Colliding light to make dark matter & measure tau $g - 2$

Fermilab LPC Physics Forum

Halloween Edition | 31 October 2019

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University of Chicago

THE UNIVERSITY OF CHICAGO

In collaboration with Lydia Beresford (University of Oxford)

Informal plan

Motivation

5 ± 5 mins

Briefly celebrate why you & I love science

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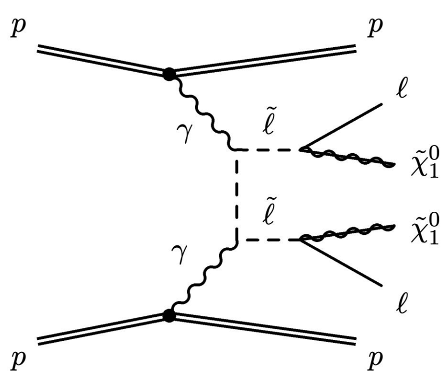
2 proposals colliding light

2 × (15 ± 5 mins)



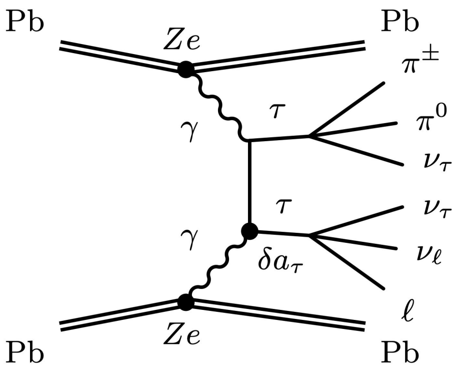
Make dark matter

Measure p(miss) 4-vector

Lydia Beresford, JL

[1811.06465, PRL **123** (2019) 141801]

Based on 15 min Durham YETI talk



Measure tau $g - 2$

Using heavy ion beams

Lydia Beresford, JL

[1908.05180]

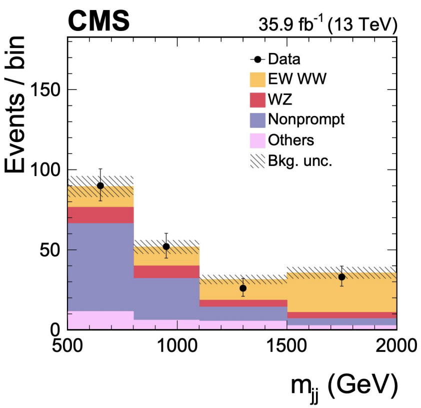
Based on 15 min Higgs Couplings talk

Backdrop: LHC golden age of seeing new phenomena

Observed VBS

Higgs unitarises scattering

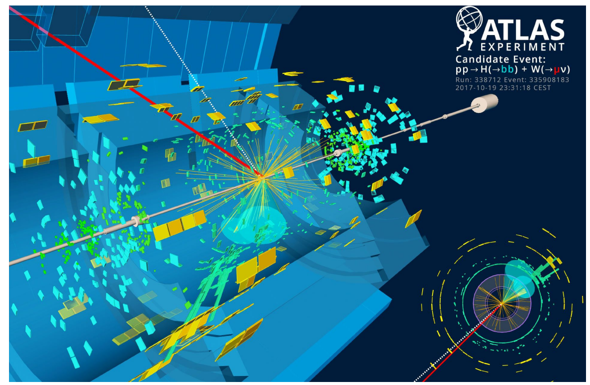
[1709.05822, 1906.03203]



Observed VH & H→bb

Boson–fermion non-universality

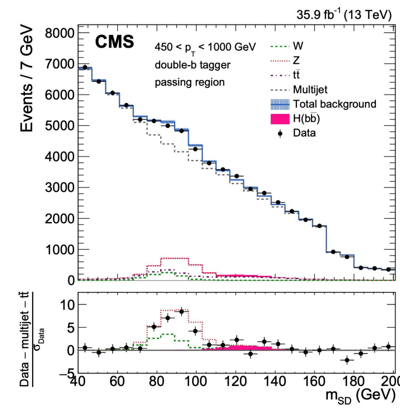
[1808.08238, 1808.08242]

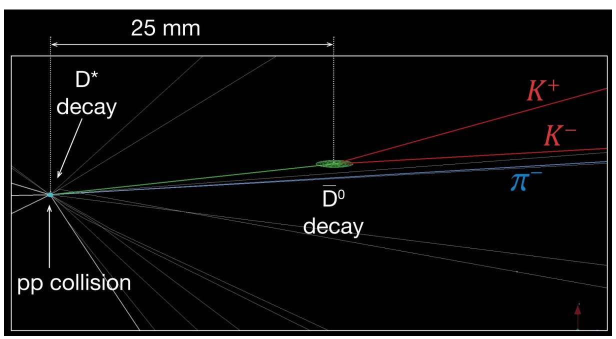


Observed Z→bb with a jet

Jet substructure for DM & Higgs

[1709.05543, ATLAS-CONF-2018-052]

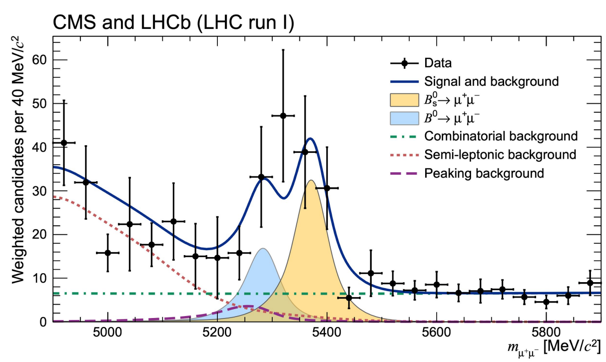




Observed charm CP violation

Landmark in flavour physics

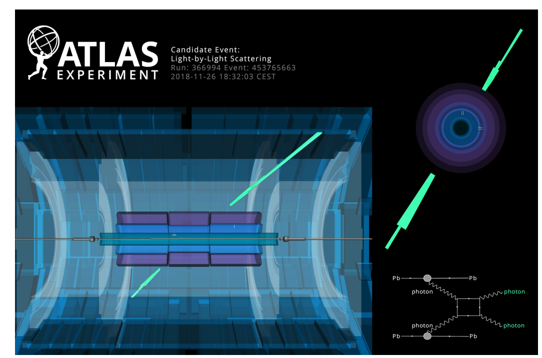
[1903.08726]



Observed $B_s \to \mu\mu$

Decades-long search for rare decay

[1411.4413]



Observed light-by-light

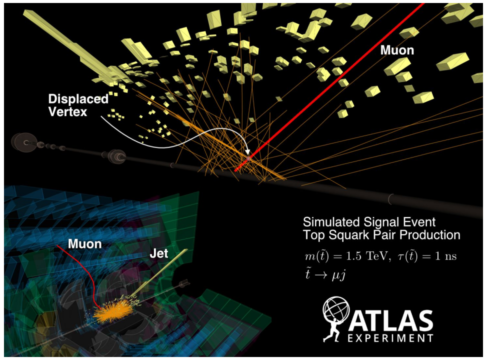
Light self-couples @ 1-loop

[1904.03536]

Amidst exciting measurements, searches & upgrades

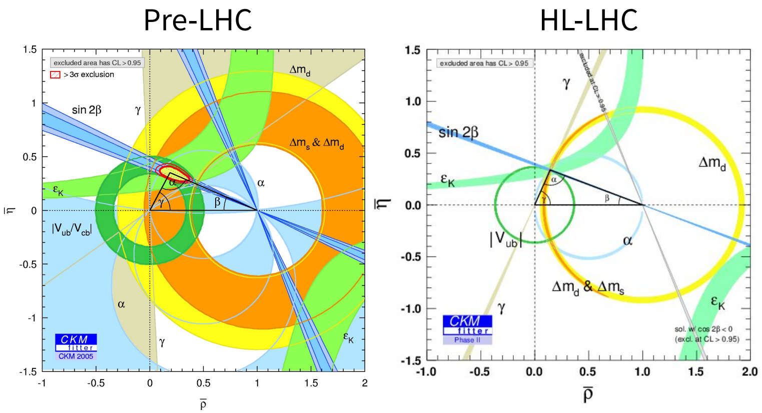
Long-lived searches

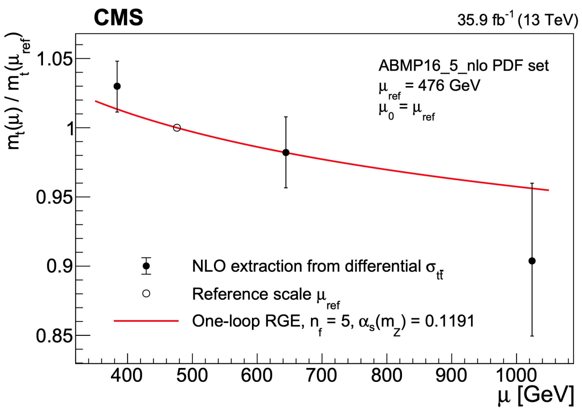
[ATLAS-CONF-2019-006]

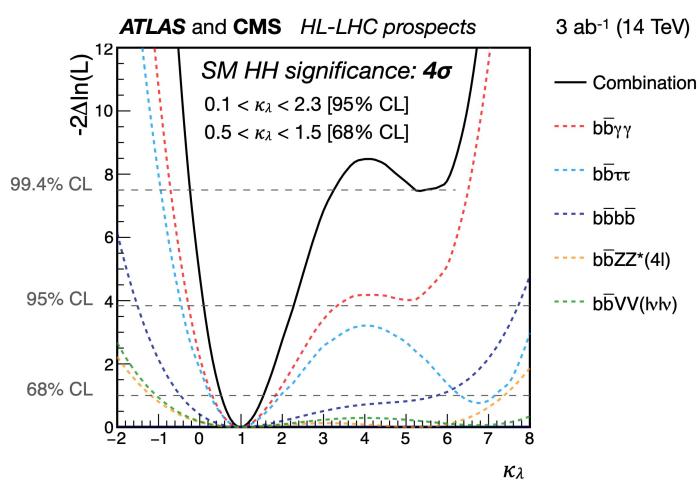


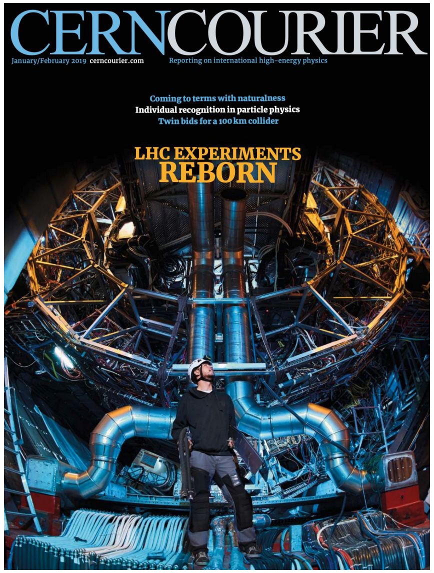
Unitarity triangle

[CKMfitter WG]









Top mass measurements

[1909.09193]

Higgs self-coupling

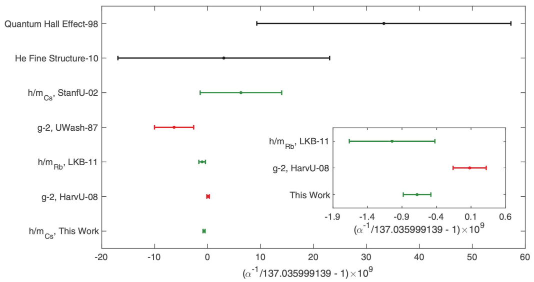
[HL-LHC Physics WG]

Upgrade overhaul

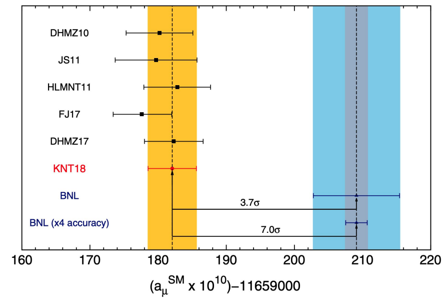
[CERN Courier Jan/Feb 2019]

Motivation: widespread indirect evidence for BSM physics

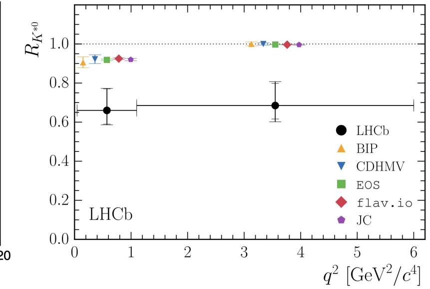
Electron $g-2$ [Science (2018)]



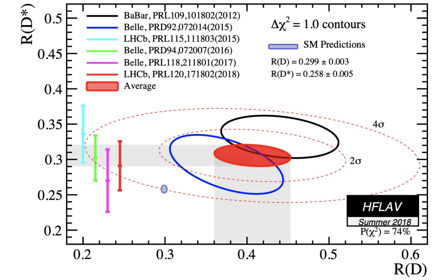
Muon $g-2$ [PRD (2018)]



$B \to K\ell\ell$ [JHEP (2017)]



$B \to D\tau\nu$ [HFLAV (2018)]



Lepton anomalies

Involves e/μ/τ across different labs

Indirect evidence of new particles (in loops)

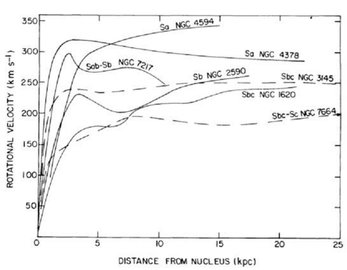
(Also neutrino anomalies but beyond today's scope)

Dark matter

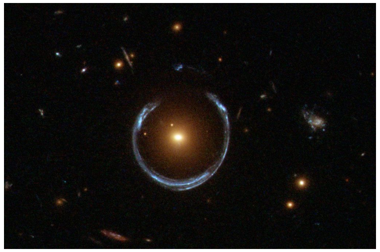
Sub-galactic to cosmological scales

Indirect evidence for particle nature

(Also dark energy but way beyond my pay grade)

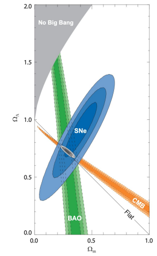


Galaxy rotation spectra
[ApJ (1978)]

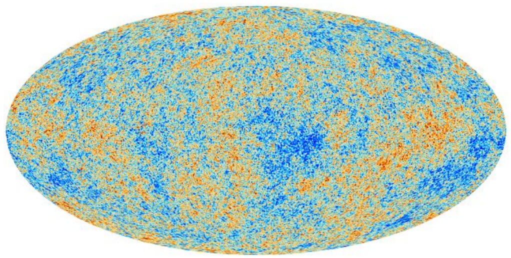


Gravitational lensing
[ESA/Hubble & NASA]

Galaxy cluster collisions
[NASA/CXC/CfA/STScI/ESO WFI]



Supernovae/BAO
[ApJ (2008)]



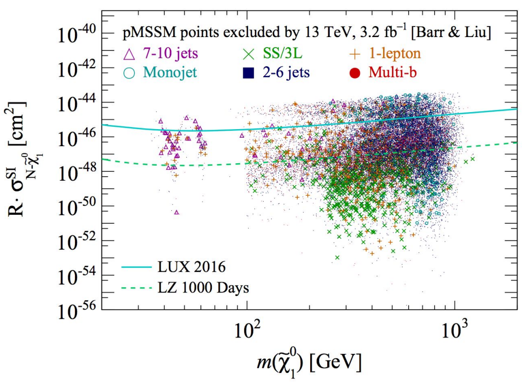
Cosmic microwave background
[ESA/Planck]

My recent science

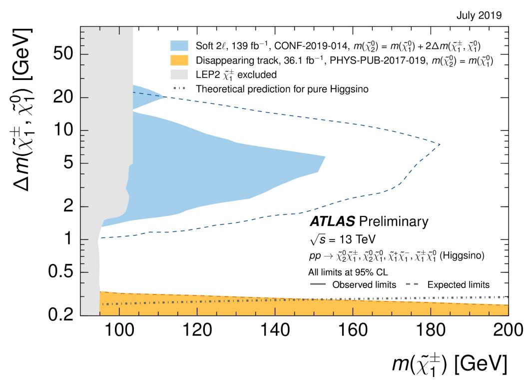
How can we use the LHC in overlooked ways to solve pressing physics problems?

My recent science

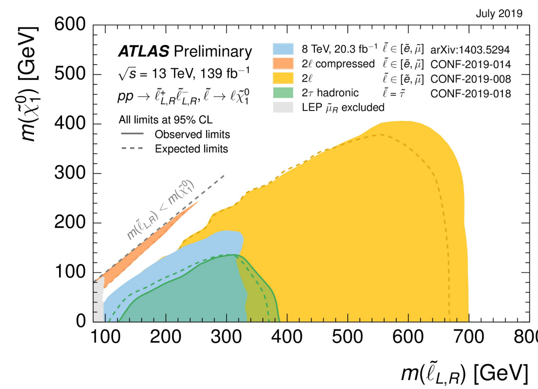
pMSSM dark matter
[1605.09502, 1608.05379]

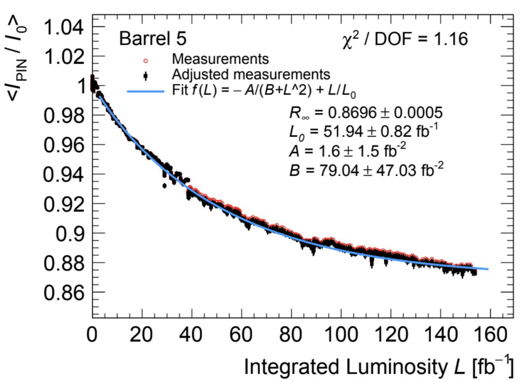


Higgsino DM searches
[1712.08119, CONF-2019-014]

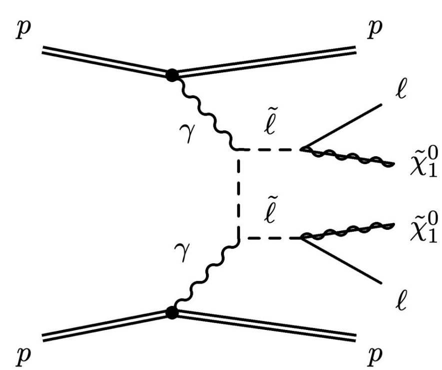


Slepton coannihilation
[1712.08119, PHYS-PUB-2019-022]

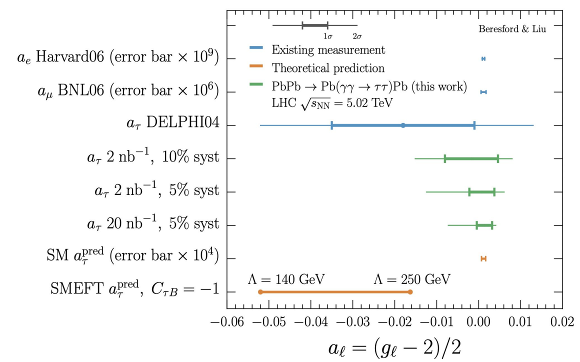




Tracker radiation damage
[JINST 14 (2019) 07, P07014]



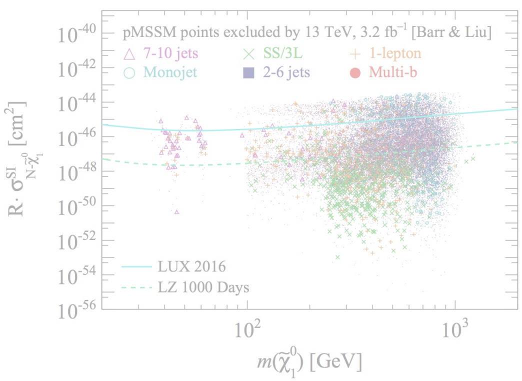
Measure p(miss) 4-vector
[1811.06465, PRL **123** (2019) 141801]



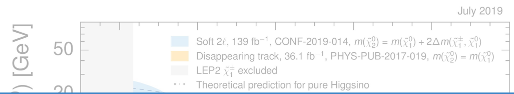
Measure tau *g* – 2
[1908.05180]

My recent science

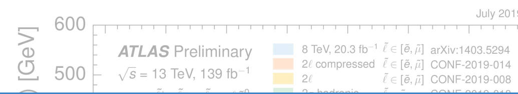
pMSSM dark matter
[1605.09502, 1608.05379]



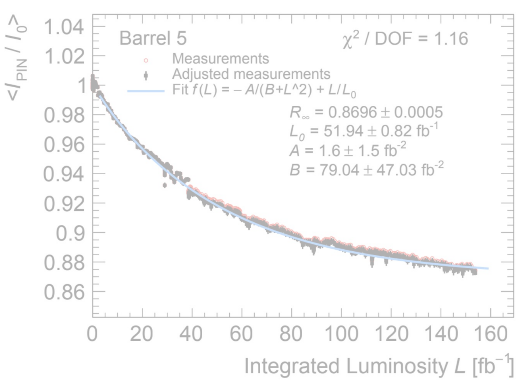
Higgsino DM searches
[1712.08119, CONF-2019-014]



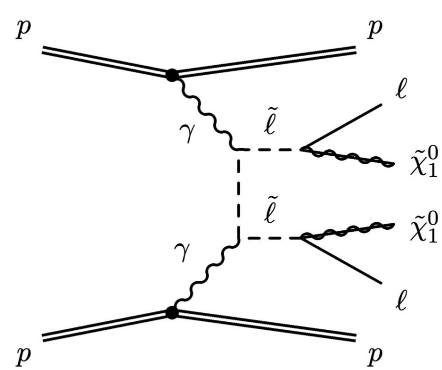
Slepton coannihilation
[1712.08119, PHYS-PUB-2019-022]

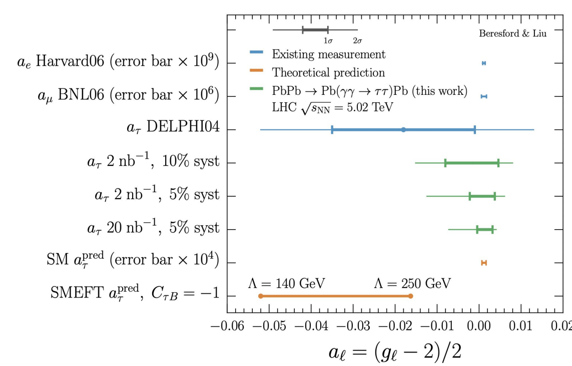


Colliding light
New solutions to longstanding problems



Tracker radiation damage
[JINST 14 (2019) 07, P07014]





Measure p(miss) 4-vector
[1811.06465, PRL **123** (2019) 141801]

Measure tau *g* – 2
[1908.05180]

NEW PROPOSAL 1

Colliding light to make dark matter

Measure p(miss) 4-vector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Search Strategy for Sleptons and Dark Matter Using the LHC as a Photon Collider

Lydia Beresford and Jesse Liu

Phys. Rev. Lett. **123**, 141801 – Published 3 October 2019

Beresford, JL [1811.06465, PRL **123** (2019) 141801]

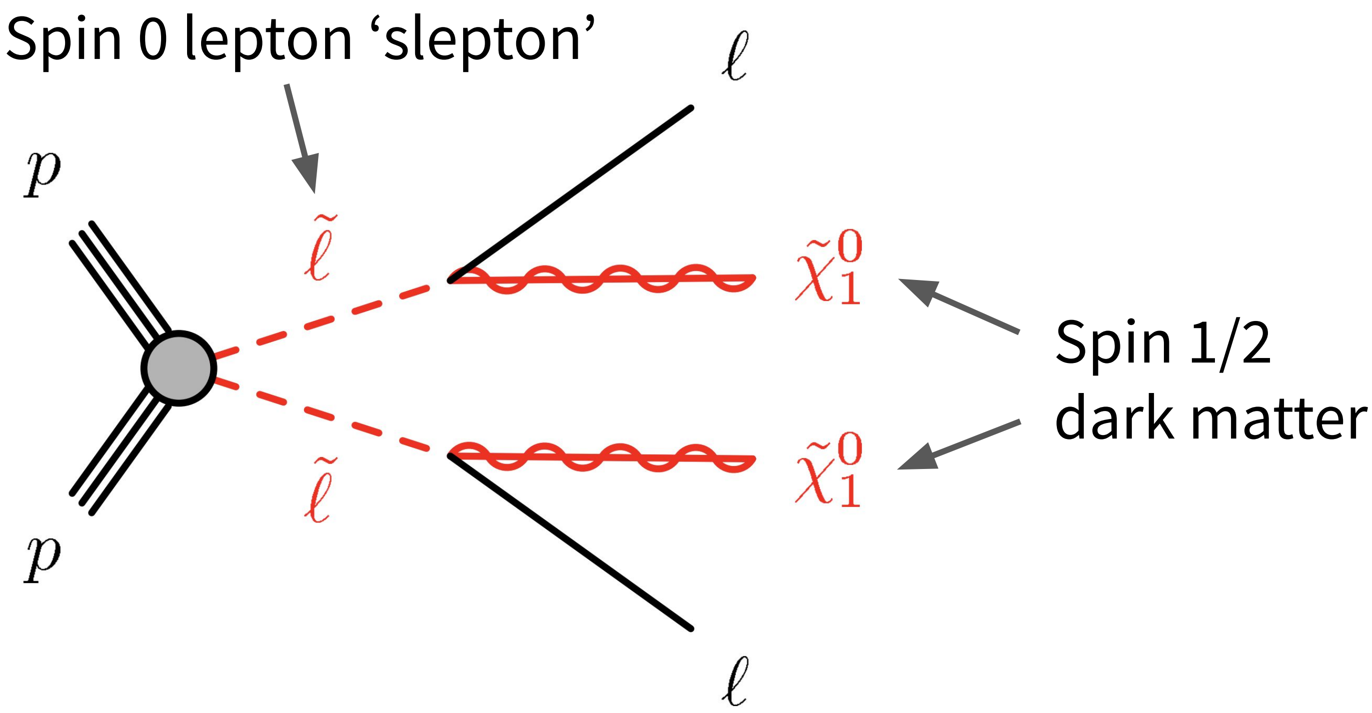
PROLOGUE

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

Case study: minimal extension to SM

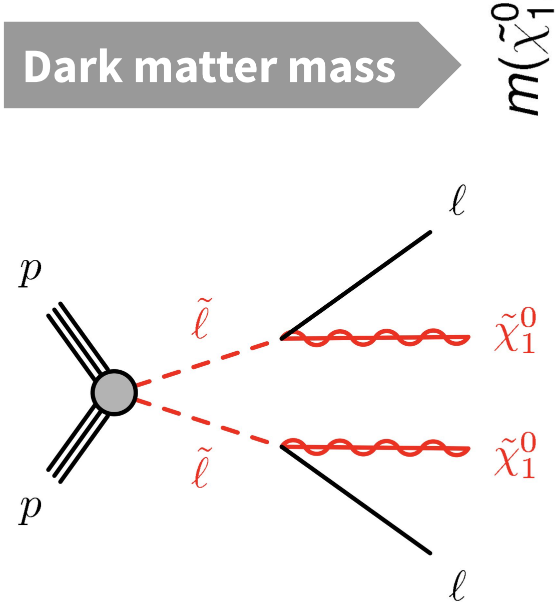


PHYSICALLY MOTIVATED
Explain dark matter, $(g-2)_\mu$

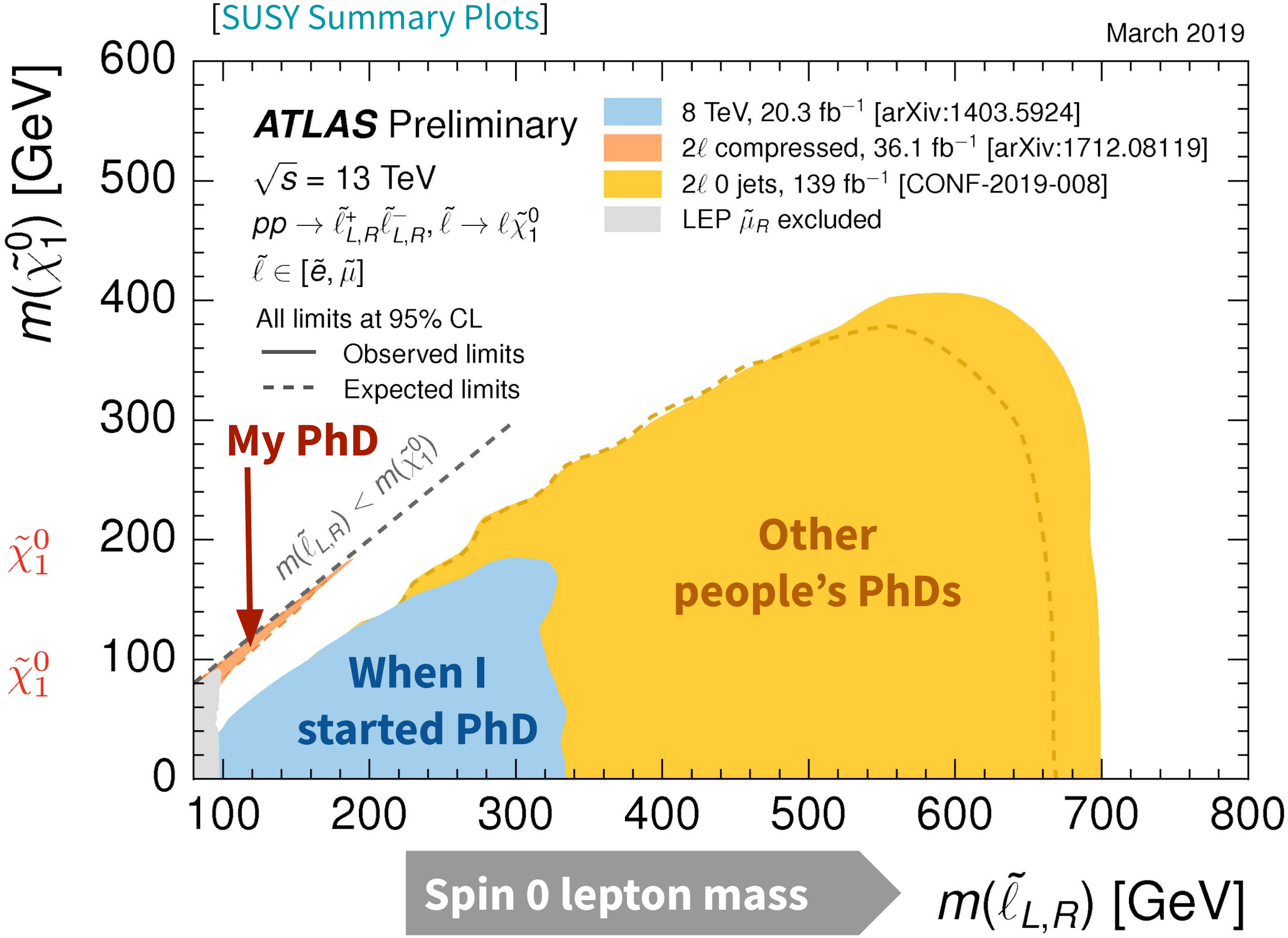
THEORETICALLY SIMPLE
2 free parameters

EXPERIMENTALLY CLEAN
2 leptons + missing E_T

Recent advances in sensitivity

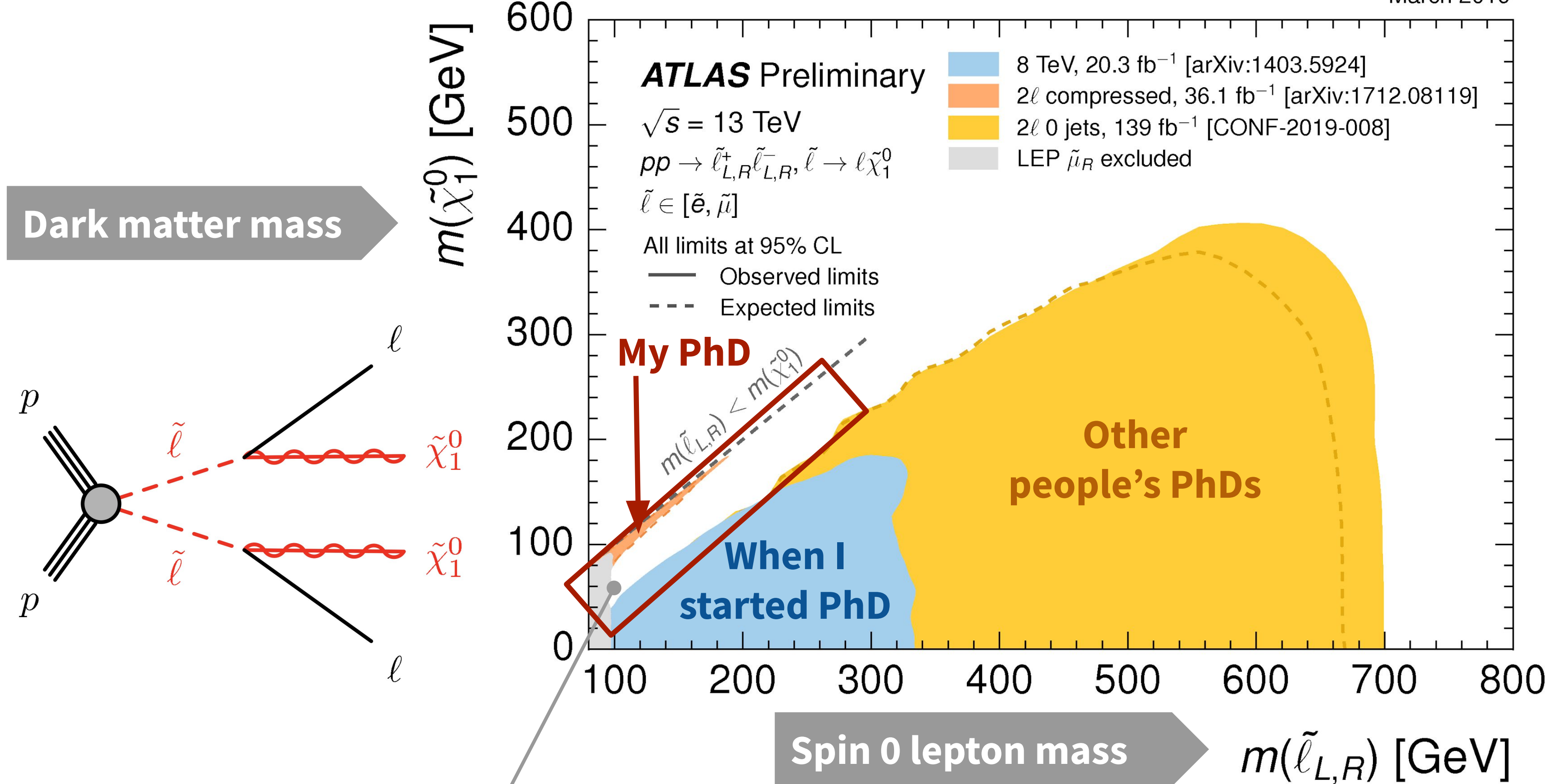


[SUSY Summary Plots]



Striking blind spot

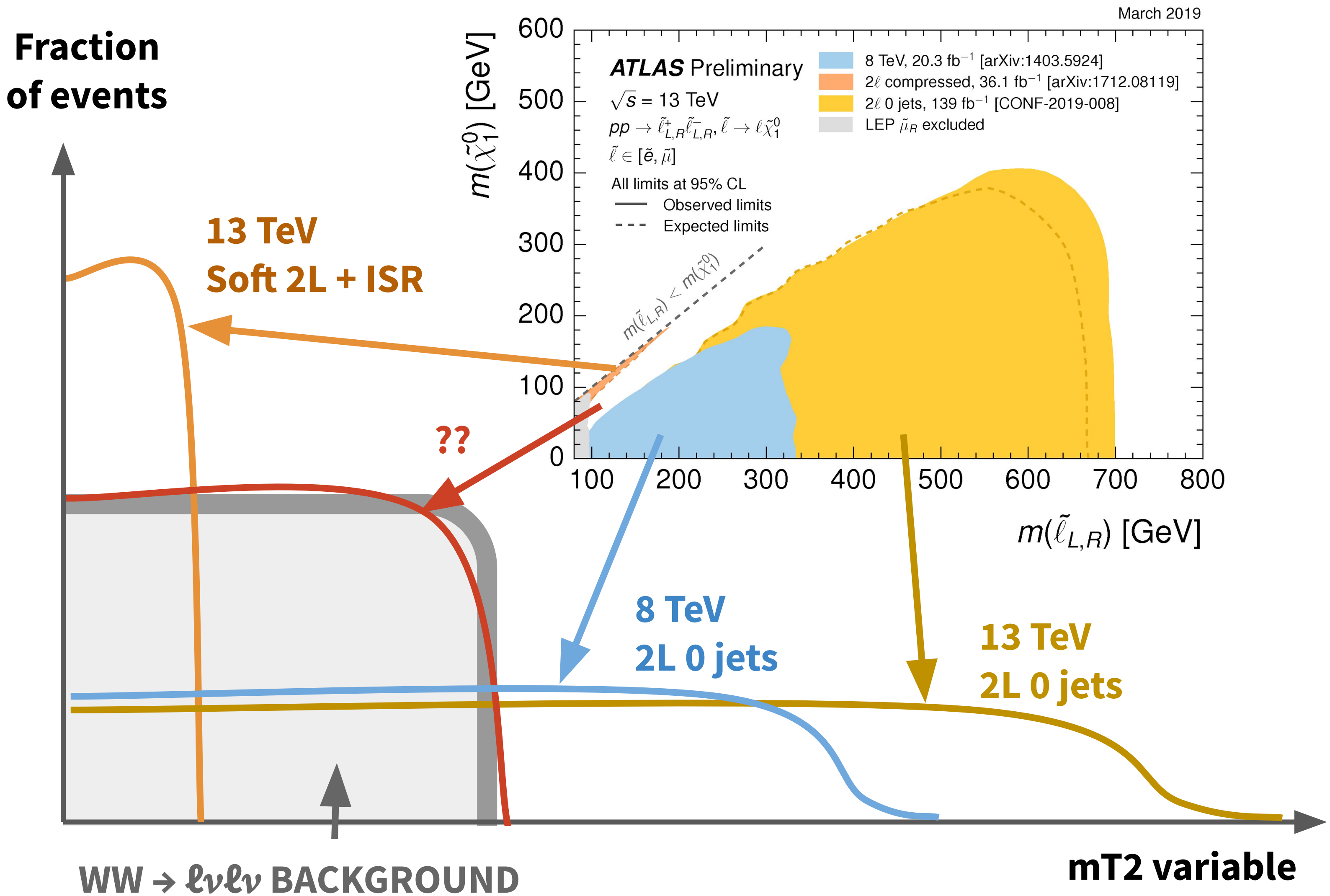
[SUSY Summary Plots]



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]

Heart of longstanding problem

Desirable

Measure missing momentum 4-vector

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

Obstruction

In all hadron colliders: Tevatron, LHC, FCC-hh, orbital space collider…

$$p_{\text{initial}}(\text{quarks, gluons}) \quad \text{immeasurable}$$

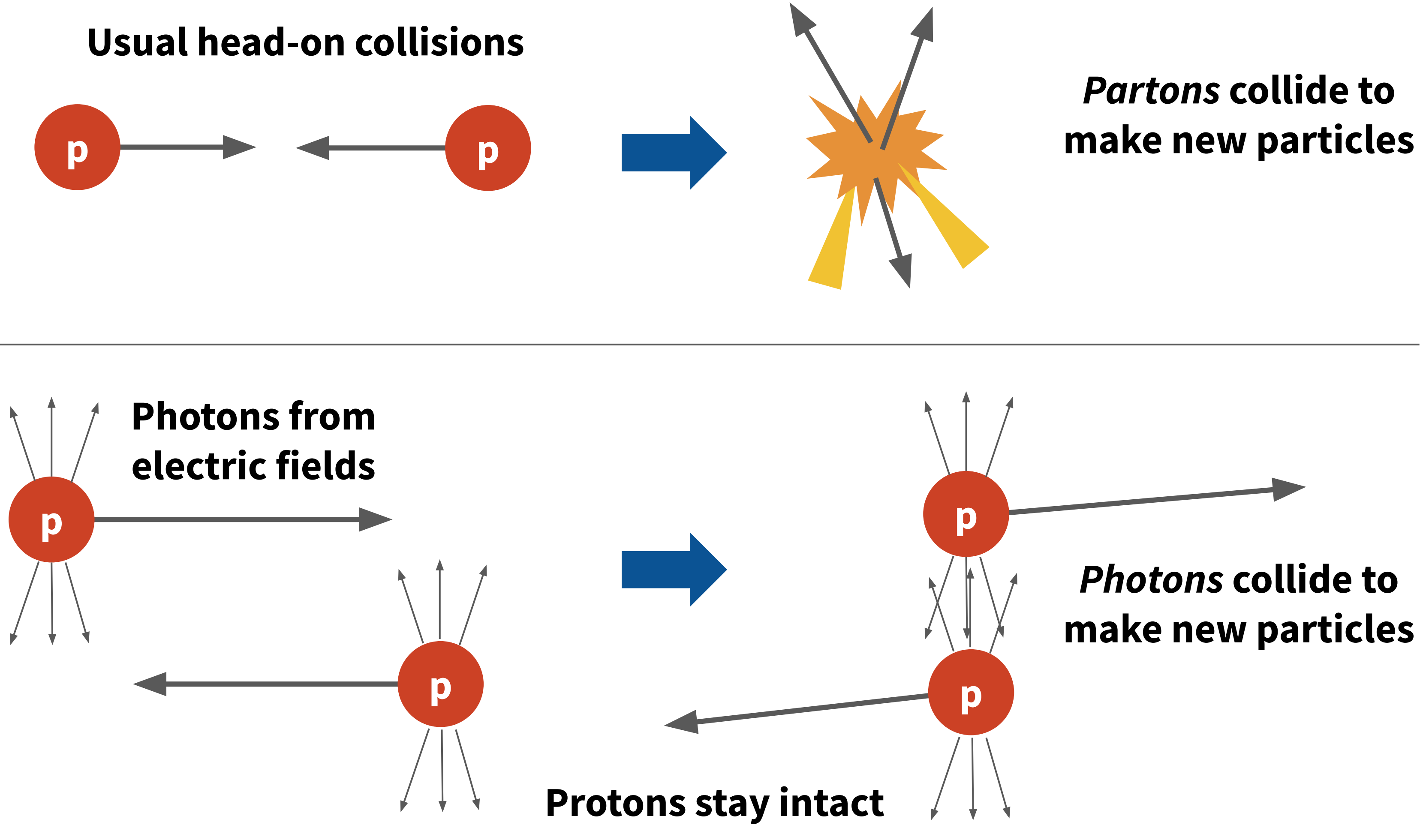
Consequence

Only transverse 2-vector measurable

$$\mathbf{p}_{\text{T}}^{\text{miss}} = \mathbf{0} - \sum_{\text{final}} \mathbf{p}_{\text{T}}^{\text{final}}$$

⇒ Impedes *massless* neutrinos vs *massive* dark matter discrimination

Colliding light @ LHC

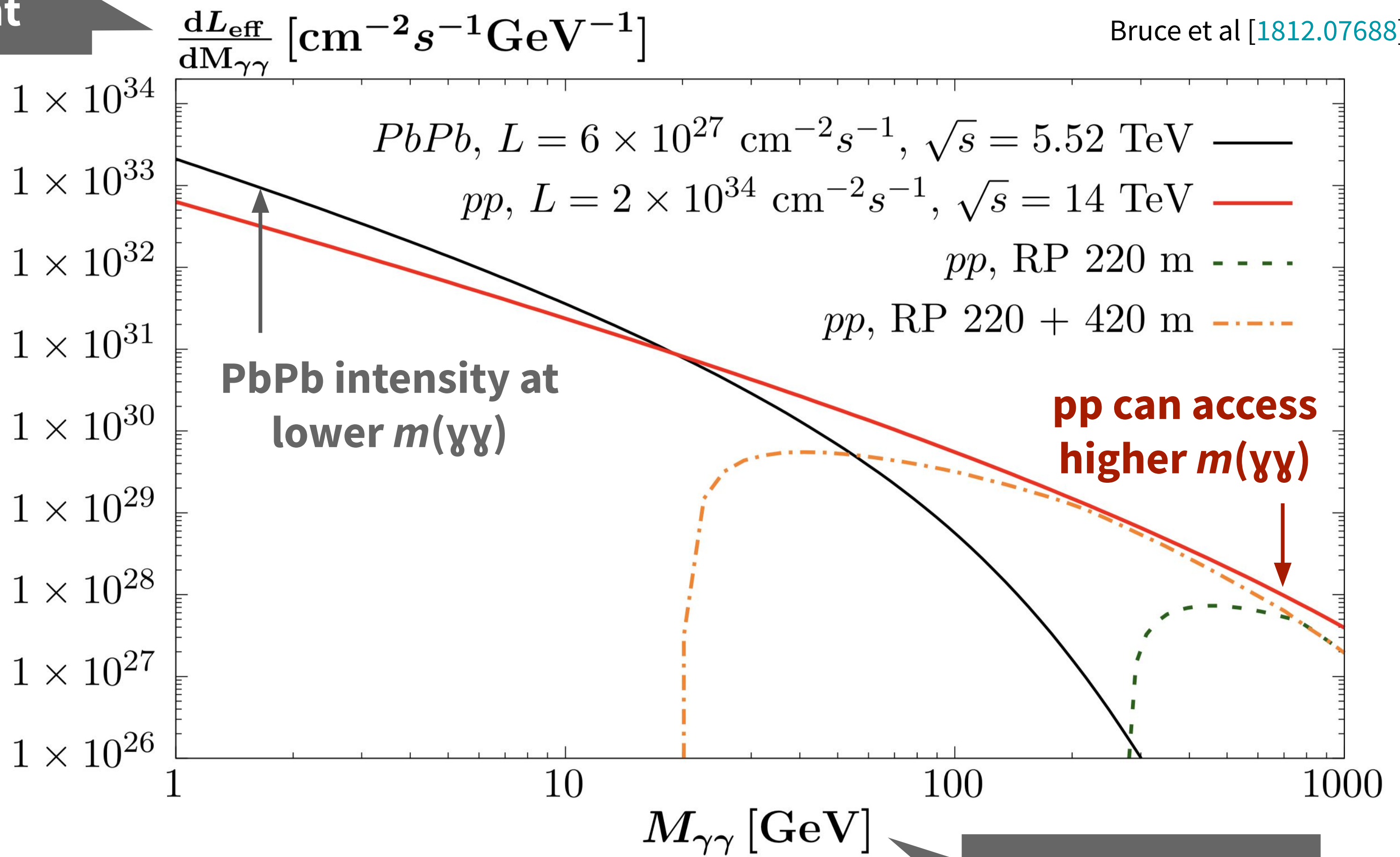


Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Schwinger (1952), Budnev, Ginzburg, Meledin, Serbo (1975)
d'Enterria and da Silveira [1305.7142], ATLAS [1702.01625, 1904.03536], CMS [1810.04602], Bruce et al [1812.07688]

Colliding photon spectrum

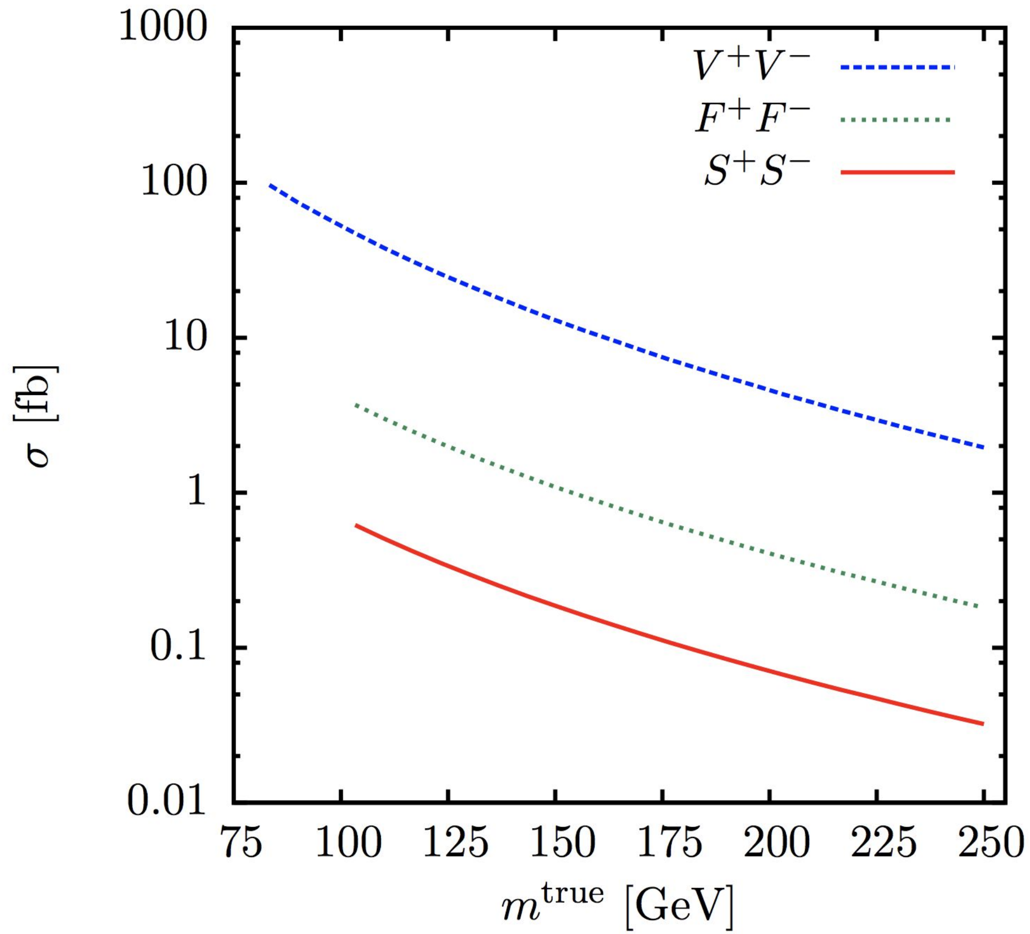
How bright is your light

Bruce et al [1812.07688]



Mass of colliding light

Cross-sections: QED pair production

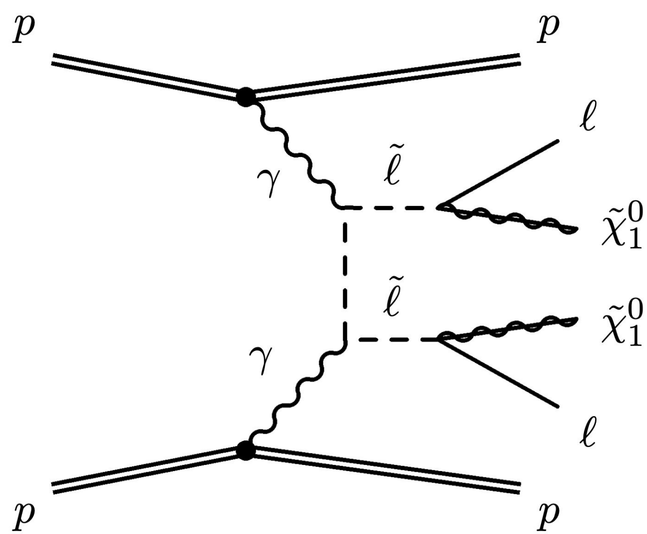


14 TeV pp → p (ɣɣ → XX) p

QED production fixed by mass & spin

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

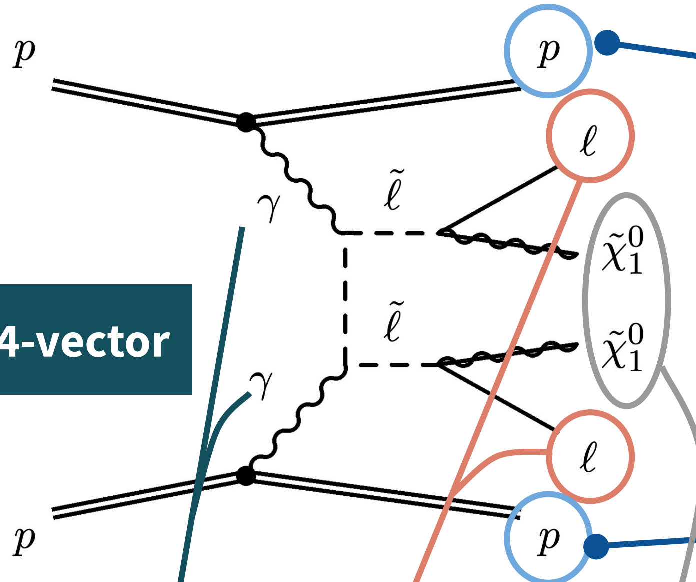
QED production of charged scalars



~ 2.5 fb for *m* ~ 100 GeV

⇒ 100s of events @ 140/fb

Initial state & missing momentum 4-vector



1) Measure intact protons

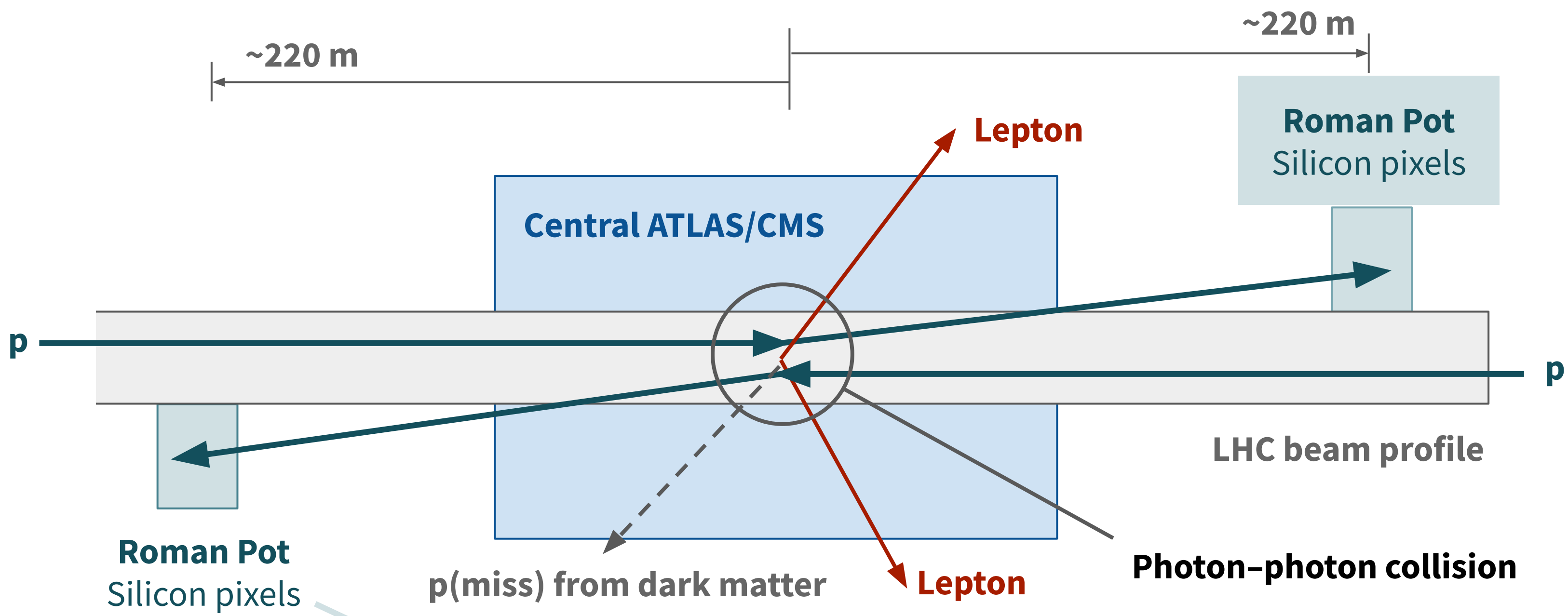
2) Compute photon 4-vector

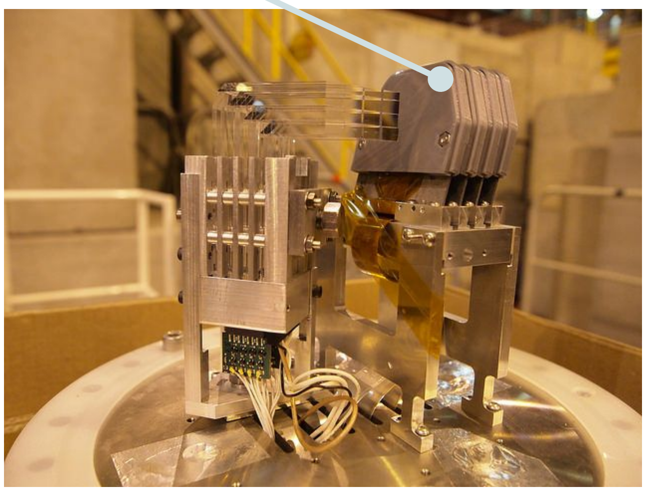
$$p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_f^{\text{visible}} \quad \Rightarrow \quad m^2_{\text{miss}} = p^2_{\text{miss}}$$

"Impossible @ hadron colliders"
no more

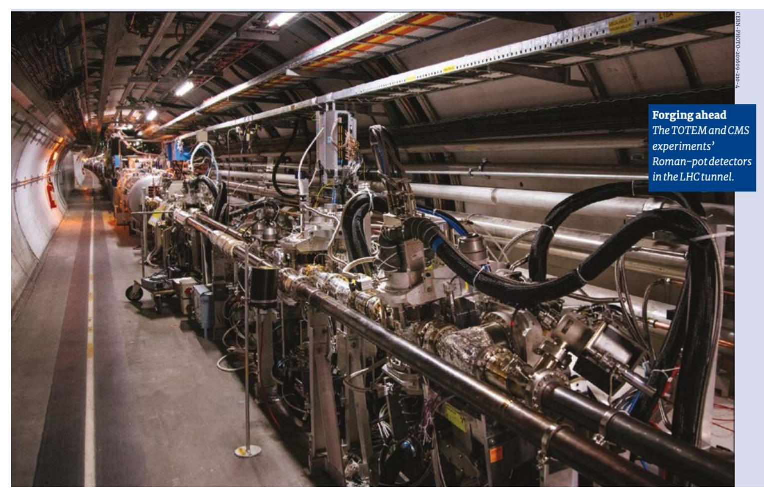
3) Square 4-vector for dark matter mass :)

Roman Pots (AFP/CT-PPS) fully installed 2017/16





[AFP TDR]

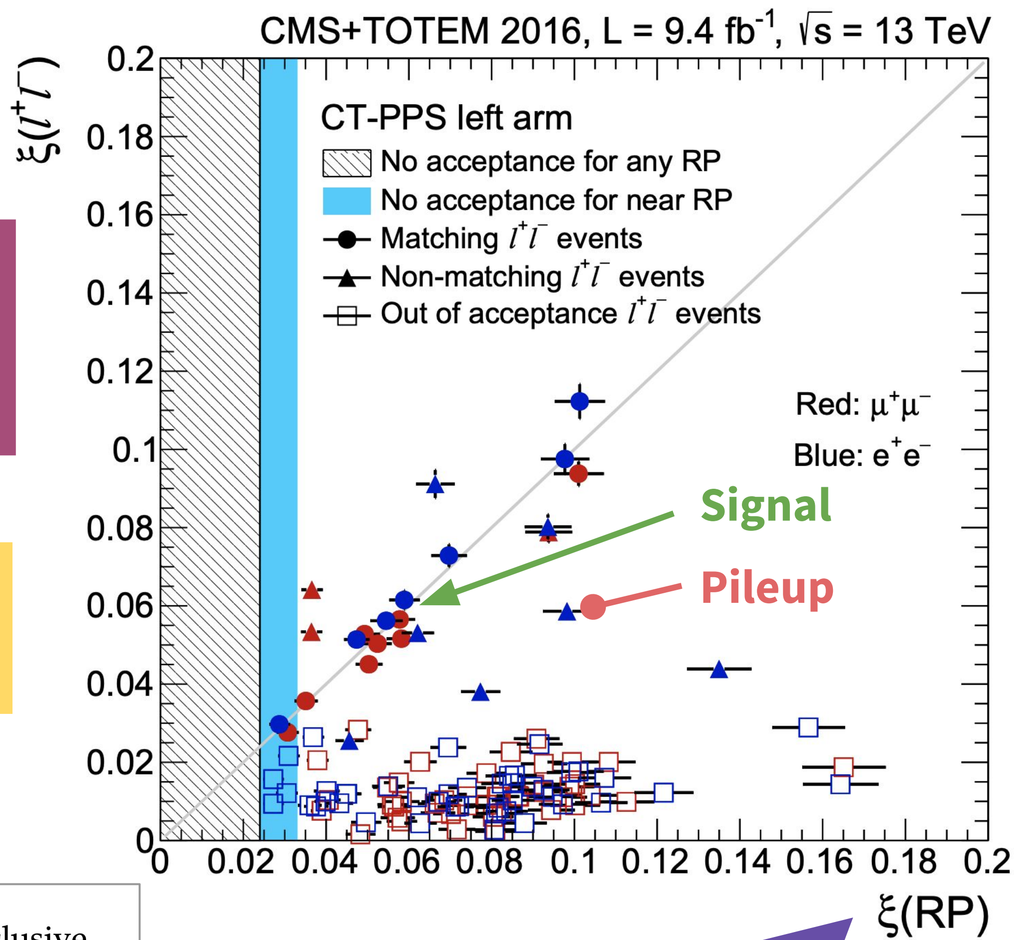


[CT-PPS TDR]

Prove we can see protons using pp → p(γγ → ℓℓ)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

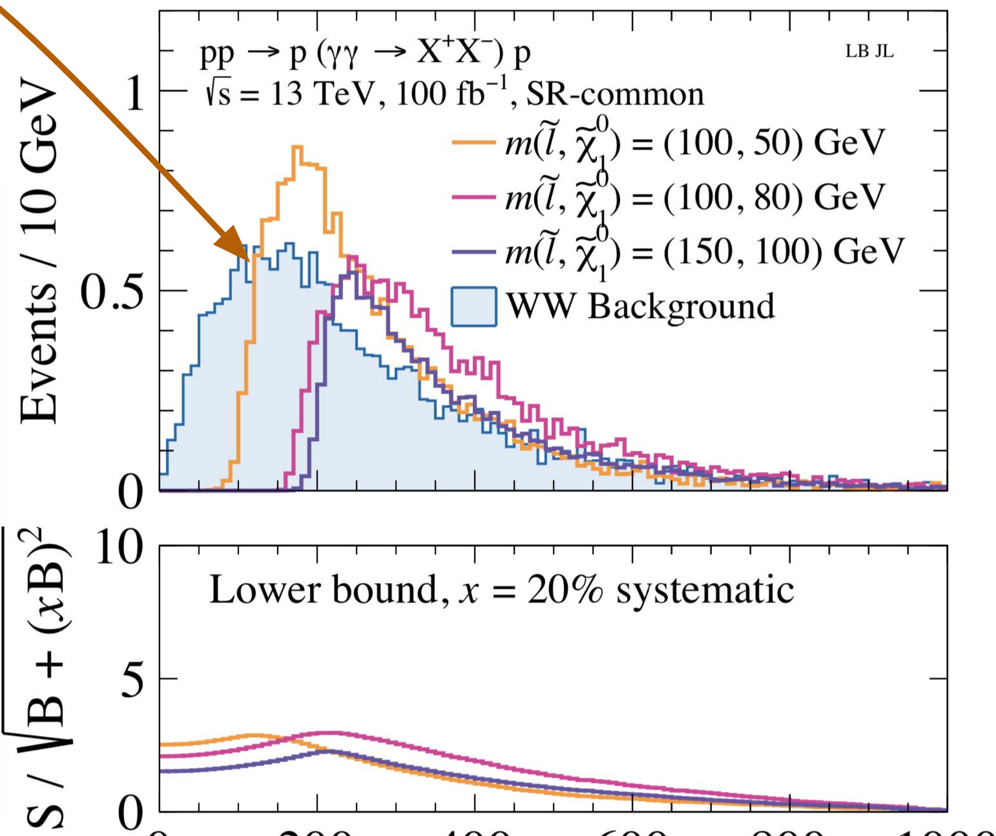
CMS and TOTEM [1803.04496]

World first missing mass @ hadron colliders imminent?

Wow! Threshold @ 2 × DM mass

Impossible without Roman Pots!

Missing mass

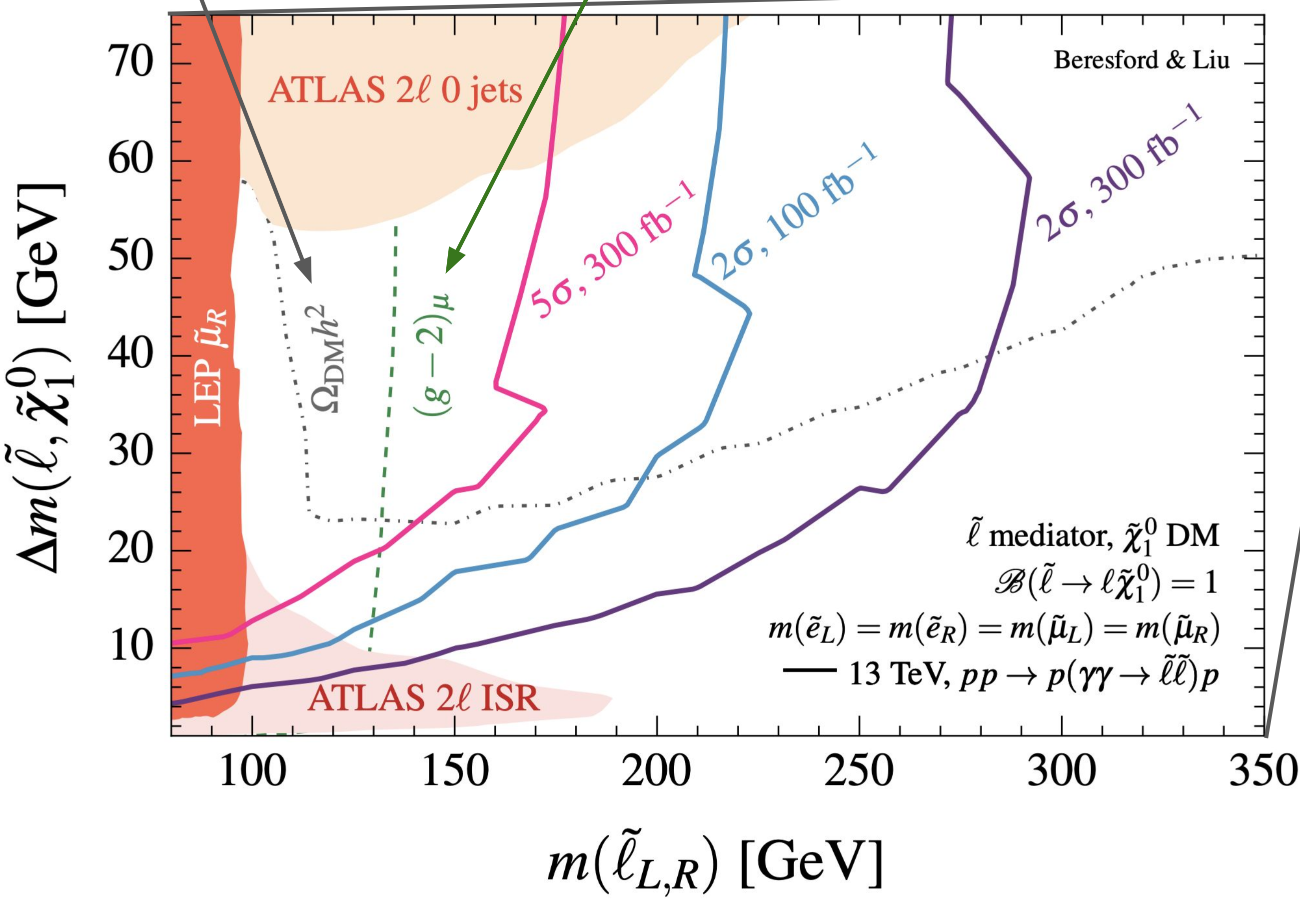


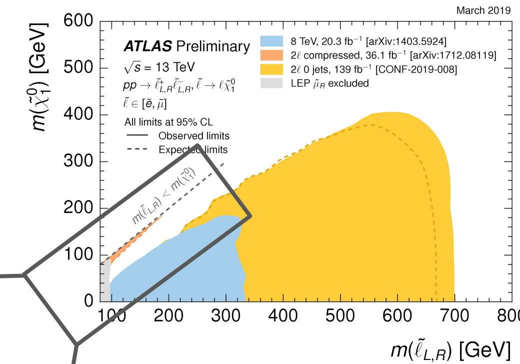
$$W_{miss} = \sqrt{(p_1^\gamma + p_2^\gamma - p_1^l - p_2^l)^2}\ [\mathrm{GeV}]$$

Potentially striking physics impact

Favoured by dark matter abundance

Favoured by muon *g* – 2 tension





[1811.06465]

NEW PROPOSAL 2

Colliding light to measure tau $g - 2$

Using heavy ion beams

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

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

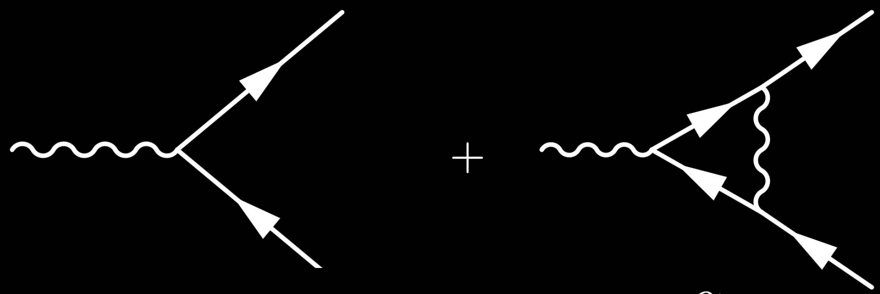
[1] *Department of Physics, University of Oxford, Oxford OX1 3RH, UK*
[2] *Department of Physics, University of Chicago, Chicago IL 60637, USA*

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.

Lydia Beresford, JL [1908.05180]

g – 2: foundational test of QED

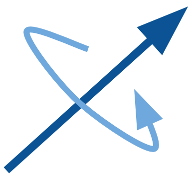
"How does light interact with matter?"



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

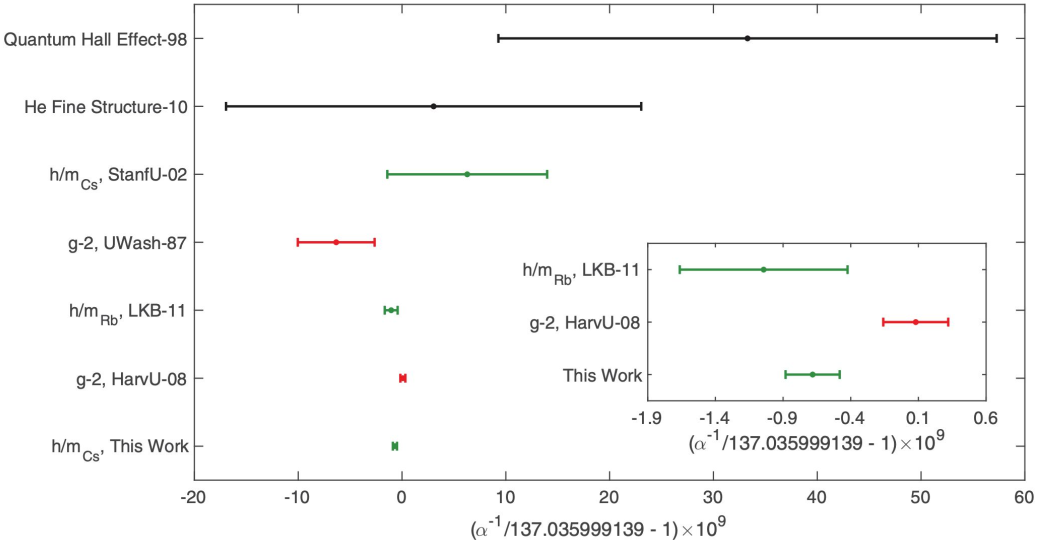
Dirac (1928) **Schwinger (1948)**

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



Directly measure via spin–magnetic precession

State of the art: cracks at the heart of QED?

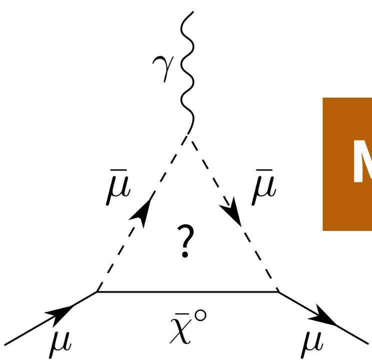


Electron $g-2$ (−2.5σ)

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"

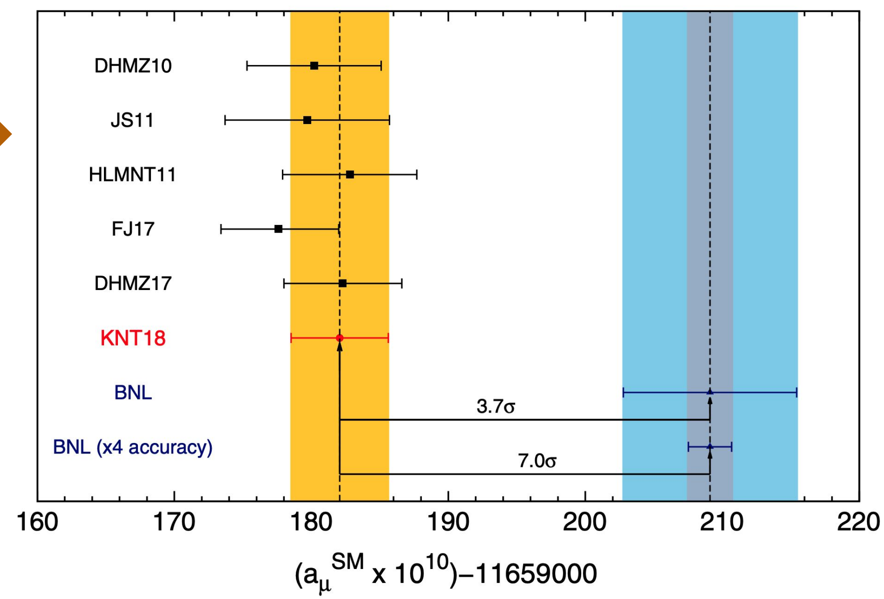


Muon $g-2$ (+3.7σ)

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?"



[Muon g–2 Experiment]

What about tau *g* – 2?

Shocking experimental ignorance!

Current PDG value is by DELPHI 2004

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

DELPHI [hep-ex/0406010]

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

Eidelman, Passera [hep-ph/0701260]

Pressing problem: no measurement!

for 70 year old prediction: $\alpha/2\pi$ = 0.001162

Schwinger (1948)

Pressing & *interesting* open problem

Huge uncertainty

⇒ huge room for new physics

$$\delta a_\ell \sim m_\ell^2 / M_{\mathrm{SUSY}}^2$$

$$m_\tau^2 / m_\mu^2 \sim 280$$

280× more sensitive

to new physics

than muon *g* – 2

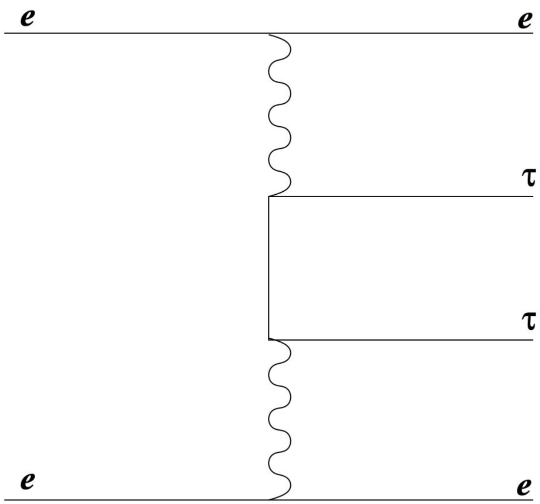
No model shortage for e & μ *g* – 2

SUSY, vector-like lepton, 2HDM, axion, dark photon, Z' …

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]
…

Correlate with tau *g* – 2?

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

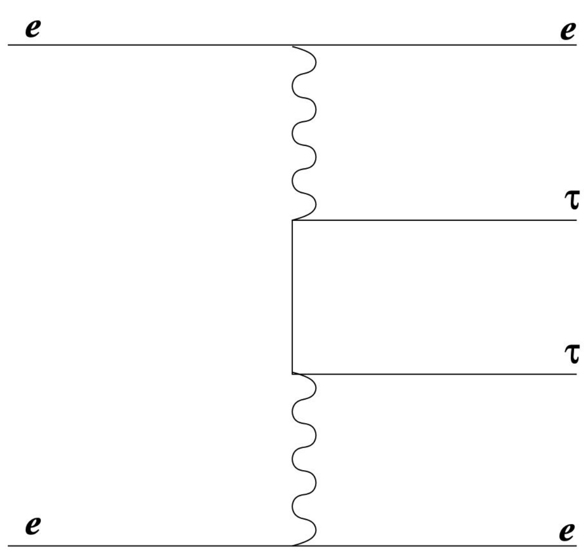
Fomin, Korchin, Stocchi, Barsuk, Robbe [1810.06699]
Fu et al [1901.04003]

Recent proposals need future datasets

Can we do better *today?*

Bring LEP success to LHC

PDG value of tau *g*– 2



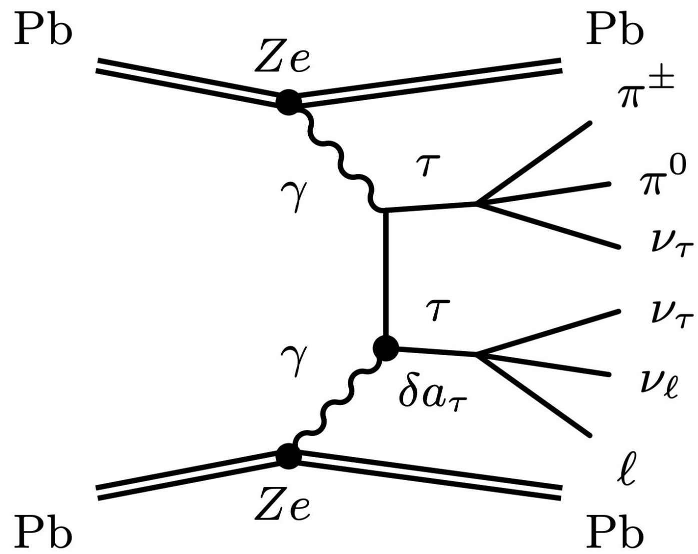
LEP photon collisions

σ ~ 400 pb

⇒ 200k events all years

DELPHI [EPJC (2004)]

Proceed analogously @ LHC?



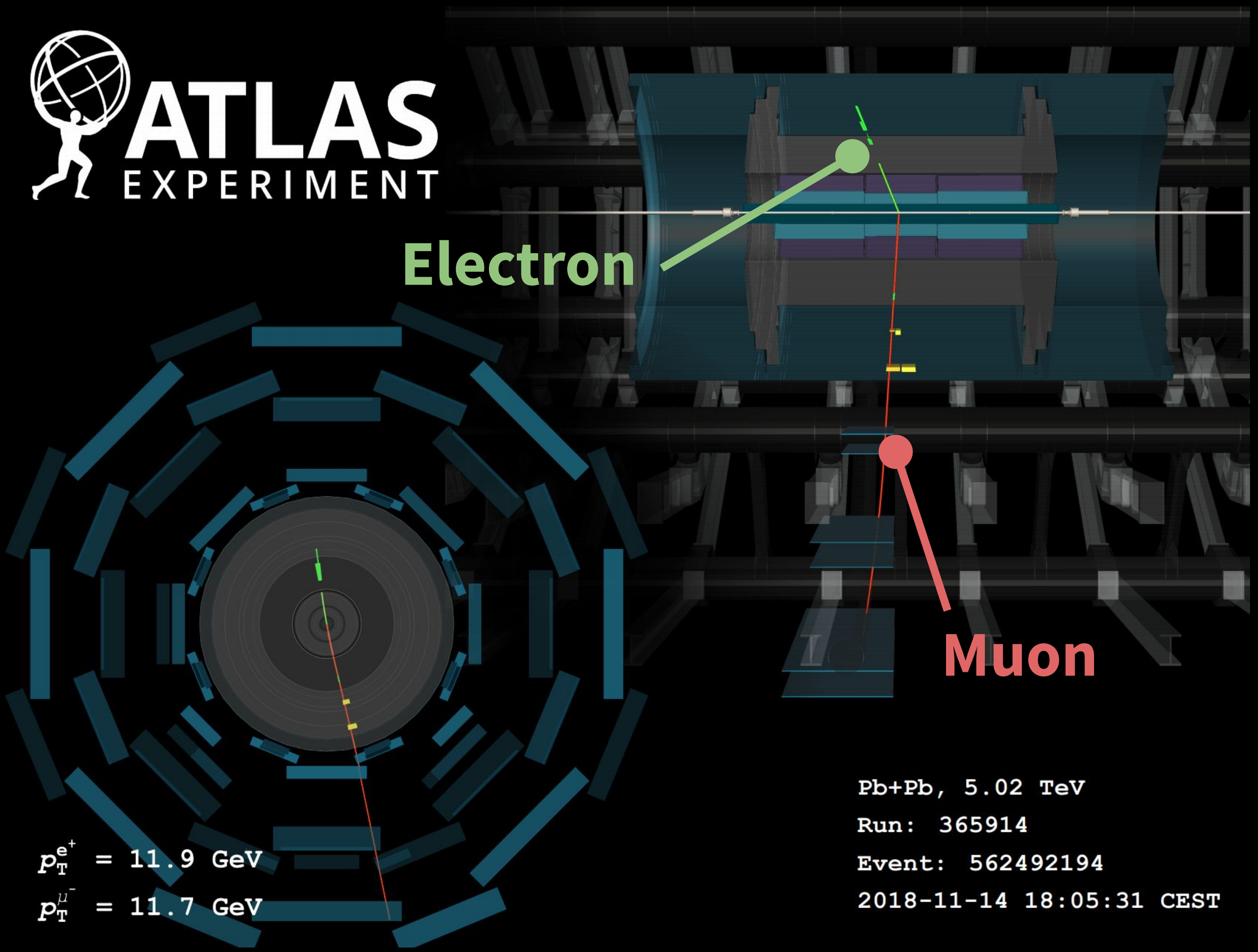
Never been seen at LHC

σ ~ Z^4 ~ 500 000 nb (Z_{Pb} = 82)

⇒ 1 million events *already*

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

Stunning events already recorded by ATLAS/CMS

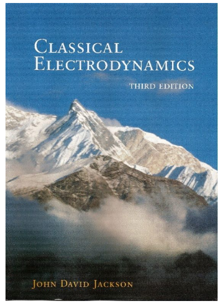


1 month to collect dataset | No pileup μ ~ 0.001 | Ultra loose triggers

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

[ATLAS Event Displays]

Photon collisions using MadGraph & SMEFTsim



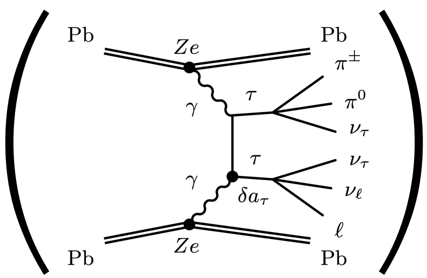
Photon flux: classical field theory

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

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

MadGraph **Jackson** **SMEFTsim**

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

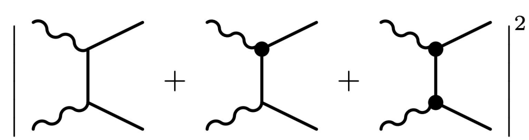


$$= \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1) n(x_2)\, \sigma_{\gamma\gamma\to XX}$$

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]

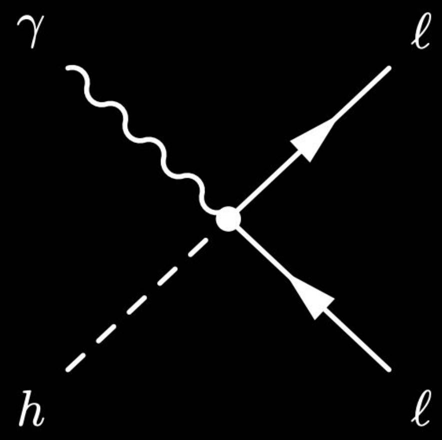
Include interference up to 2 BSM couplings



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

Only dimension-6 SMEFT operator inducing *g* – 2

$$\delta a_\tau \sim$$



$$\sim \frac{C}{\Lambda^2} \left(\bar{L}_\ell \sigma^{\mu\nu} \ell_R\right) H \left(\partial_\mu A_\nu\right)$$

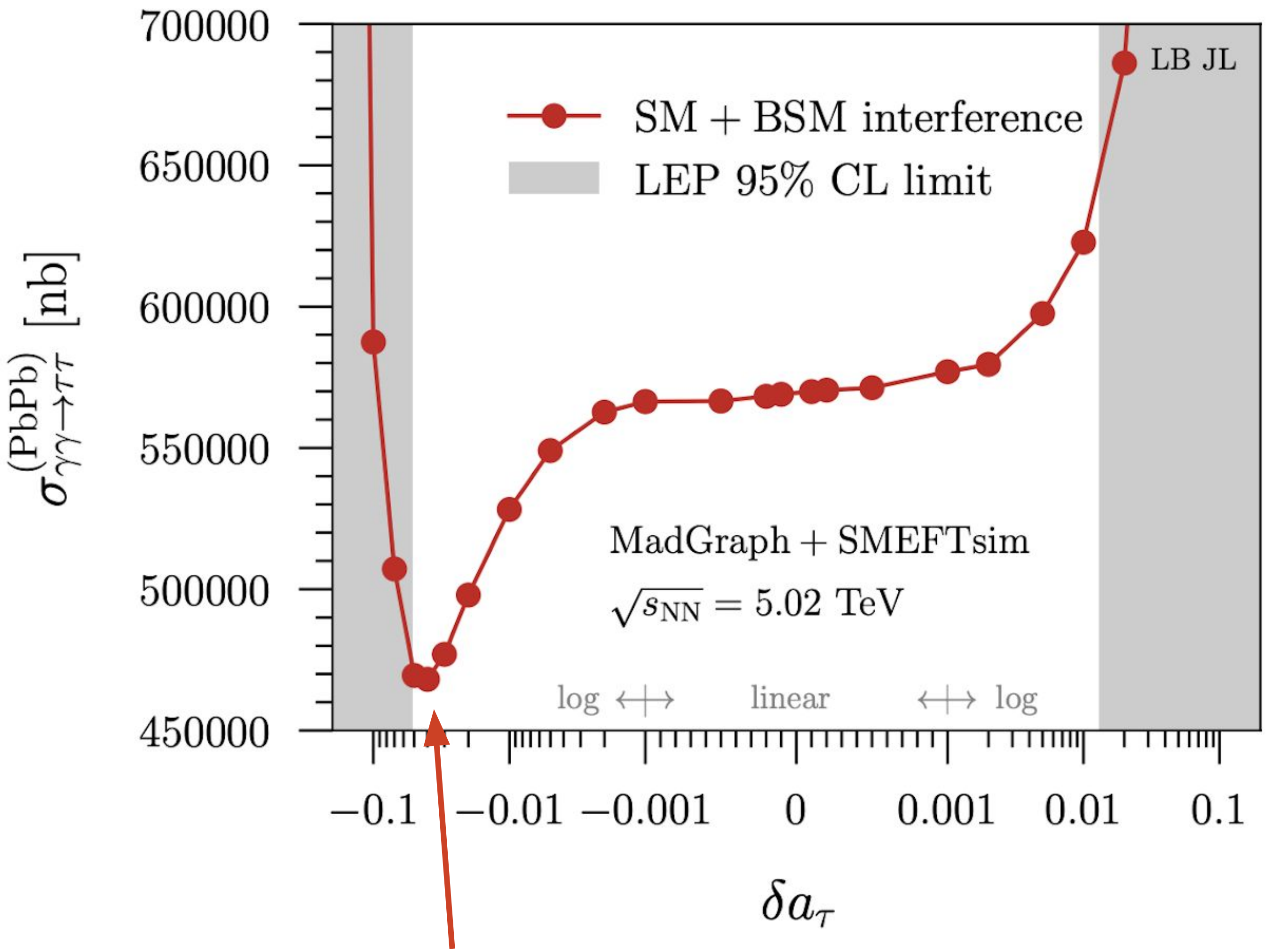
$$\downarrow \qquad\qquad \downarrow$$

$$\mathbf{S} \cdot \mathbf{B}$$

If C complex phase non-zero ⇒ CP violating electric dipole moment

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]

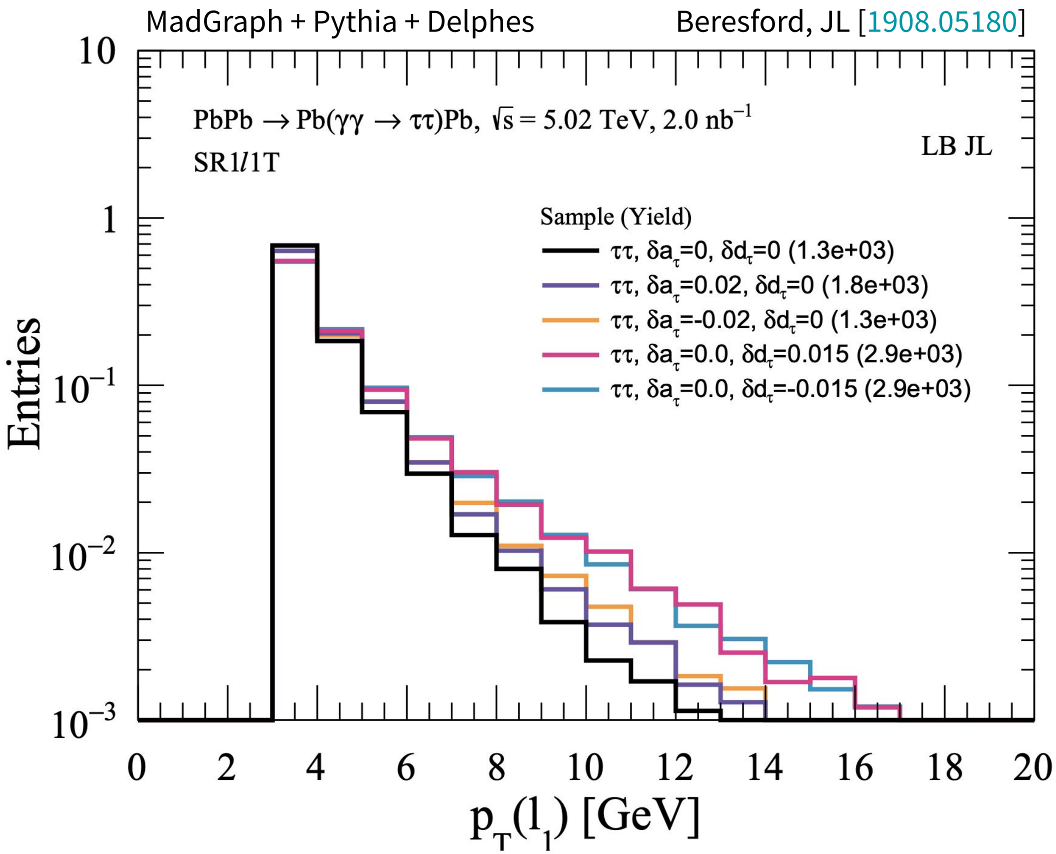
Cross-sections as function of *g* – 2 deviations (PbPb)



Maximal destructive interference

Beresford, JL [1908.05180]

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

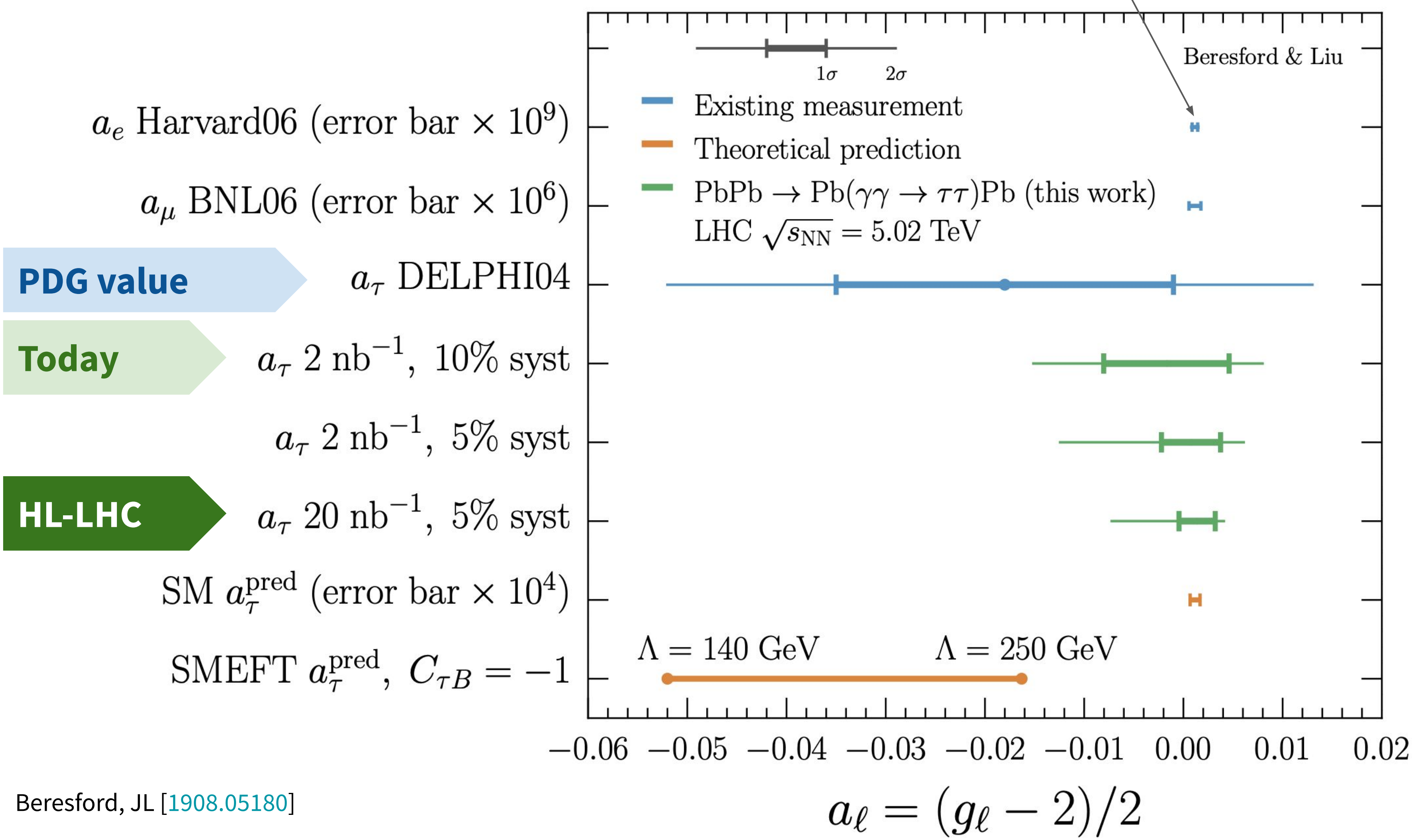
$p_T(\ell)$ sensitive to different dipole moments

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]

Prospects: surpass 15 year old LEP precision

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



Beresford, JL [1908.05180]

EPILOGUE

Neutron magnetic moment

When nature laughed in our 1930s faces

Theory: zero as it's neutral & pointlike

Nature: large ***AND*** negative haha ($g - 2 = -5.8$)

Chadwick (1932) Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)

Indirect evidence for compositeness

3 decades before deep inelastic scattering

Large moments now save lives in MRI medical imaging :)

Today: recently discovered Higgs, 3 decades until next energy frontier collider.

PRESSING PROBLEM

Tau $g-2$

Elephant in the room

1 order of magnitude from SM precision

280× more sensitive to BSM than muon g–2

Probe Higgs SMEFT & flavour problem

SUBLIME SOLUTION

Collide light

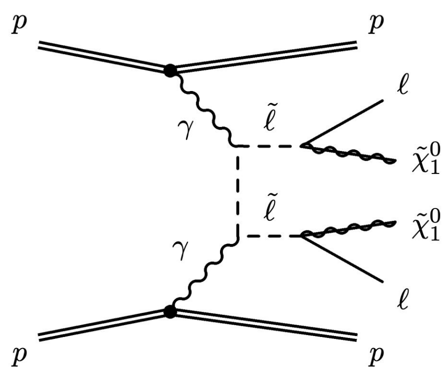
Exciting possibility today

1 million $\tau\tau$ events made in PbPb already

Soft taus in exquisite pileup free events

Could surpass 15 year old LEP precision today

Summary: colliding light as exciting opportunities

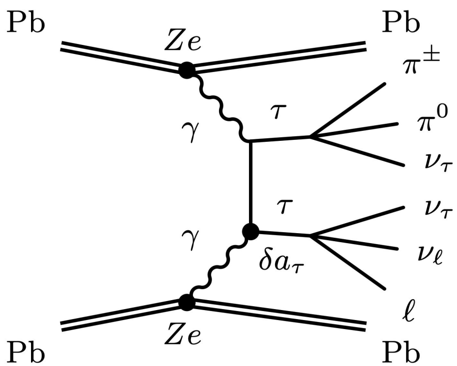


Make dark matter

Measure p(miss) 4-vector

Lydia Beresford, JL

[1811.06465, PRL **123** (2019) 141801]



Measure tau *g* – 2

Using heavy ion beams

Lydia Beresford, JL

[1908.05180]

Forward & heavy ion physics systematically overlooked

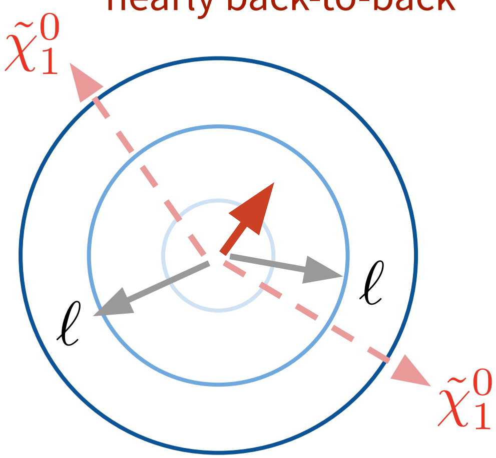
But harbour stunning solutions to pressing problems

Excitingly on the cusp of reality: data already recorded!

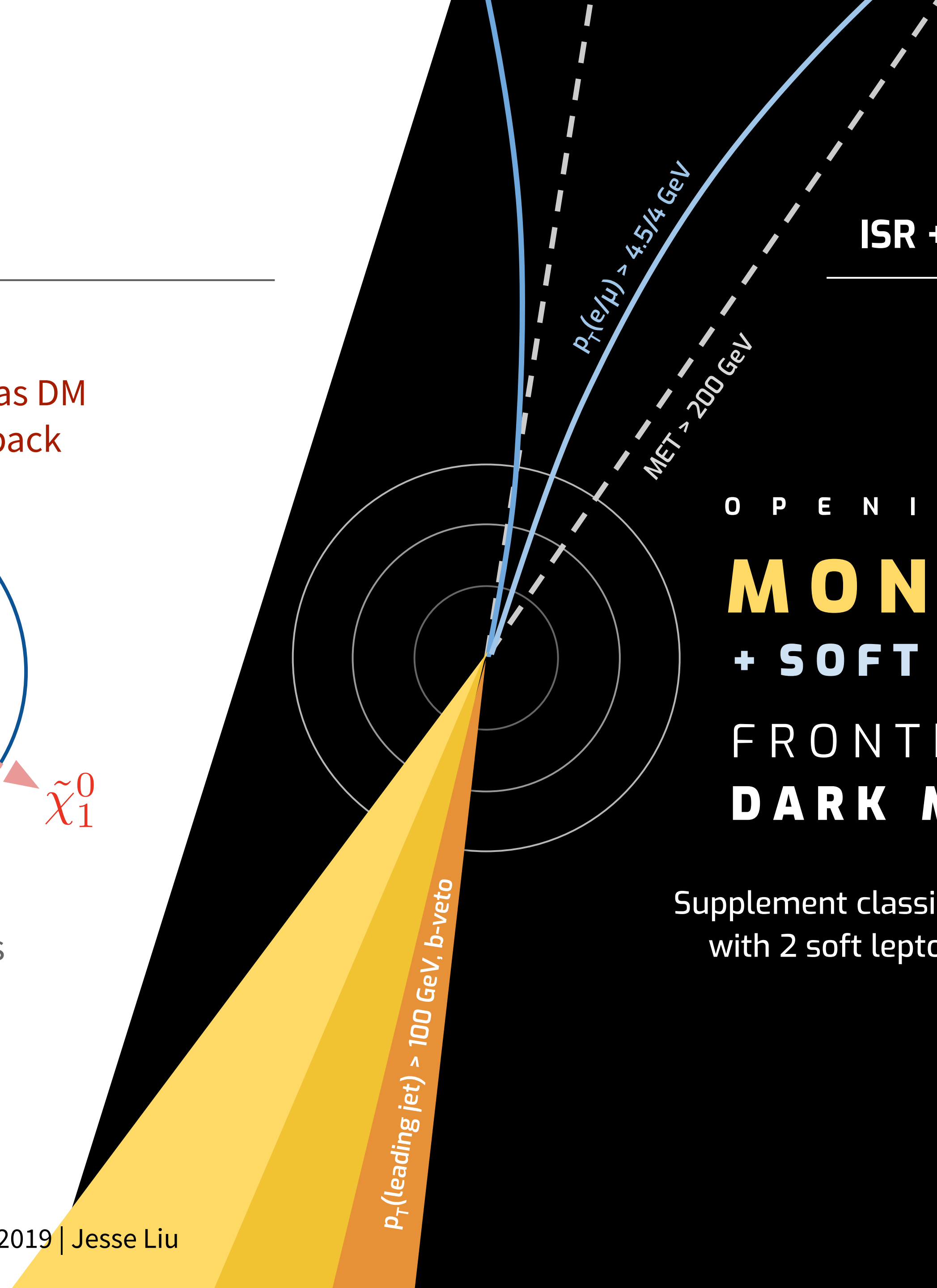
EXTRAS

PREVIOUS PROBES

Low missing E_T as DM nearly back-to-back



Leptons too soft to pass lepton triggers



ISR + Soft leptons

OPENING THE

MONOJET

+ SOFT LEPTON

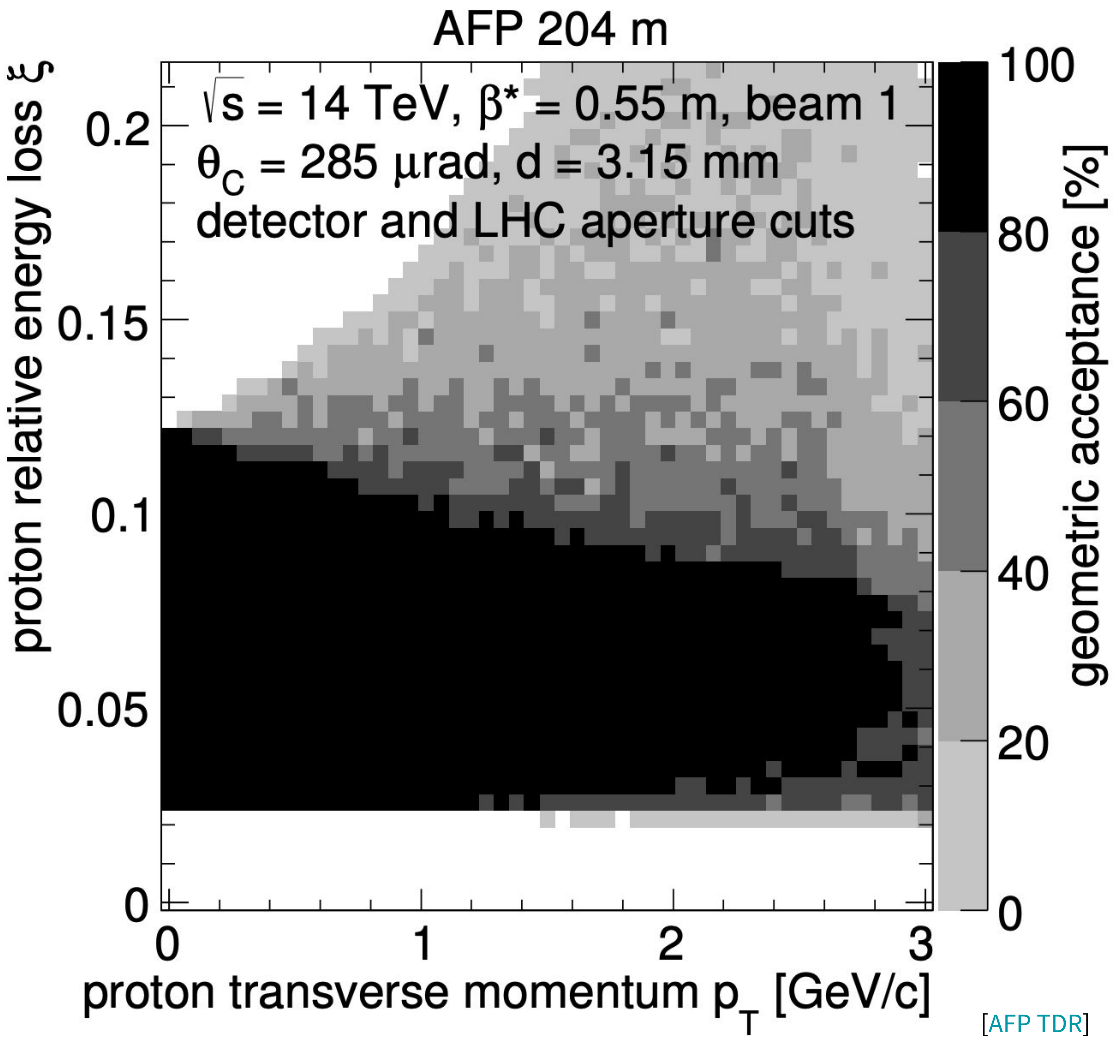
FRONTIER FOR

DARK MATTER

Supplement classic Monojet + MET with 2 soft leptons (e^+e^- or $\mu^+\mu^-$)

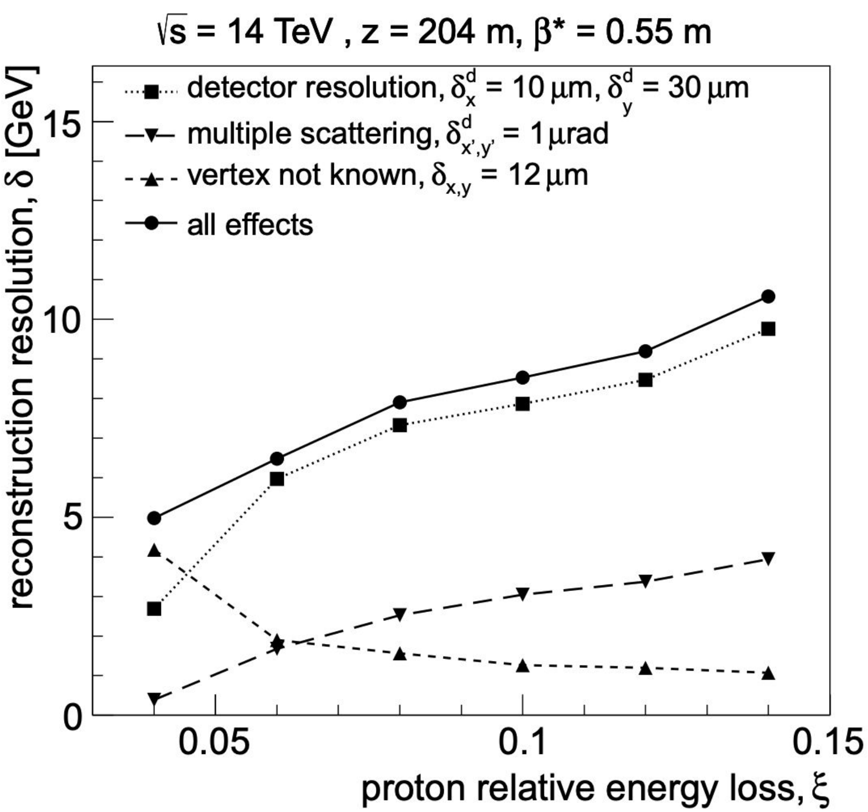
ATLAS [1712.08119]
CMS [1801.01846]
Guidice et al [1004.4902]
Gori et al [1307.5952]
Han et al [1401.1235]
Baer et al [1409.7058]
Barr et al [1501.02511]

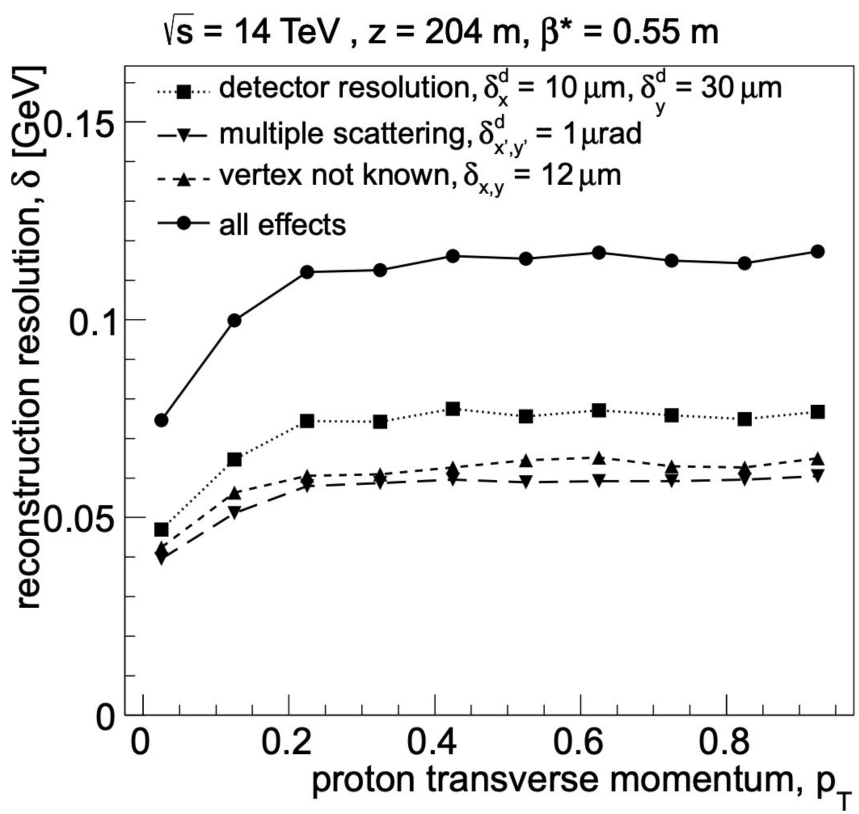
Near station geometric acceptance



[AFP TDR]

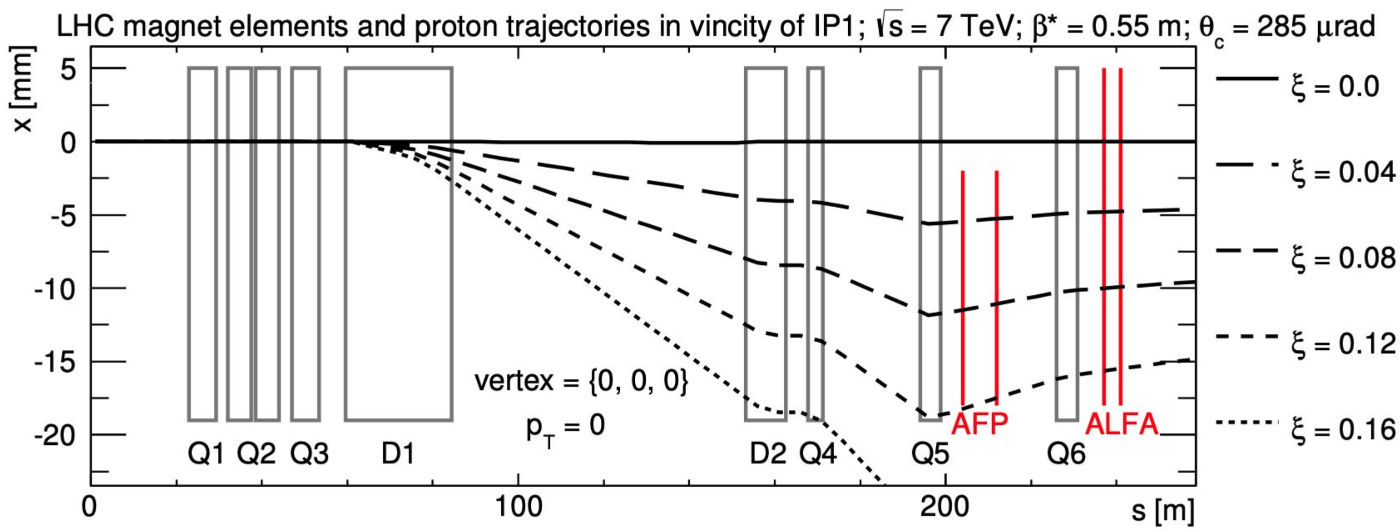
Simulated AFP energy resolution





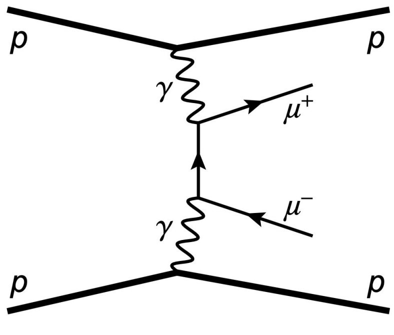
[AFP TDR]

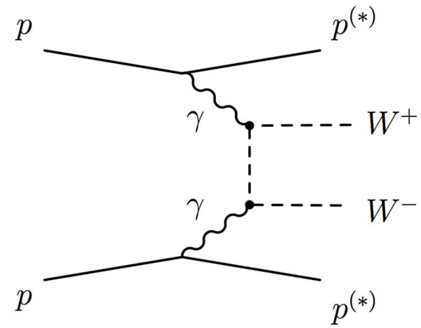
Simulated AFP transport of proton

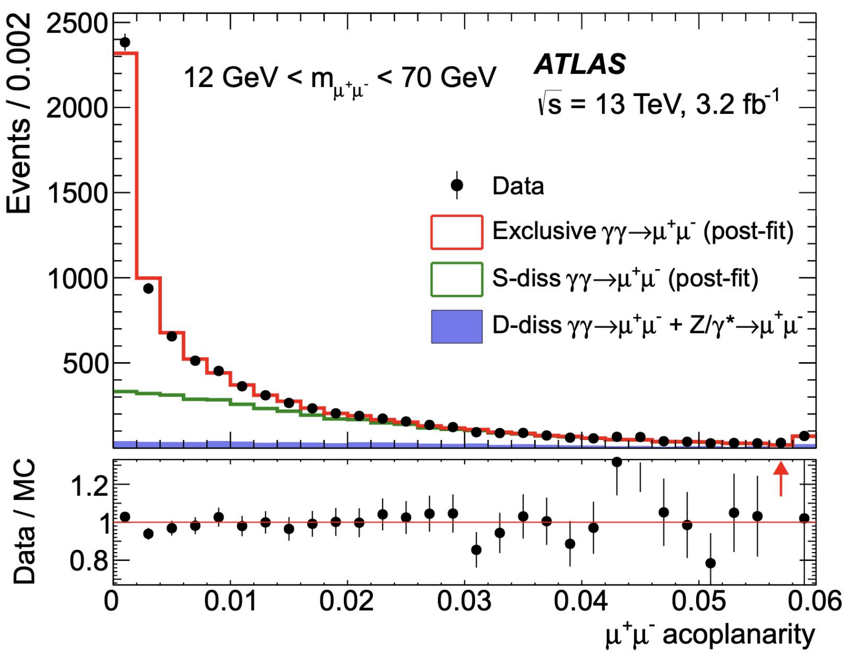


[AFP TDR]

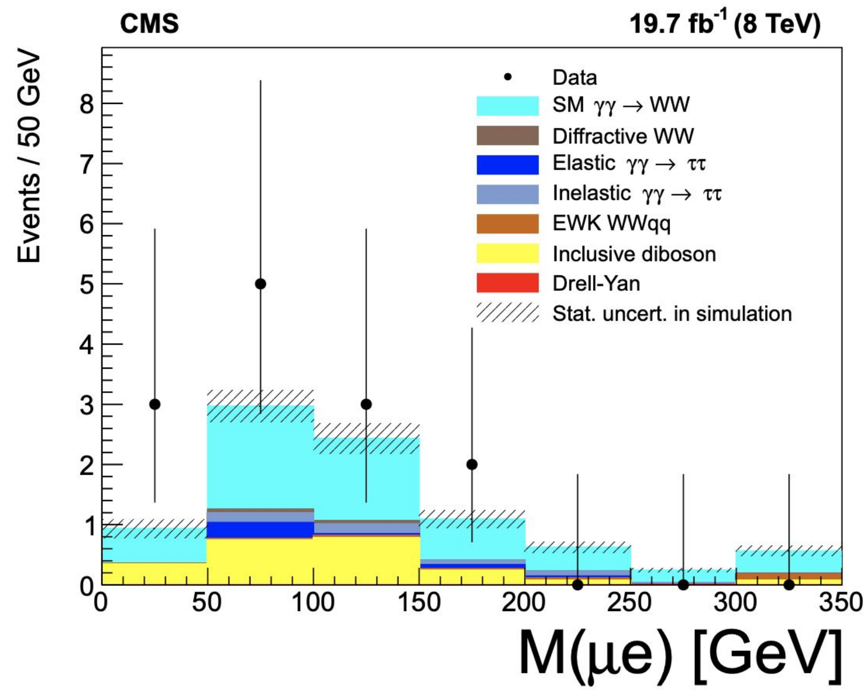
Colliding light using LHC pp beams



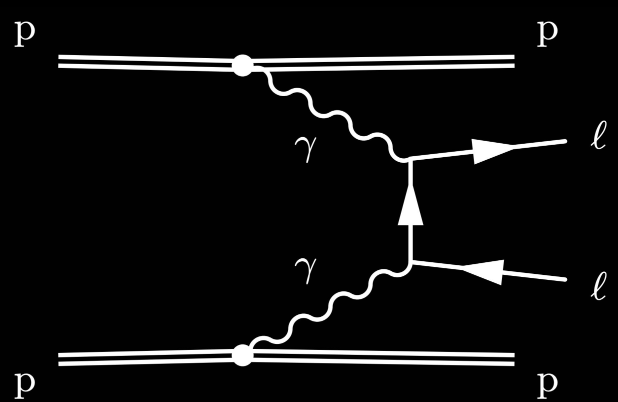




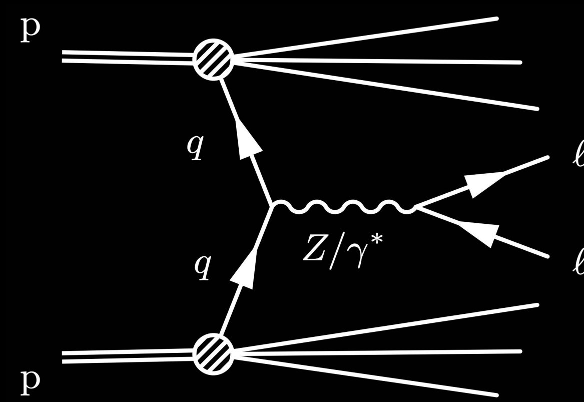
ATLAS [1708.04053]



CMS [1604.04464]



SIGNAL



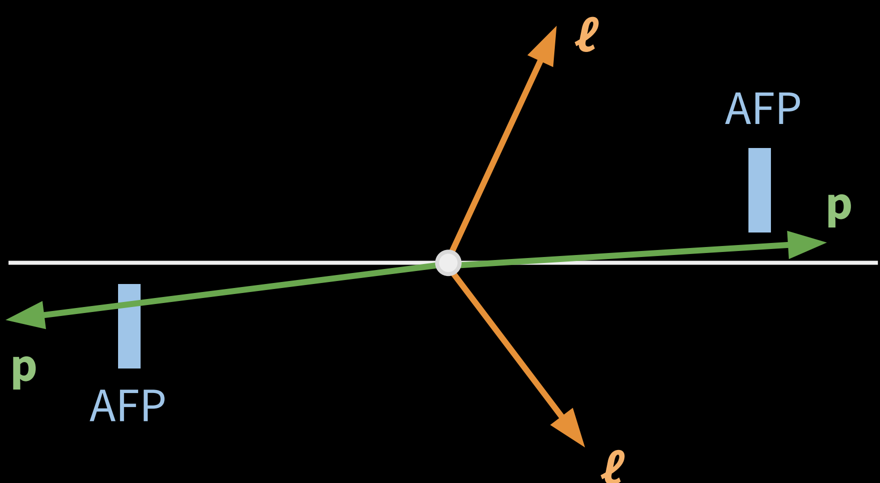
BACKGROUND

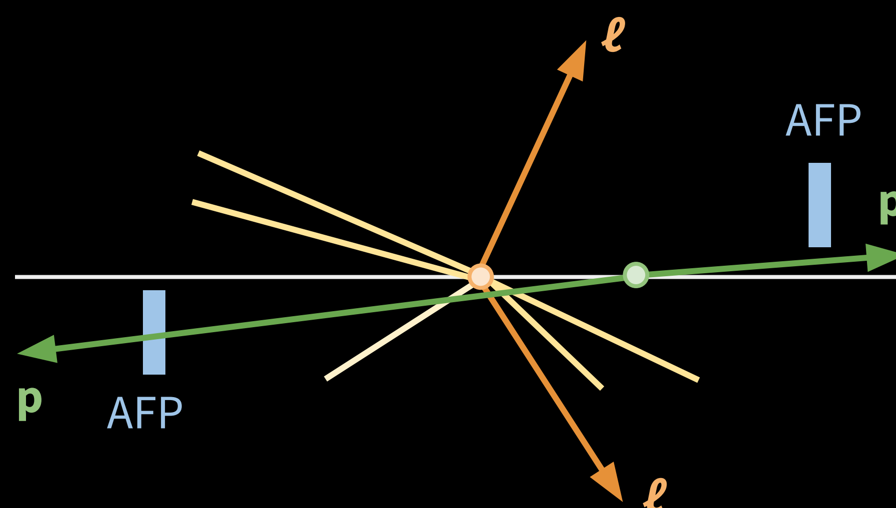
QED pp → p(γγ → ℓℓ)p

PHOTON FUSION, INTACT PROTONS IN AFP

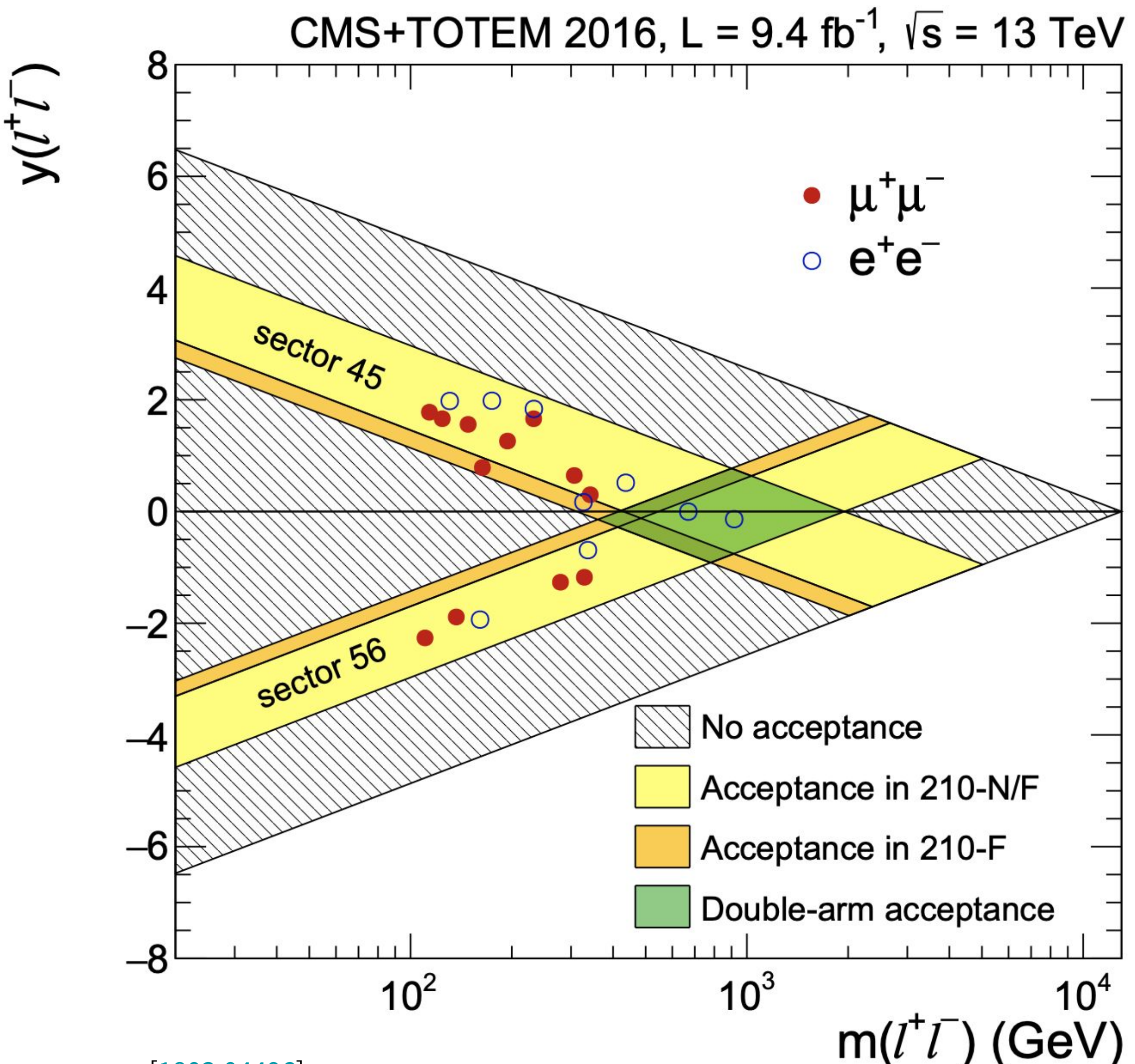
EWK DRELL–YAN (Z/γ*→ℓℓ) + pileup

QUARK FUSION, PILEUP FAKES AFP PROTON



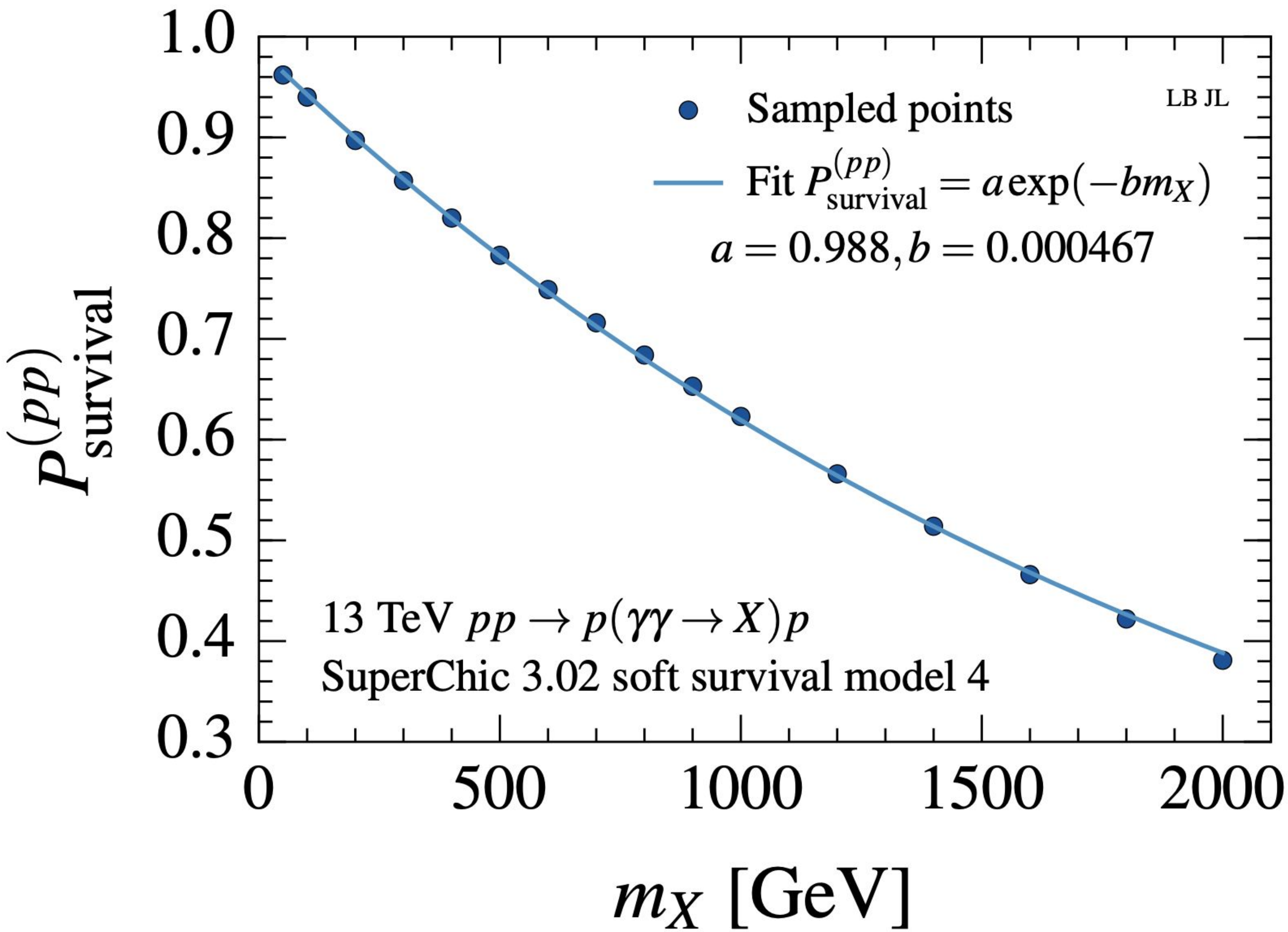


Proton tagged dilepton kinematics



[1803.04496]

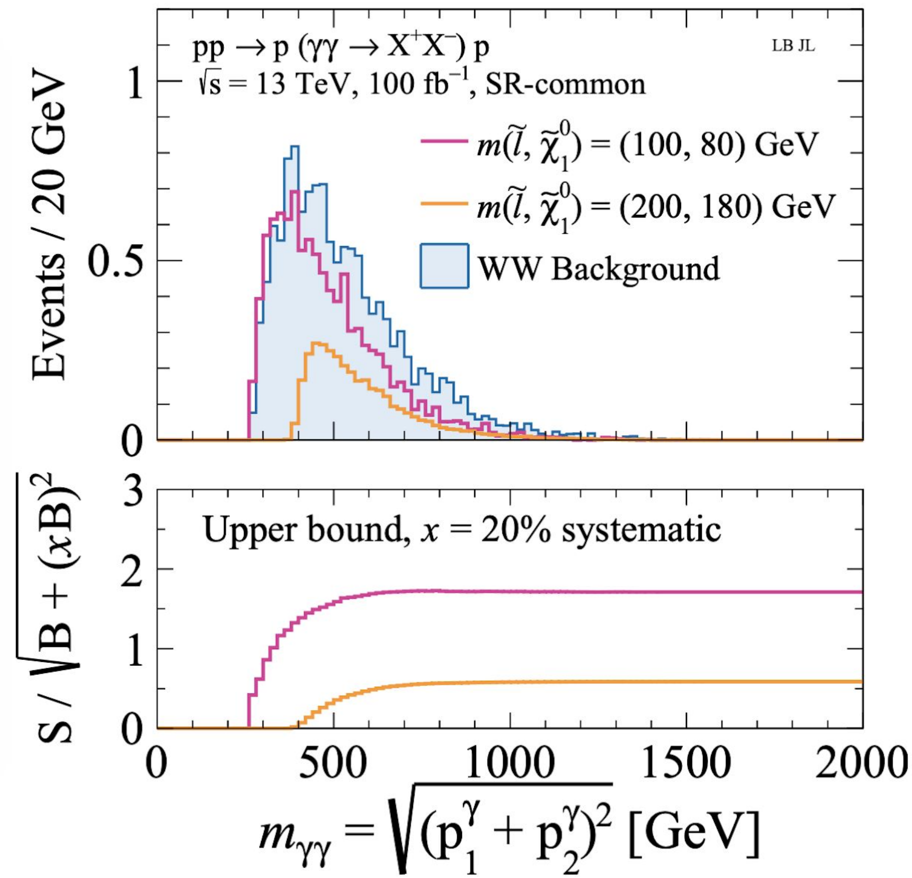
Soft survival as function of centre-of-mass

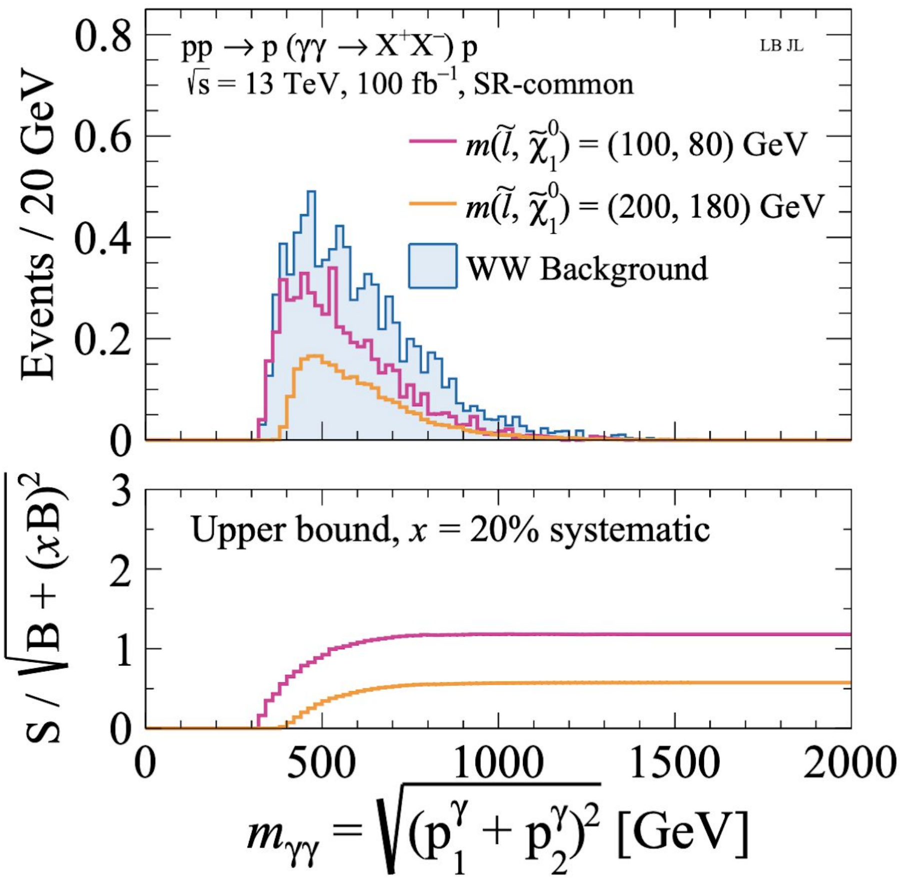


Cutflow

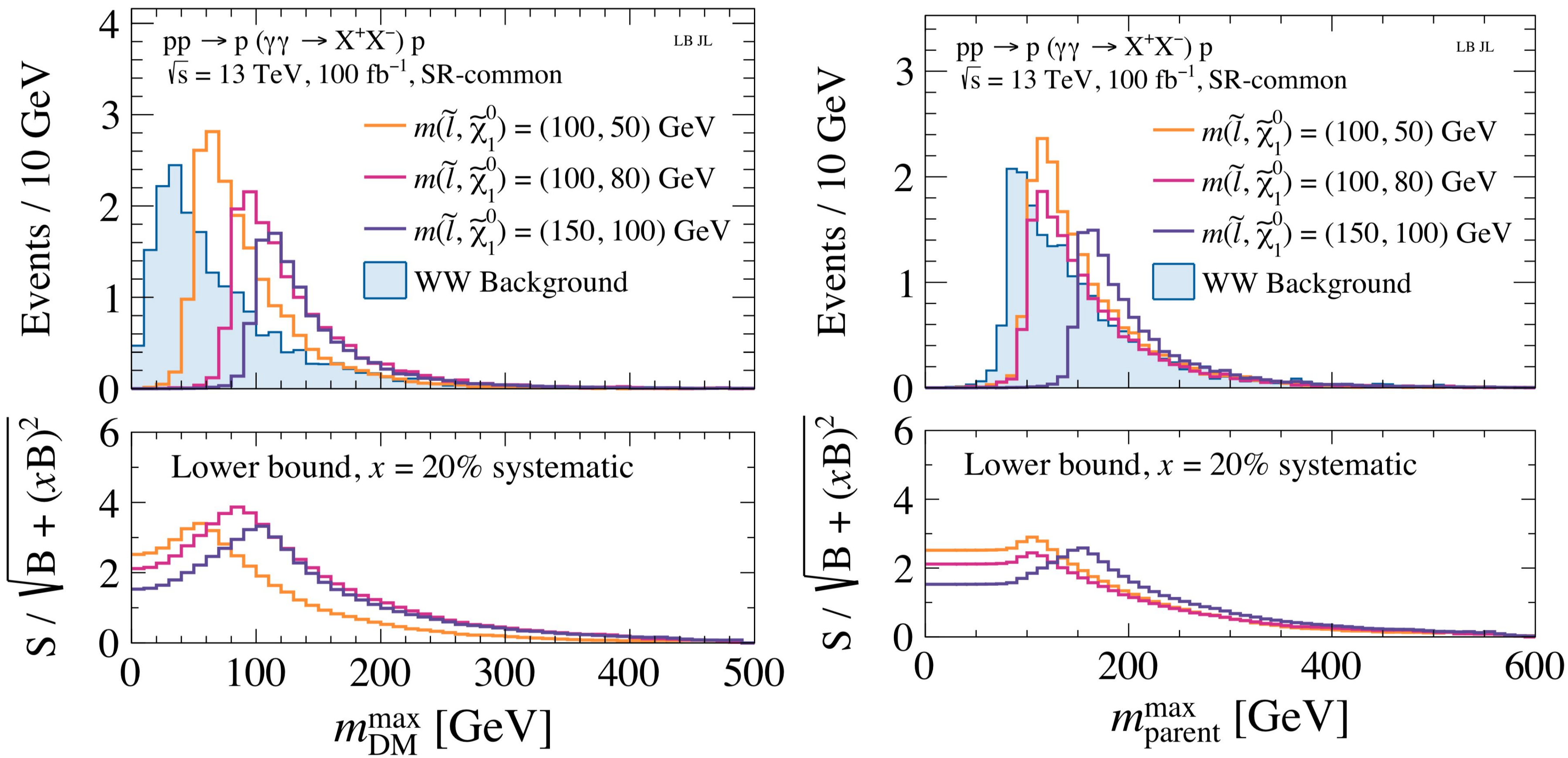
Requirement	$\tilde{\ell}: (100, 80)$	$\tilde{\ell}: (125, 80)$	$\tilde{\ell}: (125, 40)$	$WW \to \ell\nu\ell\nu$
$\sigma \times \mathrm{BR} \times \mathcal{L}$	254	124	124	471
Same flavour leptons	254	124	124	235
$m_{\mathrm{T2}}^{0} > 2$ GeV	240	120	121	230
$\lvert \cos\bar{\theta}_{\ell\ell} \rvert < 0.65$	157	78.5	79.1	83.6
$\lvert \eta_{\ell_1} \rvert < 2.5$	146	74.2	74.8	77.6
$\lvert \eta_{\ell_2} \rvert < 2.5$	130	66.8	67.2	67.5
$p_{\mathrm{T}}^{\ell_1} > 15$ GeV (trigger)	117	66.5	67.2	67.2
$p_{\mathrm{T}}^{\ell_2} > 15$ GeV (trigger)	68.1	60.7	65.1	58.1
$E_{\gamma_1} > 130$ GeV	66.2	60.7	65	53.8
$E_{\gamma_1} < 780$ GeV	53.8	48	51.2	46.3
$E_{\gamma_2} > 130$ GeV	10.9	12.3	13.2	5.05
Lepton 1 efficiencies	8.54	9.66	10.4	3.98
Lepton 2 efficiencies	6.51	7.48	8.22	3.09
$P_{\mathrm{survival}}^{(pp)}$	5.05	5.87	6.45	2.45
SR-compressed				
$m_{\mathrm{DM}}^{\max} > 0$ GeV	5.1	5.9	6.4	2.5
$m_{\mathrm{parent}}^{\max} > 80$ GeV	5	5.9	6.4	2.4
$m_{\gamma\gamma}/W_{\mathrm{miss}} < 1.5$	5	2.9	1	0.47
SR-corridor				
$m_{\mathrm{DM}}^{\max} > 80$ GeV	4.8	5.6	3.2	0.78
$m_{\mathrm{parent}}^{\max} > 120$ GeV	4.2	5.5	3.2	0.74
SR-large				
$m_{\mathrm{DM}}^{\max} > 20$ GeV	5.1	5.9	6.4	2.2
$m_{\mathrm{parent}}^{\max} > 130$ GeV	3.9	5.4	5.9	1.2

Initial state invariant mass

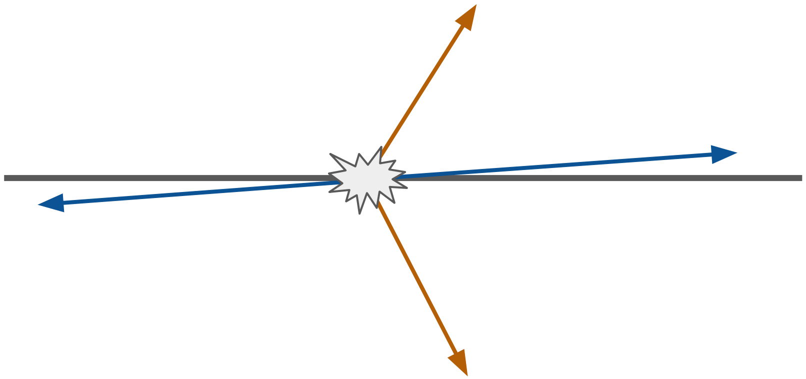




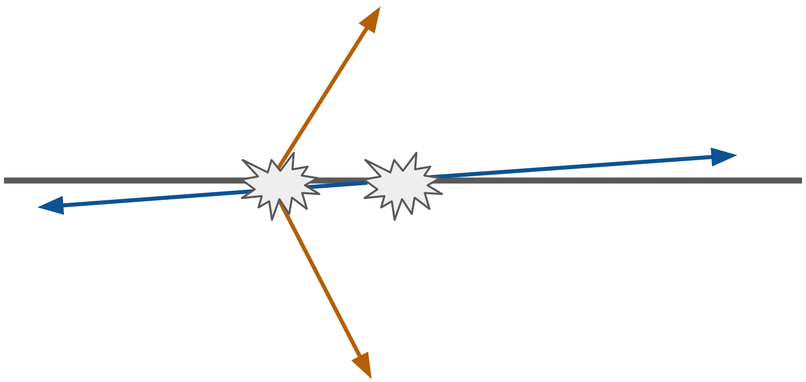
Directly measure invisible & initial state mass



Timing down to 10s of picoseconds crucial



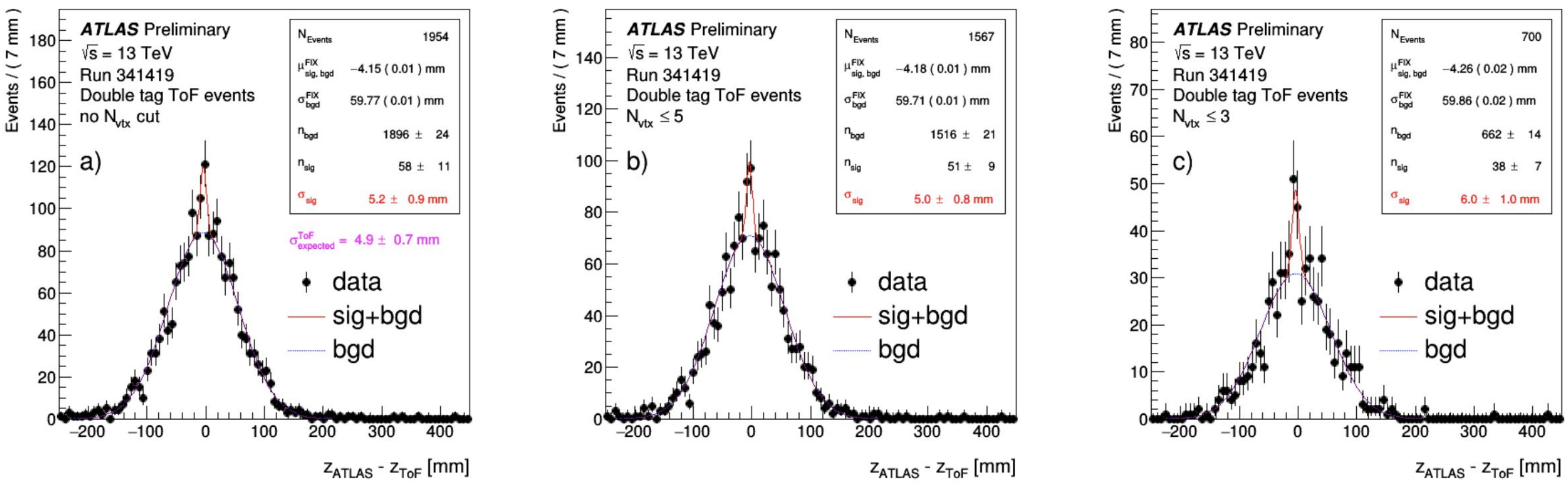
versus



Proton arrival time matched with **lepton** vertex
⇒ ULTRAPERIPHERAL

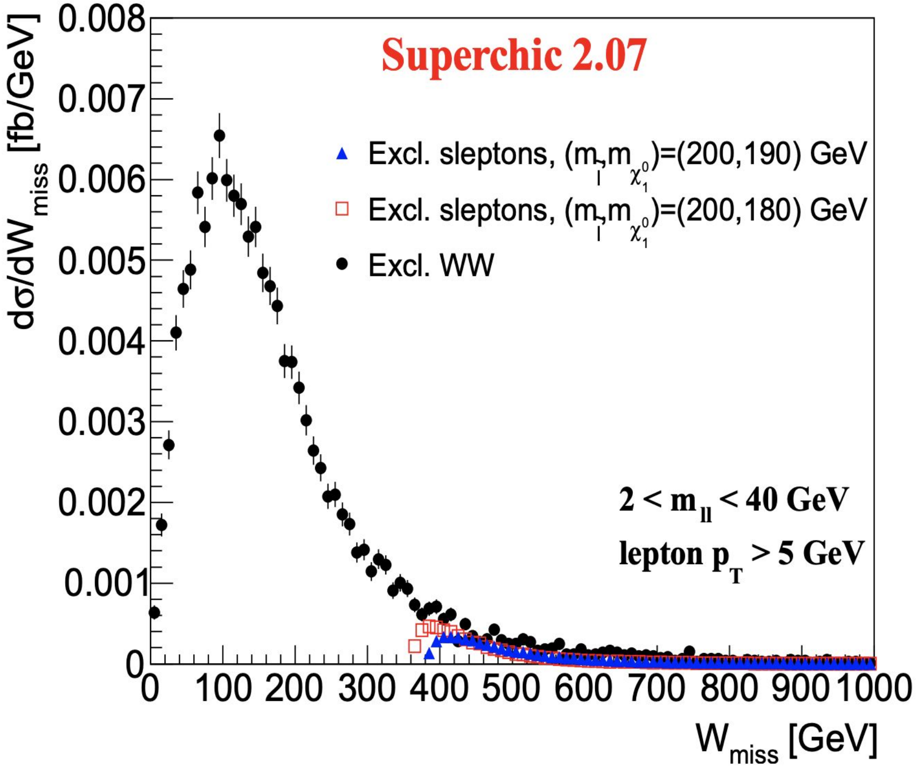
Proton arrival time NOT matched with **lepton** vertex
⇒ PILEUP

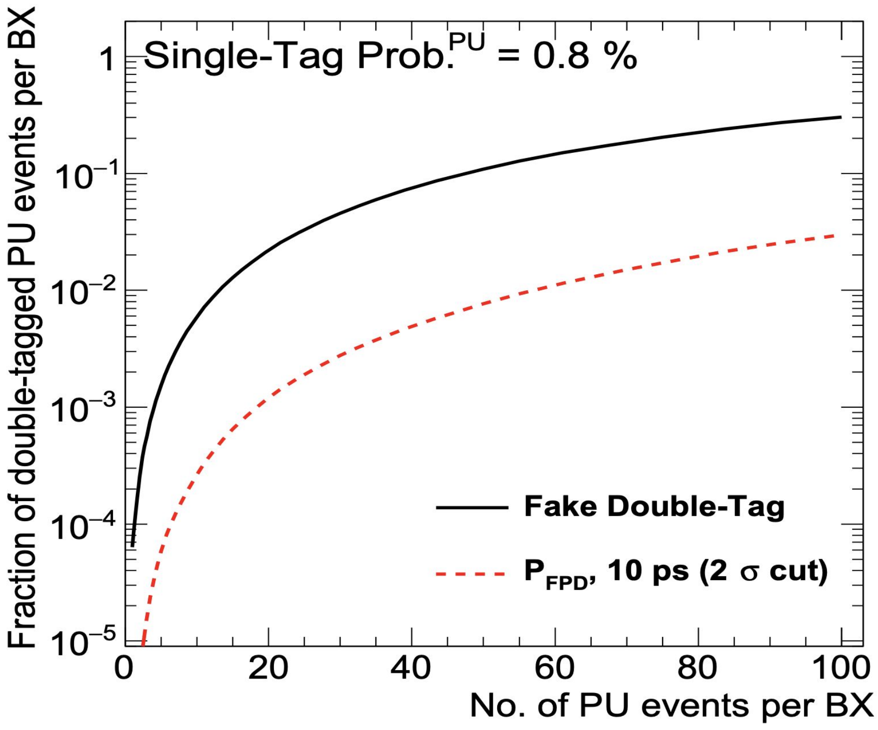
Run 2 time of flight performance



[AFP Public Results]

Measuring W(miss) will be landmark for hadron colliders





[1812.04886]

Lepton–proton matching very challenging without precise AFP timing

EXTRAS

For tau $g - 2$

UPC dimuons using PbPb

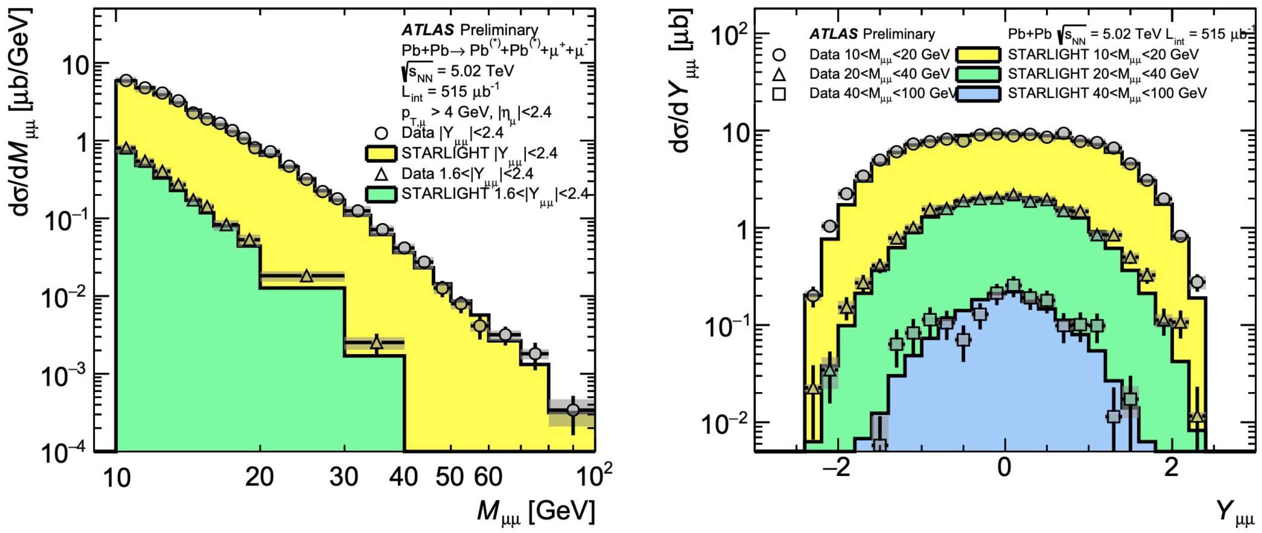
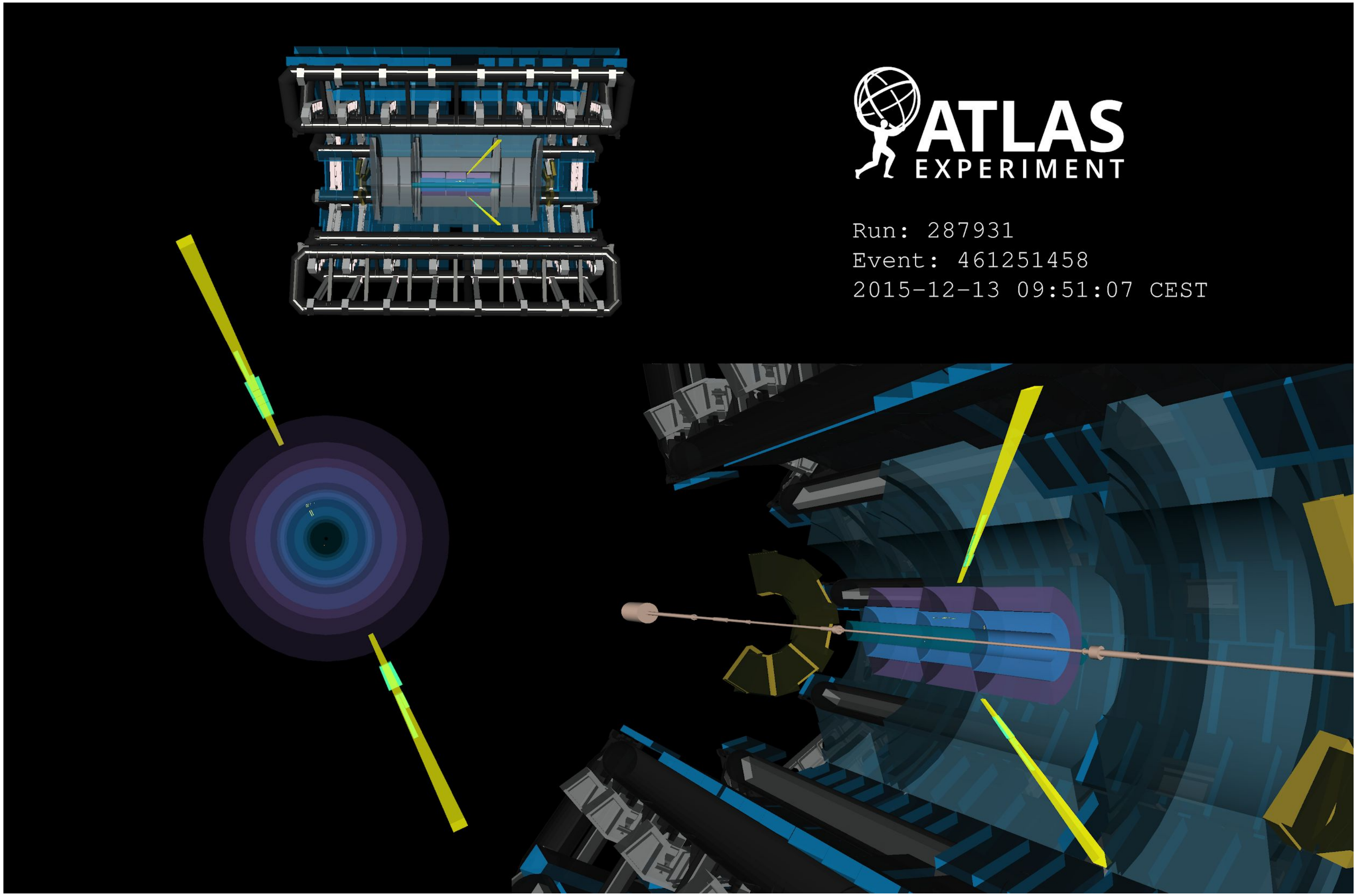


Figure 3: Cross section for dimuon production in UPC, as a function of pair mass (left) and pair rapidity (right). The data are indicated by the symbols while calculations are shown by solid histograms. The mass distribution is provided for two (overlapping) rapidity regions ($|Y_{\mu\mu}| < 2.4$ and $|Y_{\mu\mu}| > 1.6$). 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

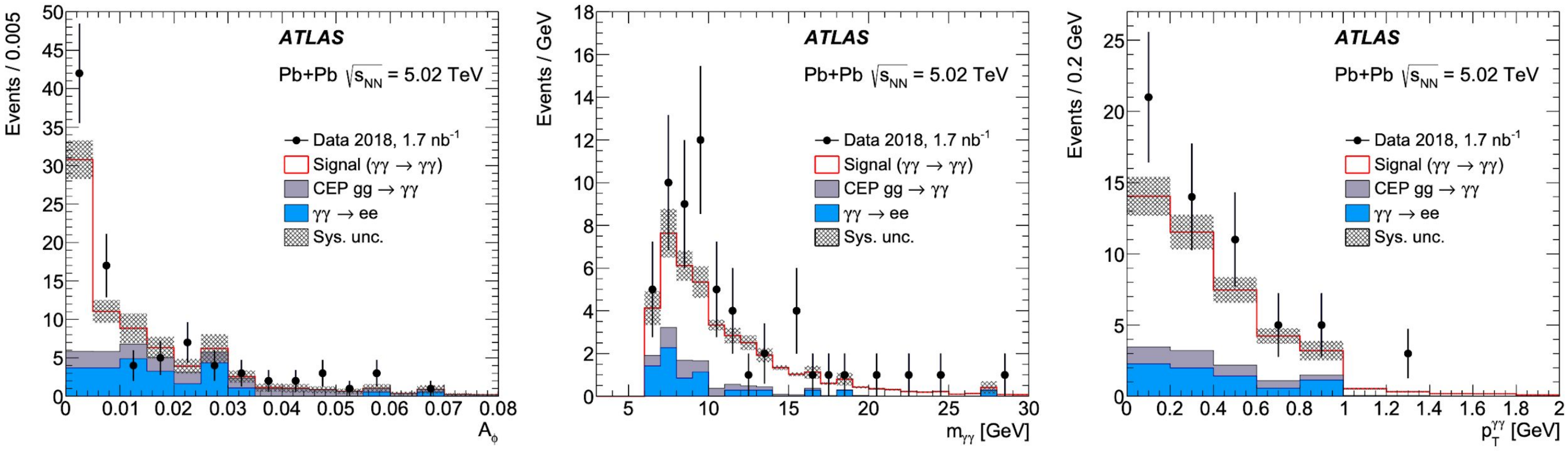
[ATLAS-CONF-2016-025]

Light-by-light scattering using PbPb



d'Enterria and da Silveira [1305.7142], ATLAS [1702.01625, 1904.03536], CMS [1810.04602]

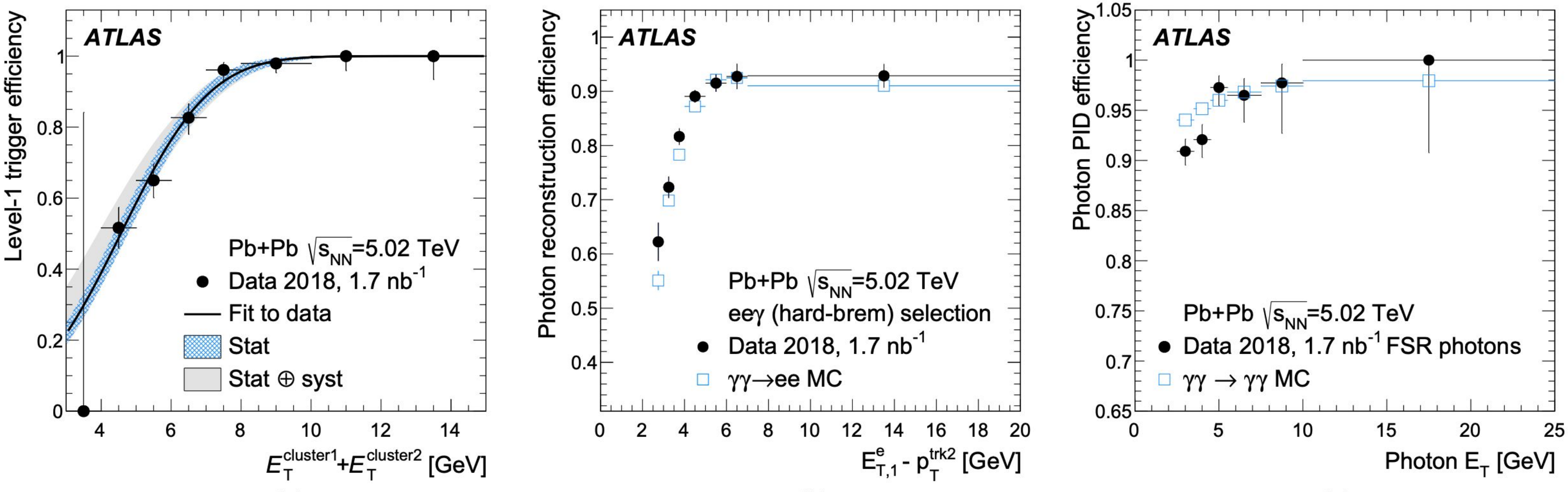
Light-by-light scattering using PbPb



Good agreement with SM predictions in Monte Carlo

ATLAS [1904.03536]

Light-by-light scattering using PbPb



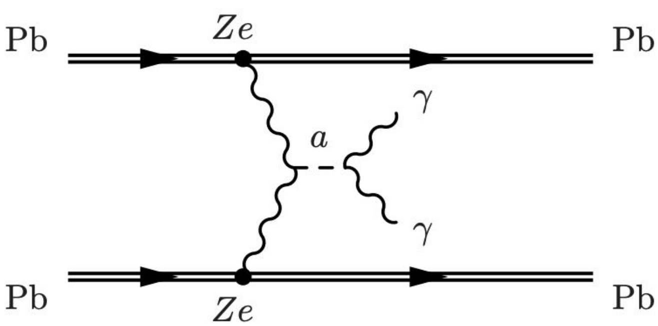
Ridiculously low trigger thresholds (for ATLAS) on EM clusters

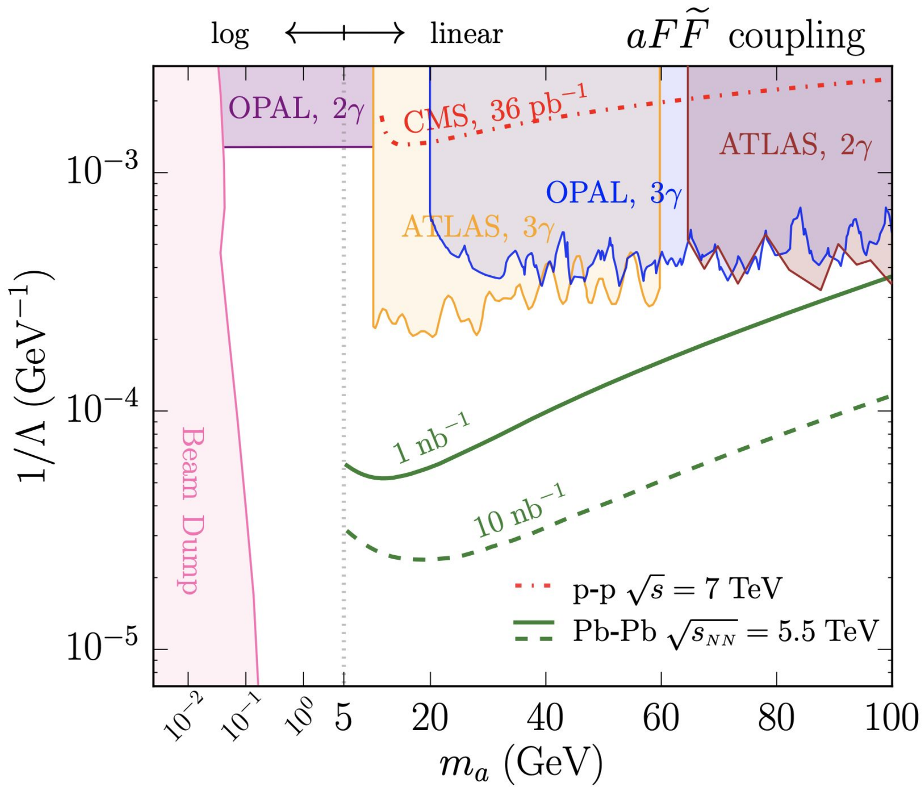
ATLAS [1904.03536]

Constraining axions using light-by-light PbPb

Searching for axion-like particles with ultra-peripheral heavy-ion collisions

Simon Knapen,[1,2] Tongyan Lin,[1,2] Hou Keong Lou,[1,2] and Tom Melia[1,2]
[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*





[1607.06083]

SM QED 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 $F_{\mu\nu}$

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

Beresford, JL [1908.05180]

SMEFT formalism of dipole moments

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

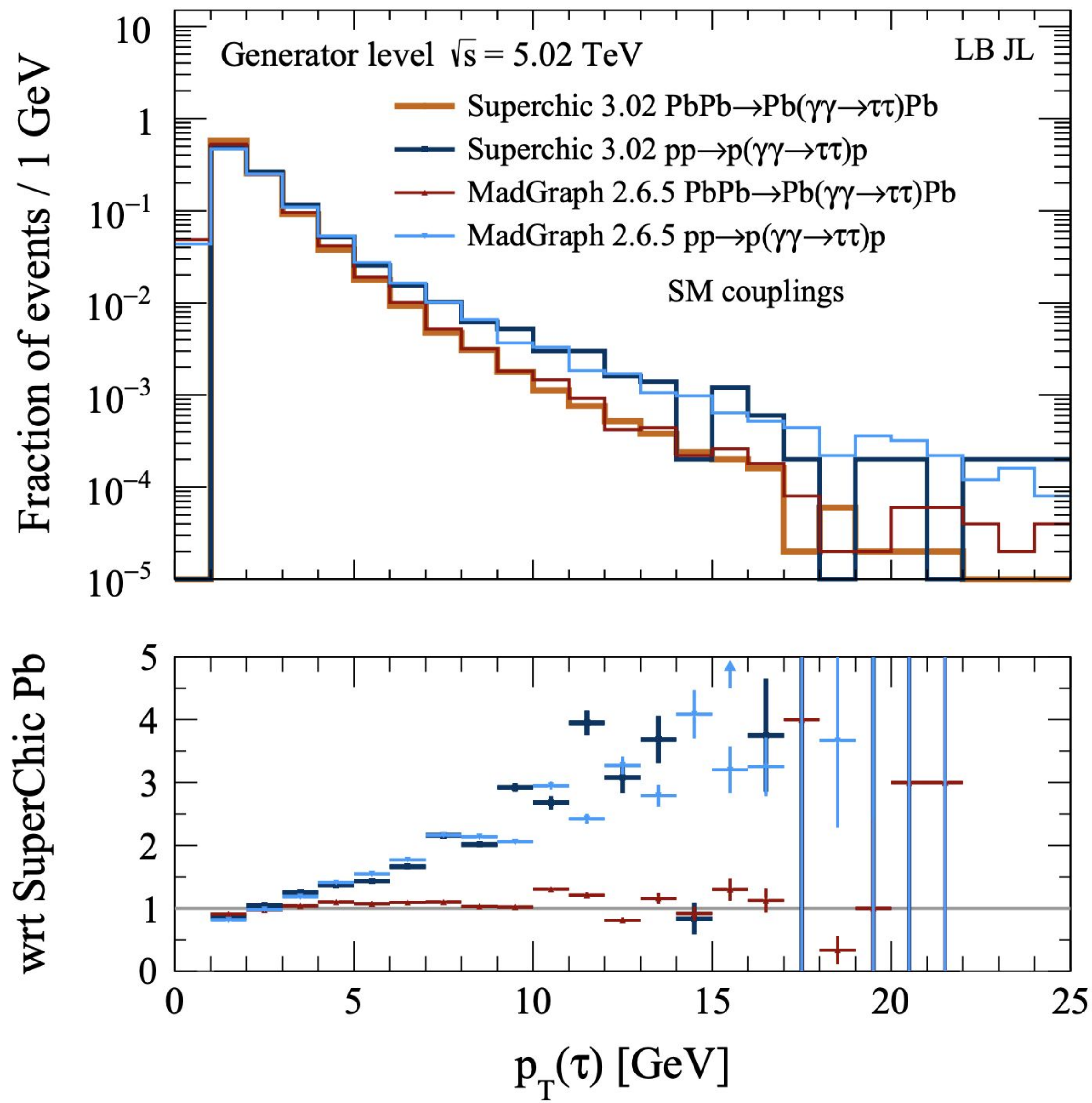
Here, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the $\mathrm{U(1)_Y}$ and $\mathrm{SU(2)_L}$ field strengths, H (L_τ) is the Higgs (tau lepton) doublet, and C_i are dimensionless, complex Wilson coefficients. We fix $C_{\tau W} = 0$ to parameterize the two modified moments $(\delta a_\tau, \delta d_\tau)$ using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

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

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.

Beresford, JL [1908.05180]

Compare MadGraph with SuperChic (PbPb)



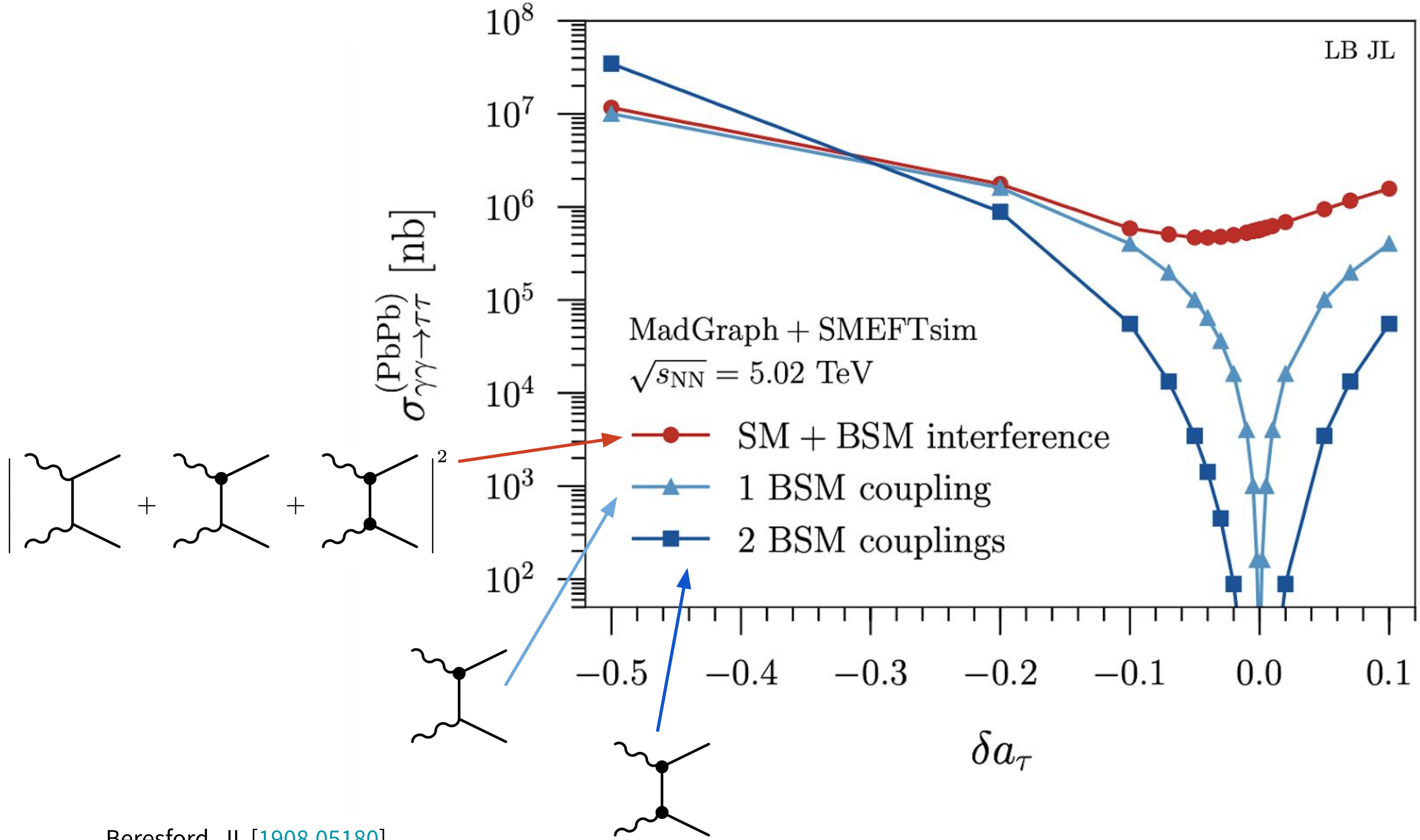
Verify that our MadGraph implementation gives correct differential distributions

Superchic includes treatment of nuclear finite size, thickness and overlap

Also compare with photon flux sourced from pp

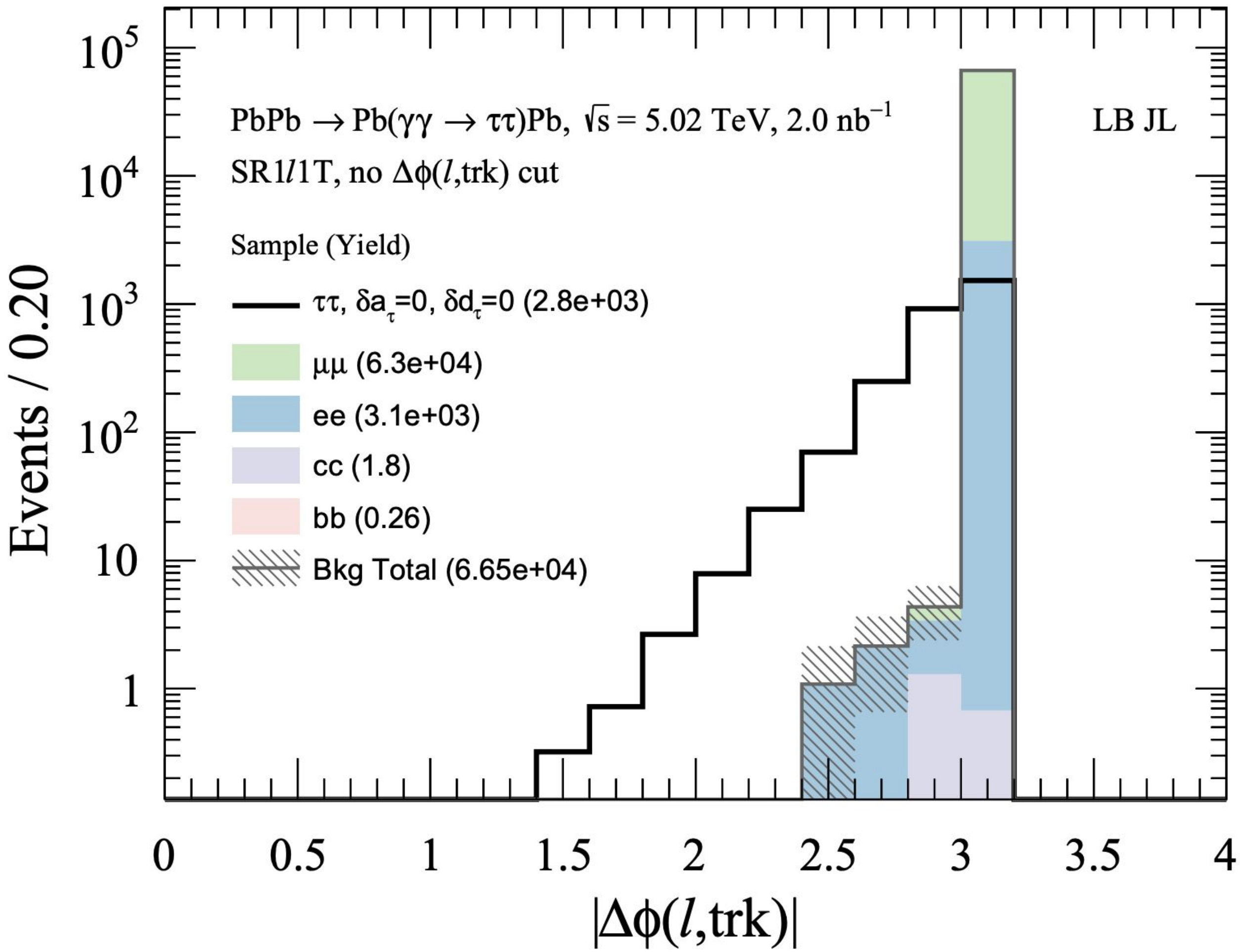
Beresford, JL [1908.05180]

Cross-sections & interference effects (PbPb)



Beresford, JL [1908.05180]

Suppression of planar dilepton backgrounds



Beresford, JL [1908.05180]

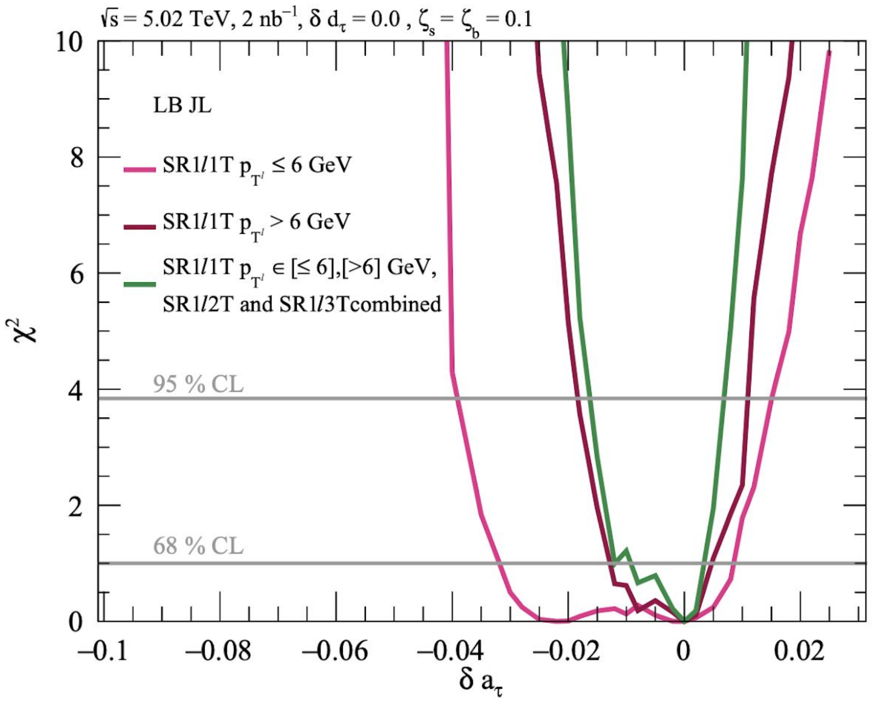
Event selection & yields normalised to 2/nb PbPb

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, $\|\eta^{e/\mu}\| < 2.5/2.4$	3659.9	3882.7	3582.8	79043	3118.9	1.1	4.8	0.0	0.0	0.0
2 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $\|\eta^{\text{trk}}\| < 2.5$	3324.5	3535.9	3256.9	78973	3117.8	1.0	3.0	0.0	0.0	0.0
$\|\Delta\phi(\ell, \text{trk})\| < 3$	1519.7	1605.7	1468.3	0.9	5.3	0.7	1.8	0.0	0.0	0.0
$m_{\ell,\text{trk}} \notin \{[3, 3.2], [9, 11]\}$ GeV	1275.1	1353.6	1242.3	0.9	5.3	0.2	1.2	0.0	0.0	0.0
$p_{\text{T}}^{\ell} \leq 6.0$ GeV	1197.7	1262.3	1154.7	0.9	0.0	0.2	1.2	0.0	0.0	0.0
$p_{\text{T}}^{\ell} > 6.0$ GeV	77.3	91.3	87.6	0.0	5.3	0.0	0.0	0.0	0.0	0.0
1 lepton + multitrack analysis (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, $\|\eta^{e/\mu}\| < 2.5/2.4$	1010.0	1073.3	978.6	12.2	4.2	1.8	13.3	0.0	0.0	0.0
3 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $\|\eta\|^{\text{trk}} < 2.5$	519.9	548.1	485.8	5.6	4.2	0.8	4.8	0.0	0.0	0.0
4 tracks, $p_{\text{T}}^{\text{trk}} > 0.5$ GeV, $\|\eta\|^{\text{trk}} < 2.5$	370.5	398.3	381.1	0.0	0.0	0.4	3.6	0.0	0.0	0.0

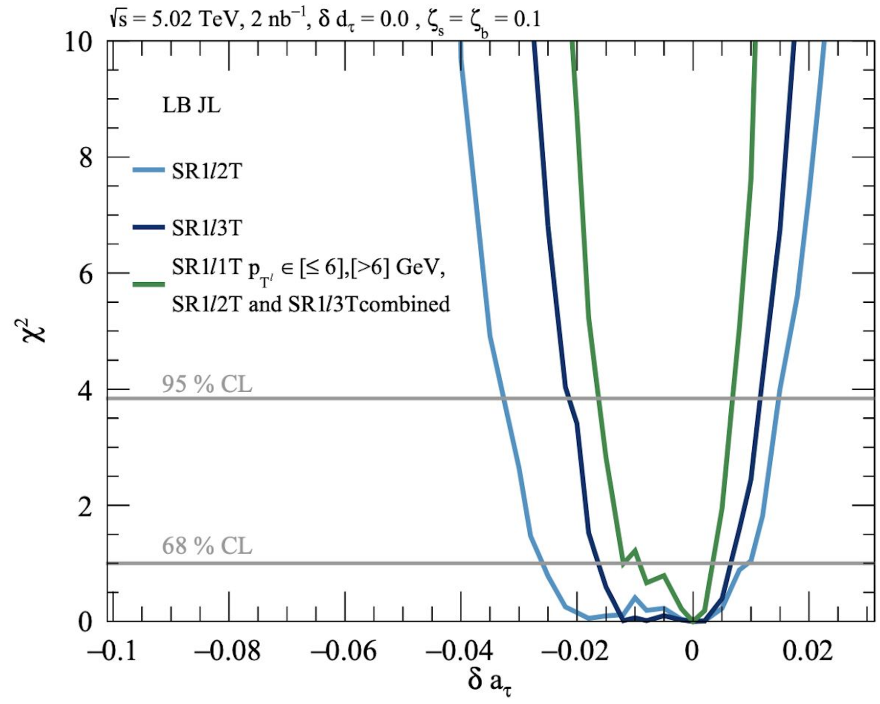
Beresford, JL [1908.05180]

Compare different analyses: magnetic dipole moment

Impact of differential analysis in lepton pT

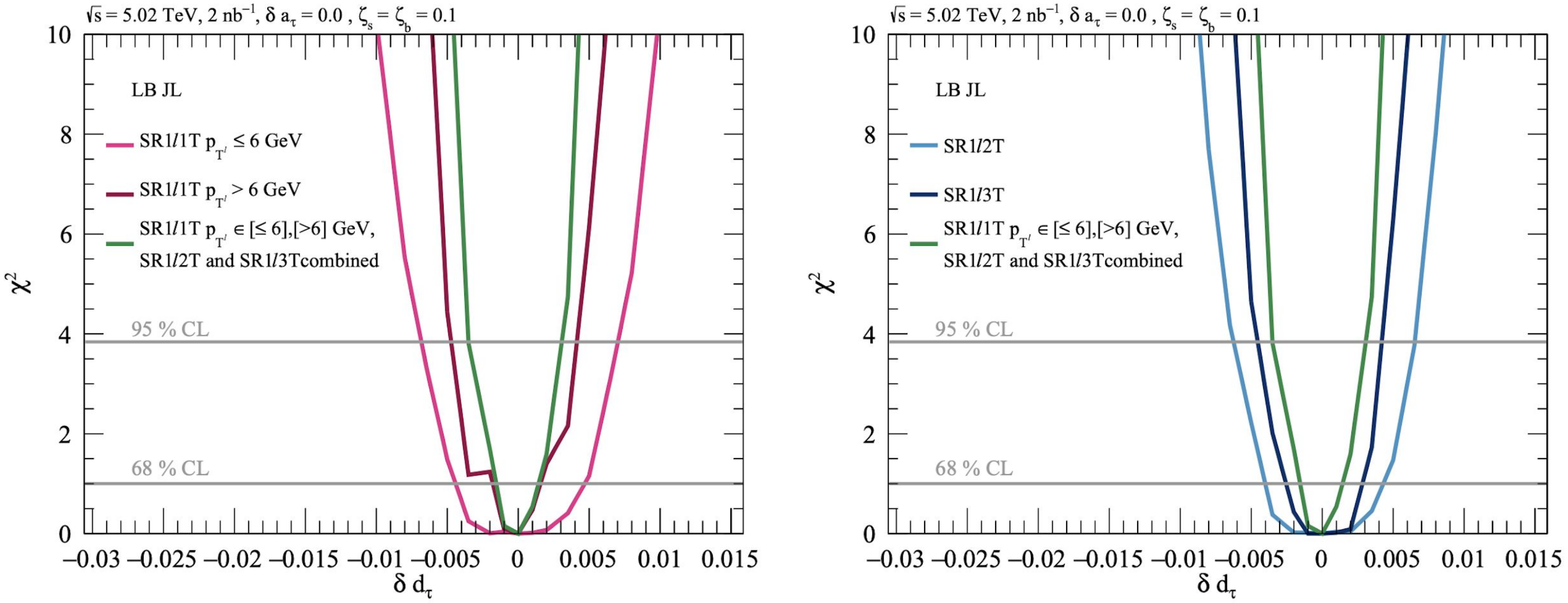


Statistical combination of 1T, 2T, 3T SRs



Beresford, JL [1908.05180]

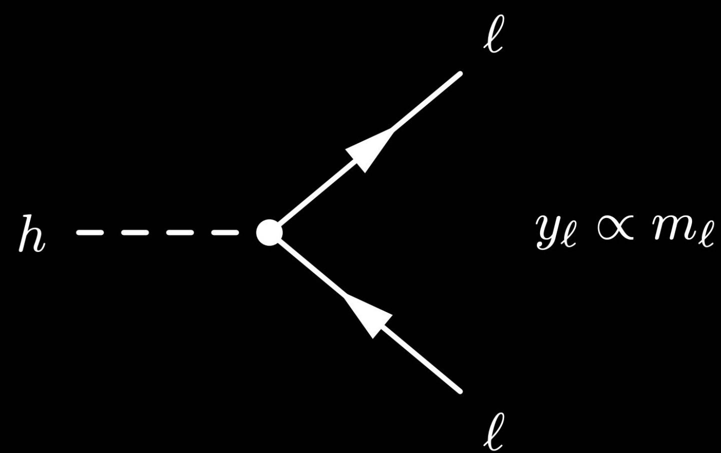
CP violating electric dipole moment constraints



An order of magnitude better than DELPHI

Beresford, JL [1908.05180]

Higgs is 1st boson observed
to violate lepton universality



Higgs → direct probe of flavour problem

Spin 0 is special: spin 1 (γ, Z) & 2 (graviton) bosons all couple universally to fermions