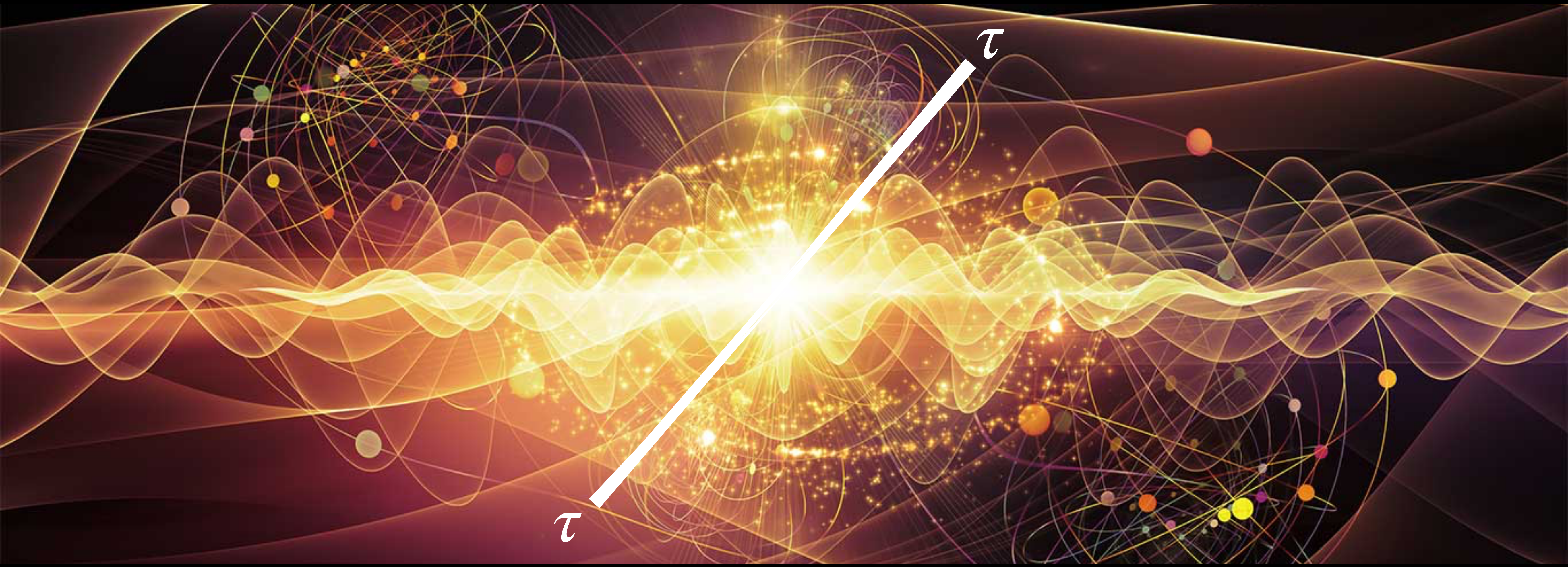
Tau g-2



Lydia Beresford in collaboration with Jesse Liu

APS Hadronic Physics Workshop 16/04/21

CERN

Our proposal

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

Lydia Beresford and Jesse Liu
Phys. Rev. D **102**, 113008 – Published 22 December 2020

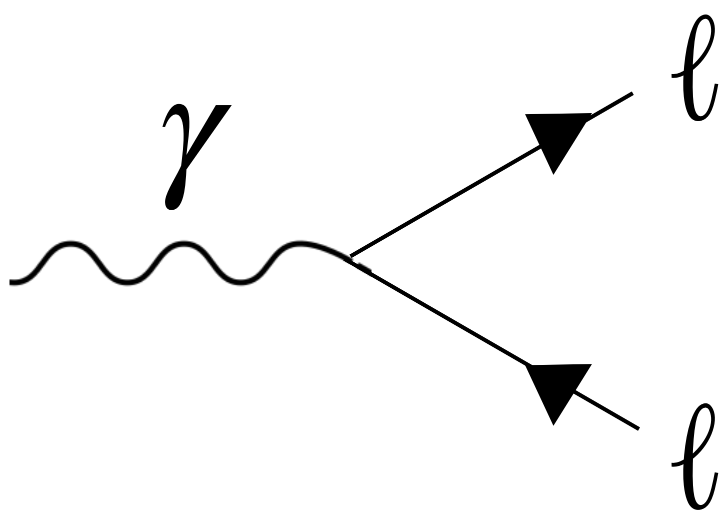
Beresford, Liu
[PhysRevD.102.113008]

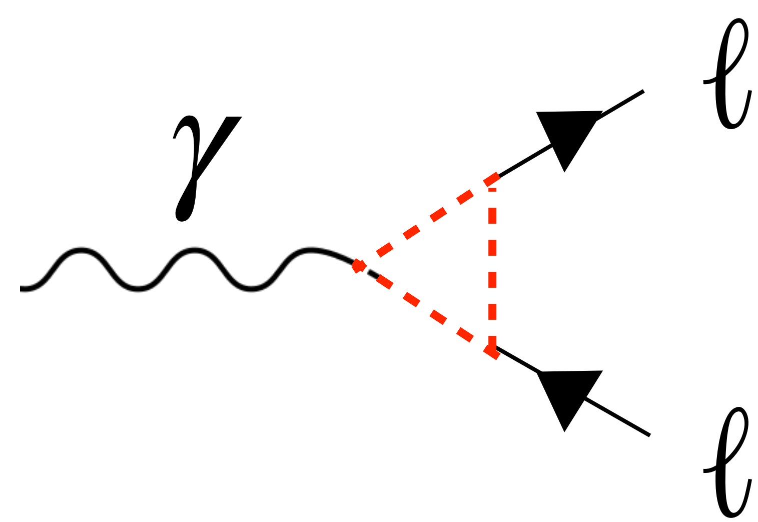
What is g-2?

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

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

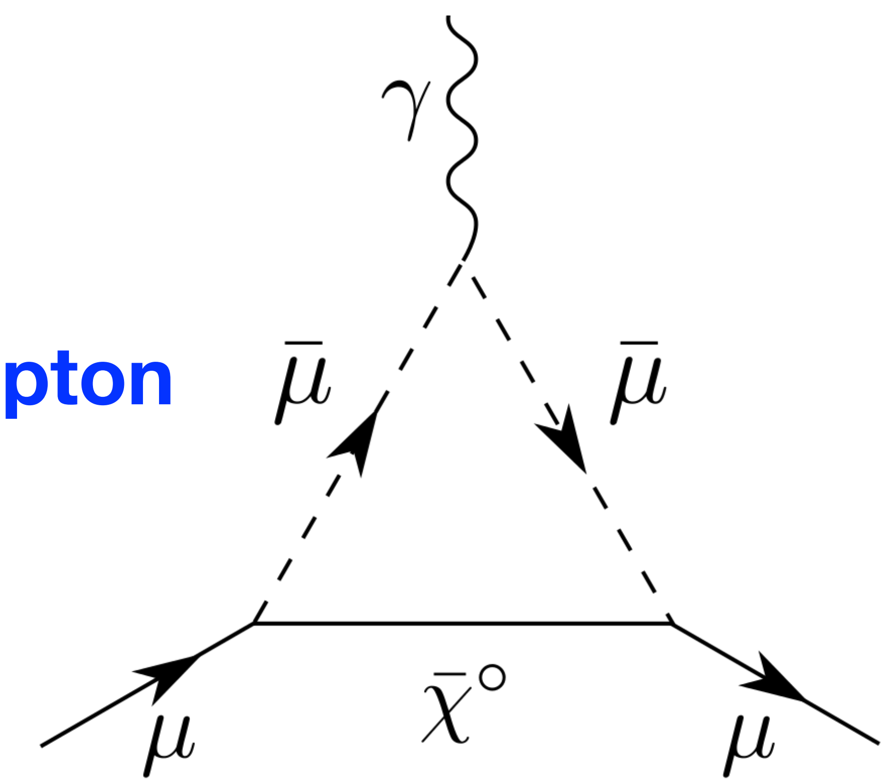
Why is it interesting?

Powerful probe of new physics

New particles could be in the loop

Example: SUSY

Scalar Lepton



Dark Matter

Why is it interesting?

Fundamental test of SM

Electron g-2: 10^{-8} precision **-2.5σ discrepancy**

Muon g-2: 10^{-7} precision **up to $\sim 4.2\sigma$ discrepancy**

What about the tau?

Electron: Odom et at PRL (2006) Bouchendira et al PRL (2011) Aoyama et al PRL (2012) Parker et al Science (2018)

Muon: BNL PRD (2006) J-PARC PTEP (2019) Muon g-2 theory initiative JPhysRept (2020) BMW collab Nature (2021)

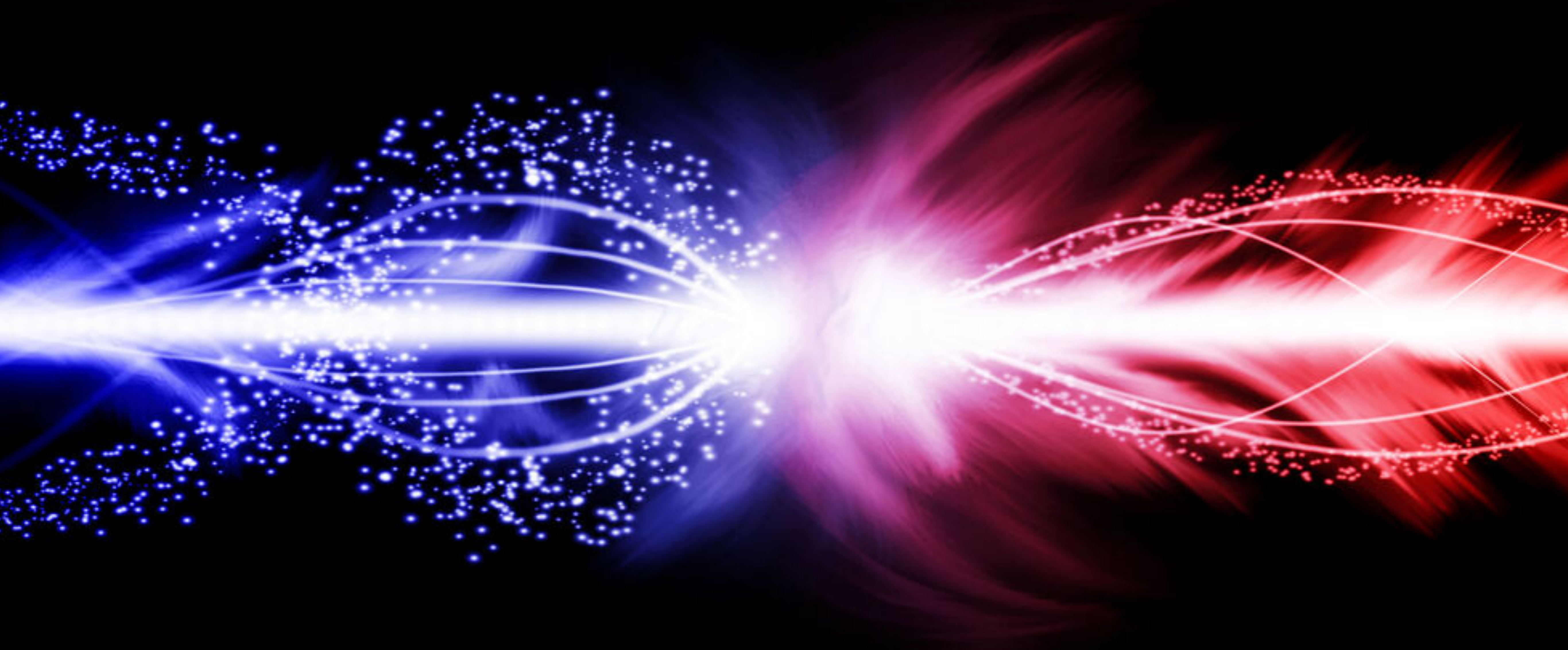
Problem: Lifetime

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

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

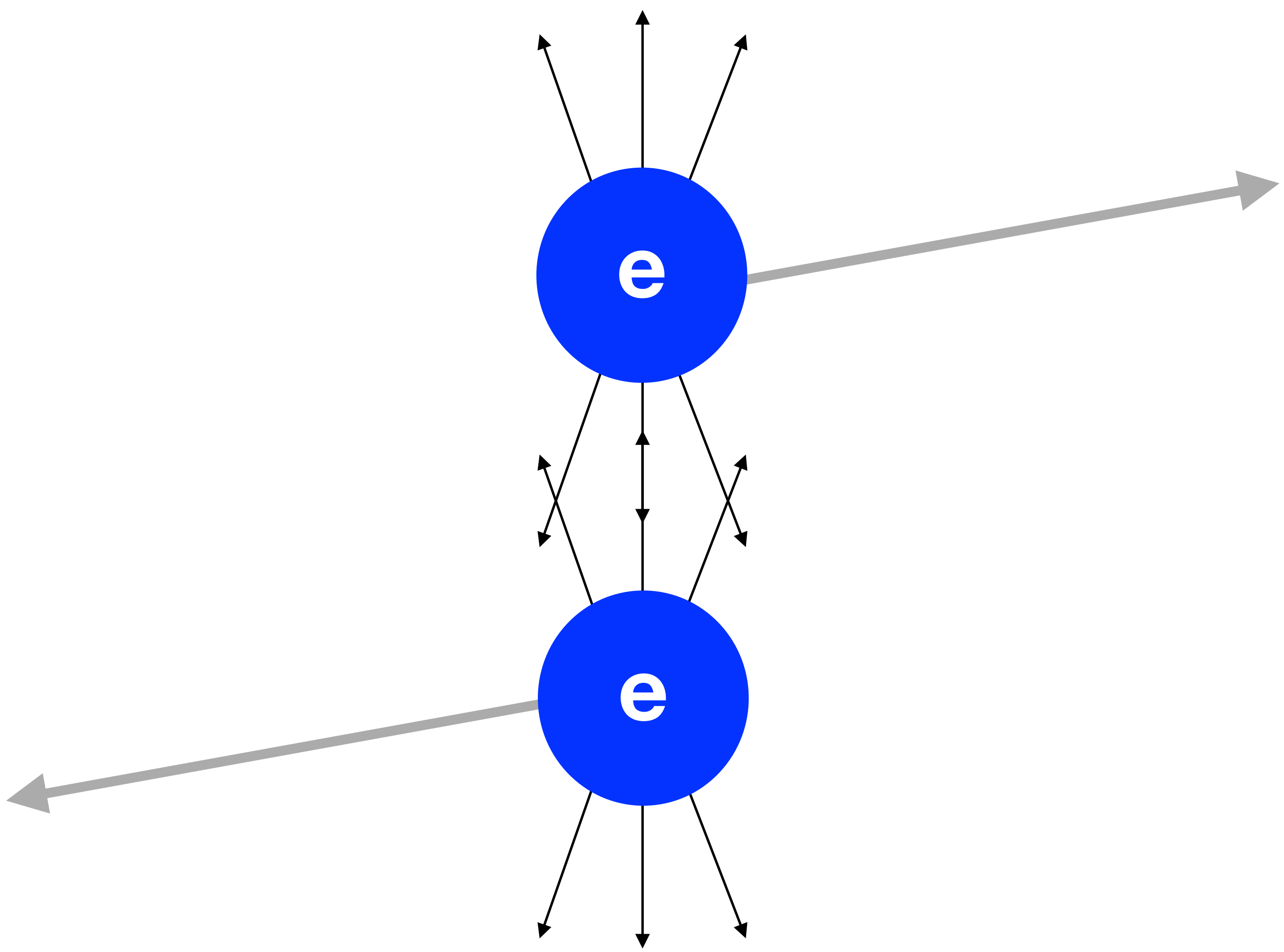
→ **Can't use same technique!**

Solution: Photon collisions



Solution: Photon collisions

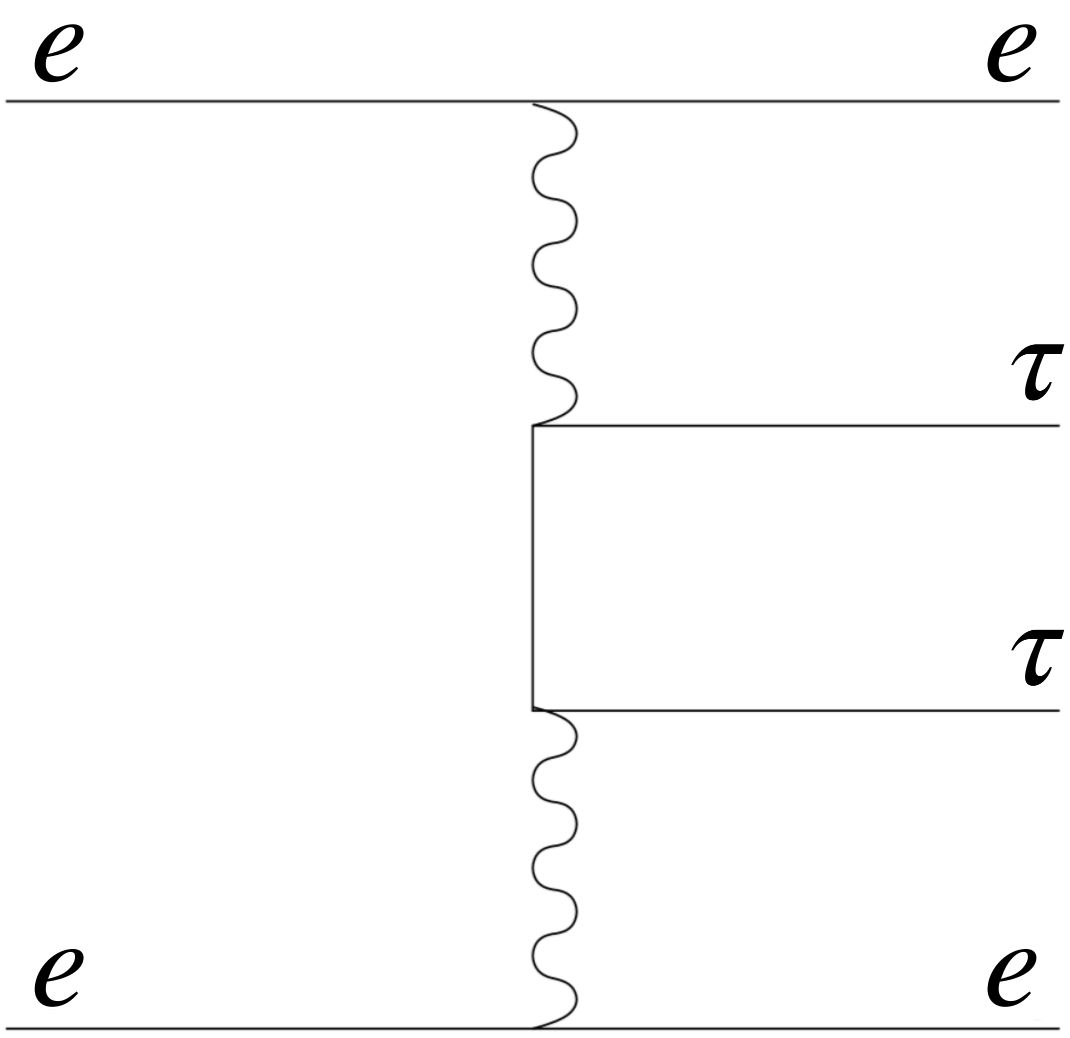
Photons from electromagnetic field surrounding electrons collide to produce new particles



PDG value

Delphi EPJC (2004)

DELPHI 2004, LEP collider



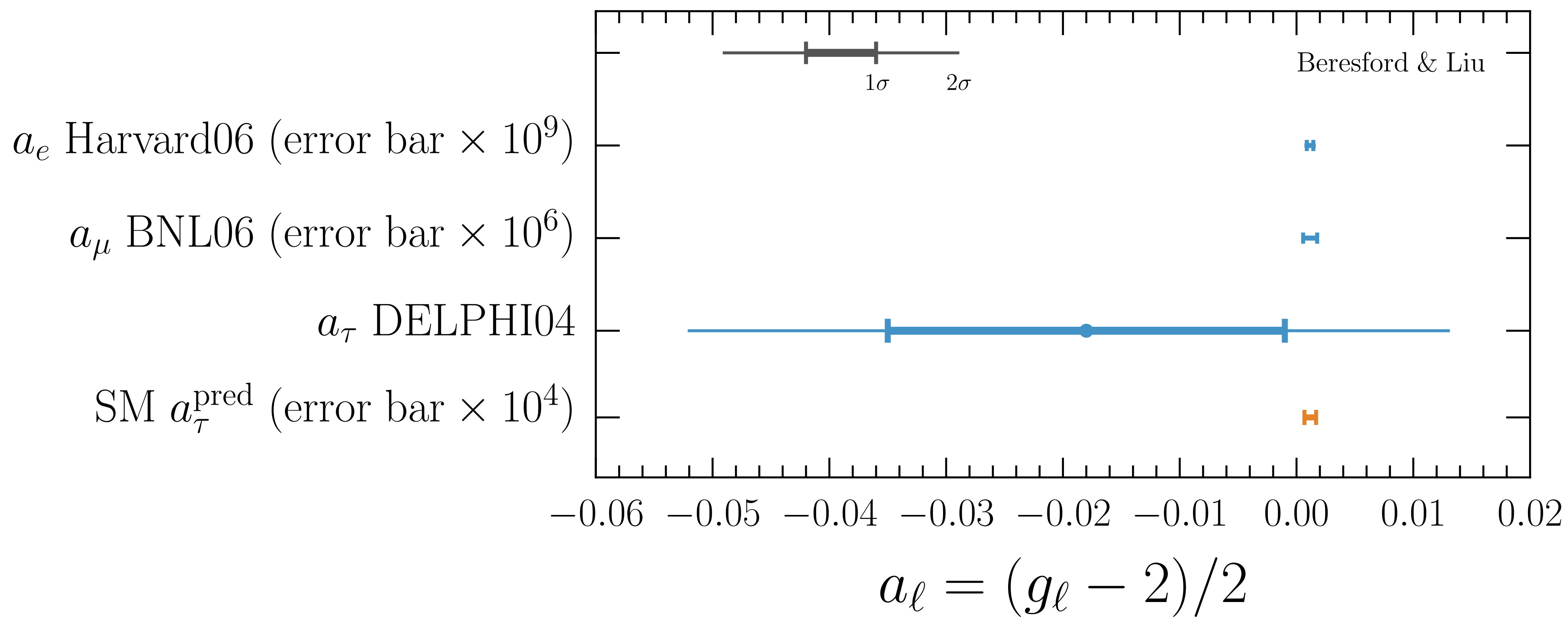
Cross section sensitive to moments

Photo production of tau pairs

Constraints also set by L3 and OPAL

Sibling Rivalry

Discrepancies for electron & muon, what about the tau?



PDG value doesn't test 1-loop QED

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

Delphi EPJC (2004)

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

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

Eidelman, Passera hep-ph/0701260

Can we beat it?

Many interesting proposals for future

Belle II

Eidelman et al JHEP (2016)
Chen, Wu JHEP (2019)

LHeC/Fcc-he

Köksal JPhysG (2019)
Gutiérrez-Rodríguez et al 1903.04135

CLIC/ILC/Fcc-ee

Koksal et al PRD (2018)
Howard et al LHEP (2019)

Bent crystal

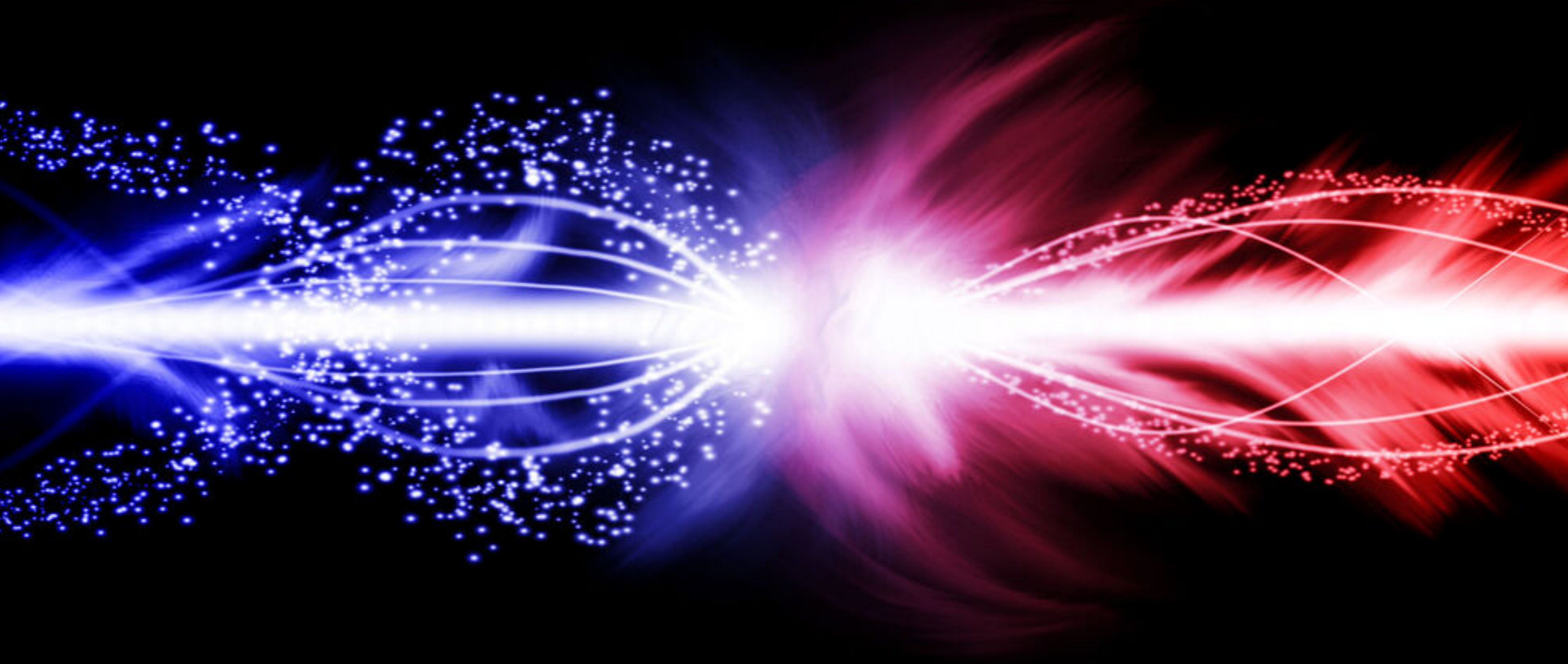
Fomin et al JHEP (2019)
Fu et al PRL (2019)

HL-LHC

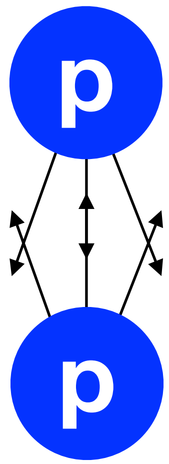
Galon, Rajaraman and Tait
JHEP (2016)

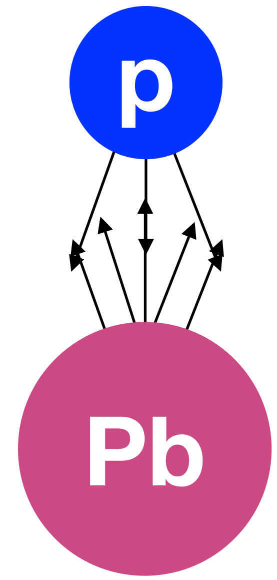
What can we do right now?

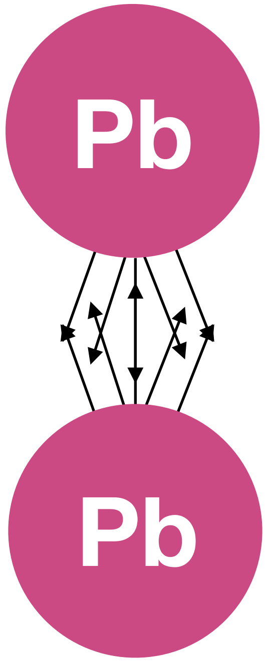
The LHC is also a photon collider



The LHC is also a photon collider







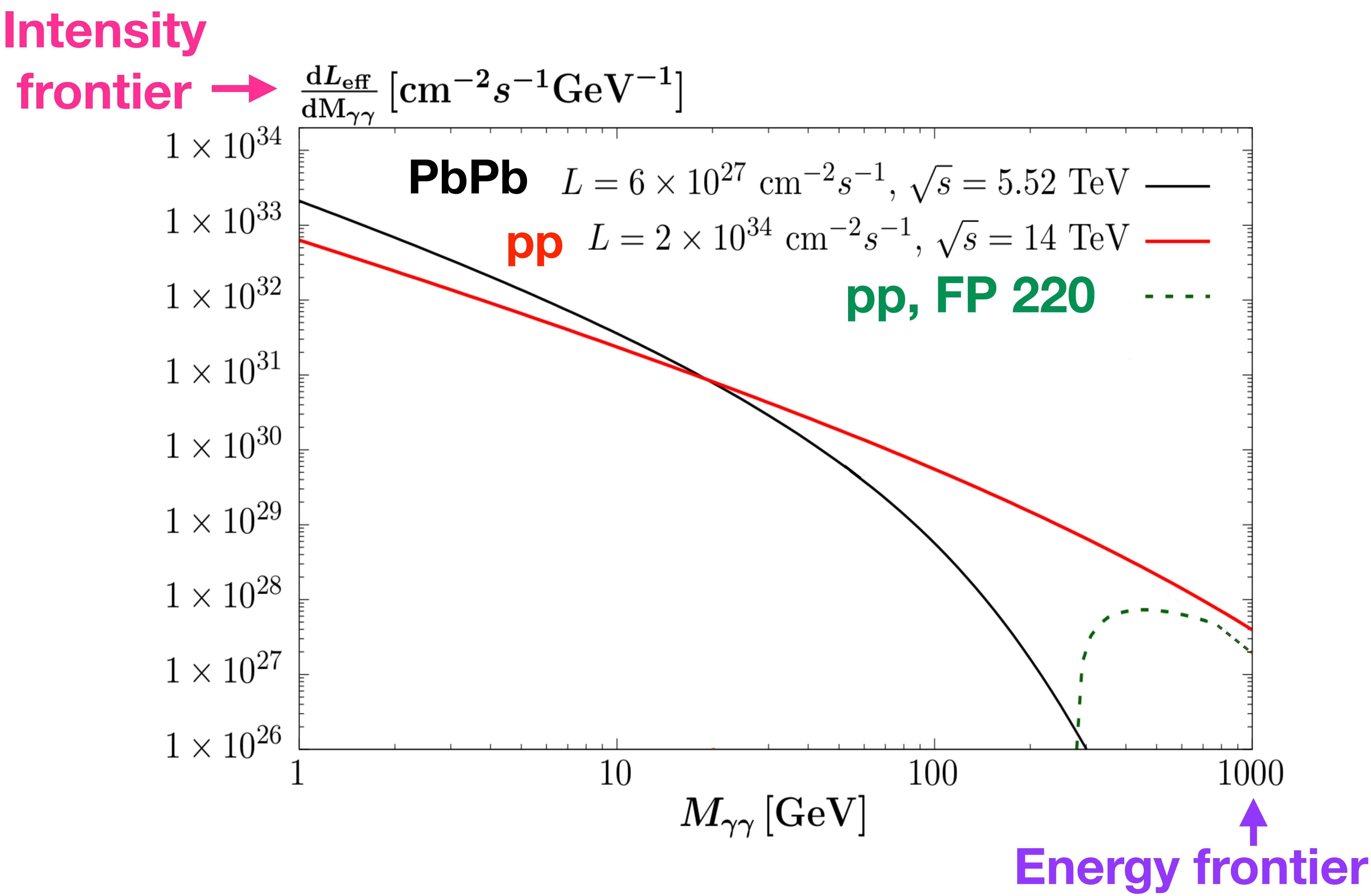
ATLAS

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

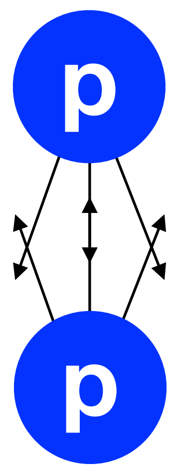
Z = 82 for Pb

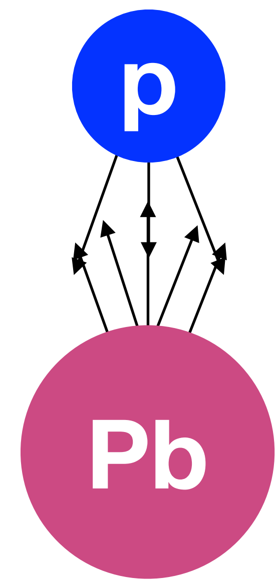
Broadband photon collider

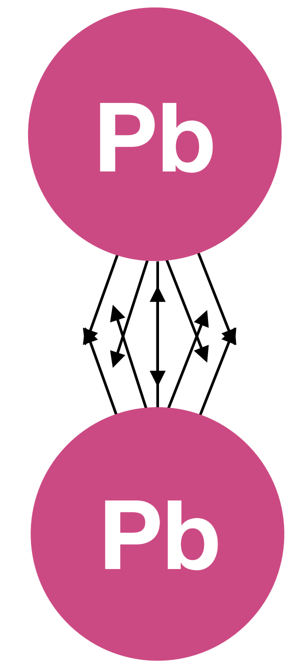
Bruce et al [JPG (2020)]



The LHC is also a photon collider







ATLAS			
$\sqrt{s}$	13 TeV	8.16 TeV	**5.02 TeV**
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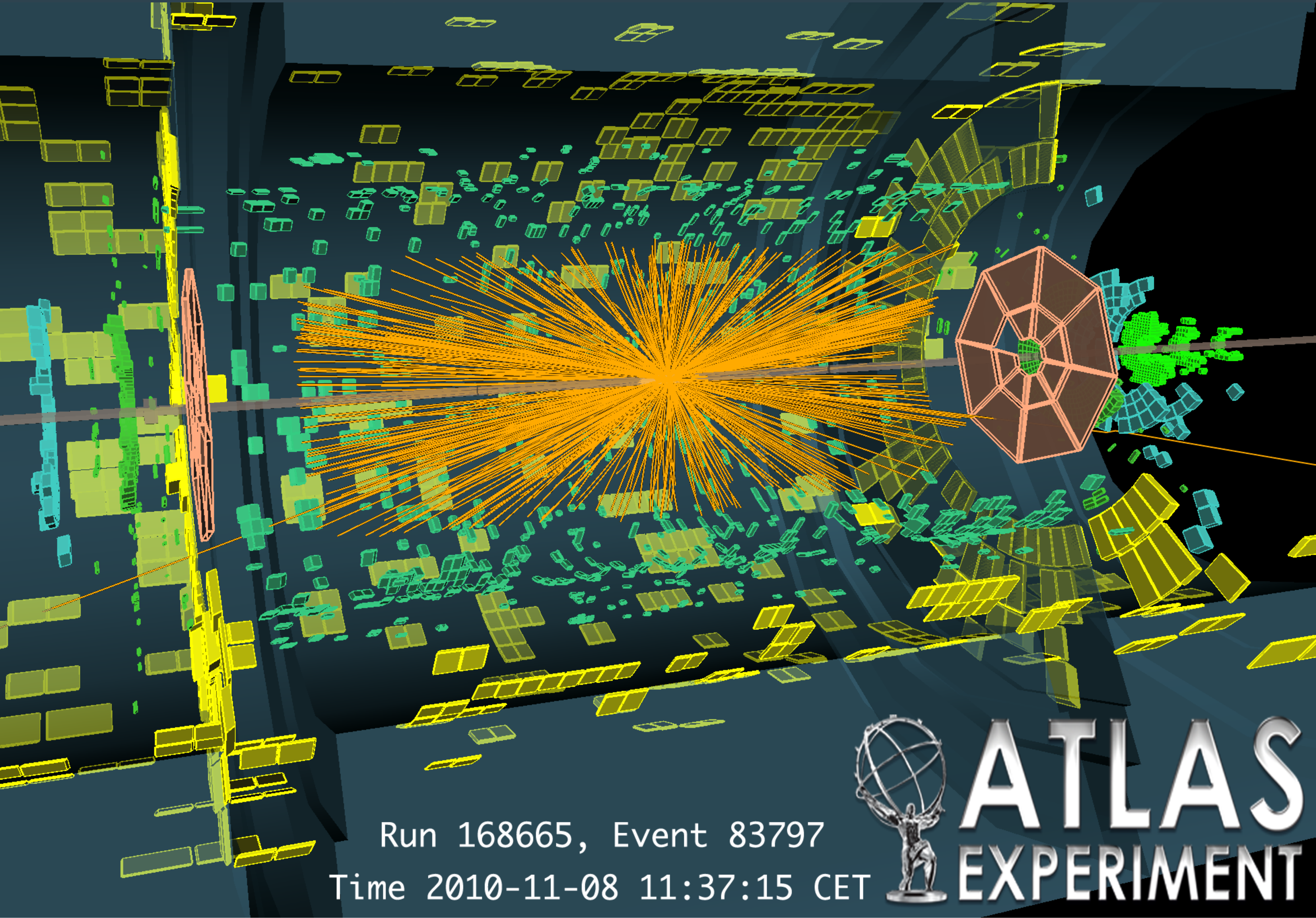
σ	-	$\propto Z^2$	**$\propto Z^4$**

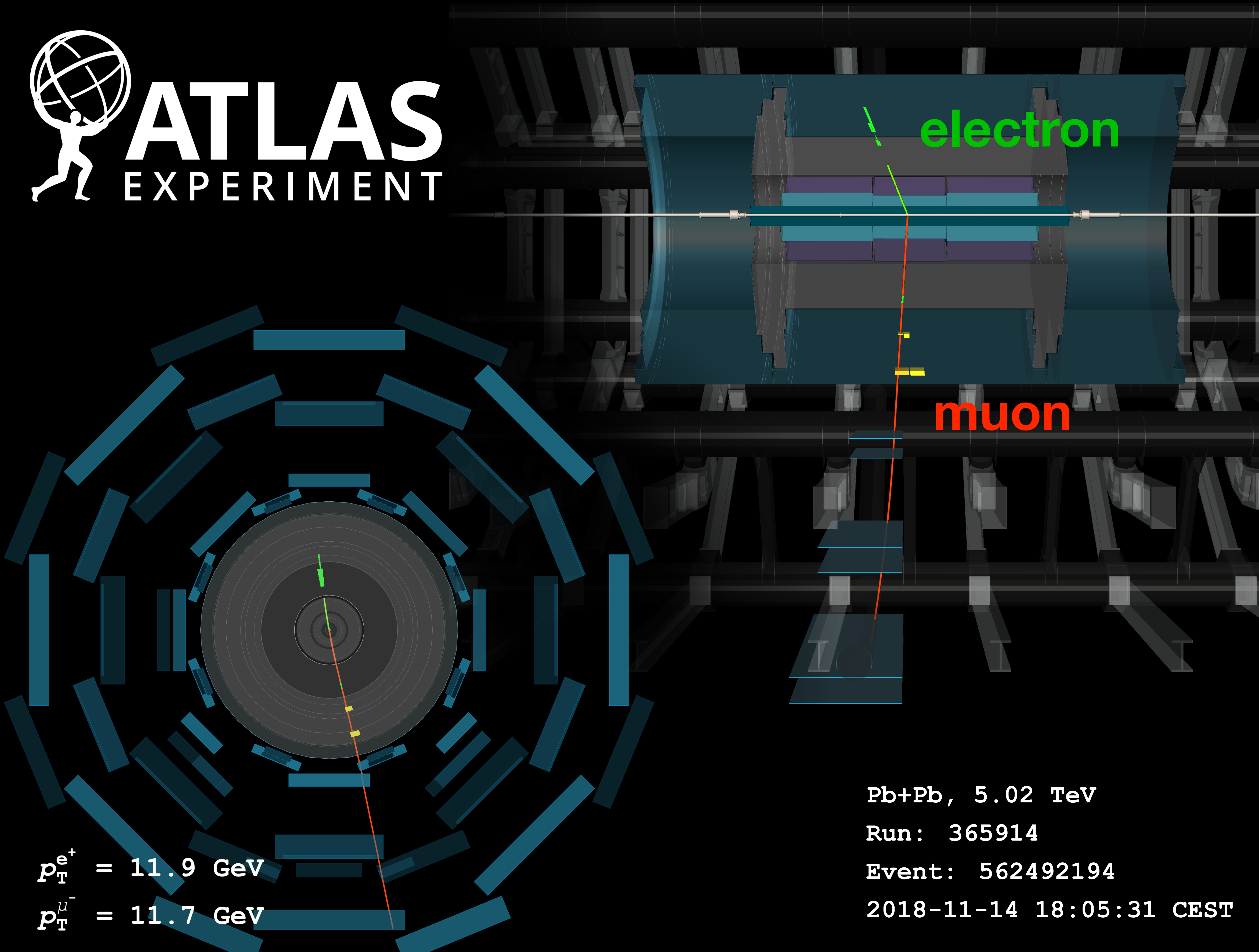
Z = 82 for Pb

Head-on PbPb collision



Ultra Peripheral PbPb collision

ATLAS EXPERIMENT



$p_T^{e^+}$ = 11.9 GeV

$p_T^{\mu^-}$ = 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 PRD (2020)
Dyndal et al PLB (2020)

LHC PbPb

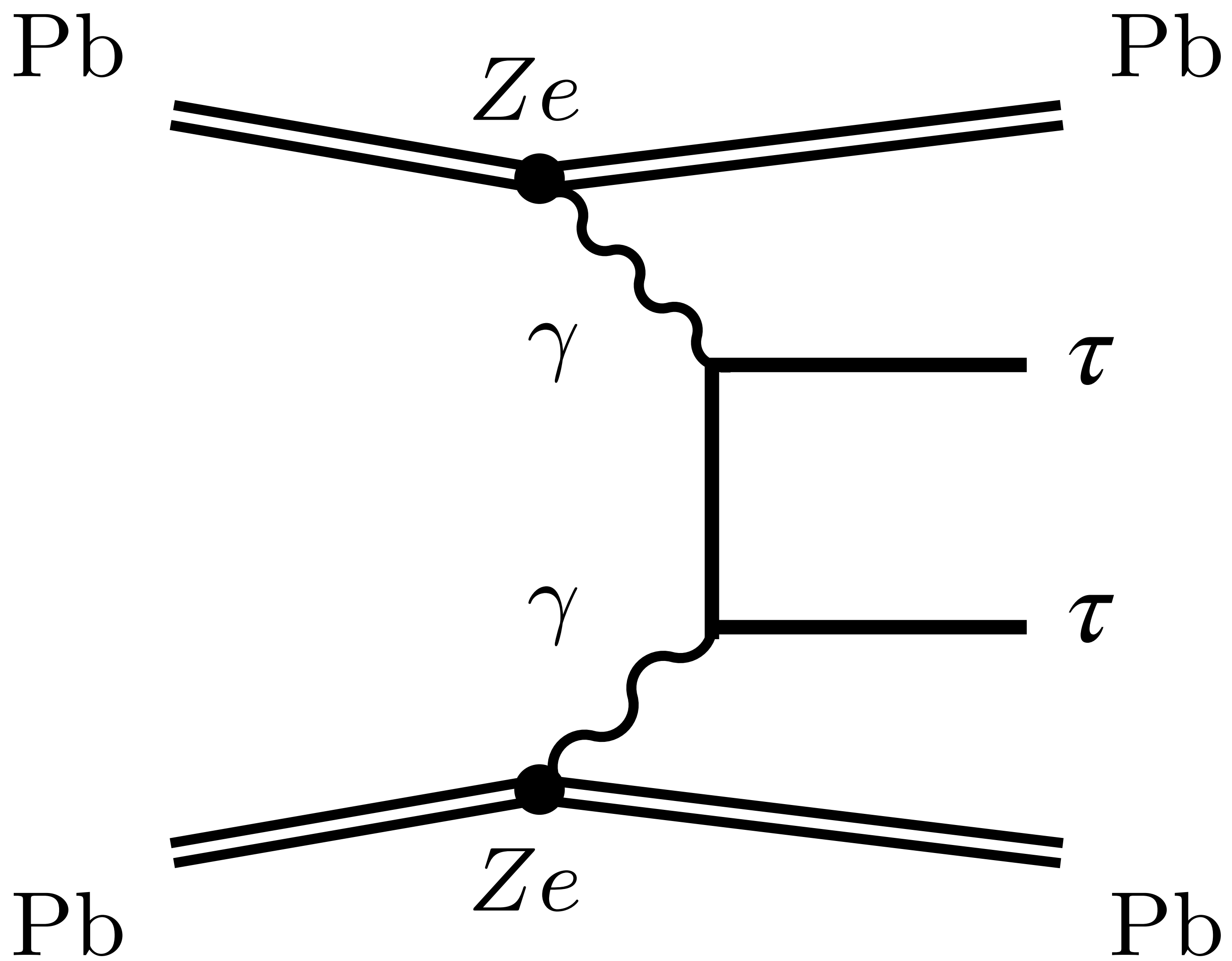


Photo production of tau pairs

Not yet observed @ LHC

Tau decays

1 prong

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

+ neutral π's

Leptonic

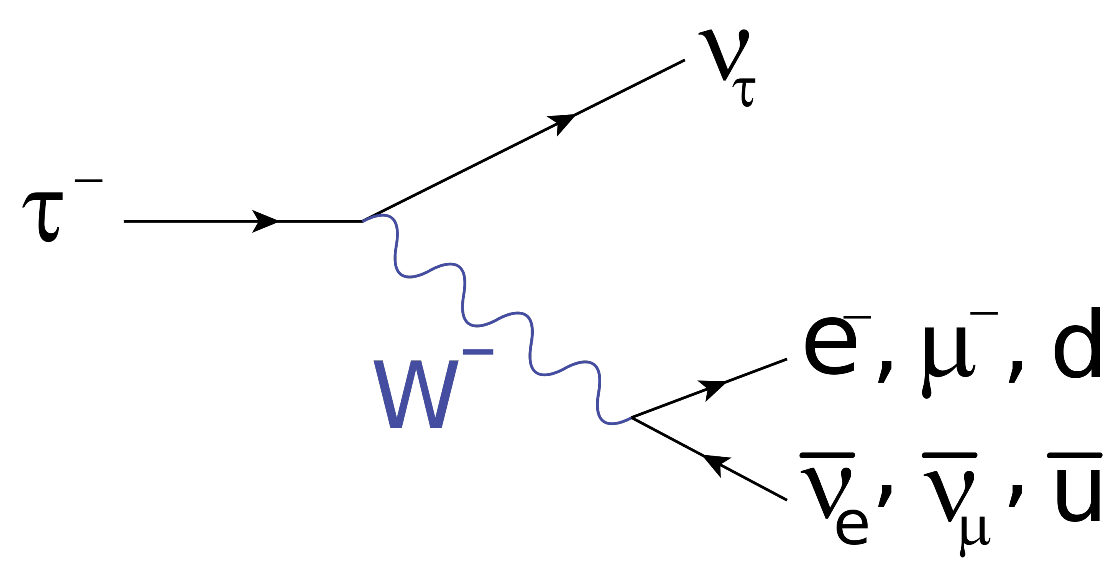
$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$

3 prong

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

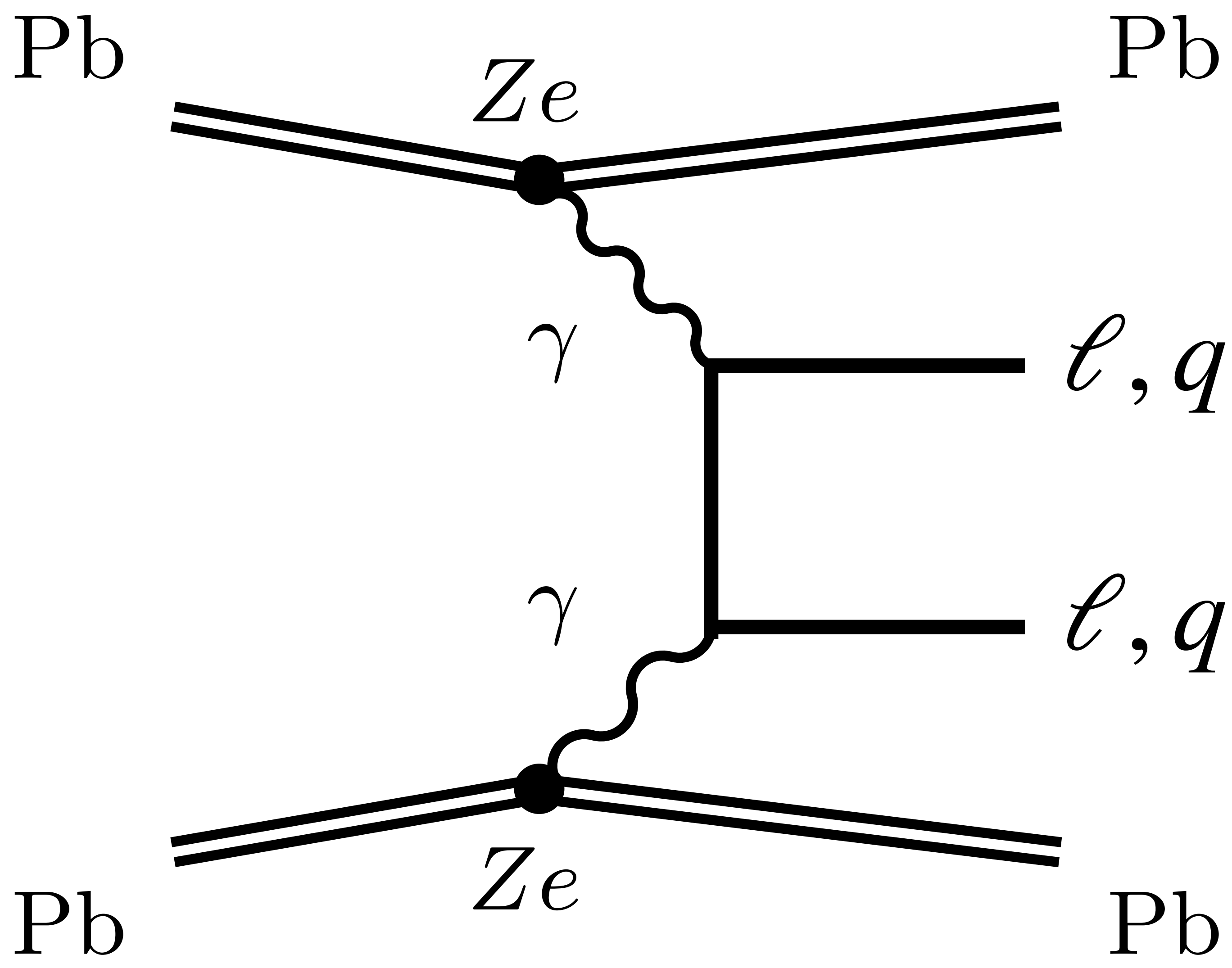
+ neutral π's

Tau is only lepton that can decay into hadrons



Backgrounds

Generated:



Signal Regions

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

Signal Regions (SRs)

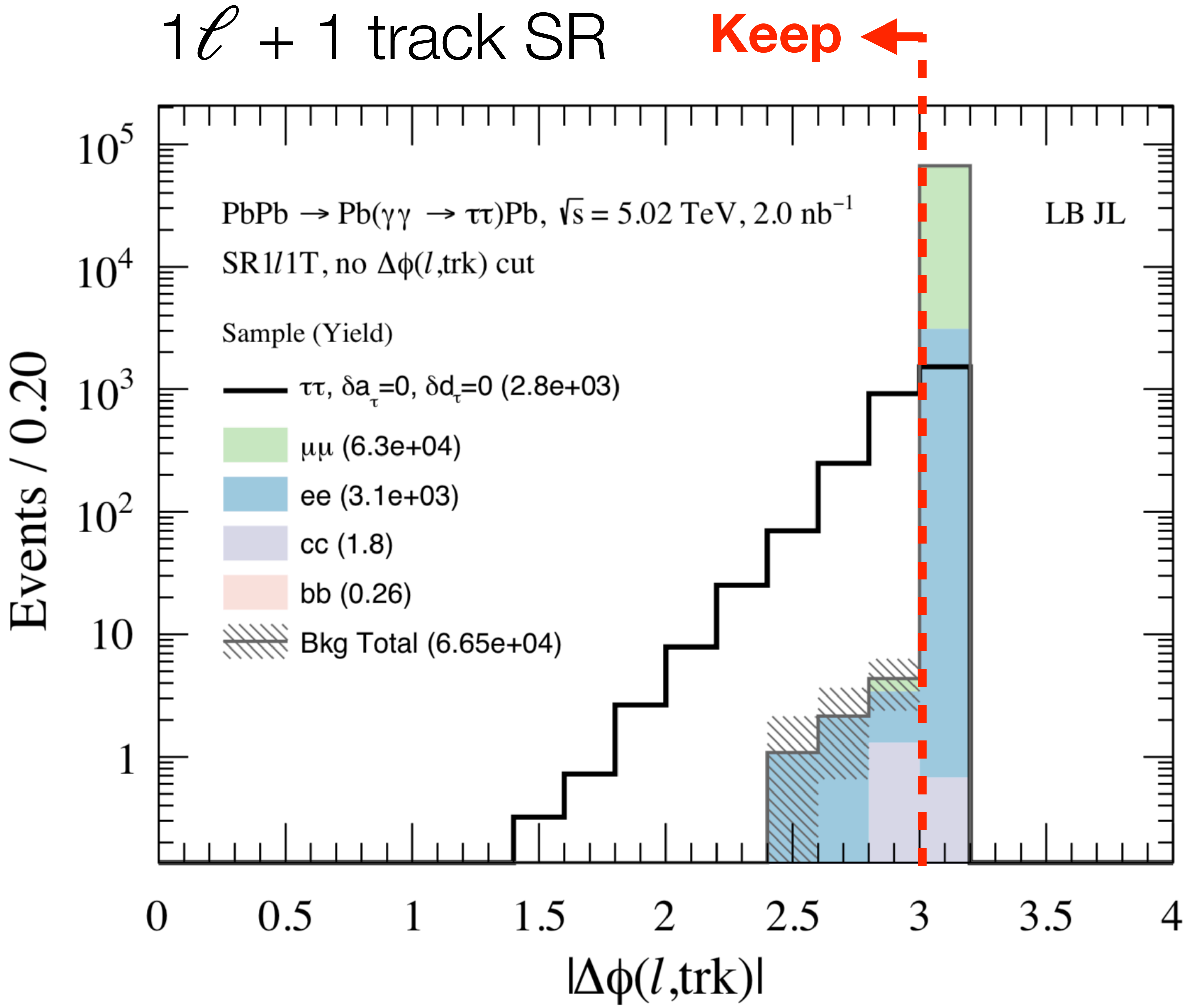
1ℓ + 1 track

1ℓ + 2 track

1ℓ + 3 track

Background mitigation

1ℓ + 1 track SR

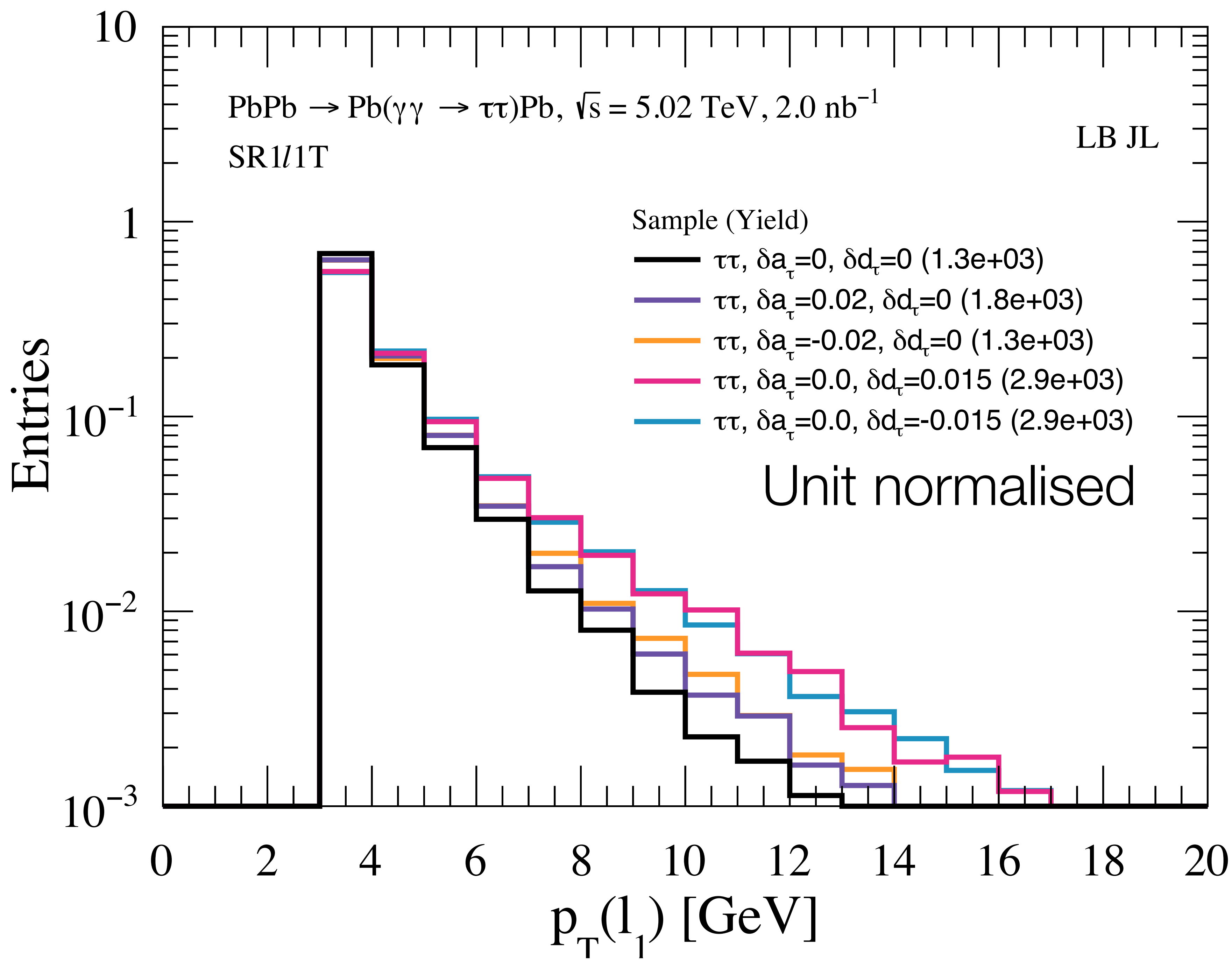


And veto J/ψ & Υ masses

Setting constraints

Also sensitive to τ EDM

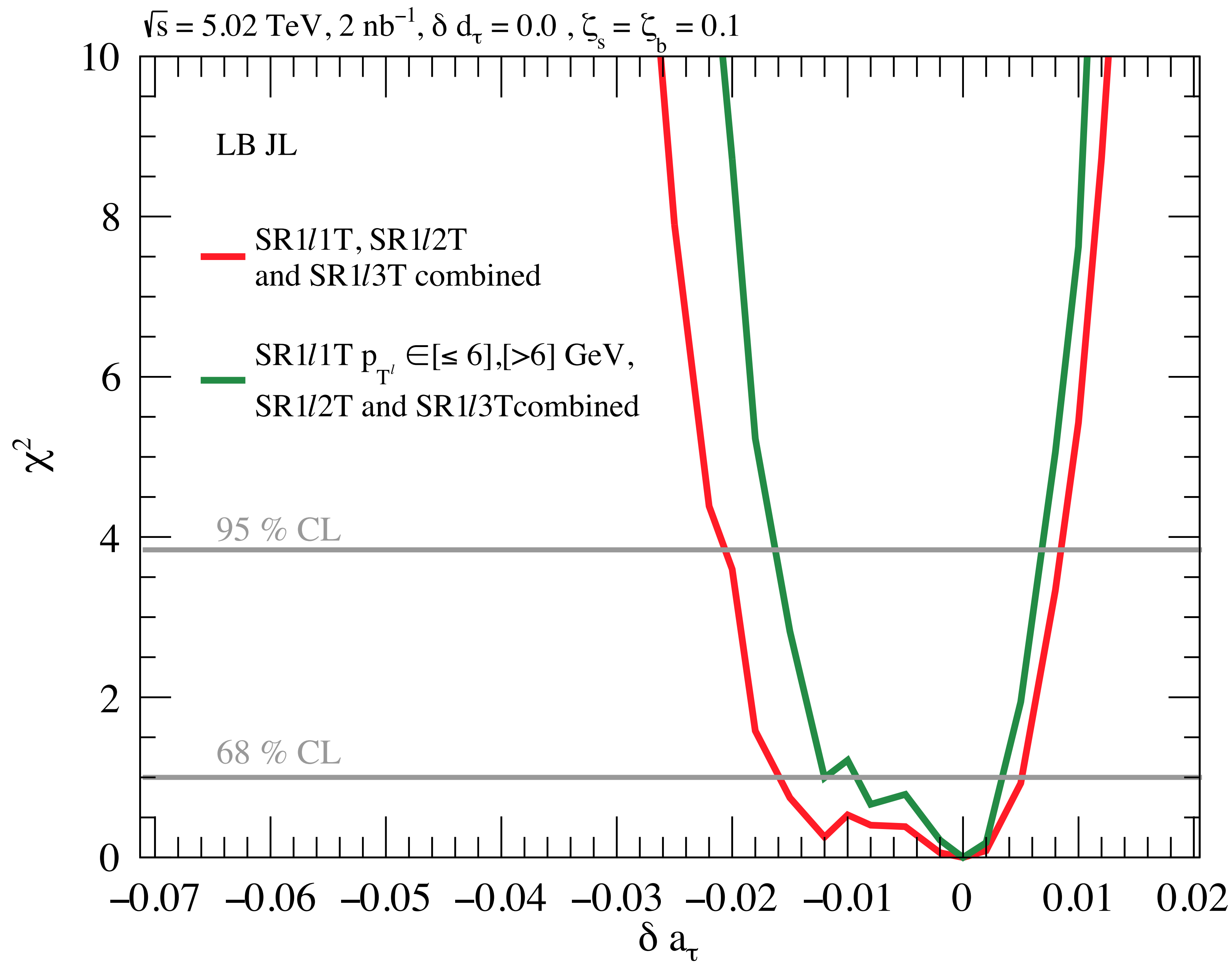
SM effective field theory for modified moments (& SM signal)



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

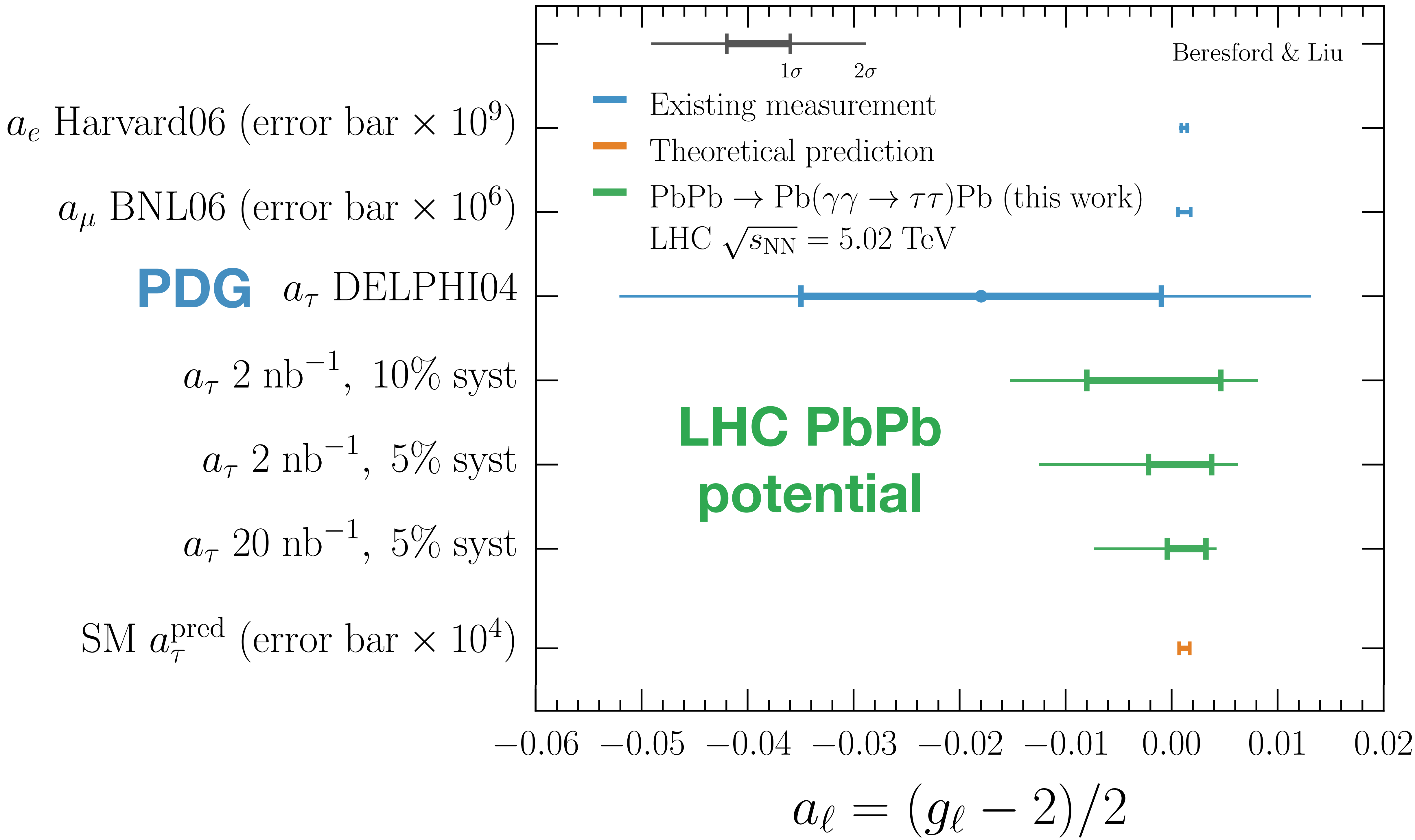
$\Sigma\chi^2$ for all SRs (orthogonal)

Shape analysis strengthens constraints :)

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

Putting it all together: a_τ

Ratio can decrease systematics $\frac{\sigma_{\gamma\gamma\to\tau\tau}}{\sigma_{\gamma\gamma\to ee,\mu\mu}}$

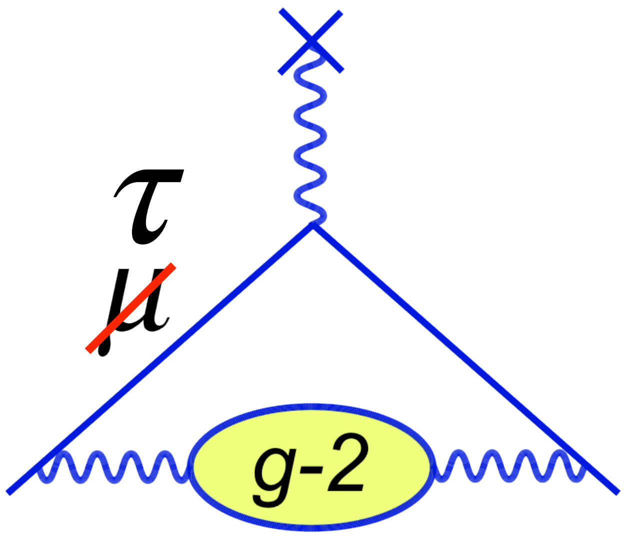


Surpass PDG … or discover tension!

Summary

Tau g-2 interesting & important

But barely constrained



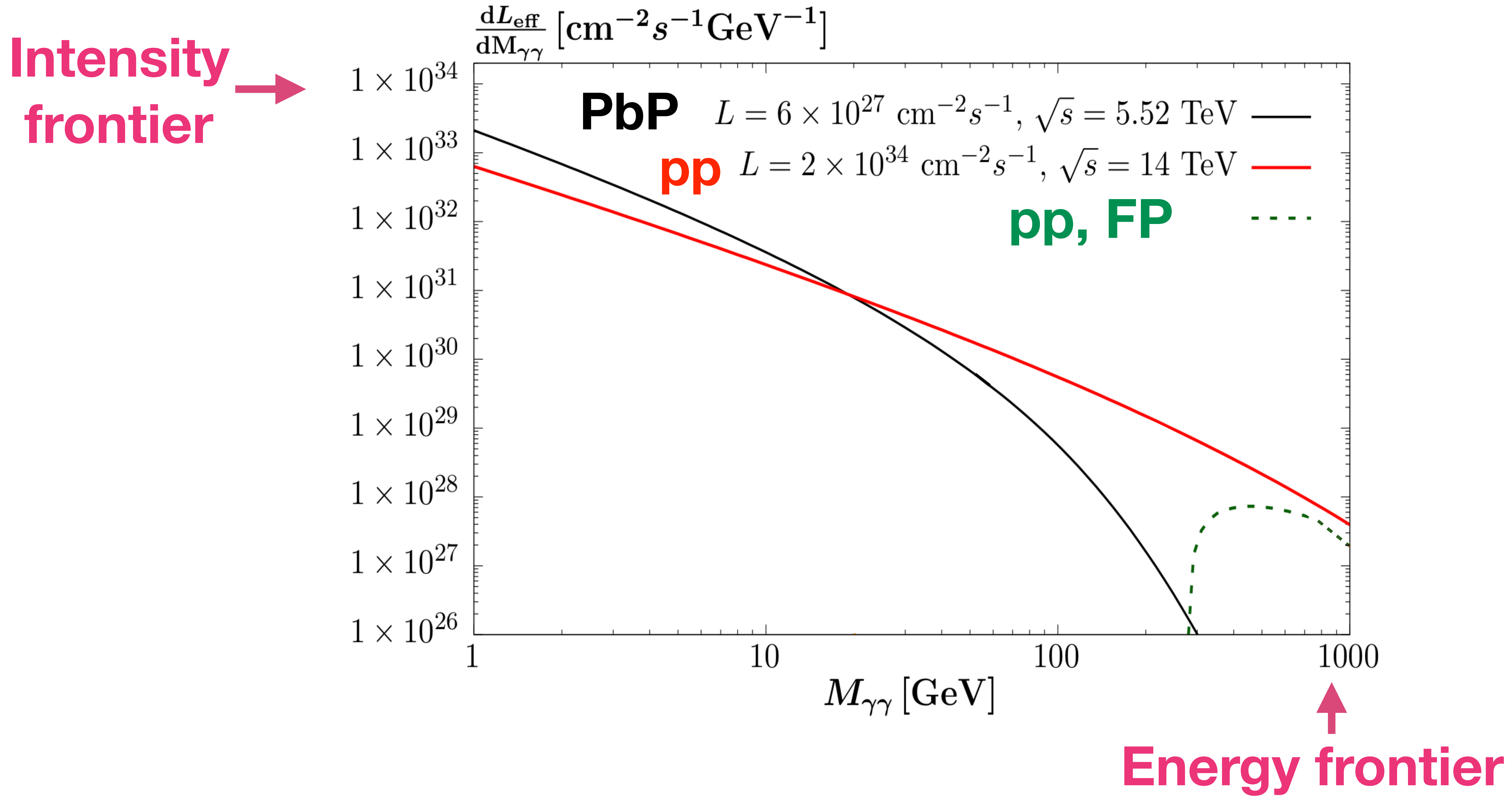
LHC photon collisions promising solution

For tau g-2 and beyond …

Backup

QED @ a range of masses

Bruce et al 1812.07688



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

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 $\hat{\sigma}$ 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

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 $F_{\mu\nu}$

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

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]

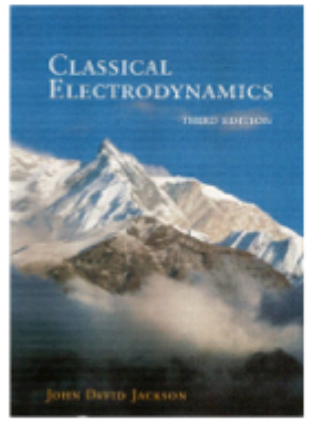
$$\mathcal{L}' = \left(\bar{L}_\tau \sigma^{\mu\nu} \tau_R\right) H \left[\frac{C_{\tau B}}{\Lambda^2} B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2} W_{\mu\nu}\right]. \quad (3)$$

Here, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the $\mathrm{U}(1)_\mathrm{Y}$ and $\mathrm{SU}(2)_\mathrm{L}$ 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.

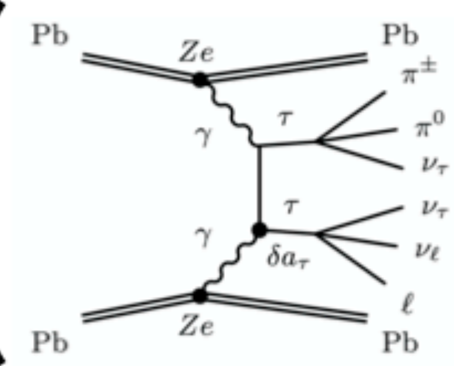
Photon collisions using MG & SMEFTsim



Photon flux: classical field theory

Look up Chapter 15 §4, put in MadGraph with Fortran77

$$n(x) = \frac{2Z^2\alpha}{x\pi}\left\{\bar{x}K_0(\bar{x})K_1(\bar{x}) - \frac{\bar{x}^2}{2}\left[K_1^2(\bar{x}) - K_0^2(\bar{x})\right]\right\}$$

$$\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX}\Bigg($$


$$\Bigg) = \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1) n(x_2)\, \sigma_{\gamma\gamma\to XX}$$

MadGraph | **Jackson** | **SMEFTsim**

SMEFTsim: implement dim-6 in Feynrules

Grzadkowski, Iskrzyński,M. Misiak, Rosiek [1008.4884]
Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921]
Brivio, Jiang, Trott [1709.06492]

Include interference up to 2 BSM couplings

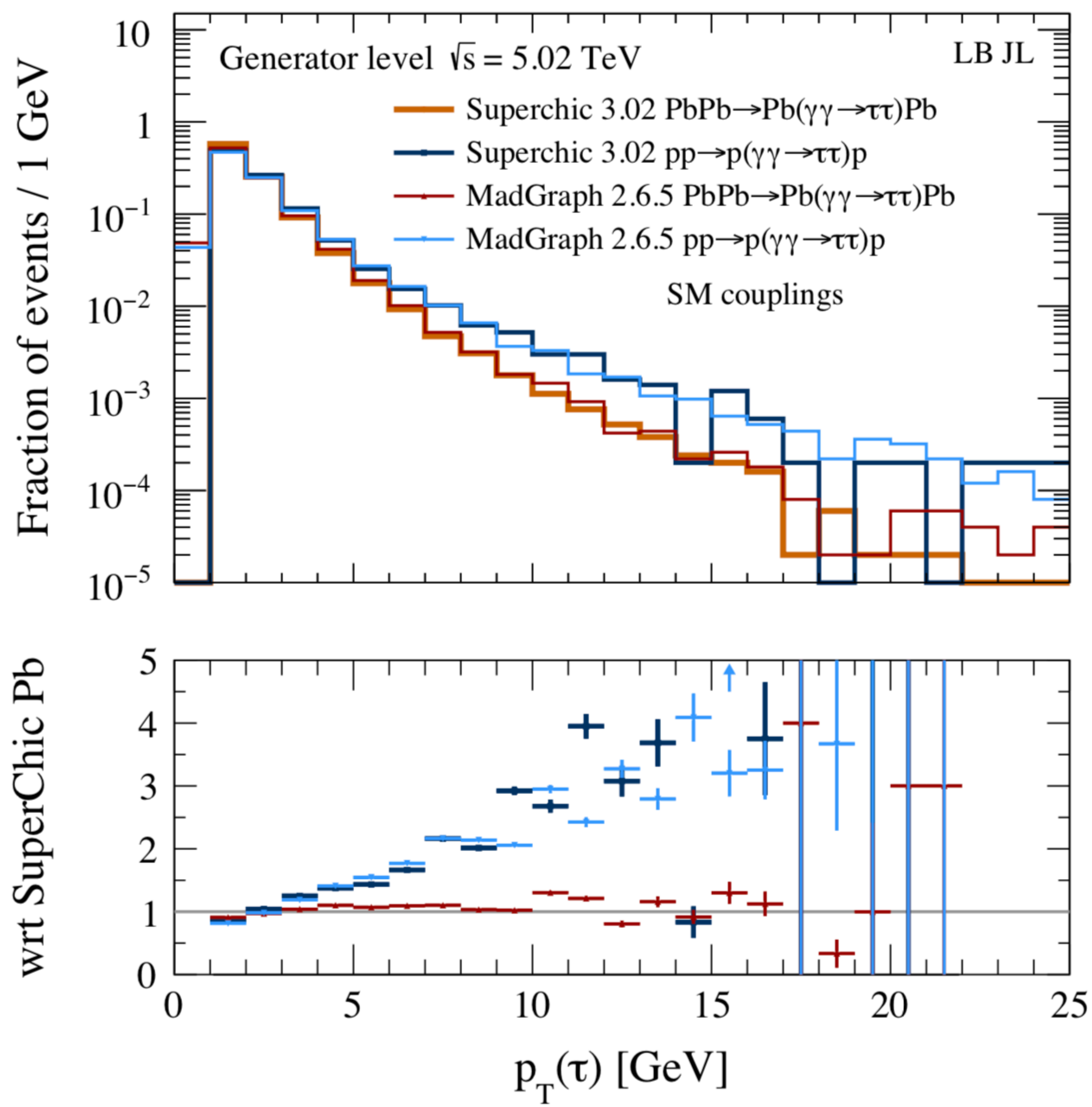
MadGraph factorised prescription
d'Enterria, Lansberg [0909.3047]
Superchic 3
Harland-Lang, Khoze, Ryskin [1810.06567]

13 | **Tau g–2** | 2 Oct 2019 | **Jesse Liu**

MG vs Super Chic

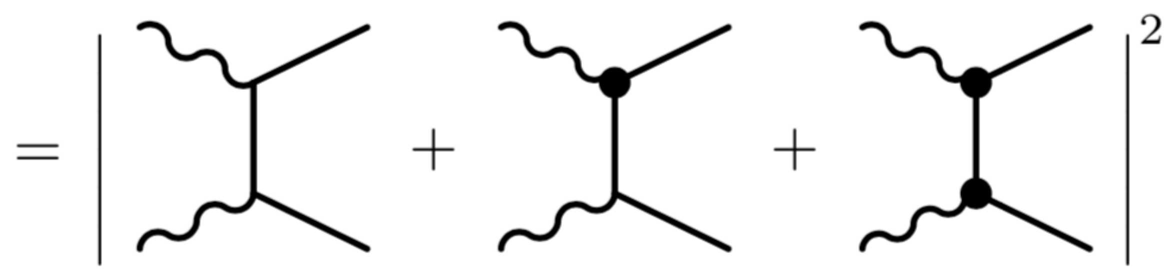
Superchic accounts for nuclear finite size, thickness and overlap

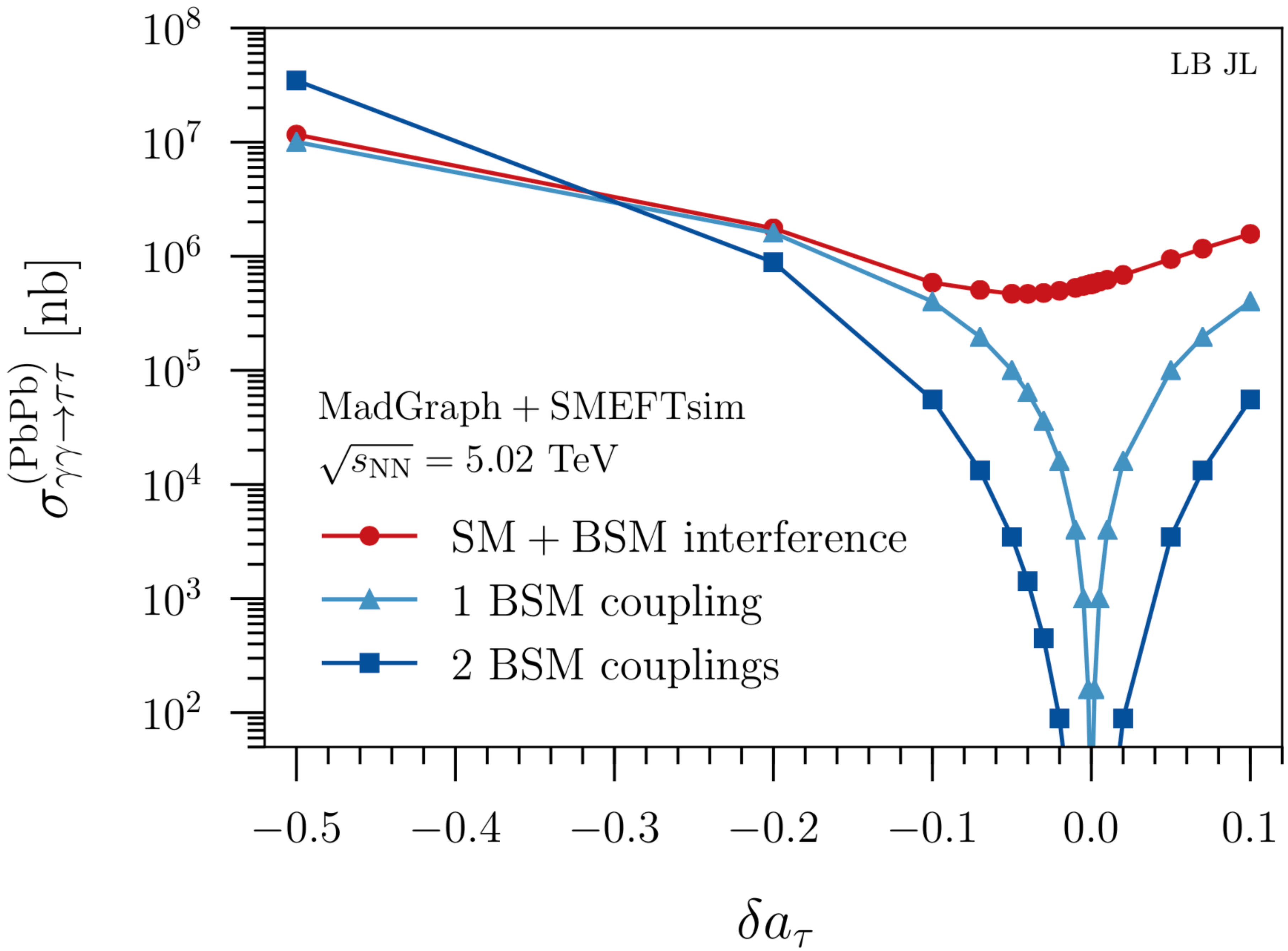
We modify MadGraph to use the photon flux Eq. (6) for evaluating $\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX}$. This prescription neglects a non-factorizable term in Eq. (5), which models the probability of hadronic interactions $P_{|\mathbf{b}_1-\mathbf{b}_2|}$, where $\mathbf{b}_i$ is the impact parameter of ion i. The SuperChic 3.02 [80] program includes a complete treatment of $P_{|\mathbf{b}_1-\mathbf{b}_2|}$, along with nuclear overlap and thickness. Using this, we validate that these simplifications in MadGraph do not majorly impact distributions relevant for this work, namely tau p_{T}.



Cross-section & interference

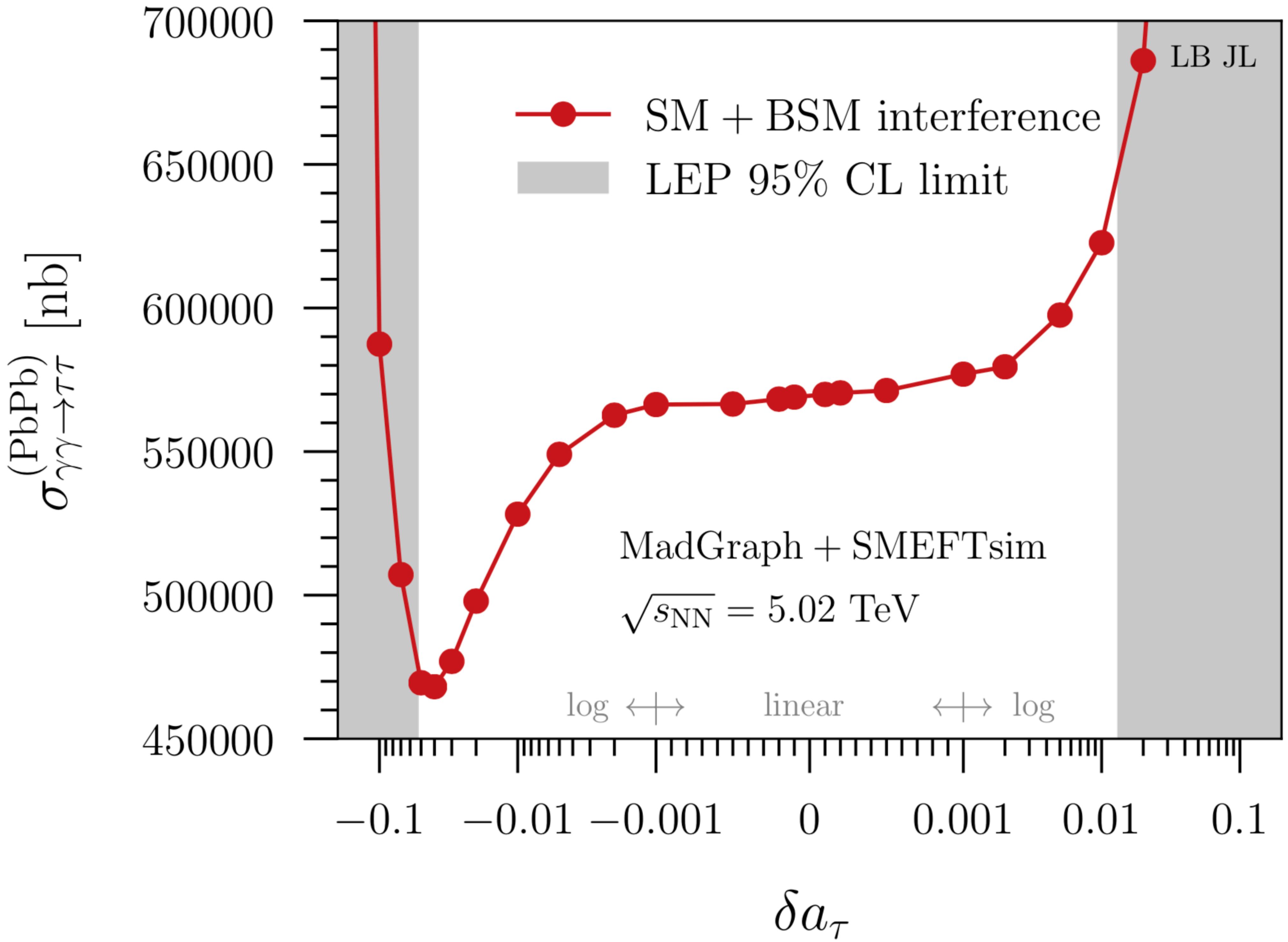
$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\text{SM}} + \mathcal{M}^{(1)}_{\text{BSM}} + \mathcal{M}^{(2)}_{\text{BSM}}\right|^2$$





Lydia Beresford

Cross-section & interference (zoomed)



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

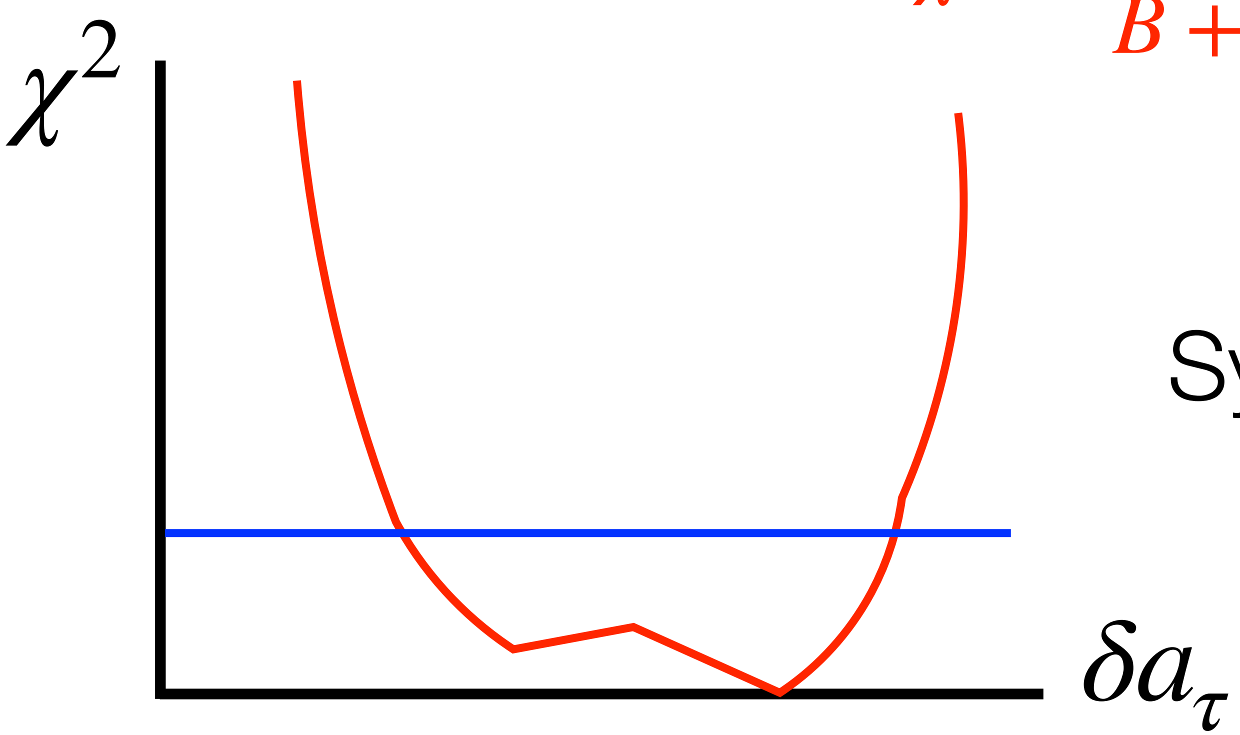
Setting constraints

To set a constraint need to deviate from SM

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

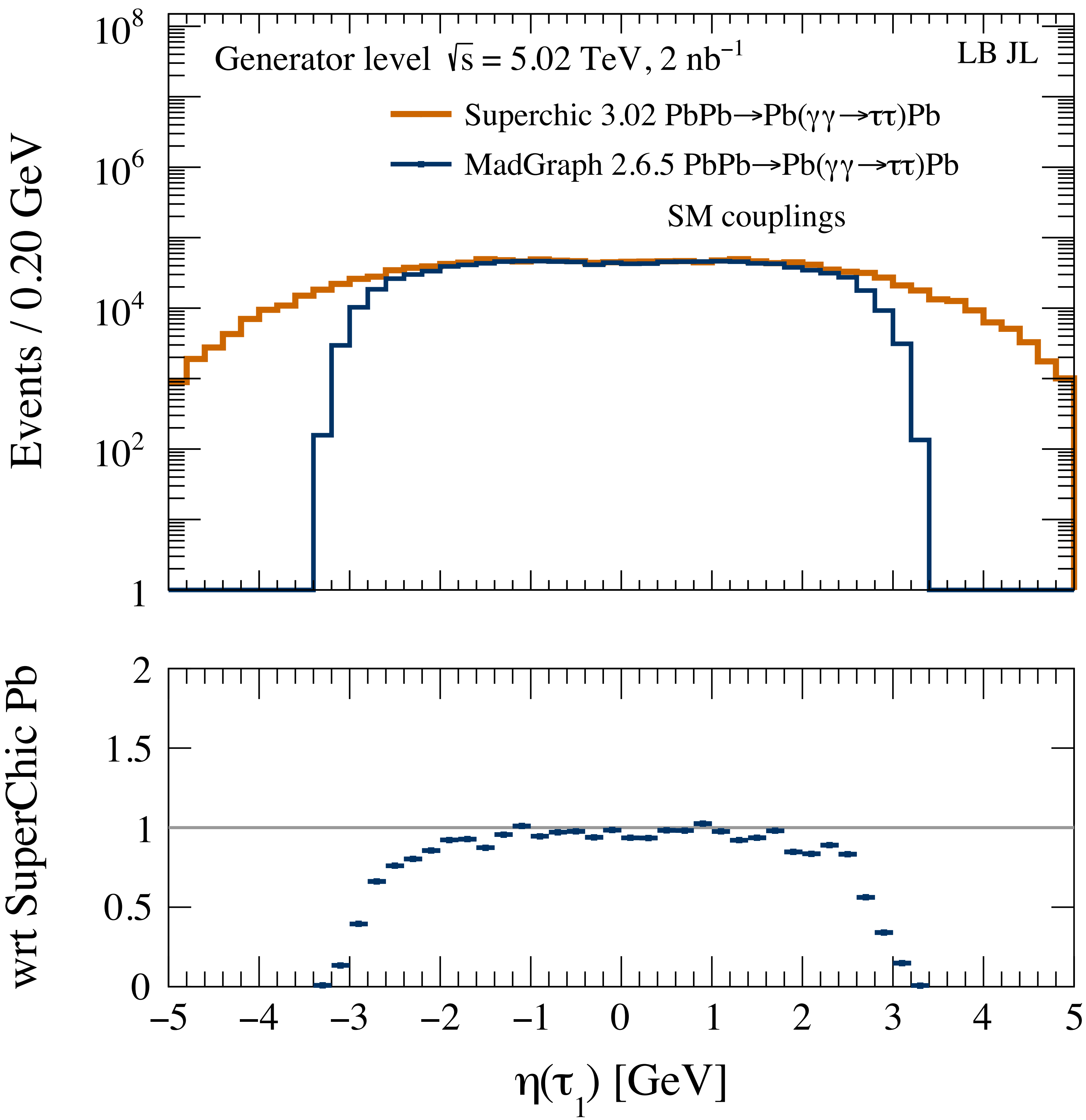
Assume observe SM & quantify constraint using χ^2

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



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

Eta distribution



Also sensitive to tau EDM

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

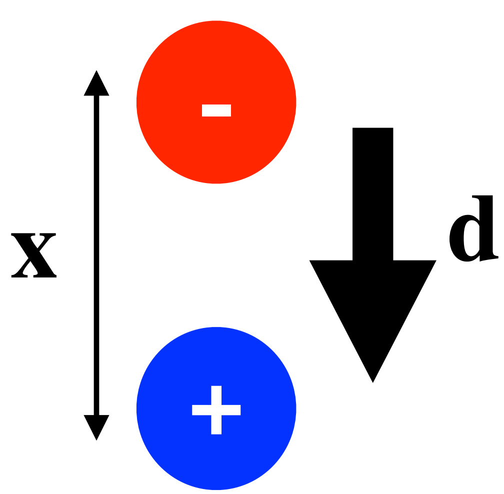
EDM = Electric Dipole Moment

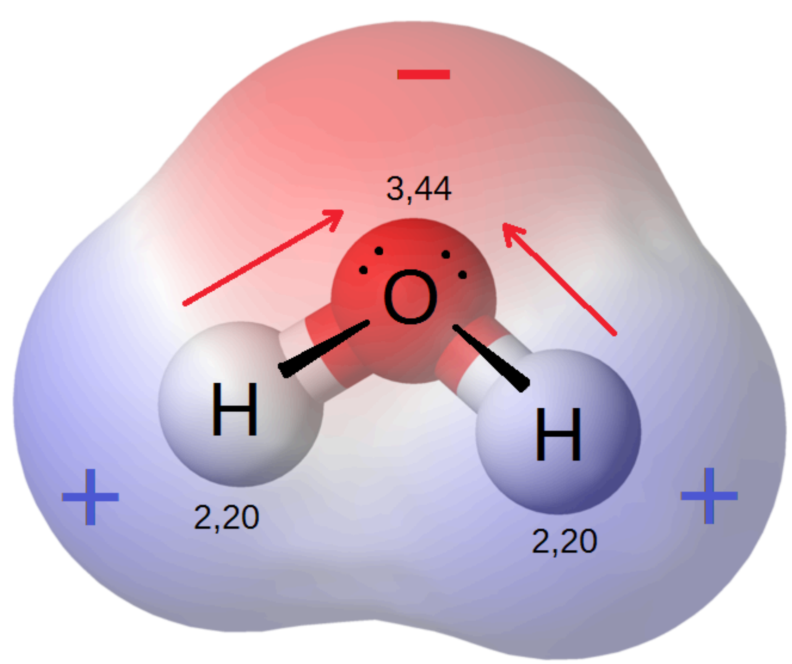
$$\boldsymbol{\tau} = \boldsymbol{d} \times \mathbf{E}$$

↑ torque ↑ electric dipole moment

Possessed by e.g. water (polarised molecule)

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





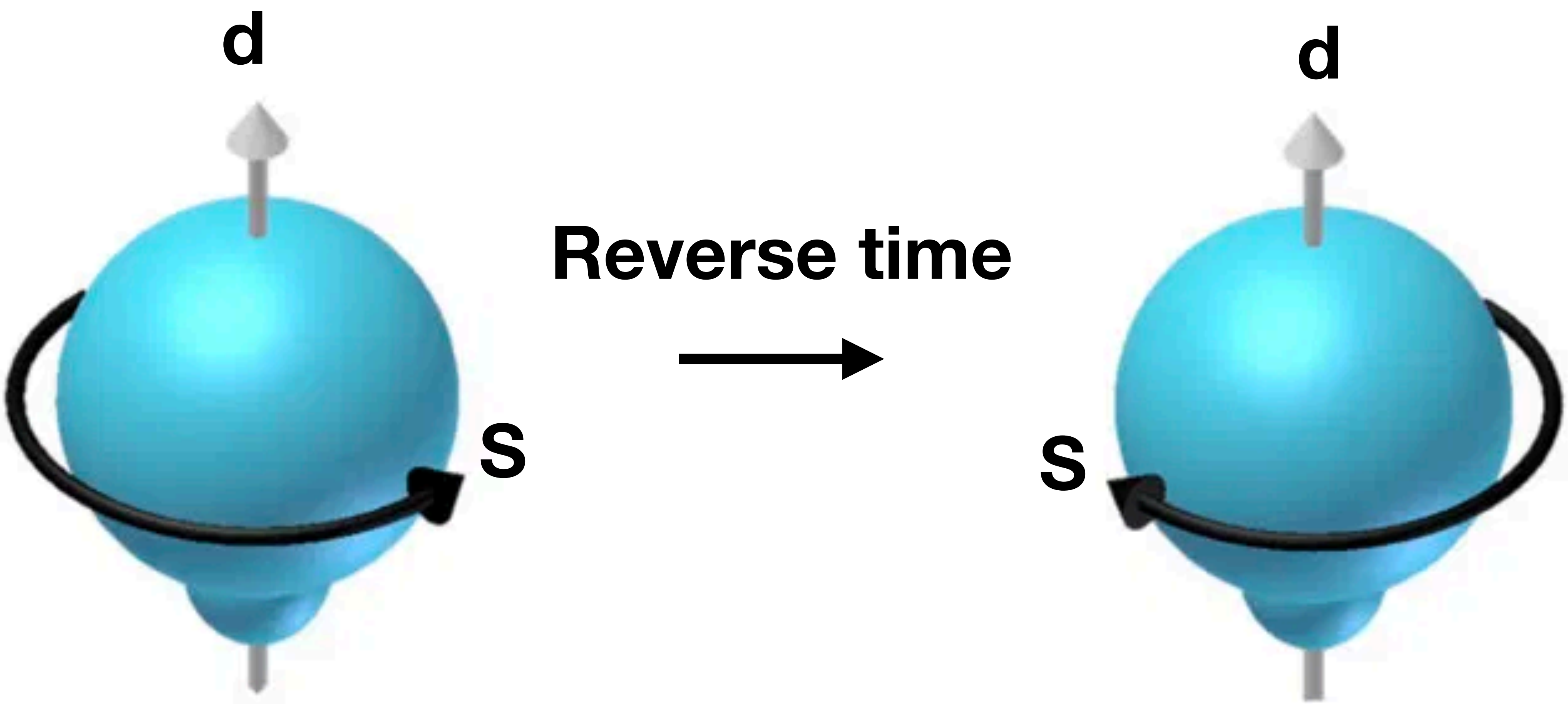
EDM tells us about charge distribution

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

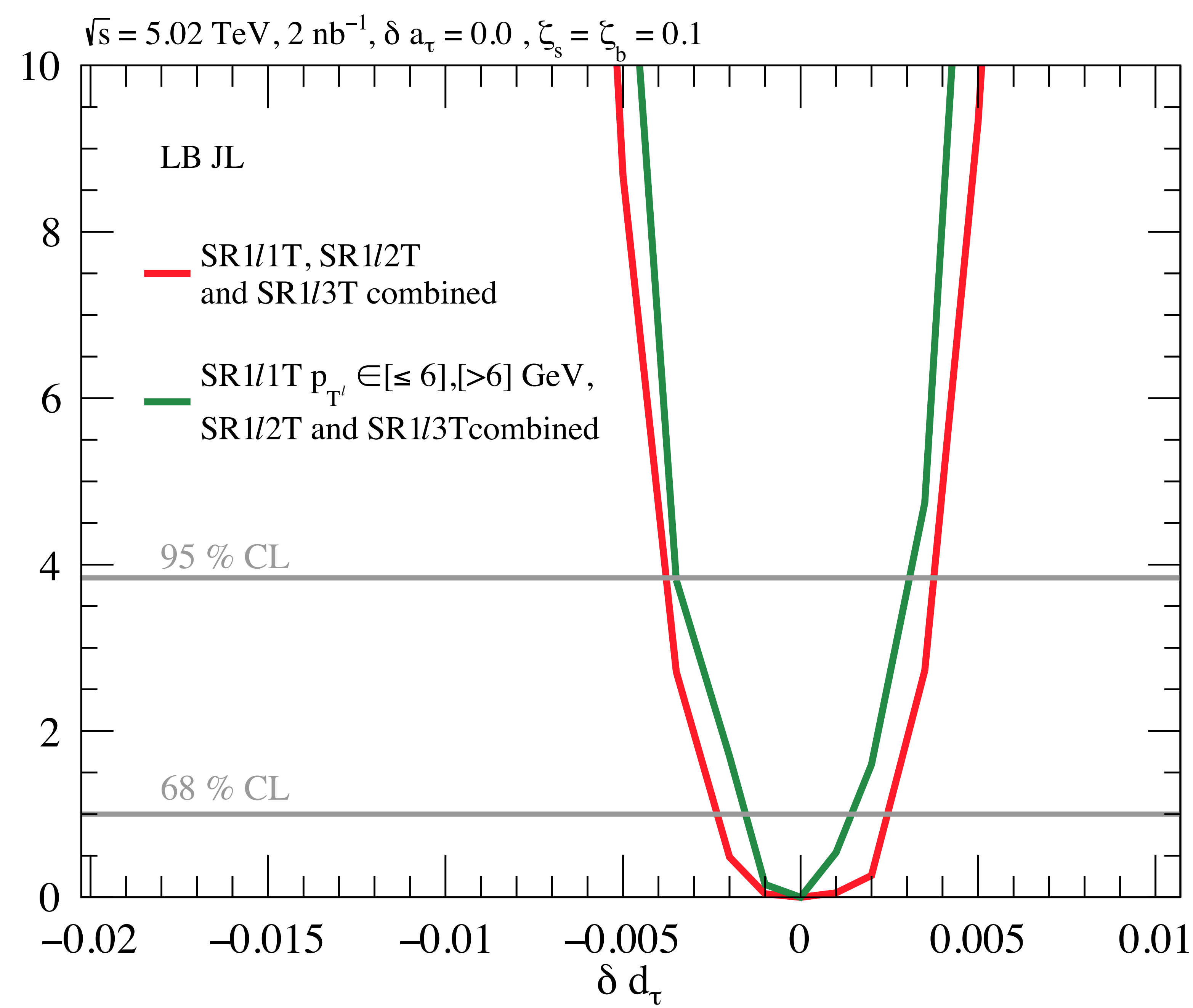
Belle PLB (2003)

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

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

@ 95% CL

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



Order mag better than DELPHI, competitive with Belle