High Sensitivity Flavor Physics Measurements at Low Energies

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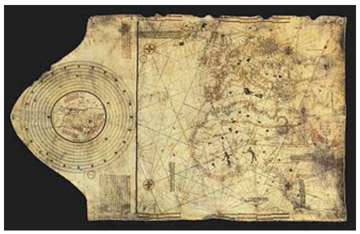
PSI Zuoz Summer School 2014

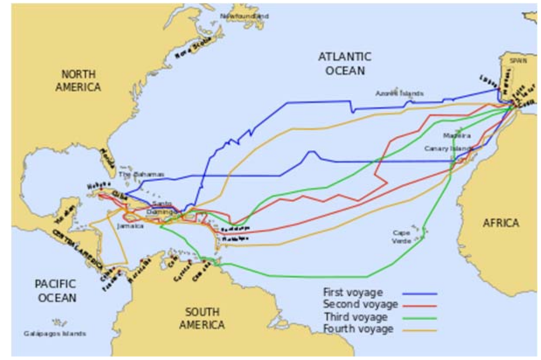
15-16th Century Explorations into Unknown Waters

Vague but well motivated ideas of what to look for --- really searching in the dark….

Christoforo Colombo– 1492 search for East Indies…



Discovered



Amerigo Vespucci– 1499 search for Asia …

Discovered

Ponce de Leon – 1513 search for the Fountain of Youth …

Discovered

Disney World

D. Bryman Zuoz 2014

21^{st}Century Explorations Into Unknown Waters

- High energy
- Dark matter
- Dark energy
- High precision, high sensitivity measurements at low energy: e.g. lepton flavor violation, universality tests, EDMs, CP violation…

Vague but well motivated ideas of what to look for --- really searching in the dark….

Here be dragons.

The 1265 Psalter world map.

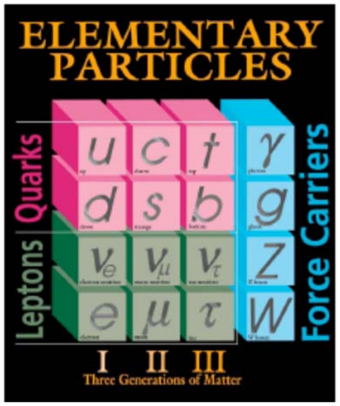
Searches for BSM Physics so Far…

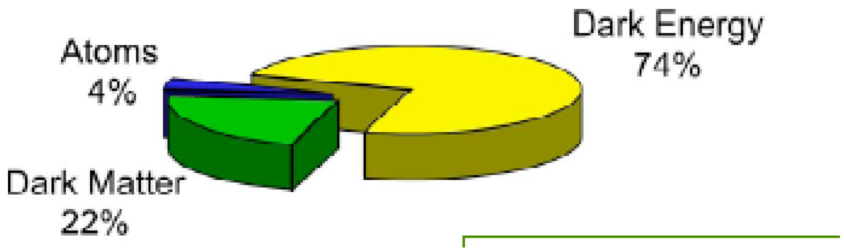
Current
Conclusion:

No experimental tail sighted …
No definite theory (but if you find it, “we’ll make one!”)

Standard Model : *A great story …*
but definitely *not the whole story…*

+ Higgs (√)





- ***Cosmological issues***: inflation, dark matter, dark energy, ***matter anti-matter asymmetry…***
- ***Theoretical issues***: gravity (CC), neutrino mass, ***flavor***, hierarchy problem, strong CP, ….

The Flavor Puzzle

Experiments ahead of theory

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

- **Weak states $\not\Leftrightarrow$ mass states**
- **Quark, lepton flavors not conserved**

Unexplained observations (no theory of flavor):

- Three ("identical") generations
- Huge mass differences between and within the generations
  Exceptionally small neutrino mass
- Universality of interactions
- CP violation
- Symmetry between lepton and quark sectors (GUT, scale?)

Probing for new physics requires a wide field of view!

"Precision" Flavor Physics at Low Energies

A small set of crucial rare particle decays extremely sensitive to new physics at high mass scales and new theories of flavor

Important Flavor-Changing Rare Processes

$\mu \rightarrow e\gamma, \mu$-e Conversion

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

$b \rightarrow s\gamma$, $\mathrm{B} \rightarrow \mu\mu$, $\tau \rightarrow \mu\gamma$...

Discoveries of new physics at the LHC and elsewhere would require a range of precision flavor physics experiments to home in on the new interpretation.

Experiments Seeking Insight into the Flavor Puzzle

- **New Physics at High Mass Scales – virtual effects**
- **Unknown Couplings**

State-of-the-art sensitivity $Br<10^{-12}$

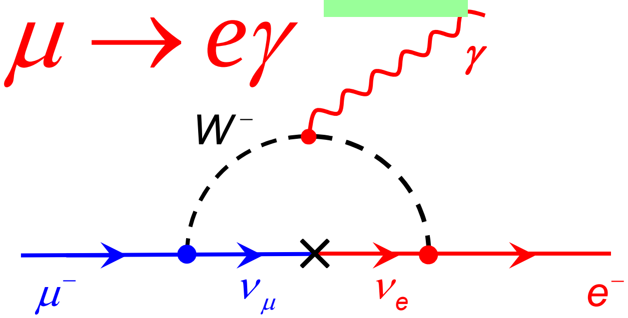
Exotic Searches ***New physics if seen.*** ***Experiments limit how far we can go***	Charged Lepton Flavor Violation $\mu \to e\gamma, 3e$ $\quad \mu^- N \to e^- N$ ("μ-e Conversion") $\tau \to e\gamma, \mu\gamma \ldots$ $\quad K_L^0 \to \mu e, B_q \to \mu e \ldots$ Baryon and Lepton Number violation/GUTS $\quad p \to \pi^0 e^+$ Lepton Number Violation/ Majorana mass $\quad \beta\beta_{0\nu}$ Sterile neutrinos/mixing $\quad \nu$ Oscillations
BSM Physics ***New physics if deviations from well-calculated SM predictions occur. Theory limits how far we can go.***	CP/T Violation $\quad e, \mu, n \ldots EDM$ $(g-2)_\mu, \mu^- H$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}, \frac{\tau^+ \to e^+\nu\nu}{\tau^+ \to \mu^+\nu\nu}$ Universality $K^+ \to \pi^+ \nu\bar{\nu}, K_L^0 \to \pi^0 \nu\bar{\nu}$ $B \to \mu\mu, b \to s\gamma, \ldots$

Lepton Flavor Violation

Neutrino oscillations ⟶ lepton flavor numbers not conserved but consequent SM charged lepton flavor violation too small to be observed.

$\mu \to e\gamma$

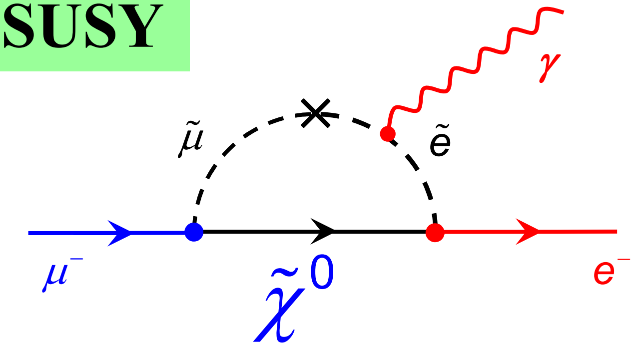
SM



$$BR(\mu^- \to e^-\gamma)\big|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-54}$$

Petcov '77, Marciano-Sanda '77

SUSY



$$BR(\mu^- \to e^-\gamma)\big|_{SUSY} \approx 10^{-5} \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}} \left(\frac{100\ \text{GeV}}{m_{SUSY}}\right)^4 \tan^2\beta \approx 10^{-13}$$

- Observation means new physics.
- Some SUSY models predict BR($\mu \to e\gamma$) near the experimental limit (always!).

$$\text{Sensitivity to new physics} \sim \frac{1}{M_H^4} \text{ with } M_H \sim 1-100\ \text{TeV}$$

$\mu - e$ Conversion

Ordinary nuclear muon capture (MC):

$$\mu^- + (Z, A) \rightarrow \nu_\mu + (Z-1, A)$$

Muon decay-in-orbit (DIO):

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

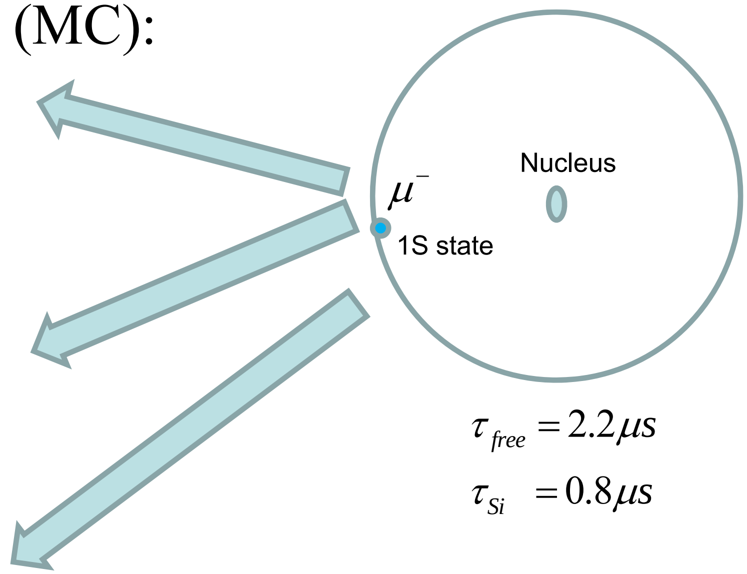
OR... Lepton Flavor Violation:

$\mu - e$ Conversion (coherent)

$$\mu^- + (Z, A) \rightarrow e^- + (Z, A)$$

$$P_e = m_\mu - B.E.$$

Muonic Atom



$\tau_{free} = 2.2\mu s$

$\tau_{Si} = 0.8\mu s$

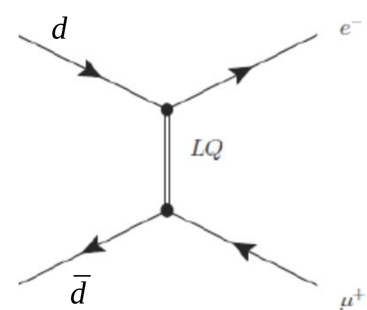
MC : DIO

H (1:1000)

Si (2:1)

Cu (13:1)

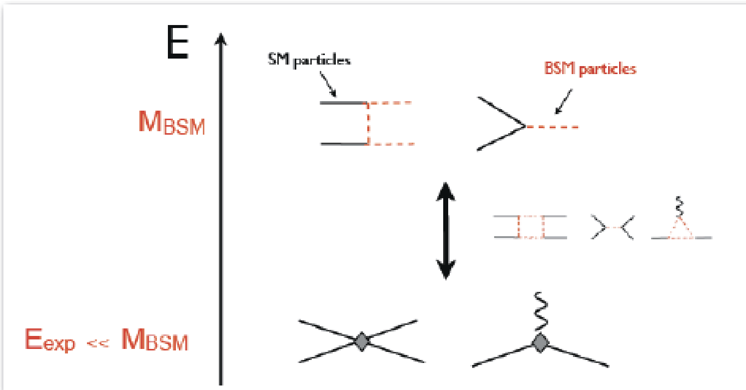
Additional new physics possibilities e.g. lepto-quarks…



Sensitivity to new physics

$\sim \frac{1}{M_H^4}$ with $M_H \sim 1-1000$ TeV

Effective theory framework



CPV and LFV

Cirigliano
IF Workshop 2013

At low energy, BSM physics is described by local operators; LFV and dipole moments probe strengths of different operators and their flavor structures

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

$\Lambda \leftrightarrow M_{\rm BSM}$ $\quad$ $C_i\ [g_{\rm BSM},\ M_a/M_b]$

Effective Operators for CP-violating EDMs and LFV processes:

Lavinac Paradisi

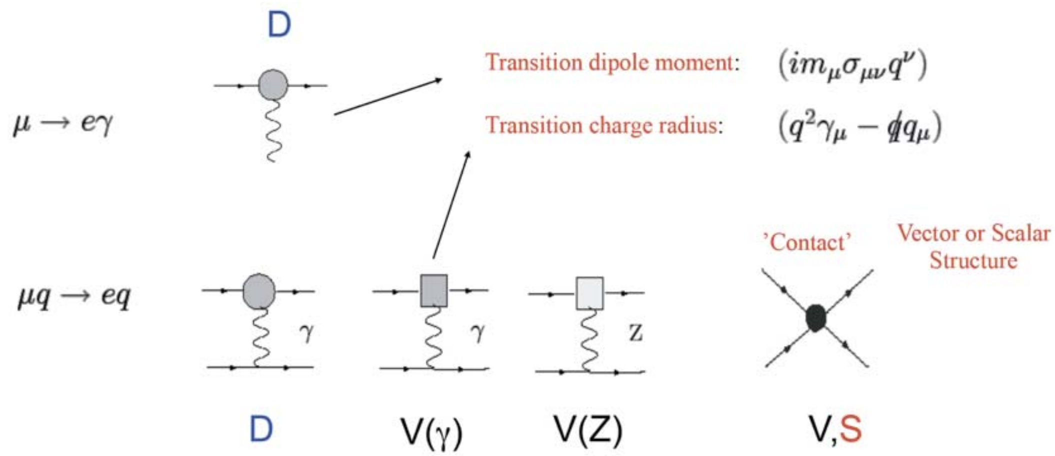
$$\bar{l}_i \sigma^{\mu\nu} \gamma_5 l_i F^{em}_{\mu\nu} \quad \bar{l}_i \sigma^{\mu\nu} l_j F^{em}_{\mu\nu} \quad \bar{l}_i \Gamma^a l_j \bar{q}_k \Gamma^a q_l \quad \bar{l}_i \Gamma^a l_j \bar{l}_k \Gamma^a l_l$$

with dimensionless coefficients $\varepsilon \sim \frac{M_W^2}{M_{NP}^2} \frac{g_{NP}^2}{g_W^2} \delta_{CPV} \delta_{mix}$

Observable	Operator	Limit on ϵ
eEDM	$\overline{e_L} \sigma^{\mu\nu} \gamma_5 e_R F_{\mu\nu}$	$\leq 1.1 \times 10^{-3}$
B($\mu \to e\gamma$)	$\overline{\mu} \sigma^{\mu\nu} e F_{\mu\nu}$	$\leq 1.4 \times 10^{-4}$
B($\tau \to \mu\gamma$)	$\overline{\tau} \sigma^{\mu\nu} \mu F_{\mu\nu}$	$\leq 2.2 \times 10^{-2}$
B($K_L^0 \to \mu^\pm e^\mp$)	$(\overline{\mu} \gamma^\mu P_L e)(\overline{s} \gamma^\mu P_L d)$	$\leq 2.9 \times 10^{-7}$

Flavour physics of leptons and dipole moments Eur.Phys.J.C57:13-182,2008

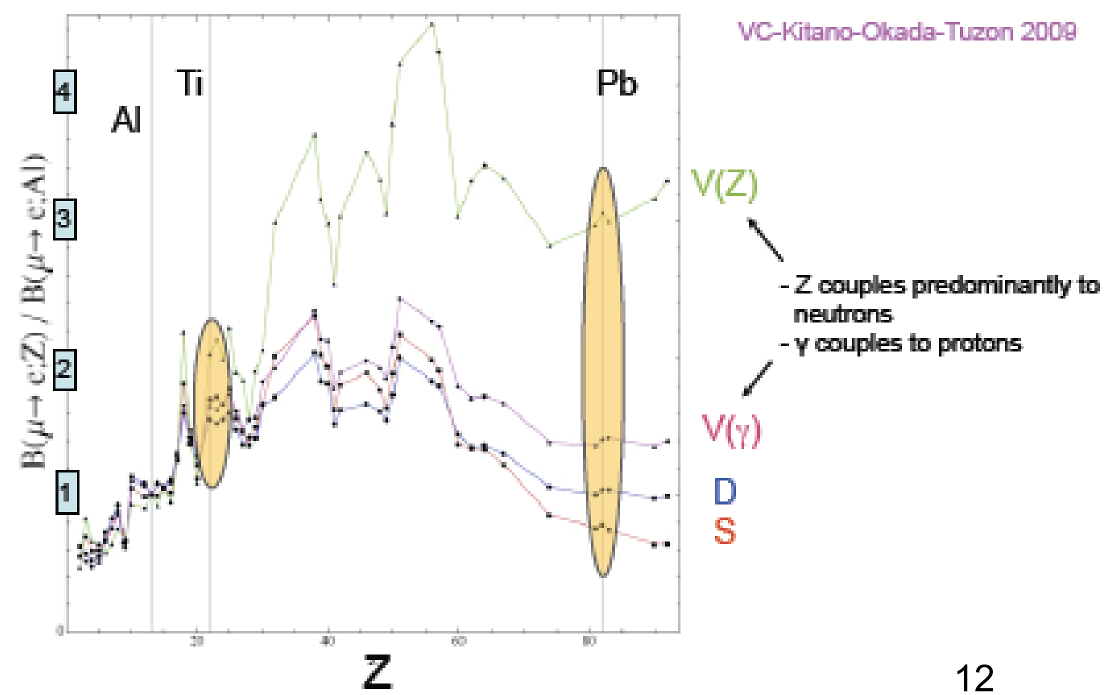
$\mu \to e\gamma$ and $\mu \to$ e Conversion Test Different Operators



Cirigliano
IF Workshop
2013

Target-dependence of μ→e rate

Some theory uncertainties cancel in ratios

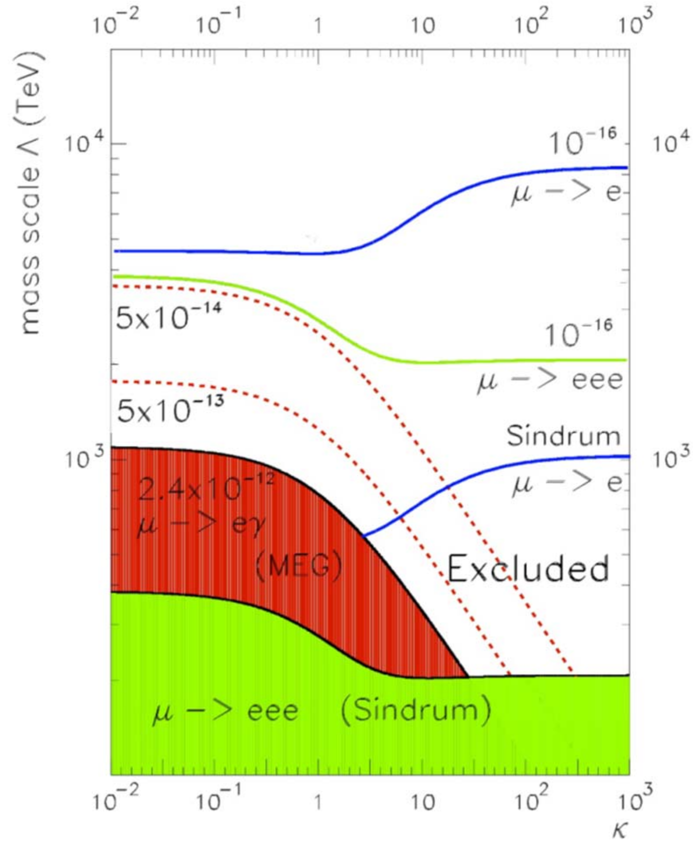


Model discriminating power by
Measuring different processes.

Two operators:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R \gamma_\mu e_L \bar{f}\gamma^\mu f$$

κ controls relative strength of
dipole vs vector operator
Λ is the mass scale (TeV)



De Gouvea, Vogel

There may also be important connections between models for Charged Lepton flavor Violating reactions, g-2, and neutrino mass generation e.g. via Seesaw types I, II, III..

Paradisi, Hambye

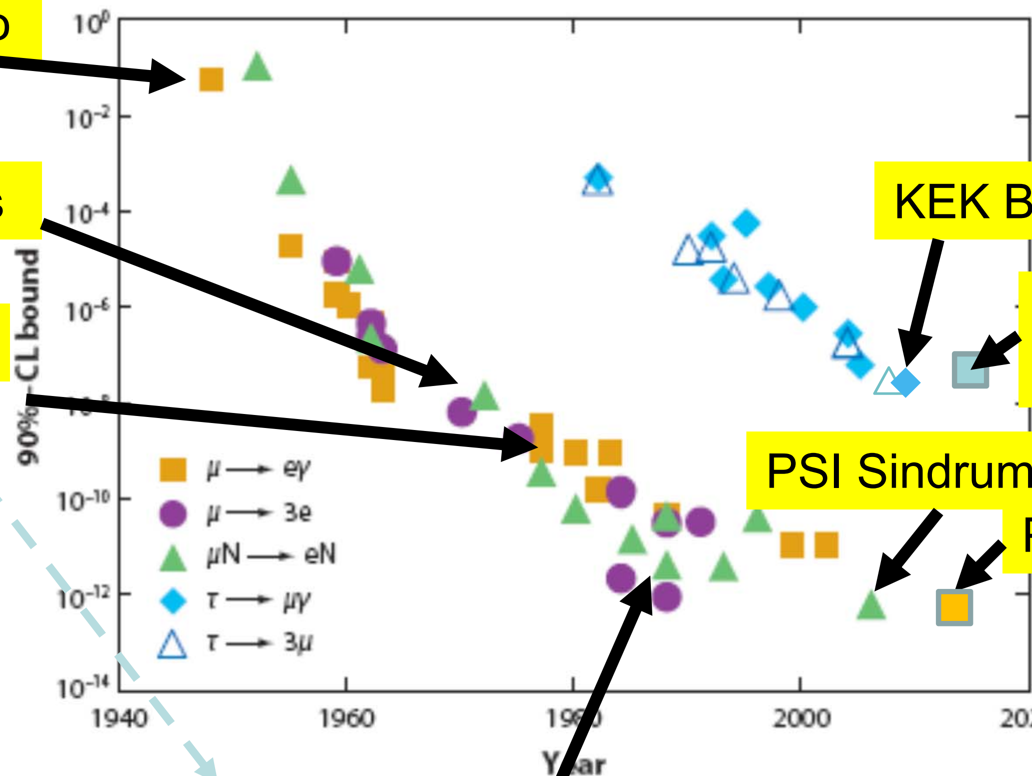
History of **Lepton Flavor Violation** Experiments

Hincks, Pontecorvo

D.B. Thesis

μ->eγ 1977

90% CL



KEK Belle

LHCb
$B_S \rightarrow \mu e$

PSI Sindrum II (2006)

PSI MEG (2013)

TRIUMF TPC (1987)

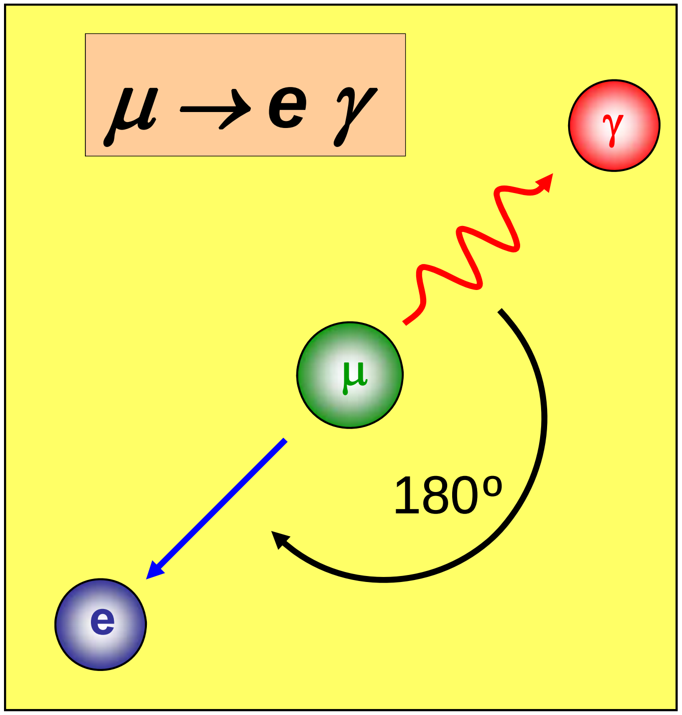
Future: Many new experiments coming.

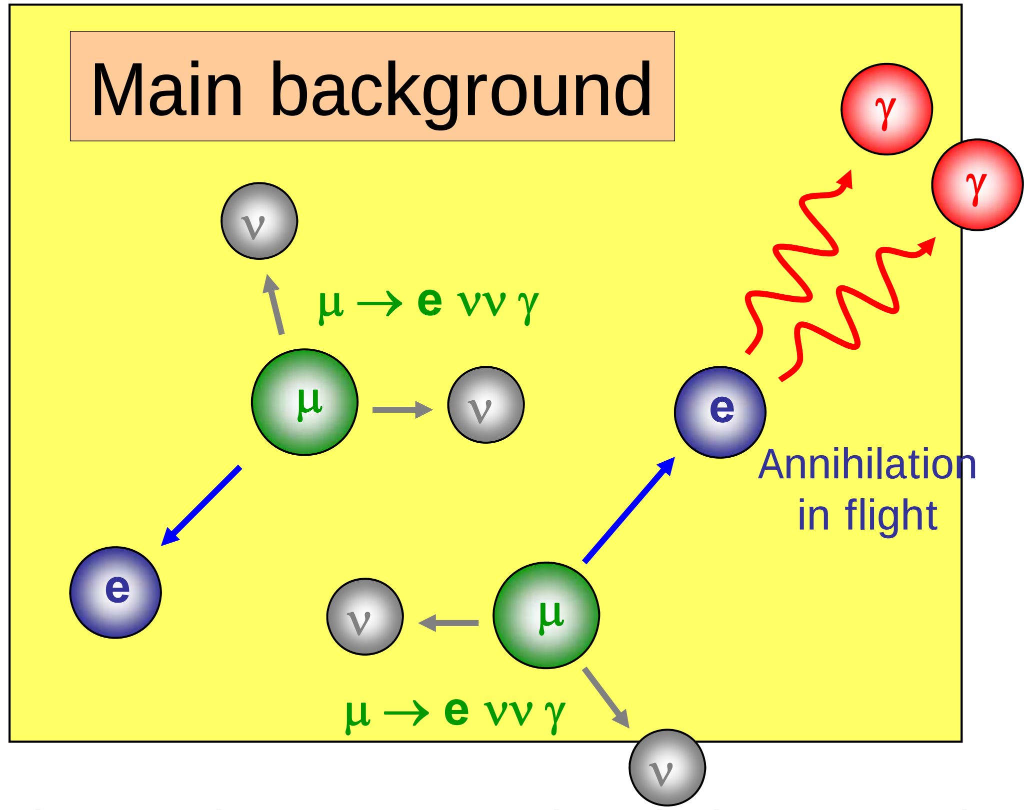
Based on Marciano, Mori, Roney 2010

Decay topology

Accidental Coincidence of 2 Muon decays:

$\mu \to e\nu\nu + \mu \to e\nu\nu\gamma$





μ → e γ signal very clean

- $E_g = E_e = 52.8$ MeV
- $\theta_{\gamma e} = 180^o$
- e and γ in time

Background: Energy, spatial, timing resolutions
Good pile-up rejection

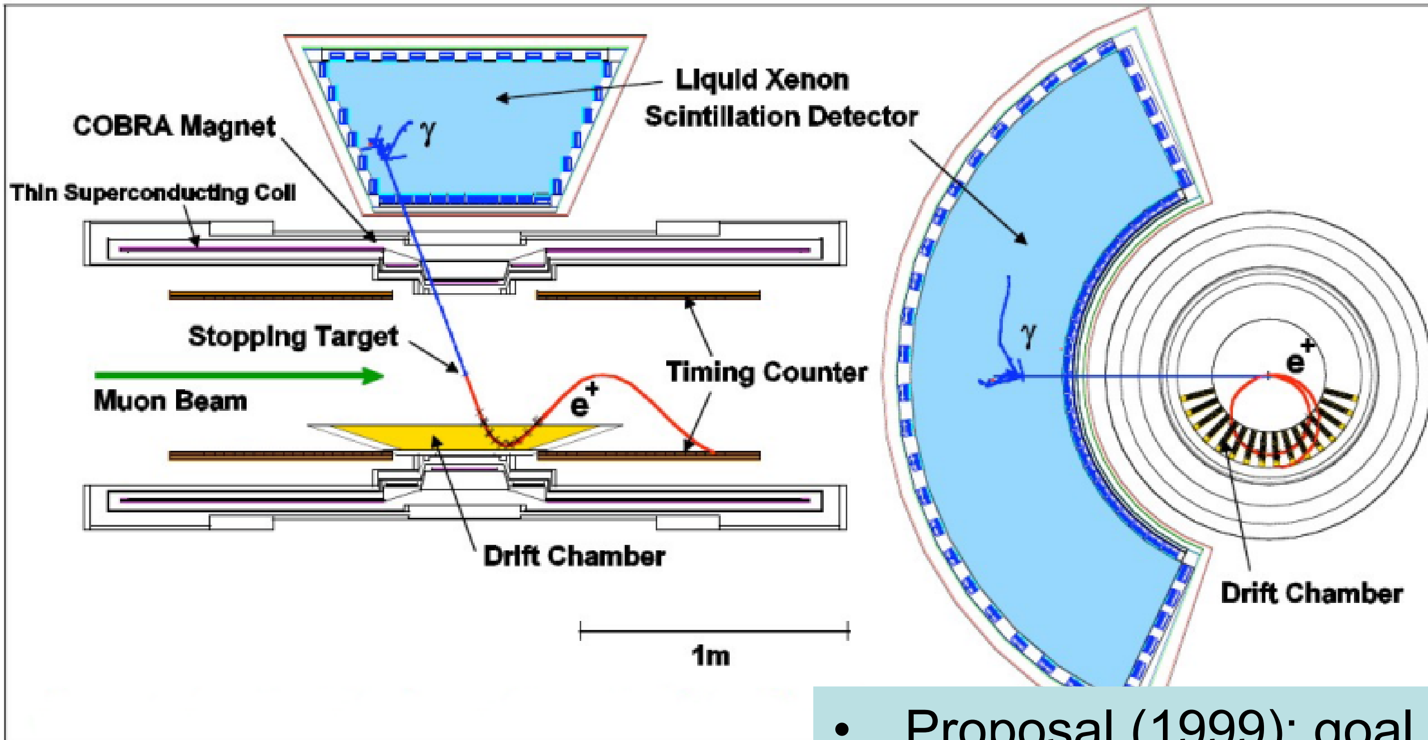
$$\Delta B(\mu \to e\gamma) = \left(\frac{R_\mu}{d}\Delta t\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta}{2}\right)^2 f\left(\theta_\gamma\right)\eta_{IVB}$$

S. Ritt 2006

M. Ahmed et al. 2002

MEG at PSI

$\mu \rightarrow e\, \gamma$



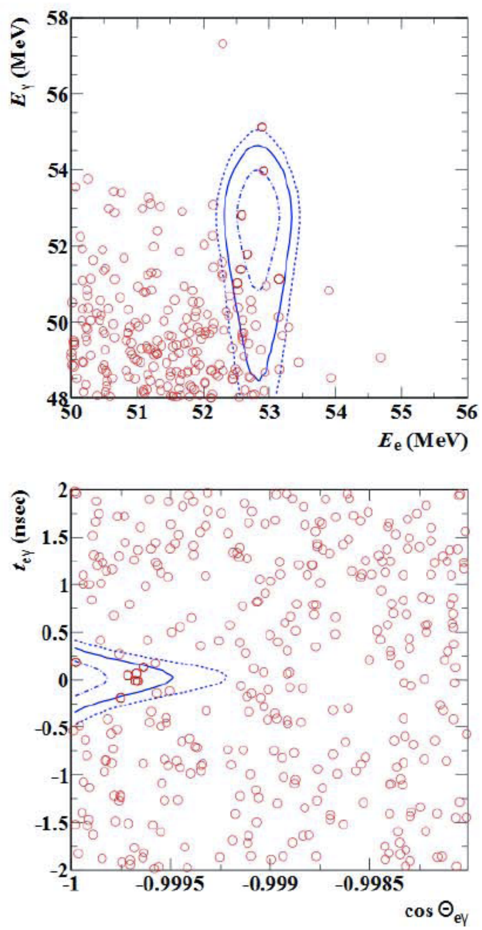
- $3x10^7$ μ/sec, 100% duty factor
- LXe for efficient γ detection
- Solenoidal magnetic spectrometer

- Proposal (1999): goal $<2x10^{-14}$ ($2.2x10^7$ s)
- 2013 Result: $<5.7x10^{-13}$
- New goal (~2020): $<6x10^{-14}$

S. Ritt

arXiv:1303.0754

MEG Current result (2013)
B <5.7 x 10^{-13} (90% c.l.)
(Additional data to be analyzed)



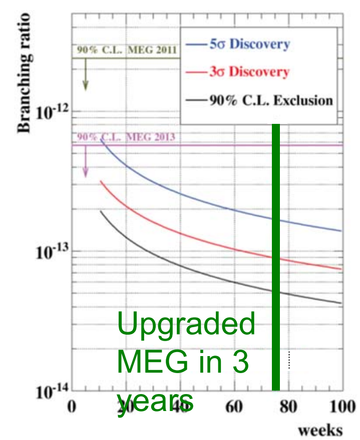
signal PDF contours at 1, 1.64 and 2 sigma

Data 2009-2011

MEG (2013) Upgrade Plan → 6x10^{-14}

TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Previously Forseen	Present MEG	Upgrade scenario
e^+ energy (keV)	(200)	306 (core)	130
e^+ θ (mrad)	(5)	9.4	5.3
e^+ ϕ (mrad)	(5)	8.7	3.7
e^+ vertex (mm) Z/Y(core)		2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >	(1.2)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$		5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	(65)	122	84
Efficiency (%)			
trigger		≈ 99	≈ 99
γ		63	69
e^+		40	88

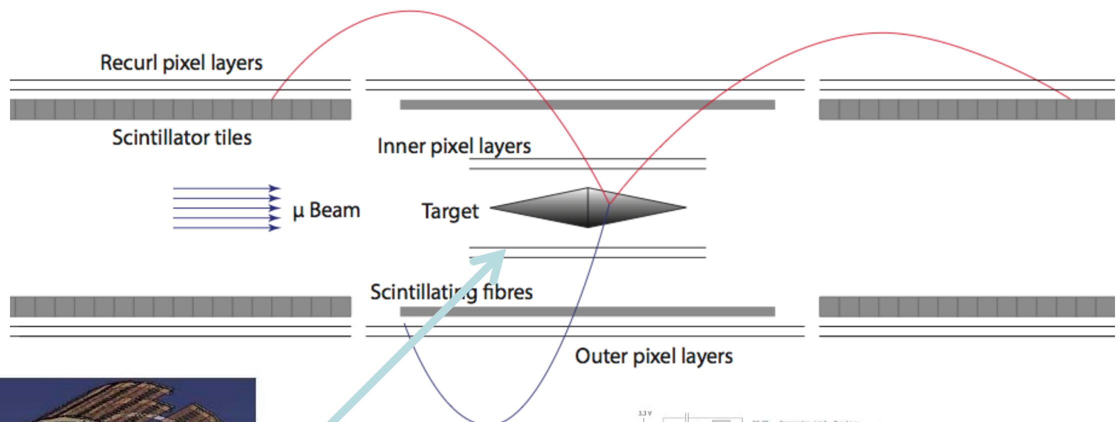


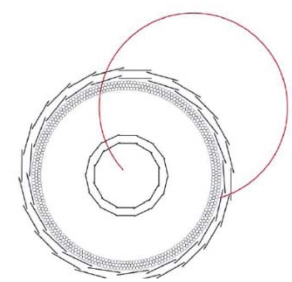
Berger

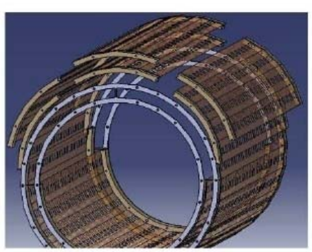
$\mu \rightarrow 3e$ at PSI: Goal $<10^{-16}$

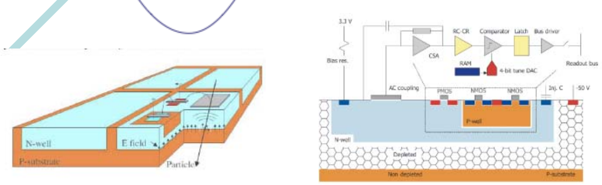
Mu3e proposal

Phase I uses MEG beamline to provide ~ 10^{8} μ^{+}/s to get to 10^{-15}
Phase II assumes construction of new high intensity beam at PSI spallation neutron source to reach 10^{-16}



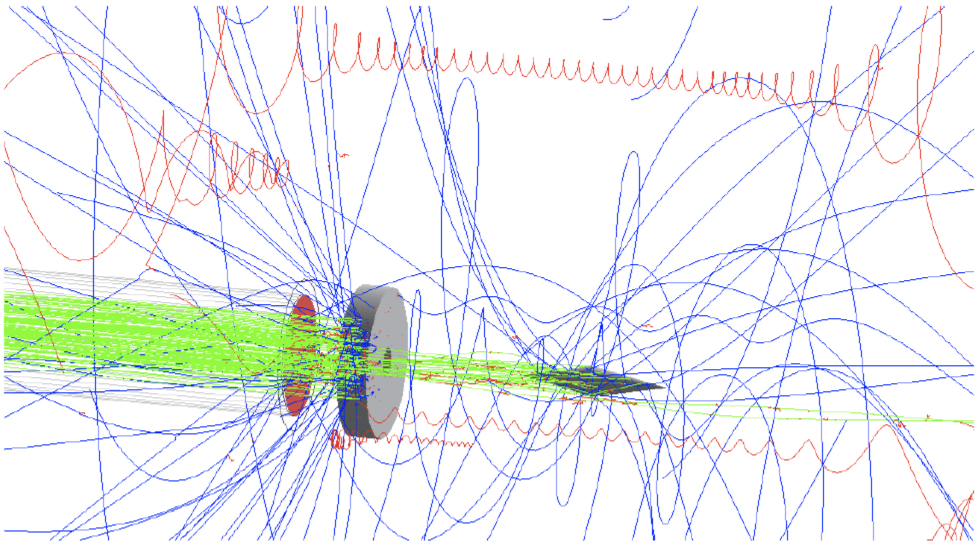




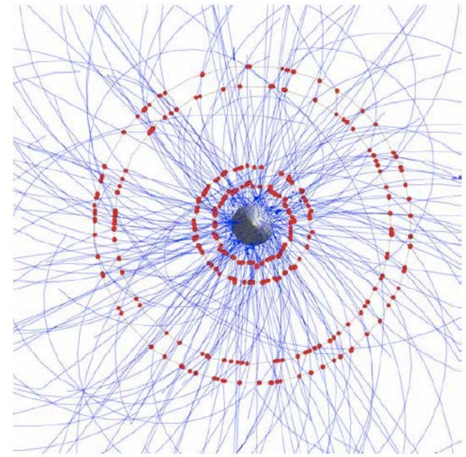


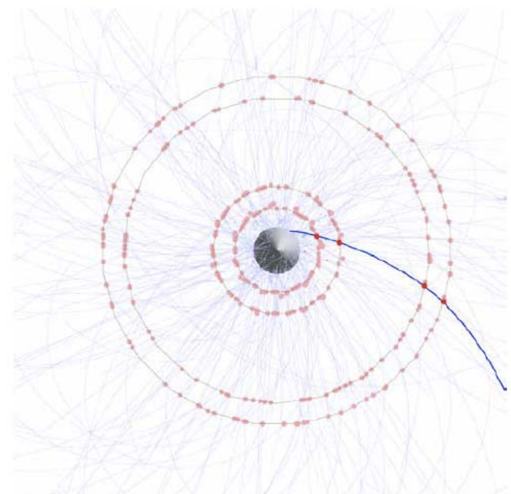
50µm Monolithic active pixel (MAP) detectors

Write a few 10'000 lines of code using Geant4



Niklaus Berger – SMIPP 2012/13 – Slide 47





Pixel detector:

- 250 million (zero suppressed) channels
- ~ 2000 hits per 50 ns frame

Fibre tracker:

- ~ 10'000 (zero suppressed) channels

For a muon stop rate of 2×10^9/s:

- Data rate ~ 150 Gbyte/s

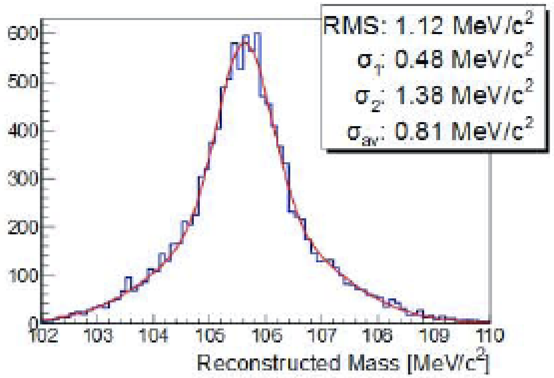


Figure 17.2: Reconstructed mass resolution for signal events in the phase IA configuration.

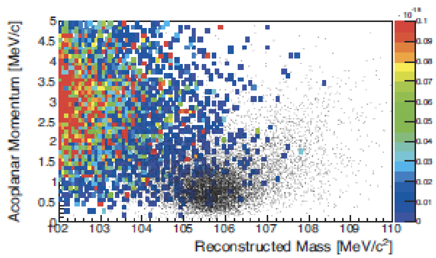
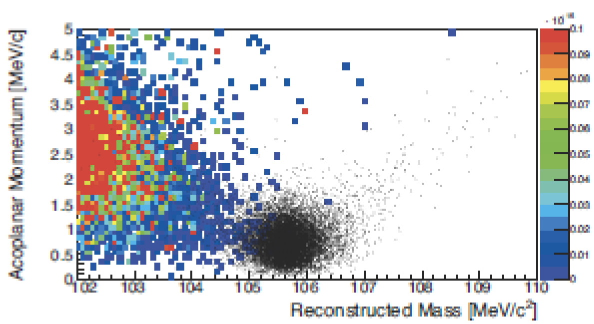
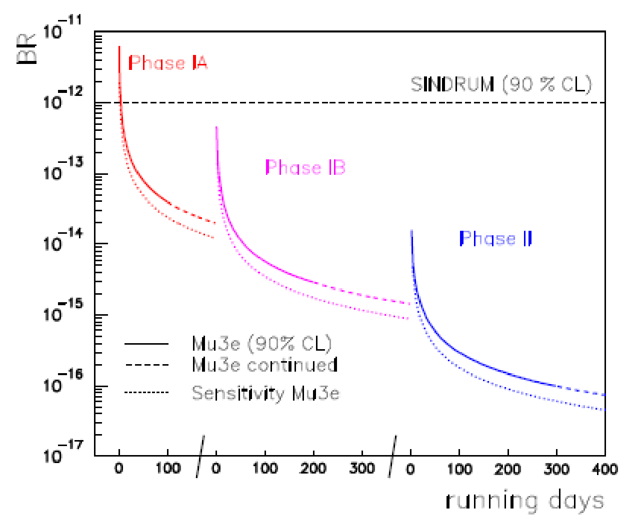


Figure 17.9: Internal conversion background (colours) and signal (black dots) in the acoplanar momentum - reconstructed mass plane for the phase IA detector configuration.



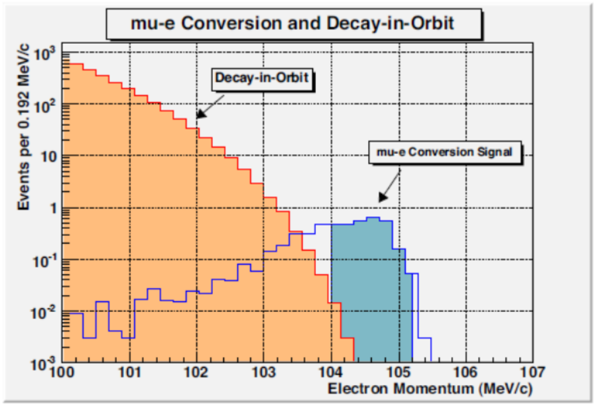
	Phase IA	Phase IB	Phase II
Backgrounds:			
Michel	0	$< 2.5 \cdot 10^{-18}$	$5 \cdot 10^{-18}$
$\mu \to ee e\nu\nu$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
$\mu \to eee\nu\nu$ and accidental Michel	0	$< 2.5 \cdot 10^{-21}$	$7.5 \cdot 10^{-18}$
Total Background	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$2.3 \cdot 10^{-17}$
Signal:			
Track reconstruction and selection efficiency	26 %	39 %	38 %
Kinematic cut (2σ)	95 %	95 %	95 %
Vertex efficiency $(2.5\sigma)^2$	98 %	98 %	98 %
Timing efficiency $(2\sigma)^2$	-	90 %	90 %
Total efficiency	24 %	33 %	32 %
Sensitivity:			
Single event sensitivity	$4 \cdot 10^{-16}$	$3 \cdot 10^{-17}$	$7 \cdot 10^{-17}$
muons on target rate (Hz)	$2 \cdot 10^7$	$1 \cdot 10^8$	$2 \cdot 10^9$
running days to reach $1 \cdot 10^{-15}$	2600	350	18
running days to reach $1 \cdot 10^{-16}$	-	3500	180
running days to reach single event sensitivity	6500	11 700	260



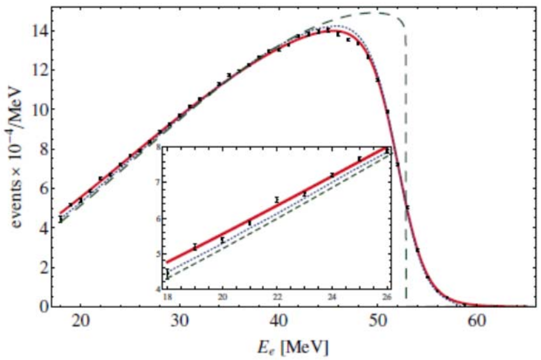
$\mu - e$ Conversion

$\mu^- N \to e^- N$ Experiments

Singles experiment allows ultra-high beam rates: observe peak at endpoint for μ decay-in-orbit ~ 104 MeV/c



Intrinsic background (μ decay-in-orbit) known and calculable.



$$N(E_e)dE_e \simeq 0.4 \cdot 10^{-21}\left(1 - \frac{E_e}{E_{\max}}\right)^5 dE_e$$

Czarnecki et al.
arXiv:1406.3575

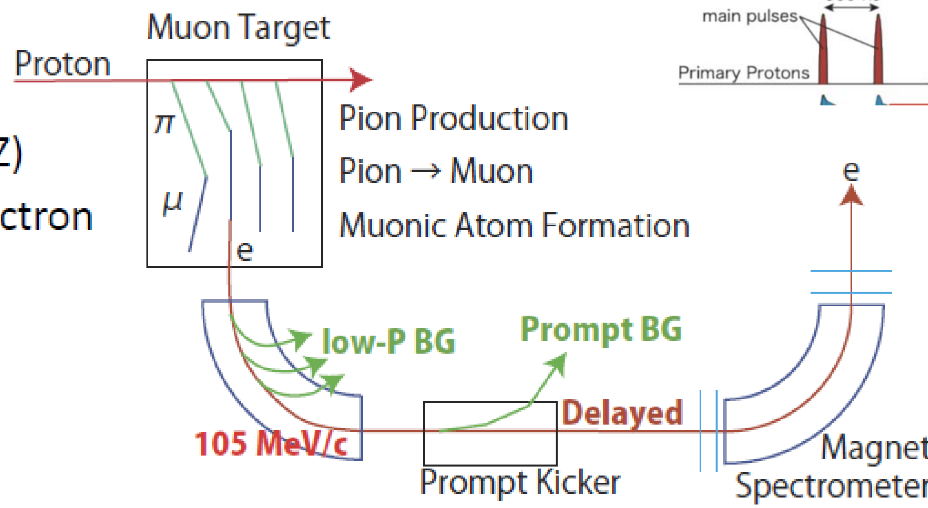
PRD84,013006,2011

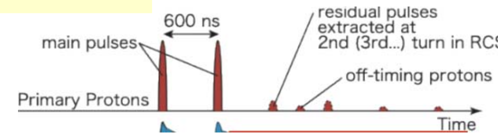
High resolution detector feasible.
Proposed improvements > 10^4 $\to$ Br<10^{-16}

$$\mu^- N \to e^- N \text{ at } < 10^{-14}$$

Hiroaki Natori
CLVF 2013

DeeMe(P41)





- Process : μ^- +(A,Z) → e^- +(A,Z)
- A single mono-energetic electron
  - 105 MeV
  - Delayed：~1μS
- No accidental backgrounds
- Physics backgrounds
- Muon Decay in Orbit (DIO)
  - E_e > 102.5 MeV (BR:10^{-14})
  - E_e > 103.5 MeV (BR:10^{-16})
- Beam Pion Capture
  - π^-+(A,Z) → (A,Z-1)* → γ+(A,Z-1)
    γ → e^+ e^-
  - Prompt timing

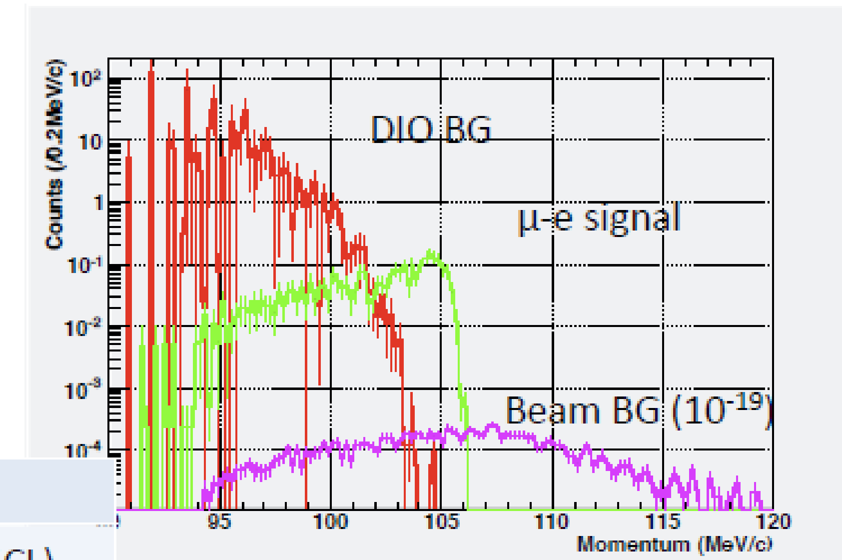
•Low Energy main part: suppressed by the beamline.
•High Energy tail: Magnet Spectrometer (Δp < 0.3%)

•Main pulse: Kicker to reduce the detector rate.
•after-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{AP}<10^{-17}$.

JPARC: DeeMe

Sensitivity and Backgrounds

- Signal Sensitivity
  - S.E.S.: 2×10^{-14} (1 MW, 2×10^{7}sec)
- Backgrounds
  - $R_{AP} < 9 \times 10^{-18}$
  - Detector live-time Duty = 1/20000

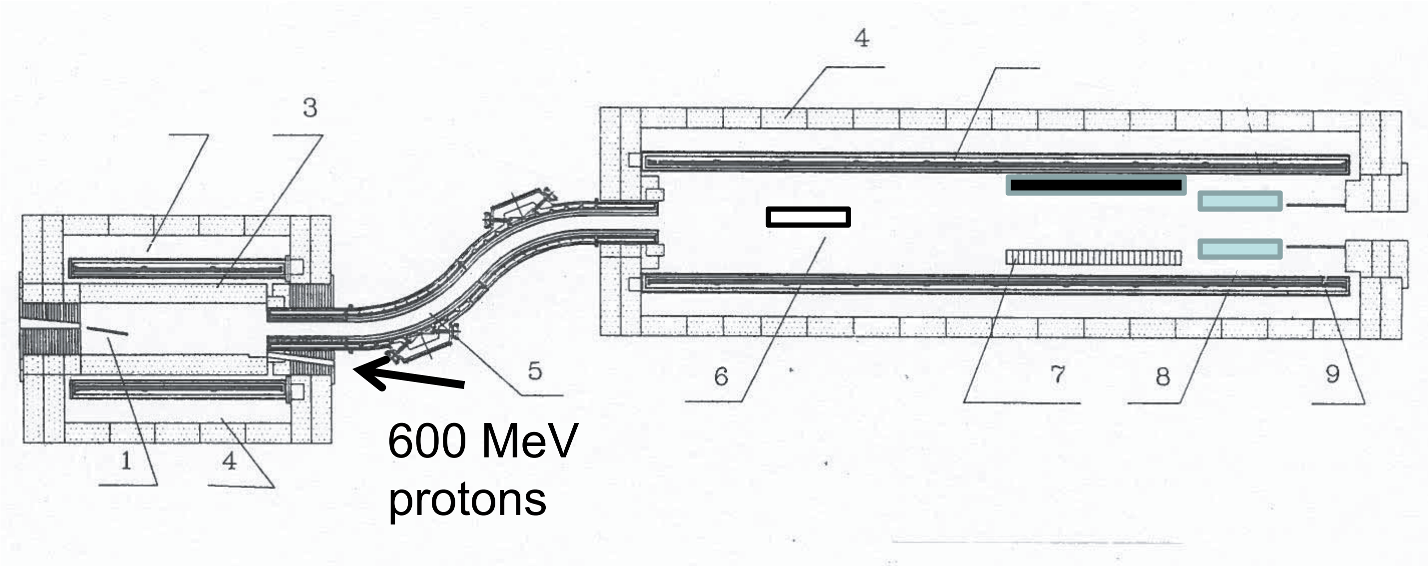


Signal Region: 102.0 -- 105.6 MeV/*c*

DIO Background	0.09
After-Proton Background	< 0.027 (<0.05 90%CL)
Cosmic-Muon Induced Electron BG	<0.018 (MC stat. limited)
Cosmic-Muon Induced Muon BG	<0.001
Radiative Muon Capture BG	<0.0009

$$\mu^- N \rightarrow e^- N \text{ at } 10^{-16}$$

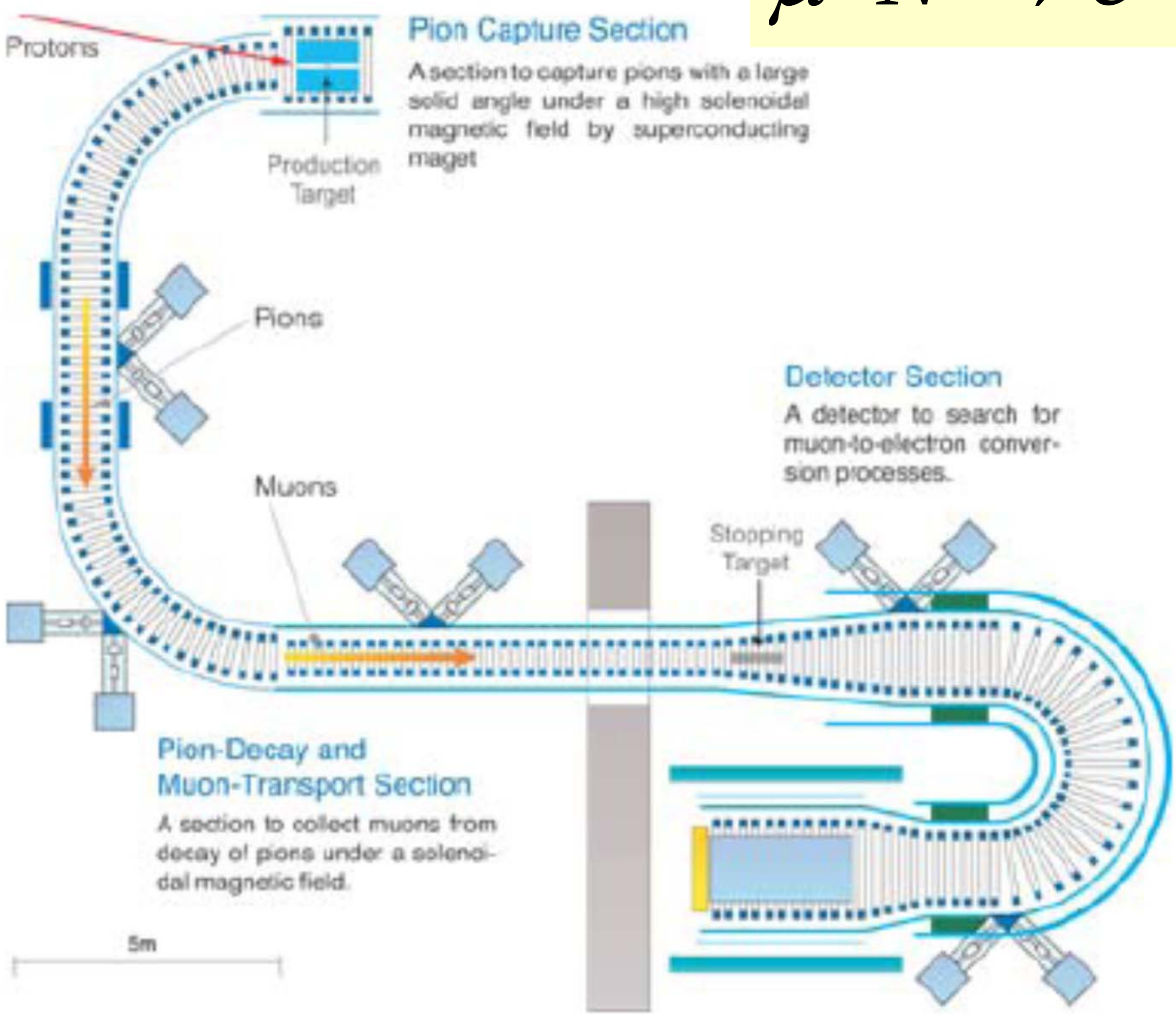
Lobashov, Djilkibaev (1980→1989): Solenoid Pion Collector; flux x 1000.

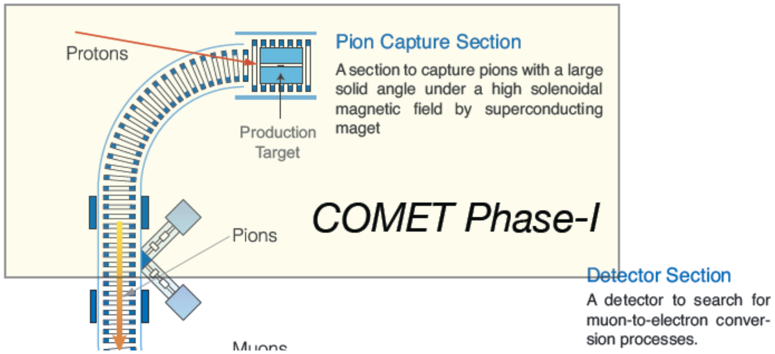


Moscow Meson Factory***

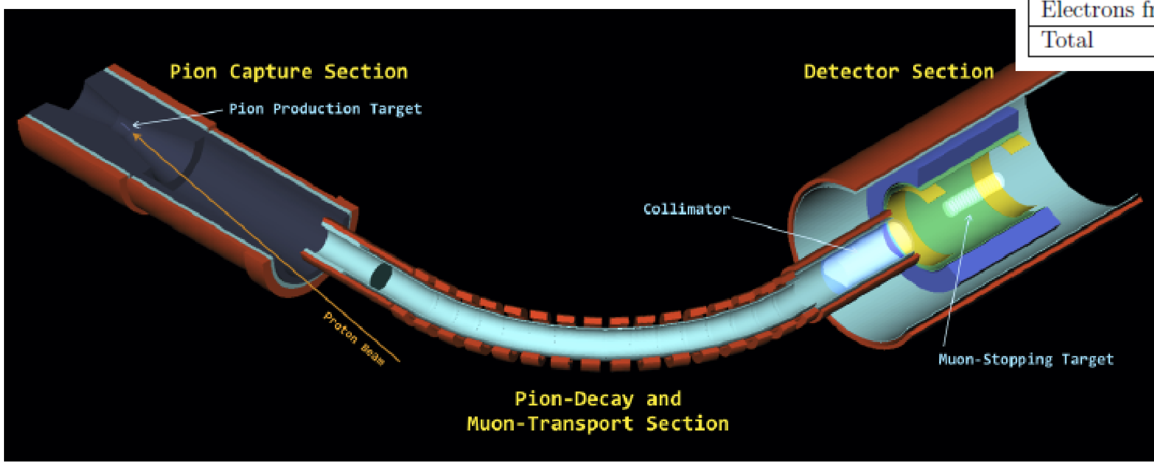
COMET at JPARC

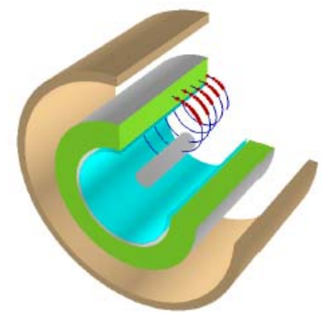
$\mu^- N \to e^- N$ at 10^{-16}



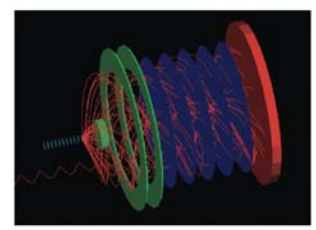


Background	estimated events
Muon decay in orbit	0.05
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.024
Beam electrons	< 01
Muon decay in flight	0.0004
Pion decay in flight	< 0.0001
Neutron induced background	0.024
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Cosmic ray muons	0.0001
Electrons from cosmic ray muons	0.0001
Total	0.11



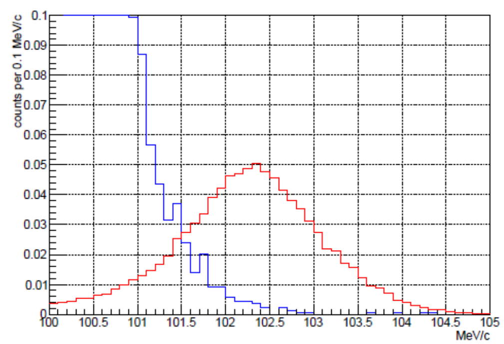


Tracker options



Comet Phase I Goal

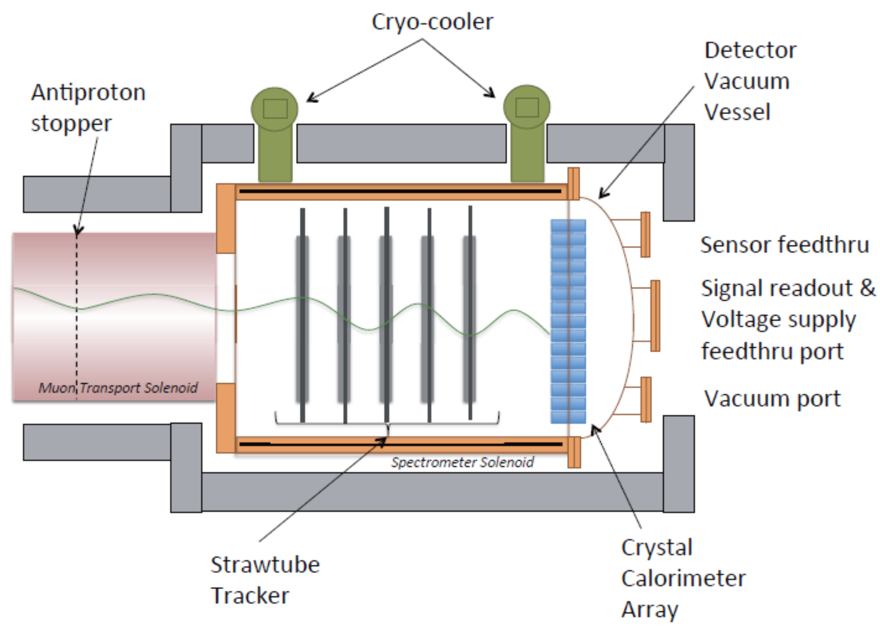
s.e.s. $3\mathrm{x}10^{-15}$



Engineering runs >2016

COMET Phase I: Background Studies

COMET Detector for Background measurements



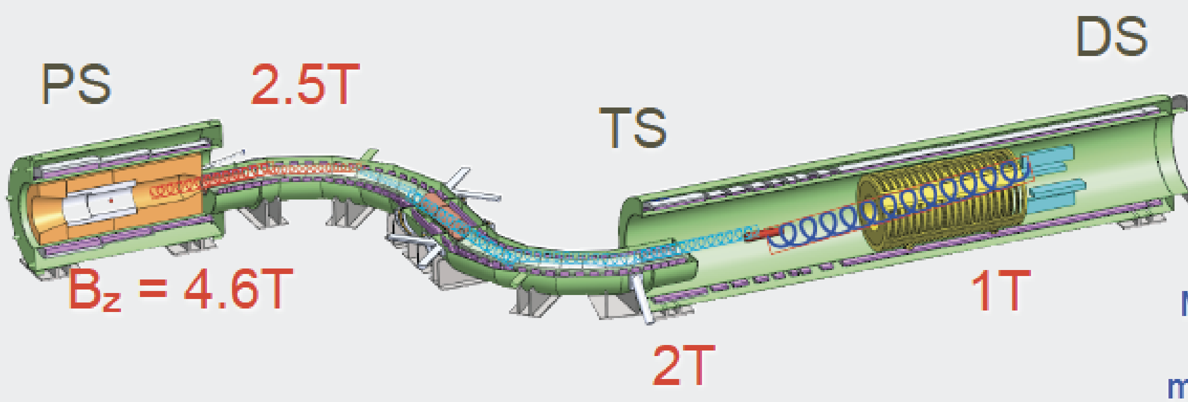
- Proton Extinction
- Particle content, rates, especially pbars
- Others?

BNL MECO $\rightarrow$ *Mu2E*
$\mu \rightarrow$ e Conversion at Fermilab

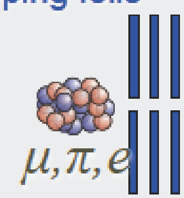
D. Brown
CLFV 2013

Mu2e Muon Beam: Three Solenoids and Gradient

4.6T ⟶ B-field gradient ⟶ 1T



Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

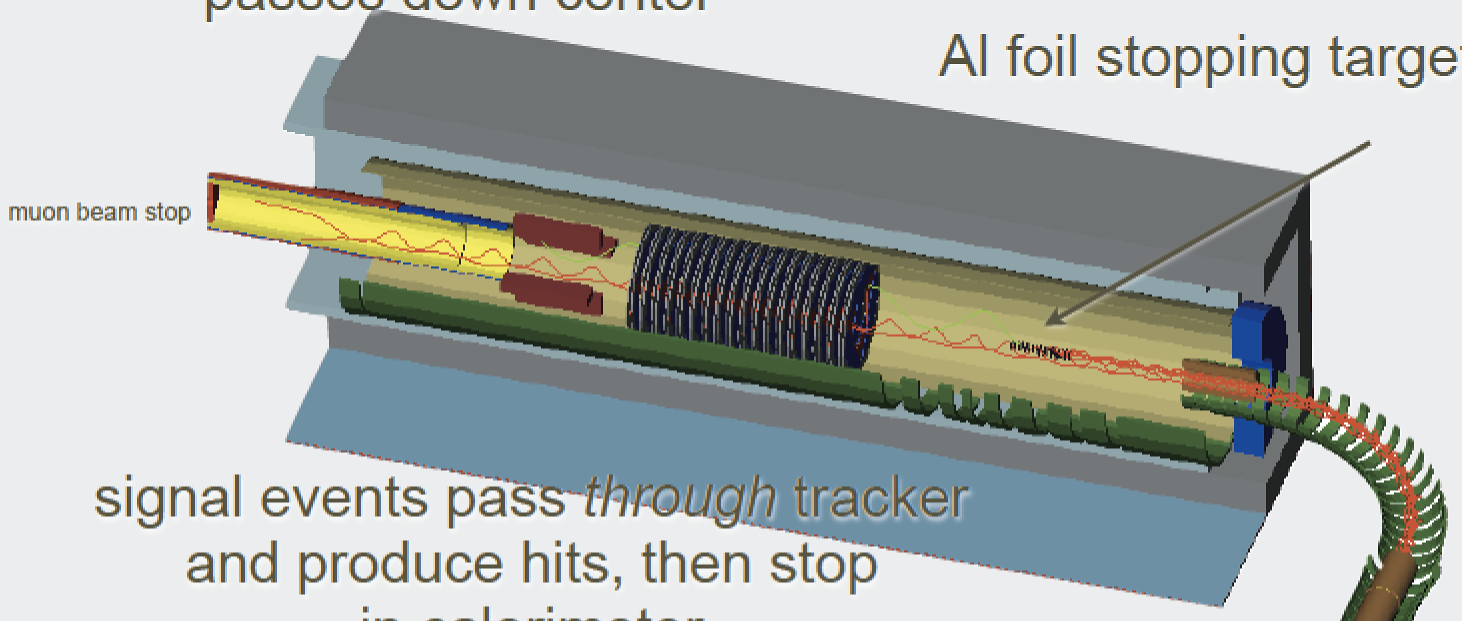
R. Bernstein, FNAL 11 Mu2e IF Workshop 25 April 2013

Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center

10 m × 0.95 m



signal events pass *through* tracker and produce hits, then stop in calorimeter

R. Bernstein, FNAL 22 Mu2e IF Workshop 25 April 2013

Backgrounds

- For $R_{\mu e}$ = 10^{-15}
  ~40 events / 0.41 bkg
  (LHC SUSY?)
- For $R_{\mu e}$ = 10^{-16}
  ~4 events / 0.41 bkg

Background	Size	Uncertainty	Source of Uncertainty
Muon Decay In Orbit	0.22	±0.06	Acceptance and Energy Loss Modeling
Antiproton RPC	0.10	±0.05	Cross-Section and Acceptance
Cosmic Rays	0.05	±0.05	Statistics of Sample
Radiative Pion Capture	0.03	±0.007	Acceptance and Reconstruction
Muon Decay-in-Flight	0.01	±0.003	Cross-Section, Acceptance and Modeling
Pion Decay-in-Flight	0.003	±0.0015	same
Beam Electrons	0.0006	±0.0003	same
Radiative Muon Capture	$< 2 \times 10^{-6}$	—	Calculation
Sum	0.41	±0.08	**Added in Quadrature**

numbers are changing at 10% level as experiment matures

Useful Advanced Measurements for μ-e Conversion Experiments

- Extinction rate
- Particle fluxes (e,μ,π,K,$\overline{\text{p}}$...)at detector (Comet phase I)
- p and n rates from μ Capture (in the works at PSI)
- Cosmic rays – could be done in a test setup?
- Radiative pion capture -> 100MeV electrons?
- Pbar background rate -> 100MeV electrons?
- …

General questions for high sensitivity μ-e Conversion Experiments

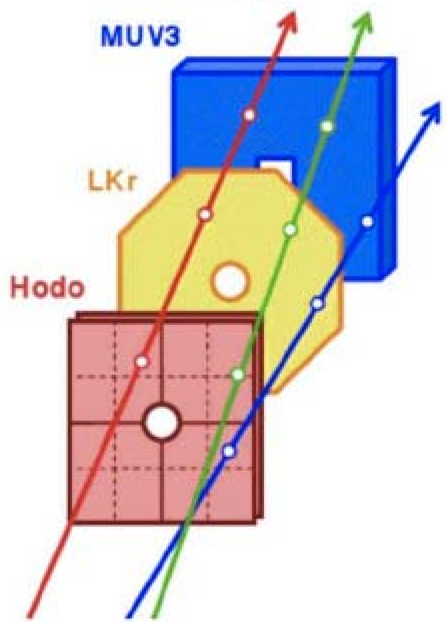
- What are the uncertainties and risk factors in the background, acceptance estimates?
- How are the backgrounds to be measured during the experiment?
- How is a blind analysis to be done?
- What would make a believable signal?

Future LFV in Kaon Decays: NA62

Triggering on lepton pairs

NA62 three-track decay rate upstream CHOD: F_{3track} = 640 kHz

→ Too high to collect all three-track decays (as NA48/2 did)



Available L0 trigger primitives:

- Q_N: at least N hodoscope quadrants;
- $LKR_N(x)$: at least N LKr clusters with energy E>x GeV;
- MUV_N: hits in at least N MUV3 pads.

Possible L0 triggers for LFV searches:

ee pair:	$Q_2 \times LKR_2(15)$
μe pair:	$Q_2 \times LKR_1(15) \times MUV_1$
μμ pair:	$Q_2 \times MUV_2$

Total lepton pair L0 rate (dominated by $K^+ \to \pi^+\pi^+\pi^-$): F = few × 10 kHz

→ *Charge-blind lepton pair collection is feasible*

E. Goudzovski / CLFV / Lecce, 7 May 2013 29

$$K_L^0 \to \mu e$$

$S.E.S$

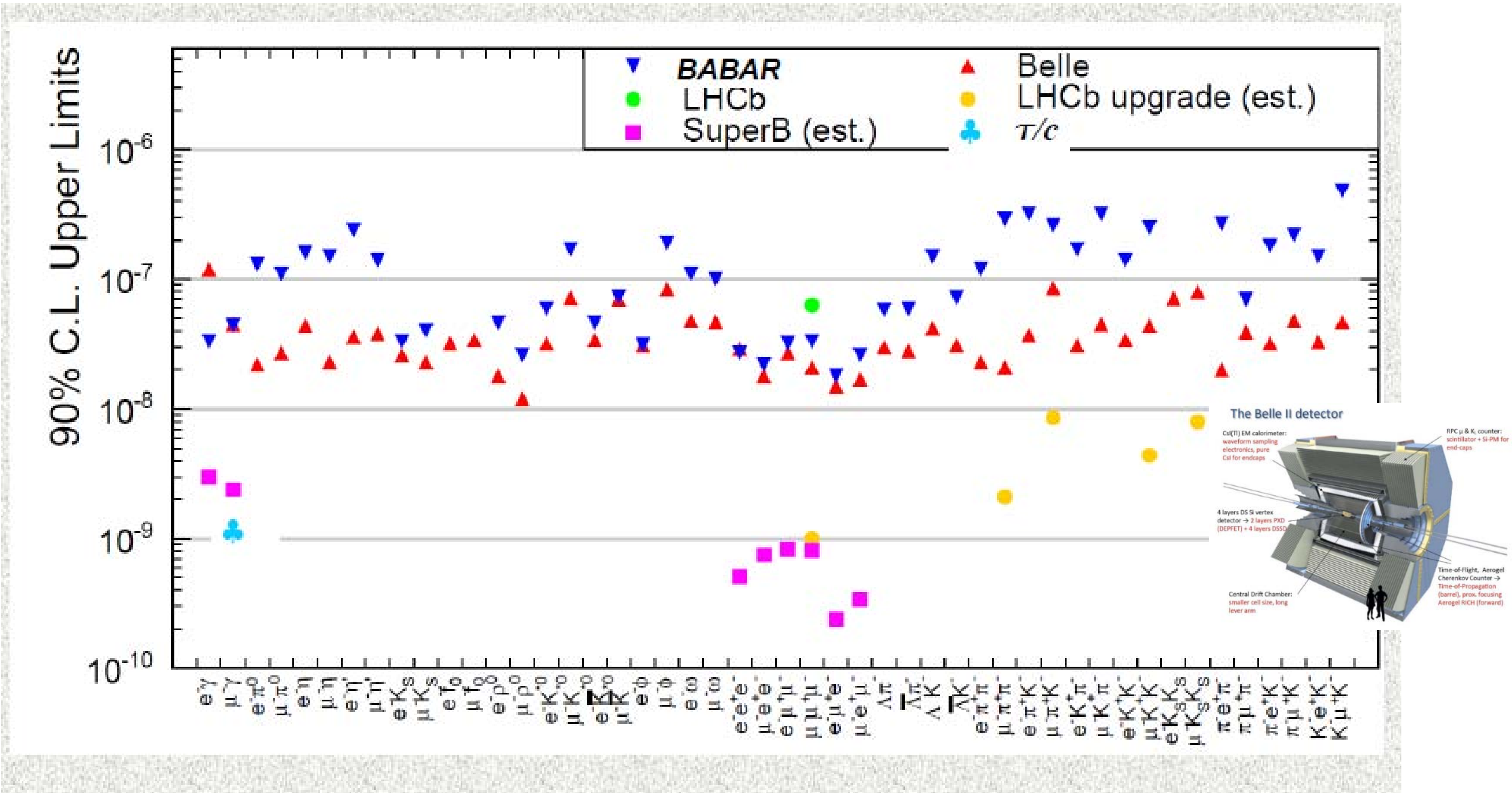
10^{-12}

LFV τ Decays

$\tau \to e\gamma, \tau \to \mu\gamma, \ldots$

$\tau \to \mu, \tau \to e, \mu \to e$ Rates are Model Dependent!

Third generation effects could dominate.



Belle II Sensitivity to LFV

Decay channel	Belle limit	Babar limit	Belle II proj. (5 ab ^{1})	Belle II proj. (50 ab ^{1})	SuperB proj.[1] (75 ab ^{1})
$\tau \to \mu\gamma$	$4.5 \cdot 10^{8}$ [26]	$4.4 \cdot 10^{8}$ [27]	$10 \cdot 10^{9}$ [42,43]	$3 \cdot 10^{9}$ [42,43]	$1.8 \cdot 10^{9}$ [96]
$\tau \to e\gamma$	$12 \cdot 10^{8}$ [26]	$3.3 \cdot 10^{8}$ [27]			$2.3 \cdot 10^{9}$ [96]
$\tau \to \mu\mu\mu$	$2.1 \cdot 10^{8}$ [34]	$3.3 \cdot 10^{8}$ [28]	$3 \cdot 10^{9}$ [42,43]	$1 \cdot 10^{9}$ [42,43]	$2 \cdot 10^{10}$ [96]
$\tau \to eee$	$2.7 \cdot 10^{8}$ [34]	$2.9 \cdot 10^{8}$ [28]			$2 \cdot 10^{10}$ [96]
$\tau \to \mu\eta$	$2.3 \cdot 10^{8}$ [25]	$15 \cdot 10^{8}$ [33]	$5 \cdot 10^{9}$ [42,43]	$2 \cdot 10^{9}$ [42,43]	$4 \cdot 10^{10}$ [96]
$\tau \to e\eta$	$4.4 \cdot 10^{8}$ [25]	$16 \cdot 10^{8}$ [33]			$6 \cdot 10^{10}$ [96]
$\tau \to \mu K_S^0$	$2.3 \cdot 10^{8}$ [35]	$4.0 \cdot 10^{8}$ [31]			$2 \cdot 10^{10}$ [96]
$\tau \to eK_S^0$	$2.6 \cdot 10^{8}$ [35]	$3.3 \cdot 10^{8}$ [31]			$2 \cdot 10^{10}$ [96]

Table 3.3: Measured and projected limits on selected lepton flavour violating τ decays (90% $C.L.$).

[1] The SuperB projections assumed a polarized electron beam; they also assumed that all backgrounds except initial state radiation can be suppressed to the desired level. The SuperB project was canceled in November 2012.

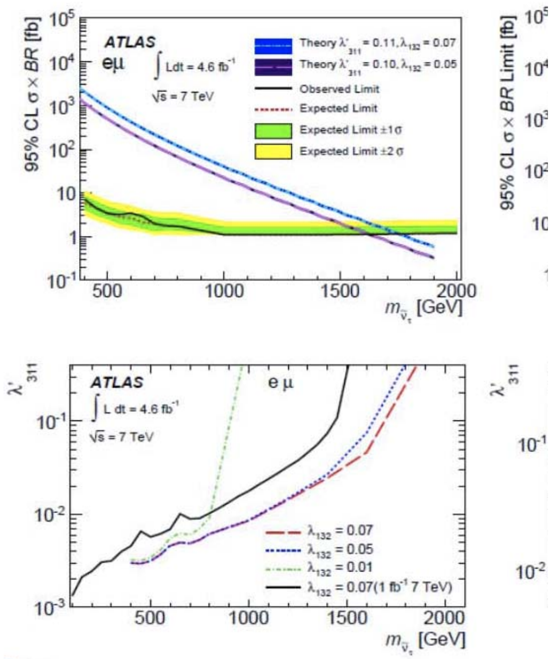
LFV at the LHC

Liu CLVF 2013

LFV topics at ATLAS

- SUSY $\tilde{\nu}_\tau$ to eμ/eτ/μτ search
  - ✓ 7TeV 35pb^{-1}, publication on PRL : Phys. Rev. Lett.106,251801
  - ✓ 7TeV 1fb^{-1}, publication on EPJC: EPJC Vol.71, 12(2011)1809
  - ✓ 7TeV 5fb^{-1}, publication on PLB : PLB_29354
- Z'→ eμ search
  - ✓7TeV 35pb^{-1}, published together with $\tilde{\nu}_\tau$ on PRL
  - ✓ 7TeV 1fb^{-1}, published together with $\tilde{\nu}_\tau$ on EPJC
- stop →eμ continuum search
  - ✓ 7TeV 2fb^{-1}, publication on EPJC: Eur. Phys. J. C (2012) 72:2040
- (≥)4-lepton search
  - ✓ 7TeV, 5fb^{-1}, published on JHEP: JHEP12(2012)124
  - ✓ 8TeV, 21fb^{-1}, conference note for Moriond: ATLAS-CONF-2013-036
- μ+displaced vertex
  - ✓ 7TeV 35pb^{-1}, published on PLB: Physics Letters B 707 (2012) 478-496
  - ✓ 7TeV 5fb^{-1}, published on PLB: Physics Letters B 719 (2013) 280-298

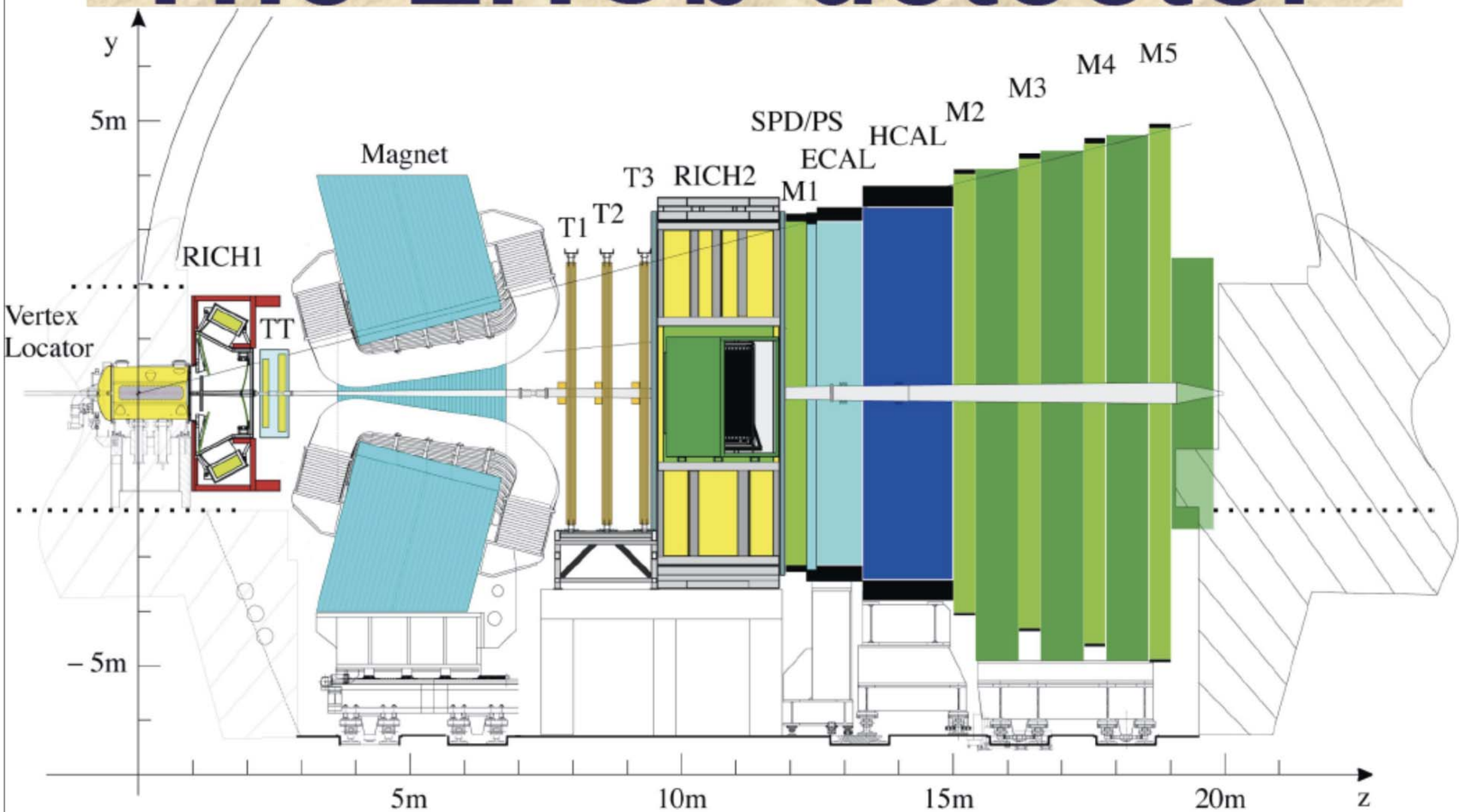
Limits to new physics



eμ channel

$$\tilde{\nu}_\tau \rightarrow e\mu$$

The LHCb detector

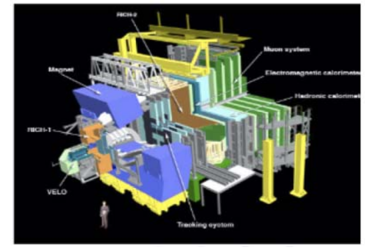


Marina Artuso FPCP 2014 Marseille 4

B. Khanji, LHCb (Milano-Bicocca, INFN)

LHCb

Joining the LFV Club



$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 8.3(10.2) \times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$

Becoming Competitive.

$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 4.6(5.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 5.4(6.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$

New

$$\mathcal{B}(\mathrm{D}^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5) \times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$

$$\mathcal{B}(\mathrm{D_s} \to \pi^-\mu^+\mu^+) < 1.2(1.4) \times 10^{-7} \text{ at } 90\% \ (95\%) \text{ CL}$$

Best So far.

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^+\mu^-\mu^-) < 6.9 \times 10^{-7} \text{ at } 95\% \text{ CL}$$

Best

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^*\mu^-\mu^-) < 2.4 \times 10^{-6} \text{ at } 95\% \text{ CL}$$

New

$$\mathcal{B}(\mathrm{B}^- \to \pi^+\mu^-\mu^-) < 1.3 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

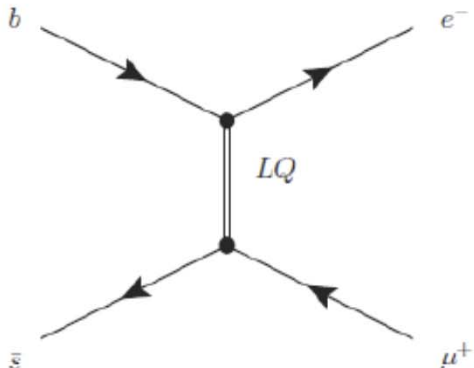
$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}_s^+\mu^-\mu^-) < 5.8 \times 10^{-7} \text{ at } 95\% \text{ CL}$$

Best So far.

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^0\pi^+\mu^-\mu^-) < 1.5 \times 10^{-6} \text{ at } 95\% \text{ CL}$$

Search for the Lepton-Flavor-Violating Decays $B_s^0 \to e^\pm \mu^\mp$ and $B^0 \to e^\pm \mu^\mp$

Search for LFV e.g. involving lepto-quarks (Pati, Salam (1974); multi-generational effects….



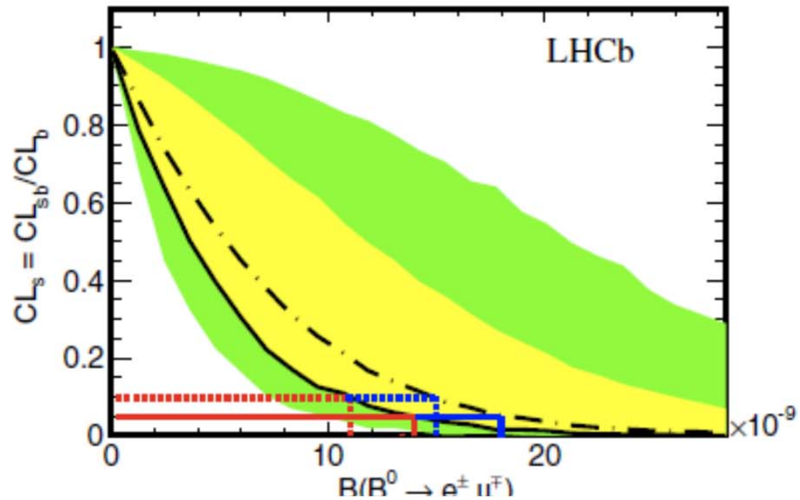


TABLE II. Expected (background only) and observed limits on the $B^0_{(s)} \to e^\pm \mu^\mp$ branching fractions.

Mode	Limit	90% C.L.	95% C.L.
$B_s^0 \to e^\pm \mu^\mp$	Expected	1.5×10^{-8}	1.8×10^{-8}
	Observed	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm \mu^\mp$	Expected	3.8×10^{-9}	4.8×10^{-9}
	Observed	2.8×10^{-9}	3.7×10^{-9}

$$m_{LQ_s}(B_s^0 \to e\mu) > 107(101)\, TeV/c^2 \text{ @ } 90(95)\%\ CL$$

$$m_{LQ_d}(B^0 \to e\mu) > 135(126)\, TeV/c^2 \text{ @ } 90(95)\%\ CL$$

R. Aaij et al. (LHCb Collaboration) Phys. Rev. Lett. 111, 141801 (2013)

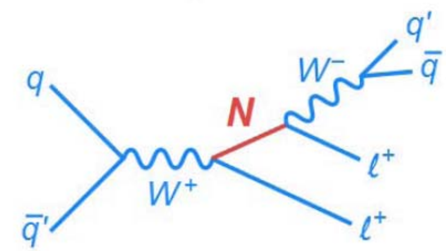
CMS LFV Searches

Lusito
CLFV 2013

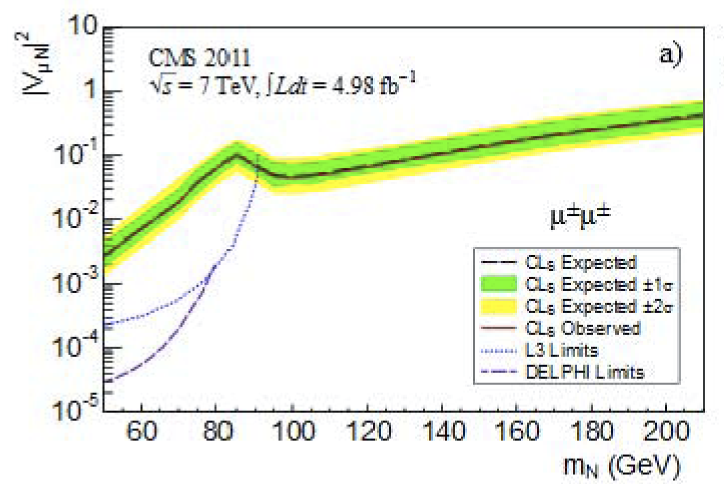
Outline

1. Motivation
   - Physics motivations
   - The CMS detector
2. Narrow resonances
   - Search for narrow resonances in dilepton mass spectra
3. Heavy neutrinos
   - Search for heavy lepton partners of neutrinos in pp collisions at $\sqrt{s}$ = 7 TeV, in the context of the Type III seesaw mechanism.
   - Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$+jets and $e^{\pm}e^{\pm}$+jets in pp collisions at $\sqrt{s}$ = 7 TeV
   - Heavy neutrino and right-handed W of the left-right symmetric model
4. Leptonic-RPV SUSY searches
   - Search for RPV supersymmetry with three or more leptons and b-tags
   - Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags

Experimental strategy



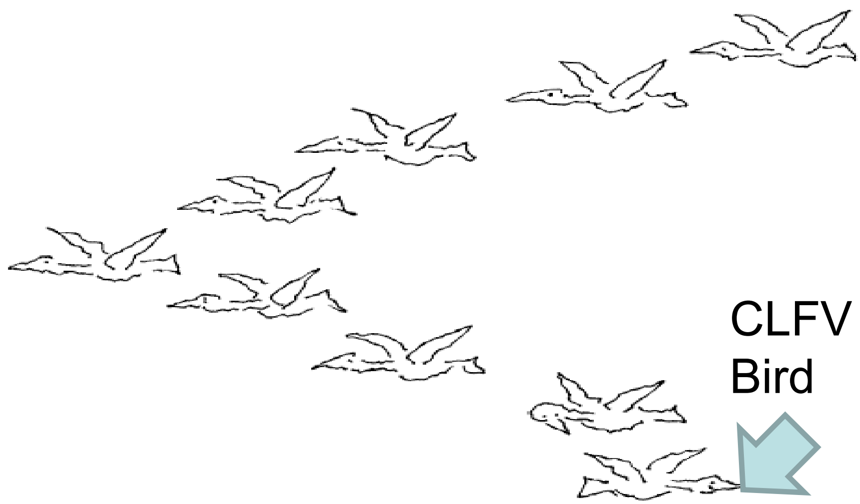
Heavy Majorana Neutrino



Some LFV Limits and Prospects

Reaction	Present limit	Future Possibilities Planned
$\mu+ \rightarrow e+\gamma$	$< 5.7 \times 10-13$	6x10-14 (PSI)
$\mu+ \rightarrow e+e+e-$	$< 1.0 \times 10-12$	10-16 (PSI)
$\mu-Ti \rightarrow e-Ti$	$< 4.6 \times 10-12$	Si/Al 10-14→10-16
$\mu-Au \rightarrow e-Au$	$< 7 \times 10-13$	(Fermilab, JPARC)
$\mu+e- \rightarrow \mu-e+$	$< 8.3 \times 10-11$	
$\tau \rightarrow e\gamma$	$< 1.1 \times 10-7$	<10-9 (KEK Belle II)
$\tau \rightarrow \mu\gamma$	$< 4.4 \times 10-8$	
$\tau \rightarrow \mu\mu\mu$	$< 2.1 \times 10-8$	~10-9 LHCb
$\tau \rightarrow eee$	$< 3.6 \times 10-8$	
$\pi^0 \rightarrow \mu e$	$< 8.6 \times 10-9$	10-11 NA62
$K^0{}_L \rightarrow \mu e$	$< 4.7 \times 10-12$	10−12 NA62
$K+ \rightarrow \pi+\mu+e-$	$< 2.1 \times 10-10$	10-12 NA62
$K^0{}_L \rightarrow \pi^0 \mu+e-$	$< 3.1 \times 10-9$	
$B_S \rightarrow \mu e$	<1.1 x 10-8	10-9 (LHCB)?
$Z_0 \rightarrow \mu e$	$< 1.7 \times 10-6$	
$Z_0 \rightarrow \tau e$	$< 9.8 \times 10-6$	
$Z_0 \rightarrow \tau\mu$	$< 1.2 \times 10-5$	

Interim Summary for Charged Lepton Flavor Violation (CLFV):

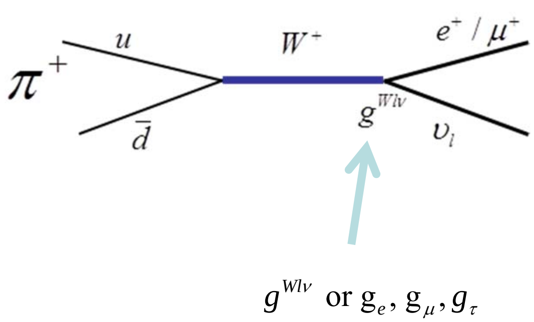


“Hope springs eternal”
but
"Wishing does not make a poor man rich."
(*Arabian Proverb*)

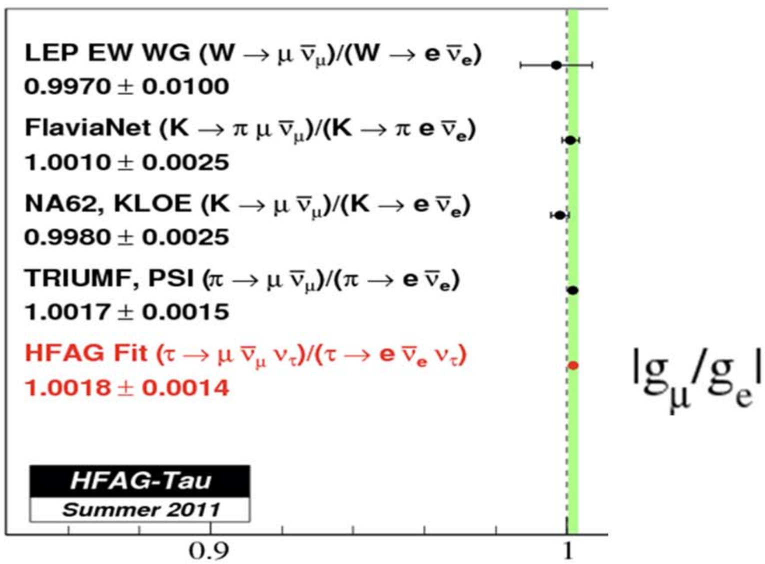
$e-\mu-\tau$ Universality

Standard Model assumes the same couplings of $e-\mu-\tau$ to gauge bosons W, Z.

This may not be true -- or BSM physics may modify.

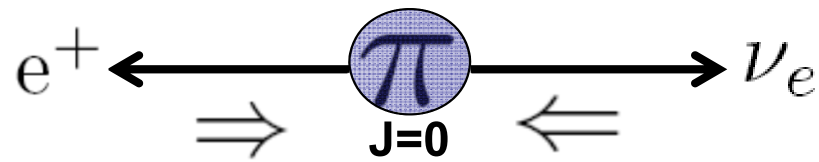


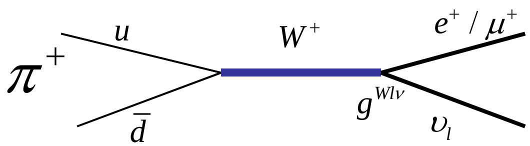
$e-\mu$ Universality Tests



Lepton Universality: π → eυ Branching Ratio

Classic SM process.
V-A interactions.





$$R^{th}_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = \left(\frac{g^{We\nu}}{g^{W\mu\nu}}\right)^2 \frac{m_e^2}{m_\mu^2} \left(\frac{1-\frac{m_e^2}{m_\pi^2}}{1-\frac{m_\mu^2}{m_\pi^2}}\right)^2 \left(1-\delta R_{e/\mu}\right)$$

$$= 1.2352(1)\, x10^{-4} \quad (\pm 0.008\%)$$

$\delta R_{e/\mu}$ = radiative corrections

Possibly, the most precise SM weak interaction observable involving quarks!

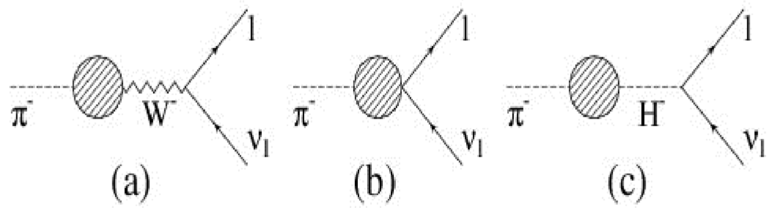
Extremely sensitive to new physics – particularly with pseudoscalar (P) and scalar (S) interactions – at high mass scales.

Cirigliano,Rosell 2007

Universality Tests: Sensitive to high mass scales

Example: Non-standard Higgs couplings e.g.
Pseudoscalar or Scalar interactions

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$$



$$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

Sensitivity to new physics $\sim \frac{1}{M_H^2}$

0.05 % Measurement $R_{e/\mu} \to \Lambda_{eP} > 1000$ TeV

Charged Higgs mass $m_{H^\pm} \sim 200$ TeV probed.

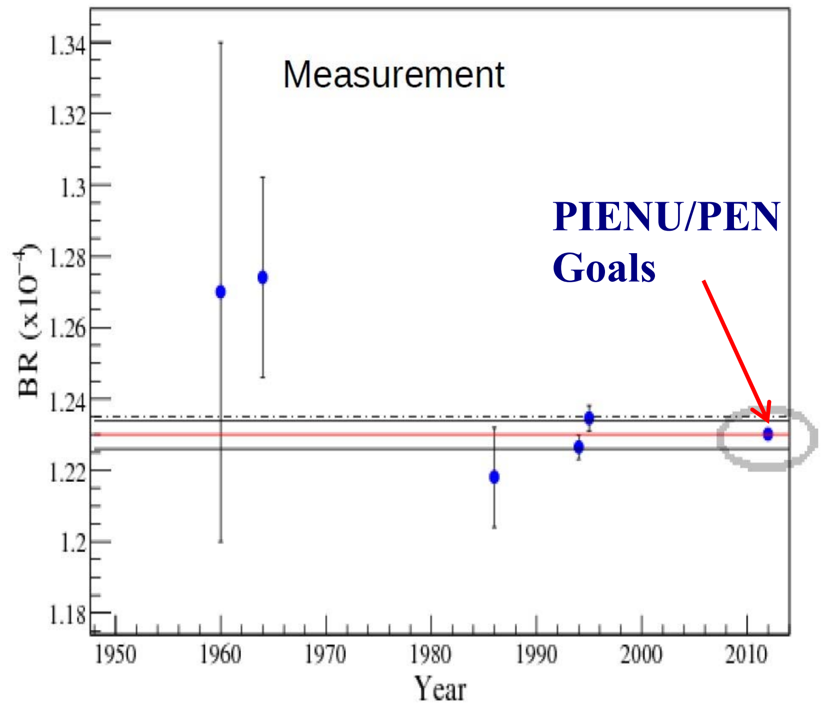
π → eυ Branching Ratio-- Experiments

Experimental status:

R_{exp}= 1.2265 (34) (44) x 10^{-4} (TRIUMF, 1992)
1.2346 (35) (36) x 10^{-4} (PSI, 1993)

$$R_{e/\mu}^{\exp\pi}\ (\pm 0.4\%)$$

$$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 43(37)x10^{-8}$$



Order of magnitude difference in precision between theory and experiment → **window for new effects!**

Endo, Yoshinaga (2014)
arXiv:1404.4498

A Global look at e-μ Universality

- Flavor couplings of W and Z bosons
- Pion decay
- New leptons

$\pi \to e\nu$ Branching Ratio corrected for new physics:

$$R_{e/\mu}^{th} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = (1 - 2\delta g^{We\nu} + 2\delta g^{W\mu\nu}) R_{e/\mu}^{SM}$$

Corrected gauge couplings relative to SM values:

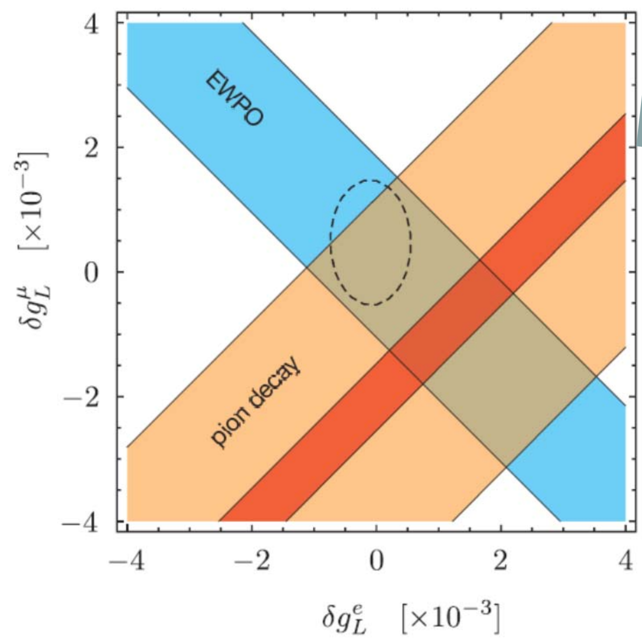
$$\Delta g^{We\nu} = 1 - \delta g^{We\nu}, \ \Delta g^{W\mu\nu} = 1 - \delta g^{W\mu\nu}$$

Endo, Yoshinaga (2014)

New Physics and Pion Decay

Global fit to Electroweak precision measurements (EWPO):

- Z bosons decaying to leptons
- W bosons contributing to G_F (muon lifetime)
- W boson decay width



PEN/PIENU

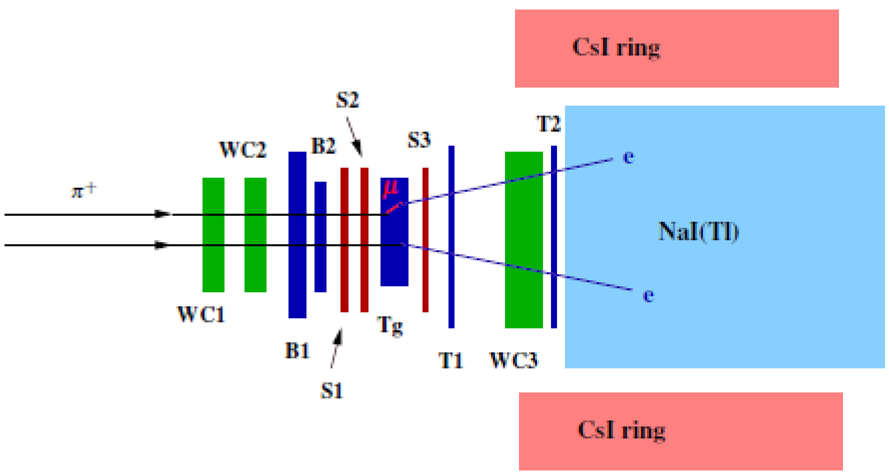
Limit from EWPO with new lepton if $\delta g_L^{Z\ell\ell} = \delta g^{W\ell\nu_\ell} \equiv \delta g_L^\ell$

$\pi^+ \rightarrow e^+\nu$ Experiments

Precision goals: <0.1%

TRIUMF PIENU

PI E NU

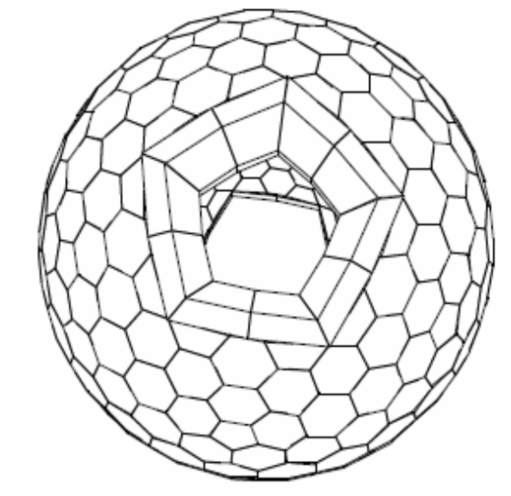


Canada-China,Japan-UK-US

ASU, BNL, Glasgow, KEK, Osaka, TRIUMF, Tsinghua, UBC, UNBC, VPI

PSI PEN

PIBETA Spectrometer



PSI, Zurich

PI E NU

Experiment Concepts

TRIUMF
500 MeV
Cyclotron

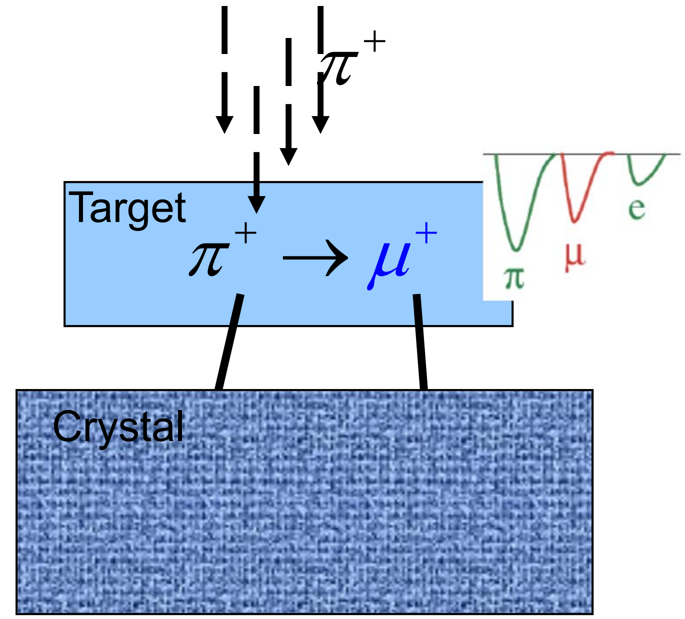
Stop π^+ in target; Measure positrons in a crystal spectrometer:

$$\left[\pi^+ \rightarrow e^+ \nu\right] \quad P_e = 70 MeV/c,\ \tau_\pi = 26 ns$$

$$\left[\pi^+ \rightarrow \mu^+ \nu\right] \quad P_\mu = 30 MeV/c,\ \tau_\mu = 2.2 \mu s$$

$$T_\mu = 4.2 MeV,\ R_\mu = 1.4 mm$$

$$\left[\mu \rightarrow e^+ \nu \bar{\nu}\right] \quad P_e = 0 - 53 MeV$$



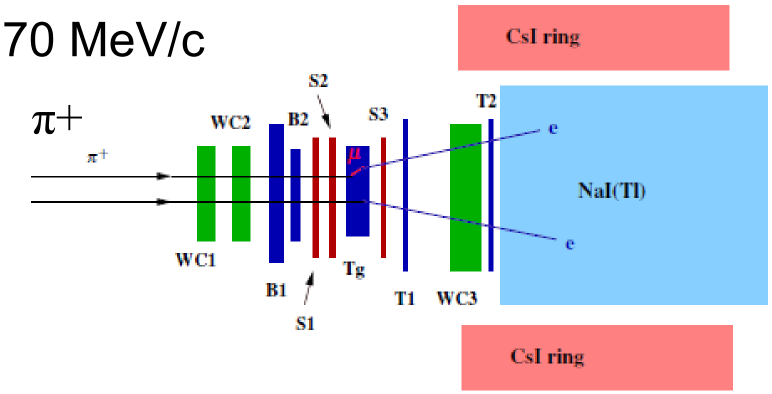
Systematic effects cancel (to 1st order) in the ratio $\dfrac{\Gamma(\pi \rightarrow \mathrm{e})}{\Gamma(\pi \rightarrow \mu \rightarrow \mathrm{e})}$

e.g. solid angle, MCS, $\dfrac{dE}{dx}$, anihillation, bremsstrahlung, timing ..

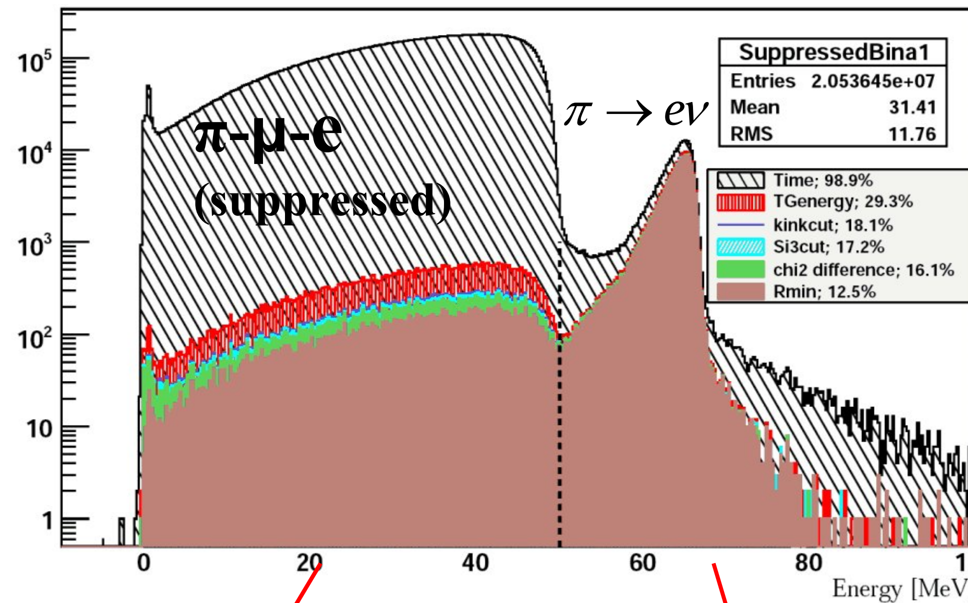
TRIUMF PIENU

Measure Energy and time in a precision crystal spectrometer

70 MeV/c



Energy Spectrum from stopped pions



Time Spectra

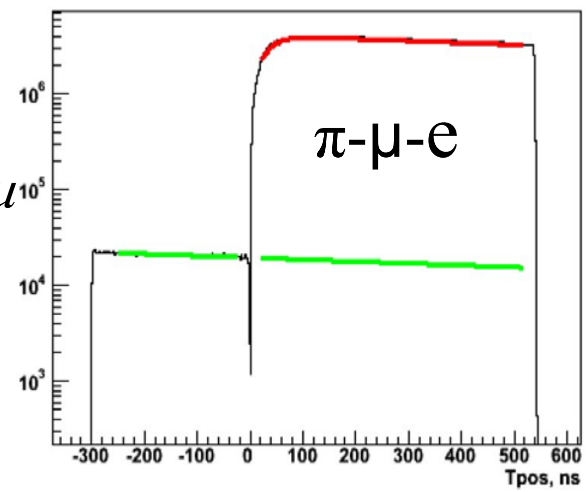
Fit time spectra simultaneously

$-\pi \rightarrow e\nu, \pi-\mu-e, \pi DIF, \ old\,\mu$

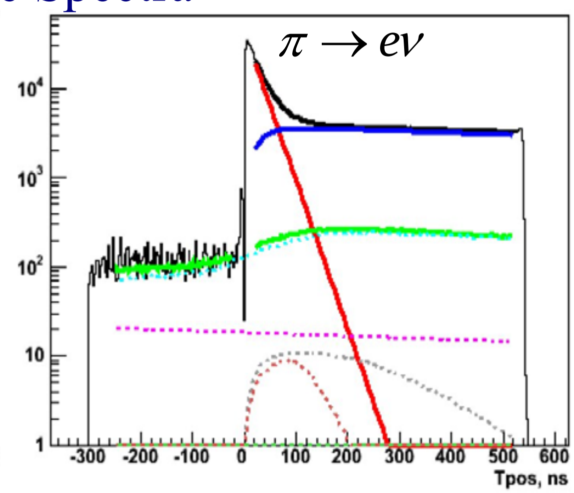
$-radiative\ \pi\ decays$

$-\pi + \ old\,\mu \ \rightarrow$ pile-up

$-(\mu DIF)$

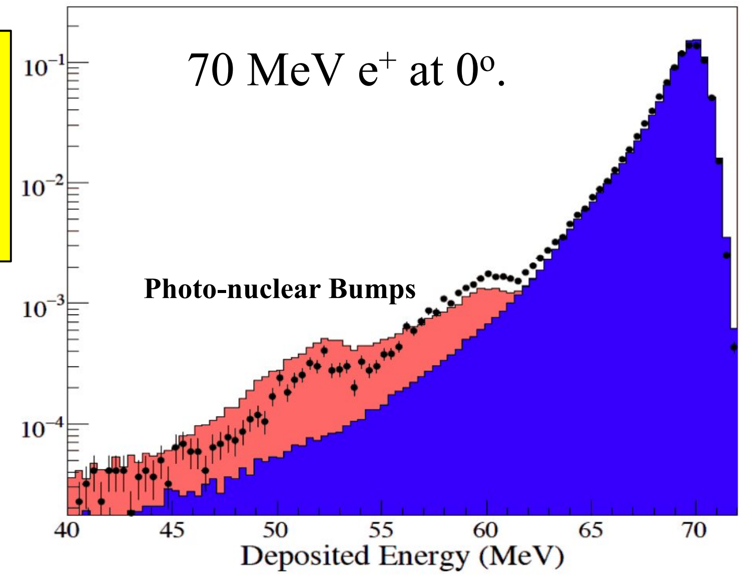


Low Energy



High Energy

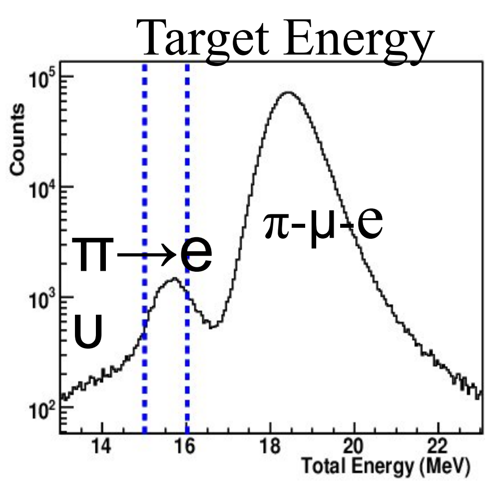
Suppress Backgrounds,
Make small systematic corrections for NaI lineshape and other tiny effects.

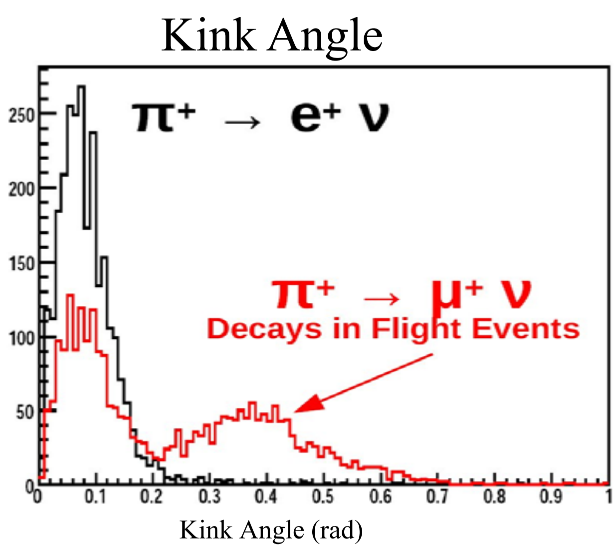


Response function measurements showed up photo-nuclear n emission.

Background Suppression

-Suppress π-μ-e background with target energy
-Remove πDIF background with track angles
-Correct for selection bias

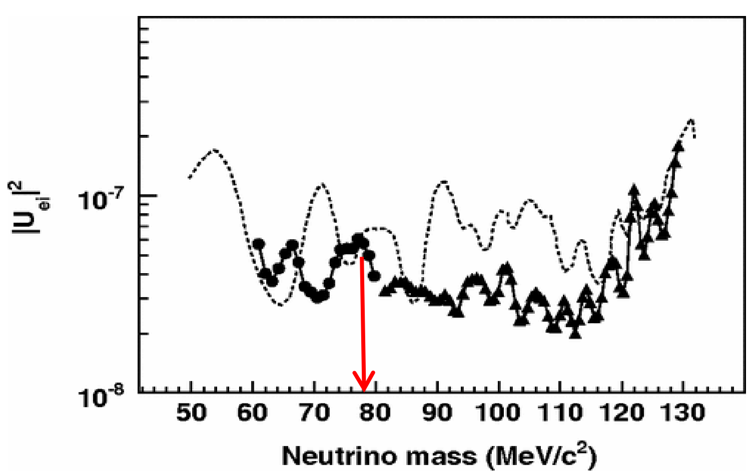




PIENU: Summary of Expected Uncertainties

Source	Old TRIUMF	PIENU Goals
Statistics	0.0028	0.0005
Low-energy tail	0.0025	0.0003
Acceptance corrections	0.0011	0.0003
Pion lifetime	0.0009	0.0002
Other	0.0011	0.0003
Total	0.0047	0.0006

Current PIENU result for heavy sterile neutrinos:

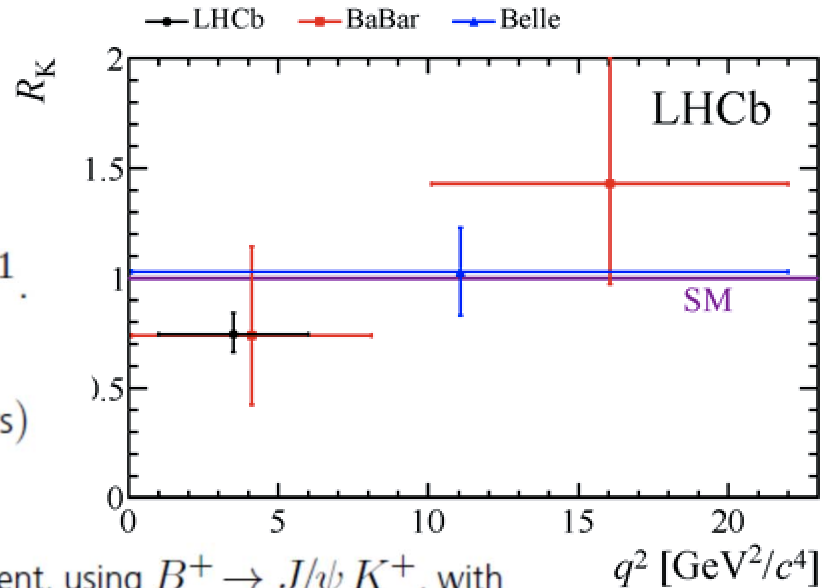


LHCb Universality Test (2014)

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

First analysis by LHCb, uses 3 fb^{-1}.

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{sys})$$



- Relative branching fraction measurement, using $B^+ \to J/\psi K^+$, with $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$ as normalisation channels.
- $B^+ \to K^+e^+e^-$ challenging:
  - Recover loss by Bremsstrahlung by adding ECAL cluster energy (> 75 MeV).
  - Signal shape strongly depends on number of Bremsstrahlung photons, p_T and occupancy of the event → split analysis in 3 trigger categories.
  - $B^0 \to K^*e^+e^-$ largest contribution to part. background.
  - About 5× less signal than in $B \to K\mu^+\mu^-$, mainly due to low trigger and reconstruction efficiency.

Electroweak penguin decays at LHCb

LHCP 2014, New York
2nd June 2014

Michel De Cian, University of Heidelberg
on behalf of the LHCb collaboration

Summary: e-μ Universality Tests

Mode	g_e/g_μ
$\pi \to e\nu / \pi \to \mu\nu$	0.9979 ± 0.0016
$K \to e\nu / K \to \mu\nu$	1.0022 ± 0.0018
$\tau \to e\nu\nu / \tau \to \mu\nu\nu$	0.9980 ± 0.0015
ν_e/ν_μ scattering	1.10 ± 0.05
W decays	0.999 ± 0.011

±0.0003 PIENU/PEN (2014-15)

±0.0010 NA62/TREK (>2018)

Belle II

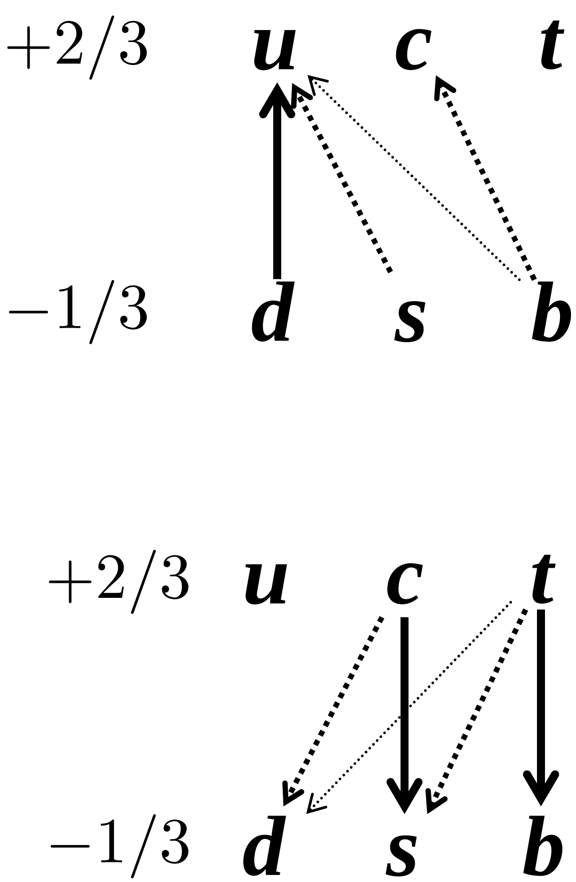
Sometimes, the absence of an effect is highly significant….

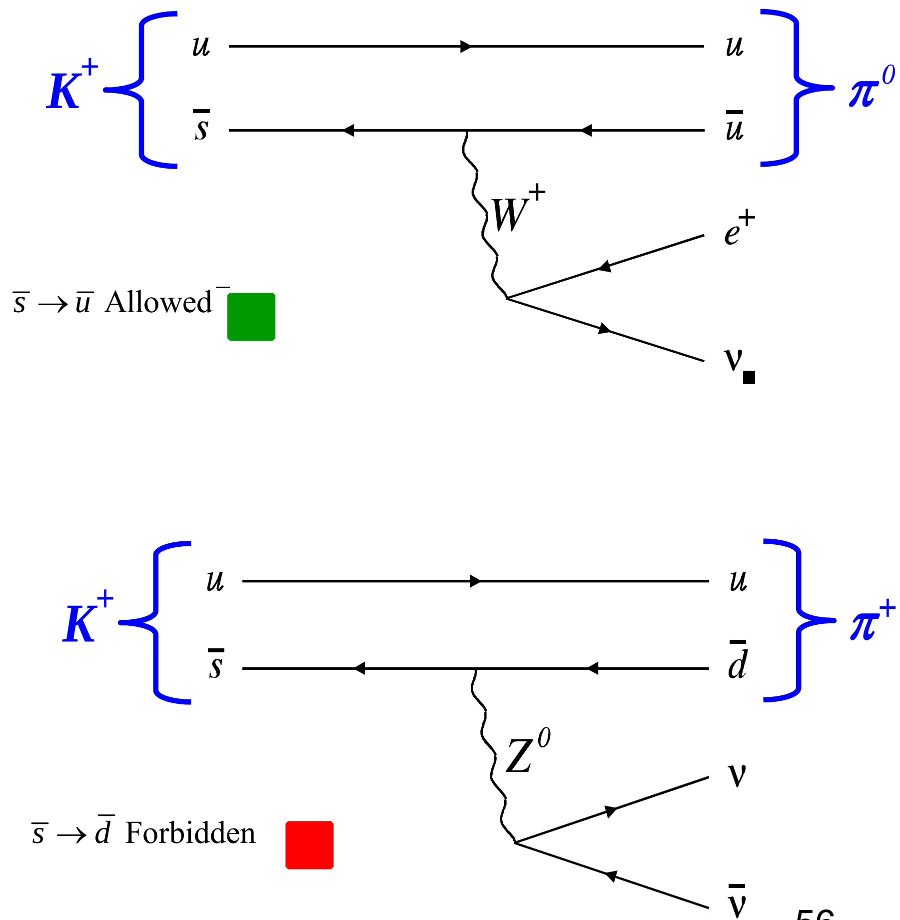
..the curious incident of the dog in the night-time...

"The dog did nothing in the night-time."
"That was the curious incident,"
remarked Sherlock Holmes.

Sherlock Holmes in "Silver Blaze"

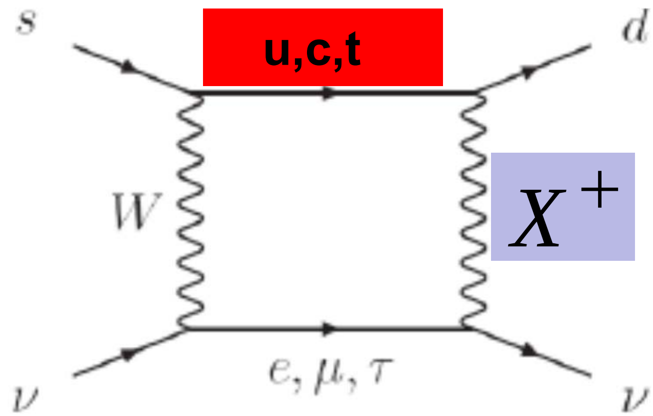
Direct flavor-changing neutral currents (e.g. s → d) are absent in the Standard Model:

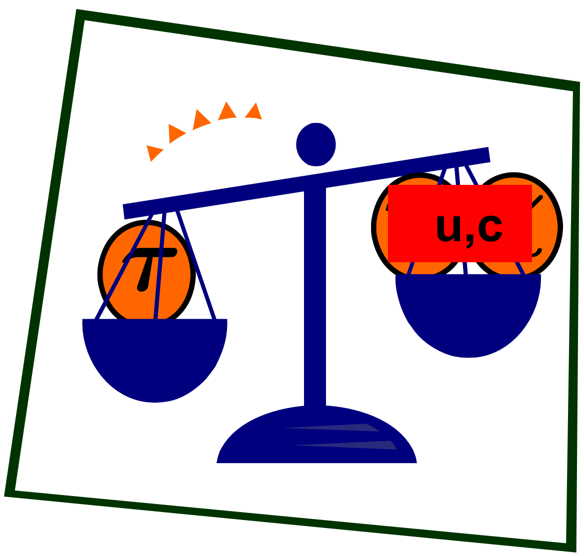




Flavor Changing Neutral Current Reactions occur in the Standard Model via 2nd order effects

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





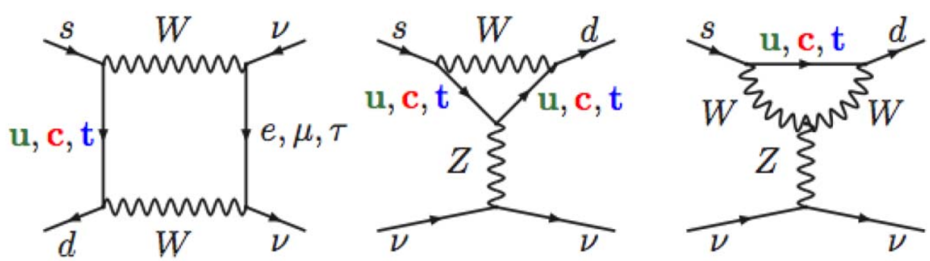
These effects are dominated by the heavy top quark. The predicted branching fractions are very small:

$B_{SM}(K^+ \rightarrow \pi^+ \nu \overline{\nu}) = (8.5 \pm 0.7) \times 10^{-11}$

This opens the door for other heavy particles to contribute.

The $K \to \pi \nu \bar{\nu}$ decays are among the few most precisely predicted FCNC decays .

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



A single effective operator $(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$

Dominated by top quark exchange

Sensitive to both CP-violating and CP-conserving effects

Hadronic matrix from well-measured $K^+ \to \pi^0 e^+ \nu$

$$B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \text{ x } 10^{-11}$$

$$B_{SM}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (2.6 \pm 0.4) \text{ x } 10^{-11}$$

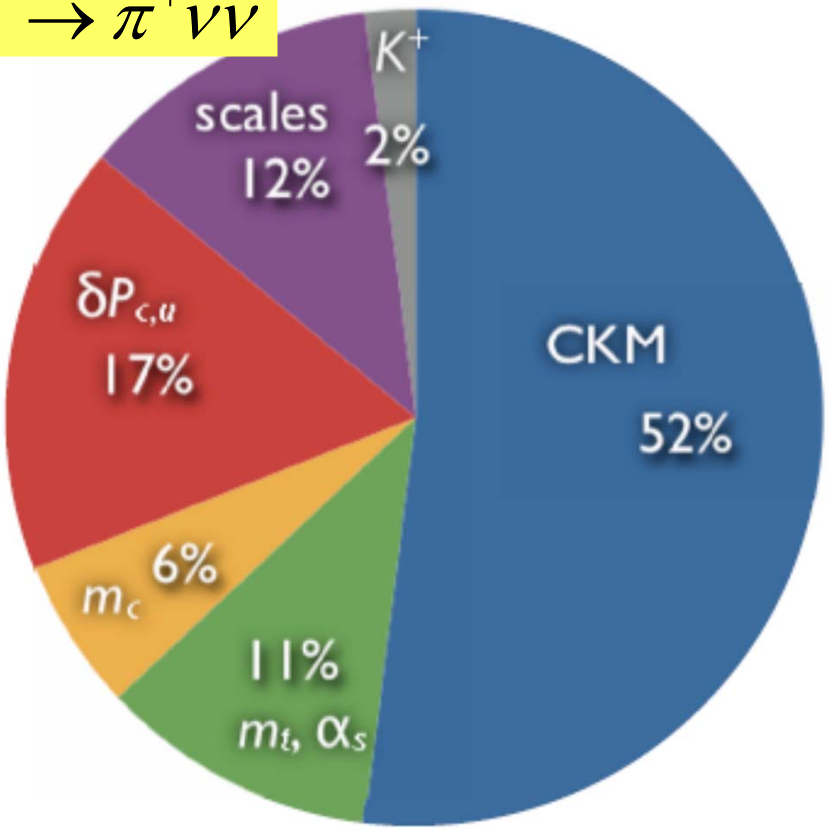
Buras et al. (2013) http://dx.doi.org/10.1007/JHEP04(2013)168

Uncertainties expected to improve to <7%.

Summary of SM Theory Uncertainties

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

CKM (quark mixing) parameter uncertainties dominate the error budget today.



With foreseeable improvements, expect total SM theory error ≤6%.

A. Kronfeld (FNAL)

Unmatched by any other FCNC process (K or B).

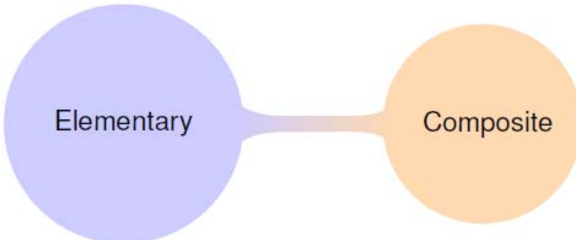
30% deviation from the SM would be a 5σ signal of NP

SM theory error for $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode exceeds that for $K^+ \to \pi^+ \nu\bar{\nu}$.

U. Haisch, arXiv:0707.3098

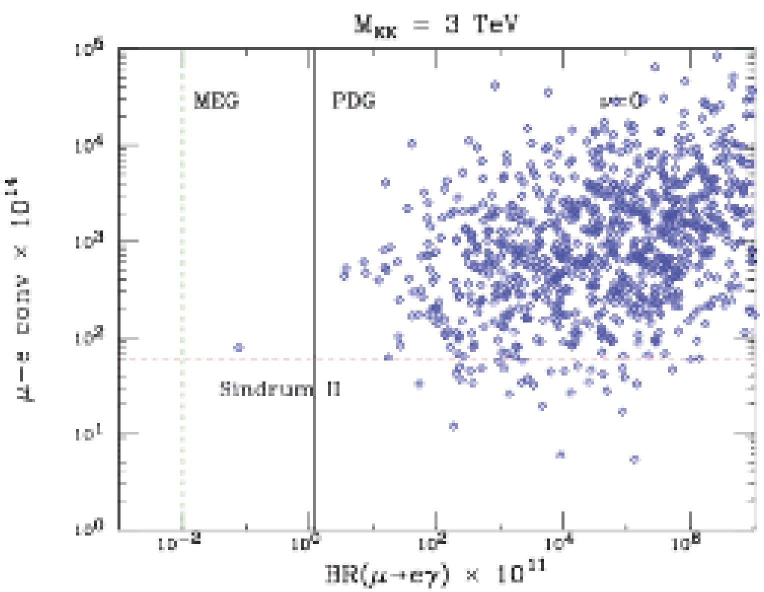
Bauer Redi
CLVF 2013

Flavor Physics Testing COMPOSITE HIGGS MODELS



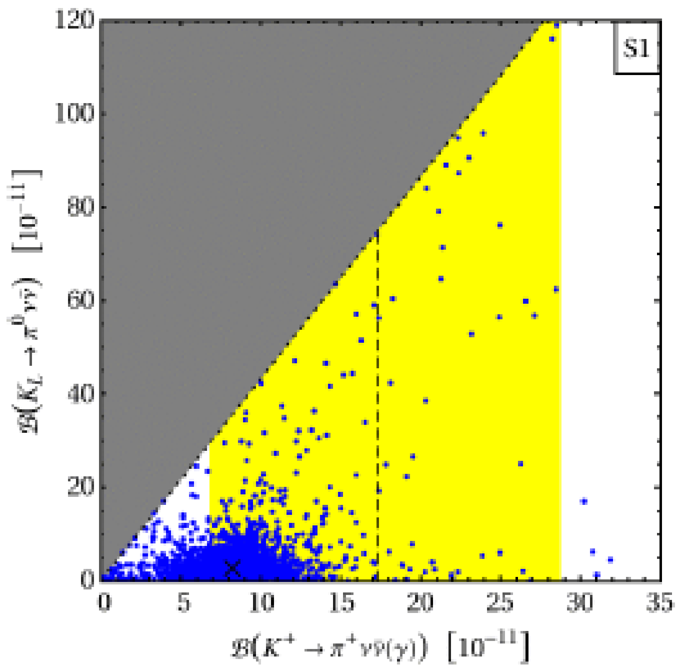
Randall Sundrum Model
Warped extra dimensions

μe Conversion vs $\mu \to e\gamma$



Some parameters are not viable anymore.

$K_L^0 \to \pi^0 \nu\bar{\nu}$ vs $K^+ \to \pi^+ \nu\bar{\nu}$



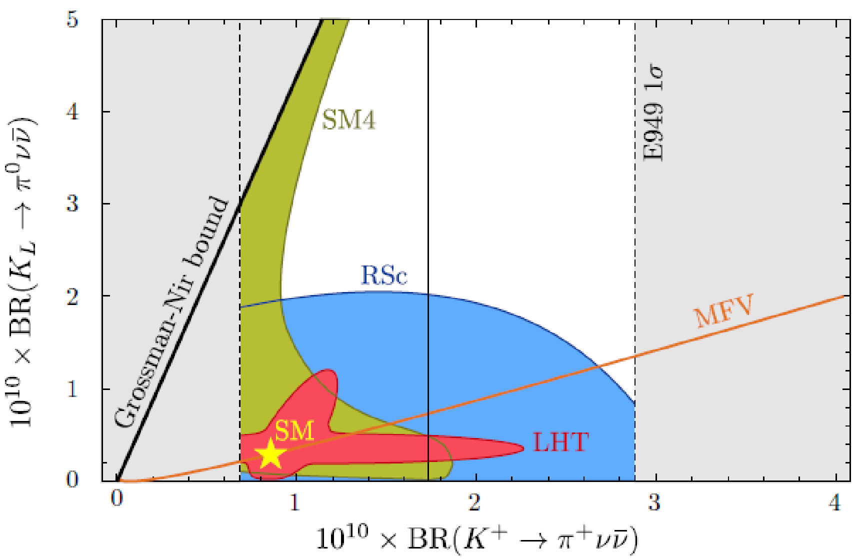
Large parameter space open.

$K \to \pi\nu\bar{\nu}$: High Sensitivity to New Physics

Sensitivity to new physics at high mass scales complementary to studies of B decays and lepton flavor violation.

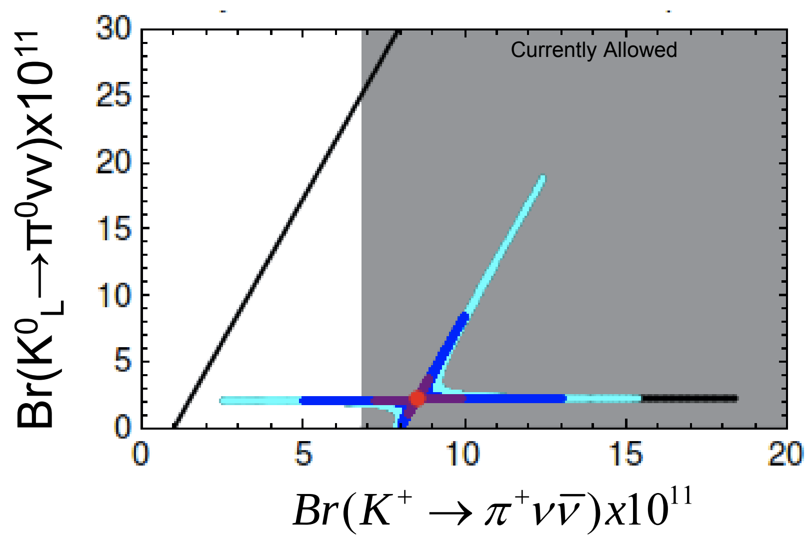
Extra Dimensions as a Theory of Flavor,Z', Dark Sector, Sterile Neutrinos…

$\mathrm{B}(K_L^0 \to \pi^0\nu\bar{\nu})$ vs. $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$



D. M. Straub, arXiv:1012.3893

$Z'\ (m_{Z'} = 5-30\,TeV)$



Large effects in K decays; <10% in B decays.

Buras, De Fazio, Girrbach,arXiv:1211.1896

***

“FCNC portals to the dark sector”

Dark Sector Decays $K \to \pi^{+} X(X)$ may also be sought....

Operator Dimensional Analysis

$$\frac{m_I^{n-6}}{\Lambda^{n-4}} \approx \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}\left|V_{tI}V_{tJ}\right|$$

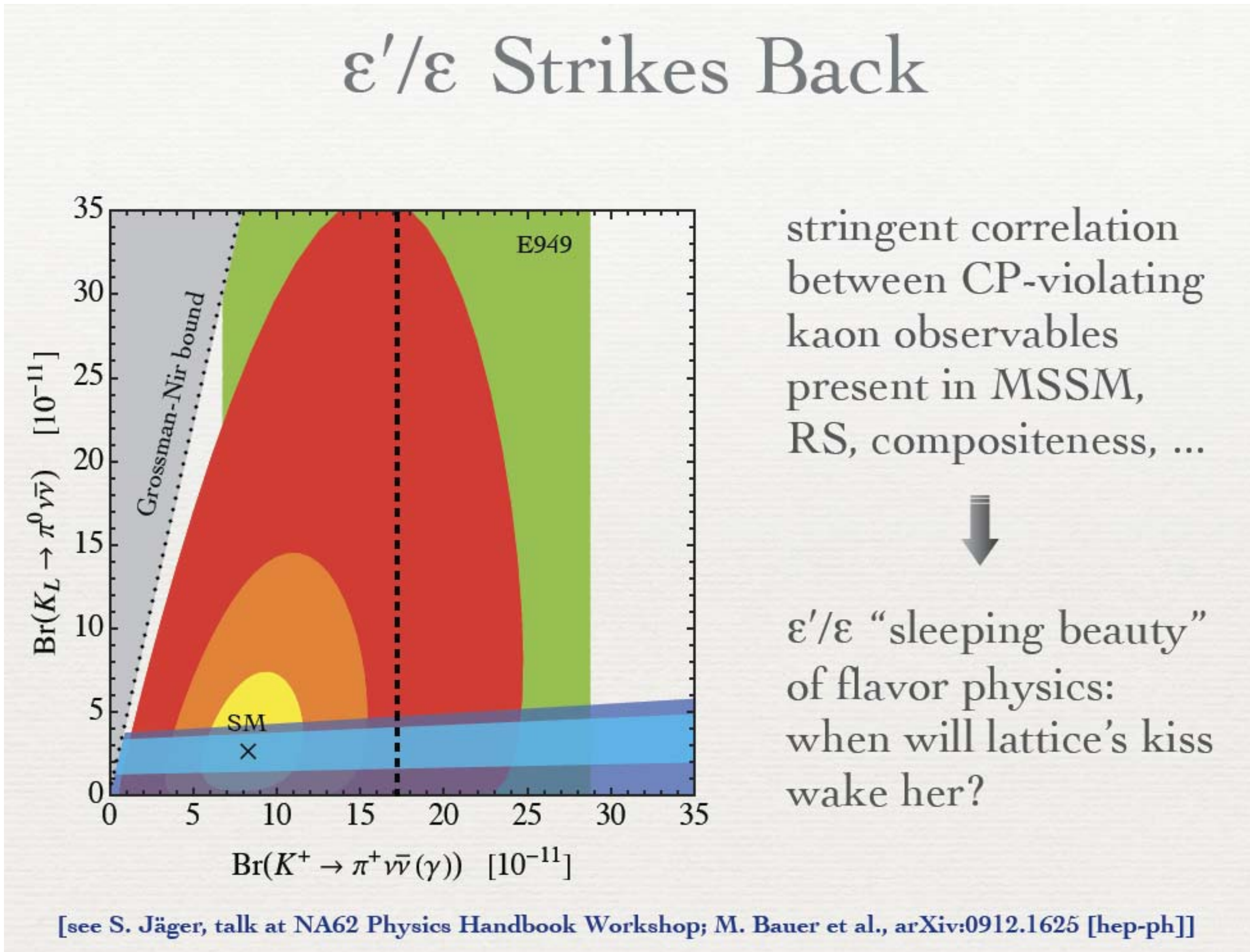
K *decays*
Highly sensitive
for low dimension
operators

	$n=5$	$n=6$	$n=7$	$n=8$	$n=9$
$s \to d$	$3.3\,10^{7}\,TeV$	$130TeV$	$2TeV$	$0.25TeV$	$0.07TeV$
$b \to d$	$1.3\,10^{5}\,TeV$	$26TeV$	$1.5TeV$	$0.37TeV$	$0.16TeV$
$b \to s$	$2.7\,10^{4}\,TeV$	$12TeV$	$0.9TeV$	$0.25TeV$	$0.11TeV$

Kamenik and Smith (2012) link.springer.com/content/pdf/10.1007/JHEP03(2012)090

ASIDE: U. Haisch Proj. X workshop 2012

$K_L^0 \to \pi^0 \nu\bar{\nu}$ may be further constrained by ε'/ε – measure of direct CP violation in $K_L^0 \to \pi^0\pi^0$ decays.

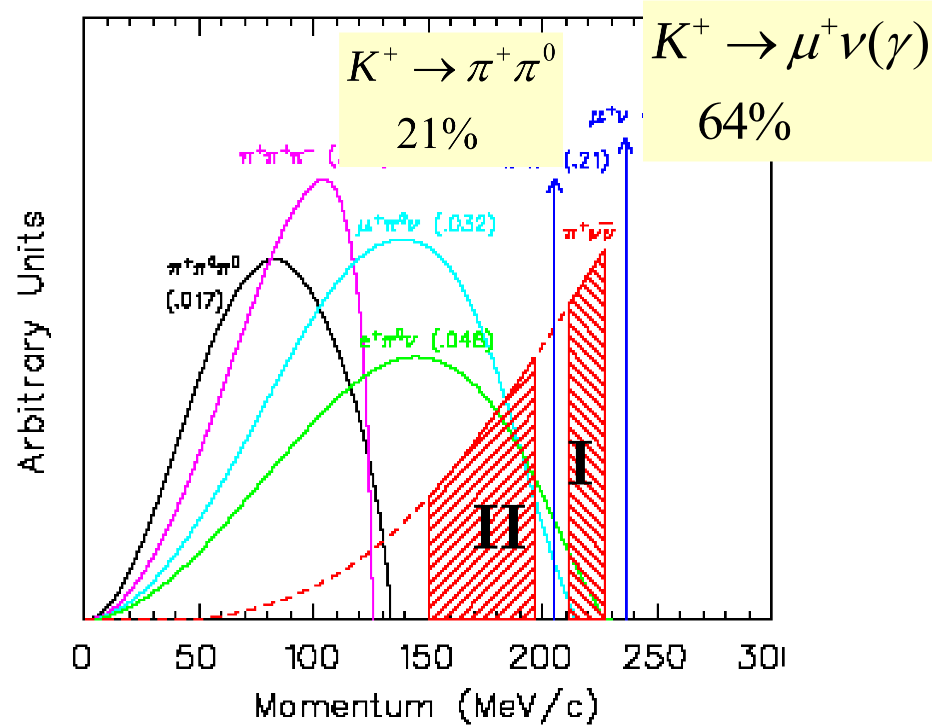


Challenges for Measuring

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

$B_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$

Experimentally weak signature: backgrounds exceed signals by $>10^{10}$



Determine everything possible about the K and π

- π^+/μ^+ particle ID better than 10^6 ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$)
- Work in the CM system (stopped K^+)

Eliminate events with extra charged particles or ***photons***

* π^0 inefficiency $< 10^{-6}$

Suppress backgrounds well below the expected signal (S/N~10)

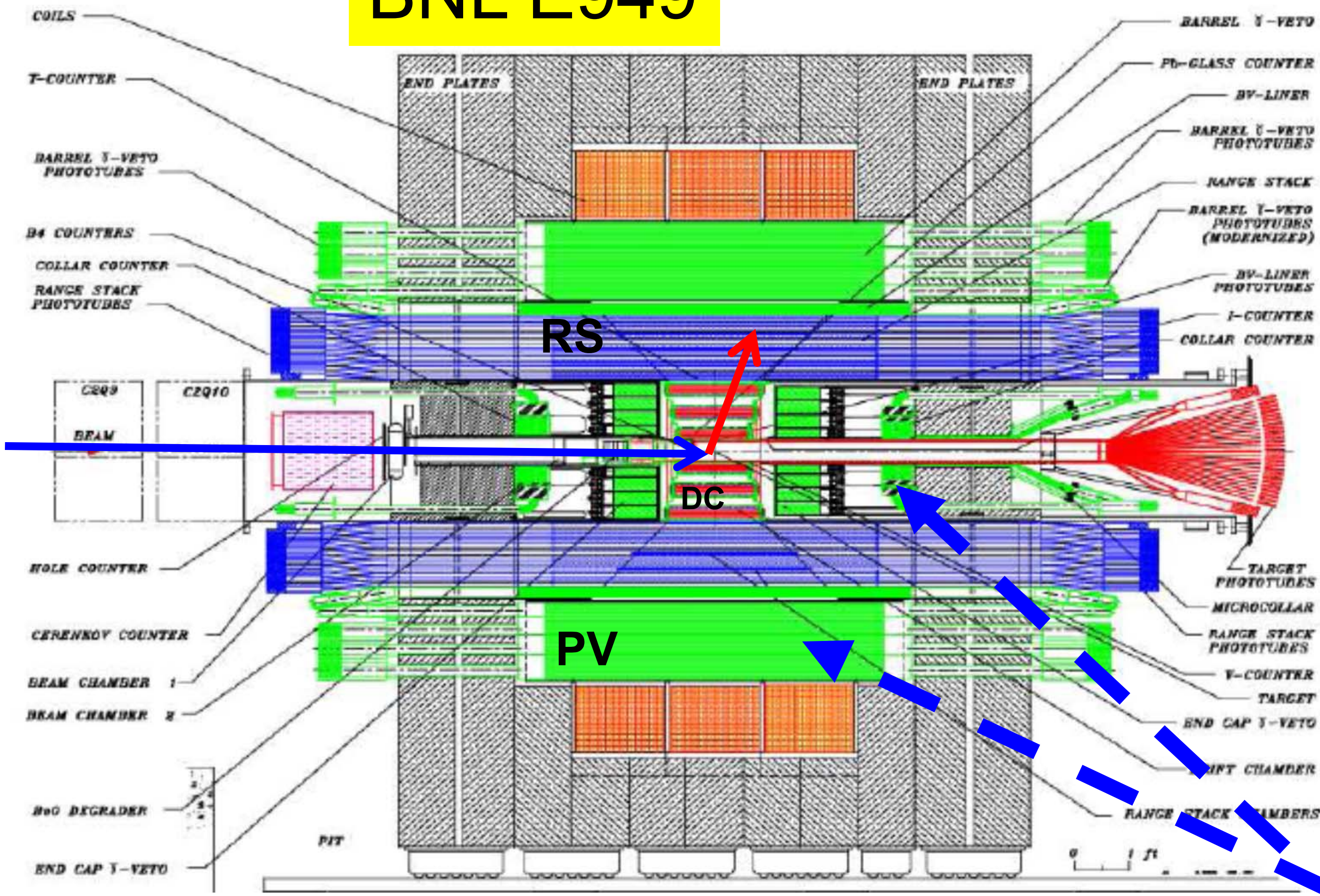
* Predict backgrounds *from data*: dual independent cuts
* Use "Blind analysis" techniques
* Test predictions with outside-the-signal-region measurements

Evaluate candidate events with S/N function

"…**when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth**? "

Sherlock Holmes in The Sign of the Four (1890)

BNL E949



Stop 700 MeV/c K^+

Scintillating fiber tgt.

π^+ Momentum in DC

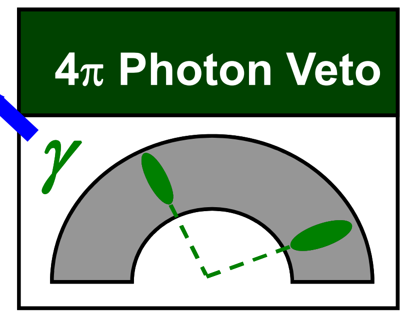
Energy, range in RS

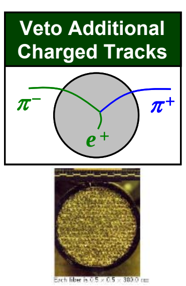
$\pi \to \mu \to e$

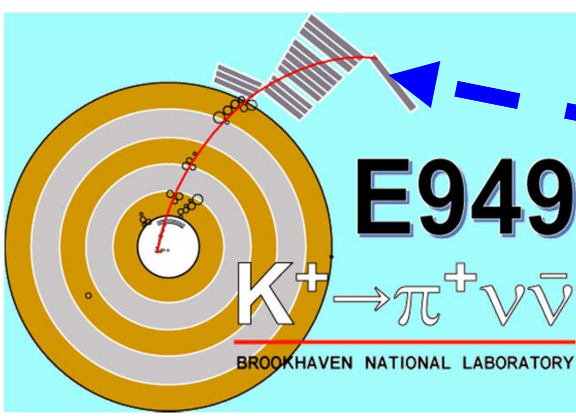
$>10^6$ μ suppression

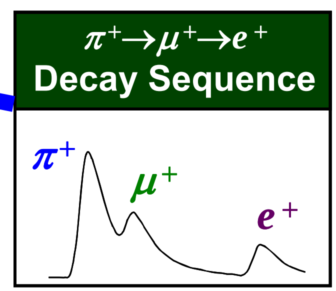
4π Photon Veto

$>10^6 \pi^0$ suppression



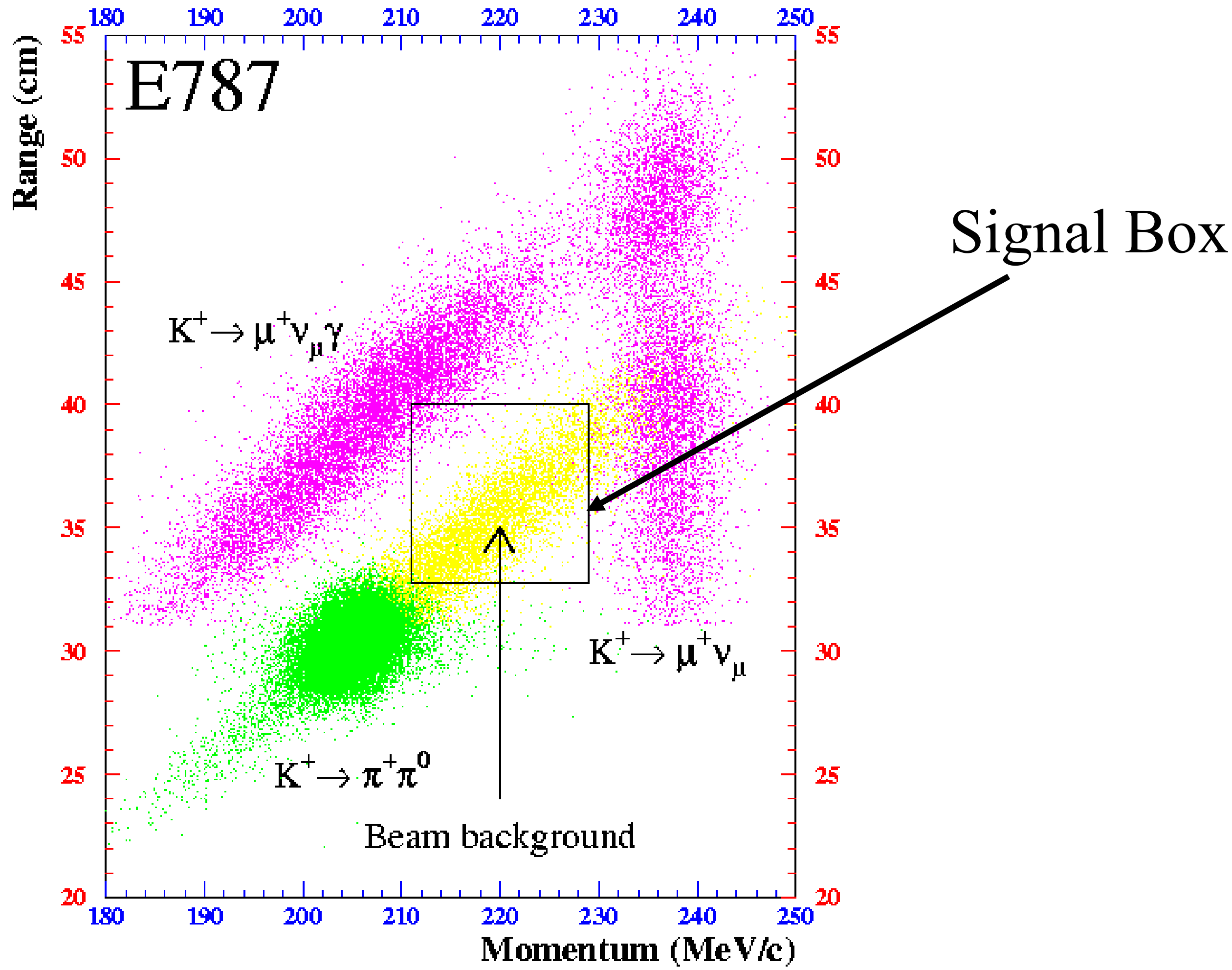






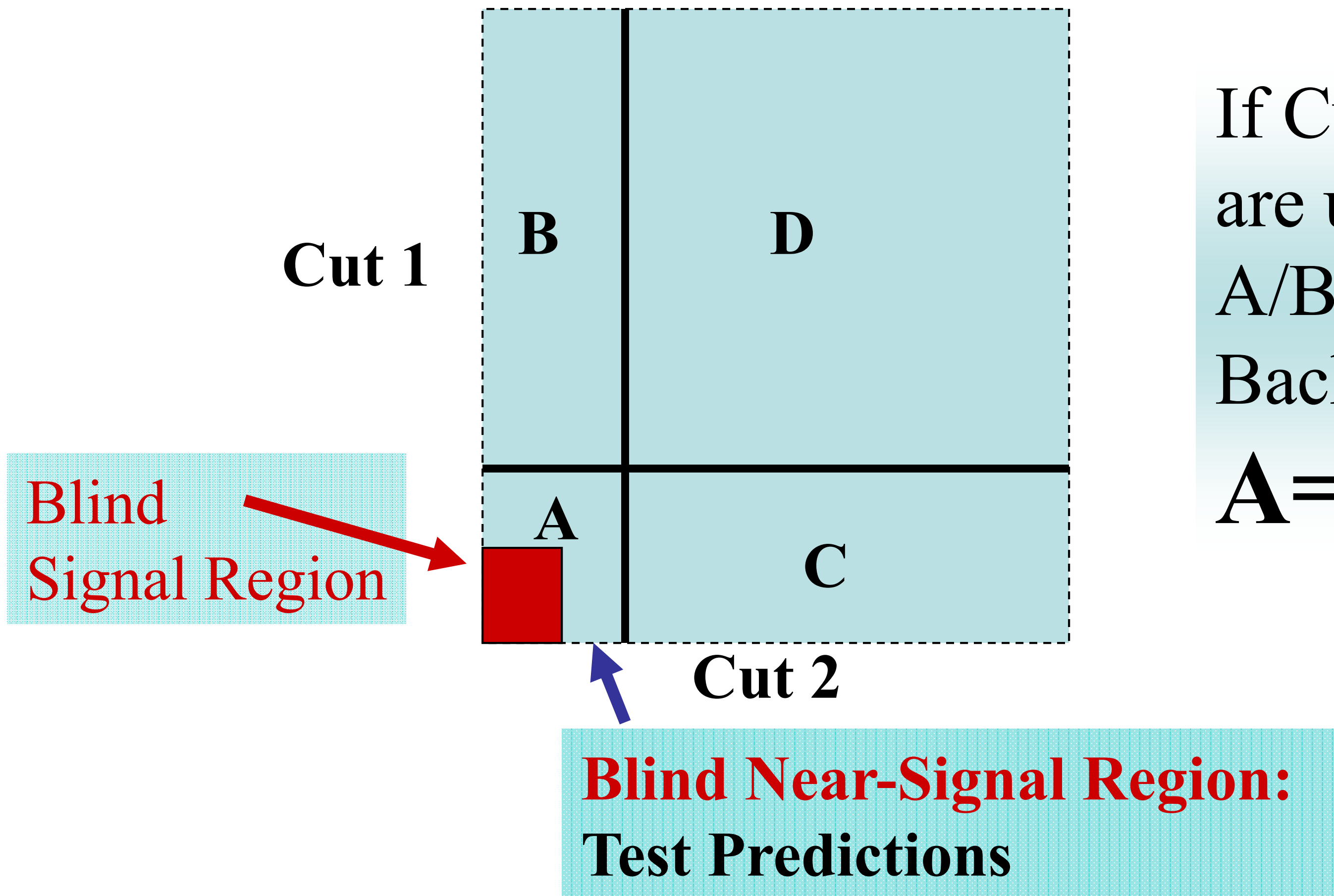
500 MHz digitizers

Background Processes: Pion Range vs. Momentum



Estimating Backgrounds 10^{-12} Level
Dual-Cut BLIND Analysis Method

Cut 1 *vs* Cut 2



If Cuts 1 and 2 are uncorrelated:

A/B=C/D

Background in A:

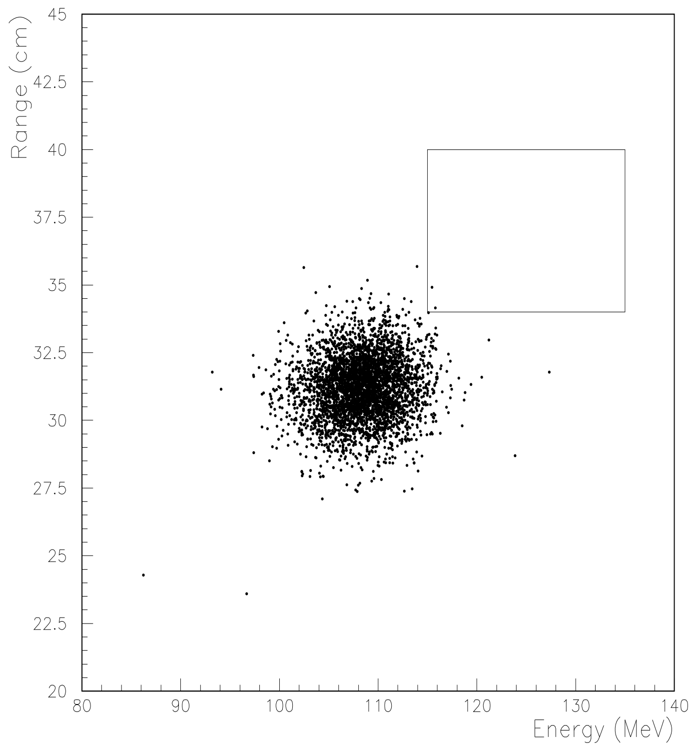
A=B C/D

$K^+ \rightarrow \pi^+\pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

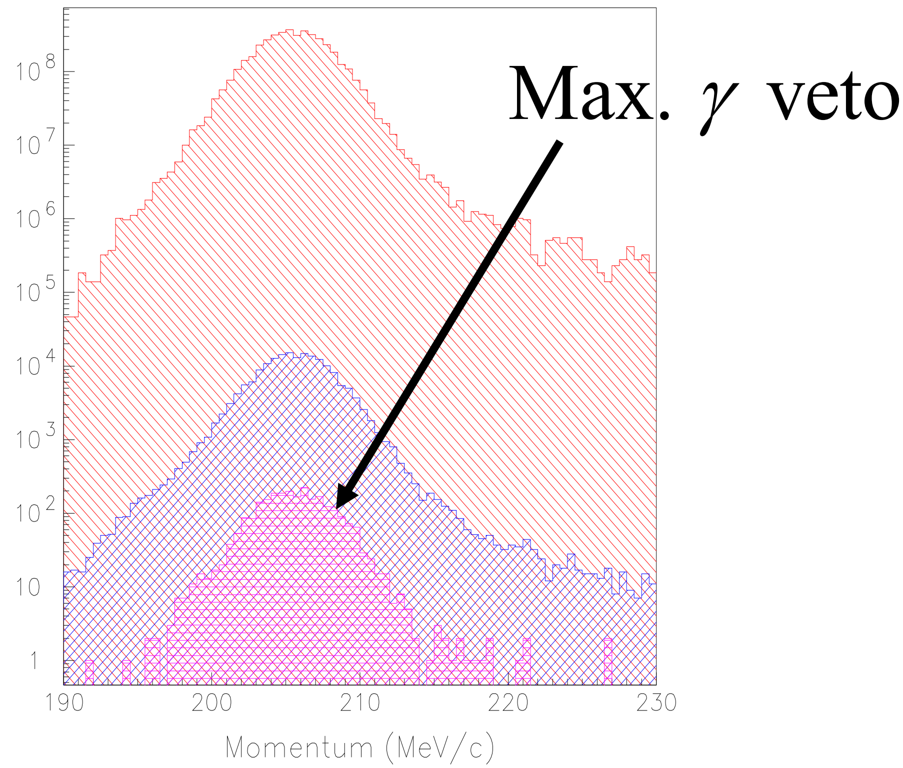
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



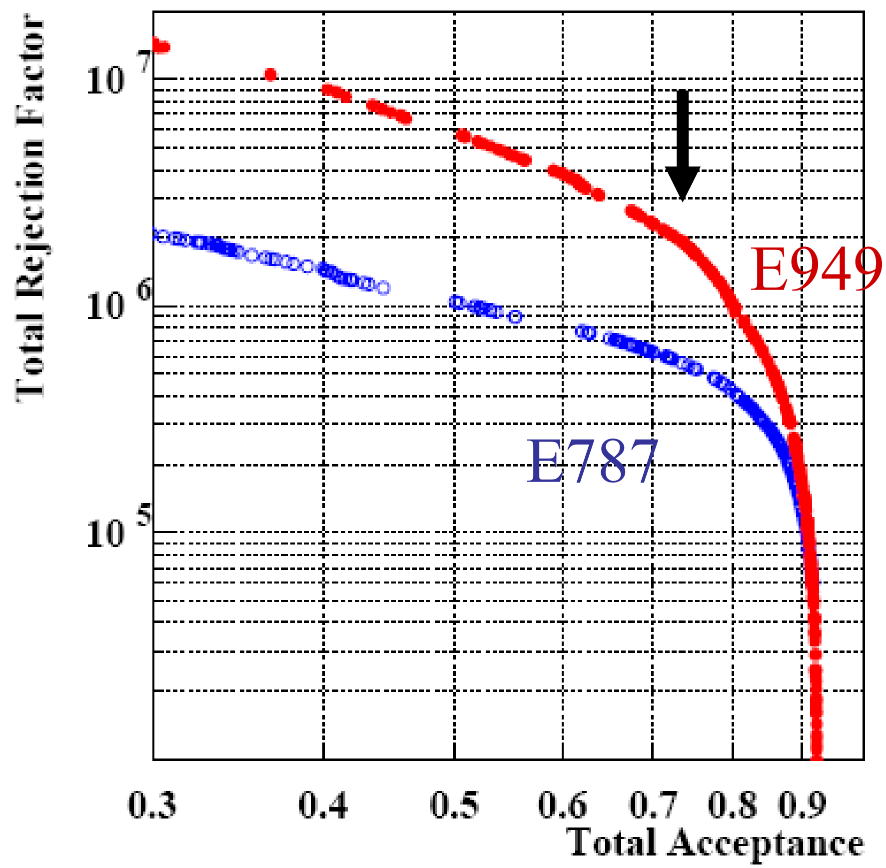
Check for correlations

Background Suppression: E949 Extreme Photon Detection Efficiency

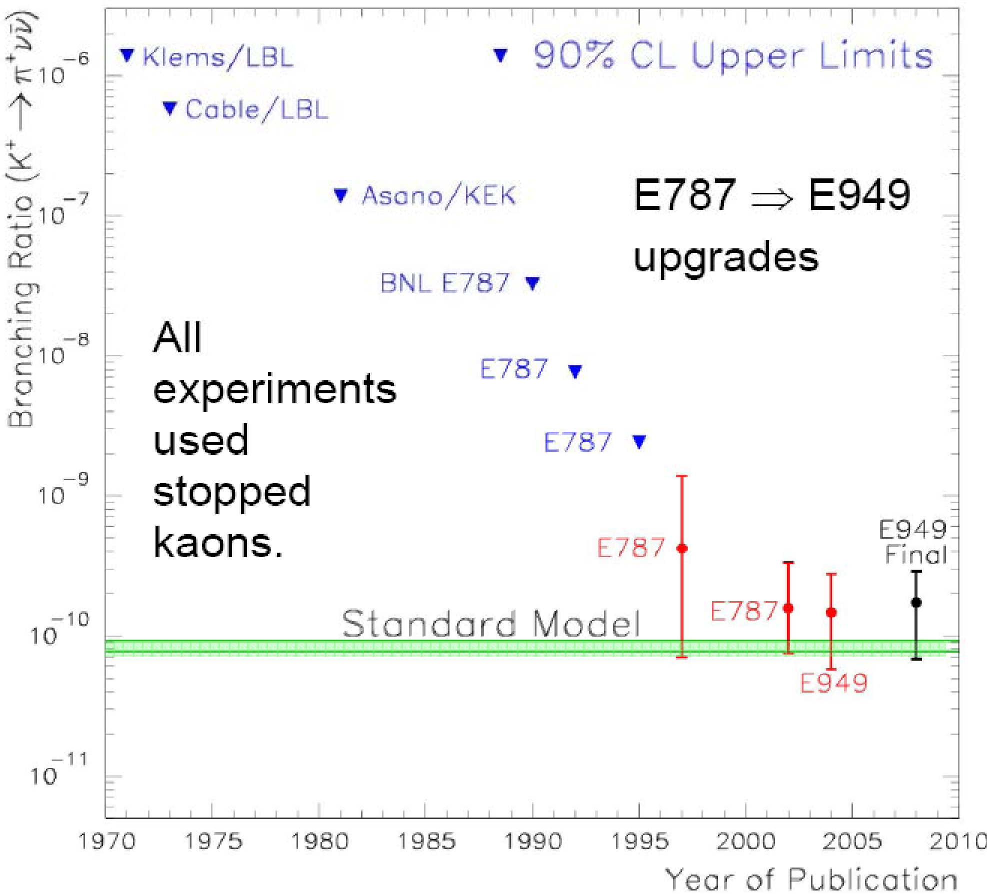
π^0 Rejection: $>10^6 - 10^7$

Possibly the most efficient photon detector built so far.

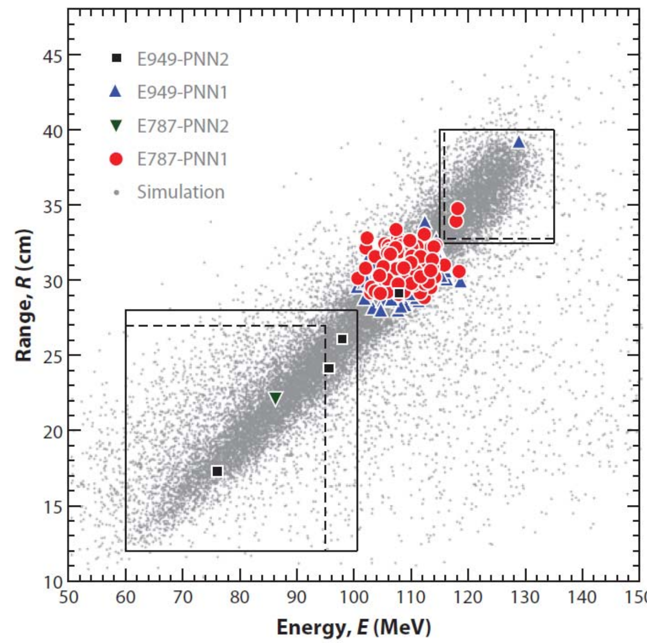
Rejection vs. Acceptance



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



Pion Range vs. Energy



E787/E949 Final: 7 events observed

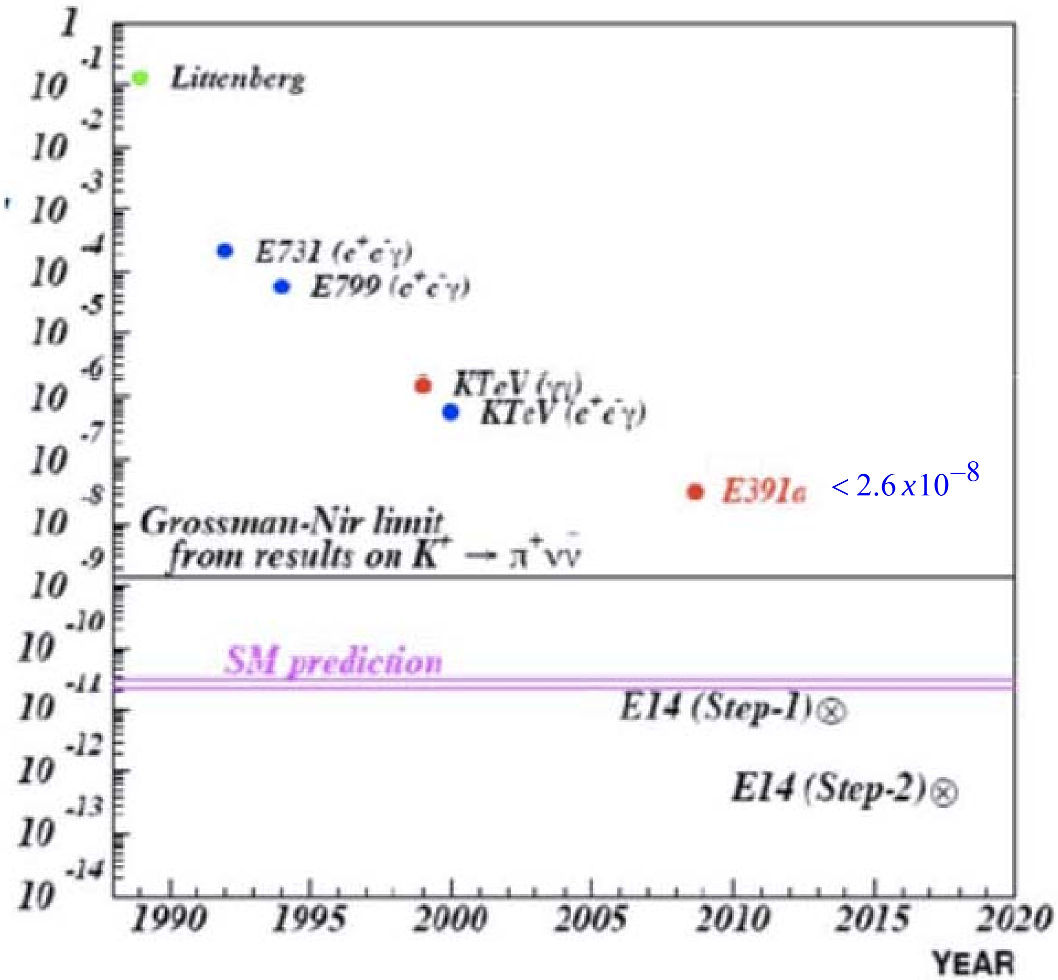
$B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

Standard Model:

$B(K^+ \to \pi^+ \nu \bar{\nu})$ = (0.78+-0.08) $x10^{-10}$

*A.V. Artamonov *et al.,* PHYS. REV. D 79, 092004 (2009).

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



J. Ma 2011

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

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

Builds on NA-31/NA-48
Un-separated GHz beam
Aim: 80 events at SM
2015-18 (LHC Run II)

J-PARC $K_L^0 \to \pi^0\nu\bar{\nu}$

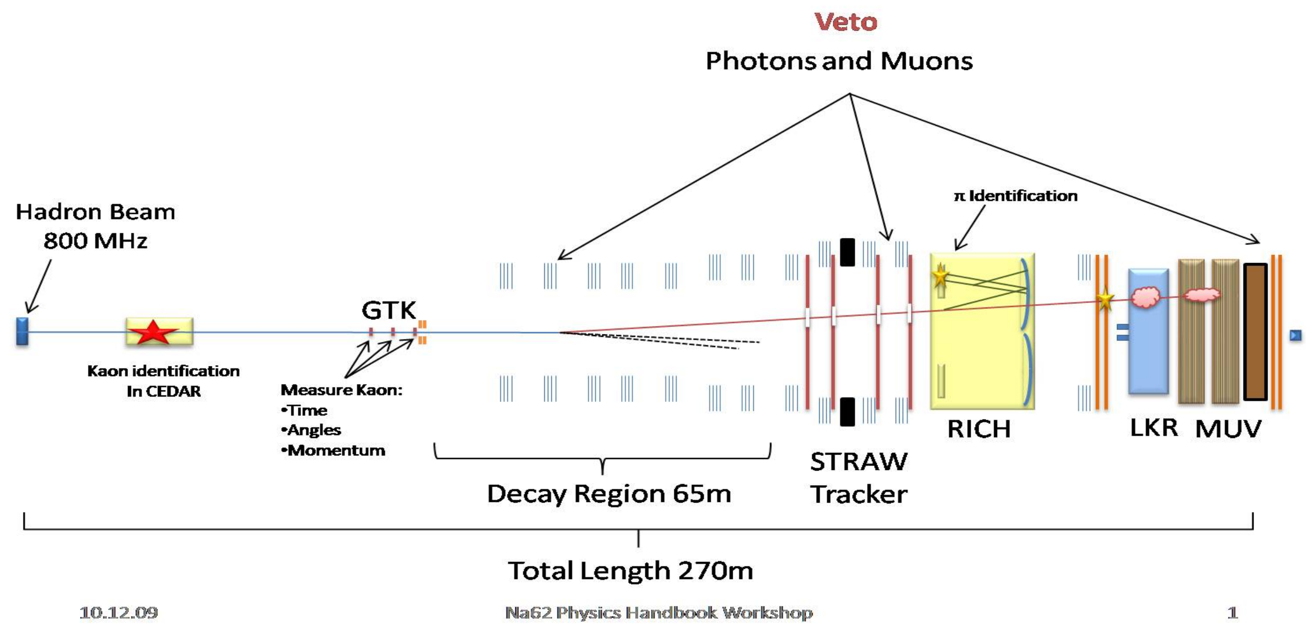
Upgraded from KEK experiment E391a
Aim: few events (S/B~1) at SM (Phase I)
Commissioning 2013

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

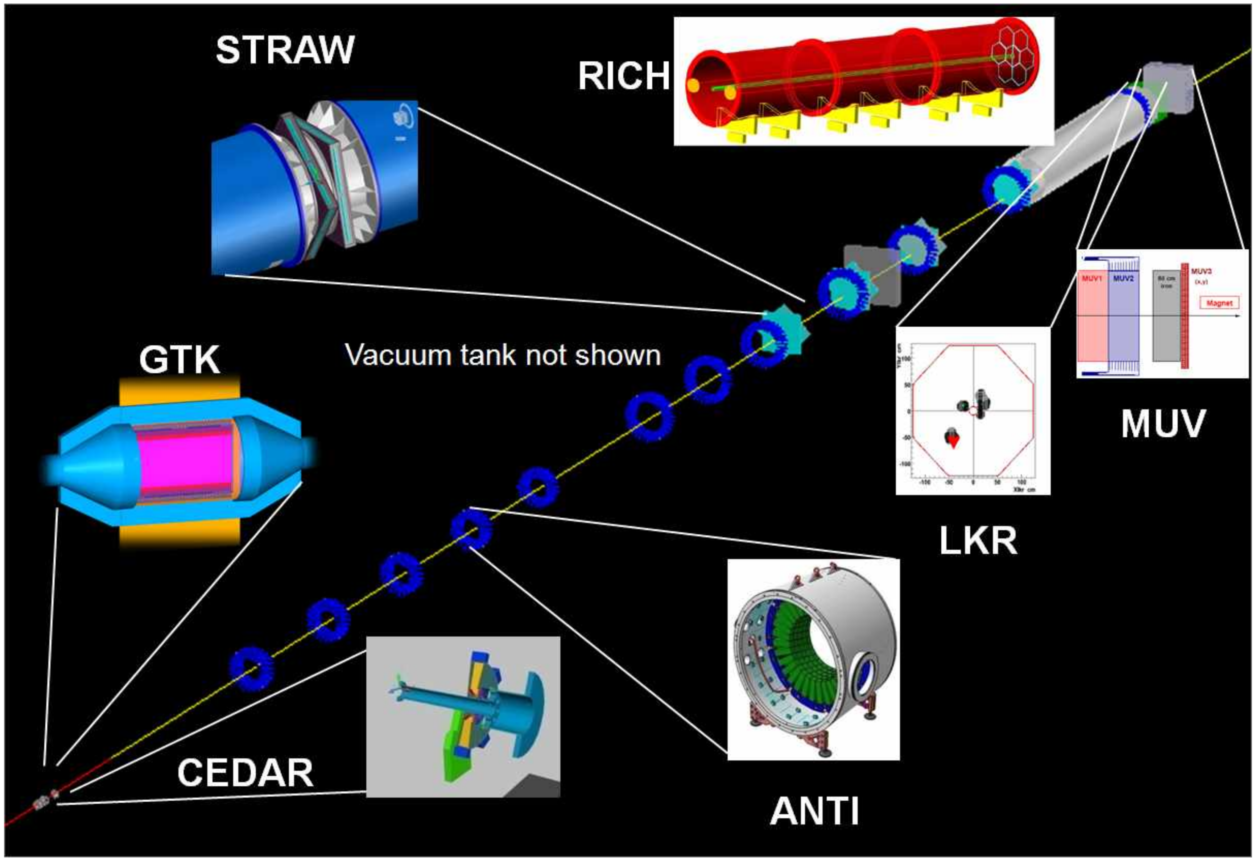
$K^+ \to \pi^+\nu\bar{\nu}$ at CERN

75 GeV Kaon Decays-in-flight

Proton beam from SPS



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 40-50 events/yr at SM
- Under construction; start 2015



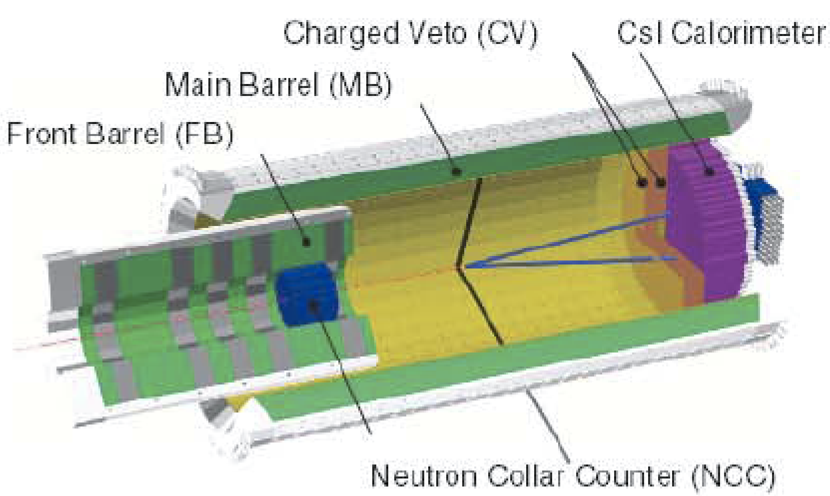
π^0 Rejection goal: 10^8 μ Rejection goal: 10^5

π / μ RICH separation up to 35 GeV/c

Beam tracking: 40 MHz/cm^2

$K_L^0 \to \pi^0 \nu \bar{\nu}$ at J-PARC

Improved setup based on KEK E391a $(< 2.6 x 10^{-8})$

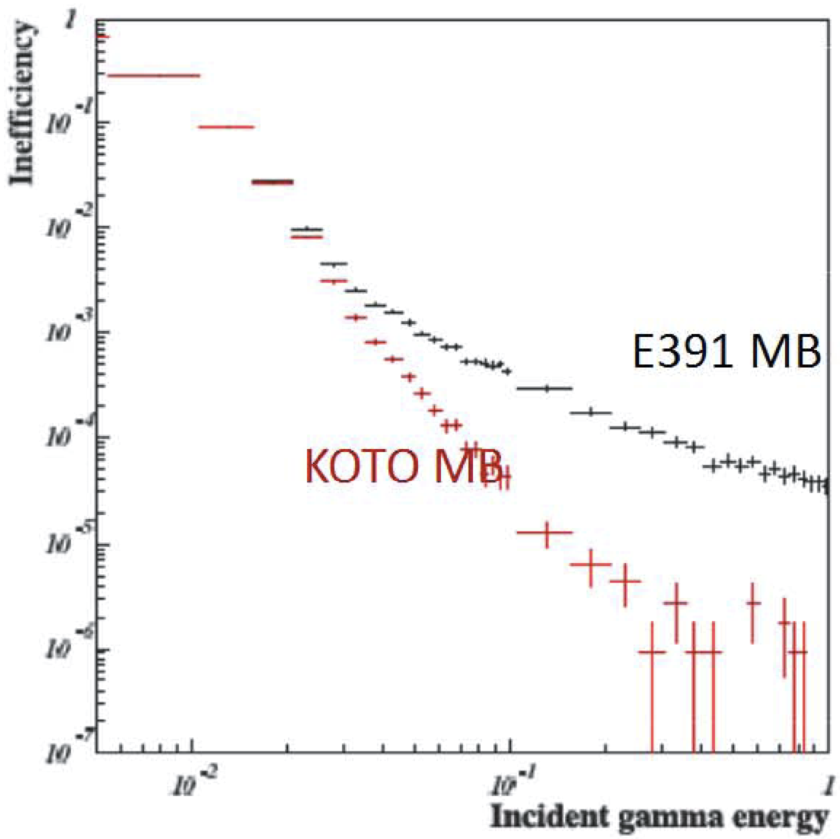


Improved J-PARC Beam line
Upgraded Detector
100 x proton intensity
Aim: few events (S/B~1) at SM
Under construction; start 2013

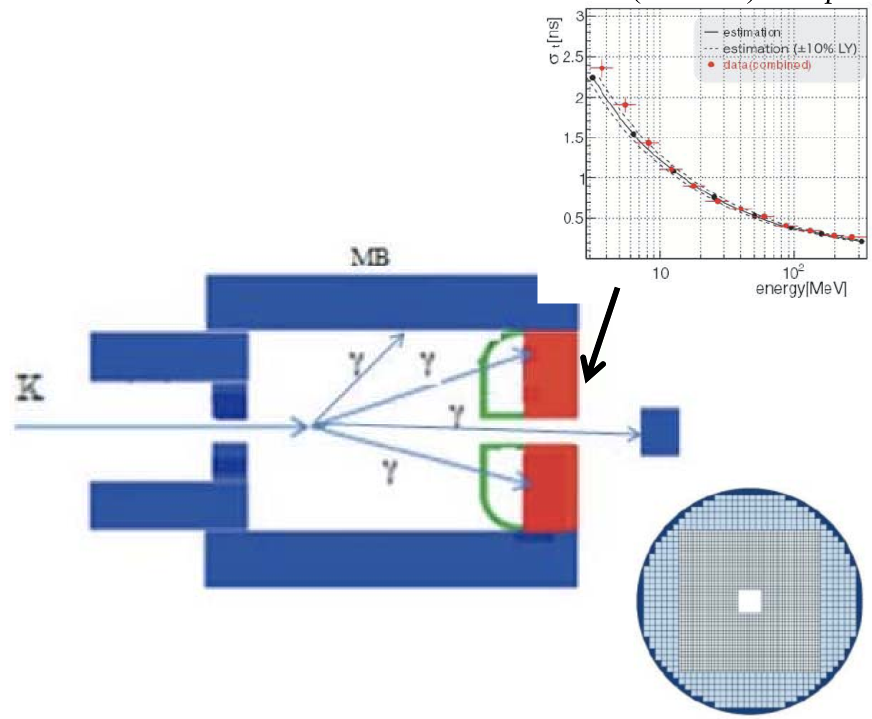
Background source	#evts
$K_L \to \pi^0 \pi^0$	1.8
$K_L \to \pi^+ \pi^- \pi^0$	0.46
n + residual gas	0.04
n + upstream veto	0.13
accidental coincidence	0.10
sum	2.5
$K_L \to \pi^0 \nu \bar{\nu}$ signal	3.5

Expected Photon Veto Performance

Principal background: $K_L^0 \rightarrow \pi^0\pi^0$



CsI Calorimeter: Δt (50 MeV)~500 *ps*



	J-PARC KOTO	KEK-E391a	improvement
KL yield/spill	8.1×10^{6}	3.3×10^{5}	x30/sec
Run time	12 months	2 months	x6
Decay prob.	3.6%	2.1%	x2
Acceptance	4.7%	1%	x3.6
Sensitivity	0.8×10^{-11}	1.1×10^{-8}	x1300

J. Ma 2011, T. Yamanaka 2012

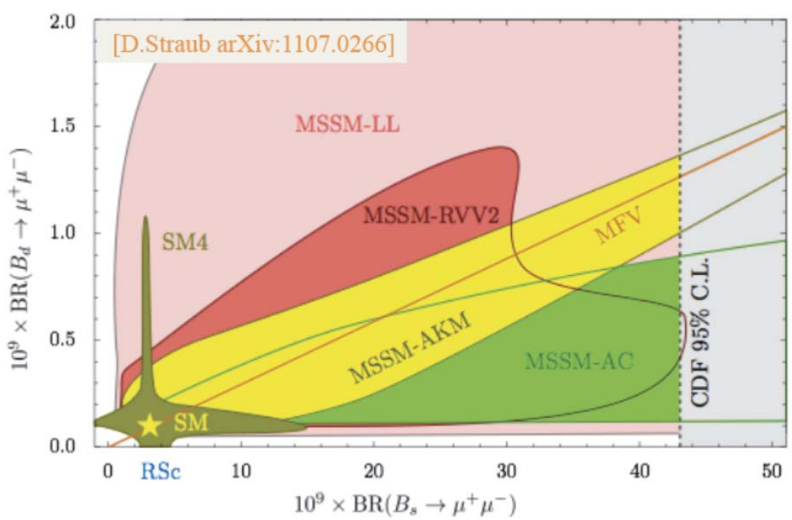
Rare B Decays—Entering the Precision Regime

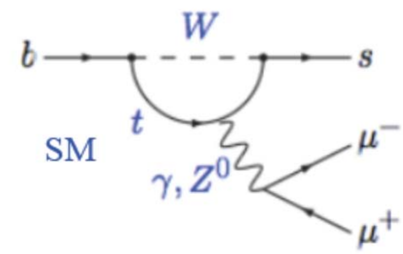
Standard Model Predictions for $B_q \rightarrow \mu\mu$

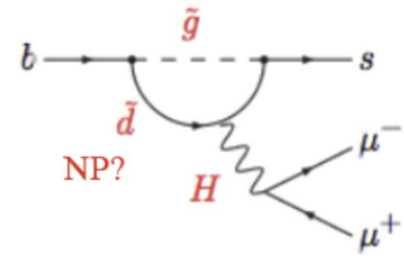
$$B(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23)\, x10^{-9}$$

$$B(B_d \rightarrow \mu\mu) = (1.06 \pm 0.09)\, x10^{-10}$$

PRL 112 (2014)101808, JETP 1312 (2013)097,PRD 89(2014)034023

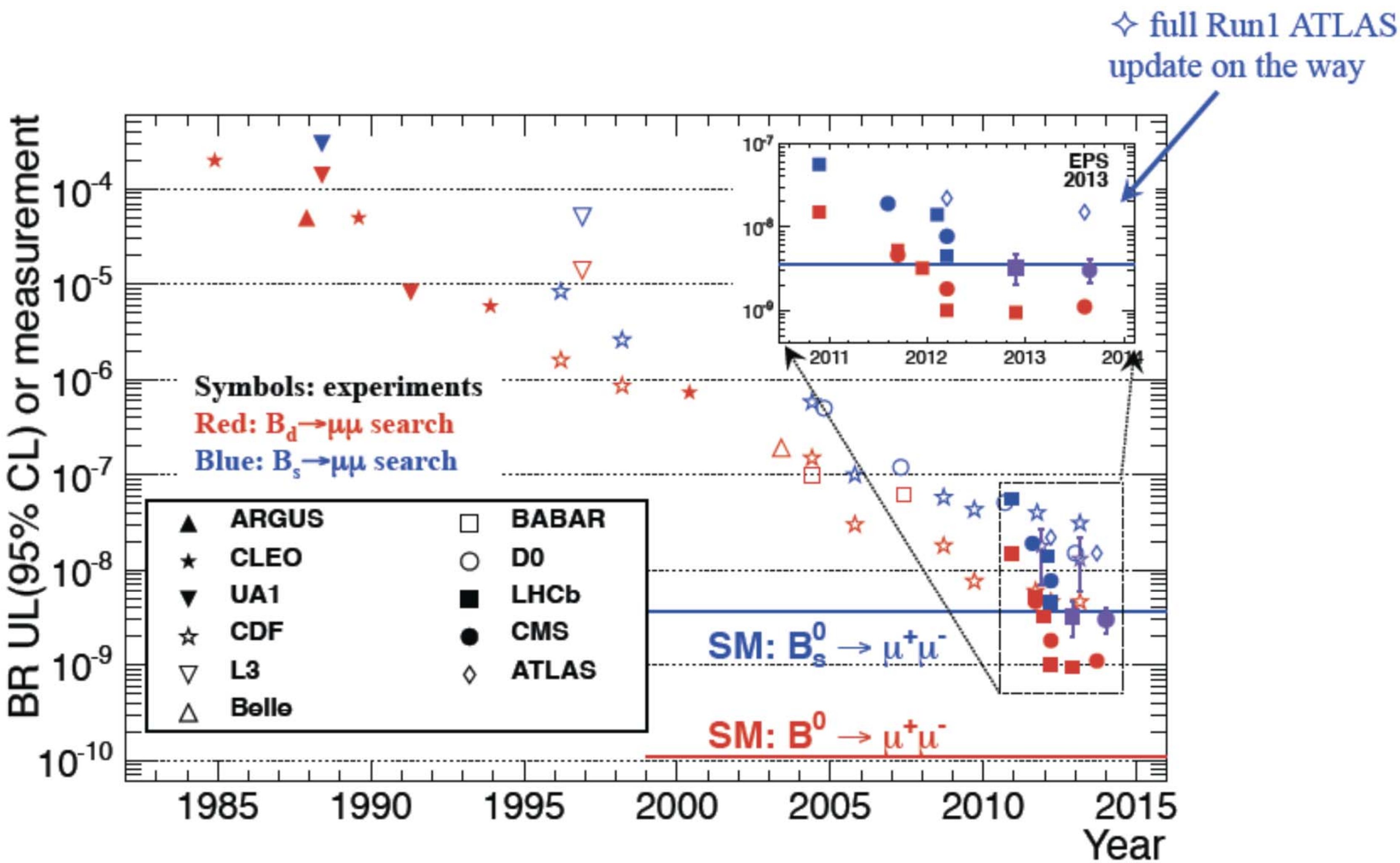






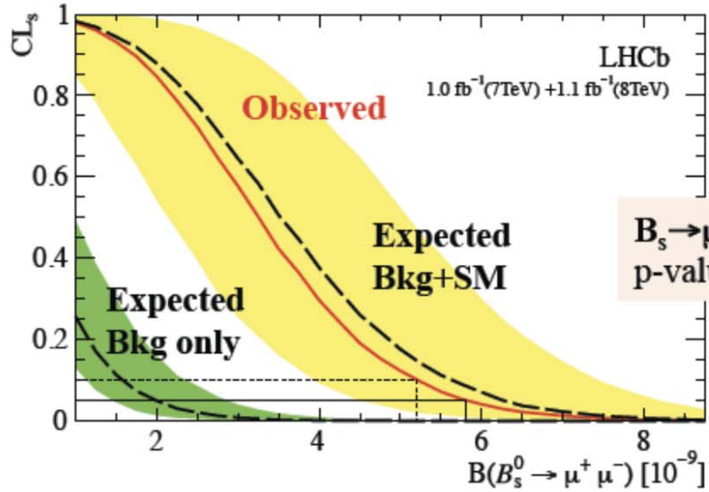
B.Sciascia INFN -Very rare B decays- FPCP, Marseille 27 May 2014

30 Year Quest for $B_s \to \mu\mu$



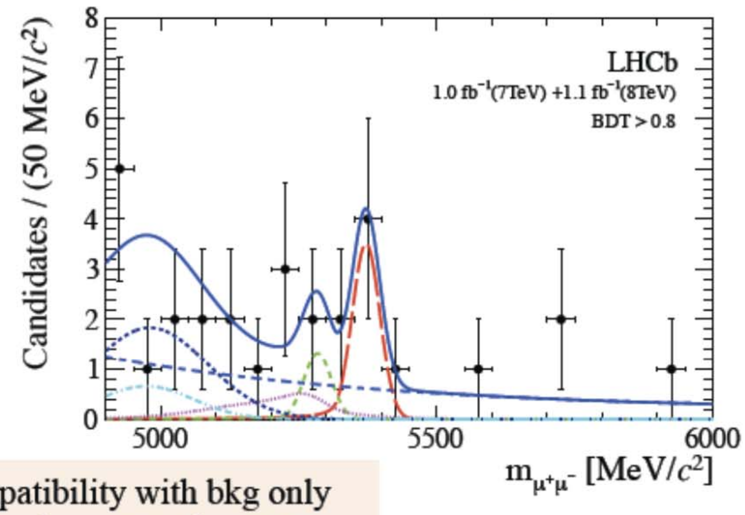
$B_s \to \mu\mu$: first observation (LHCb)

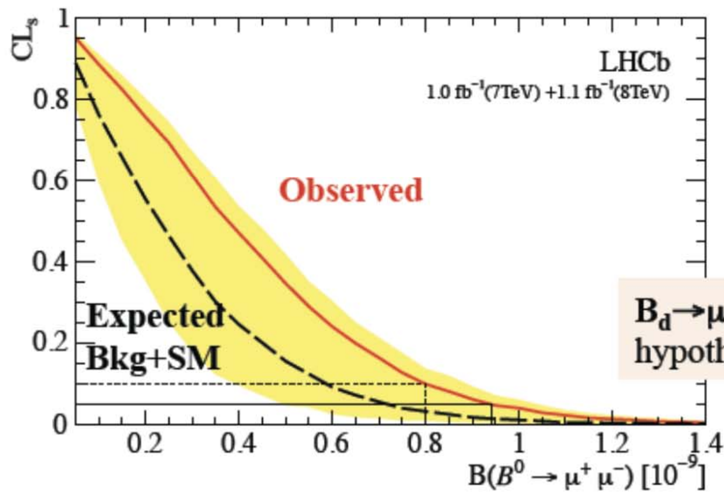
[LHCb, PRL 110(2013)021801]



November 2012
1/fb (7 TeV) + 1.1/fb (8 TeV)

$B_s \to \mu\mu$, compatibility with bkg only hypothesis:
p-value = 1-CLb = 5.3×10^{-4} (**3.5 σ excess**)





$B_d \to \mu\mu$, compatibility with bkg only hypothesis: p-value = 1-CLb = 0.11

$B_{(s)} \to \mu\mu$: evidence at LHCb

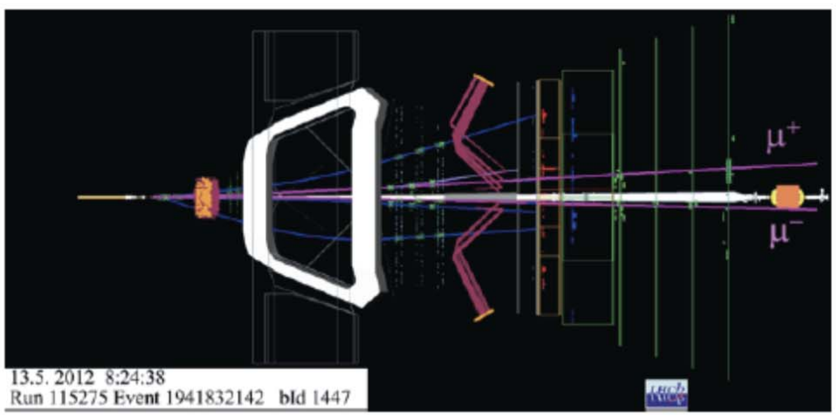
[PRL 111(2013)101805]

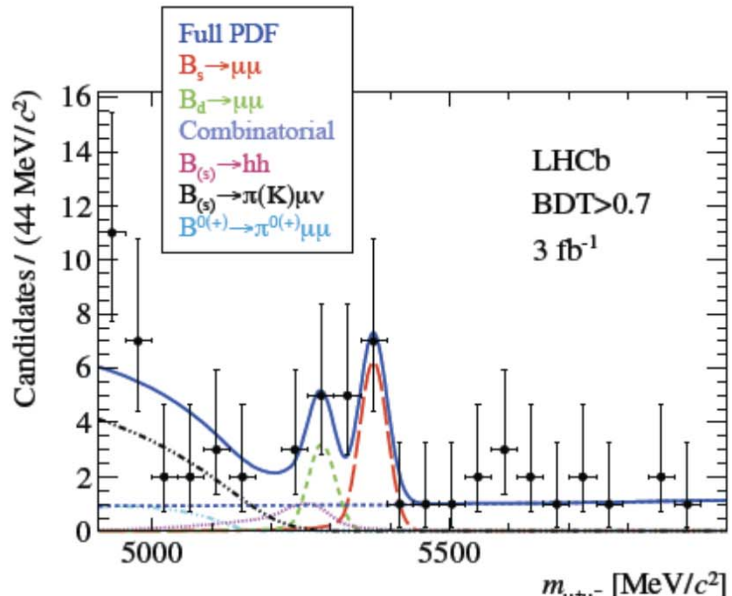
Simultaneous UML fit to mass spectra on 8 BDT bins.
Combinatorial bkg, B_s and B_d: yields free
Exclusive bkg: yields and PDFs constrained to their expectations.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$

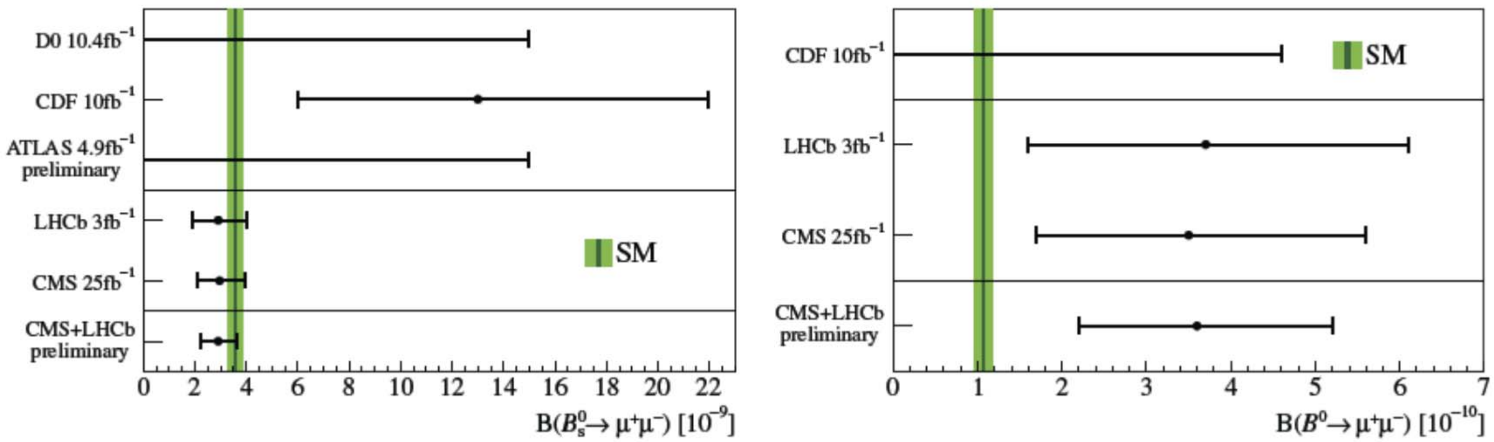
significances:
$B_s\mu\mu$ 4.0 σ
[expected 5 σ (median)]
$B_d\mu\mu$ 2.0 σ





$B_{(s)} \to \mu\mu$: LHCb+CMS average

[LHCb-CONF-2013-012, CMS-PAS-BPH-13-007]



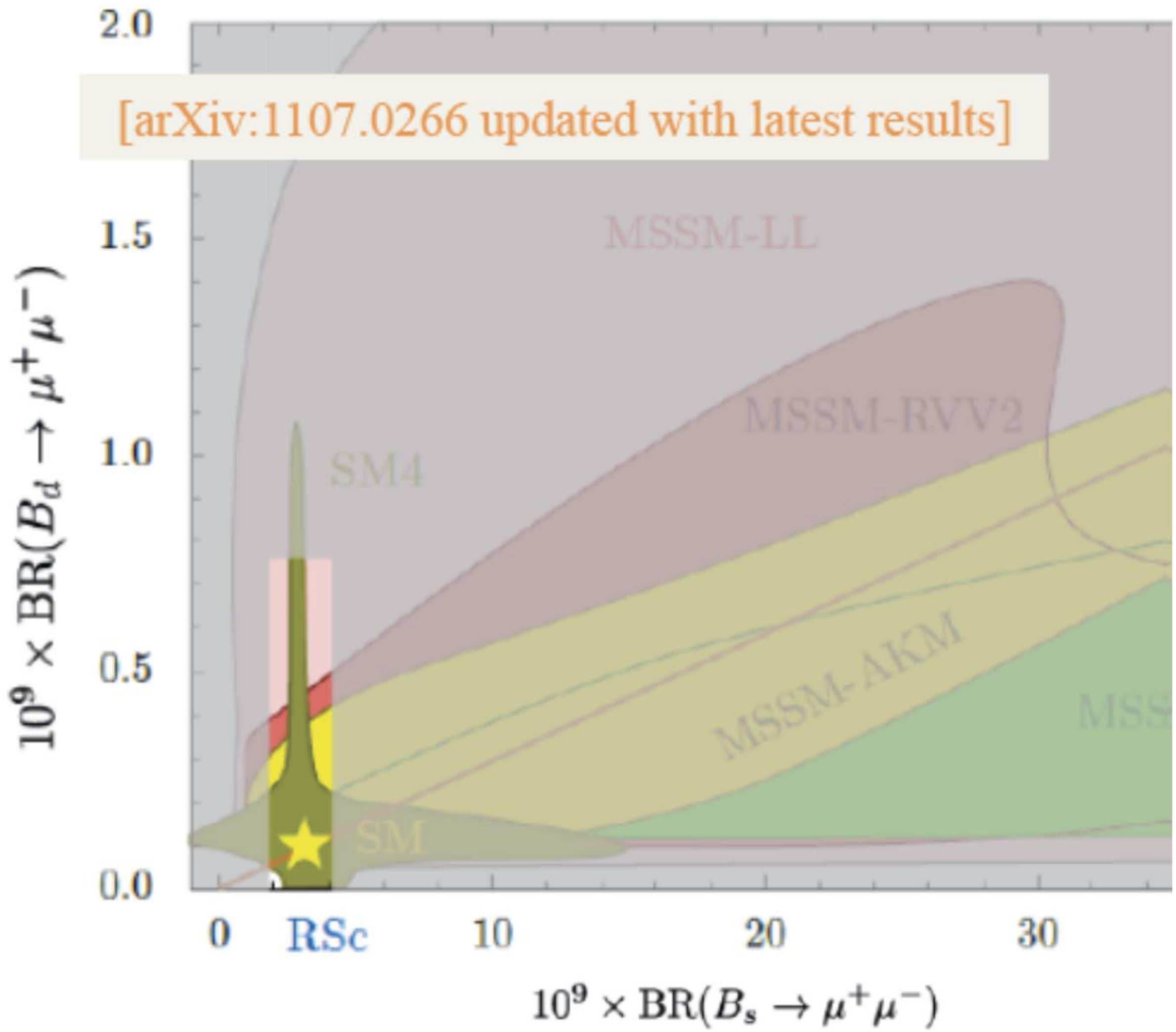
Naive combination (central values, no significance assessment)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \cdot 10^{-10}$$

Work is ongoing to do a **full combination** of LHCb and CMS measurements: combined fit to the two datasets, sharing of all PDFs and correlated parameters (f_s/f_d, BR($B^+ \to J/\psi\, K+$),…).

Output: combined BF and 2D scans, significances. **Results expected end of summer**.

Limited Openings remaining for New Physics after latest results….



B.Sciascia INFN -Very rare B decays- FPCP, Marseille 27 May 2014

Baryon and Lepton Number Violation

Stability of matter depends on B conservation!
Global symmetry, approximate symmetry?
But B violation needed to explain matter asymmetry of the Universe

Grand Unified Theories (GUT) – SU(5), SO(10) -- would explain a lot:

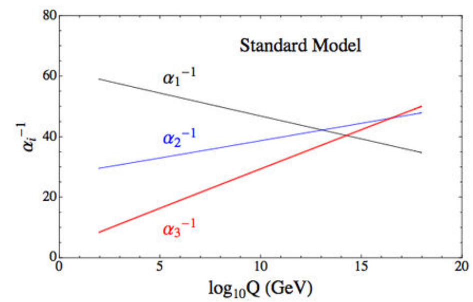
quarks and leptons in a common representation

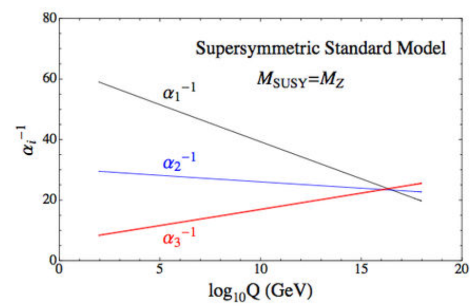
$Q_e = -Q_p$

scale unification at 10^{16}GeV, ….

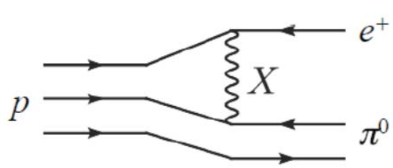
right handed heavy neutrinos -> tiny neutrino mass,lepto-genesis…

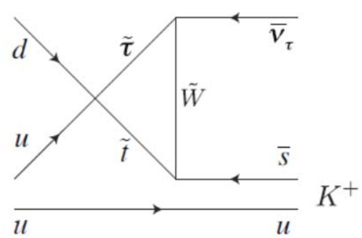
B-L conservation





SUSY-GUT *e.g.* $p \to e^+\pi^0$ $\frac{\tau_p}{Br} \sim 10^{34\pm1}$ also $p \to \mu^+\pi^0$, $p \to K^+\nu$





X, Y gauge bosons mediate proton decay p->π/K e

Ref: J. Hewett et al. arXiv:1401.6077

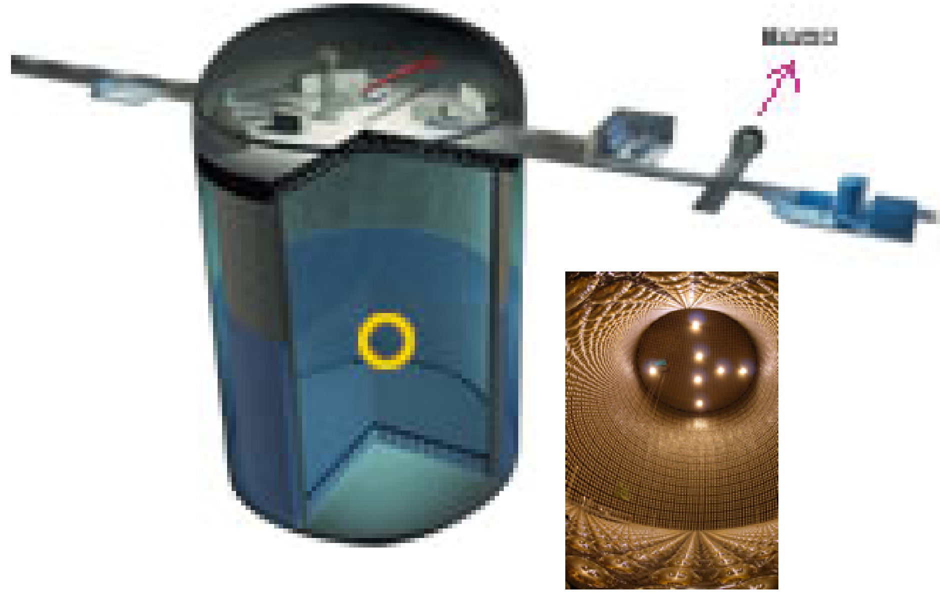
$\Delta(B\text{-}L)=0$

SuperKamiokande

$$\frac{\tau}{Br}(p \to e^{+}\pi^{0}) > 1.4x10^{34}\, yrs$$

$$\frac{\tau}{Br}(p \to \nu K^{+}) > 5.9x10^{33}\, yrs$$

Mass scale probed: $10^{16} GeV$

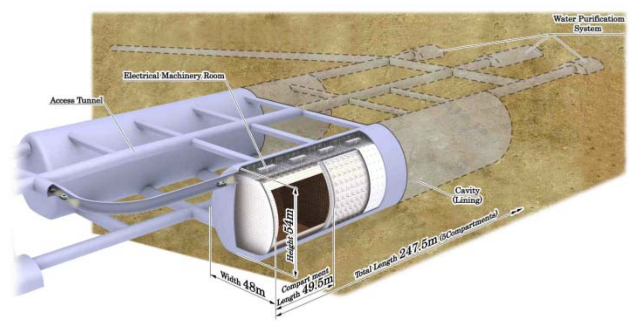


50 Kton Water Cerenkov Detector

$\frac{\tau}{Br} \equiv$ partial mean life, where τ is the total mean life and
Br is the branching fraction for the decay mode in question

Proposed HyperK:

Possible sensitivity: $\frac{\tau}{Br}(p \to e^{+}\pi^{0}) > 10^{35}\, yrs$



0.56 Mton Water Cerenkov Detector

Other Possibilities

$\Delta(B-L)=0;\ \Delta B=\Delta L=2:$

2 nucleon decays: $\frac{\tau}{Br} > 10^{30}\,yrs$ First 2 Generations (e,μ)

$$\mathrm{pn} \to \mathrm{e}^+\overline{\nu},\quad n\mathrm{p} \to \mu^+\overline{\nu}$$

$$pp \to \mathrm{e}^+\mathrm{e}^+,\ pp \to \mu^+\mu^+,\ pp \to \mathrm{e}^+\mu^+ \ldots$$

$$nn \to \overline{\nu\nu}$$

Mass scale probed: few TeV

PDG $10^{30}\,yrs$

$\Delta B = 2$ dinucleon modes

τ_{64}	$pp \to \pi^+\pi^+$	> 0.7	CL=90%
τ_{65}	$pn \to \pi^+\pi^0$	> 2	CL=90%
τ_{66}	$nn \to \pi^+\pi^-$	> 0.7	CL=90%
τ_{67}	$nn \to \pi^0\pi^0$	> 3.4	CL=90%
τ_{68}	$pp \to e^+e^+$	> 5.8	CL=90%
τ_{69}	$pp \to e^+\mu^+$	> 3.6	CL=90%
τ_{70}	$pp \to \mu^+\mu^+$	> 1.7	CL=90%
τ_{71}	$pn \to e^+\bar{\nu}$	> 2.8	CL=90%
τ_{72}	$pn \to \mu^+\bar{\nu}$	> 1.6	CL=90%
τ_{73}	$nn \to \nu_e\bar{\nu}_e$	> 1.4	CL=90%
τ_{74}	$nn \to \nu_\mu\bar{\nu}_\mu$	> 1.4	CL=90%
τ_{75}	$pn \to$ invisible	> 0.000021	CL=90%
τ_{76}	$pp \to$ invisible	> 0.00005	CL=90%

3^{rd} Generation Effects

$\mathrm{p} \rightarrow \tau^{+}\pi^{0}$ Not allowed kinematically

But $\mathrm{np} \rightarrow \tau^{+}\overline{\nu}$ is allowed.

Available energy $: 1868 MeV$

$m_{\tau} = 1776.8 MeV / c^{2}$

$P = 79 MeV / c$

$T = 1.8 MeV$

$\mathrm{np} \rightarrow \tau^{+}\overline{\nu} : \frac{\tau}{Br} > 1 \mathrm{x} 10^{30}\, yrs$

Result based on IMB3* limit on $\mathrm{p} \rightarrow \mathrm{e}^{+}\nu\nu$

using $\tau^{+} \rightarrow \mathrm{e}^{+}\nu\nu$:

(D.B.Phys.Lett.B (2014))

Future: SuperK sensitivity $\sim 10^{33}\, yrs$

Also possible:

$\mathrm{pp} \rightarrow \tau^{+}\mathrm{e}^{+}$

*IMB3 Collab, Phys.Rev.D59(1999)052004.

Summary: Scenarios for Discovery of New Physics

New Physics found at LHC or in K decays, Universality tests, LFV, B decays …
⇒ New effects with unknown flavor- and CP-violating couplings

Precision Flavor-physics experiments needed to do studies of flavor- and CP-violating effects to interpret New Physics models.

New Physics NOT found at LHC or in K decays, Universality tests, LFV, B decays…

Precision Flavor physics experiments needed to give orders of magnitude additional mass reach; sensitive to New Physics at mass scales beyond the LHC (through virtual effects).

Concluding Observations

- Precision low energy experiments are powerful searches for new physics at high mass scales
- Charged LFV remains popular in most BSM theories but target sensitivities are obscure and gains in mass scale ($Br \sim 1/M^4$) are slow
- Many measurements e.g. tests of Universality, with precise SM observables are especially sensitive to new physics
- Big gains in experimental sensitivity are in the works
- Worthwhile to keep at it until BSM physics becomes clearer or experimental capabilities wane (or experiments become too expensive!)