Constraining tau g–2 at the (HL-)LHC

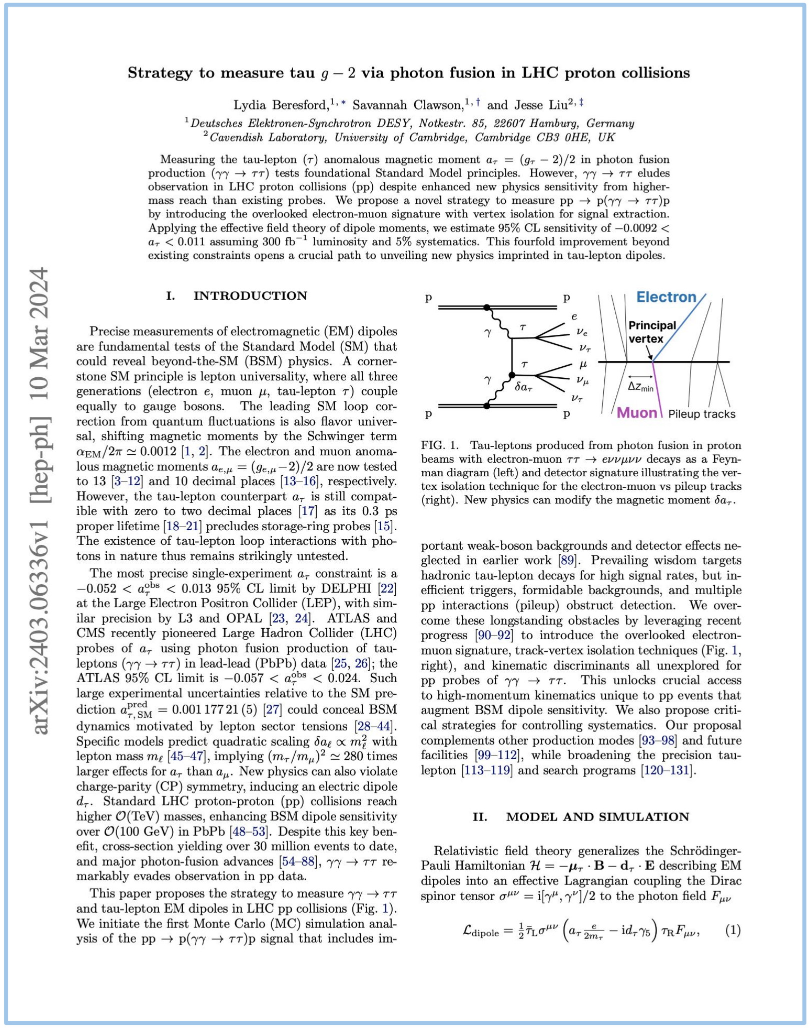
Savannah Clawson (DESY)

LHC FWD WG Meeting
15th July 2024

HELMHOLTZ DESY. ATLAS EXPERIMENT

Introduction

- This talk is based on arXiv:2403.06336 [Lydia Beresford, SC, Jesse Liu]



arXiv:2403.06336v1 [hep-ph] 10 Mar 2024

Strategy to measure tau $g-2$ via photon fusion in LHC proton collisions

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Measuring the tau-lepton (τ) anomalous magnetic moment $a_\tau = (g_\tau - 2)/2$ in photon fusion production ($\gamma\gamma \to \tau\tau$) tests foundational Standard Model principles. However, $\gamma\gamma \to \tau\tau$ eludes observation in LHC proton collisions (pp) despite enhanced new physics sensitivity from higher-mass reach than existing probes. We propose a novel strategy to measure pp $\to$ p($\gamma\gamma \to \tau\tau$)p by introducing the overlooked electron-muon signature with vertex isolation for signal extraction. Applying the effective field theory of dipole moments, we estimate 95% CL sensitivity of $-0.0092 < a_\tau < 0.011$ assuming 300 fb^{-1} luminosity and 5% systematics. This fourfold improvement beyond existing constraints opens a crucial path to unveiling new physics imprinted in tau-lepton dipoles.

I. INTRODUCTION

Precise measurements of electromagnetic (EM) dipoles are fundamental tests of the Standard Model (SM) that could reveal beyond-the-SM (BSM) physics. A cornerstone SM principle is lepton universality, where all three generations (electron e, muon μ, tau-lepton τ) couple equally to gauge bosons. The leading SM loop correction from quantum fluctuations is also flavor universal, shifting magnetic moments by the Schwinger term $\alpha_{\text{EM}}/2\pi \simeq 0.0012$ [1, 2]. The electron and muon anomalous magnetic moments $a_{e,\mu} = (g_{e,\mu} - 2)/2$ are now tested to 13 [3–12] and 10 decimal places [13–16], respectively. However, the tau-lepton counterpart a_τ is still compatible with zero to two decimal places [17] as its 0.3 ps proper lifetime [18–21] precludes storage-ring probes [15]. The existence of tau-lepton loop interactions with photons in nature thus remains strikingly untested.

The most precise single-experiment a_τ constraint is a $-0.052 < a_\tau^{\text{obs}} < 0.013$ 95% CL limit by DELPHI [22] at the Large Electron Positron Collider (LEP), with similar precision by L3 and OPAL [23, 24]. ATLAS and CMS recently pioneered Large Hadron Collider (LHC) probes of a_τ using photon fusion production of tau-leptons ($\gamma\gamma \to \tau\tau$) in lead-lead (PbPb) data [25, 26]; the ATLAS 95% CL limit is $-0.057 < a_\tau^{\text{obs}} < 0.024$. Such large experimental uncertainties relative to the SM prediction $a_{\tau,\text{SM}}^{\text{pred}} = 0.001\,177\,21\,(5)$ [27] could conceal BSM dynamics motivated by lepton sector tensions [28–44]. Specific models predict quadratic scaling $\delta a_\ell \propto m_\ell^2$ with lepton mass m_ℓ [45–47], implying $(m_\tau/m_\mu)^2 \simeq 280$ times larger effects for a_τ than a_μ. New physics can also violate charge-parity (CP) symmetry, inducing an electric dipole d_τ. Standard LHC proton-proton (pp) collisions reach higher $\mathcal{O}$(TeV) masses, enhancing BSM dipole sensitivity over $\mathcal{O}$(100 GeV) in PbPb [48–53]. Despite this key benefit, cross-section yielding over 30 million events to date, and major photon-fusion advances [54–88], $\gamma\gamma \to \tau\tau$ remarkably evades observation in pp data.

This paper proposes the strategy to measure $\gamma\gamma \to \tau\tau$ and tau-lepton EM dipoles in LHC pp collisions (Fig. 1). We initiate the first Monte Carlo (MC) simulation analysis of the pp $\to$ p($\gamma\gamma \to \tau\tau$)p signal that includes important weak-boson backgrounds and detector effects neglected in earlier work [89]. Prevailing wisdom targets hadronic tau-lepton decays for high signal rates, but inefficient triggers, formidable backgrounds, and multiple pp interactions (pileup) obstruct detection. We overcome these longstanding obstacles by leveraging recent progress [90–92] to introduce the overlooked electron-muon signature, track-vertex isolation techniques (Fig. 1, right), and kinematic discriminants all unexplored for pp probes of $\gamma\gamma \to \tau\tau$. This unlocks crucial access to high-momentum kinematics unique to pp events that augment BSM dipole sensitivity. We also propose critical strategies for controlling systematics. Our proposal complements other production modes [93–98] and future facilities [99–112], while broadening the precision tau-lepton [113–119] and search programs [120–131].

FIG. 1. Tau-leptons produced from photon fusion in proton beams with electron-muon $\tau\tau \to e\nu\nu\mu\nu\nu$ decays as a Feynman diagram (left) and detector signature illustrating the vertex isolation technique for the electron-muon vs pileup tracks (right). New physics can modify the magnetic moment δa_τ.

II. MODEL AND SIMULATION

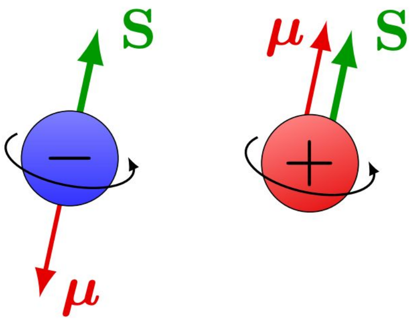
Relativistic field theory generalizes the Schrödinger-Pauli Hamiltonian $\mathcal{H} = -\boldsymbol{\mu}_\tau \cdot \mathbf{B} - \mathbf{d}_\tau \cdot \mathbf{E}$ describing EM dipoles into an effective Lagrangian coupling the Dirac spinor tensor $\sigma^{\mu\nu} = \mathrm{i}[\gamma^\mu, \gamma^\nu]/2$ to the photon field $F_{\mu\nu}$

$$\mathcal{L}_{\text{dipole}} = \tfrac{1}{2}\bar{\tau}_{\text{L}}\sigma^{\mu\nu}\left(a_\tau \tfrac{e}{2m_\tau} - \mathrm{i}d_\tau\gamma_5\right)\tau_{\text{R}}F_{\mu\nu}, \quad (1)$$

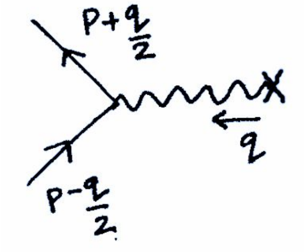
As always, with many slides shamelessly stolen from Jesse

Lepton magnetic moments

- Lepton spin, **S**, and magnetic moment, **μ**, linked through gyromagnetic factor, **g**
  - → Dirac equation predicts $g = 2$



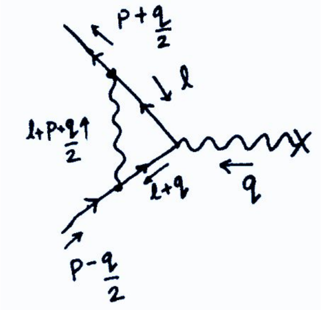
$$\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S}$$



+

- Quantum corrections give rise to anomalous magnetic moments:

$$a_l = (g - 2) / 2$$



- Leading SM loop correction is the Schwinger term:

$$a_l = \alpha_{\mathrm{EM}} / 2\pi \cong 0.0012$$

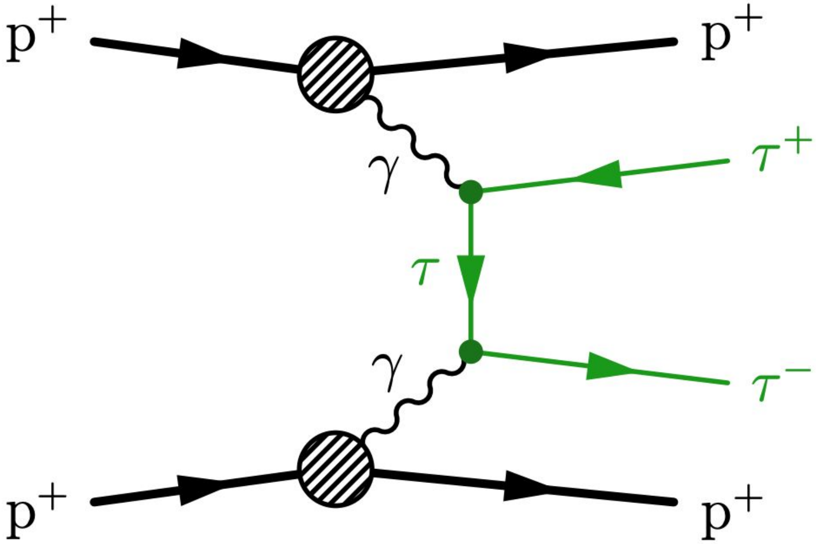
+

. . .

- Electron and muon g-2 among some of the most precisely measured quantities in physics
  - → Interesting tension between experiment and theory in muon g-2
- Tau g-2 evades precise measurement due to short tau lifetime

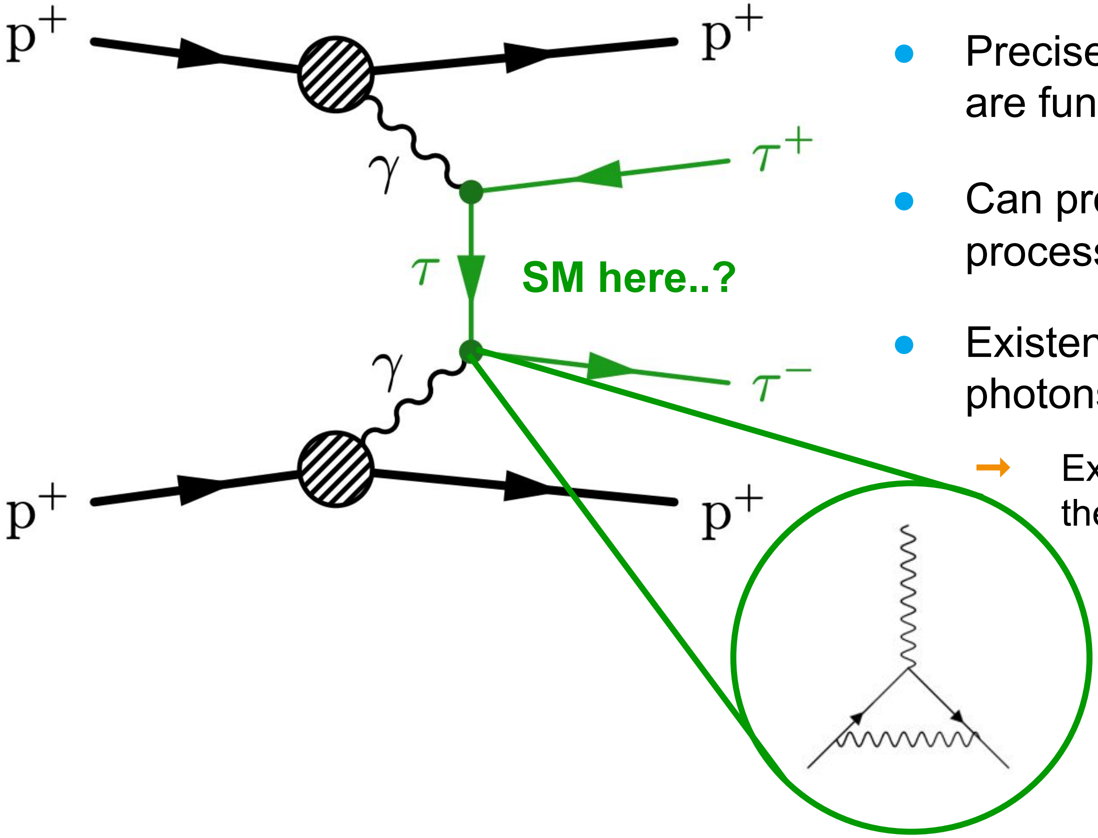
$a_\tau^{\mathrm{SM}} \cong$ **0.0018**

Motivation



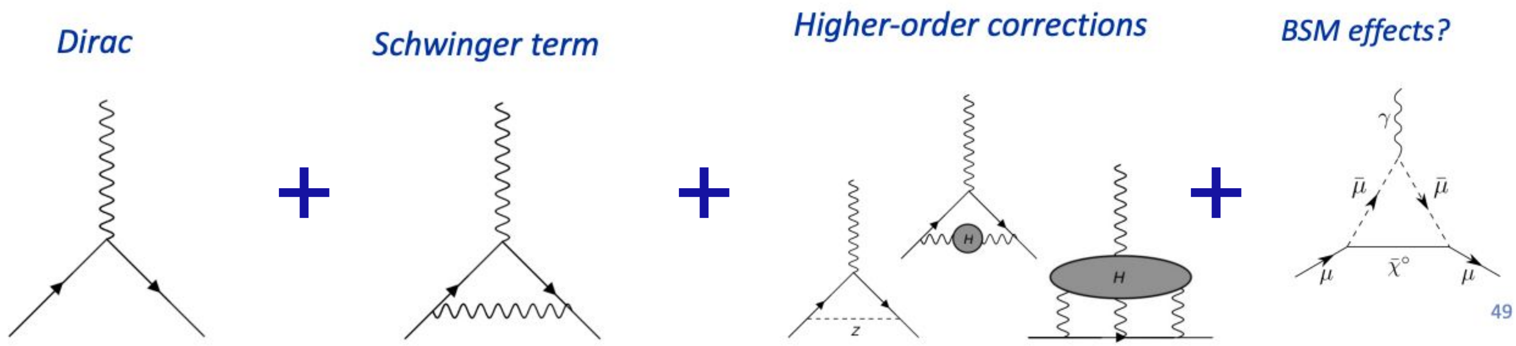
- Precise measurements of EM dipoles are fundamental tests of the SM
- Can probe EM dipoles through $\gamma\gamma \rightarrow \tau\tau$ process

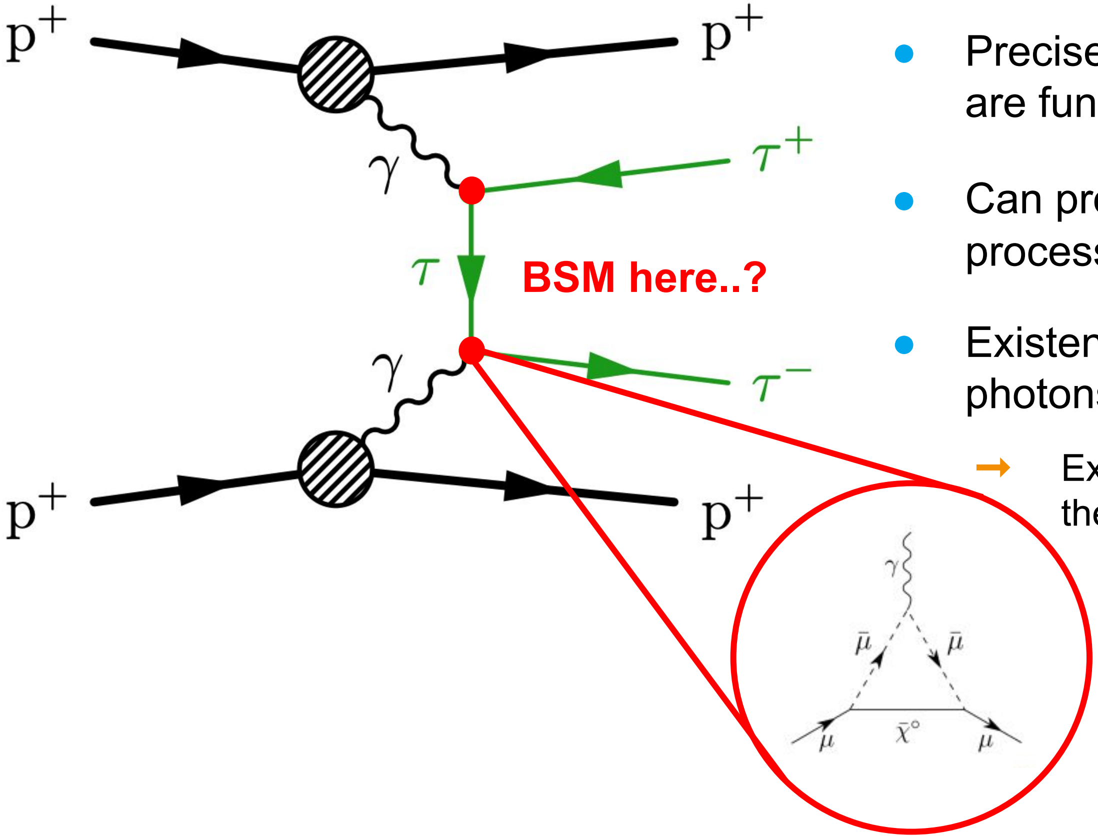
Motivation



- Precise measurements of EM dipoles are fundamental tests of the SM
- Can probe EM dipoles through $\gamma\gamma \rightarrow \tau\tau$ process
- Existence of tau loop interactions with photons remains strikingly untested
  - → Experimental precision is still far below the Schwinger term!

Motivation





BSM here..?

- Precise measurements of EM dipoles are fundamental tests of the SM
- Can probe EM dipoles through γγ→ττ process
- Existence of tau loop interactions with photons remains strikingly untested
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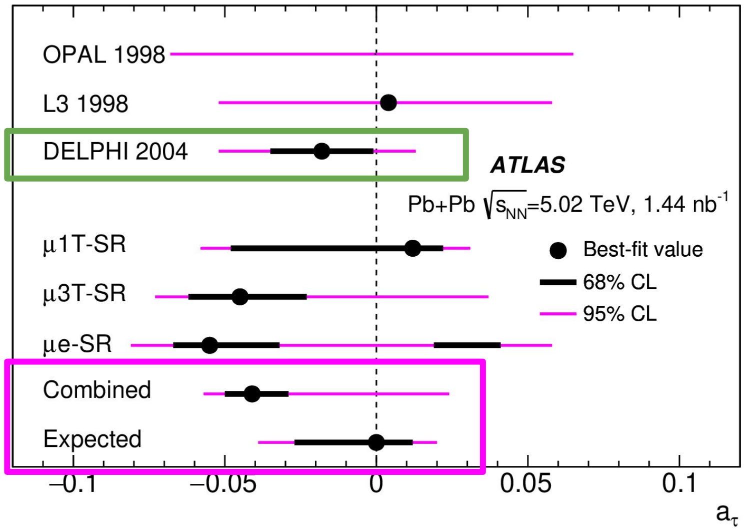
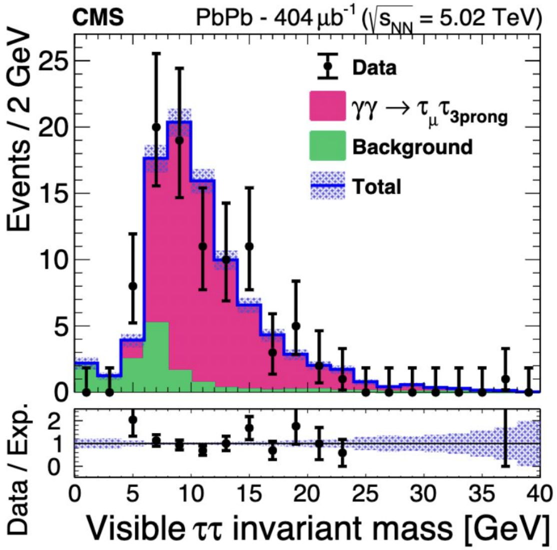
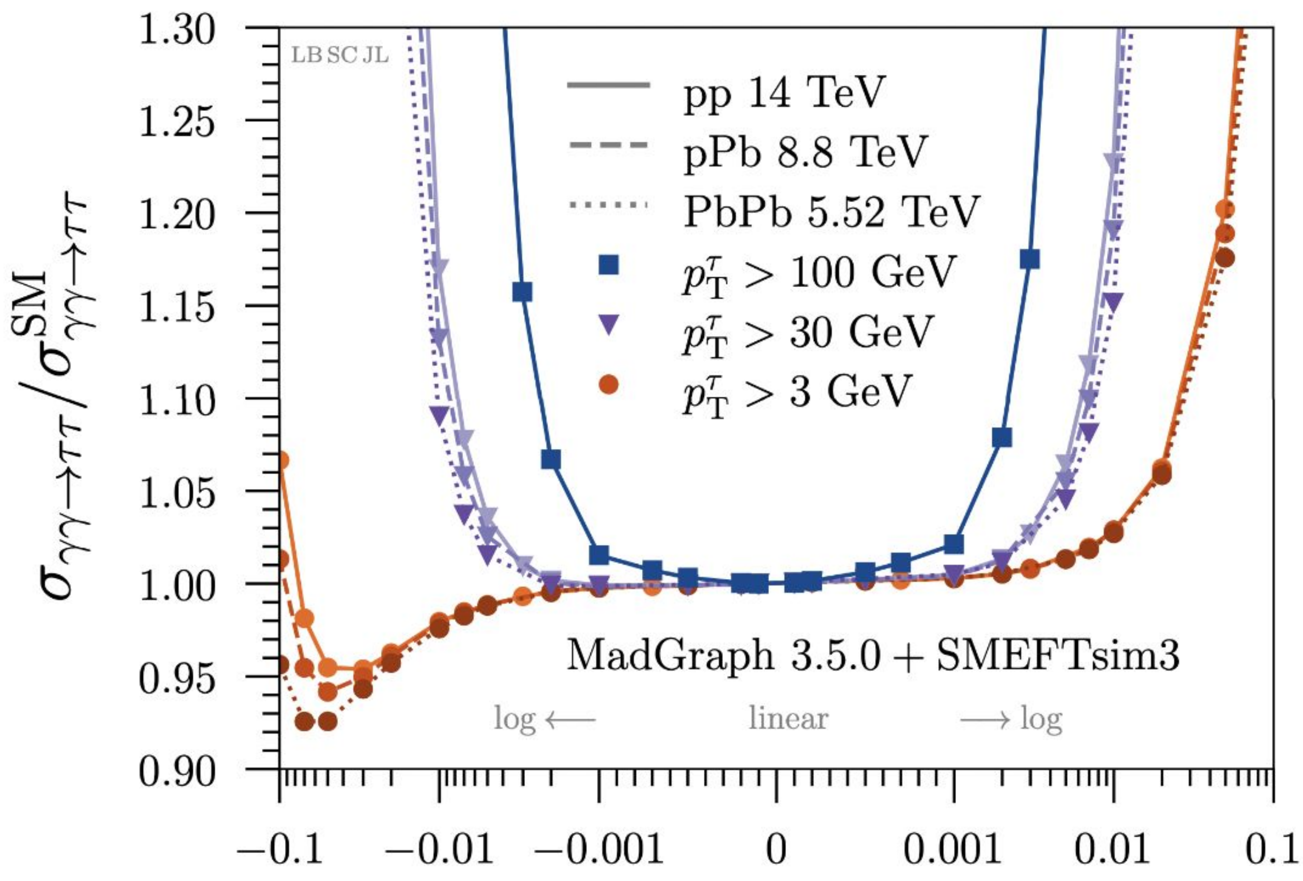
Motivation

- **This process had previously only been measured in Ultra-peripheral Heavy Ion (HI) collisions (UPC) at the LHC**
  - ➞ Proposals by Beresford & Liu [arXiv:1908.05180],
    Dyndal, Klusek-Gawenda, Schott, Szczurek [arXiv:2002.05503]
  - ➞ Expect SM process to be low-mass, observation of $\gamma\gamma\rightarrow\tau\tau$ already performed in HI collisions by both **ATLAS** [PRL 131 (2023) 151802] and **CMS** [PRL 131 (2023) 151803]
  - ➞ HI analyses only just approaching same sensitivity to tau g-2 as 20 year old limit set at **LEP** [EPJC 35, 159–170 (2004)]
  - ➞ However, **better constraining power on anomalous tau g-2 in pp collisions** due to higher mass reach





Effective field theory approach



$$\delta a_\tau \sim \frac{\mathrm{Re}[C_{\tau B}]}{\Lambda^2} (\bar{L}_\tau \sigma^{\mu\nu} \tau_R)\, H B_{\mu\nu}$$

Dipole effective field theory of new physics quantum fluctuations

Per-mille a_τ shifts ⇒ measurable percent cross-section shifts

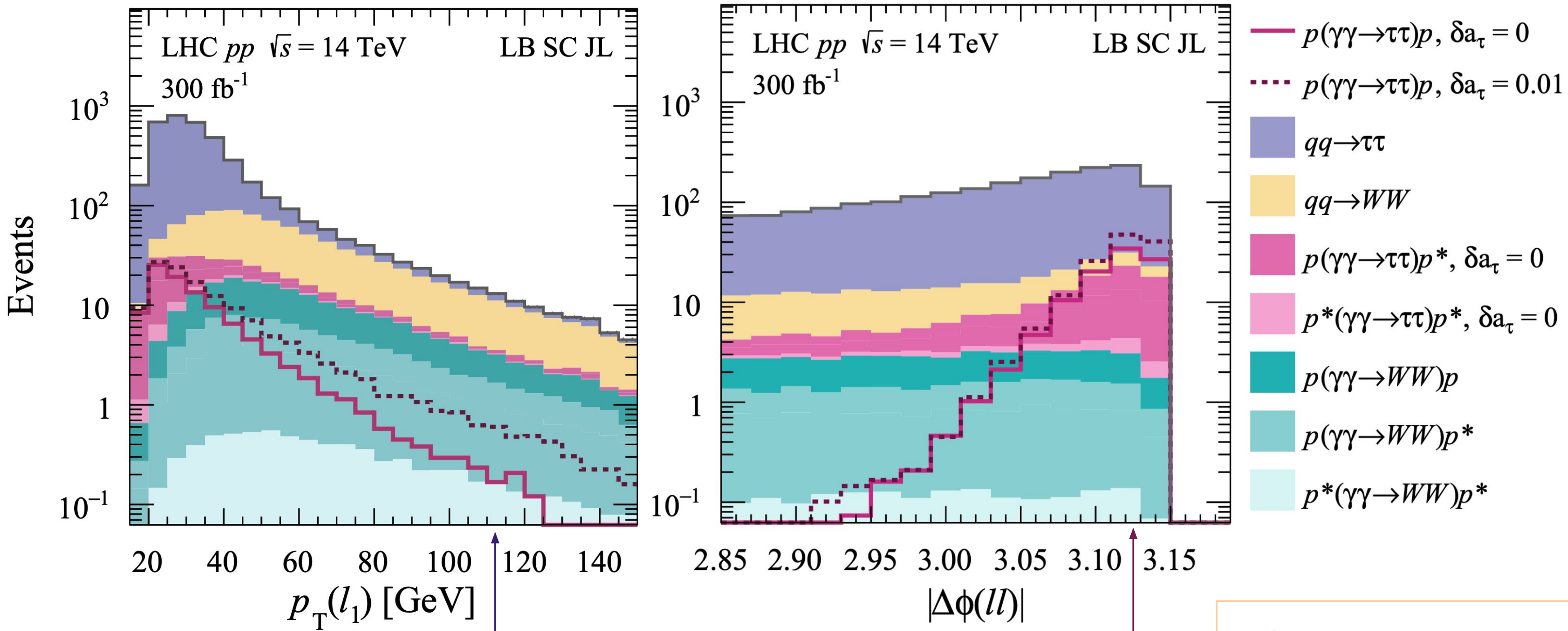
Must overcome 10^4× pileup and background for pp advantages vs PbPb

Analysis strategy

Fully leptonic tau decays: opposite-sign (OS) eμ

Trigger $p_T(e/\mu) > 18/15$ GeV | **$\Delta z_{min} > 1$ mm efficiency**: $\varepsilon_{quark} = 0.4\%$, signal $\varepsilon_{pileup} = 50\%$

ATLAS (SC Editor) PHYS-PUB-2021-026, Beresford, SC & Liu 2403.06336



$p_T(e/\mu)$ shape probes BSM a_τ

Bin ∈ [18/15, 40, ∞] GeV

Signal back-to-back

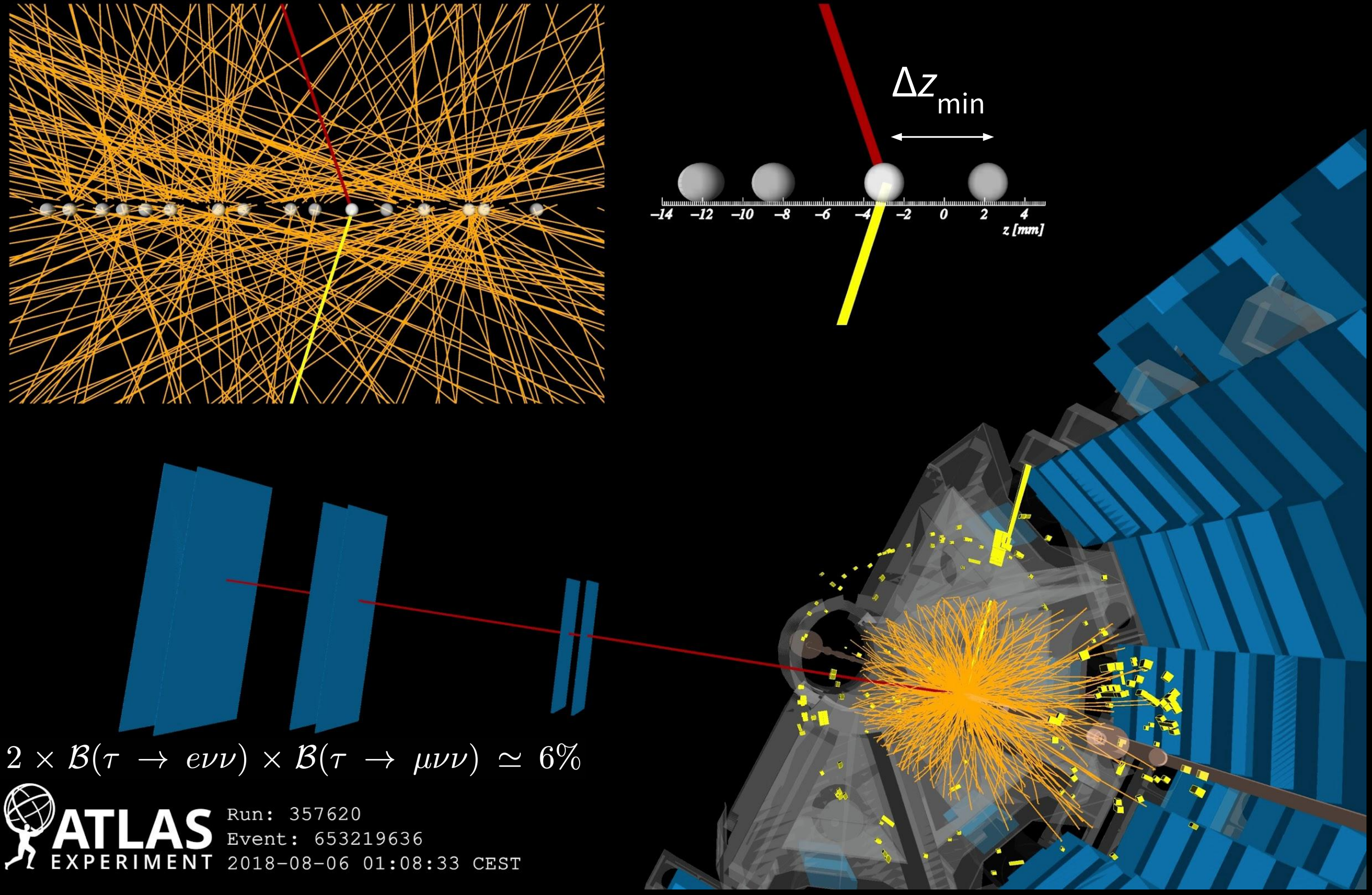
Require $|\Delta\phi(\ell\ell)| > 3.1$

SM event rate

S = 121, B = 443

Z = 5.4 (1% syst)

Unconventional: intact protons ⇒ isolated vertex



$$2 \times \mathcal{B}(\tau \to e\nu\nu) \times \mathcal{B}(\tau \to \mu\nu\nu) \simeq 6\%$$

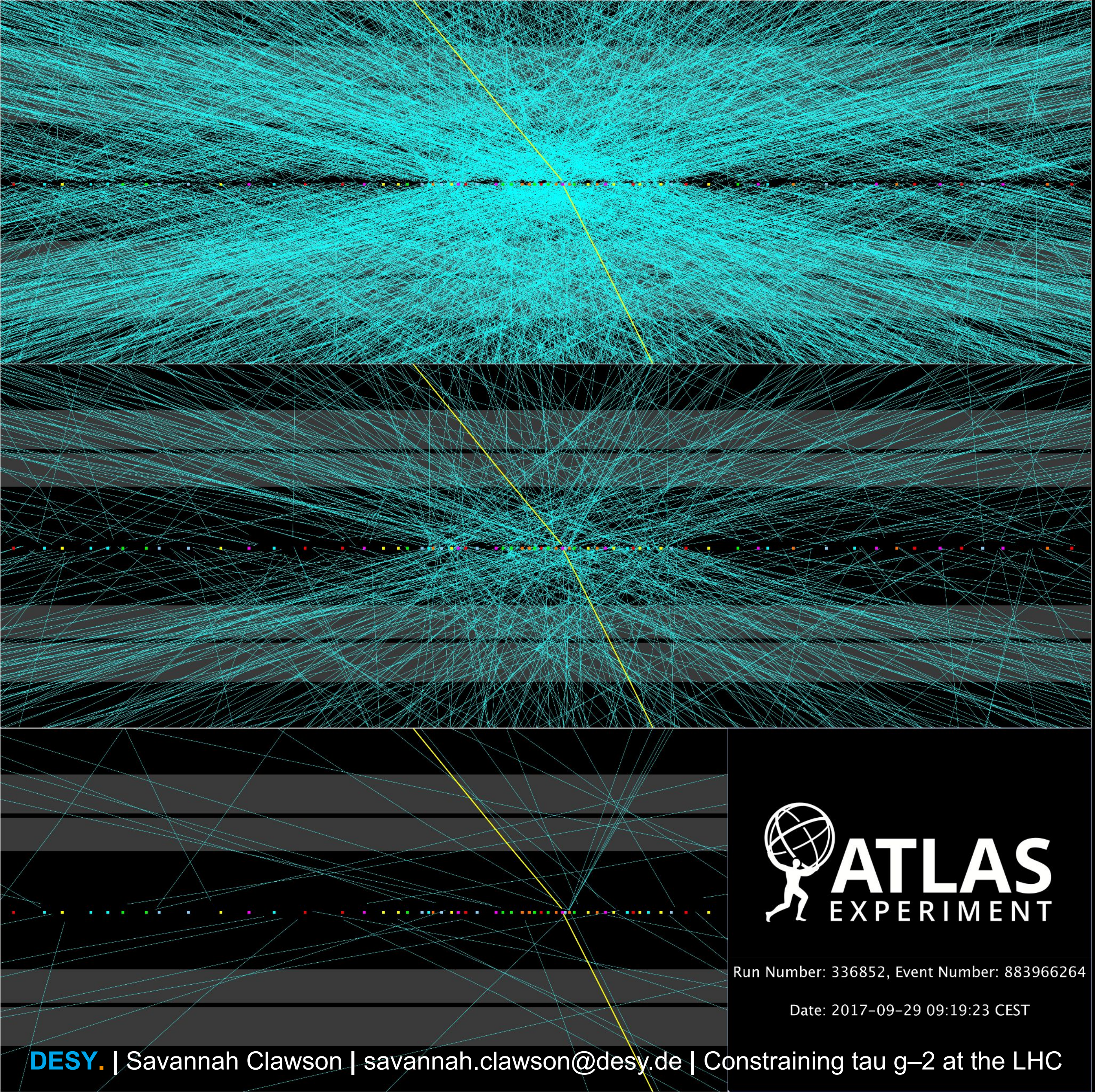
Apply γγ → WW → $e\nu\mu\nu$ breakthroughs to γγ → $\tau\tau$ → $e\nu\nu\mu\nu\nu$

ATLAS PLB 816 (2021) 136190 & SC thesis (ATLAS Thesis Award 2023)

The power of tracking thresholds

Analysis strategy relies on track veto

- ➔ Veto on additional activity surrounding ditau vertex
- ➔ Power of this veto depends on tracking capabilities!



Run Number: 336852, Event Number: 883966264

Date: 2017-09-29 09:19:23 CEST

track-p_T > 100 MeV

track-p_T > 1 GeV

track-p_T > 5 GeV

The power of tracking thresholds

- Increasing track-p_T thresholds mean
  - → We are less impacted by pileup
  - → But we lose ability to reject our backgrounds with underlying events
- We quantify these effects in our study via two efficiencies:

ε_{PU}

The **efficiency of the signal** passing the track veto requirement in the presence of **pileup** tracks

We want this efficiency to be as high as possible

ε_{UE}

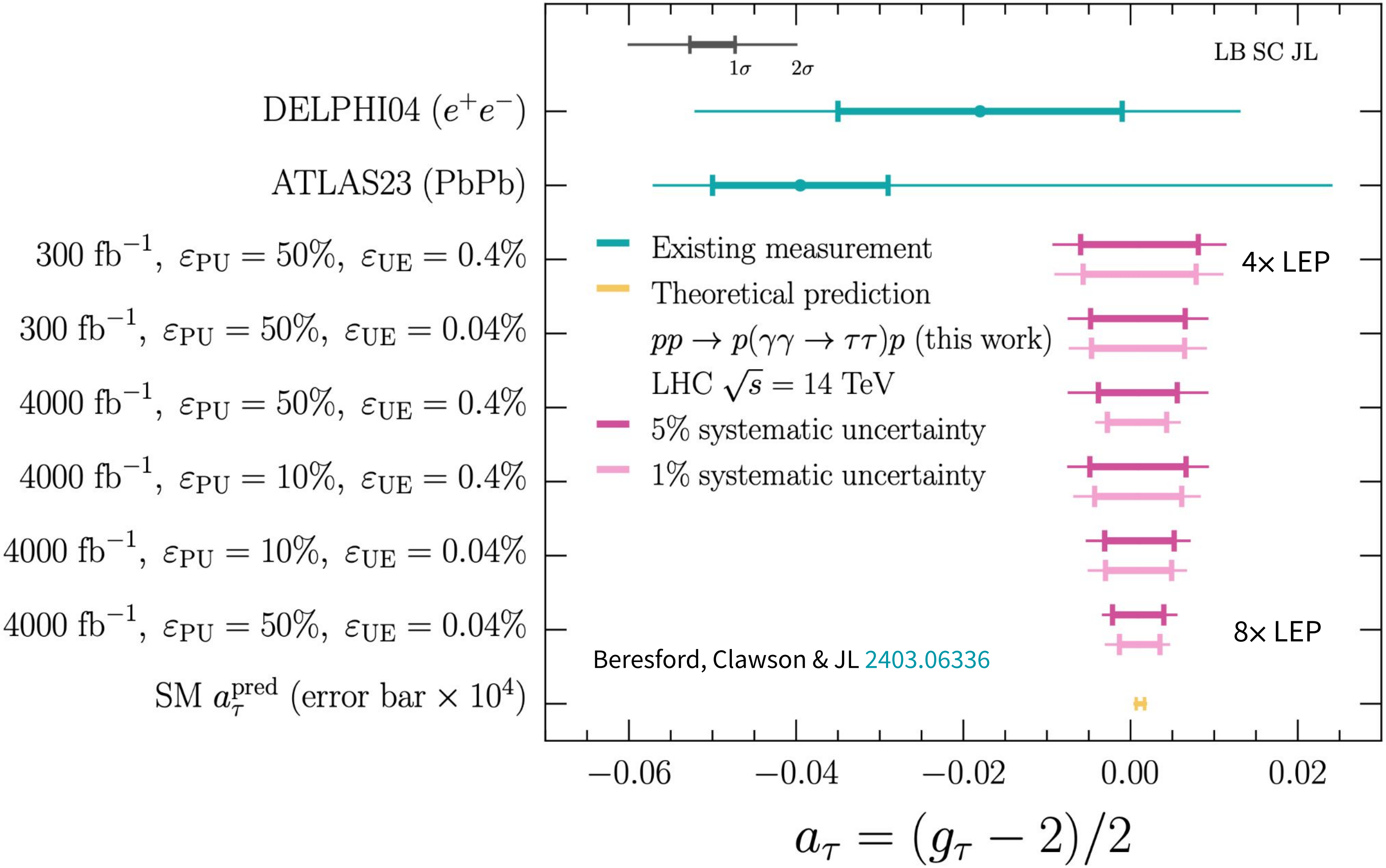
The **efficiency of the QCD backgrounds** passing the track veto requirement due to tracks in the **underlying event**

We want this efficiency to be as low as possible

For more details, see ATL-PHYS-PUB-2021-026 (SC Editor)

Projected sensitivity

Sensitivity: 4× to 8× improvement via eμ alone



4× LEP

8× LEP

Beresford, Clawson & JL 2403.06336

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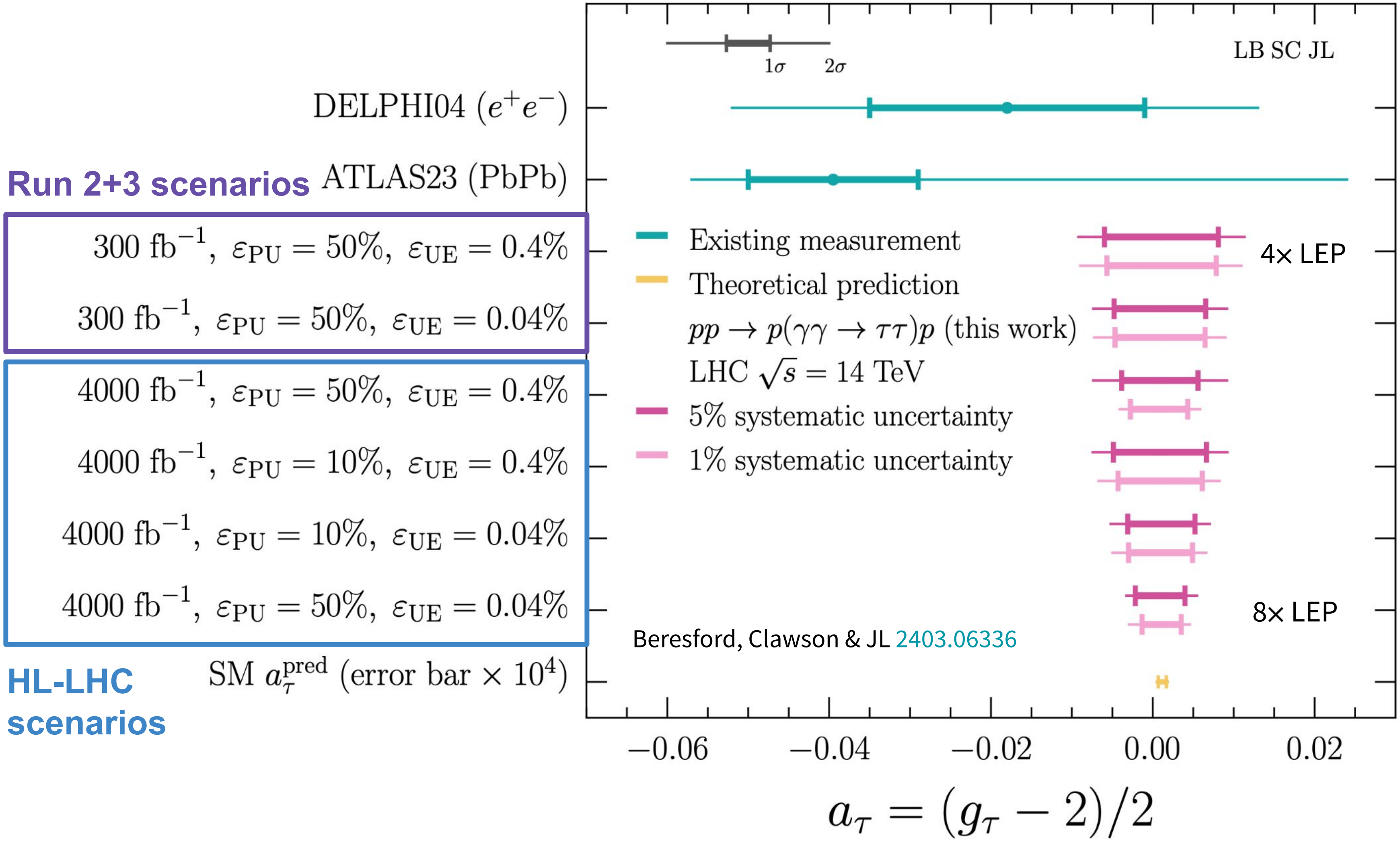


Run 2+3 scenarios

HL-LHC scenarios

4× LEP

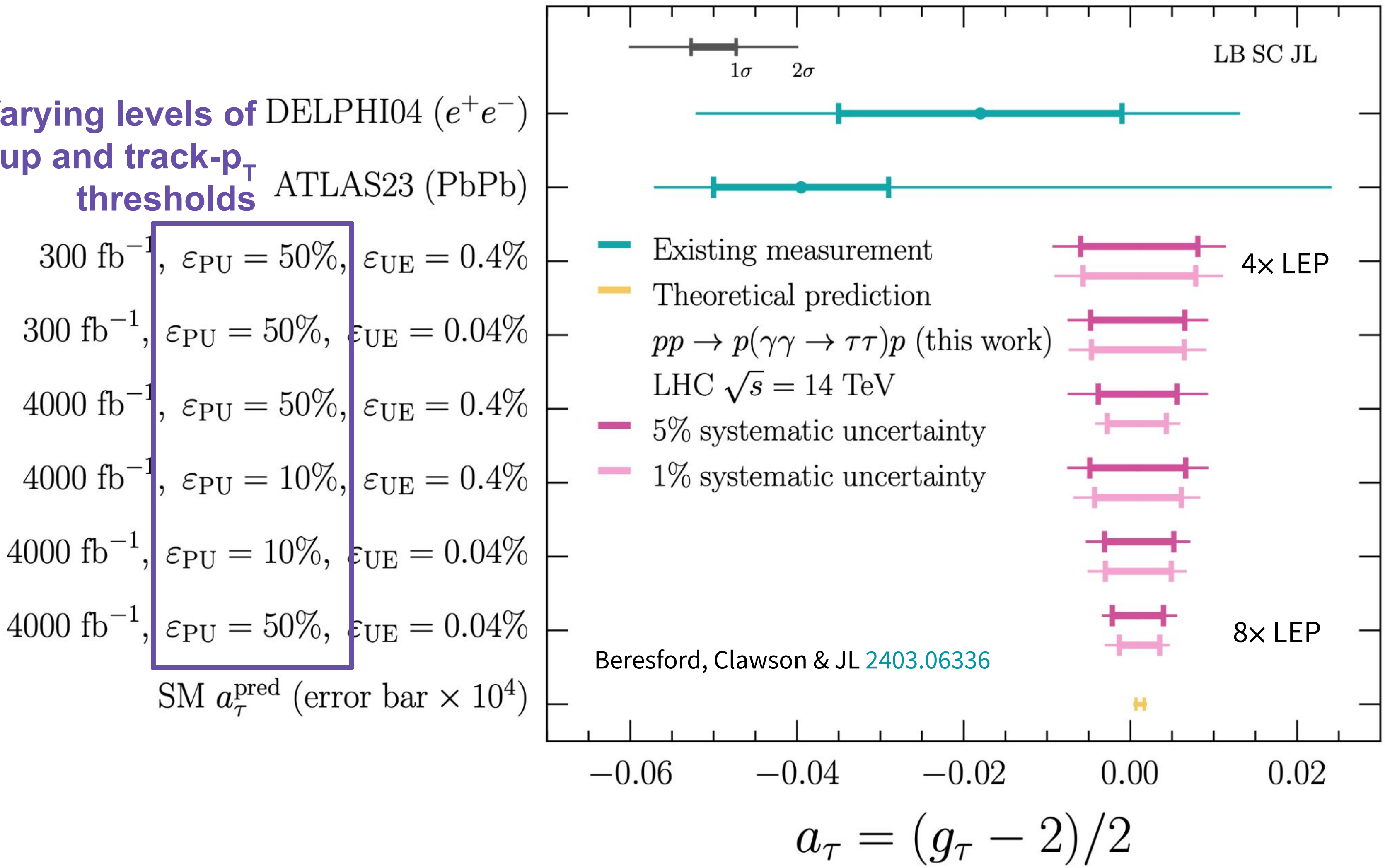
8× LEP

Beresford, Clawson & JL 2403.06336

Projected sensitivity

Sensitivity: 4× to 8× improvement via eμ alone

Varying levels of pileup and track-p_T thresholds



4× LEP

8× LEP

Beresford, Clawson & JL 2403.06336

Projected sensitivity

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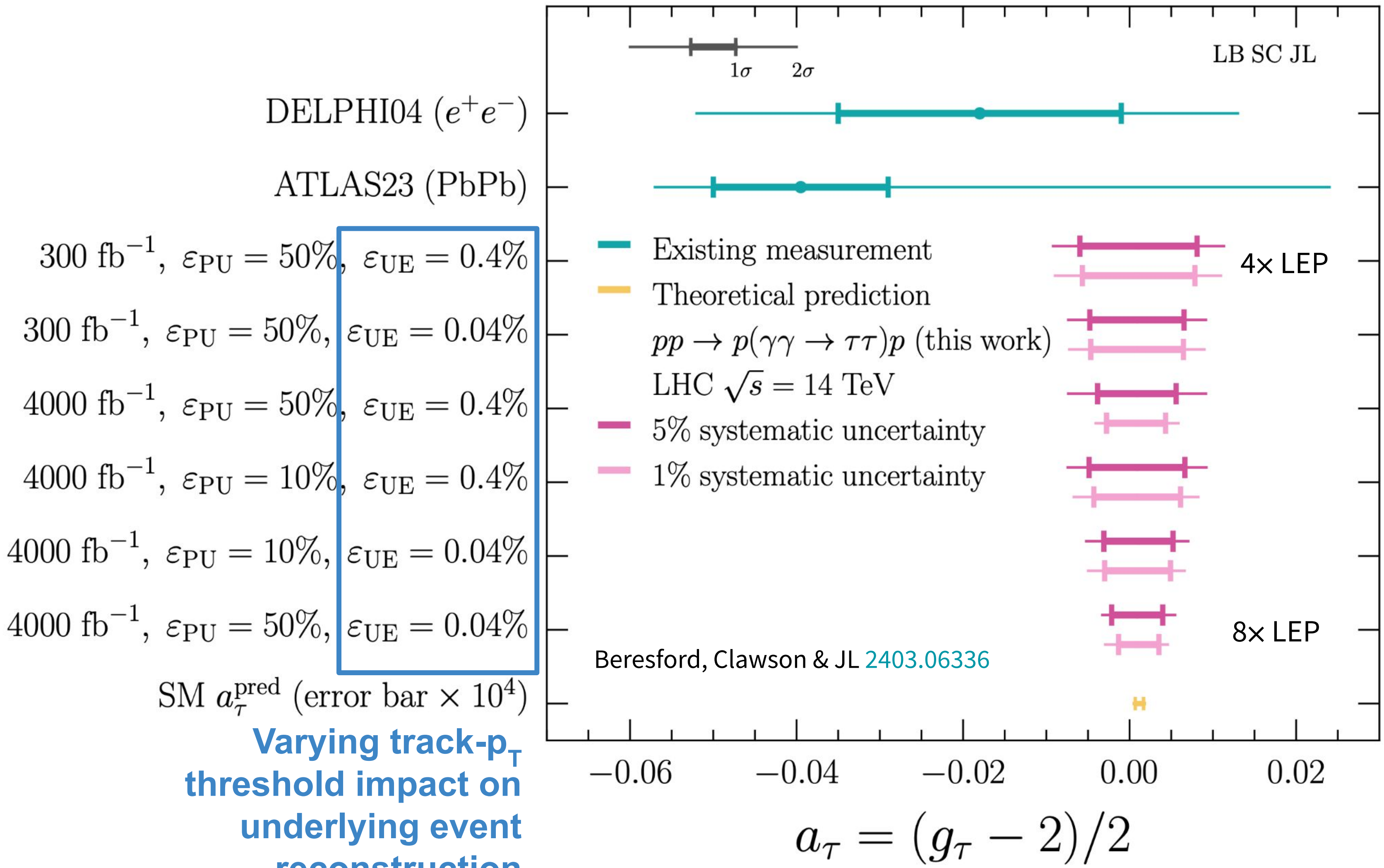


4× LEP

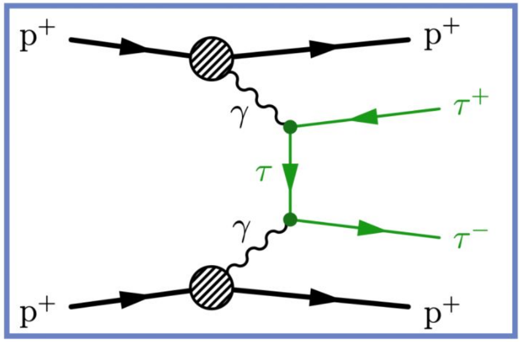
8× LEP

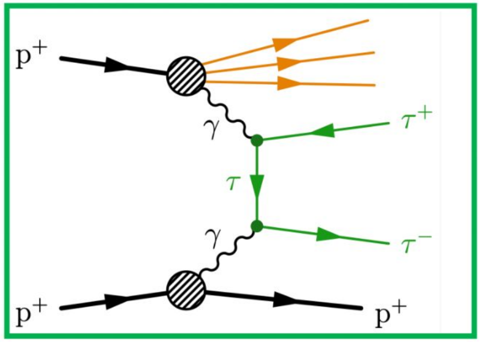
Beresford, Clawson & JL 2403.06336

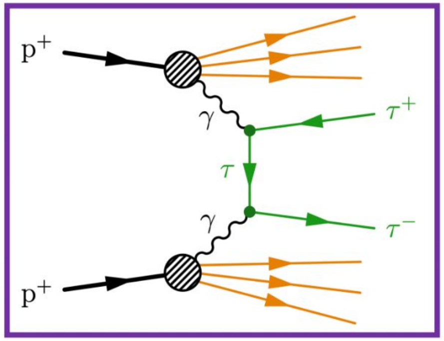
Varying track-p_T threshold impact on underlying event reconstruction

Experimental results

- Recent Run 2 CMS analysis [arXiv:2406.03975], improving 20 year old LEP limits on tau g-2 by a **factor of five!!**
  - → Observed (expected) significance of 5.3σ (6.5σ)
  - → Combined fully leptonic (OS) tau decays with semi-leptonic + fully hadronic
    - ○ 94% of all final states considered, compared to 6% in our study
  - → Combined elastic + dissociative production
    - ○ ~ 3x increase in yields







  - → Analysis uses many **methods from ATLAS $\gamma\gamma\to WW$ observation** [PLB 816 (2021) 136190] related to charged particle multiplicity and signal modelling

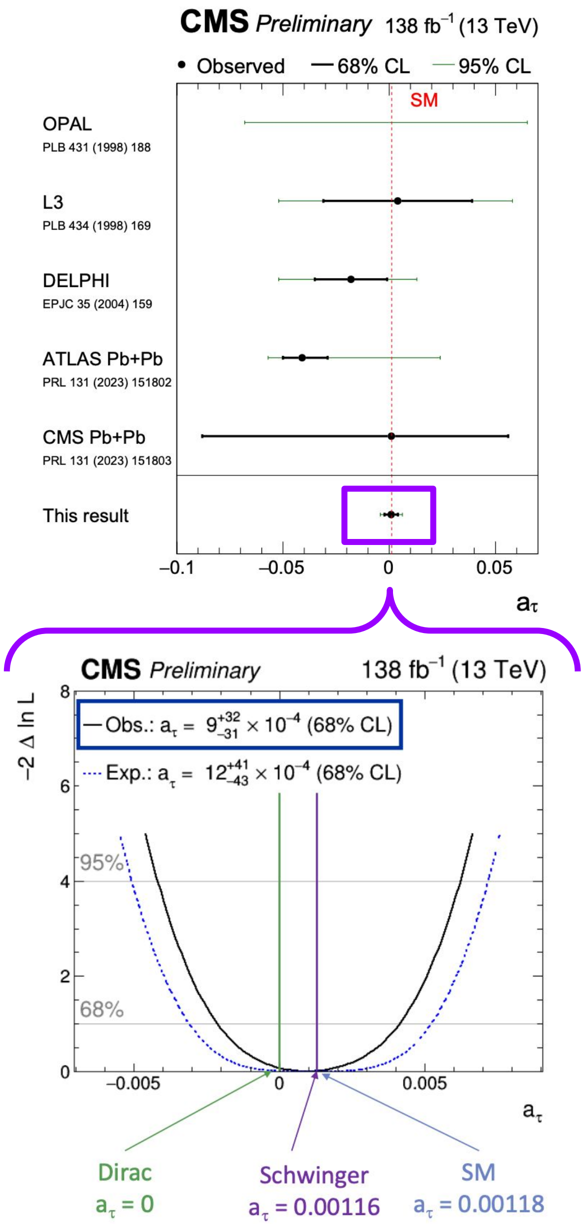
Experimental results

Recent Run 2 CMS analysis [arXiv:2406.03975], improving 20 year old LEP limits on tau g-2 by a **factor of five!!**

- Precision on tau g-2 still 3× Schwinger term
- Constraint on anomalous tau g-2 limited by statistical uncertainty

$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(\text{syst})^{+0.0028}_{-0.0027}\,(\text{stat})$$

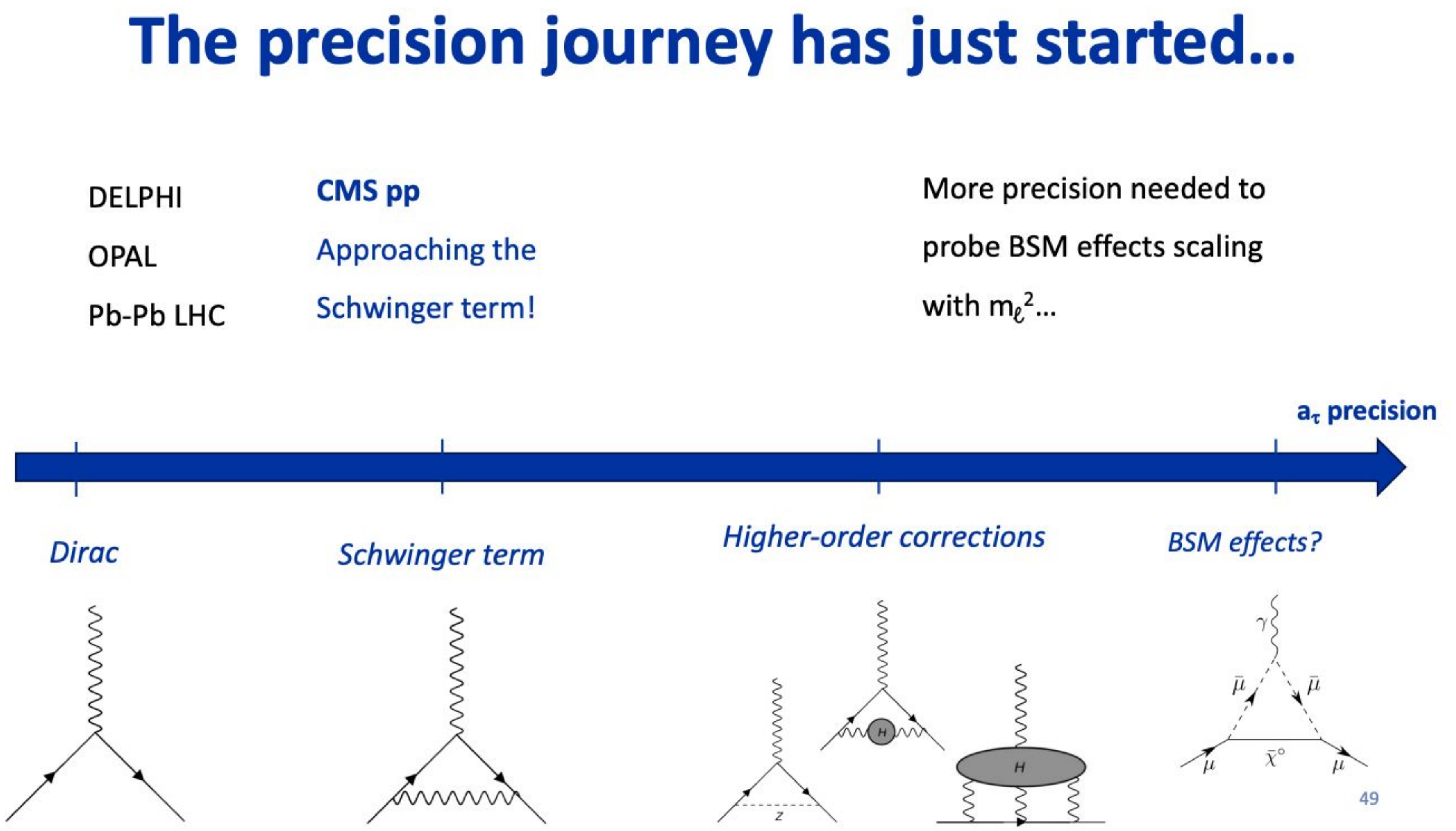
Corresponding to $-0.0042 < a_\tau < 0.0062$



C. Caillol, CERN - LPCC seminar, March 12th 2024

Pinning down tau g-2

C. Caillol, CERN - LPCC seminar, March 12th 2024



The precision journey has just started…

DELPHI
OPAL
Pb-Pb LHC

CMS pp
Approaching the
Schwinger term!

More precision needed to probe BSM effects scaling with m_ℓ^2…

a_τ precision

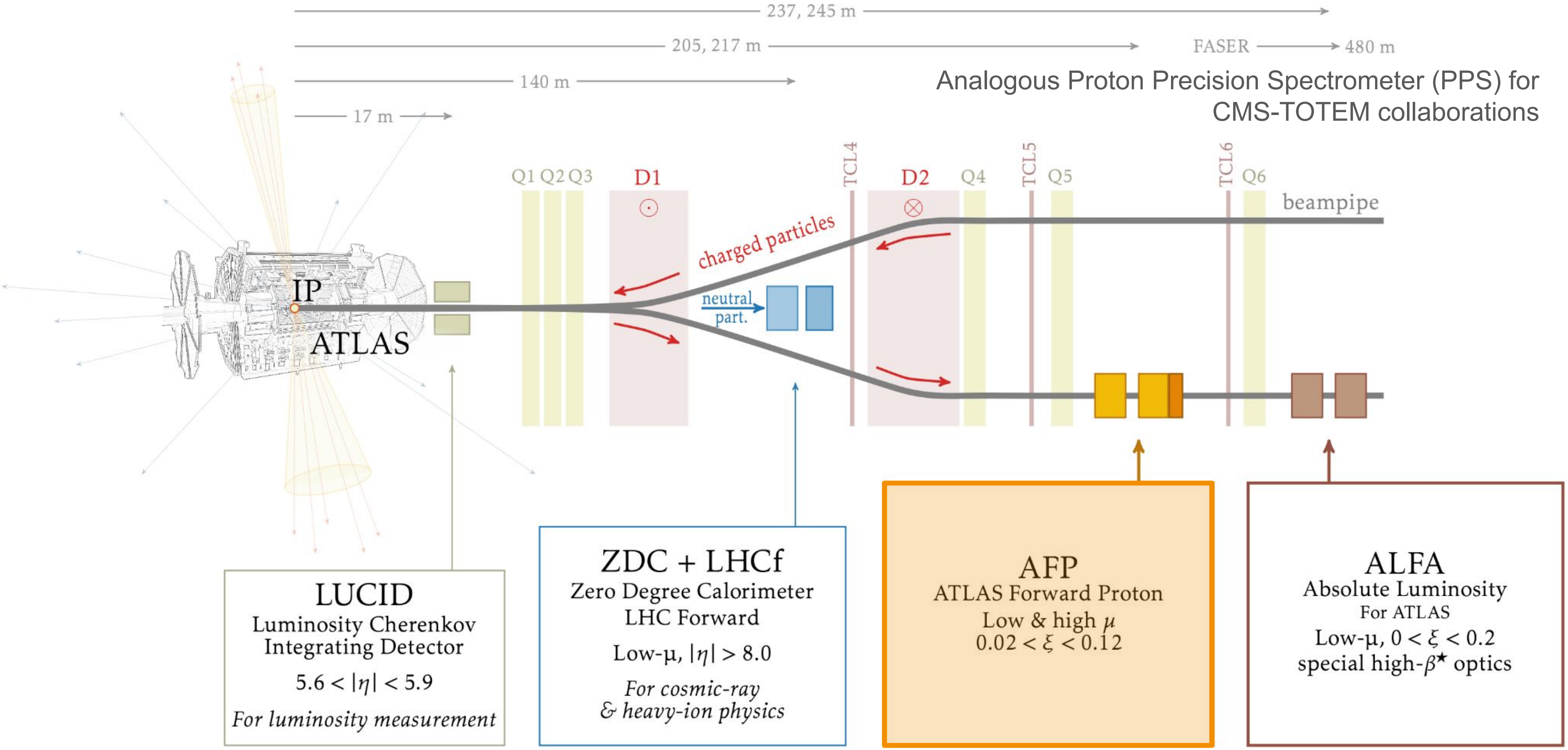
Dirac

Schwinger term

Higher-order corrections

BSM effects?

Possible extensions



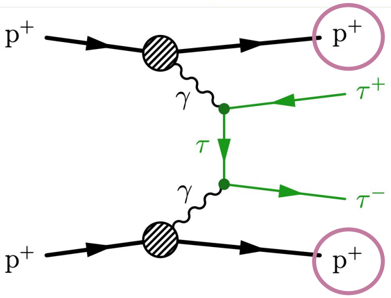
Analogous Proton Precision Spectrometer (PPS) for CMS-TOTEM collaborations

LUCID
Luminosity Cherenkov Integrating Detector
$5.6 < |\eta| < 5.9$
For luminosity measurement

ZDC + LHCf
Zero Degree Calorimeter
LHC Forward
Low-μ, $|\eta| > 8.0$
For cosmic-ray & heavy-ion physics

AFP
ATLAS Forward Proton
Low & high μ
$0.02 < \xi < 0.12$

ALFA
Absolute Luminosity
For ATLAS
Low-μ, $0 < \xi < 0.2$
special high-$\beta^\star$ optics



- Can further suppress backgrounds with forward proton tagging
- Limited acceptance of forward detectors
  - → Typical mass acceptance of $m_{\tau\tau} \gtrsim 350$ GeV

Summary

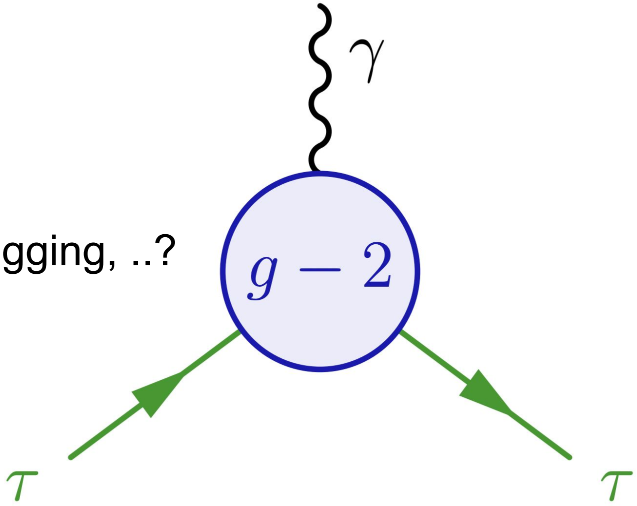
- Photon-fusion events in HI UPC and pp collisions can probe the anomalous magnetic moment of the tau

- Strategy to measure the $\gamma\gamma \rightarrow \tau\tau$ process in pp collisions proposed in arXiv:2403.06336

- Recent Run 2 result from CMS with 5✕ improved precision on tau g-2!!

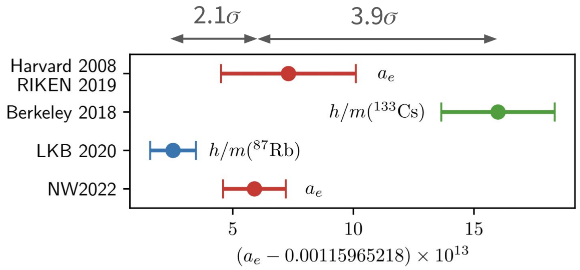
- Analyses are still trying to probe LO SM loop corrections
  - ➞ Far off precision needed to probe BSM effects
  - ➞ More data helps: a_τ constraint stats limited
  - ➞ But also room for new techniques and ideas
    - ○ low-p_T tracking, new triggers, forward proton tagging, ..?

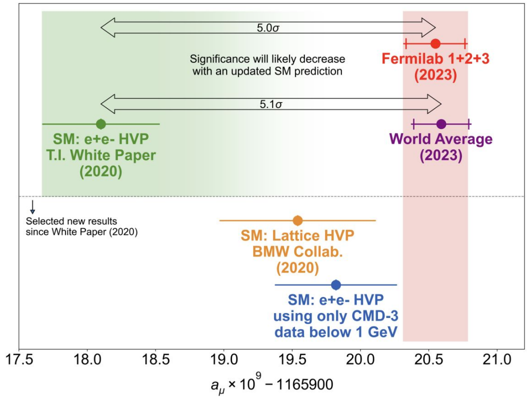
Like what you see? Join the Cross Collider Talk on Thursday morning

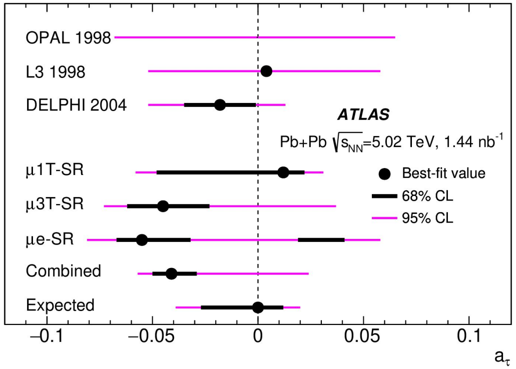


Backup

Motivation







Definition: $a = (g - 2)/2$

Electron: 13 decimal places

Fan et al PRL 2023, Morel et al Nature 2022, Parker et al Science 2018

a_e (exp) = 0.001 159 652 180 59(13)

a_e (pred) = 0.001 159 652 181 61(23)

Muon: 10 decimal places

FNAL Muon *g*–2 PRL 2023, Muon *g*–2 theory Phys Rept 2020, Lattice *g*–2 Nature 2021

a_μ (exp) = 0.001 165 920 55(24)

a_μ (pred) = 0.001 165 918 10(43)

Tau: 2 decimal places

ATLAS (JL Editor) PRL 2023, DELPHI EPJC 2004, Eidelman & Passera MPLA 2007

a_τ (exp) = –0.018(17) ← **PRESSING PROBLEM**

a_τ (pred) = 0.001 177 21(5)

Much room for physics beyond SM

Martin & Wells PRD 64 (2001) 035003

$$\delta a_\ell \sim m_\ell^2/M_{\mathrm{SUSY}}^2 \quad m_\tau^2/m_\mu^2 \sim 280$$

Tau decay modes

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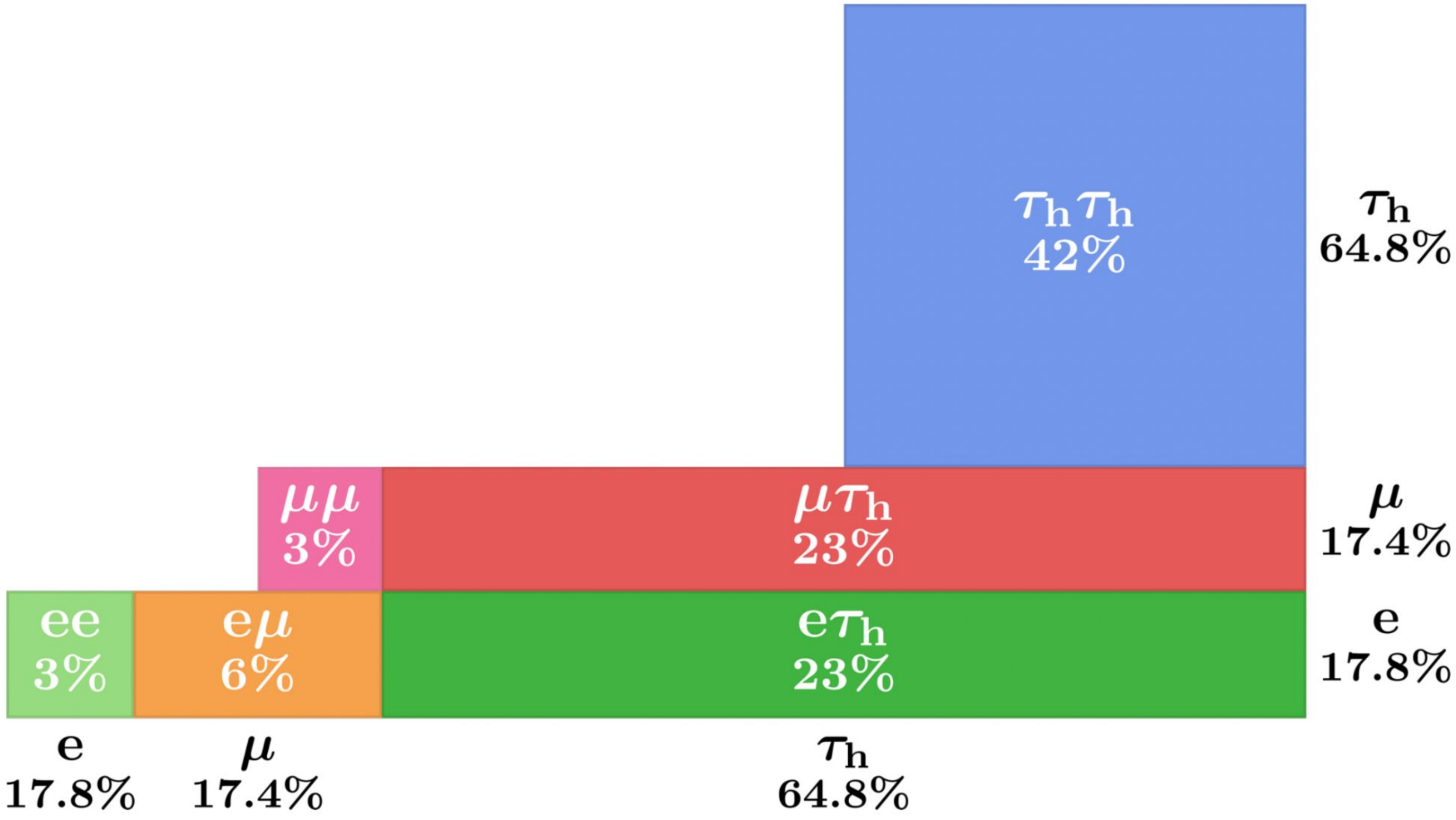
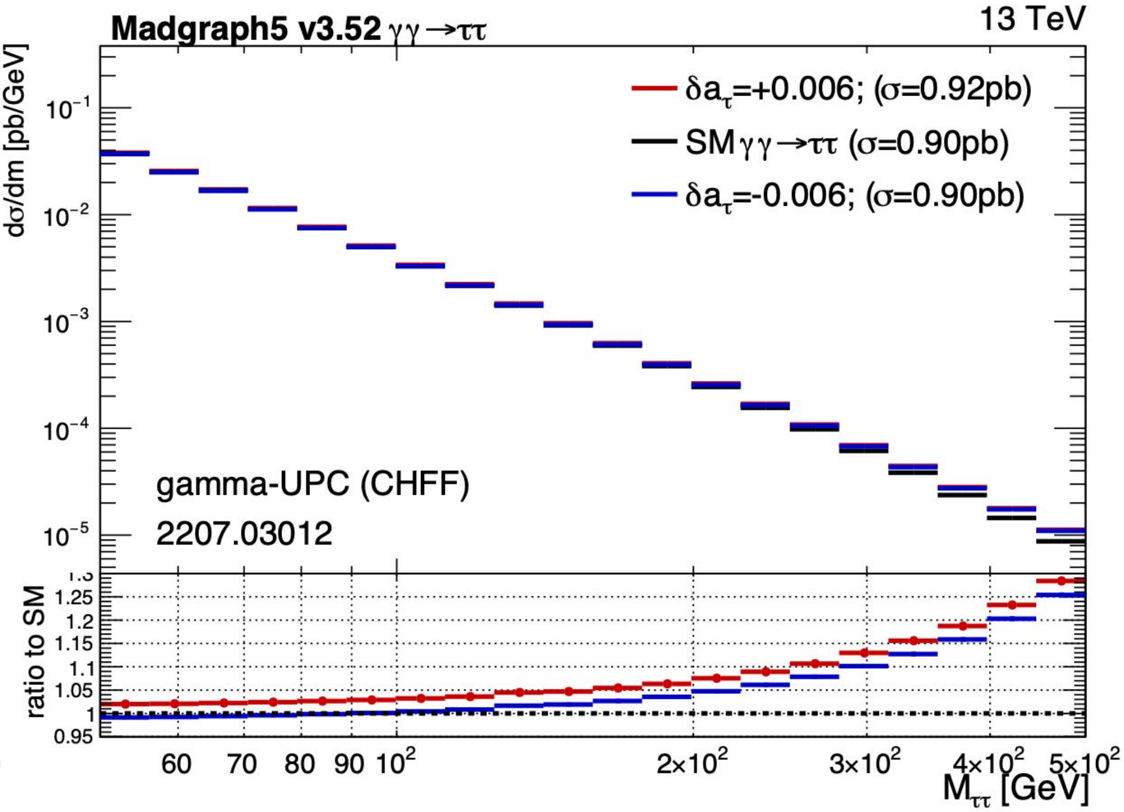


Power of pp vs PbPb

- BSM effects are more pronounced at high tau p_T and ditau mass
- Can access much higher mass scales in pp collisions = better constraining power on anomalous g-2

C. Caillol, CERN - LPCC seminar, March 12th 2024



HI analyses can access $m(\tau\tau) \lesssim 25$ GeV