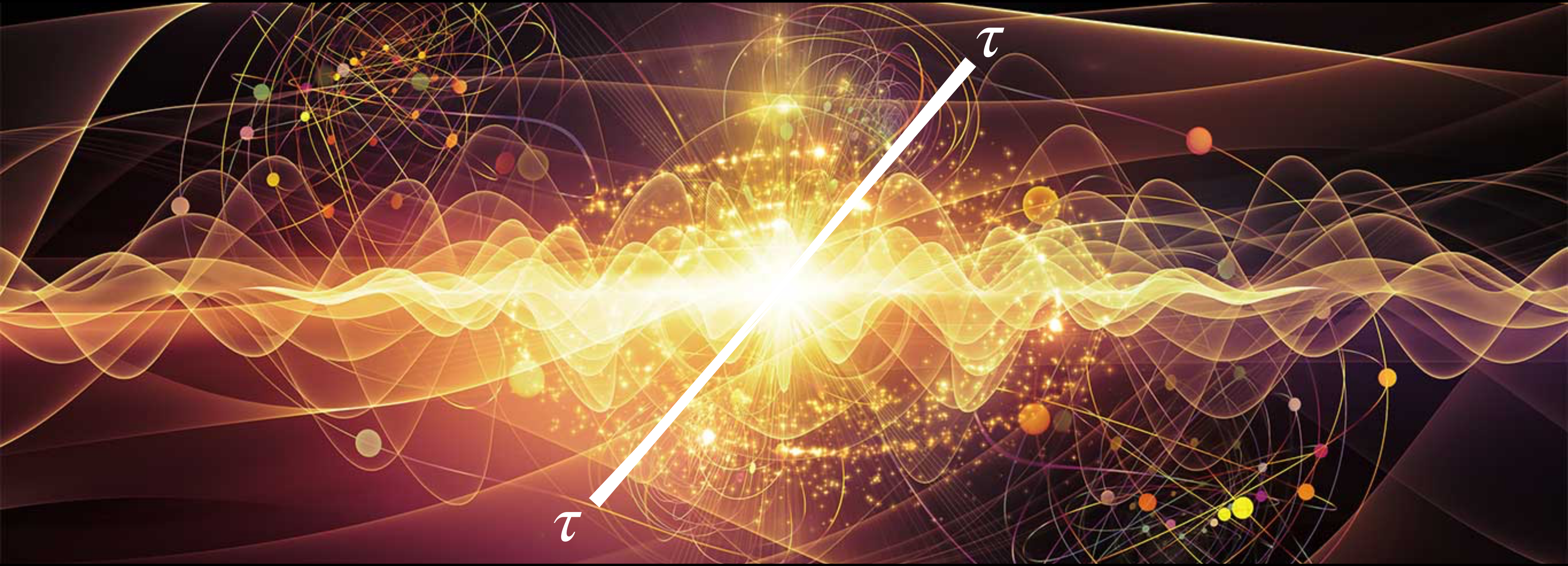
The LHC as a photon collider



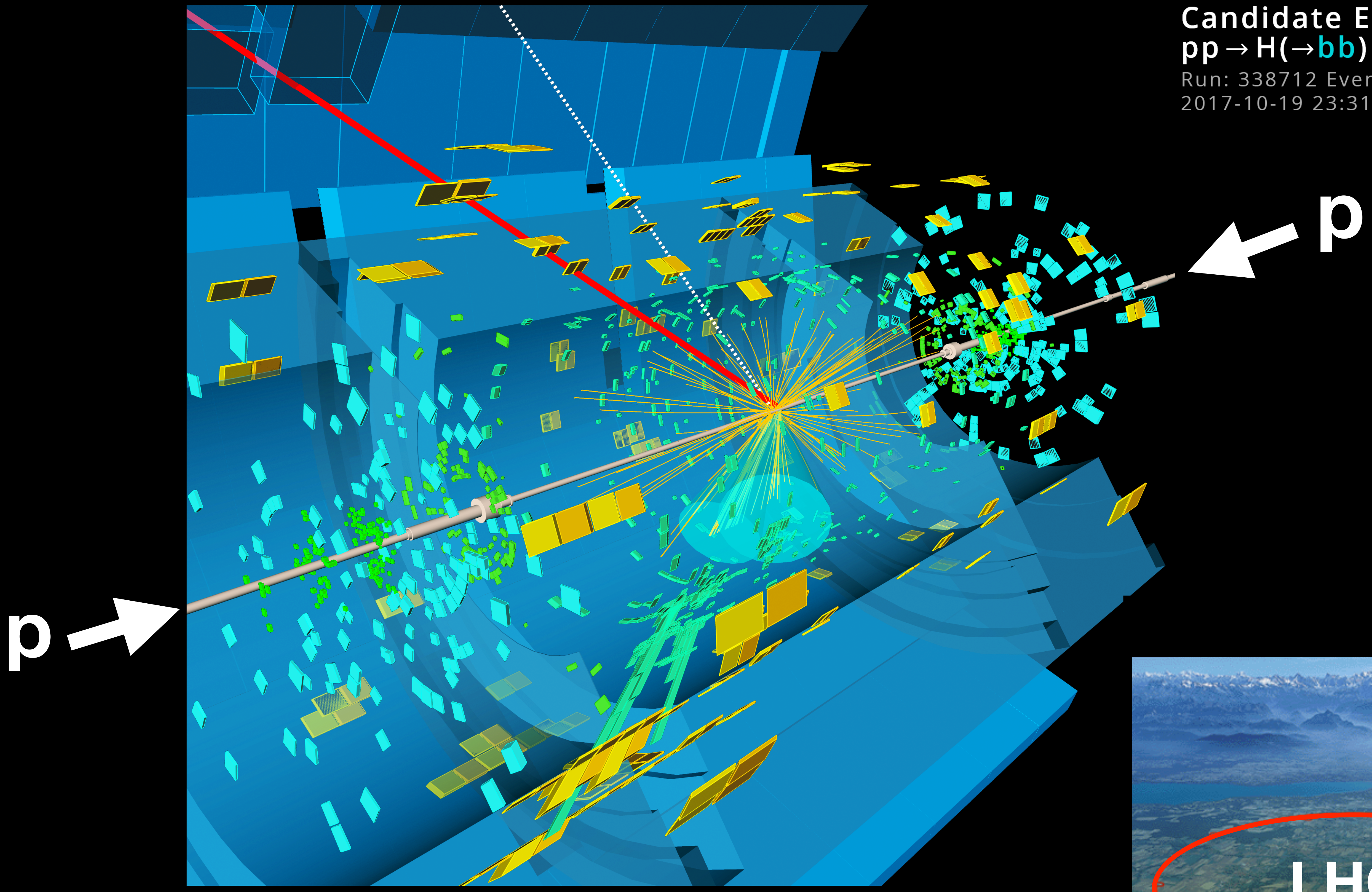
Lydia Beresford

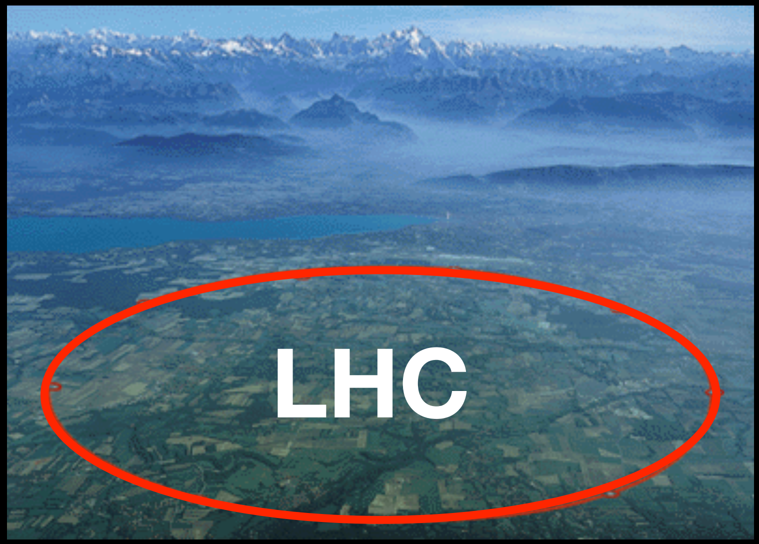
APEC Seminar, Kavli IPMU 16/06/21

LHC collisions

ATLAS
EXPERIMENT

Candidate Event:
$pp \rightarrow H(\rightarrow bb) + W(\rightarrow \mu\nu)$
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

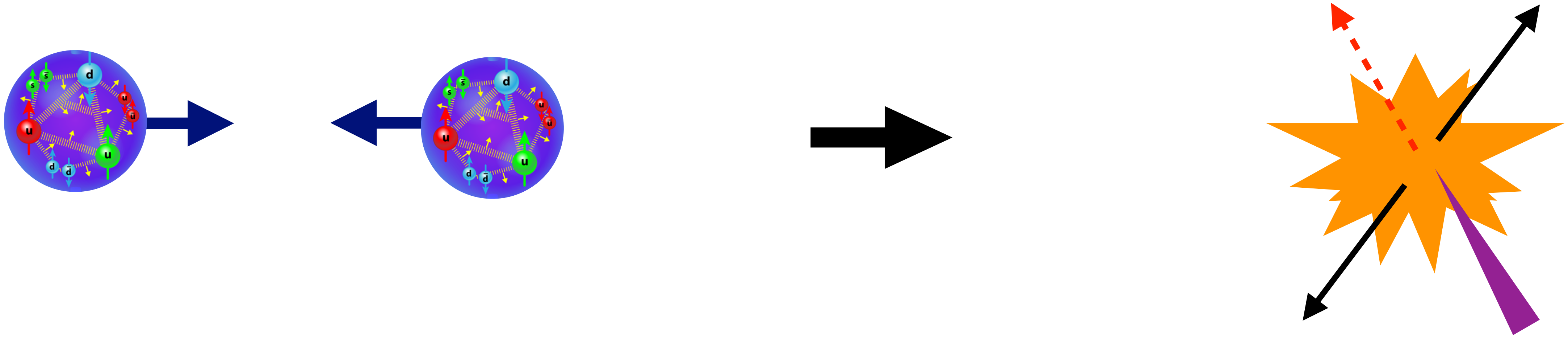




LHC as a photon collider

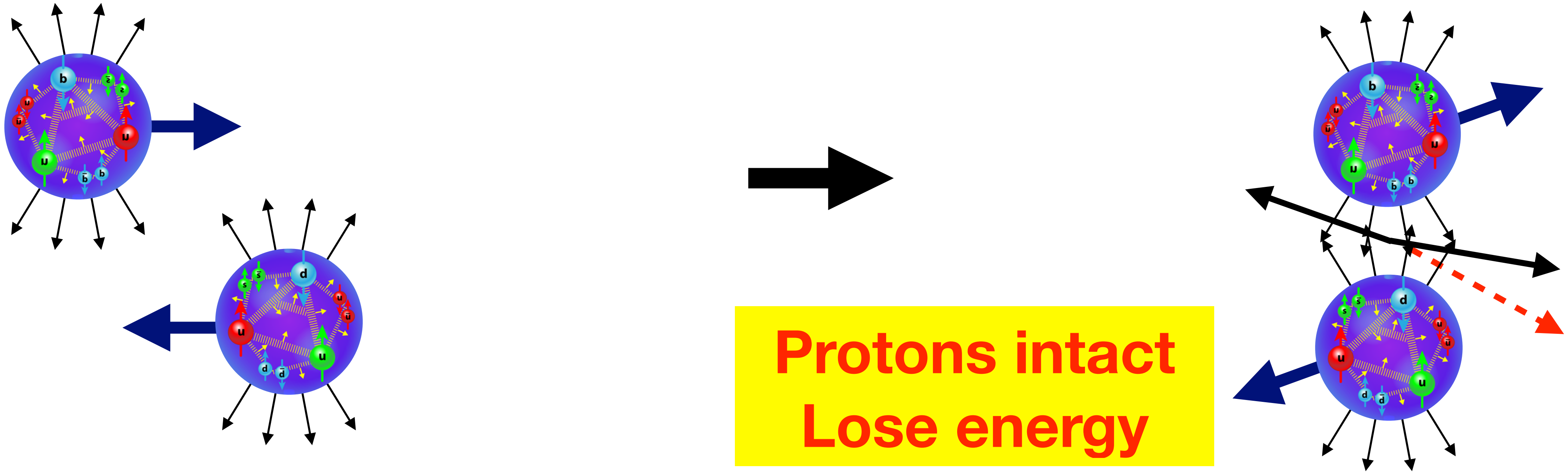
Head-on collision

Partons collide
to produce new particles



Protons ‘miss’

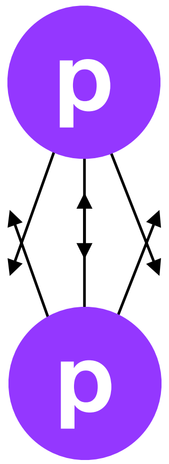
Photons collide
to produce new particles

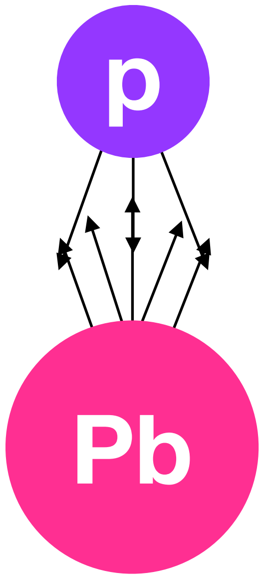


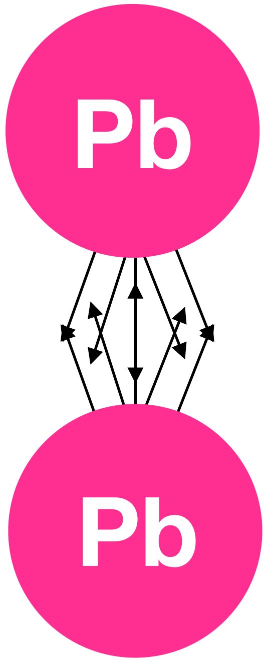
Protons intact
Lose energy

Types of LHC collision

LHC Run 2
2015-2018







ATLAS

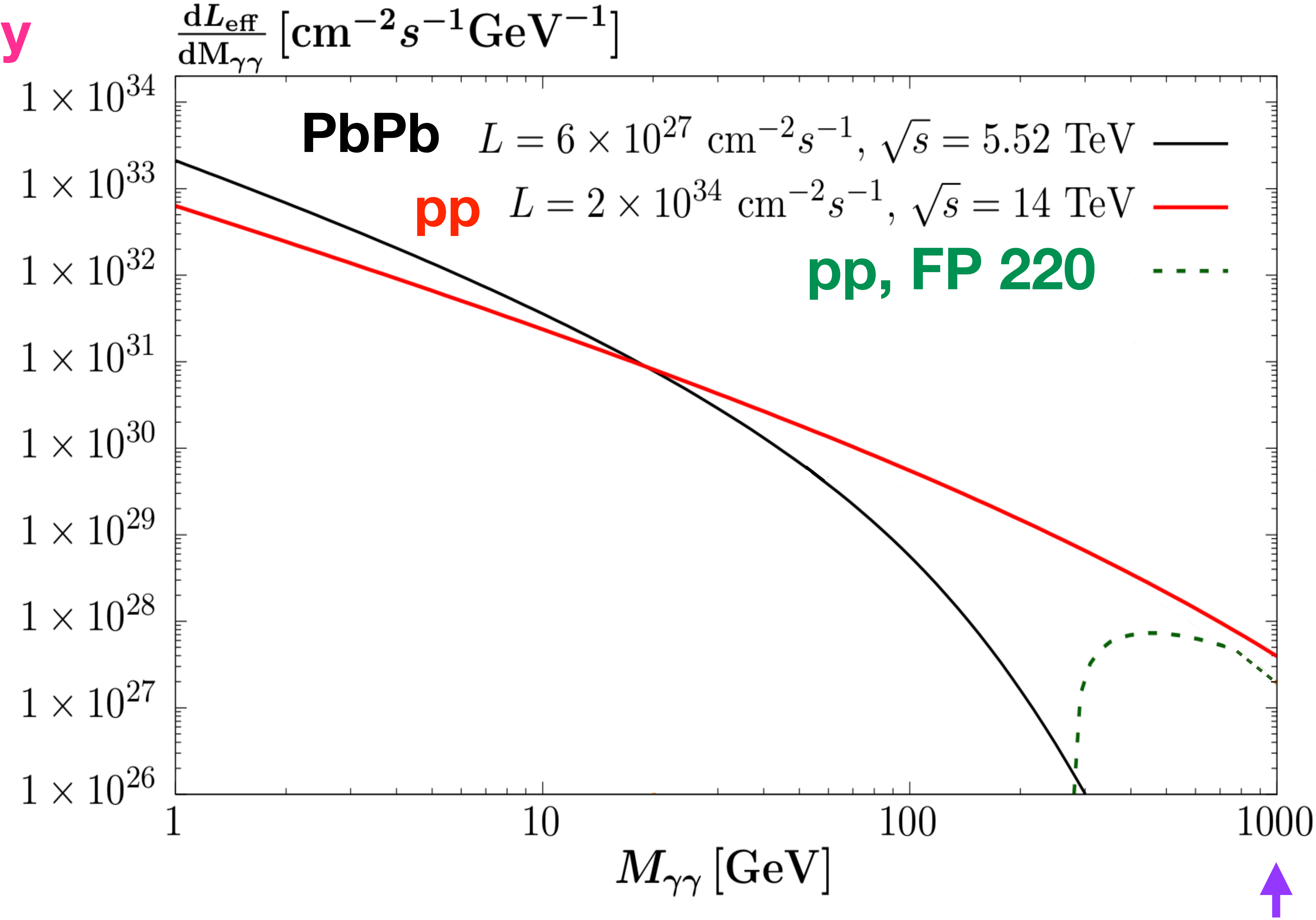
$\sqrt{s}$	13 TeV	8.16 TeV	5.02 TeV
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	~2 nb^{-1}
σ	-	$\propto Z^2$	$\propto Z^4$

Z = 82 for Pb

Broadband photon collider

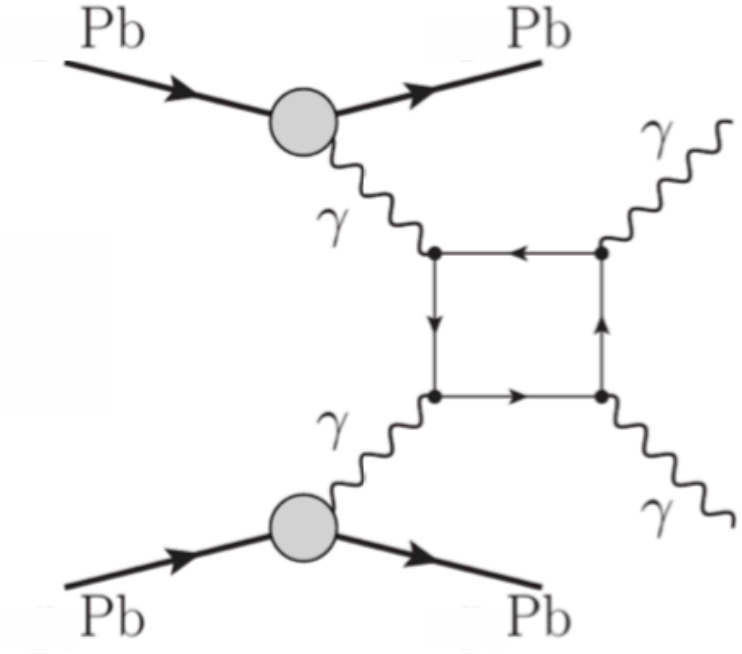
Bruce et al JPG (2020)

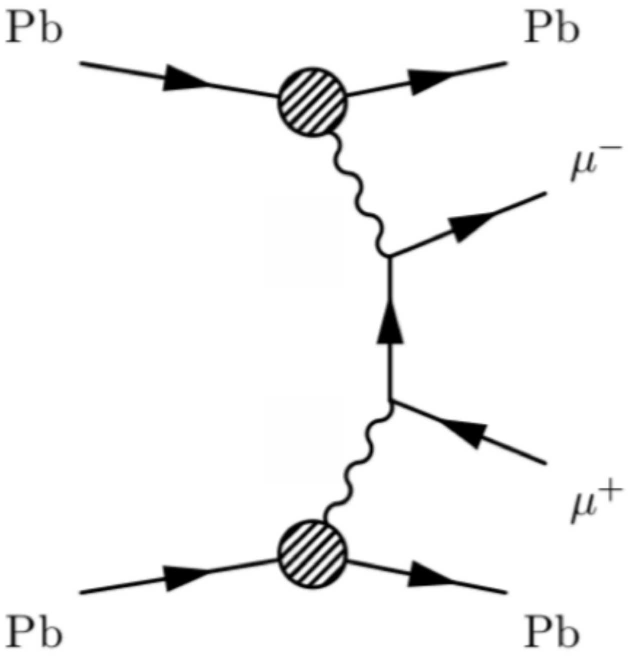
Intensity frontier →



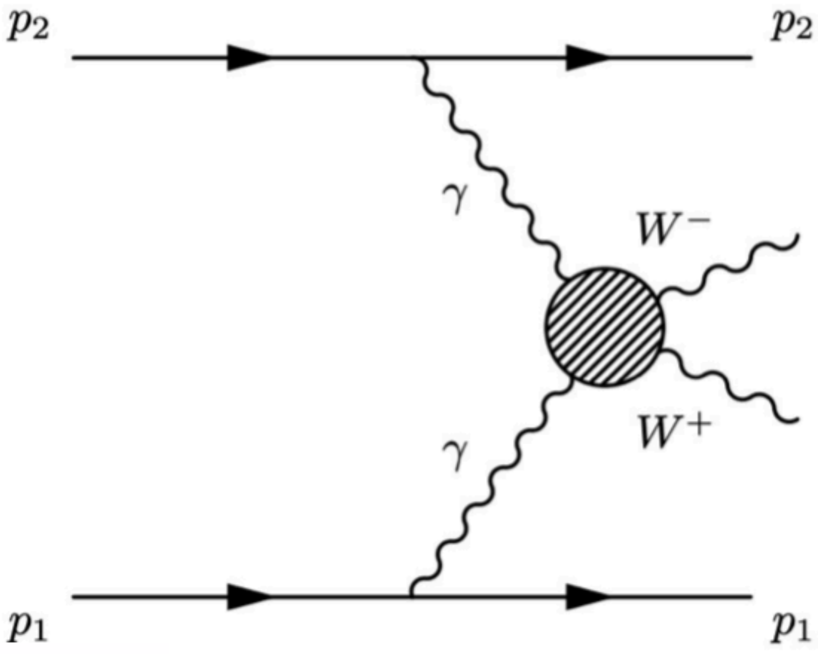
Energy frontier

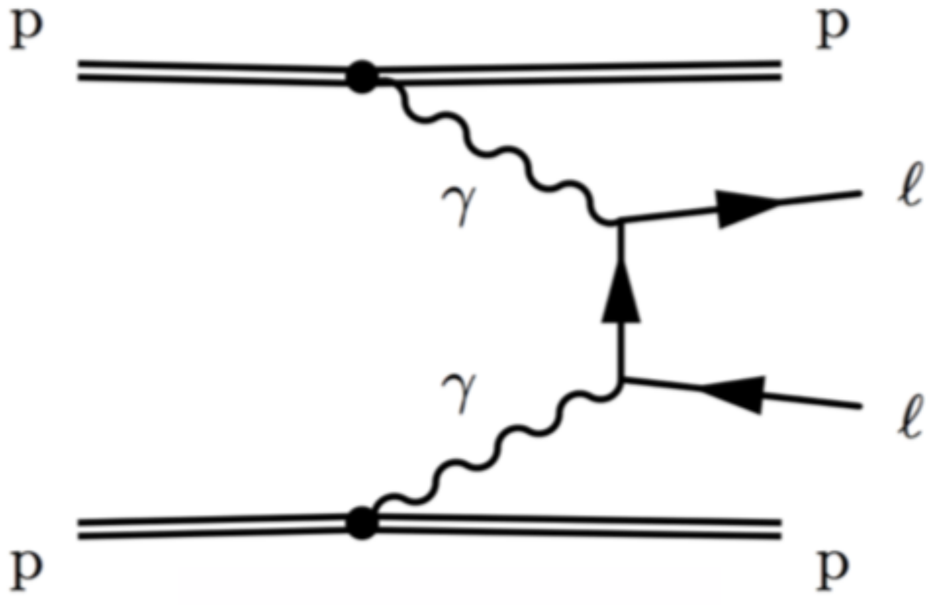
LHC is world's highest energy photon collider up to ~TeV energies



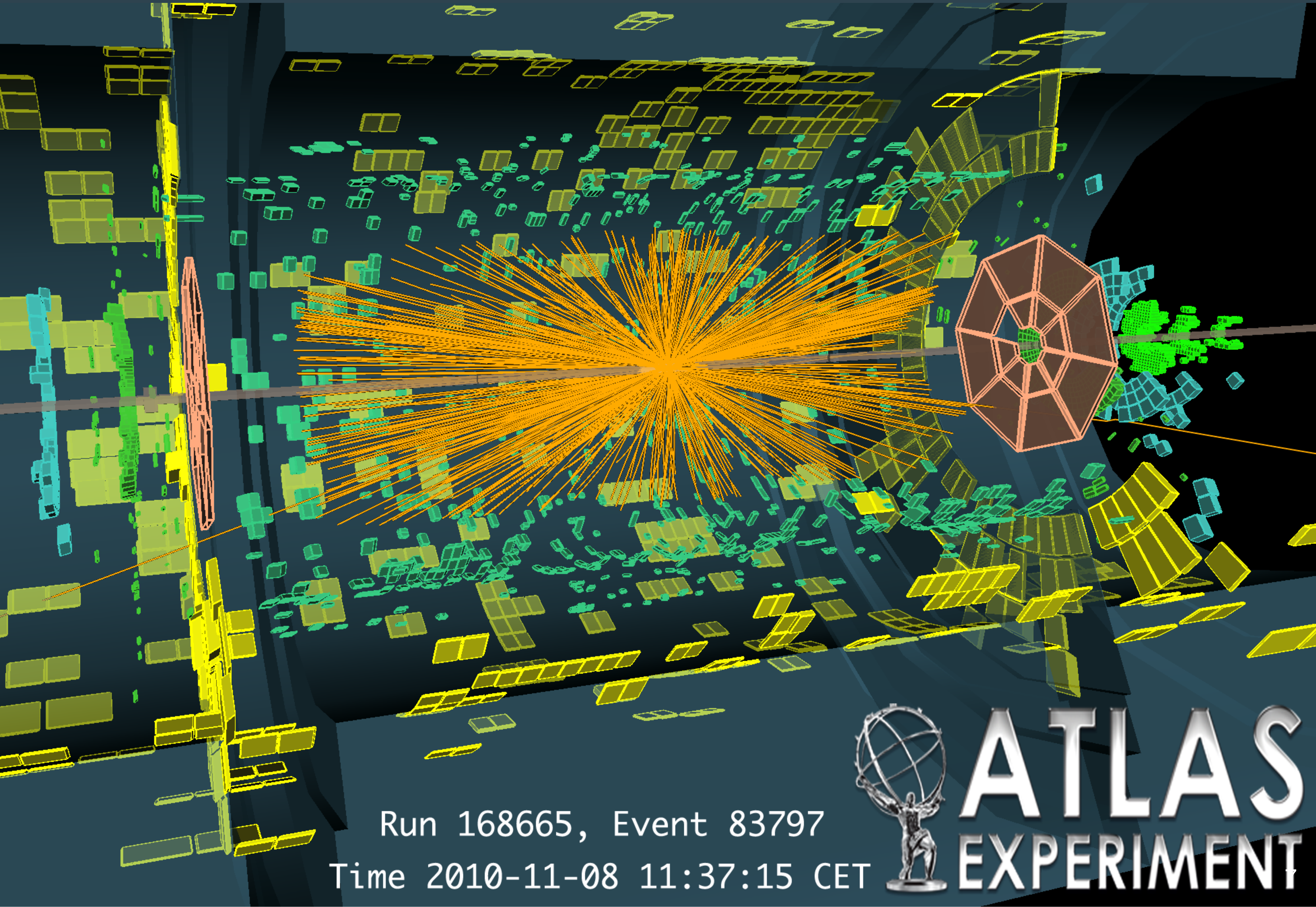


How to find photon collisions?

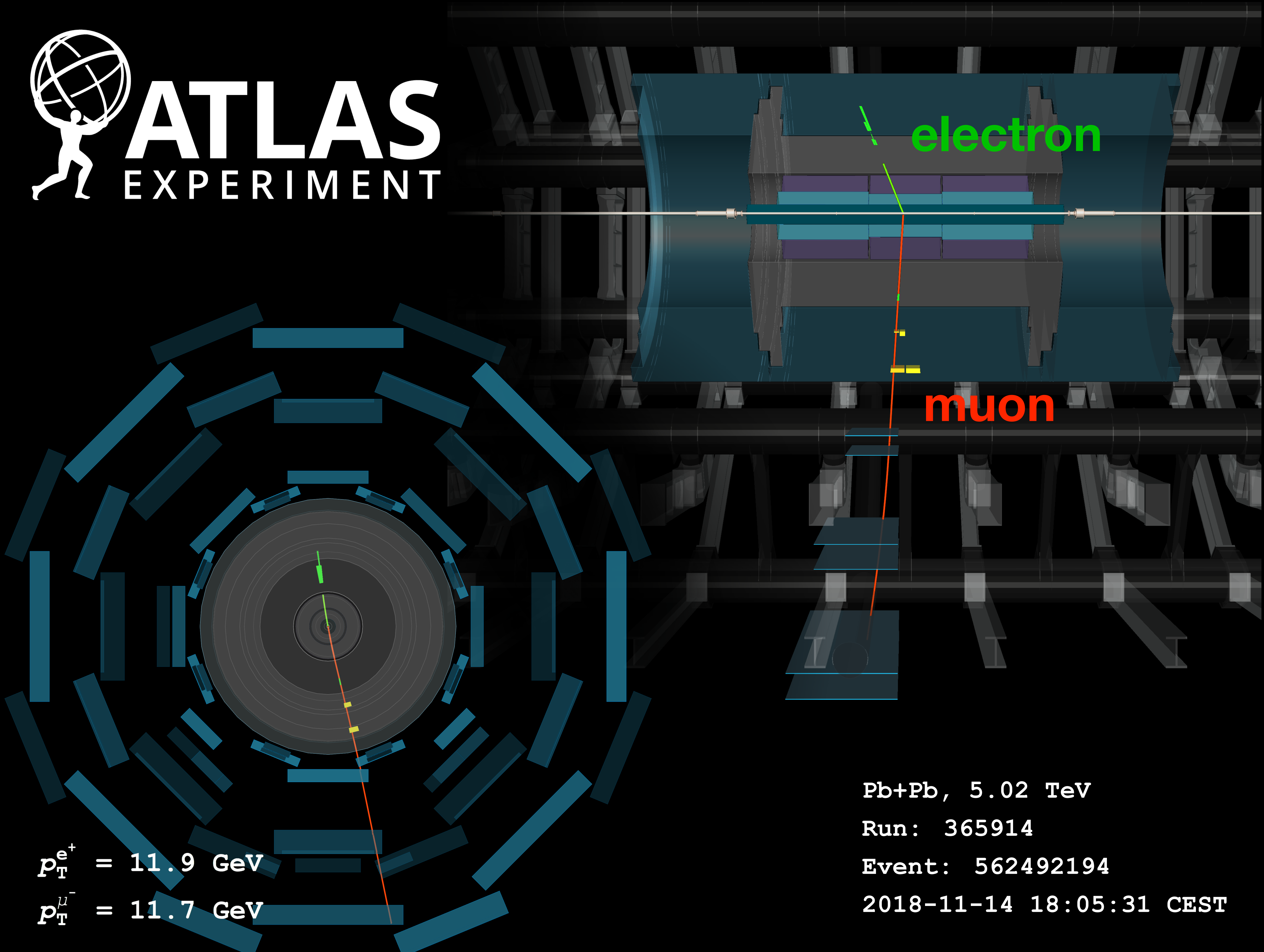




PbPb head-on collision



PbPb photon collision

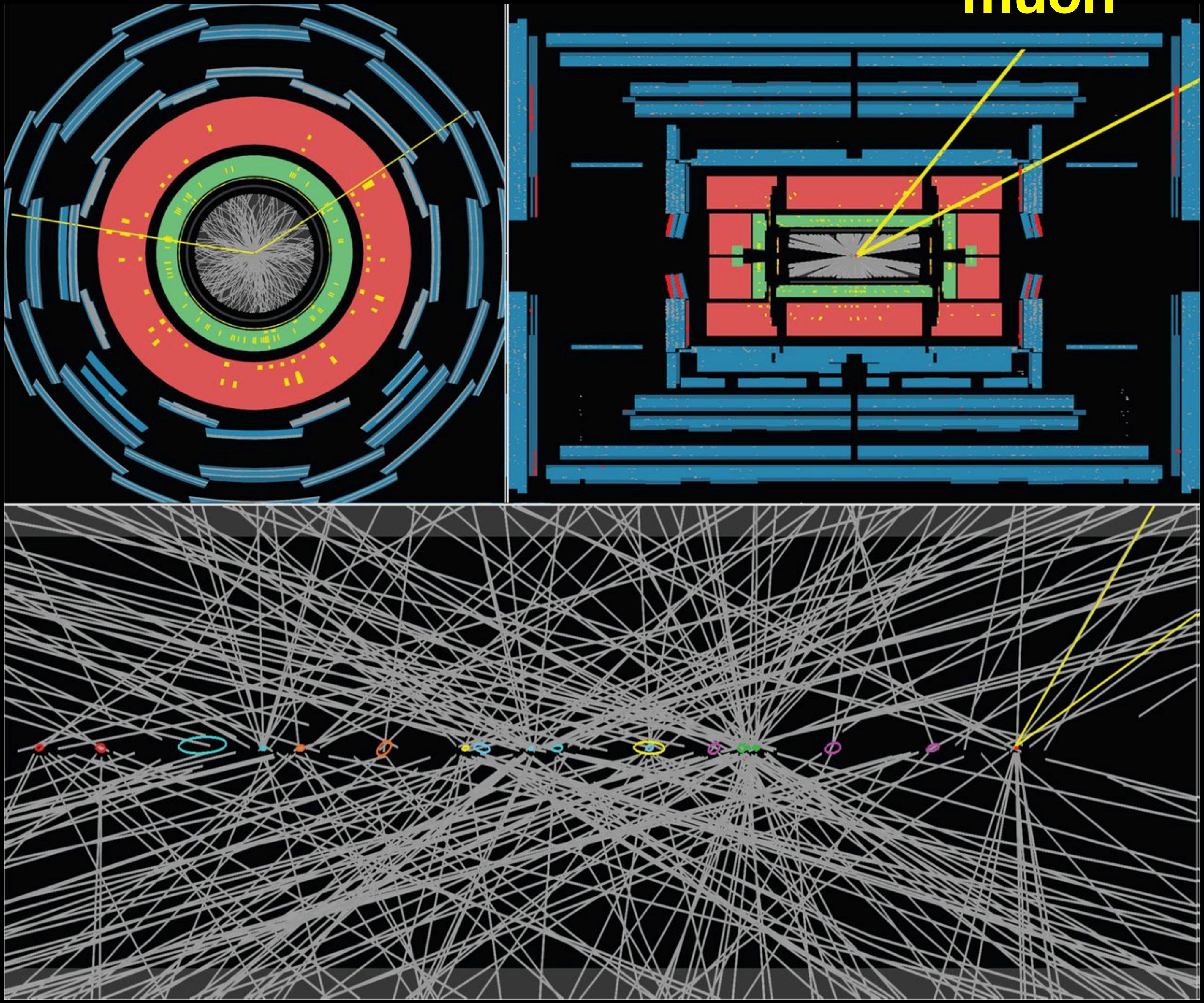


$p_{\mathrm{T}}^{e^+}$ = 11.9 GeV

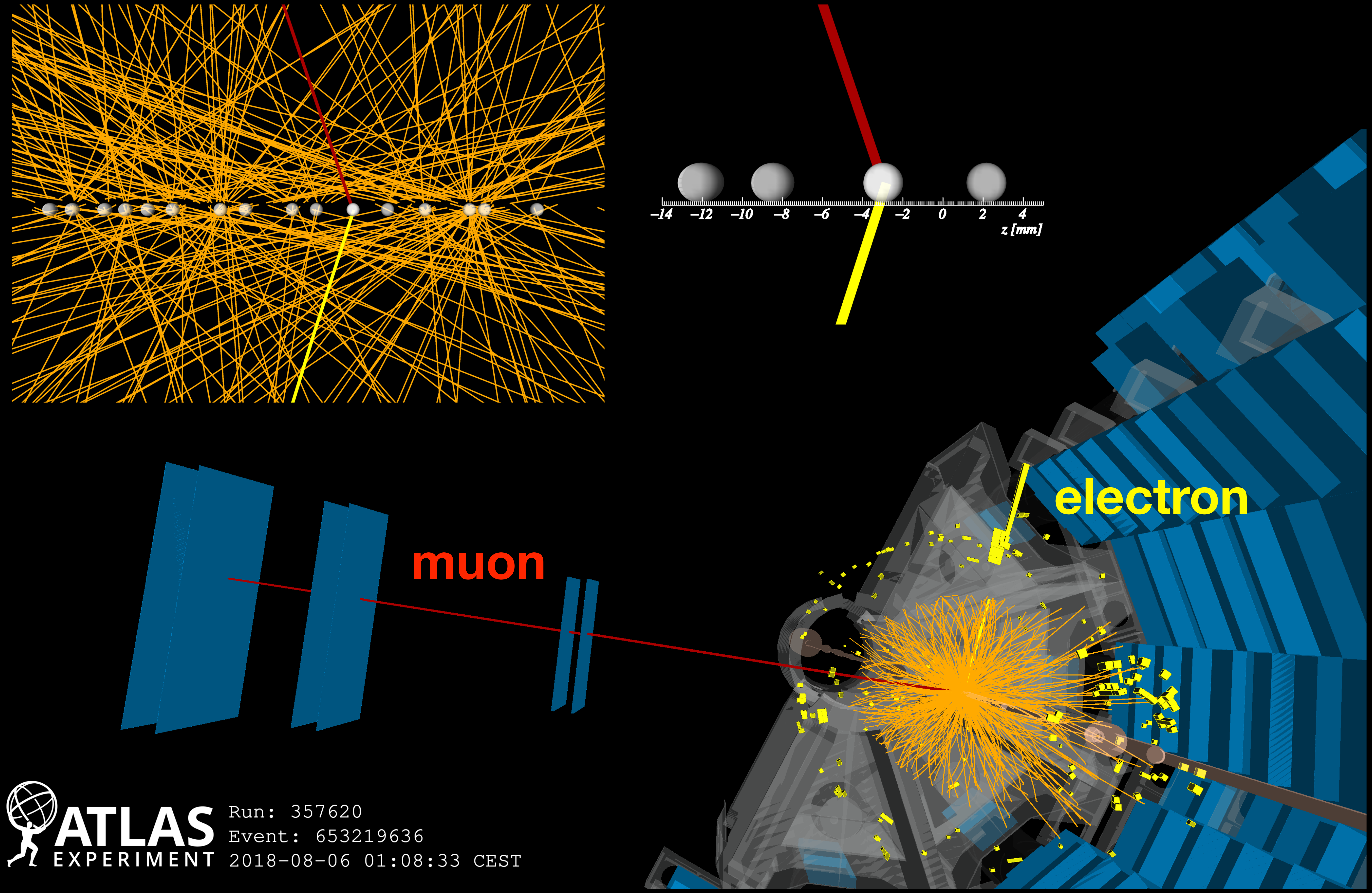
$p_{\mathrm{T}}^{\mu^-}$ = 11.7 GeV

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

pp head-on collision

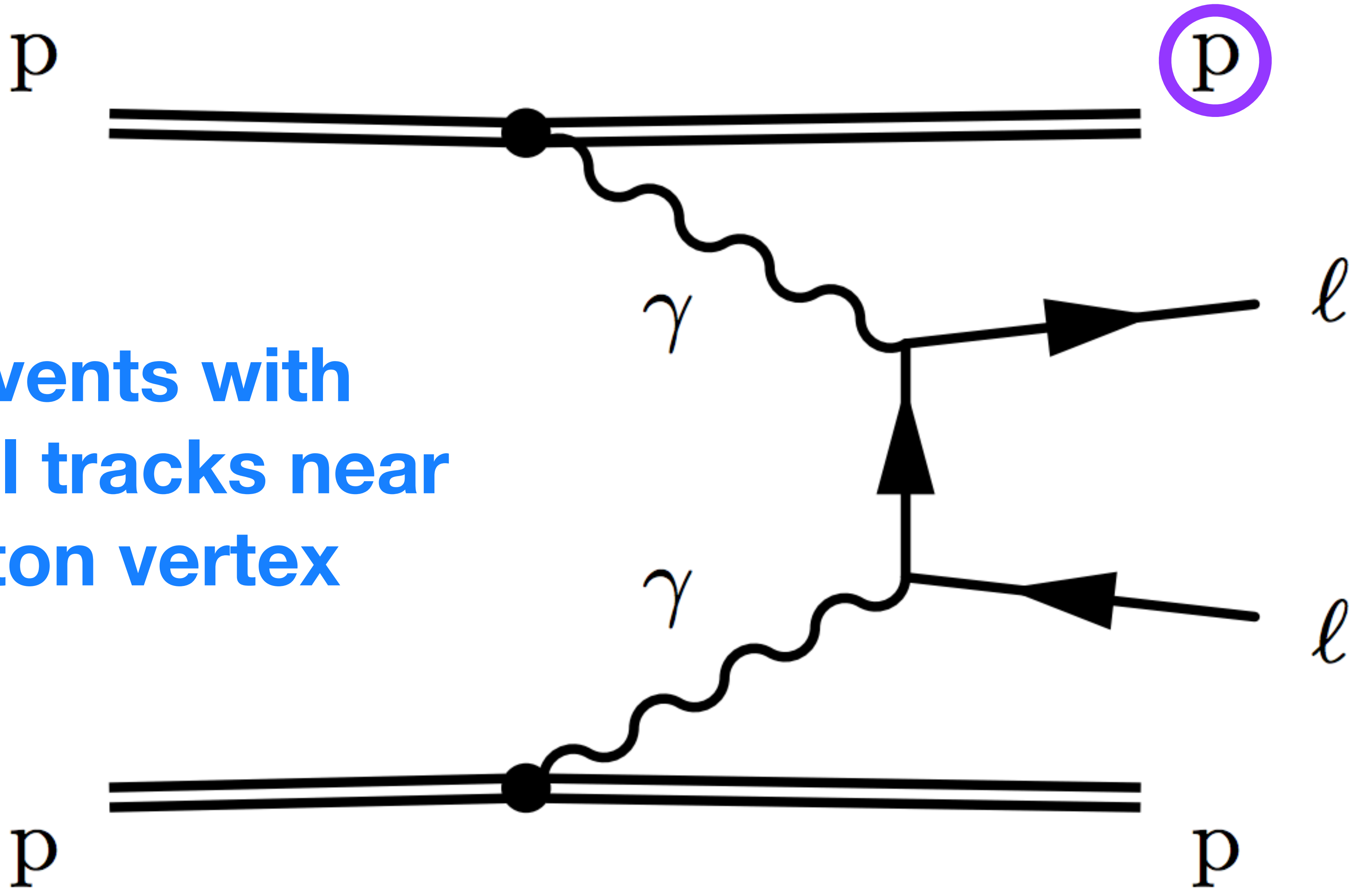


pp photon collision



Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Tracking detectors are key!



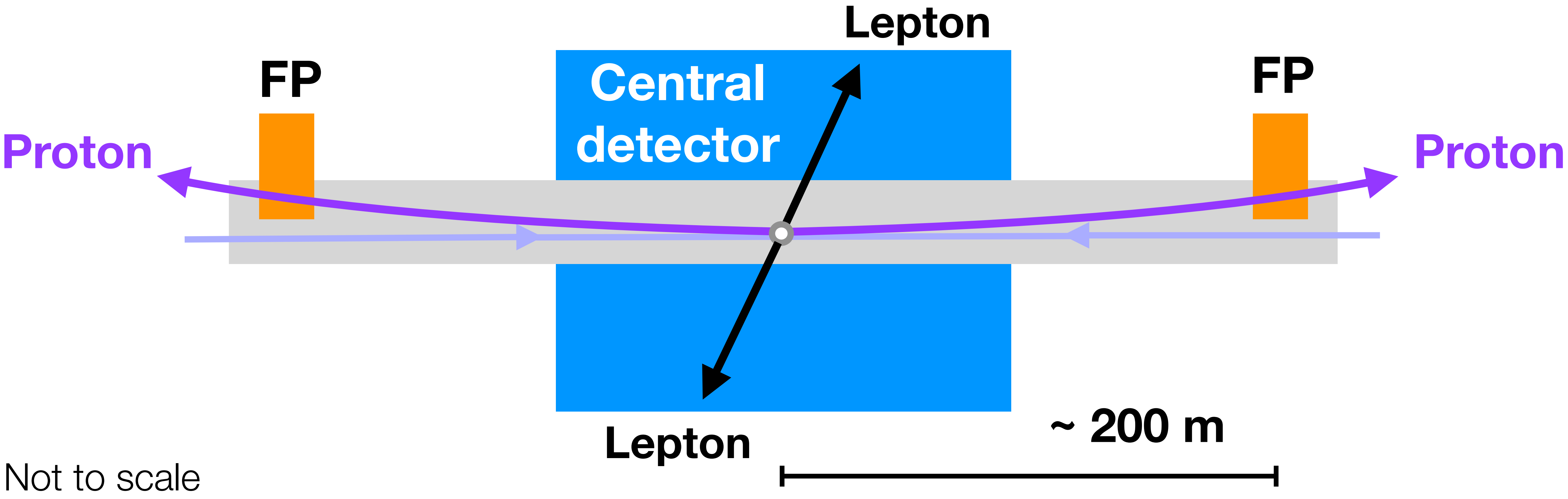
Tag intact proton

Veto events with additional tracks near di-lepton vertex

Forward Proton detectors

Data taking from 2016/2017:

- ATLAS Forward Proton (AFP)
- CMS-TOTEM Precision Proton Spectrometer (CT-PPS)



Incoming proton E known (6.5 TeV)

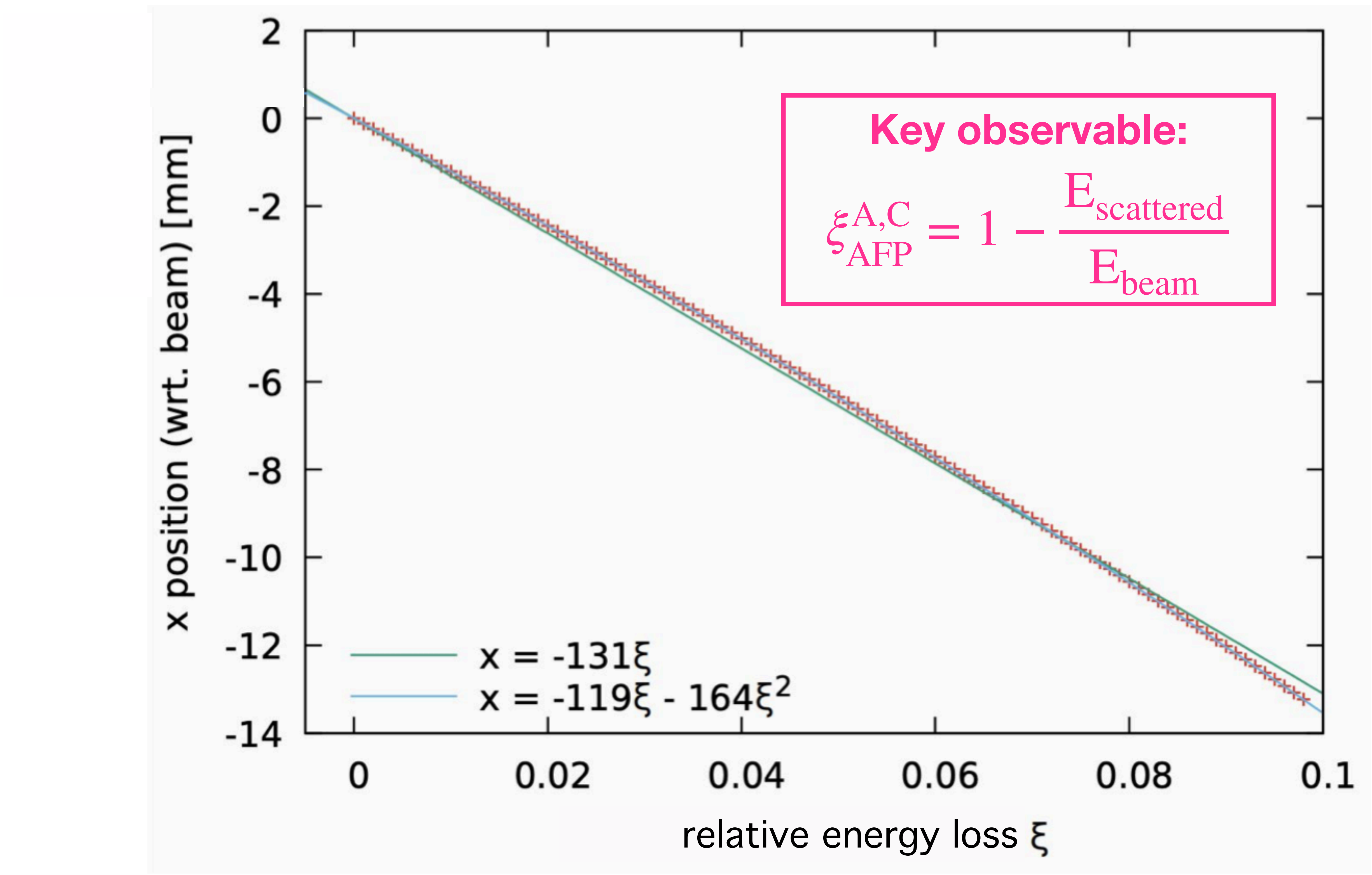
Outgoing proton E measured with forward detector

→ **Calculate proton energy loss!**

Proton Spectrometer

Protons deflected by LHC magnets

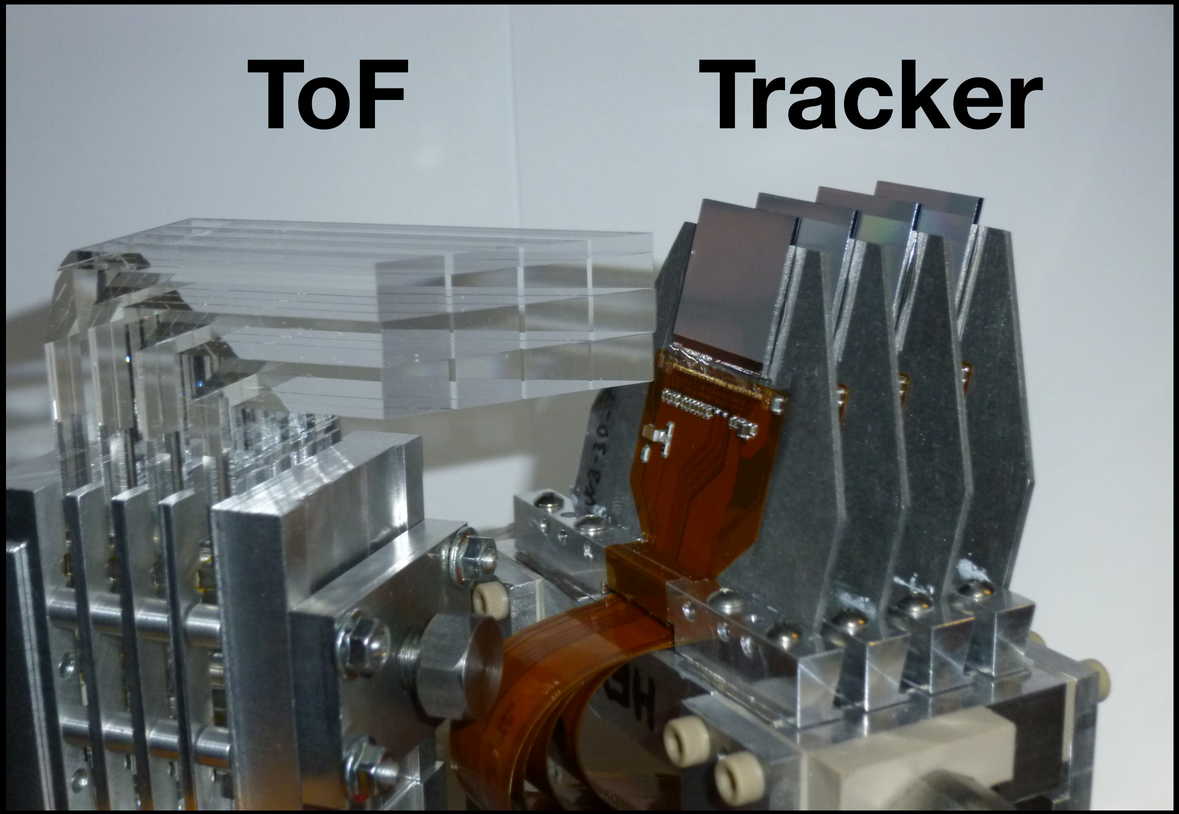
MAD-X beam propagation simulation



Key observable:

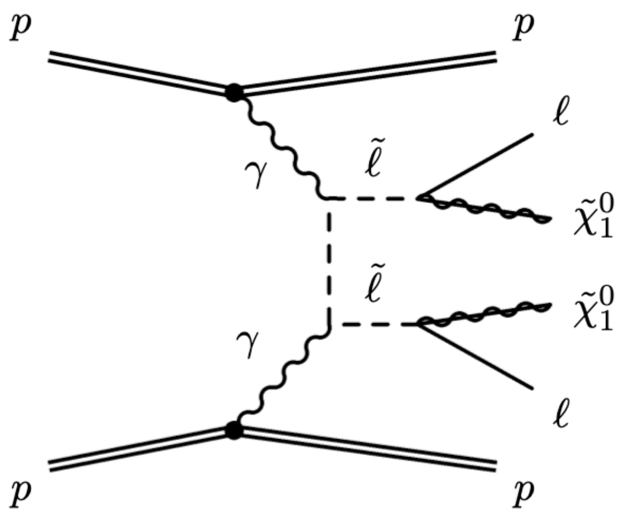
$$\xi_{\mathrm{AFP}}^{\mathrm{A,C}} = 1 - \frac{\mathrm{E_{scattered}}}{\mathrm{E_{beam}}}$$

AFP installation



Talk outline

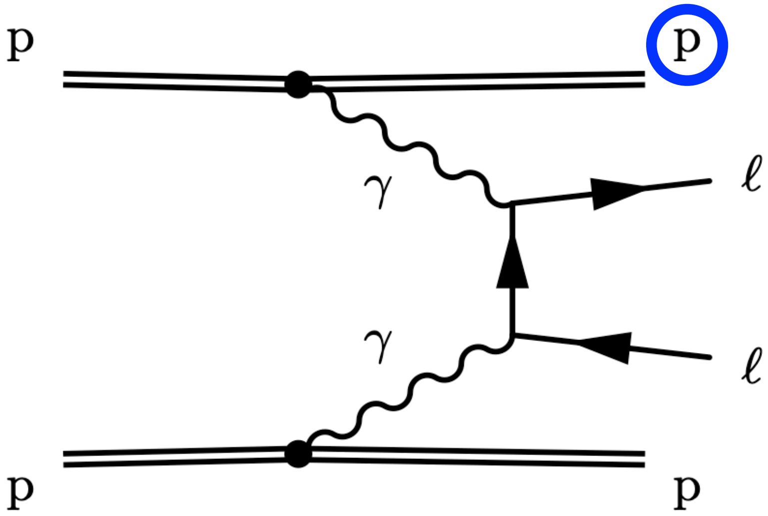
pp **Dark Matter**



Beresford & Liu, PRL (2019)

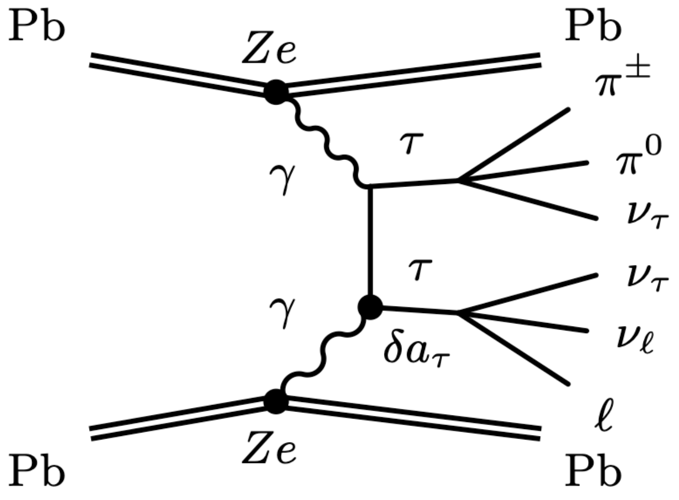
ATLAS EXPERIMENT

$\ell = e/\mu$



PRL (2020)

PbPb **Tau g-2**



Beresford & Liu, PRD (2020)

Outlook 1: Turning light into dark matter

PHYSICAL REVIEW LETTERS

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, Liu PhysRevLett.123.141801

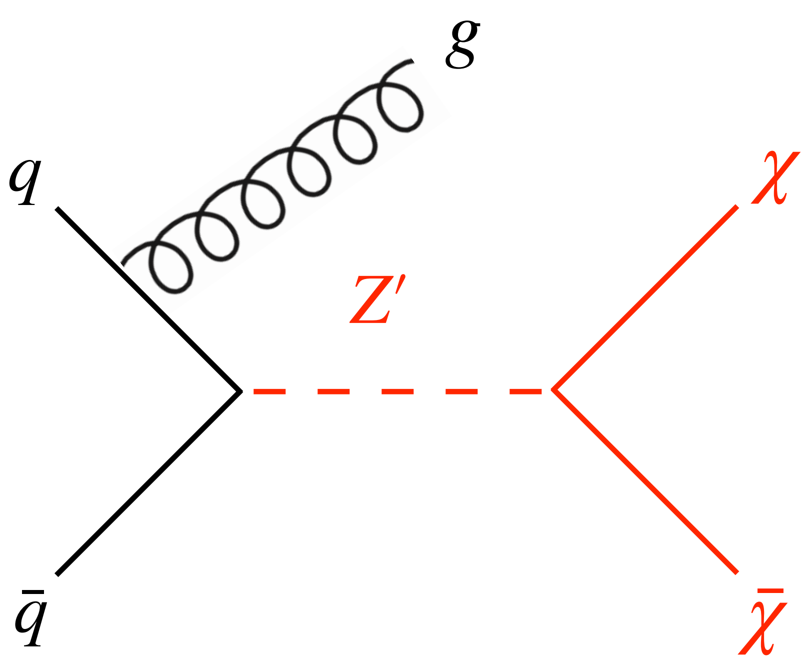
See also: Ohnemus et al. PLB 328 369-373 (1994), de Favereau de Jeneret et al. arXiv 0908.2020, Harland-Lang et al. EPJC 72 1969 (2012), Khoze et al. JPhys G 44 055002 (2017), Harland-Lang et al. JHEP 2019 10 (2019)

LHC Dark Matter Searches

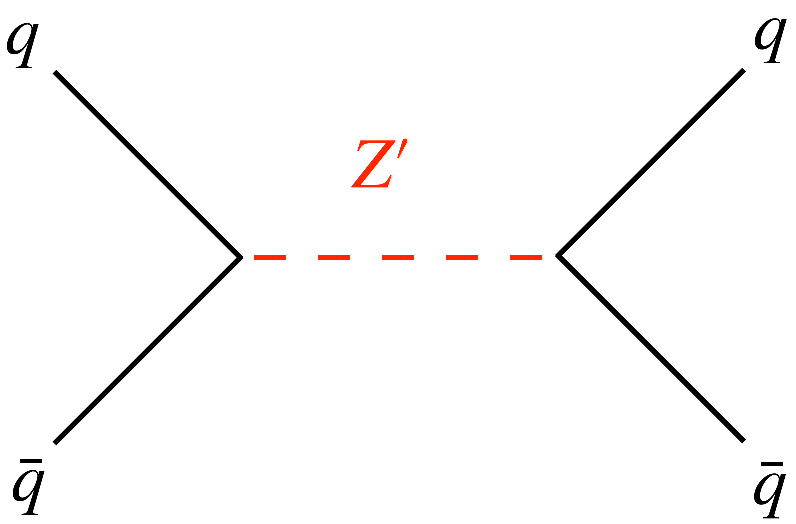
Nature of dark matter is a fundamental question in physics

Search for dark matter (or DM mediator) in LHC collisions

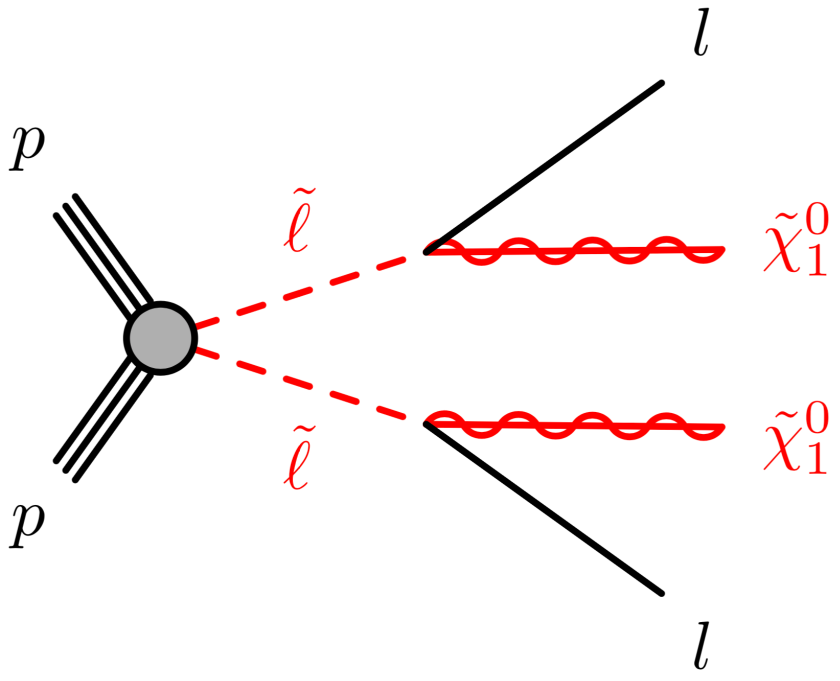
Mono-X



DM mediator search



SUSY



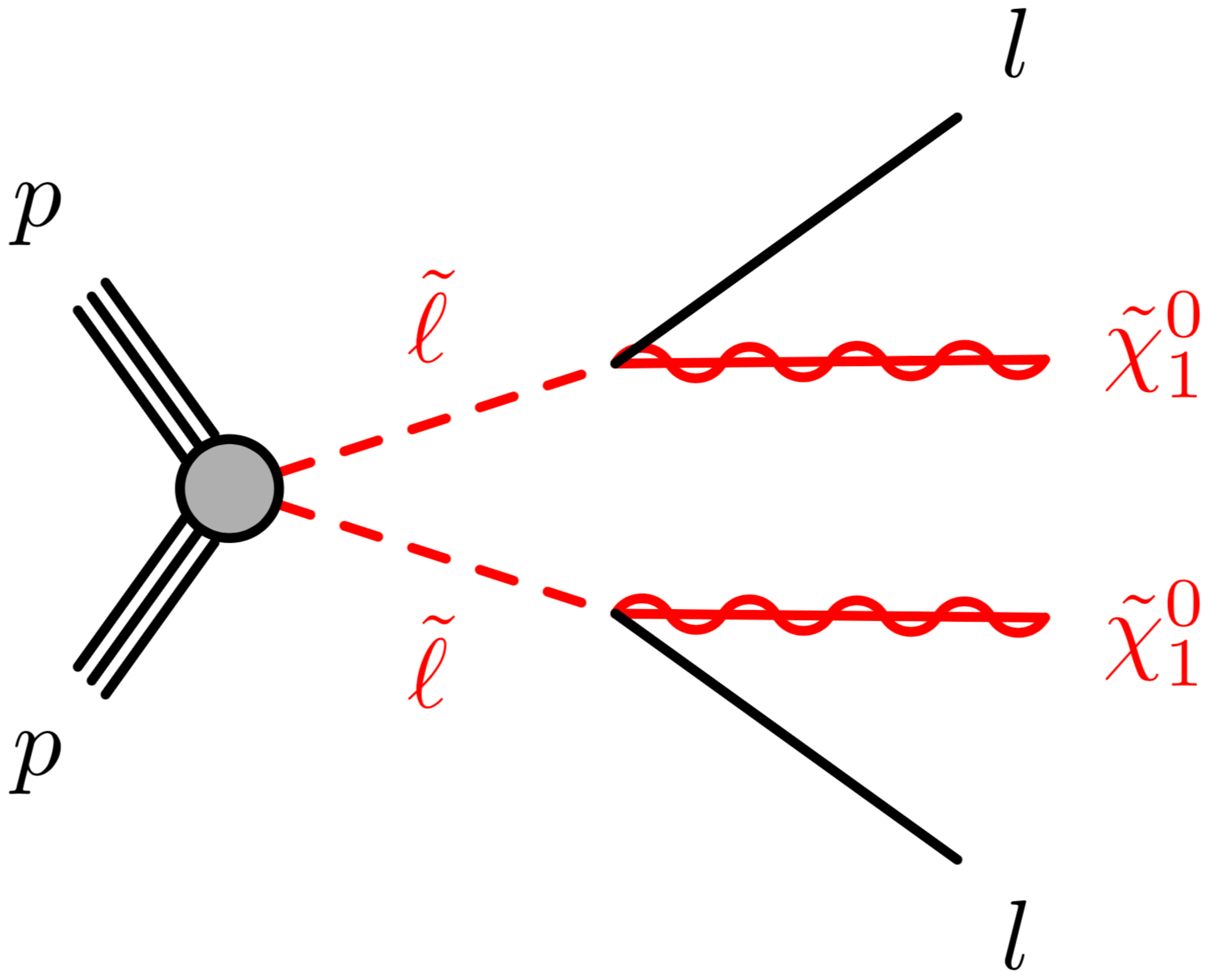
Examples

Lydia Beresford

Simple Benchmark Model

Charged **scalar lepton (slepton)** $\tilde{\ell}$

Considered scalar electrons & scalar muons in this work



Fermion

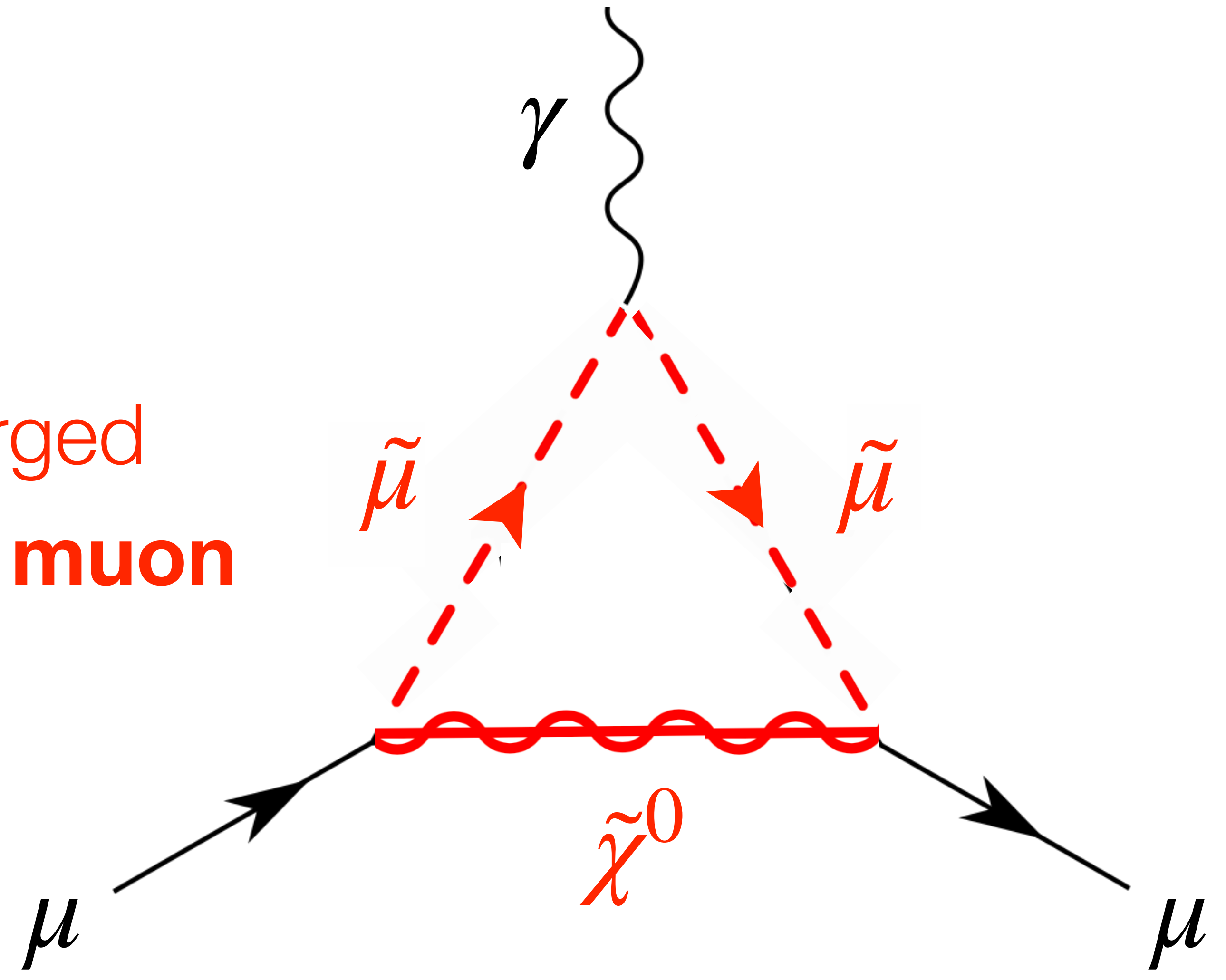
dark matter

(neutralino)

Assume mass degeneracy $m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$

Simple Benchmark Model

Potential explanation for muon g-2 anomaly

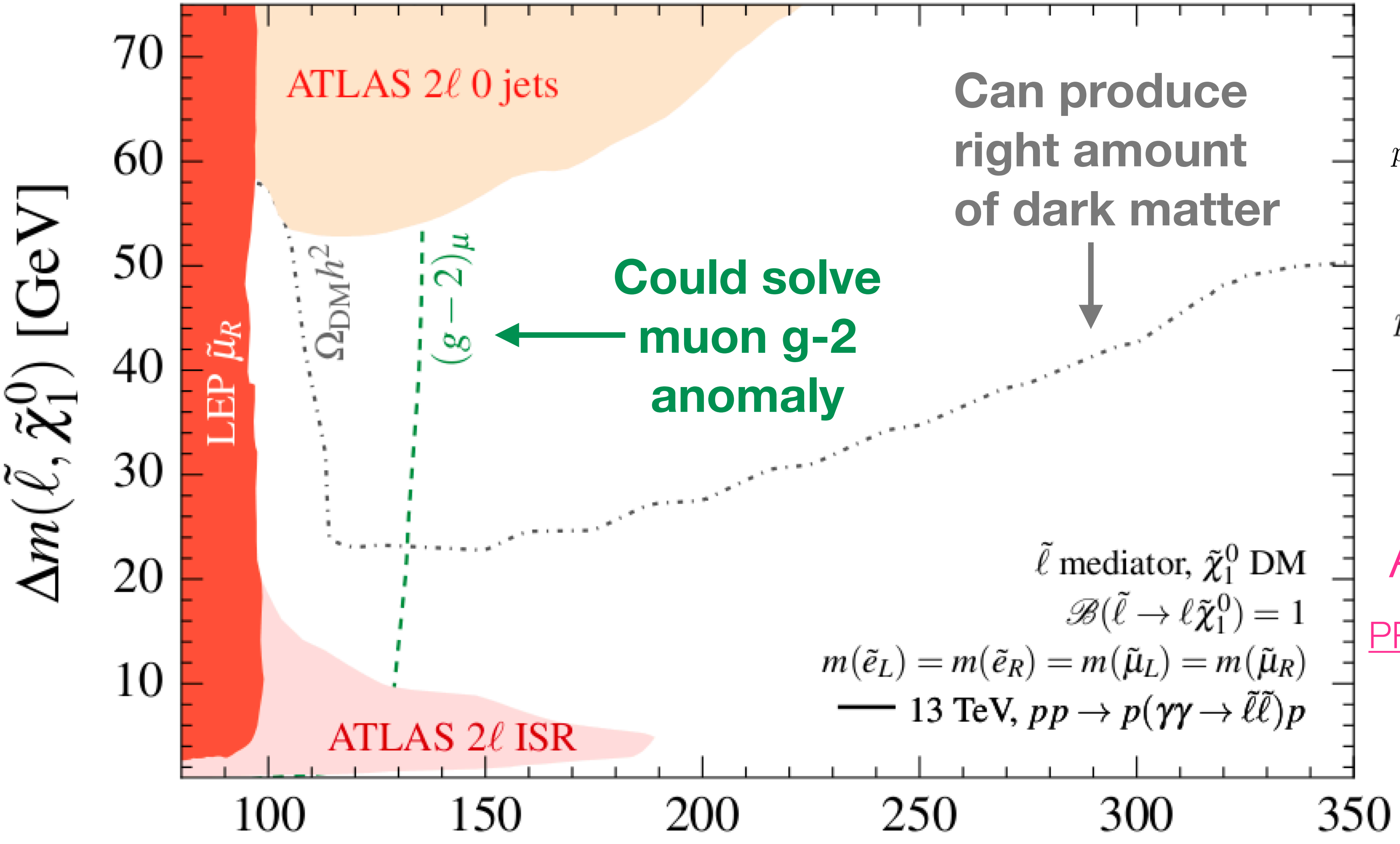


Charged
scalar muon

Fermion **dark matter**
(neutralino)

Motivation

Unexplored dark matter & g-2 favoured regions

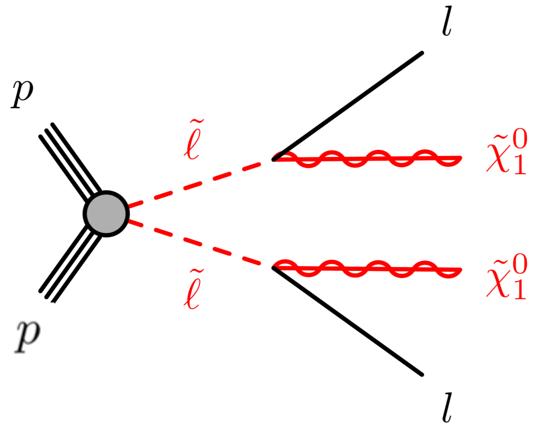


Mass difference (Slepton,DM)

Can produce right amount of dark matter

Could solve muon g-2 anomaly

Slepton $m(\tilde{\ell}_{L,R})$ [GeV]



NB recent ATLAS results:

PRD 101 052005 (2020)

EPJC 80 123 (2020)

Constraints much weaker for right handed sleptons

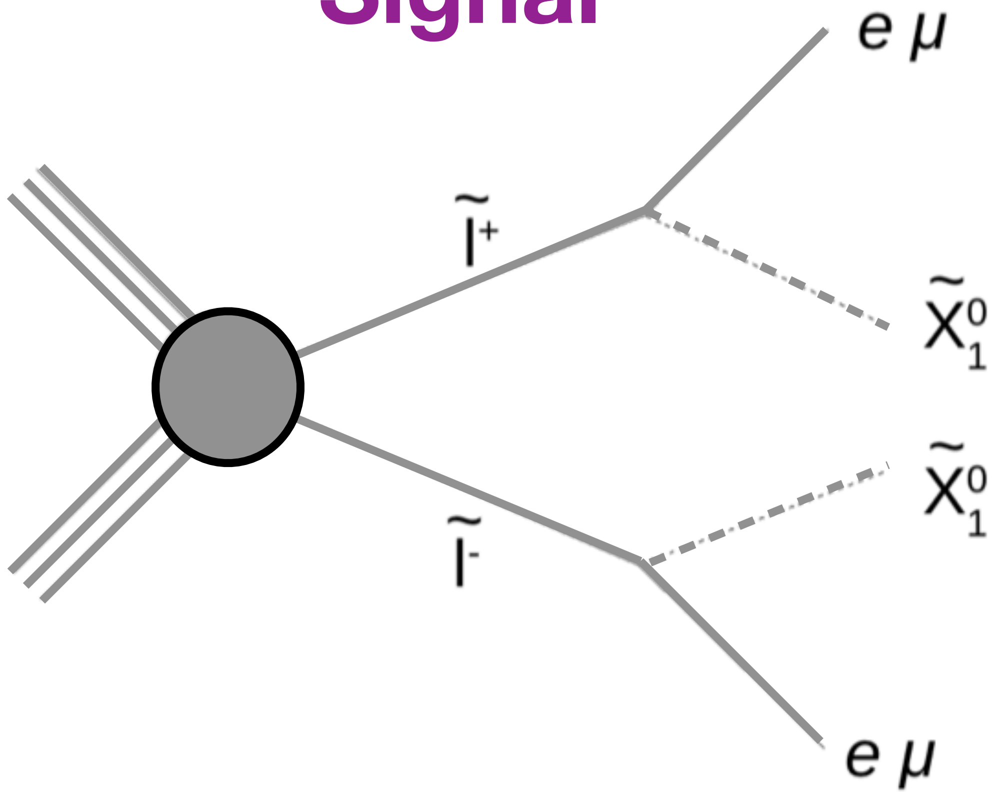
Why is it so challenging to probe?

Substantial cross-section: 730 fb (100 GeV slepton)

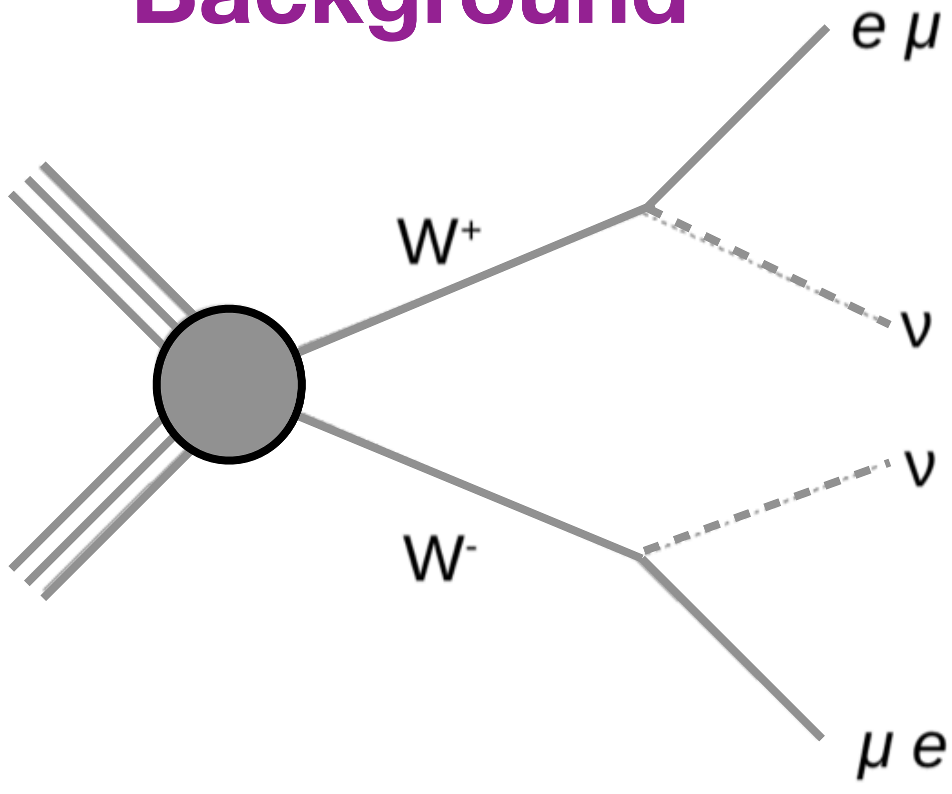
→100,000 events with 140 fb^{-1} dataset

But …

Signal



Background



Key differences: Mediator spin, decay channels, DM mass, mediator mass

Why is it so challenging to probe?

Key differences:

Mediator spin: slepton is **scalar**, W boson is **vector**

→ Use **spin sensitive variable** (scalar decays more central)

Decay channels: pair of sleptons $\tilde{\ell}\tilde{\ell} \rightarrow ee, \mu\mu$; WW $\rightarrow ee,\ \mu\mu, e\mu$

→ Require **same flavour** leptons

Dark matter mass: may not be equal to neutrino mass

Slepton mass: may not be equal to W mass

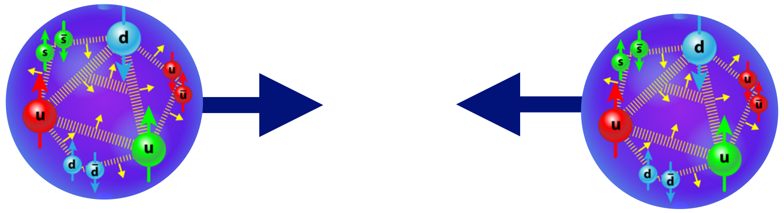
↓

Fundamental Hadron Collider problem

Why is it so challenging to probe?

Fundamental Hadron Collider problem

Head-on collision



Don’t know the parton momentum in direction of the beam

→ Use **missing transverse momentum**

Why is it so challenging to probe?

Fundamental Hadron Collider problem

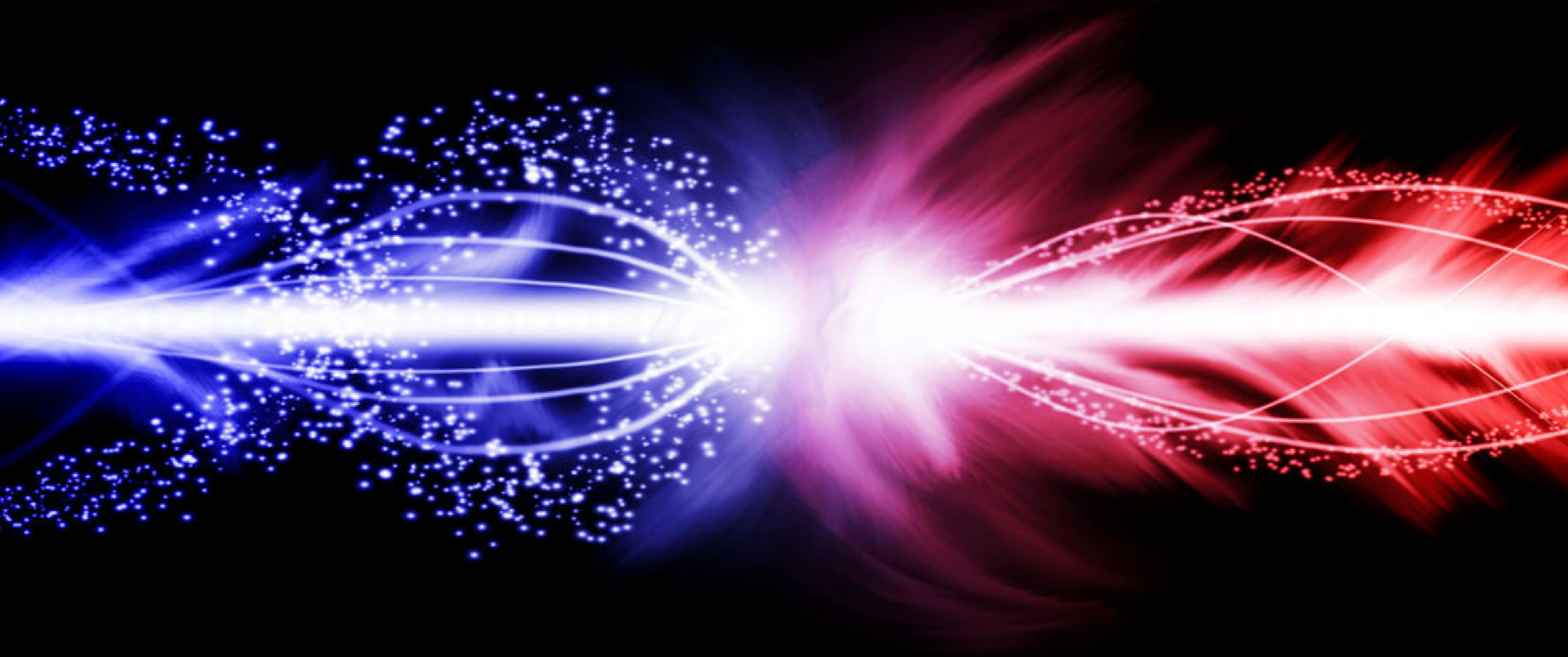
- Don’t have access to initial state kinematics

  → Can only use **missing transverse momentum**
- Combine it with lepton kinematics & approx slepton mass using **mT2** relies on DM mass assumption

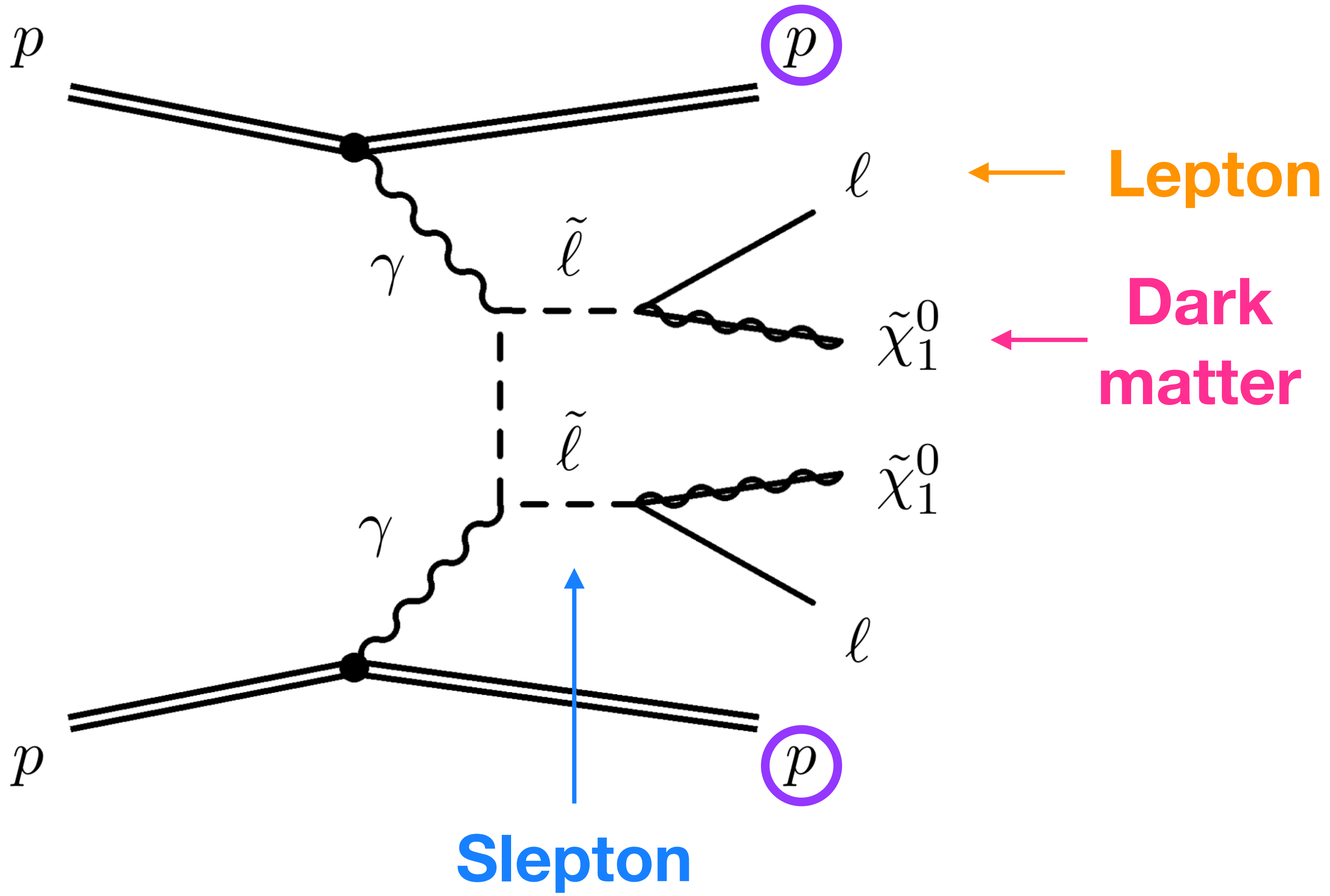
- In $15 \lesssim \Delta m(\tilde{l}, \tilde{\chi}^0) \lesssim 60$ gap **mT2 similar shape** for sleptons & WW
- Discrimination very challenging

→ **Need more information!**

Solution: Photon collisions



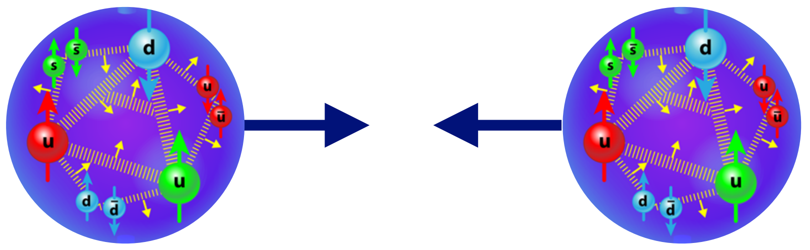
Turning light into dark matter



The holy grail

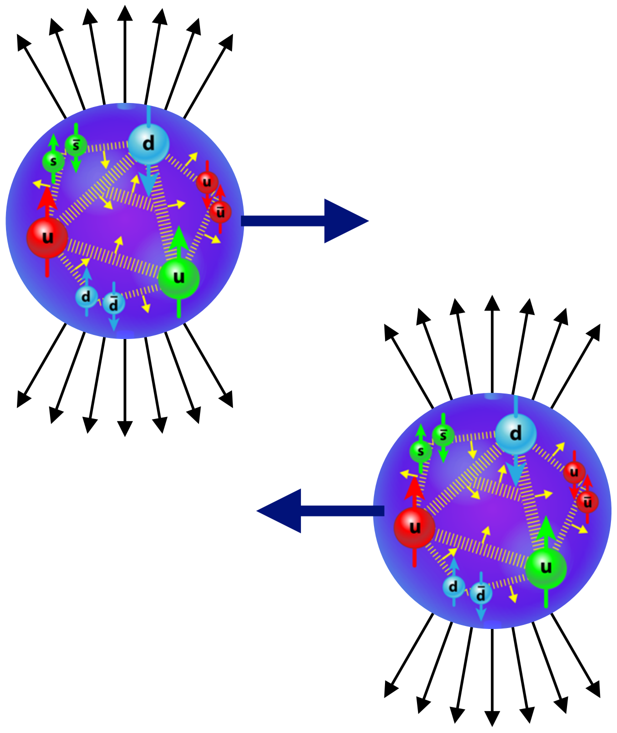
Dark matter is invisible to our detectors

Fundamental hadron collider problem



Don’t know the parton momentum in direction of the beam

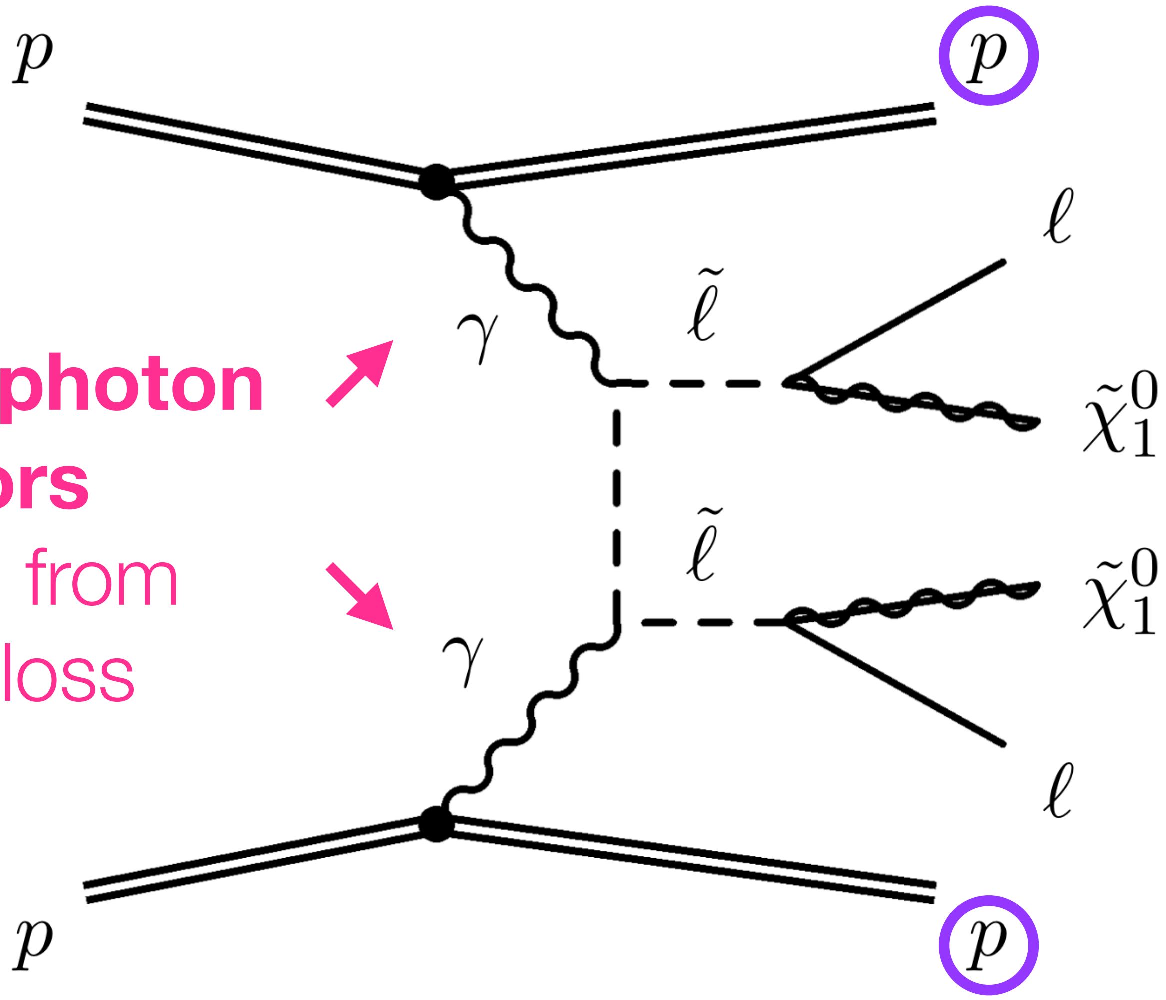
→ Use **missing transverse momentum**



Initial proton E is known (6.5 TeV)
Measure scattered proton E using
Forward proton detector

→ Initial state kinematics known
Can calculate **total missing momentum!**

Search strategy



Initial state photon 4-vectors

Calculated from proton E loss

Missing momentum 4-vector

Calculated from photon & lepton 4-vectors

Living the dream: Access initial state & total missing momentum

Similar to e^+e^- collider

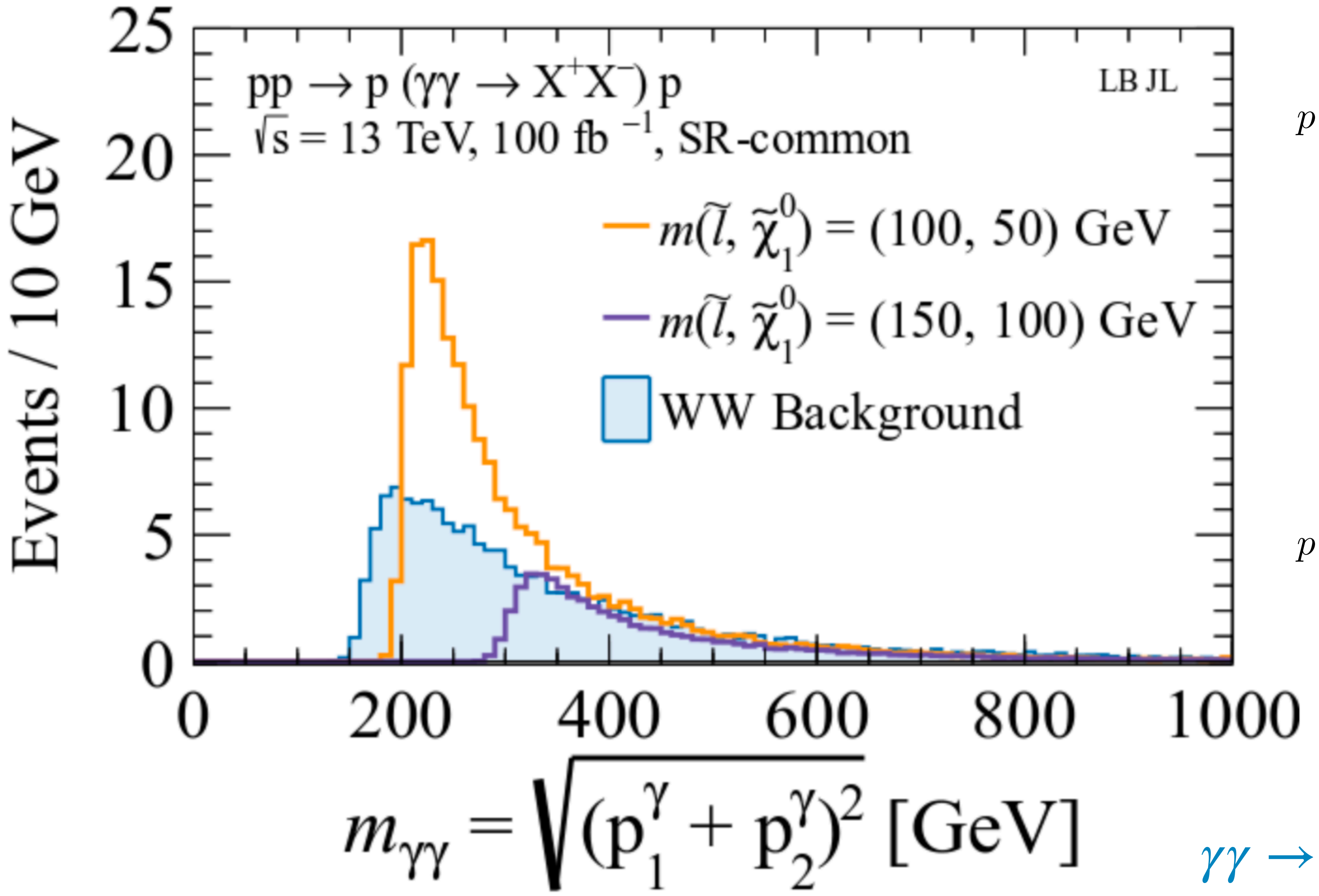
Usually impossible in LHC searches!

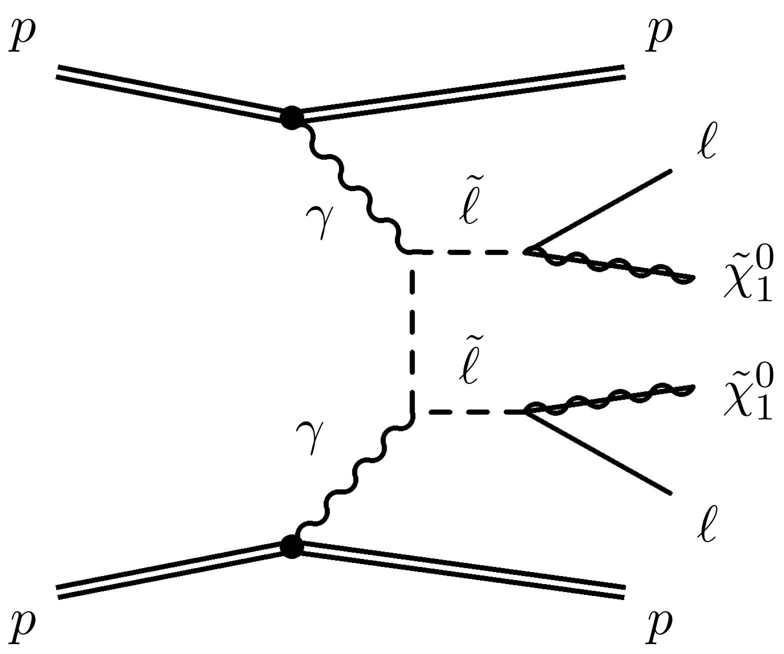
Living the dream: Slepton mass

Calculated from proton energy loss

$$m_{\gamma\gamma} = \sqrt{\xi_1 \xi_2 s}$$

Slepton mass is measurable



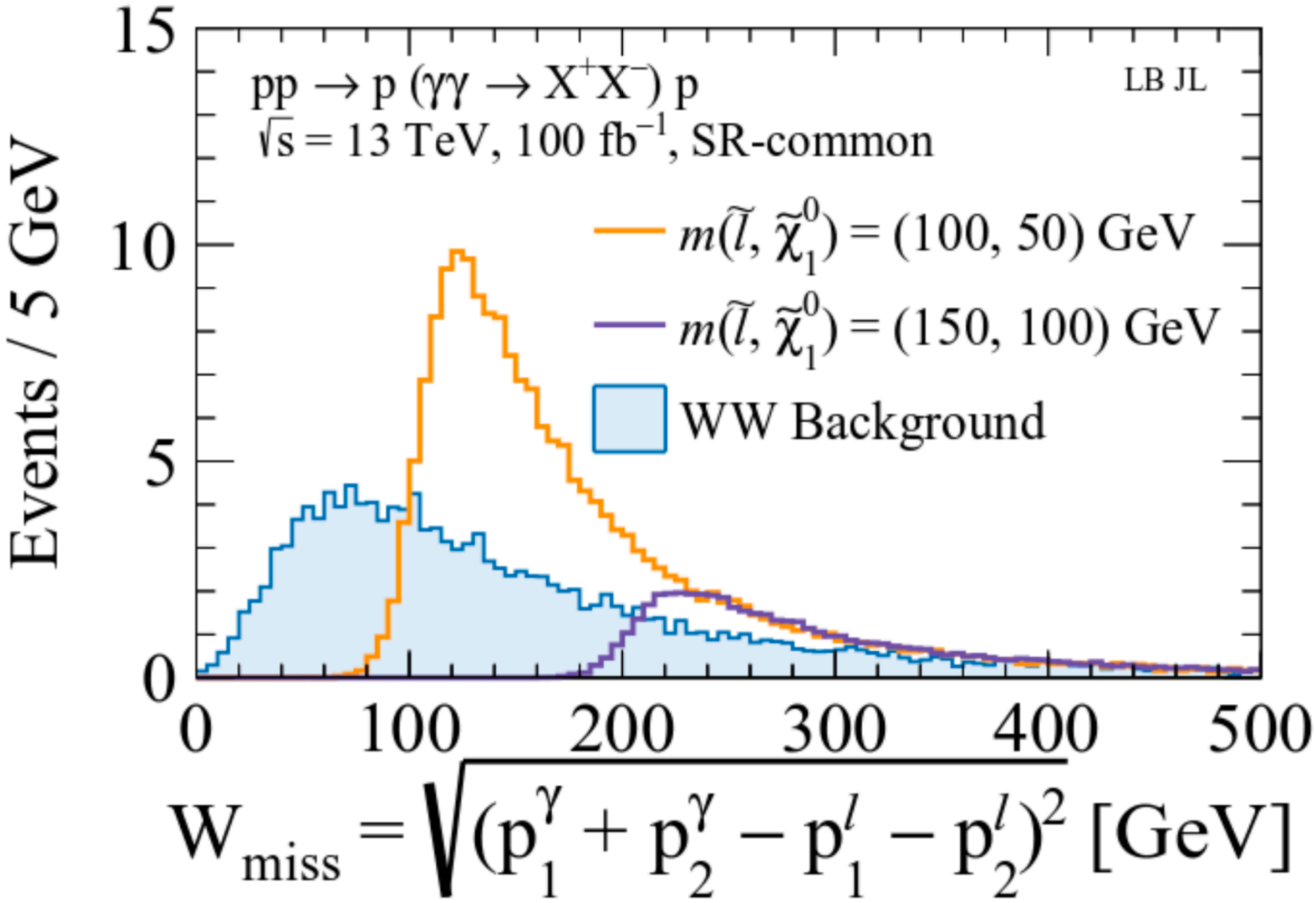


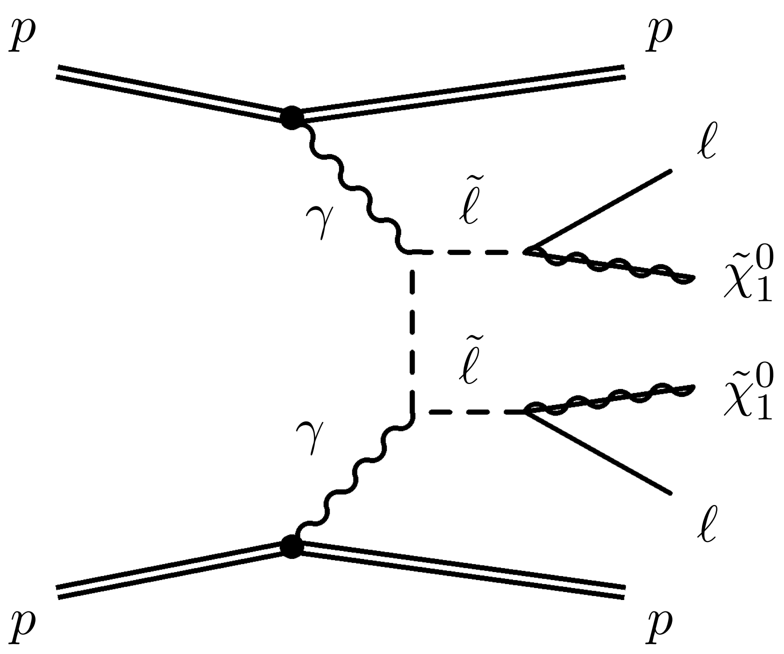
$\gamma\gamma \rightarrow WW$ recently observed
ATLAS PLB 816 136190 2021

Illustrative plot: acceptance & efficiencies not applied here, only resolution smearing

Living the dream: DM mass

Dark matter mass is measurable





Illustrative plot: acceptance & efficiencies not applied here, only resolution smearing

Analysis

Madgraph MC for signal & irreducible $\gamma\gamma \rightarrow WW$ background

Emulate: Detector acceptance
Resolution smearing
Reconstruction efficiency
Proton soft survival

Selection cuts: Same flavour di-lepton selection each with $p_T > 15$ GeV
Select more central events to exploit spin difference

3 signal regions: Target different slepton and DM mass differences using variables based on $m_{\gamma\gamma}$ & W_{miss}

Count signal and background → Calculate significance

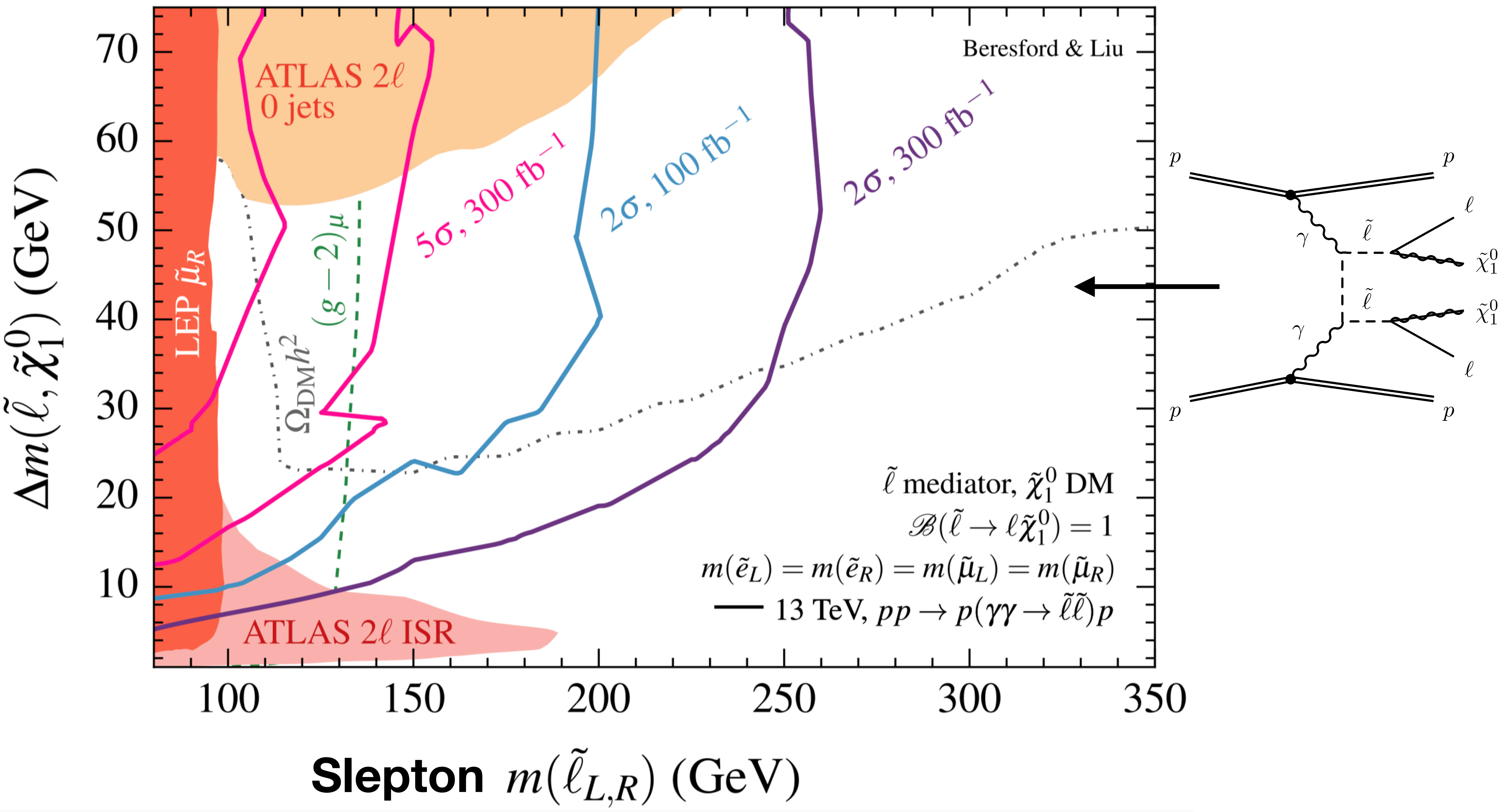
Details in backup

Powerful Potential

Beresford, Liu
PRL 123 141801 (2019)

Potential to probe well motivated blind spot

Mass difference (Slepton,DM)



Slepton

$\gamma\gamma$-production: Equal cross-sections for left & right handed sleptons!

First measurement using AFP

PHYSICAL REVIEW LETTERS

Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS

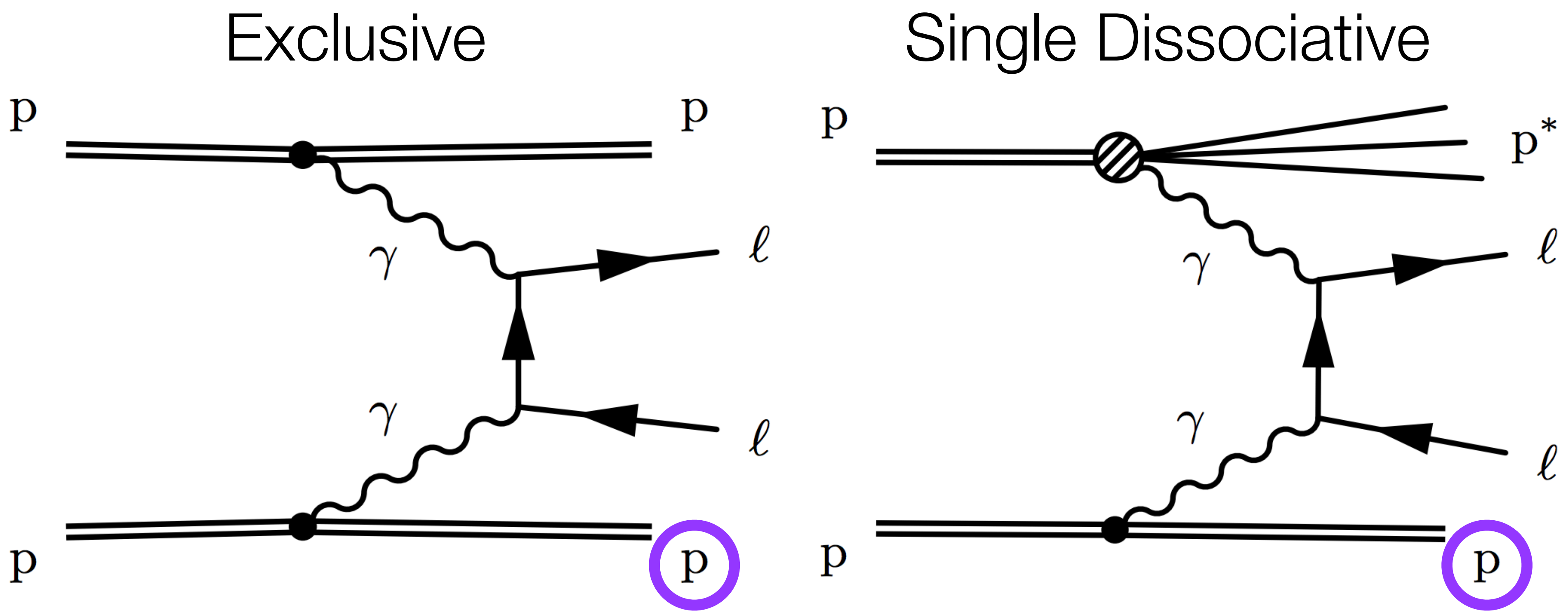
G. Aad *et al.* (ATLAS Collaboration)
Phys. Rev. Lett. **125**, 261801 – Published 23 December 2020

PhysRevLett.125.261801

First measurement using AFP *Turning light into matter :)*

Observe $(\gamma\gamma \rightarrow \ell^+\ell^-) + p$ & measure cross-section

Previous ATLAS measurements don't tag a proton!

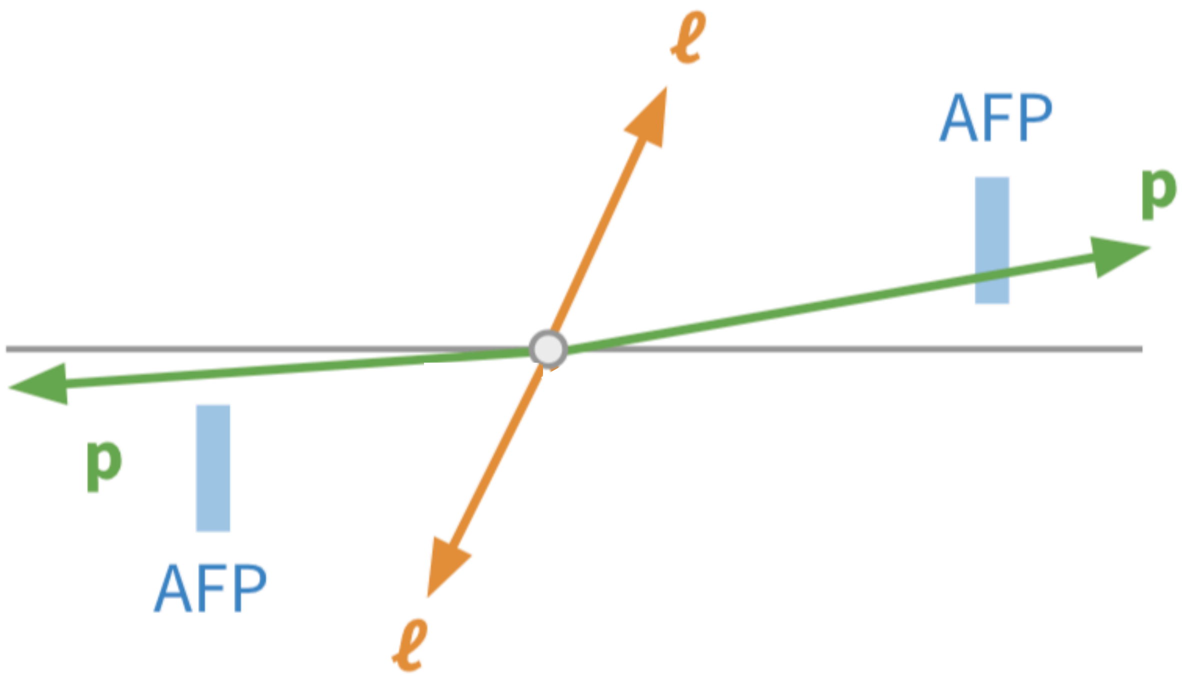


Direct access to protons provides truly new info to exploit!

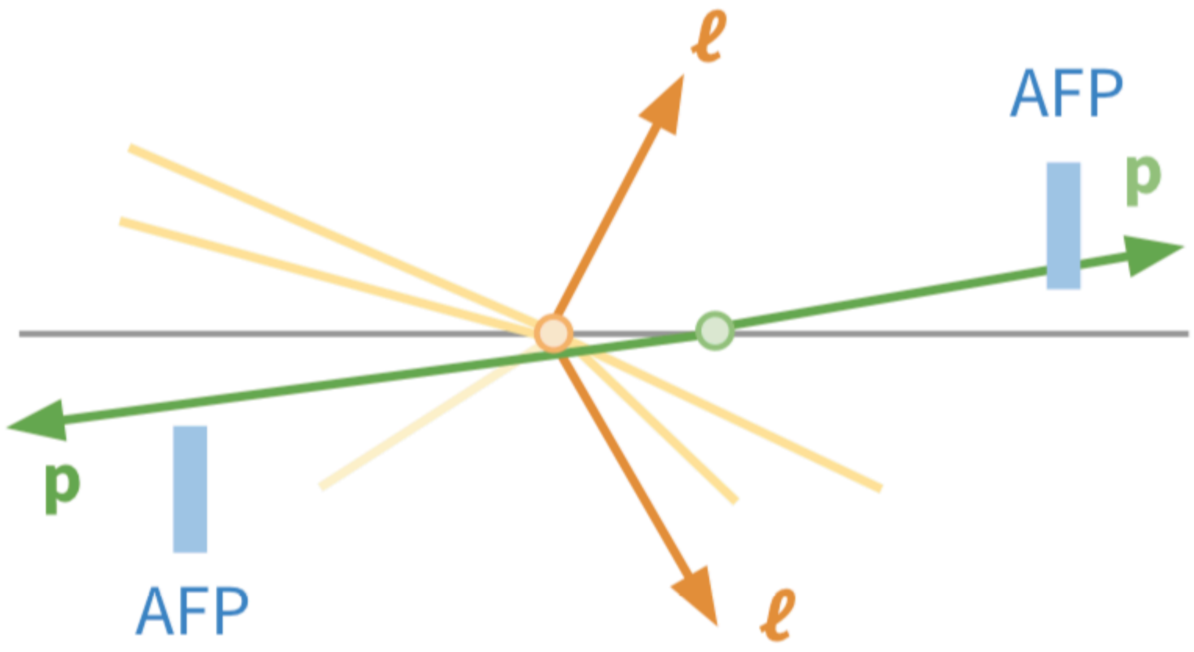
- Powerful background rejection
- Novel constraints on proton soft survival probability

Kinematic correlation

Signal



Background



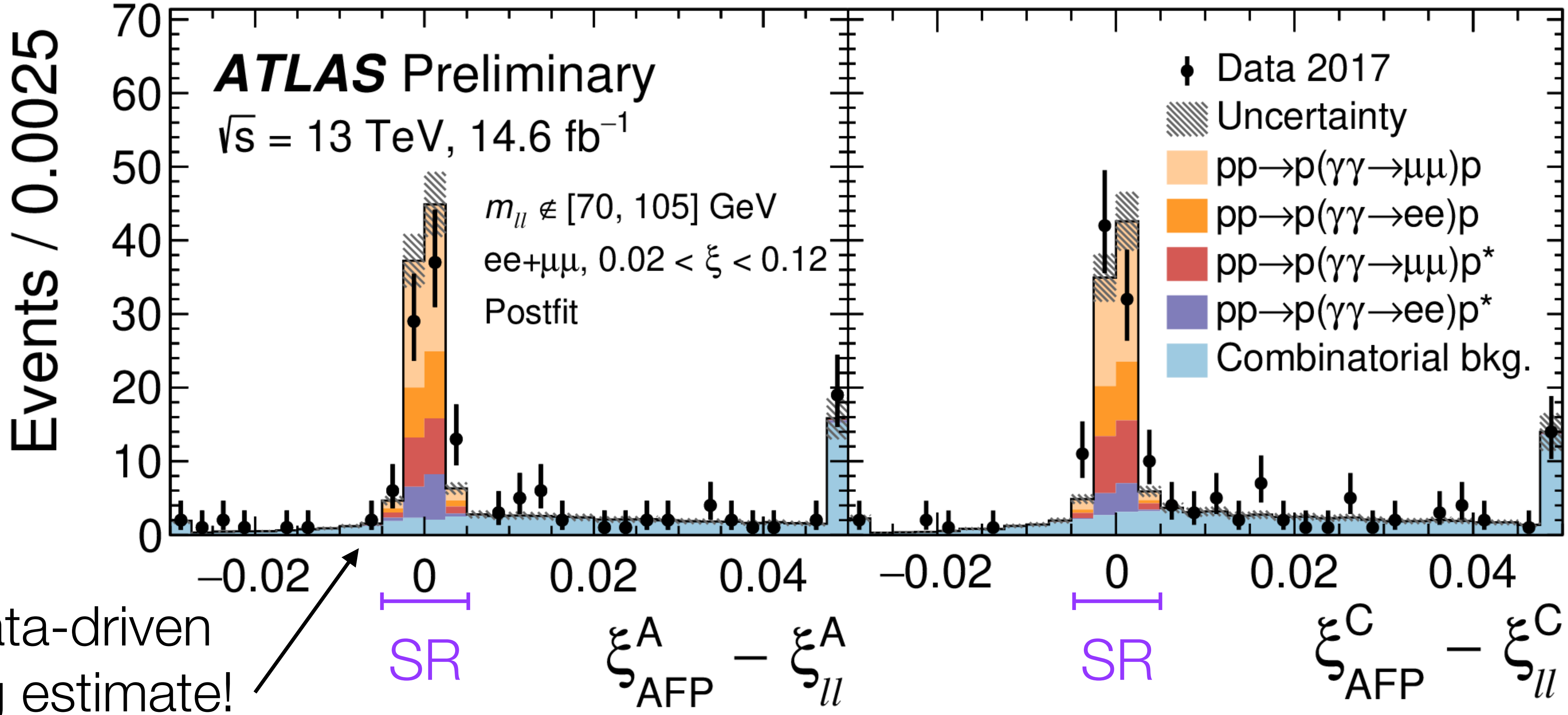
e.g. Z → $\ell\ell$
+ pileup proton

Kinematic correlation

SR: 95% signal retention
85% bkg rejection

Observe ee+p and $\mu\mu$+p > 9σ in each channel

cf CMS-TOTEM 2.6σ, 4.3σ



Data-driven
bkg estimate!

Measured with AFP

$$\xi^{A,C}_{AFP} = 1 - E_{forward}/E_{beam}$$

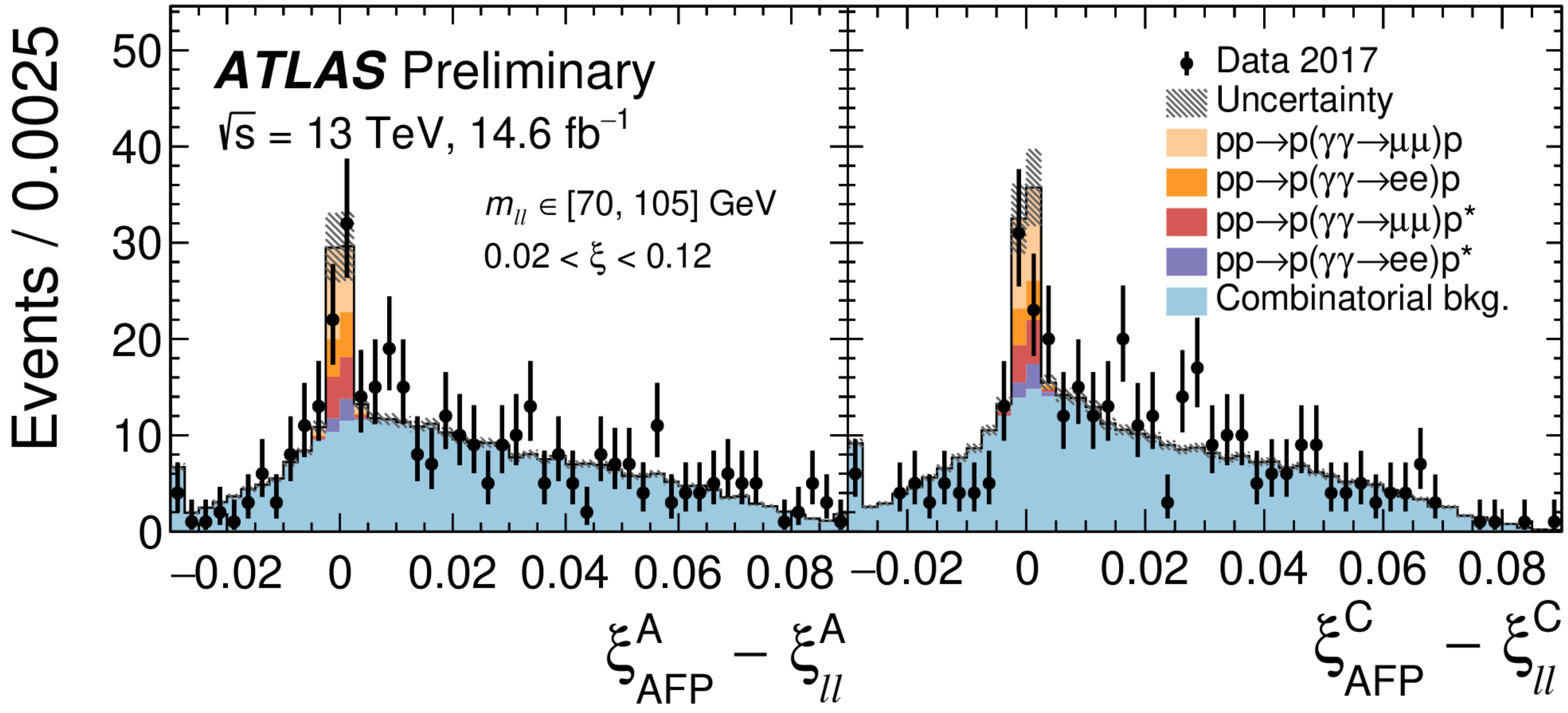
Measured with ATLAS

$$\xi^{\pm}_{ll} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}$$

Background rejection

Powerful background suppression

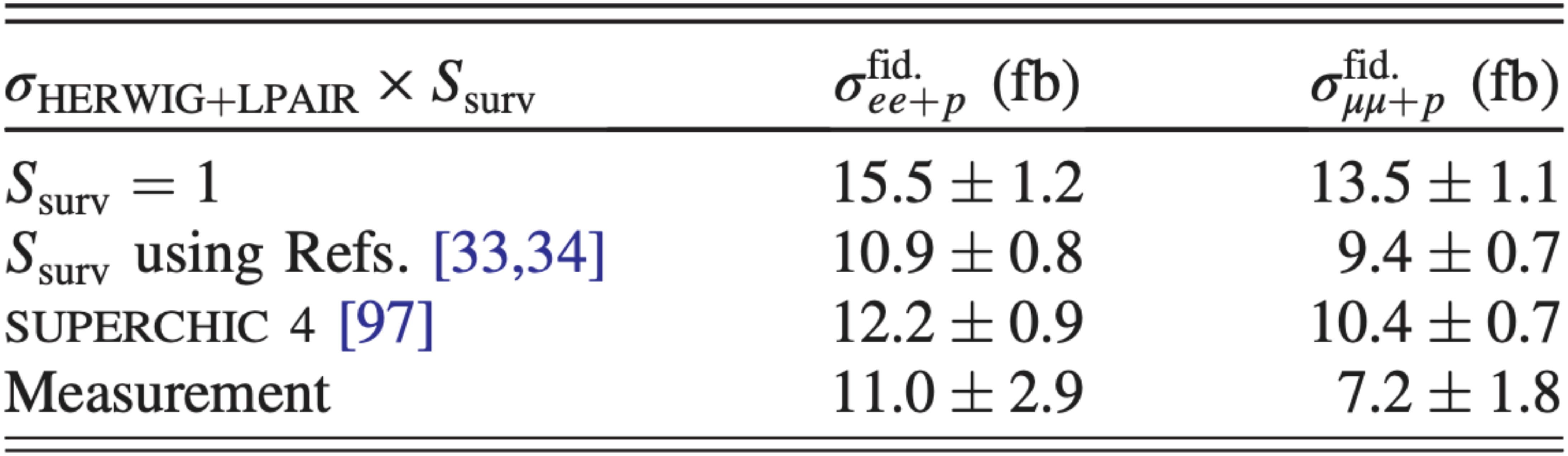
Can see photo-production of di-leptons above Drell-Yan background



Run 3: Time-of-flight detector will further suppress

Results

1st LHC cross-section measurements for this process



$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [33,34]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

Fiducial cross-sections $\xi \in [0.035,0.08]$
compared to proton soft survival models

[33] Eur. 314 Phys. J. C 76 (2016) 9
[34] Phys. Lett. B 741 (2015) 66
[97] Eur. Phys. J. C 80, 925 (2020)

First step towards diverse program exploiting AFP

Outlook 2: Measure tau g-2

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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

Lydia Beresford and Jesse Liu

Phys. Rev. D **102**, 113008 – Published 22 December 2020

Beresford, Liu PhysRevD.102.113008

See also: Aguila, Cornet and Illana PLB (1991), Dyndal et al PLB (2020)

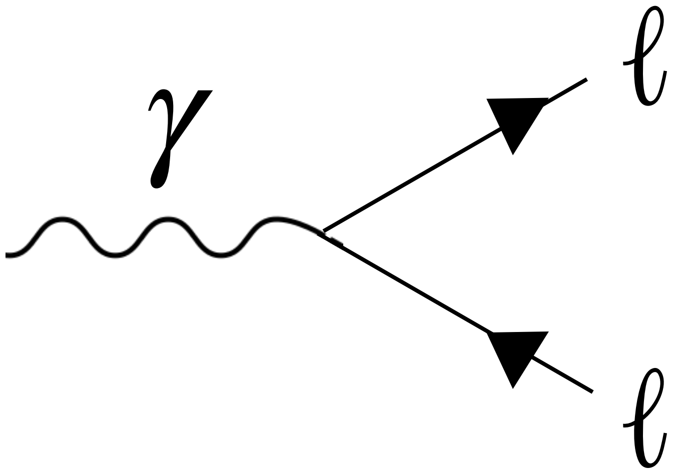
Measure tau g-2

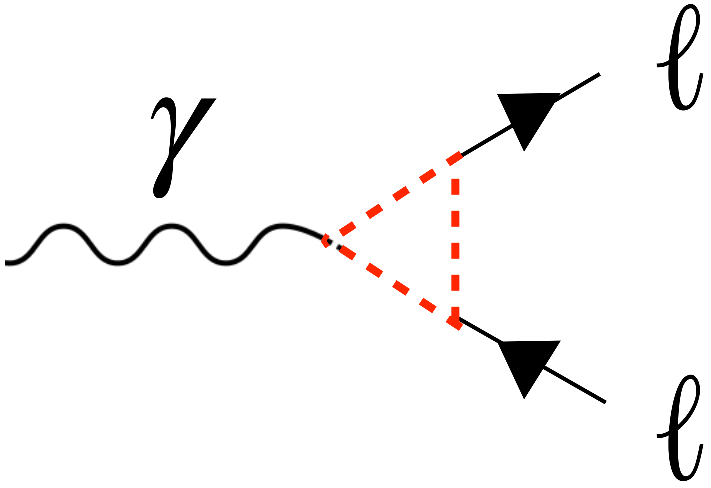
*How particles interact with a **magnetic** field*

Particles can have intrinsic **magnetic moment**

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

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





g = 2 + loop corrections

Dirac, 1928

Measure tau g-2

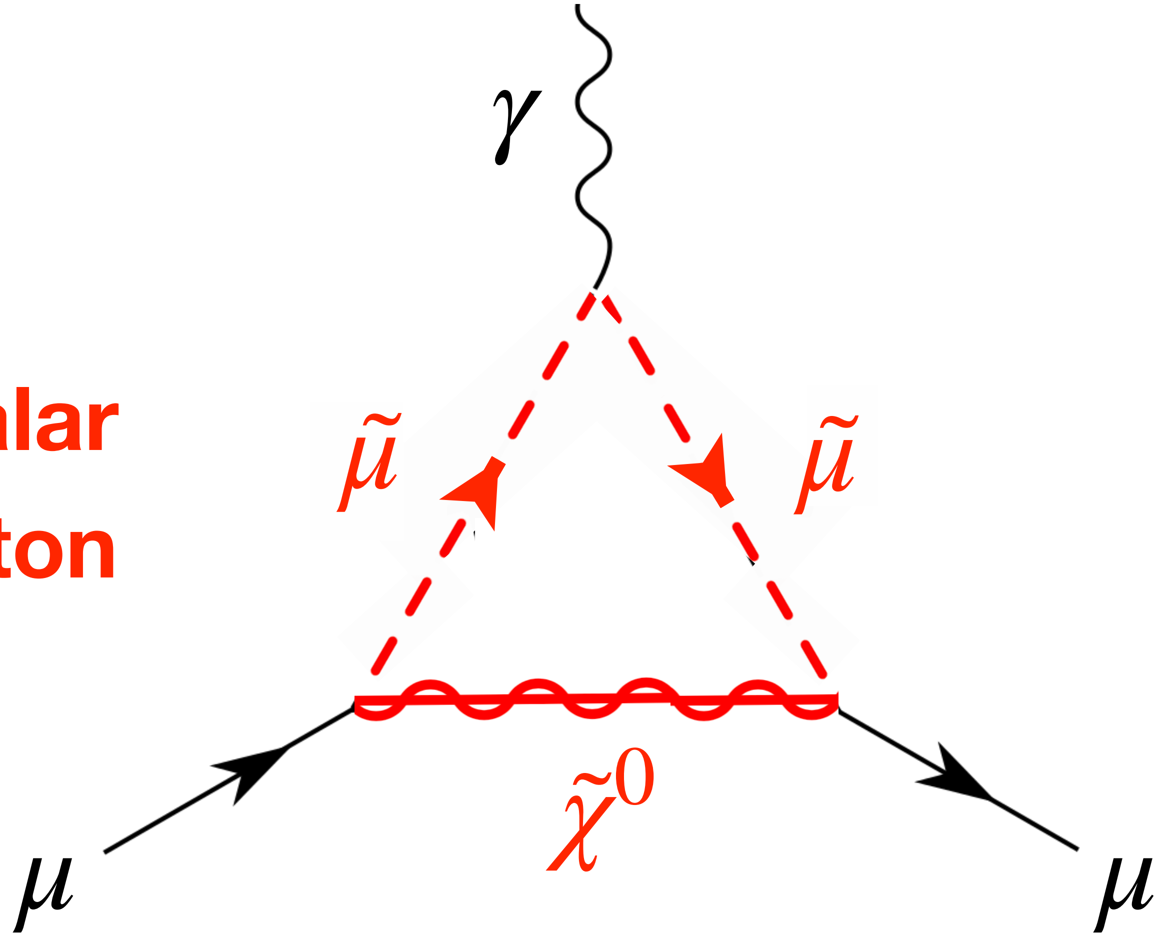
Anomalous magnetic moment

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

Why is it interesting?

New particles could be in the loop

Example: SUSY



Scalar lepton

Dark matter

Why is it interesting?

Does light couple to all lepton generations in the same way?

Fundamental test of SM

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

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

What about the tau?

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

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

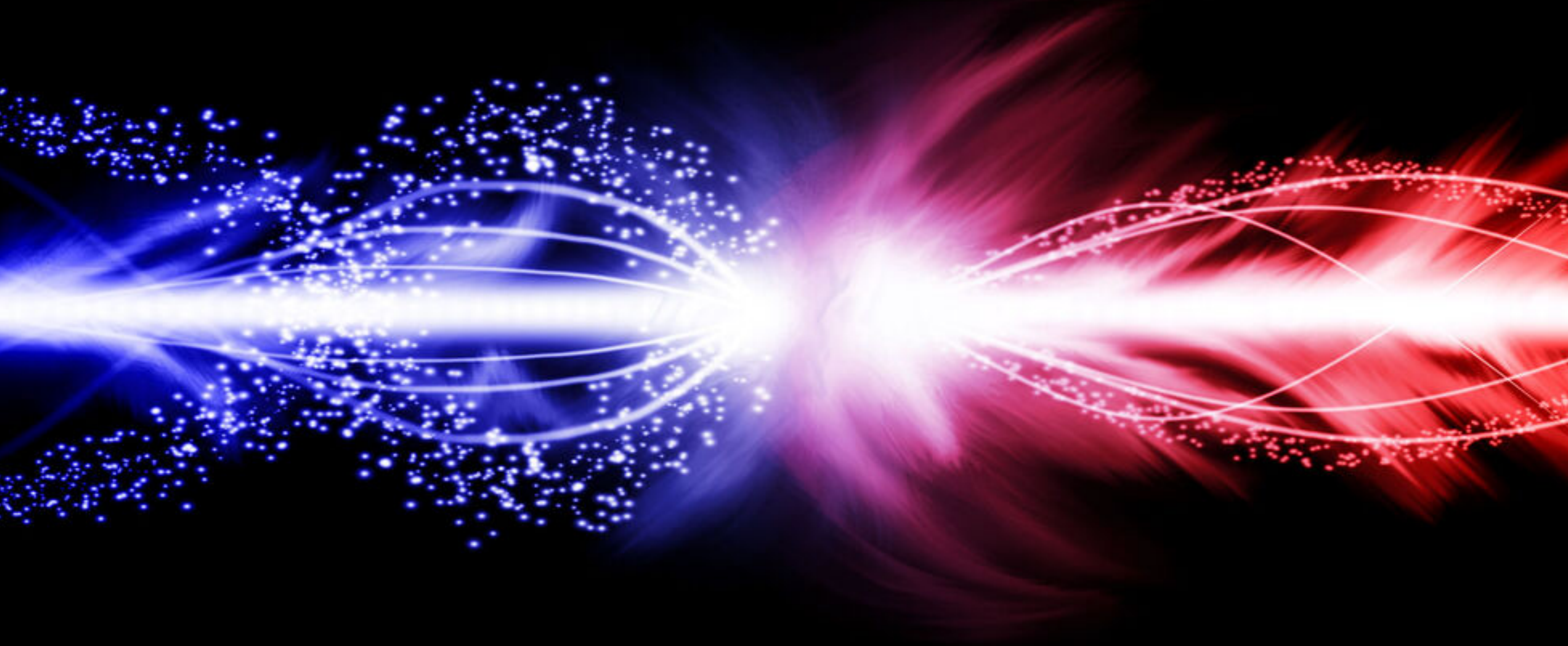
Problem: Lifetime

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

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

→ **Can’t use same technique!**

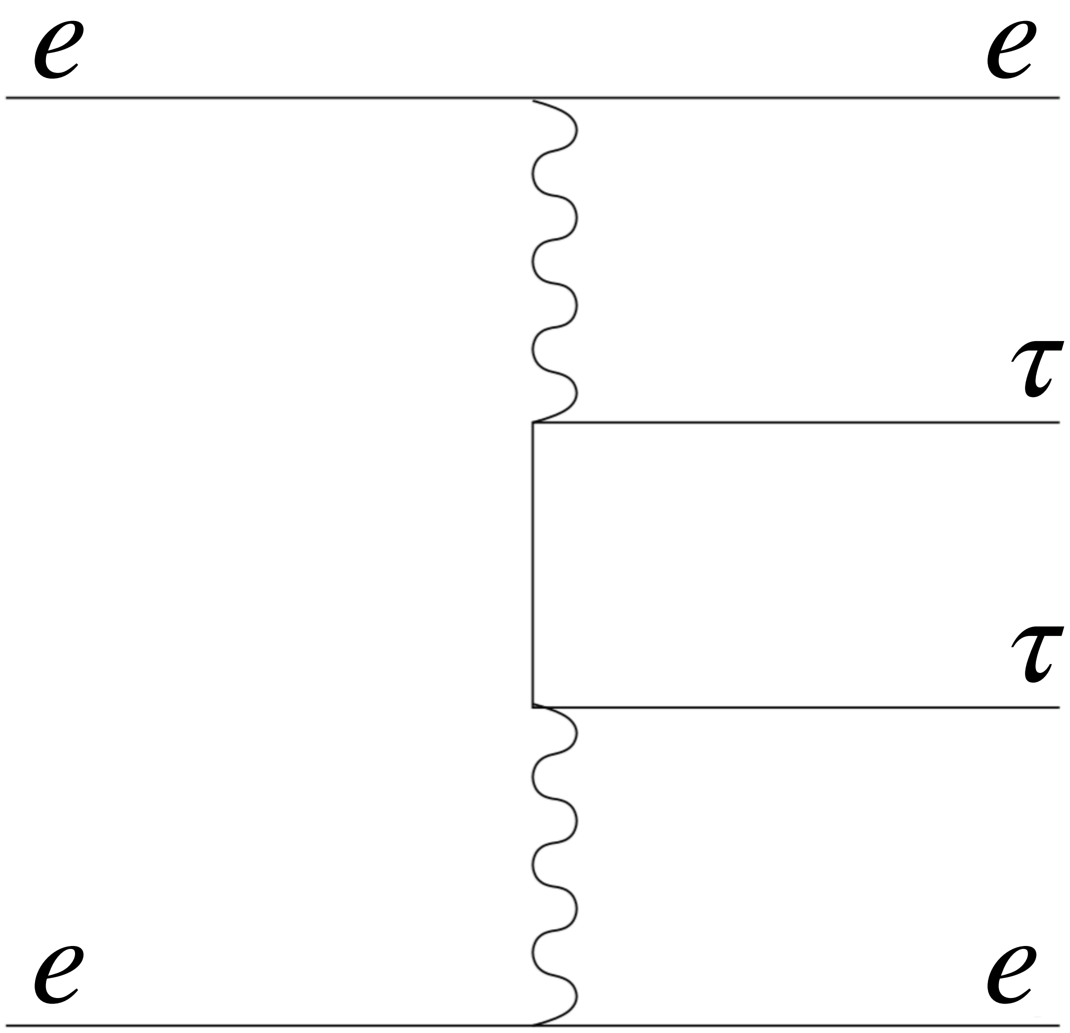
Solution: Photon collisions



PDG value

Delphi EPJC (2004)

DELPHI 2004, LEP collider



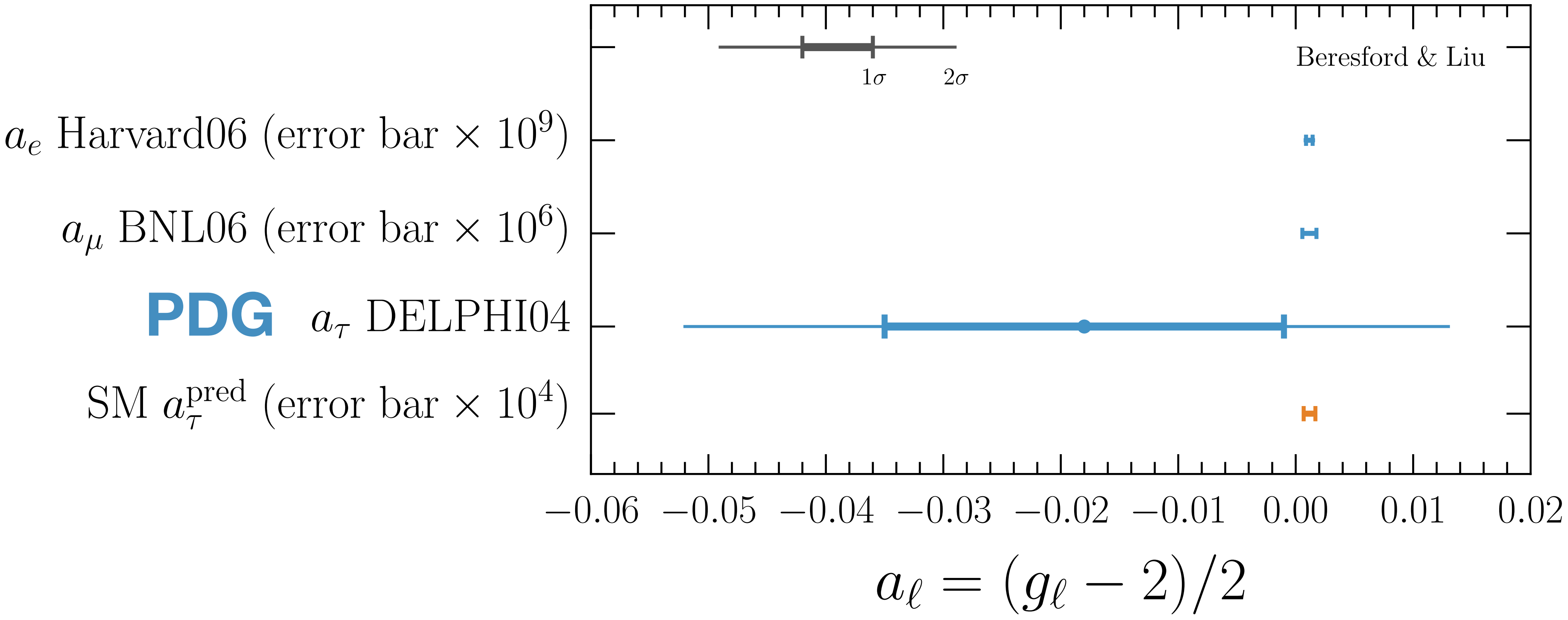
Cross section sensitive to **g-2**

Photo production of tau pairs

Constraints also set by L3 and OPAL

Sibling rivalry

What about the tau?



Order of magnitude apart

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

PDG best single experiment constraint
Delphi EPJC (2004)
Constraints also set by L3 and OPAL

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

1-loop, Schwinger $a = \alpha/2\pi$ = 0.0012
Eidelman, Passera MPL (2007)

Can we beat it?

Many interesting proposals for future

Belle II

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

LHeC/Fcc-he

Köksal JPhysG (2019)
Gutiérrez-Rodríguez et al 1903.04135

CLIC/ILC/Fcc-ee

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

Bent crystal

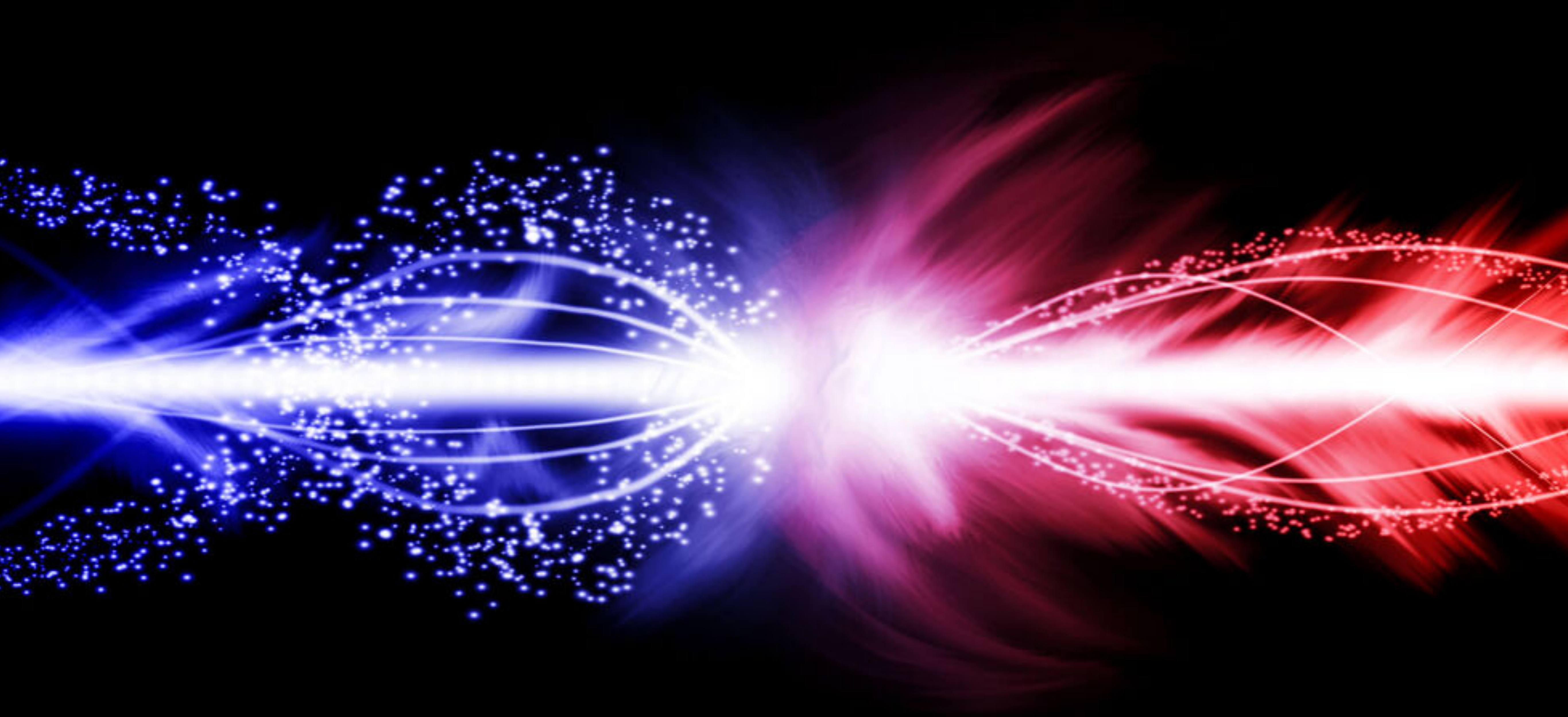
Fomin et al JHEP (2019)
Fu et al PRL (2019)

HL-LHC

Galon, Rajaraman and Tait JHEP (2016)

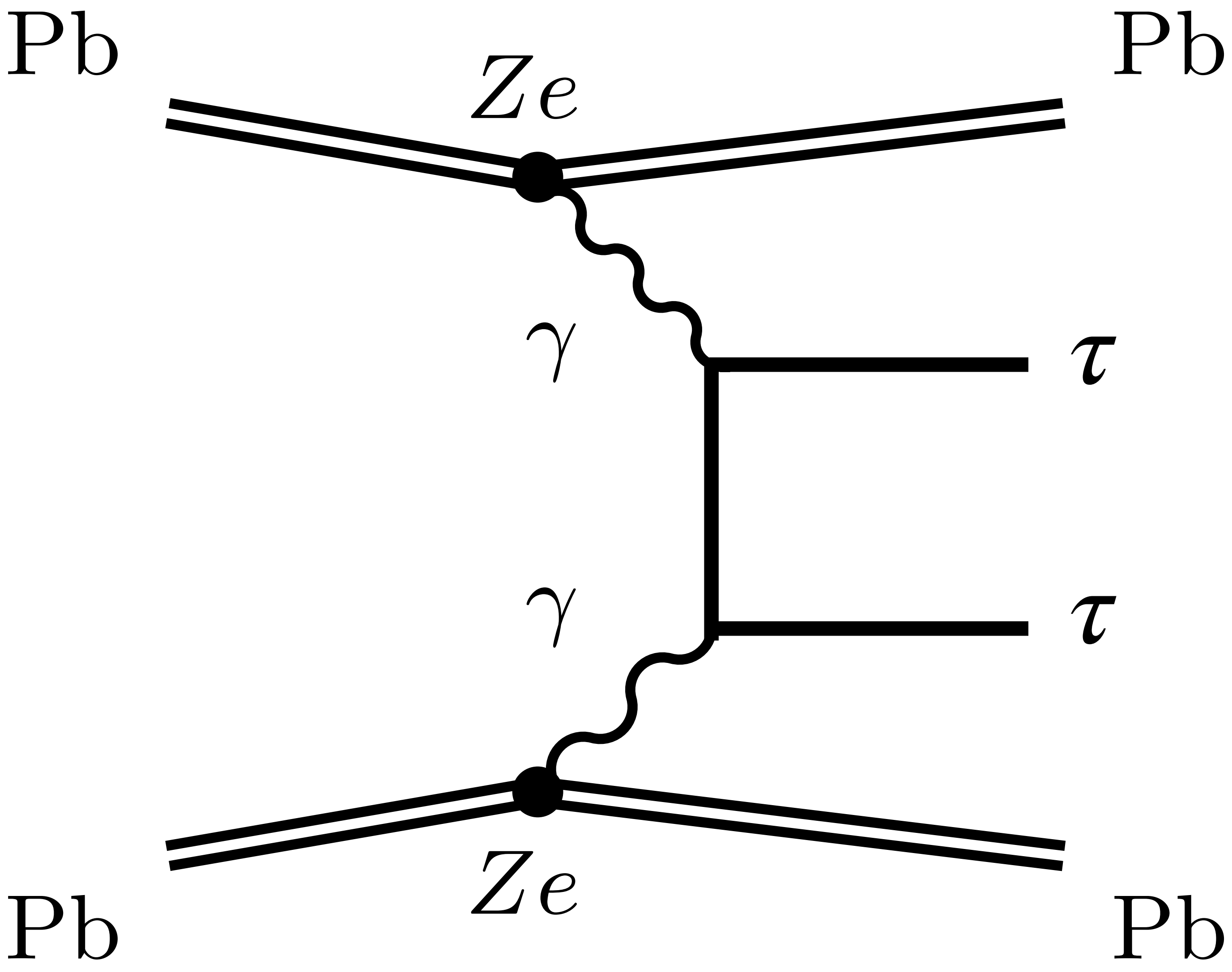
What can we do right now?

The LHC is also a photon collider



Di-tau production

Photo production of tau pairs

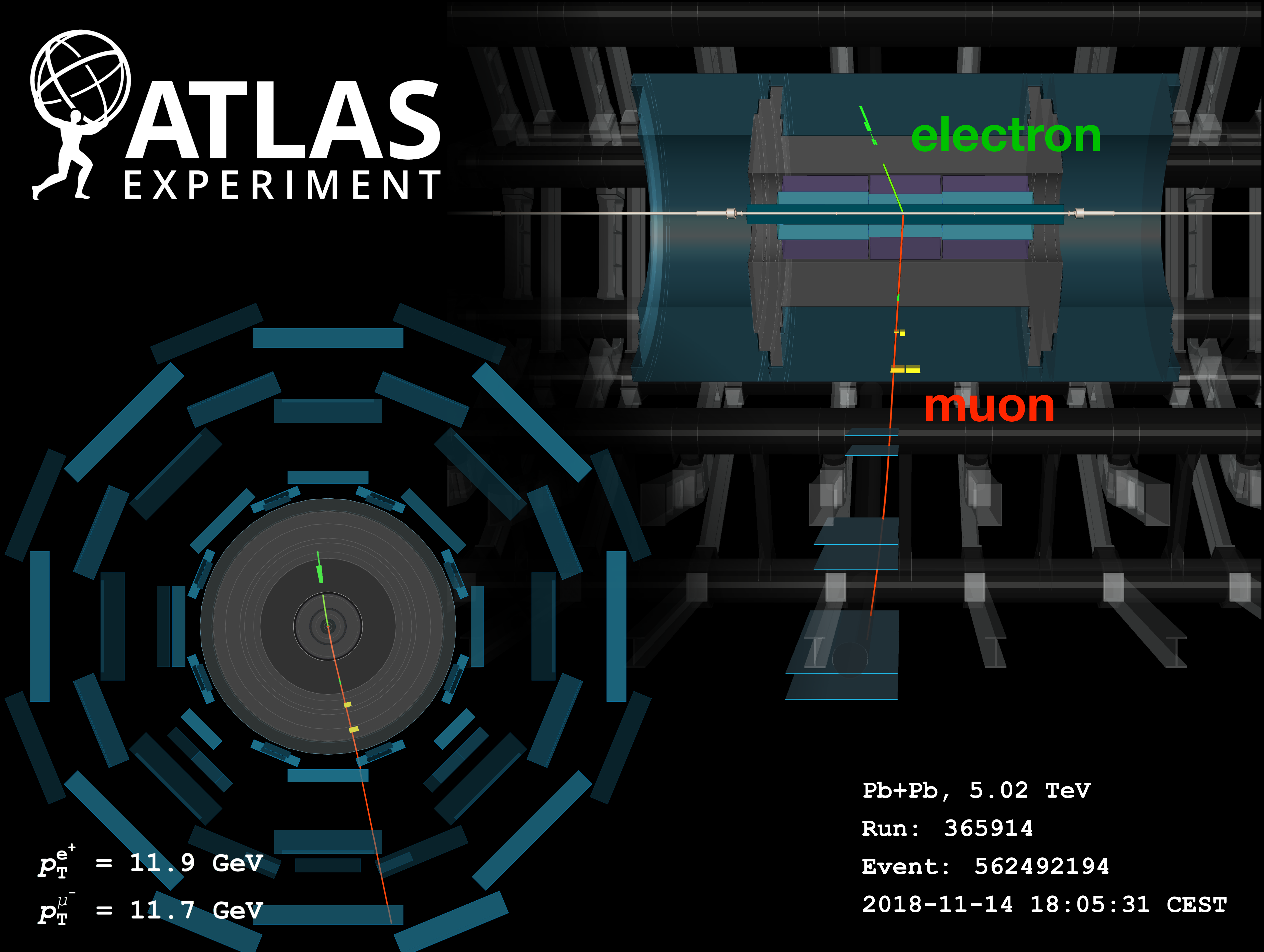


Cross section
sensitive to **g-2**

Z⁴ ~ 10^5 (Z_{Pb}=82)
enhancement

PbPb $\tau\tau$ candidate

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

Ultra-peripheral PbPb collisions

Super clean with ~ 0 pile-up

Low trigger thresholds → Trigger on soft taus!

→ Quantify potential using MC

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

Tau decays

1 prong

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

+ neutral π’s

Leptonic

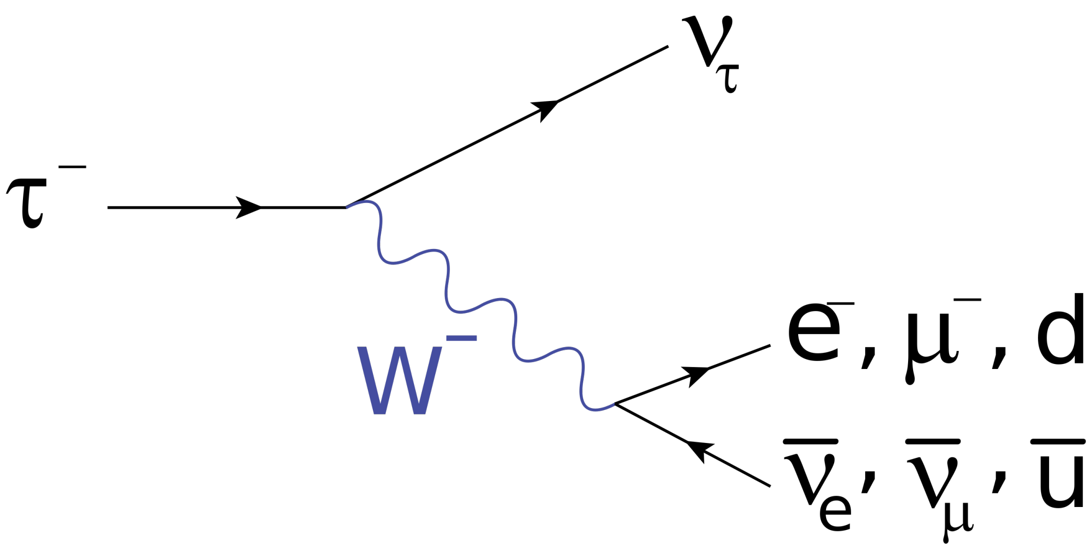
$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$

3 prong

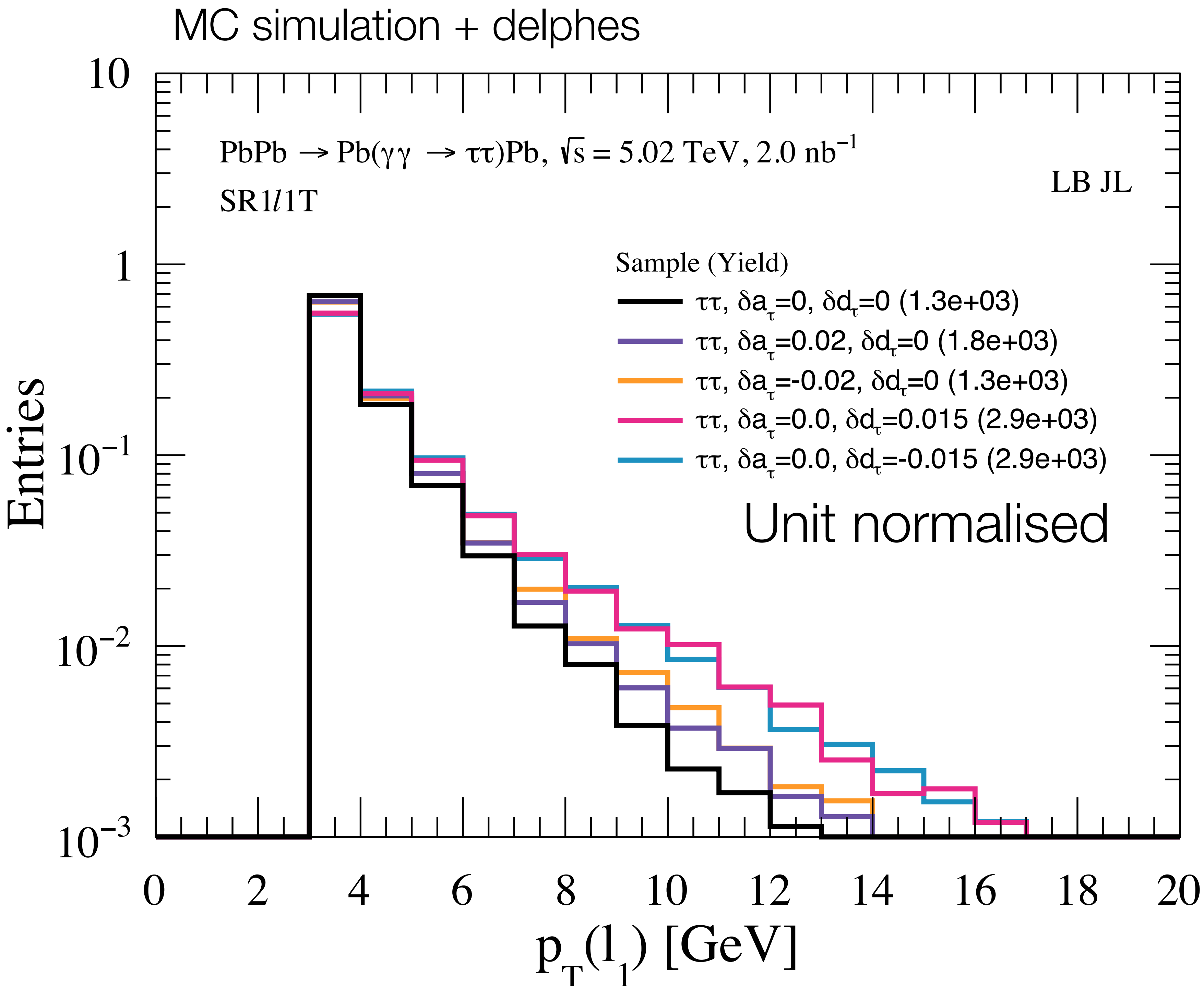
$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

+ neutral π’s

Tau is only lepton that can decay into hadrons



Setting constraints



Lepton ID

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

→ Suppress hadronic backgrounds

Signal regions

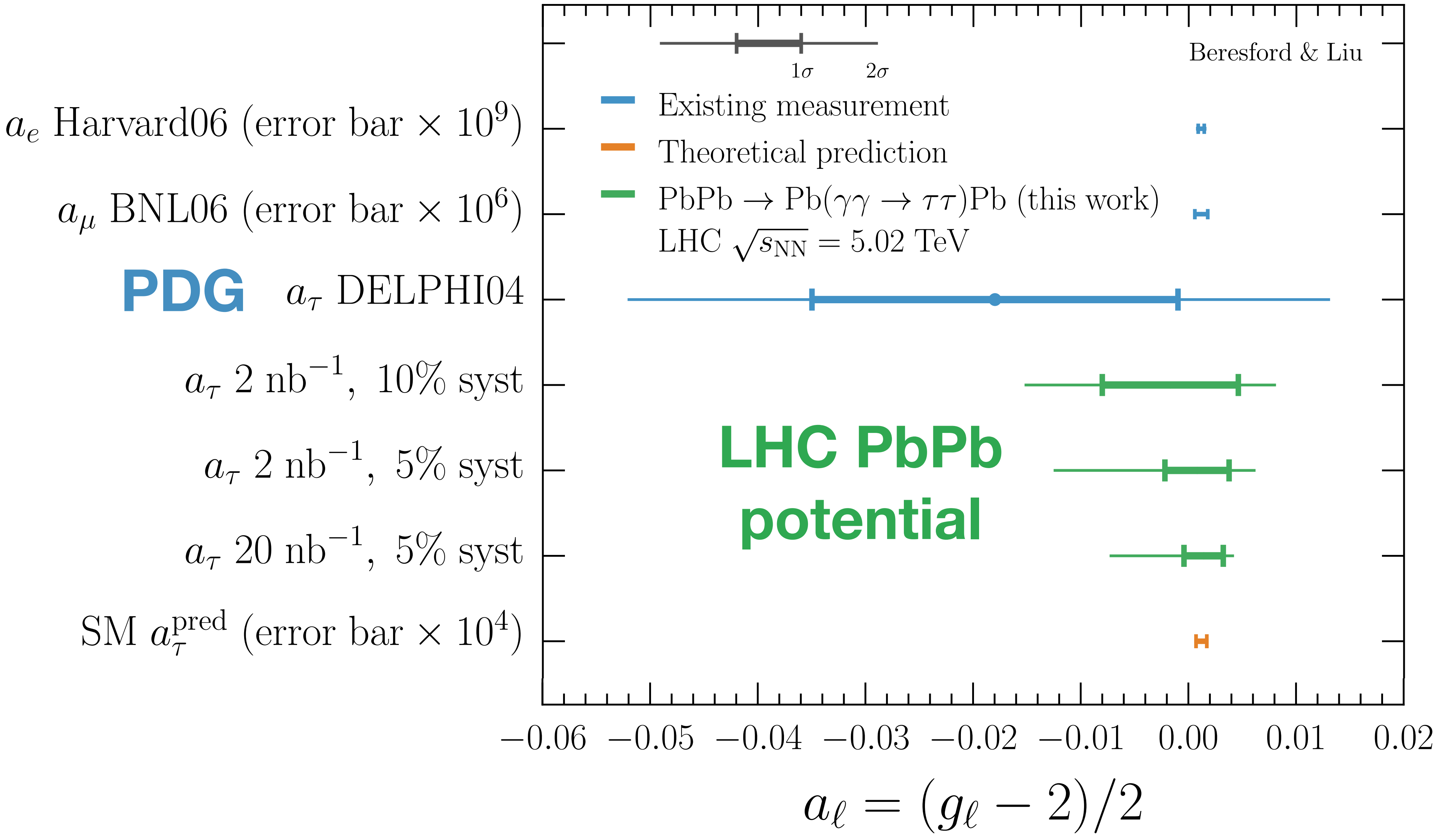
1ℓ + 1 track

1ℓ + 2/3 track

Modifying moments alters **shape** of lepton p_T

Promising prospects

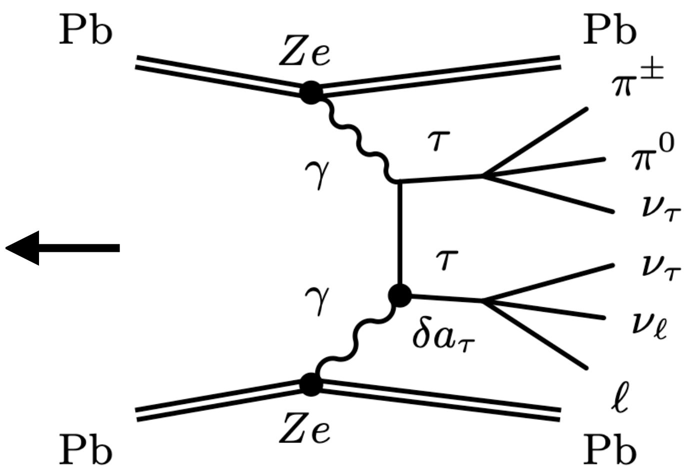
Beresford, Liu PRD (2020)



PDG

LHC PbPb potential

Prospects for PbPb

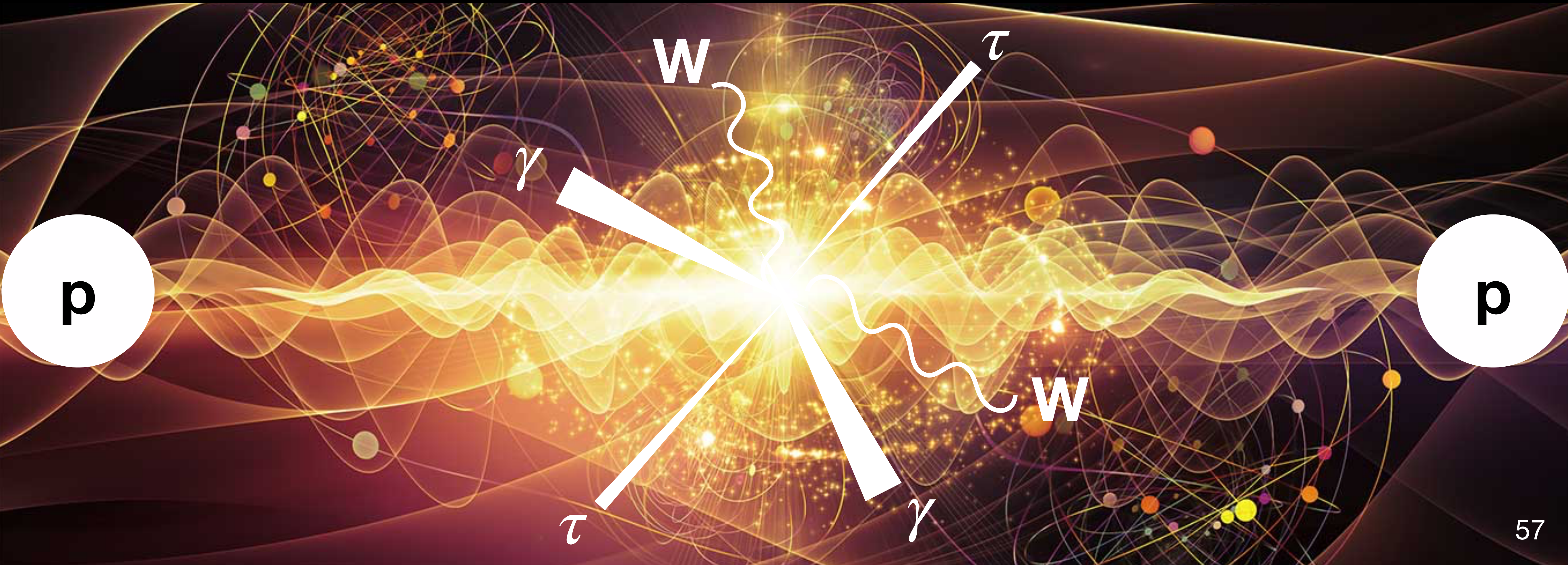


Surpass PDG value … or discover tension!

The future is bright

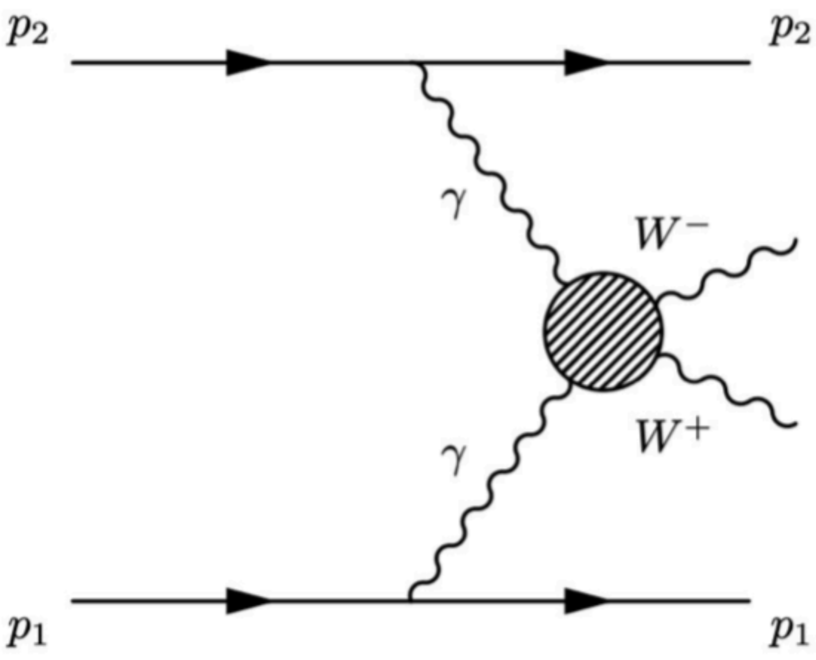
Rich LHC photon collision program

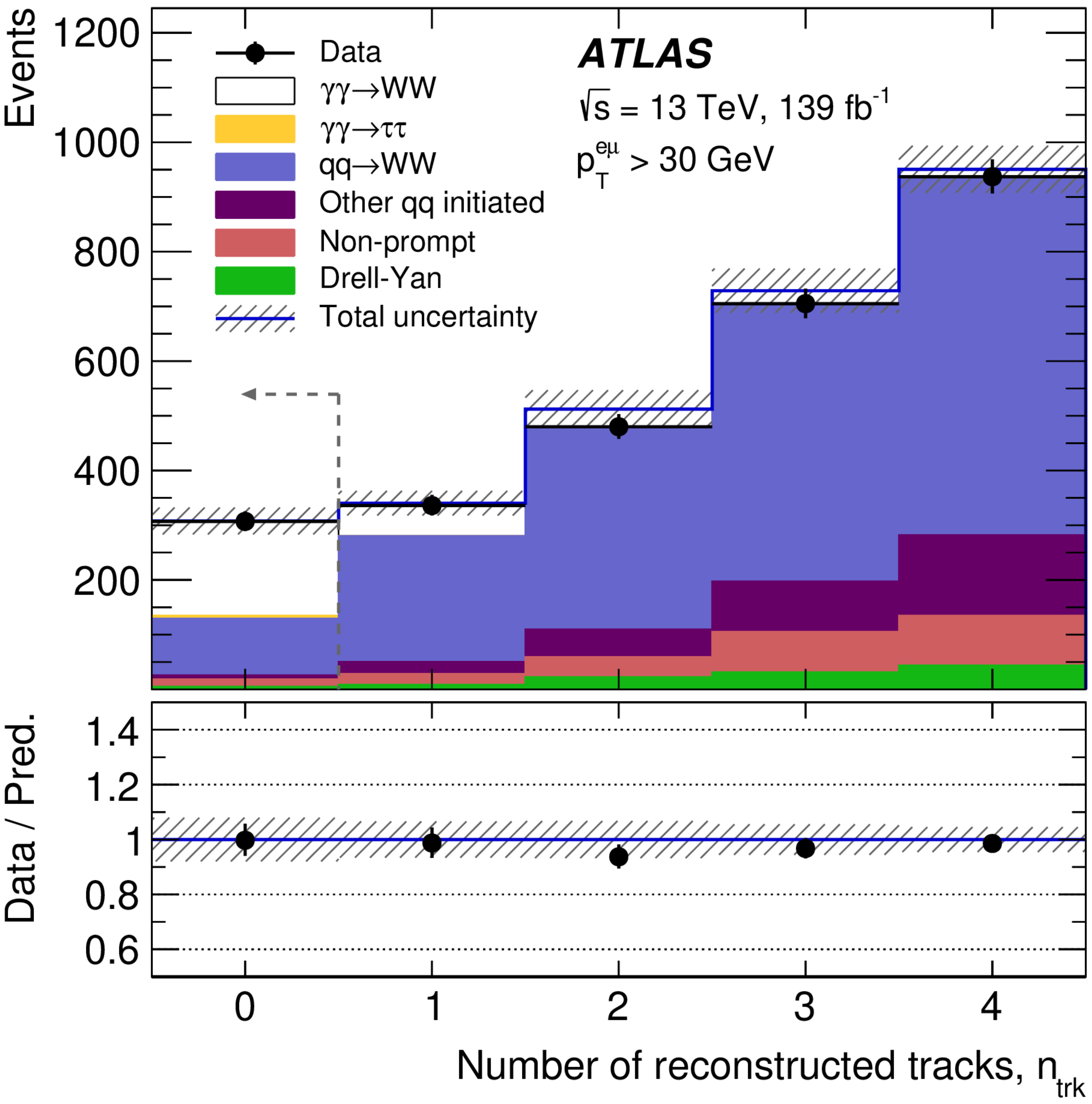
Only the beginning …



Backup

ATLAS tracking

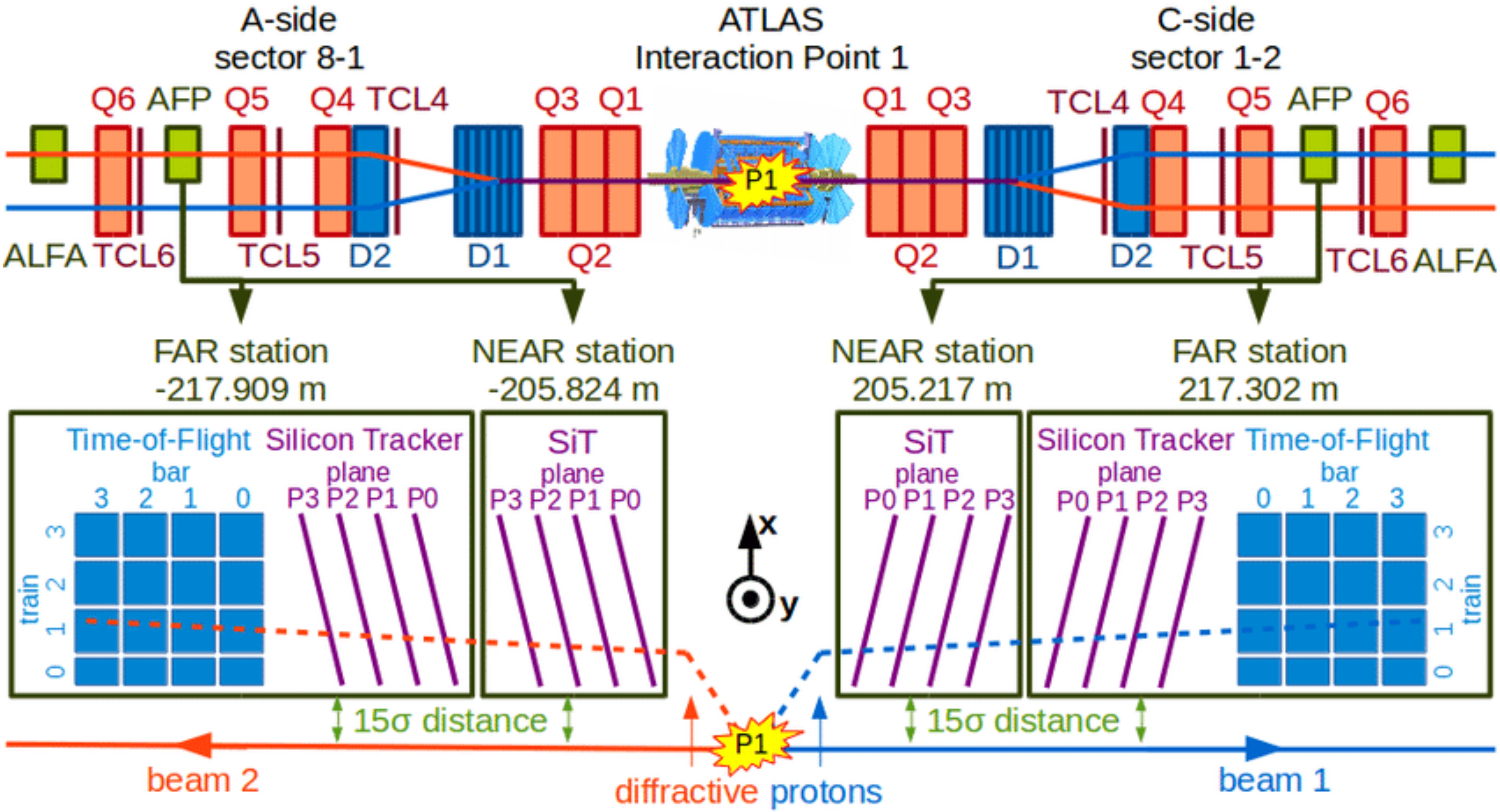




Key discriminant:

No additional tracks near $e\mu$ vertex

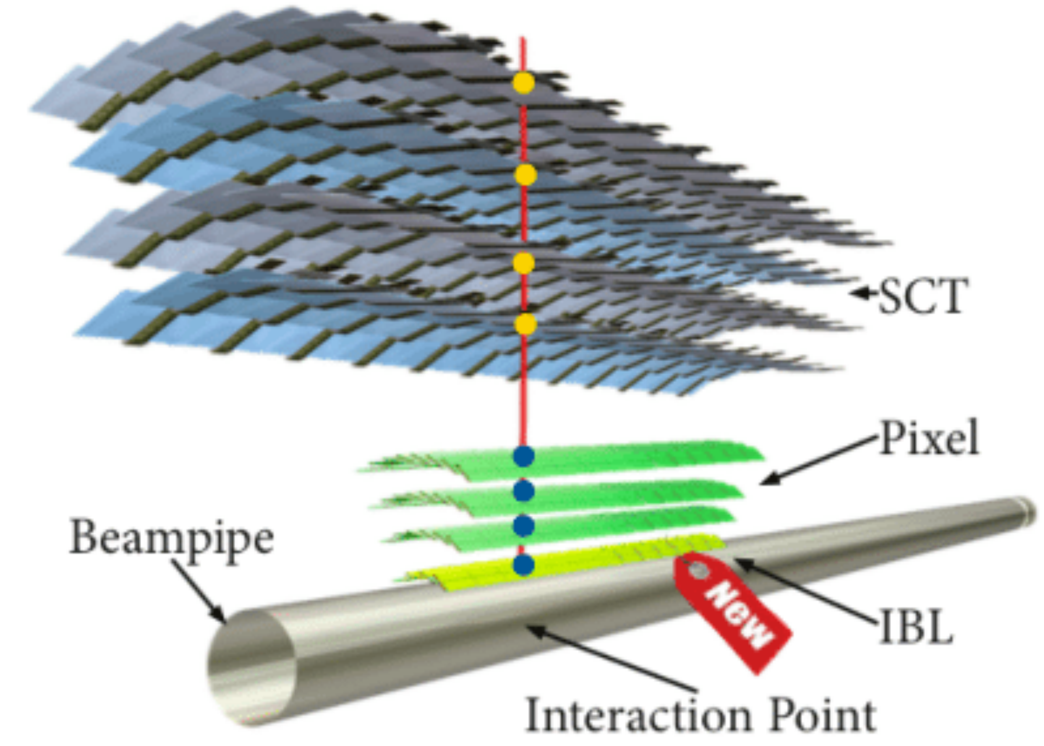
ATLAS Forward Detectors

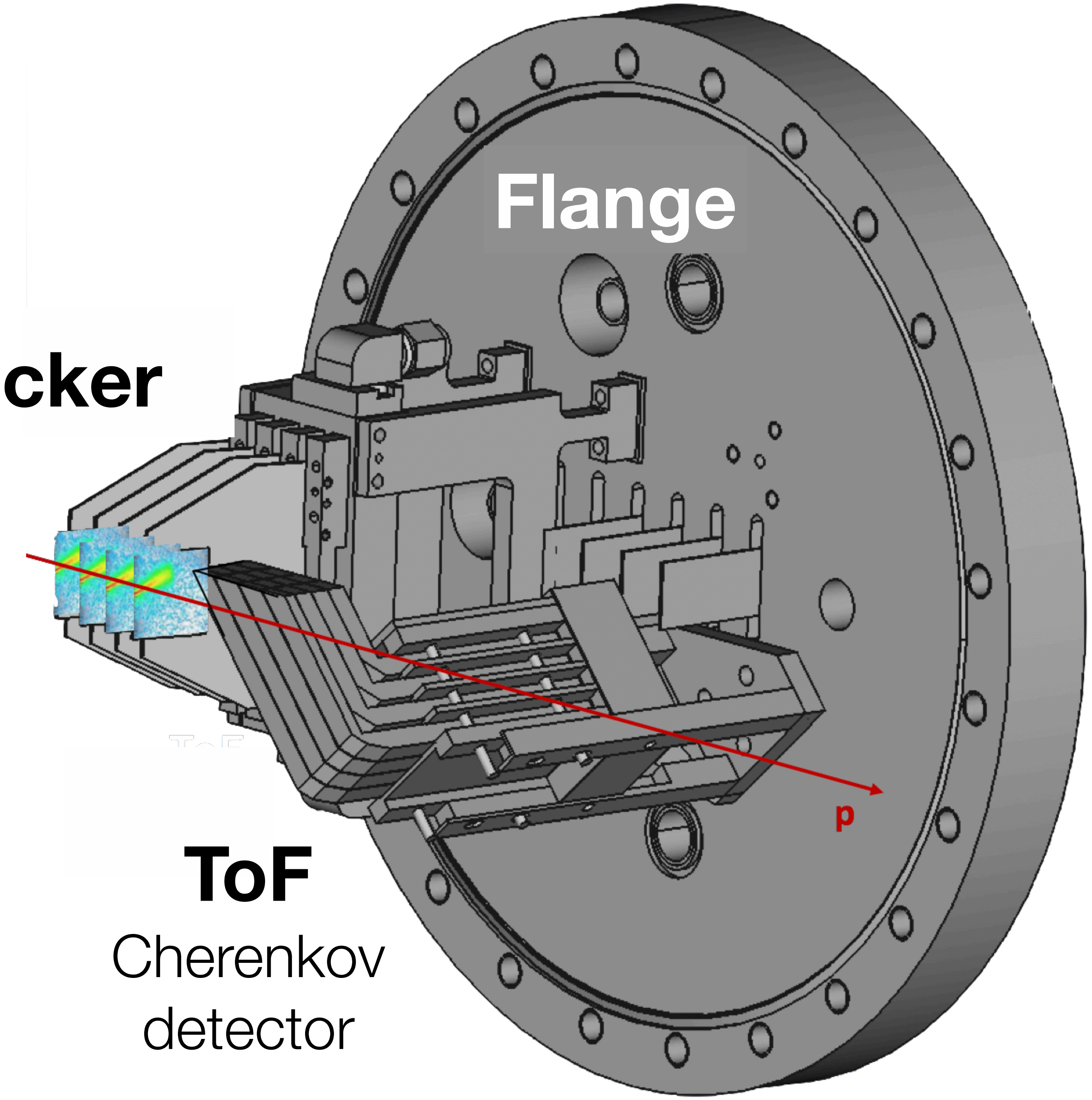


ATLAS Forward Proton (AFP)

Silicon Tracker

- Within ~2 mm of beam
- ‘slim-edge’ ~100 μm





Tracker

ToF
Cherenkov
detector

→ Use 3D silicon pixels a la the ATLAS insertable B-layer (IBL)

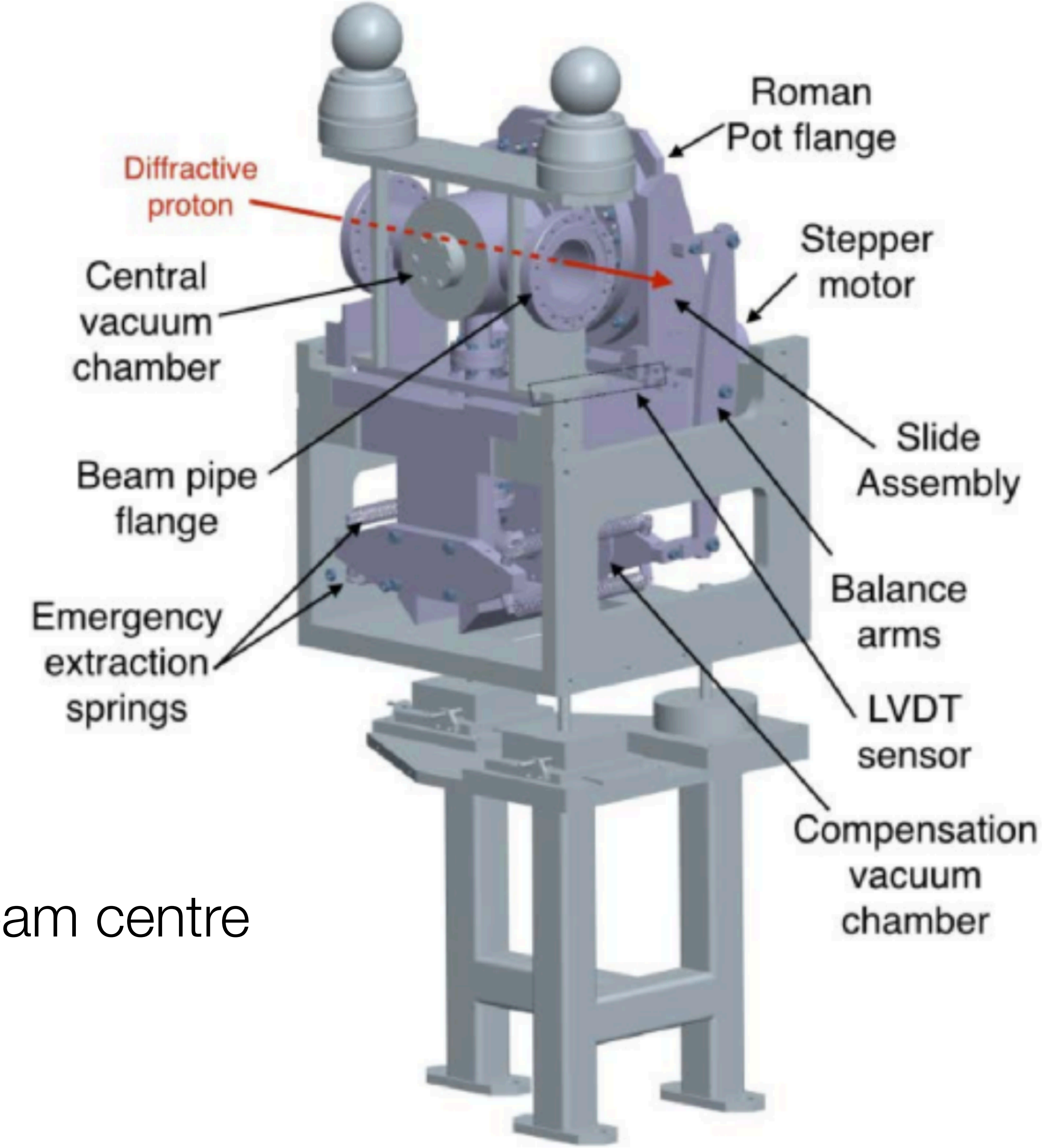
Roman pot

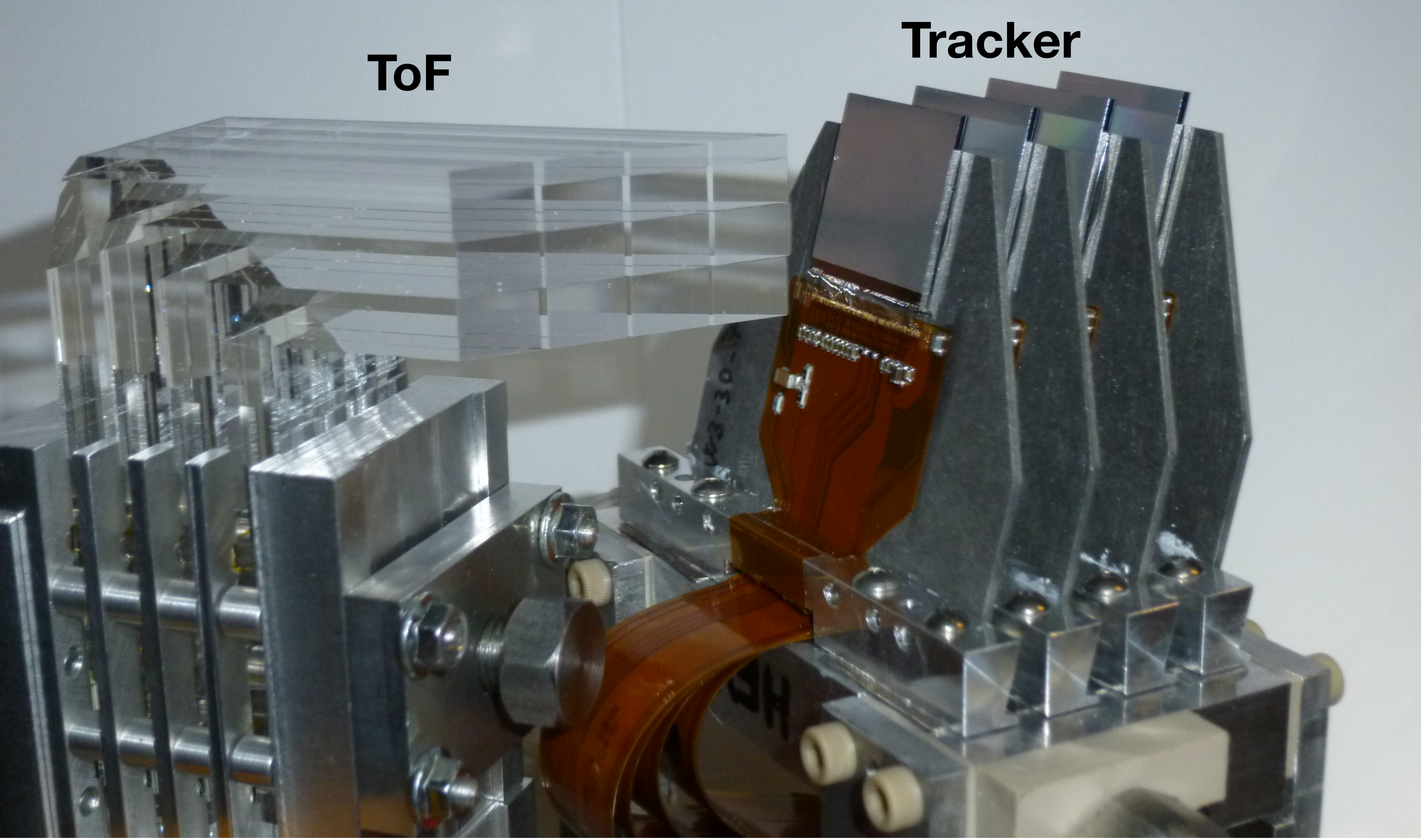
Beam size & position depends on LHC settings

Moveable detectors

Unstable beams:
Detectors ‘in garage’
40 mm away

Stable beams:
Detectors ~2 mm from beam centre

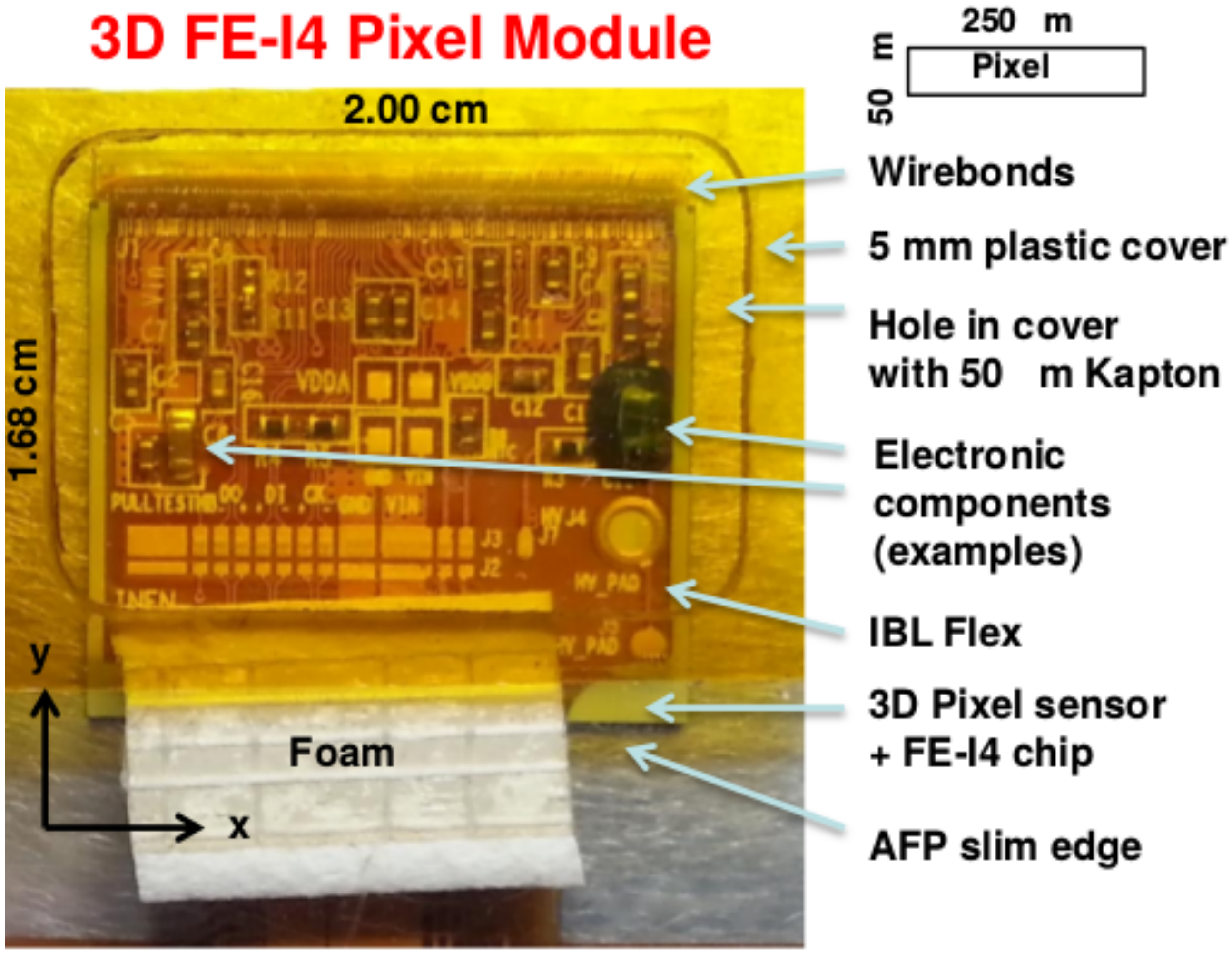




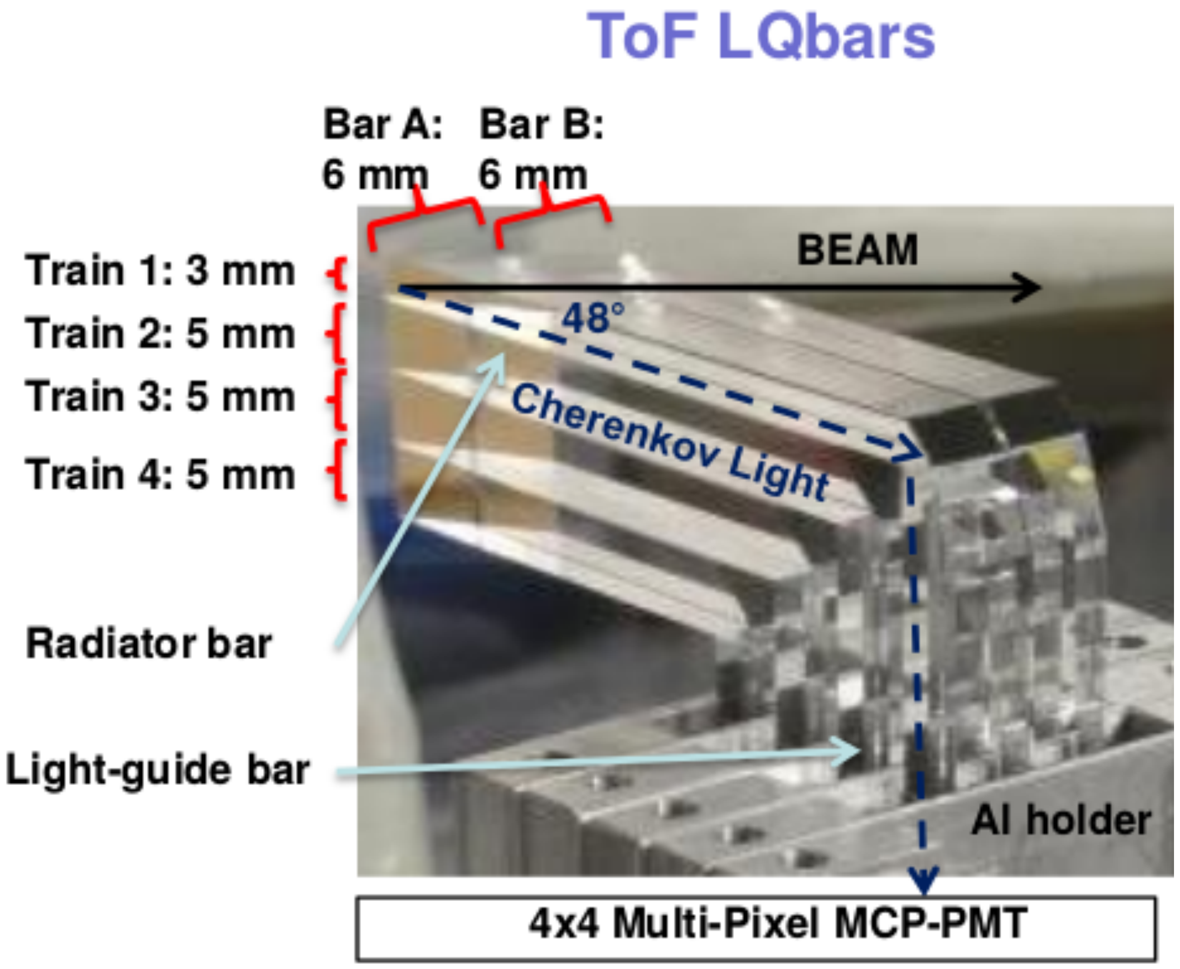
Cherenkov detector
L-shaped quartz bars
Microchannel Plate PMT
$\sim$ 30 ps timing resolution

Each plane = 336×80 pixels
Pixel size of 50×250 μm^2
Thickness of 230 μm
Active area 1.68 x 2 cm^2

AFP detectors



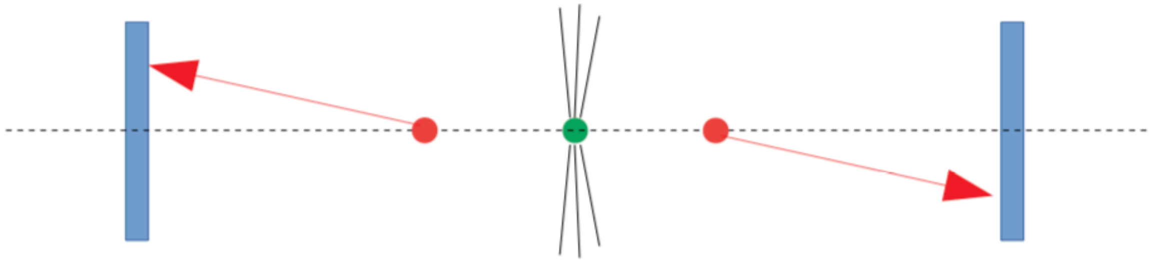
3D FE-I4 Pixel Module



ToF LQbars

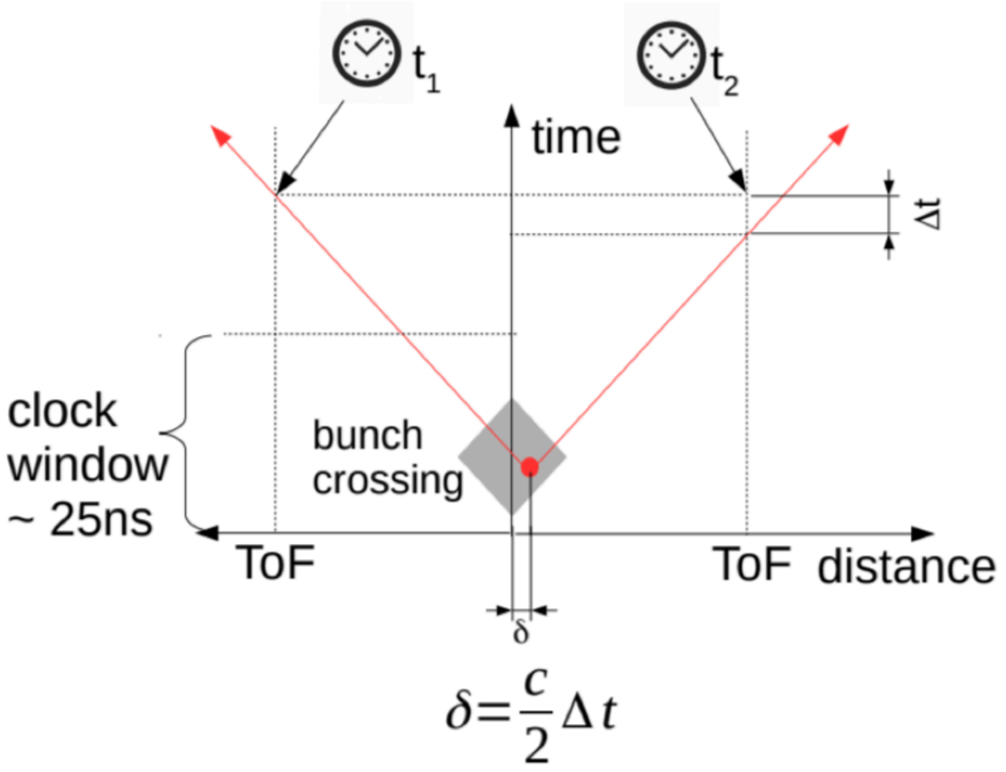
Time-of-Flight method

Diffractive interactions from pile-up can mimic the signal in AFP.



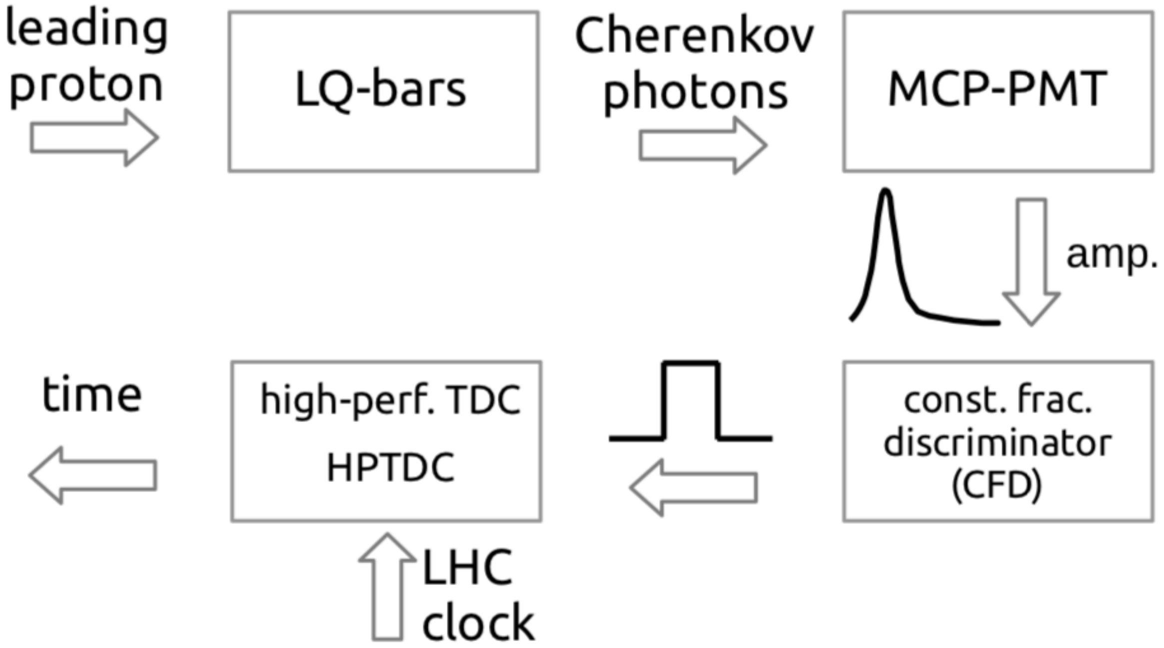
Comparison of arrival times on both sides provides z-position of the pp → pXp interaction.

The two outermost AFP stations are equipped with Cherenkov **T**ime-**o**f-**F**light (ToF) detectors



Karel Černý, AFP/ToF performance, ICHEP 2020

Time-of-Flight detectors



leading proton

LQ-bars

Cherenkov photons

MCP-PMT

amp.

const. frac. discriminator (CFD)

high-perf. TDC

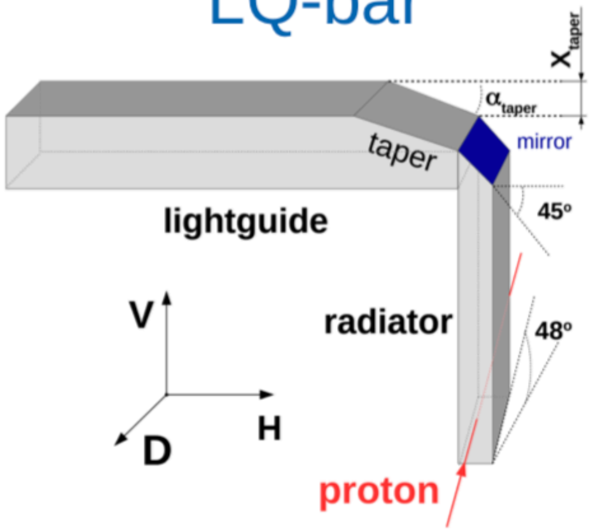
HPTDC

LHC clock

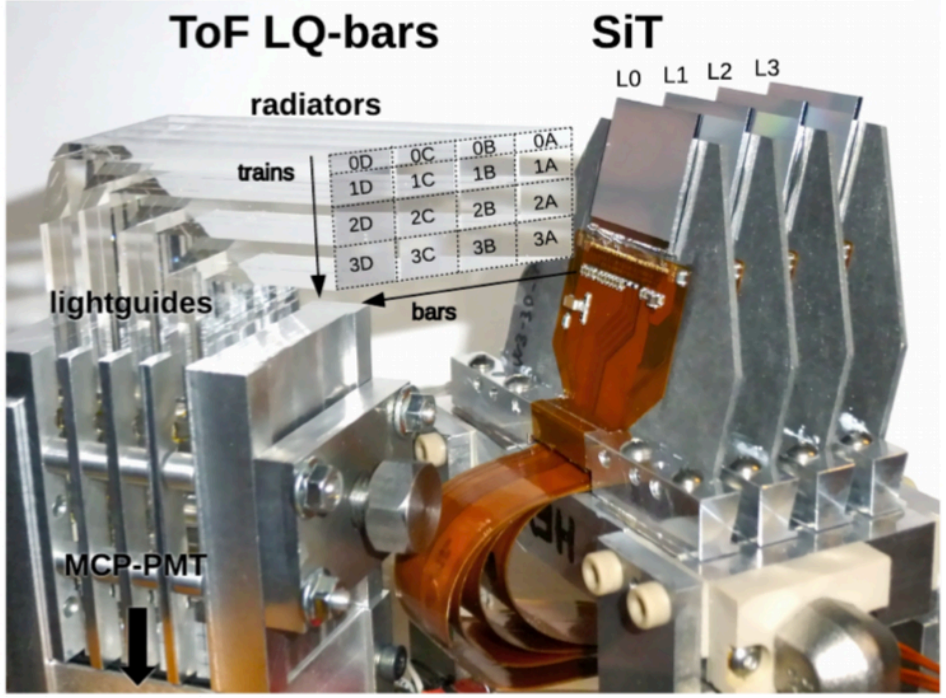
time

Function of the detectors is based on collection of Cherenkov photons in L-shaped Quartz bars (LQ-bars).

LQ-bar

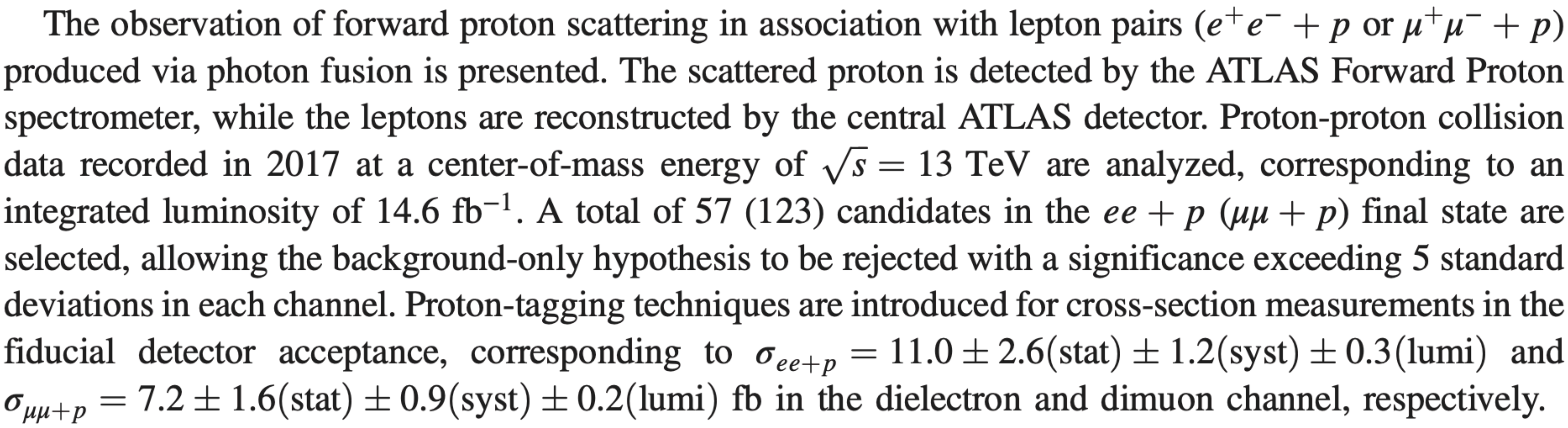


Stacked in a 4x4 (train x channel) matrix mounted to a multi-anode microchannel-plate photomultiplier (MCP-PMT).

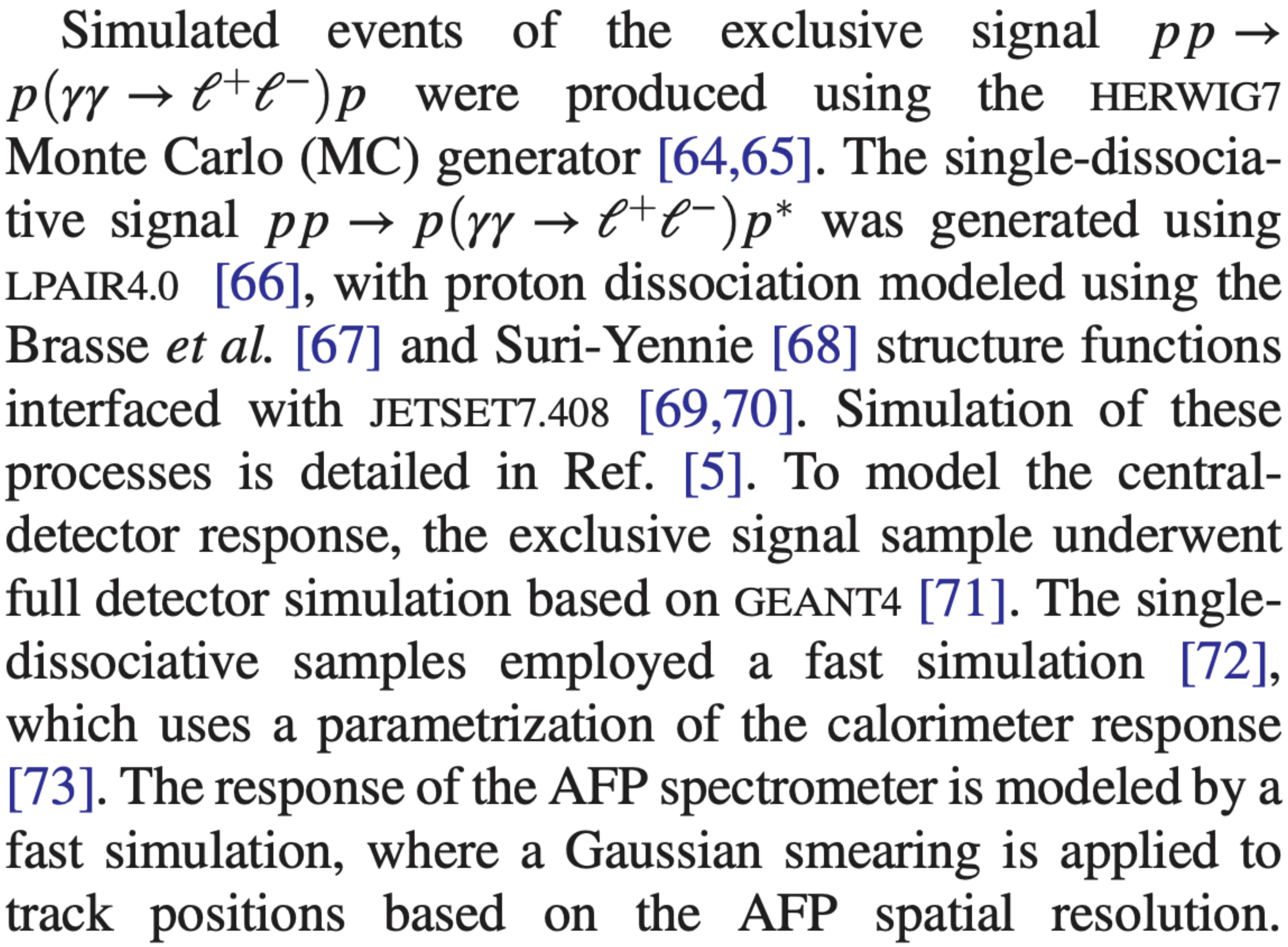


Karel Černý, AFP/ToF performance, ICHEP 2020

AFP di-lepton

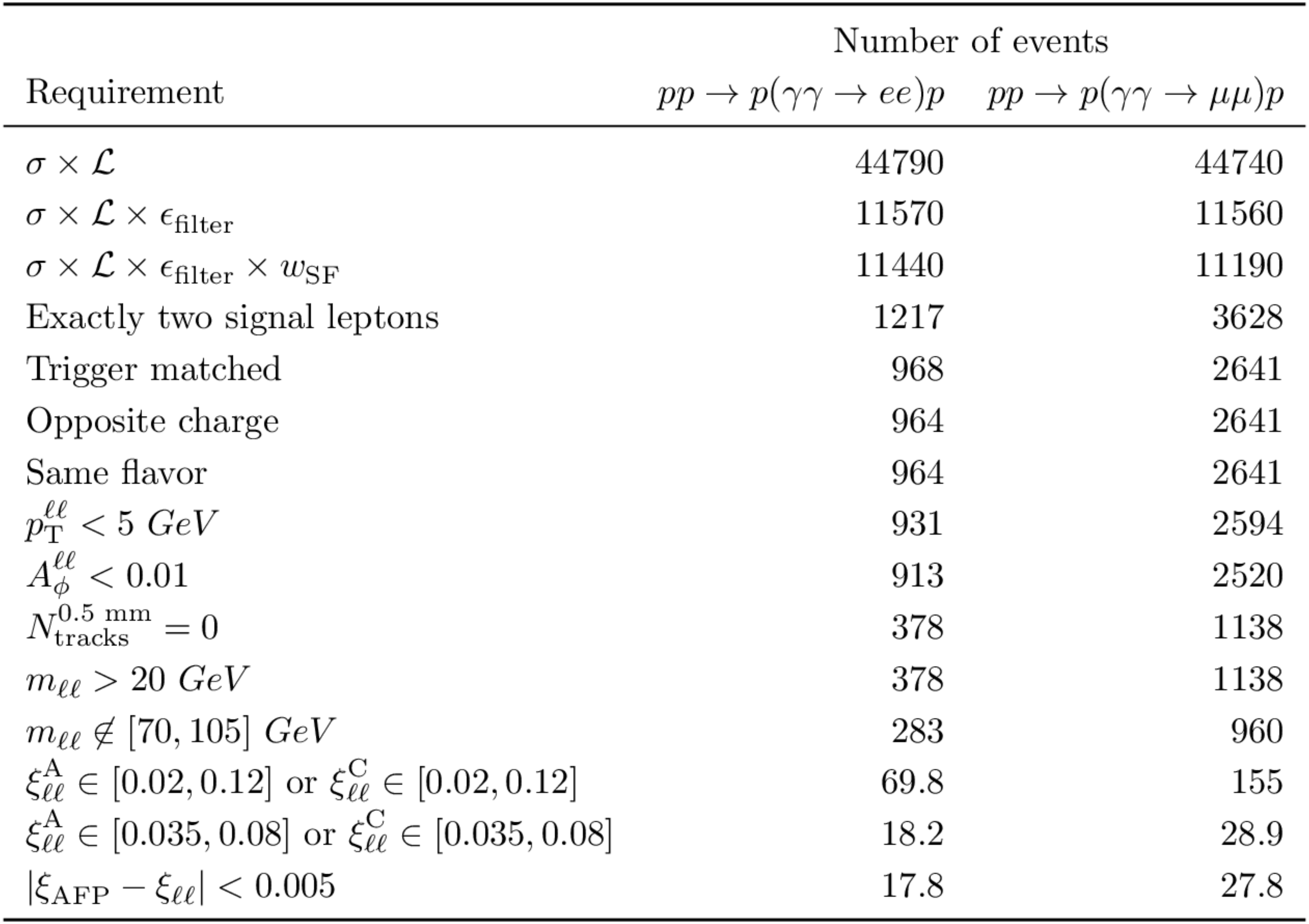


The observation of forward proton scattering in association with lepton pairs ($e^+e^- + p$ or $\mu^+\mu^- + p$) produced via photon fusion is presented. The scattered proton is detected by the ATLAS Forward Proton spectrometer, while the leptons are reconstructed by the central ATLAS detector. Proton-proton collision data recorded in 2017 at a center-of-mass energy of $\sqrt{s} = 13$ TeV are analyzed, corresponding to an integrated luminosity of 14.6 fb^{-1}. A total of 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state are selected, allowing the background-only hypothesis to be rejected with a significance exceeding 5 standard deviations in each channel. Proton-tagging techniques are introduced for cross-section measurements in the fiducial detector acceptance, corresponding to $\sigma_{ee+p} = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi})$ and $\sigma_{\mu\mu+p} = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi})$ fb in the dielectron and dimuon channel, respectively.



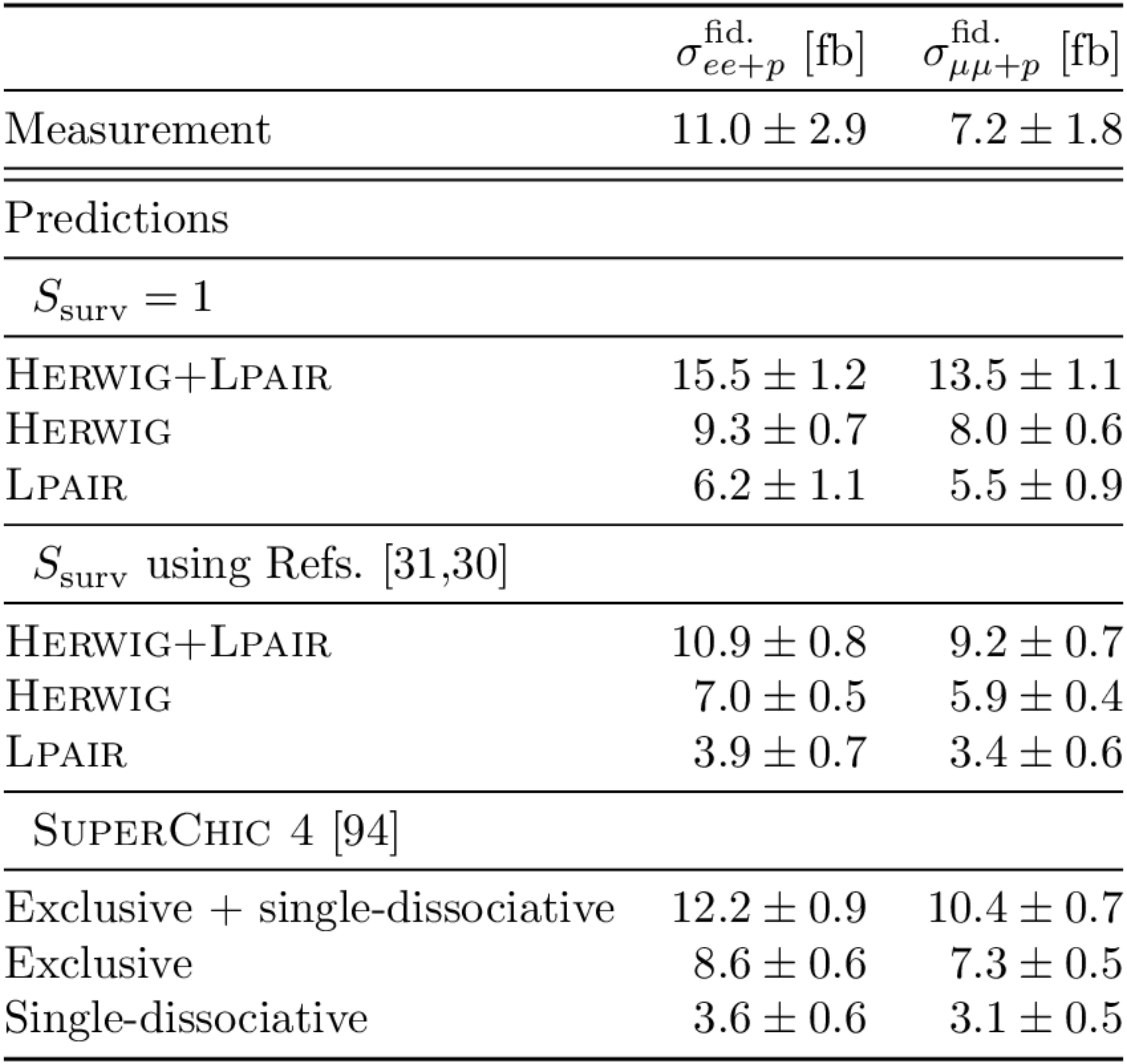
Simulated events of the exclusive signal $pp \to p(\gamma\gamma \to \ell^+\ell^-)p$ were produced using the HERWIG7 Monte Carlo (MC) generator [64,65]. The single-dissociative signal $pp \to p(\gamma\gamma \to \ell^+\ell^-)p^*$ was generated using LPAIR4.0 [66], with proton dissociation modeled using the Brasse *et al.* [67] and Suri-Yennie [68] structure functions interfaced with JETSET7.408 [69,70]. Simulation of these processes is detailed in Ref. [5]. To model the central-detector response, the exclusive signal sample underwent full detector simulation based on GEANT4 [71]. The single-dissociative samples employed a fast simulation [72], which uses a parametrization of the calorimeter response [73]. The response of the AFP spectrometer is modeled by a fast simulation, where a Gaussian smearing is applied to track positions based on the AFP spatial resolution.

AFP di-lepton



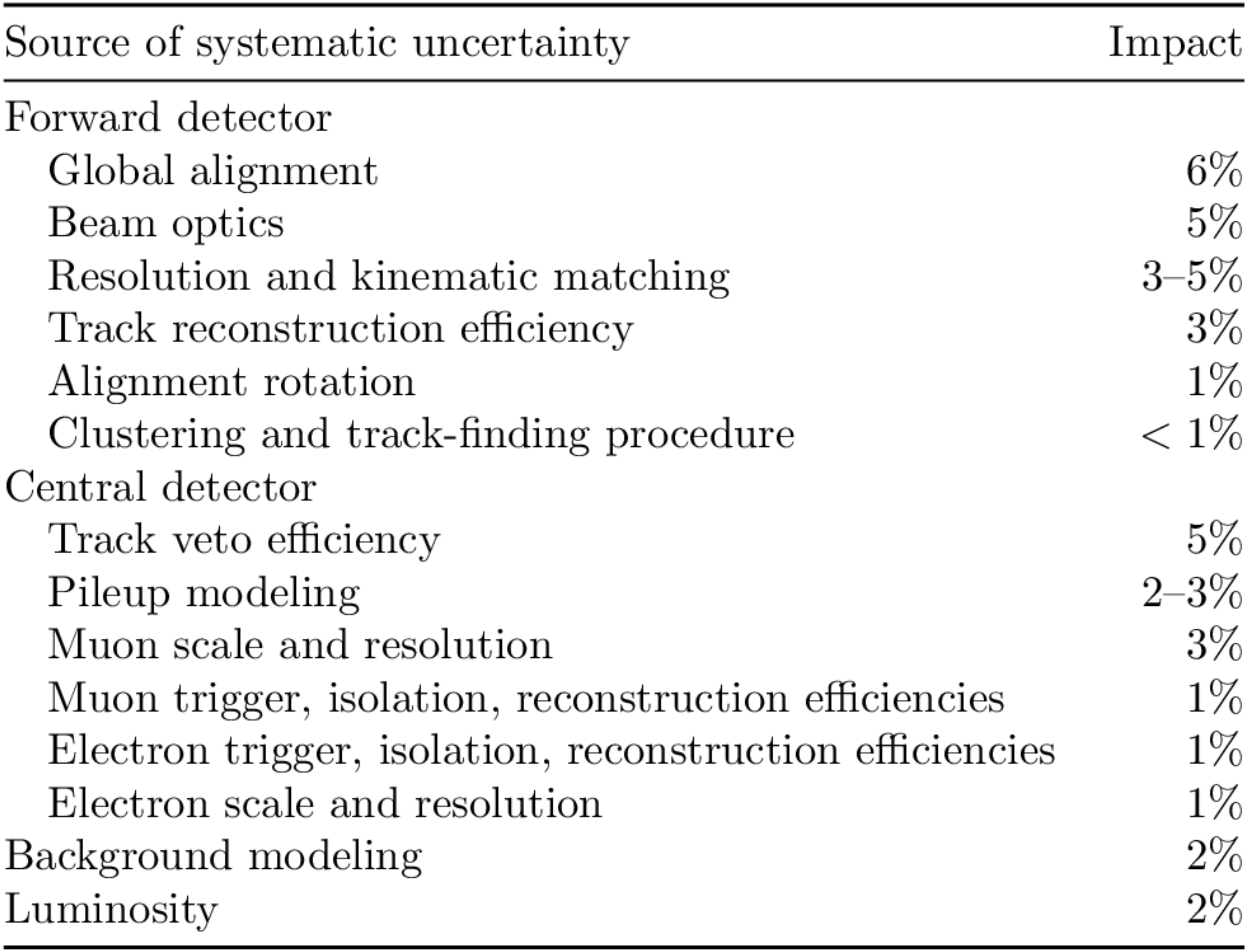
	Number of events	
Requirement	$pp \to p(\gamma\gamma \to ee)p$	$pp \to p(\gamma\gamma \to \mu\mu)p$
$\sigma \times \mathcal{L}$	44790	44740
$\sigma \times \mathcal{L} \times \epsilon_{\mathrm{filter}}$	11570	11560
$\sigma \times \mathcal{L} \times \epsilon_{\mathrm{filter}} \times w_{\mathrm{SF}}$	11440	11190
Exactly two signal leptons	1217	3628
Trigger matched	968	2641
Opposite charge	964	2641
Same flavor	964	2641
$p_{\mathrm{T}}^{\ell\ell} < 5\ GeV$	931	2594
$A_{\phi}^{\ell\ell} < 0.01$	913	2520
$N_{\mathrm{tracks}}^{0.5\ \mathrm{mm}} = 0$	378	1138
$m_{\ell\ell} > 20\ GeV$	378	1138
$m_{\ell\ell} \notin [70, 105]\ GeV$	283	960
$\xi_{\ell\ell}^{\mathrm{A}} \in [0.02, 0.12]$ or $\xi_{\ell\ell}^{\mathrm{C}} \in [0.02, 0.12]$	69.8	155
$\xi_{\ell\ell}^{\mathrm{A}} \in [0.035, 0.08]$ or $\xi_{\ell\ell}^{\mathrm{C}} \in [0.035, 0.08]$	18.2	28.9
$\lvert\xi_{\mathrm{AFP}} - \xi_{\ell\ell}\rvert < 0.005$	17.8	27.8

AFP di-lepton



	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
Herwig+Lpair	15.5 ± 1.2	13.5 ± 1.1
Herwig	9.3 ± 0.7	8.0 ± 0.6
Lpair	6.2 ± 1.1	5.5 ± 0.9
S_{surv} using Refs. [31,30]		
Herwig+Lpair	10.9 ± 0.8	9.2 ± 0.7
Herwig	7.0 ± 0.5	5.9 ± 0.4
Lpair	3.9 ± 0.7	3.4 ± 0.6
SuperChic 4 [94]		
Exclusive + single-dissociative	12.2 ± 0.9	10.4 ± 0.7
Exclusive	8.6 ± 0.6	7.3 ± 0.5
Single-dissociative	3.6 ± 0.6	3.1 ± 0.5

AFP di-lepton

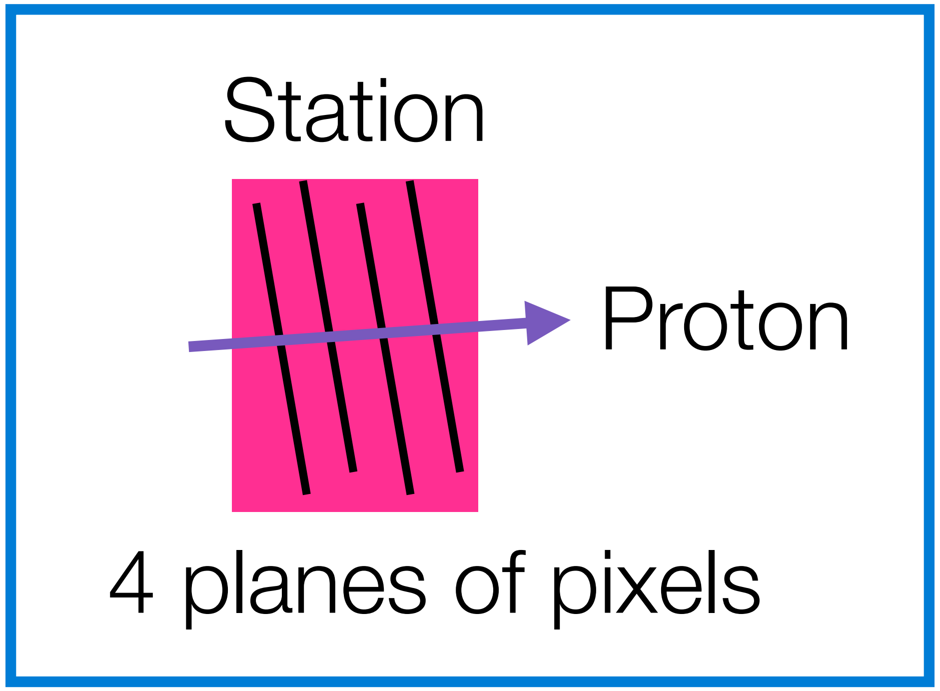


Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	$< 1\%$
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon scale and resolution	3%
Muon trigger, isolation, reconstruction efficiencies	1%
Electron trigger, isolation, reconstruction efficiencies	1%
Electron scale and resolution	1%
Background modeling	2%
Luminosity	2%

AFP Alignment

Inter-plane:

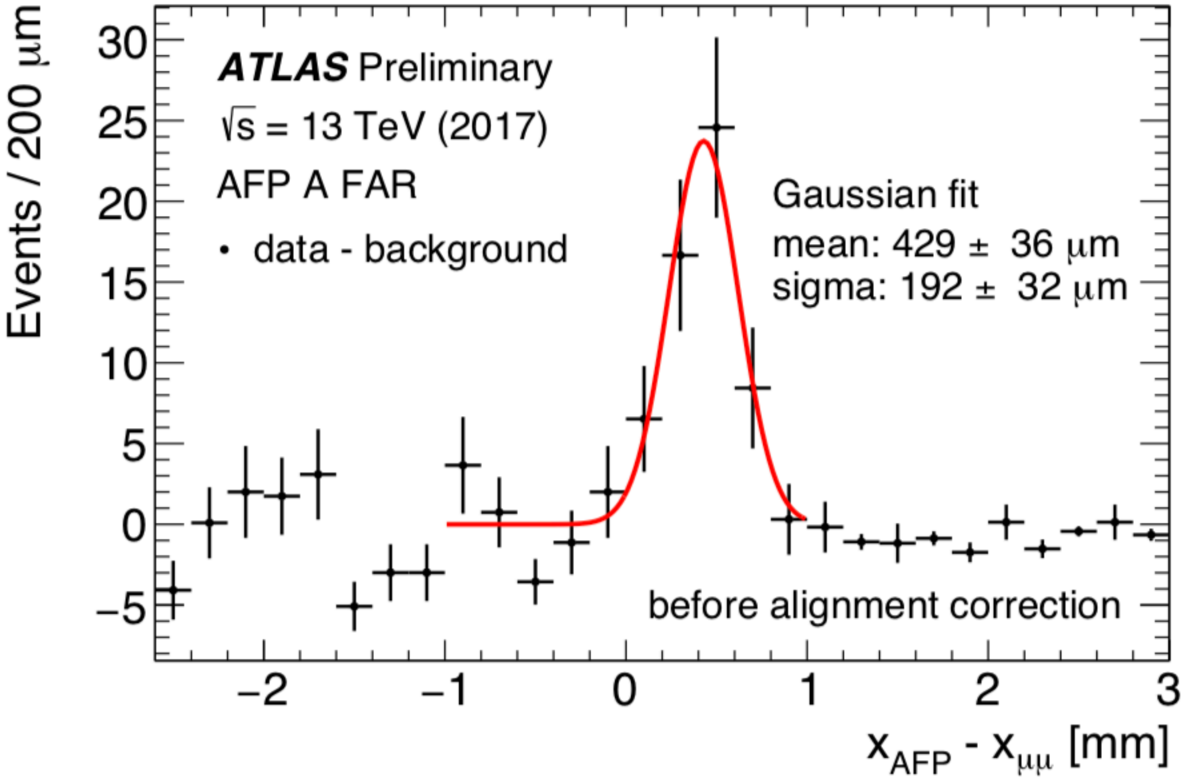
Use differences in track & hit positions to correct for mis-alignments



Global:

Measurements of tracker, beam & roman pot position used

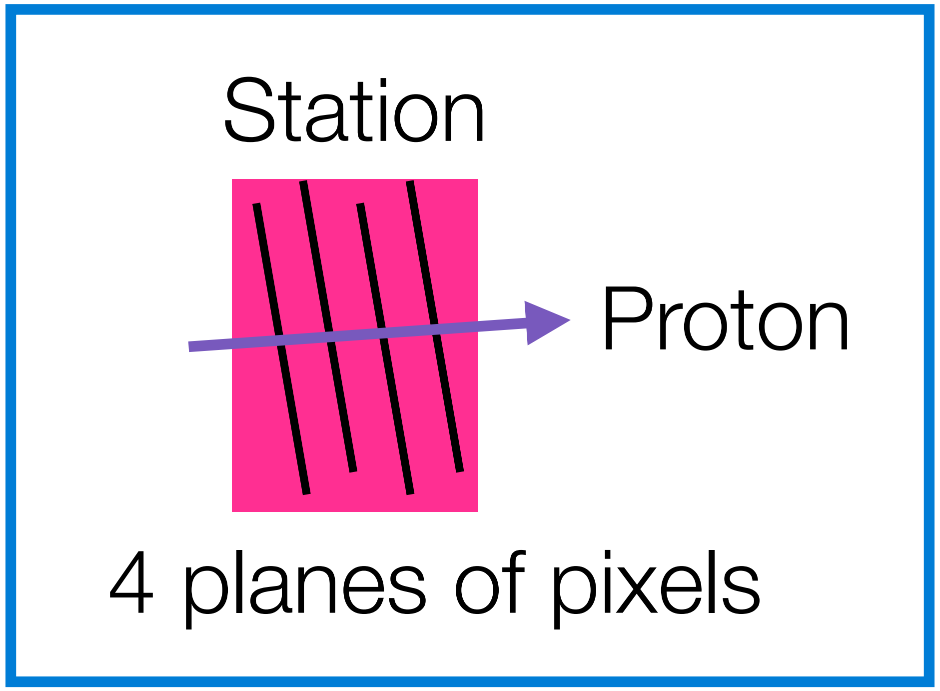
+ di-muon in situ correction →



AFP Alignment

Inter-plane:

Use differences in track & hit positions to correct for mis-alignments



Global:

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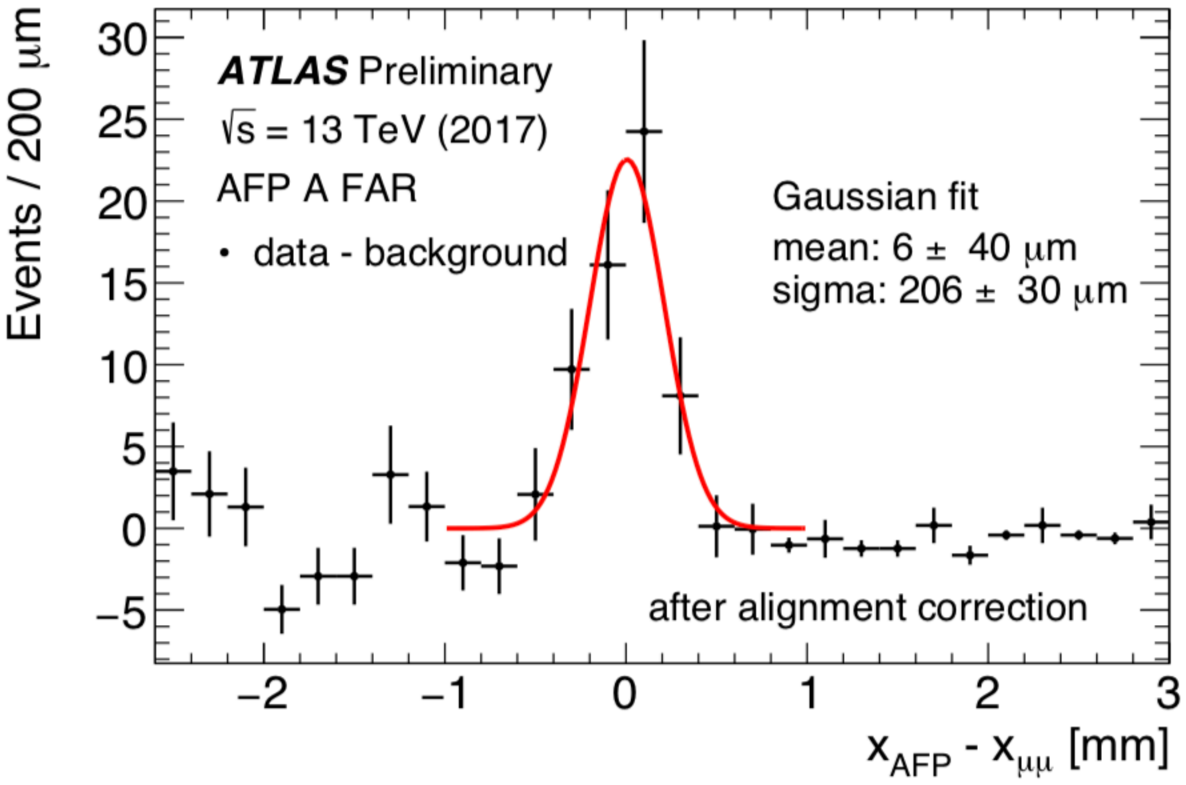
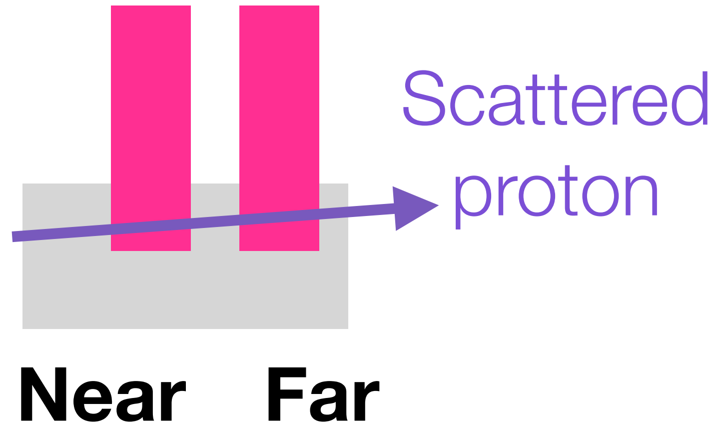


AFP Efficiency

Needed to correct for detector effects

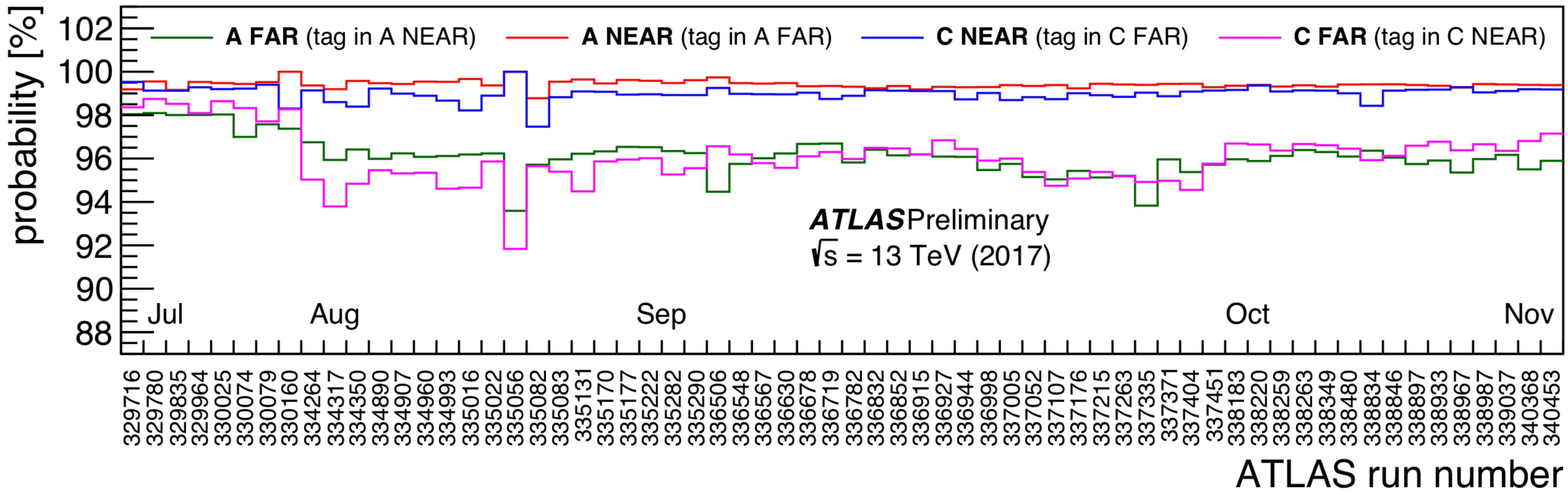
AFP side A



Station tag and probe:

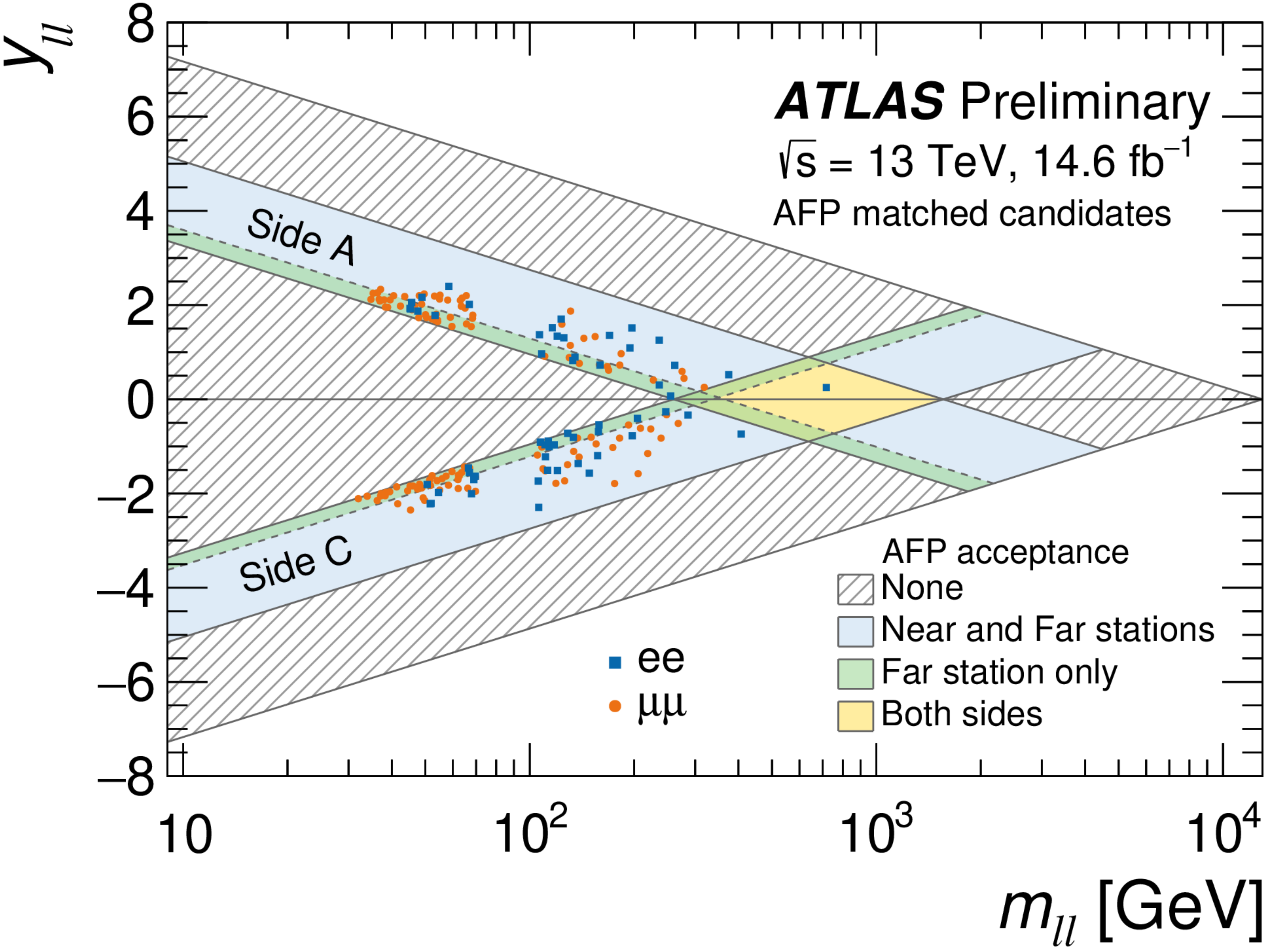
- ‘Tag’ track in near station (require exactly 1)
- Check if track in far (within $|x_{near}-x_{far}| < 2$ mm)

& vice versa



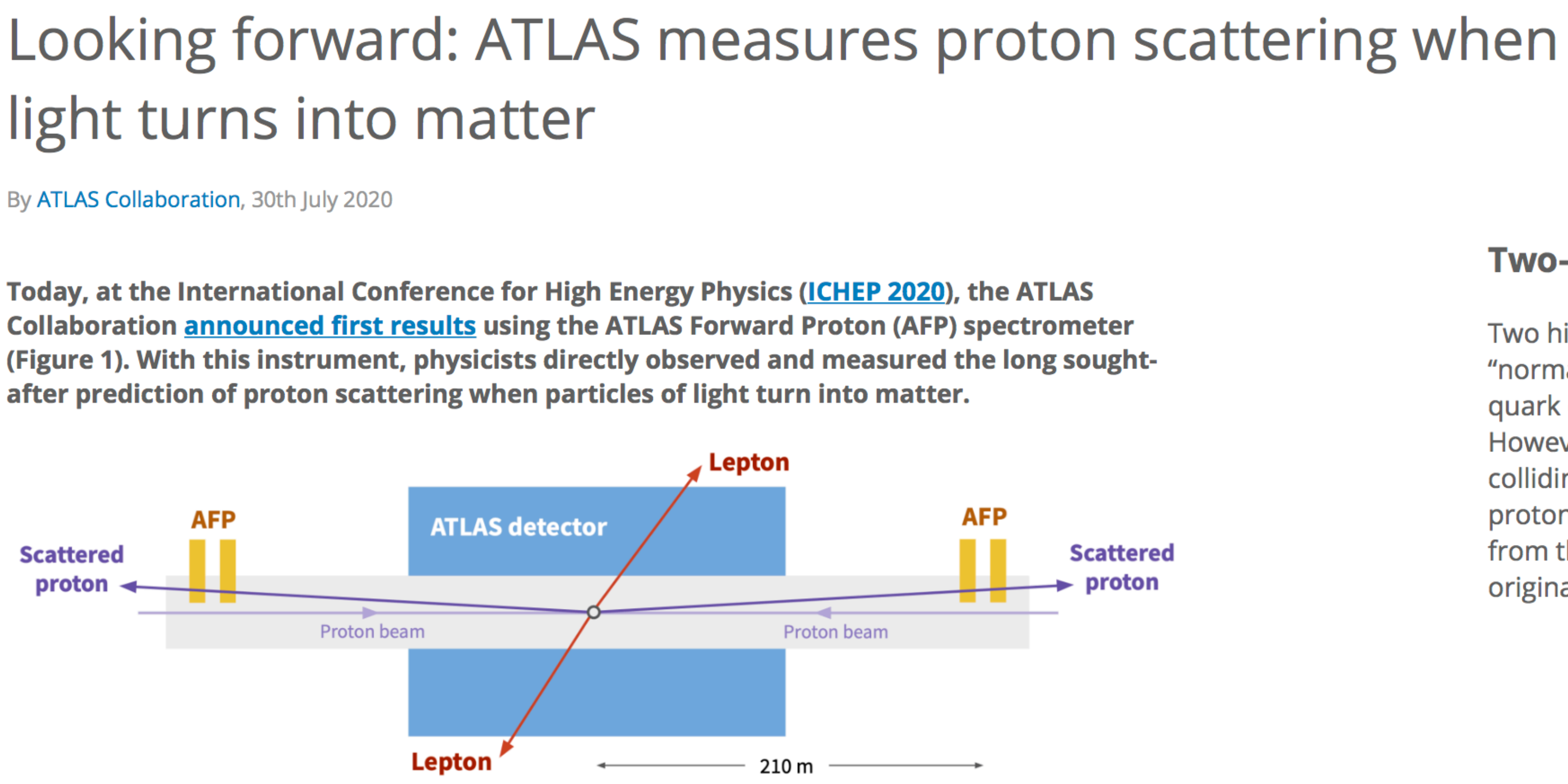
Lower efficiency in far station due to showers

Matched candidates



More?

[Physics briefing]

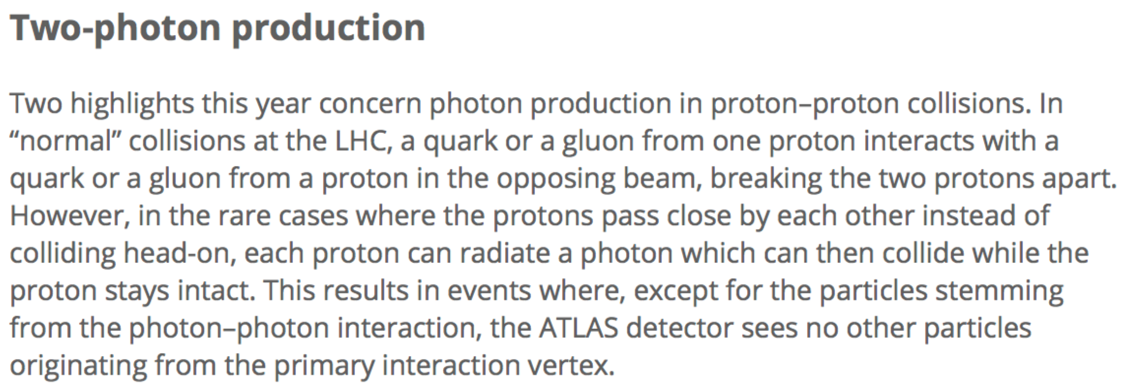


Looking forward: ATLAS measures proton scattering when light turns into matter

By ATLAS Collaboration, 30th July 2020

Today, at the International Conference for High Energy Physics (ICHEP 2020), the ATLAS Collaboration announced first results using the ATLAS Forward Proton (AFP) spectrometer (Figure 1). With this instrument, physicists directly observed and measured the long sought-after prediction of proton scattering when particles of light turn into matter.

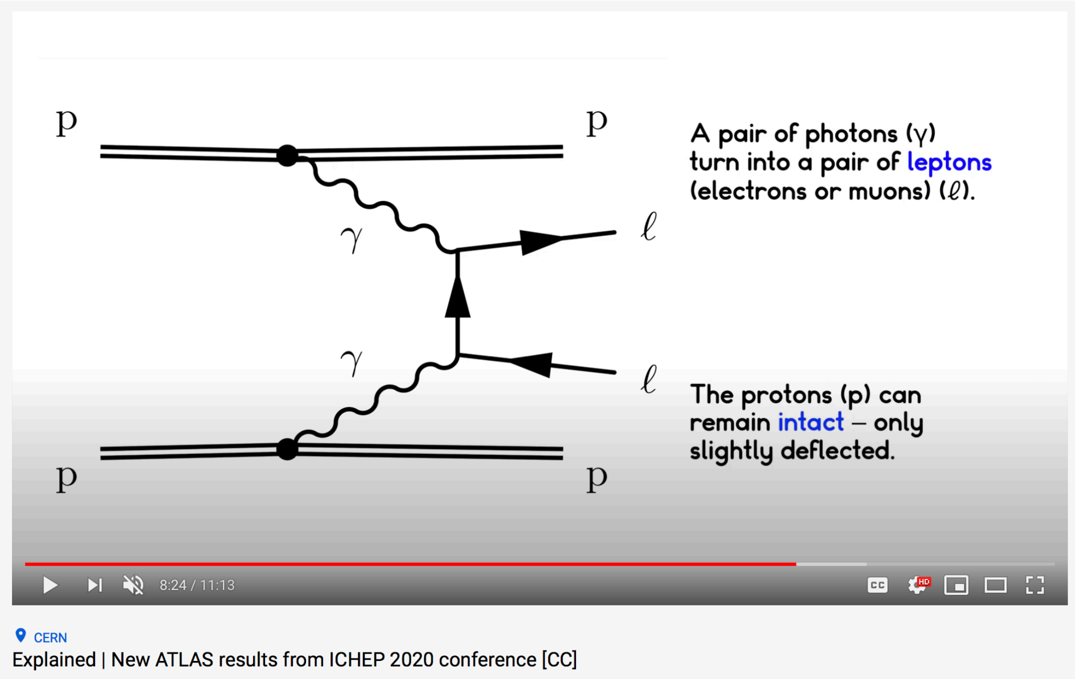
[ATLAS ICHEP highlights]



Two-photon production

Two highlights this year concern photon production in proton–proton collisions. In “normal” collisions at the LHC, a quark or a gluon from one proton interacts with a quark or a gluon from a proton in the opposing beam, breaking the two protons apart. However, in the rare cases where the protons pass close by each other instead of colliding head-on, each proton can radiate a photon which can then collide while the proton stays intact. This results in events where, except for the particles stemming from the photon–photon interaction, the ATLAS detector sees no other particles originating from the primary interaction vertex.

[ATLAS ICHEP highlights]



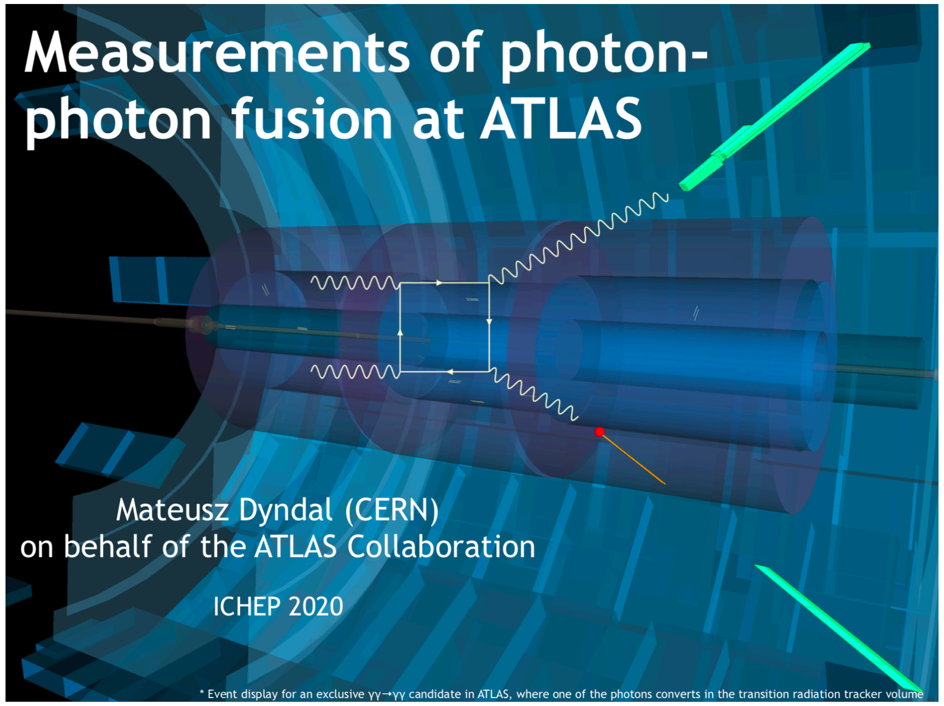
A pair of photons (γ) turn into a pair of leptons (electrons or muons) (ℓ).

The protons (p) can remain intact – only slightly deflected.

CERN

Explained | New ATLAS results from ICHEP 2020 conference [CC]

[ICHEP Talk] & [interview]



Measurements of photon-photon fusion at ATLAS

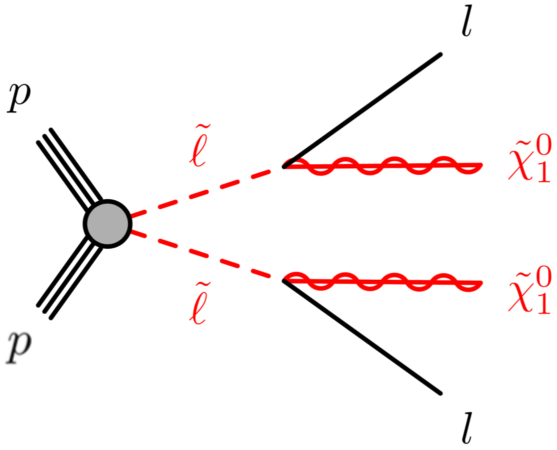
Mateusz Dyndal (CERN)
on behalf of the ATLAS Collaboration

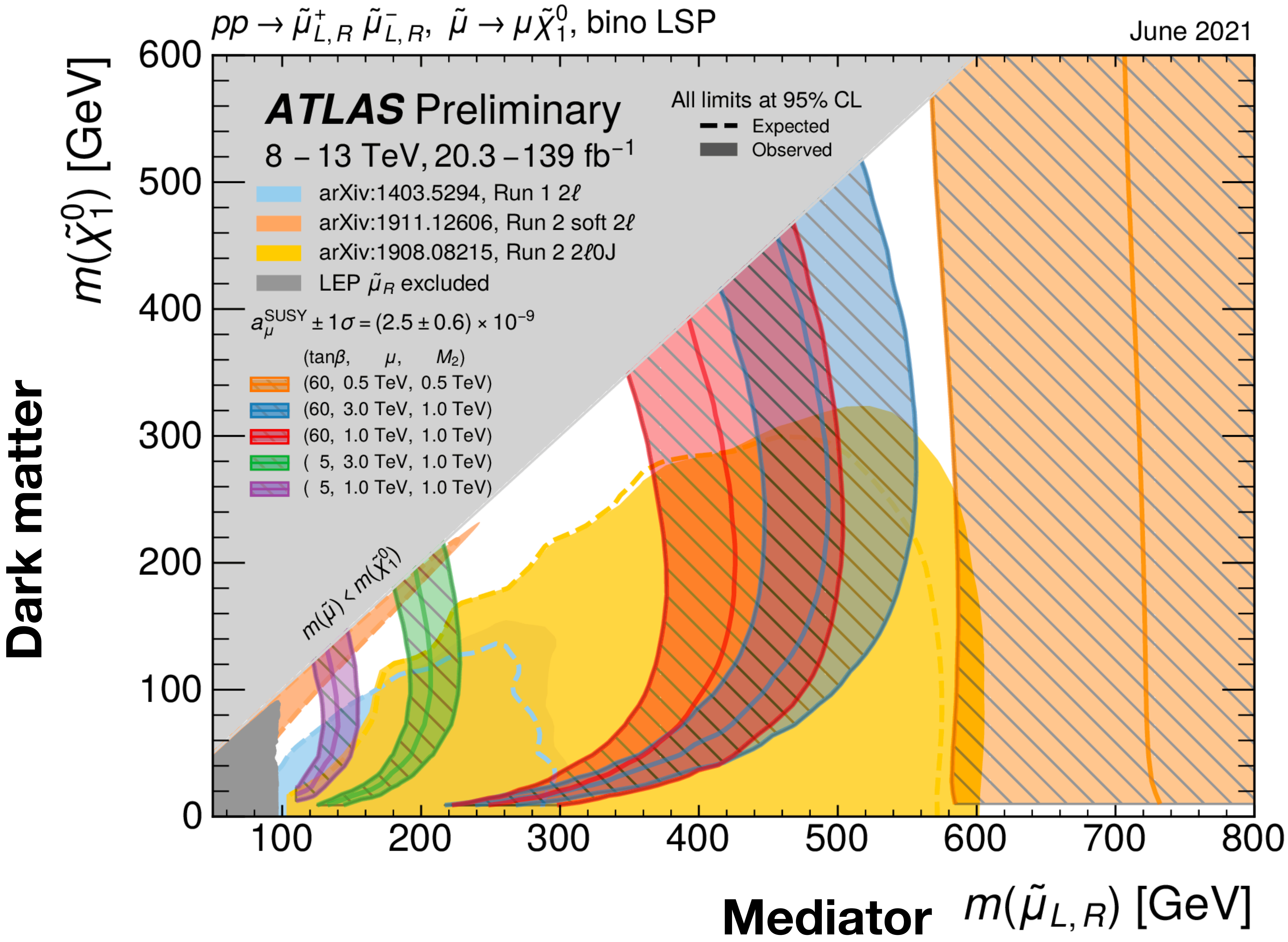
ICHEP 2020

* Event display for an exclusive γγ→γγ candidate in ATLAS, where one of the photons converts in the transition radiation tracker volume

Motivation

Gap in sensitivity for electroweak scale sleptons Link





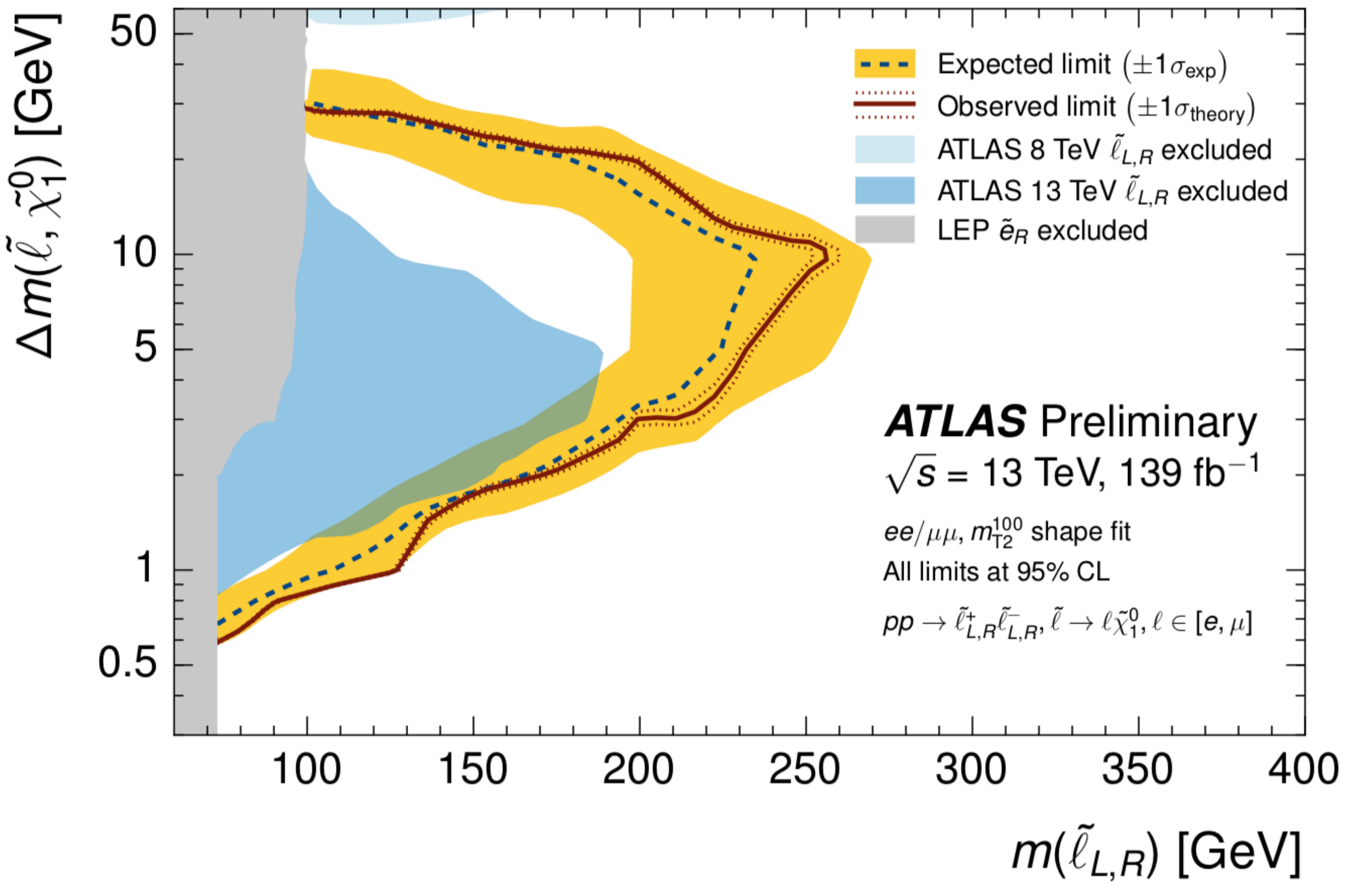
Dark matter

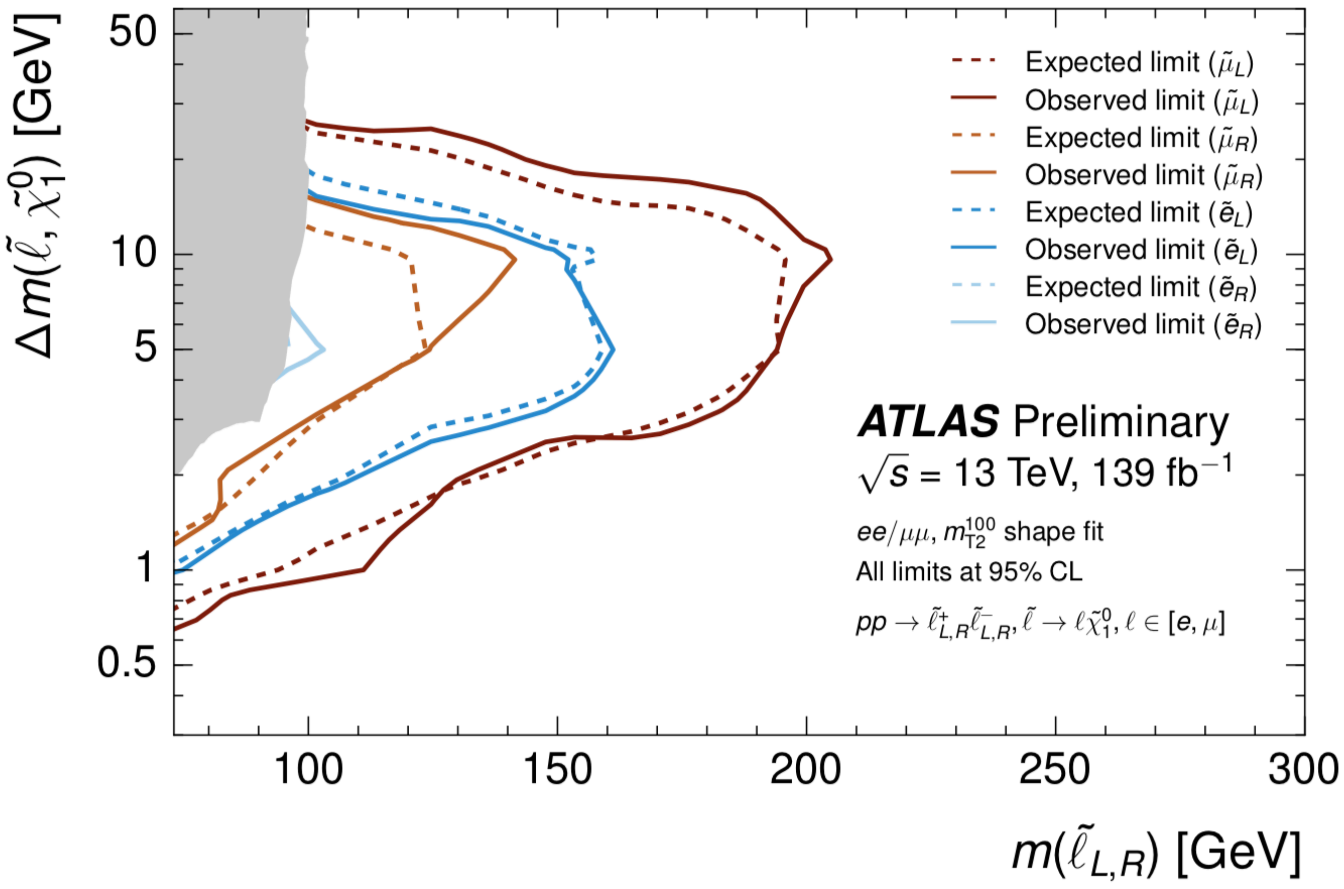
Mediator

ATLAS current - 2L ISR

Relax mass degeneracy & split into left and right handed sleptons

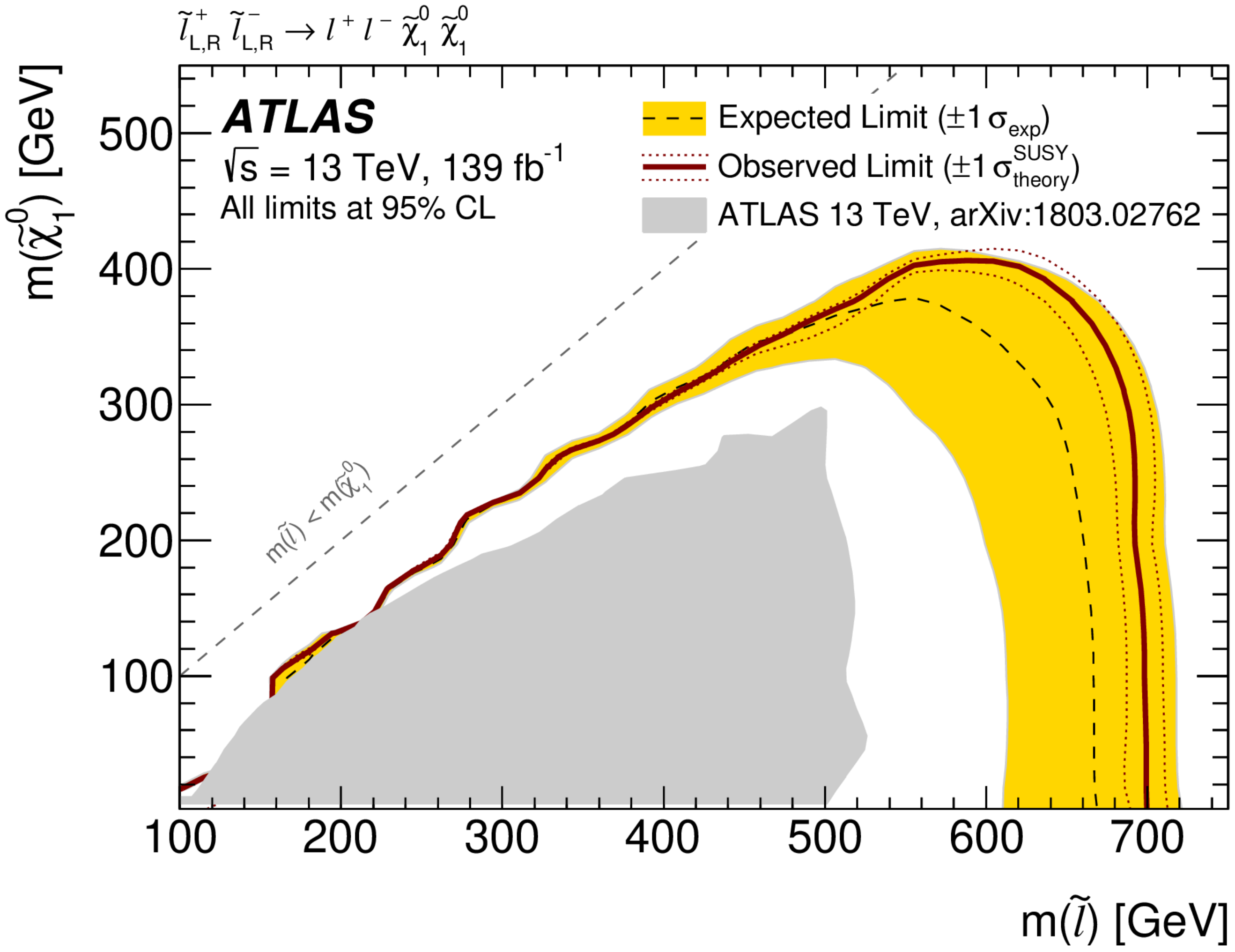
-> Weaker limits for right handed (lower cross-section)

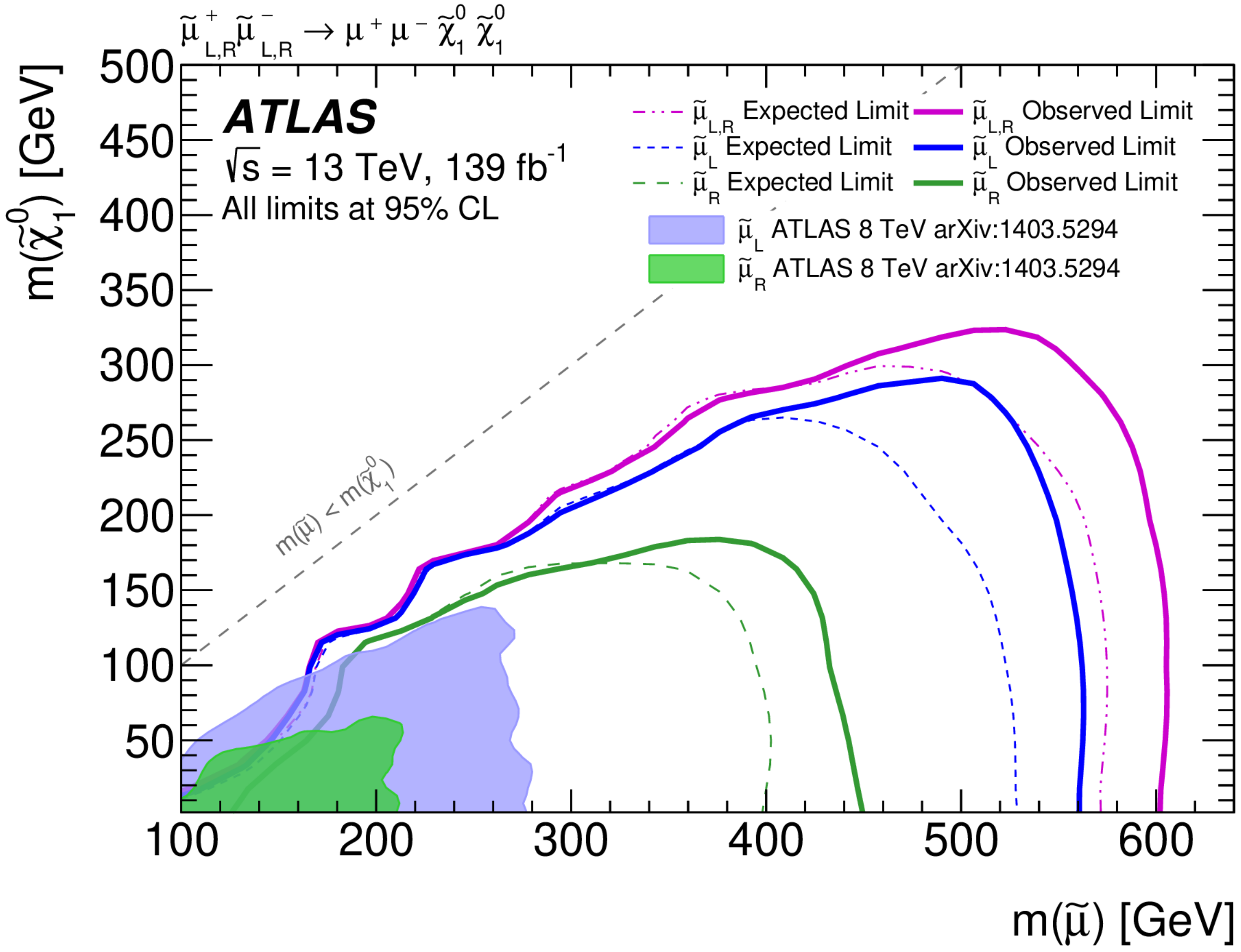


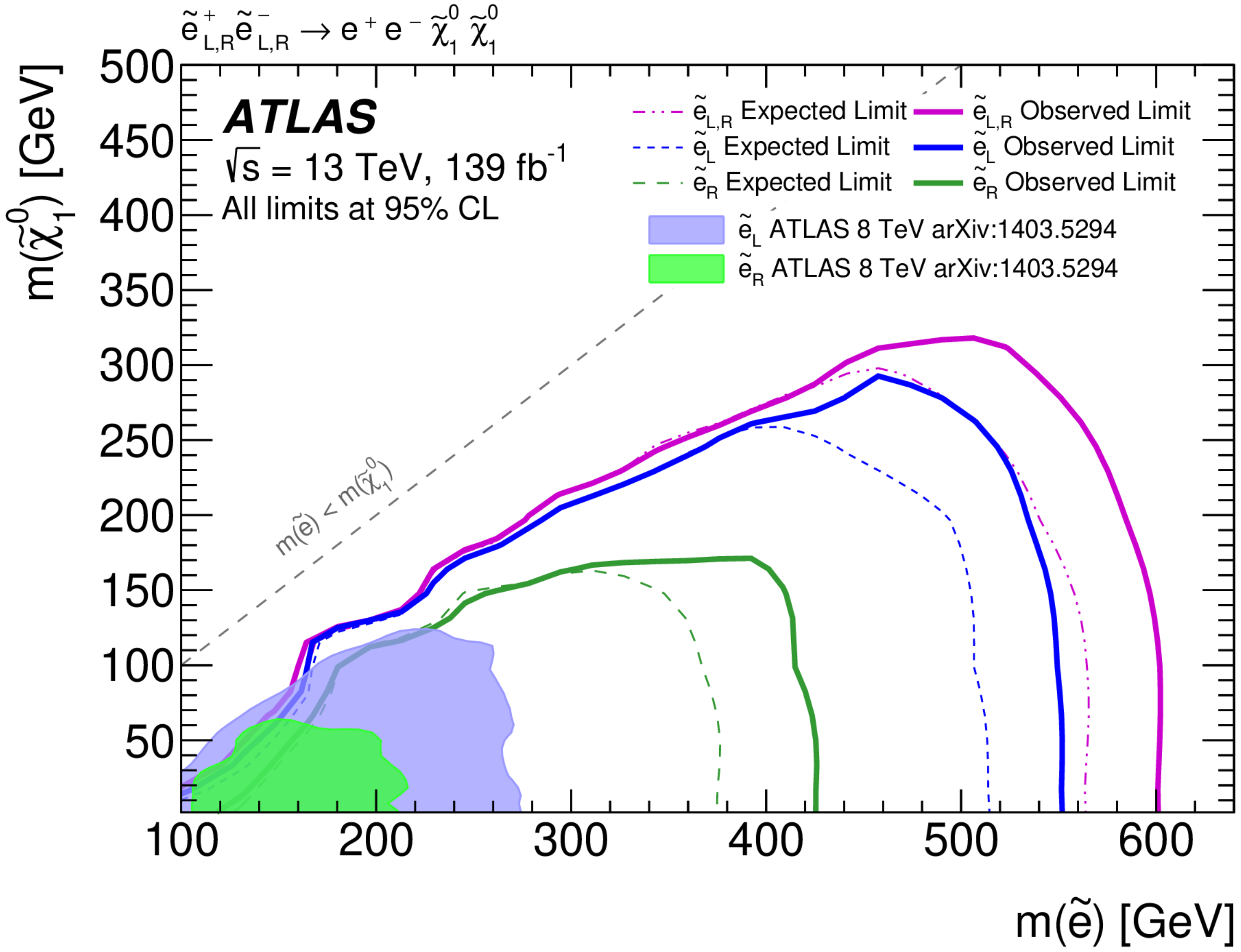


QED production:
Equal cross-sections for
left and right handed!

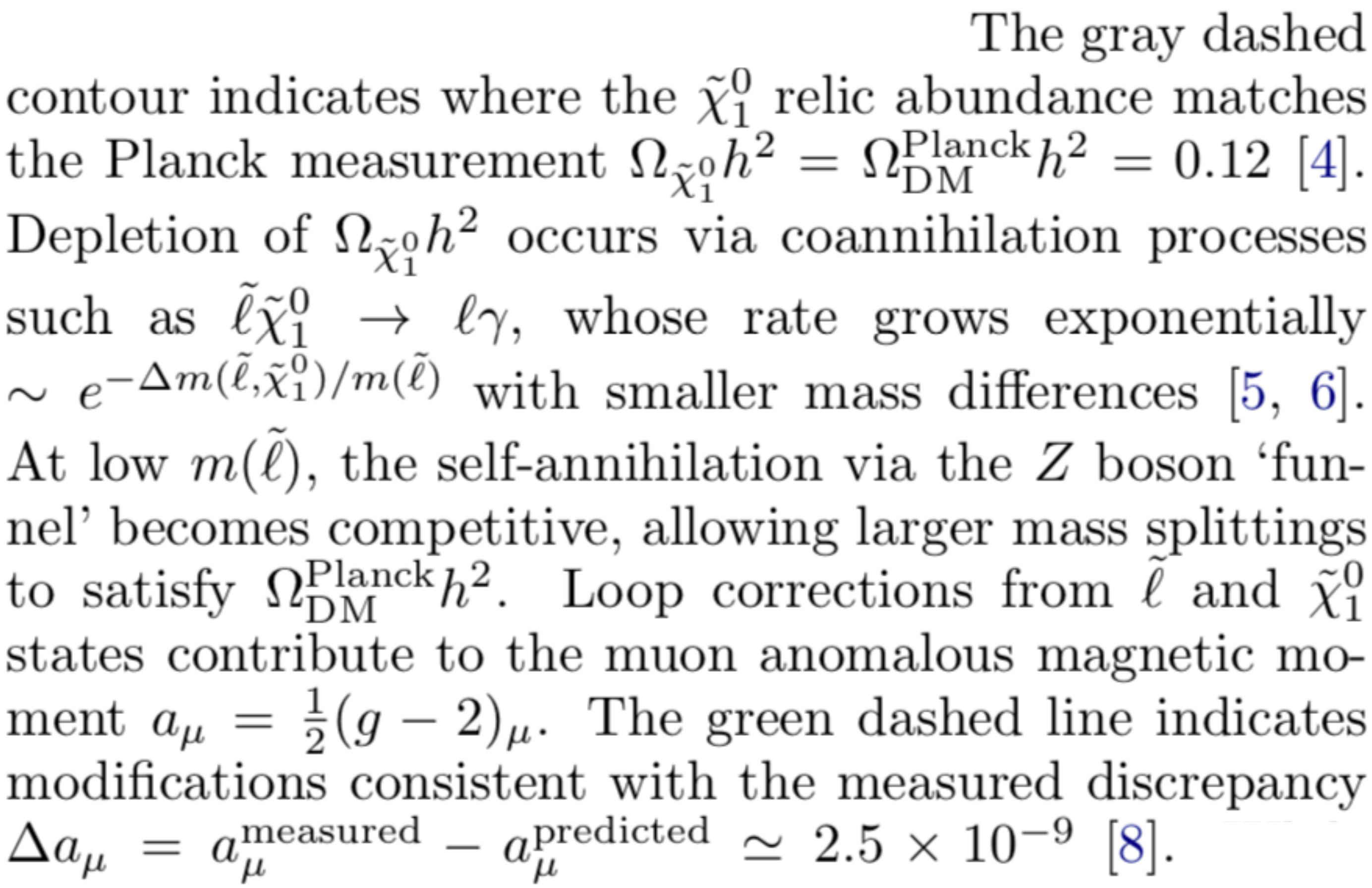
ATLAS current - 2L 0 jets





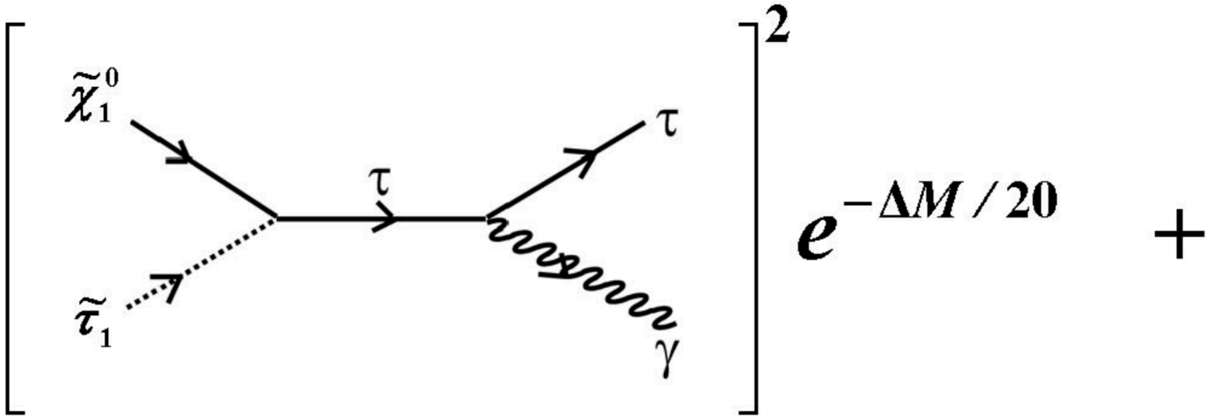


Relic abundance and g-2

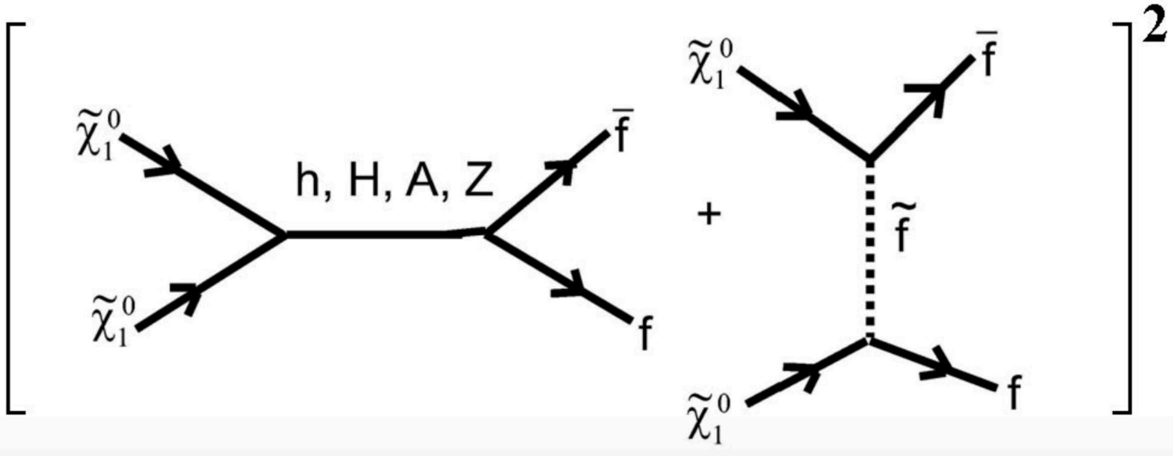


The gray dashed contour indicates where the $\tilde{\chi}_1^0$ relic abundance matches the Planck measurement $\Omega_{\tilde{\chi}_1^0} h^2 = \Omega_{\rm DM}^{\rm Planck} h^2 = 0.12$ [4]. Depletion of $\Omega_{\tilde{\chi}_1^0} h^2$ occurs via coannihilation processes such as $\tilde{\ell}\tilde{\chi}_1^0 \to \ell\gamma$, whose rate grows exponentially $\sim e^{-\Delta m(\tilde{\ell},\tilde{\chi}_1^0)/m(\tilde{\ell})}$ with smaller mass differences [5, 6]. At low $m(\tilde{\ell})$, the self-annihilation via the Z boson 'funnel' becomes competitive, allowing larger mass splittings to satisfy $\Omega_{\rm DM}^{\rm Planck} h^2$. Loop corrections from $\tilde{\ell}$ and $\tilde{\chi}_1^0$ states contribute to the muon anomalous magnetic moment $a_\mu = \frac{1}{2}(g-2)_\mu$. The green dashed line indicates modifications consistent with the measured discrepancy $\Delta a_\mu = a_\mu^{\rm measured} - a_\mu^{\rm predicted} \simeq 2.5 \times 10^{-9}$ [8].

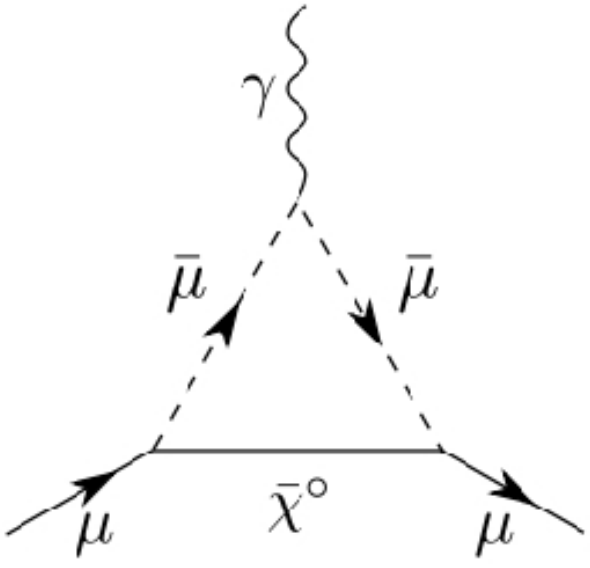
Coannihilation

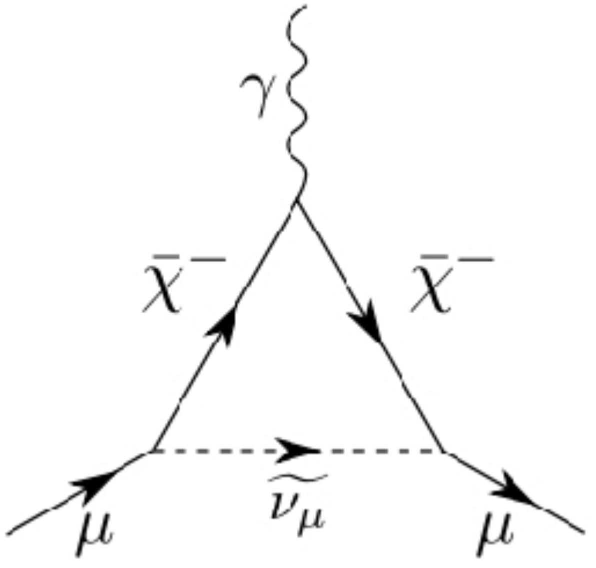


Self-annihilation

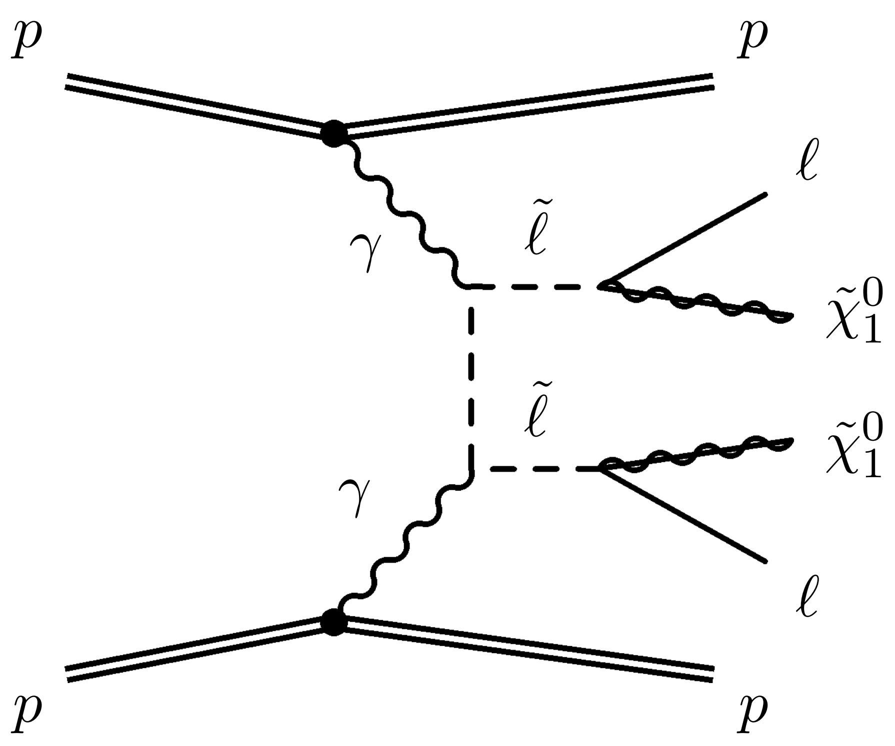


g-2





Analysis selection



Leptons

- 2 same flavour ($ee, \mu\mu$)
- $p_T > 15$ GeV (trigger emulation)
- $|\eta| < 2.5$ (tracking acceptance)
- Smear 4-momentum by 5% or less (resolution)
- p_T dependent reco efficiency parametrised from ATLAS

Protons/photons

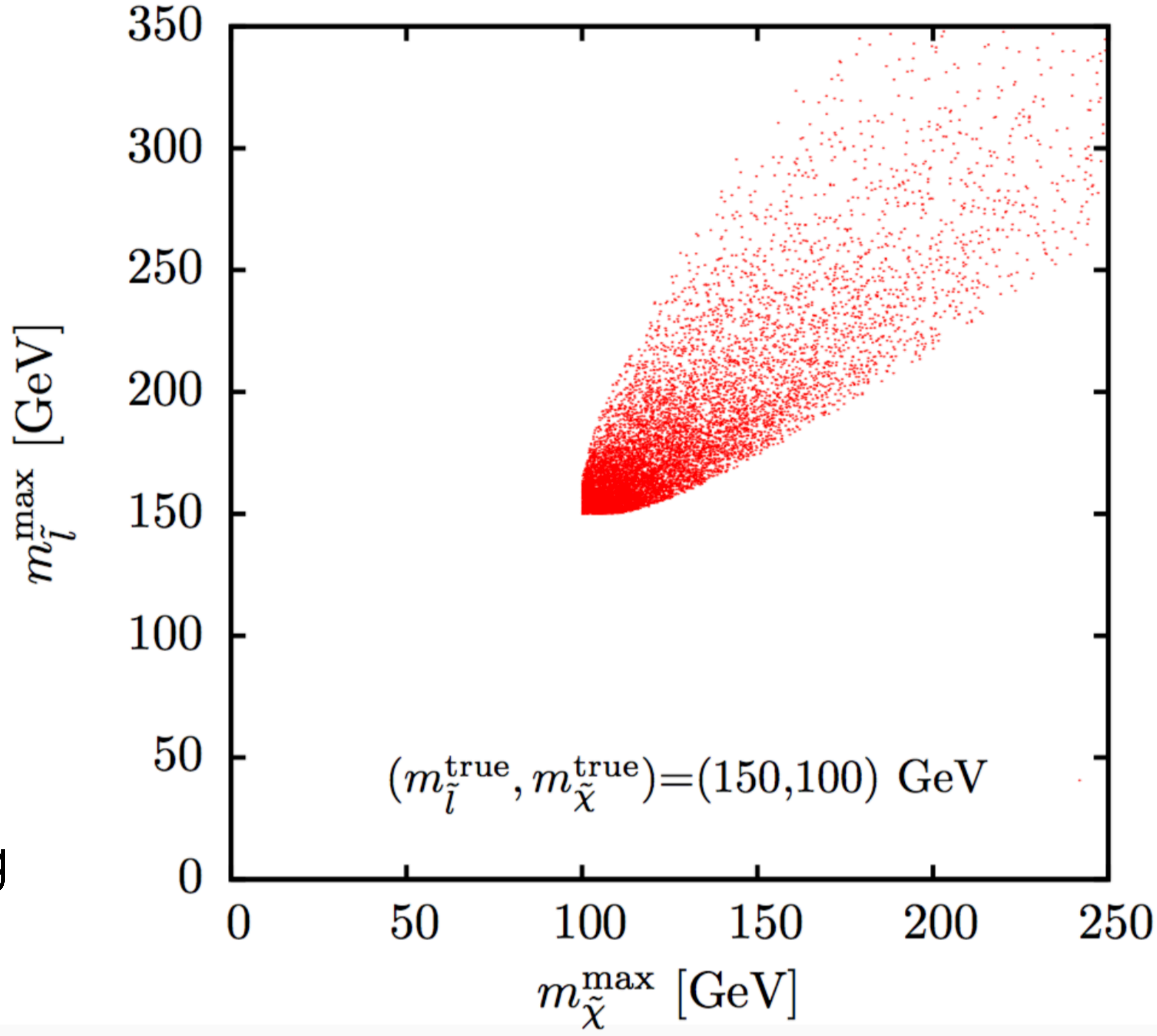
- Acceptance: 100% $130 \leq E_\gamma \leq 780$ GeV $(0.02 \lesssim \xi \lesssim 0.12, \xi = 1 - \frac{E_{forward}}{E_{beam}})$
- Smear photon 4-momentum by 5% (resolution)
- Proton survival probability parametrised from SUPERCHIC generator

Mass measurement

Harland-Lang et al.
EPJC 72 1969 (2012)
new variables $m_{\tilde{\ell}}^{max}$, m_{DM}^{max}

Uses photon & missing momentum 4-vectors & assume decay topology for additional kinematic constraints

→ Sharpens tails improving signal vs bkg discrimination



Analysis selection

Signal Regions (SRs)

Design **3 SRs** targeting different mediator and DM mass splittings: small (compressed), medium (corridor) & large

	$m^{max}_{mediator}$	m^{max}_{DM}	$m_{\gamma\gamma}/W_{miss}$
- small:	> 80 GeV	> 0 GeV	< 1.4
- medium:	> 120 GeV	> 80 GeV	
- large:	> 130 GeV	> 20 GeV	

In each SR exploit spin difference between S and B (S more central):

cos($\bar{\theta}_{ll}$) < 0.65 $\bar{\theta}_{ll}$ evaluated in di-lepton centre-of-mass frame

$$\cos\bar{\theta}_{\ell\ell} = \tanh\left[\tfrac{1}{2}(\bar{\eta}_{\ell_1} - \bar{\eta}_{\ell_2})\right]$$

Barr JHEP 02 042 (2006)
Melia JHEP 01 143 (2012)

Soft survival

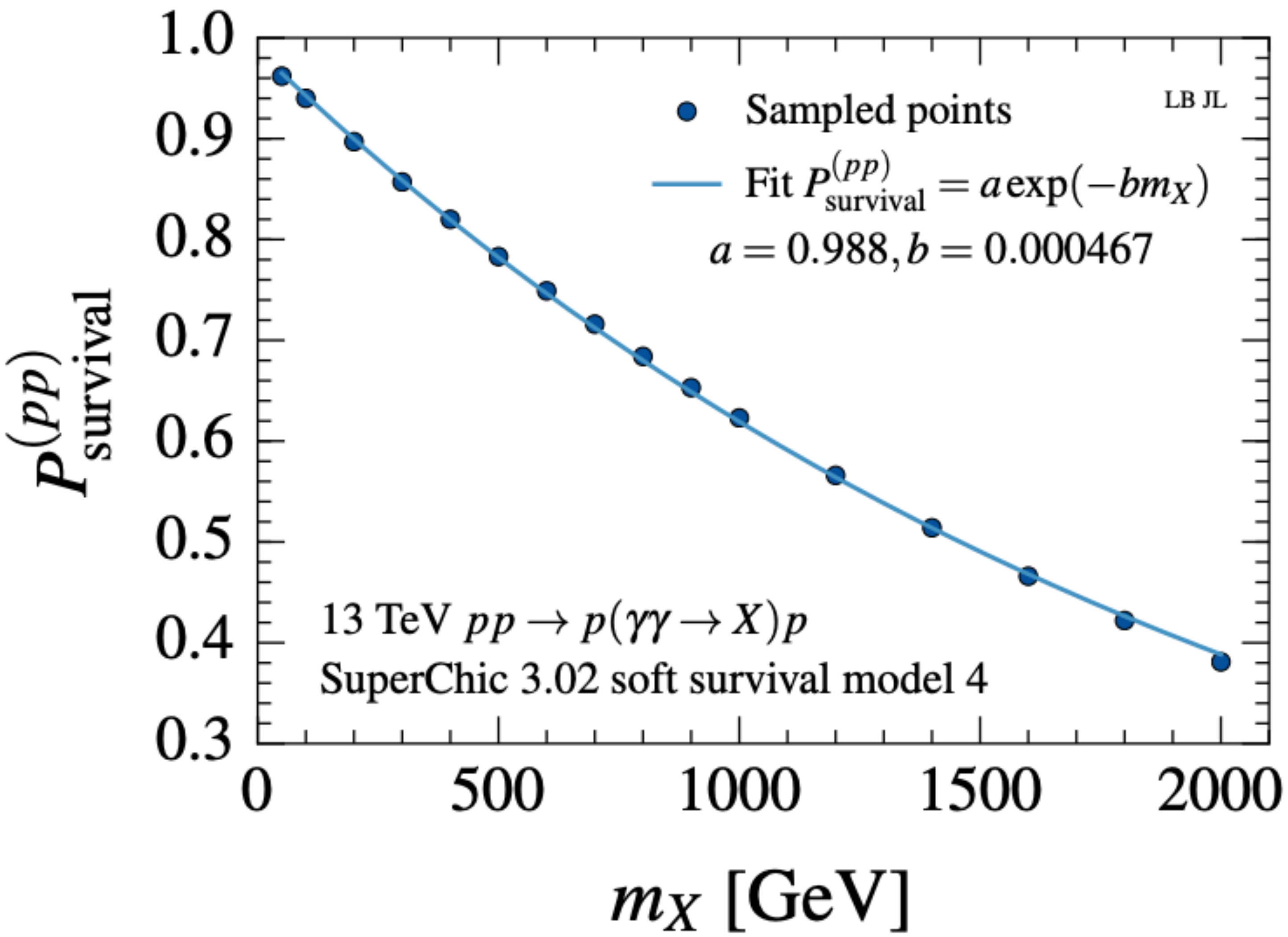
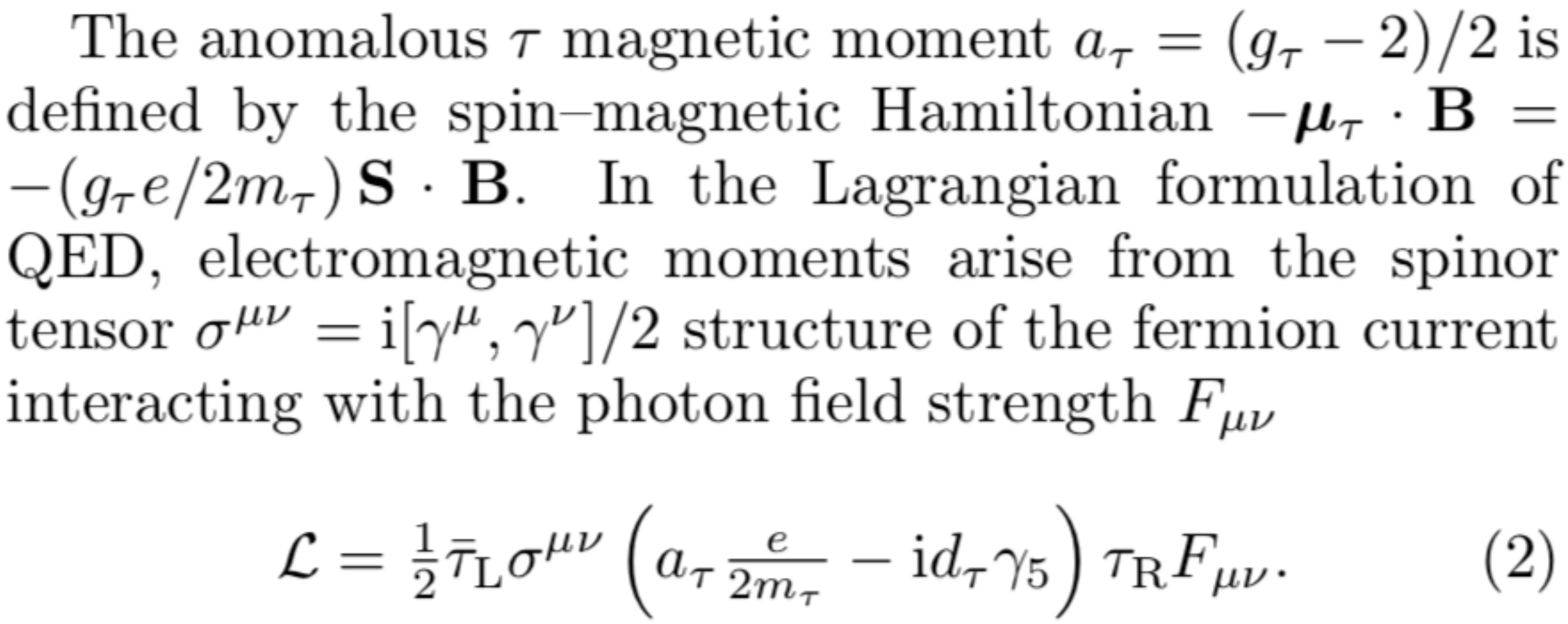


FIG. 5. Soft survival probability $P^{(pp)}_{\mathrm{survival}} = \sigma_{\mathrm{soft\ survival}}/\sigma_{\mathrm{no\ soft\ survival}}$ for different centre-of-masses m_X computed using `Superchic` 3.02 for soft survival model `isurv` 4 [58] in $pp \to p(\gamma\gamma \to X)p$ processes. The scanned points (blue circles) are fit to an exponential $P^{(pp)}_{\mathrm{survival}} = a\exp(-bm_X)$ (blue line).

[58] Khoze et al. EPJC 23 311 (2002)

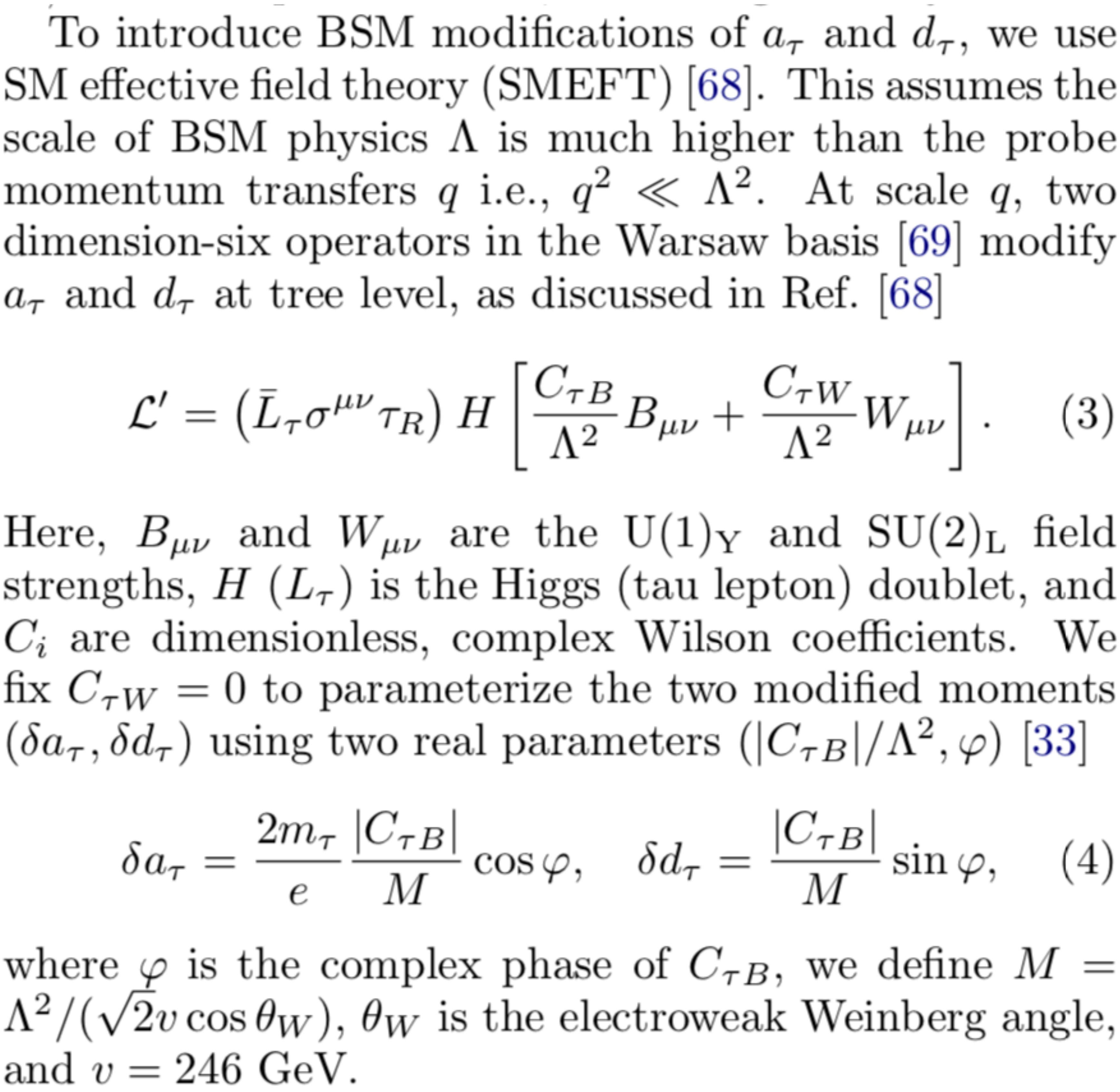
Tau g-2 SM QED



The anomalous τ magnetic moment $a_\tau = (g_\tau - 2)/2$ is defined by the spin–magnetic Hamiltonian $-\boldsymbol{\mu}_\tau \cdot \mathbf{B} = -(g_\tau e/2m_\tau)\,\mathbf{S} \cdot \mathbf{B}$. In the Lagrangian formulation of QED, electromagnetic moments arise from the spinor tensor $\sigma^{\mu\nu} = \mathrm{i}[\gamma^\mu, \gamma^\nu]/2$ structure of the fermion current interacting with the photon field strength $F_{\mu\nu}$

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

Tau g-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]

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

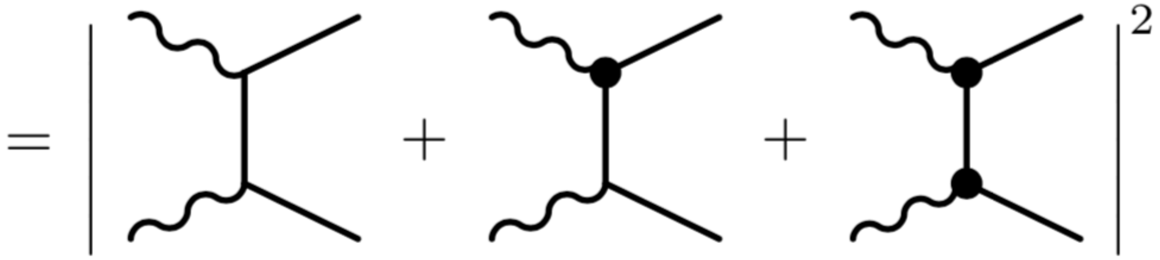
Here, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the $\mathrm{U(1)_Y}$ and $\mathrm{SU(2)_L}$ field strengths, H (L_τ) is the Higgs (tau lepton) doublet, and C_i are dimensionless, complex Wilson coefficients. We fix $C_{\tau W} = 0$ to parameterize the two modified moments $(\delta a_\tau, \delta d_\tau)$ using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

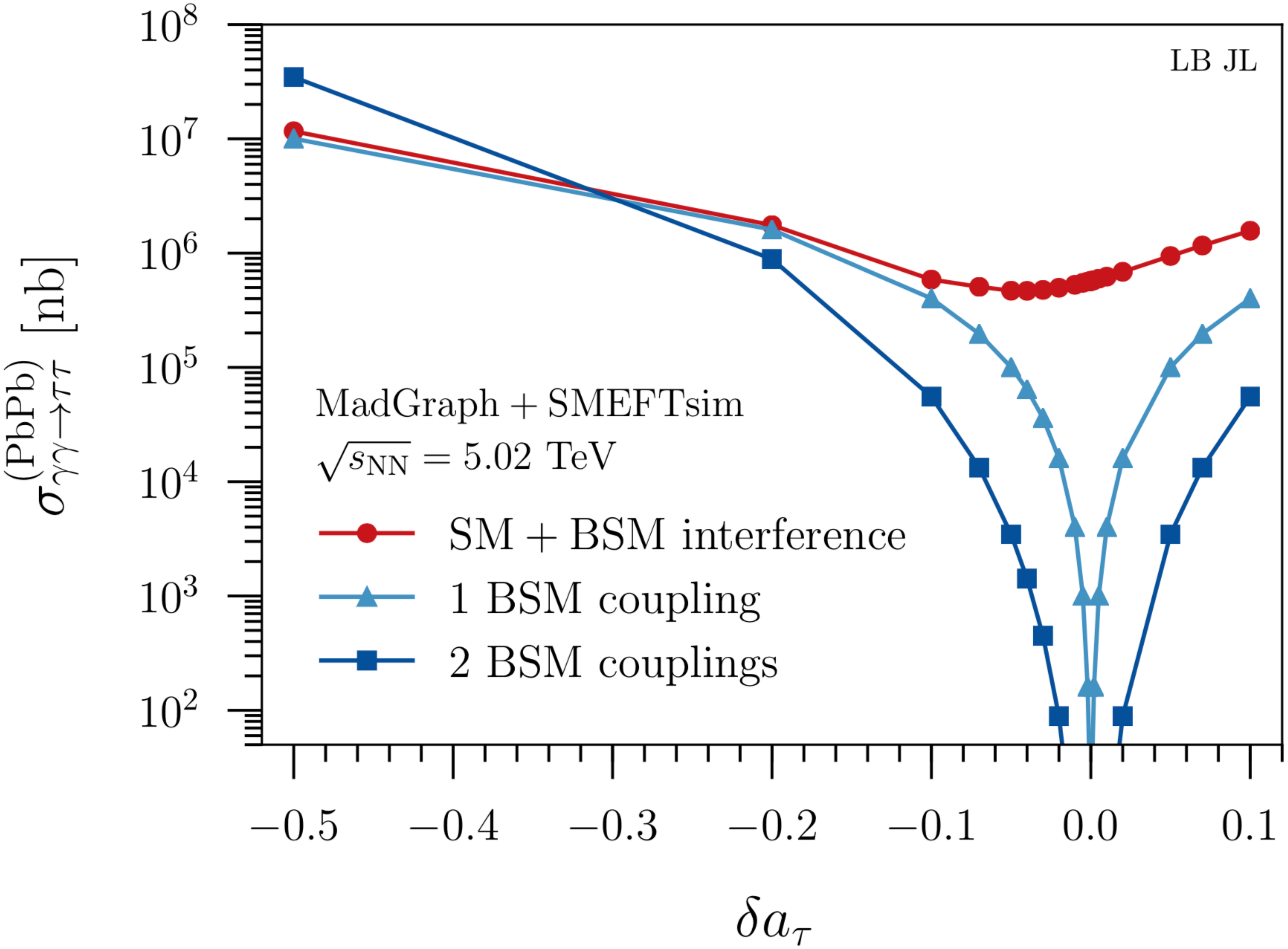
$$\delta a_\tau = \frac{2m_\tau}{e} \frac{|C_{\tau B}|}{M} \cos\varphi, \quad \delta d_\tau = \frac{|C_{\tau B}|}{M} \sin\varphi, \quad (4)$$

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

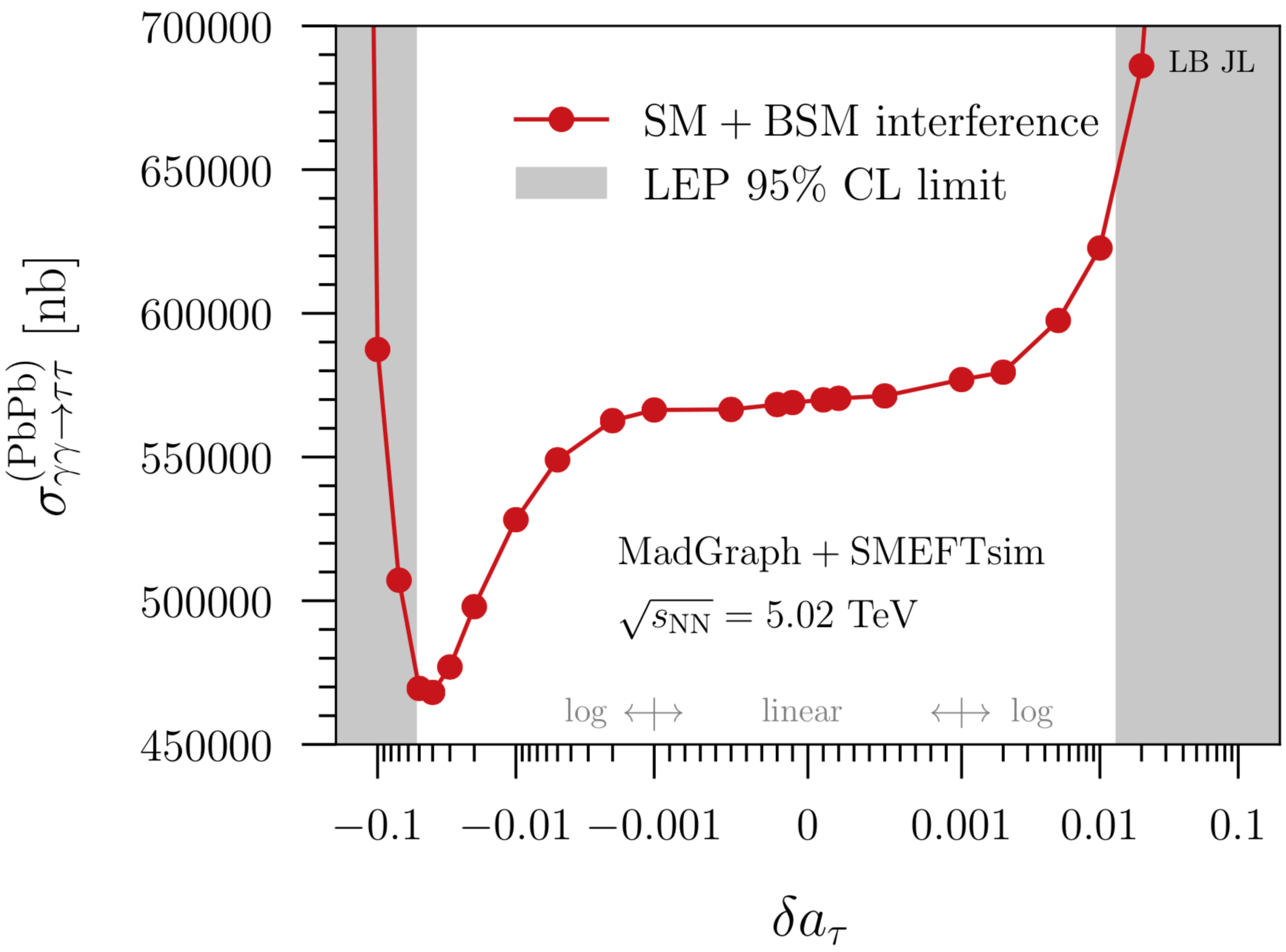
cross-section & interference

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



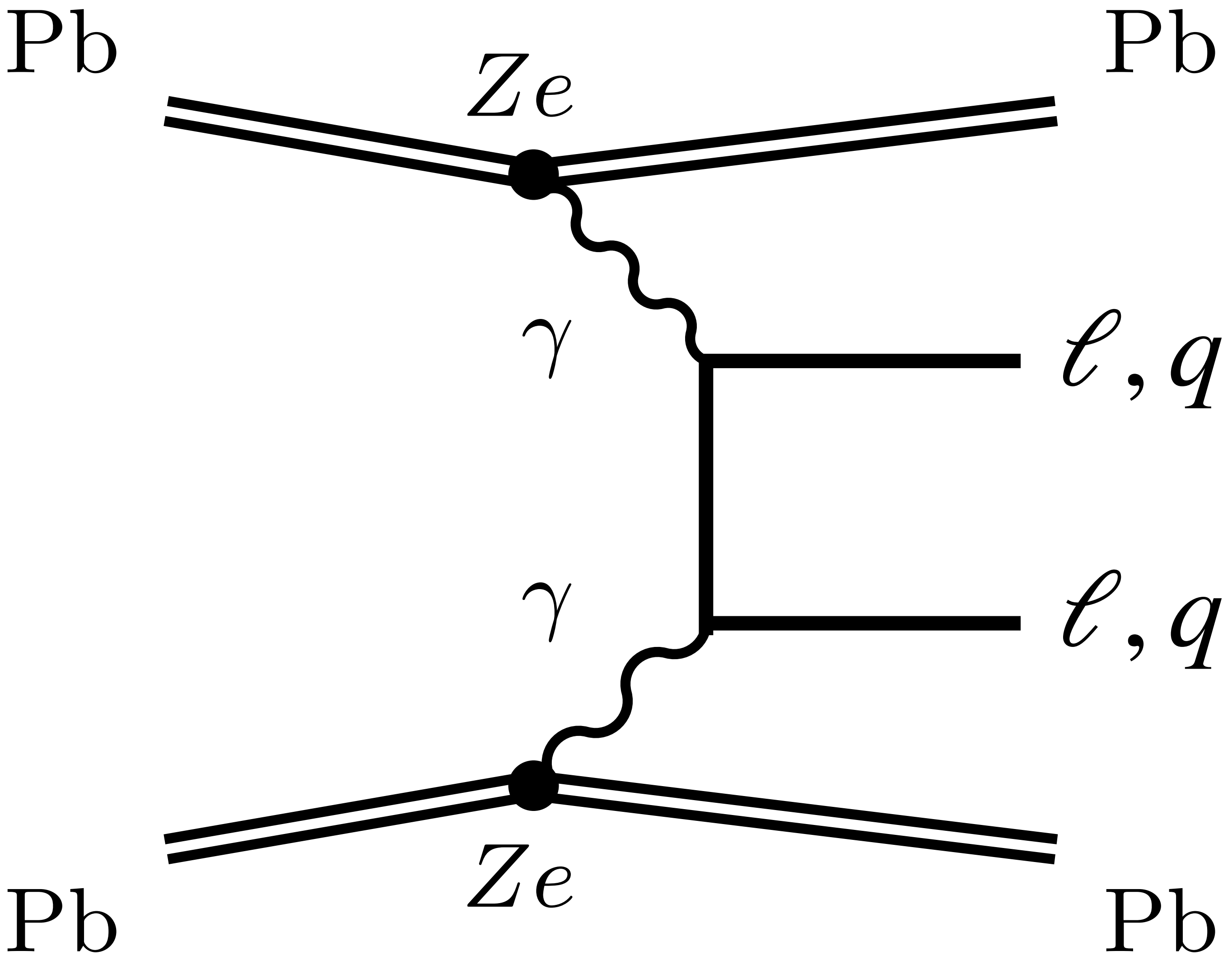


Cross-section & interference (zoomed)



Backgrounds

Generated:



Signal Regions

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

Signal Regions (SRs)

1ℓ + 1 track

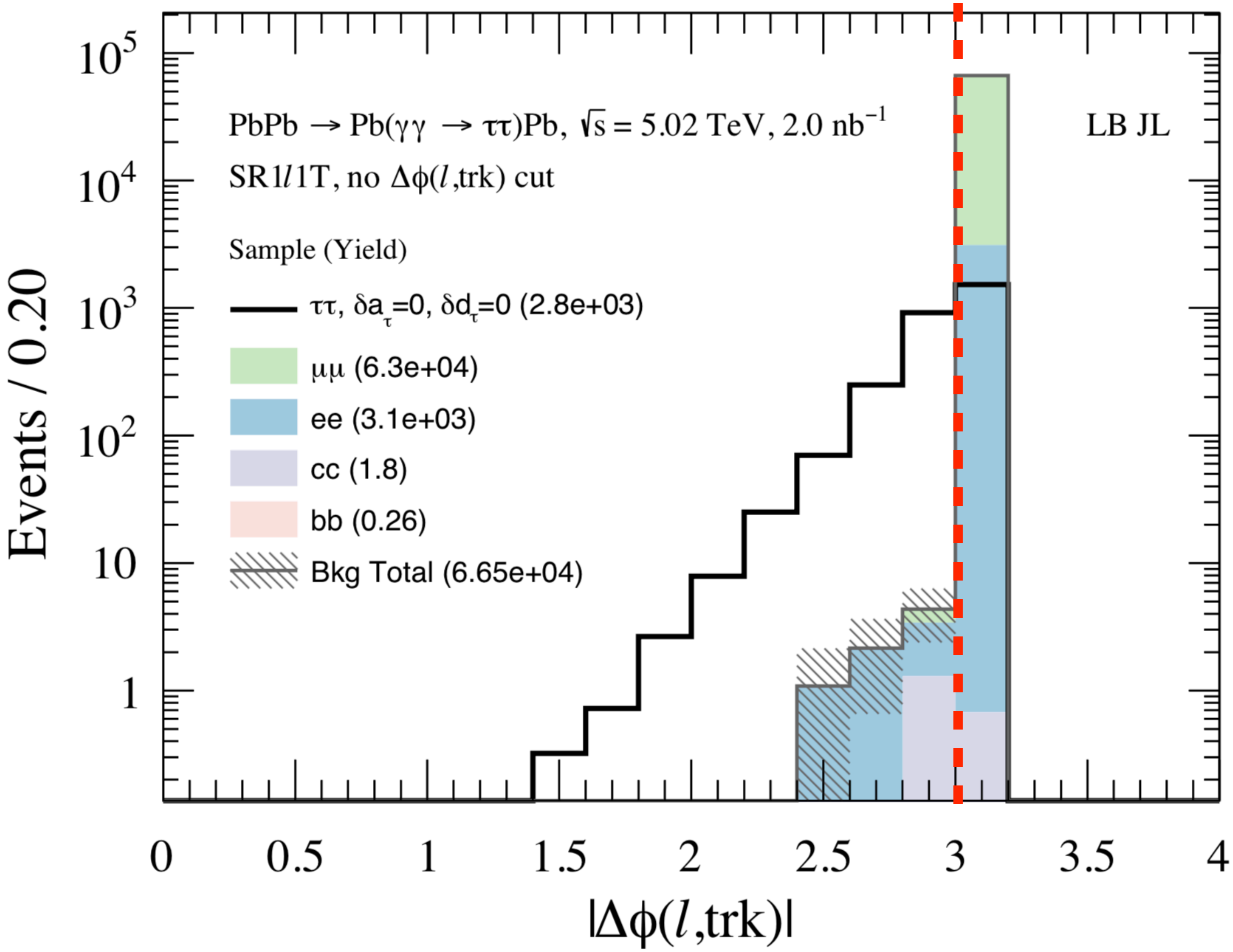
1ℓ + 2 track

1ℓ + 3 track

Background mitigation

$1\ell + 1$ track SR

Keep

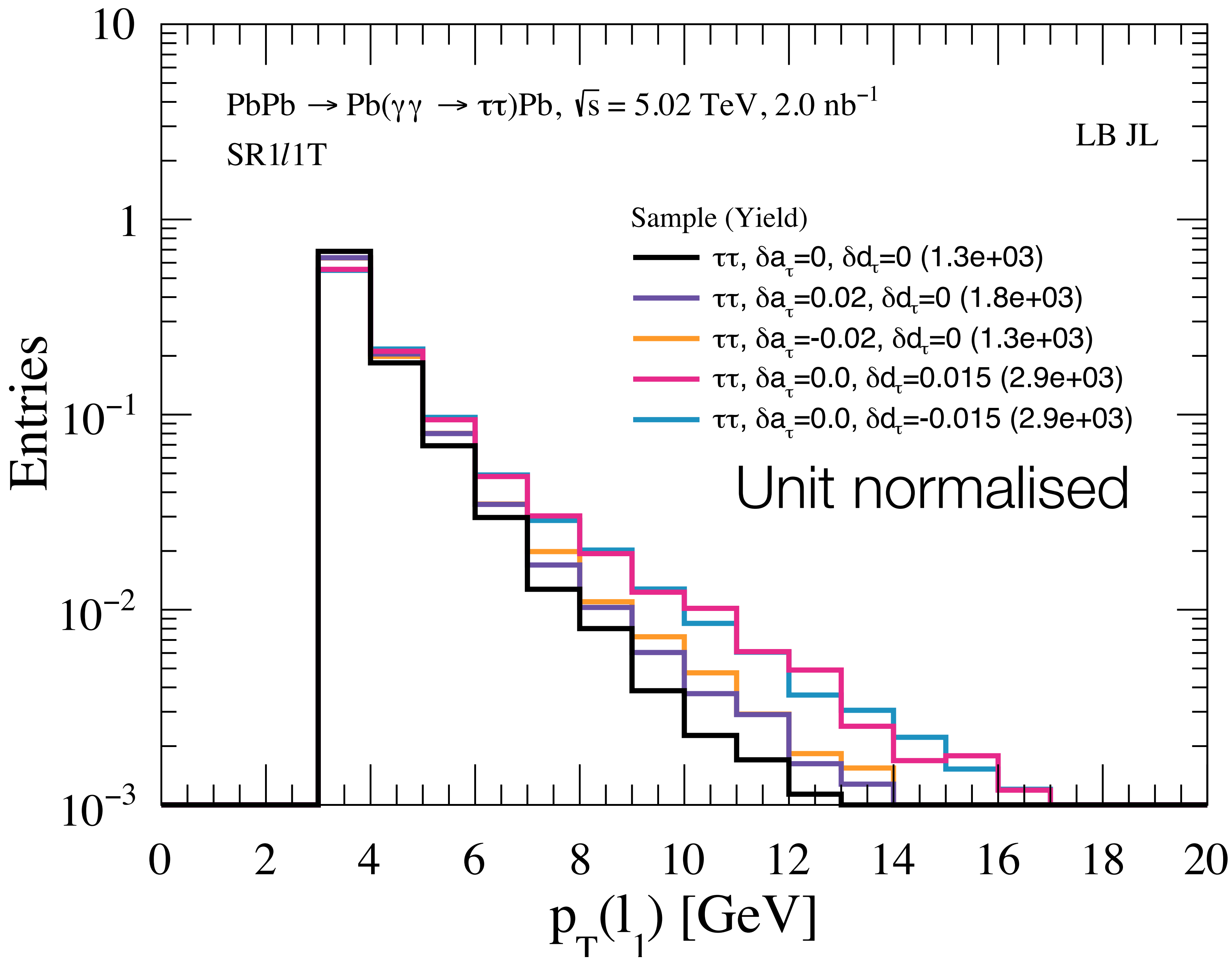


And veto J/ψ & Υ masses

Setting constraints

Also sensitive to τ EDM

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



Modifying moments alters **shape** of lepton p_T

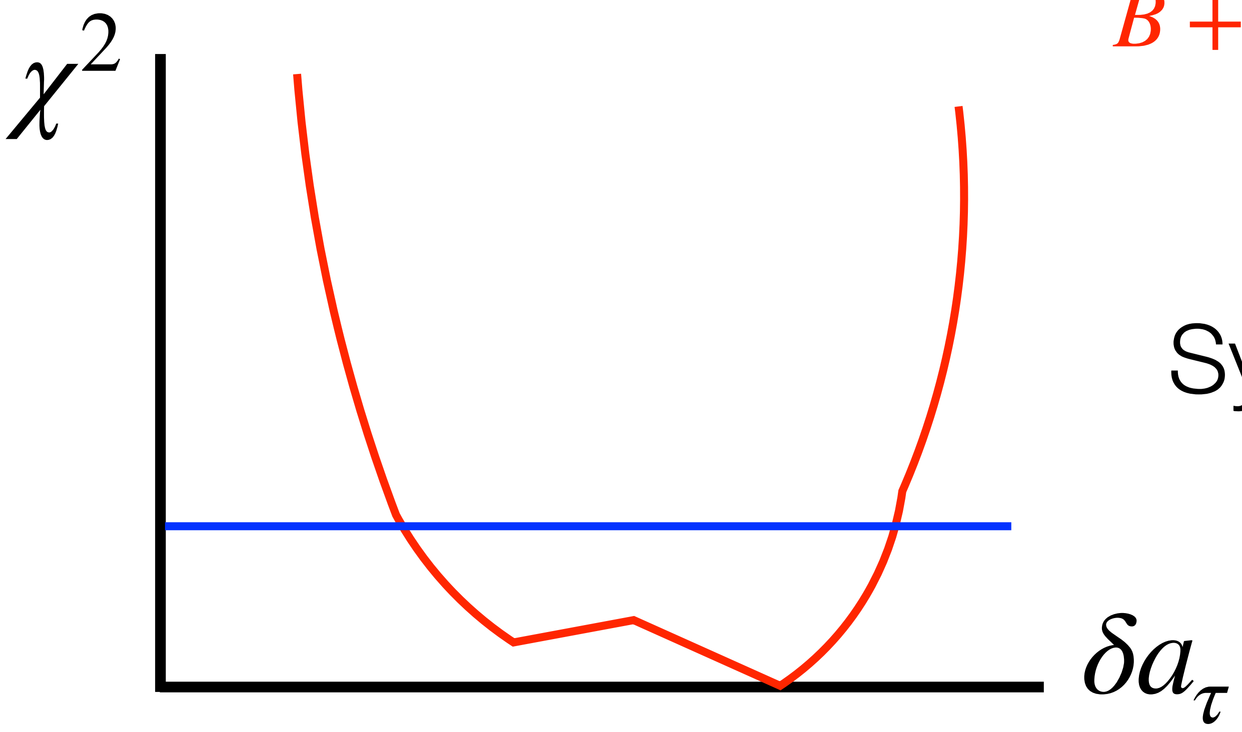
Setting constraints

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

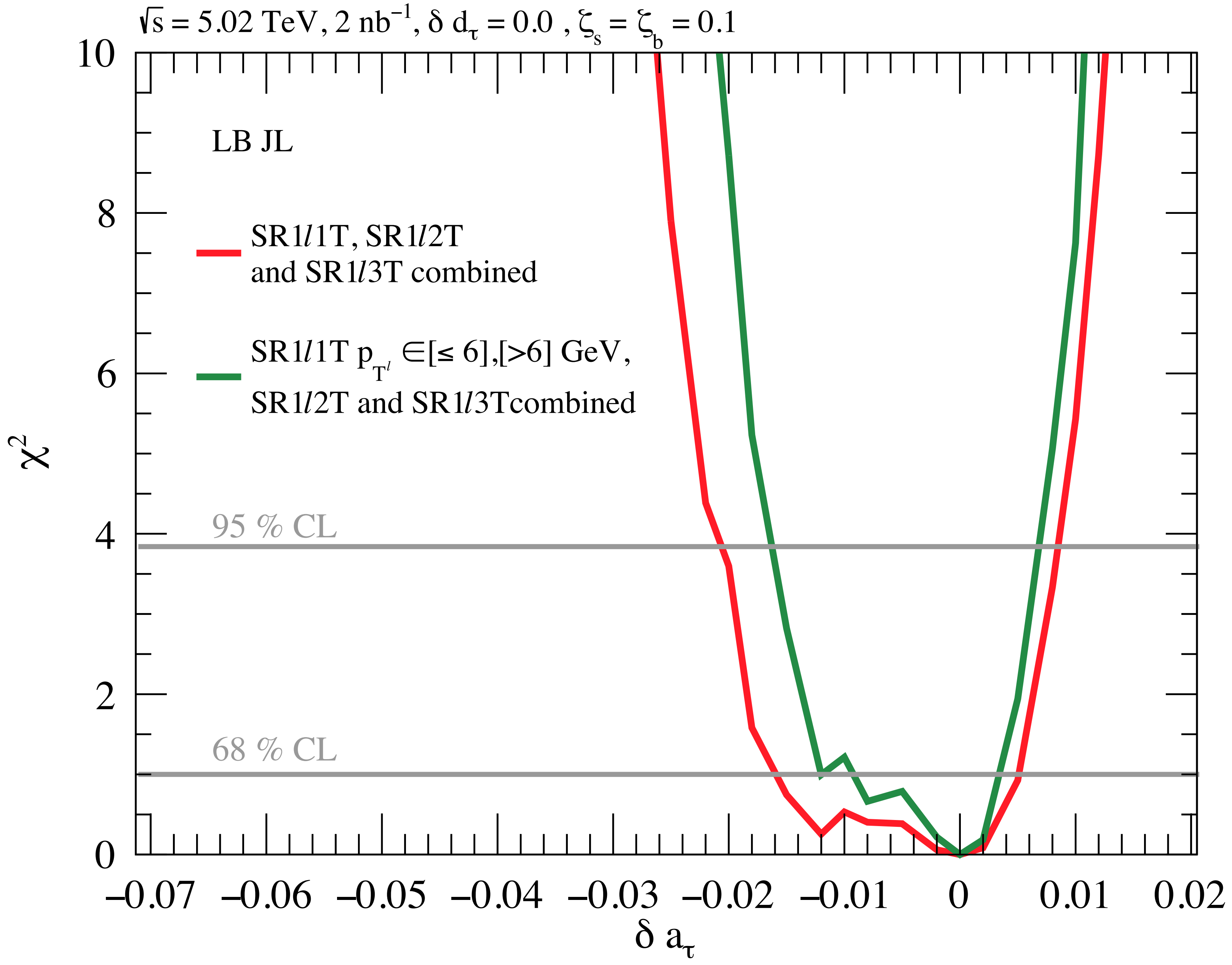
$$\chi^2 = \frac{(S_{\text{SM+BSM}} - S_{\text{SM}})^2}{B + S_{\text{SM+BSM}} + (\zeta_s S_{\text{SM+BSM}})^2 + (\zeta_b B)^2}$$



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

Putting it all together: a_τ

Assume observe SM & quantify constraint using χ^2



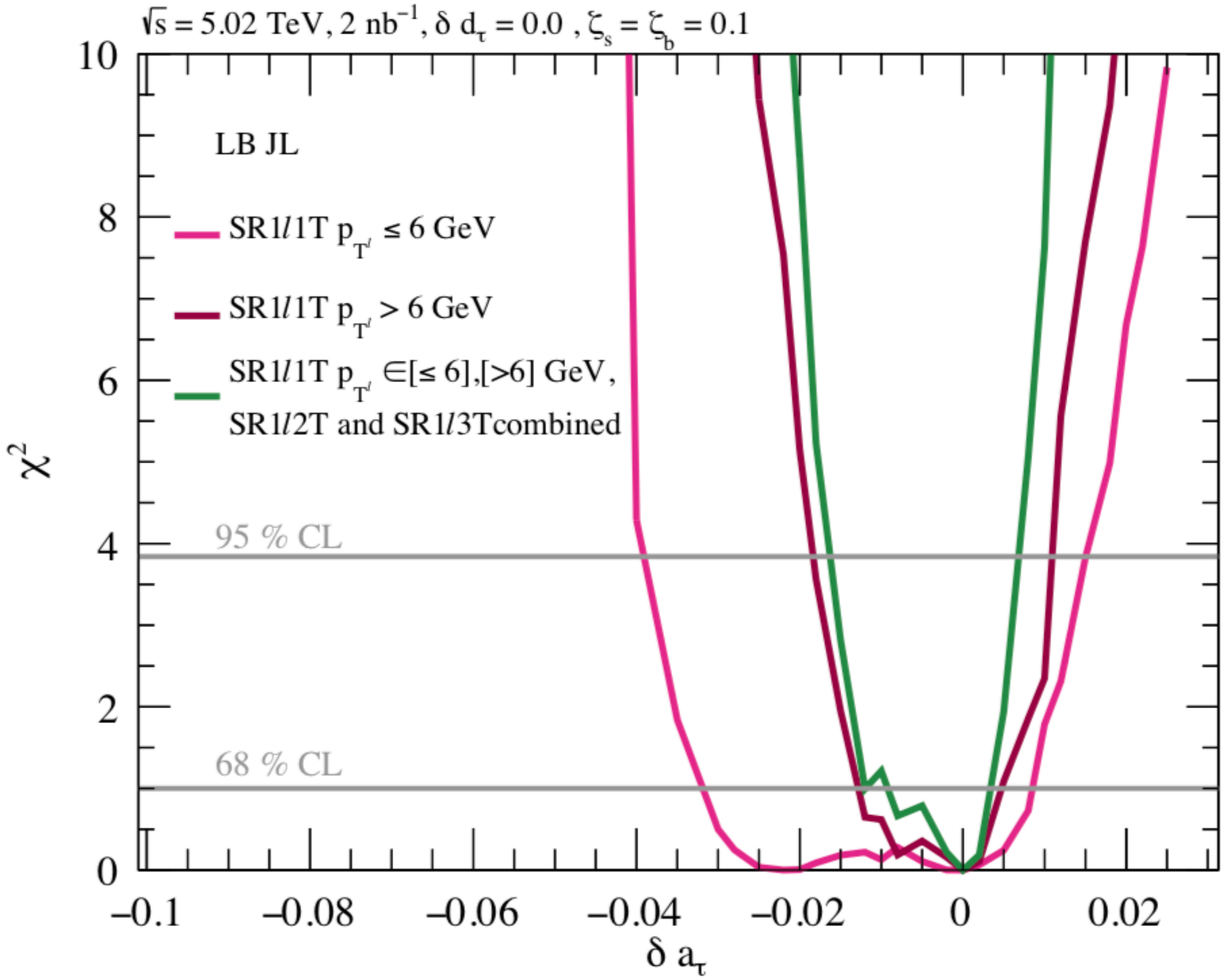
Assuming 10% systematic

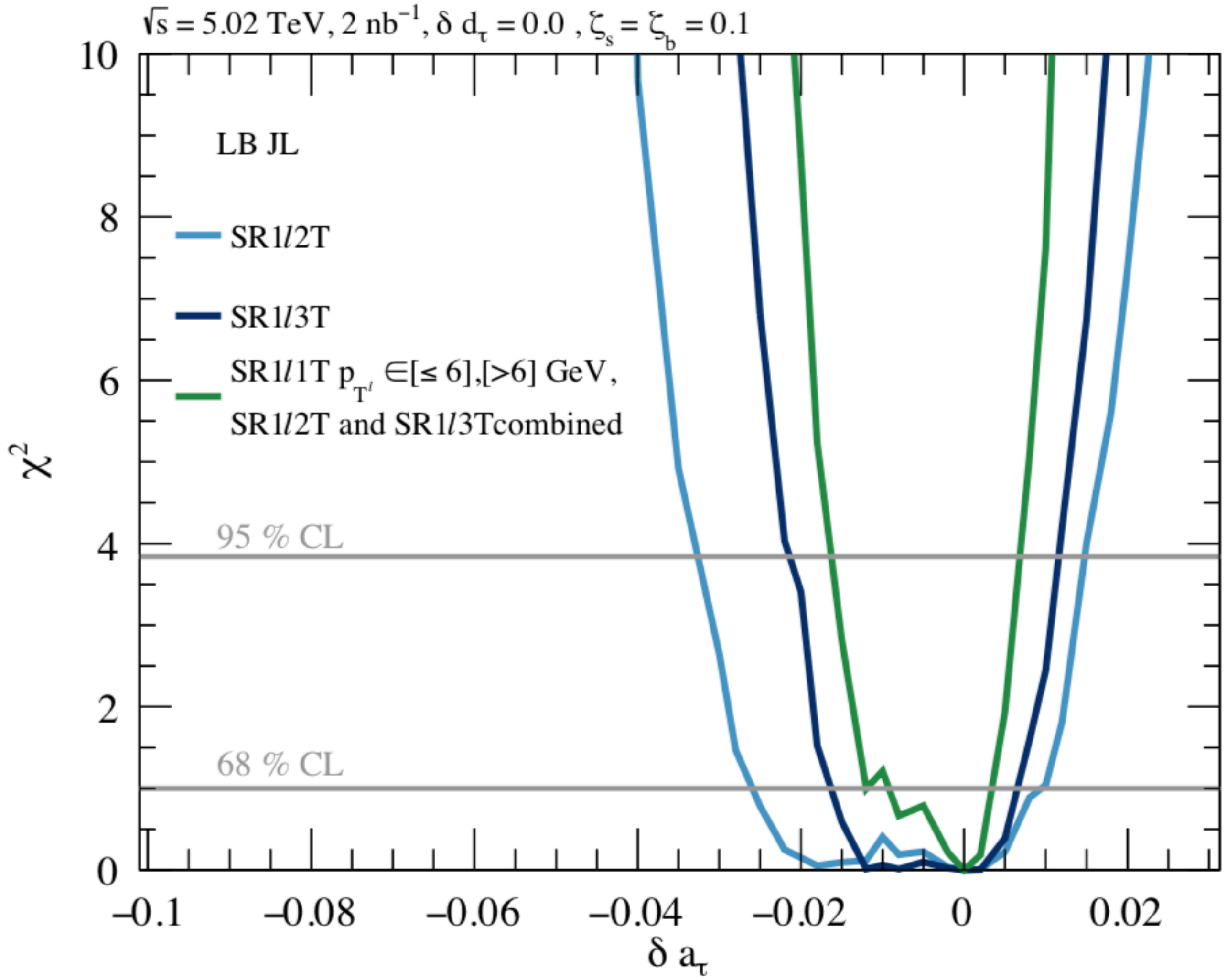
$\Sigma\chi^2$ for all SRs (orthogonal)

Shape analysis strengthens constraints :)

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

SR Break down: a_τ





Also sensitive to tau EDM

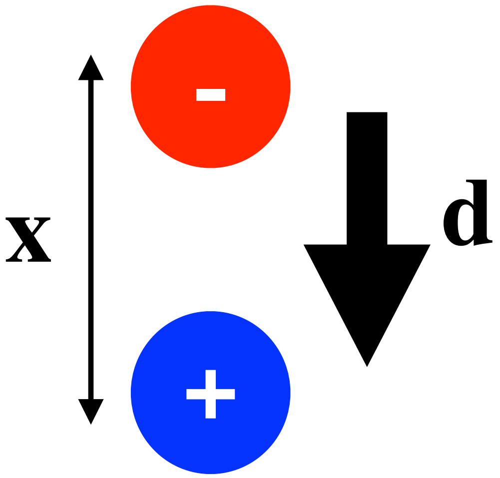
*How objects interact with an **electric** field*

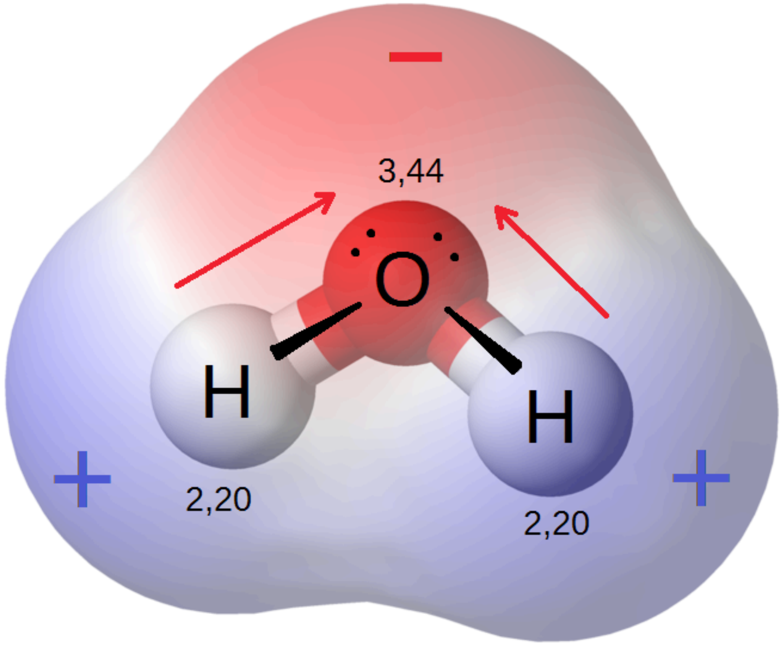
EDM = Electric Dipole Moment

$$\underset{\substack{\uparrow\\\text{torque}}}{\boldsymbol{\tau}} = \underset{\substack{\uparrow\\\text{electric dipole moment}}}{\boldsymbol{d}} \times \mathbf{E}$$

Possessed by e.g. water (polarised molecule)

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





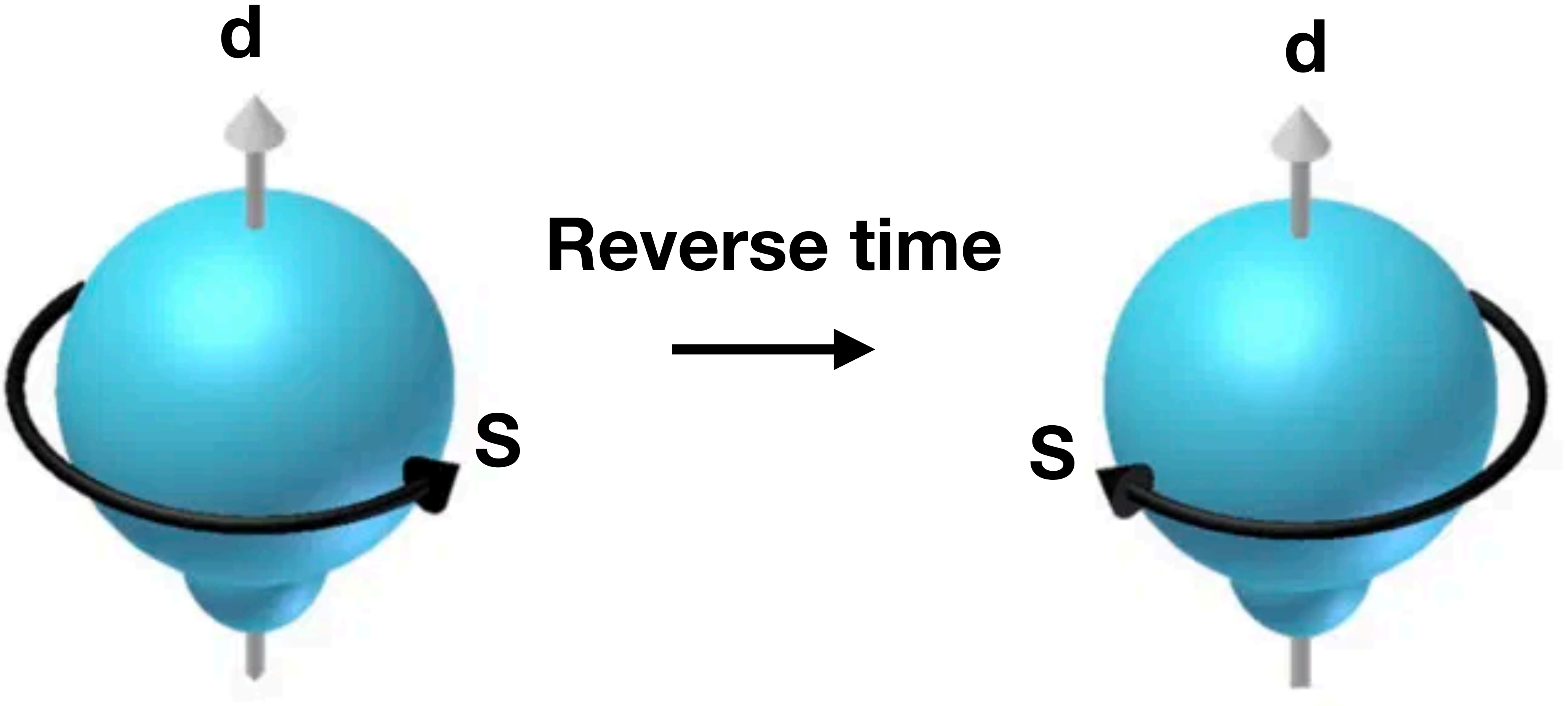
EDM tells us about charge distribution

Why are EDMs interesting?

Further details

Non-zero EDM → CP violation!

assuming CPT conserved



EDM tiny in SM, observation = New Physics!