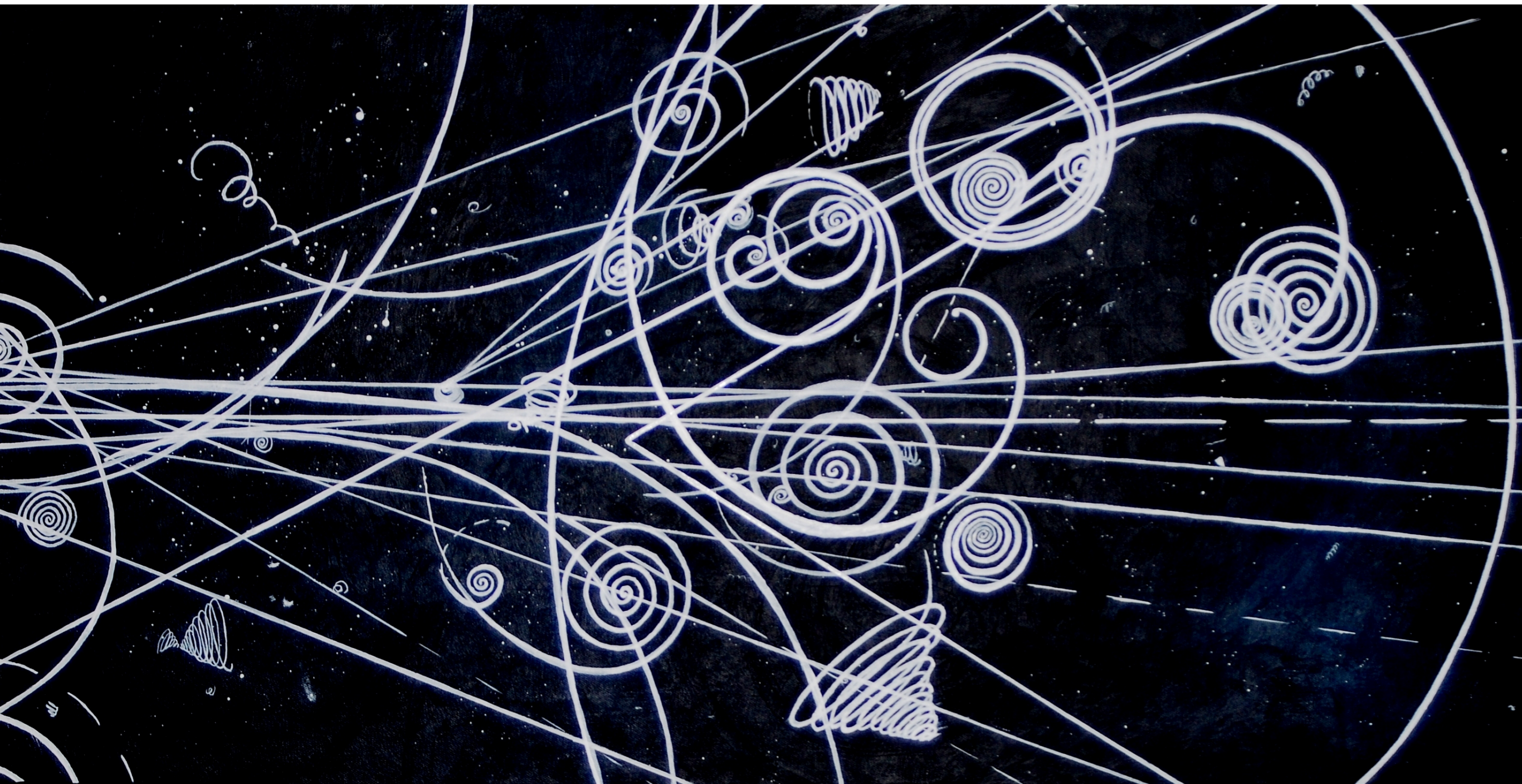


Tau g-2

Lydia Beresford

HEP Seminar Warwick, 31st October 2019



Our proposal

New physics and tau $g - 2$ using LHC heavy ion collisions

Lydia Beresford^{1,*} and Jesse Liu^{1,2,†}

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²*Department of Physics, University of Chicago, Chicago IL 60637, USA*

The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement, but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments δd_τ . We introduce a suite of one electron/muon plus track(s) analyses, leveraging the exceptionally clean photon fusion $\gamma\gamma \rightarrow \tau\tau$ events to reconstruct both leptonic and hadronic tau decays sensitive to $\delta a_\tau, \delta d_\tau$. Assuming 10% systematic uncertainties, the current 2 nb^{-1} lead–lead dataset could already provide constraints of $-0.0080 < a_\tau < 0.0046$ at 68% CL. This surpasses 15 year old lepton collider precision by a factor of three while opening novel avenues to new physics.

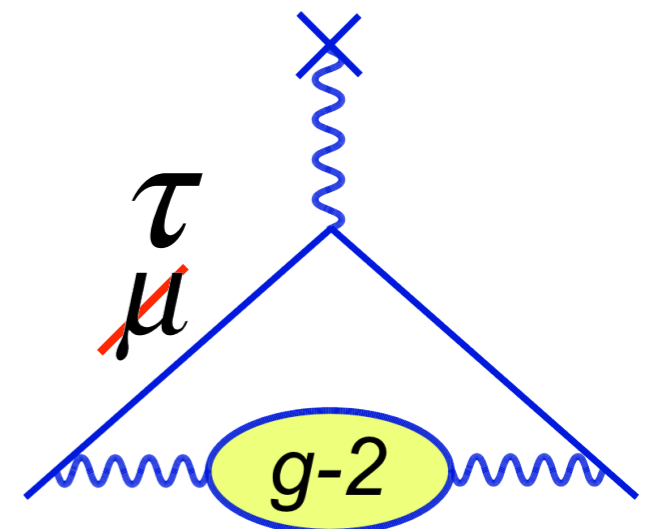
1908.05180

... October 2018

23 Oct 2018 14:15	Dennis Sciama Lecture Theatre	<u>Muon (g-2) at Fermilab: Run 1 Status</u>	Professor Lee Roberts (Boston University)
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↓ **One year on**

31 October	Lydia Beresford (Oxford)	New physics and tau g – 2 using LHC heavy ion collisions
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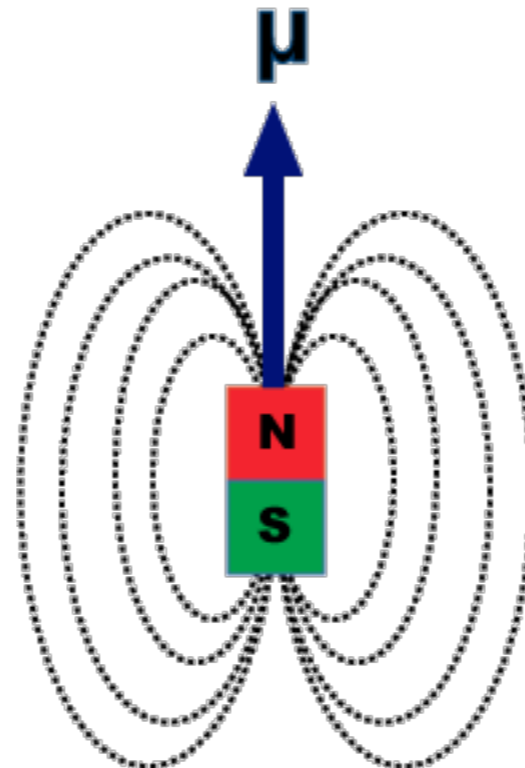
What is g-2?

*How objects interact with a **magnetic** field*

Magnetic moment: Quantifies torque experienced in **B** field

$$\begin{array}{c} \boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B} \\ \uparrow \qquad \uparrow \\ \text{torque} \quad \text{magnetic moment} \end{array}$$

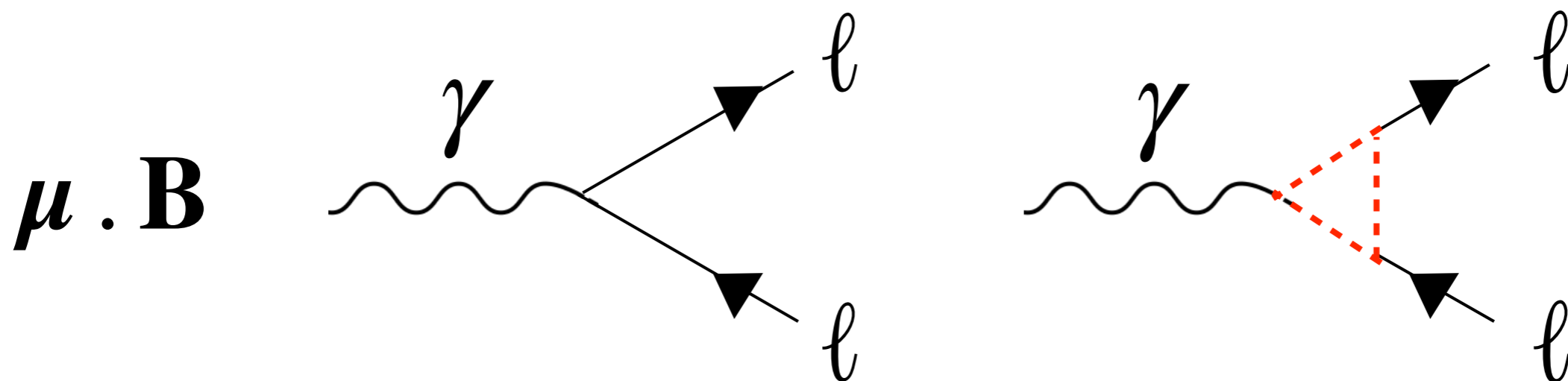
Possessed by e.g. bar magnet, loop of current etc.



What is g-2?

Charged particles with spin have an intrinsic **magnetic moment**

For spin 1/2 particles: $\boldsymbol{\mu} = g \frac{q}{2m} \mathbf{S}$



$g = 2 + \text{loop corrections}$

What is g-2?

Anomalous magnetic moment

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

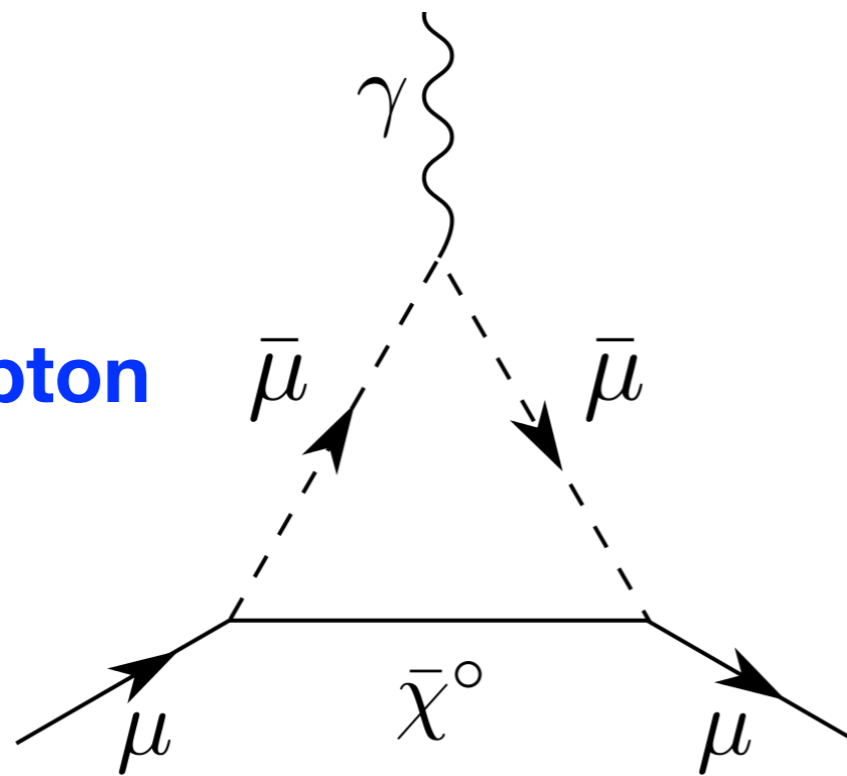
Why is it interesting?

Powerful probe of new physics

New particles could be in the loop

Example: SUSY

Scalar Lepton



Dark Matter



Why is it interesting?

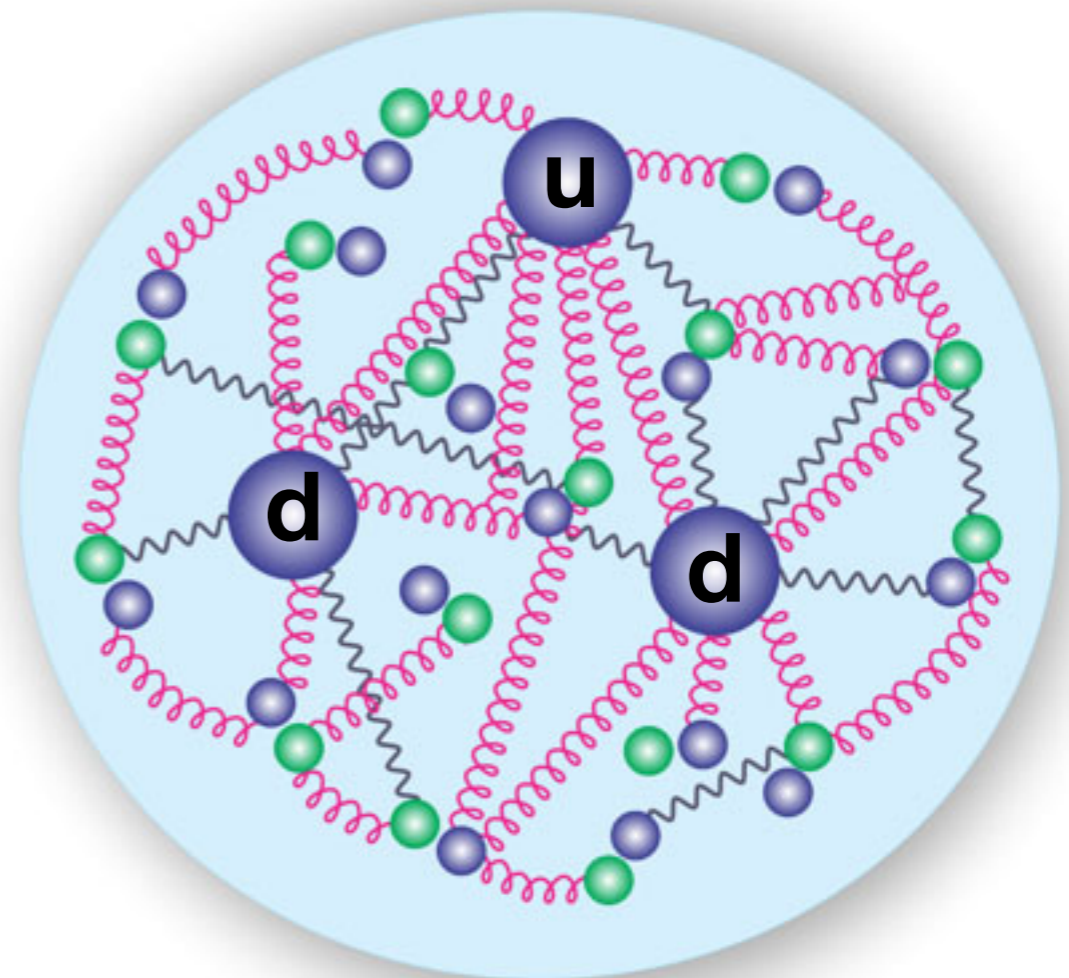
Powerful probe of new physics

Sensitive to compositeness

Historical examples: proton, neutron

Neutron $g-2$: **-5.8**

→ **Composite!**



Why is it interesting?

Fundamental test of QED

Electron g-2: 10^{-8} precision

-2.5σ tension

Muon g-2: 10^{-7} precision

$3-4\sigma$ tension

Electron: Odom et al [PRL \(2006\)](#) Bouchendirra et al [PRL \(2011\)](#) Aoyama et al [1205.5368](#) Parker et al [Science \(2018\)](#)

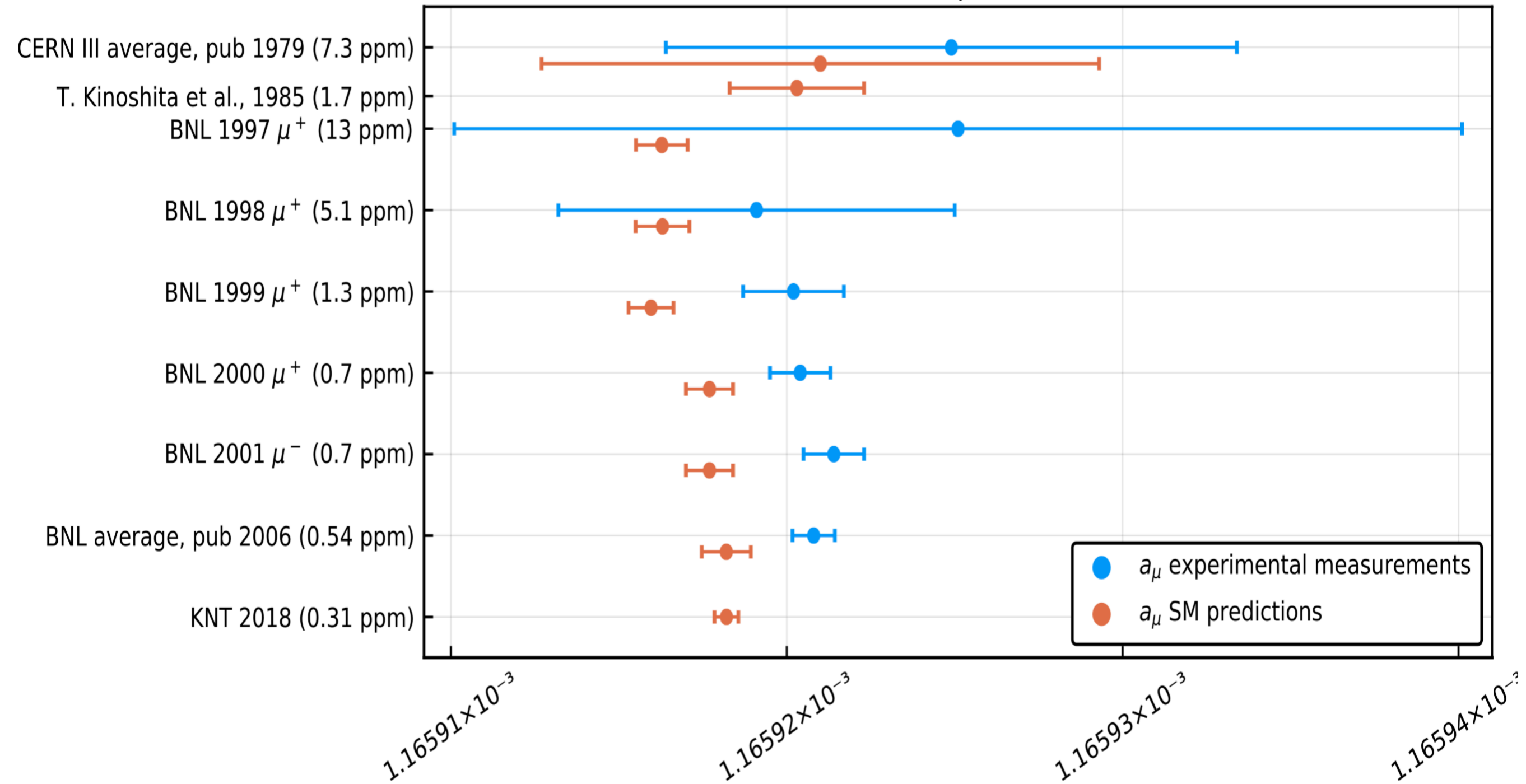
Muon: BNL E821 [hep-ex/0602035](#) J-PARC [1901.03047](#) Davier et al [1908.00921](#)

Keshavarzi, Nomura and Teubner [1802.02995](#)

a_μ time evolution

Lusiani (2019)

a_μ



● a_μ experimental measurements
● a_μ SM predictions

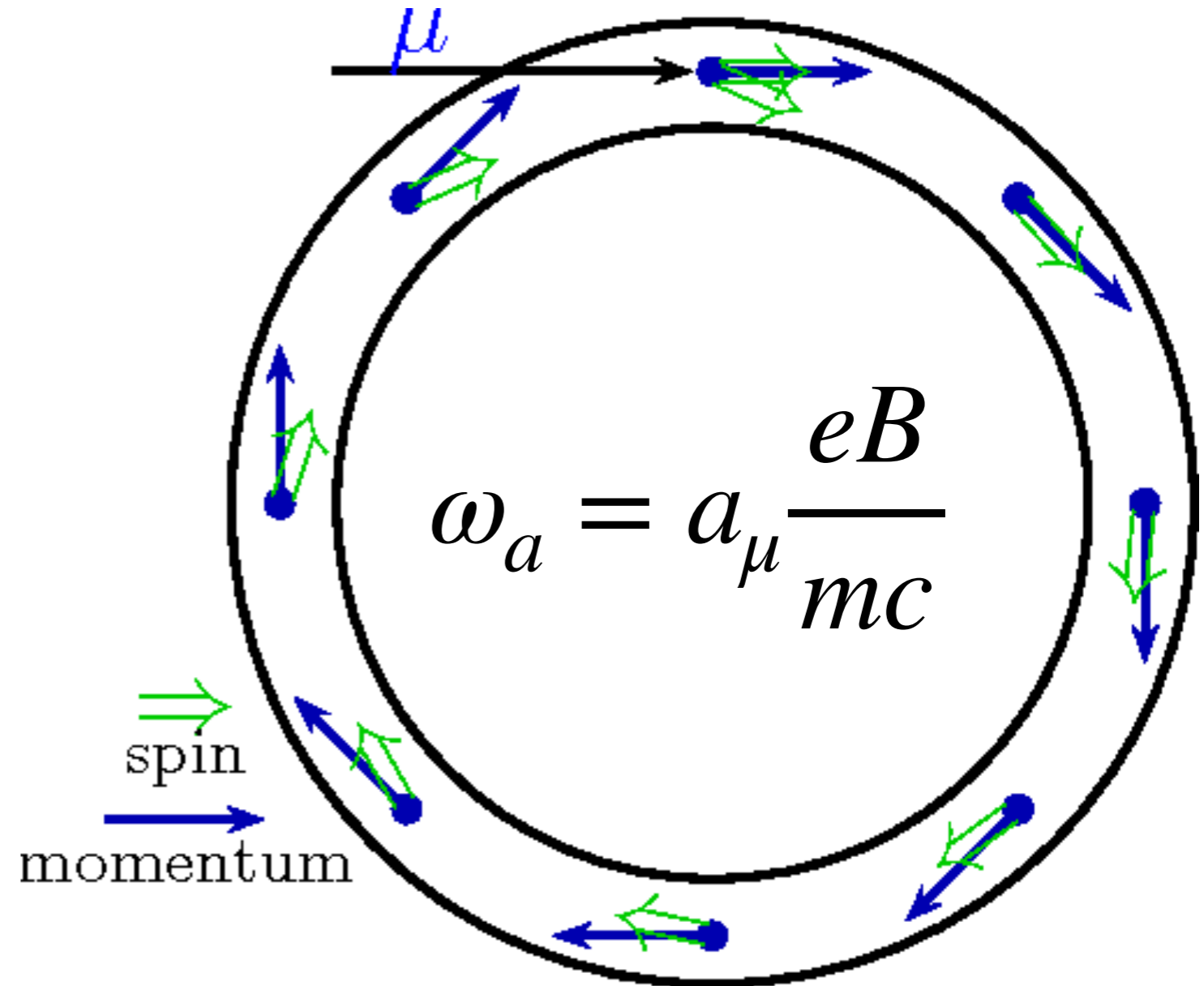
Muon g-2 experiment @ Fermilab



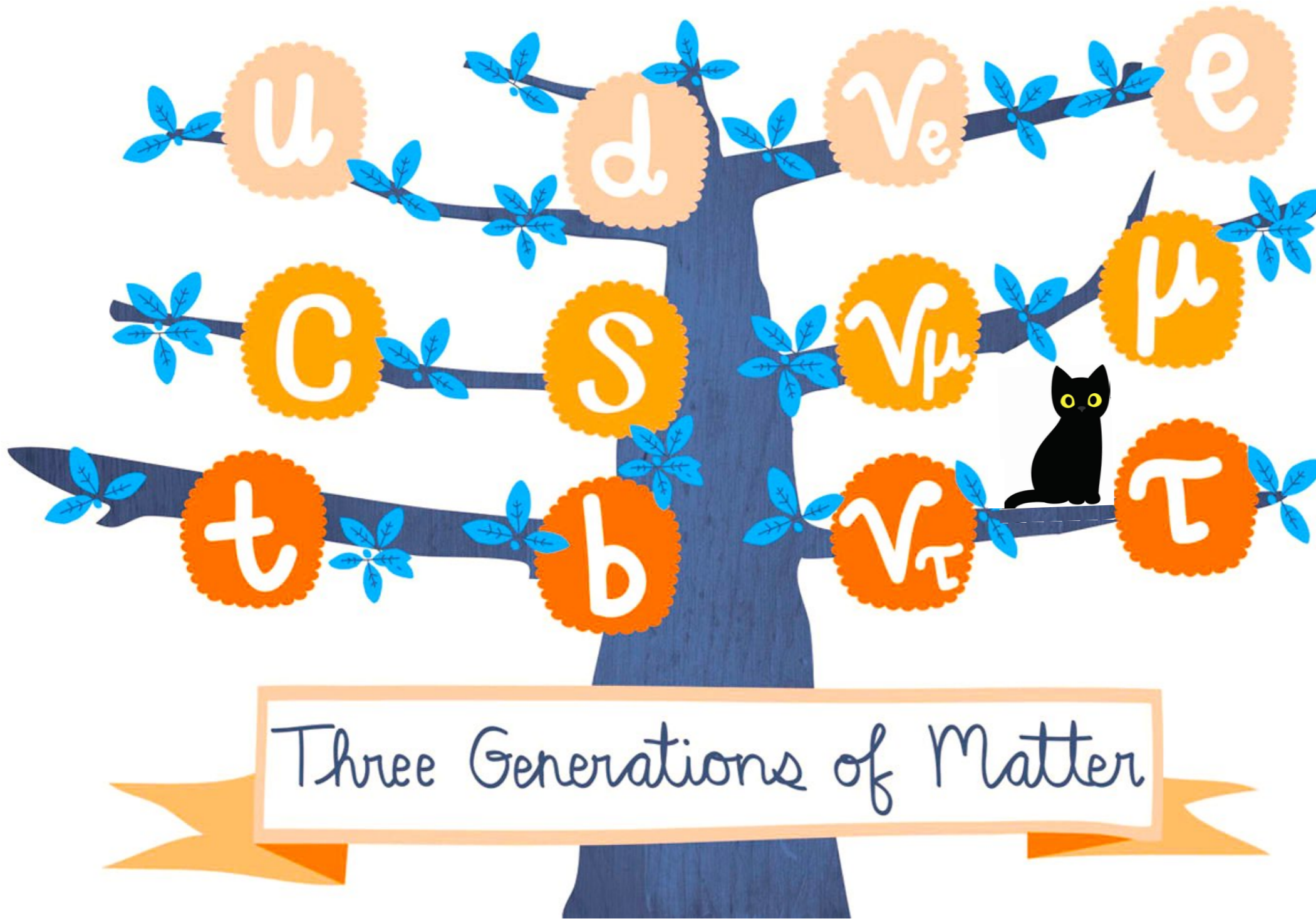
‘if I were to put my money on something that would signal new physics, it’s the [muon] g-2 experiment at Fermilab’ **Brian Cox**

Basic idea:

- Inject polarised muons
- Spin precesses around **B** at rate related to a_μ
- Measure precession rate via decay to positron



What about tau g-2?



Mass

0.511 MeV

106 MeV

1.7 GeV

What about tau g-2?

$m_\tau > m_\mu$ by order of magnitude!

→ Composite?

280x more sensitive than a_μ

$$\delta a_\tau \propto m_l^2 / m_{\text{SUSY}}^2 \quad \text{and} \quad m_\tau^2 / m_\mu^2 = 280$$

Martin and Wells [PRD \(2001\)](#)

Models for electron & muon g-2 could apply here too
e.g. Z' , dark photon, 2HDM ...

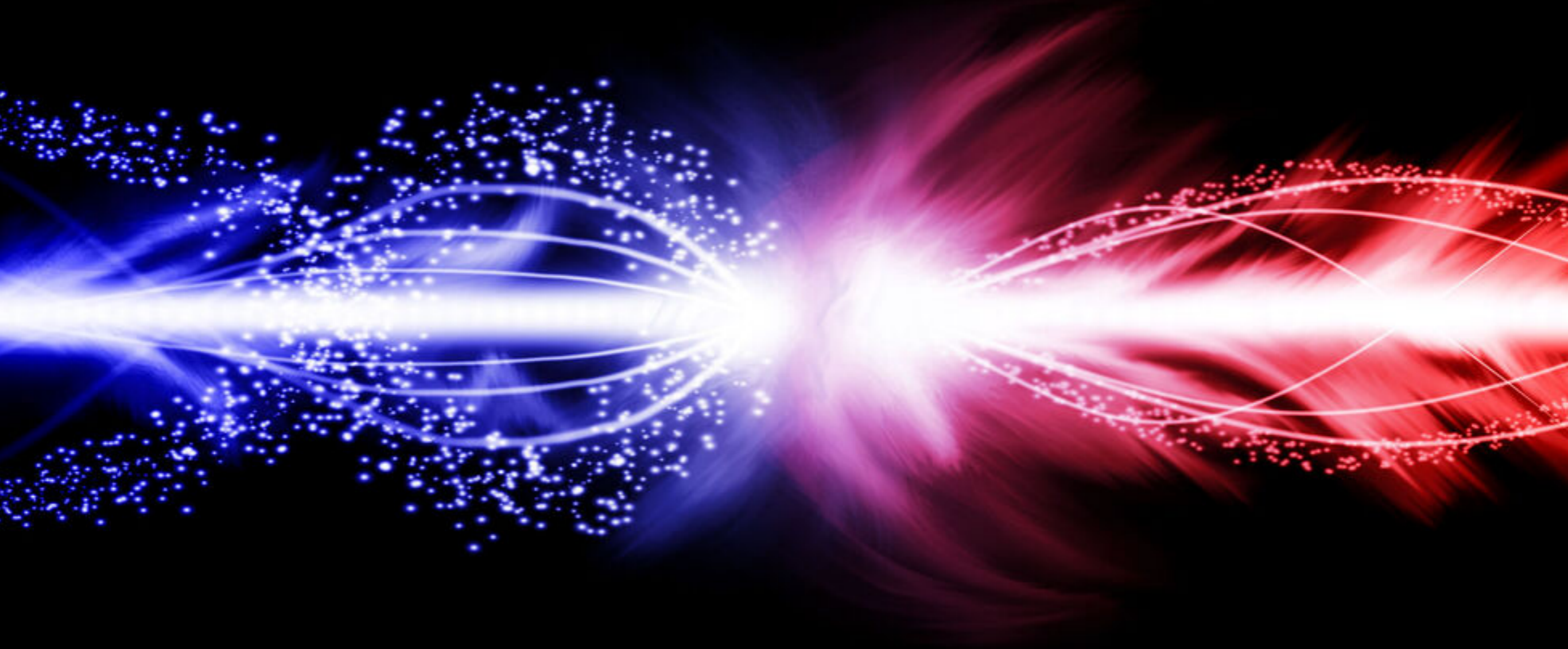
Problem: Lifetime

$$\tau \sim 10^{-13} \text{ s}$$

$$\mu \sim 10^{-6} \text{ s}$$

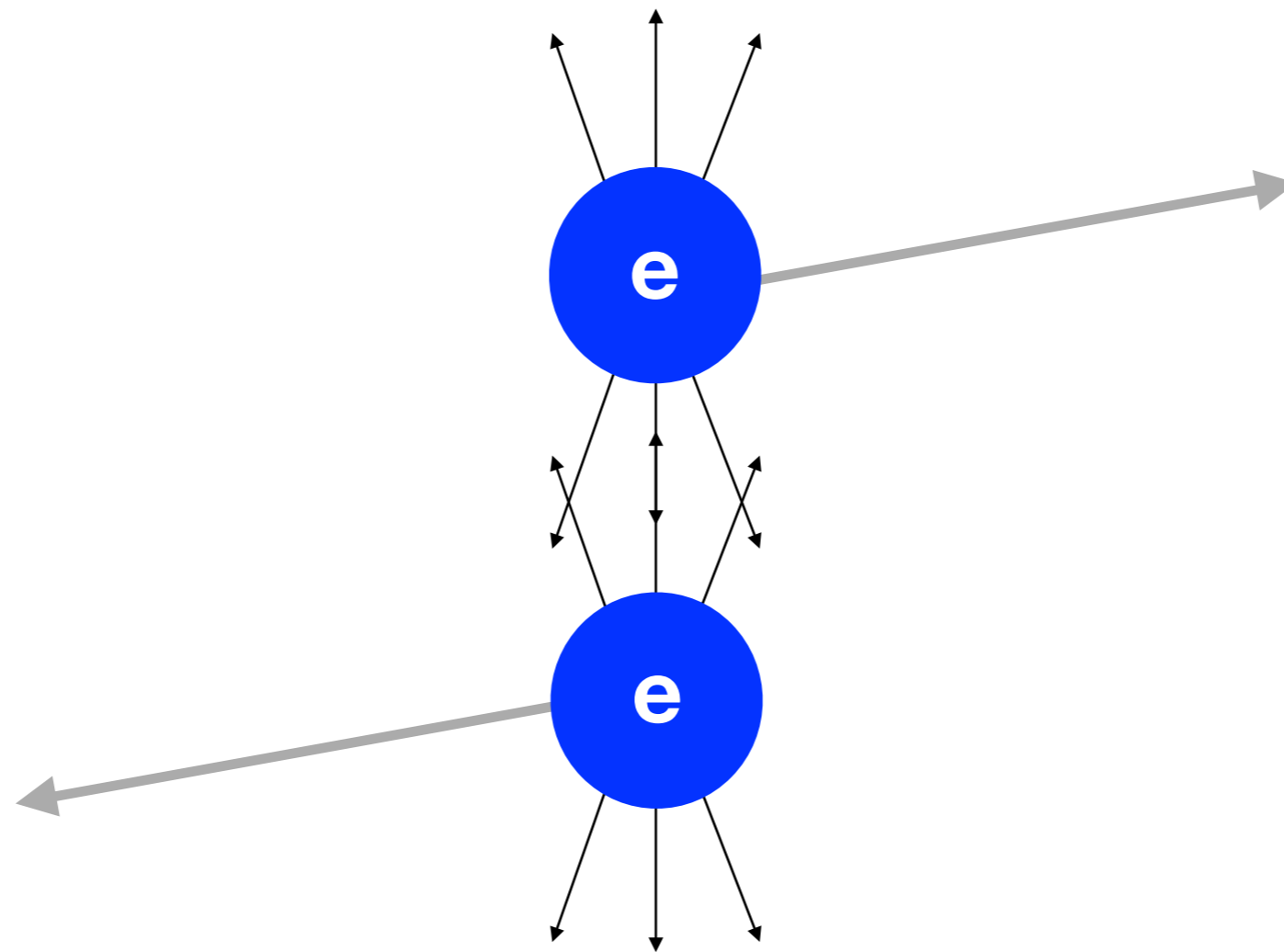
→ **Can't use same technique!**

Solution: Photon collisions

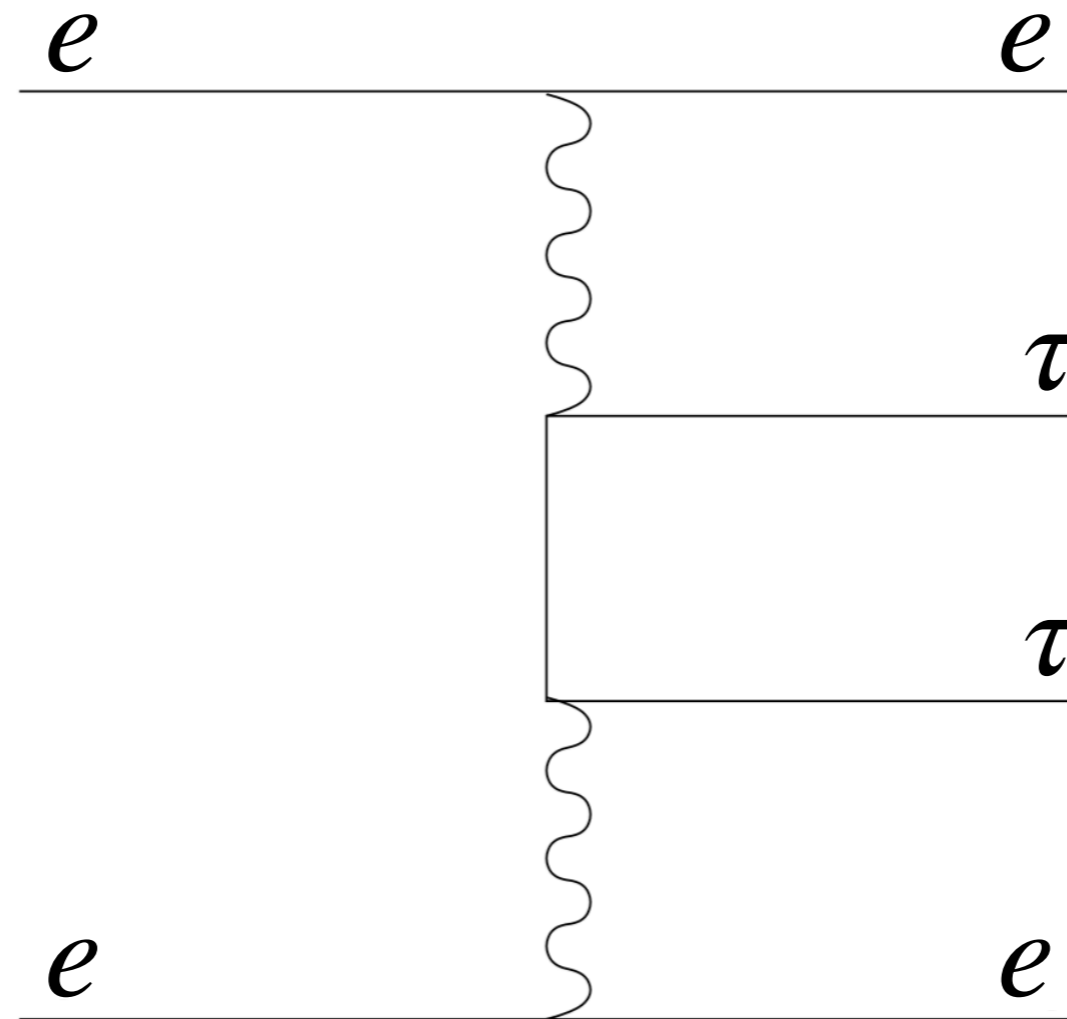


Solution: Photon collisions

Photons from electric field surrounding electrons collide to produce new particles



DELPHI 2004, LEP collider



**Cross section
sensitive to
moments**

Photo production of tau pairs

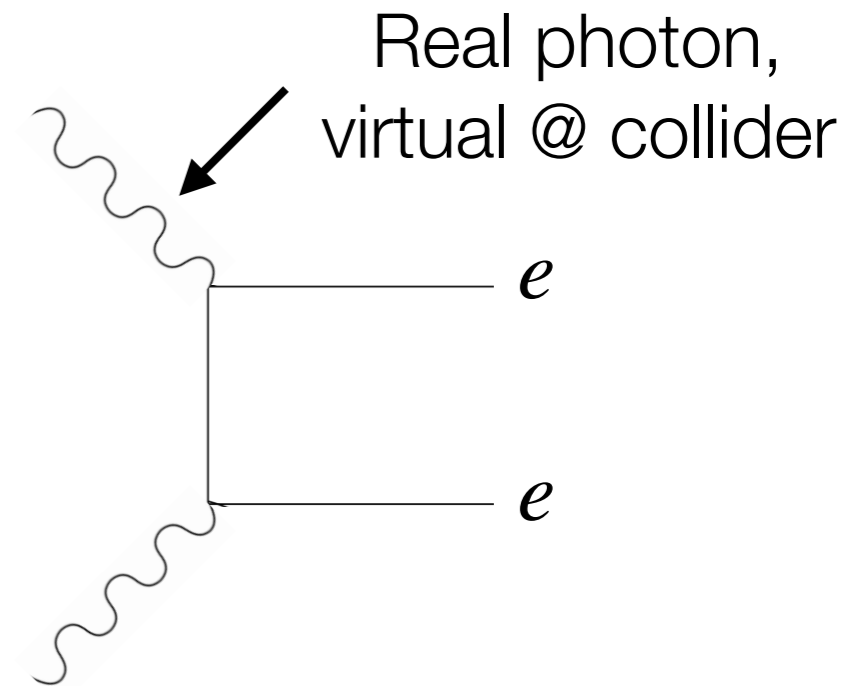
Disgression

**Turning light into matter
major goal in laser physics**

Disgression

Turning light into matter
major goal in laser physics

Breit Wheeler process




nature
photonics

Proposal paper

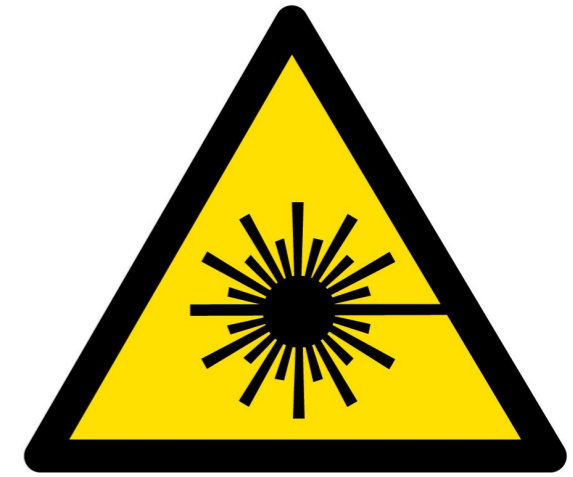
Letter | Published: 18 May 2014

A photon–photon collider in a vacuum hohlraum

O. J. Pike , F. Mackenroth, E. G. Hill & S. J. Rose

Nature Photonics **8**, 434–436 (2014) | [Download Citation](#) 

Disgression



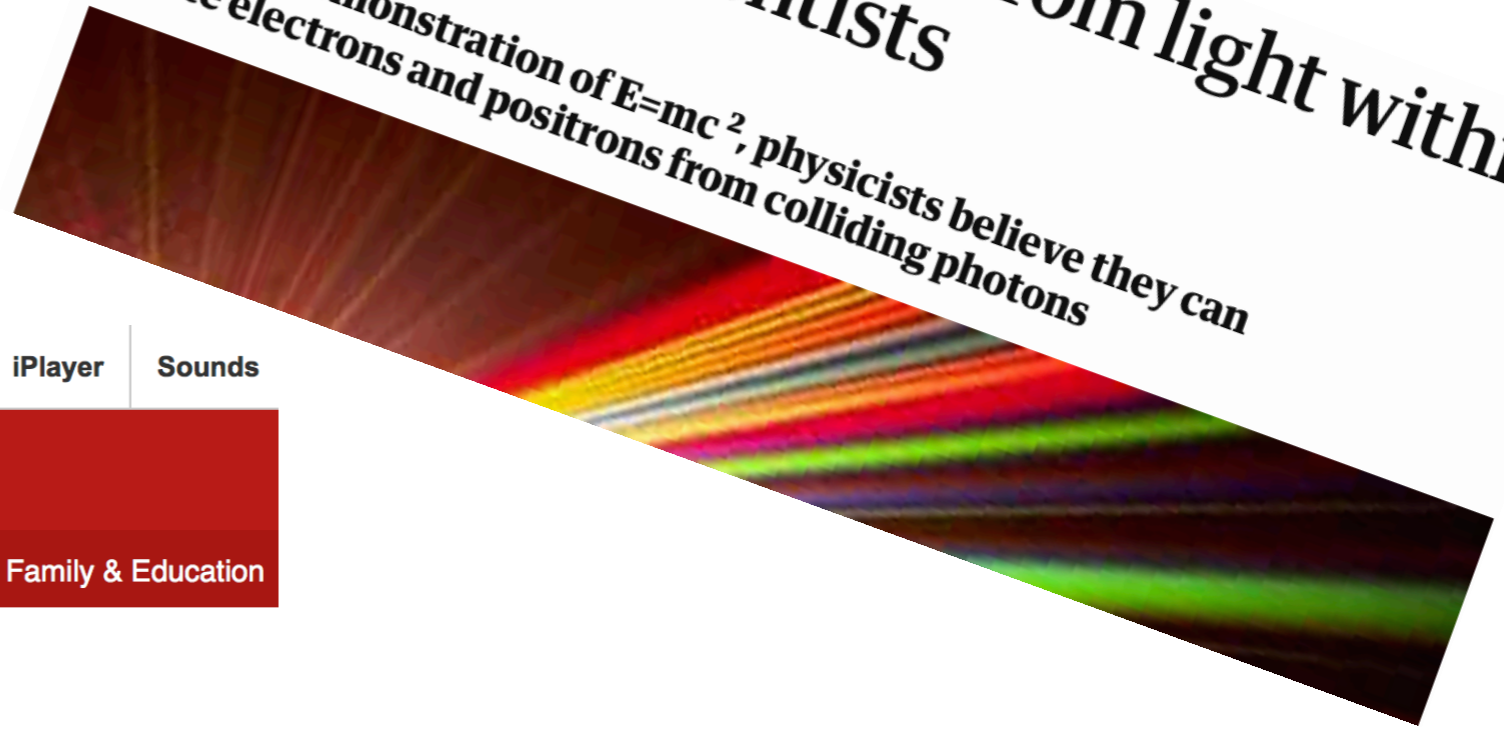
SCIENCE / PHYSICS

Physicists Attempt to Turn Light Into Matter with 84-Year-Old Theory

A team of researchers from the UK are coming closer to being able to prove that light can be transformed into matter.

Matter will be created from light within a year, claim scientists

In a neat demonstration of $E=mc^2$, physicists believe they can create electrons and positrons from colliding photons



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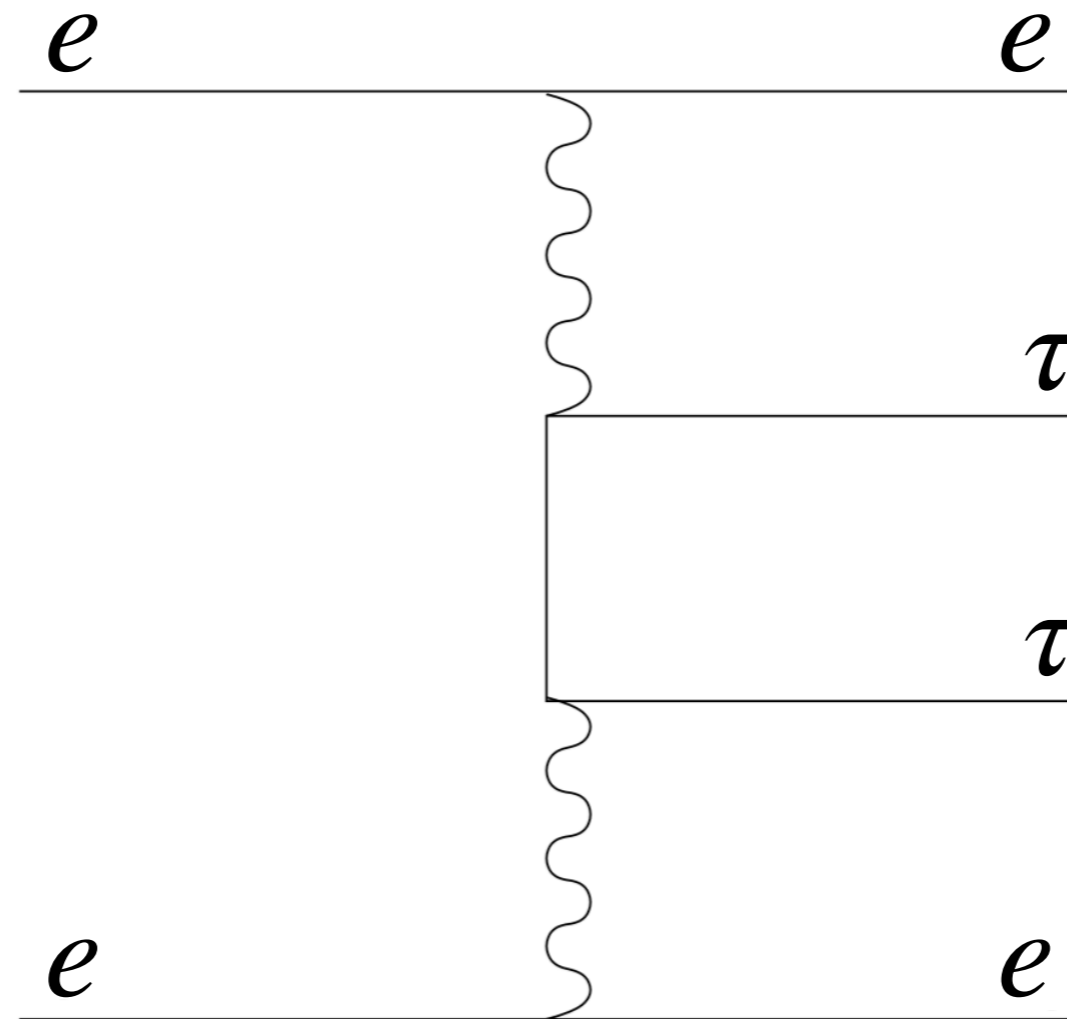
UK design 'starts race' to turn pure light into matter

By Jonathan Webb
Science reporter, BBC News

© 24 June 2014



DELPHI 2004, LEP collider

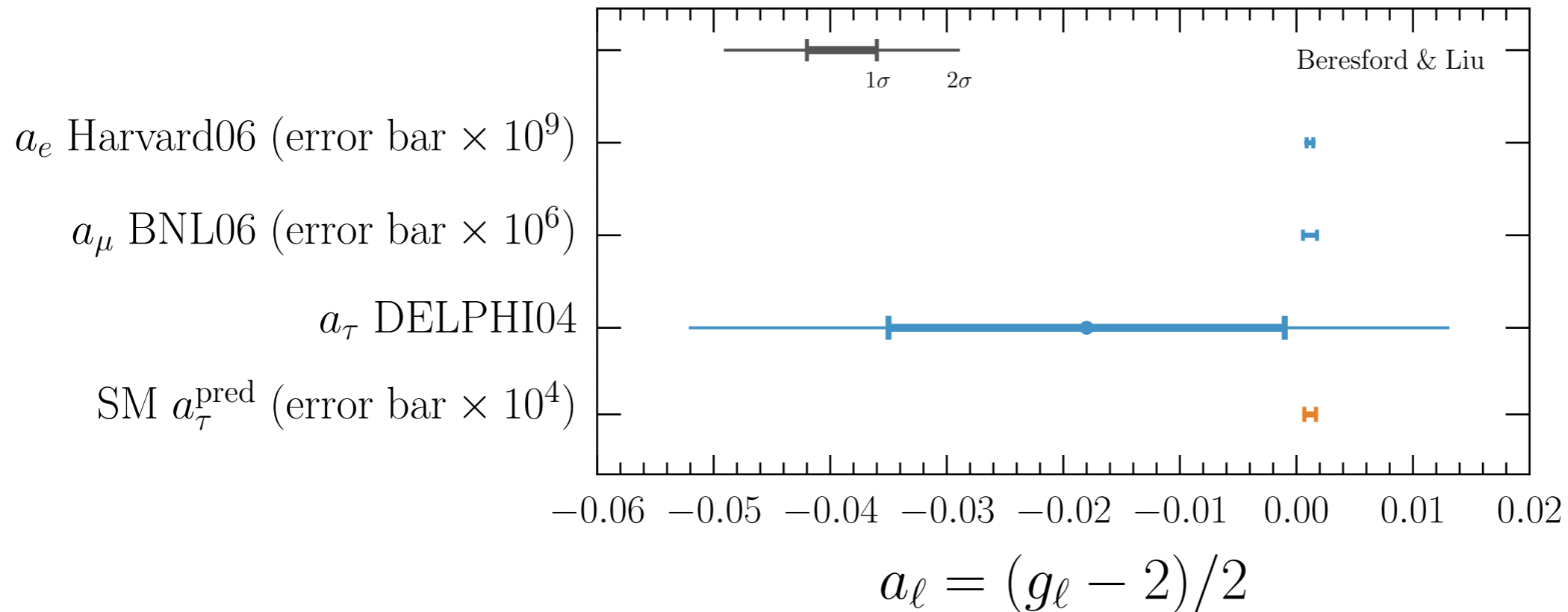


**Cross section
sensitive to
moments**

Photo production of tau pairs

Sibling Rivalry

Tensions seen for electron & muon, what about the tau?



$$a_\tau^{\text{exp}} = -0.018 (17)$$

$$a_\tau^{\text{theory}} = 0.00117721 (5)$$

Can we beat it?

Many interesting proposals for future

Belle II

Eidelman et al [1601.07987](#)

Chen, Wu [1803.00501](#)

LHeC/Fcc-he

Köksal [1809.01963](#)

Gutiérrez-Rodríguez et al [1903.04135](#)

CLIC/ILC/Fcc-ee

Köksal et al [1804.02373](#)

Howard et al [1810.09570](#)

Bent crystal

Fomin et al [1810.06699](#)

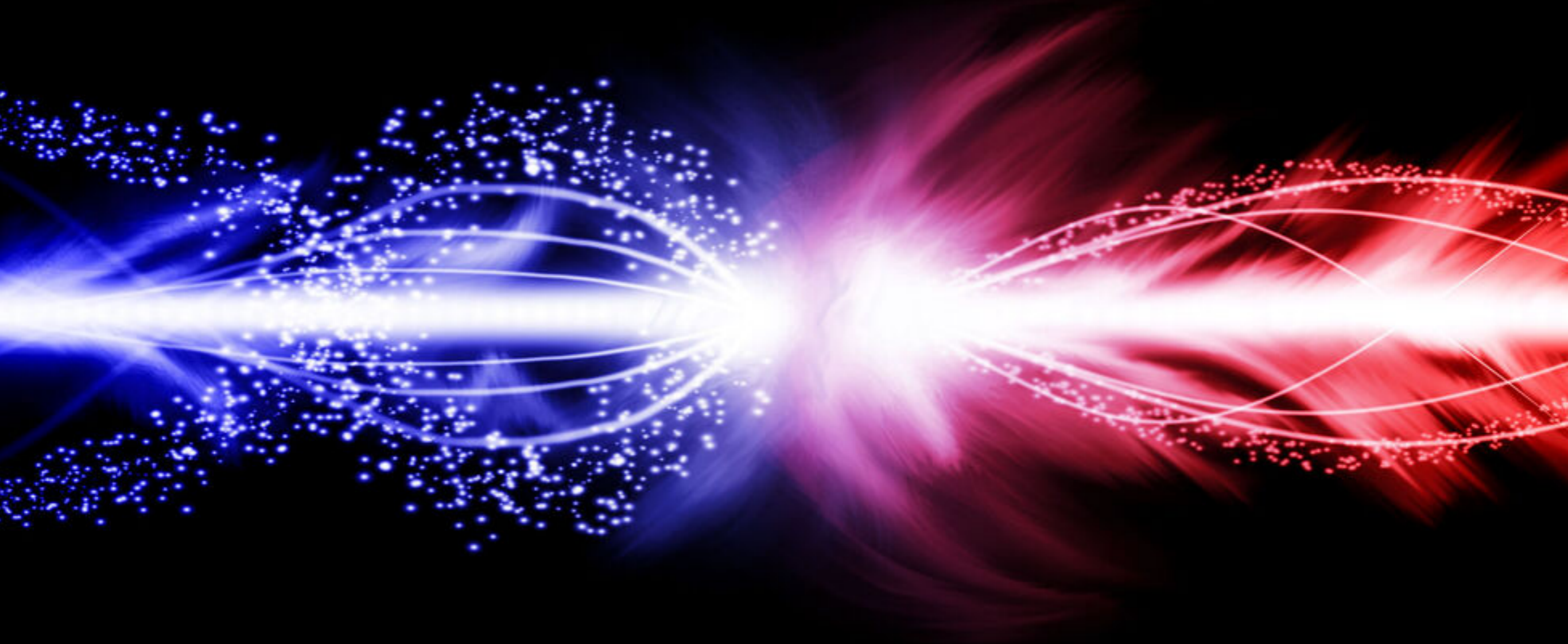
Fu et al [1901.04003](#)

HL-LHC

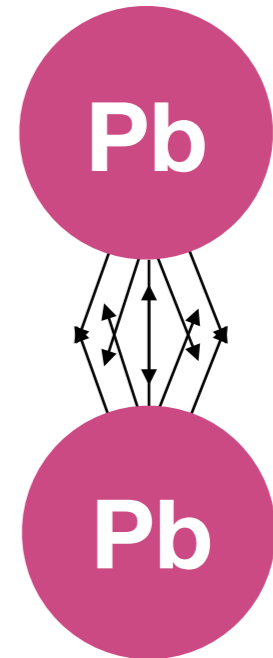
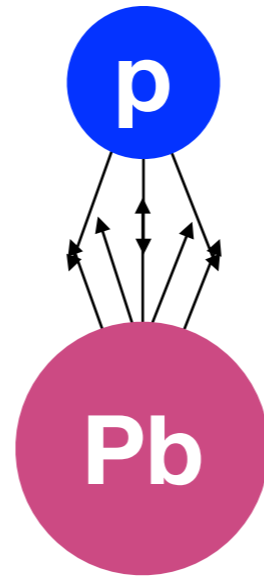
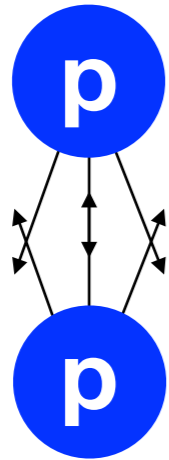
Galon, Rajaraman and Tait
[1610.01601](#)

Can we beat it right now?

The LHC is also a photon collider



The LHC is also a photon collider



ATLAS

\sqrt{s} 13 TeV

\mathcal{L} $\sim 140 \text{ fb}^{-1}$

σ -

8.16 TeV

$\sim 170 \text{ nb}^{-1}$

$\propto Z^2$

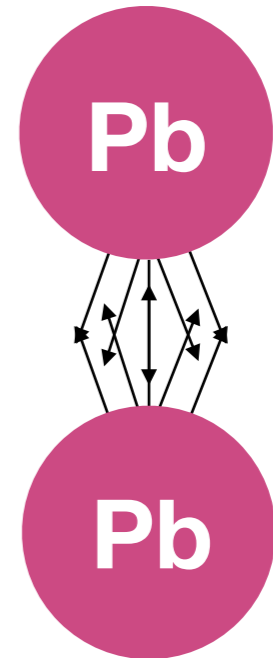
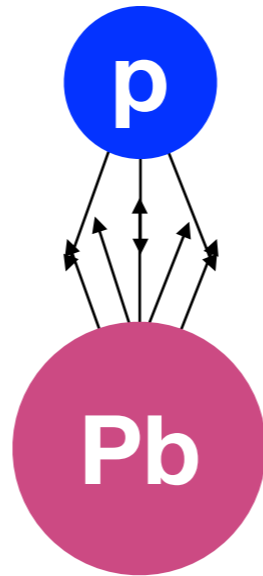
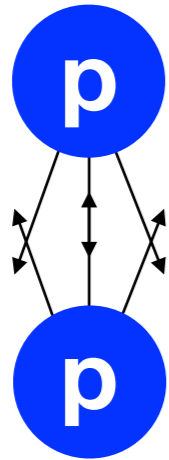
5.02 TeV

$\sim 2 \text{ nb}^{-1}$

$\propto Z^4$

Z = 82 for Pb

The LHC is also a photon collider



ATLAS

$$\sqrt{s} \quad 13 \text{ TeV}$$

$$\mathcal{L} \quad \sim 140 \text{ fb}^{-1}$$

$$\sigma \quad -$$

$$8.16 \text{ TeV}$$

$$\sim 170 \text{ nb}^{-1}$$

$$\propto Z^2$$

$$\mathbf{5.02 \text{ TeV}}$$

$$\sim \mathbf{2 \text{ nb}^{-1}}$$

$$\propto \mathbf{Z^4}$$

$$\mathbf{Z = 82 \text{ for Pb}}$$

Head on PbPb collision



Run 168665, Event 83797

Time 2010-11-08 11:37:15 CET



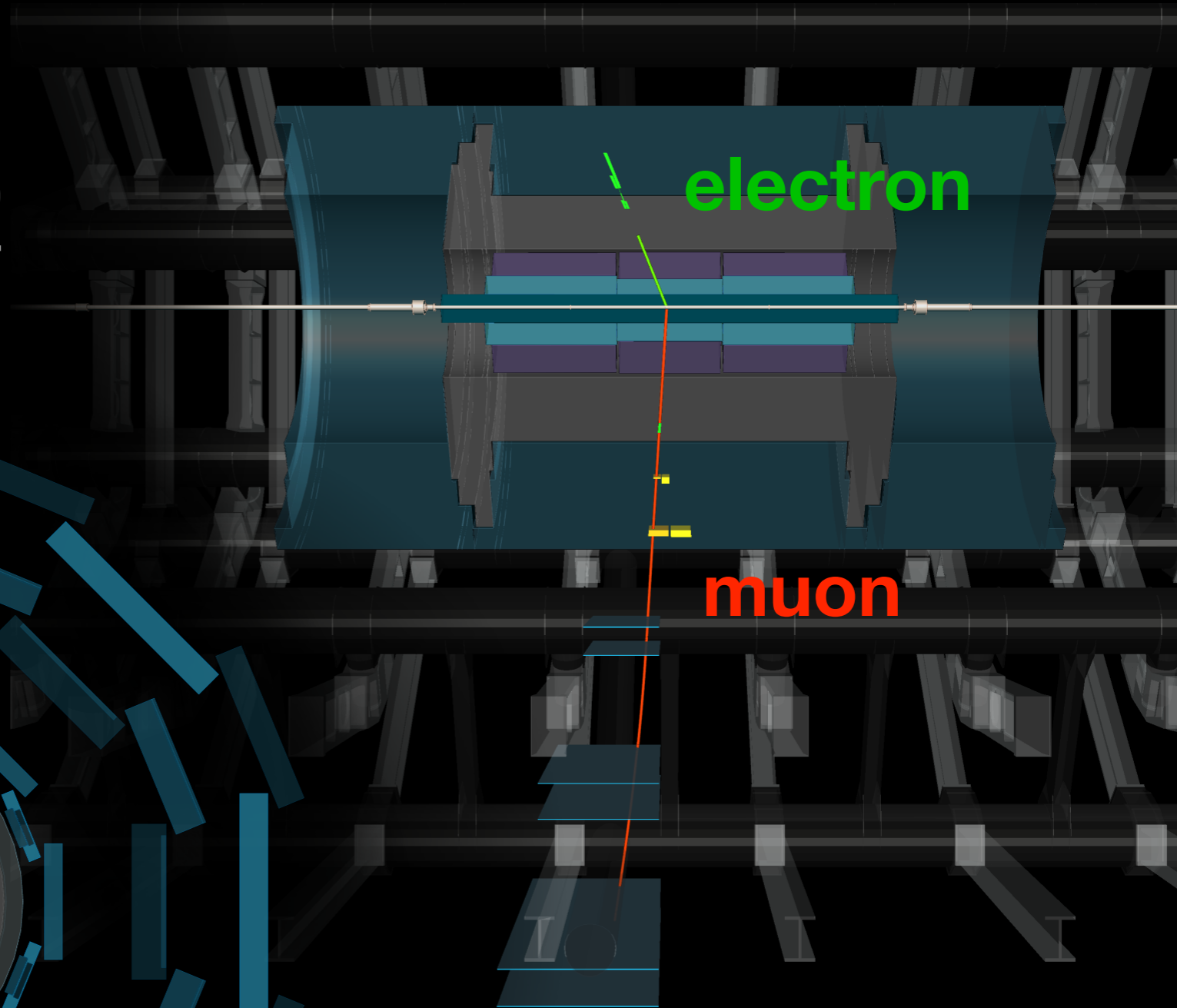
ATLAS EXPERIMENT

Ultra Peripheral PbPb collision



$$p_{T}^{e^+} = 11.9 \text{ GeV}$$

$$p_{T}^{\mu^-} = 11.7 \text{ GeV}$$



Pb+Pb, 5.02 TeV

Run: 365914

Event: 562492194

2018-11-14 18:05:31 CEST

All calo cells with $E_T > 500 \text{ MeV}$ shown

Ultra Peripheral PbPb collisions

Super clean with ~ 0 pile-up

One month to gather dataset

Low trigger thresholds \rightarrow Trigger on soft taus!

Di-tau Production

Aguila, Cornet and Illana [PLB \(1991\)](#)

Beresford, Liu [1908.05180](#)

LHC PbPb

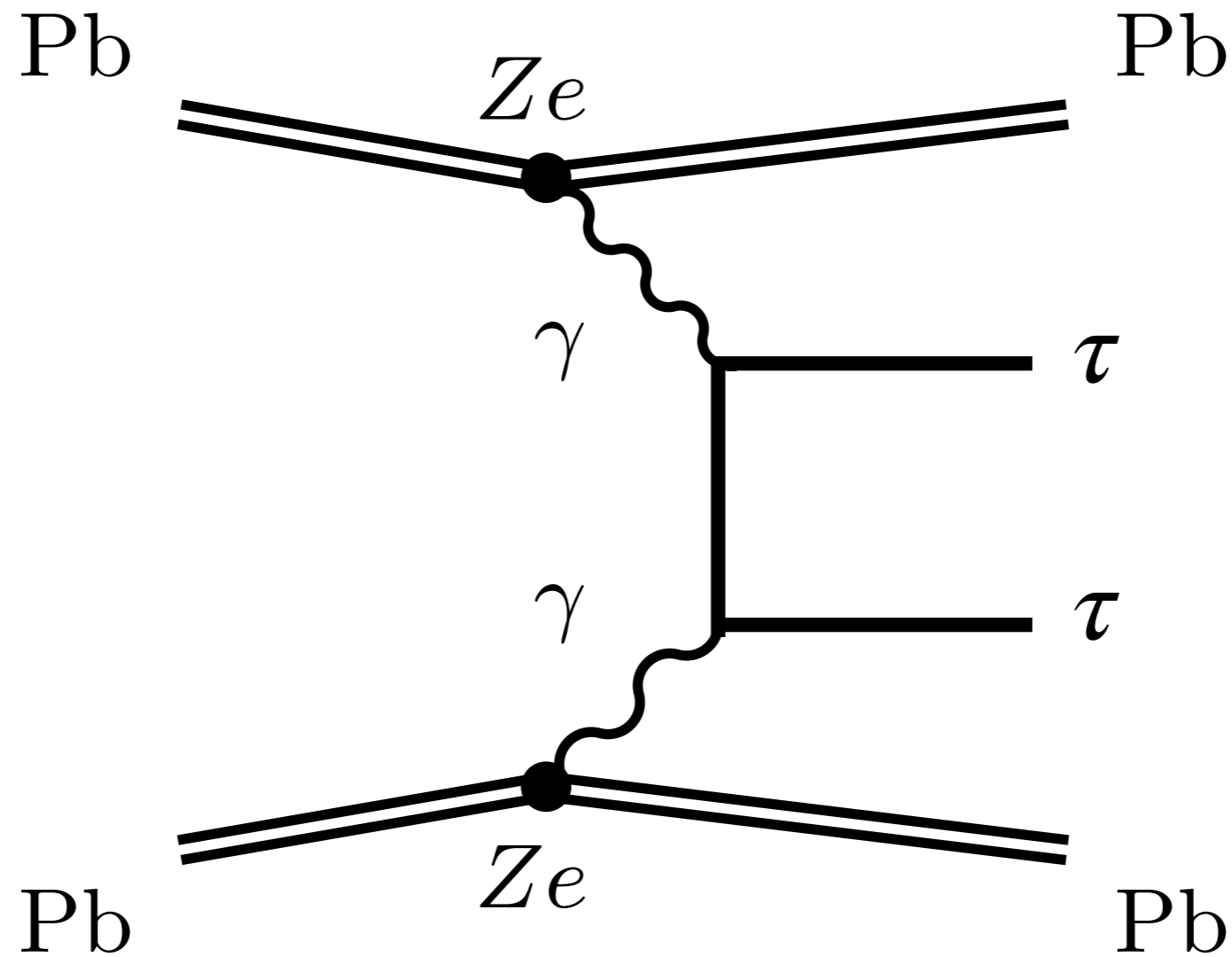


Photo production of tau pairs

Not yet observed @ LHC

LHC vs LEP

Higher \sqrt{s}

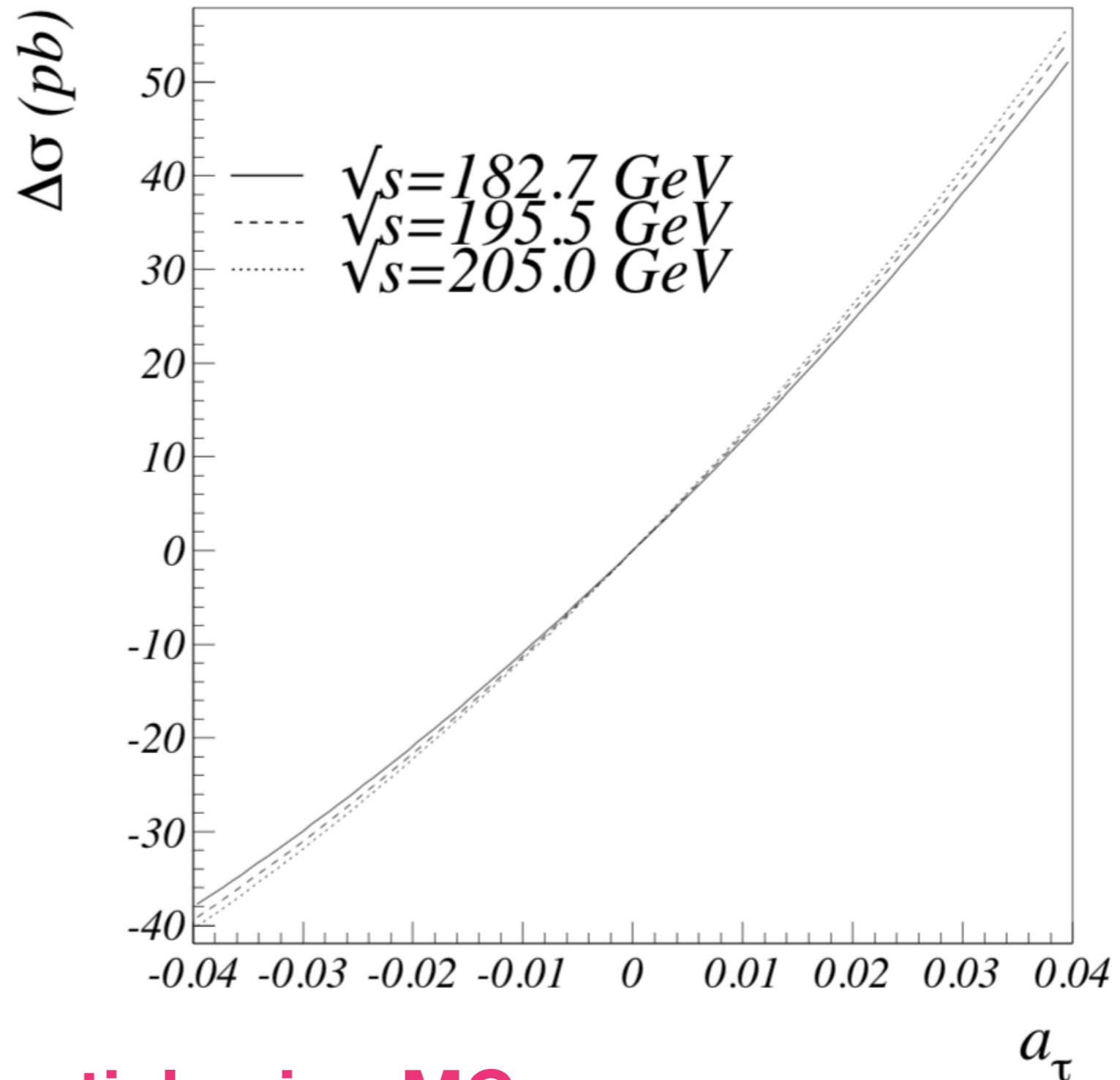
205 GeV \rightarrow **5.02 TeV**

Larger σ

400 pb \rightarrow **500,000 nb**

200k events \rightarrow **1m so far!**

DELPHI



\rightarrow Quantify potential using MC

Tau decays

46%

1 prong
 $\tau^\pm \rightarrow \pi^\pm \nu_\tau$
 + neutral π 's

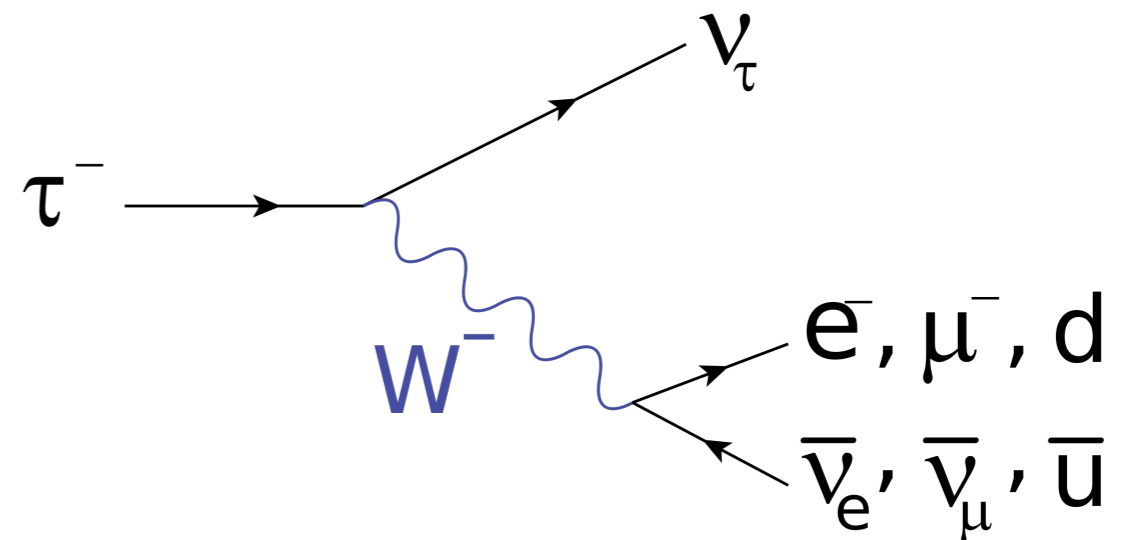
35%

Leptonic
 $\tau^\pm \rightarrow l^\pm \nu_l \nu_\tau$

19%

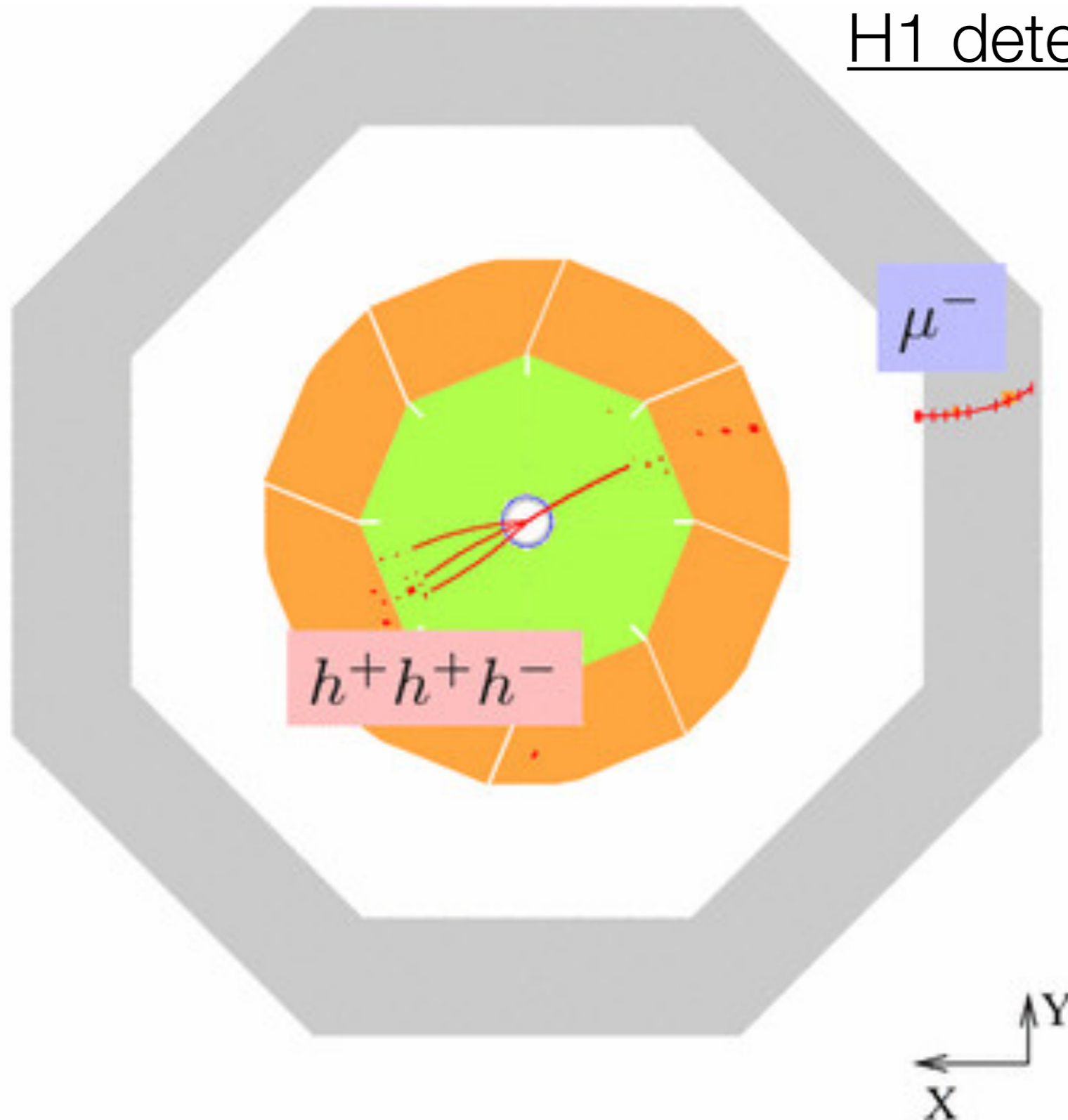
3 prong
 $\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_\tau$
 + neutral π 's

Tau is only lepton that
 can decay into hadrons



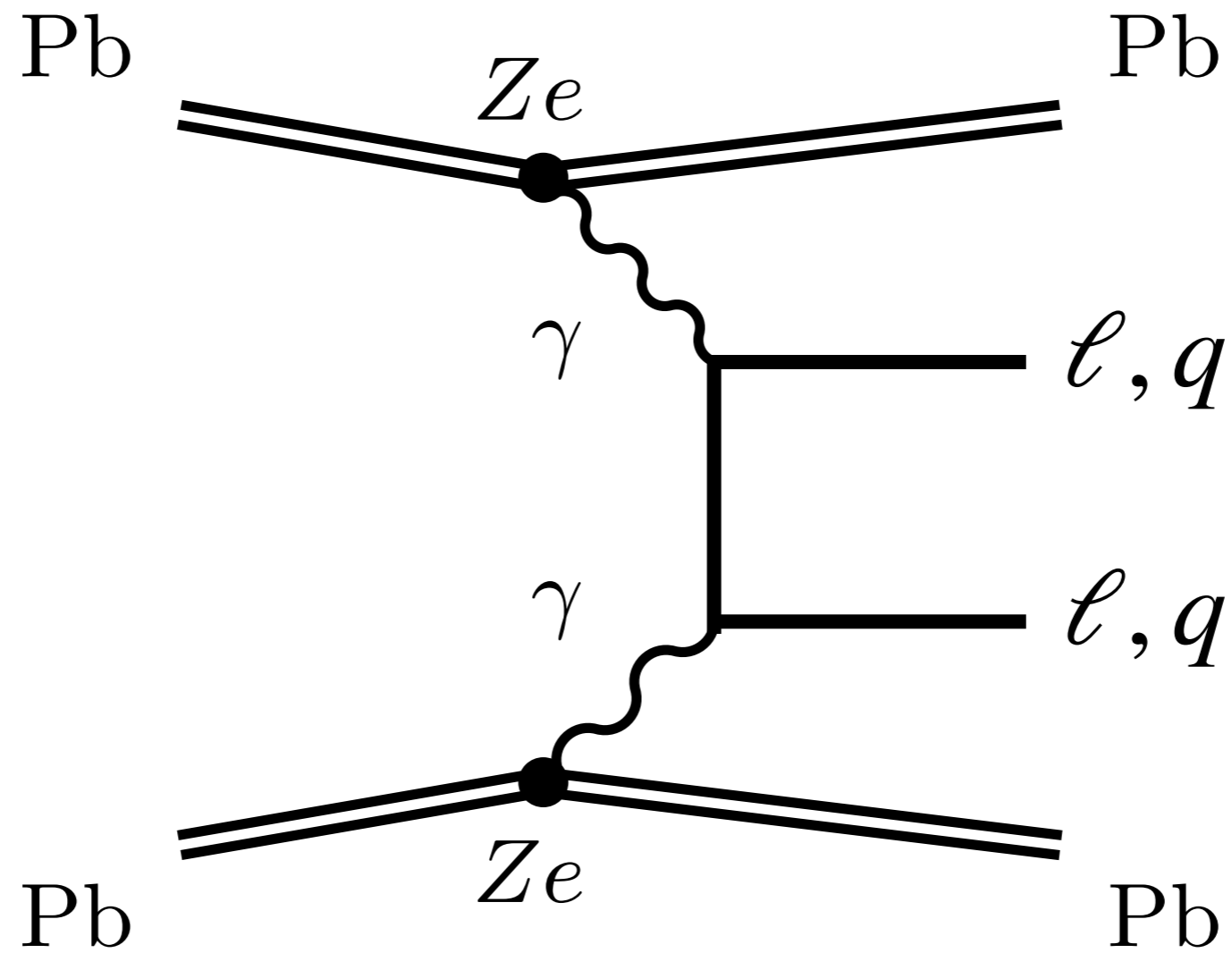
Tau decays

Di-tau pair
H1 detector @ HERA



Backgrounds

Generated:



Signal Regions

Need low p_T : e, mu, track $> 4.5, 3, 0.5$ GeV

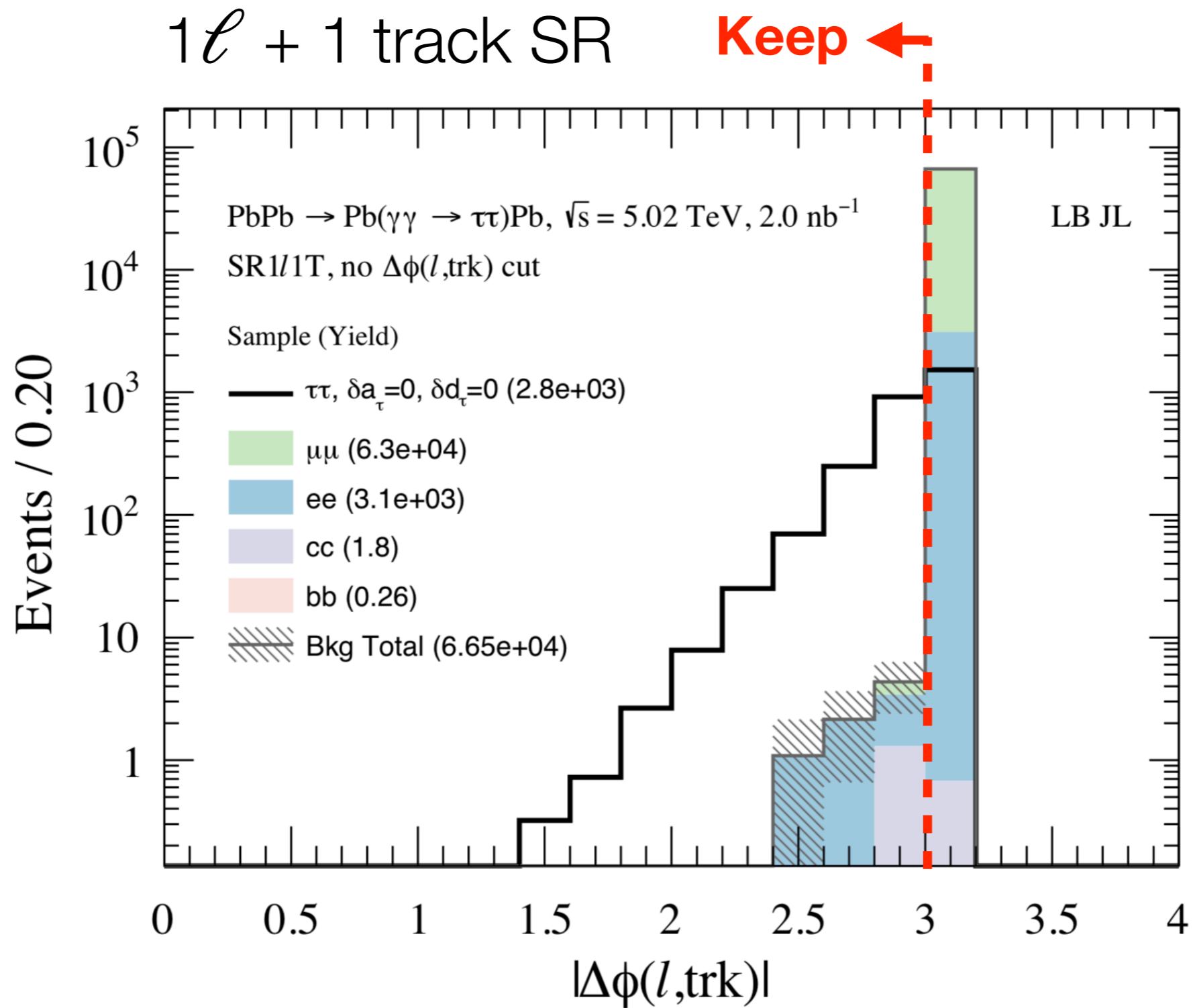
Signal Regions (SRs)

$1\ell + 1$ track

$1\ell + 2$ track

$1\ell + 3$ track

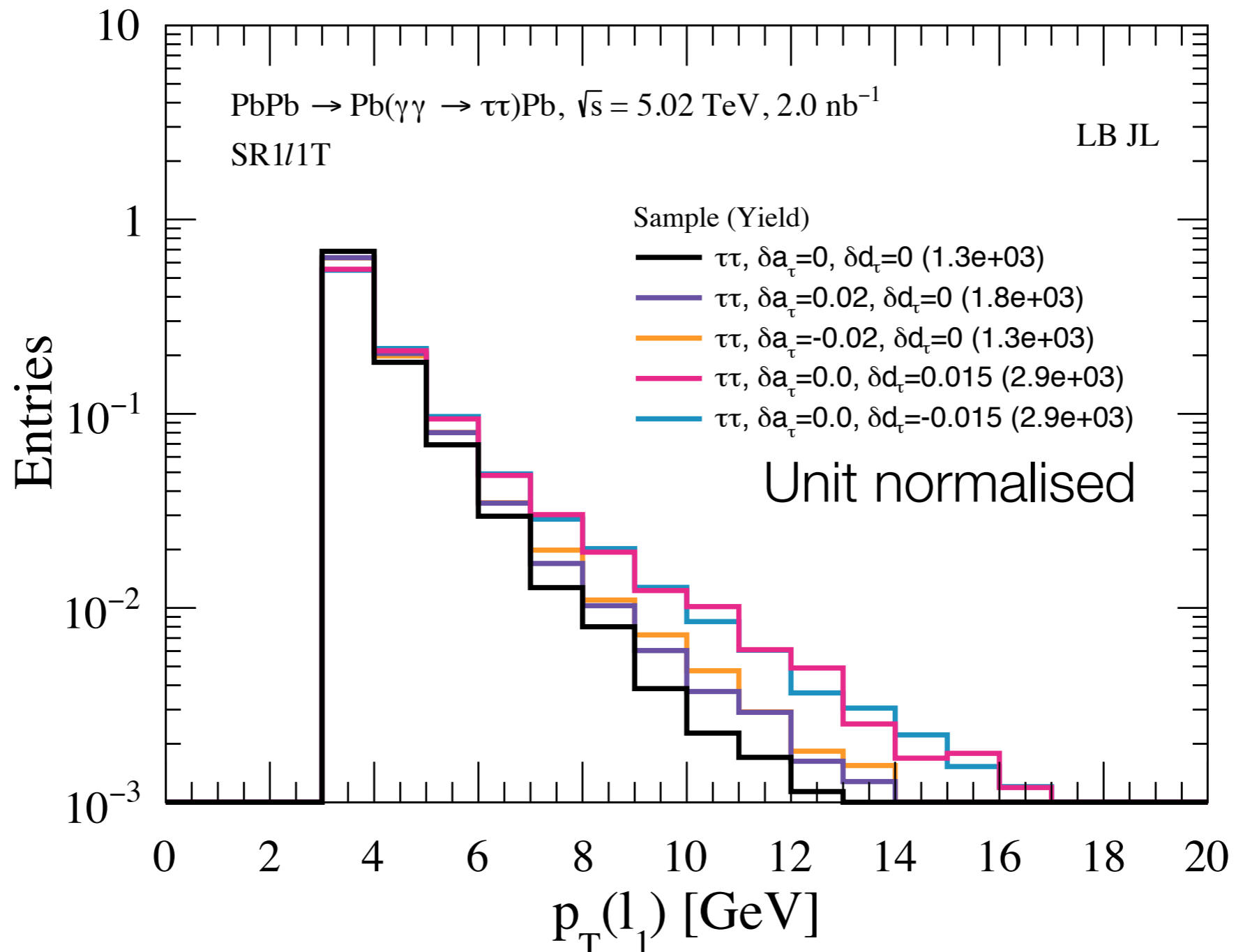
Background mitigation



And veto J/ψ & Υ masses

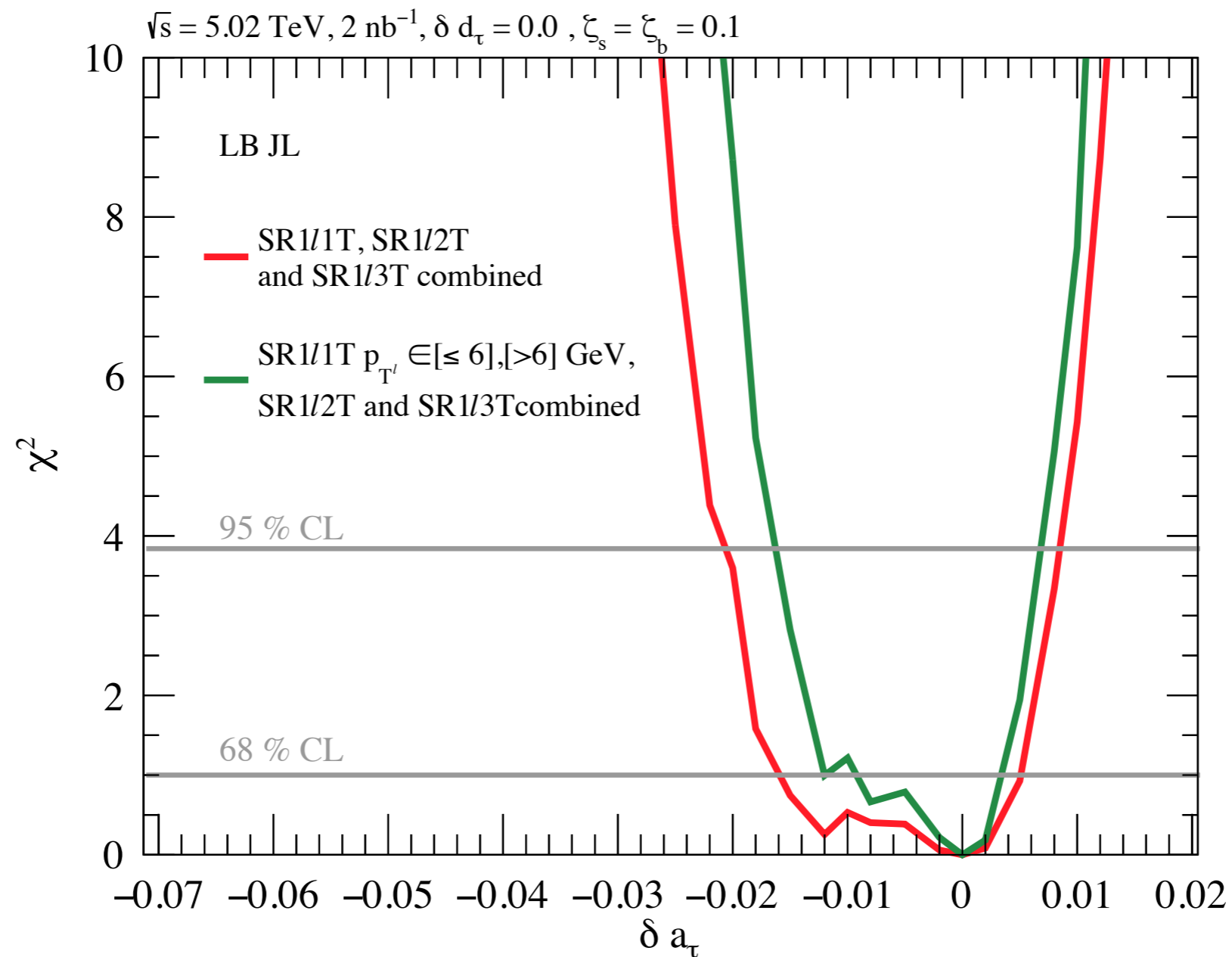
Setting constraints

SM effective field theory for modified moments (& SM signal)



Putting it all together: a_τ

Assume observe SM & quantify constraint using χ^2



Assuming 10% systematic

$\Sigma \chi^2$ for all SRs (orthogonal)

Shape analysis strengthens constraints :)

Lydia Beresford Split $1\ell + 1$ track SR @ 6 GeV \rightarrow Coarse shape analysis

Putting it all together: a_τ

a_e Harvard06 (error bar $\times 10^9$)

a_μ BNL06 (error bar $\times 10^6$)

PDG a_τ DELPHI04

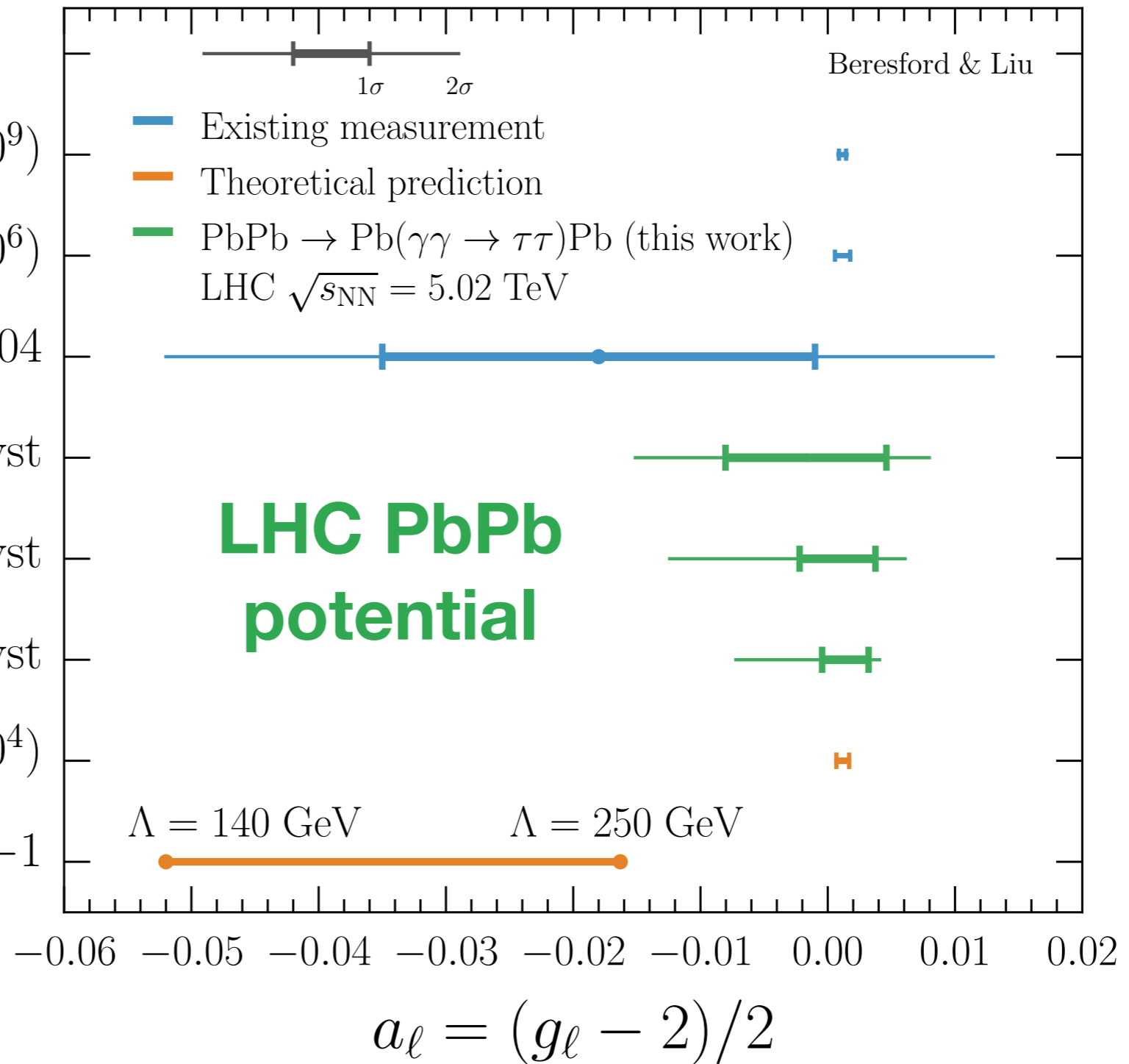
a_τ 2 nb $^{-1}$, 10% syst

a_τ 2 nb $^{-1}$, 5% syst

a_τ 20 nb $^{-1}$, 5% syst

SM a_τ^{pred} (error bar $\times 10^4$)

SMEFT a_τ^{pred} , $C_{\tau B} = -1$



Also sensitive to tau EDM

*How objects interact with an **electric** field*

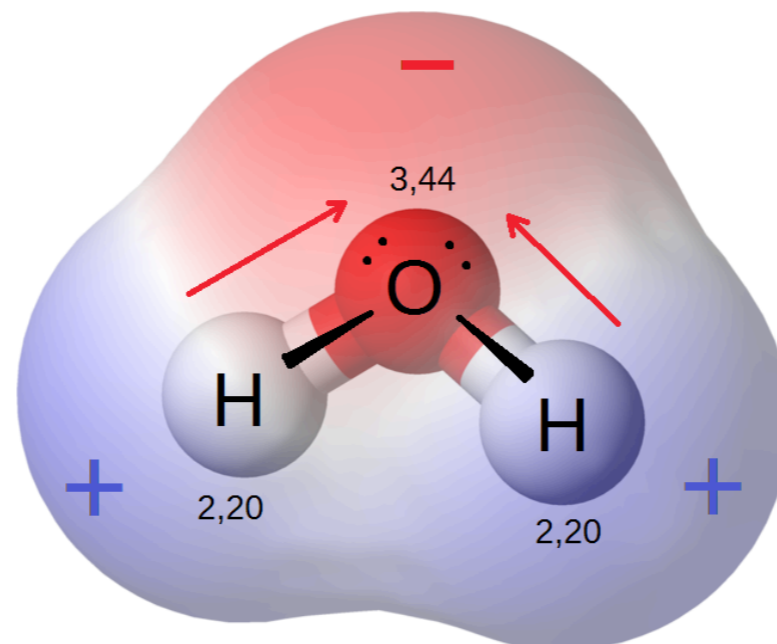
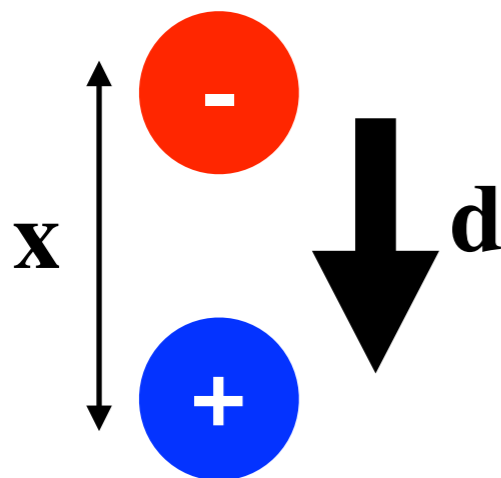
EDM = Electric Dipole Moment

$$\boldsymbol{\tau} = \mathbf{d} \times \mathbf{E}$$

↑ ↑
torque electric dipole moment

Possessed by e.g. water (polarised molecule)

$$\mathbf{d} = q\mathbf{x}$$

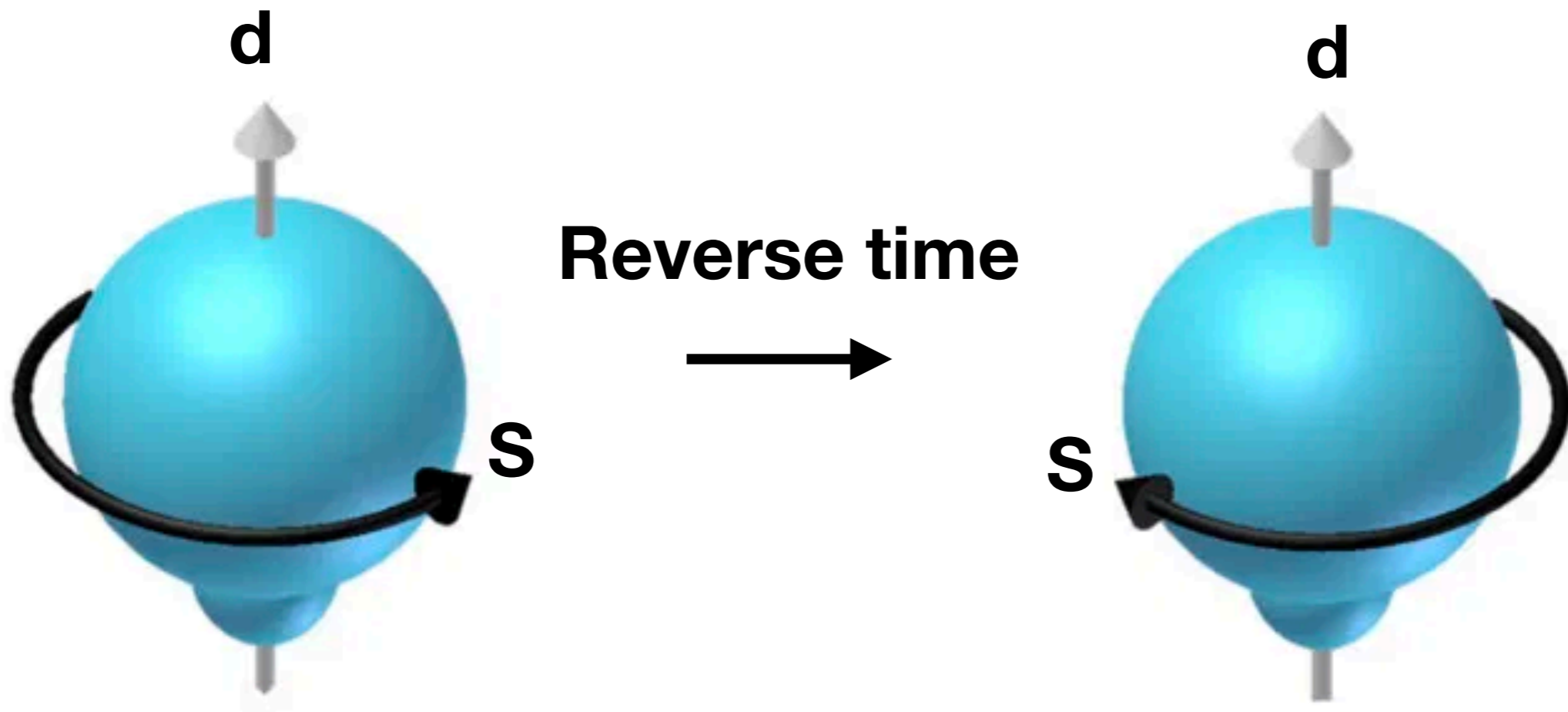


EDM tells us about charge distribution

Why are EDMs interesting?

Further details

Non-zero EDM \rightarrow CP violation!
assuming CPT conserved



EDM tiny in SM, observation = New Physics!

Putting it all together: d_τ

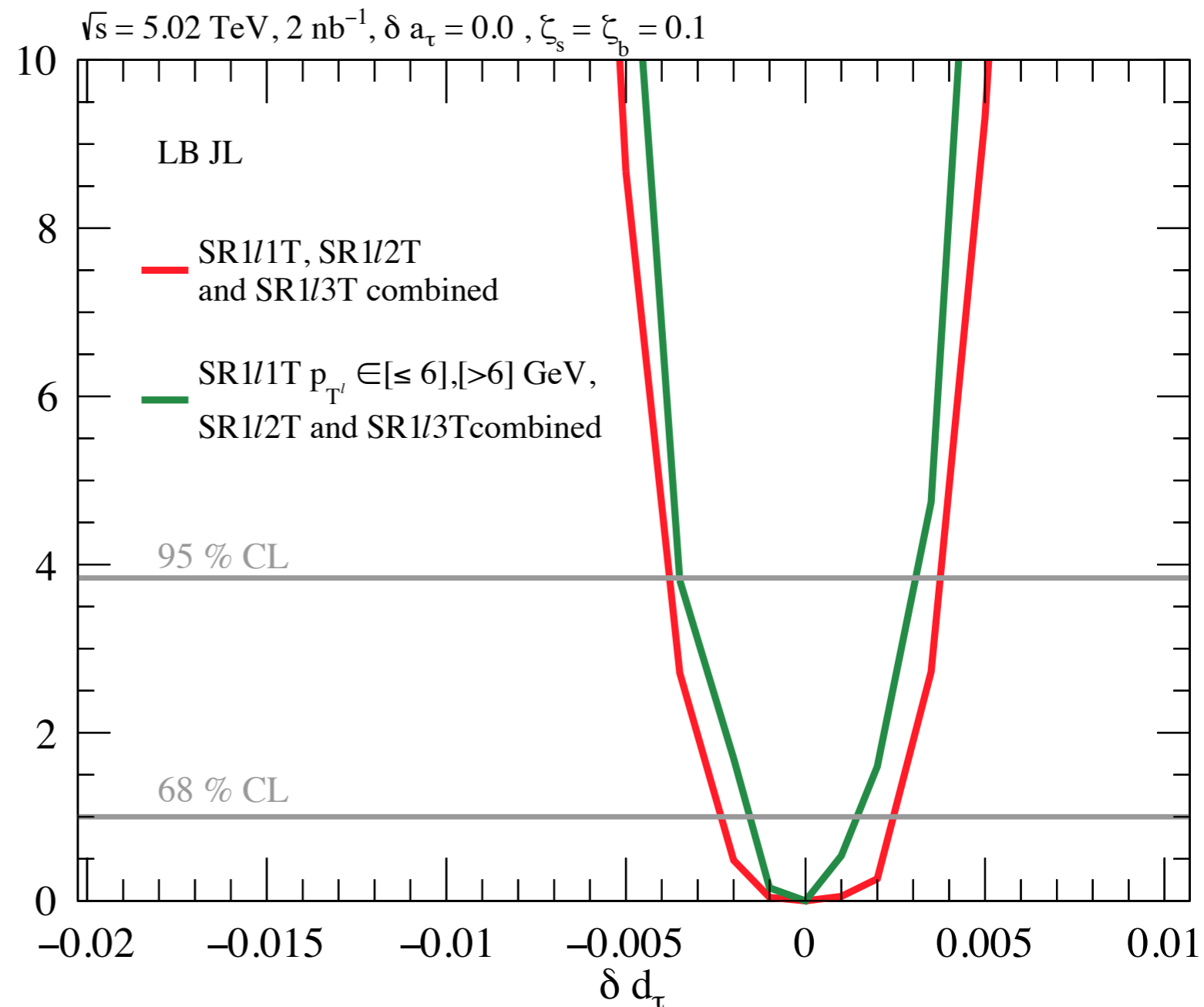
Belle [PLB \(2003\)](#)

$\Sigma\chi^2$ for all signal regions (orthogonal)

$$|d_\tau| = (e/m_\tau)\delta d_\tau$$

$$|d_\tau| < 3.4 \times 10^{-17} \text{ e cm} \quad \chi^2$$

@ 95% CL



Order mag better than DELPHI, competitive with Belle 44

Why stop there?

Demonstrated PbPb potential for ATLAS/CMS

Goal: Combined effort!

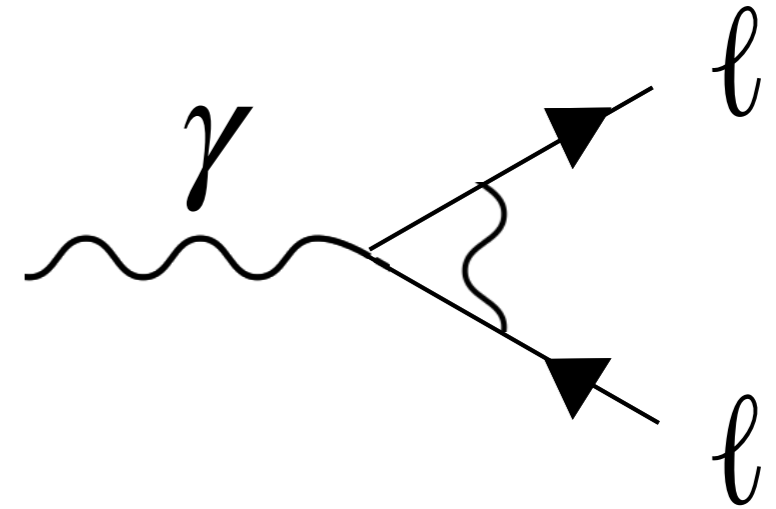
PbPb & pPb

ATLAS, CMS, LHCb & ALICE

RHIC & lepton colliders

Why stop there?

$$a = \frac{(g - 2)}{2} = \frac{\alpha}{2\pi} + \dots$$



Schwinger, 1948

The Schwinger term, $\alpha/2\pi$, in a_τ has the value

$$a_\tau = 0.0012.$$

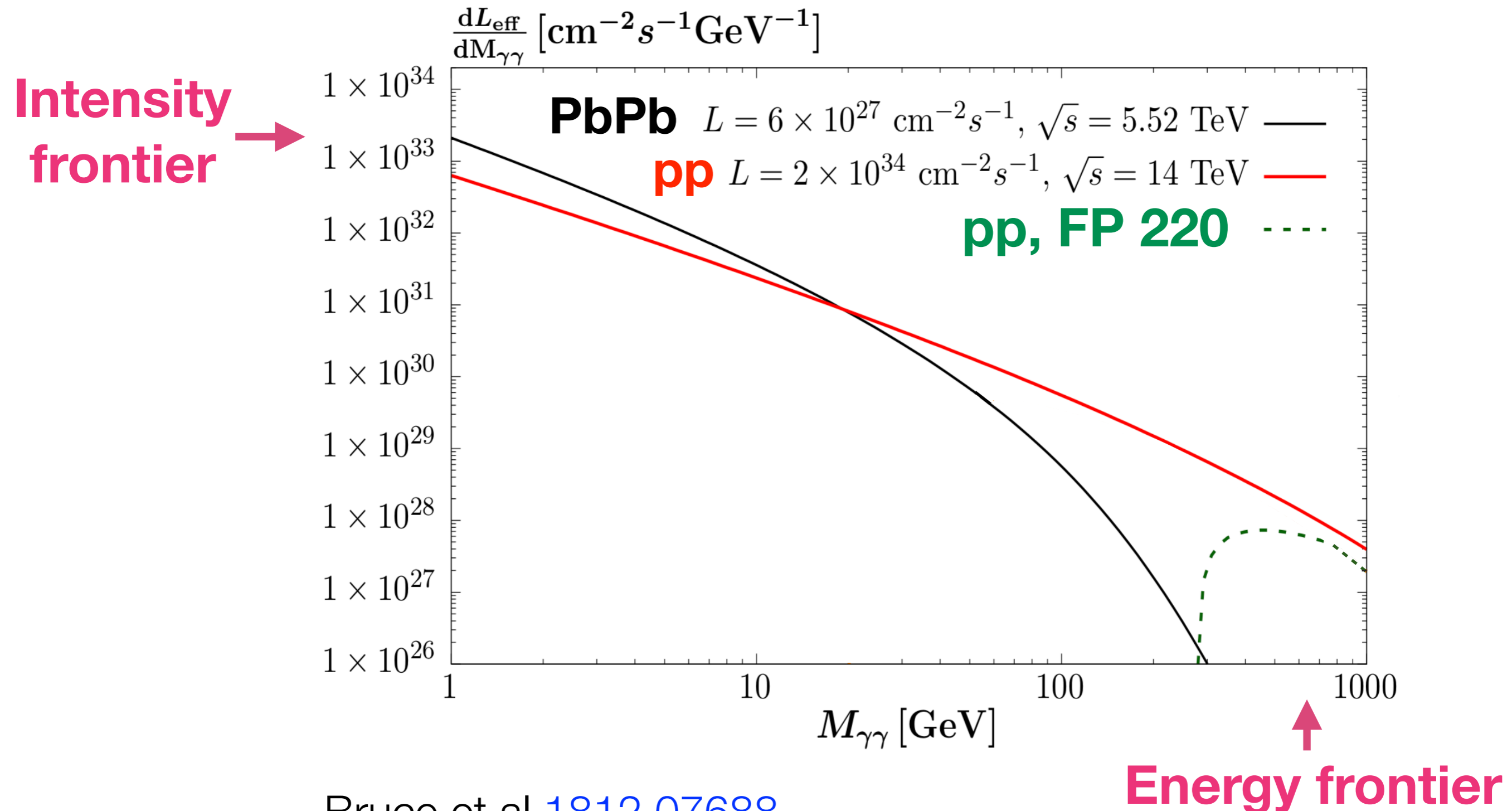
It would be very nice to measure μ_τ with enough precision to check this, as it was checked for the e and the μ years ago. *At present such precision is a dream.* **Martin Perl, 1998**

Photon collisions: **Not a one trick pony**



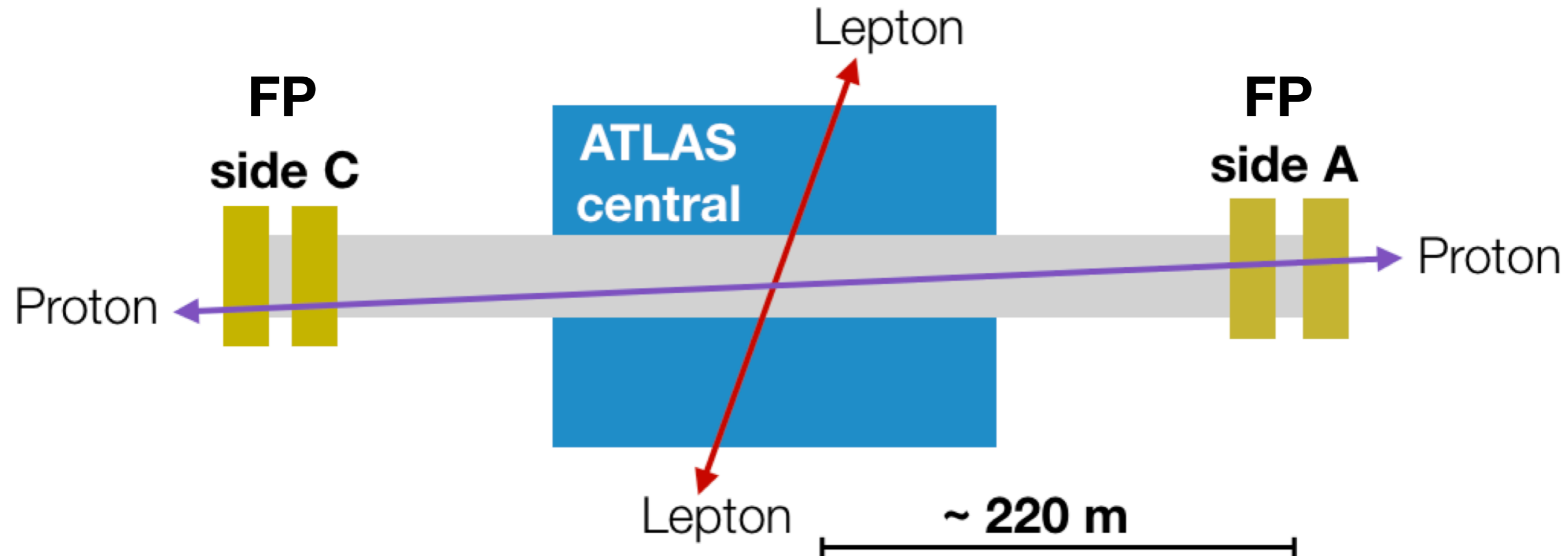
QED @ range of masses

Photon collisions from **protons & heavy ions**



pp, FP 220 Forward Proton detectors

ATLAS (AFP)
CMS (CT-PPS)



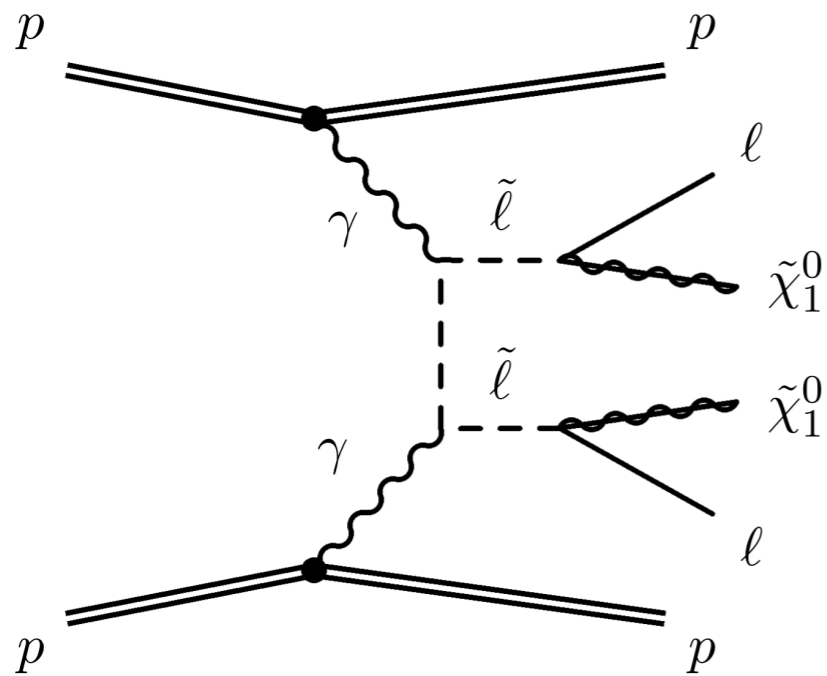
Incoming proton E known (6.5 TeV)

Outgoing proton E measured with forward detector

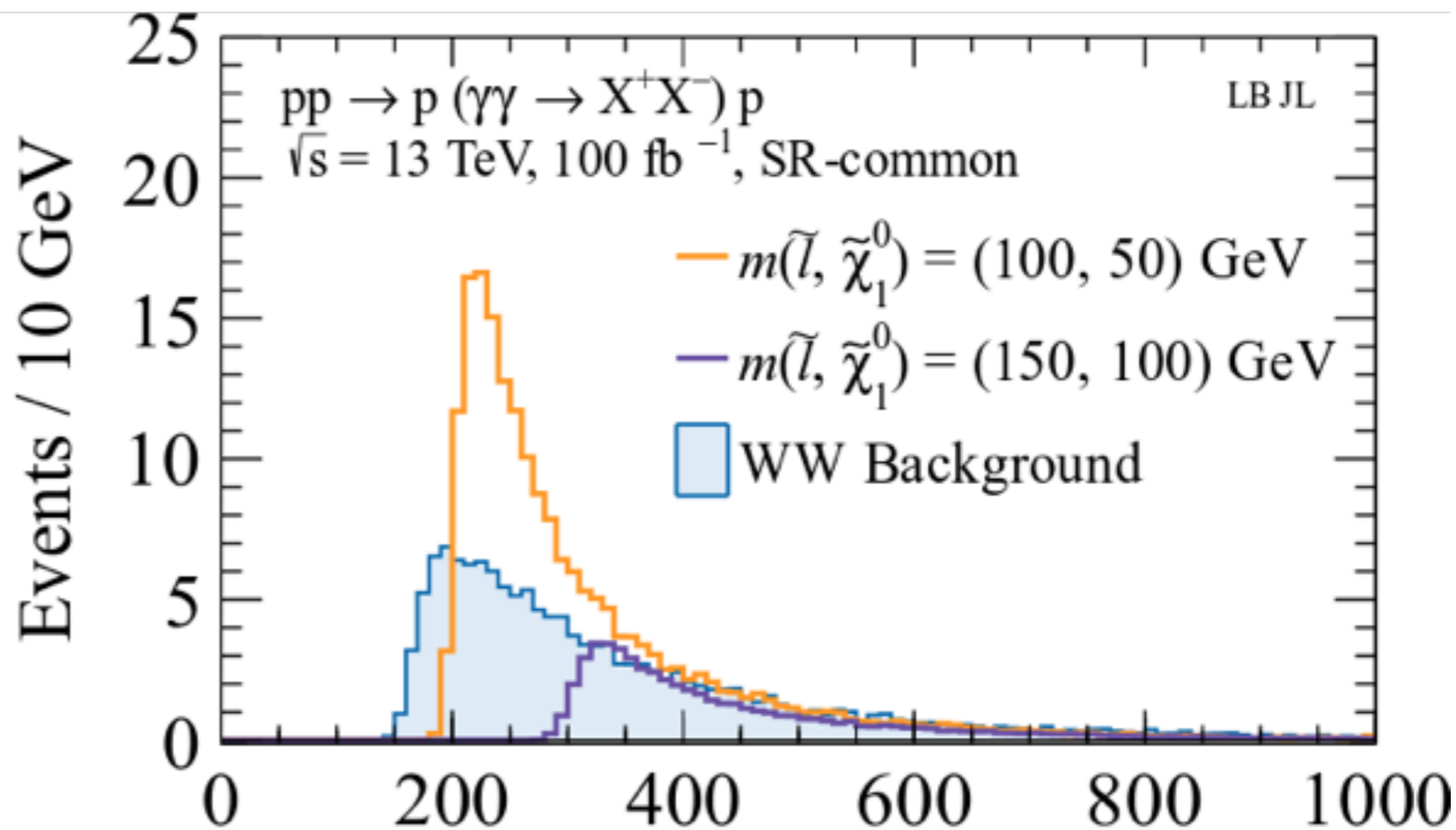
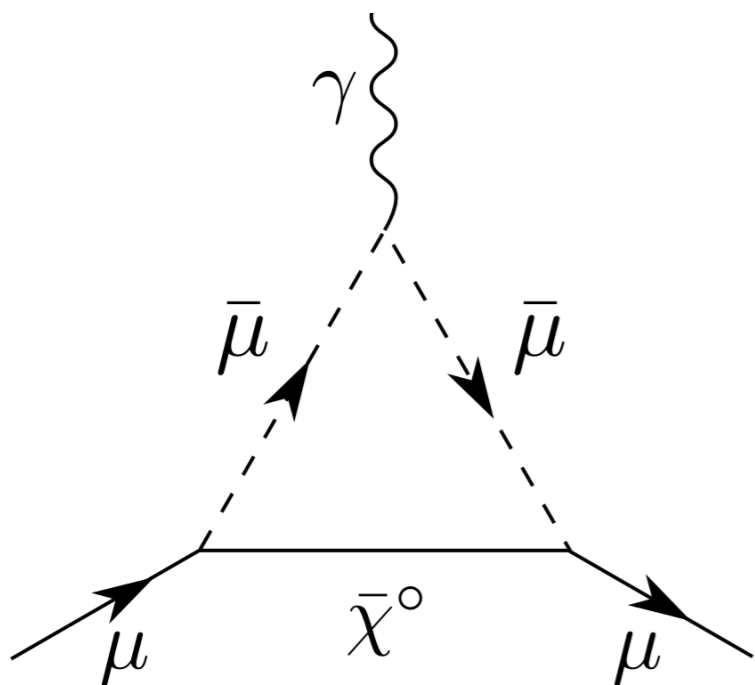
→ **Calculate proton energy loss!**

→ Search for production threshold

Illustrative plot
FP acceptance
not applied



Recall



$$m_{\gamma\gamma} = \sqrt{(p_1^\gamma + p_2^\gamma)^2} \text{ [GeV]}$$

Calculated from proton energy loss

Beresford, Liu [PRL \(2019\)](#)

What if new physics ...

Is invisible to detector?

Decays to a cascade of soft particles?

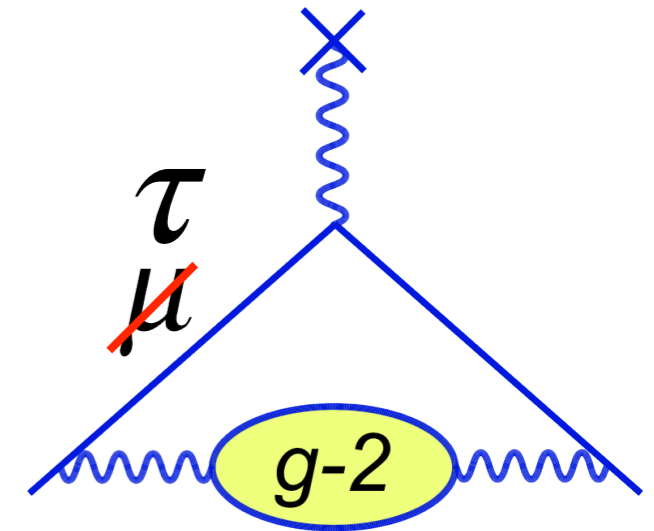
Is a broad resonance?

Is a long lived particle?

Summary

Tau $g-2$ interesting & important

But barely constrained



LHC photon collisions promising solution

For tau $g-2$ and beyond!

SM QED

The anomalous τ magnetic moment $a_\tau = (g_\tau - 2)/2$ is defined by the spin-magnetic Hamiltonian $-\boldsymbol{\mu}_\tau \cdot \mathbf{B} = -(g_\tau e/2m_\tau) \mathbf{S} \cdot \mathbf{B}$. In the Lagrangian formulation of QED, electromagnetic moments arise from the spinor tensor $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$ structure of the fermion current interacting with the photon field strength $F_{\mu\nu}$

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

SMEFT

To introduce BSM modifications of a_τ and d_τ , we use SM effective field theory (SMEFT) [68]. This assumes the scale of BSM physics Λ is much higher than the probe momentum transfers q i.e., $q^2 \ll \Lambda^2$. At scale q , two dimension-six operators in the Warsaw basis [69] modify a_τ and d_τ at tree level, as discussed in Ref. [68]

$$\mathcal{L}' = (\bar{L}_\tau \sigma^{\mu\nu} \tau_R) H \left[\frac{C_{\tau B}}{\Lambda^2} B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2} W_{\mu\nu} \right]. \quad (3)$$

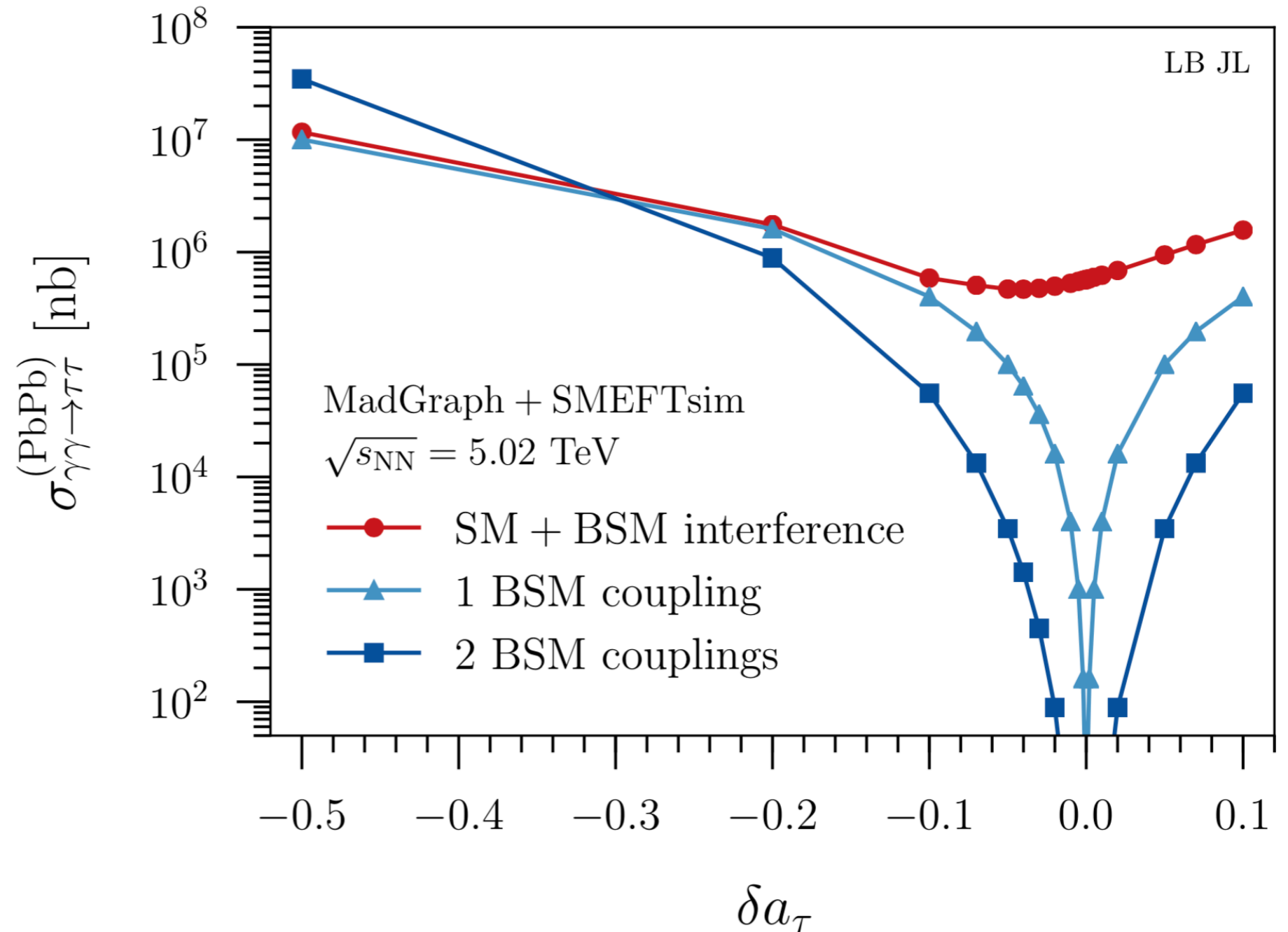
Here, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the $U(1)_Y$ and $SU(2)_L$ field strengths, H (L_τ) is the Higgs (tau lepton) doublet, and C_i are dimensionless, complex Wilson coefficients. We fix $C_{\tau W} = 0$ to parameterize the two modified moments $(\delta a_\tau, \delta d_\tau)$ using two real parameters $(|C_{\tau B}|/\Lambda^2, \varphi)$ [33]

$$\delta a_\tau = \frac{2m_\tau}{e} \frac{|C_{\tau B}|}{M} \cos \varphi, \quad \delta d_\tau = \frac{|C_{\tau B}|}{M} \sin \varphi, \quad (4)$$

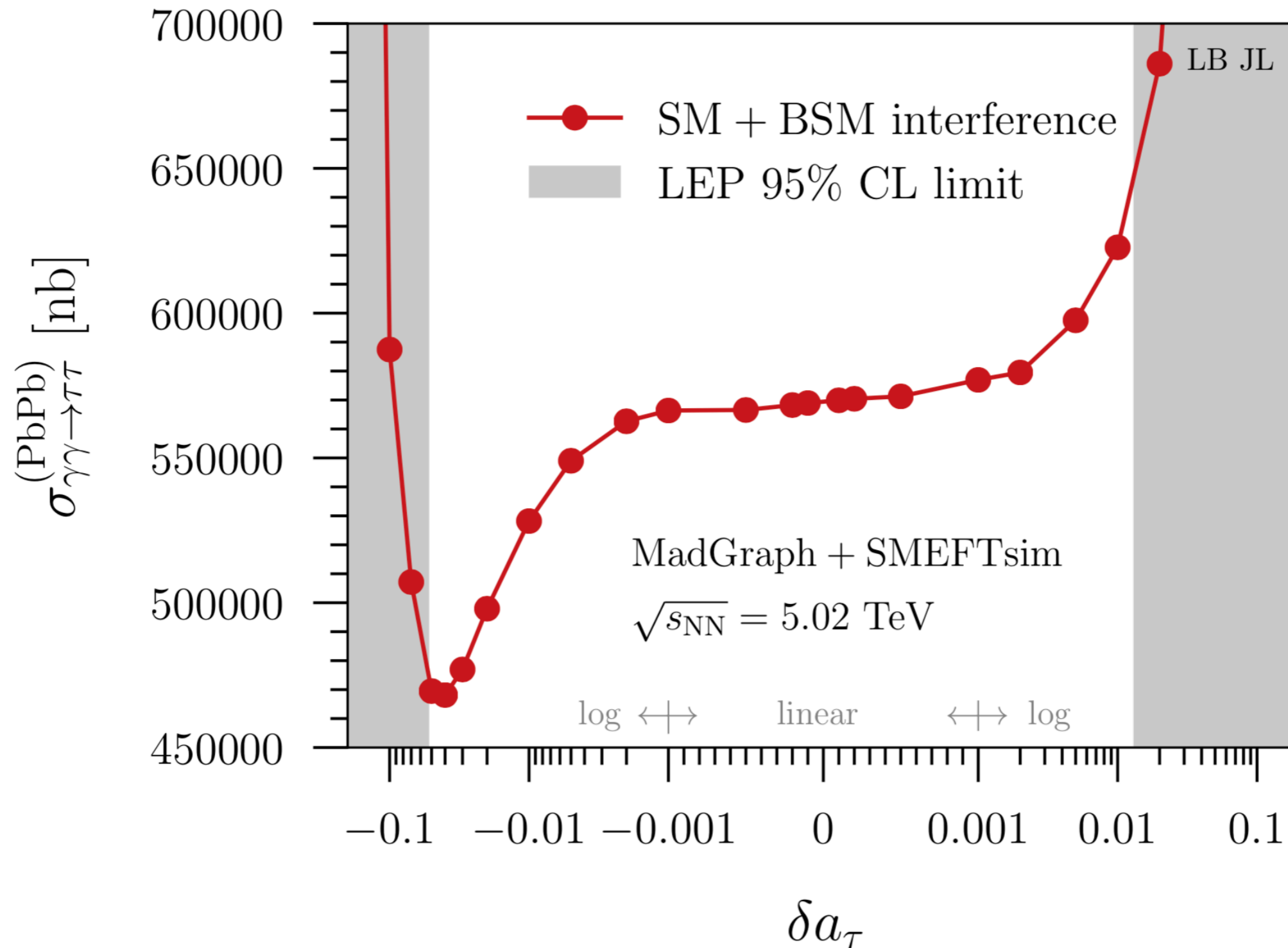
where φ is the complex phase of $C_{\tau B}$, we define $M = \Lambda^2 / (\sqrt{2}v \cos \theta_W)$, θ_W is the electroweak Weinberg angle, and $v = 246$ GeV.

Cross-section & interference

$$\begin{aligned}
 |\mathcal{M}|^2 &= \left| \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{BSM}}^{(1)} + \mathcal{M}_{\text{BSM}}^{(2)} \right|^2 \\
 &= \left| \text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} \right|^2
 \end{aligned}$$

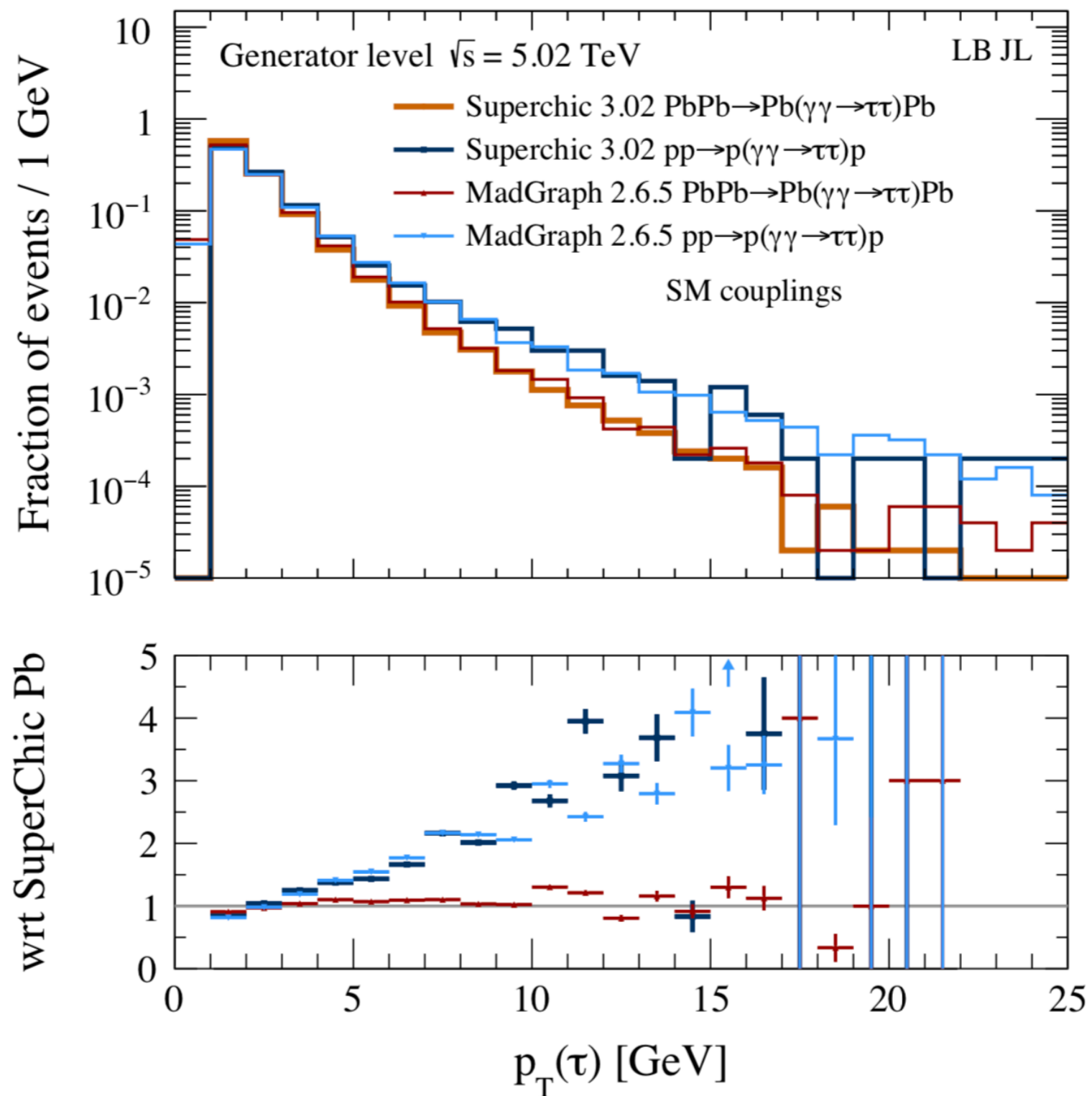


Cross-section & interference (zoomed)

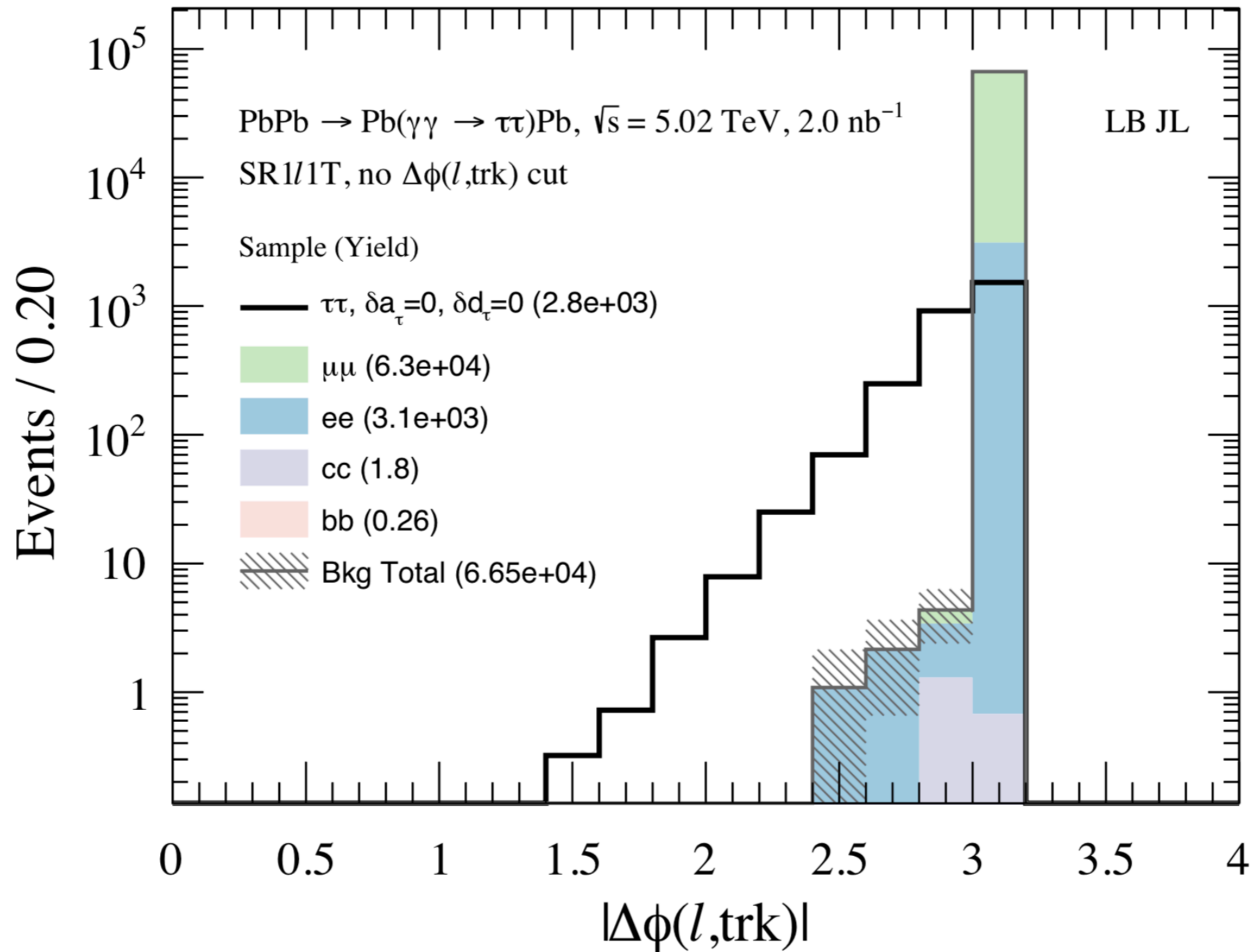


MG vs Super Chic

Superchic accounts for nuclear finite size, thickness and overlap



SR111T non-planar requirement



Cutflow

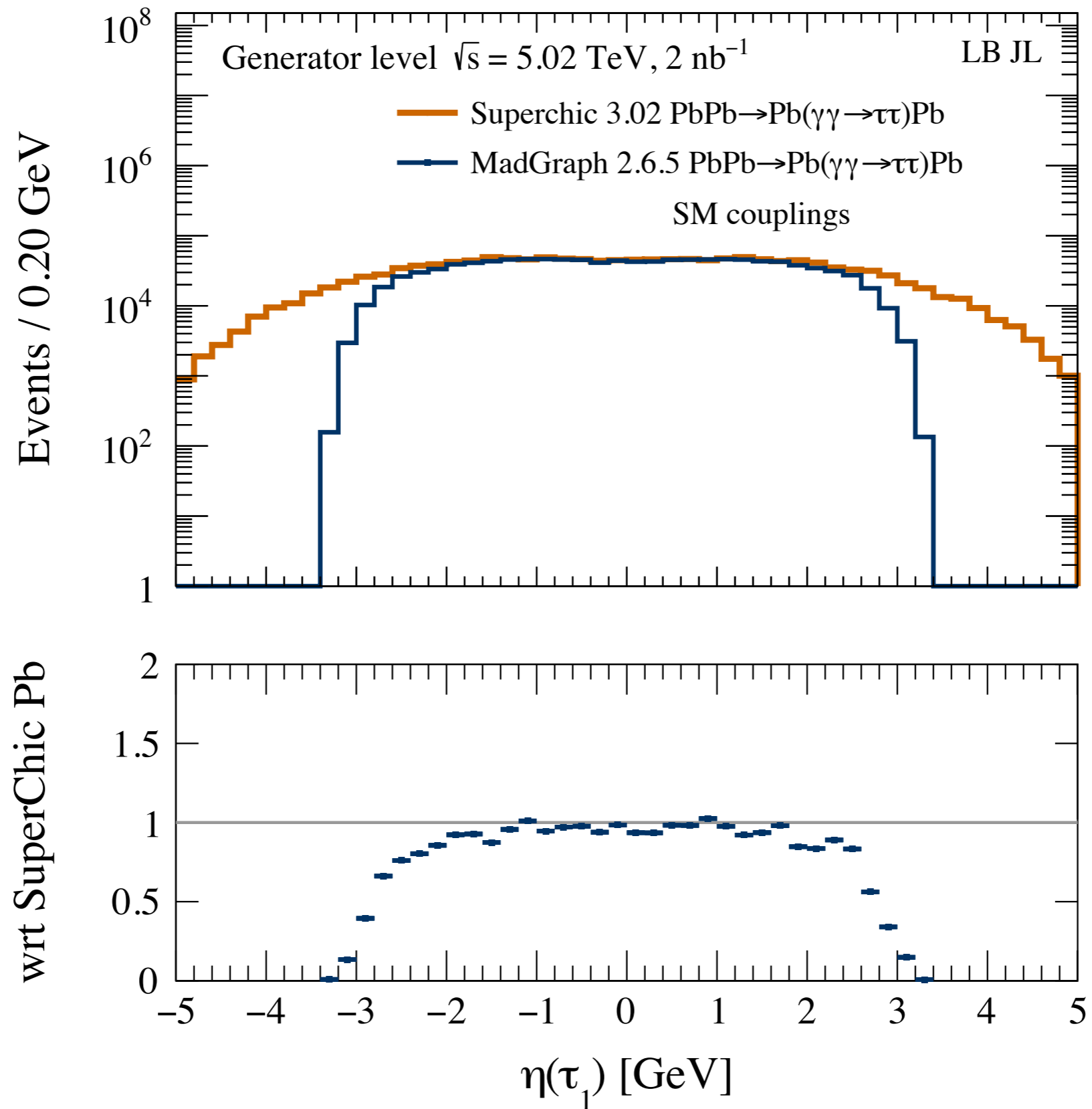
Requirement	$\tau\tau$ (0, 0)	$\tau\tau$ (0.005, 0)	$\tau\tau$ (-0.01, 0)	$\mu\mu$	ee	bb	cc	ss	uu	dd
1 lepton + 1 track analysis (SR1 ℓ 1T)										
$\sigma \times \mathcal{L}$	1139800	1195060	1056400	844080	844080	2999	604080	37754	604080	37754
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	241140	253920	226300	844080	844080	2999	604080	37754	604080	37754
1 ℓ plus 1 track	20492.2	21619.3	19348.4	263443	3299.3	5.4	2905.0	0.3	5.4	0.2
$p_{\text{T}}^{e/\mu} > 4.5/3$ GeV, $ \eta^{e/\mu} < 2.5/2.4$	3659.9	3882.7	3582.8	79043	3118.9	1.1	4.8	0.0	0.0	0.0
2 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $ \eta^{\text{trk}} < 2.5$	3324.5	3535.9	3256.9	78973	3117.8	1.0	3.0	0.0	0.0	0.0
$ \Delta\phi(\ell, \text{trk}) < 3$	1519.7	1605.7	1468.3	0.9	5.3	0.7	1.8	0.0	0.0	0.0
$m_{\ell, \text{trk}} \notin \{[3, 3.2], [9, 11]\}$ GeV	1275.1	1353.6	1242.3	0.9	5.3	0.2	1.2	0.0	0.0	0.0
$p_{\text{T}}^{\ell} \leq 6.0$ GeV	1197.7	1262.3	1154.7	0.9	0.0	0.2	1.2	0.0	0.0	0.0
$p_{\text{T}}^{\ell} > 6.0$ GeV	77.3	91.3	87.6	0.0	5.3	0.0	0.0	0.0	0.0	0.0
1 lepton + multitrack analysis (SR1 ℓ 2/3T)										
$\sigma \times \mathcal{L}$	1139800	1195060	1056400	844080	844080	2999	604080	37754	604080	37754
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	241140	253920	226300	844080	844080	2999	604080	37754	604080	37754
1 ℓ plus 2 or 3 tracks	5945.1	6260.1	5572.2	33.8	23.2	43.8	8056.6	5.4	132.9	6.8
$p_{\text{T}}^{e/\mu} > 4.5/3$ GeV, $ \eta^{e/\mu} < 2.5/2.4$	1010.0	1073.3	978.6	12.2	4.2	1.8	13.3	0.0	0.0	0.0
3 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $ \eta ^{\text{trk}} < 2.5$	519.9	548.1	485.8	5.6	4.2	0.8	4.8	0.0	0.0	0.0
4 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $ \eta ^{\text{trk}} < 2.5$	370.5	398.3	381.1	0.0	0.0	0.4	3.6	0.0	0.0	0.0

DELPHI Cutflow

Year	Observed	Expected	σ_{meas}, pb	σ_{MC}, pb	$\sigma_{meas}/\sigma_{MC}$
1997	211	224 ± 18	$401 \pm 32 \pm 36$	428.2 ± 0.5	0.94 ± 0.11
1998	629	652 ± 24	$419 \pm 19 \pm 18$	436.7 ± 0.5	0.96 ± 0.06
1999	909	937 ± 39	$436 \pm 16 \pm 21$	448.5 ± 0.5	0.97 ± 0.06
2000	641	665 ± 32	$443 \pm 20 \pm 24$	459.4 ± 0.5	0.97 ± 0.07

Table 8: The numbers of observed and expected events, measured cross-sections, QED predictions and their ratios. The first error on the measured cross-sections is statistical, the second is systematic.

Eta distribution

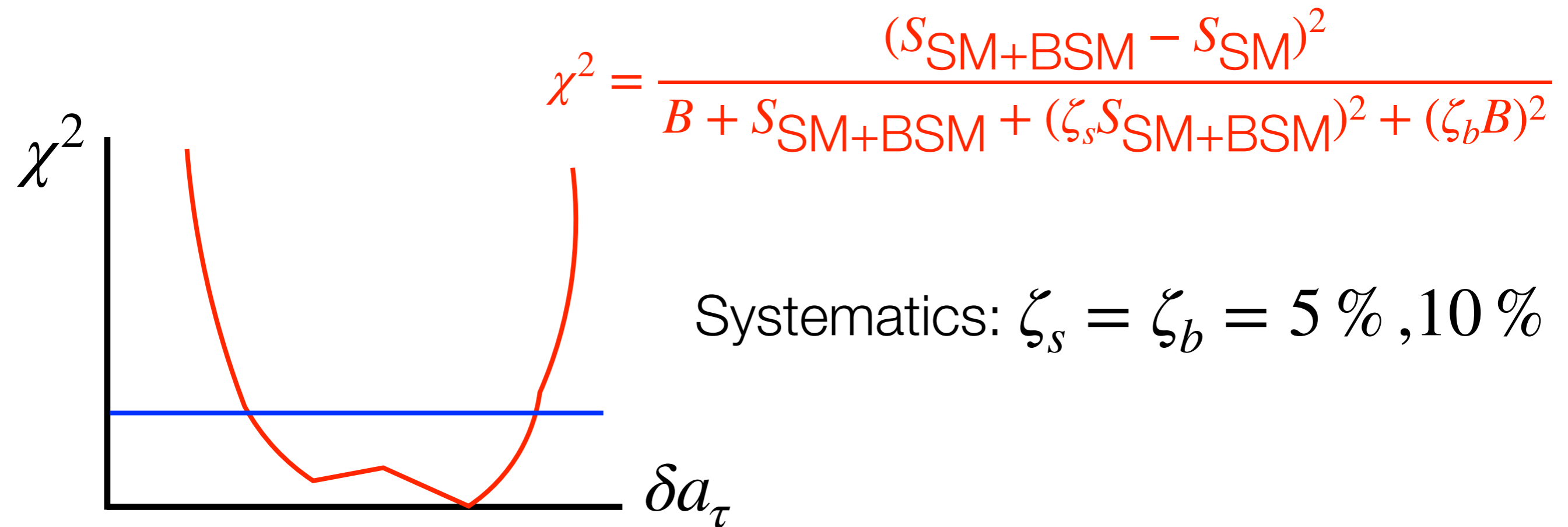


Setting constraints

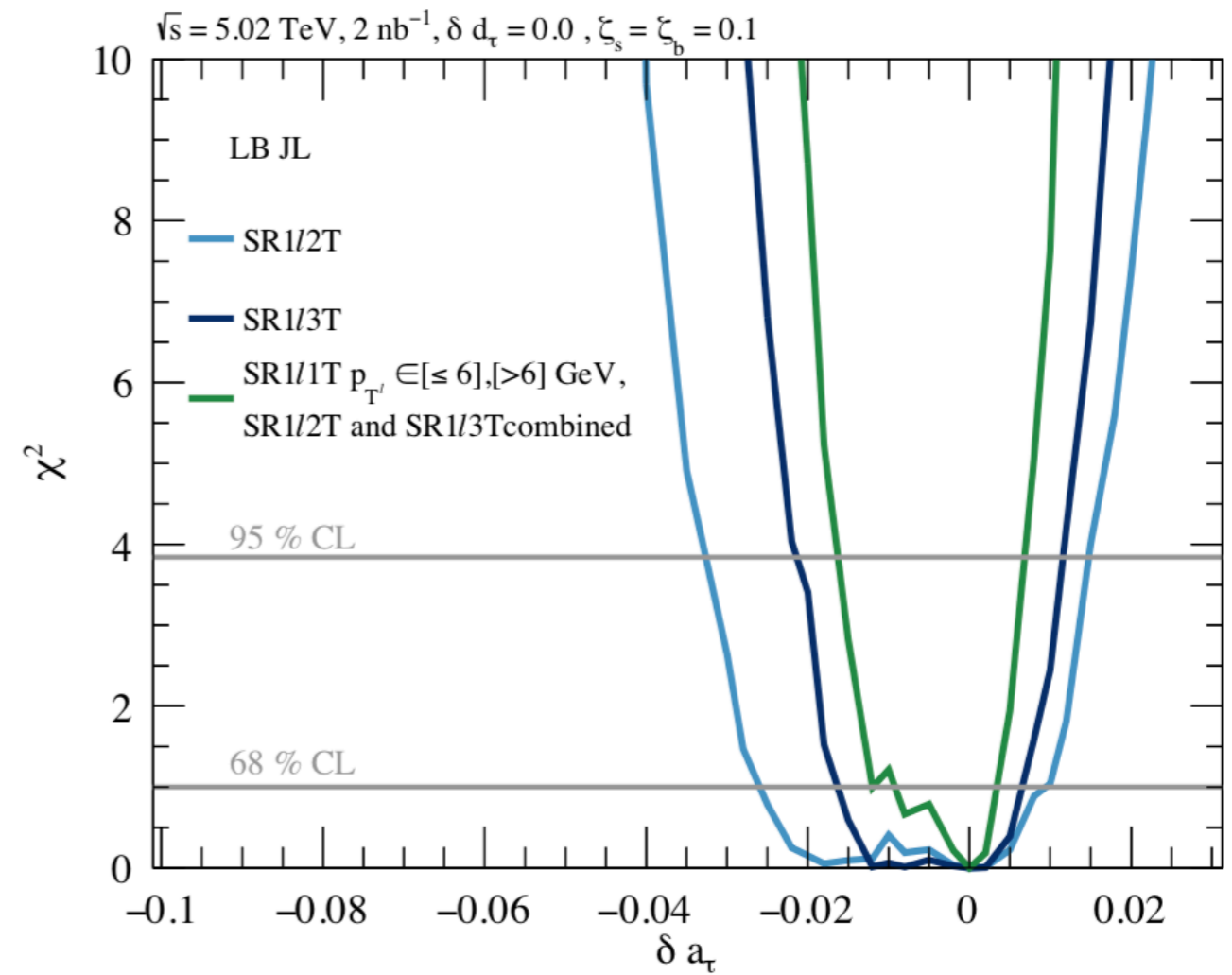
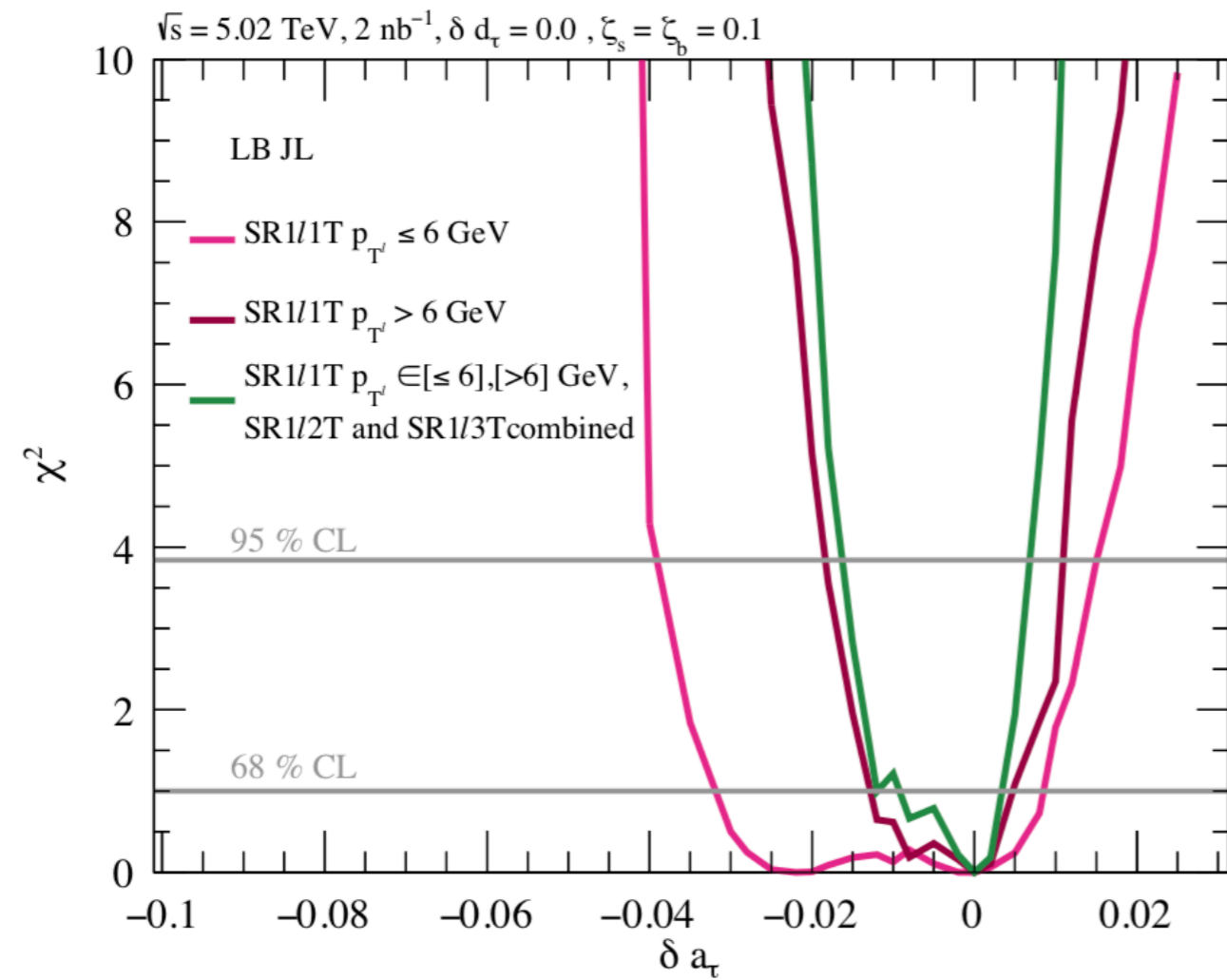
To set a constraint need to deviate from SM

We use SM effective field theory (assumes $q^2 \ll \Lambda^2$)

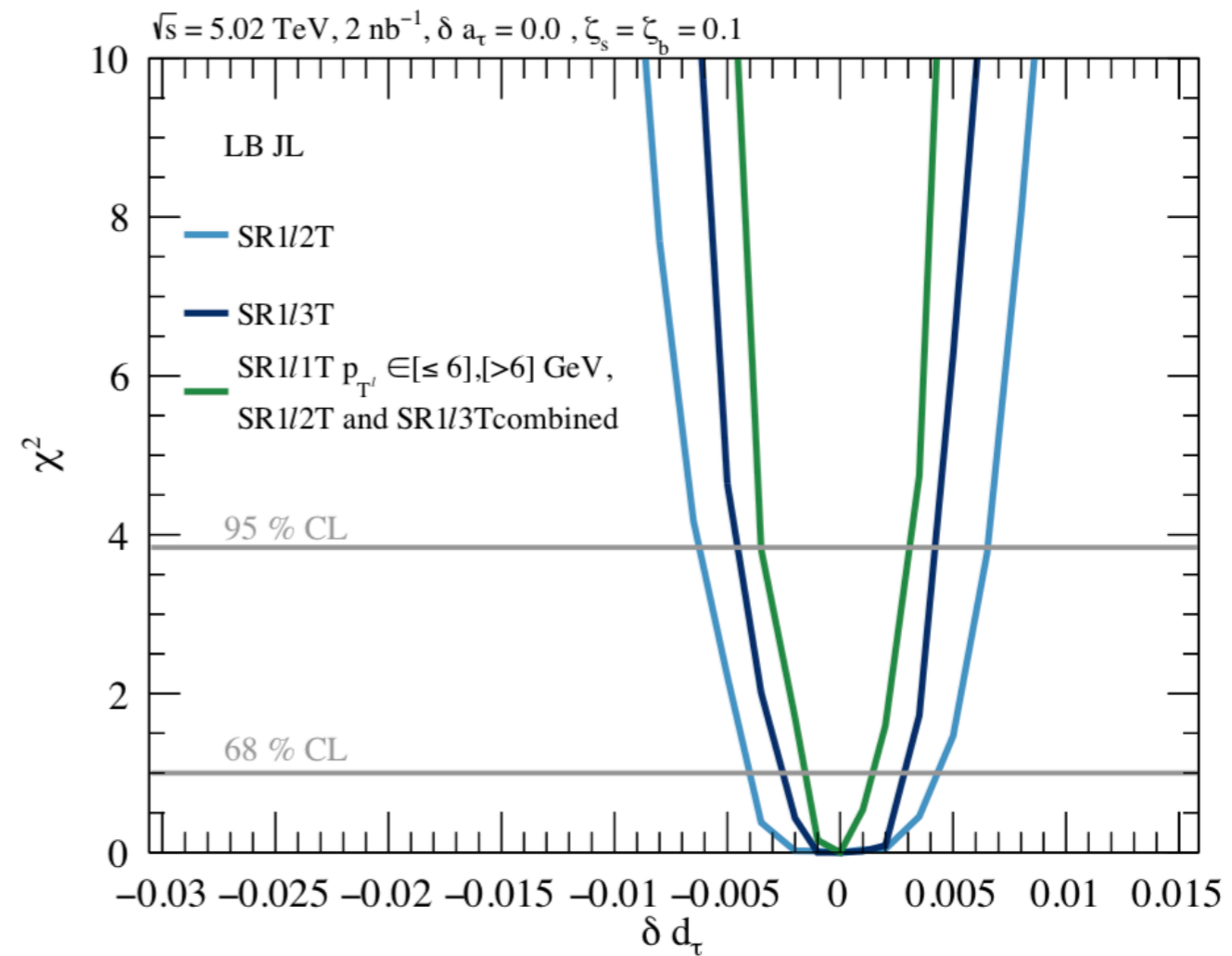
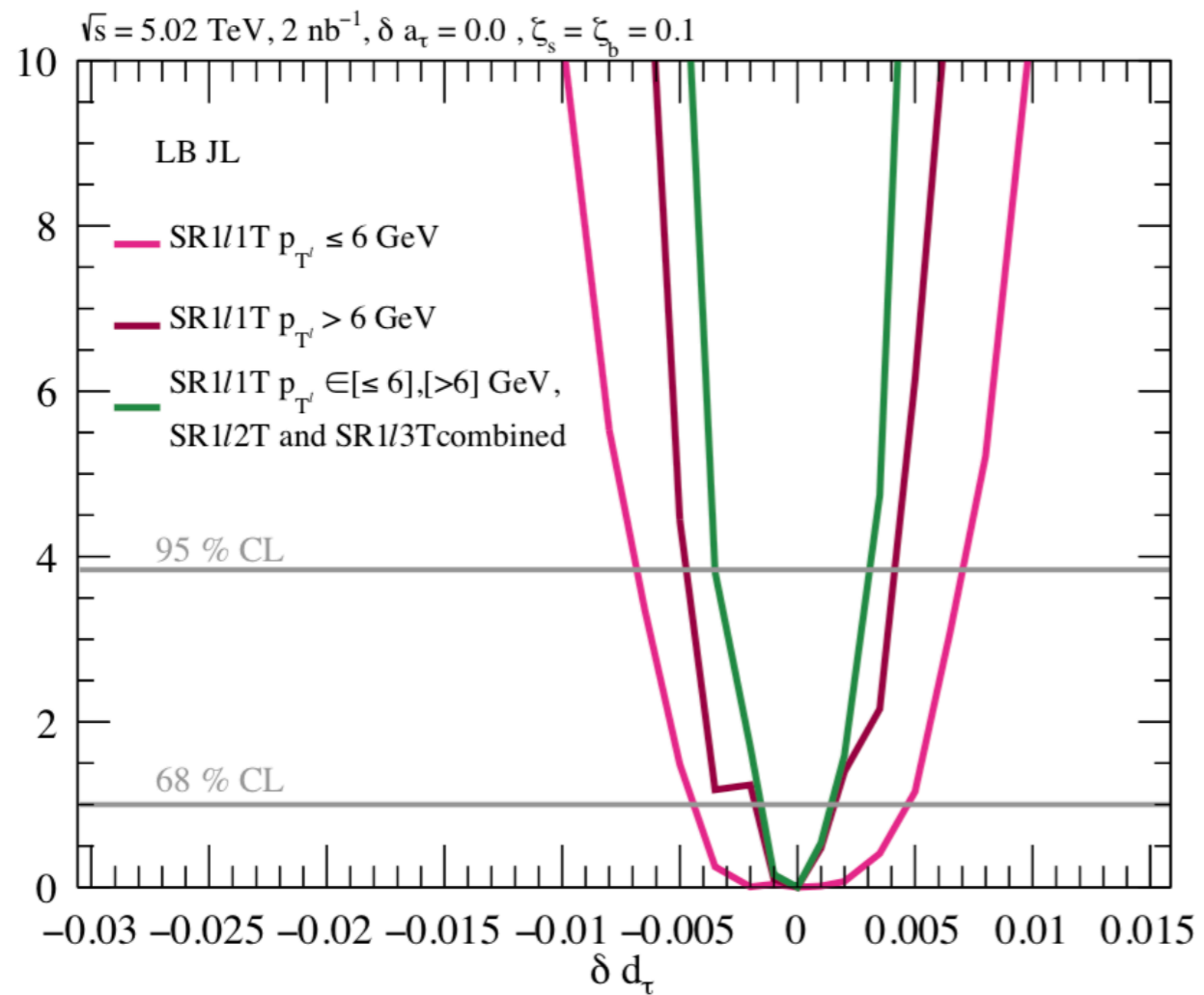
Assume observe SM & quantify constraint using χ^2

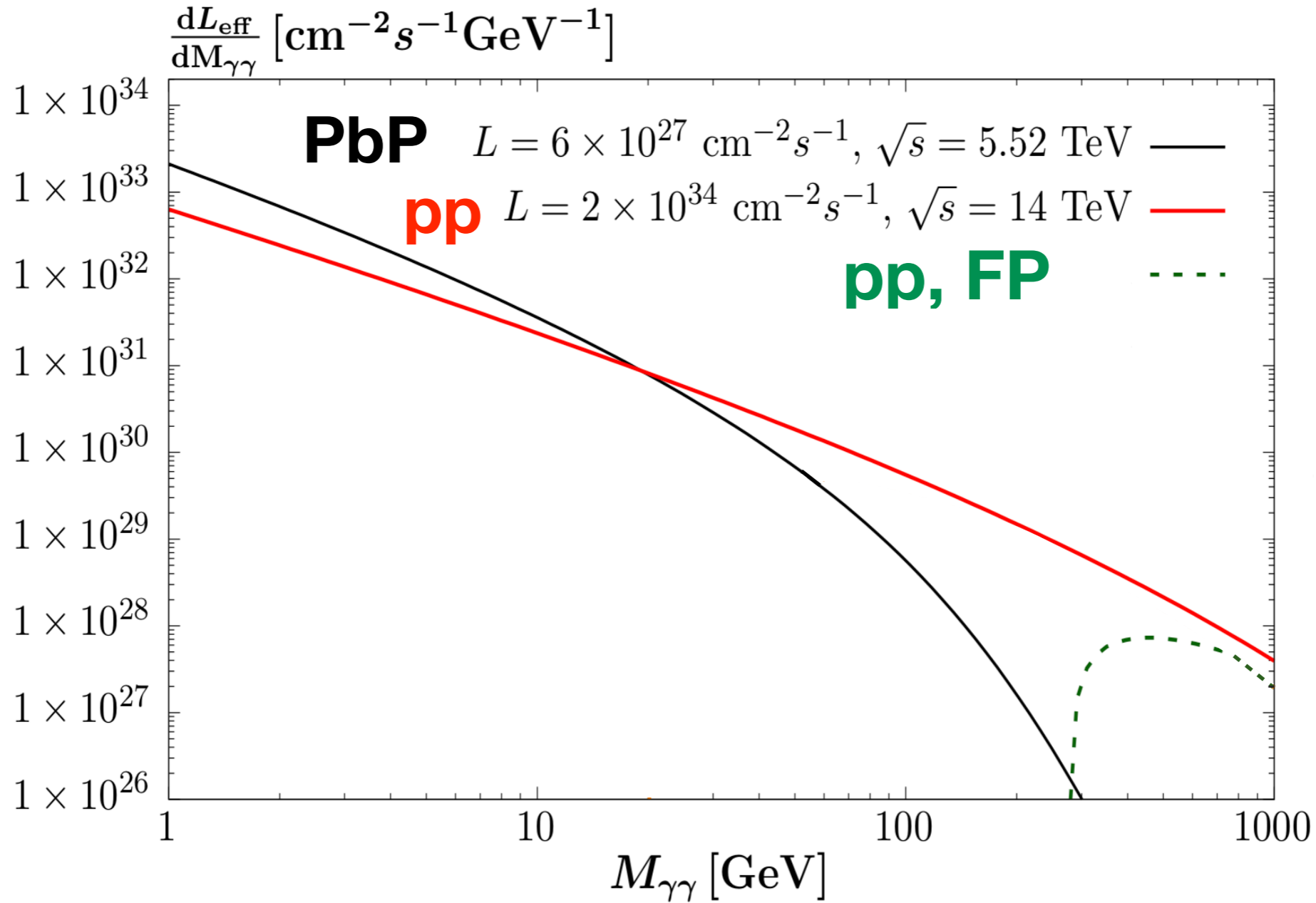


SR Break down: a_τ



SR Break down: d_τ





$$\sigma_{A_1 A_2 \rightarrow A_1 X A_2} = \int dx_1 dx_2 n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \rightarrow X} = \int dm_{\gamma\gamma} \frac{d\mathcal{L}_{\text{eff}}}{dm_{\gamma\gamma}} \hat{\sigma}_{\gamma\gamma \rightarrow X}, \quad (1)$$

where x_i is the longitudinal momentum fraction of the photon emitted by ion A_i . This factorizes the result in terms of a $\gamma\gamma \rightarrow X$ subprocess cross section $\hat{\sigma}$ of a (BSM) system X , and fluxes $n(x_i)$ of photons emitted by the ions. The latter are precisely determined in terms of the ion EM form factors, and are in

Example tau decays

