DPF 2024 PHENO

Latest topics in particle physics and related issues in astrophysics and cosmology

APS | DIVISION OF PARTICLES & FIELDS

Exploring the Frontiers: Experimental Endeavors in CLFV

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Outline

- What is Charged Lepton Flavor Violation (CLFV) and why it is interesting?
- How does it fit into the search for Physics Beyond the Standard Model (BSM)?
- What are the experiments that have been done, are being done now, and will being done in the future?

What is CLFV?

- A transition among μ, e, τ that doesn't conserve lepton family number
  - **Muon decay**: $\mu \rightarrow e \, \nu \, \nu$ has two neutrinos
  - CLFV is predicted in (for example) $\mu \rightarrow e \, \gamma$ or $\mu \rightarrow 3e$ with **NO neutrinos**
  - Similar τ decays: $\tau \rightarrow$ μ, e + X (and no neutrinos)
  - In neutral K system, $K \rightarrow \mu$, e, and charged B, K to dileptons
  - $H \rightarrow \mu$, e, τ + X

Family number: not a fundamental Symmetry

- Family number is not a symmetry of Lagrangian like the charge

  ✓ Quark family number is violated in weak decays in the CKM matrix

  ✓ We know it's violated in neutral leptons: neutrino oscillations (PMNS matrix)

- **But we've never seen it in charged leptons.**

- Most "natural" new physics models predict we should have seen it already, even if small.

  Why haven't we?

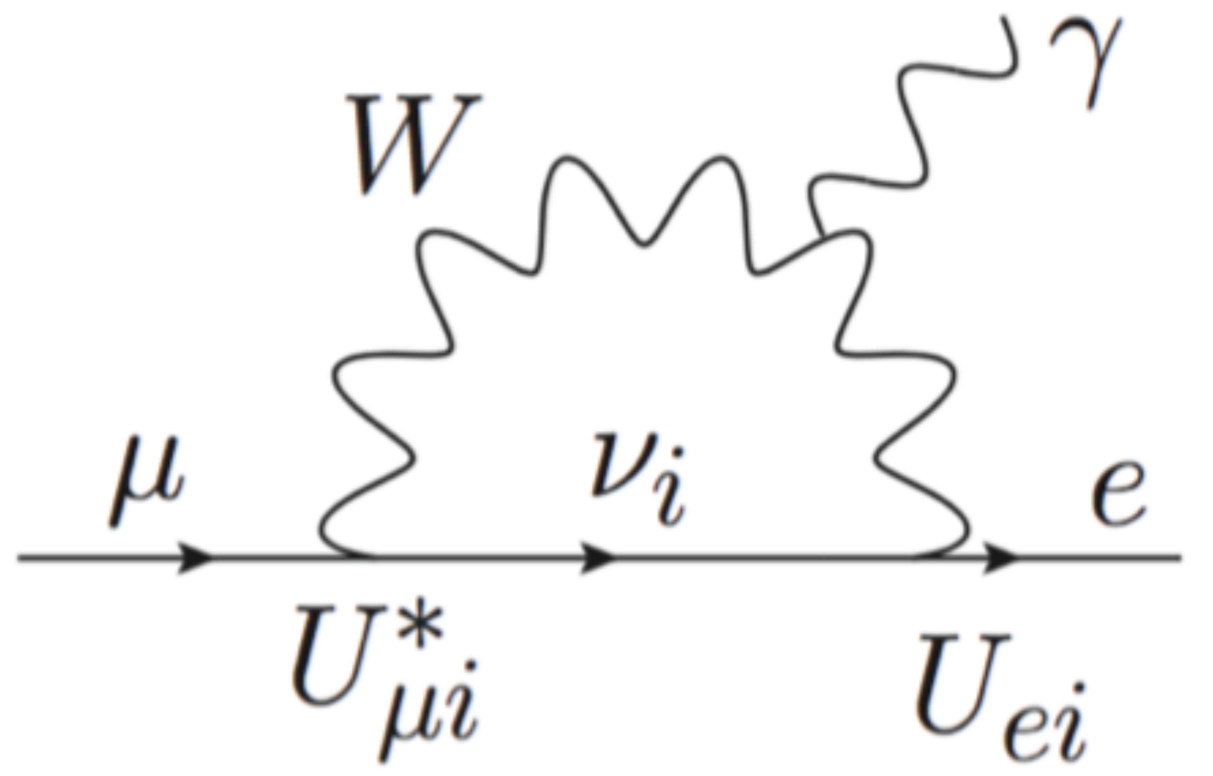
CLFV in the Standard Model

- The Standard Model doesn't predict neutrino oscillations nor include neutrino masses
- We need to extend the SM

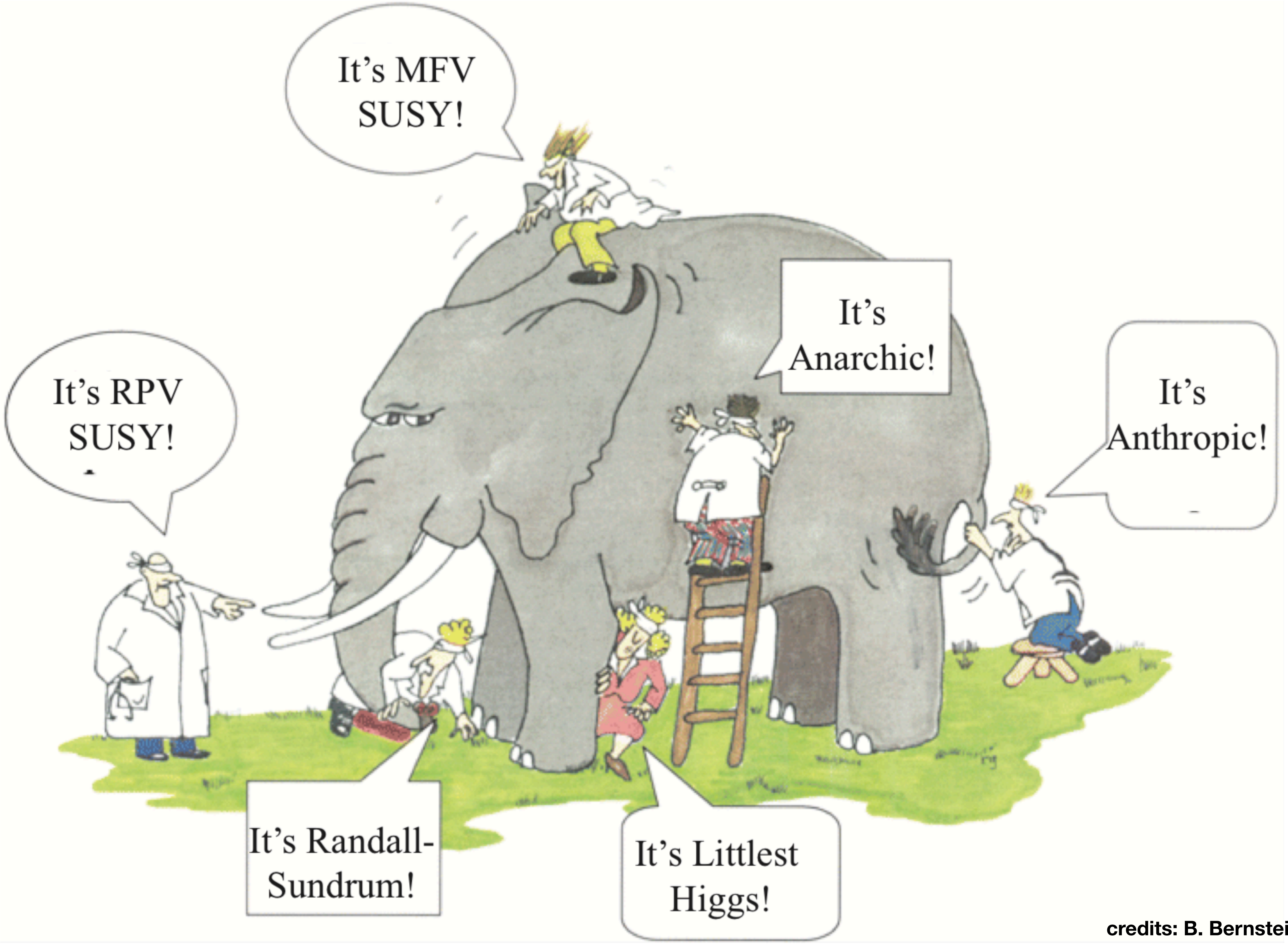
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

- Charged leptons: SM background free search!

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$



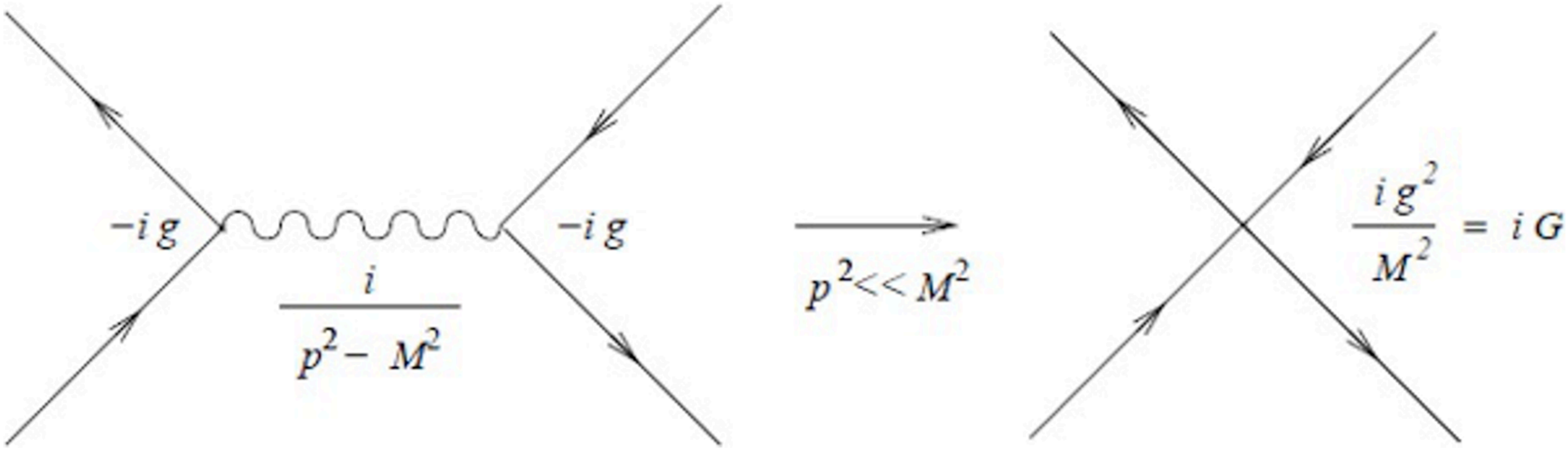
Discovery of Charged Lepton Flavor Violation is New Physics!
violation of a (so-far) conservation law



credits: B. Bernstein

Two Ways to Look at CLFV

1. What is the mass scale of new physics?
   - Muon Lifetime and Size of G_F told us about a mass scale M_W; $\mathcal{L} = \frac{\text{couplings}}{\Lambda^n}$



2. What are the symmetries and flavor structure of new physics?
   - the mass scale is not everything; you don't know the couplings or the sizes of mixing angles (the "Yukawas")

Dedicated Muon beam, colliders and B factory

- Can make very intense **muon beams**
  - High statistics, focused experiments to look for very rare processes

- But muon beams can't study **Higgs**, τ, ***B*** and ***J/ψ*** **decays** directly
  - Colliders win there: LHC and BELLE-II
  - Large production cross-section
  - Well defined initial state in the *B*-factory case

Search for rare μ processes

- $\mu \rightarrow e\gamma$
  - Oldest studied, most powerful limits and best experiment so far: MEG at PSI
- $\mu^- N \rightarrow e^- N$
  - Muon to electron conversion: muon converts in field of nucleus, leaving nucleus unchanged (coherent process)

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

  - Experiments upcoming at Fermilab and at JPARC
- $\mu \rightarrow eee$
  - Ambitious: coming experiment Mu3e at PSI
- $\mu^- N \rightarrow e^+ N'$
  - Sensitive also to Majorana neutrinos. Looking at in Mu2e and COMET phase I

μ-processes: comparison

Process	Signature	Pros	Cons
$\mu \rightarrow e\gamma$	• monochromatic e and γ • same vertex • same time • emitted back-to-back	• clean signature • using μ^+, we can stay away form the μ-capture products	• background scales as (beam-intensity)^2
$\mu \rightarrow eee$	• same vertex • $\Sigma p = 0$ • invariant mass = m_μ	• using μ^+, we can stay away form the μ-capture products	• background scales as (beam-intensity)^2
$\mu^- N \rightarrow e^- N$	• 1 monochromatic e- at large energy (~ m_μ)	• clean signature wo problems from accidental backgrounds	• we are forced to use μ^- • μ-capture products generates lot of activity in the detectors
$\mu^- N \rightarrow e^+ N'$	• 1 monochromatic e+ at large energy (~ 90 MeV)	• clean signature wo problems from accidental backgrounds	• we are forced to use μ^- • μ-capture products generates lot of activity in the detectors

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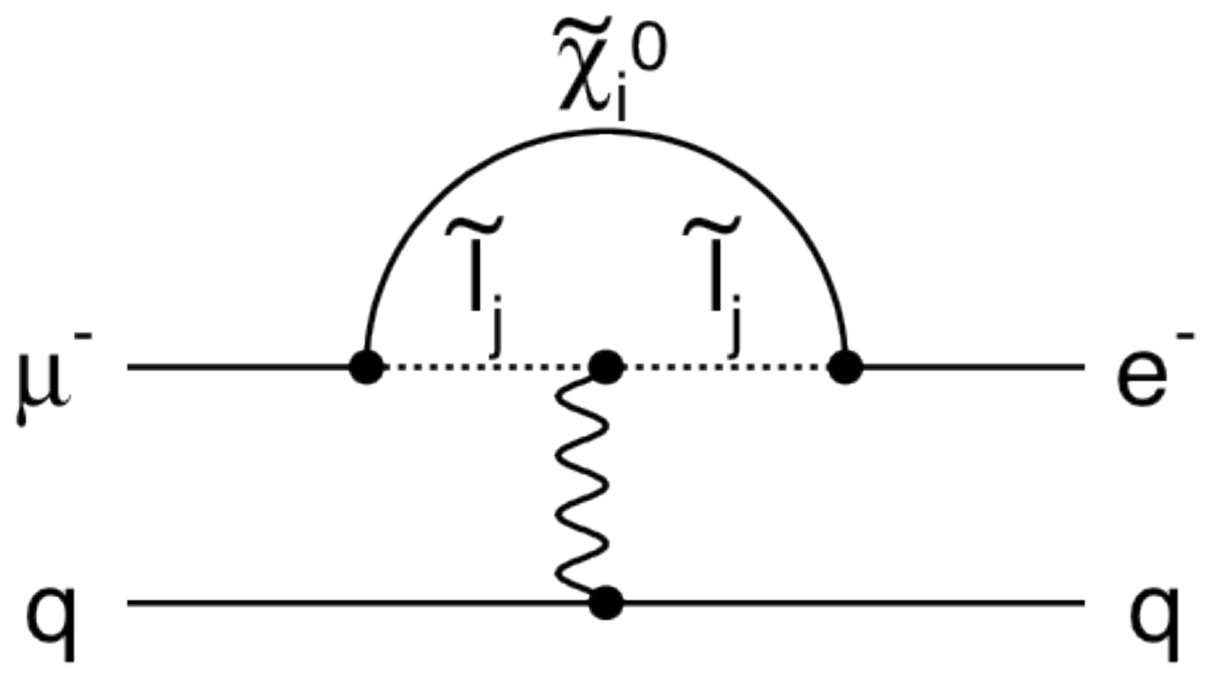
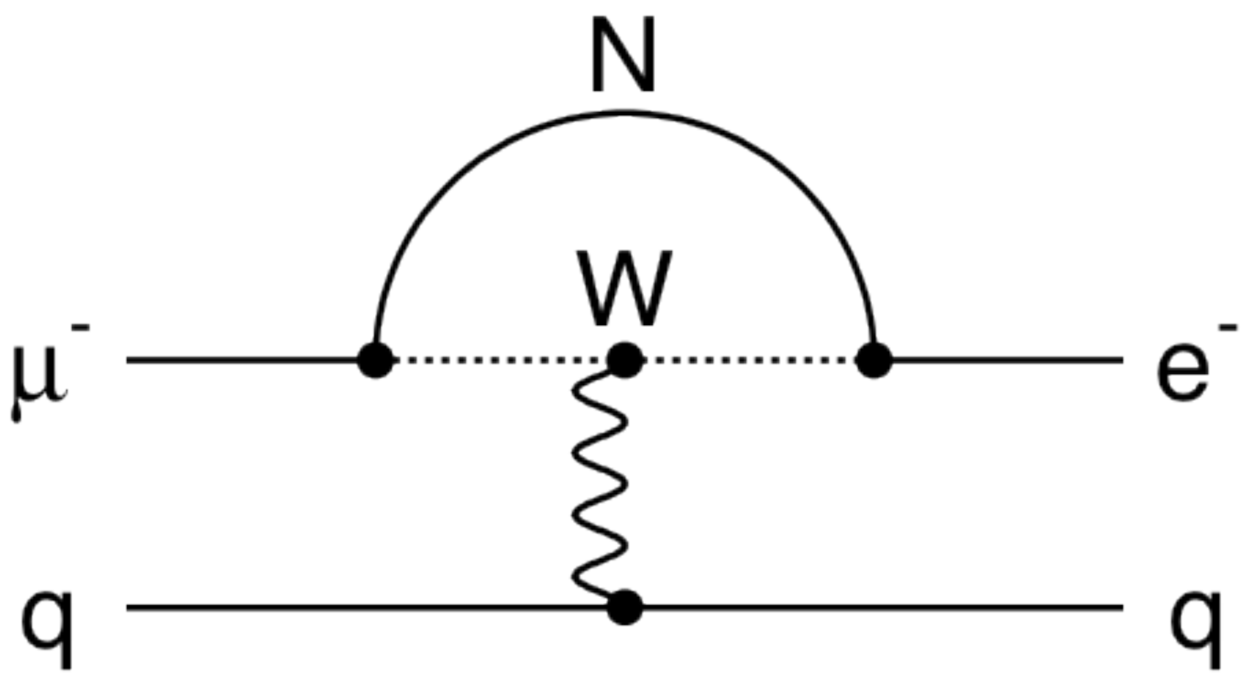
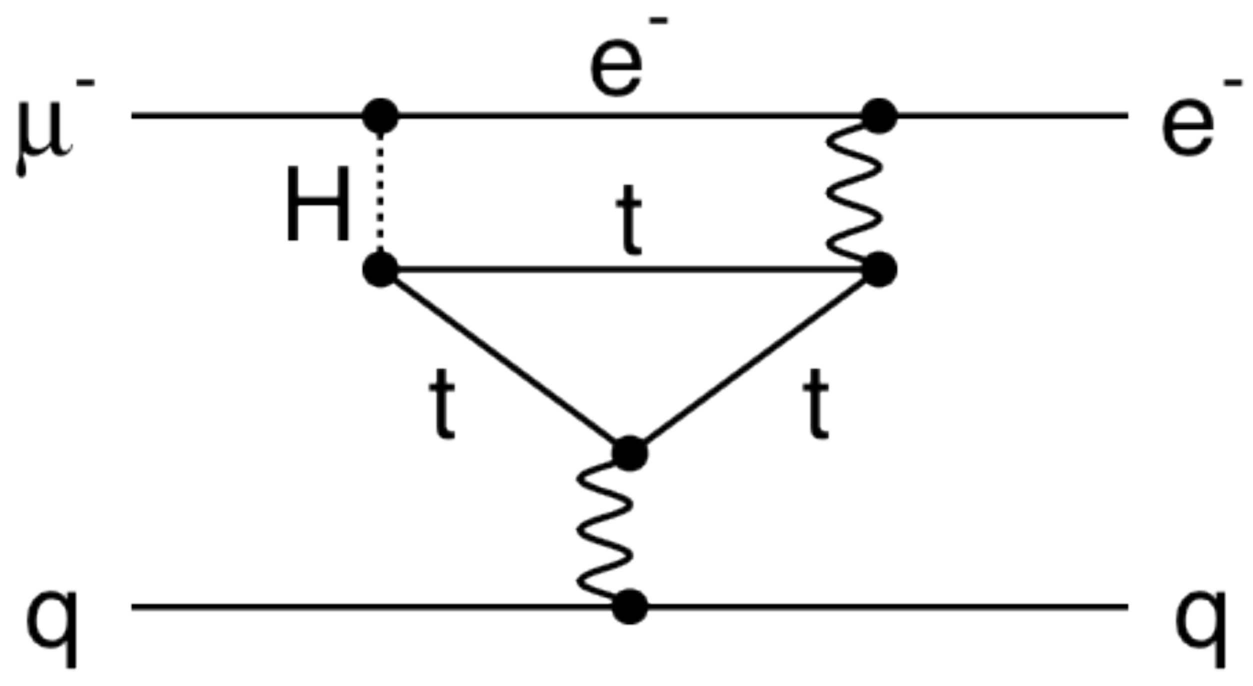
Possible contributions to CLFV



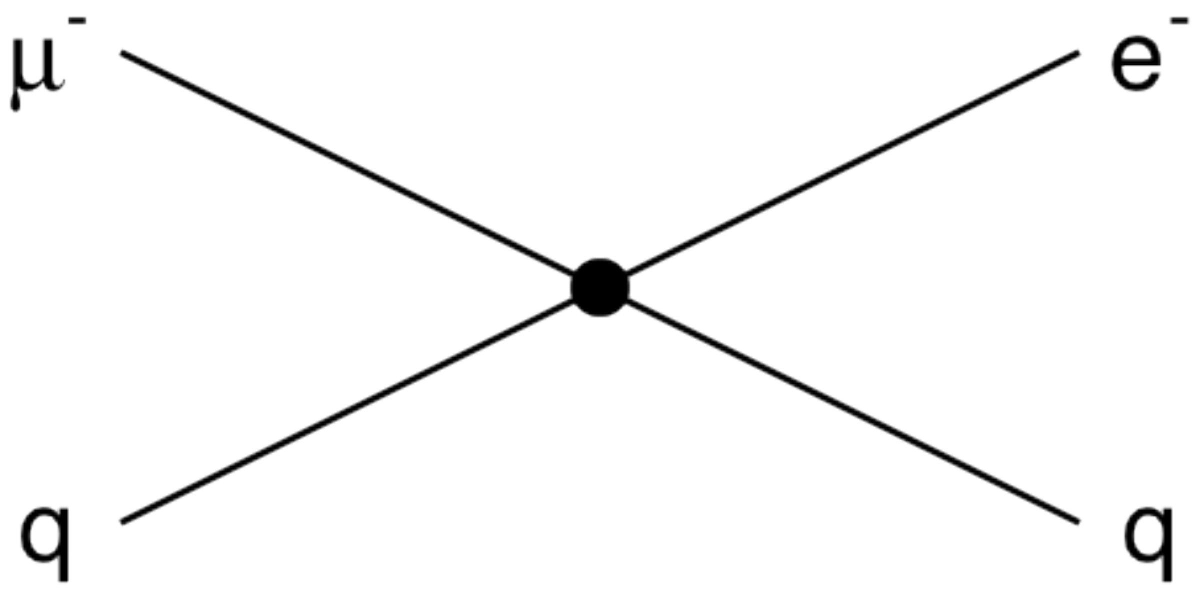
SUSY



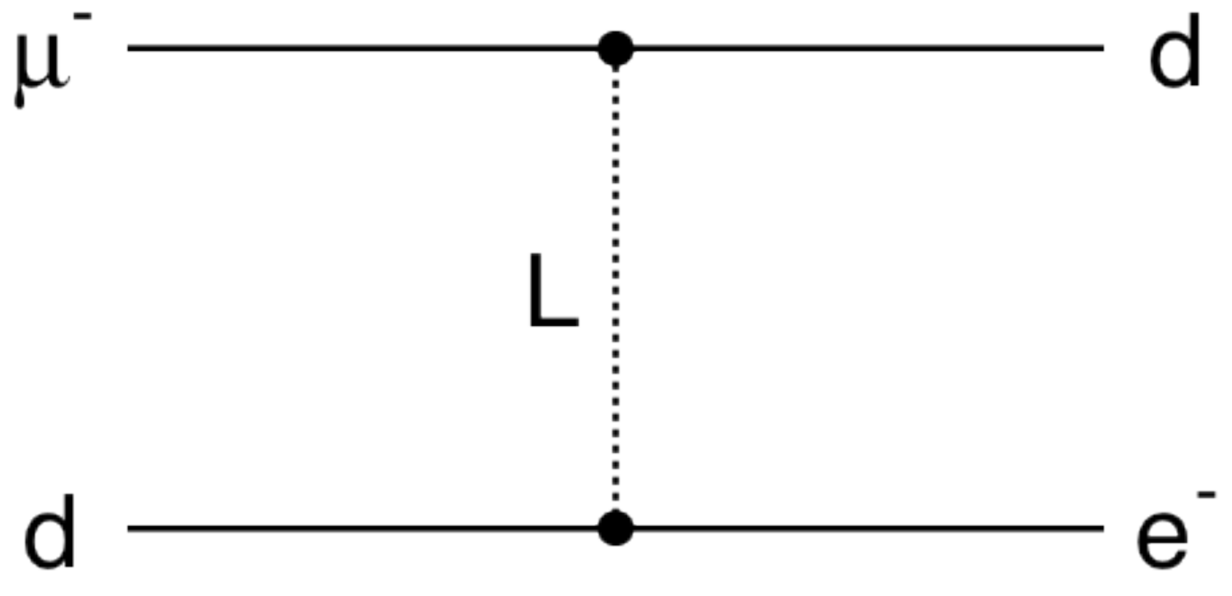
Heavy neutrino



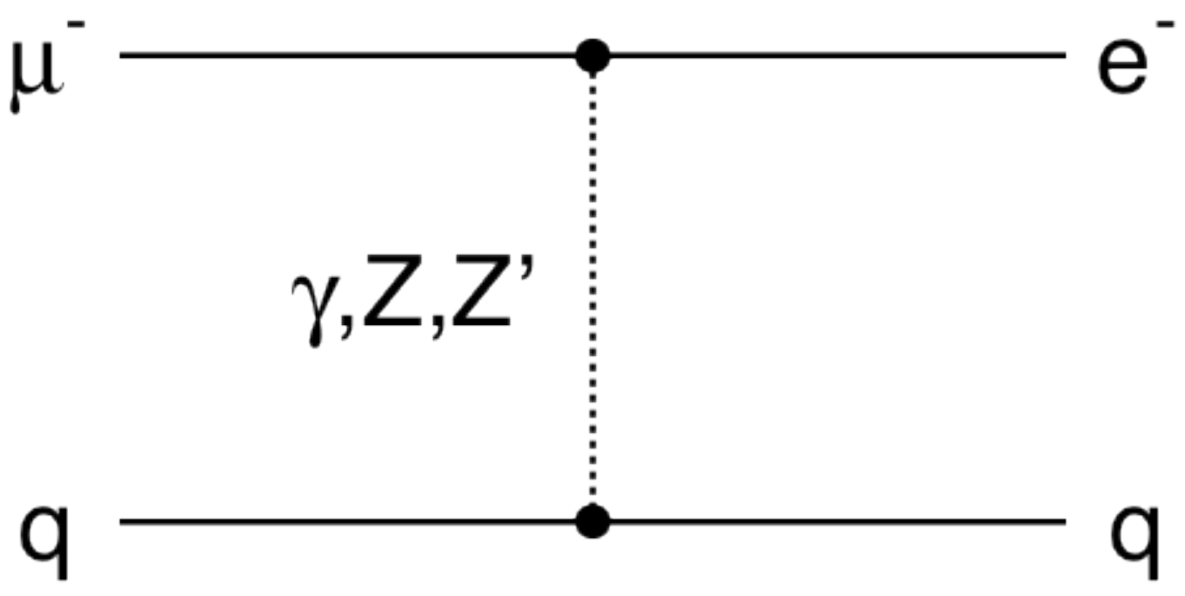
Two Higgs doublet



Compositeness



Leptoquarks

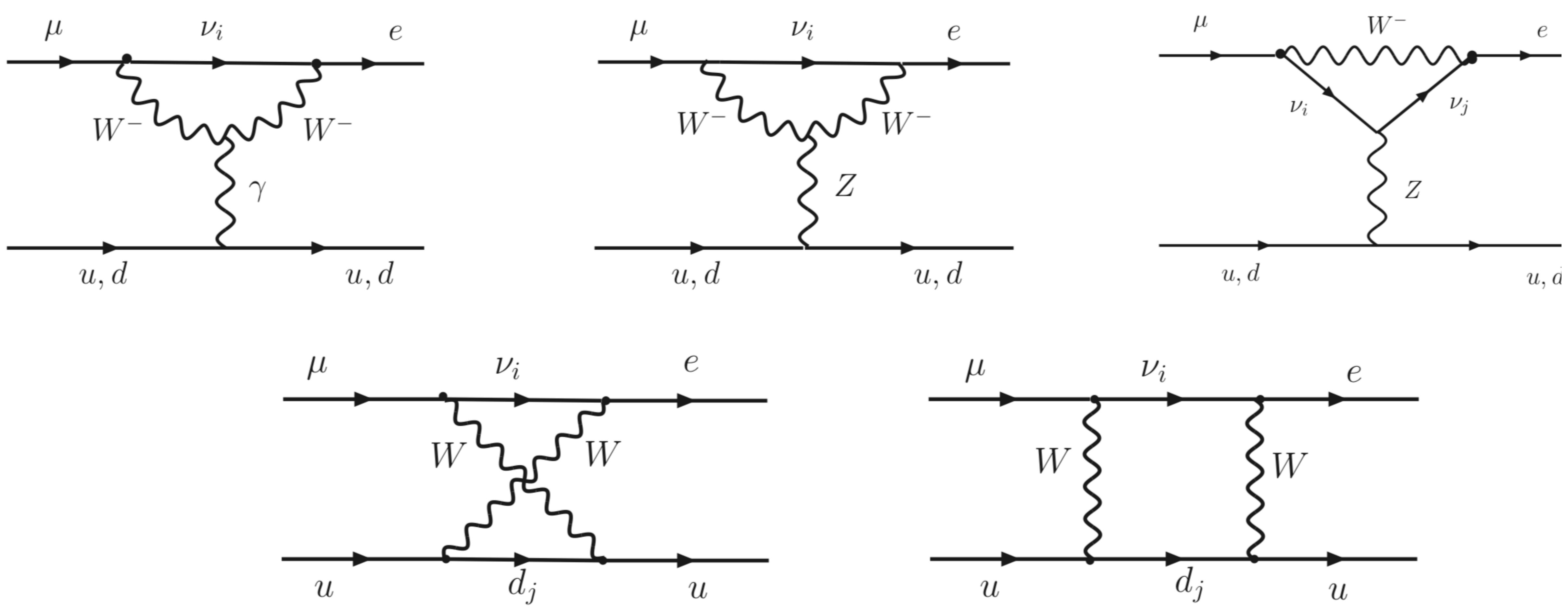


Z'/anomalous couplings

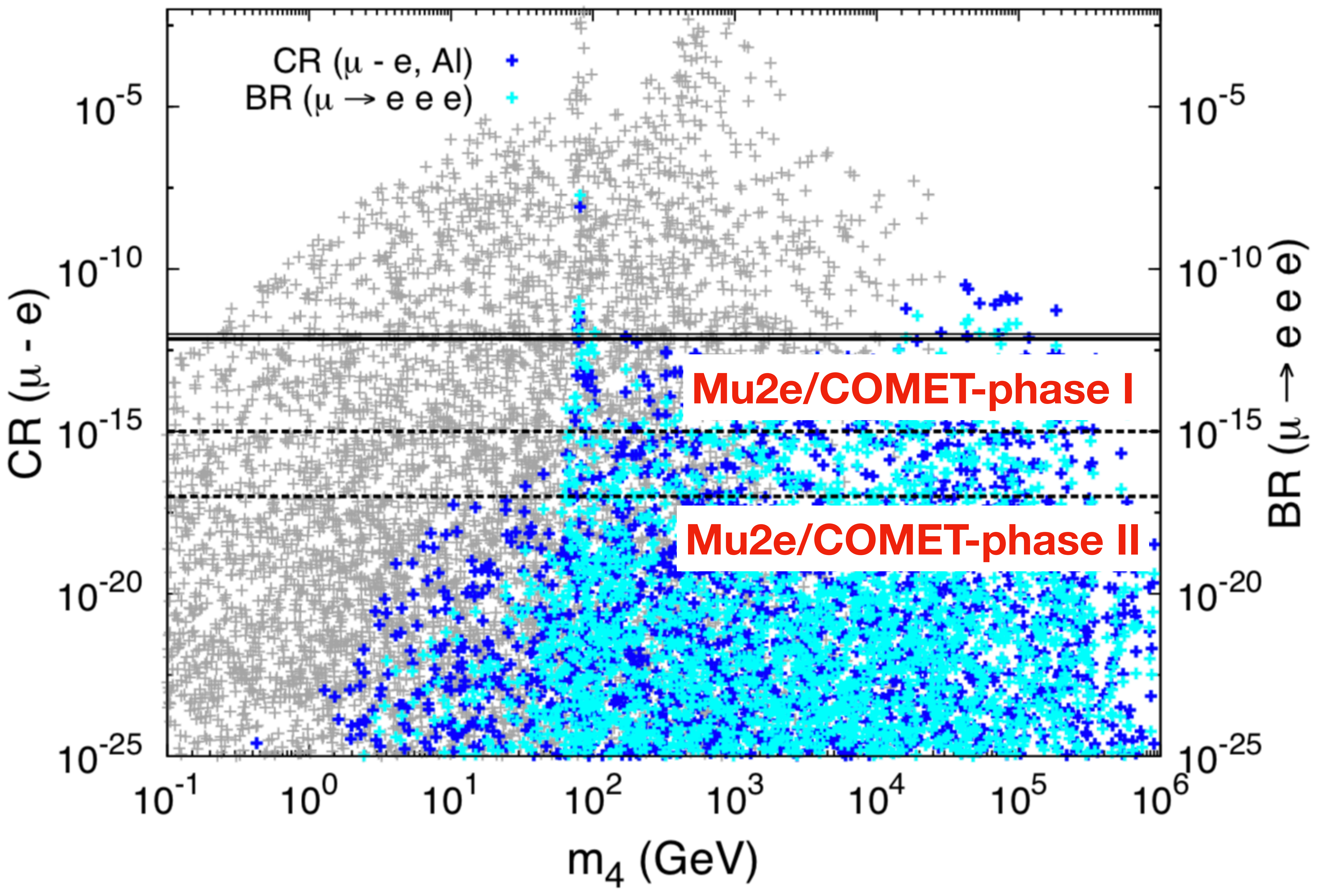
- Any signal observation would be an unambiguous sign of new physics

Sterile neutrinos and CLFV

- Effect on Lepton Universality and W and Z vertex
- Sterile neutrino can contribute to CLFV processes



Abada, V. De Romeri, A. M. Teixeira arXiv:1510.06657



- Contributions to μ2e conversion
- i=1,2,3,**4** while j=1,2,3

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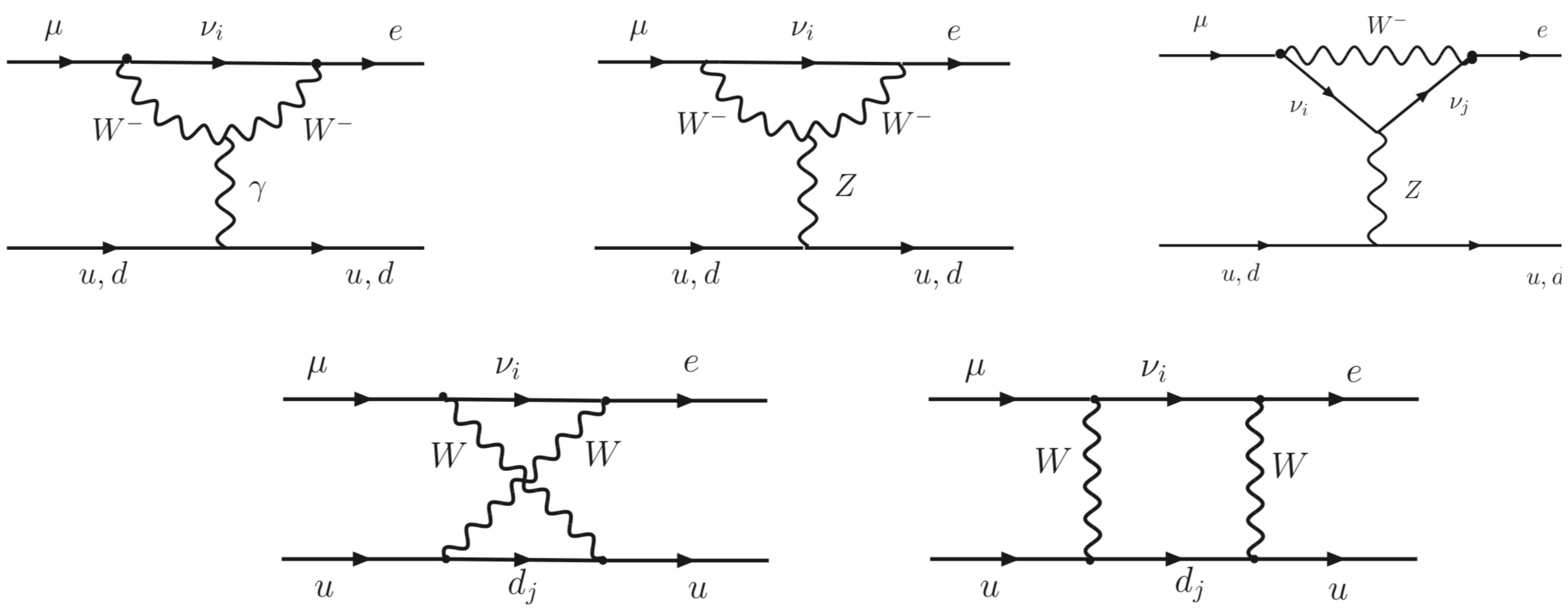

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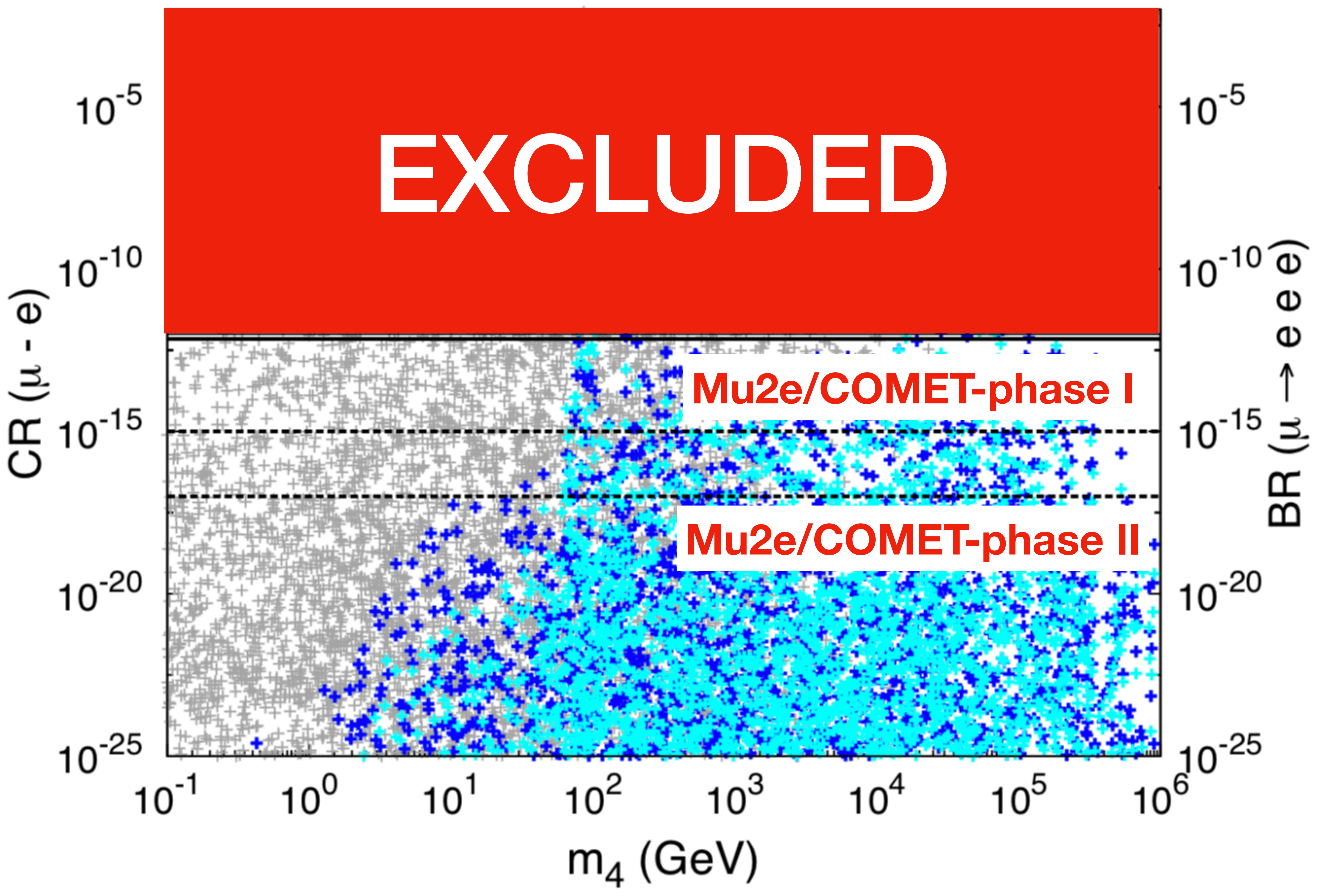


Constrains on Higgs

- **Muons** provide strong limits on LFV Higgs decays for 1st and 2nd generations
- **But not if tau involved:** 1st-3rd or 2nd-3rd

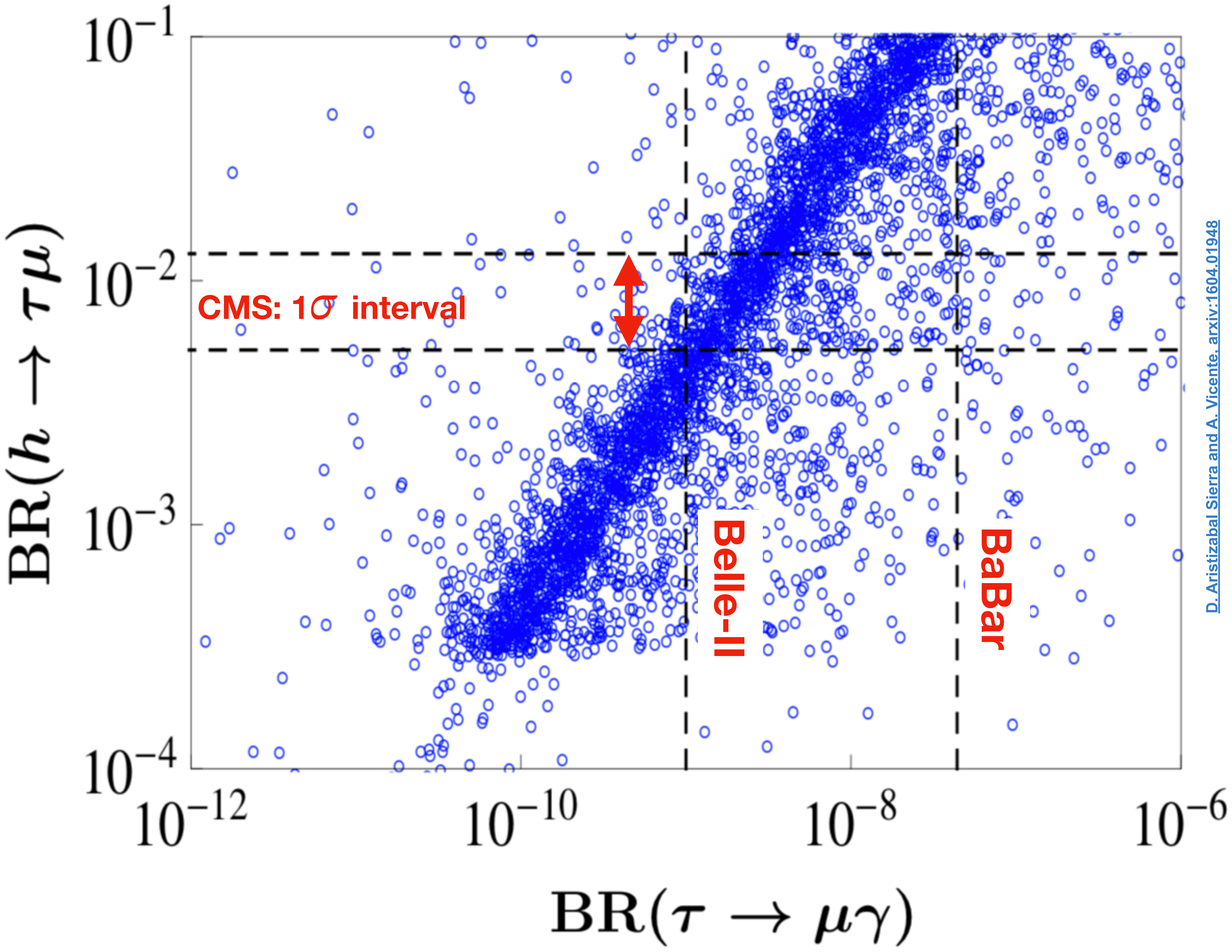
$$\begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

Hiroshi Okada, et al: arxiv.org/pdf/1604.01948.pdf

Two Higgs doublet models

- Induces flavor violation in both quarks and leptons
  - coupling constants $\rho_{ij} \propto \sqrt{m_i m_j}$
  - automatically suppresses 1st and 2nd generation coupling!

$$\mathrm{BR}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h}\left(|g_{h\tau\mu}|^2 + |g_{h\mu\tau}|^2\right)$$



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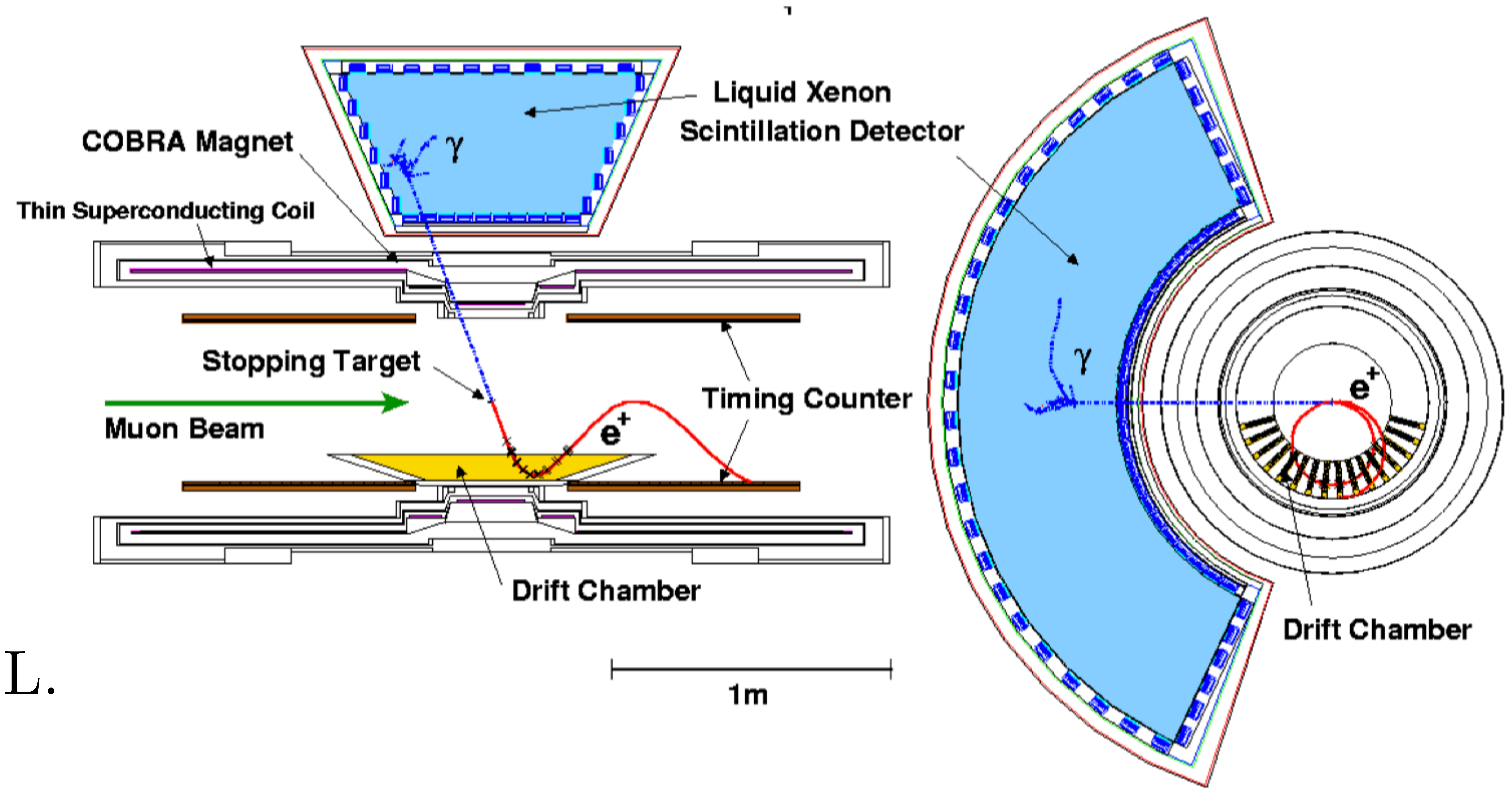
MEG: μ→eγ

- 2-body decay at rest in $e^+ + \gamma$:
  - monochromatic products
  - angular correlation
  - timing correlation
- Current best limit:

$$B(\mu \to e\gamma) < 4.2 \times 10^{-13} \text{ @ } 90\%\text{C.L.}$$



μ+ beam

stopped beam of 3 x 10^7 μ /s in a 205 μm polyethylene target

e+ detection

magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum plastic counters for timing

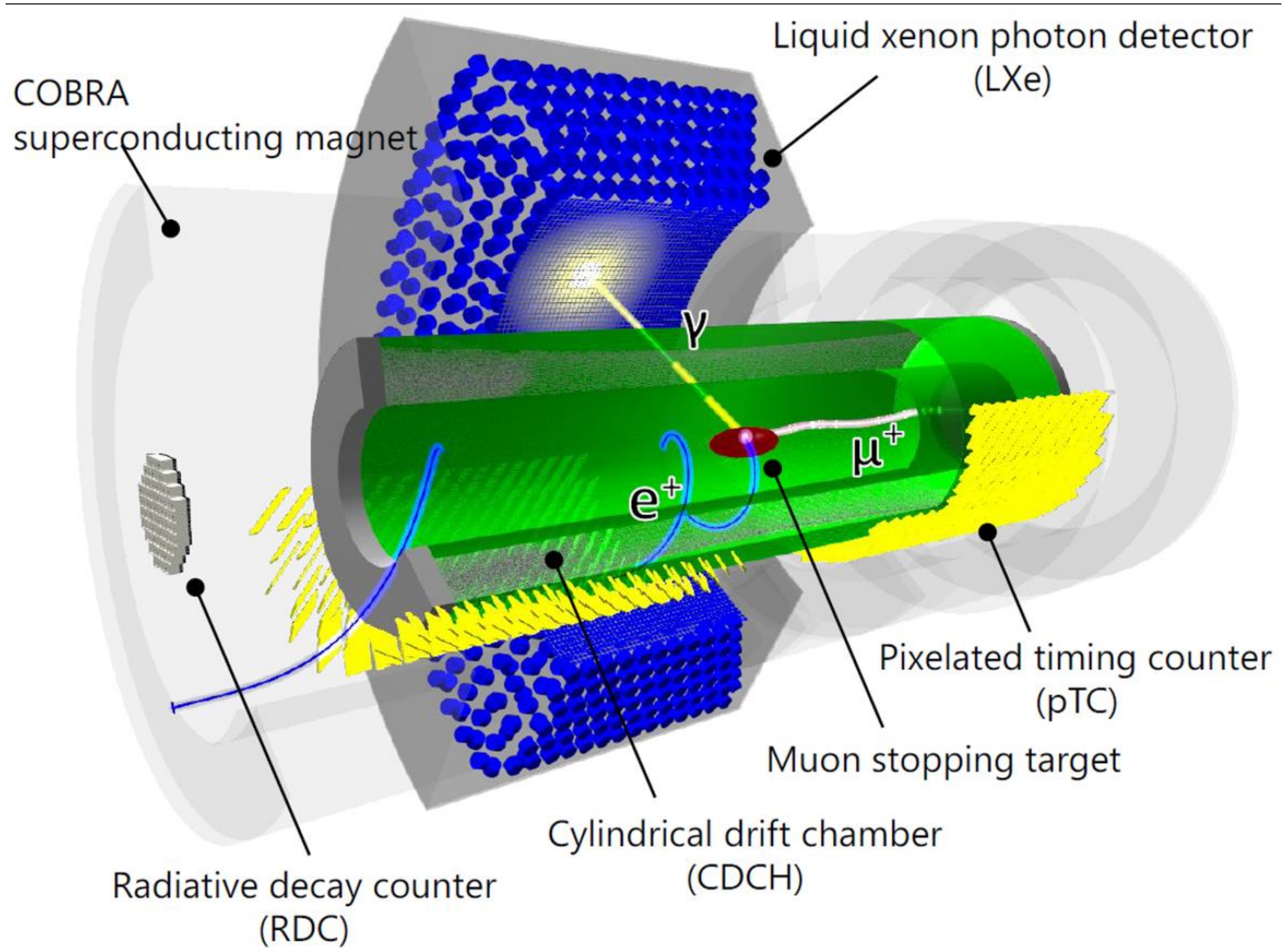
γ detection

Liquid Xenon detector based on scintillation light
- fast: 4 / 22 / 45 ns
- high LY: ~ 0.8 x NaI
- short X_0: 2.77 cm

MEG II

- MEG II: 2021~2026, aims at 4×10^{-14}
- Detector resolution and efficiency x2
- Beam intensity x2: $3\text{x}10^7/s \rightarrow 5\text{x}10^7/s$.
  - Can achieve: $10^8/s$.

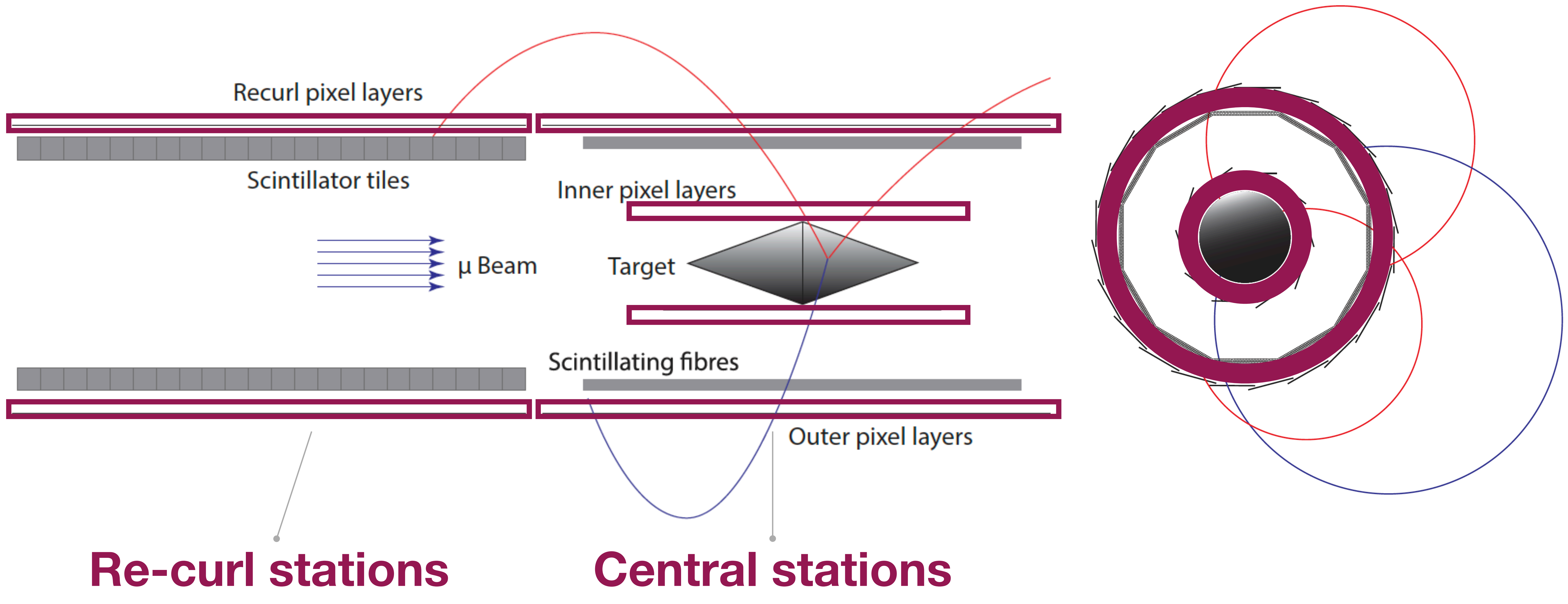
	MEG	MEG II (design)	MEG II (Meas.)
ΔE_e [keV]	380	130	90
$\Delta\theta_e$ / $\Delta\varphi_e$ [mrad]	9/9	7.0/5.5	8/7
e^+ Eff. [%]	40	70	65
ΔE_γ [%] (deep/shallow)	1.7/2.4	1.0/1.1	1.7/2.0
Δpos_γ [mm]	5	2.4	2.5
γ Eff. [%]	60	70	60
$\Delta t_{e\gamma}$ [ps]	120	85	80



Mu3e: μ→eee

- 3-body decay at rest in $e^+e^-e^+$:
  - $E=m_\mu$
  - $\Sigma\, pi = 0$
- Current bet limit:

$$B(\mu \to eee) < 1 \times 10^{-12} \text{ @ } 90\ \%\text{C.L.}$$



μ+ beam

stopped beam of $O(10^8$ μ/s) in a Mylar double hollow cone (L=100 mm, R=19 mm)

timing detection

fibers O(1 ns), tiles O(0.1 ns)

pixel tracker

pixel dimension: 80 x 80 μm^2, thickness: 50 μm (0.01% X_0/layer), time resolution: < 20 ns

How to search for a μ2e conversion?

1. We need to produce lot of μ

   ✓~10^{18} μ to meet the sensitivity goal

2. We need to stop the μ in a target

   ➡slow moving μ are preferable

3. We need to detect an e- @ E=105 MeV

   ✓accuracy <1% to provide signal-to-background separation

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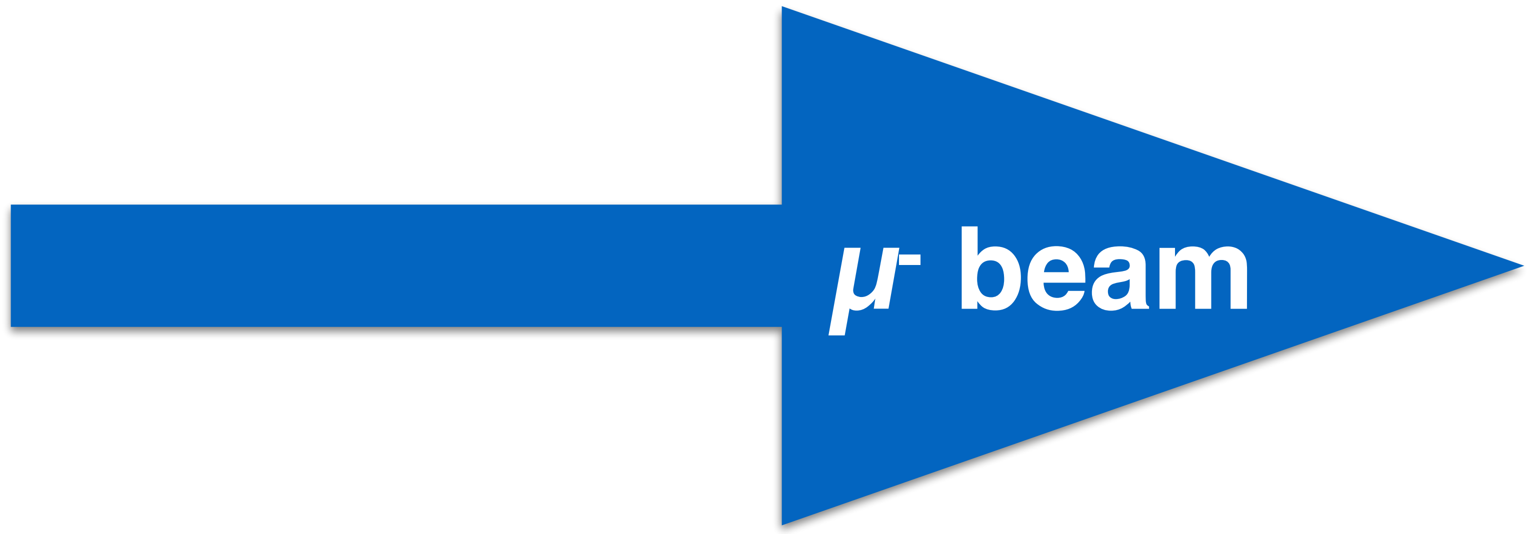

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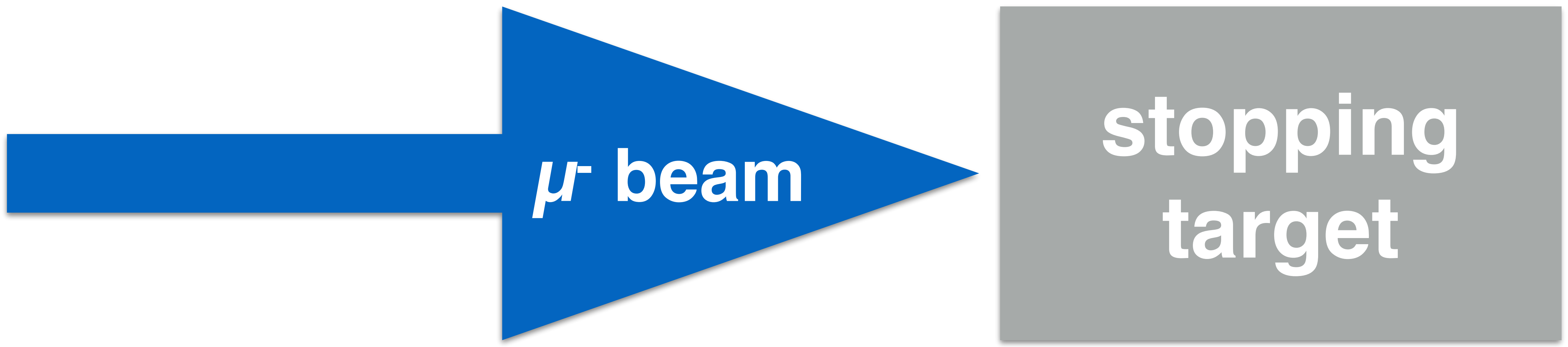

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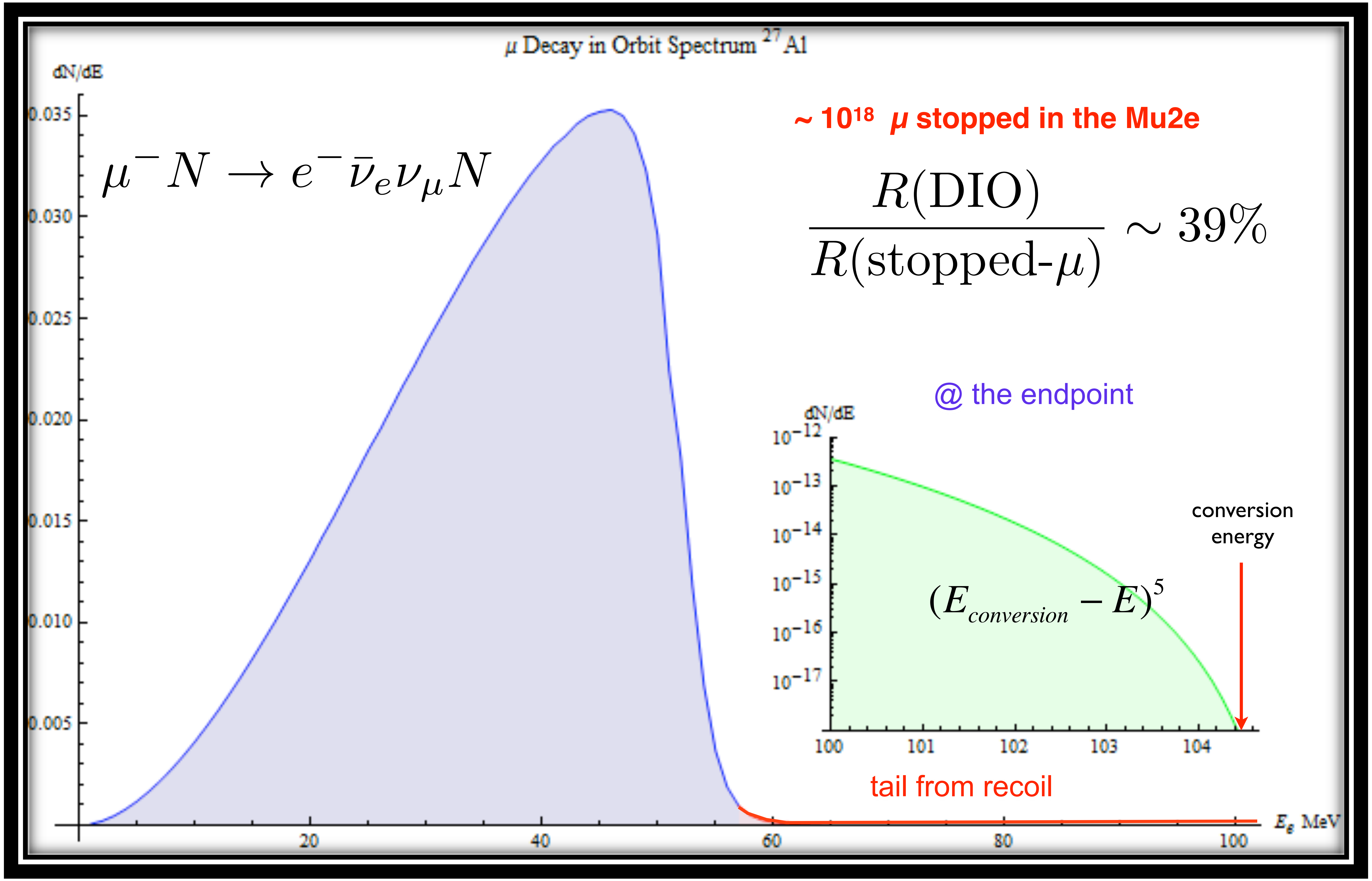
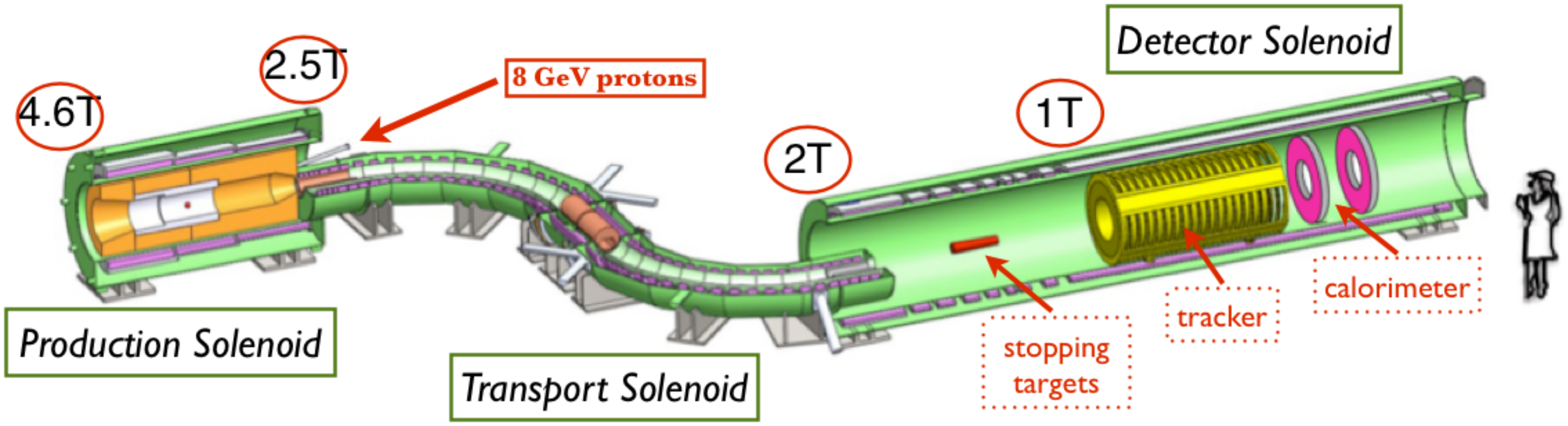
μ-conversion background: μ decay-in-orbit



R. Szafron, A. Czarnecki https://doi.org/10.1016/j.physletb.2015.12.008

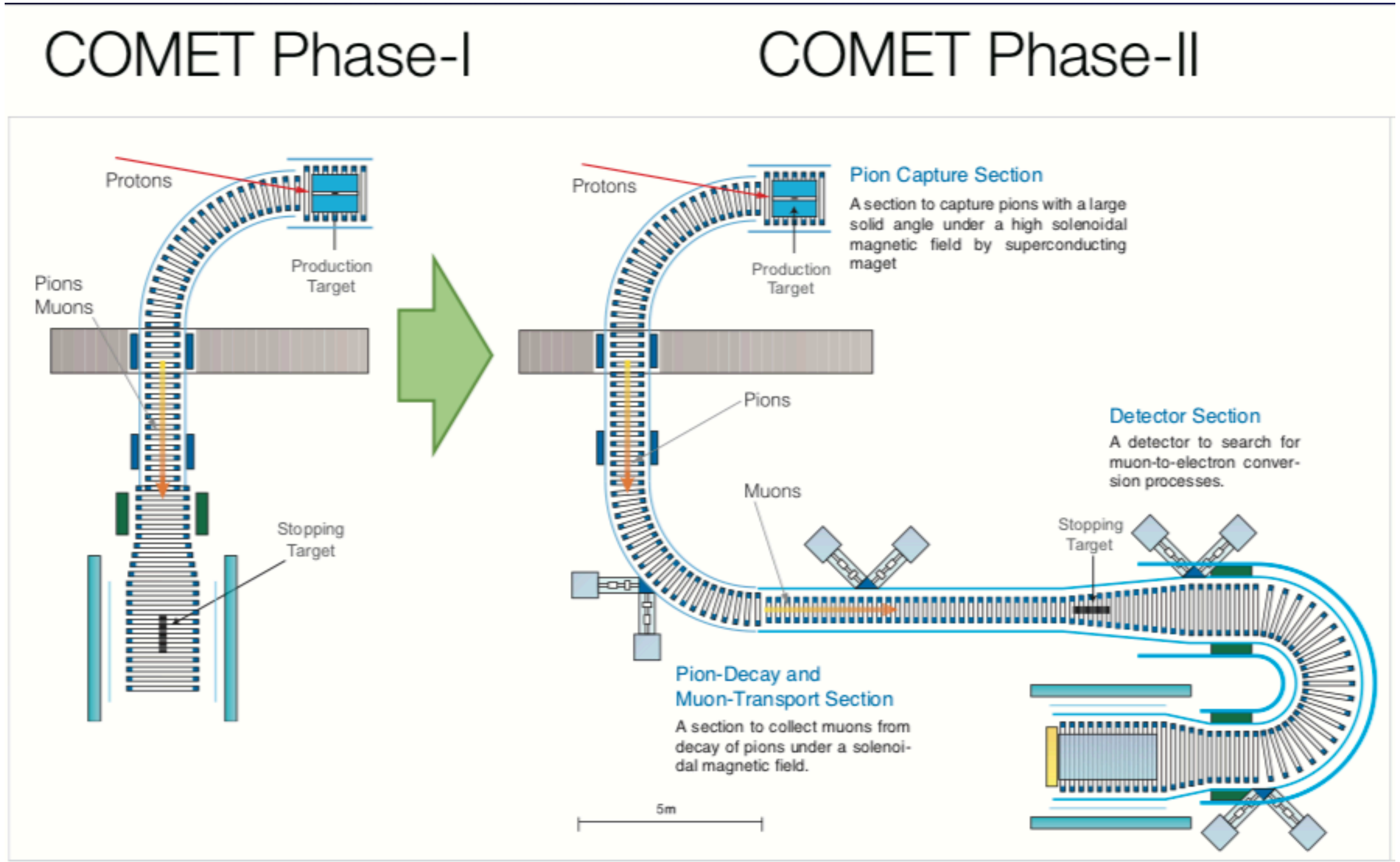
Muon conversion: Mu2e @ Fermilab



- Target protons at 8 GeV inside superconducting solenoid at 8kW
- Focus muons and guide through S-shaped region to Al stopping target
- Stop muons, let them fall into a “1s” state
- Check for outgoing electrons

Muon conversion: COMET @ JPARC

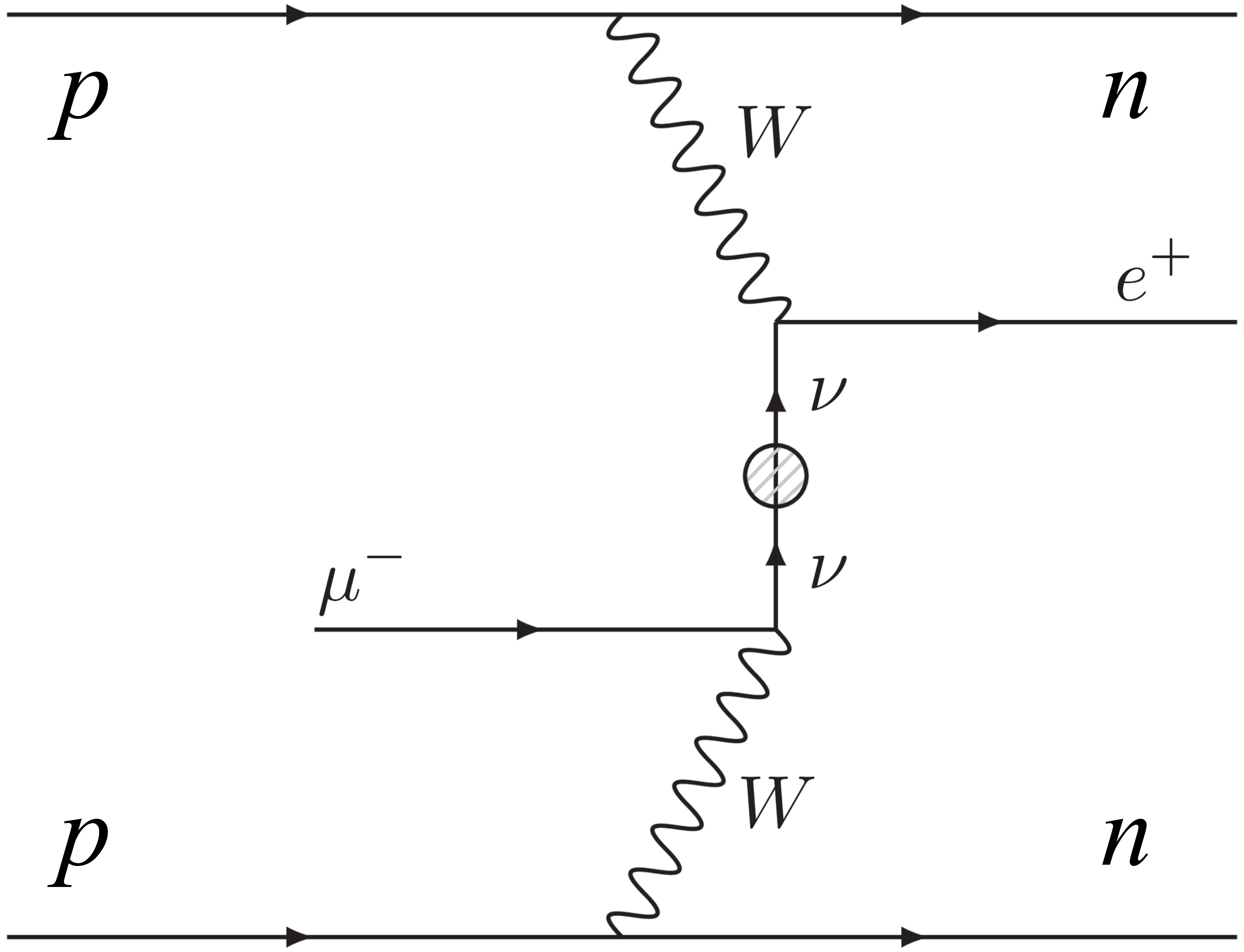
- Stage I aims for x100 improvement:
  - cylindrical drift chamber surround the stopping target
  - scint and Cherenkov hodoscopes for Triggering
- Stage II ~ Mu2e
  - important difference is the C-shape solenoid



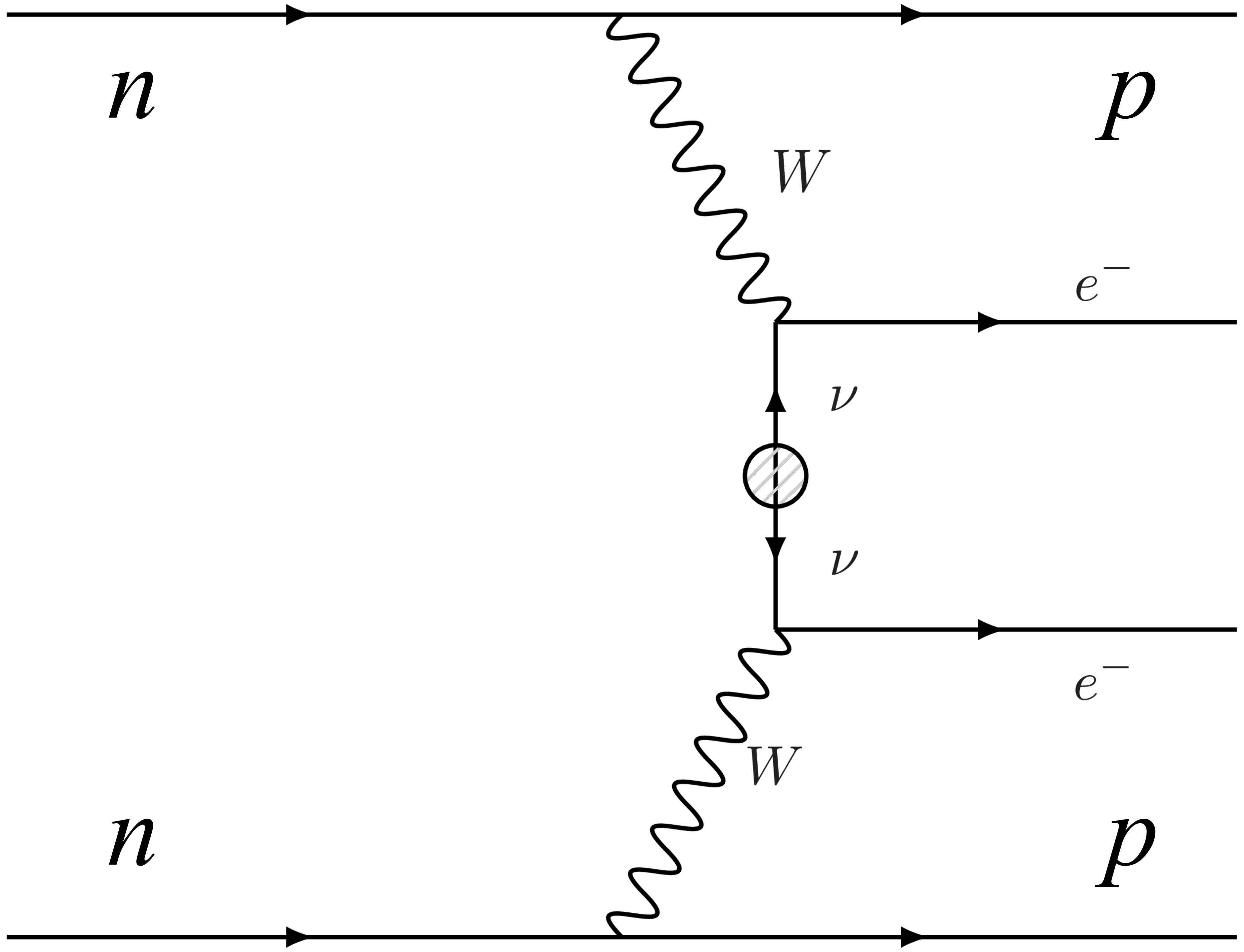
μ- to e+ conversion search

- Closely related to 0ν2β
  - or a leptoquark (not shown), …

More in Michael Mackenzie's talk!



0ν2β



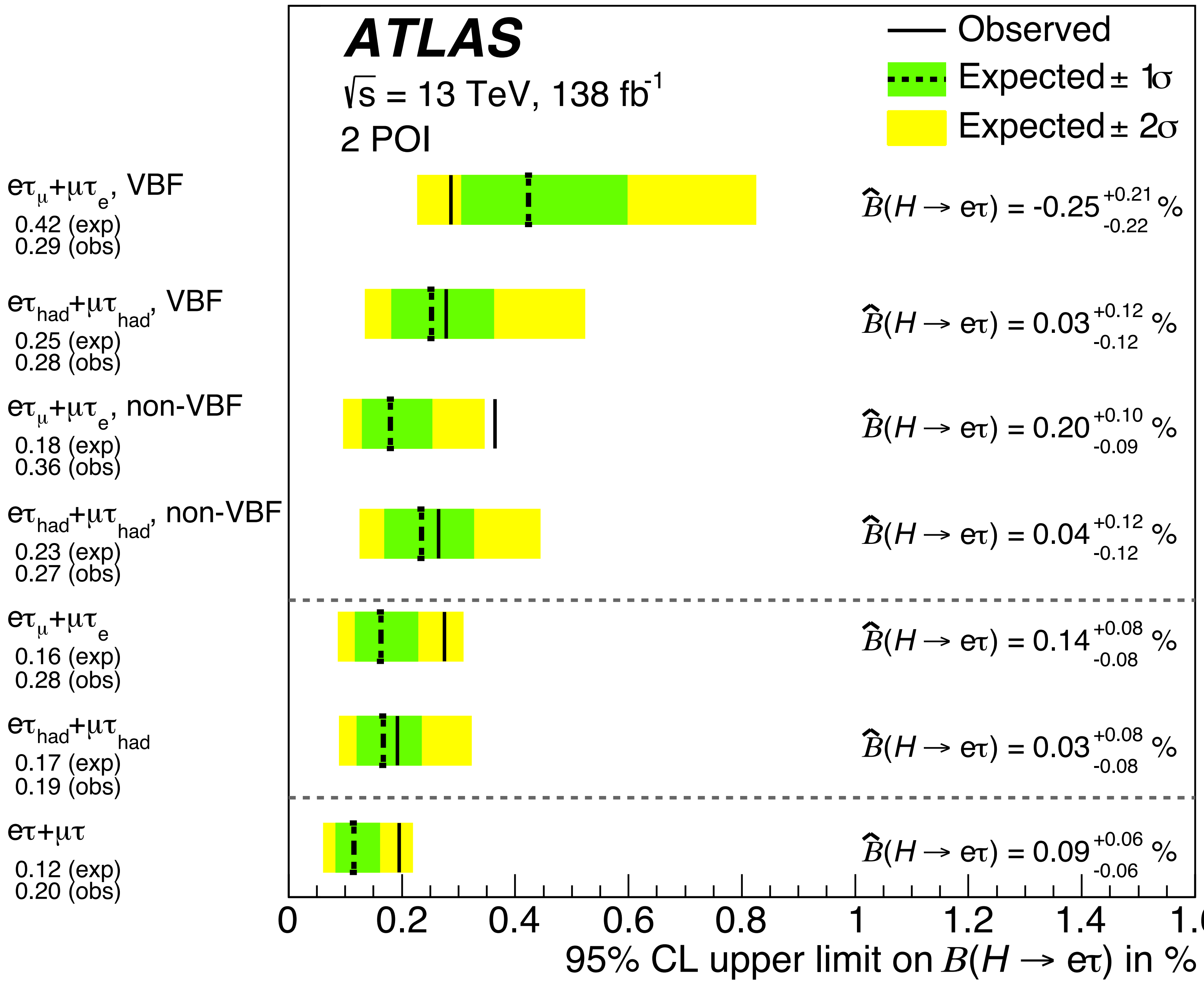
https://doi.org/10.1103/PhysRevD.95.115010, Physics Letters B 764 (2017) 157–162

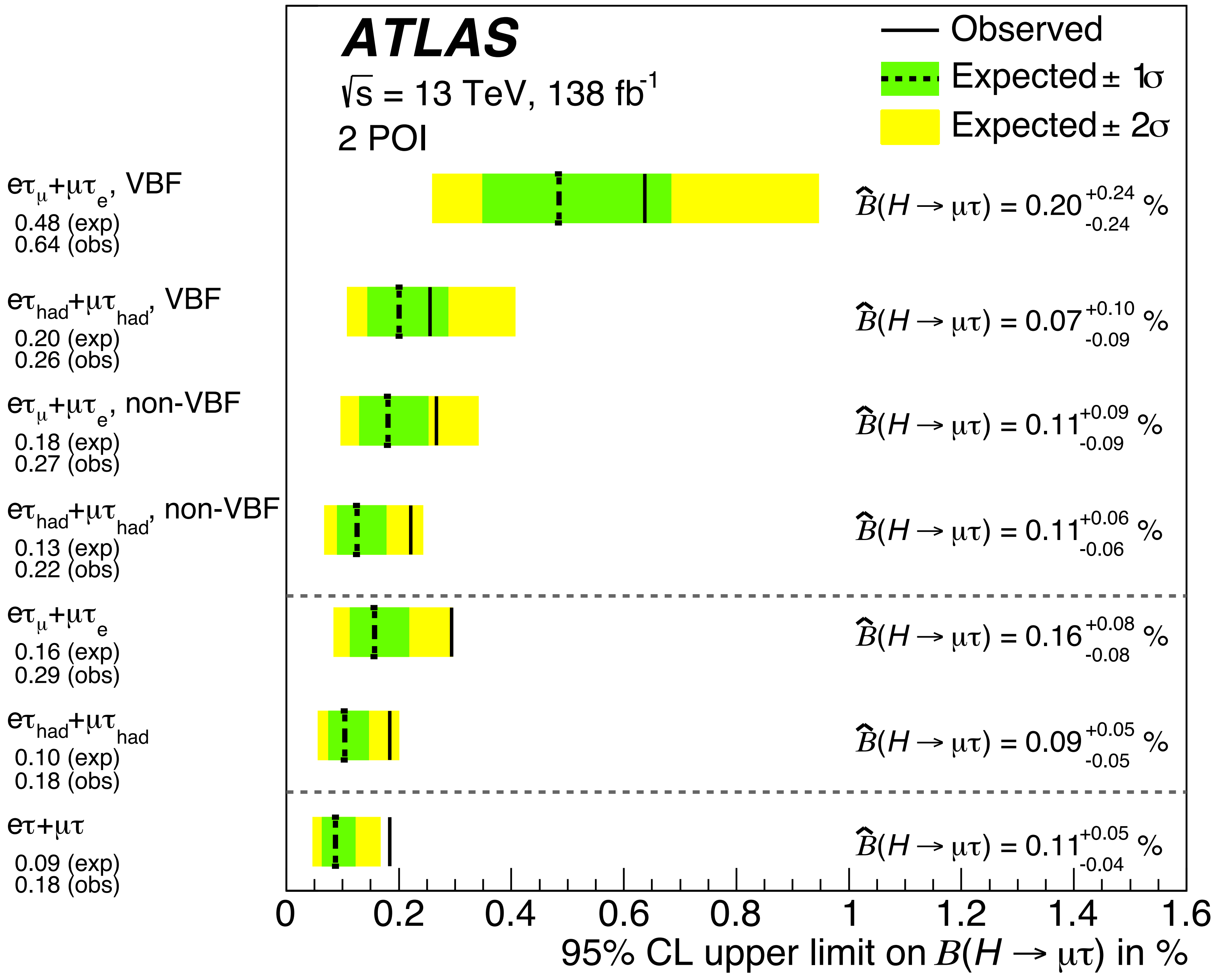
Mu2e and COMET: differences

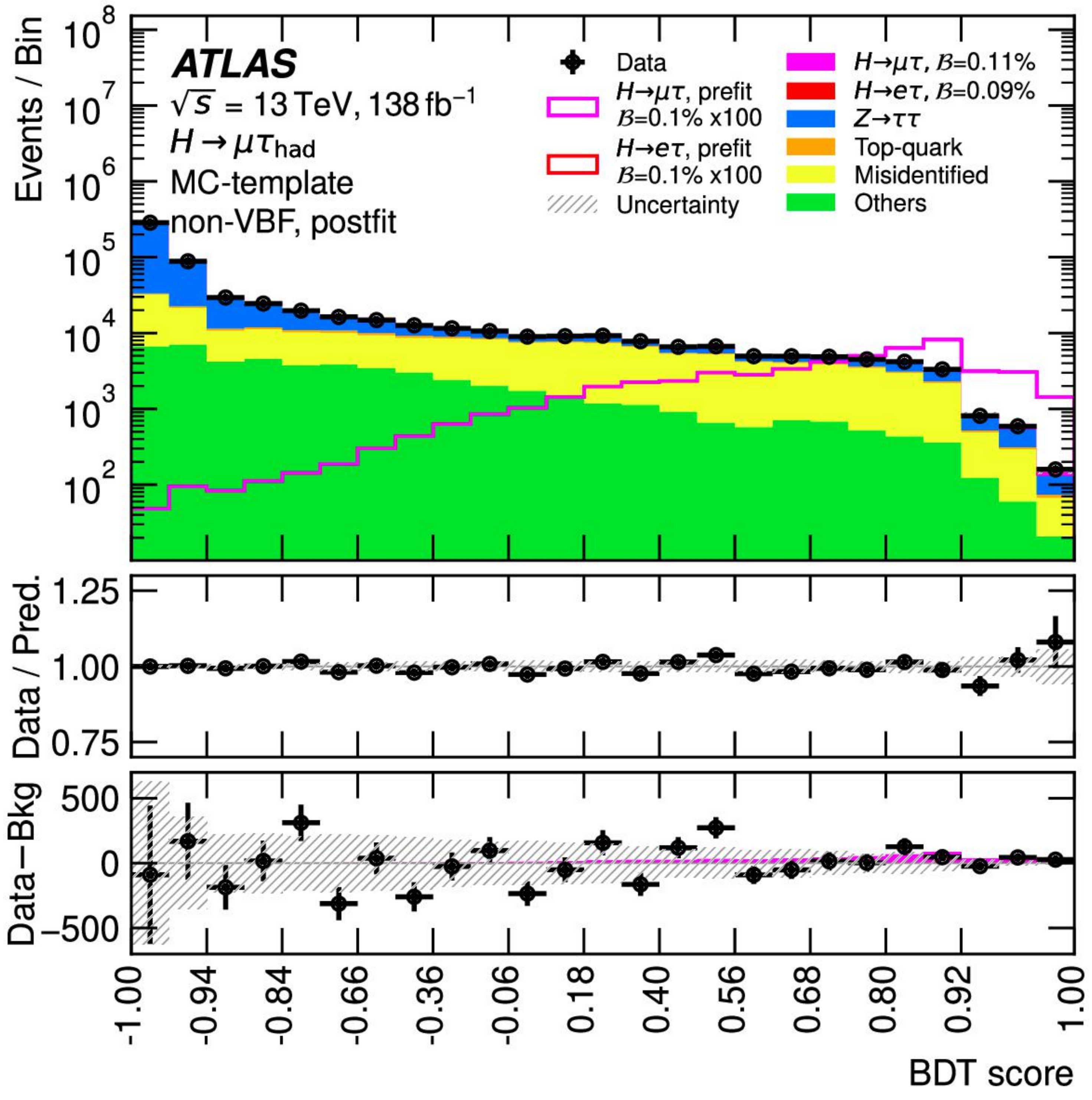
- COMET staging has obvious advantages for learning as you go
- Charge Symmetry of Detector:
  - Mu2e: charge symmetric, e+e- the same
  - 2nd Bend in COMET Stage II momentum selects ~ 105 MeV e- only
- Mu2e needs a hollow, COMET does not

Search for $H \to l\tau$ (l=e or μ) in ATLAS

- The main backgrounds are: $Z \to \tau\tau$, Top processes, W+jets and QCD
- Misidentified tau well modeled using a data-driven method
- MVA to discriminate signal from background





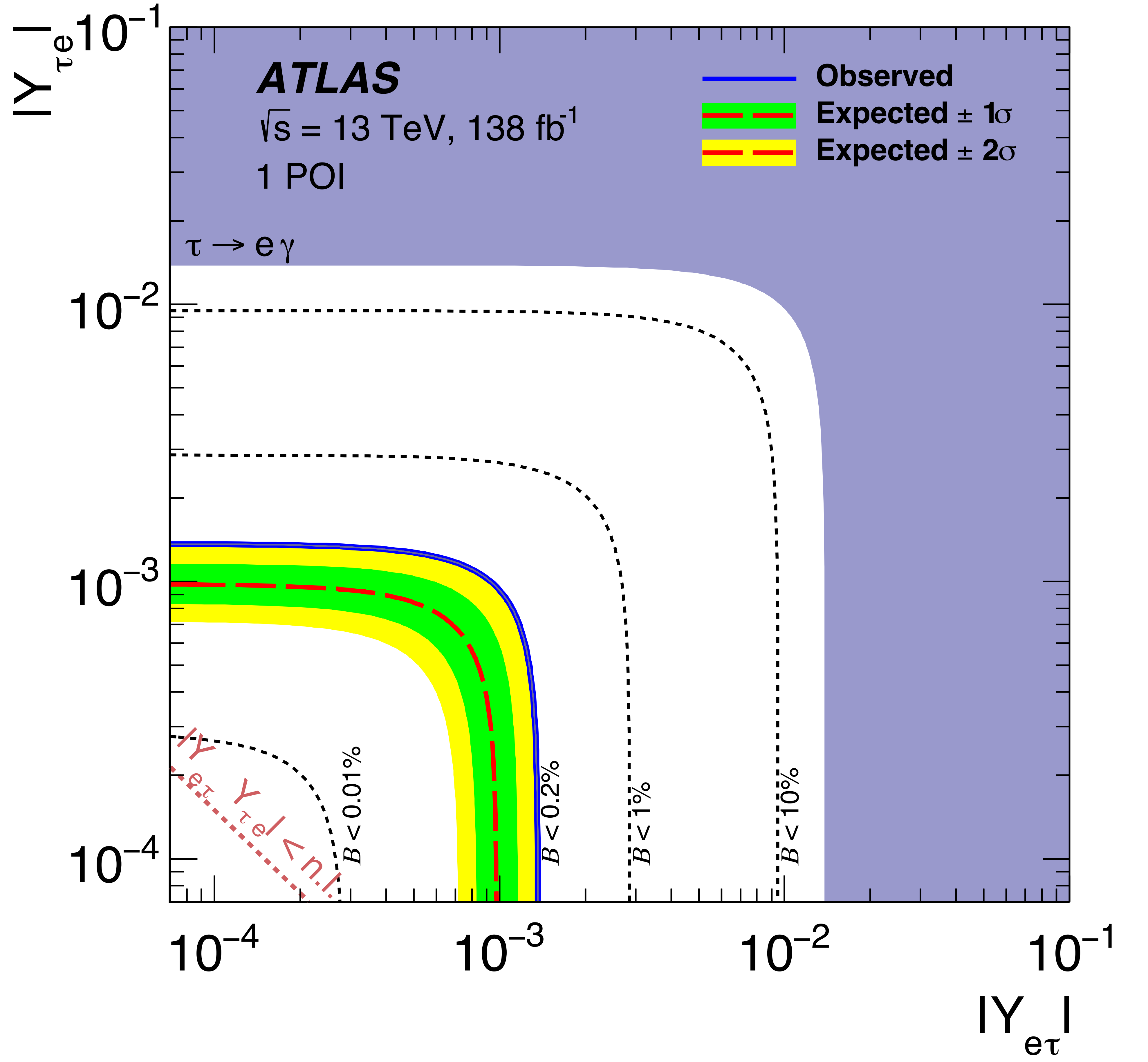


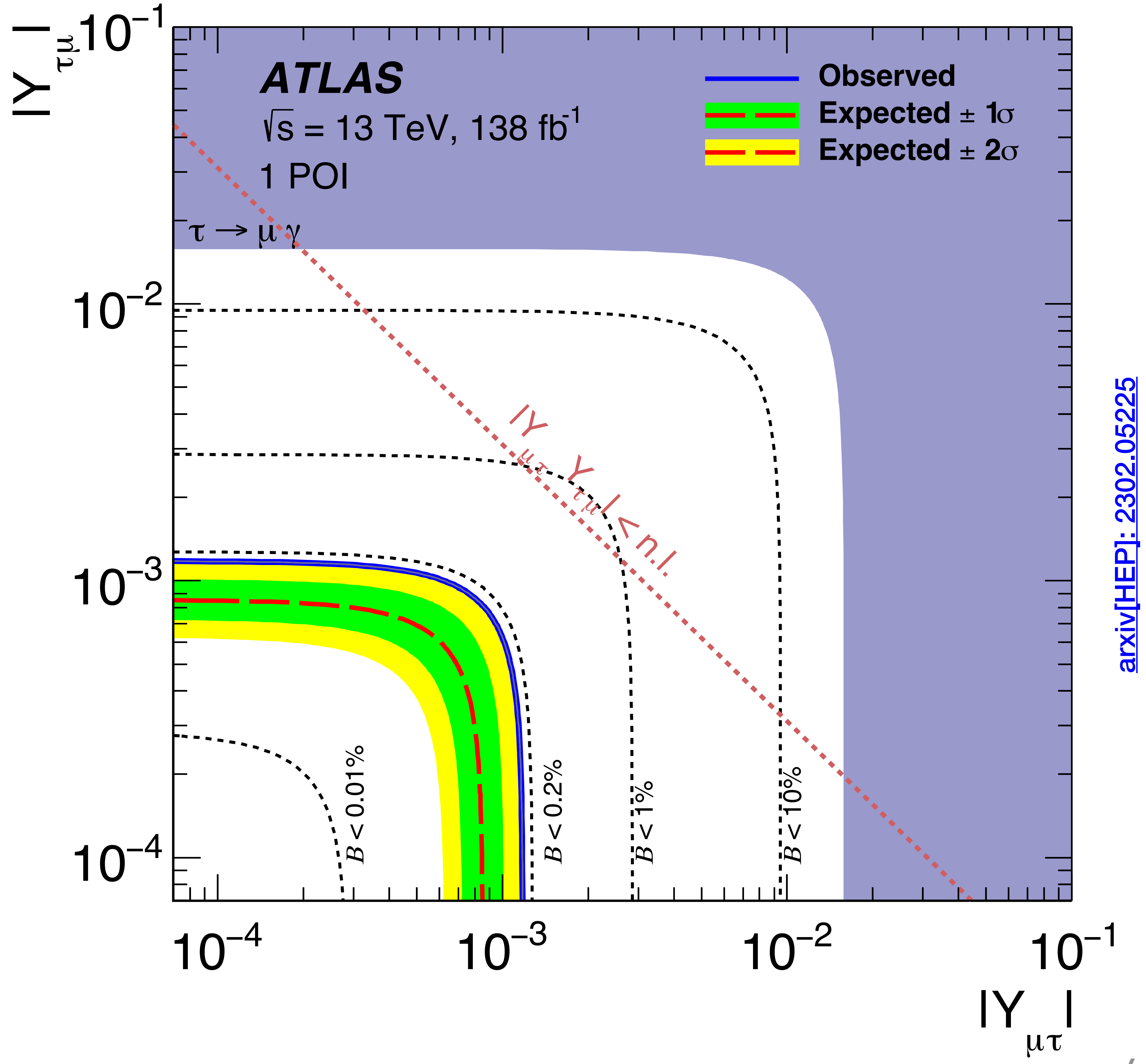
arxiv[HEP]: 2302.05225

Search for $H \to l\tau$ (l=e or μ) in ATLAS

- The $B(H \to l\tau)$ is related to the non-diagonal Yukawa coupling matrix elements

$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \to \ell\tau)}{1 - \mathcal{B}(H \to \ell\tau)} \Gamma_H(\mathrm{SM})$$





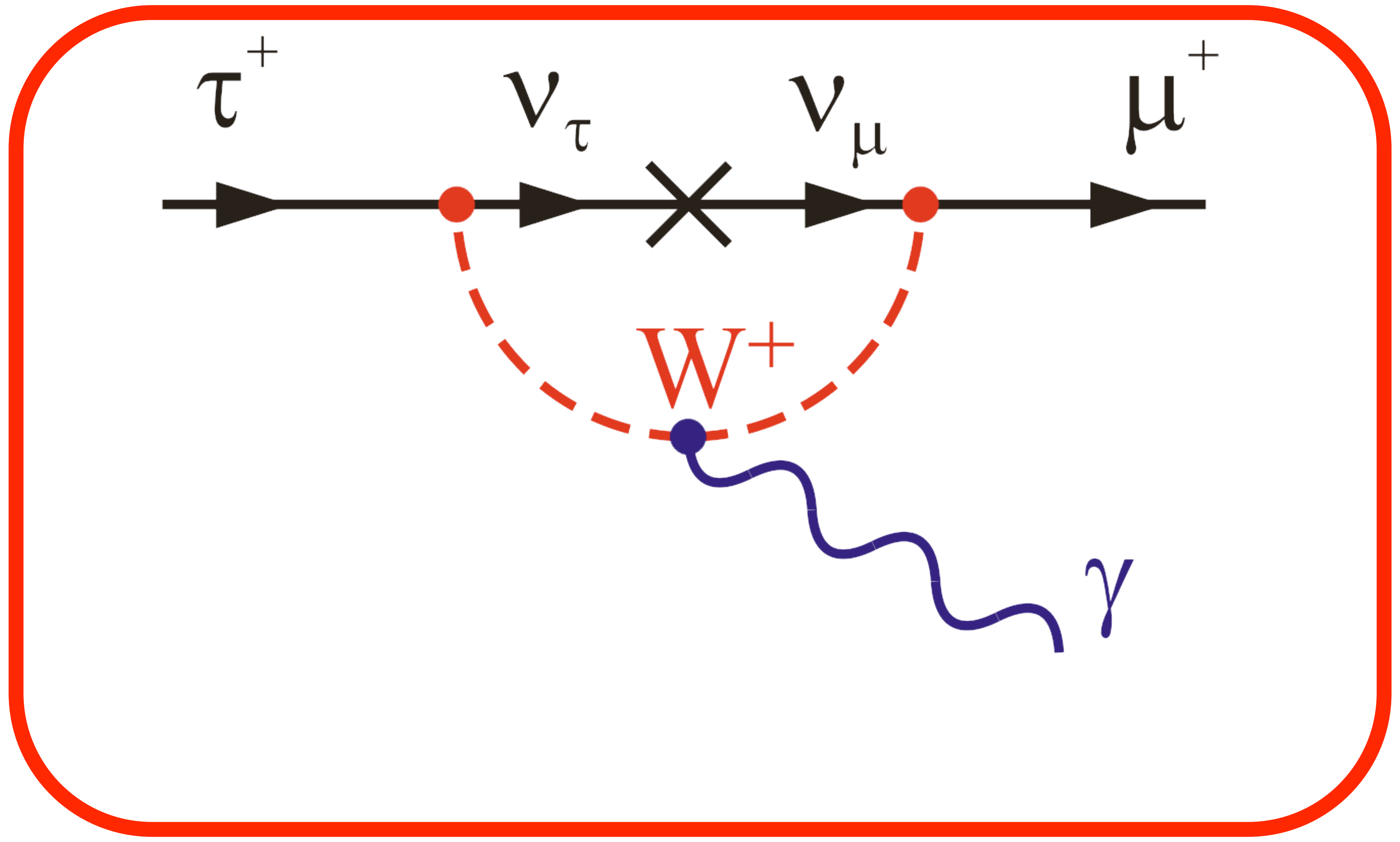
arxiv[HEP]: 2302.05225

CLFV and τ decays

- τ processes also suppressed in Standard Model but less w.r.t. μ:

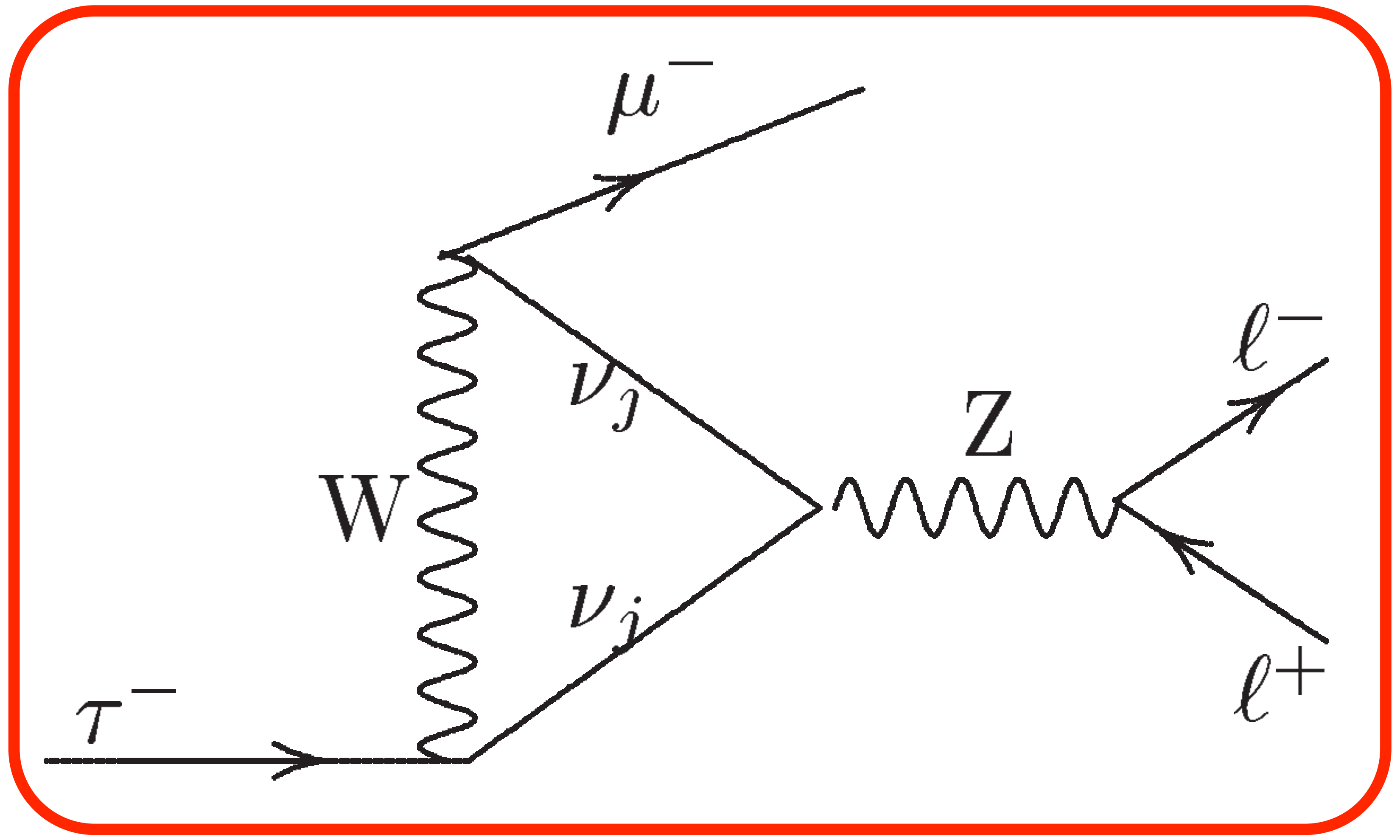
More in Swagato Banerjee's talk!

SM rate ~ 10^{-49}



Lee, Shrock, Phys.Rev.D16:1444,1977

SM rate ~ 10^{-14}

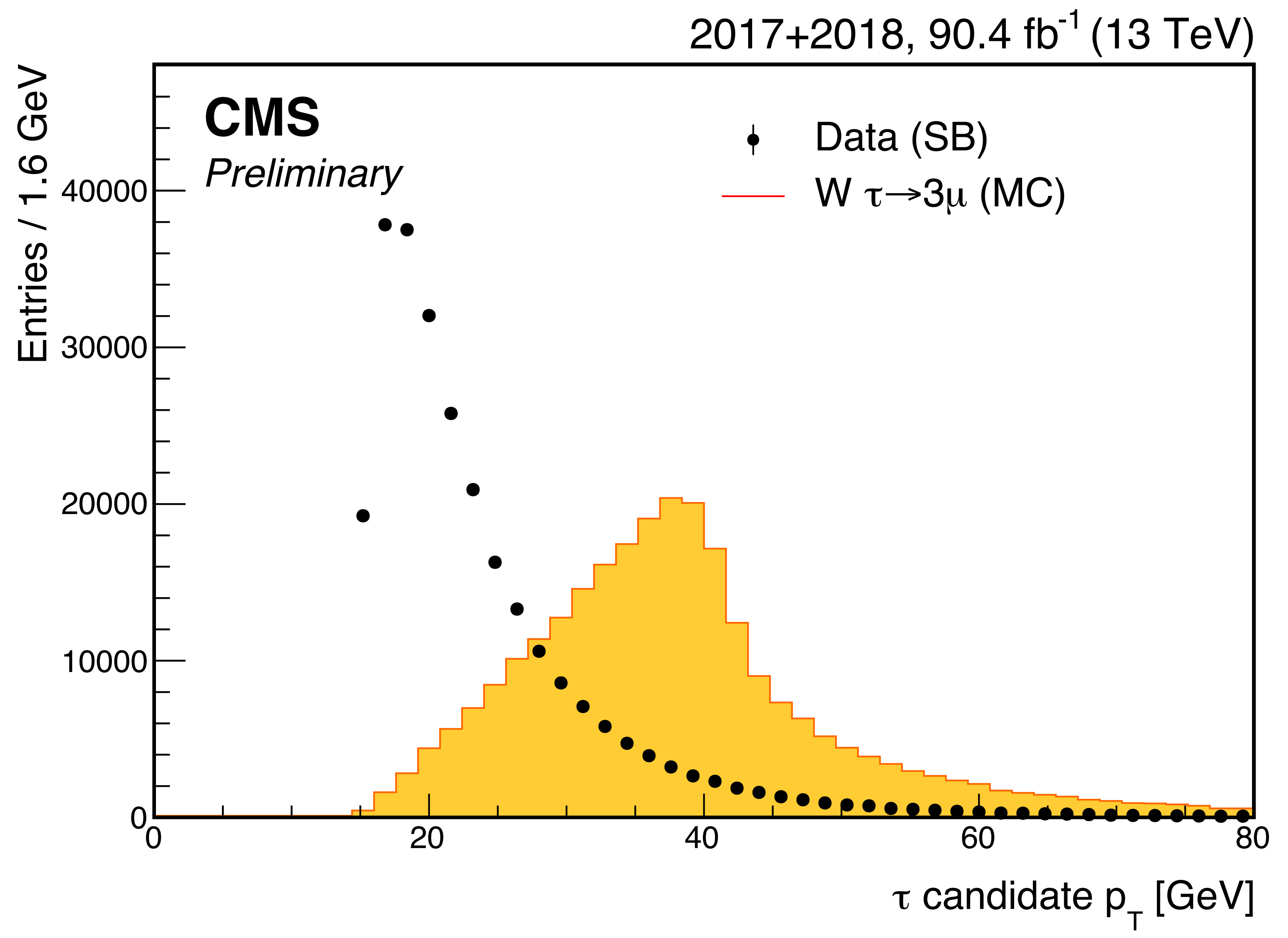


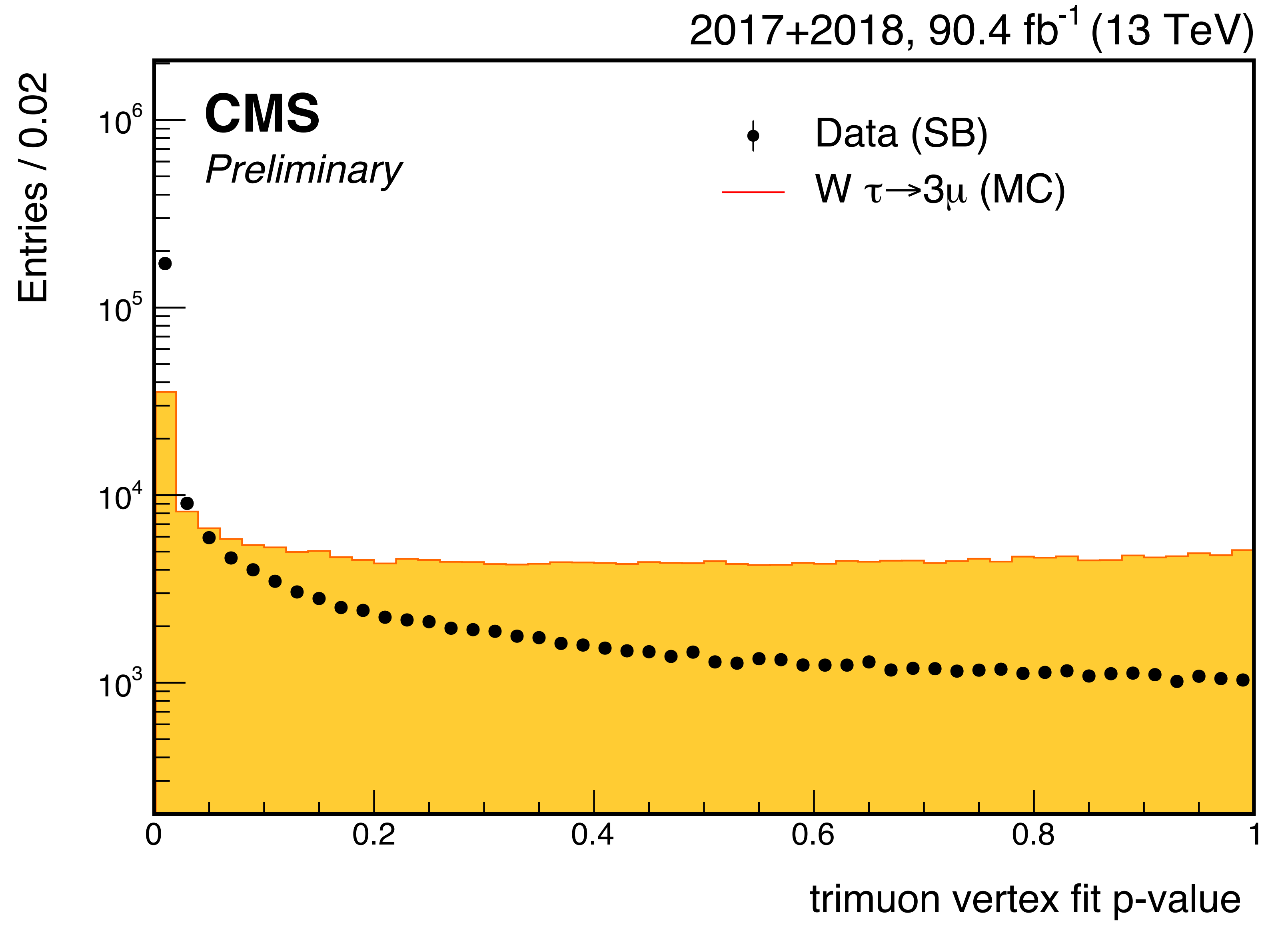
Pham, hep-ph/9810484

- **Advantage:** BSM rates can be orders of magnitude larger than in associated μ decays
- **Disadvantage:** τ's hard to produce. ~10^{10} τ/yr vs ~10^{11}μ/s in upcoming μ-experiments

$\tau \to \mu\mu\mu$ decay at CMS

- Search for LFV $\tau \to \mu\mu\mu$ decay with 90.4 fb^{-1}
- It includes tau production from heavy flavor (B, D) and W decays
  - $W \to \tau\nu$ populates more the high pT
- Muon pT>7, 1, 1 GeV fit to common vertex
- pT(3μ) > 15 GeV
- BDT to separate signal from background
  - Muon identification
  - $\tau \to \mu\mu\mu$ vertex: chi2, pointing angle
- Split into three categories based on 3μ mass resolution

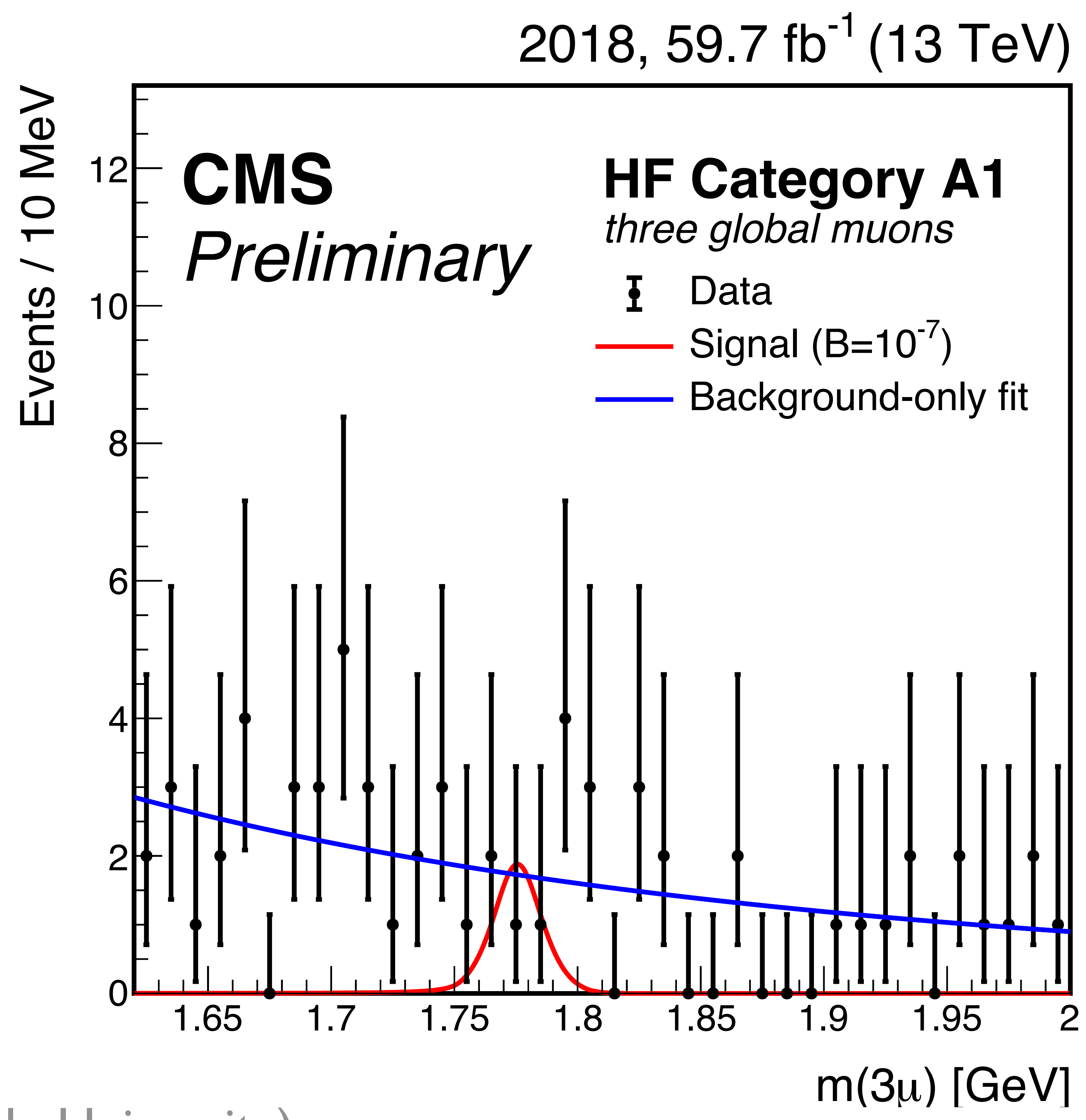


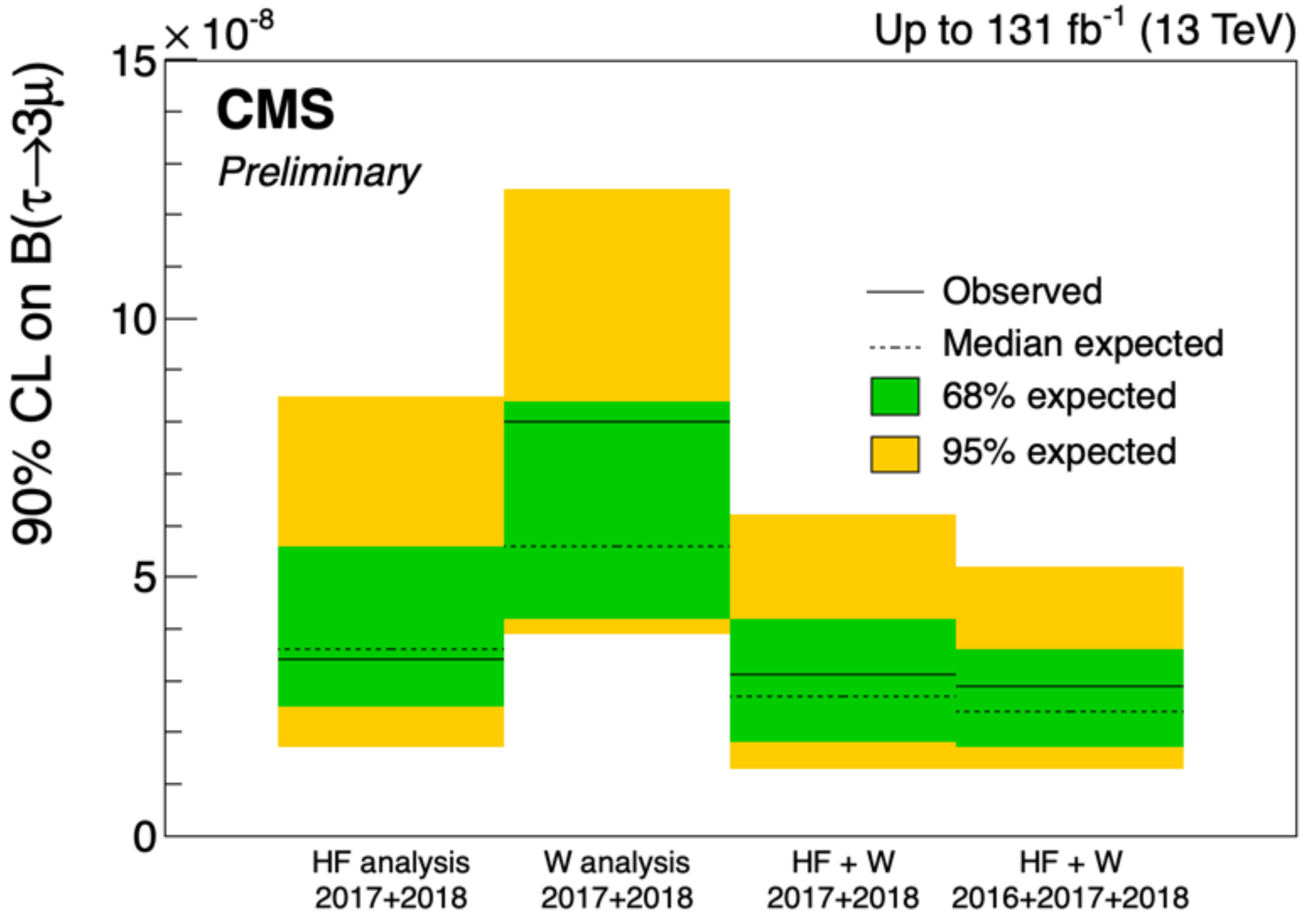


PAS-BPH-21-005

$\tau \to \mu\mu\mu$ decay at CMS

- Final result extracted from simultaneous parametrized fit to all the signal regions including the results from 2016 data
- Br($\tau \to \mu\mu\mu$) < 2.9 x10^{-8} at 90% CL
  - Getting very close to the world limit from Belle (2.1x10^{-8} at 90% CL)

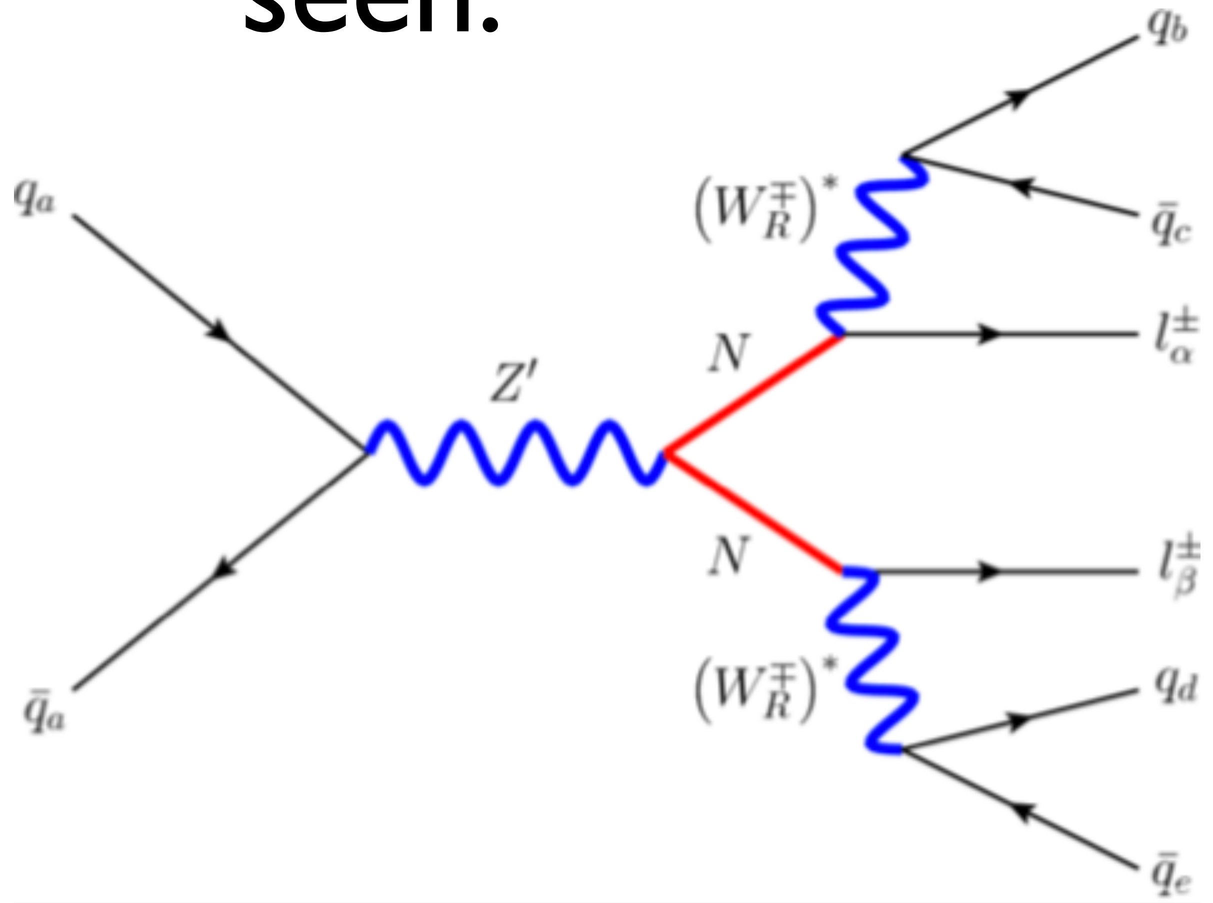


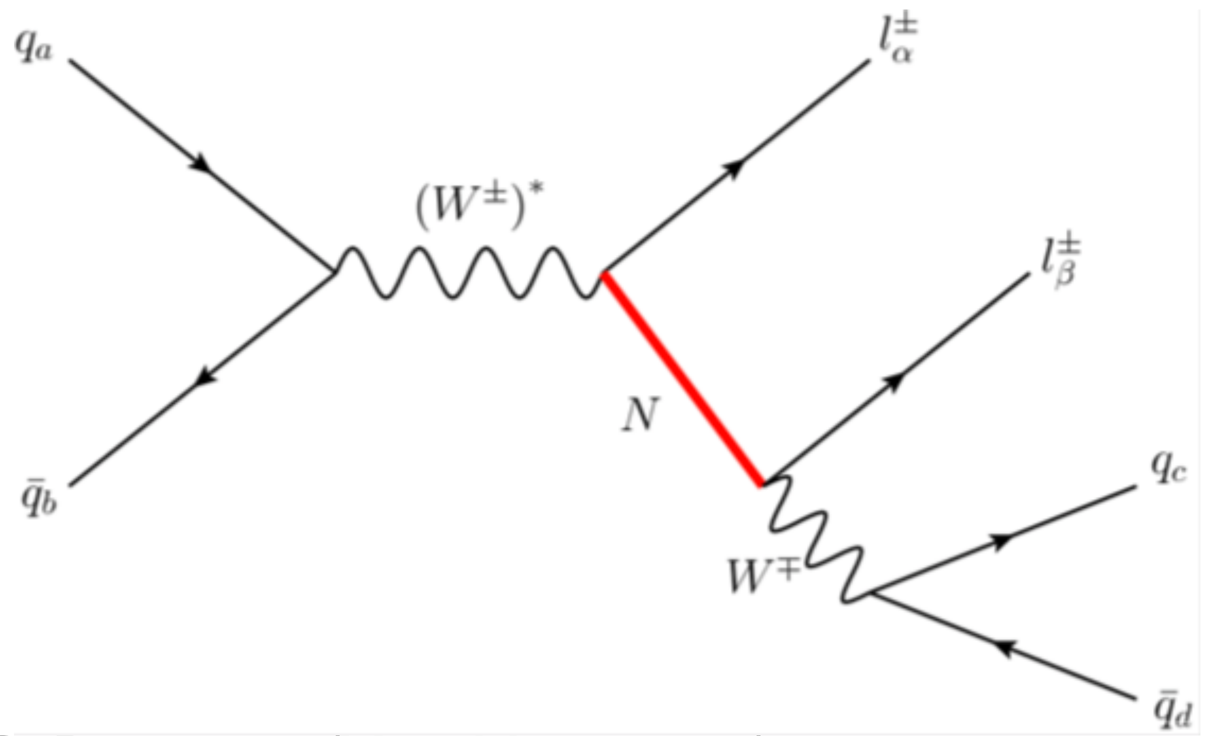


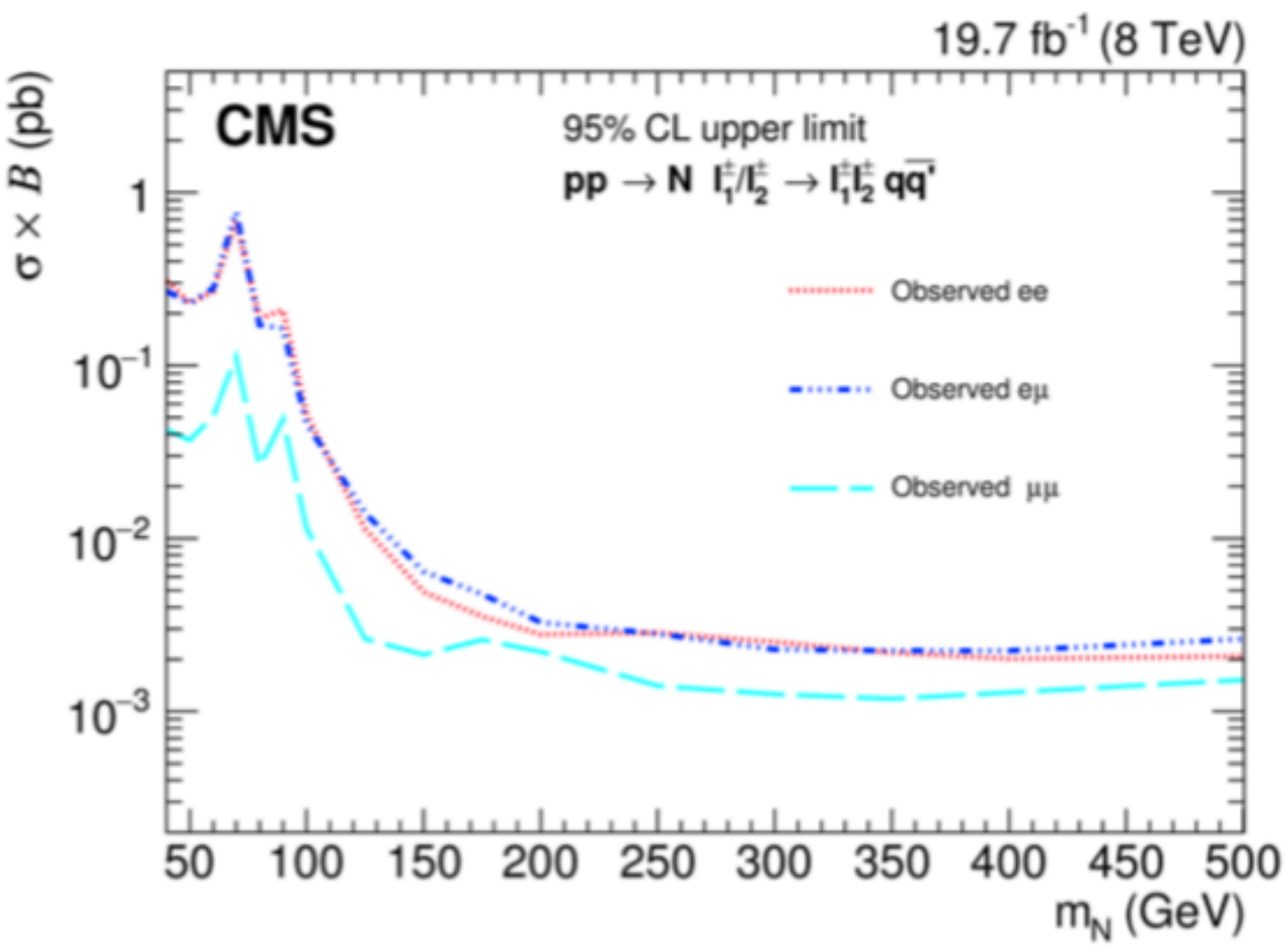
PAS-BPH-21-005

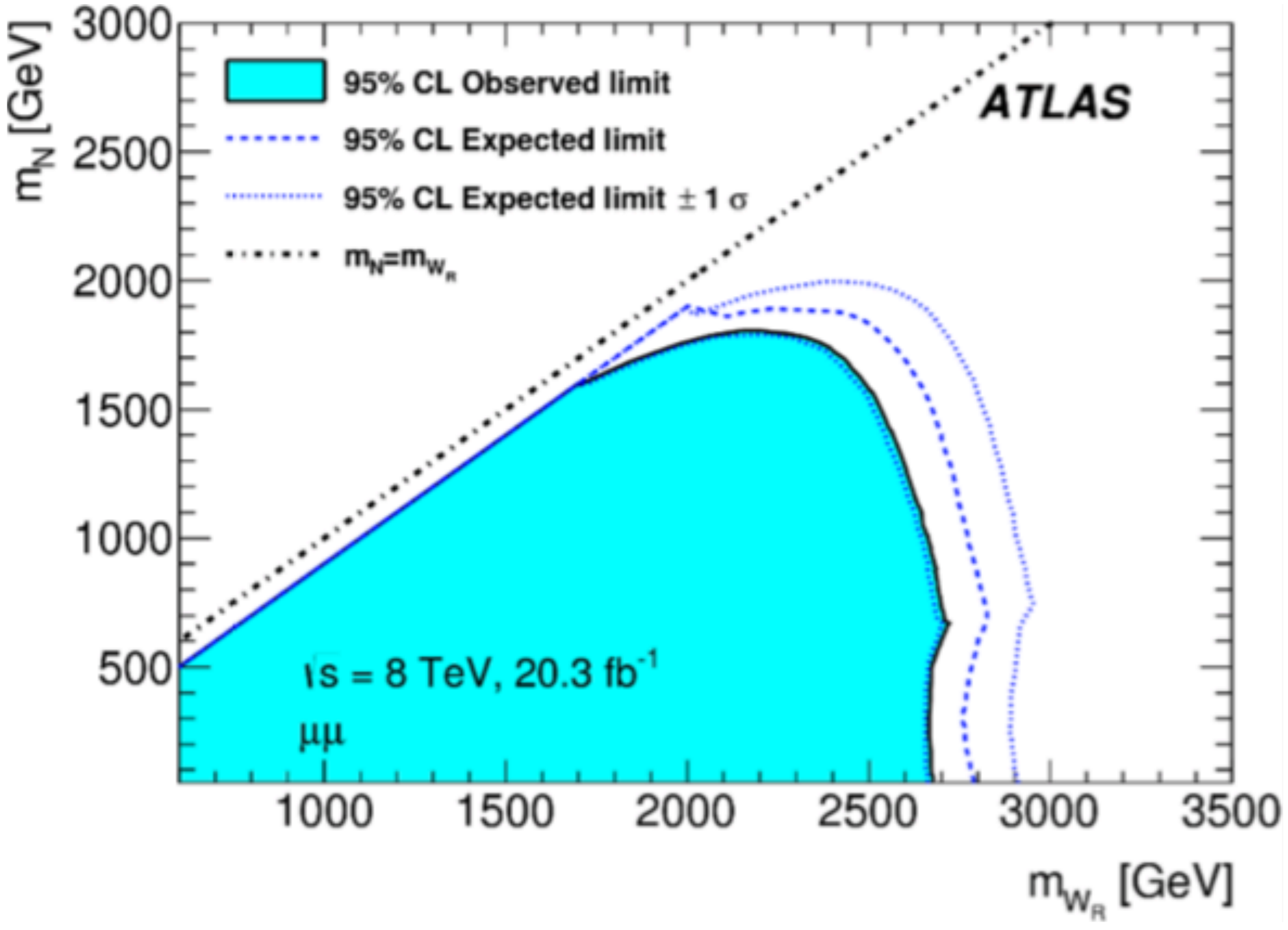
Majorana neutrinos at ATLAS/CMS

- Theories with heavy neutrinos (such as Seesaw models) may have lepton flavor and number violation.
- Search for events with same-sign dileptons ($e^{\pm}e^{\pm}$ or $\mu^{\pm}\mu^{\pm}$) and at least two jets. No excess seen.





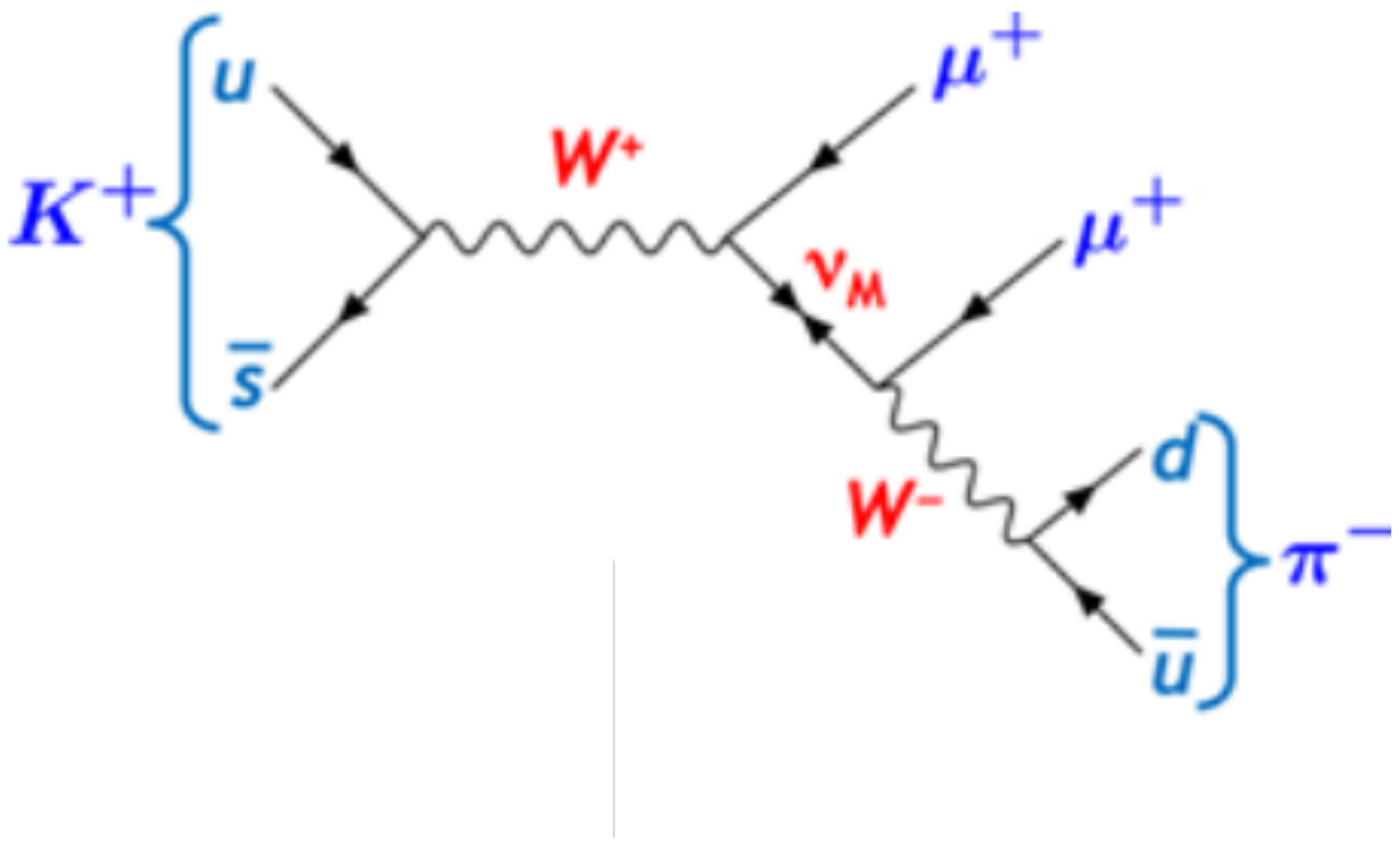


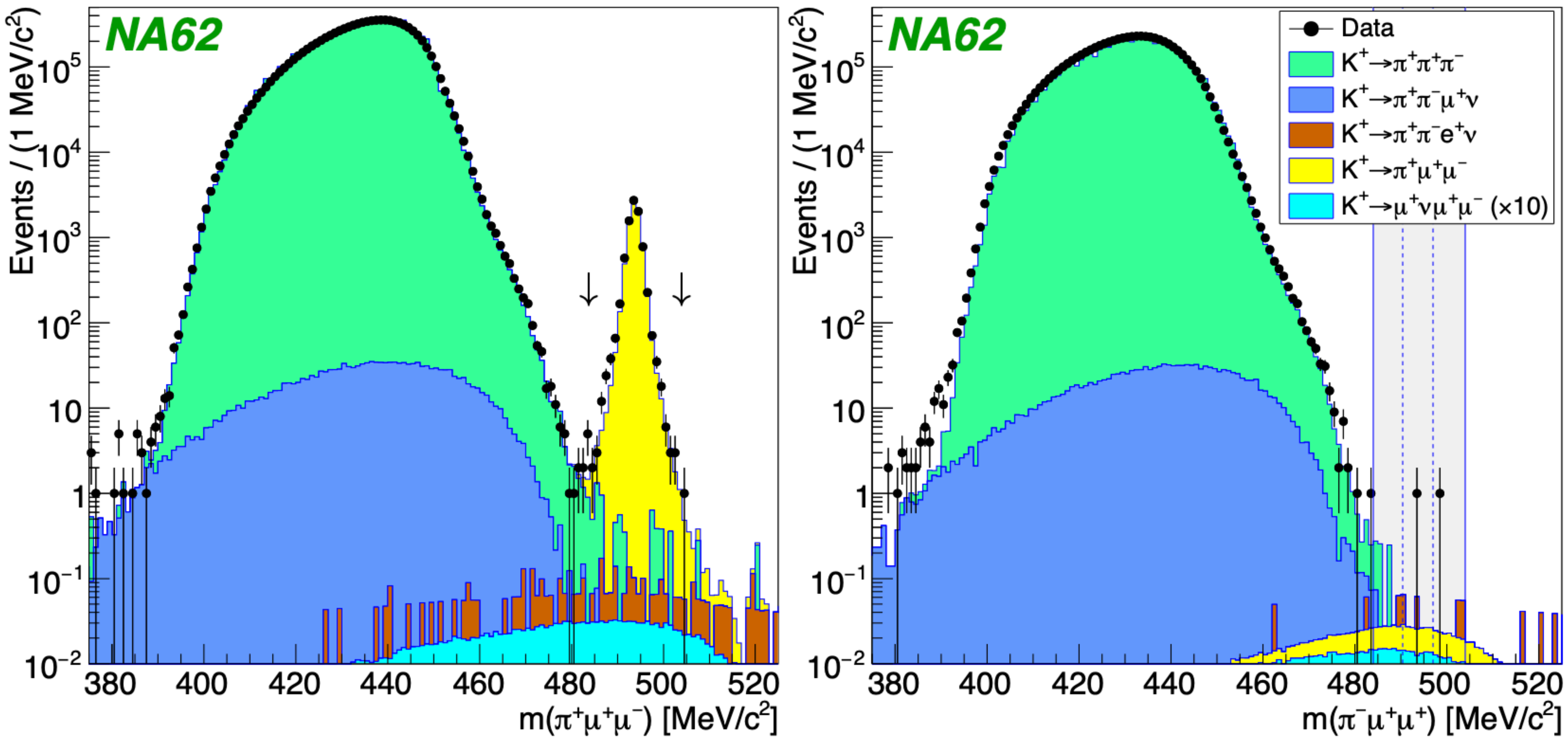


LNV in Kaons decay

- K decays can be accurately calculated in the SM
- NA62 used only ~30% of the data collected in 2016-2018

$$\mathcal{B}(K^+ \to \pi^- e^+ e^+) \quad < \quad 2.2 \times 10^{-10}$$
$$\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) \quad < \quad 4.2 \times 10^{-11}$$





PLB797 (2019)

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

CLFV within the US prioritization

- The P5 acknowledged and supports the current CLFV program

Exploring the Quantum Universe

Recommendation 1

Not Rank-Ordered

In addition, we recommend continued support for the following ongoing experiments at the medium scale (project costs > $50M for DOE and > $4M for NSF), including completion of construction, operations, and research:

d. **NOvA**, **SBN**, **T2K**, and **IceCube** (*elucidate the mysteries of neutrinos*, section 3.1).
e. **DarkSide-20k**, **LZ**, **SuperCDMS**, and **XENONnT** (*determine the nature of dark matter*, section 4.1).
f. **DESI** (*understand what drives cosmic evolution*, section 4.2).
g. **Belle II**, **LHCb**, and **Mu2e** (*pursue quantum imprints of new phenomena*, section 5.2).

The agencies should work closely with each major project to carefully manage the costs and schedule to ensure that the US program has a broad and balanced portfolio.

Exploring the Quantum Universe

Recommendation 4

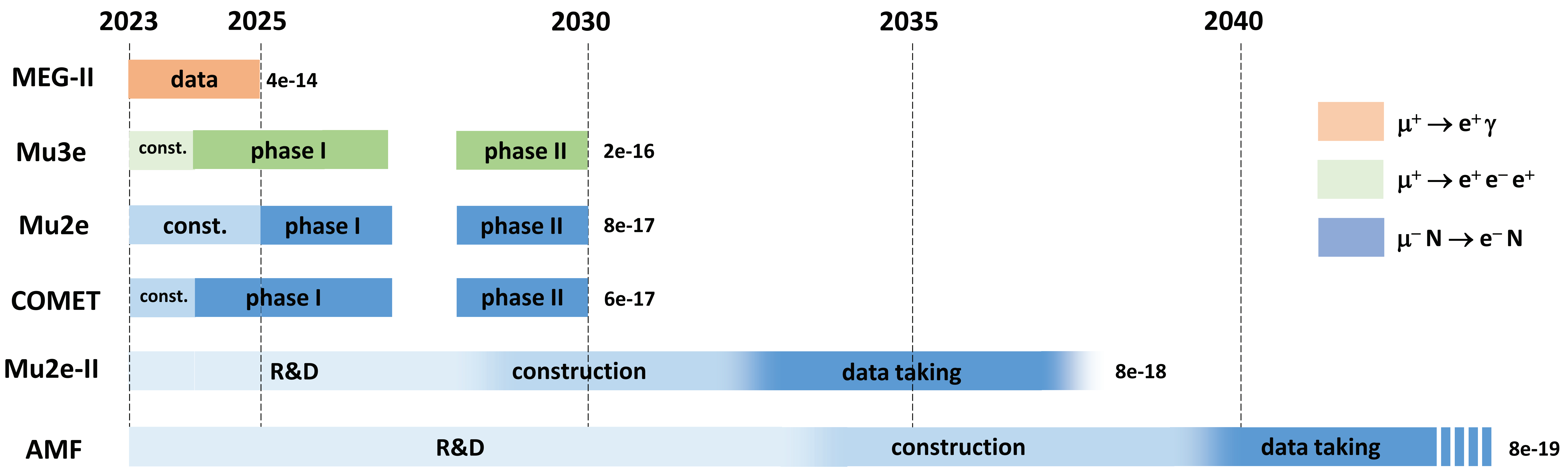
Not Rank-Ordered

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).
c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).
e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).
f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).
g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

- The P5 recommendations include R&D efforts towards Advanced muon facilities and Mu2e upgrade

Muon-beam based experiments - timelines

- Mu2e and COMET are under construction at Fermilab and J-PARK respectively
- Phase-I aims to reach x1,000 improvement w.r.t. the current best limit
- Phase-II will push the sensitivity at 6-8e-17



What I hope you will remember

- CLFV is about why there are flavors and generations.
  - not only the mass scale, but the couplings.
- Any signal is unambiguously new physics. We need multiple measurements to understand what we do or don't see
  - CLFV, neutrinos, K, dark matter,... are tightly linked and models have to fit all the data
  - low- and high-energy experiments are closely interrelated as well
- The experiments are challenging theories and getting better fast, with upgrades on the way.
- Within next ~5 years: muons will improve sensitivity by 10^4; Run-II data; e+e- and LHCb will probe τ , B sectors

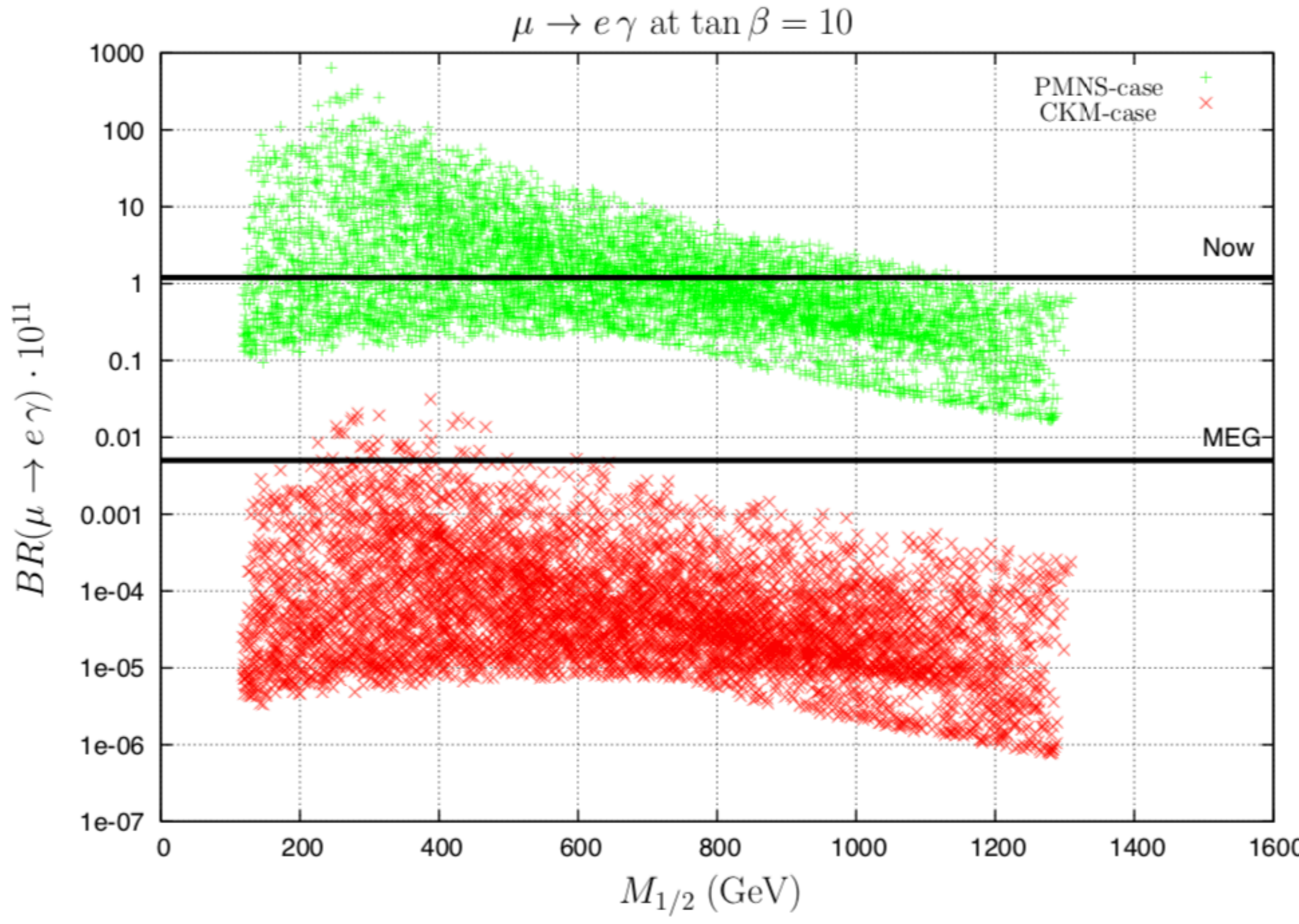
backup slides

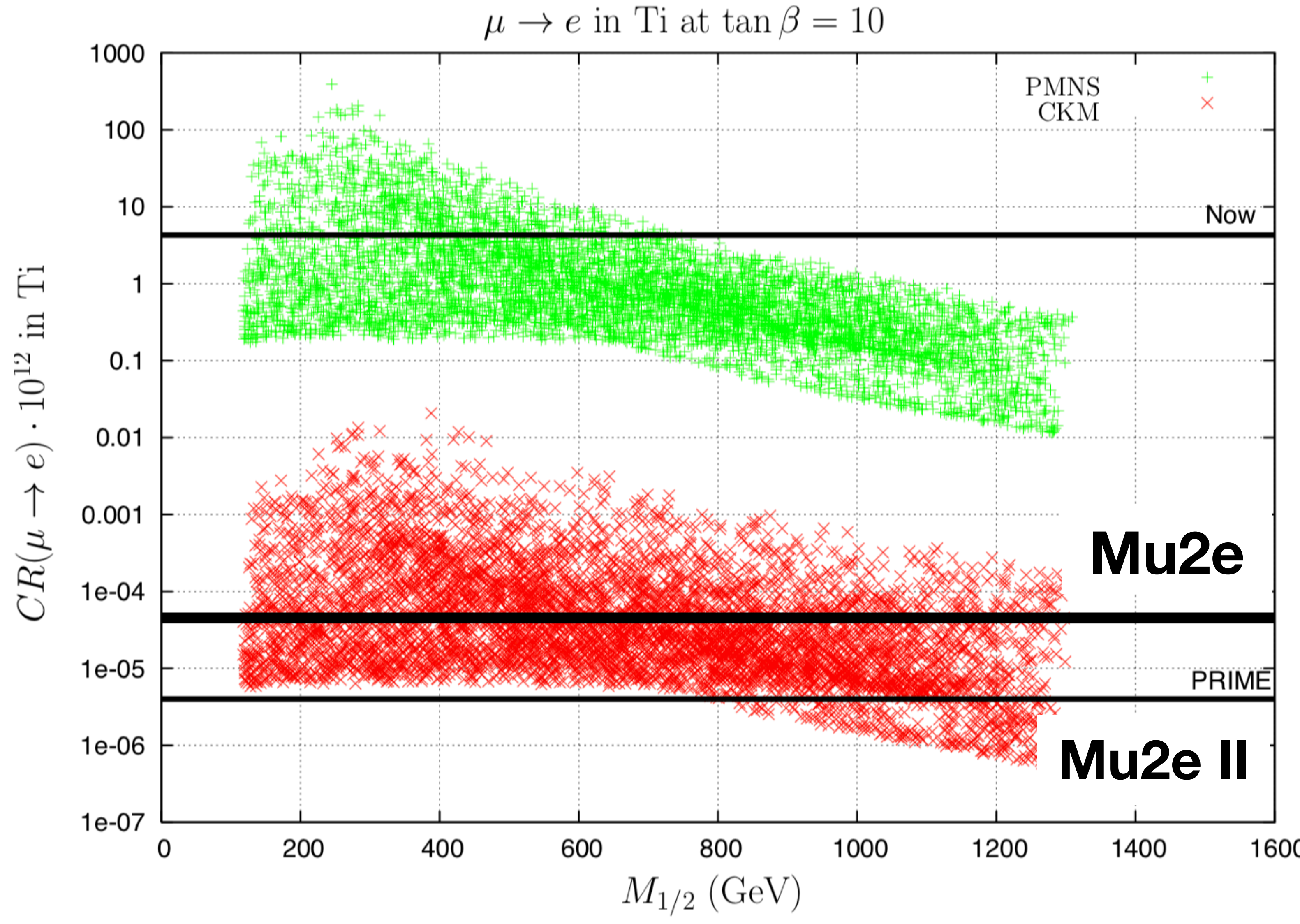
Review papers

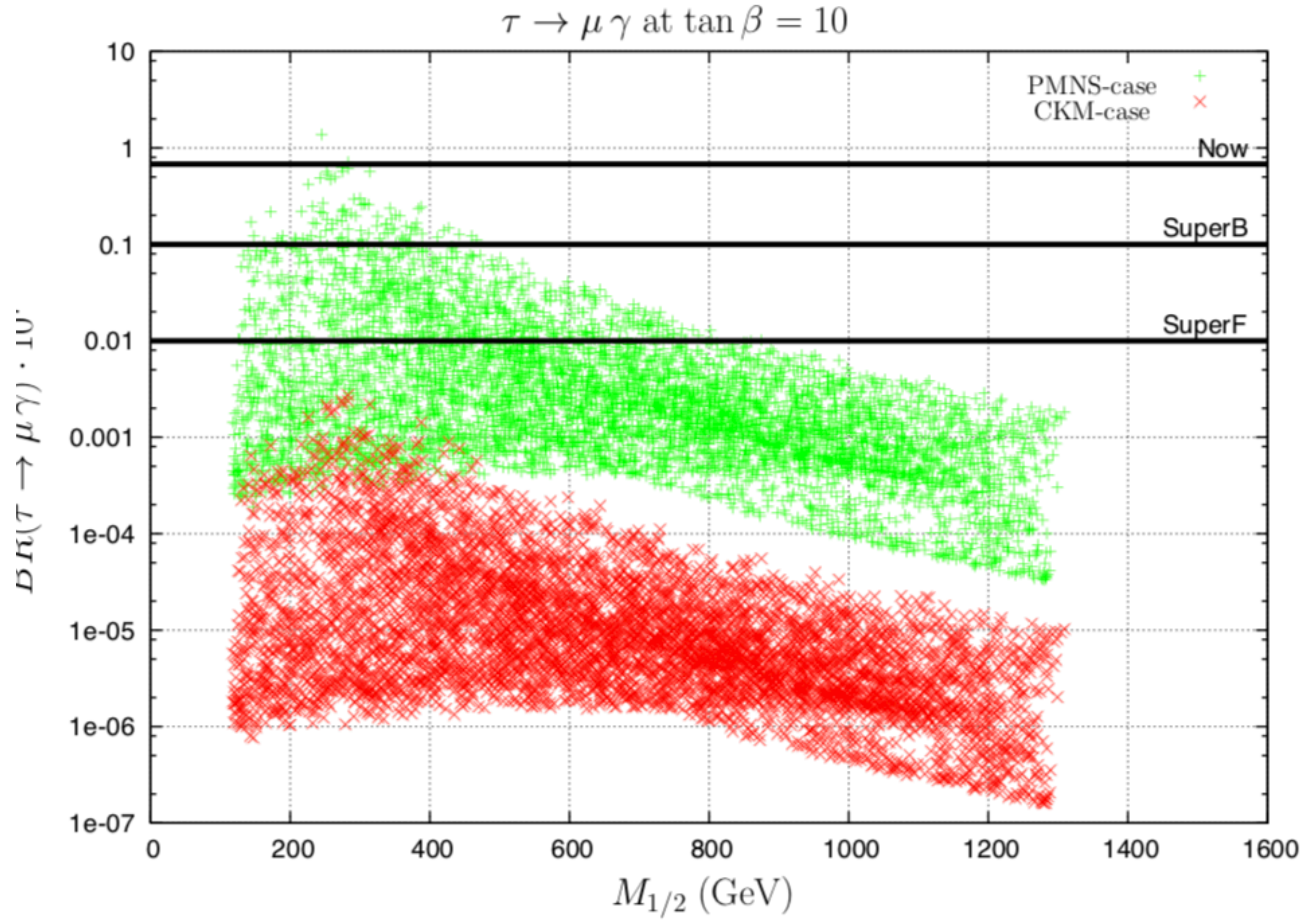
- André de Gouvêa and P.Vogel, https://arxiv.org/abs/1303.4097 S. Mihara et al. www.annualreviews.org/doi/abs/10.1146/ annurev-nucl-102912-144530
- Lorenzo Calibbi, Giovanni Signorelli, https://arxiv.org/abs/1709.00294
- RHB and P. Cooper, arxiv.org/abs/1307.5787, 10.1016/j.physrep.2013.07.002
- M. Raidal et al., Flavour physics of leptons and dipole moments, arXiv:0801.1826
- Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi: 10.1146/ annurev.nucl.58.110707.171126
- Y. Kuno and Y. Okada, 10.1103/RevModPhys.73.151, arXiv:hep-ph/9909265

Structure of Mass/Mixing matrix

- neutrino mass via the see-saw mechanism; SUSY-GUT framework
- upcoming measurements can distinguish between small-mixing ("**CKM-case**") and large-mixing ("**PMNS-case**")
- Muon-conversion experiments show the largest discovery potential





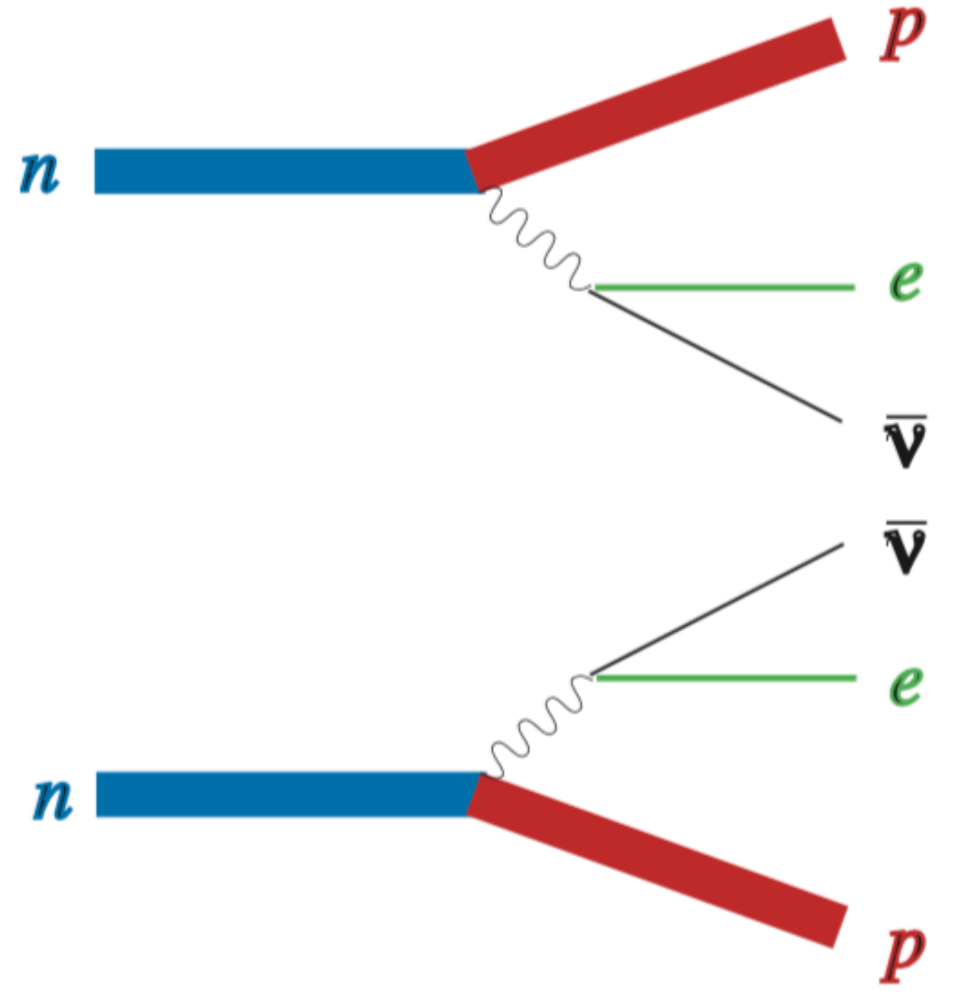


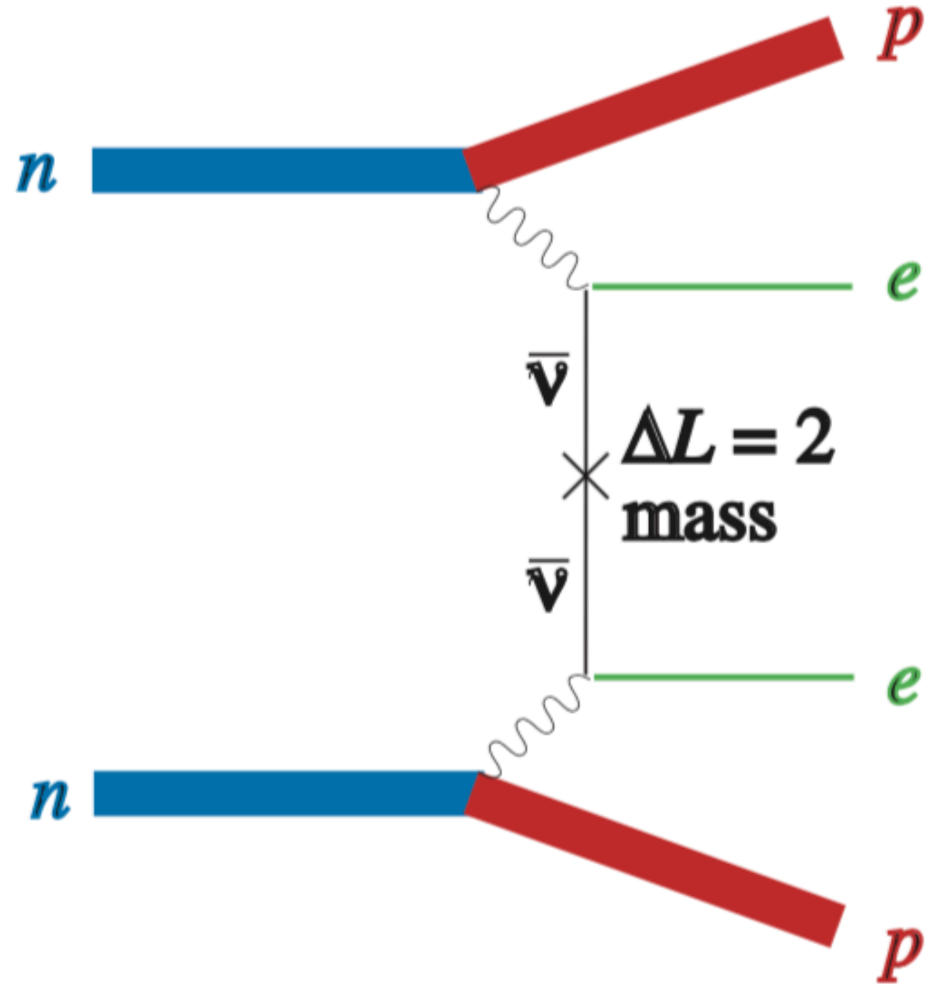
L. Calibbi, A. Faccia, A. Masiero S. Vempati

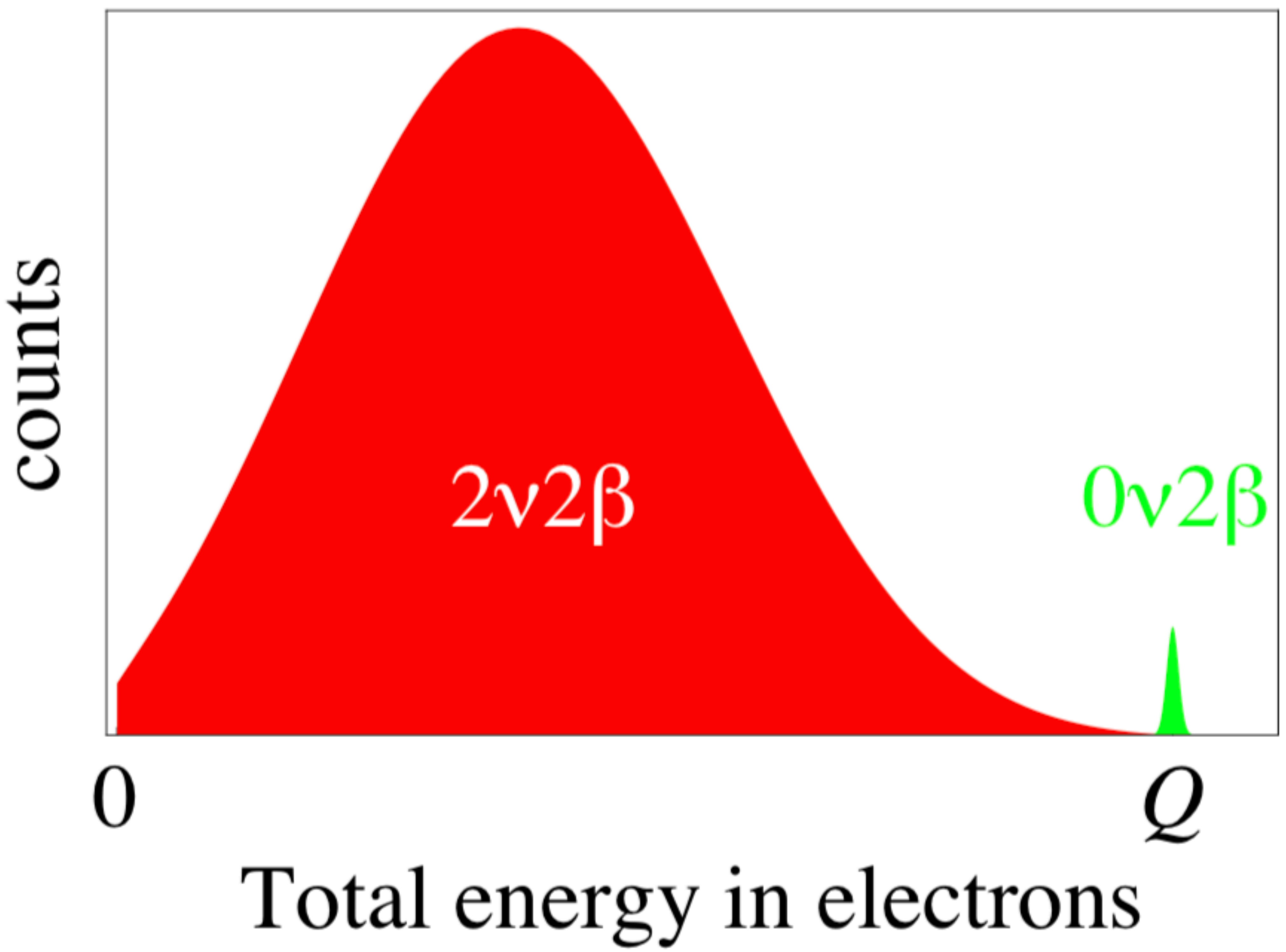
- $M_{1/2}$ is the "*sleptons*" mass, tanβ is the ratio btw the Higgs masses (2 doublets in SUSY!)

2ν2β and 0ν2β

- Double β decay: Ge(76,32) cannot β-decay to As(76,33) that is heavier, so it ββ decays
- Neutrino-less double β decay: rate = $|\Sigma V_{ei}^2 m_i|^2$ x uncertain nuclear physics.





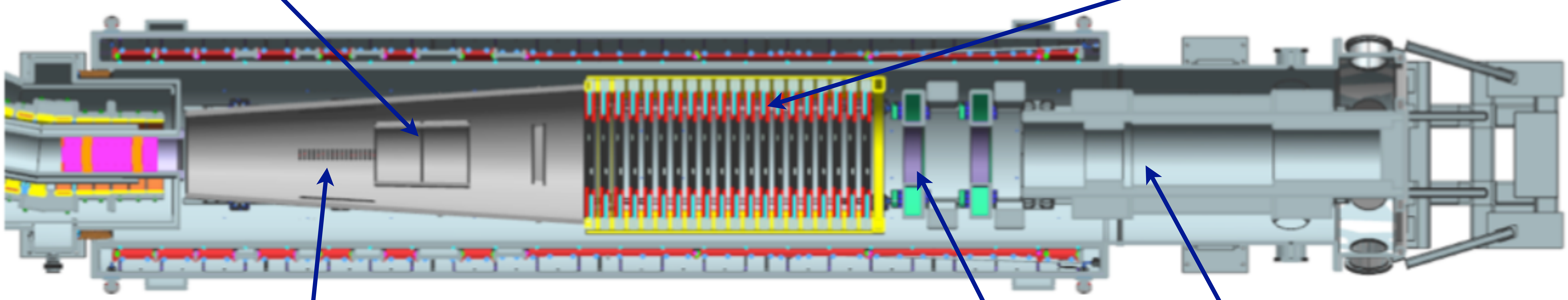


$$\tau \left(^{36}_{32}Ge \rightarrow ^{36}_{32} Se\ ee\bar{\nu}_e\bar{\nu}_e \right) \sim 10^{21} yr$$

Mu2e detector

- *Proton absorber:*
  - ❖ made of high-density polyethylene
  - ❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- *Tracker:*
  - ❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - ❖ Expected momentum resolution < 200 keV/c



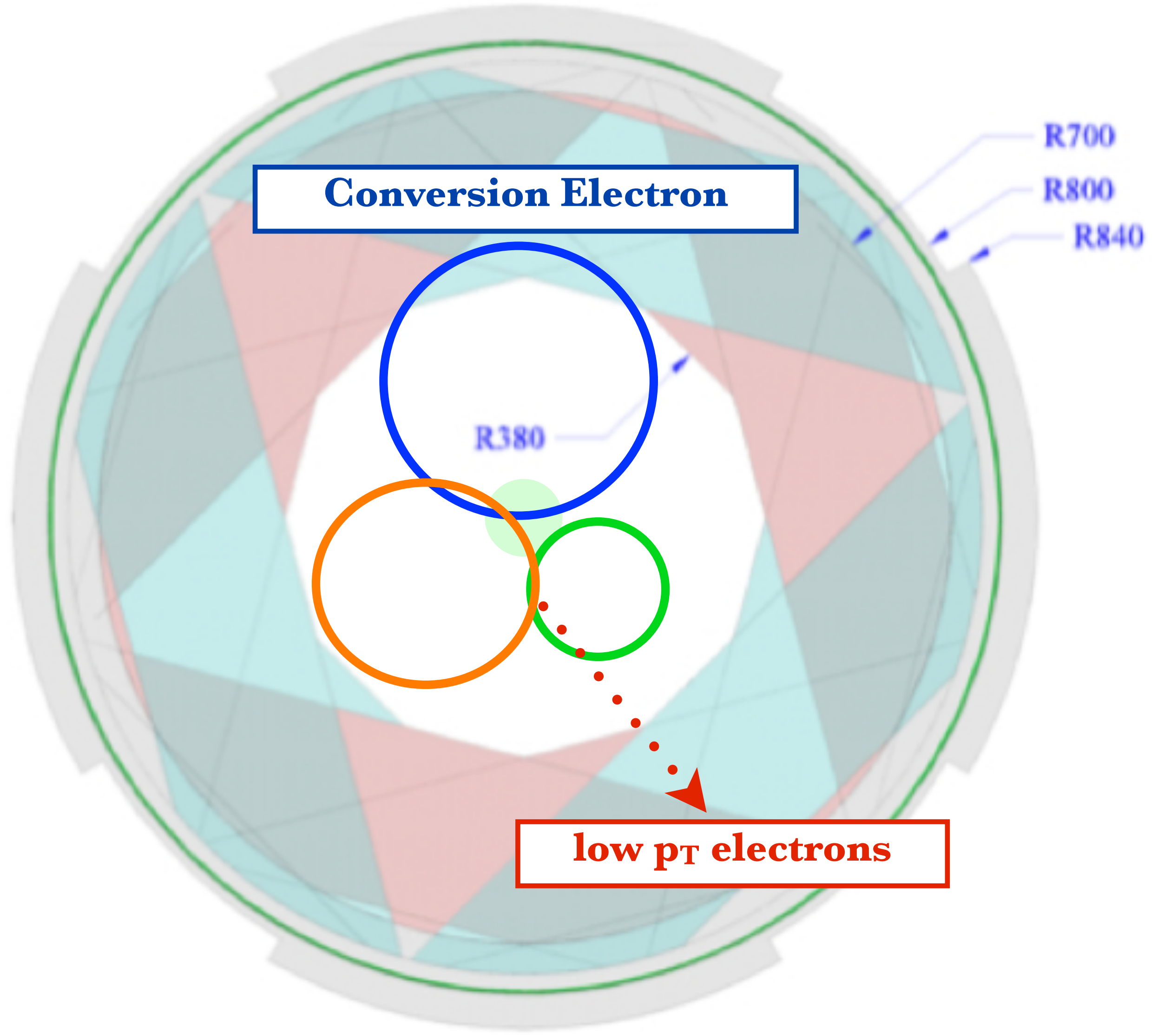
- *Targets:*
  - ❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

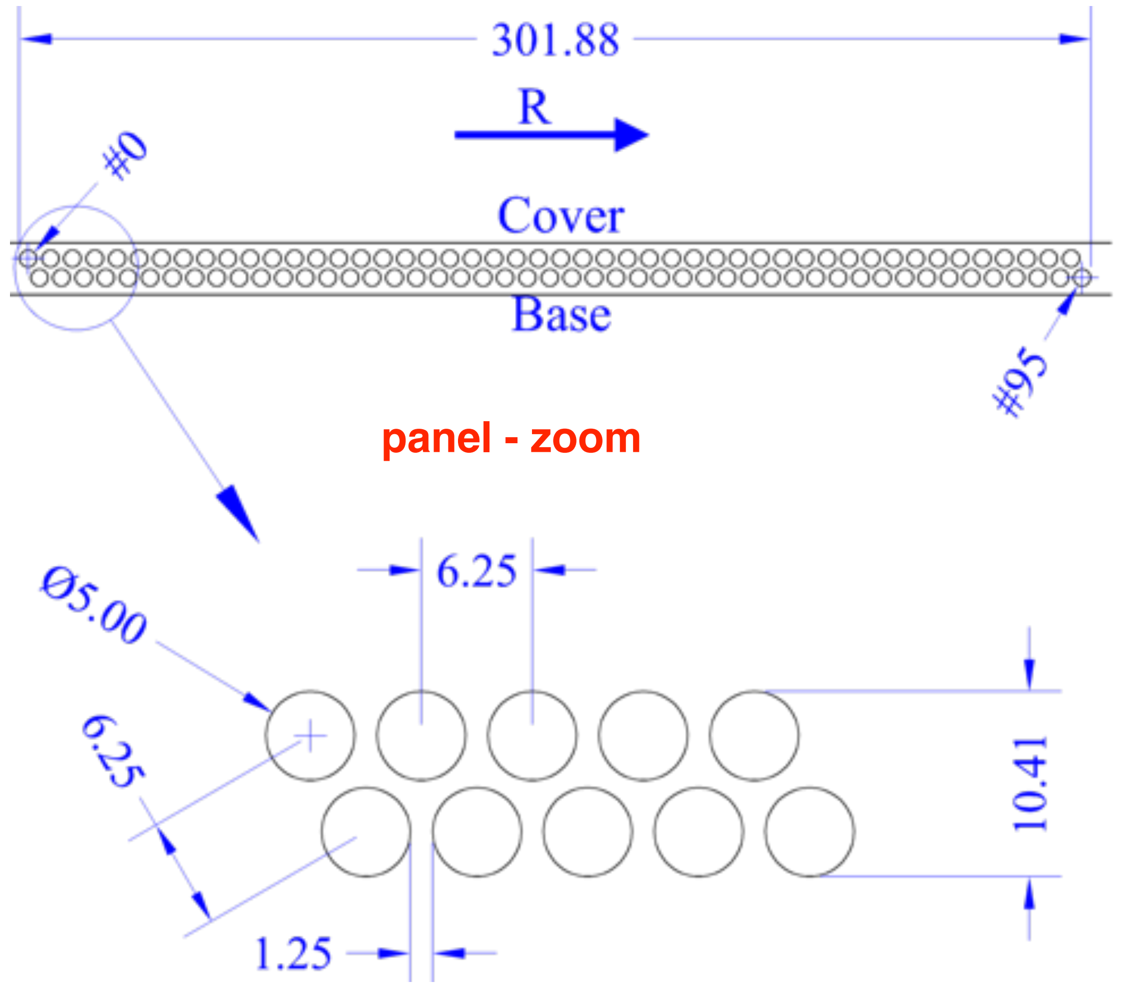
- *Calorimeter:*
  - ❖ 2 disks composed of undoped CsI crystals

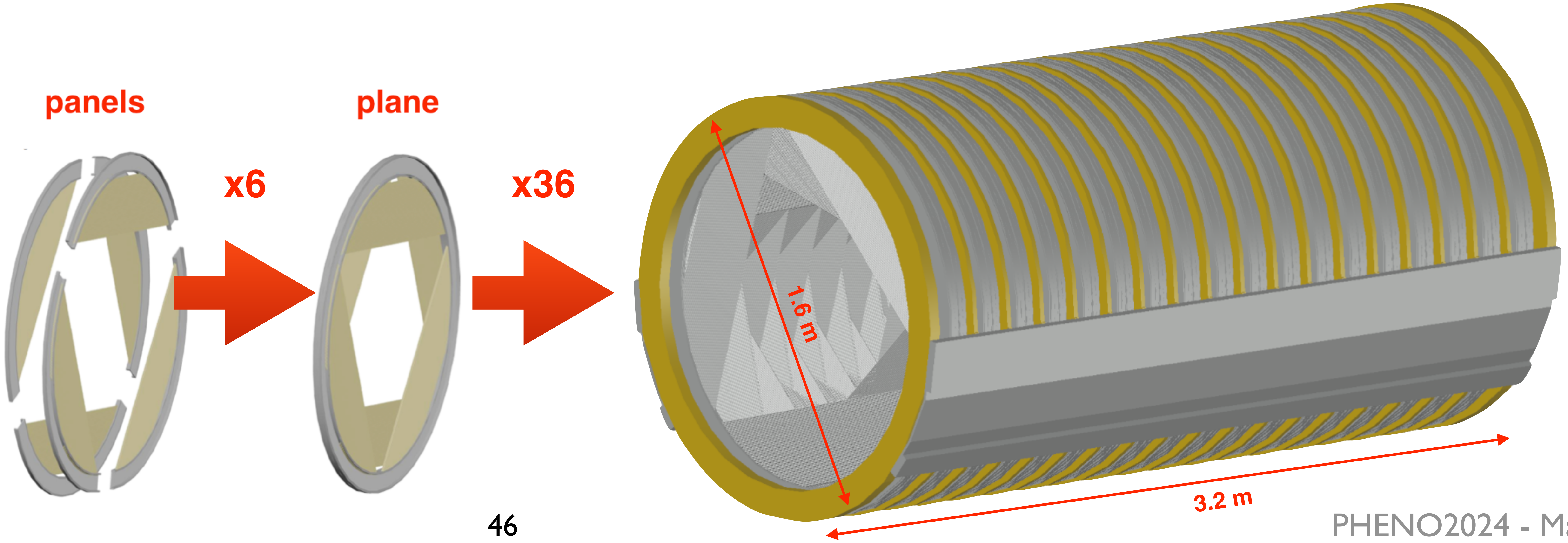
- *Muon beam stop:*
  - ❖ made of several cylinders of different materials: stainless steel and polyethylene

Mu2e tracker

- 36 planes equally spaced with straws transverse to the beam
- Straw technology employed:
  - ✓5 mm diameter, 12 μm Mylar walls
  - ✓25 μm Au-plated W sense wire
  - ✓80/20 Ar/CO_2 with HV ~ 1500 V
- Inner 38 cm un-instrumented:
  - ✓blind to beam flash
  - ✓blind to **low** pT particles, almost all the DIO



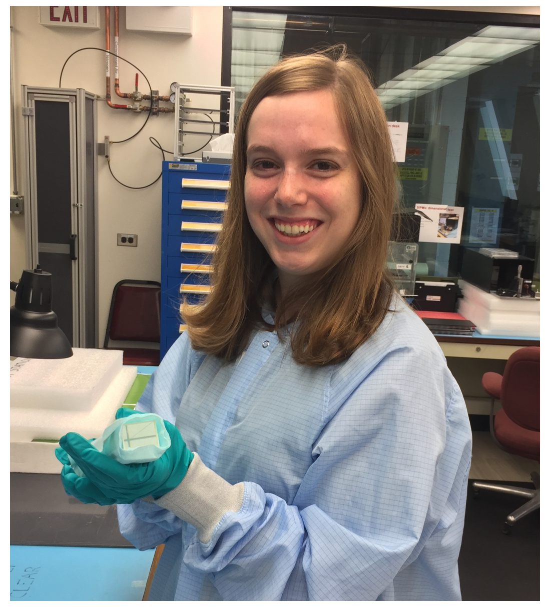


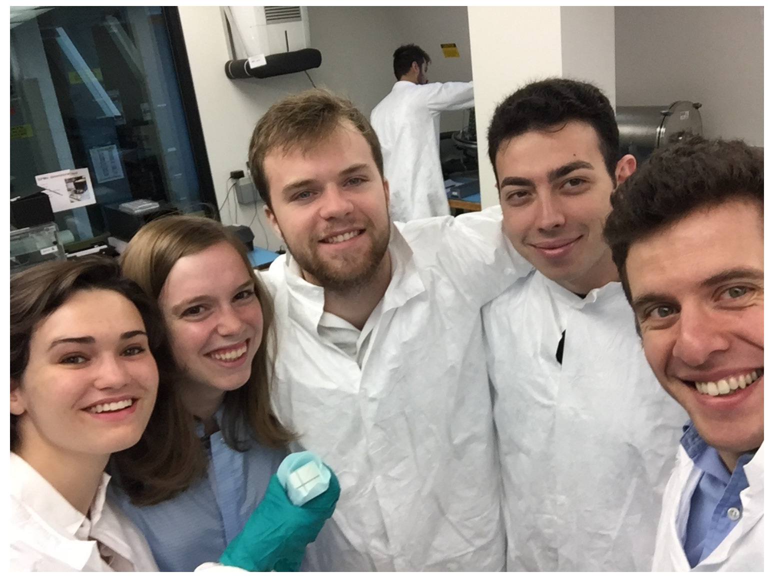


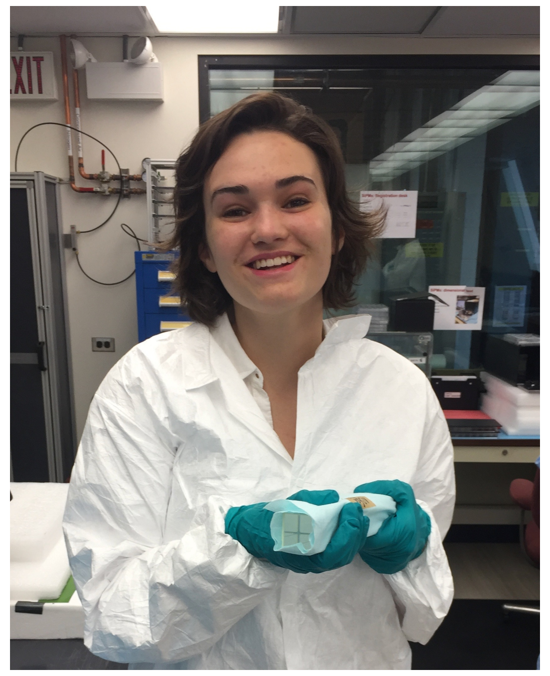
Mu2e calorimeter

- 2 disks; each disk contains 930 undoped CsI crystals 20 x 3.3 x 3.3 cm^3
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Readout system:
  ➡2 large area SiPM-array/crystal
  ➡12 bit, 200 MHz waveform-based digitizer boards

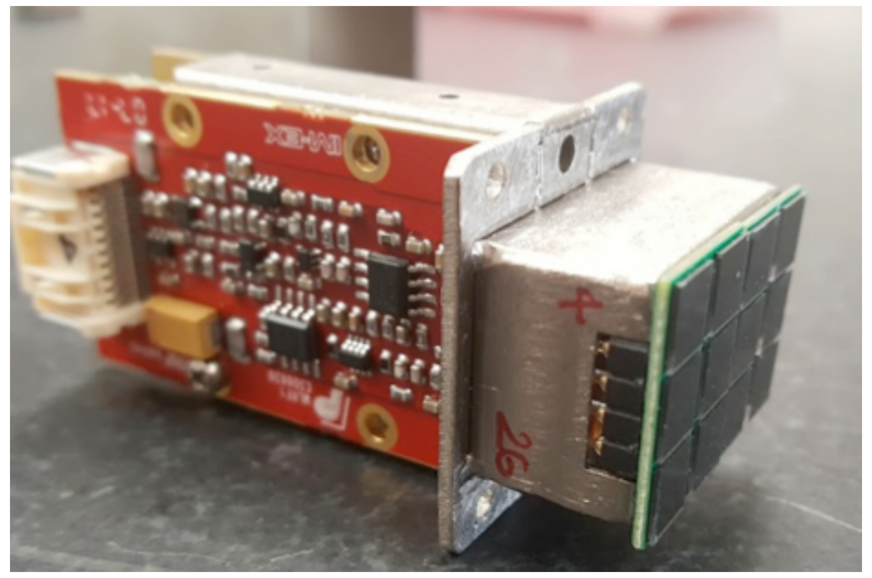
undoped CsI

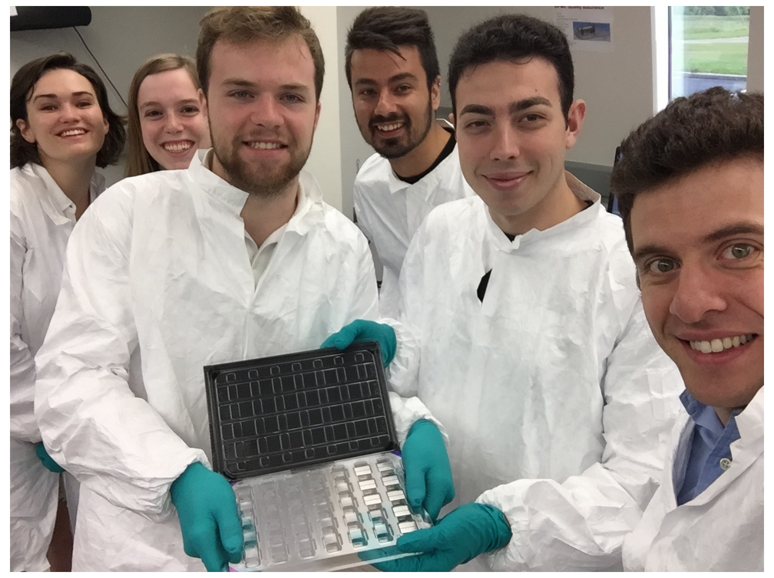




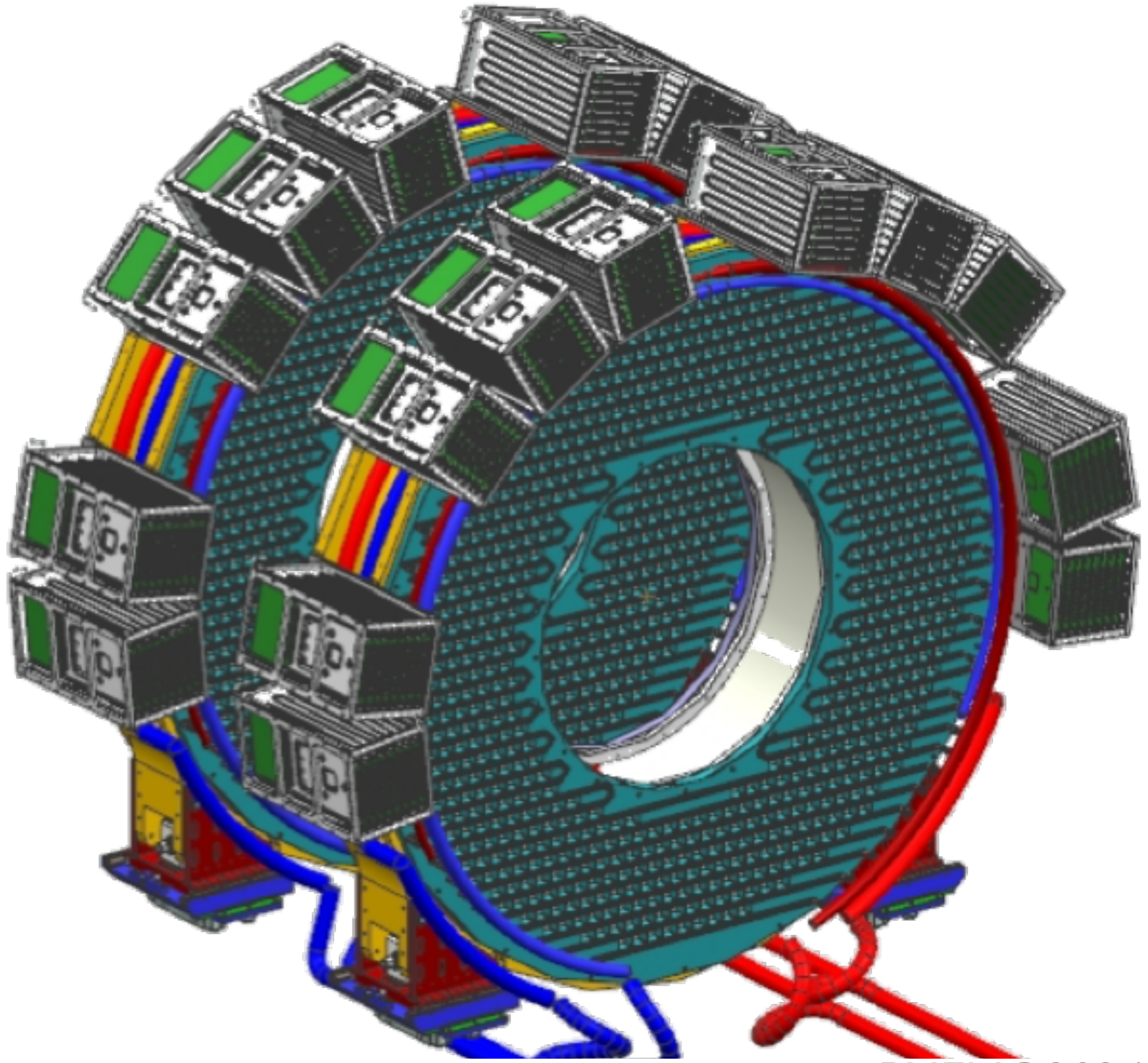


SiPM array





Calorimeter



Muonic atom life times