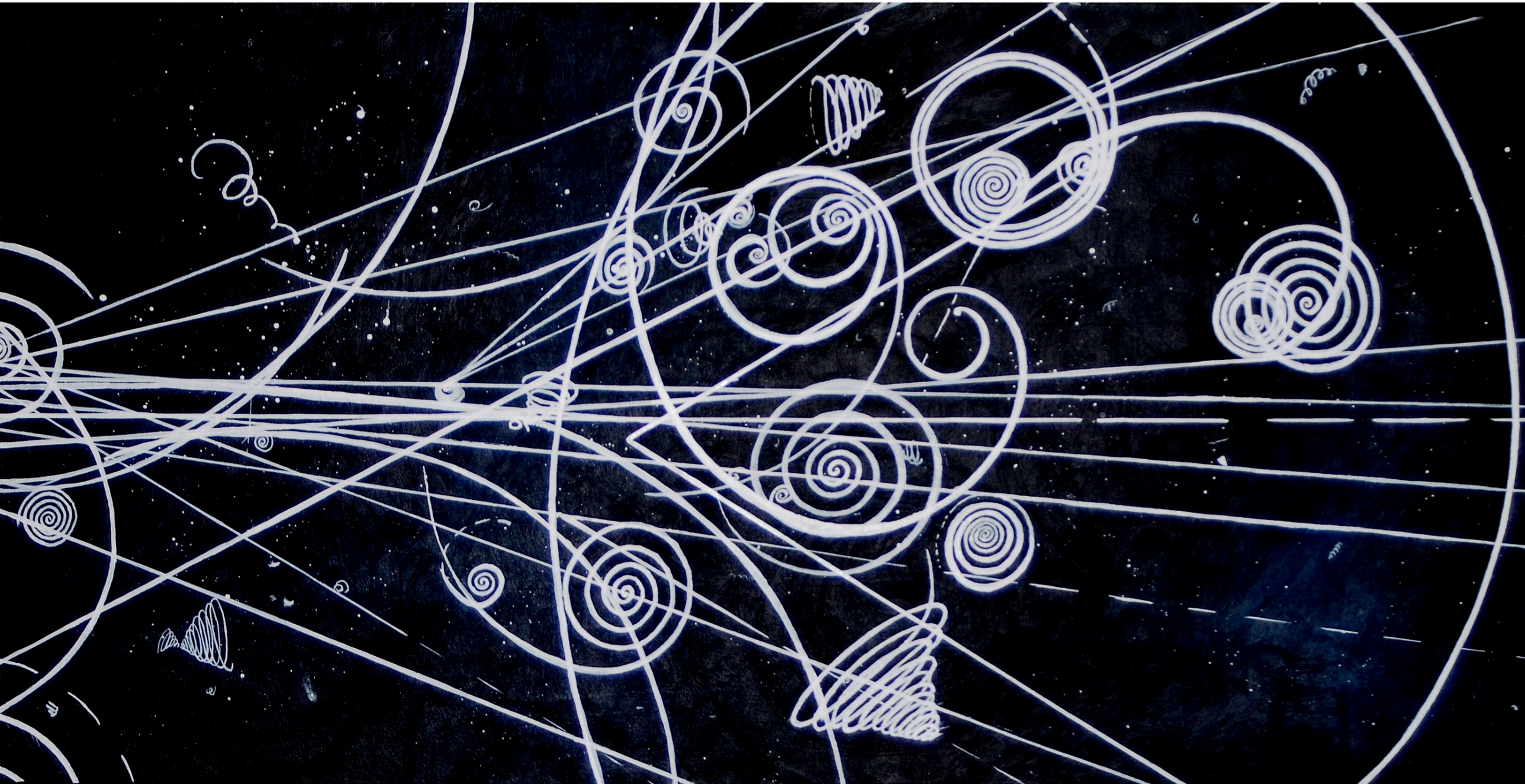
Tau g-2

Lydia Beresford in collaboration with Jesse Liu

ICHEP, 29th July 2020



Our proposal

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

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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

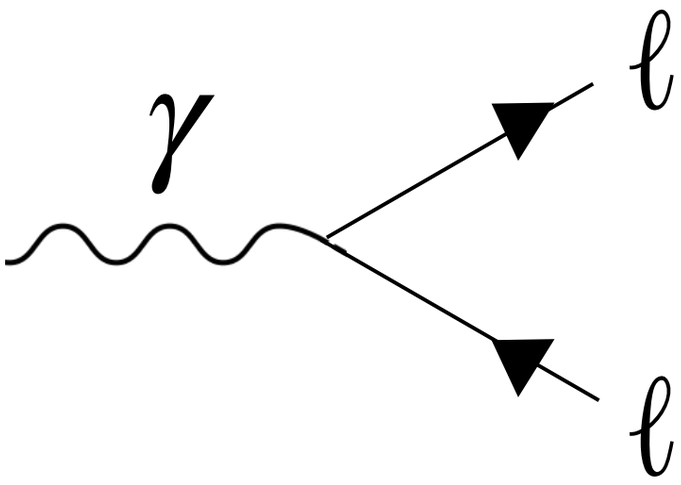
What is g-2?

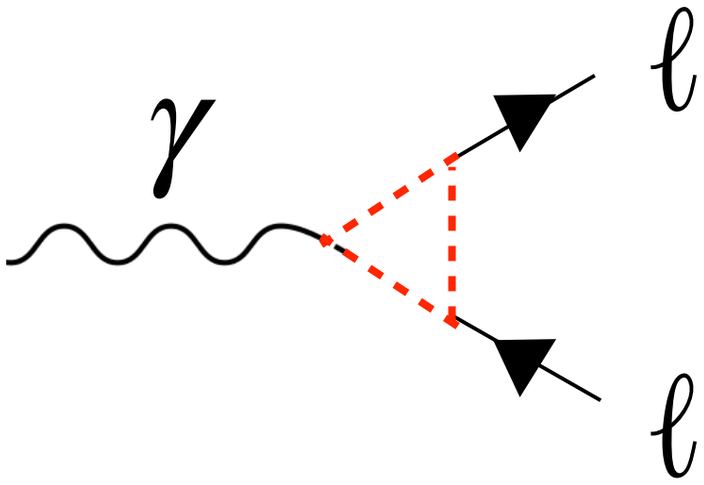
*How particles interact with **light***

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

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

$\boldsymbol{\mu} \cdot \mathbf{B}$





g = 2 + loop corrections

Dirac, 1928

What is g-2?

Anomalous magnetic moment

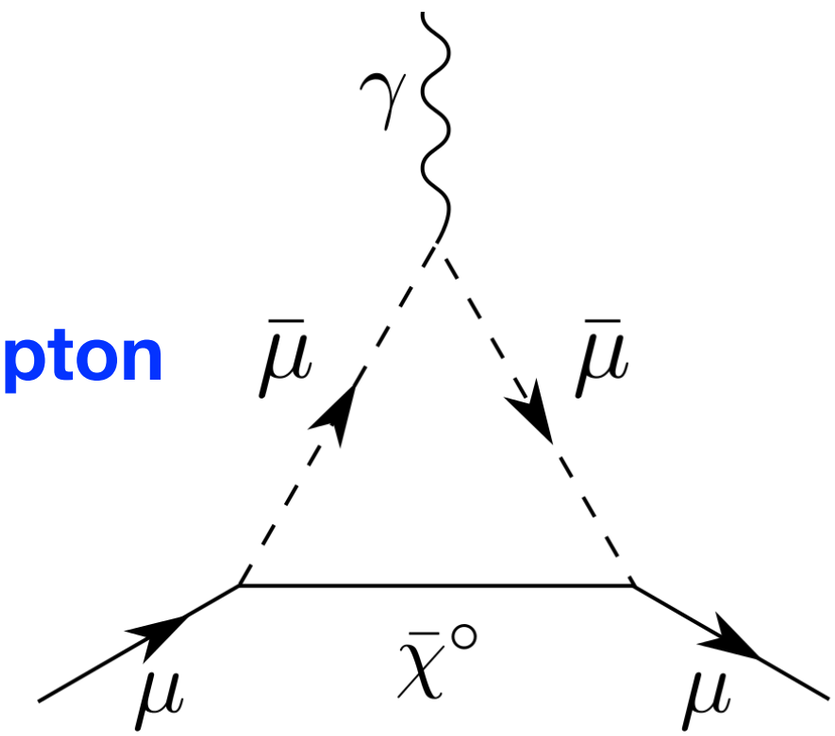
$$a = \frac{(g-2)}{2}$$

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?

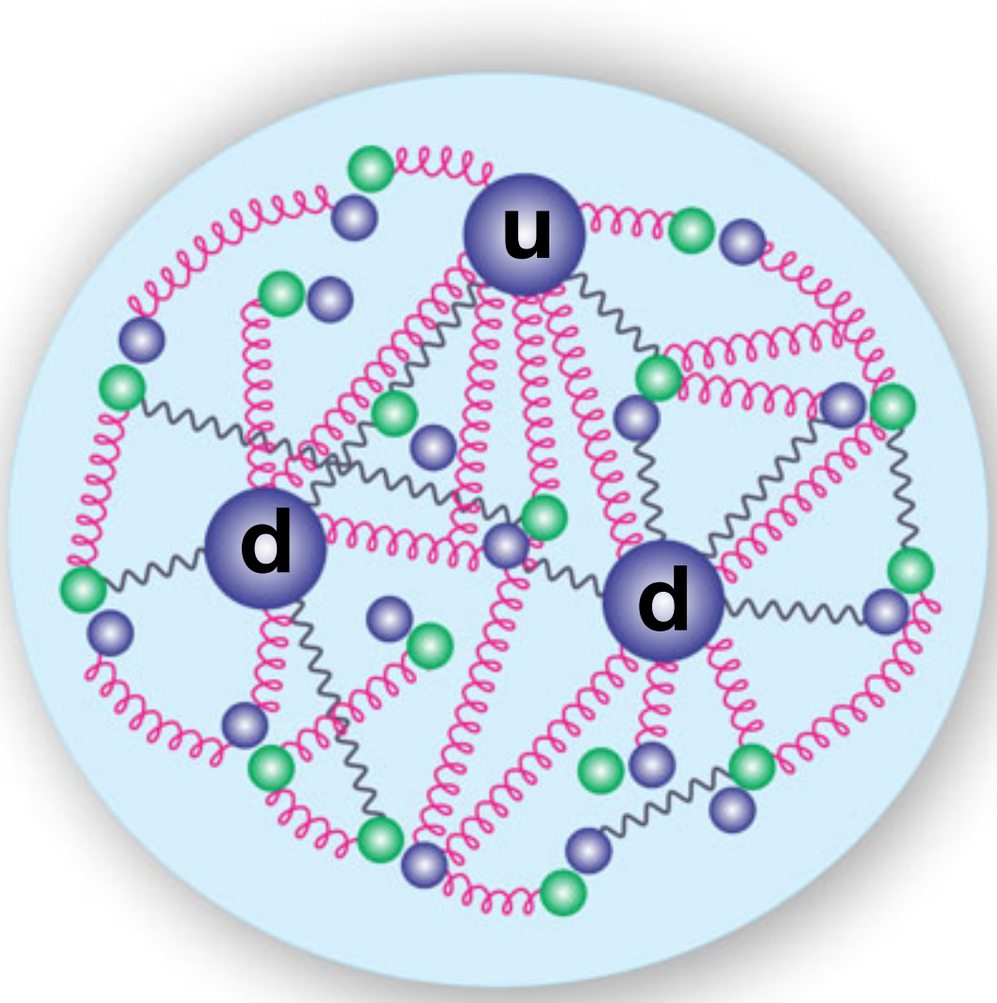
Powerful probe of new physics

Sensitive to compositeness

Historical examples: proton, neutron

Neutron g-2: **-5.8**

→ **Composite!**



Why is it interesting?

Fundamental test of QED

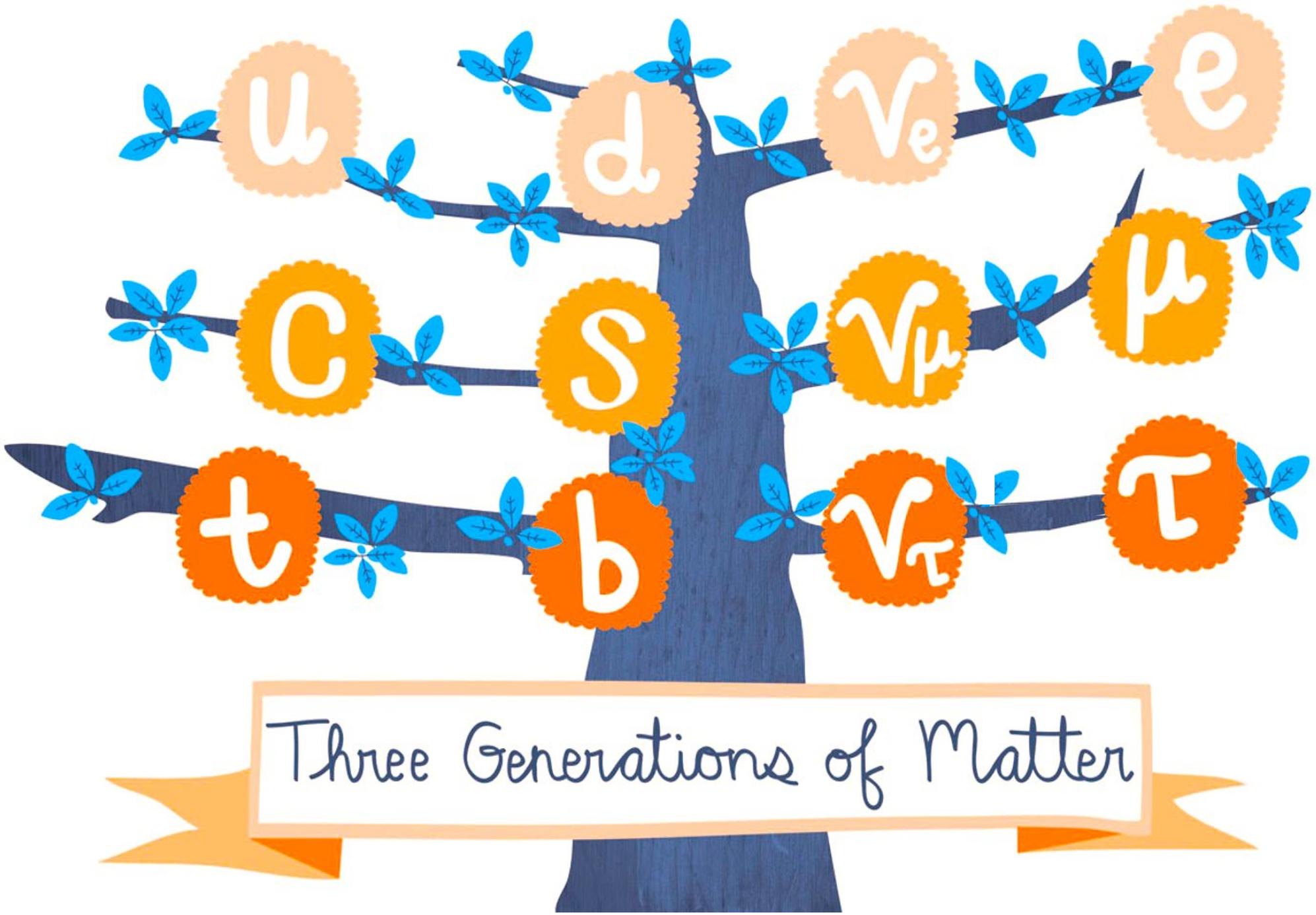
Electron g-2: 10^{-8} precision **-2.5σ tension**

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

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?

New physics contributions can scale with mass

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

Martin and Wells PRD (2001)

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

Problem: Lifetime

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

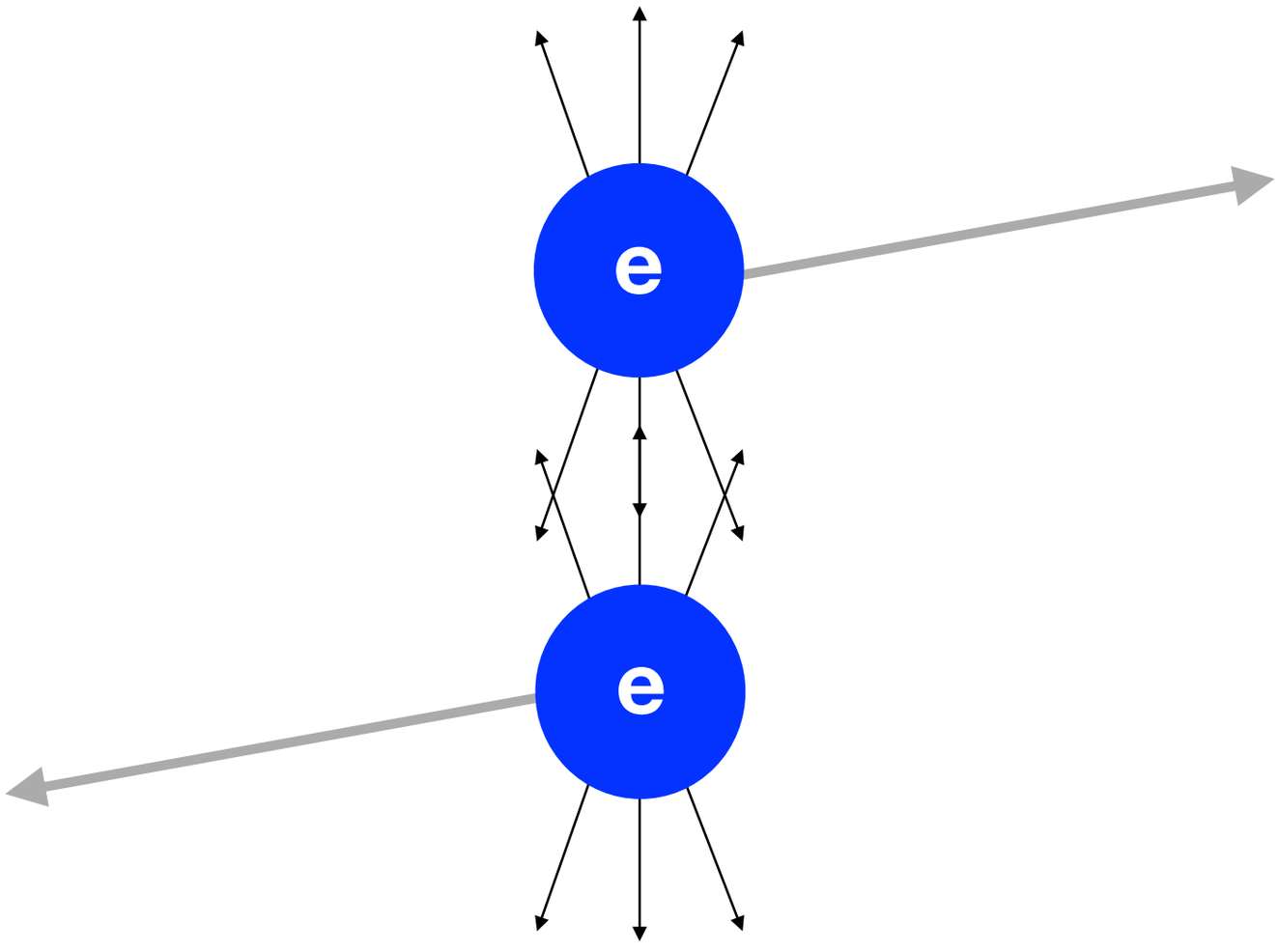
$$\mu \sim 10^{-6}\ \mathrm{s}$$

→ **Can’t use same technique!**

Solution: Photon collisions

Solution: Photon collisions

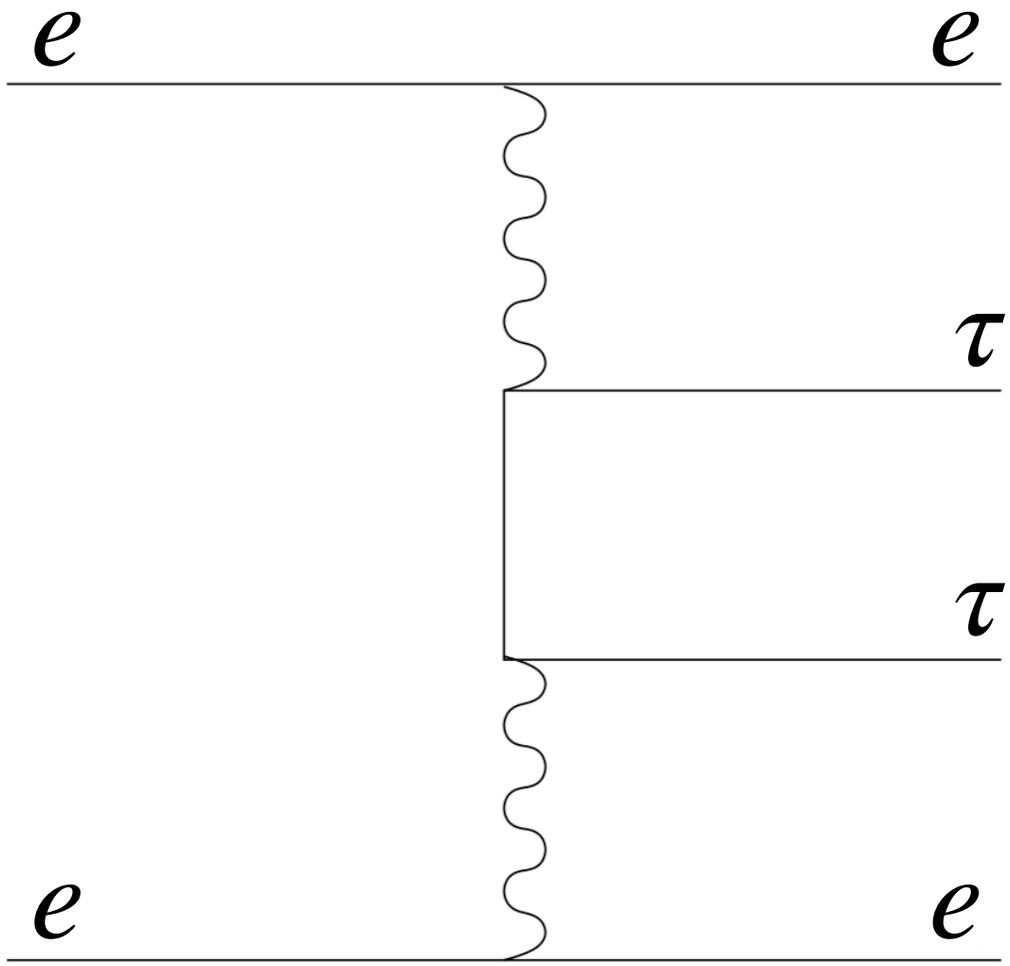
Photons from electromagnetic field surrounding electrons collide to produce new particles



PDG value

Delphi EPJC (2004)

DELPHI 2004, LEP collider



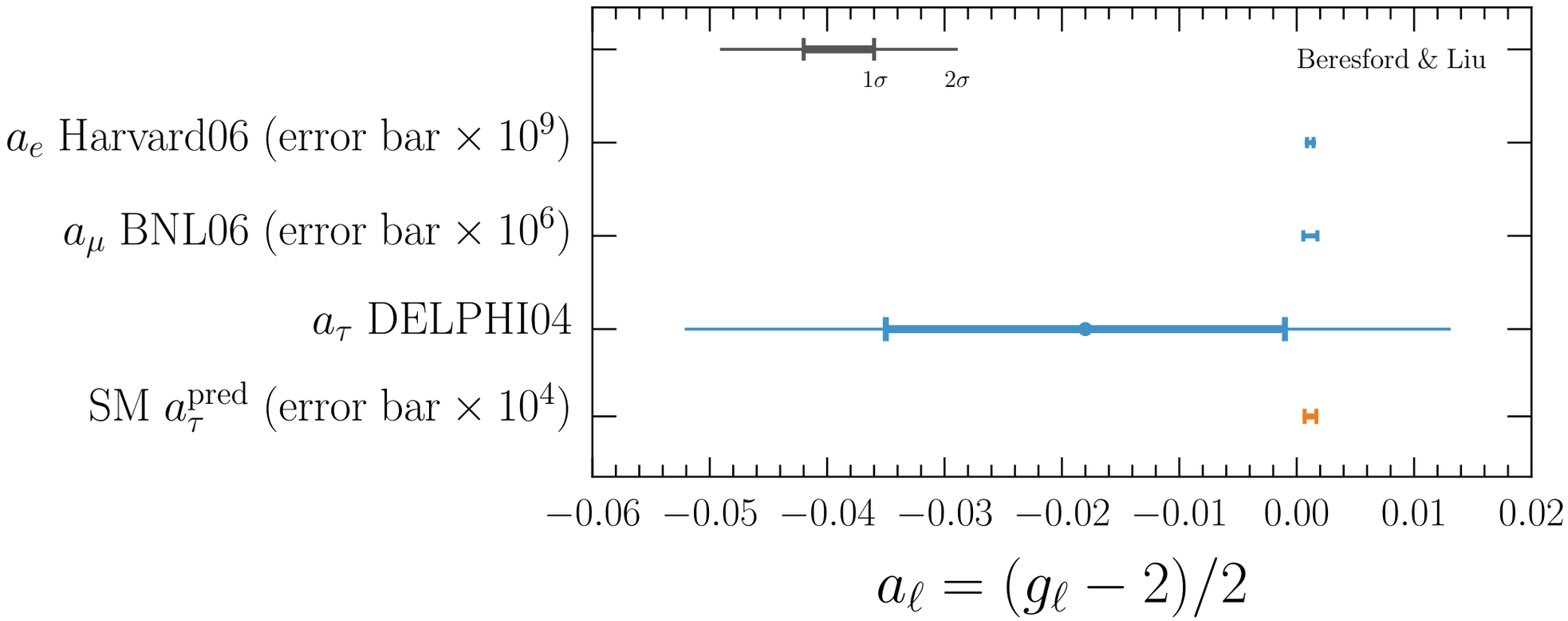
Cross section sensitive to moments

Photo production of tau pairs

Constraints also set by L3 and OPAL

Sibling Rivalry

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



PDG value doesn't test 1-loop QED

$$a_\tau^{\rm exp} = -0.018\ (17) \qquad a_\tau^{\rm theory} = 0.00117721\ (5)$$

Delphi EPJC (2004)

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 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

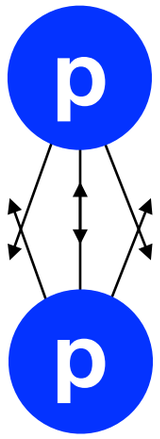
HL-LHC

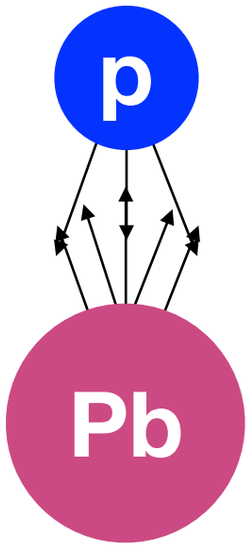
Galon, Rajaraman and Tait
1610.01601

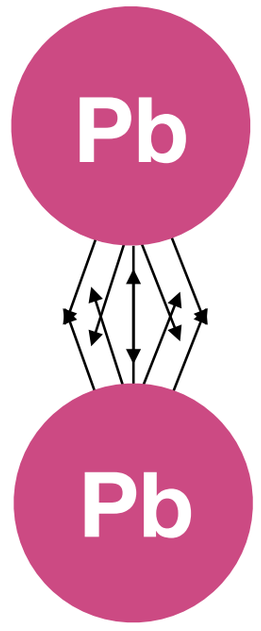
What can we do right now?

The LHC is also a photon collider

The LHC is also a photon collider





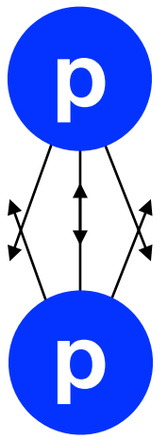


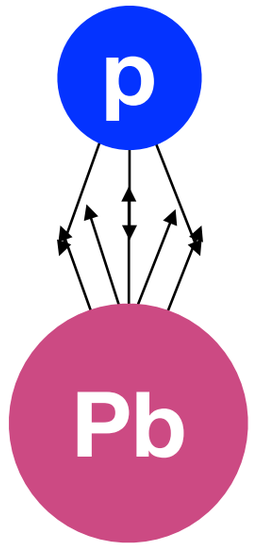
ATLAS

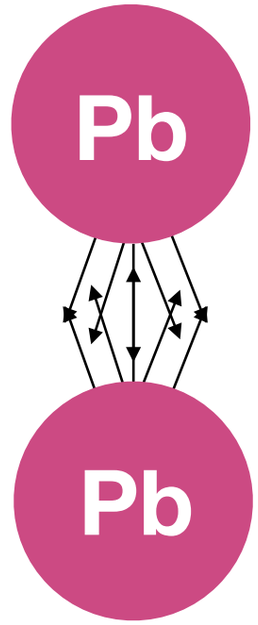
$\sqrt{s}$	13 TeV	8.16 TeV	5.02 TeV
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	~2 nb^{-1}
σ	-	$\propto Z^2$	$\propto Z^4$

Z = 82 for Pb

The LHC is also a photon collider







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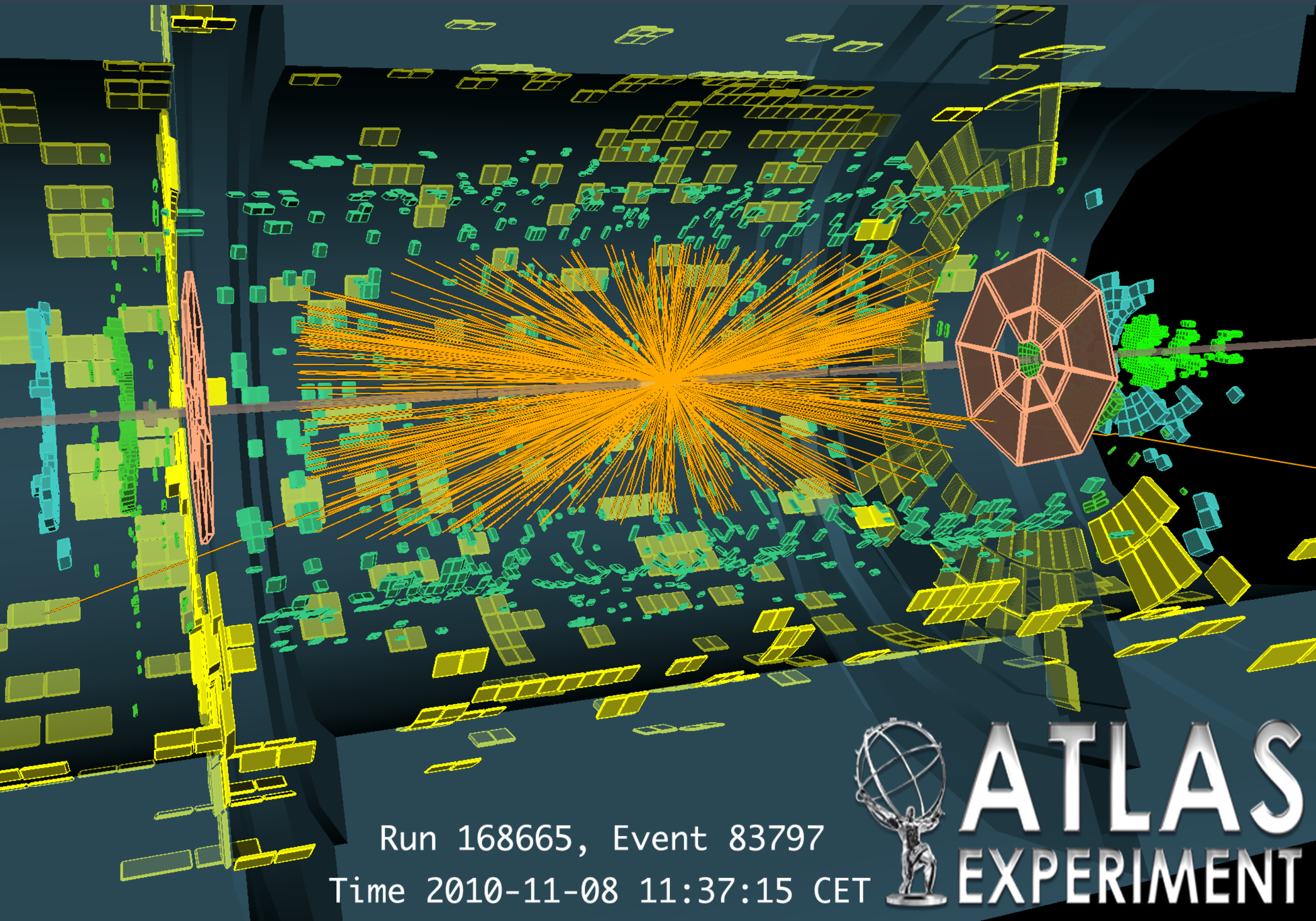
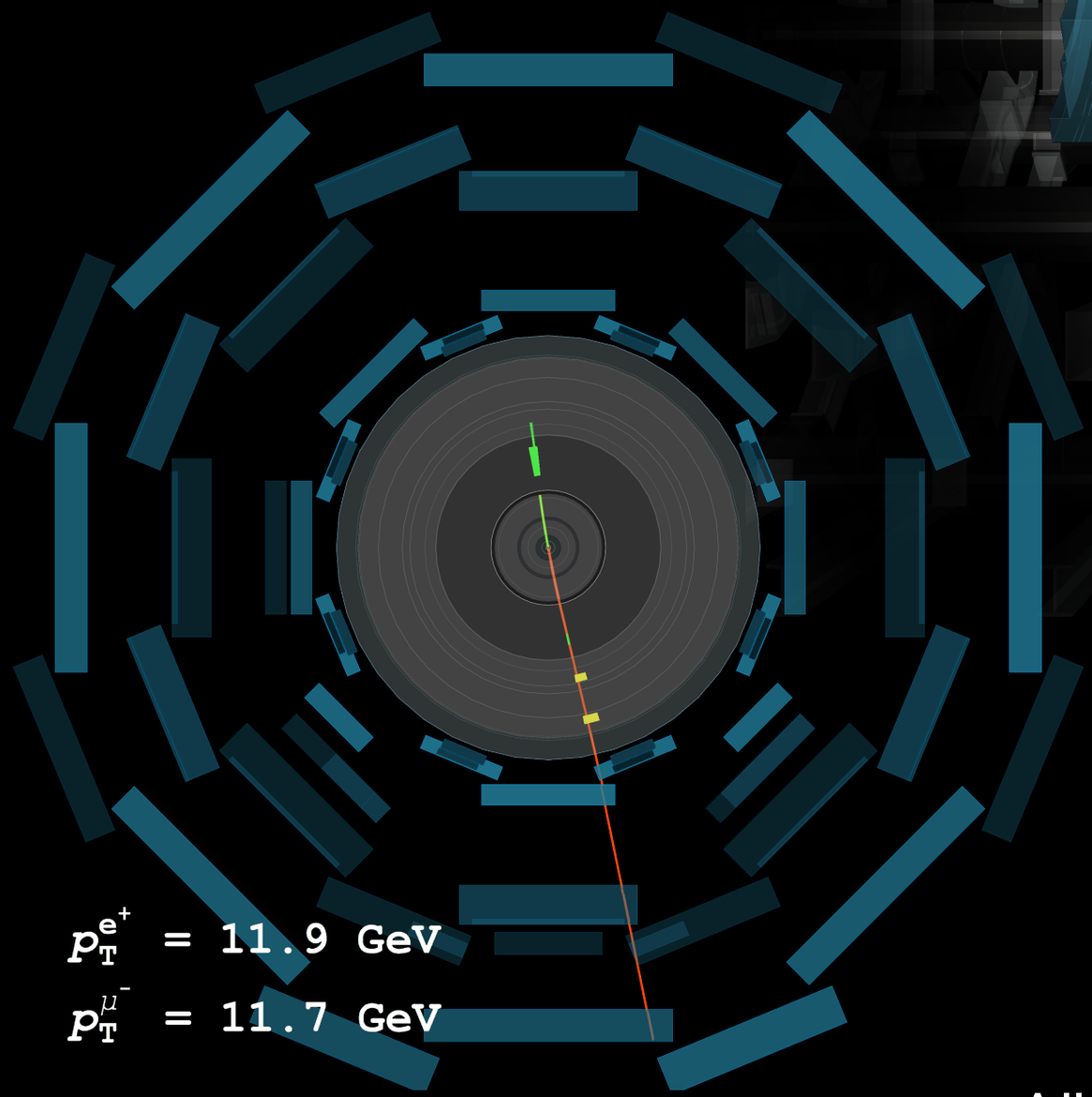
Z = 82 for Pb

Head on PbPb collision



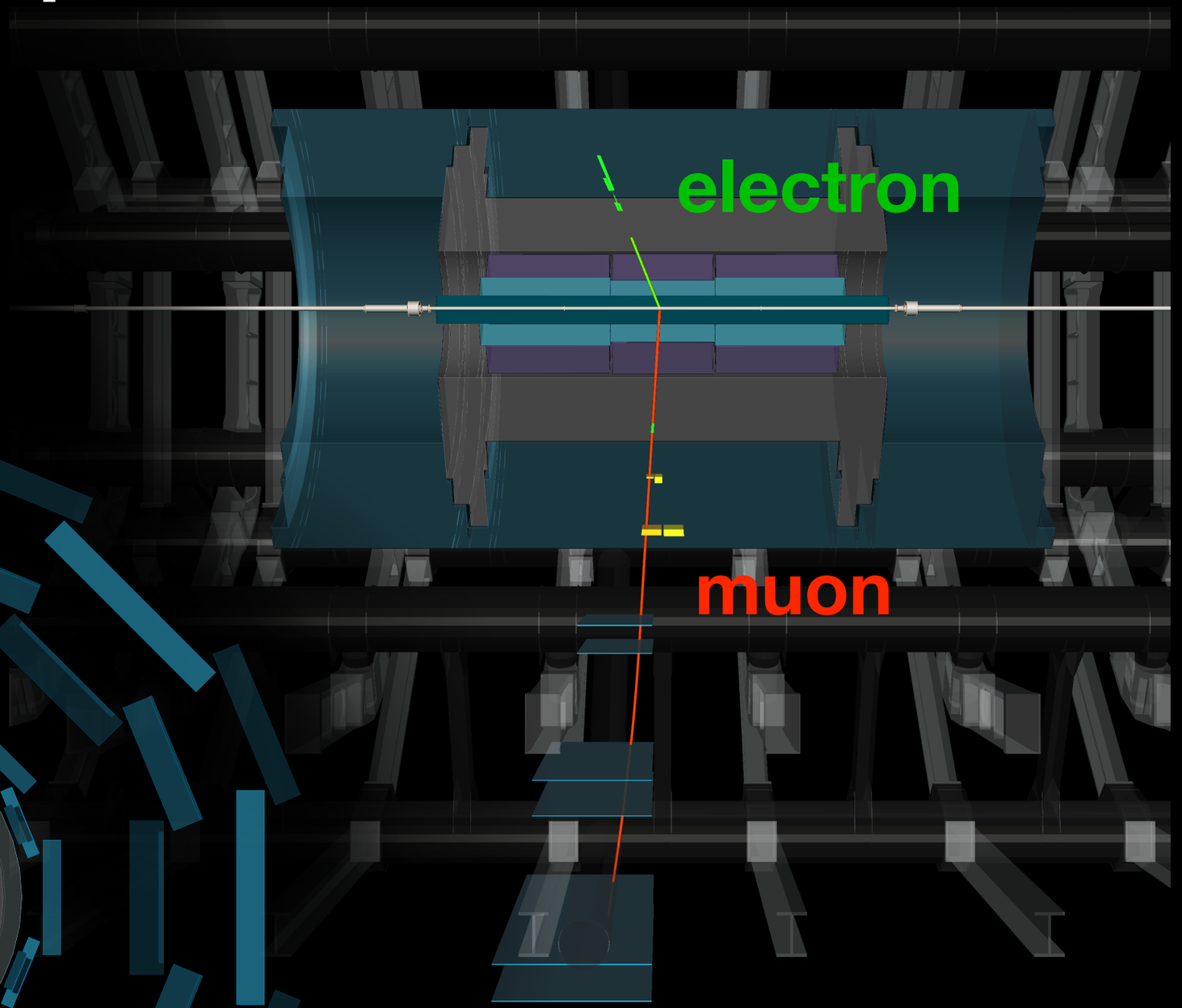
Ultra Peripheral PbPb collision

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 1908.05180
Dyndal et al 2002.05503

LHC PbPb

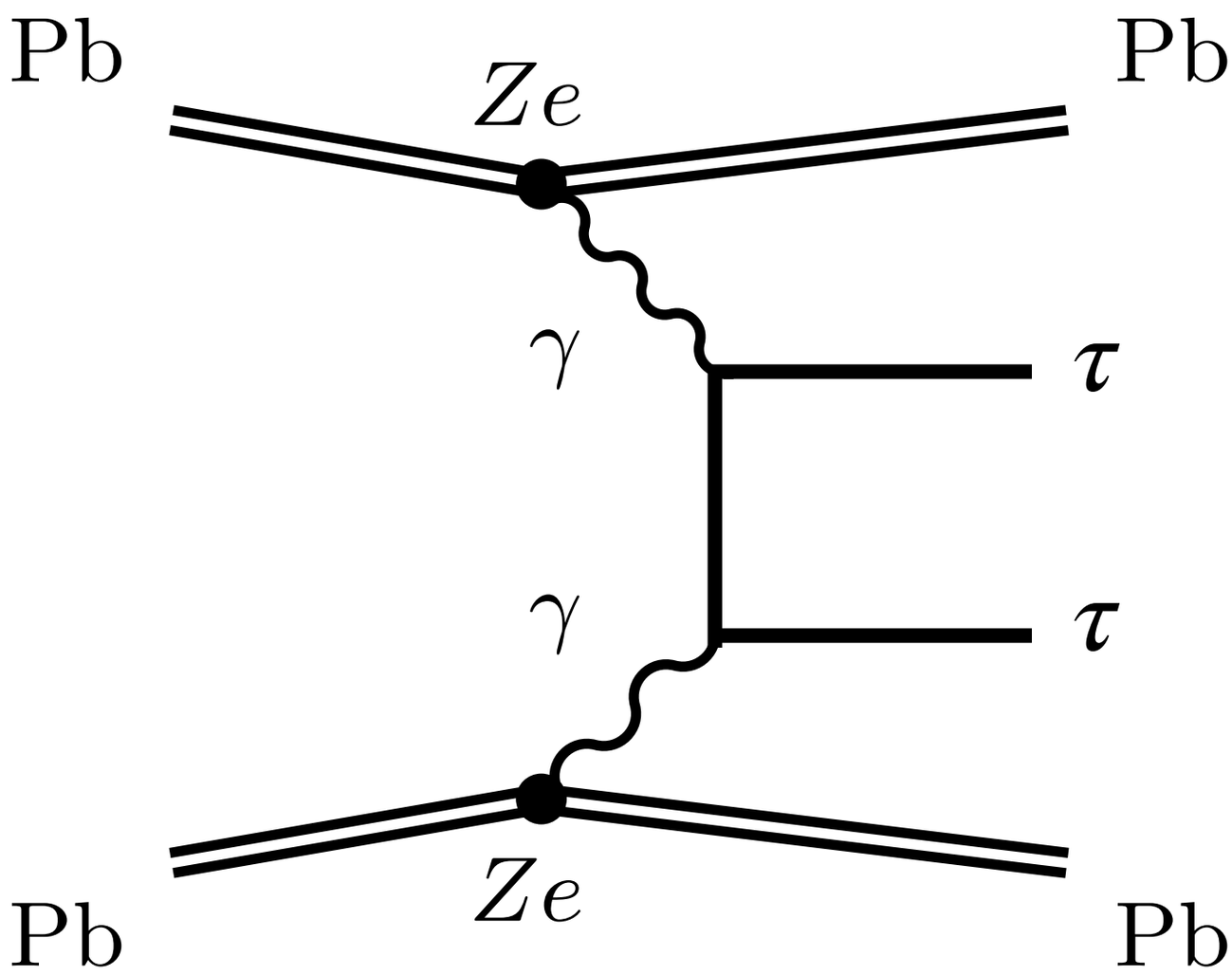


Photo production of tau pairs

Not yet observed @ LHC

Tau decays

1 prong

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

+ neutral π's

Leptonic

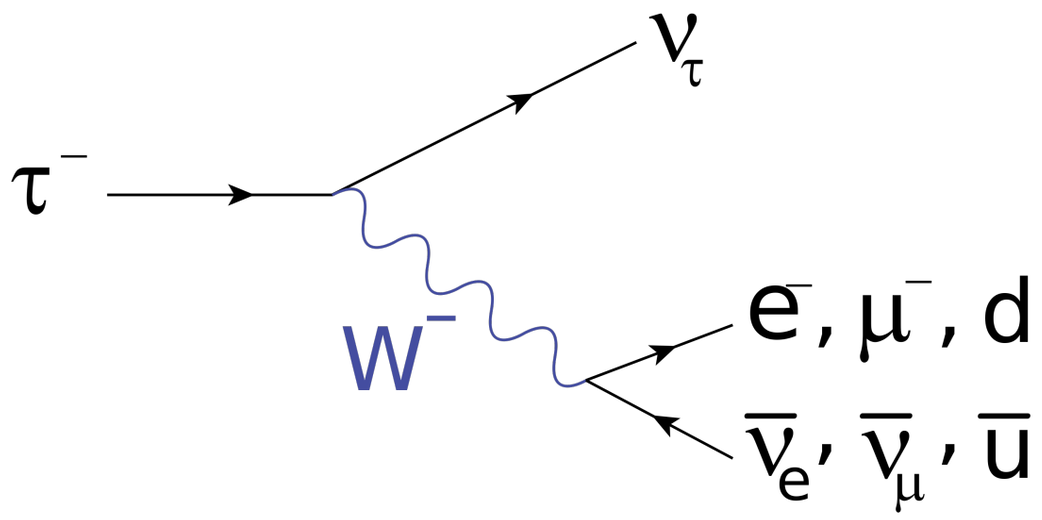
$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$

3 prong

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

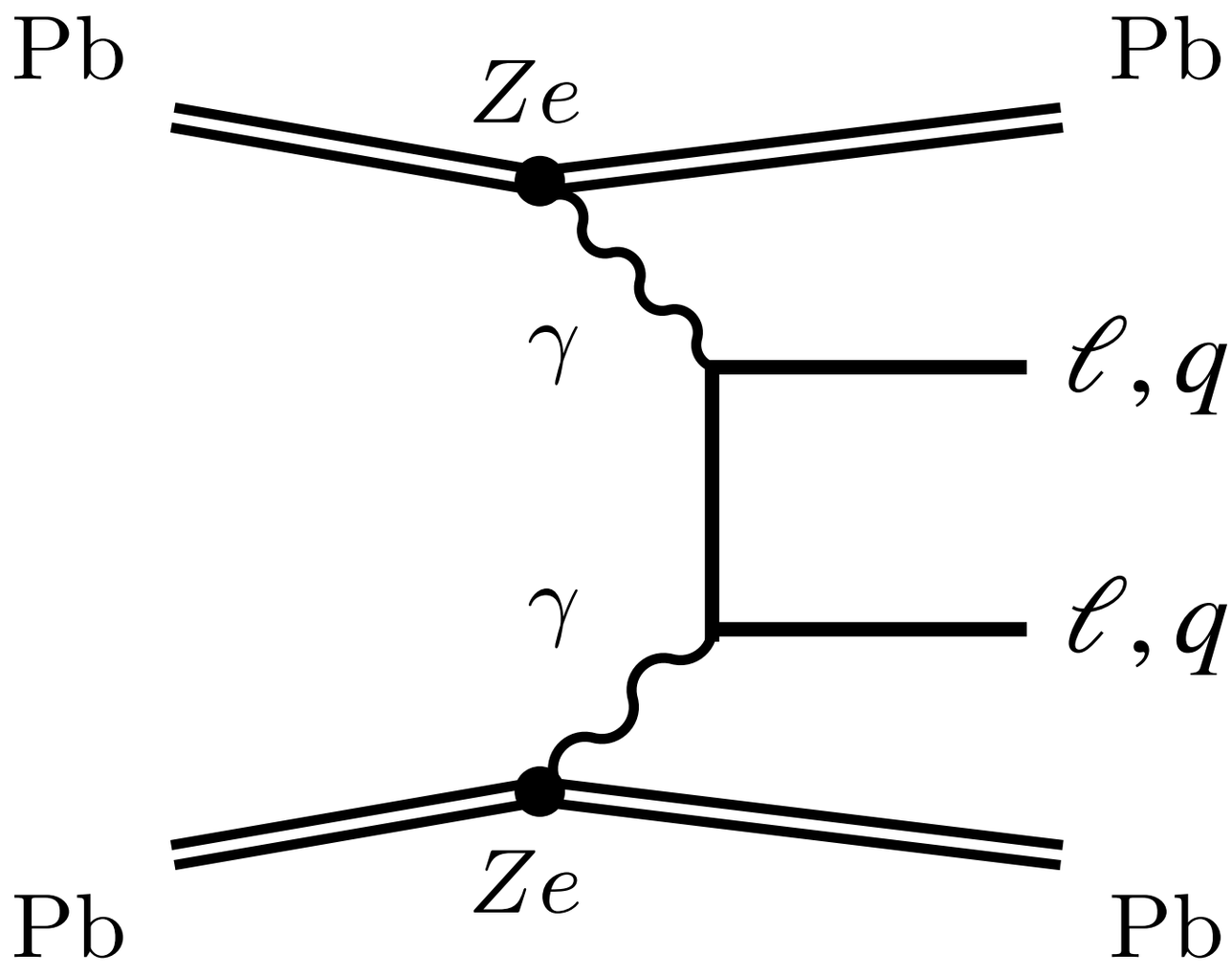
+ neutral π's

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

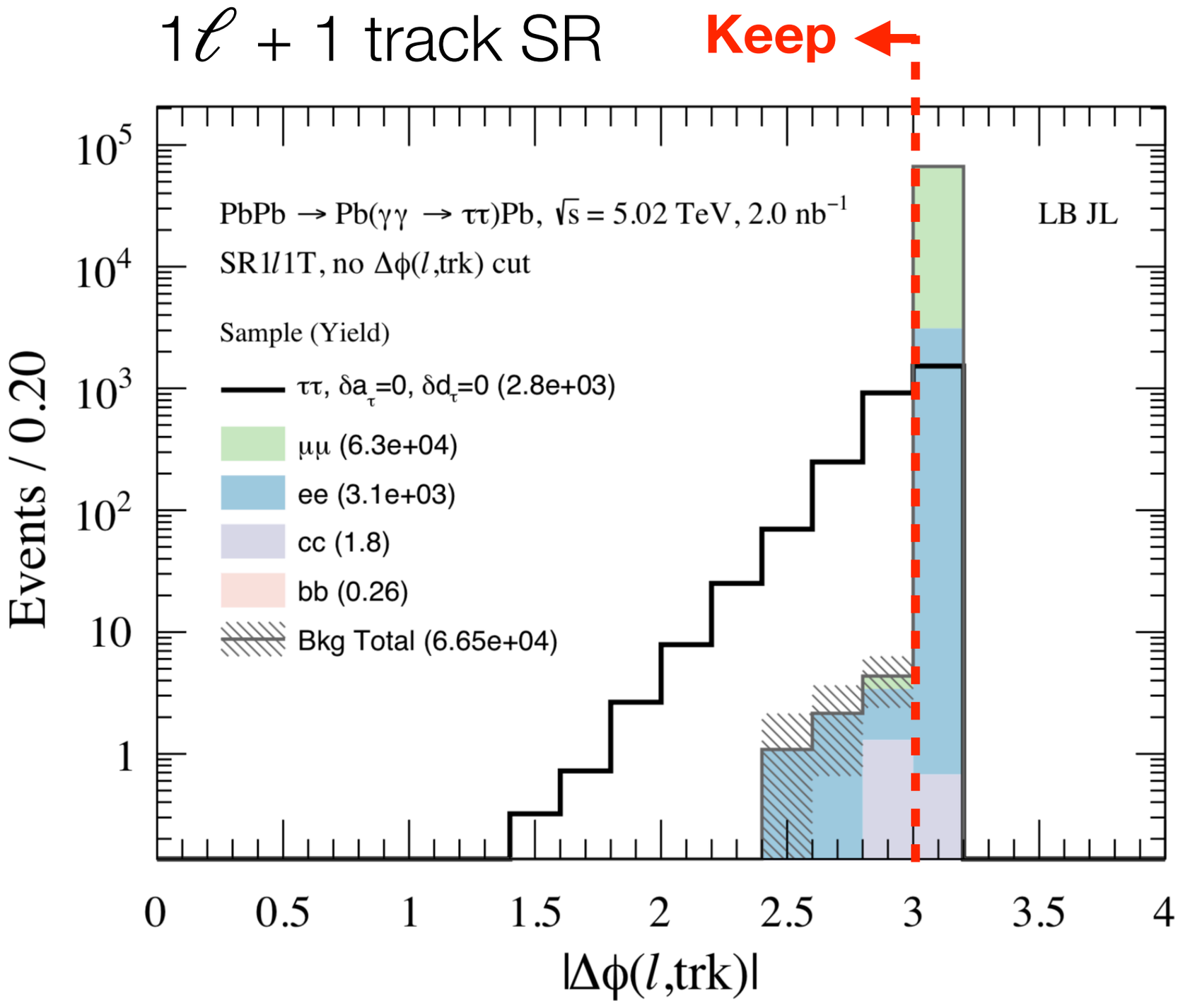
Signal Regions (SRs)

1ℓ + 1 track

1ℓ + 2 track

1ℓ + 3 track

Background mitigation

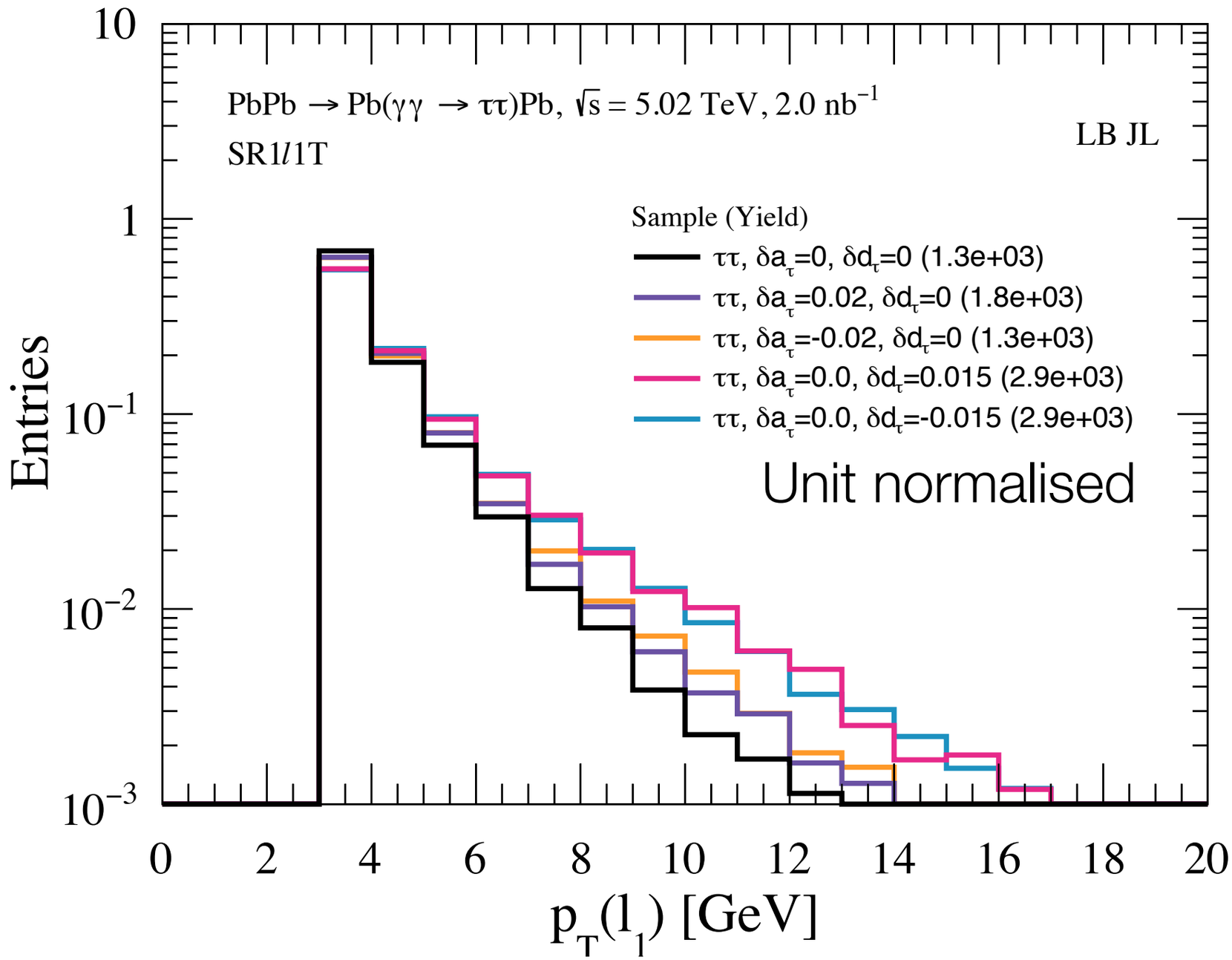


And veto J/ψ & Υ masses

Setting constraints

Also sensitive to τ EDM

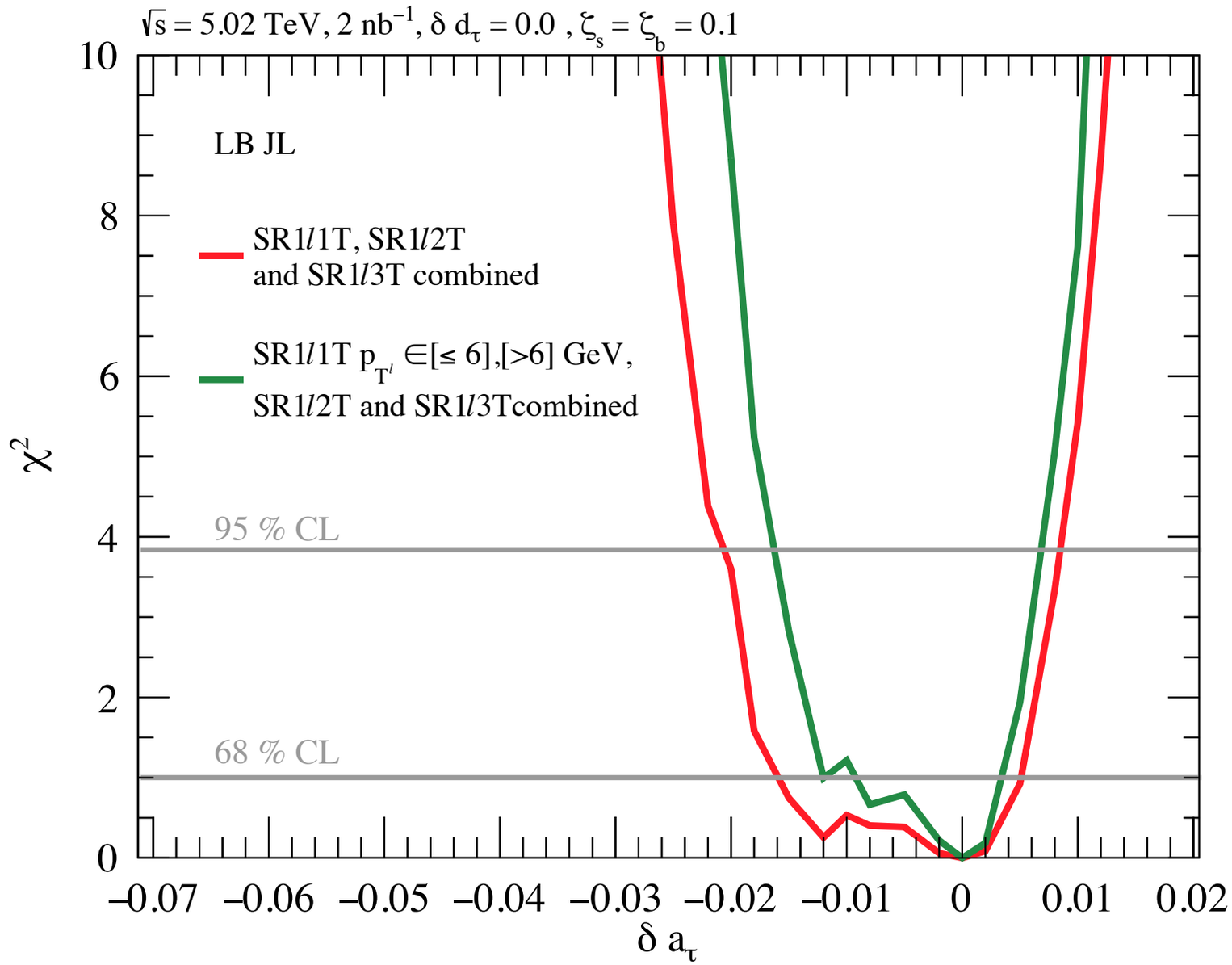
SM effective field theory for modified moments (& SM signal)



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

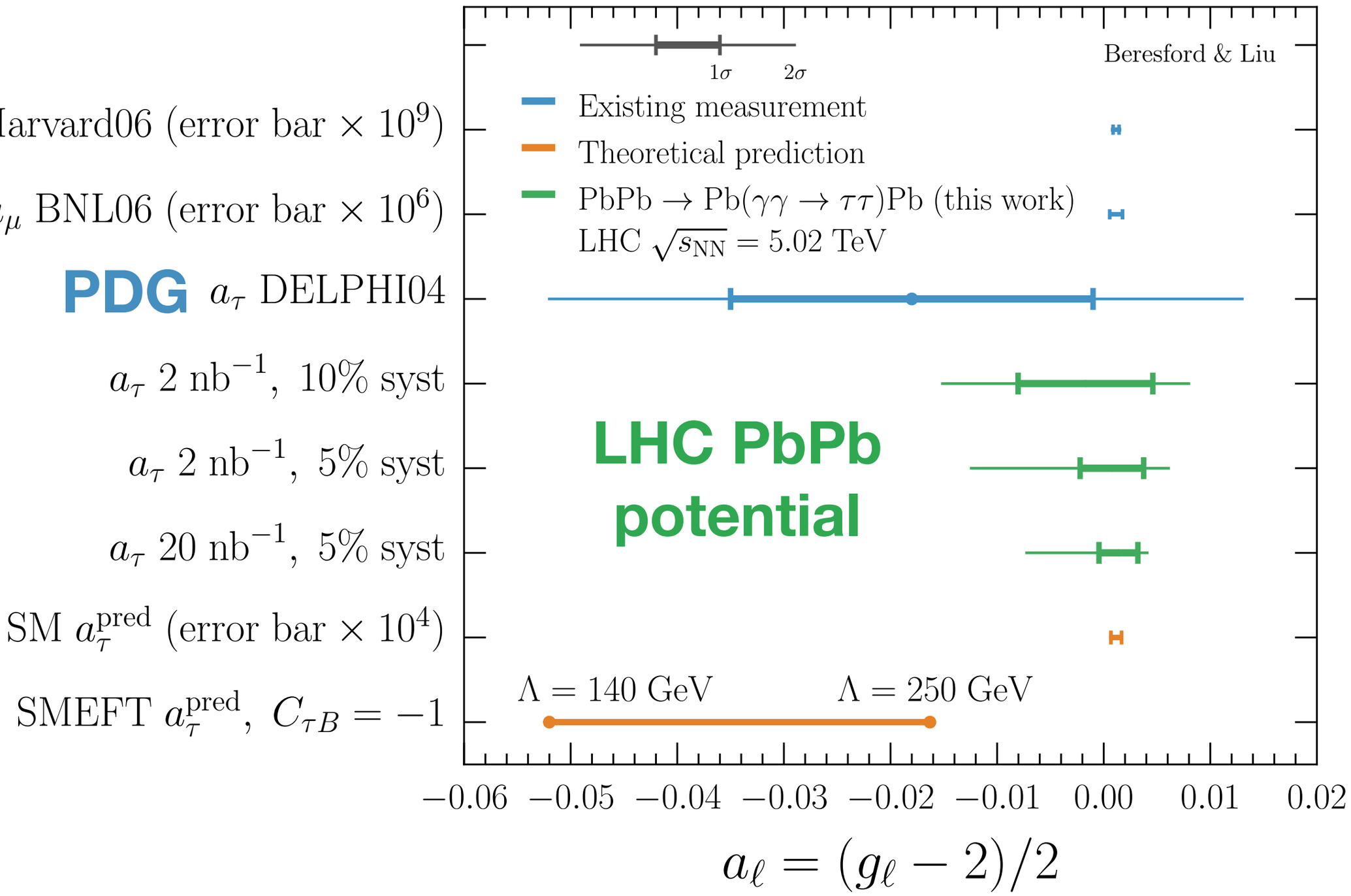
$\Sigma\chi^2$ for all SRs (orthogonal)

Shape analysis strengthens constraints :)

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

Putting it all together: a_τ

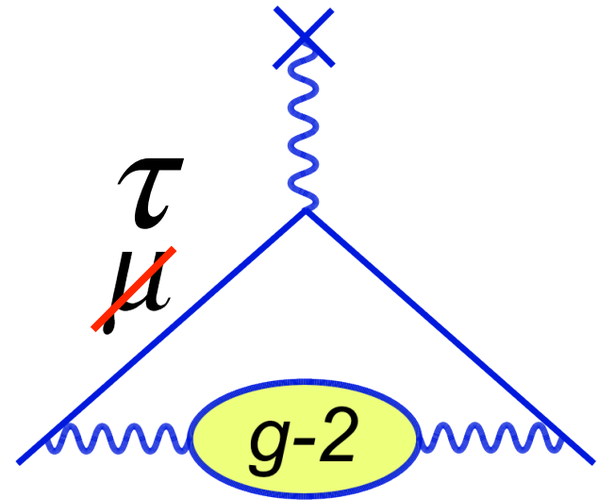
See also link



Surpass DELPHI … or discover tension!

Summary

Tau g-2 interesting & important



But barely constrained

LHC photon collisions promising solution

For tau g-2 and beyond …

… ICHEP photon collisions

Theory

$\gamma\gamma \to \gamma\gamma$ prospects link

Probing CPV in $\gamma\gamma$ link

Dielectron production link

Producing heavy particle pairs link

Colliding light to produce dark matter link

Photoproduction of J/ψ link

Constraining tau g-2 & EDM link

& likely more
I missed

ALICE

Vector meson photo-production link

CMS

Diffractive & exclusive link

LbyL & ALPS link

ATLAS

Photon-fusion measurements link

LHCb

Quarkonia photo-production link

STAR

J/ψ photoproduction link

H1

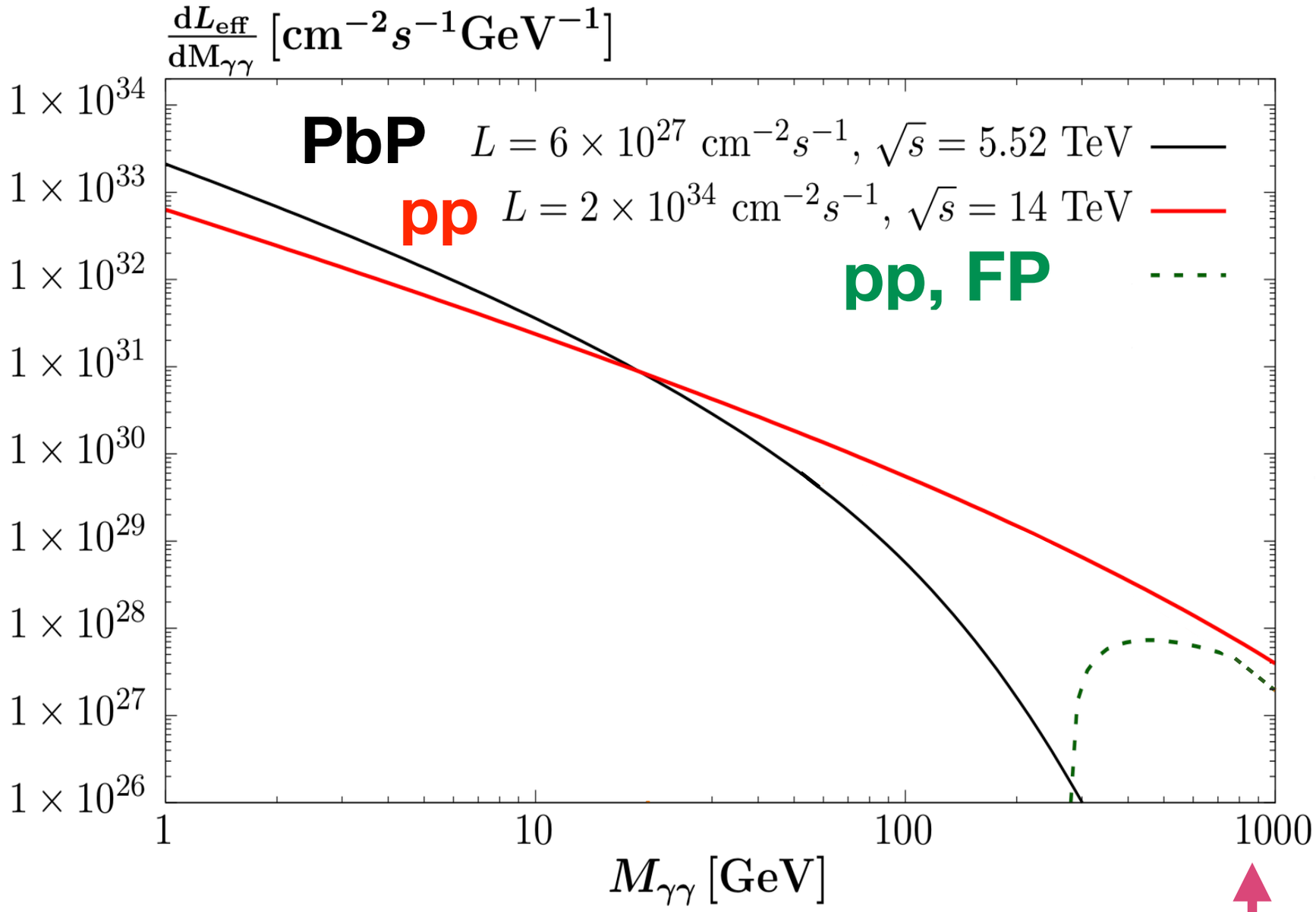
rho(770) photoproduction link

Backup

QED @ a range of masses

Bruce et al [1812.07688](1812.07688)

Intensity frontier →



Energy frontier ↑

$$\sigma_{A_1A_2\to A_1XA_2} = \int dx_1 dx_2\, n(x_1)n(x_2)\widehat{\sigma}_{\gamma\gamma\to X} = \int dm_{\gamma\gamma}\, \frac{d\mathcal{L}_{\rm eff}}{dm_{\gamma\gamma}}\widehat{\sigma}_{\gamma\gamma\to X}\ , \qquad (1)$$

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

What is g-2?

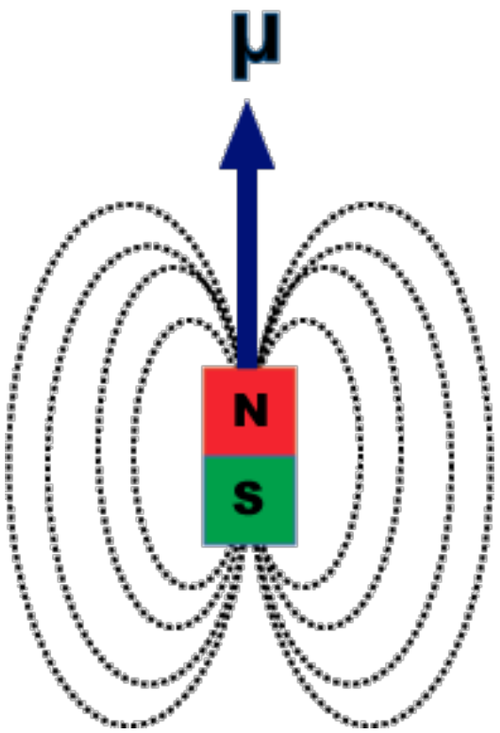
*How objects interact with a **magnetic** field*

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

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$$

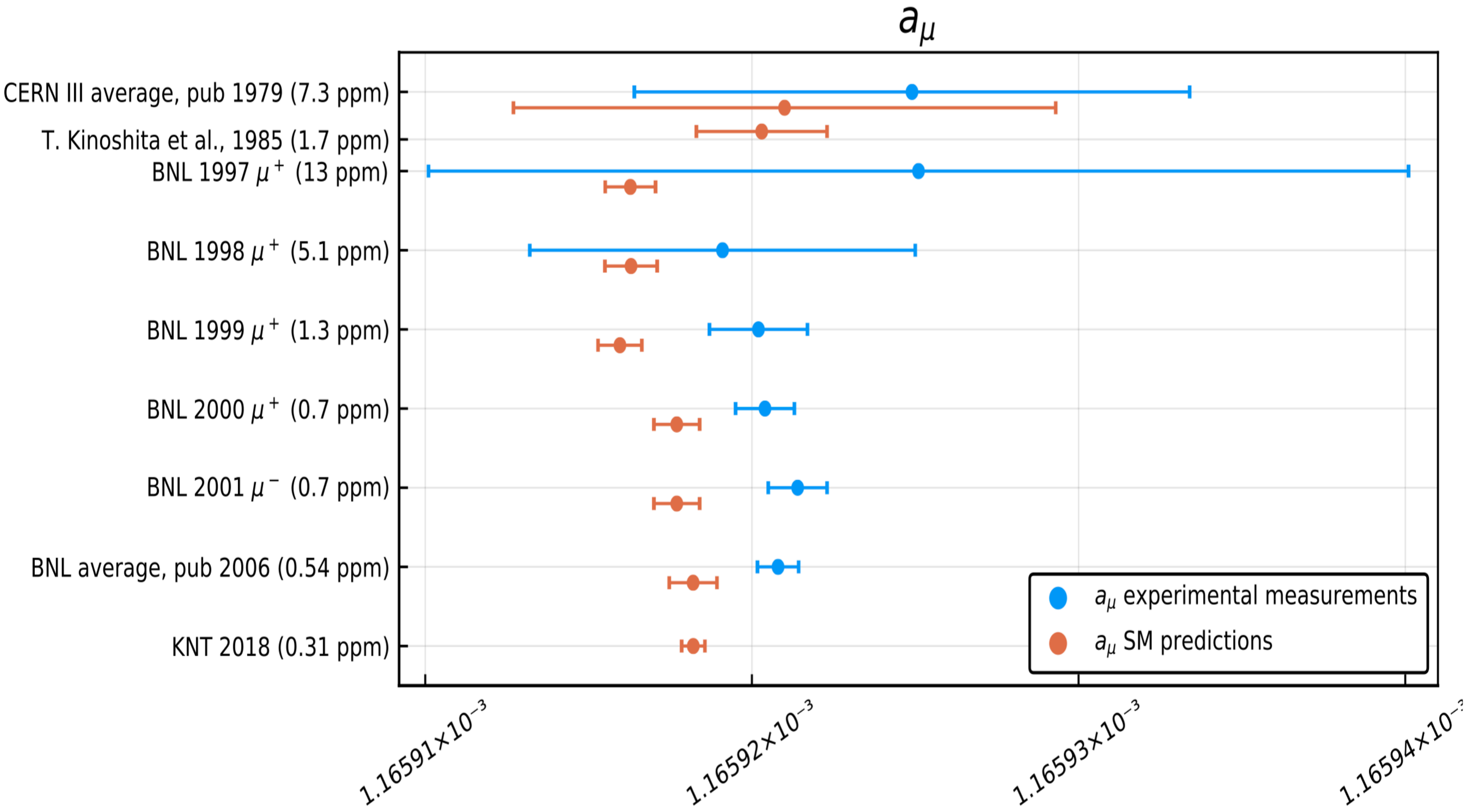
torque magnetic moment

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



a_μ time evolution

Lusiani (2019)



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 $F_{\mu\nu}$

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

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 $\mathrm{U(1)_Y}$ 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]

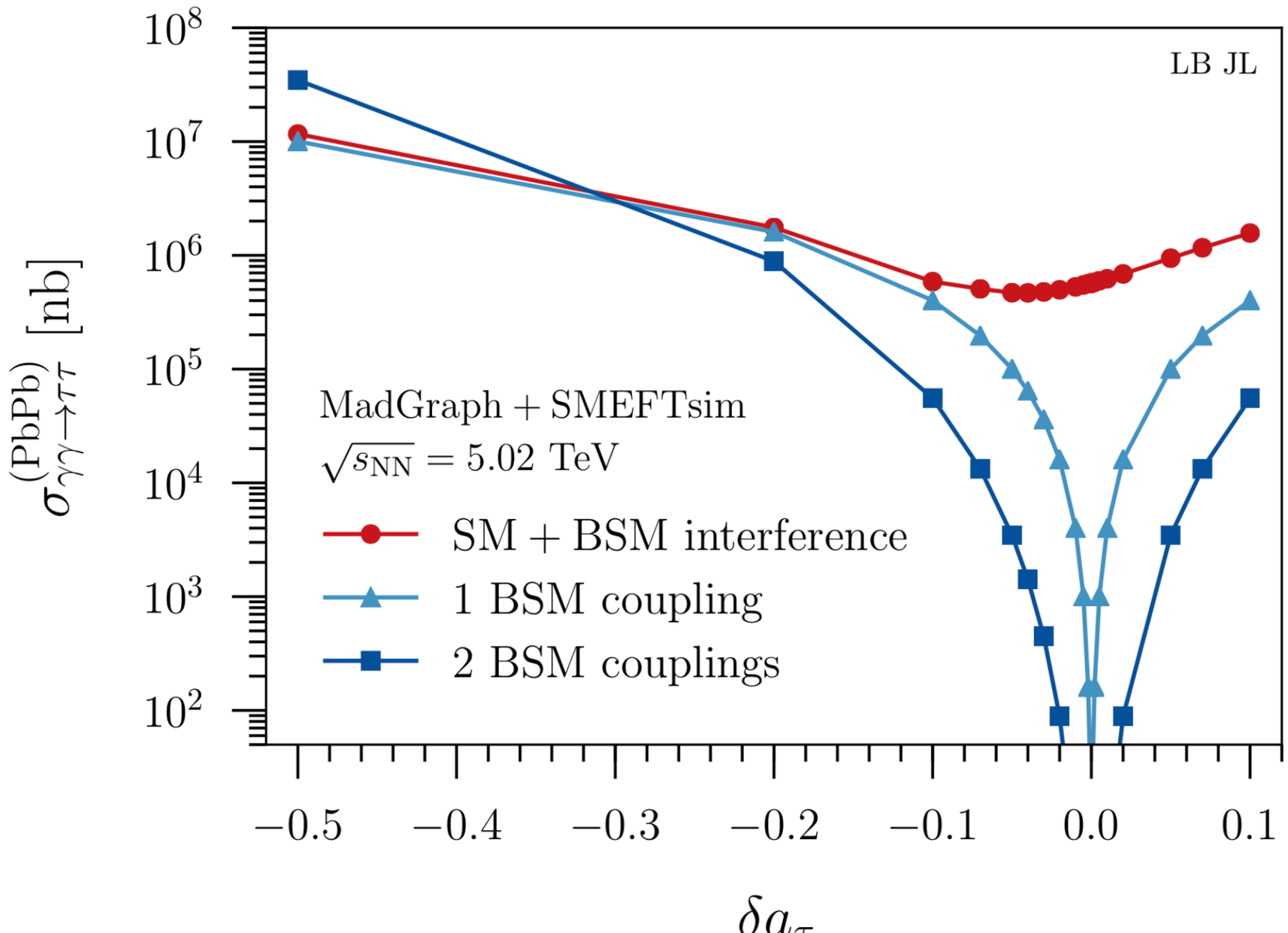
$$\delta a_\tau = \frac{2 m_\tau}{e} \frac{|C_{\tau B}|}{M} \cos\varphi, \quad \delta d_\tau = \frac{|C_{\tau B}|}{M} \sin\varphi, \quad (4)$$

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.

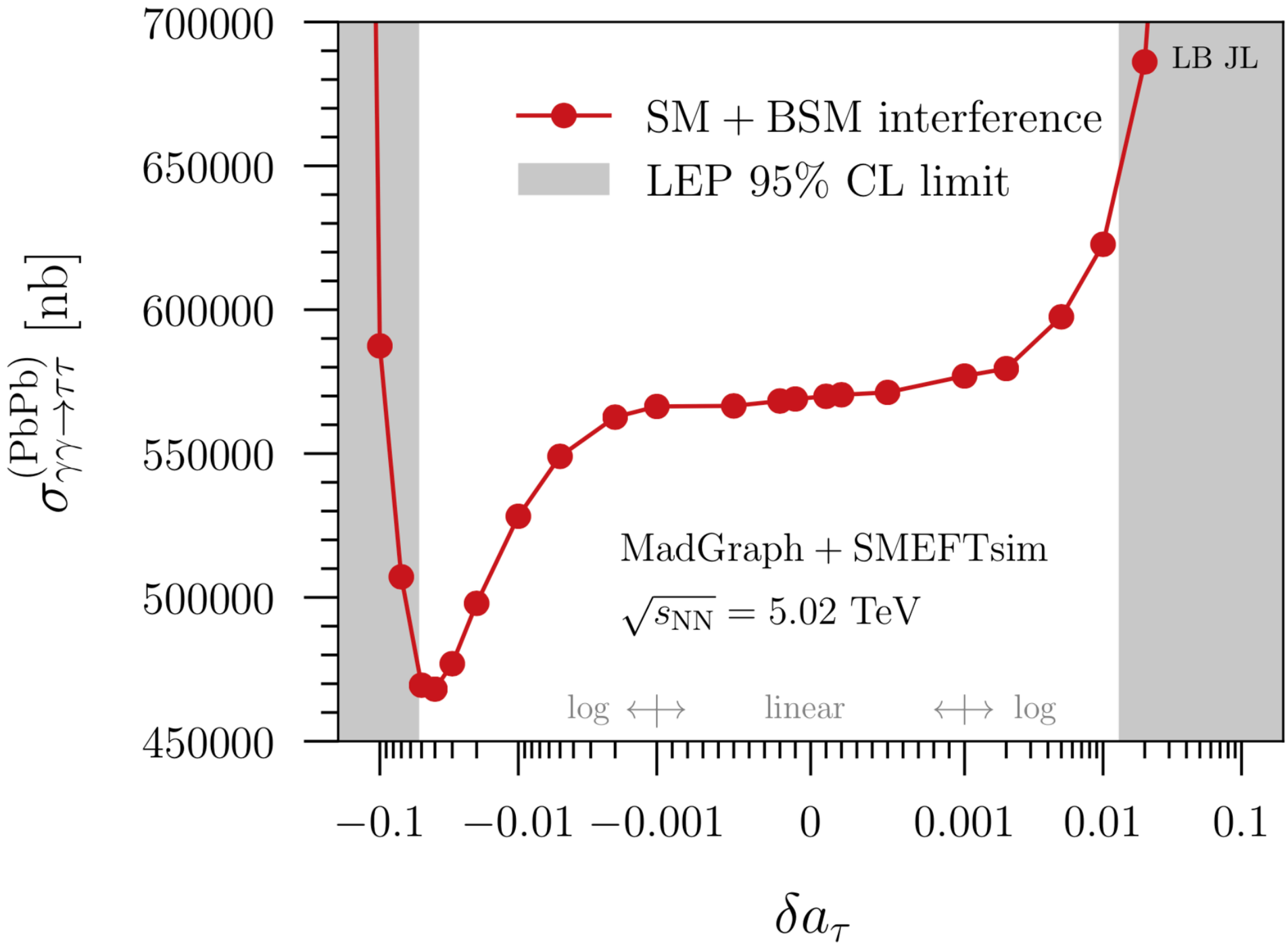
Cross-section & interference

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

$$= \left| \quad + \quad + \quad \right|^2$$

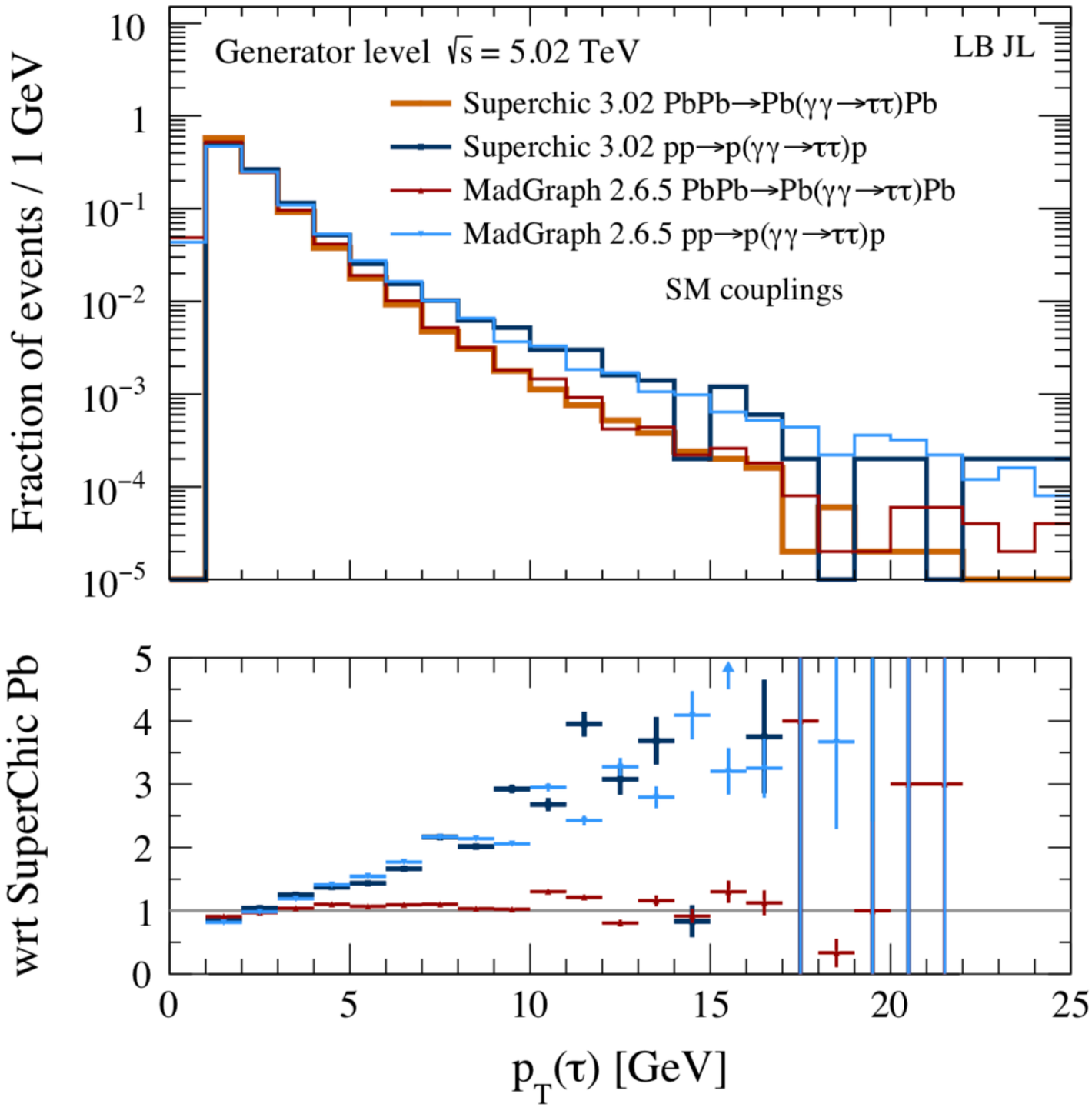


Cross-section & interference (zoomed)

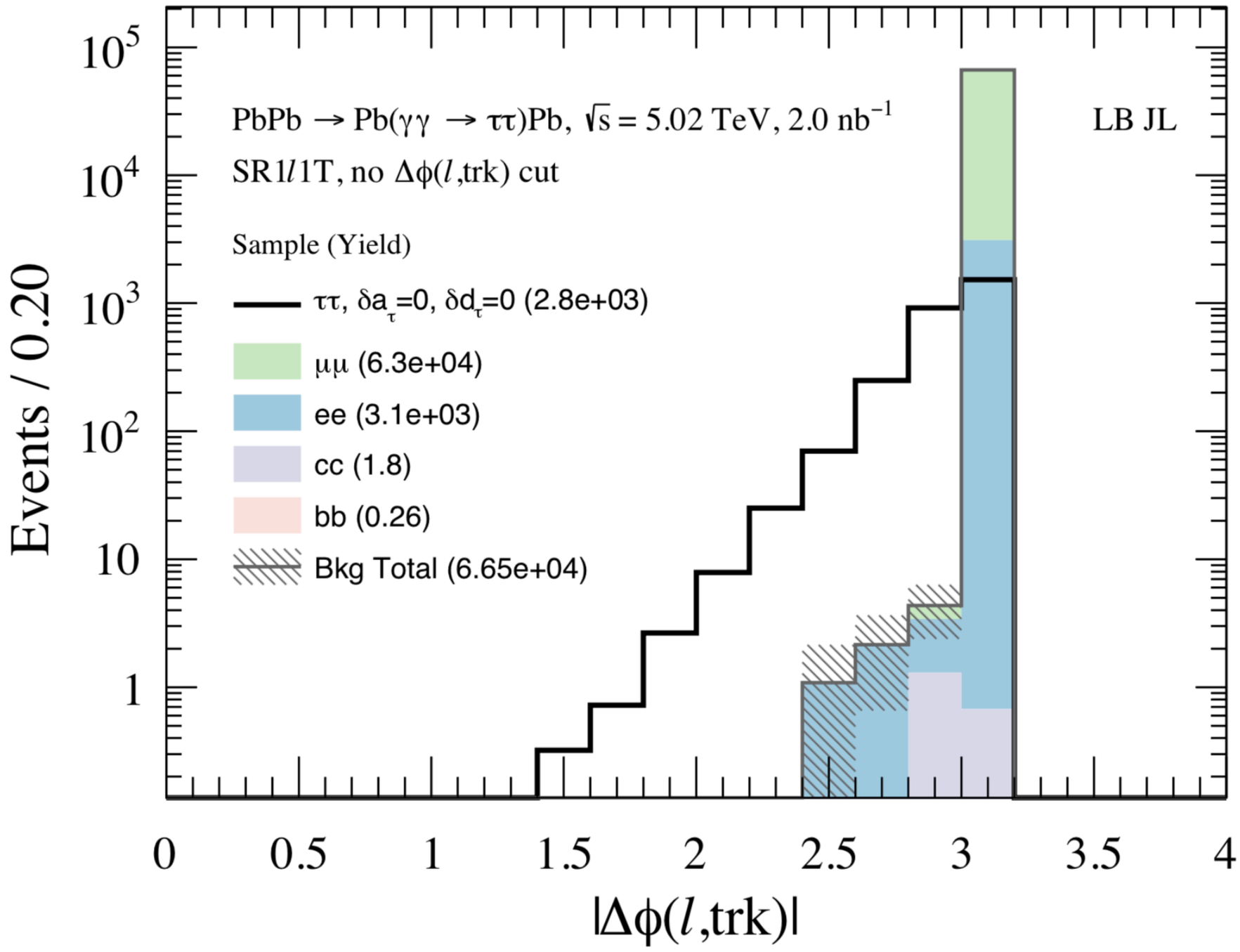


MG vs Super Chic

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.

Why stop there?

Demonstrated PbPb potential for ATLAS/CMS

Goal: Combined effort!

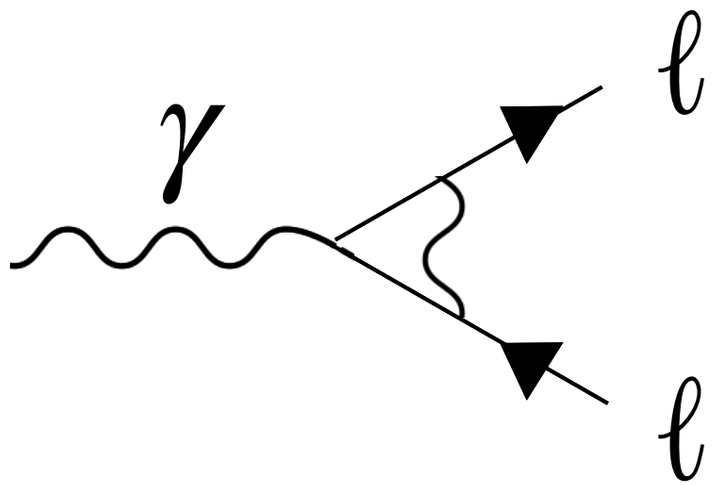
PbPb, pPb, pp?

ATLAS, CMS, LHCb & ALICE

RHIC & lepton colliders

Why stop there?

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



Schwinger, 1948

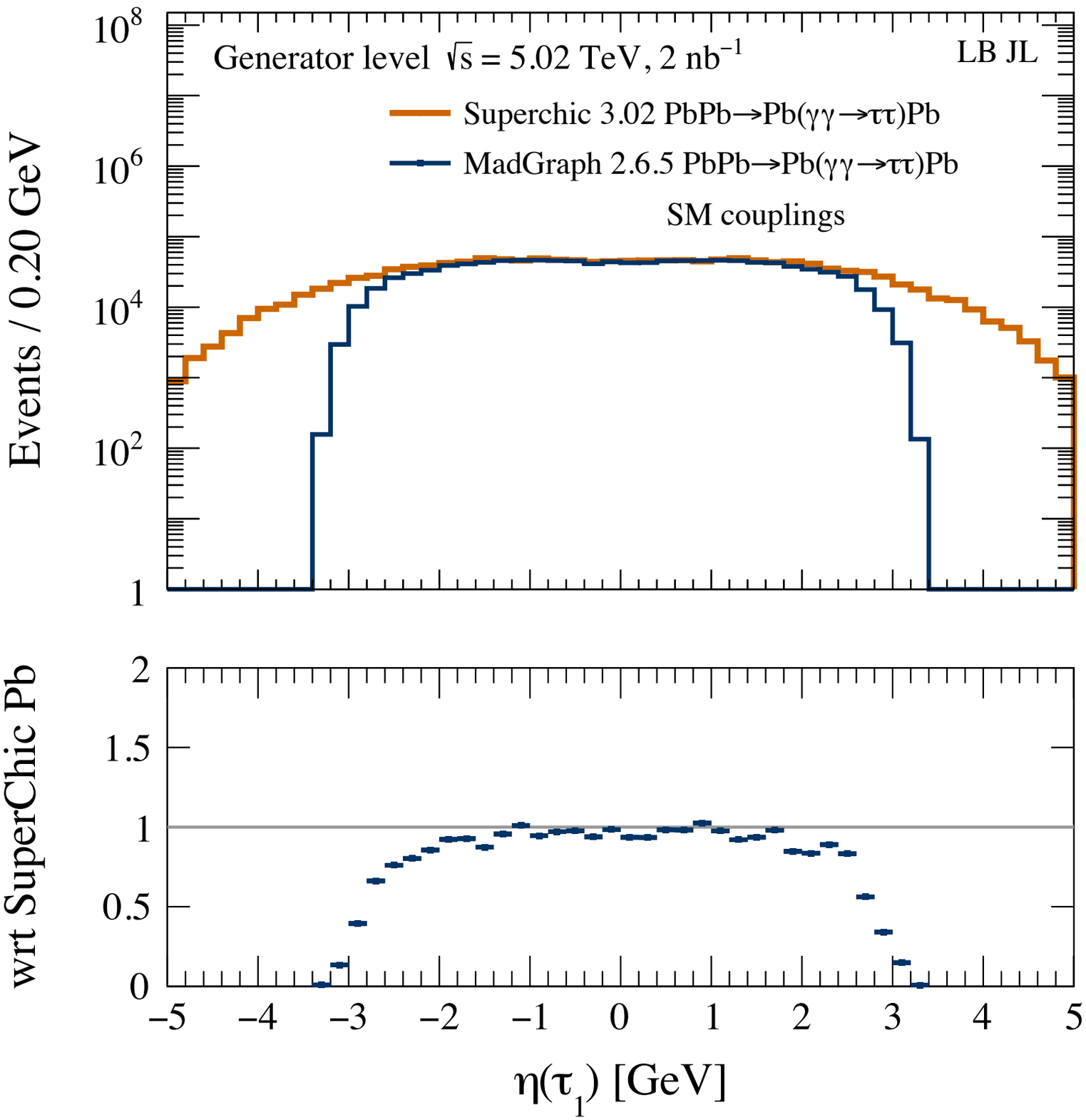
The Schwinger term, $\alpha/2\pi$, in a_τ has the value

$$a_\tau = 0.0012.$$

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

Eta distribution



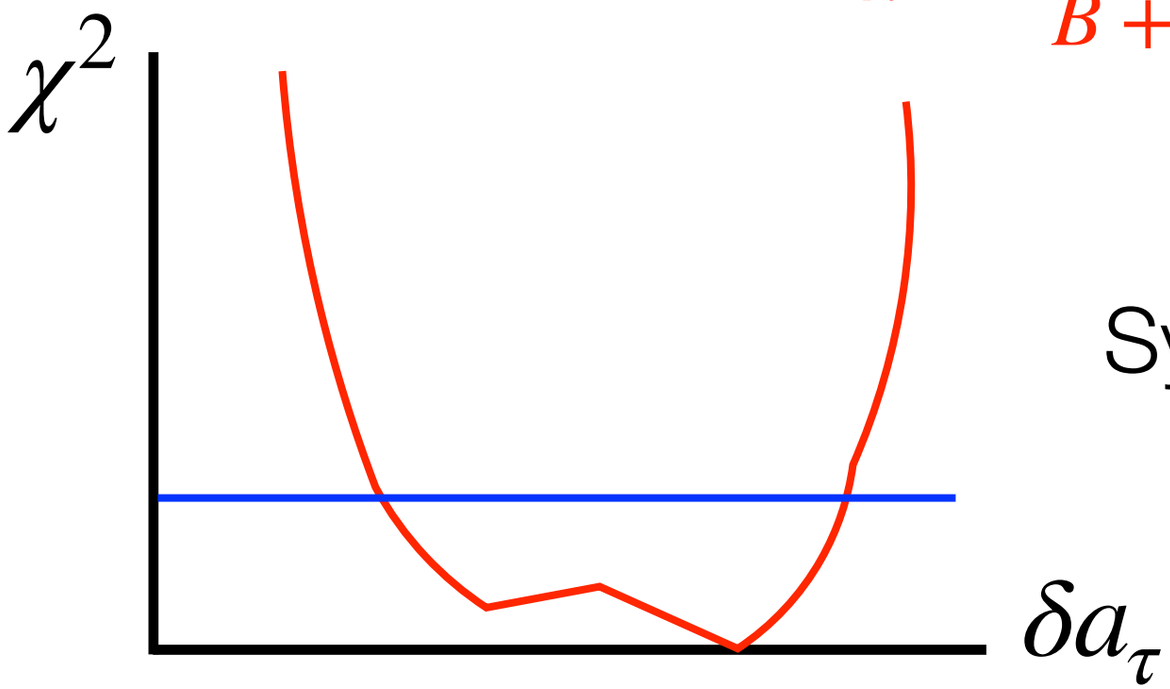
Setting constraints

To set a constraint need to deviate from SM

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

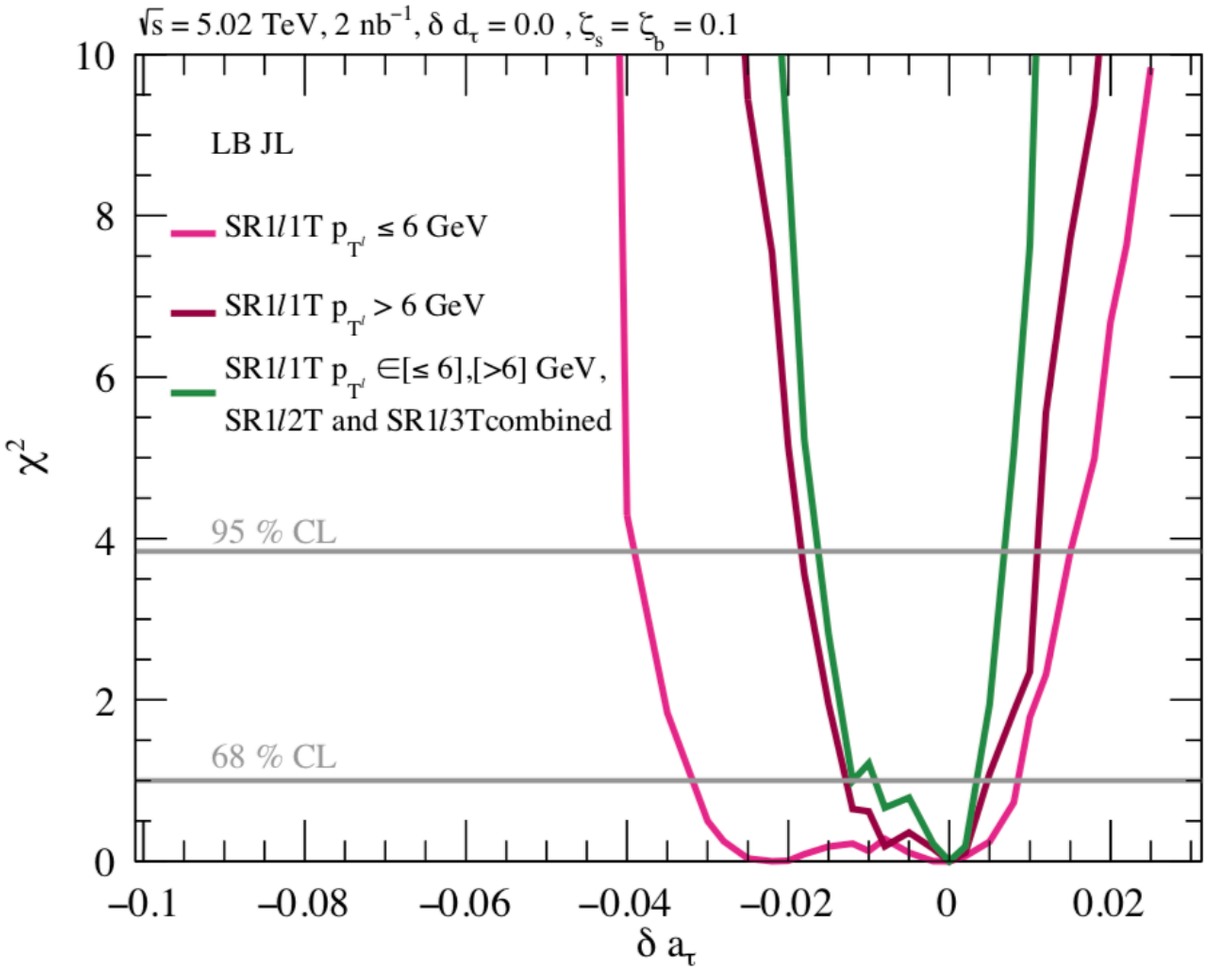
Assume observe SM & quantify constraint using χ^2

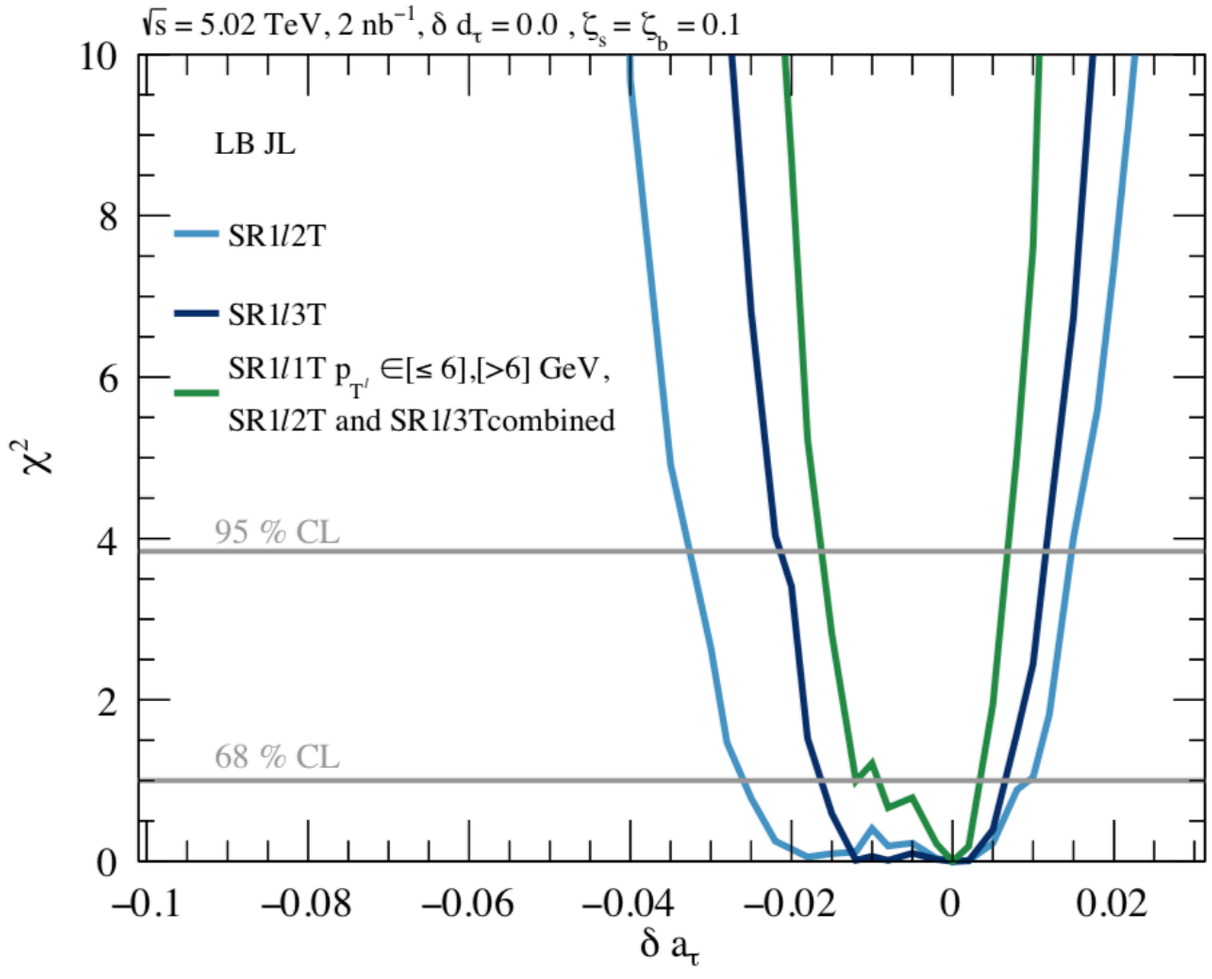
$$\chi^2 = \frac{(S_{\text{SM+BSM}} - S_{\text{SM}})^2}{B + S_{\text{SM+BSM}} + (\zeta_s S_{\text{SM+BSM}})^2 + (\zeta_b B)^2}$$



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

SR Break down: a_τ





Also sensitive to tau EDM

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

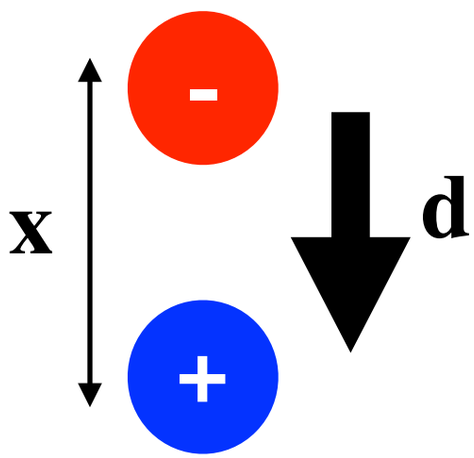
EDM = Electric Dipole Moment

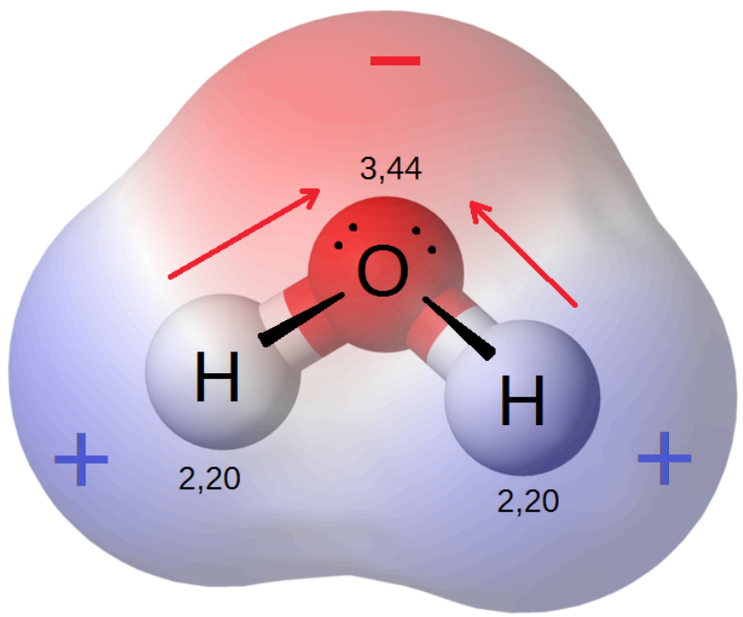
$$\boldsymbol{\tau} = \boldsymbol{d} \times \mathbf{E}$$

↑ torque ↑ electric dipole moment

Possessed by e.g. water (polarised molecule)

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





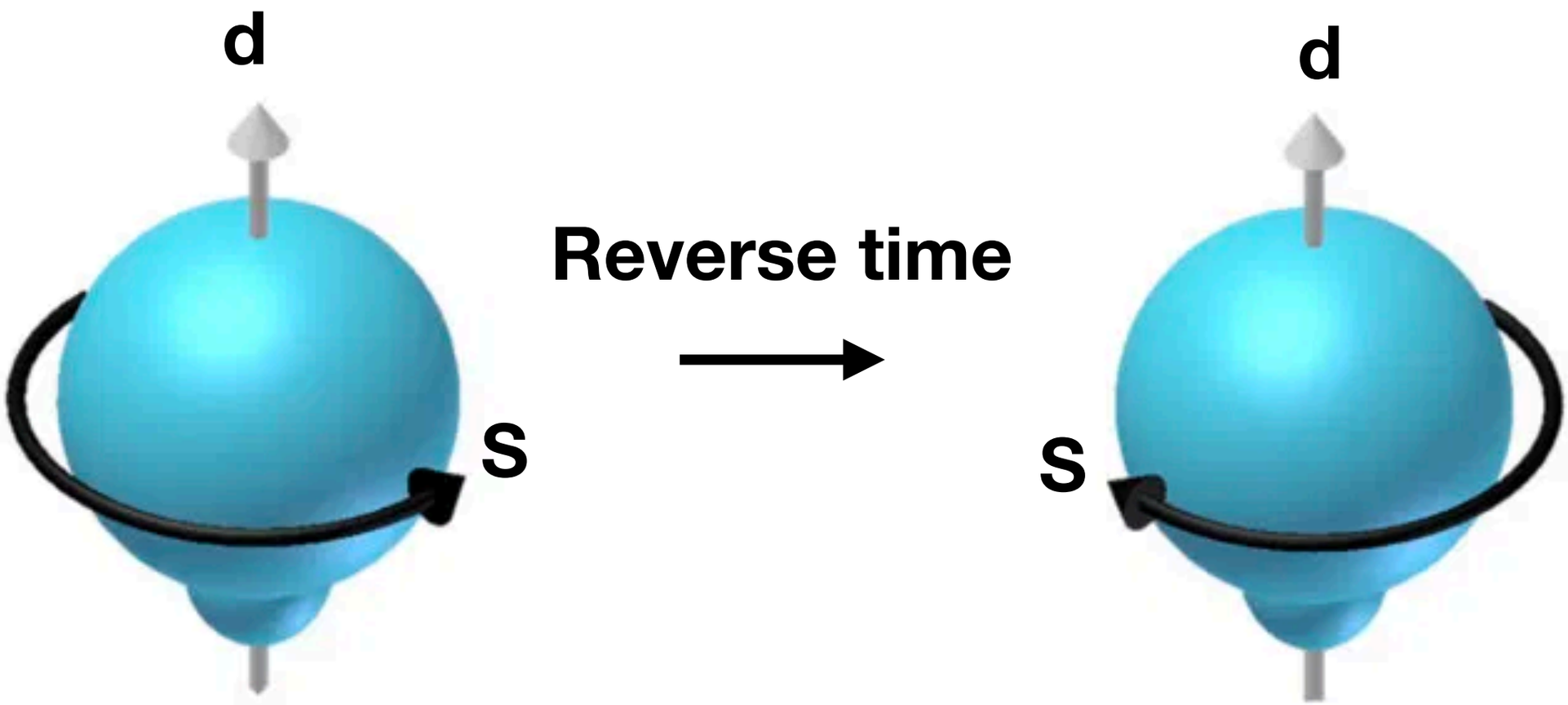
EDM tells us about charge distribution

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

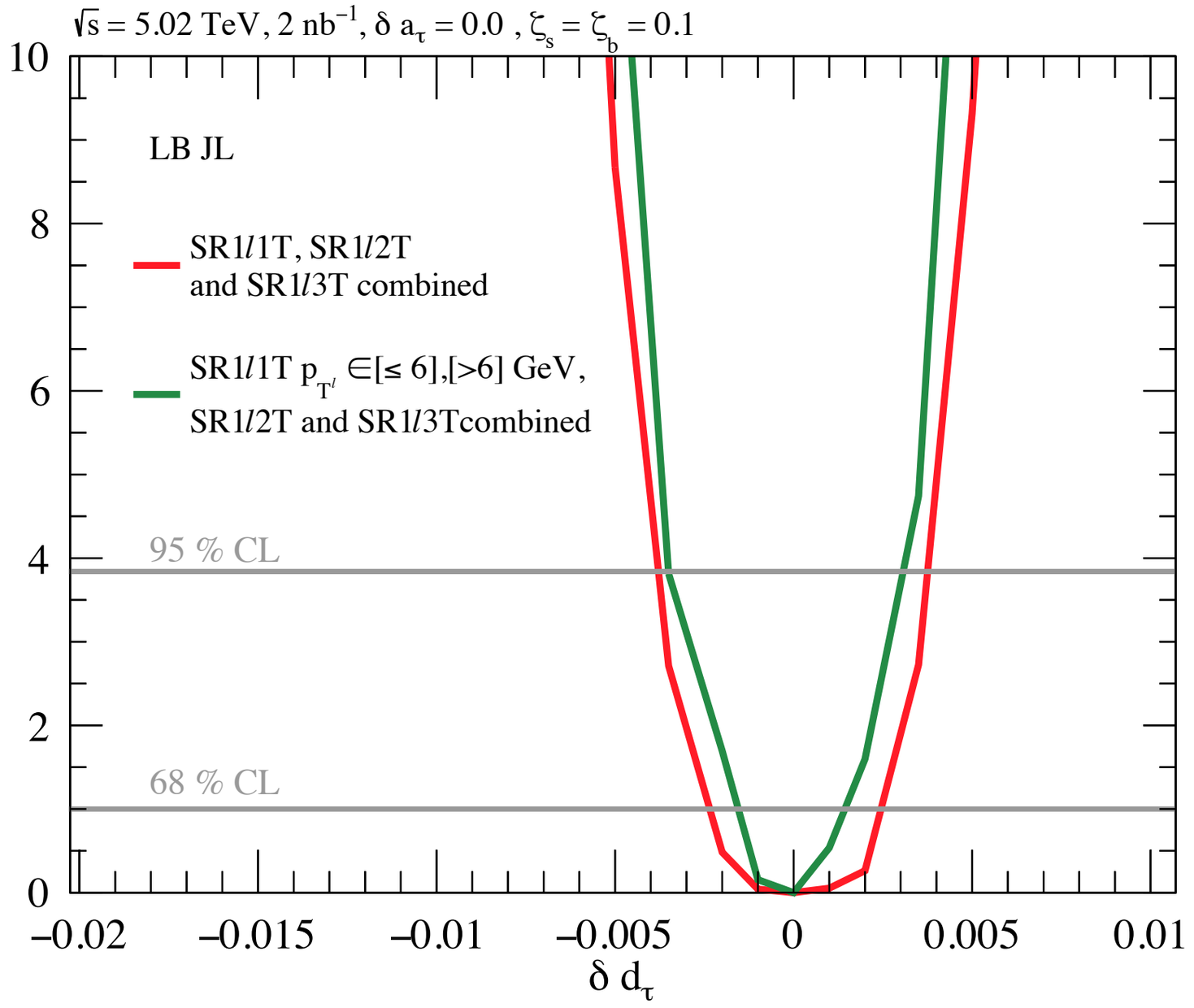
Belle PLB (2003)

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

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

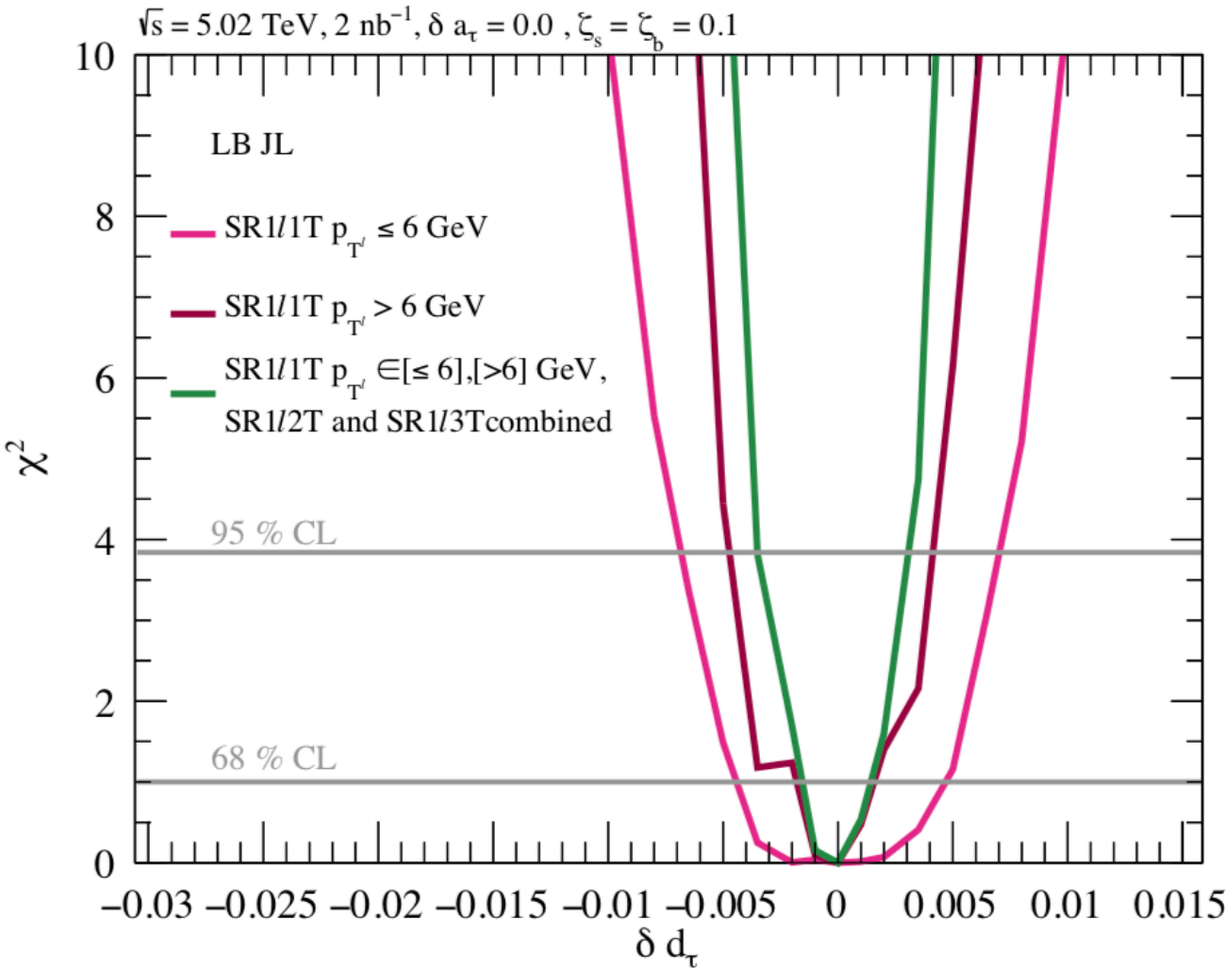
@ 95% CL

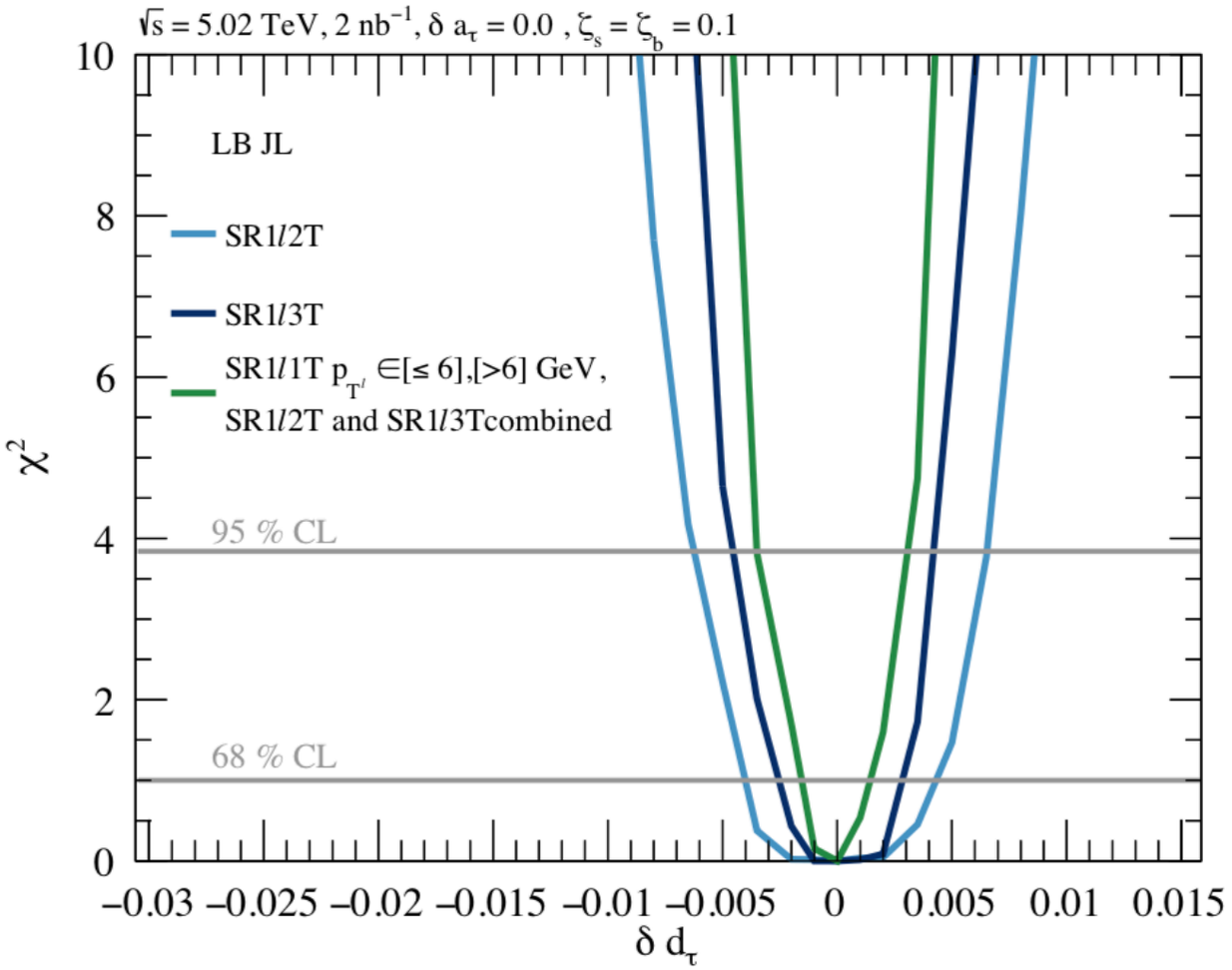
$\Sigma\chi^2$ for all signal regions (orthogonal)



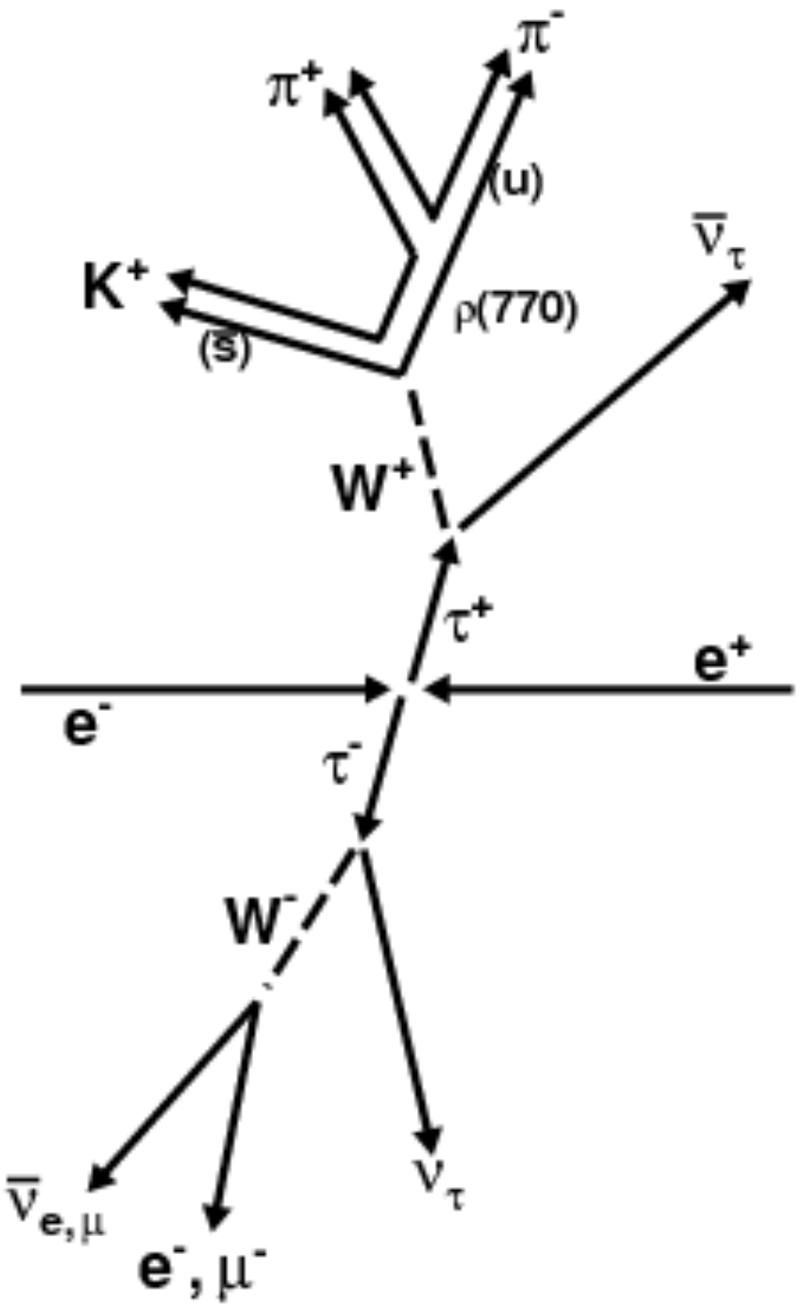
Order mag better than DELPHI, competitive with Belle

SR Break down: d_τ

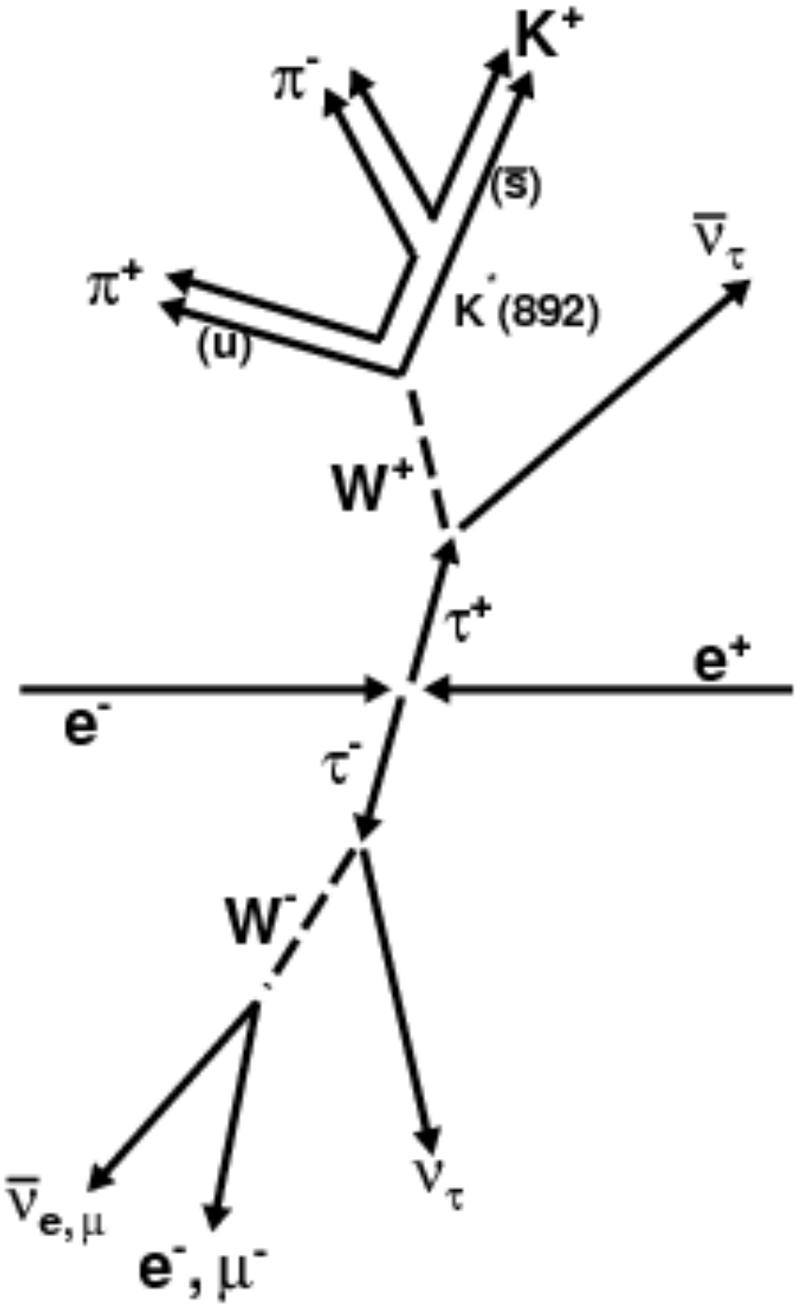




Example tau decays



(a)



(b)