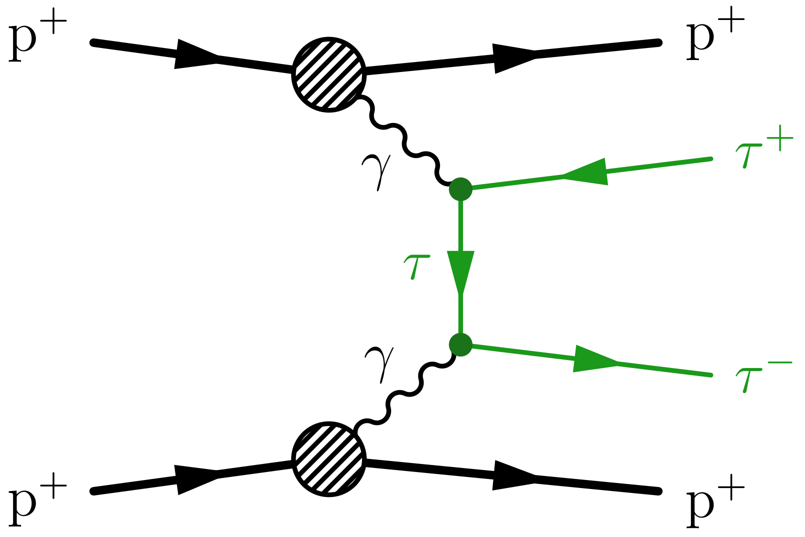


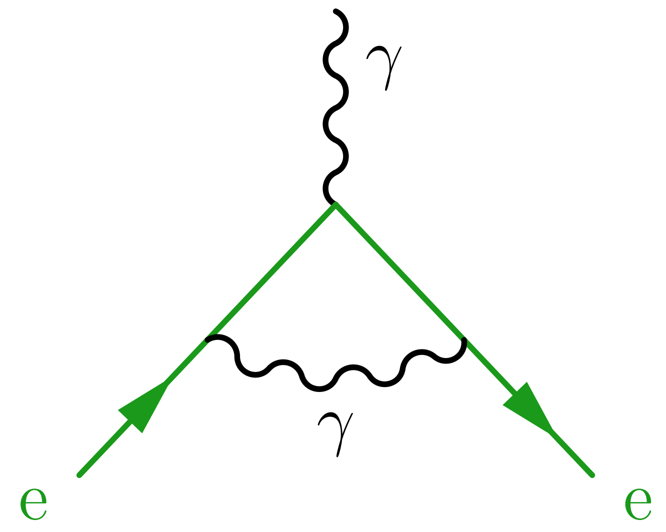
Measurement of the τ anomalous magnetic moment (g – 2) at CMS

Izaak Neutelings (CERN)
izaak.neutelings@cern.ch

13/05/2024, UZH Particle Physic Seminar

Overview

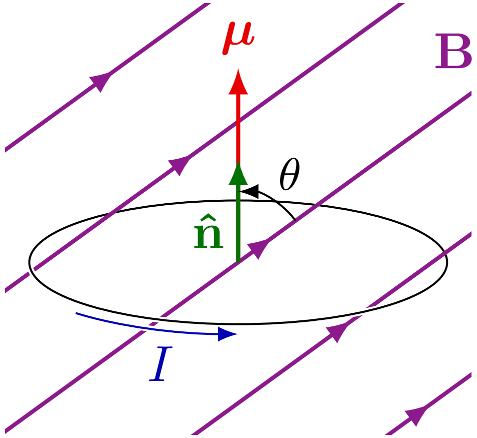
- Introduction
  - Electron & muon
  - Tau
- **$\gamma\gamma \to \tau\tau$ in pp**
- Corrections
- Results
  - Observation of $\gamma\gamma \to \tau\tau$
  - Constraints on a_τ & d_τ
- Summary



INTRODUCTION

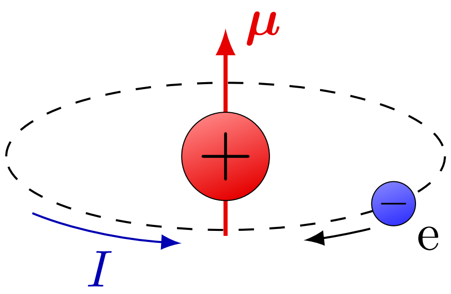
Electron & muon magnetic dipole moment

Quick recap : What is magnetic momentum ?



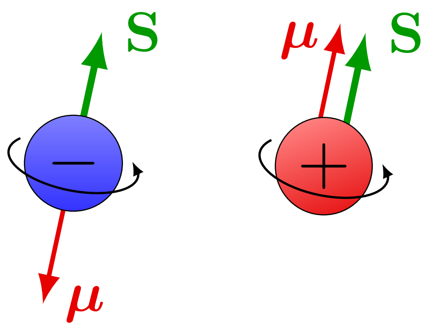
loop of **current *I*** in a **B field** experiences a torque

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}, \quad \text{with} \quad \boldsymbol{\mu} = I A \hat{\mathbf{n}}$$



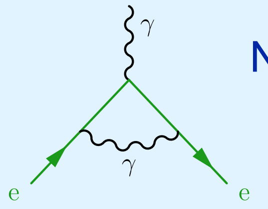
orbiting e^- is a current

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



spinning $e^\pm$ as well !

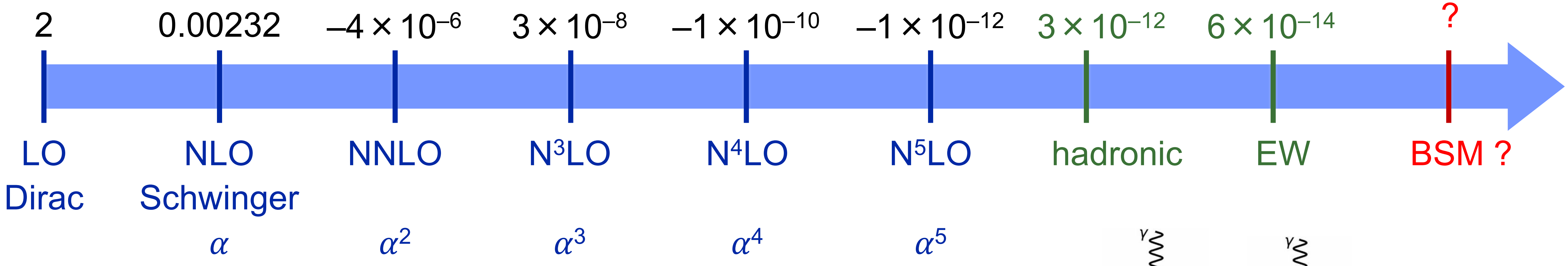
$$\boldsymbol{\mu}_e = g\frac{e}{2m}\mathbf{S} \longrightarrow \begin{cases} g = 1: \text{ classical} \\ g = 2: \text{ Dirac} \\ g \approx 2.002: \text{ QED} \end{cases}$$

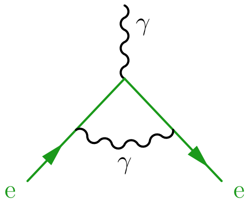


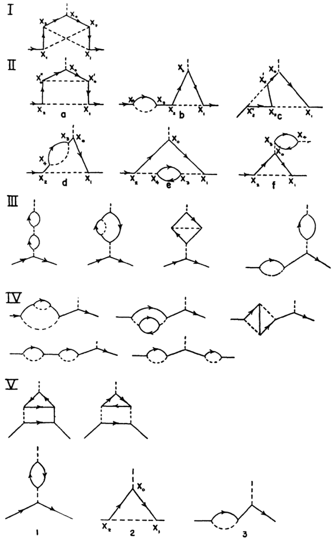
NLO quantum corrections (Schwinger)

Quantum corrections to $(g - 2)_e$

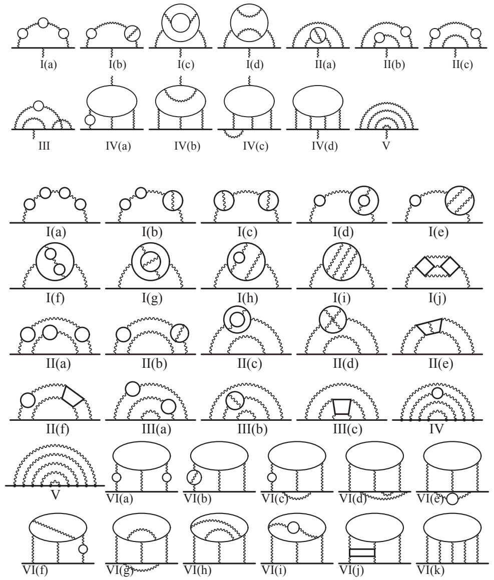
$g = 2.002\ 319\ 304\ 361$

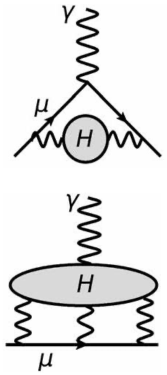


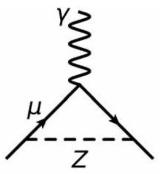




…







Schwinger (1948)

Karplus & Kroll (1950)
Sommerfeld, Petermann (1957)

Aoyama et al.

Quick history: Electron g – 2

- **1927**: Dirac equation predicts

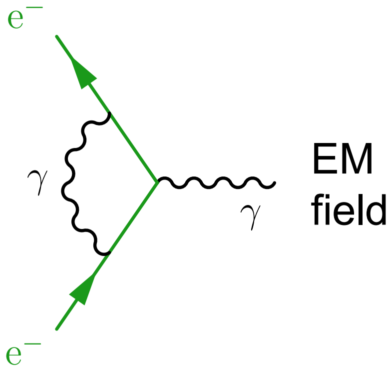
  $g = 2$ (LO)

- **1947–1951**: Kusch & Foley measure $g > 2$:

  $(g - 2)/2 = 0.001\ 19\ (5) \sim 4\%$

- **1948**: Schwinger computes

  $(g - 2)/2 \approx 0.001\ 161 \approx \alpha/2\pi$ (NLO)



- **1969**: Gräff et. al. with Penning trap

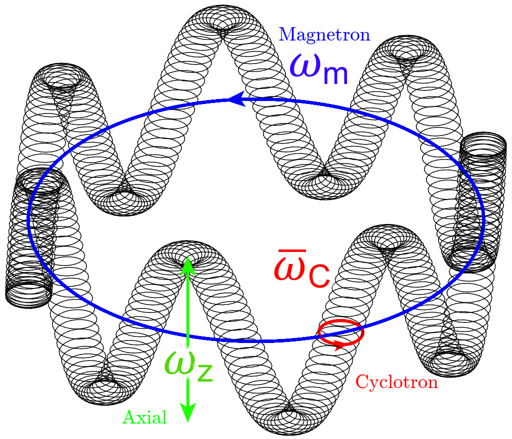
  $(g - 2)/2 = 0.001\ 159\ 66\ (30) \sim 300$ ppm

- **1987**: Dehmelt et. al.

  $(g - 2)/2 = 0.001\ 159\ 652\ 188\ 4\ (43) \sim 4$ ppt

- **2006–2022**: Gabrielse et. al.

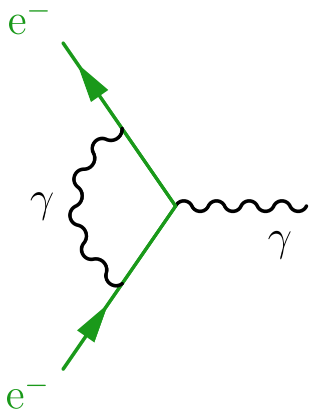
  $(g - 2)/2 = 0.001\ 159\ 652\ 180\ 59\ (31) \sim 0.13$ ppt



Status in 1972...

anomalous magnetic moment

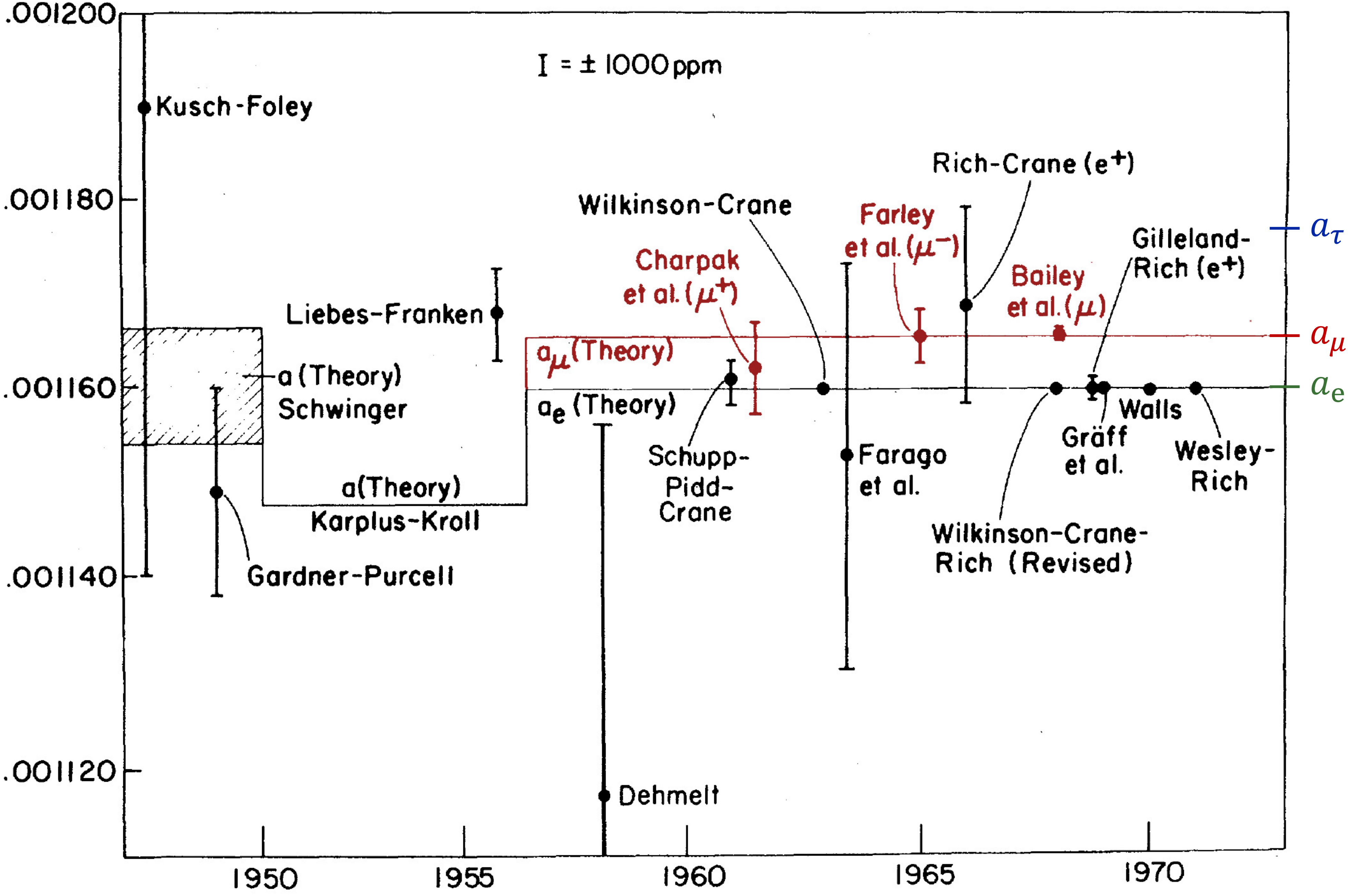
$$a = \frac{g-2}{2}$$



$g = 2 + 2a$

≈ 2.00232

"radiative corrections"



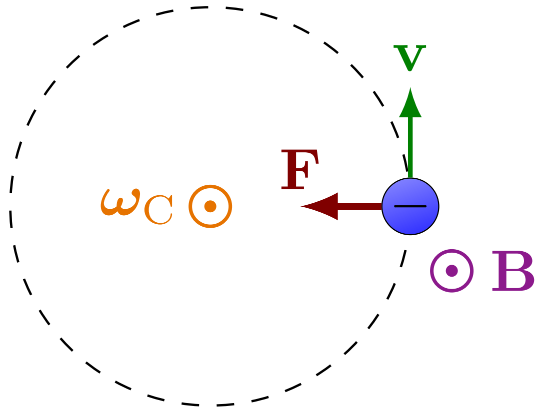
The Current Status of the Lepton g Factors, A. Rich & J.C. Wesley (1972)
https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.44.250

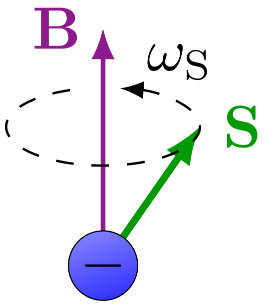
How to measure g – 2 ?

cyclotron oscillation $\omega_{\mathrm{C}} = \frac{e}{m} B$

anomalous frequency $\omega_{\mathrm{a}} = \omega_{\mathrm{S}} - \omega_{\mathrm{C}} \sim O(10^{-3})$

Larmor precession $\omega_{\mathrm{S}} = g \frac{e}{2m} B$



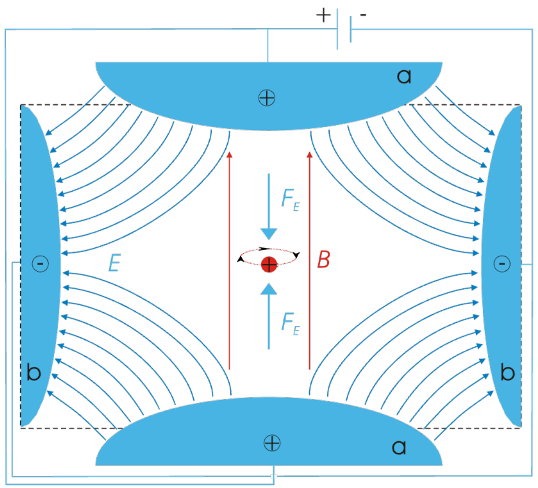


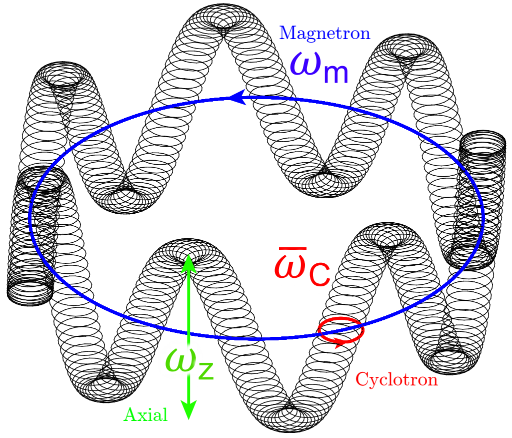
$$\Rightarrow \frac{g}{2} = \frac{\omega_{\mathrm{S}}}{\omega_{\mathrm{C}}} = 1 + \frac{\omega_{\mathrm{a}}}{\omega_{\mathrm{C}}} \text{ by measuring } \omega_{\mathrm{a}}/\omega_{\mathrm{C}}$$

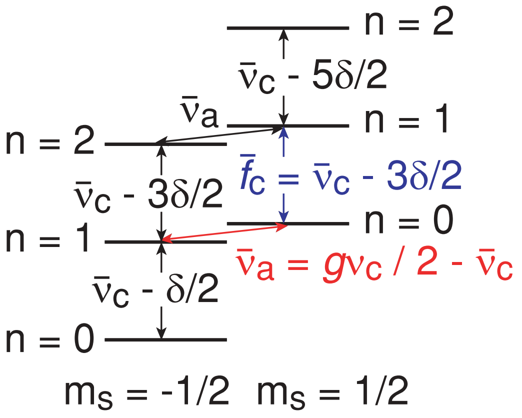
arXiv:2209.13084

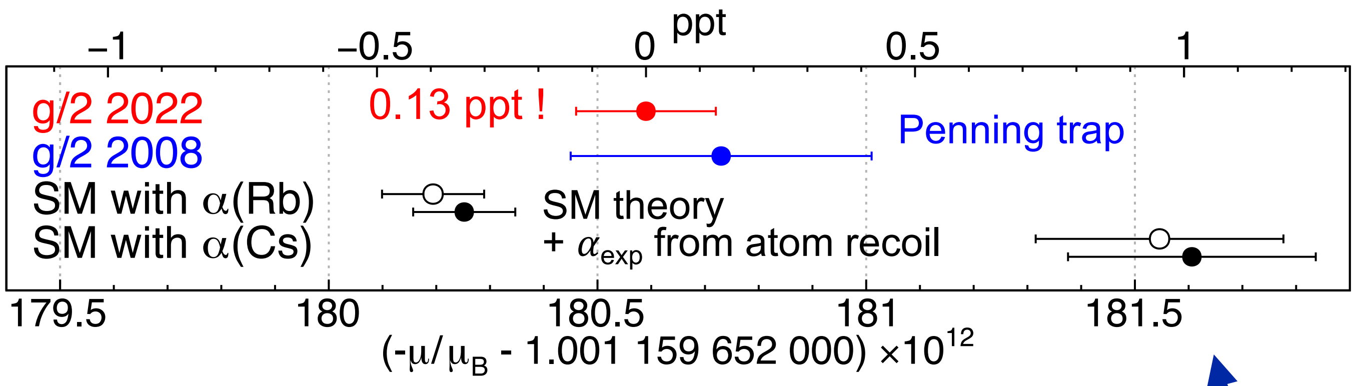
Measurement of electron g – 2 in Penning traps

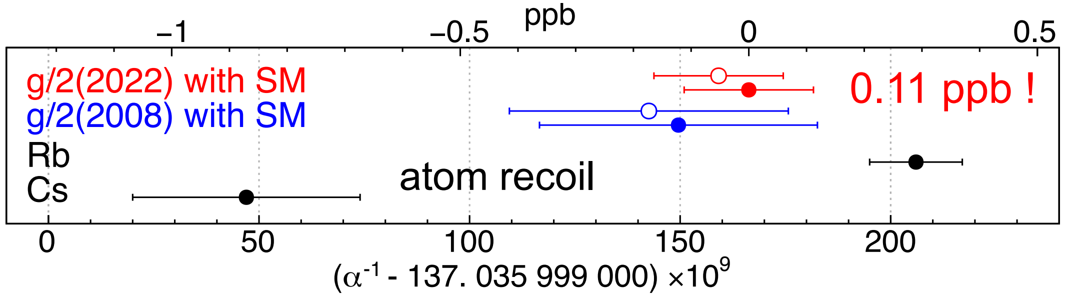
- oscillate electron in **nonuniform E field**, but **uniform B field**
- measure resonance frequencies





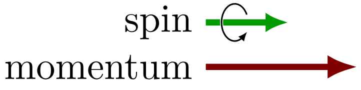




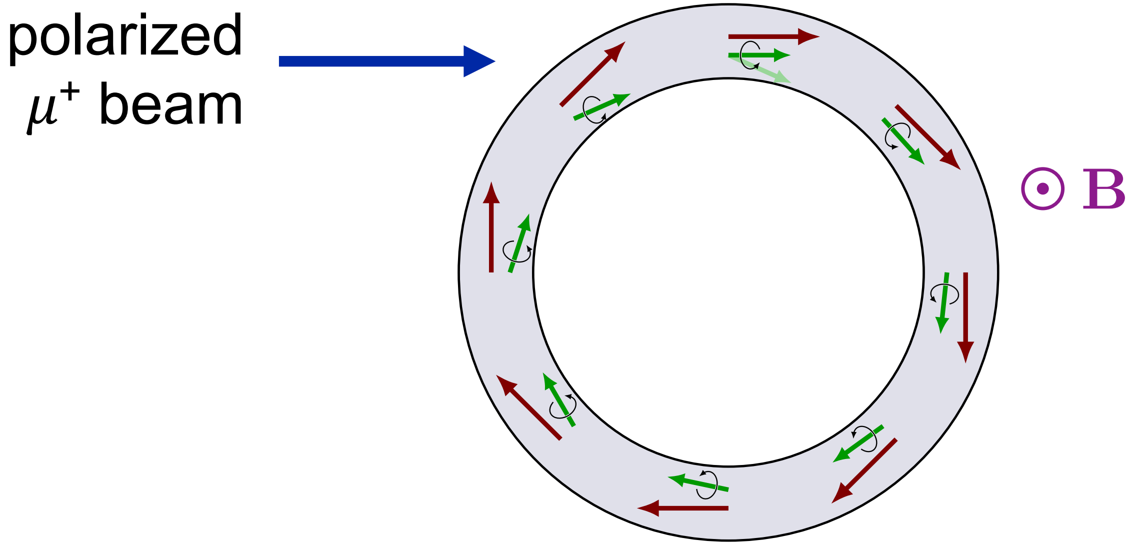


$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + \ldots + a_{\mu,\tau} + a_{\text{had}} + a_{\text{weak}}$$

Measurement of muon g – 2 in cyclotrons



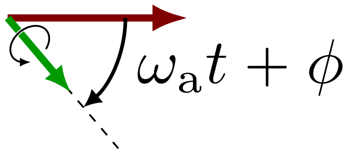
- muon lifetime ~ 2.2 μs
  ⇒ use cyclotrons



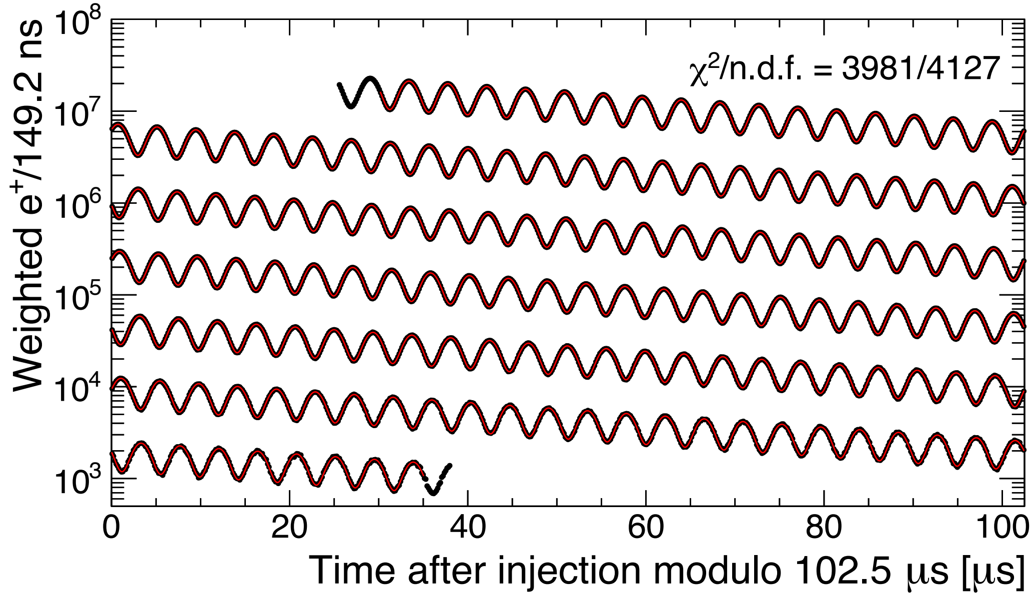
- spin precesses faster than momentum
  in cyclotron magnetic field:

Larmor precession ω_S > cyclotron oscillation ω_C

$$\omega_a = \omega_S - \omega_C = \frac{g-2}{2}\frac{e}{m_\mu}B \sim 230\,\text{kHz}$$



oscillations in number of e⁺ with E > 1.8 GeV



- measure oscillation in $\mu^+ \to e^+$ energy spectrum

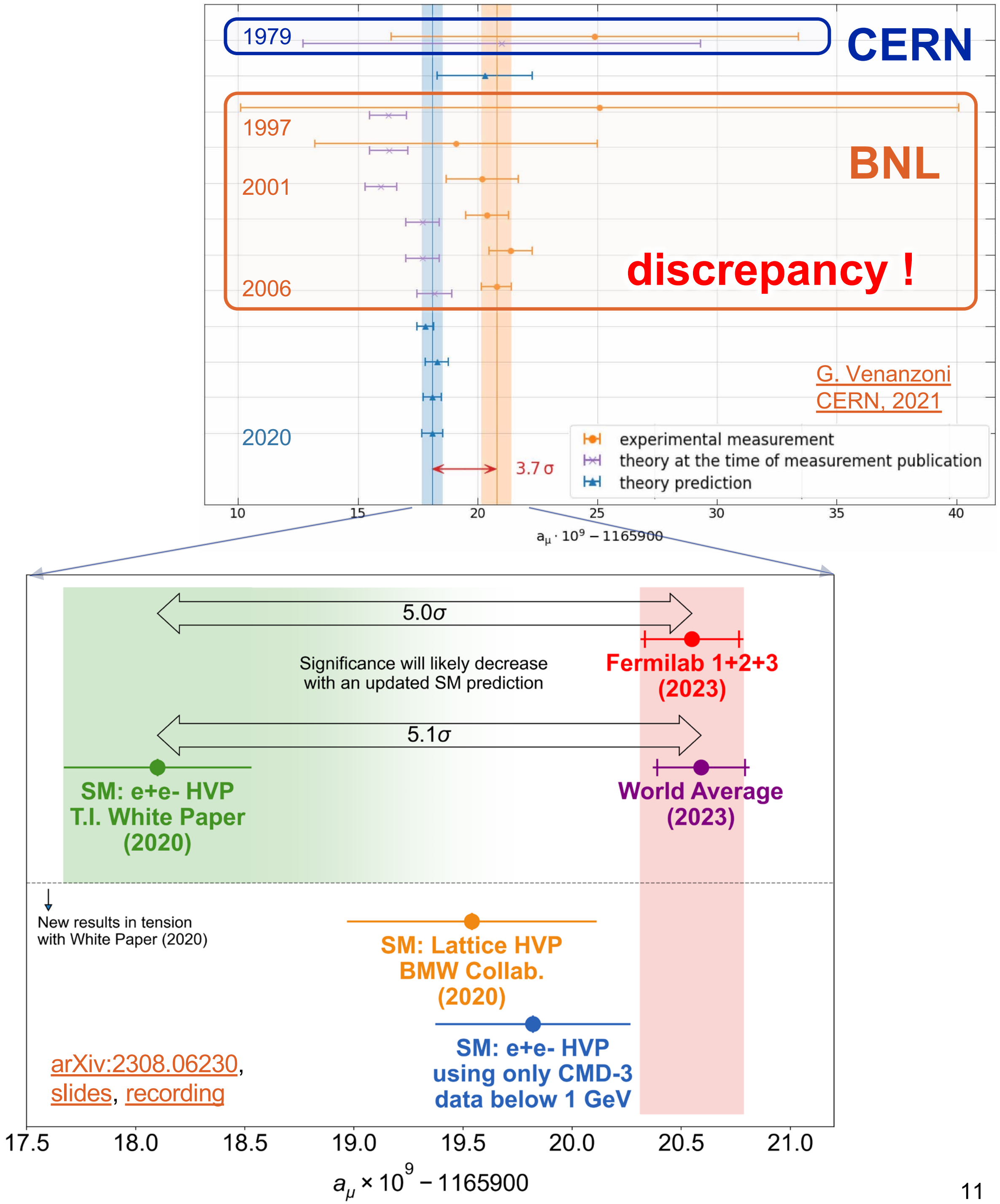
arXiv:2308.06230

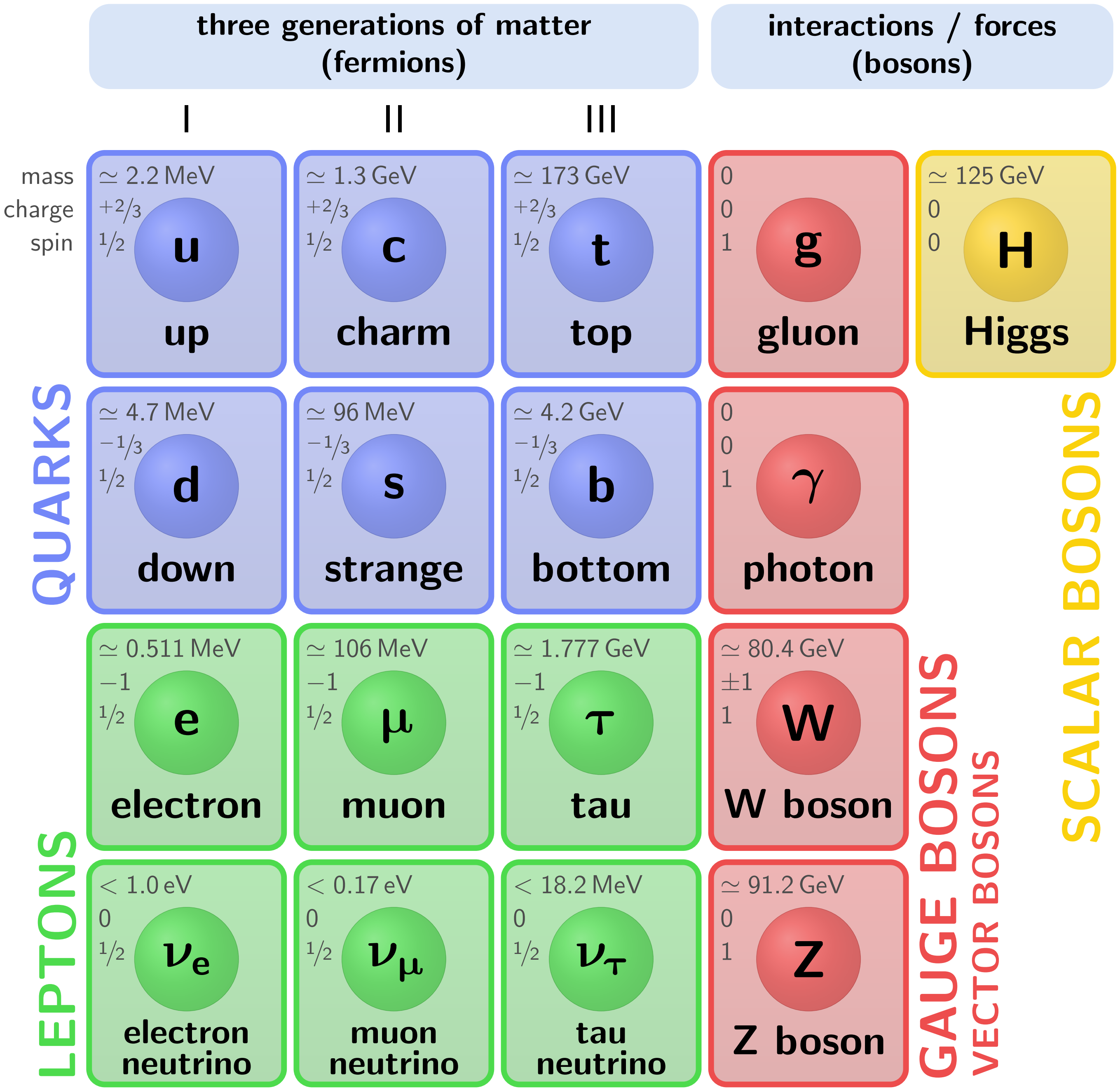
Quick history: Muon g – 2

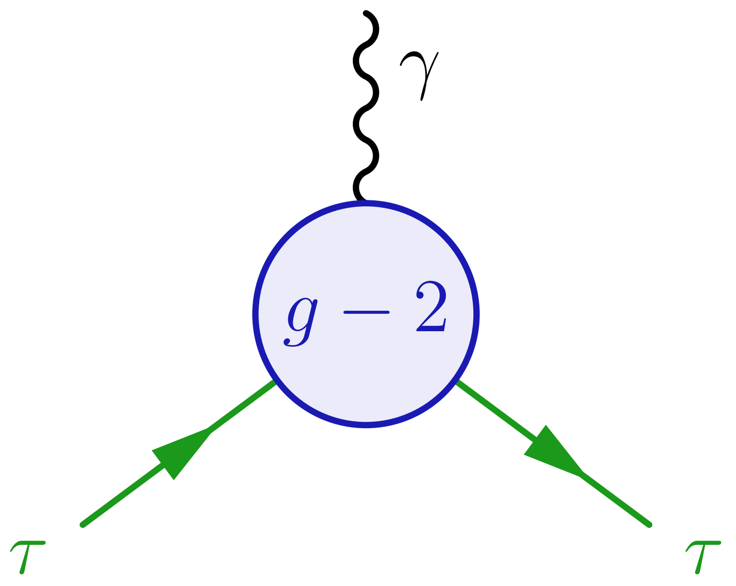
- **CERN**:
  - **1961**: ~0.2%
  - **1979**: ~7.30 ppm
- **BNL**:
  - **1999**: ~1.30 ppm
  - **2001**: ~0.54 ppm

  ⇒ discrepancy with **theory !**
- **FNAL**:
  - **2021**: ~0.46 ppm
  - **2023**: ~0.20 ppm

  ⇒ still tension




three generations of matter
(fermions)
interactions / forces
(bosons)
I
II
III
mass
charge
spin
≃ 2.2 MeV
+2/3
1/2
u
up
≃ 1.3 GeV
+2/3
1/2
c
charm
≃ 173 GeV
+2/3
1/2
t
top
0
0
1
g
gluon
≃ 125 GeV
0
0
H
Higgs
QUARKS
≃ 4.7 MeV
−1/3
1/2
d
down
≃ 96 MeV
−1/3
1/2
s
strange
≃ 4.2 GeV
−1/3
1/2
b
bottom
0
0
1
γ
photon
SCALAR BOSONS
≃ 0.511 MeV
−1
1/2
e
electron
≃ 106 MeV
−1
1/2
μ
muon
≃ 1.777 GeV
−1
1/2
τ
tau
≃ 80.4 GeV
±1
1
W
W boson
LEPTONS
< 1.0 eV
0
1/2
νe
electron neutrino
< 0.17 eV
0
1/2
νμ
muon neutrino
< 18.2 MeV
0
1/2
ντ
tau neutrino
≃ 91.2 GeV
0
1
Z
Z boson
GAUGE BOSONS
VECTOR BOSONS



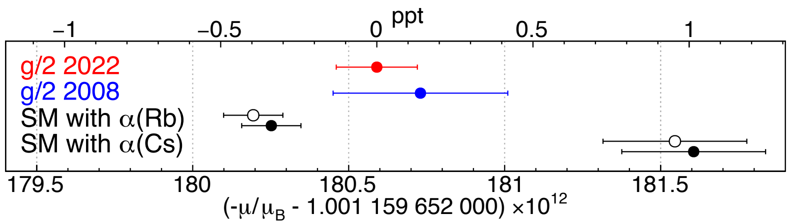
INTRODUCTION

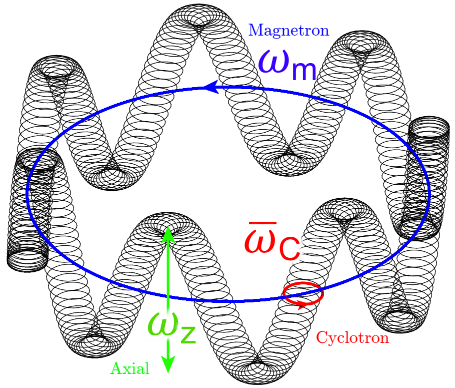
Tau magnetic moment

Measurement of lepton g – 2

electron

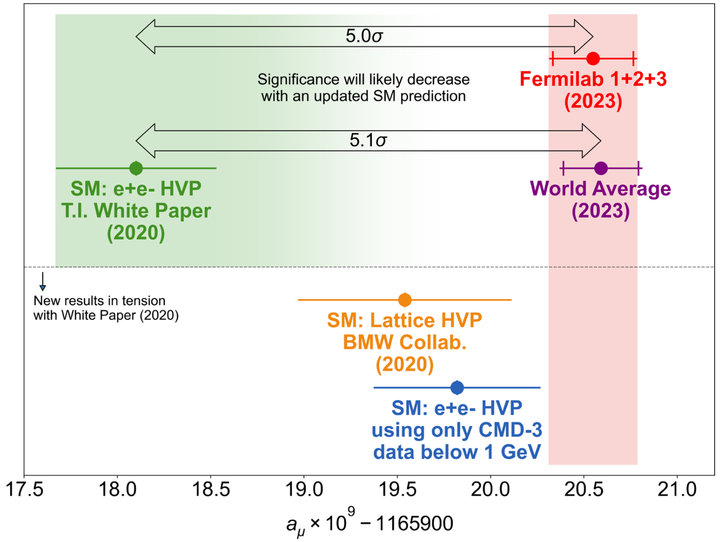
- stable
- Penning traps
- 0.13 ppt !
- agrees with SM 1 ppt





muon

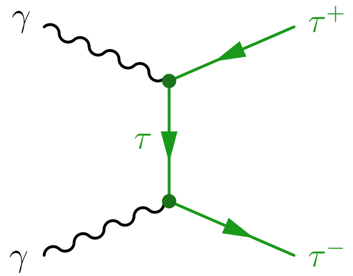
- lifetime ~2.2 × 10^{-6} s
- cyclotrons
- 0.20 ppm !
- tension with theory ?



tau

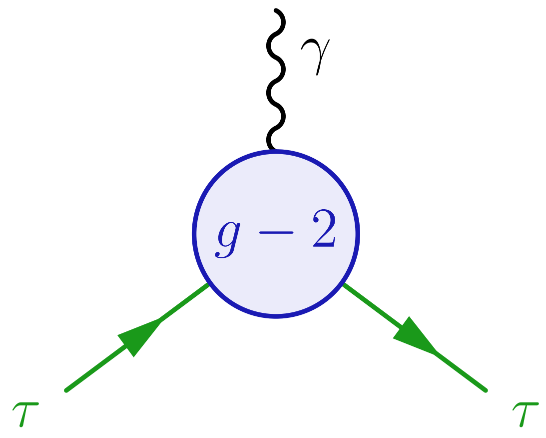
- lifetime ~2.9 × 10^{-13} s
- $\gamma\gamma \to \tau\tau$ process in colliders !
- limit by LEP ~20 times Schwinger term
- many **BSMs** predict enhancement e.g. O$(m_\tau^2/m_\mu^2) \approx 280$

⇒ probe for NP ?

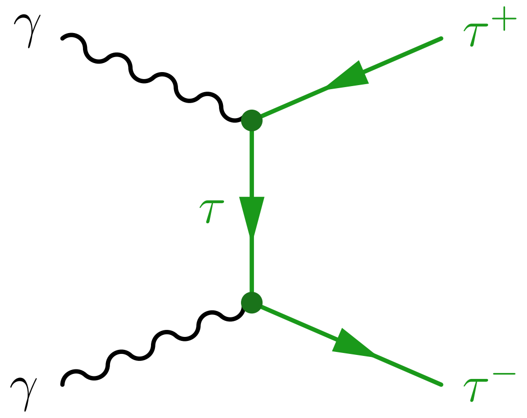


How to measure the tau g – 2

- a_τ & electric dipole moment d_τ can be probed from **$\gamma\tau\tau$ vertex**



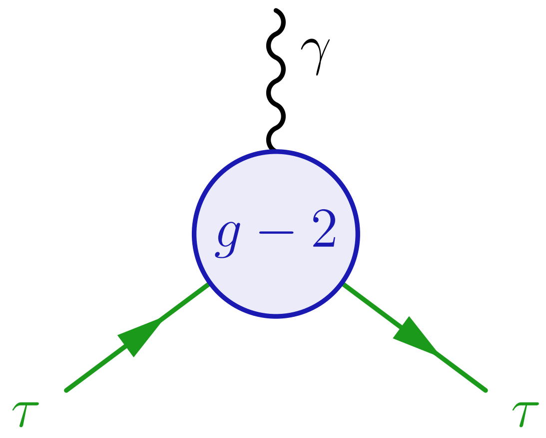
- $\gamma\gamma \to \tau\tau$ process contains 2 $\gamma\tau\tau$ vertices



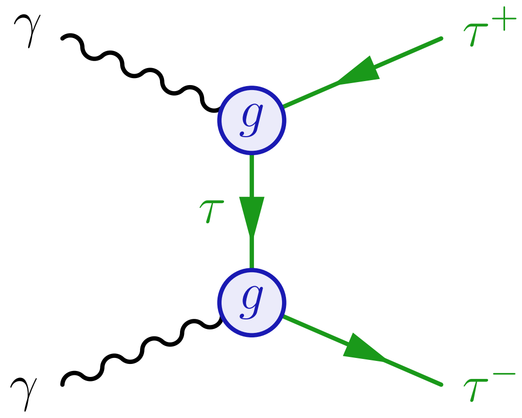
- contraints on electromagnetic moments a_τ & d_τ from *form factors* or *SMEFT*
- in the SM: $d_\tau \sim 10^{-37}$ ecm via CP violation in CKM, but could be much larger in BSMs

How to measure the tau g – 2

- a_τ & electric dipole moment d_τ can be probed from **$\gamma\tau\tau$ vertex**



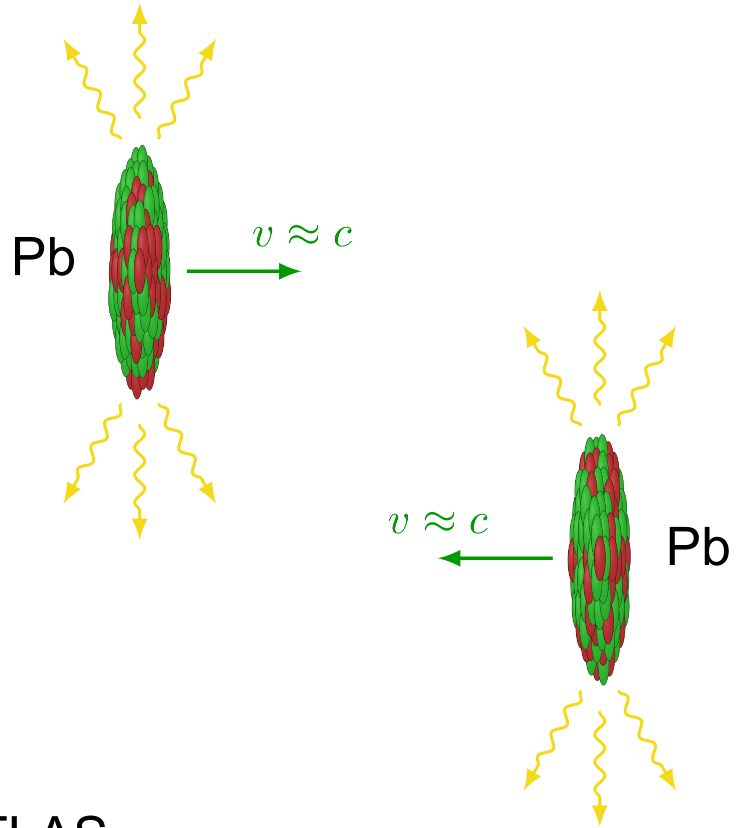
- $\gamma\gamma \to \tau\tau$ process contains 2 $\gamma\tau\tau$ vertices



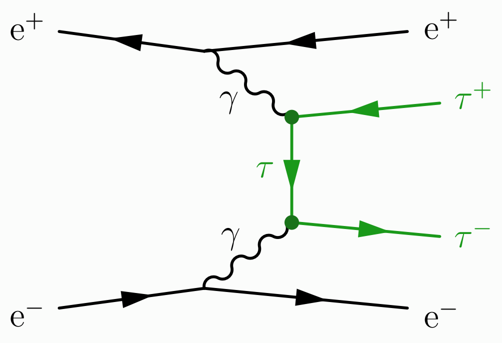
- contraints on electromagnetic moments a_τ & d_τ from *form factors* or *SMEFT*
- in the SM: $d_\tau \sim 10^{-37}$ ecm via CP violation in CKM, but could be much larger in BSMs

Photon-induced processes

- collide charged particles at high energies
  ⇒ intense electromagnetic fields
  ⇒ **photon-photon collisions**
- cross section $\sigma \propto Z^4$
  ⇒ PbPb collisions enhanced w.r.t. pp

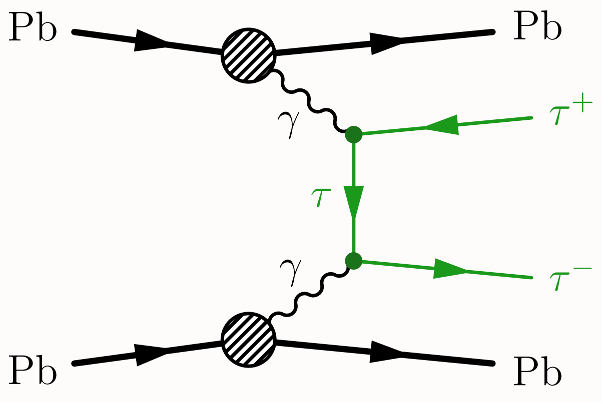


LEP: DELPHI, L3, ...

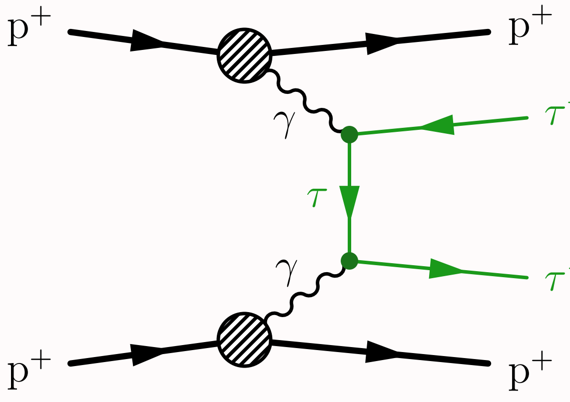


$e^+e^- \rightarrow e^+e^- \tau^+\tau^-$
or $e^+e^- \rightarrow Z \rightarrow \tau\tau\gamma$

LHC: CMS, ATLAS, ...



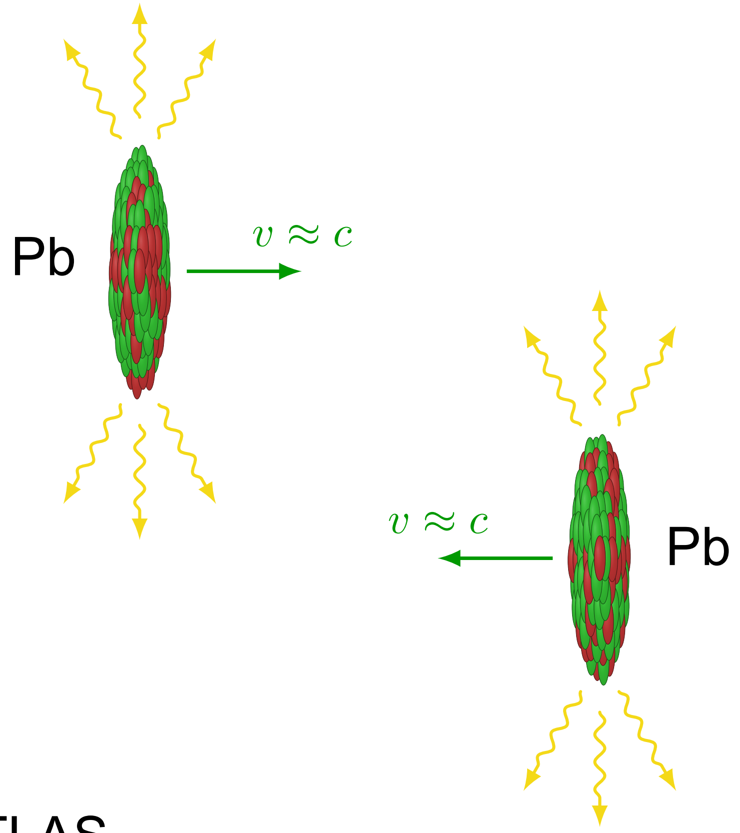
$PbPb \rightarrow PbPb\, \tau^+\tau^-$



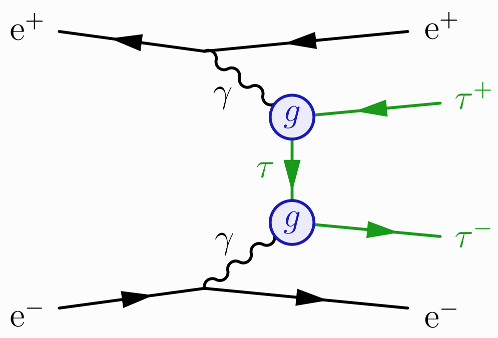
$pp \rightarrow pp\, \tau^+\tau^-$

Photon-induced processes

- collide charged particles at high energies
  ⇒ intense electromagnetic fields
  ⇒ **photon-photon collisions**
- cross section $\sigma \propto Z^4$
  ⇒ PbPb collisions enhanced w.r.t. pp

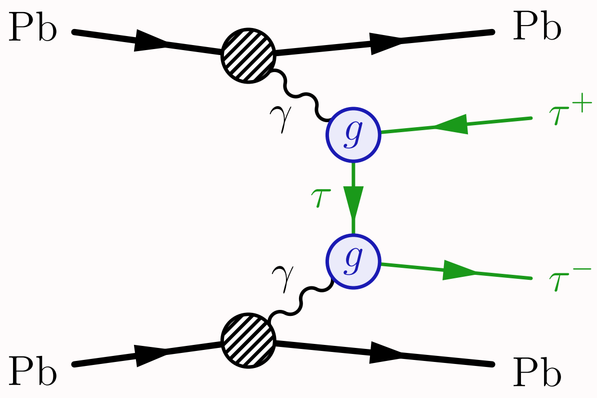


LEP: DELPHI, L3, ...

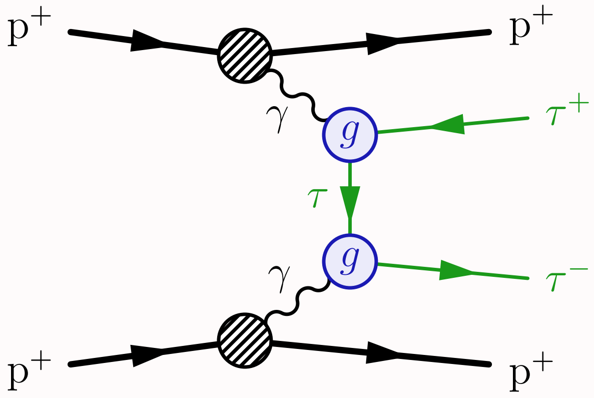


$e^+e^- \to e^+e^- \tau^+\tau^-$
or $e^+e^- \to Z \to \tau\tau\gamma$

LHC: CMS, ATLAS, ...



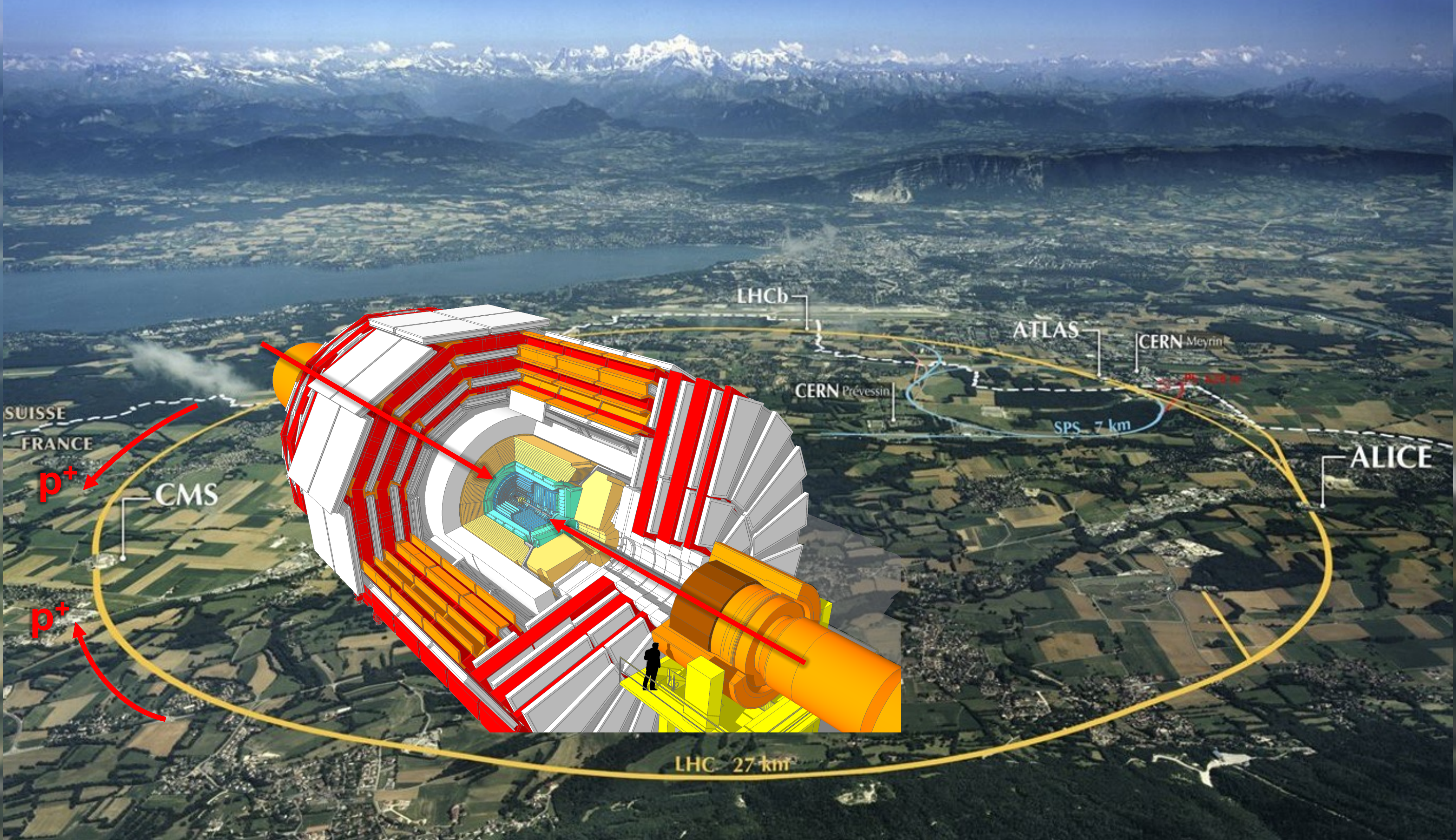
$PbPb \to PbPb\, \tau^+\tau^-$



$pp \to pp\, \tau^+\tau^-$

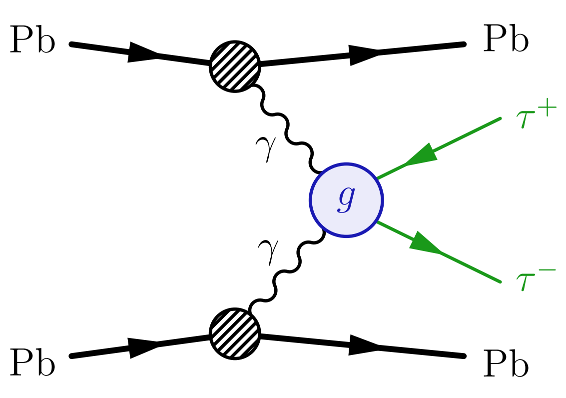
LHC accelerator

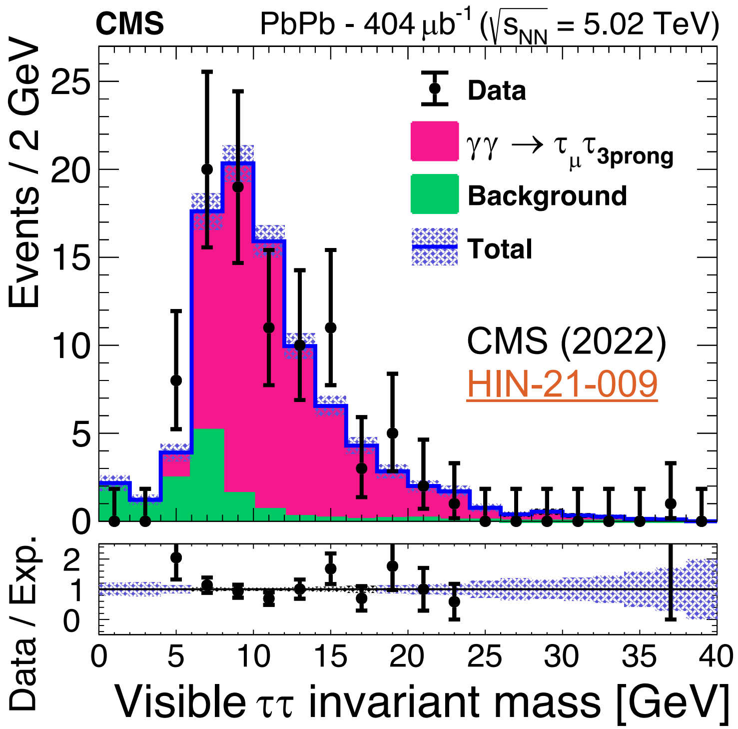
proton collisions @ 13 TeV



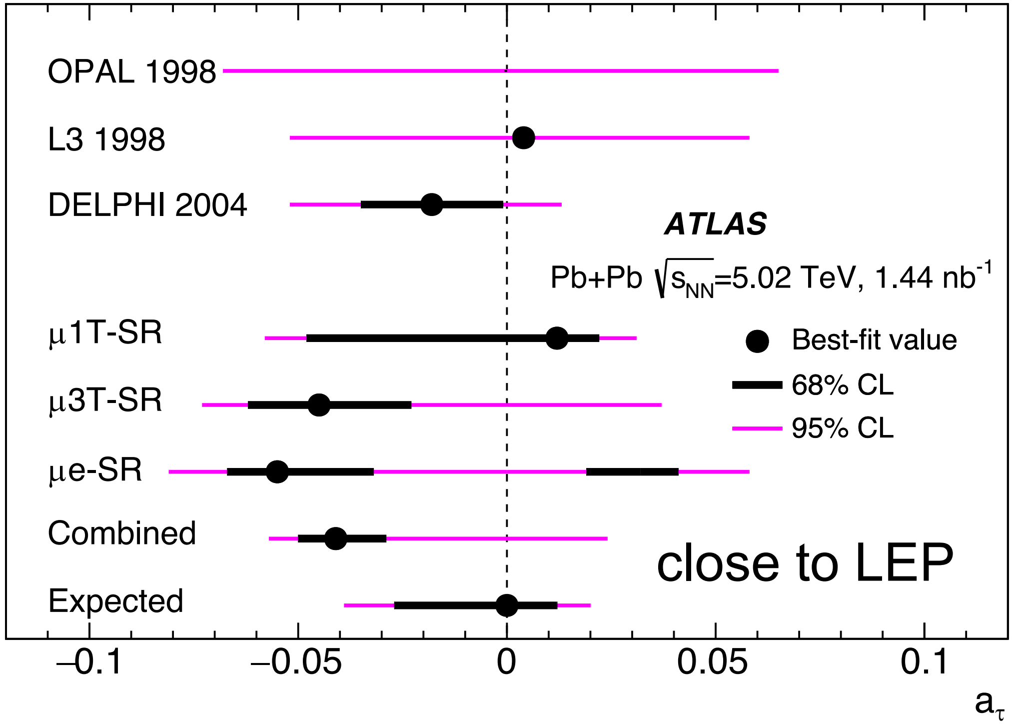
$\gamma\gamma \to \tau\tau$ in ultraperipheral PbPb collisions

- 2022: first observed of $\gamma\gamma \to \tau\tau$ in PbPb by CMS & ATLAS
- $\sigma \propto Z^4$ enhancement
- clean channel: small backgrounds
- phase space $m_{\tau\tau}$ < 40 GeV



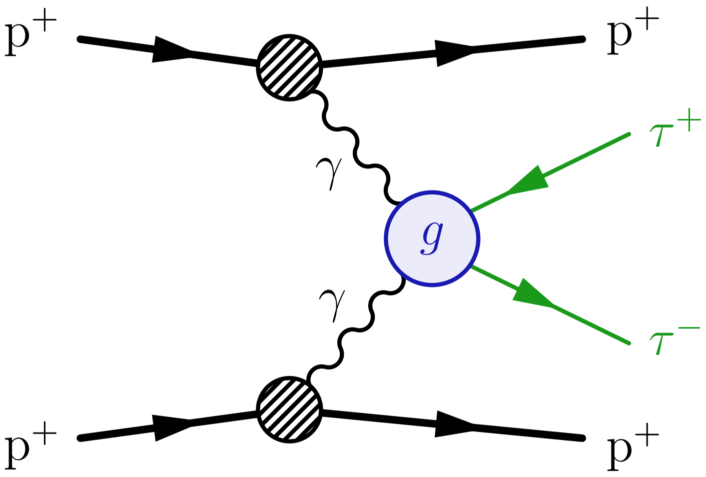


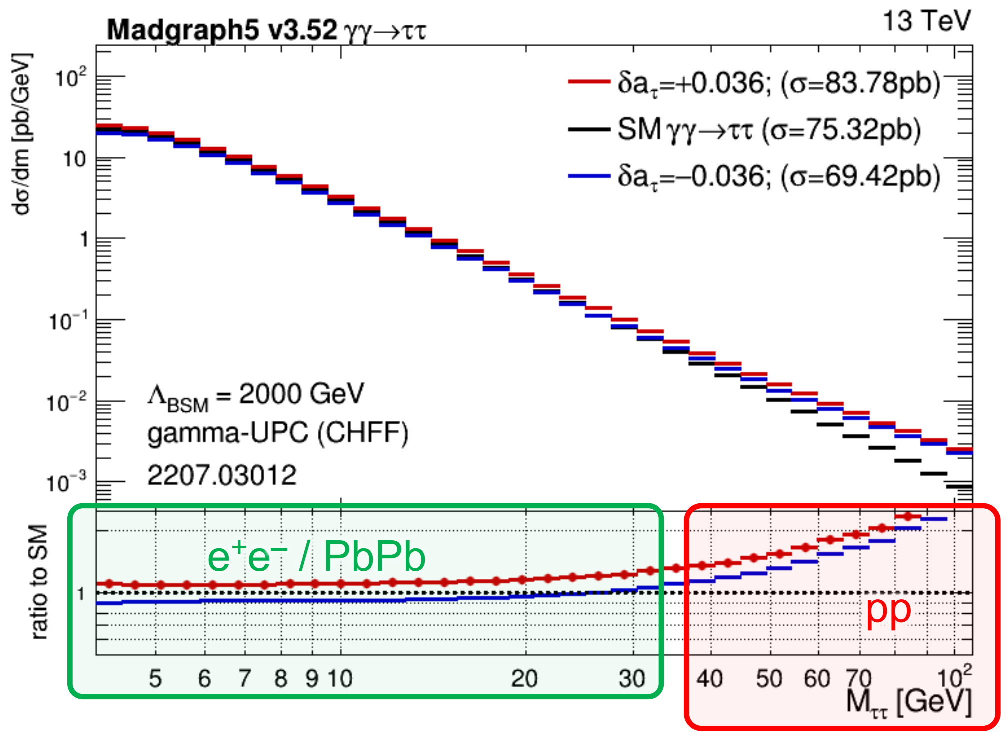
ATLAS (2022) STDM-2019-19

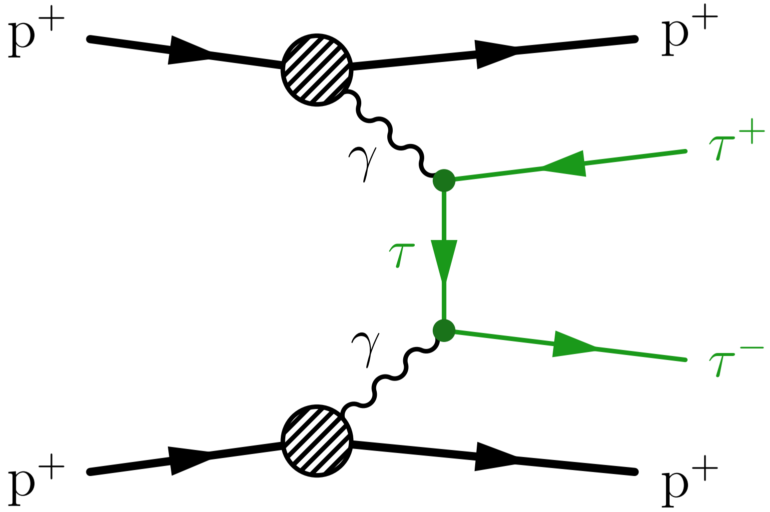


$\gamma\gamma \to \tau\tau$ in pp collisions

- **cons**:
  - no $\sigma \propto Z^4$ enhancement
  - soft signal: low acceptance
  - large background
  - high pileup
- **pros**:
  - much larger data set: ~ O(10^8)
  - much more sensitive to a_τ modifications: expect large BSM enhancement at high τ p_T and $m_{\tau\tau}$



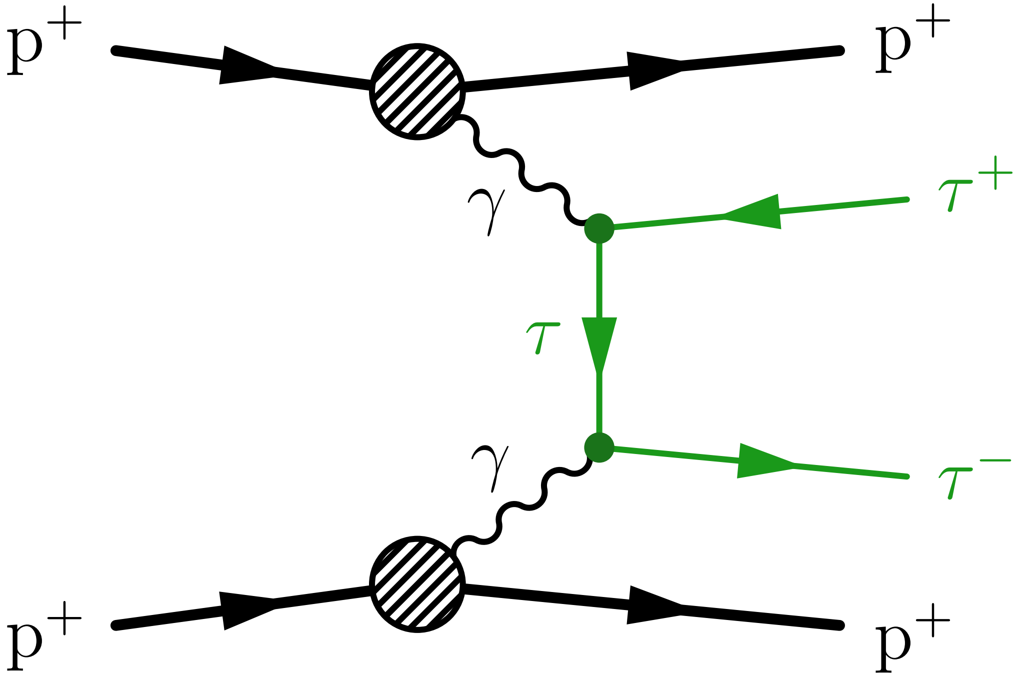




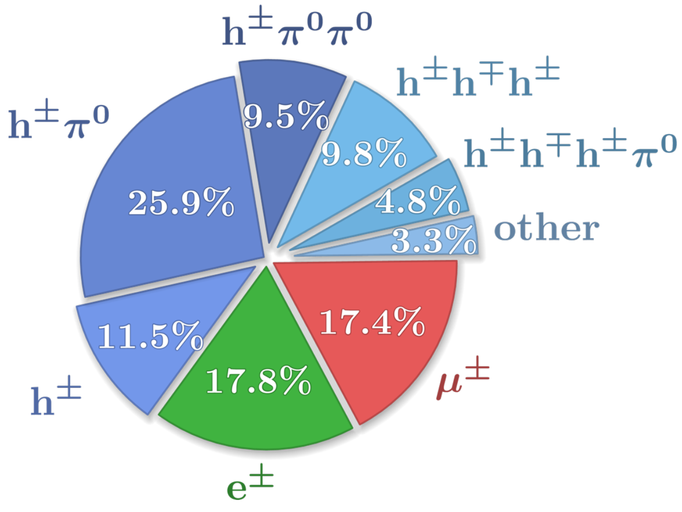
$\gamma\gamma \to \tau\tau$ in pp

SMP-23-005

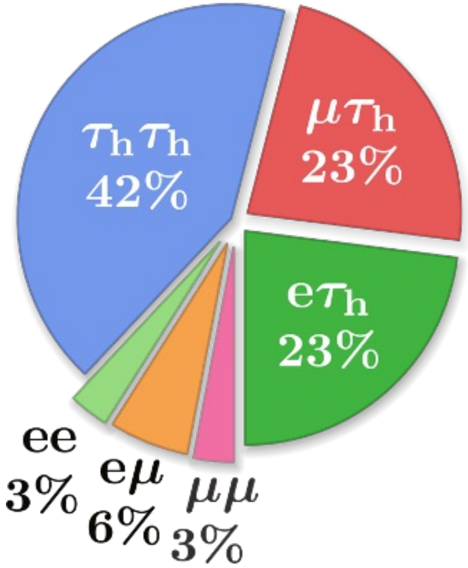
$\gamma\gamma \to \tau\tau$ signature



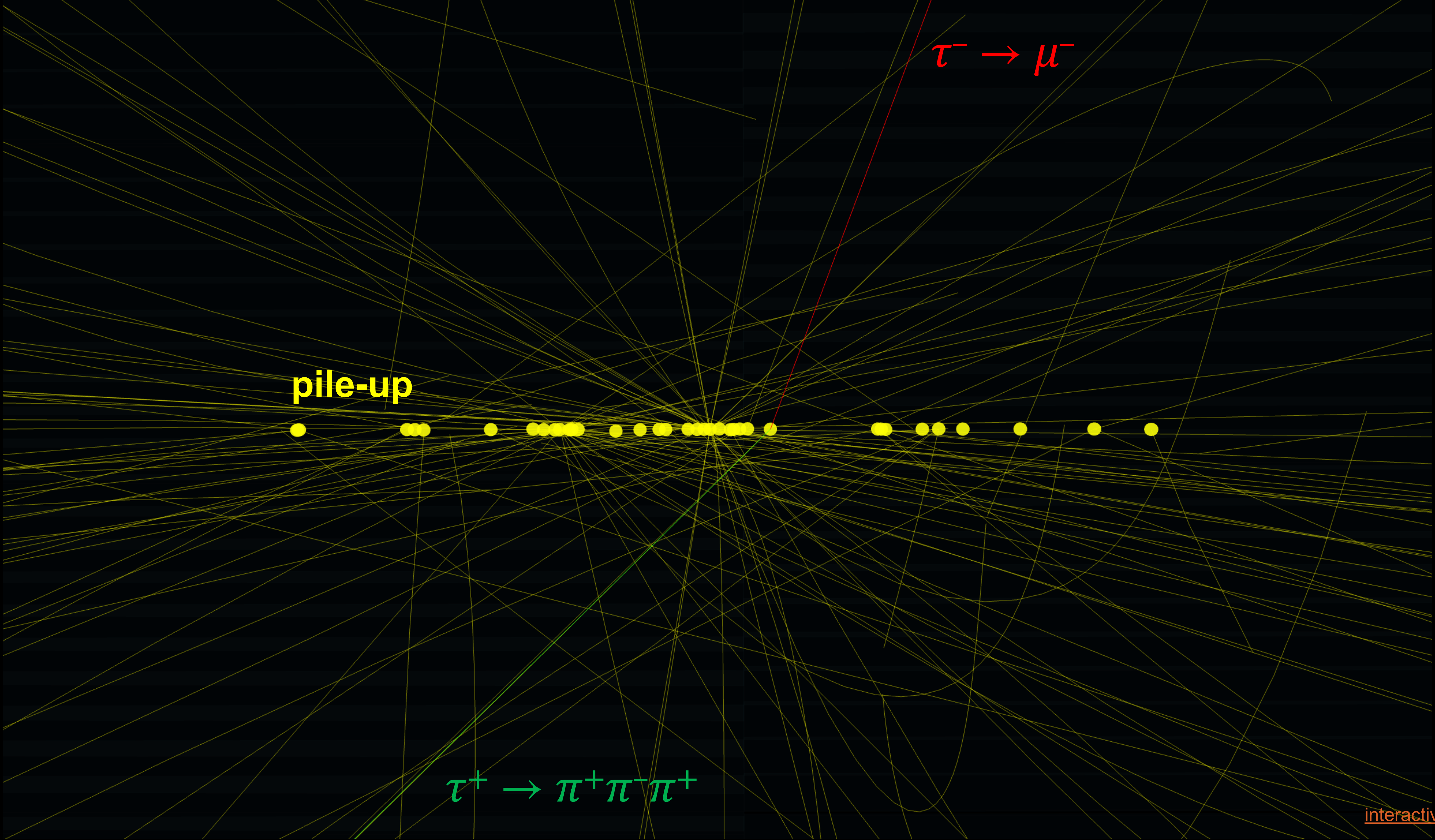
- **2 τ leptons**
  - opposite charge sign
  - back-to-back: $|\Delta\phi| \approx \pi$
  - τ decays:



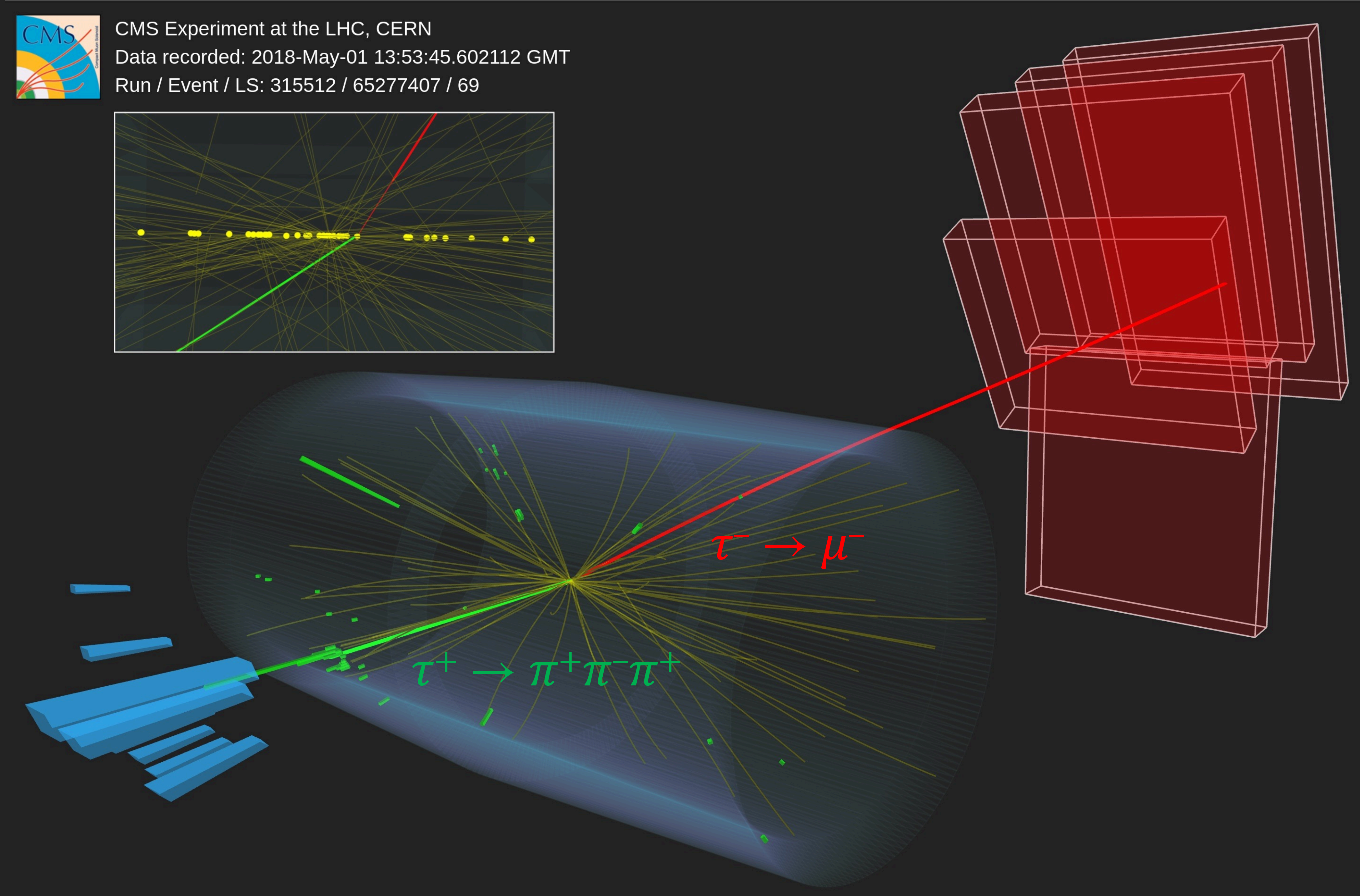
$\tau\tau$ decays:



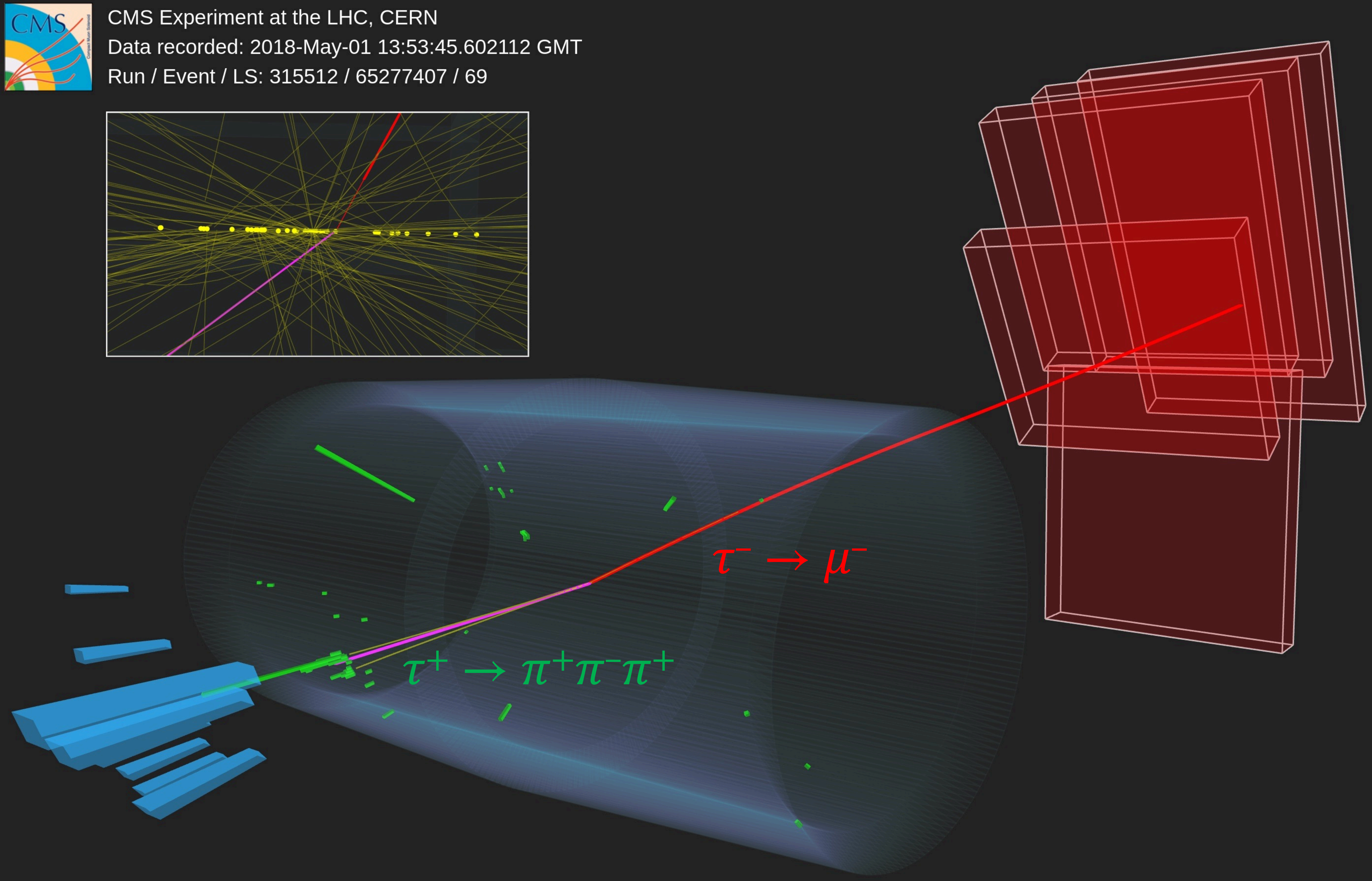
- **2 diffracted protons**
  - no hadronic activity close to $\tau\tau$ vertex



interactive

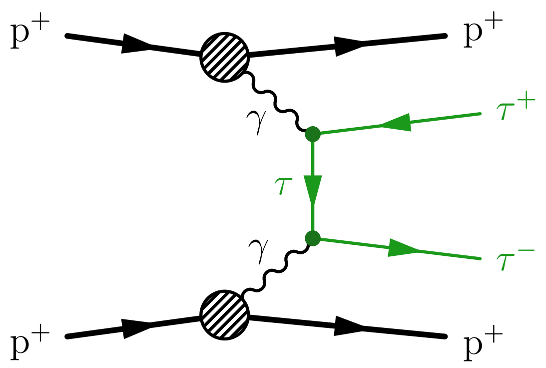


interactive



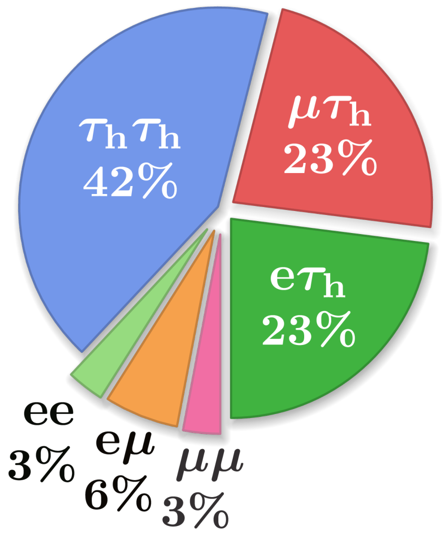
interactive

Strategy to find $\gamma\gamma \to \tau\tau$ in pp



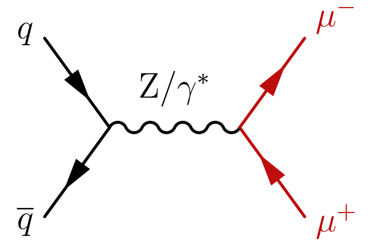
- select events with opposite sign $\tau^+\tau^-$
  - combine 4 $\tau\tau$ final states: eμ, eτ_h, $\mu\tau_h$, $\tau_h\tau_h$
  - **exclusivity cuts**:
    - back-to-back: $|\Delta\phi| \approx \pi$
    - low activity around $\tau\tau$ vertex (low N_{tracks})
- use $\mu\mu$ events (Z $\to \mu\mu$, $\gamma\gamma \to \mu\mu$) to measure corrections to simulation
- measure $\gamma\gamma \to \tau\tau$ from observed $m_{\tau\tau}$ shape & yield in **50 < $m_{\tau\tau}^{\text{vis}}$ < 500 GeV**:
  - above e^+e^- & PbPb ($m_{\tau\tau} \lesssim$ 50 GeV)
  - $m_{\tau\tau}^{\text{vis}} \lesssim$ 500 GeV to ensure unitarity in signal samples

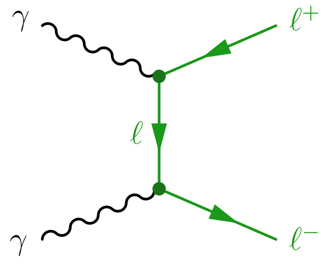
$\tau\tau$ decay channels:

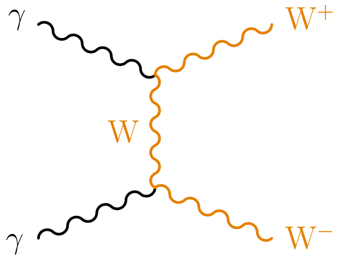


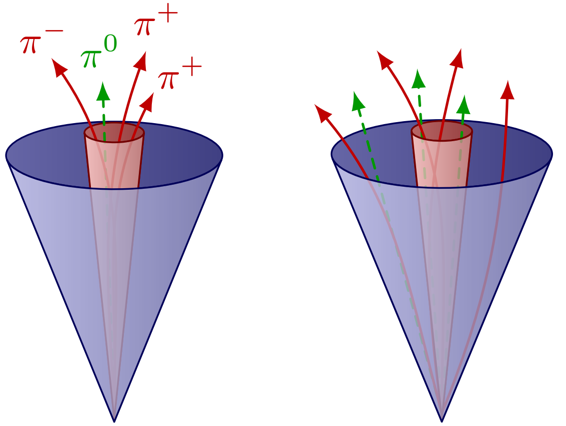
Backgrounds to $\gamma\gamma \to \tau\tau$ search

- **MC simulation**
  - Drell–Yan ($Z/\gamma^* \to \ell\ell$): dominant at low mass
  - exclusive $\gamma\gamma \to$ ee, $\mu\mu$, WW production
  - inclusive WW production (small)
- **data-driven**: misidentified hadronic jets
  - $j \to \tau_h$: $e\tau_h$, $\mu\tau_h$ & $\tau_h\tau_h$ channels
  - $j \to e/\mu$: $e\mu$ channels









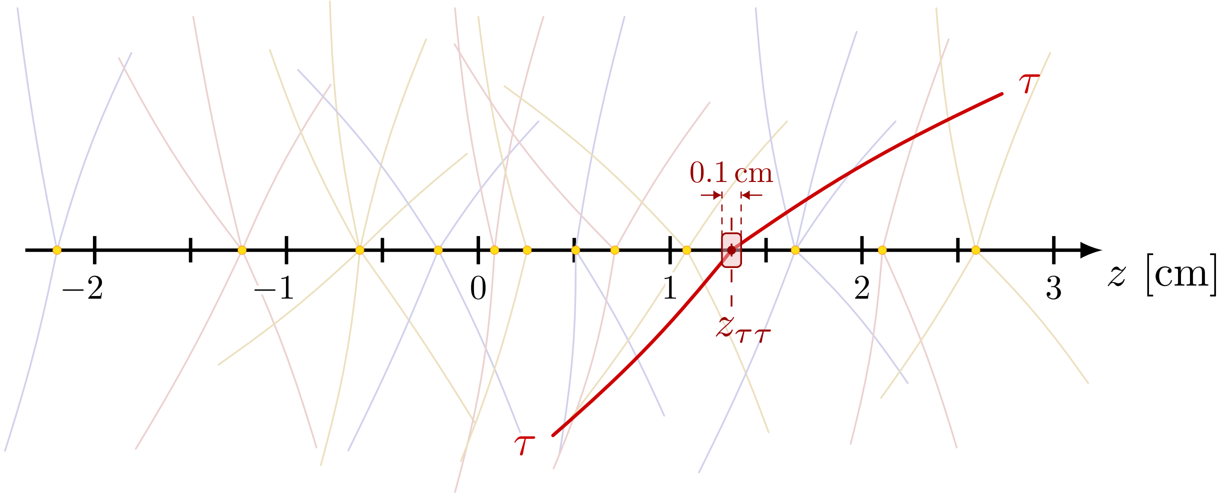
hadronic τ_h jet

hadronic quark/gluon jet

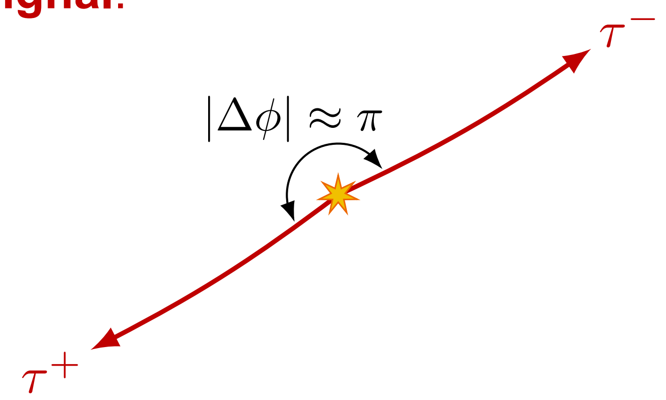
Exclusivity cuts

define **signal regions** based on exclusivity cuts

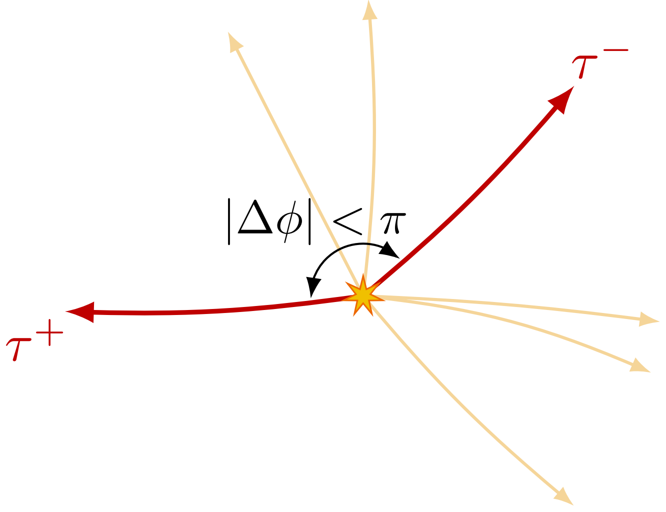
- **acoplanarity** $A = 1 - \frac{|\Delta\phi|}{\pi}$
  - **A < 0.015**: >95% signal efficiency, and <30% Drell–Yan efficiency
- N_{tracks}: count tracks with in 0.1 cm window around $\tau\tau$ vertex
  - $\tau\tau$ vertex reconstructed as $z_{\tau\tau} = \frac{1}{2}\left(z_{\tau_1} + z_{\tau_2}\right)$
  - two categories: N_{tracks} **= 0 or 1**: ≈75% signal efficiency, and reduces backgrounds (like Drell–Yan) by ~10^3



signal:



Drell–Yan background:



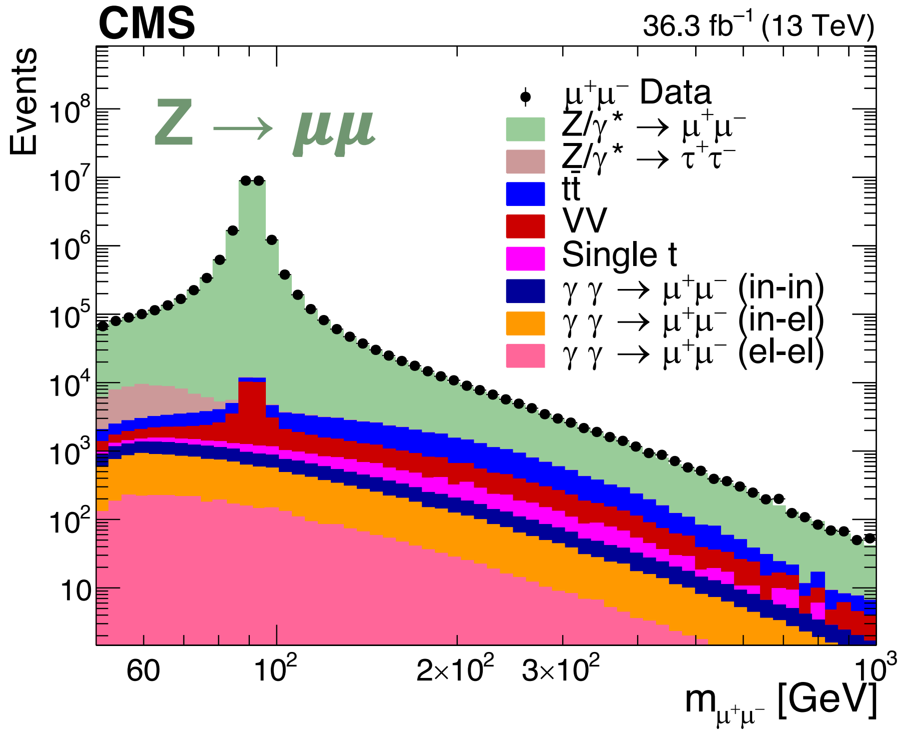
CORRECTIONS

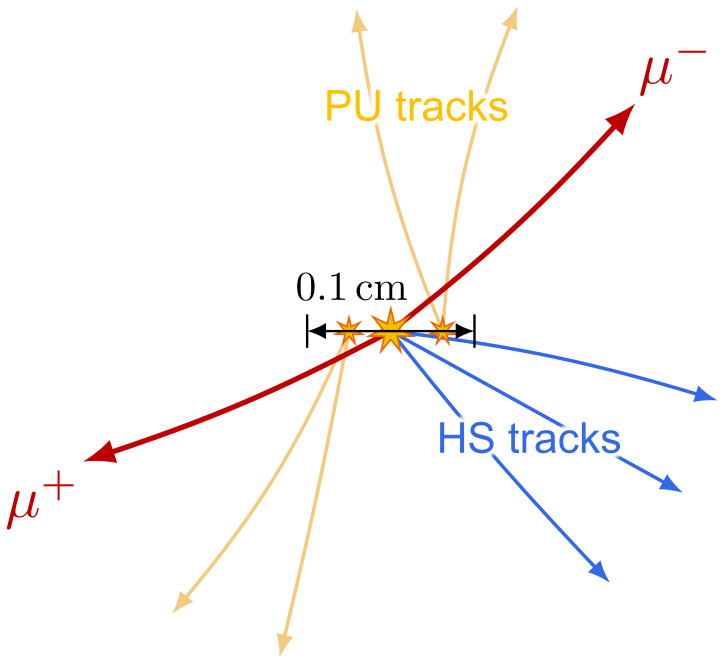
Corrections to simulation

modeling of observed data is not perfect

⇒ derive corrections in pure **dimuon ($\mu\mu$) sample**

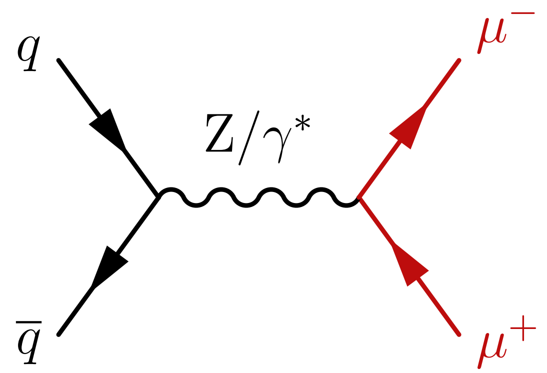
1. **acoplanarity** in **Drell–Yan**
2. **pileup tracks**: $N_{\mathrm{tracks}}^{\mathrm{PU}}$ in all simulation
3. **hard scattering tracks**: $N_{\mathrm{tracks}}^{\mathrm{HS}}$ in **Drell–Yan**
4. **nonelastic contributions** of $\gamma\gamma \to \ell\ell$ simulation

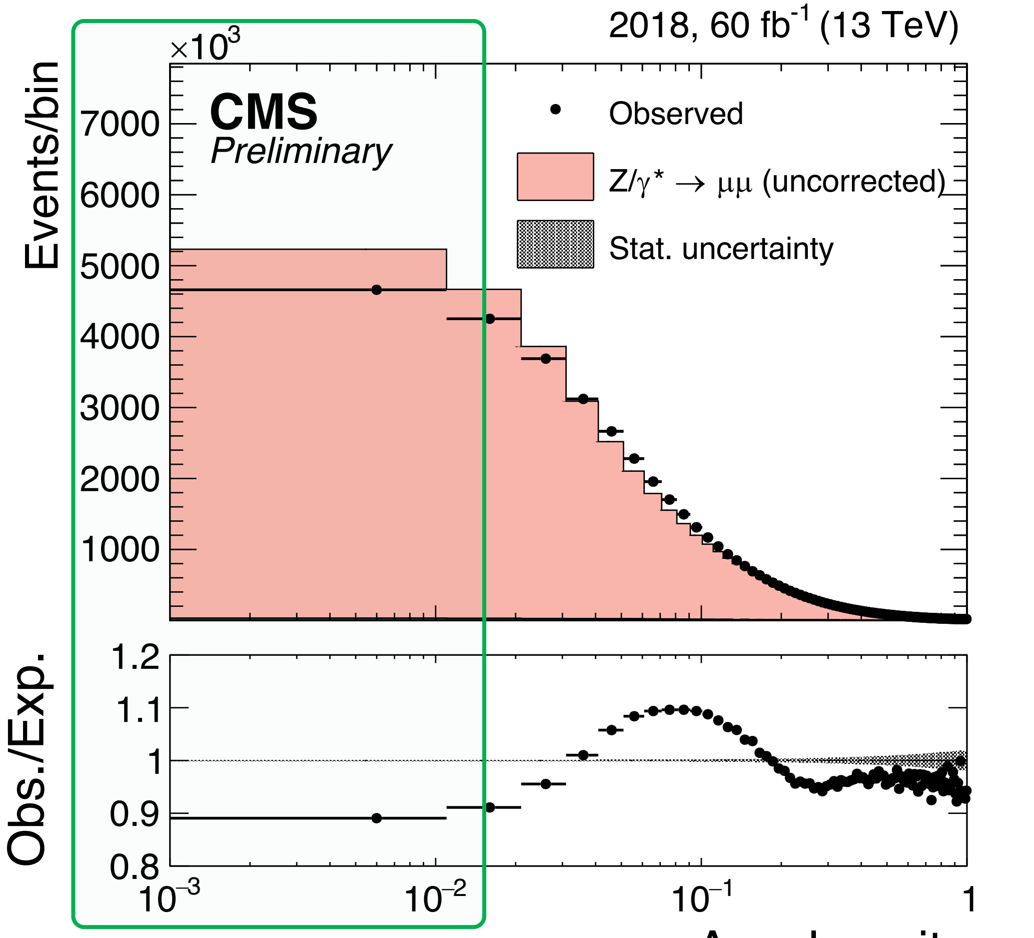




1. Acoplanarity corrections

- Drell–Yan generated by aMC@NLO does not describe well
  - Z boson p_T
  - acoplanarity A
- measure corrections in pure $Z/\gamma^* \rightarrow \mu\mu$ sample
- apply correction as a function of
  - acoplanarity A
  - leading and subleading muon p_T

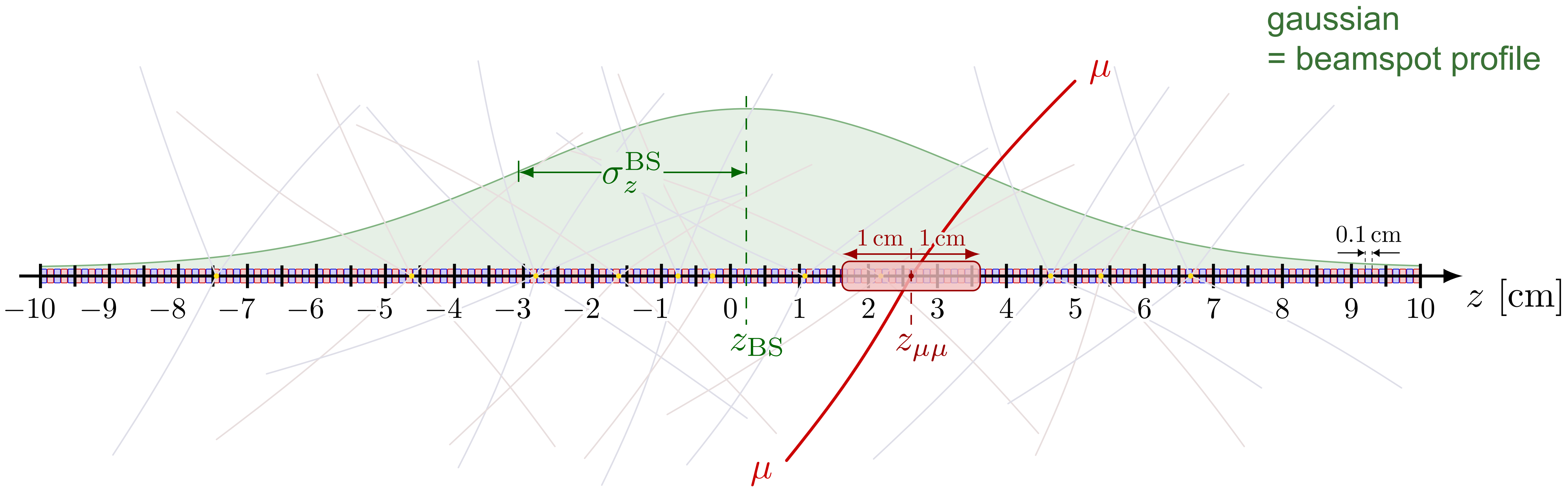




SR: A < 0.015

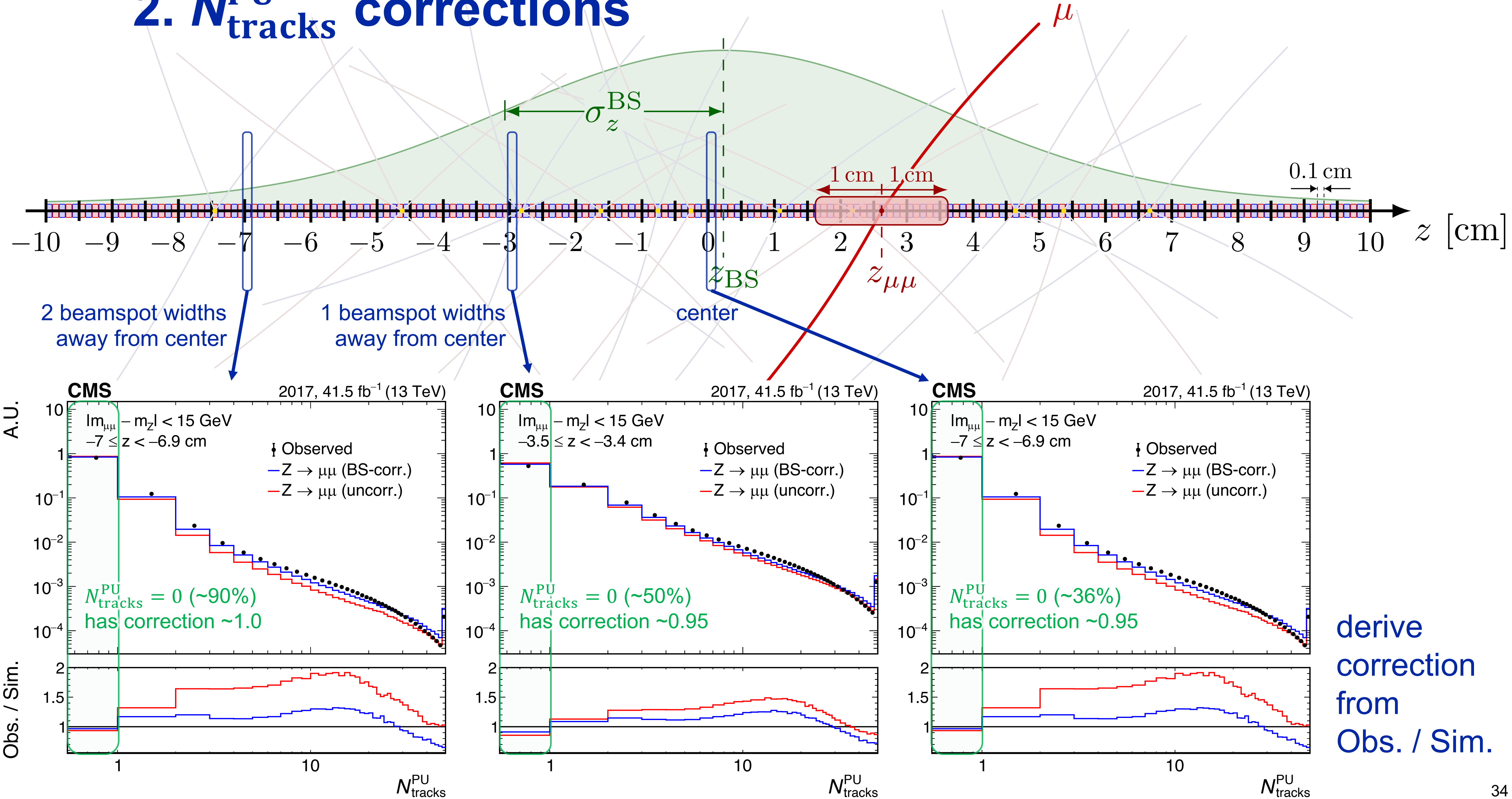
2. $N_{\text{tracks}}^{\text{PU}}$ corrections

applied to all simulation



- use Z → $\mu\mu$ events at Z peak, $|m_{\mu\mu} - m_Z| < 15$ GeV
- count number of PU tracks in small z windows (far away from $\mu\mu$ vertex)
- derive correction from obs. / sim. ratio as a function of z and N_{tracks}

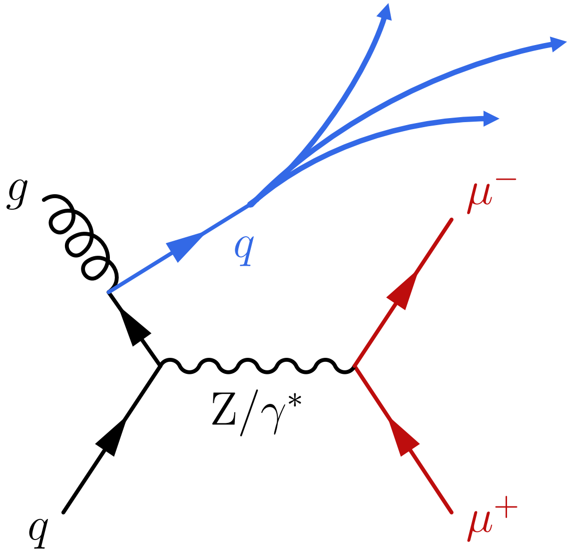
2. $N_{\text{tracks}}^{\text{PU}}$ corrections



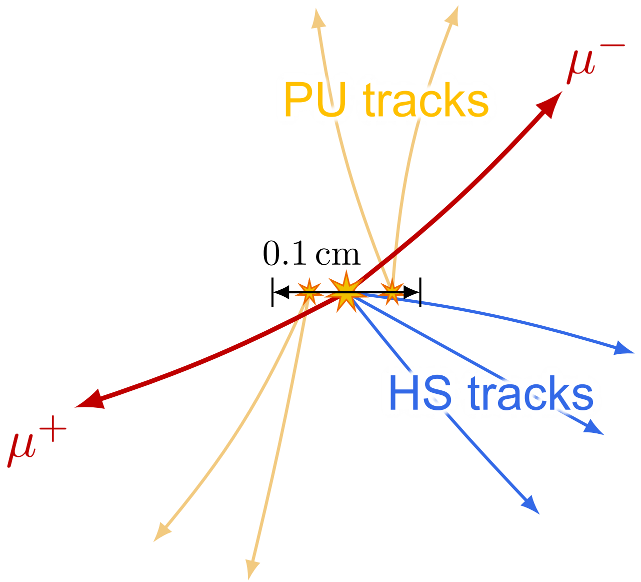
derive correction from Obs. / Sim.

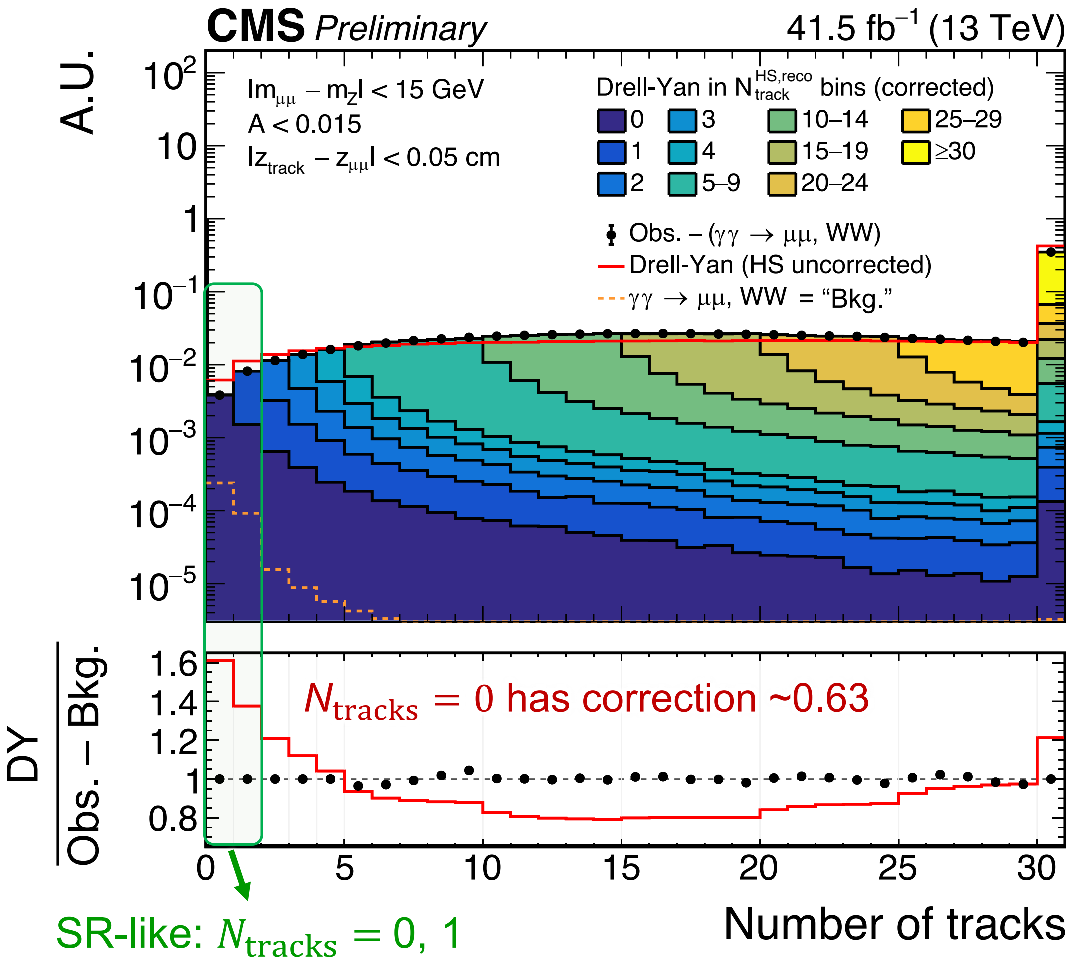
3. $N^{\mathrm{HS}}_{\mathrm{tracks}}$ correction

- use $Z \to \mu\mu$ events at Z peak
- count N_{tracks} in signal window (0.1 cm) around $\mu\mu$ vertex
- separate Drell–Yan into bins of $N^{\mathrm{HS}}_{\mathrm{tracks}}$ by gen-matching reco tracks



Drell-Yan ($Z/\gamma^* \to \mu\mu$) with initial-state radiation





$$N_{\mathrm{tracks}} = N^{\mathrm{HS}}_{\mathrm{tracks}} + N^{\mathrm{PU}}_{\mathrm{tracks}}$$

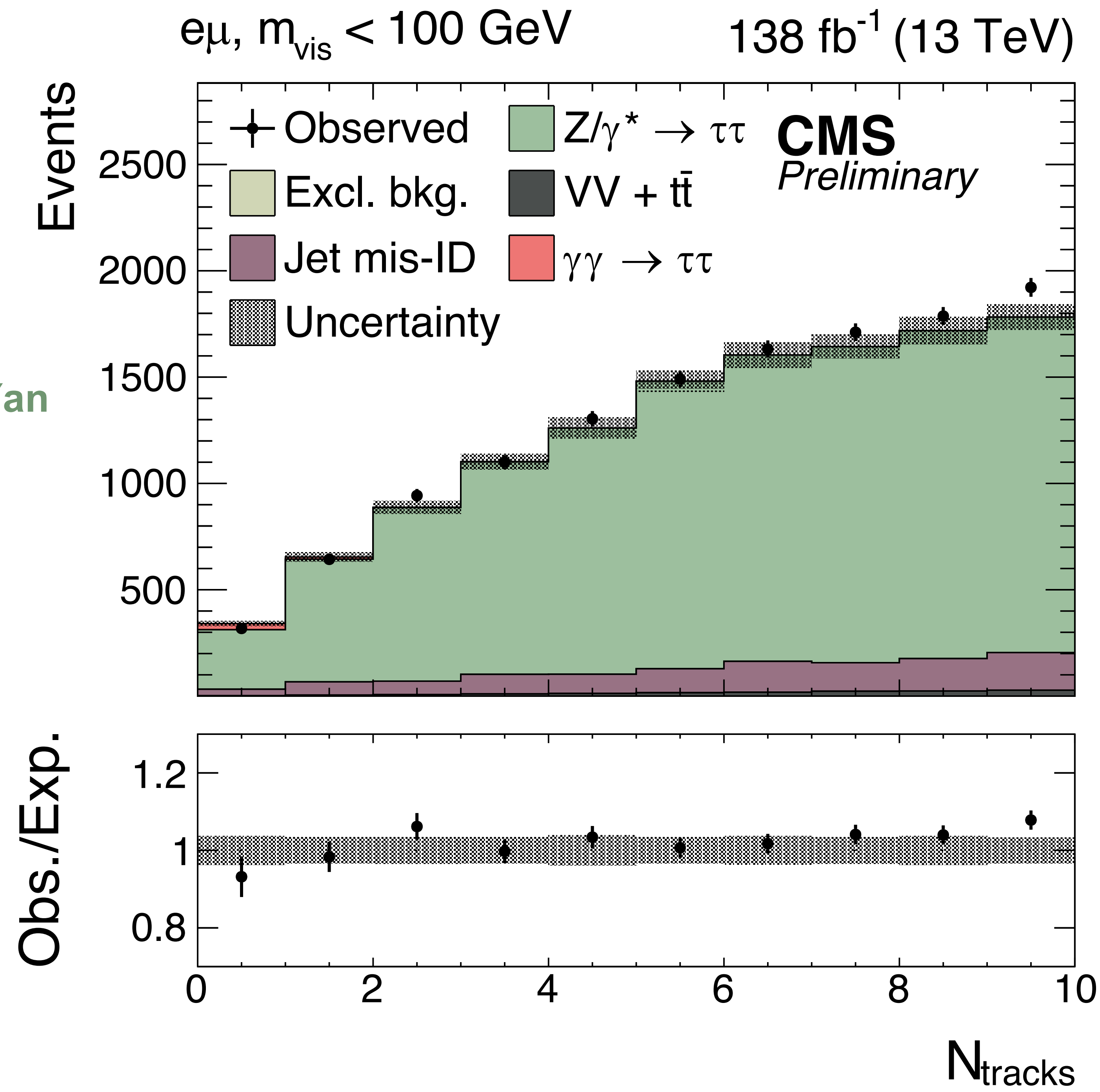
in signal window (0.1 cm)

After corrections

1. acoplanarity in **Drell–Yan**
2. pileup tracks: $N_{\mathrm{tracks}}^{\mathrm{PU}}$ in all simulation
3. hard scattering tracks: $N_{\mathrm{tracks}}^{\mathrm{HS}}$ in **Drell–Yan**

simulation describes observed data well after these corrections !

- $m_{\mathrm{vis}}(\tau\tau) < 100$ GeV (low signal efficiency)
- in all $\tau\tau$ final states

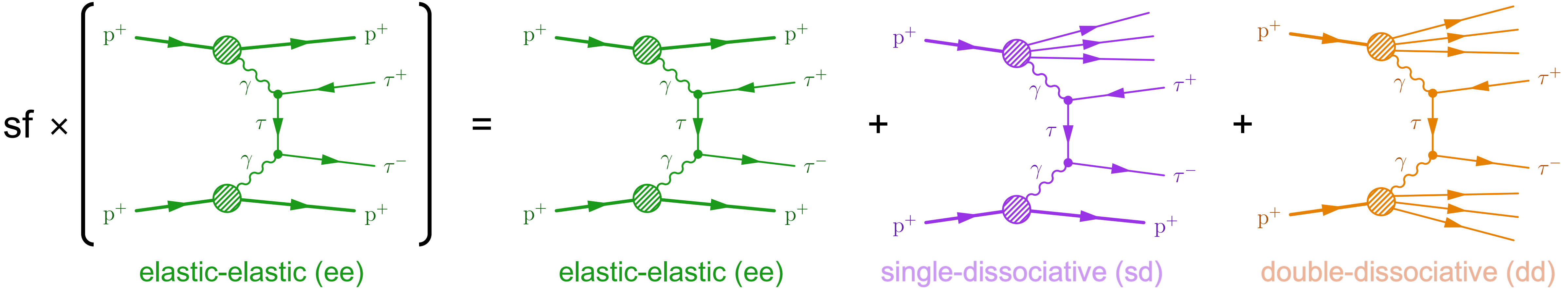


4. Elastic rescaling

applied to photon-induced simulation ($\gamma\gamma \to \ell\ell$, WW)

- signal samples only include **elastic-elastic (ee)** process generated by gammaUPC
- **single-dissociative (sd)** and **double-dissociative (dd)** processes not included
  - have larger cross section
  - can have an exclusive signature
- estimate dissociative contributions (incl. higher-order corrections) by rescaling elastic-elastic $\gamma\gamma \to \mu\mu$ signal in $\mu\mu$ data

$$\Rightarrow \text{measure rescaling factor} = \frac{(\mathbf{ee}+\mathbf{sd}+\mathbf{dd})_{\text{obs}}}{(\mathbf{ee})_{\text{sim}}}$$

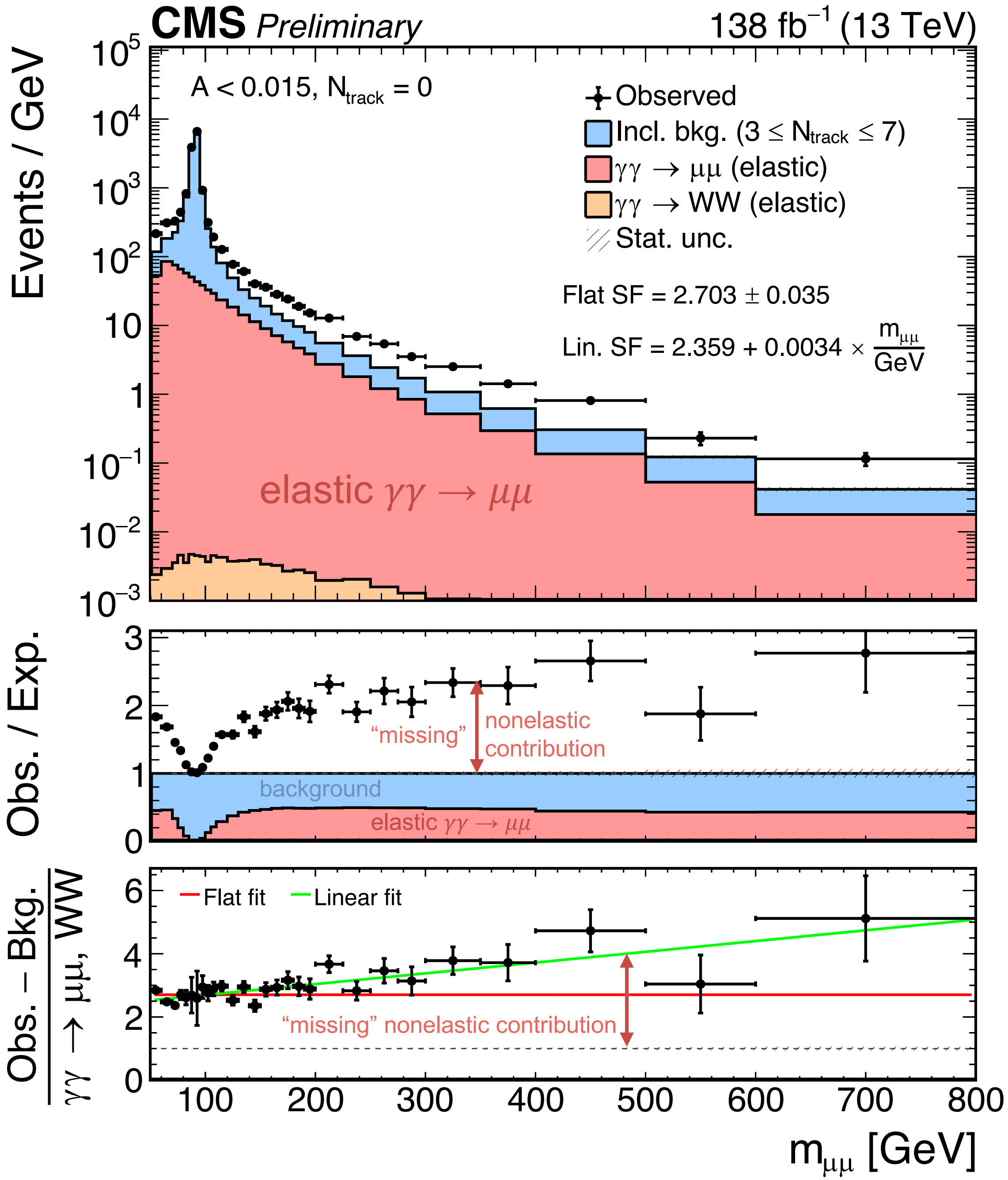


4. Elastic rescaling

- rescaling factor measured in $m_{\mu\mu}$ distribution in dimuon events with A < 0.015 and N_{tracks} = 0 or 1
- **inclusive background** (mostly Drell–Yan)
  - estimated from data in $3 \leq N_{\text{tracks}} \leq 7$ region
  - normalized to Z peak
- **elastic $\gamma\gamma \rightarrow \mu\mu$/WW "signal"**
  - contributes significantly $m_{\mu\mu}$ > 150 GeV
  - rescale to data to estimate nonelastic contribution
- fits:
  - **linear fit** applied as nominal corrections to all elastic simulation ($\gamma\gamma \rightarrow ee, \mu\mu, \tau\tau$, WW)
  - **flat fit (~2.7)** used to obtain uncertainty (conservative)

$$\text{rescaling factor} = \frac{(\mathrm{ee}+\mathrm{sd}+\mathrm{dd})_{\mathrm{obs}}}{(\mathrm{ee})_{\mathrm{sim}}} = \frac{\text{Obs.} - \text{Bkg.}}{\gamma\gamma \rightarrow \mu\mu, \text{WW}}$$

applied to photon-induced simulation ($\gamma\gamma \rightarrow \ell\ell$, WW)

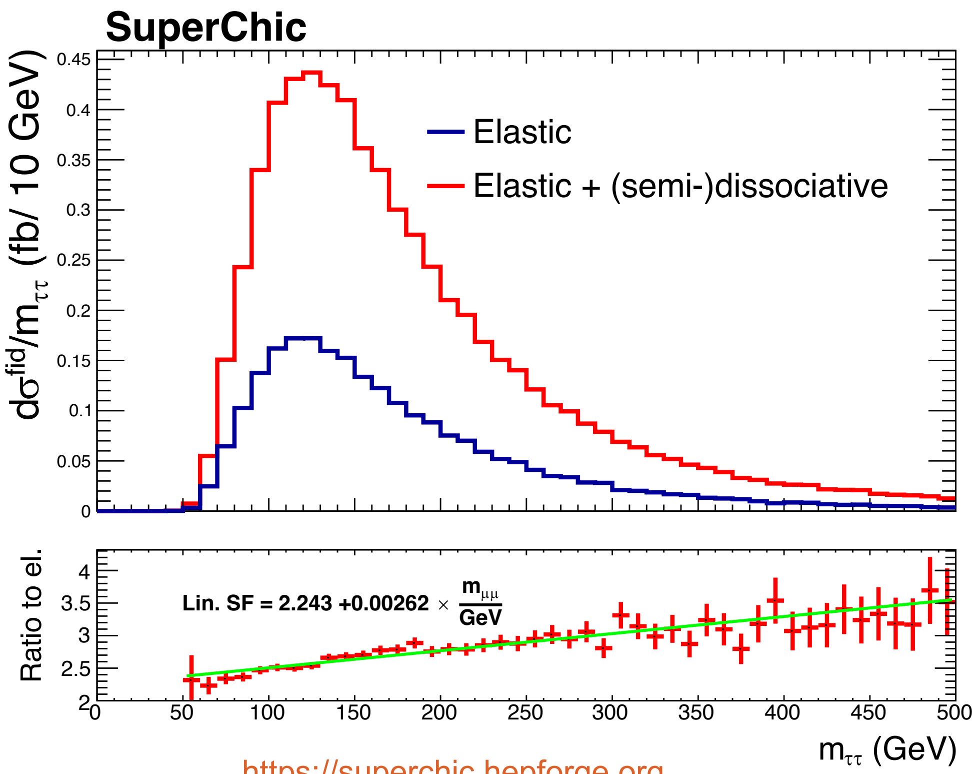


4. Elastic rescaling

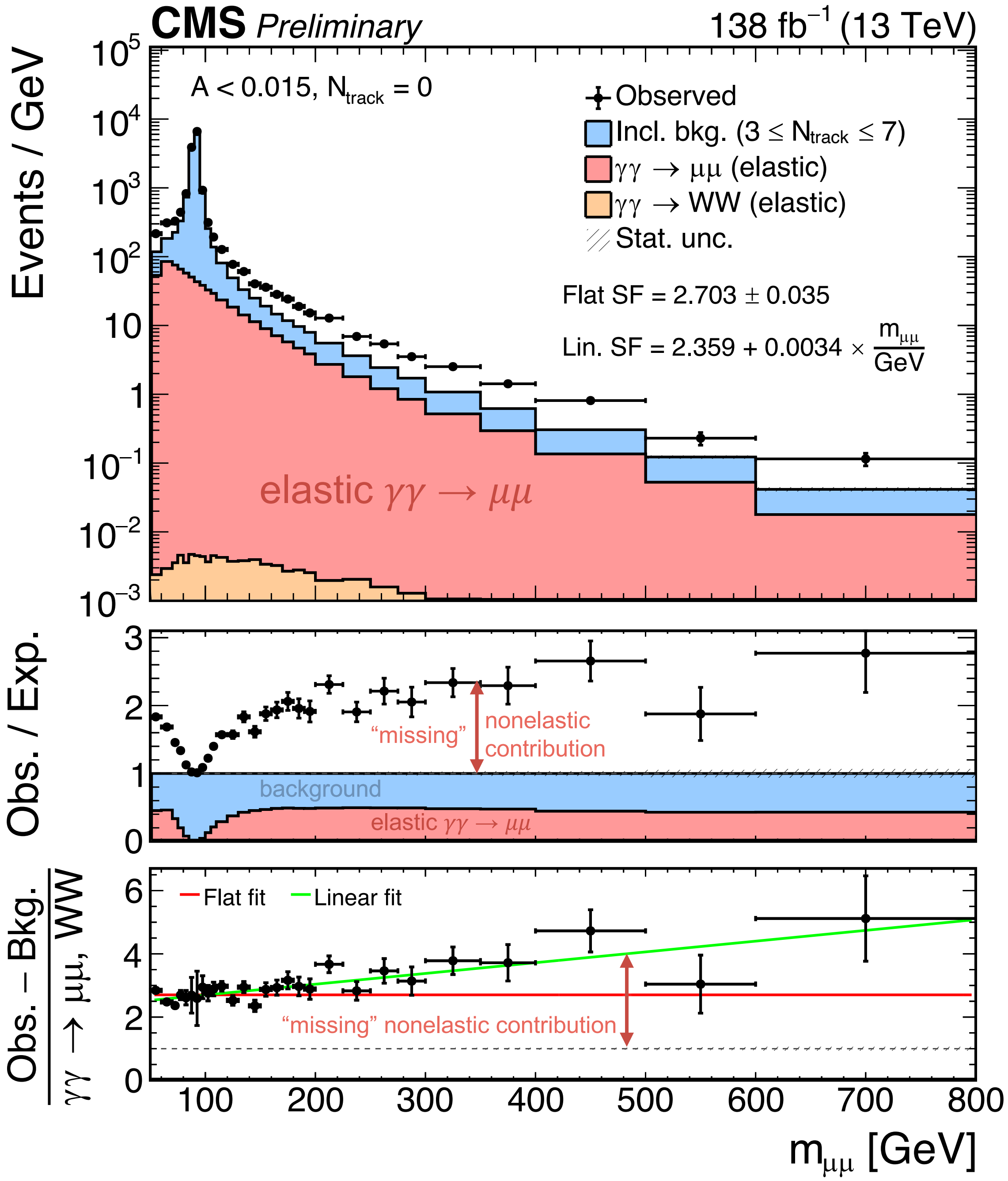
applied to photon-induced simulation ($\gamma\gamma \to \ell\ell$, WW)

measured rescaling factor consistent with prediction by **SuperChic** generator within uncertainties!

- Measured: SF = 2.359 + 0.0032 × $\frac{m_{\mu\mu}}{\mathrm{GeV}}$
- SuperChic: SF = 2.243 + 0.0026 × $\frac{m_{\mu\mu}}{\mathrm{GeV}}$

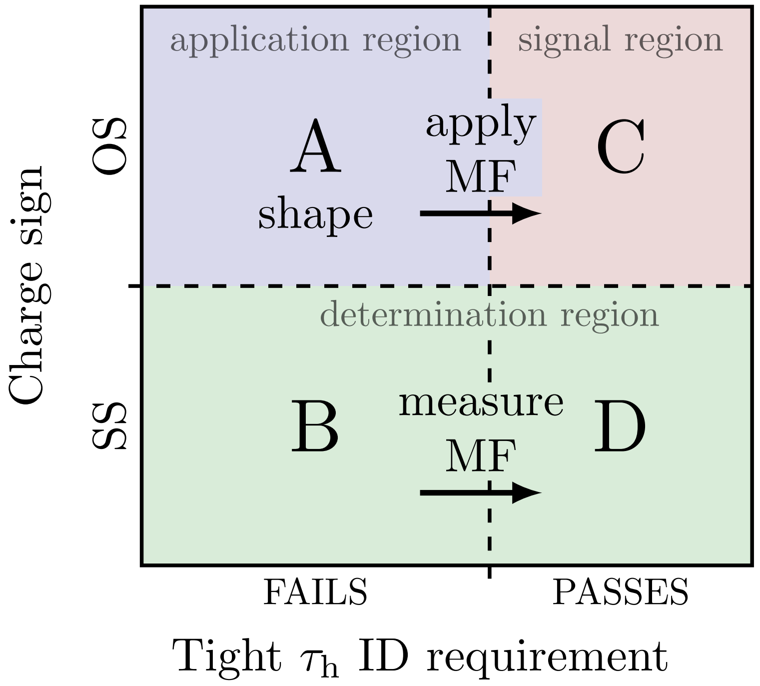


https://superchic.hepforge.org



BACKGROUND ESTIMATION

$j \to \tau_h$ mis-ID background estimation



- background from $j \to \tau_h$ mis-IDs mostly include **QCD multijet** and **W + jets** events
- estimated in a **data-driven** way
- measure **"mis-ID rate" (MF)** in several CRs

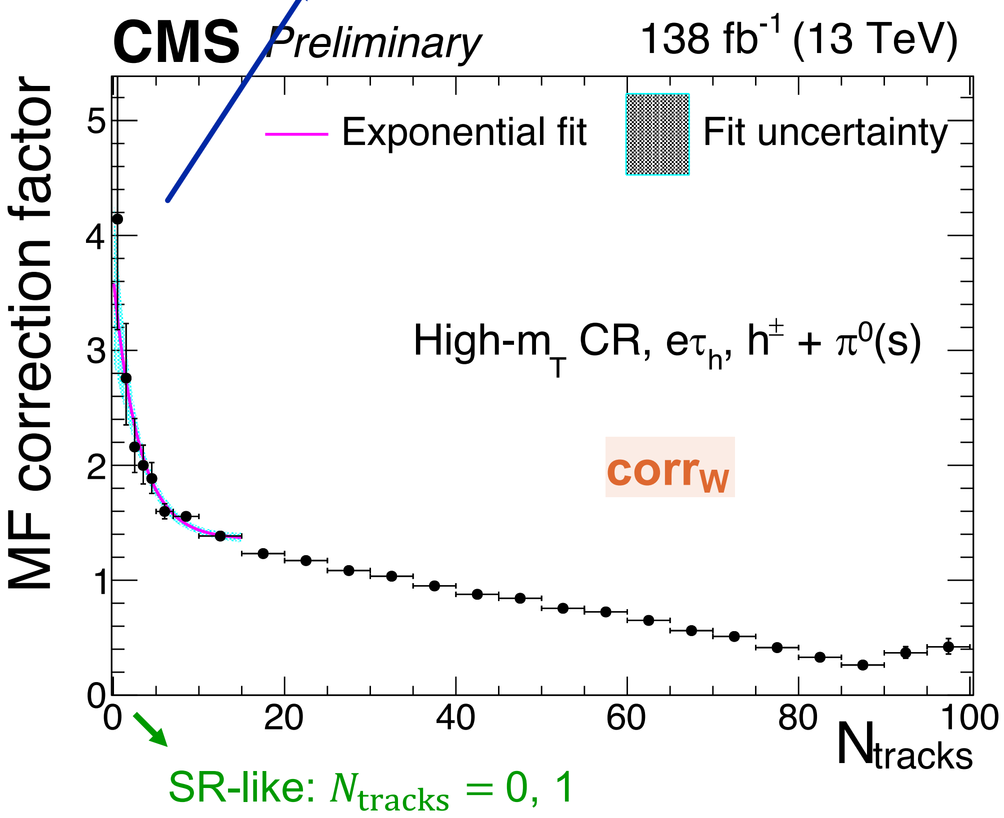
$$\text{MF} = \frac{N(j \to \tau_h \text{ passes } \textbf{tight } \tau_h \text{ ID requirement})}{N(j \to \tau_h \text{ fails } \textbf{tight}\text{, but passes } \textbf{looser } \tau_h \text{ ID requirement})}$$

- as a function of τ_h p_T & decay mode

Corrections to $j \to \tau_h$ MF in $e\tau_h$ & $\mu\tau_h$

jet is 4 times more likely to pass the tight τ_h ID criteria if there is no other track at the vertex

- MFs & corrections measured in separate CRs:
  - W + jets: m_T > 75 GeV
  - QCD: SS, m_T < 75 GeV
- fewer tracks lead to more isolated τ_h
  ⇒ higher fake rates
  ⇒ apply corrections as a function of N_{tracks}
- total fake rate "$j \to \tau_h$ misidentification factors":

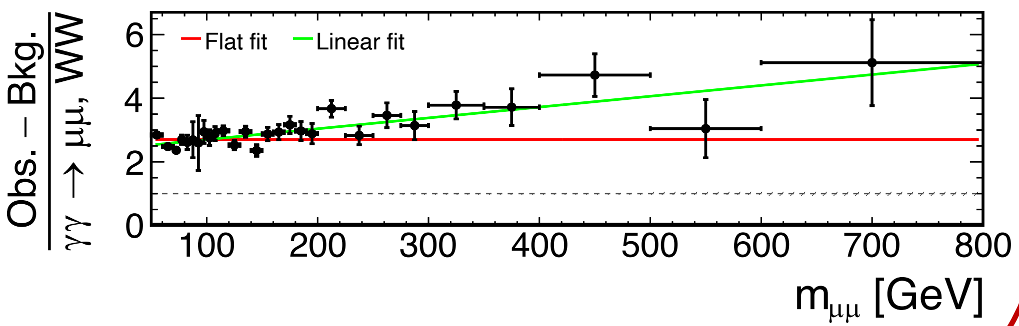


$$\mathrm{MF} = f_{\mathrm{W}}(m_{\mathrm{vis}}, m_{\mathrm{T}}) \times \mathrm{MF}_{\mathrm{W}}(p_{\mathrm{T}}^{\tau_h}, \mathrm{DM}^{\tau_h}) \times \mathrm{corr}_{\mathrm{W}}(N_{\mathrm{tracks}}, \mathrm{DM}^{\tau_h})$$
$$+ \left(1 - f_{\mathrm{W}}(m_{\mathrm{vis}}, m_{\mathrm{T}})\right) \times \mathrm{MF}_{\mathrm{QCD}}(p_{\mathrm{T}}^{\tau_h}, \mathrm{DM}^{\tau_h}) \times \mathrm{corr}_{\mathrm{QCD}}(N_{\mathrm{tracks}}, \mathrm{DM}^{\tau_h})$$

RESULTS

Observation of $\gamma\gamma \rightarrow \tau\tau$ in pp

Leading systematics

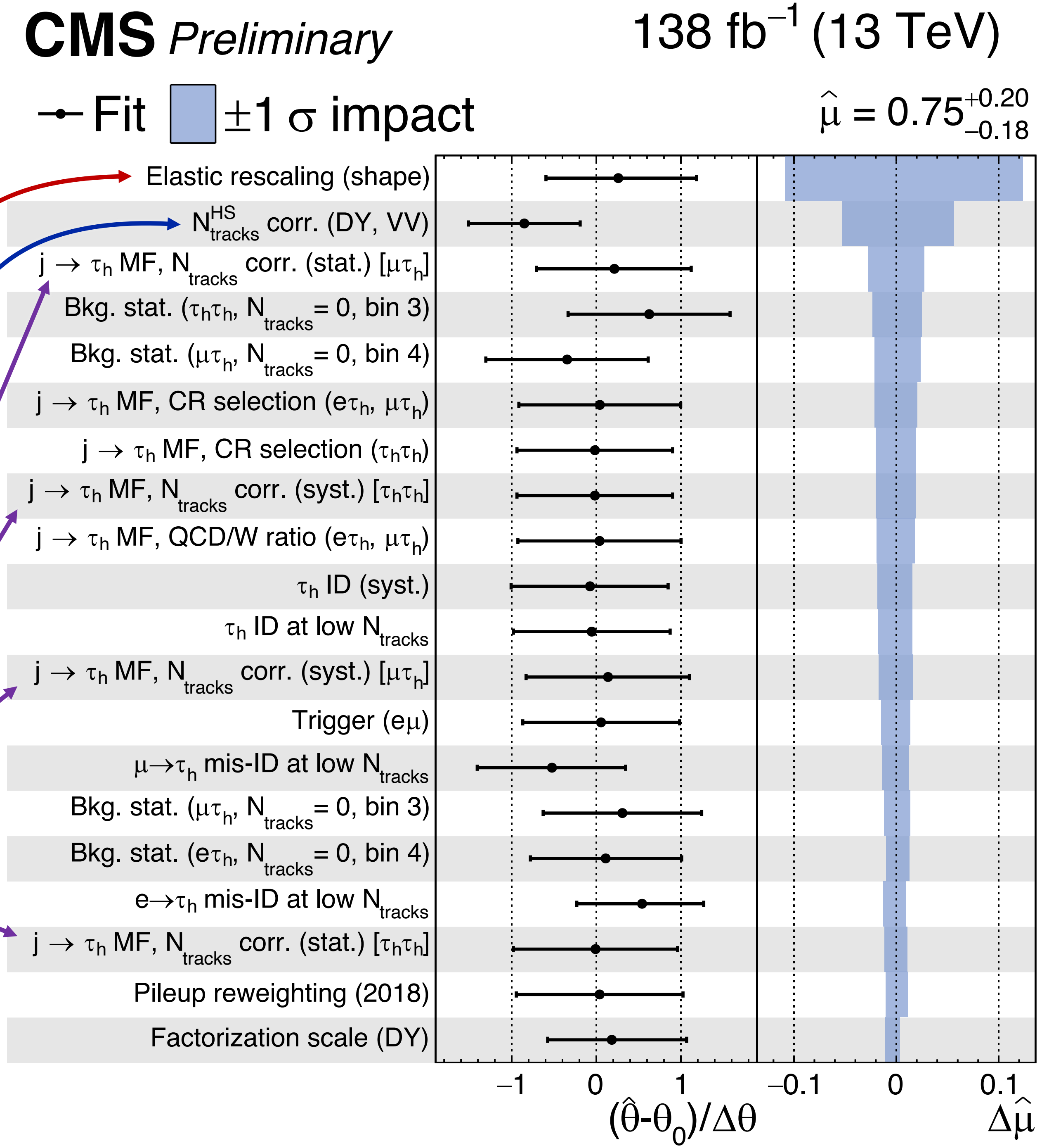


rescaling of elastic simulation ($\gamma\gamma \to \ell\ell$, WW)

- use linear fit to estimate uncertainty
- dominant systematic

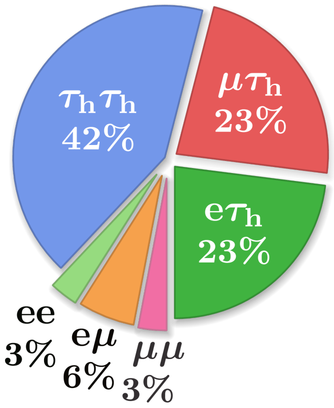
$N^{\mathrm{HS}}_{\mathrm{tracks}}$ correction in Drell–Yan (~6.5% in N_{tracks} = 0)

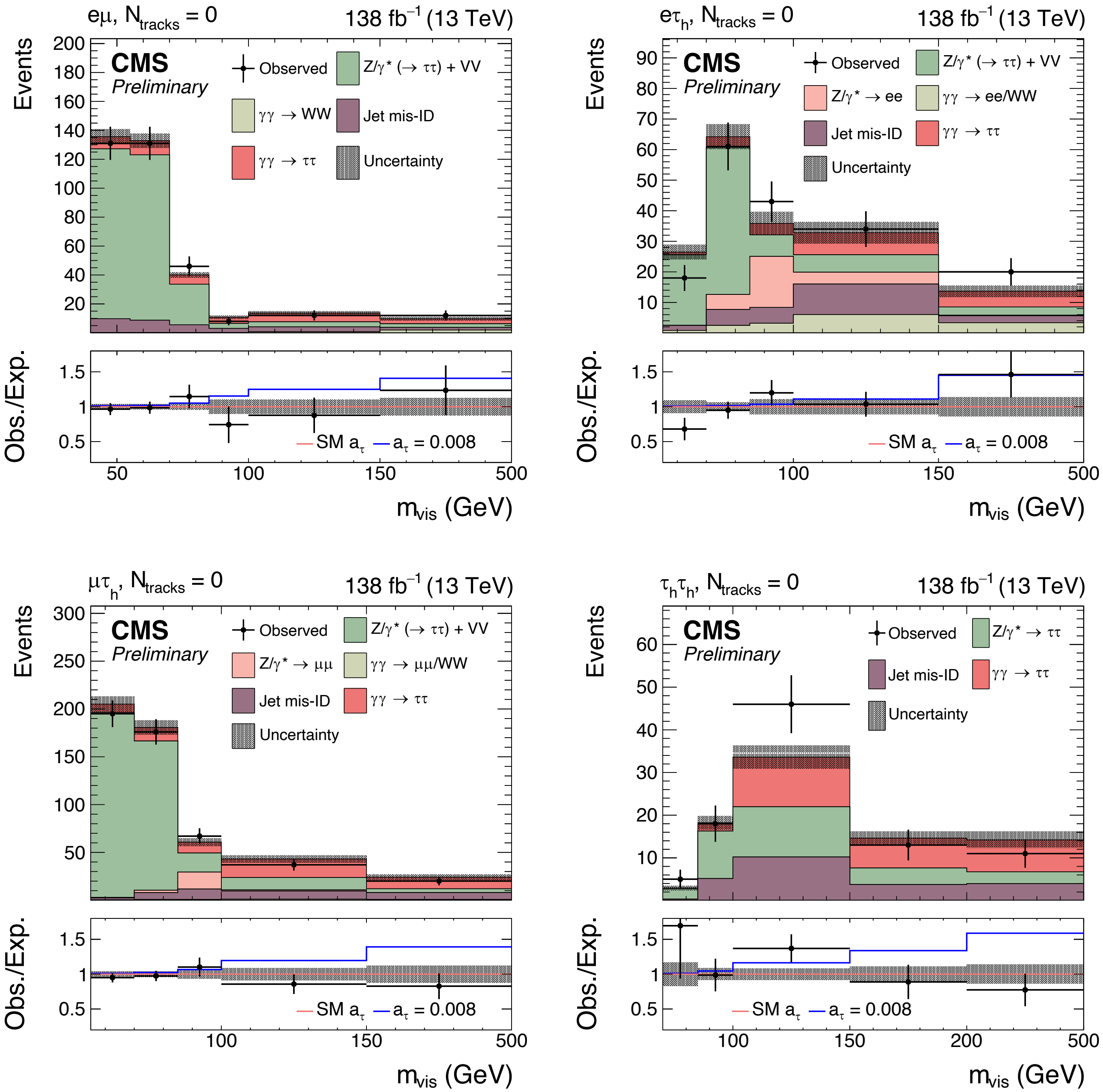
N_{tracks} extrapolation to $j \to \tau_{\mathrm{h}}$ mis-ID rate (up to ~20%)



SR with N_{tracks} = 0

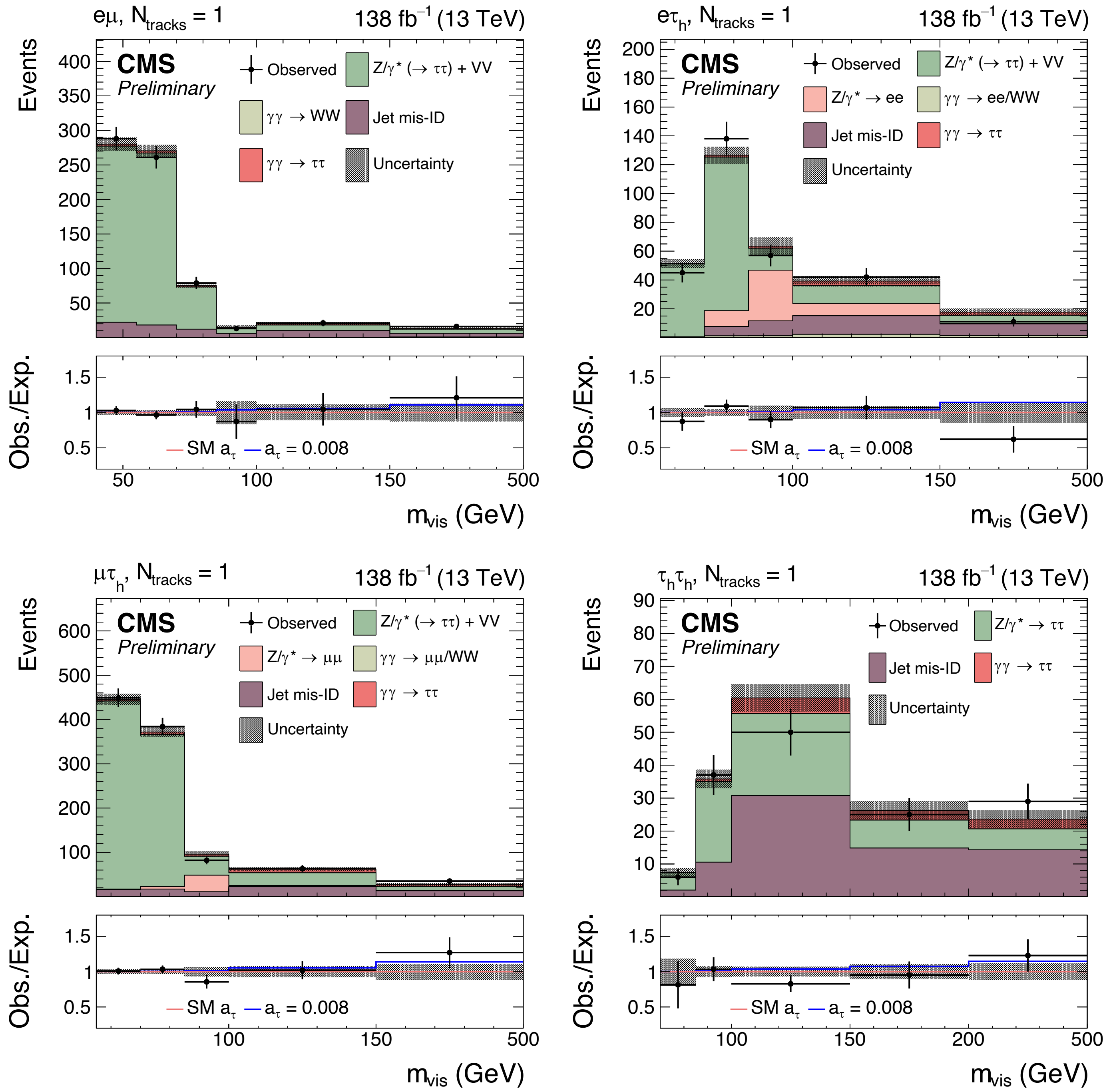
- after maximum-likelihood fit to observed data
- assuming SM a_τ & d_τ
- signal clearly visible in high $m_{vis}(\tau\tau)$ bins





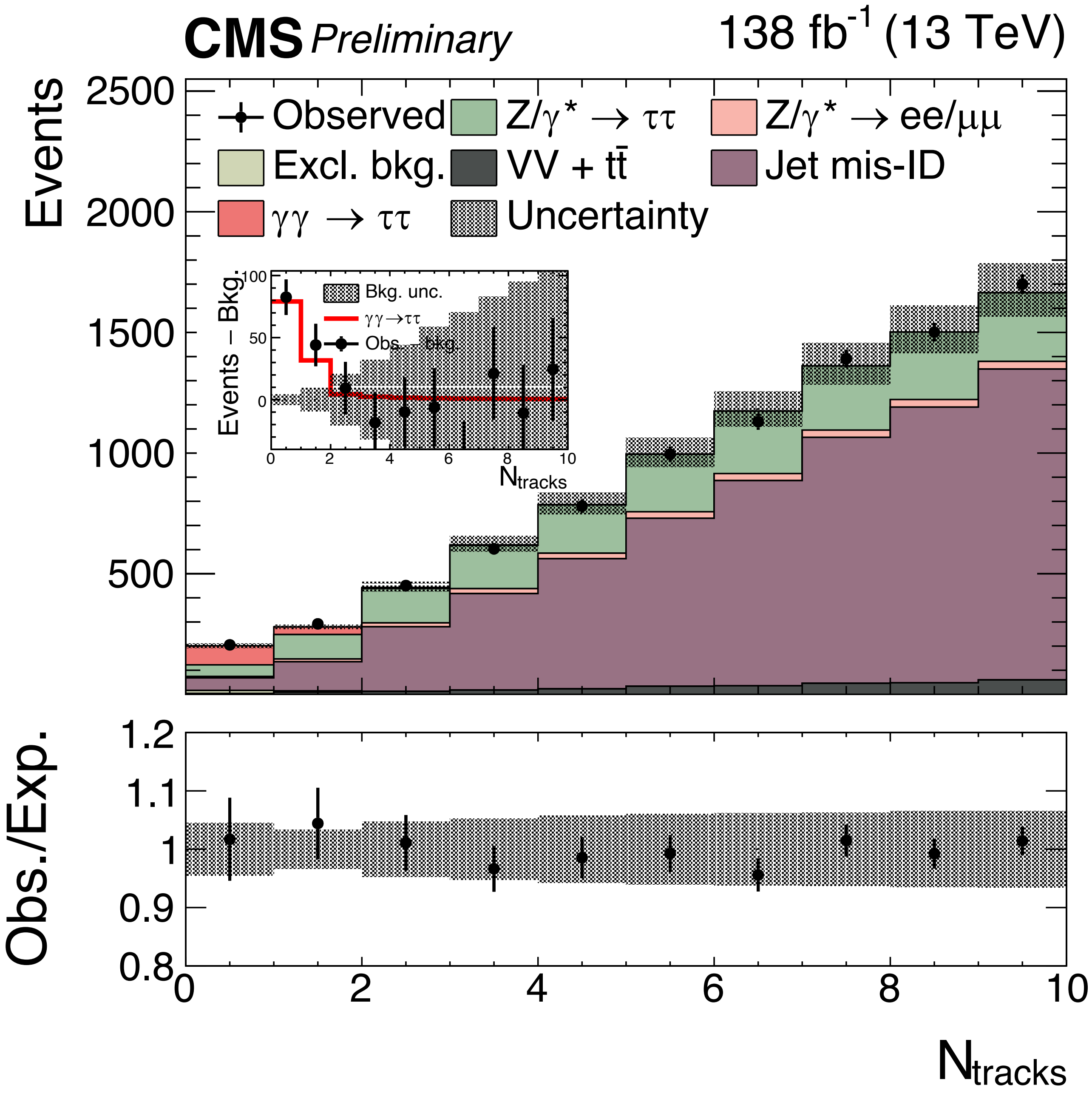
SR with N_{tracks} = 1

- after maximum-likelihood fit to observed data
- assuming SM a_τ & d_τ
- lower signal efficiency, but
  - still adds sensitivity
  - allows for validation of background modeling



N_{tracks} distributions

- same selections as SR, but
  - allowing N_{track} < 10
  - **m_{vis} > 100 GeV**
- combination of
  - all $\tau\tau$ channels
  - all data-taking years
- very nice modeling of N_{track} !
- signal clearly visible



First observation of $\gamma\gamma \to \tau\tau$ in pp collisions !

- combined observed significance of **5.3σ** (6.5σ expected) assuming SM a_τ

  ⇒ *first* observation of $\gamma\gamma \to \tau\tau$ in pp !

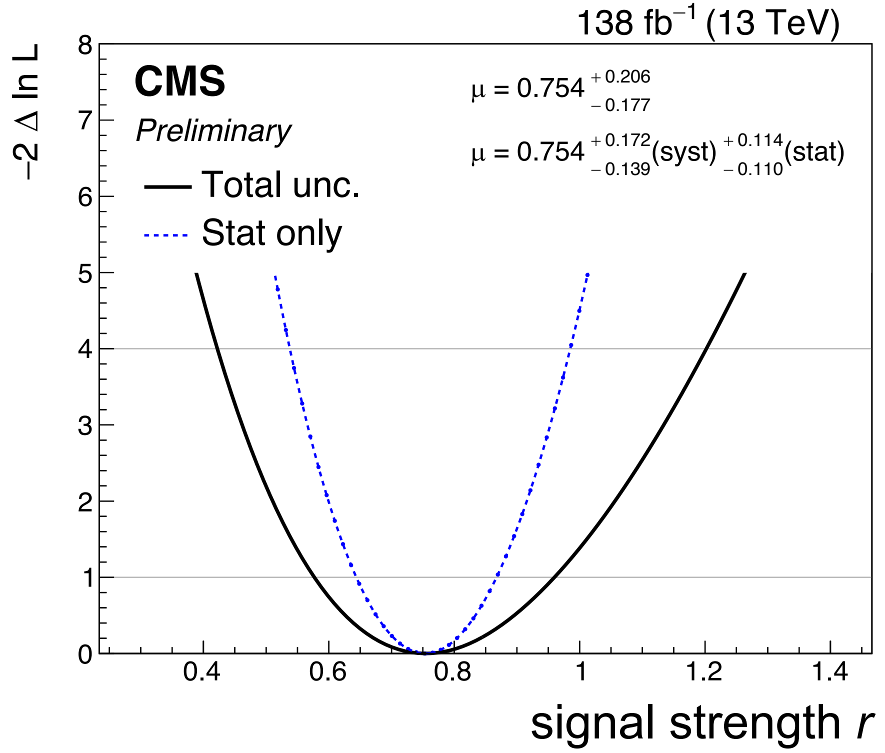
- combined **signal strength**

  r = 0.75 +0.21 –0.18

  w.r.t. gammaUPC elastic prediction

  × rescaling measured in $\mu\mu$ data

$\tau\tau$ channel	Observed	Expected
$e\mu$	2.3σ	3.2σ
$e\tau_h$	3.0σ	2.1σ
$\mu\tau_h$	2.1σ	3.9σ
$\tau_h\tau_h$	3.4σ	3.9σ
Combined	5.3σ	6.5σ



RESULTS

Contraints on a_τ & d_τ

EFT interpretation to contrain a_τ

- previous analyses used form factors (DELPHI, ATLAS, CMS), but we use an SMEFT approach (equivalent for $q^2 \to 0$)
- deviations of δa_τ & δd_τ from the SM can be parametrized in terms of a BSM Lagrangian with dim-6 operators with NP scale Λ:

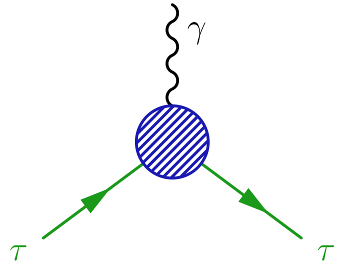
$$\mathcal{L}_{\mathrm{BSM}} = \bar{L}_\tau \sigma^{\mu\nu} \tau_R H \left[\frac{C_{\tau B}}{\Lambda^2} B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2} W_{\mu\nu} \right]$$

- contributions to a_τ & d_τ are linearly dependent to the *complex* Wilson coefficients:

$$\delta a_\tau = \frac{2m_\tau}{e} \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Re}[\cos\theta_W \, C_{\tau B} - \sin\theta_W \, C_{\tau W}]$$

$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Im}[\cos\theta_W \, C_{\tau B} - \sin\theta_W \, C_{\tau W}]$$

- scan a_τ & d_τ values in $\gamma\gamma \to \tau\tau$ signal samples:
  - by scanning $C_{\tau B}$ and $C_{\tau W}$ in matrix element reweighting
  - varying a_τ or d_τ changes the cross section and $m_{\tau\tau}$ distribution
  - we fix $\Lambda = 2\ \mathrm{TeV}$ (although result *independent* of choice of Λ)

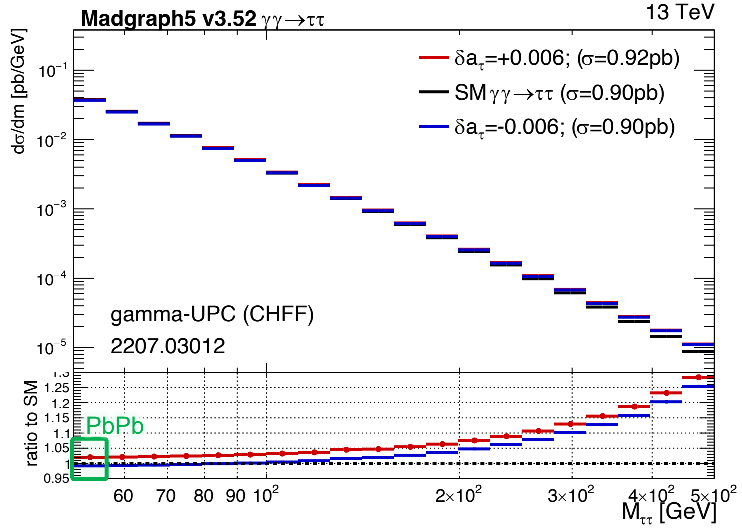


$a_\tau^{\mathrm{SM}} \approx 0.001\,177$

$a_\tau = \frac{g-2}{2} = a_\tau^{\mathrm{SM}} + \delta a_\tau$

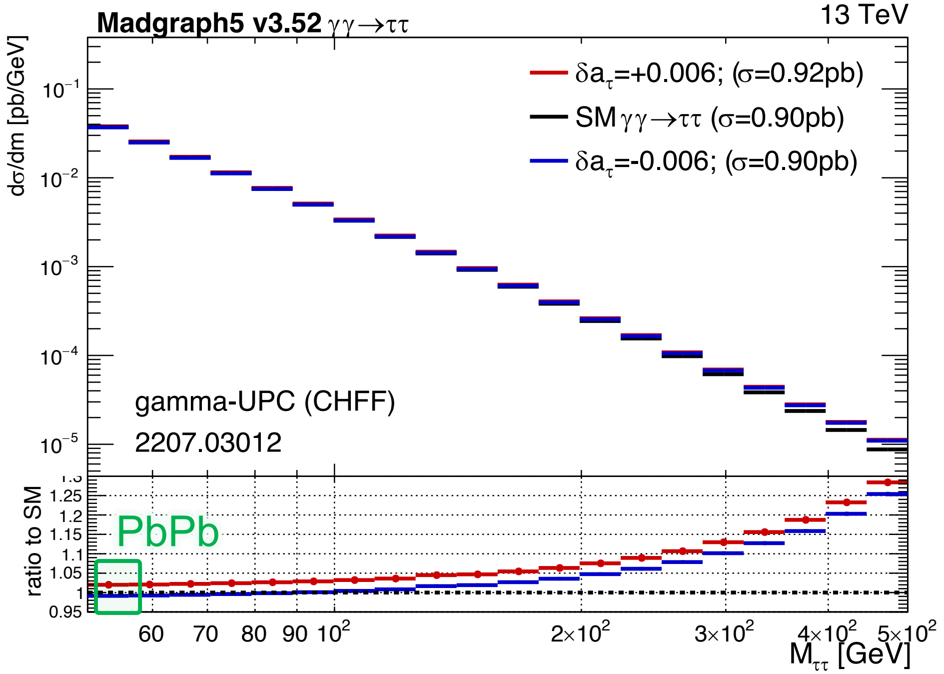
CP violation in CKM:
$d_\tau^{\mathrm{SM}} \approx 10^{-37}\ \mathrm{ecm}$

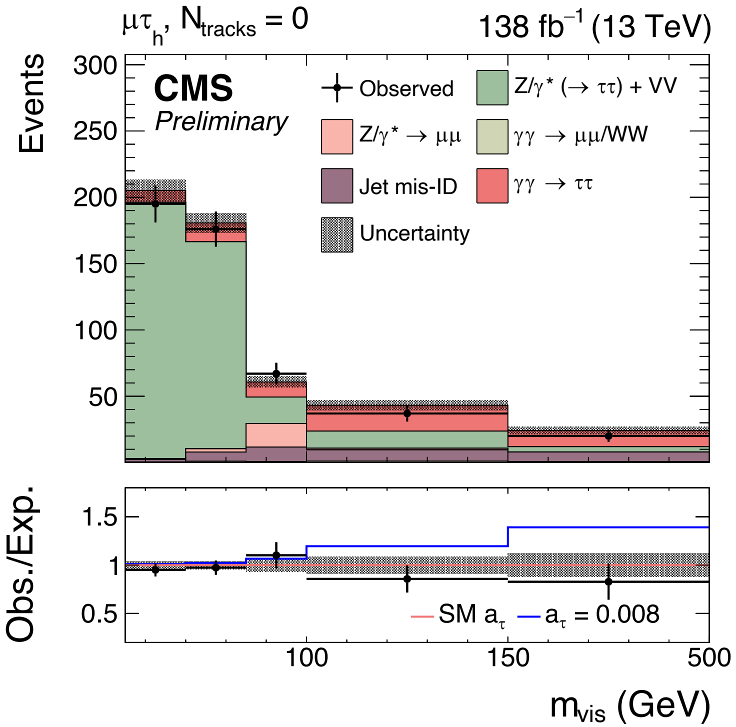
some BSMs predict:
$d_\tau \approx 10^{-19}\ \mathrm{ecm}$



How BSM in a_τ affects $\gamma\gamma \rightarrow \tau\tau$

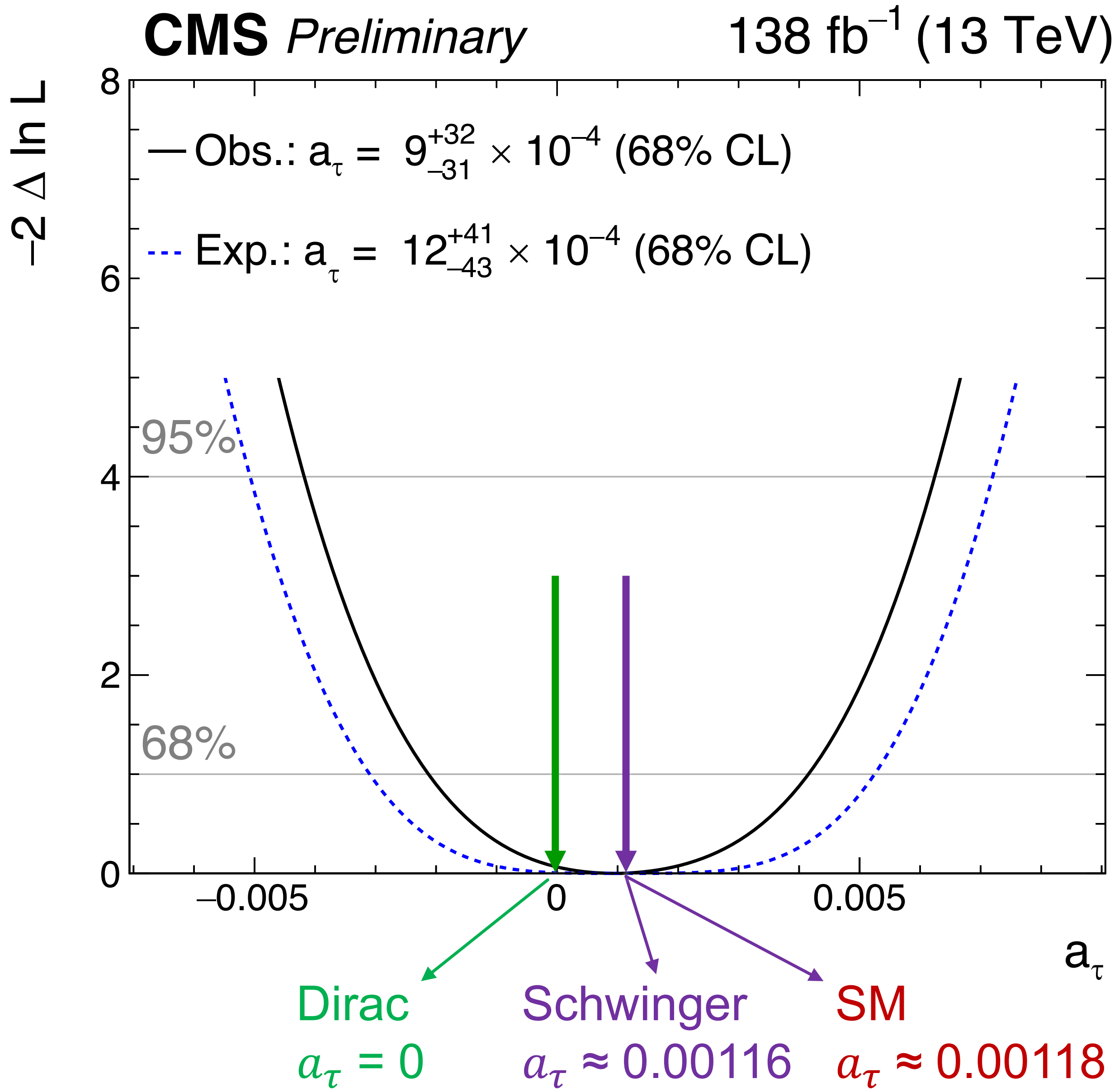
- at $m_{\tau\tau}$ > 100 GeV:
  - cross section grows with $m_{\tau\tau}$
  - for both $\delta a_\tau > 0$ & $\delta a_\tau < 0$
- constrain a_τ by measuring the **yield** *and* $\boldsymbol{m_{\tau\tau}}$ distribution of $\gamma\gamma \rightarrow \tau\tau$
- pp data looks at $m_{\tau\tau}$ > 50 GeV
  ⇒ better sensitivity than PbPb !





differences increase with $m_{\tau\tau}$

Constraints on a_τ



- fit all $m_{\tau\tau}$ distributions
- scan likelihood over a_τ
- small $\gamma\gamma \to \tau\tau$ deficit observed
  ⇒ tighter contrain than expected
- but compatible with the SM

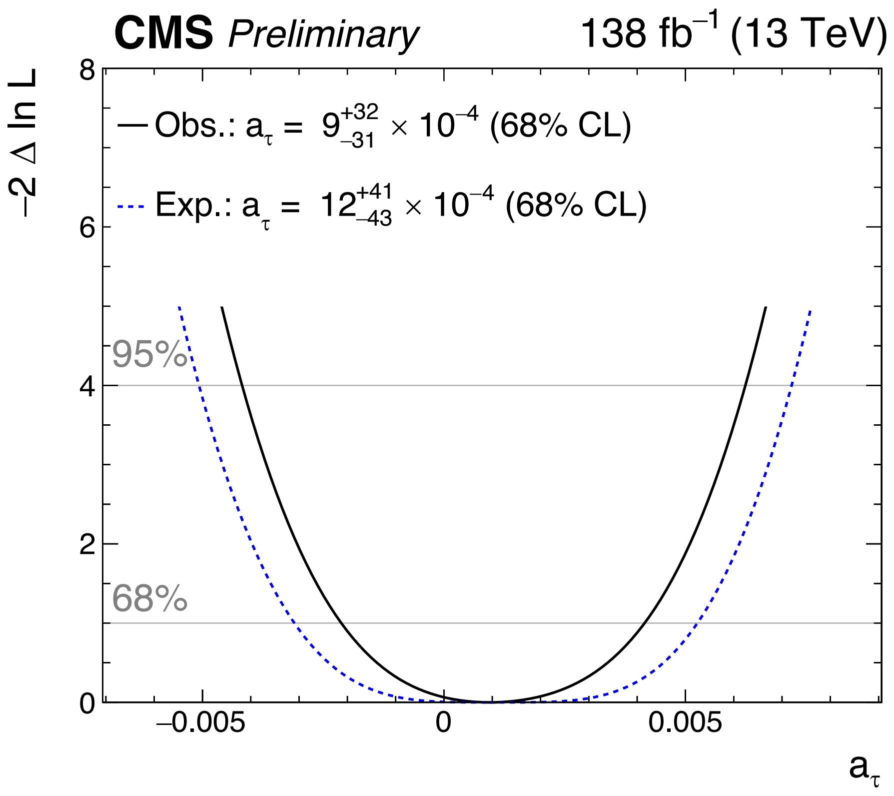
Schwinger: $a_\tau = 0.001\,161\,4$

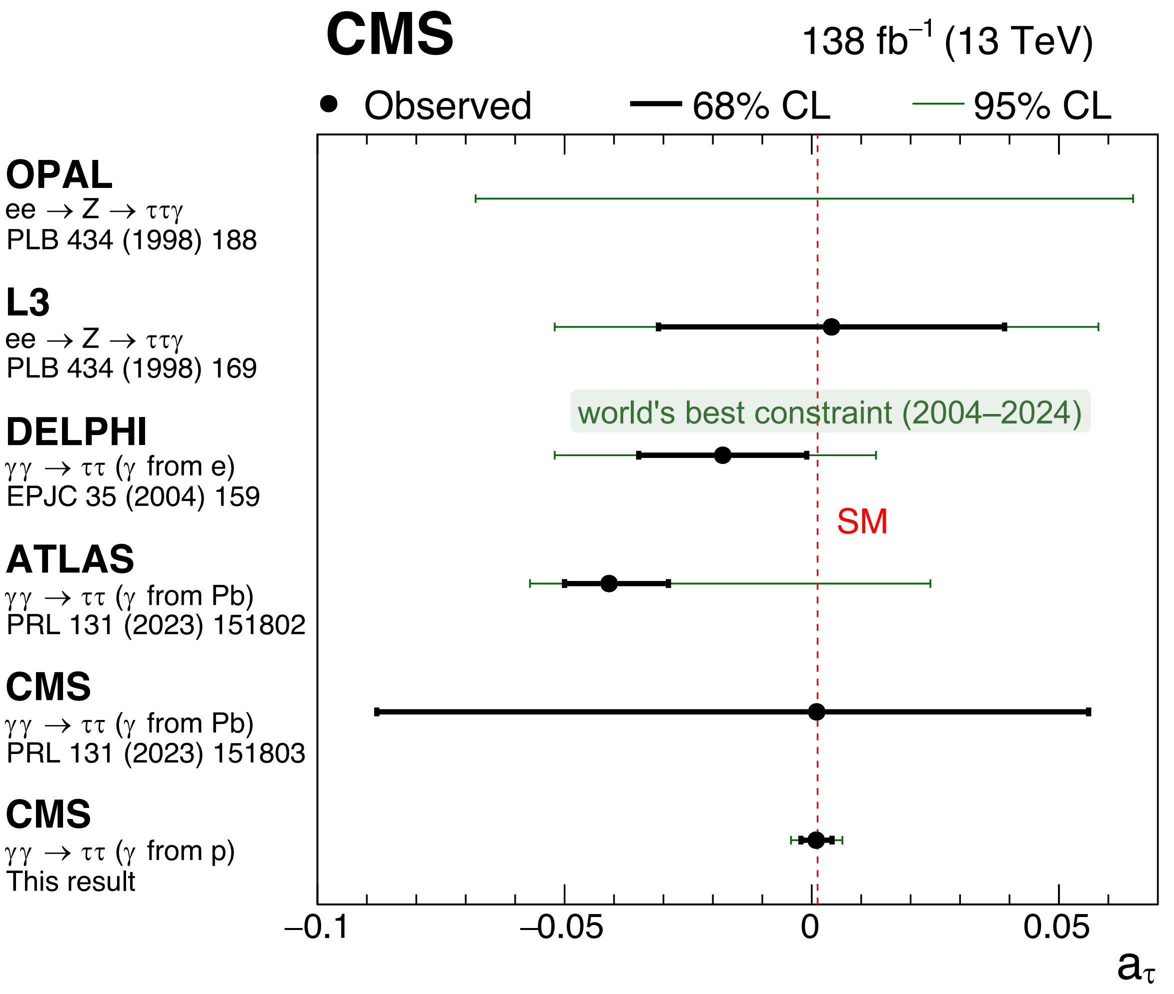
SM: $a_\tau = 0.001\,177\,21(5)$

our result: $a_\tau = 0.0009\,(32)$

⇒ uncertainty ~3 × Schwinger !

Constraints on a_τ

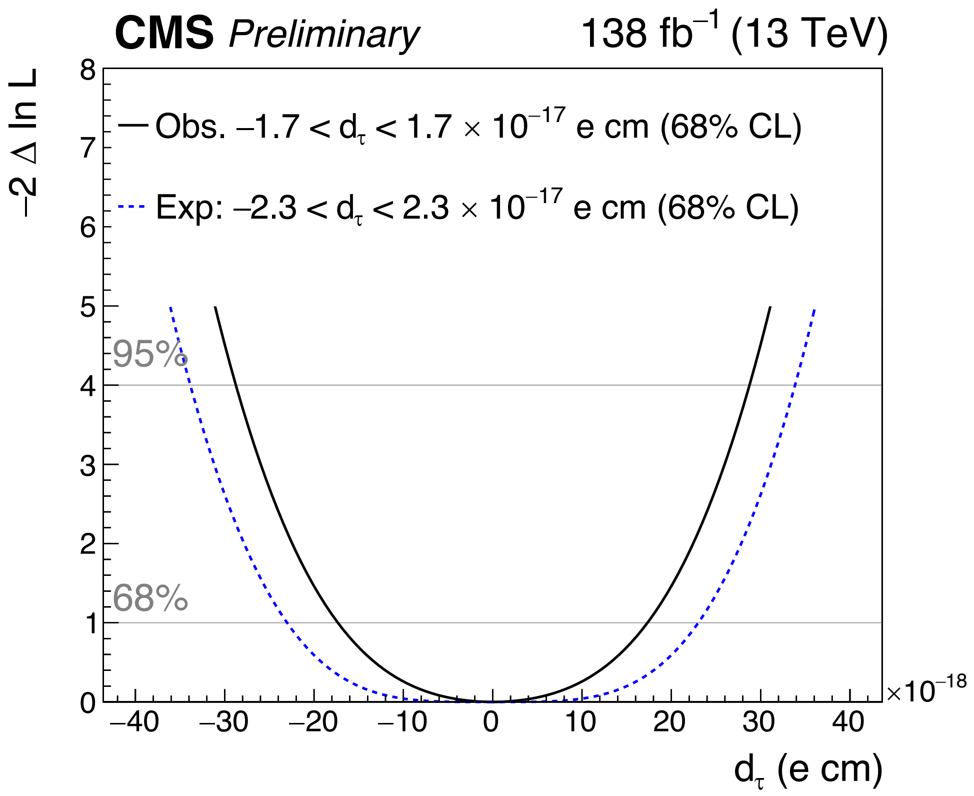


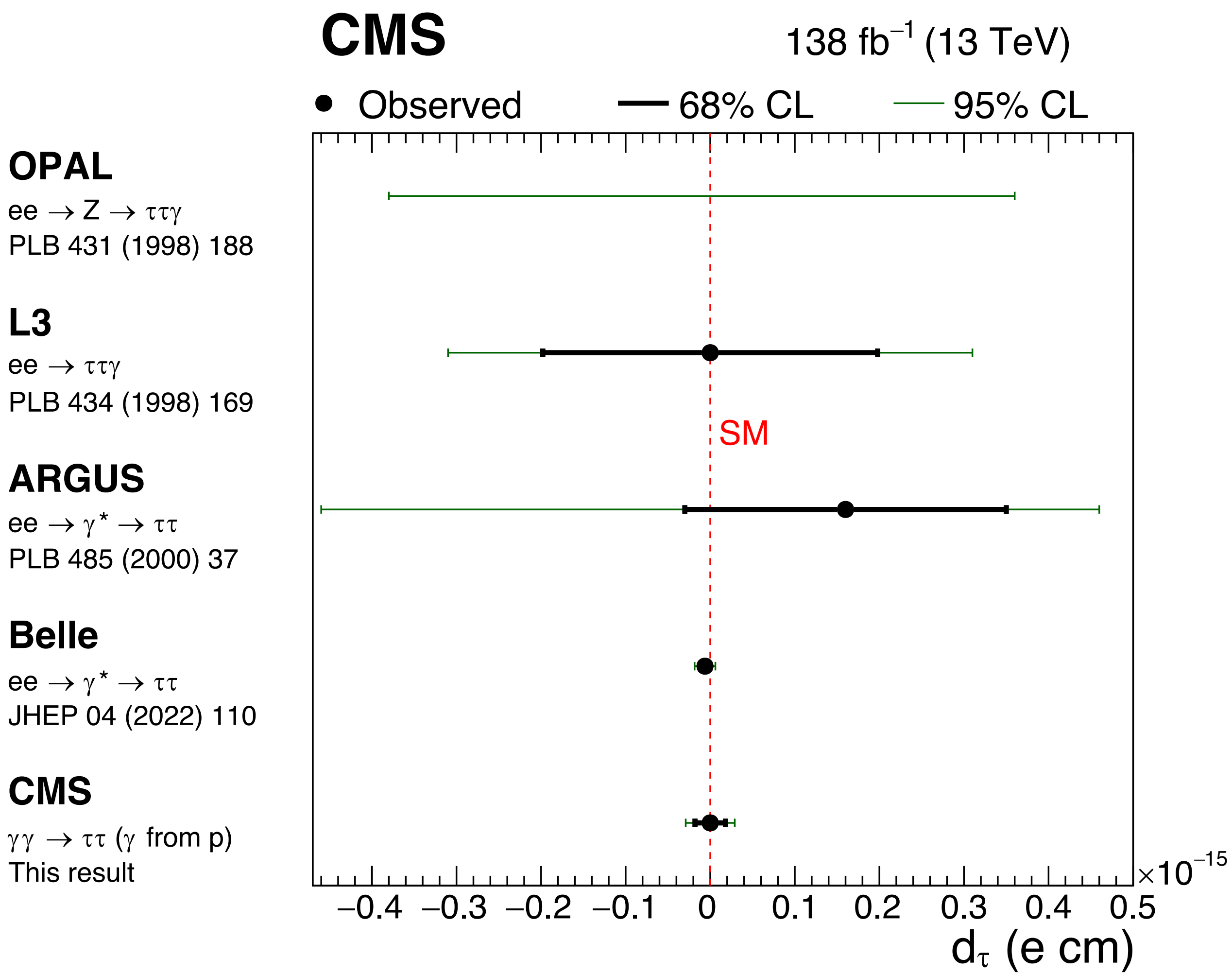


- SM: $a_\tau = 0.001\,177\,21(5)$
- DELPHI: $a_\tau = -0.018 \pm 0.017$
- ATLAS: $a_\tau = -0.041 +0.012 -0.009$
- CMS HIN: $a_\tau = 0.001 +0.055 -0.089$
- our result: $a_\tau = 0.0009 +0.0032 -0.0031$

~2.7x above SM, >5x better than LEP !

Constraints on d_τ

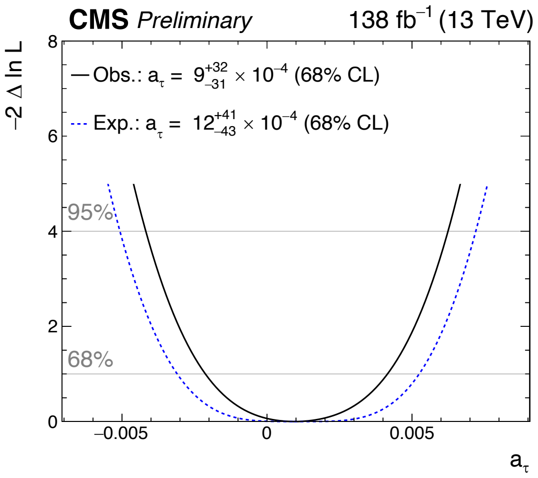


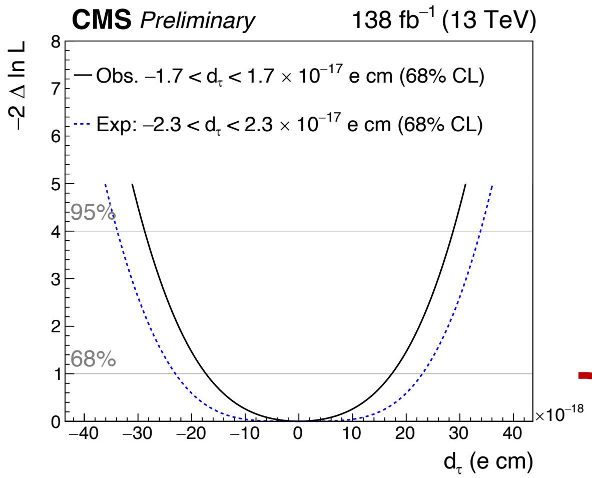


- SM: $d_\tau \sim 10^{-37}$ ecm (due to CPV in CKM)
- Belle: $-1.85 < d_\tau < 0.61 \times 10^{-17}$ ecm (95%)
- our result: $-1.70 < d_\tau < 1.70 \times 10^{-17}$ ecm (68%)

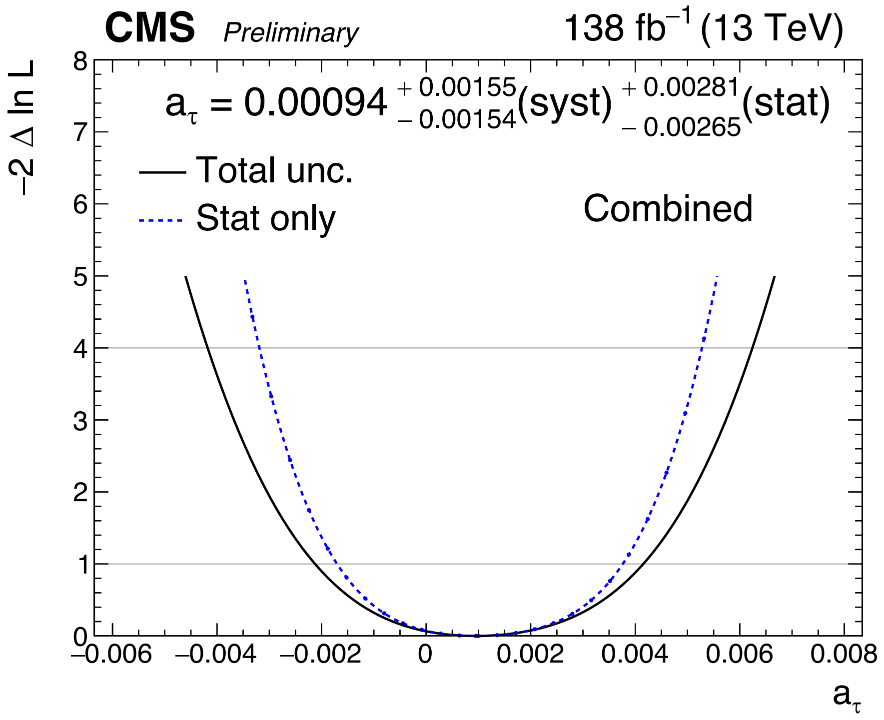
approaching Belle !

NLL breakdown by stat. & syst.

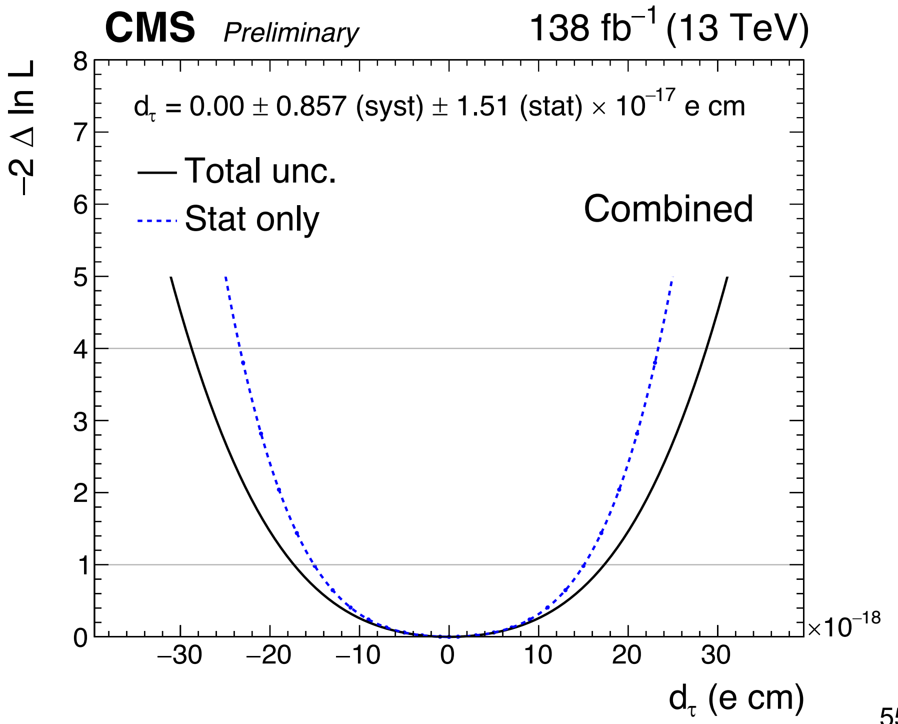




measurements mostly statistically limited !



breakdowns of likelihood profiles into **stat.** & **syst.** components



Constraints on Wilson coefficients

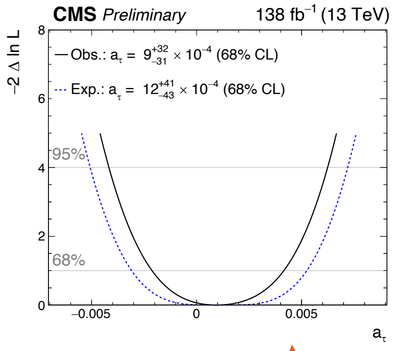
$a_\tau = a_\tau^{SM} + \delta a_\tau = \frac{g-2}{2}$

$d_\tau = d_\tau^{SM} + \delta d_\tau$

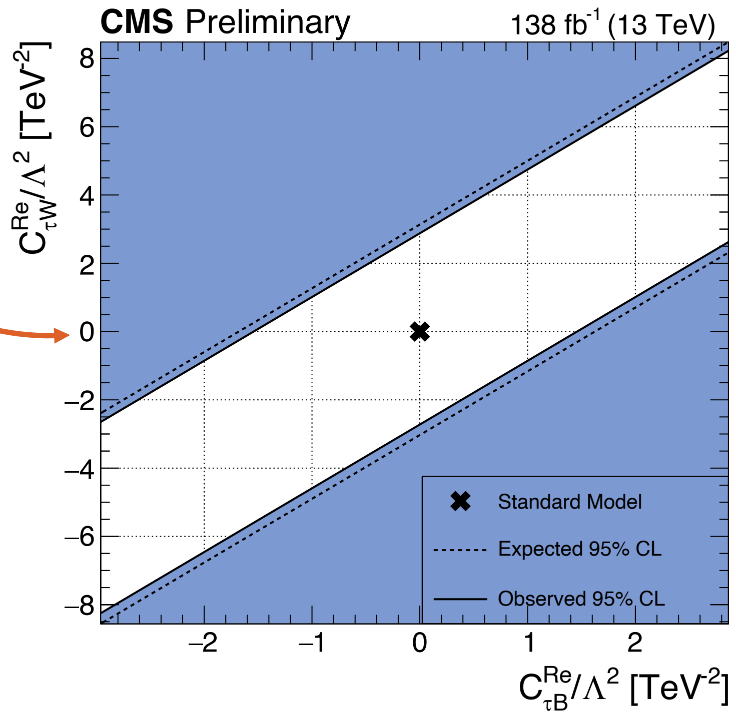
recast results to make exclusion of $C_{\tau B}/\Lambda^2$ vs. $C_{\tau W}/\Lambda^2$:

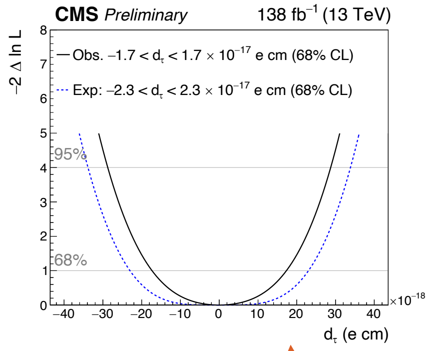
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathbf{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathbf{Im}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

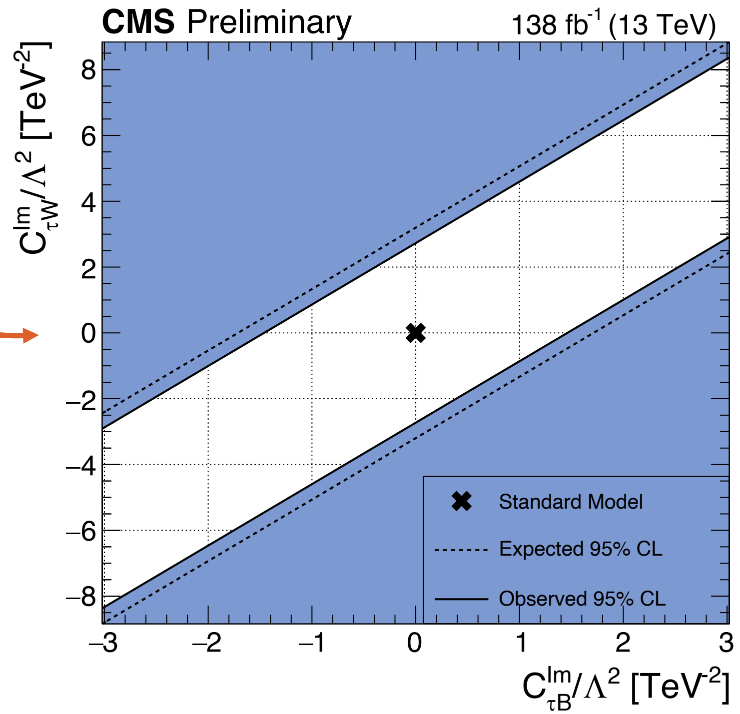


real part:

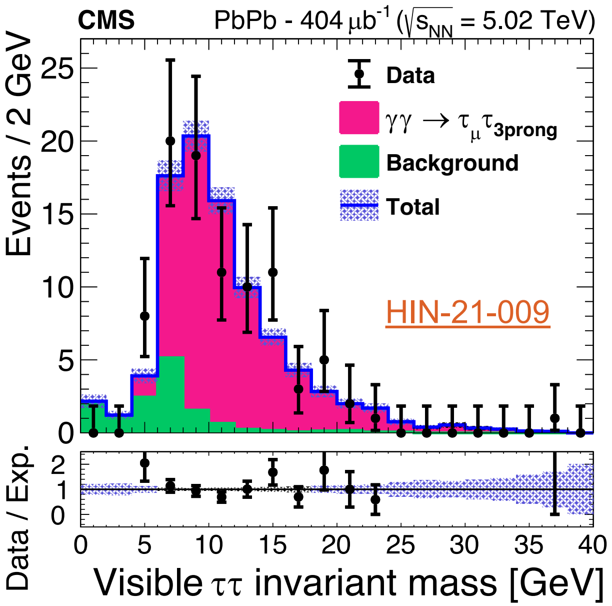


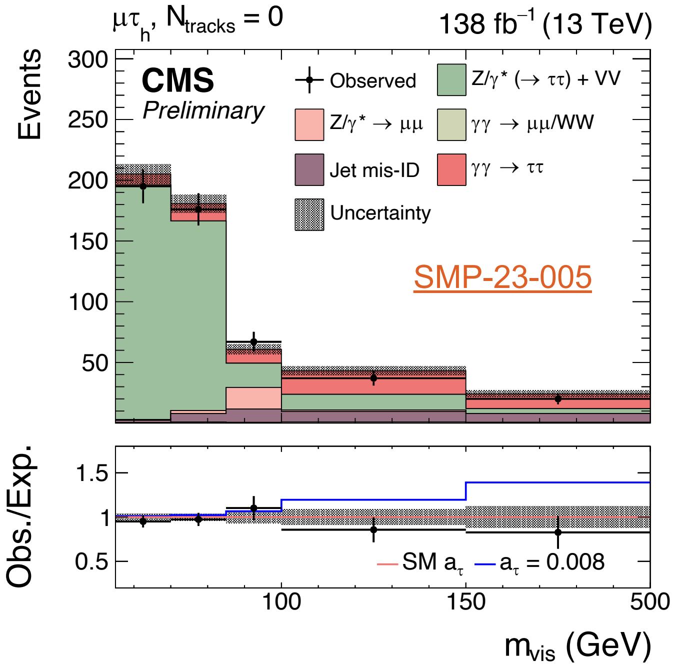


imaginary part:

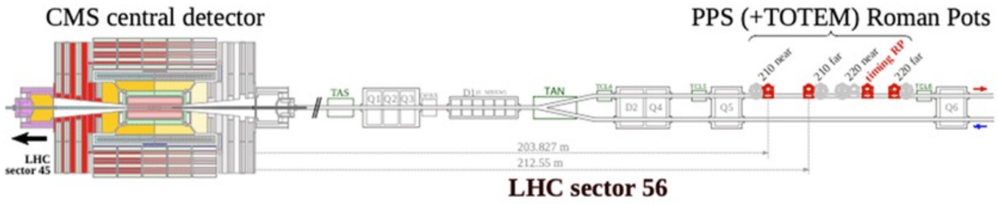


Bigger picture





Precision Proton Spectrometer



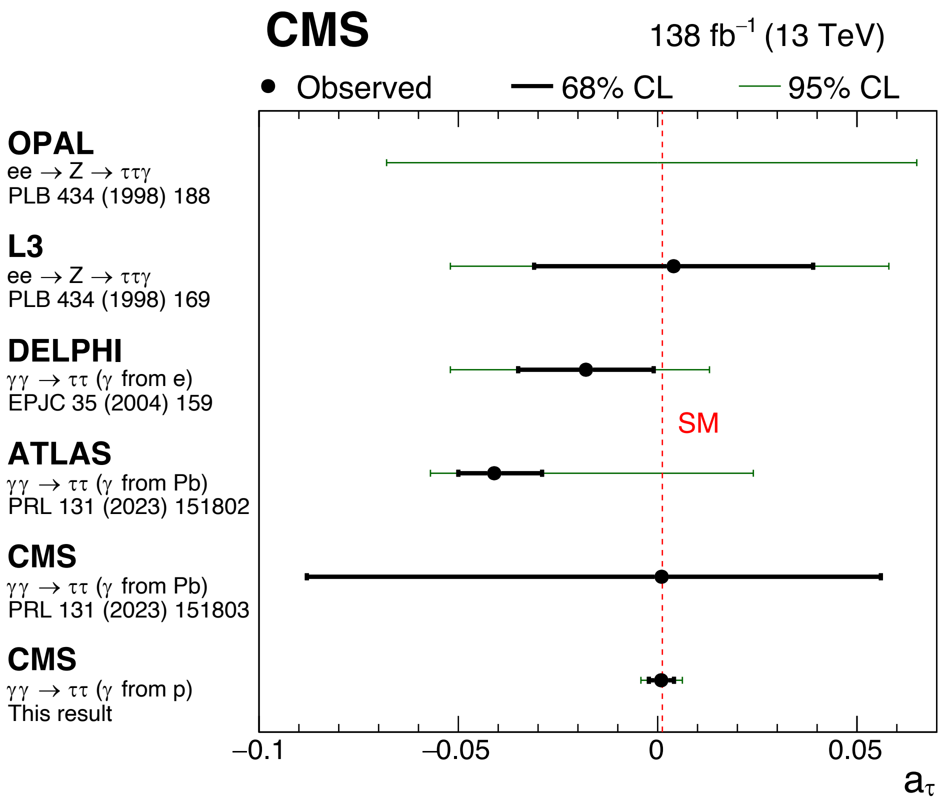
ultra-peripheral PbPb | pp with track counting | pp with forward proton tagging

0 GeV | 50 GeV | 350 GeV | 2 TeV

SUMMARY

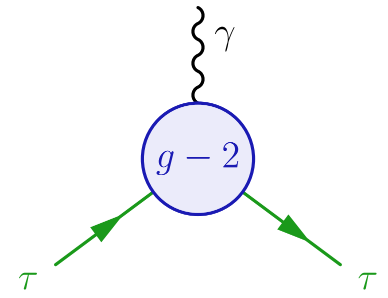
Summary

- measuring the electromagnetic momenta the electron and muon has a long & interesting history
  - **$(g-2)_e$ @ 0.13 ppt** in Penning traps
  - **$(g-2)_\mu$ @ 0.20 ppm** in cyclotrons
- **$(g-2)_\tau$** has strong potential to search new physics
- new preliminary result in **pp** by CMS (SMP-23-005) puts strong contraints on a_τ & d_τ
  - using exclusivity cuts on **acoplanarity** & N_{tracks}
  - from shape and yield in $m_{\tau\tau}$ > 50 GeV
  - full Run-2 UL data analyzed in 4 $\tau\tau$ final states
- first-time observation of $\gamma\gamma \to \tau\tau$ process in pp (5.3σ) and constraints on
  - a_τ: > 5x better than LEP
  - d_τ: same order as Belle



a_τ = 0.0009 +0.0032 –0.0031

g_τ = 2.0018 +0.0064 –0.0062 (0.3%)



References

Theory & phenomenology

- gammaUPC (2022) arXiv:2207.03012
- Beresford, Liu (2020) arXiv:1908.05180
- Dynal et al. (2020) arXiv:2002.05503
- Haisch et al. (2023) arXiv:2307.14133
- Beresford et al (2024) arXiv:2403.06336

Experiment

- a_e Penning Trap (2023) arXiv:2209.13084
- a_μ FNAL (2023) arXiv:2308.06230
- a_τ DELPHI (2004) arXiv:hep-ex/0406010
- d_τ Belle (2022) arXiv:2108.11543
- $\gamma\gamma \to$ WW ATLAS (2021) arXiv:2010.04019
- $\gamma\gamma \to$ ee ATLAS (2023) arXiv:2207.12781
- $\gamma\gamma \to$ tt CMS (2023) arXiv:23w10.11231

$(g-2)_\tau$ with UPC PbPb ($m_{\tau\tau}$ < 50 GeV):

- a_τ CMS (2022) HIN-21-009
- a_τ ATLAS (2022) STDM-2019-19

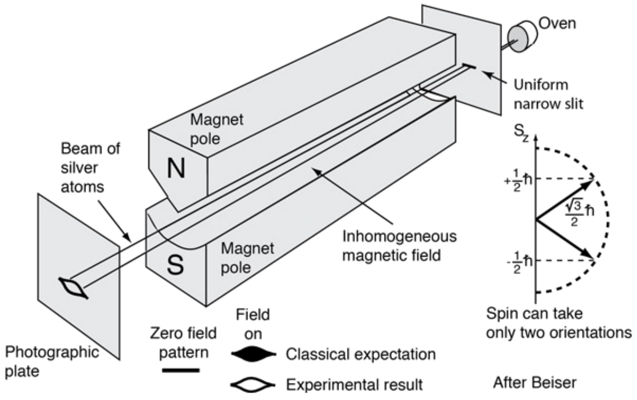
$(g-2)_\tau$ with pp (50 < $m_{\tau\tau}$ < 500 GeV):

- a_τ CMS (2024) PAS-SMP-23-005
  - talks: LHC seminar, Moriond
  - press: CMS, CERN, Courier

BACK UP

Quick history: Electron spin & g – 2

- **1922**: Stern & Gerlach discover Ag atoms in B field separate discretely
- **1925**: Uhlenbeck & Goudsmit introduce electron spin to explain spectroscopy (Zeeman effect)
- **1927**: Phipps & Taylor confirm electron spin in SG experiment with H atoms



- **1927**: Dirac equation predicts $g = 2$
- **1947–1951**: Kusch & Foley measure $g > 2$ with Ga atoms:

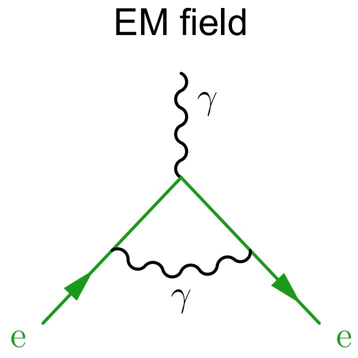
  $(g – 2)/2 = 0.001\ 19(5)$ ~ 4%
- **1948**: Schwinger computes

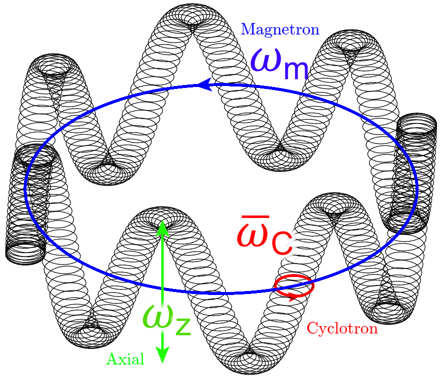
  $(g – 2)/2 \approx 0.001\ 161 = \alpha/2\pi$
- **1969**: Gräff et. al. with Penning trap

  $(g – 2)/2 = 0.001\ 159\ 66(30)$ ~ 300 ppm
- **1987**: Dehmelt et. al. improve

  $(g – 2)/2 = 0.001\ 159\ 652\ 188\ 4(43)$ ~ 4 ppt
- **2006–2008**: Gabrielse et. al. improve

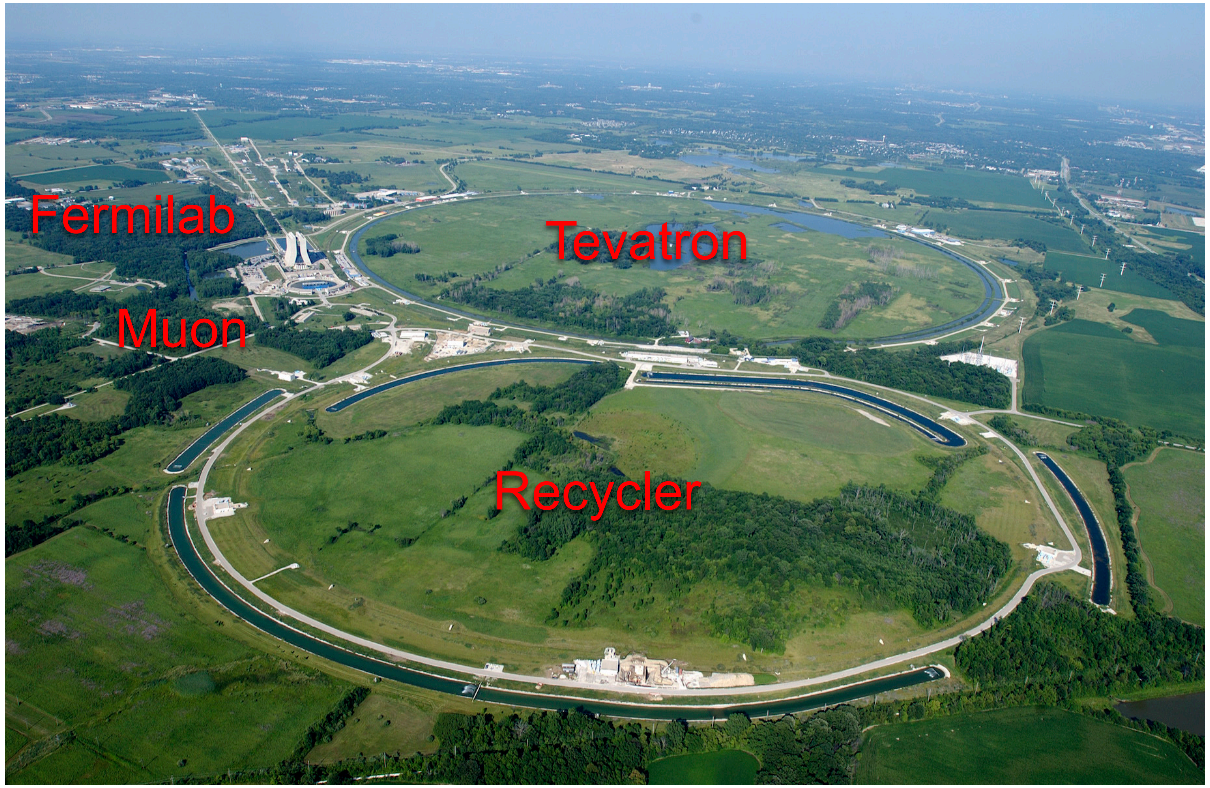
  $(g – 2)/2 = 0.001\ 159\ 652\ 180\ 73(28)$ ~ 0.2 ppt

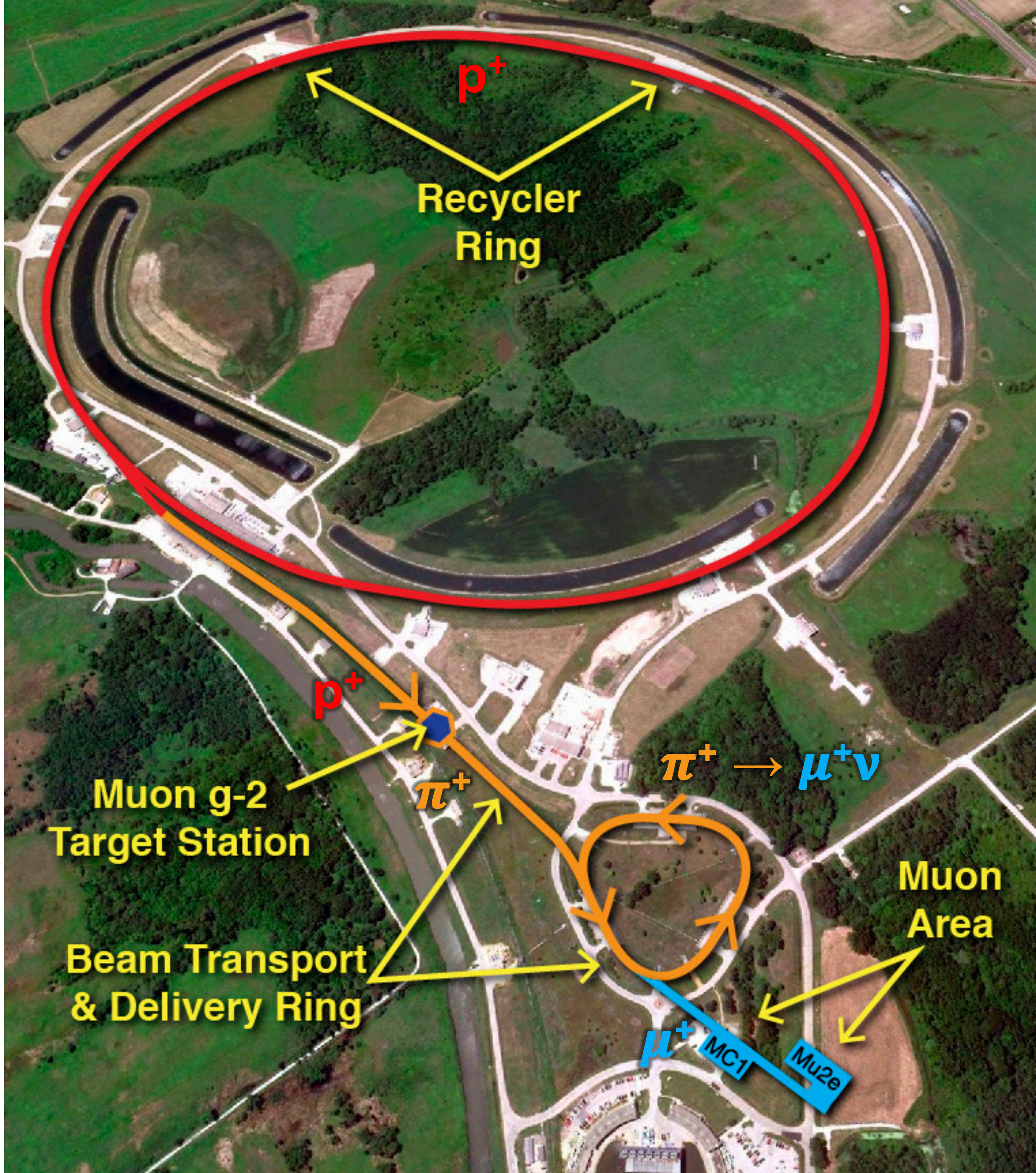




Fermilab Muon campus

- Recycler provides bunches of 10^{12} **protons** @ 8 GeV
- nickel-iron target: produce π+ @ ~ 3.11 GeV
- purify in delivery ring and let decay to polarized μ+ beam

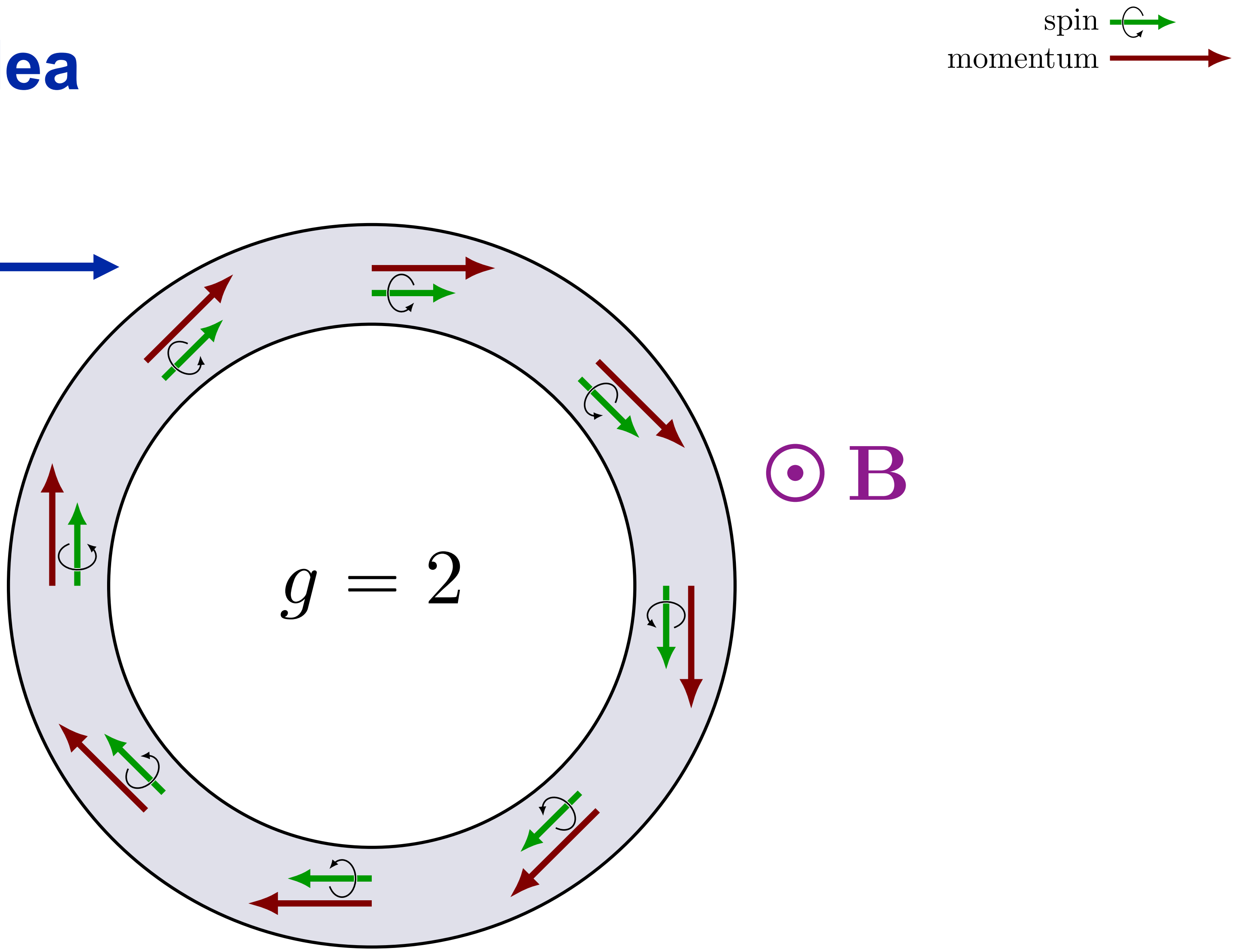




Muon g – 2 main idea

polarized μ^+ beam

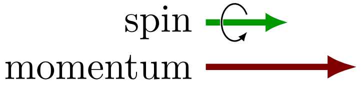
$$\omega_a = \omega_S - \omega_C = \frac{g-2}{2}\frac{e}{m_\mu}B = 0$$



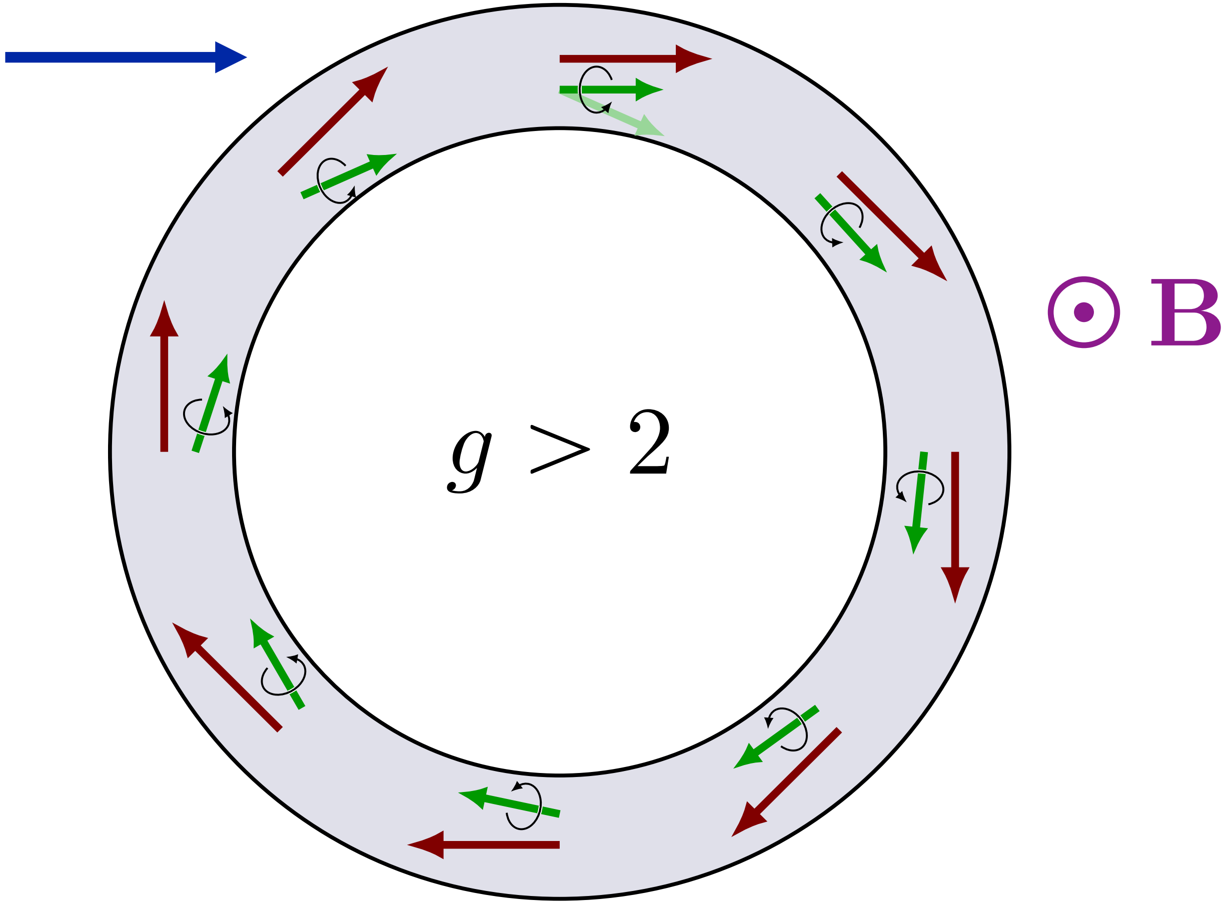
g = 2 ⇒ Larmor precession ω_S = cyclotron oscillation ω_C

$\sim 6.7\,\mathrm{MHz}$ $\sim 6.7\,\mathrm{MHz}$

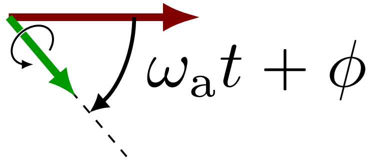
Muon g – 2 main idea



polarized μ^+ beam



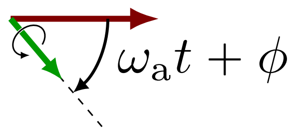
$$\omega_\mathrm{a} = \omega_\mathrm{S} - \omega_\mathrm{C}$$
$$= \frac{g-2}{2}\frac{e}{m_\mu}B$$
$$\sim 230\,\mathrm{kHz}$$



$g > 2$ ⇒ Larmor precession ω_S > cyclotron oscillation ω_C

$\sim 6.93\,\mathrm{MHz}$ $\sim 6.7\,\mathrm{MHz}$

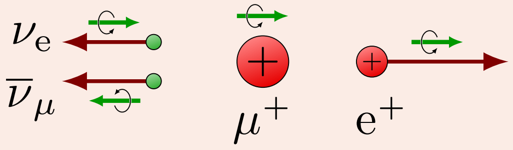
Positron measurement



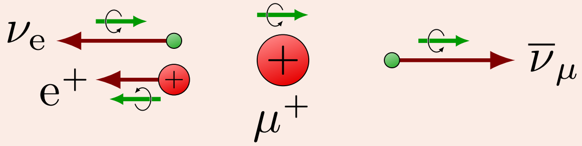
$$N(t) = N_0 e^{-t/\tau}\left(1 + A(E)\cos(\omega_a t + \phi)\right)$$

rest frame

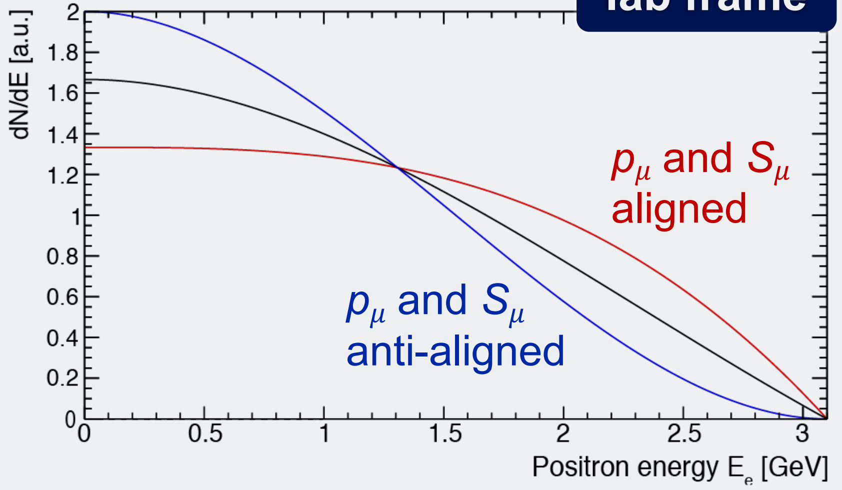
e^+ parallel:
maximal E_e

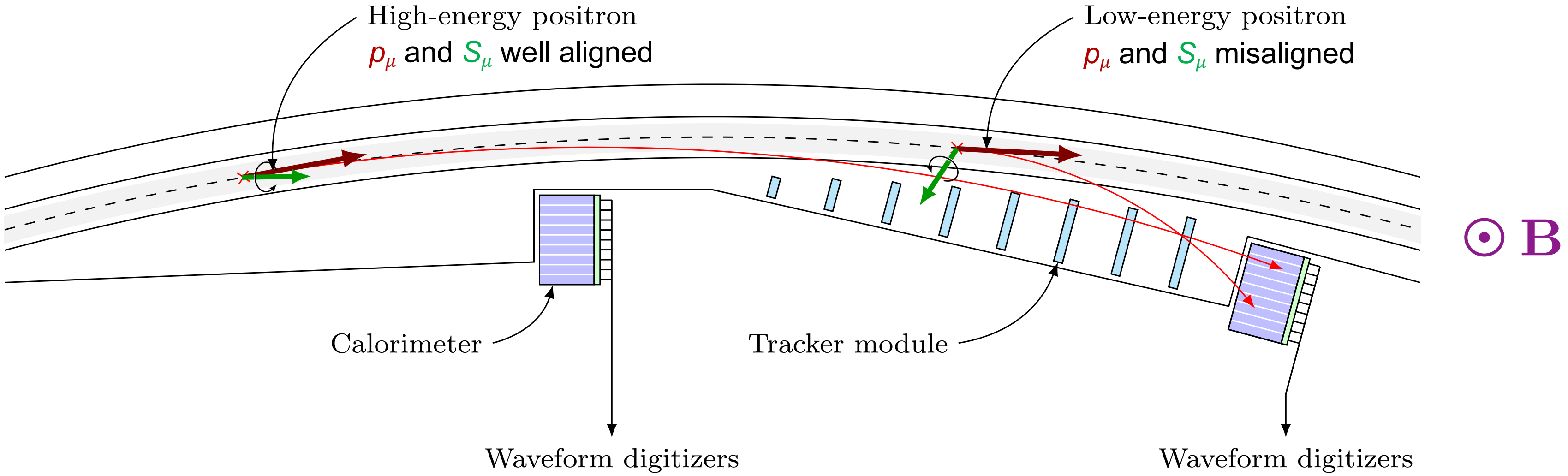


e^+ anti-parallel:
minimum E_e

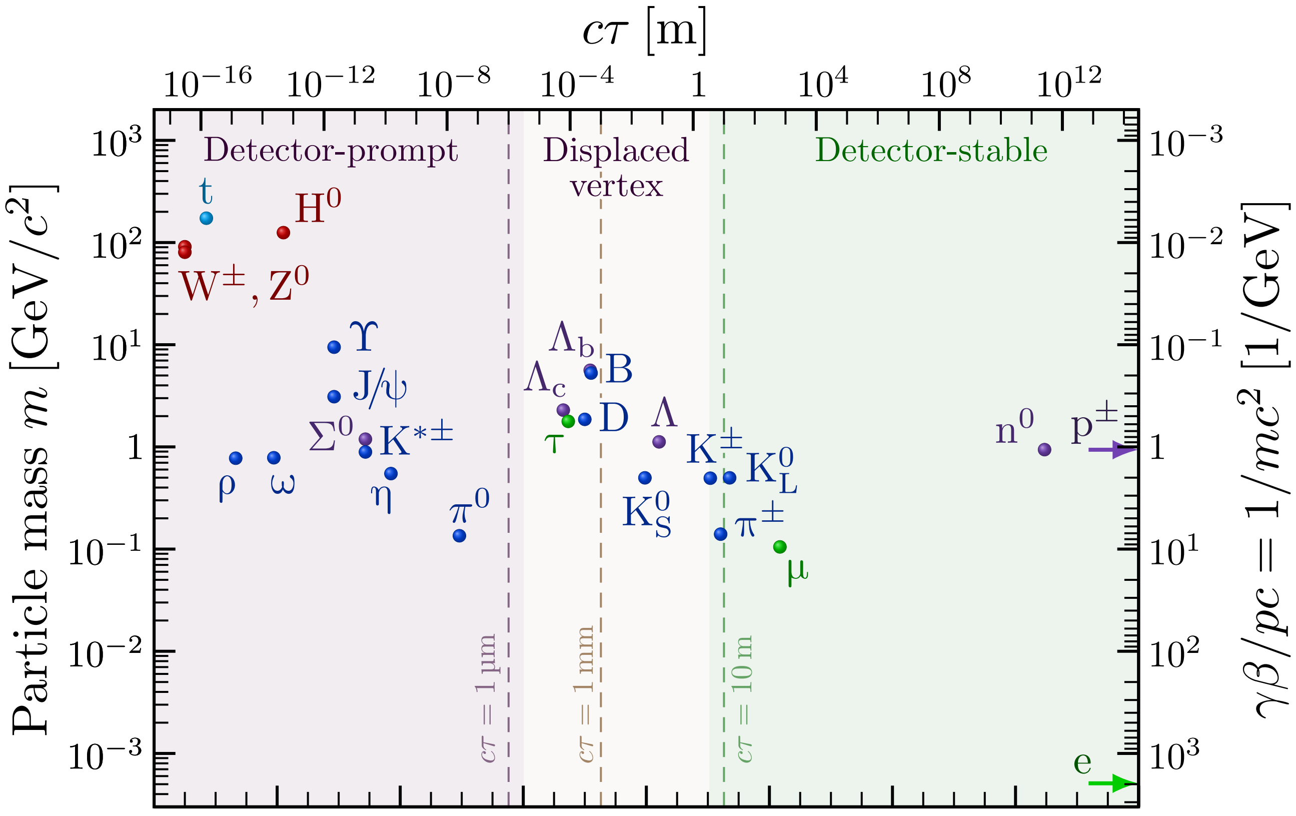


lab frame





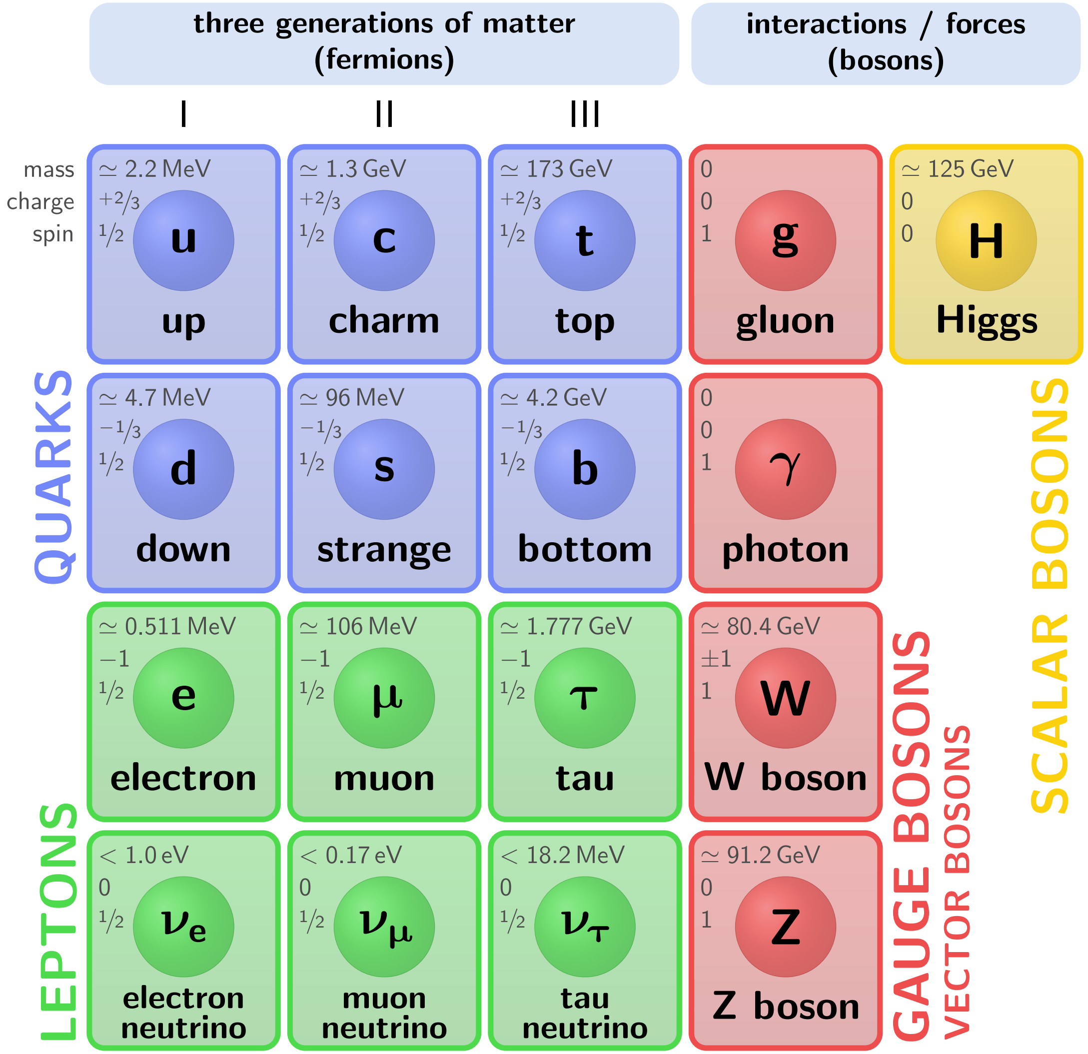
Lepton lifetimes



decay length not measureable

decay vertex displaced from production vertex

particles travel into the detector



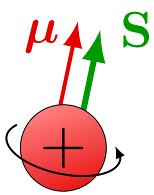
tau lifetime $\tau = 2.9 \times 10^{-13}$ s

⇒ $\gamma c\tau$ ~ **1 mm** (20 GeV)

⇒ secondary vertex

Note: time dilation: decay length L = $\gamma\beta c\tau$, with $\gamma\beta$ = p/mc

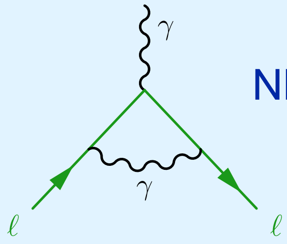
What is $g - 2$?



$$\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S} \longrightarrow \begin{cases} g = 1: & \text{classical} \\ g = 2: & \text{Dirac} \\ g \approx 2.002: & \text{QED} \end{cases}$$

- particles with spin **S** have a **magnetic moment $\boldsymbol{\mu}$**
- obtains quantum corrections with
  gyromagnetic factor / "g-factor" $\boldsymbol{g} \approx 2.002\ 32$ for spin ½

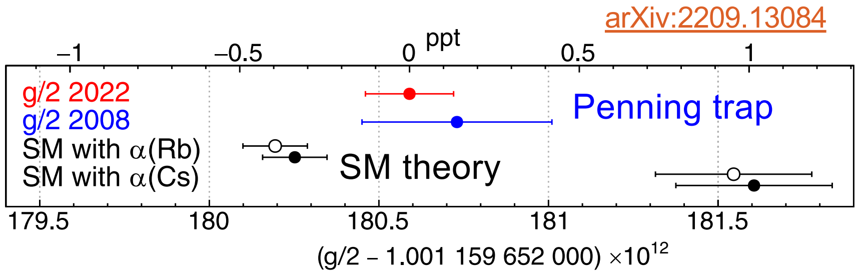
  ⇒ **anomalous magnetic moment** $\boldsymbol{a} = \frac{g-2}{2} \approx 0.001\ 16$



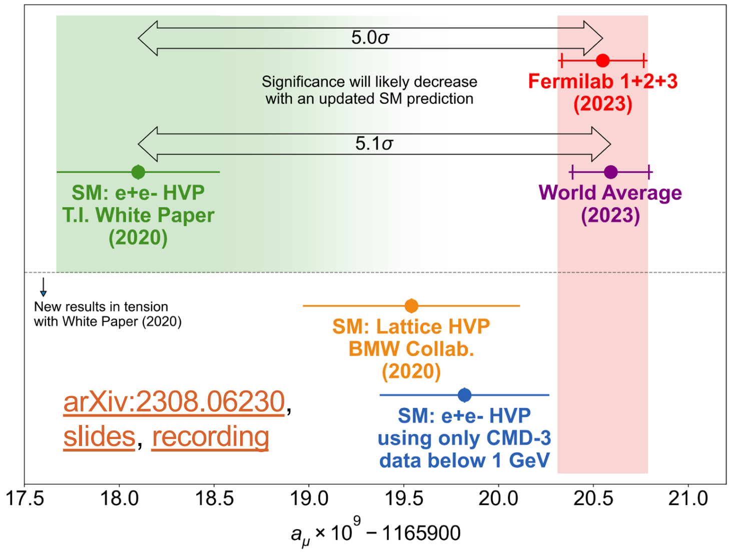
NLO correction (Schwinger)

$a = \frac{\alpha}{2\pi} \approx 0.001\ 16$

- measurements of $(g-2)_e$ in Penning traps are the "most precise in physics"



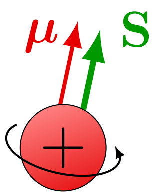
- measurements of $(g-2)_\mu$ in storage rings are in longstanding tension with theoretical computations



0.20 ppm !

BNL + FNAL

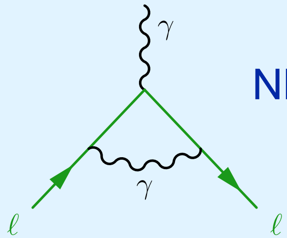
What is $g - 2$?



$$\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S} \longrightarrow \begin{cases} g = 1: \text{ classical} \\ g = 2: \text{ Dirac} \\ g \approx 2.002: \text{ QED} \end{cases}$$

- particles with spin **S** have a **magnetic moment** $\boldsymbol{\mu}$
- obtains quantum corrections with gyromagnetic factor / "g-factor" $\boldsymbol{g} \approx 2.002\ 32$ for spin ½

  ⇒ **anomalous magnetic moment** $\boldsymbol{a} = \frac{g-2}{2} \approx 0.001\ 16$

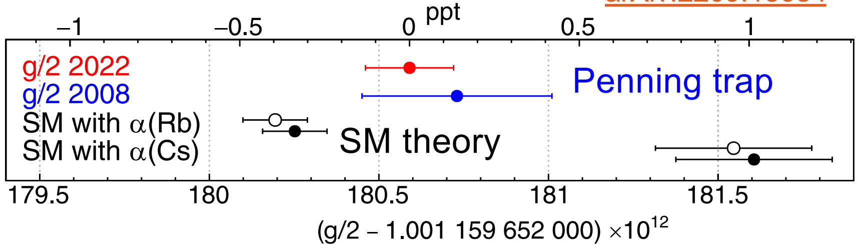


NLO correction (Schwinger)

$$a = \frac{\alpha}{2\pi} \approx 0.001\ 16$$

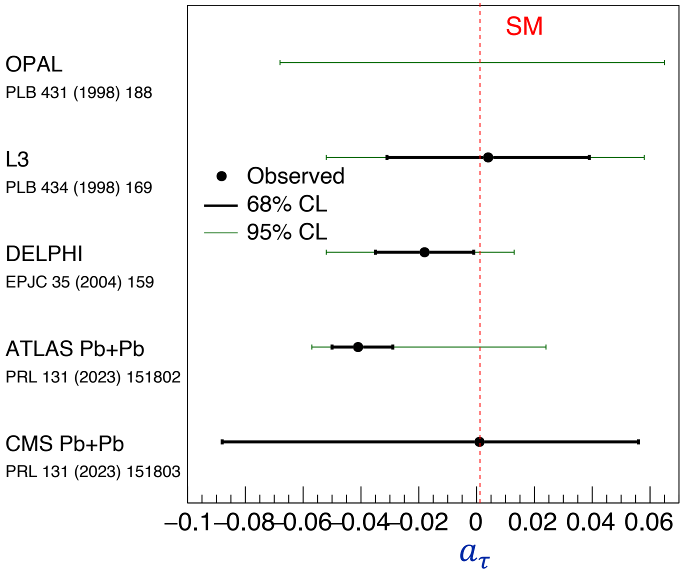
- measurements of $(\boldsymbol{g-2})_e$ in Penning traps are the "most precise in physics"

arXiv:2209.13084



- measurements of $(\boldsymbol{g-2})_\mu$ in storage rings are in longstanding tension with theoretical computations
- constraints on $(\boldsymbol{g-2})_\tau$ in e^+e^- or PbPb collisions:
  - DELPHI@LEP: $-0.052 < a_\tau < 0.013$ (95% CL)
  - CMS HIN: $-0.088 < a_\tau < 0.056$ (68% CL)
  - ATLAS HIN: $-0.057 < a_\tau < 0.024$ (95% CL)

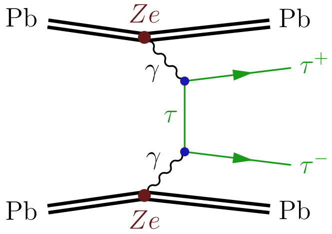
world's best since 2004



- many **BSMs** predict enhancement for $\boldsymbol{\tau}$ lepton

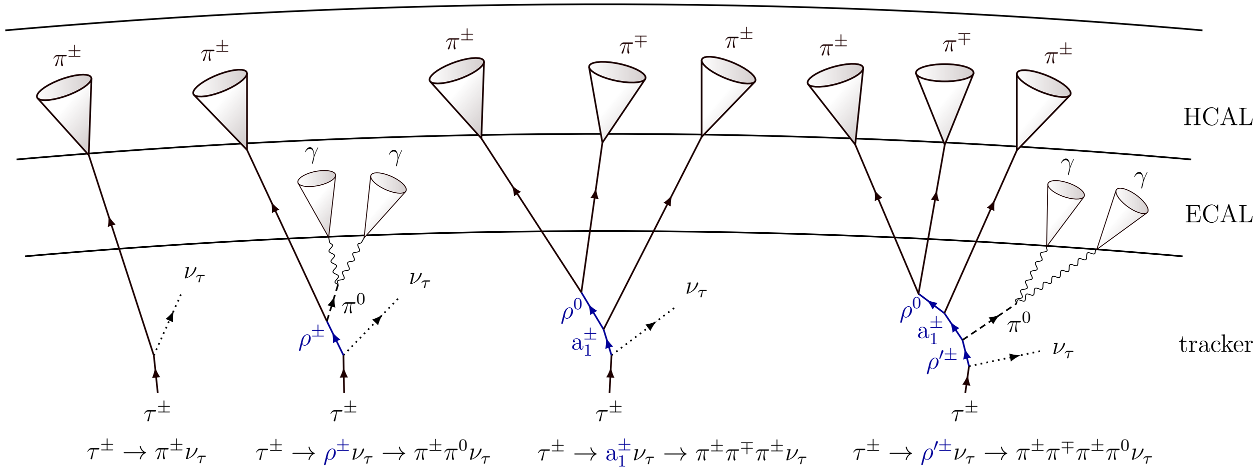
  e.g. Yukawa-like coupling: $\frac{m_\tau^2}{m_\mu^2} \approx 280$

  ⇒ probe for NP ?



Object reconstruction & selection

- **e**: MVA WP80, p_T > 15 GeV, $|\eta|$ < 2.5
- $\boldsymbol{\mu}$: medium ID, medium isolation, p_T > 10 GeV, $|\eta|$ < 2.4
- $\boldsymbol{\tau_h}$: HPS, p_T > 30 GeV, $|\eta|$ < 2.3, DeepTau v2p1 (VSe, VSmu, VSjet), four decay modes:

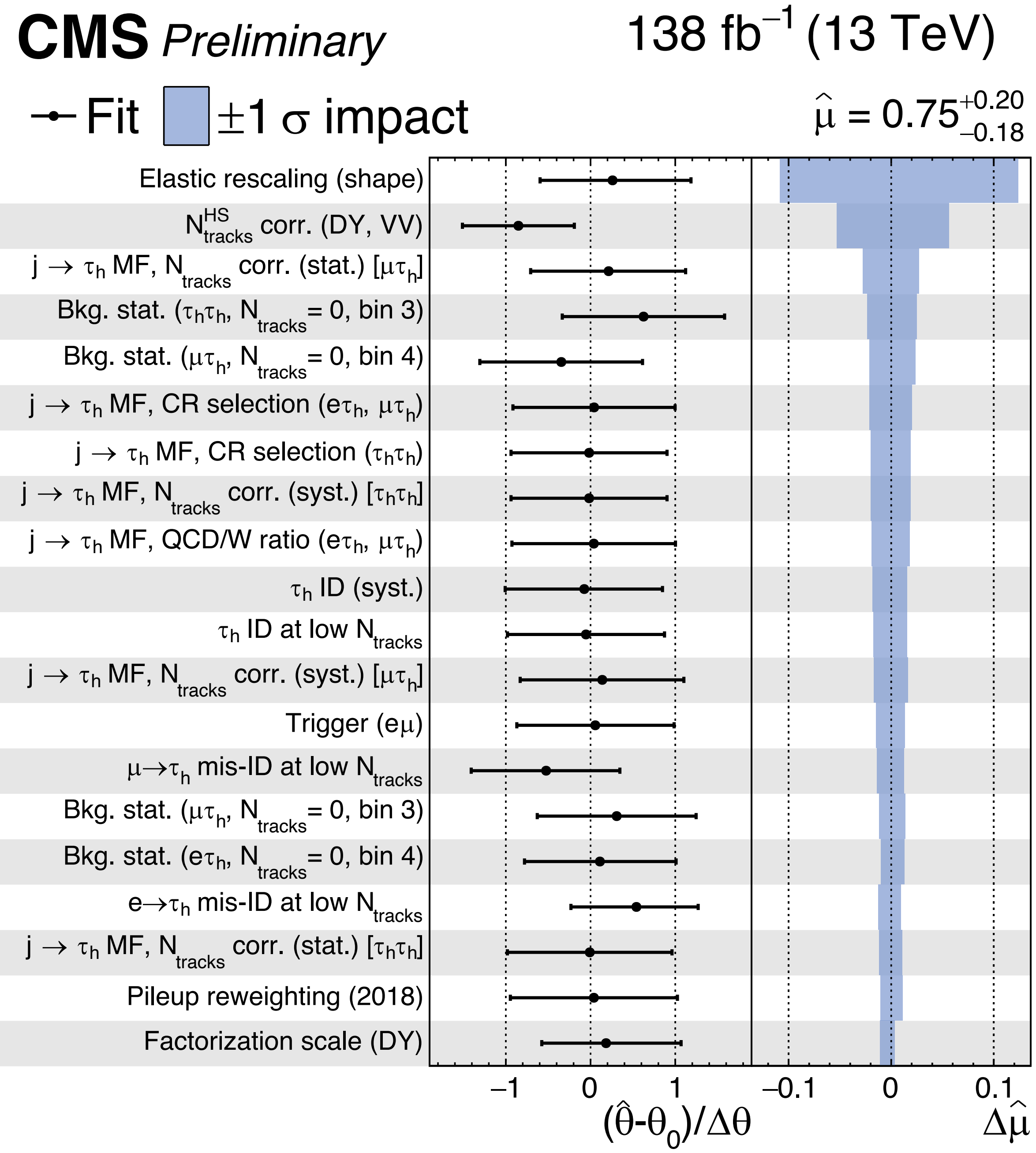


- **MET**: PFMET reconstruction
- **tracks**: charged PFCandidate collection in miniAOD, p_T > 0.5 GeV, $|\eta|$ < 2.5

Inclusive pre-selections

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$\mu\mu$
p_T^e (GeV)	$> 15/24$	$> 25 - 33$	—	—	—
$\lvert\eta^e\rvert$	< 2.5	$< 2.1 - 2.5$	—	—	—
p_T^{μ} (GeV)	$> 24/15$	—	$> 21 - 29$	—	$> 26 - 29/10$
$\lvert\eta^{\mu}\rvert$	< 2.4	—	$< 2.1 - 2.4$	—	
$p_T^{\tau_h}$ (GeV)	—	$> 30 - 35$	$> 30 - 32$	> 40	—
$\lvert\eta^{\tau_h}\rvert$	—	$< 2.1 - 2.3$	$< 2.1 - 2.3$	< 2.1	—
$m_{\mu\mu}$ (GeV)	—	—	—	—	> 50
OS	yes	yes	yes	yes	yes
$\lvert d_z(\ell, \ell')\rvert$ (cm)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$\Delta R(\ell, \ell')$	> 0.5	> 0.5	> 0.5	> 0.5	> 0.5
$m_T(e/\mu, \vec{p}_T^{miss})$ (GeV)	—	< 75	< 75	—	—

Systematics



Uncertainty	Process	Magnitude
Luminosity	All simulations	1.6%
DY cross section	DY	2%
Inclusive diboson cross section	WW, WZ, ZZ	5%
e ID, iso, trigger	All simulations	up to 2%
e ID low-N_{tracks} correction	All simulations	1%
μ ID, iso, trigger	All simulations	< 2%
τ_h ID	All simulations	1–5%
τ_h trigger	All simulations	up to 5%
$e \to \tau_h$ mis-ID	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	< 10%
$\mu \to \tau_h$ ID	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	< 10%
τ_h energy scale	All simulations	< 1.2%
$e \to \tau_h$ energy scale	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	< 5%
$\mu \to \tau_h$ energy scale	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	< 1%
τ_h ID low-N_{tracks} correction	All simulations	2.1%
e ID low-N_{tracks} correction	All simulations	2.0%
$e \to \tau_h$ ID low-N_{tracks} correction	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	22%
$\mu \to \tau_h$ ID low-N_{tracks} correction	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	15%
N^{PU}_{tracks} reweighting	All simulations	2%
N^{HS}_{tracks} reweighting	DY and inclusive VV	1.5–6.5%
Acoplanarity correction	DY	5%
DY extrapolation from $N_{tracks} < 10$	DY simulation	1.4–2.0%
μ_R, μ_f	DY simulation	Shape
PDF	DY simulation	Shape
jet→ τ_h MF, extrapolation with $p_T^{\tau_h}$	jet→ τ_h mis-ID bkg.	< 50%
jet→ τ_h MF, N_{tracks} extrapolation (stat.)	jet→ τ_h mis-ID bkg.	6–18%
jet→ τ_h MF, inversion of CR selection	jet→ τ_h mis-ID bkg.	< 10%
jet→ τ_h MF, x^{QCD} fraction	jet→ τ_h mis-ID bkg.	9%
jet→ τ_h MF, N_{tracks} extrapolation (syst.)	jet→ τ_h mis-ID bkg.	< 10%
jet→ e/μ OS-to-SS (stat.)	jet→ e/μ mis-ID bkg.	< 20%
jet→ e/μ OS-to-SS (syst.)	jet→ e/μ mis-ID bkg.	10%
jet→ e/μ OS-to-SS N_{tracks} extrapolation	jet→ e/μ mis-ID bkg.	8%
Elastic rescaling (stat.)	$\gamma\gamma \to \tau\tau/\mu\mu/ee$, WW	1.3–3.7%
Elastic rescaling (syst., shape)	$\gamma\gamma \to \tau\tau/\mu\mu/ee$, WW	Mass-dependent
Limited statistics	All processes	Bin-dependent
Pileup reweighting	All simulations	Event-dependent

Signal simulation

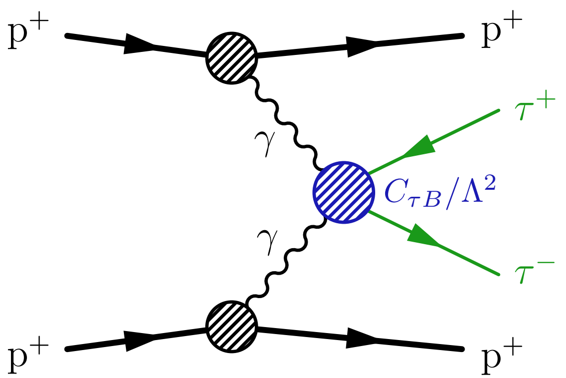
- **elastic-elastic events** are generated using gammaUPC generator with k_t smearing (arXiv:2207.03012)
- charged form factors to correct the photon flux are used (recommended by gammaUPC authors)
- a_τ & d_τ interpretation using the **EFT approach** with the SMEFTsim package, simplifying with $C_{\tau W} = 0$:

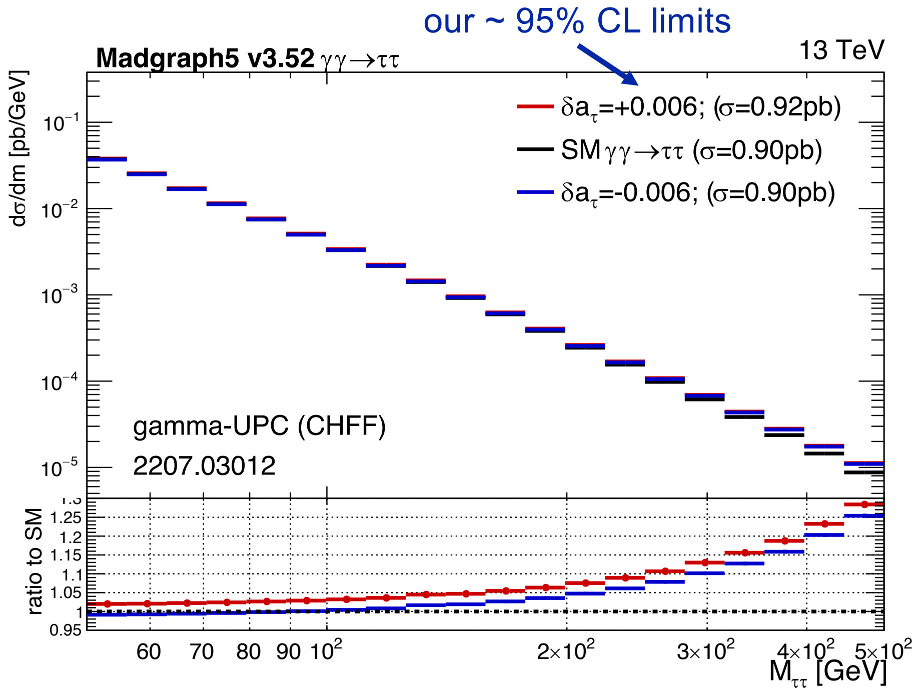
$$\delta a_\tau \propto \frac{\mathrm{Re}[C_{\tau B}]}{\Lambda^2}, \qquad \delta d_\tau \propto \frac{\mathrm{Im}[C_{\tau B}]}{\Lambda^2}$$

- scan a_τ & d_τ values through matrix element reweighting in two *independent* 1D grids of 100 points for $C_{\tau B}$:

$$\mathrm{Re}[C_{\tau B}] \in [-40, 40], \quad \mathrm{Im}[C_{\tau B}] \in [-40, 40]$$

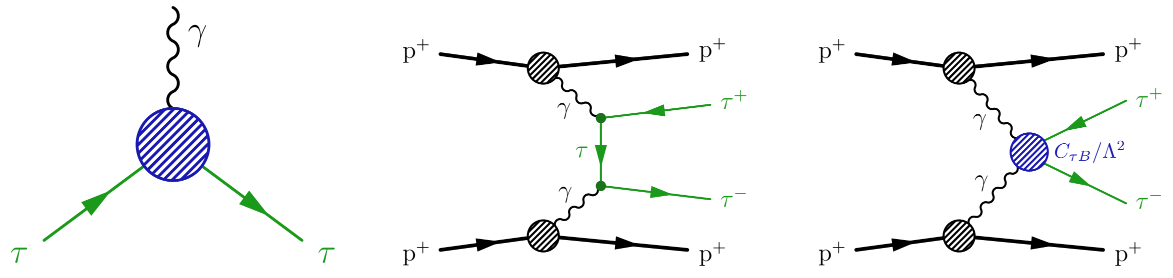
- varying a_τ or d_τ changes the cross section and $m_{\tau\tau}$ distribution
- hadronized using Pythia 8.24, switching off multi-parton interaction
- result *independent* of choice of Λ, because $C_{\tau B}$ and $C_{\tau W}$ scale with Λ^2, but we fix $\Lambda = 2$ TeV in event generation





Form factors vs. EFTs

spin tensor $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$



in the **SM Lagrangian** electromagnetic moments arise from:

$$\mathcal{L} \supset \mathcal{L}_{\tau\tau\gamma} = \frac{1}{2}\bar{\tau}\sigma^{\mu\nu}\left(a_\tau \frac{e}{2m_\tau} - i d_\tau \gamma_5\right)\tau_R F_{\mu\nu}$$

- previous analyses by DELPHI & ATLAS used **form factors** to parametrize the $\gamma\tau\tau$ vertex:

$$\Gamma_\mu(q^2) = ie\left[F_1(q^2)\gamma_\mu + \frac{1}{2m_\tau}\left(iF_2(q^2) + F_3(q^2)\gamma_5\right)\sigma_{\mu\nu}q^\nu\right]$$

- $F_1(q^2)$ parametrises the vector part of the electromagnetic current and is identified at zero-momentum transfer ($q^2 = 0$) with the electric charge e, implying $F_1(0)$ = 1
- the asymptotic values of the form factors ($q^2 \to 0$) are the electromagnetic moments a_τ and d_τ:

$$a_\tau = F_2(0)$$
$$d_\tau = \frac{e}{2m_\tau}F_3(0)$$

- the virtualities of exchanged photons in $\gamma\gamma \to \ell\ell$:
  - PbPb UPC : $Q^2_{1,2} \lesssim 0.001\ \mathrm{GeV}^2$
  - pp: $Q^2_{1,2} \lesssim 0.08\ \mathrm{GeV}^2$
  - LEP e⁺e⁻: $Q^2_{1,2} < 1\ \mathrm{GeV}^2$

- we use **SMEFT model** to parametrize deviations a_τ and d_τ from the SM can be parametrized in terms of a BSM Lagrangian with dim-6 operators with NP scale Λ:

$$\mathcal{L}_{\mathrm{BSM}} = \bar{L}_\tau \sigma^{\mu\nu}\tau_R H\left[\frac{C_{\tau B}}{\Lambda^2}B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2}W_{\mu\nu}\right]$$

- after symmetry breaking:

$$\mathcal{L}_{\mathrm{BSM}} \supset \mathcal{L}^{\mathrm{BSM}}_{\tau\tau\gamma} = \bar{\tau}_L\sigma^{\mu\nu}\tau_R\frac{v}{\sqrt{2}\Lambda^2}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]F_{\mu\nu}$$

- $\gamma\tau\tau$ vertex:

$$\Gamma_\mu(q^2) = ie\left[\ldots + \frac{1}{2m_\tau}\frac{v}{\sqrt{2}\Lambda^2}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]\frac{2m_\tau}{e}(i+\gamma_5)\sigma_{\mu\nu}q^\nu\right]$$

- then δa_τ & δd_τ are linearly dependent through the *complex* Wilson coefficients:

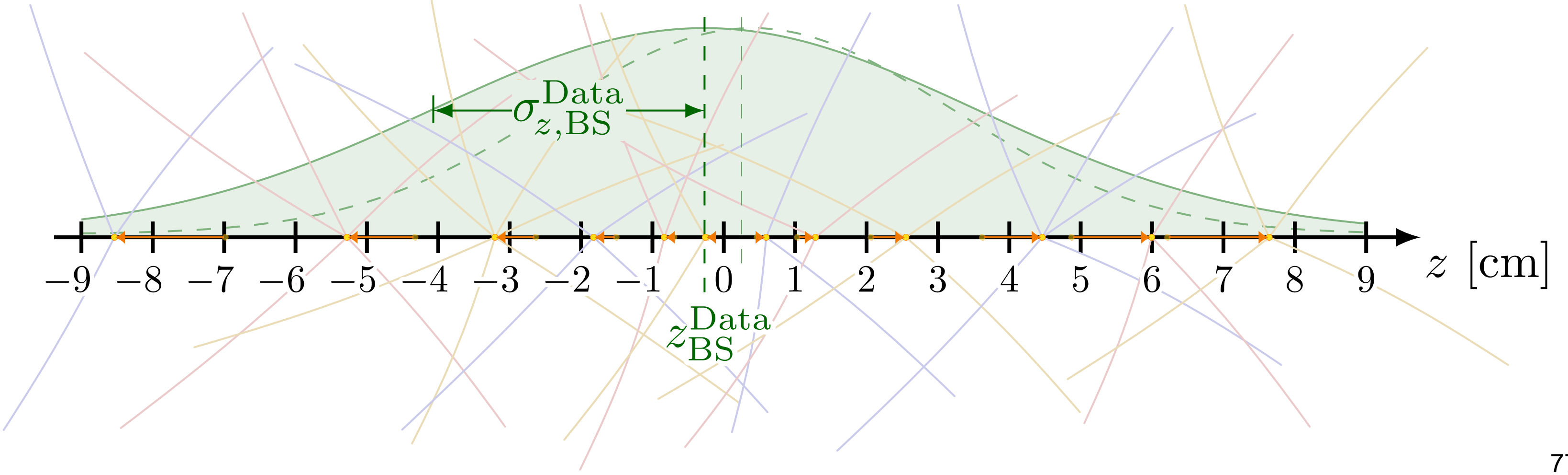
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$
$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

see Dynal et al. [arXiv:2002.05503], gammaUPC [arXiv:2207.03012], Haisch et al. [arXiv:2307.14133]

Beamspot smearing to pileup tracks

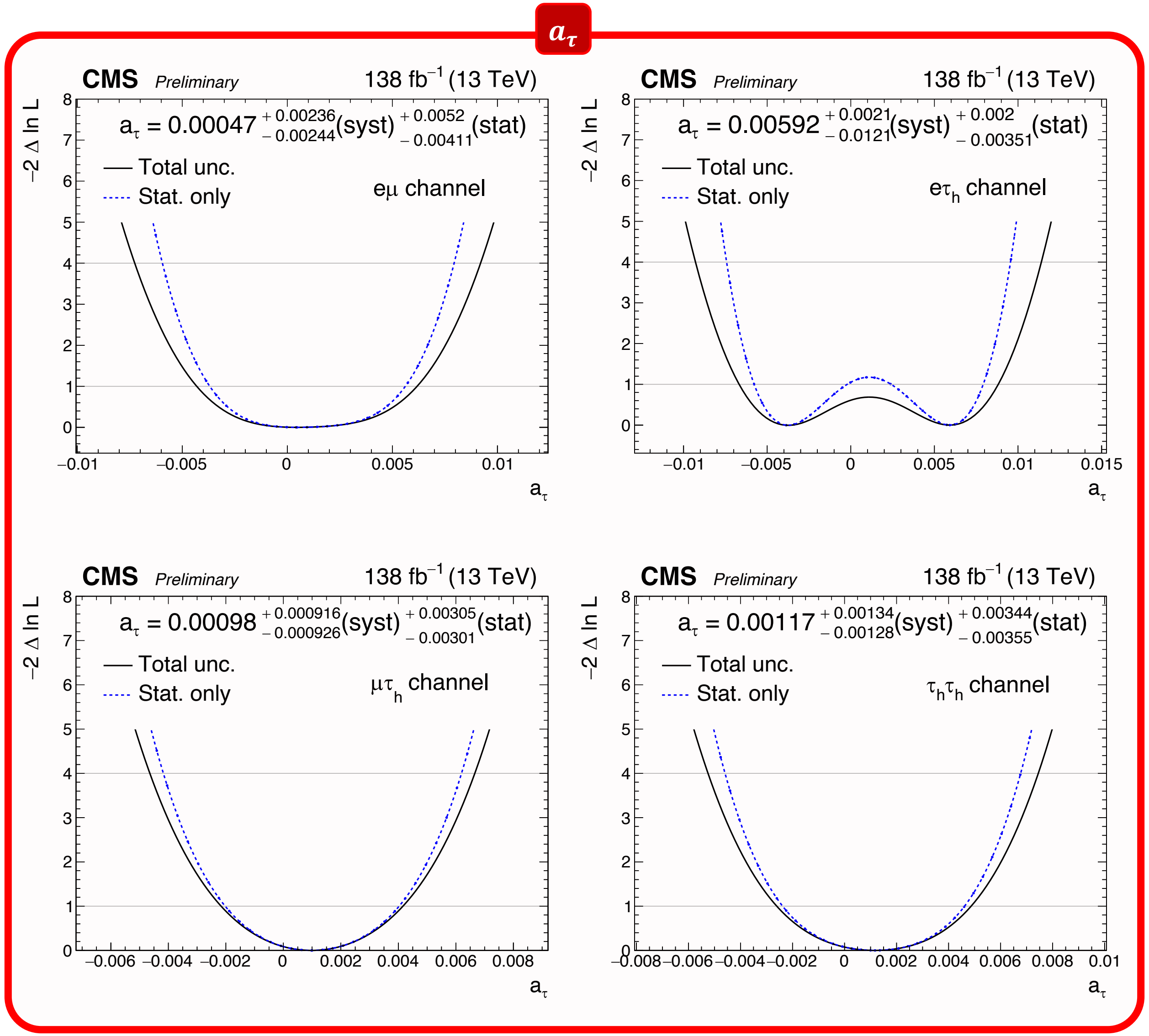
applied to all simulation

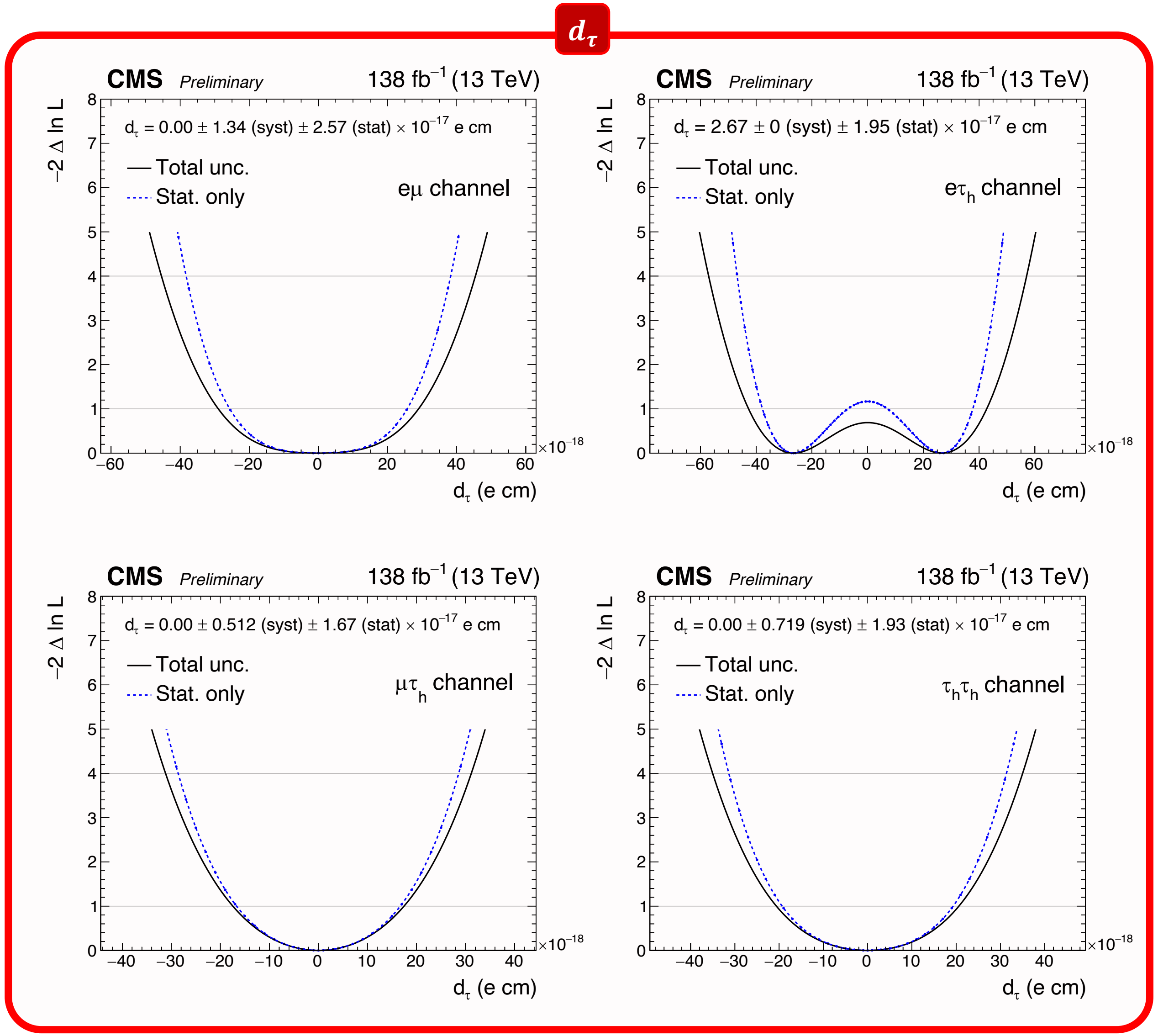
- **simulated events** have a *fixed* beamspot *z* position and width for a given era
- **in data**, beamspot *z* position and width are *run-dependent*
- to each simulated event, randomly assign a BS position $z_{\text{data}}^{\text{BS}}$ & a BS width $\sigma_{\text{data}}^{\text{BS}}$ by sampling the BS distributions in data
- correct *z* position of the pileup tracks
  - smear: $z^{\text{corr}} = z_{\text{MC}}^{\text{BS}} + \frac{\sigma_{\text{MC}}^{\text{BS}}}{\sigma_{\text{data}}^{\text{BS}}}\left(z - z_{\text{MC}}^{\text{BS}}\right)$
  - shift: $z^{\text{corr}} = z + \left(z_{\text{data}}^{\text{BS}} - z_{\text{MC}}^{\text{BS}}\right)$



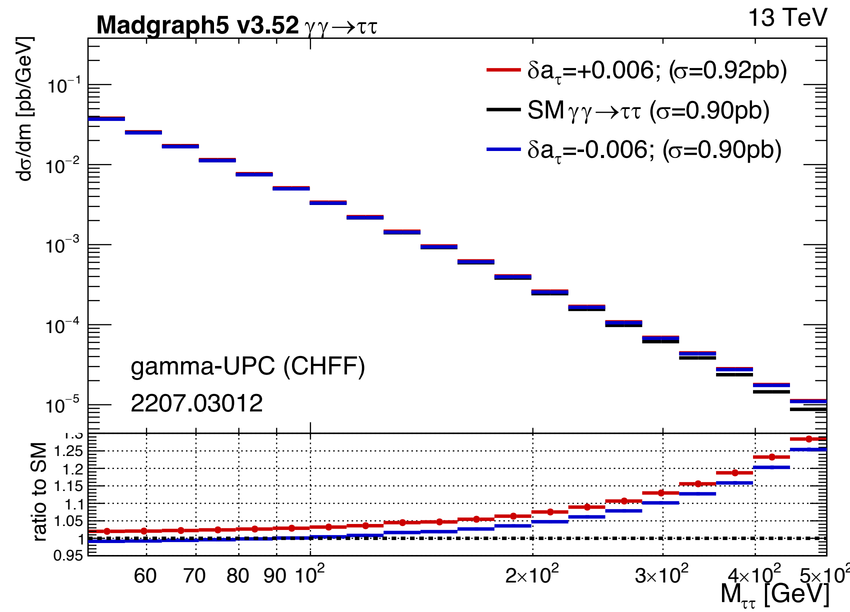
NLL breakdowns by channel

double minima caused by small excess in $e\tau_h$
and the fact that BSM deviations go in the same direction





Form factors vs. EFTs



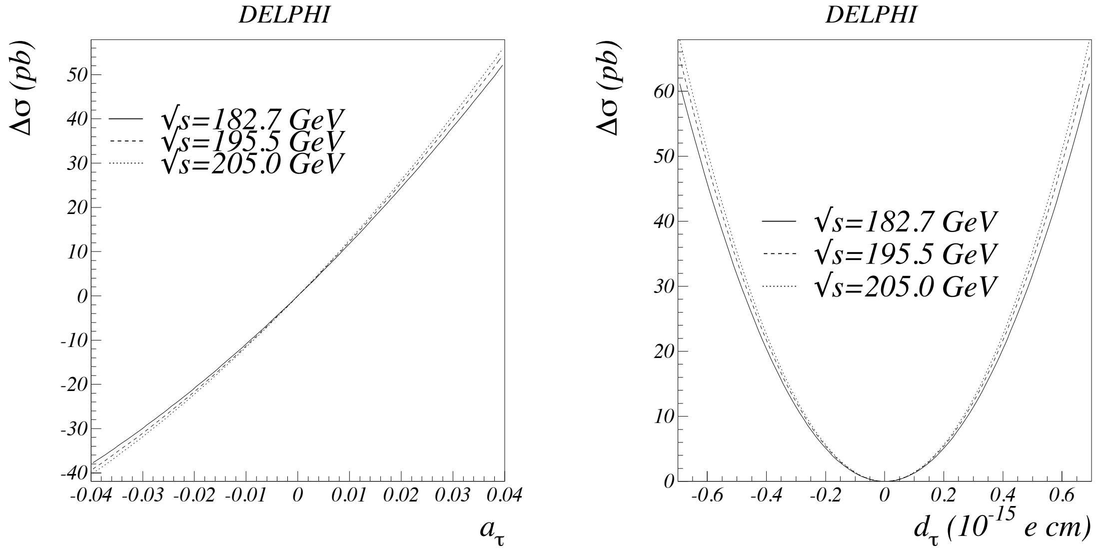


Figure 7: Total cross-section change as a function of anomalous magnetic moment and as a function of electric dipole moment.

DELPHI (2004) arXiv:hep-ex/0406010

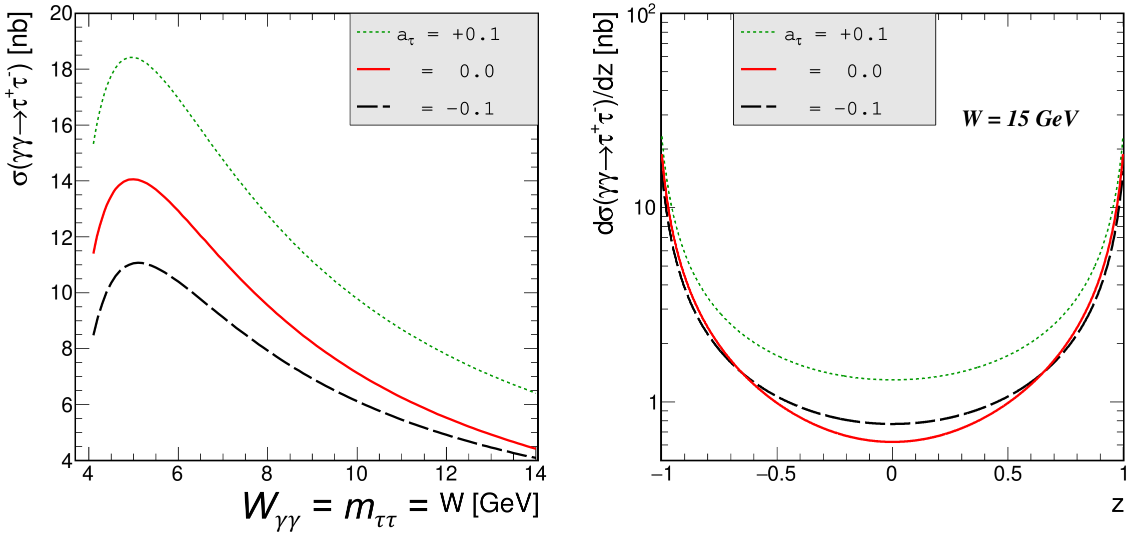


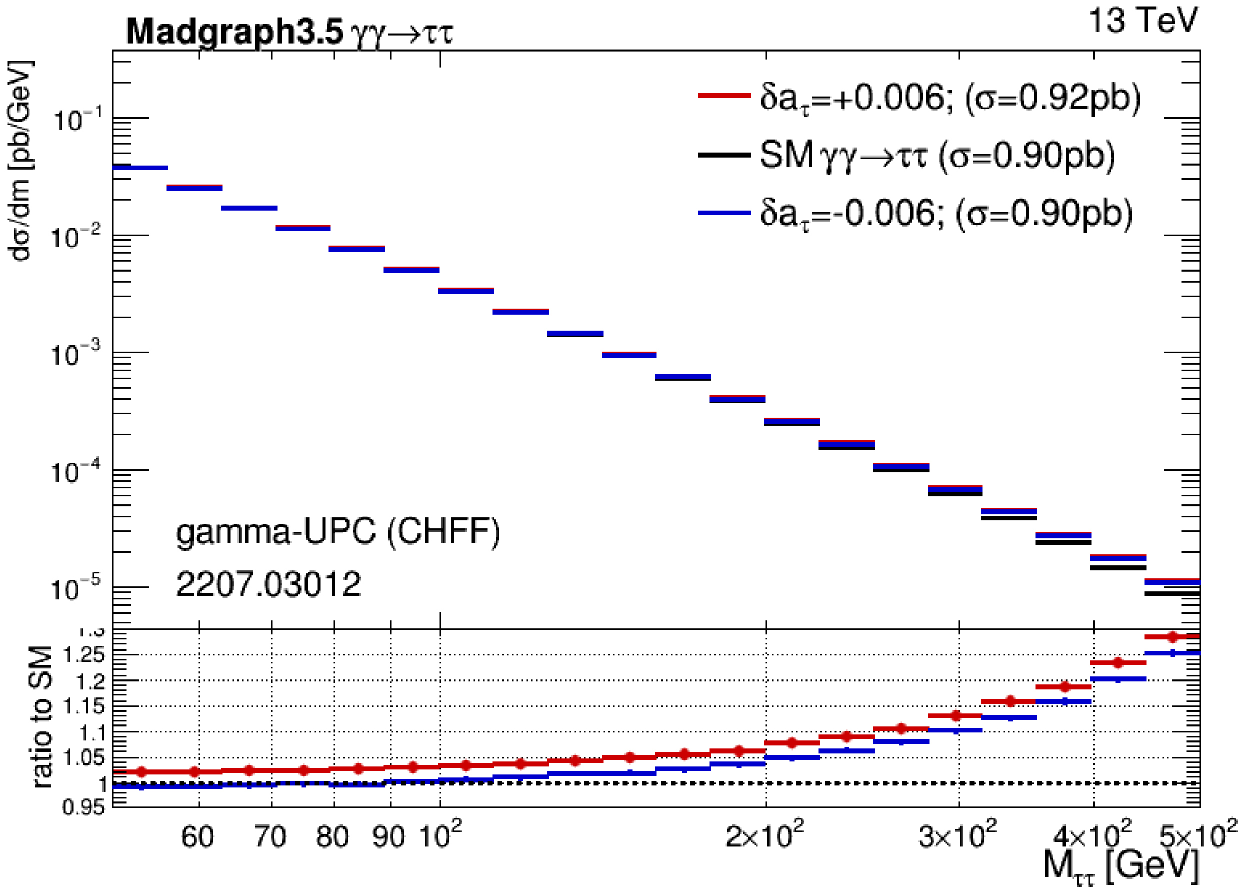
FIG. 1. Elementary cross section for $\gamma\gamma \to \tau^+\tau^-$ process as a function of $W_{\gamma\gamma} = m_{\tau\tau}$ (left) and as a function of $z = \cos\theta$ for $W_{\gamma\gamma} = 15$ GeV (right).

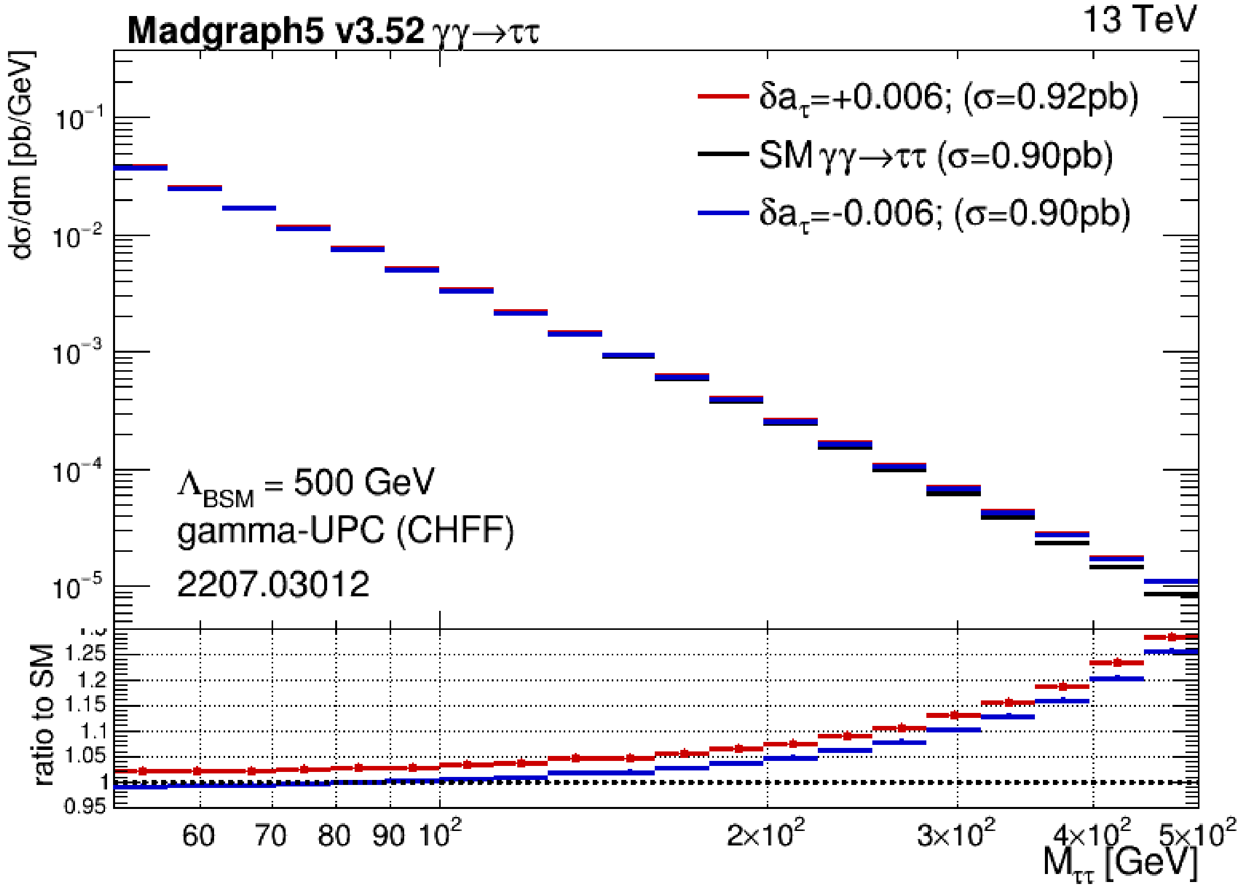
Dynal et al. (2020) arXiv:2002.05503

- **BSM Scale dependence**:

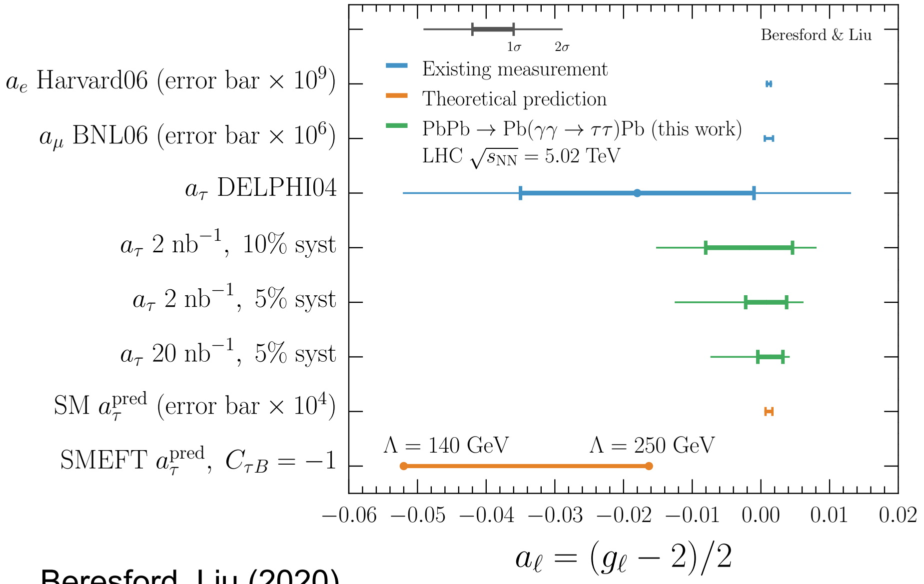
$$\mathcal{L}_{BSM} = \bar{L}_\tau \sigma^{\mu\nu} \tau_R H \left[\frac{C_{\tau B}}{\Lambda^2} B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2} W_{\mu\nu}\right]$$, if $C_{\tau W}$=0 then $\delta\alpha_\tau = \frac{2m_\tau}{e} Re(C_{\tau B}) \frac{\sqrt{2}v \cdot cos\theta_W}{\Lambda^2}$

Two options tested: $C_{\tau W}$=6.7, Λ=2TeV and $C_{\tau W}$=6.7/16, Λ=500GeV

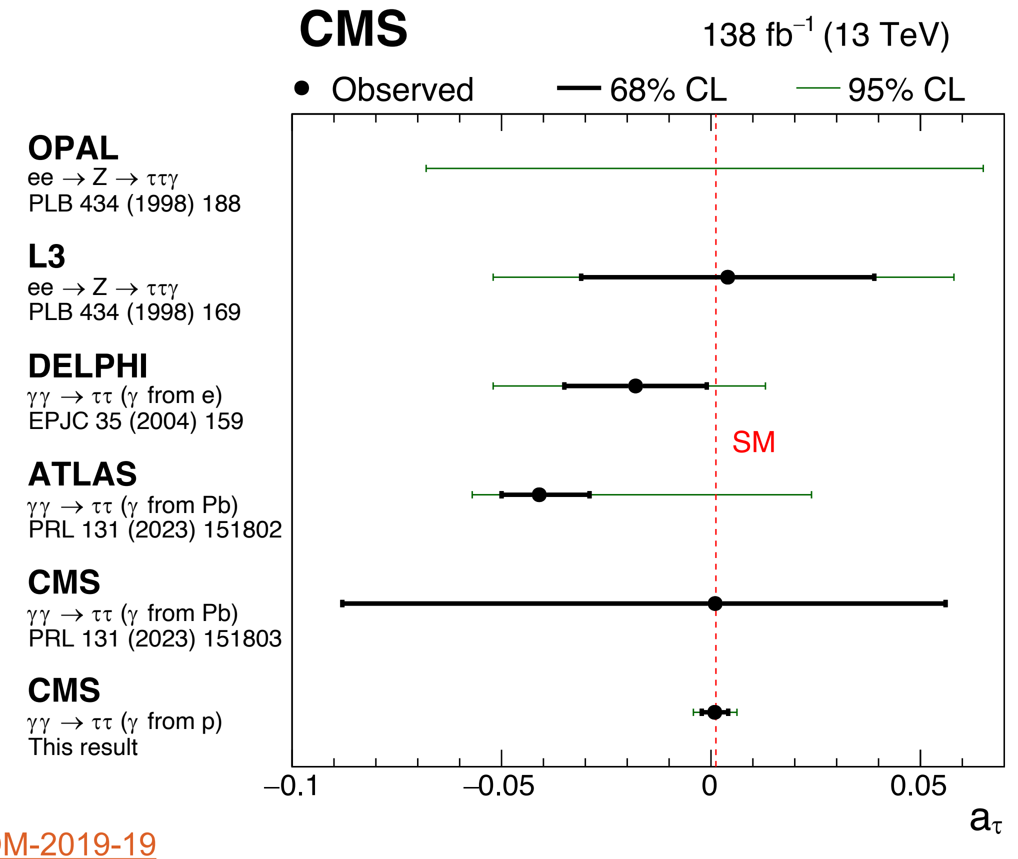




a_τ comparisons



Beresford, Liu (2020)
arXiv:1908.05180



ATLAS (2022) STDM-2019-19