TAU 2023 ~~Summary~~

a personal (and thus biased) selection of highlights

Soeren Prell (Iowa State University)

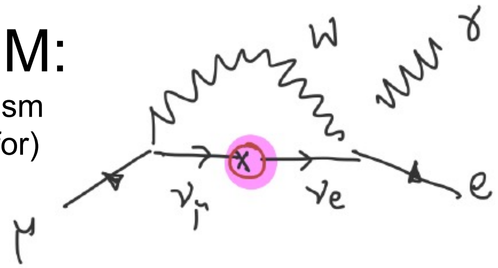
Tau 2023

December 4-6, 2023

Louisville, Kentucky

Searches for cLFV in τ decays

cLFV in SM:
(not the mechanism we are looking for)



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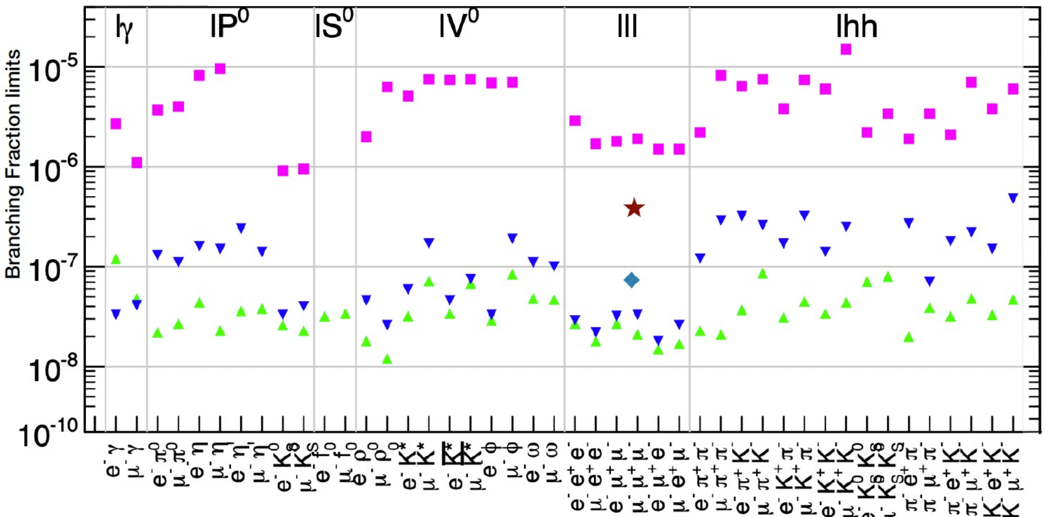
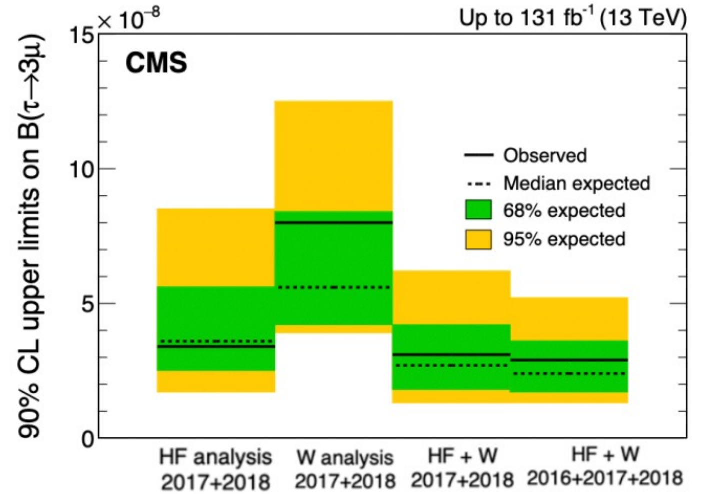
Petcov, 1977



- *New limits on $\tau \to V^0 \ell$ from Belle*

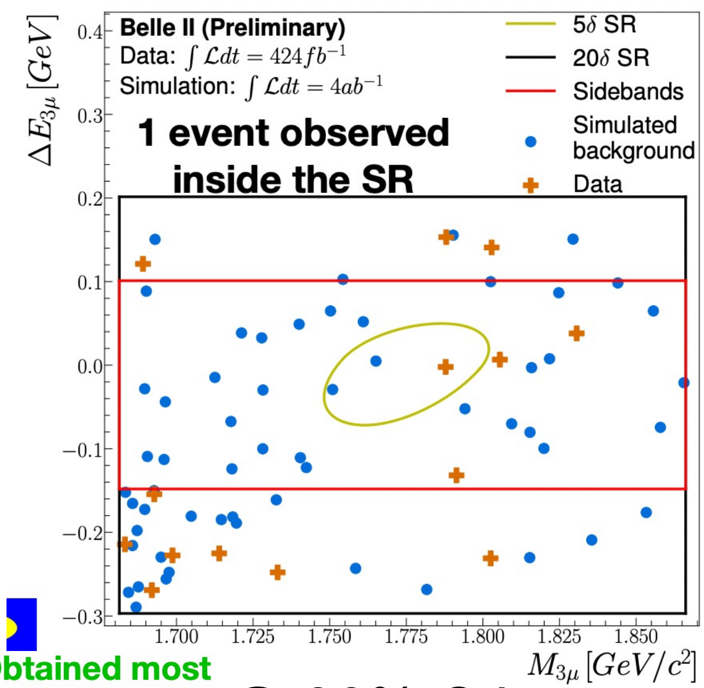
Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)	
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7	
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2	
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3	•
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0	•
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9	•
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4	•
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9	•
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9	•
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3	•
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7	•

- *New limits on $\tau \to 3\mu$ from CMS and Belle II*
  - *Belle II limit better than Belle with ½ the data*



observed (expected) upper limit @ 90% of CL

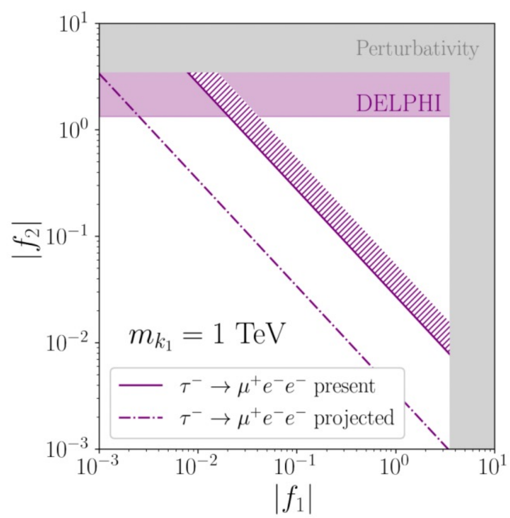
$B(\tau \to 3\mu) < 2.9\ (2.4) \times 10^{-8}$



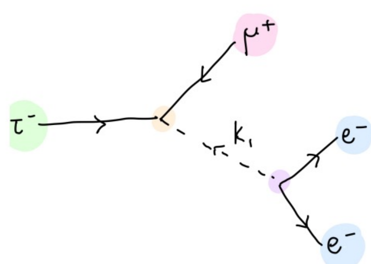
Obtained most stringent limit
1.9×10^{-8} @ 90% C.L

cLFV (theory I)

- *τ decays may be good place to look for LFV*
  - *LFV may only occur in some τ decays (and not in μ decays at all) if **lepton flavor triality** is conserved*



T=1 scalar



$$\mathcal{L}_{k_1} = \frac{1}{2}\left(2 f_1 \overline{\tau_R^c} \mu_R + f_2 \overline{e_R^c} e_R\right) k_1 + h.c.$$

- *Note to experimenters: Dalitz plot searches can be more sensitive to specific models*

The idea: each charged lepton is *charged* under this Z3 (flavour triality)

$$\psi_T \to \left(e^{2\pi i/3}\right)^T \psi .$$

T is a triality charge.

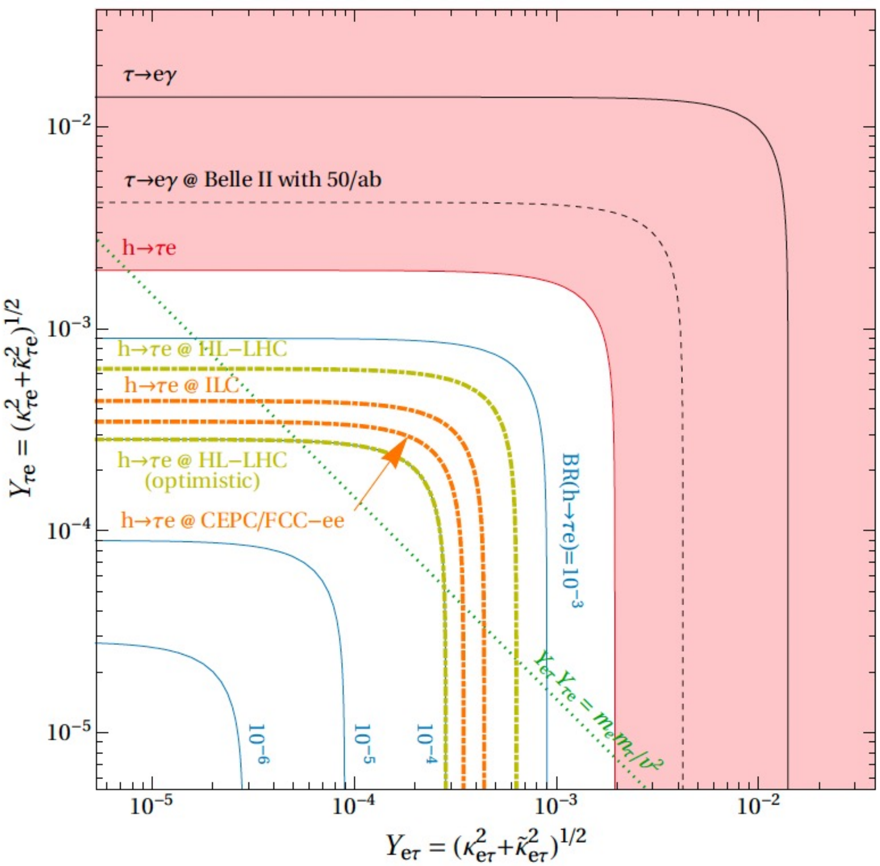
electron : T = 1
muon : T = 2
tau : T = 3
} In line with generation.

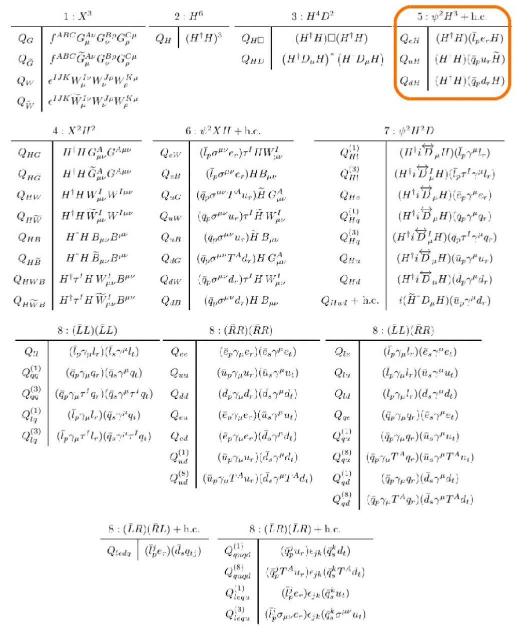
Triality-preserving charged-lepton decays:

Observable	Present constraint	Projected sensitivity
$BR(\tau^- \to \mu^- \mu^- e^+)$	$< 1.7 \times 10^{-8}$ [1]	2.6×10^{-10} [2]
$BR(\tau^- \to \mu^+ e^- e^-)$	$< 1.5 \times 10^{-8}$ [1]	2.3×10^{-10} [2]

cLFV (theory II)

- *Look everywhere. Sensitivities to NP are often complementary*
  - *Example: strong constraints from $\mu \to e\gamma$ on all LFV Higgs ($\to \ell\ell'$) decays*





2499 baryon number conserving dim. 6 operators in total

Grzadkowski et al. 1008.4884

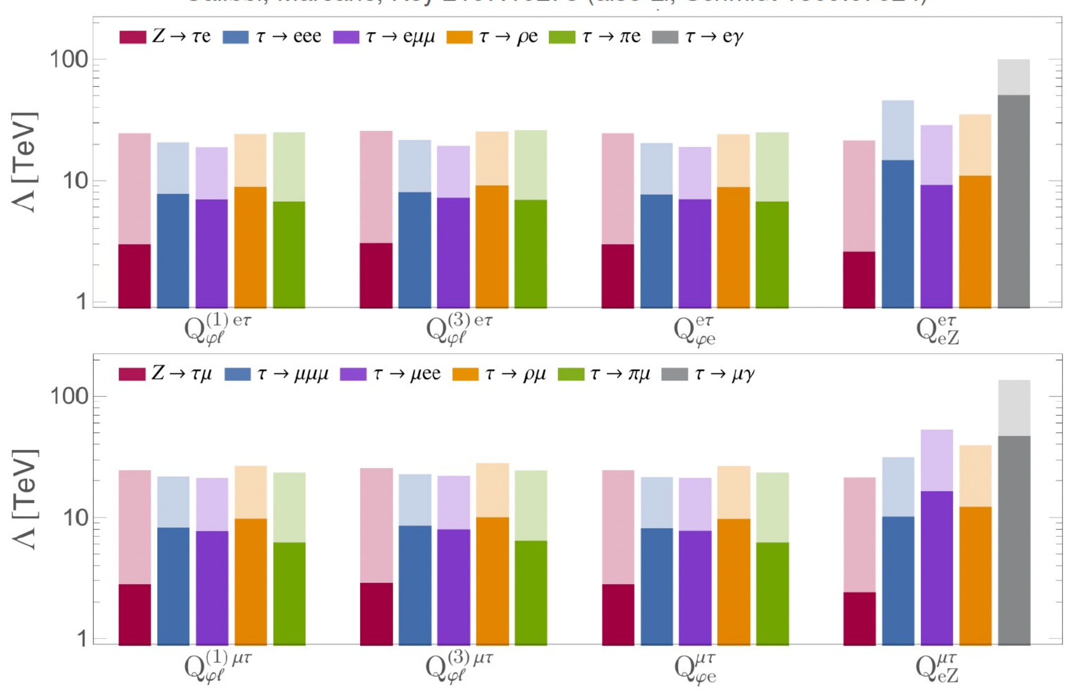
4 fermion interactions

dipole transitions

"Z-penguins"

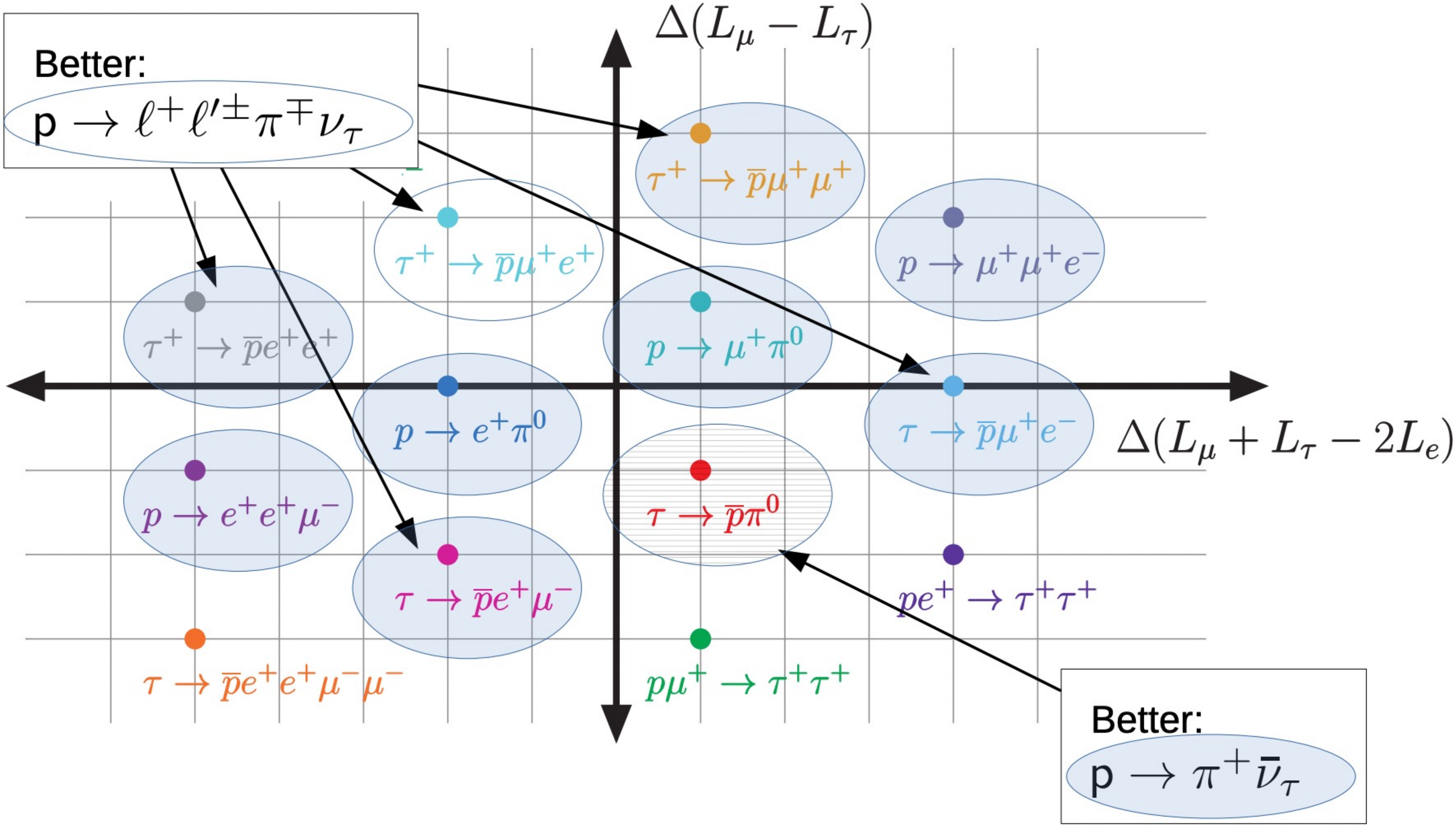
"Higgs penguins"

Calibbi, Marcano, Roy 2107.10273 (also Li, Schmidt 1809.07924)



cLFV (theory III)

- *Consider classes of models related by EFT operators*
  - *Don't be discouraged to look for ΔB tau decays!*
  - *… but sometimes proton decay may be more sensitive*



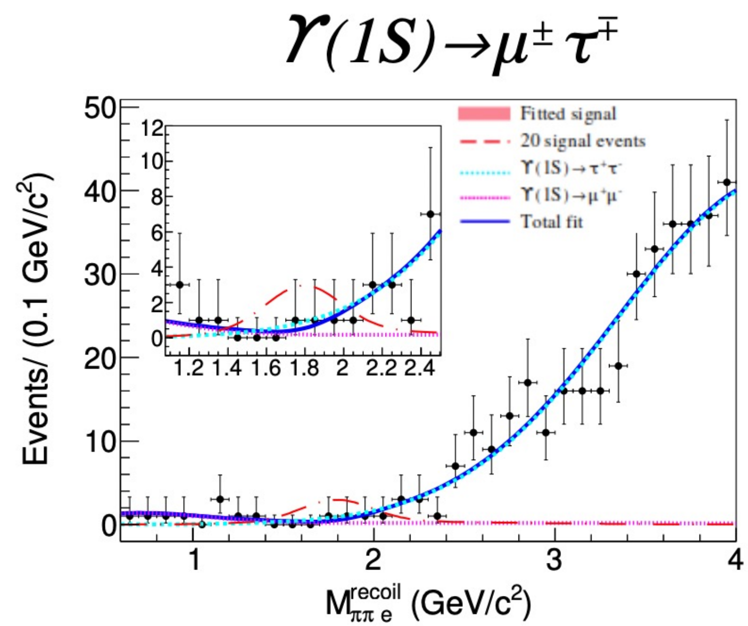
[Marciano, NPB '95]

cLFV in τ final states (I)

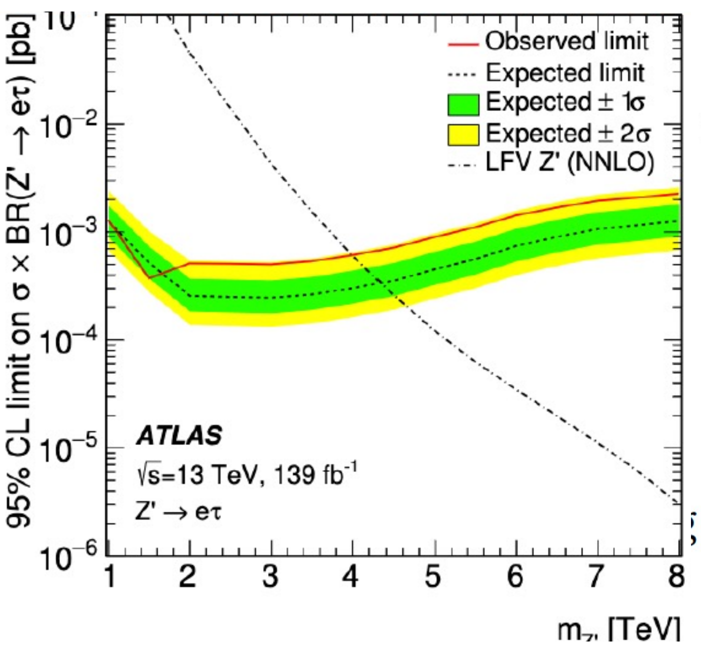
Patra
Oncel
Carratta

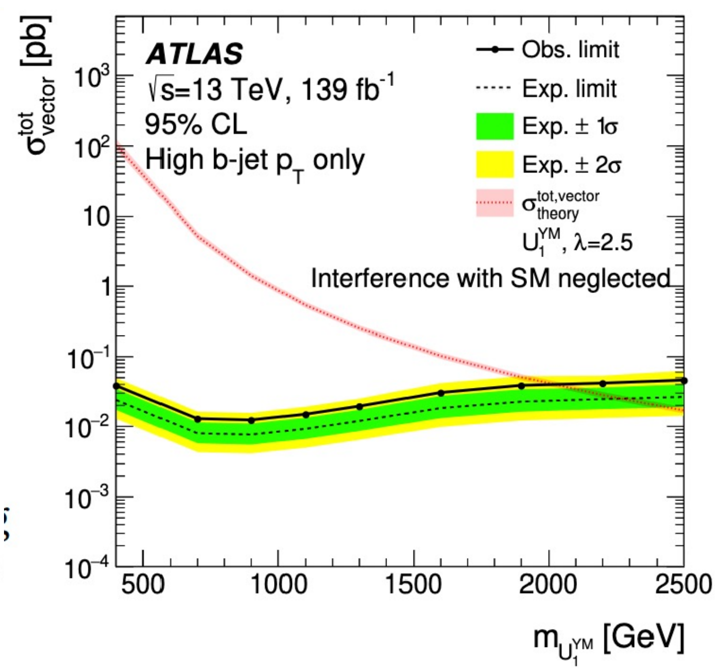
- *New limits from Belle on $B_s \to \ell\tau$, $B \to K\tau\ell$, and $\Upsilon(1S) \to \ell\ell'(\gamma)$*

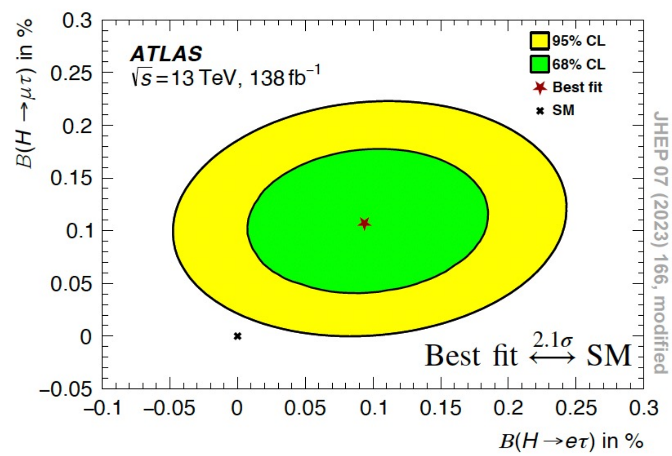
Decay	ϵ (%)	$N_{\rm sig}^{\rm fit}$	$N_{\rm sig}^{\rm UL}$	UL (90%CL)
$\Upsilon(1S) \to e^{\pm}\mu^{\mp}$	32.5	-1.3 ± 3.7	3.6	3.9×10^{-7}
$\Upsilon(1S) \to \mu^{\pm}\tau^{\mp}$	8.8	-1.5 ± 4.3	6.8	2.7×10^{-6}
$\Upsilon(1S) \to e^{\pm}\tau^{\mp}$	7.1	-3.5 ± 2.7	5.3	2.7×10^{-6}



- *Many new limits from ATLAS on $H \to \ell\tau$, $Z' \to \tau\ell$, $LQ(b\tau)$, etc.,*







MCT ($\ell\tau_{\rm lep}$+$\ell\tau_{\rm had}$)

New best

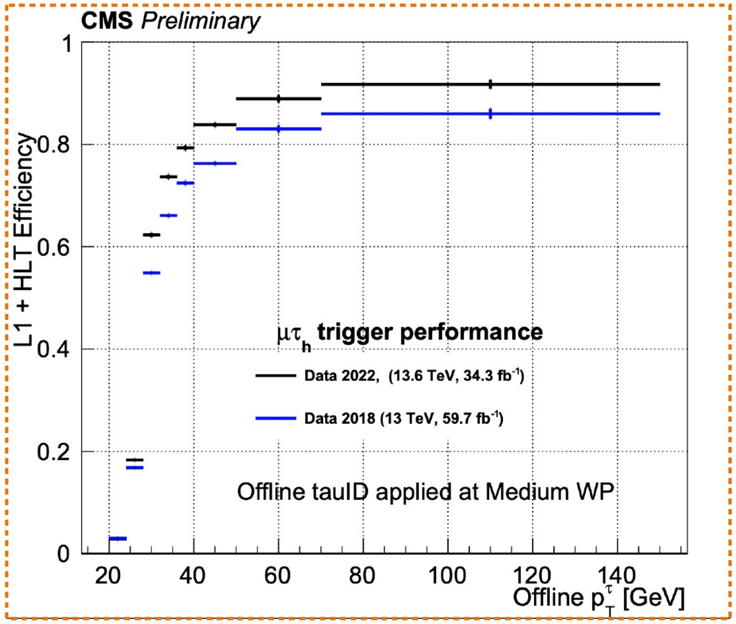
BR($H \to e\tau$) < 0.20% (0.11%) @ 95% CL

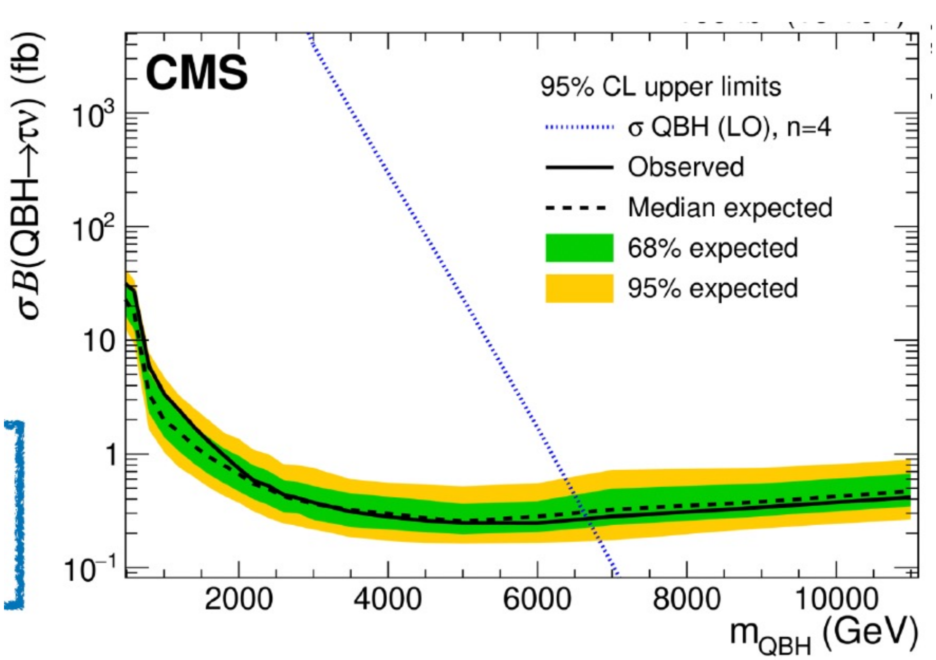
BR($H \to \mu\tau$) < 0.18% (0.09%) @ 95% CL

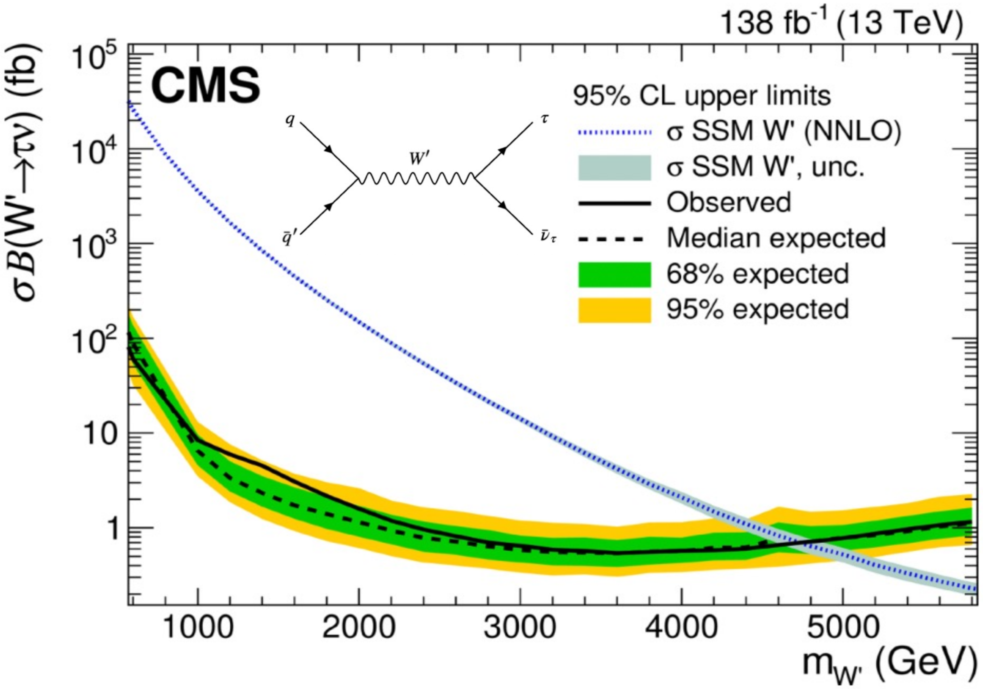
LFV and other NP with τ final states

New limits from CMS on production of W' (up to 4.8 TeV), LQ, QBH (6.6 TeV)

- *Expect better τ reconstruction in Run 3 from reconstruction and tagging improvements*



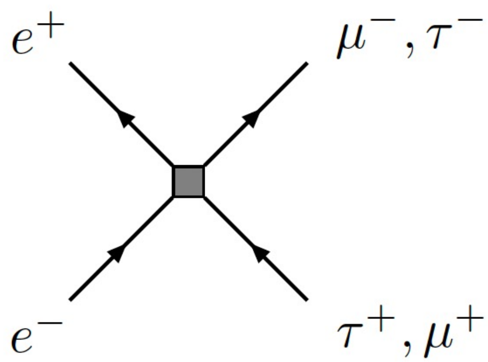




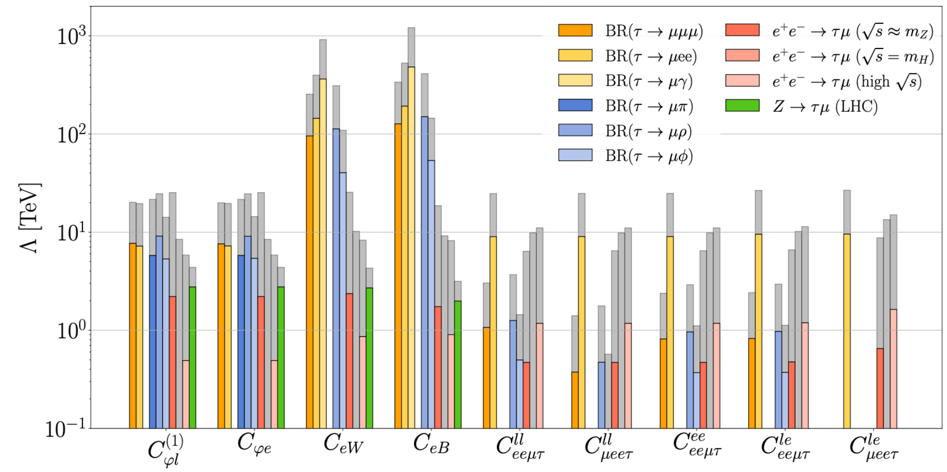
Mantry
Munbodh

cLFV at future colliders

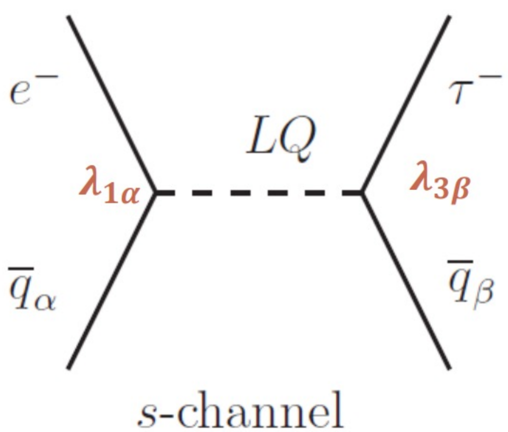
- *FCC-ee and CEPC can provide constraints on CLFV complimentary to LFV tau decays*

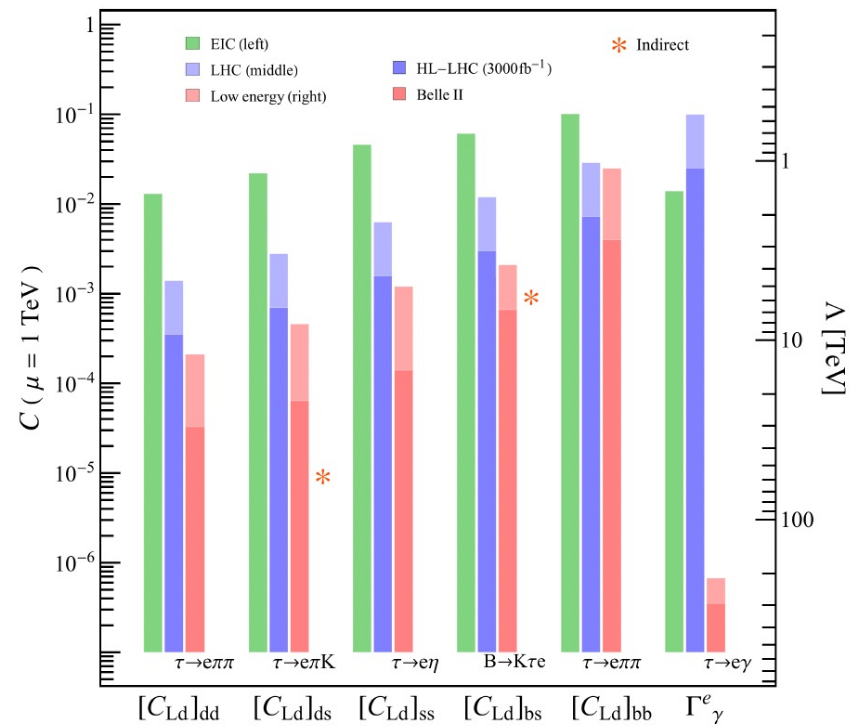


W. Altmannshofer, P.M. and T. Oh   arXiv: 2305.03869



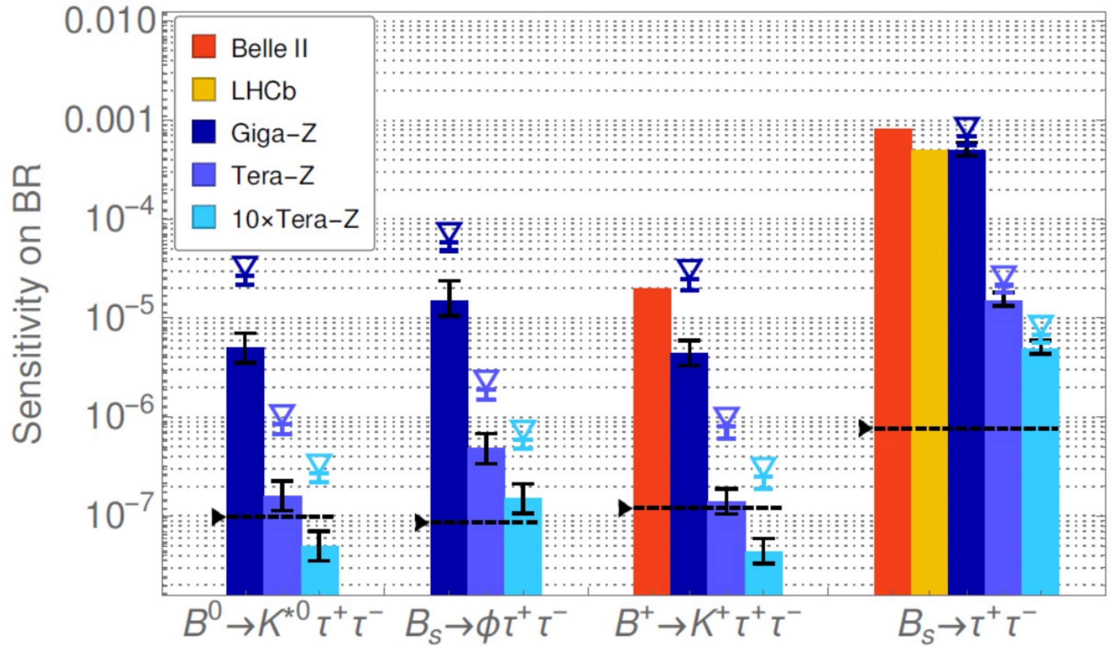
- *EIC can provide tight constraints on cLFV (esp. on LQ models)*



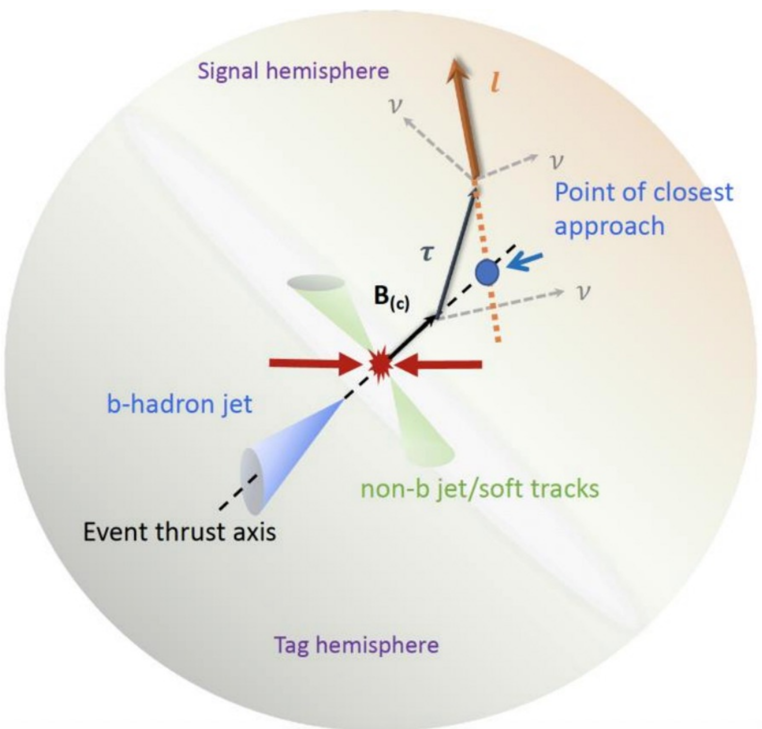


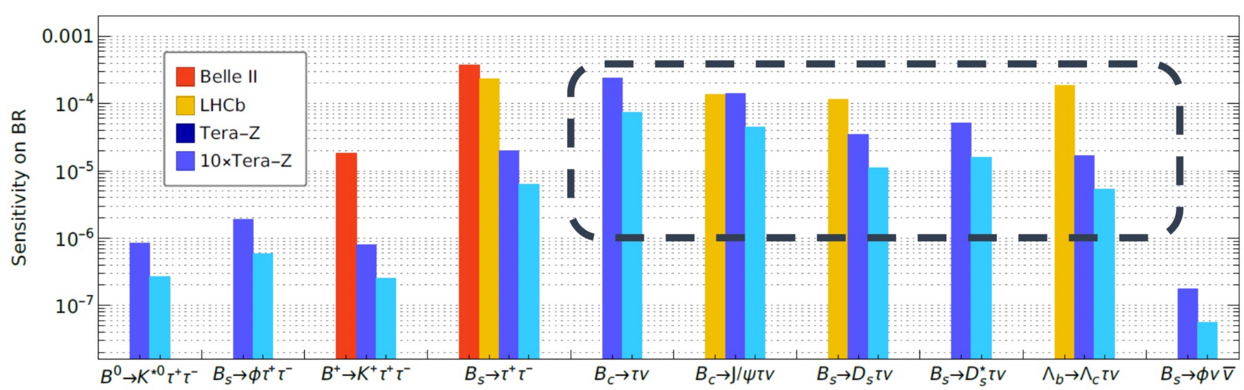
Rare τ final states at future e^+e^- colliders

Clean environment and highly boosted Z's at a Tera-Z factory (Mega-LEP) provide a high sensitivity to b decays to τ final states



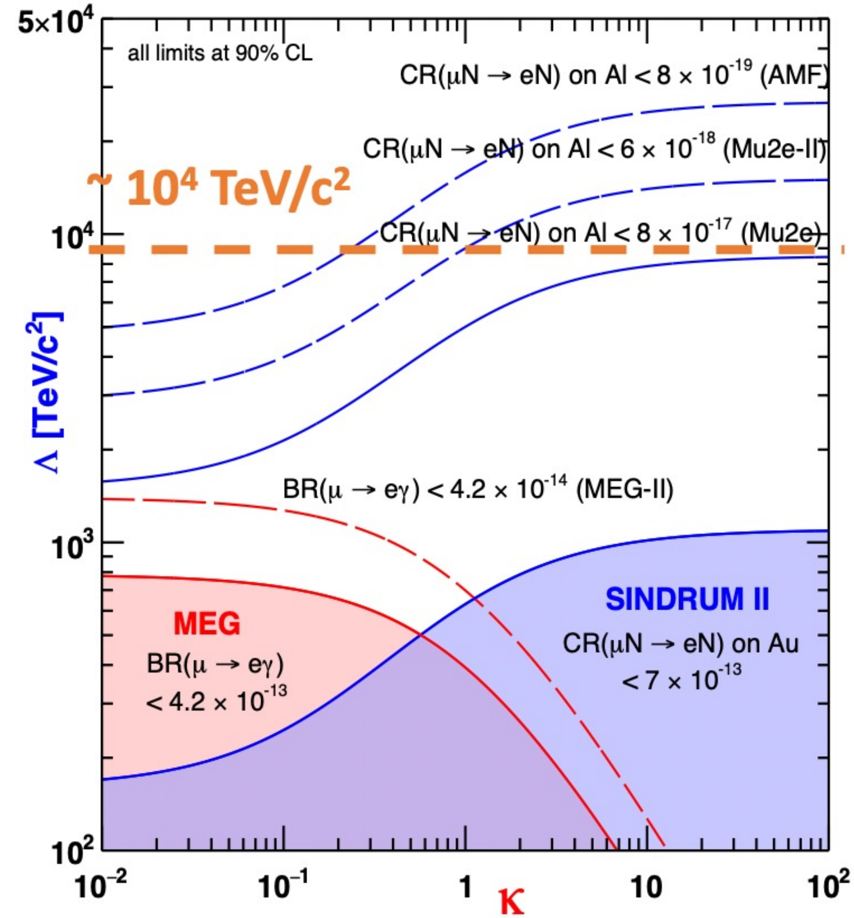
Tau LFUV @ Tera Z+ | Lingfeng Li, Brown U.

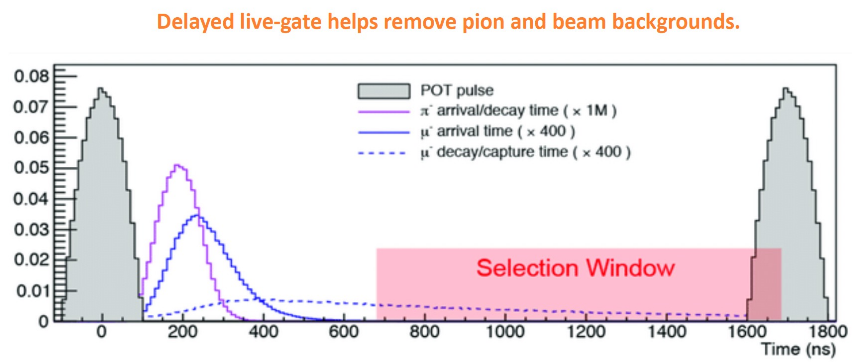


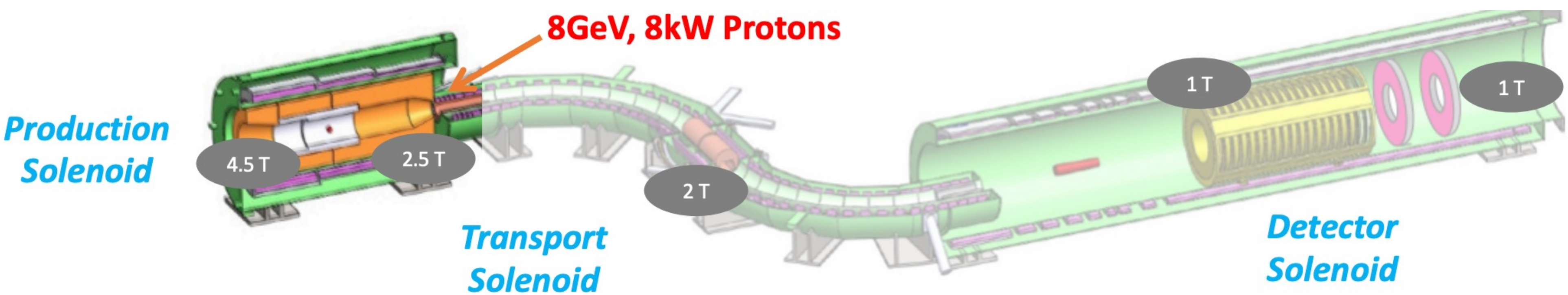


Middleton
Chithirasreemadam
Yucel

- *Mu2e will look for μ to e conversions in the electric field of a nucleus*
  - *Expect to reach* $BF(\mu N \rightarrow \mathrm{e}N) < 8{\times}10^{-17}$
- *On track for commissioning to start 2024 with cosmics, with beam in 2025, and first physics data taking in 2026*
- *Mu2e-II will increase sensitivity by another order of magnitude with higher beam intensity*



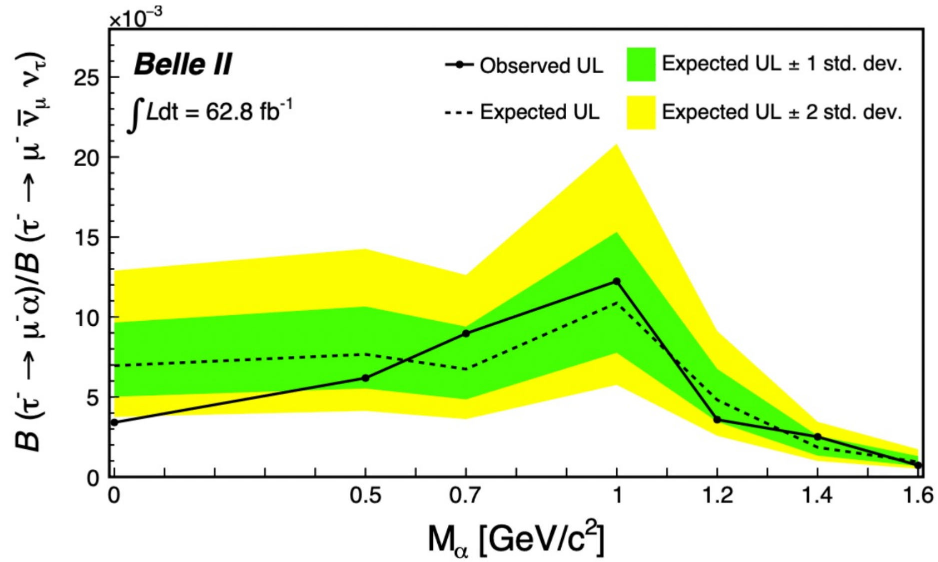


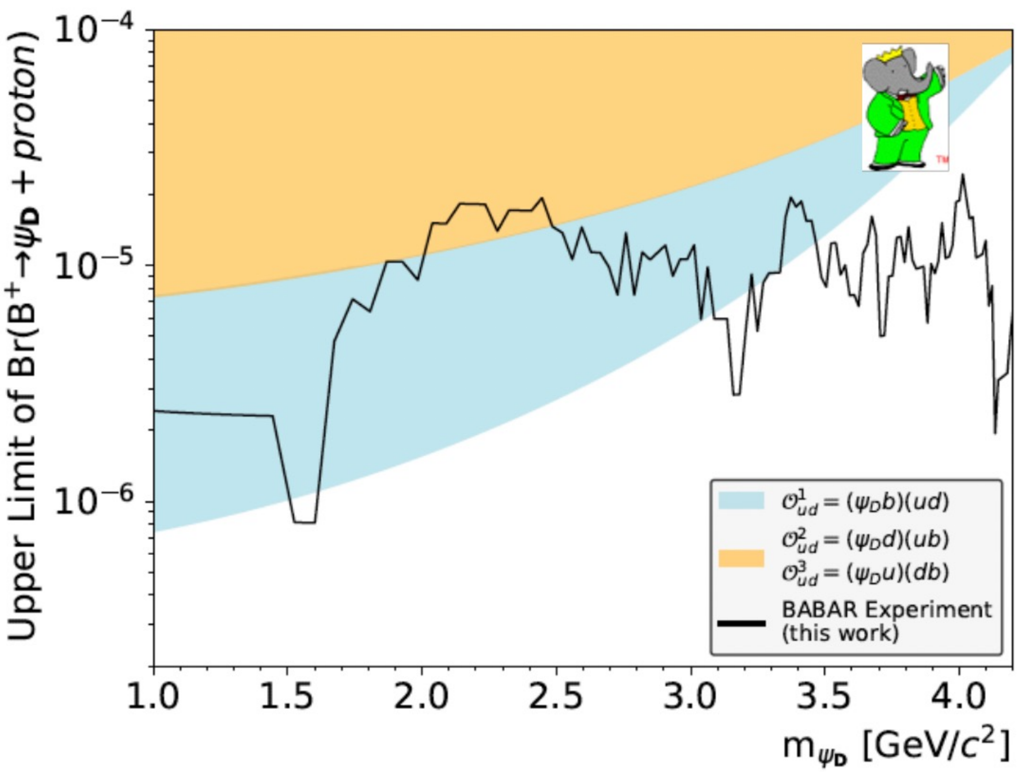


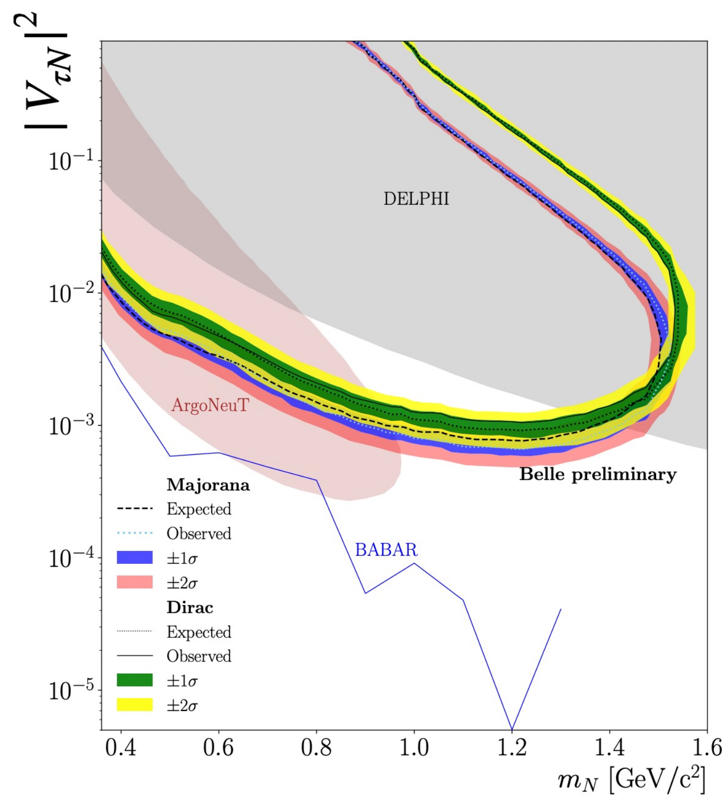
Dark Searches (low mass)

Brown
Dey
Middleton

- *New Belle I/II searches for*
  - *A long-lived HNL, a leptophilic scalar, a scalar in $\tau \rightarrow \ell\alpha$, a $\tau\tau$ resonance*
- *New BaBar searches for*
  - *A HNL, a dark baryon*

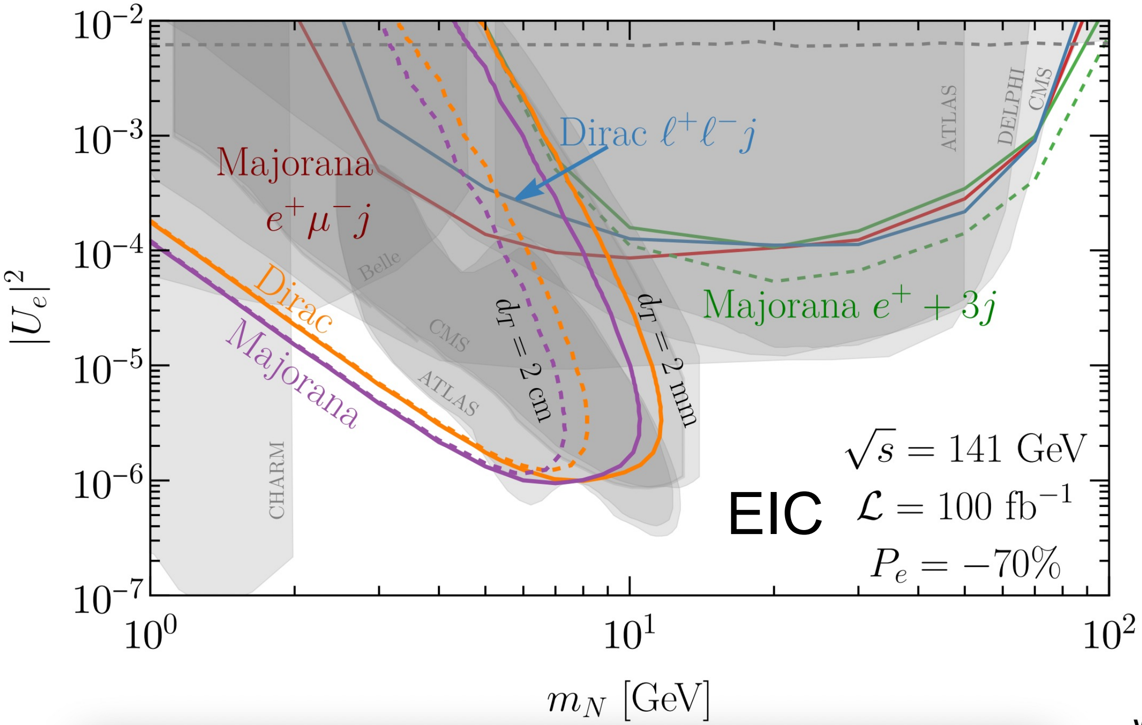


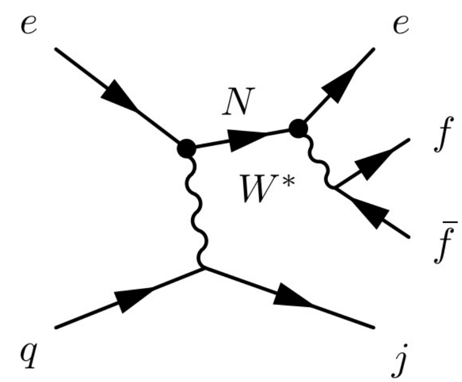




Dark searches at future experiments

Xie
Hitlin
Kose

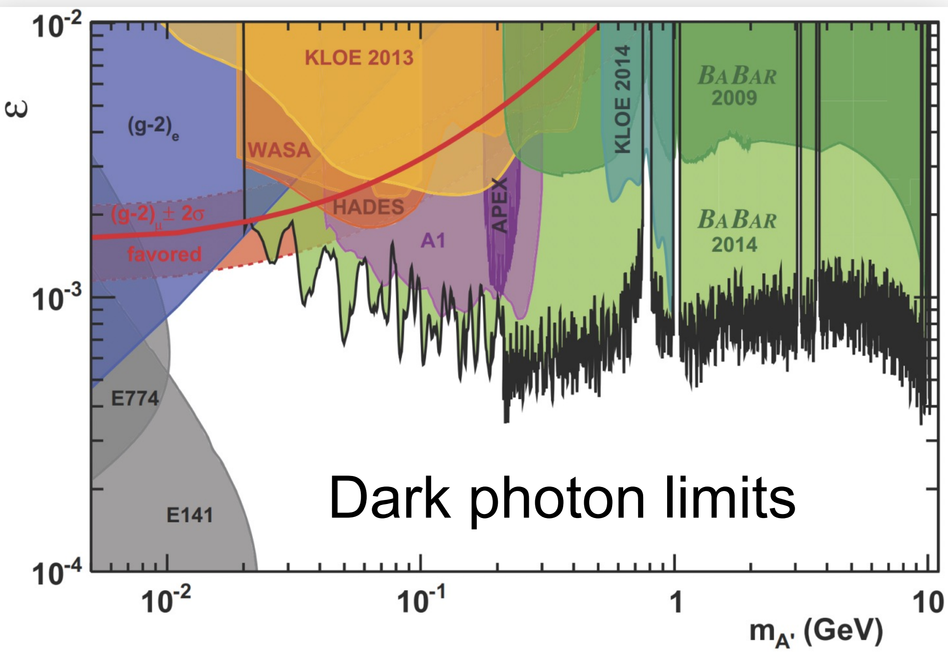


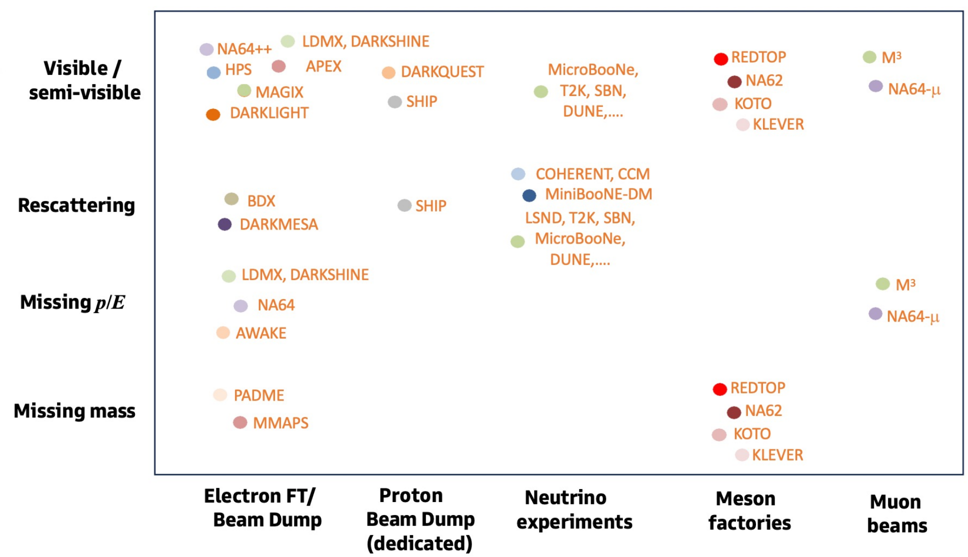


Consider 3 final states

- Majorana: e^+3j
- Majorana: $e^+\mu^-j + \not{E}_T$
- Dirac: $\ell^+\ell^-j + \not{E}_T$

Also sensitive to invisible HNL decays via mono-jets





Extensive program of dark searches at fixed target and beam dump expts, also Faser

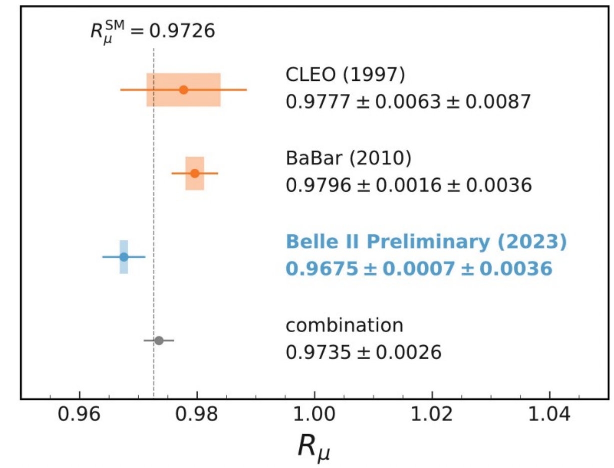
LFU tests in τ decays

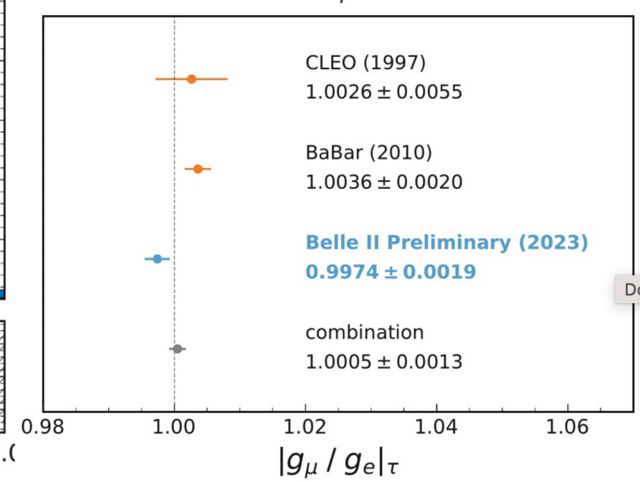
- *Same coupling of the charged leptons to the gauge bosons*
  - $g_e = g_\mu = g_\tau$ *(SM)*

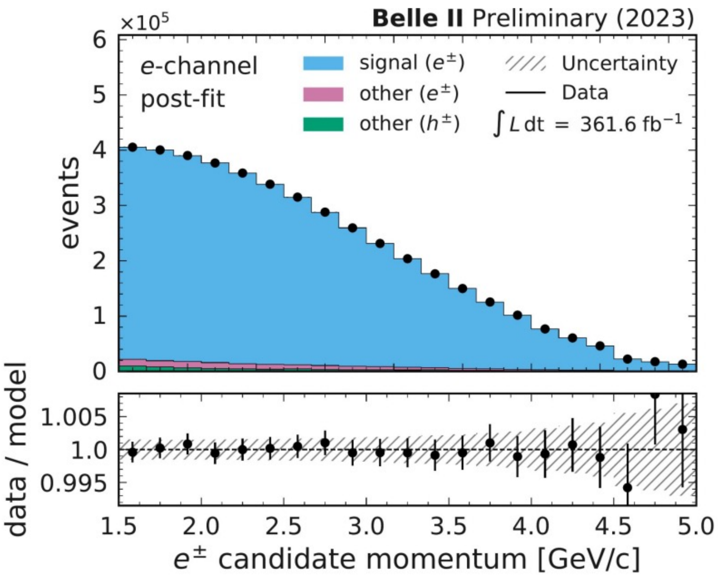
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$ **= 1 in SM**

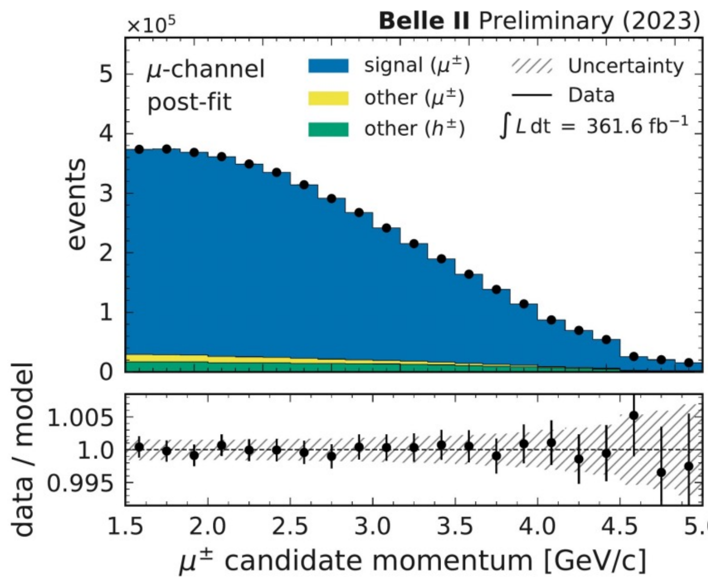
$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))} \overset{\text{SM}}{=} 0.9726$$

- ***Brand-new result from Belle II***
  - *systematically limited by LID*



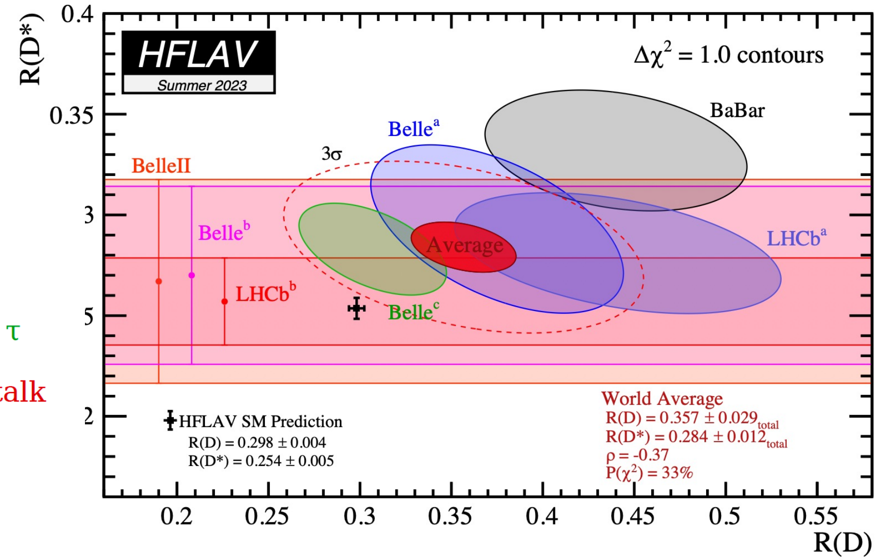




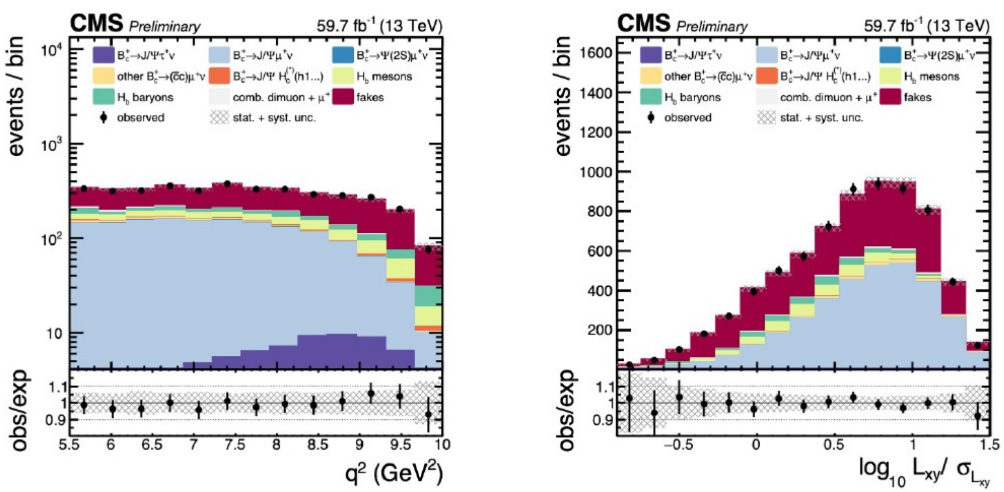


Lupato
Brossa
Guzzi

LFU tests with $b \to c\tau\nu$

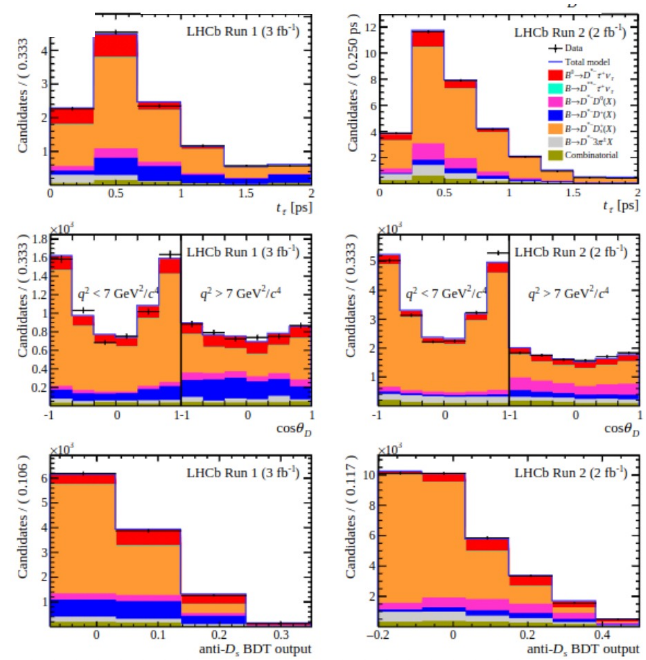


- *New measurements of $b \to c\tau\nu$ decays*
  - *LHCb:*
    - Measurement of the ratios of branching fractions R(D*) and R(D⁰) [Phys.Rev.Lett. 131 (2023) 111802]
    - Test of Lepton flavour universality using $B^0 \to D^{*-}\tau^+\nu$ decay with hadronic τ channels [Phys. Rev. D108 (2023) 012018] → Arnau's talk
    - Observation of the decay $\Lambda^0_b \to \Lambda_c^+ \tau \bar{\nu}$ [Phys. Rev. Lett. 128 (2022) 191803]
    - Measurement of D* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu$ decays [arXiv:2311.05224 – Submitted to PRD]
  - *CMS: $R(J/\psi)$*



$$R_{J/\psi} = 0.17^{+0.18}_{-0.17}\,(\text{stat})^{+0.21}_{-0.22}(\text{syst})^{+0.19}_{-0.18}\,(\text{theo})$$

compatible with the SM prediction within the experimental uncertainty (0.2582)

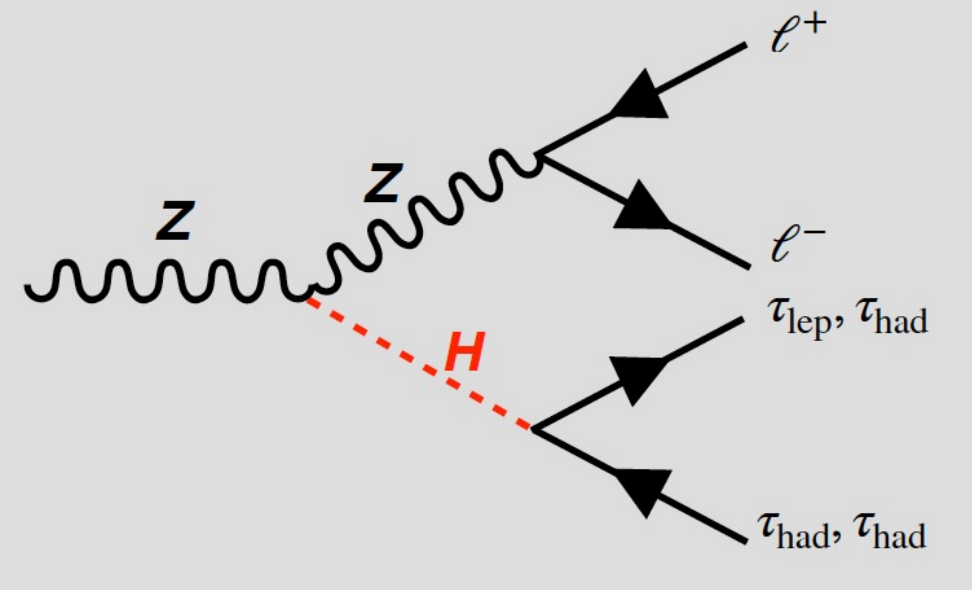


D* long. pol. consistent with SM (1σ)

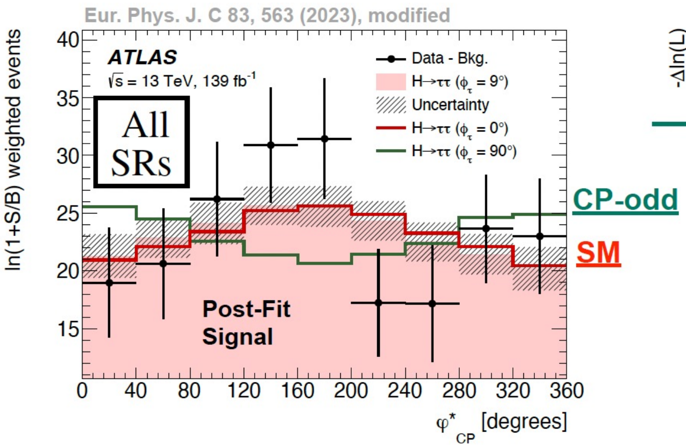
LHCb, B->D* tau nu

$q^2 < 7\,\text{GeV}^2/c^4$: $0.51 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$,
$q^2 > 7\,\text{GeV}^2/c^4$: $0.35 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst})$,
q^2 whole range : $0.43 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst})$.

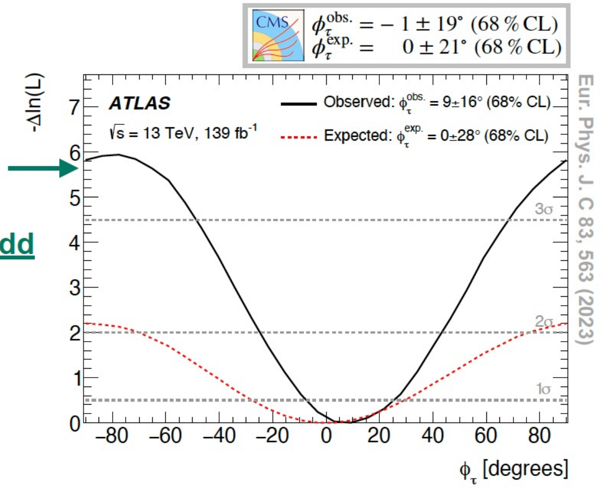
SM H physics with τ final states



- ATLAS sees evidence for associated $VH(\rightarrow \tau\tau)$ production at 4.2σ
- ATLAS measures CP of $H (\rightarrow \tau\tau)$ and rejects pure CP-odd at 3.4σ

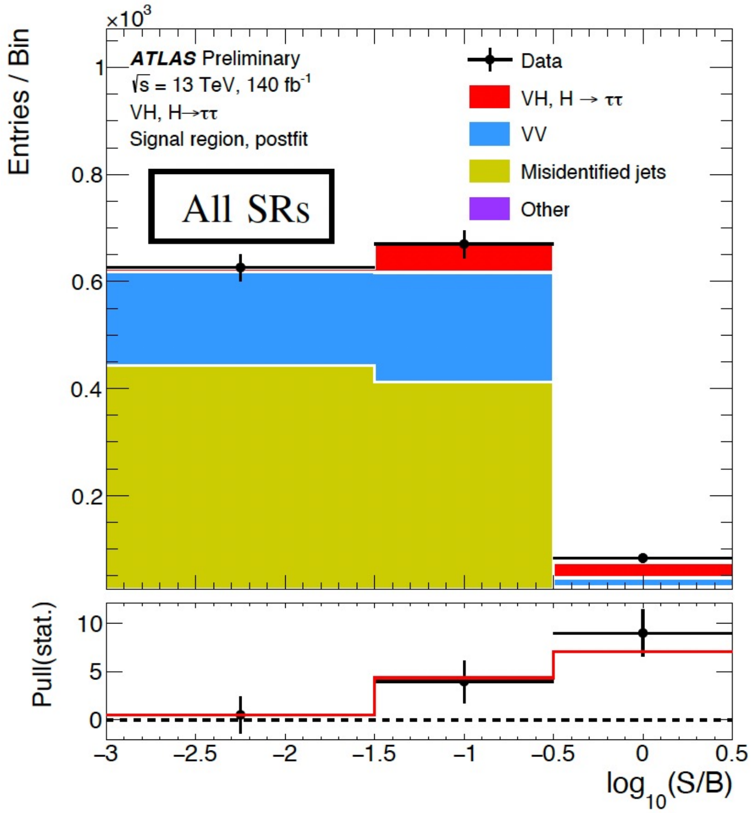


SM Higgs normalization is left unconstrained →Using only the shape



$\phi_\tau^{obs.}$ $(\phi_\tau^{exp.}) = 9 \pm 16°$ $(0 \pm 28°)$

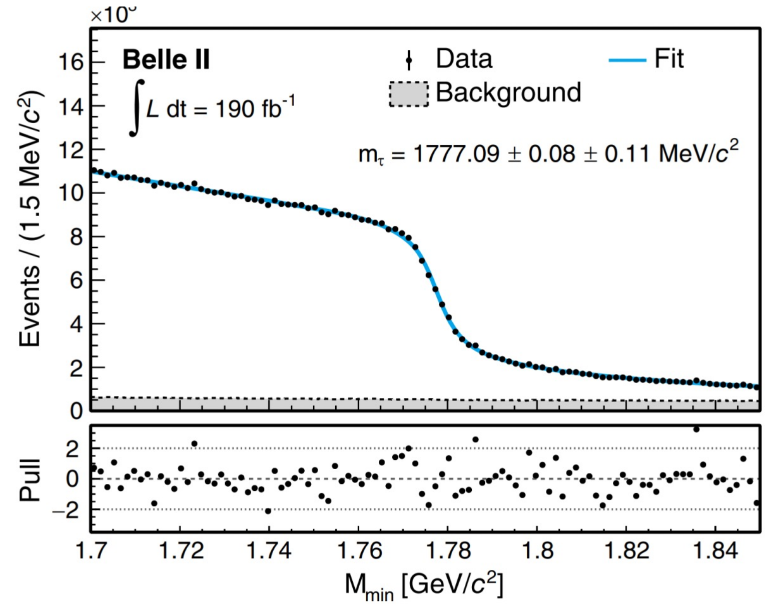
Pure CP-odd hypothesis is rejected with 3.4σ (CMS: 3σ)



τ properties I (mass, EDM)

Inami
Springberg
Zlebcik
Lusiani

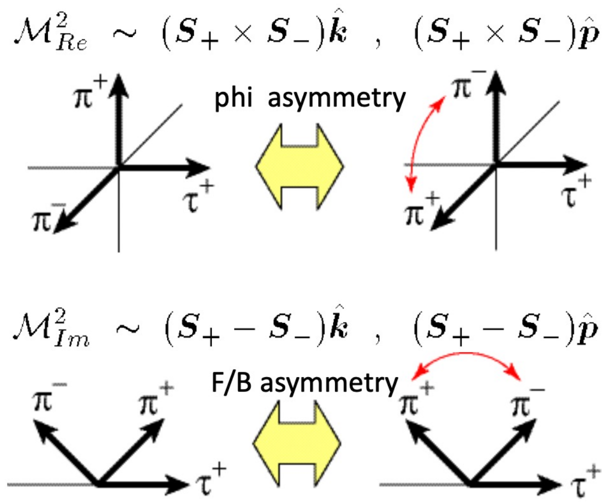
- *Most precise tau **mass** measurement from Belle II*
  - *Improved on results from threshold experiments by **reducing systematics from beam energy and momentum measurement***

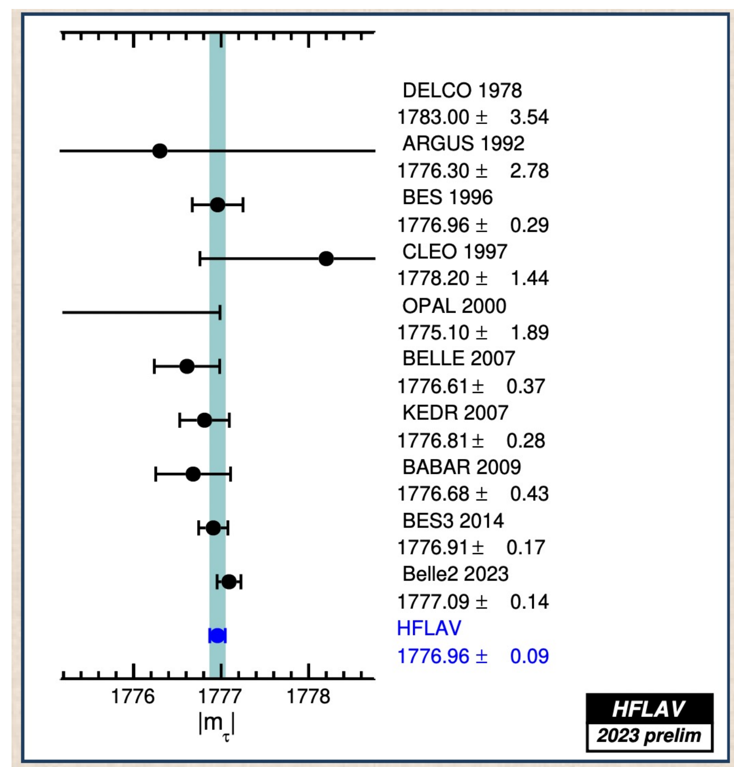


- *New measurement of tau **EDM** from Belle using spin correlations*

$$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ \mathrm{ecm},$$
$$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ \mathrm{ecm}.$$

  - *Expect to reduce to $(1-2)\times10^{-19}$ ecm with improved technique and Belle II data, esp. with pol. beams*



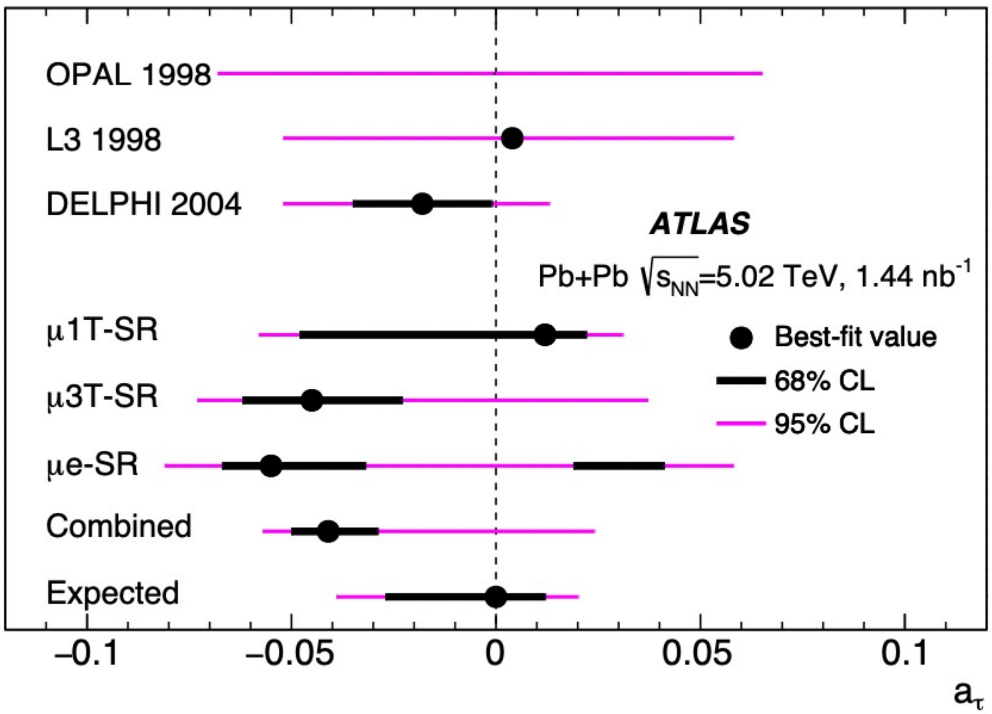


τ properties II $(g-2)$

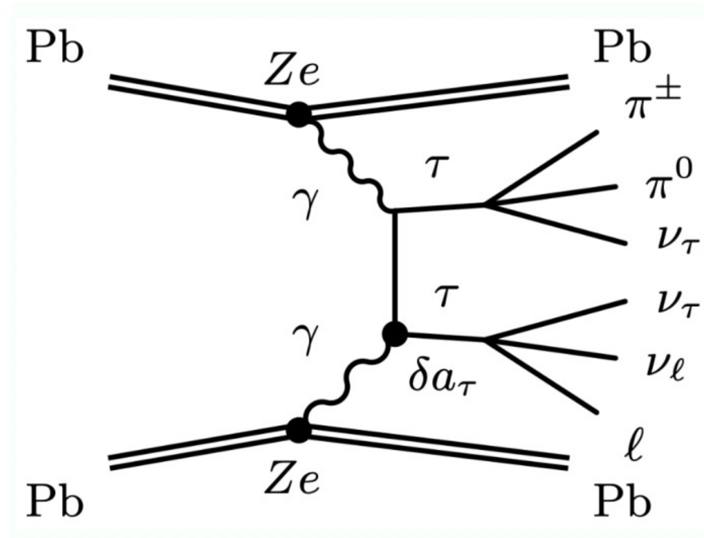
Buat
Buhler
Sprinberg

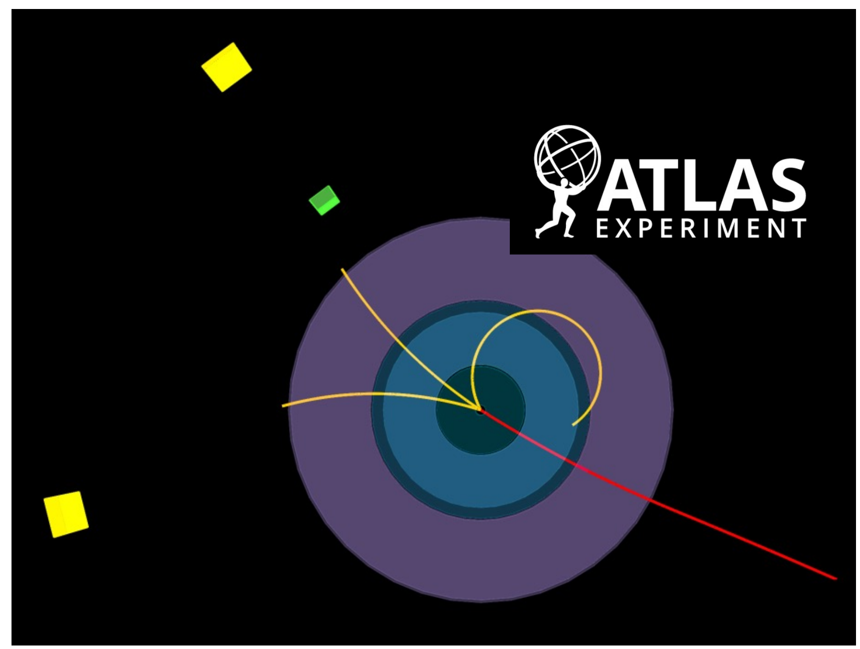
Ultra peripheral Pb-Pb collisions

- *Photoproduction cross-section of τ pairs depends on a_τ*
  - *ATLAS result has similar precision to DELPHI result; ALICE analysis is in progress*
- *Also possible at Belle II (pol. beams help)*



1-loop QED, Schwinger term
$\alpha/2\pi = 0.0012$





τ properties III (polarization)

Miller, Mohammadi

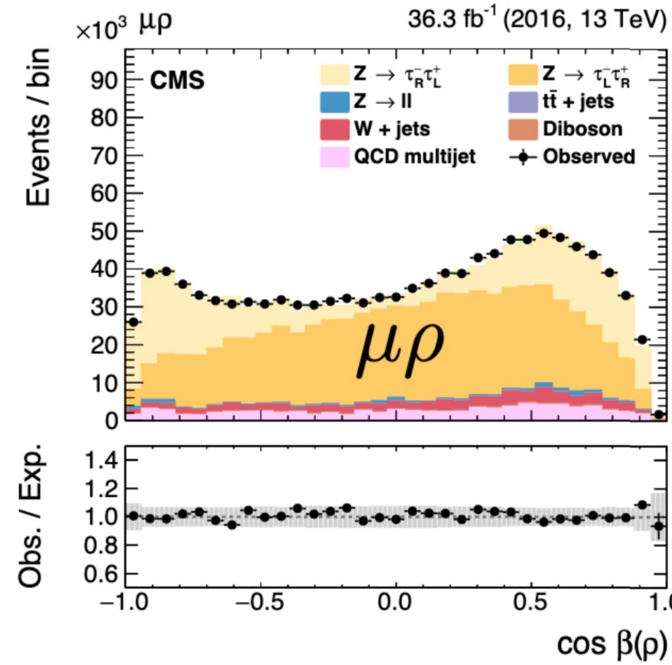
CMS measures tau pol. in Z decays and extracts $\sin^2\theta_W$

$$\langle \mathcal{P}_\tau \rangle_{75-120\,\text{GeV}} = -0.140 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst}) = -0.140 \pm 0.015.$$

$\mathcal{P}_\tau$ (Z) = −0.144 ±0.015

$$\mathcal{P}_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2\frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}}).$$

$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst}) = 0.2319 \pm 0.0019.$$



BABAR measures e⁻ beam pol. with τ polarization

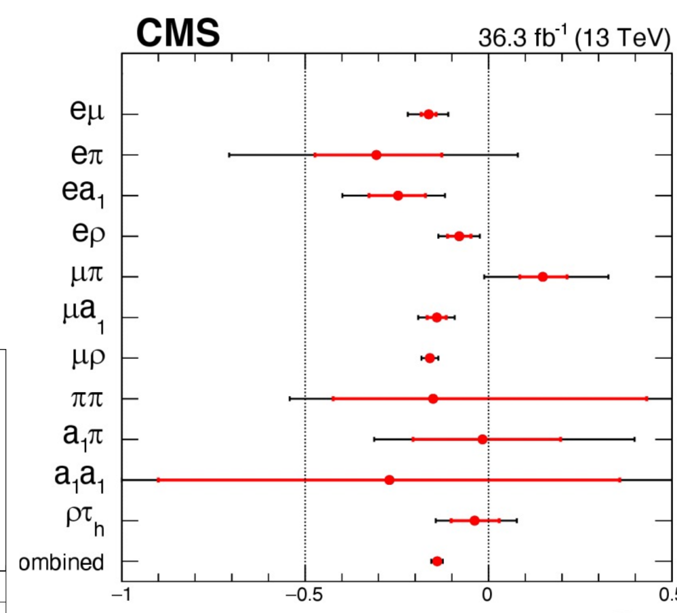
$$P_{\tau^-} = P_e \frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

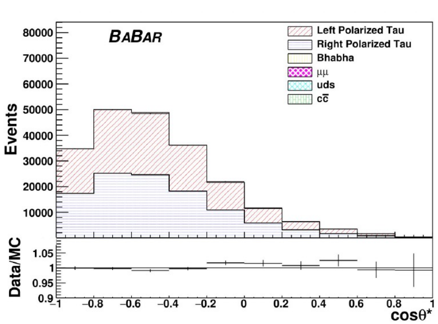
EM term

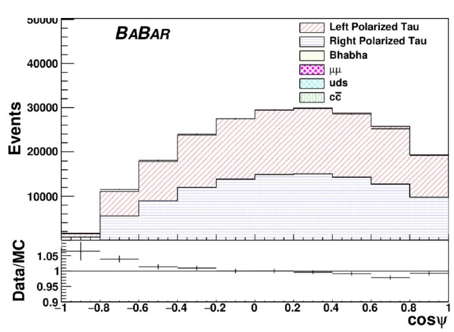
Electroweak correction ~0.003

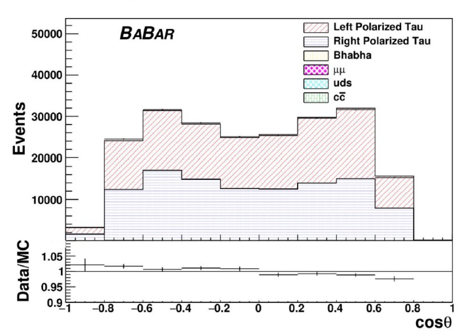
consistent with null expectation

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} + 0.0029_{\text{sys}}$$





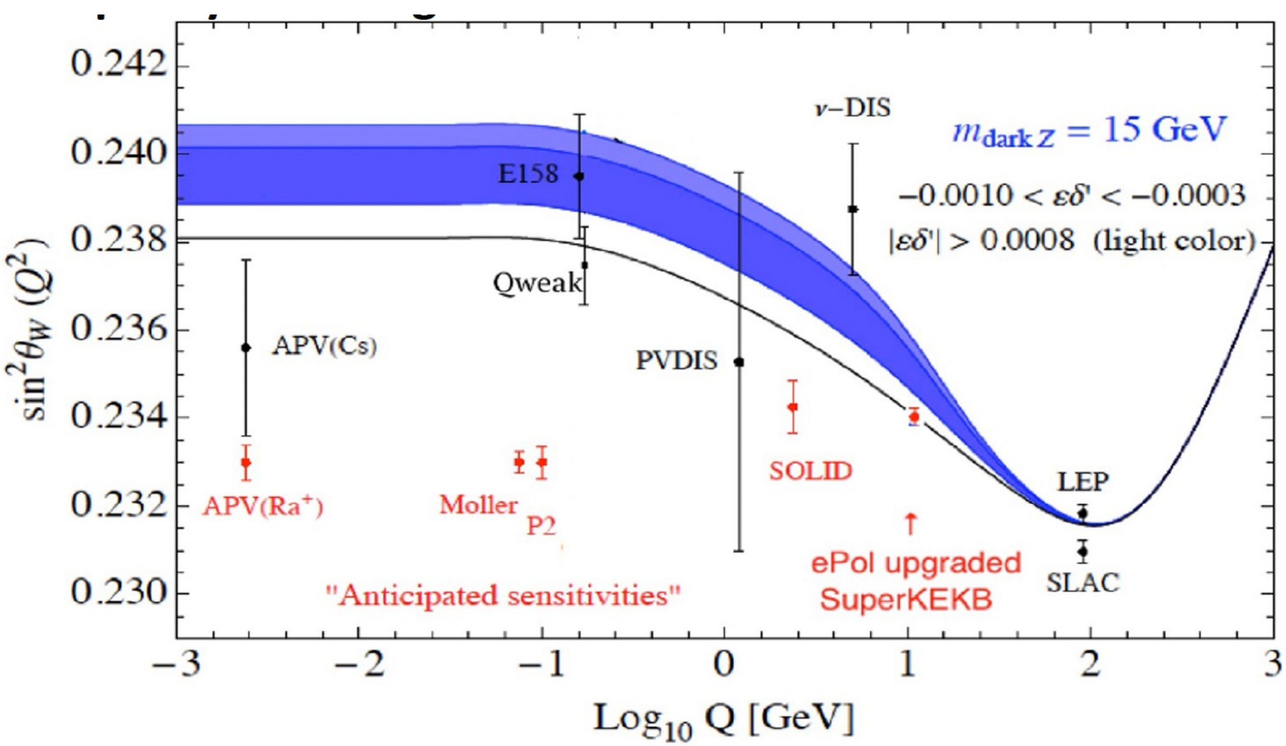


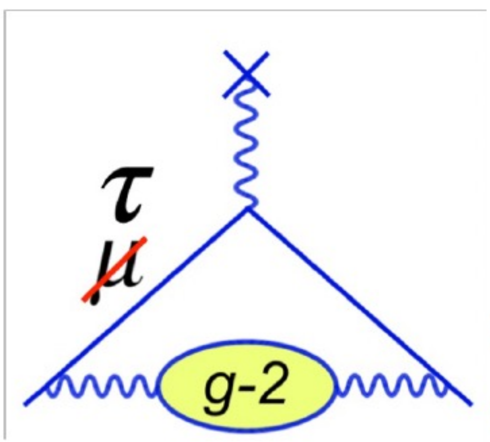


Chiral Belle

Upgrade SuperKEKB beams at $\sqrt{s}$ =10.58 GeV to 70% beam polarization

Plan for end of decade





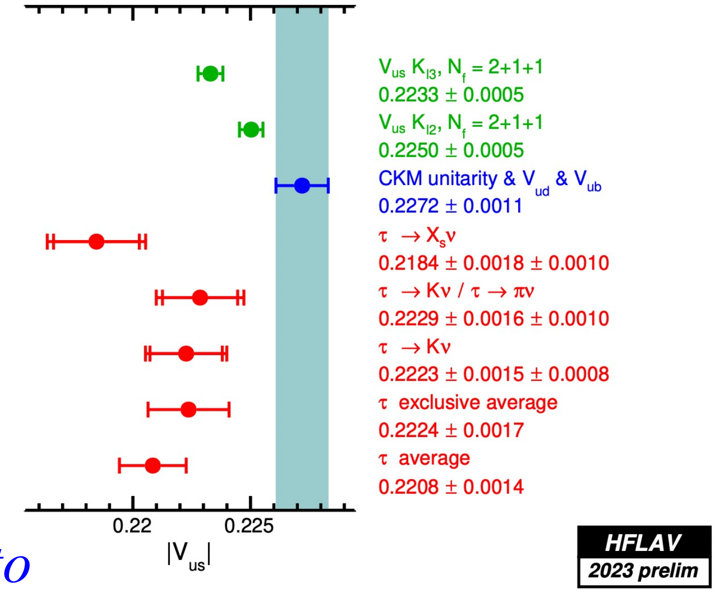
$$a_\tau^{\text{BSM}} \sim a_\mu^{\text{BSM}} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 10^{-6}$$

Current bound in tau ~ $\mathcal{O}(10^{-2})$
Chiral Belle reach ~ $\mathcal{O}(10^{-5})$ with $50 ab^{-1}$

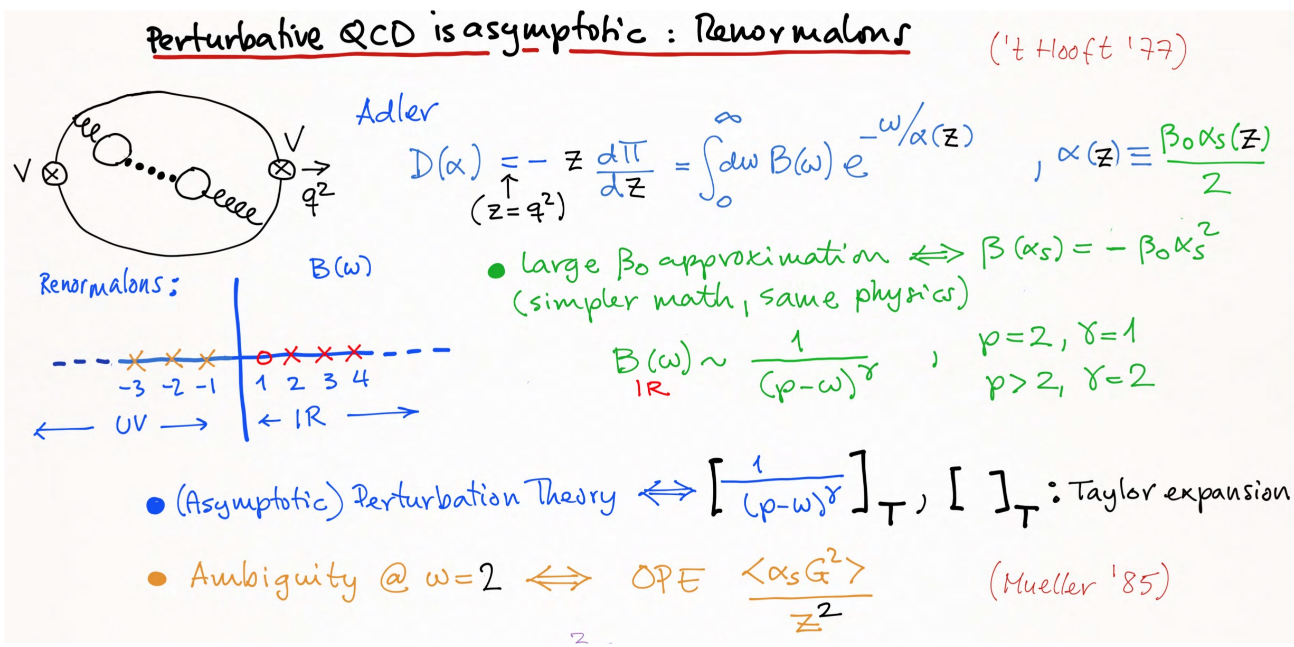
Hadronic τ decays (theory)

Miranda Sanchez
Golterman Was
Takaura Peris
Calderon

- *Updated τ generators*
  - *KKMC for $e^+e^- \to \tau^+\tau^-(n\gamma)$ incl. τ decays*
  - *Emission of additional pairs of SM and NP*
  - *Anomalous MDM and EDM*
- *Precise BFs of hadronic τ decays can limit NP contributions*
  - *E.g., new work on structure-dep. contributions to rad. corrections in hadronic τ decays reduces uncertainty x2*
- *New theory work on V_{us} and α_s*
  - *Unfortunately, no new experimental τ results in these areas*



Flash back to grad student times →



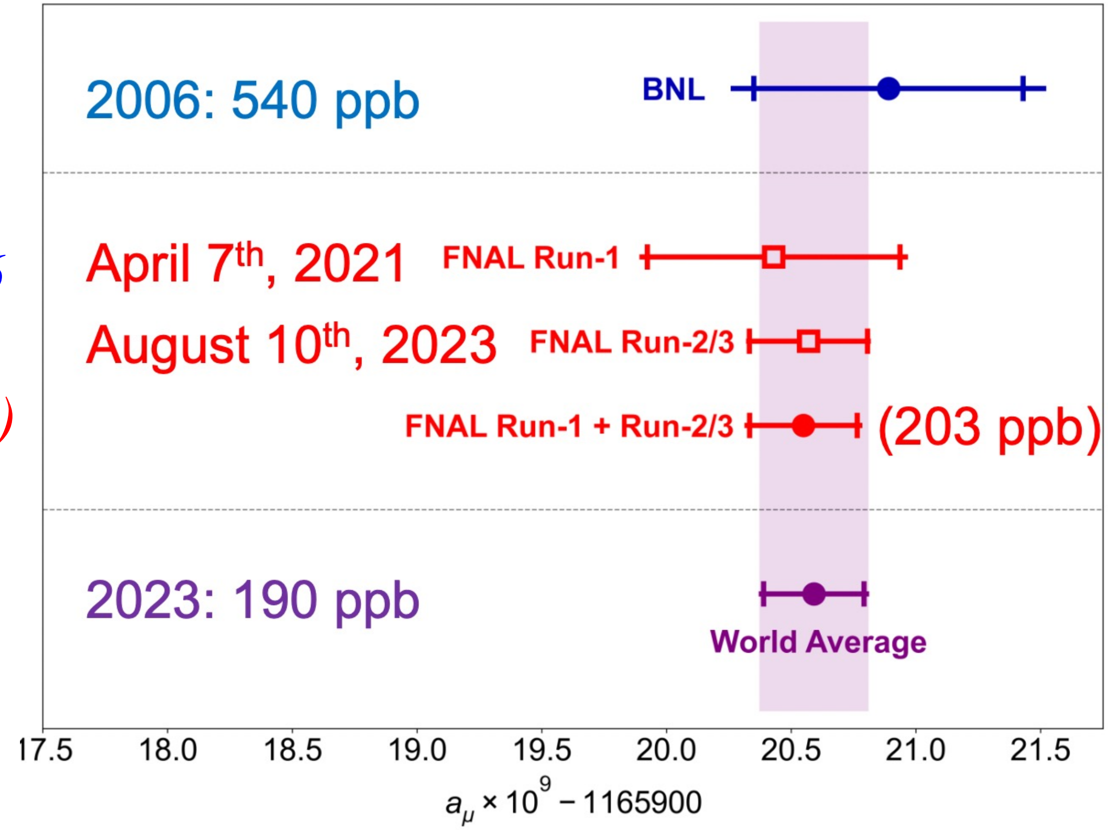
Cotrozzi
Mibe

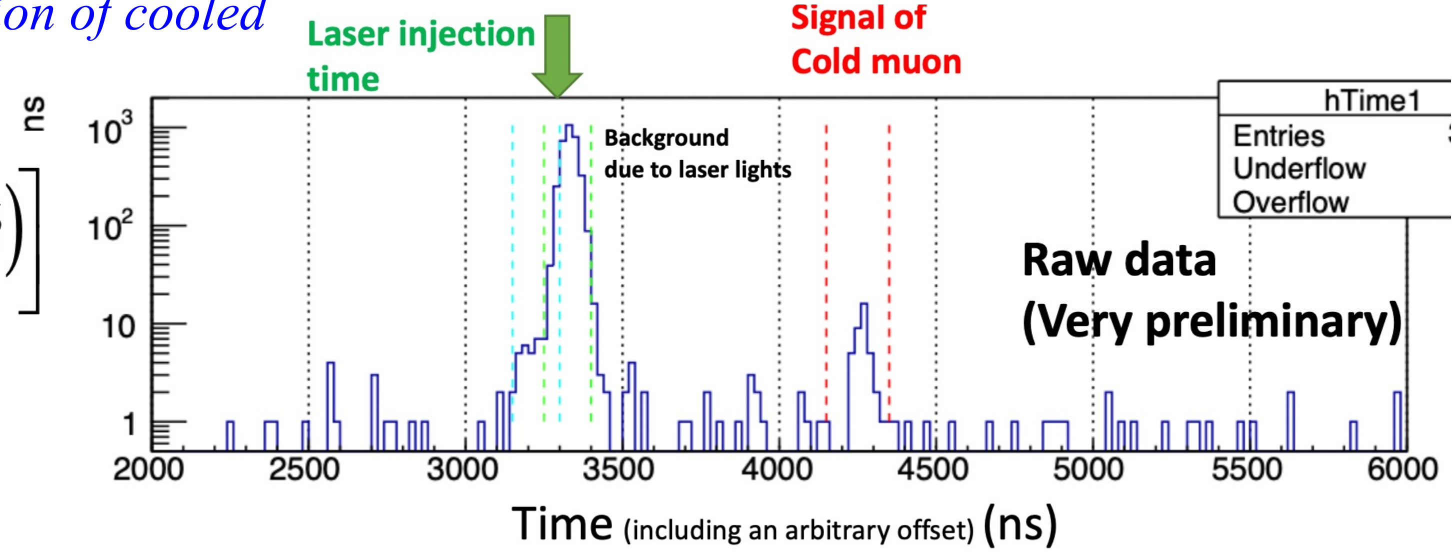
$\mu\ (g-2)$

- *New FNAL $\mu\ (g-2)$ result from Run 2+3 at 200 ppb precision*
  - *Error is statistically limited, expect to < 100 ppb with Run 1-6 (data taken this year)*
- *J-PARC Muon EDM / g-2 (2028+)*
  - *Not quite at the same precision*
  - *Different approach with low emittance μ beam and no strong focusing is more sensitive to EDM (10^{-21})*
  - *First demonstration of cooled muons*

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

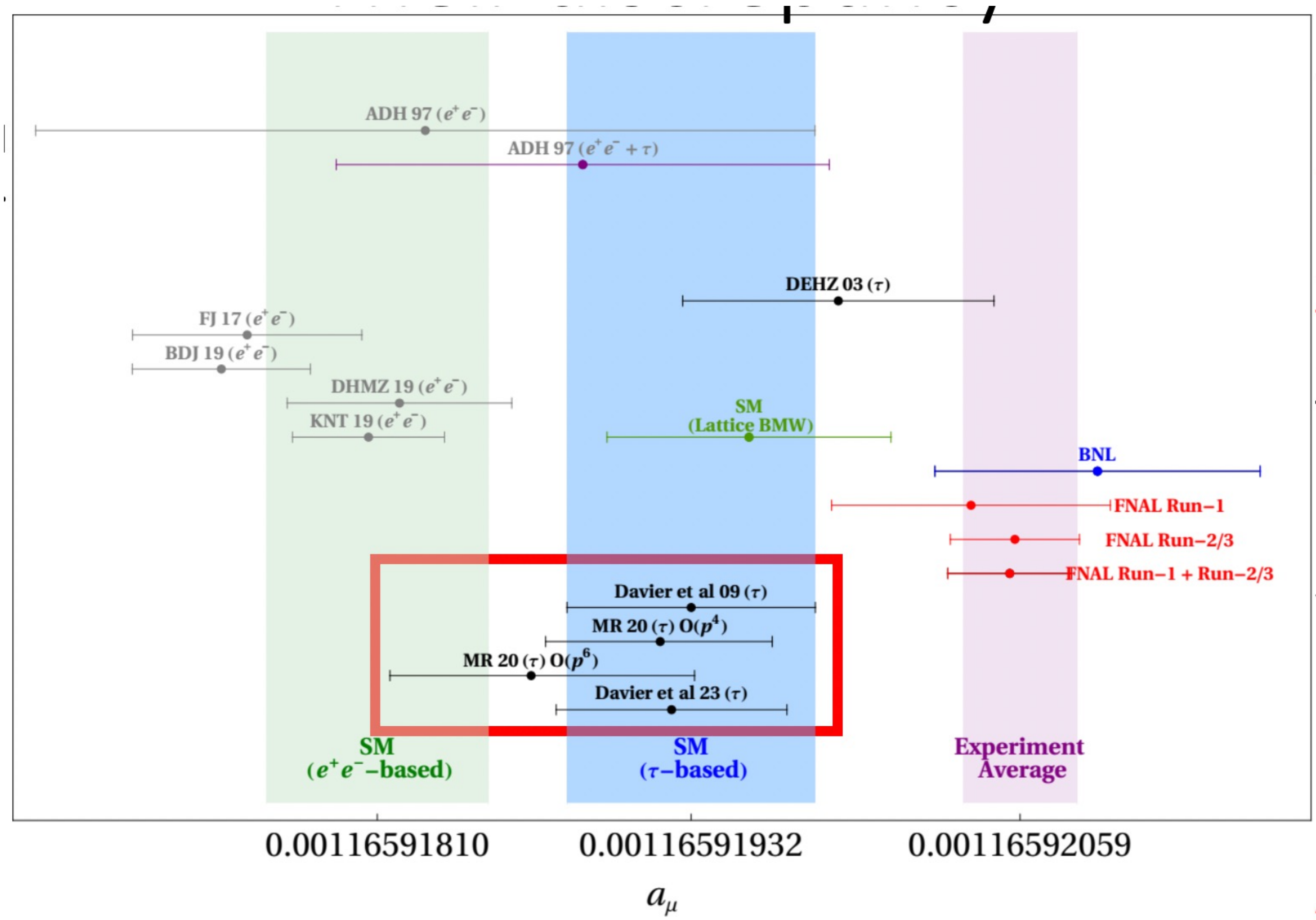
J-PARC E34

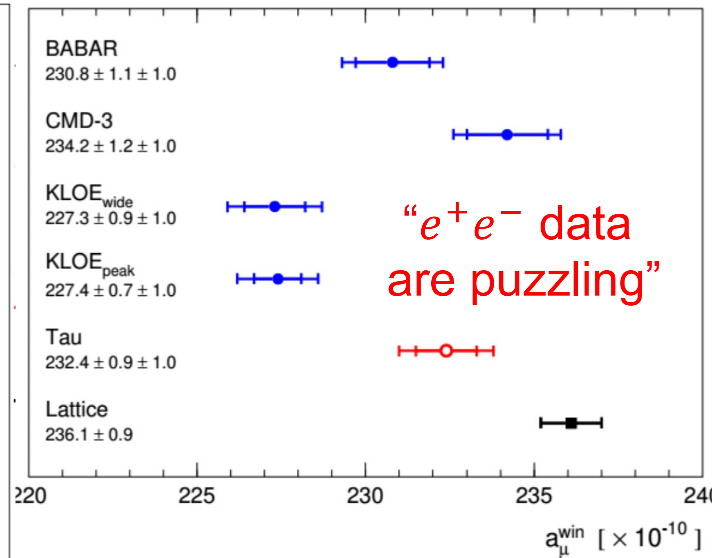




$\mu\,(g-2)$

Maltman
Pilato
Roig
Kuberski





e^+e^- data needs to be understood!

New measurements of HVP contribution expected from KLOE, BESIII, SND, Belle II (eventually also from τ decays)

- *Experimental a_μ value has been stable … what is the SM prediction?*
- *Expected theory progress*
  - *Radiative corrections and MC generators are being scrutinized*
  - *New LQCD results for total HVP contribution and "window observables" and data-driven approach … goal is < 0.5% precision*
  - *MUonE will provide new method to compute the HVP contribution (2026+)*

Some stats

- *89 plenary talks*
- *90 participants*
- *6 Kentucky bourbons … maybe more* 

Many thanks !

Many thanks to Sourav Patra and Naveen Kumar Baghel for taking care of the registration and Indico and Zoom connections

Many thanks to Swagato for hosting this great event !!!

Conclusions

We have seen a lot of exciting results since the last TAU conference

Tau physics is going strong !

I am looking forward to TAU 2025

τ2025 The 18th International Workshop on Tau Lepton Physics

The 18th International Workshop on Tau Lepton Physics will be held in autumn of 2025 hosted by Aix-Marseille Université in Marseille, France

Justine Serrano serrano@cppm.in2p3.fr serving as Chair of the Local Organizing Committee

Exact dates are to be decided later

Back-Up Slides