Experimental review of LFV searches.

Michel Hernandez Villanueva
DESY

The 2022 Conference on Flavor Physics and CP Violation (FPCP2022)
May 23-28, 2022

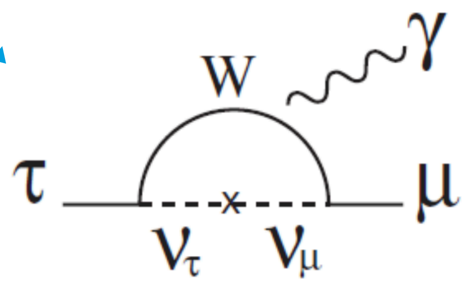
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Charged Lepton Flavor Violation

Clear signature for physics beyond the SM

- Quarks change generations.
- Neutrinos change flavor.
  - Lepton Flavor Violation (LFV) is an established fact, but only in neutrinos.
- What about charged leptons?
  - Neutrinos with mass —> CLFV
  - But extremely suppressed.

SM case:
BR ~10^{-54}



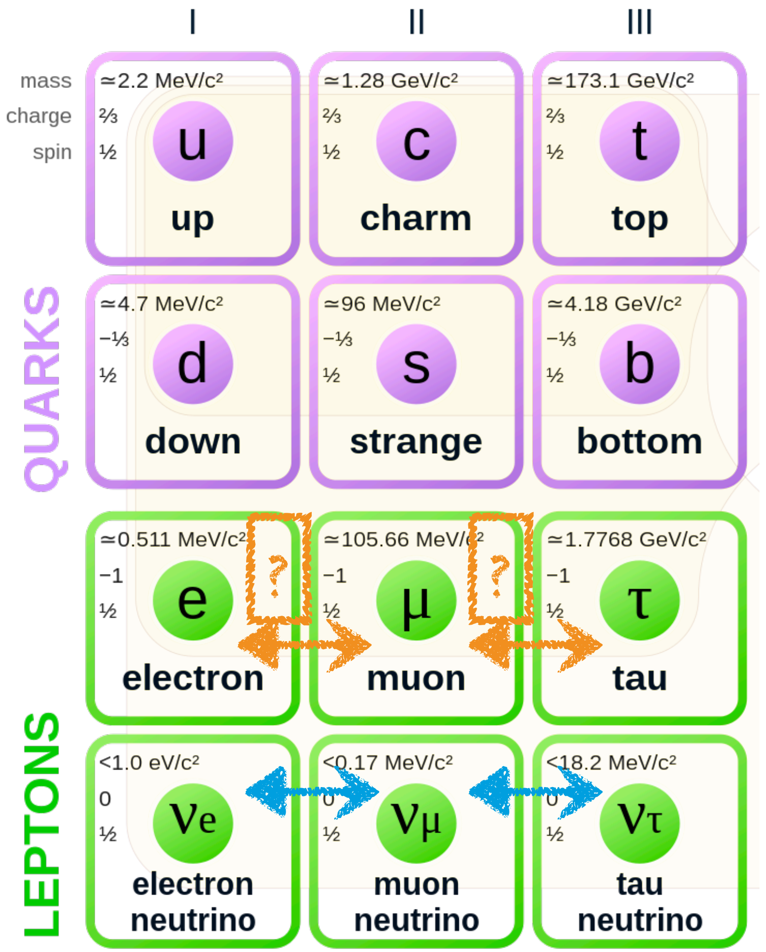


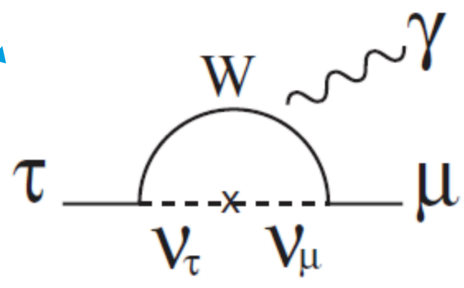
Figure: Wikipedia

Charged Lepton Flavor Violation

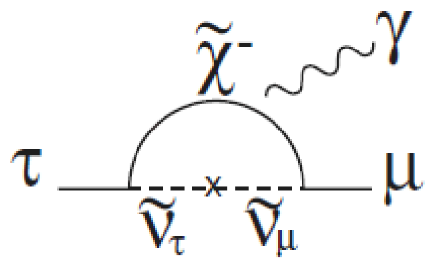
Clear signature for physics beyond the SM

- Quarks change generations.
- Neutrinos change flavor.
  - Lepton Flavor Violation (LFV) is an established fact, but only in neutrinos.
- What about charged leptons?
  - Neutrinos with mass —> CLFV
  - But extremely suppressed.
- **Observation of CLFV is a clear signature of New Physics!**

SM case:
BR ~10^{-54}



NP case:
BR ~10^{-7} - 10^{-10}



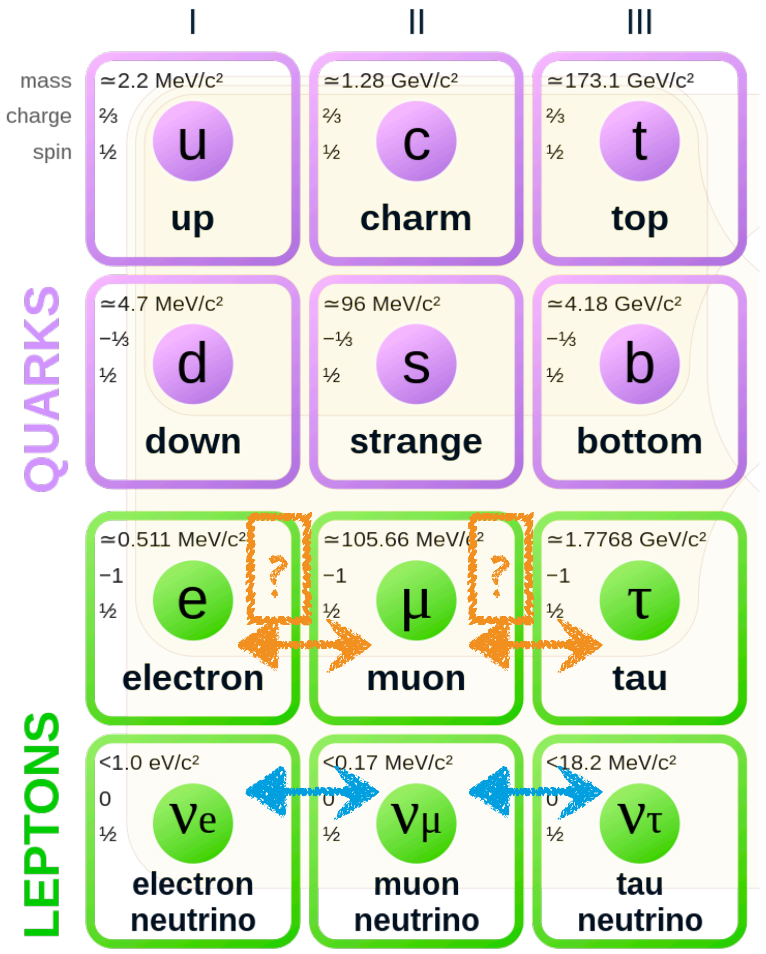
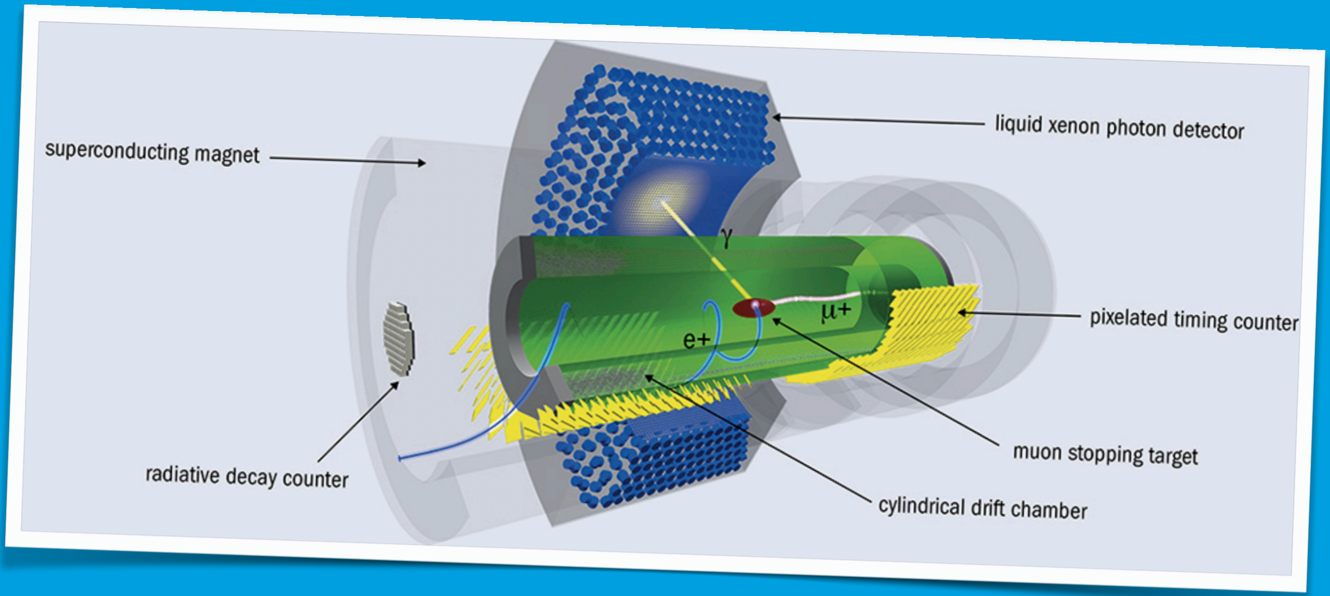
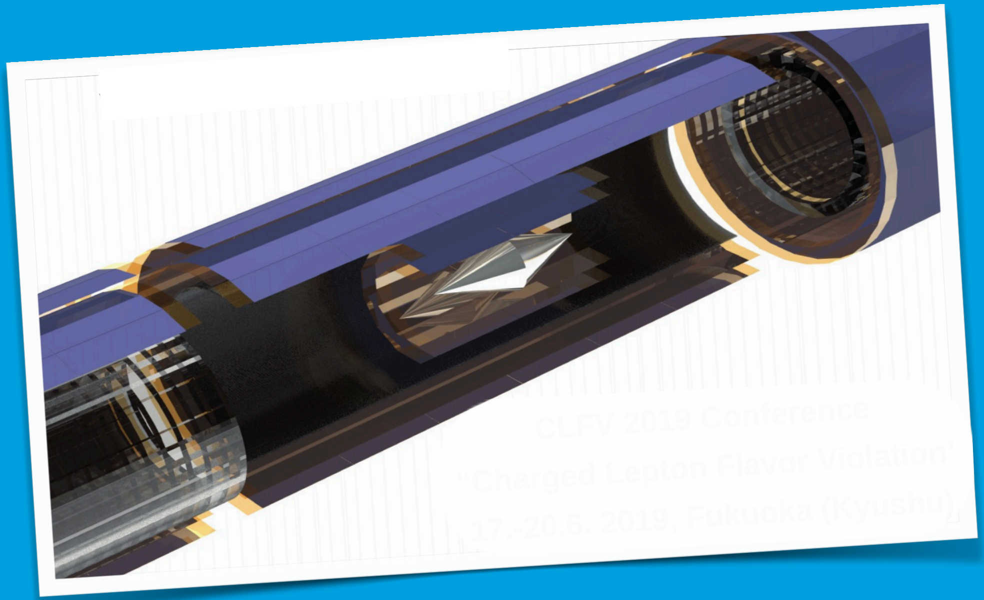


Figure: Wikipedia

CLFV in muons

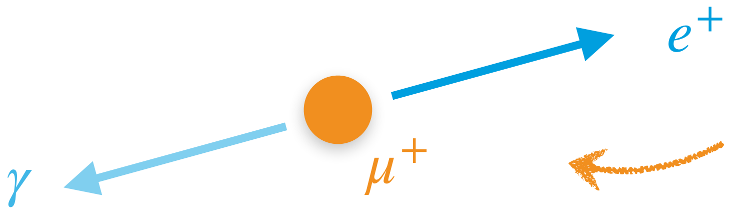




$\mu^+ \to e^+\gamma$

Oldest and most-constrained LFV mode.

- In the CMS, the final state is a back-to-back, **monochromatic** (52.8 MeV) positron and photon.

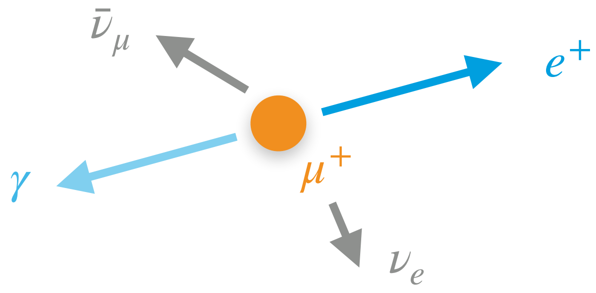


1) μ^+ cannot be captured in Nuclei.
2) The muon beam comes from proton-target interactions.

- Two sources of background:

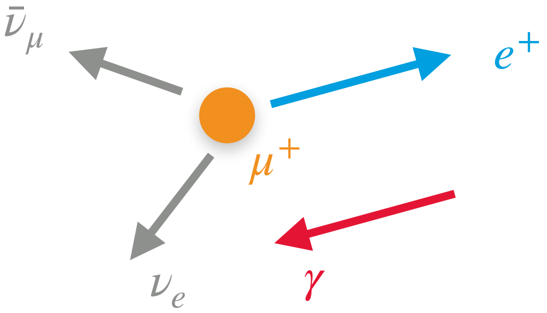
Irreducible background

$\mu^+ \to e^+\gamma\nu_e\bar{\nu}_\mu$



“Accidental” background

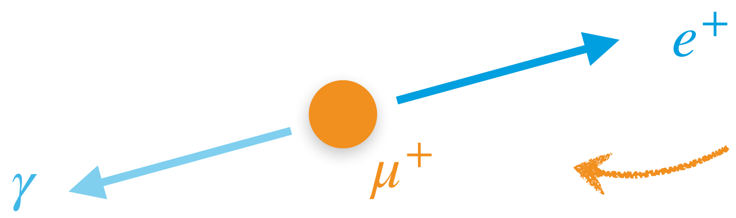
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu + \gamma$ from elsewhere.



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

Oldest and most-constrained LFV mode.

- In the CMS, the final state is a back-to-back, **monochromatic** (52.8 MeV) positron and photon.

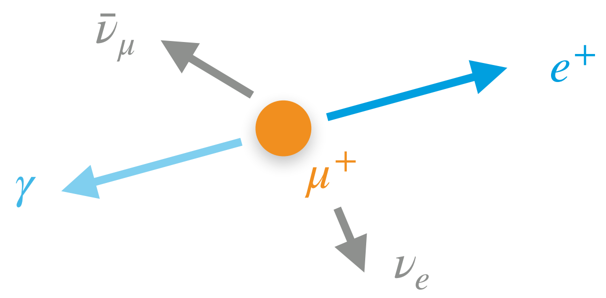


1) μ^+ cannot be captured in Nuclei.
2) The muon beam comes from proton-target interactions.

- Two sources of background:

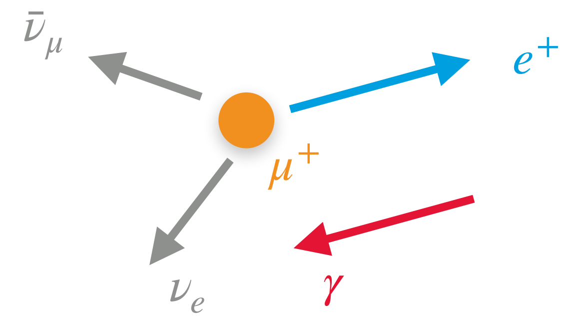
Irreducible background

$\mu^+ \to e^+\gamma\nu_e\bar{\nu}_\mu$



"Accidental" background

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu + \gamma$ from elsewhere.



- First search of a CLFV mode (even before the neutrino was discovered):

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. HINCKS AND B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
December 9, 1947

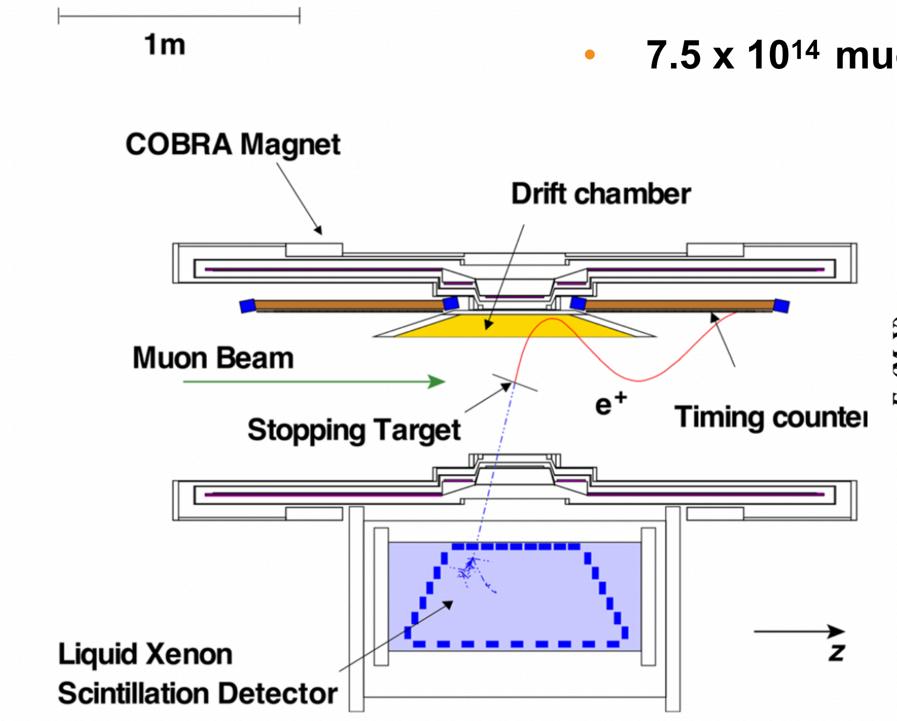
THE meson decay process which is identified by a mean life of 2.2 microseconds[1] has been usually thought of as consisting of the emission of an electron and a single neutrino, as suggested by the well-known Yukawa explanation of the ordinary beta-process in nuclei. However, the Yukawa theory is at variance with the results of the experiment of Conversi, Pancini, and Piccioni,[2] and since there remains no strong justification for the electron-neutrino hypothesis,[3] a direct experiment to test an alternative hypothesis—*that the decay process consists of the emission of an electron and a photon, each of about 50 Mev*—has been performed.

Phys.Rev. 73 (1948) 257-258

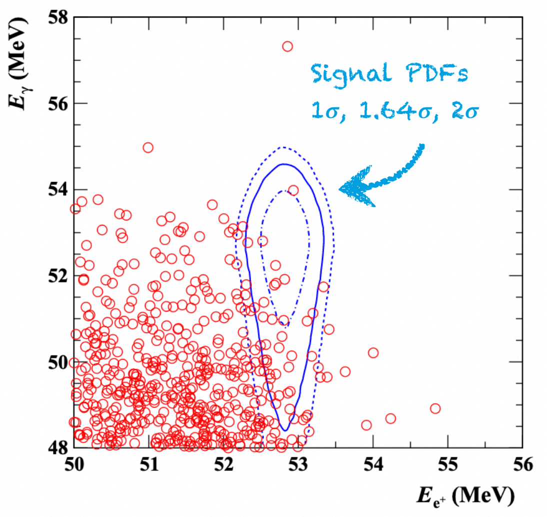
$\mu^+ \to e^+\gamma$

Current status and prospects

- Best limit from the MEG @ PSI experiment:
  BR($\mu^+ \to e^+\gamma$) < 4.2 x 10^{-13}



- **7.5 x 10^{14} muons**

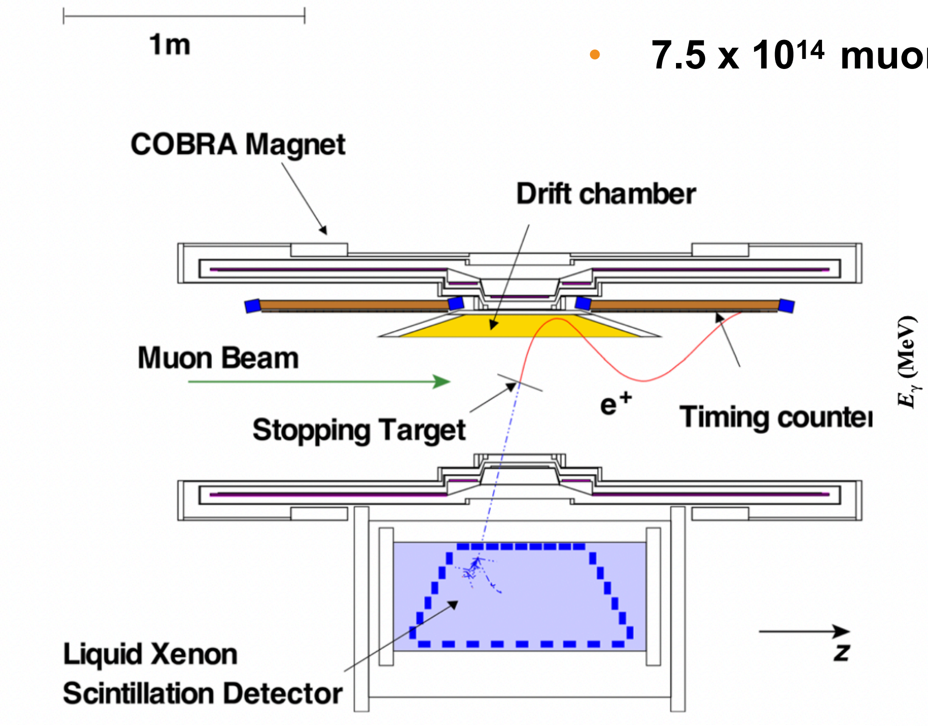


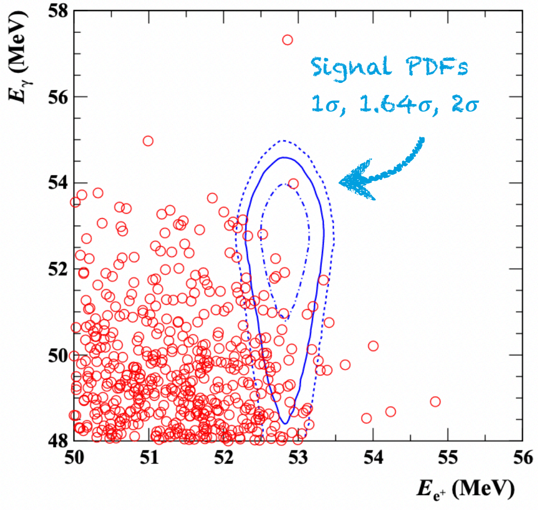
[Eur.Phys.J.C 76 (2016) 8, 434]

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

Current status and prospects

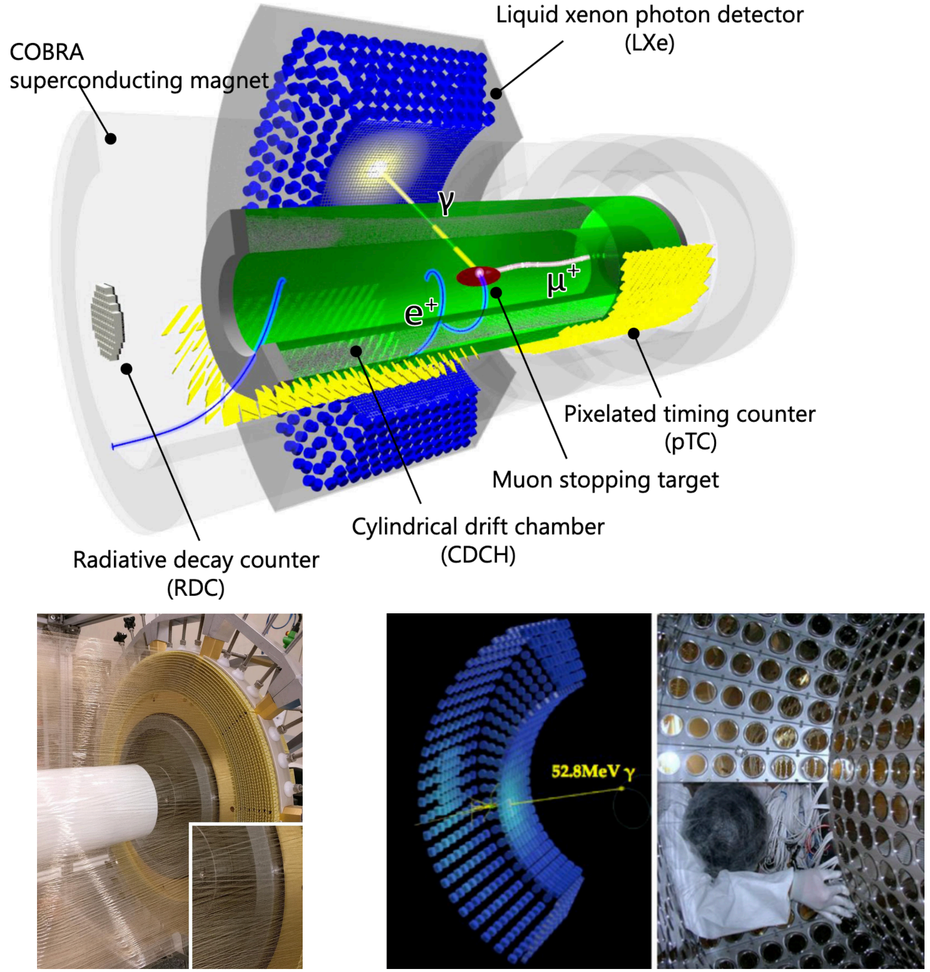
- Best limit from the MEG @ PSI experiment: BR($\mu^+ \to e^+\gamma$) < 4.2 x 10^{-13}
- **7.5 x 10^{14} muons**





Eur.Phys.J.C 76 (2016) 8, 434

- The upgraded version, MEG-II, expects to reach a sensitivity **~10^{-14}** with a 3 year run.

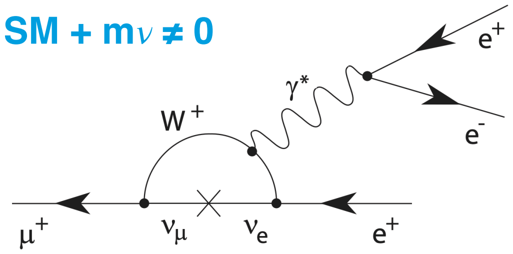


Eur.Phys.J.C 78 (2018) 5, 380

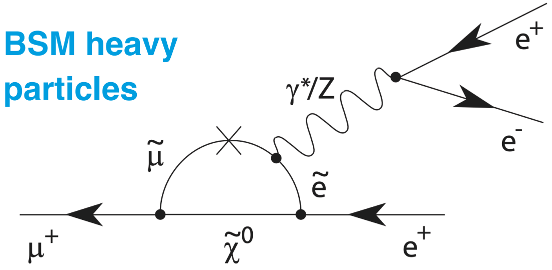
$\mu^+ \rightarrow e^+e^-e^+$

Current status and prospects

SM + mν ≠ 0

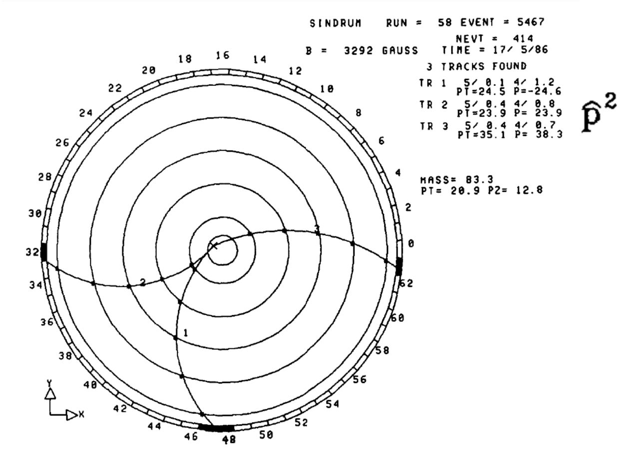


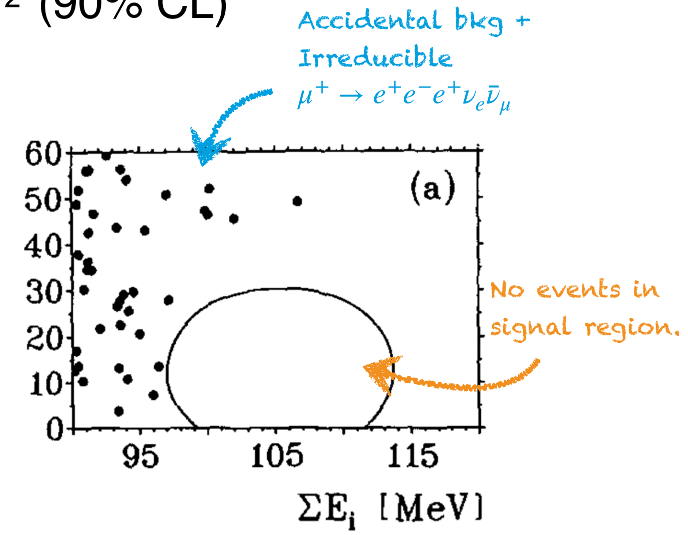
BSM heavy particles



- Best limit from the SINDRUM experiment @ PSI:

  BR($\mu^+ \rightarrow e^+e^-e^+$) < 1.0 x 10^{-12} (90% CL)



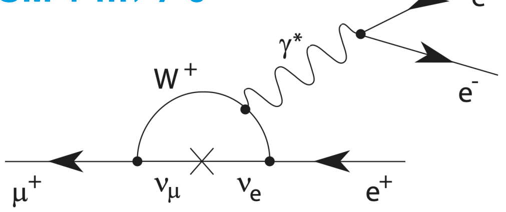


Nucl.Phys.B 299 (1988) 1-6

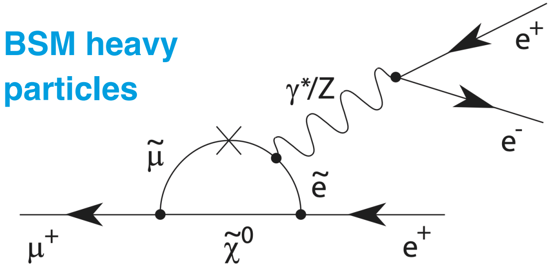
$\mu^+ \rightarrow e^+e^-e^+$

Current status and prospects

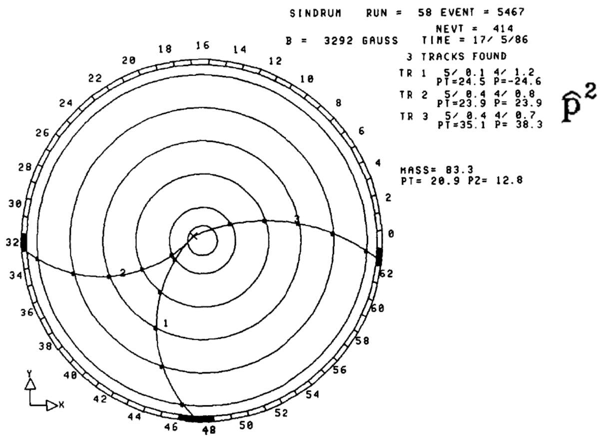
SM + mν ≠ 0

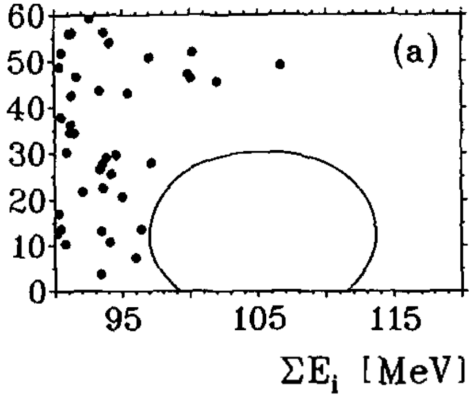


BSM heavy particles



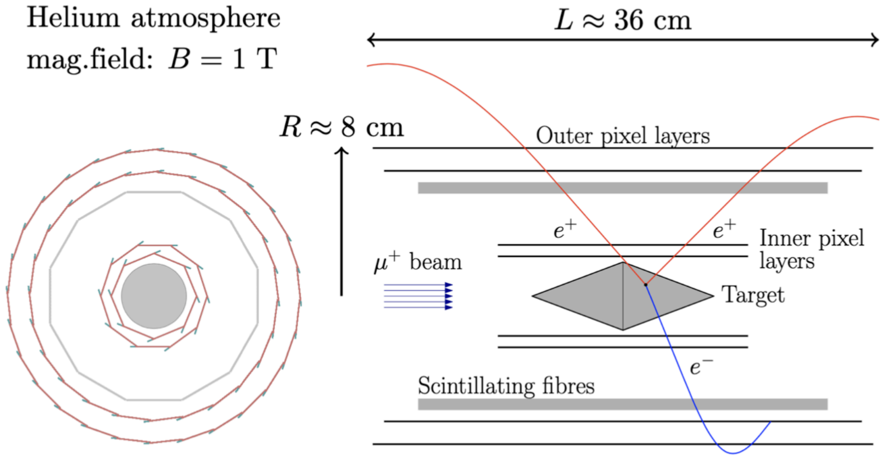
- Best limit from the SINDRUM experiment @ PSI: BR($\mu^+ \rightarrow e^+e^-e^+$) < 1.0 x 10^{-12} (90% CL)

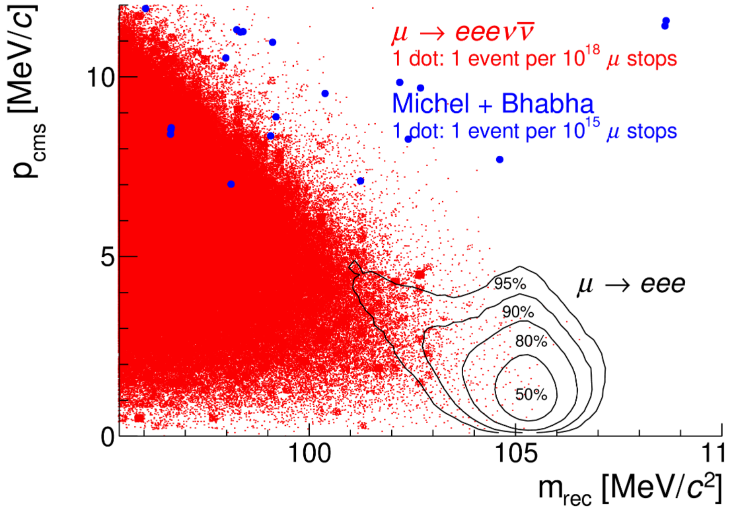




Nucl.Phys.B 299 (1988) 1-6

- Sensitivity from Mu3e @ PSI experiment: **~10^{-16}**





SciPost Phys. Proc. 5, 020 (2021)

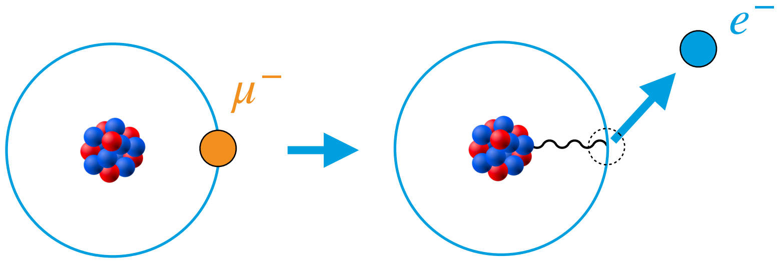
The challenge:

- High-intensity muon beams.
- Extremely low-density silicon pixel detectors.
- Upgraded DAQ for handling the extremely high rates.

$\mu^- N \rightarrow e^- N$

μ - e conversion in the field of a nucleus

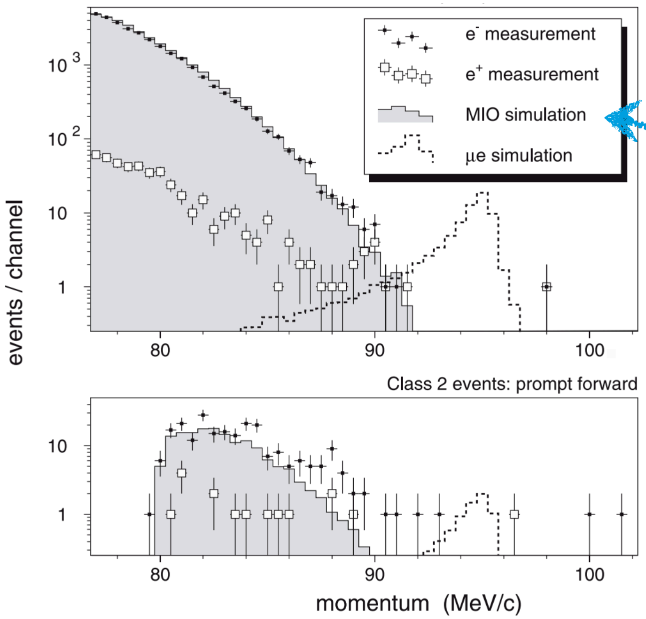
- Mono-energetic electron $E_e = m_\mu - E_{\text{binding}} - E_{\text{recoil}}$ (~ 104.97 MeV for an Al target).



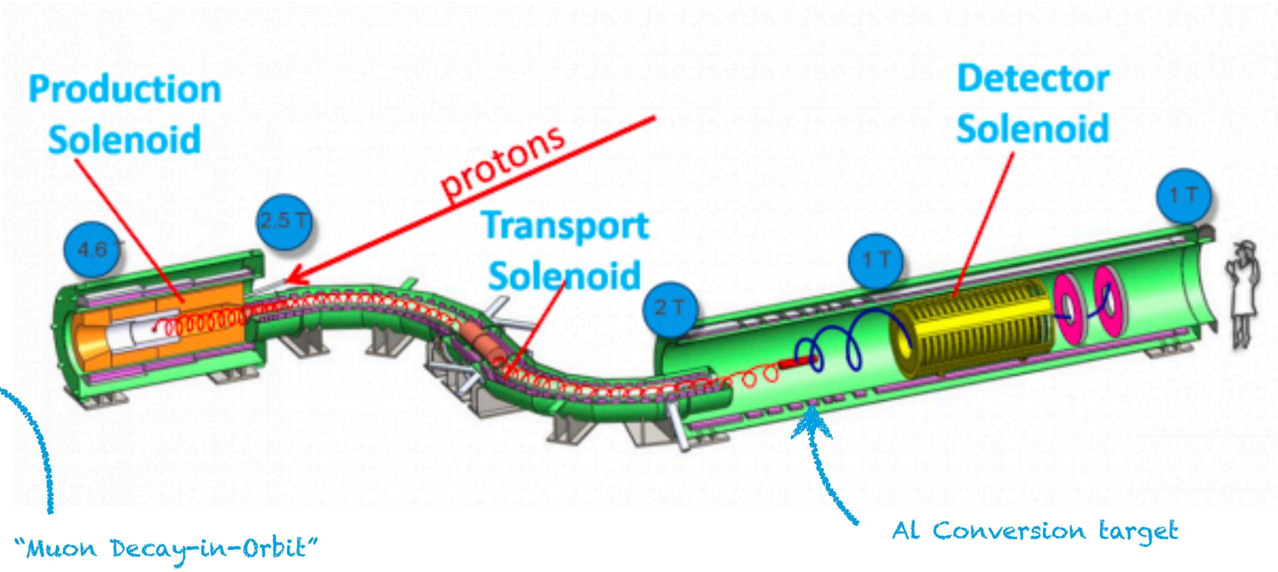
- Current limits from SINDRUM II @ PSI

$$\frac{\mu^- N \rightarrow e^- N}{\text{captured } \mu - N} < 3.3 \times 10^{-13}$$

Eur.Phys.J.C 47 (2006) 337-346



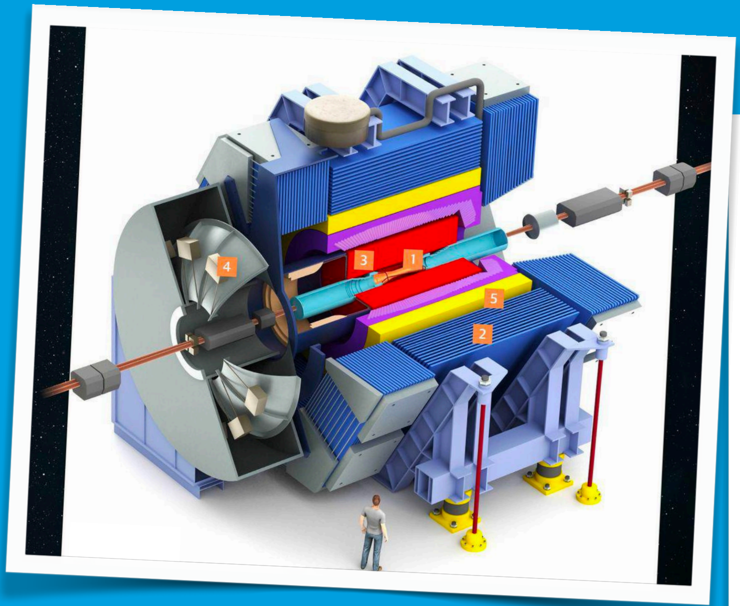
- Future facilities: COMET (J-PARC), DeeME (J-PARC), Mu2e (FNAL).
  - Sensitivity of **~10^{-17}**.

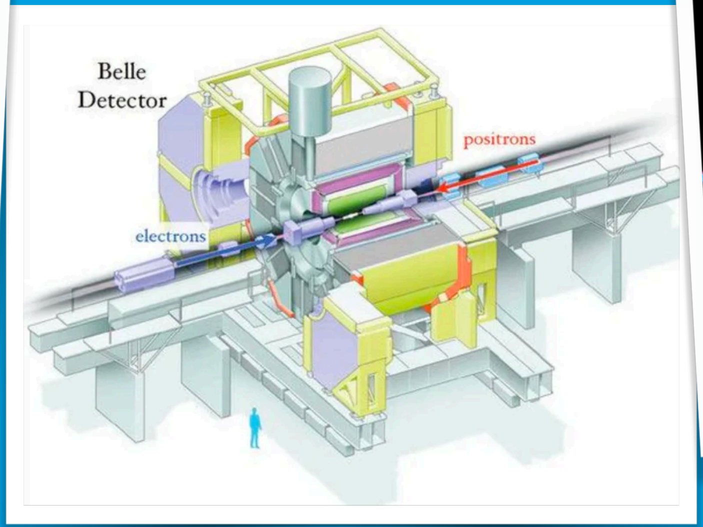


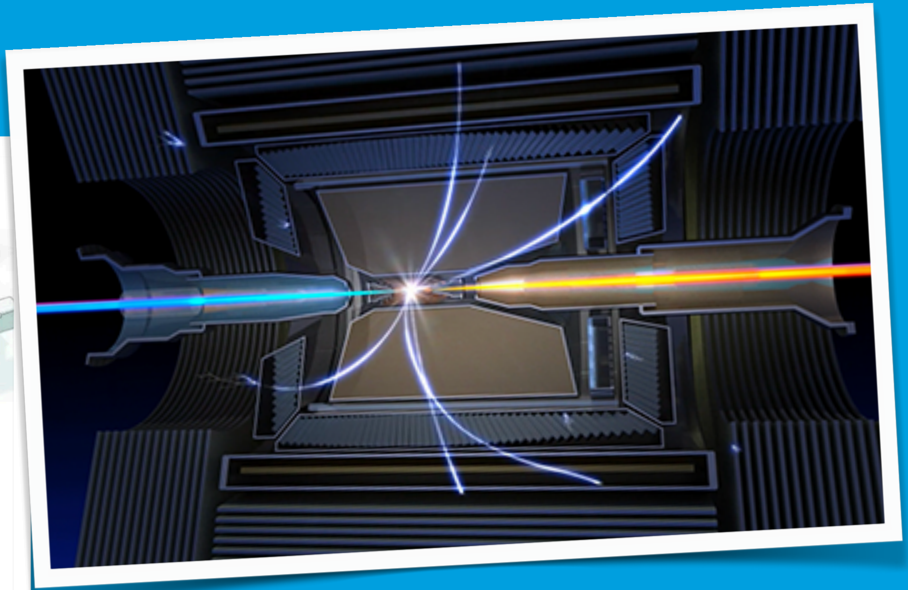
Later today:
CLFV and the Mu2e experiment

A Search for New Physics in the Lepton Sector: Charged Lepton Flavor Violation and the Mu2e Experiment *Mete YUCEL*

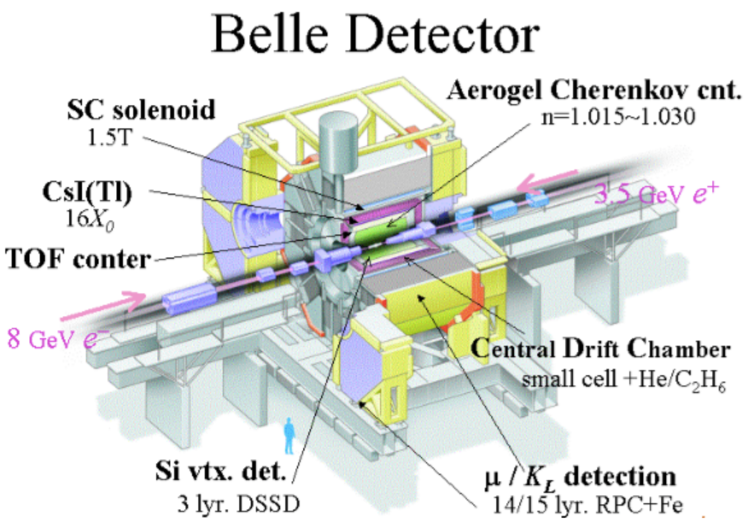
CLFV in tau leptons

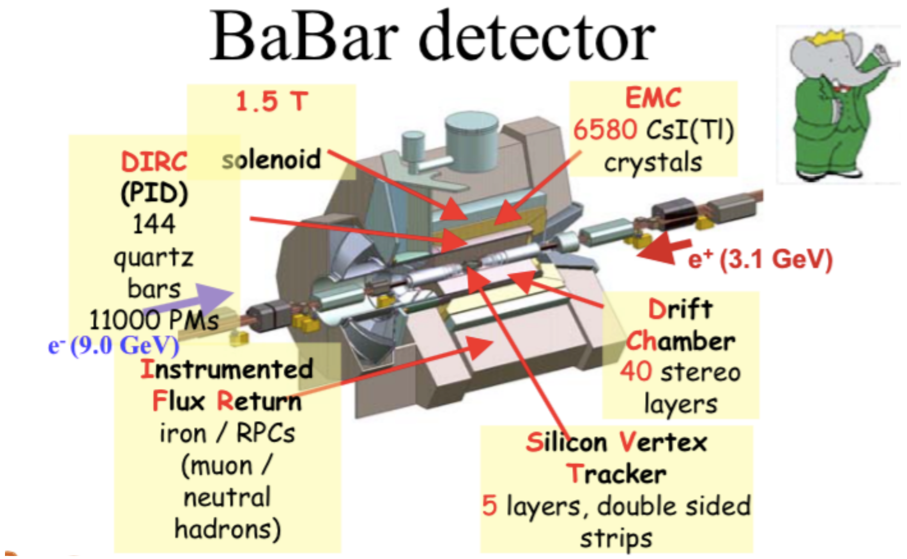






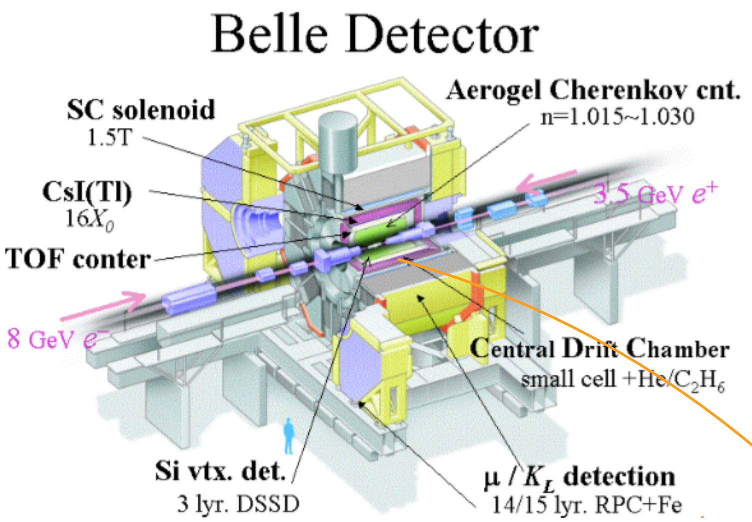
B-Factories

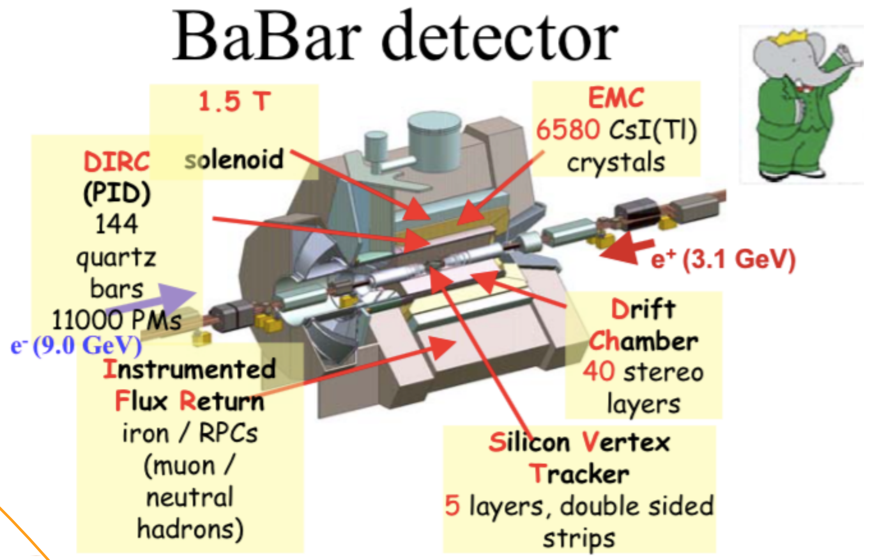




- Common characteristics:
  - Well-defined initial state (up to ISR).
  - High vertex resolution.
  - Excellent calorimetry
  - Sophisticated particle ID

B-Factories

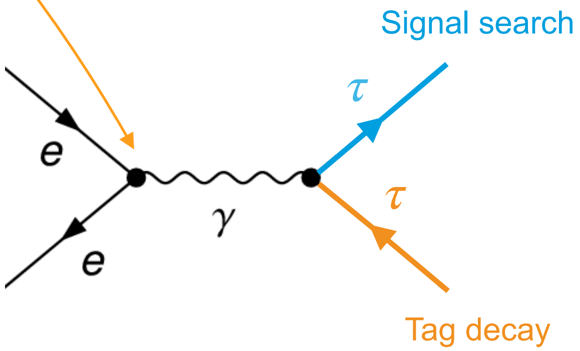




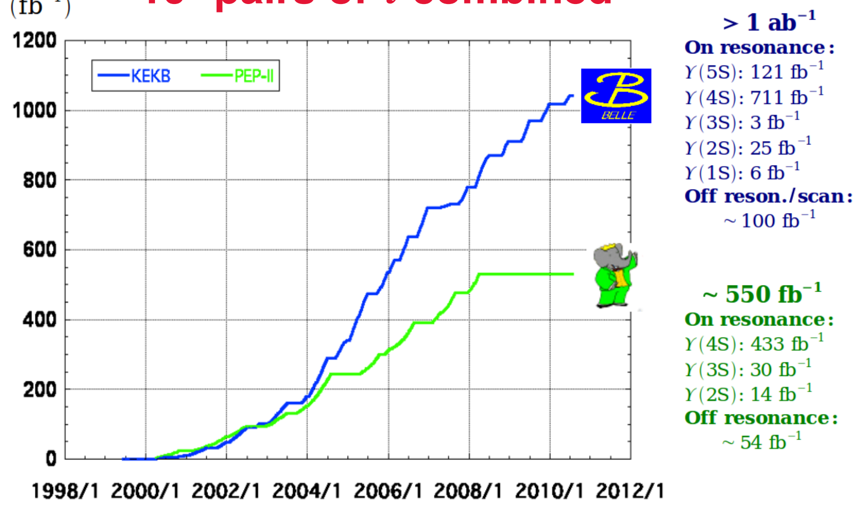
- Common characteristics:
  - Well-defined initial state (up to ISR).
  - High vertex resolution.
  - Excellent calorimetry
  - Sophisticated particle ID

- At Y(4S):
  - σ(e^+e^- --> BB) = 1.05 nb
  - σ(e^+e^- --> τ +τ-) = **0.92 nb**

- **B-Factories are also τ-factories**



~ 10^9 pairs of τ combined



- Thanks to the larger m_τ, hadrons can also be produced in the τ decay.

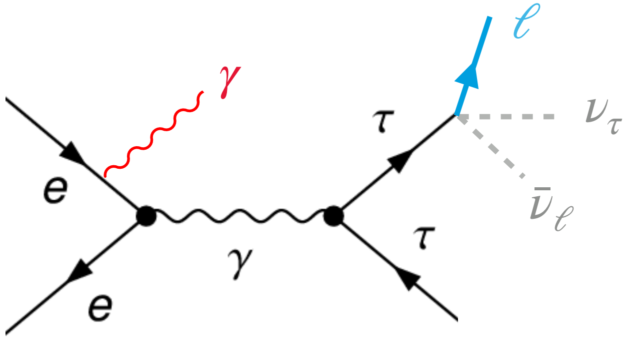
$\tau^+ \to \ell^+\gamma$

Highest non-SM branching ratio

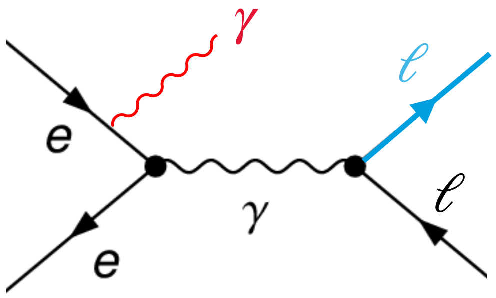
- Considered the golden modes for search of CLFV.
  - τ's rate production (10^{10}/yr) is much lower w.r.t. μ's (10^{11} /sec).
  - However, BSM branching ratios can be orders of magnitude larger than in associated muon decays.

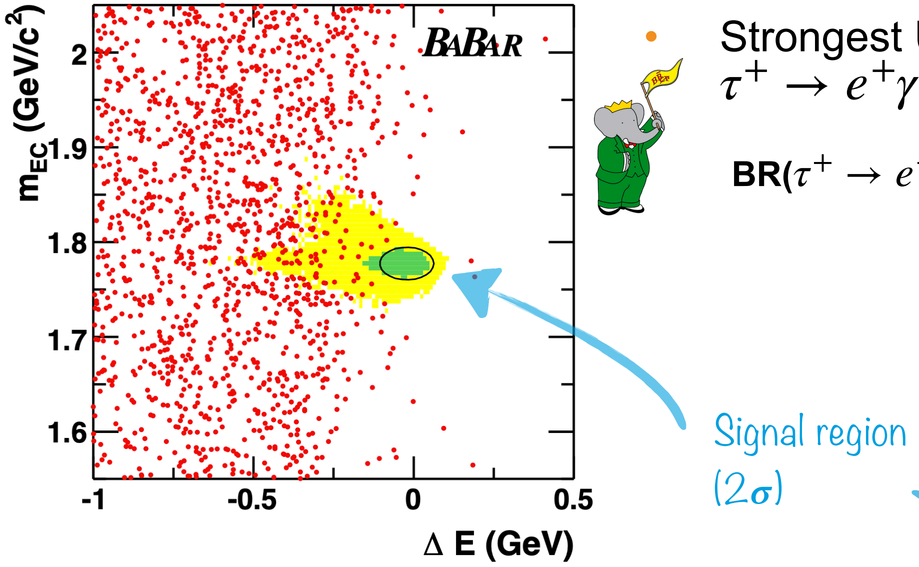
- Searching for signal events in a 2D region.
- Strong background contributions:

Irreducible background



Mis-id tagging





Phys.Rev.Lett. 104 (2010) 021802

- Strongest UL for $\tau^+ \to e^+\gamma$ from BaBar

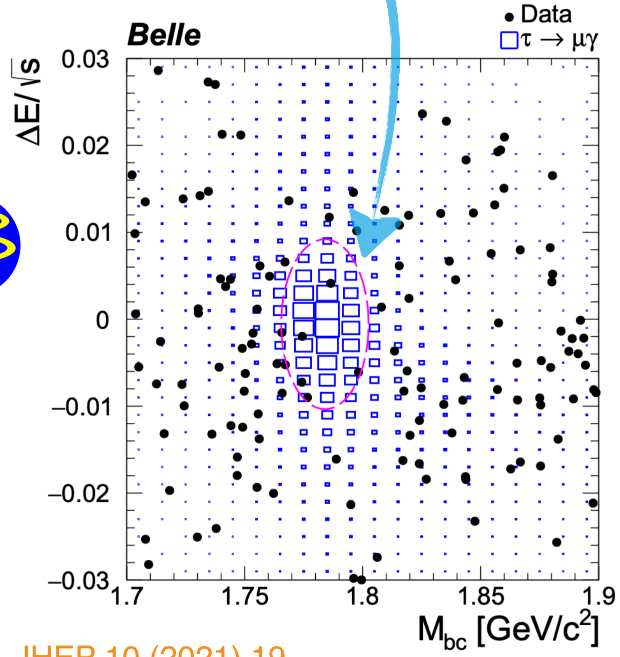
BR($\tau^+ \to e^+\gamma$) < 3.3 x 10^{-8}

- Most recent result from Belle, setting the strongest UL for $\tau^+ \to \mu^+\gamma$

BR($\tau^+ \to \mu^+\gamma$) < 4.2 x 10^{-8}

$$M_{\rm bc} = \sqrt{(E_{\rm beam}^{\rm CM})^2 - |\vec{p}_{\ell\gamma}^{\,\rm CM}|^2},$$

$$\Delta E/\sqrt{s} = (E_{\ell\gamma}^{\rm CM} - \sqrt{s}/2)/\sqrt{s},$$



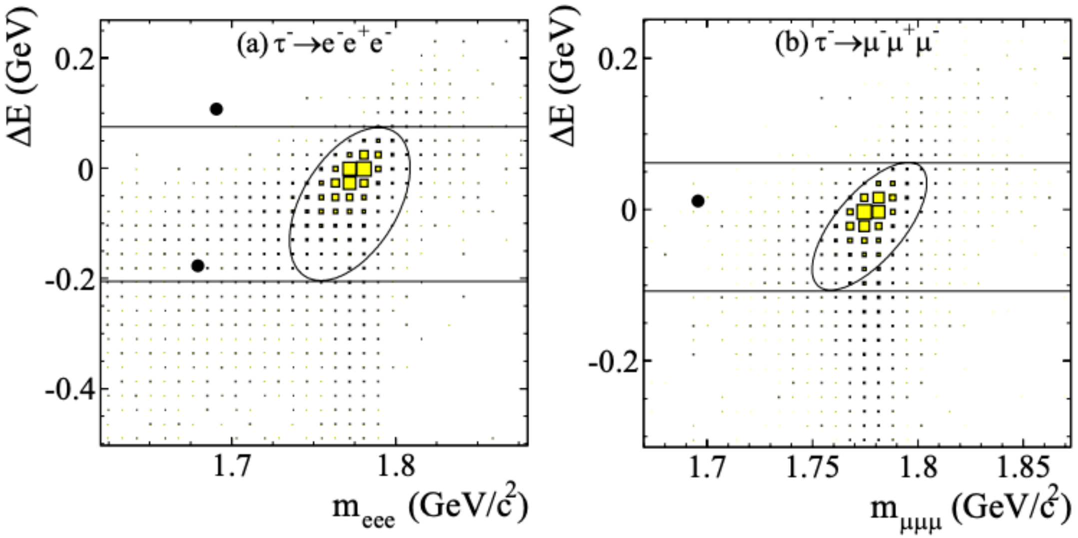
JHEP 10 (2021) 19

$\tau^+ \to \ell^+\ell^-\ell^+$

Clean modes with better resolution

- Six modes:
  $\tau^- \to \ell^-\ell^+\ell^-$, $\ell^-\ell'^+\ell''^-$, or $\ell^+\ell'^-\ell''^-$
  with $\ell^- = e^-$ or μ^-.
- Signal: 3 leptons with $M_{inv} = m_\tau$; Ecms = $\sqrt{s}/2$.
- Strongest UL for 3-lepton LFV modes from **Belle**.
  - Signal: 3 leptons with $M_{inv} = m_\tau$; Ecms = $\sqrt{s}/2$.

BR($\tau^+ \to \ell^+\ell^-\ell^+$) < [1.8 - 2.7] x 10^{-8} (90% CL)



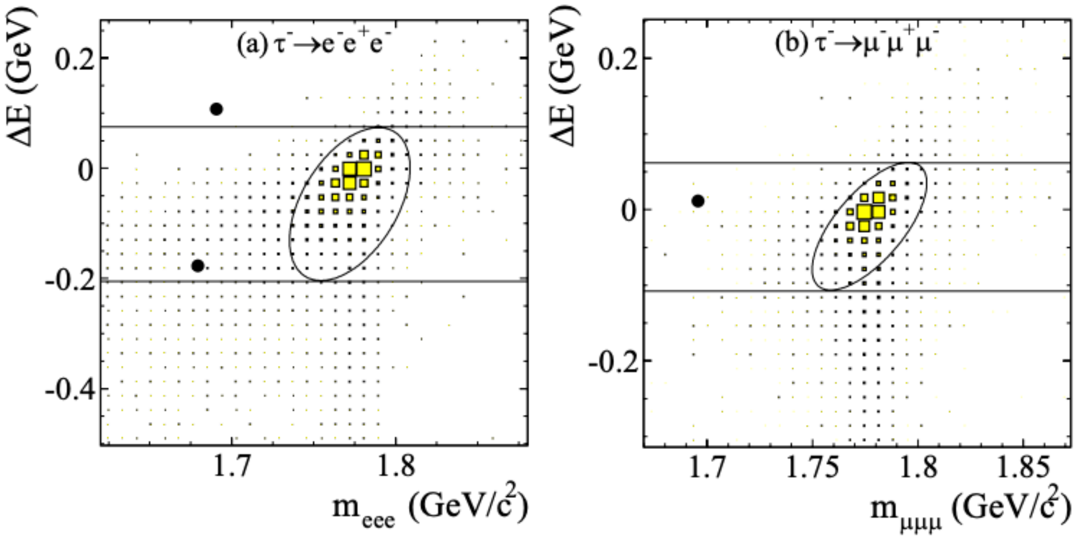
Phys.Lett.B 687 (2010) 139-143

$\tau^+ \to \ell^+\ell^-\ell^+$

Clean modes with better resolution

- Six modes:
  $\tau^- \to \ell^-\ell^+\ell^-$, $\ell^-\ell'^+\ell''^-$, or $\ell^+\ell'^-\ell''^-$
  with $\ell^- = e^-$ or μ^-.
- Signal: 3 leptons with $M_{inv} = m_\tau$; Ecms = $\sqrt{s}/2$.
- Strongest UL for 3-lepton LFV modes from **Belle**.
  - Signal: 3 leptons with $M_{inv} = m_\tau$; Ecms = $\sqrt{s}/2$.

BR($\tau^+ \to \ell^+\ell^-\ell^+$) < [1.8 - 2.7] x 10^{-8} (90% CL)

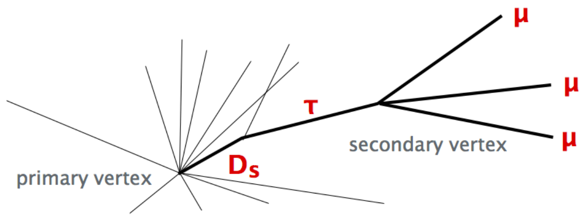


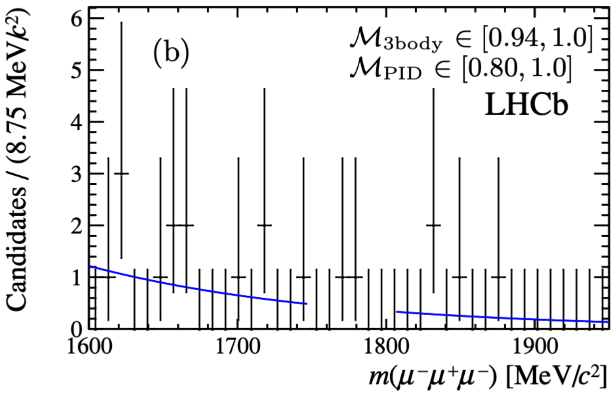
[Phys.Lett.B 687 (2010) 139-143](#)

- In particular, $\tau^+ \to \mu^+\mu^-\mu^+$ can be searched in pp collisions at LHC.
  - **Search @ LHCb:**
    - τ^- coming from the semileptonic decays of b and c hadrons (cross-section = 85 μb at 7 TeV).
    - Muons provide a clean signature for the trigger.
    - Two MVA classifier used to perform signal discrimination.

BR($\tau^+ \to \mu^+\mu^-\mu^+$) < 4.6 x 10^{-8} (90% CL)

stat dominated (3 fb-1 of data)





[JHEP 02 (2015) 121](#)

Prospects of CLFV @ Belle II

Using tau lepton pairs

- At Belle II an increase in the signal efficiency will be achieved thanks to:
  - Higher trigger efficiencies.
  - Improvements in the reconstruction.
- In addition to a better understanding of physics backgrounds.

$\boldsymbol{\tau \to \ell\ell\ell}$ ← Can be competitive with early Belle II data

$\tau \to \ell K_s, \Lambda h$

$\tau \to \ell V_0 (\to hh')$

$\tau \to \ell P^0 (\to \gamma\gamma)$

$\tau \to \ell hh'$

$\boldsymbol{\tau \to \ell\gamma}$ ← Stronger backgrounds, hard to control.

- Searches of $\tau \to 3\mu$ @ Belle II in progress.
  - Improved Belle II μID algorithm using KLM.
  - Extract the best combination of tight cuts for the analysis also at low momentum (not used by Belle/BaBar).

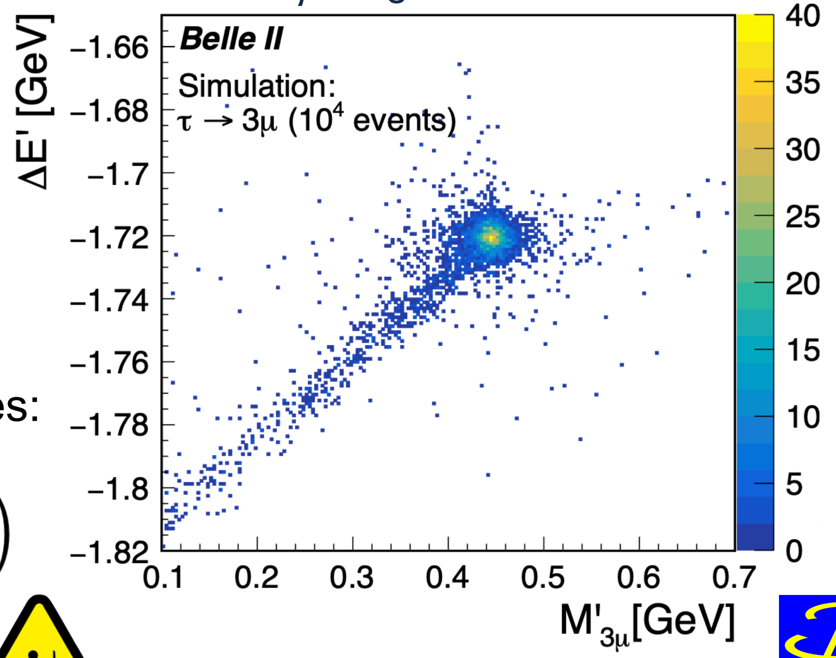
$$\Delta\mathbf{E} \equiv \mathbf{E}_\tau - \mathbf{E}_{\mathbf{beam}}$$

$E_\tau \to E_{3\mu}$, $\mathbf{E}_{\mathbf{beam}} \to \sqrt{s}/2$

Axis rotation to reduce correlation between variables:

$$\begin{pmatrix} M'_{3\mu} \\ \Delta E' \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} M_{3\mu} \\ \Delta E \end{pmatrix}$$

$\tau \to 3\mu$ signal events



WORK IN PROGRESS

Upper limits on CLFV tau decays

Current bounds and projection of expected ULs

- Neutrinoless 2-body or 3-body decays to 52 final states.
- In some SM extensions, cLFV decays are expected at rates only one order of magnitude below present bounds.

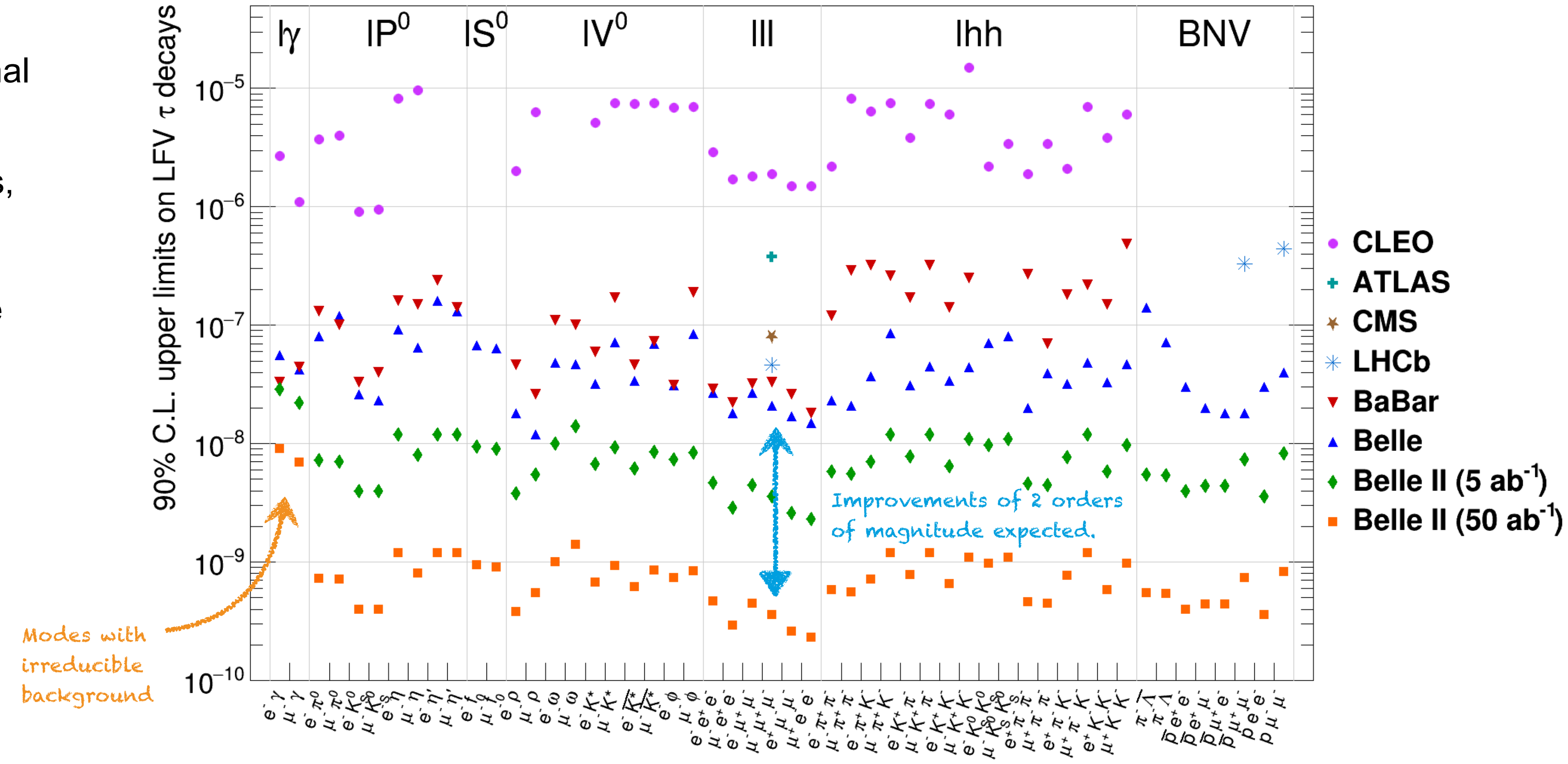
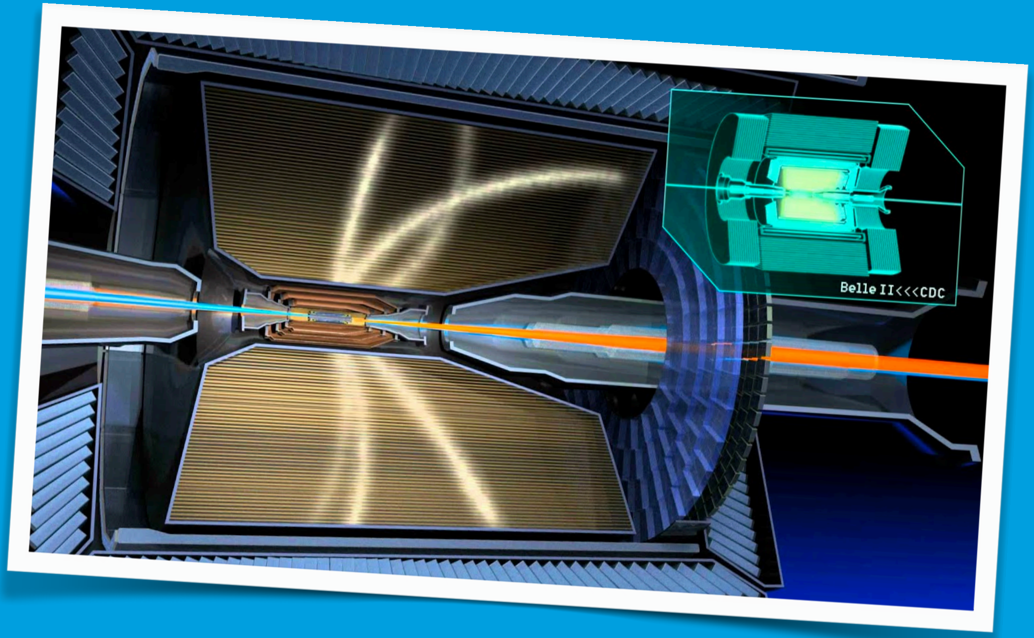
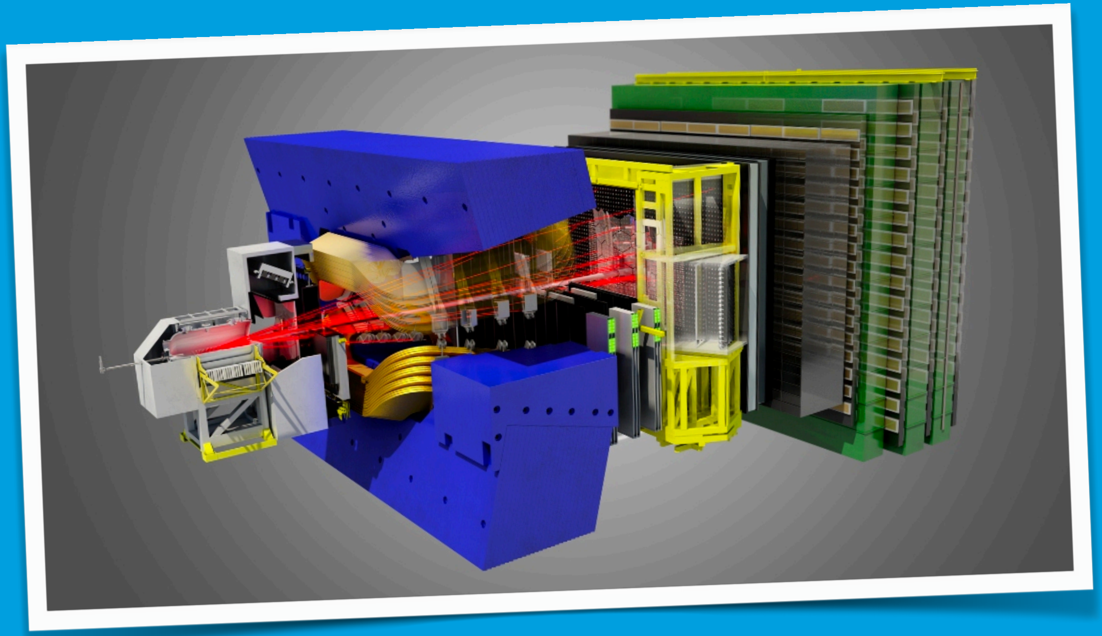


Figure: arXiv:2203.14919 (2022)

Searches of CLFV with B decays

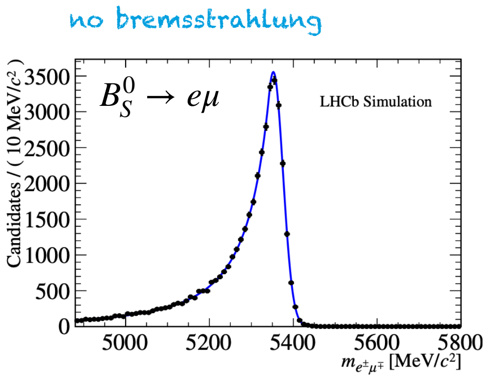


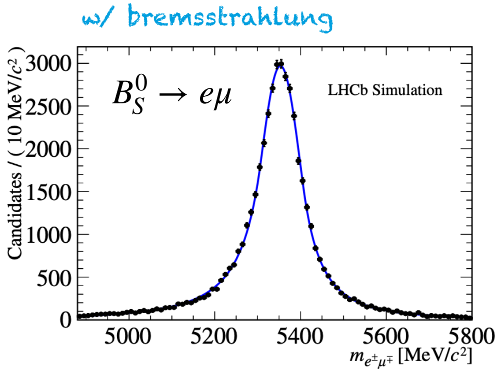


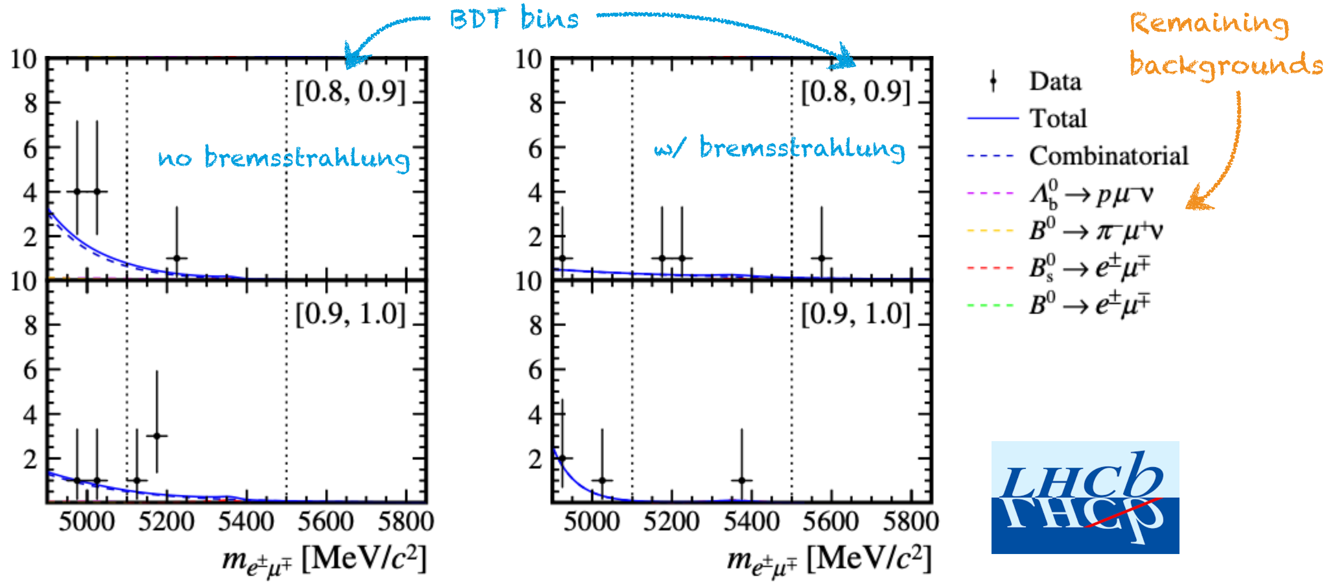
Searches for $B^0_{(s)} \to e\mu$ decays

Best limits from LHCb

- Search with 3 fb^{-1} at 7 and 8 TeV.
- Two tracks, identified as muon and electron, with a common vertex.
- Major background contributions: B decays with missing/mis-ID final states.
- A BDT used to discriminate signal events from combinatorial.
    - Both candidates with and without bremsstrahlung correction considered.







BR($B^0 \to e\mu$) < 1.3 x 10^{-9} (95% CL)

BR($B^0_S \to e\mu$) < 6.3 x 10^{-9} (95% CL)

Later today:
LFV in B decays at LHCb

LFV in B decays at LHCb	Dr. Niladri SAHOO
Bryant Hall, University of Mississippi	14:00 - 14:15

JHEP 03 (2018) 078

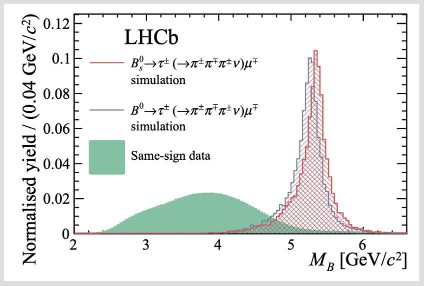
CLFV in $B^0_{(s)} \to \tau\ell$ decays

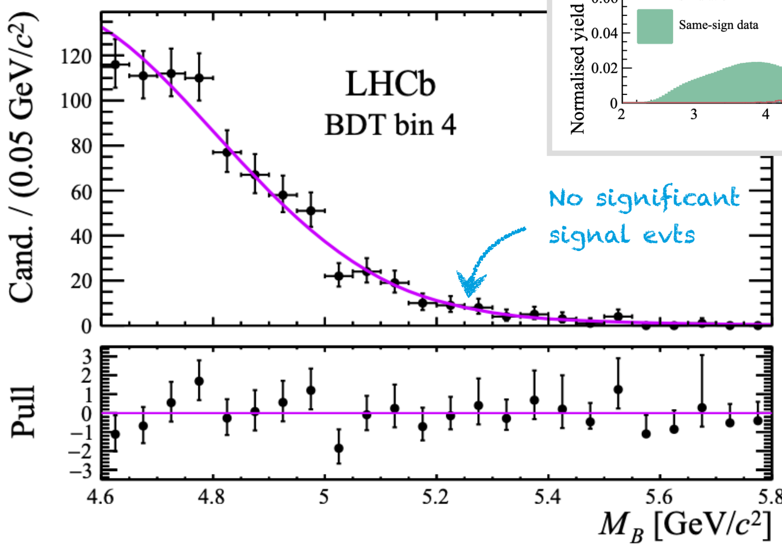
Current limits from LHCb and Belle

- Final state involving τ makes harder the reconstruction due to the presence of missing energy.
- **LHCb**
  - τ candidate reconstructed from $\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu$.
  - Simultaneous fits on 4 regions of the BDT response.

BR($B^0 \to \tau\mu$) < 1.4 x 10-5 (95% CL)

BR($B^0_s \to \tau\mu$) < 4.2 x 10-5 (95% CL)





Phys.Rev.Lett. 123 (2019) 21, 211801

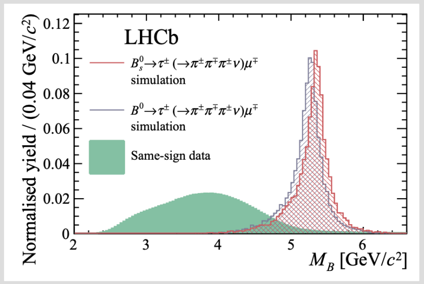
CLFV in $B^0_{(s)} \to \tau\ell$ decays

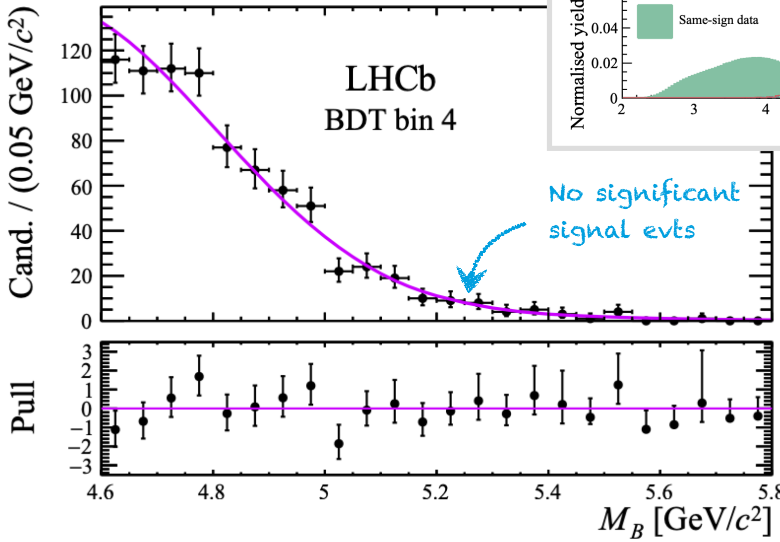
Current limits from LHCb and Belle

- Final state involving τ makes harder the reconstruction due to the presence of missing energy.
- **LHCb**
  - τ candidate reconstructed from $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu$.
  - Simultaneous fits on 4 regions of the BDT response.

BR($B^0 \to \tau\mu$) < 1.4 x 10-5 (95% CL)

BR($B^0_s \to \tau\mu$) < 4.2 x 10-5 (95% CL)



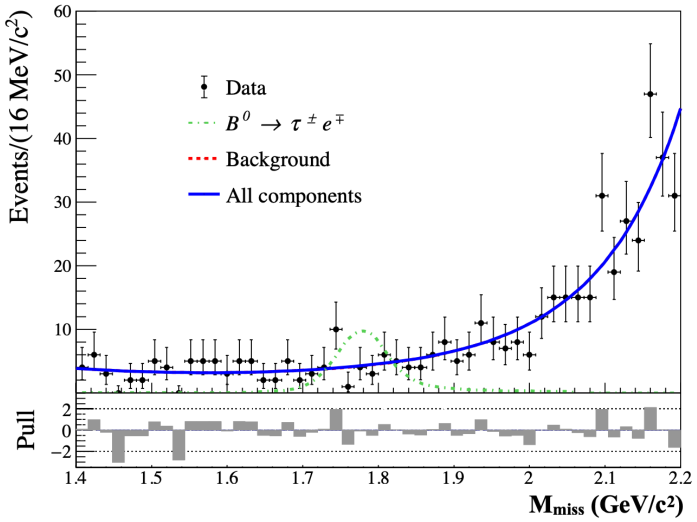


Phys.Rev.Lett. 123 (2019) 21, 211801

- **Belle**
  - Hadronic tag used to infer the moment of the signal side.
    - The τ candidate does not need to be reconstructed.

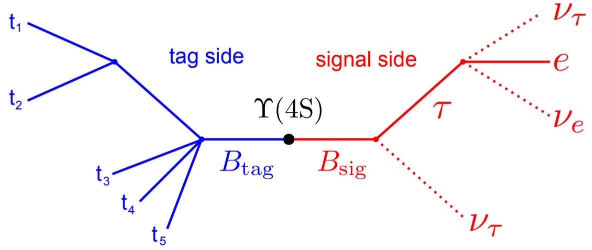
$$M_{\text{miss}} = \sqrt{(E_{B_{\text{sig}}} - E_\ell)^2/c^4 - (\vec{p}_{B_{\text{sig}}} - \vec{p}_\ell)^2/c^2}$$

BR($B^0 \to \tau e$) < 1.6 x 10-5 (90% CL)



Phys.Rev.D 104 (2021) 9, L091105

1104 exclusive decay channels were reconstructed, employing 71 neural networks altogether.

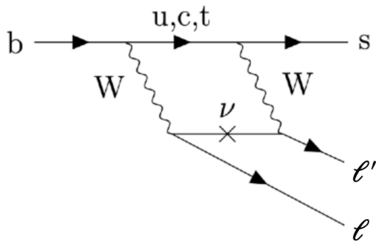


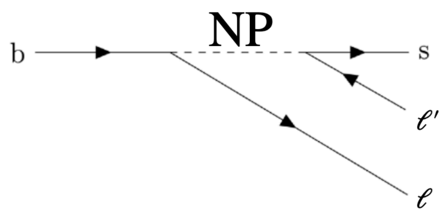
Nucl.Instrum.Meth.A 654 (2011) 432-440

CLFV in $b \to s\ell\ell'$ transitions

Current status and prospects

- Models of LFV can produce signatures with different charge configurations.





Mode	U.L. (90% CL)	Experiment
$B^+ \to K^+\mu^-e^+$	7.0 x 10^{-9}	LHCb
	3.0 x 10^{-8}	Belle
$B^+ \to K^+\mu^+e^-$	6.4 x 10^{-9}	LHCb
	8.5 x 10^{-8}	Belle
$B^0 \to K^0\mu e$	3.8 x 10^{-8}	Belle
$B^0 \to K^{*0}\mu^+e^-$	5.7 x 10^{-9}	LHCb (prelim.)[1]
$B^0 \to K^{*0}\mu^-e^+$	6.7 x 10^{-9}	LHCb (prelim.)[1]
$B^0 \to K^{*0}\mu e$	9.9 x 10^{-9}	LHCb (prelim.)[1]
$B^0 \to \phi\mu e$	1.6 x 10^{-8}	LHCb (prelim.)[1]
$B^+ \to K^+\tau\mu$	4.8 x 10^{-5}	BaBar
$B^+ \to K^+\tau e$	3.0 x 10^{-5}	BaBar
$B^+ \to K^+\tau^+\mu^-$	3.9 x 10^{-5}	LHCb

[1] J. Basels, Moriond 2022

- LHCb upgrades and Belle II will improve limits by 1-2 orders.
  - Not only larger statistics, but also improved hardware/tools.

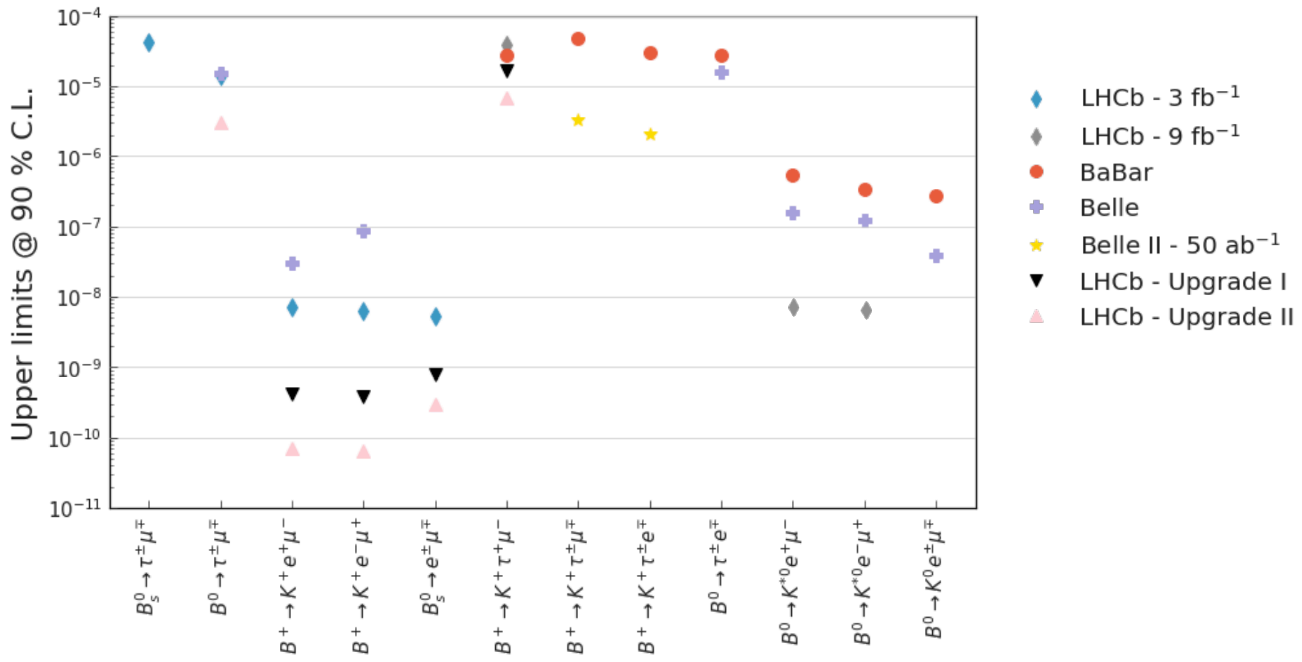
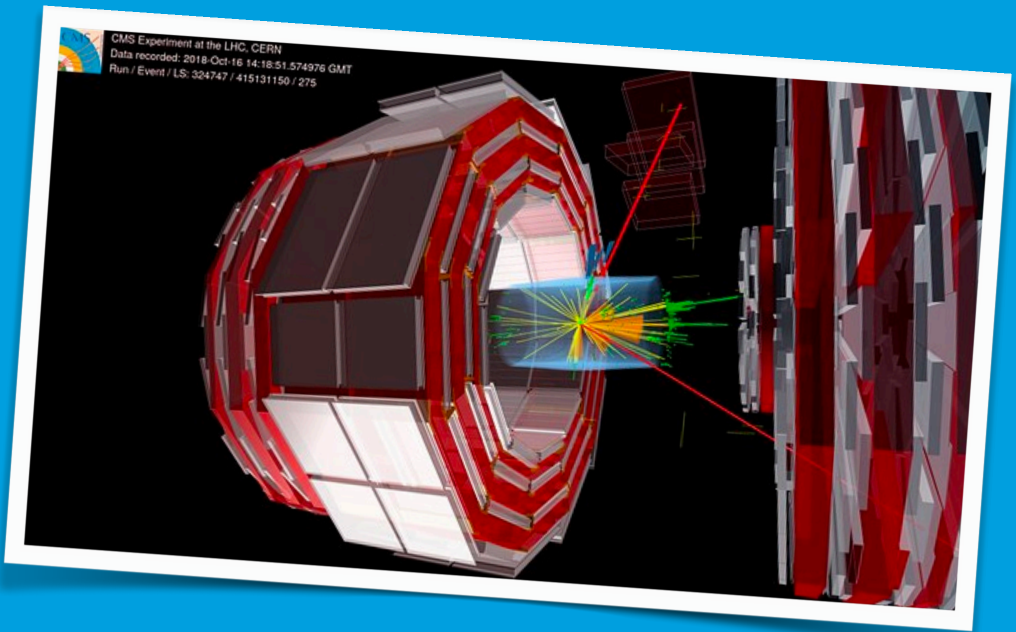
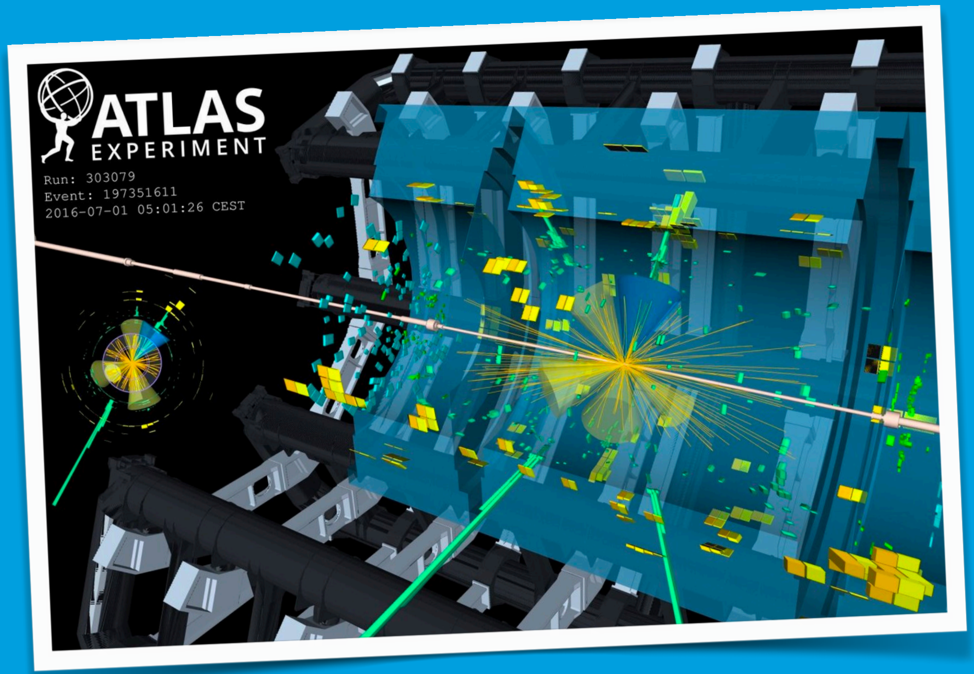


Figure (Modified): G. de Marino, Anomalies and Precision in the Belle II era (2021)

Searches of CLFV with bosons



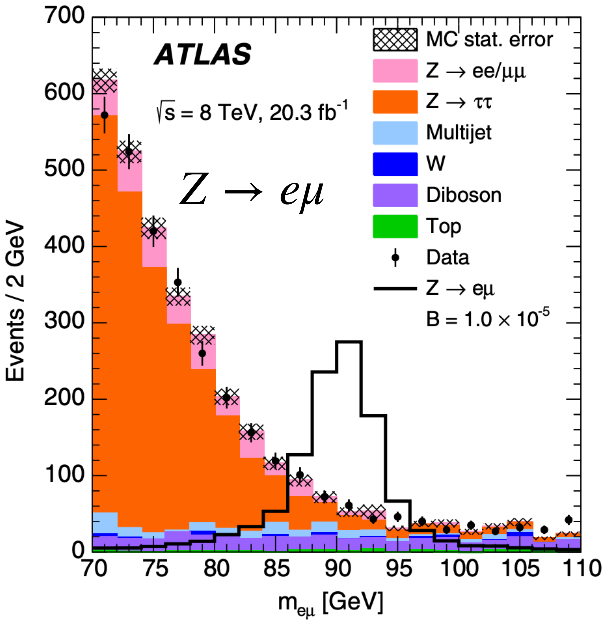


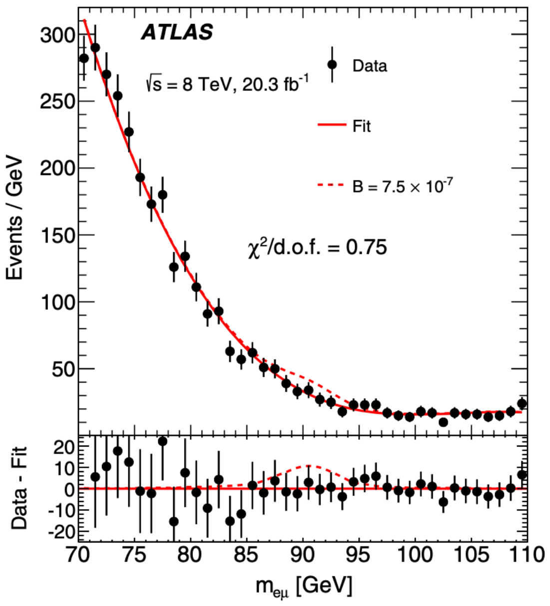
Search for CLFV in Z^0 decays

Current limits

- Direct searches of $Z \to \ell\ell'$. Current best limits are shown.
- **ATLAS**
  - Two high-pT isolated, oppositely charged leptons of different flavor.

BR($Z \to e\mu$) < 7.5 x 10^{-7} (95% CL)

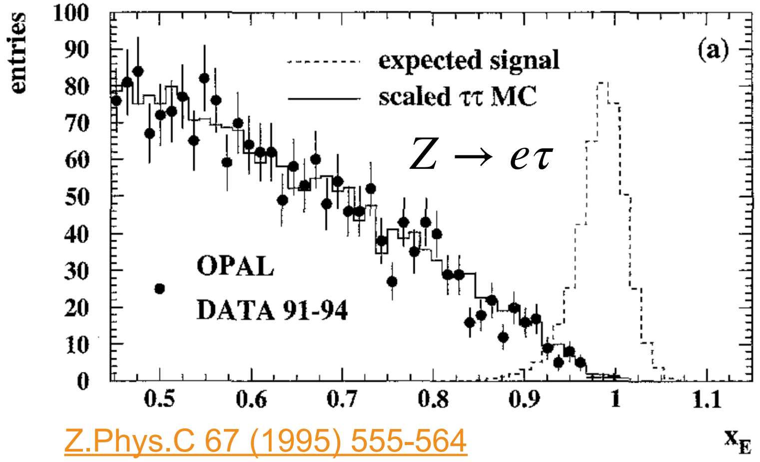




Phys.Rev.D 90 (2014) 7, 072010

- **OPAL and DELPHI (LEP)**
  - Criteria optimised for Identification of e/μ and a cone as τ.
  - Main background from $Z \to (\tau \to \ell\nu\nu)\tau$

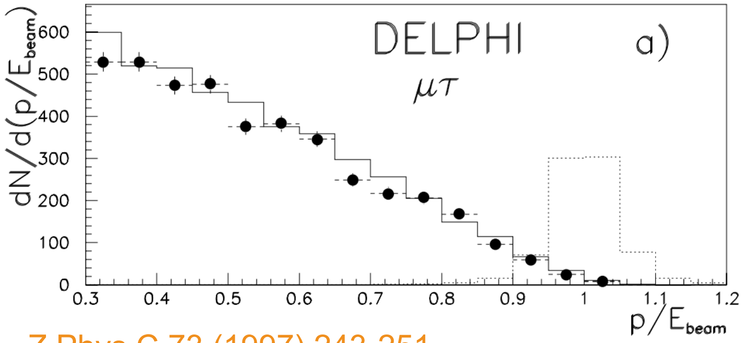
BR($Z \to e\tau$) < 9.8 x 10^{-6} (95% CL)



Z.Phys.C 67 (1995) 555-564

EM cone energy divided by Ebeam

BR($Z \to \mu\tau$) < 1.2 x 10^{-5} (95% CL)



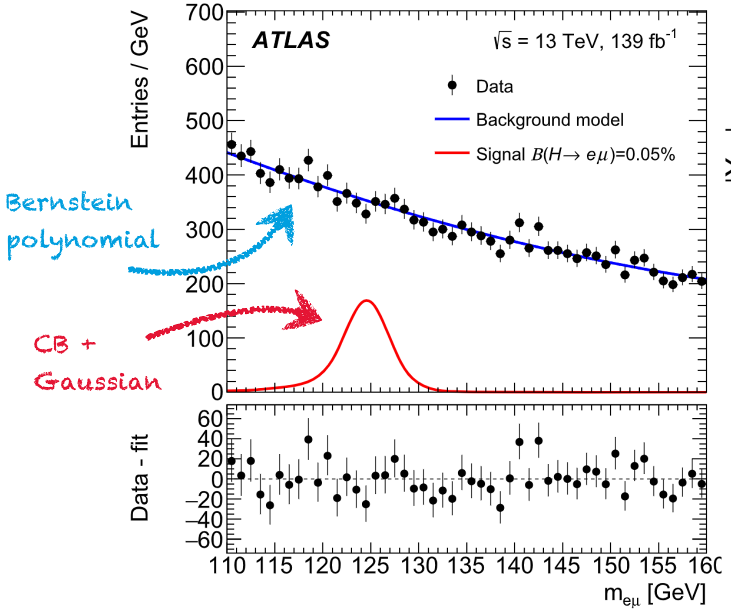
Z.Phys.C 73 (1997) 243-251

In all modes: **Improvement by factor ~10 at HL-LHC.**

Search for CLFV in Higgs decays

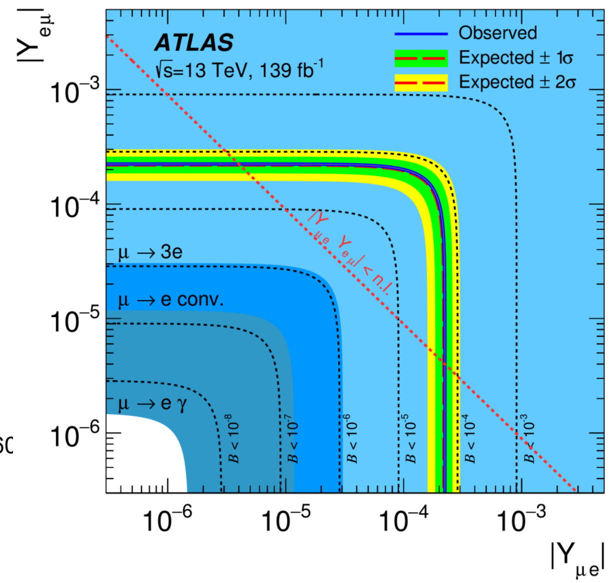
Current limits

- $H \to e\mu$
  - Strong indirect constrains from $\mu \to e\gamma$.
  - Main backgrounds coming from $Z \to \tau\tau$, top-quark production, W + jets.
- $H \to e\tau/\mu\tau$
  - τ candidates from both $\tau \to \ell\nu\bar{\nu}$ and $\tau \to \mathrm{hadrons} + \nu$.
  - Lepton from H and τ of different flavor because of the strong di-lepton background from Drell–Yan process.



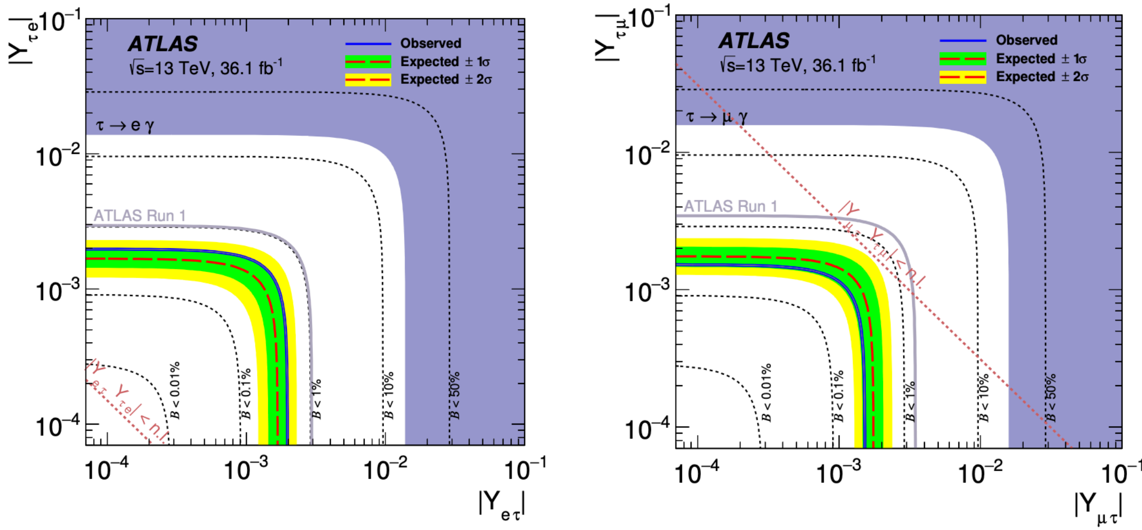
Phys.Lett.B 801 (2020) 135148

BR($H \to e\mu$) < 6.1 x 10^{-5} (95% CL)



BR($H \to e\tau$) < 4.7 x 10^{-3} (95% CL)

BR($H \to \mu\tau$) < 2.5 x 10^{-3} (95% CL)



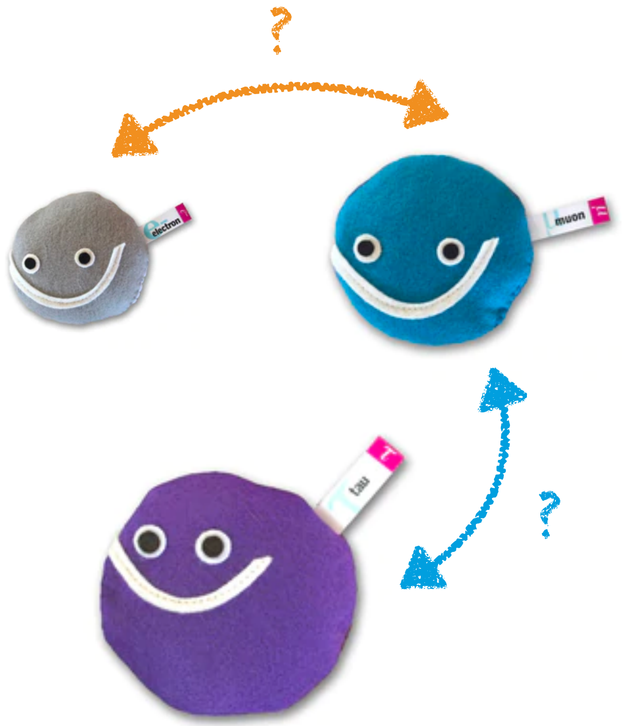
Phys.Lett.B 800 (2020) 135069

Summary

- A (quick) experimental overview of CLFV searches has been presented.
  - Emphasis in the strongest limits set to the date.

- Other possibilities not discussed during this talk (but not less important!)
  - Light mesons: $\pi^0 \to \mu e$; kaons: $K_L^0 \to \mu e$, $K^+ \to \pi^+\mu^+e^-$, etc.
  - $J/\psi \to \mu e$, $J/\psi \to \tau e$, $J/\psi \to \tau\mu$. (best limits from BES III).
  - CLFV decays with BSM particles: $\tau^- \to \ell^-\alpha, Z' \to \ell\ell'$, …

- Prospects in all the sectors for accessing BSM regions in the coming years.
  - Stay tuned! Exciting times ahead.



Figures: The particle zoo.

References

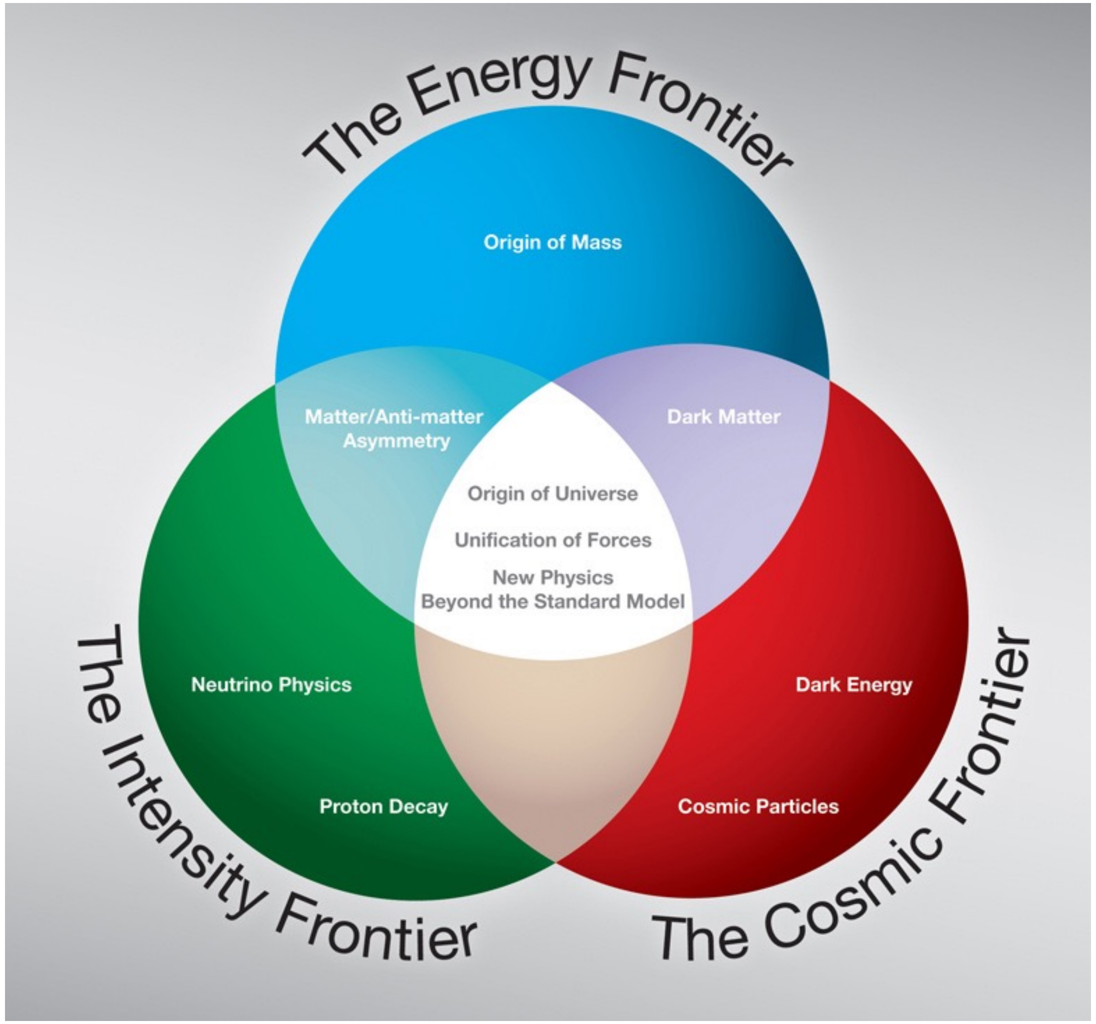
Many in the slides, and additionally:

- Ardu, Marco, and Gianantonio Pezzullo. "Introduction to Charged Lepton Flavour Violation." *arXiv preprint arXiv:2204.08220* (2022)
- Calibbi, Lorenzo, and Giovanni Signorelli. "Charged lepton flavour violation: an experimental and theoretical introduction." *La Rivista del Nuovo Cimento* 41.2 (2018): 71-174.
- Bernstein, Robert H., and Peter S. Cooper. "Charged lepton flavor violation: an experimenter's guide." Physics Reports 532.2 (2013): 27-64.
- Cei, Fabrizio, and Donato Nicolo. "Lepton flavour violation experiments." *Advances in High Energy Physics* 2014 (2014).
- Banerjee, Swagato, et al. "Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector." *arXiv preprint arXiv:2203.14919* (2022).

Thank You

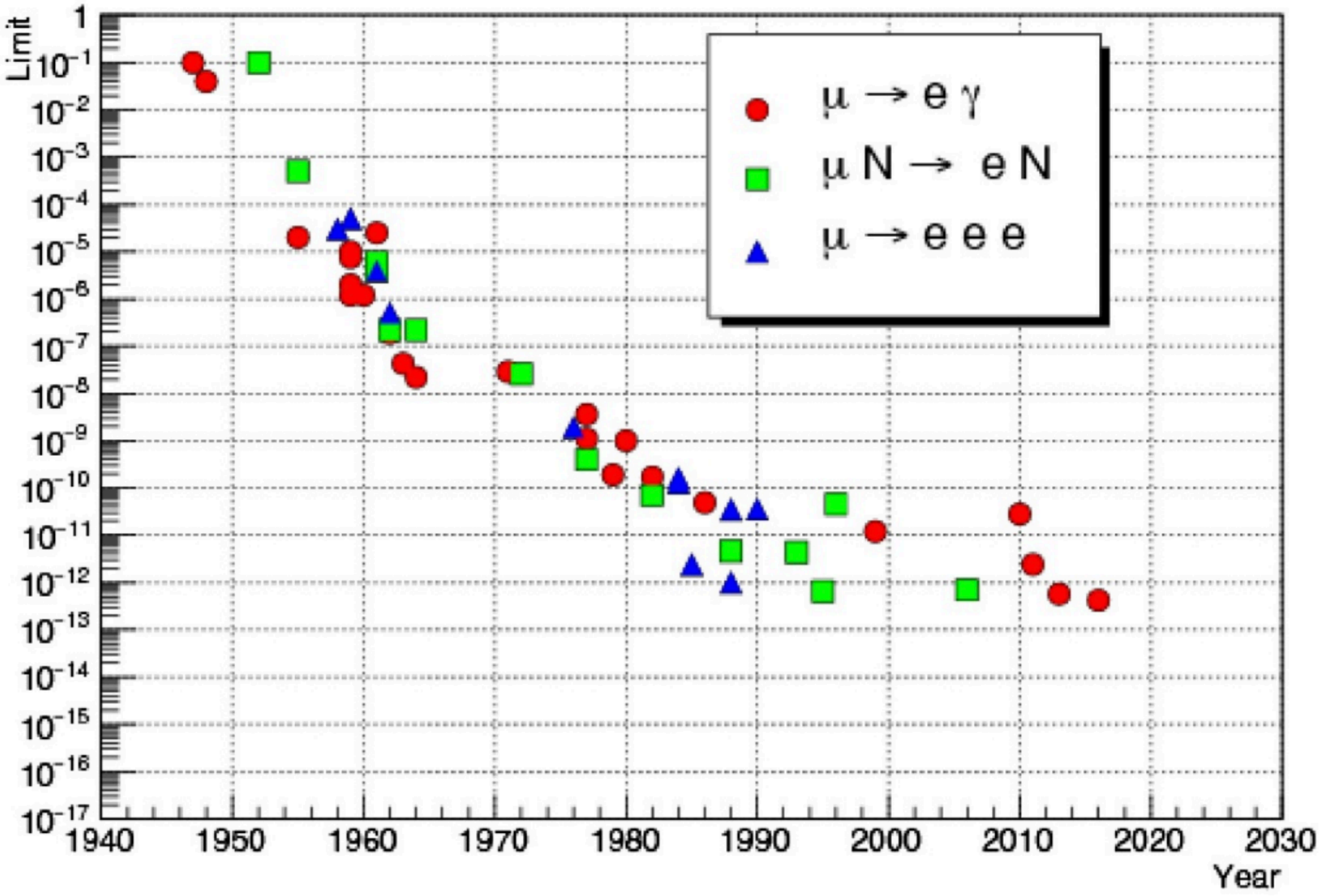
Backup

Experiments searching CLFV



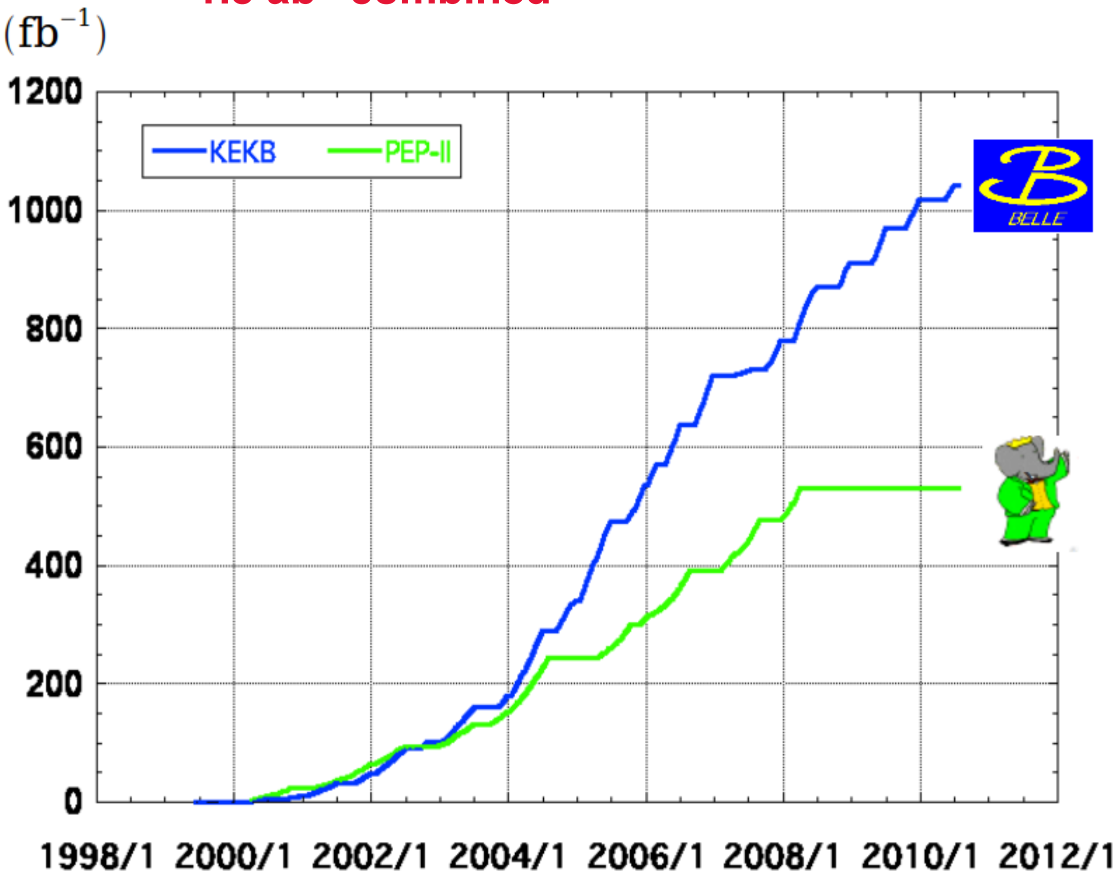
Upper limits on CLFV muon decays

Current bounds and projection of expected ULs



Luminosity at B-Factories

~1.5 ab^{-1} combined



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

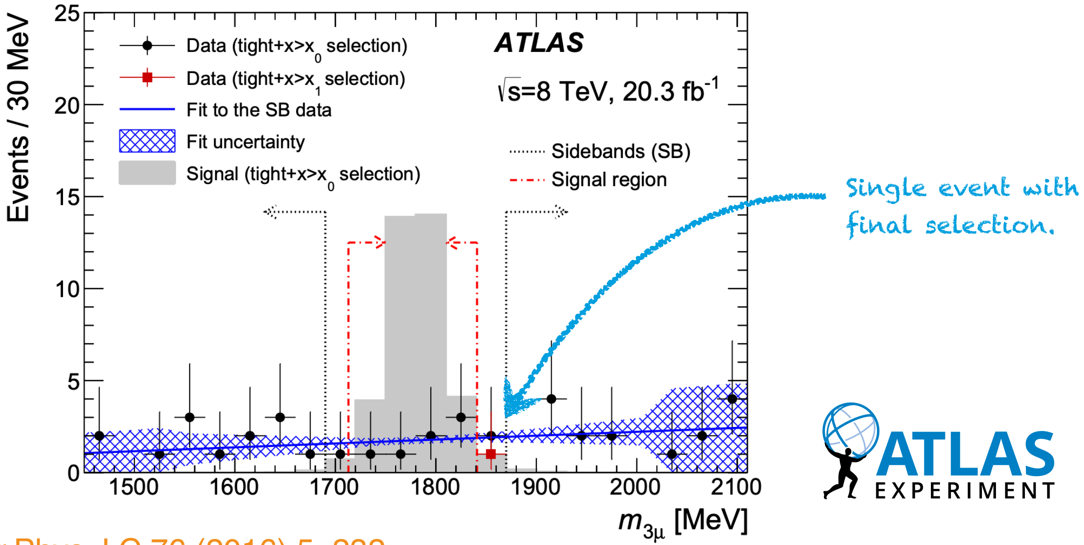
$\sim 54\ fb^{-1}$

Searches for $\tau^+ \to \mu^+\mu^-\mu^+$ at LHC

ATLAS

- **Search @ ATLAS:**
  - Search via $W^- \to \tau^-\nu_\nu$, or heavy hadron decays, with the subsequent τ^- LFV decay.
  - Training a BDT with loose selection, and performing the search with a tight selection + BDT.

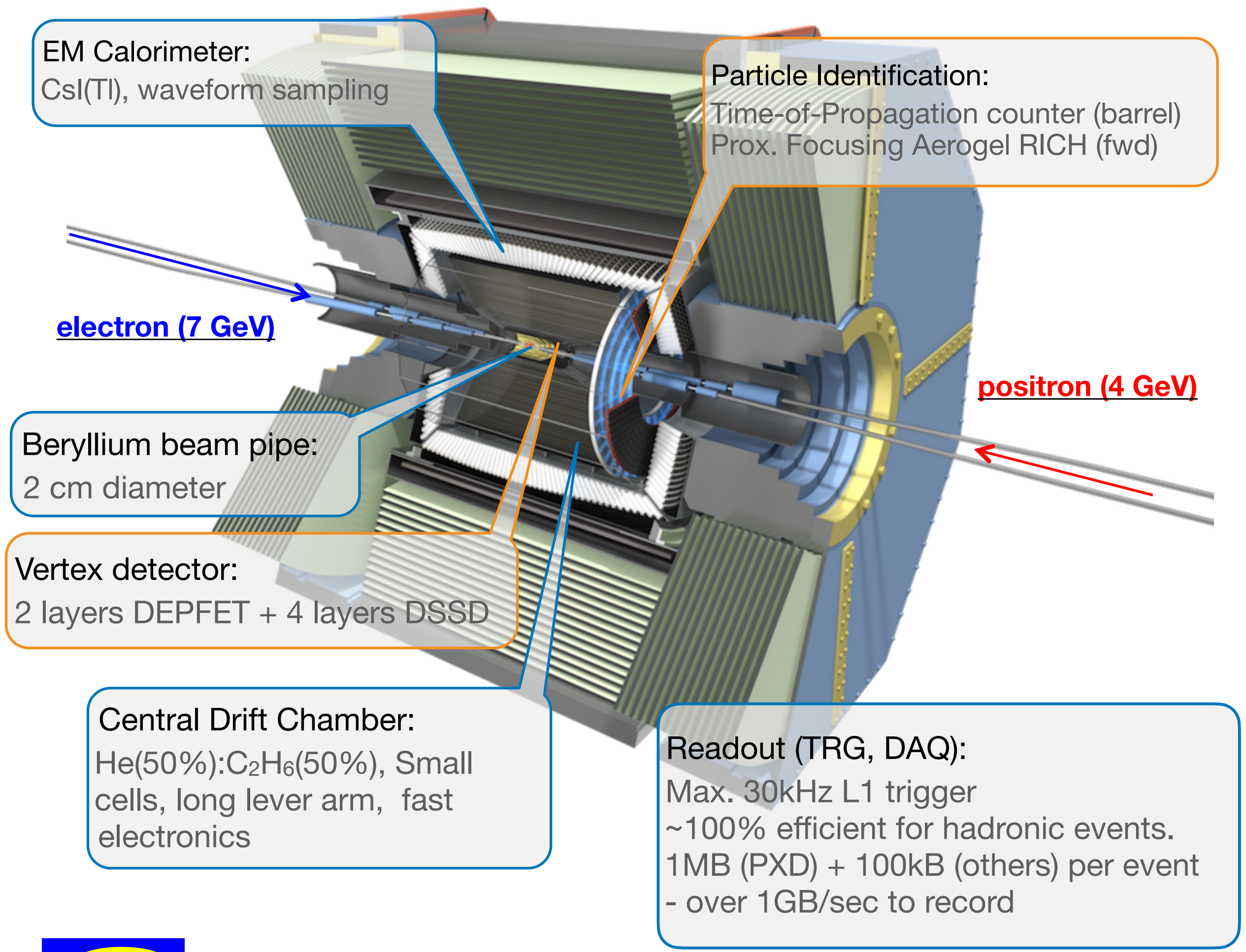
BR($\tau^+ \to \mu^+\mu^-\mu^+$) < 1.0 x 10^{-7} (90% CL)



Eur.Phys.J.C 76 (2016) 5, 232

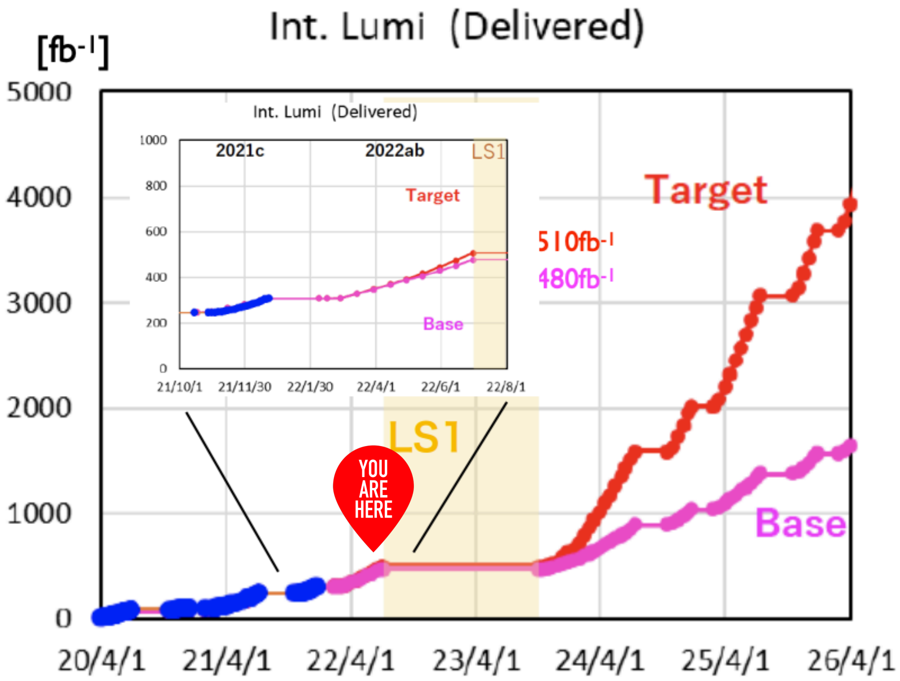
The Belle II Experiment

A B-Factory of next generation



PTEP 2019 (2019) 12, 123C01

- 50 ab^{-1} at the end of the experiment (x50 than the previous B factories)
- ~10^{11} τ lepton decays recorded at the end of the experiment.



Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Michel Hernandez Villanueva
michel.hernandez.villanueva@desy.de
Orcid: 0000-0002-6322-5587