Charged Lepton Flavor Violation Experiments

Toshinori MORI

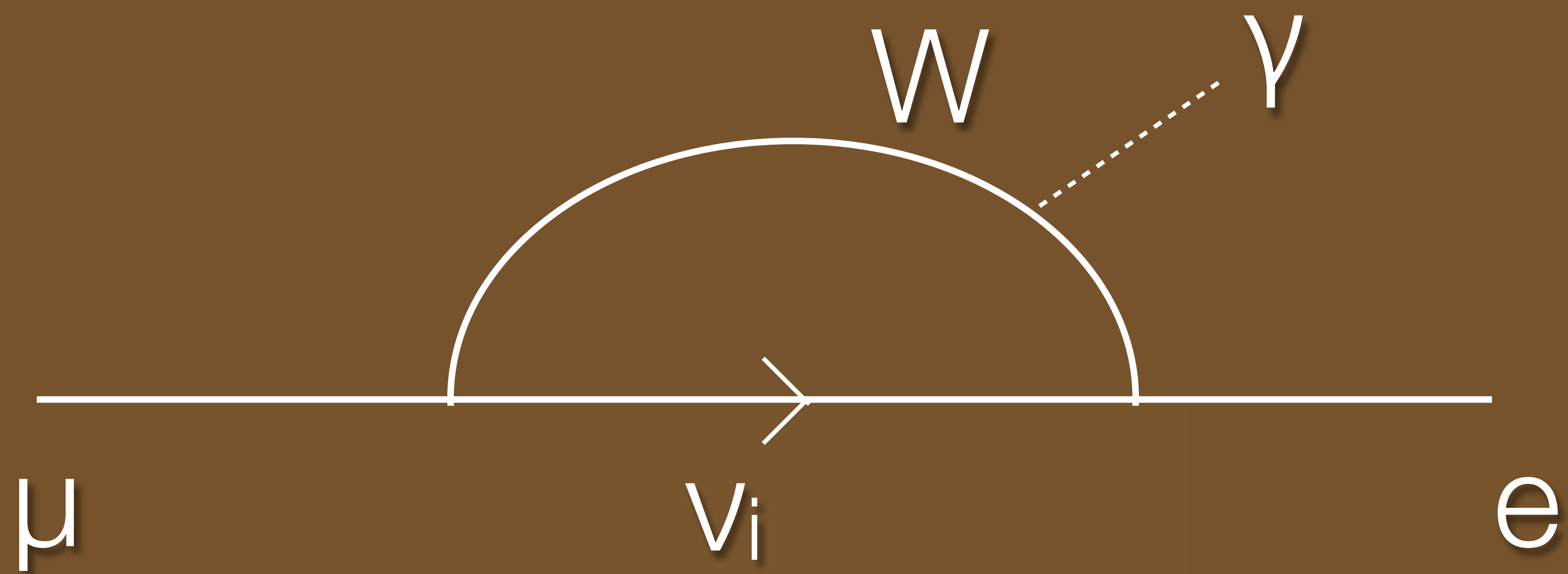
The University of Tokyo

Lepton Flavor Violation

i.e. mixings between generations

- Lepton flavor is severely violated in neutrino oscillations
- It must be violated in charged leptons !!

Charged leptons should also mix flavors!

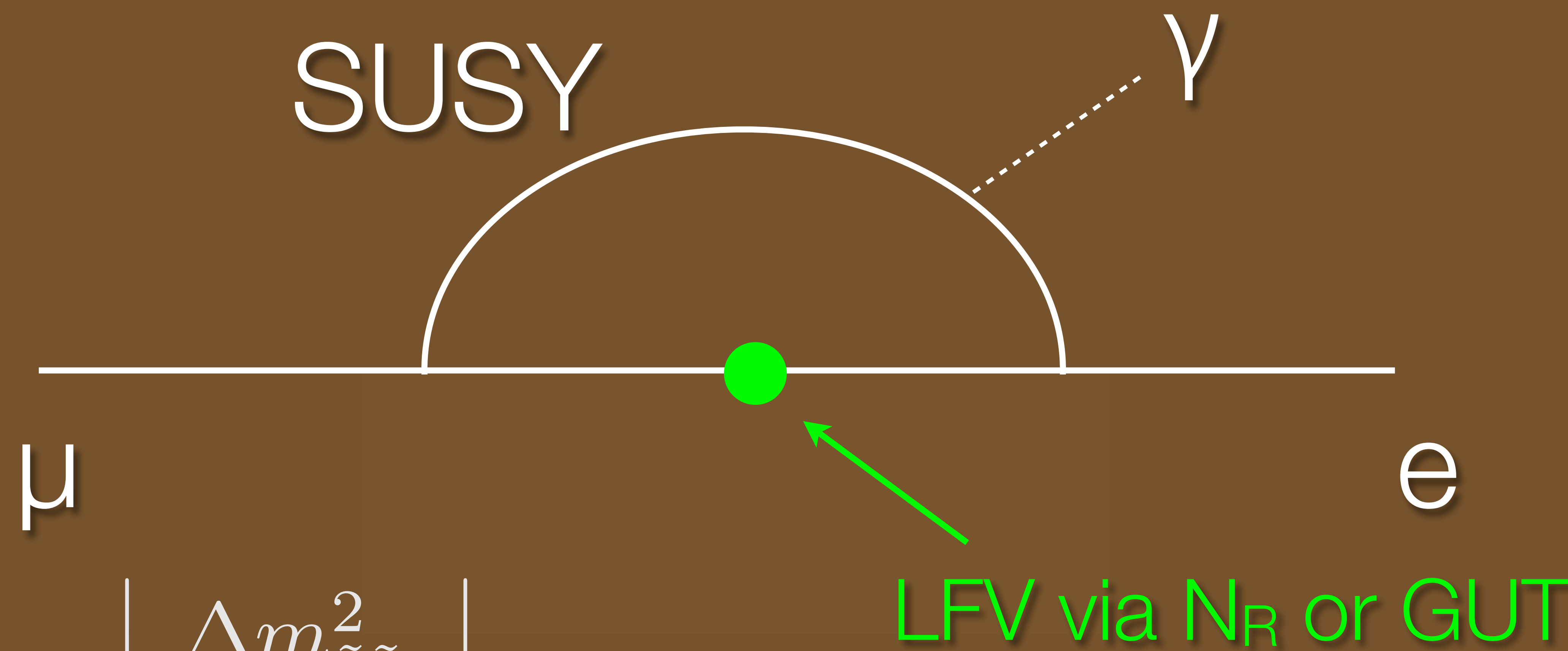


$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-50}$$

neutrinos are too light

...but practically no mixing

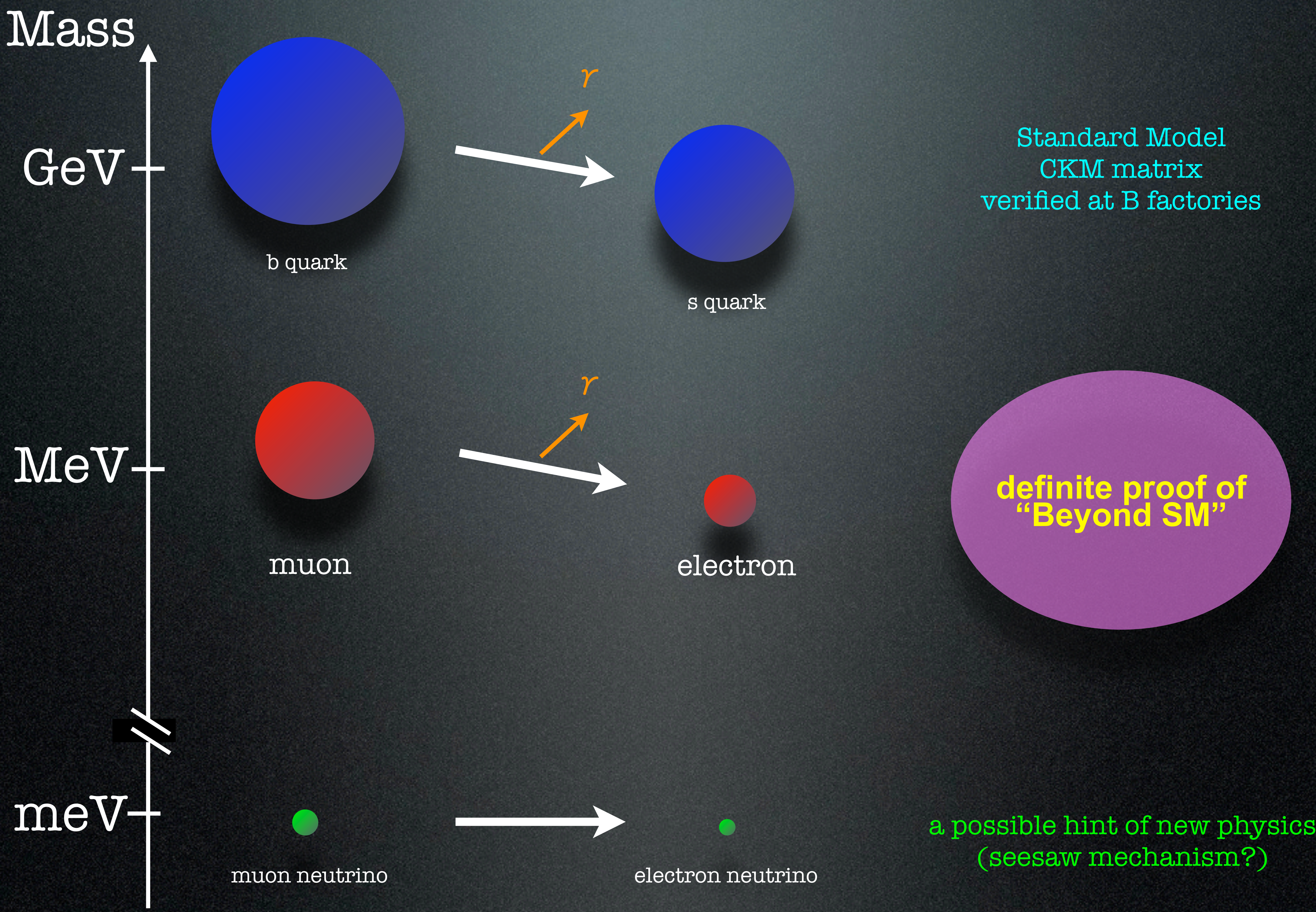
TeV scale physics helps them mix !



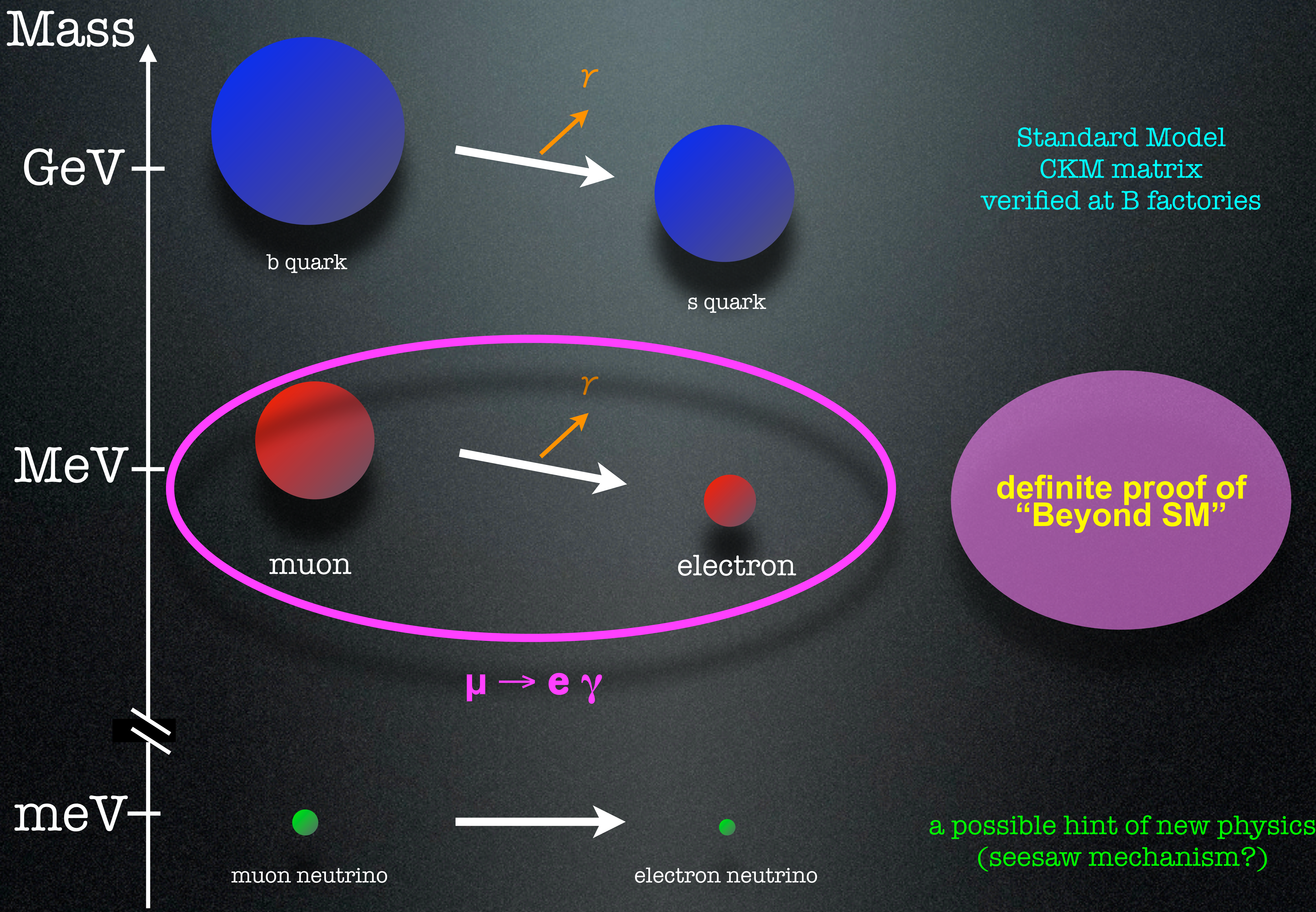
$$\left|\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}}\right| \rightarrow \sim 10^{-12}$$

Perhaps we can observe!

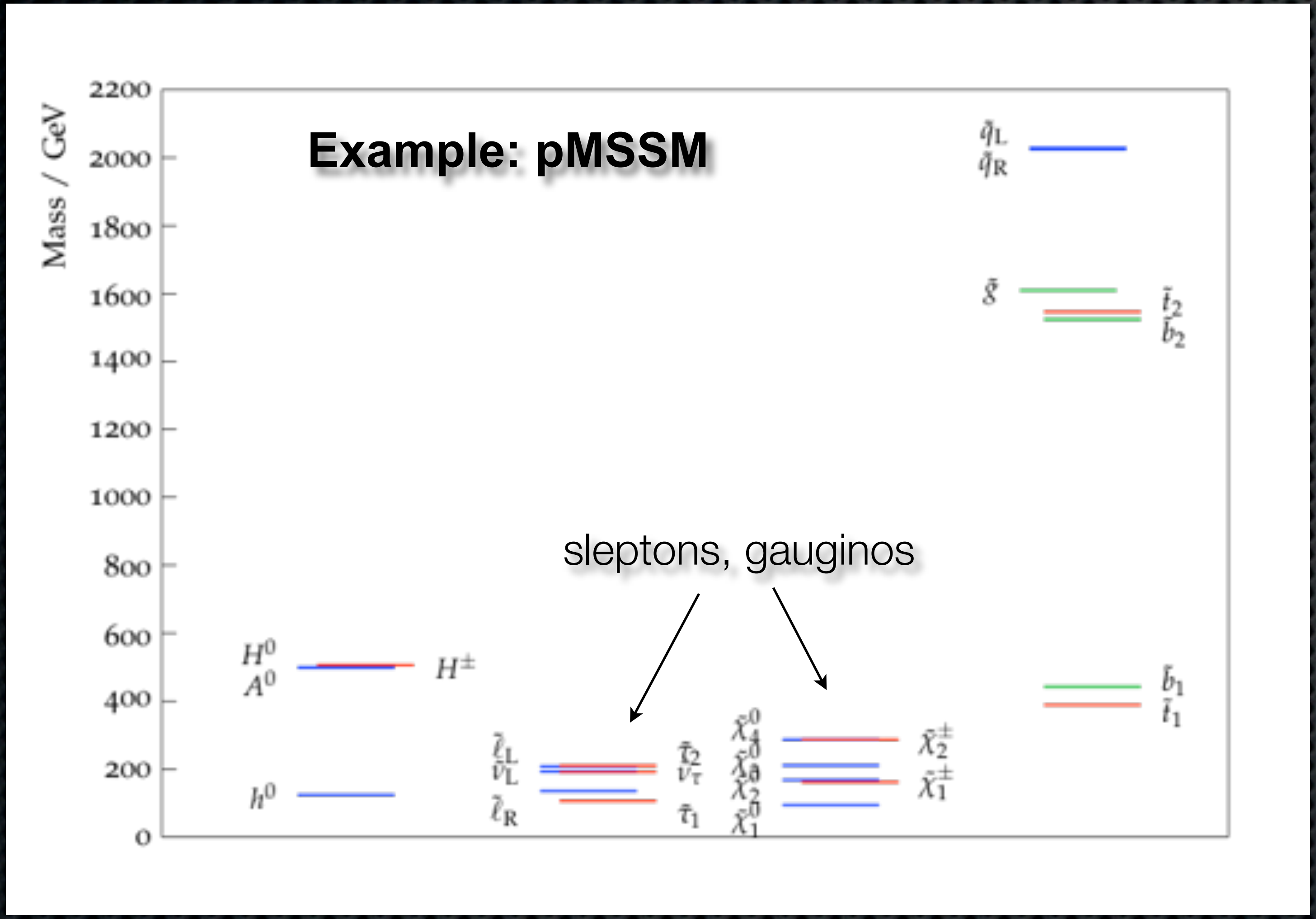
Transitions Between Generations



Transitions Between Generations



TeV scale physics strongly constrained by LHC



- Particle not strongly interacting are NOT strongly constrained
- Dark matter may come from TeV scale physics!

and not necessarily SUSY

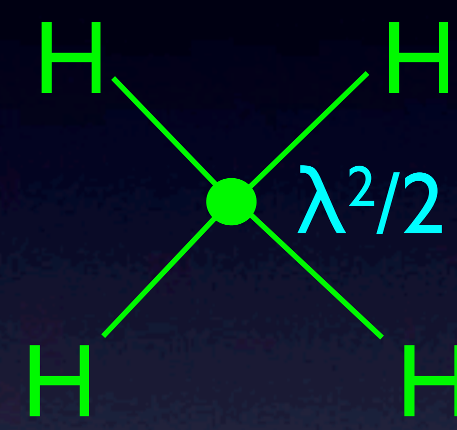
Complementary to LHC + sources of LFV

GUT , seesaw

Recent Progress in Particle Physics

- Discovery of "Higgs"
  - Higgs is light (125GeV)

$M_H = \lambda\, v$



→ Higgs is unlikely to be composite

→ Good prospects for GUT

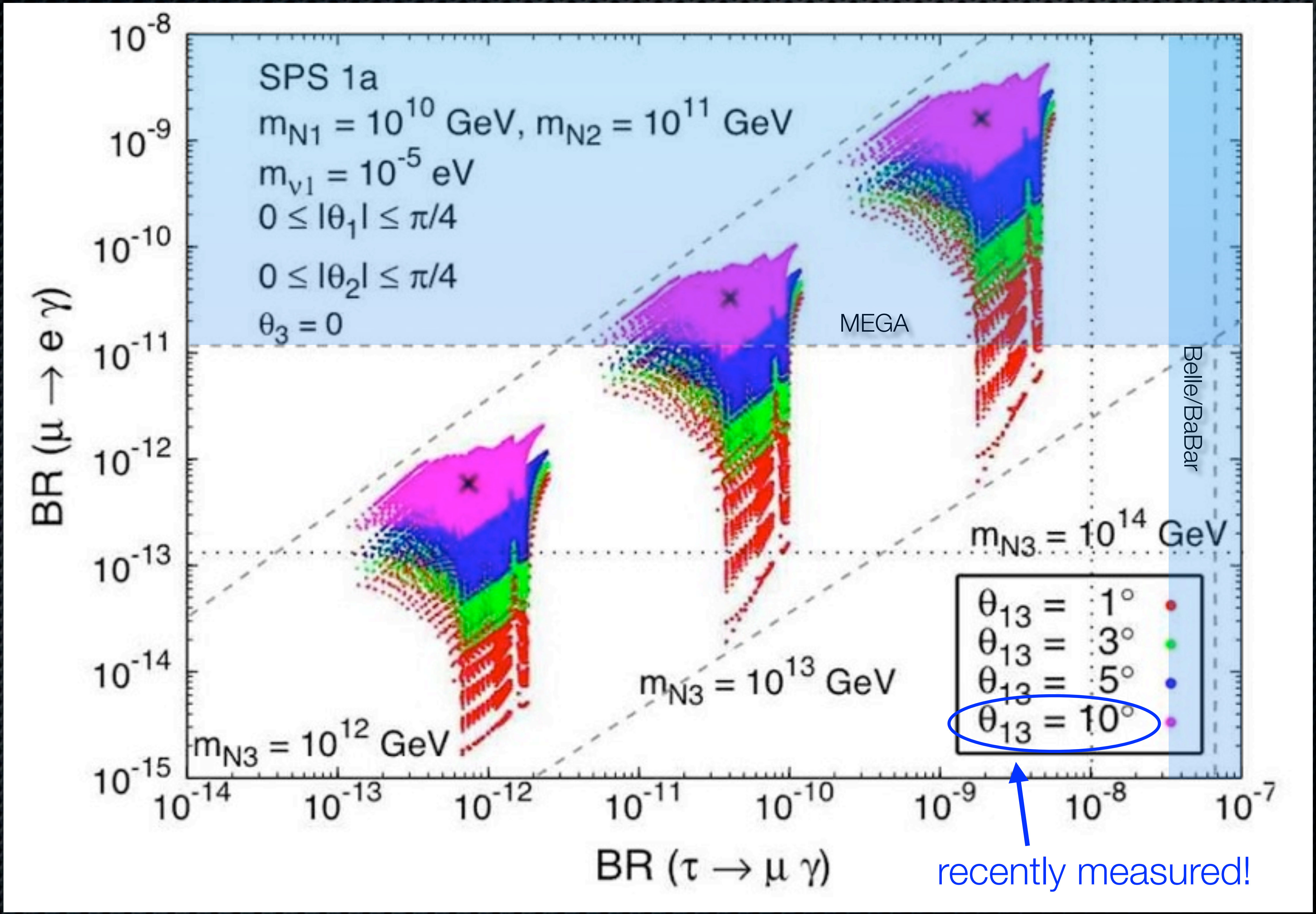
- Discovery of the third neutrino oscillation
  - Mixing is large (mixing angle ~9deg)

→ Large cLFV expected, e.g. $\mu \to e\gamma$

Expectations rising high for cLFV searches

Implication of Large θ_{13}

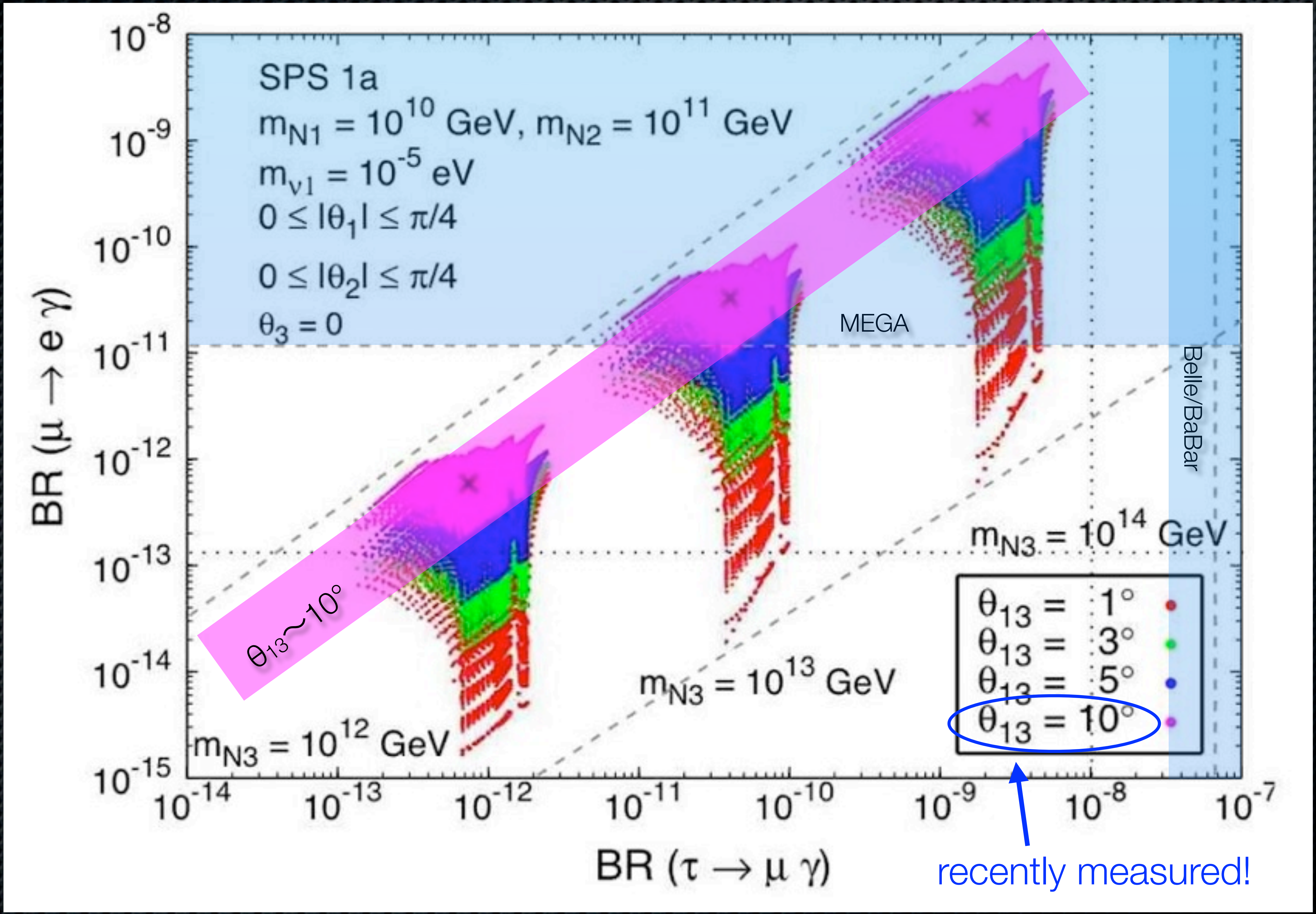
$\longrightarrow$ larger BR($\mu \to e\gamma$)



S. Antusch et al. JHEP11 (2006) 090

Implication of Large θ_{13}

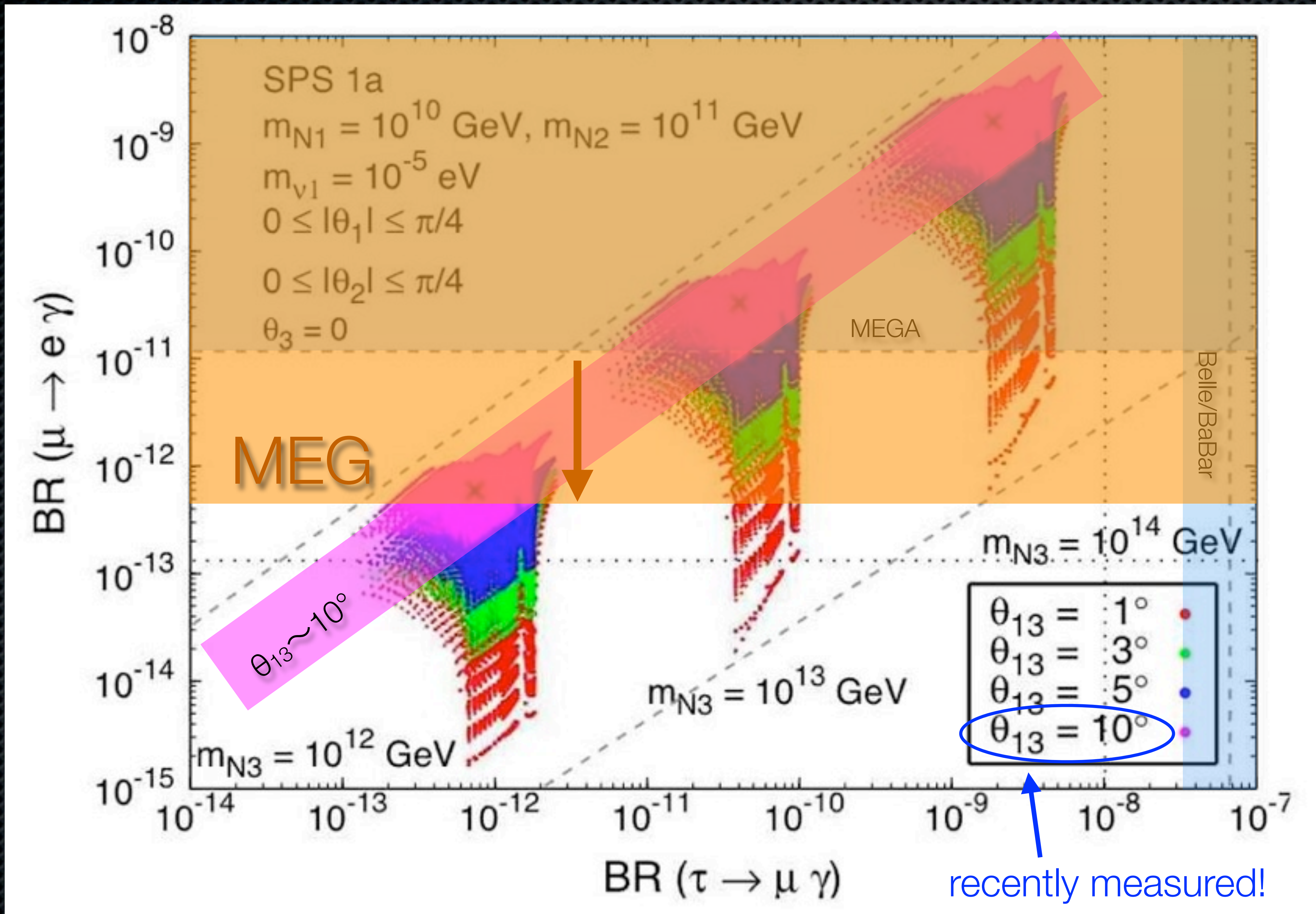
$\longrightarrow$ larger BR($\mu \to e\gamma$)



S. Antusch et al. JHEP11 (2006) 090

Implication of Large θ_{13}

→ larger $BR(\mu \to e\gamma)$



S. Antusch et al. JHEP11 (2006) 090

I will NOT discuss...

LFV in K, D, B, …

NOT DISCUSSED IN THIS TALK

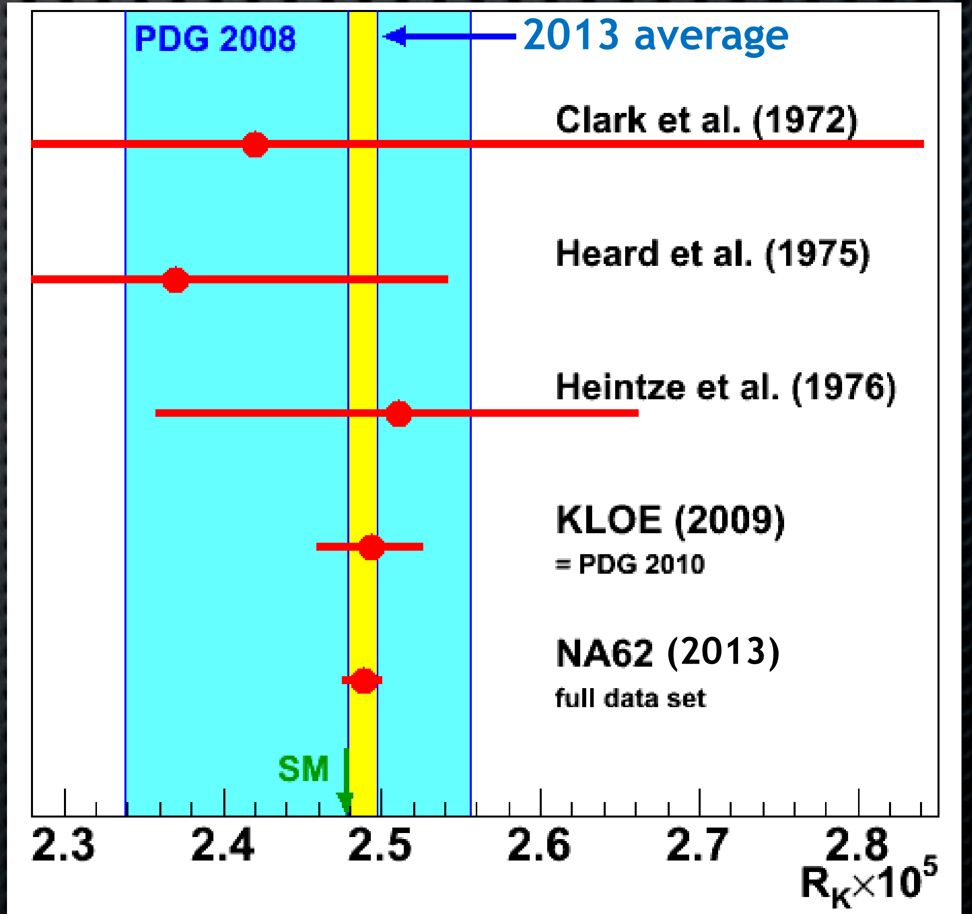
Table 4 Bounds at 90% CL on selected lepton flav… pseudoscalar mesons

Channel	Upper limit	Experiment	Reference
$\pi^0 \to \mu^\pm e^\mp$	3.59×10^{-10}	KTeV	75
$\eta \to \mu^\pm e^\mp$	6×10^{-6}	Saturne SPES2	76
$K_L^0 \to \pi^0 \mu^\pm e^\mp$	7.56×10^{-11}	KTeV	75
$K_L^0 \to 2\pi^0 \mu^\pm e^\mp$	1.64×10^{-10}	KTeV	75
$K_L^0 \to \mu^+ e^-$	4.7×10^{-12}	BNL E871	74
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	BNL E865, E777	73
$D^+ \to \pi^+ \mu^\pm e^\mp$	3.4×10^{-5}	Fermilab E791	77
$D^+ \to K^+ \mu^\pm e^\mp$	6.8×10^{-5}	Fermilab E791	77
$D^0 \to \mu^\pm e^\mp$	8.1×10^{-7}	BaBar	78
$D_s^+ \to \pi^+ \mu^\pm e^\mp$	6.1×10^{-4}	Fermilab E791	77
$D_s^+ \to K^+ \mu^\pm e^\mp$	6.3×10^{-4}	Fermilab E791	77
$B^0 \to \mu^\pm e^\mp$	9.2×10^{-8}	BaBar (347 fb^{-1})	79
$B^0 \to \tau^\pm e^\mp$	1.1×10^{-4}	CLEO (9.2 fb^{-1})	80
$B^0 \to \tau^\pm \mu^\mp$	3.8×10^{-5}	CLEO (9.2 fb^{-1})	80
$B^+ \to K^+ e^\pm \mu^\mp$	9.1×10^{-8}	BaBar (208 fb^{-1})	81
$B^+ \to K^+ e^\pm \tau^\mp$	7.7×10^{-5}	BaBar (348 fb^{-1})	82
$B_s^0 \to e^\pm \mu^\mp$	6.1×10^{-6}	CDF (102 pb^{-1})	83

Marciano, Mori, Roney

More decay modes have been recently explored also by LHCb

R_K



World average	$R_K \times 10^5$	Precision
PDG 2008	2.447 ± 0.109	4.5%
2013	2.488 ± 0.009	0.4%

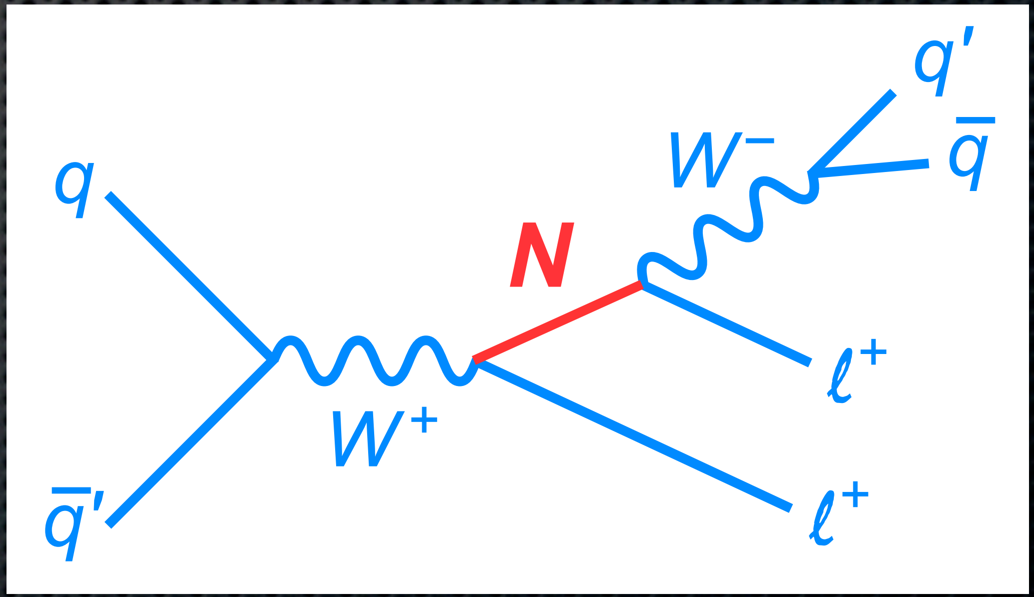
Summary of results in LFV searches

channel	limit		
$\mathcal{B}(B^- \to \pi^+ e^- e^-)$	$< 2.3 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^+ e^- e^-)$	$< 3.0 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^{*+} e^- e^-)$	$< 2.8 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to \rho^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to D^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to D^+ e^- \mu^-)$	$< 1.8 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-)$	$< 1.3 \times 10^{-8}$	@95 % CL	[d]
$\mathcal{B}(B^- \to K^+ \mu^- \mu^-)$	$< 5.4 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^+ \mu^- \mu^-)$	$< 6.9 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-)$	$< 2.4 \times 10^{-6}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D_s^+ \mu^- \mu^-)$	$< 5.8 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^0 \pi^- \mu^- \mu^-)$	$< 1.5 \times 10^{-6}$	@95 % CL	[d]

[a] BaBar, Phys. Rev. D **85**, 071103 (2012)
[b] CLEO, Phys. Rev. D **65**, 111102 (2002)
[c] Belle, Phys. Rev. D **84**, 071106(R), (2011)
[d] LHCb, Phys. Rev. D **85**,112004 (2012)
[e] LHCb, Phys. Rev. Lett. 108 101601 (2012)

Direct Searches for New Particles with cLFV Decays at LHC

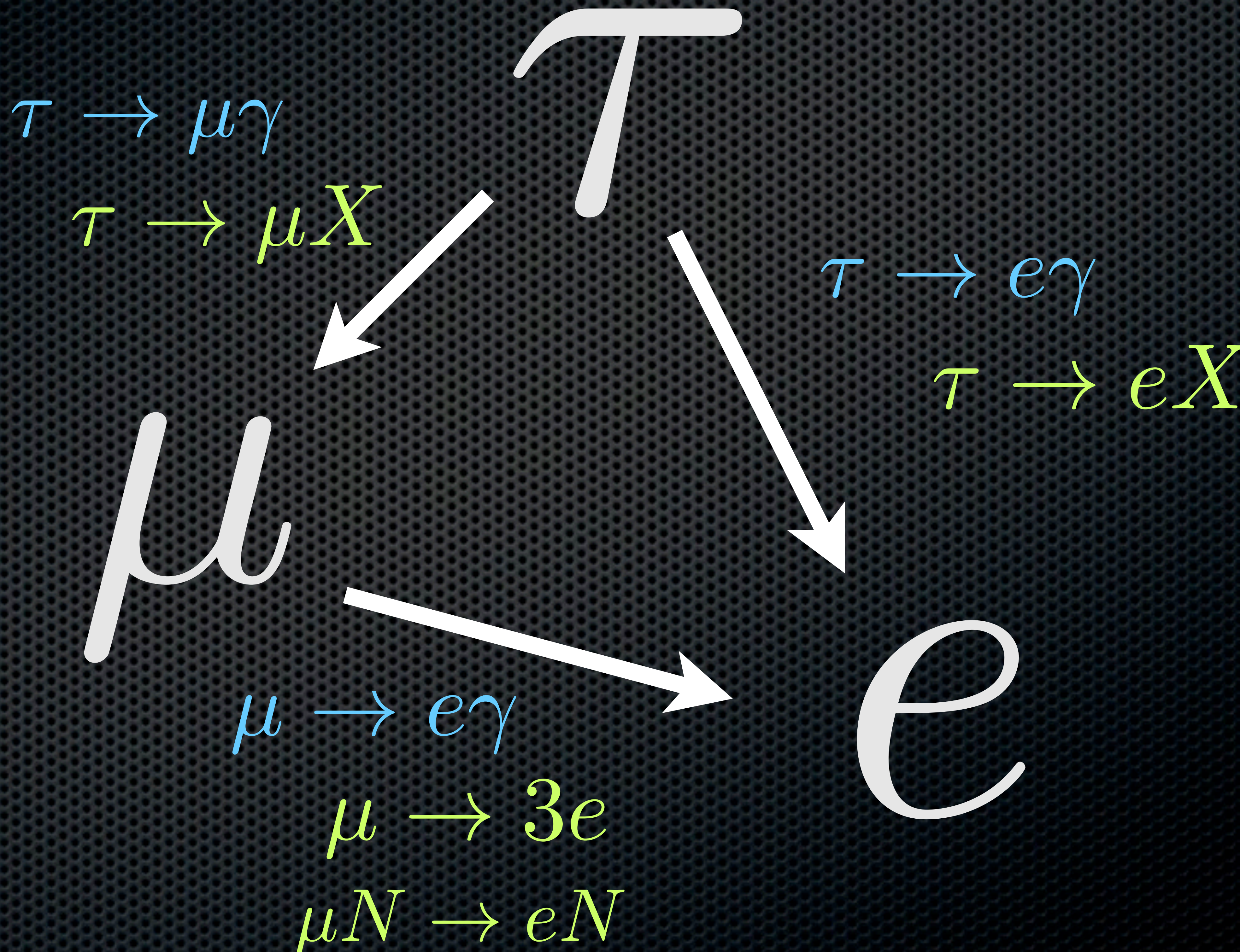
- RPV SUSY $W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k$
- Heavy Majorana neutrino
- $Z' \to \ell_1 \ell_2$



NOT DISCUSSED IN THIS TALK

I will mainly discuss...

cLFV Processes

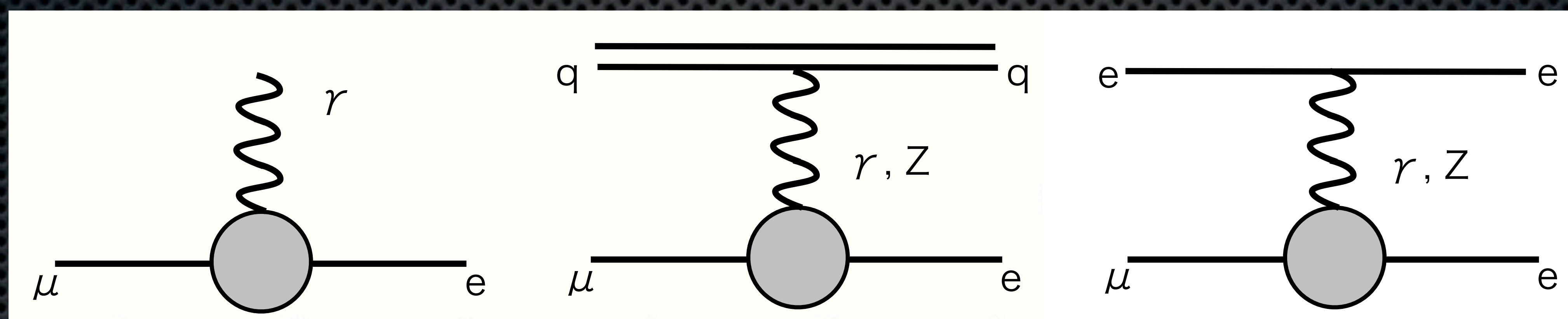


Sensitivity comparisons

$\mu \to e\gamma$ $\quad\quad$ $\mu N \to eN$ $\quad\quad$ $\mu \to 3e$

"dipole" dominant

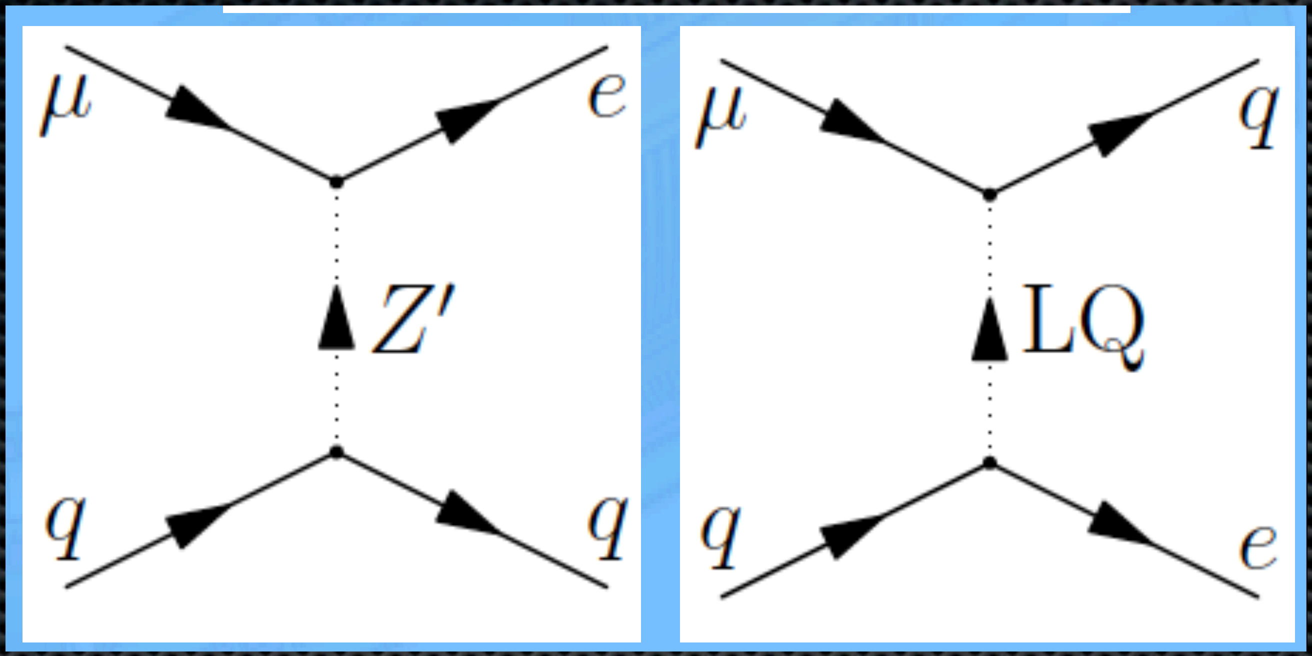
(SUSY etc)



1 : 1/390 : 1/170

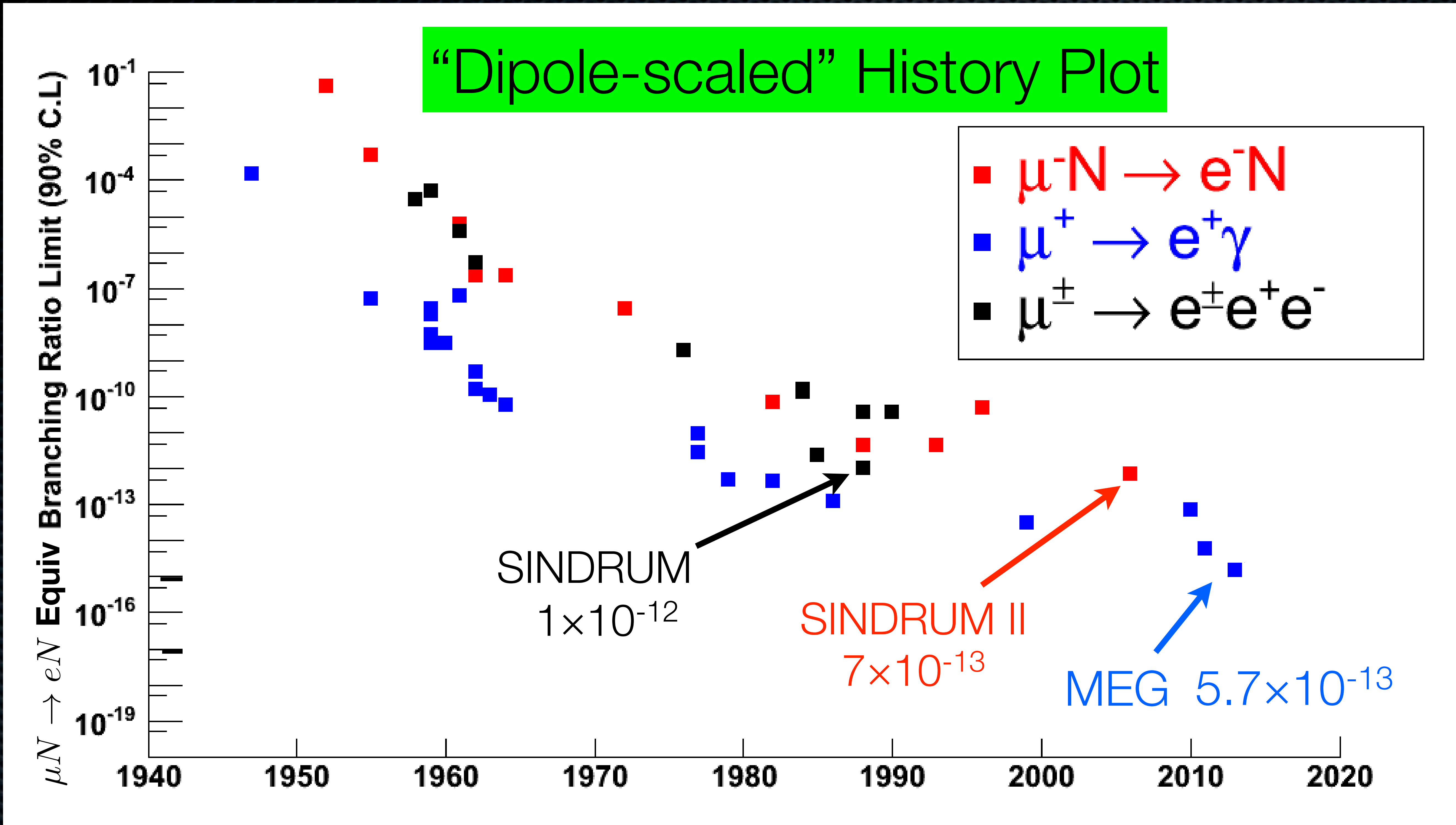
BR = 4×10^{-14} : 1×10^{-16} : 2×10^{-16}

~MEG II goal $\quad\quad$ for Al target



Some models have contact terms which strongly enhance

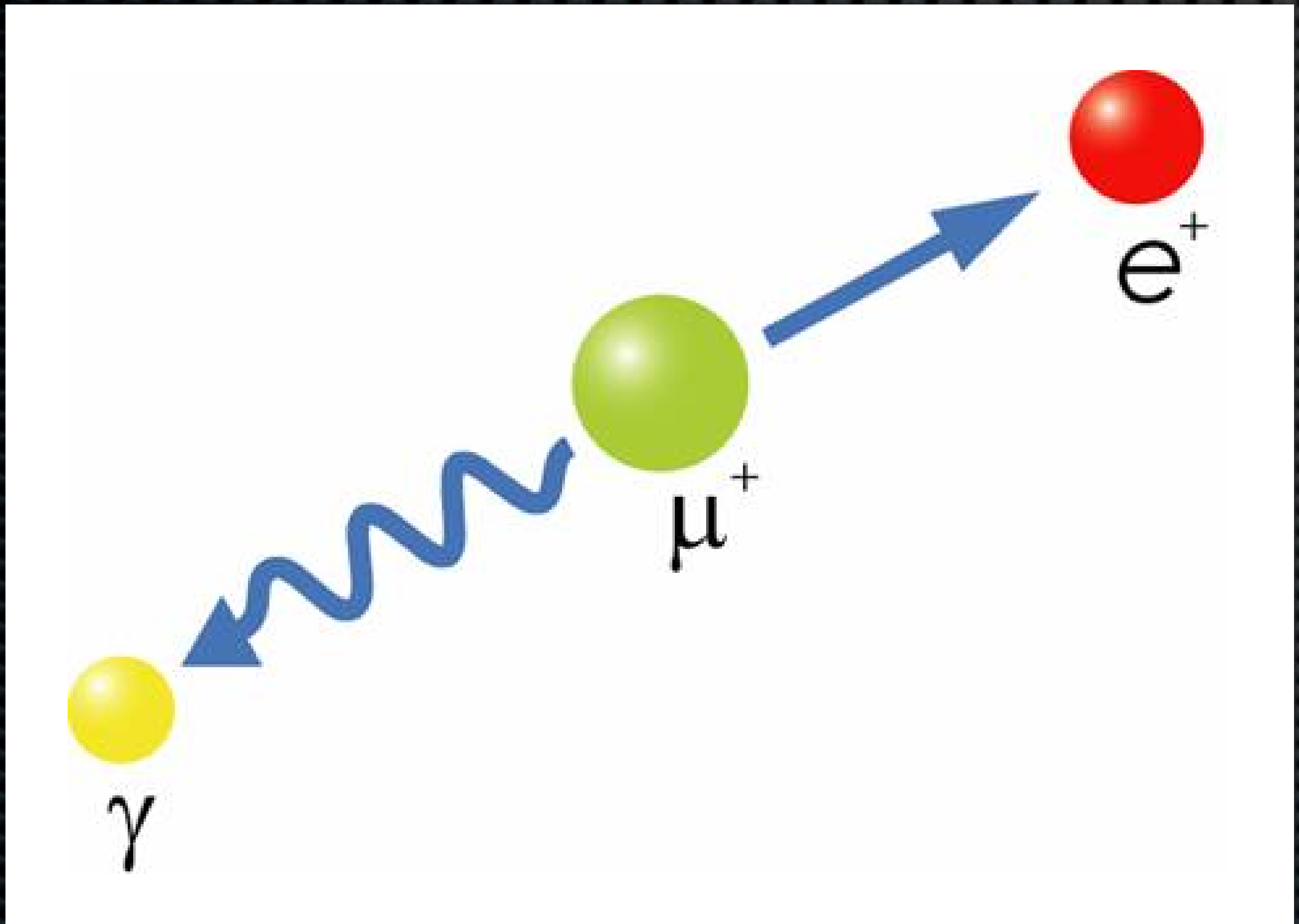
$\mu N \to eN$ $\quad\quad$ $\mu \to 3e$



A. Edmonds, cLFV Lecce, May 2013 (modified by TM)

$\mu \rightarrow e\gamma$ has been always leading the race

The $\mu^+ \to e^+\gamma$ process



- clear 2-body kinematics
- need positive muons to avoid formation of muonic atoms
- accidental background limits the experiment
  - DC beam, rather than pulsed beam, gives lowest instantaneous rate and thus lowest background

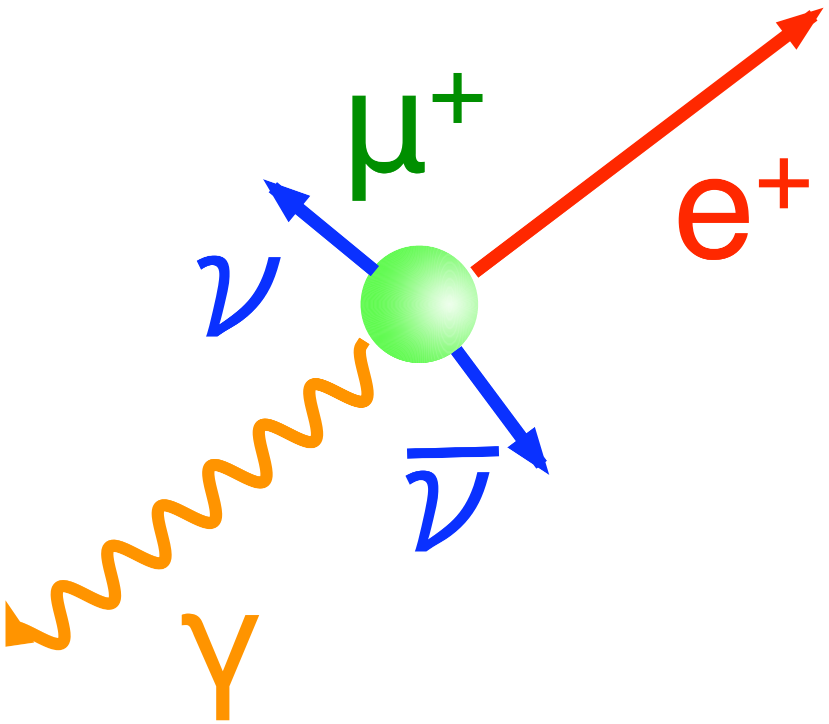
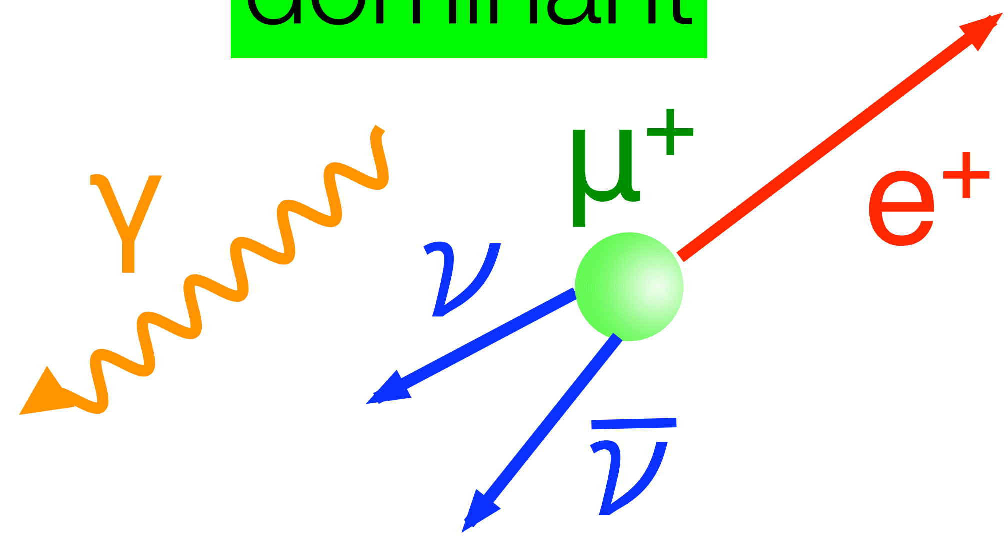
Searching for 1 out of 10^{13}

- Need to measure at least 10^{13} muons within ~1 year (~10^{7}sec)
  - 10^{13} muons / 10^{7} sec / efficiency
    = $10^{7\text{-}8}$ muons /sec

↓

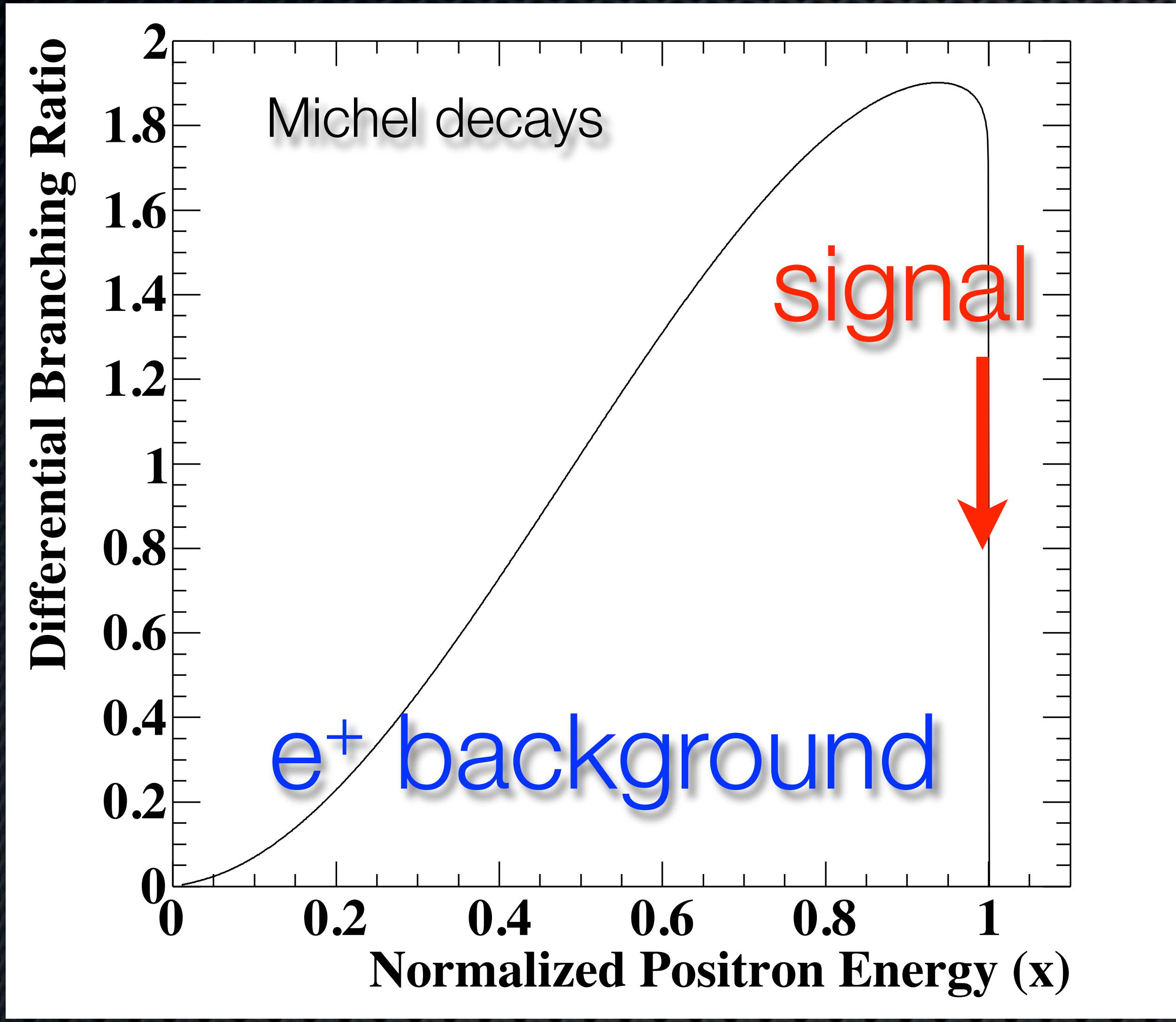
Need a high power accelerator
to produce lots of muons

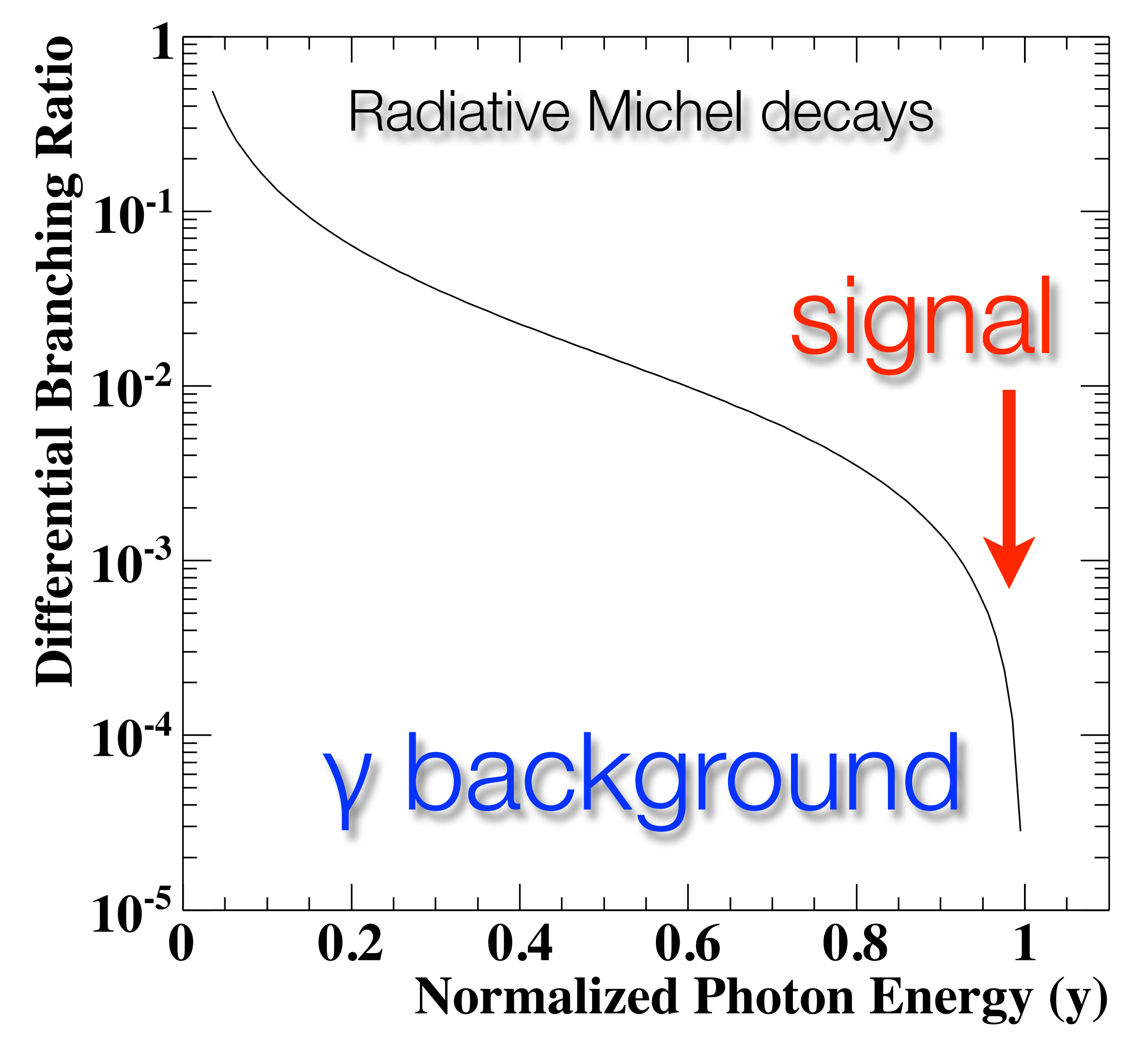
Background

Prompt Background	Accidental Background
	dominant 

Radiative muon decay	Accidental pileup
Any angle	Any angle
< 52.8 MeV/c	< 52.8 MeV/c
Same time	Flat

Accidental Background Distribution





must manage high rate e^+

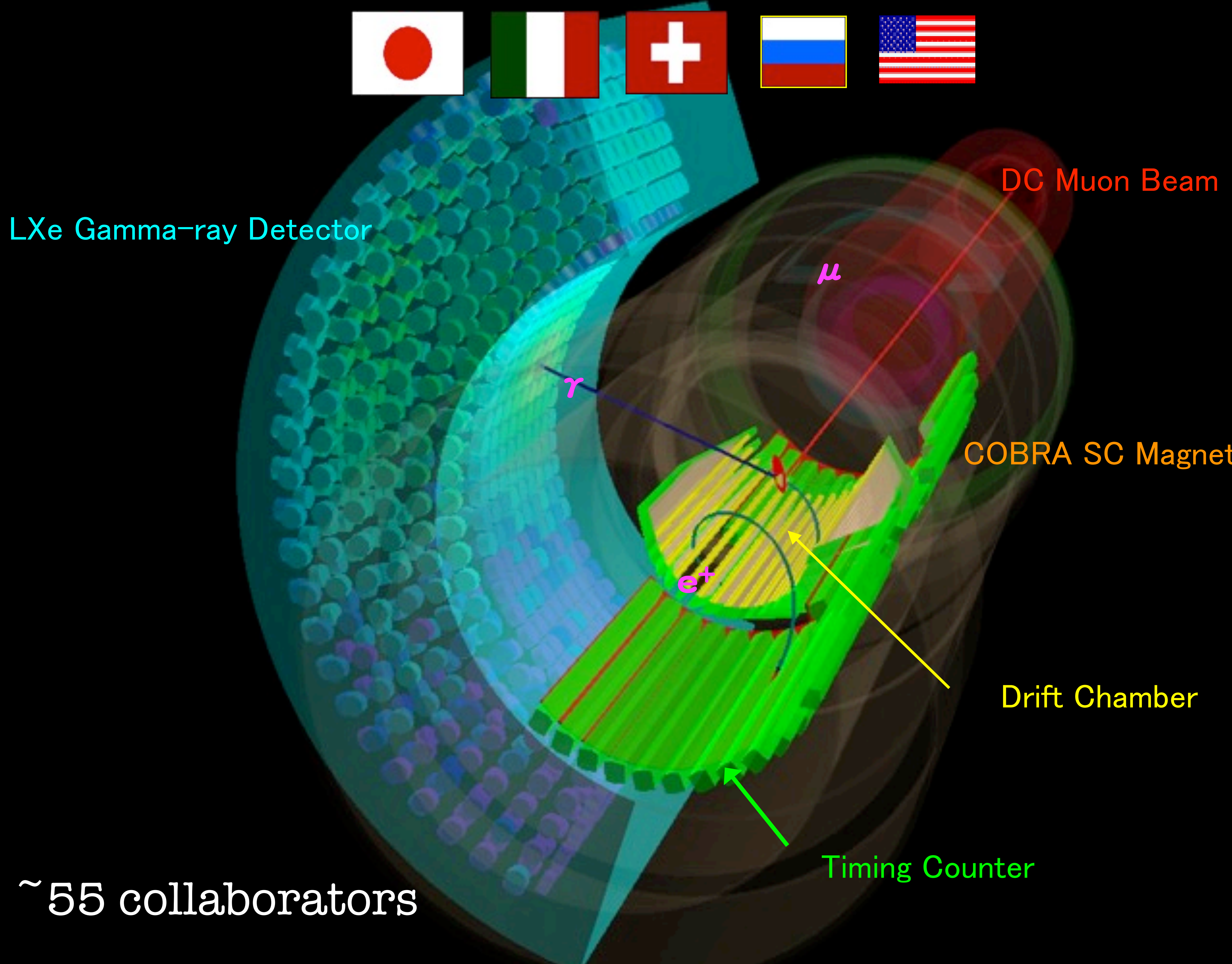
good γ resolution is
most important !

So the experiment needs:

- High intensity (~10^7/sec) DC muon beam
- e^+ spectrometer that can manage high rate
- High resolution gamma-ray detector

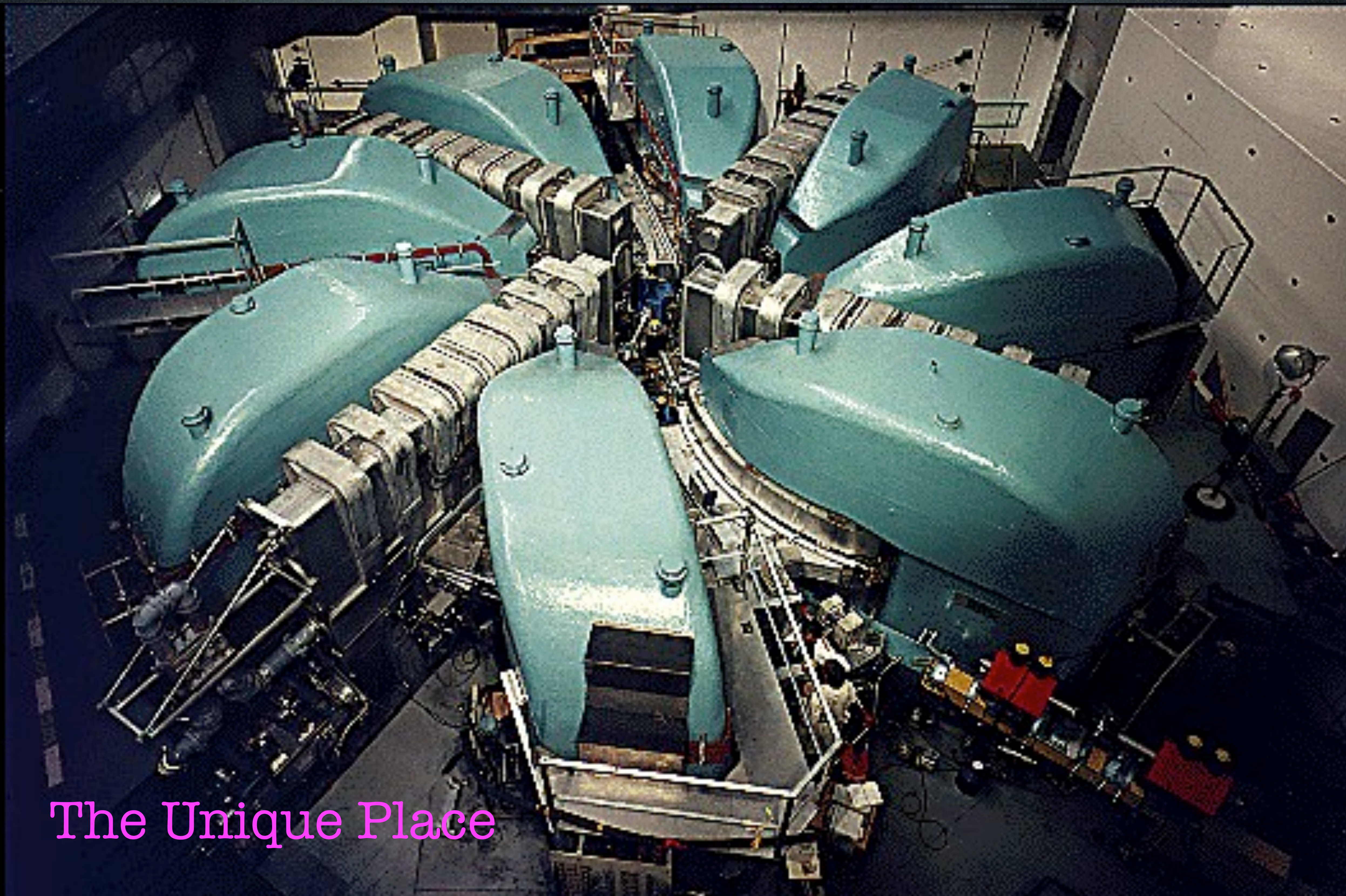
→ MEG Experiment at PSI

The MEG Experiment



~55 collaborators

1.3MW Proton Cyclotron at PSI

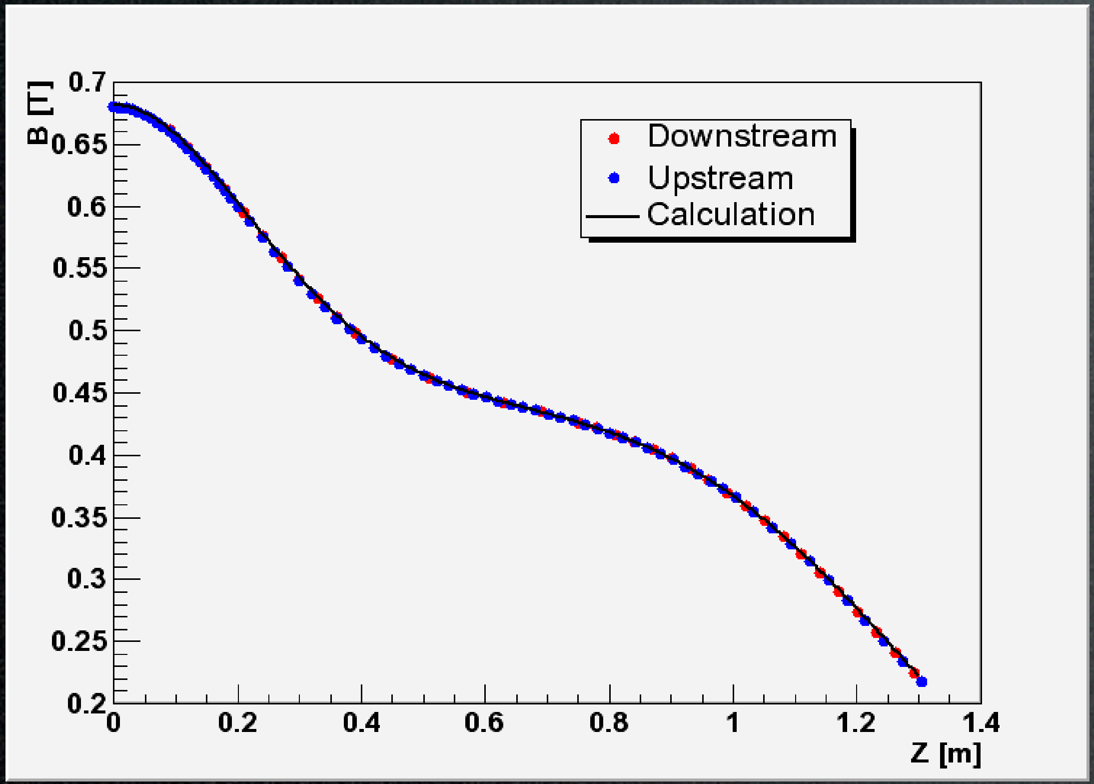


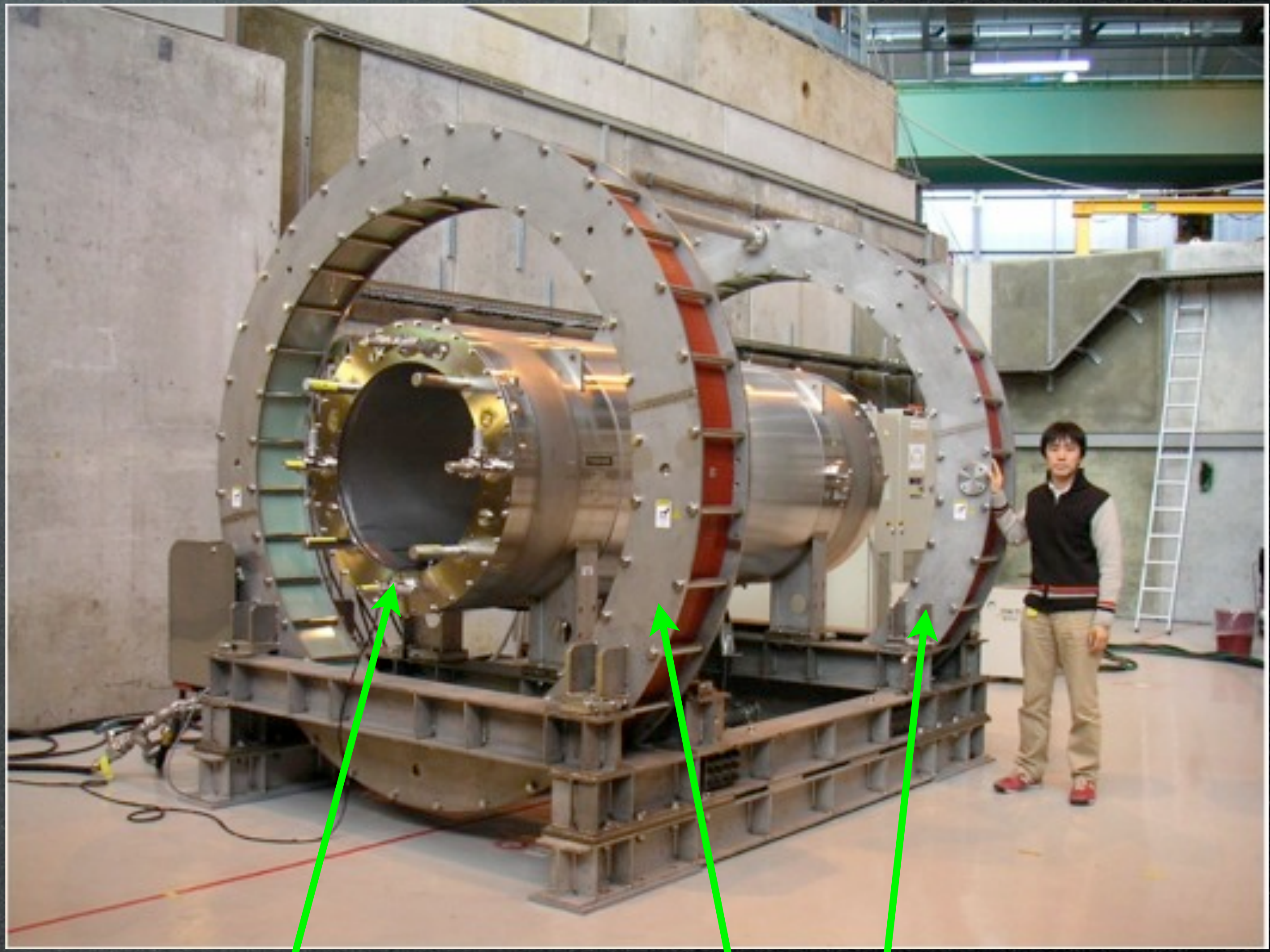
Provides world's most powerful DC muon beam > 10^8/sec

COBRA Positron Spectrometer

Gradient B field helps to manage high rate e^+

- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla





COBRA

compensation coils

2.7t Liquid Xenon Photon Detector

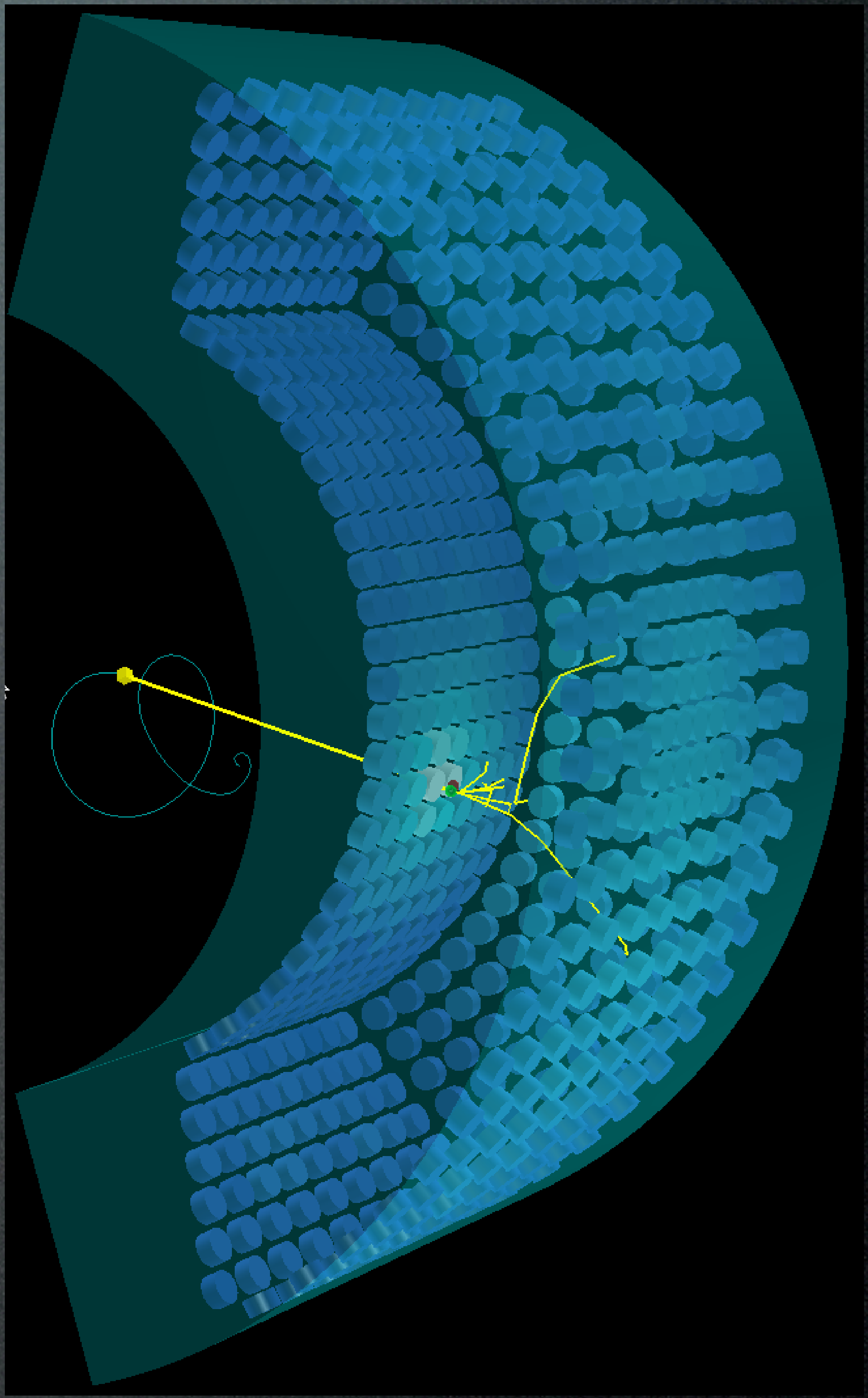
High resolution detector

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon

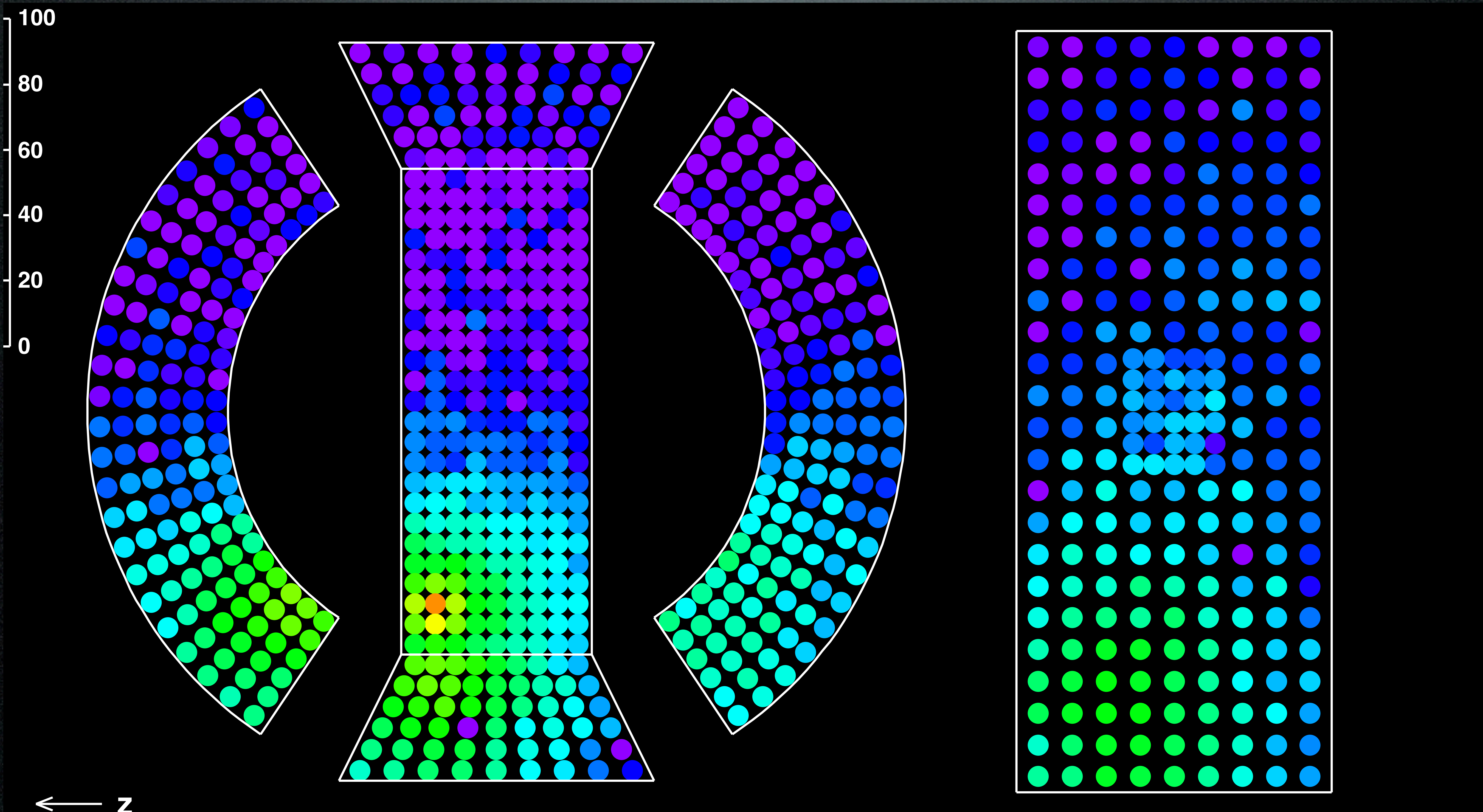
- fast response & high light yield provide good resolutions of E, time, position

- kept at 165K by 200W pulse-tube refrigerator

- gas/liquid circulation system to purify xenon to remove contaminants

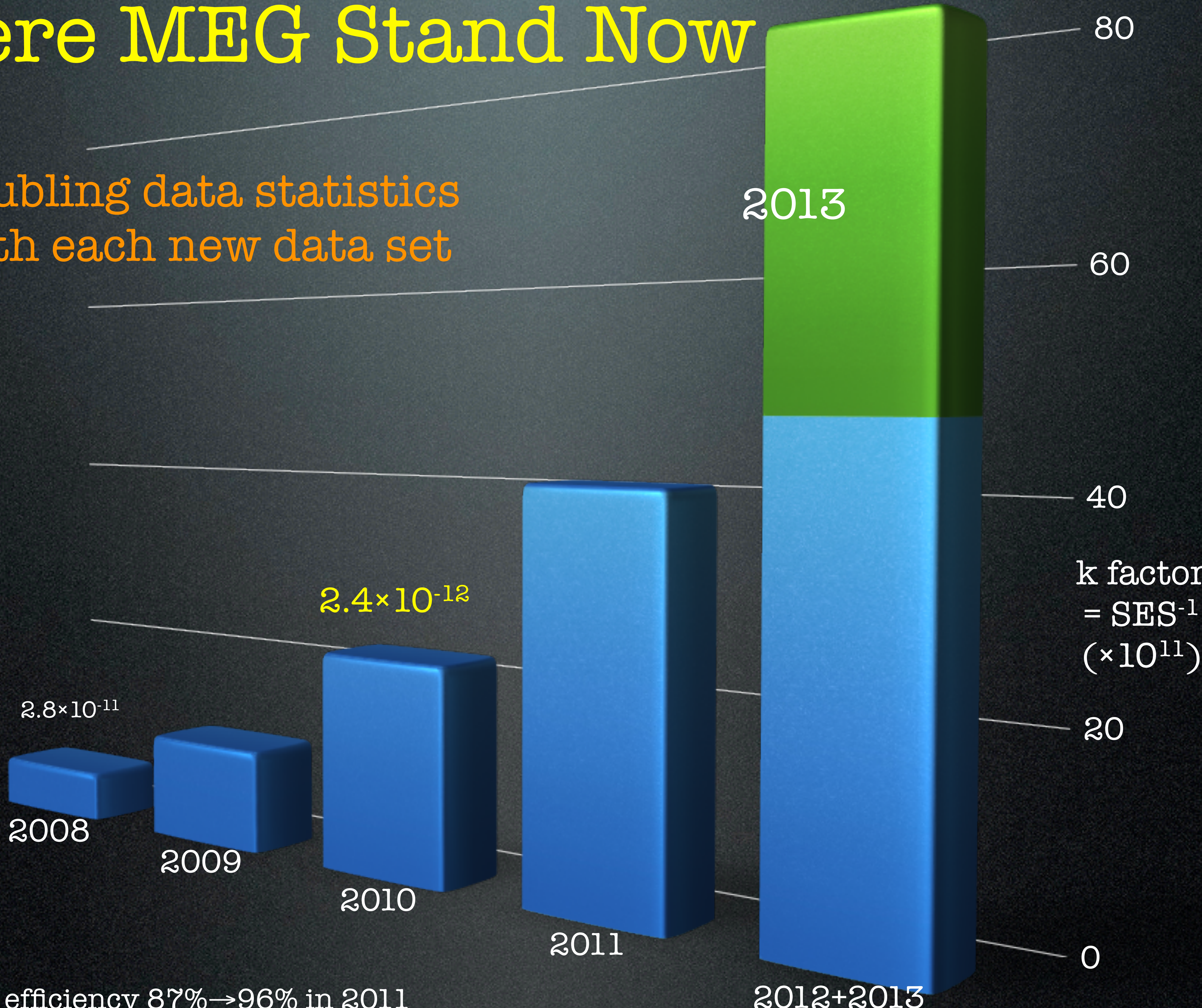


Energy = total light yield
Position = light peak



Where MEG Stand Now

Doubling data statistics
with each new data set



DAQ efficiency 87%→96% in 2011

Where MEG Stand Now

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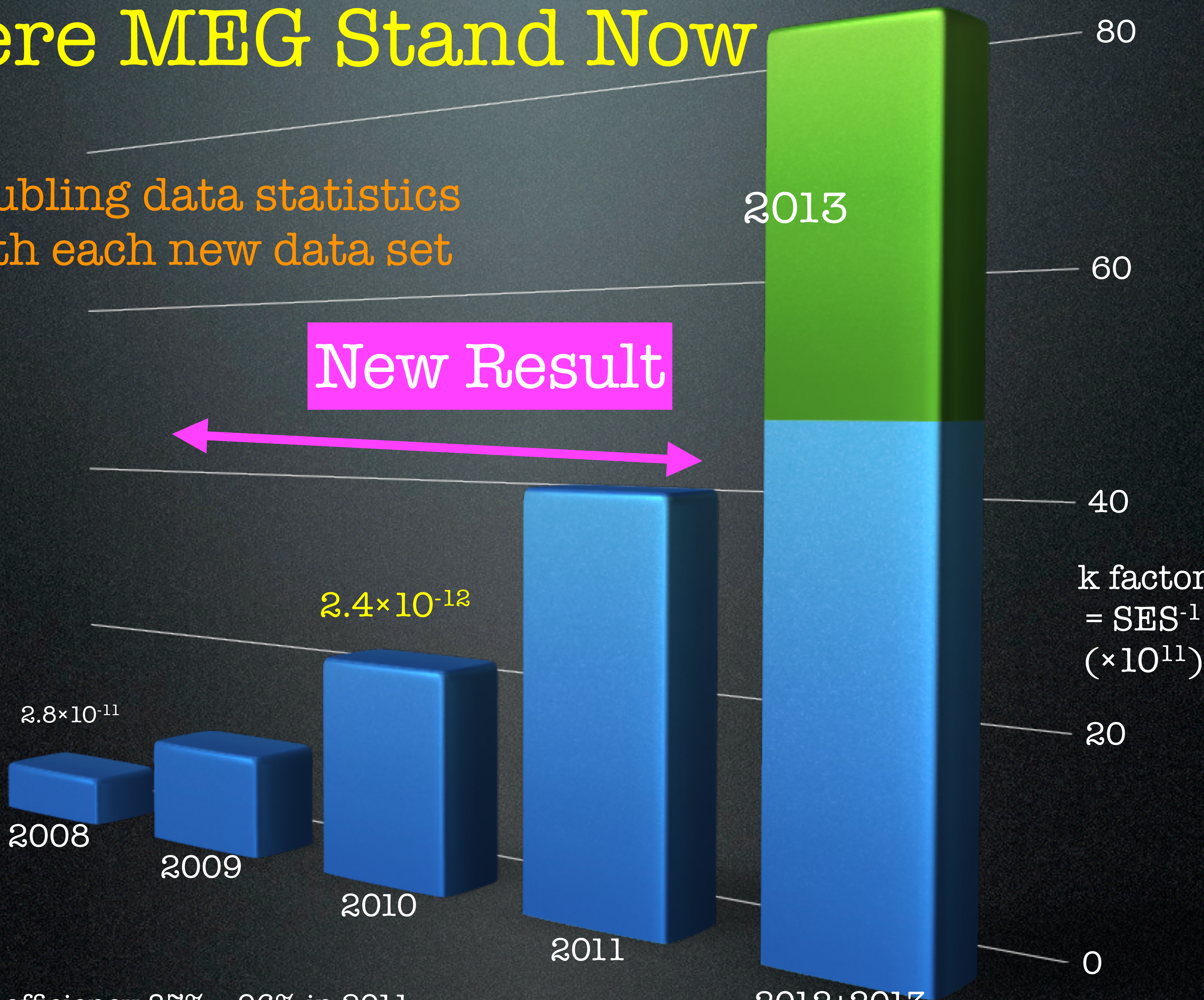
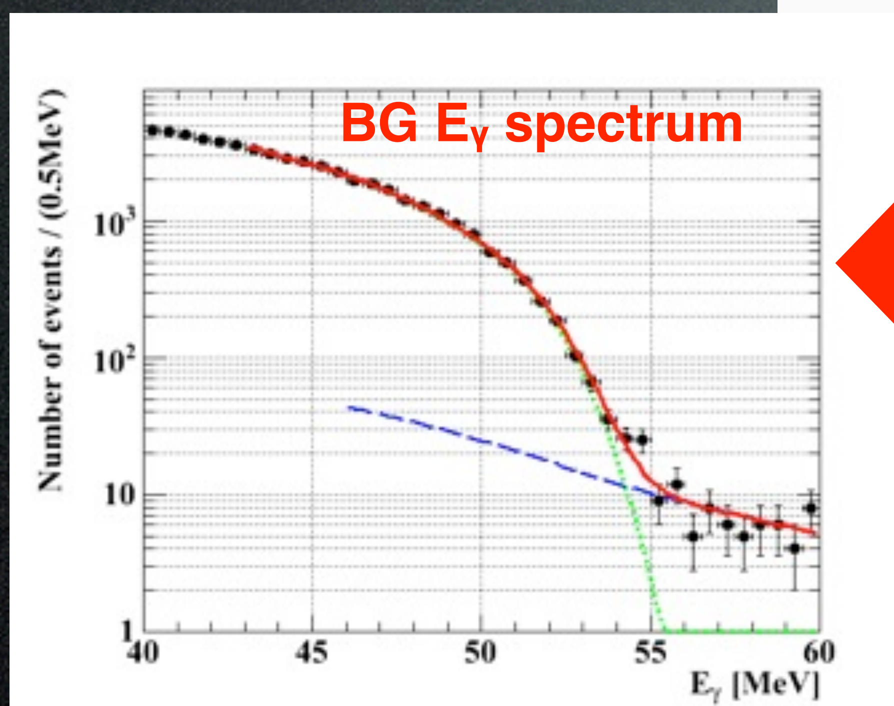


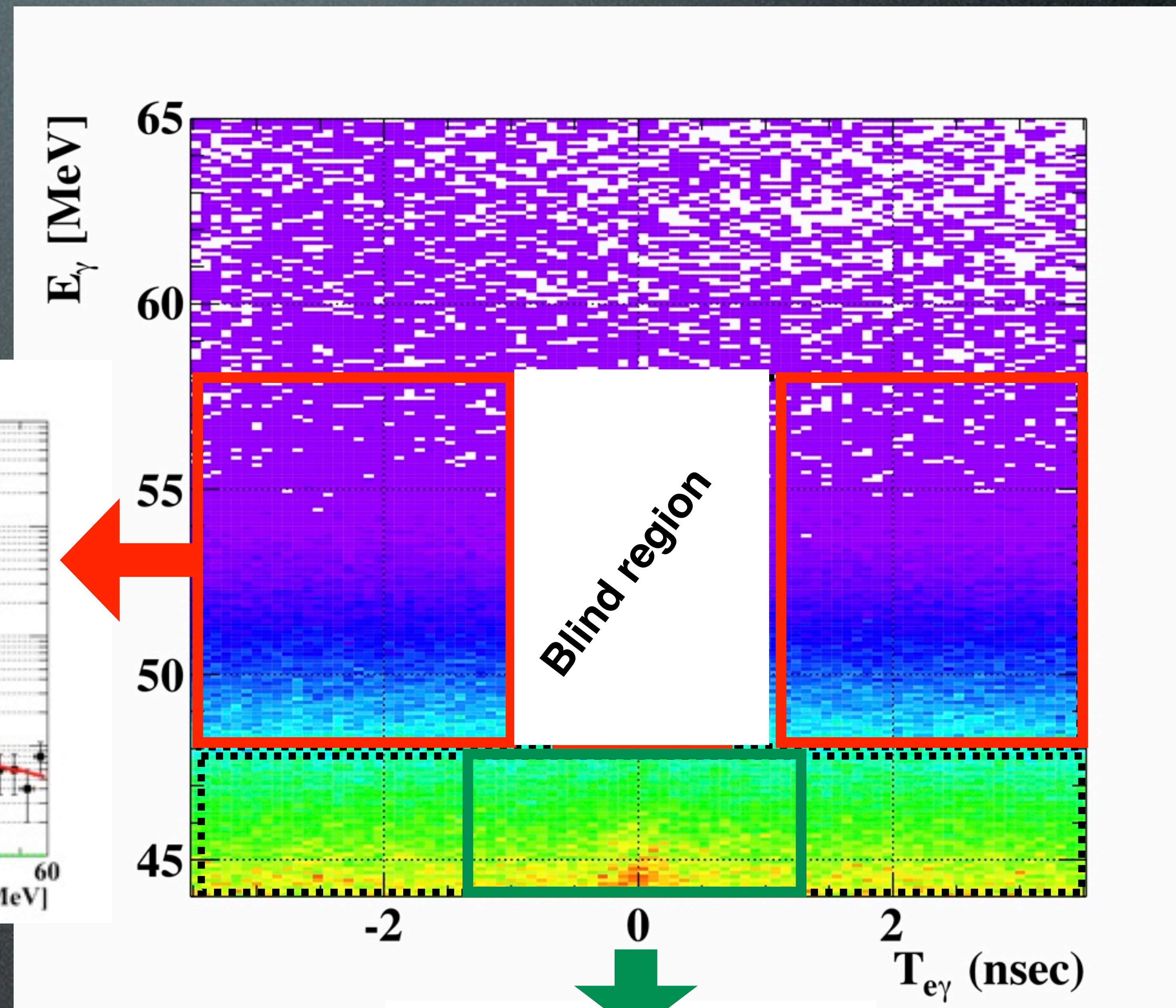
DAQ efficiency 87%→96% in 2011

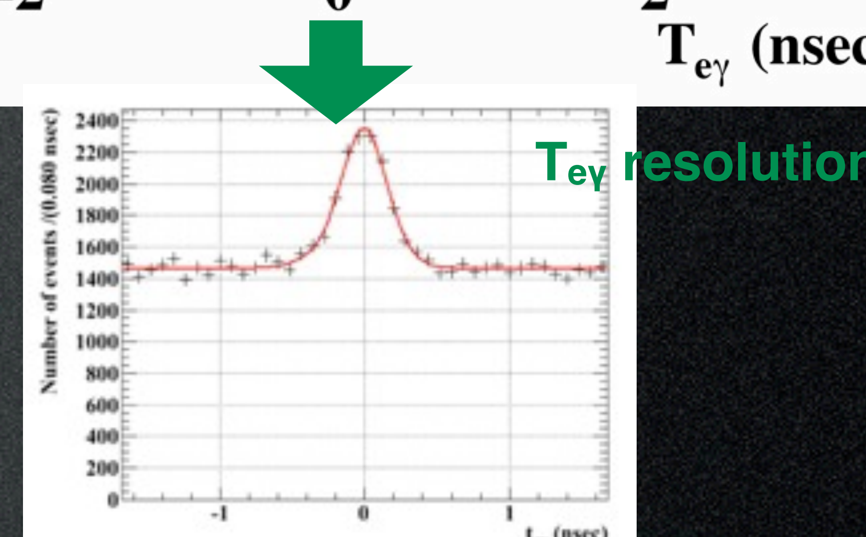
Blind & Likelihood Analysis

(E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$)

→ signal, acc BG, RD BG







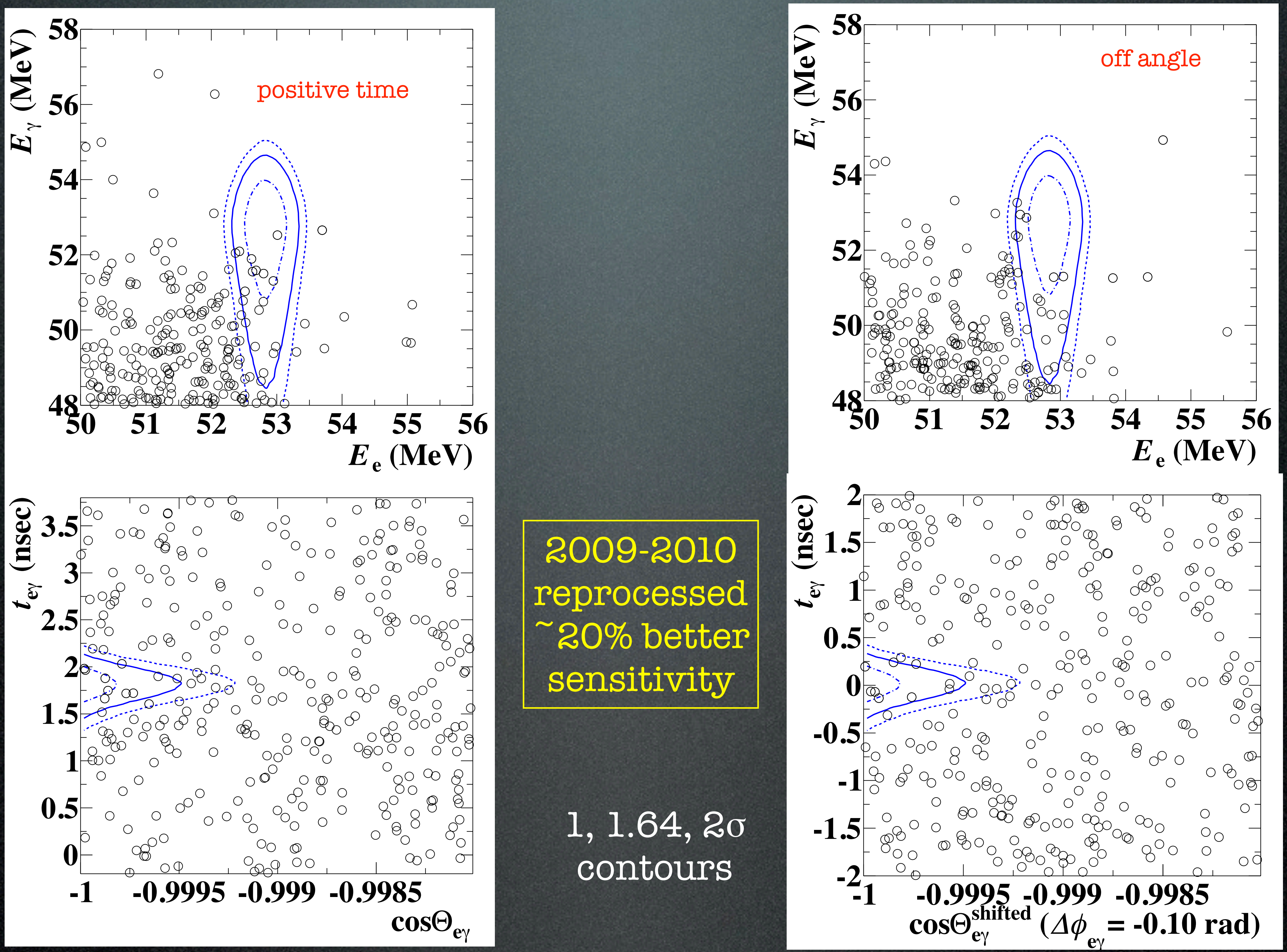
PDFs mostly from data

accidental BG: side bands

signal: measured resolution

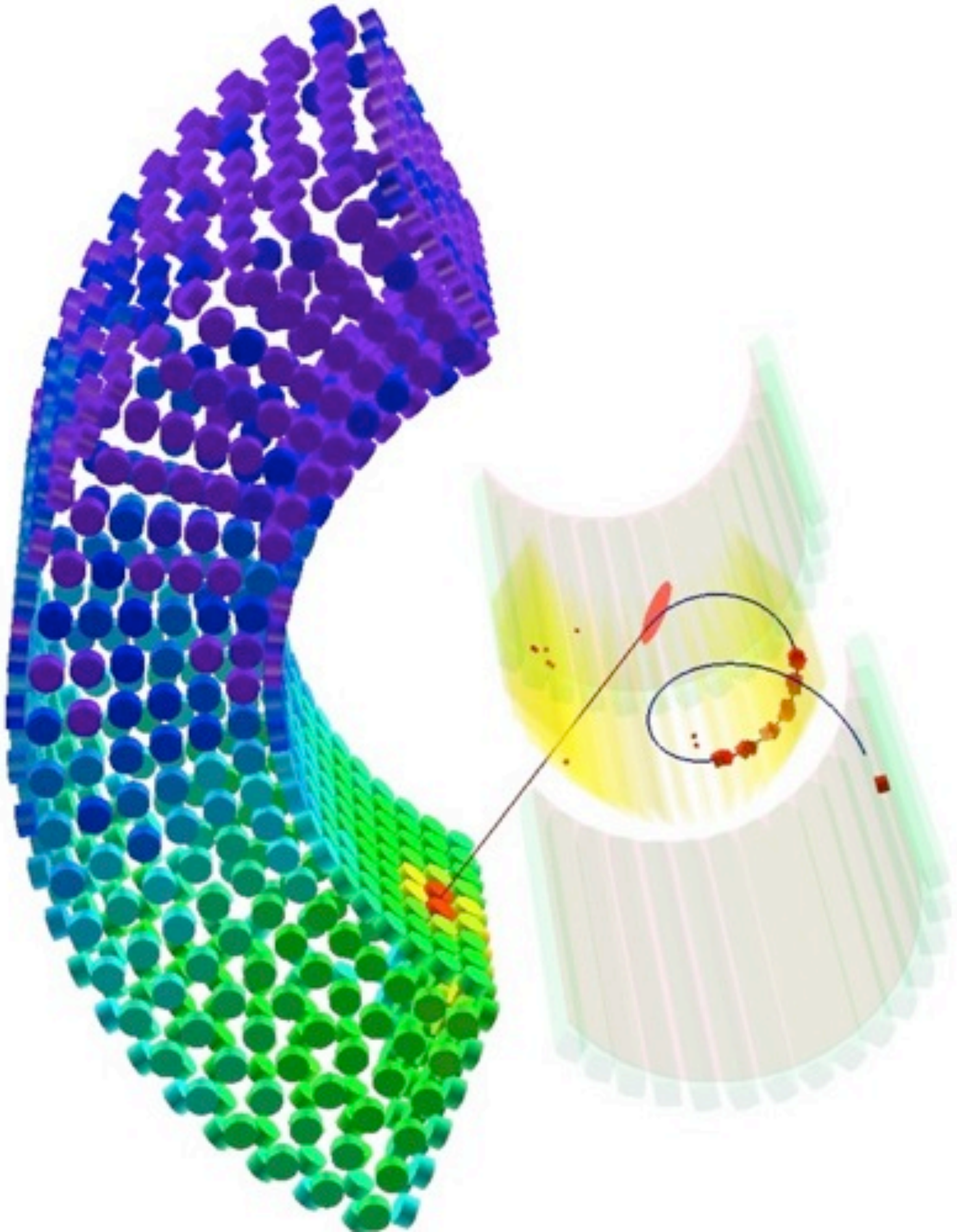
radiative BG: theory + resolution

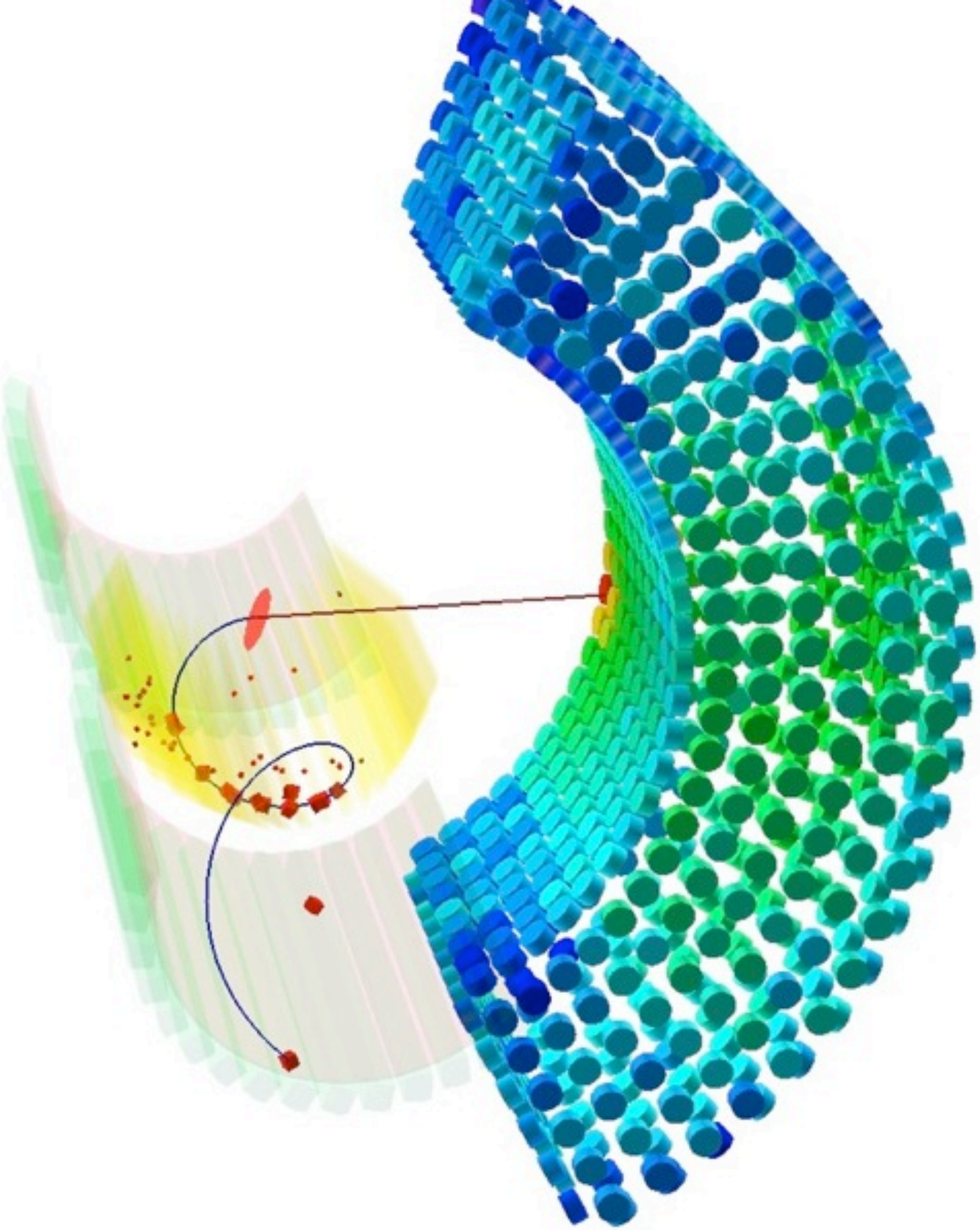
2009-2011 Side band data



side band BG rates are consistent with the expected sensitivity for 2009-11 data = 7.7×10^{-13} @90% C.L.

BLIND BOX OPENED!

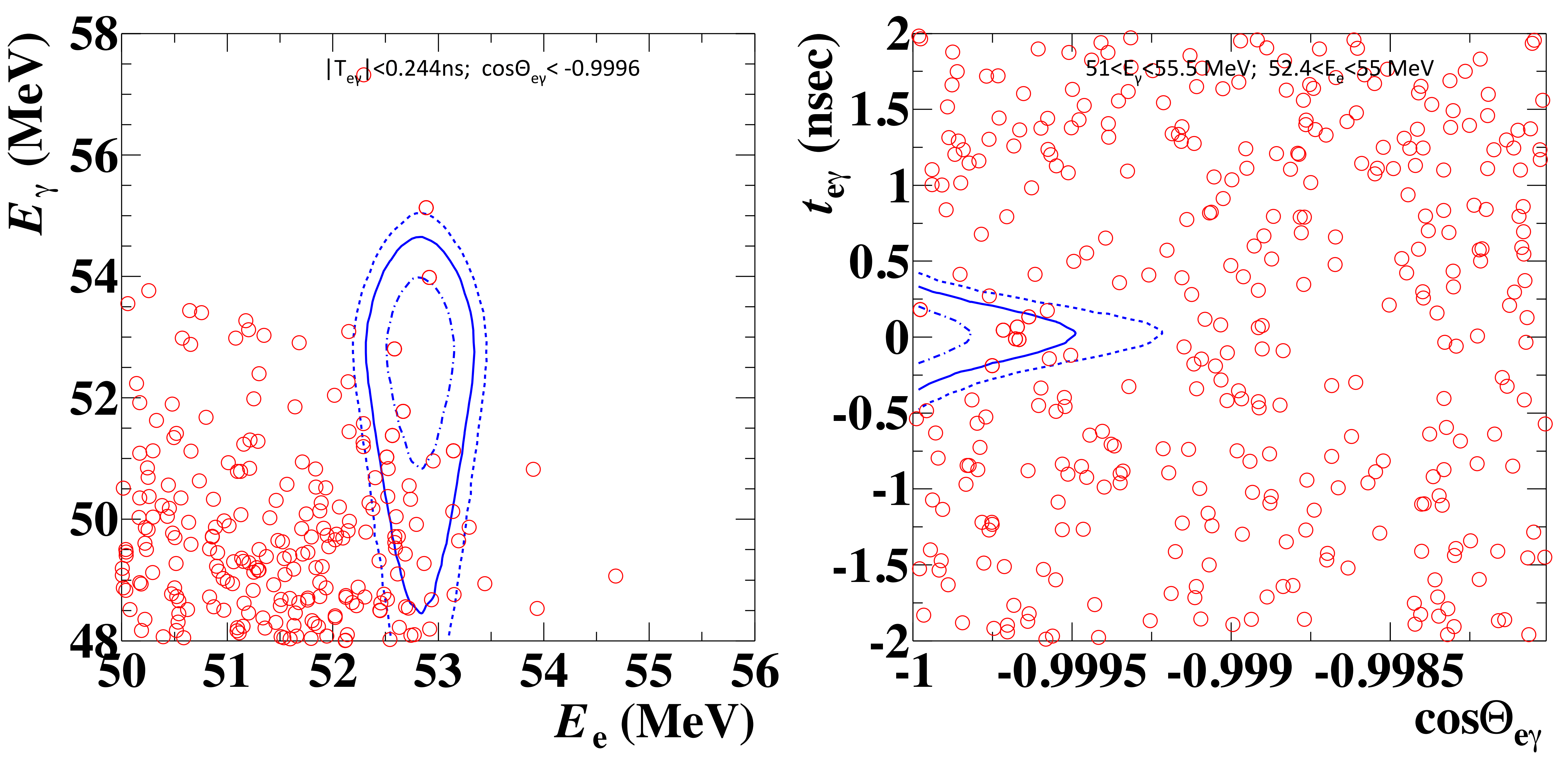




a few examples of events

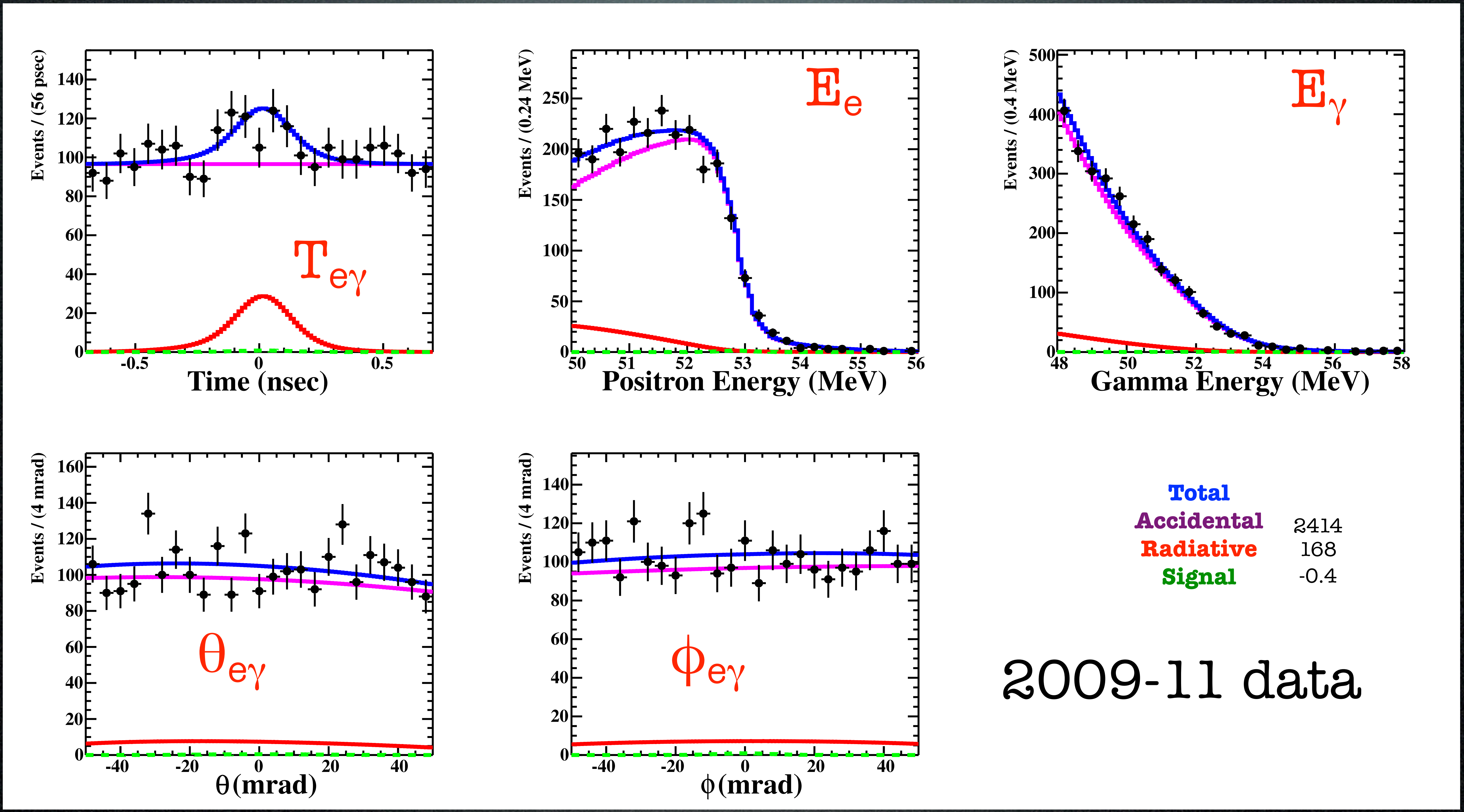
2009-2011 combined data

unblinded data

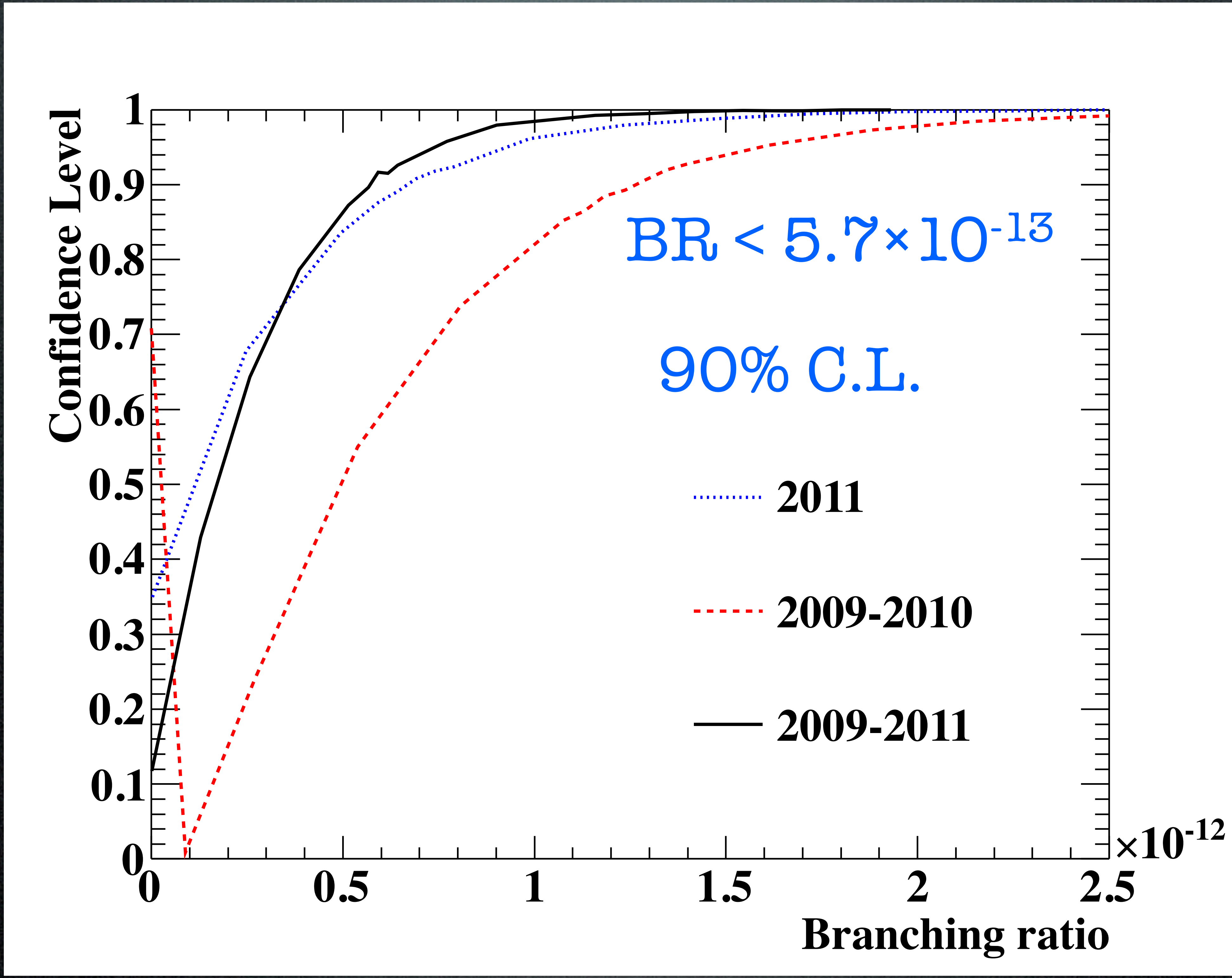


1, 1.64, 2σ
contours

Likelihood Fit - 2009-2011 Data



Likelihood Analysis



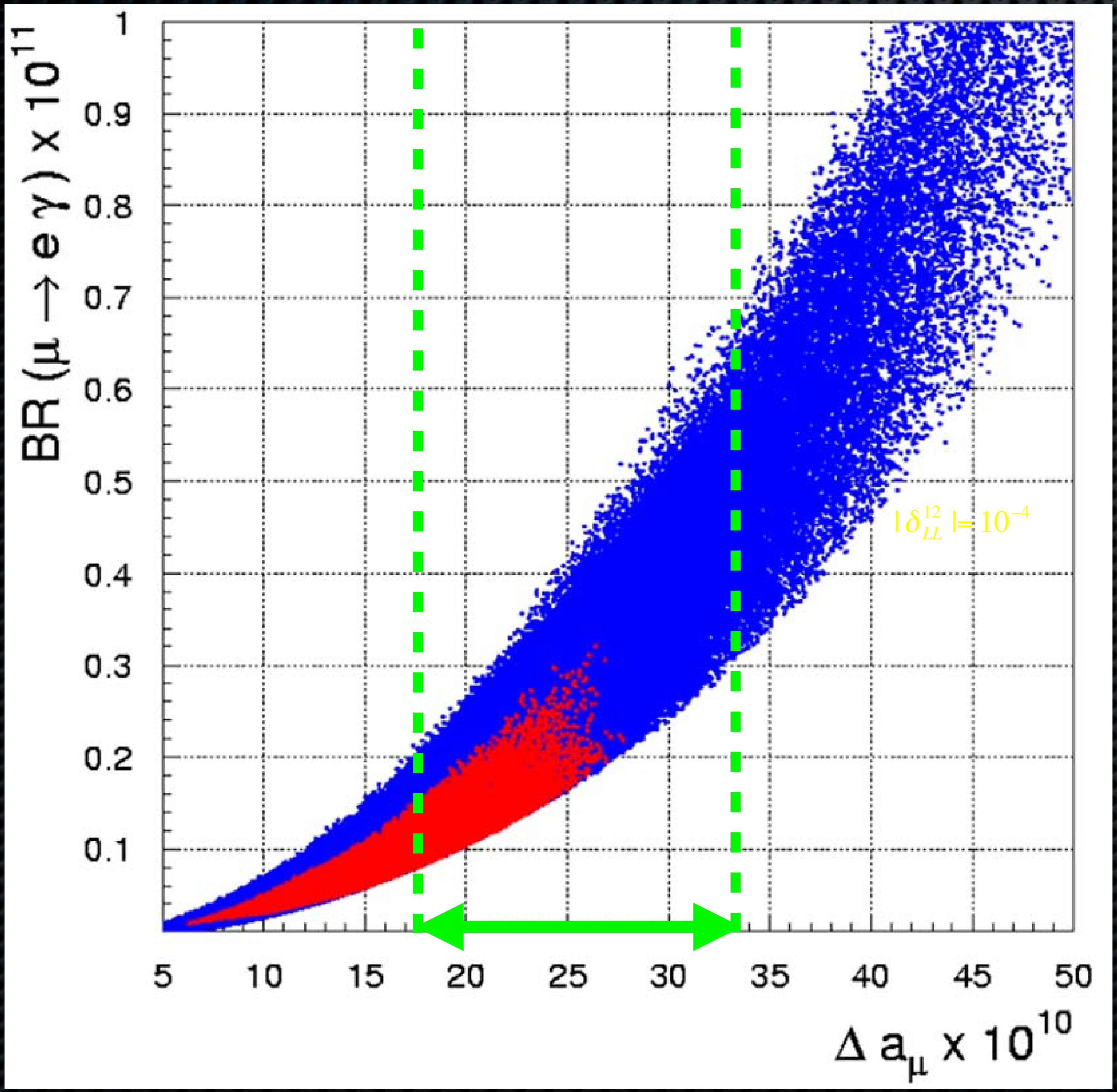
Likelihood Analysis Results

	BR(fit)	90% UL	sensitivity
2009+2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	0.67×10^{-12}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	0.57×10^{-12}	0.77×10^{-12}

combined result

4× improved upper limit than previous 2.4×10^{-12}

muon (g-2) anomaly

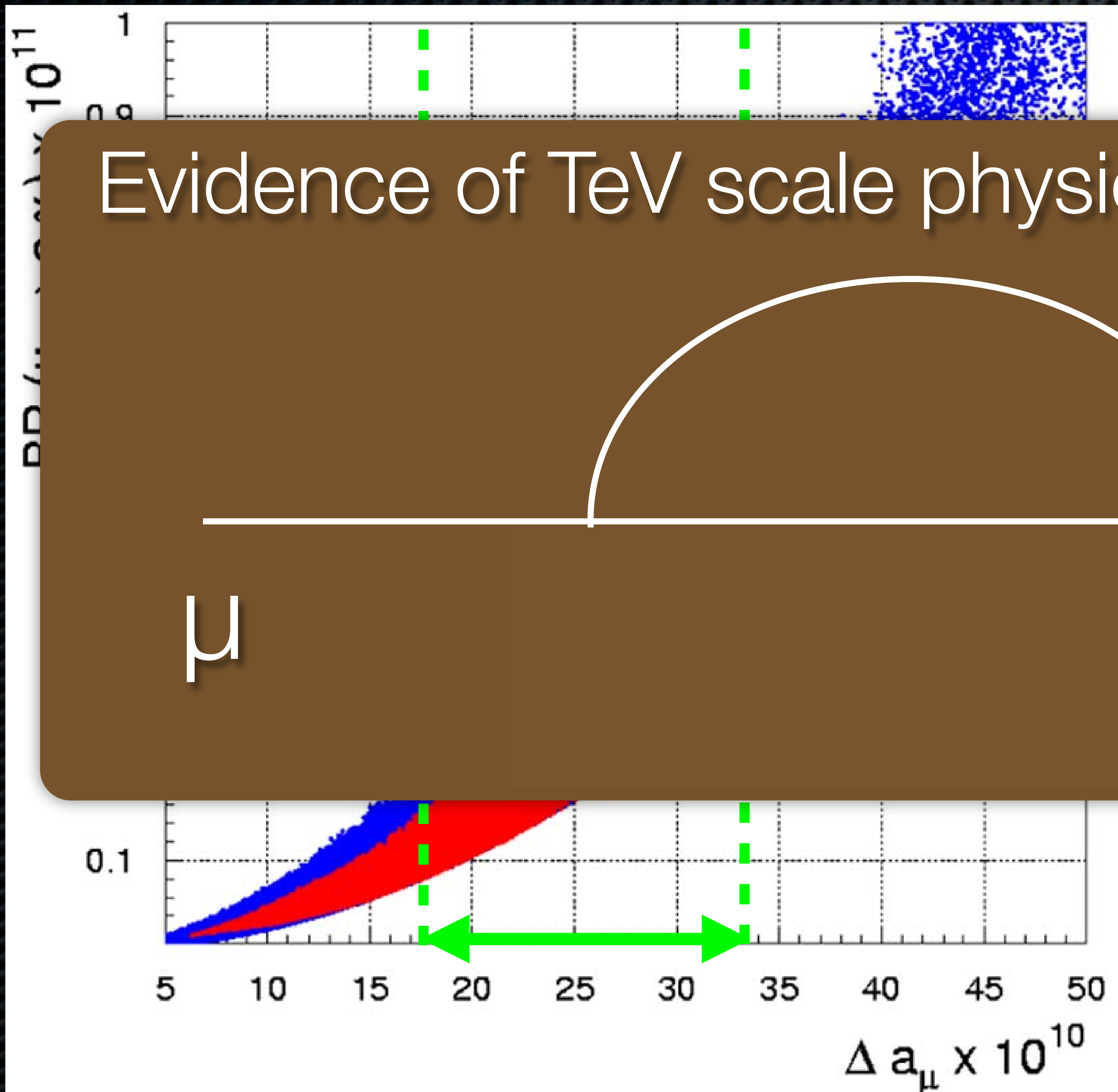


G.Isidori et al. PRD75, 115019

Here TeV SUSY is assumed,
but the relation should be more generic independent of whatever TeV physics might be

$|\delta_{LL}^{12}| = 10^{-4}$ assumed

muon (g-2) anomaly



G.Isidori et al. PRD75, 115019

Here TeV SUSY is

n

re

of

/

physics might be

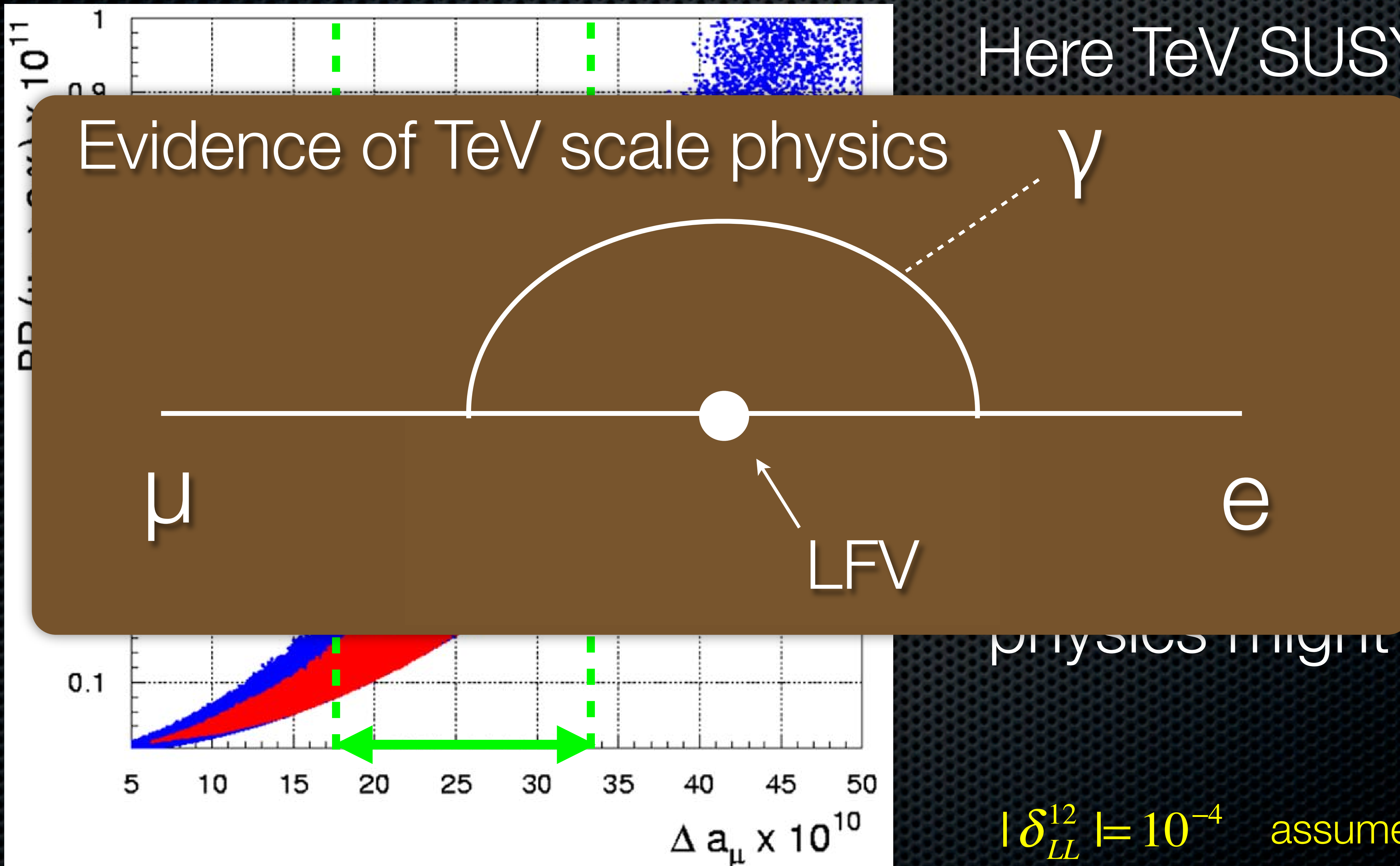
$|\delta_{LL}^{12}| = 10^{-4}$ assumed

Evidence of TeV scale physics

γ

μ

muon (g-2) anomaly



Here TeV SUSY is

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physics might be

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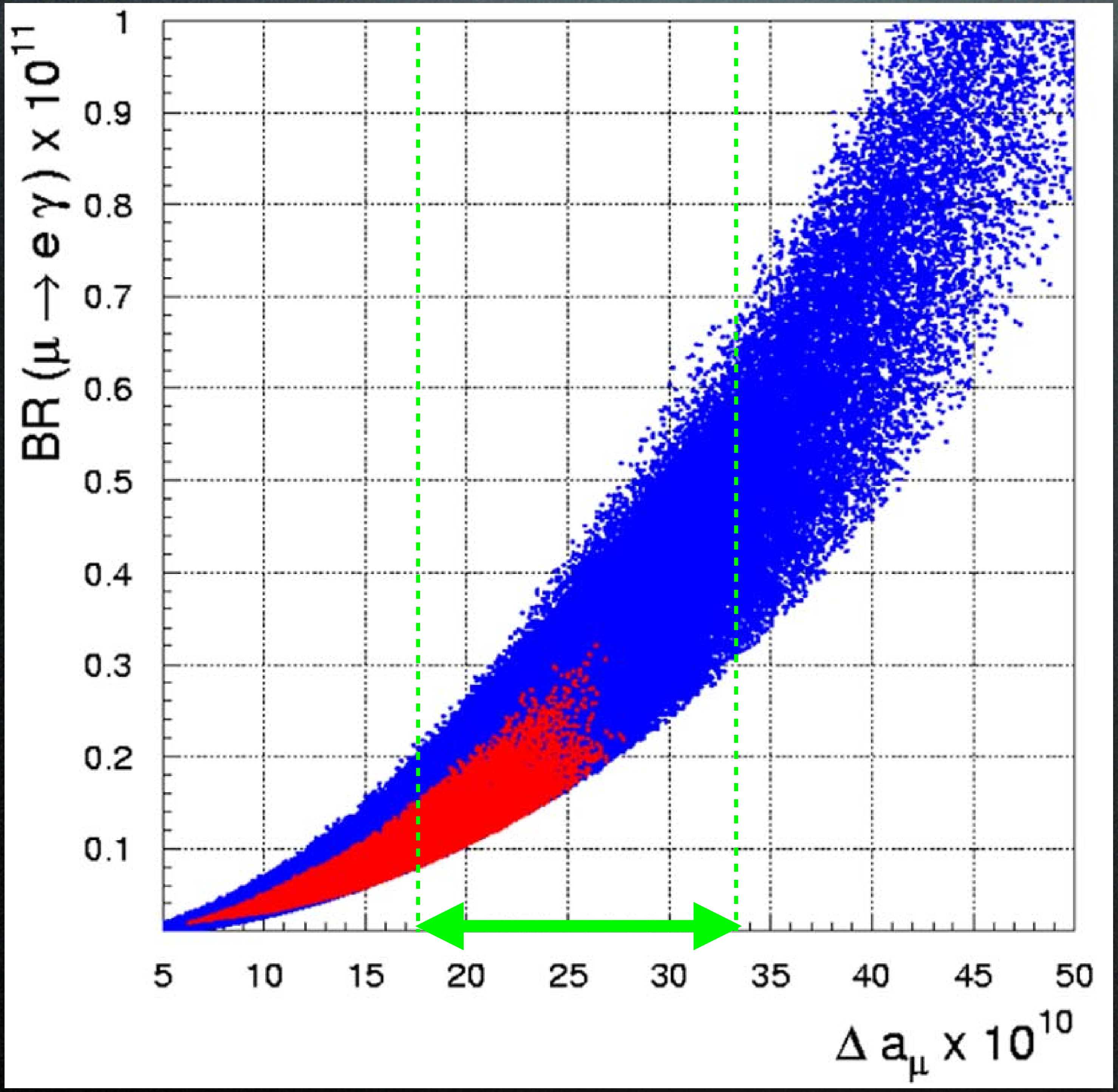

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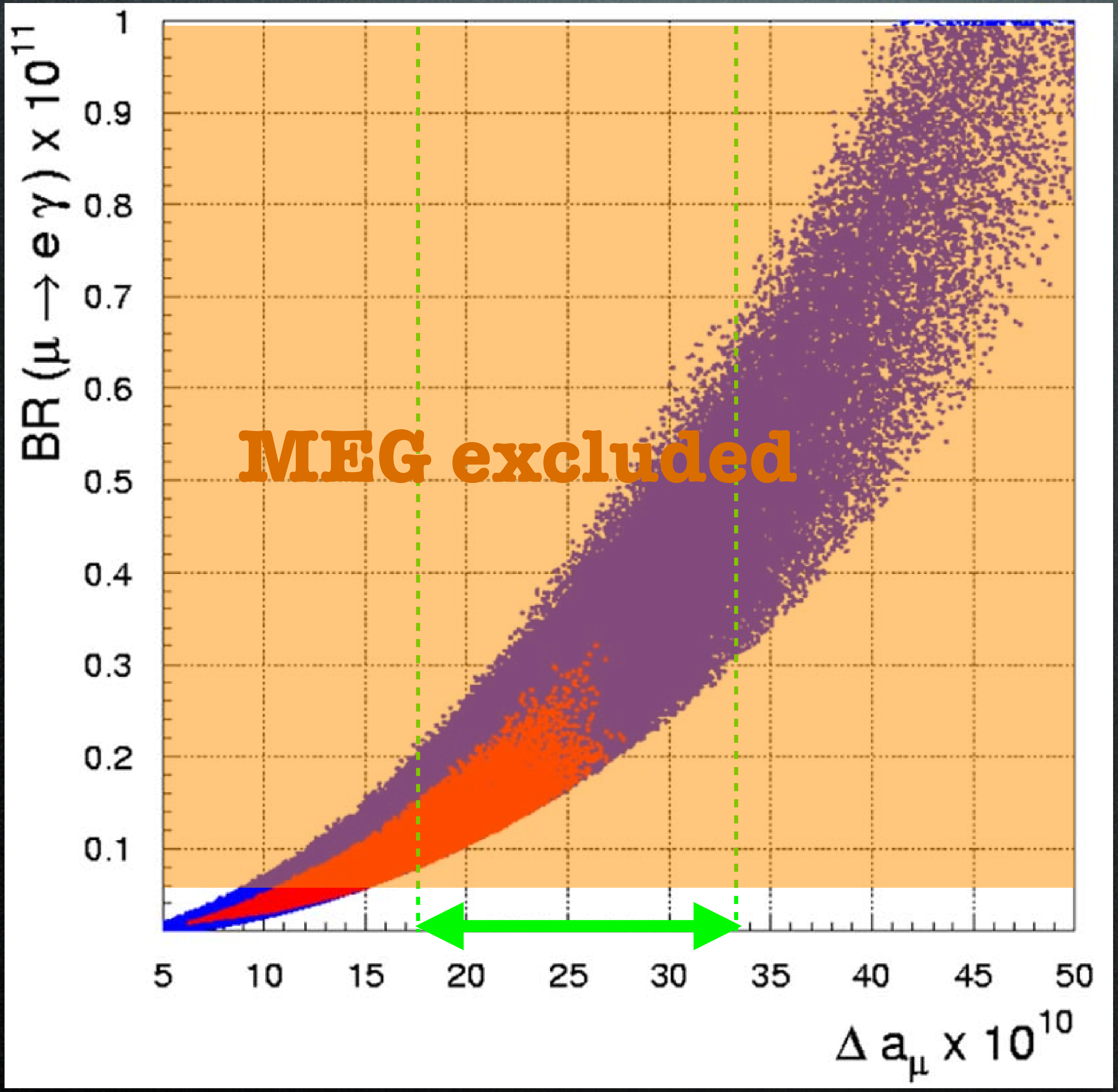
G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment

muon (g-2) anomaly



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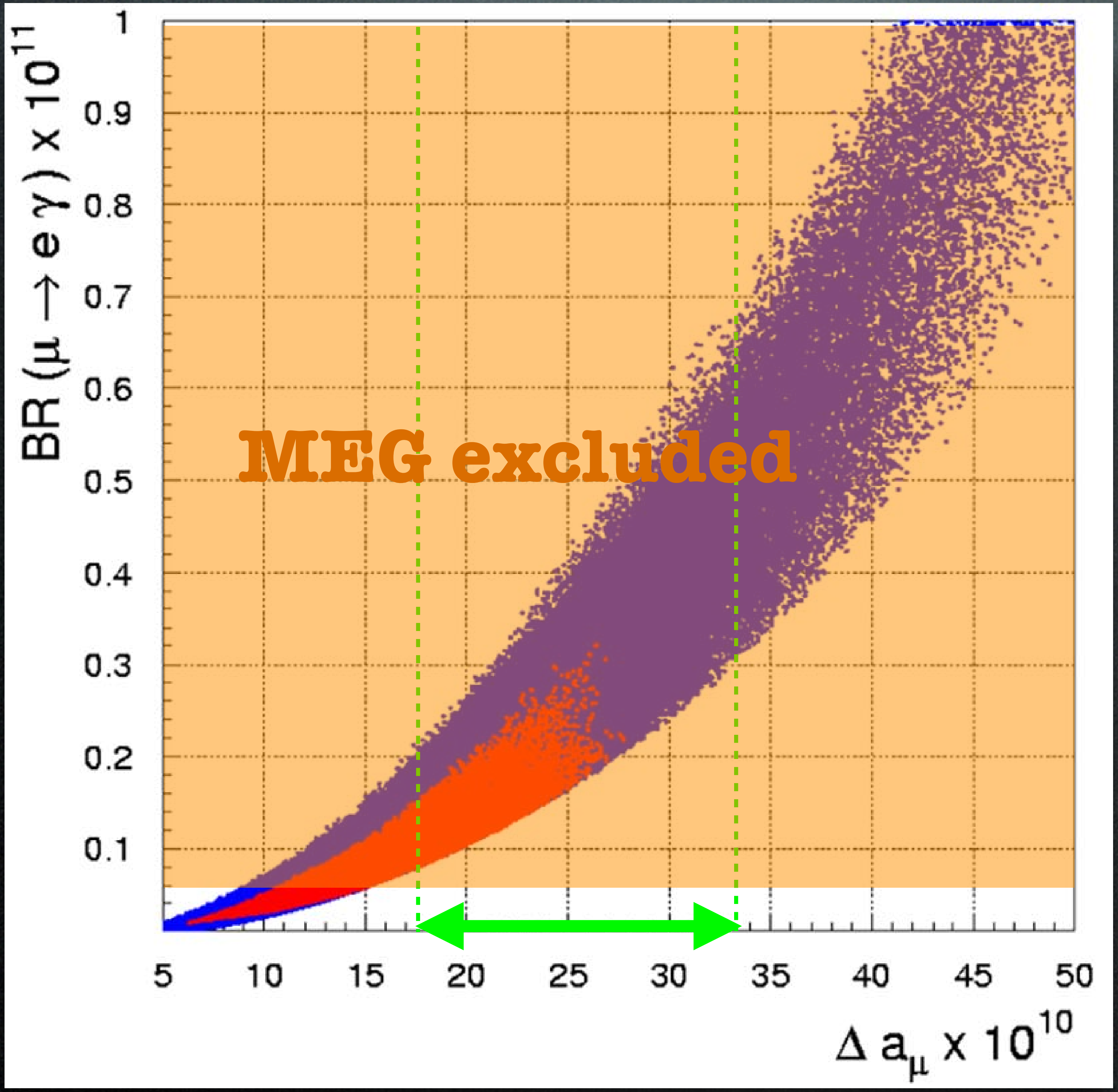


G.Isidori et al. PRD75, 115019

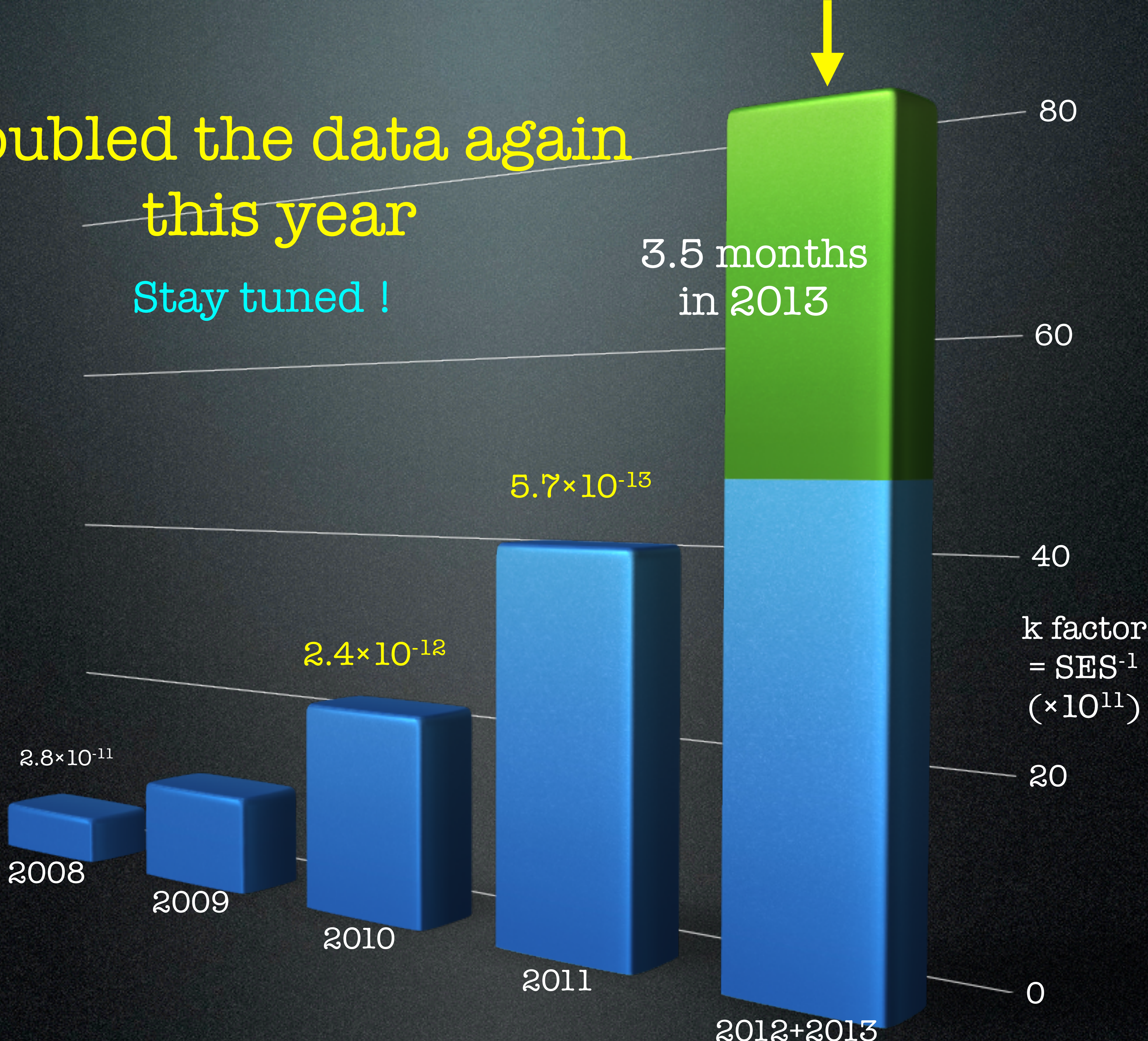
Re-analysis using the updated result is urgent !

$|\delta_{LL}^{12}| = 10^{-4}$ assumed

muon's anomalous magnetic moment

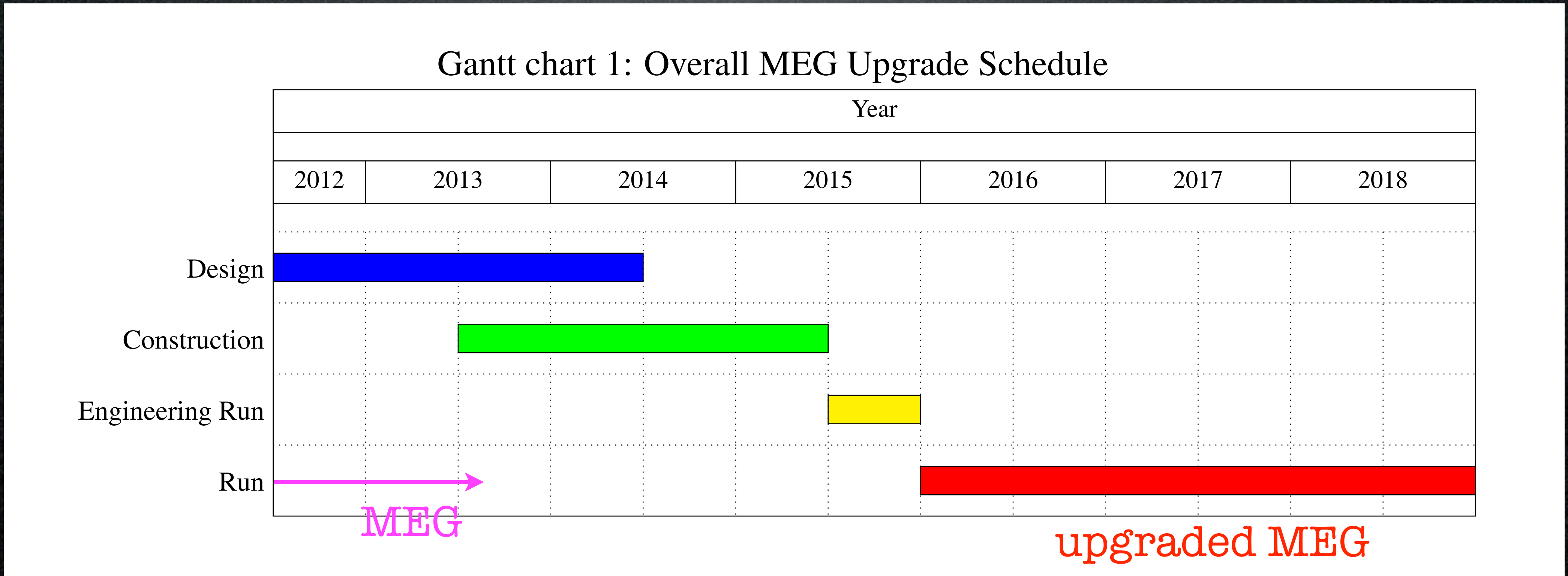
Doubled the data again this year

Stay tuned !



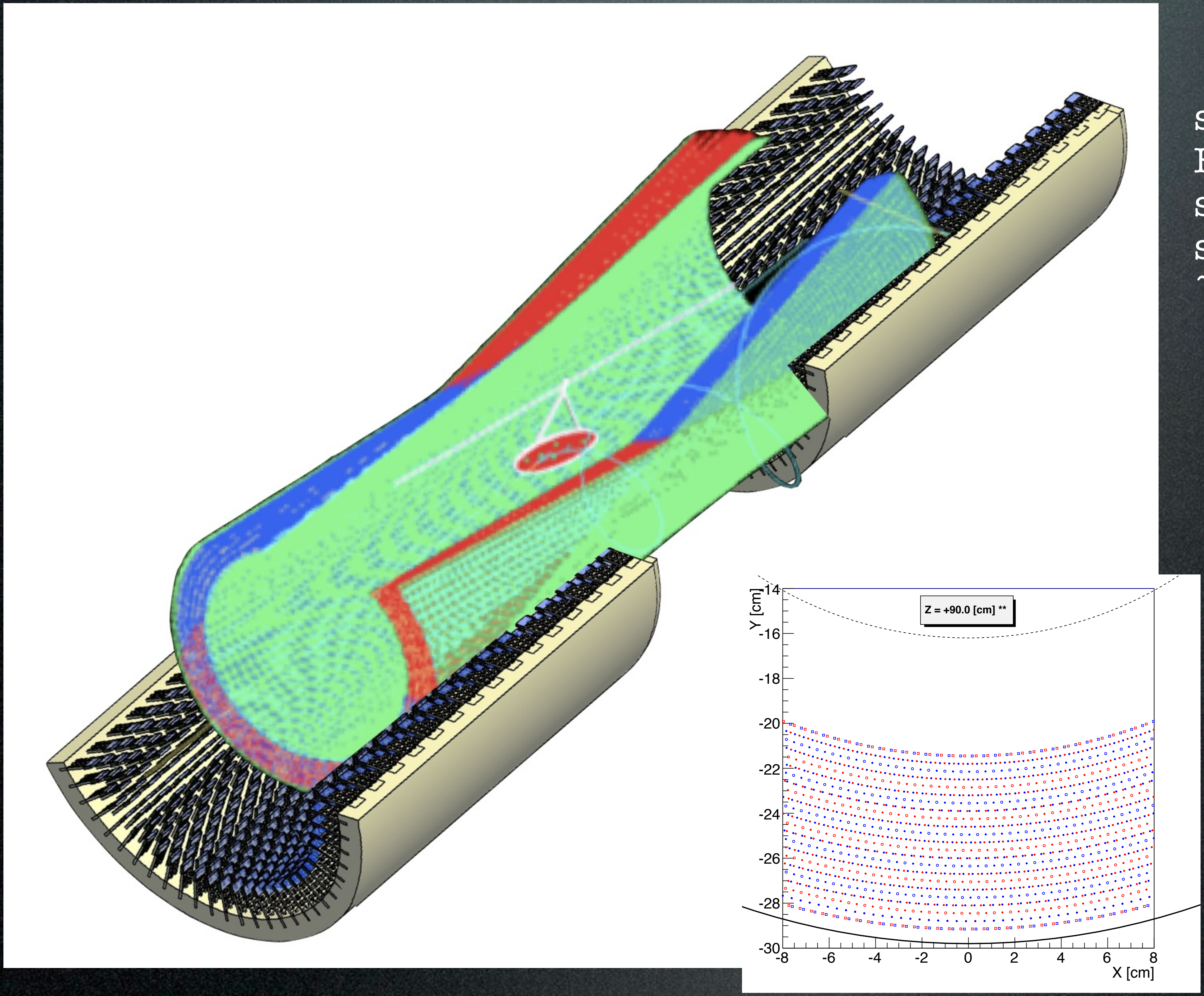
MEG upgrade

- MEG upgrade proposal was submitted to PSI, December 2012
- Approved by PSI committee, January 2013



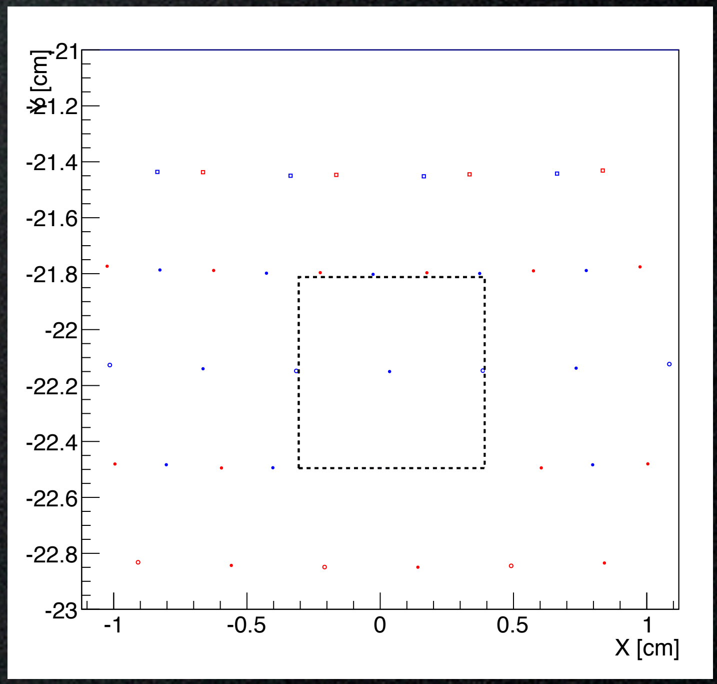
Drift Chamber

- sustain higher muon rate & ageing
- finer granularity & better resolution
- lager combined DC+TC acceptance



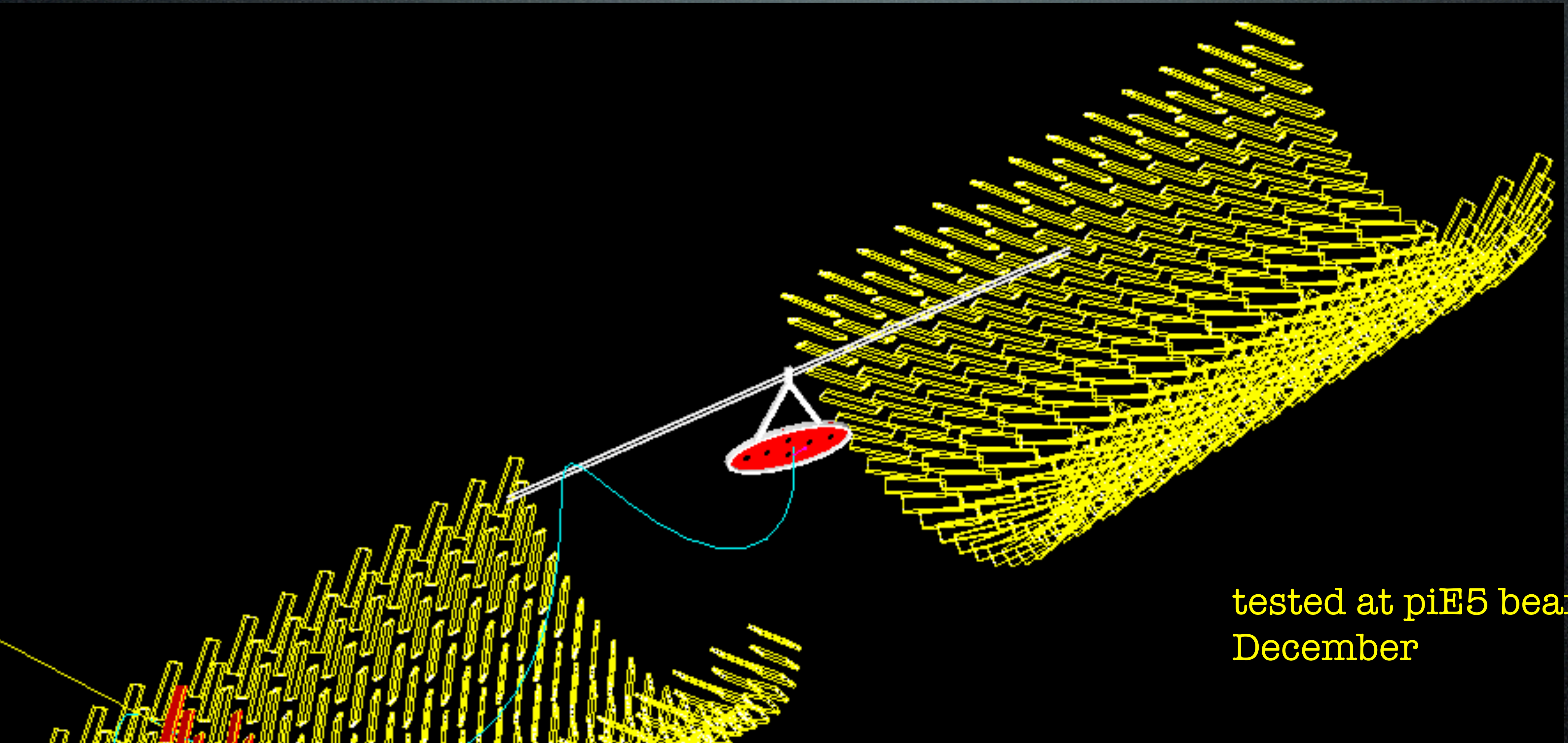
single volume
He-based gas
small cell size
stereo wires
~130μm hit resolution

most challenging
element of upgrade

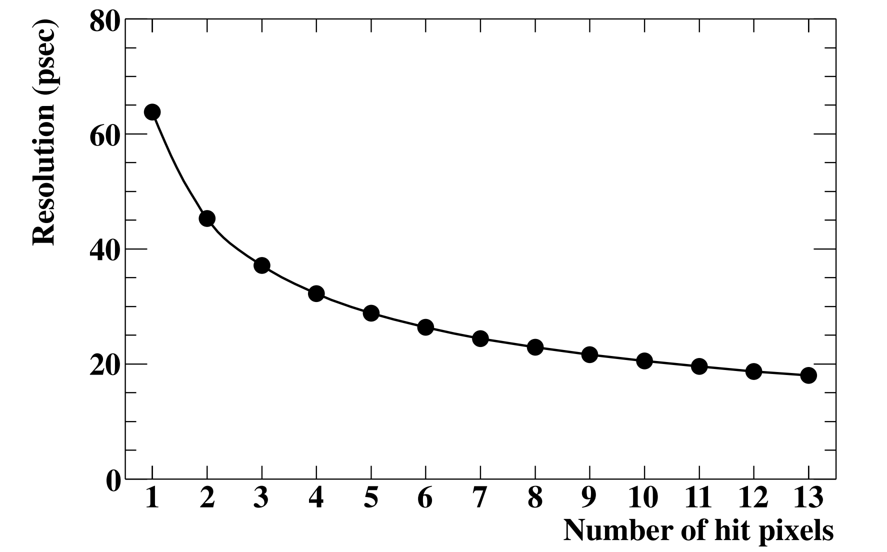


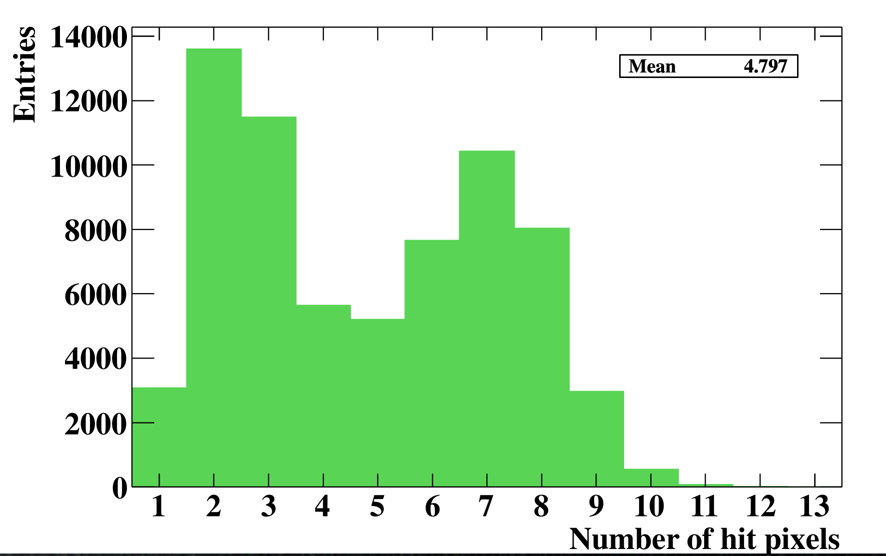
Timing Counters

- proven technology using SiPM
- excellent resolutions expected using multiple counters



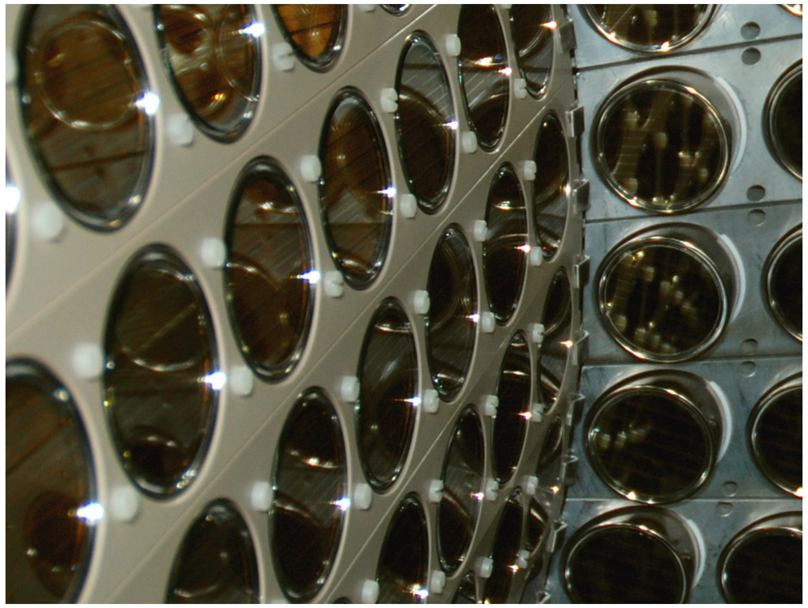
tested at piE5 beam line in December



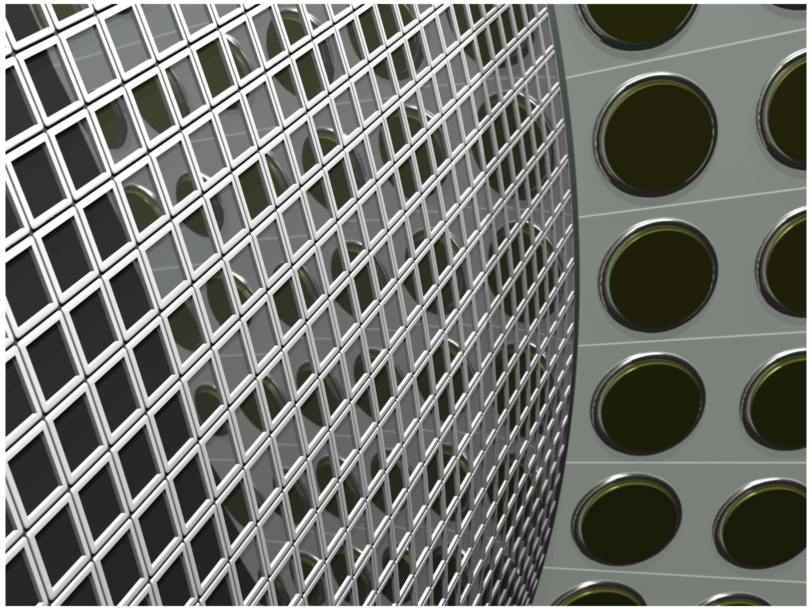


LXe Detector

- finer photon sensors at entrance face
- better uniformity - better resolution
- better handles for pile ups

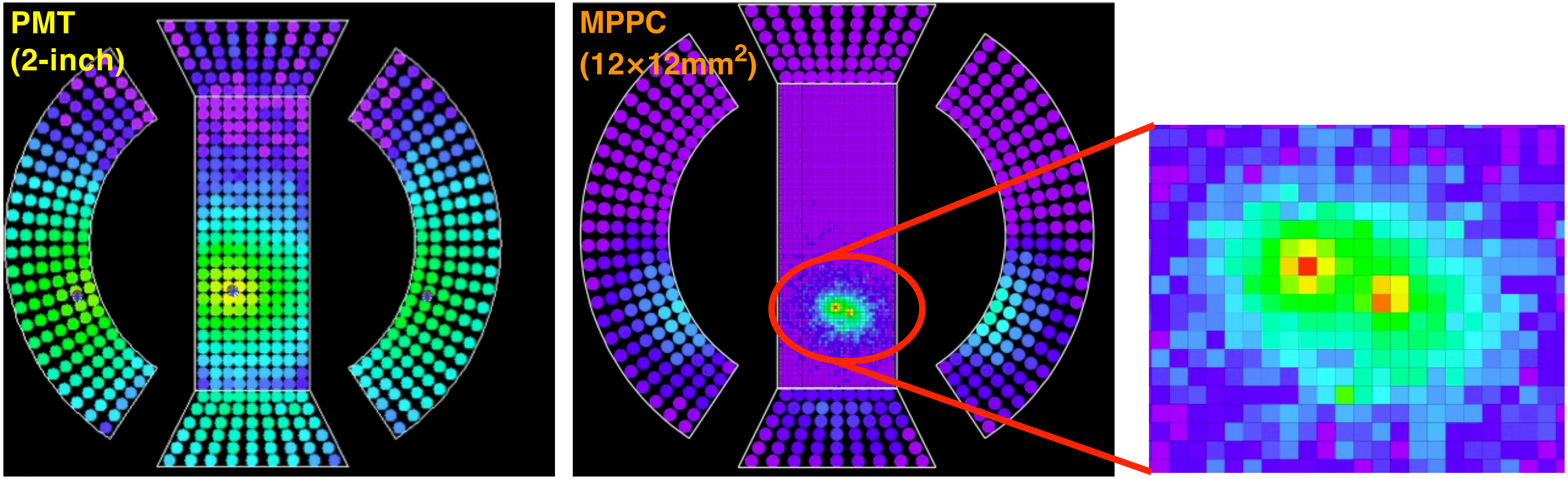


(a) Present detector



(b) Upgraded detector (CG)

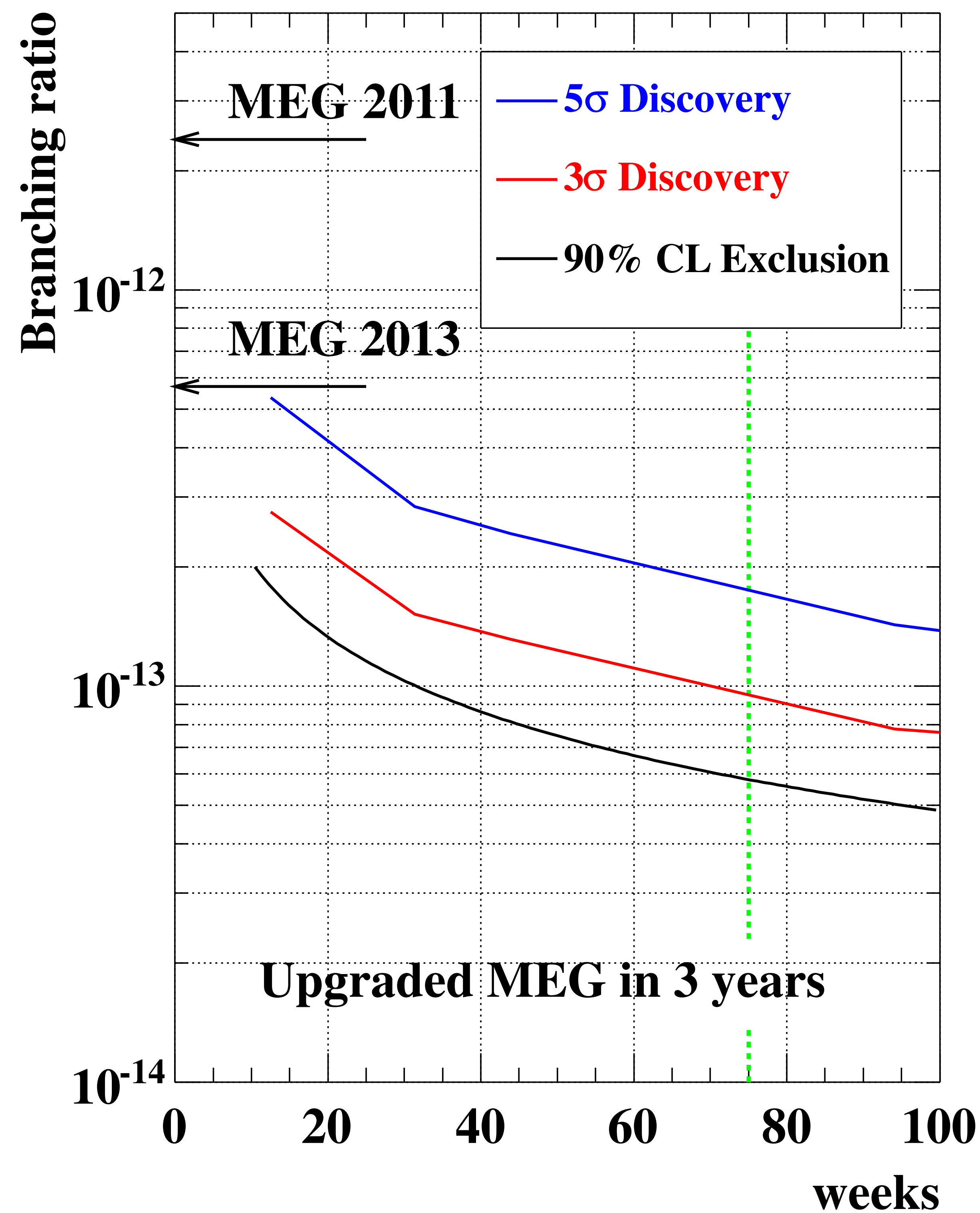
LXe detector proved to work at 10^8 muons/s w/o pileup issues



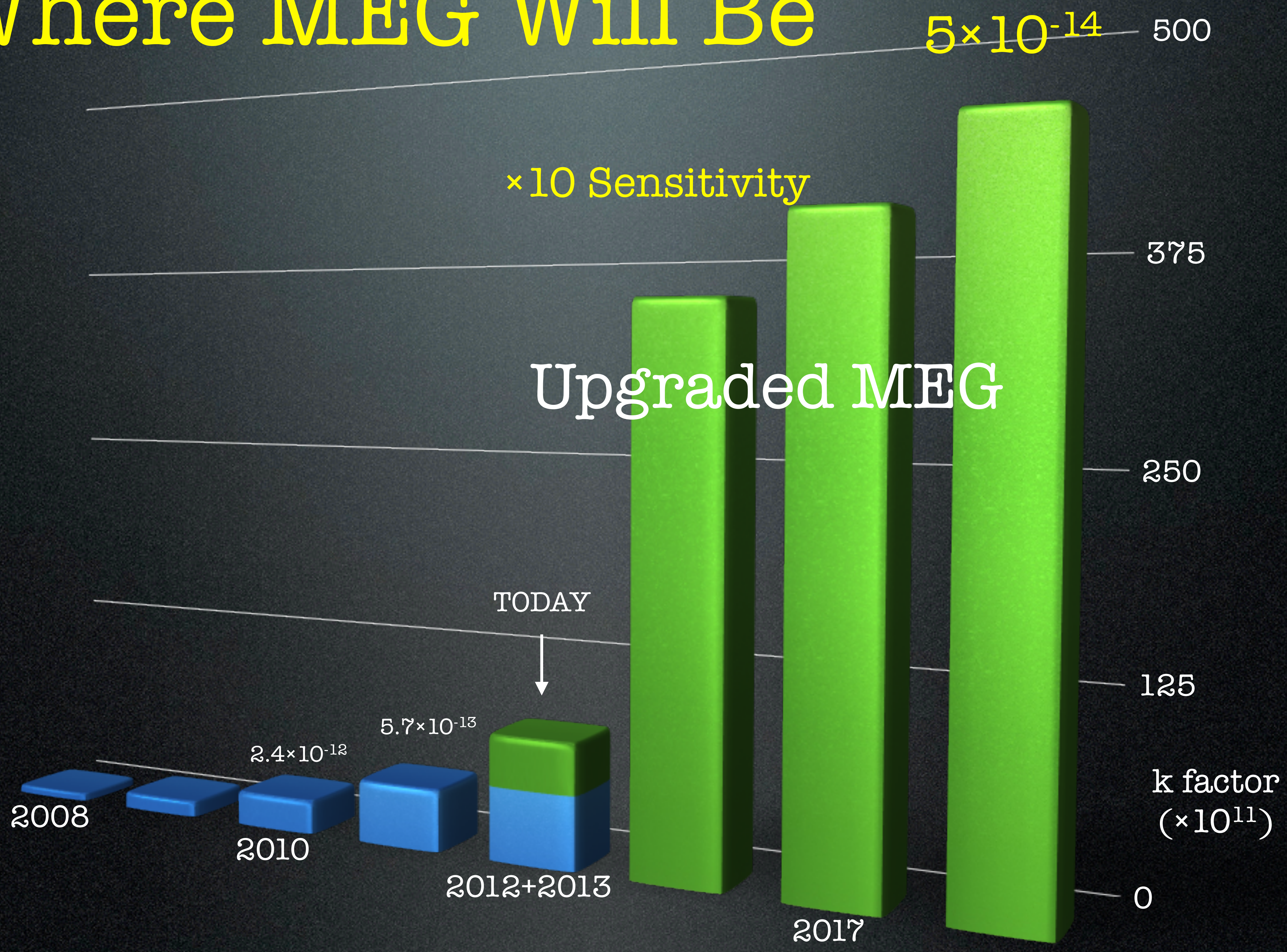
Resolutions, Efficiencies, & Sensitivity

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

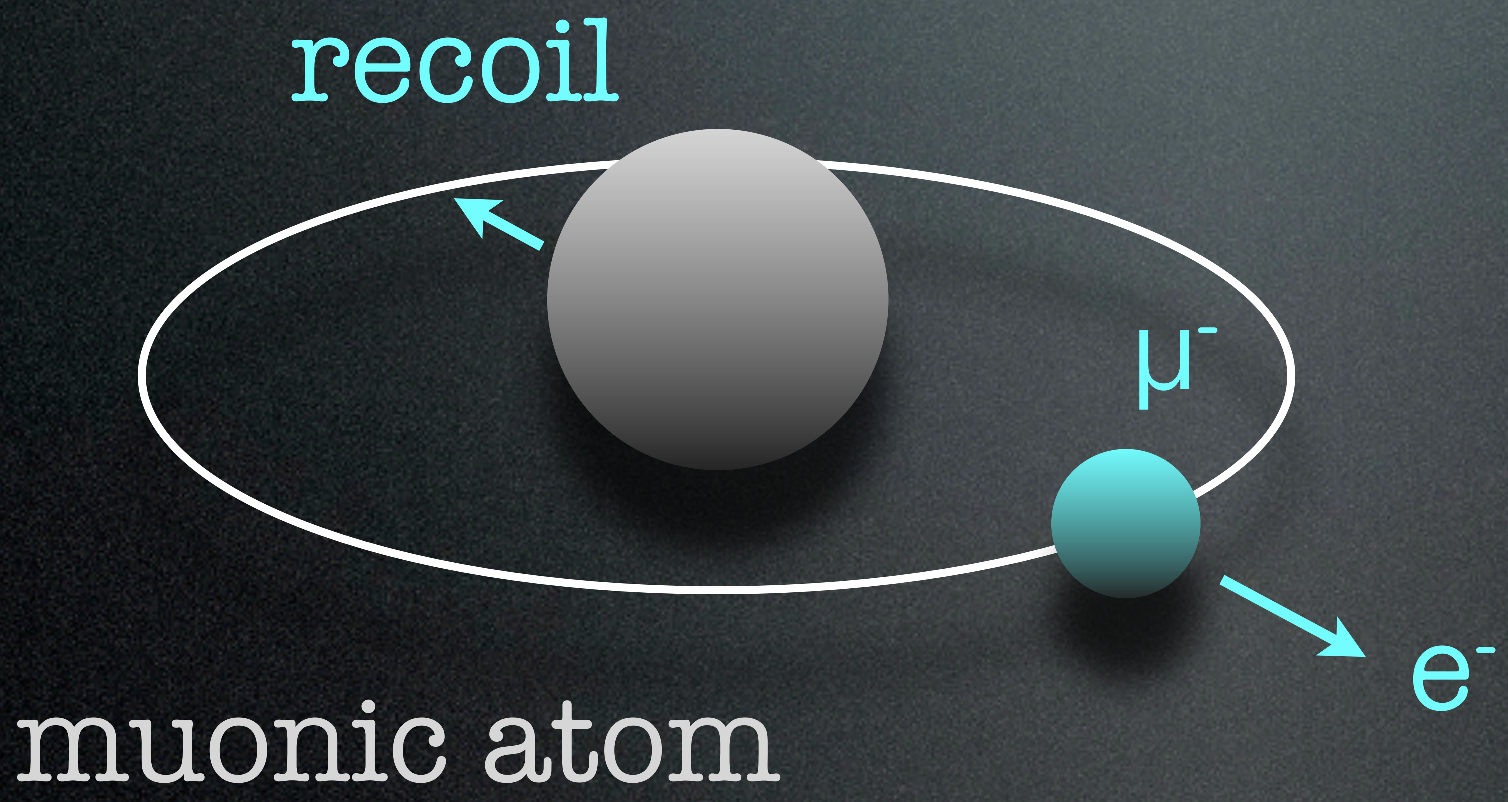
PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88
muon rate	3.3×10^7/sec	7×10^7/sec



Where MEG Will Be



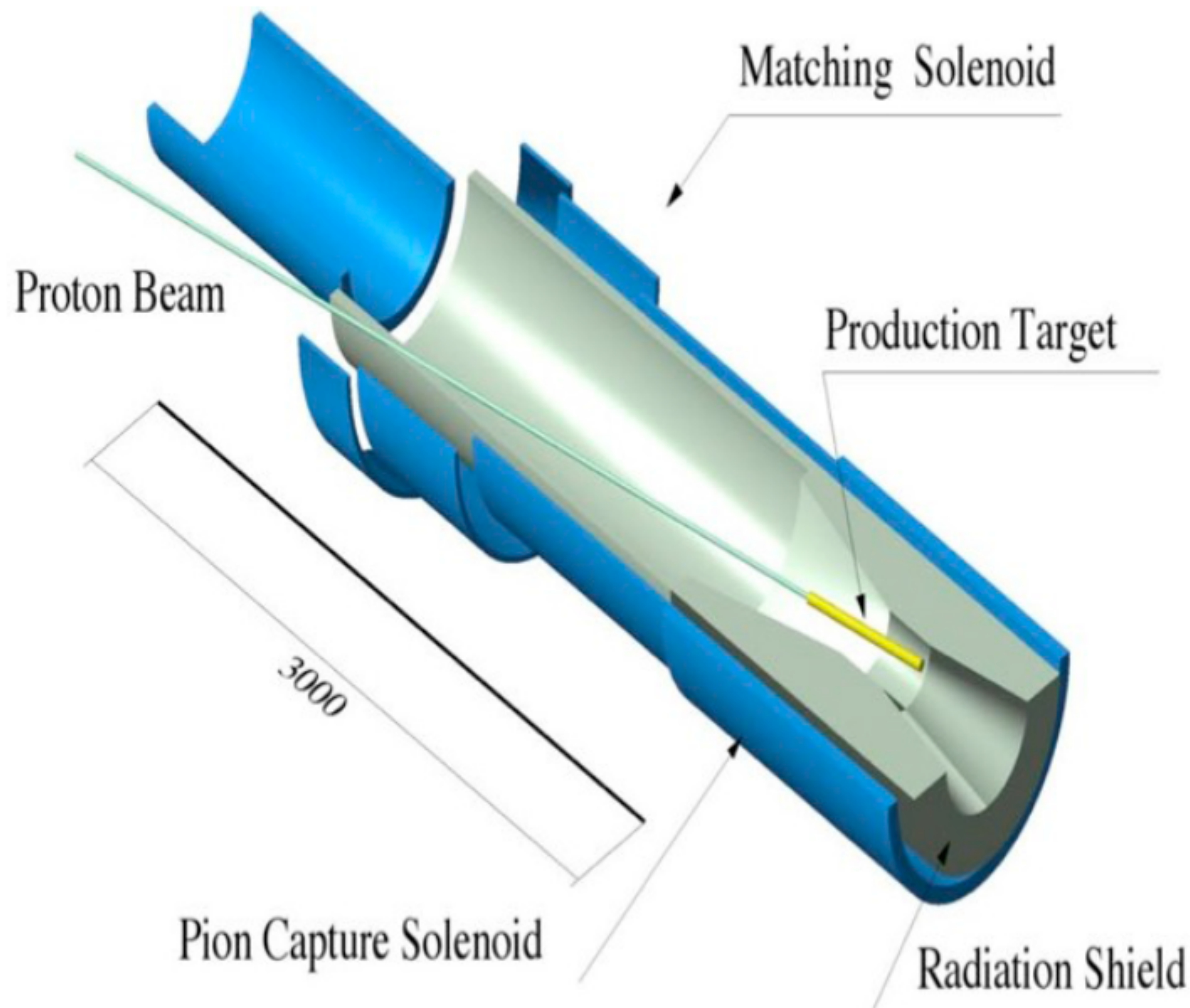
μ→e conversion $\mu N \to e N$



- negative muons to make muonic atoms
- signal:
  - a single electron
    $E_e = M_\mu - \delta$
- background:
  - decay in orbit
    $(E_{max} - E_e)^5$
  - beam related
    e.g. pion capture

Lots of muons are needed

Pion Capture Solenoid System



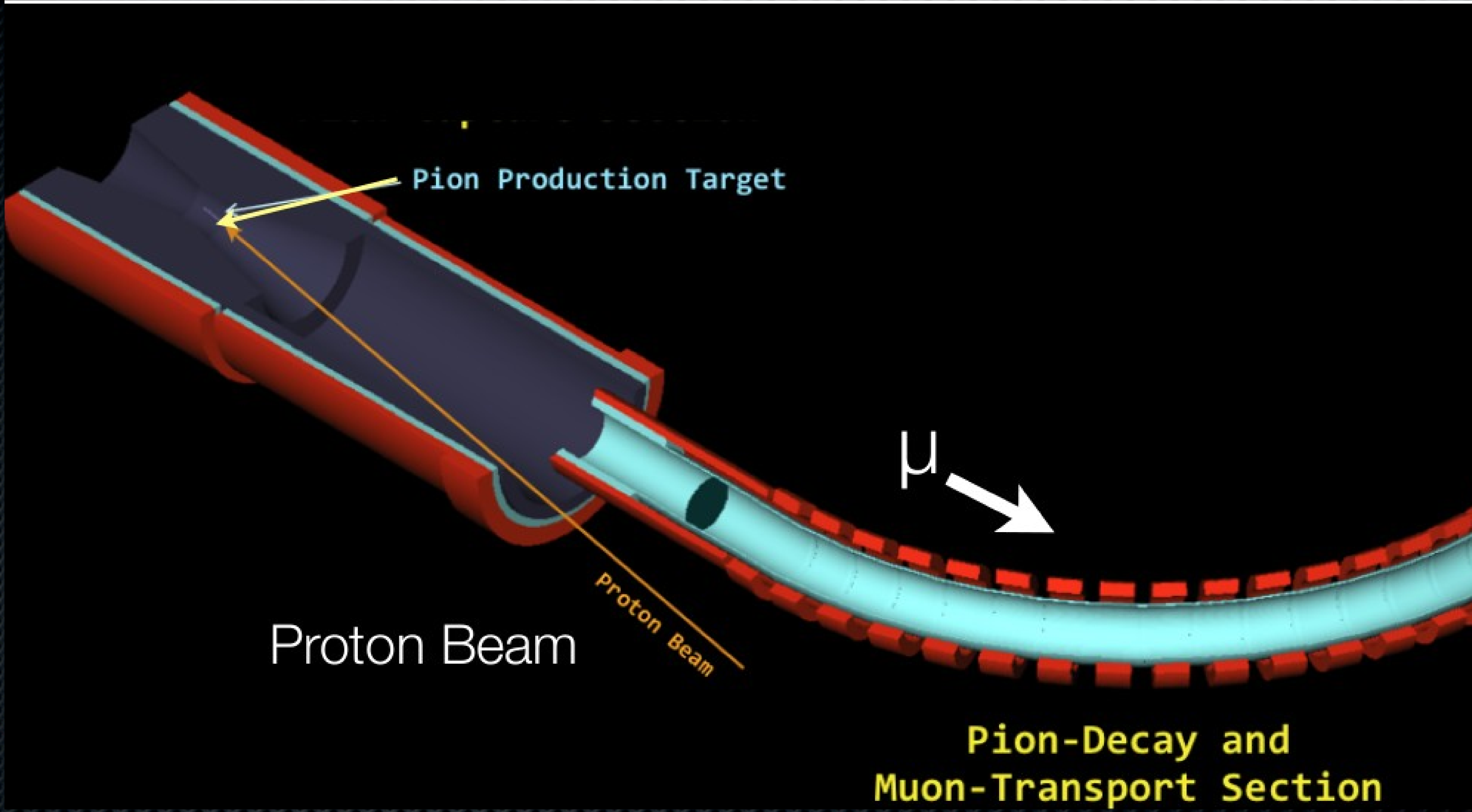
- Large muon yield by Large Solid Angle
  - Powerful Solenoid
  - Surround p target

$$P_T(\mathrm{GeV}/c) = 0.3 \times B(\mathrm{T}) \times \left[\frac{R(m)}{2}\right]$$

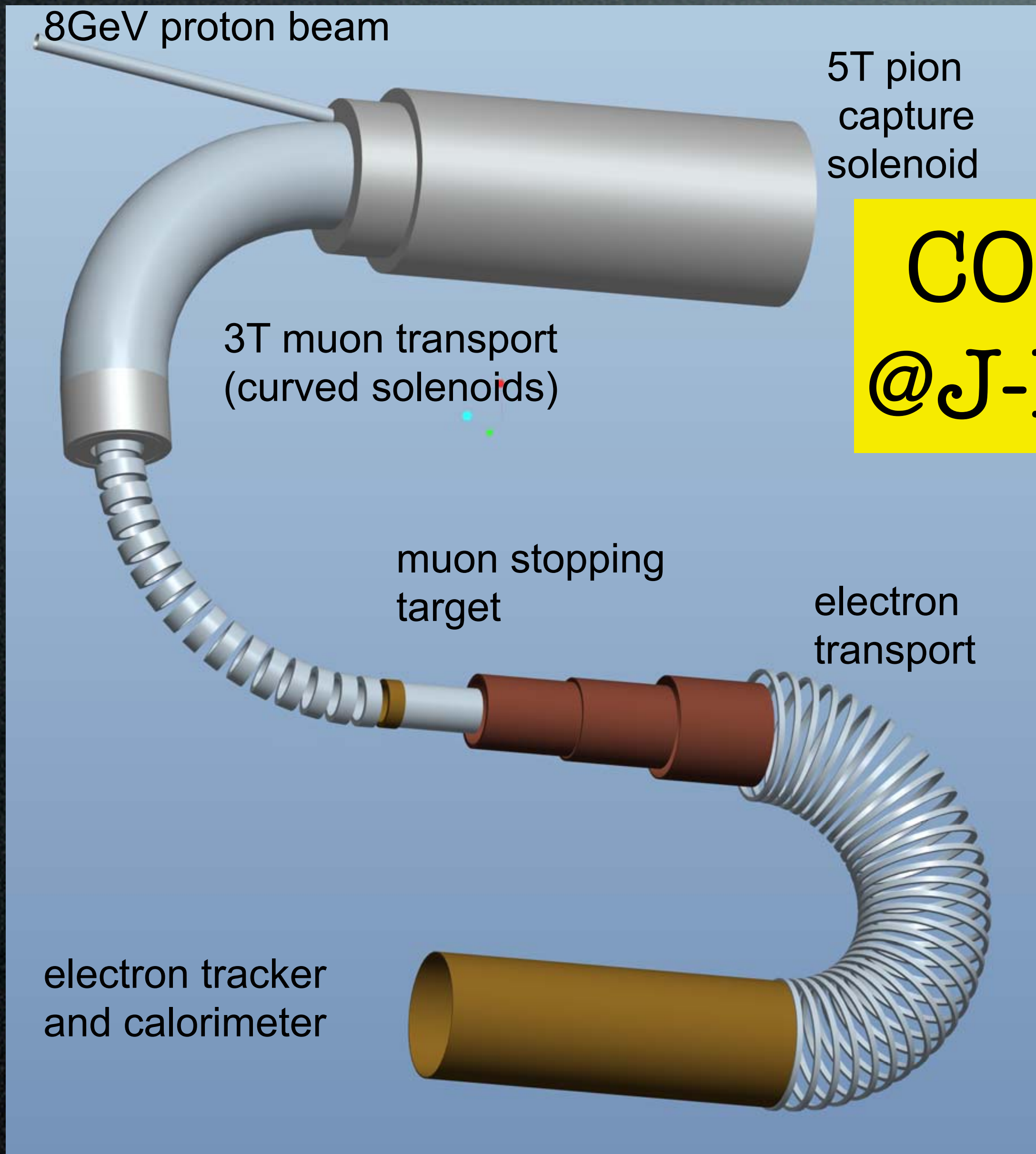
B=5T, R=0.2m → P_T=150MeV/c

- Super-conducting solenoidal magnet
  - 15cm radium bore
  - 5T
  - 30 cm thick W shield.
- Issue : Heat Load

Captured pions are transported and momentum selected by solenoids



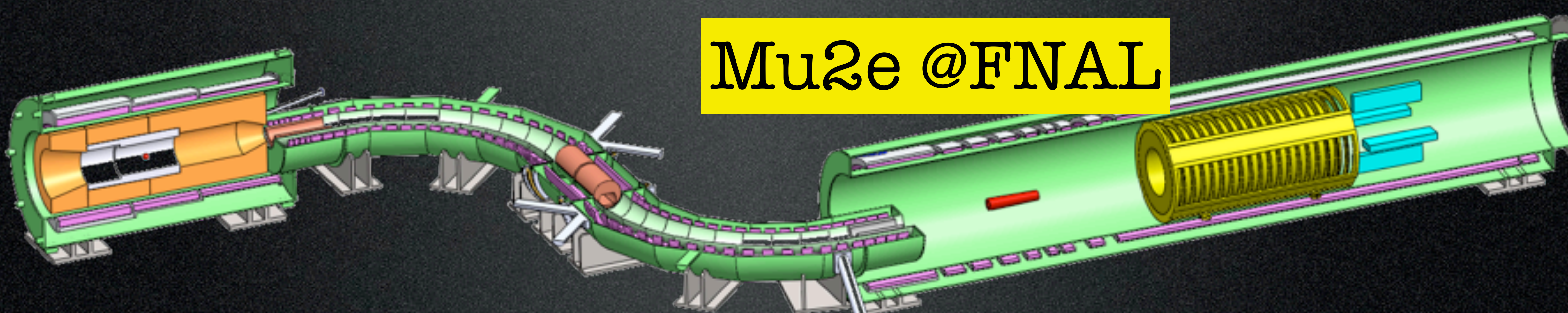
$\mu \rightarrow e$ conversion at 6×10^{-17}



COMET @J-PARC

stopping target & detectors are also in solenoids

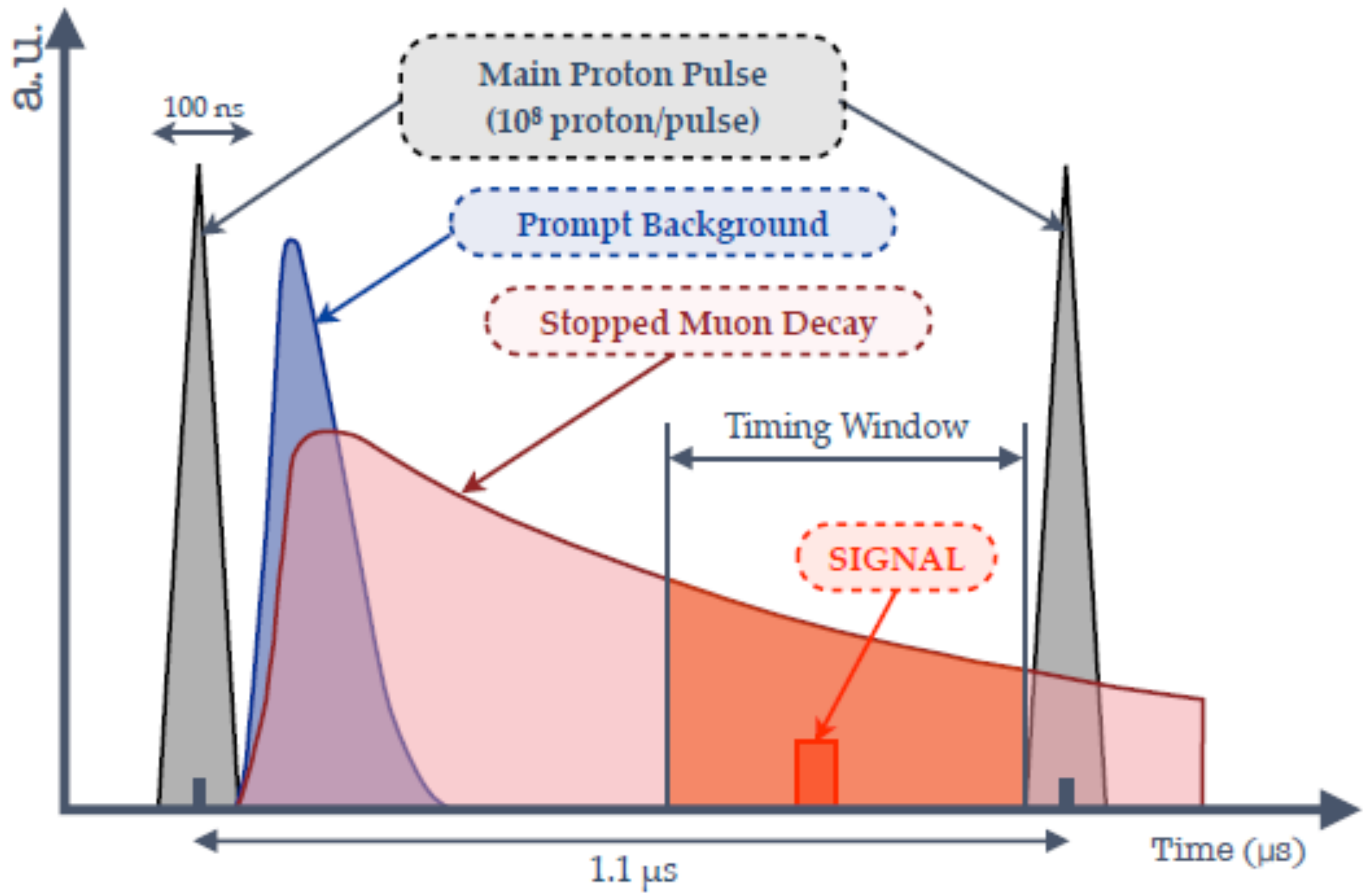
Mu2e @FNAL



Pulsed Proton Beam

- **Extinction** (= Residual protons in between the pulses)

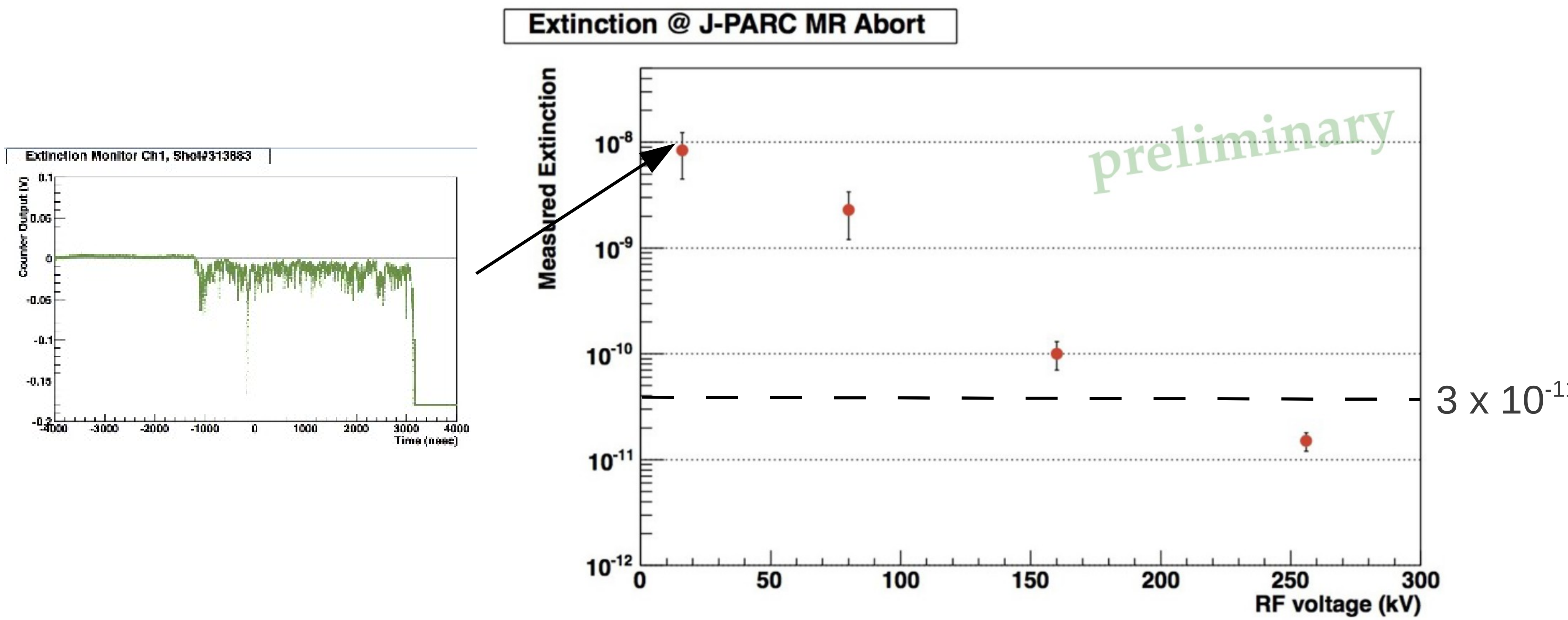
- Dominant Backgrounds
  - Beam Pion Capture
    - $\pi + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1),\ \gamma \rightarrow e^+e^-$
    - Prompt Timing
    - *cf.* $\tau_{(\text{muonic Al})} = 0.88\mu s$
  - Muon DIO, e^- scattering



Extinction should be $<10^{-9}$: To achieve 10^{-17} Single Event Sensitivity

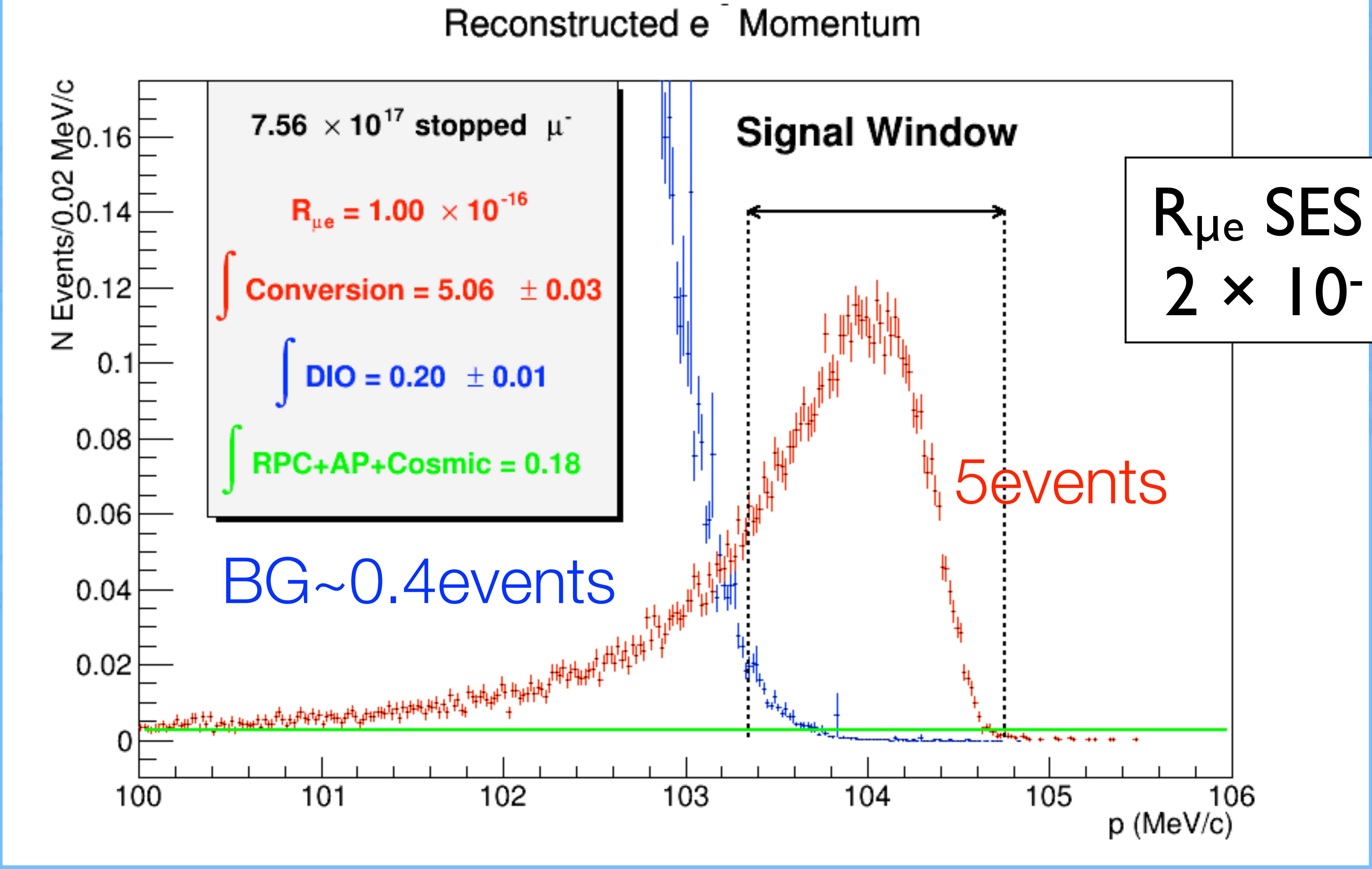
Proton Beam Extinction

- Single bunch kick injection method successfully demonstrated in June 2012 at J-PARC



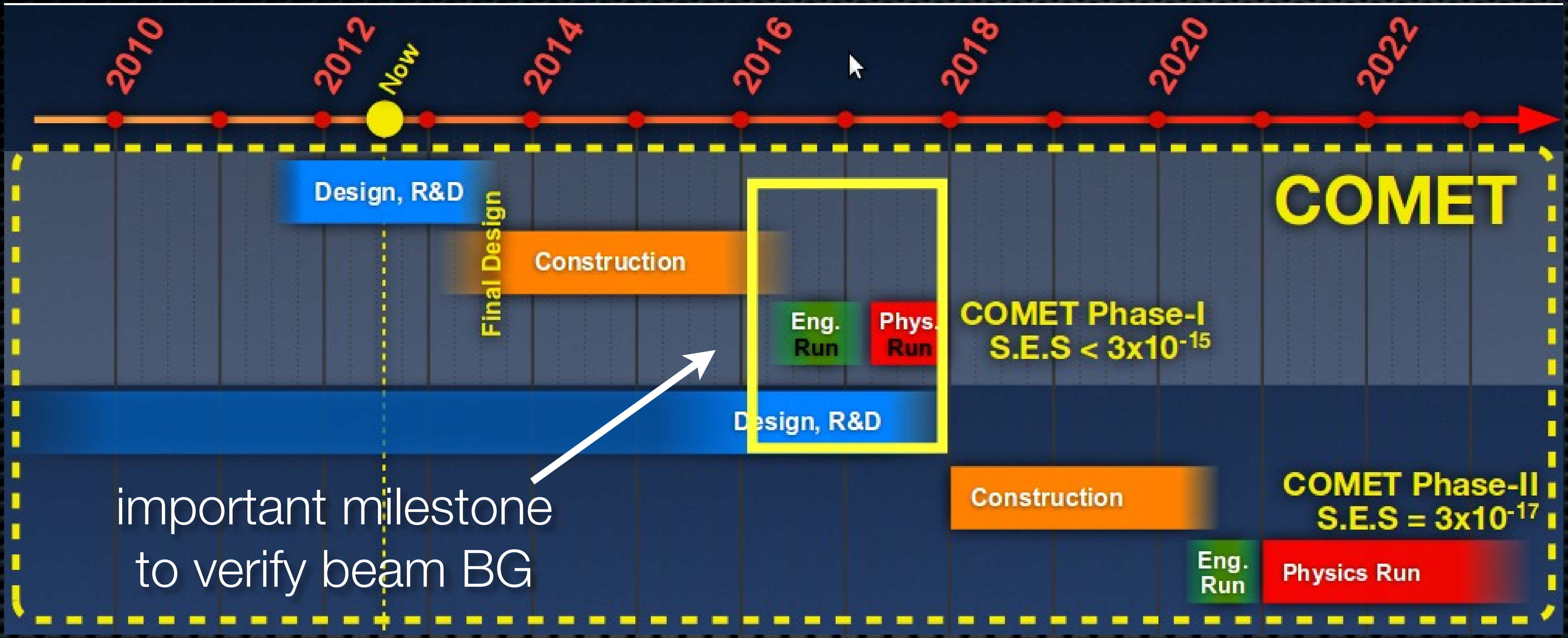
Mu2e Signal Sensitivity

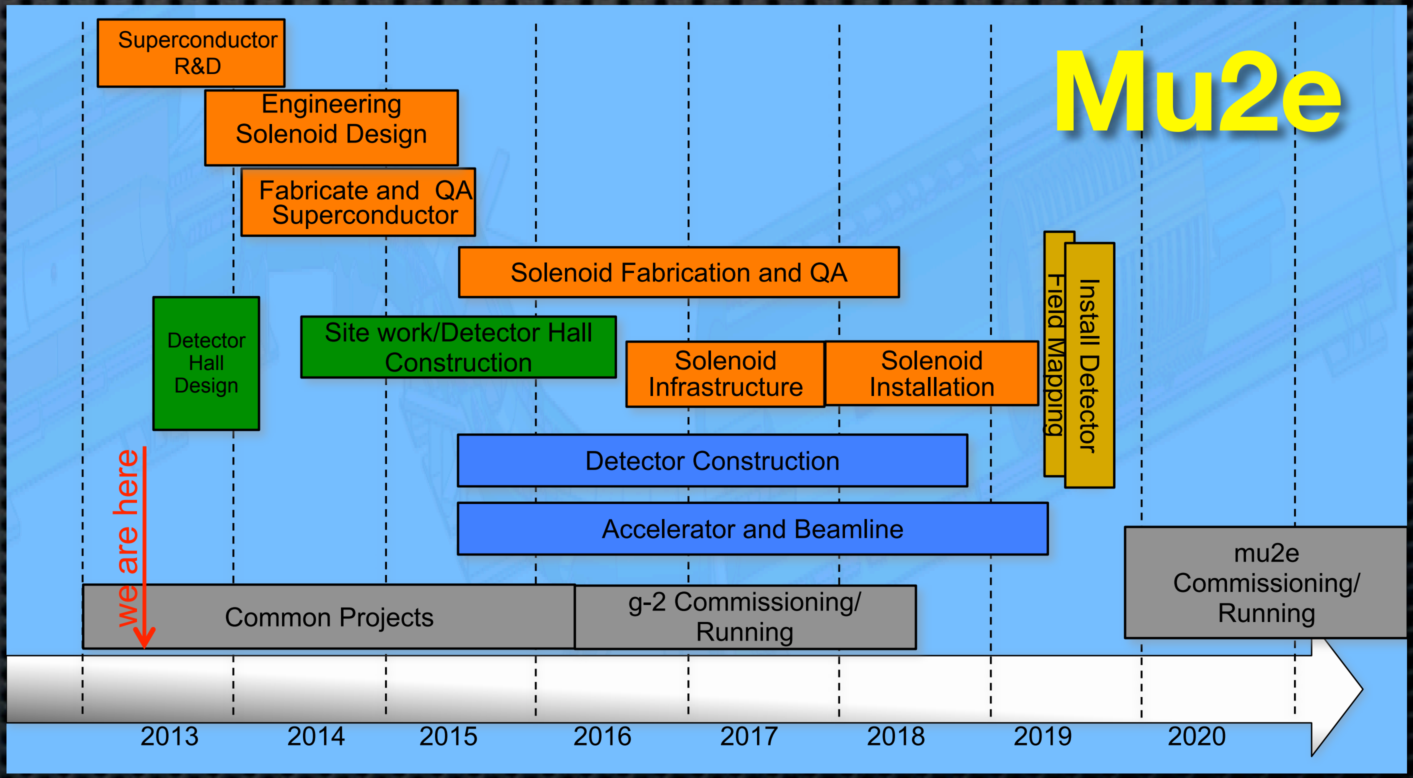
Full G4 detector simulation, background overlay, reconstruction



$R_{\mu e}$ SES = 2×10^{-17}

TimeLine

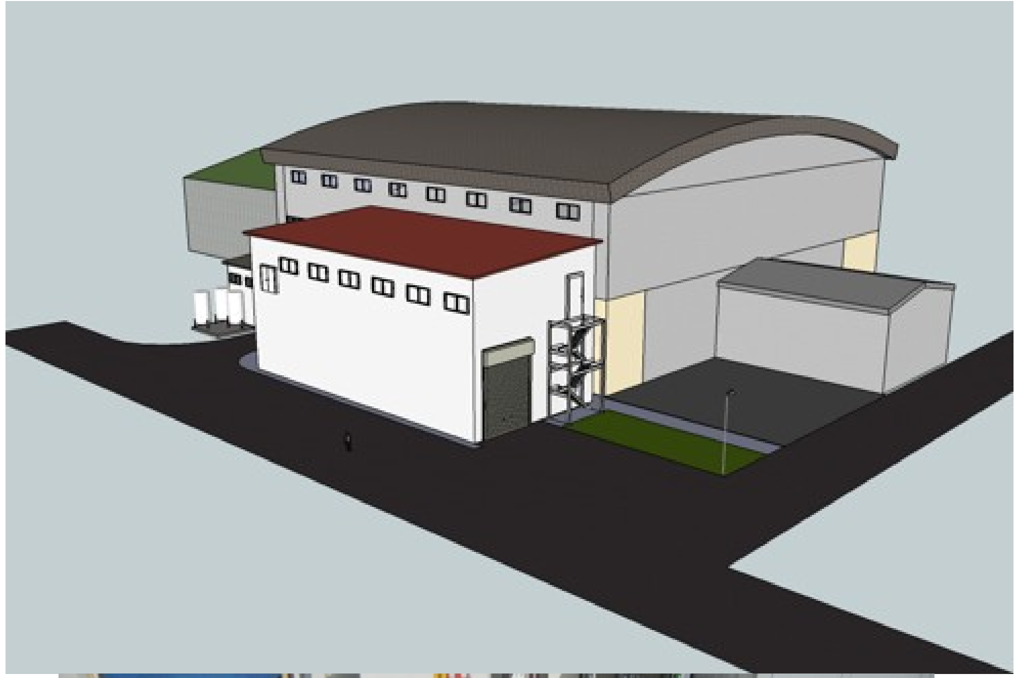




commissioning
~2020

Facility Construction

- Work already under way on the facility construction



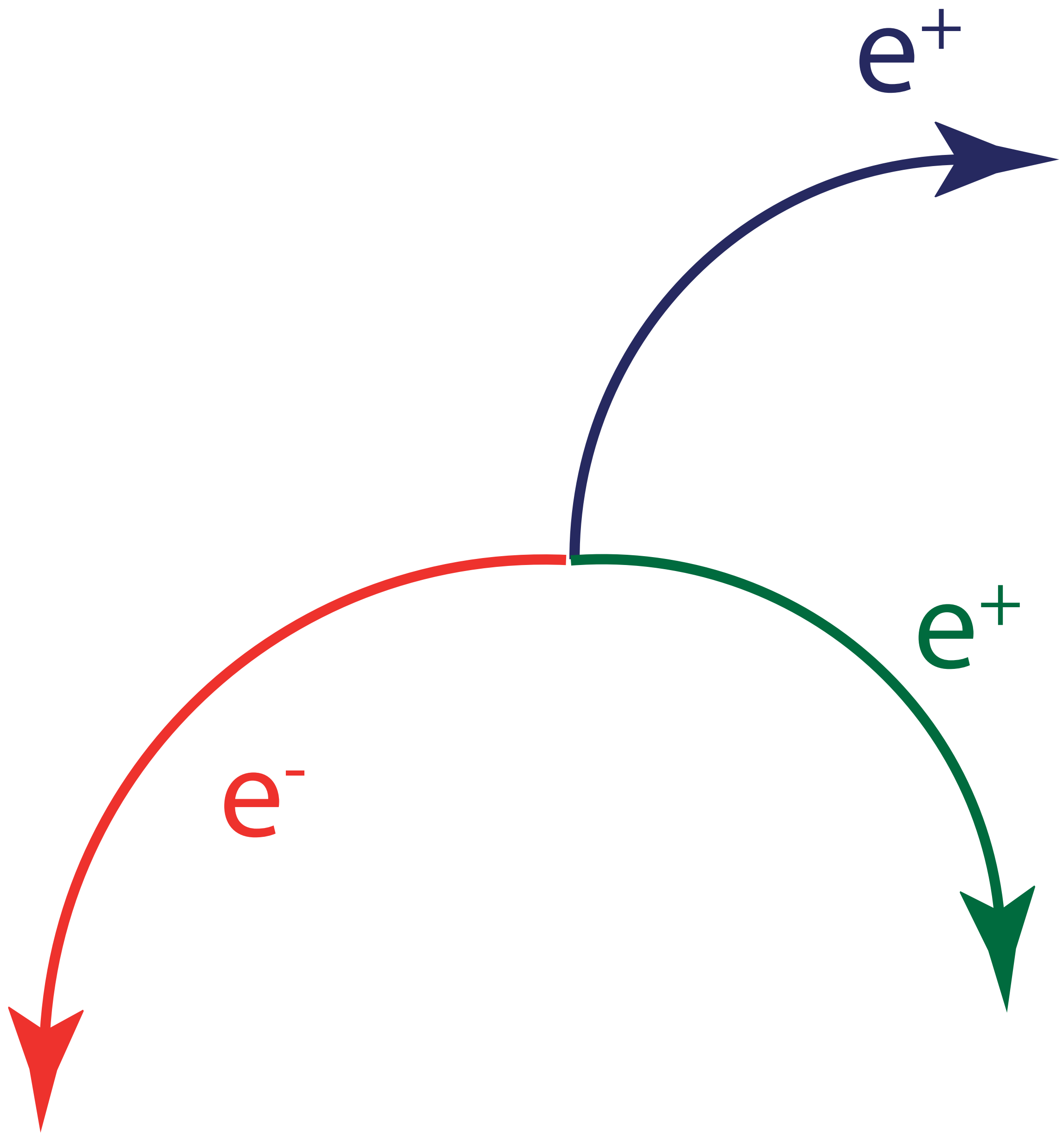
$$\mu^+ \longrightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$$

$\mu \to 3e$

- Needs a sensitivity of 10^{-16} to be competitive
- Dominated by accidental overlaps
  - DC muon beam: PSI - 10^{-15} possible?
- Biggest issue is high rate tracking

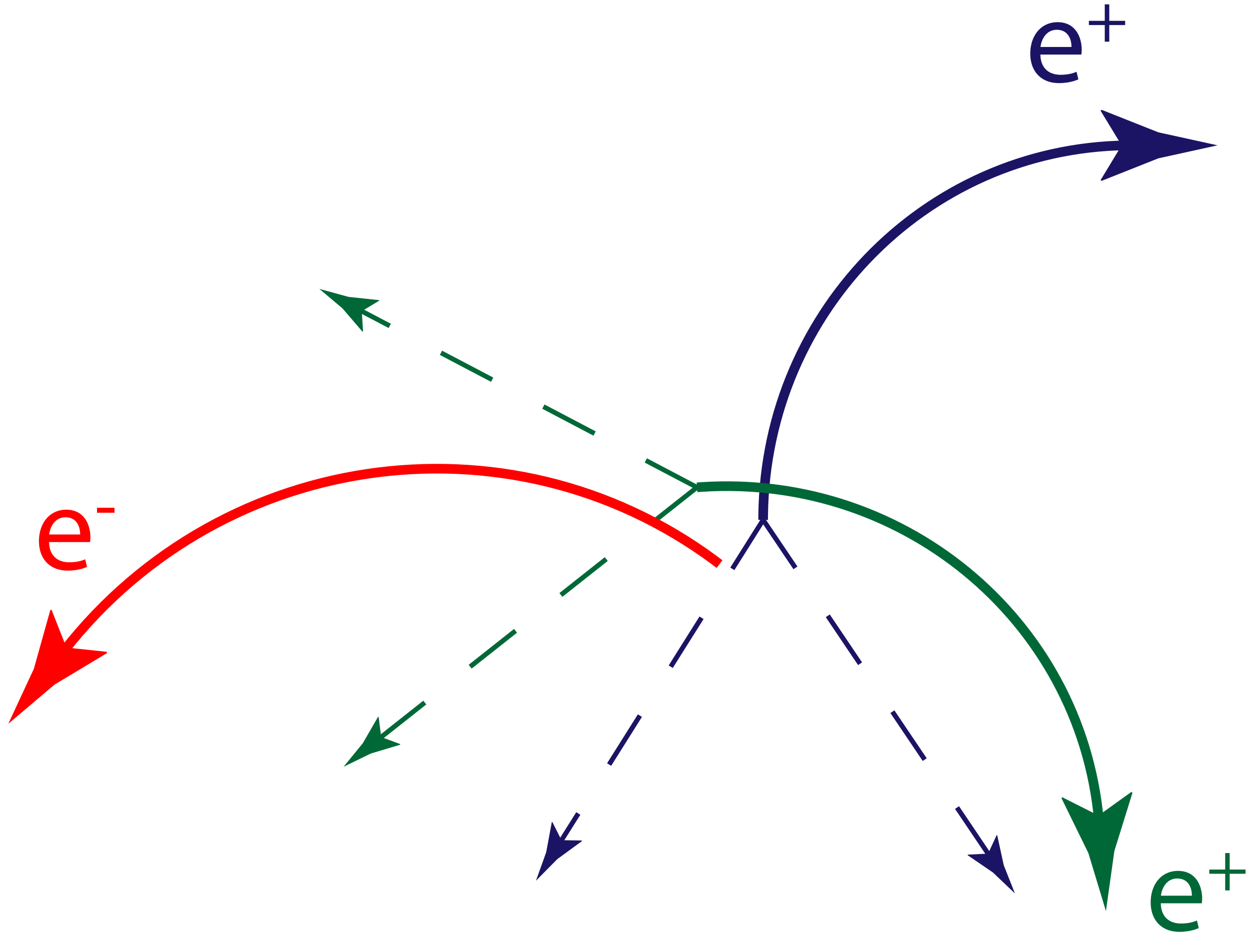
The signal

need large acceptance to fully contain 3-body kinematics



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: ½ m_μ = 53 MeV/c

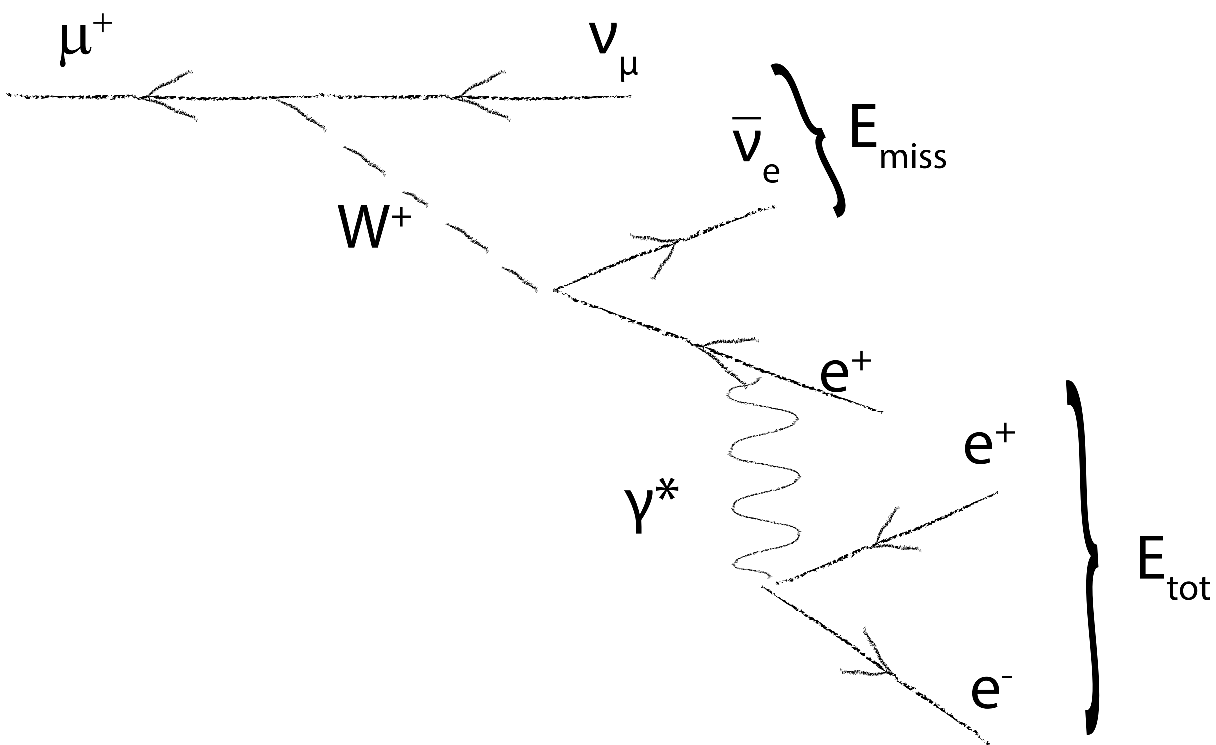
Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution

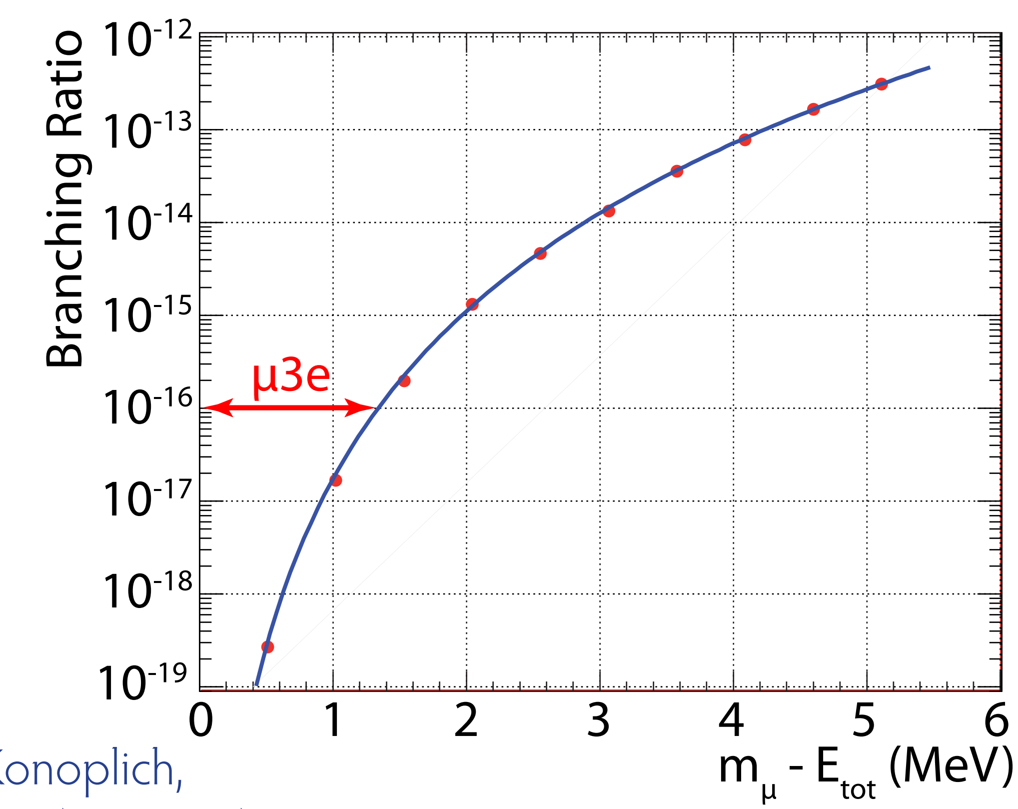
Internal conversion background



- Allowed radiative decay with internal conversion:

$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos



(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

- Need excellent momentum resolution

$$\mu^+ \to e^+e^-e^+$$

$\mu \to 3e$

- Needs a sensitivity of 10^{-16} to be competitive
- Dominated by accidental overlaps
  - DC muon beam: PSI - 10^{-15} possible?
- Biggest issue is high rate tracking
  - gain by better vertexing & momentum resolution over the previous experiment

Mu3e experiment at PSI

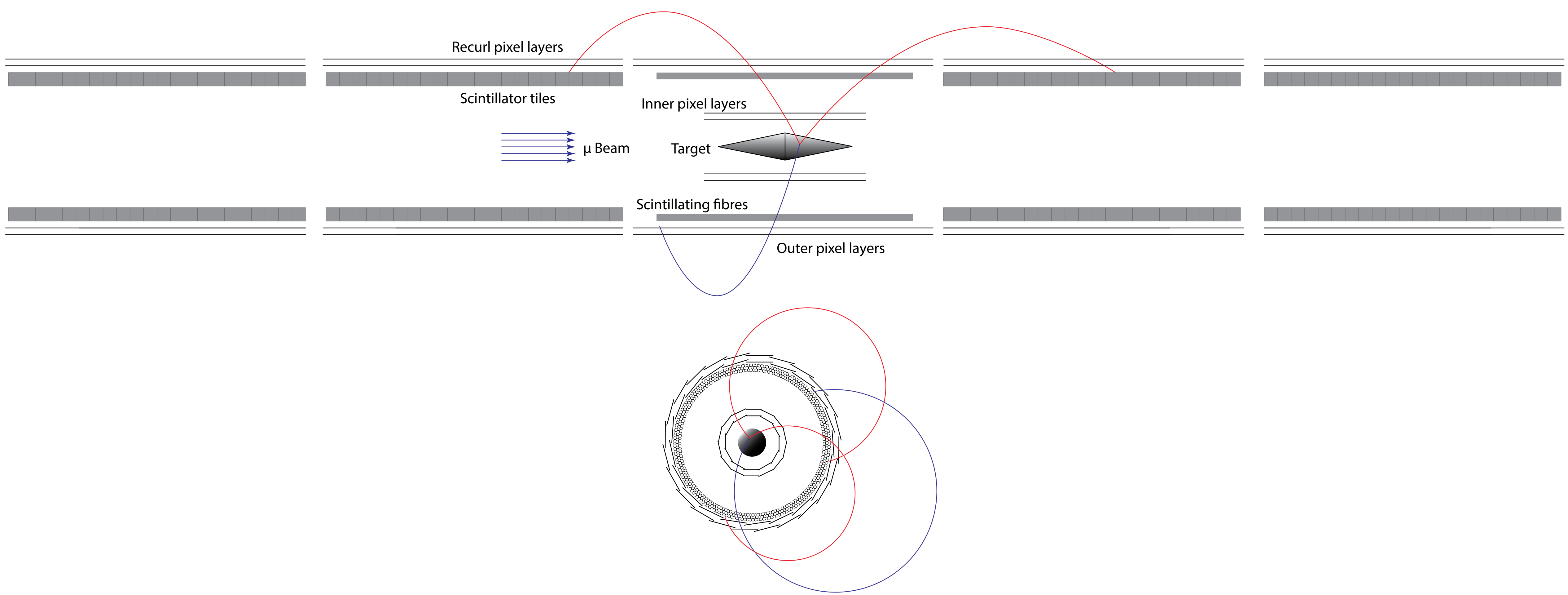
HV-MAPS high voltage monolithic active pixel sensors

50μm Si + 25μm Kapton flexprint w/ Al traces + 25μm Kapton frame

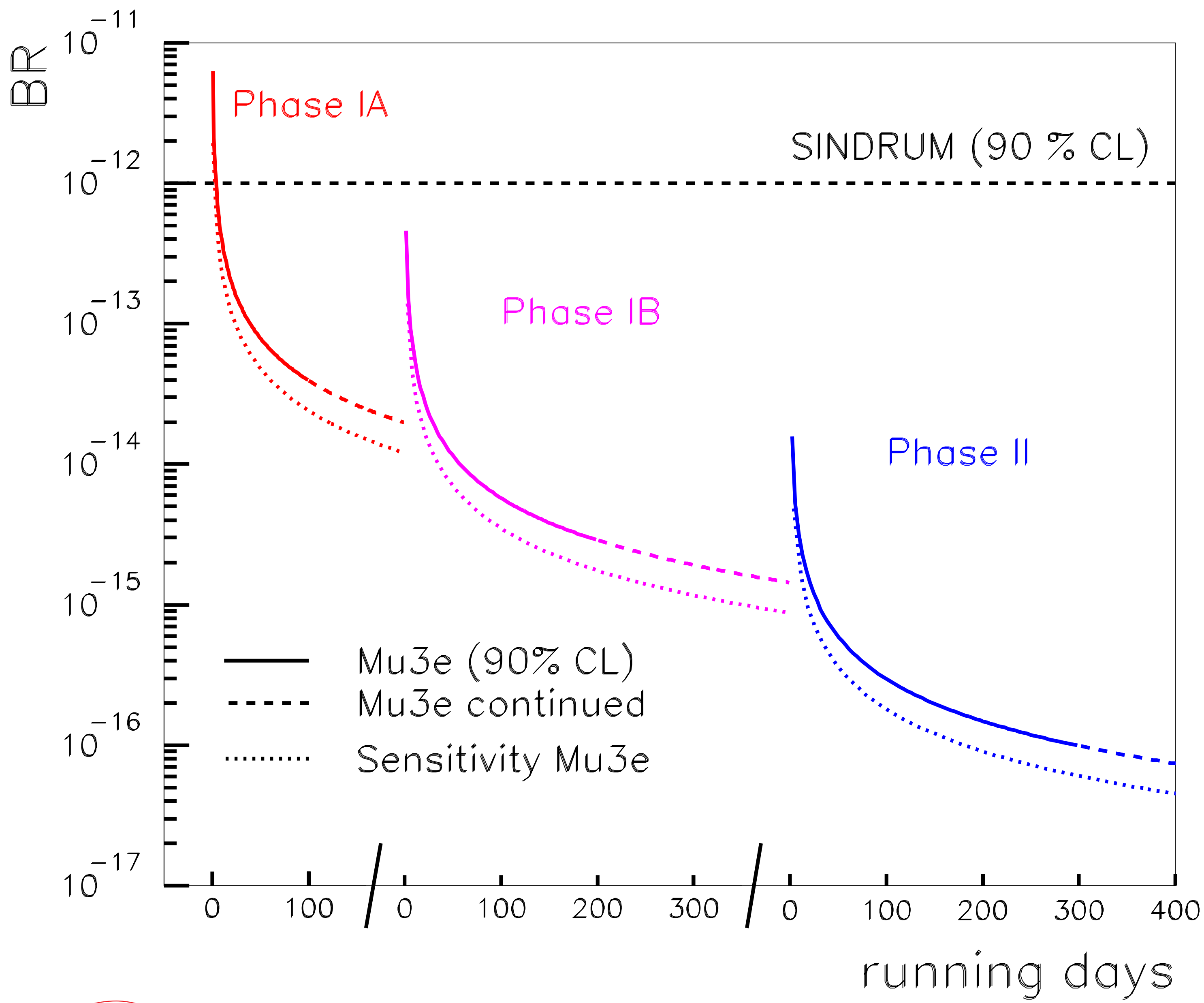
< 0.1% X_0 / layer

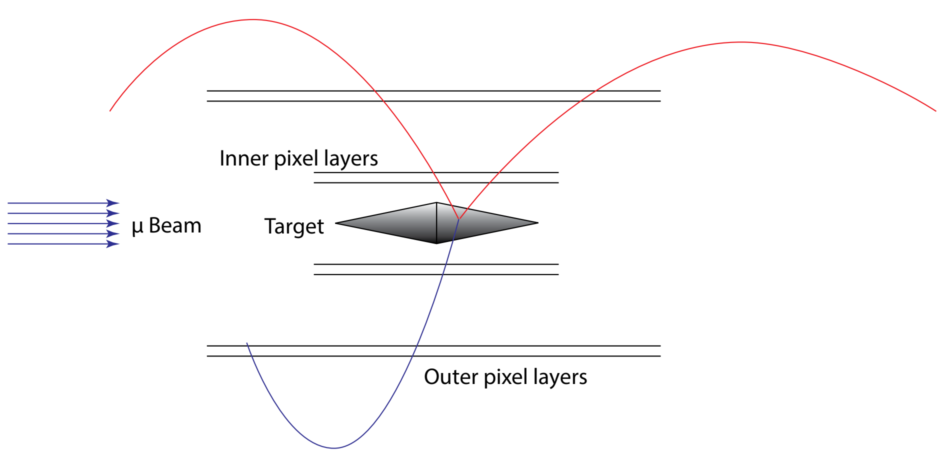
cf. 0.2% X_0 / e^+ trajectory for MEG spectrometer

Detector Design

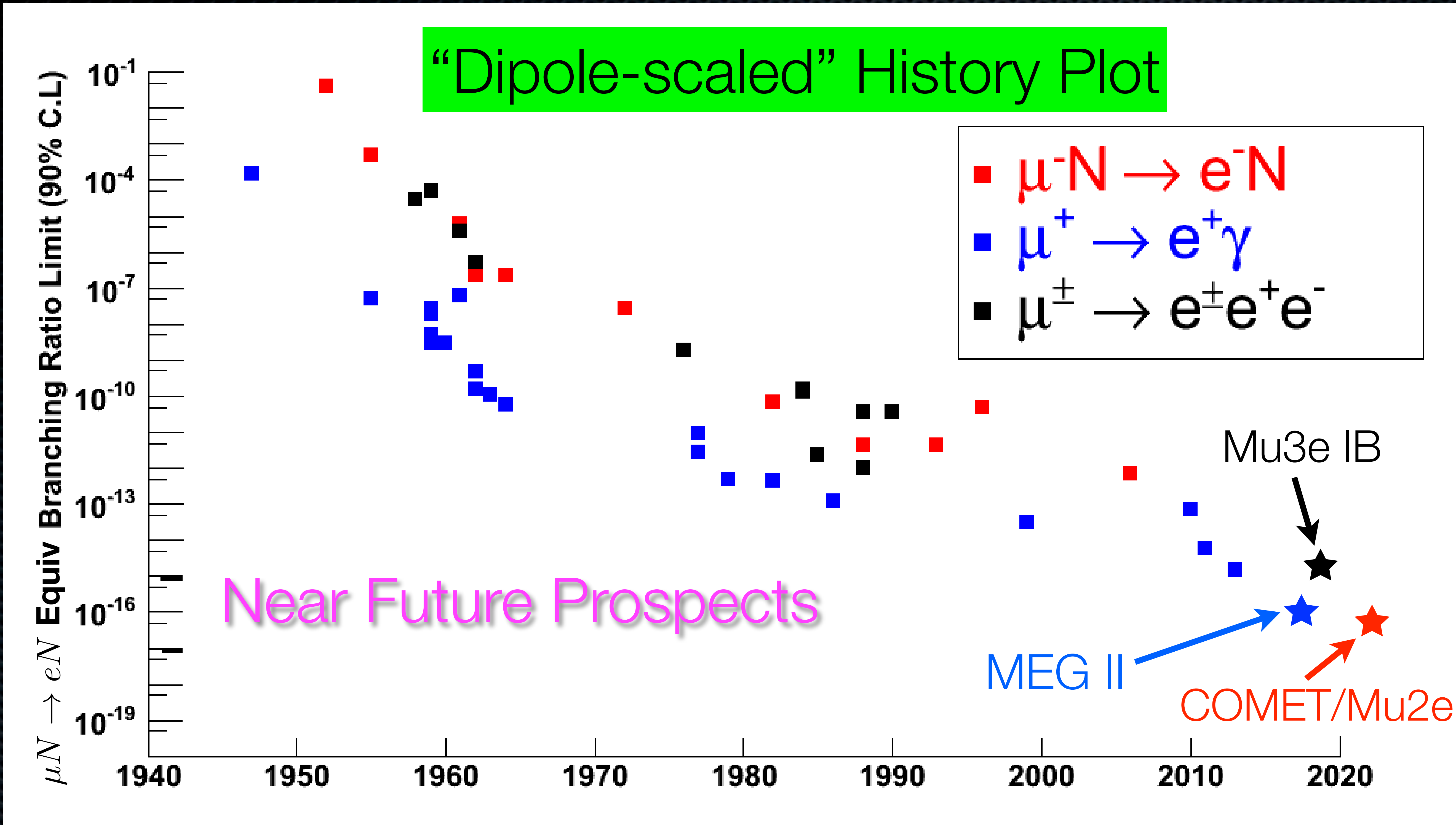


Sensitivity





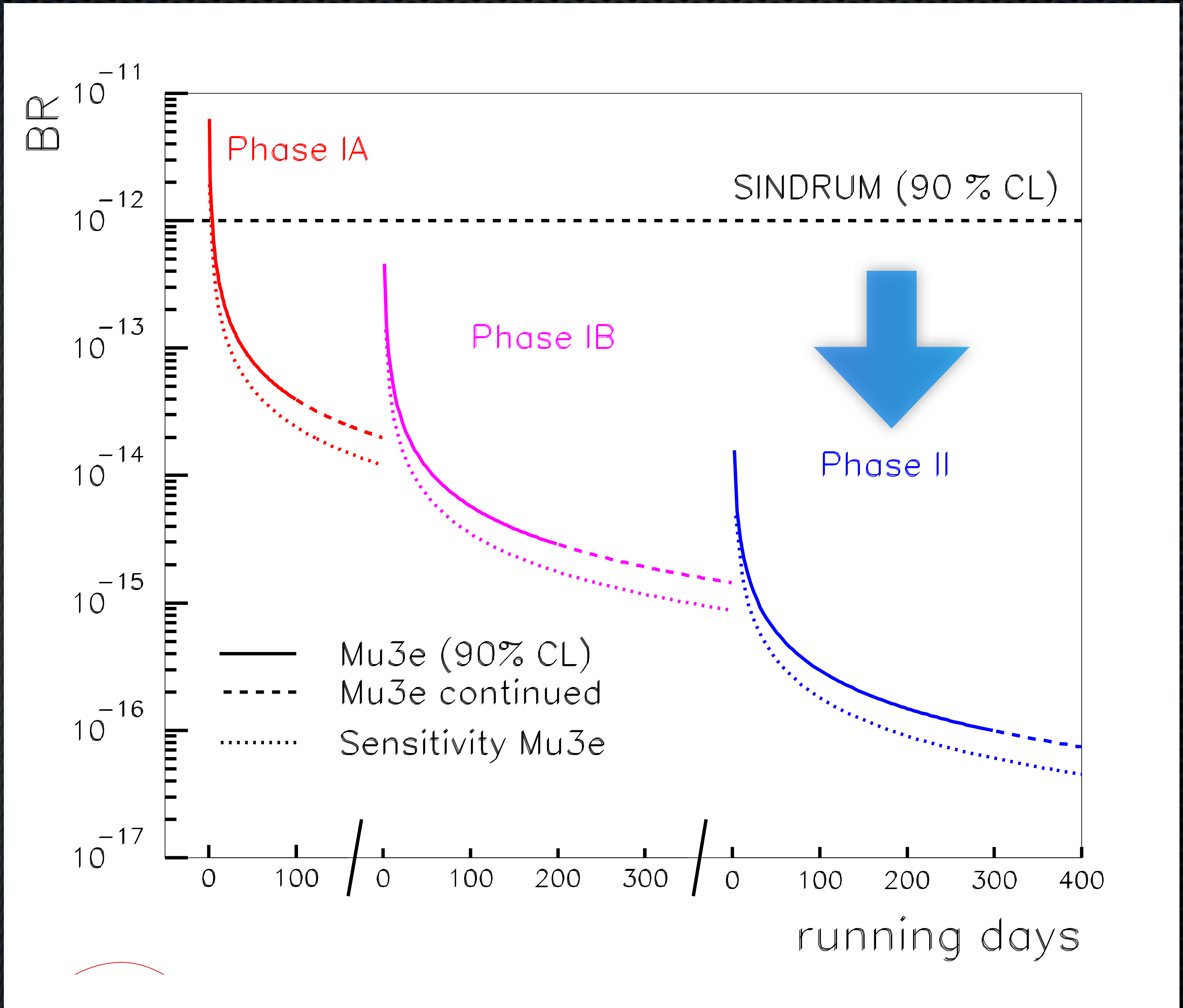
Phase IA: Starting 2015



A. Edmonds, cLFV Lecce, May 2013 (modified by TM)

The other modes are catching up with $\mu \rightarrow e\gamma$

New muon source w/ higher intensity is necessary for further developments

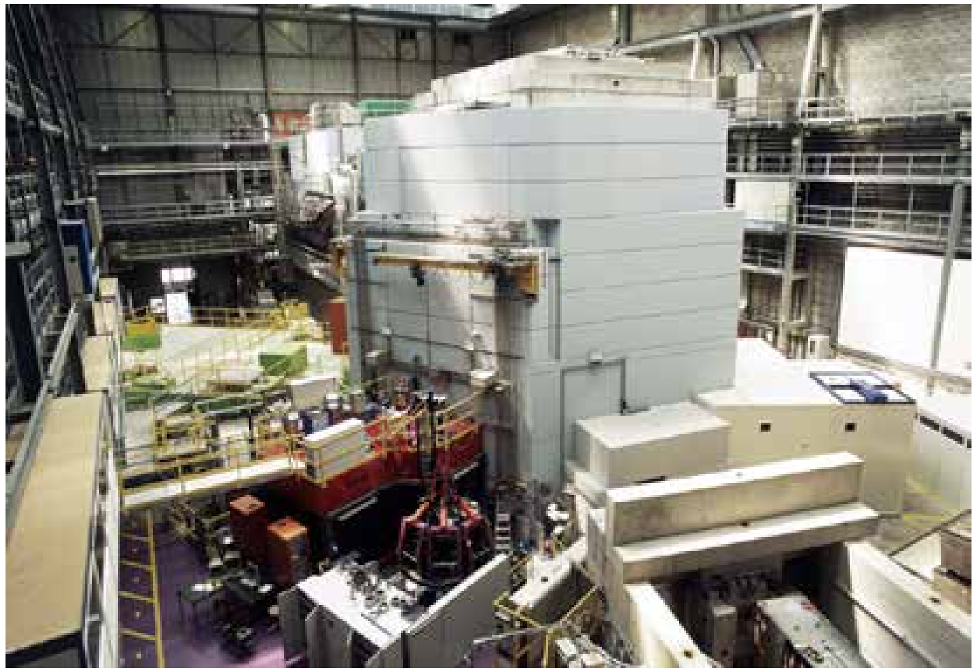


$\mu \to e\gamma$

$\mu N \to eN$

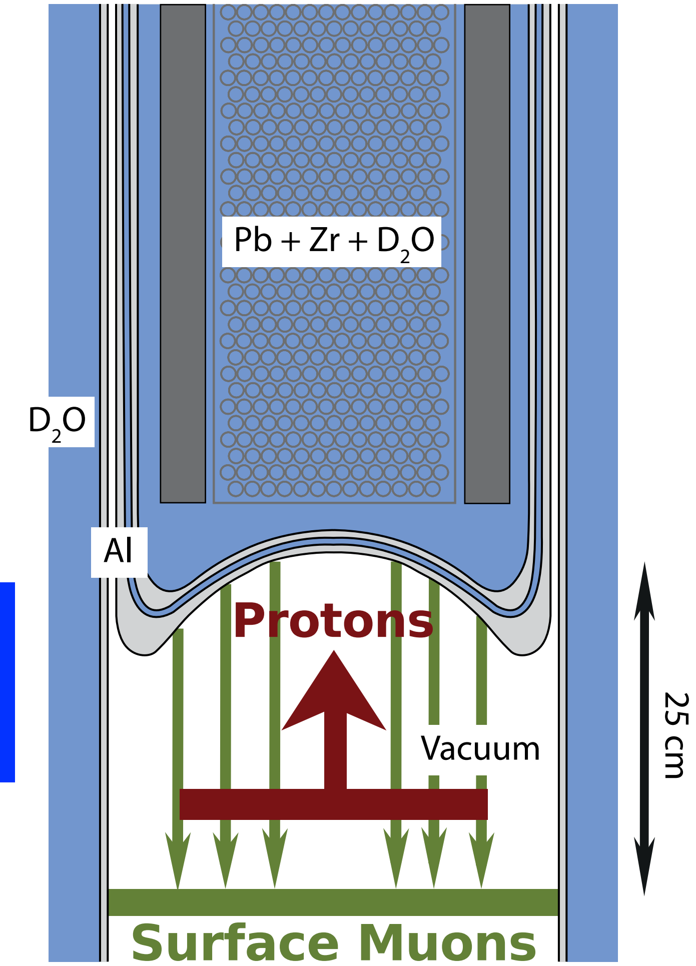
also benefit

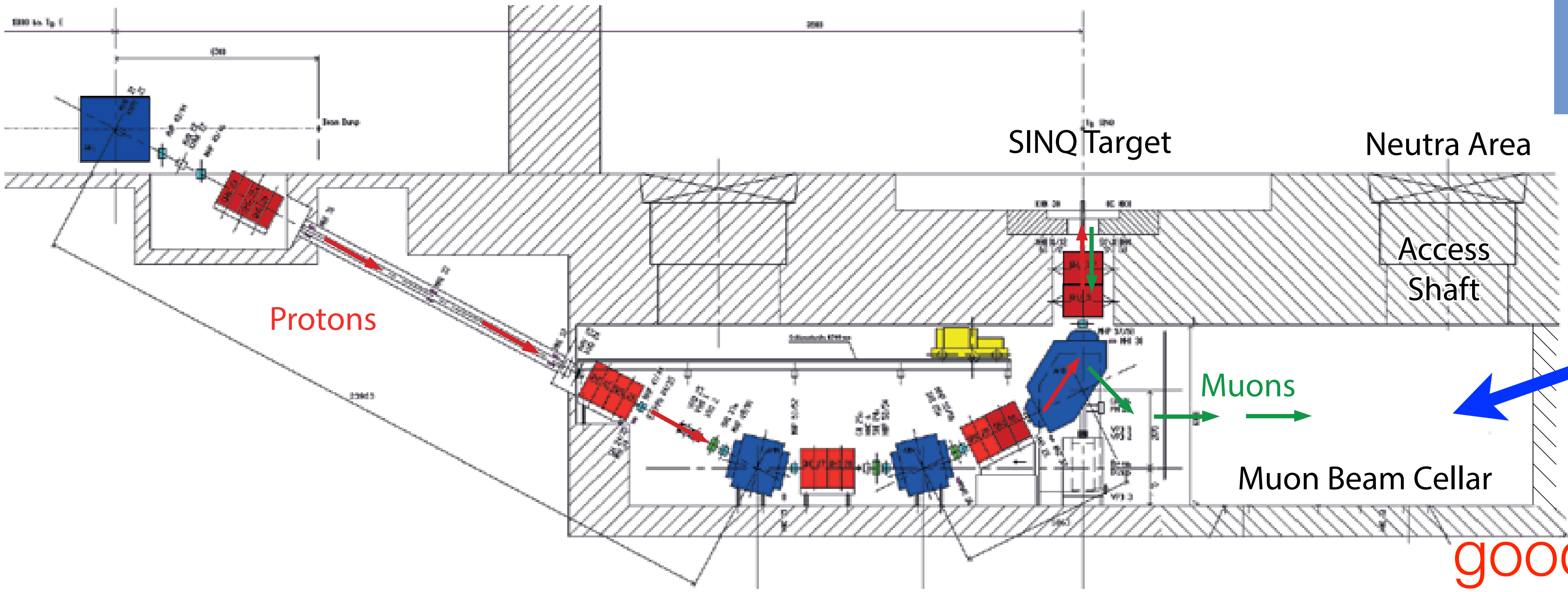
High Intensity Muon Beamline at PSI



- Muon rates in excess of 10^{10}/s in acceptance
- $2 \cdot 10^{9}$/s needed for $\mu \to eee$ at 10^{-16}
- Not before 2017

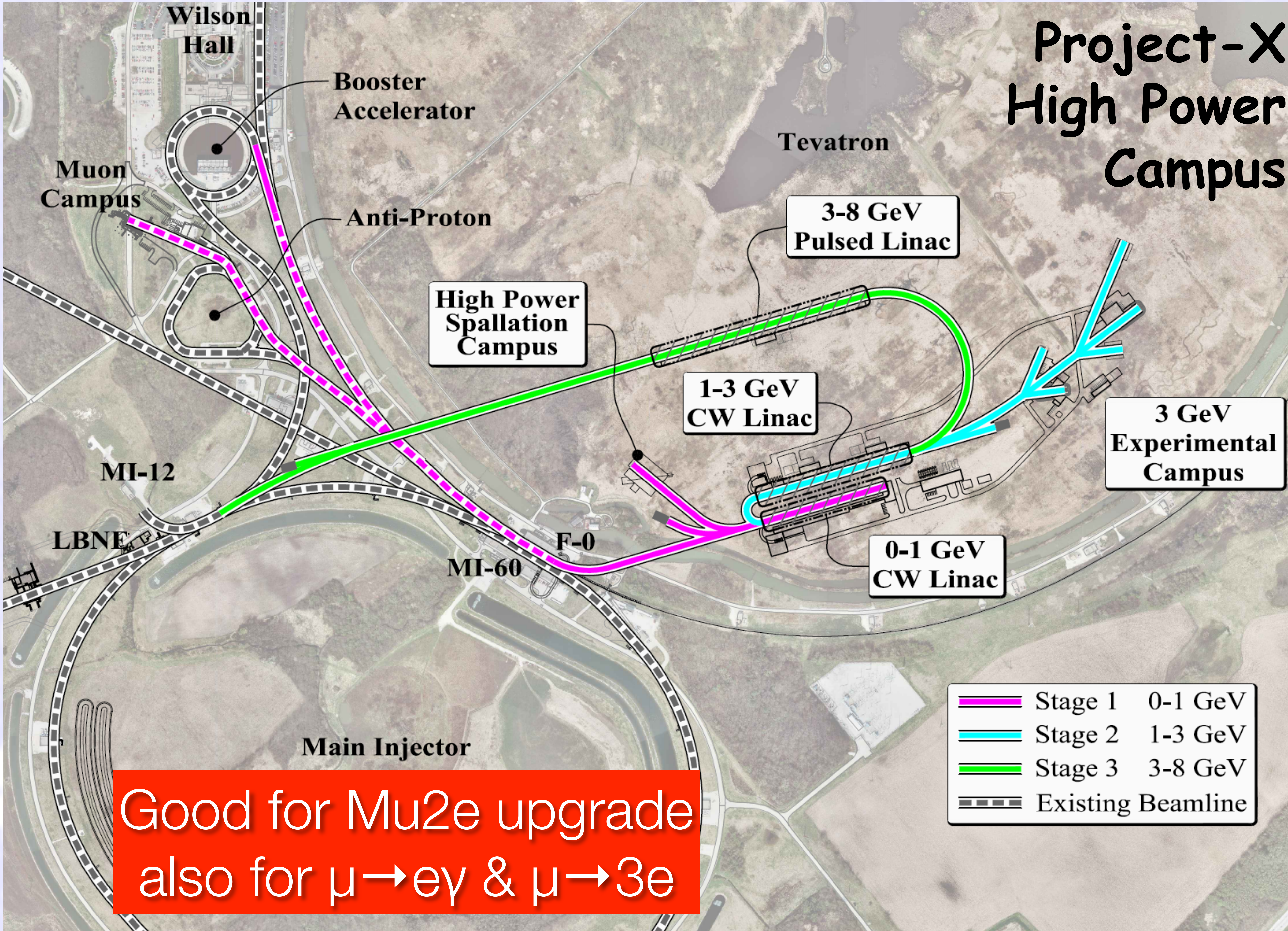
SINQ target
(spallation neutron source)





experimental area

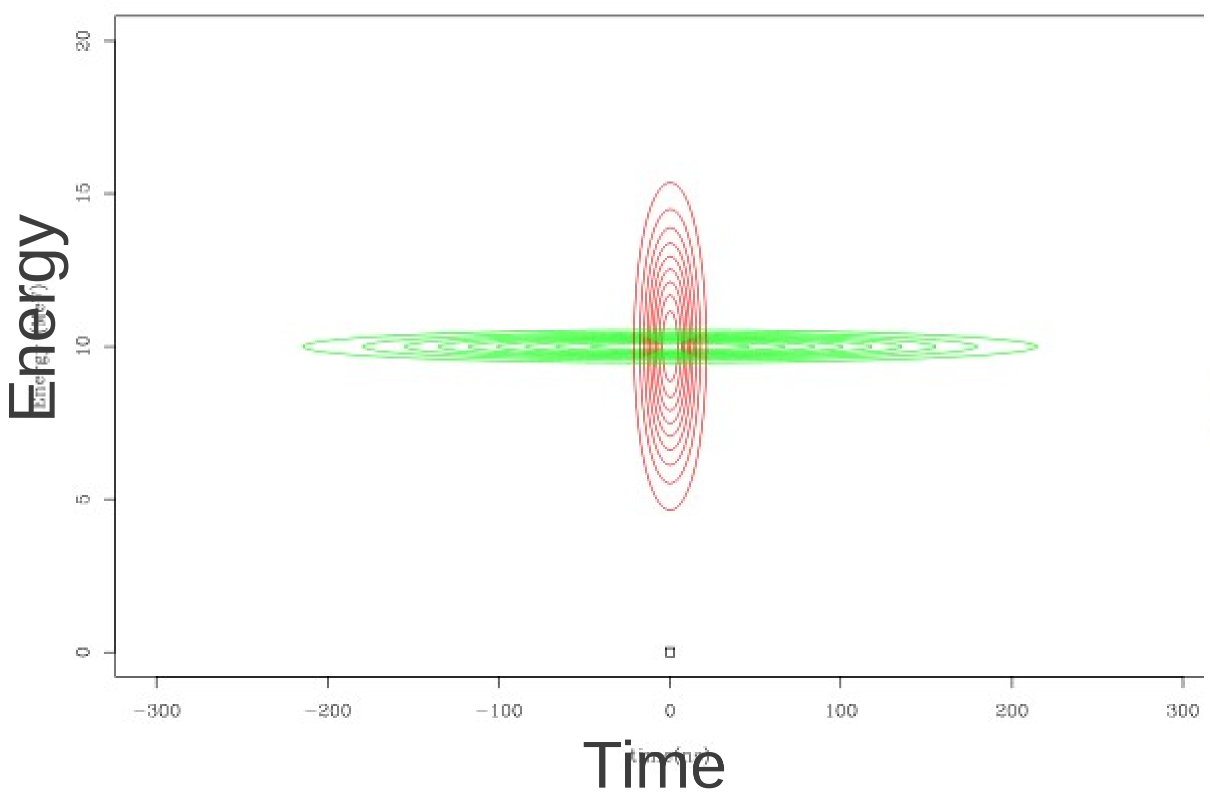
good also for $\mu \to e\gamma$


Project-X
High Power
Campus
Wilson Hall
Booster Accelerator
Tevatron
Muon Campus
Anti-Proton
3-8 GeV Pulsed Linac
High Power Spallation Campus
1-3 GeV CW Linac
3 GeV Experimental Campus
MI-12
LBNE
F-0
MI-60
0-1 GeV CW Linac
Main Injector
Stage 1 0-1 GeV
Stage 2 1-3 GeV
Stage 3 3-8 GeV
Existing Beamline
Good for Mu2e upgrade
also for μ→eγ & μ→3e

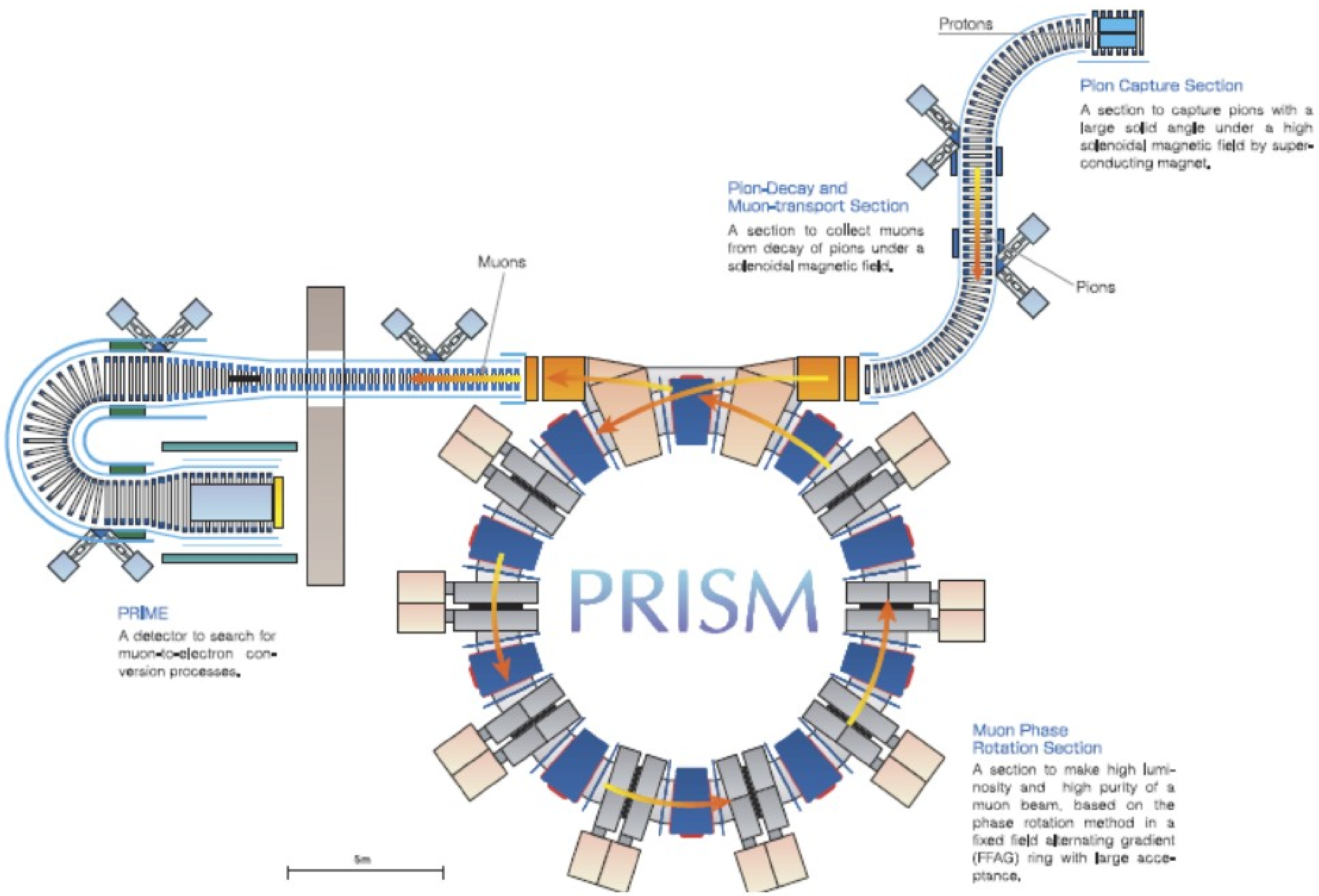
PRISM/PRIME

mu-e conversion

- To get down to 10^{-18} and beyond PRISM/PRIME propose to use an FFAG ring
- This gives the muon beam a small momentum width which allows the use of one target disk

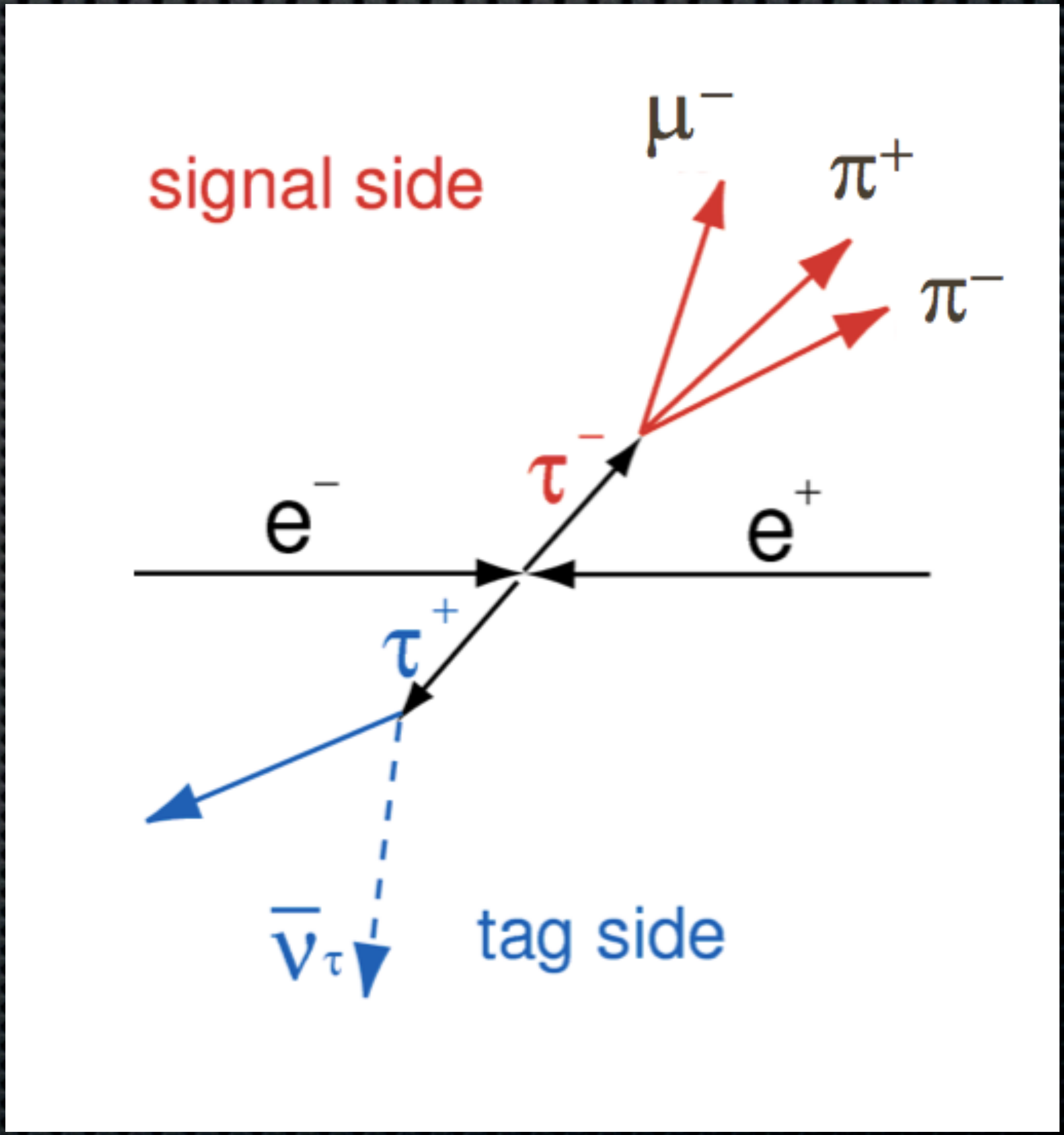


Before phase rotation (red)
After phase rotation (green)



cLFV in τ decays

- e^+e^- B factories
- τ always pair-produced
  - tag one τ, and
  - look for LFV in the other side

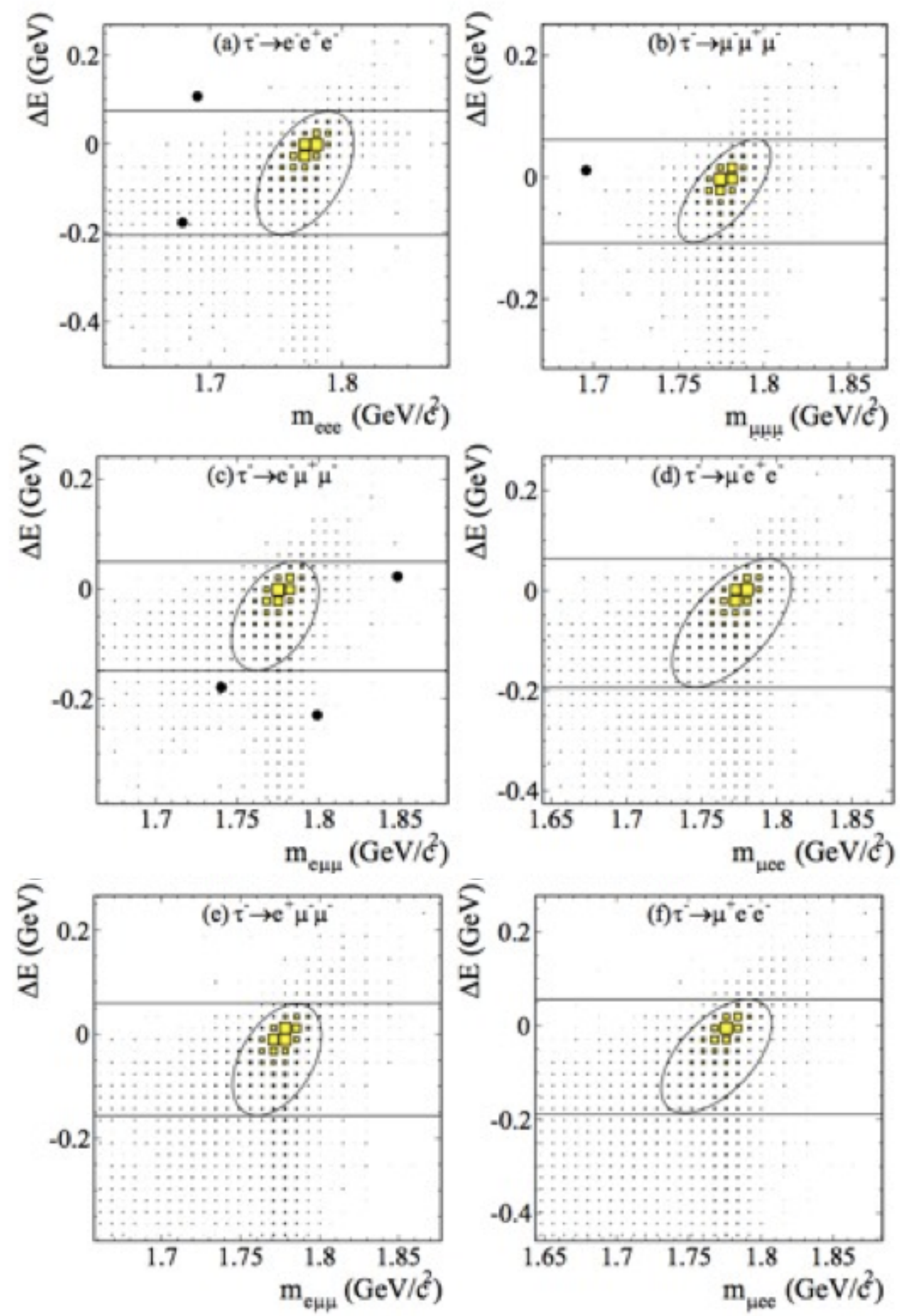


$\tau^+ \rightarrow l^+l^-l^+$

Phys. Lett. B687, 139 (2010)

- Based on 782/fb of Belle data
- Virtually background free due to good lepton ID
- Zero events observed in all 6 modes

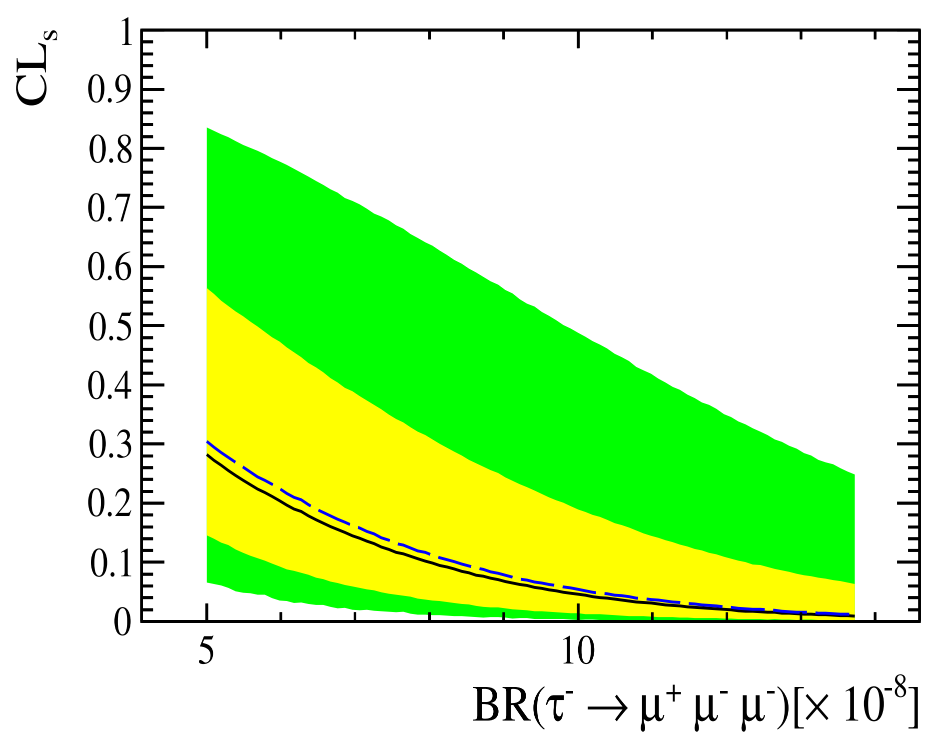
90% C.L. upper limits between 1.5×10^{-8} and 2.7×10^{-8}



Mode	ϵ (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^-e^+e^-$	6.0	0.21±0.15	9.8	0	<2.7
$\tau^- \to \mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	0	<2.1
$\tau^- \to e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	0	<2.7
$\tau^- \to \mu^-e^+e^-$	9.3	0.04±0.04	7.8	0	<1.8
$\tau^- \to e^+\mu^-\mu^-$	10.1	0.02±0.02	7.6	0	<1.7
$\tau^- \to \mu^+e^-e^-$	11.5	0.01±0.01	7.7	0	<1.5

Results

- Expected & observed limit as a function of branching fraction
  - yellow 68% region, green 95% region
- Limits are quoted for the phase-space model of τ decay
  - Variation of efficiencies in Dimuon mass range is small ($< 20\%$)
- Upper limits:



LHCb is now joining forces!

fully charged modes only

8.0×10^{-8} published

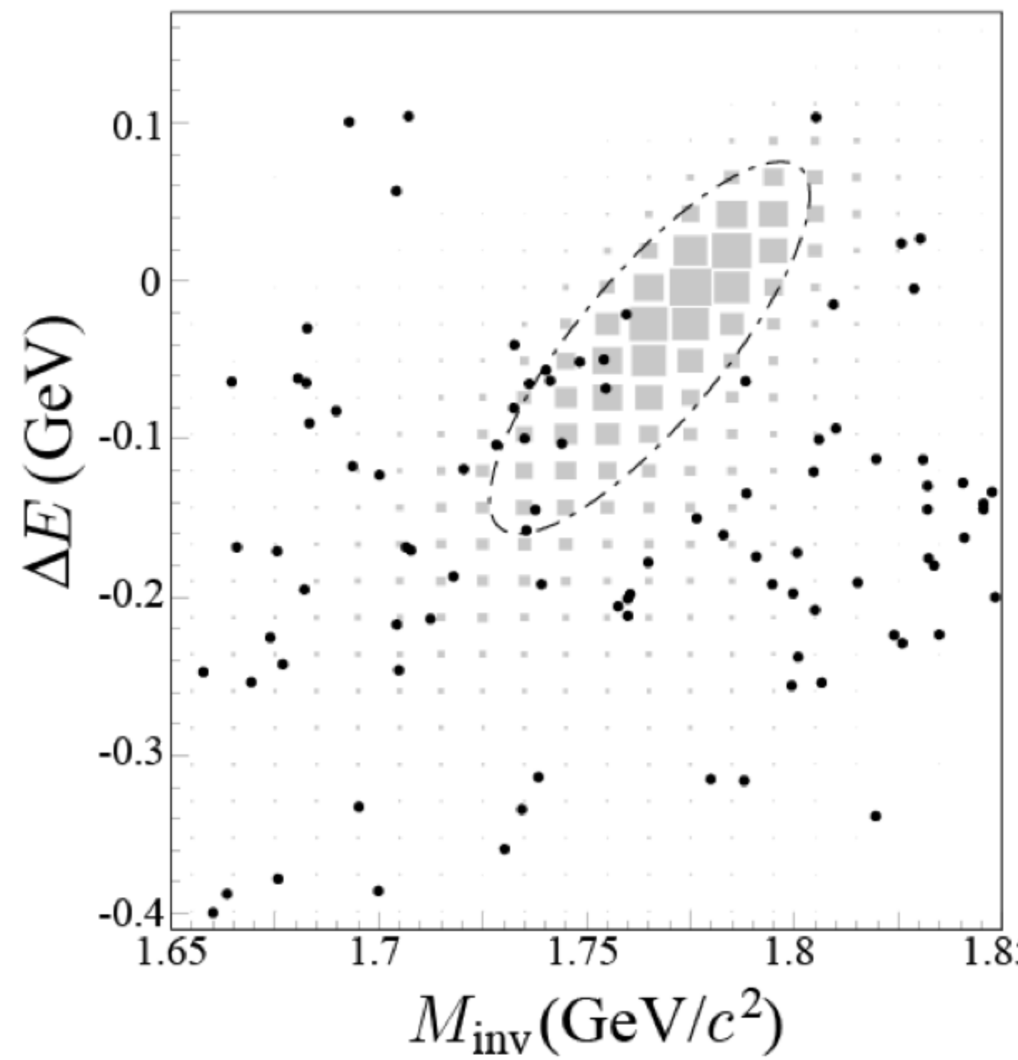
$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 8.3(10.2) \times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$

little worse than Belle, first upper limit for $\tau^- \to \mu^+\mu^-\mu^-$ in proton collider

Old result for $\tau \rightarrow \mu\gamma$

Phys. Lett. B666, 16 (2008)

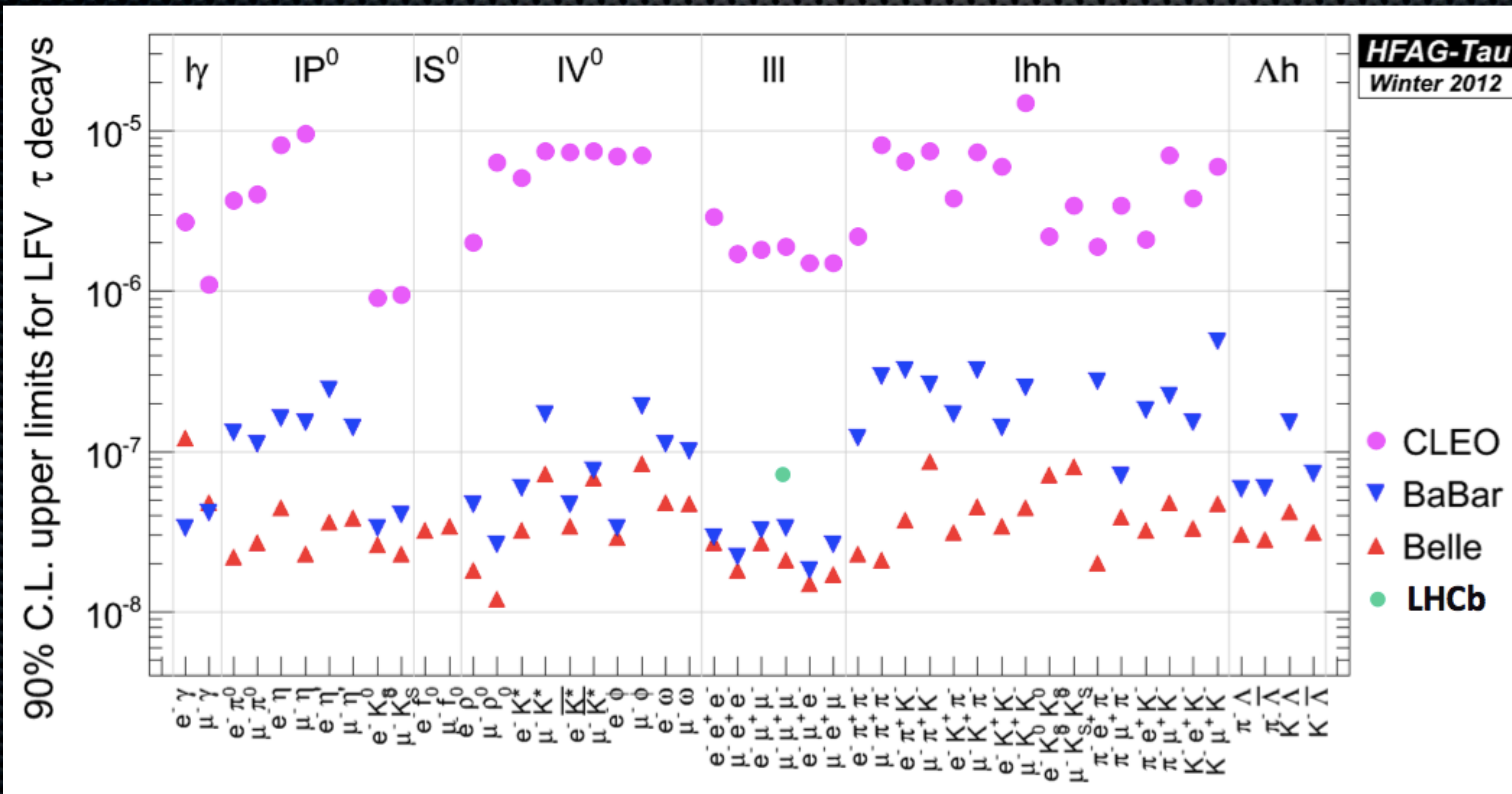
- Based on 545/fb data
- Main backgrounds: $\tau \rightarrow \mu\nu\nu$ and dimuon events with ISR
- 94 events found in the 5σ signal region, while expecting (88 +/- 7)
- 90% C.L. upper limits
  - Expected: 7.8×10^{-8}
  - Observed: 4.5×10^{-8}

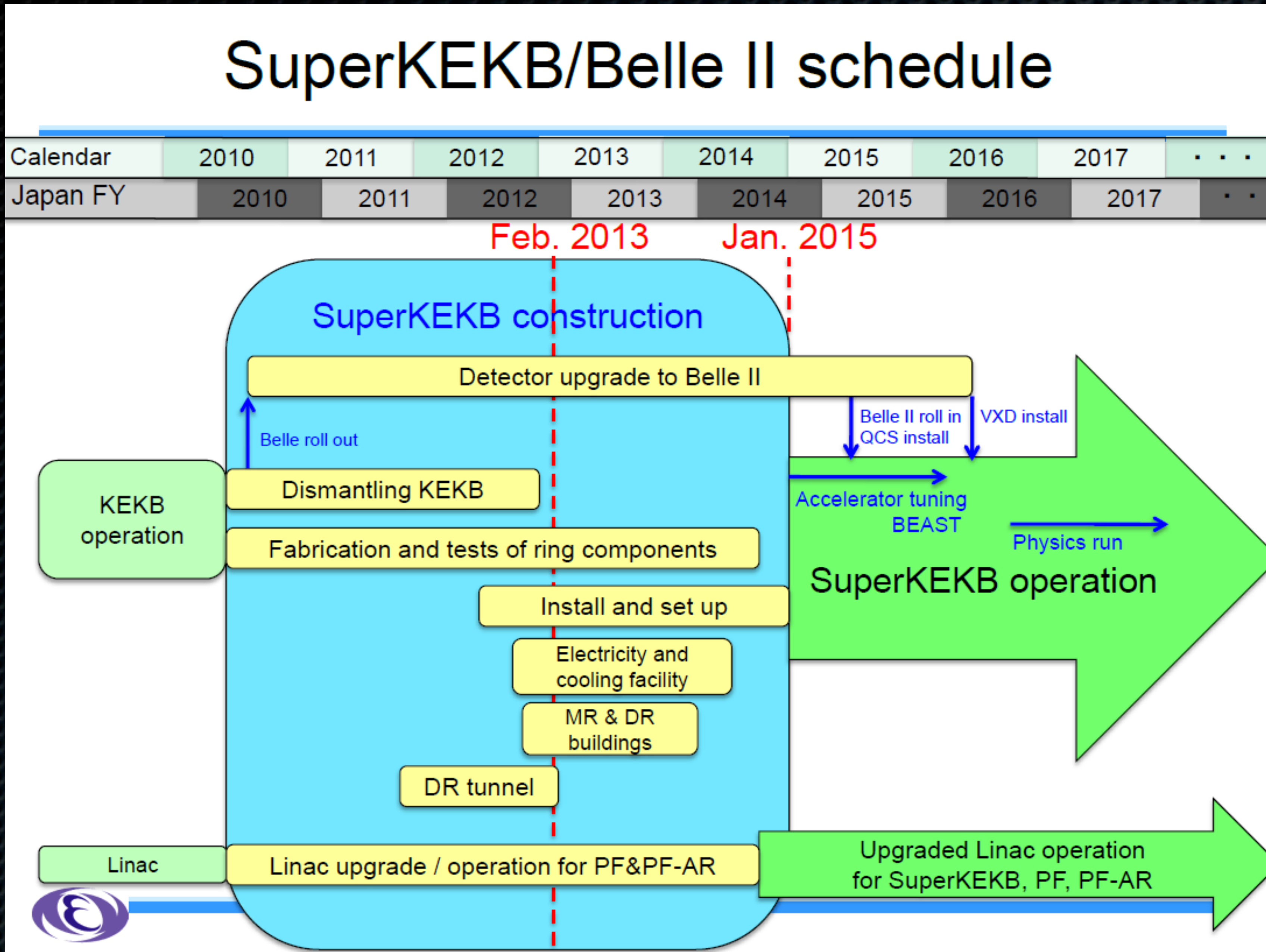


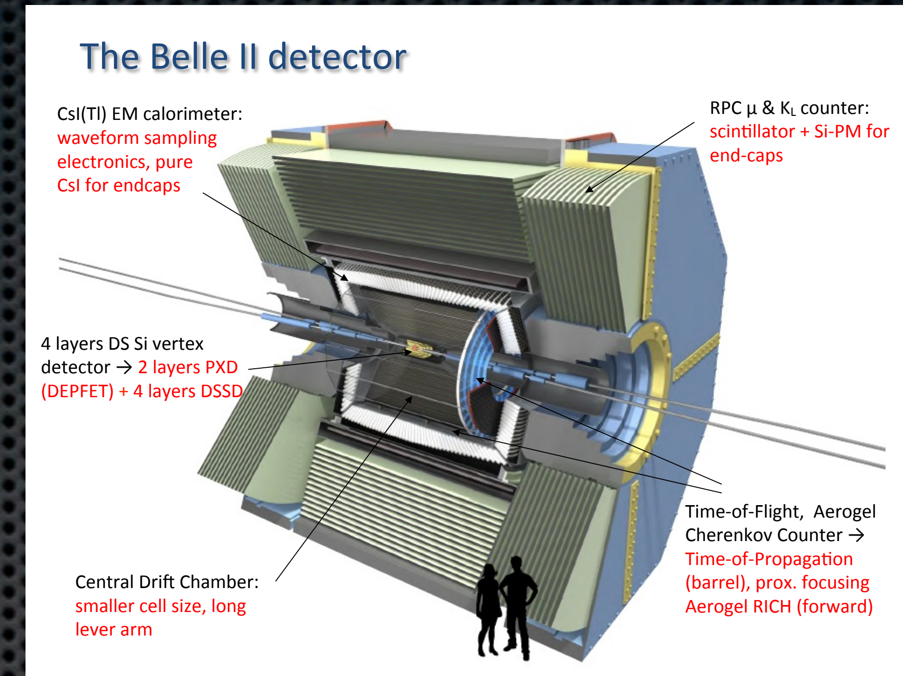
Now updating to the full Belle dataset (980/fb)…

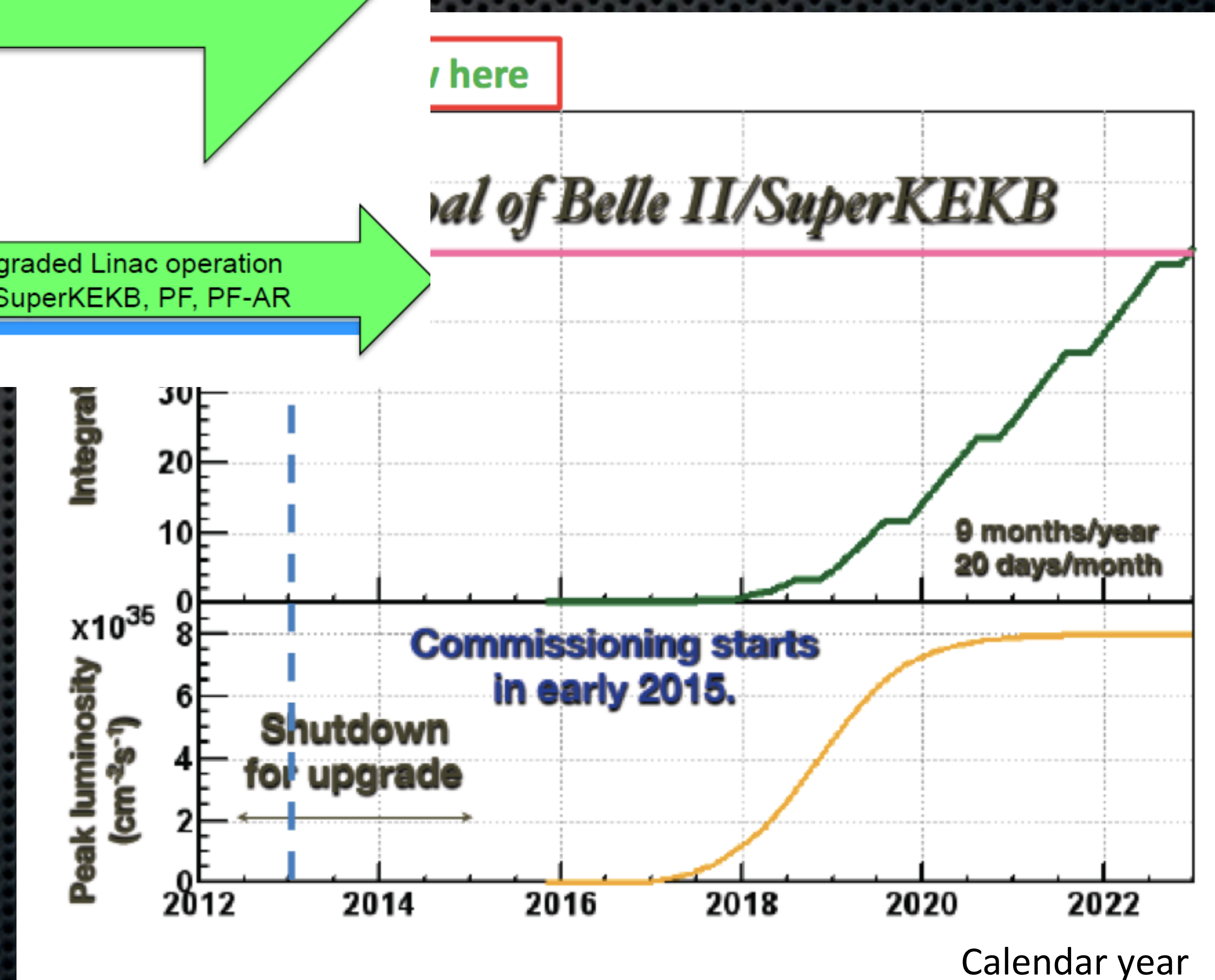
better sensitivity at τ/c factory?

cLFV searches in τ decays





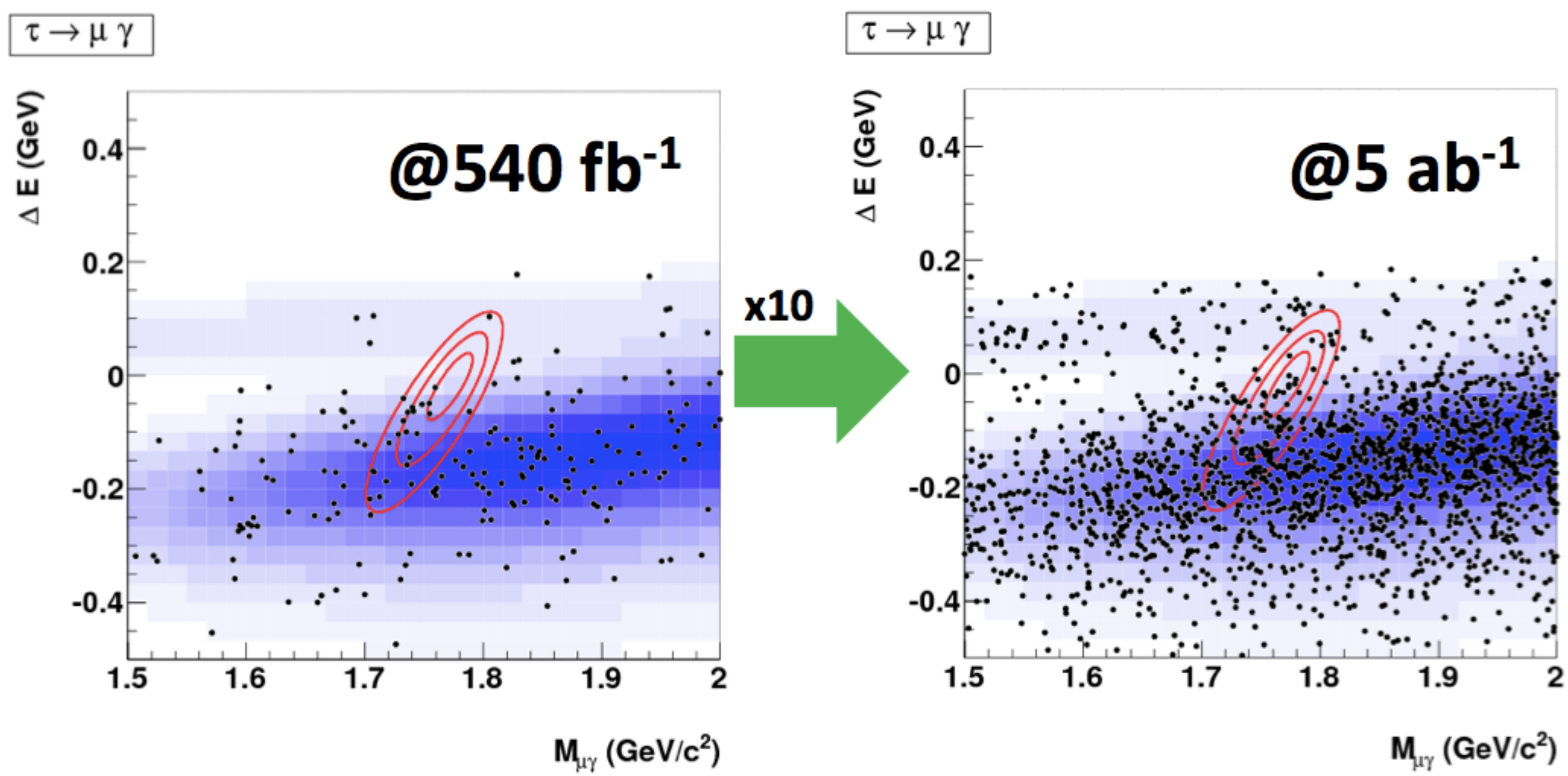




FUTURE

50/ab by end of 2022

$\tau \to \mu\gamma$ background at Belle II



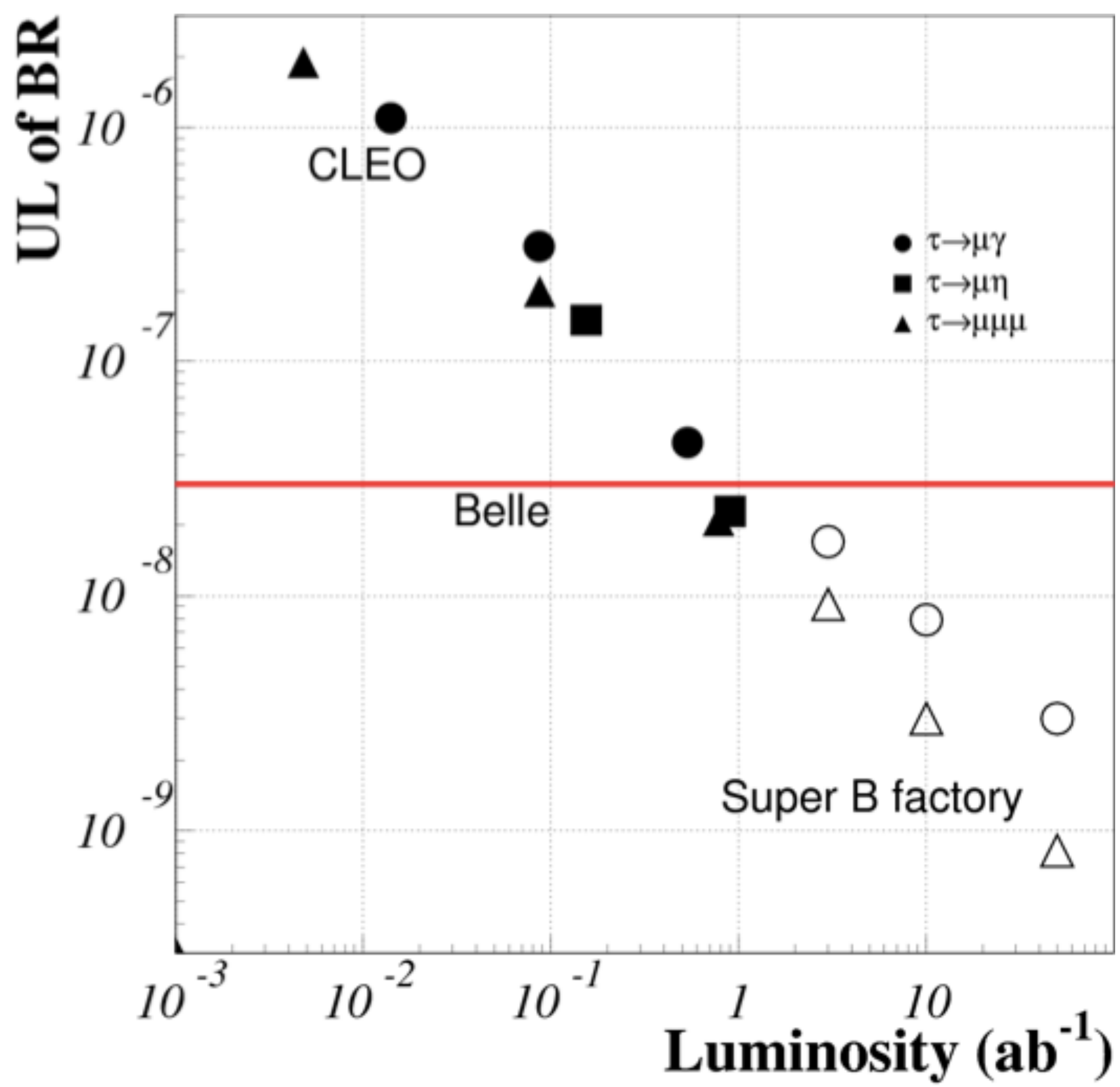
180 BG events in total

1800 BG events in total

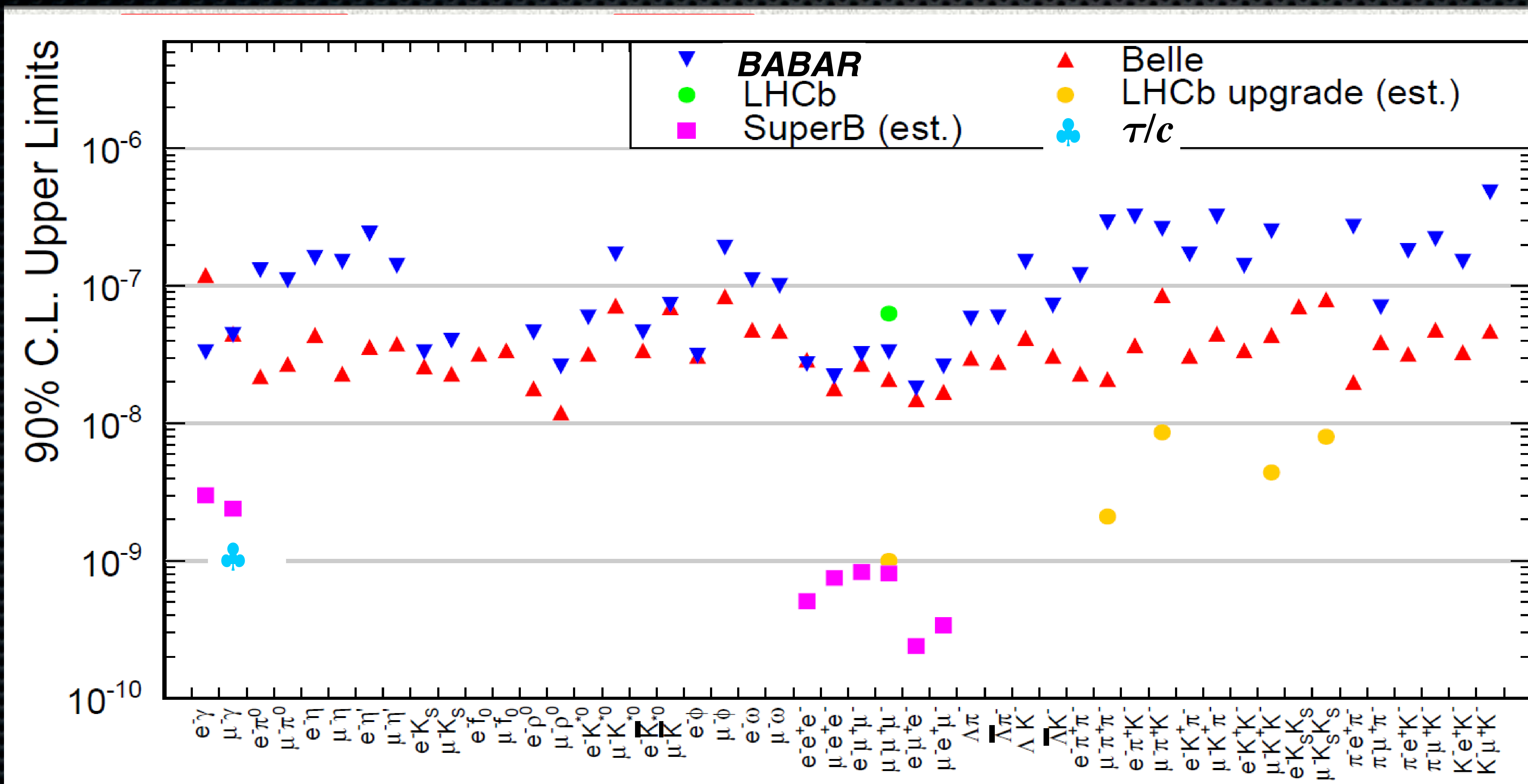
But people and analysis methods are evolving...

Prospects for τ LFV at Belle II

- Belle II will collect $\sim 10^{11}$ τ-leptons (50/ab)
- Sensitivity depends on the background level
  - $\tau \rightarrow 3l$ still clean even at Belle II
  - For $\tau \rightarrow \mu\gamma$ better understanding of backgrounds, signal resolution and intelligent selections are needed



τ - future prospects



D. Hitlin, cLFV Lecce, May 2013

Conclusion

- Researches on Charged Lepton Flavor Violation
  - Pioneered by MEG and e^+e^- B factories
  - Complementarity and synergy with LHC
  - High expectations for discoveries (or constraints)
  - Preparations for next generation experiments going on
  - Bright future prospects even beyond