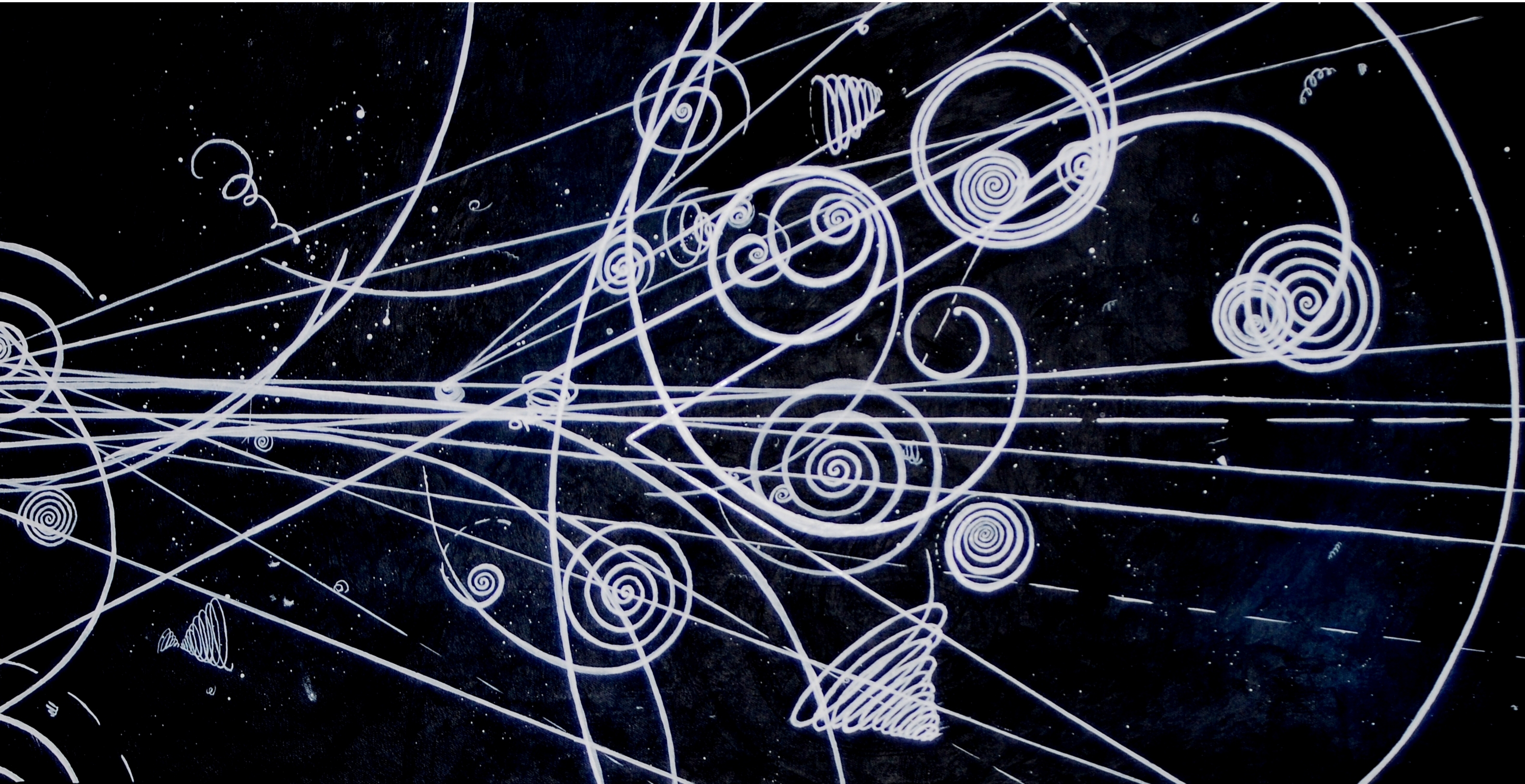
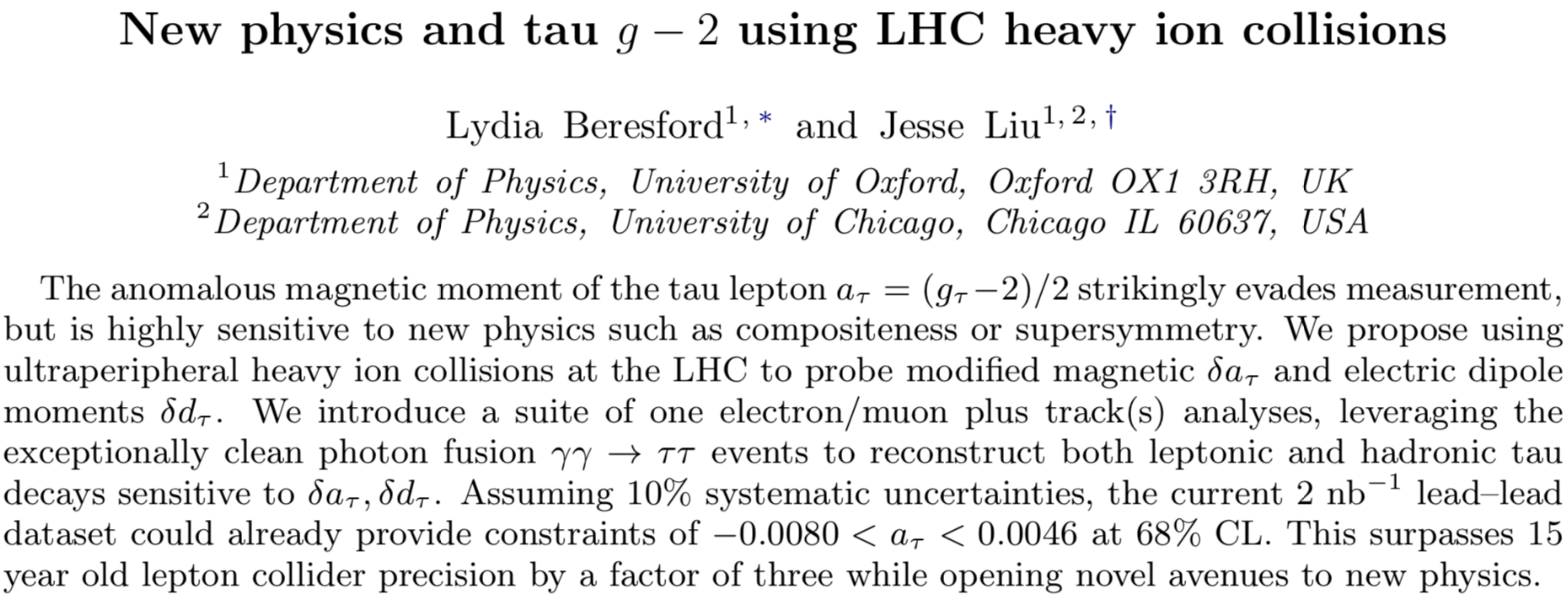
Tau g-2 and beyond

Lydia Beresford

HEP Seminar Birmingham, 29th January 2019



Our proposal



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

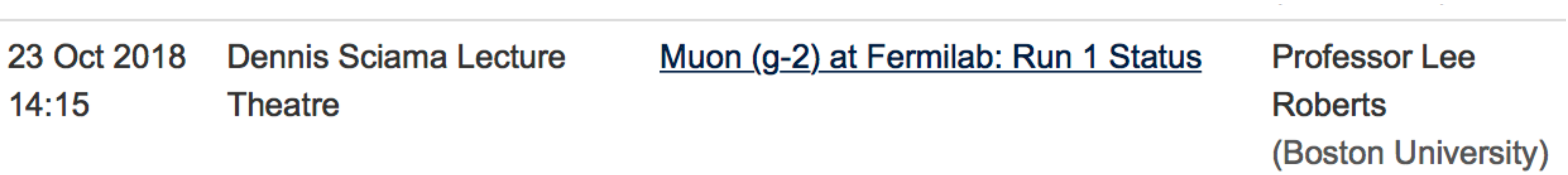
Lydia Beresford[1,*] and Jesse Liu[1,2,†]

[1] *Department of Physics, University of Oxford, Oxford OX1 3RH, UK*
[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 $\gamma\gamma \to \tau\tau$ 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.

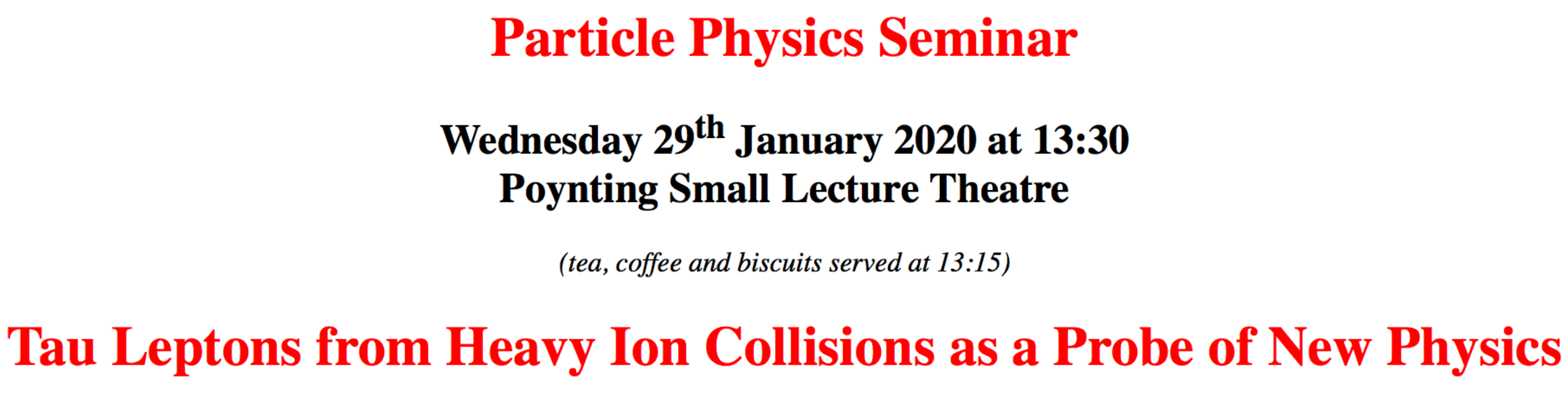
1908.05180

… October 2018



23 Oct 2018 14:15	Dennis Sciama Lecture Theatre	Muon (g-2) at Fermilab: Run 1 Status	Professor Lee Roberts (Boston University)

~ One year on



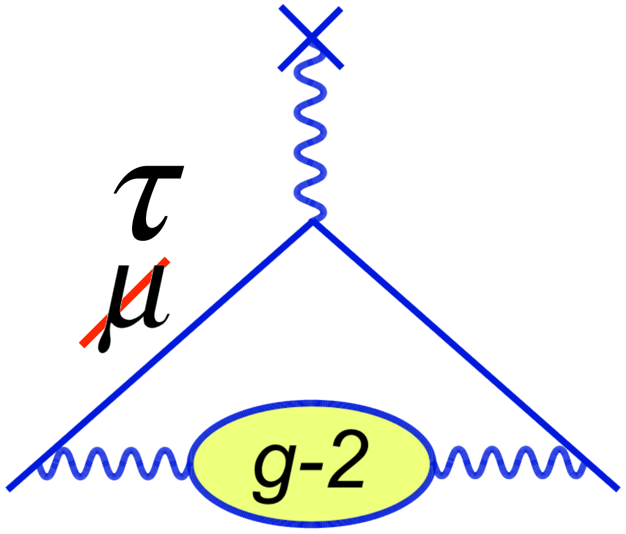
Particle Physics Seminar

Wednesday 29th January 2020 at 13:30
Poynting Small Lecture Theatre

(tea, coffee and biscuits served at 13:15)

Tau Leptons from Heavy Ion Collisions as a Probe of New Physics

Lydia Beresford (Oxford University)



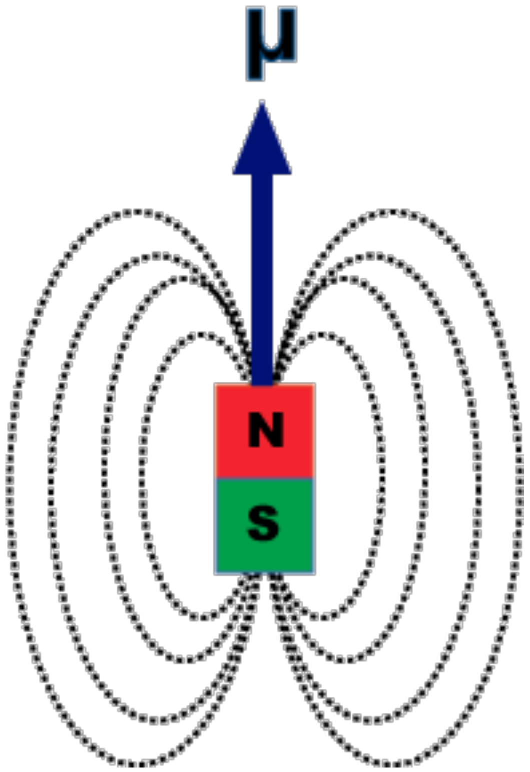
What is g-2?

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

Magnetic moment: Quantifies torque experienced in $\mathbf{B}$ field

$$\underset{\uparrow\atop\text{torque}}{\boldsymbol{\tau}} = \underset{\uparrow\atop\text{magnetic moment}}{\boldsymbol{\mu}} \times \mathbf{B}$$

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

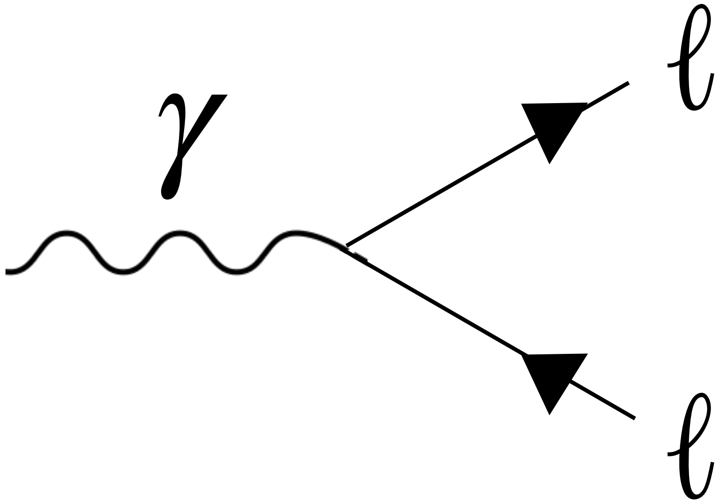


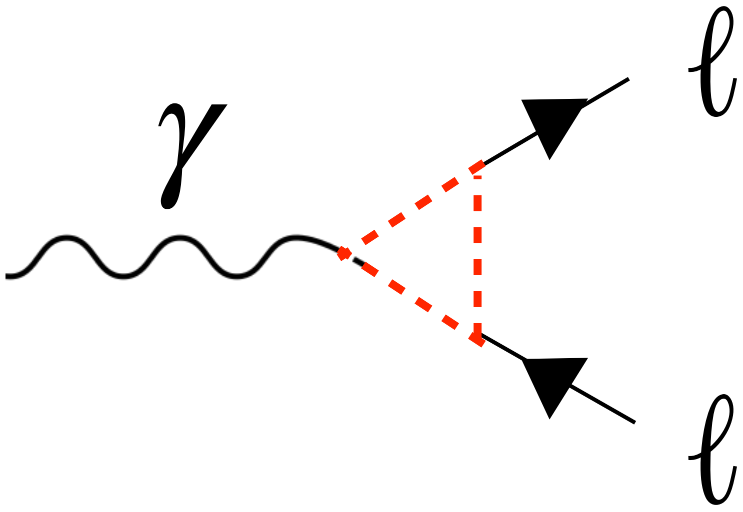
What is g-2?

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

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

$\boldsymbol{\mu} \,.\, \mathbf{B}$





g = 2 + loop corrections

Dirac, 1928

What is g-2?

Anomalous magnetic moment

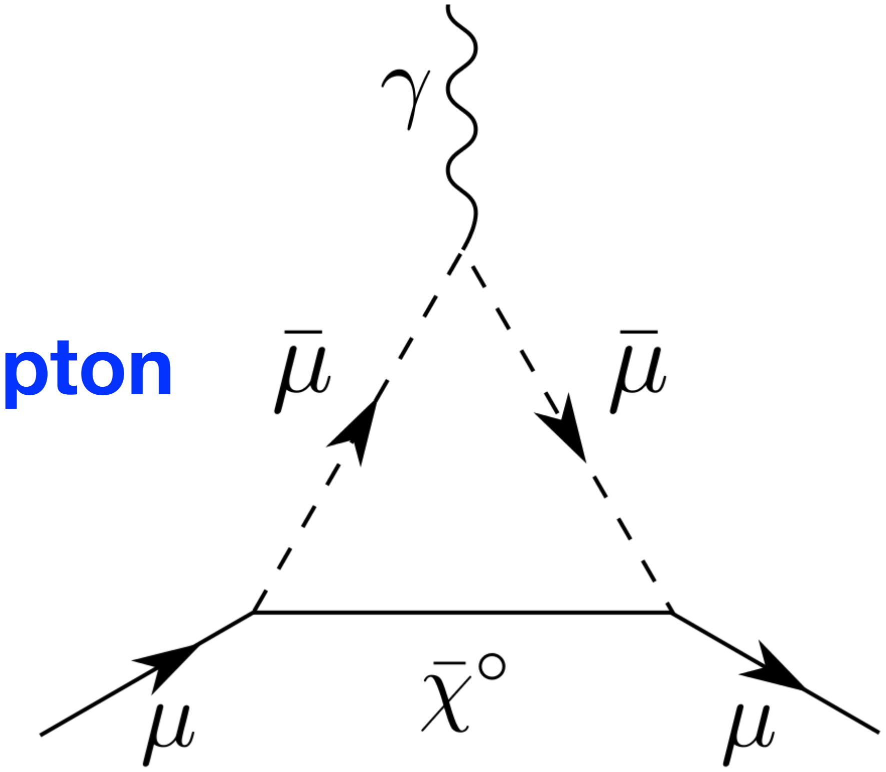
$$a = \frac{(g-2)}{2}$$

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?

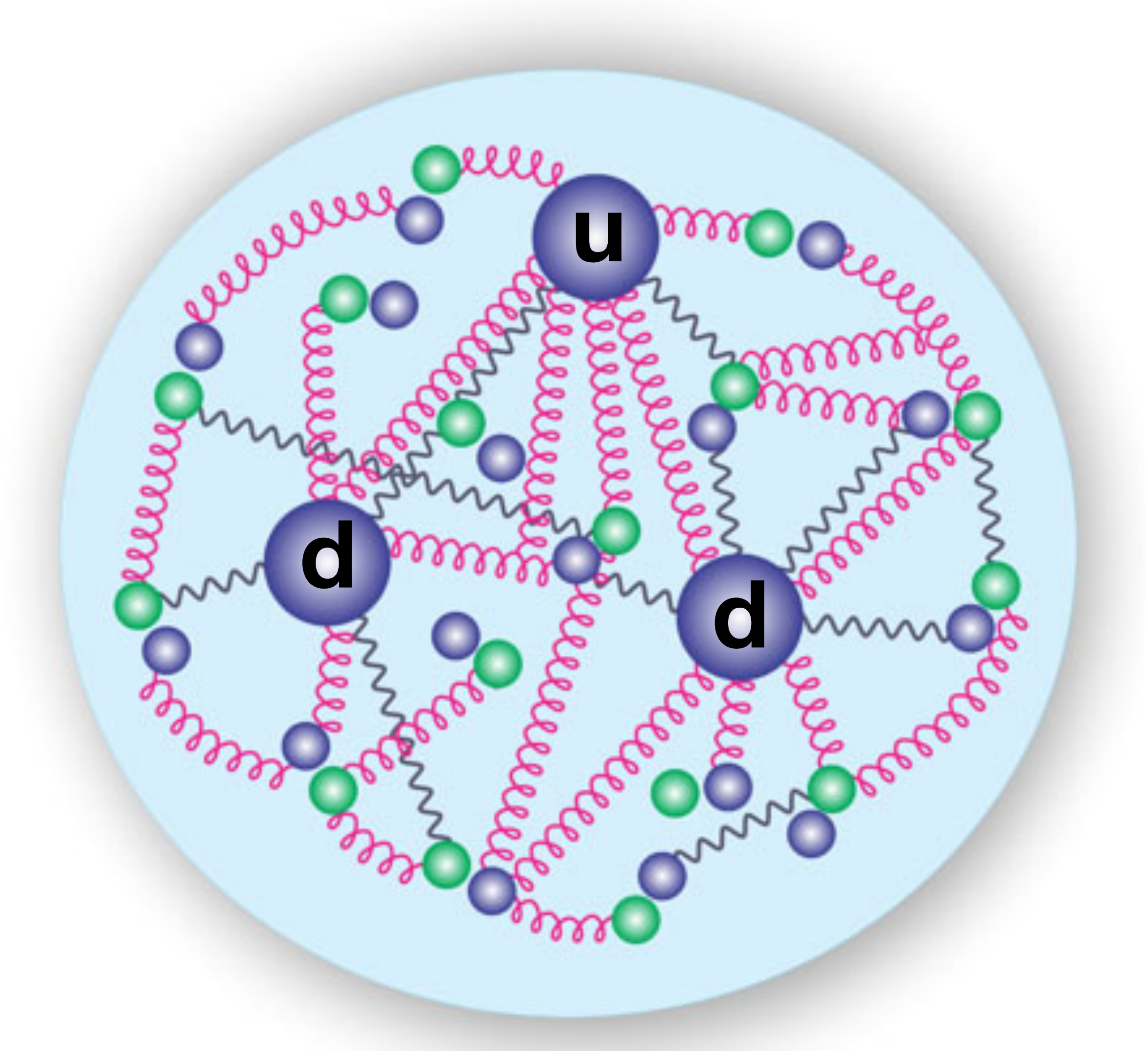
Powerful probe of new physics

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**

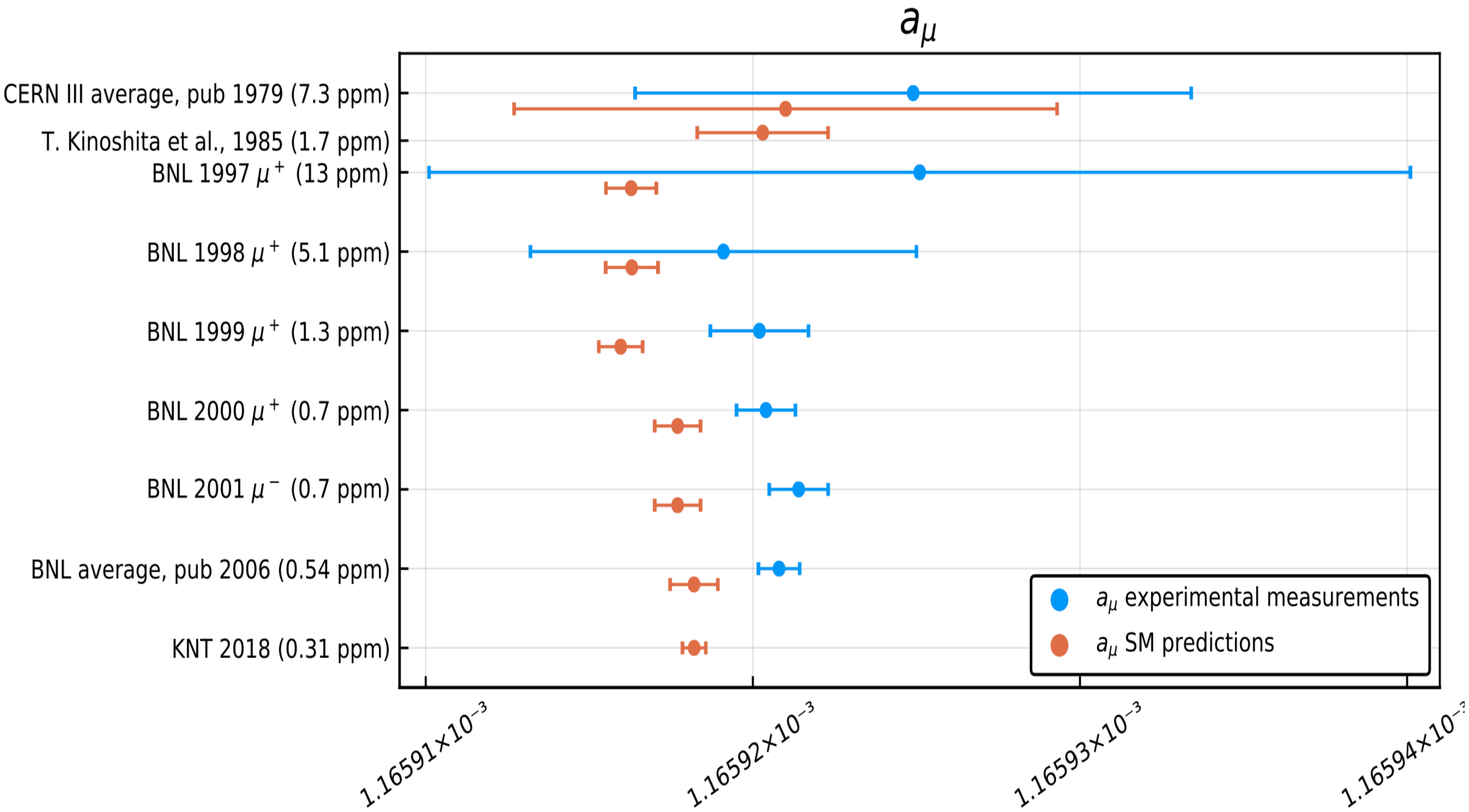
Muon g-2: 10^{-7} precision **$3\text{-}4\sigma$ tension**

Electron: Odom et at PRL (2006) Bouchendira et al PRL (2011) Aoyama et al 1205.5368 Parker et al Science (2018)

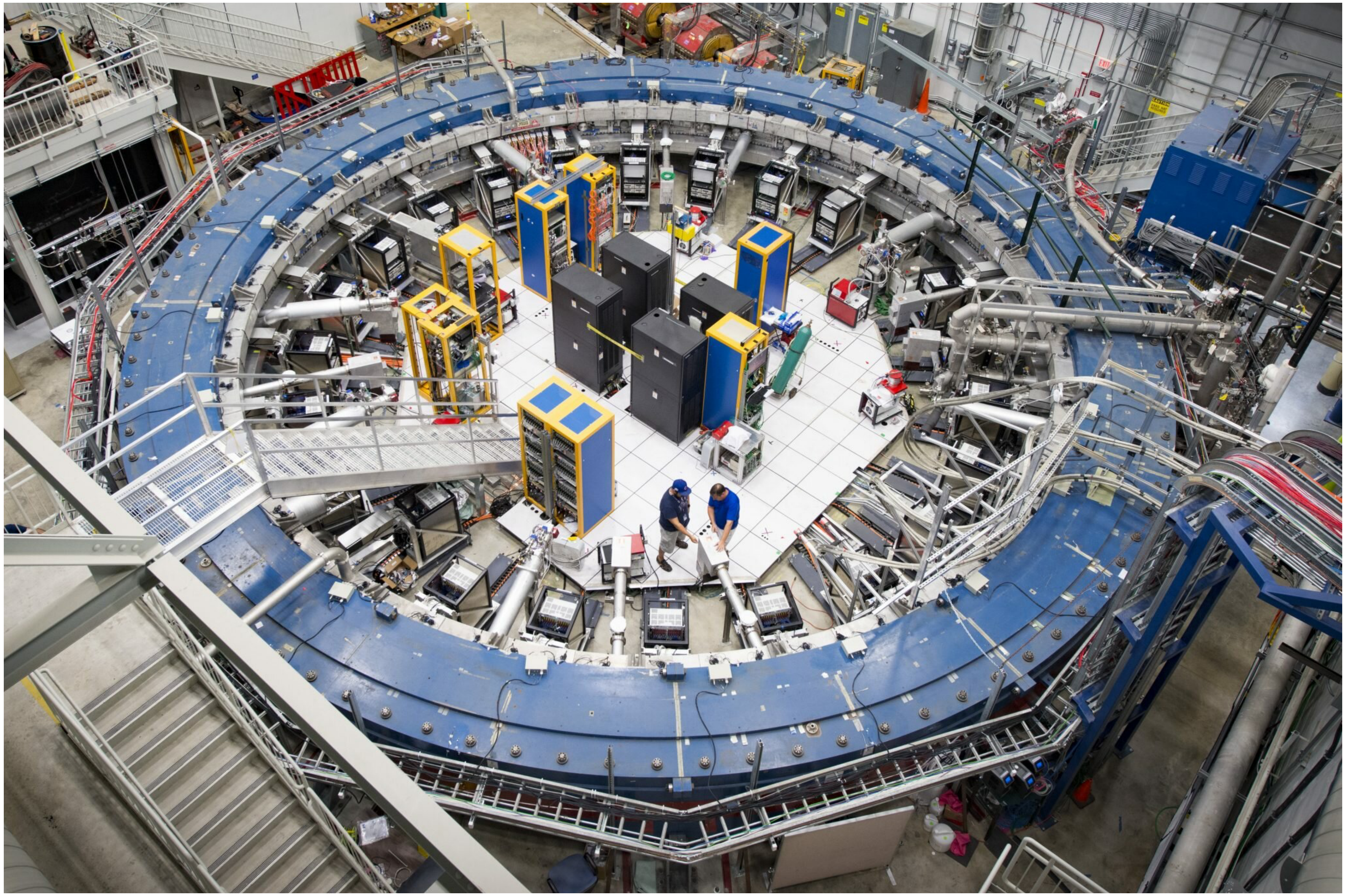
Muon: BNL E821 hep-ex/0602035 J-PARC 1901.03047 Davier et al 1908.00921
Keshavarzi, Nomura and Teubner 1802.02995

a_μ time evolution

Lusiani (2019)



Muon g-2 experiment @ Fermilab



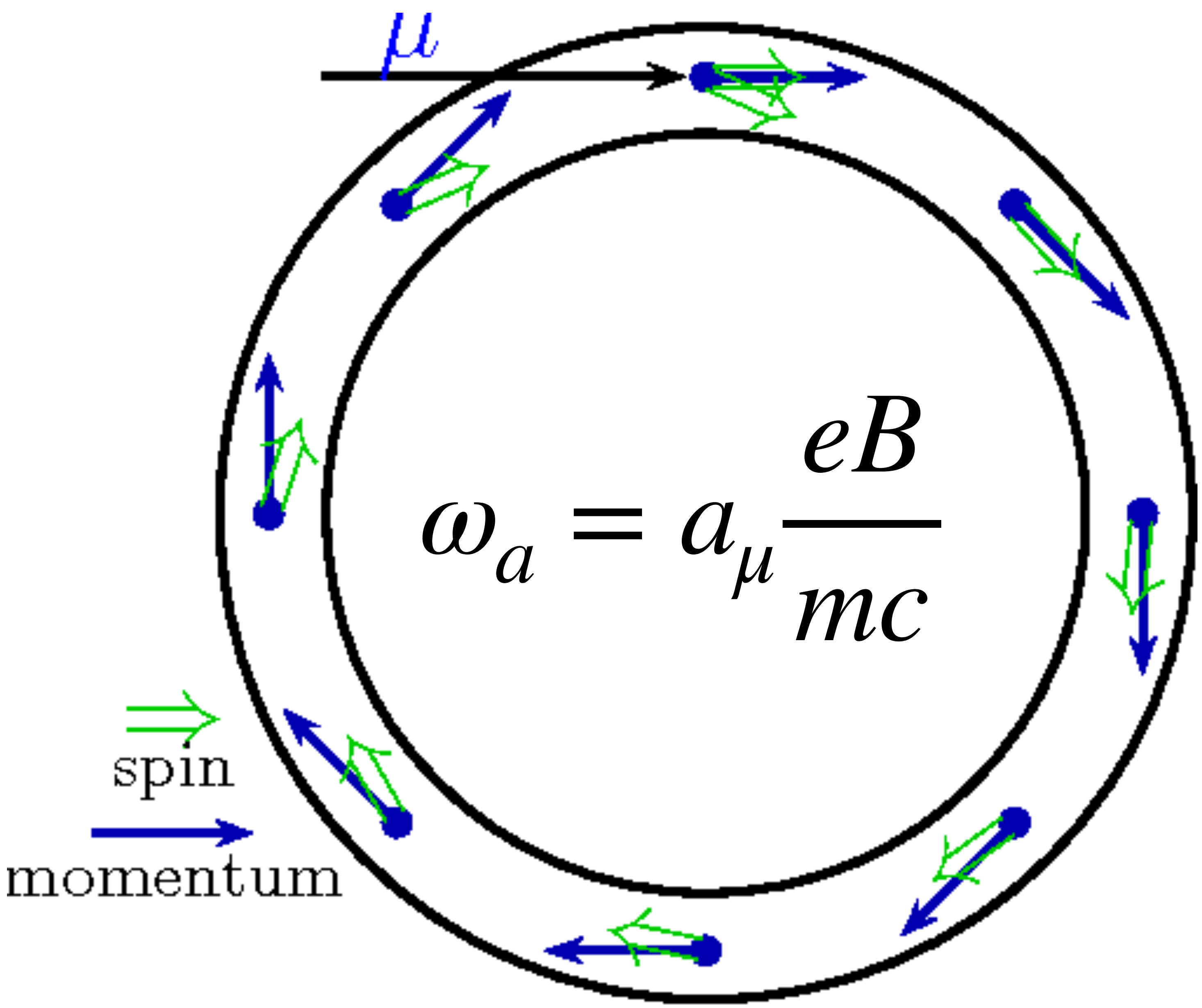
'if I were to put my money on something that would signal new physics, it's the [muon] g-2 experiment at Fermilab' **Brian Cox**

Muon g-2 experiment @ Fermilab

Further details

Basic idea:

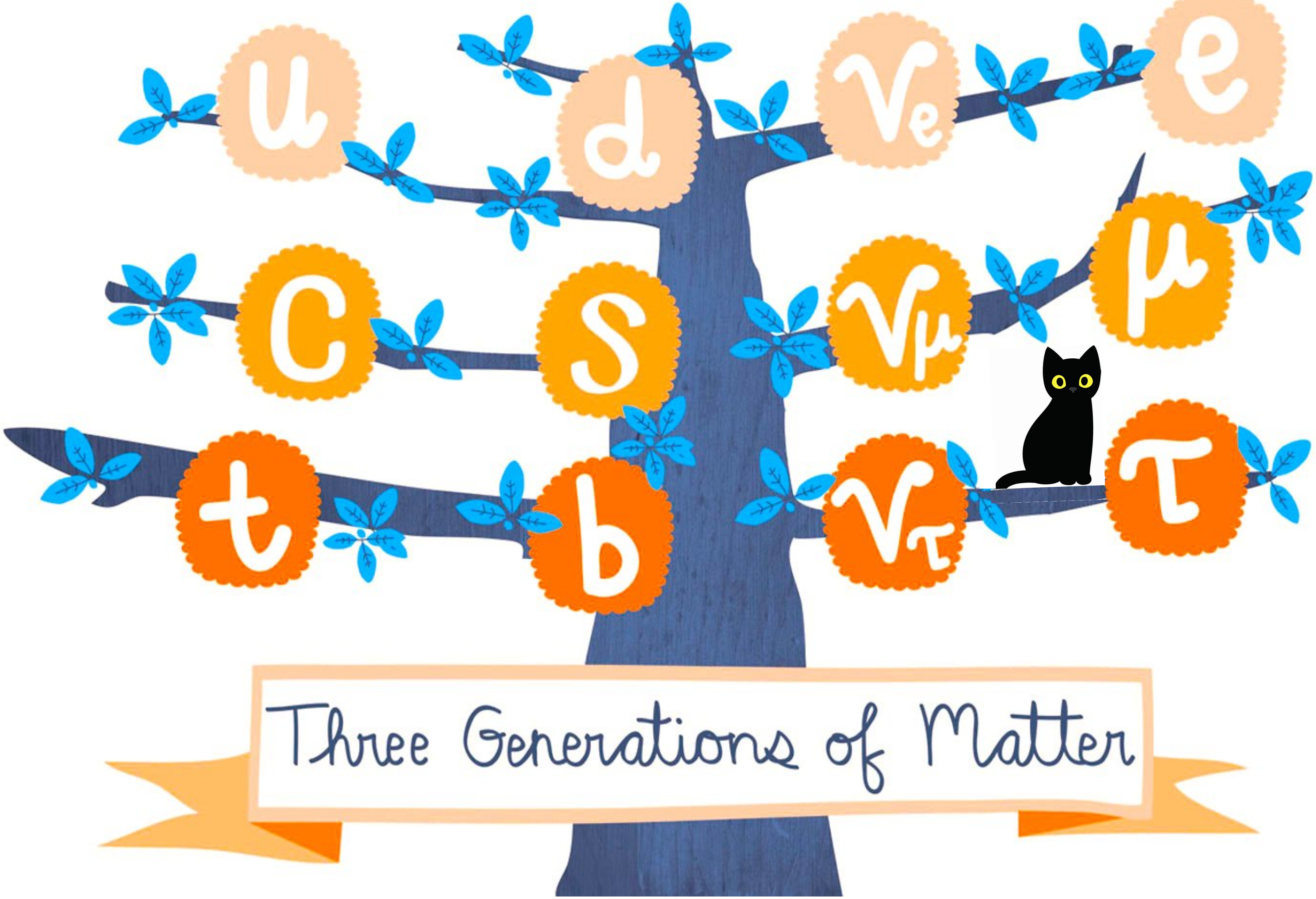
- Inject polarised muons
- Spin precesses around **B** at rate related to a_μ
- Measure precession rate via decay to positron



$$\omega_a = a_\mu \frac{eB}{mc}$$

New muon g-2 results coming soon - one to watch!

What about tau g-2?



Mass

0.511 MeV

106 MeV

1.7 GeV

What about tau g-2?

m_τ > m_μ by order of magnitude!

→ Composite?

280x more sensitive than a_μ

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

Martin and Wells PRD (2001)

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

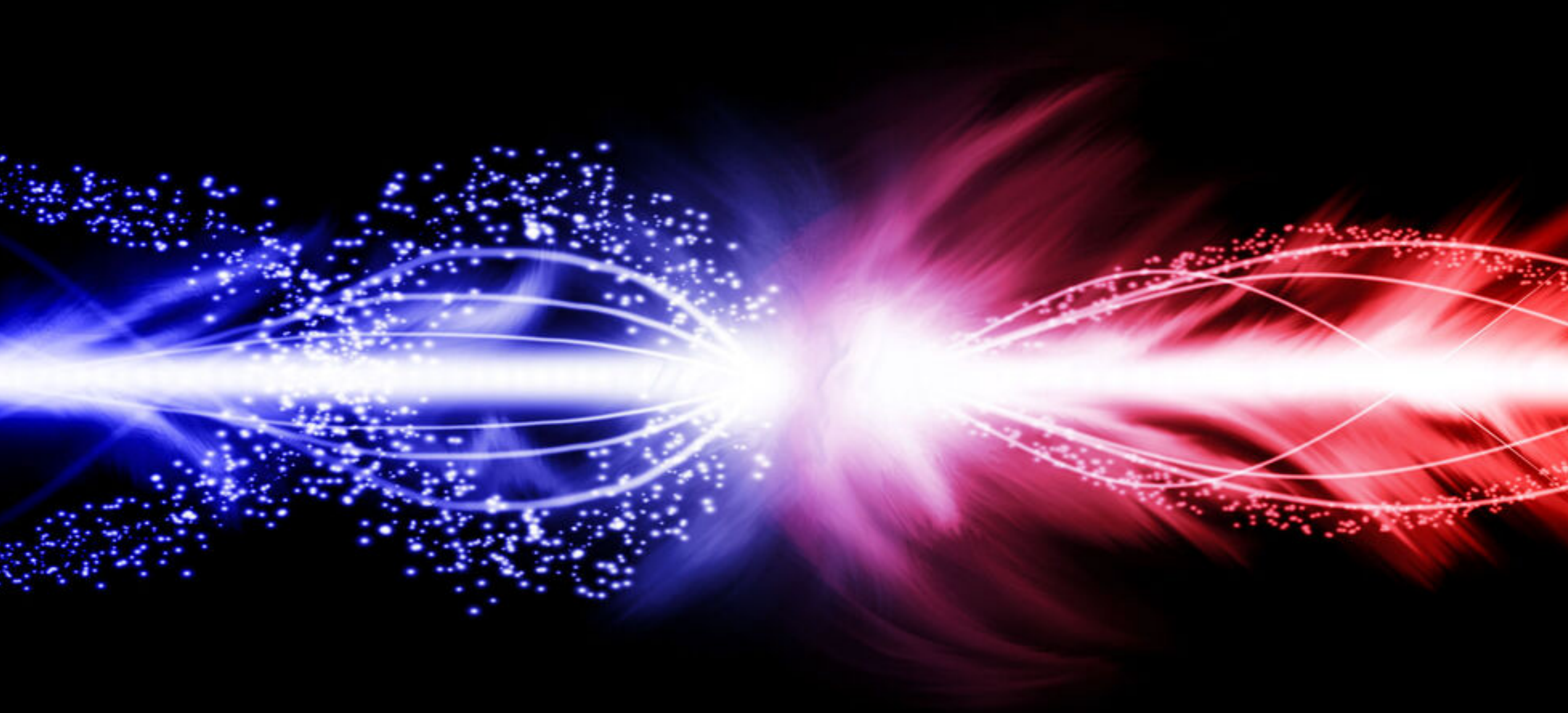
Problem: Lifetime

τ ~ 10^{-13} s

μ ~ 10^{-6} s

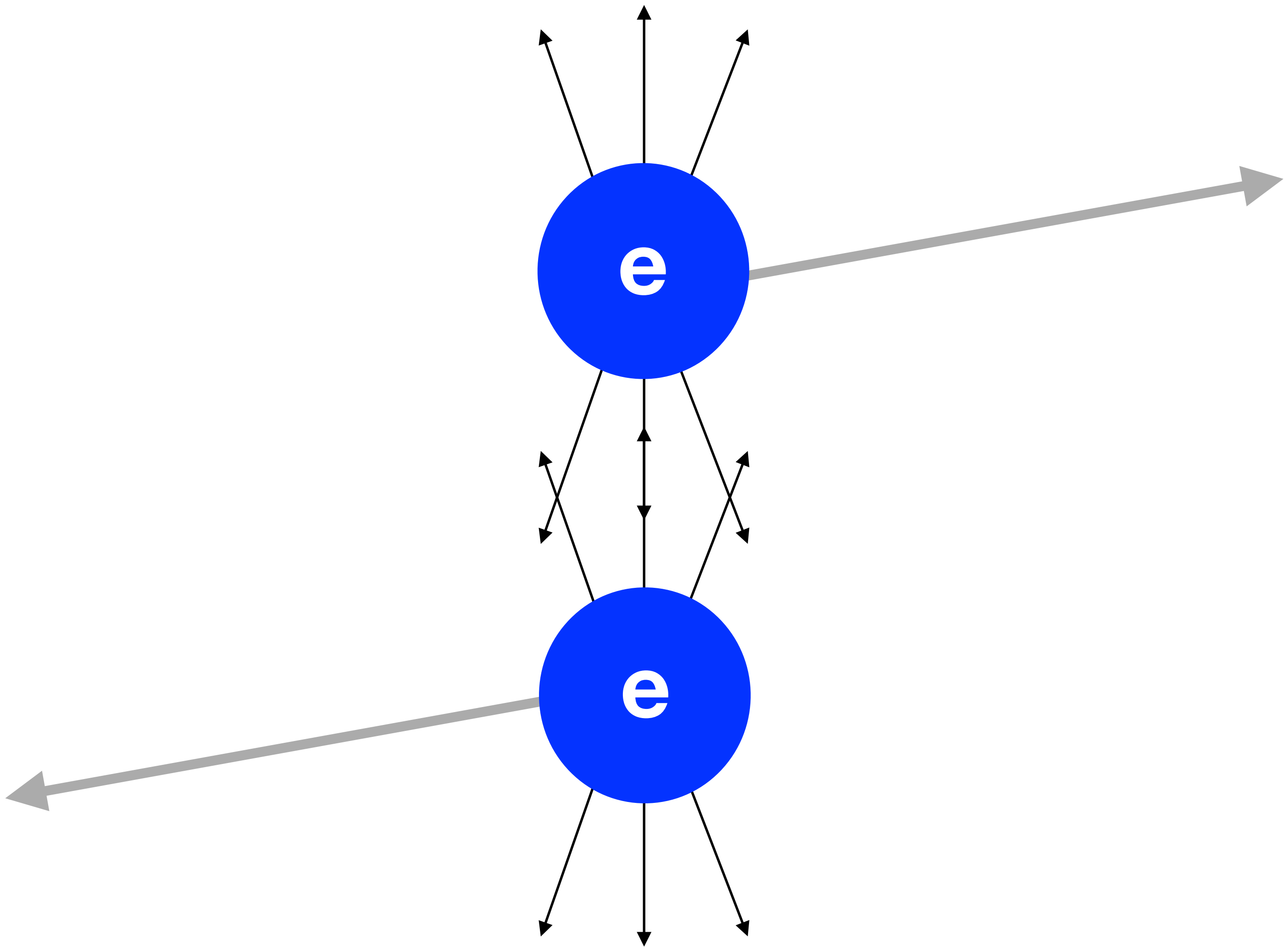
→ **Can't use same technique!**

Solution: Photon collisions



Solution: Photon collisions

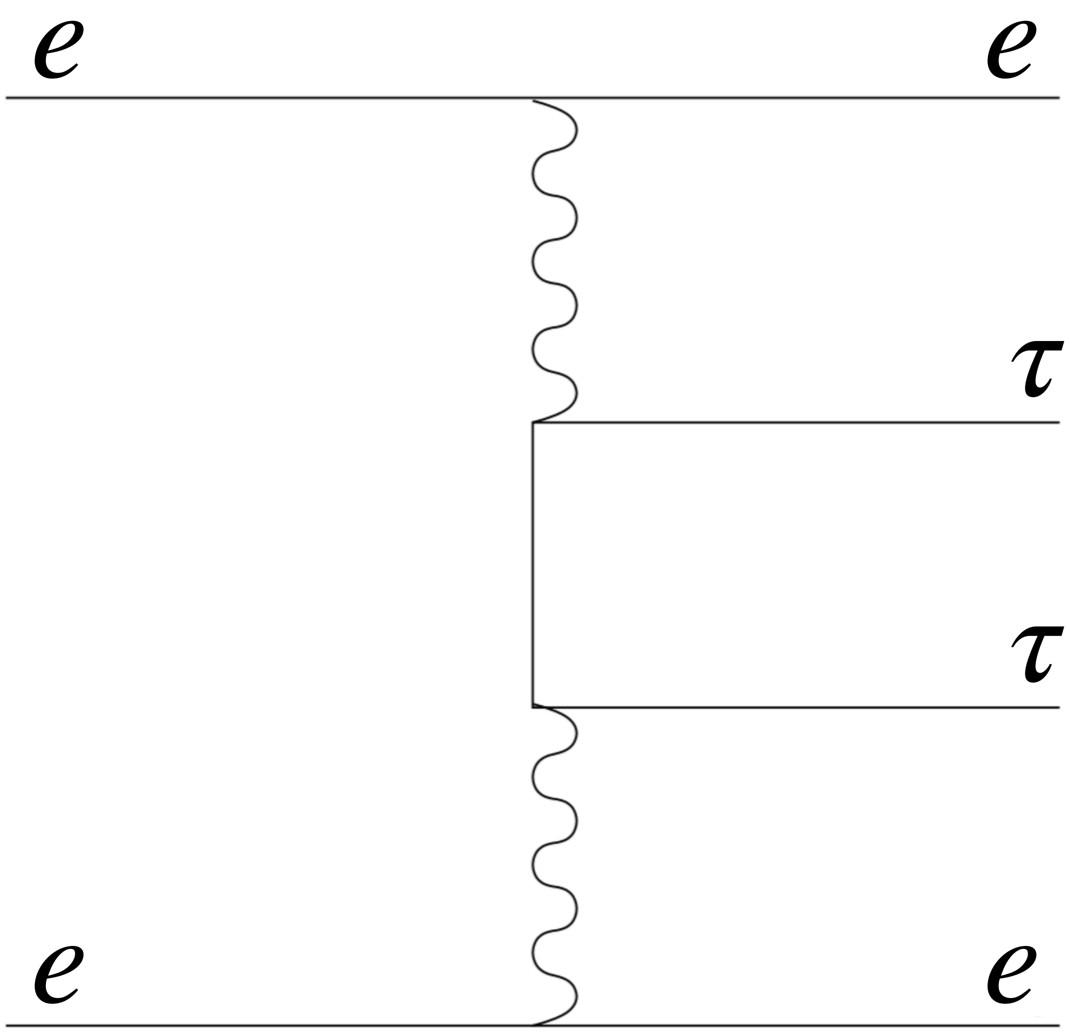
Photons from electric field surrounding electrons collide to produce new particles



PDG value

Delphi EPJC (2004)

DELPHI 2004, LEP collider



Cross section sensitive to moments

Photo production of tau pairs

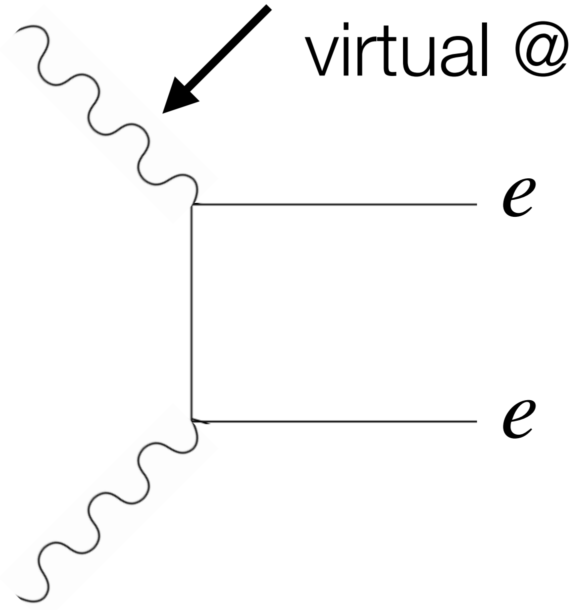
Disgression

Turning light into matter
major goal in laser physics

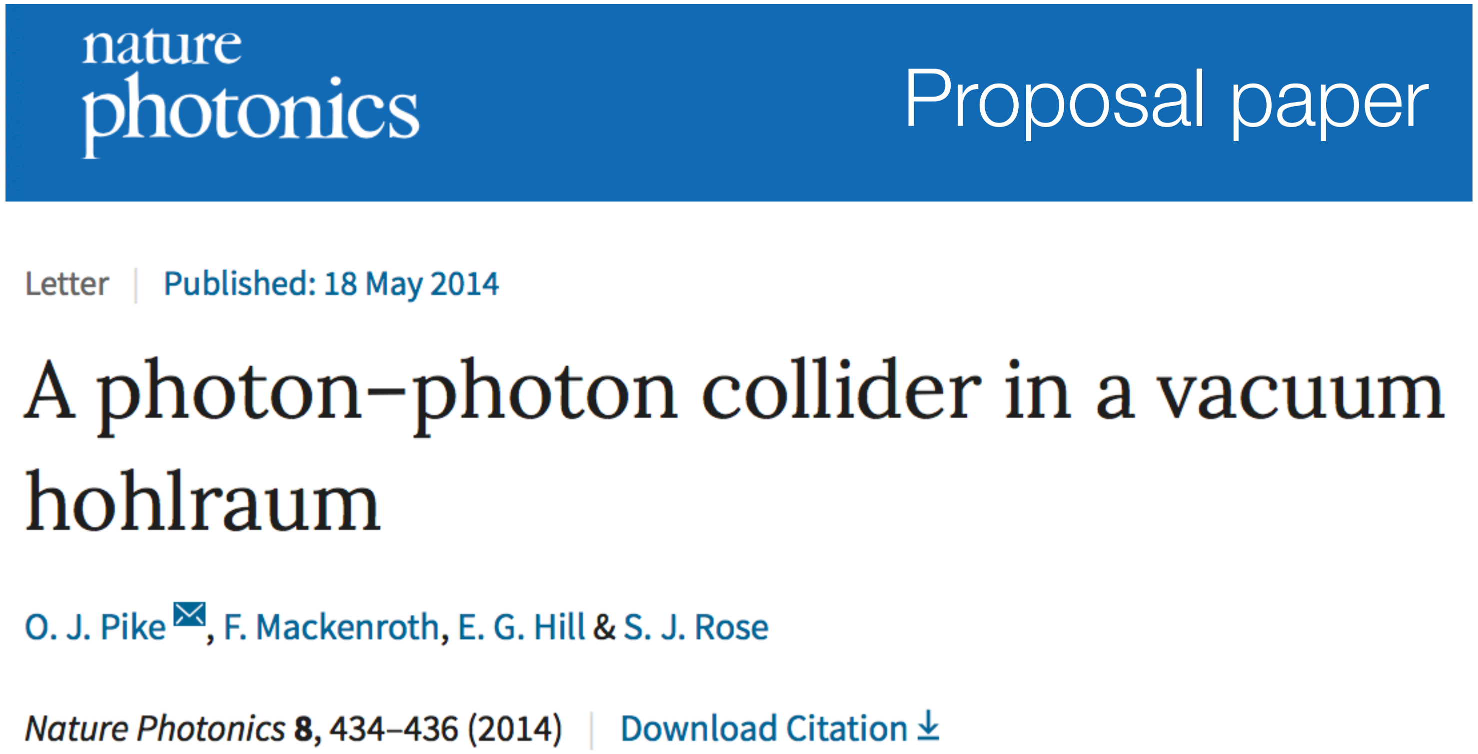
Disgression

Turning light into matter major goal in laser physics

Breit Wheeler process



Real photon,
virtual @ collider



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

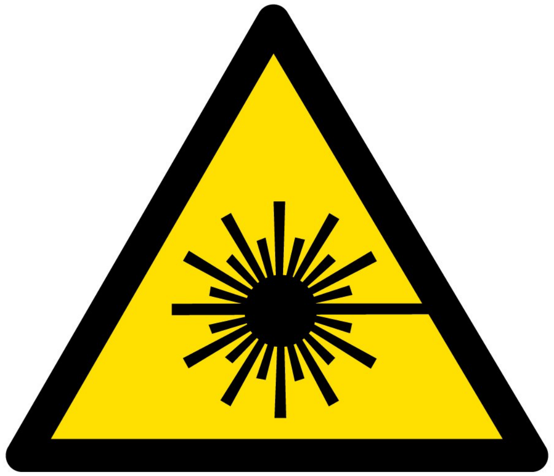
Nature Photonics **8**, 434–436 (2014) | Download Citation

Disgression

SCIENCE / PHYSICS

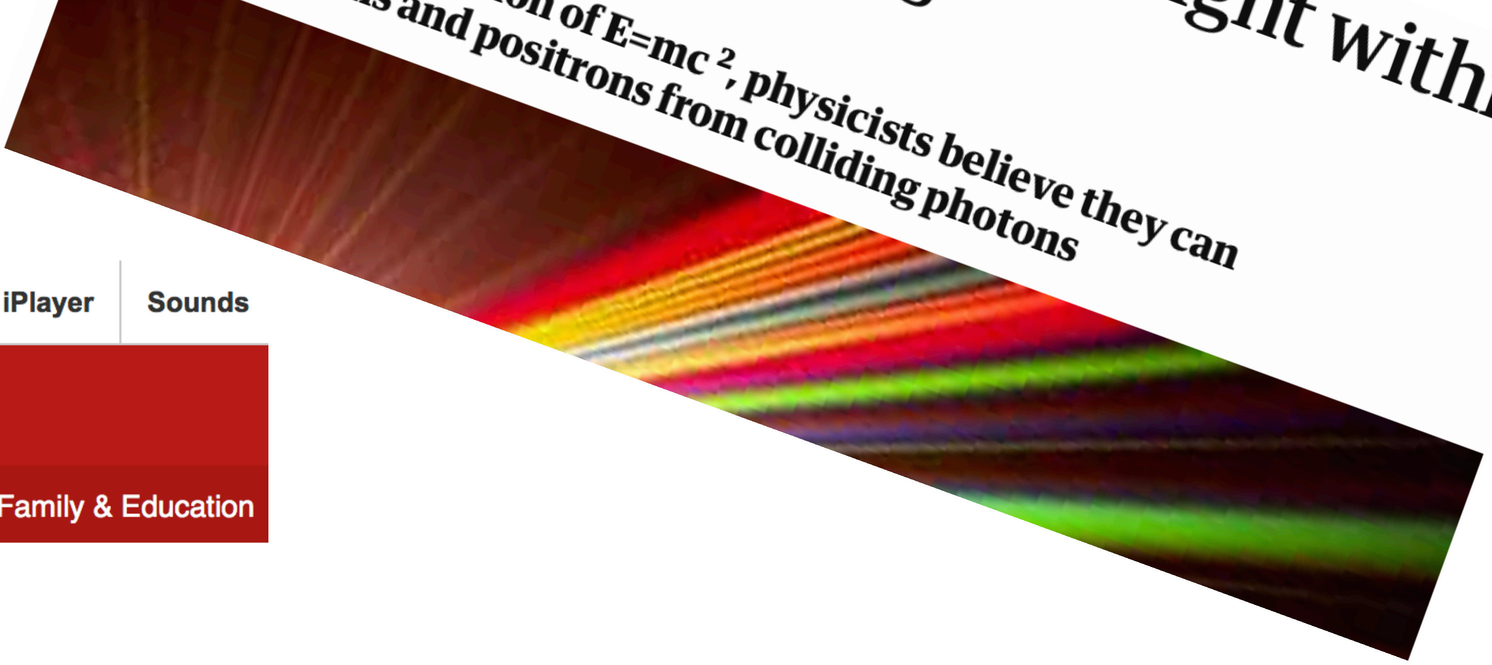
Physicists Attempt to Turn Light Into Matter with 84-Year-Old Theory

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



Science & Environment

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

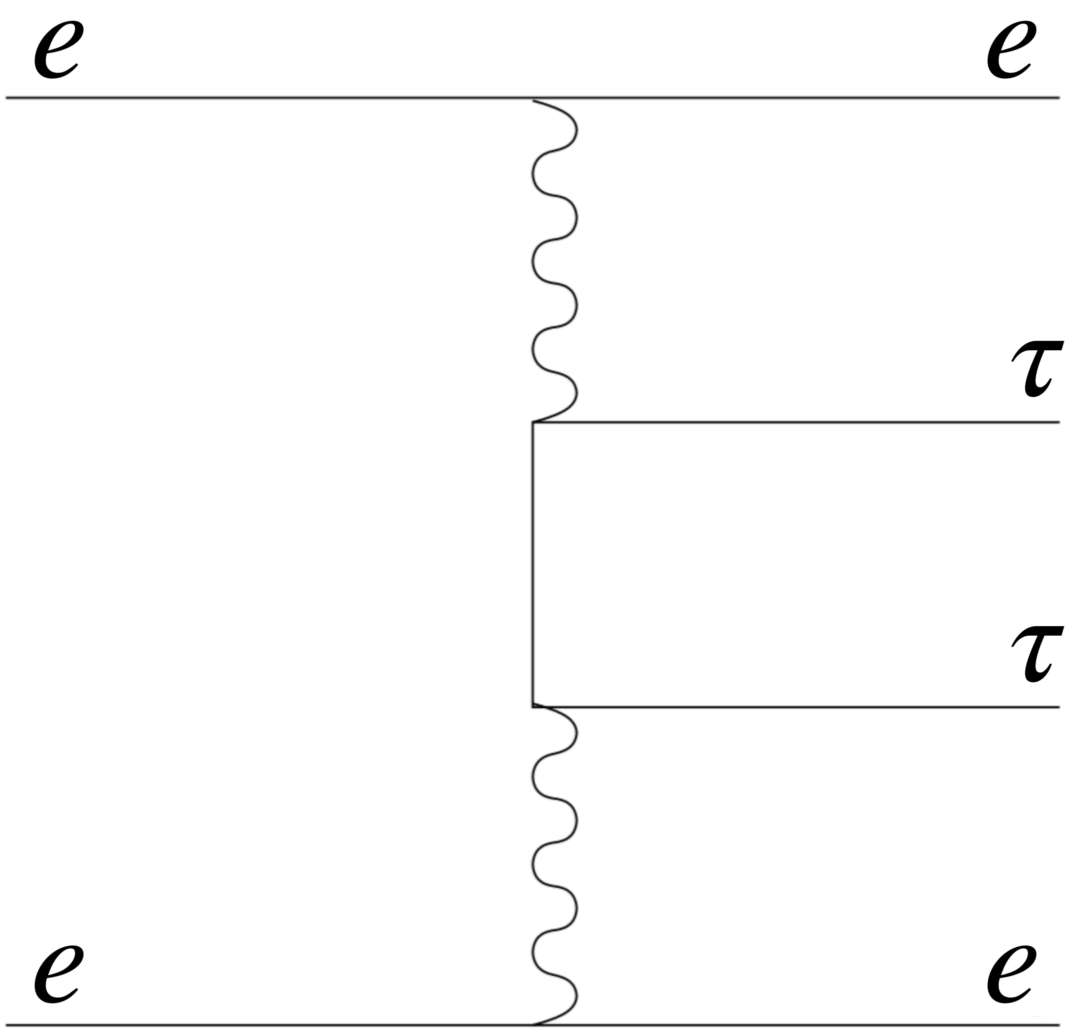
By Jonathan Webb
Science reporter, BBC News

24 June 2014

PDG value

Delphi EPJC (2004)

DELPHI 2004, LEP collider



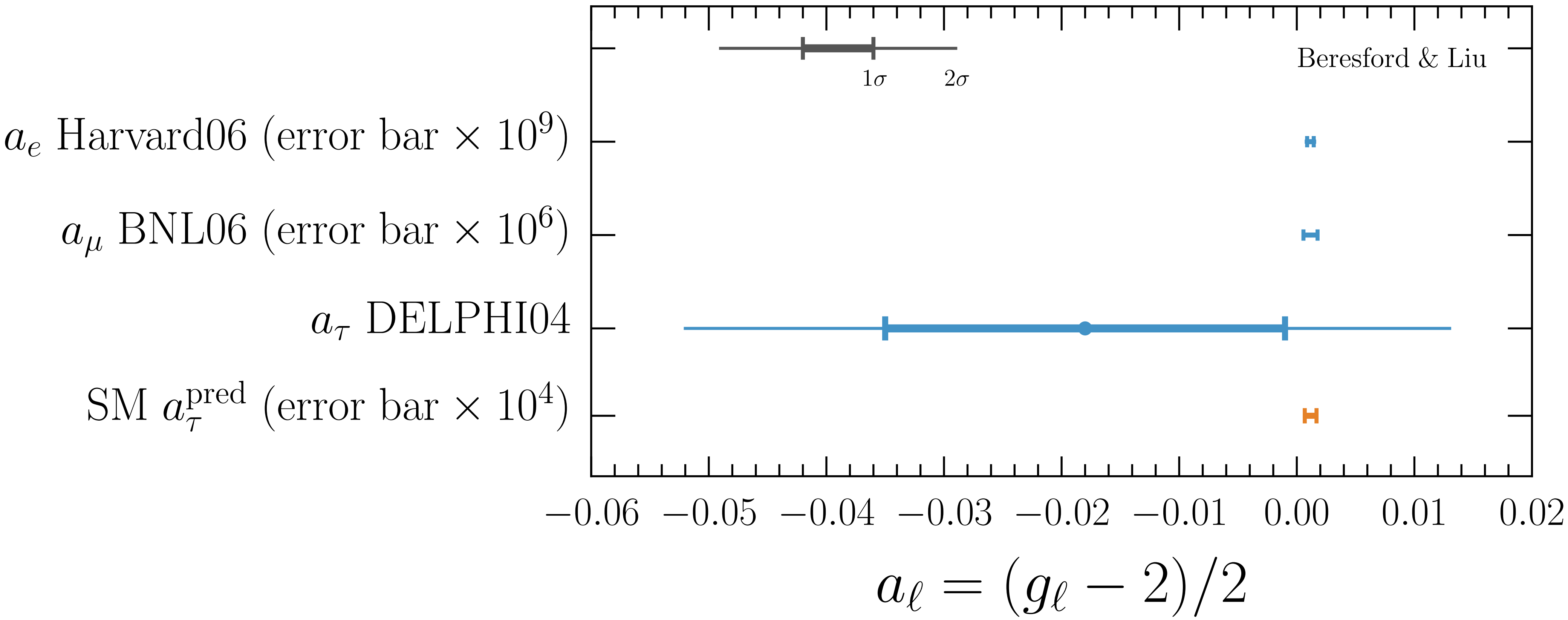
Cross section sensitive to moments

Photo production of tau pairs

Sibling Rivalry

a_τ^{exp} Delphi EPJC (2004)
a_τ^{theory} Eidelman, Passera hep-ph/0701260

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

Koksal et al 1804.02373
Howard et al 1810.09570

Bent crystal

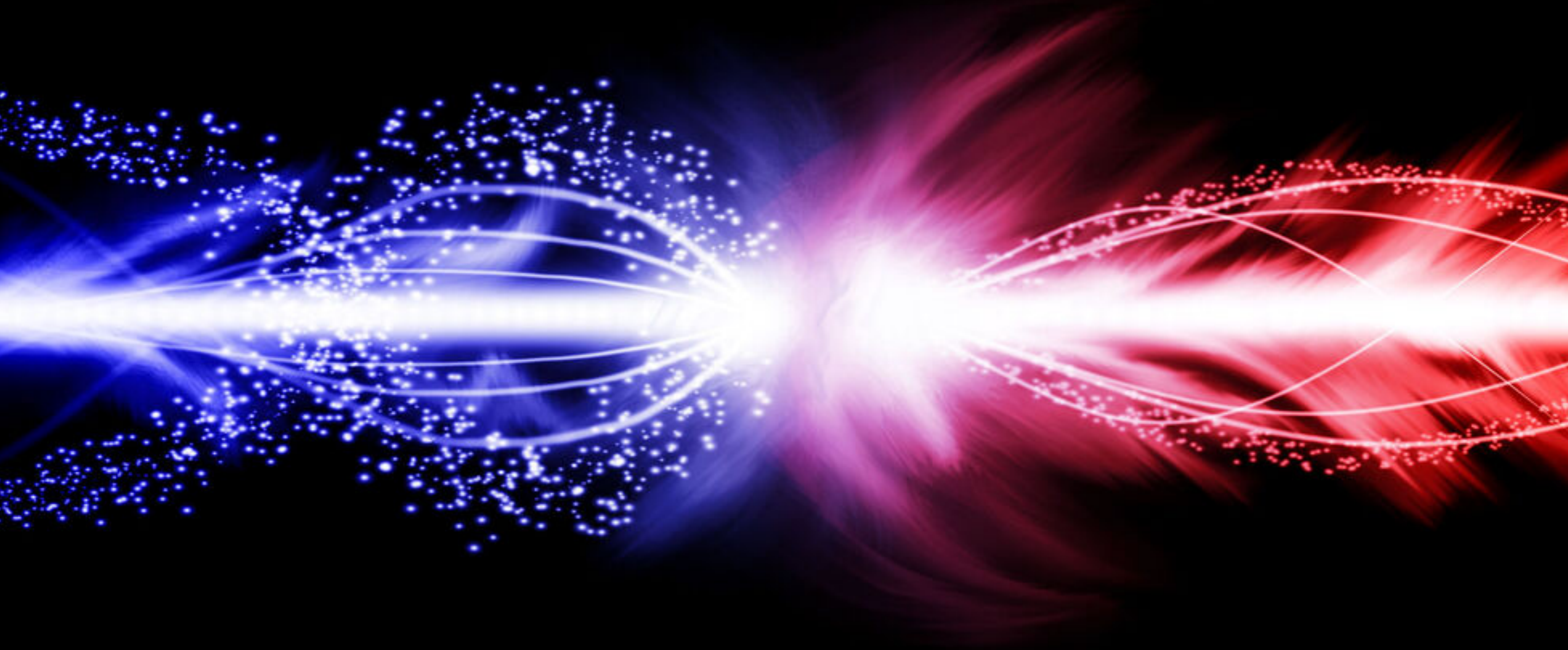
Fomin et al 1810.06699
Fu et al 1901.04003

HL-LHC

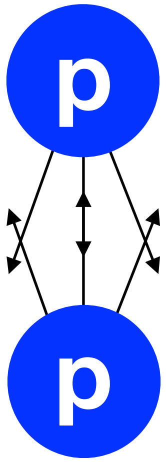
Galon, Rajaraman and Tait
1610.01601

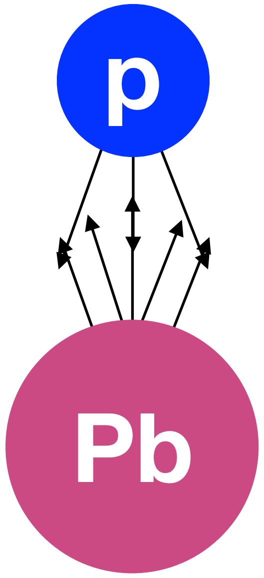
What can we do right now?

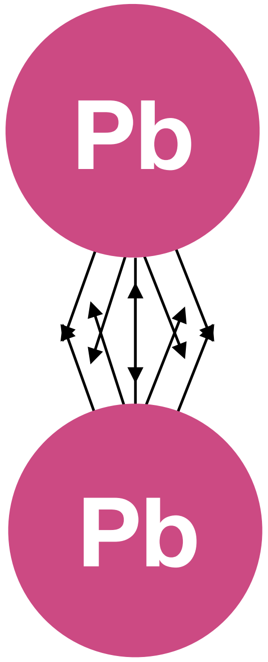
The LHC is also a photon collider



The LHC is also a photon collider





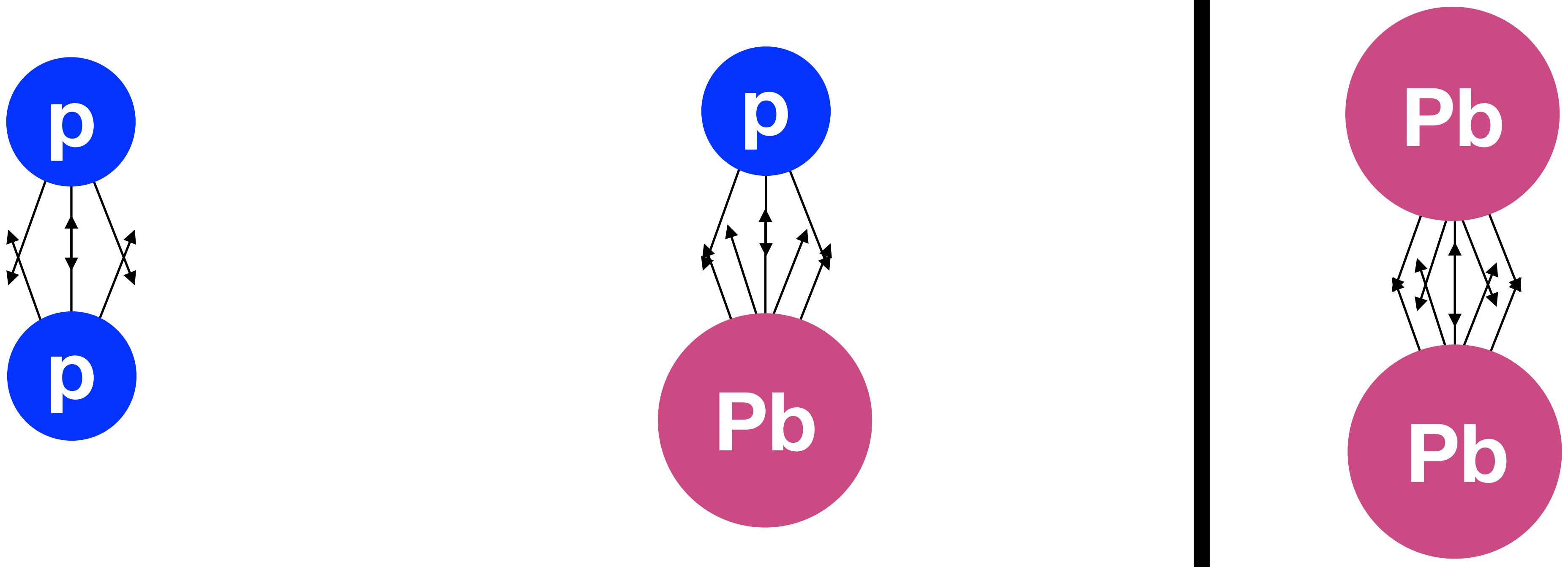


ATLAS

$\sqrt{s}$	13 TeV	8.16 TeV	5.02 TeV
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	~2 nb^{-1}
σ	-	$\propto Z^2$	$\propto Z^4$

Z = 82 for Pb

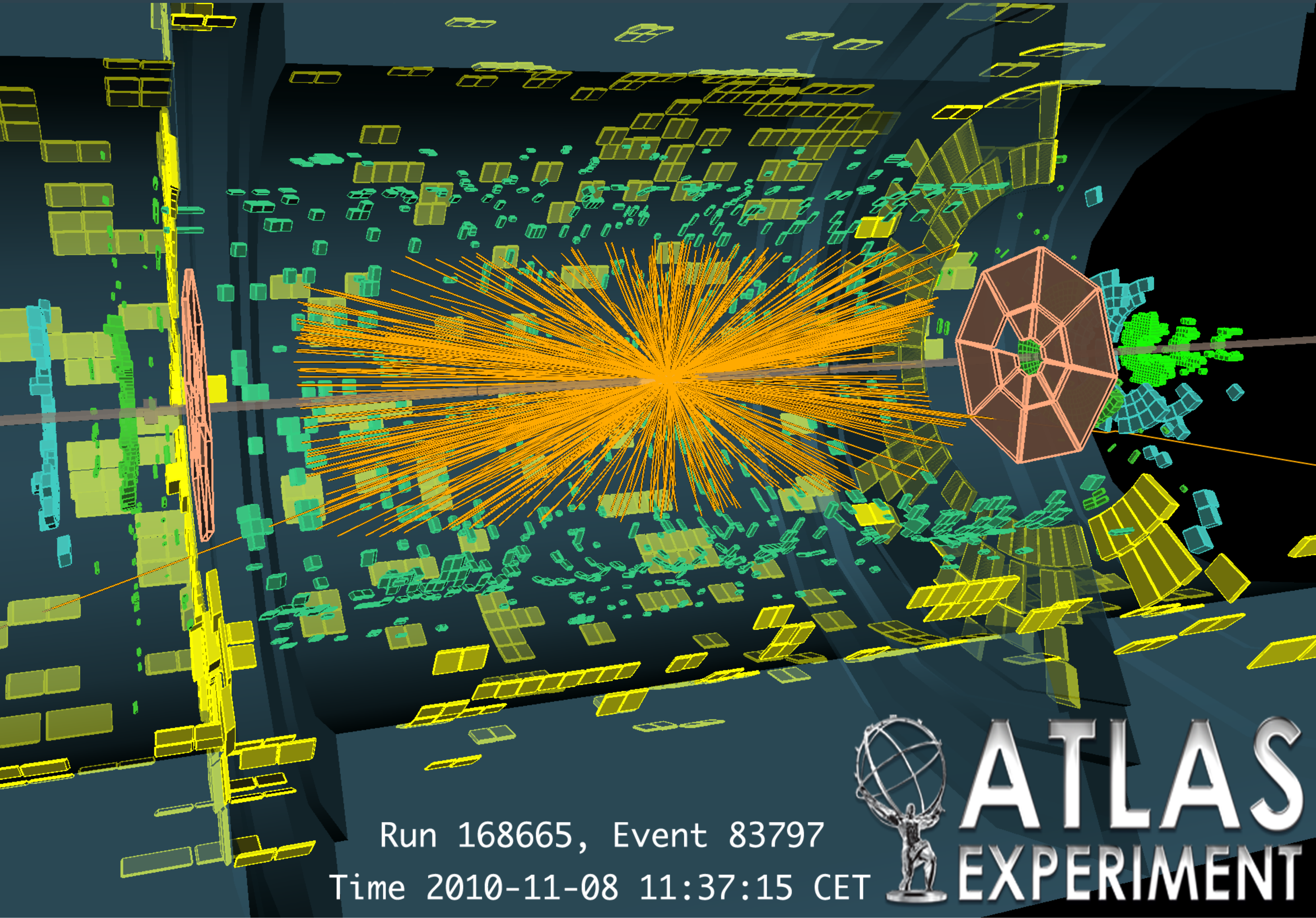
The LHC is also a photon collider



ATLAS			
$\sqrt{s}$	13 TeV	8.16 TeV	**5.02 TeV**
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	**~2 nb^{-1}**
σ	-	$\propto Z^2$	$\propto \mathbf{Z^4}$

Z = 82 for Pb

Head on PbPb collision

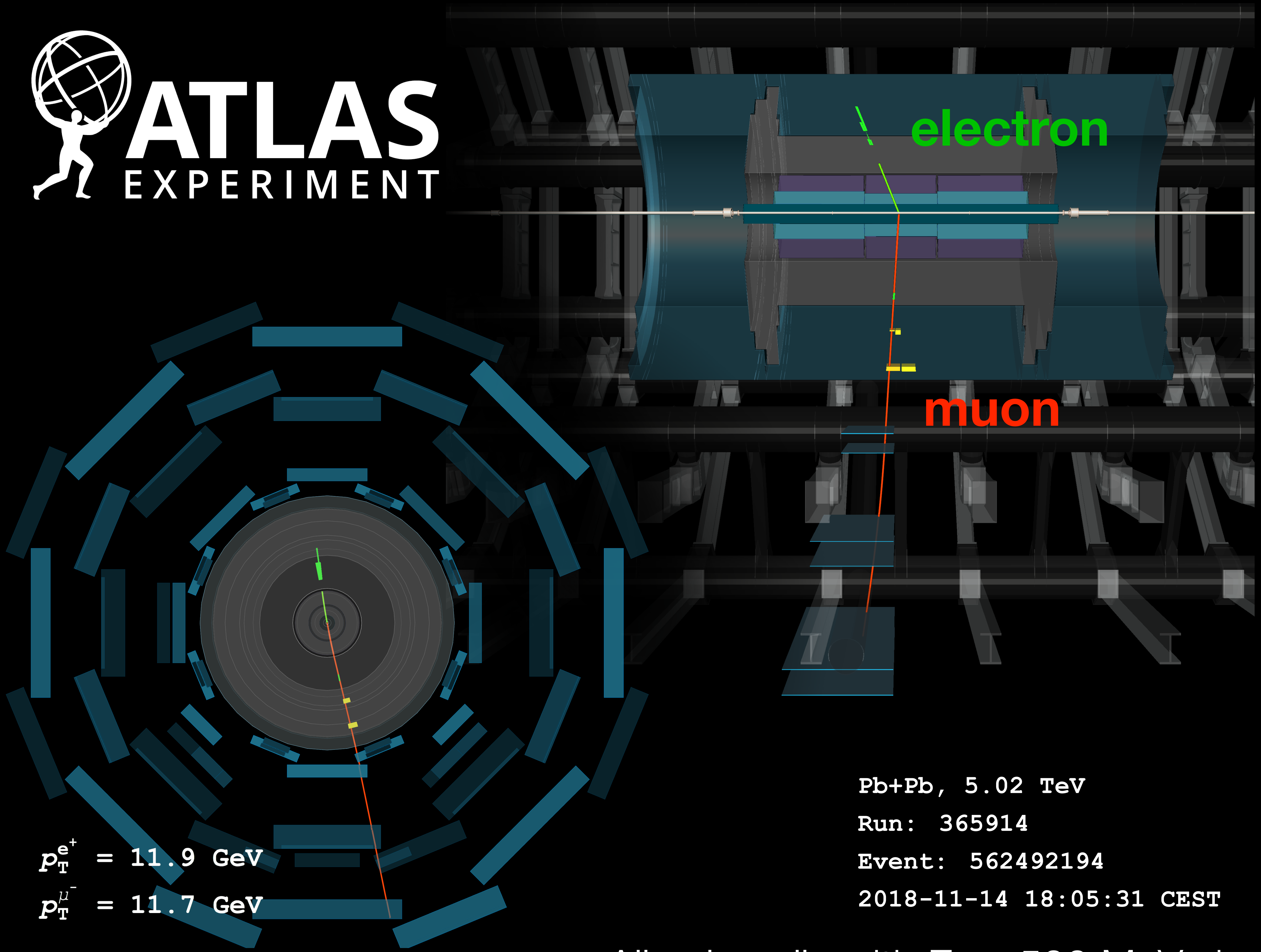


Run 168665, Event 83797

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

Ultra Peripheral PbPb collision

ATLAS EXPERIMENT



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

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

Pb+Pb, 5.02 TeV
Run: 365914
Event: 562492194
2018-11-14 18:05:31 CEST

All calo cells with E_T > 500 MeV shown

Ultra Peripheral PbPb collisions

Super clean with ~ 0 pile-up

One month to gather dataset

Low trigger thresholds → Trigger on soft taus!

→ Quantify potential using MC

MG with modified photon flux + Pythia + Delphes (ATLAS)

Di-tau Production

Aguila, Cornet and Illana PLB (1991)
Beresford, Liu 1908.05180

LHC PbPb

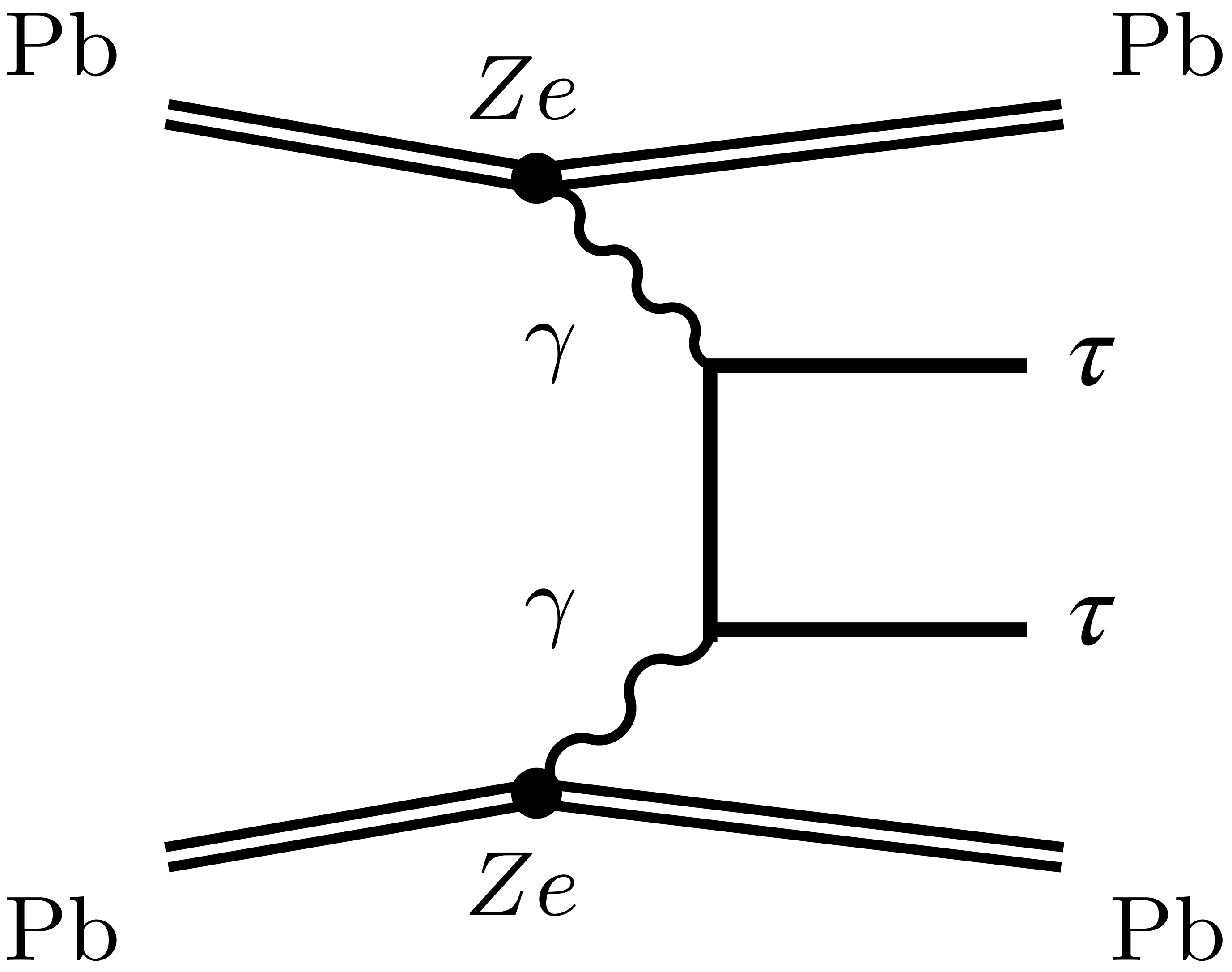


Photo production of tau pairs

Not yet observed @ LHC

Tau decays

1 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\nu_{\tau}$

+ neutral π's

Leptonic

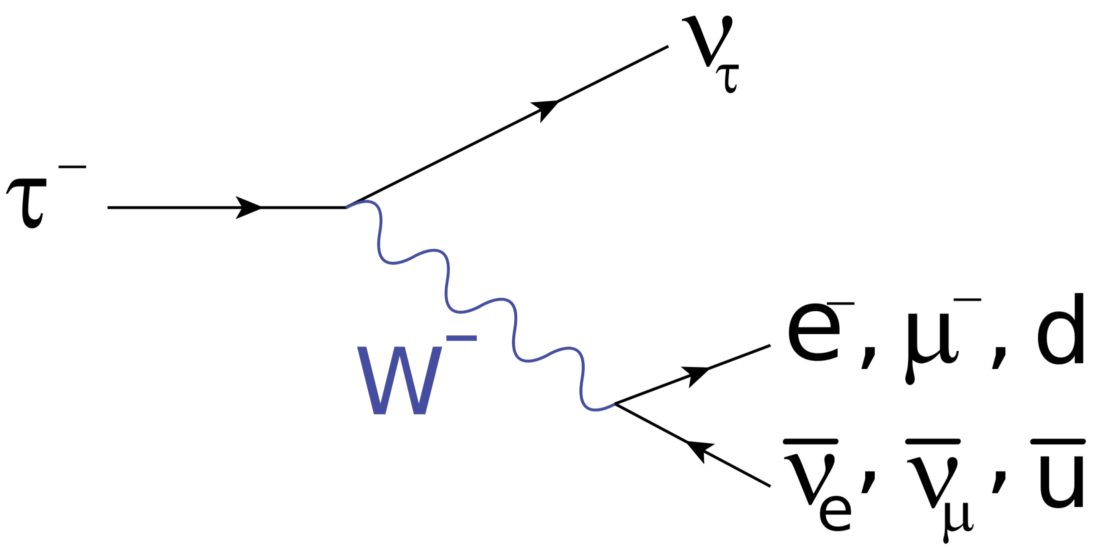
$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$

3 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

+ neutral π's

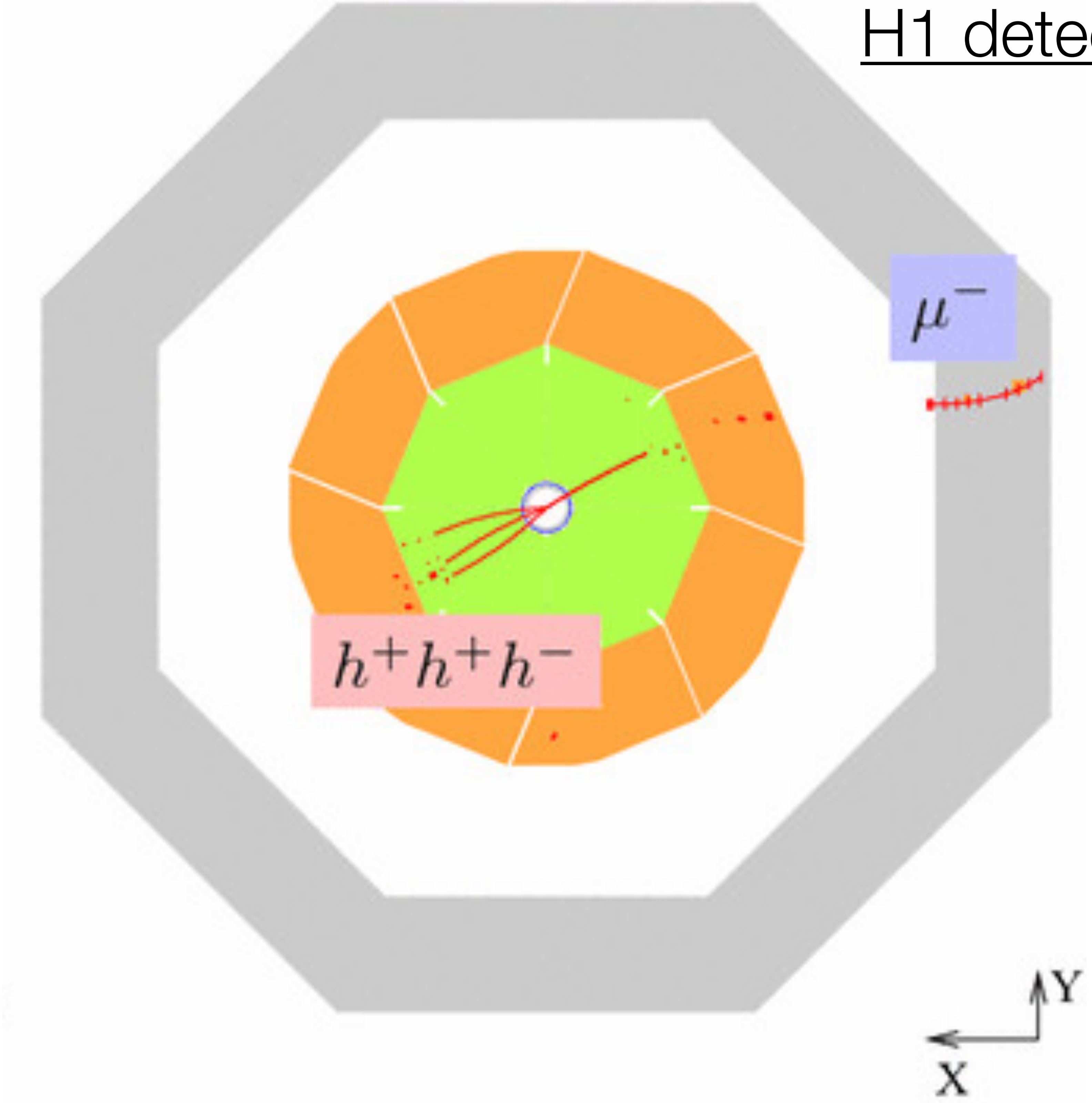
Tau is only lepton that can decay into hadrons



Tau decays

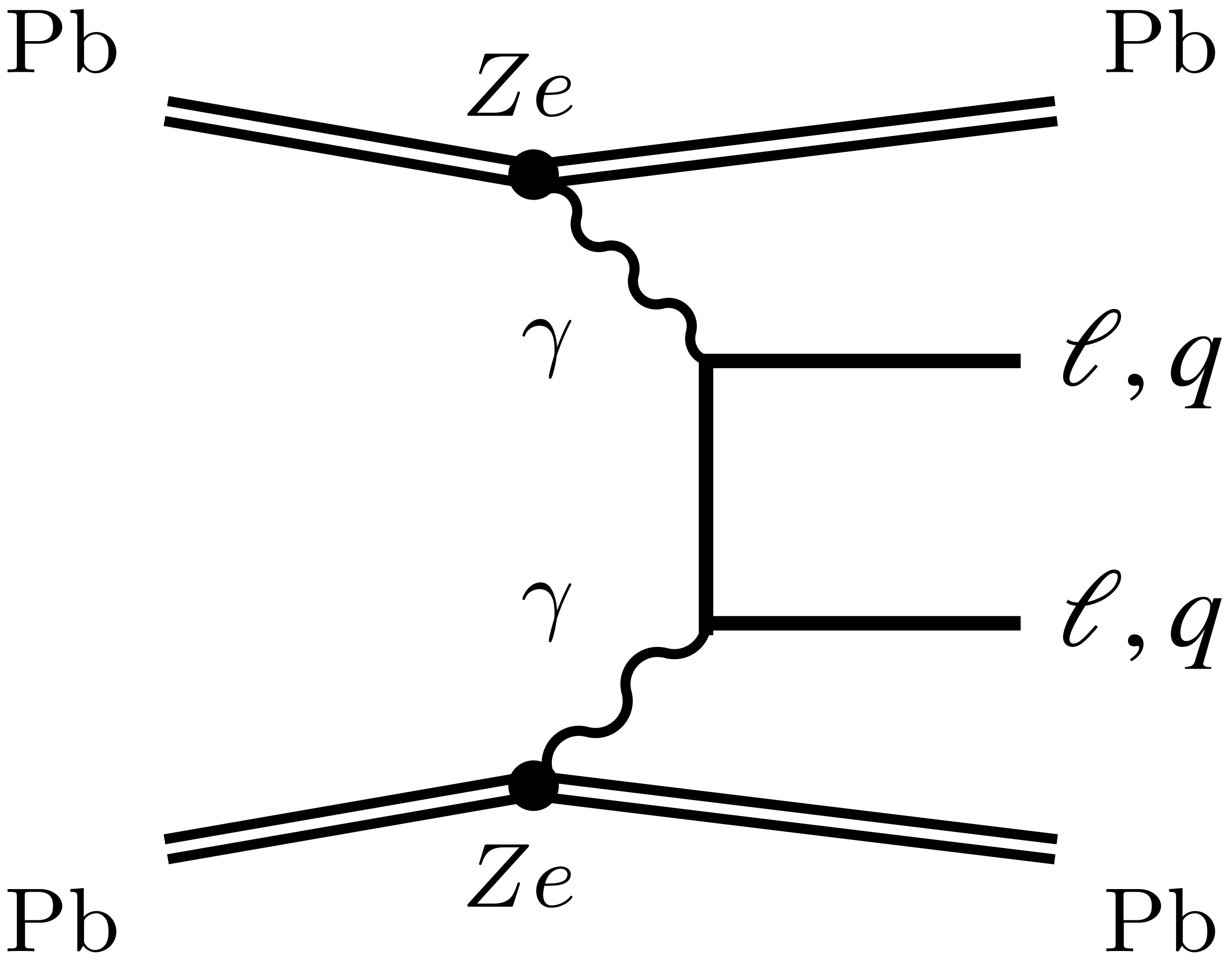
Di-tau pair

H1 detector @ HERA



Backgrounds

Generated:



Signal Regions

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

Signal Regions (SRs)

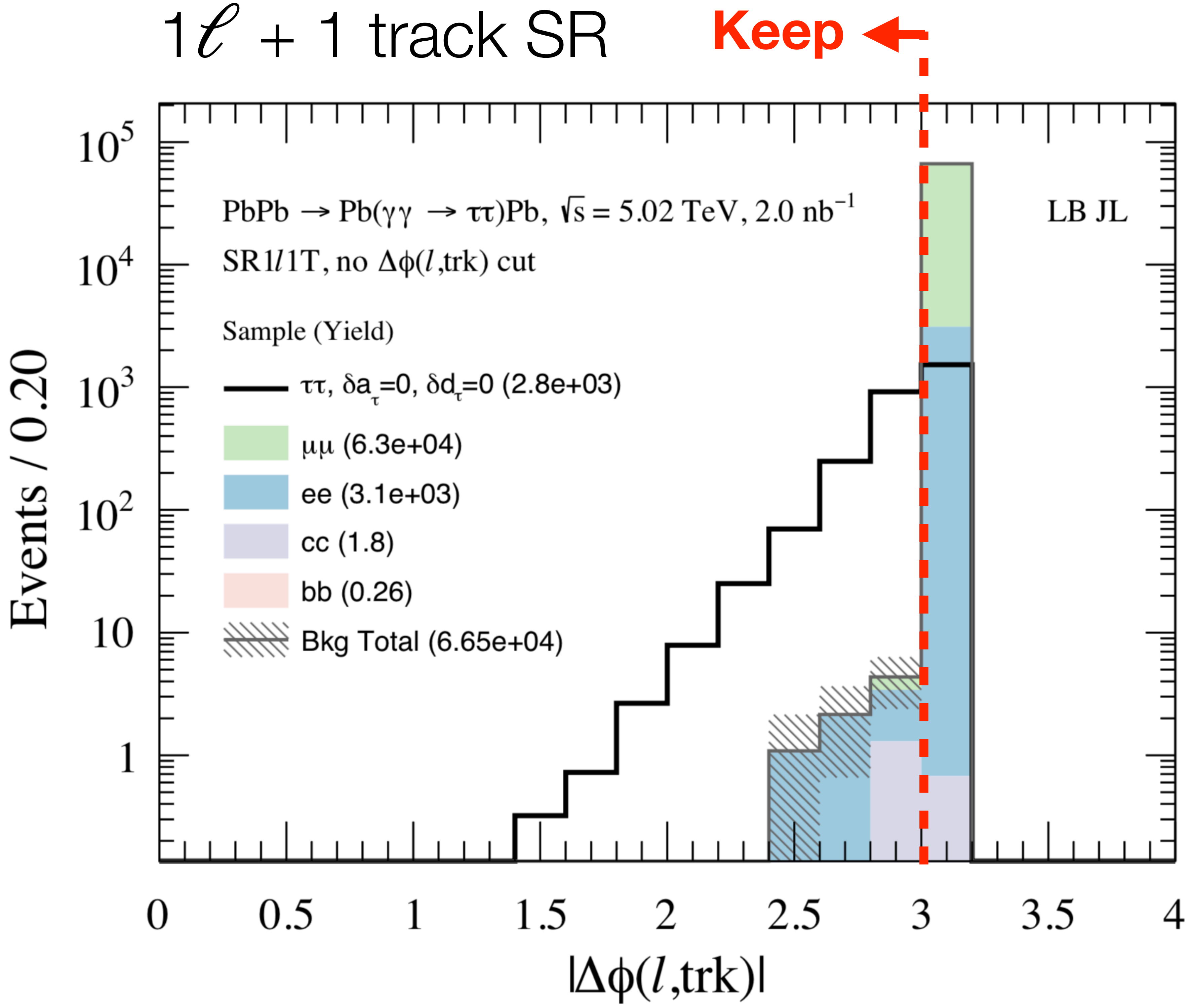
1ℓ + 1 track

1ℓ + 2 track

1ℓ + 3 track

Background mitigation

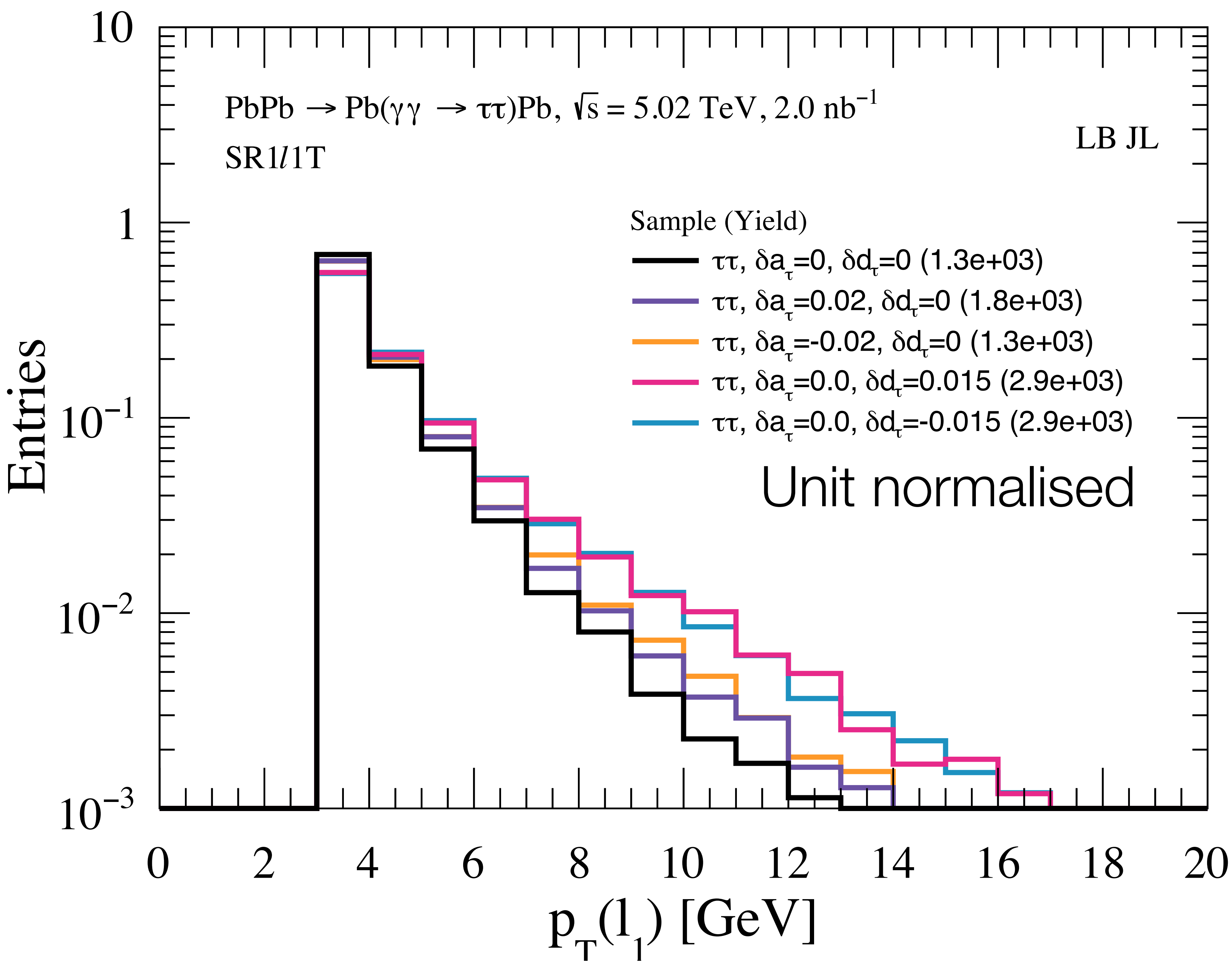
1ℓ + 1 track SR



And veto J/ψ & Υ masses

Setting constraints

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

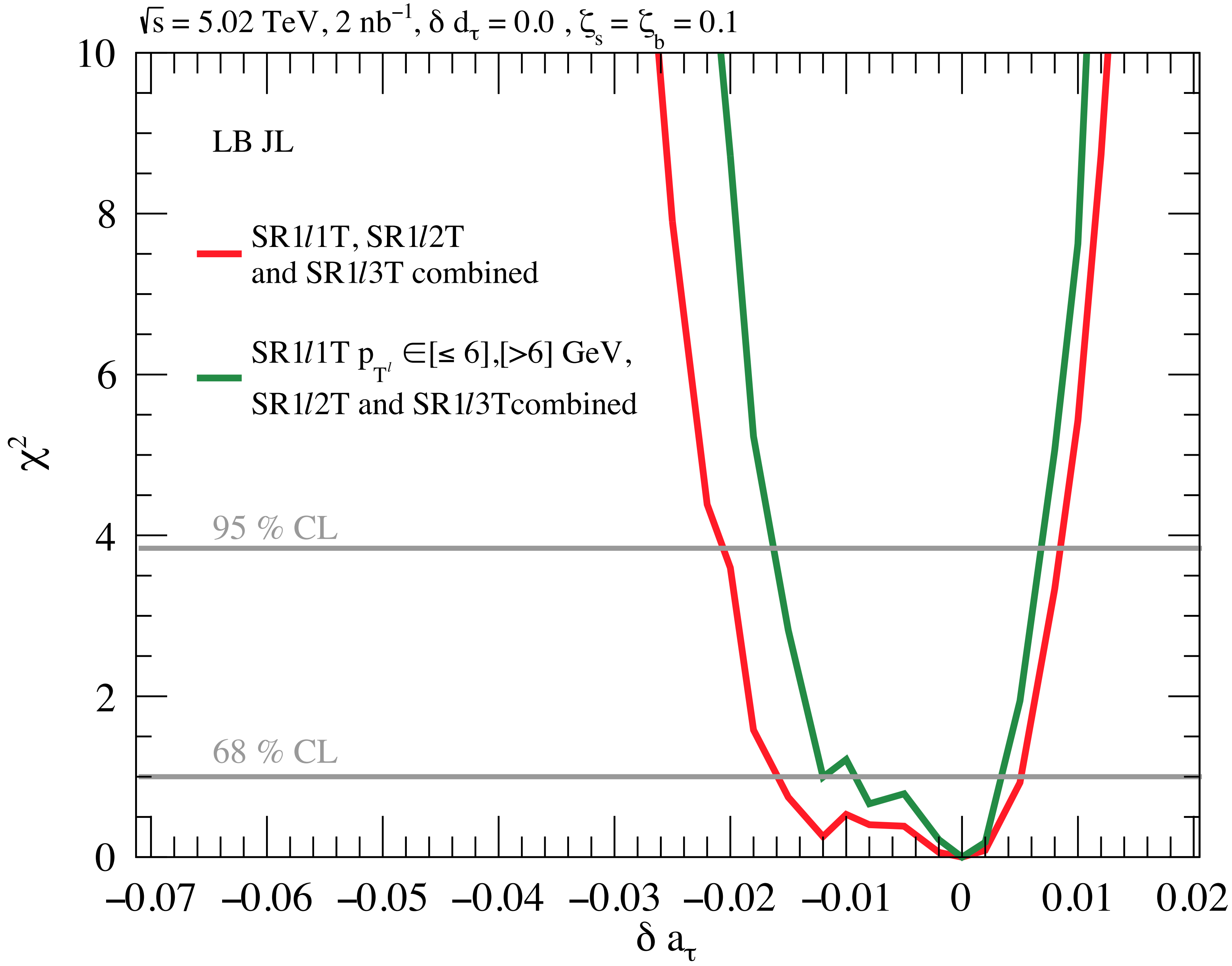


Unit normalised

Modifying moments alters **shape** of lepton p_T

Putting it all together: a_τ

Assume observe SM & quantify constraint using χ^2



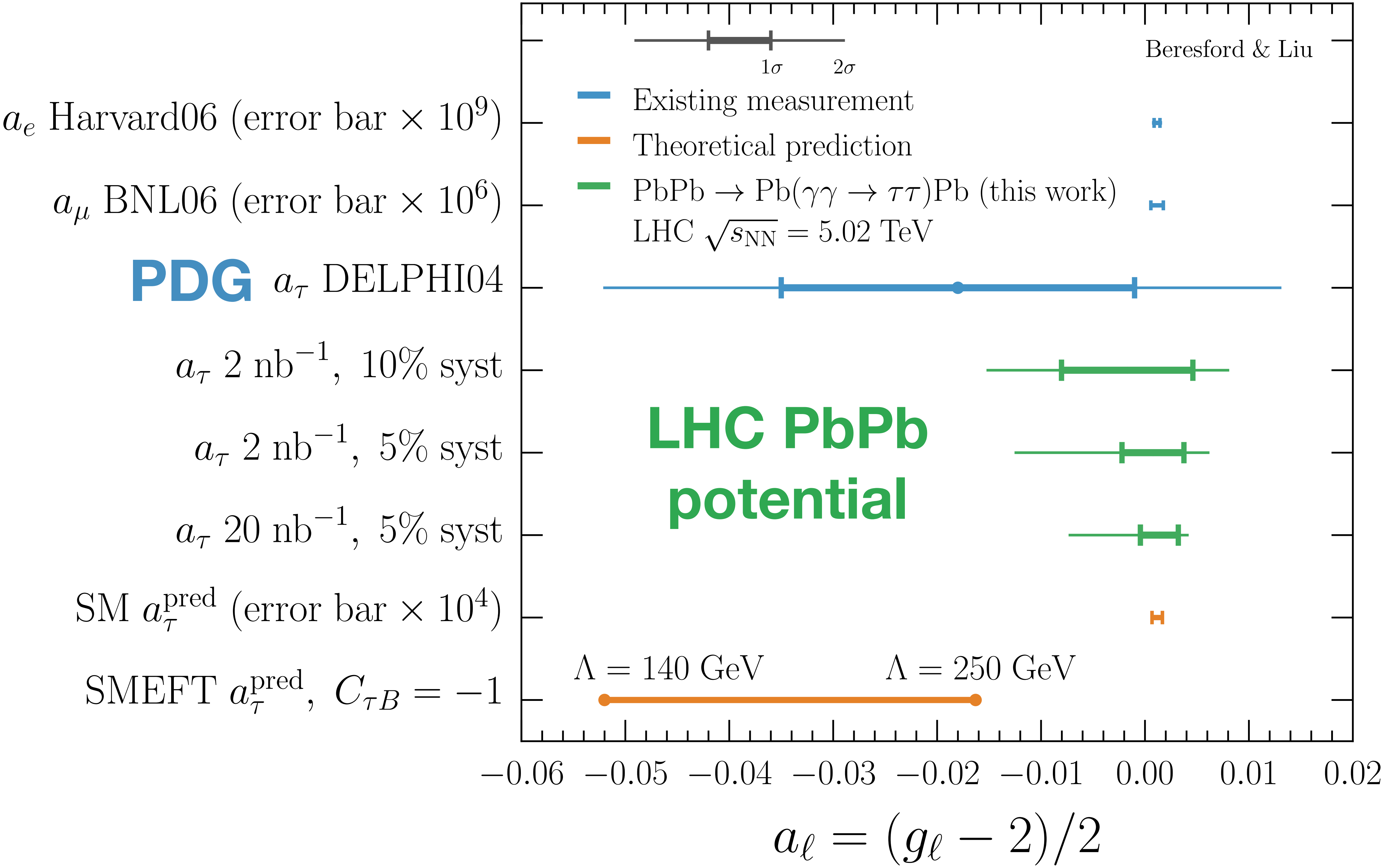
Assuming 10% systematic

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

Shape analysis strengthens constraints :)

Split 1ℓ + 1 track SR @ 6 GeV → Coarse shape analysis

Putting it all together: a_τ



PDG

LHC PbPb potential

Surpass DELPHI … or discover tension!

Also sensitive to tau EDM

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

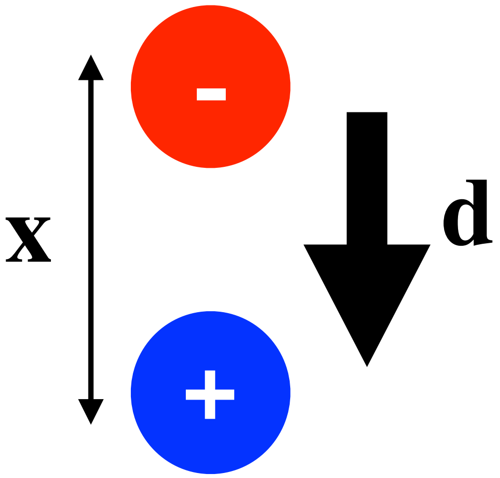
EDM = Electric Dipole Moment

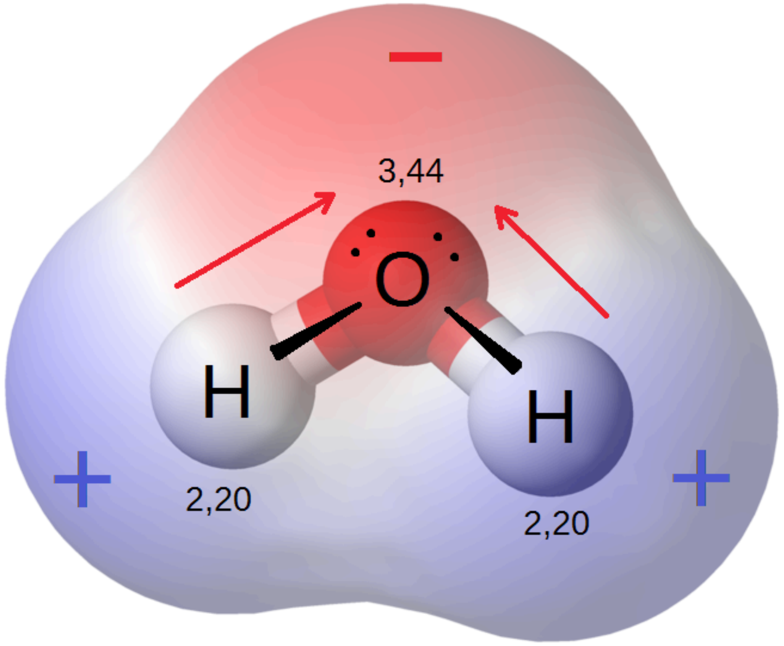
$$\boldsymbol{\tau} = \boldsymbol{d} \times \mathbf{E}$$

↑ torque ↑ electric dipole moment

Possessed by e.g. water (polarised molecule)

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





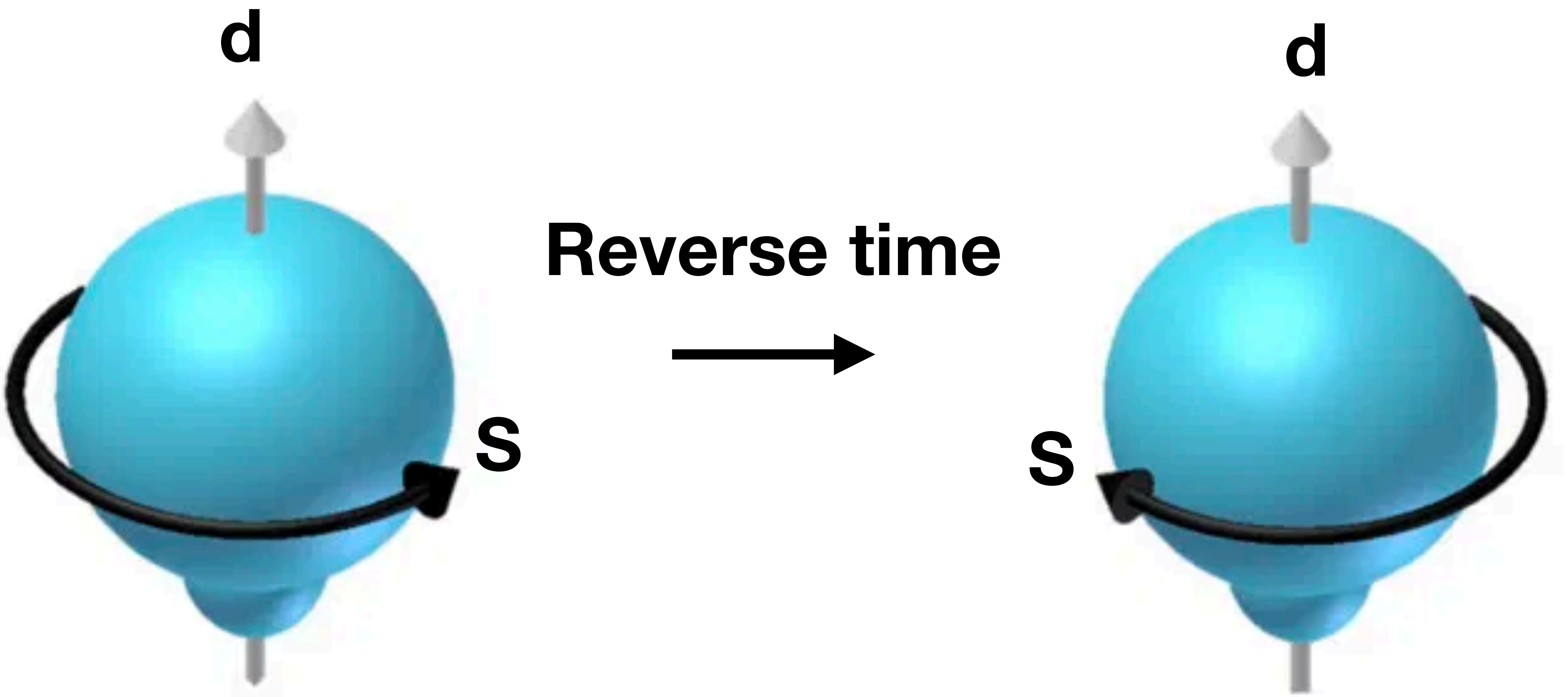
EDM tells us about charge distribution

Why are EDMs interesting?

Further details

Non-zero EDM → CP violation!

assuming CPT conserved



EDM tiny in SM, observation = New Physics!

Putting it all together: d_τ

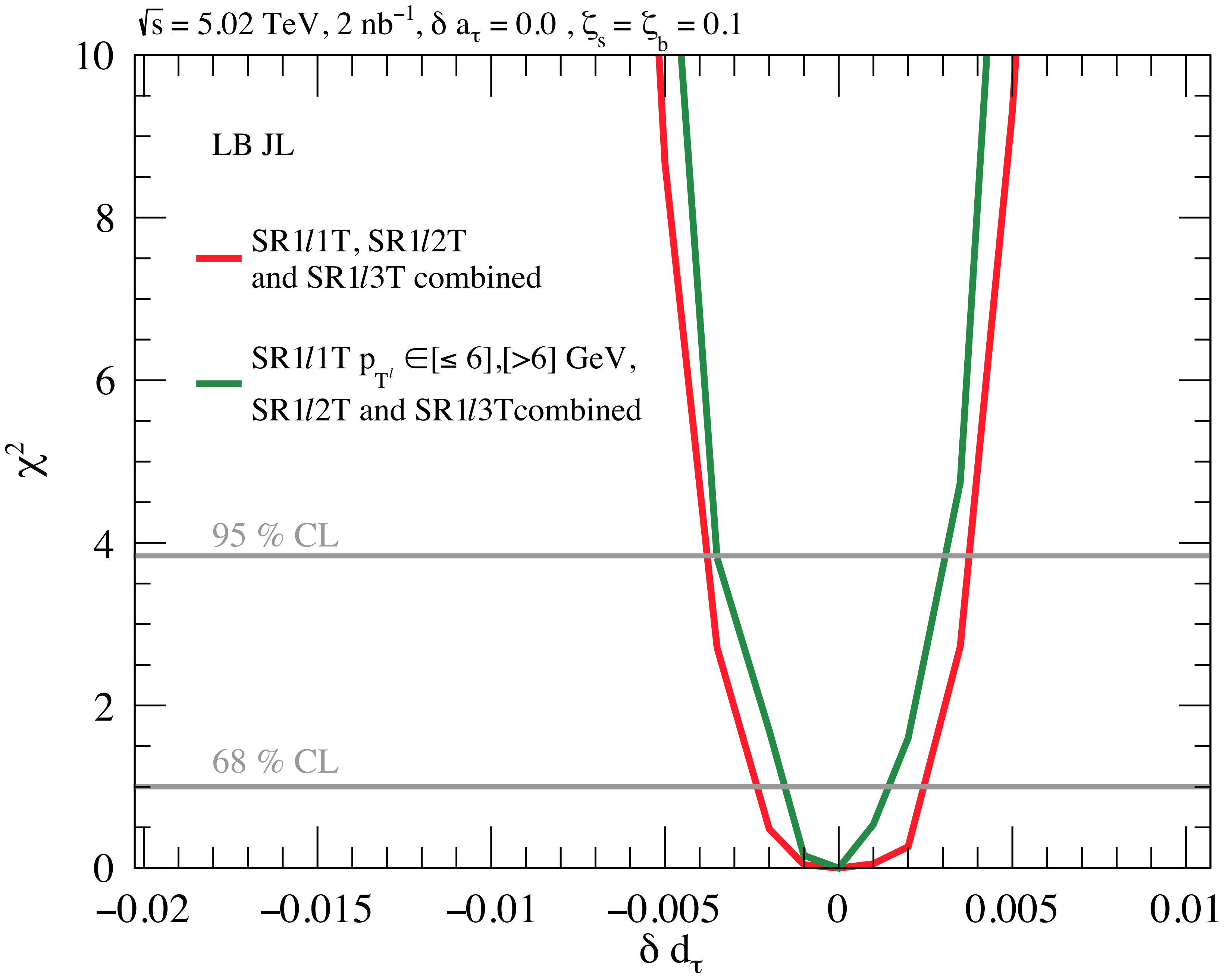
Belle PLB (2003)

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

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

@ 95% CL

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



Order mag better than DELPHI, competitive with Belle

Why stop there?

Demonstrated PbPb potential for ATLAS/CMS

Goal: Combined effort!

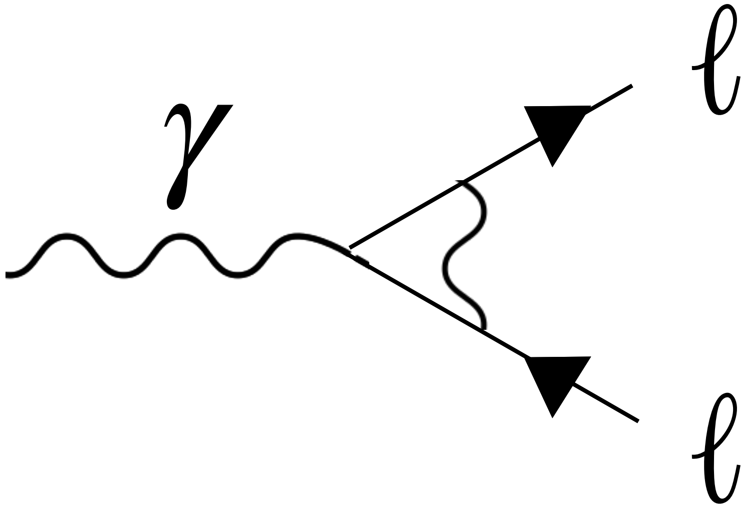
PbPb, pPb, pp?

ATLAS, CMS, LHCb & ALICE

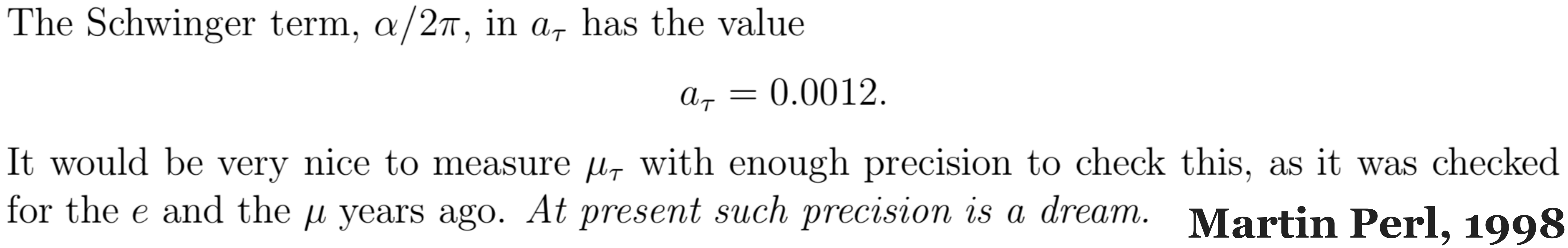
RHIC & lepton colliders

Why stop there?

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



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.*

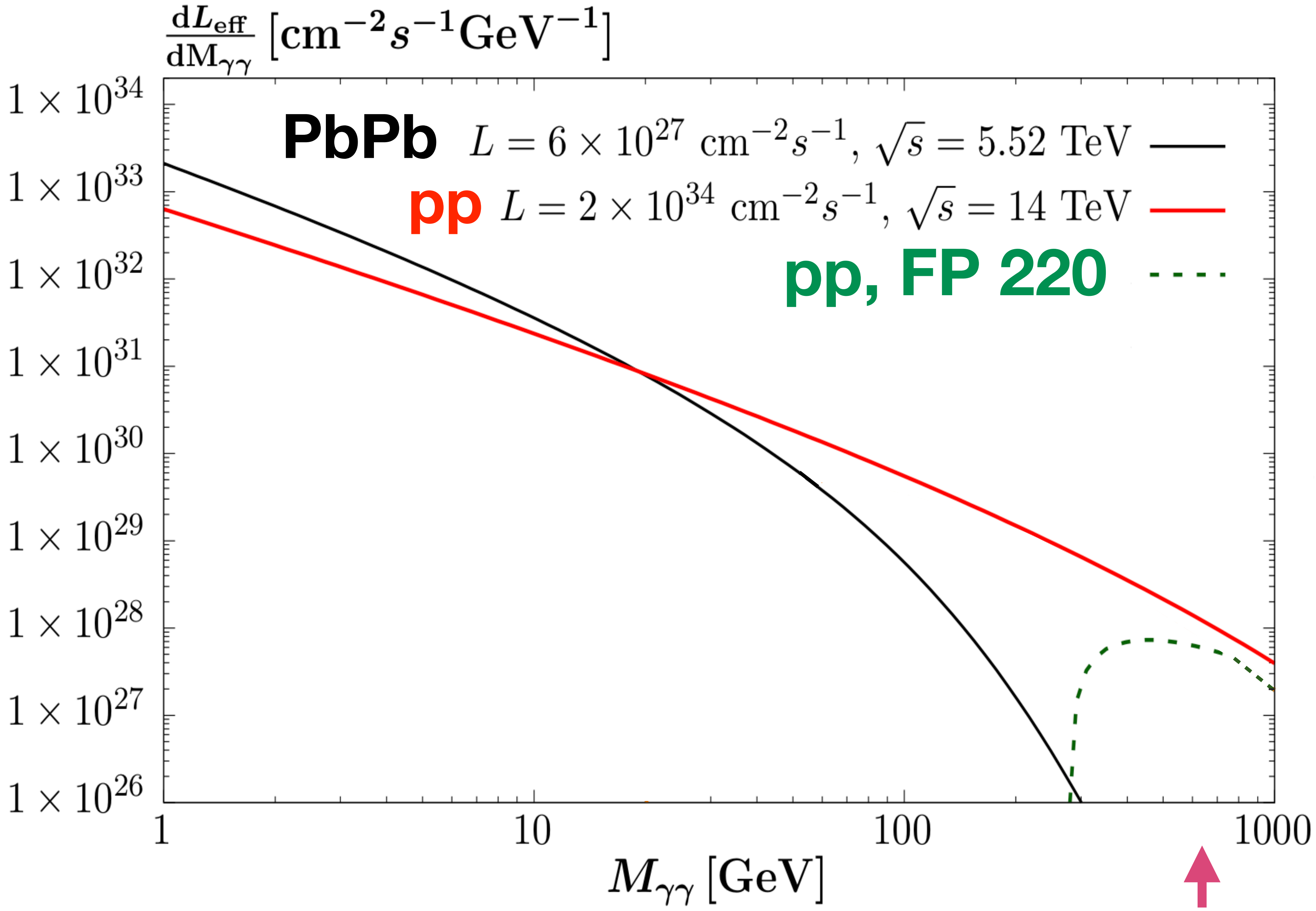
Martin Perl, 1998

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

QED @ range of masses

Photon collisions from **protons & heavy ions**

Intensity frontier

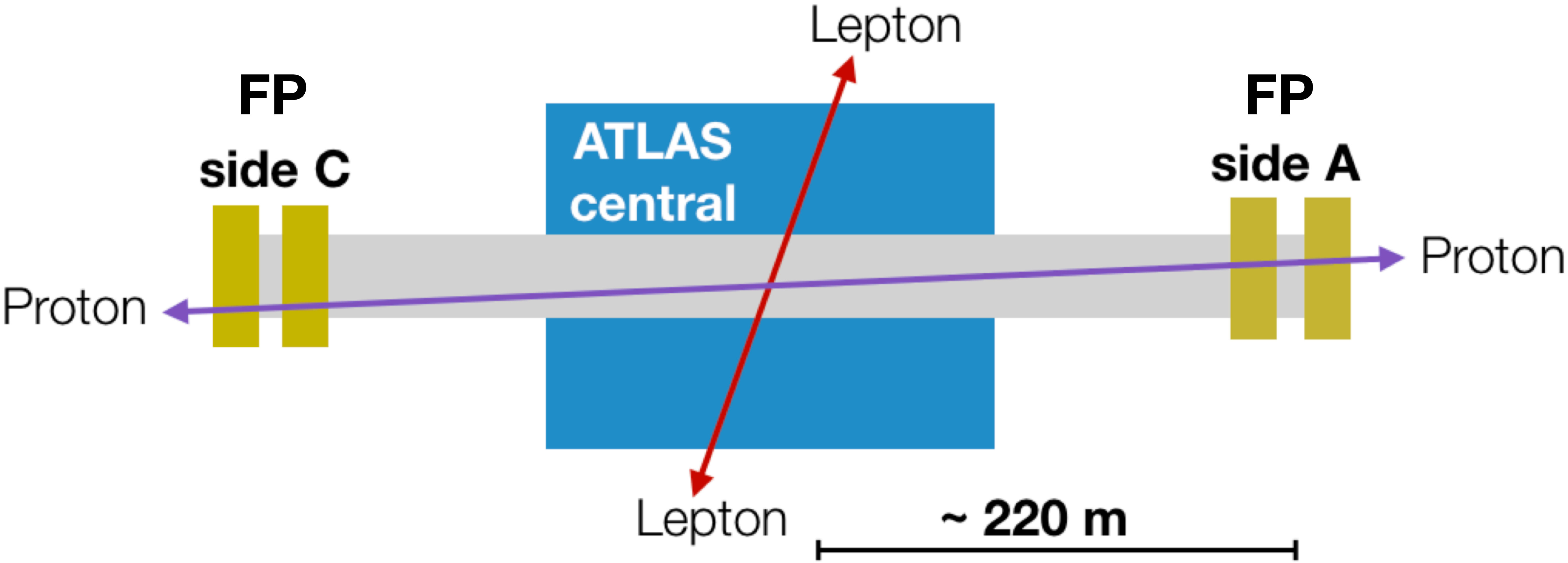


Energy frontier

Bruce et al [1812.07688](https://arxiv.org/abs/1812.07688)

pp, FP 220 Forward Proton detectors

ATLAS (AFP)
CMS (CT-PPS)



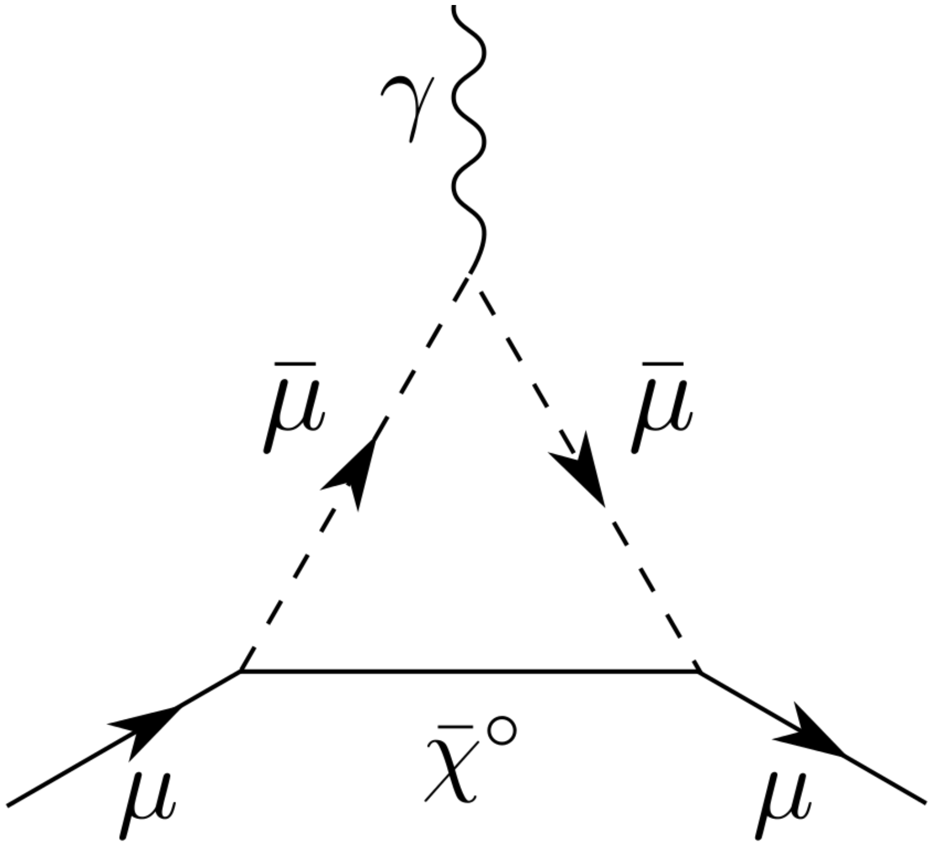
Incoming proton E known (6.5 TeV)

Outgoing proton E measured with forward detector

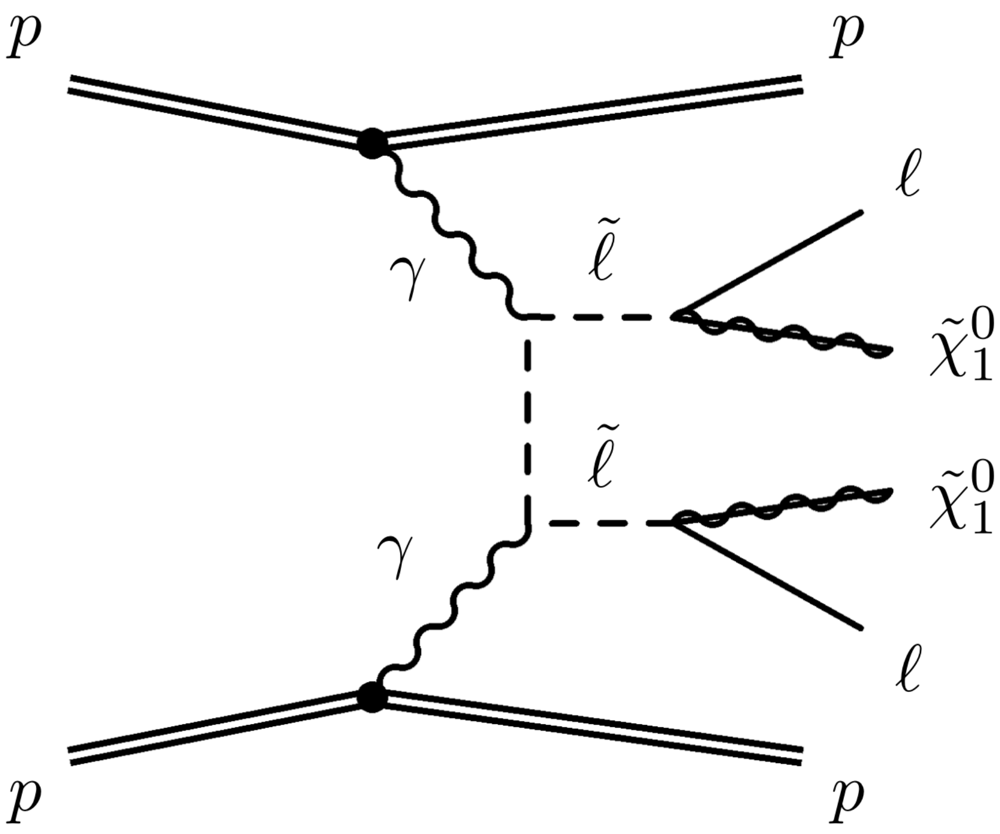
→ **Calculate proton energy loss!**

One motivation: Muon g-2

Recall

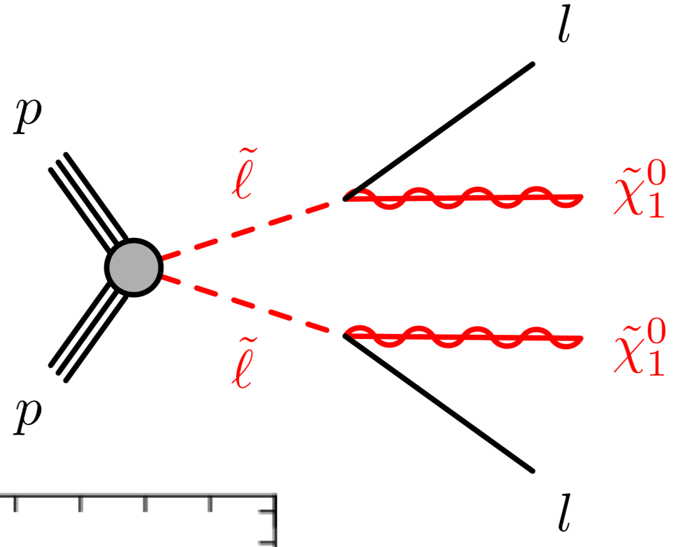


Unpack the loop

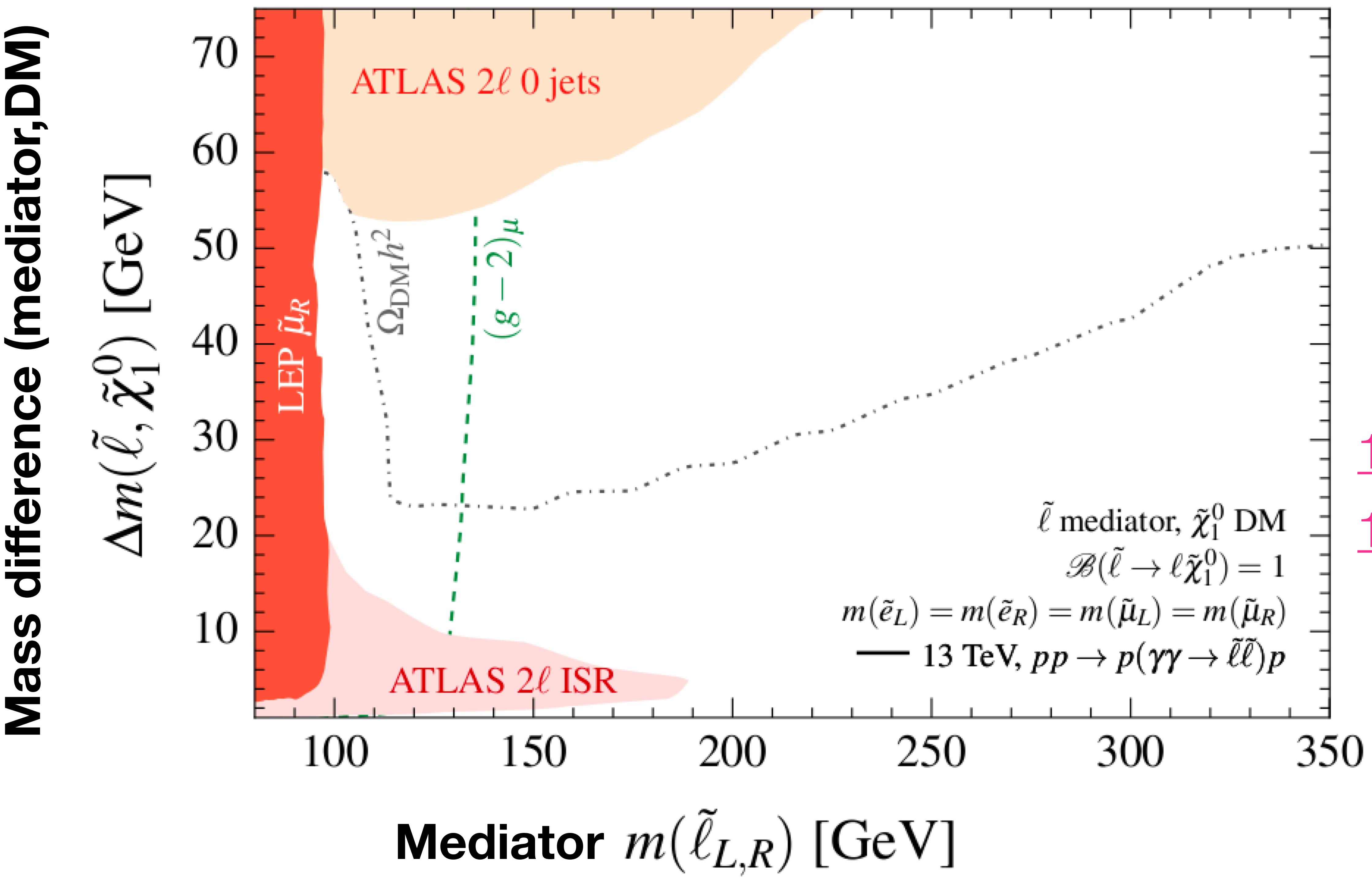


Can search for these new particles directly at the LHC

Constraints



Blind in dark matter & g-2 favoured regions



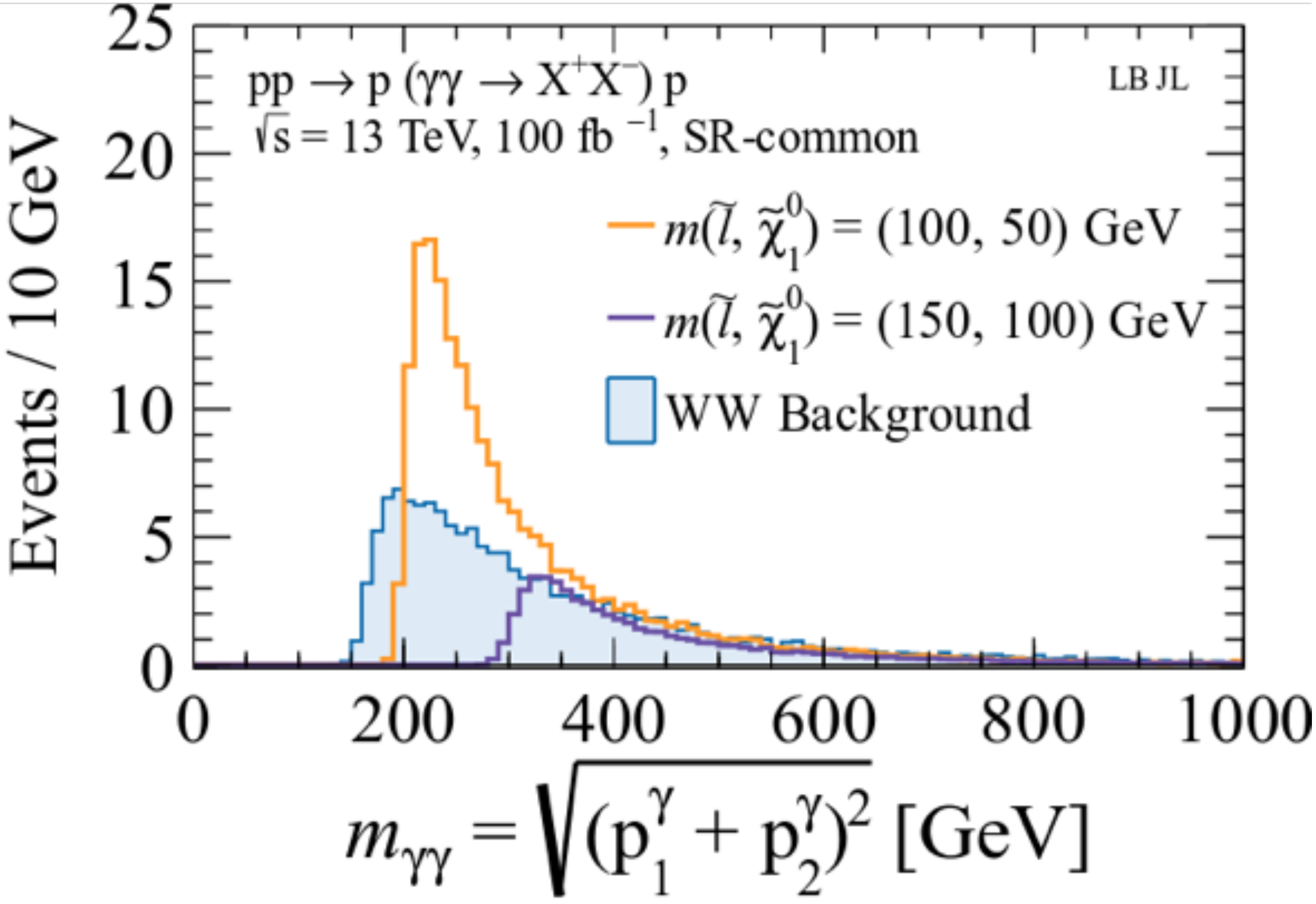
NB most recent ATLAS results:

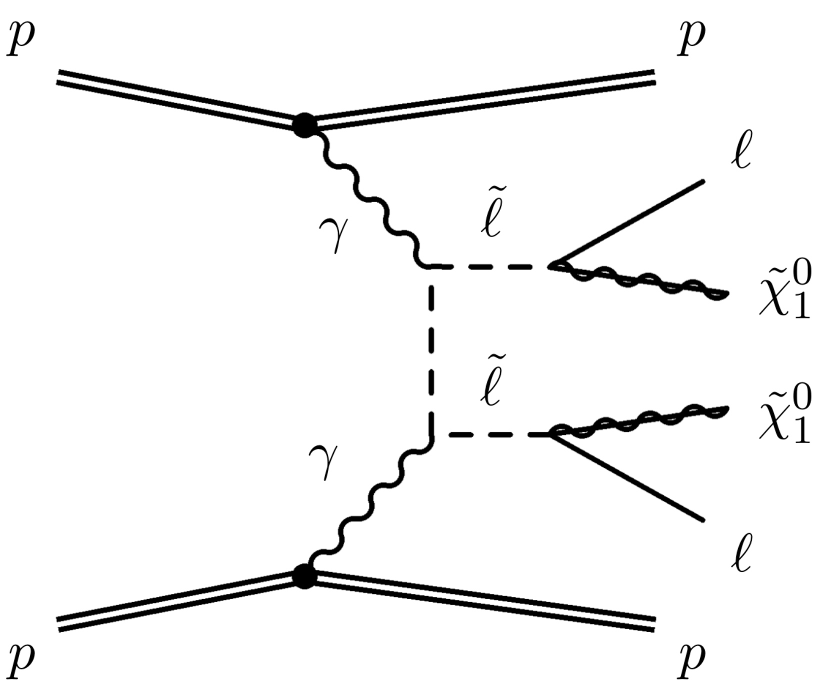
1911.12606

1908.08215

→ Search for production threshold

Illustrative plot FP acceptance not applied





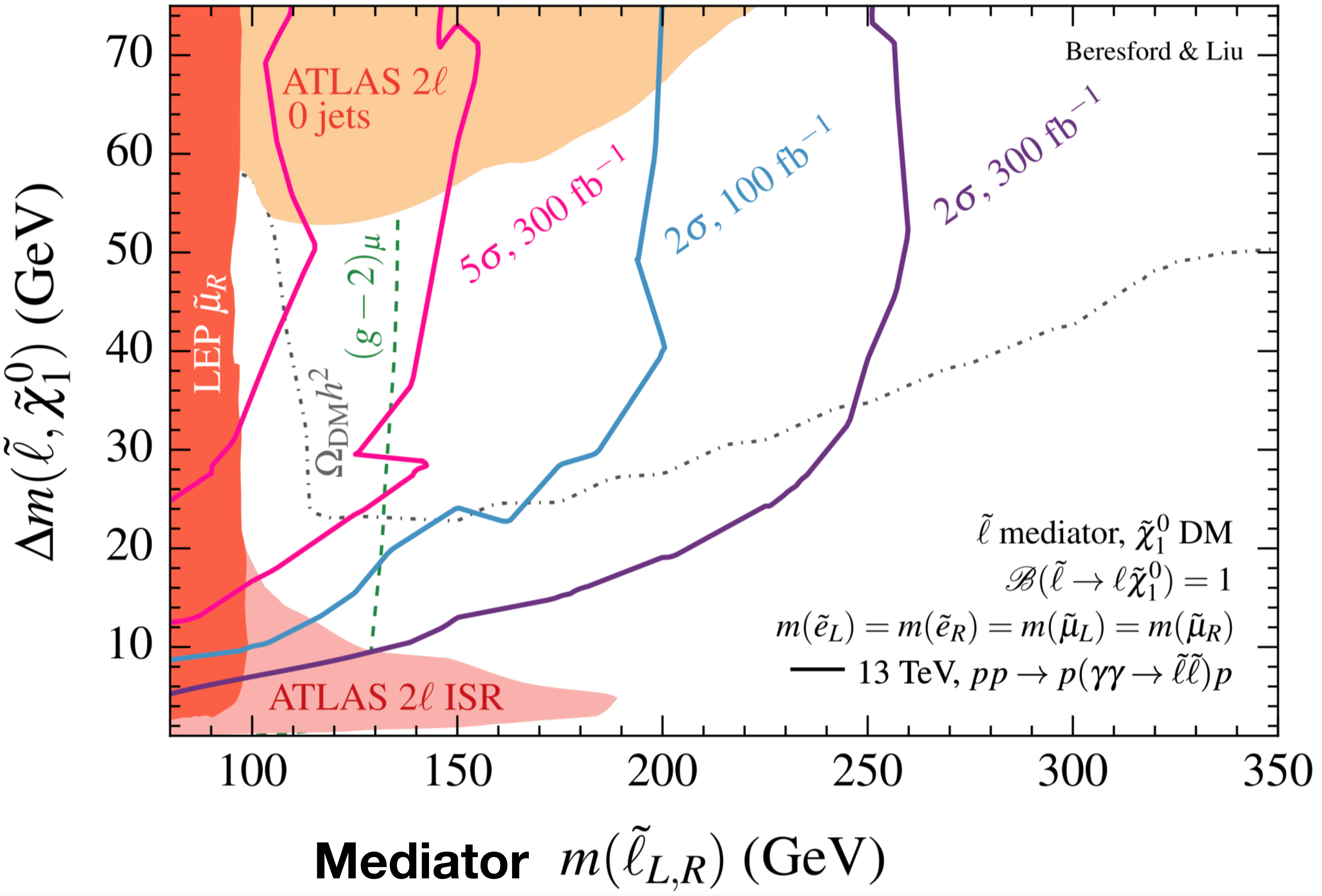
Calculated from proton energy loss

Powerful Potential

Beresford, Liu PRL (2019)

Potential to probe well motivated ATLAS blind spots
& perform landmark measurements of new LHC observables!

Mass difference (mediator,DM)



Mediator

What if new physics …

Is invisible to detector?

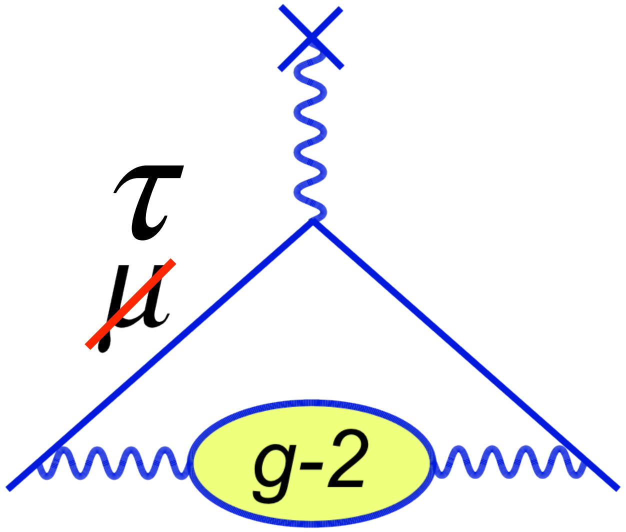
Decays to a cascade of soft particles?

Is a broad resonance?

Is a long lived particle?

Summary

Tau g-2 interesting & important



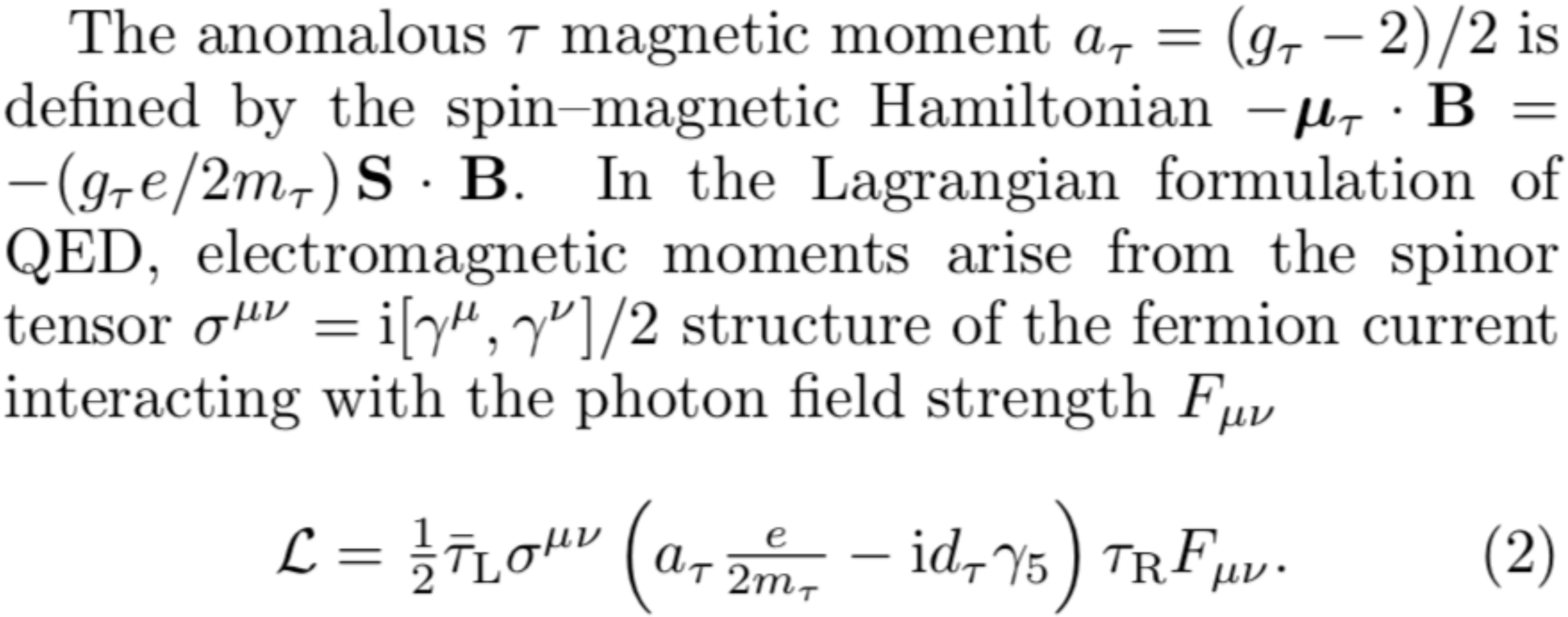
But barely constrained

LHC photon collisions promising solution

For tau g-2 and beyond!

Backup

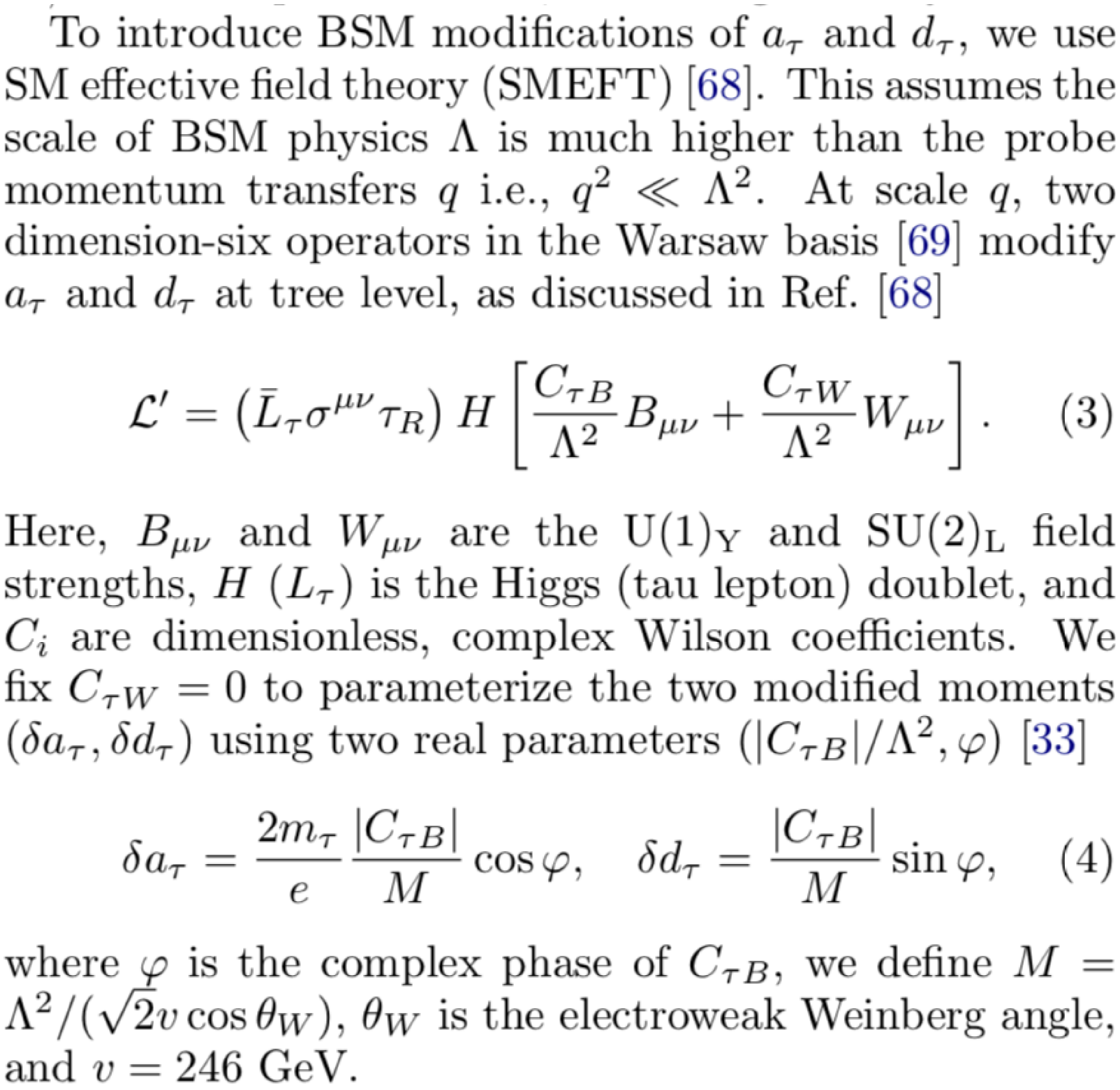
SM QED



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 $\sigma^{\mu\nu} = \mathrm{i}[\gamma^\mu, \gamma^\nu]/2$ structure of the fermion current interacting with the photon field strength $F_{\mu\nu}$

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

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]

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

Here, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the $\mathrm{U(1)_Y}$ and $\mathrm{SU(2)_L}$ 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]

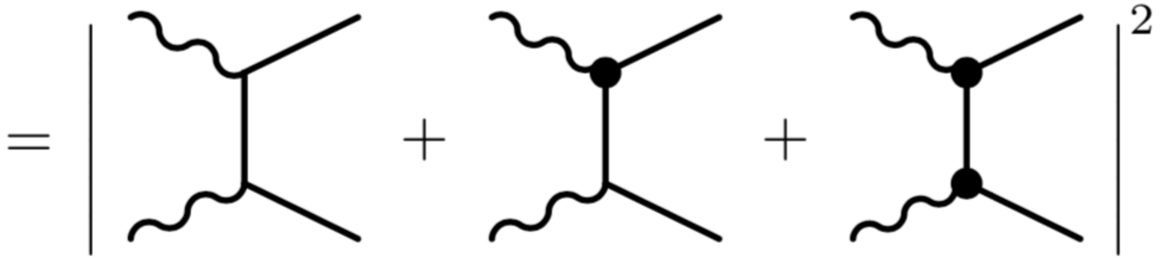
$$\delta a_\tau = \frac{2m_\tau}{e} \frac{|C_{\tau B}|}{M} \cos\varphi, \quad \delta d_\tau = \frac{|C_{\tau B}|}{M} \sin\varphi, \qquad (4)$$

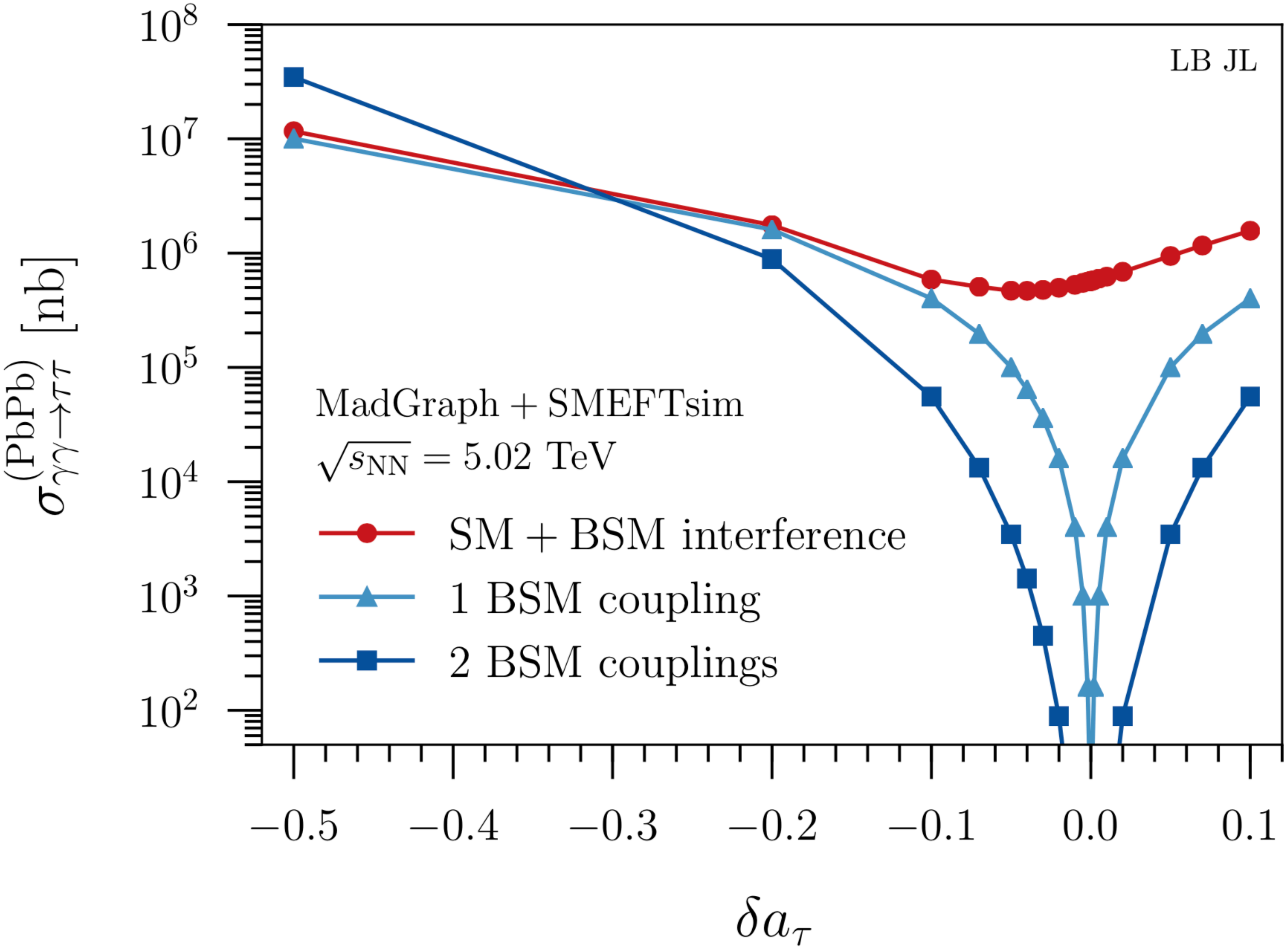
where φ is the complex phase of $C_{\tau B}$, we define $M = \Lambda^2/(\sqrt{2} v \cos\theta_W)$, θ_W is the electroweak Weinberg angle, and $v = 246$ GeV.

Lydia Beresford

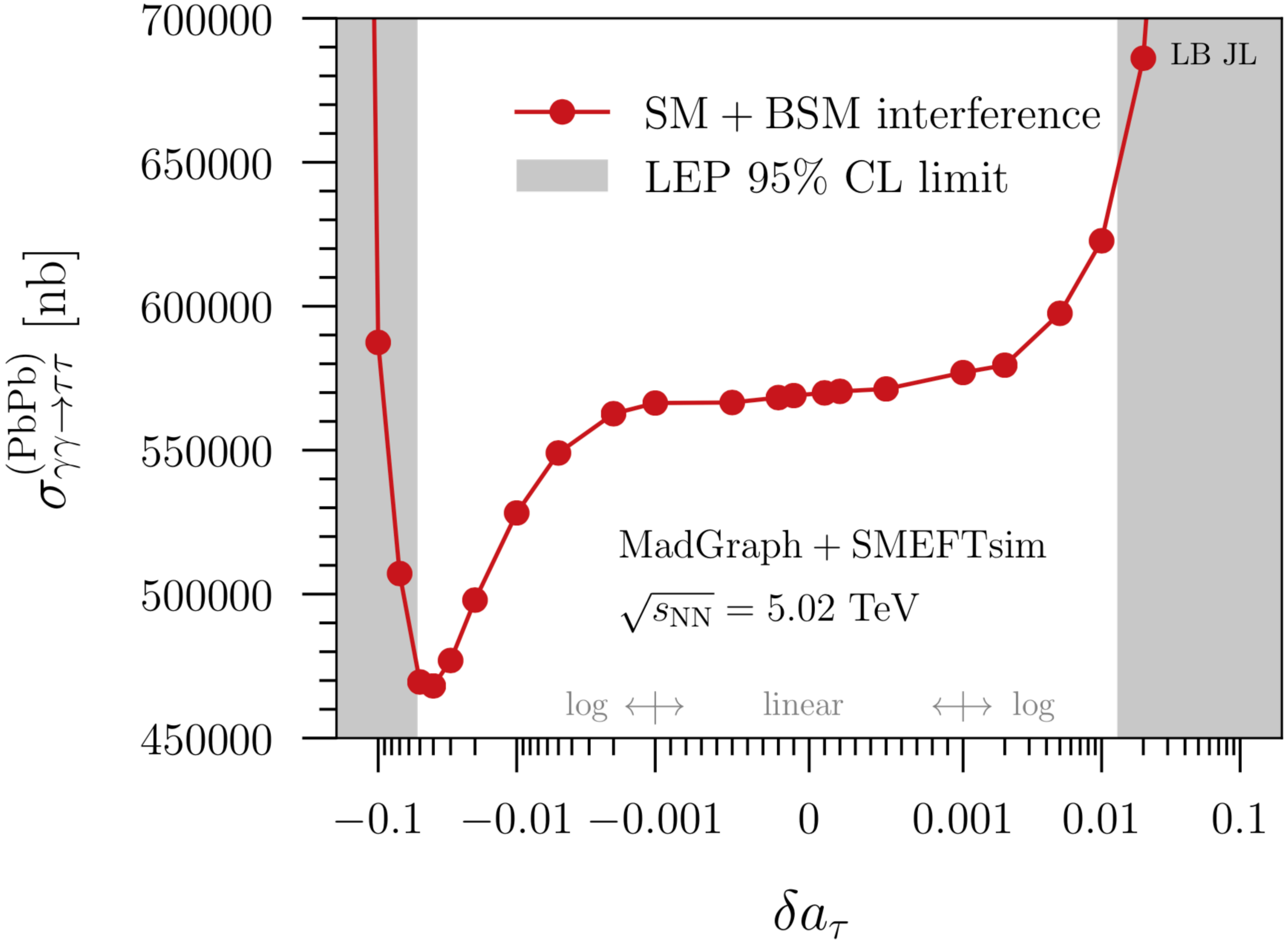
Cross-section & interference

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\mathrm{SM}} + \mathcal{M}^{(1)}_{\mathrm{BSM}} + \mathcal{M}^{(2)}_{\mathrm{BSM}}\right|^2$$



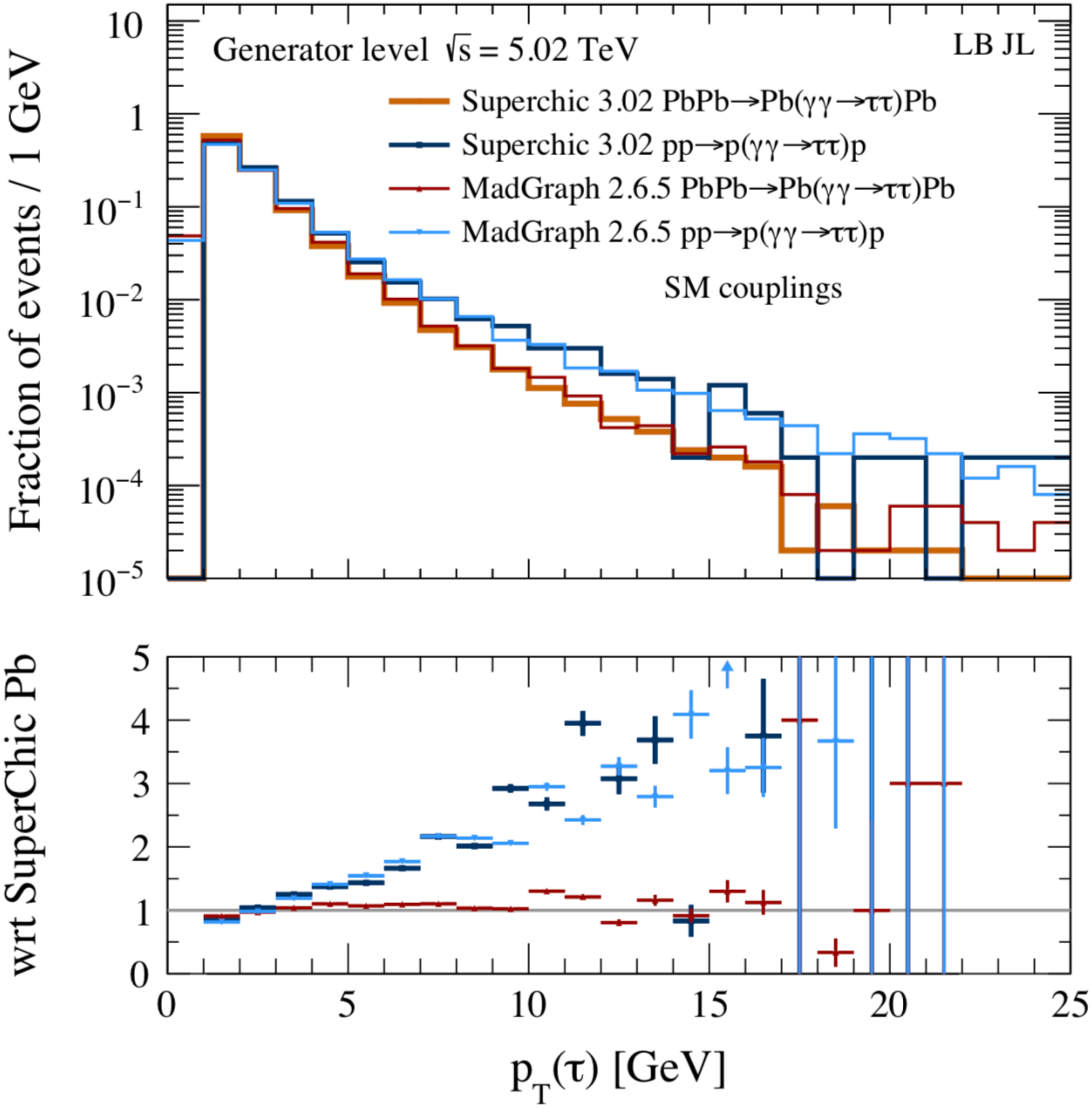


Cross-section & interference (zoomed)

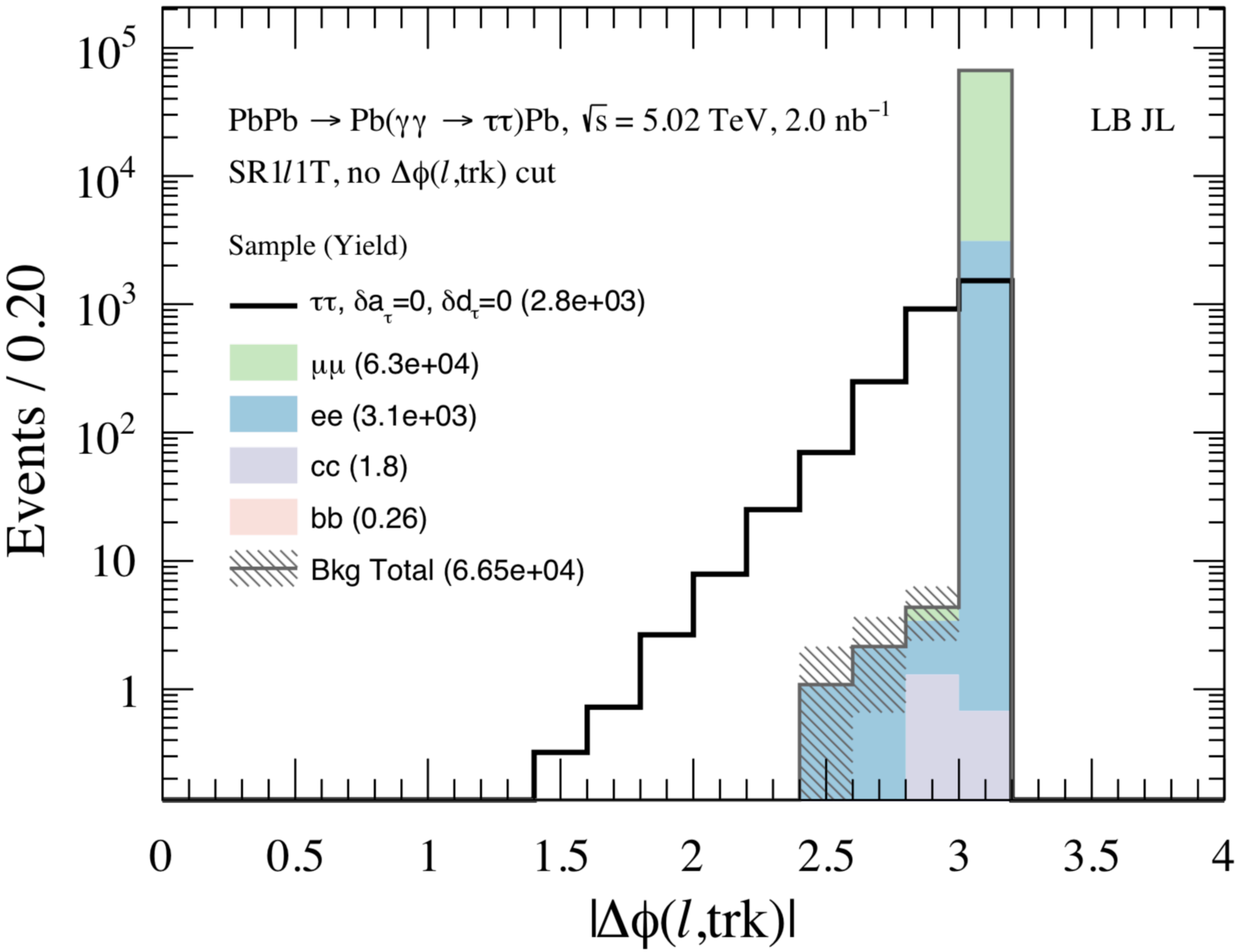


MG vs Super Chic

Superchic accounts for nuclear finite size, thickness and overlap



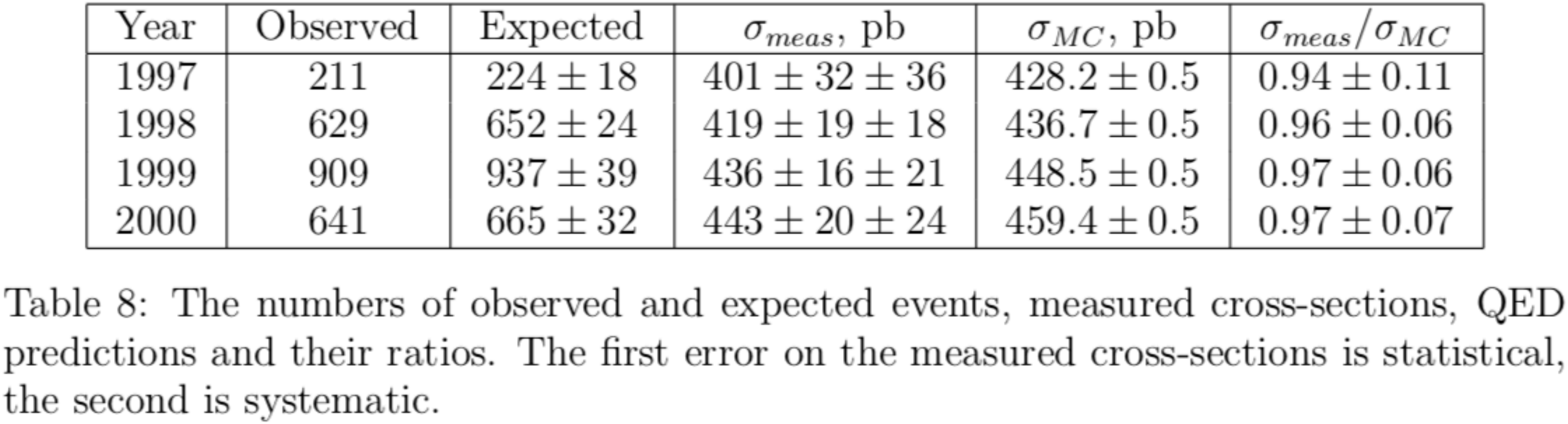
SR1l1T non-planar requirement



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 (SR1ℓ1T)										
$\sigma \times \mathcal{L}$	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
1ℓ 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, $\lvert\eta^{e/\mu}\rvert < 2.5/2.4$	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, $\lvert\eta^{\text{trk}}\rvert < 2.5$	3324.5	3535.9	3256.9	78973	3117.8	1.0	3.0	0.0	0.0	0.0
$\lvert\Delta\phi(\ell, \text{trk})\rvert < 3$	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 (SR1ℓ2/3T)										
$\sigma \times \mathcal{L}$	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
1ℓ 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, $\lvert\eta^{e/\mu}\rvert < 2.5/2.4$	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, $\lvert\eta\rvert^{\text{trk}} < 2.5$	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, $\lvert\eta\rvert^{\text{trk}} < 2.5$	370.5	398.3	381.1	0.0	0.0	0.4	3.6	0.0	0.0	0.0

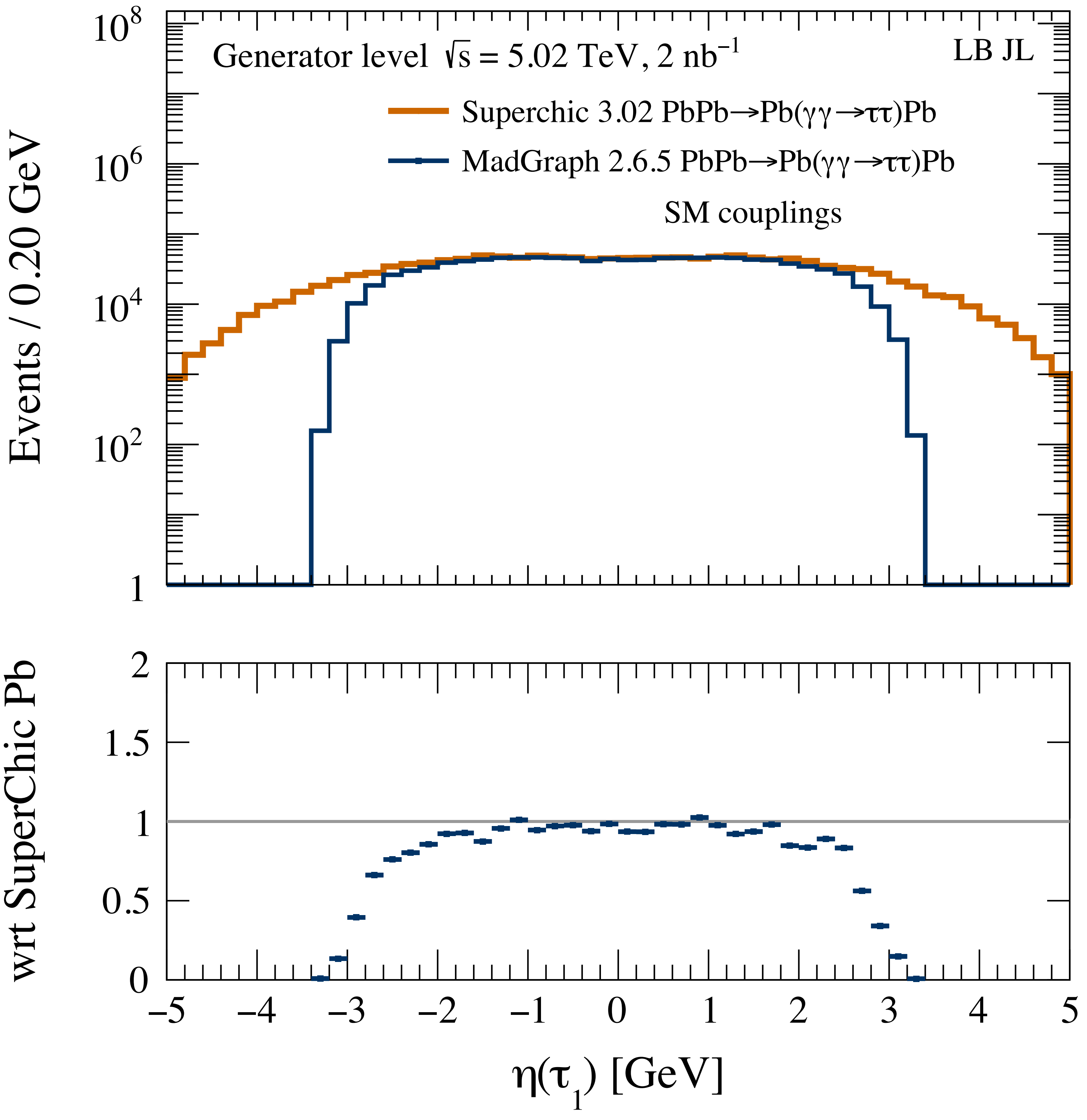
DELPHI Cutflow



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



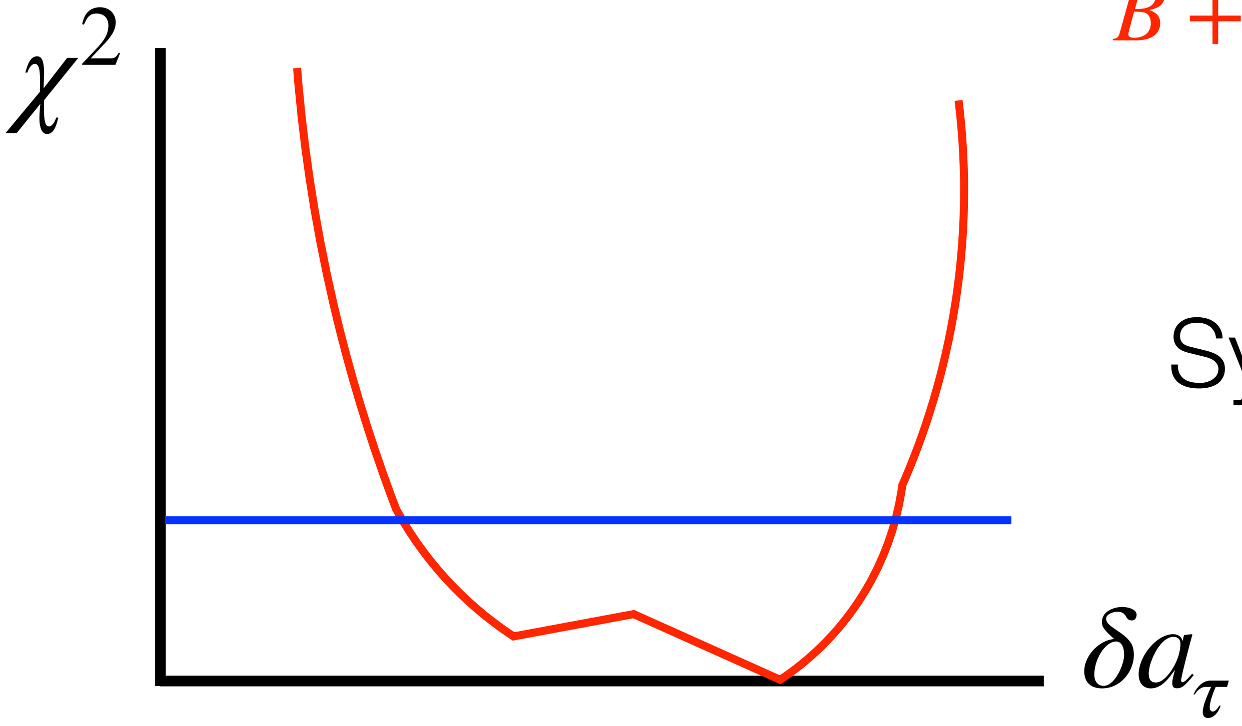
Setting constraints

To set a constraint need to deviate from SM

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

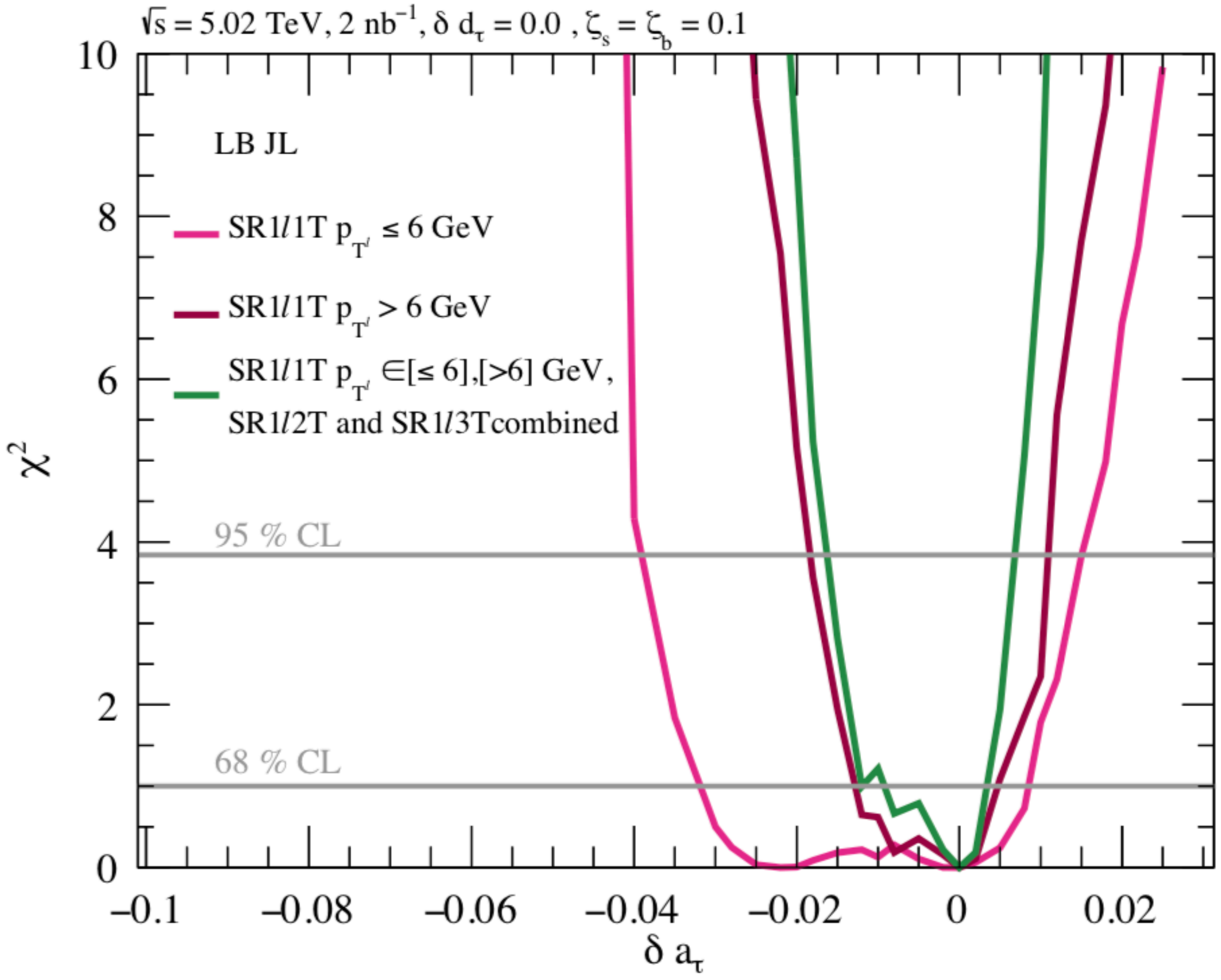
Assume observe SM & quantify constraint using χ^2

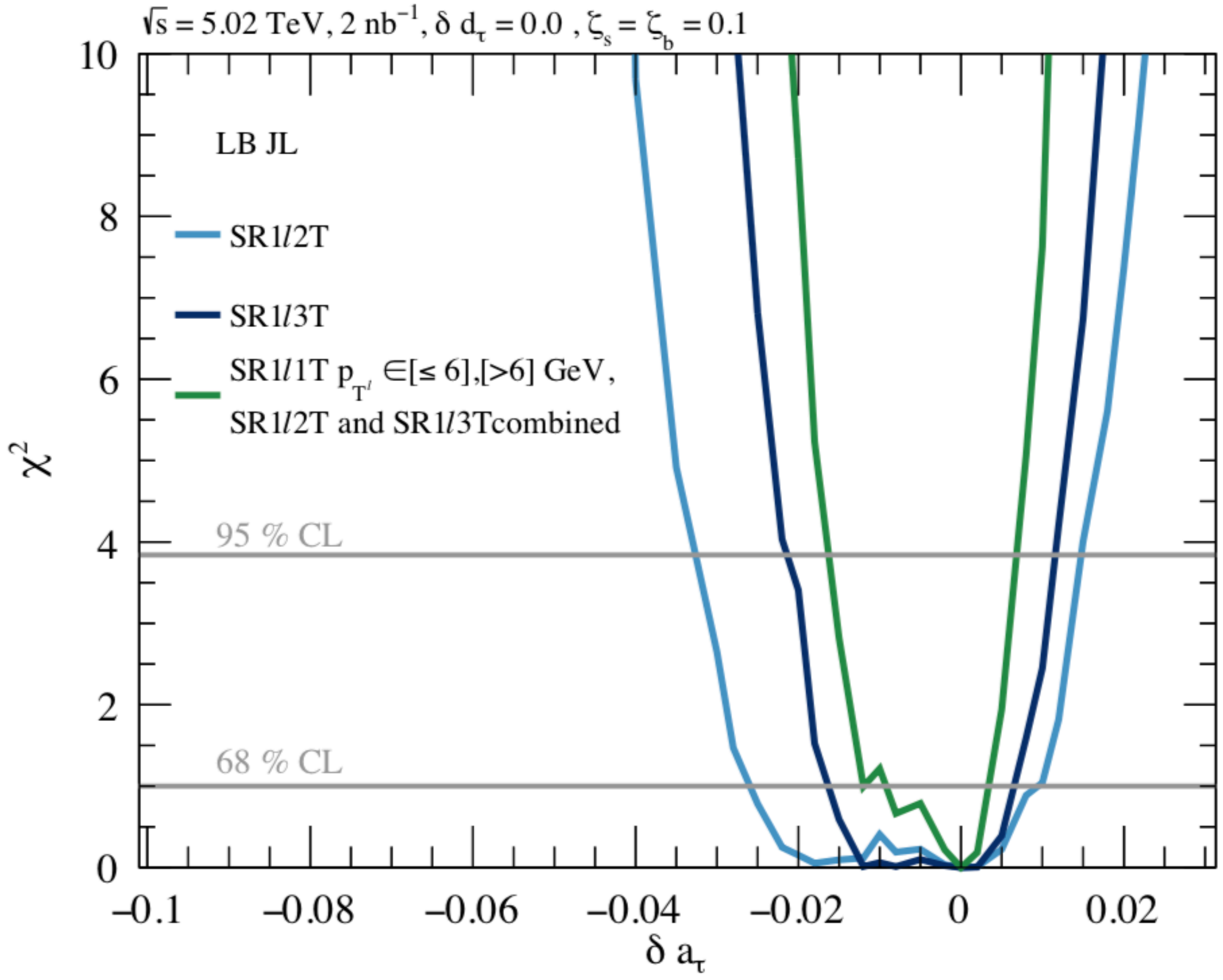
$$\chi^2 = \frac{(s_{\mathrm{SM+BSM}} - s_{\mathrm{SM}})^2}{B + s_{\mathrm{SM+BSM}} + (\zeta_s s_{\mathrm{SM+BSM}})^2 + (\zeta_b B)^2}$$



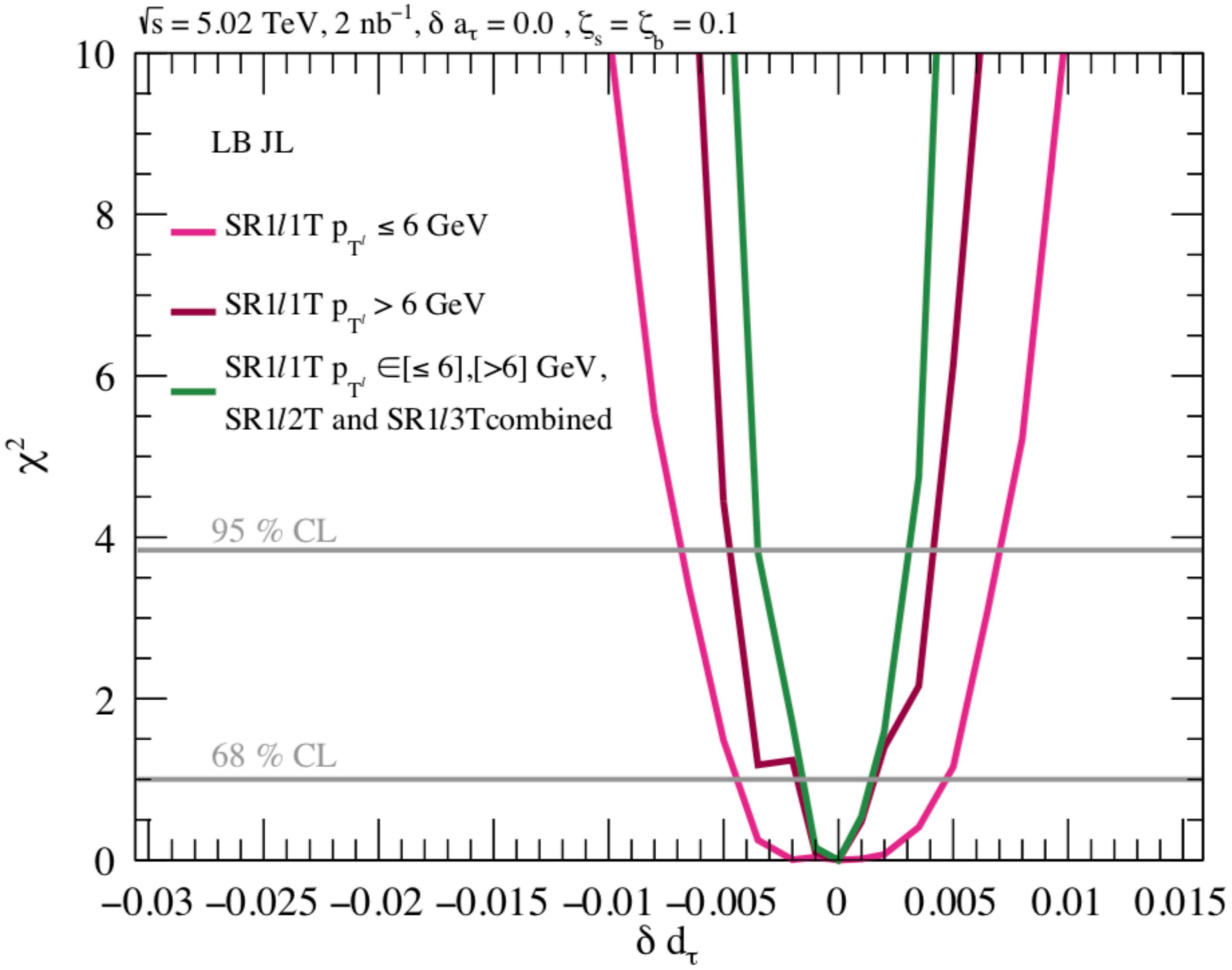
Systematics: $\zeta_s = \zeta_b = 5\,\%, 10\,\%$

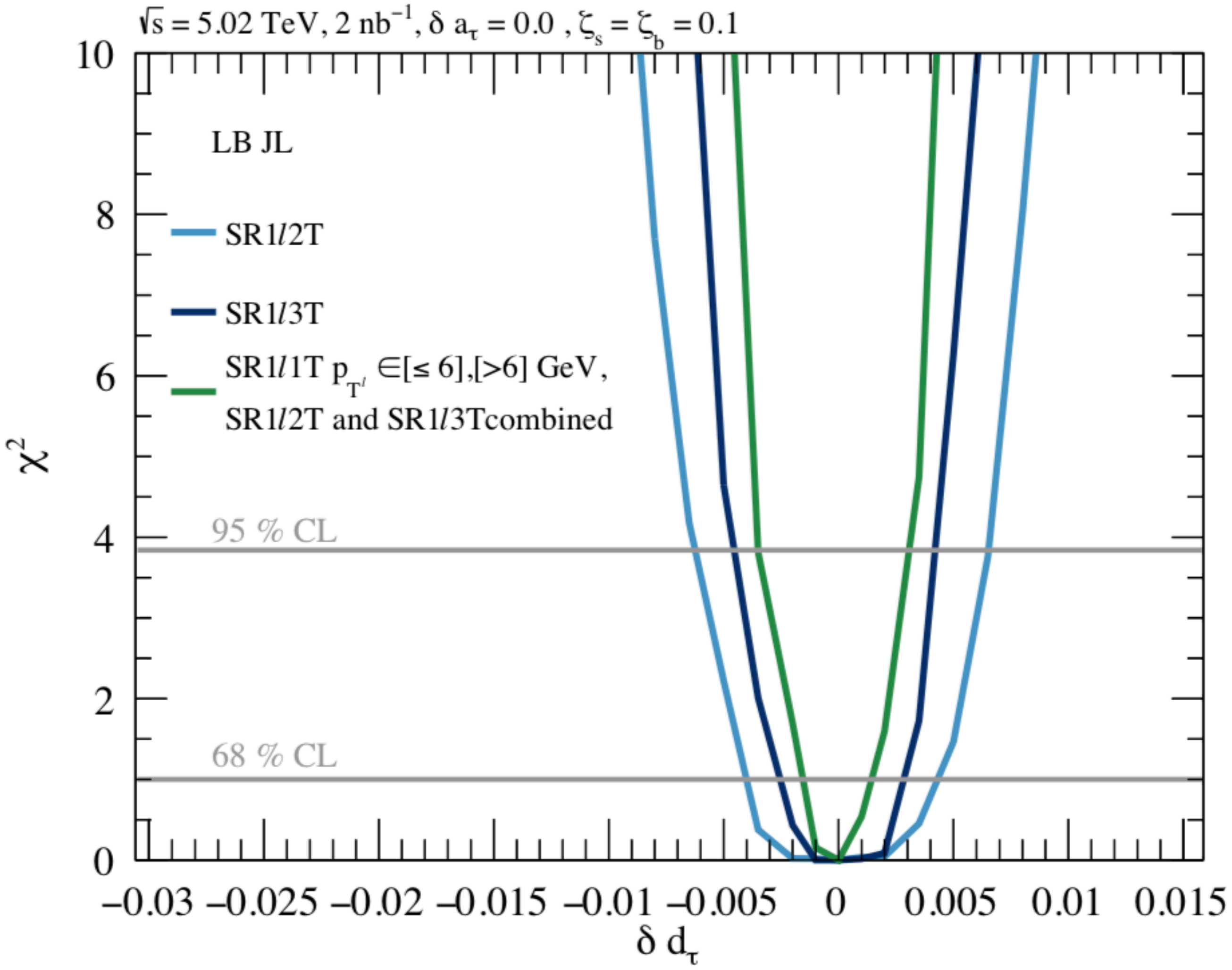
SR Break down: a_τ





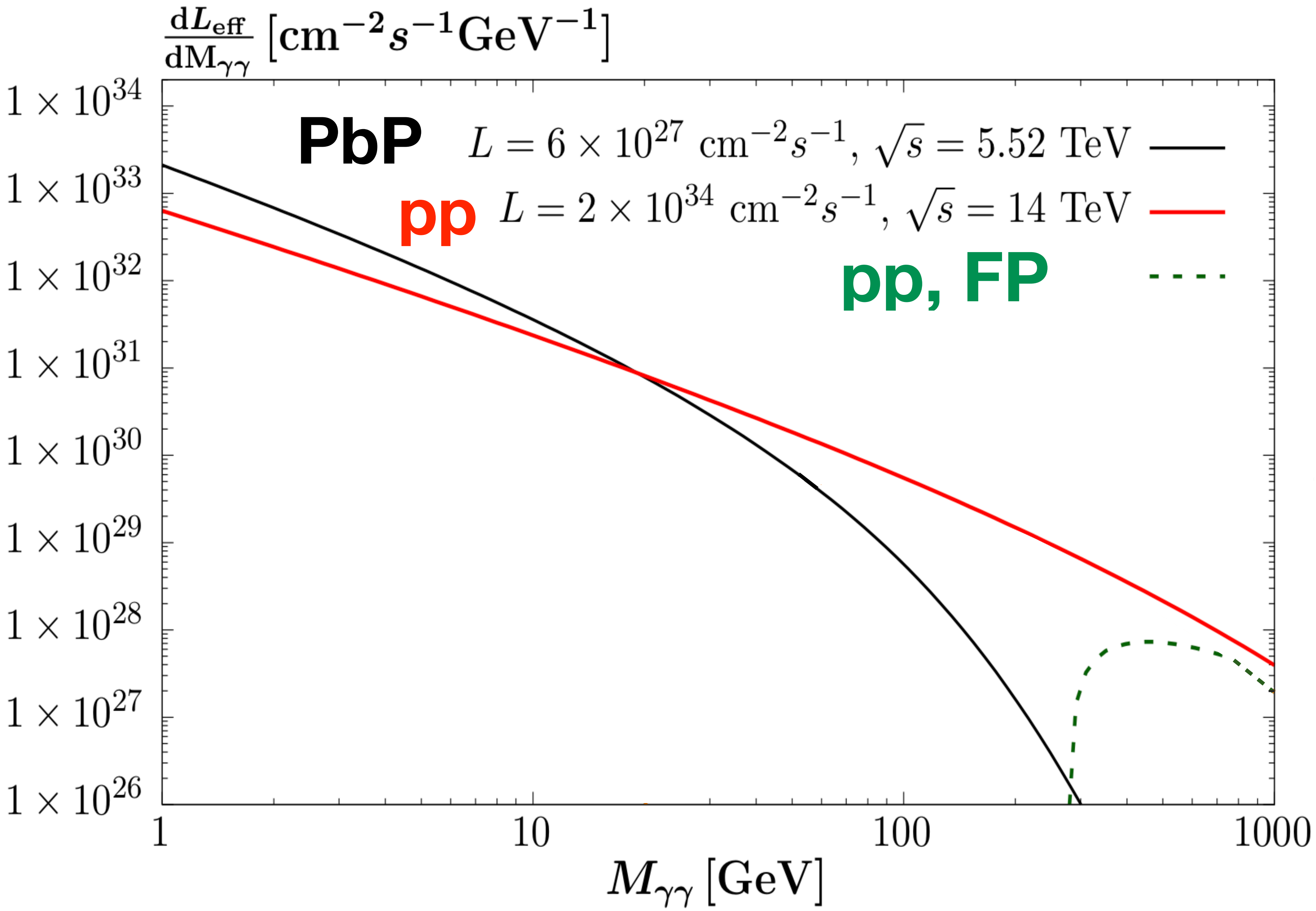
SR Break down: d_{τ}

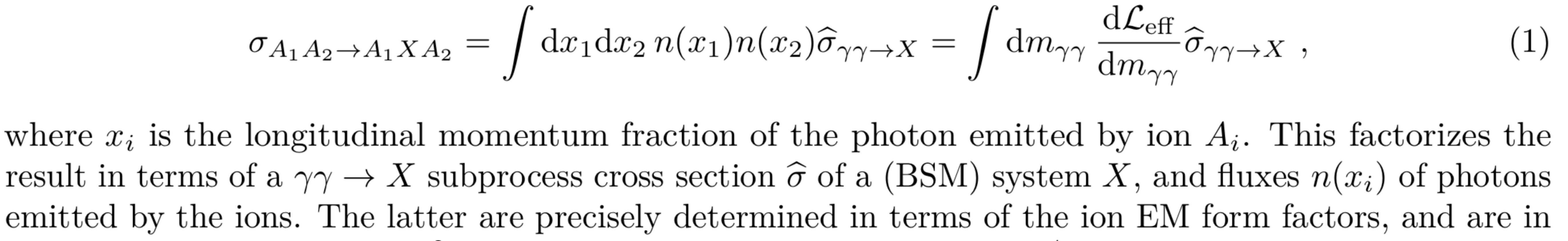




QED @ a range of masses

Bruce et al [1812.07688](https://arxiv.org/abs/1812.07688)

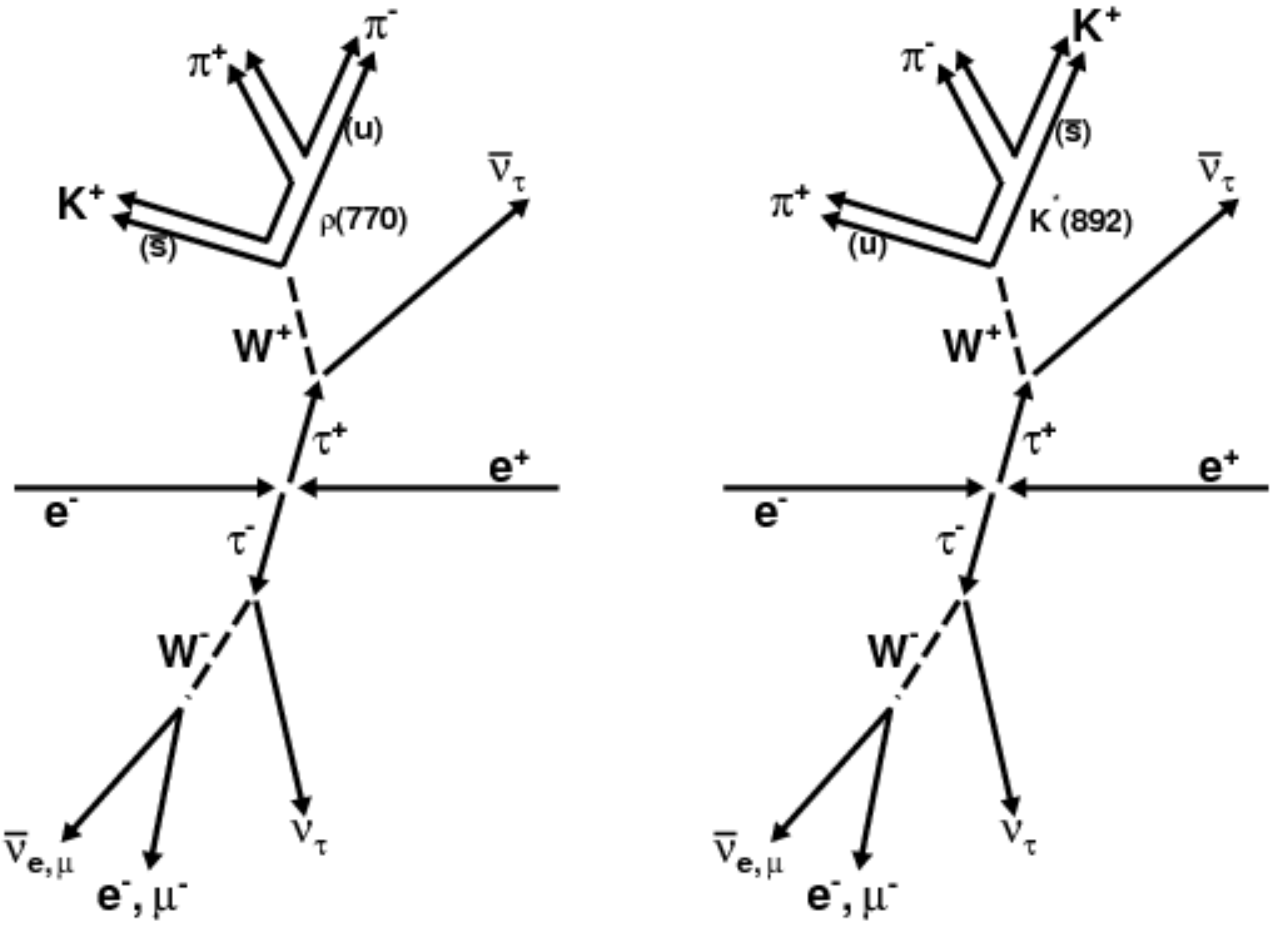




$$\sigma_{A_1A_2\to A_1XA_2} = \int {\rm d}x_1{\rm d}x_2\, n(x_1)n(x_2)\widehat{\sigma}_{\gamma\gamma\to X} = \int {\rm d}m_{\gamma\gamma}\, \frac{{\rm d}\mathcal{L}_{\rm eff}}{{\rm d}m_{\gamma\gamma}}\widehat{\sigma}_{\gamma\gamma\to X}\ , \tag{1}$$

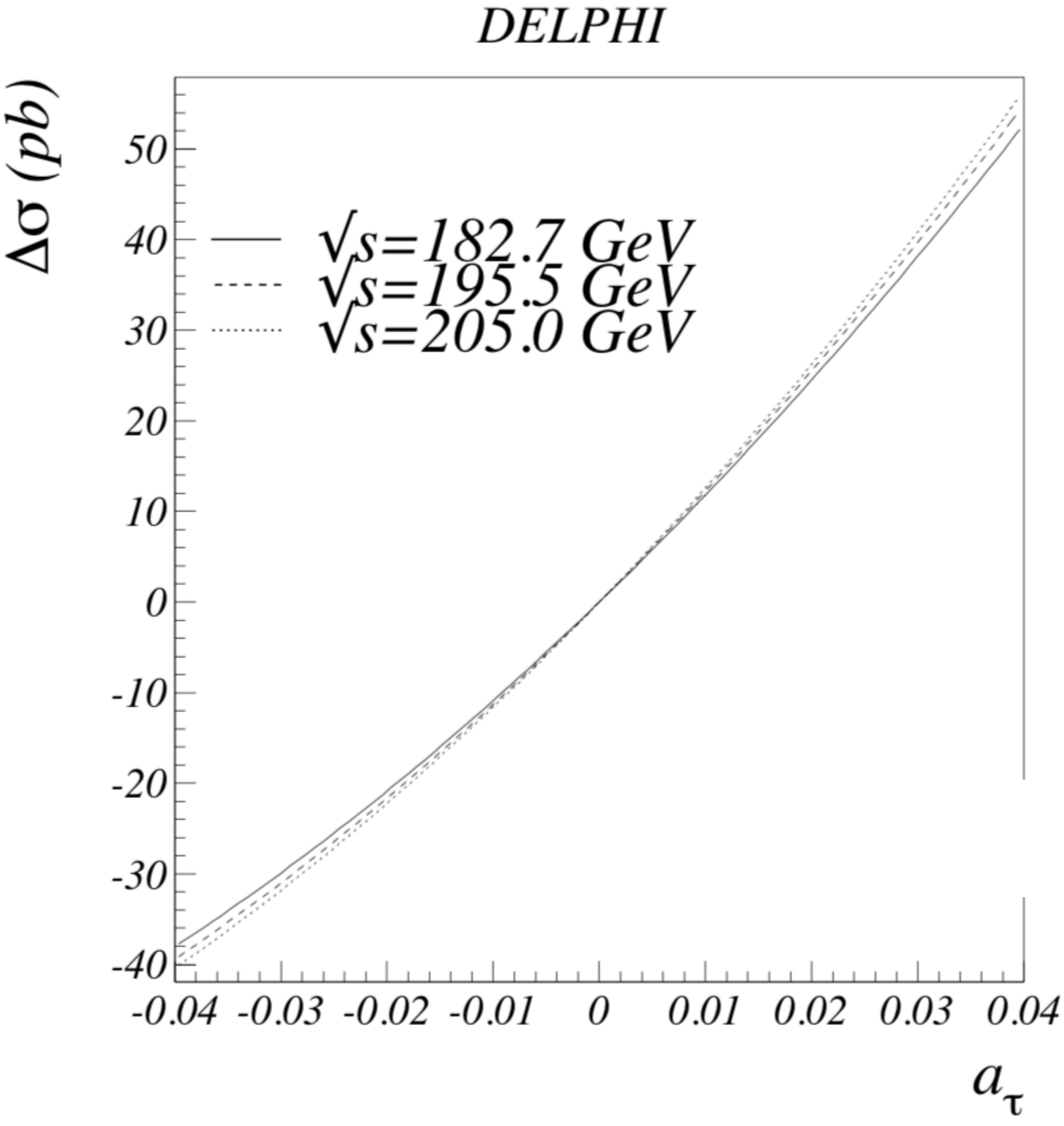
where x_i is the longitudinal momentum fraction of the photon emitted by ion A_i. This factorizes the result in terms of a $\gamma\gamma\to X$ subprocess cross section $\widehat{\sigma}$ of a (BSM) system X, and fluxes $n(x_i)$ of photons emitted by the ions. The latter are precisely determined in terms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

Example tau decays



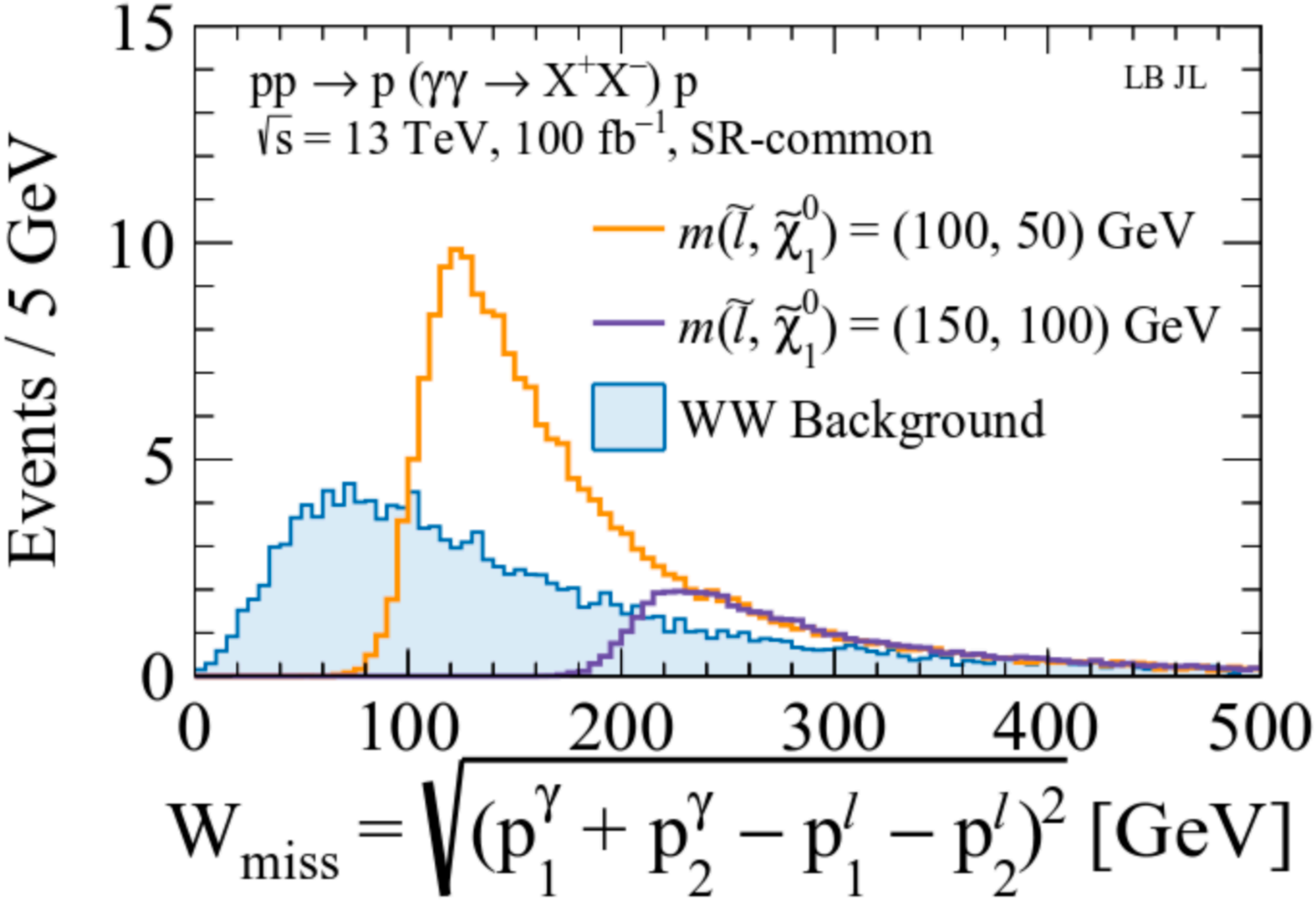
(a) (b)

$\sqrt{s}$ Dependence



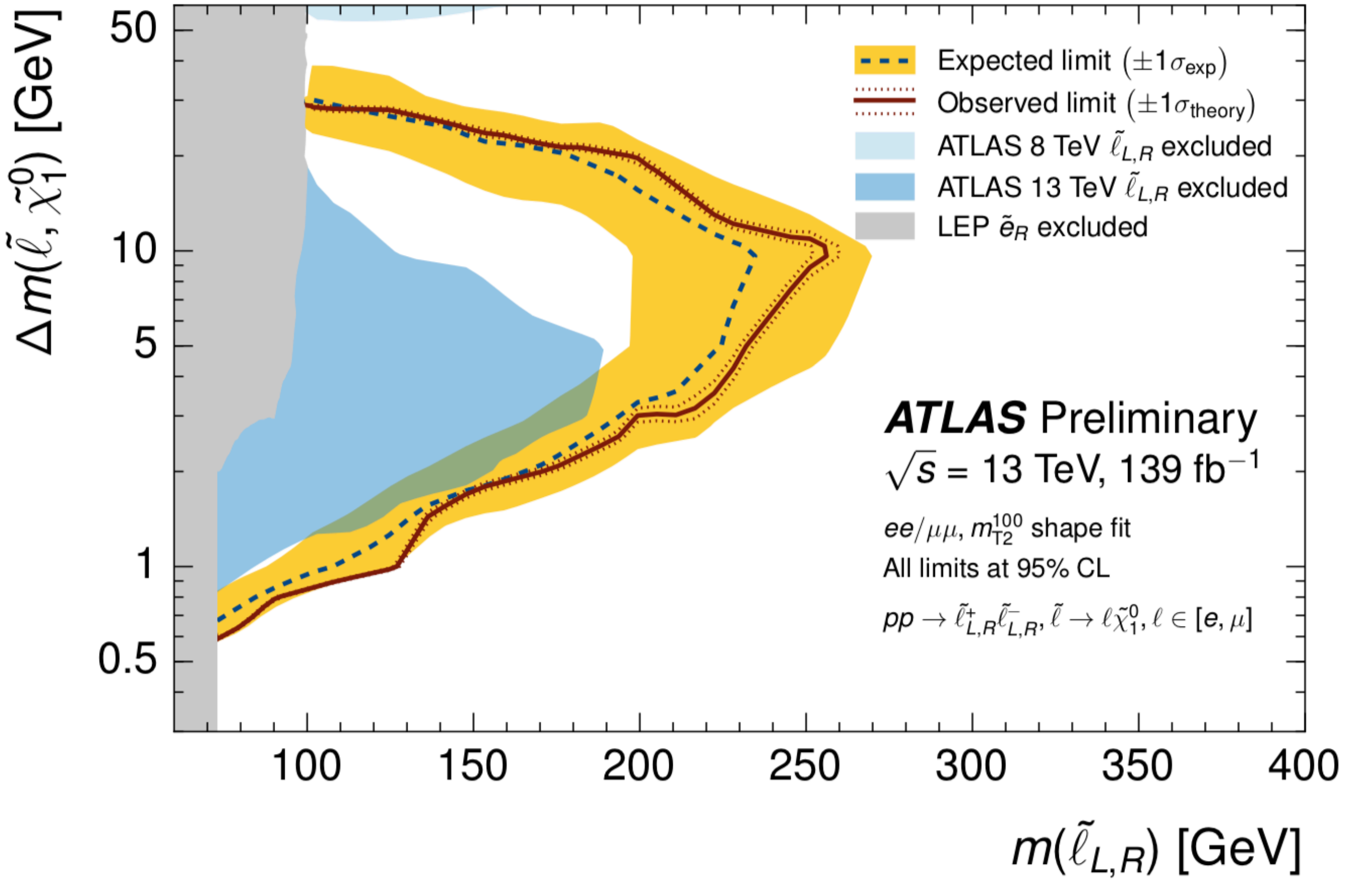
DM Mass Threshold

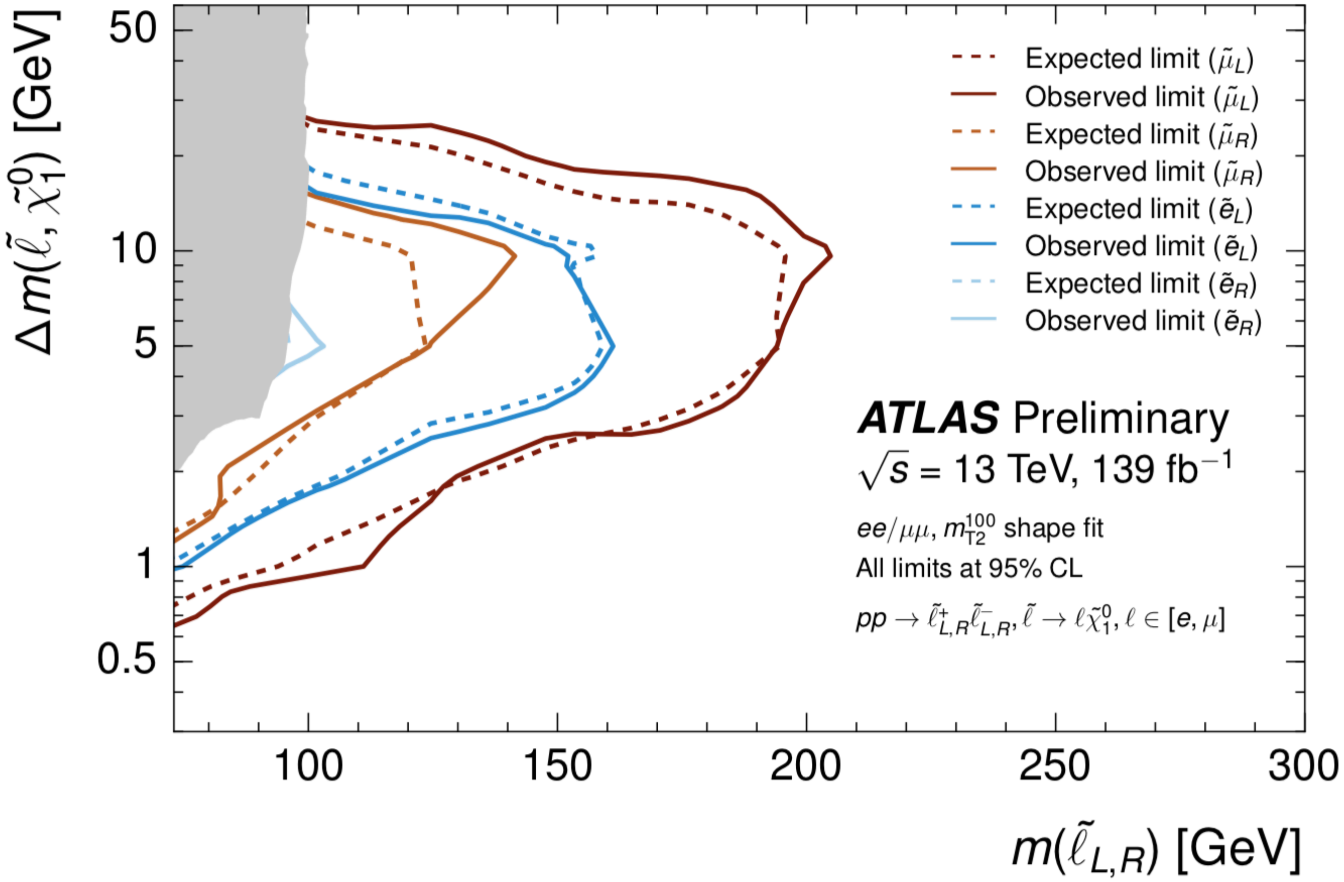
min(W_{miss}) = 2 x m_{DM}



Note: acceptance & efficiencies not applied, only resolution smearing

ATLAS latest - 2L ISR





ATLAS latest
- 2L 0 jets