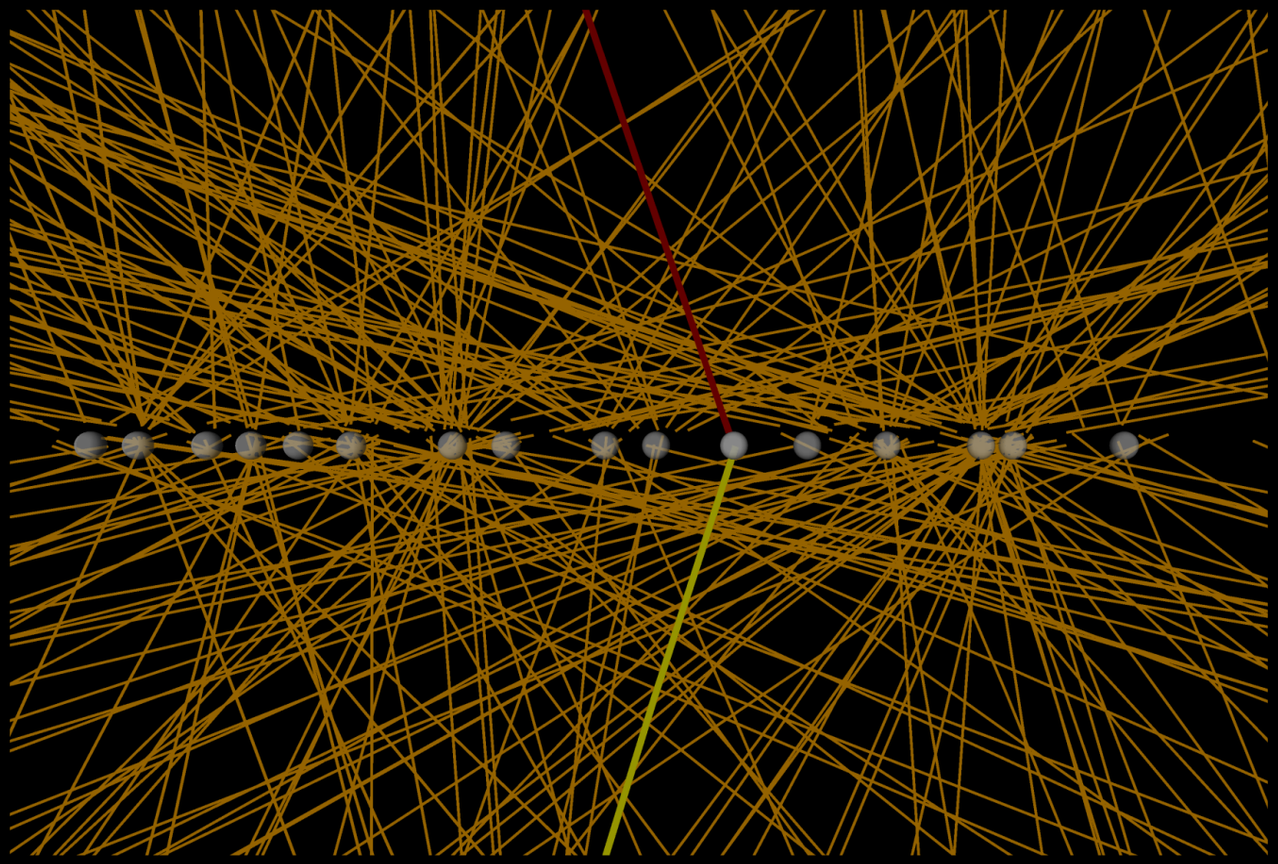
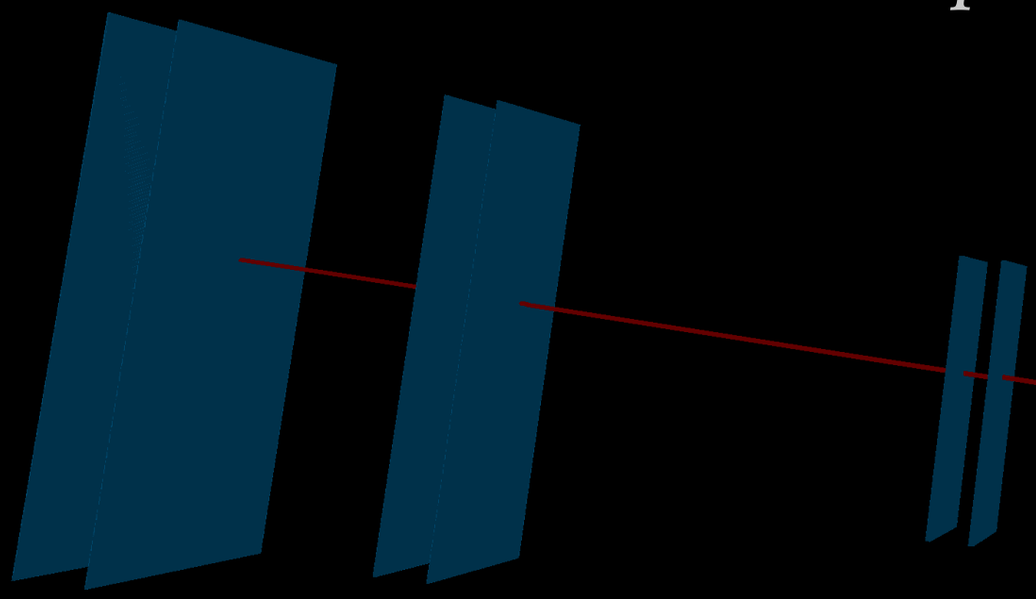
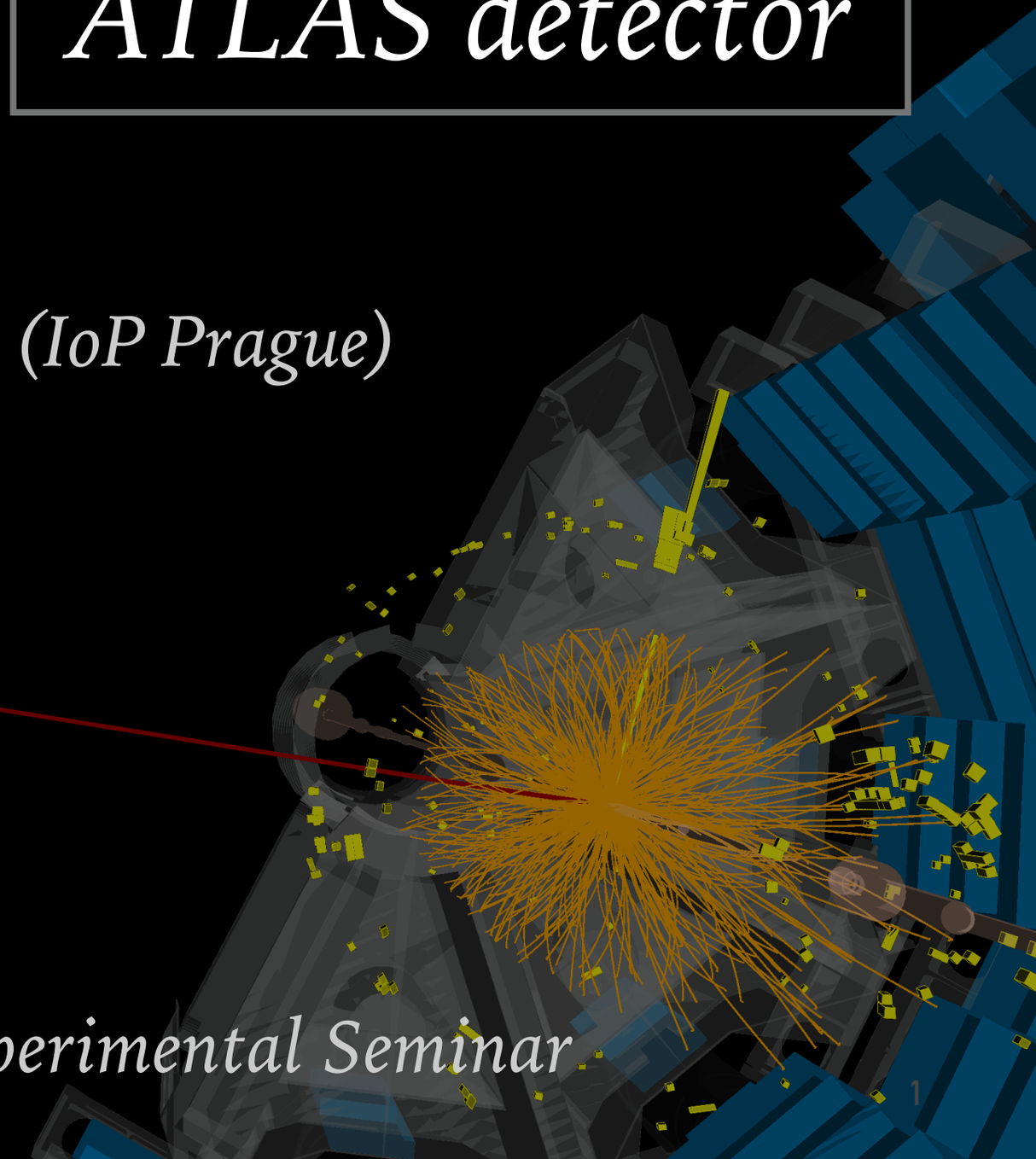


Using LHC as photon-photon collider with the ATLAS detector

Oldřich Kepka (IoP Prague)





ATLAS EXPERIMENT

27/08/2020 FPD Experimental Seminar

Outline

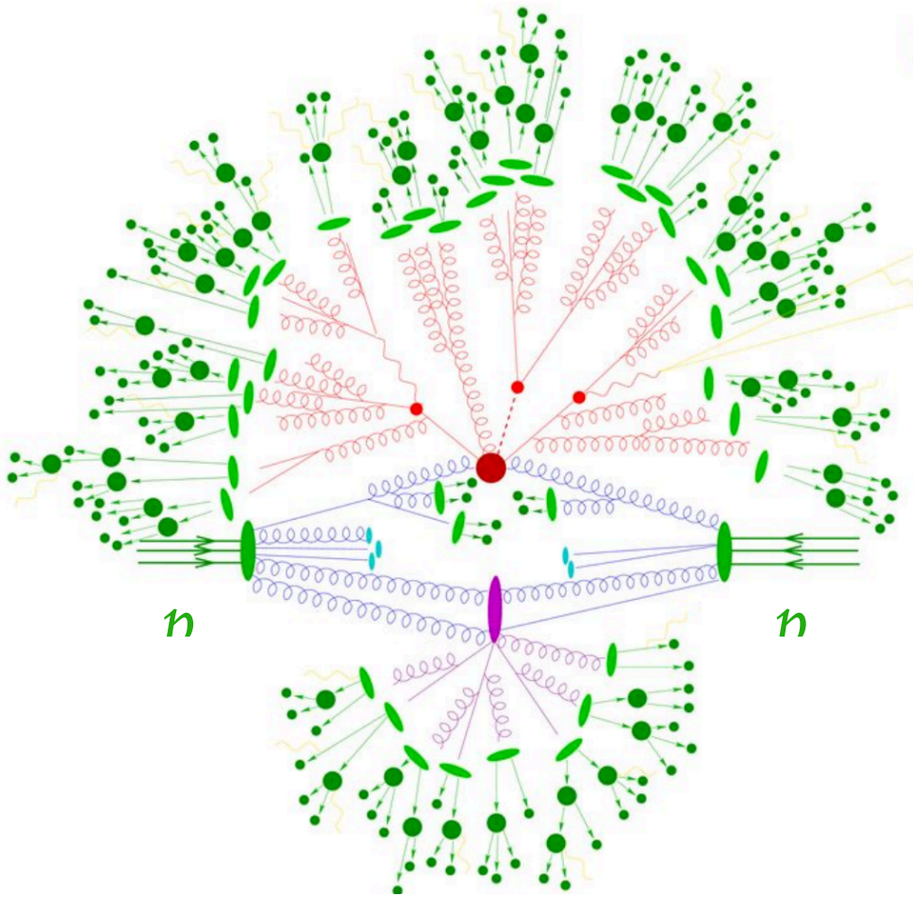
- New ATLAS measurements presented

- Photon-induced measurements in proton-proton at $\sqrt{s}$ = 13 TeV
  - $\gamma\gamma \to W^+W^-$ [ATLAS-CONF-2020-038]:
    Observation of photon-induced diboson production, complete Run 2 dataset
  - $\gamma\gamma \to \ell^+\ell^-$ [ATLAS-CONF-2020-041]:
    Measurement of **forward proton scattering** in association with lepton pairs

- Photon-induced measurements in ultra-peripheral lead-lead $\sqrt{s_{NN}}$ = 5.02 TeV
  - $\gamma\gamma \to \gamma\gamma$ [arXiv:2008.05355]:
    Differential measurement of light-by-light scattering and **search for axion-like particles**, complete Run 2 dataset

  - $\gamma\gamma \to \mu^+\mu^-$ [CERN-EP-2020-138]:
    Differential measurement of exclusive dimuon production with **forward neutron** information

Typical proton-proton collision

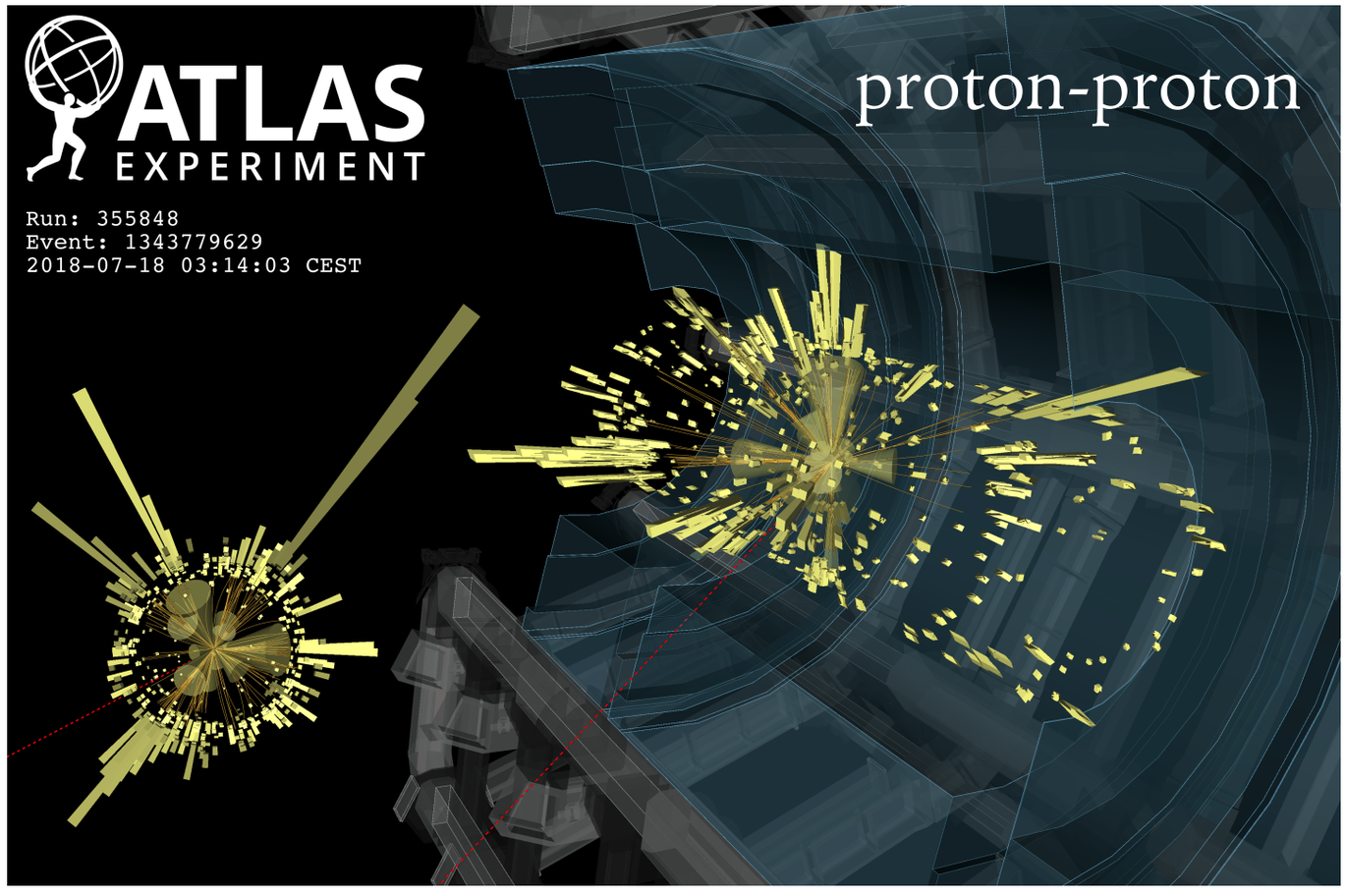


[Sherpa authors]

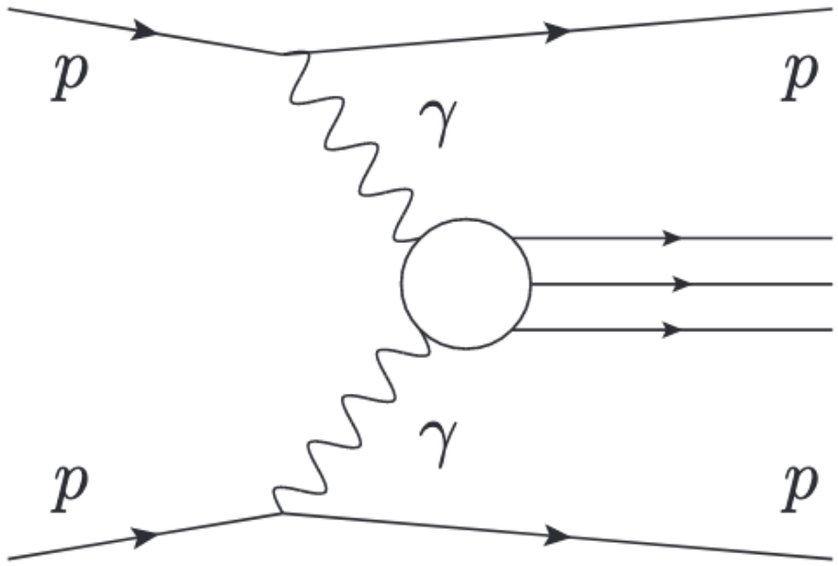
QCD induced interactions are very busy

- Hard scattering initiated by q/g
- Parton shower
- Multi-parton interactions & Underlying event
- Hadronization

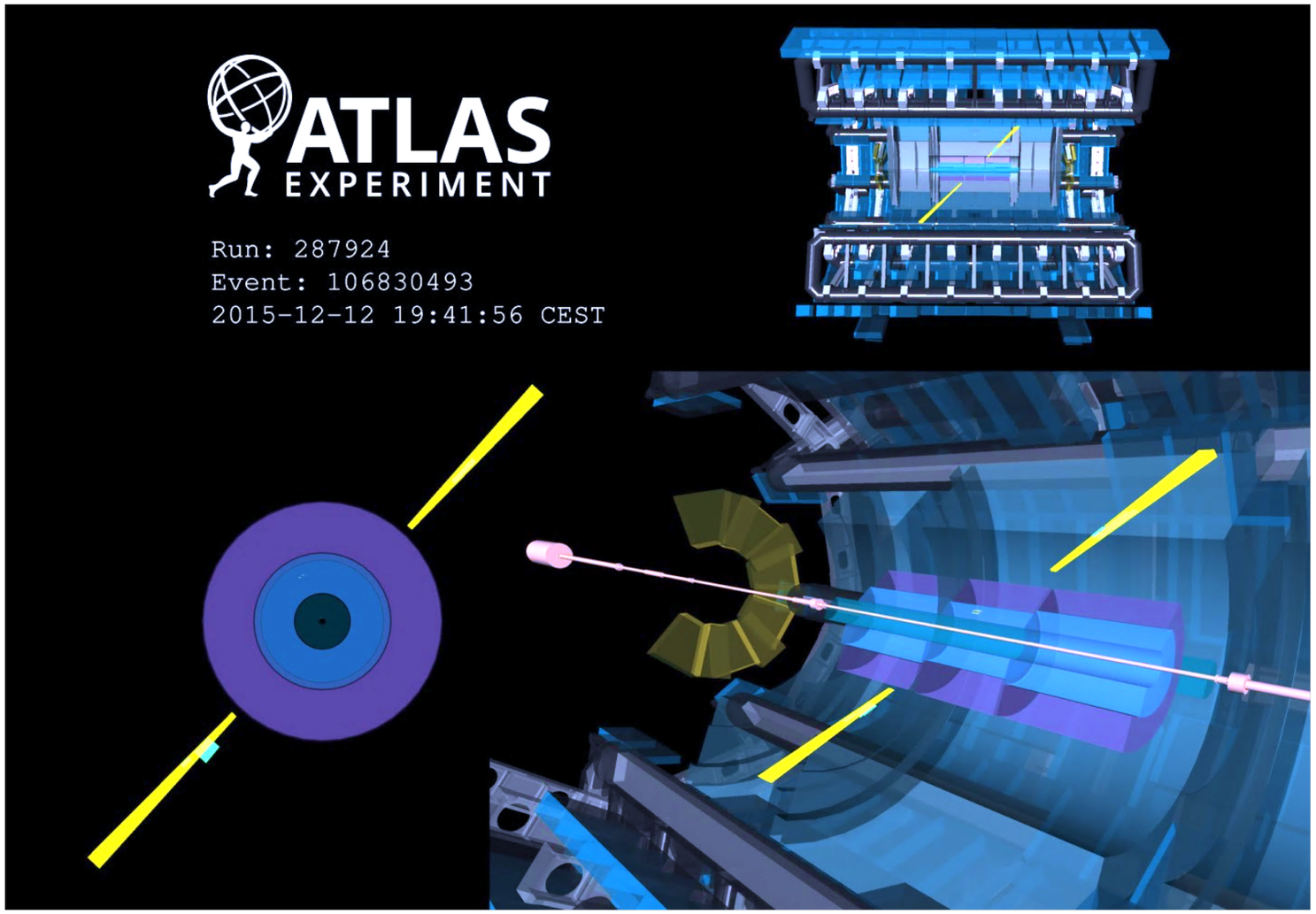
Additional activity in PbPb reactions from spectator nucleon-nucleon interactions



Coherent photon-induced reaction



- Protons (and Pb) beams are source of intense light
- Clean events when both protons emit **coherently** a photon
- Protons stay intact, no other particles produced
- No color flow between protons (small rescattering corrections later)



Coherent photon-induced reaction

- Photon flux derived from EM form factors of the p/nucleon
- Photons are quasi-real → small momentum transfer to the produced system
  - Important experimentally

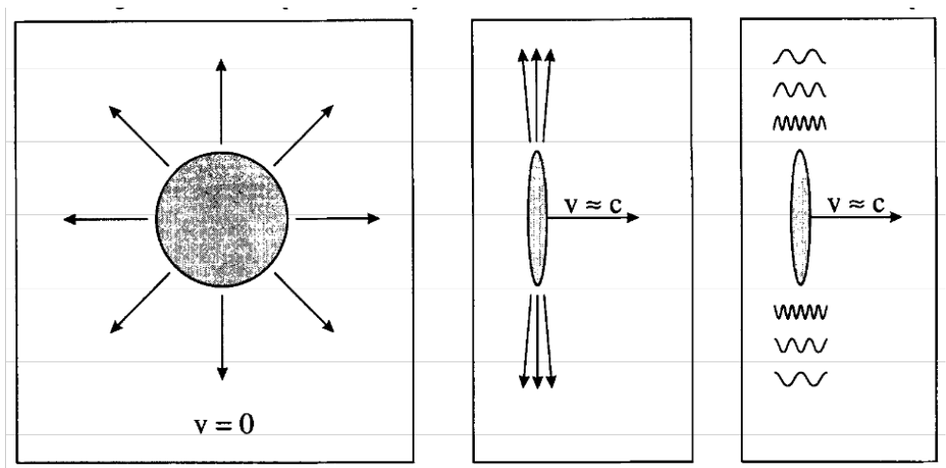
Q ~1/R ≲ 0.3 GeV (protons)
≲ 0.06 GeV (Pb ions)

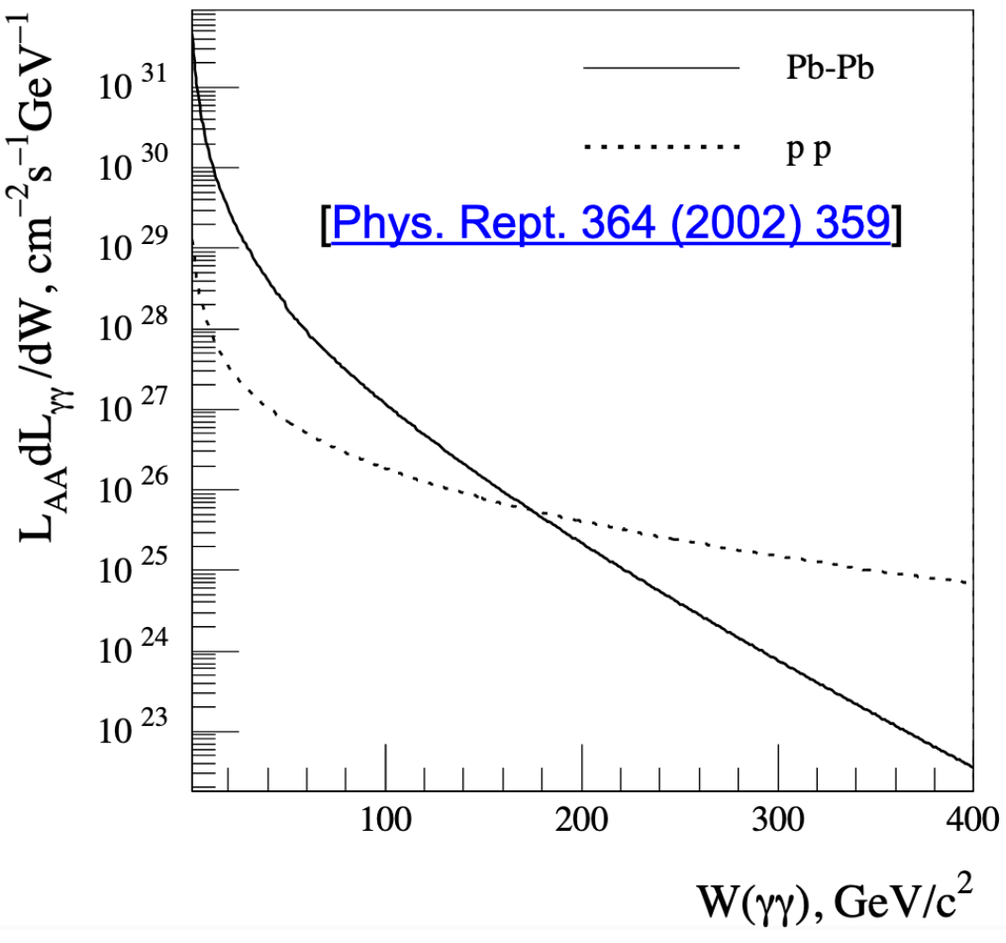
E_{max} ~ 2.5 TeV (protons)
~ 80 GeV (Pb ions)

$$\frac{d\sigma}{d\Omega} = \int \frac{d\sigma_{\gamma\gamma\to X}(W)}{d\Omega} \frac{dL_{\gamma\gamma}}{dW} dW$$

- Production enhanced by $Z^4 = 5\text{x}10^7$ in PbPb, Z=82
- Opportunity to measure EW interactions

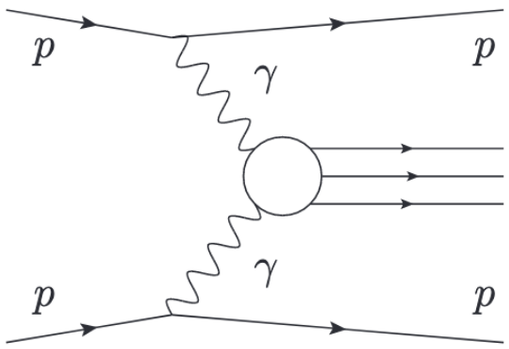
Contracted EM field for fast moving charge



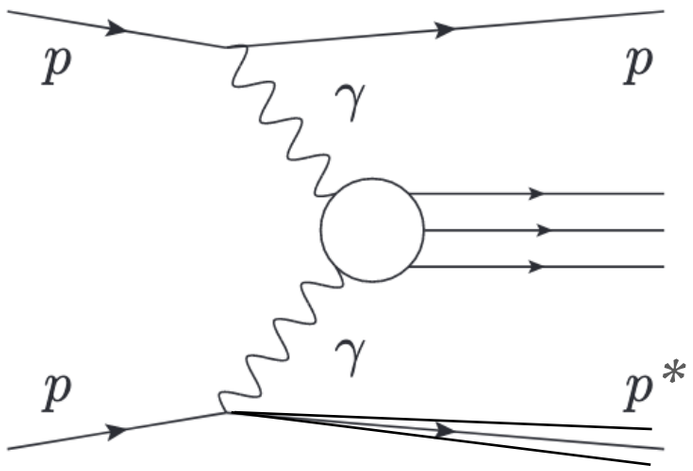


Types of photon-photon induced reactions

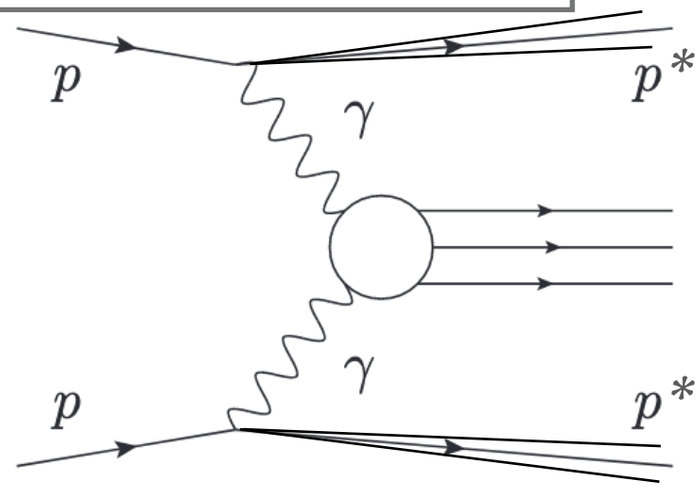
Either or both protons dissociate due to inelastic collision



Coherent
(elastic, exclusive)



Single-dissociative
(semi-exclusive, semi-coherent)



Double-dissociative
(inelastic, incoherent)

Photon in the proton: $f_{\gamma/p}$ = elastic + inelastic contributions

Dissociative contribution significant in pp

- Larger transverse momentum transferred to X
- Higher particle activity

In Pb+Pb - dissociative contributions small

- Scattering on single nucleon, no *Z* enhancement
- **Forward neutrons emitted** with $E_{beam}/N_{nucleon}$ energy, ion easily disrupted, binding energy small (~ 10 MeV)

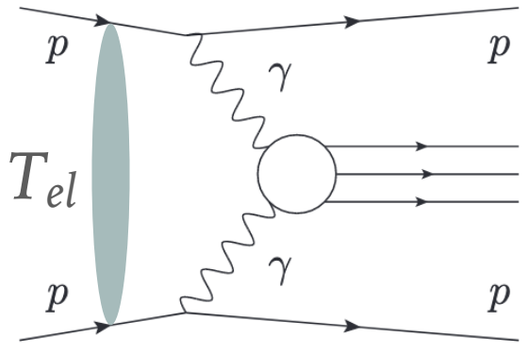
MRST2004, CT14qed ($f_{\gamma/p}$ modelled)

NNPDF23QED, NNPDF30QED ($f_{\gamma/p}$ fitted)

LUXqed17, NNPDF31, MMHT2015qed ($f_{\gamma/p}$ from DIS structure functions, reduced uncertainty, some include coherent)

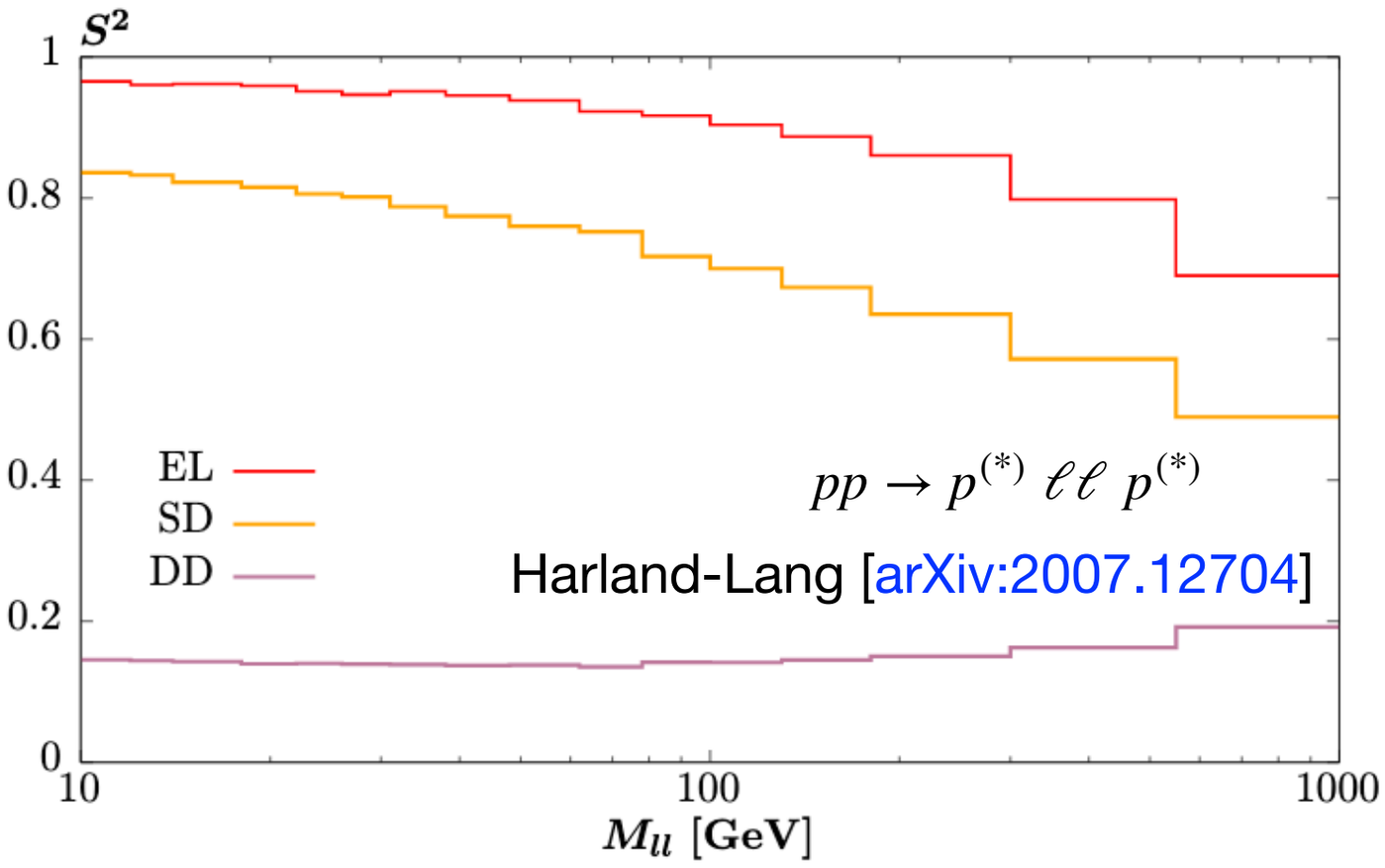
Survival probability

- $\gamma\gamma$ initiated processes also have underlying event
- Final state with no additional particle production is required (X + nothing else) → accounted for with **survival factor**
- Only allow those rescattering, which do not break the proton Harland-Lang [arXiv:1601.03772]



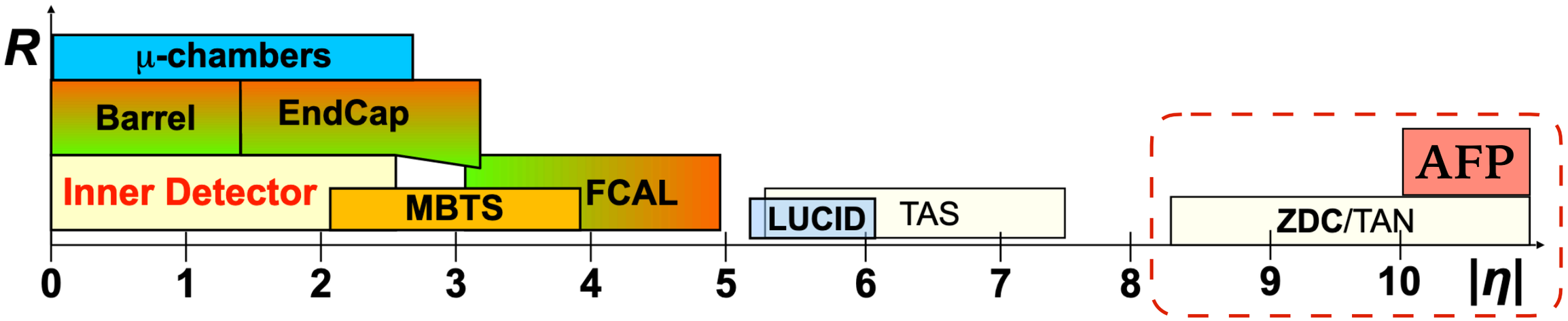
$$\langle S^2_{\text{eik}} \rangle = \frac{\int \mathrm{d}^2\mathbf{b}_{1t}\,\mathrm{d}^2\mathbf{b}_{2t}\,|T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2 \exp(-\Omega(s,b_t))}{\int \mathrm{d}^2\,\mathbf{b}_{1t}\mathrm{d}^2\mathbf{b}_{2t}\,|T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2}$$

Prb. that there is no inelastic scattering, proton opacity Ω extracted from pp elastic scattering



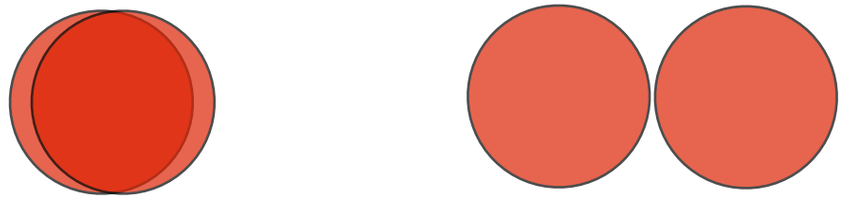
- Implementation without explicit dependence on the hard sub-process Dyndal [arXiv:1410.2983]
- In general, lack of implementation in MC generators
- NEW: implementeted for $\gamma\gamma \to ll$ for elastic and inelastic in SuperChic 4.0
- SD/DD occur at smaller impact parameter → smaller S^2

Techniques to detect $\gamma\gamma$ interactions in ATLAS



- **Large pp** dataset with **pileup**
- Signal isolated from QCD background by requiring **0 tracks found around hard vertex region using ID**
- Unique opportunity to **tag the outgoing protons in AFP** forward detector in ATLAS

- **No pileup** in PbPb
- Reject activity in all detectors: ID, Calo, MBTS, Forward detectors
- **ZDC to identify / reject background**
- Dedicated triggers to select ‘silent’ ultra-peripheral collisions (UPC)

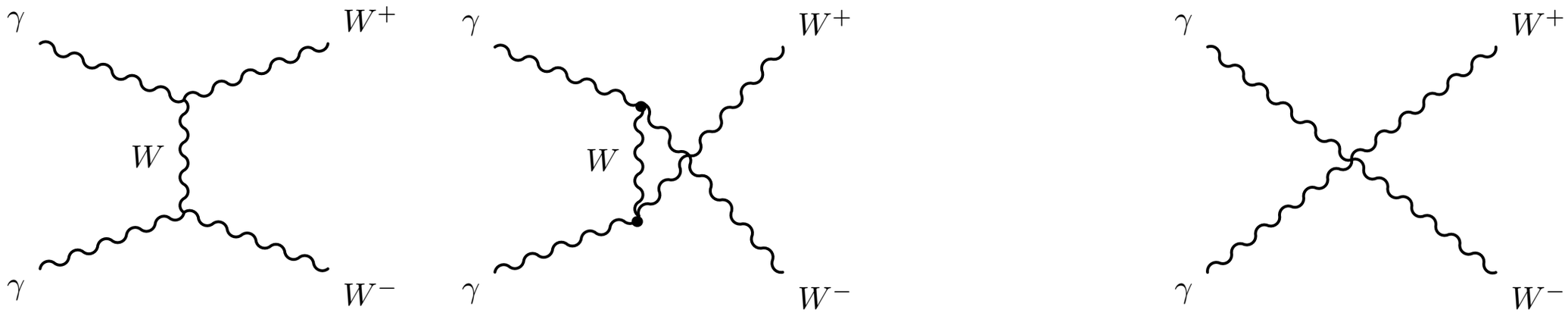


Central collisions UPC

Observation of photon-induced $\gamma\gamma \rightarrow W^+W^-$ production in pp collisions at $\sqrt{s}$ =13 TeV using the ATLAS detector [ATLAS-CONF-2020-038]

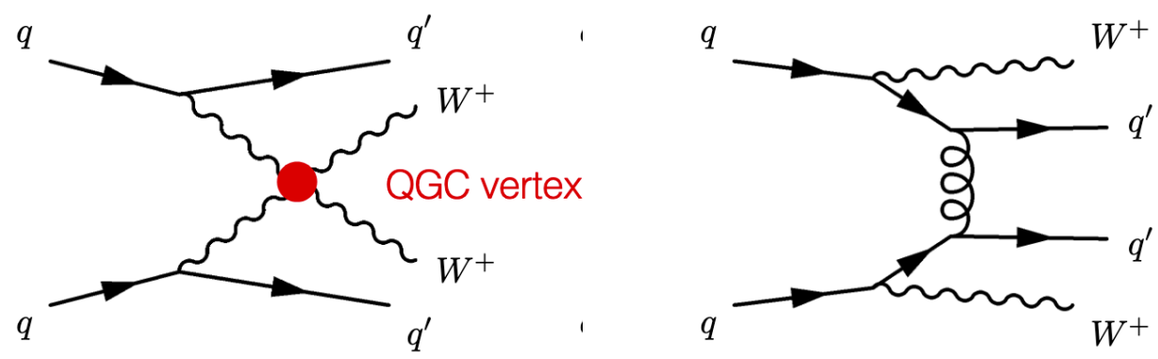
$\gamma\gamma \to W^+W^-$: Motivation

- Excellent laboratory to test EW sector of SM
  - Direct access to **triple** γW^+W^- and **quartic** $\gamma\gamma W^+W^-$ interactions, $\mathrm{O}(\alpha_{\mathrm{EM}}^2)$ process
  - No coupling to Z or H at LO



- Tree-level unitarity required for SM to be renormalizable theory
- Amplitude of individual diagrams grows with CME (longitudinal polarizations of W)
- Both linear and quadratic divergence cancelled in the sum.

- Clear interpretation - only EW fields interacting at LO
  - Compare with e.g. same-sign WW which includes strong production



$\gamma\gamma \to W^+W^-$: Analysis overview

- Cross section measurement using leptonic decays of W: 139 fb^{-1}, full Run 2 dataset
- Previous measurements at 7/8 TeV
  - ATLAS/CMS 3σ evidence [arXiv:1607.03745], [arXiv:1604.04464]
- Only central detector, no proton tagging
- **Dissociative production is part of signal**

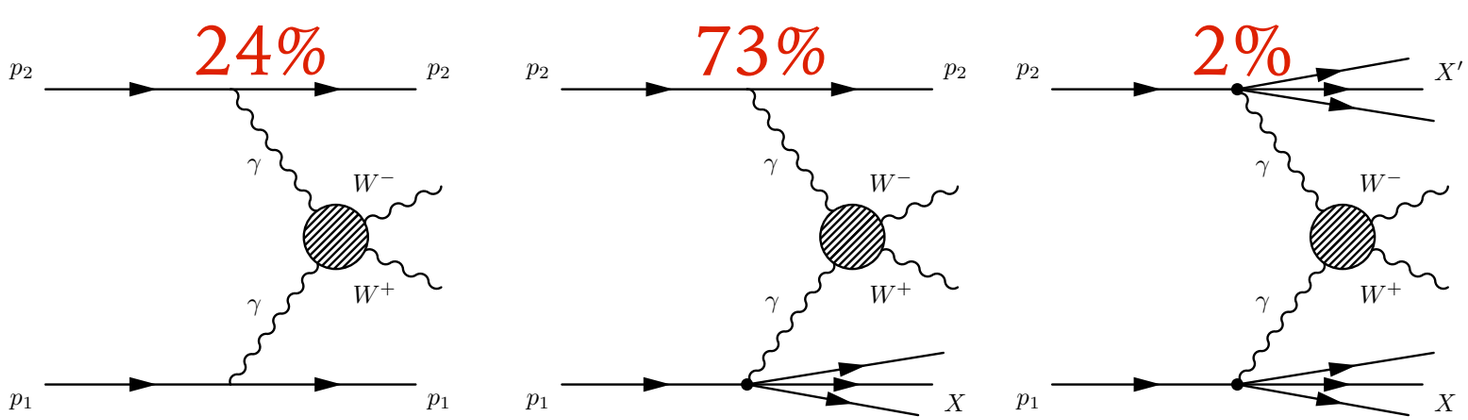
Exactly **one electron and muon** with opposite charge

$p_{\mathrm{T}}^{\mathrm{lep}} > 27,\ 20\ \mathrm{GeV}$

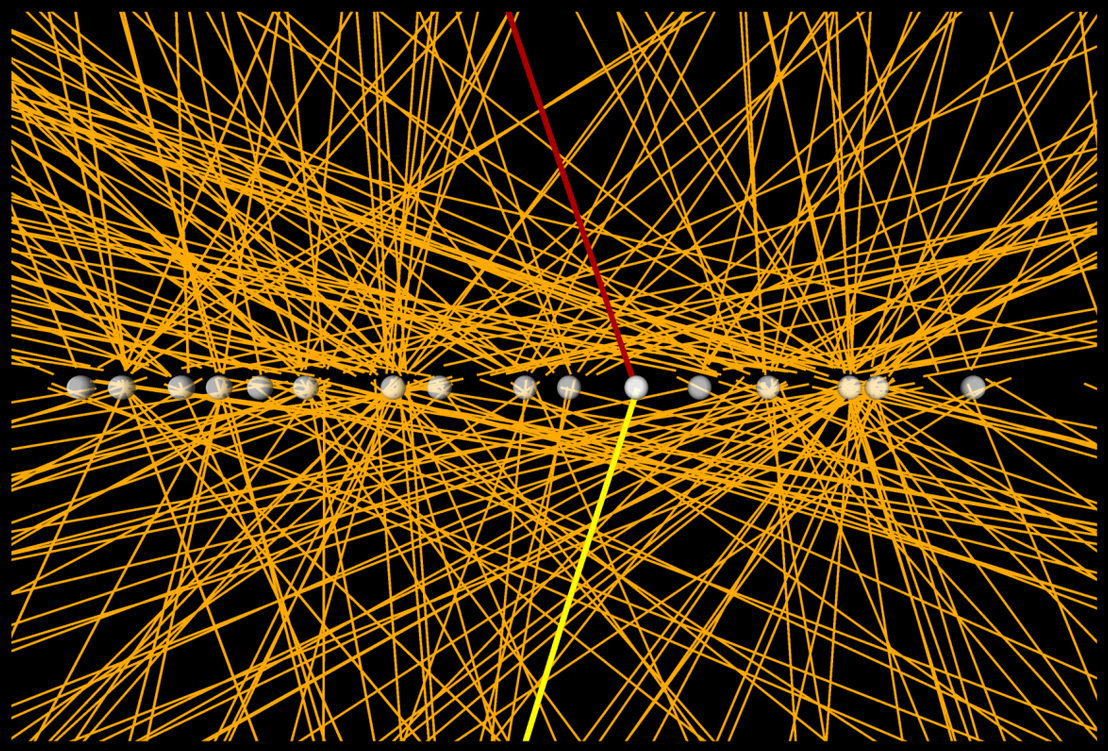
$p_{\mathrm{T}}(e\mu) > 30\ \mathrm{GeV}, m_{e\mu} > 20\ \mathrm{GeV}$

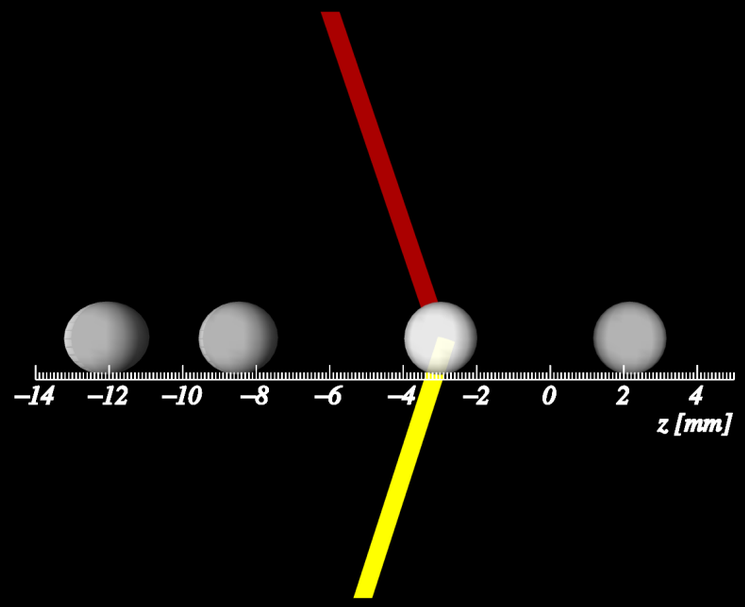
No track associated with the hard scatter vertex

- Signal modelling
  - Elastic: Herwig7
  - Dissociative productions: MG5_aMC@NLO+Pythia8
  - No soft survival, LO only



- Main backgrounds:
  - pp → WW and pp → Z → $\tau\tau$ events with 0 tracks: Powheg+Pythia8/Herwig7, Sherpa
  - Photon-induced dilepton production: Herwig7, MG5+Py8



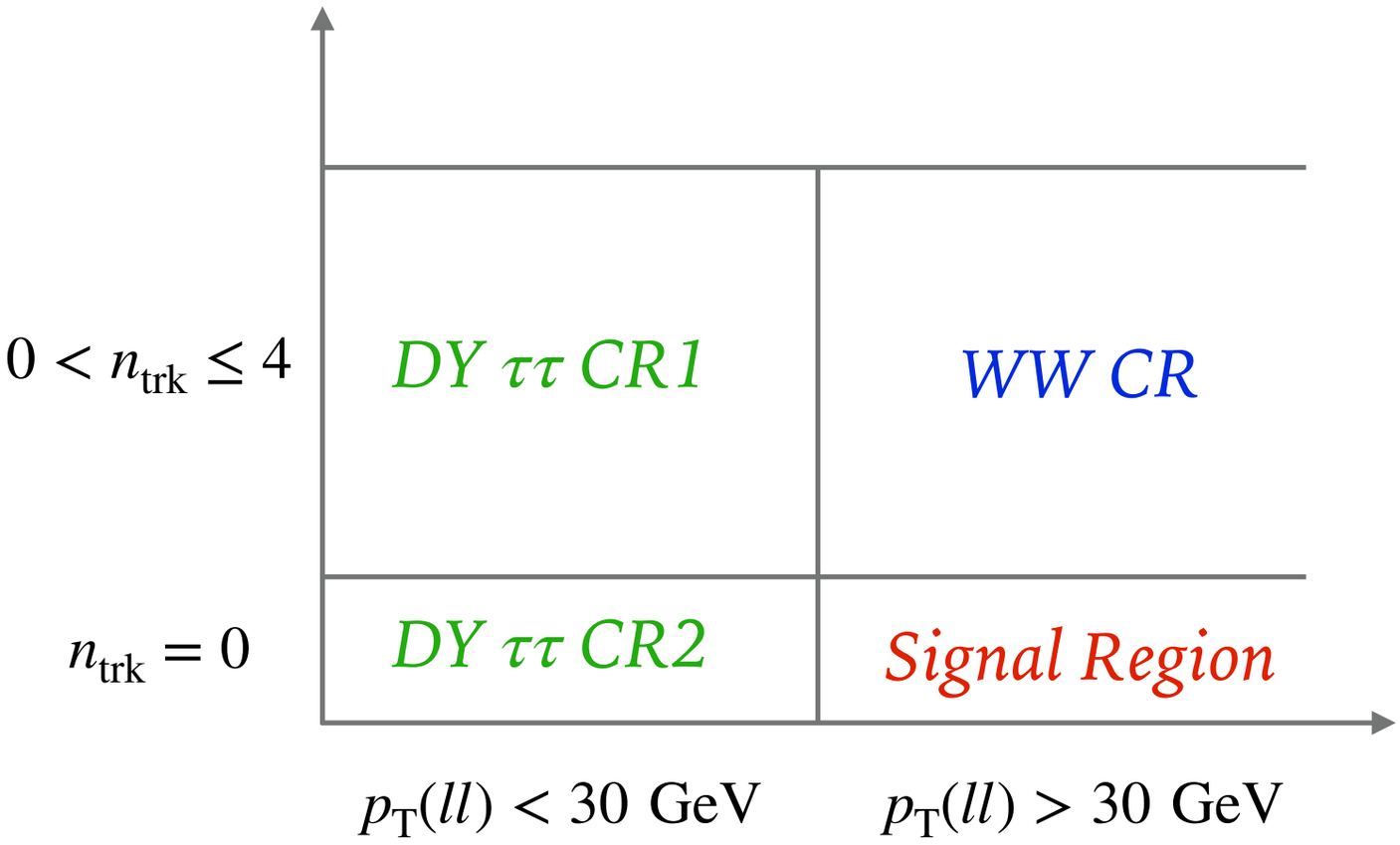


22 reconstructed vertices in the event, 16 displayed

ATLAS EXPERIMENT

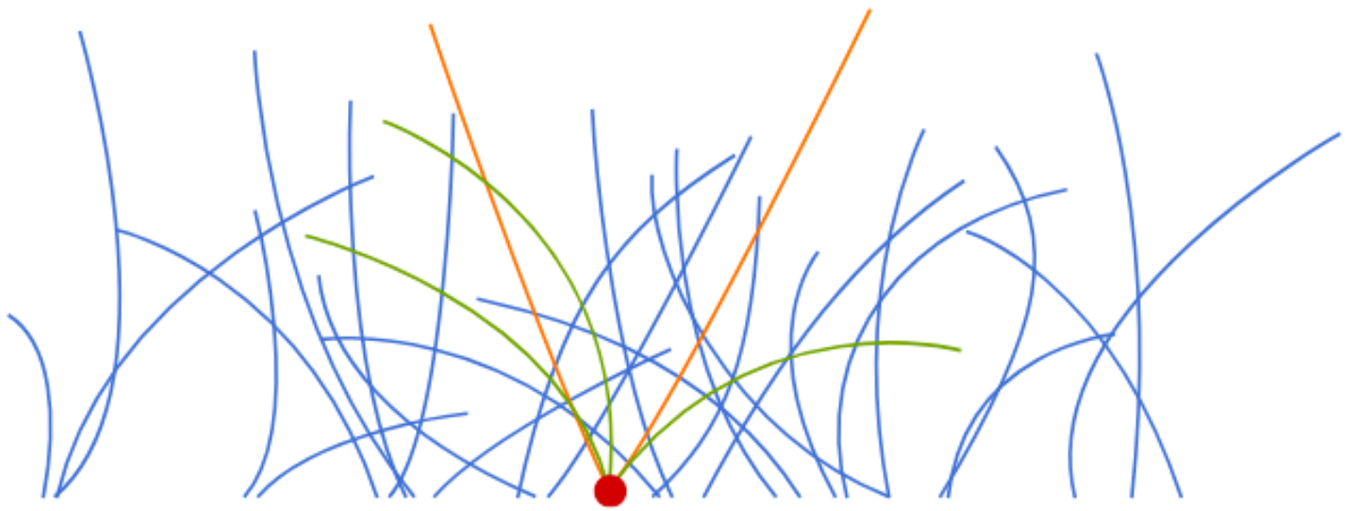
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Analysis strategy



- Analysis relies on precise modelling of low number of tracks

Experimental technique



Experimental techniques

- Harsh LHC environment
- Typical selected event has primary interaction vertex, and leptons from hard interaction, particles from underlying event and pileup

Dedicated algorithms or data driven corrections

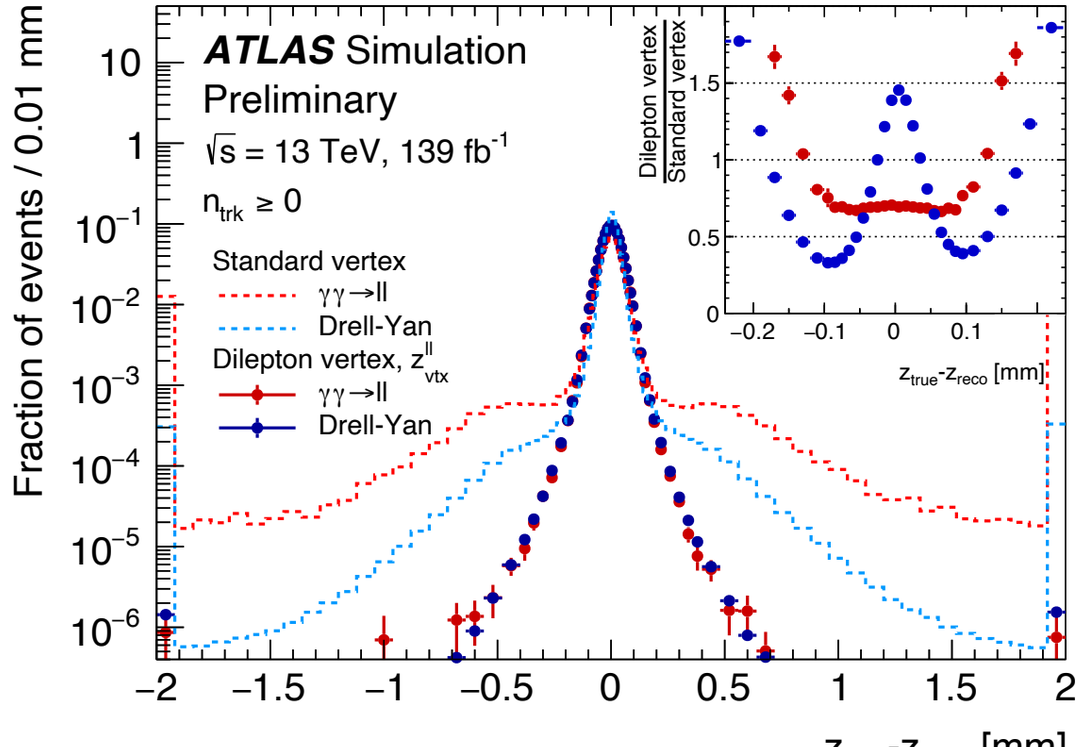
- Special vertex reconstruction
- Underlying event correction for background
- Pileup density and track multiplicity correction
- Modelling correction for signal (account for dissociation and survival factor)

Vertex reconstruction and track selection

- Lepton tracks used to define interaction vertex

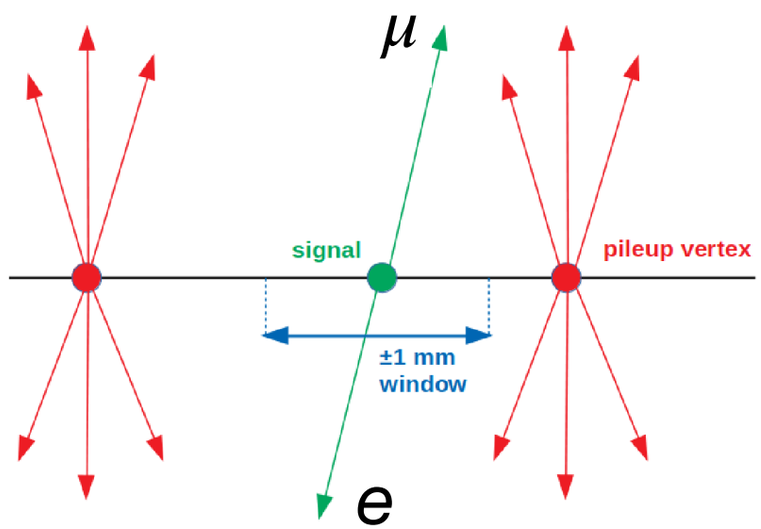
$$z_{\mathrm{vtx}}^{\ell\ell} = \frac{z_{\ell_1} \sin^2\theta_{\ell_1} + z_{\ell_2} \sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

- $\sin^{-1}\theta_\ell$ parameterises the uncertainty of the measured z_ℓ position
- Position not biased by nearby pileup tracks
- Advantage compared to ATLAS standard vertex (selected with max sum p_{T}^2)



- Reconstructed tracks selection
  - $p_{\mathrm{T}} > 500$ MeV, $|\eta| < 2.5$
  - Not associated to any lepton
  - Transverse and longitudinal impact parameters $|d_0|, |z_0| < 1$ mm

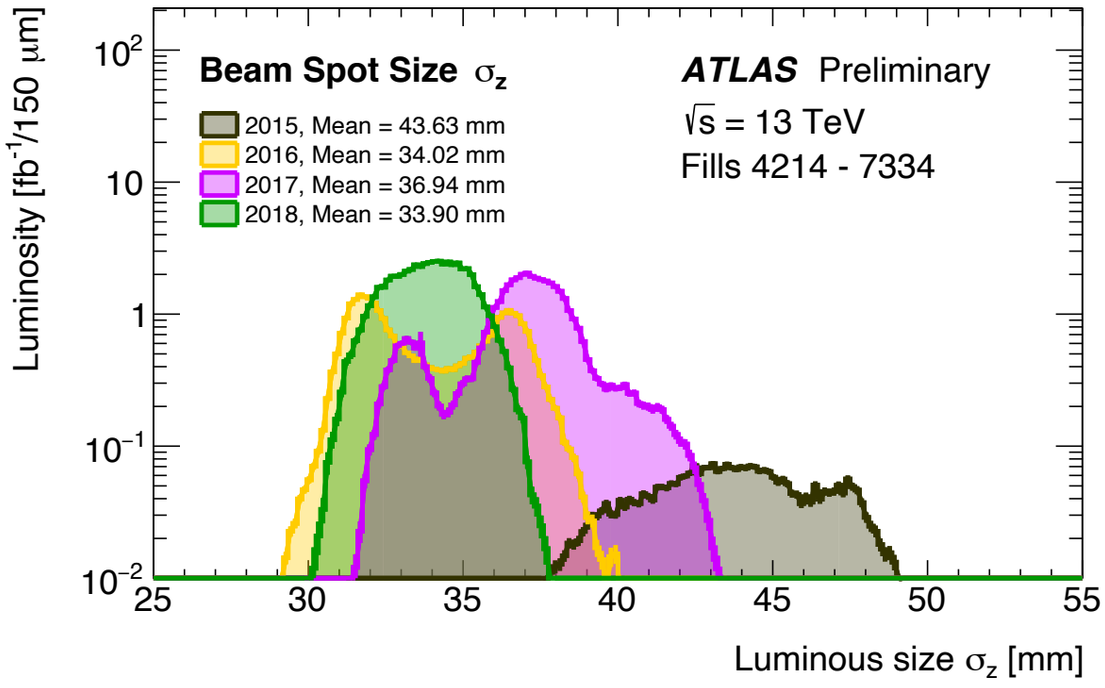
$$n_{\mathrm{trk}} = n_{\mathrm{trk}}^{\mathrm{UE}} + n_{\mathrm{trk}}^{\mathrm{PU}} + \varepsilon(\mathrm{fakes}, \ldots)$$



Pileup and beamspot

Issue: longitudinal size of luminous region time dependent and smaller than in MC

- $\sigma^{\mathrm{BS}}_{\mathrm{Data}} = 36\ \mathrm{mm}, \sigma^{\mathrm{BS}}_{\mathrm{MC}} = 42\ \mathrm{mm}$
- Exclusive selection more efficient in MC due to smaller pileup track density

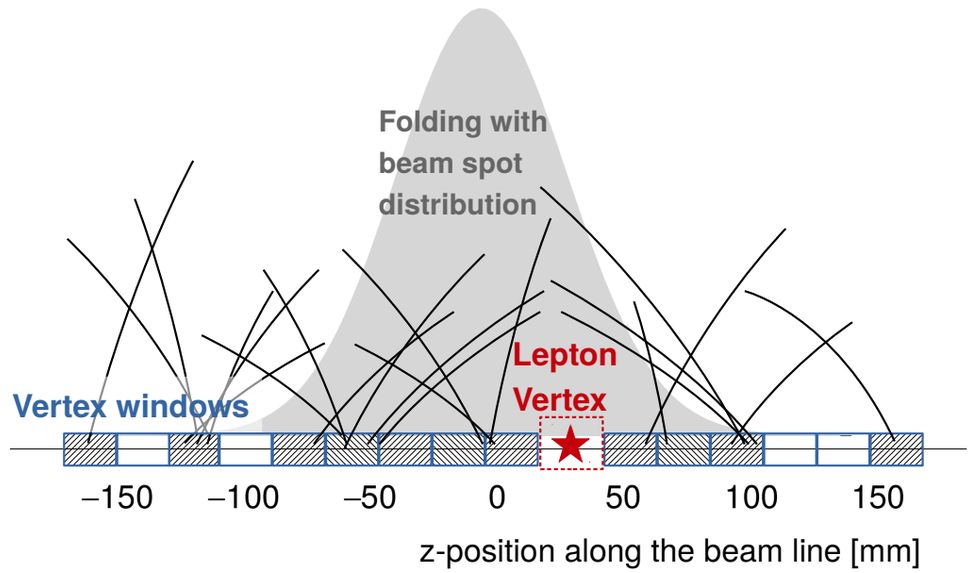


Beamspot size correction

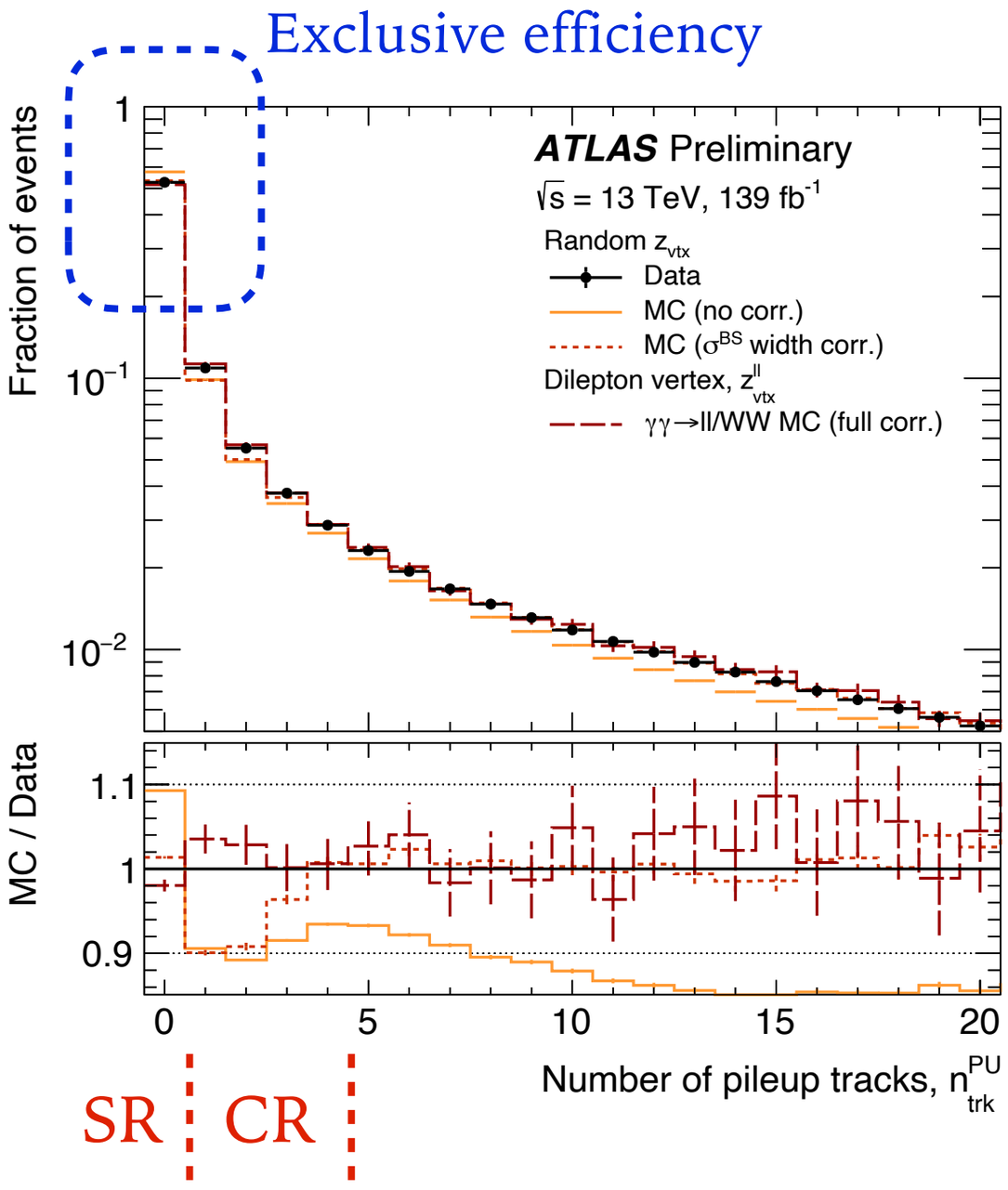
- Corrected by scaling z_0 impact parameter of pileup tracks with $\sigma^{\mathrm{BS}}_{\mathrm{Data}}/\sigma^{\mathrm{BS}}_{\mathrm{MC}}$
- Dedicated samples for signal samples matching the BS size in data

Validation

- Pileup modelling as a function of z validated using “tail positions” in Drell-Yan events
- Tracks counted in 2 mm windows, well, separated from lepton vertex $|z^{\ell\ell}_{\mathrm{vtx}} - z_{\mathrm{trk}}| > 10\ \mathrm{cm}$
- Data/MC differences applied as additional correction



Pileup correction

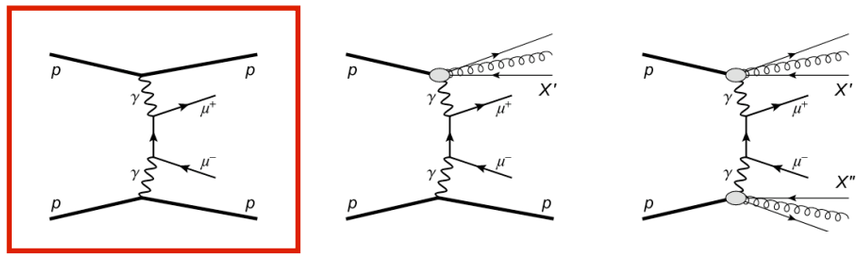


- Pileup correction applied as a function of $z_{\mathrm{vtx}}^{\ell\ell}$ and number of pileup tracks
- Without correction 20% discrepancy between SR and CR
- Excellent modelling of the expected number tracks around lepton vertex after track z_0 scaling and pile-up correction
- Obtained by folding in the beam spot distribution
- **52.6% average Run 2 exclusive efficiency,** $\langle\mu\rangle = 33.7$

Signal modelling

- MC with complete modelling of $\gamma\gamma \to W^+W^-$ not available
  - MG5-Pythia8 interface issues for single-diss sample (FSR emitted from intact p)
  - No survival effects for dissociate contributions

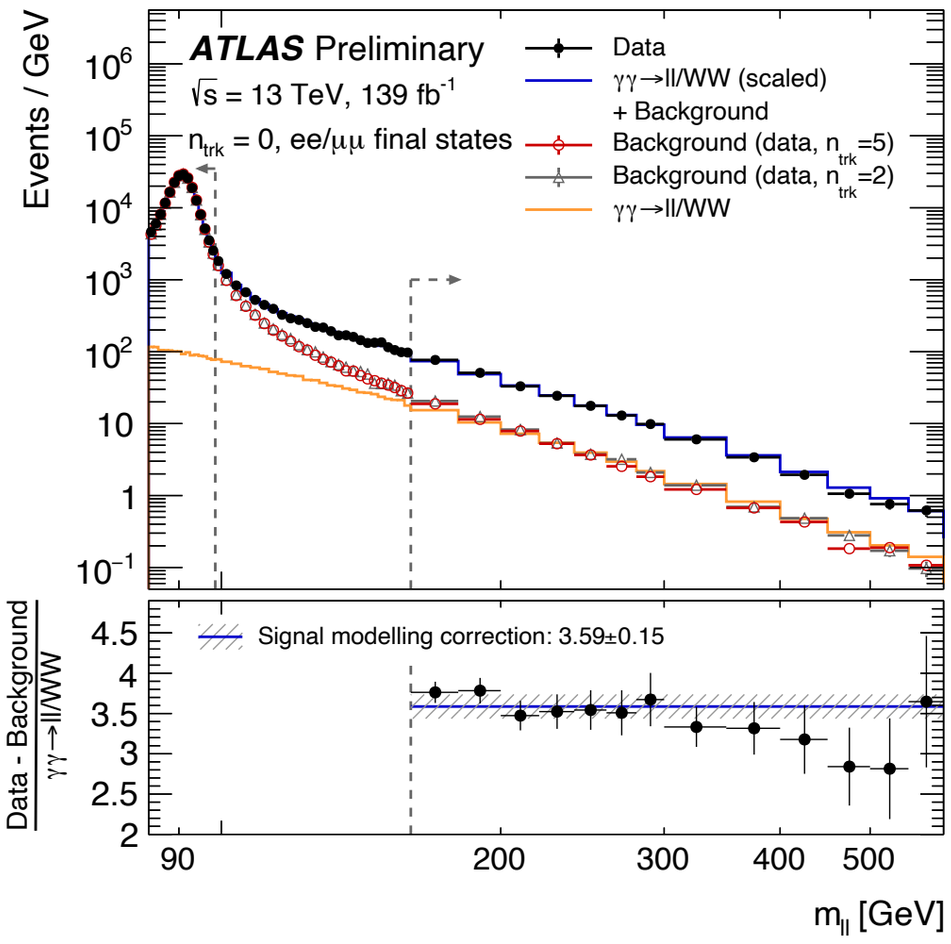
- **Use data to estimate missing components and scale elastic WW (Herwig7)**



- Scale factor measured in $\gamma\gamma \to ll$ events with $n_{\text{trk}} = 0,\ m_{ll} > 160\ \text{GeV}$ in data

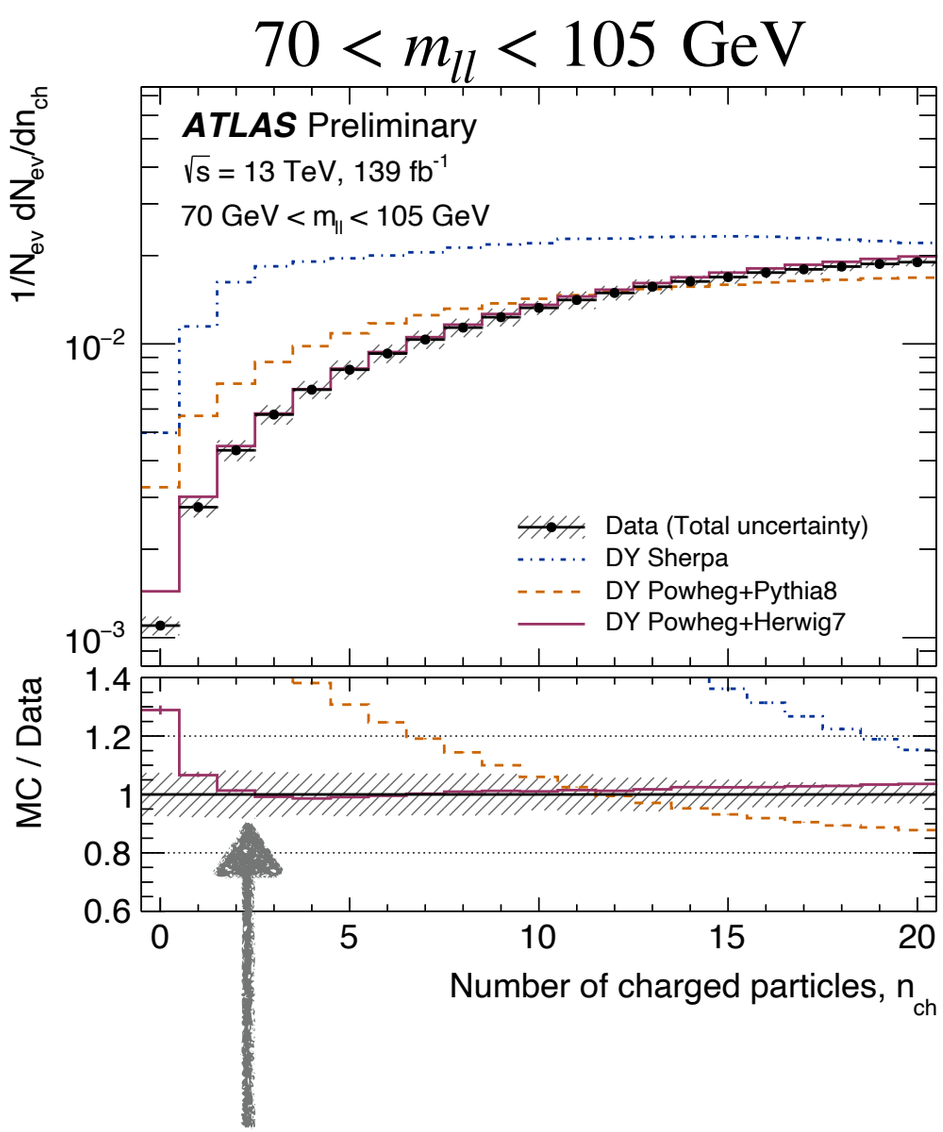
$$\text{SF} = \frac{N_{\text{data}} - N_{\text{DY}}}{N^{\text{MC,Elastic}}_{\gamma\gamma\to ll}} = 3.59 \pm 0.15\ (\text{stat} + \text{syst})$$

- DY background from data, selected with $n_{\text{trk}} = 2$ and $n_{\text{trk}} = 5$, normalized in Z peak
- Uncertainty of ±4.1%, accounts also for $\gamma\gamma \to ll$ contamination in normalization region and background templates



Background modelling - underlying event

- Charge-particle multiplicity measured in Drell-Yan events in bins of p_T(ll)
  - $\gamma\gamma \to ll$ contributions subtracted
- Data/MC weights at particle level to Pythia8, Herwig7 and Sherpa
- Correct qq induced WW, WZ, ZZ and Drell-Yan backgrounds
  - As a function of p_T(V) and p_T(VV)
  - This assumption is verified using several hadronization models. Universality of UE → systematic uncertainty small
- Up to factor of 5 correction in n_{trk}=0!

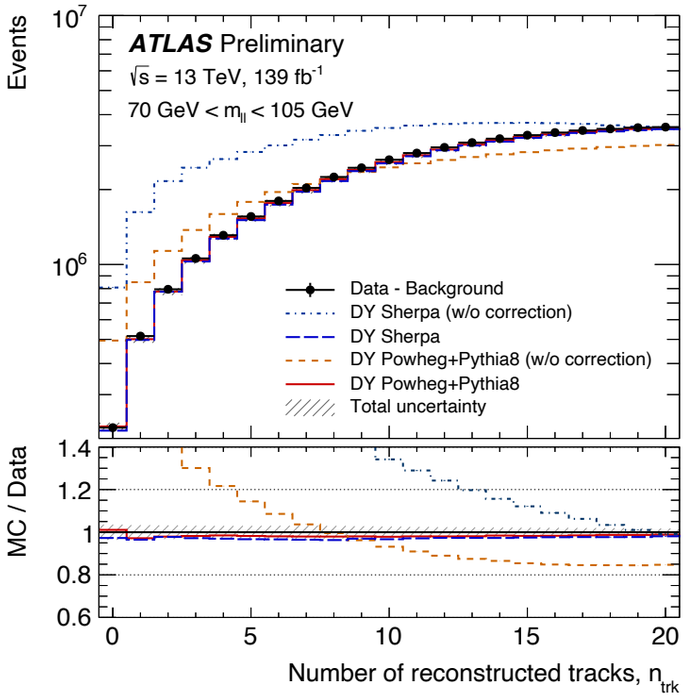


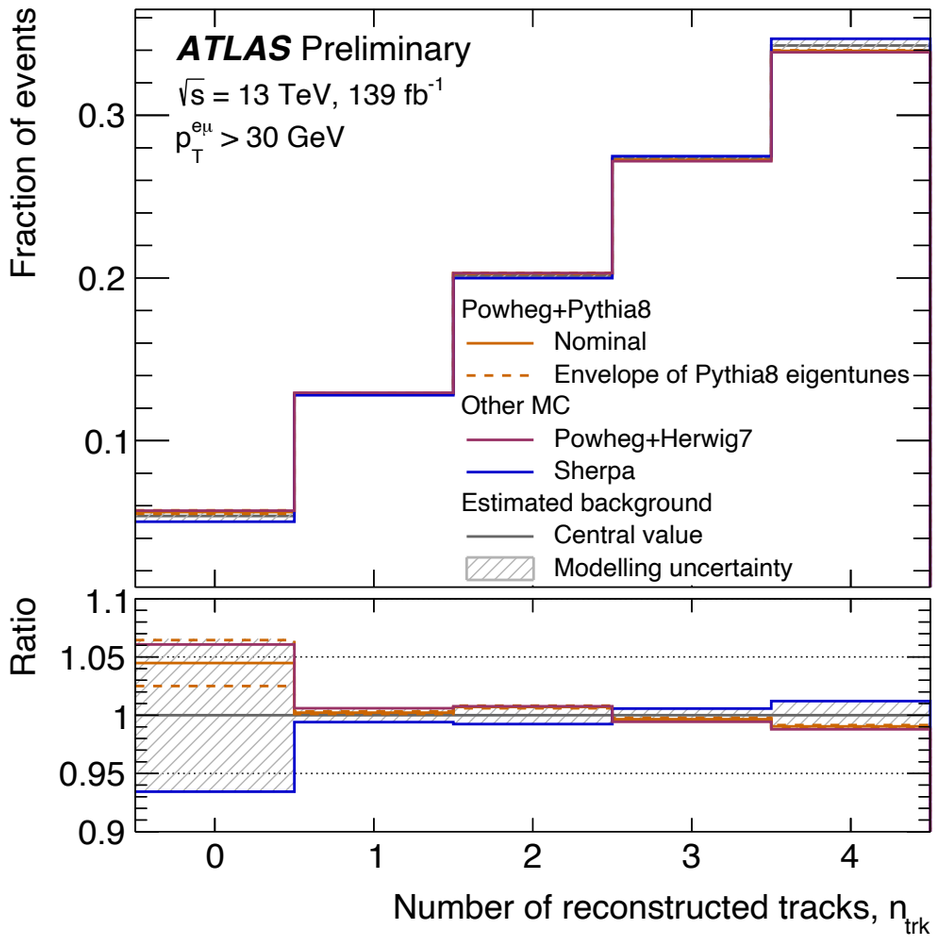
Herwig7 well performing

Application of UE correction

- Excellent modelling of DY using $p_T(Z)$ dependent correction for both Powheg and Sherpa

From qq→Z to qq→WW





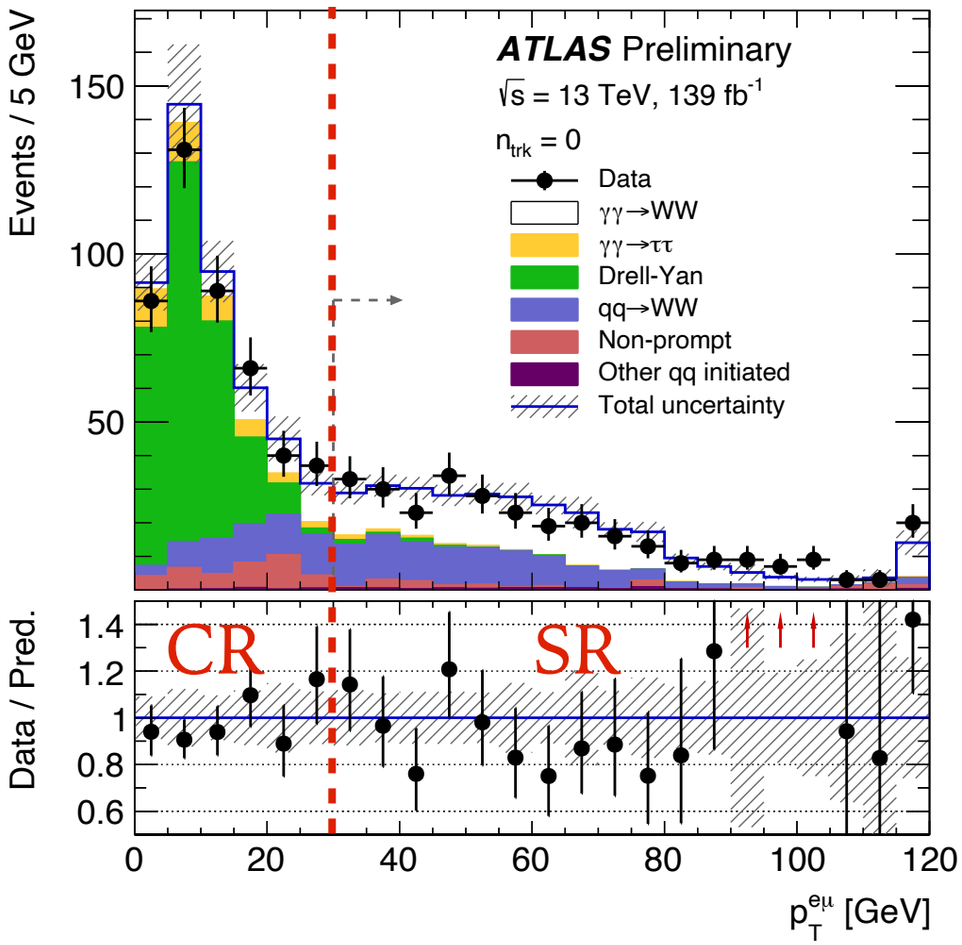
- **$0 < n_{trk} \leq 4$**: excellent agreement for WW using $p_T(WW)$ dependent correction for all generators / tune variations
- **Extrapolation to SR**: expected WW yield taken as midpoint between predictions,

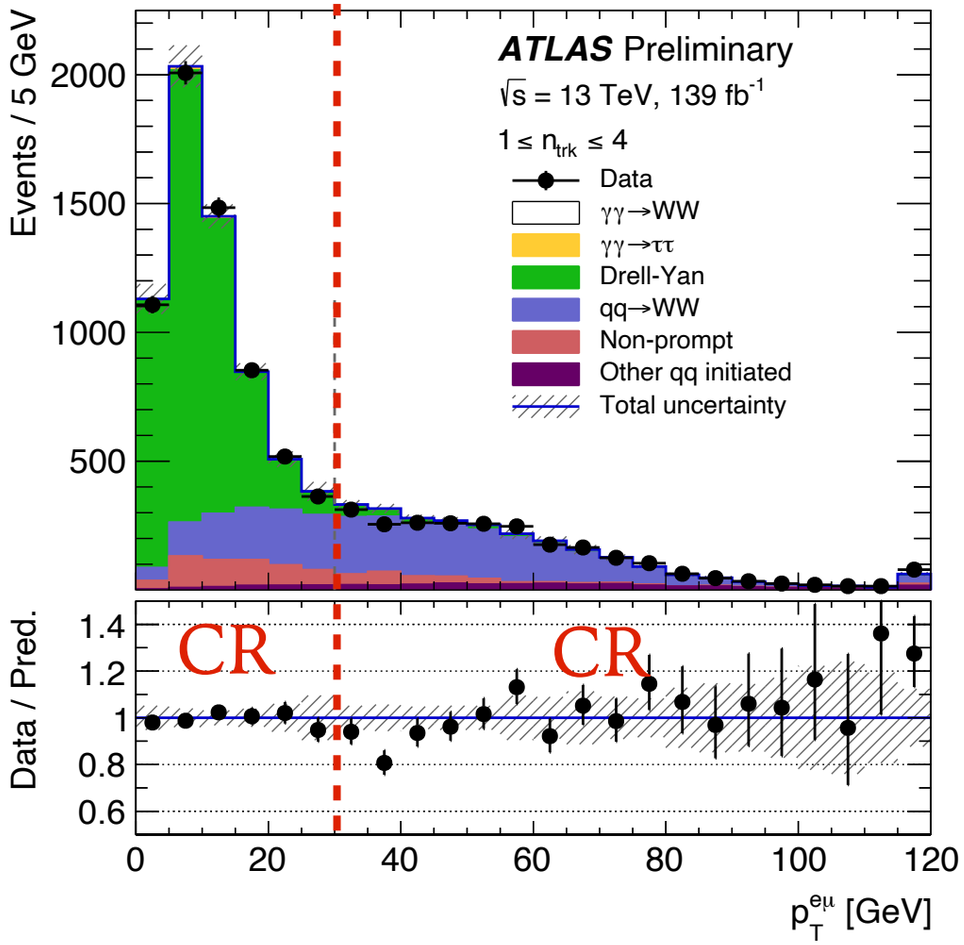
  Powheg+Pythia8 and UE eighteen tune variations
  Powheg+Herwig7
  Sherpa

- Maximum deviation taken as uncertainty

Signal and control regions

- Signal extracted in a profile likelihood fit
  - four bins with $p_T(ll) < 30$ GeV or $p_T(ll) > 30$ GeV, and $1 \leq n_{\mathrm{trk}} \leq 4$ or $n_{\mathrm{trk}} = 0$
  - one bin for signal modelling correction (m(ll)>160GeV)
  - four free parameters:
    normalizations of $\gamma\gamma \to WW$, $\gamma\gamma \to ll$, Drell-Yan and *WW*





Results

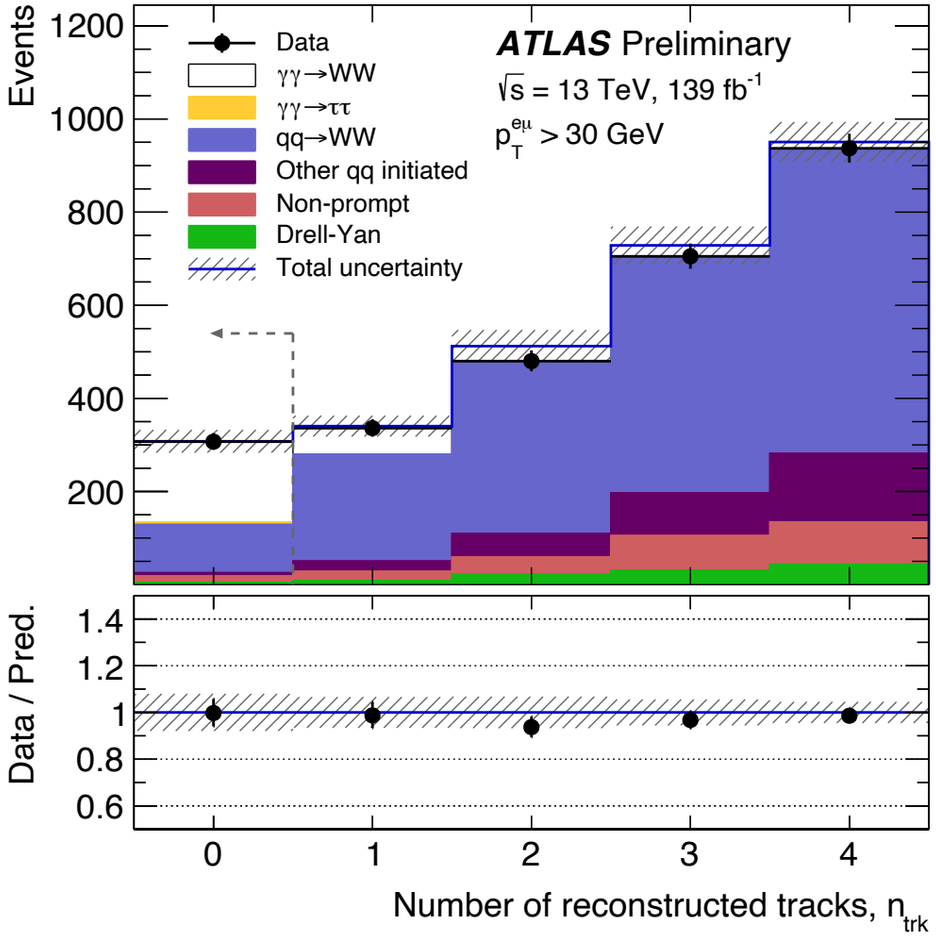
- 307 observed, 132 background events expected

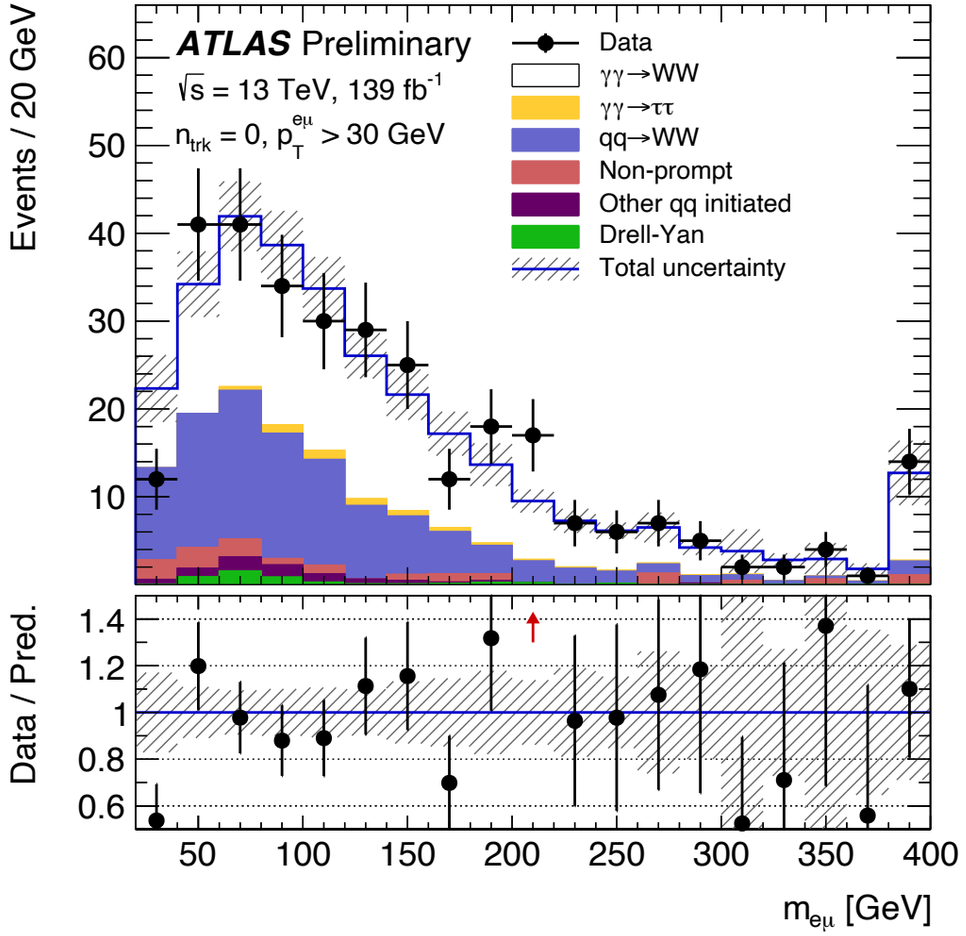
$$\beta_{WW} = 1.21^{+0.19}_{-0.23}$$
$$\beta_{DY} = 1.16^{+0.10}_{-0.12}$$
$$\beta_{\gamma\gamma\to ll} = 3.59 \pm 0.15$$

- Signal normalization is expressed relative to scaled predictions using high-mass $\gamma\gamma \to ll$

$$\mu_{\gamma\gamma\to WW} = 1.33 \pm 0.14\ (\text{stat.})^{+0.22}_{-0.17}\ (\text{syst.})$$

- Background only hypothesis rejected with 8.4σ (6.7σ expected)





Fiducial cross section

- Measured for 0 additional charged particles, p_T(em) > 30 GeV + other kinem requirements

$$\sigma_{\text{fid}} = 3.13 \pm 0.32\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{fb}$$

- Dominant systematic uncertainties
  - WW modelling in the SR
  - Signal modelling scale factor: evaluated as a change of the SF over 160 GeV < m(ll) < 400 GeV
  - Statistical uncertainty on the background (includes CR for misidentified leptons)

Source	Impact [%]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons	1.5
Background, statistical	6.7
Modelling	
Pileup modelling uncertainties	1.1
Underlying event modelling uncertainties	1.4
Signal modelling uncertainties	2.1
WW modelling uncertainties	4.0
Other background uncertainties	1.7
Luminosity	1.7
Total	8.9

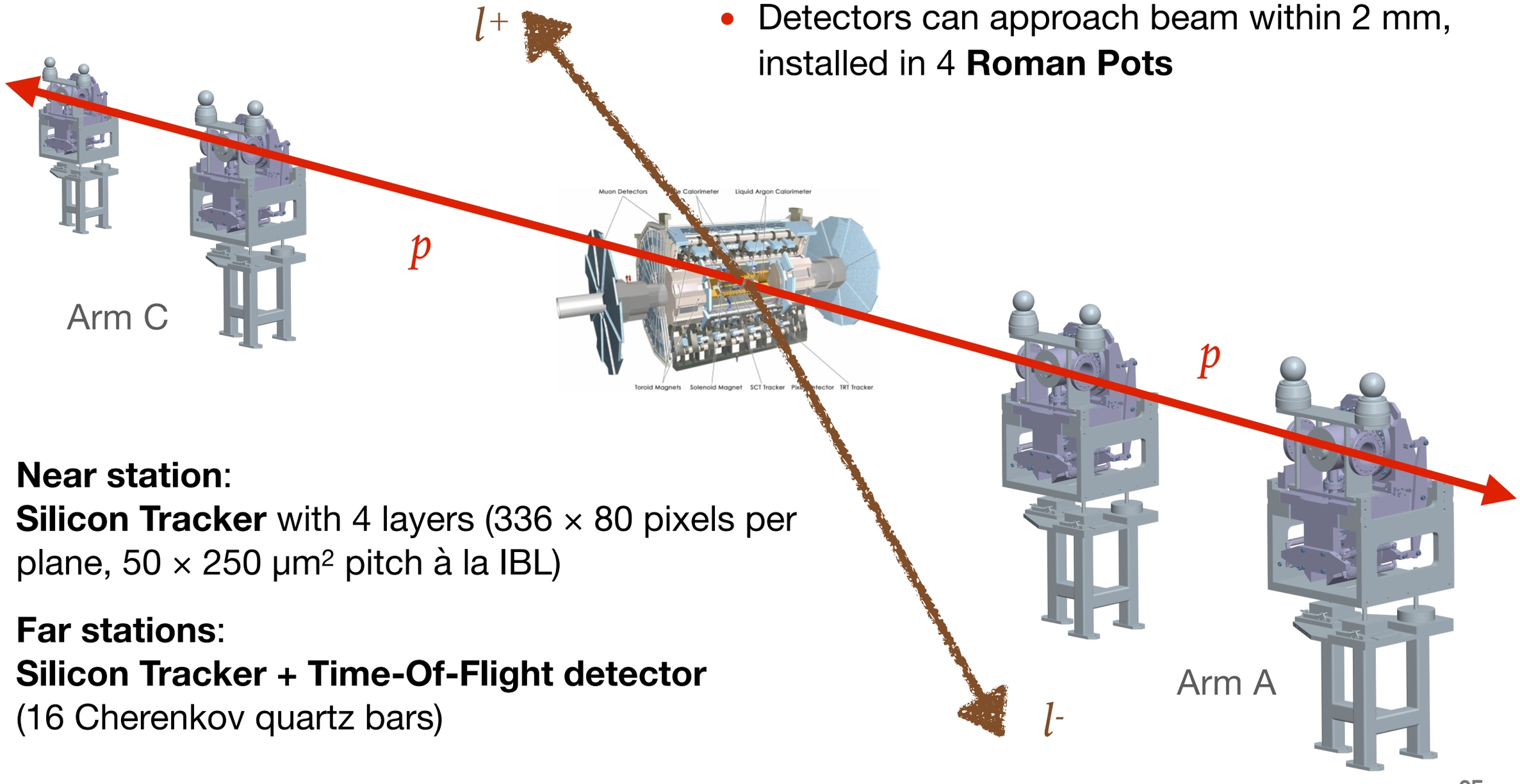
- Theoretical prediction
  - Elastic Herwig7 (scaled using data): $\sigma^{\gamma\gamma\to WW}_{\text{MC,Elastic}} \times 3.59 = 2.34 \pm 0.27$ fb
  - Madgraph+Pythia8: $\sigma_{\text{MG5}} = 3.2 \pm 0.6\ (\text{scale}) \pm 1.32\ (\text{PDF})$ fb
    - No predictions of soft rescattering effects in WW available
      MG5-Pythia8 interface issues for single-diss sample (ISR emitted from intact p)

- Small tension observed, modelling of diboson system would profit from improvements
- Outlook: differential distribution and BSM interpretations

Observation and measurement of **forward proton scattering** in association with lepton pairs produced via the photon fusion mechanism at ATLAS [ATLAS-CONF-2020-041]

ATLAS Forward Proton (AFP) Detector

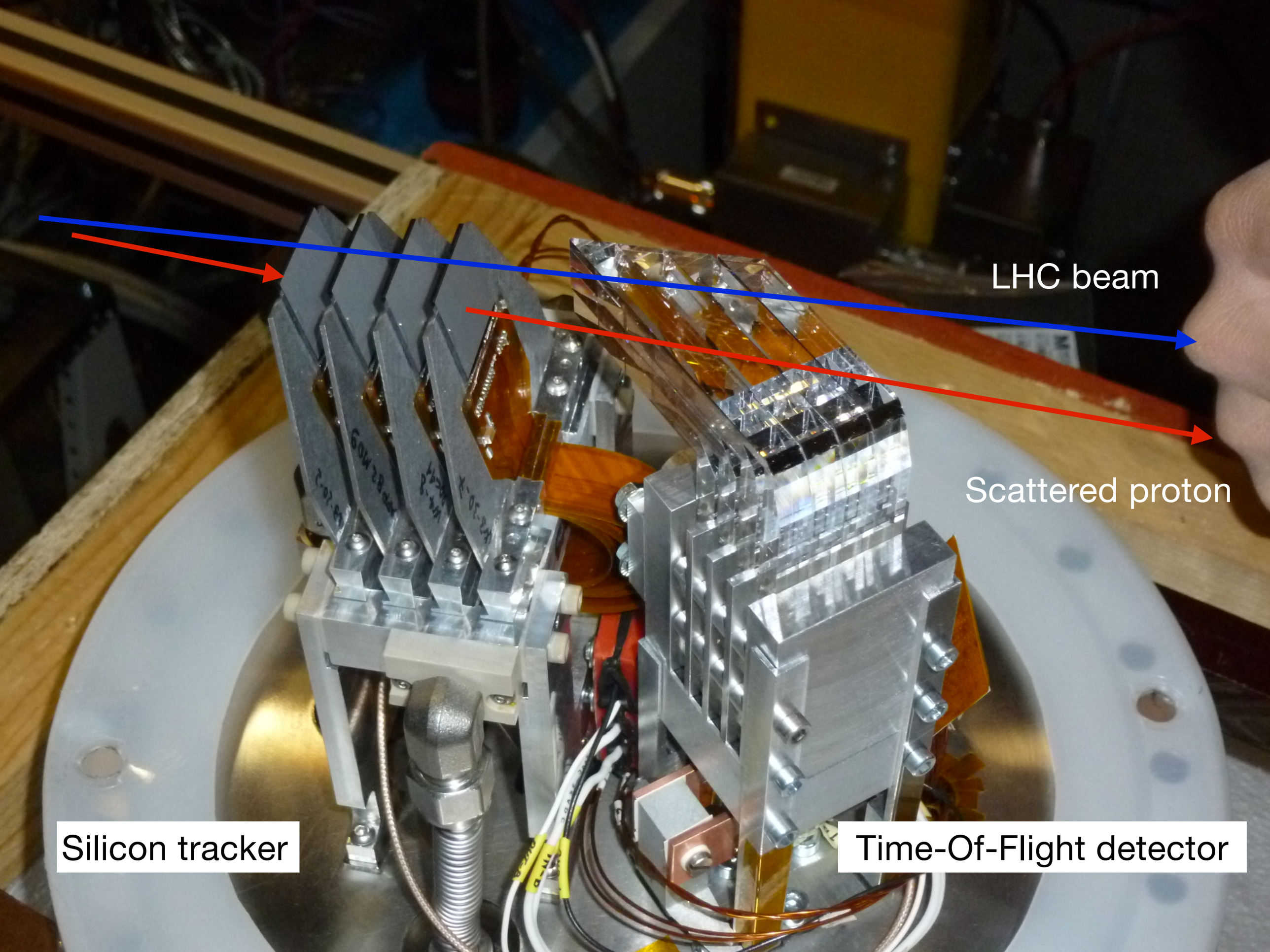
- Directly measure intact protons 220 m from the ATLAS interaction point
  - Open new physics program of diffractive & photon collisions
- Both A and C arms installed in 2017 for standard high-luminosity LHC data-taking



- Detectors can approach beam within 2 mm, installed in 4 **Roman Pots**

Near station:
Silicon Tracker with 4 layers (336 × 80 pixels per plane, 50 × 250 μm² pitch à la IBL)

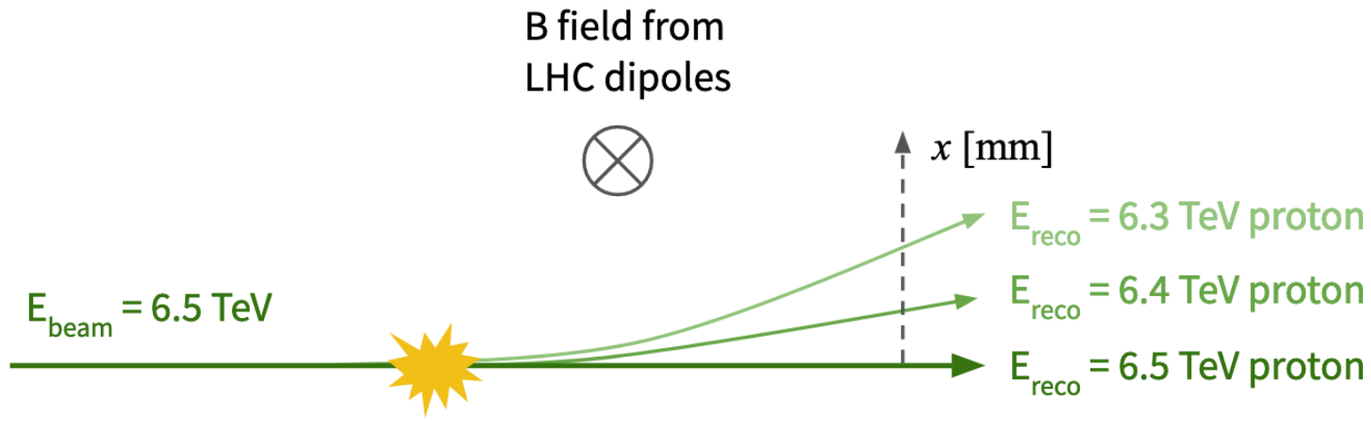
Far stations:
Silicon Tracker + Time-Of-Flight detector
(16 Cherenkov quartz bars)


LHC beam
Scattered proton
Silicon tracker
Time-Of-Flight detector

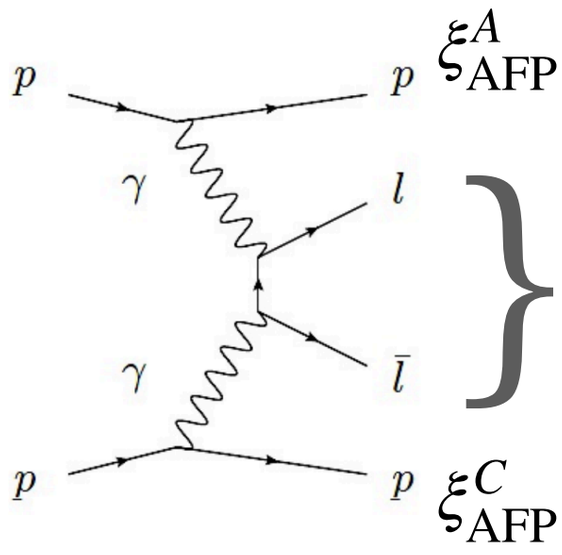
AFP TeV spectrometer

- Infer energy lost by proton from displacement from the beam

$$\xi_{\mathrm{AFP}} = 1 - E_{\mathrm{reco}}/E_{\mathrm{beam}}$$



- Acceptance: $0.02 < \xi < 0.1$
- Performance (see backup for details)
  - Inter-plane alignment using proton tracks
  - Global position using beam-based alignment
  - In-situ calibration using $\gamma\gamma \to ll$
  - Beam optics
- **Calculate** expected proton energy loss from dilepton system
- **Match** with the measurement in AFP
  - Uncertainty for leptons ~5%,
    AFP: ~10% (optics), 25% at small ξ (alignment)



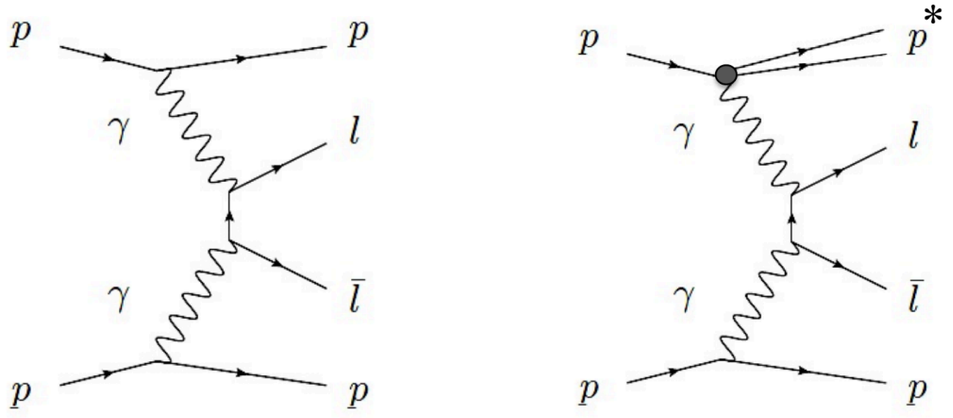
$$\xi_{ll}^{A,C} = (m_{ll}/\sqrt{s})e^{\pm y_{ll}}$$

$$|\xi_{\ell\ell} - \xi_{\mathrm{AFP}}| < \sigma(\xi_{\ell\ell}) + \sigma(\xi_{\mathrm{AFP}})$$

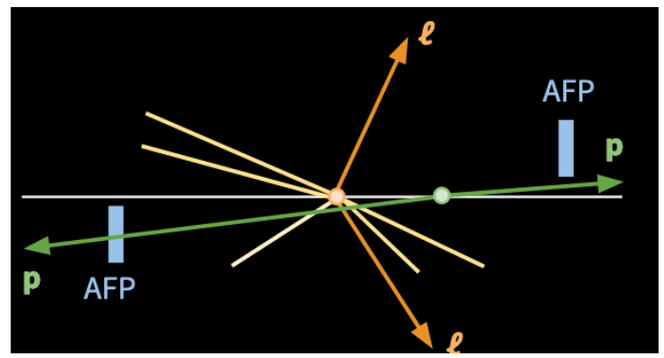
- **Selection allows efficient background suppression**

Analysis overview $\gamma\gamma \to l^+l^-$ + AFP

- Exactly 2 electrons/muons with opposite charge
  - $p_{\mathrm{T}}^{e}(p_{\mathrm{T}}^{\mu}) > 18,\ 15$ GeV, flavor dependent
- No track associated with hard scatter vertex
- Only 1 proton tag required to increase acceptance
- Kinematic match $|\xi_{\ell\ell} - \xi_{\mathrm{AFP}}| < 0.005$
- $m_{ll} > 20$ GeV, $m_{ll} \notin [70,105]$ GeV
- Acoplanarity $A_{\phi}^{ll} < 0.1$, $p_{\mathrm{T}}(ll) < 2$ GeV

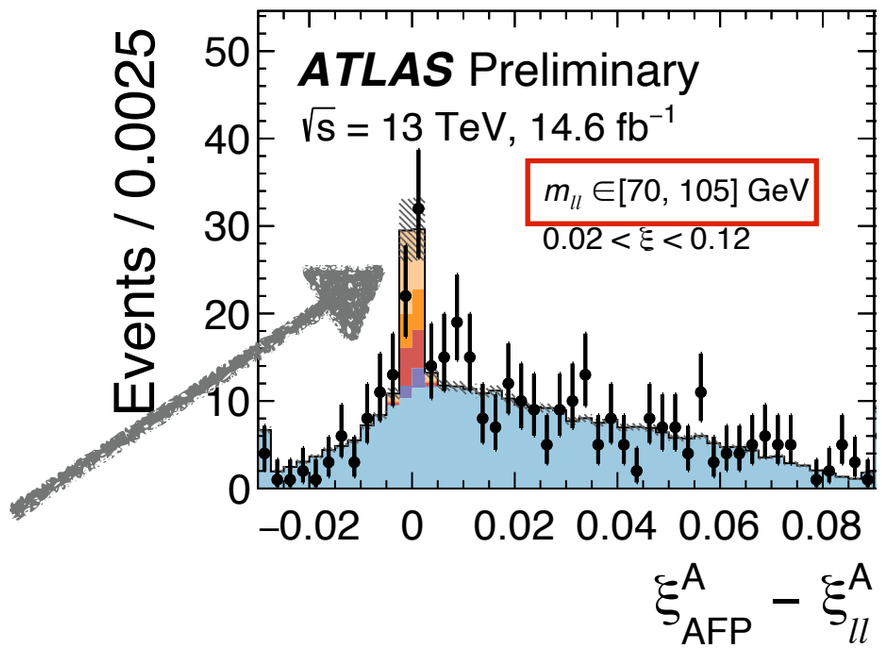


- Signal includes single-dissociation
  - Exclusive: Herwig7 (LO, no survival)
  - Single-diss: LPair 4.0 (LO, no survival)

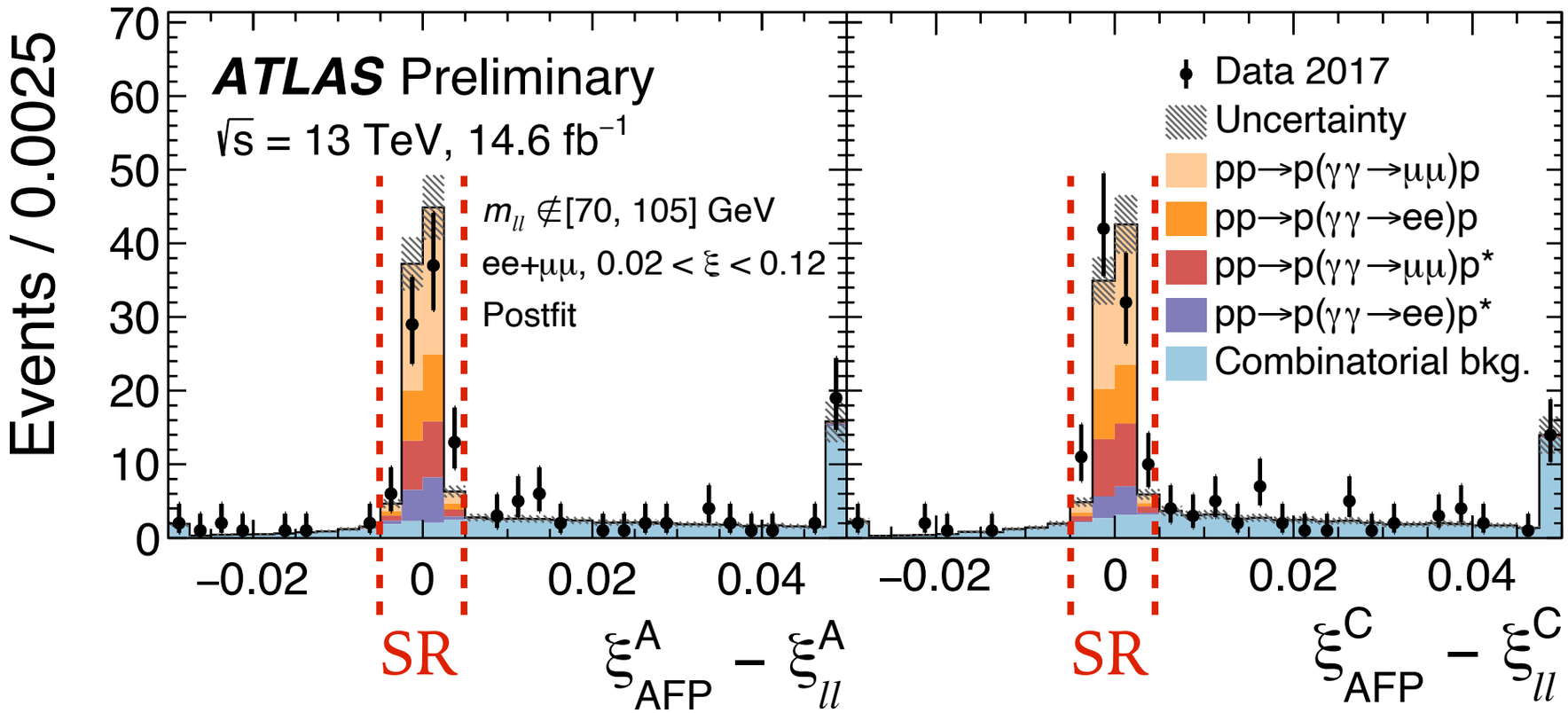


- Background dominated by Drell-Yan + random protons from pileup
  - Robust data-driven estimate for combinatoric background
  - Mixing events + side-band fit to $|\xi_{ll} - \xi_{\mathrm{AFP}}| > 0.005$
  - Cross-check in 70 < m_{ll} < 105 GeV region

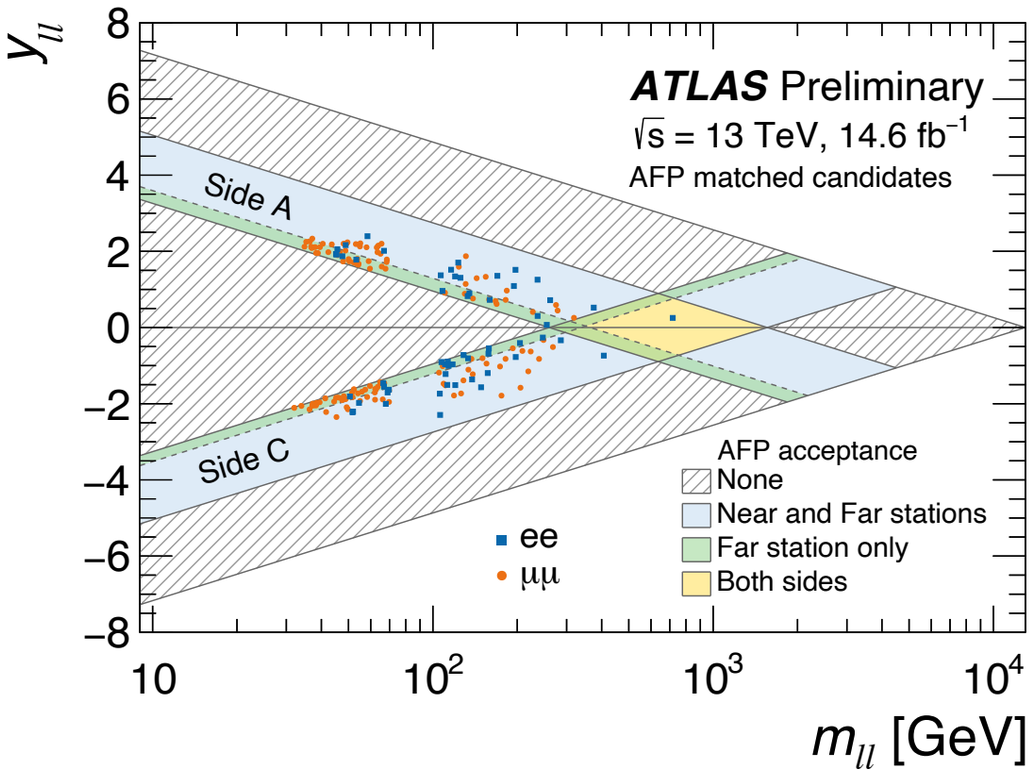
S/B discrimination even under Z peak thanks to AFP!



Observation



- Observed 57 (123) ee + p (μμ + p) data candidates with $|\xi_{ll} - \xi_{\mathrm{AFP}}| < 0.005$
- Signal significance per channel largely exceeds 5σ
  - Initial observation at LHC by CMS+CT-PPS [JHEP 07 (2018) 153] with ee/μμ combined
- Mostly single tag events, with $30 < m_{ll} < 630$ GeV
- AFP double tag acceptance: $300\ \mathrm{GeV} < M_{\mathrm{AFP}} < 1.5\ \mathrm{TeV}$



Cross section measurement

- Measured in tighter phase-space $0.035 < |\xi| < 0.08$ (both arms required)
  - to control proton reconstruction corrections (tag-and-probe measurements between near and far stations)
- Statistically dominated measurement (~25%), systematic uncertainties (~10%) dominated by proton reconstruction related effect (alignment & resolution, knowledge of beam optics)

- Rescattering effects observed in data
- Results can be used to test different models of survival probability

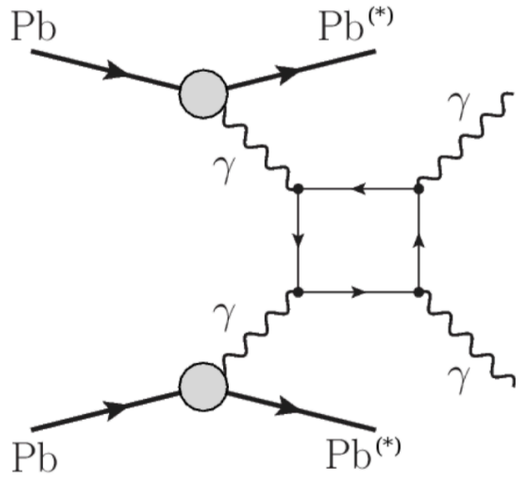
$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.3 ± 1.1
$S_{\text{surv}}(m_{ll} = 100\ \text{GeV})$ [30]	13.0 ± 1.0	11.1 ± 0.8
$m_{\ell\ell}$-dependent S_{surv} [31]	10.9 ± 0.8	9.2 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

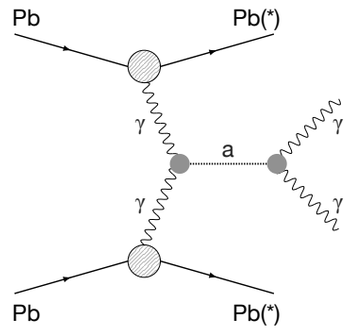
- The first cross section measurement using proton tagging at the LHC
- Proof of principle measurement employing forward proton tagging at high luminosity in ATLAS

Measurement of **light-by-light scattering** and **search for axion-like particles** with 2.2 nb−1 of Pb+Pb data with the ATLAS detector [arXiv:2008.05355]

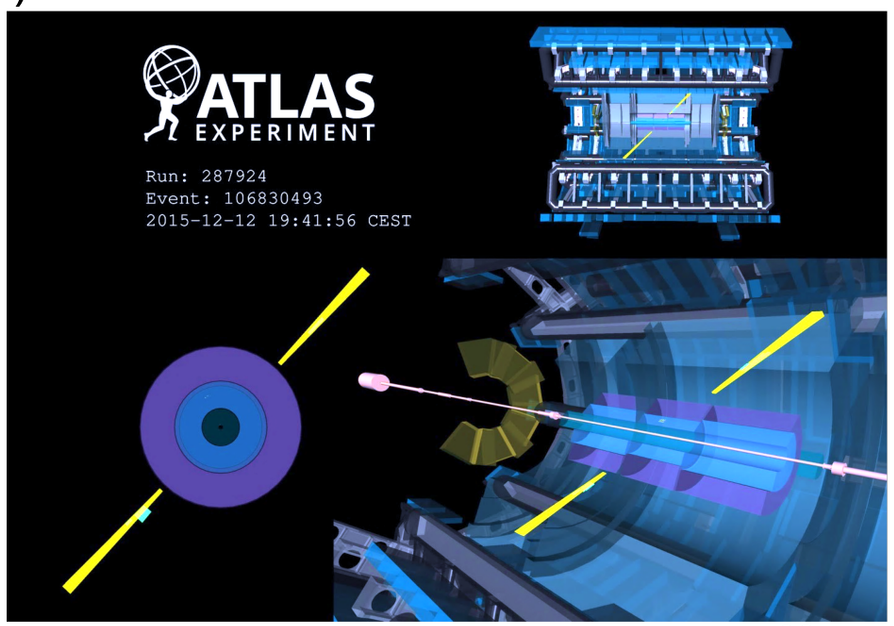
Light-by-Light Scattering

- Rare process $O(\alpha_{EM}^4)$
- 8.2 σ observation with 2018 data, [PRL 123 (2019), 052001]
  - Evidence [Nature Phys. 13 (2017) 9, 852]
- New measurement using the full Run 2 PbPb dataset (2015+2018)
  - E_T>3 GeV -> E_T>2.5 GeV
  - Differential cross section measurement
  - Results used to set limits on BSM axion-like particles





- Detector selection at the limit of ATLAS capabilities
  - Very low E_T photons, **E_T>2.5 GeV**
  - Track veto (**p_T > 100 MeV**) + pixel track veto (**p_T>50 MeV**) in the vicinity of the photon to reject mis-reconstructed electrons
- Dedicated selections at trigger level
  - L1: Minimal energy in the calorimeters
  - HLT: Limited number of hits in Pixel and MBTS detector, Veto in forward calorimeter

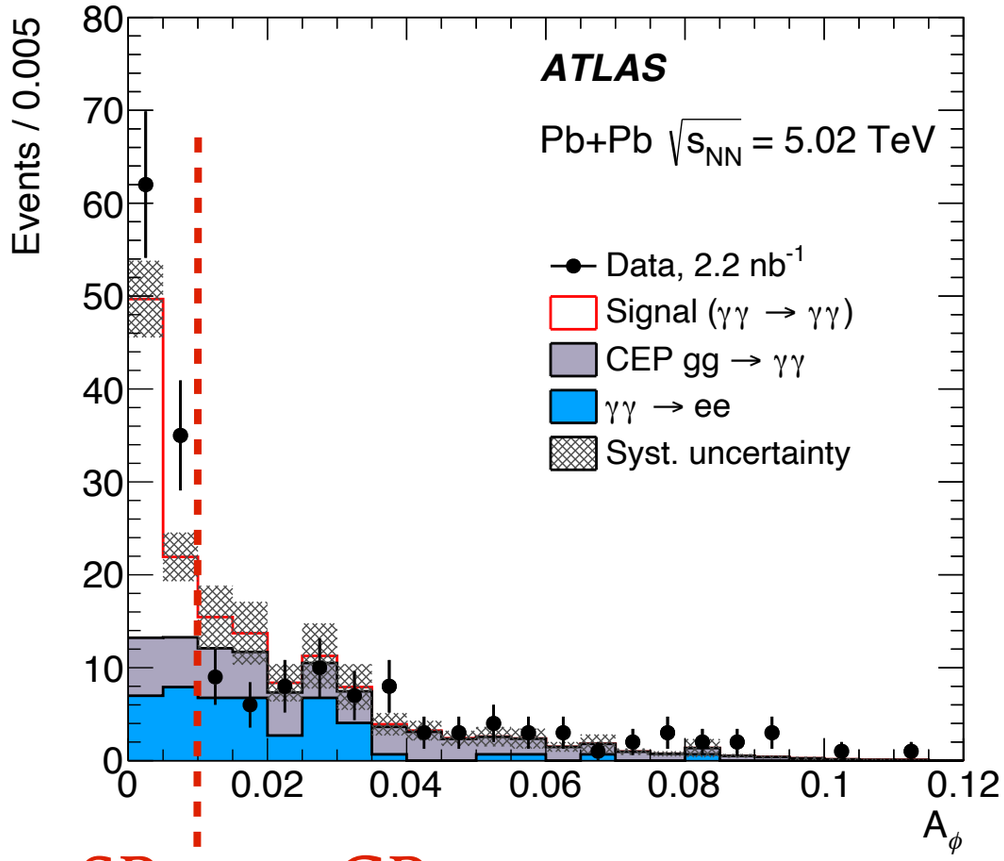


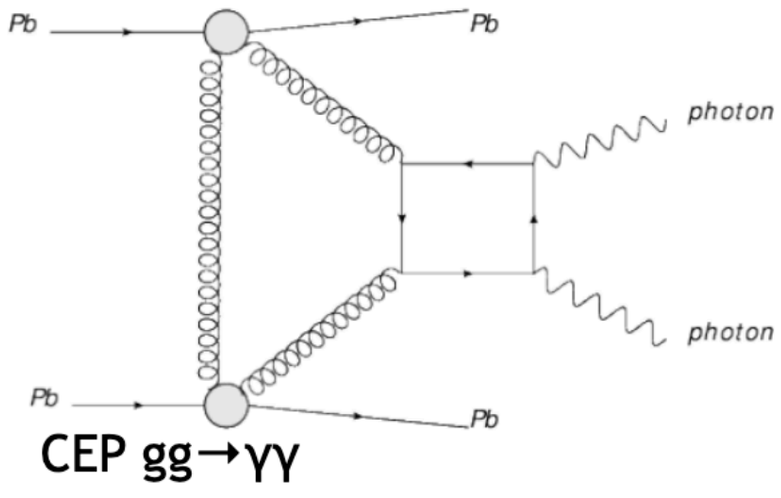
Signal+Background

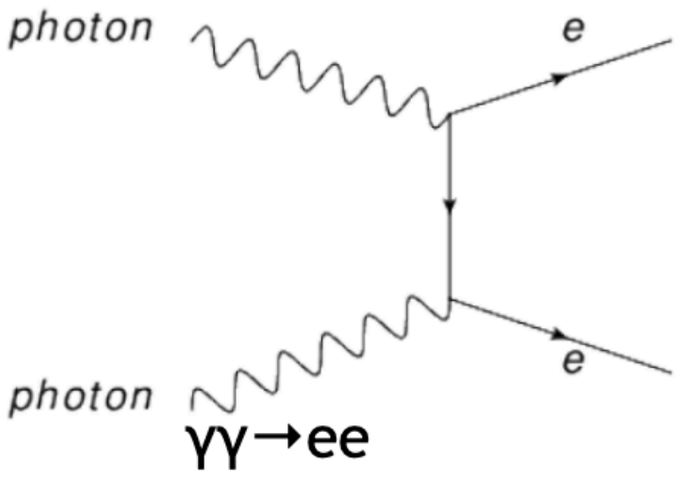
- **Signal**: SuperChic 3.0 (LO, fermion and boson loops) and calculation in PRC 93 (2016) 044907

- **CEP background**
  - Gluon-induced production with larger initial transverse momentum → broader Acoplanarity
  - Evaluated using SuperChic MC normalized in (Aco>0.01) CR

- $\gamma\gamma \to e^+e^-$ **background**
  - Data driven estimate propagated from CR (0 track, 1-2 PixelTrack) to SR

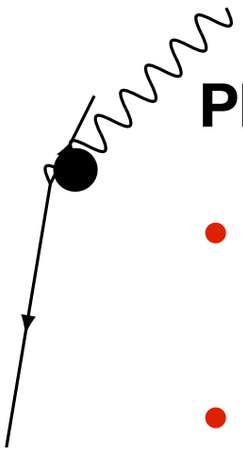






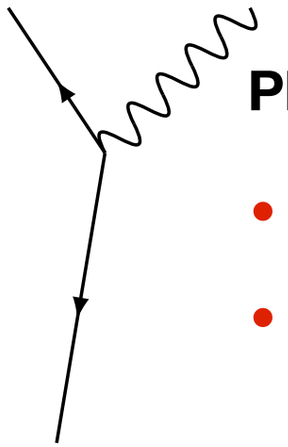
$\gamma\gamma \to e^+e^-$ and $\gamma\gamma \to e^+e^-\gamma$ photon-induced events used to check electron / photon performance

Photon efficiency and ID performance



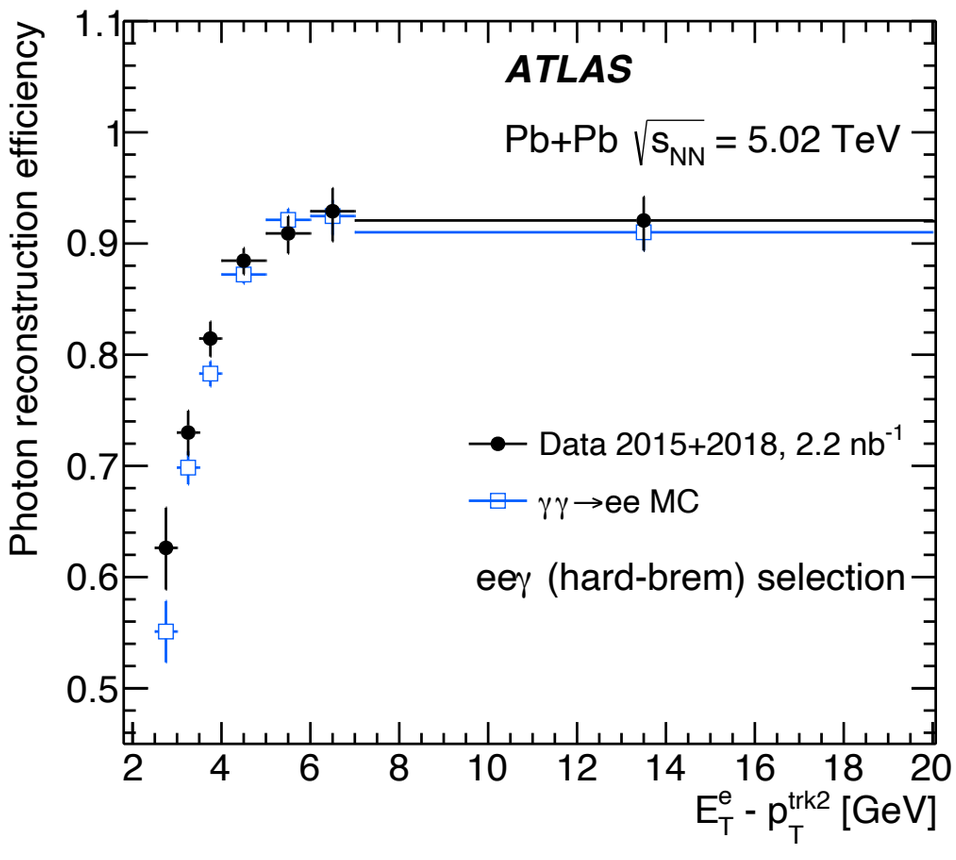
Photon efficiency

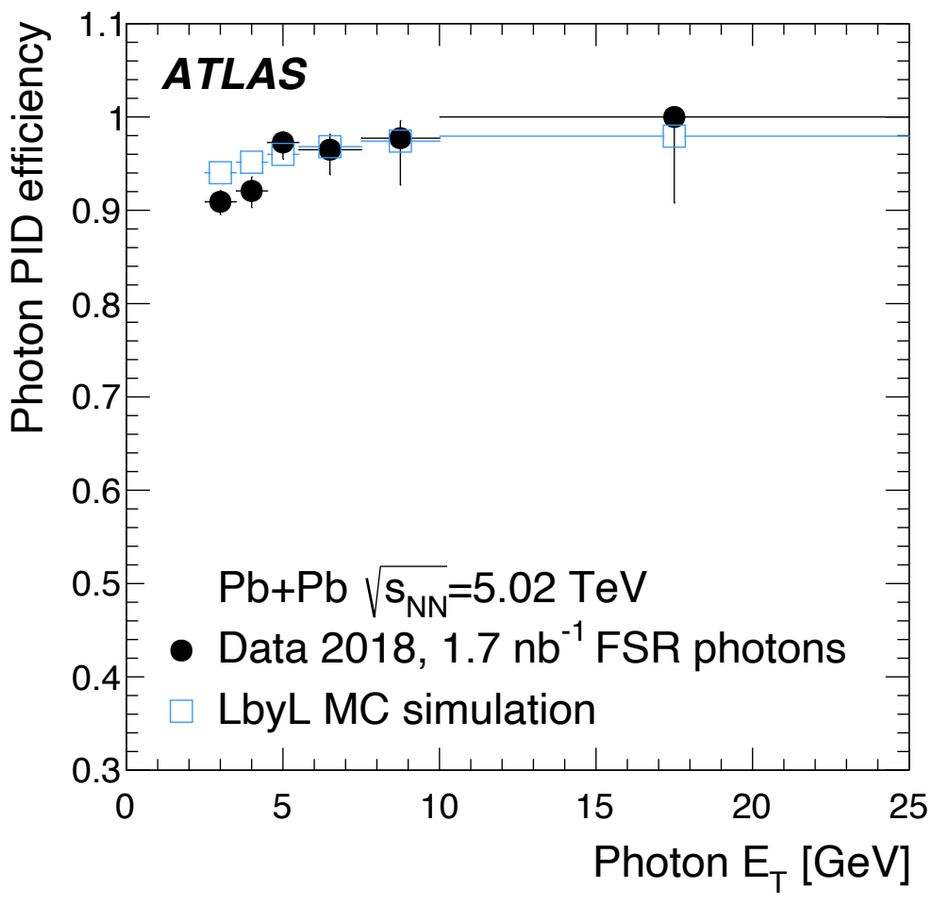
- $\gamma\gamma \to e^+e^-\gamma$ with bremsstrahlung due interaction with ID material
- 1 (tag) electron reconstructed
- 2 pixel tracks, one low-p_T



Photon identification

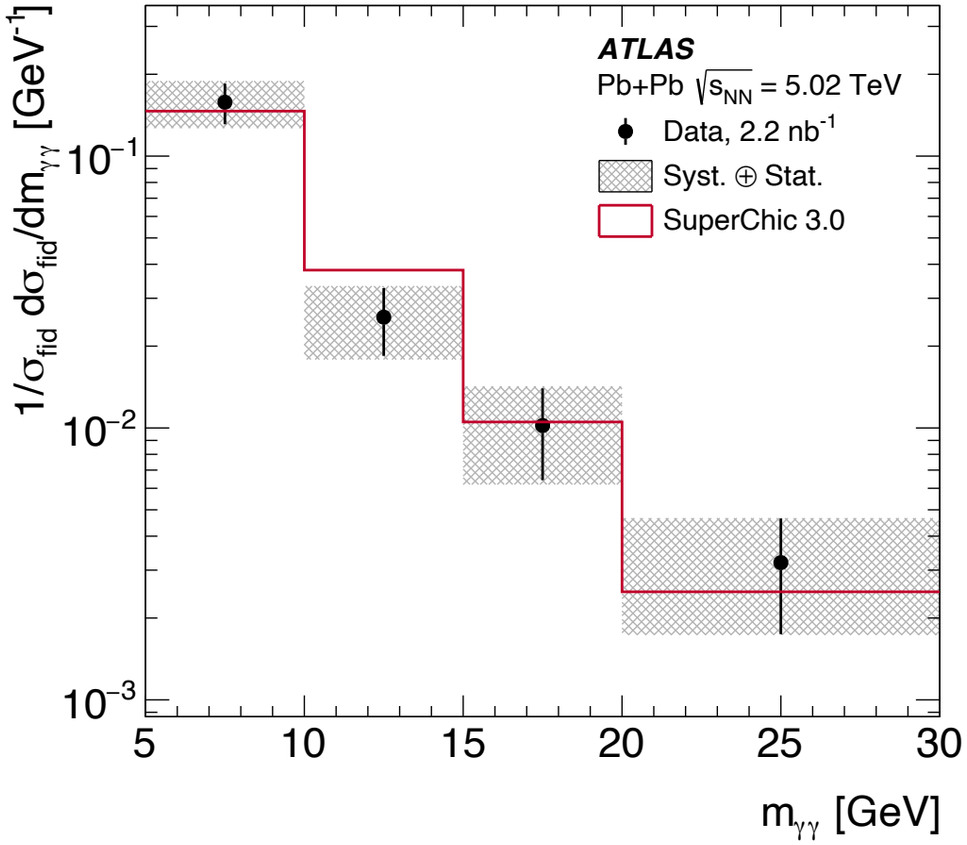
- $\gamma\gamma \to l^+l^-\gamma$ with hard FSR photons
- Verify photon shower shapes and efficiency for good photon to pass photon identification

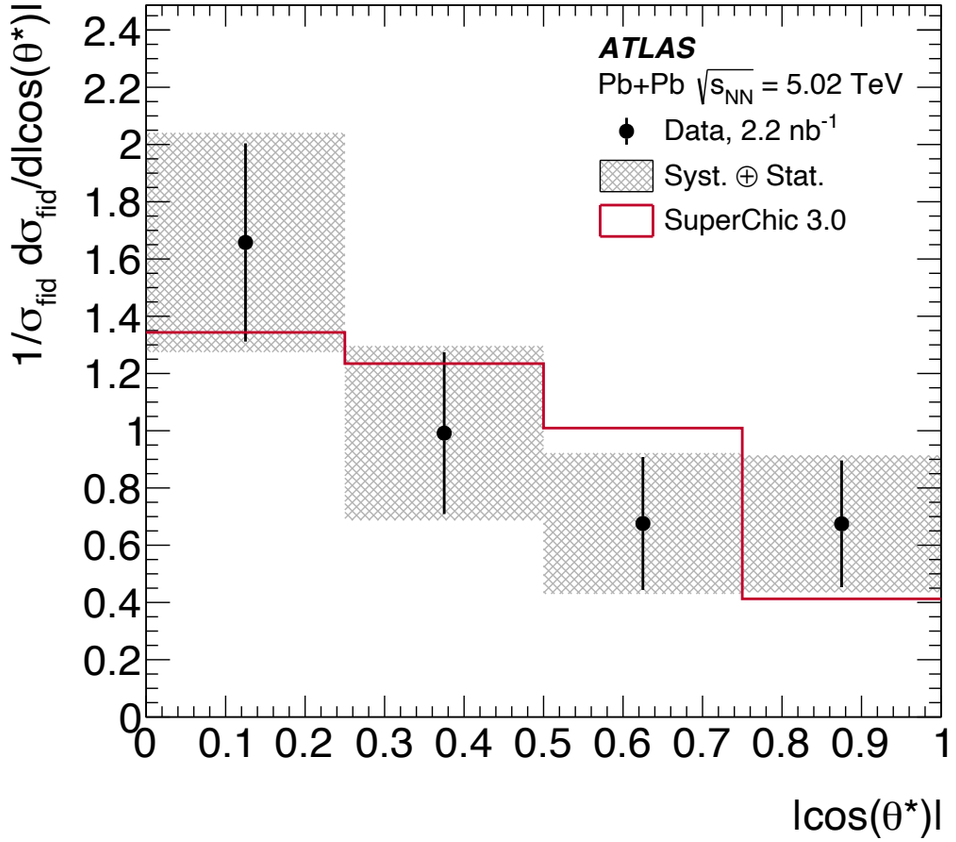




2015+2018 PbPb data

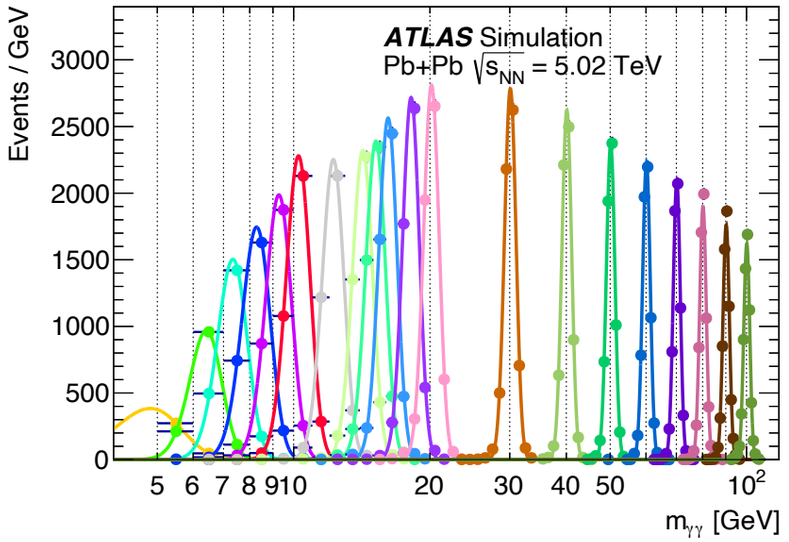
- 97 events observed, 45 signal + 27 expected
- Measured cross section: $\sigma_{\text{fid}} = 120 \pm 17\ (\text{stat.}) \pm 14\ (\text{syst.}) \pm 4\ (\text{lumi.})\ \text{nb}$
  - Dominant sources of uncertainty: trigger efficiency, photon reconstruction eff, $\gamma\gamma \to e^+e^-$ background estimate (statistics in CR)
- Distributions unfolded to particle level ($m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$, $|\cos(\theta^*)|$)
- Fiducial cross section about 1.7σ higher than predictions

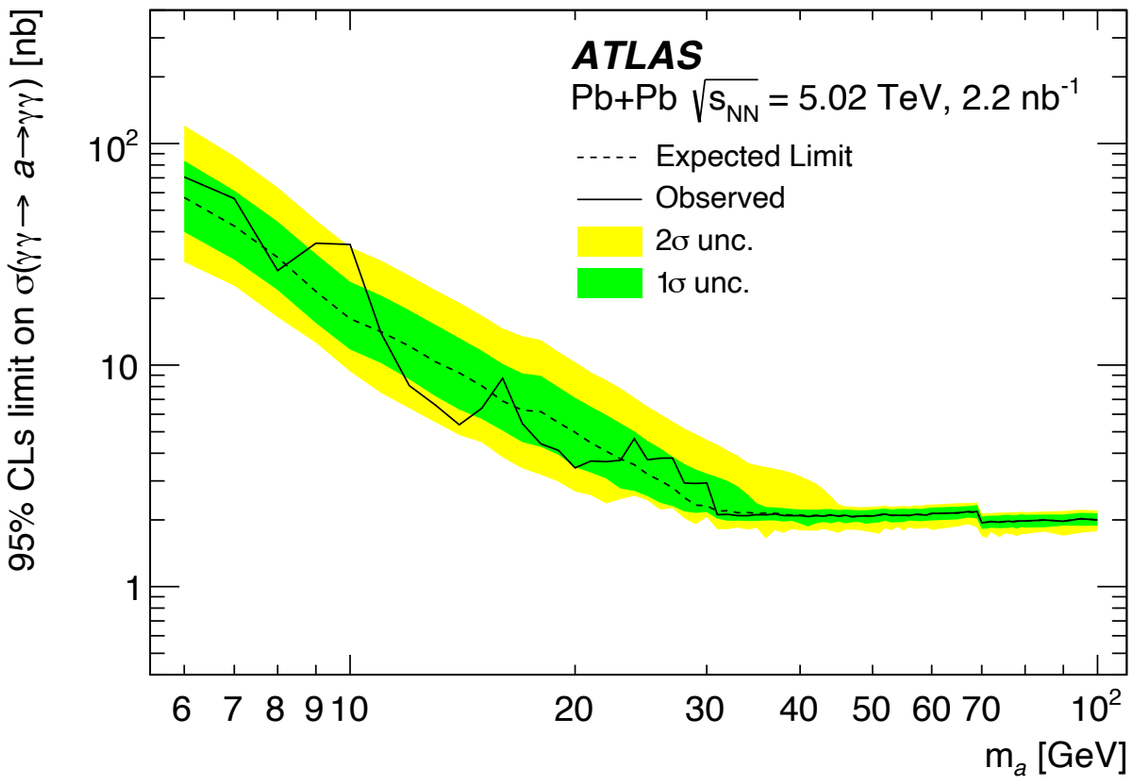


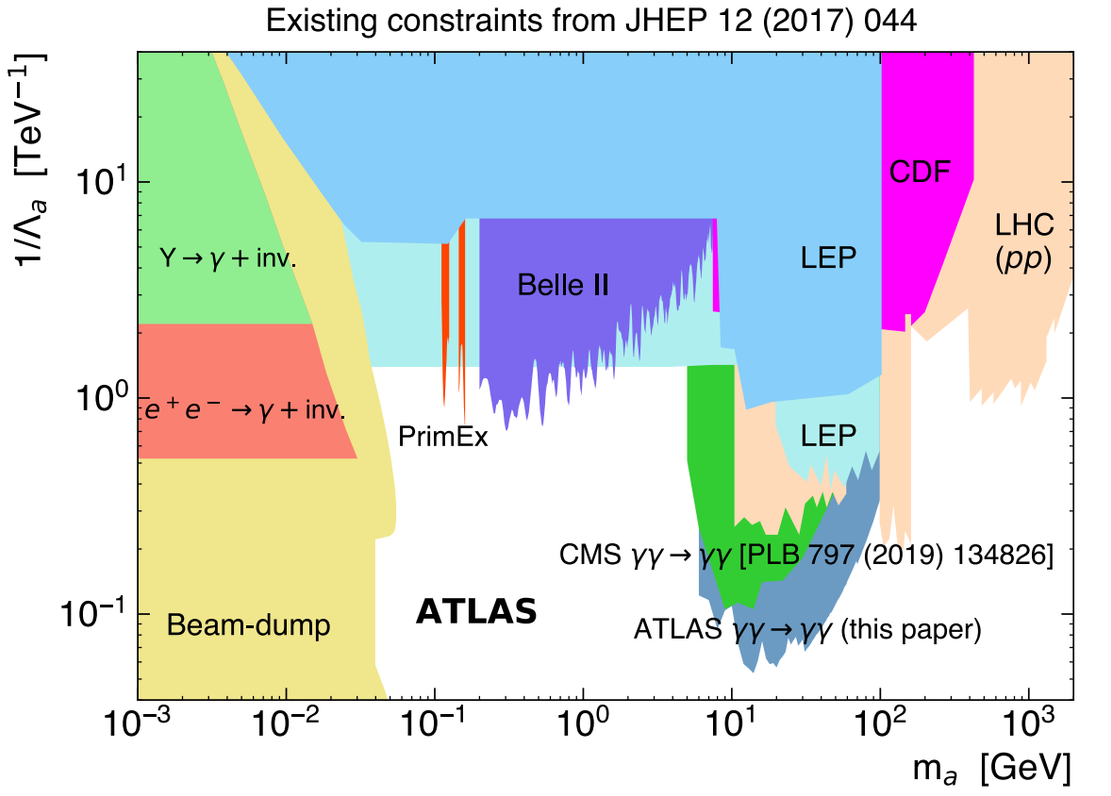


Search for Axion-Like-Particles

- Search for (pseudo) scalar $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ resonance, Axion-Like-Particles
  - Background includes SM LbyL, CEP $\gamma\gamma$ and ee
  - ALP signal produced using STARlight for various m_a
- Limits on $\sigma_{\gamma\gamma\rightarrow a\rightarrow\gamma\gamma}$ extracted
  - Cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$) assuming BR(a→$\gamma\gamma$)=1
  - Most stringent ALP limits for medium masses



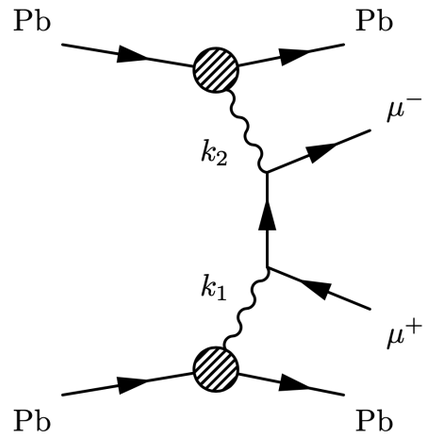


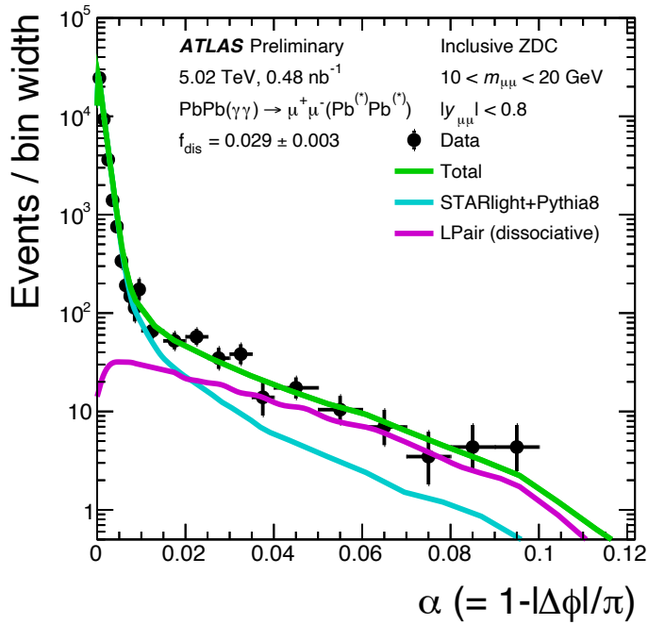


Exclusive dimuon production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ATLAS [CERN-EP-2020-138]

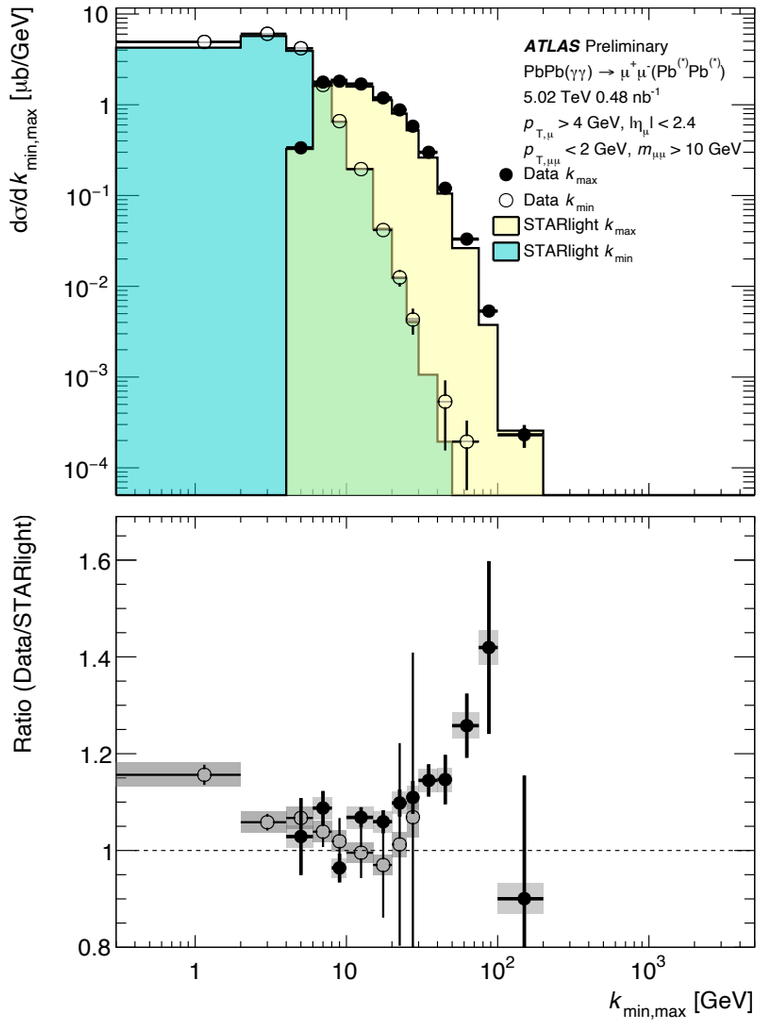
$\gamma\gamma \to \mu^+\mu^-$ in UPC Pb+Pb

- Can we constraint photon fluxes? Yes, by measuring $\gamma\gamma \to \mu^+\mu^-$





- Signal and dissociative background templates modelled by STARlight+Pythia8 and LPair
- $m_{\mu\mu}$, $|y_{\mu\mu}|$, $\cos(\theta^*_{\mu\mu})$, Acoplanarity measured



- Small discrepancy seen in low and high rapidities
- Interpreted as discrepancy at low and high photon energies

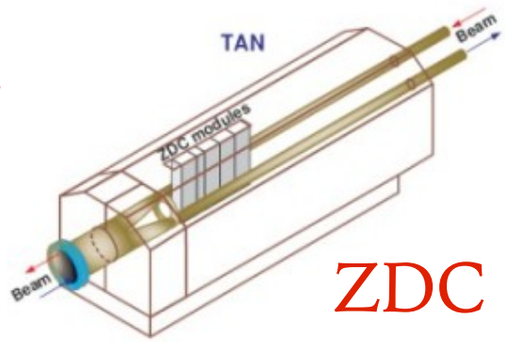
$$k_{\mathrm{min,max}} = (1/2) m_{\mu\mu} e^{\mp y_{\mu\mu}}$$

$$\frac{d^2 N_{\gamma\gamma}}{dk_1 dk_2} \propto \int_{b_1 > R_A} d^2 b_1 \int_{b_2 > R_A} d^2 b_2 \; n(k_1, b_1)\, n(k_2, b_2)\, P(b)$$

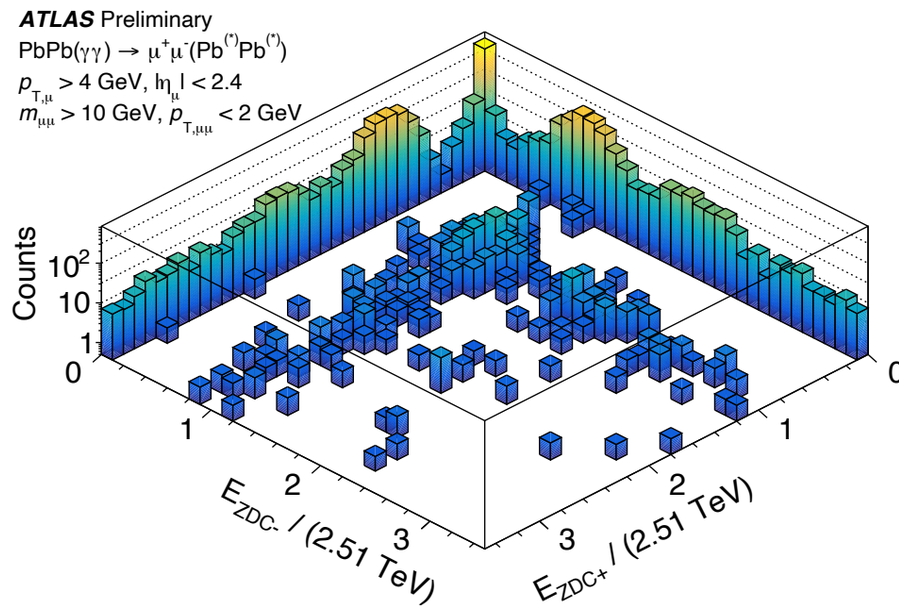
Integration limits ensuring that produced particles do not break the nucleus. Might be too strict for lepton pairs that weakly interact with nuclei

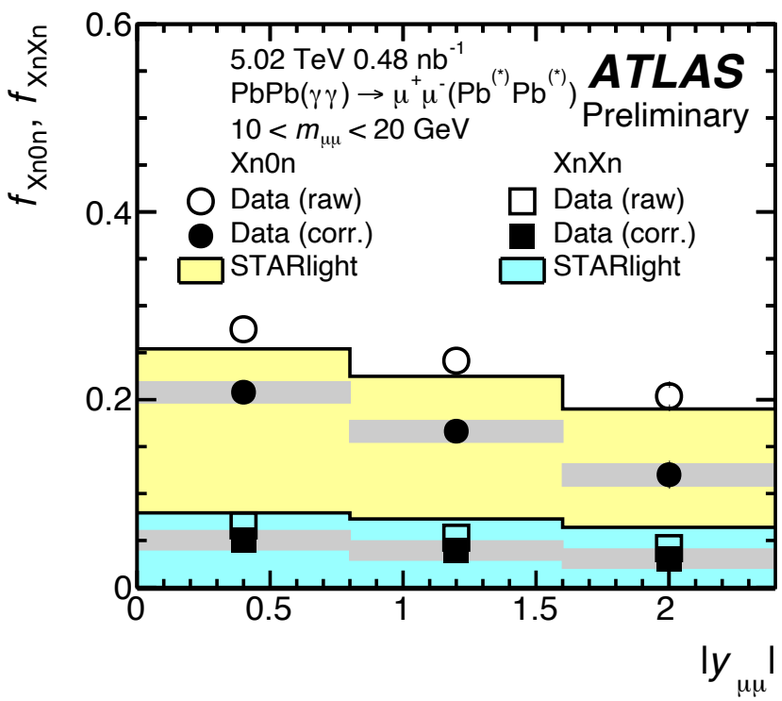
$\gamma\gamma \to \mu^+\mu^-$ in Pb+Pb: forward neutrons

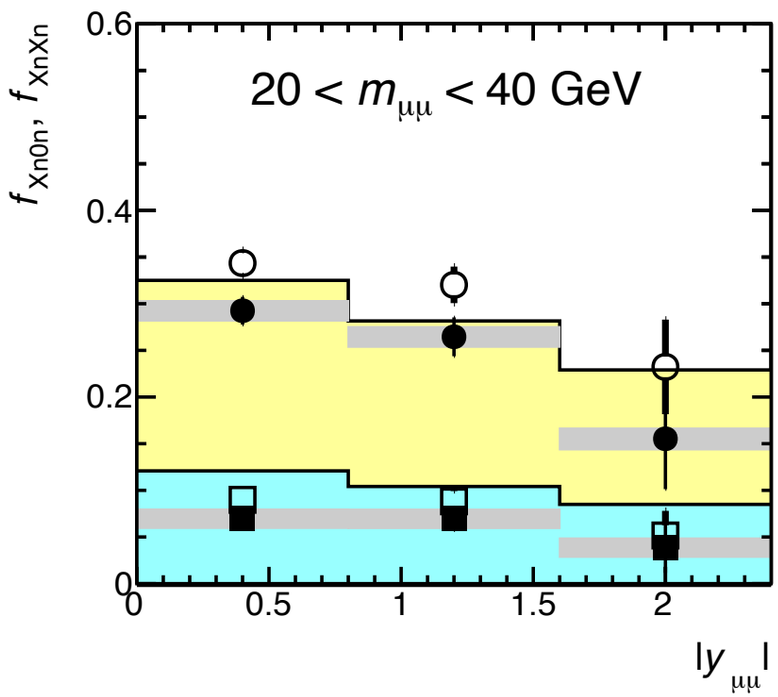
- Understand backgrounds in UPC events (e.g. nucleon dissociation)
- Categorize events with **0n0n, Xn0n, XnXn**
  - Categories defined by cutting on the ZDC energy
- Measured fraction with different activity (0nXn, XnXn)
  - Sensitive to additional EM interactions between ions leading to Pb dissociation and forward neutrons
    → impact parameter dependence of the photon fluxes
  - Correction for 'EM pileup' - other PbPb interaction can produce neutrons
- Forward neutrons more likely to be produced in simulation

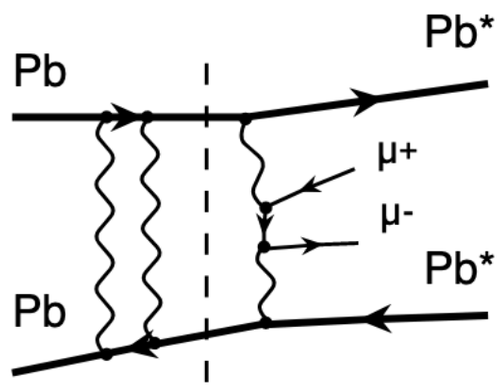


ZDC









Summary

Photon physics offers extremely rich and unique program in both pp and PbPb

ATLAS is making big progress measuring photon-induced processes in pp

- Observation of the photon-induced WW production at the LHC
- Proof of principle with AFP proton tagger
- The first cross-section measurement of the photon-induced process with a forward proton at the LHC

ATLAS is exploring clean photon-induced events in UPC PbPb

- Differential measurement and BSM interpretation of the light-by-light scattering using complete Run 2 dataset
- Detailed measurement of the standard candle process to improve modelling of the photon fluxes and forward neutron activity
- Central detector performance pushed to the limit, ZDC to detect forward neutrons
- More complex final states in the future

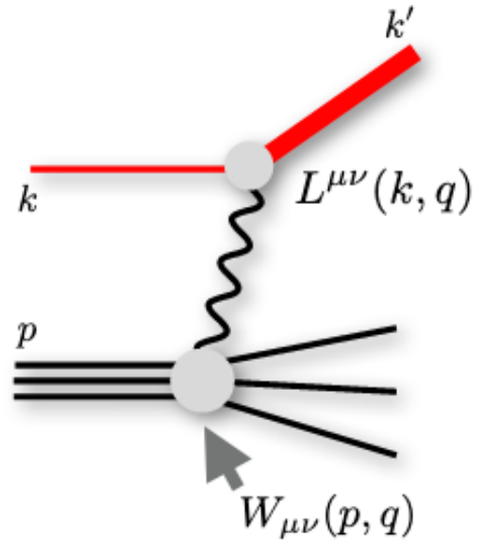
Thanks for your attention!

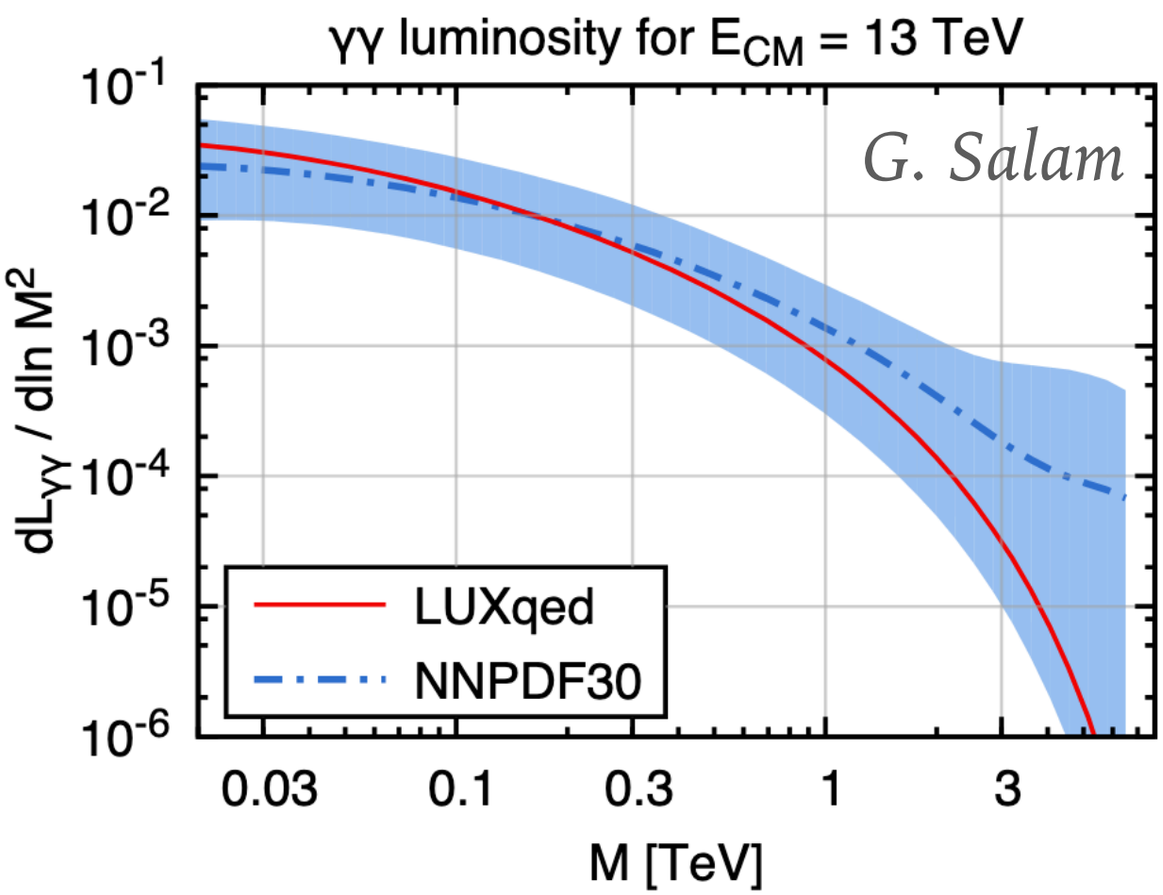
How bright is the proton?

- Approaches to inelastic part in the past (list not exhaustive)
  - Photon is modelled, radiated from constituent quarks q→q**γ**: MRST2004, CT14qed
  - Photon PDF is constrained by pp→l^+l^-: NNPDF23QED, NNPDF30QED
- Large uncertainties (~100%), impact on precision physics (W/Z fusion, WH production)

LuxQED advancement [arXiv:1607.04266]

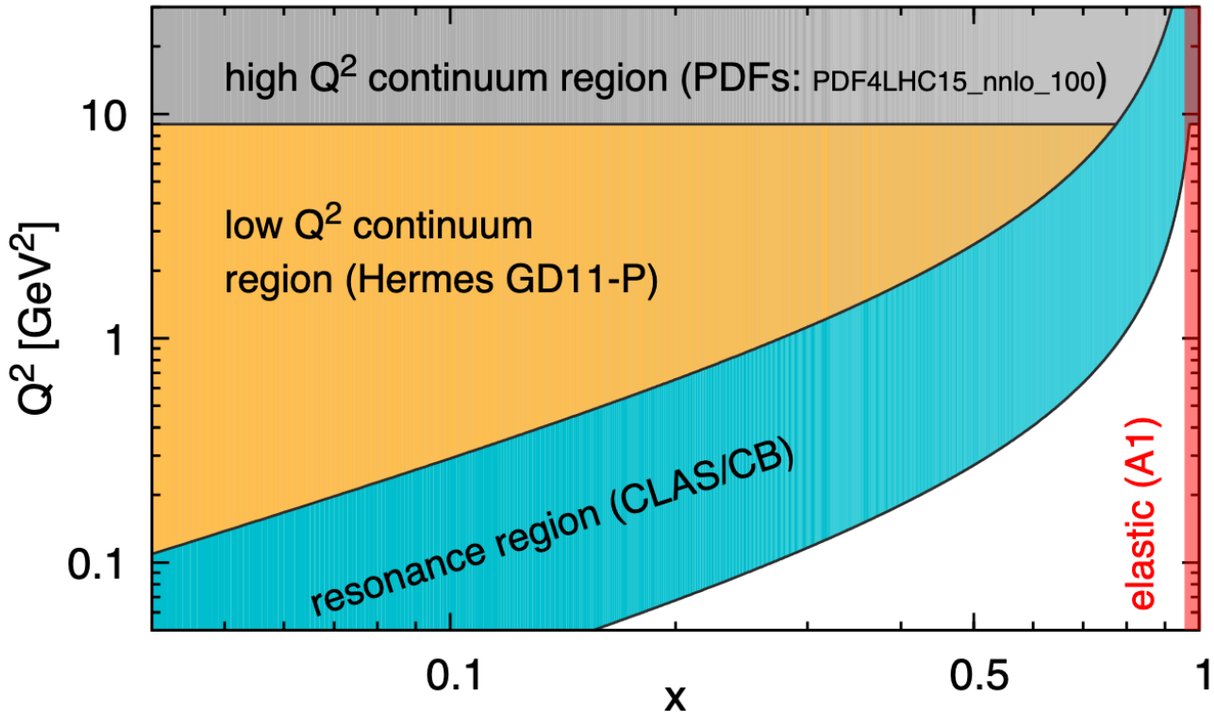
- $f_{\gamma/p}$ computed from the structure functions of DIS
- Viewed as lepton scattering on a photon inside proton
- Uncertainties at 1% level



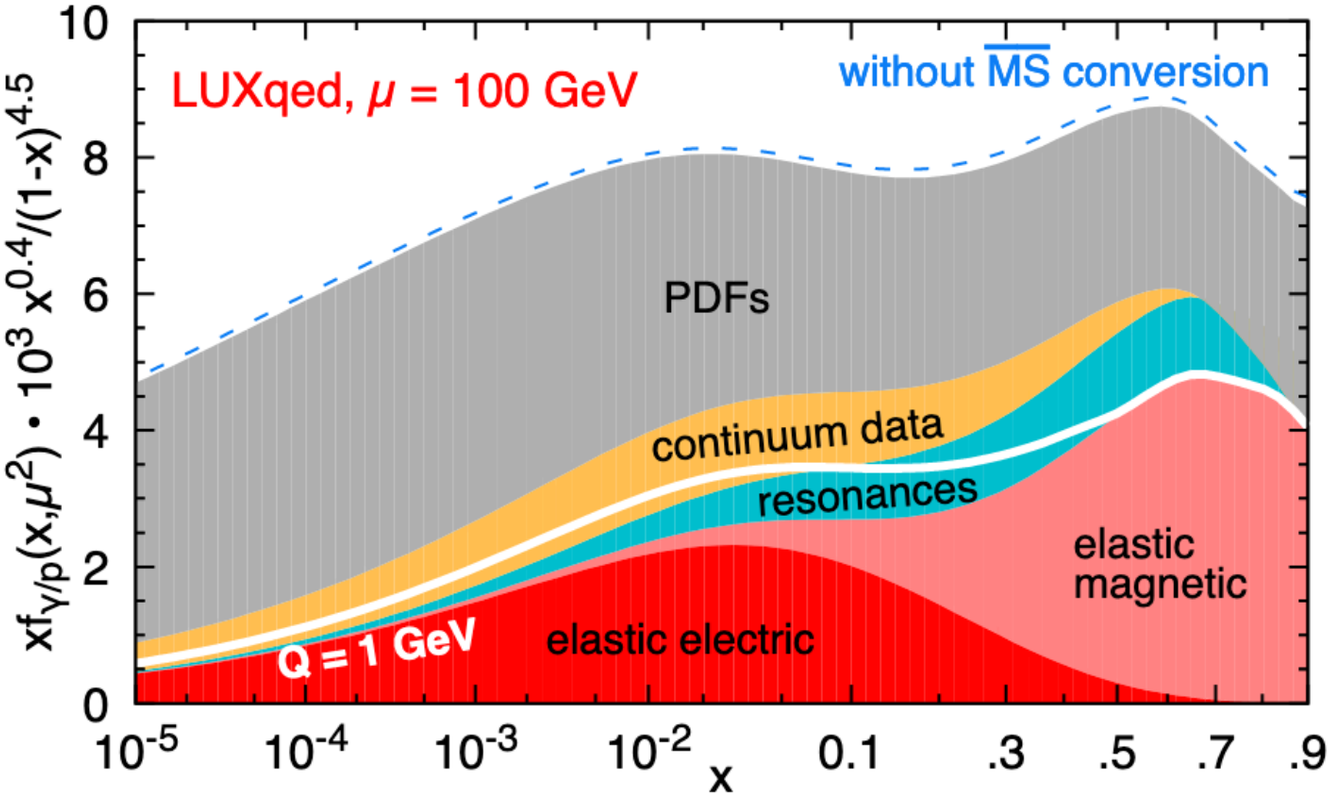


$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\right.$$
$$\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$
$$\left. - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}$$

Photon PDF composition



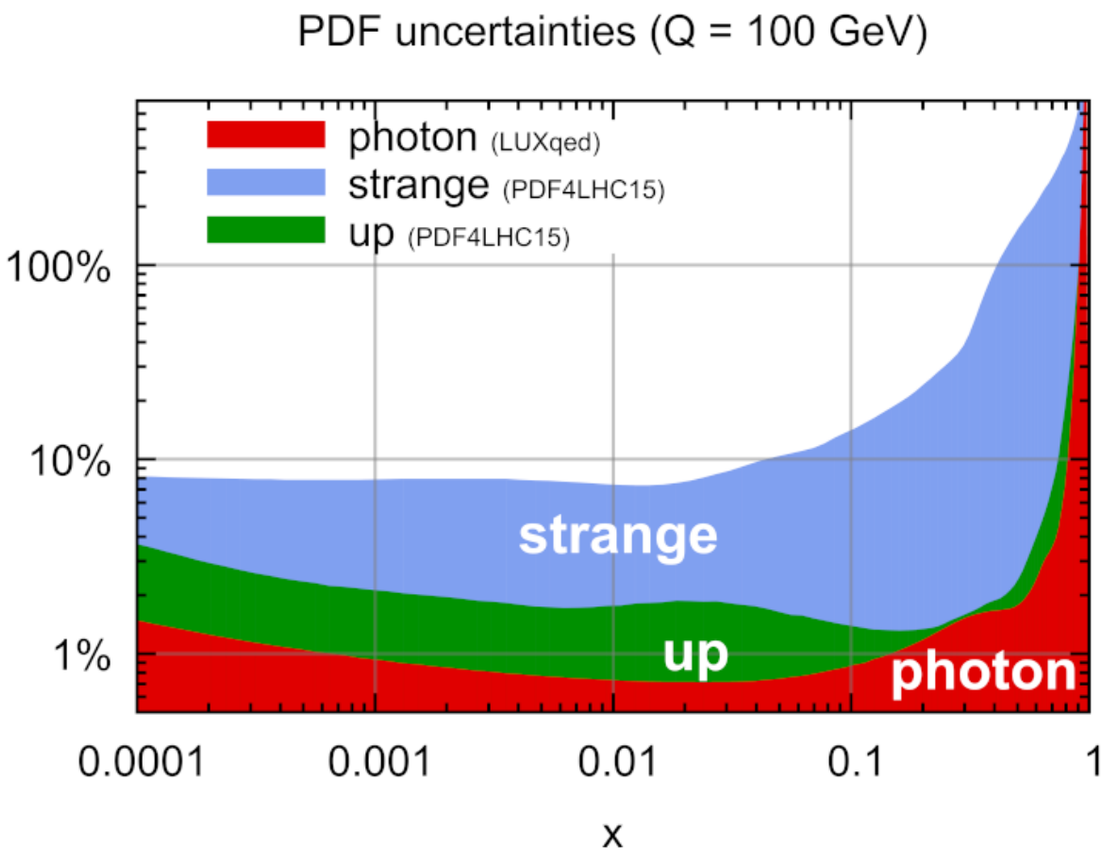
Input data sources in x and Q^2 plane

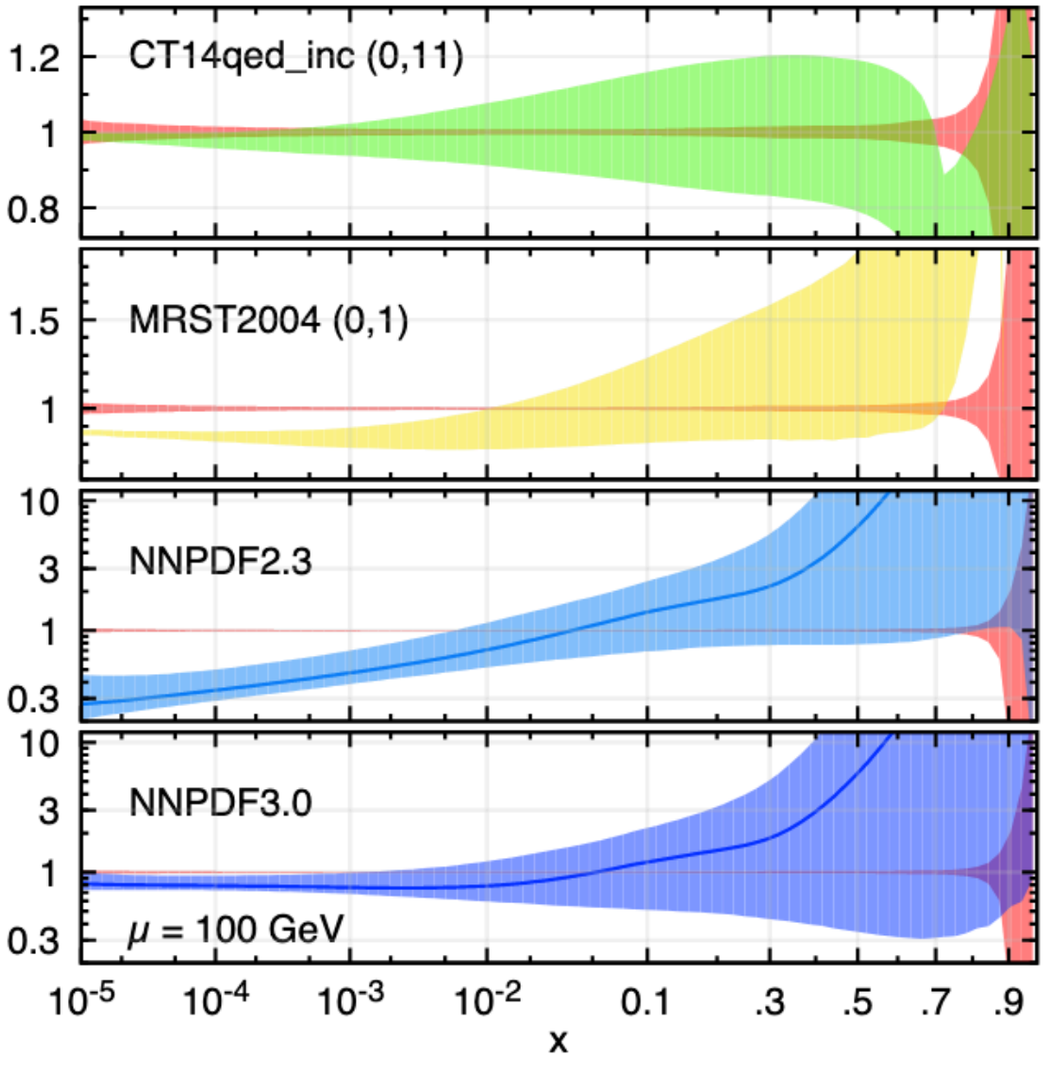


Photon PDF composition μ = 100 GeV scaled by $1000x^{0.4}/(1-x)^{4.5}$

Photon PDF uncertainties

[arXiv:1607.04266]





Photon PDFs and interface to generators

- PDF sets using modern LuxPDF approach
- Elastic, inelastic, and combined versions

LUXqed17_plus_PDF4LHC15_nnlo_100
NNPDF31_nlo_as_0118_luxqed
NNPDF31_nnlo_as_0118_luxqed
MMHT2015qed_nnlo_total
MMHT2015qed_nnlo_inelastic
MMHT2015qed_nnlo_elastic

- The use of these PDFs in generators would benefit from improvements
  - Modules responsible for showering should not touch the ‘elastic’ proton

- **Example**: single dissociative production in MG5_aMC@NLO+Pythia8
  - To much radiation despite setting appropriate parameters (BeamRemnants:unresolvedHadron)
  - Pythia8 runs FSR on the intact proton (but not hadronization)
  - Charged particle spectra re-weighted to LPair to make of the SD sample

- LPair can only produce *ll* final states and uses obsoleted Suri-Yennie photon structure functions obtained at smaller scales

$\gamma\gamma \rightarrow WW$: Previous measurements

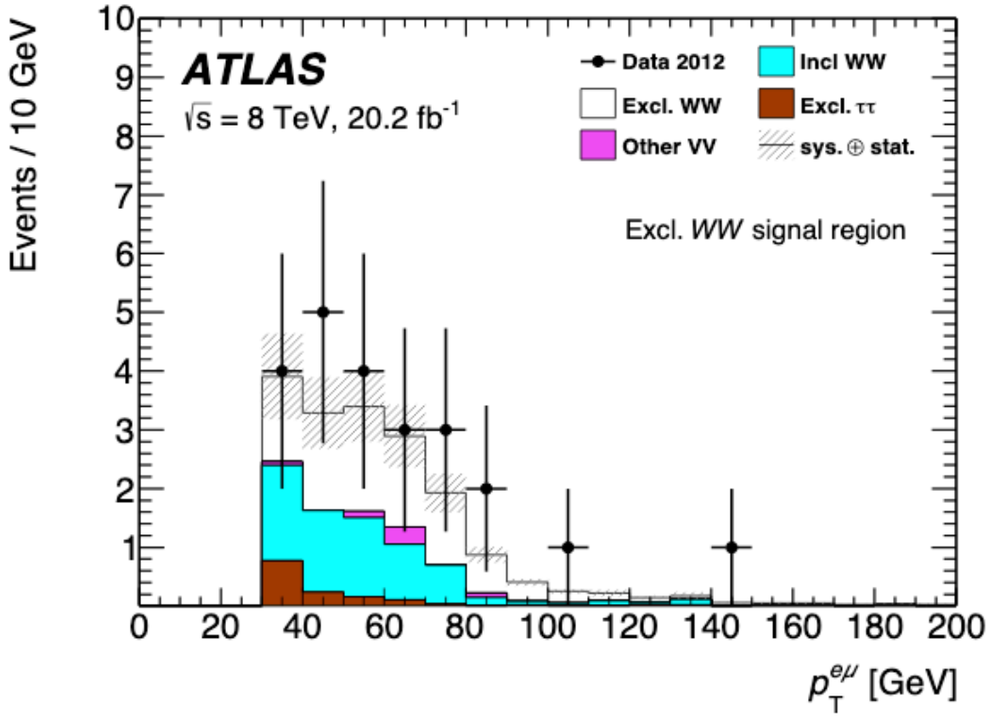
- 3σ evidence with Run 1 data by ATLAS/CMS

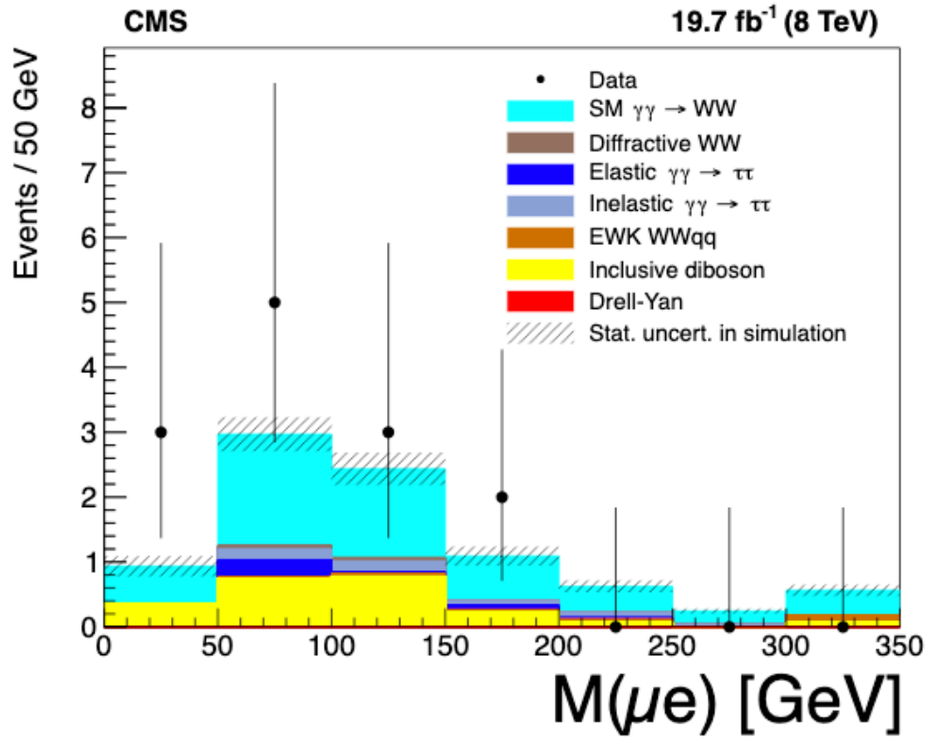
- ATLAS 8 TeV measurement arXiv:1607.03745
  - 23 observed events, 8.3±2.6 expected background events

- CMS 7+8 TeV measurement arXiv:1604.04464
  - 13 observed events with 3.9±0.6 expected at 8 TeV

- Similar sensitivity between ATLAS/CMS on anomalous quartic coupling

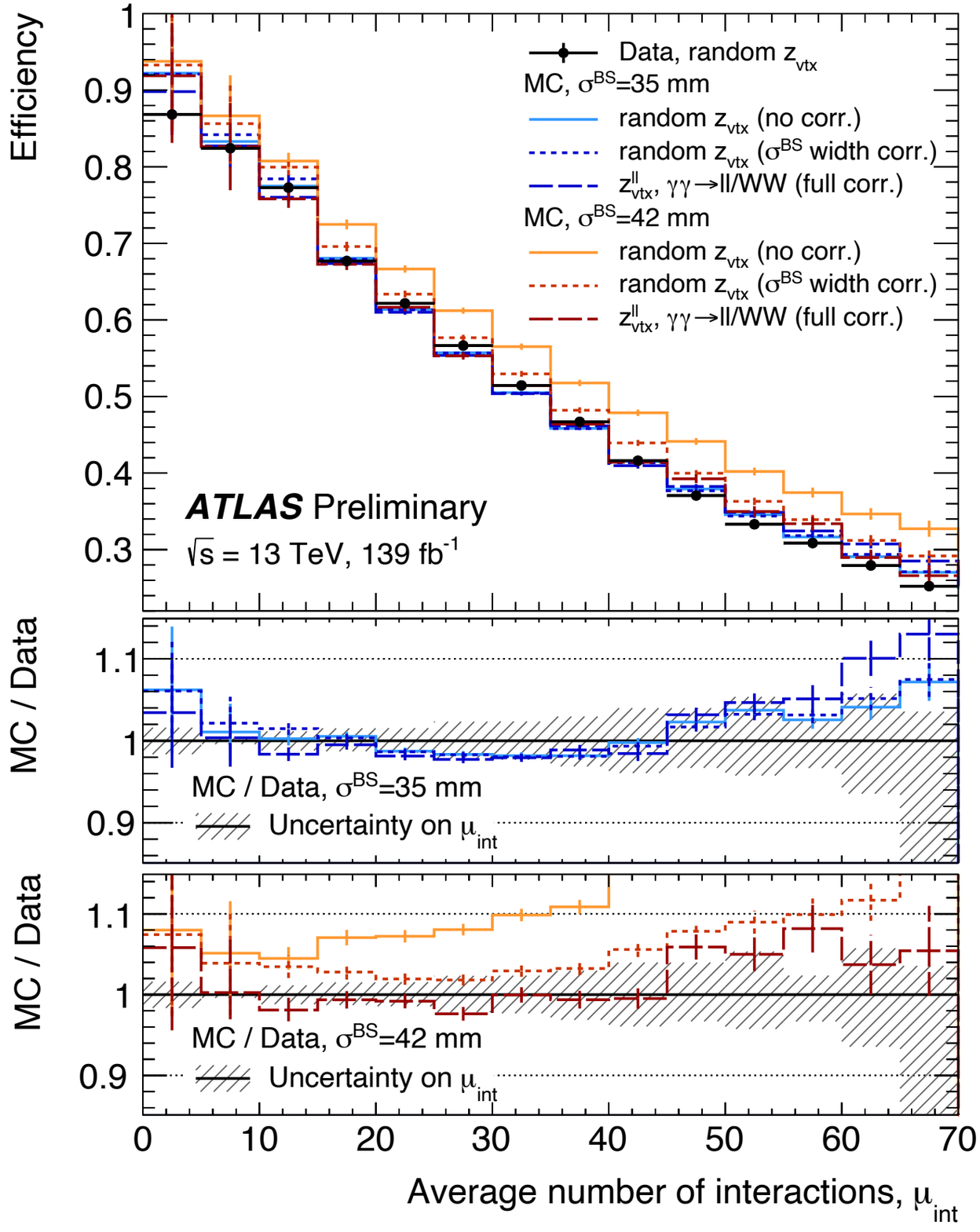
- At the time, up to factor ~10 better sensitivity than inclusive WWγ measurements





$\gamma\gamma \rightarrow WW$: Exclusive efficiency

- Run 2 average exclusive efficiency (n_{trk}=0 selection): 52 %
- Strong dependence on μ - number of *pp* interactions per crossing
- Modelled within 2% across the full μ range



$\gamma\gamma \to$ WW yields

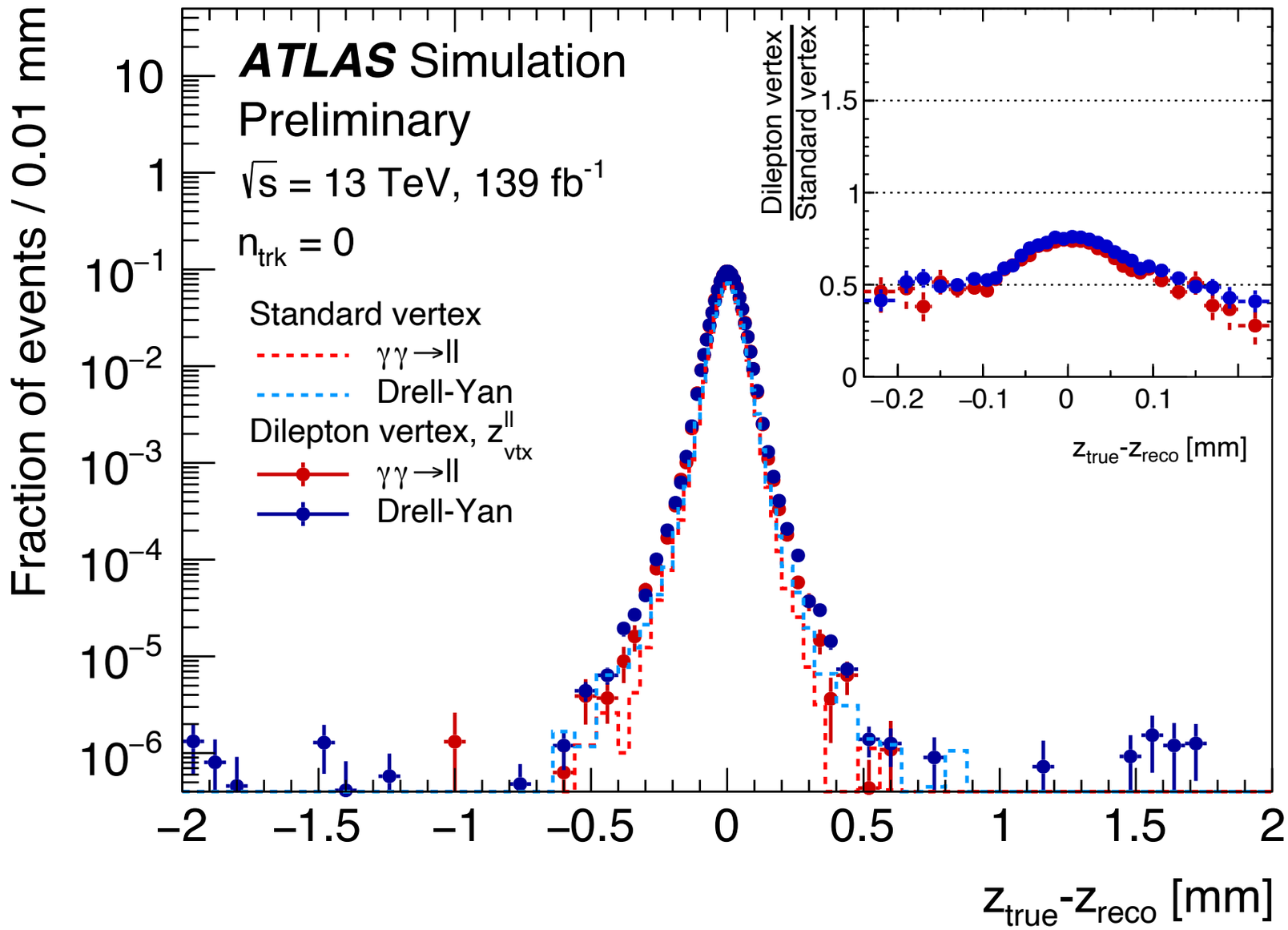
- 307 candidate observed, 132 background events expected
- All normalizations are measured approximately 1σ higher
- Signal normalization is expressed relative to scaled predictions using high-mass $\gamma\gamma \to ll$

$$\beta_{WW} = 1.21^{+0.19}_{-0.23}$$
$$\beta_{DY} = 1.16^{+0.10}_{-0.12}$$
$$\beta_{\gamma\gamma\to ll} = 3.59 \pm 0.15$$
$$\mu_{\gamma\gamma\to WW} = 1.33 \pm 0.14\ (\text{stat.})^{+0.22}_{-0.17}\ (\text{syst.})$$

	Signal region		Control regions	
n_{trk}	$n_{\text{trk}} = 0$		$1 \le n_{\text{trk}} \le 4$	
$p_{\text{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell-Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other qq initiated	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

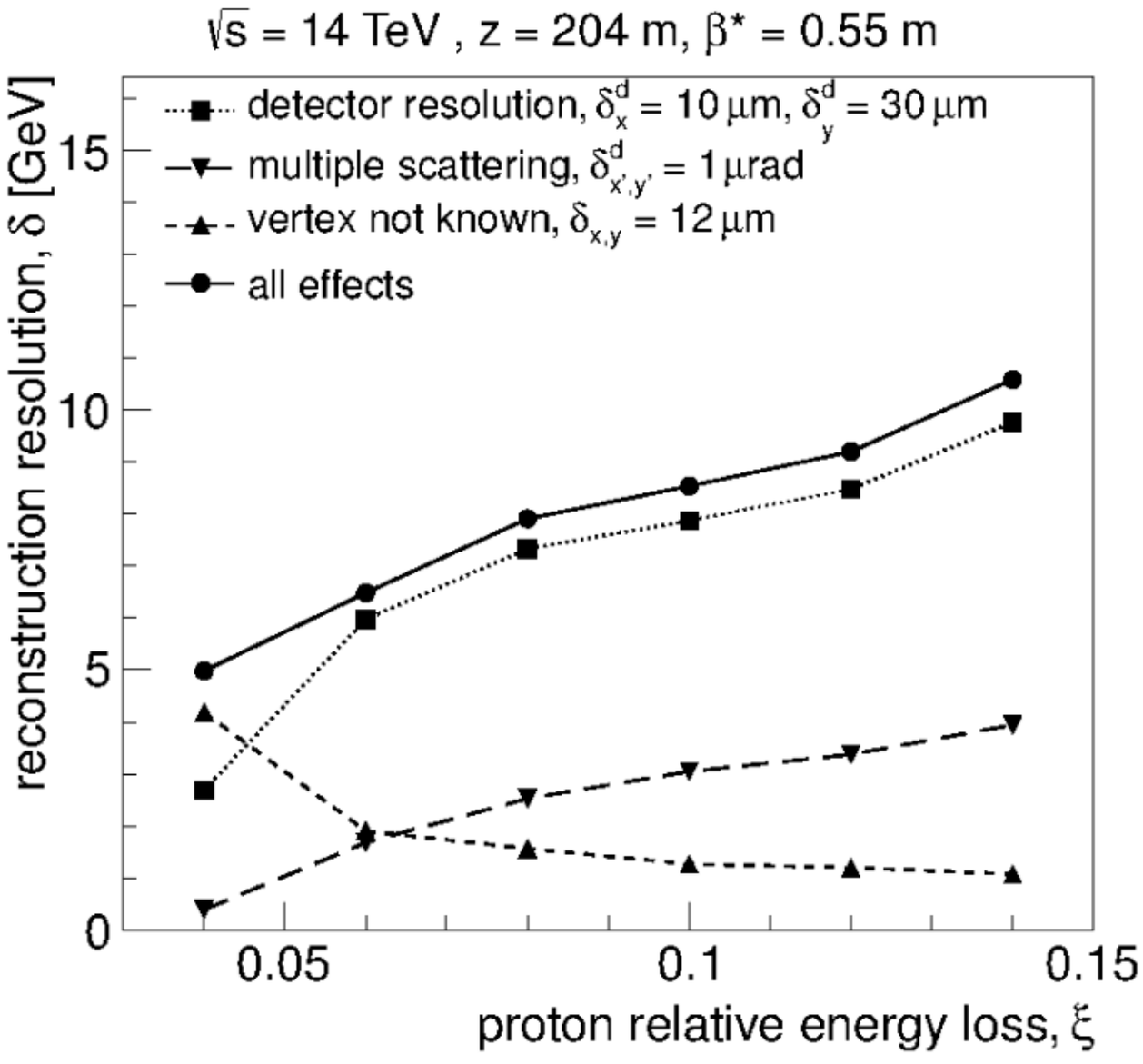
$\gamma\gamma \rightarrow$ WW vertex performance

- True vs. reconstructed vertex for events with no tracks



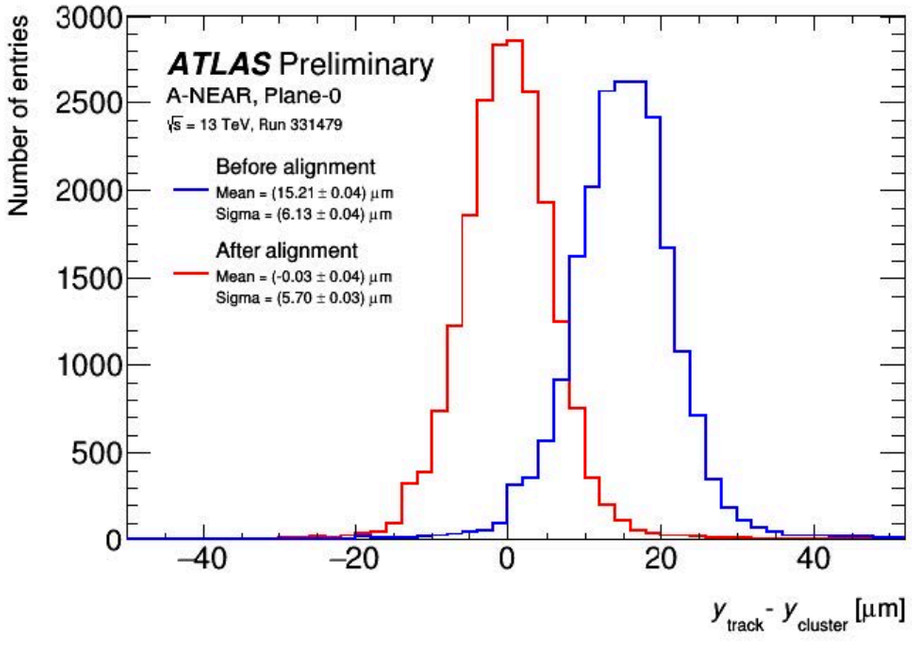
AFP momentum reconstruction

- Different contributions deteriorating the momentum resolution of the proton.

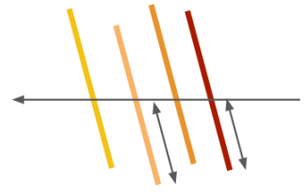


From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024

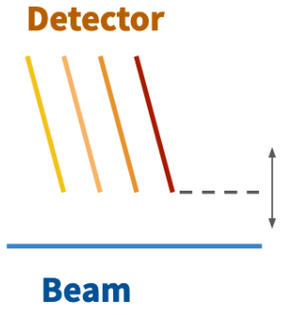
AFP Alignment



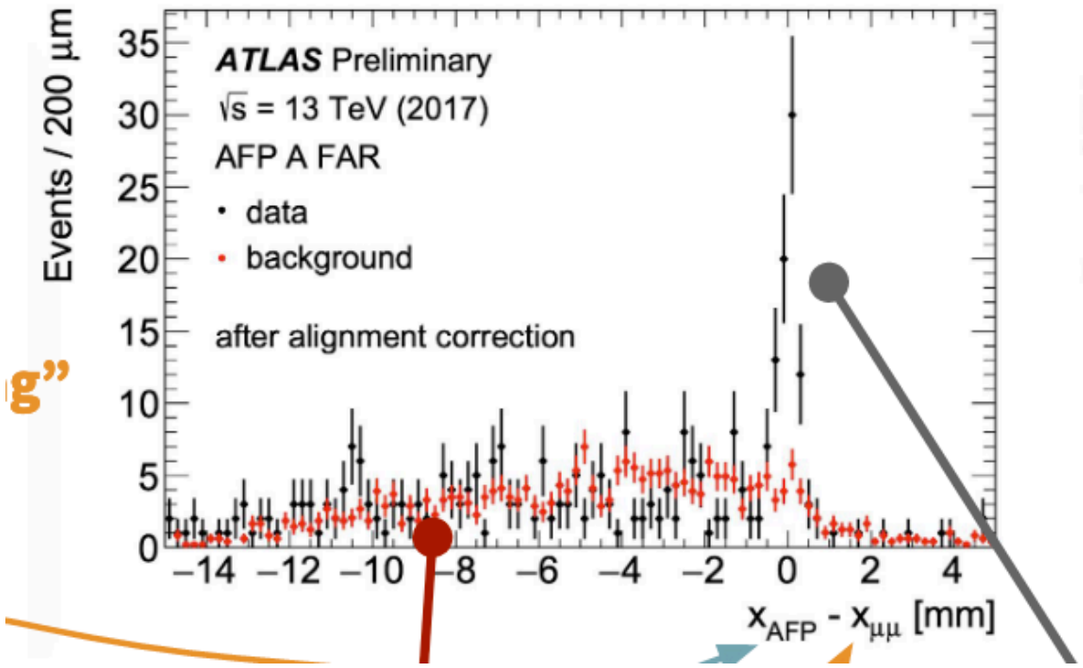
- **Inter-plane alignmen**t - minimize pixel-cluster residuals from the track, precision several μm

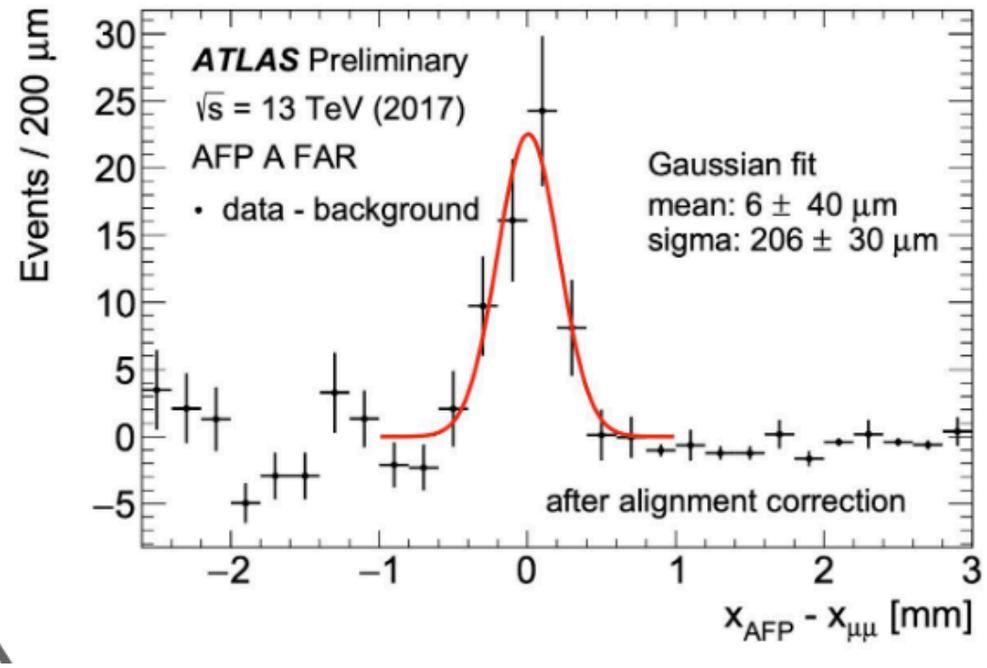


- **Global position** using beam based alignment - approach collimated beam to scape beam envelope, precision $\sim 300\mu m$



- Validated using $\xi_{ll} - \xi_{\mathrm{AFP}}$ correlation
- **ξ** resolution ~10% (optics), 25% at small **ξ** (alignment)

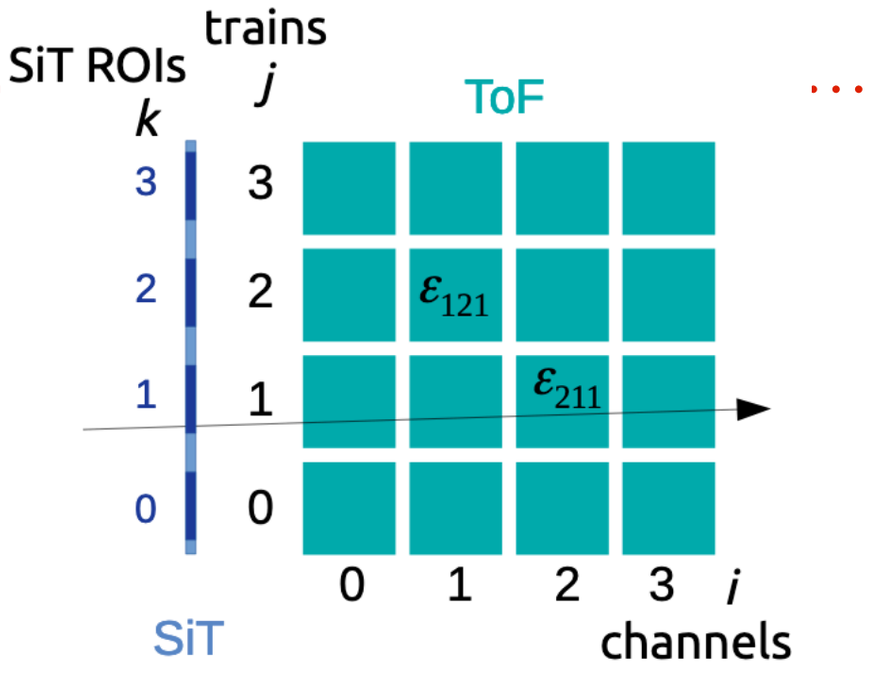


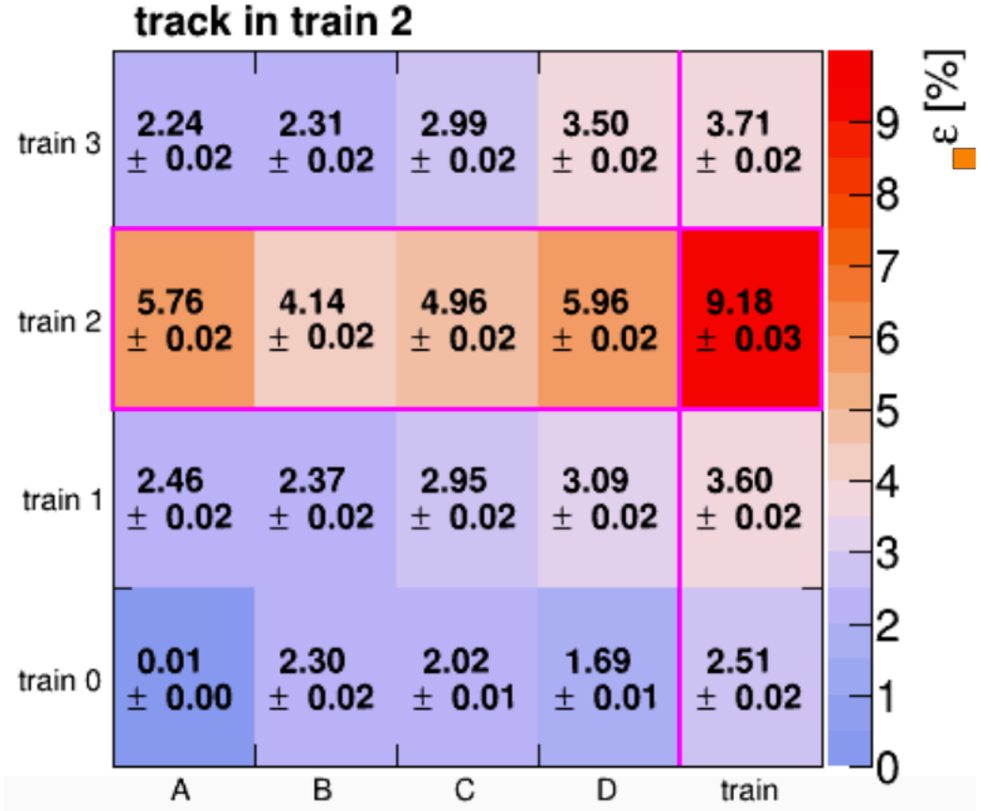


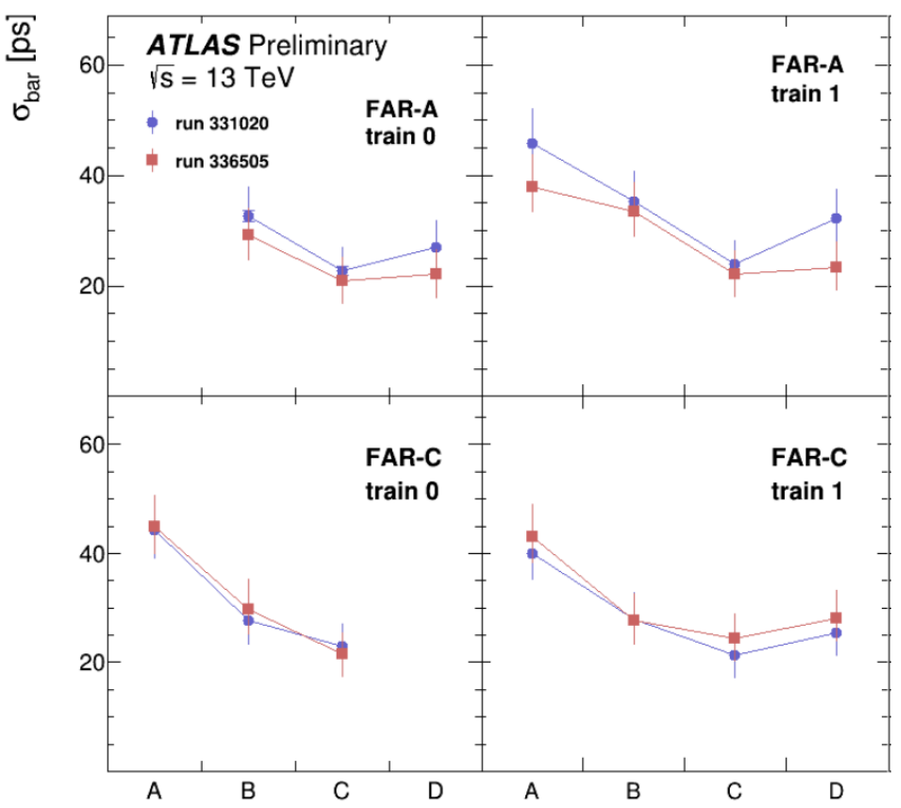
- see [ICHEP talk] for details

AFP ToF Detector

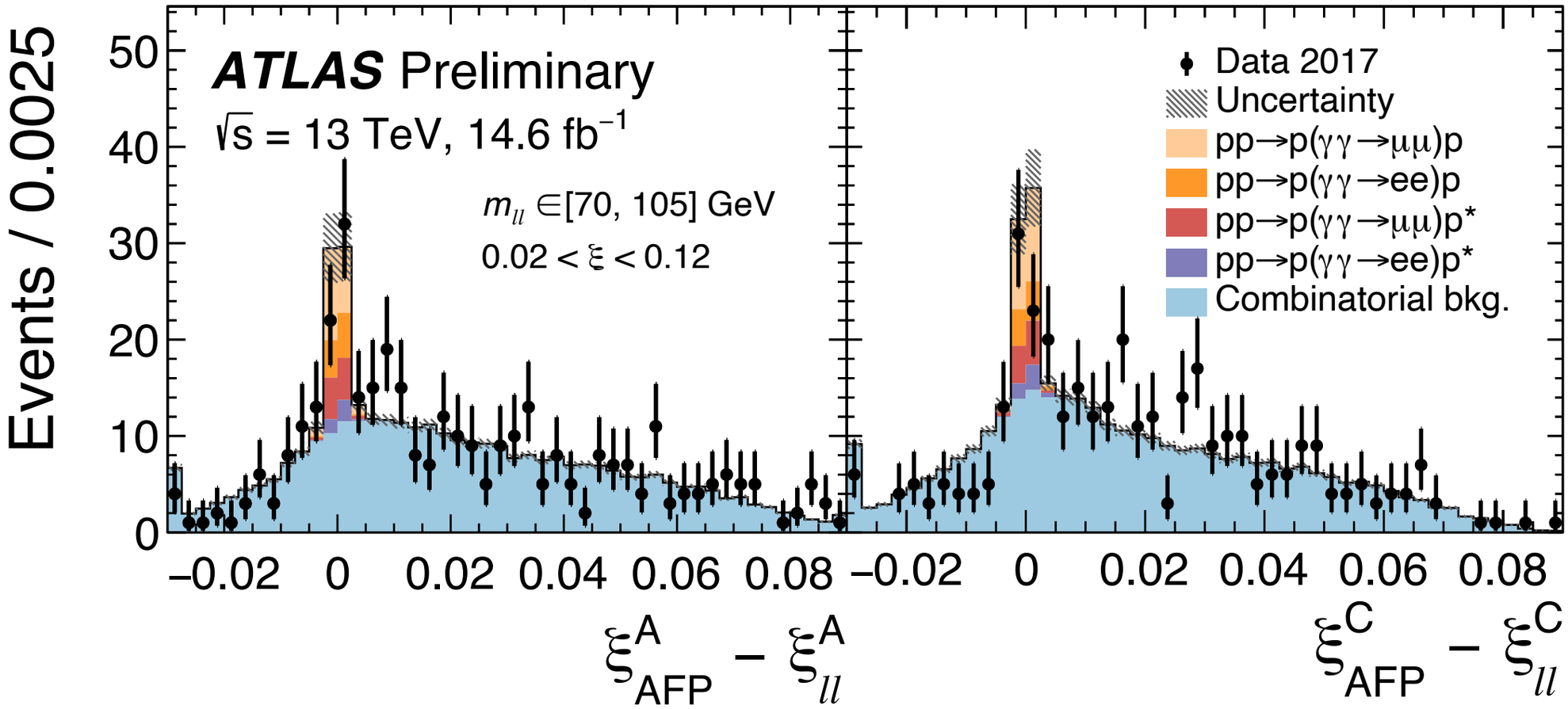
- Analyzed 2017 data
- 20-30 ps achieved timing resolution, 40-50 ps in the first channel (no enrichment from the previous bars)
- Efficiency limited (few %) in 2017 due due to PMT deterioration with radiation





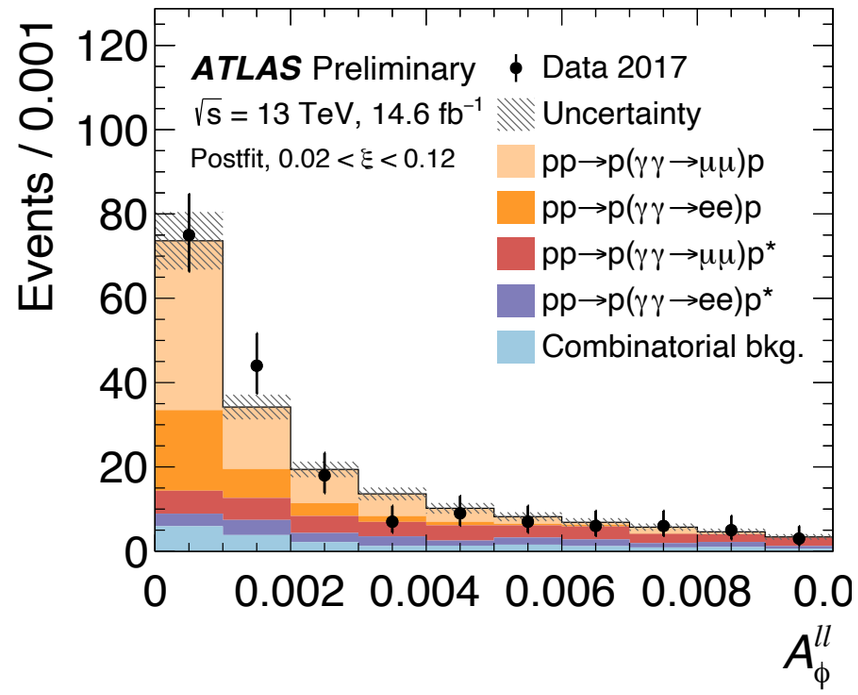


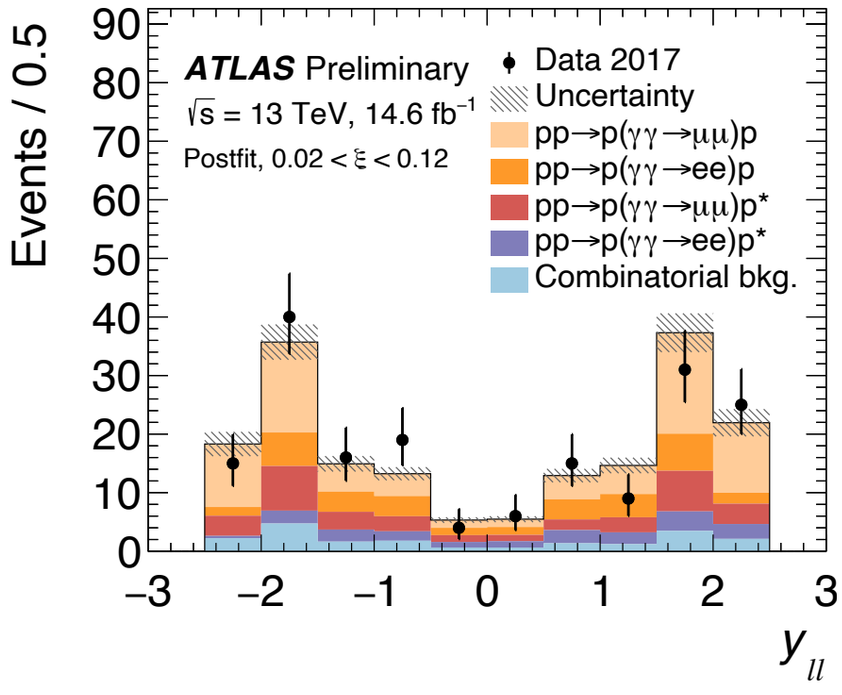
AFP $\gamma\gamma \rightarrow$ ll: background control region

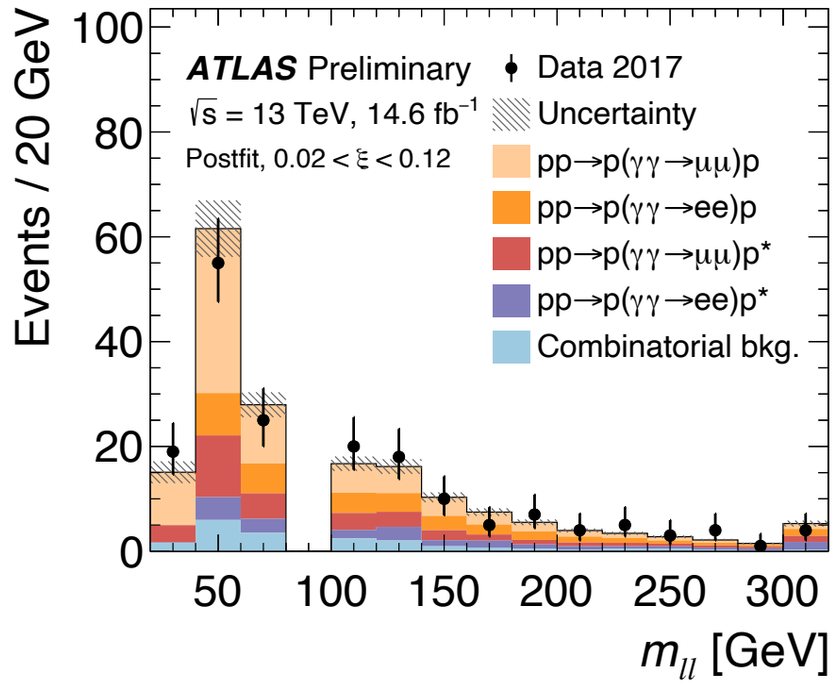


AFP $\gamma\gamma \rightarrow ll$: control distributions

- Shapes of distributions modelled well by Herwig7+LPair
- Postfit distribtion of AFP single tag events

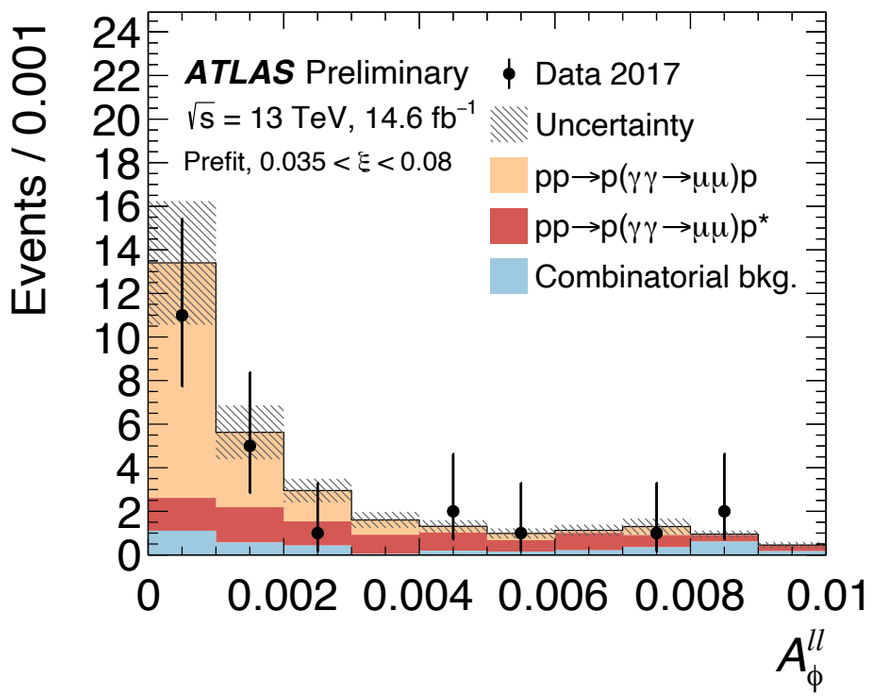


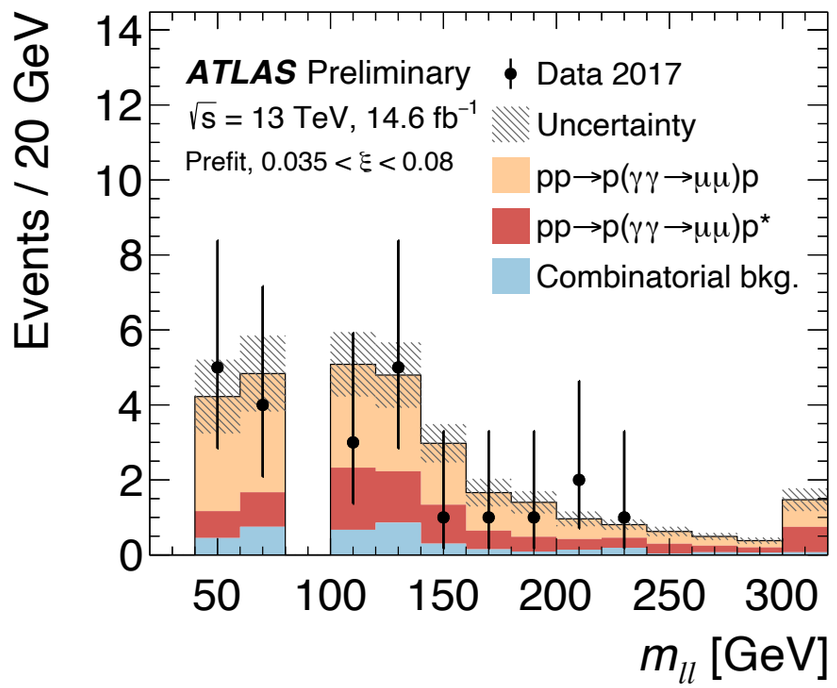




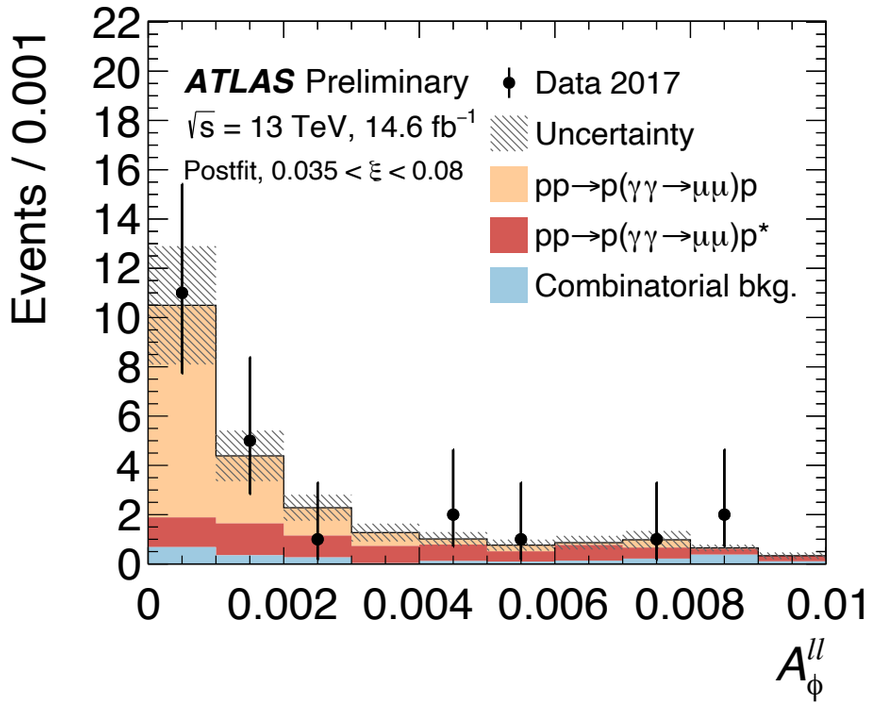
AFP $\gamma\gamma \rightarrow$ ll: Measurement prefit and postfit distributions

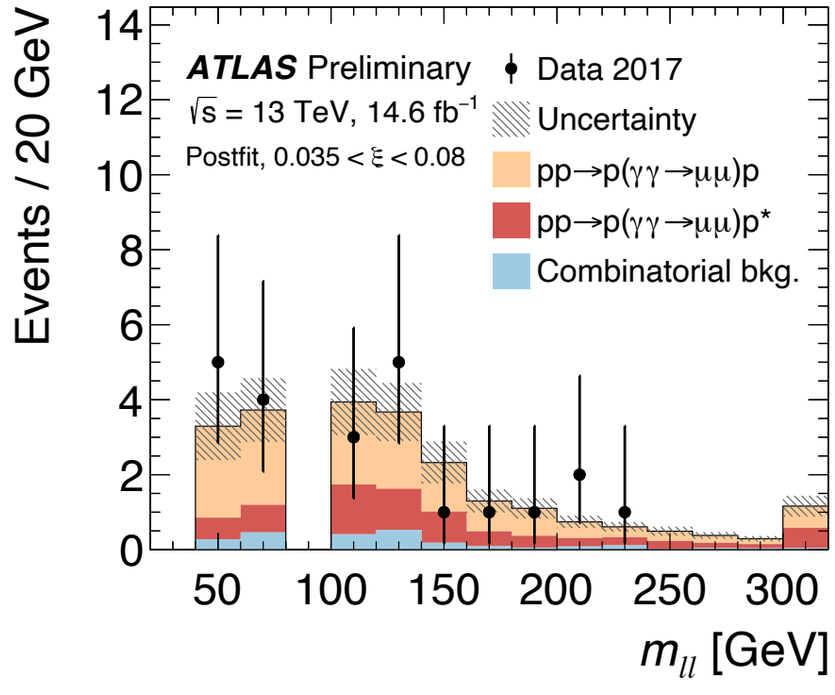
Prefit





Postfit





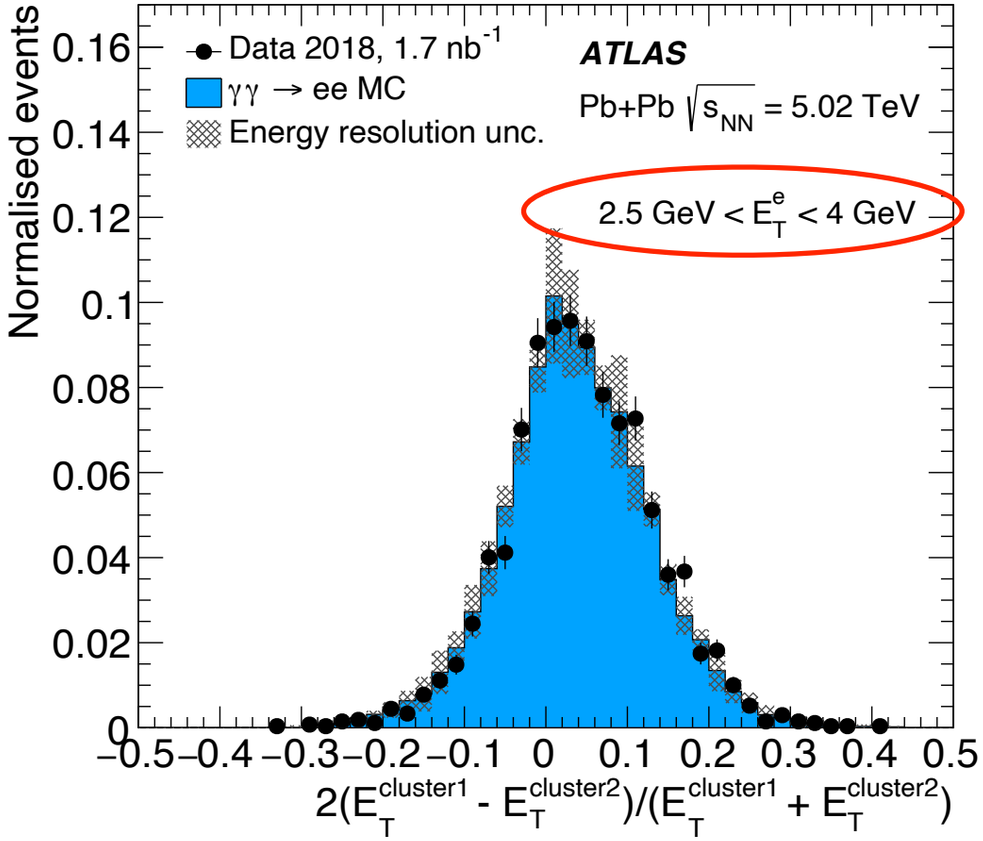
AFP $\gamma\gamma \to ll$: Systematic uncertainties

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%

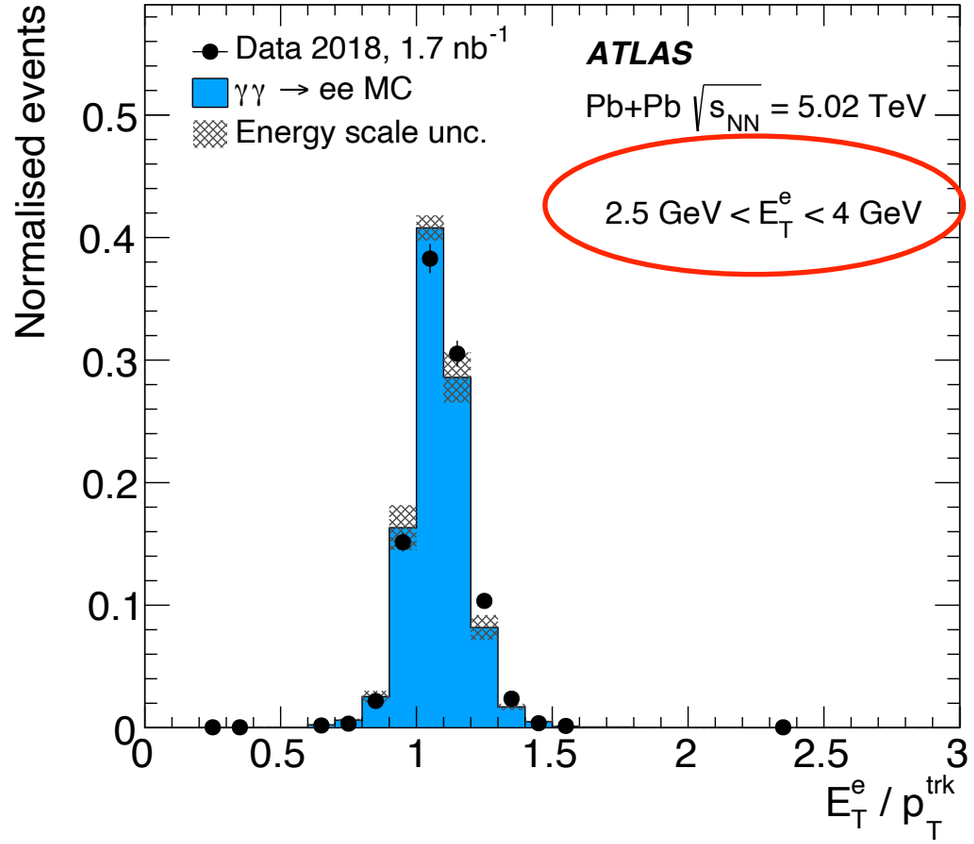
Electron/photon calibration

- Cross-check of electron energy calibration using $\gamma\gamma \rightarrow e^+e^-$ sample
  - Observed energy disbalance due to detector, initial photons have very small transverse momentum
- Good Data/MC agreement down to 2.5 GeV

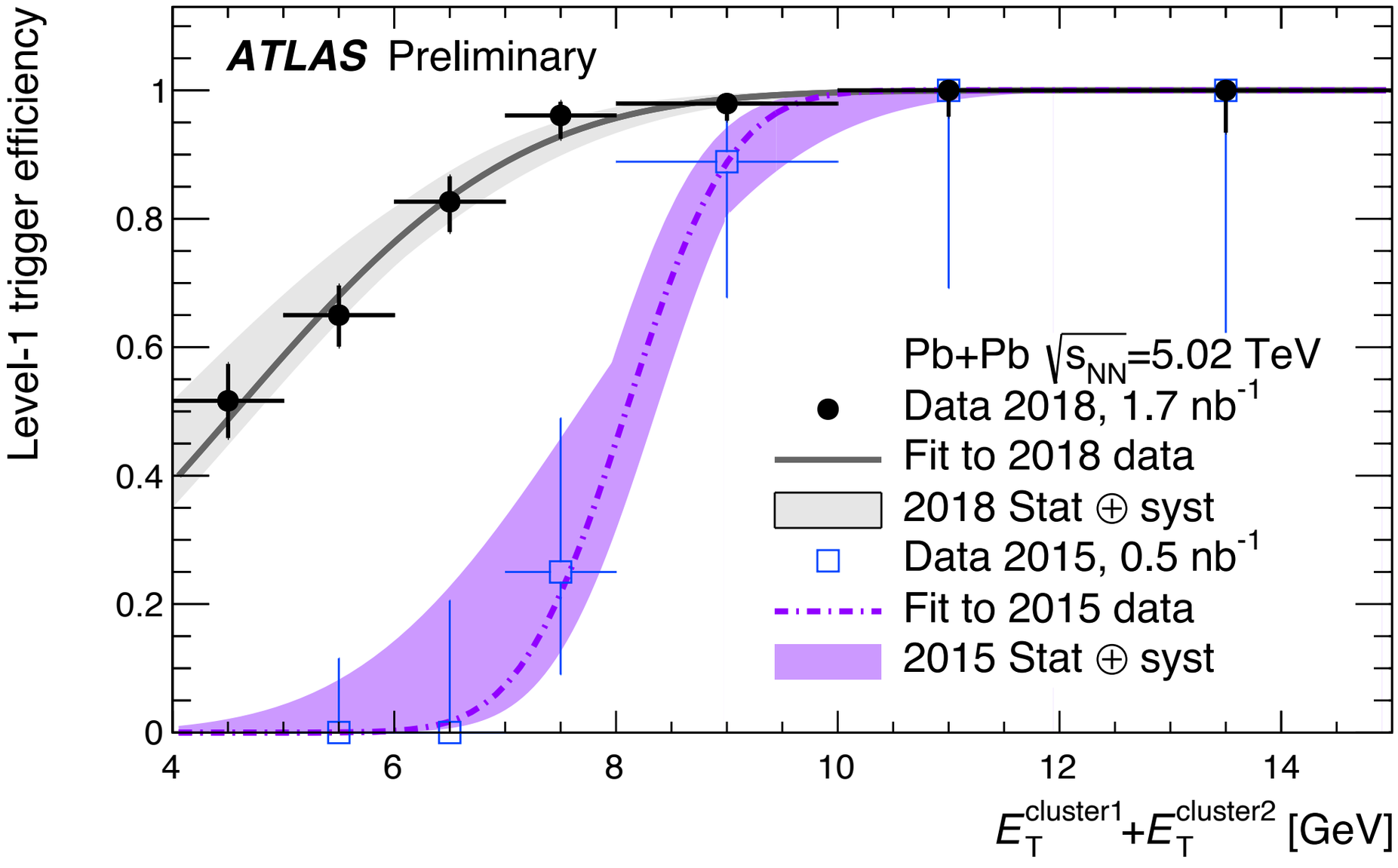
Electron resolution
Difference between two electrons E_T



Electron scale
Asses with electron/track p_T ratio



LbyL Trigger Strategy



LbyL systematic uncertainties

Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%

Exclusive dimuons in UPC Pb+Pb

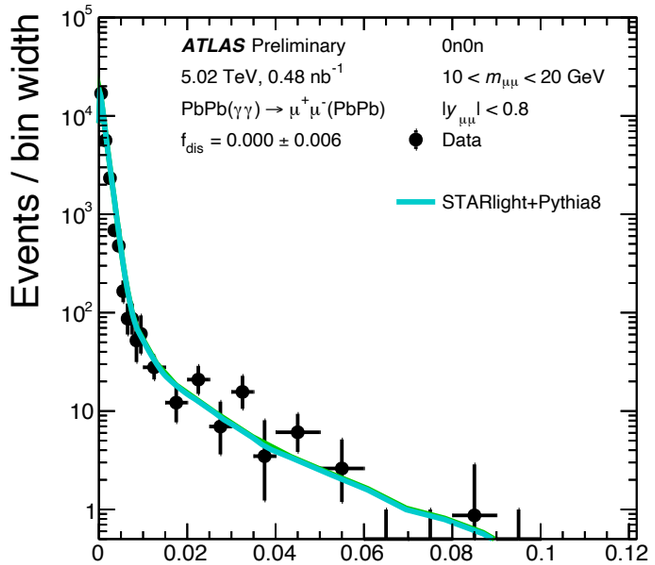
- Sensitive to higher order effects (FSR photons, Coulomb)

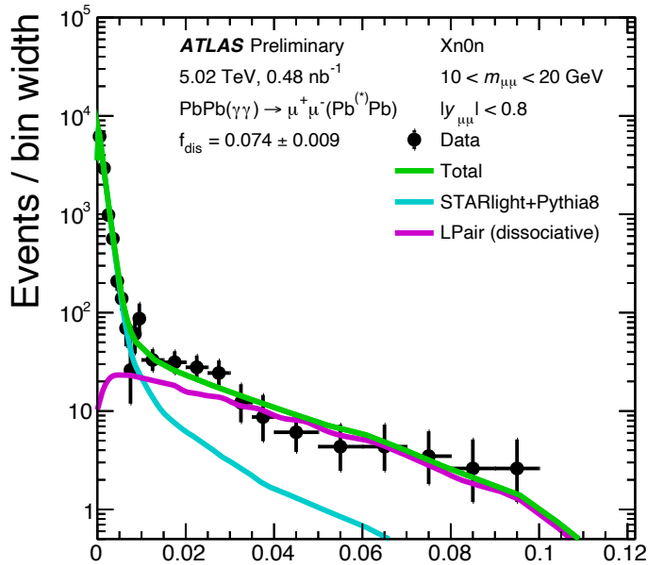
- Signal and background modelling
  - Signal: Starlight+Pythia8 (LO+ FSR)
  - Semi-coherent: LPair (pp)

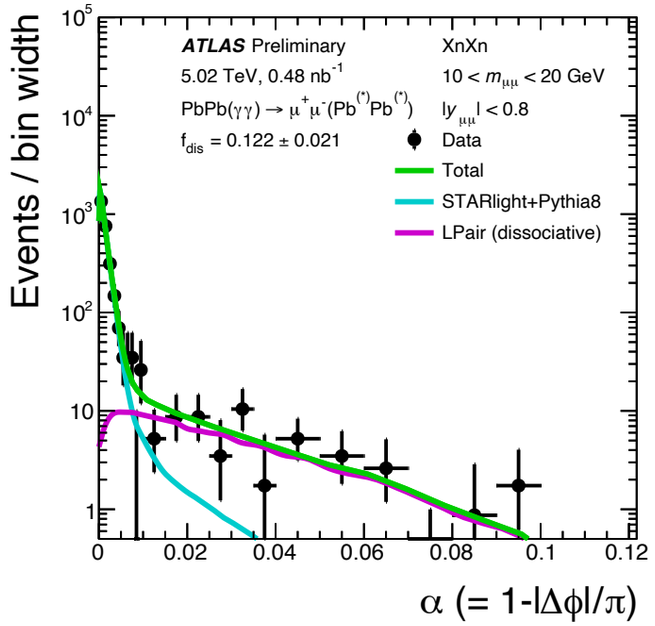
- Signal extraction obtained fitting Acoplanarity distribution

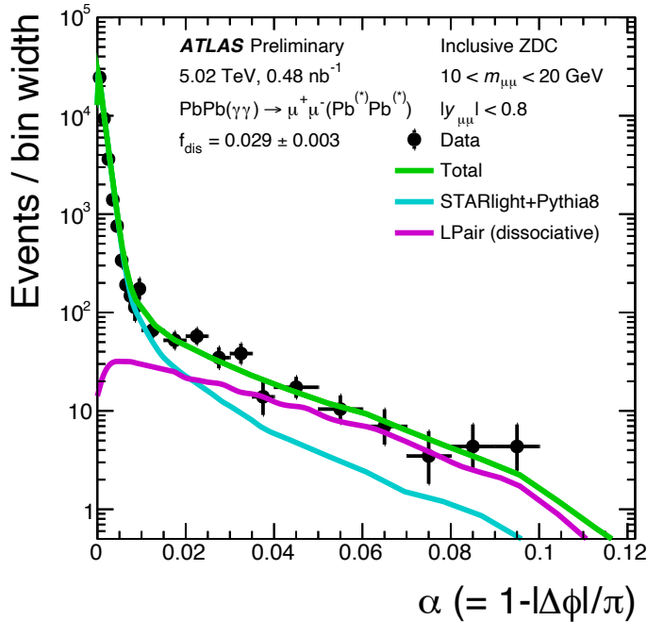
- ZDC selections have strong effect on acoplanarity

- LPair provides satisfactory description of dissociative background



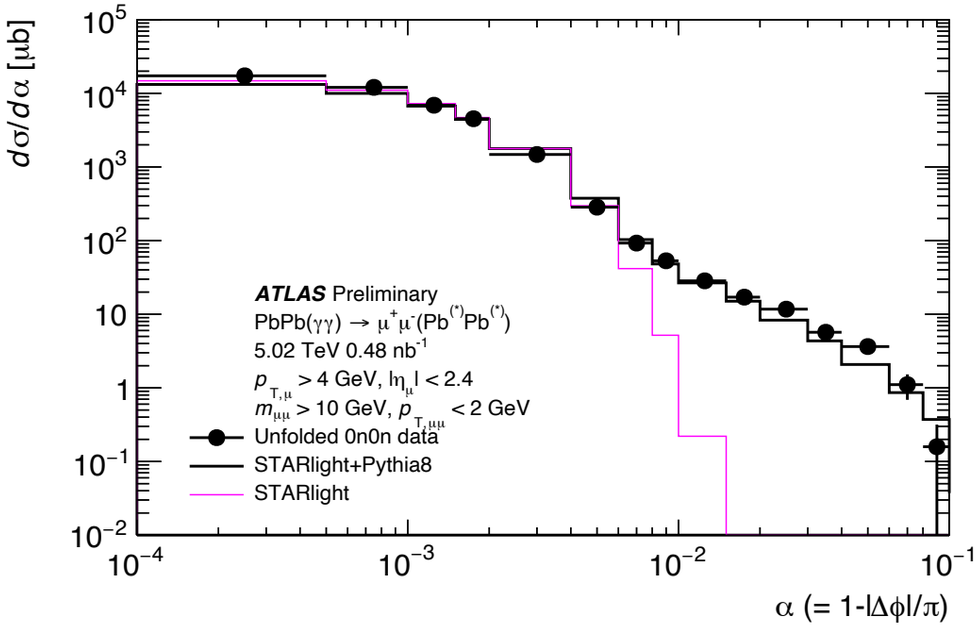


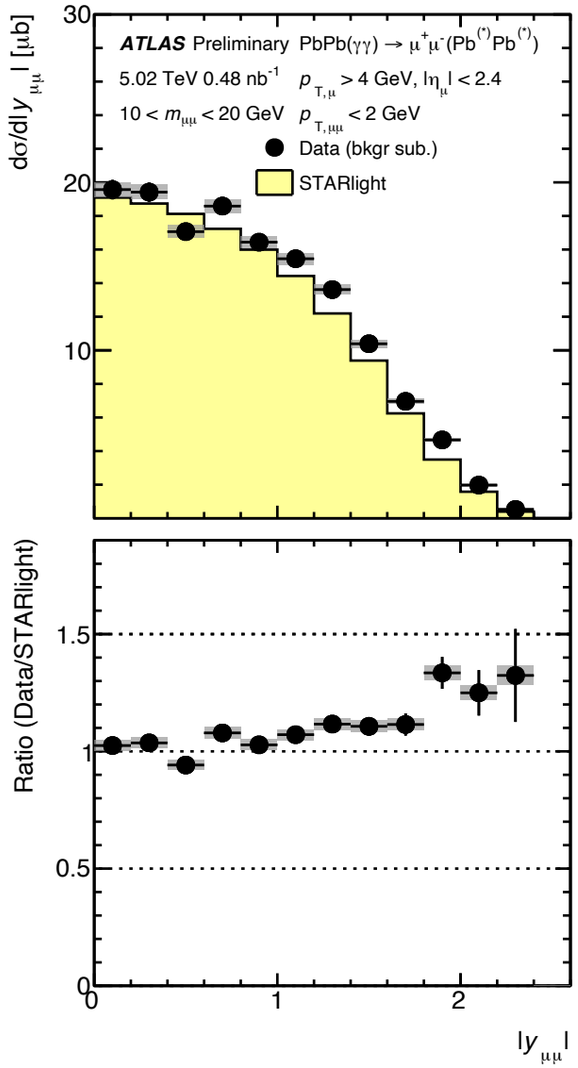




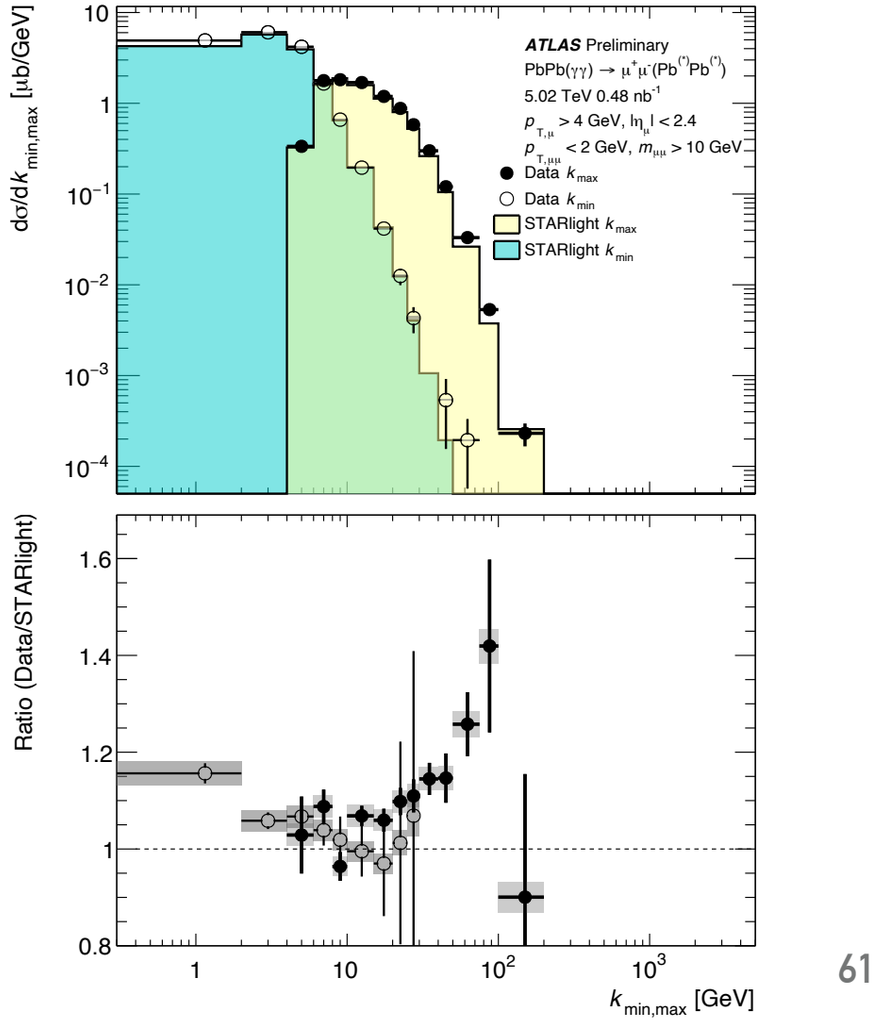
Cross section measurment

- Fiducial measurement as a function of
  - $m_{\mu\mu}$, $|y_{\mu\mu}|$, $\cos(\theta^*_{\mu\mu})$, Acoplanarity
- Some disagreement seen at small and high rapidity
- Interpreted as discrepancy at low and high photon energies



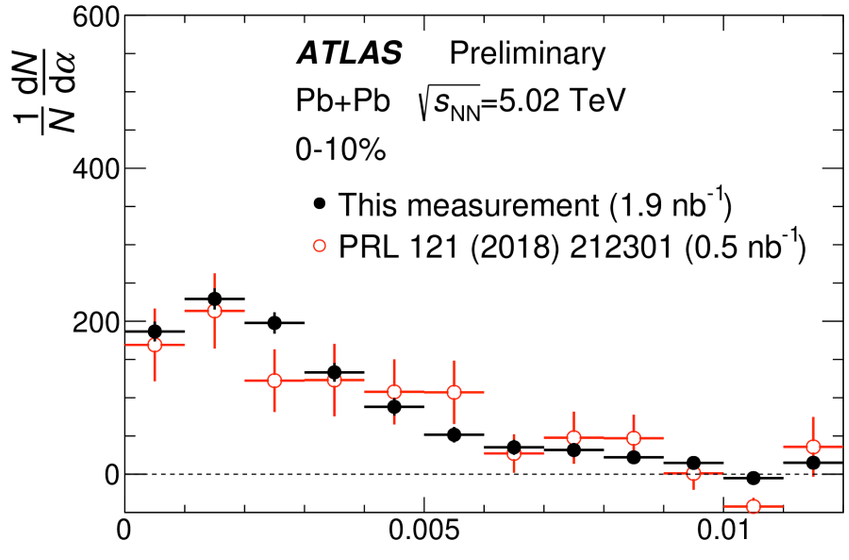


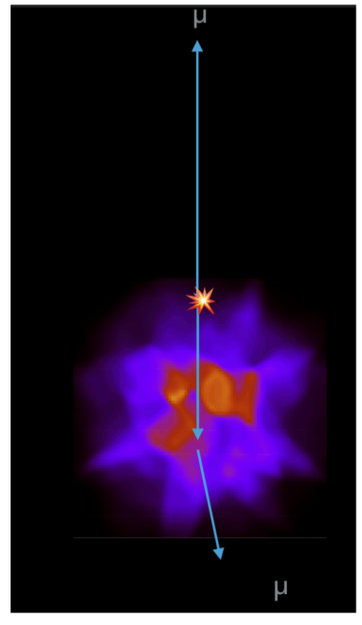
$$k_{\mathrm{min,max}} = (1/2)m_{\mu\mu}e^{\mp y_{\mu\mu}}$$



Non-UPC $\gamma\gamma \to \mu^+\mu^-$ 2015+2018 PbPb

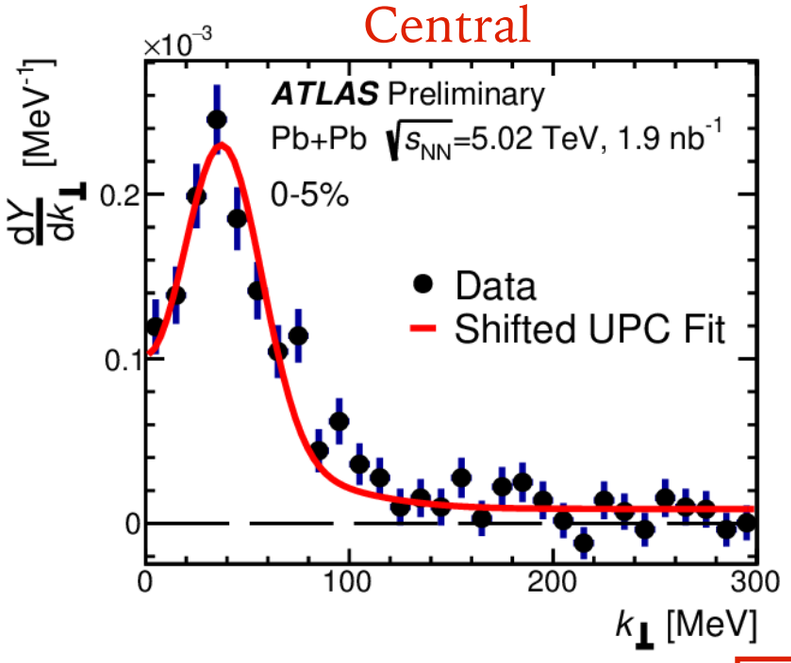
- Follow-up measurement for observation [PRL 121 (2018), 212301]
  - Broadening of acoplanarity distribution in central collisions
  - Due to muon interaction with el. charges in QGP
- Measured as a function of event centrality, muon $\bar{p}_{\mathrm{T}}$ and $y_{\mu\mu}$
- Observed shift in the peak of the k_{T} as a function of centrality

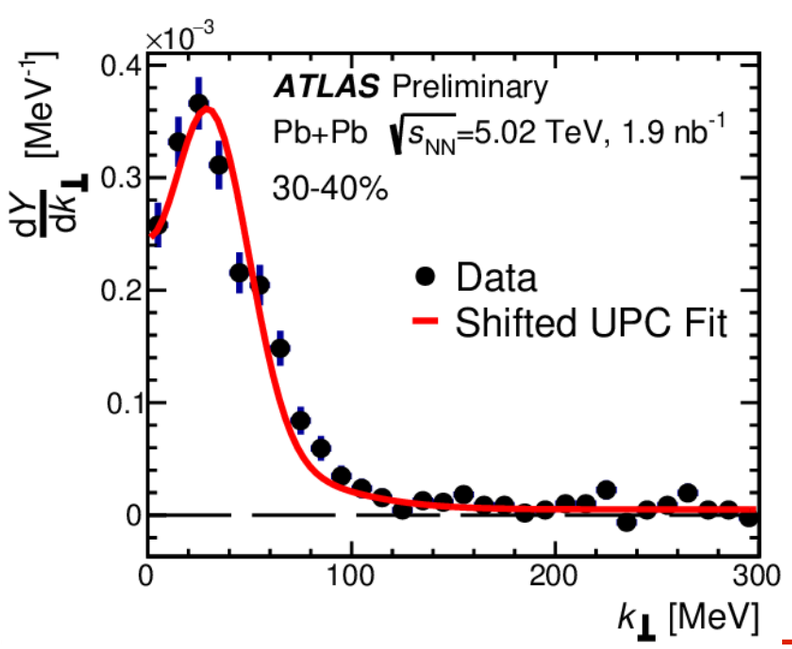




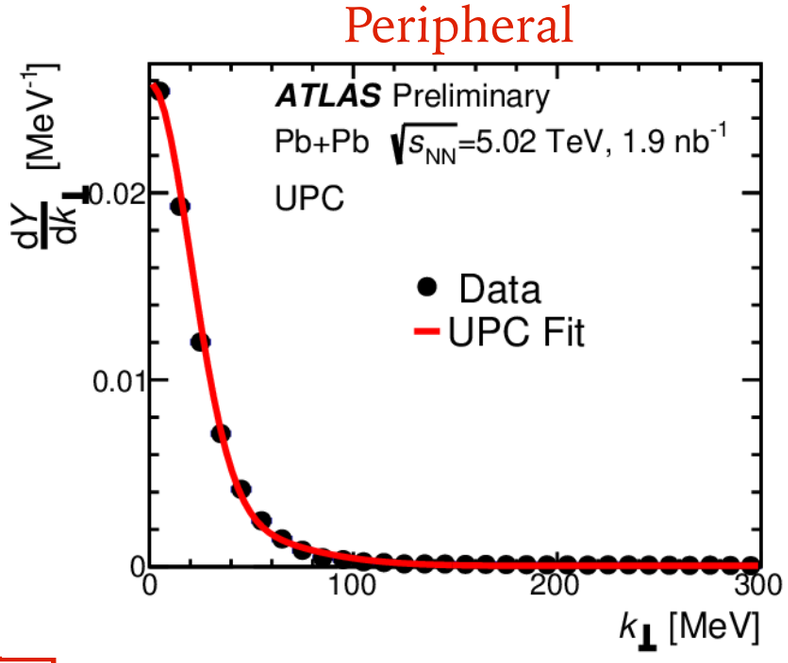
[ATLAS-CONF-2019-051]

Central





Peripheral



$$k_\perp \equiv (p_{\mathrm{T}1} + p_{\mathrm{T}2})\,|(\pi - \Delta\phi)|/2 = \pi\alpha\bar{p}_{\mathrm{T}}$$