Two-photon fusion processes at ATLAS + CMS

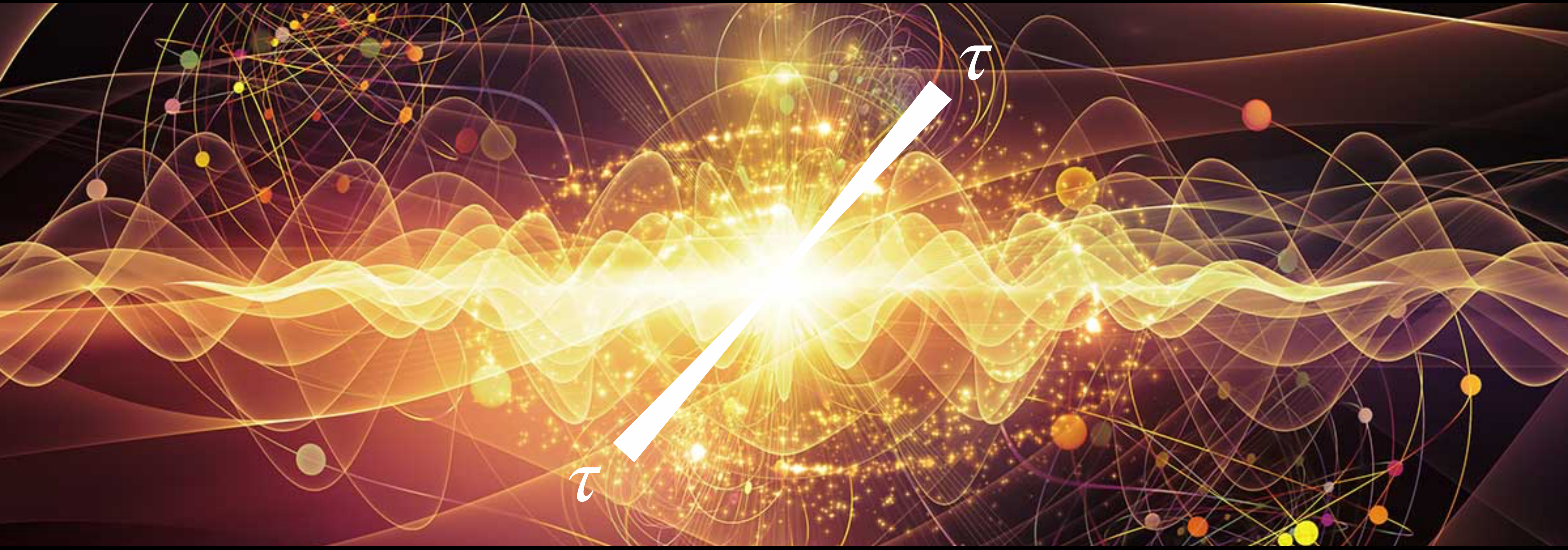


Image by Shutterstock

Lydia Beresford on behalf of the ATLAS & CMS collaborations

MPI@LHC 2023

20-24 November 2023

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

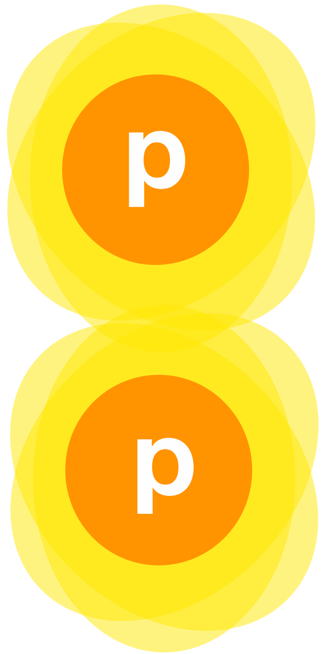
DESY.

The LHC as a photon collider

Surrounding electromagnetic field

→ Coherent flux of photons

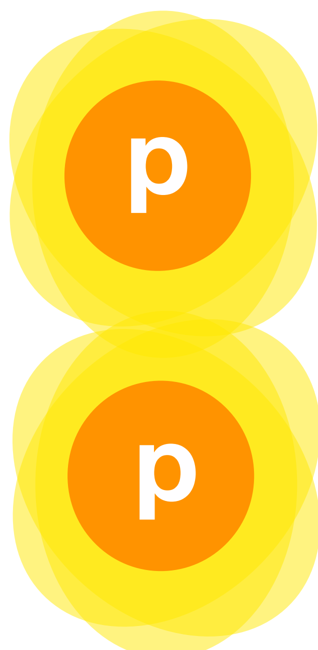
Photon-photon collision!

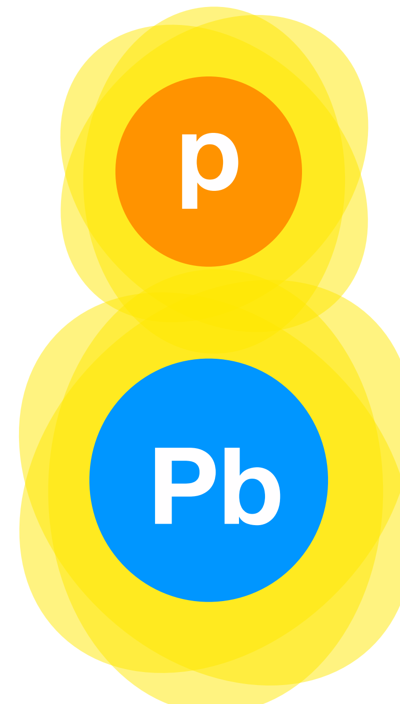


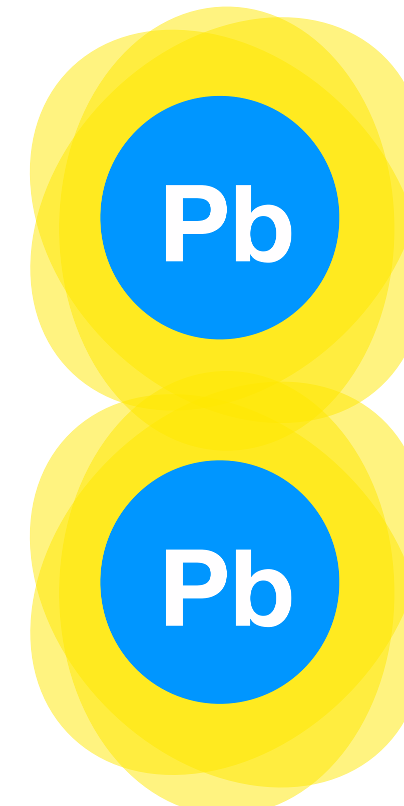
Budnev et al [Phys.Rept. 15 (1975) 181-281]

LHC collisions

LHC Run 2
2015-2018





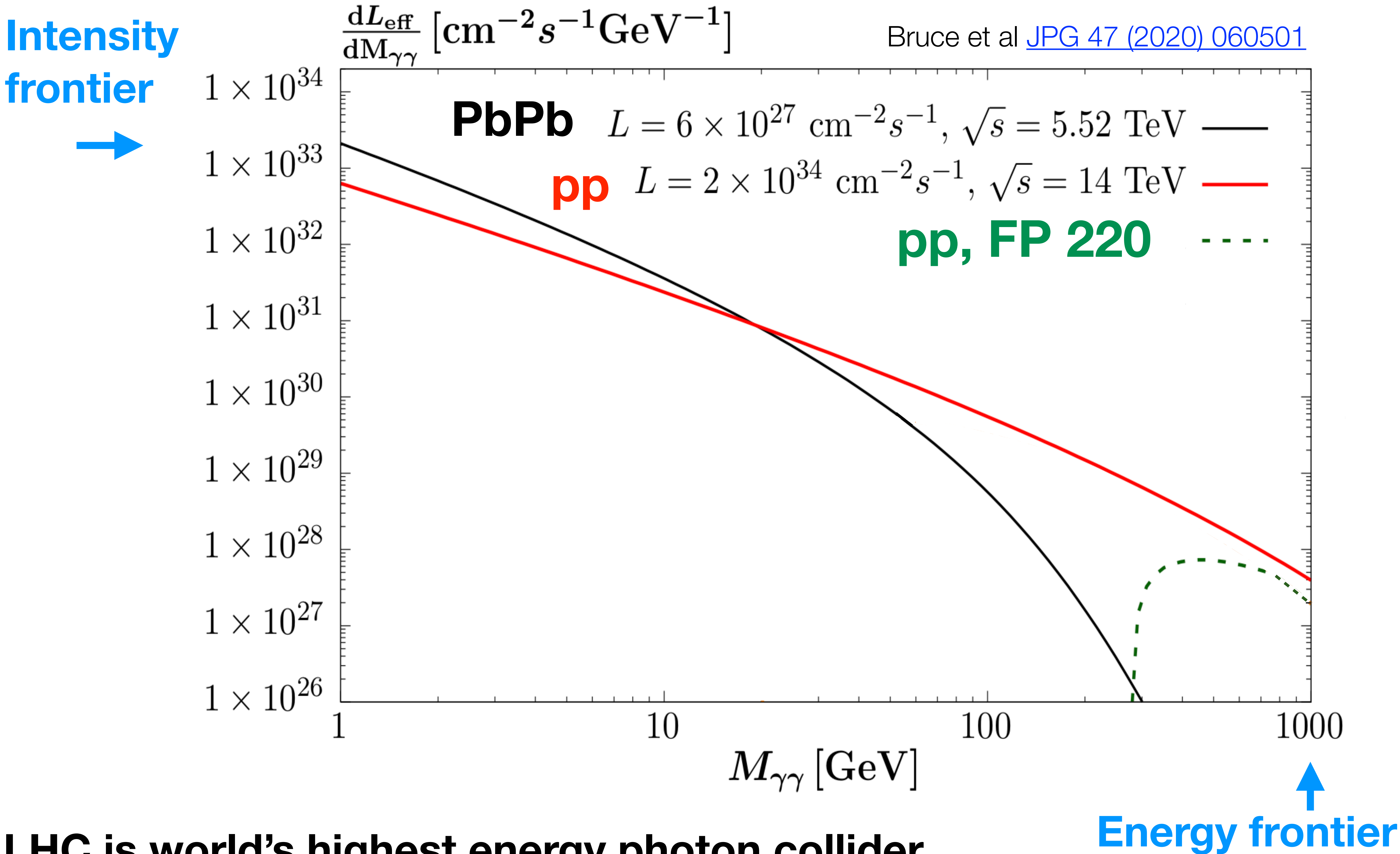


ATLAS

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

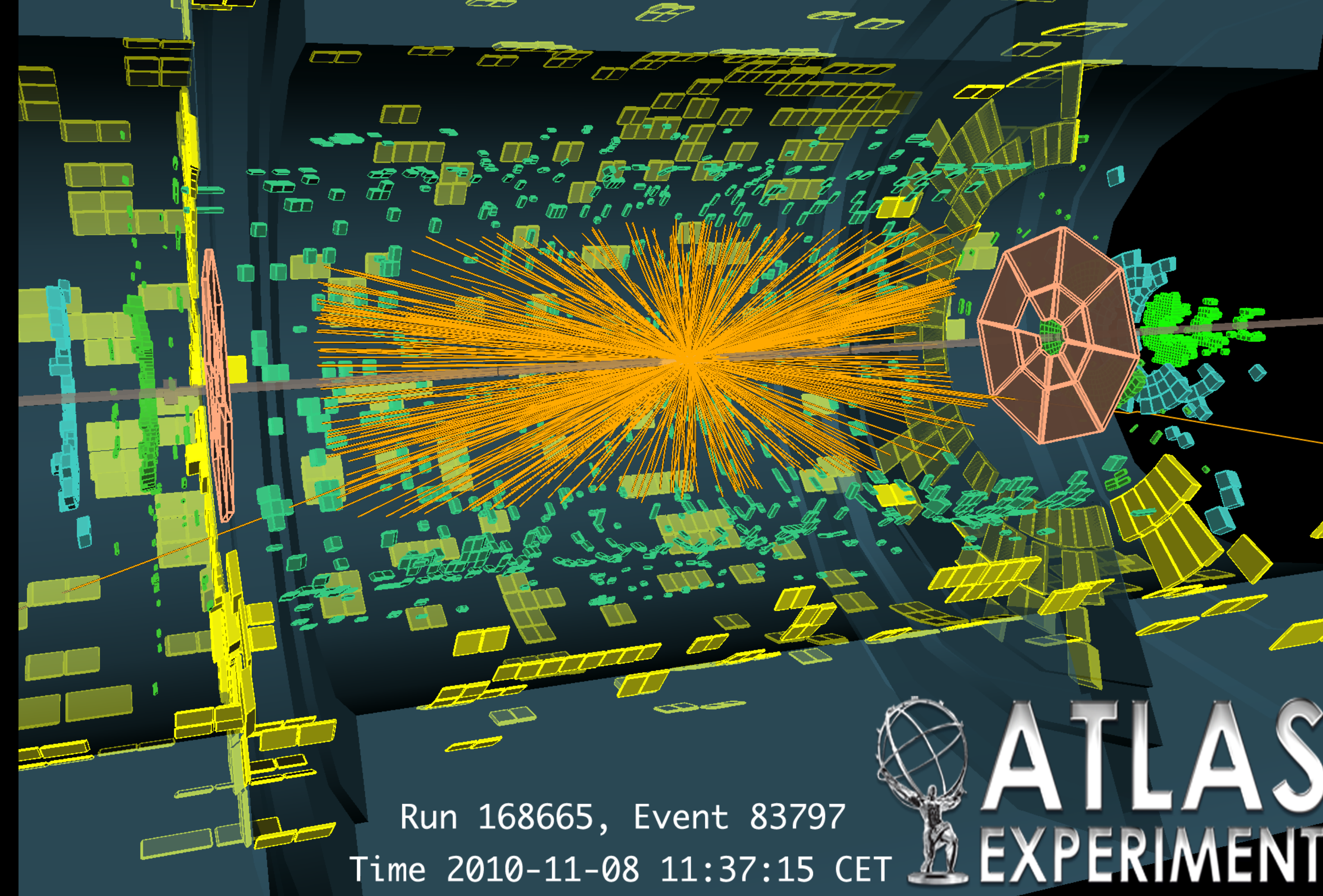
Z = 82 for Pb

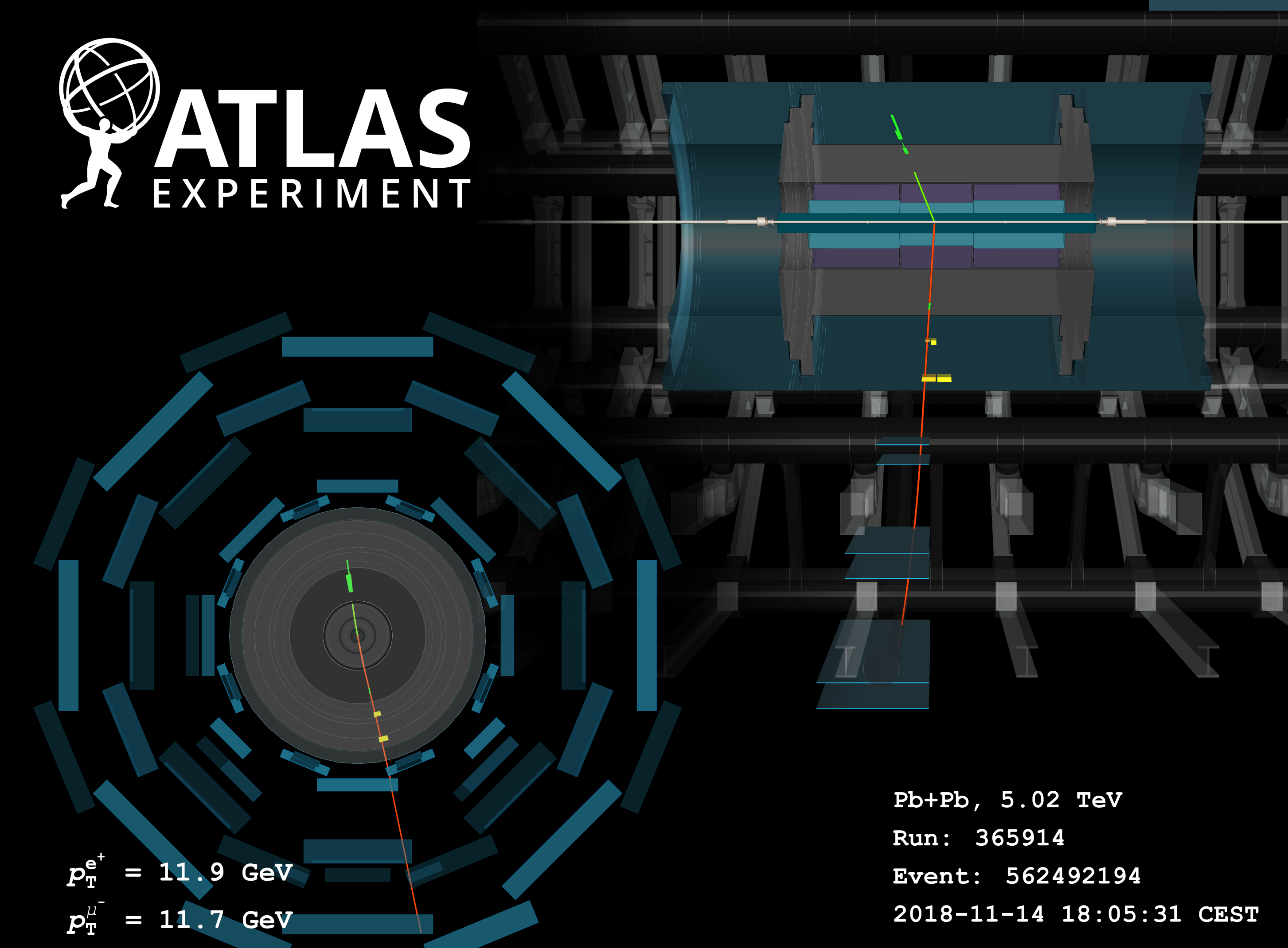
Broadband photon collider



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

Head-on Pb+Pb collision





Ultra-peripheral Pb+Pb collision

ATLAS forward detectors & LHCf

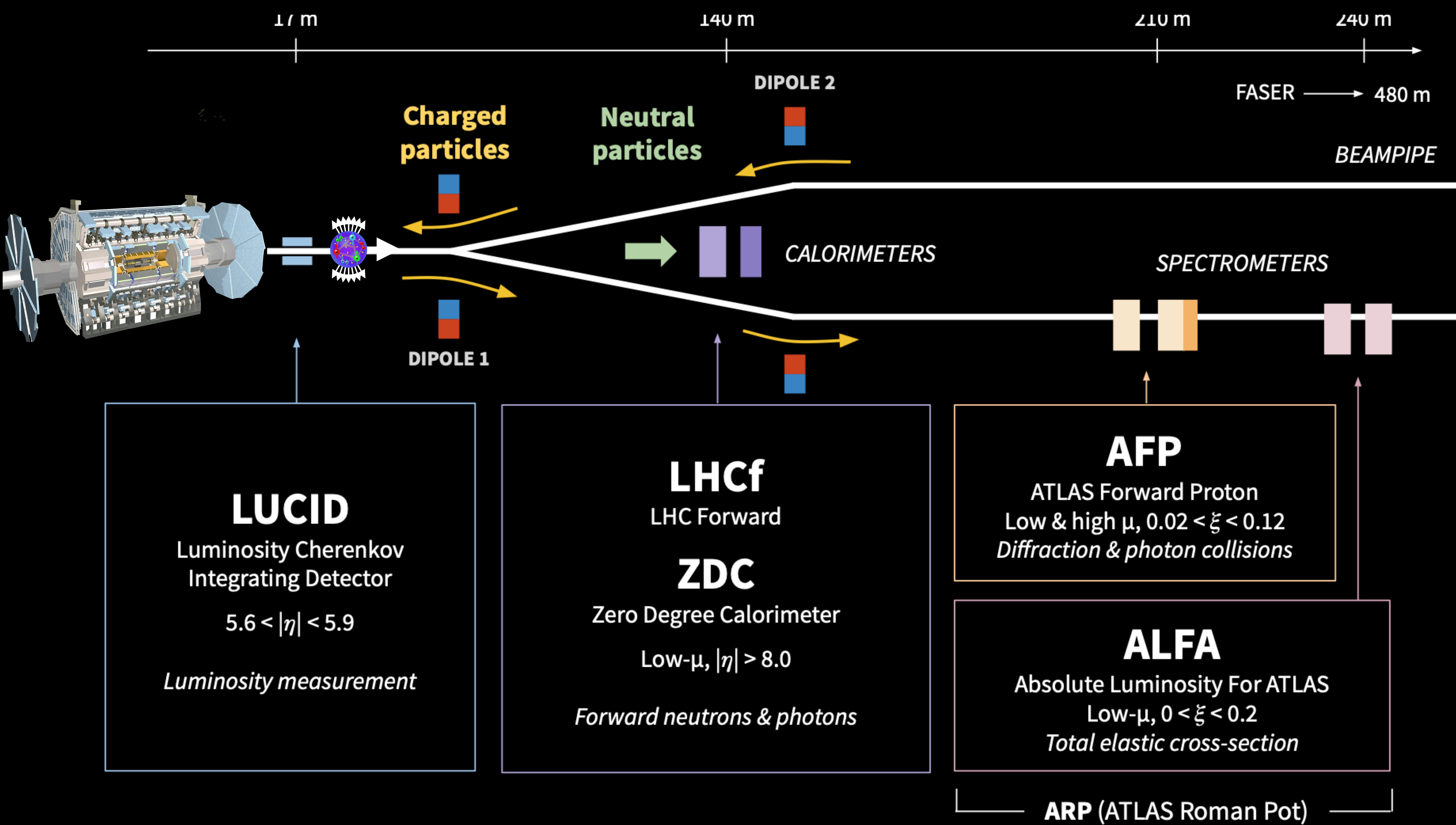
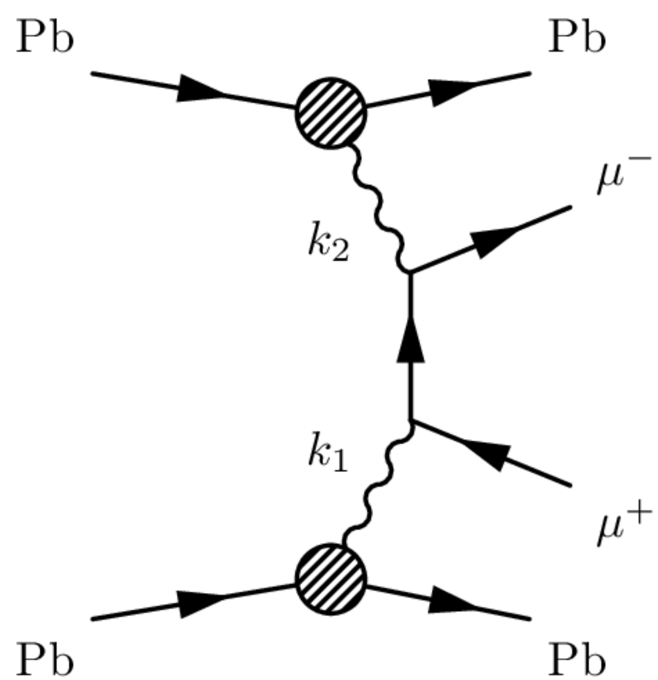


Diagram by Jesse Liu

ATLAS Pb+Pb UPC $\gamma\gamma \to \mu\mu$

PRC 104 (2021) 024906

Goal: Study γ flux & dependence on neutron emission

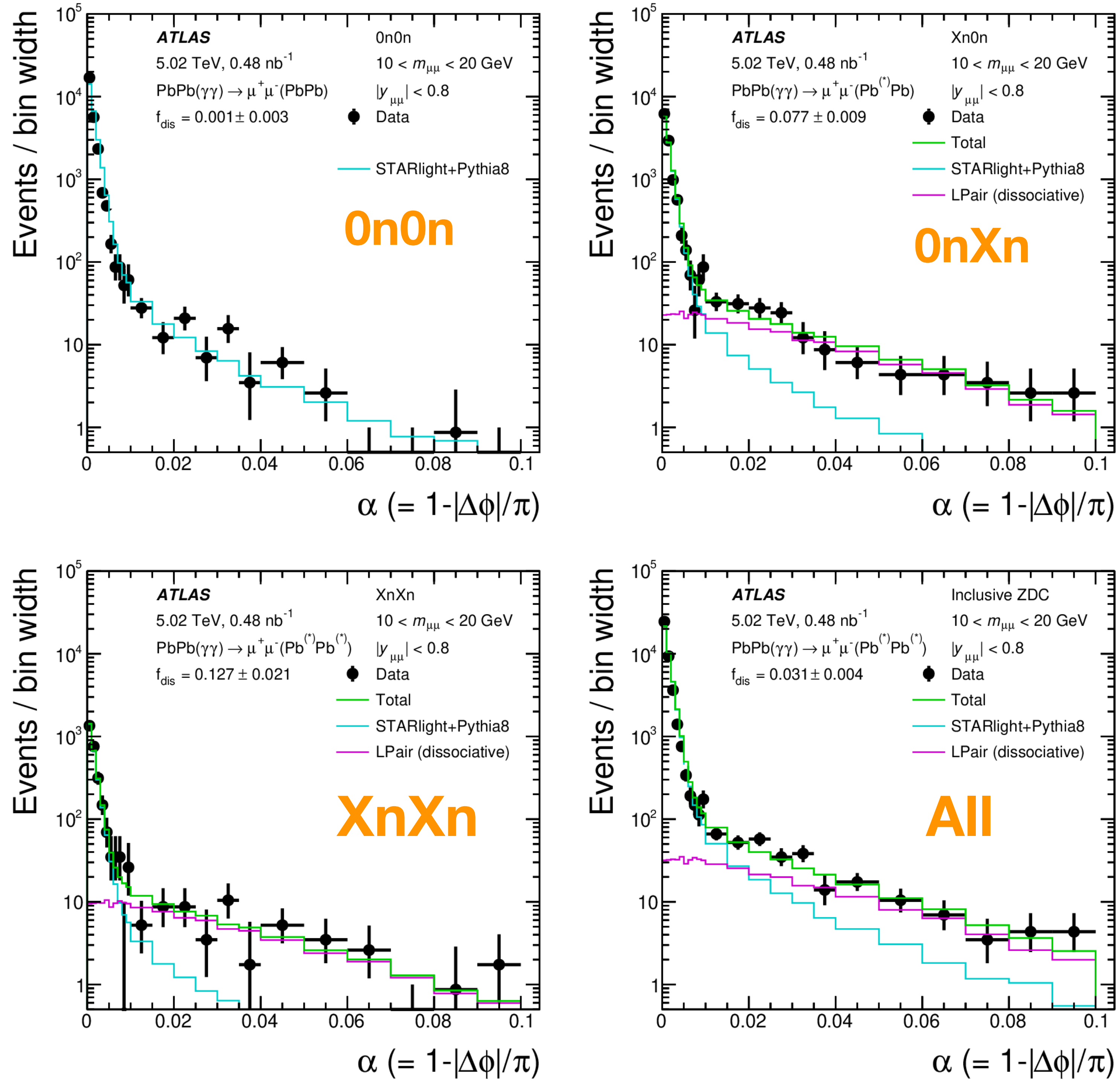


Acoplanarity tails depend on neutron topology

Dissociation is dominant effect

→ Described by LPair

& by SuperChic in ee channel



Use ZDC to categorise events:

0n0n no neutrons in ZDCs, **0nXn** no neutrons in one, $\geq$ 1 in other, **XnXn** $\geq$ 1 neutron in both

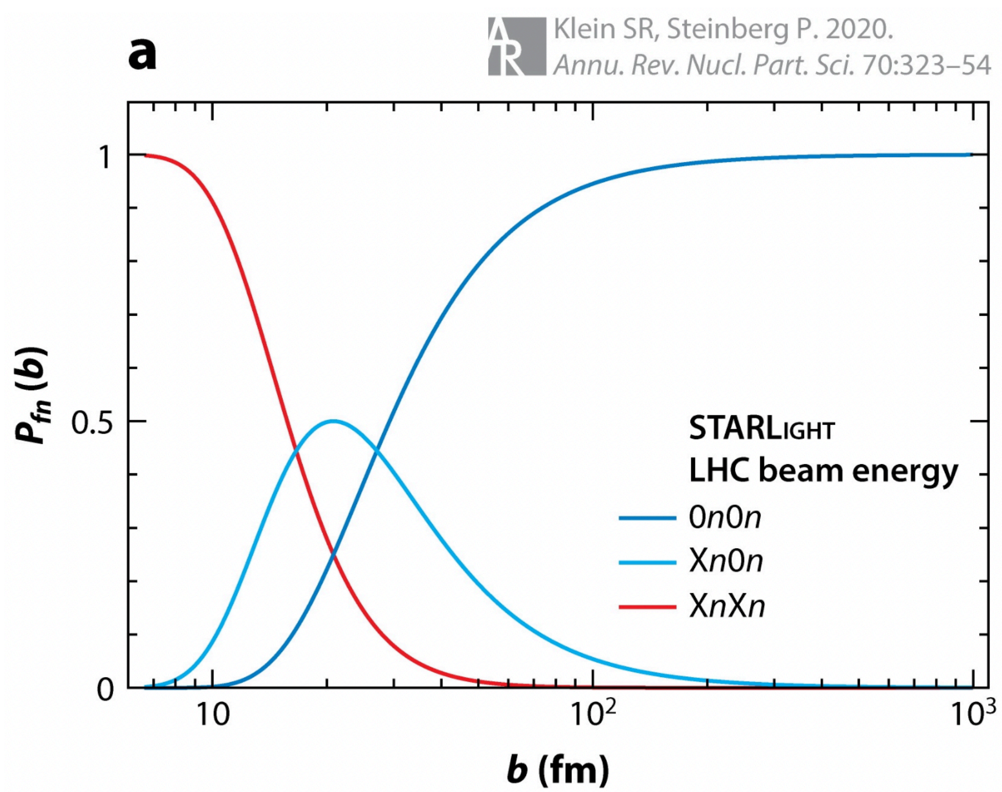
CMS Pb+Pb UPC $\gamma\gamma \rightarrow \mu\mu$

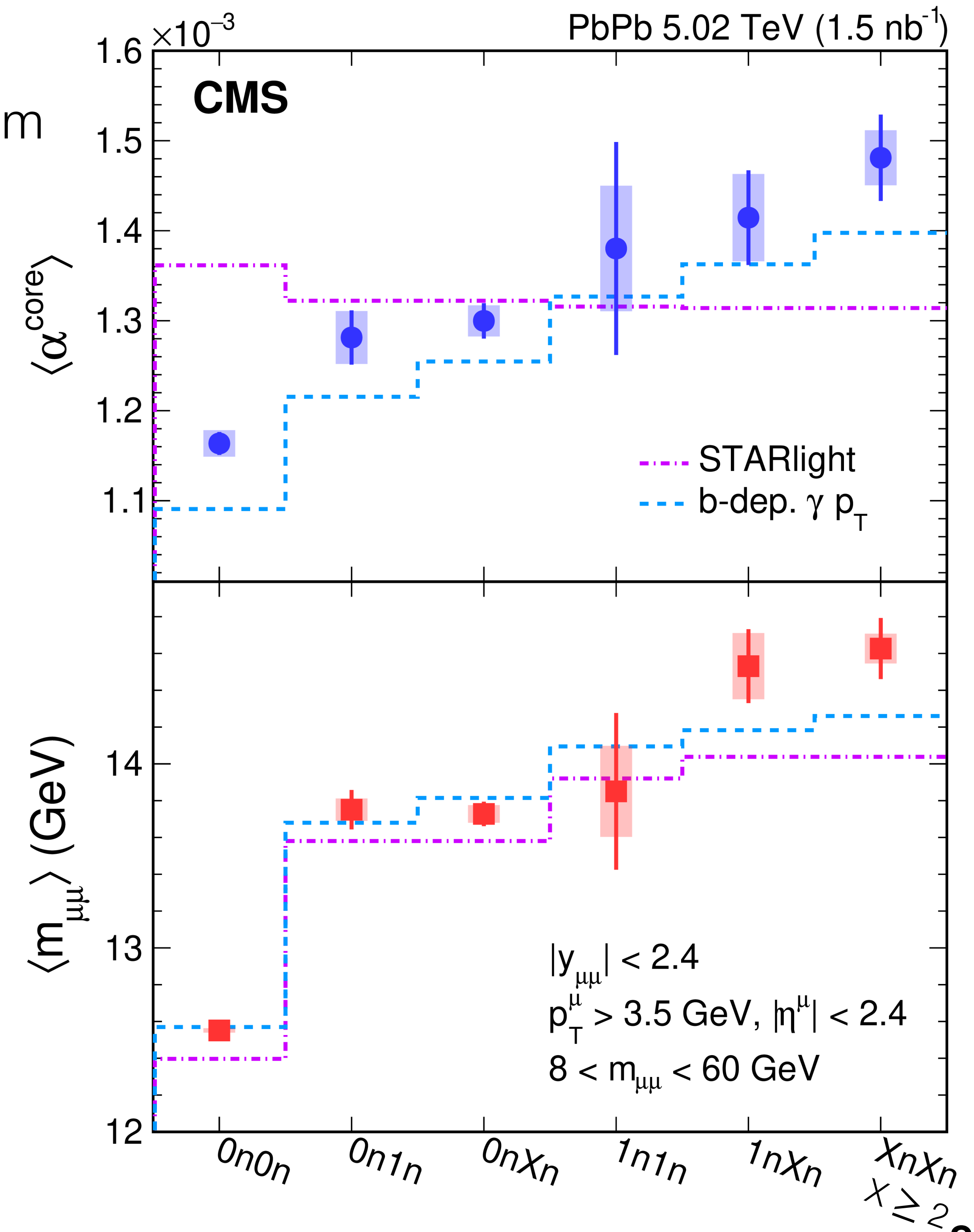
[PRL 127 (2021) 122001]

Goal: Study γ flux & dependence on neutron emission

Requiring ZDC signal

→ Smaller impact parameter (b), harder γ spectrum





Strong dependence on n multiplicity

- Acoplanarity broadening
- Higher mass

Qualitatively described by LO QED model with b dependence of initial γ p_T

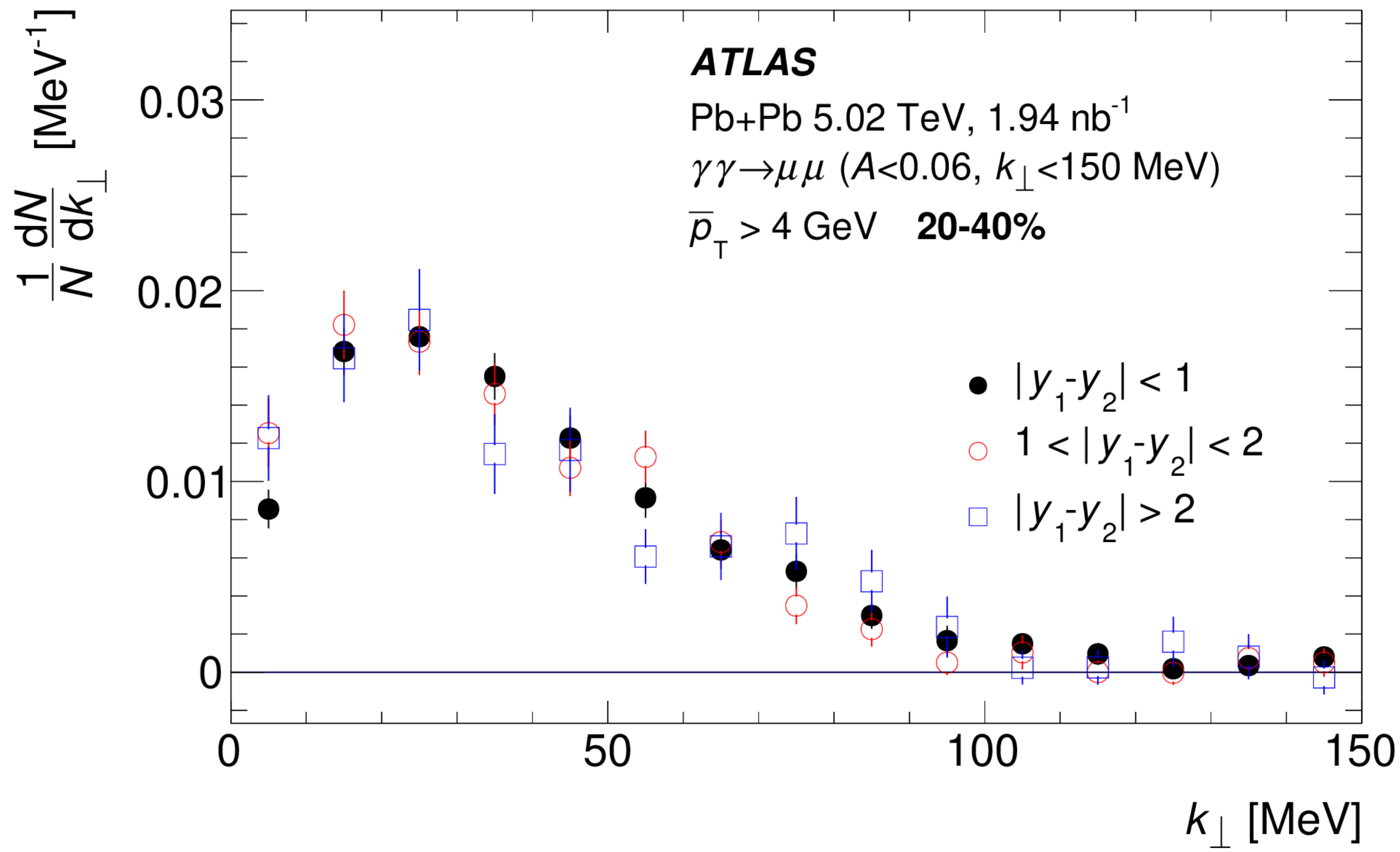
ATLAS Pb+Pb non-UPC $\gamma\gamma \rightarrow \mu\mu$

PRC 107 (2023) 054907

Acoplanarity & $k_\perp$ broadening for less peripheral collisions

UPC: peaked at zero

More central Pb+Pb: peaked away from zero



Is it due to muons being deflected in magnetic fields generated in QGP?

Prediction from PRL 122 132301: Broadening would vary as $\tanh|\Delta y|$

(suppression near $k_\perp = 0$ greater for larger $|\Delta y|$)

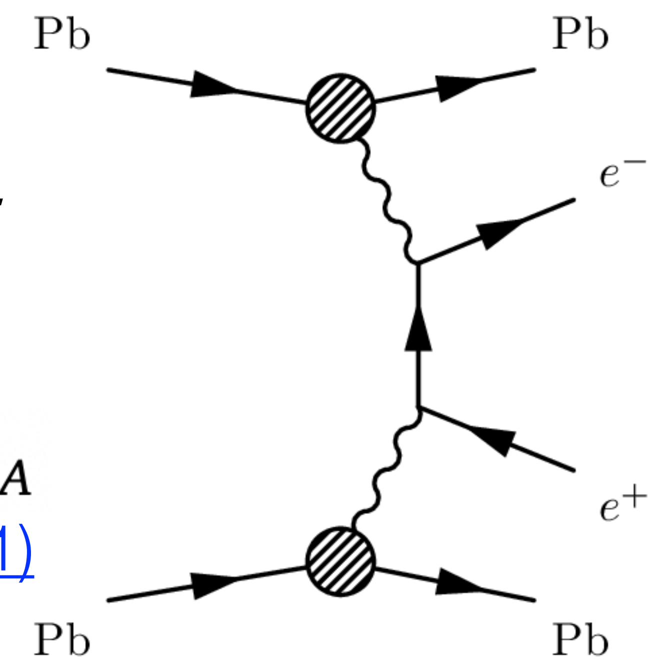
No strong dependence on $|\Delta y|$ observed

$$k_\perp \equiv \frac{1}{2}(p_{T1} + p_{T2})(\pi - |\phi_1 - \phi_2|) = \pi\alpha\bar{p}_T$$

ATLAS Pb+Pb UPC $\gamma\gamma \to ee$

JHEP 06 (2023) 182

Goal: Study γ flux & dependence on neutron emission

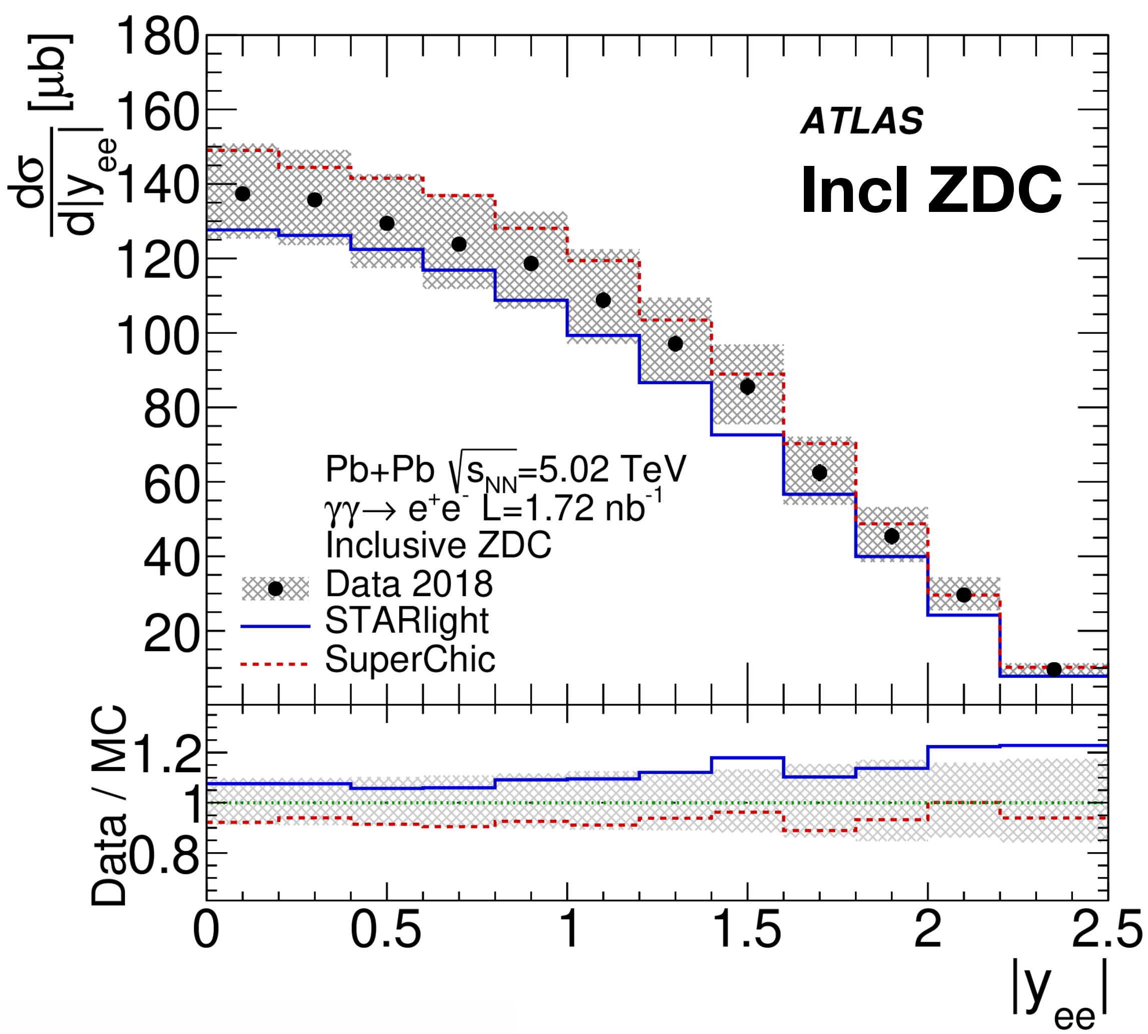


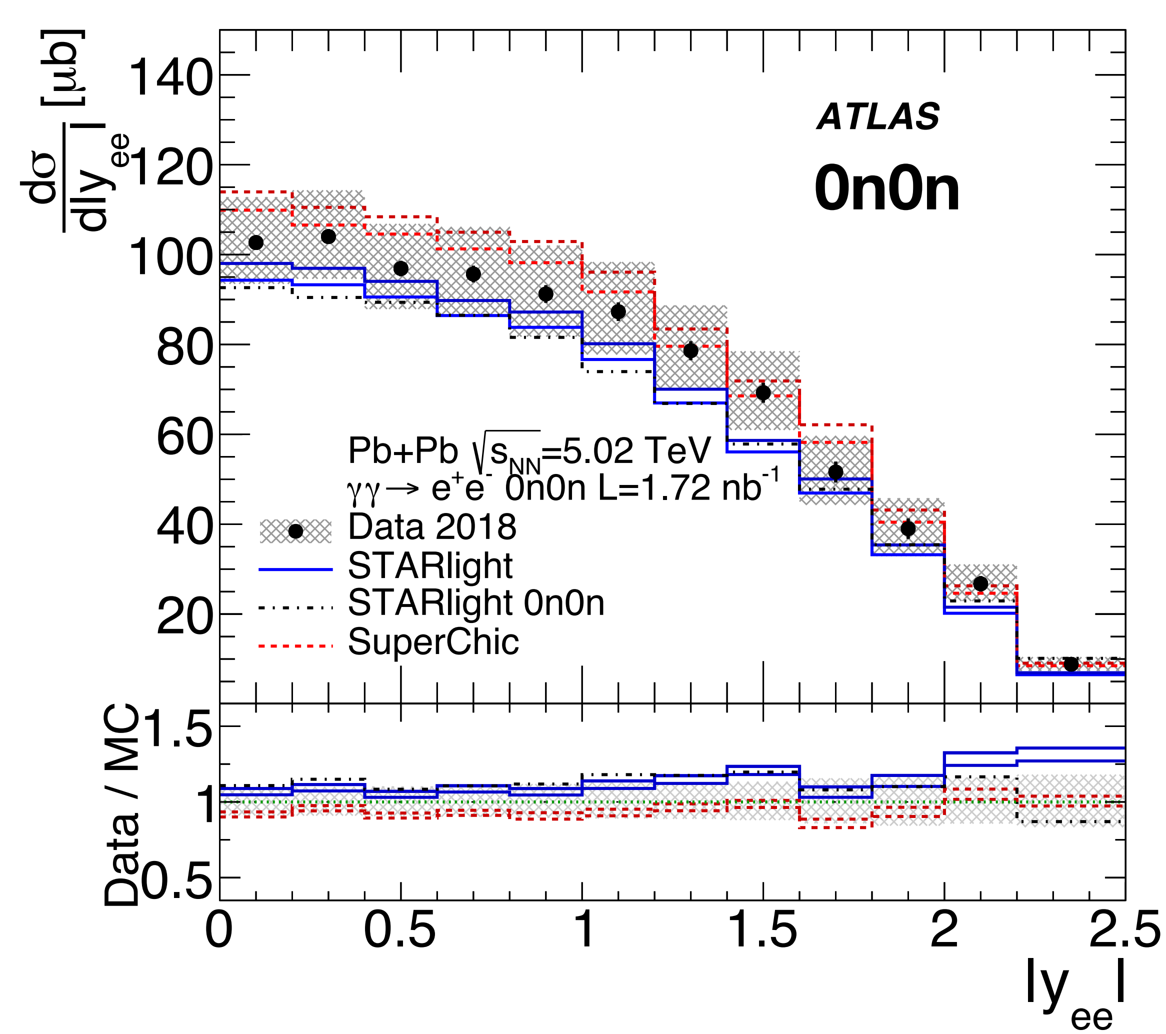
Measure cross-section after subtracting dissociation, Υ & $\tau\tau$

For inclusive ZDC (All) & 0n0n:

- STARlight underestimates Esp. at high $|y_{ee}|$ as require $b_{i\perp} > R_A$
- SuperChic overestimates

SPP 11 064 (2021)

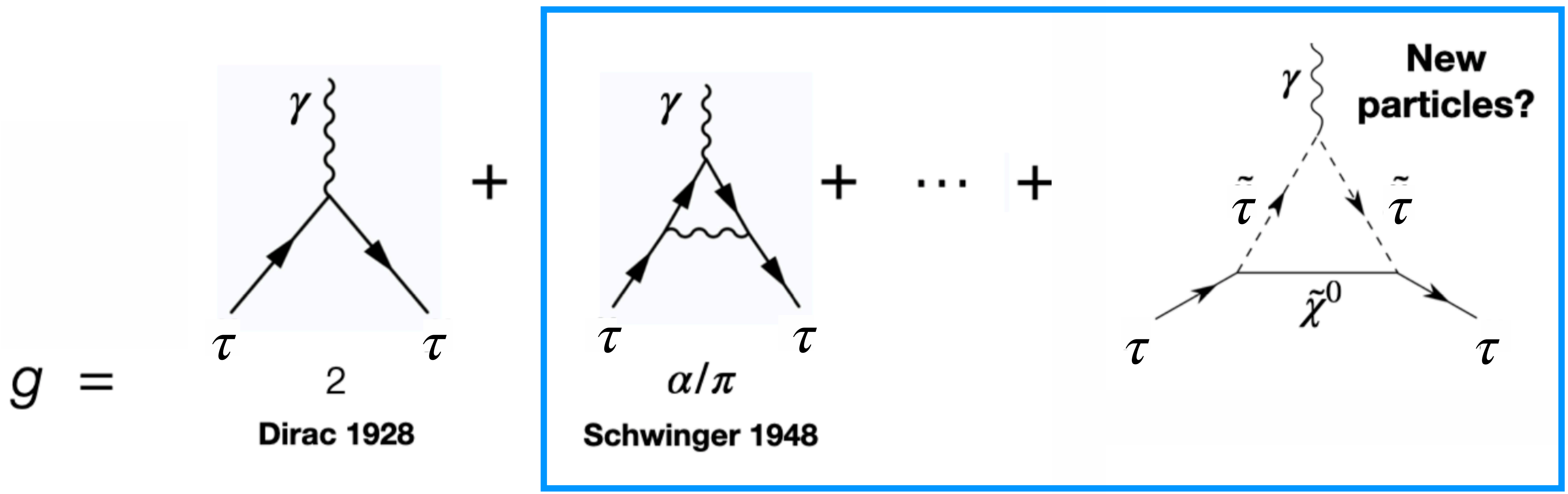




ATLAS & CMS Pb+Pb UPC $\gamma\gamma \rightarrow \tau\tau$

Goal: measure the tau anomalous magnetic moment 'g-2'

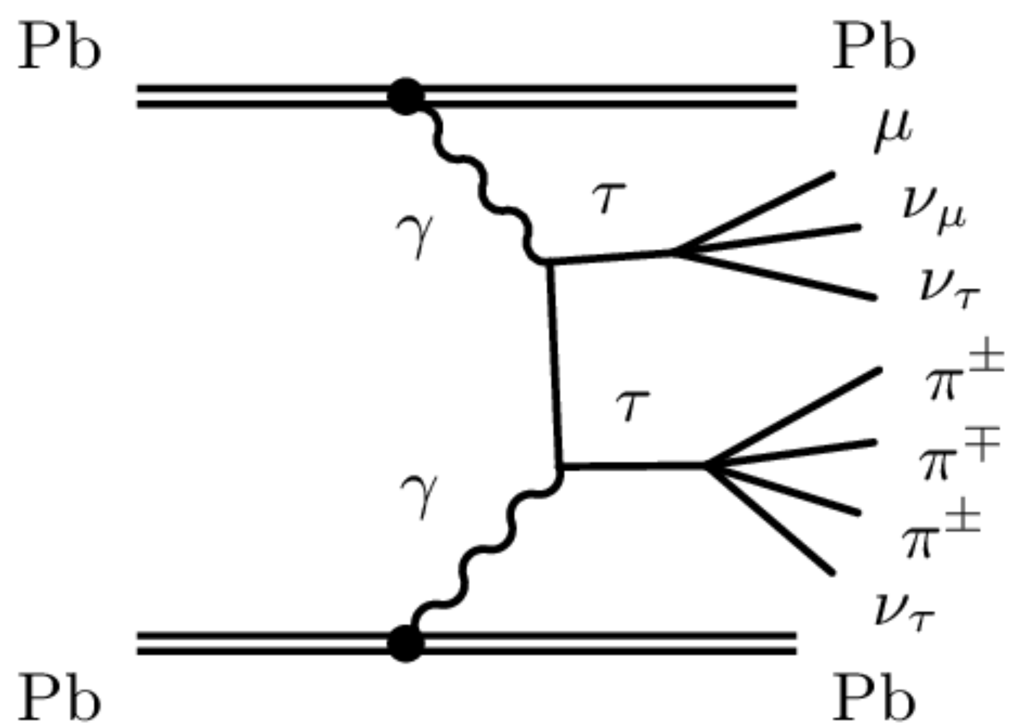
Spin 1/2 charged particles **magnetic moment:** $\boldsymbol{\mu} = g \frac{q}{2m} \boldsymbol{S}$



Anomalous magnetic moment: $a = \frac{(g-2)}{2}$

ATLAS & CMS Pb+Pb UPC $\gamma\gamma \to \tau\tau$

$\gamma\gamma \to \tau\tau$ cross-section & lepton p_T sensitive to tau g-2



ATLAS: 2018 data ~1.5 nb^{-1}

$e\mu$, μ+1 track & μ+3 tracks (μ p_T > 4 GeV)

- Measure differentially in muon p_T
- Constrain γ-flux in $\gamma\gamma \to \mu\mu$ CR

CMS: 2015 data ~0.5 nb^{-1}

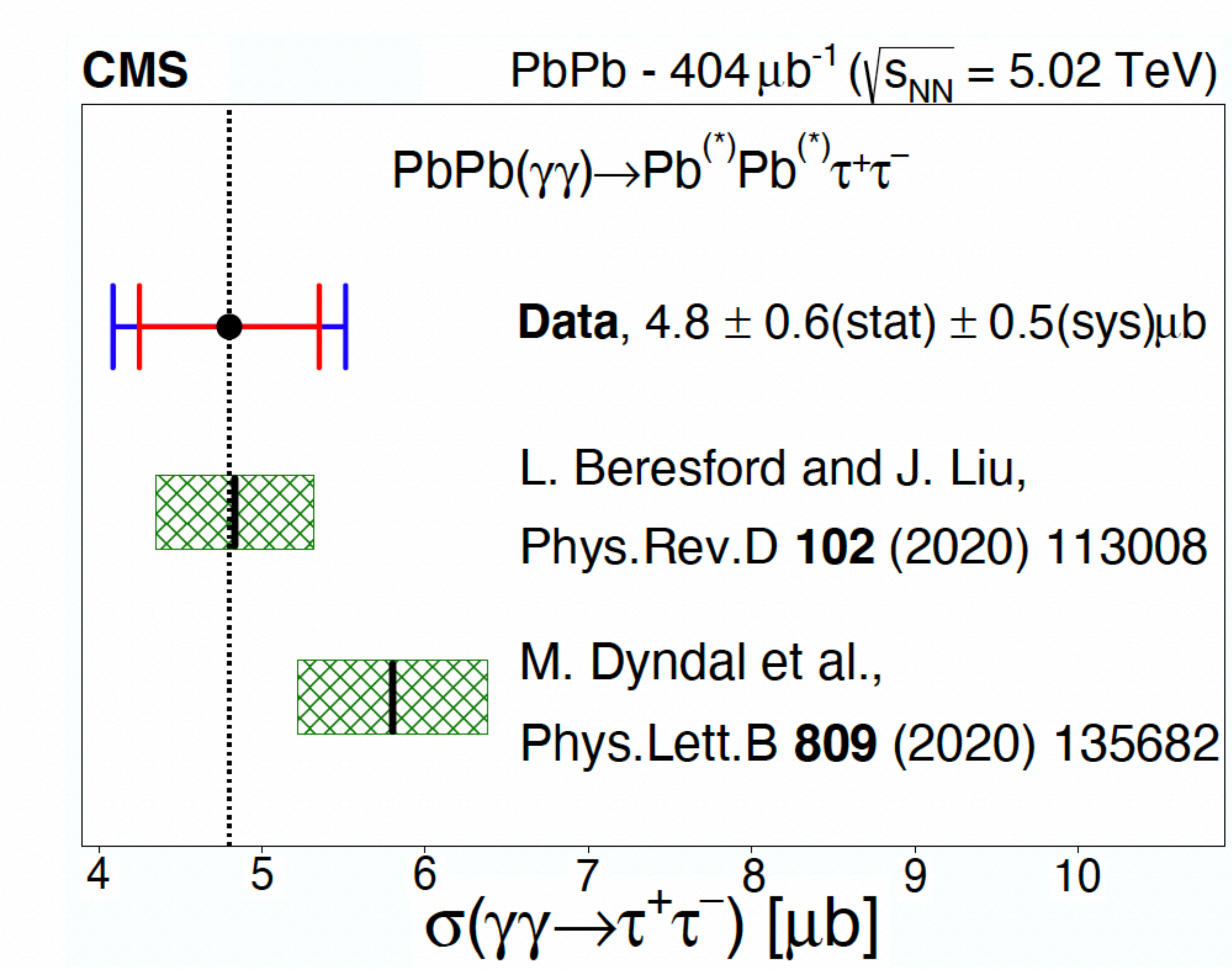
μ+3 tracks (μ p_T > 2.5 GeV)

ATLAS & CMS clear observation of $\gamma\gamma \to \tau\tau$ in Pb+Pb

CMS Pb+Pb UPC $\gamma\gamma \to \tau\tau$

PRL 131 (2023) 151803

Cross-section measurement of $\gamma\gamma \to \tau\tau$

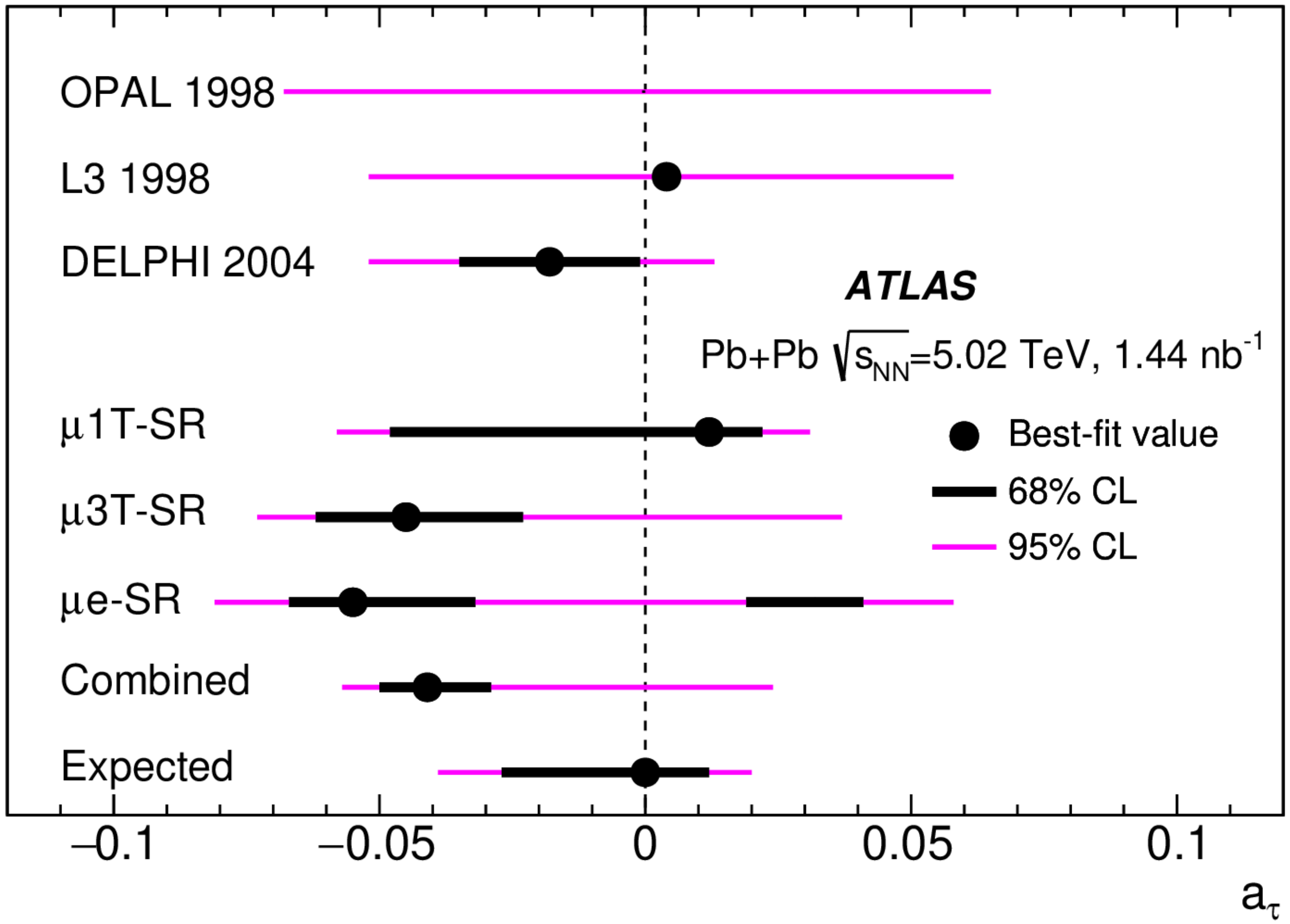


$$a_\tau = 0.001^{+0.055}_{-0.089}$$ at 68% CL

ATLAS Pb+Pb UPC $\gamma\gamma \rightarrow \tau\tau$

PRL 131 (2023) 151802

ATLAS constraints competitive with DELPHI



ATLAS & CMS set first new constraints on a_τ since 2004

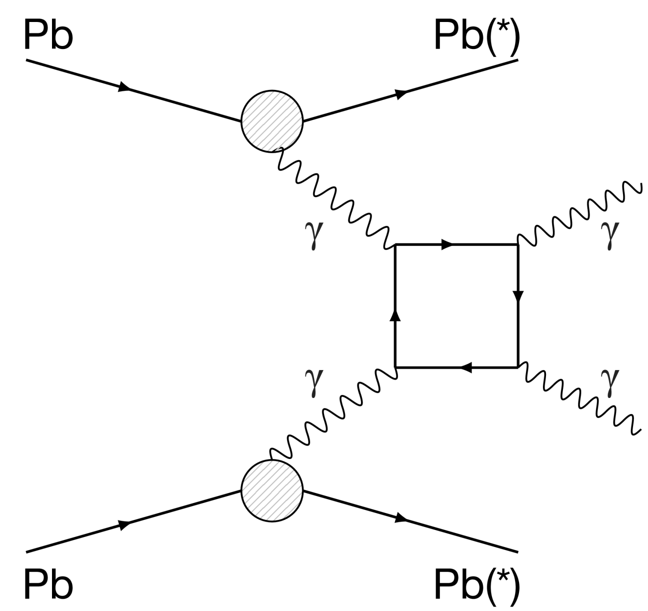
For both ATLAS & CMS statistical uncertainty dominates

First measurements of τ leptons in heavy ion collisions

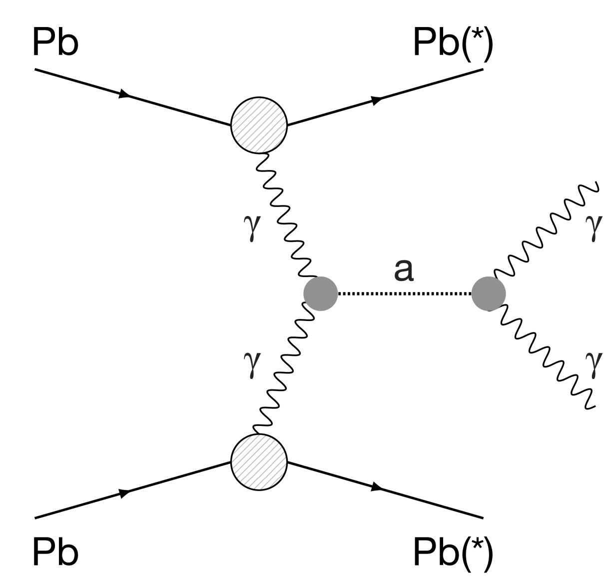
ATLAS & CMS Pb+Pb UPC $\gamma\gamma \rightarrow \gamma\gamma$

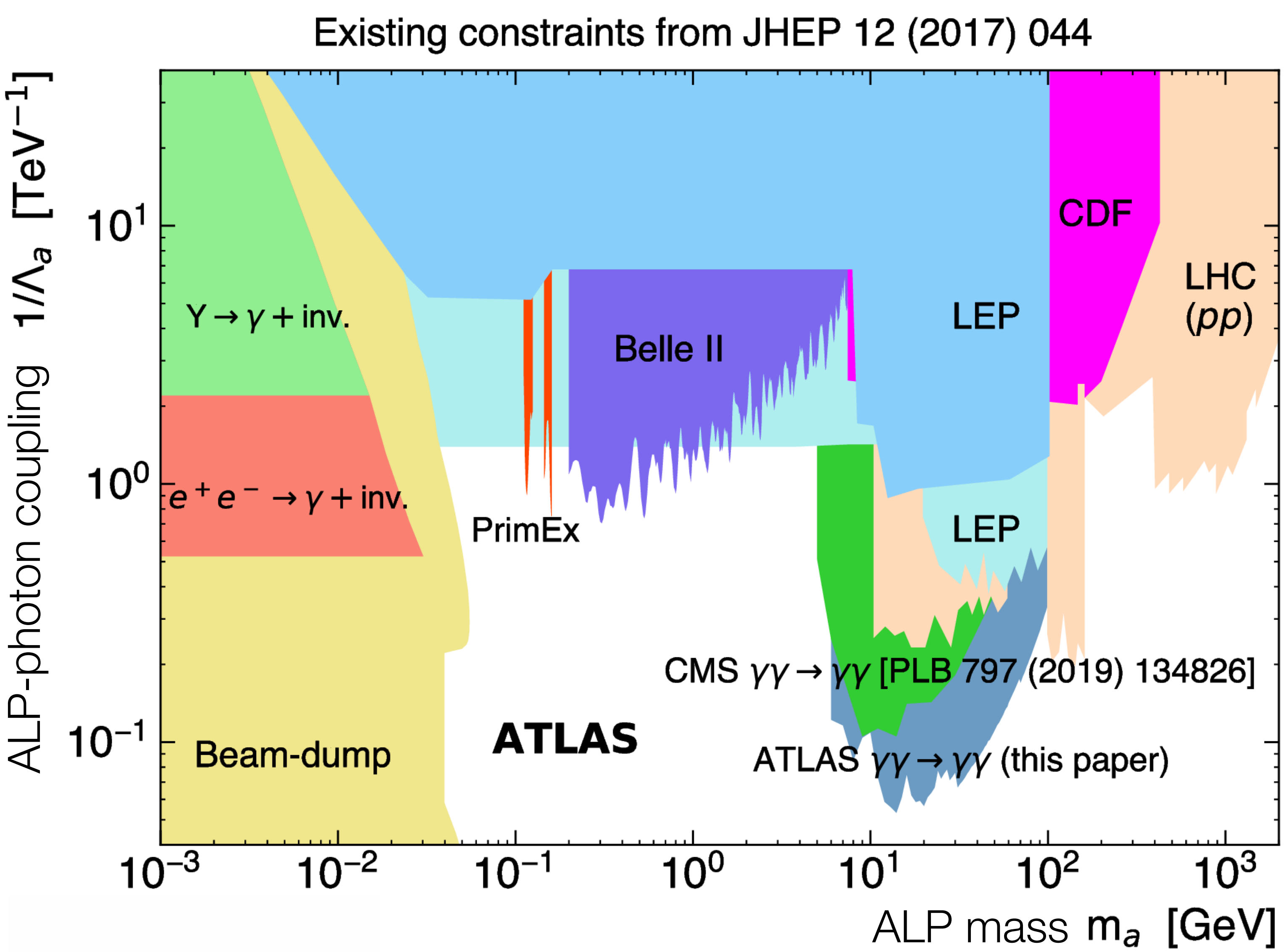
PLB 797 (2019) 134826
JHEP 03 (2021) 243

SM light-by-light scattering discovered at ATLAS



BSM Axion-Like-Particle (ALP)

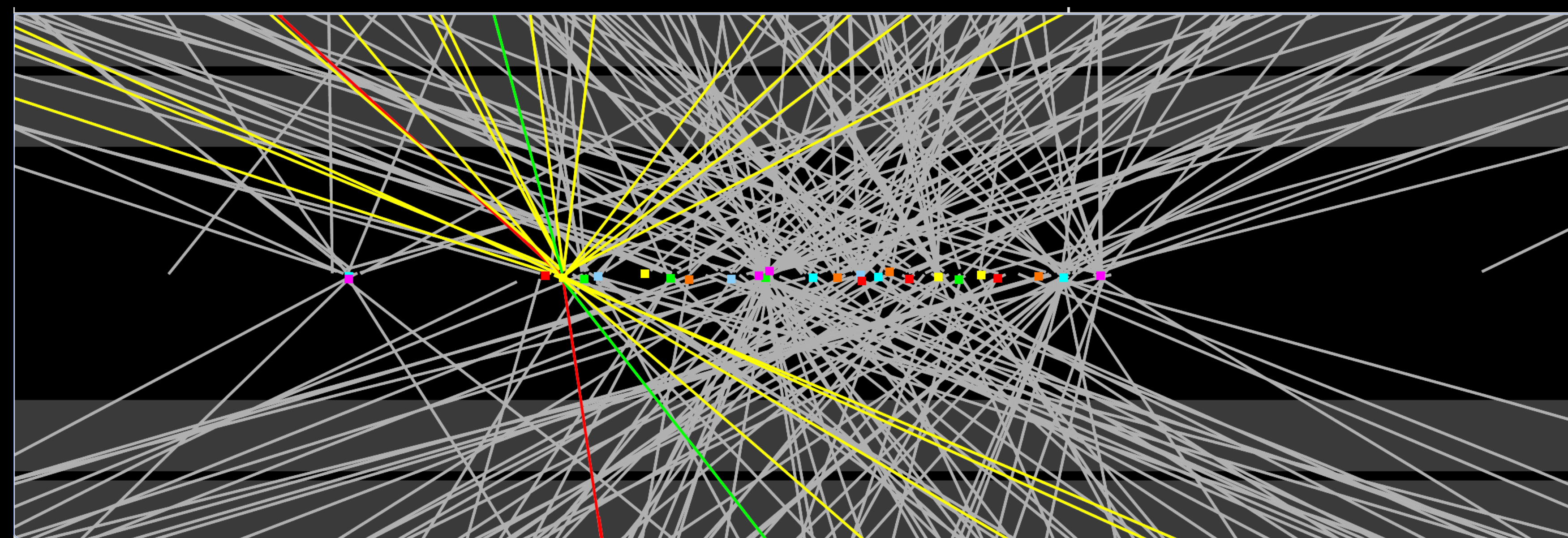




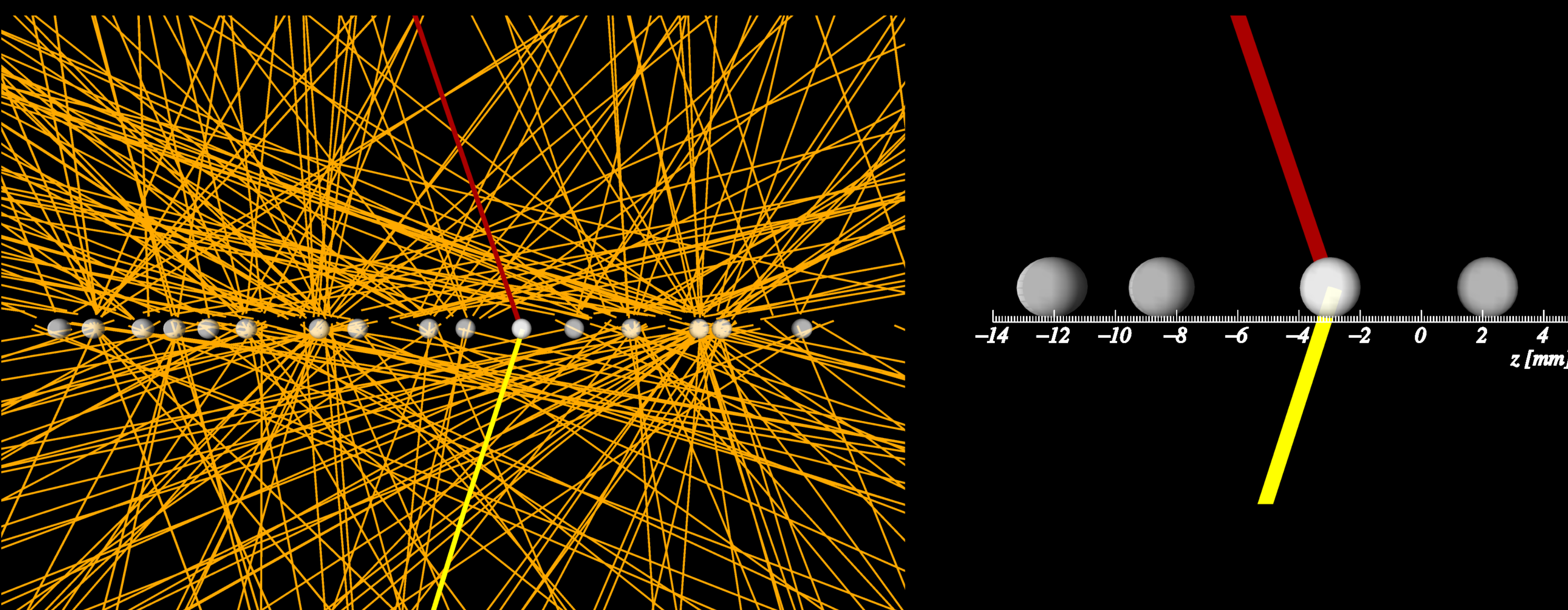
Look for narrow resonance in $m_{\gamma\gamma}$

ATLAS: $E_\gamma > 2.5$ GeV, CMS: $E_\gamma > 2$ GeV

Head-on pp collision



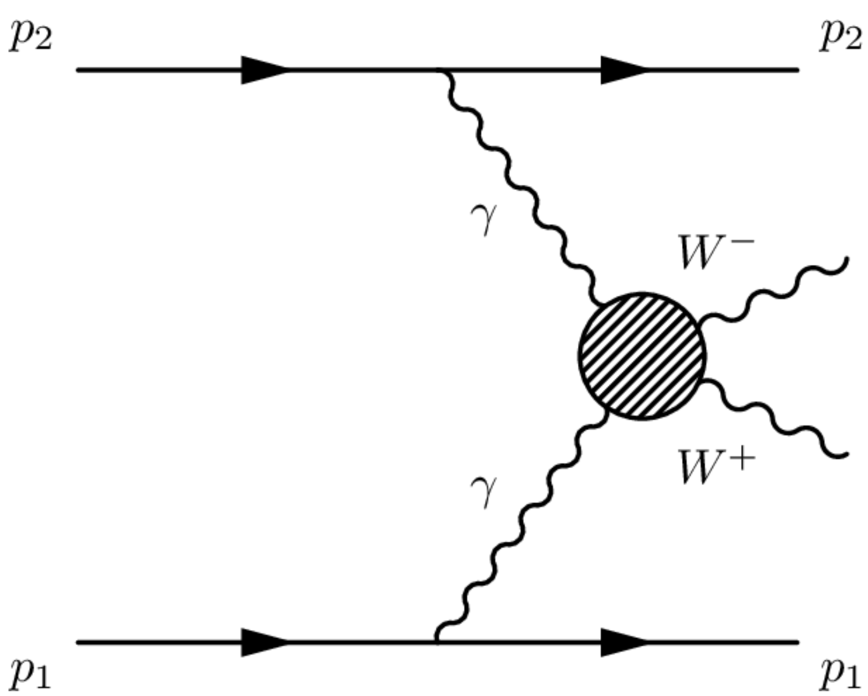
Photon-fusion pp collision



ATLAS pp $\gamma\gamma \to WW$ leptonic

PLB 816 (2021) 136190

Observation of new process

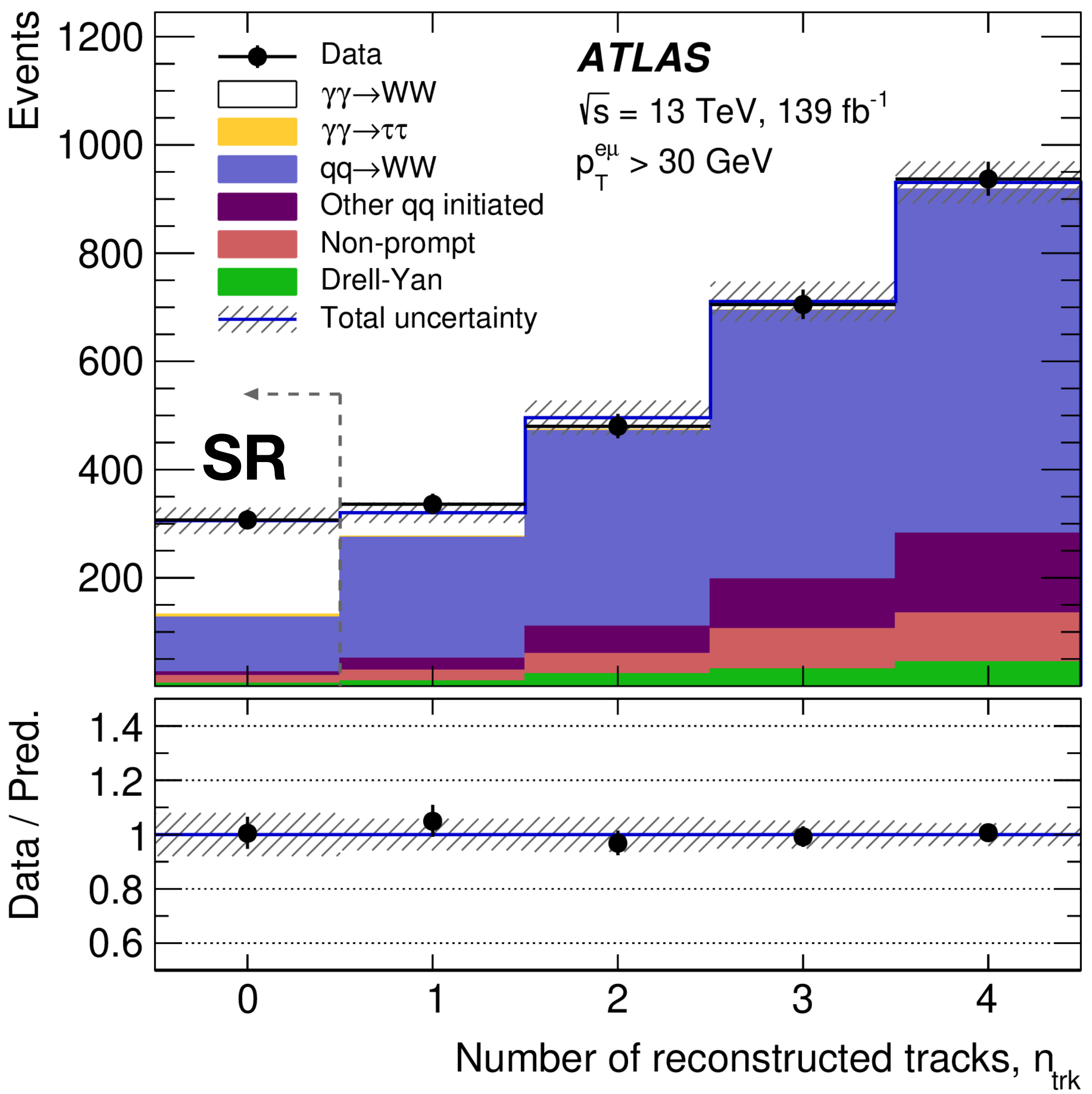


8.4σ significance

$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\text{ fb}$$

Sensitive to anomalous gauge self-interactions

Key variable



Exploit track veto within 1 mm window of $e\mu$ vertex

ATLAS forward detectors & LHCf

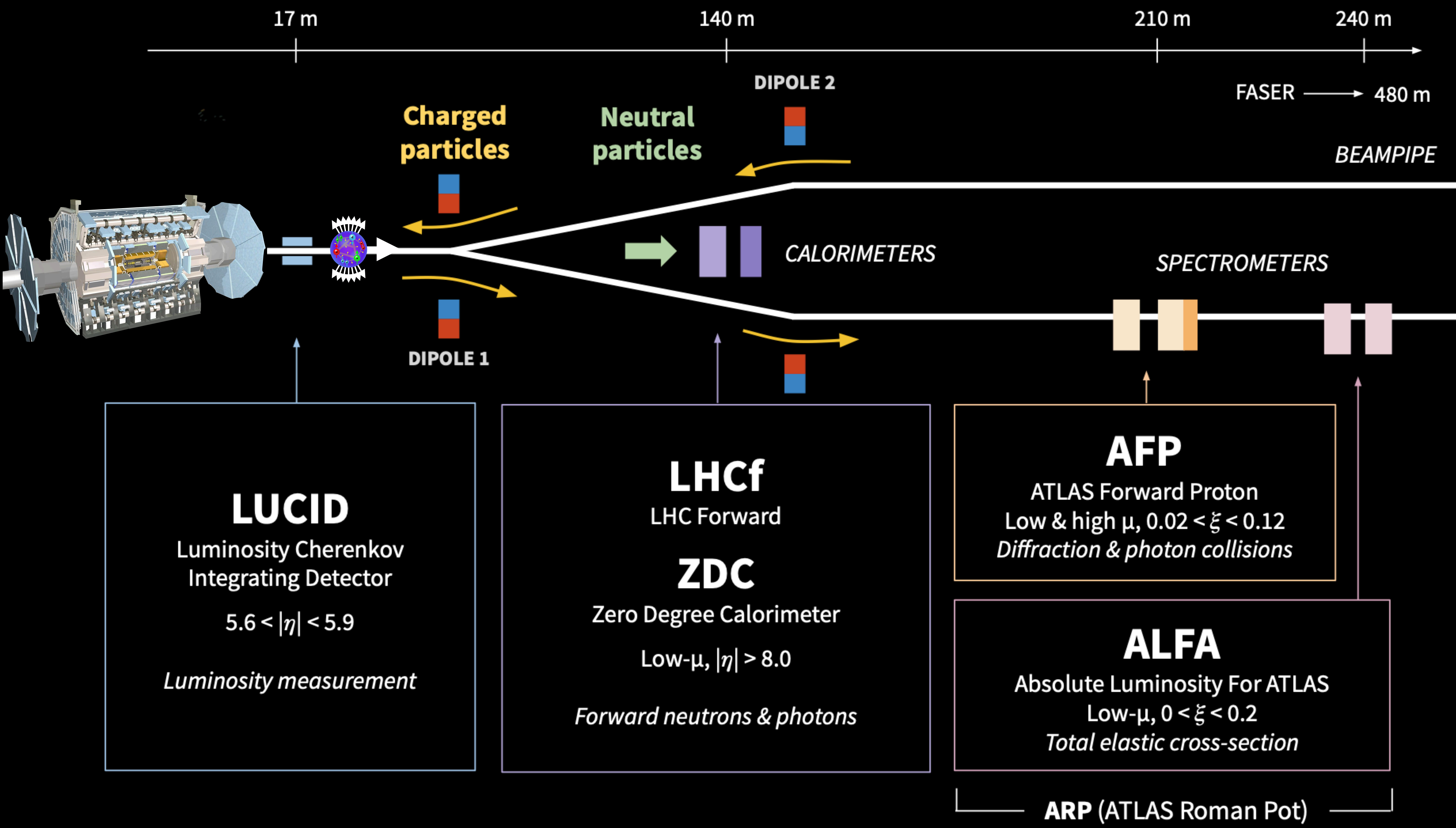
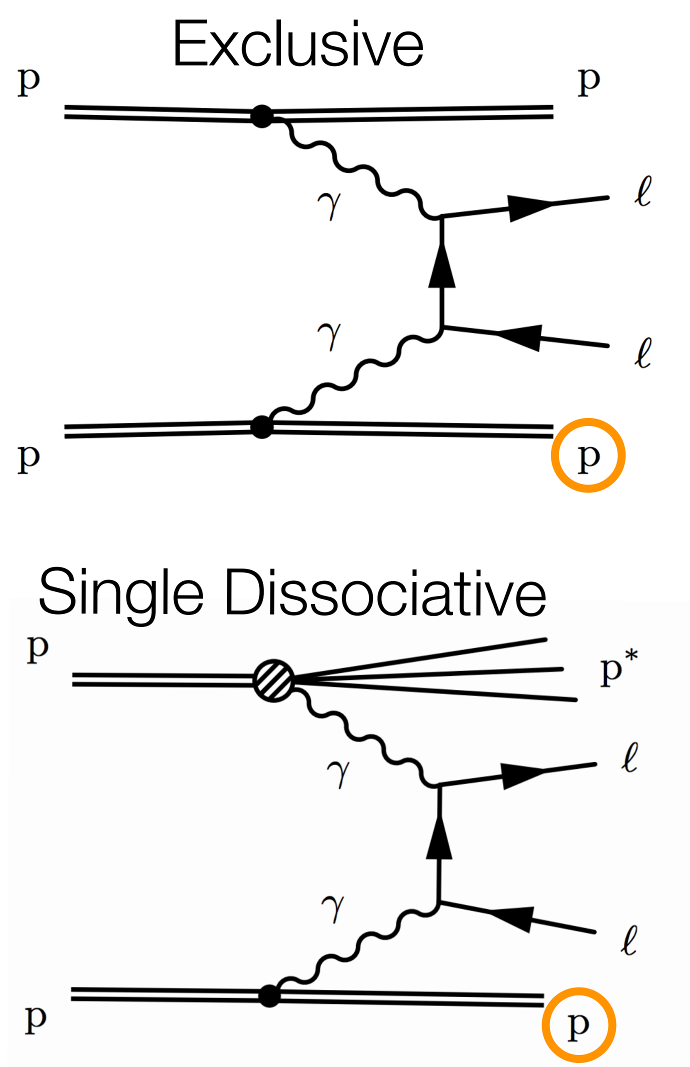


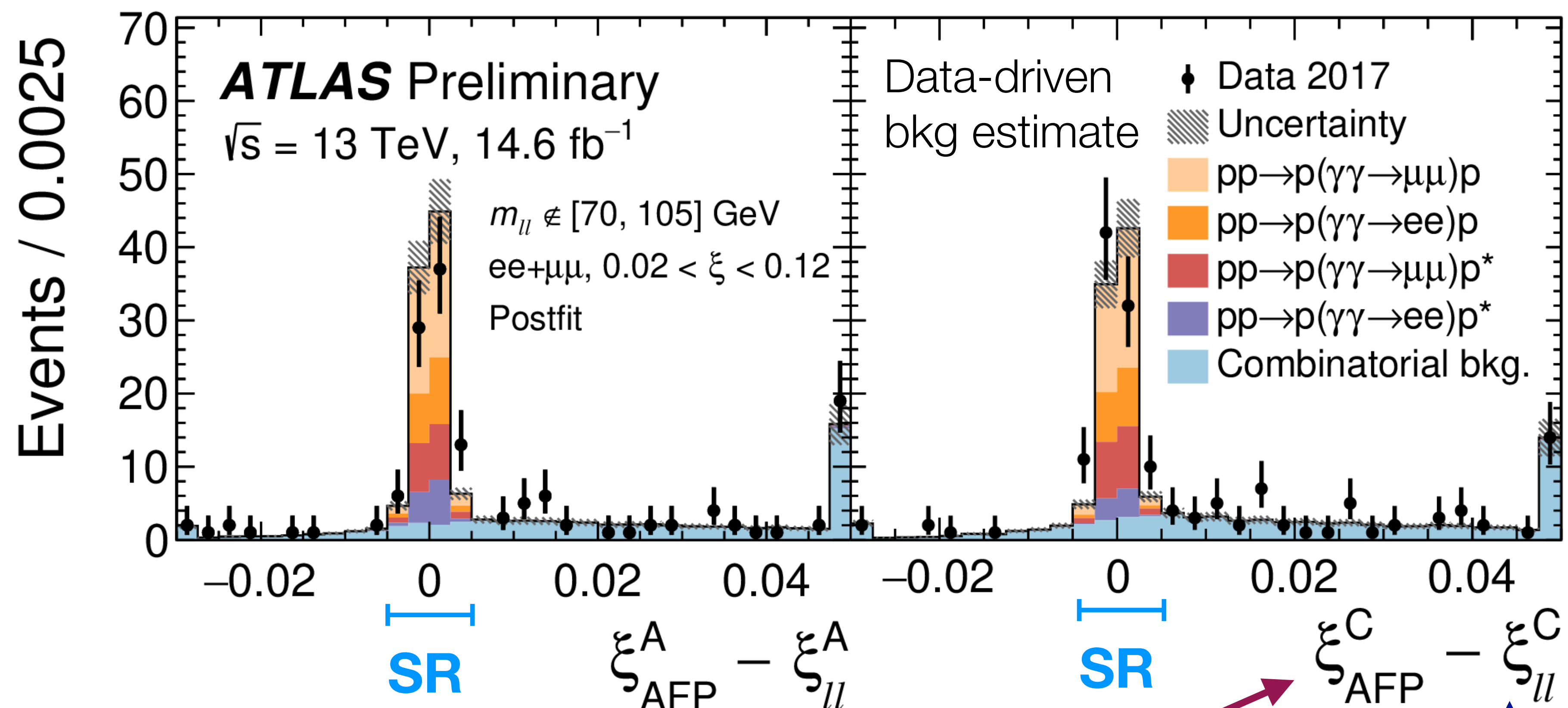
Diagram by Jesse Liu

ATLAS & CMS pp $\gamma\gamma \to ll$ + AFP/PPS

CMS pp ll + p: 1st observation using CMS-PPS JHEP 07 (2018) 153

ATLAS $ee/\mu\mu$ + p: observation & 1st σ measurement PRL 125 (2020) 261801





Measure protons → Truly new info & powerful bkg rejection!

SR: keep 95% signal, 85% bkg rejection

Measure with AFP

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

Measure with ATLAS

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

CMS pp $Z/\gamma + X$ + PPS

EPJC 83 (2023) 827

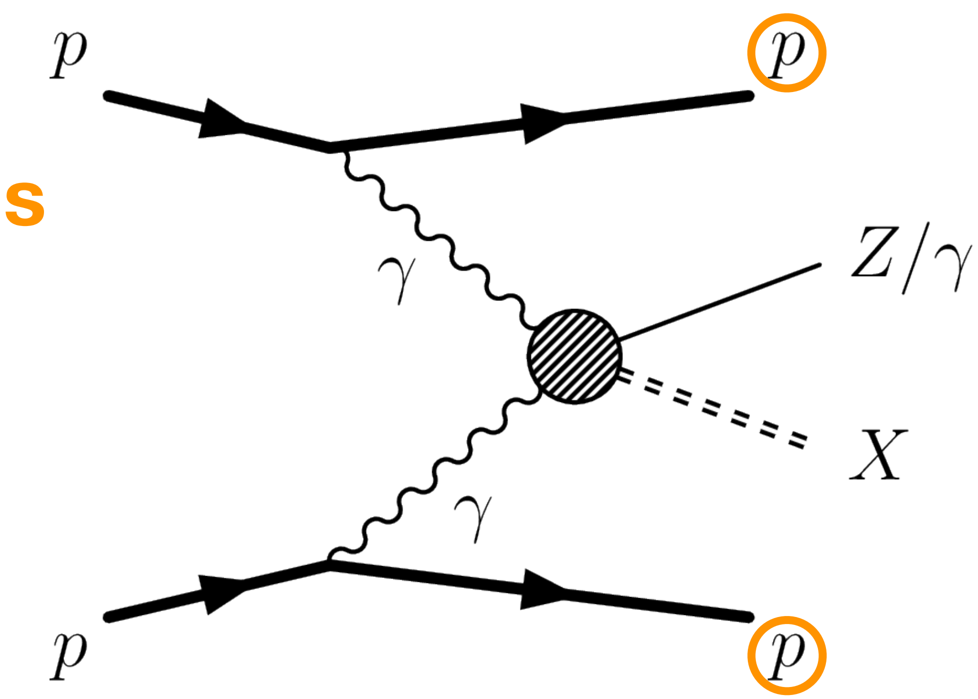
Search for $Z/\gamma + X$ + pp events

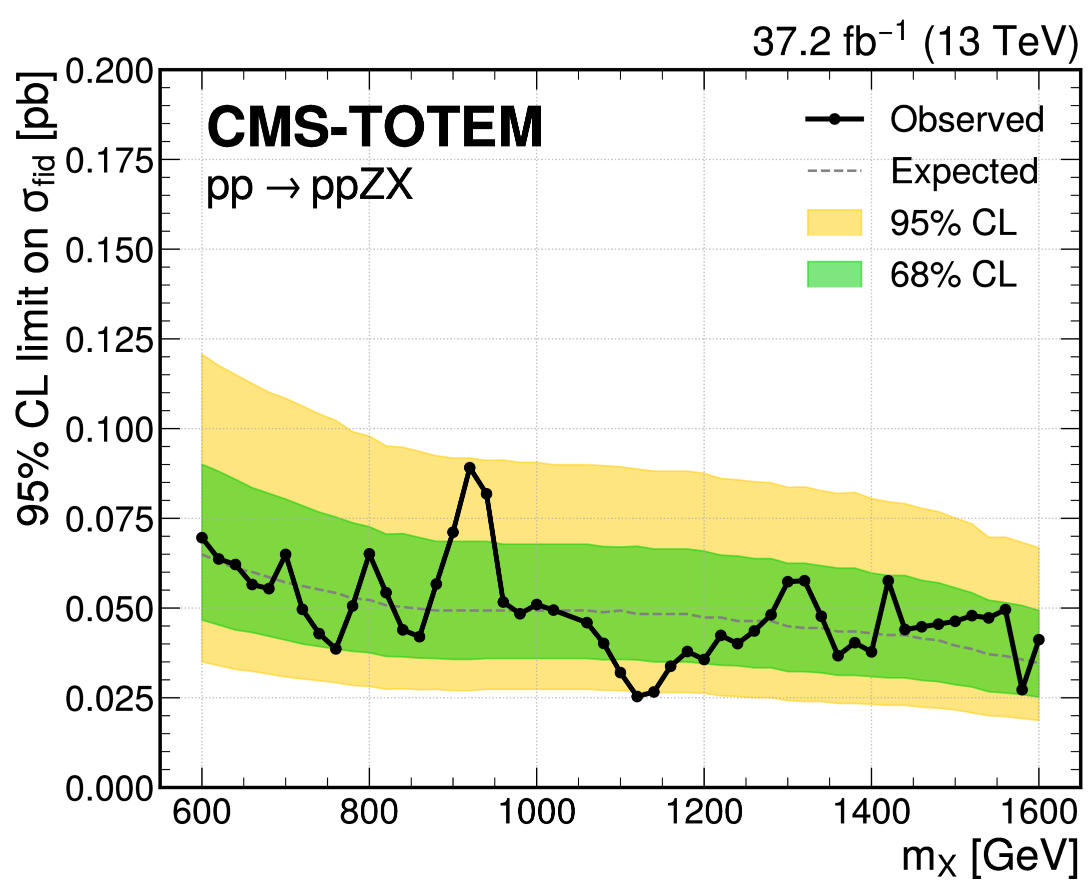
Use novel info from both intact protons

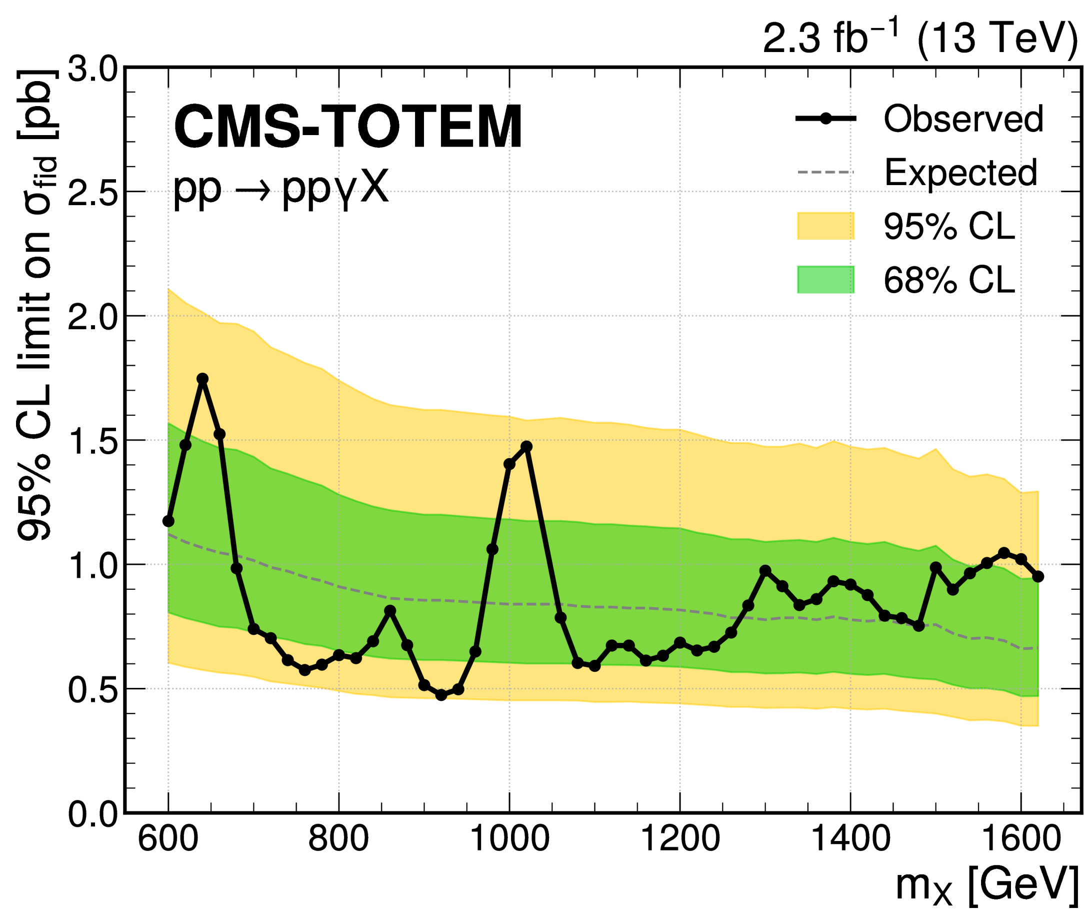
→ Total reconstructed mass

→ Calculate mass of X (missing mass)

X could be invisible, not-reconstructed







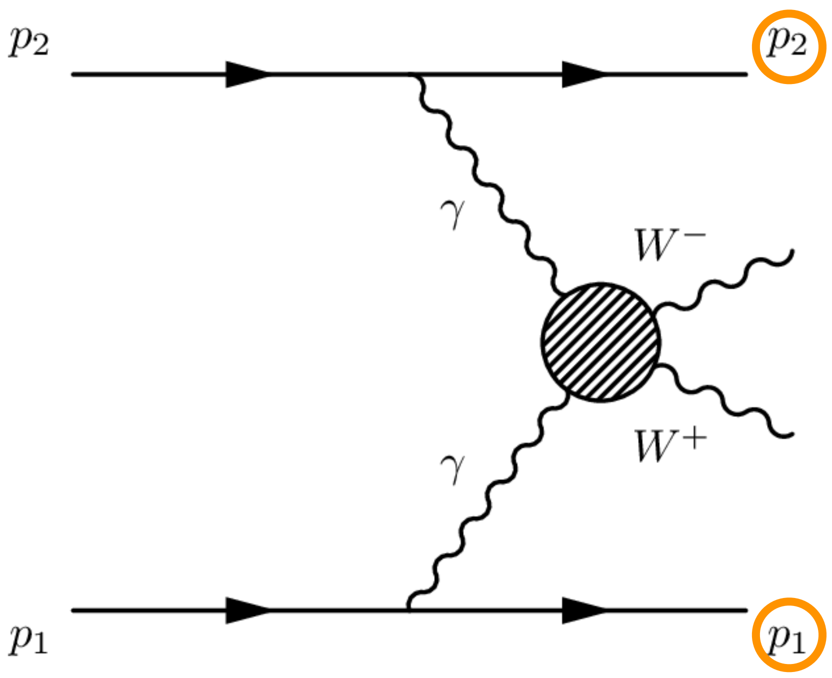
CMS pp $\gamma\gamma \rightarrow VV$ hadronic + PPS

JHEP 07 (2023) 229

Targets high mass, hadronic WW/ZZ + pp

Standard Model:

- ZZ not allowed at tree level
- WW mainly at low mass (negligible here)



Sensitive to BSM e.g. anomalous QGC

2 Large-R (0.8) jets + proton on either side

kinematic matching to reject bkg

- **1st limits via yy→ ZZ production**
- **Dim-6 yyWW aQCG: 15-20x tighter than Run 1 limits w/o protons**
- Dim-8 results close to CMS ssWW & WZ 13 TeV results after unitarisation
- Fiducial cross-section limits

See backup for search for exclusive $t\bar{t}$ + pp by CMS

ATLAS & CMS pp $\gamma\gamma \to \gamma\gamma$ + AFP/PPS

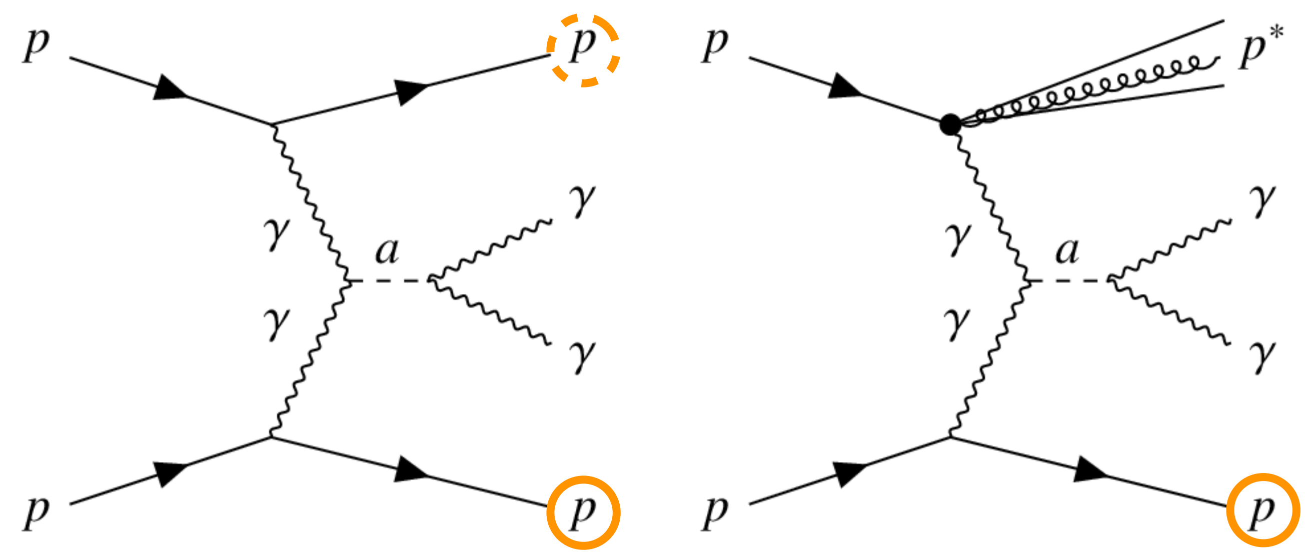
JHEP 07 (2023) 234

arxiv 2311.02725

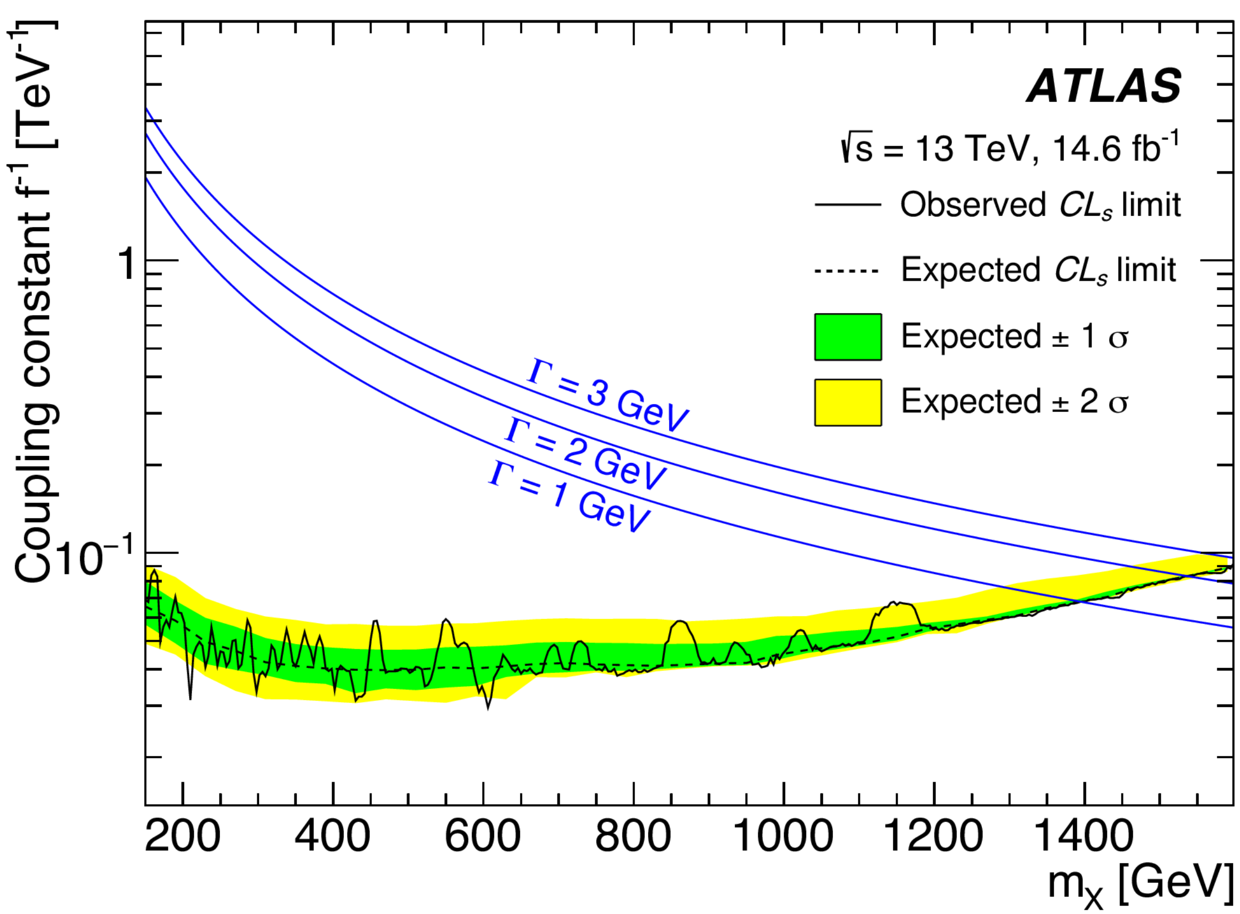
Search for:

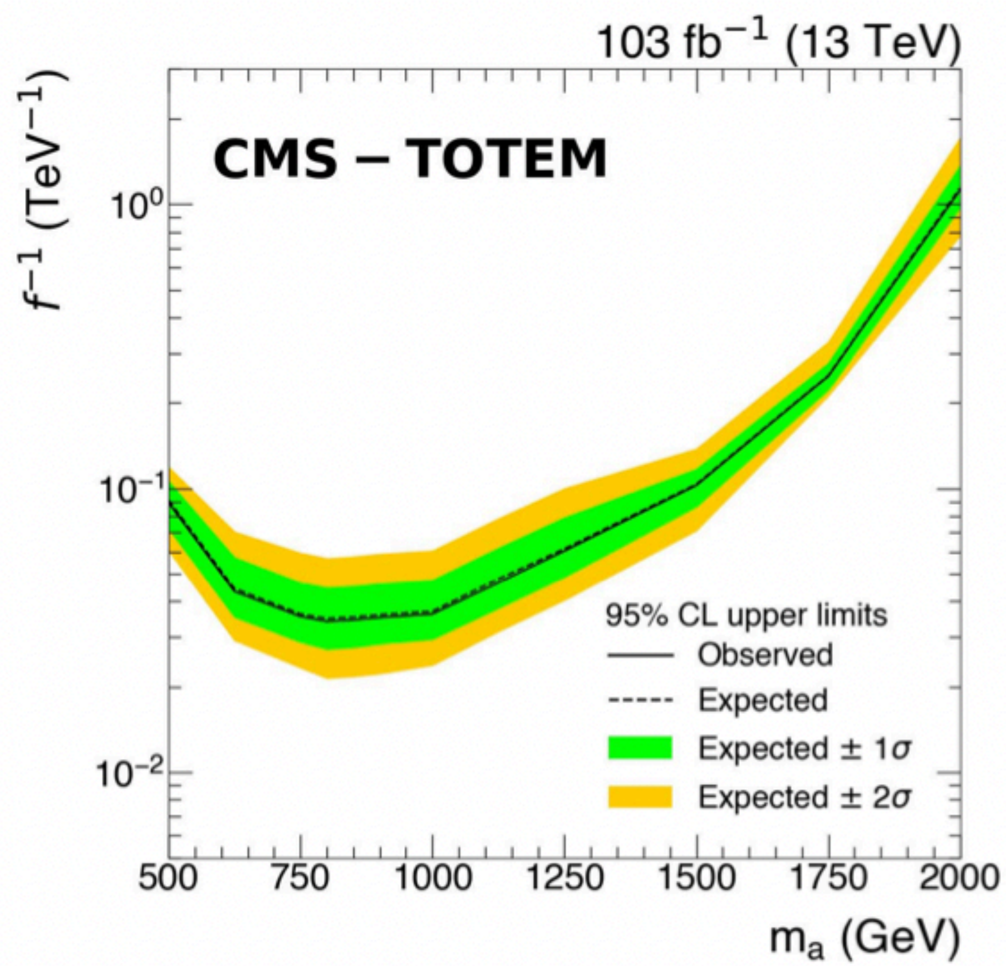
$\gamma\gamma$ + p (ATLAS); $\gamma\gamma$ + pp (CMS)

Kinematic matching to reject bkg



ATLAS 7x smaller dataset but profits from single proton requirement





CMS also set limits on 4γ couplings, see backup

Summary

Broad range of interesting two-photon fusion results

Typically statistically limited → Big gains for larger dataset

More p+p & heavy ion data being recorded!

(2023 Pb+Pb data already doubles existing dataset)

See Orlando Villalobos Baillie talk for more

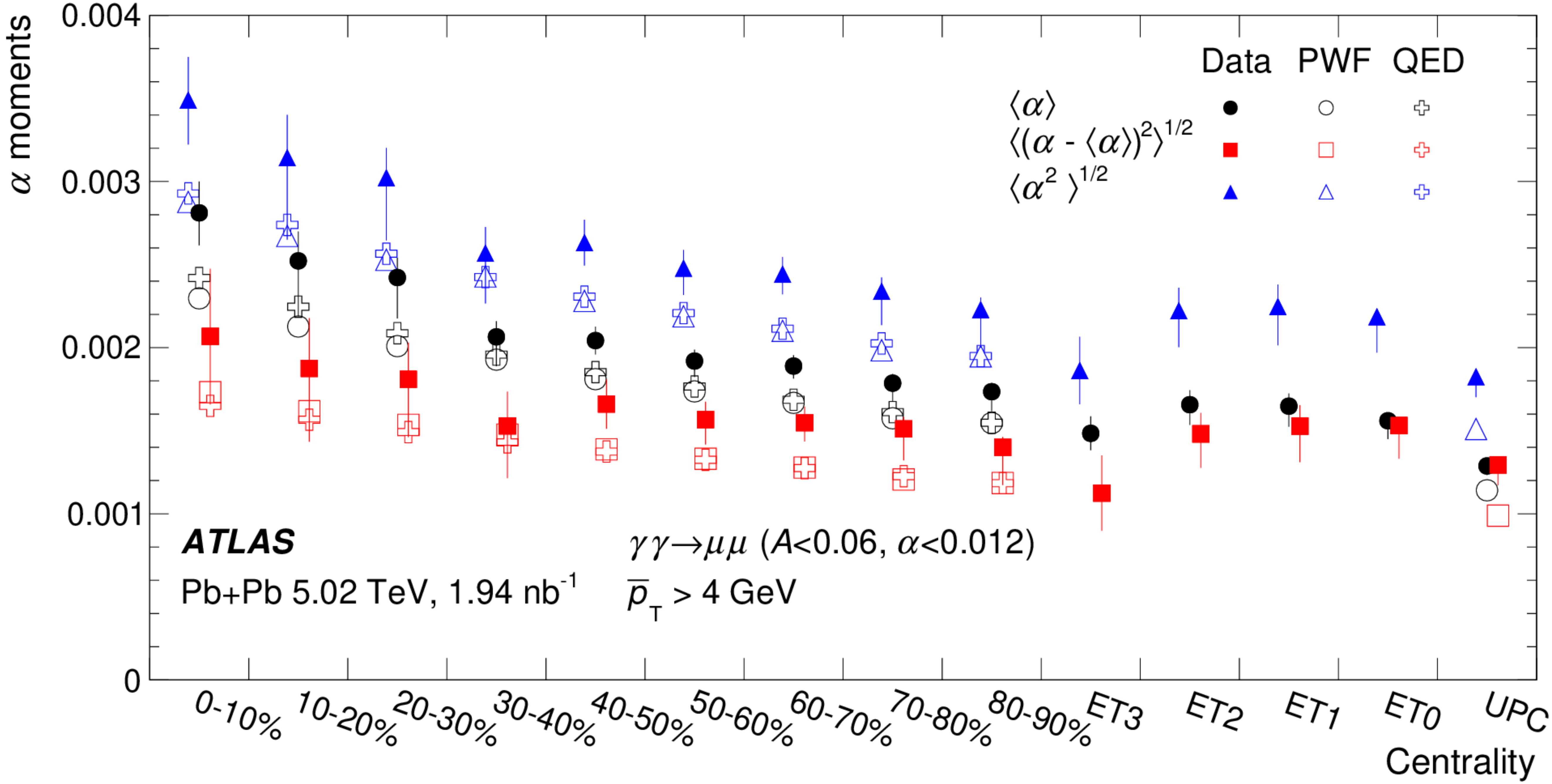
Image by Shutterstock

Backup

ATLAS Pb+Pb non-UPC $\gamma\gamma \rightarrow \mu\mu$

PRC 107 054907

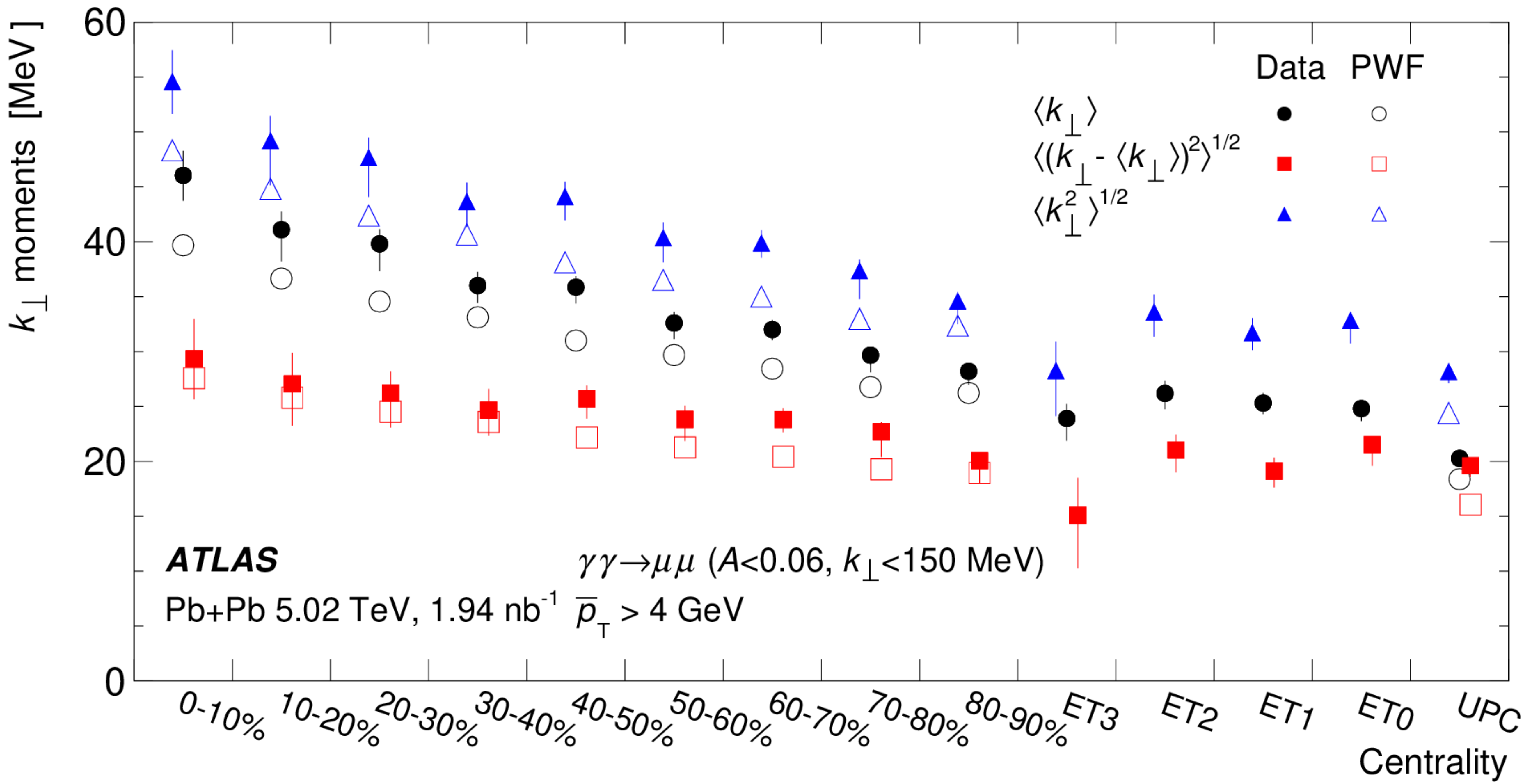
Acoplanarity broadening for less peripheral collisions



ATLAS Pb+Pb non-UPC $\gamma\gamma \rightarrow \mu\mu$

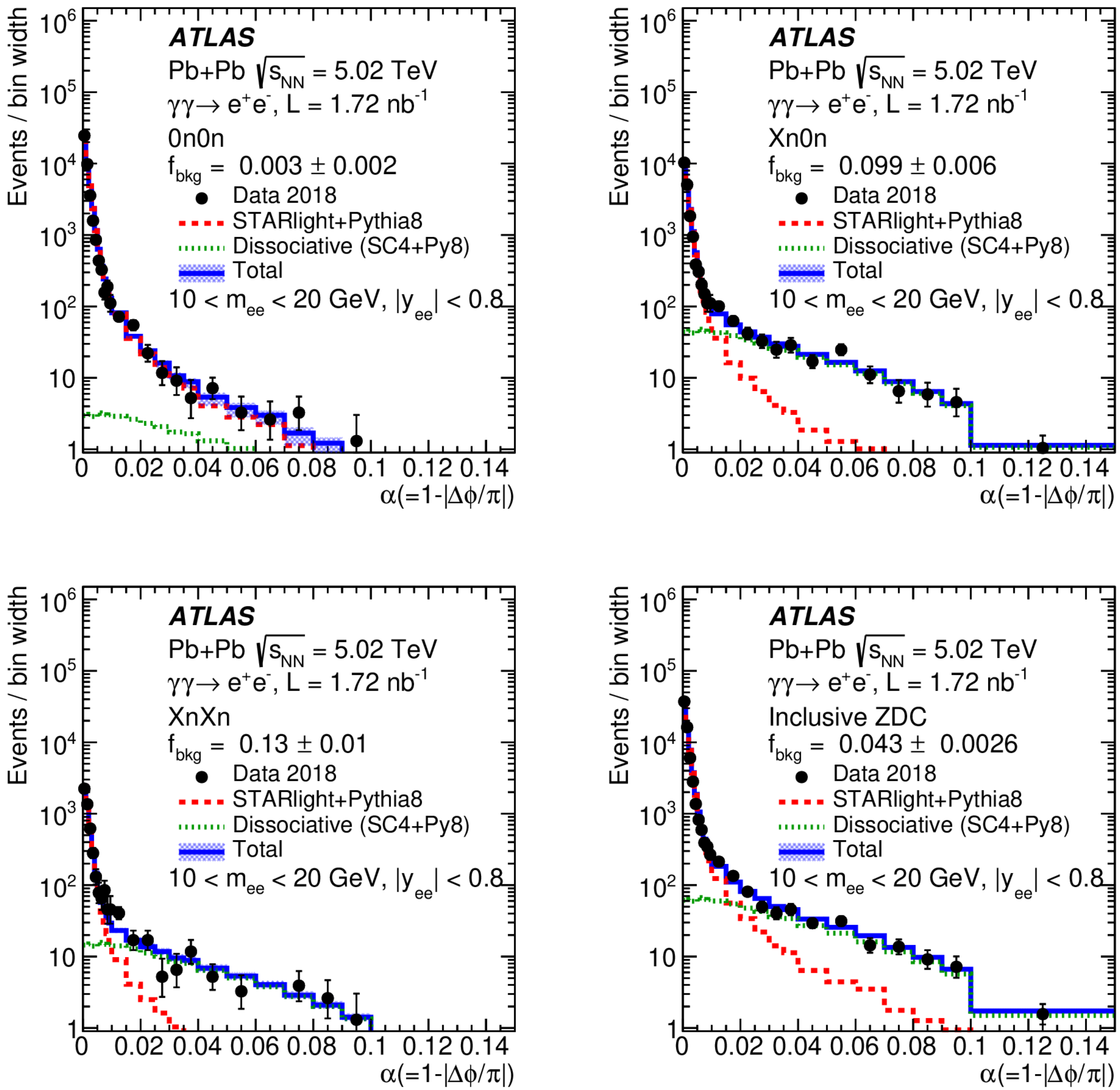
PRC 107 054907

$k_\perp$ broadening for less peripheral collisions



ATLAS Pb+Pb UPC $\gamma\gamma \rightarrow ee$

JHEP 06 (2023) 182



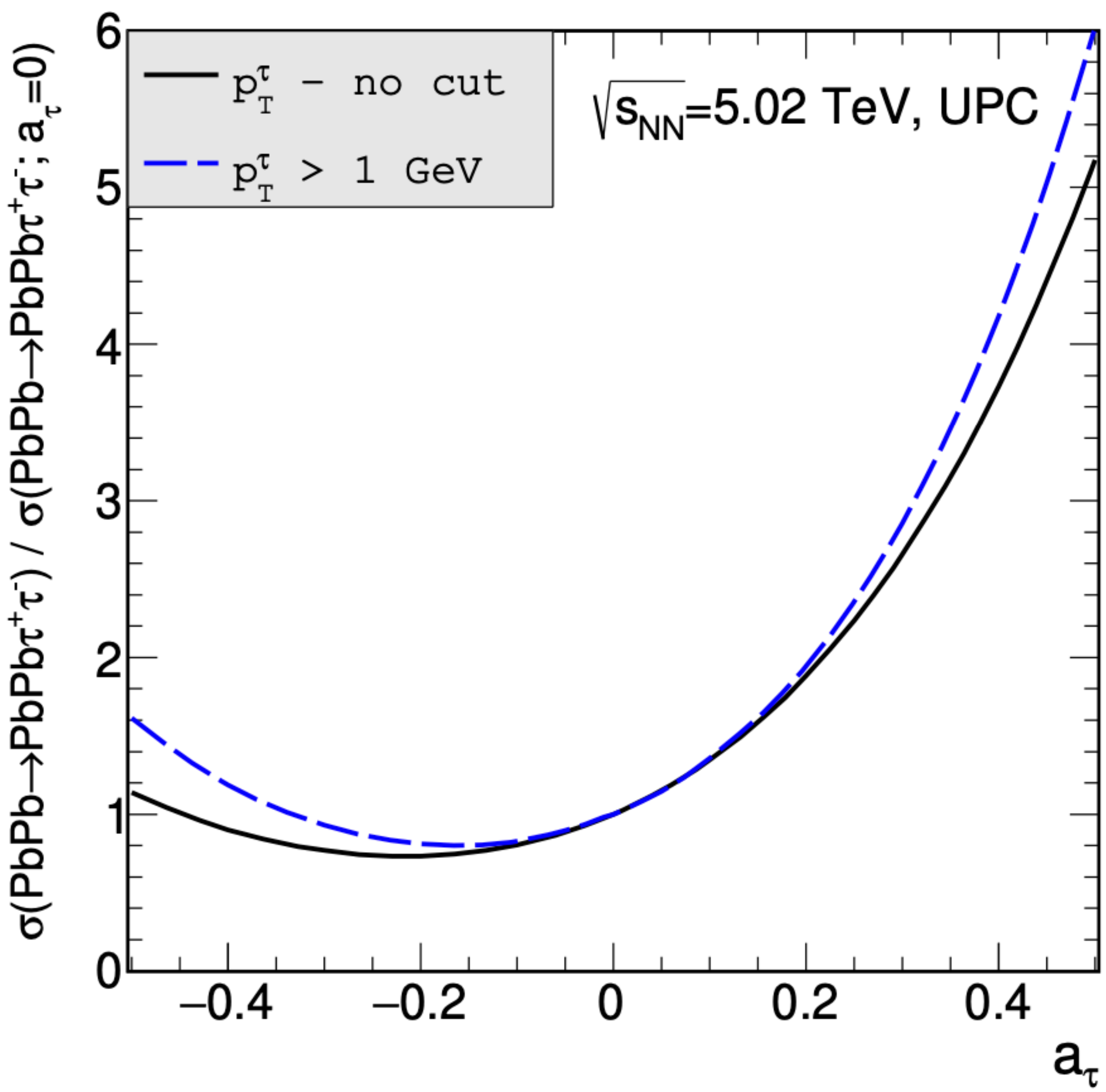
ATLAS Pb+Pb UPC BSM Tau g-2

Re-weight SM signal MC to BSM a_τ values based on PLB 2020 135682

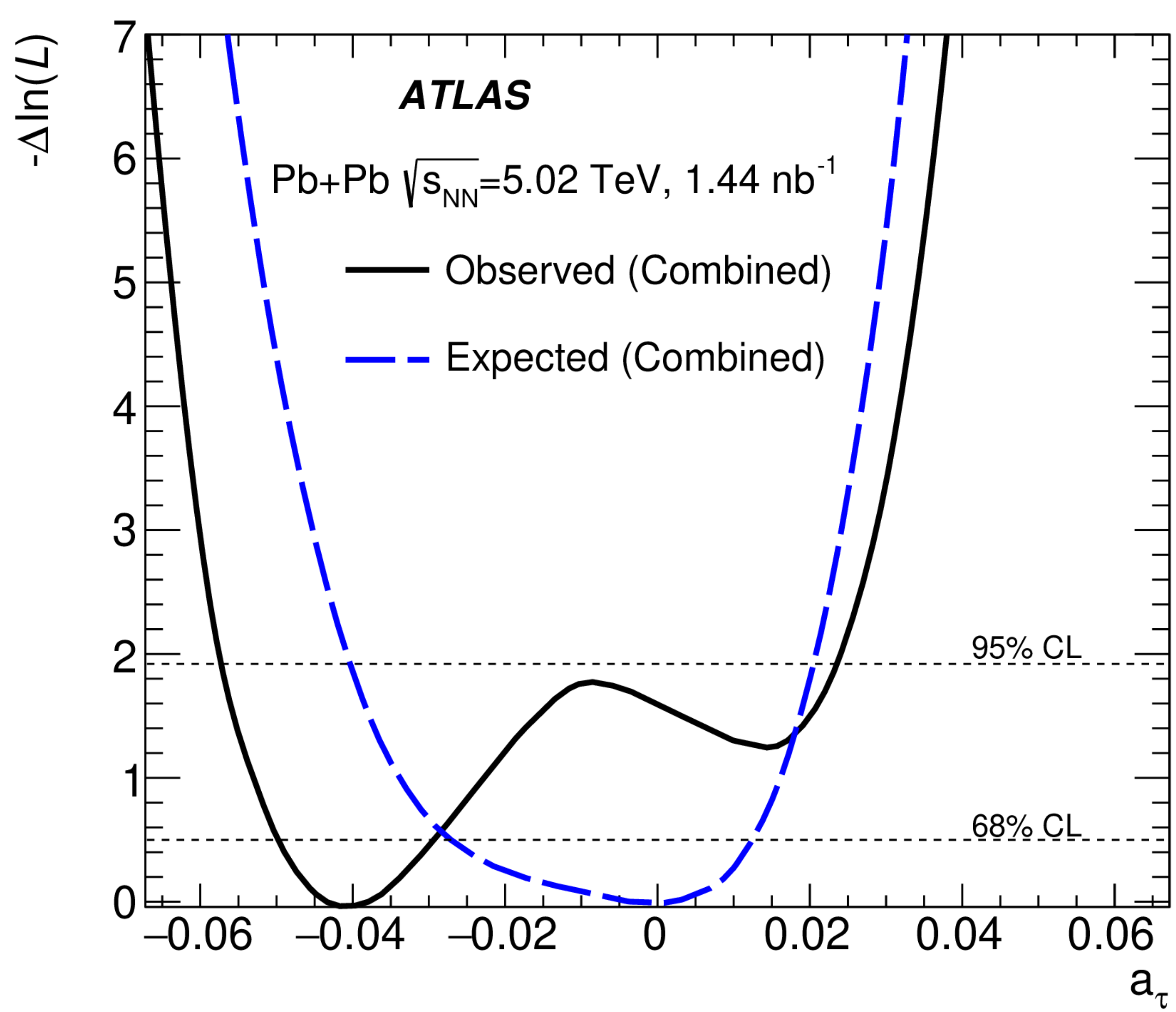
3D weighting in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$

Calculations based on same parametrisation as LEP

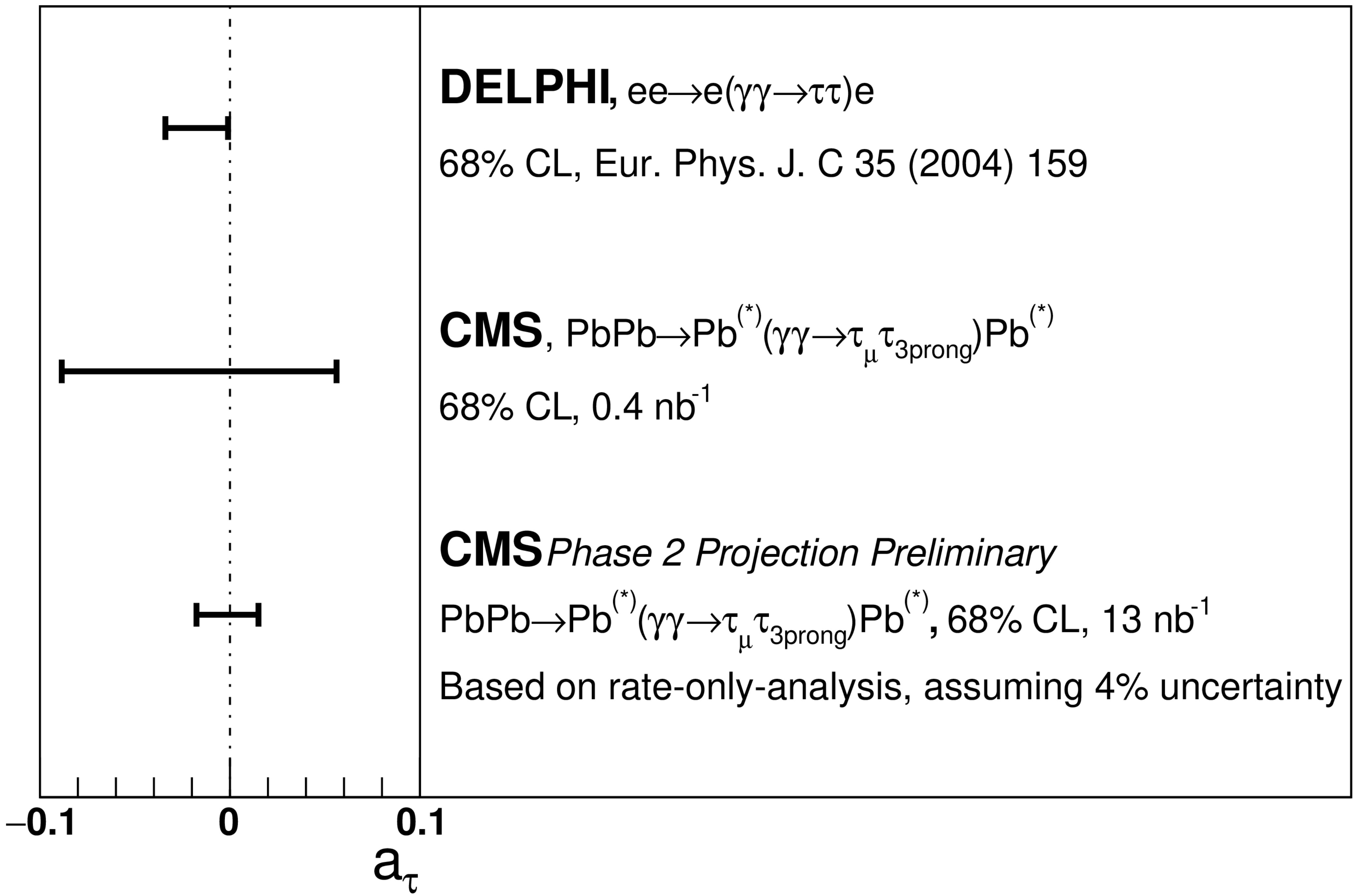
PLB 2020 135682



PRL 131 151802



CMS Pb+Pb UPC Tau g-2



ATLAS pp $\gamma\gamma \rightarrow ll$ + AFP

PRL 125 (2020) 261801

1st LHC cross-section measurements for this process with a tagged proton

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (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] Harland-Lang et al EPJC 76 (2016) 9
[34] Dyndal & Schoffel PLB 741 (2015) 66
[97] Harland-Lang et al EPJC 80, 925 (2020)

Slight undershoot of data wrt to Superchic 4, especially for $\mu\mu$

CMS pp $Z/\gamma + X$ + PPS

EPJC 83 (2023) 827

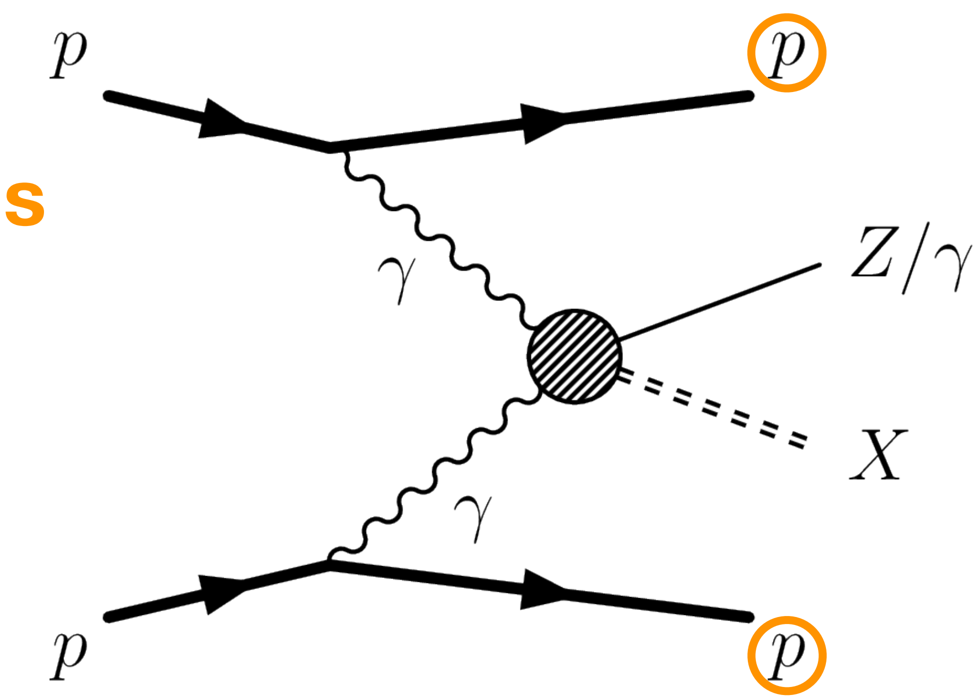
Search for $Z/\gamma + X$ events

Use novel info from both intact protons

→ Total reconstructed mass

→ Calculate mass of X (missing mass)

X could be invisible, not-reconstructed



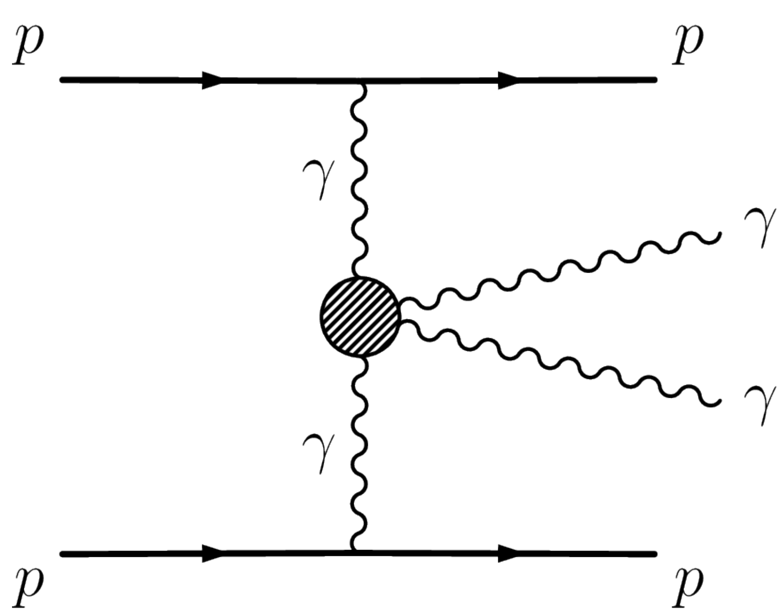
The missing mass is defined as:

$$m_{\mathrm{miss}}^2 = \left[(P_{\mathrm{p}_1}^{\mathrm{in}} + P_{\mathrm{p}_2}^{\mathrm{in}}) - (P_{\mathrm{V}} + P_{\mathrm{p}_1}^{\mathrm{out}} + P_{\mathrm{p}_2}^{\mathrm{out}})\right]^2, \qquad (1)$$

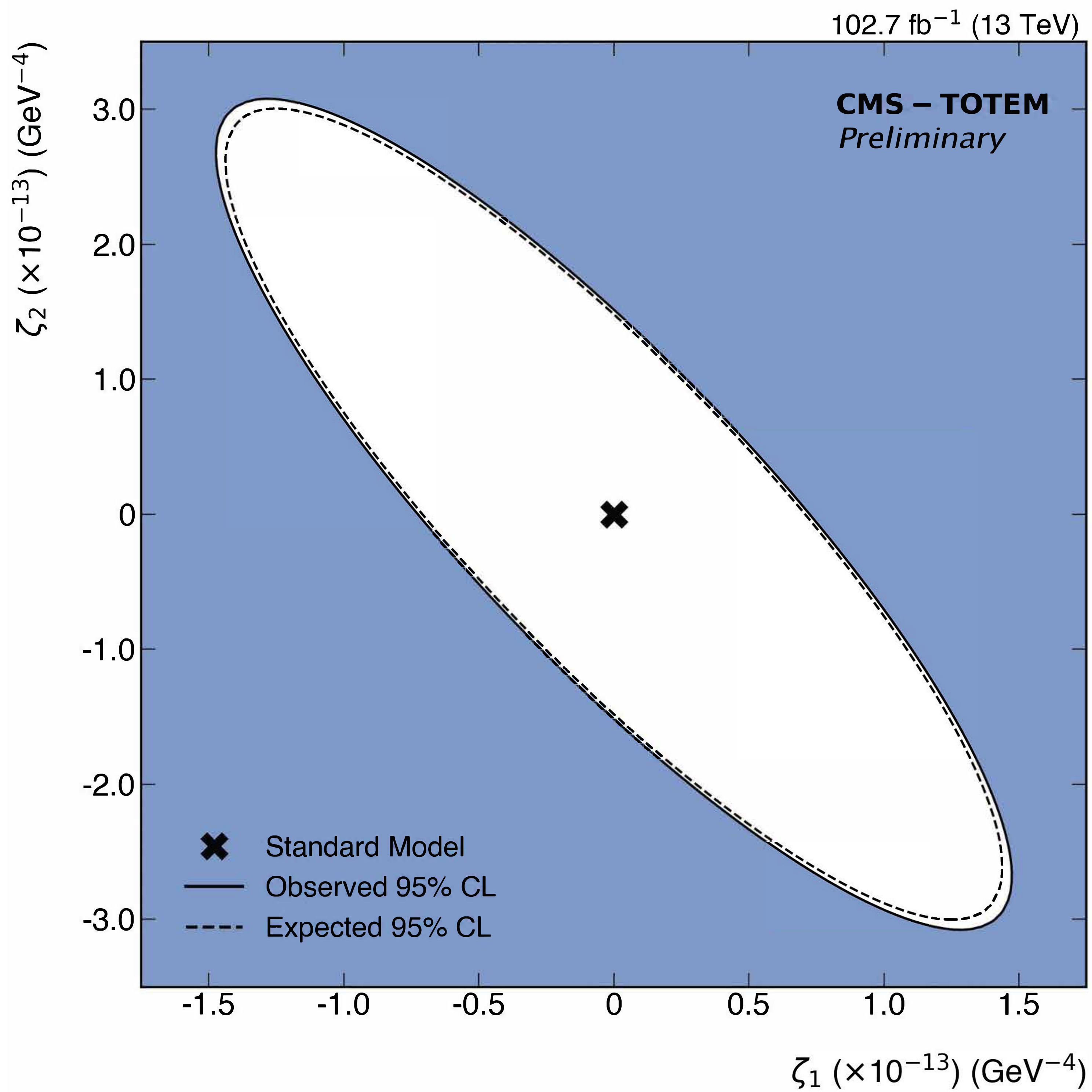
where P_{V} is the four-momentum of the boson and $P_{\mathrm{p}_i}^{\mathrm{out,in}}$ $(i = 1, 2)$ are the four-momenta of the outgoing and incoming protons, respectively.

CMS pp $\gamma\gamma \rightarrow \gamma\gamma$ + PPS

[CMS-PAS-EXO-21-007]

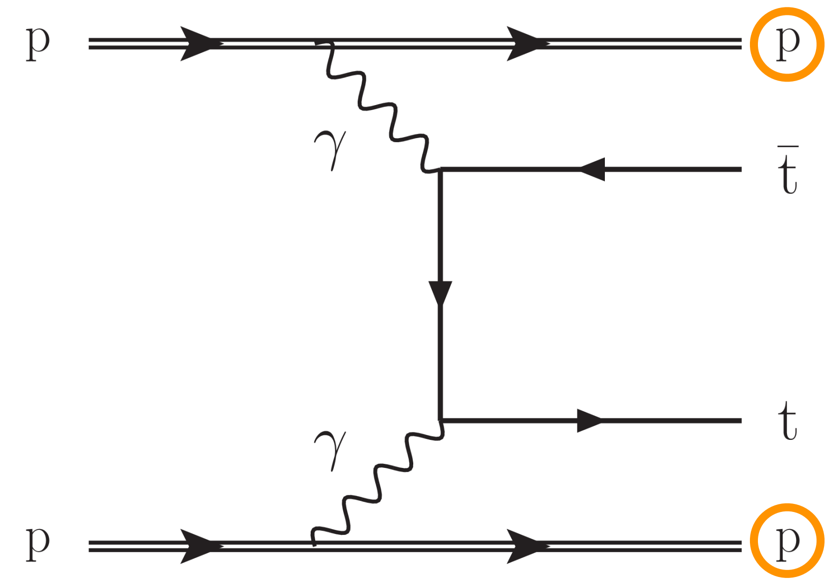


$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$



CMS pp $\gamma\gamma \rightarrow t\bar{t}$ + PPS

2310.11231



1st search for exclusive $t\bar{t}$ + pp

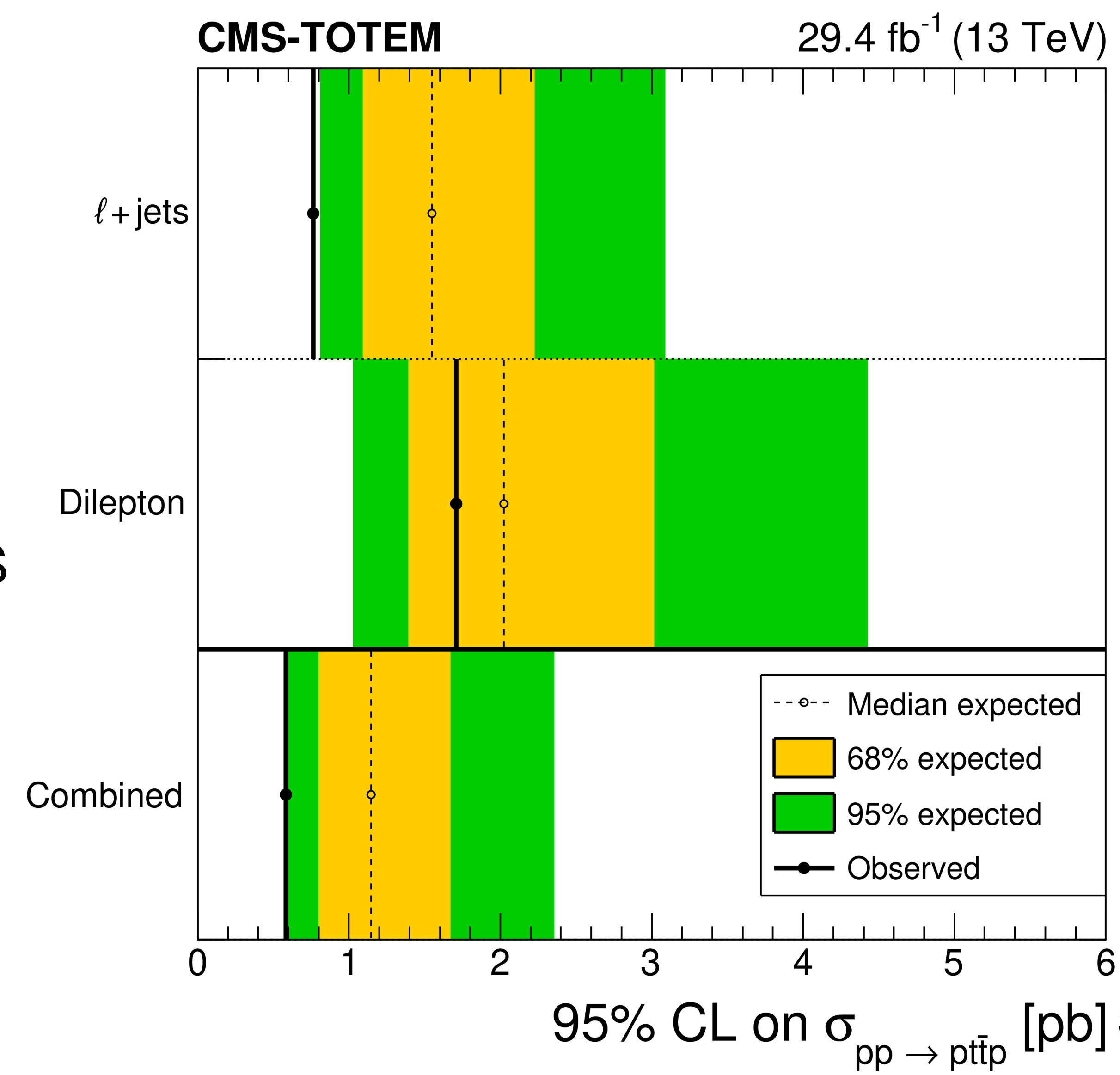
Not expected to be sensitive to SM production (~0.2 fb in PPS acceptance)

Focus on two channels: $\ell\ell$ & ℓ+jets

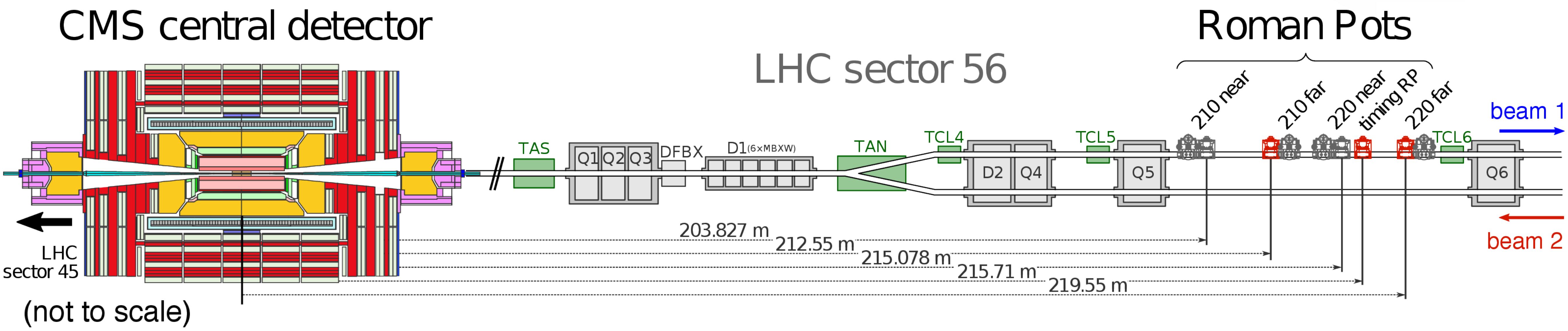
Kinematic fitter to improve resolution of $t\bar{t}$ kinematic variables

BDT for signal vs bkg separation
→ Fit BDT score & extract upper limits

Upper limit of 0.59 pb^{-1} at 95% CL



CMS PPS



CMS central detector
LHC sector 56
Roman Pots
210 near
210 far
220 near
timing RP
220 far
beam 1
beam 2
TAS
Q1
Q2
Q3
DFBX
D1(6×MBXW)
TAN
TCL4
D2
Q4
TCL5
Q5
TCL6
Q6
203.827 m
212.55 m
215.078 m
215.71 m
219.55 m
LHC
sector 45
(not to scale)