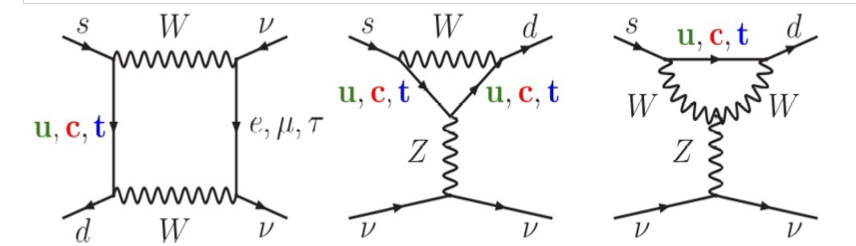
Rare Processes with Kaons and Muons

- $K \rightarrow \pi\nu\nu$
- $\mu \rightarrow e\gamma$, 3e
- μ-e conversion

Augusto Ceccucci/CERN

The Future of Particle Physics: A Quest for Guiding Principles
Karlsruhe, 01.10.2018

$K \rightarrow \pi \nu \nu$ and SM

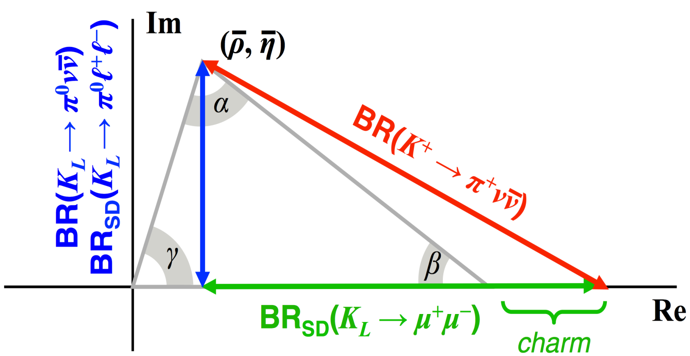


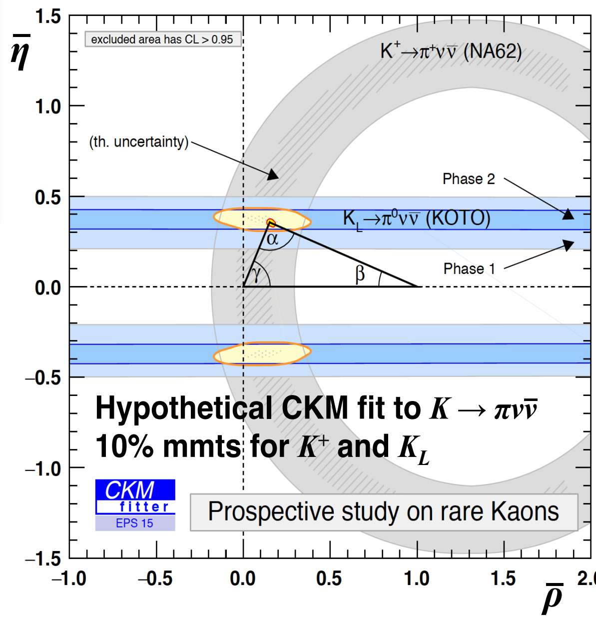
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$BR(K_L \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

NNLO QCD: Buras, Gorbahn, Haisch, Nierste PRL95 (2005) arXiv:hep-ph/0508165

The very small hadronic error makes these decays special





Precision of prediction limited by CKM parameters themselves

→ Knowledge of γ, V_{cb} and V_{ub} will be improved by LHCb & Belle II

Overconstrain UT triangle to reveal possible New Physics

Prospects to measure $K_L \to \pi^0 \nu\nu$ at the SPS – M. Moulson (Frascati) – Physics Beyond Colliders – CERN – 7 Sept 2016 3

SM prediction [Buras et al. JHEP 1511 (2015) 33] $BR(K^+ \to \pi^+ \nu\bar\nu) = (8.4 \pm 1.0) \cdot 10^{-11}$

Experimental status (E787, E949) $BR(K^+ \to \pi^+ \nu\bar\nu) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

[Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

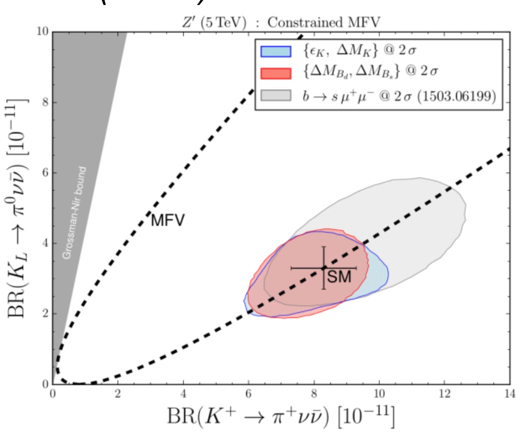
(Decays at rest)

Large gap between Theory and Experiment

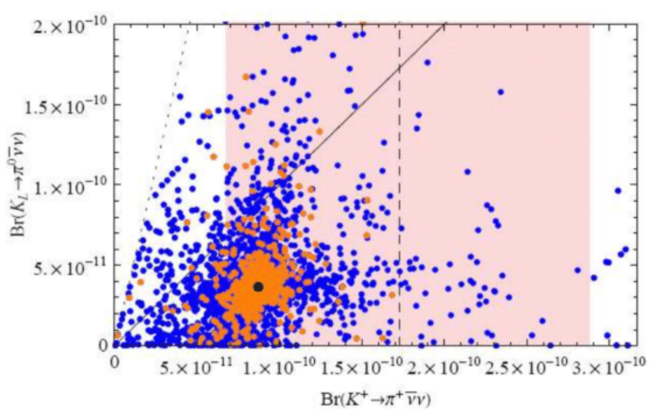
$K^+ \to \pi^+ \nu \bar{\nu}$ Beyond the Standard Model

- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM gluino-squark box diagrams [Crivellin,D'Ambrosio, Kitahara, Nierste, PRD96 (2017), 015023]
- MSSM analyses [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

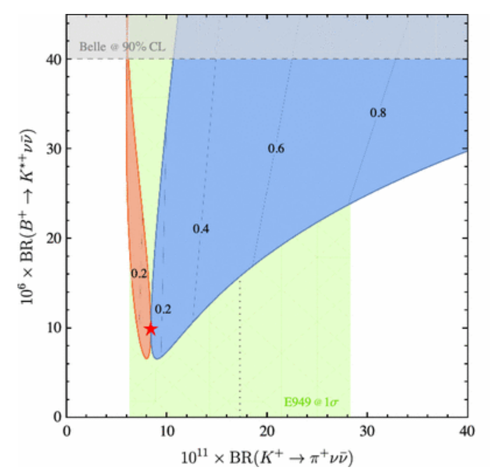
Z'(5 TeV) in Constrained MFV



Randall Sundrum

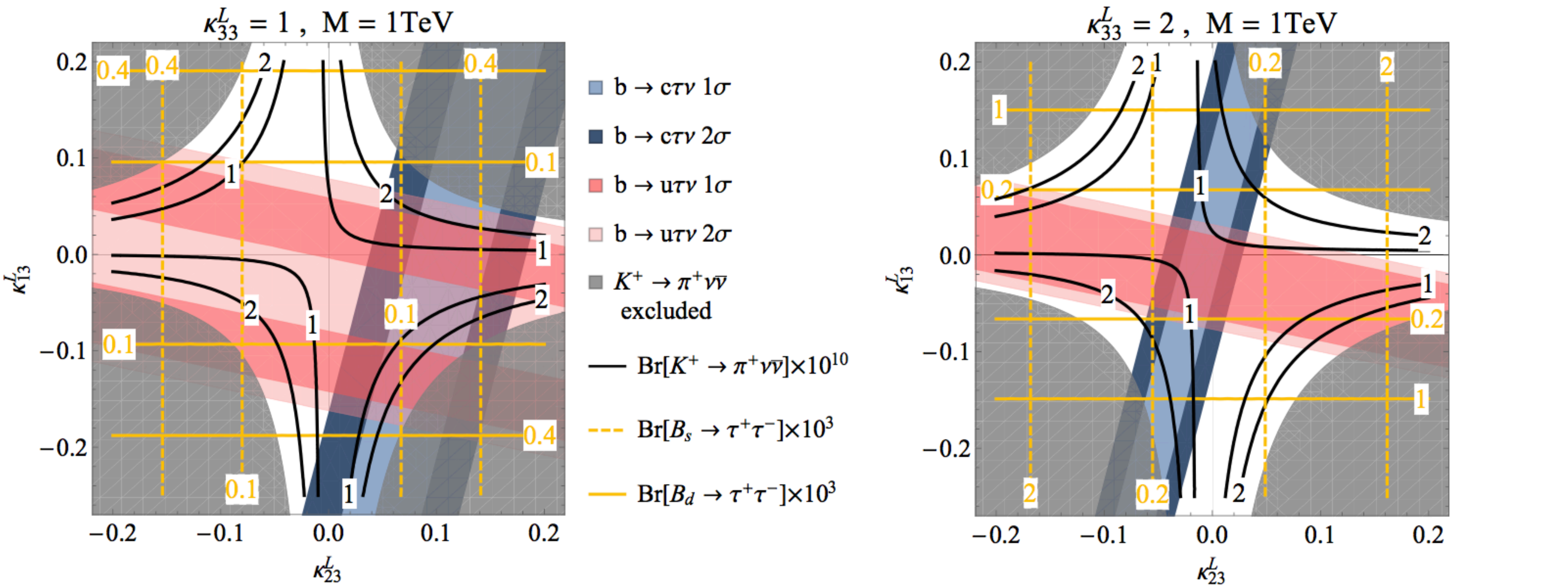


LFU violation



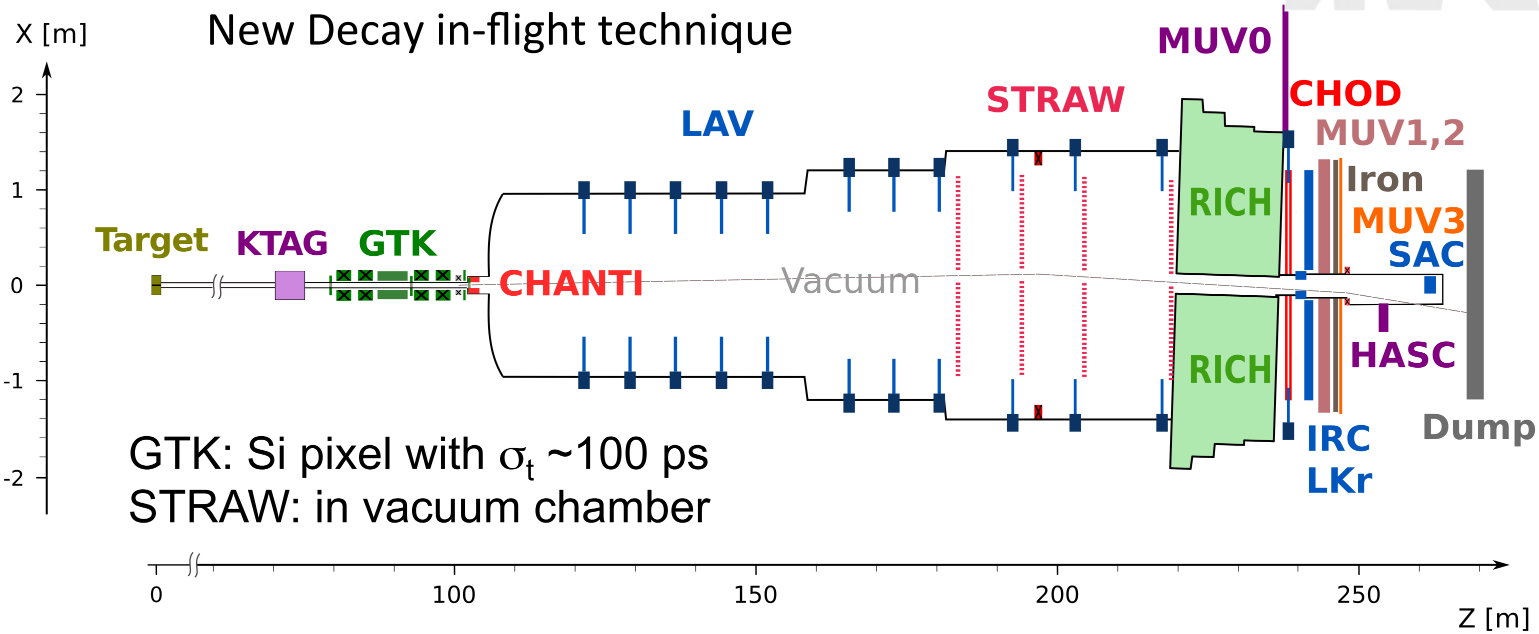
Loop Effects from Vector Leptoquarks

arXiv:1007.02068 A. Crivelling, C. Greub, F. Saturnino



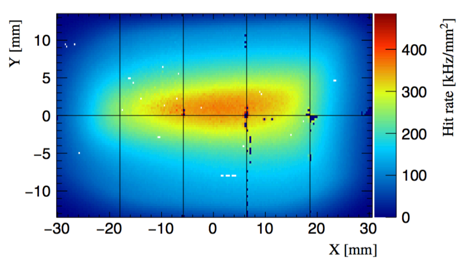
NA62 at the CERN SPS

NA62 beam and detector



GTK: Si pixel with σ_t ~100 ps
STRAW: in vacuum chamber

- **SPS Beam:**
  - 400 GeV/c protons
  - 2.10^{12} protons/spill
  - 5s spill [3s eff.] / ~16 s



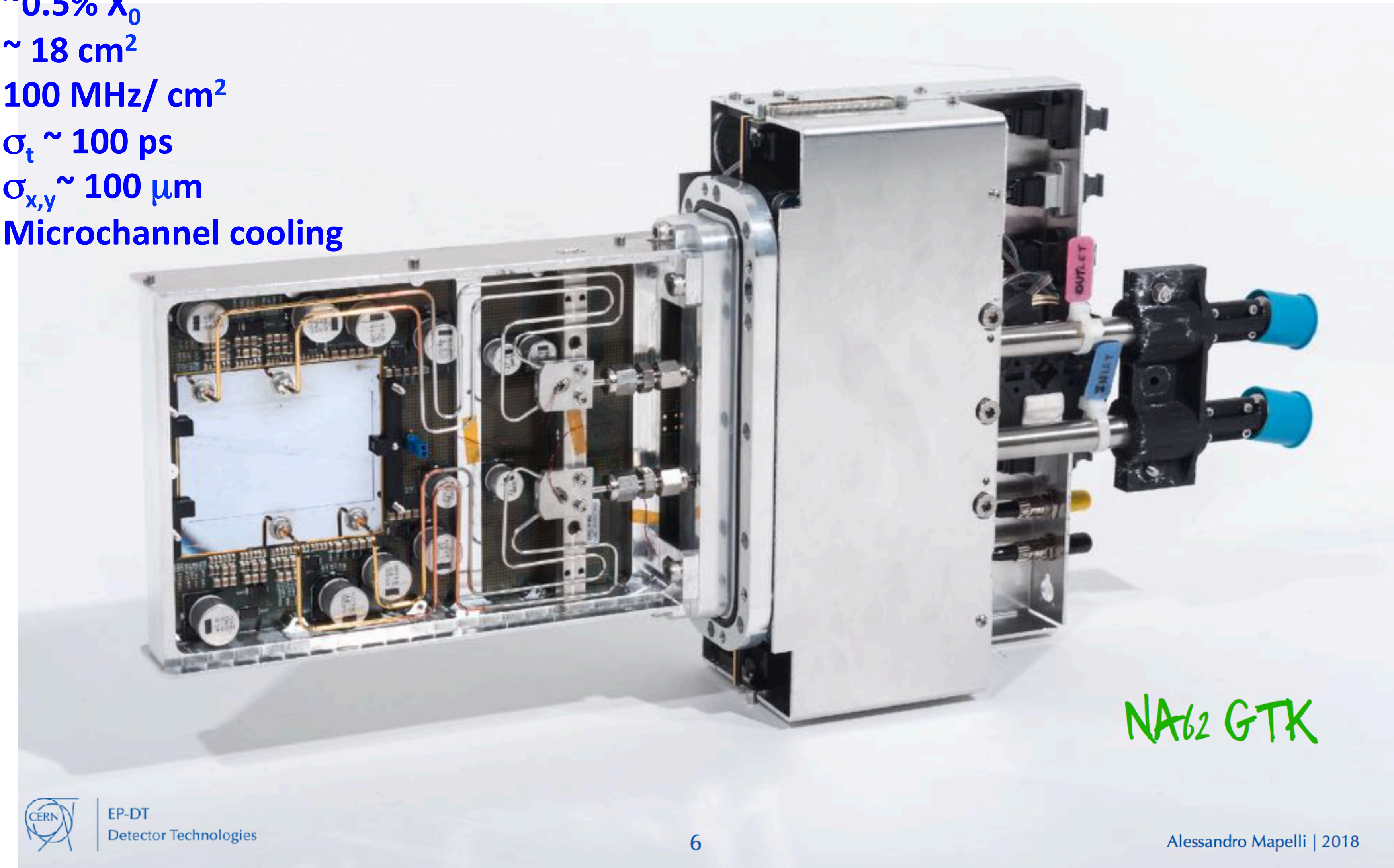
- **Secondary positive Beam:**
  - 75 GeV/c momentum, 1 % bite
  - 100 μrad divergence (RMS)
  - 60x30 mm^2 transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - For 33×10^{11} ppp on T10
  - → 750 MHz at GTK3

- **Decay Region:**
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

Detector and Performances: arXiv:1703.08501

NA62 Gigatracker

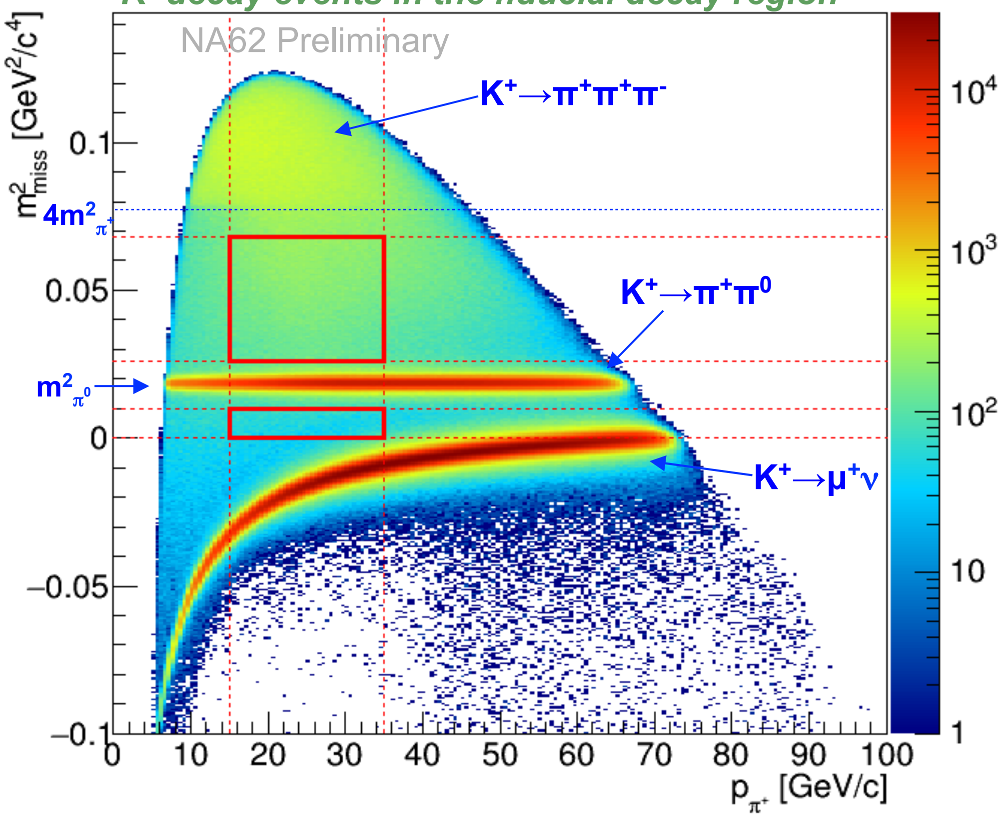
Si pixel
~0.5% X_0
~ 18 cm^2
100 MHz/ cm^2
σ_t ~ 100 ps
$\sigma_{x,y}$~ 100 μm
Microchannel cooling

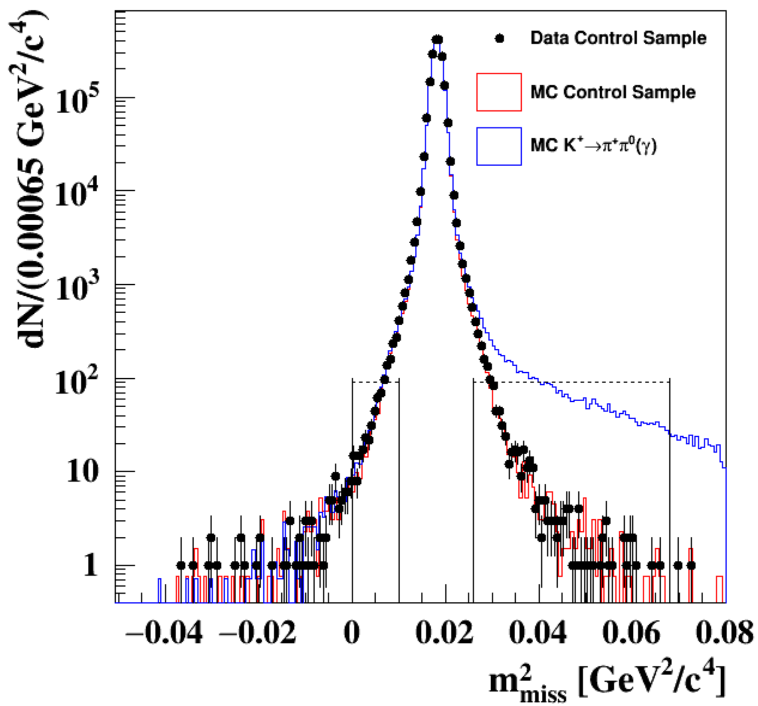


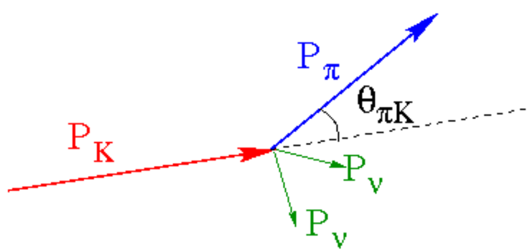
Signal Region Definition

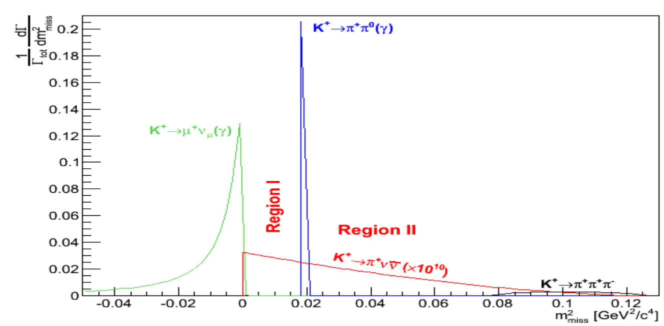
The main backgrounds are bound kinematically while the signal is not

K^+ decay events in the fiducial decay region

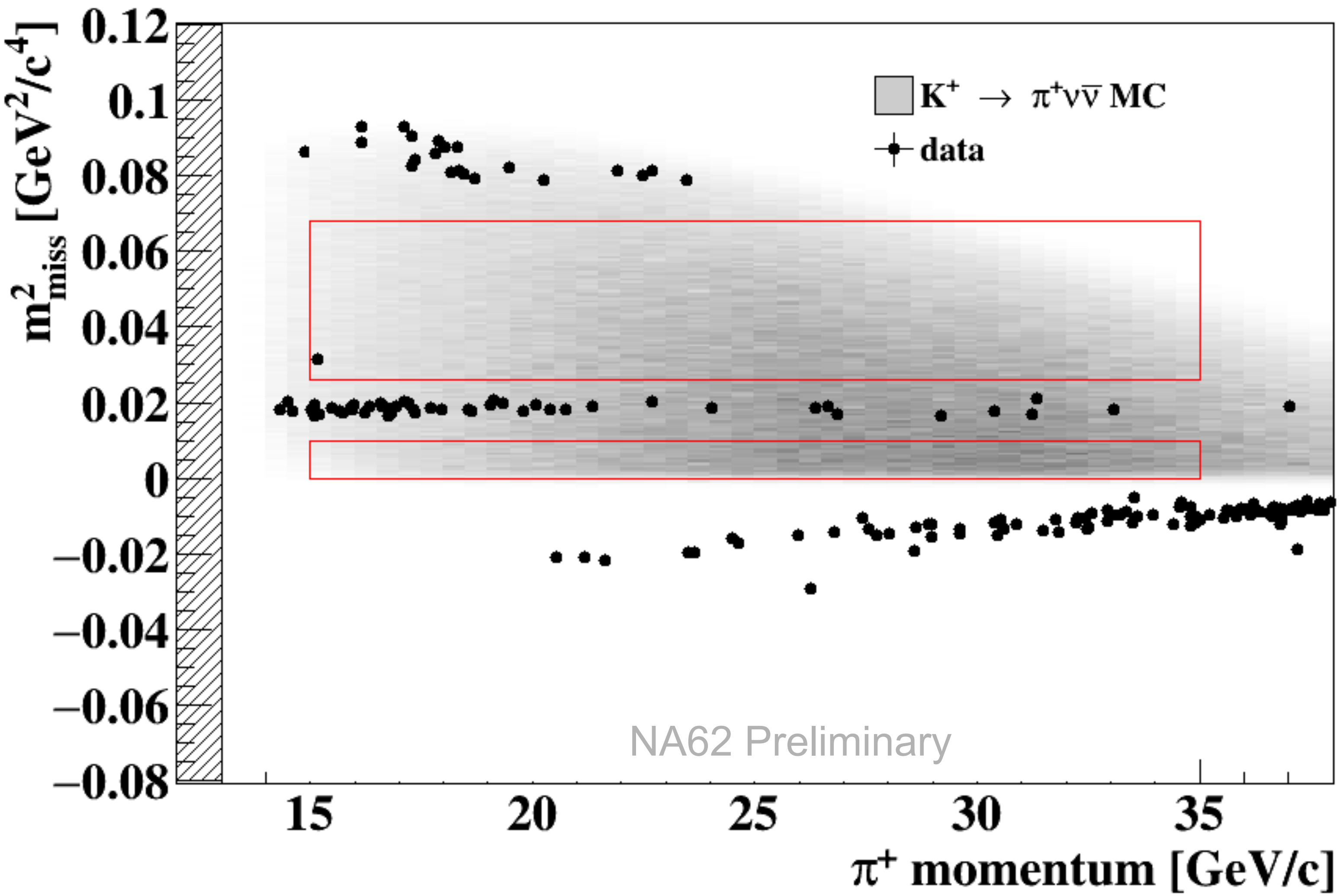






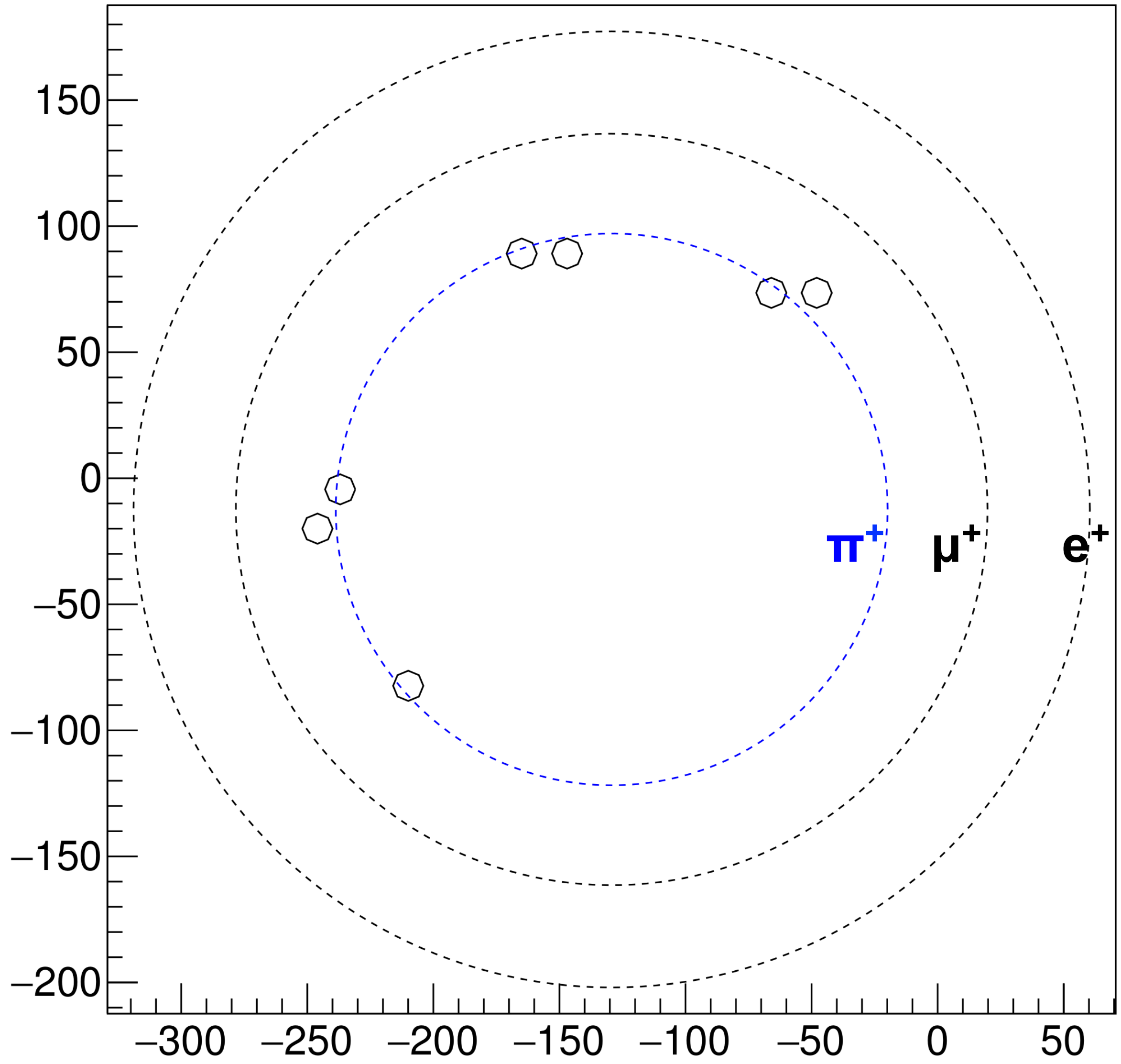


First Results: 2016 data



One candidate observed with 0.27 SM and 0.15 background expected

RICH ring for the candidate



Mom 15.3, Mirror 24 (258.8), Frac M 1.000 0.000, PMT 1.000 0.000

Results

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10} \text{ @ } 90\% \; CL$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\% \; CL$$

- One event observed in Region 2, paper in preparation
- The results are compatible with the Standard Model
- For comparison, taking the candidate to be signal:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = 28^{+44}_{-23} \times 10^{-11} \text{ @ } 68\% \; CL$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

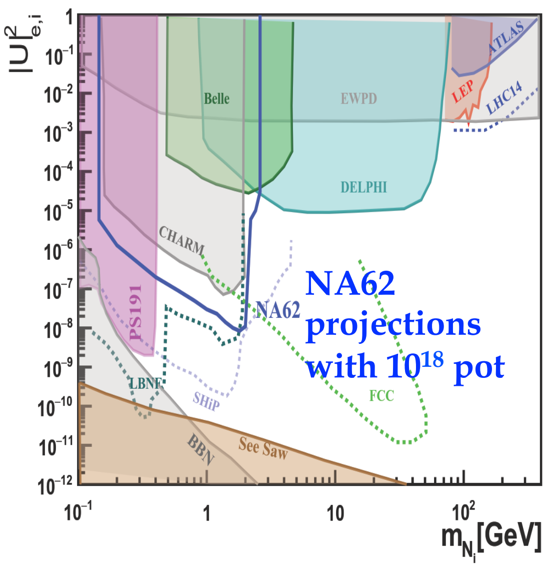
$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

NA62 Prospects

- **2017 Data**
  - ~20 times 2016 statistics
  - Reduction of upstream backgrounds
- **2018 Data**
  - Data taking until mid November
  - Further reduction of backgrounds
  - Expect ~ 20 SM events with data collected before LS2
- **2021 – 2023** . . .
  - Data Taking to complete PNN program to 10% precision
  - Running in dump mode to study the Dark Sector

Heavy Neutral Leptons in NA62 (Dump)

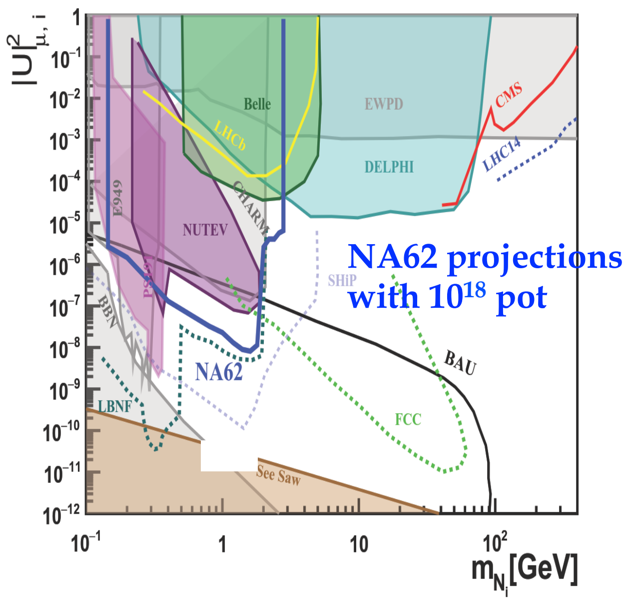
Scenario 1



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$

Normal hierarchy of active **ν** masses

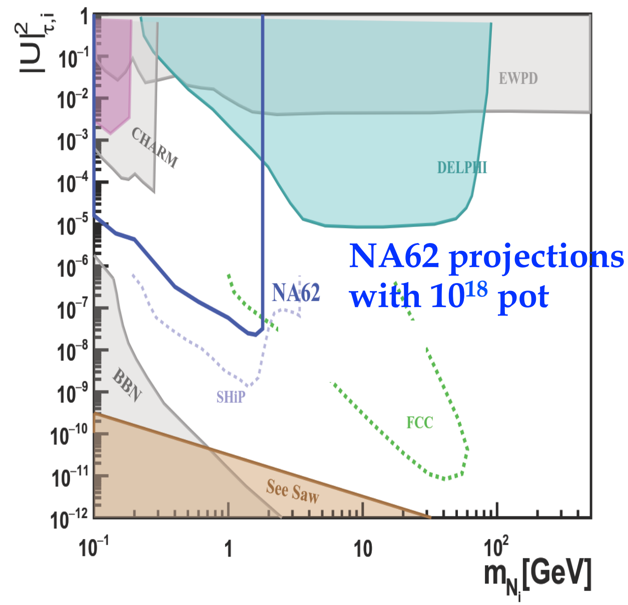
Scenario 2



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$

Normal hierarchy of active **ν** masses

Scenario 3



$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$

Normal hierarchy of active **ν** masse

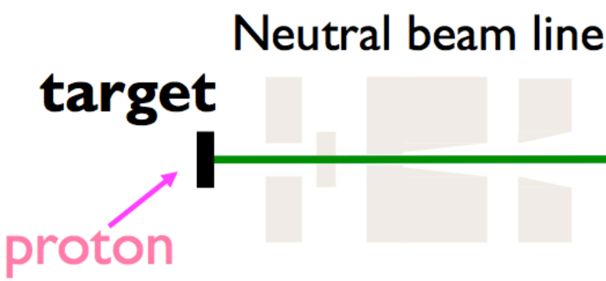
These sensitivities assume to detect all 2-track final states, including open channels, and zero background

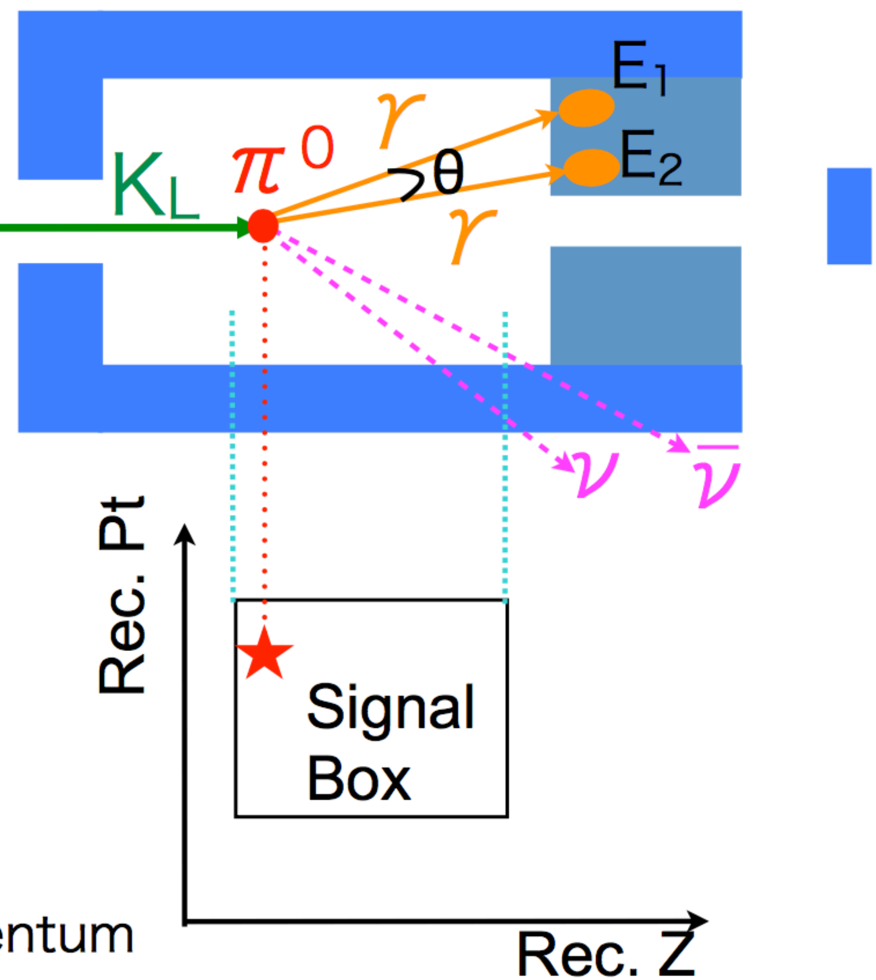
Window of Opportunity to search for HNL and Dark Particles in dump mode in the near future

KOTO Principle

K. Shiomi, ICHEP 2018

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





"2γ+Nothing+$\not{P}t$"

Assuming 2γ from π^0,
Calculate z vertex.

$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

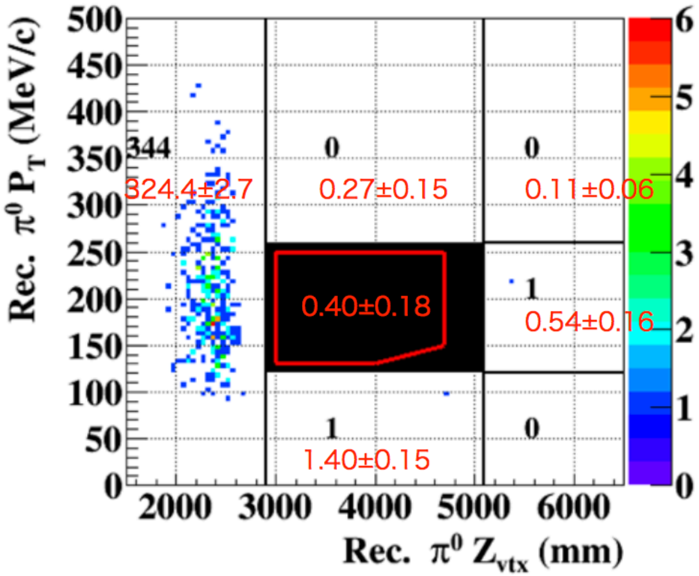
Calculate π^0 transverse momentum

Preliminary

Results of 2015 analysis

Summary of background inside the signal box

background source	#BG
Halo neutron hitting CSI	0.24±0.17
Halo neutron hitting upstream detectors	0.04±0.03
η background	0.03±0.02
KL->$\pi^+\pi^-\pi^0$	0.05±0.02
KL->$2\pi^0$	0.02±0.02
other BG sources	0.02±0.02
Sum	0.40±0.18



S.E.S: 1.3×10^{-9} cf. Grossman-Nir bound <1.5e-9

No Candidate events found: BR < 3 x 10^{-9} 90%CL

For the future increase intensity from 50 to 90 kW

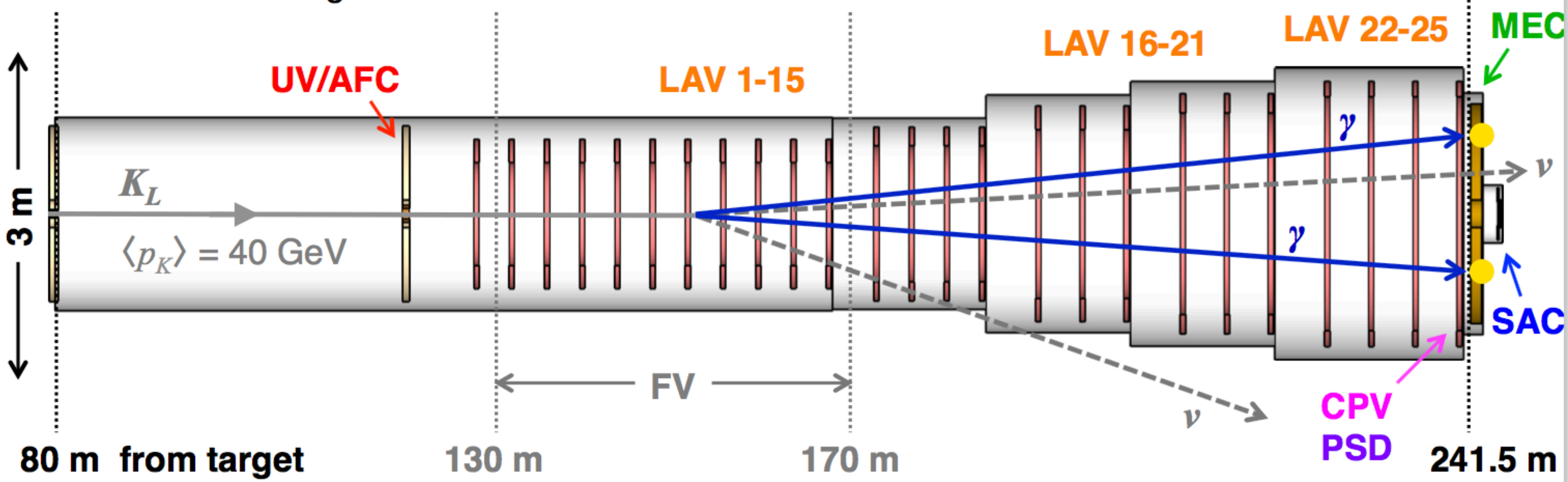
"Aiming to go below 10^{-10} in a timely manner"

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS

KLEVER

400-GeV SPS proton beam (2×10^{13} pot/16.8 s)
incident on Be target at z = **0 m**

M. Moulsson, ICHEP 2018



KLEVER target sensitivity:

5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$

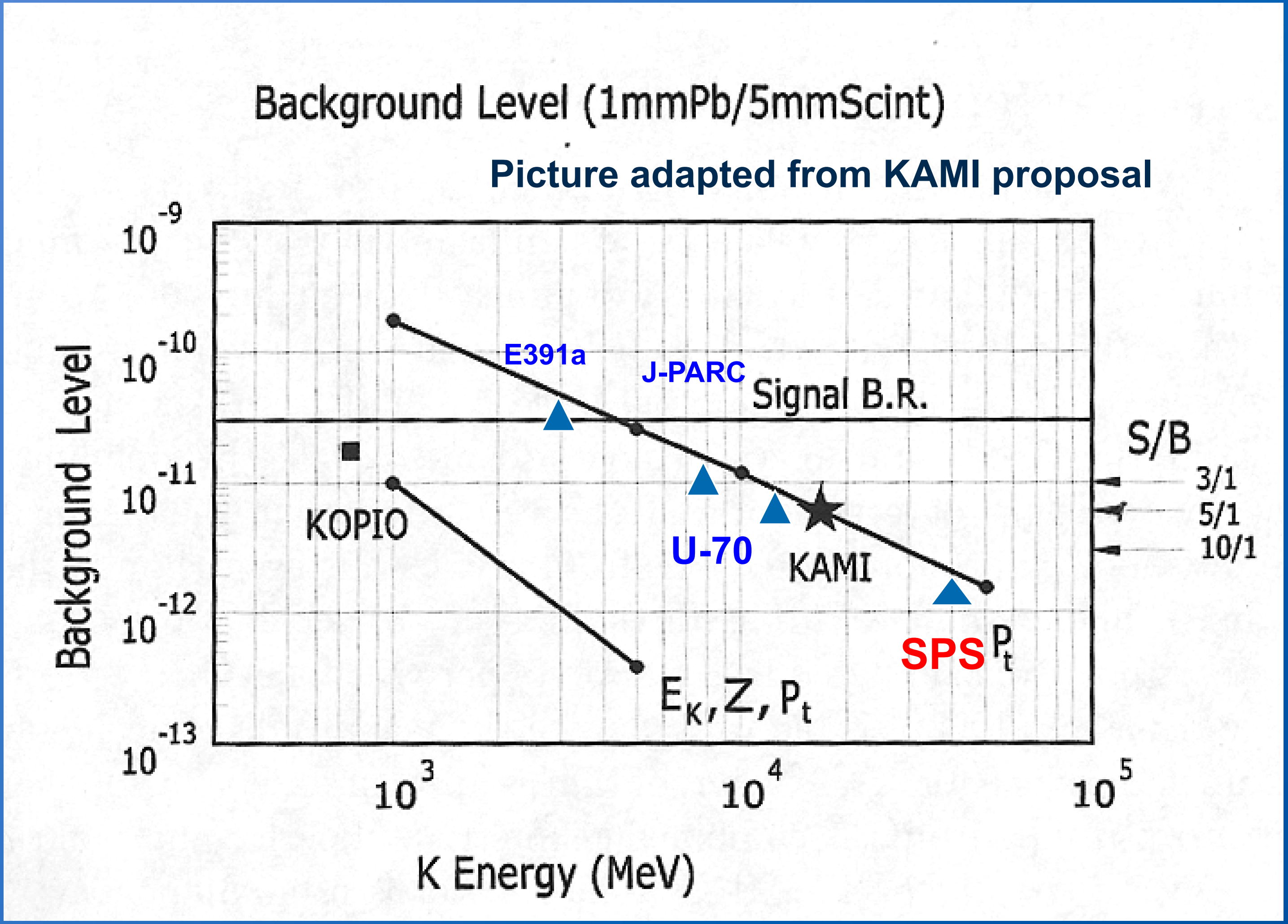
S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

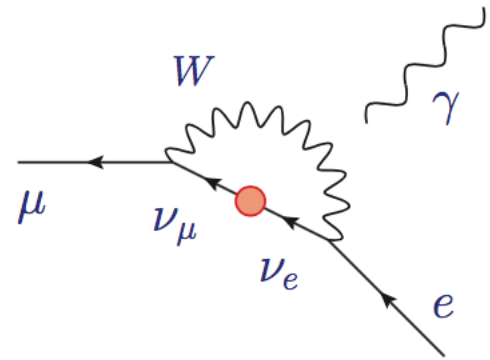
$K_L \to \pi^0 \nu\nu$: Comparison of Techniques



KLEVER@SPS SES is unique if the E391a/KOTO technique is established
KOPIO (Time of Flight) technique at the needs 100 ps long proton bunches

Charged Lepton Flavour Violation

- It is not 0 in the SM!
- **BR($\mu \rightarrow e\,\gamma$) ~ α ($\Delta m^2/m^2_W)^2$~10^{-54}**
- LFV exists in neutrino oscillations (first place where BSM physics is expected to appear if SM is an EFT)
- cLFV is "natural" in BSM extensions
- Any measurable effect would be a sign of new physics
- Evidence would be indirect, **need more than one experimental signature to reveal BSM structure**

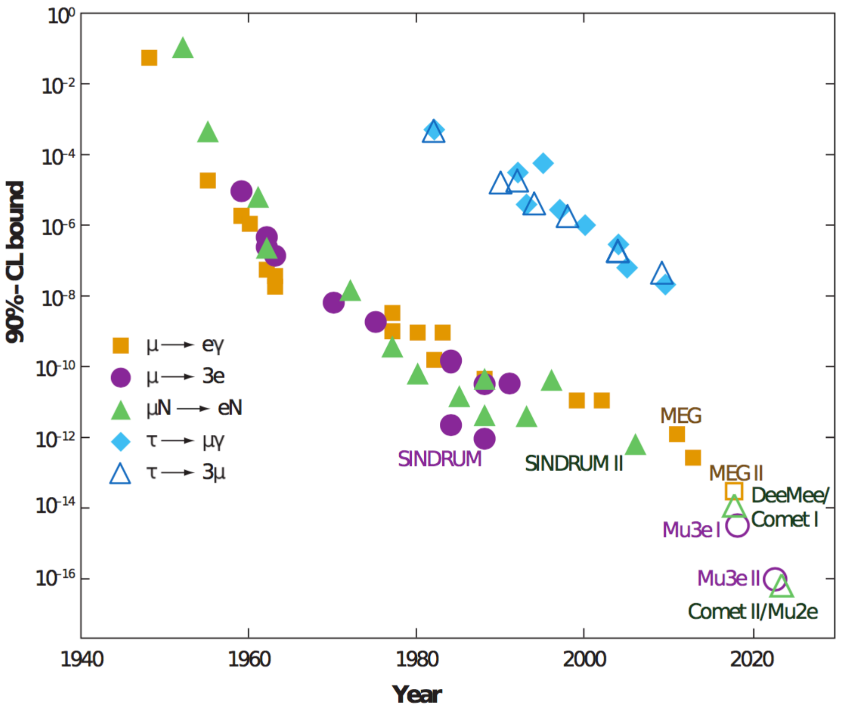


Golden observables: State of the art

- Br($\mu \to e\,\gamma$) < 4.2 x 10^{-13} 90% CL (MEG, 2016)
- Br($\mu \to eee$)< 1 x 10^{-12} 90% CL (Sindrum, 1988)
- $\mu N \to eN$ (Mu e conversion)

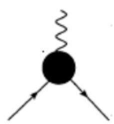
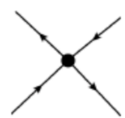
  Br(μ Au $\to$ e Au)< 7 x 10^{-13} 90% CL

  (Sindrum II, 2006)
- Br($\tau \to \mu\gamma$)< 4.4 x 10^{-8} 90% CL (Babar, 2010)
- Br($\tau \to 3\mu$) < 2.1 x 10^{-8} 90% CL (Belle, 2010)

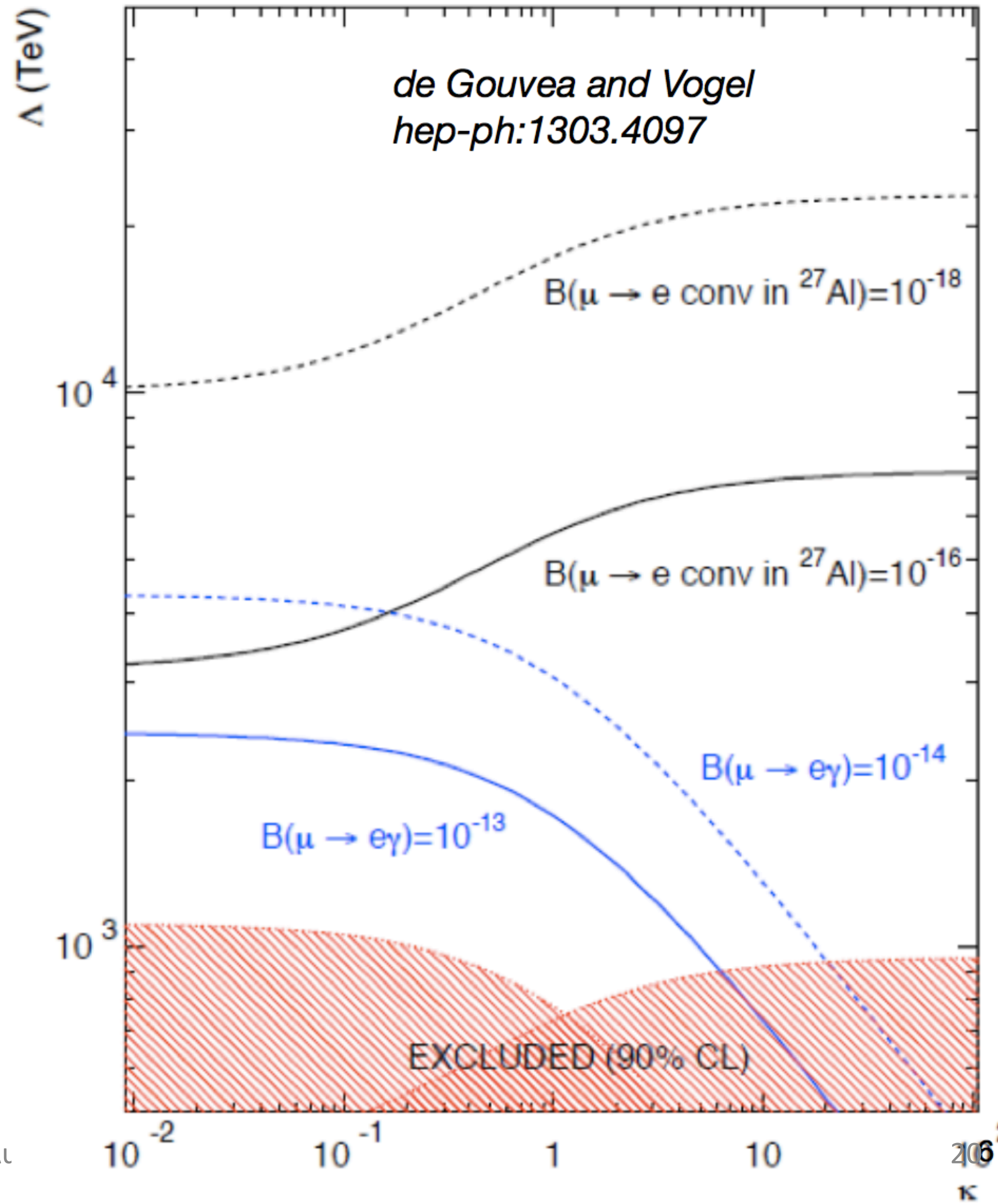


cLFV with “effective” Lagrangian

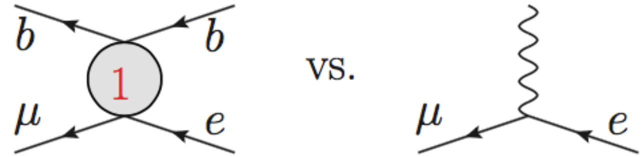
Model independent lagrangian

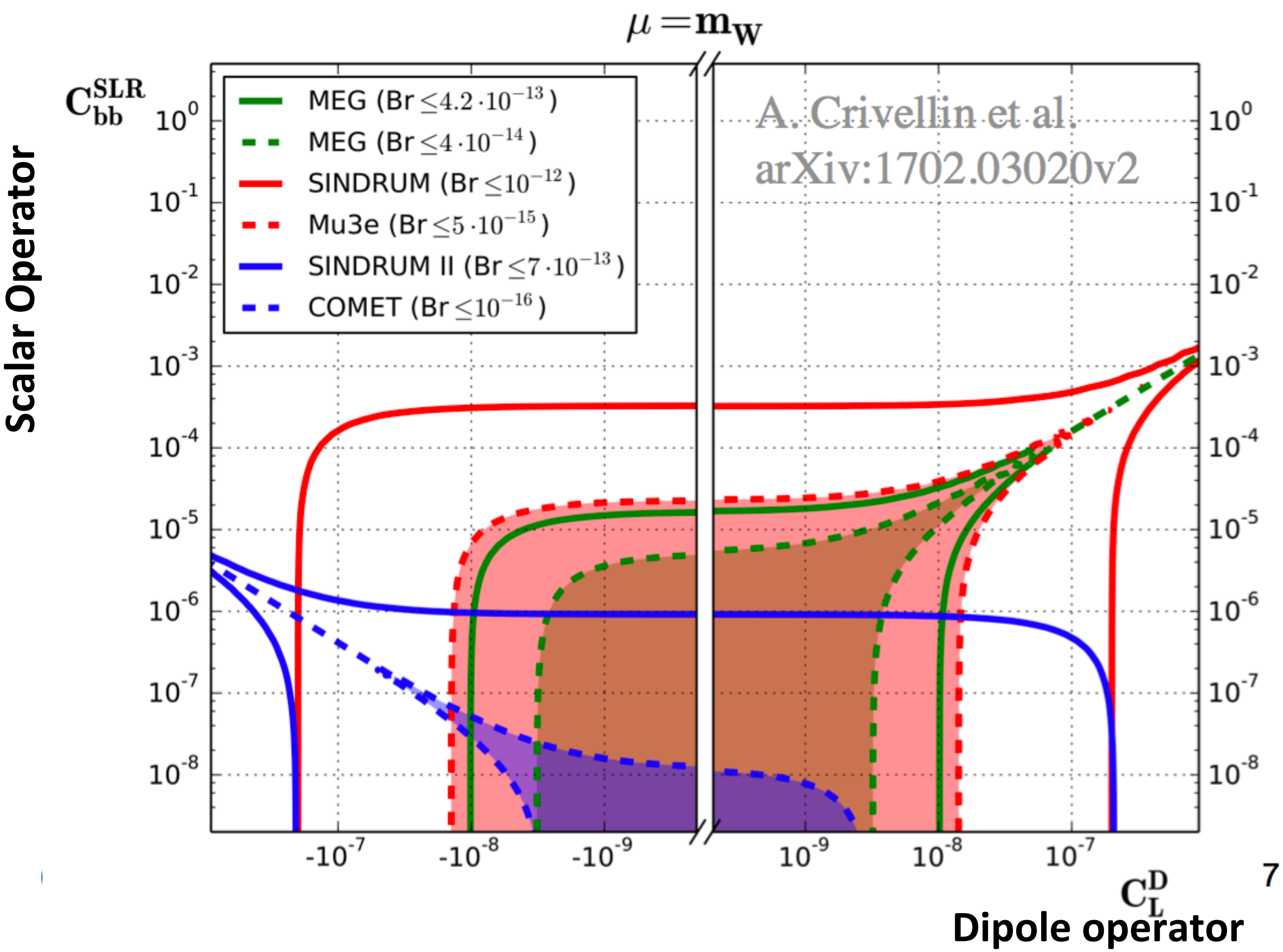
$$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$$  $$+ \frac{\kappa}{(\kappa+1)\Lambda^2} \times$$ 

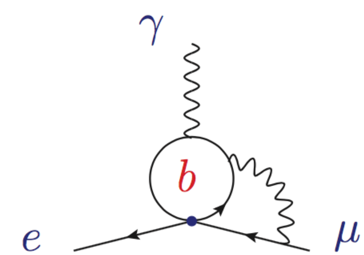
dipole term	contact term
$\mu \to e\gamma$	
$\mu \to eee$	
$\mu N \to eN$	



Example from systematic EFT approach (Crivellin, Davidson, Pruna, Signer)



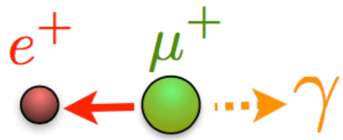




7

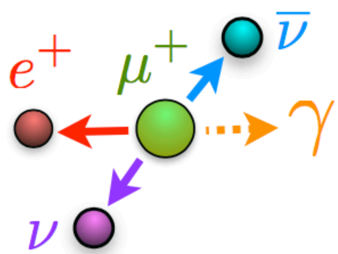
μ → e γ

Signature

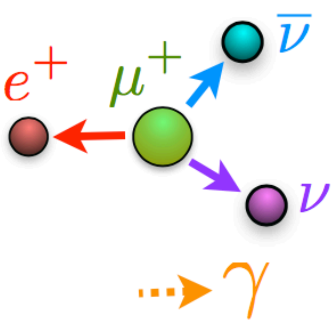


Signal: back-to-back topology, time coincidence

Backgrounds

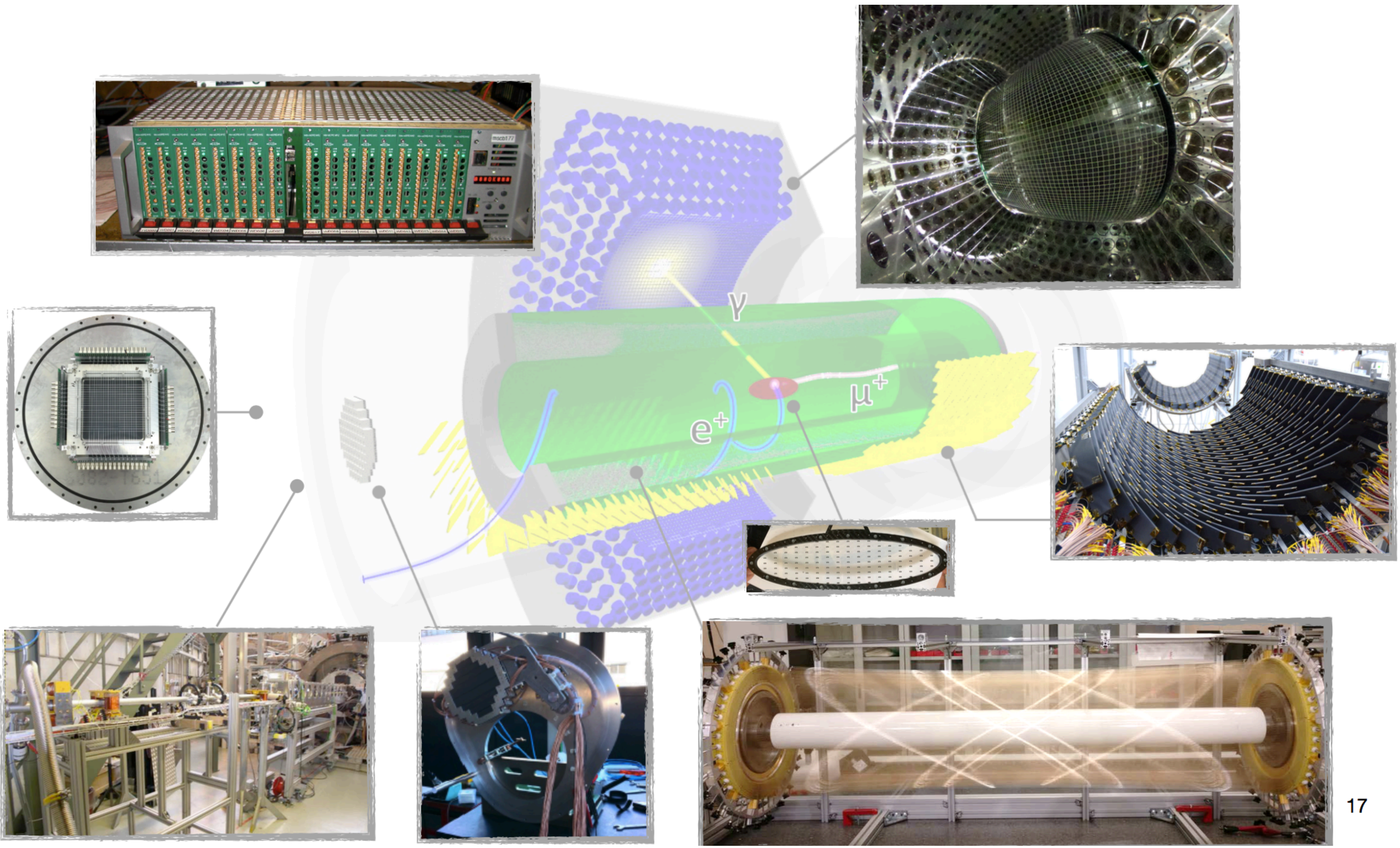


Irreducible: radiative decay with very little missing momentum (cf. Pruner, Signer, Ulrich, arXiv:1705.03787)

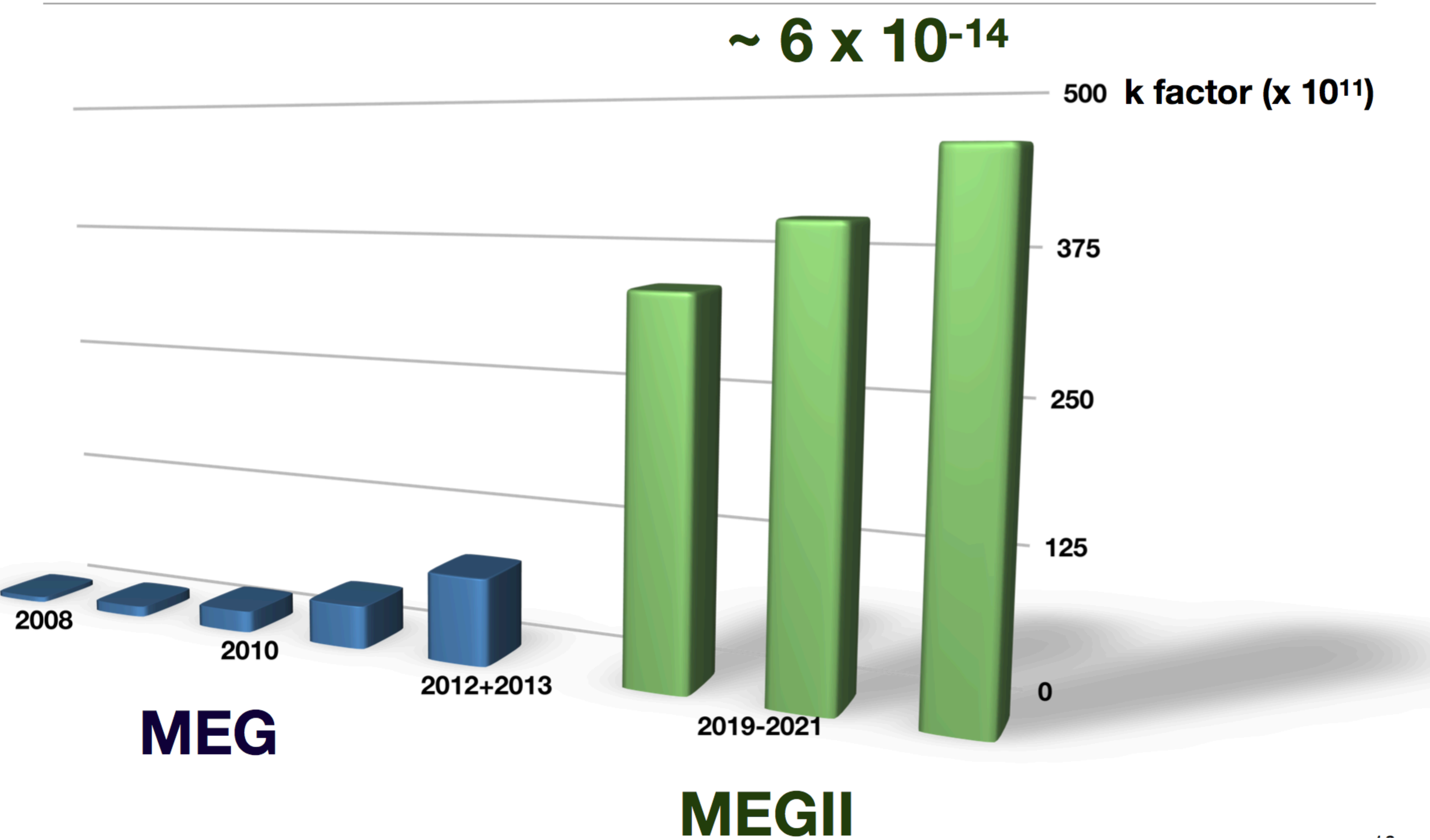


Reducible: Accidental photon overlapping to a Michel electron
→ Push timing, vertex, momentum and energy resolution

MEG2: Status

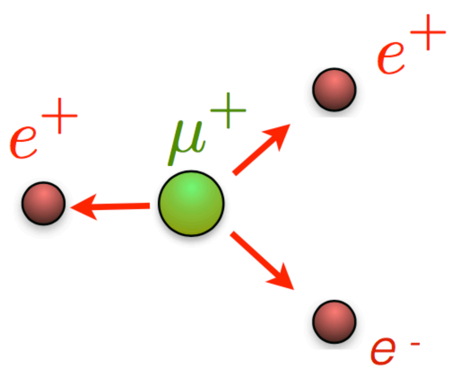


MEGII: Projection



$\mu \rightarrow eee$

Signature

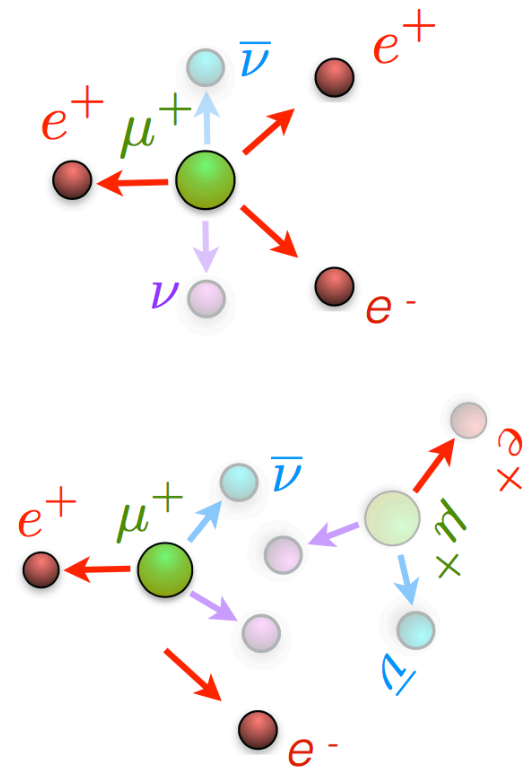


$$\Delta t_{eee} = 0$$

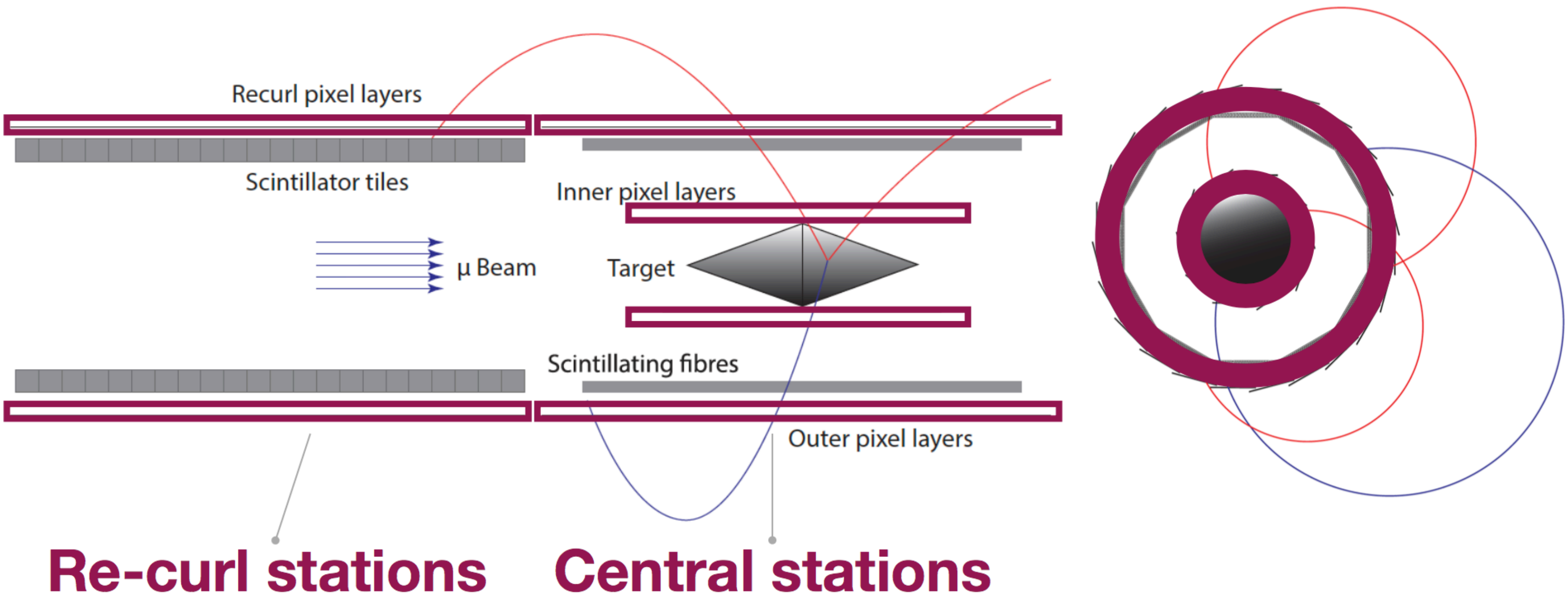
$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

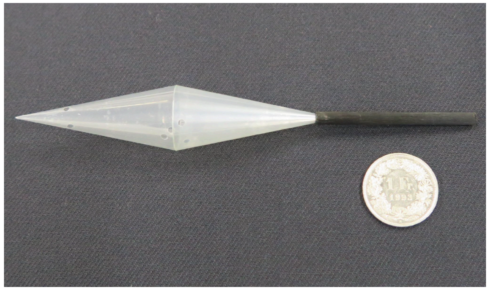
Background



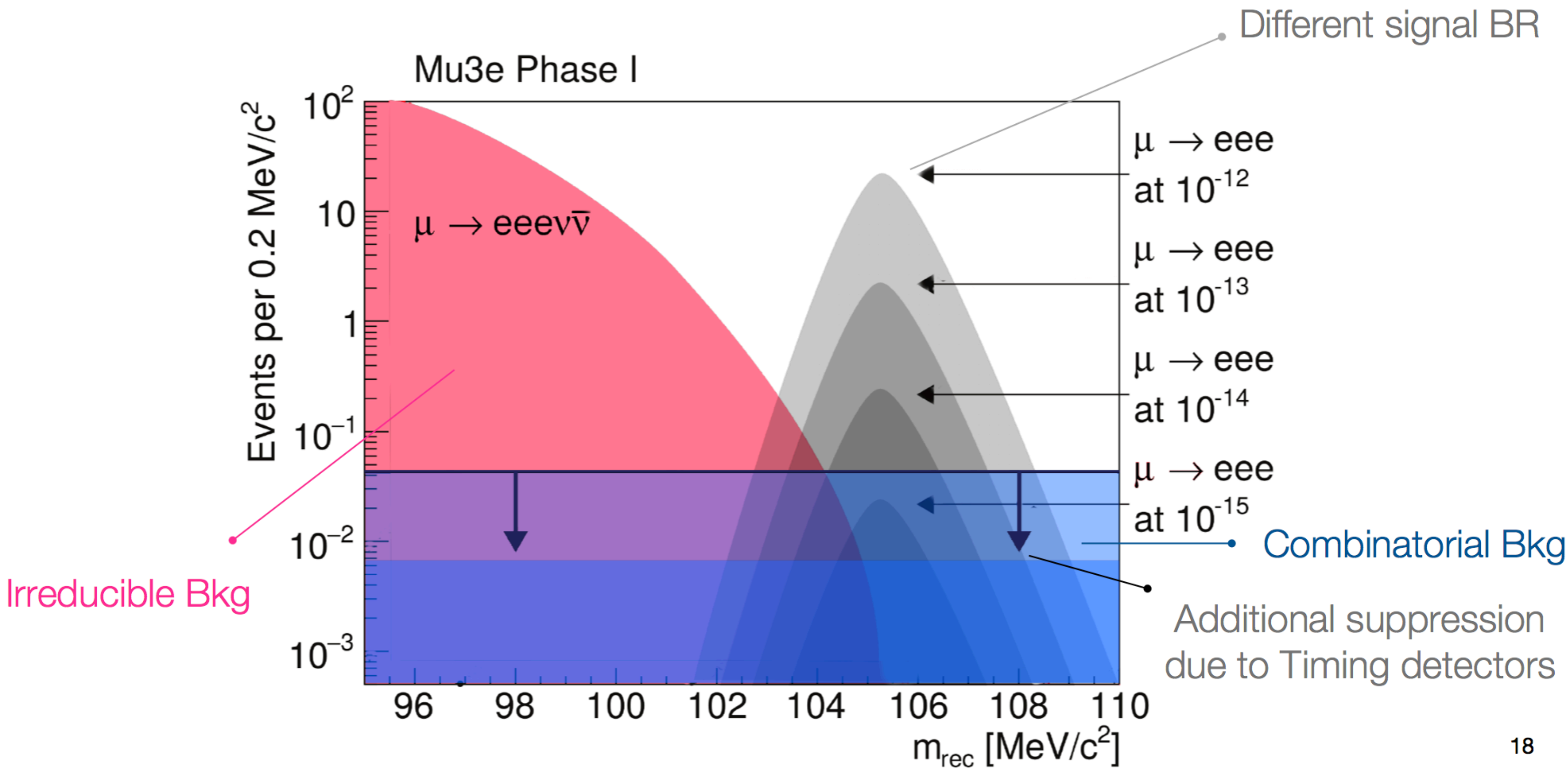
Mu3e



PSI PiE5 Beam: > 10^8 μ/s, 28 MeV/c
Target: mylar double hollow cone:
R=19 mm
L = 100 mm



Mu3e: Sensitivity



Data Taking from > 2021

μ – e conversion

- μ converts to an electron in the presence of a nucleus $\mu^- N \rightarrow e^- N$

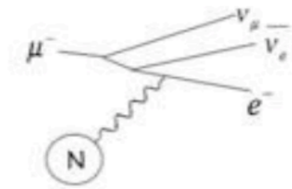
$$\mathrm{E}_e = \mathrm{m}_\mu\ \mathrm{c}^2 \text{ - } \mathrm{B}_\mu(\mathrm{Z}) \text{ - } \mathrm{C}(\mathrm{A}) = 104.973\ \mathrm{MeV}$$

- for Aluminum: $\begin{cases} \mathrm{B}_\mu(\mathrm{Z}) \text{ is the muon binding energy (0.48 MeV)} \\ \mathrm{C}(\mathrm{A}) \text{ is the nuclear recoil energy (0.21 MeV)} \end{cases}$

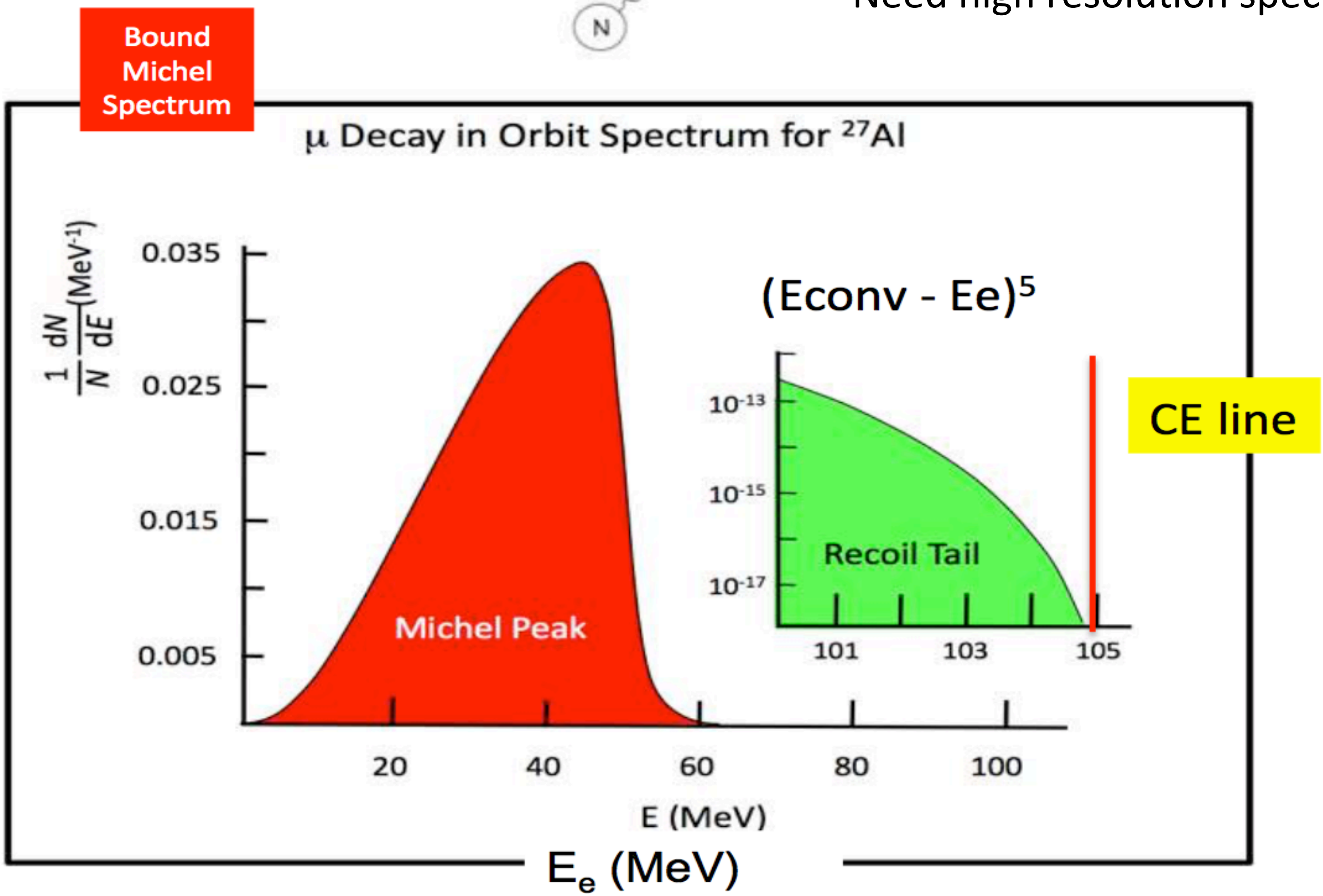
- Signal normalization:

$$\mathrm{R}_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

Decays in orbit



Modified Michel Spectrum
Recoil tail up to end-point
Need high resolution spectrometer

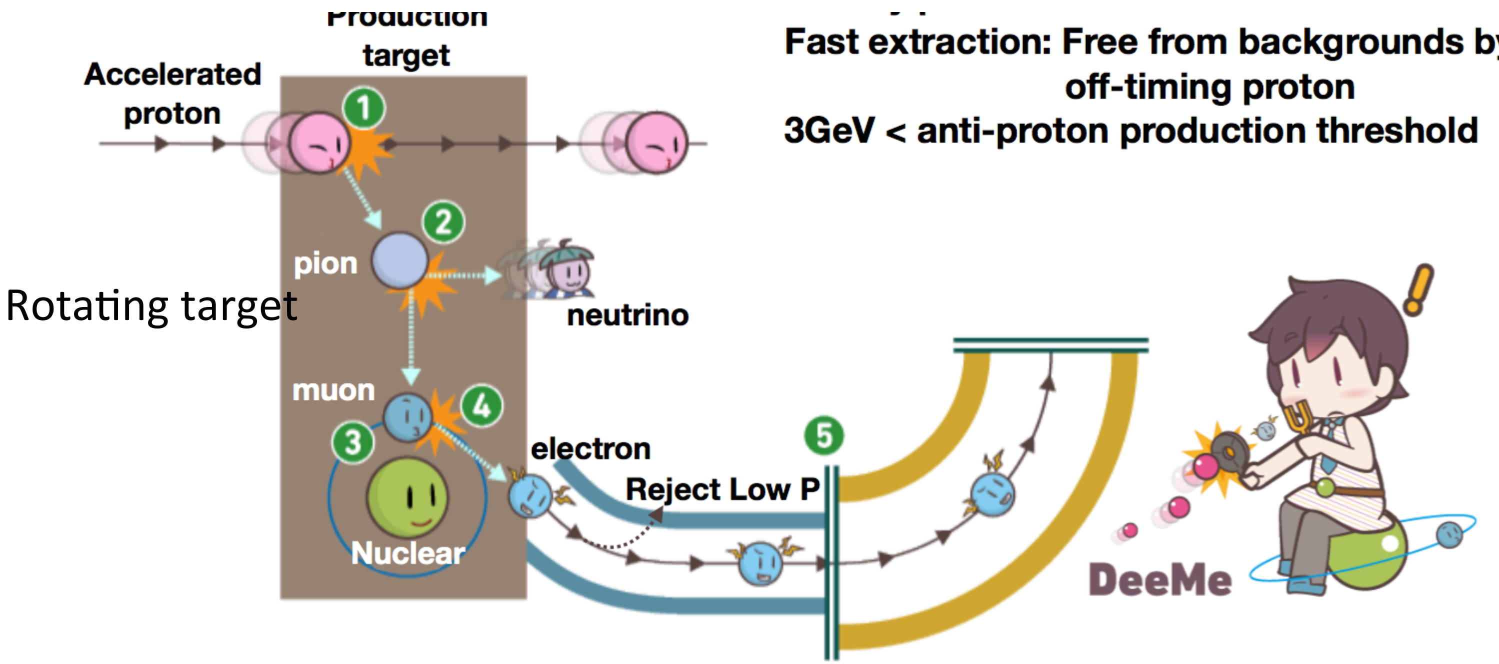


Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv: 1106.4756v2

DeeMe @ MLF 3 GeV RCS

Fast extraction: Free from backgrounds by off-timing proton

3GeV < anti-proton production threshold



1. Pion production by accelerated proton hits on target
2. $\pi^- \rightarrow \mu^- + \nu_\mu$
3. μ^- trapped by a nuclear. Muonic atom formation
4. Particles emitted from muonic atom
5. Extract electron via secondary beam line and measure the momentum

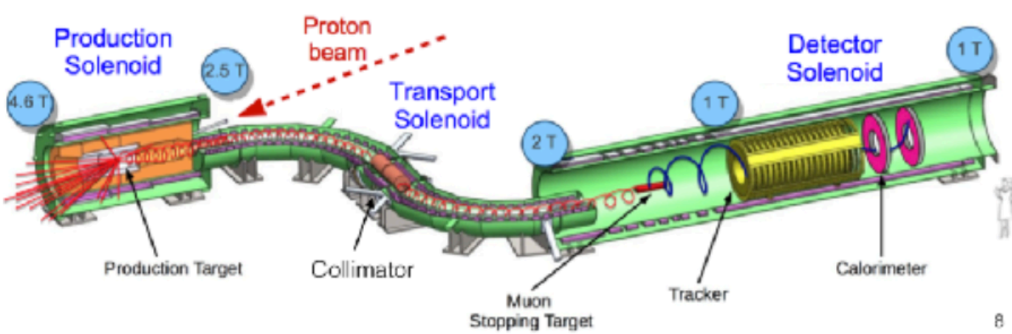
C target: 8×10^{-14} (1 y)

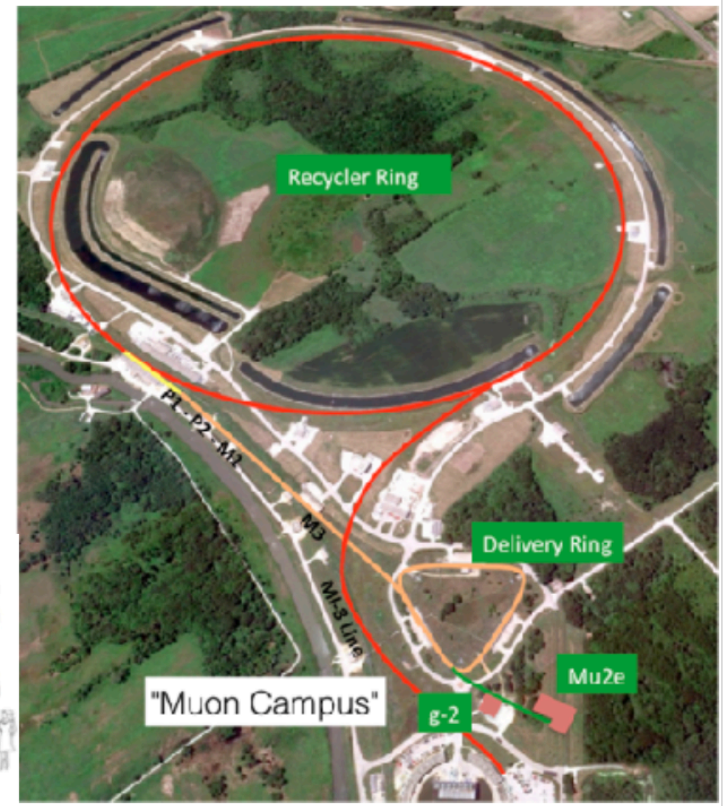
SiC target: 2×10^{-14} (1 y)

5×10^{-15} (4 y)

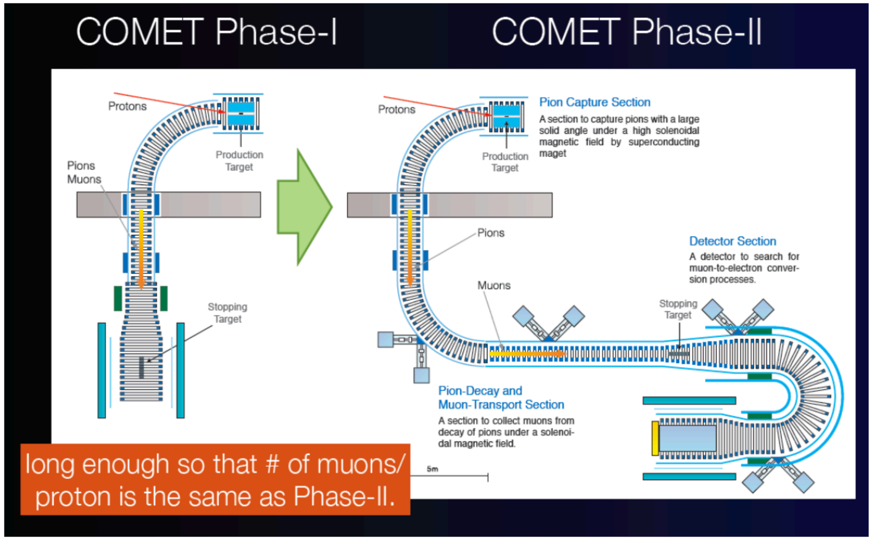
Mu2e

- 8GeV protons from FNAL accelerator complex
- Re-bunching in the Delivery Ring
- Injected onto the tungsten target located in Capture Solenoid magnet
- Single event sensitivity: 3×10^{-17}
- DAQ starts in 2022, 1 yr commissions and 3 yrs running.

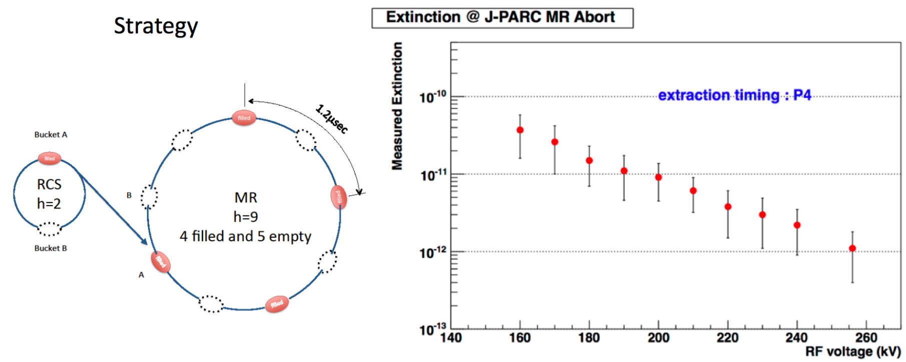




COMET Plans



The extinction



The new measurements with slow extraction are made. The data is under analysis.
The preliminary result meets the requirements of the experiment.

Phase I commissioning to start end of 2019

Parameter	Phase 1	Phase 2
Bending	90 degrees (beam) + 0 degrees (detector)	180 degrees (beam) + 180 degrees (detector)
SES	3×10^{-15}	3×10^{-17}
Beam power	3.2 kW	56 kW
POT	3×10^{19}	3×10^{21}
Stopped muons on target	$1,5\times10^{16}$	$1,5\times10^{18}$
Running time	O(100 days)	O(1 year)

SES ~ 3×10^{-15}

Outlook

- Testing forbidden and rare processes complements the particle physics done at colliders
- It exploits existing proton complex
- $K \rightarrow \pi \nu\nu$ decays, the "holy grail" of K physics, are being studied in detail, much progress expected within ~two years
- An Incisive Lepton Flavour Violation program in μ decays is in place
- Within a decade the current round of experiments will have explored a lot of unchartered territory

SPARES

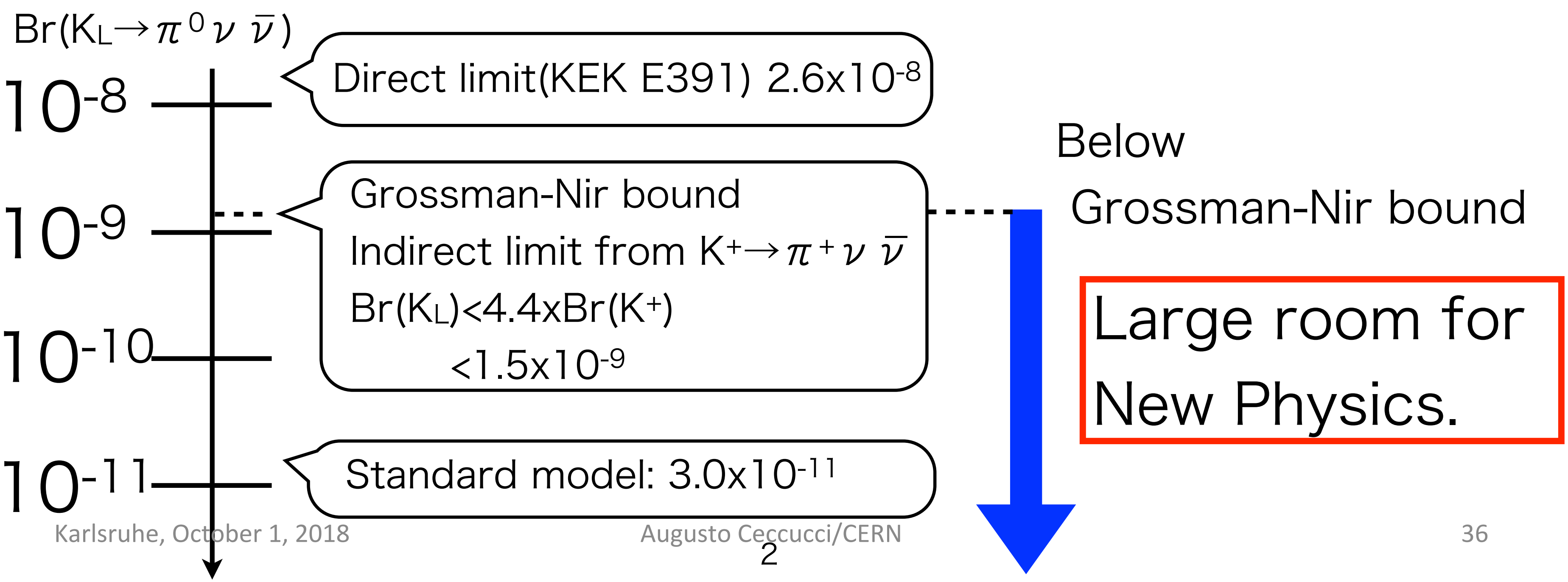
Background summary

Process	Expected events in R1+R2
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

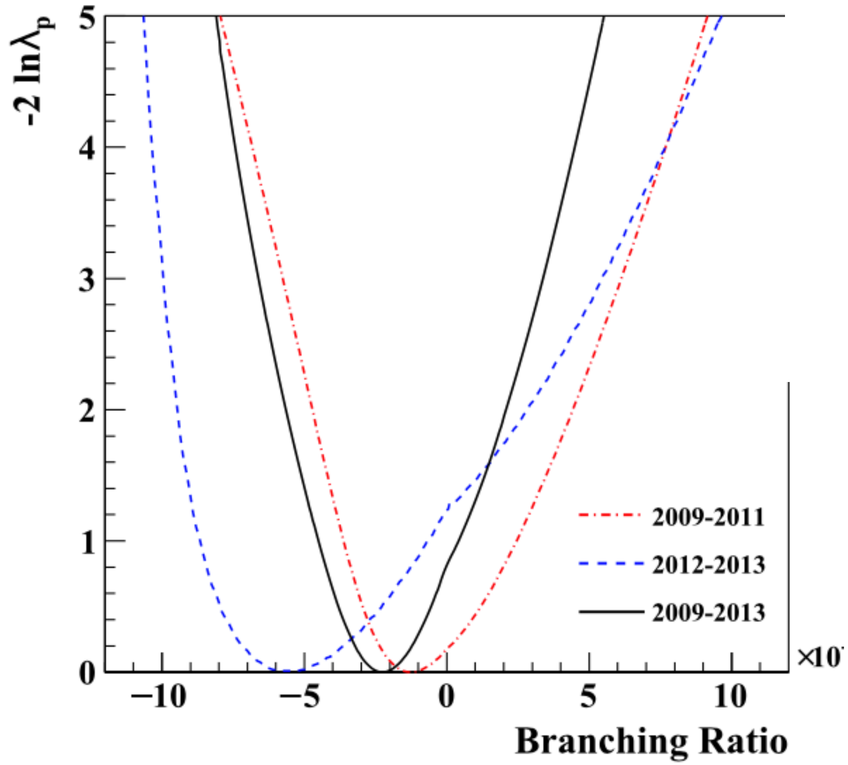
$K_L \to \pi^0 \nu \bar{\nu}$ decay

- Breaks CP symmetry directly
- Small theoretical uncertainty:2%
- Suppressed in the SM

-> Sensitive to New Physics



MEG: Result 2009-2013



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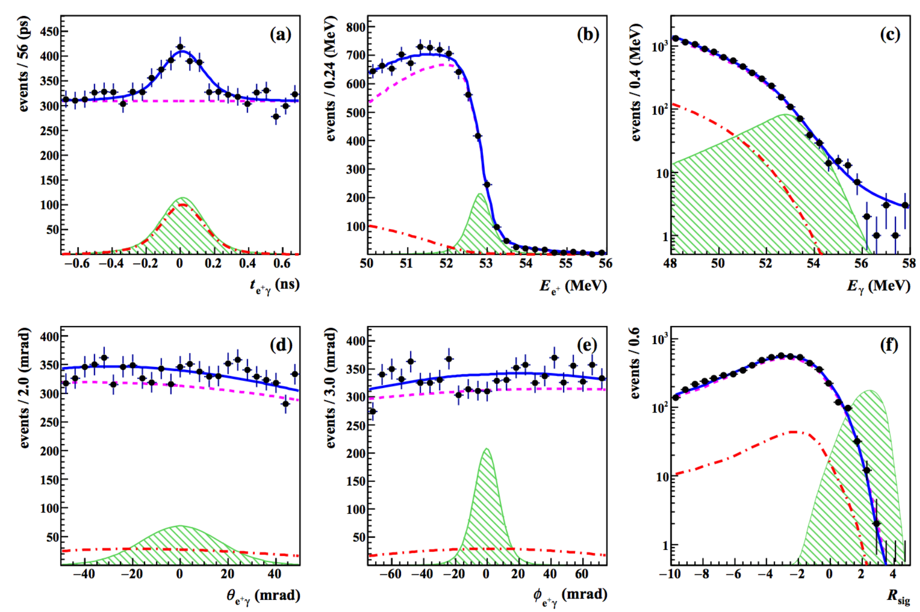
arXiv:1605.05081

Br(μ → e γ) < 4.2 x 10^{-13}
90% CL

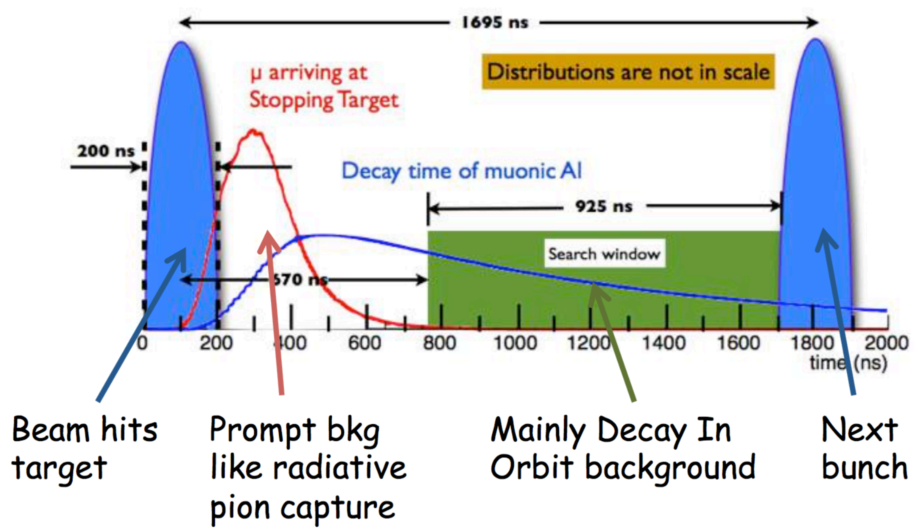
Table 2 Best fit values of the branching ratios ($\mathcal{B}_{fit}$), upper limits at 90 % C.L. ($\mathcal{B}_{90}$) and sensitivities ($\mathcal{S}_{90}$)

Dataset	2009–2011	2012–2013	2009–2013
$\mathcal{B}_{fit} \times 10^{13}$	−1.3	−5.5	−2.2
$\mathcal{B}_{90} \times 10^{13}$	6.1	7.9	4.2
$\mathcal{S}_{90} \times 10^{13}$	8.0	8.2	5.3



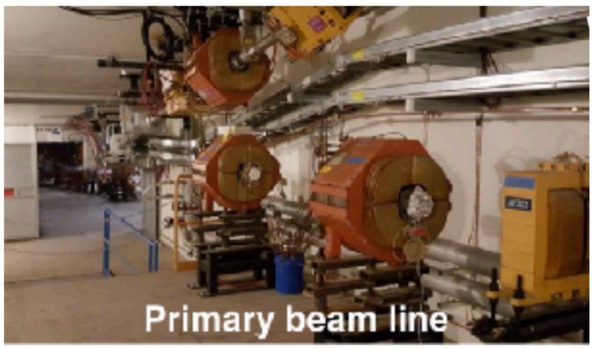
Suppression of Prompt Backgrounds

- Employ pulsed beams to avoid prompt backgrounds from pion/kaon decays
- Observing window starts ~ 1 μs after proton pulse
- Must eliminate out-of-time protons to 10^{-10} or better→ extinction measurements

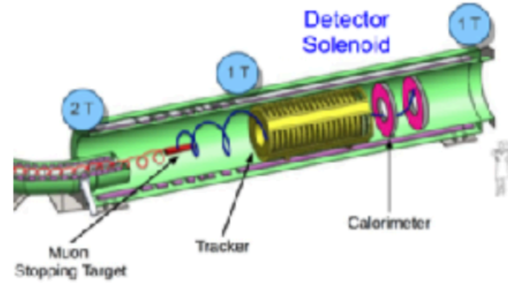


Mu2e

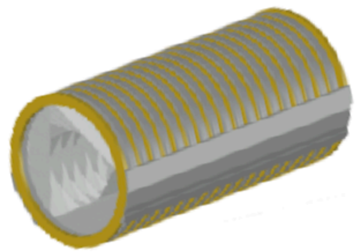
Facility Construction



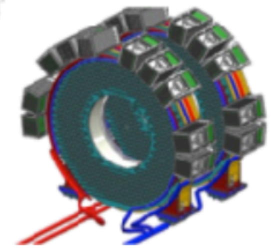
Detector Building



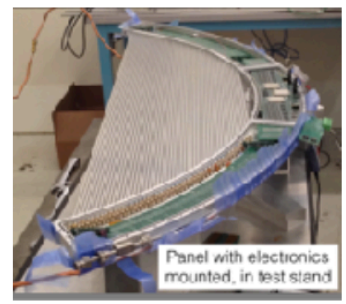
Straw Tube Tracker

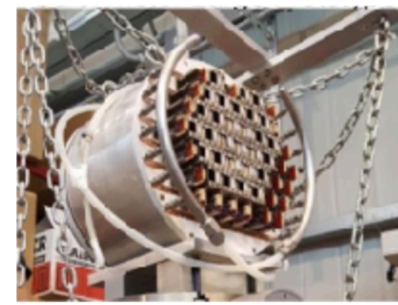


CsI Calorimeter

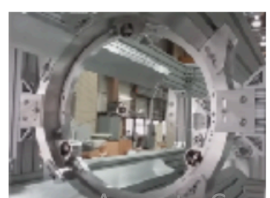


2 disks, each disk contains 674 undoped CsI crystals of $20x3.4x3.4cm^3$

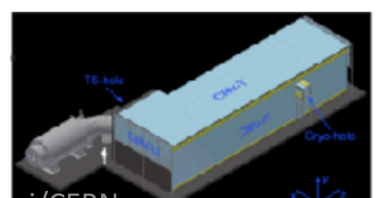




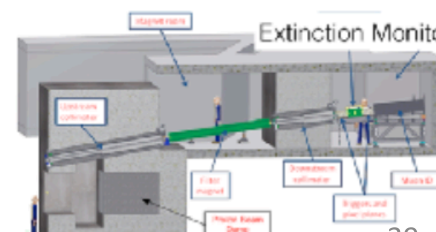
Other essential components



Target remote handling



CR Veto



Extinction monitor