Search for new physics at Super Tau-Charm Facility

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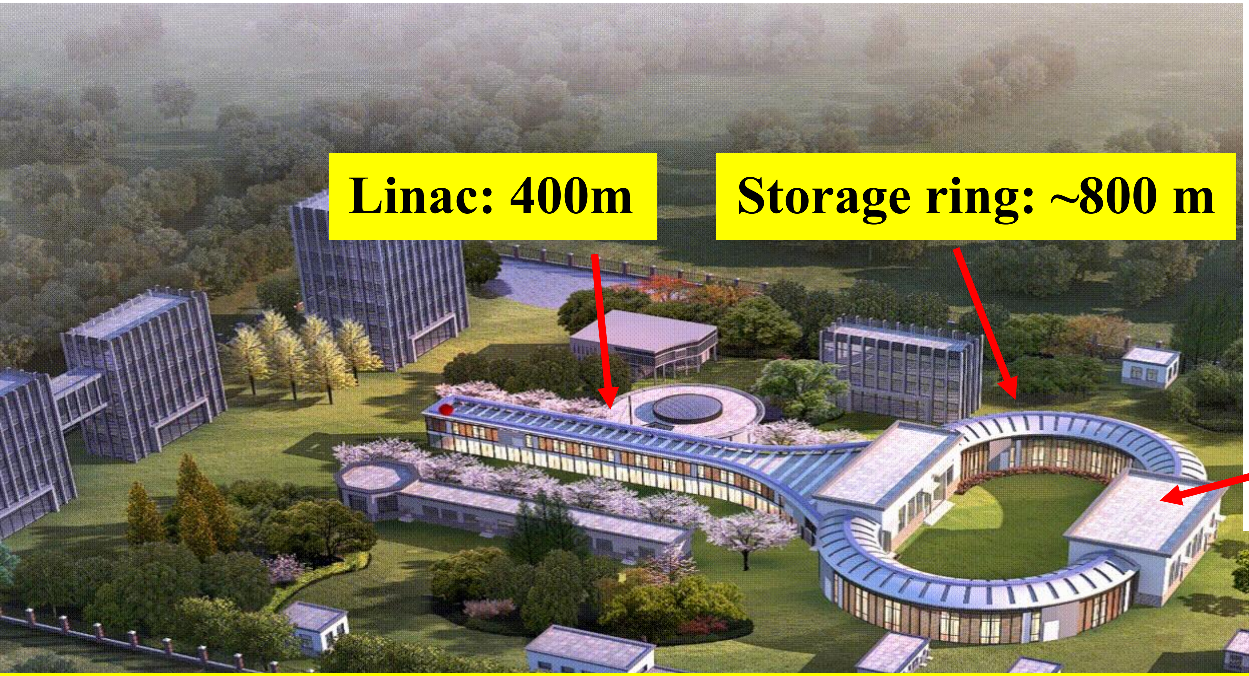
for the STCF working group

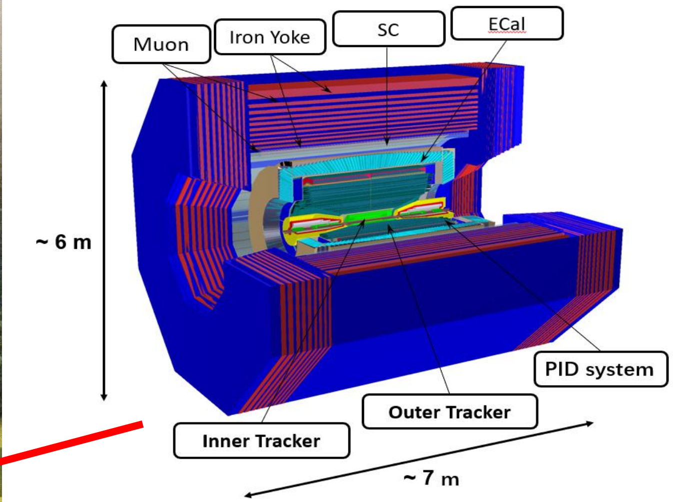
NPG Workshop 13/10/2023

Outline

- Introduction
  - Experiment facility
  - Expected data samples
  - Oppotunities of (new) physics studies
- Tau LFV studies
- Rare and forbidden decays
- CP violation studies
- Summary and prospects

Super Tau-Charm Facility in China



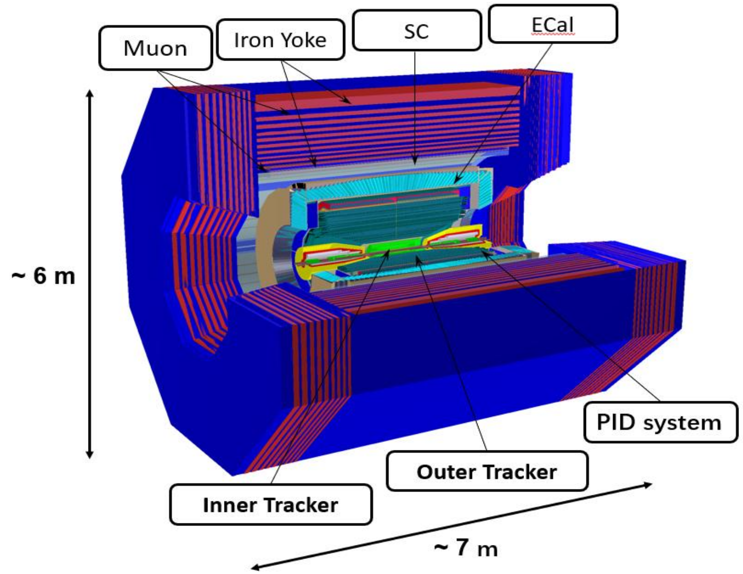


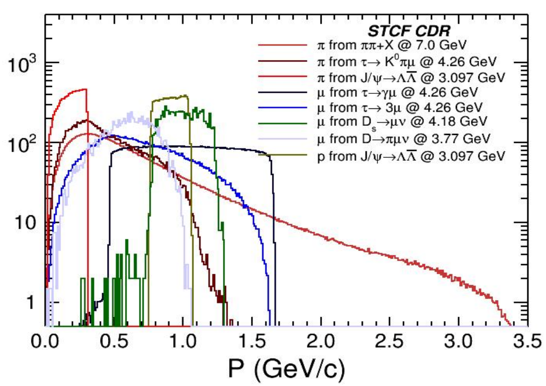
- Peak luminosity $>0.5\times10^{35}$ $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2-7 GeV
- Potential to increase luminosity & realize beam polarization
- R&D project (0.42B RMB), total cost: 4.5B RMB

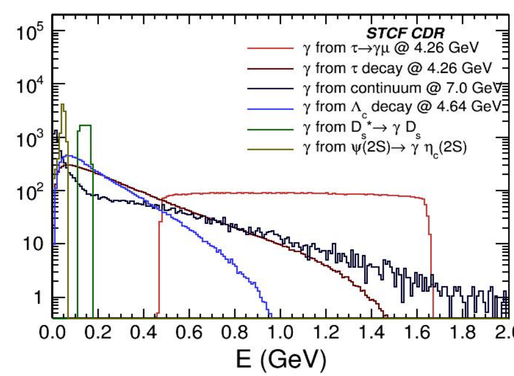
- 1 ab^{-1} data expected per year
- Rich of physics program, unique for physics with *c* quark and τ leptons,
- Important playground for study of QCD, exotic hadrons, flavor physics and search for new physics.

STCF Detector

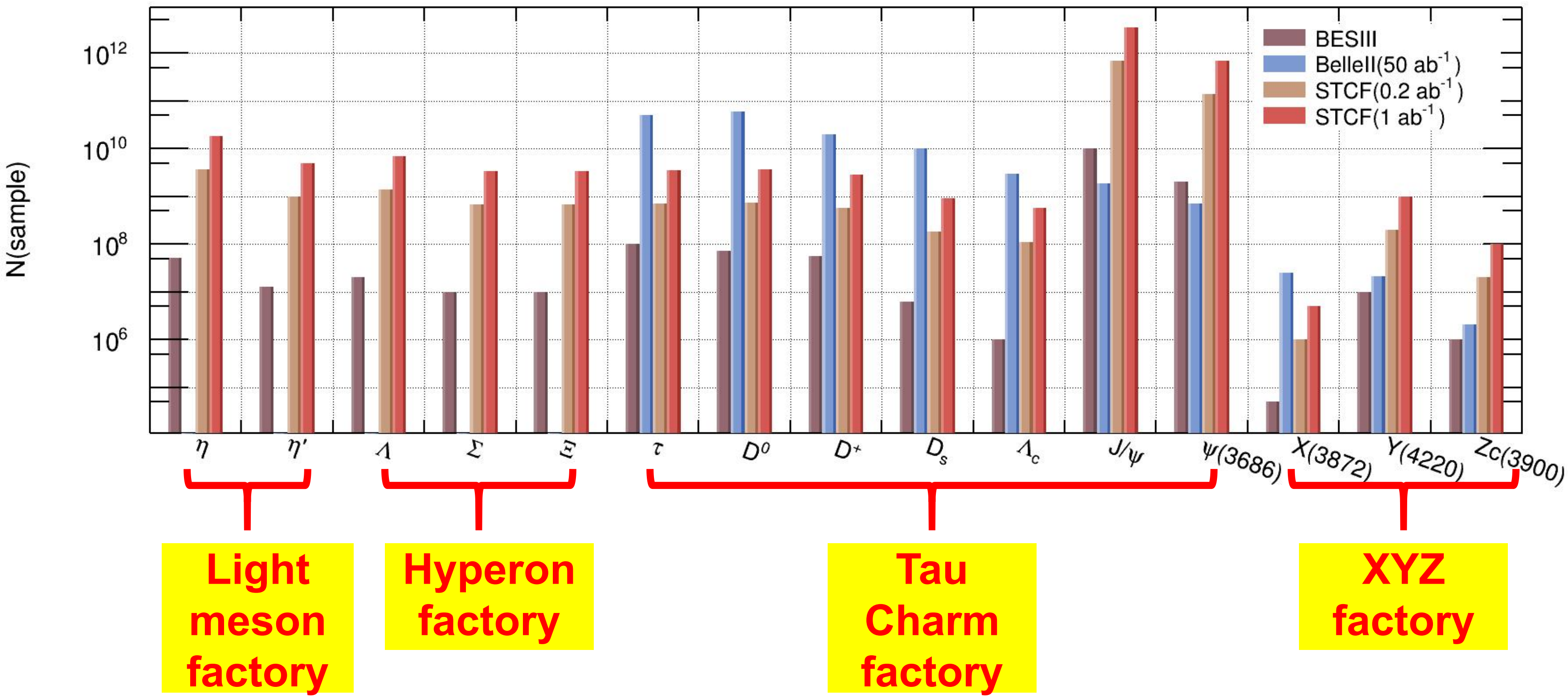
- **Inner Tracker (ITK)**
  - ~0.15% X_0 / layer
  - σ_{xy} ~ 50 μm
- **Out Tracker (MDC)**
  - σ_{xy}~130 μm, σ_p/p~0.5%@1GeV/c
  - dE/dx ~ 6%
- **PID system (RICH)**
  - π/K (K/P) 3-4σ separation up to 2 GeV/c
- **ECal**
  - Range: 0.02 – 3 GeV
  - Resolution (1GeV): 2.5% (barrel) and 4% (endcap)
- **Muon system**
  - Pion suppression power: >10 and as low as 0.4 GeV/c







Expected data samples at STCF



- STCF is expected to have higher detection efficiency and low background with productions near threshold
- STCF is designed to have excellent resolution, kinematic constraining
- Opportunities at 5-7 GeV which is experimentally blank before

Physics programs of STCF

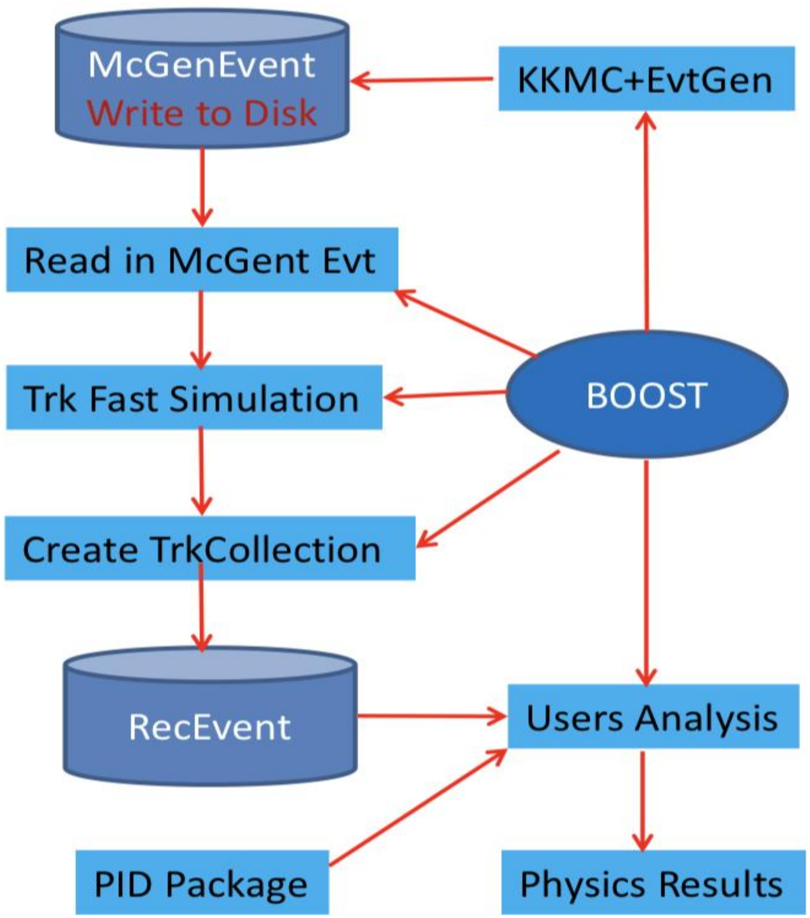
STCF CDR: Volume 1 -- Physics & Detector arXiv:2303.15790

Physics at STCF

- **QCD and hadronic physics**
  - **XYZ Properties:** e+e-→Y→γX,ηX,ϕX; e+e-→Y→πZc, KZcs
  - **Hadron Spectroscopy:** Excited ccbar and their transition, Charmed hadron spectroscopy, Light hadron spectroscopy
  - **R value:** e+e-→inclusive; τ mass: e+e-→τ+τ-
  - **Nucleon Form Factors:** e+e-→BBbar from threshold
  - **Pentaquarks:** e+e-→J/ψppbar, Λc Dbar pbar, Σc Dbar pbar
    Di-charmonium: e+e-→J/ψηc, J/ψhc
  - **Muon g-2:** e+e-→π+ π-, π+ π- π0, 4π, K+ K-, γγ→π0, η(′),π+ π-
  - **Fragmentation functions:** e+e-→(π,K,p,Λ,D)+X, e+e-→(ππ,KK,πK)+X
- **Flavor Physics and CP Violation**
  - **CKM matrix (Vcd, Vcs):** D_(s)+→l+v, D→P l+ v
  - **Charm hadron decay:** Λc+, Σc, Ξc, Ωc decay
  - **CPV in Hyperons:** J/ψ→ΛΛbar, ΣΣbar, Ξ- Ξ+bar, Ξ0 Ξ0bar
  - **D0-D0bar mixing:** ψ(3770)→(D0 D0bar)(CP=-), ψ(4140)→π0 (D0 D0bar)(CP=-) or γ(D0 D0bar)(CP=+)
  - **CPV in τ:** τ→Ks πv, EDM of τ, τ→π/K π0 v for polarized e- beam
  - **CPV in Charm:** D0→K+K-/π+π-, Λc→pK-π+π0/Λπ+π+π-/pKs π+π
  - **γ/ϕ3 measurement:** D0→K(s/L) π+ π-, K(s/L) K+ K-,K3π, 4π
  - **γ polarization:** D0→K1 e+ v_e
- **Forbidden/Rare decay and New Particle**
  - **LNV, BNV:** D(s)+→l+ l+ X-, J/ψ→Λc e-, B→Bbar…
  - **Symmetry violation:** η(′)→llπ0, η′→ηll…
  - **FLV decays:** τ→γl, lll,l P1 P2 , J/ψ→ll′, D0→ll′ (l′≠l)…
  - **FCNC:** D→γV, D0→l+ l-, e+e-→D∗ , Σ+→pl+ l-…
  - **Dark photon:** e+e-→γA′(→l+ l-), J/ψ→e+e-A′…
    Millicharged: e+e-→χχ̄ γ…

- **Leading role**
- In Competition with Belle II/LHCb
- **Synergy with BelleII/LHCb/Eic/EicC**

Fast simulation tools



Studying the physics sensitivity, guiding the optimization of Detector design

- **Based on BESIII BOOST framework, same as BESIII analysis procedures**
- **Implementing all the expected performance for the STCF detector.**
- **The input performances are flexible and adjustable for detector optimization**
- **Acceptable CPU and storage consumption**

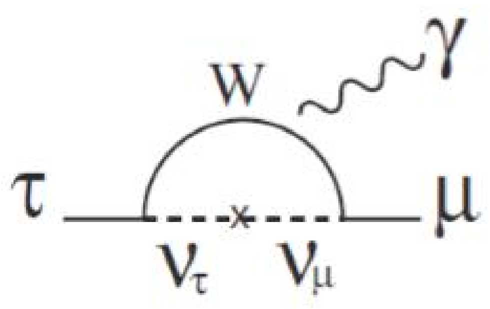
Friendly to BESIII users

Lepton Flavor Conservation

- **In quark sector**: flavor mixing is well established
- **Neutrino mixing**: =>lepton flavor symmetry is violated (a sign of LFV beyond the SM!)

How about charged lepton sector??

- The charged LFV processes can occur through oscillations in loops
- Immeasurable small rates (10^{-54}-10^{-49}) for all the LFV μ and τ decays



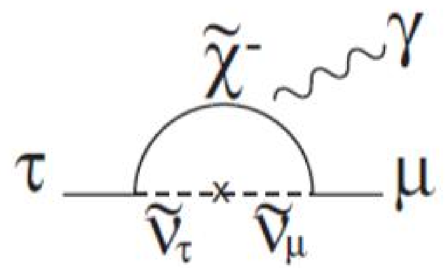
$$\mathfrak{B}(l_1 \to l_2\gamma) \propto \alpha\left(\frac{\Delta m^2}{m_W^2}\right)^2$$

Any observation of LFV in charged lepton will be a signature of NP !

LFV: a gateway to BSM

- Many extensions of SM naturally introduces cLFV at order ~**10^{-7} – 10^{-10}** (an crucial place to test BSM)

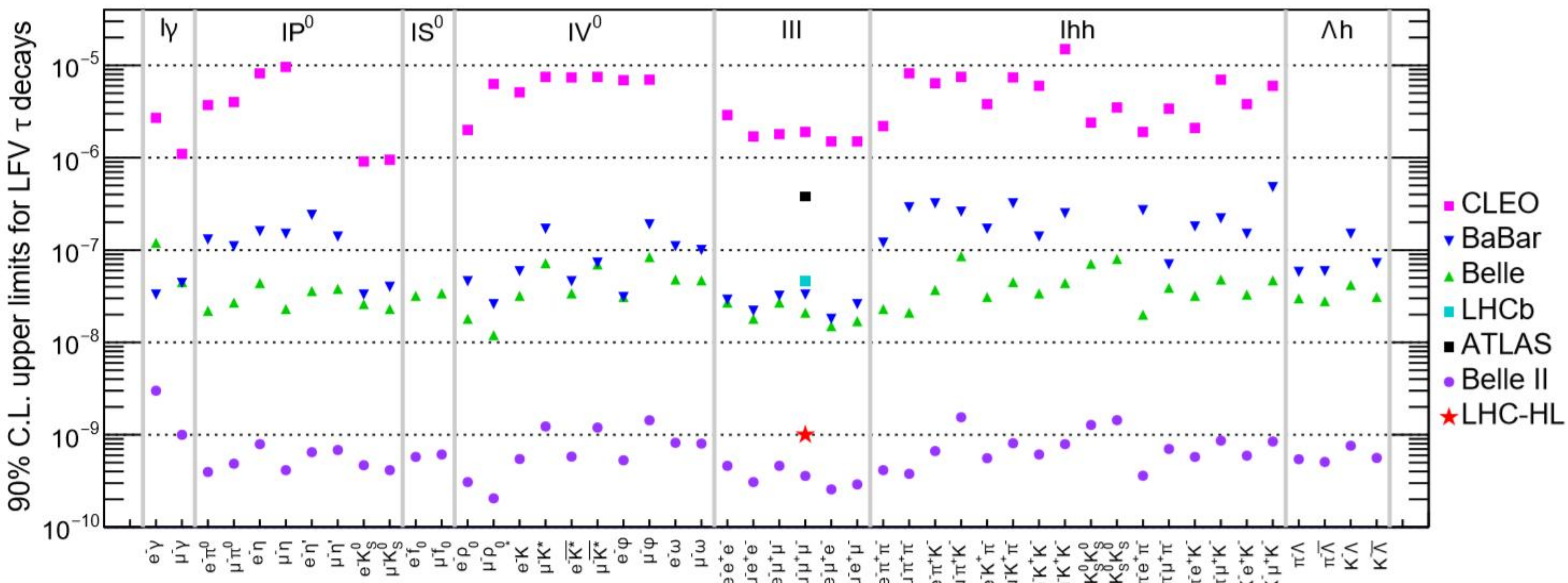
Model	Ref.	τ→μγ	τ→μμμ
SM + heavy majorana	PRD 66.034008	10^{-9}	10^{-10}
Non-universal Z′	PLB 547(3)252	10^{-9}	10^{-8}
SUSY + seesaw	PRL 89:241802	10^{-10}	10^{-7}
SM + 4th generation	arXiv.1006.530 6	10^{-8}	10^{-8}



- Different cLFV experiments are necessary (as a part of 'global' programme): $l_i \to l_j\gamma,\ l_i \to l_j l_k l_k,\ \tau \to lh\ldots$

τ LFV searches

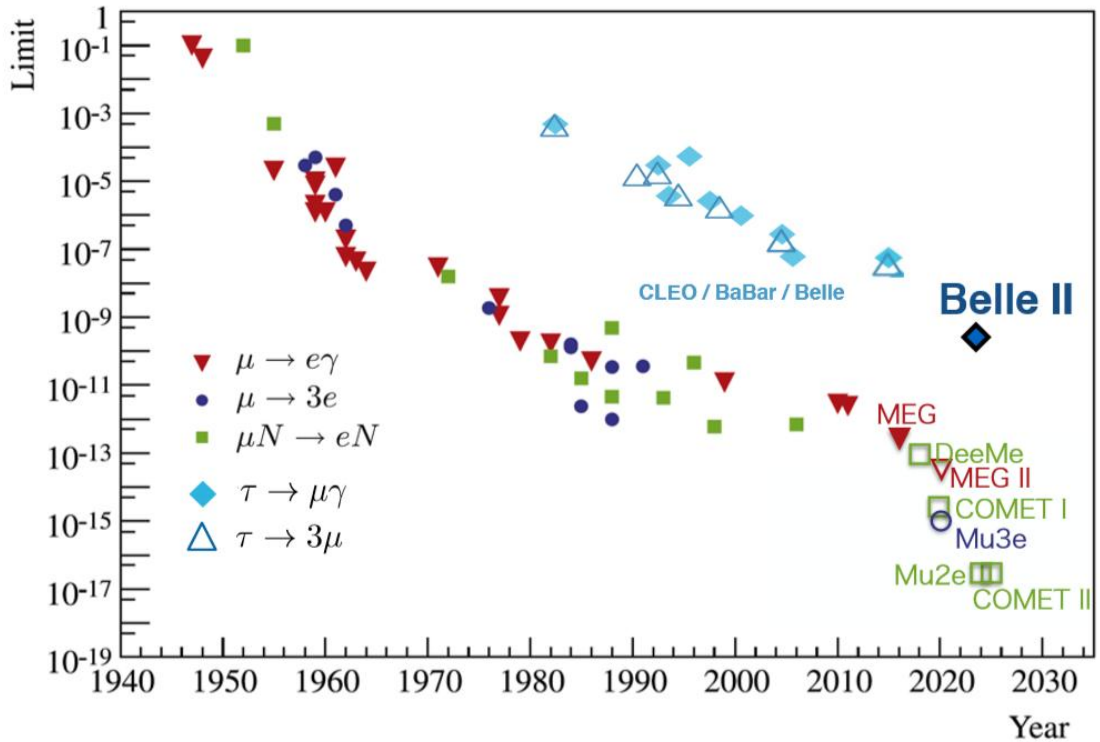
- τ—the heaviest charged lepton:
  - Various decay modes for LFV search, include decay to hadron
  - Strength of interaction relate to new physics is naively expected to be mass-dependent
  - $\tau \to l\gamma$ and $\tau \to lll$ are golden mode, which are expected to have largest branching fraction



CERN Yellow Rep.Monogr. 7 (2019) 867-1158

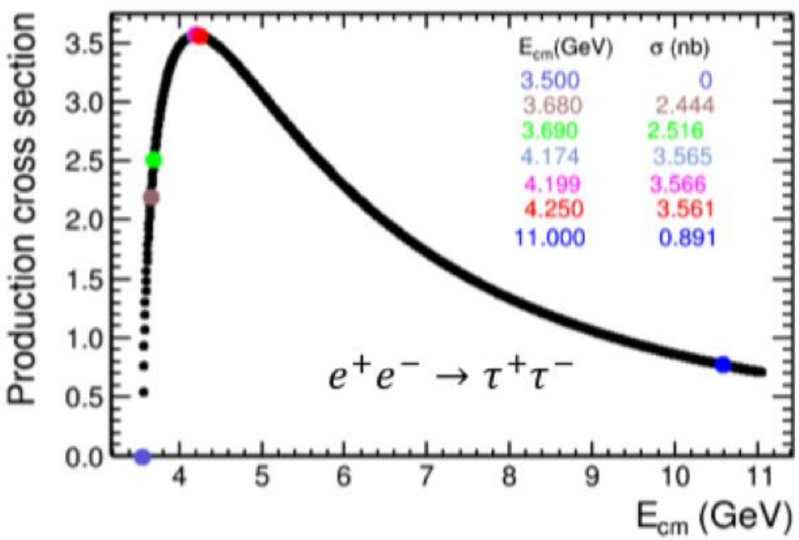
Evolution of limits

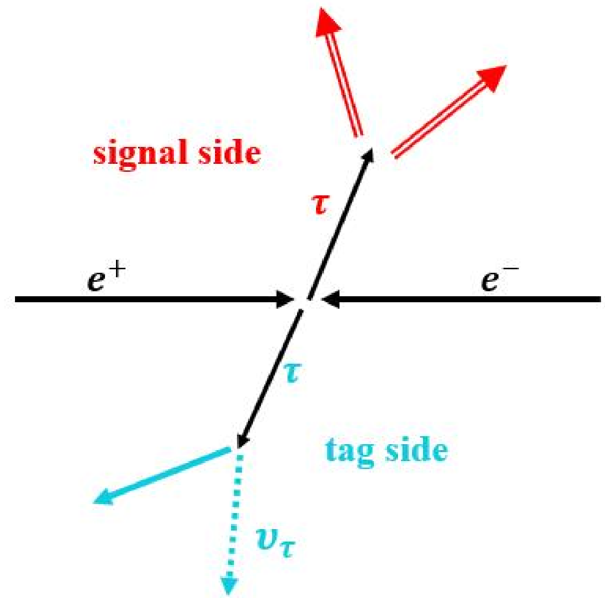
- Very rich experimental programme with substantial improvements expected in near future.
- Remarkable progress expected on Muon LFV searches.
- B factories expected to be the most powerful for tau LFV .



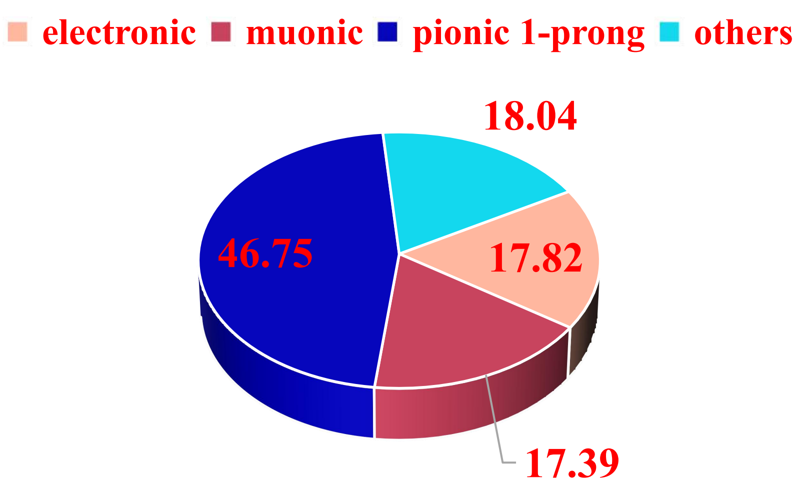
How about LFV at Super tau-charm factory?

τ lepton studies at STCF





3.5×10^9 τ lepton pairs /ab at 4.26 GeV

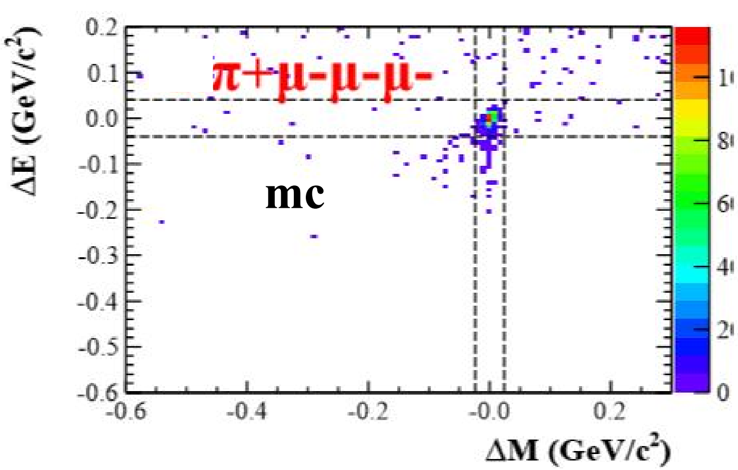


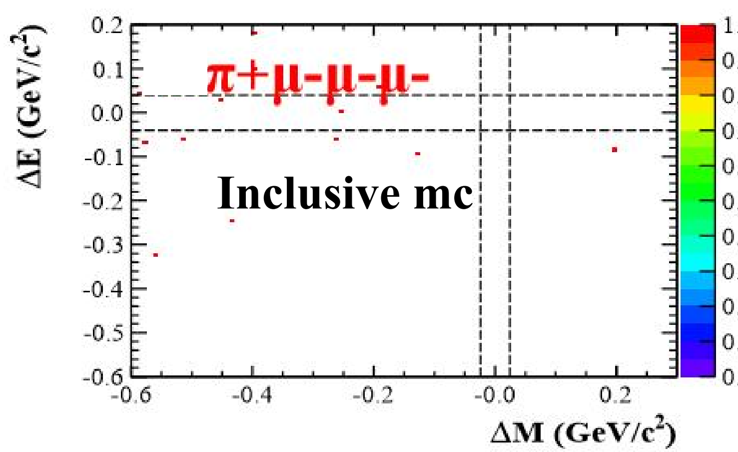
- **Double tag method**
- **Signal side: full reconstruction**
- **Tag side: decays with netrino(s)**

$\tau \to e\upsilon\bar{\upsilon},\ \mu\upsilon\bar{\upsilon},\ \pi\upsilon + n\pi^0$ (total branching fraction $\approx$ 82%)

$\tau \to 3l$ decays

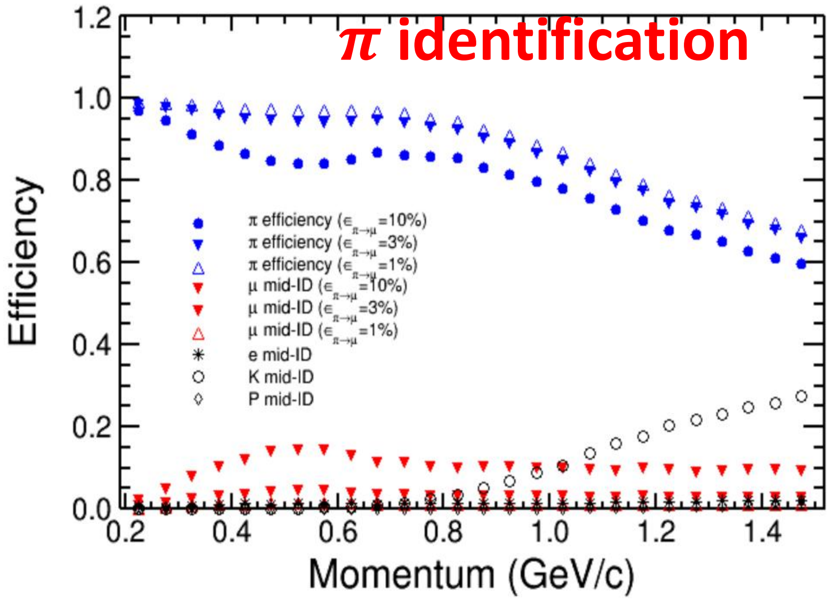
Signal side	Tag side
6 decays $\mu^+\mu^-\mu^-$, $e^+e^-e^-$, $e^+e^-\mu^-$, $\mu^+\mu^-e^-$, $\mu^+e^-e^-$, $e^+\mu^-\mu^-$	1-prong ($\pi/e/\mu$+neutrals+neutrinos) (82% of total BF)
γ-conversion background $\langle e^+e^-\rangle$>5 degrees, M_{ee}>0.5 GeV$/c^2$	Hadronic mode $M^2_{\text{miss}} < 0.2$ GeV$^2/c^4$
Multiple candidates smallest $\chi^2_{\tau\text{ mass}} + \chi^2_{\Delta\text{E}}$	Hadronic mode $M^2_{\text{miss}} < 2$ GeV$^2/c^4$
Signal Extraction Beam energy and mass difference	Total momentum of the 1-prong side larger than 0.4 GeV$/c$
Angle between the 1 prong and 3 prong decay less than 175 degrees	

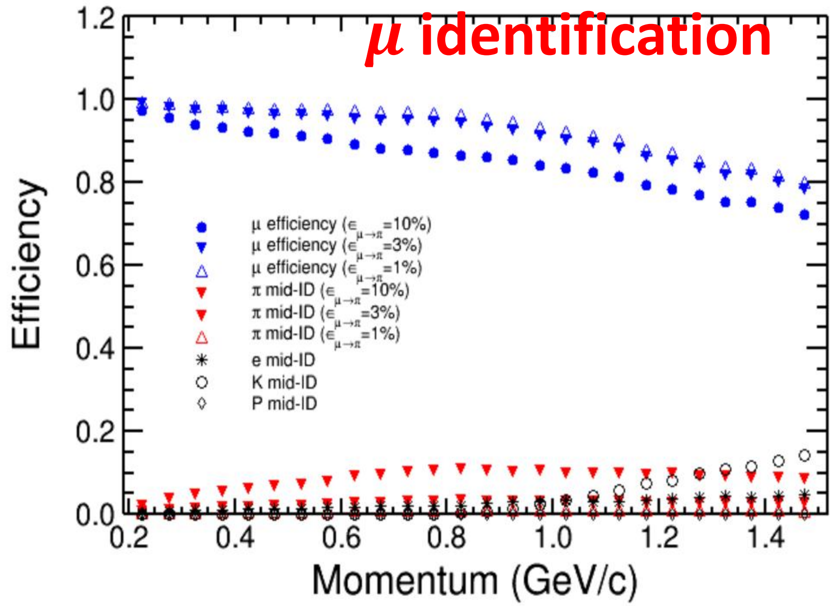




$\tau \rightarrow 3l$ decays

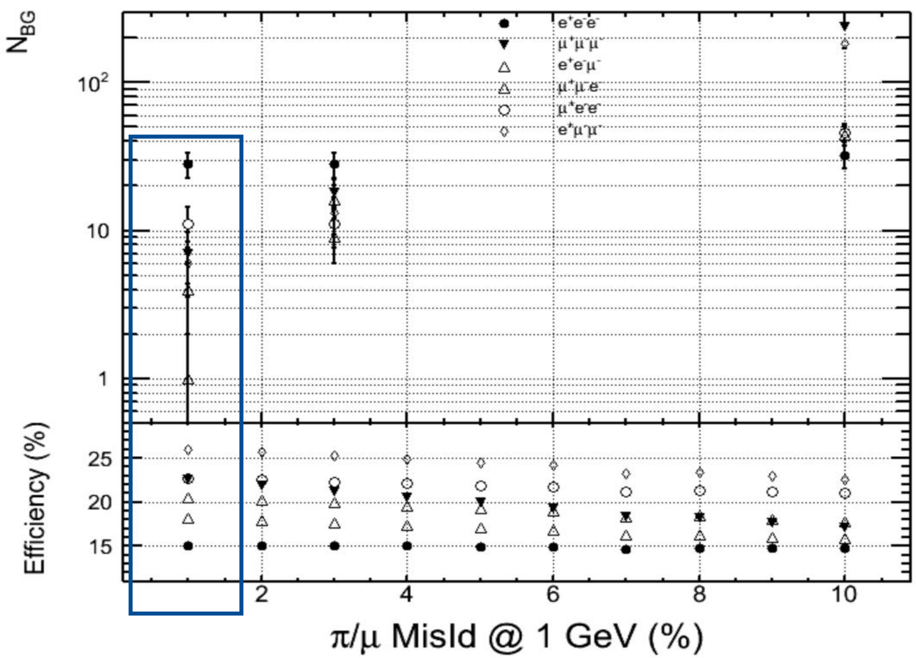
- The PID efficiency in fast simulation is obtained from BESIII, using dE/dx and TOF information. (The mis-ID rate of π/μ can be as large as 30%).
- By scaling the π/μ mis-ID rate to 10%, 3%, 1% at 1GeV, different π/μ PID efficiencies are used.
- Following are the distributions of π/μ PID efficiencies and their mis-ID rates (the mis-ID rates to e, K, P are not changed in this analysis).





$\tau \to 3l$ decays

- The number of survived events N_{BG} using 1 ab^{-1} simulated sample @ 4.26 GeV are obtained for the six decay modes of $\tau \to 3l$, with scaling π/μ mis-ID rate to 10%, 3%, 1%.
- The MC selection efficiency are also obtained by varying π/μ mis-ID rate from 10% to 1%.



- **At STCF, 3.5×10^9 tau pairs @ 4.26 GeV per year. If π/μ mis-ID rate is 1% at 1 GeV, the upper limit is predicted to be:**

$$\mathcal{B}_{UL}^{90}(\tau \to 3l) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 1.4 \times 10^{-8}$$

- **If taken 10 years data, the best upper limit for $\tau \to 3l$ will reach 10^{-9} level**
- **$\tau \to \mu\mu\mu$ is the most sensitive decay**

$\tau \to \gamma\mu$ decay

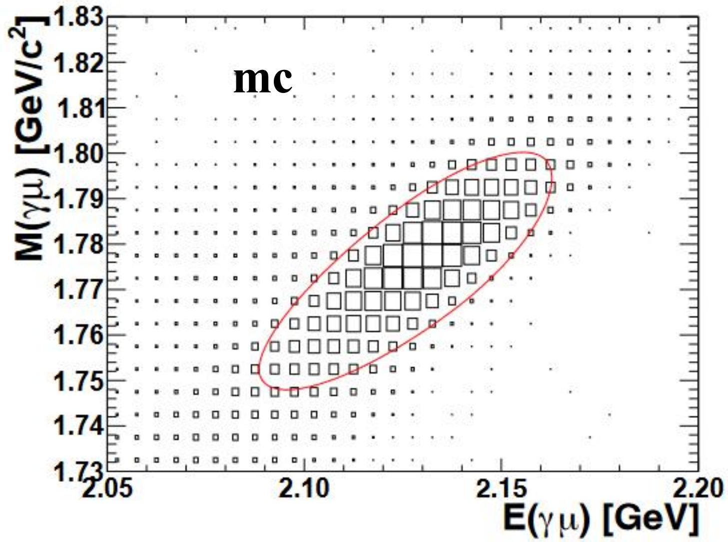
tag mode	selection criteria	N_{bkg} (ε) before	N_{bkg} (ε) after
$e^+\nu_e\bar{\nu}_\tau$	$\cos\theta_{sig\_\gamma,tag\_charged} < -0.2$ $p_{tag\_charged} > 0.5\,GeV/c$ $E_{miss} < 1.7\,GeV$	1.5×10^2 (2.6 %)	0 (1.1 %)
$\pi^+\bar{\nu}_\tau$	$E_{miss} > 0.7\,GeV$ $\|\cos\theta_{miss}\| < 0.6$ $E_{sig\_\gamma} > 0.8\,GeV$ $M^2_{miss} < 0.050\,GeV^2/c^4$	1.4×10^4 (4.0 %)	0.3 (0.5 %)
$\pi^+\pi^0\bar{\nu}_\tau$	$M^2_{miss} < 0.075\,GeV^2/c^4$ $\cos\theta_{sig\_mu\_in\_tau,tau\_in\_cm} < 0.8$ $\|\cos\theta_{miss}\| < 0.9$	1.2×10^3 (2.6 %)	1.2 (1.5 %)
total		1.6×10^4 (9.2 %)	1.5 (3.1 %)

Tag 54% of total tau decay BF

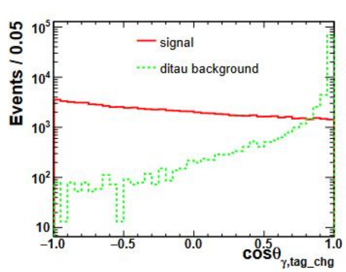
arXiv:2305.00483

Not using decays with muons to aviod huge di-muon background

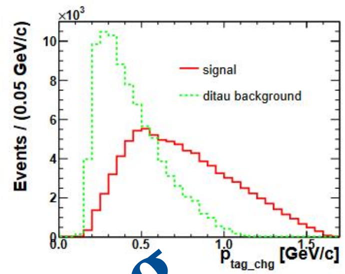
Not using decays with multiple $\pi^0 s$ due to low efficiency and large combinatorial background



$\tau \to \gamma\mu$ decay

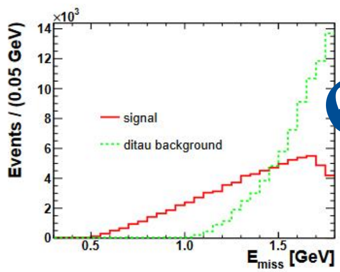


(a)

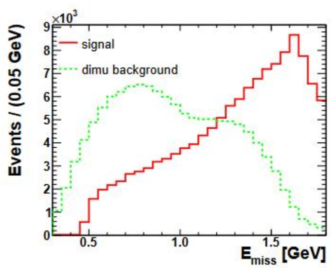


(b)

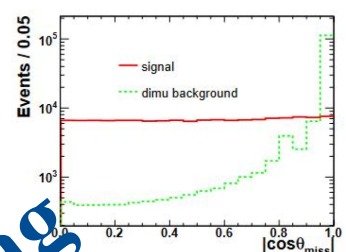
$e\upsilon\bar{\upsilon}$ tag



$\pi\upsilon$ tag



(a)



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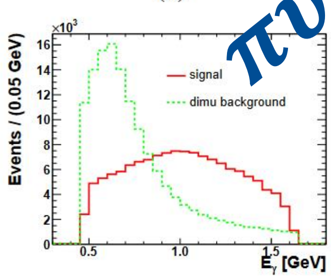
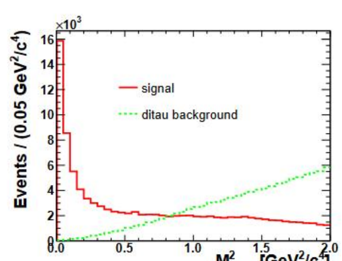
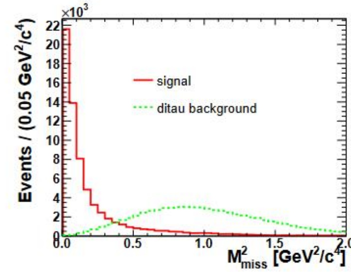




$\pi\pi^0\upsilon$ tag



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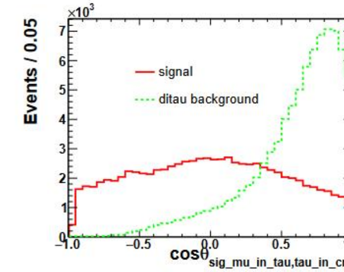

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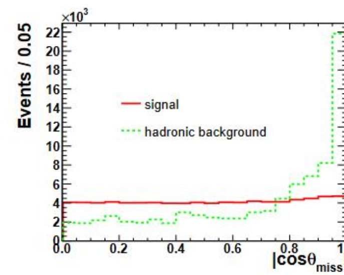
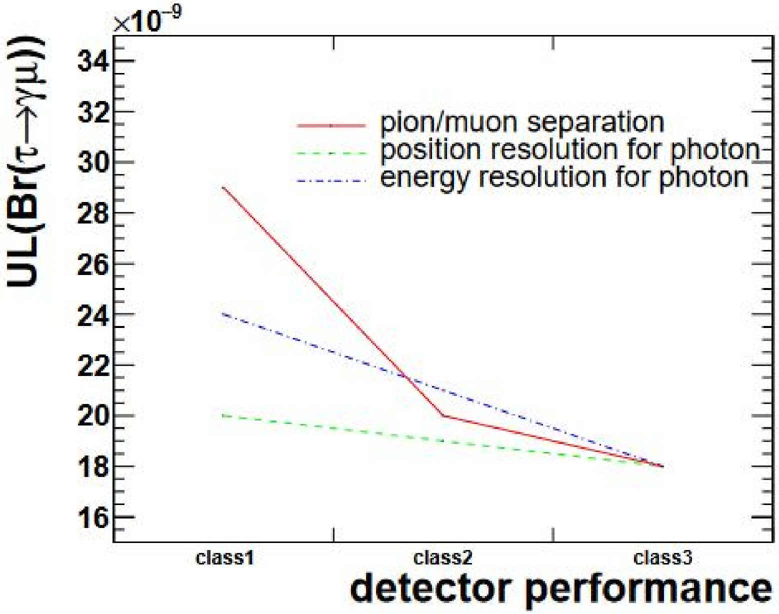


(c)

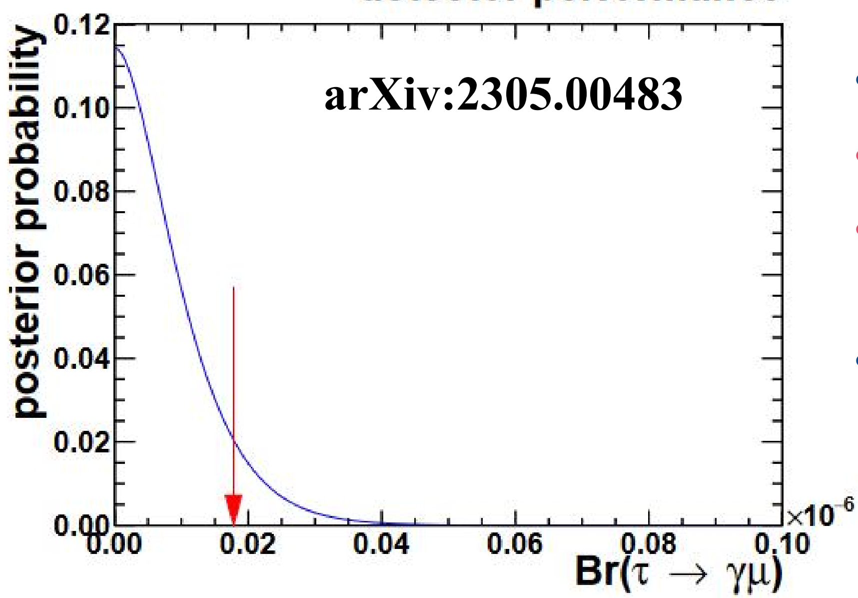
arXiv:2305.00483

- Optimized with the Punzi FOM
- Bkg suppressed to only a few, with ~3% signal efficiency
- $e\upsilon\bar{\upsilon}$ tag bkg: SM muonic decays and randomly choosen photon
- $\pi(\pi^0)\upsilon$ tag bkg: 1/2-prong with multiple π^0s and μ/π misID

$\tau \to \gamma\mu$ decay



π/μ mis-ID rate: 3%, 1.7%, 1% at 1 GeV
photon position resolution: 6mm, 4.2mm, 3mm
photon energy resolution: 2.5%, 2.25%, 2%

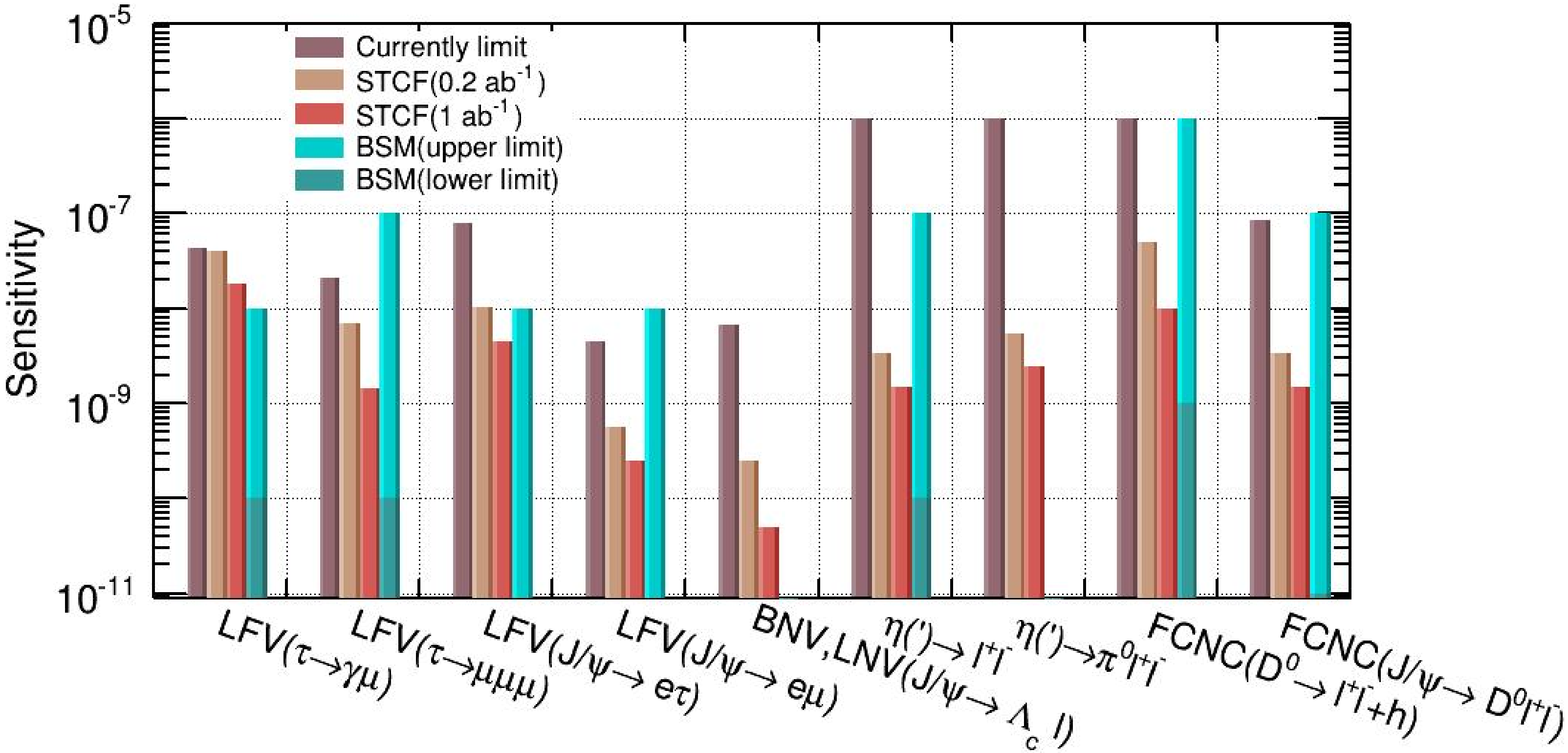


- 3.5×10^9 tau pairs @ 4.26 GeV per year
- π/μ mis-ID rate is 1% at 1 GeV
- 3 mm and 2% for photon position and energy resolutions
- The upper limit is predicted to be:

$$\mathcal{B}_{UL}^{90}(\tau \to \gamma\mu) < 1.8 \times 10^{-8}$$

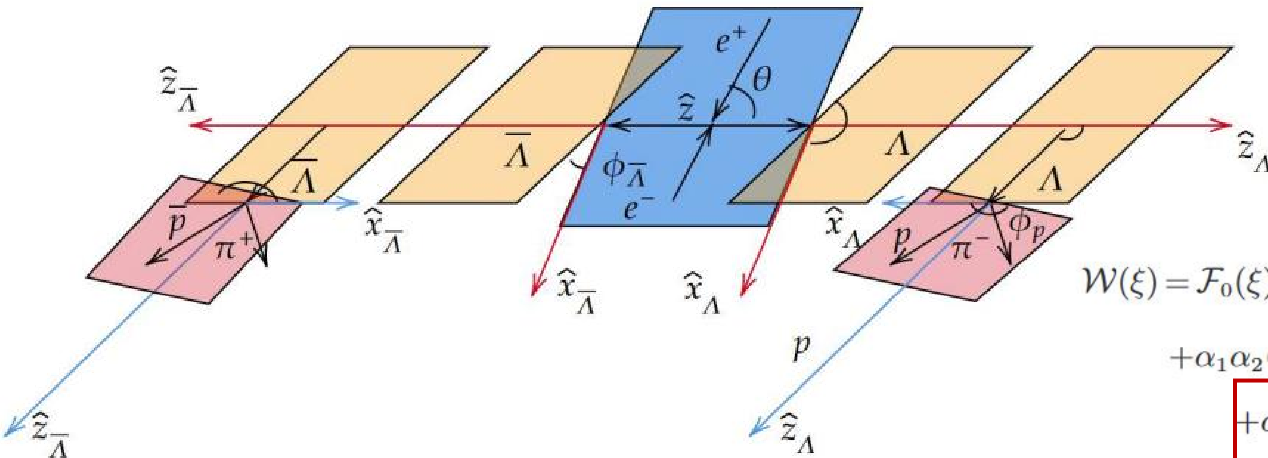
5.7×10^{-9} for ten-year data taking

Sensitivity of rare/forbidden decays



- Sensitivity of rare/forbidden decays from STCF measurements would be able to verify various beyond SM model predictions.

CPV in Λ decay with polarized electron beam



$$\mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)(\alpha_2\cdot\mathcal{F}_3 - \alpha_1\cdot\mathcal{F}_4) + \alpha_1\alpha_2(\mathcal{F}_1 + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\cdot\mathcal{F}_2 + \alpha_\psi\cdot\mathcal{F}_5) + \boxed{\alpha_1\cdot\mathcal{F}_6 + \alpha_2\cdot\mathcal{F}_7 - \alpha_1\alpha_2\cdot\mathcal{F}_8,}$$

$$-\ln\mathcal{L} = -\sum_{i=1}^{N}\ln\mathcal{C}\mathcal{W}(\xi^i, \alpha_\psi, \alpha_1, \alpha_2, \Delta\Phi)\epsilon(\xi^i).$$

$\alpha_{1,2}$: decay parameters of $\Lambda/\bar{\Lambda}$ decays

$$A_{CP} = \frac{\alpha_1+\alpha_2}{\alpha_1-\alpha_2}?=0$$

$$\mathcal{F}_0(\xi) = 1 + \alpha_\psi\cos^2\theta,$$
$$\mathcal{F}_1(\xi) = \sin^2\theta\sin\theta_1\cos\varphi_1\sin\theta_2\cos\varphi_2 - \cos\theta^2\cos\theta_1\cos\theta_2,$$
$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta(\sin\theta_1\cos\theta_2\cos\varphi_1 - \cos\theta_1\sin\theta_2\cos\varphi_2),$$
$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\varphi_2,$$
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\varphi_1,$$
$$\mathcal{F}_5(\xi) = \sin^2\theta\sin\theta_1\sin\varphi_1\sin\theta_2\sin\varphi_2 - \cos\theta_1\cos\theta_2,$$
$$\mathcal{F}_6(\xi) = P_e(\gamma_\varphi\sin\theta\sin\theta_1\cos\varphi_1 - (1+\alpha_\psi)\cos\theta\cos\theta_1),$$
$$\mathcal{F}_7(\xi) = P_e(\gamma_\varphi\sin\theta\sin\theta_2\cos\varphi_2 + (1+\alpha_\psi)\cos\theta\cos\theta_2),$$
$$\mathcal{F}_8(\xi) = P_e\beta_\varphi\sin\theta(\cos\theta_1\sin\theta_2\sin\varphi_2 + \sin\theta_1\sin\varphi_1\cos\theta_2).$$

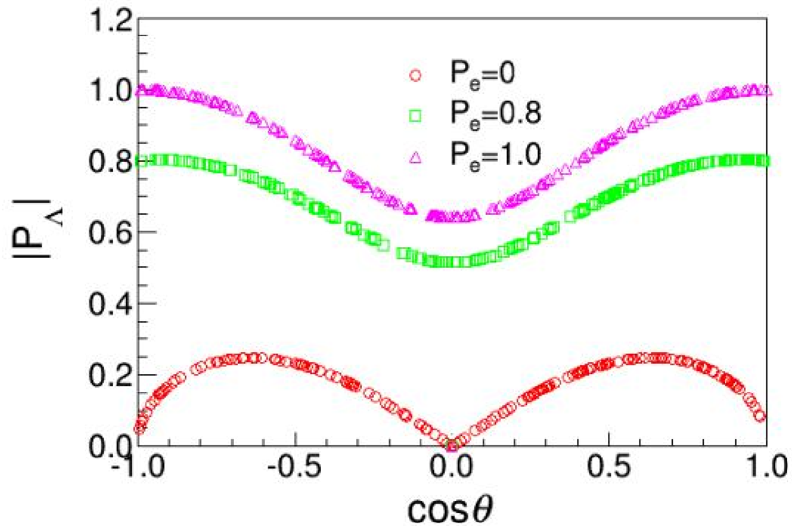
Electron beam polarization provide additional observables

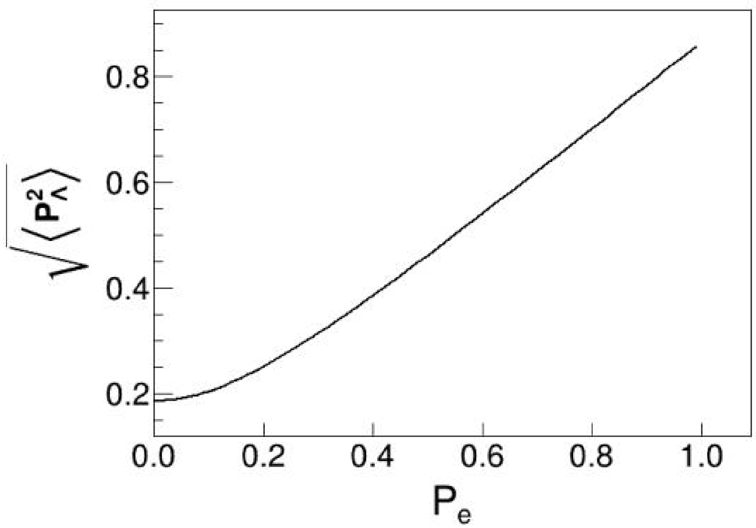
BESIII: -0.0025±0.0046±0.0012

SM: 10^{-5}

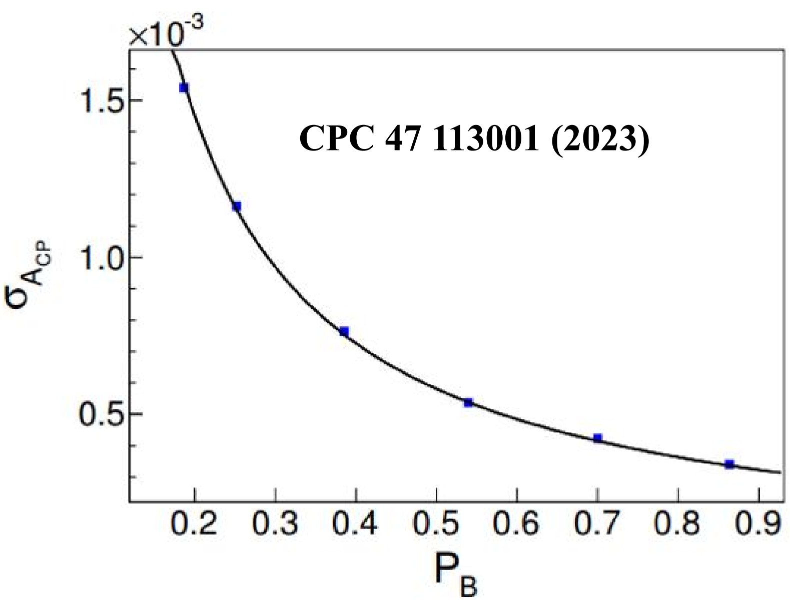
STCF: ?

CPV in Λ decay with polarized electron beam





$$\mathbf{P}_\Lambda = \frac{\gamma_\psi P_e \sin\theta \hat{x}_1 - \beta_\psi \sin\theta\cos\theta \hat{y}_1 - (1+\alpha_\psi) P_e \cos\theta \hat{z}_1}{1+\alpha_\psi\cos^2\theta}.$$



CPC 47 113001 (2023)

The sensitivity of CPV follows :

$$\boxed{\sigma_{A_{CP}} \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_1 \sqrt{N_{sig}} \sqrt{\langle P_B^2 \rangle}}.}$$

$$\xRightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.1} \sigma_{A_{CP}} \sim 1.4\times10^{-4}$$

$$\xRightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.8} \sigma_{A_{CP}} \sim \mathbf{0.5\times10^{-5}}$$

Probe CP violation at tau-charm factory

Billions hyperon pairs from J/ψ decay, clean topology, background free

Transversely polarized, spin correlation

Sensitivity: $\boldsymbol{A_{CP}\sim 10^{-4}, \xi\sim 0.05^{\circ}}$

CP in hyperon decay

CP in tau decay/production

Peak cross section in $\sqrt{s}$ =4-5 GeV, $\sigma_{\tau\tau} \approx$ 3.5 nb, 10 ab^{-1} data in total

Sensitivity of τ decay with 1ab^{-1} @ 4.26 GeV $\sim\boldsymbol{9.7\times 10^{-4}}$

CP in charm mixing

Billions $D^0/\overline{D}^0$, threshold production, quantum coherence with $(D^0\overline{D}^0)_{\mathrm{CP}=-}$ or $(D^0\overline{D}^0)_{\mathrm{CP}=+}$

Sensitivity: $x\sim 0.035\%$, y$\sim 0.023\%$, $\boldsymbol{r_{CP}\sim 0.017, \alpha_{CP}\sim 1.3^{\circ}}$

CPT in kaon mixing

CP tagging and flavor tagging of $K^0/\overline{K}^0$ available from J/ψ decay

CP variables determined with time-dependent decay rate

CPT Sensitivity: $\boldsymbol{\eta_{\pm}\sim 10^{-3}, \Delta\phi_{\pm}\sim 0.05^{\circ}}$

More sensitivity studies are ongoing

Summary

- **STCF is the next generation tau-charm factory, one of the crucial precision frontiers aiming for understanding QCD, testing EW models and probing new physics.**

- **Many activities of sensitivity studies are going on.**

- **Physics reaches are still highly extendable, including probing new physics.**

Tentative plan

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032-2042	2043-2046
Form collaboration																
Conception design CDR																
R&D (TDR)																
Construction																
Operation																
Upgrade																

Backups

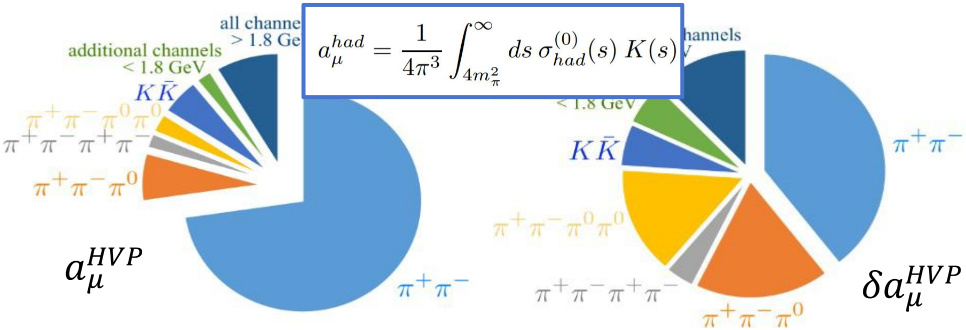
Muon g-2: HVP contribution

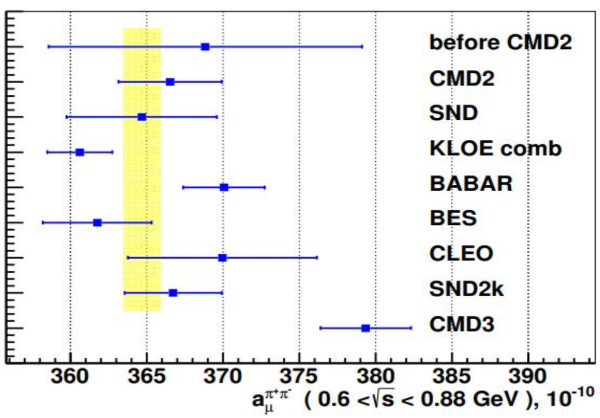
- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$
- The $\pi^+\pi^-$ channel accounts for 75% of the full a_μ^{Had}
  - Typical uncertainty around 0.6%-1.0%

$$\sigma^{\text{bare}}_{\pi\pi(\gamma_{\text{FSR}})} = \frac{N_{\pi\pi\gamma} \cdot (1+\delta^{\pi\pi}_{\text{FSR}})}{\mathcal{L} \cdot \epsilon^{\pi\pi\gamma}_{\text{global}} \cdot H(s) \cdot \delta_{\text{vac}}}$$

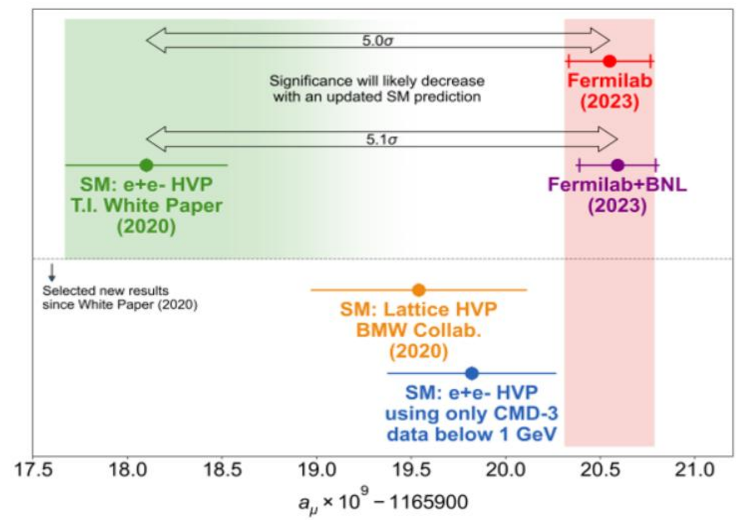
arXiv:2302.08834

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \sigma^{(0)}_{had}(s)\, K(s)$$





Discrepancies between experiments now over (3-5)σ need to be understood/resolved!



Muon g-2: Lattice HVP

- Programs to be improved on a_μ^{Had} by 2025: refer to Aida X. El-Khadra
  - Data-driven HVP: ~0.3%
  - Lattice HVP: ~0.5%
  - Dispersive HLbL: ~10%
  - Lattice HLbL: ~10%
- At STCF, 1 ab-1 $\psi(3770)$ data, by the ratio method

$$\sigma^{\text{bare}}_{\pi\pi(\gamma_{\text{FSR}})} = \frac{N_{\pi\pi\gamma}}{N_{\mu\mu\gamma}} \cdot \frac{\epsilon^{\mu\mu\gamma}_{\text{global}}}{\epsilon^{\pi\pi\gamma}_{\text{global}}} \cdot \frac{1+\delta^{\mu\mu}_{\text{FSR}}}{1+\delta^{\pi\pi}_{\text{FSR}}} \cdot \sigma^{\text{bare}}_{\mu\mu}$$

  - The statistical uncertainty would be negligible
  - Systematic uncertainties due to the luminosity, radiator function, and VP are canceled
  - The systematic uncertainty due to the track reconstruction and particle identification need to be carefully studies