Dark matter & tau $g-2$

Using the LHC as a photon collider

Snowmass Energy Frontier

Open Questions and New Ideas | 8 July 2020

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University of Chicago

THE UNIVERSITY OF CHICAGO

In collaboration with Lydia Beresford (University of Oxford)

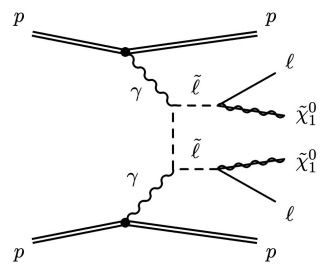
Who we are

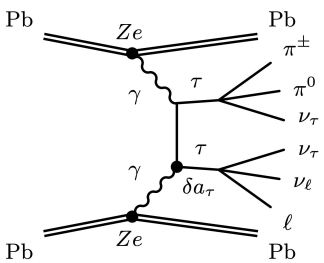
Jesse Liu
University of Chicago
Background: SUSY pMSSM
Higgsino DM searches

Lydia Beresford
University of Oxford
Background: dijet (+ISR)
Exotics/Higgs/DM searches

Common interests: discover new physics, ATLAS experiment, phenomenology, ATLAS Forward Proton detector, photon collisions, dark matter, Higgs self-coupling, anomalous EM moments, novel measurements & searches, new ideas & synergies

Our 2 proposals as key science targets for this decade





Hot topic
Flagship science, has $$$$

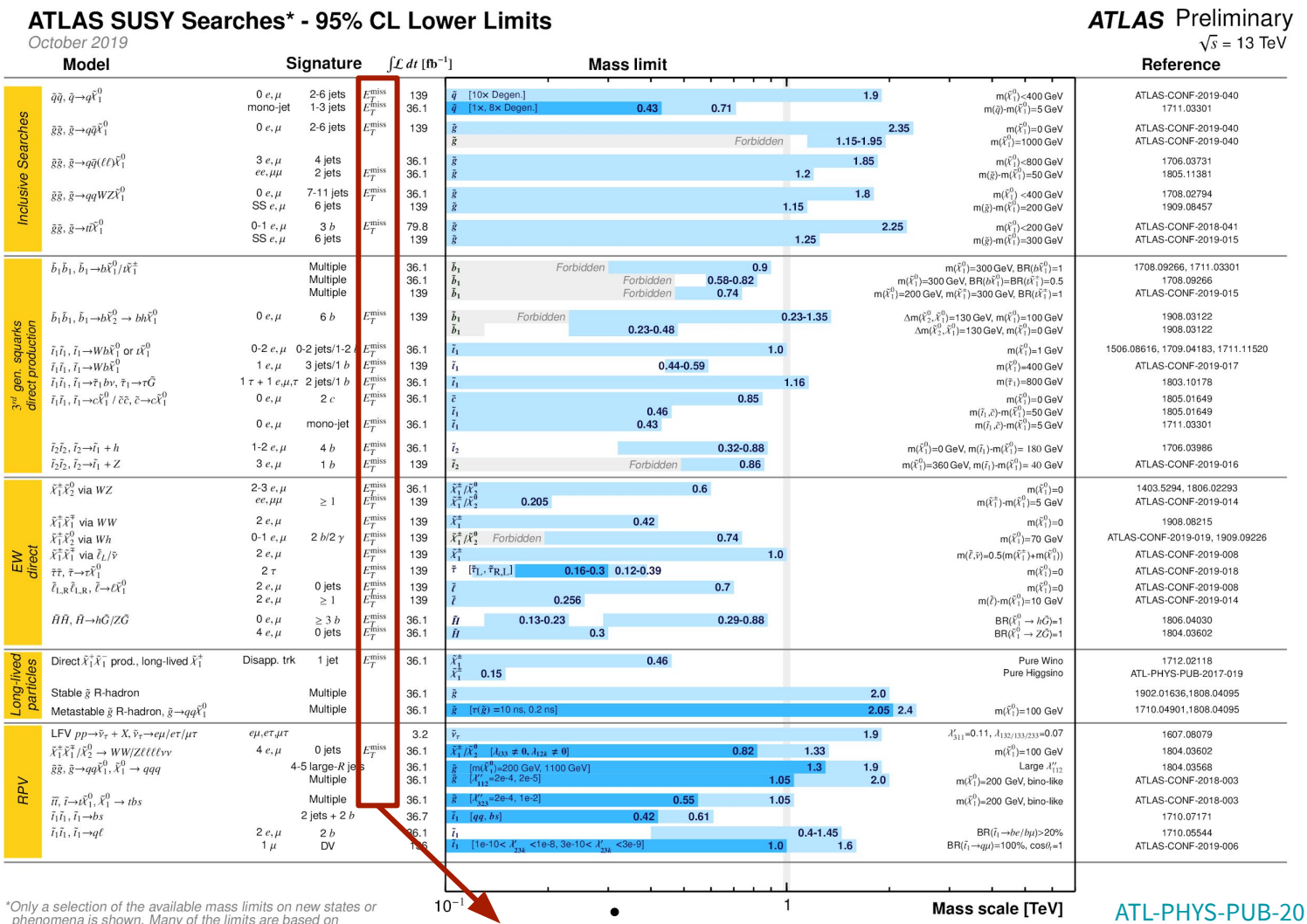
Critical problem
Dismissed as hopeless $

Creative solution
From overlooked areas $

Breakthrough
New field, attract $$$$

What is dark matter?	**Muon *g* – 2 tension?**
p_{miss} 4-vector immeasurable	**Tau *g* – 2 immeasurable**
***Collide light* to tag protons**	***Collide light* with heavy ions**
Direct dark matter mass measurement	**Test 70 year old QED 1-loop prediction**
LB JL [PRL **123** (2019) 141801]	LB JL [1908.05180]

All existing LHC dark matter searches are “MET + X”



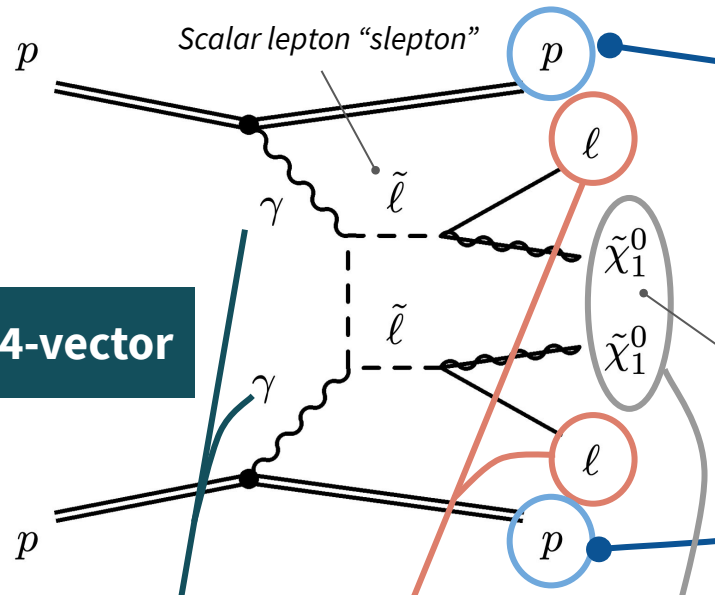
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATL-PHYS-PUB-2019-044
See also EF08, EF10

E_T^{miss}

Transverse – but really we want 4-vector!

Impossible no more: 4-vector p_{miss} + X @ LHC



1

Measure intact protons

2

Compute photon 4-vector

$$p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_f^{\text{visible}} \quad \Rightarrow \quad m_{\text{miss}}^2 = p_{\text{miss}}^2$$

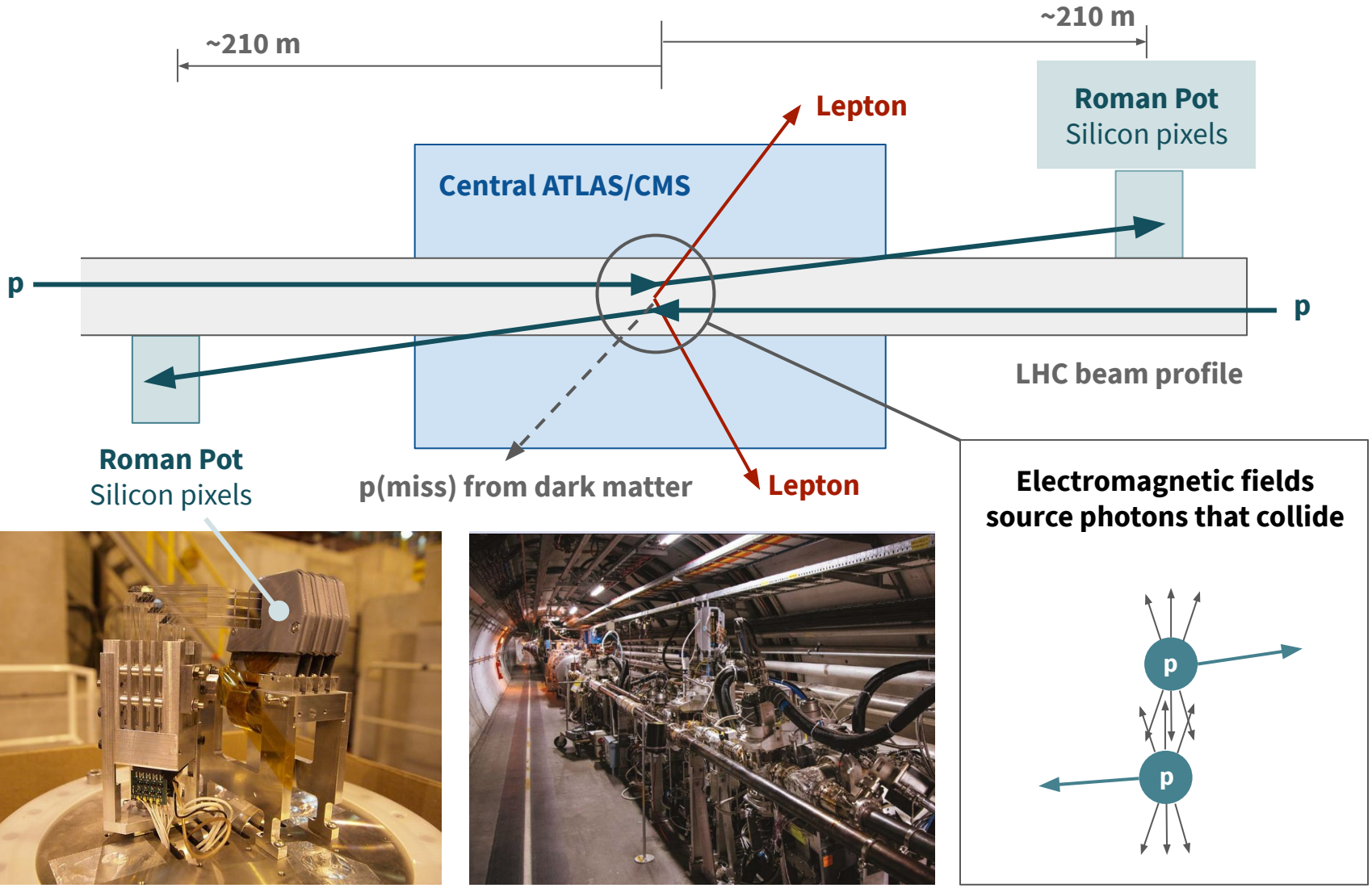
3

"Impossible @ hadron colliders"
no more

Square 4-vector to measure dark matter mass!

Beresford & JL 1811.06465, Harland-Lang, Khoze, Ryskin & Tasevsky 1812.04886

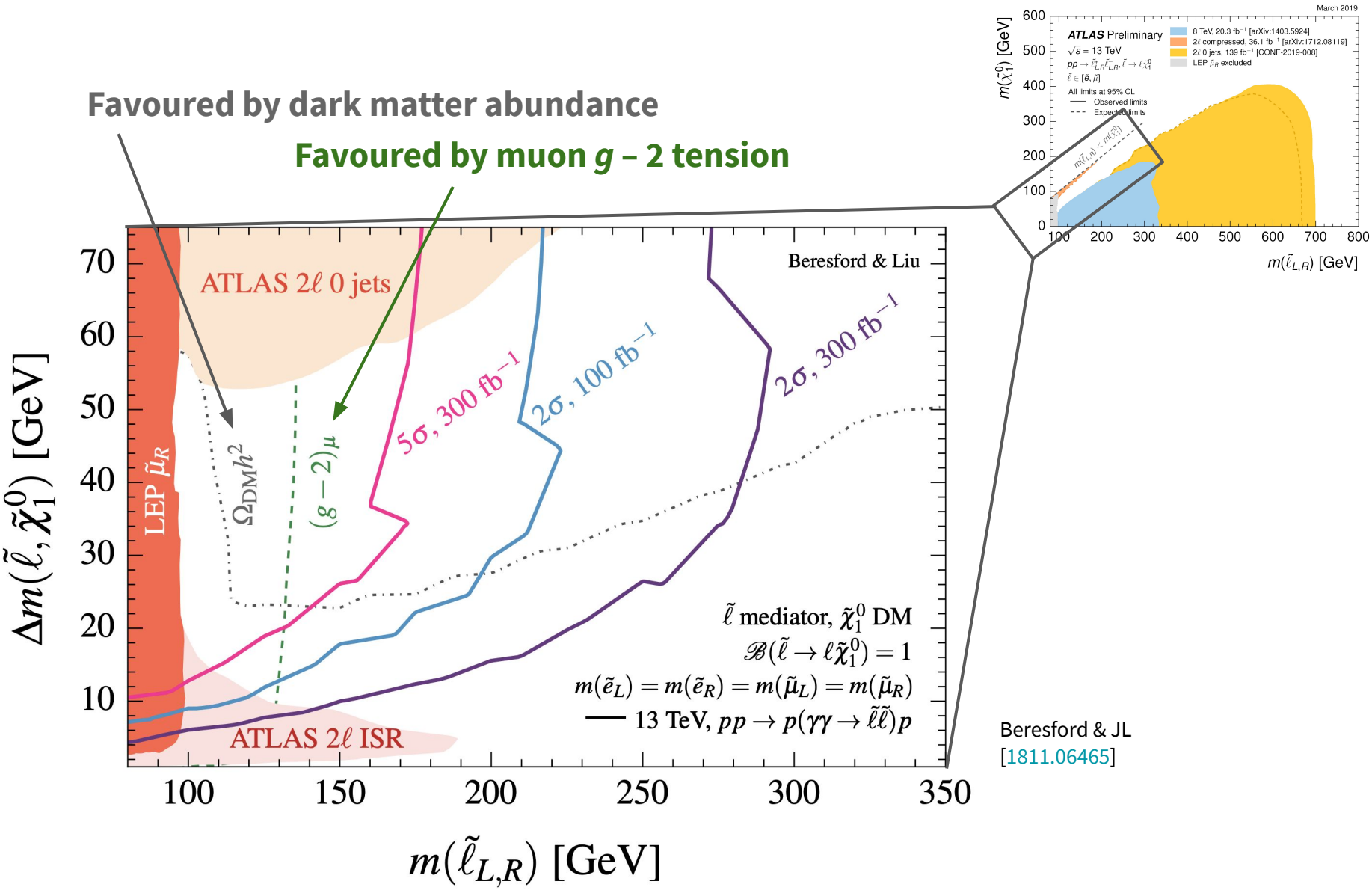
Pioneering proton detectors operated 2017/16



ATLAS Forward Proton [TDR]

CMS–TOTEM Precision Proton Spectrometer [TDR]

Turning light into dark matter by next Snowmass?



Beresford & JL
[1811.06465]

What about tau *g* – 2?

Shocking experimental ignorance!

Current PDG value is by DELPHI 2004

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

DELPHI [hep-ex/0406010]

$$a_{\tau,\,\rm SM}^{\rm pred} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

Pressing problem: no measurement!

Not even testing 1-loop QED: $\alpha/2\pi$ = 0.001162

Schwinger (1948)

Pressing & *interesting* open problem

Huge uncertainty
⇒ huge room for new physics

$$\delta a_\ell \sim m_\ell^2 / M_{\rm SUSY}^2$$
$$m_\tau^2 / m_\mu^2 \sim 280$$

280× more sensitive
to new physics
than muon *g* – 2

No model shortage for e & μ *g* – 2!

SUSY, vector-like lepton, 2HDM, axion, dark photon, Z' e.g.
Martin, Wells [hep-ph/0103067]
Czarnecki, Marciano [hep-ph/0102122]
Pospelov [0811.1030]
Cahill-Rowley, Hewett, Ismail, Rizzo [1407.4130]
Ajaib, Dutta, Ghosh, Gogoladze, Shafi [1505.05896]
Allanach, Queiroz, Strumia, Sun [1511.07447]
Di Chiara, Fowlie, Fraser, Marzo, Marzola, Raidal, Spethmann [1704.06200]
Poh, Raby [1705.07007]
Cherchiglia, Stöckinger, Stöckinger-Kim [1711.11567]
Davoudiasl, Marciano [1806.10252]
Crivellin, Hoferichter, Schmidt-Wellenburg [1807.11484]
Li, Li, Yang [1808.02424]
Liu, Wagner, Wang [1810.11028]
Dutta, Mimura [1811.10209]
Mohlabeng [1902.05075]
Endo, Wen [1906.08768]
Badziak, Sakurai [1908.03607]
Bauer, Neubert, Renner, Schnubel, Thamm [1908.00008]
…

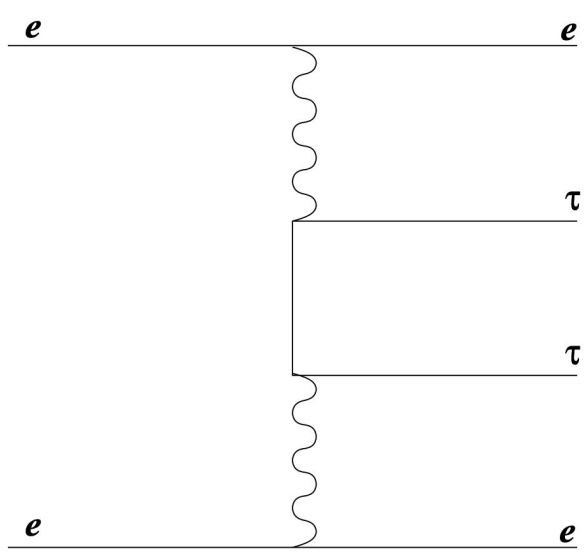
How can we measure tau *g* – 2?

Belle-II/CLIC/ILC/FCC-ee:
Eidelman, Epifanov, Fael, Mercolli, Passera [1601.07987]
Chen, Wu [1803.00501]
Koksal, Billur, Gutierrez-Rodriguez, Hernandez-Ruiz [1804.02373]
Howard, Rajaraman, Riley, Tait [1810.09570]
LHeC/FCC-eh:
Köksal [1809.01963],
Gutiérrez-Rodríguez, Köksal, Billur, Hernández-Ruíz [1903.04135]
Proton fixed target & bent crystals:
Fomin, Korchin, Stocchi, Barsuk, Robbe [1810.06699]
Fu et al [1901.04003]

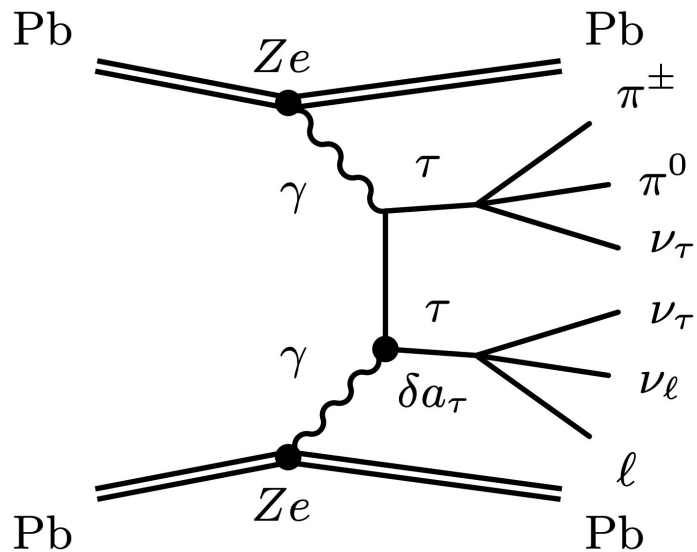
Currently a few ideas: progress requires community investment, strategy & consensus [RF03 synergies]

Low hanging fruit: bring LEP success to LHC?

PDG value of tau *g* – 2



Proceed analogously @ LHC?



LEP photon collisions

$\sigma \sim 400$ pb

$\Rightarrow$ 200k events all years

DELPHI [EPJC (2004)]

Never been measured at LHC

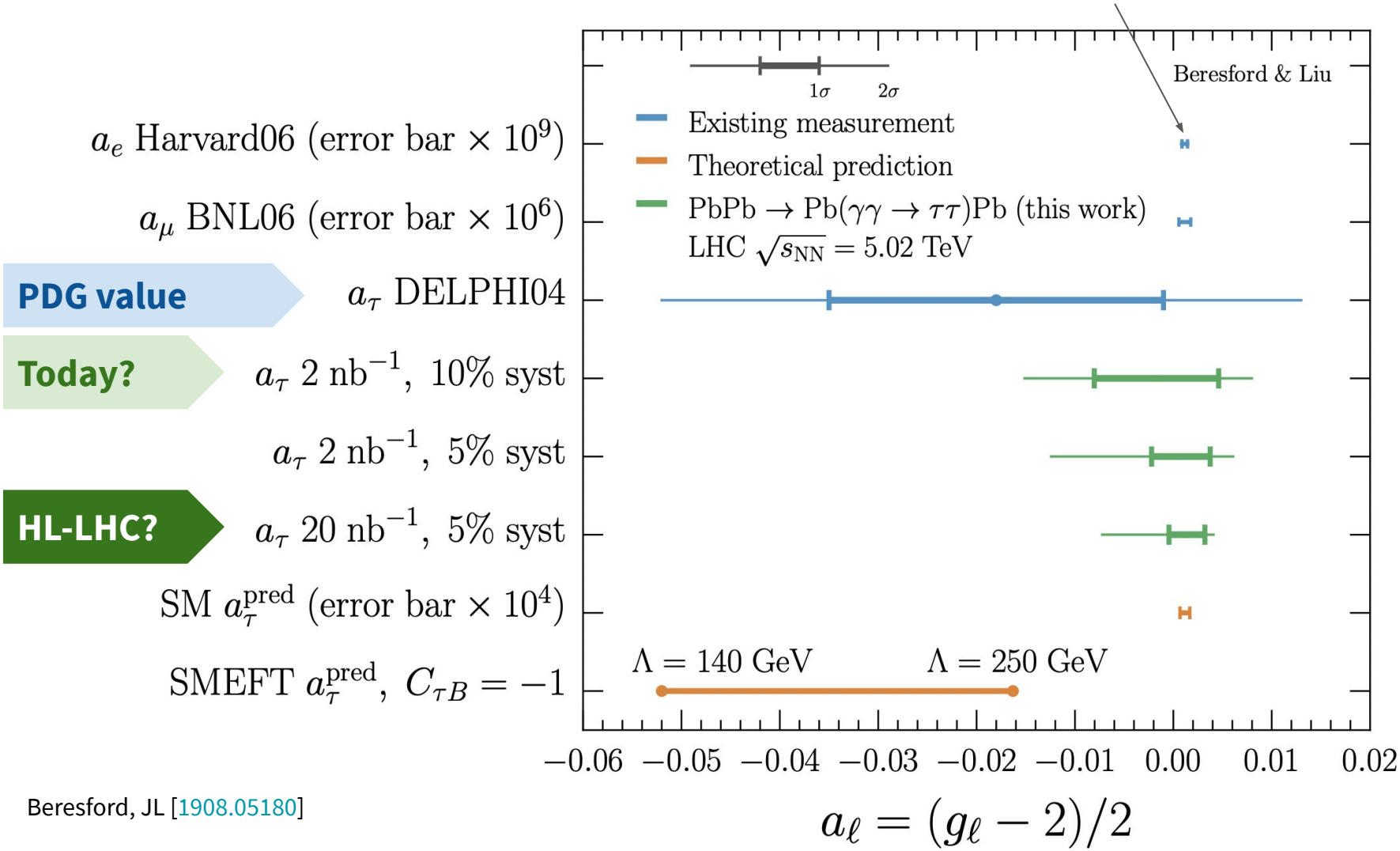
$\sigma \sim Z^4 \sim 500\,000$ nb ($Z_{Pb} = 82$)

$\Rightarrow$ 1 million events *already*

del Aguila, Cornet, Illana (PLB 1991)
Beresford, JL [1908.05180]

Discover huge $g_\tau - 2$ or reach 1-loop QED by next Snowmass?

If to scale, error bar would be **width of atom** on this screen



Beresford, JL [1908.05180]

Our Snowmass Letter of Interest: building a programme

Our LoI [SNOWMASS21-EF9-019] EF09 as home + EF06–10 cross-topic; RF03, RF06, CF07, IF03, TF07, AF3 cross-frontier synergies

Strategic vision for energy frontier photon collider science

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

[1] *Department of Physics, University of Oxford, Oxford OX1 3RH, UK*
[2] *Department of Physics, University of Chicago, Chicago IL 60637, USA*

(Dated: June 30, 2020)

Recent landmark results are renewing interest in using the LHC as a photon–photon $\gamma\gamma$ collider. We initiate our strategic vision to transform QED production at the LHC and beyond into a flagship programme with a thriving community this decade. This defines the science drivers for precision measurements and new physics searches such as electromagnetic dipole moments and dark sectors. We identify opportunities to invest in technology and theory, interdisciplinary synergies with laser science and astrophysics, and community outreach to expand this exciting programme.

Science drivers & big questions | **Physics targets, probes, benchmarks** | **Facilities, instrumentation, software** | **Interdisciplinary synergies** | **Outreach, education, applications**

Expanding benchmarks interesting but we'll likely not do new MC studies ourselves.
We plan a survey-vision paper on photon collider science at the LHC & beyond*.
Snowmass ideal to explore new synergies & define our vision for next decade.

See also EF07 meeting [24 Jun], AF+EF meeting [1 Jul], LoI [SNOWMASS21-EF1-AF1-015]

* *beyond* broadly defined

EPILOGUE

DEEPEST SCIENTIFIC TRAGEDY

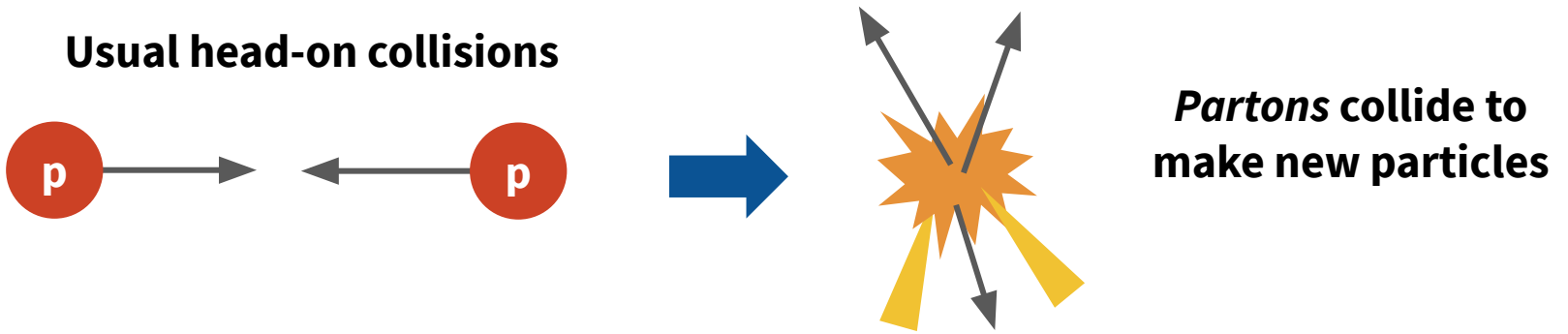
is not if new physics were absent at the weak scale

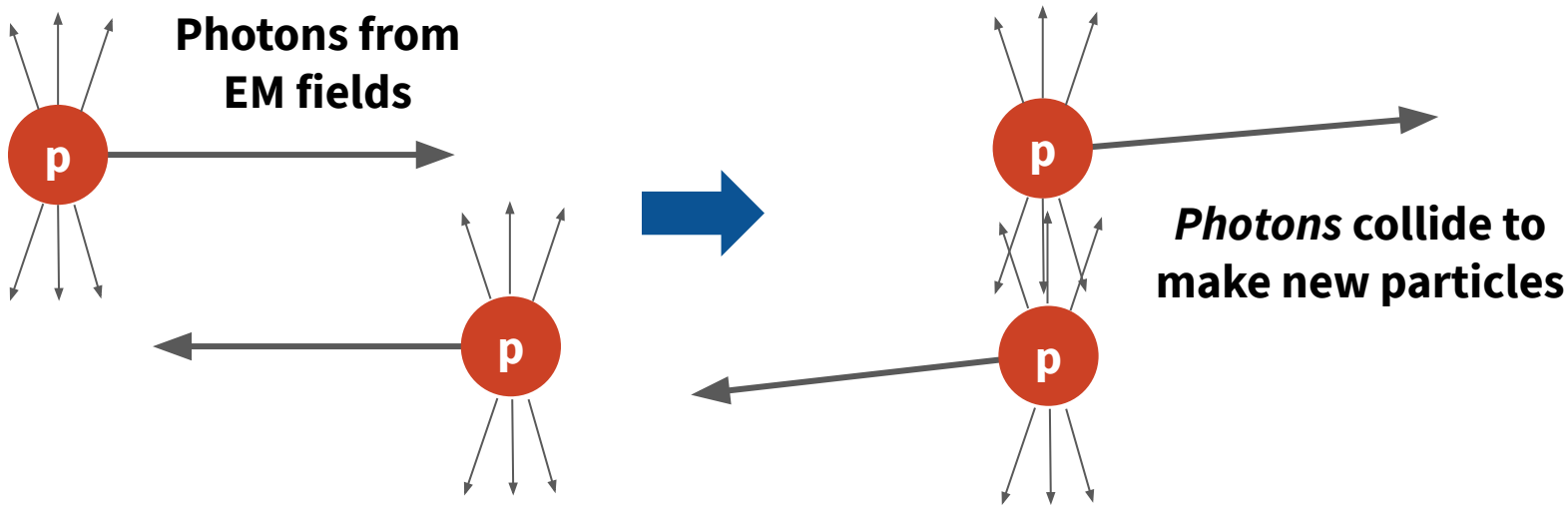
It's if we were **capable of making** new physics
but **incapable of seeing** it

We must keep looking at nature in ways we have never done before
and ensure we can see transformative "*Who ordered that?!*" surprises

EXTRAS

Colliding light at LHC

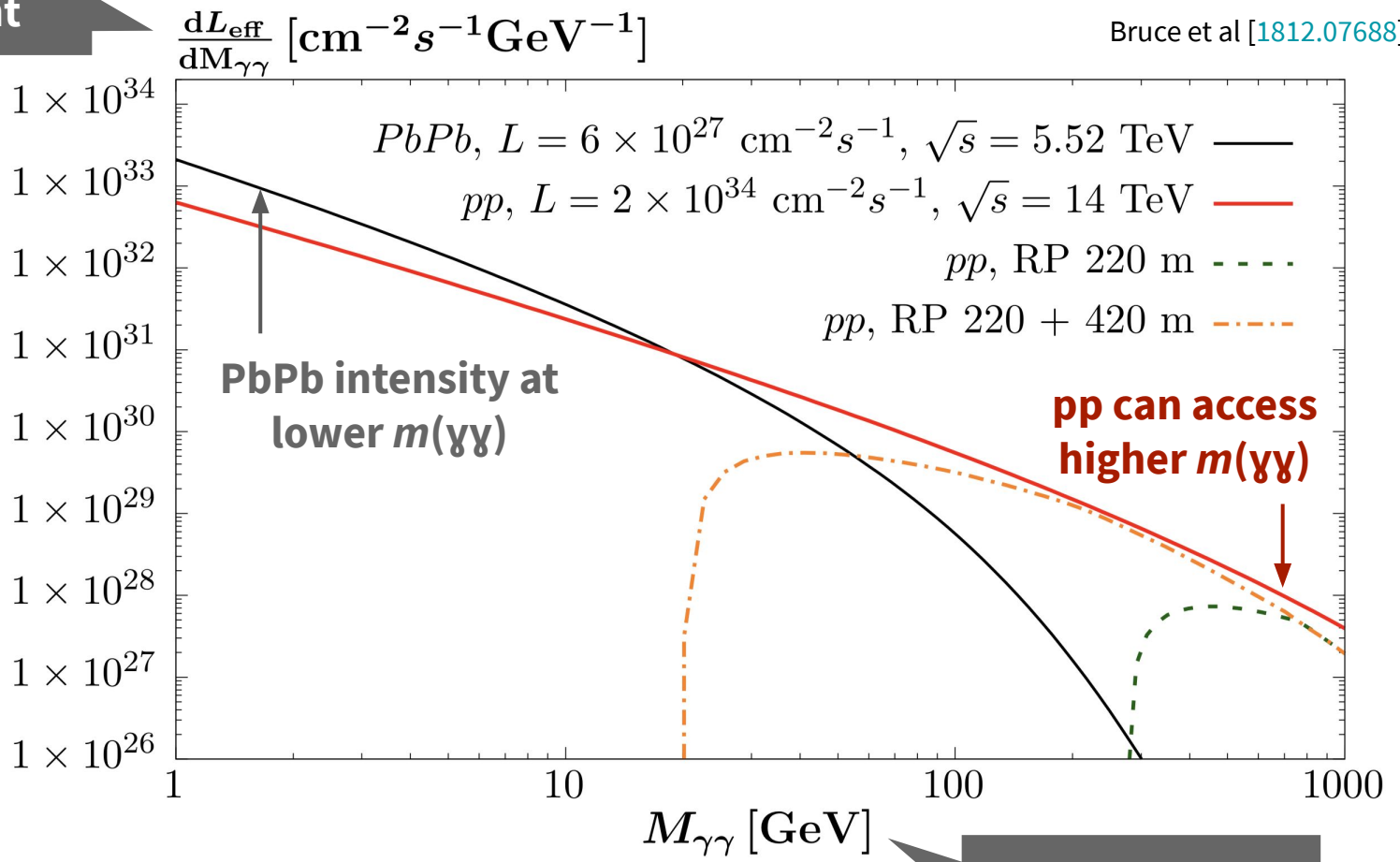




Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Schwinger (1952)
Brodsky, Kinoshita, Terazaw (1971), Budnev, Ginzburg, Meledin, Serbo (1975)
d'Enterria and da Silveira [1305.7142], ATLAS [1702.01625, 1904.03536], CMS [1810.04602], Bruce et al [1812.07688]

Colliding photon spectrum

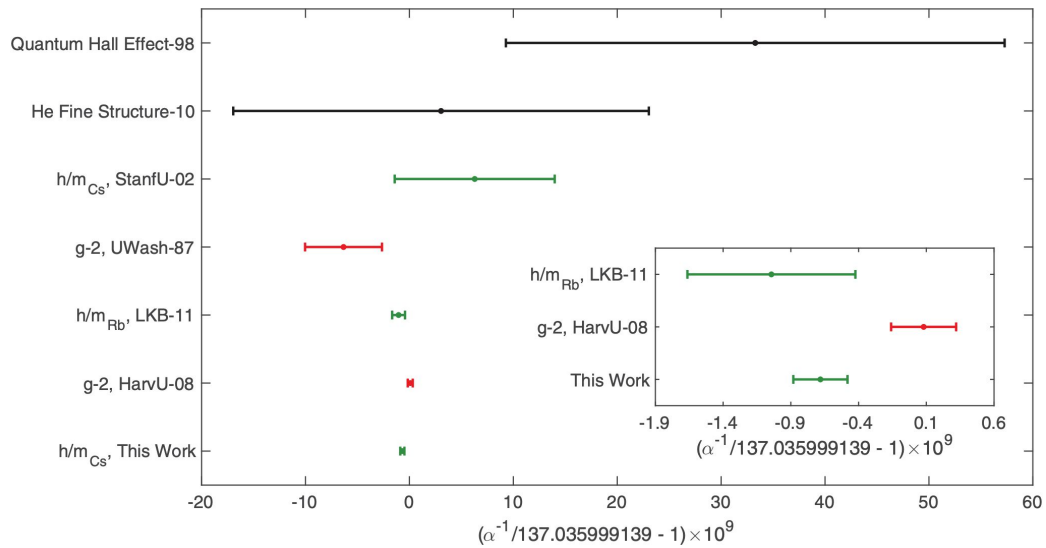
How bright is your light



Bruce et al [1812.07688]

Mass of colliding light

When we say "*g* – 2" most people think this right?

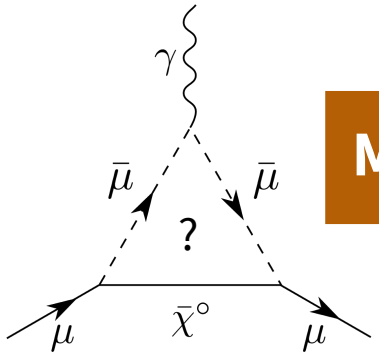


Electron *g* – 2 (–2.5σ)

Odom, Hanneke, D'Urso, Gabrielse [PRL (2006)]
Bouchendira et al [PRL (2011)]
Aoyama, Hayakawa, Kinoshita, Nio [1205.5368]
Parker, Yu, Zhong, Estey, Müller [Science (2018)]

0.2 parts per billion

"Triumph of quantum electrodynamics"

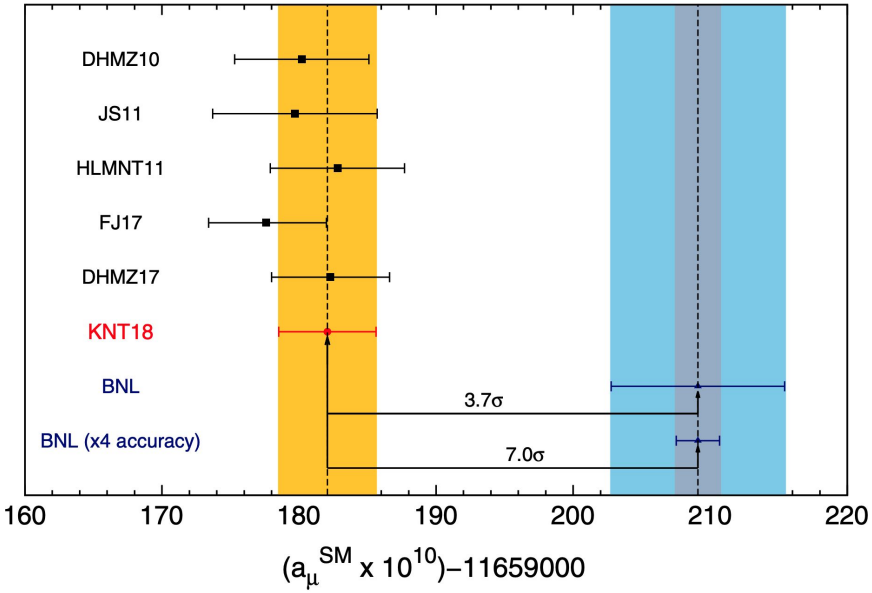


Muon *g* – 2 (+3.7σ)

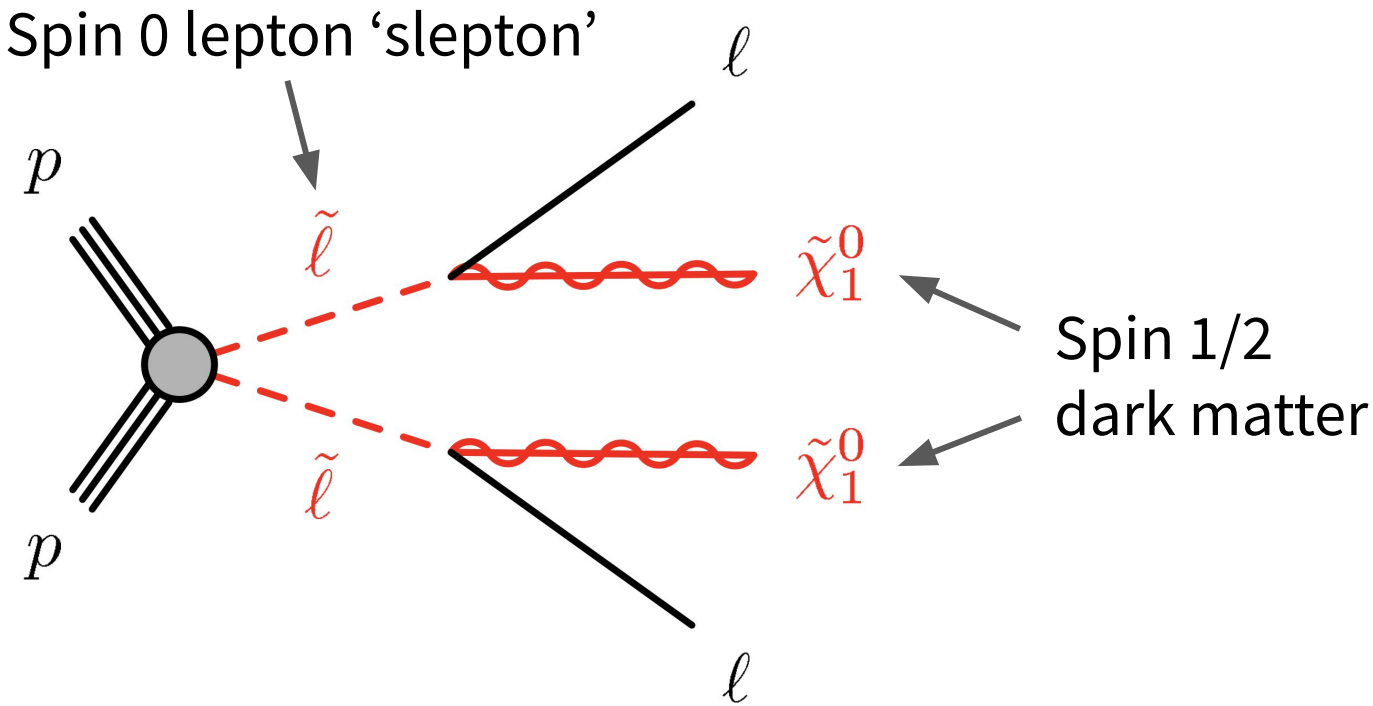
BNL E821 [hep-ex/0602035]
Fermilab E989 [1501.06858]
J-PARC [1901.03047]
Keshavarzi, Nomura, Teubner [1802.02995]
Davier, Hoecker, Malaescu, Zhang [1908.00921]

0.5 parts per million

"Hadronic ignorance or harbinger of new physics?"



Case study: minimal extension to SM



PHYSICALLY MOTIVATED
Explain dark matter, $(g-2)_\mu$

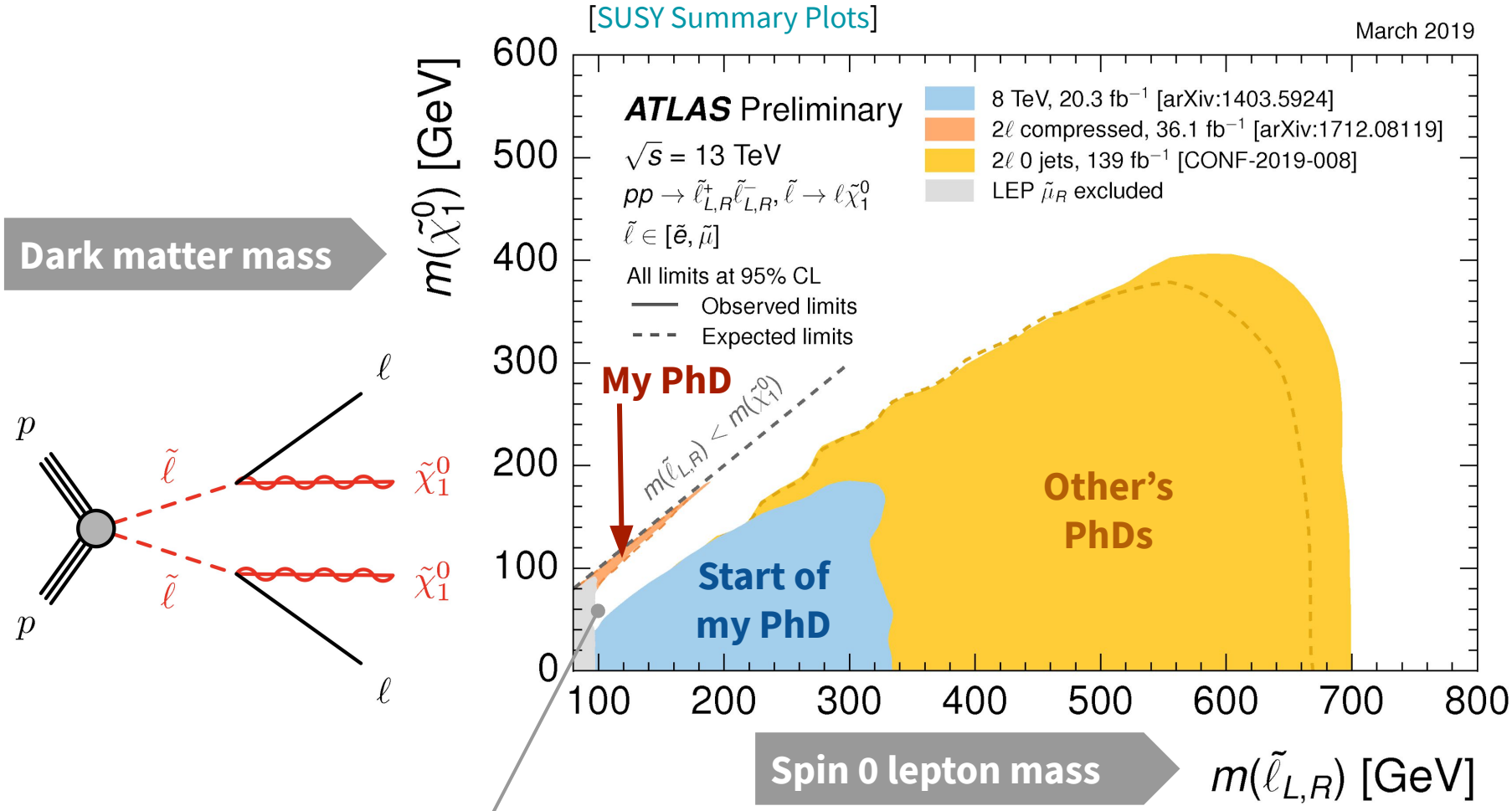
THEORETICALLY SIMPLE
2 free parameters

EXPERIMENTALLY CLEAN
2 leptons + missing E_T

Generic desirables for any contemporary simplified model

E.g. Alwall, Schuster, Toro [0810.3921]

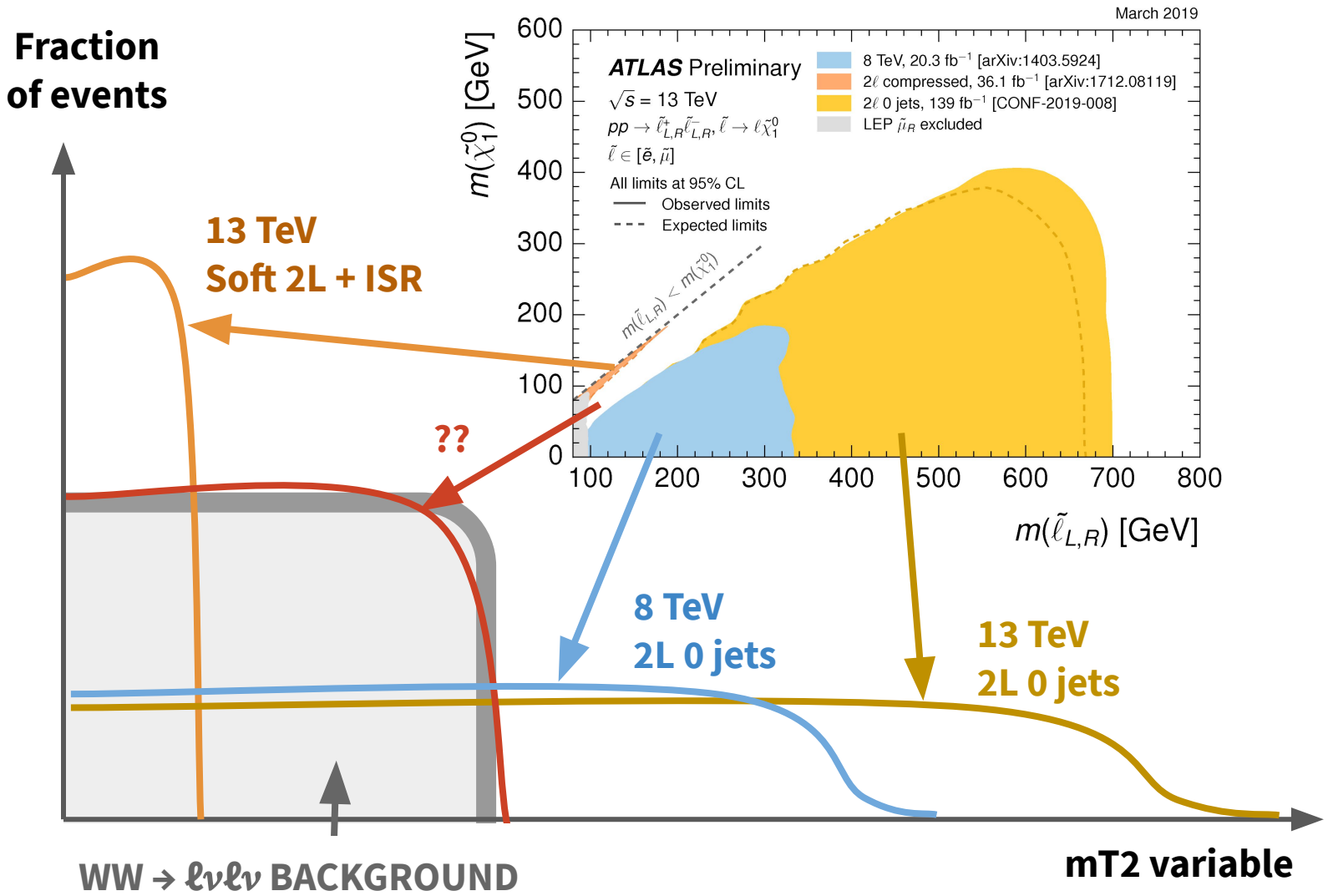
Striking blind spot remained $15 \lesssim \Delta m \lesssim 60$ GeV



As scientists our job is to see, but here we are blind

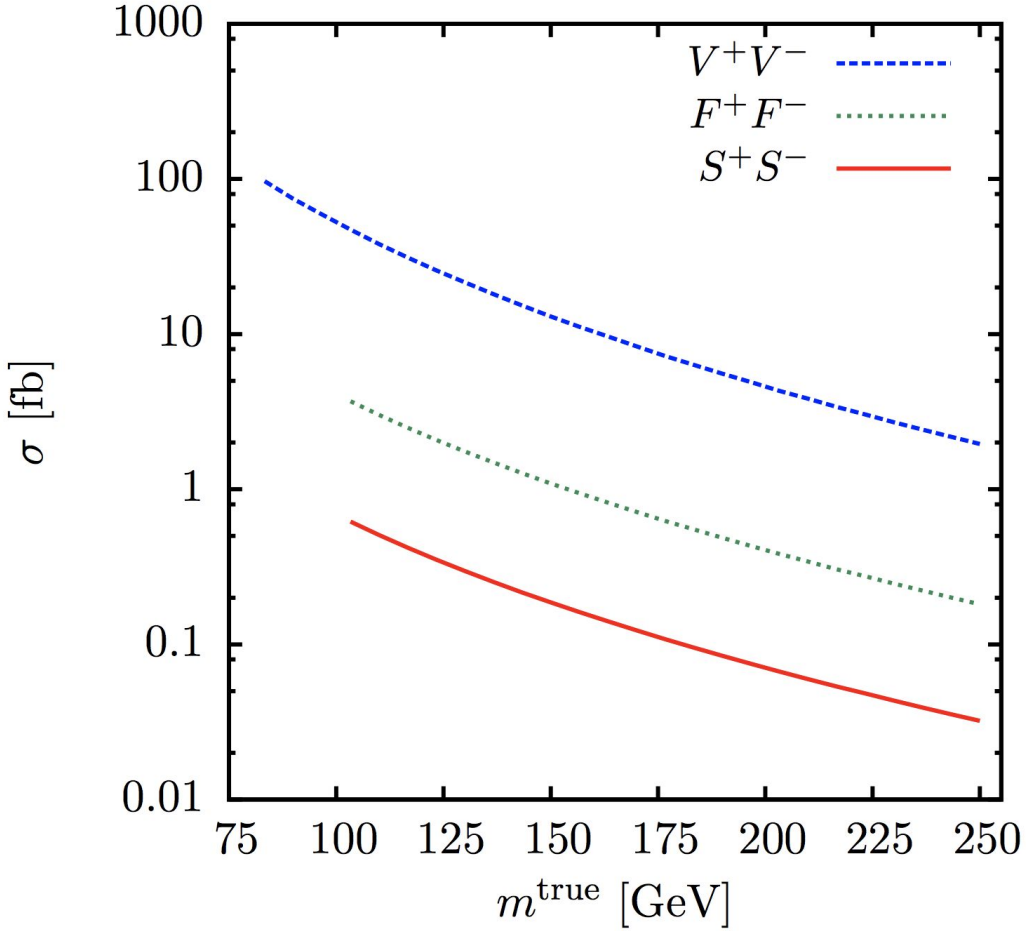
$m(\tilde{\ell}) \sim 100$ GeV: $\sigma(pp \to \tilde{\ell}\tilde{\ell}) \times \mathscr{L} \sim 730$ fb $\times$ 140 fb^{-1} $\sim$ 100 000 events

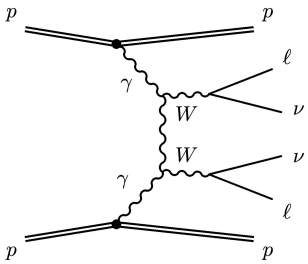
Why can't we see?



Lester, Summers [hep-ph/9906349]
Barr, Lester Stephens [hep-ph/0304226]

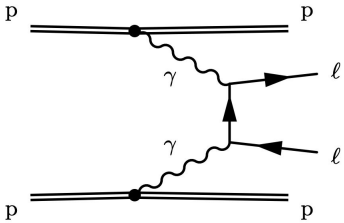
Cross-sections: QED pair production





γγ → WW

Evidence in Run 1
CMS 1604.04464
ATLAS 1607.03745



γγ→ ee/μμ

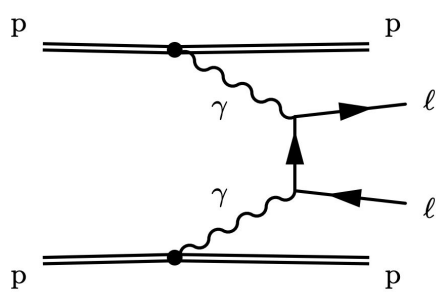
CMS 1209.1666
ATLAS 1506.07098
ATLAS 1708.04053
ATLAS CONF-2016-025

14 TeV pp → p (γγ → XX) p

QED production fixed by mass & spin

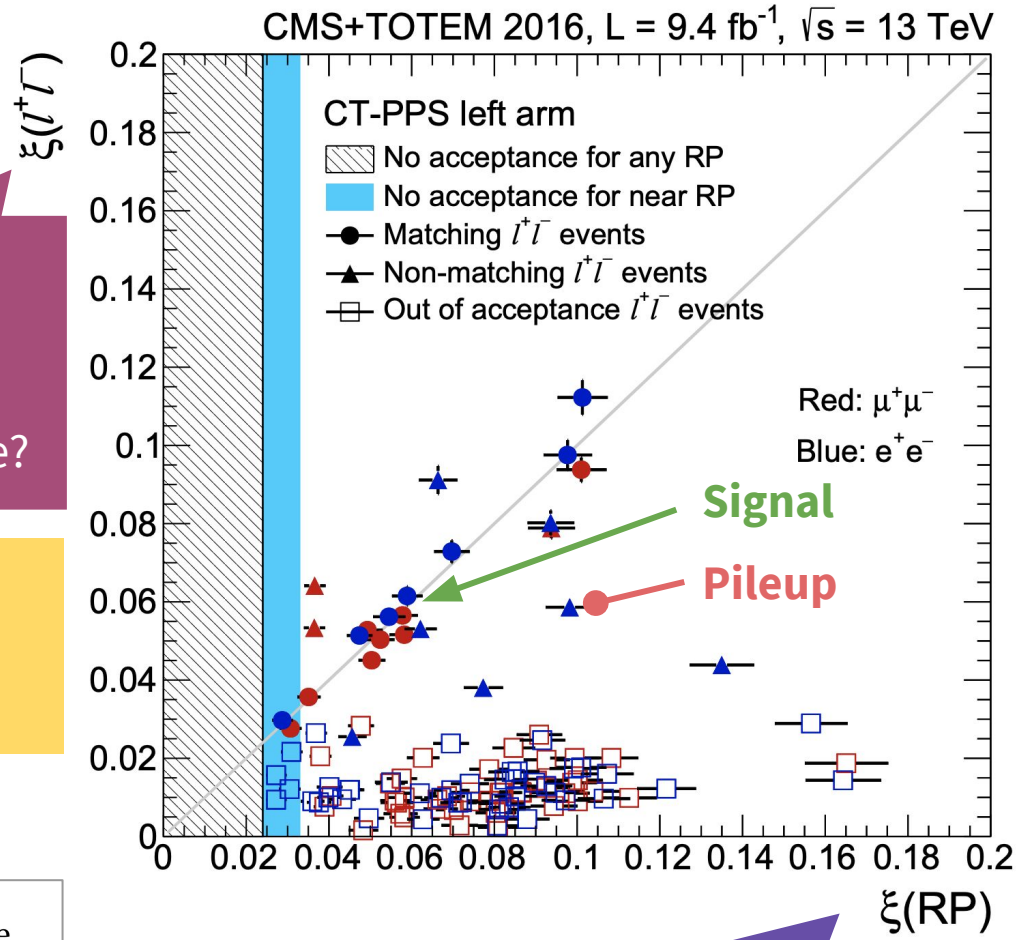
Harland-Lang, Kom, Sakurai, Stirling [1110.4320]

Prove we can see protons using $pp \to p(\gamma\gamma \to \ell\ell)p$



TAG FINAL STATE What *should* Roman Pot see?

ξ = proton fractional energy loss

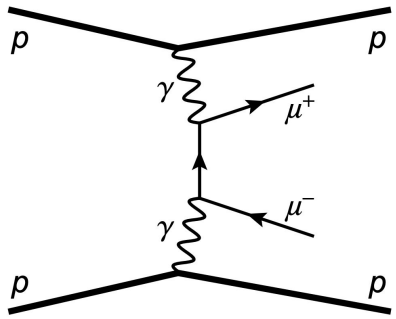


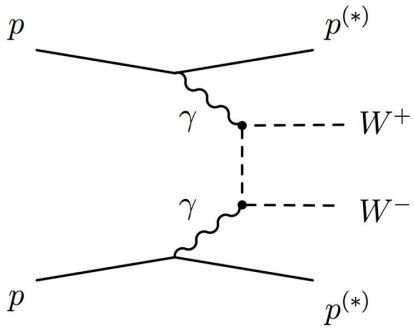
PROBE INITIAL STATE What *does* Roman Pot see?

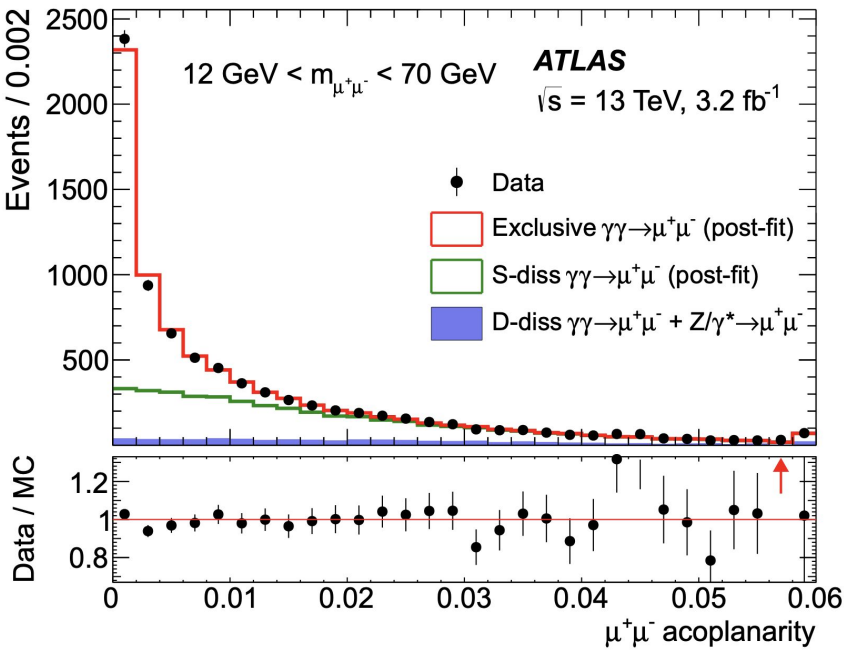
Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS–TOTEM precision proton spectrometer

CMS and TOTEM [1803.04496]

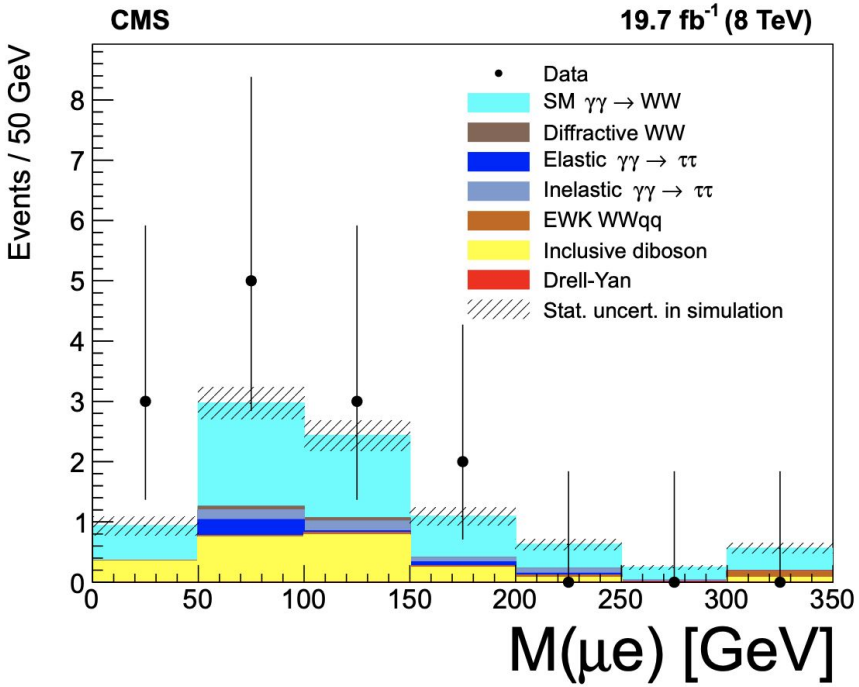
Colliding light using LHC pp beams







ATLAS [1708.04053]



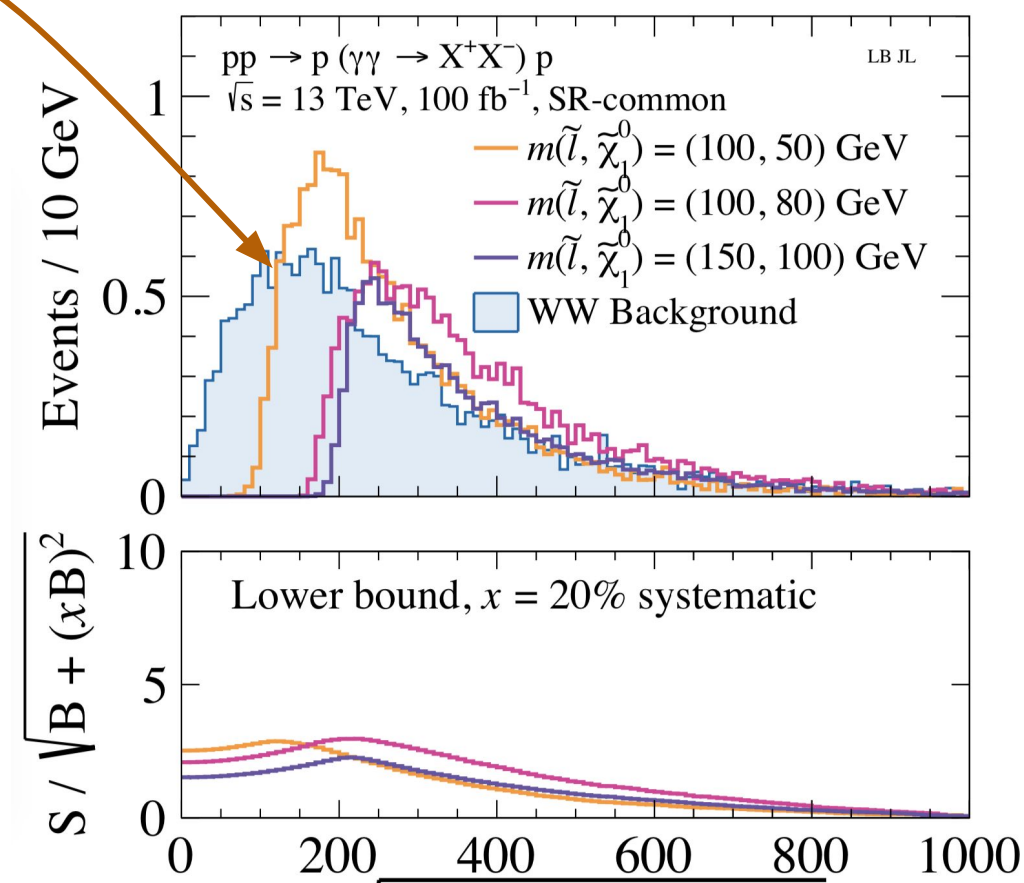
CMS [1604.04464]

World first missing mass @ hadron colliders imminent?

Wow!
Threshold @
2 × DM mass

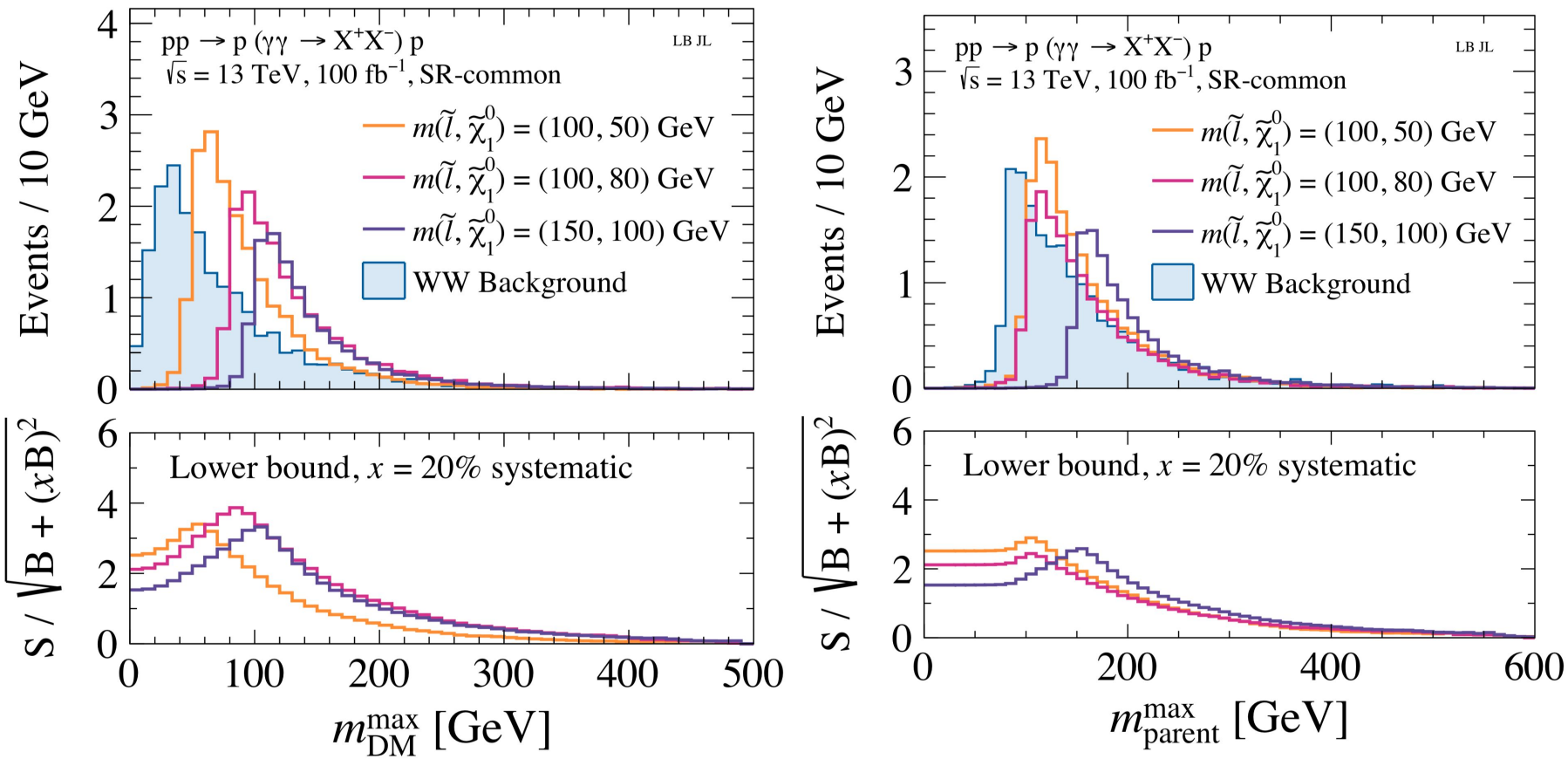
Impossible without Roman Pots!

Missing mass

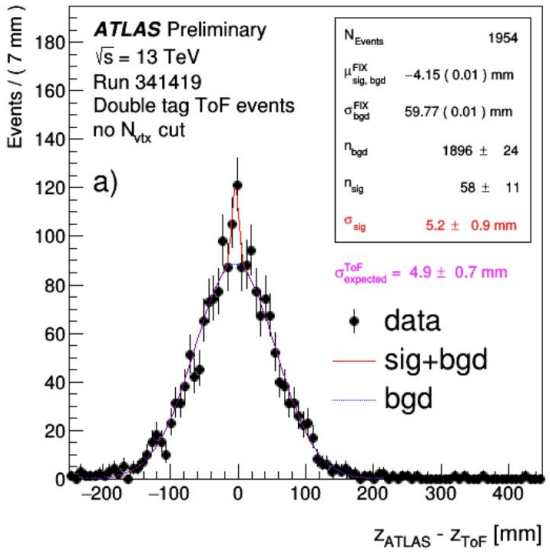


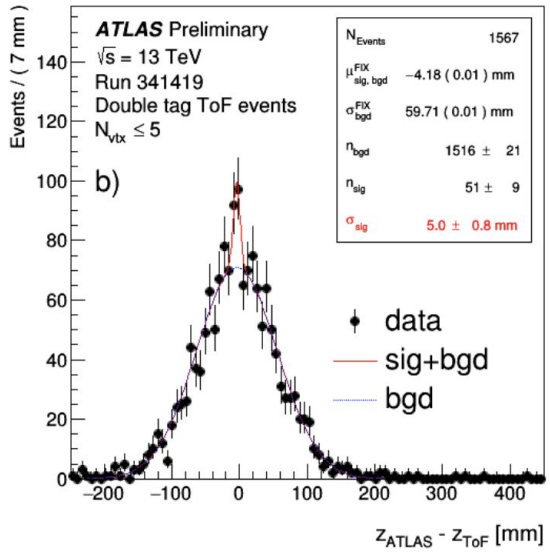
$$W_{miss} = \sqrt{(p_1^\gamma + p_2^\gamma - p_1^l - p_2^l)^2}\ [\mathrm{GeV}]$$

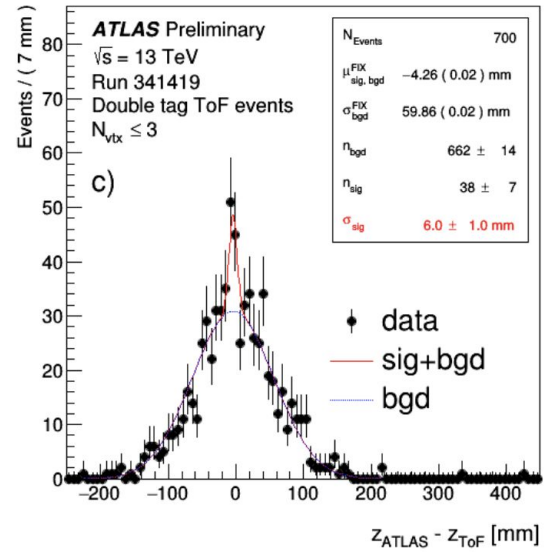
Directly measure invisible & initial state mass



Run 2 time of flight performance





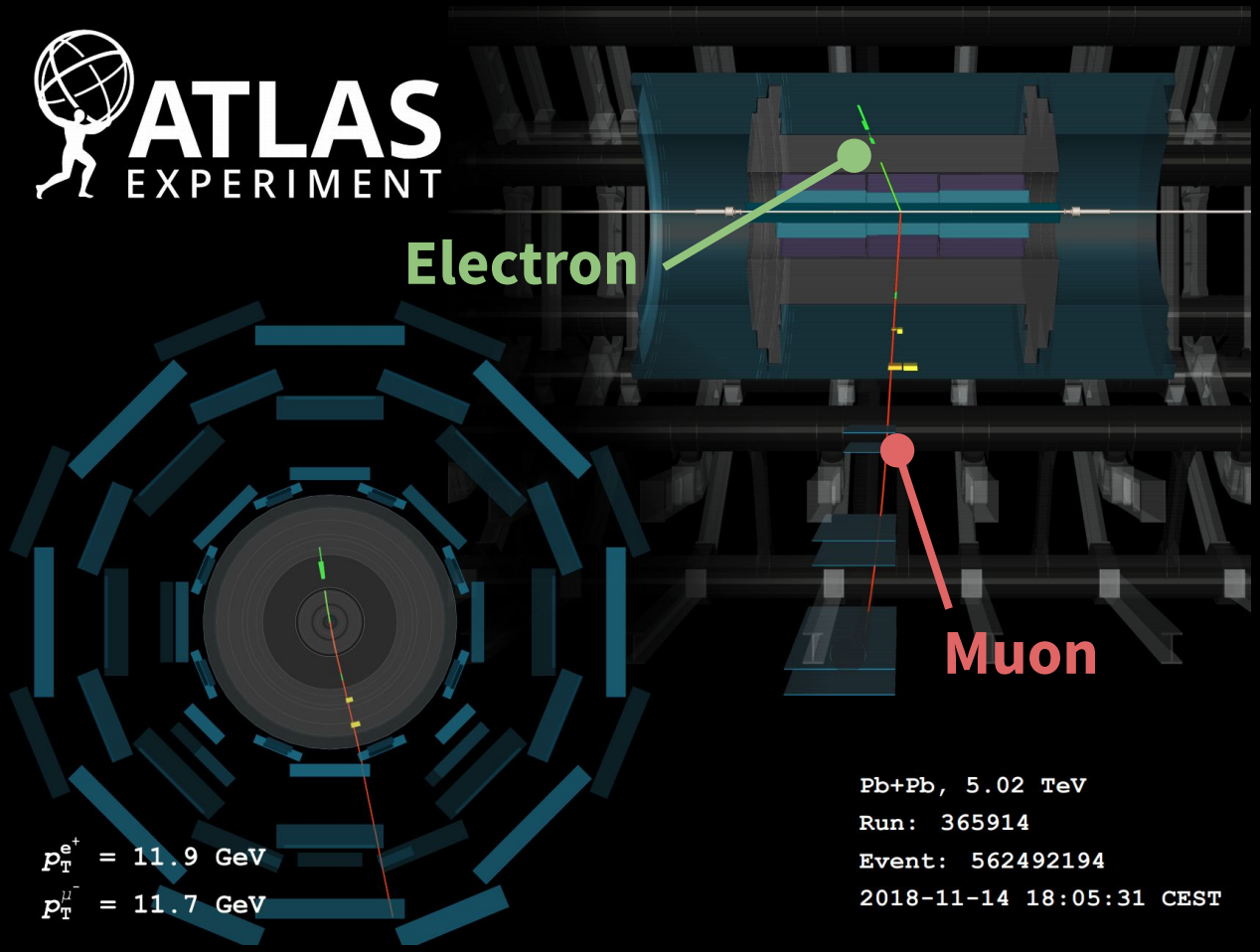


[AFP Public Results]

EXTRAS

For tau $g - 2$

Stunning PbPb events already recorded by ATLAS/CMS



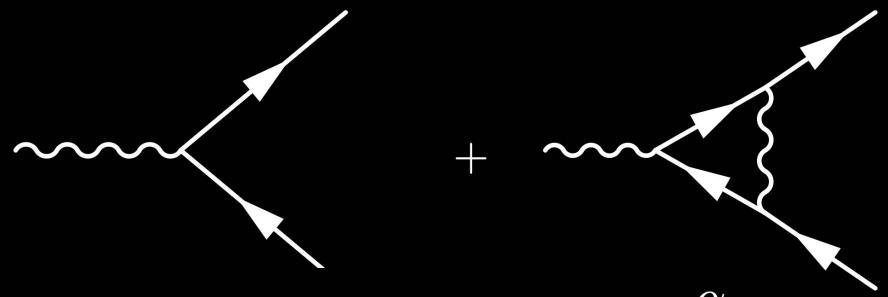
1 month to collect dataset | No pileup μ ~ 0.001 | Ultra loose triggers

"All calorimeter cells with a transverse energy above 500 MeV are shown."

[ATLAS Event Displays]

g – 2: foundational test of QED

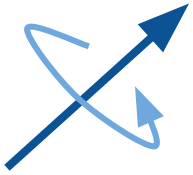
"How does light interact with matter?"



$$g = 2 + \frac{\alpha}{\pi}$$

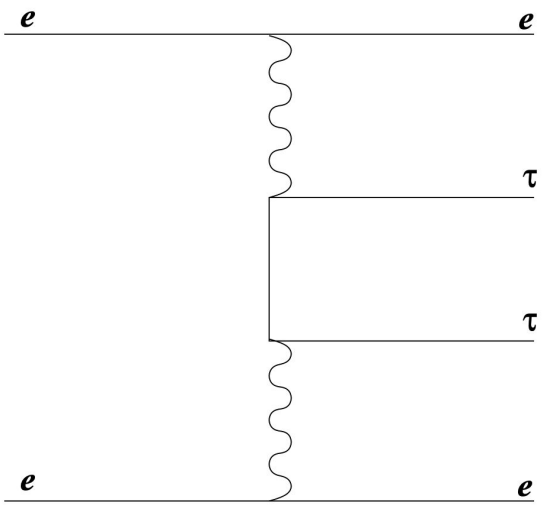
Dirac (1928) **Schwinger (1948)**

$$\boldsymbol{\mu}_f \cdot \mathbf{B} = \frac{g_f e}{2m_f} \mathbf{S} \cdot \mathbf{B}$$



Directly measure via spin–magnetic precession

How do we measure tau *g* – 2?



DELPHI [hep-ex/0406010]

LEP photon collisions

Belle-II (ee)

Eidelman, Epifanov, Fael, Mercolli, Passera [1601.07987]
Chen, Wu [1803.00501]

CLIC/ILC/FCC-ee

Koksal, Billur, Gutierrez-Rodriguez, Hernandez-Ruiz [1804.02373]
Howard, Rajaraman, Riley, Tait [1810.09570]

LHeC/FCC-eh

Köksal [1809.01963]
Gutiérrez-Rodríguez, Köksal, Billur, Hernández-Ruíz [1903.04135]

Proton fixed target & bent crystals

Fomin, Korchin, Stocchi, Barsuk, Robbe [1810.06699]
Fu et al [1901.04003]

Recent proposals need future datasets

Can we do better *today?*

UPC dimuons using PbPb

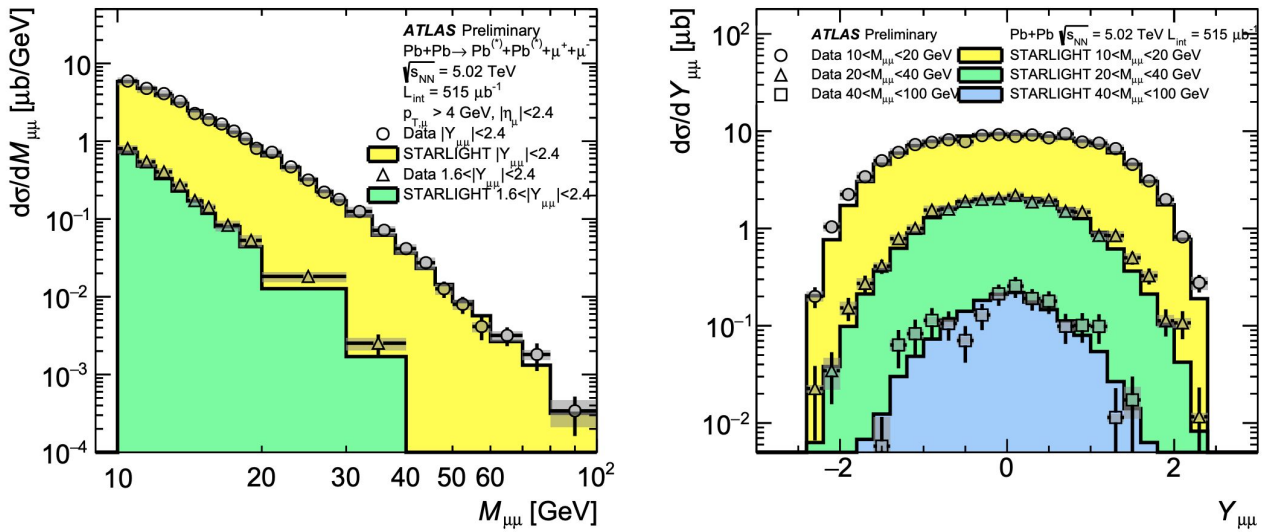


Figure 3: Cross section for dimuon production in UPC, as a function of pair mass (left) and pair rapidity (right). The data are indicated by the symbols while calculations are shown by solid histograms. The mass distribution is provided for two (overlapping) rapidity regions ($|Y_{\mu\mu}| < 2.4$ and $|Y_{\mu\mu}| > 1.6$). The rapidity distribution is provided for three ranges ($10 < M_{\mu\mu} < 20$ GeV, $20 < M_{\mu\mu} < 40$ GeV, $40 < M_{\mu\mu} < 100$ GeV). Error bars indicate statistical uncertainties while the grey bands indicate the combined systematic uncertainties, including the 7% global luminosity uncertainty.

Reasonable agreement with SM predictions in Monte Carlo

[ATLAS-CONF-2016-025]

Formalism: fermion dipole moments

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 $F_{\mu\nu}$

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

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]

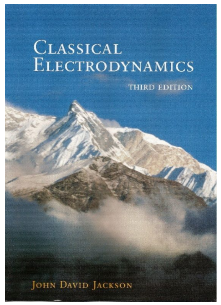
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{|C_{\tau B}|}{M}\cos\varphi, \quad \delta d_\tau = \frac{|C_{\tau B}|}{M}\sin\varphi, \qquad (4)$$

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.

Escribano & Masso [PLB (1993)], Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]
Eidelman, Epifanov, Fael, Mercolli, and Passera [1601.07987]
On-shell Higgs: h → $\tau\tau\gamma$ to measure g – 2 suggested by Galon, Rajaraman, Tait [1610.01601]

Beresford, JL [1908.05180]

Photon collisions using MadGraph & SMEFTsim

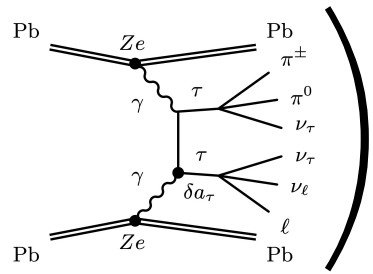


Photon flux: classical field theory

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

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

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



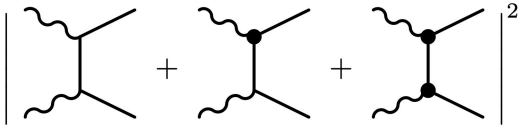
$$= \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1)n(x_2)\, \sigma_{\gamma\gamma\to XX}$$

MadGraph **Jackson** **SMEFTsim**

SMEFTsim: implement dim-6 in Feynrules

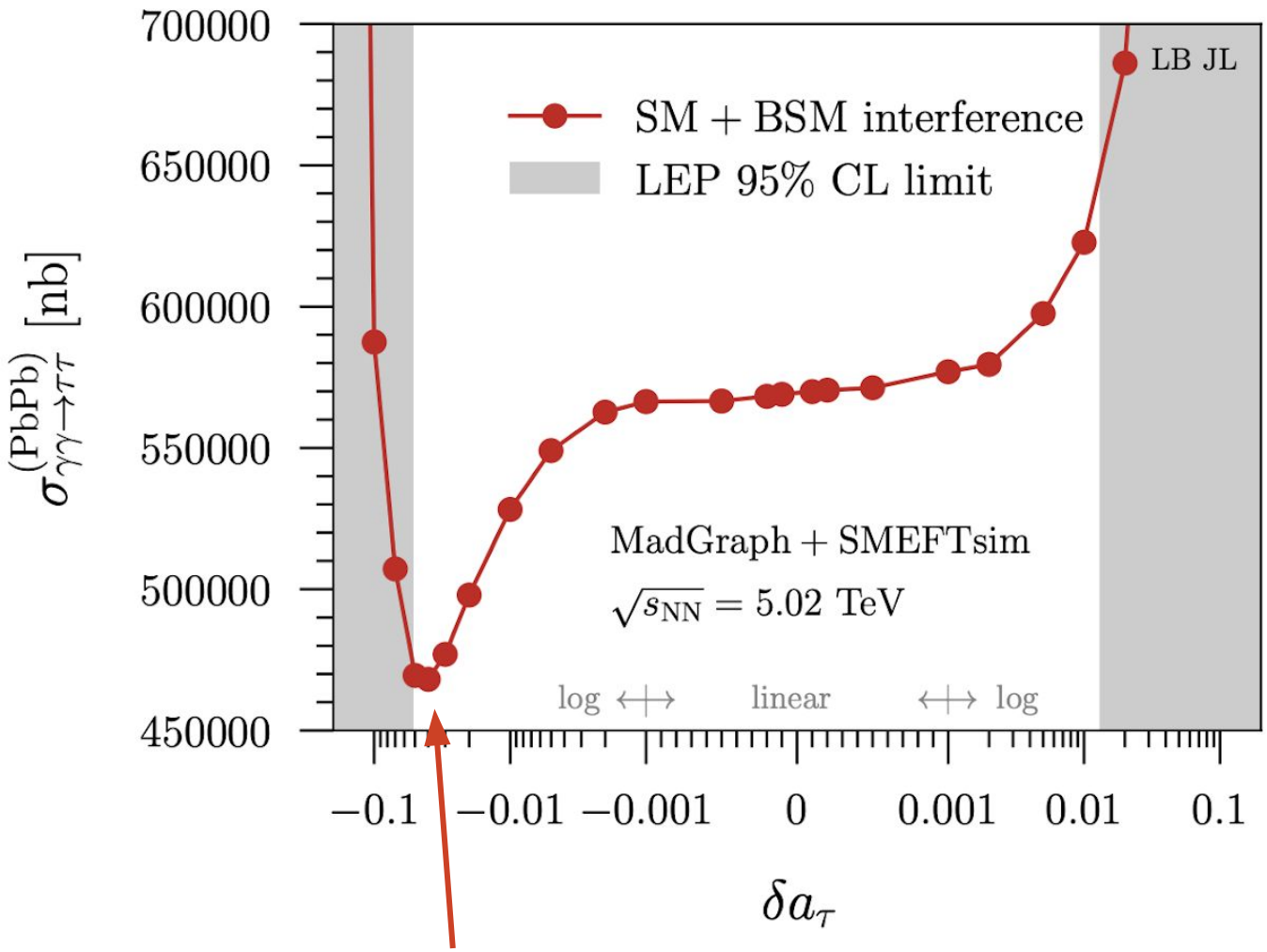
Grzadkowski, Iskrzyński,M. Misiak, Rosiek [1008.4884]
Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921]
Brivio, Jiang, Trott [1709.06492]

Include interference up to 2 BSM couplings



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

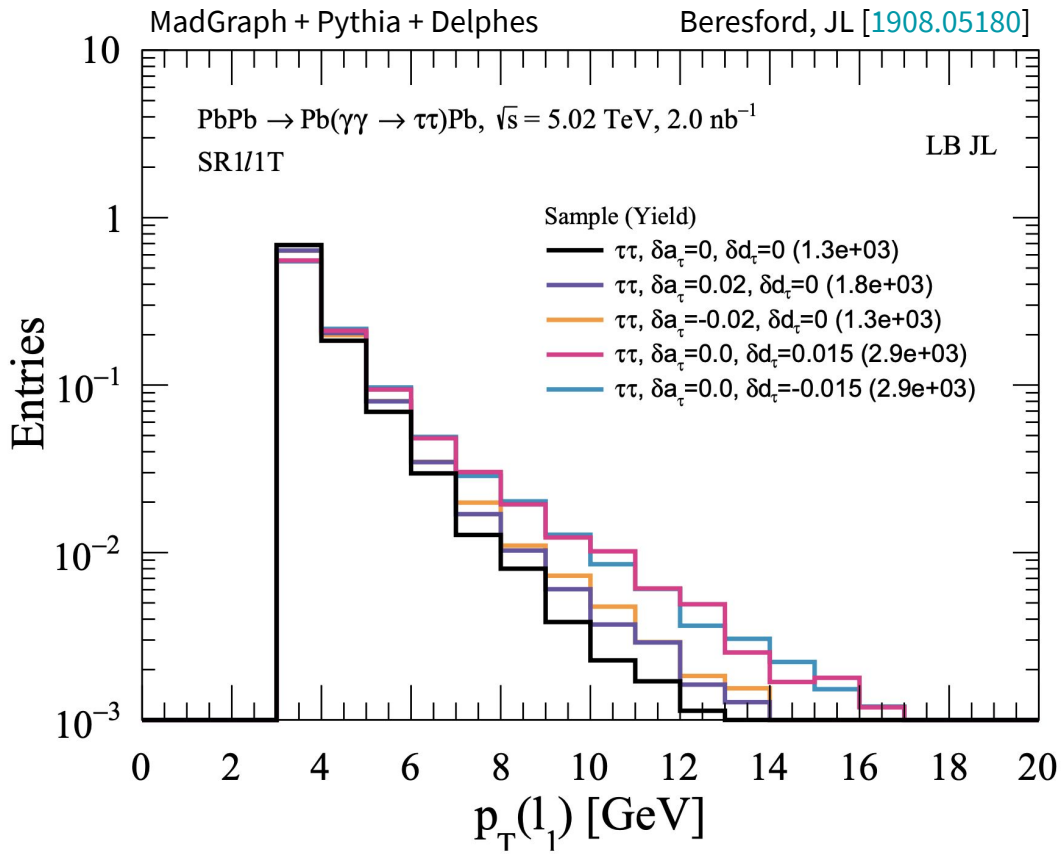
Cross-sections as function of $g-2$ deviations (PbPb)



Beresford, JL [1908.05180]

Maximal destructive interference

Recent ATLAS/CMS breakthroughs in soft leptons crucial



Soft lepton ID

$p_T(e/\mu) > 4.5/3$ GeV suppresses hadronic backgrounds

1 lepton + 1 track

Target 2ℓ or $1\ell+1\pi$ decays

28% of ditau events

1 lepton + 2/3 tracks

Target 3π decays

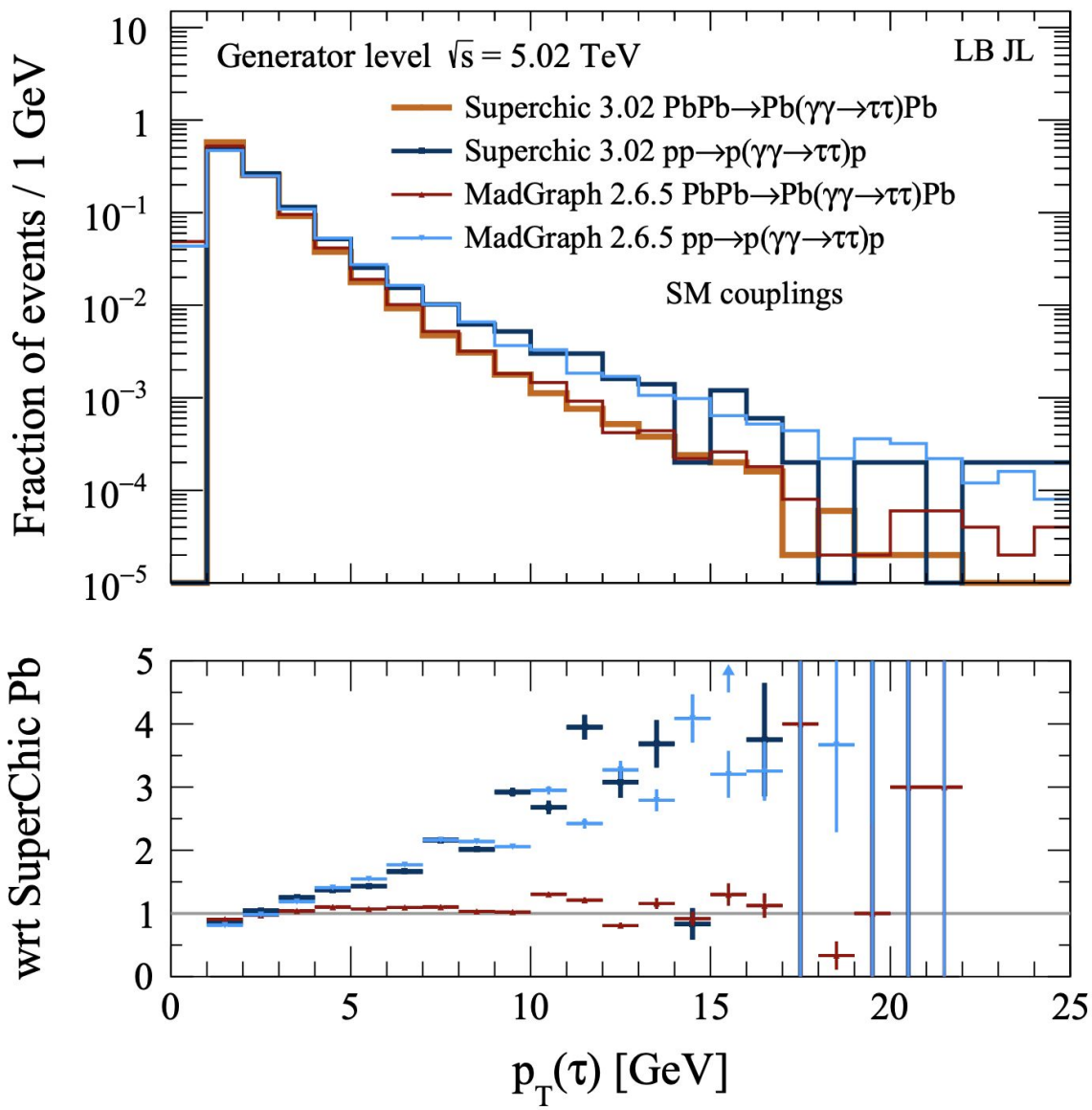
7% of ditau events

$p_T(\ell)$ sensitive to different dipole moments

Soft leptons in ATLAS [1712.08119, CONF-2019-014] & CMS [1801.01846]

Tracks pT > 100 MeV, E_T > 1 GeV EM cluster trigger [1904.03536], p_T > 0 GeV muon trigger [CONF-2016-025]

Compare MadGraph with SuperChic (PbPb)



Verify that our MadGraph implementation gives correct differential distributions

Superchic includes treatment of nuclear finite size, thickness and overlap

Also compare with photon flux sourced from pp

Beresford, JL [1908.05180]