Muon and Tau CLFV studies from Belle II and J-PARC experiments

MyeongJae Lee (SKKU), Apr 20, 2023, KPS

Lepton Flavor in Standard Model

LEPTONS

~~ν_{e_R}~~	~~ν_{μ_R}~~	~~ν_{τ_R}~~
ν_{e_L}	ν_{μ_L}	ν_{τ_L}
e_R	μ_R	τ_R
e_L	μ_L	τ_L

QUARKS

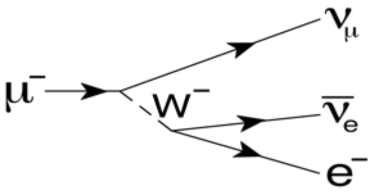
$u_R^{r,g,b}$	$c_R^{r,g,b}$	$t_R^{r,g,b}$
$u_L^{r,g,b}$	$c_L^{r,g,b}$	$t_L^{r,g,b}$
$d_R^{r,g,b}$	$s_R^{r,g,b}$	$b_R^{r,g,b}$
$d_L^{r,g,b}$	$s_L^{r,g,b}$	$b_L^{r,g,b}$

GAUGE BOSONS

g
γ
W
Z

\+ **H** Higgs

- No Right-handed neutrino : Left-right non-symmetric
- Lepton Flavor is exact symmetry and conserved



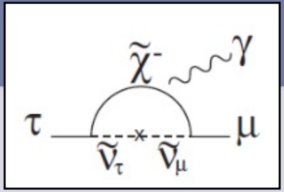
	Initial state	Final state
Muon #	1	1
Electron #	0	(-1)+1 = 0
Lepton #	1	2 -1 = 1

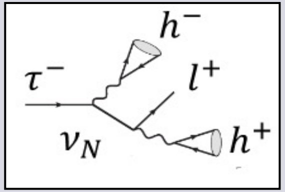
- Lepton Flavor is NOT conserved, if, for example
  - Right-handed neutrino exist
  - Massive majorana neutrino

} Neutrino oscillation

CLFV Researches

Tau





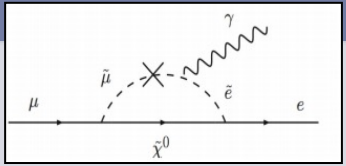
$\tau \to \ell\gamma,\ \tau \to \ell\ell\ell$

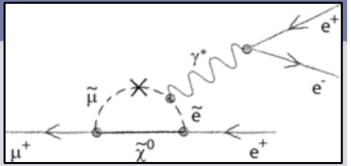
$\tau \to \ell P^0,\ \tau \to \ell V^0,\ \tau \to \ell S^0$

$\tau \to \ell hh$

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

Muon





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

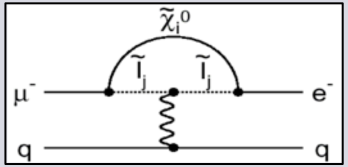
$\mu^+ \to e^+e^-e^+$

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

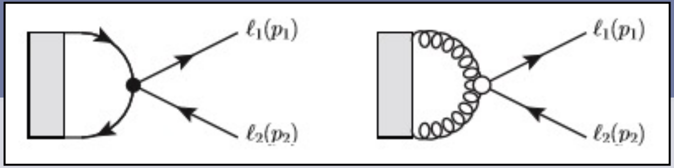
$\mu^- + N \to e^+ + N'$

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

Muonium Oscillation



Hadron

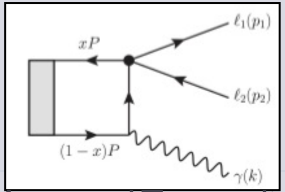


$P(V) \to \ell_1\ell_2$

$V = \Upsilon, J/\psi, \phi, \rho, \varpi$

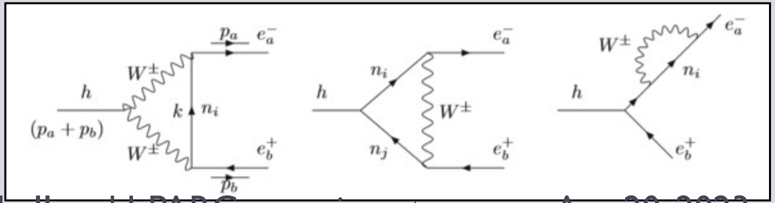
$P = \pi^0, K^0, D^0, \eta^{(\prime)}_{(c,b)}, B^0_{(d,s)}$

$V \to \gamma\ \ell_1\ell_2$

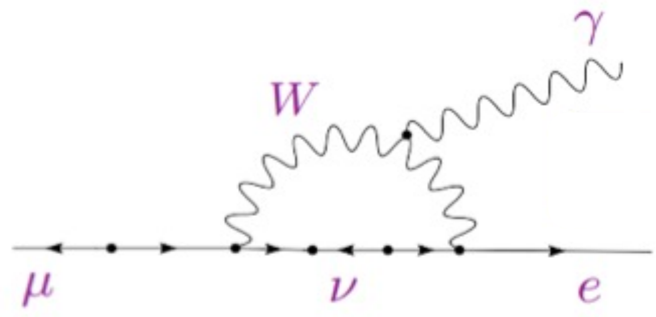


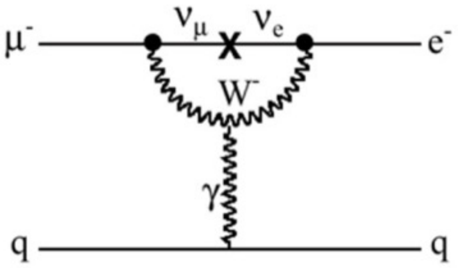
Gauge boson, Higgs

$h \to \ell_1\ell_2,\ Z \to \ell_1\ell_2$



Muon LFV in Standard Model (SM)





$$\mathrm{BR}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{j=1}^{3} U_{\ell_1 j}U^{*}_{\ell_2 j}\frac{m^2_{\nu_j}}{M^2_W}\right|^2$$

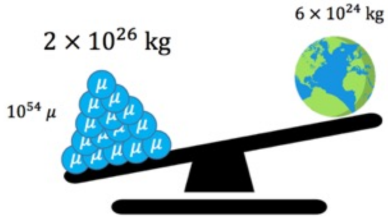
$$\cong \mathcal{O}(10^{-55} - 10^{-54})$$

$$R_{\mu e} = \frac{\Gamma(\mu \to e)}{\Gamma(\mathrm{capture})}$$

$$\cong \mathrm{O}(\alpha)\times\mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-54}$$

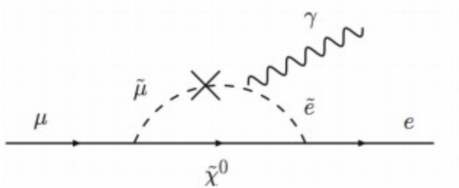
In SM, we need 30x more muon than the Earth.

CLFV observation= Signature of New physics in BSM



Muon LFV in BSM Searches

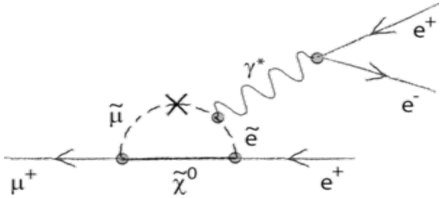
$\mu^+ \to e^+ \gamma$



- MEG
- MEG II (PSI)

<4.2x10^{-13} @90% CL
MEG, 2016

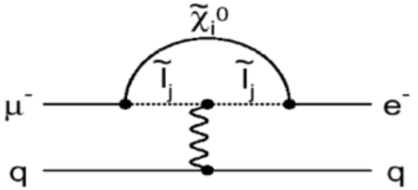
$\mu^+ \to e^+ e^- e^+$



- Mu3e (PSI)

<1.0x10^{-12} @90% CL
SINDRUM, 1988

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



- DeeMe (J-PARC)
- **COMET (J-PARC)**
- Mu2e (FNAL)
- Mu2e-II (FNAL)
- PRISM/PRIME

<7x10^{-13} @Au, 90% CL
SINDRUM-II 2006

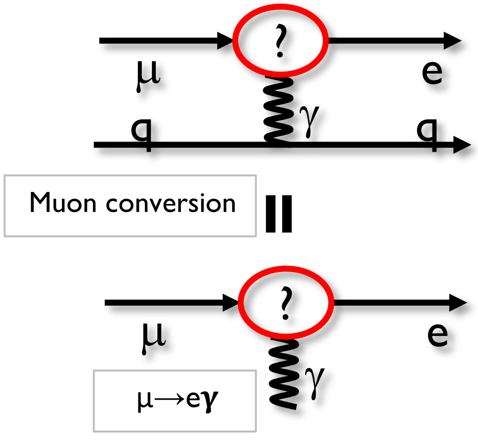
Other searches

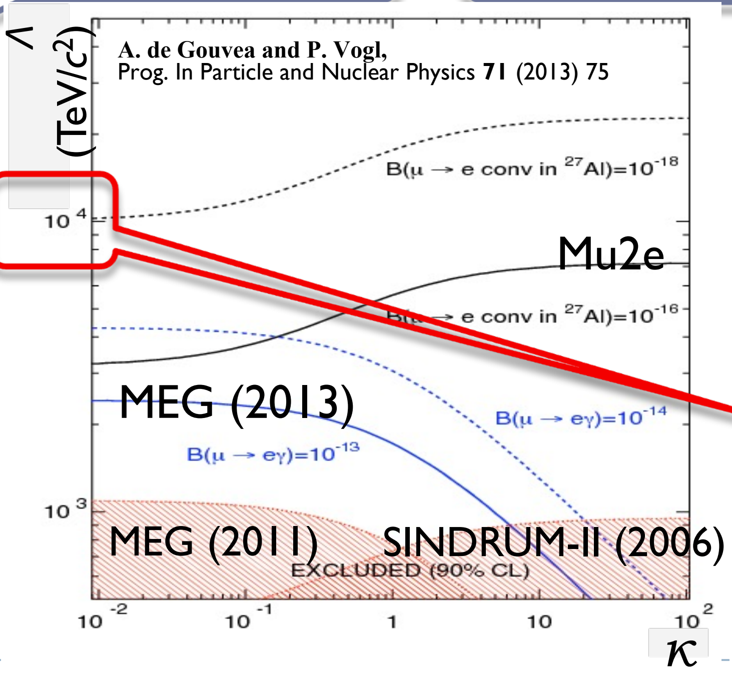
- $\mu^- N \to e^+ N'$
- $\mu^- e^- \to e^- e^-$
- $\mu^- \to e^- X$
- Muonium Oscillation

Dipole or Direct interactions

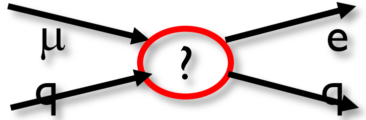
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma_\mu q_L\right)$$

Dipole Interaction





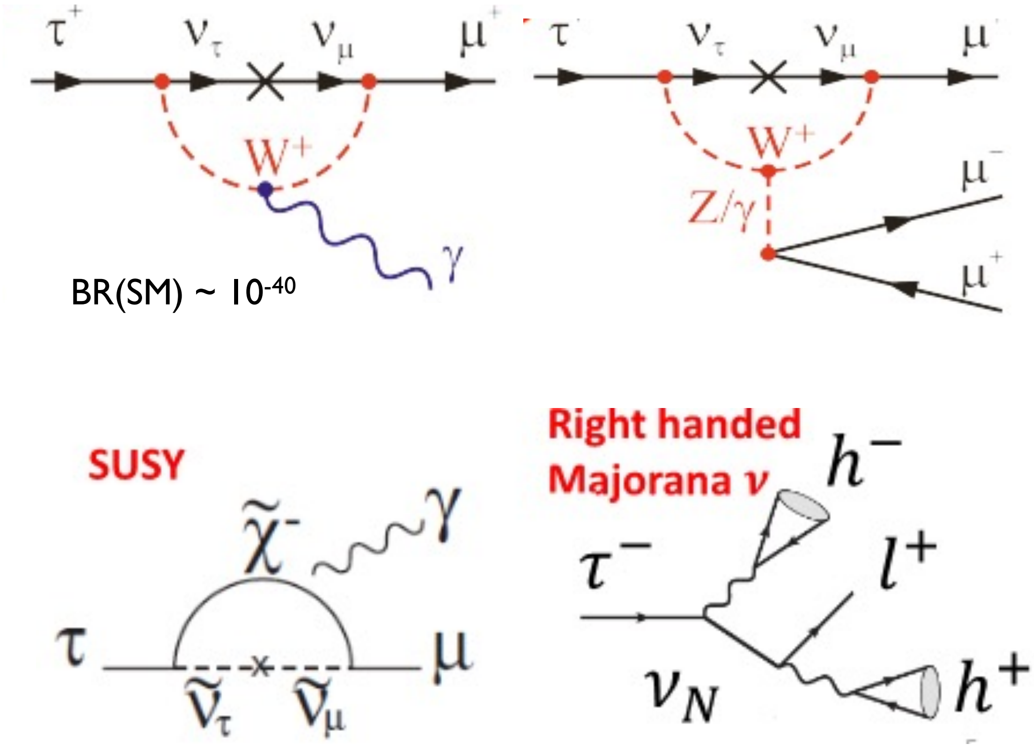
Contact interaction



Probing $O(10^4)$ TeV mass scale,

➔Much higher energy scale than LHC

LFV in τ Lepton



Pros:

- Several order larger rate than muon LFV
- Many possible LFV modes due to heavier mass

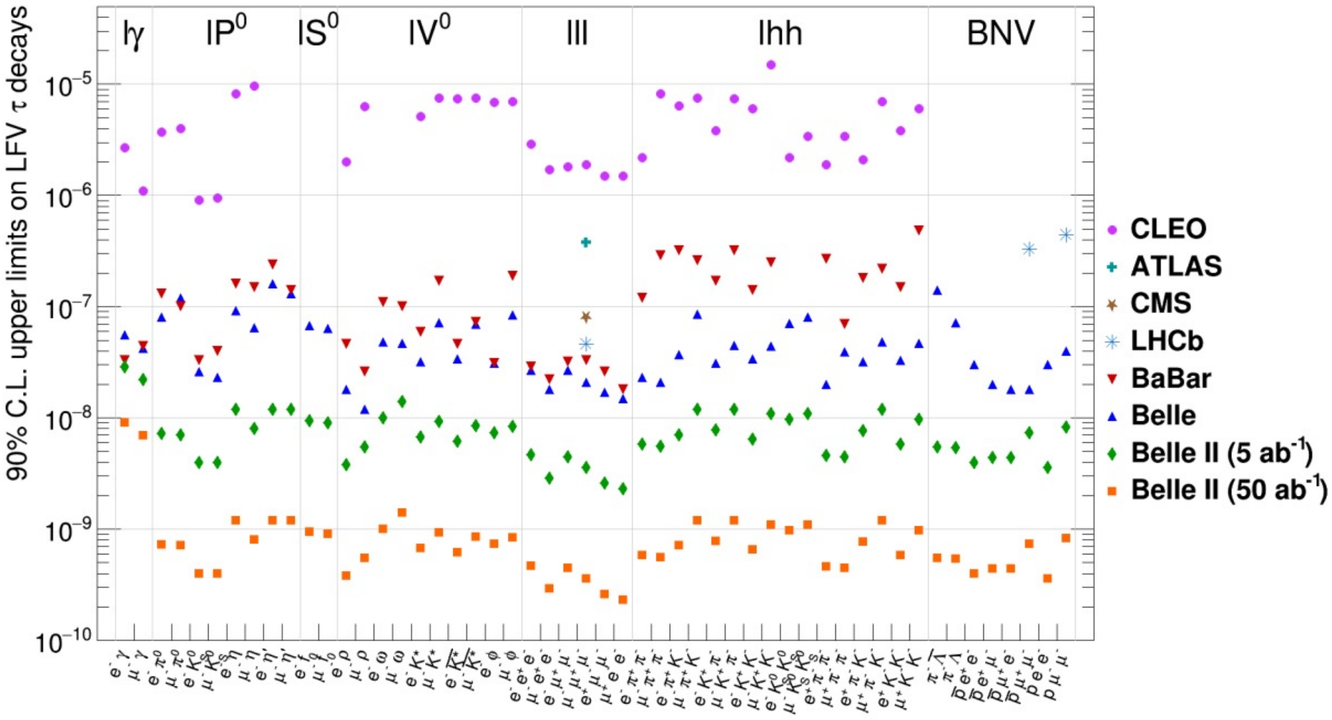
Cons:

- Not easy to produce τ lepton
  : 1~10 τ/sec at B-factory

  (Note : 10^{13}~10^{14} μ/sec at Mu2e)

LFV in τ Lepton

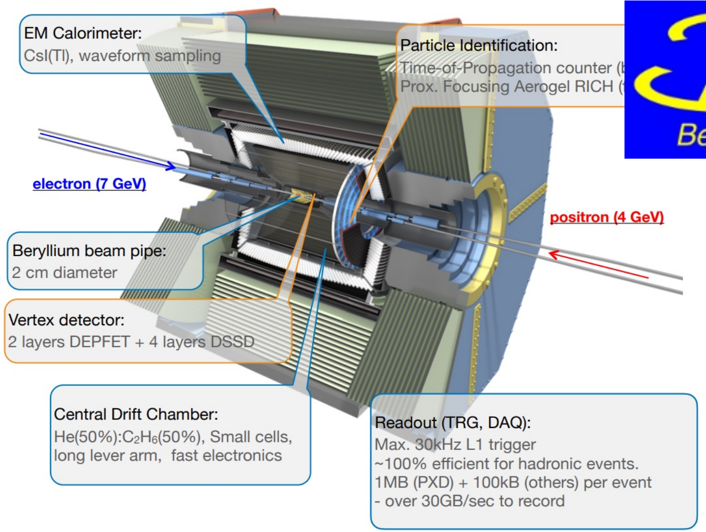
- $\tau \to \ell\ell\ell$
  - Possible to access in early Belle II
- $\tau \to \ell h h'$
  - Both LFV and Lepton Number Violation (LNV) decays
- $\tau \to \ell\gamma$
  - Sensitive to many New Physics models but seriously affected by beam background

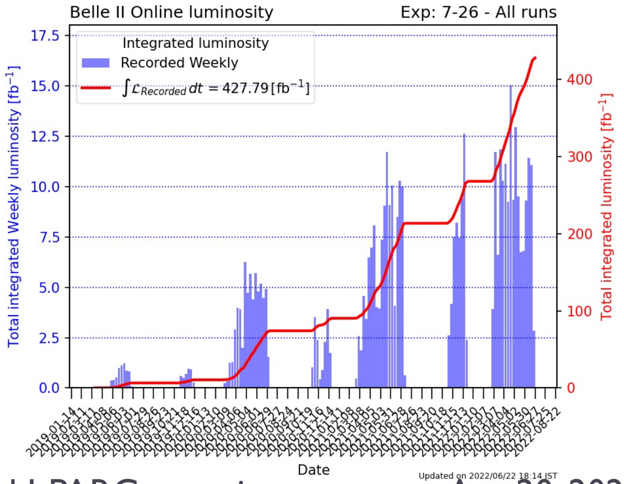


(CLFV @ Snowmass 2021 arXiv:2203.14919 (2022))

Belle II Experiment

- Collected ~420 fb^{-1} so far, Long shutdown in 2022-2023
- World record peak luminosity : $4.7\times10^{34}\ cm^{-2}s^{-1}$ (Goal : $6\times10^{35}\ cm^{-2}s^{-1}$)
- "Tau factory"
  - $\sigma(e^+e^- \to \Upsilon(4S)) = 1.05\ \text{nb}$
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.919\ \text{nb}$
  - Tau LFV decays up to 10^{-10} sensitivity is expected



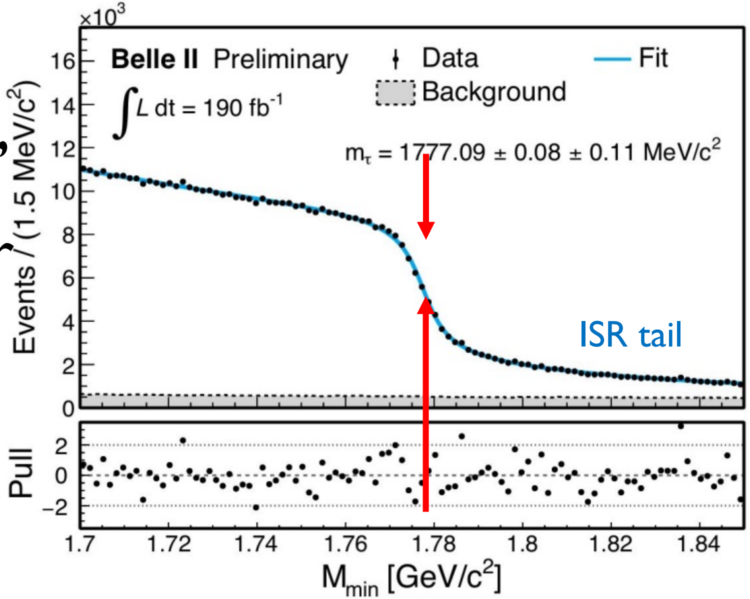


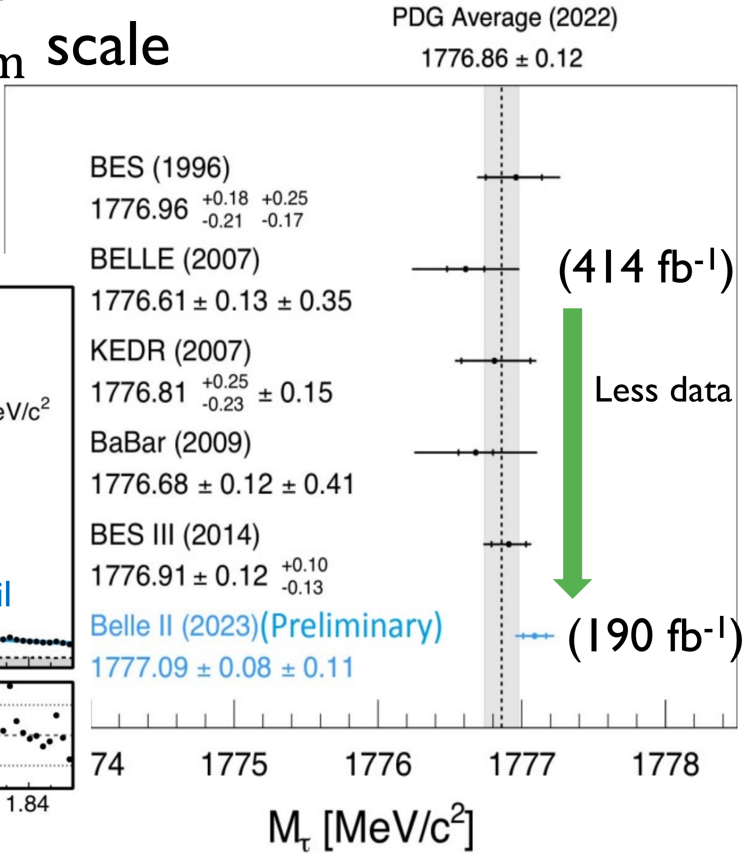
Performance : Tau mass measurement

- Measurement limited p_{track} scale & E_{beam} scale
- Pseudo-endpoint method :

$$M_{\min} = [M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)]^{1/2} \leq M_\tau$$

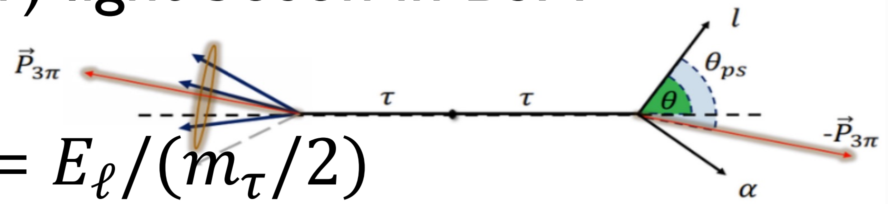
- Less Data,
  Better sys err.,
  Better stat. err.,
  owing to
  Better detector
  - Improved measurement of endpoint slope

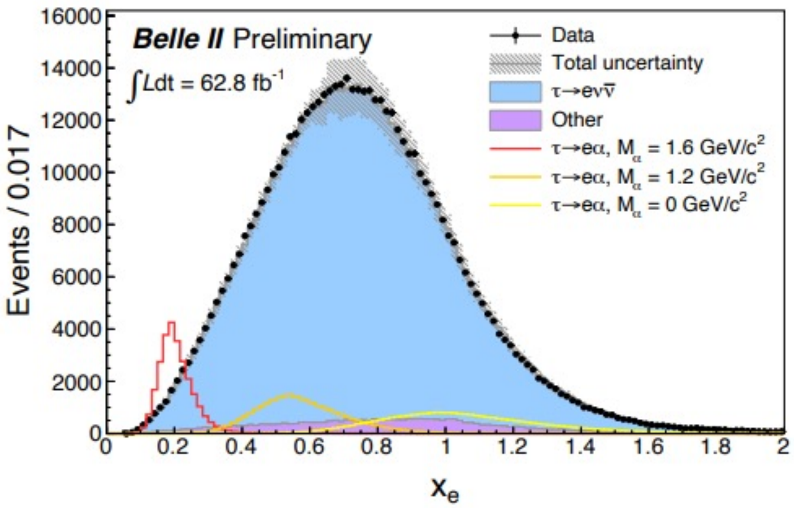


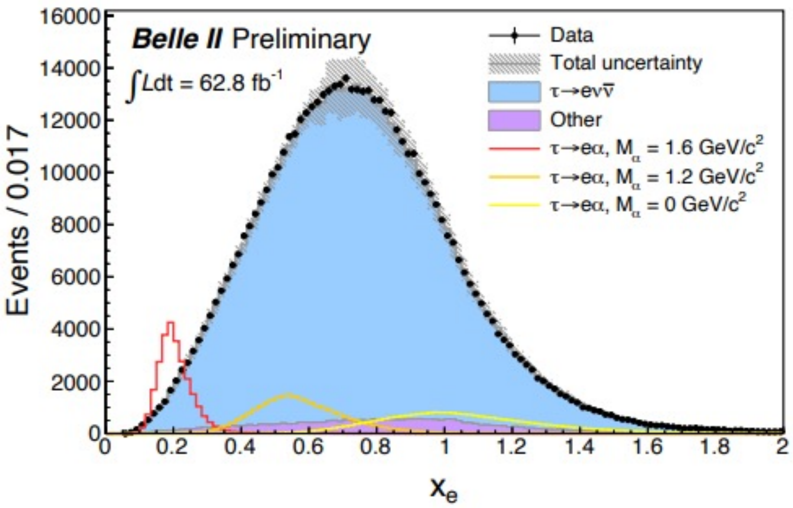


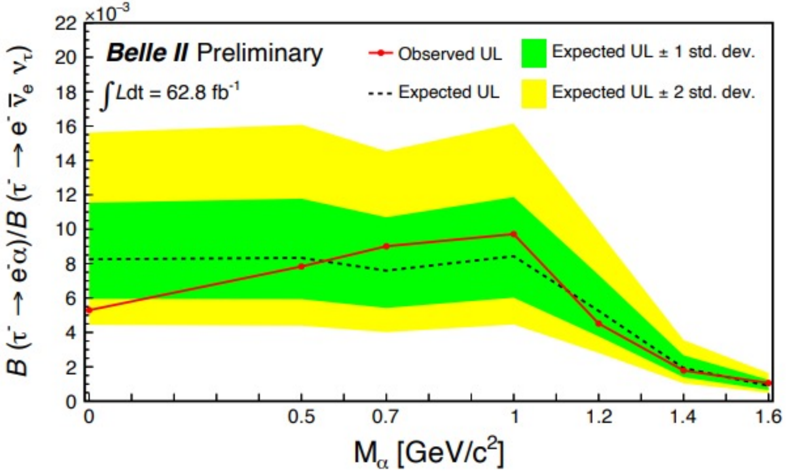
Recent results: BSM boson search of τ→ℓα

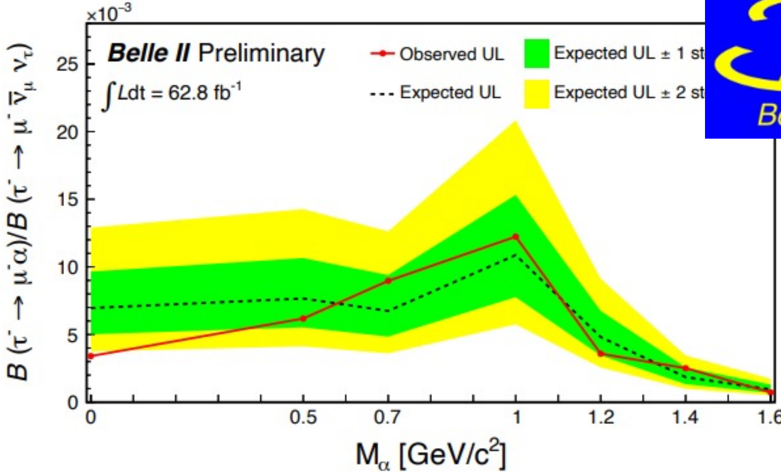
- α is an invisible (pseudo scalar) light boson in BSM (possible similar with axion)
- Template fit with pdfs on $x_\ell = E_\ell/(m_\tau/2)$





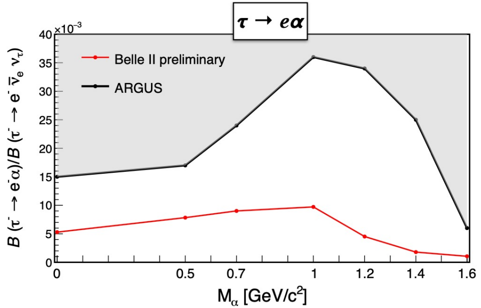


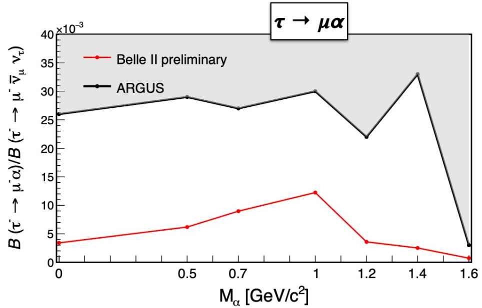




- Using the most early data ($62.8fb^{-1}$), the most stringent limit, 3 – 7 times better than ARGUS measurement (1995, $476pb^{-1}$) was achieved.

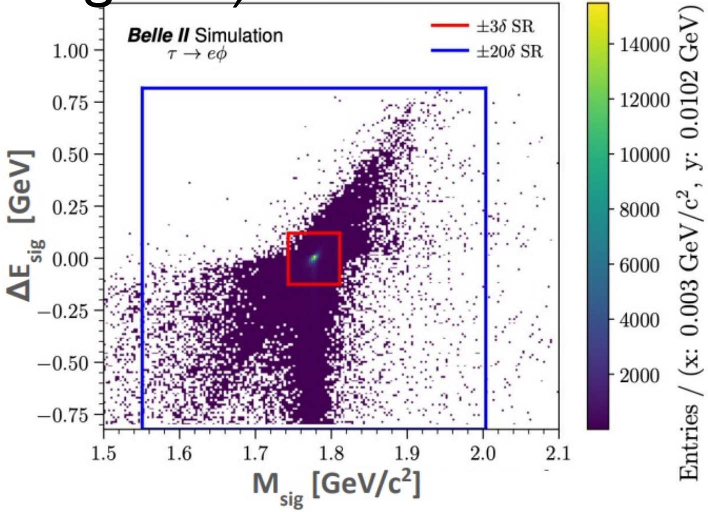
 (arXiv: 2212.03634)

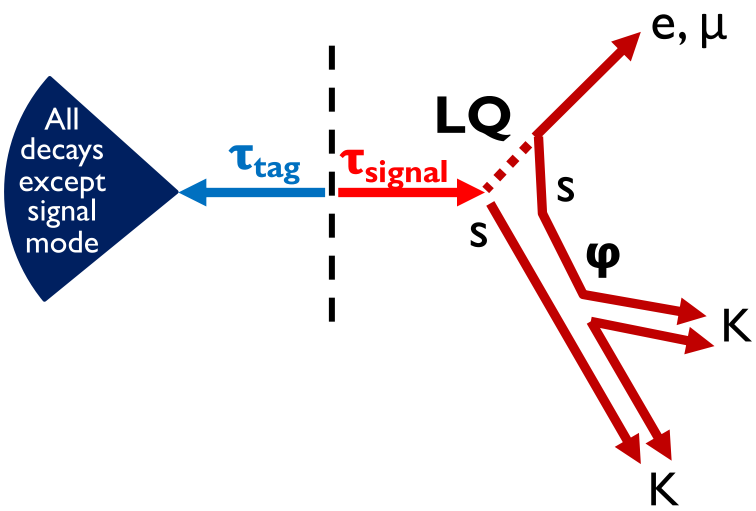


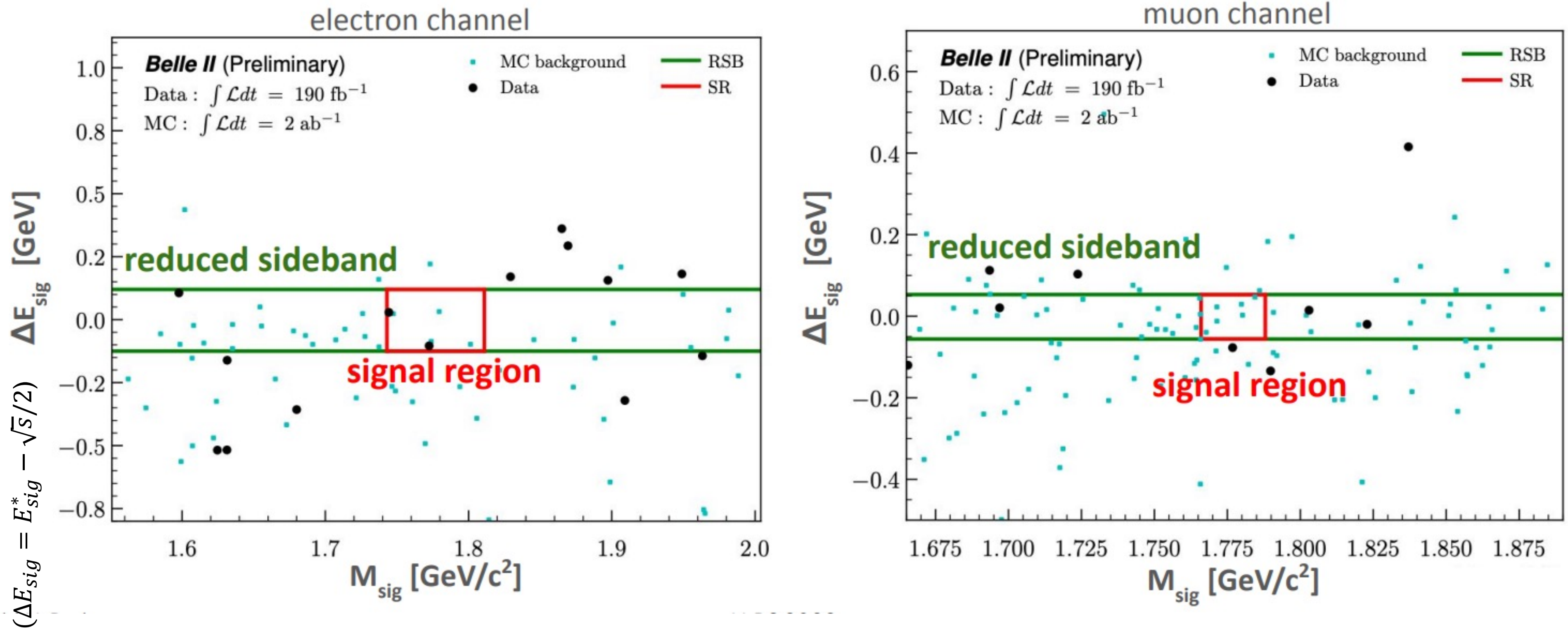


Recent results: LFV decay of $\tau \rightarrow \ell\phi$

- Highly suppressed in SM ($\sim 10^{-50}$) but much higher in Leptoquark model ($\sim 10^{-8} - 10^{-10}$)
- Improved efficiency (6.5%, 2xBelle) due to "Rest of Everything" (on tag side) method + BDT



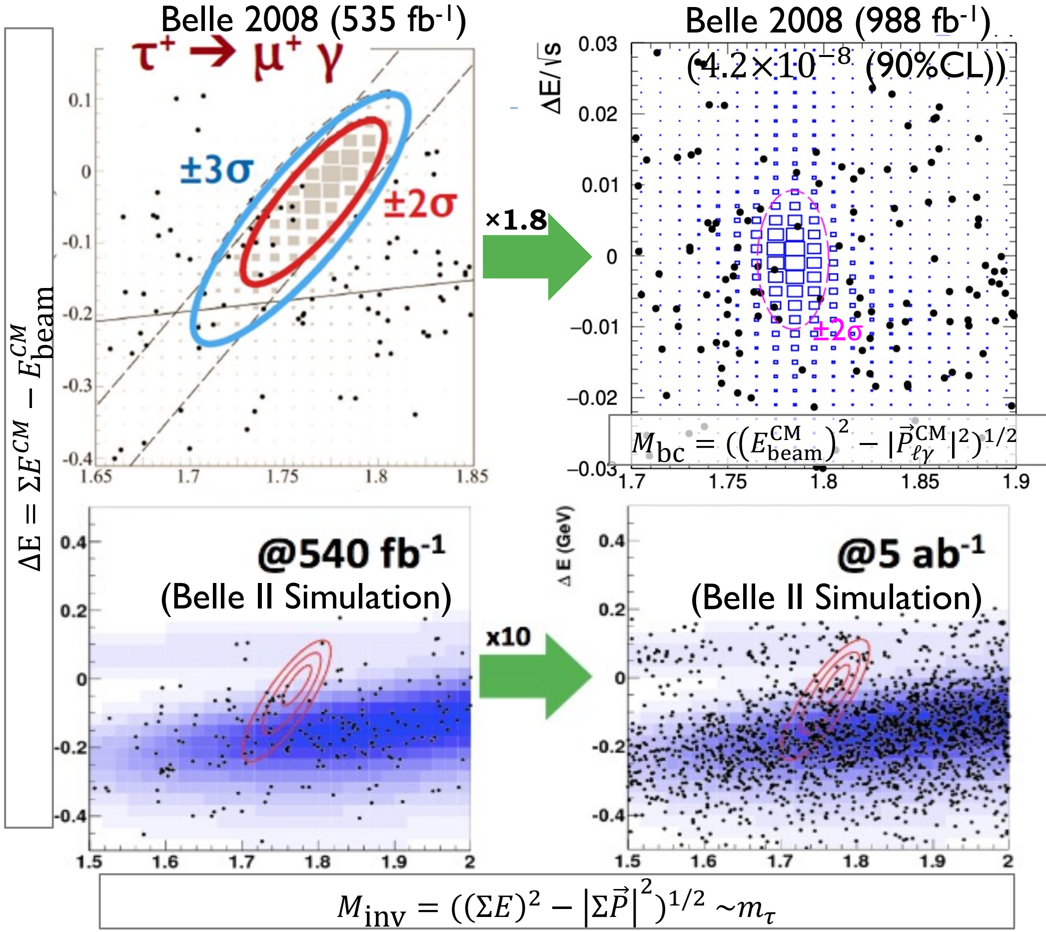




- BF($\tau \rightarrow e\phi$, 90%CL)=2.3x10^{-7}, BF($\tau \rightarrow \mu\phi$, 90%CL)=9.7x10^{-8}
- Statistically limited (~1/5 x Belle), but inclusive tagging successfully applied.

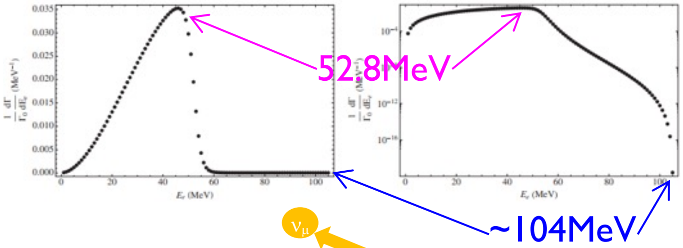
Prospect: $\tau \to \ell\gamma$ at Belle II

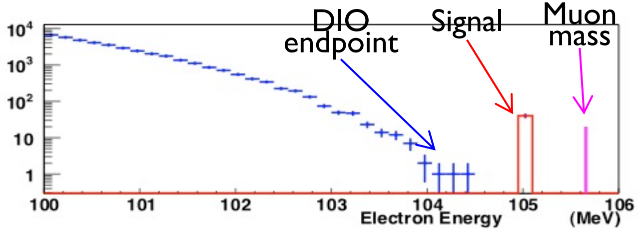
- 50 ab^{-1} = 5x10^{10} τ pairs
  $\Rightarrow$ UL ~ 10$^{-8\sim-9}$
- Sensitivity depends on background level
  - New BG rejection method using kinematic relation enabled fewer BG with increased dataset

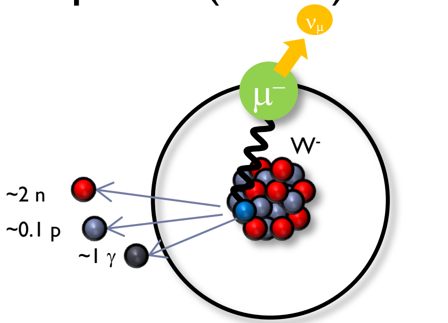


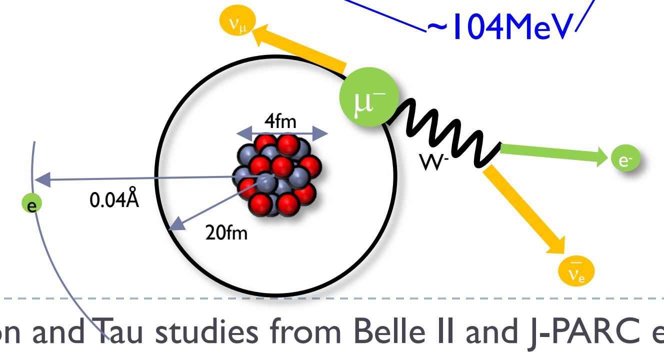
Muon Conversion (for CLFV)

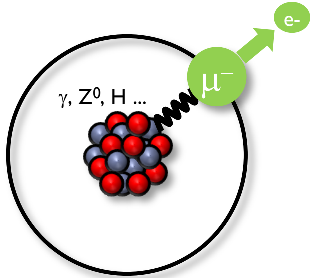
Muon Capture (61% (Al))	**Decay in orbit(DIO)** (39% (Al))	**$\mu^- \rightarrow e^-$ conversion**
$\mu^- + p \rightarrow \nu_\mu + n$	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	$\mu^- + N \rightarrow e^- + N$
Muon decay with nucleus	Bound muon decay	$E(e^-;Al) = m_\mu - E_{rec} - E_B$ = 104.97 MeV : **Signal**
BG hit source / Radiative Muon Capture (RMC) **BG**	Major **BG** source	



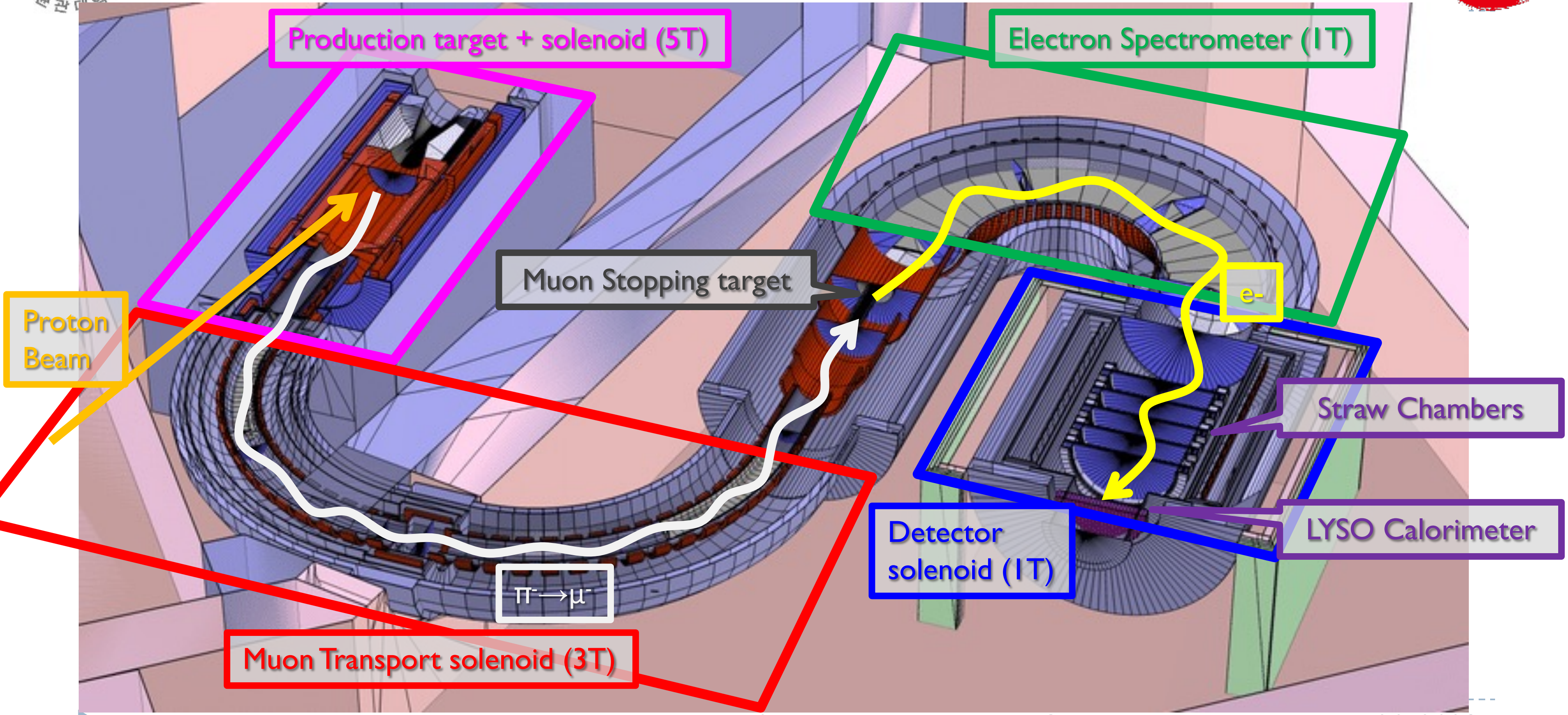




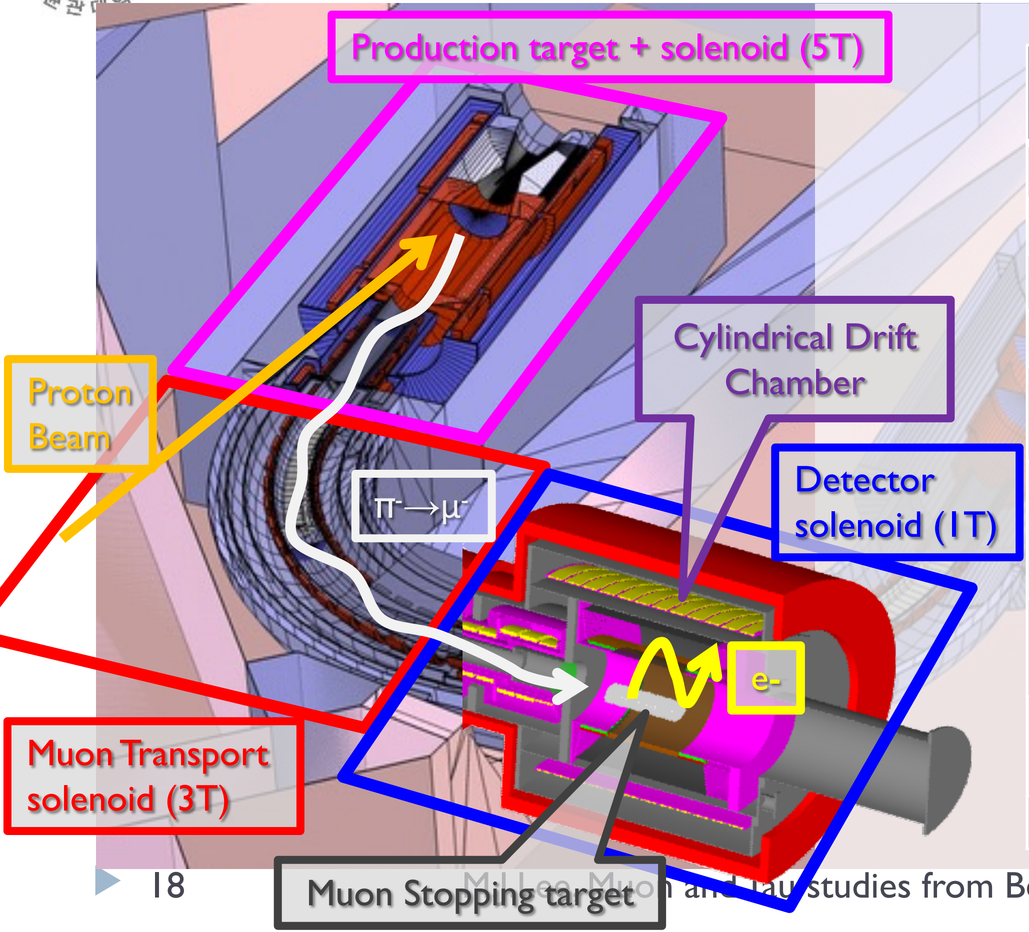




COMET for Muon Conversion Search

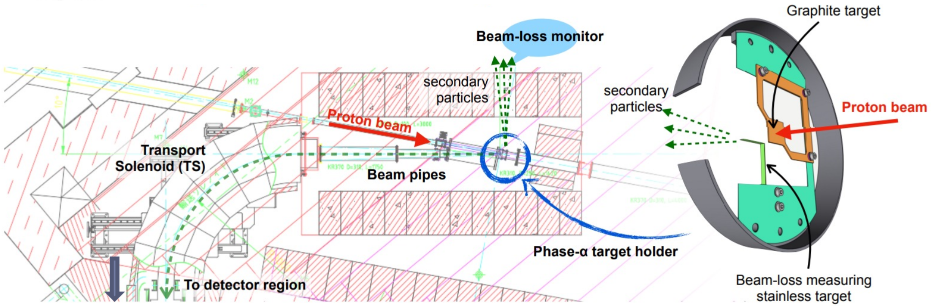


COMET Phase-I



	COMET Phase-I	COMET Phase-II
E(Proton)	8 GeV	
P(Proton)	3.2 kW	56 kW
N (proton)	3.2×10^{19}	6.8×10^{20}
Proton Target	Graphite	Tungsten
Muon Target	Aluminum	Aluminum ?
Detector	Drift chamber	Straw + calorimeter
Sensitivity (90% CL)	7×10^{-15}	2.6×10^{-17} ~10^{-18}
DAQ start	2025	203X -
DAQ Time (days)	~150	180 ~ 300

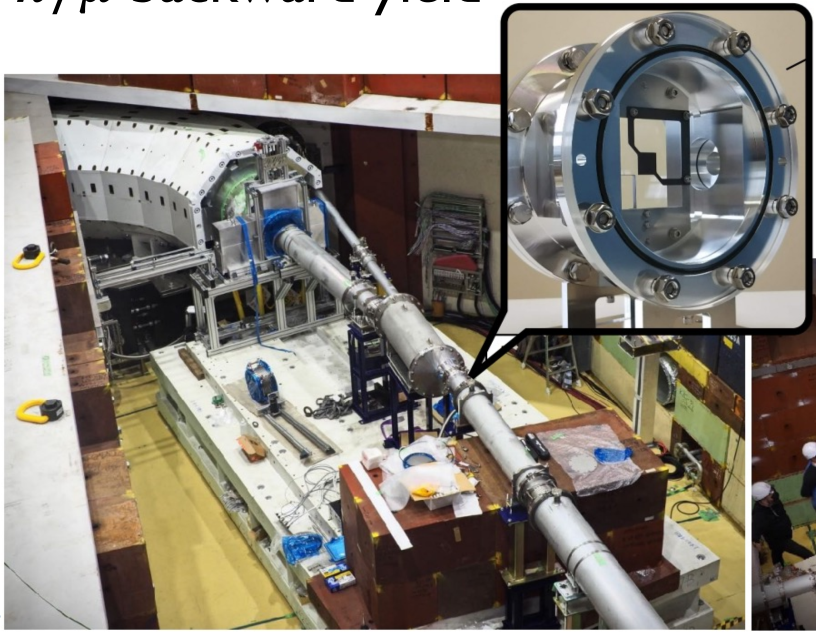
COMET Phase-α



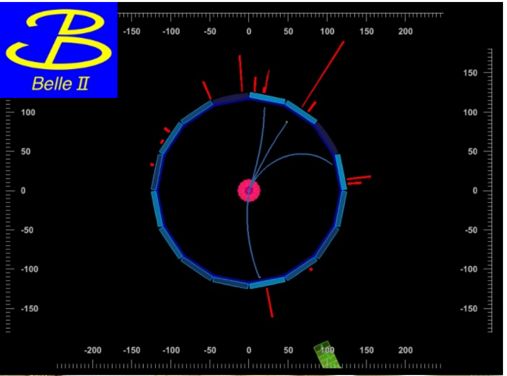
Beam counting detectors

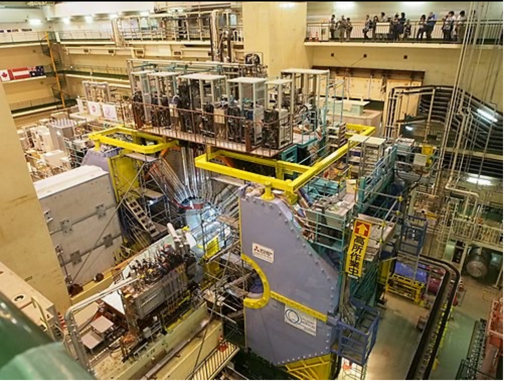
A Preliminary data plot

- A low beam-intensity run to study the beamline, in March 2023
- Measurement of the proton beam and π/μ backward yield



Prospects





- CLFV is promising on finding a signature on BSM
- Belle II started CLFV analysis on tau decays for BSM. Still it's limited by statistics, but $O(10^{-10})$ sensitivity is feasible.
- Muon CLFV experiments such as COMET will provide a hint on BSM. COMET starts DAQ at 2025 (Mu2e at 2026)
- CLFV measurements of Tau and Muon are complementary