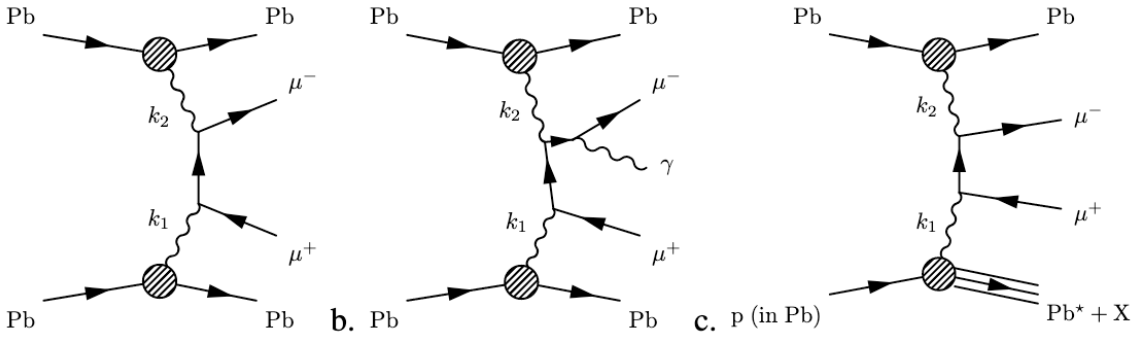
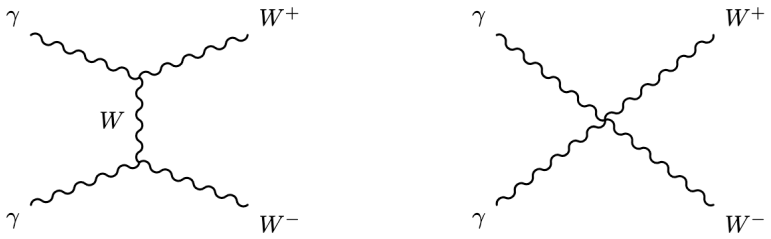
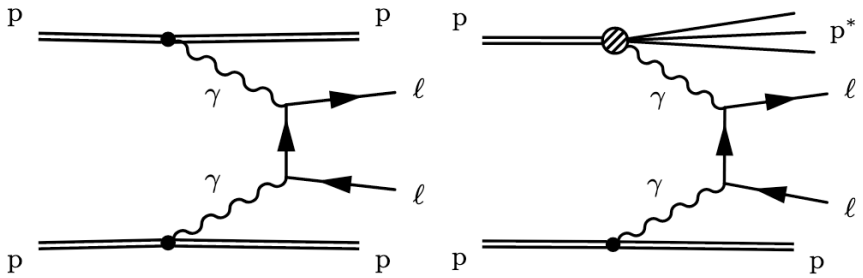
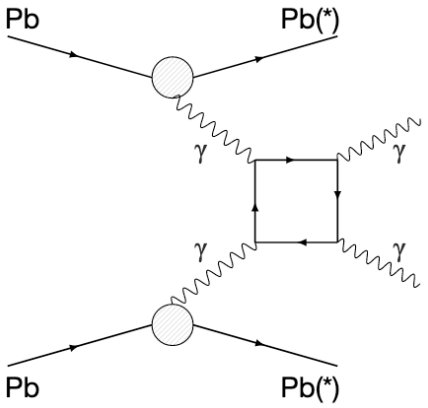
Measurements of photon-photon fusion at ATLAS









Patrick McCormack (UC Berkeley/LBNL)

On Behalf of ATLAS

ICNFP 2020

The LHC as a photon collider?

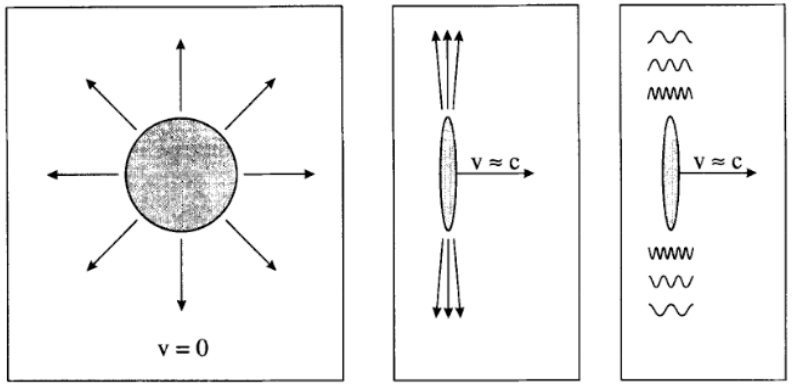
- A highly boosted electric field can be represented as a flux of photons
  - Find such fields near LHC Pb's and p's!
- This is the "equivalent photon approximation" (EPA)
- **Photon collisions provide an interesting avenue to probe otherwise hard to access SM and BSM physics**

Data Type (for LHC Run 2)	$\sqrt{s}$ (per nucleon)	~Max photon E $E_{max} \approx \frac{\gamma}{R}$	Photon flux factor: $\propto Z^4$	Integrated luminosity $[\mathrm{nb}^{-1}]$	Typical num. of interactions per bunch crossing
PbPb	5.02 TeV	**80 GeV**	4.5×10^7	2.2	**1**
pp	13 TeV	**2 TeV**	1	1.4×10^8	**20-60**

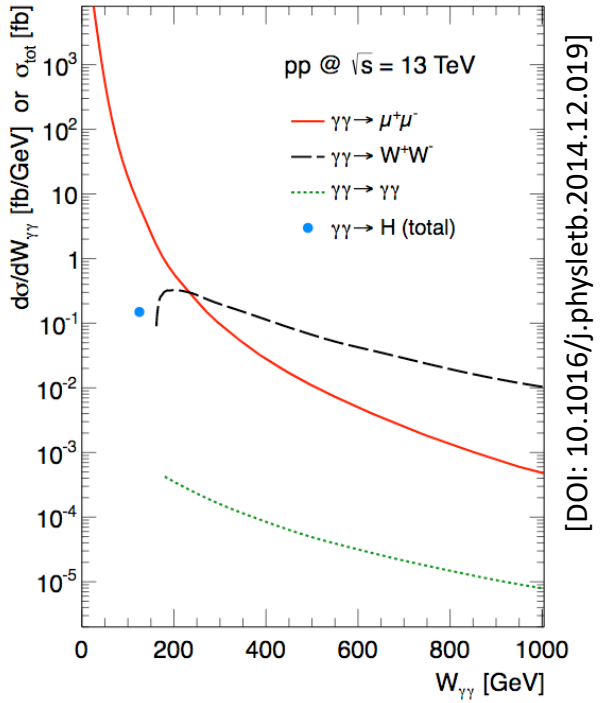
There is a trade-off:

- PbPb collision events are much cleaner
- The photons in pp bunch crossings have higher energy

(Amount of data collected for pp approximately cancels out the higher photon flux for PbPb)



The EM field around a boosted ion behaves like photons [Prog. Part. Nucl. Phys. 39 (1997) 503]

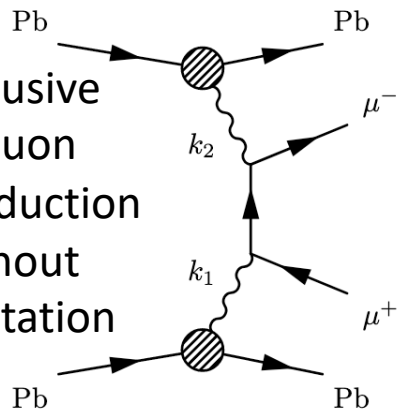


Differential cross-sections for $\gamma\gamma$ induced processes in pp beams with $\sqrt{s} = 13$ TeV as a function of $\mathrm{W} = \mathrm{m}_{\gamma\gamma}$

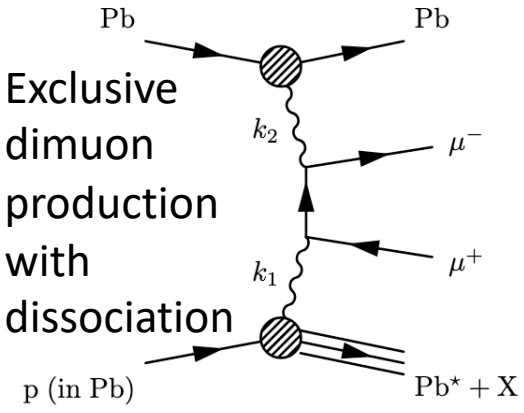
Identifying $\gamma\gamma$-induced ("exclusive") events

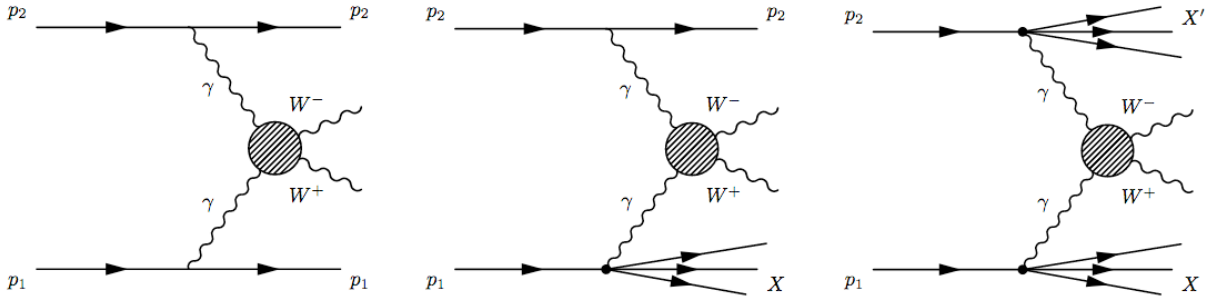
- **Key signature: little central activity** other than product of $\gamma\gamma$ collision
- There may be some forward activity
  - In pp running, one or both protons might **dissociate due to recoil**
  - In PbPb running, **soft γs might excite Pb**, leading to forward neutrons
  - Also in PbPb running, γ might have been **emitted by nuclear proton**, leading to forward dissociation

Exclusive dimuon production without excitation



Exclusive dimuon production with dissociation





(a) Elastic production (b) Single-dissociation (c) Double-dissociation

Important detector elements

Central ATLAS detector:

- Pixel and strip detectors for tracking charged particles with $|\eta| < 2.5$ (here electrons, muons, converted photons, or UE particles)
- EM calorimeter (photon and electron detection, in conjunction with tracking)
- Muon spectrometer (muon detection, in conjunction with tracking)
- Forward calorimeters (detecting forward hadronic activity $3.1 < |\eta| < 4.9$)

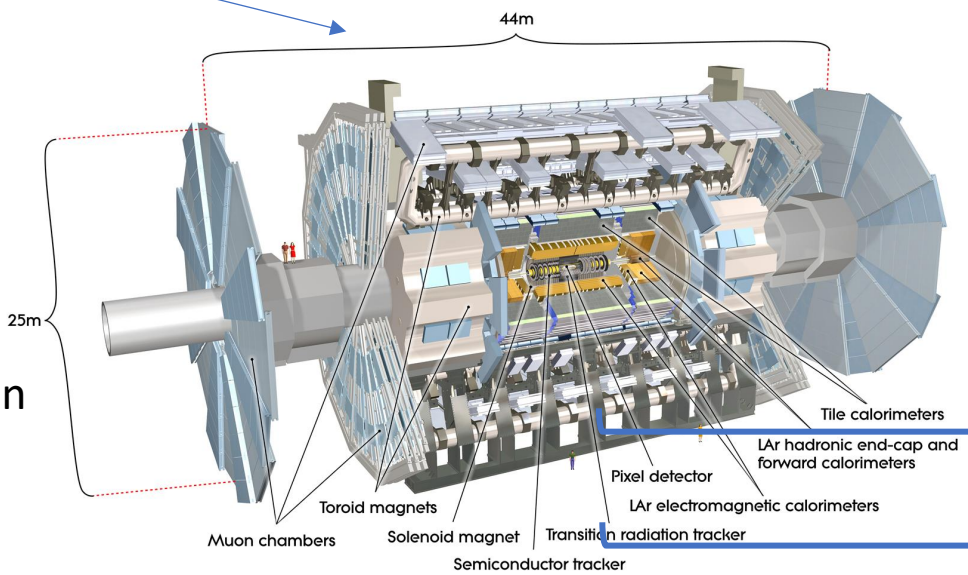
Zero Degree Calorimeter (ZDC):

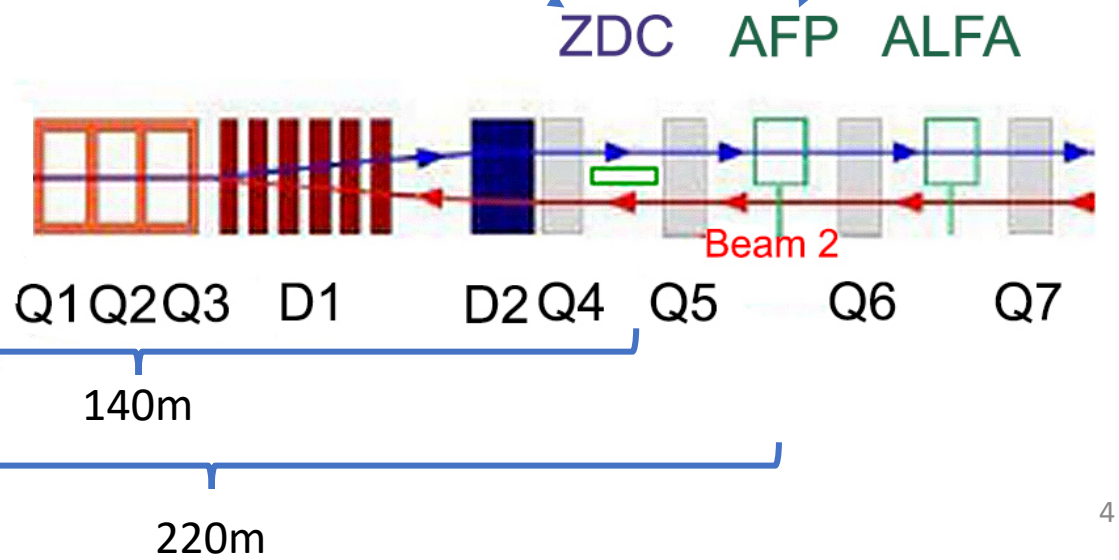
- Placed at junction of beam pipes in Heavy Ion Runs
- Covers $|\eta| > 8.3$ for neutral particles
- 4.6 interaction lengths of tungsten absorber

ATLAS Forward Proton Detector (AFP):

- 2 stations of Roman Pot detectors close to beampipe, 205 and 217m downstream of interaction point
- Multilayer tracking detector for detecting lightly deflected intact protons
- Use deflection to determine proton energy loss given known magnet conditions

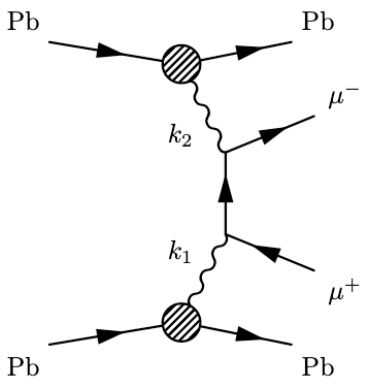
Forward detectors duplicated on this side too

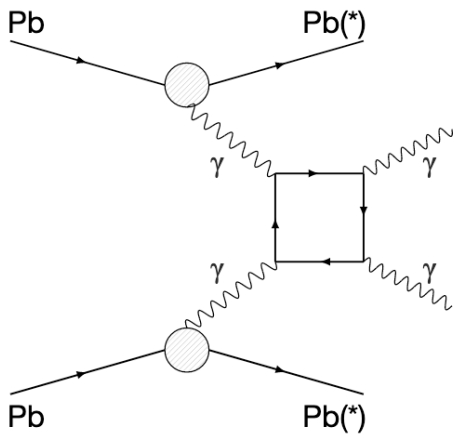


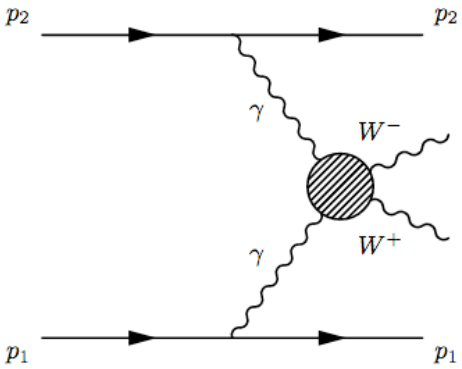


Why study photon-fusion?

	Process	Goals and Motivation
PbPb	"Exclusive Dimuon Production" $\mathrm{PbPb}(\gamma\gamma) \to \mu^+\mu^-(\mathrm{Pb}^{(*)}\mathrm{Pb}^{(*)})$ [CERN-EP-2020-138]	• "Standard Candle" measurement • **Measure incoming photon fluxes** • Sensitive to higher order corrections
PbPb	"Light-by-Light Scattering" $\mathrm{PbPb}(\gamma\gamma) \to \gamma\gamma(\mathrm{Pb}^{(*)}\mathrm{Pb}^{(*)})$ [CERN-EP-2020-135]	• Study a process that only proceeds via loops in SM • **Sensitive to BSM physics** • Here used to **constrain axion-like particle (ALP) models**
pp	"Exclusive WW production" $pp(\gamma\gamma) \to W^+W^-(p^{(*)}p^{(*)})$ [ATLAS-CONF-2020-038]	• **New observation** of rare SM process • Measure quartic gauge boson coupling and test SM EWK gauge structure • Can be used to constrain dim-6 and dim-8 EFT models
pp	"Exclusive di-lepton production associated with a tagged forward proton" $pp(\gamma\gamma) \to l^+l^-\, p\, p^{(*)}$ [ATLAS-CONF-2020-041]	• Higher energy probe of QED than PbPb exclusive dimuons • **Novel use of forward proton tagging** • **Study cross-section suppression** due to additional interaction between the scattered protons ("S_{surv}")



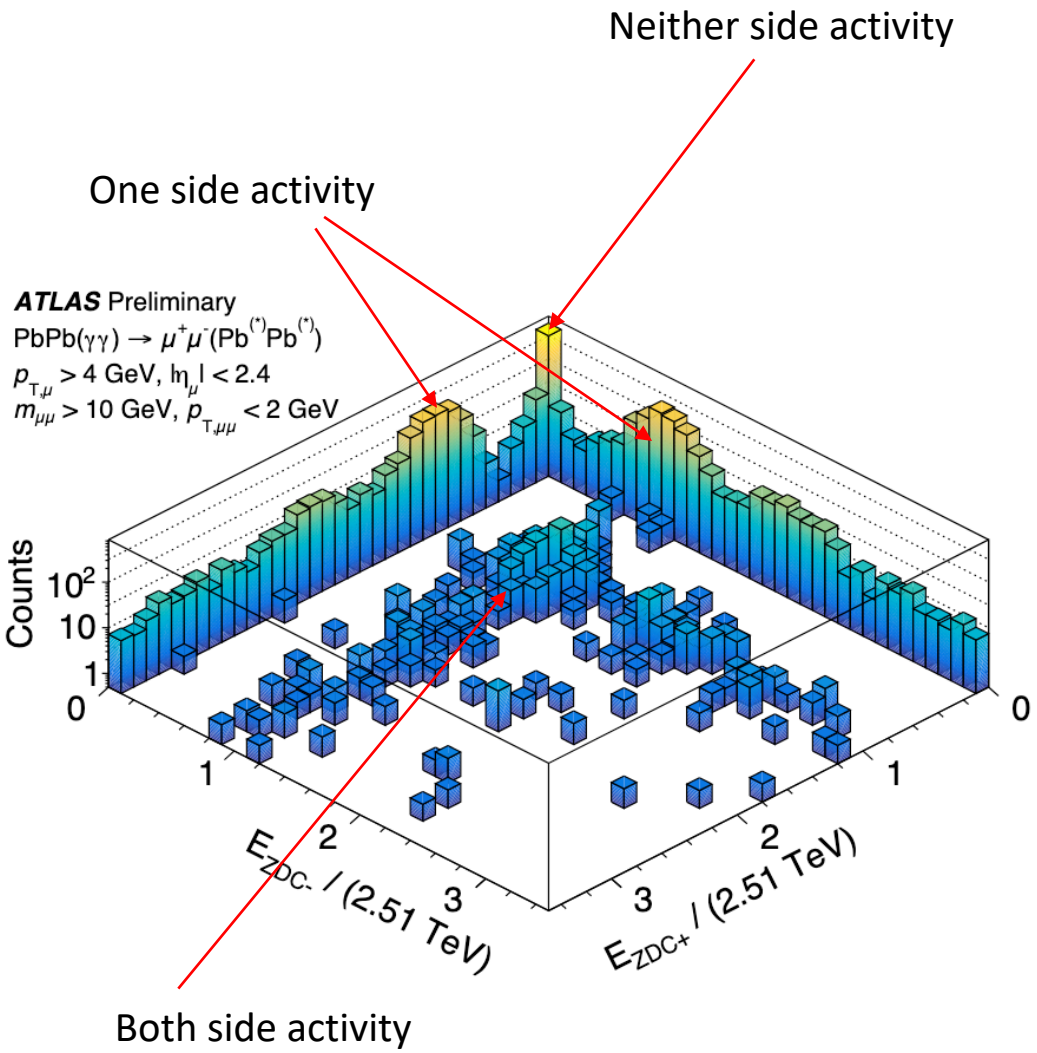




The * indicates potential excitation or dissociation

Exclusive Dimuon (with PbPb)

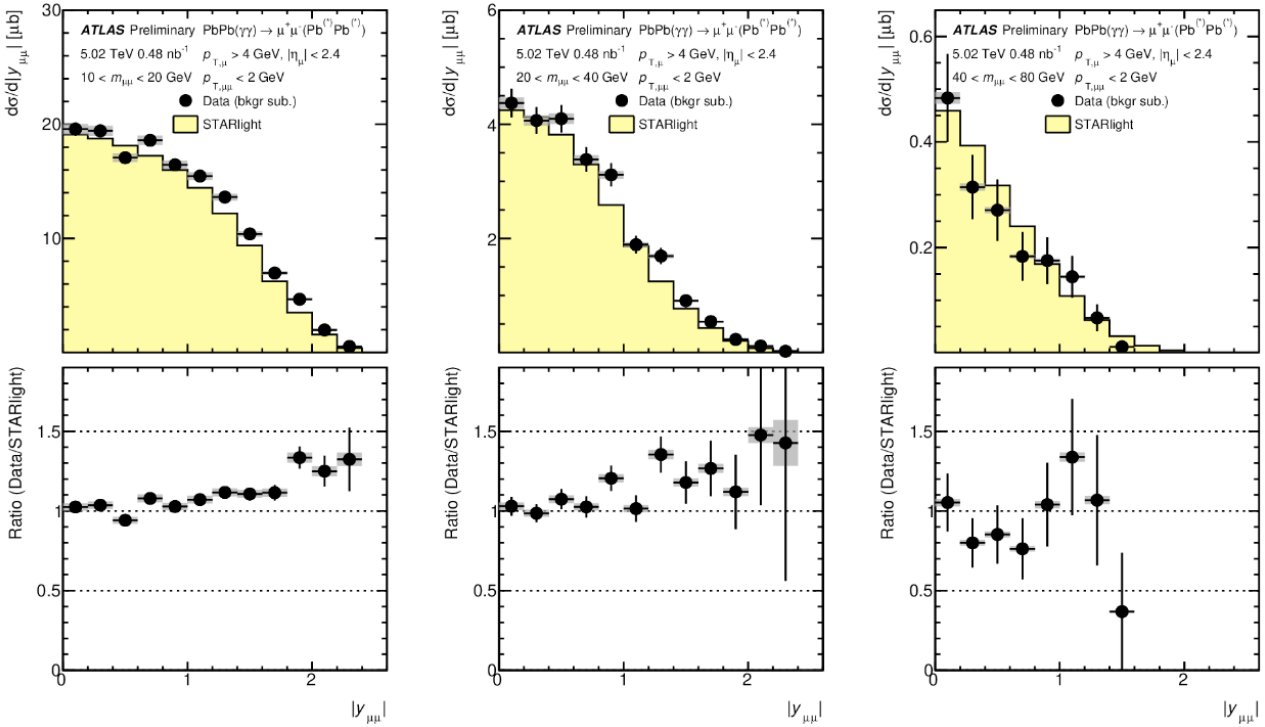
- Signal can have non-excited or excited Pb
  - Proton-radiated production is background
- Tagging Events:
  - Look for events with two opposite charge muons
  - We want no other central activity: reject any event with a non-muon track with pT > 100 MeV
  - Use the ZDC to classify events: activity in neither side, one side, or both sides
    - EM pileup means that this isn't a direct mapping to Pb-excitation/dissociation
    - Classification used to subtract dissociative background
- Simulation:
  - STARLIGHT is main generator (does not generate dissociative events)
  - Interface with Pythia8 for FSR
  - Use LPair 4.0 for dissociative background



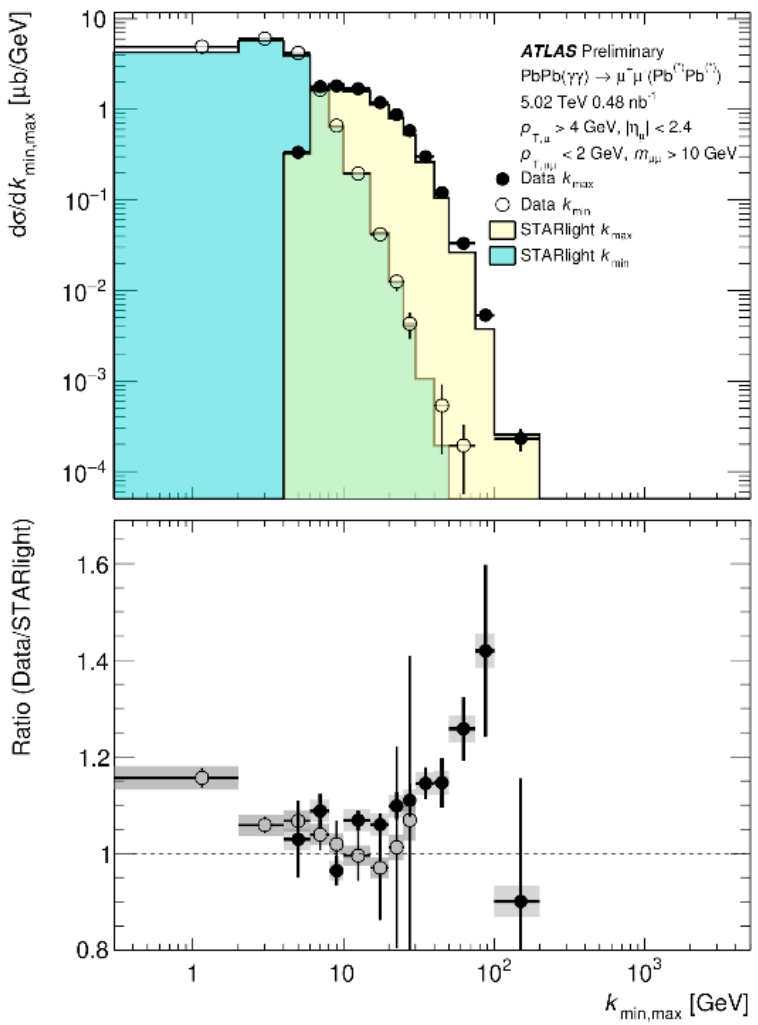
2D ZDC measurements

[CERN-EP-2020-138]

Exclusive Dimuon (with PbPb)



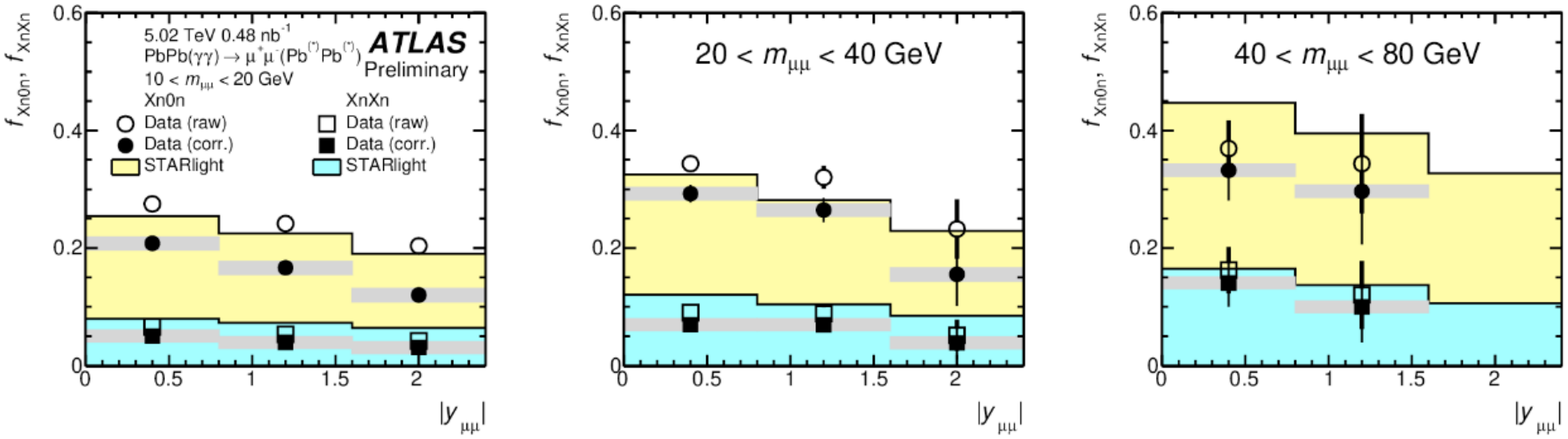
Dimuon rapidity plotted for bins of dimuon mass. Distributions are also made of dimuon mass, acoplanarity, and the cosine of the center-of-mass frame scattering angle.



Plot of the estimated initial photon energies: $k_{1,2} = \frac{1}{2} m_{\mu\mu} e^{\pm y_{\mu\mu}}$. Discrepancies here could be partially resolved in the model by allowing photon-photon interactions to occur slightly within the nuclei.

[CERN-EP-2020-138]

Exclusive Dimuon (with PbPb)

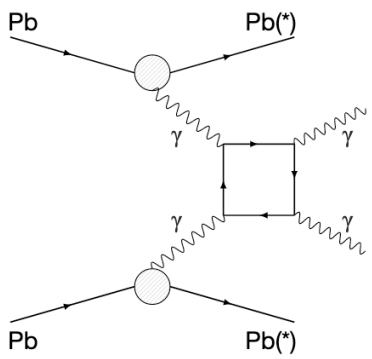


Data here is being corrected for EM pileup

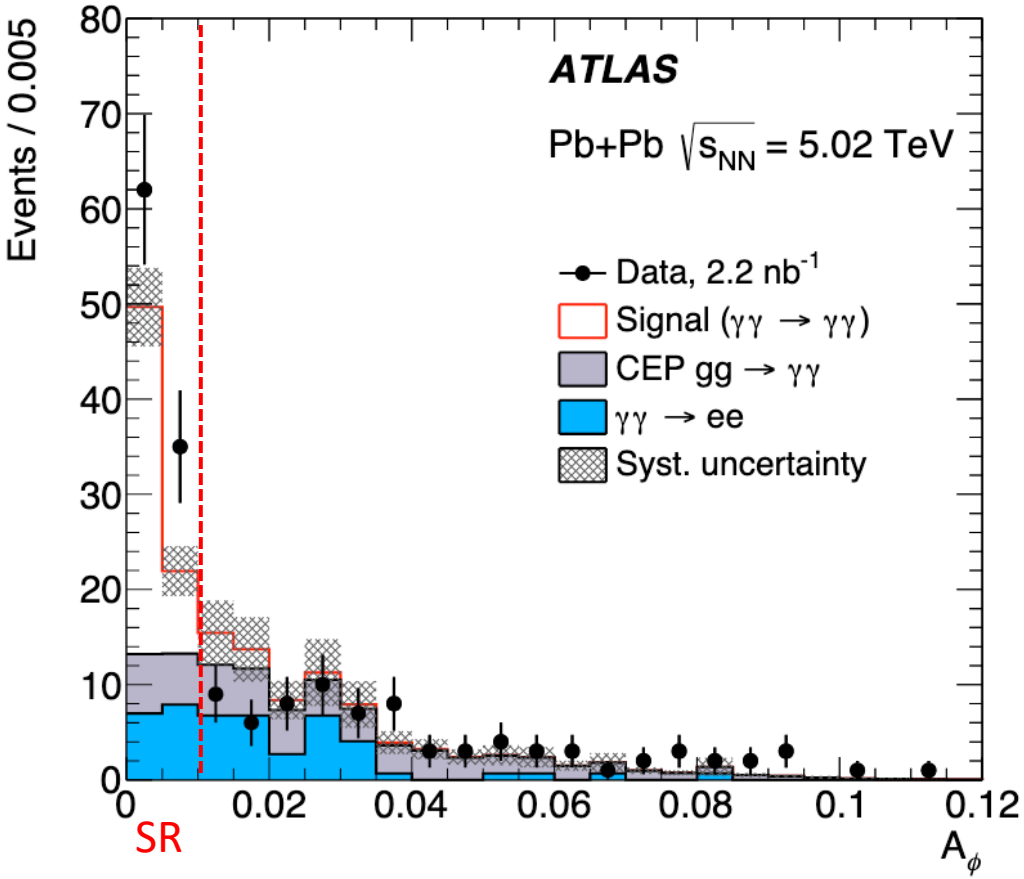
- STARLIGHT MC tends to overpredict the rate of forward activity
- Use of this measurement will allow for improved modelling of photon fluxes and reduction of uncertainties for measurements of rarer processes!

[CERN-EP-2020-138]

Light by light scattering (with PbPb)



- This is not the first observation of LByL scattering, which was formalized by ATLAS in 2019
  - Evidence from ATLAS and CMS in 2017 and 2018 respectively
- Improvements in this analysis:
  - Combination of 2015 and 2018 data = more luminosity
  - Improved diphoton mass and single photon energy range increases signal yield by 50%
  - Presentation of differential distributions
  - Constraints on ALPs



Signal and main background yields. Slight data/MC disagreement in signal region (1.7σ).

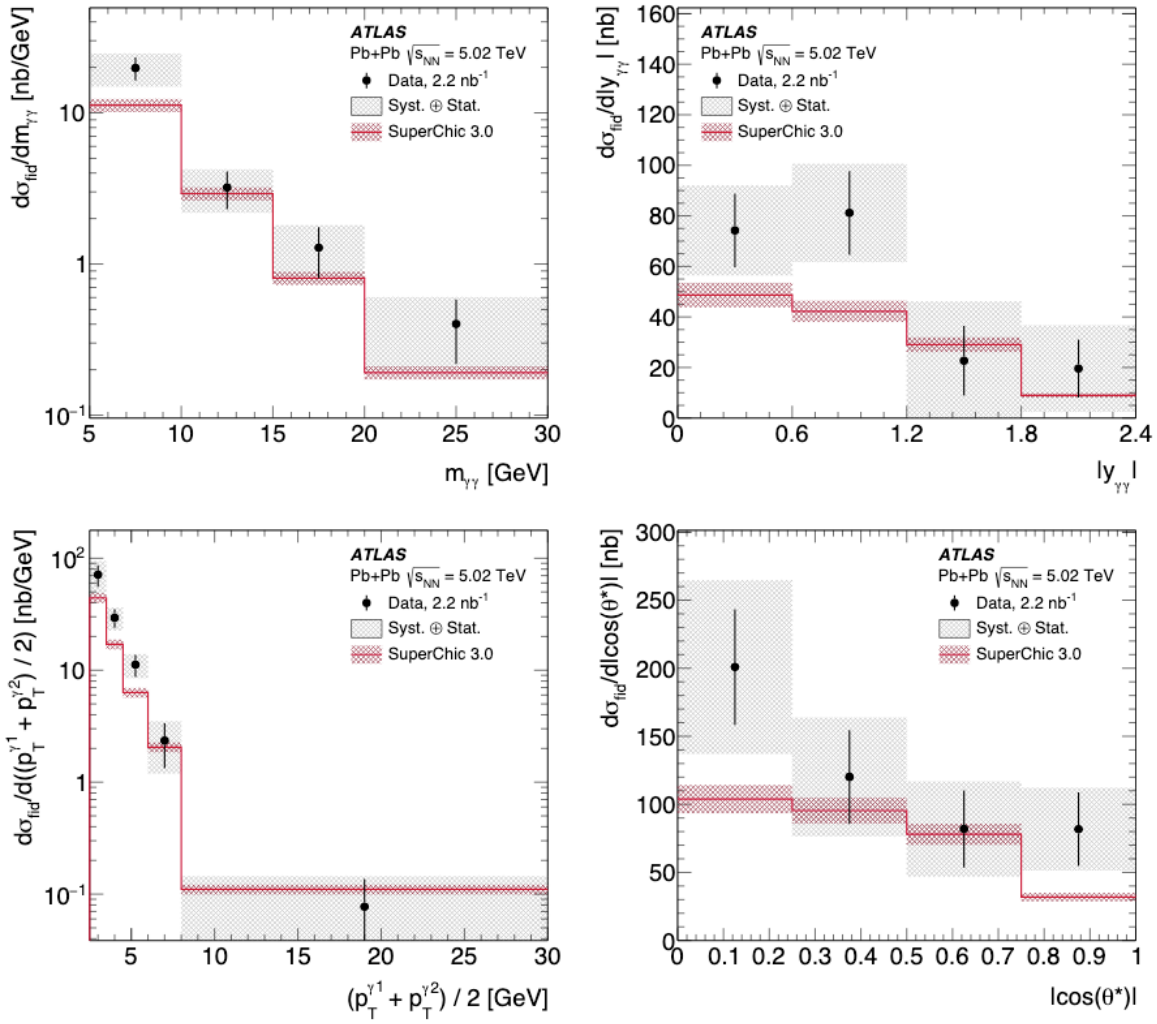
[CERN-EP-2020-135]

Light by light scattering (with PbPb)

Selection	Notes
• Must have two photons with pT > 2.5 GeV • Diphoton mass > 5 GeV	Selection of photons
• Veto on tracks with pT > 100 MeV ($\lvert\eta\rvert < 2.5$) • Veto on pixel tracks with pT > 50 MeV within η of 0.5 of a photon	Factor of 10^4 reduction in $\gamma\gamma \to e^+e^-$ background
• $p_T^{\gamma\gamma}$ < 1 GeV for $m_{\gamma\gamma} < 12$ GeV • $p_T^{\gamma\gamma}$ < 2 GeV for $m_{\gamma\gamma} > 12$ GeV	Reduce background from calorimeter noise and cosmic rays
• Acoplanarity: $1 - \frac{\Delta\phi_{\gamma\gamma}}{\pi} < 0.01$	To reduce gg $\to \gamma\gamma$ background

- Measured fiducial cross section is
  $120 \pm 17(\text{stat.}) \pm 13(\text{syst.}) \pm 4(\text{lumi.})$ nb
  - Compare to 78 ± 8 nb predicted by SuperChic
  - Data to theory ratio of 1.5 ± 0.32

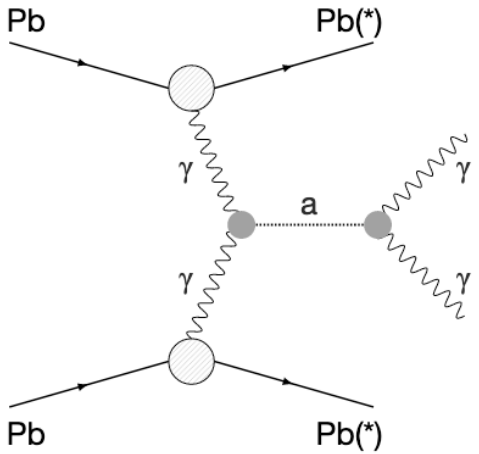
[CERN-EP-2020-135]

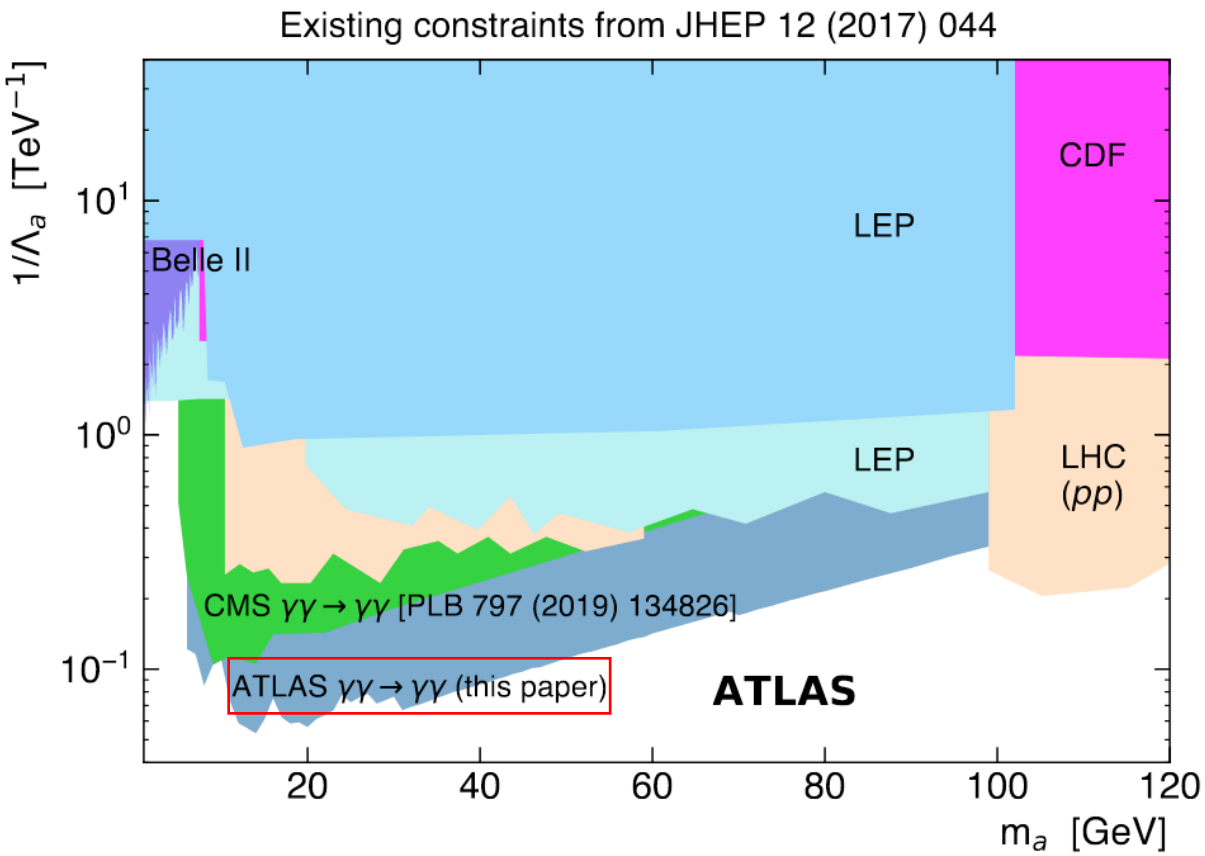


Differential cross section distributions.
Some normalization disagreement.

Light by light scattering (with PbPb)

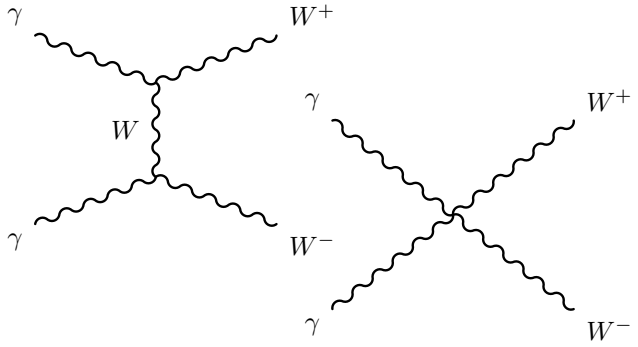
- Search for resonant ALP production
- Model of ALP production from STARLIGHT
- Cut-and-count analysis performed in mass bins ranging from 6-100 GeV
- **Leading constrains place on this region**



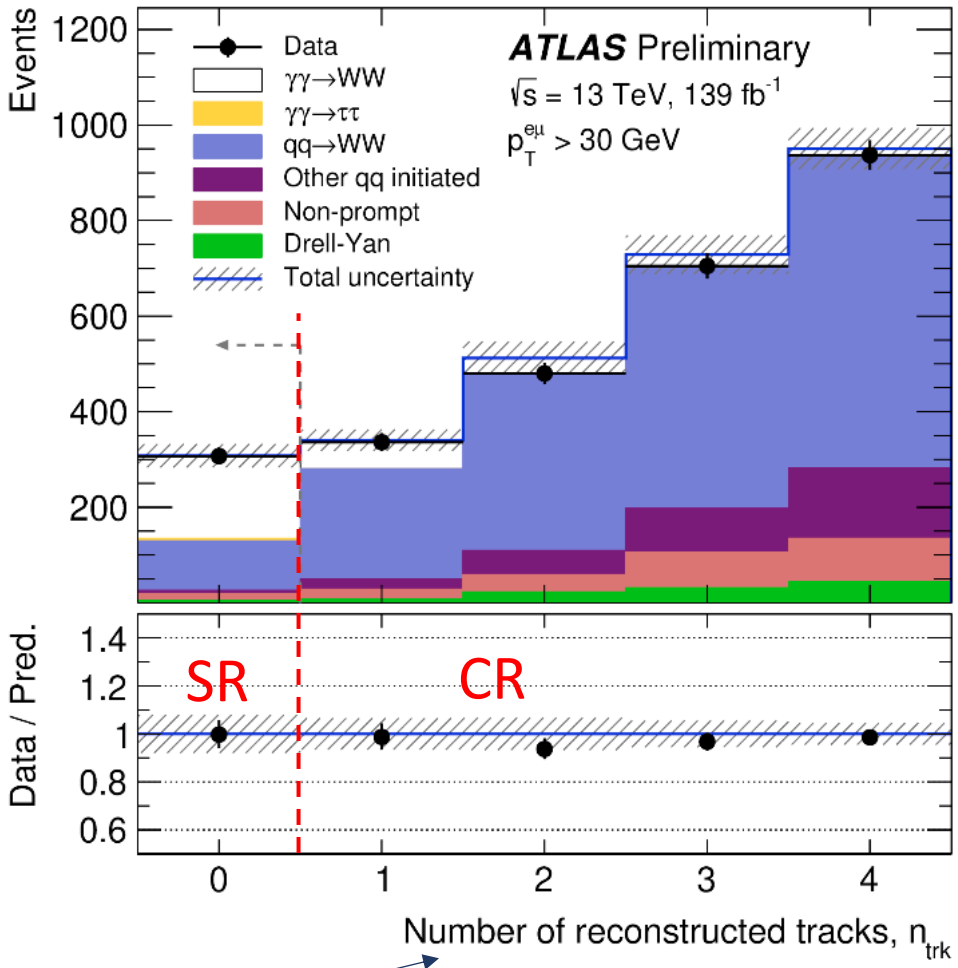


[CERN-EP-2020-135]

Exclusive WW production (with pp)



- First observation of this rare process!
  - Previous evidence from ATLAS and CMS in 2016
- A key difference from the PbPb data is **high PU**
  - Use normal LHC pp data: 20-60 collisions per crossing
  - There will be a lot of detector activity from the PU (e.g. tracks and calo hits)
  - **Must use directional reconstructed objects to determine exclusivity (ie tracks)**
- Signal selection:
  - Tag $e^{\pm}\mu^{\mp}$ pairs with $p_{T,ll}$ > 30 GeV ($p_{T,ll}$ as a MET/neutrino proxy)
  - **Key signature:** No tracks near leptons with p_T > 500 MeV
- **Main background:** QCD-induced WW events with no tracks mimic the signal
- **Central challenge:** Physics modelling of events with few or no tracks



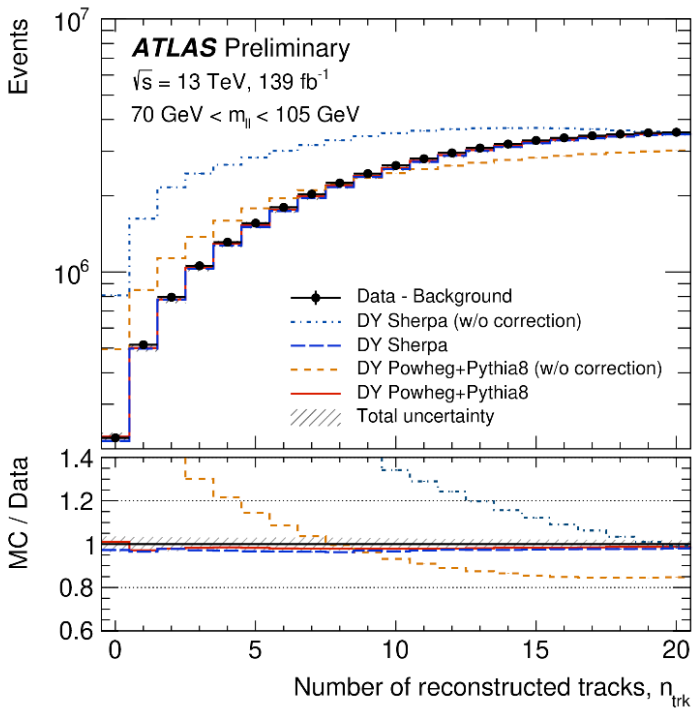
Counting the number of tracks within ±1mm window in z of weighted average of z-position of e and μ

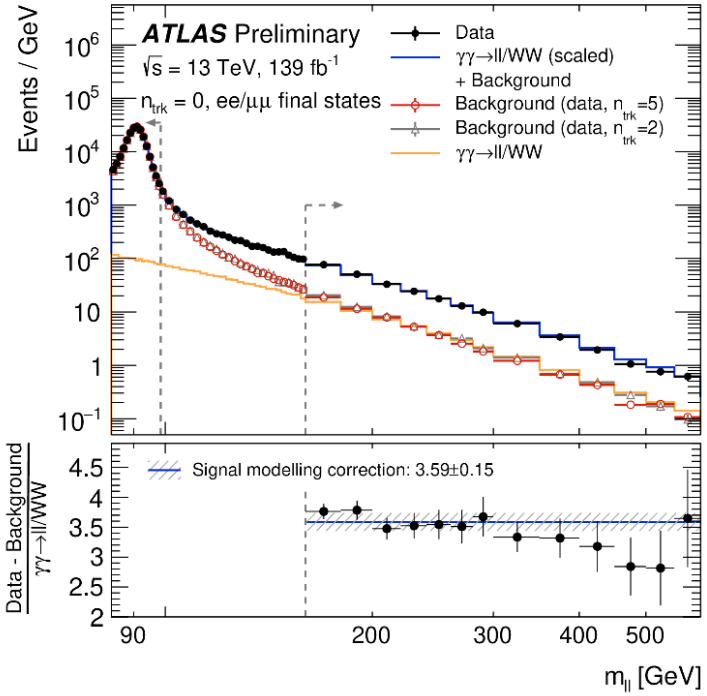
[ATLAS-CONF-2020-038]

Exclusive WW production (with pp)

Modelling challenge	Reason
Pileup	• Must model density of tracks in beamspot correctly (solution: shift PU track position in MC to match data)
Background	• Must model number of tracks from background processes correctly
Signal	• We only use MC for non-dissociative signal • Must predict how many dissociative events in signal region

Background modeling:
Reweight inclusive WW and DY background MC samples so that spectrum of num_tracks matches in MC and data





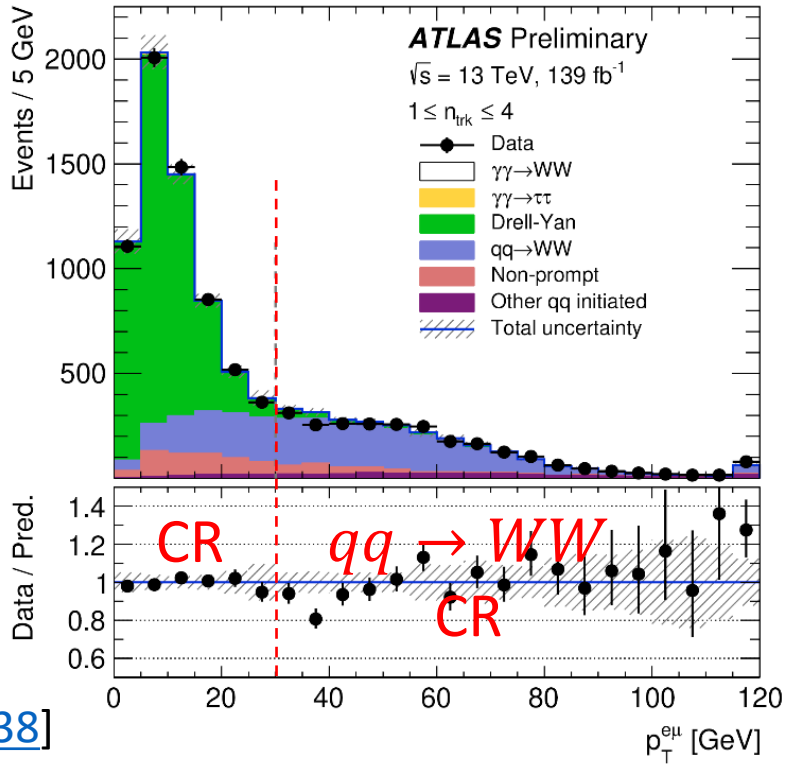
Signal modeling:
Extract dissociative scale factor by comparing m_{ll} spectra ($m_{ll} > 2 * M_W$) of di-lepton events with 0 tracks against >0 tracks

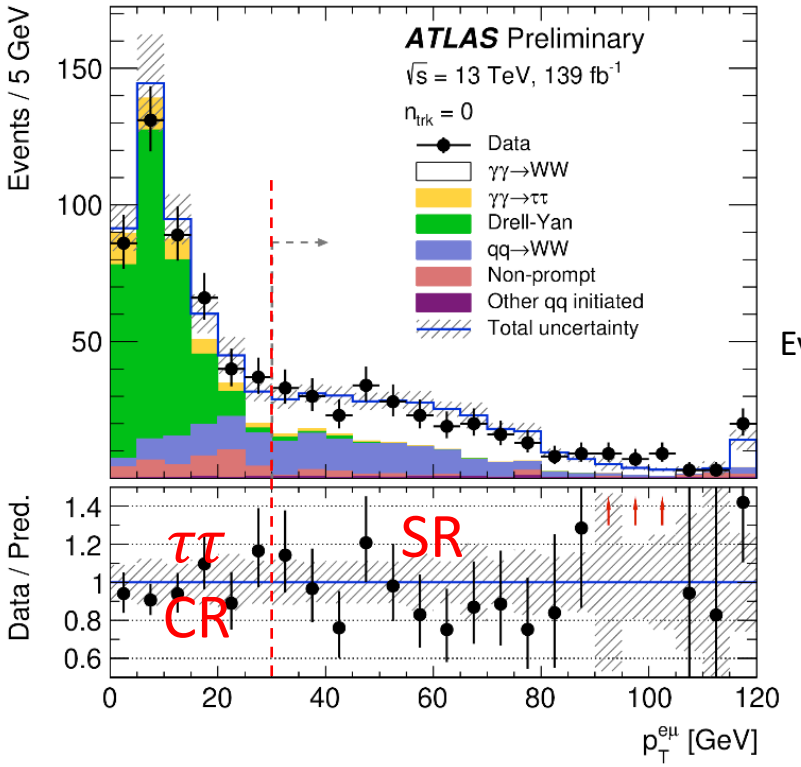
[ATLAS-CONF-2020-038]

Exclusive WW production (with pp)

- $\gamma\gamma \rightarrow W^+W^-$ **observed with a significance of 8.4 σ** (6.7 σ expected)
  - Signal strength $1.33^{+0.14}_{-0.14}(\text{stat.})^{+0.22}_{-0.17}(\text{syst.})$ observed w.r.t. prediction
  - Fiducial cross-section of $3.13^{+0.30}_{-0.29}(\text{stat.})^{+0.31}_{-0.28}(\text{syst.})$ fb

Events with 1-4 tracks



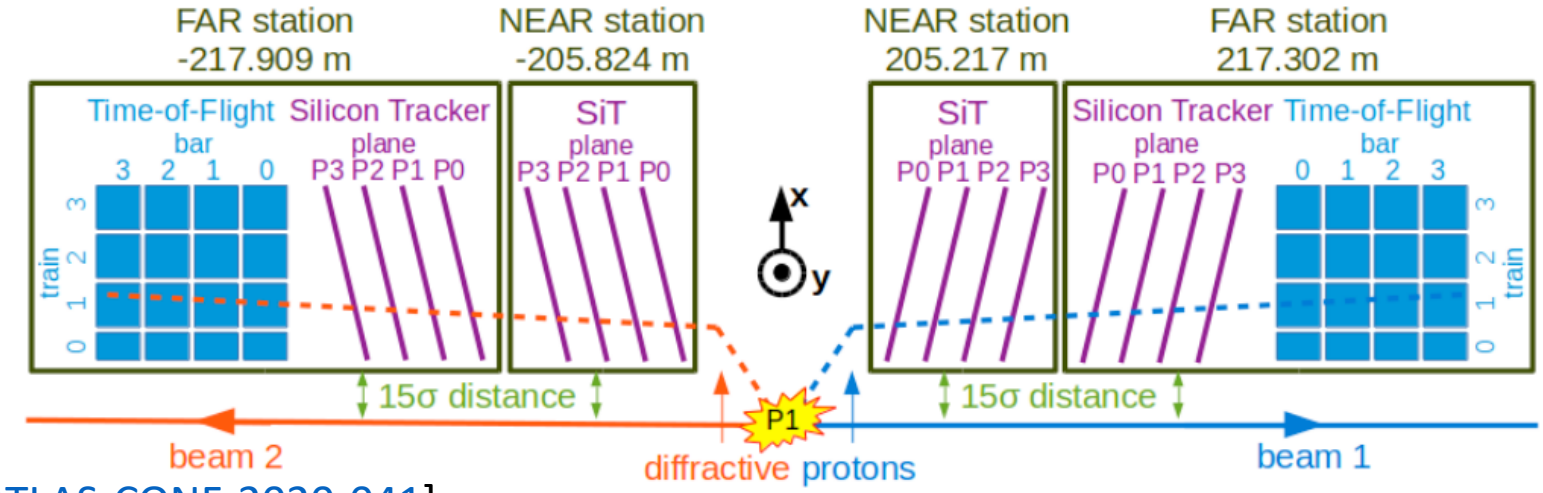


Events with 0 tracks

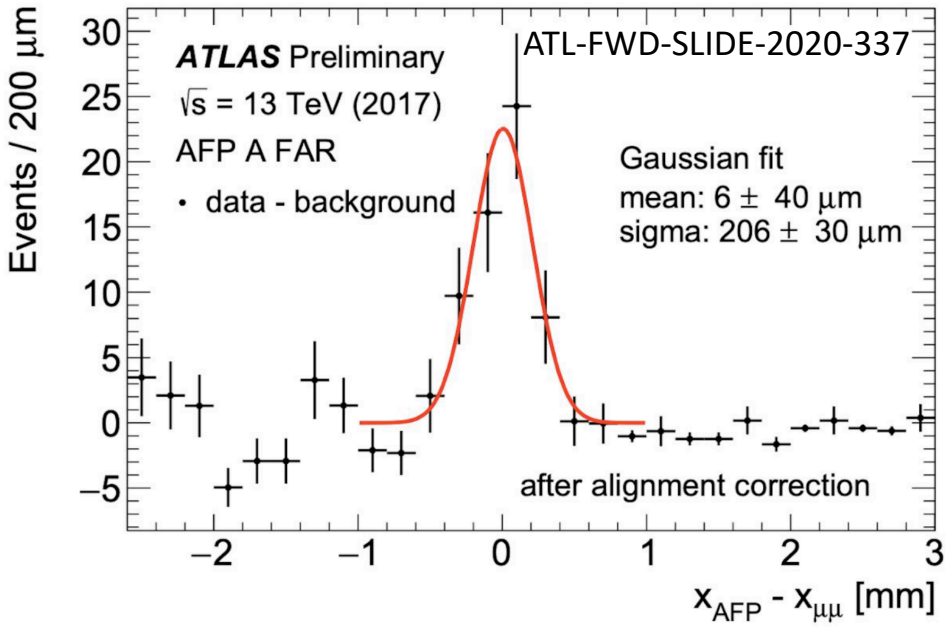
[ATLAS-CONF-2020-038]

Exclusive di-lepton using AFP

- AFP is 2 sets of 4-layer pixel detectors in Roman pots close to beampipe on both sides of the detector ($50\times250\ \mu m^2$ pixels; 336×80 pixels per layer), in conjunction with a time-of-flight detector
  - Used to "track" slightly deflected protons ~200 m down the beampipe
  - Active for most of 2017 data taking ($14.7\ fb^{-1}$ int. lumi. available)
  - In this analysis, used to detect protons that have lost 130-780 GeV of energy (Fractional energy loss is "ξ")
  - MAD-X simulation used to generate proton transport function
- Use tag-and-probe method to determine detection efficiency
- Largest single uncertainty is detector alignment (beam loss monitors used to check relative position of beam and detector)



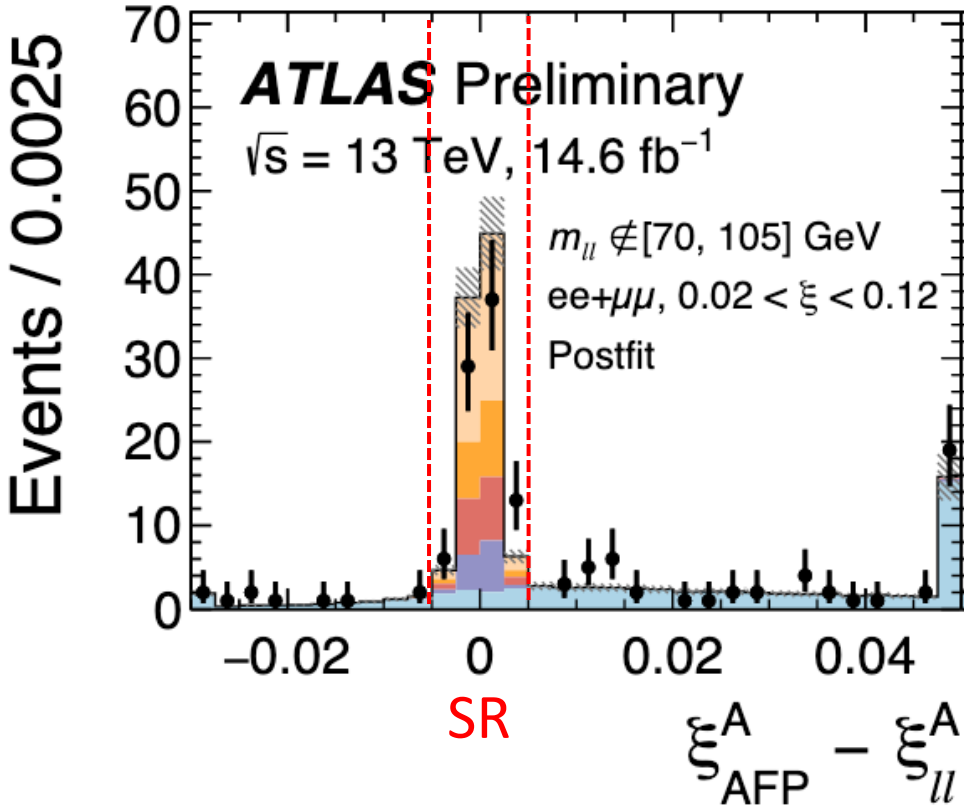
[ATLAS-CONF-2020-041]



Correlation of proton position as measured in AFP and position as predicted from lepton kinematics

Exclusive di-lepton using AFP

- Event selection:
  - $m_{ll} > 20$ GeV and $m_{ll} \notin [70,105]$ GeV (avoid quarkonia and Z backgrounds)
  - $p_T^{ll} < 5$ GeV and $1 - \frac{|\Delta\phi_{ll}|}{\pi} < 0.01$ (should be back-to-back)
  - No non-lepton tracks pointing within 0.5 mm of lepton vertex (exclusivity)
- Expected proton energy loss fraction $\xi_{ll}^{\pm} = \left(\frac{m_{ll}}{\sqrt{s}}\right) e^{y_{ll}^{\pm}}$
  - $\pm$ refers to the proton side
- There is a prediction of $\xi_{ll}^{\pm}$ from the lepton observation and a measurement from the AFP (ξ_{AFP}); they should match!
  - Signal will be when $|\xi_{AFP} - \xi_{ll}| < 0.005$



Main background is inclusive di-lepton with a pileup proton in the AFP. Background estimated in SR using sidebands (validated with CR).

[ATLAS-CONF-2020-041]

Exclusive di-lepton using AFP

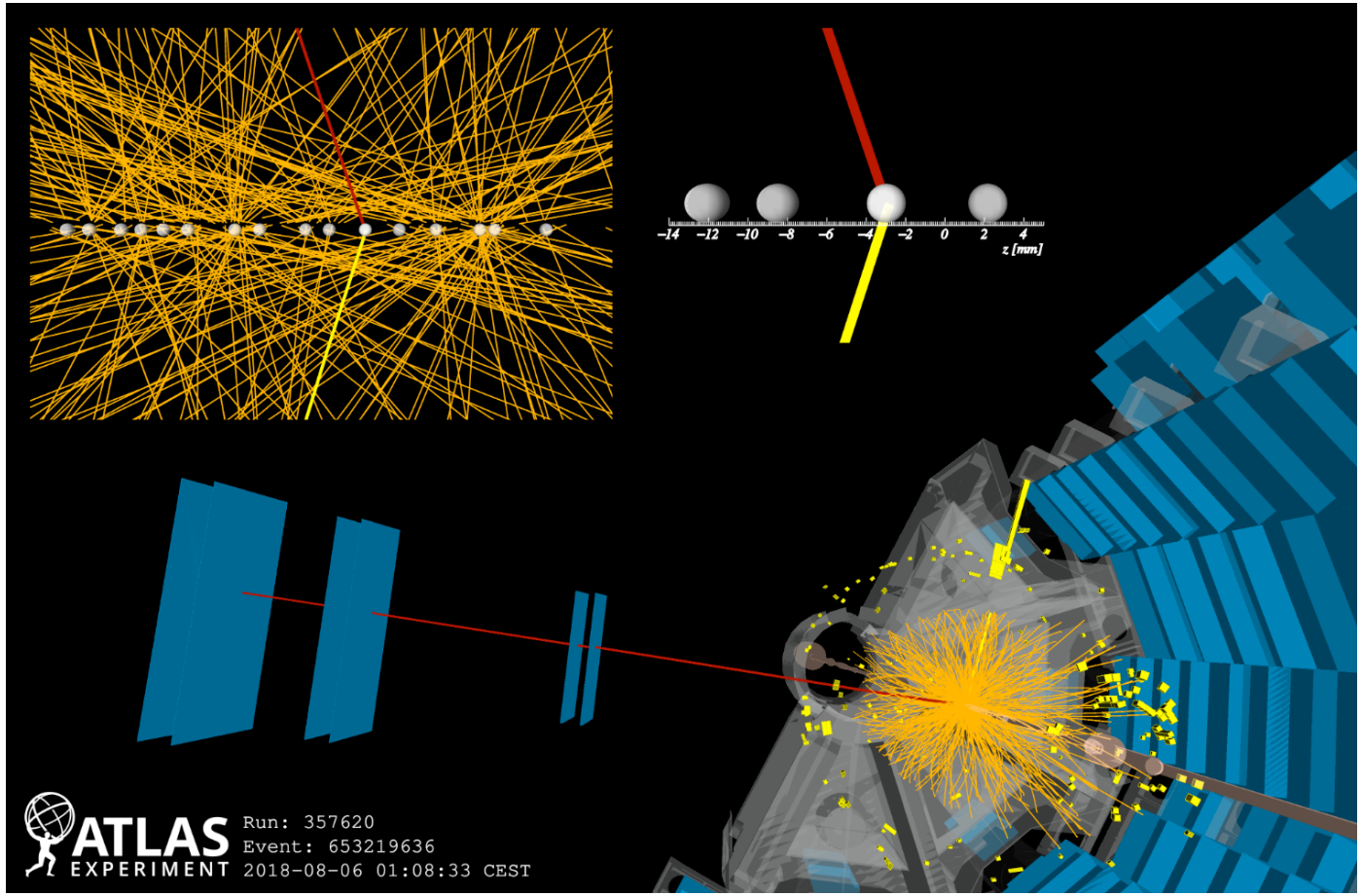
- Cross section measured in fiducial region $0.035 < |\xi_{\mathrm{AFP}} - \xi_{ll}| < 0.08$:
  - $\sigma^{\mathrm{fid.}}_{ee+p} = 11.0 \pm 2.6(\mathrm{stat.}) \pm 1.2(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.})$ fb
  - $\sigma^{\mathrm{fid.}}_{\mu\mu+p} = 7.2 \pm 1.6(\mathrm{stat.}) \pm 0.9(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.})$ fb
- Data favors Dyndal-Schoeffel soft-survival probability
  - S_{surv} modifies EPA σ prediction due to strong force interactions between protons

	$\sigma_{\mathrm{HERWIG+LPAIR}} \times S_{\mathrm{surv}}$	$\sigma^{\mathrm{fid.}}_{ee+p}$ [fb]	$\sigma^{\mathrm{fid.}}_{\mu\mu+p}$ [fb]
	$S_{\mathrm{surv}} = 1$	15.5 ± 1.2	13.3 ± 1.1
Superchic 2 →	$m_{\ell\ell}$-independent S_{surv} [Ref]	13.0 ± 1.0	11.1 ± 0.8
Dyndal-Schoeffel →	$m_{\ell\ell}$-dependent S_{surv} [Ref]	10.9 ± 0.8	9.2 ± 0.7
	Measurement	11.0 ± 2.9	7.2 ± 1.8

[ATLAS-CONF-2020-041]

Conclusions

- Practically, photon-photon fusion measurements have given us:
  - A new observation of a rare SM process
  - Precision data for improving models
  - Constraints on BSM physics and ALP limits
  - Data using a new detector component
- Photon-induced physics provides an interesting way to **probe EWK and BSM physics**
- For the future:
  - **~10x more data with AFP possible in Run 3**-> better precision in pp studies
  - Use AFP in $\gamma\gamma \rightarrow WW$ analysis and use $\gamma\gamma \rightarrow WW$ for BSM constraints
  - Use exclusive dileptons for BSM constraints (e.g. DM/SUSY search)
  - Many other detailed studies possible!

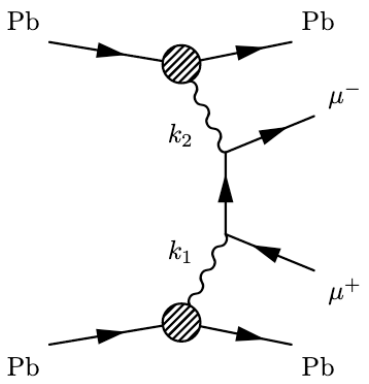


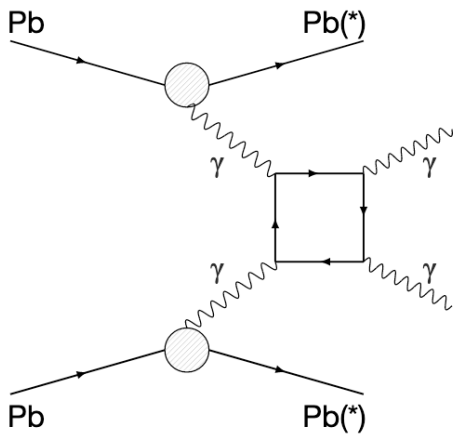
Event display for an Exclusive WW event. Notice the lack of tracks around the electron and muon.

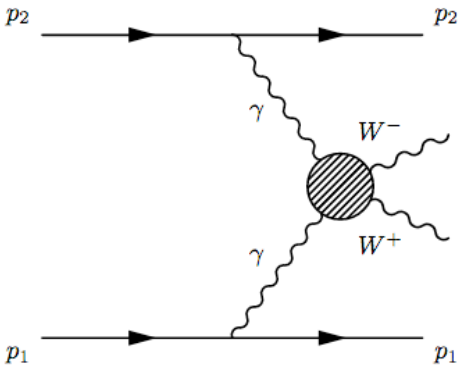
Backup

Newest ATLAS Results

- Results from PbPb data-taking
  - Exclusive Dimuon Production: $\mathrm{PbPb}(\gamma\gamma) \rightarrow \mu^+\mu^-\left(\mathrm{Pb}^{(*)}\mathrm{Pb}^{(*)}\right)$
    - [CERN-EP-2020-138]: To be made public in September
  - Light-by-Light Scattering: $\mathrm{PbPb}(\gamma\gamma) \rightarrow \gamma\gamma\left(\mathrm{Pb}^{(*)}\mathrm{Pb}^{(*)}\right)$
    - [CERN-EP-2020-135]: https://cds.cern.ch/record/2719516
- Results from pp data-taking
  - Exclusive WW production: $pp(\gamma\gamma) \rightarrow W^+W^-\left(p^{(*)}p^{(*)}\right)$
    - [ATLAS-CONF-2020-038]: https://cds.cern.ch/record/2727859
  - Exclusive di-lepton production associated with a tagged forward proton: $pp(\gamma\gamma) \rightarrow l^+l^-\ p\ p^{(*)}$
    - [ATLAS-CONF-2020-041]: https://cds.cern.ch/record/2727863





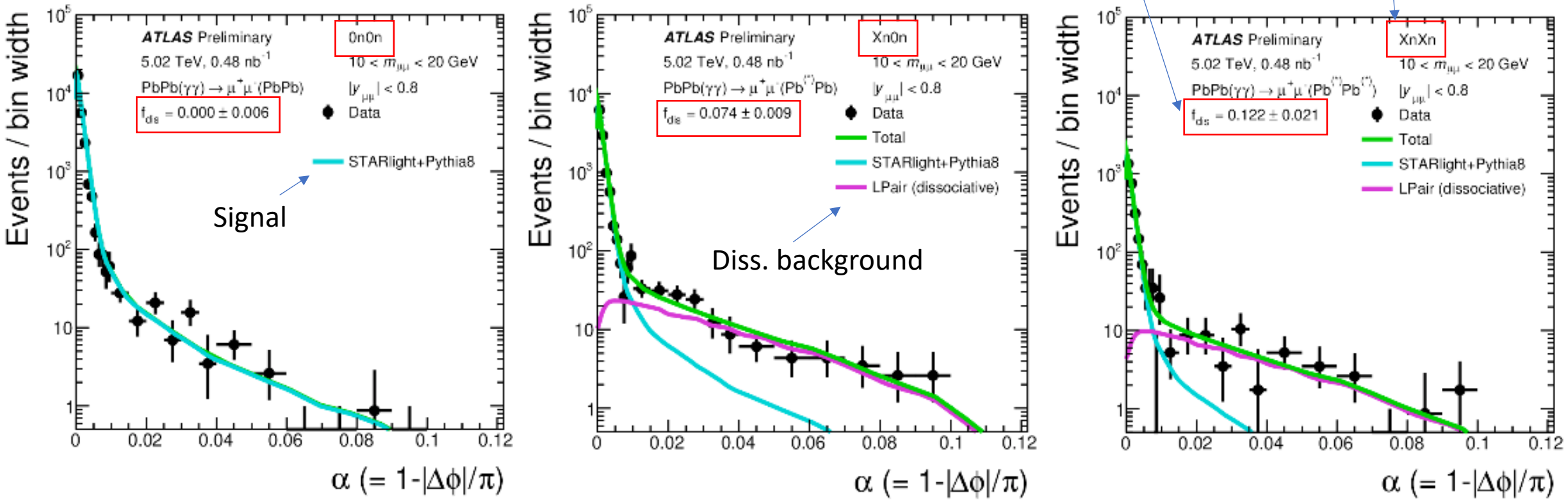


Exclusive Dimuon (with PbPb)

Example of acoplanarity distributions binned in ZDC category

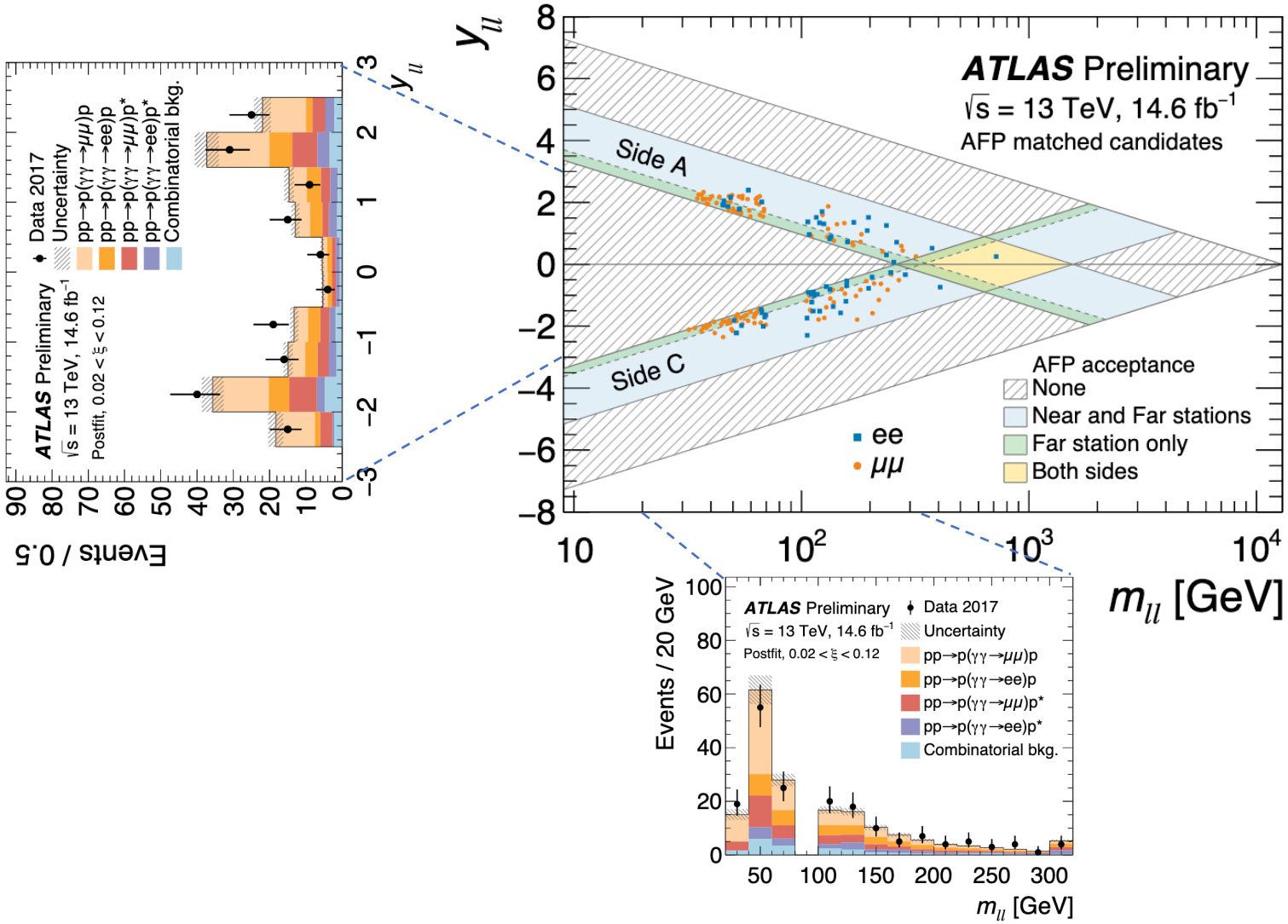
ZDC configuration

Ratio of diss. events



α is "acoplanarity", a statement about how back-to-back the muons are in the r-phi plane: 0 is exactly back-to-back. Signal muons should be almost exactly back-to-back, while dissociatively-produced muons are less back-to-back.

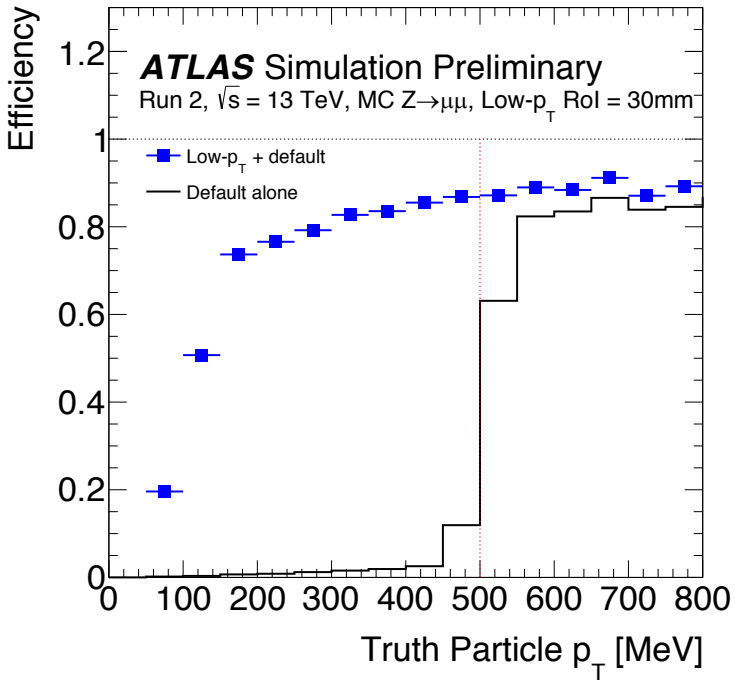
Exclusive di-lepton using AFP



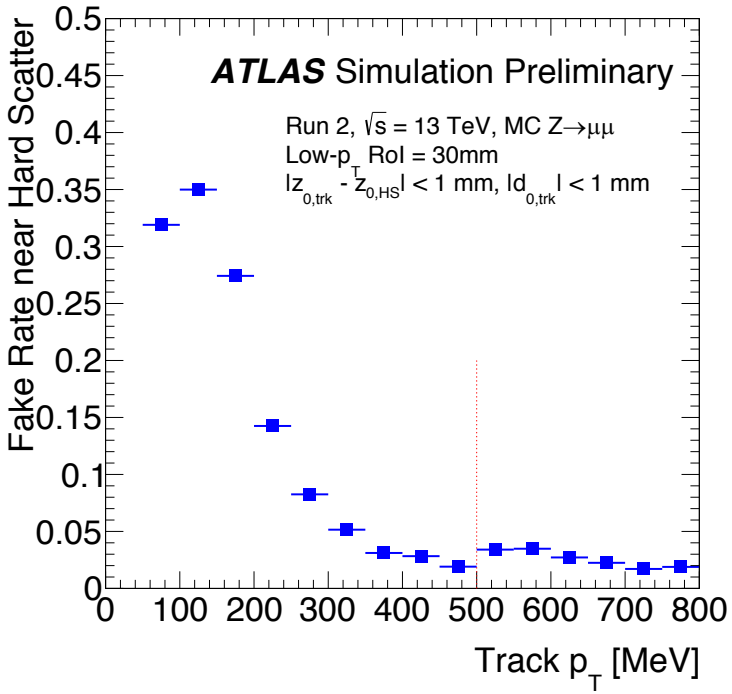
2D distribution of m_{ll} and y_{ll}, showing where they fall in AFP acceptance

Low-pT tracking for pp collisions

- High PU conditions (in pp) makes tracking computationally expensive
  - Putting a minimum track pT cut of 500 MeV reduces tracking time and storage
  - BUT ~1/2 of UE tracks have pT < 500 MeV **reconstructing these tracks would improve exclusivity selection**
- Algorithm has been developed to perform low-pt tracking (down to ~100 MeV) in events of interest to an analysis



Good efficiency down to ~150 MeV



Fake rate can be problematic below ~200 MeV.
Use offline selections to reduce fakes