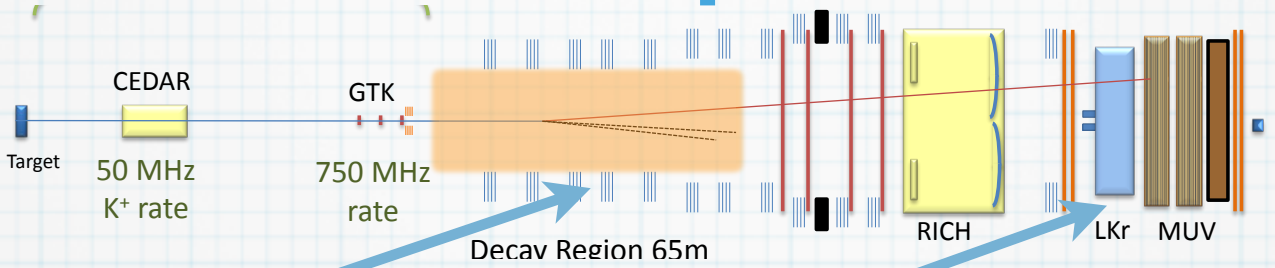


* Muon suppression
  * $O(10^{4\sim6})$ by calorimeter
  * $O(10^2)$ by π RICH





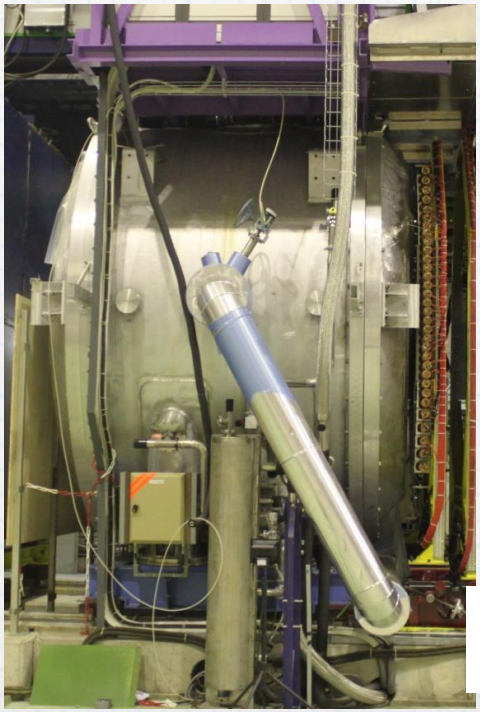
CERN NA62 photon veto

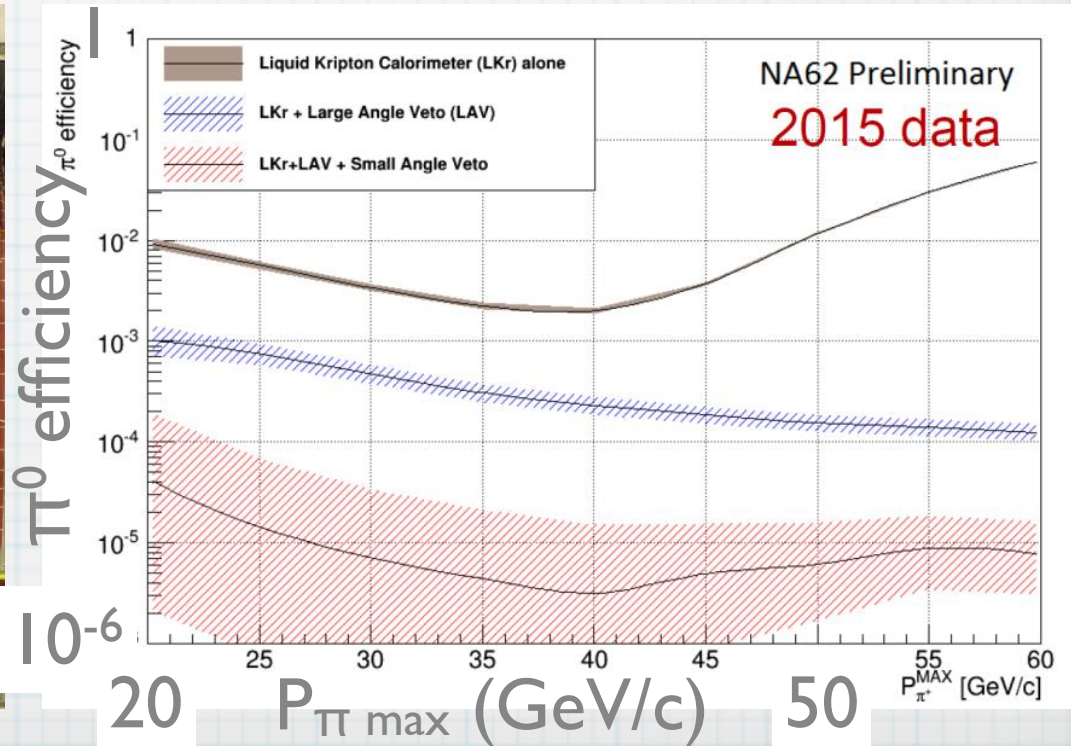


Leadglass for large angle γs

LKr calorimeter for small angle γs

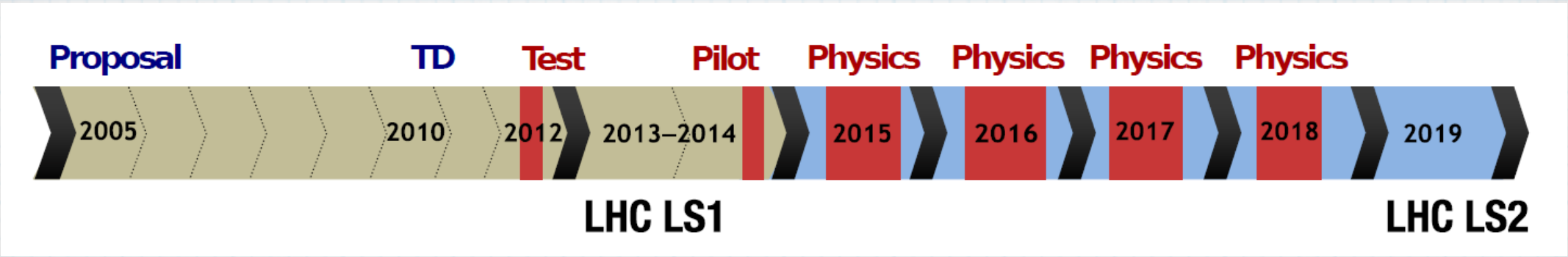
* O(10⁶) rejection of π^0 from $K^+ \rightarrow \pi^+\pi^0$





NA62 status

- ~ Finished commissioning
- Started a 200 day run in April 2016
- Runs in 2017 and 2018
- Expect O(100) events for ΔBR ~ 10%

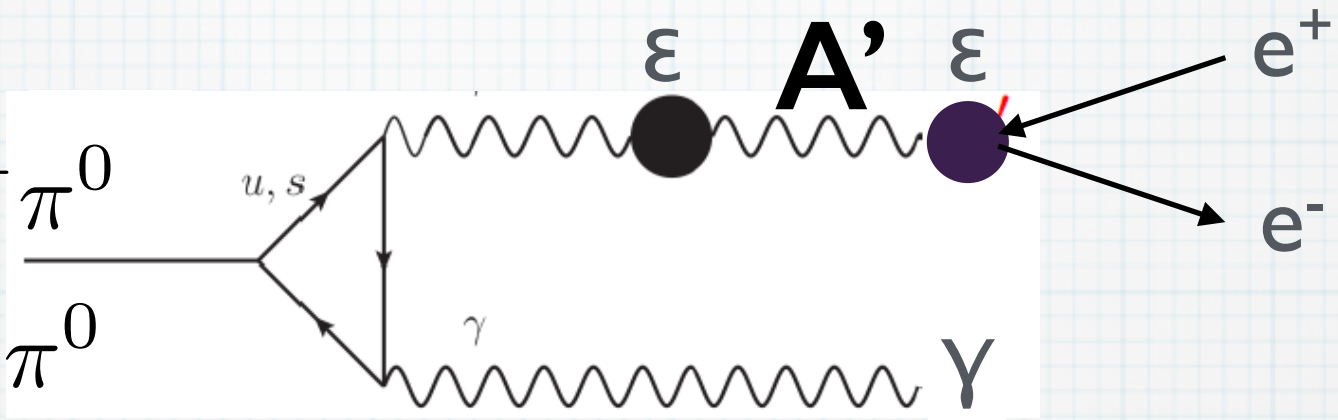


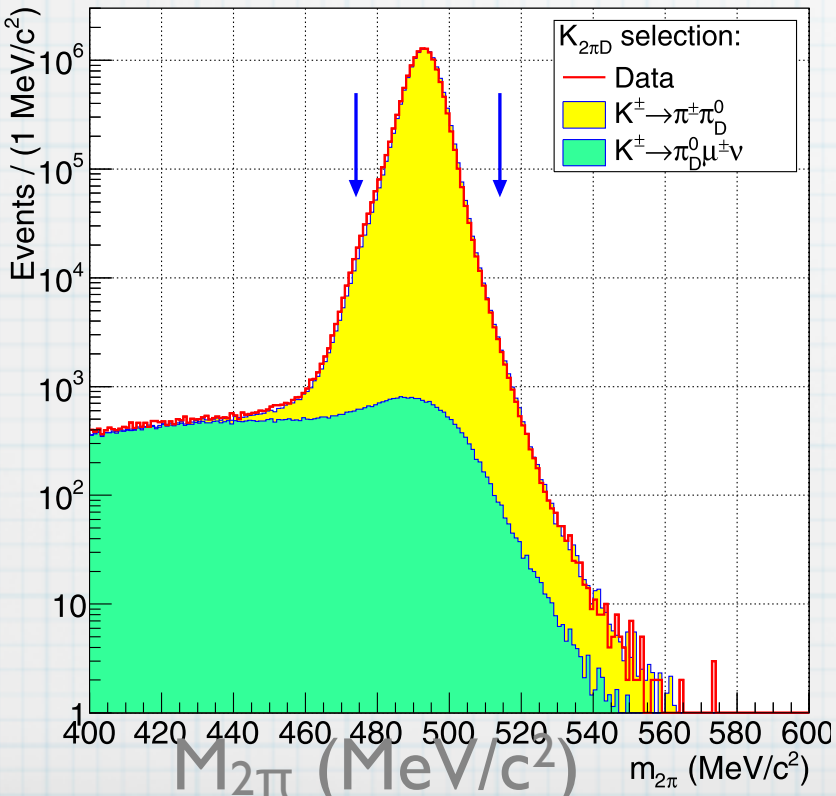
M. Mirra @HQL2016

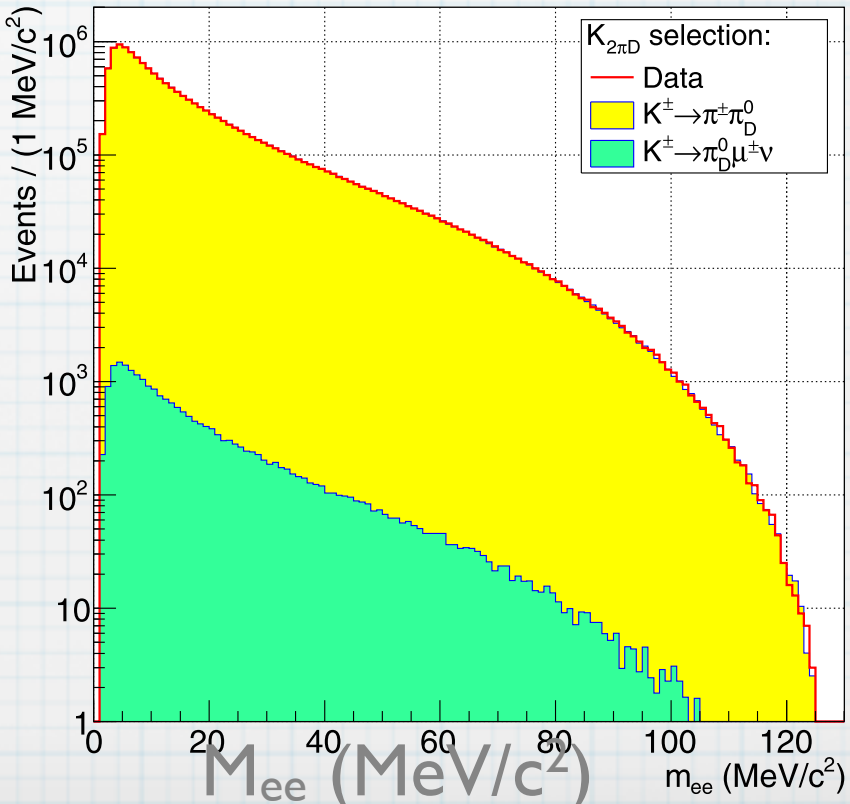
NA48/2: Dark Photon

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

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

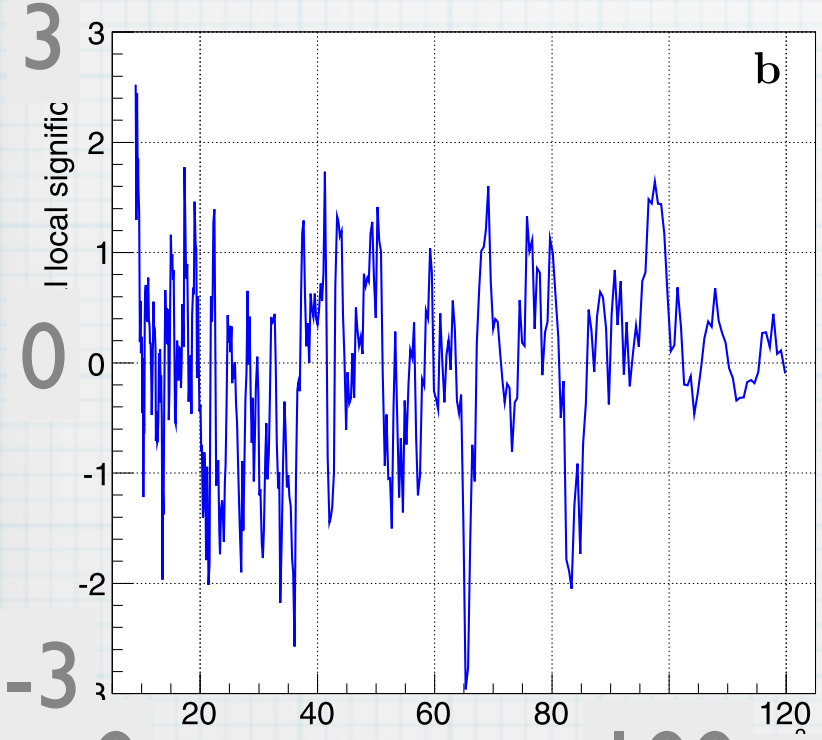


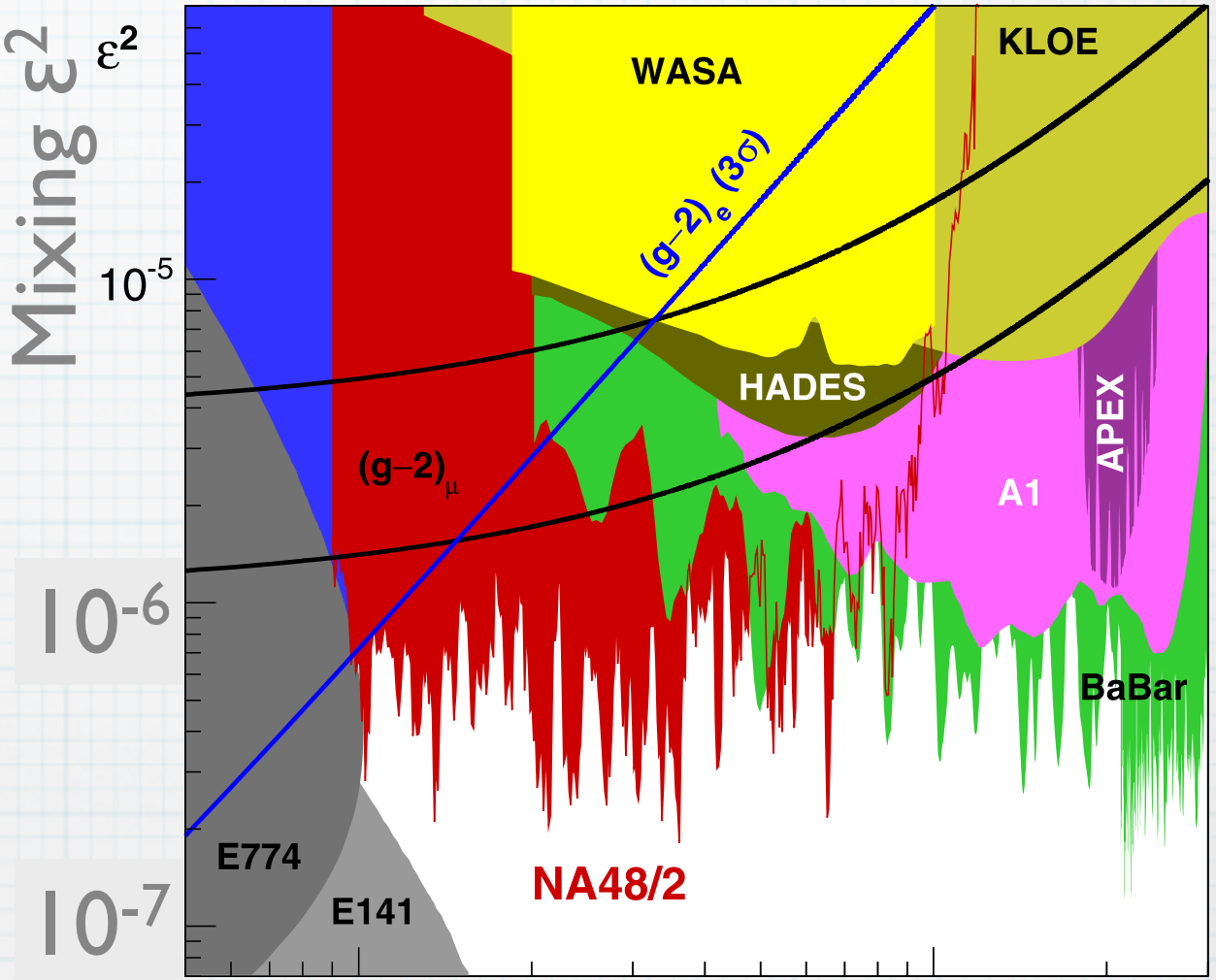




NA48/2: Dark Photon

Local significance

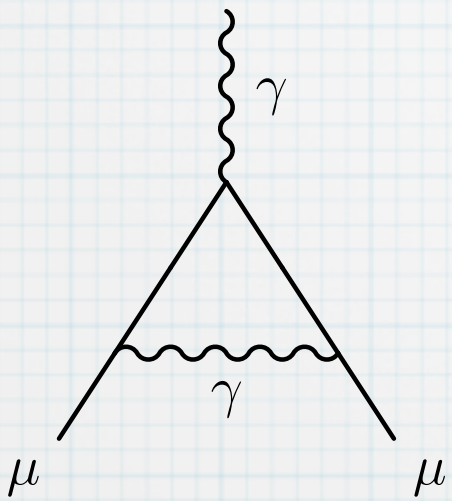


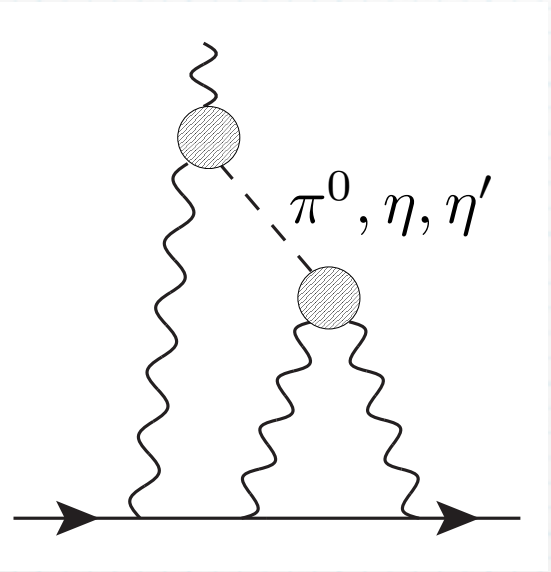


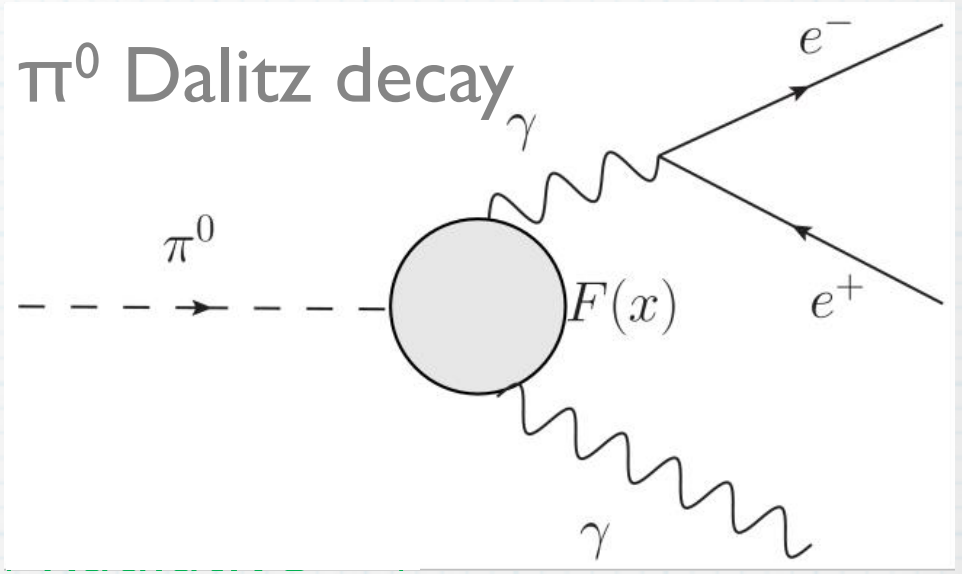
PLB 746, 178 (2015)

NA62 π^0 transition form factor

* g-2: light-by-light correction







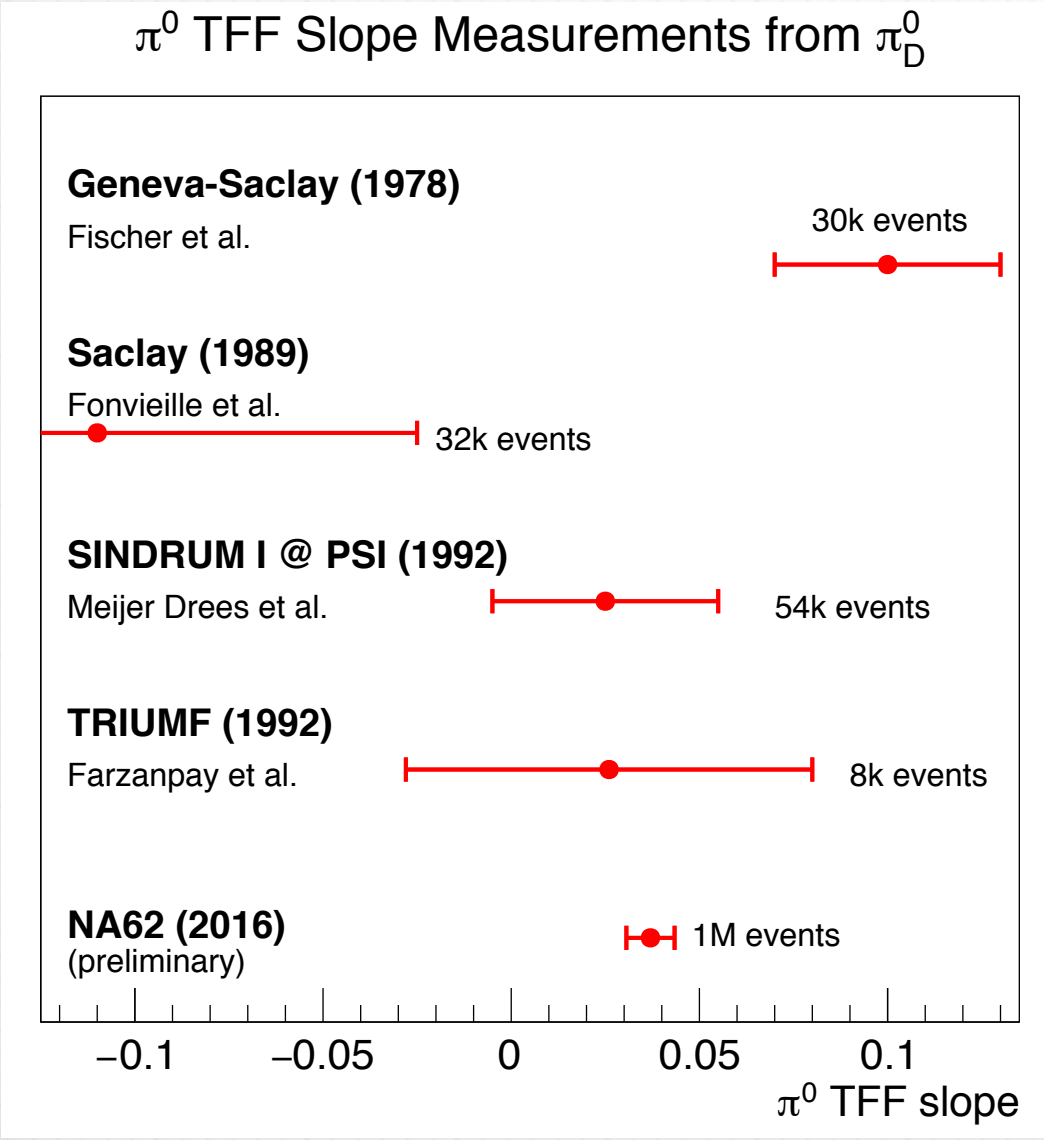
$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi}\frac{(1-x)^3}{x}(1+y^2+\frac{r^2}{x})\ (1+\delta(x,y))\ |F(x)|^2$$

Transition Form Factor (TFF)

$$x = m^2_{ee}/m^2_{\pi^0}$$

$F(x) \approx 1 + a\,x,$ $\quad a$: *TFF slope parameter*

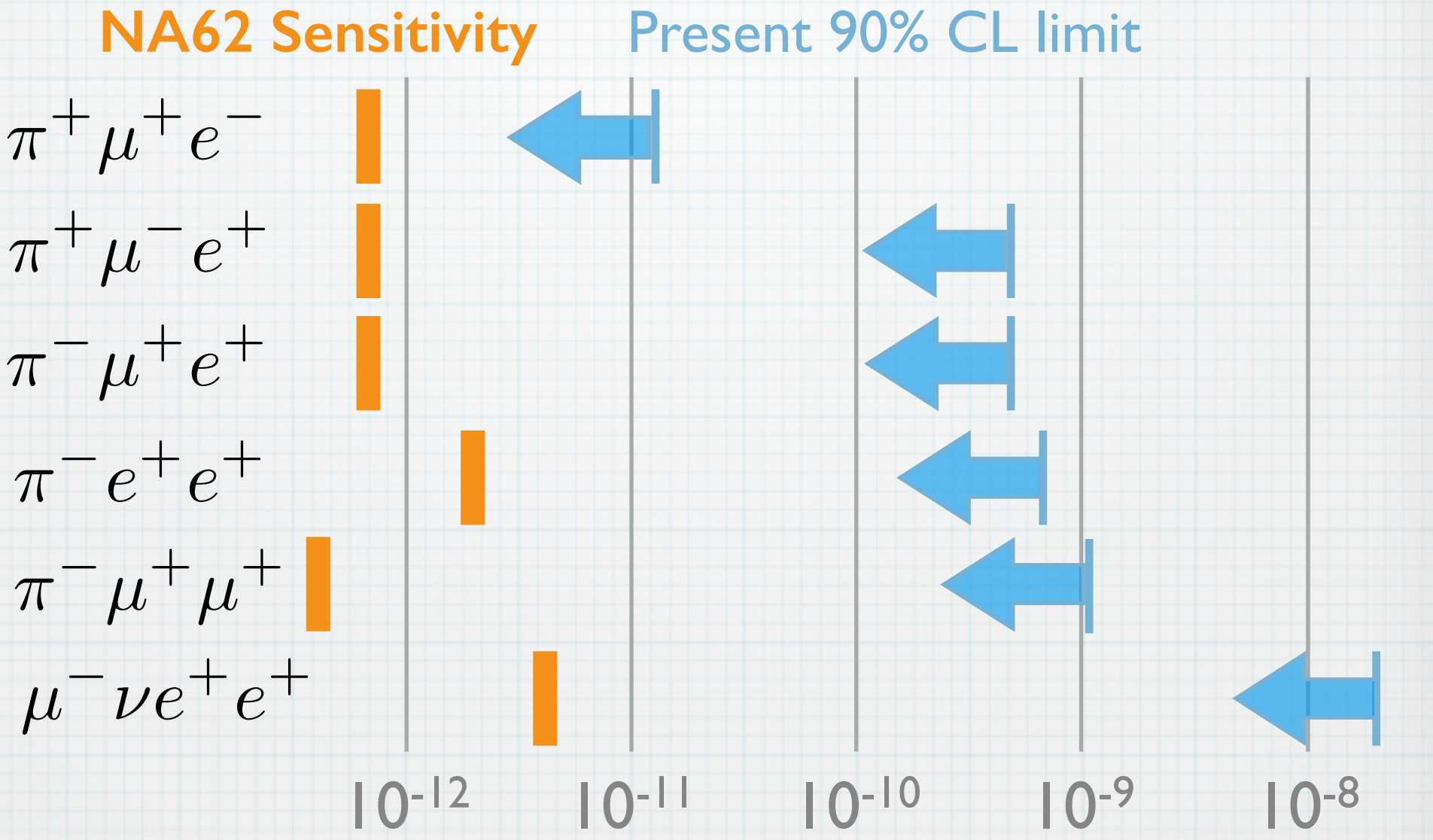
NA62 π^0 transition form factor



$a = (3.70 \pm 0.53 \pm 0.36) \times 10^{-2}$

Presented by M. Koval
@ La Thuile, March 2016

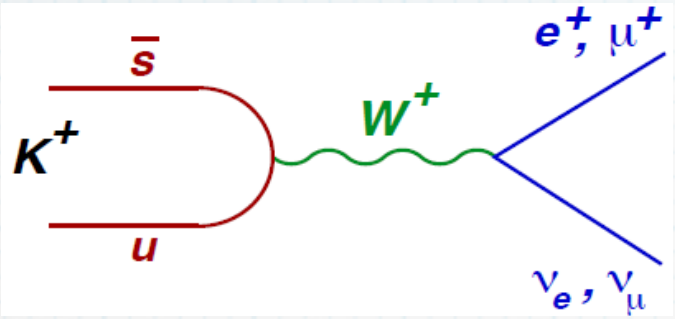
NA62: Lepton number/flavor violating K^+ decays



Numbers from Ryan Page@IPA2014

NA62: Lepton Universality

Standard Model

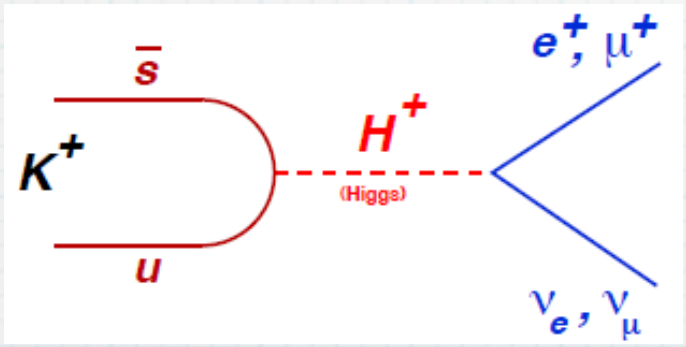


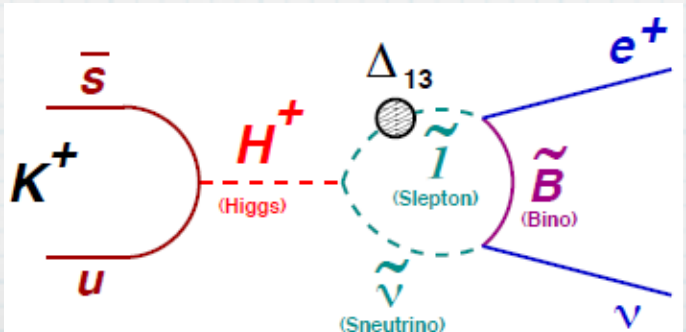
$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

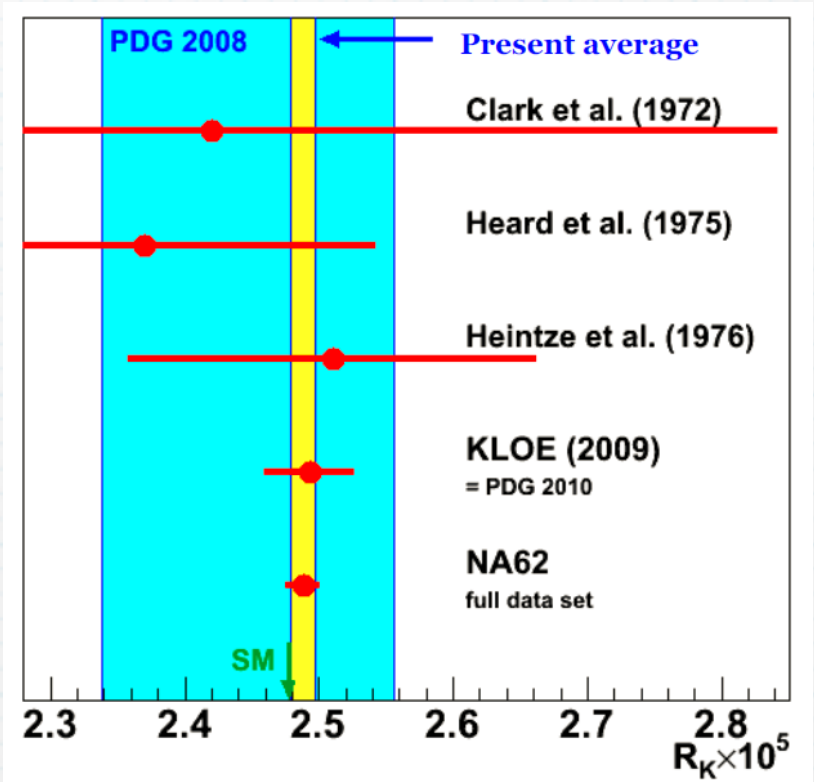
$$= (2.488 \pm 0.010) \times 10^{-5}$$

PLB 719, 326 (2013)

New Physics



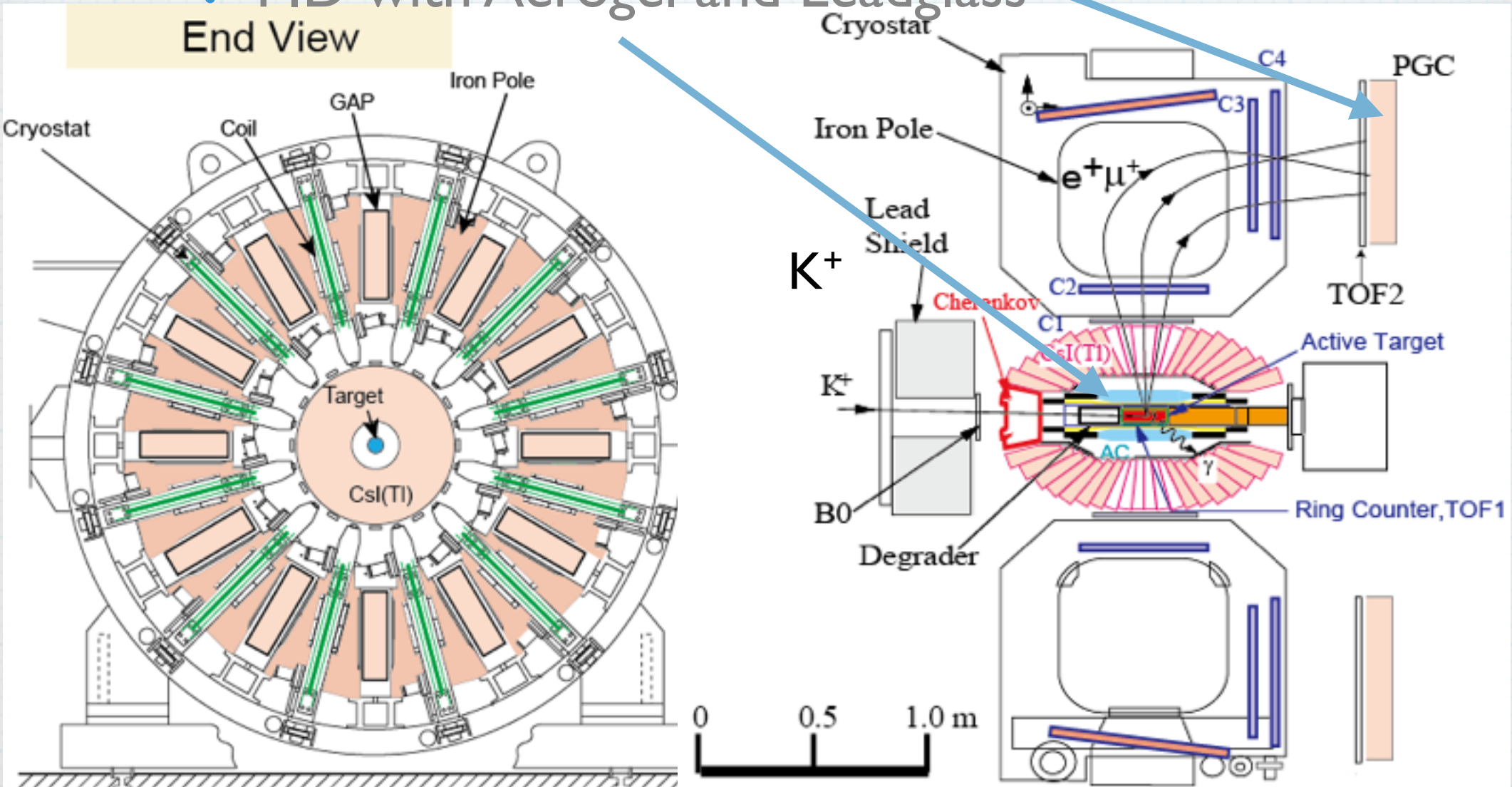




M. Piccini@SUSY2014

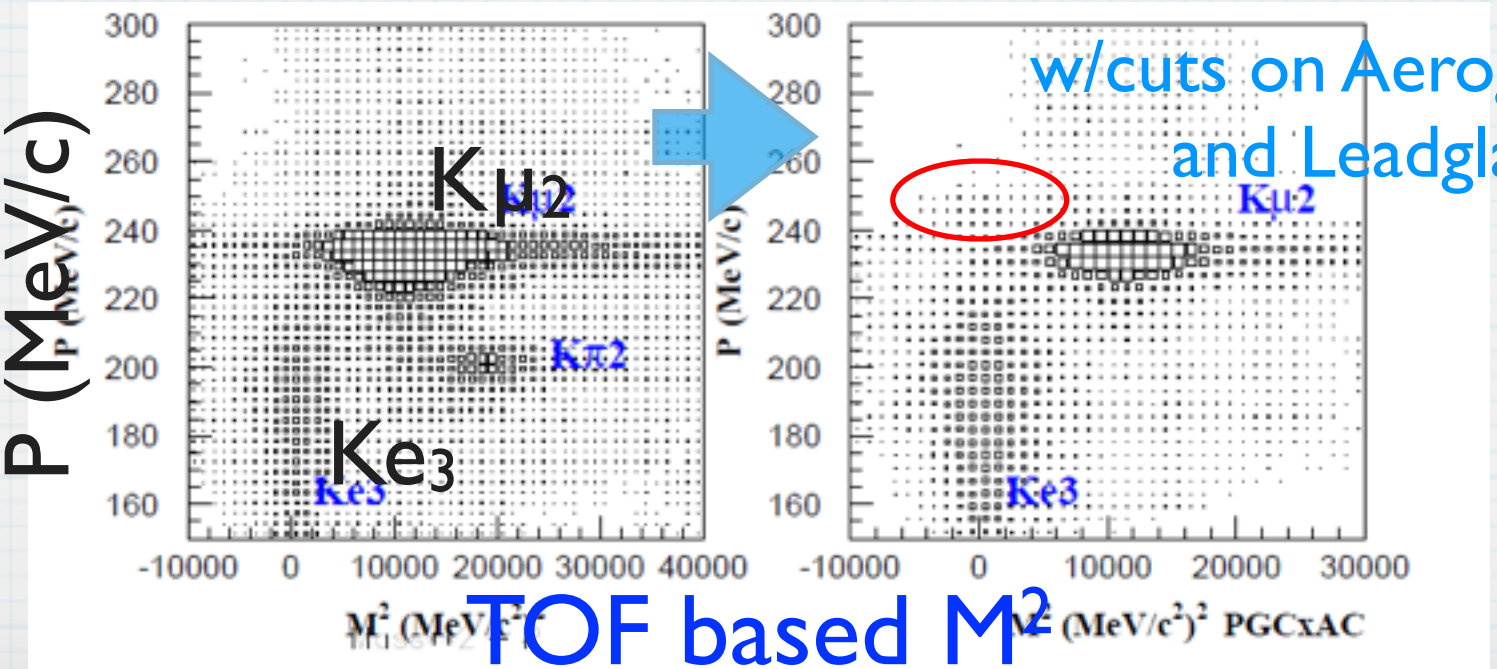
J-PARC TREK-E36 for R_K

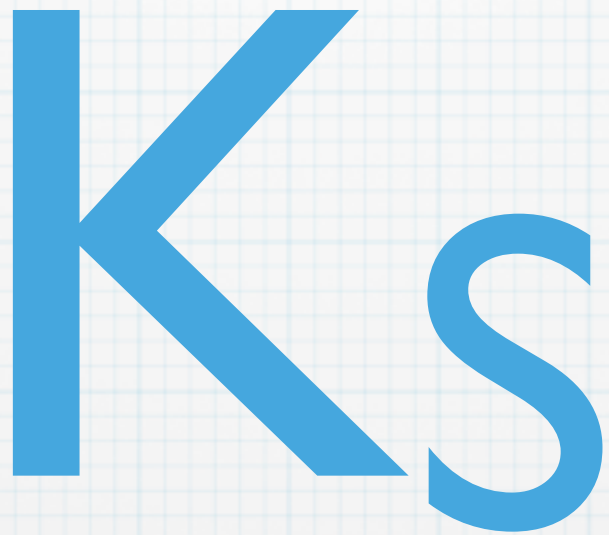
* Stopped K experiment
* PID with Aerogel and Leadglass



J-PARC TREK-E36 for R_K

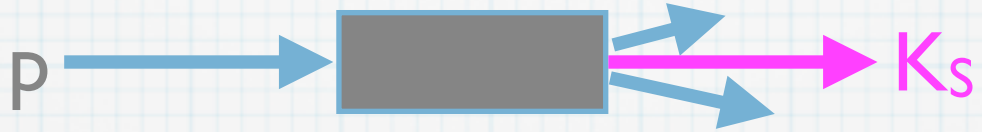
* Ran in 2015, and dismantled the detector
* Expected yield: 40k Ke2 events / 1000 kW days (1/6 of original plan)
* Expected $\Delta R_K = 0.5\%$



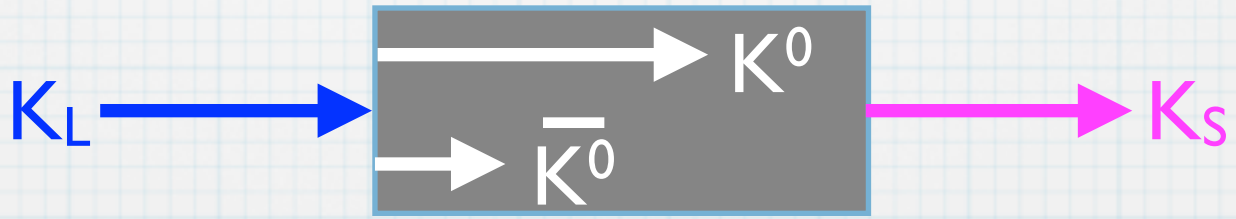

Ks

How to make K_S

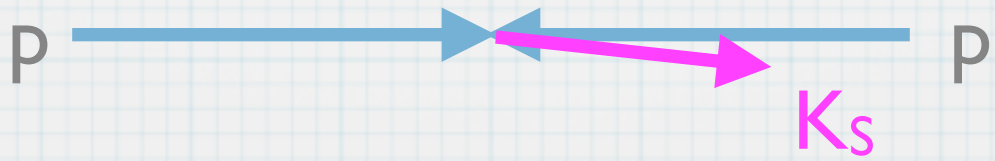
* $c\tau$ = 2.7 cm
* Fixed target



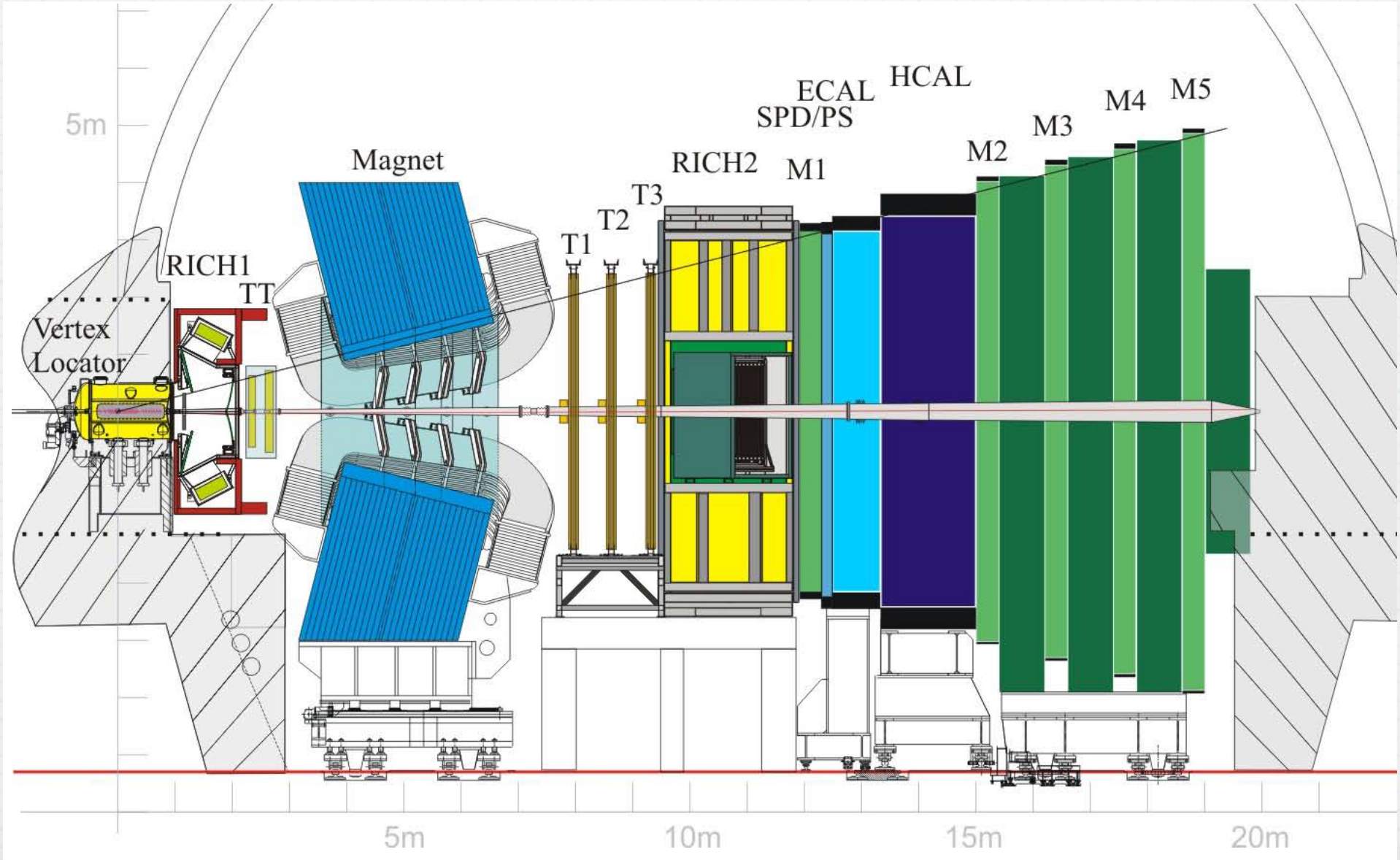
* Regeneration



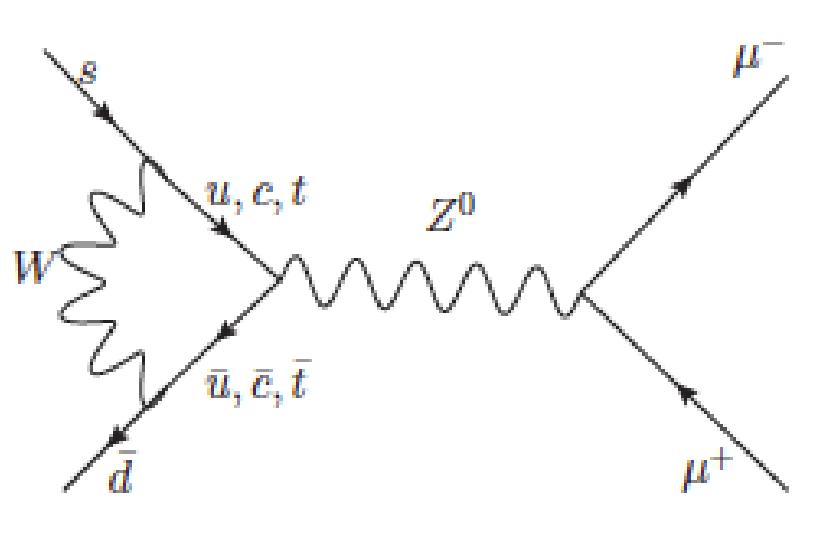
* p - p collision

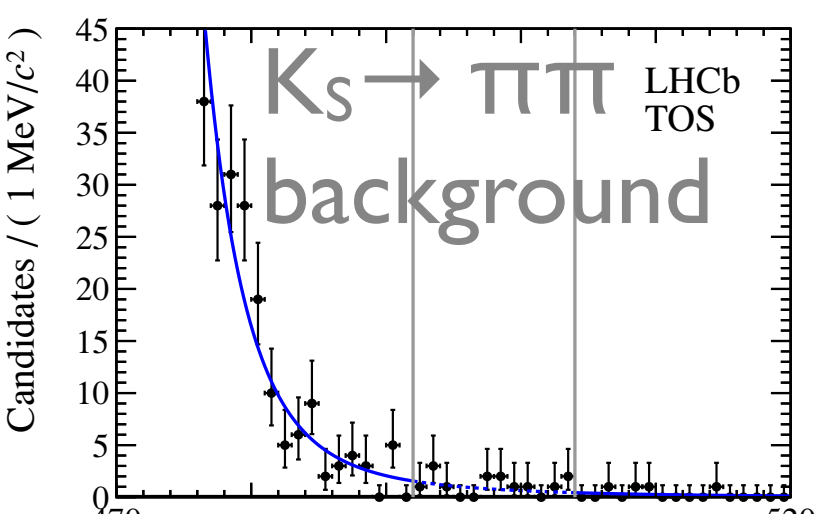


LHCb as K_S factory



$K_S \to \mu\mu$

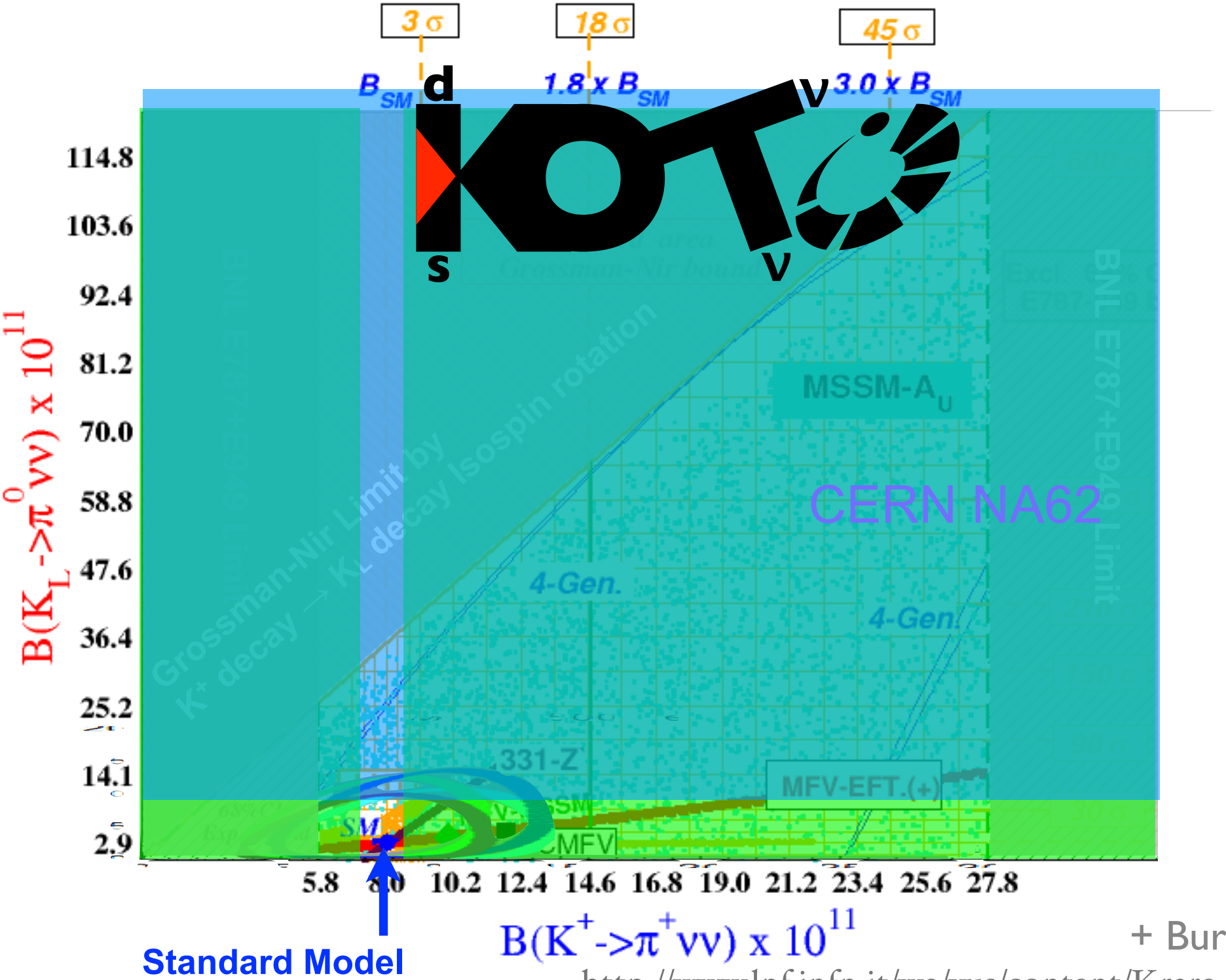




- Sensitive to New Physics
- $B_{SM} = (5.1 \pm 0.2) \times 10^{-12}$
- With 1/fb data,
  BR < 9 x 10^{-9} (90% CL)
  JHEP01 (2013) 090
- x1/30 of past (1973) limit
- Expect x40 integrated Luminosity & (x3 possible trigger improvement)

Prospects of

$K_L \to \pi^0 \nu\overline{\nu}$ & $K^+ \to \pi^+ \nu\overline{\nu}$



+ Buras 2014

http://www.lnf.infn.it/wg/vus/content/Krare.html

Summary

- Kaon experiments will explore physics beyond the standard model via
  - $K \to \pi\nu\nu$ decay modes for >10-10^3 TeV energy scale
  - Lepton flavor violation, universality
  - dark photons, …
- Stay tuned!