ATLAS results on diffraction and exclusive production

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On behalf of the ATLAS collaboration

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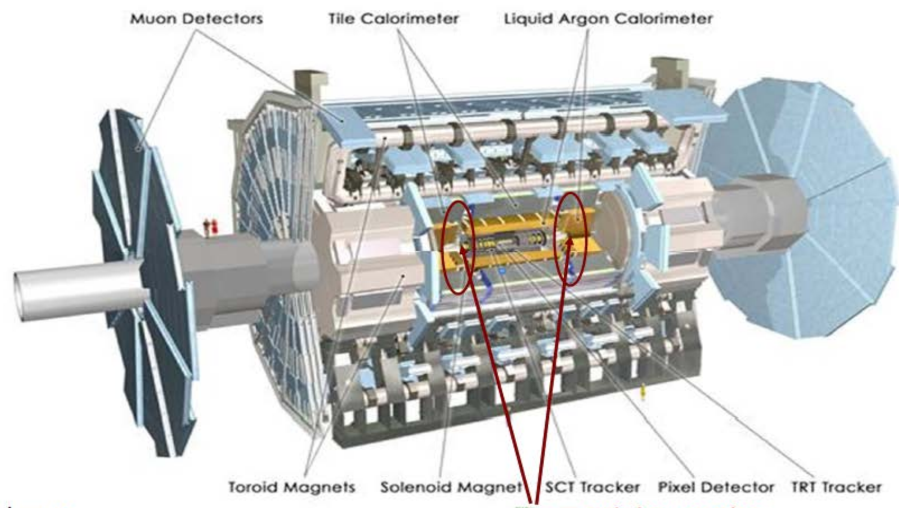
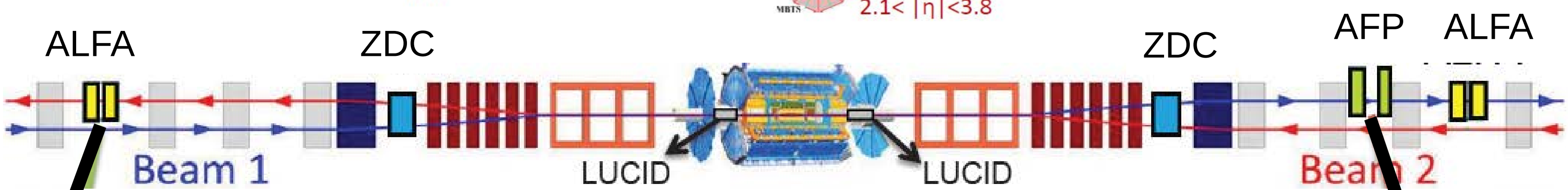
1) Diffractive dijets
2) Exclusive l^+l^-
3) Exclusive W^+W^-

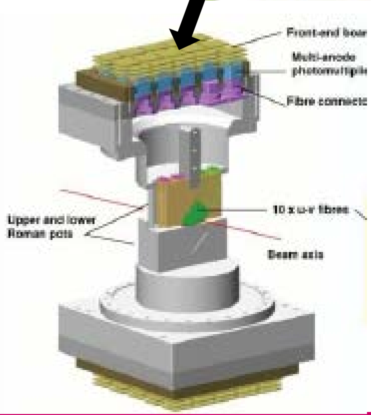
ATLAS detector and its forward subdetectors



Trackers: |η|<2.5
Calorimeters: |η|<4.9

Minimum **B**ias
Trigger **S**cintillator
2.1< |η|<3.8





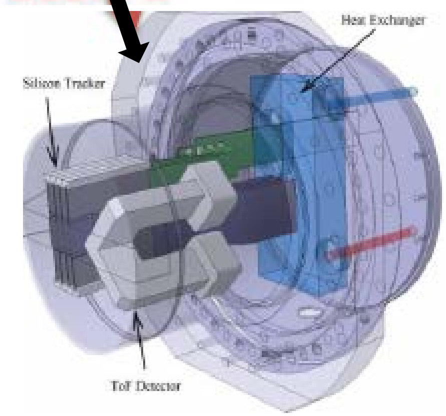
ATLAS forward proton detectors ALFA & AFP not used in diffraction and exclusive event measurements shown in this presentation. But stay tuned.

ALFA:

Elastic protons:
See Christian's talk

AFP:

Diffractive protons:
AFP took first data this year!
See Grzegorz's talk



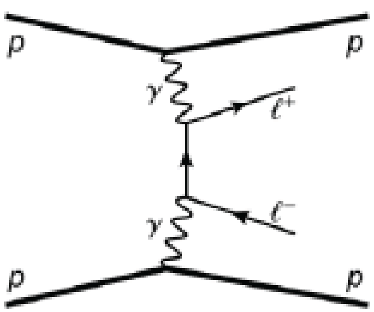
Introduction

Intact proton (or large rapidity gaps) in the final state = colorless exchange

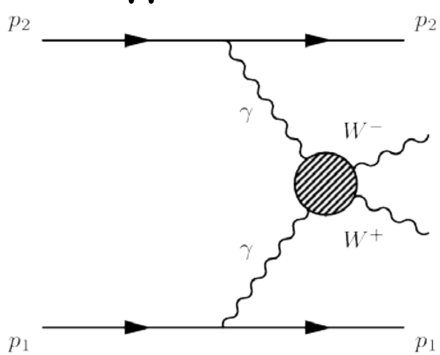
Photon-induced processes: calculated via QED

- ❖ QED Diffraction: SD, DD
- ❖ QED exclusive production (l^+l^-, W^+W^-):
- - Underlying process $\gamma\gamma \to X$ can be calculated with acc. ~2% (Based on Equivalent Photon Approach, EPA)
- - Proton absorptive corrections can reach up to 20%

$\gamma\gamma \to l^+l^-$

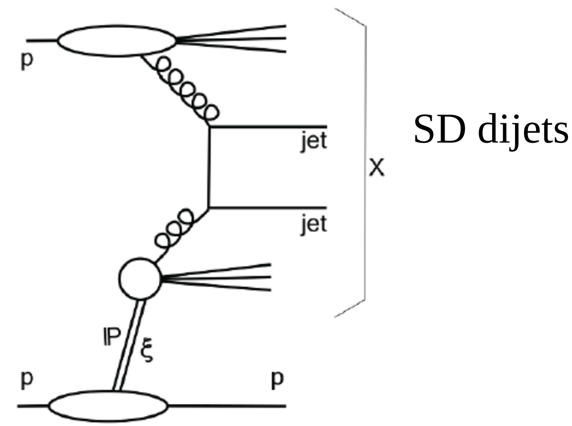


$\gamma\gamma \to W^+W^-$



Parton-induced processes: calculated via QCD

- ❖ QCD diffraction: SD, DD, DPE (Single Dissociation, Double Dissociation, Double Pomeron Exchange)
- - At hadron colliders: need to consider process-dependent soft survival probabilities
- ❖ QCD exclusive production not discussed here



❑ **The three presented ATLAS analyses have similar final states: large rapidity gaps**

In the absence of forward proton detectors, 2 approaches to suppress backgrounds

1) **Large rapidity gaps**: concentrate on low pile-up & measure large x- section processes

2) **No tracks and vertices around lepton vertex**: large pile-up & low x-section processes

Motivation

- Understand better diffraction and exclusive processes since both are often backgrounds to many LHC analyses.
- Both measured at HERA and Tevatron but cross sections are still known with a limited precision at LHC. Especially QCD (Pomeron-induced) diffraction and QCD exclusive processes need urgently an input.
- These measurements may be used in various MC tunes

PLB 754 (2016) 214

1) **Diffractive dijets:** - Provide cross sections and compare with existing models
at 7 TeV - Estimate of soft survival probability
($\mathcal{L}$ =6.8 nb^{-1})

PLB 749 (2015) 242

2) **Exclusive leptons:** - Standard candle (simple final state)
at 7 TeV - Luminosity calibration at LHC
($\mathcal{L}$ =4.6 fb^{-1}) - Alignment/Calibration of forward proton detectors (AFP, CT-PPS)

PRD 94 (2016) 032011

3) **Exclusive WW→leptons:** - Can profit from measurement of exclusive leptons
at 8 TeV - Estimate of anomalous quartic gage coupling (aQGC) γγWW
Exclusive (QCD) Higgs →WW→leptons: - Collecting first exclusive Higgs candidates
at 8 TeV fully-leptonic channel:
($\mathcal{L}$ =20.2 fb^{-1}) - least background but requires most statistics
- lowest systematics

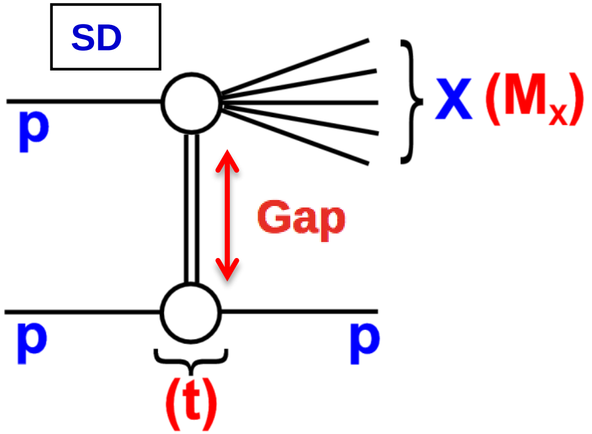
Processes involved

Analysis	Final state \ Exchange	SD	DD	DPE	Exclusive	ND / inclusive
Diffr. dijets	IP-exchange	p jj X	X jj Y	X' jj Y'	jj	jj X
Exclusive l^+l^-	γ-exchange	p l^+l^- X	X l^+l^- Y	X' l^+l^- Y'	l^+l^-	l^+l^- X
Exclusive W^+W^-	γ-exchange	p W^+W^- X	X W^+W^- Y	X' W^+W^-Y'	W^+W^-	W^+W^- X

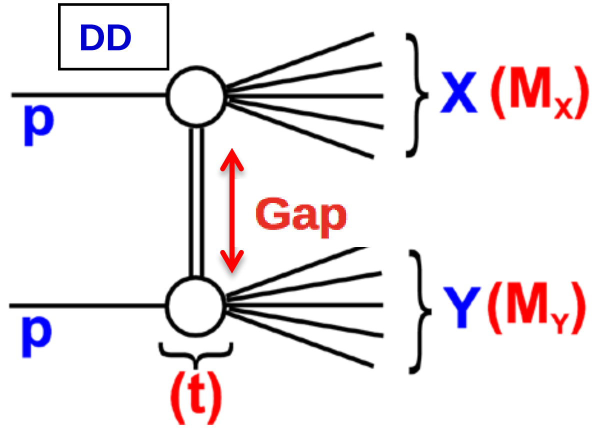
Signal Background

Backgrounds from γ (IP)-exchange to IP (γ)-exchange were found to be negligible.

Diffractive dijets: Motivation



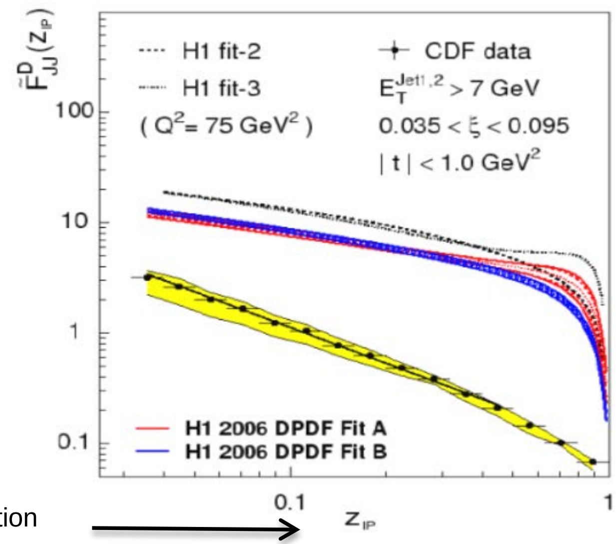
Signal



Background

Gap survival probability (S^2):

➢ Introduced to explain a big disagreement between CDF measurement and theory predictions based on measured HERA diffractive PDFs (factor of 10).



Momentum fraction of parton in Pomeron

➢ Discrepancy usually explained by rescattering of dissociated system with intact protons

What S^2 is in diffractive dijets at the LHC?

❑ Key diffractive characteristics: rapidity gap $\Delta\eta^F$

- Exchange of color singlet (Pomeron) → only remnants of Pomerons and dissociated protons, soft QCD radiation in large areas of η suppressed

- However: gaps observed also in **non-diffractive** events (explained by fluctuations in hadronization process)

Background

❑ Kinematic variables

- invariant mass of the dissociated system M_X (M_Y)
- fractional momentum loss ξ of the scattered proton:

$$\xi = (p_Z^{In} - p_Z^{Out}) / p_Z^{In} \qquad (\xi_X = M_X^2/s)$$

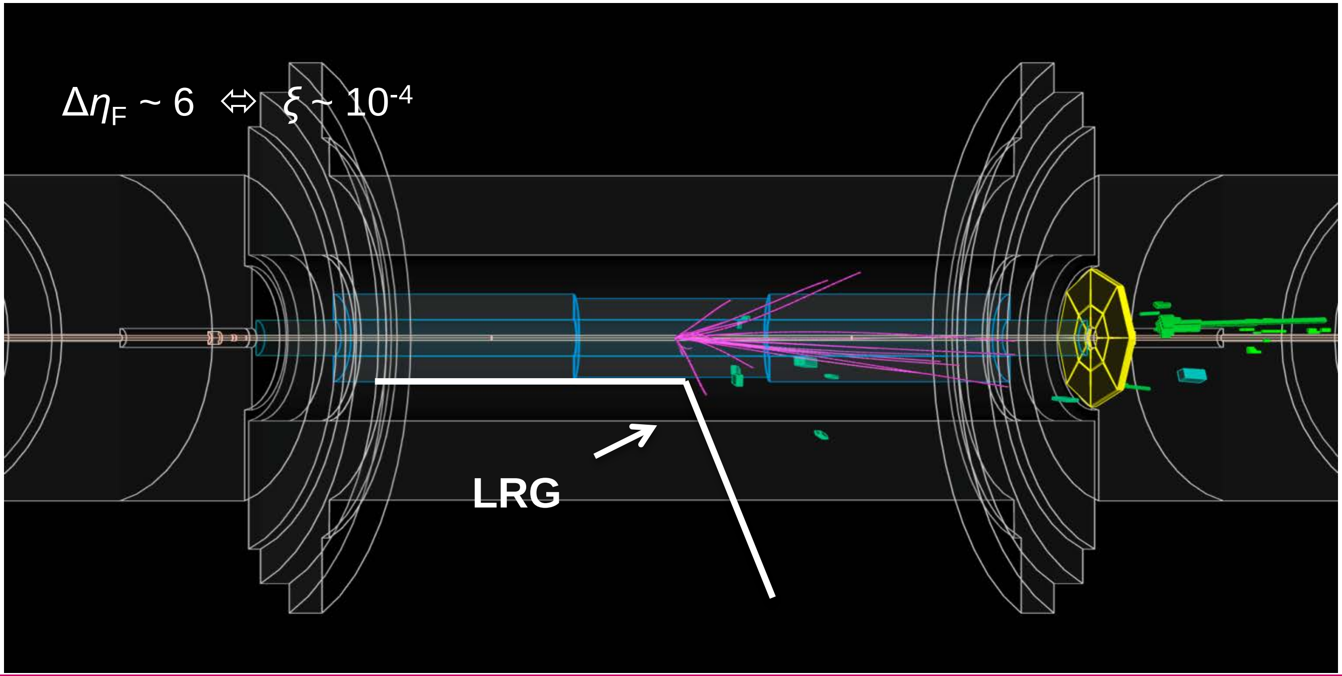
Rapidity gaps in ATLAS detector

- **Large Rapidity Gap (LRG)** : **$\Delta\eta \sim -\log \xi_X$** → small ξ_X (M_X) ~ big gap
  Region in η devoid of hadronic activity due to the exchange of colorless object (Pomeron)

- **Detector-level LRG definition : $\Delta\eta^F$**
  Largest region in η (starting at the edge of the detector $\eta = \pm 4.8$) absent of clusters and tracks

- Non-pileup environment optimal since multiple soft *pp* interactions could fill the gap

Events from early runs of 2010 (<*Nr of pile-up interactions / bunch crossing*>, < μ > ~ 0.044 – 0.144) used in the analysis

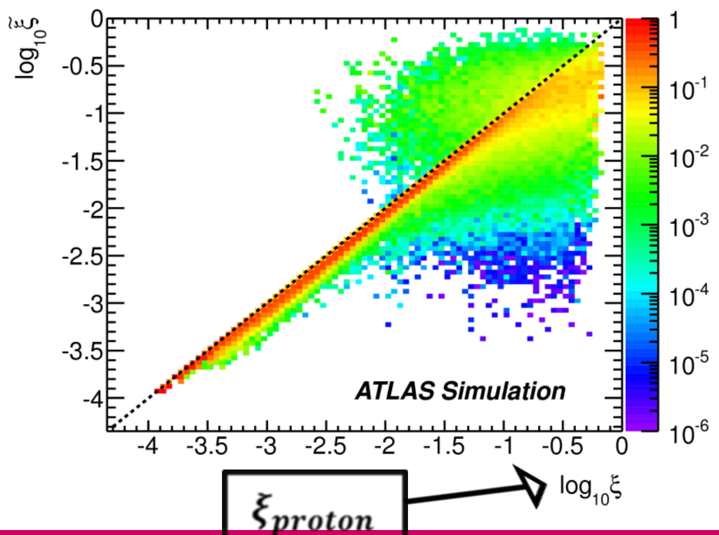


Event selection

- **Basic cuts & kinematic cuts**
  - Good primary vertex (n_{tracks}>4)
  - Jets: $p_T^{jet\ 1}$ > 20 GeV, $p_T^{jet\ 2}$ > 20 GeV, $|\eta^{jets}|$<4.4, anti-k_T R = 0.6 and 0.4
- **Pile-up suppression cut, focus on 2010 data with low pile-up** [$\mathcal{L}$ ~ 6.8 nb^{-1}]
  - no PU vertices (having n_{tracks}>1): removes ~5% of events (correction factors applied)
- **Forward gap definition ($\Delta\eta_F$)**
  - η-region devoid of activity (starting at either η=-4.8 or η=+4.8)
    - detector-level definition: tracks with p_T^{track} **> 200 MeV**

      Clusters with cell significance E_{cell}/σ_{noise} > $S_{thr}(\eta)$ (~5.5)
    - particle-level definition: $p_{ch\ (n)}^{particle}$ **> 500 (200) MeV OR** p_T **> 200 MeV**

PYTHIA 8 SD



Fractional momentum loss

ξ_{proton} = (3.5TeV – p_Z(proton))/3.5TeV

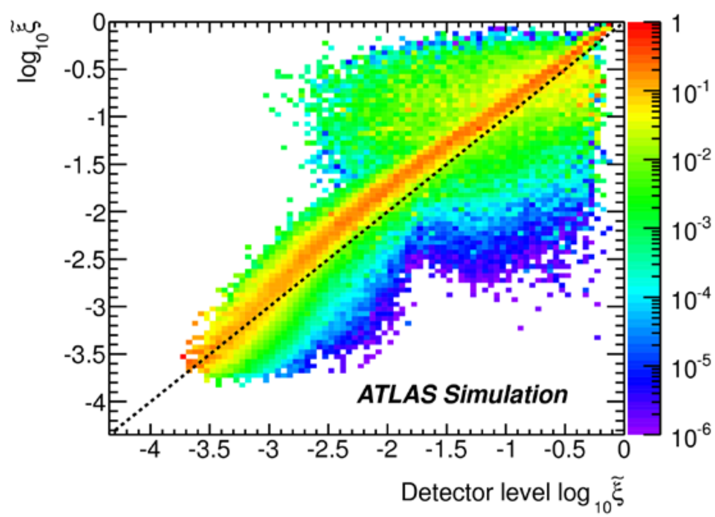
ξ estimator closer to exper. observability:

$\tilde{\xi} = \sum p_T\, e^{\pm y}$/3.5TeV

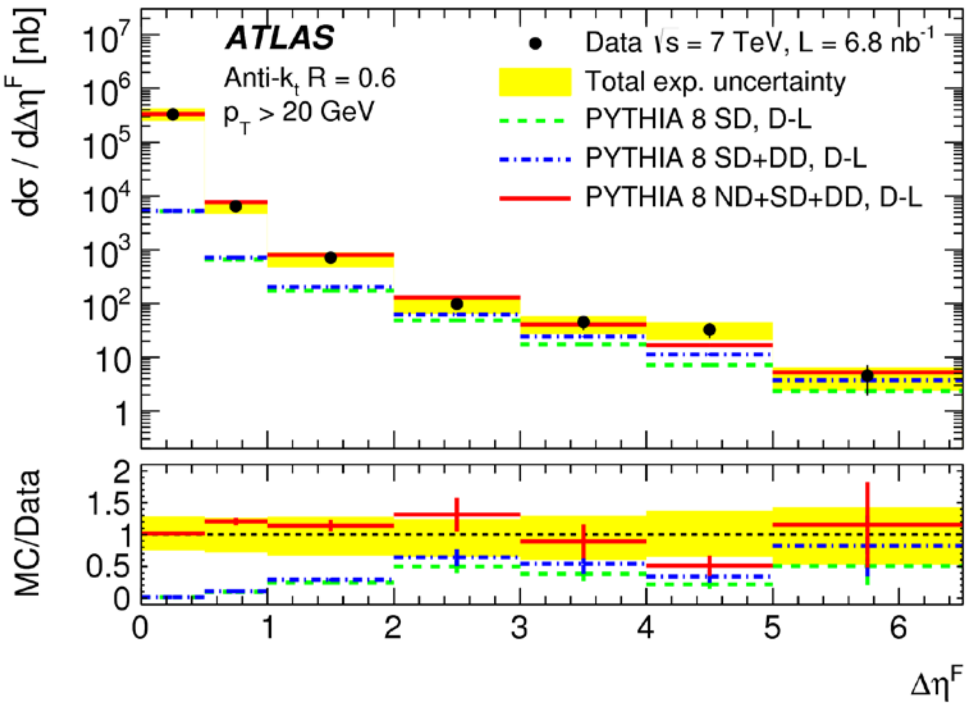
Performs well for ξ<0.01

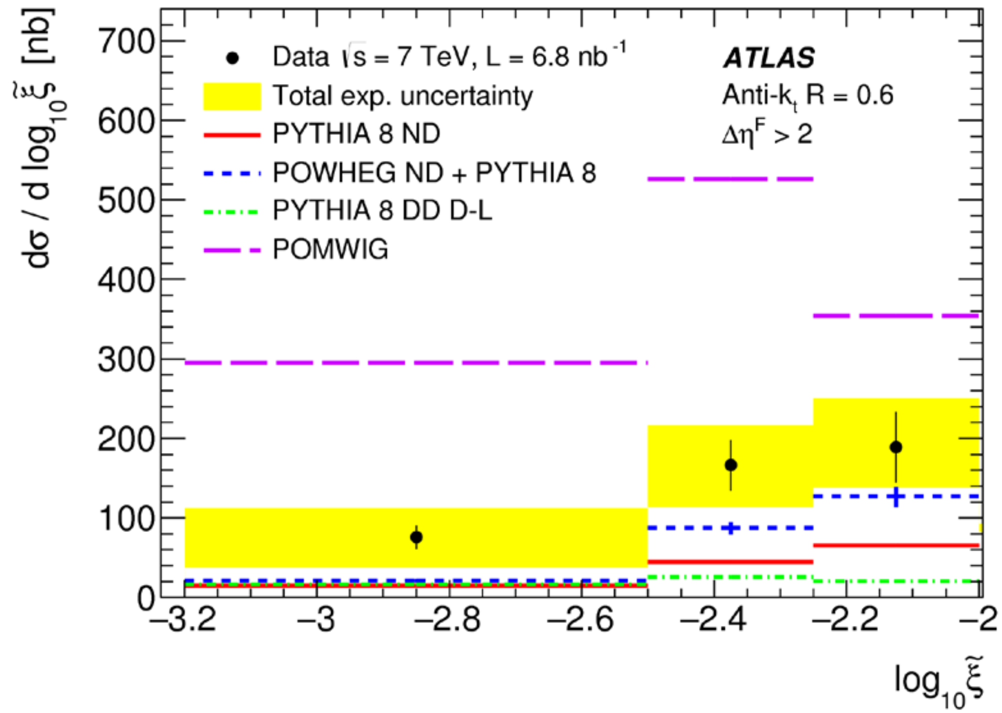
- $\tilde{\xi}$ **definition**
  - strong particle-reco level correlation with limited resolution
  - non-diagonality -> limited detector sensitivity to low energy particles

Pythia8 ND+SD+DD



Corrected data compared to various models



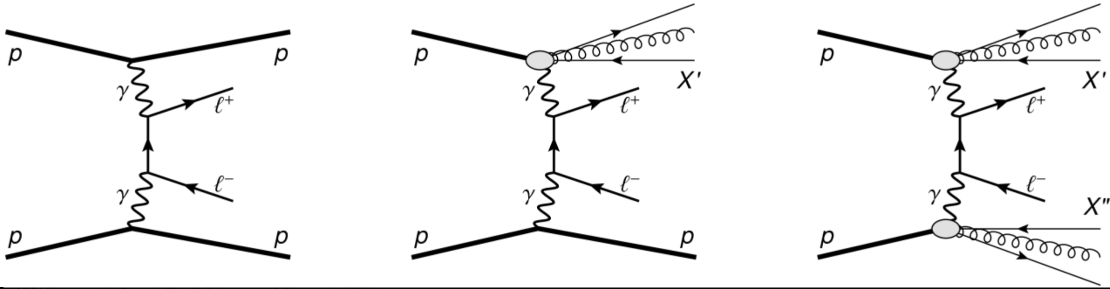


- PYTHIA8 describes data well with no need for Gap Survival factor after normalizing ND in first $\Delta\eta^F$ bin to match data and taking default SD and DD
  - Pythia8 is not a standard factorisable pomeron model
- ND contribution extends to fairly large gaps and small $\tilde{\xi}$
- *No gap plateau as observed in the inclusive gap analysis (EPJC 72 (2012) 1926)*

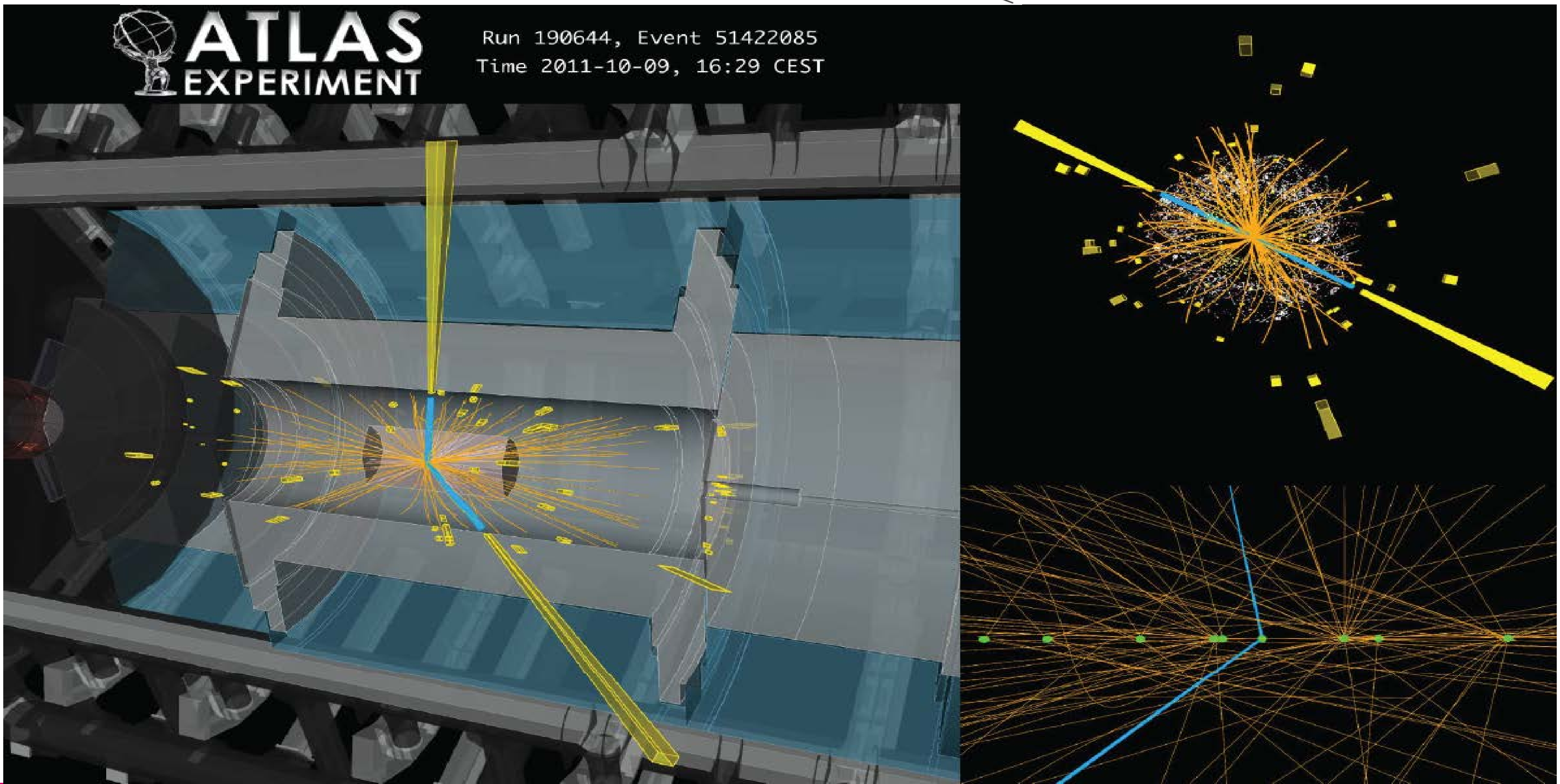
- $\tilde{\xi}$ distribution after $\Delta\eta^F$ > 2 cut: ND contribution suppressed to 20% level acc. to all available models
- Data compared to Pomwig after subtracting ND & DD from data (based on Pythia 8 D-L model) to estimate Gap Survival factor (→ S^2 is a model dependent number):

S^2 = 0.16 ± 0.04(stat) ± 0.08(syst.)
(using anti-k_T R=0.6)

Exclusive $\gamma\gamma \to l^+l^-$

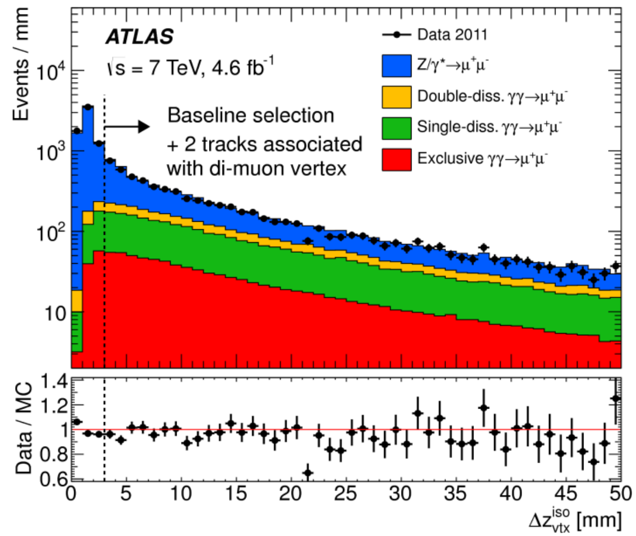


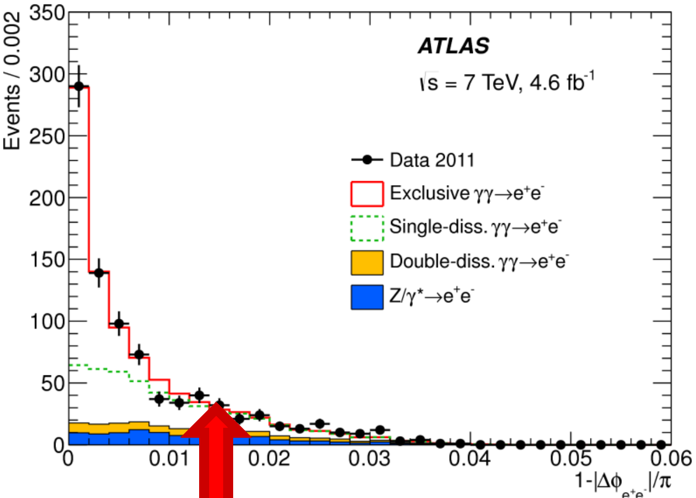
QED exclusive l^+l^- production:
Elastic, SD, DD

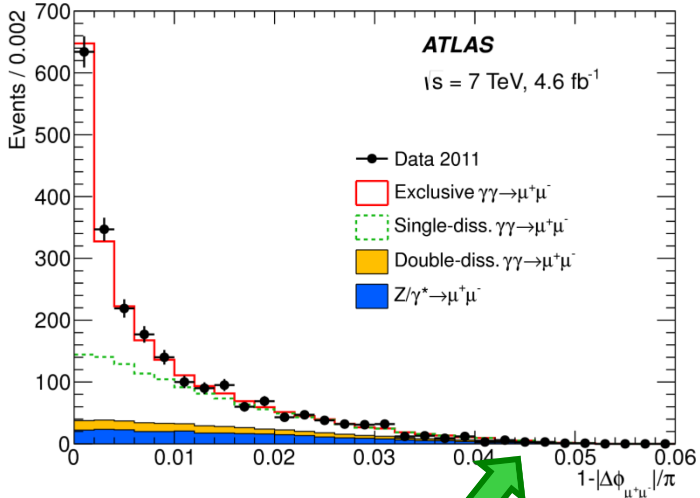


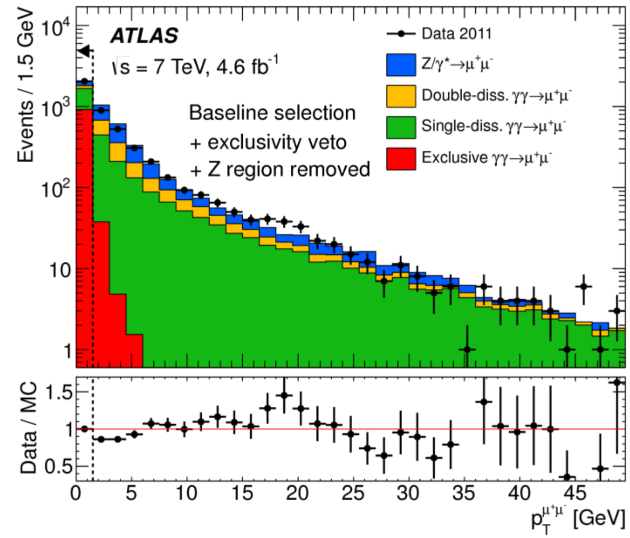
Event selection & MC scaling

Cut name	Cuts	Reduces
Muons	p_T>10 GeV, |η|<2.4, $M_{\mu\mu}$>20 GeV Isolated only	
Electrons	p_T>12GeV, |η|<2.4, M_{ee} > 24 GeV	
Exclusivity veto	No tracks with p_T>0.4GeV from l^+l^-vtx No tracks, vertices within at least 3 mm from longitudinal isolation of l^+l^- vtx	Multijets, tt, dibosons DY
Z-peak region removed	70 < M_{ll} < 105 GeV	DY
Low p_T	$p_T(l^+l^-)$ < 1.5 GeV	SD, DD









Binned maximum-likehood fit to acoplanarity distribution gives these MC scaling factors:

e^+e^- : **exclusive**: 0.863 ± 0.070(stat) ; **SD**: 0.759 ± 0.080(stat) In agreement with KMR [EPJ C76, nr.1 9 (2016)]

$\mu^+\mu^-$: **exclusive**: 0.791 ± 0.041(stat) ; **SD**: 0.762 ± 0.049(stat) [Other processes no scaled]

Results

Measured fiducial x-section for exclusive $\gamma\gamma \rightarrow l^+l^-$=
MC scaling factor for exclusive x predicted fiducial x-section for exclusive (based on EPA)

$\sigma_{excl}\ (\gamma\gamma\rightarrow e^+e^-)$ **= 0.428 ± 0.035(stat) ± 0.018(syst) pb**

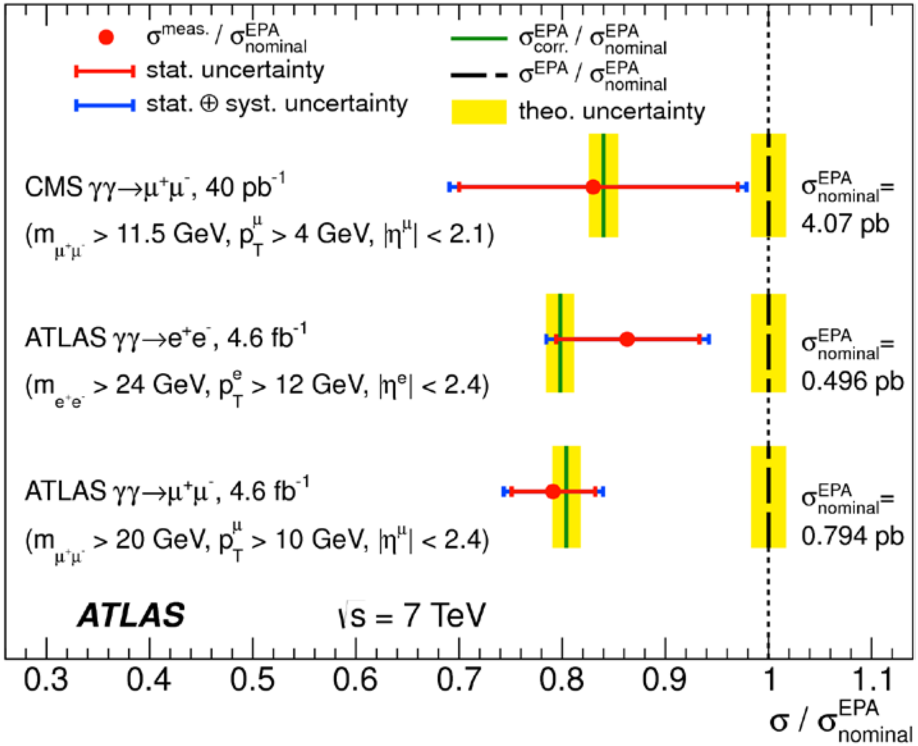
$\sigma_{excl}\ (\gamma\gamma\rightarrow \mu^+\mu^-)$ **= 0.628 ± 0.032(stat) ± 0.021(syst) pb**

Most appropriate is to compare these with x-sections based on EPA and corrected for finite size of proton (absorptive corrections) [PLB 741 (2015) 66] {~20%}:

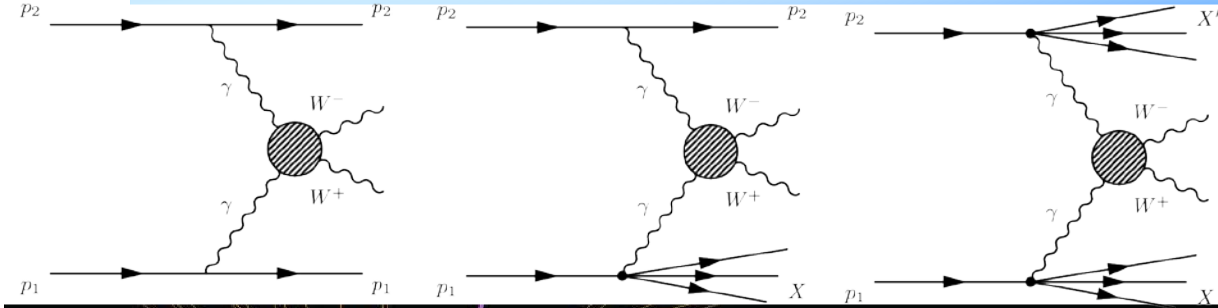
$\sigma_{excl}\ (\gamma\gamma\rightarrow e^+e^-)$ (EPA, corr.) = 0.398 ± 0.007(theor) pb

$\sigma_{excl}\ (\gamma\gamma\rightarrow \mu^+\mu^-)$ (EPA, corr.) = 0.638 ± 0.011(theor) pb

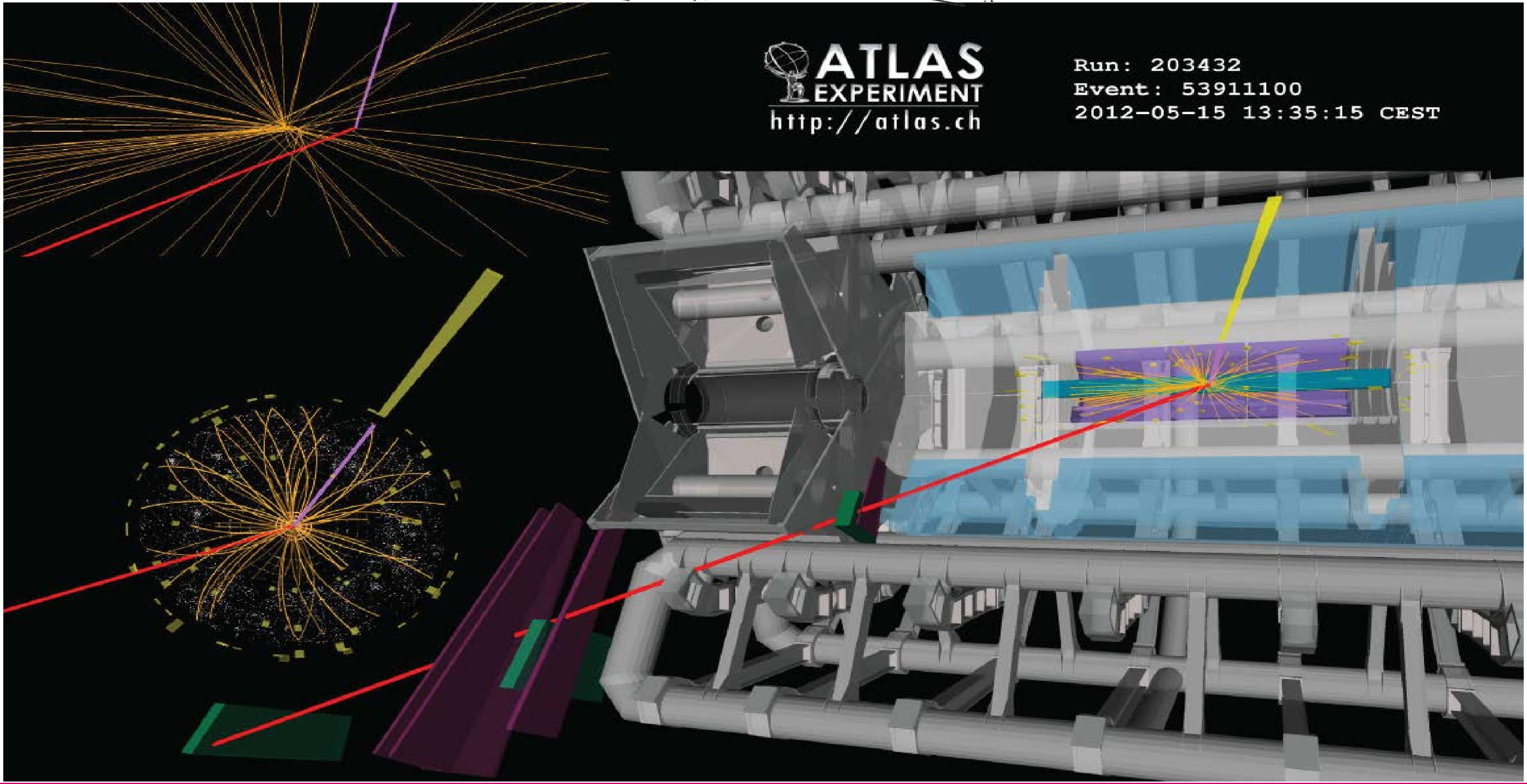
- ❑ Good agreement with theory predictions (based on EPA) after including absorptive corrections
- ❑ Improved precision and good agreement with CMS measurement



Exclusive $\gamma\gamma \rightarrow W^+W^-$



QED exclusive W^+W^- production:
Elastic, SD, DD

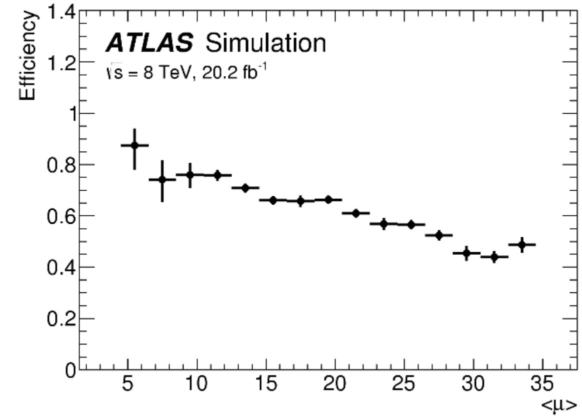


Event selection, validation & MC scaling

- $W^+W^- \rightarrow e\nu\mu\nu$ decays considered
- Complete set of cuts:

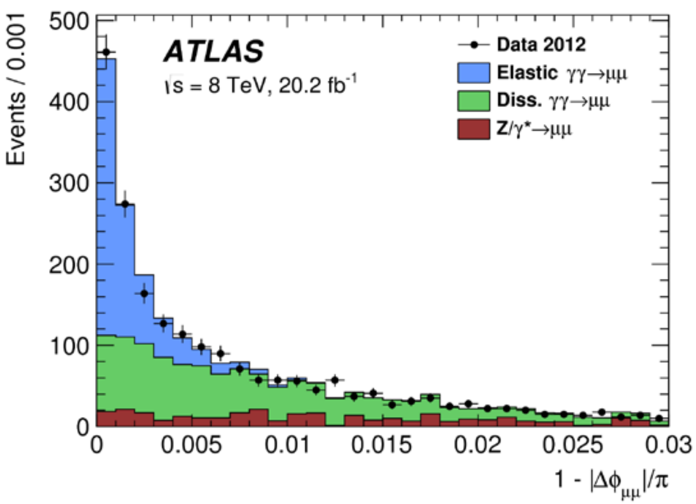
Variable	Excl W^+W^-	Excl Higgs
p_T^{lep}	> 25, 20 GeV	> 25, 15 GeV
$m_{e\mu}$	> 20 GeV	> 10 GeV
$p_T^{e\mu}$	> 30 GeV	> 30 GeV
Δz_0^{iso}	1mm	1mm
$p_T^{e\mu}$ (aQGC)	> 120 GeV	-
$m_{e\mu}$	-	< 55 GeV
$\Delta\phi_{e\mu}$	-	< 1.8
m_T	-	< 140 GeV

Efficiency of the exclusivity selection (dilepton vtx longit. isolation) as a function of <μ>:

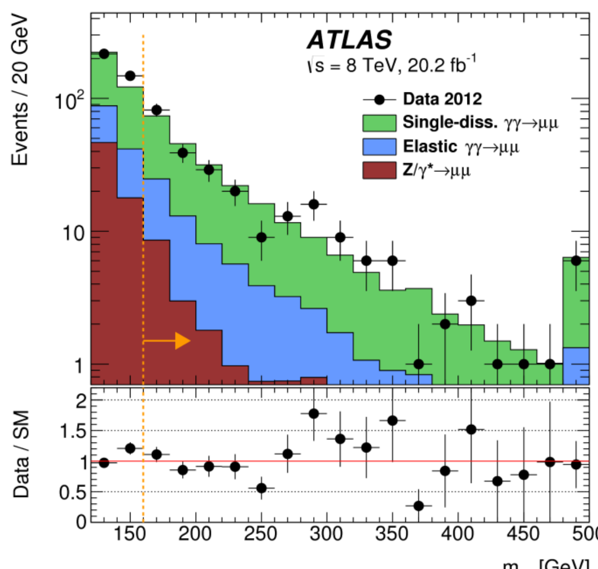


<μ>~20.7, <Eff>~58%

Validation using $\gamma\gamma \rightarrow l^+l^-$:
Ratio of observed elastic to predicted elastic (nominal EPA): 0.76 +- 0.04(stat)+-0.10(syst)



Non-existent simulation of SD and DD $\gamma\gamma\rightarrow W^+W^-$ is accounted for by multiplying predicted elastic $\gamma\gamma\rightarrow W^+W^-$ events by a factor



$$f_\gamma = \left.\frac{N_{\text{Data}} - N_{\text{Background}}^{\text{POWHEG}}}{N_{\text{Elastic}}^{\text{HERWIG++}}}\right|_{m_{\mu\mu}>160\text{ GeV}} =$$

$$3.30 \pm 0.22(\text{stat.}) \pm 0.06(\text{sys.})$$

obtained using elastic $\gamma\gamma\rightarrow l^+l^-$ events at $m_{ll} > 160$ GeV [predictions by Herwig++]

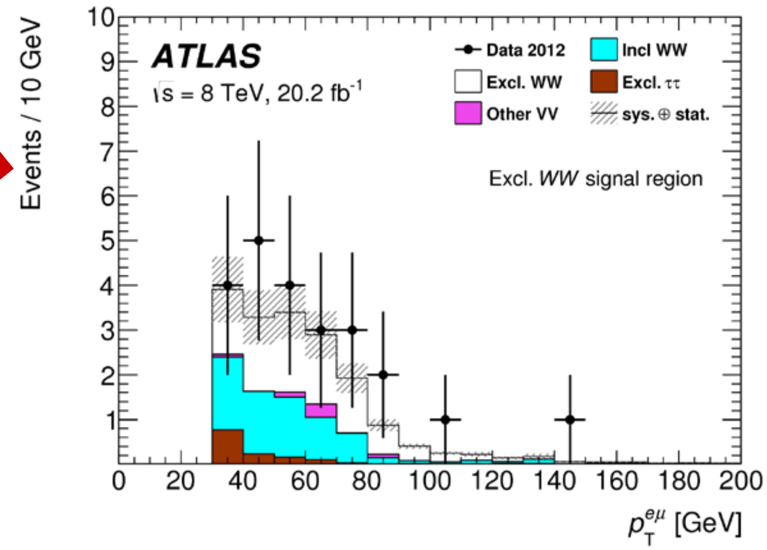
In agreement with KMR [1601.03772[hep-ph]]

Results: SM exclusive $\gamma\gamma \to W^+W^-$

❑ $\gamma\gamma \to W^+W^-$ cross section

1) Exclusive event yields:

Data = 23, Signal = 9.3 ± 1.2, Background = 8.3 ± 2.6



2) Measured cross section extrapolated to the full $W^+W^- \to e\mu X$ phase space:

$\sigma_{excl}(\gamma\gamma \to W^+W^-)$ = 6.9 ± 2.2(stat) ± 1.4(syst) fb

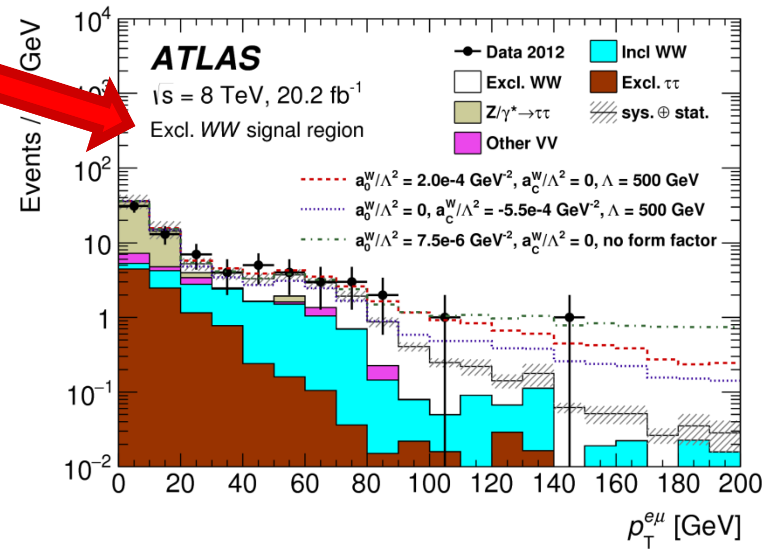
The background-only hypothesis corresponds to significance of 3.0

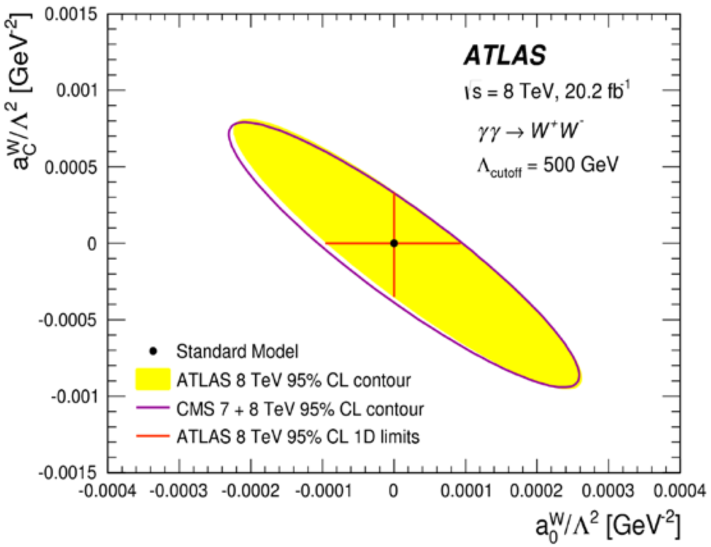
3) **Predicted cross section [by Herwig++] = 4.4 ± 0.3 fb**

❑ Limits on anomalous quartic gauge couplings aQGC

1) Event yields for $p_T(e\mu) > 120$ GeV:

Data = 1.0, SM Signal = 0.37 ± 0.04, Background = 0.37 ± 0.13





2) Limits on aQGC more stringent than published result by OPAL, D0 and CMS

Compatibility with CMS limits

Results: Exclusive Higgs

❑ **Exclusive Higgs → $W^+W^- \to e^{\pm}\mu^{\mp}X$**

1) Exclusive Higgs event yields:
Data = 6, Signal = 0.023 +- 0.003, Background = 3.0 +-0.8

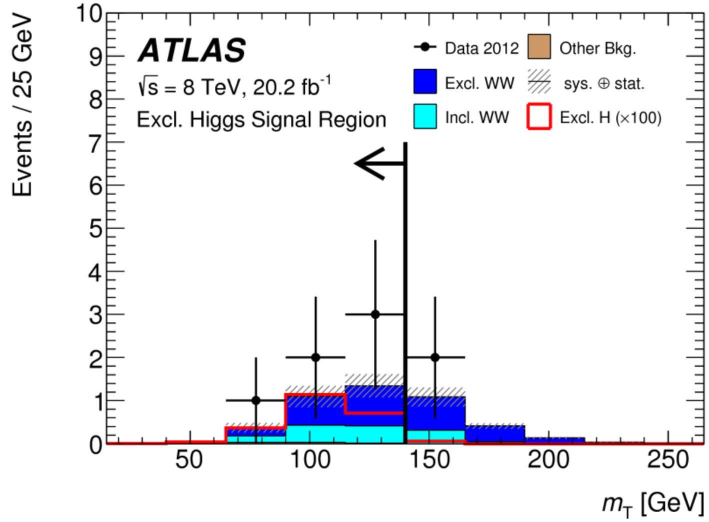
Signal = just elastic Higgs, obtained using KMR calculations (gluon-induced production)

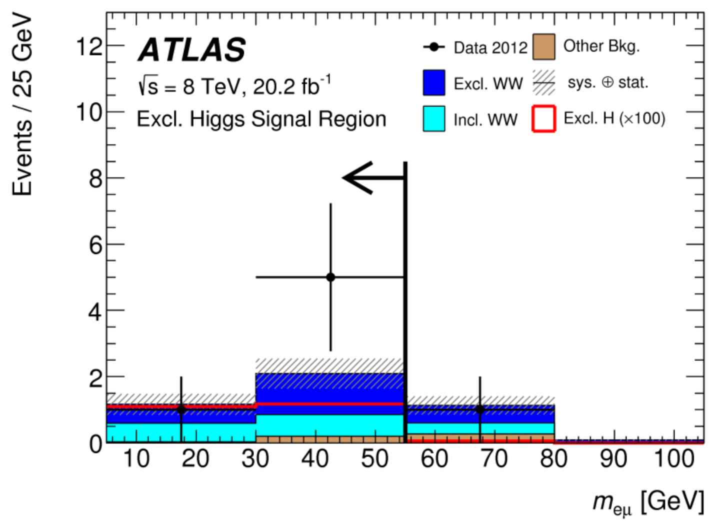
Background = dominantly exclusive W^+W^- and inclusive W^+W^-
Exclusive W^+W^- background obtained by scaling Herwig++ by f_γ=3.3

2) Yields converted to upper limits of the exclusive Higgs boson **total** production cross section using CLs technique:

σ < 1.2 pb at 95% CL (Observed)
σ < 0.7 pb at 95% CL (Expected)

σ (Higgs production by KMR) ~ 3 fb → the upper limit is 400x higher





Summary

❑ Diffractive dijets:

➢ **rapidity gap and ξ measurement at a hard scale:**
 - Measurement sensitive to hard diffractive processes
 - No gap plateau is observed – contrary to the inclusive gap analysis

➢ **Gap survival probability** S^2 = 16 ± 4 (stat.) ± 8 (syst.) % [using anti-kt R=0.6]
 (model dependent number in the context of Pomwig and Pythia 8)
 - Pythia8 ND prediction extends to very large gaps and small ξ → no need for S^2 to describe the ATLAS data

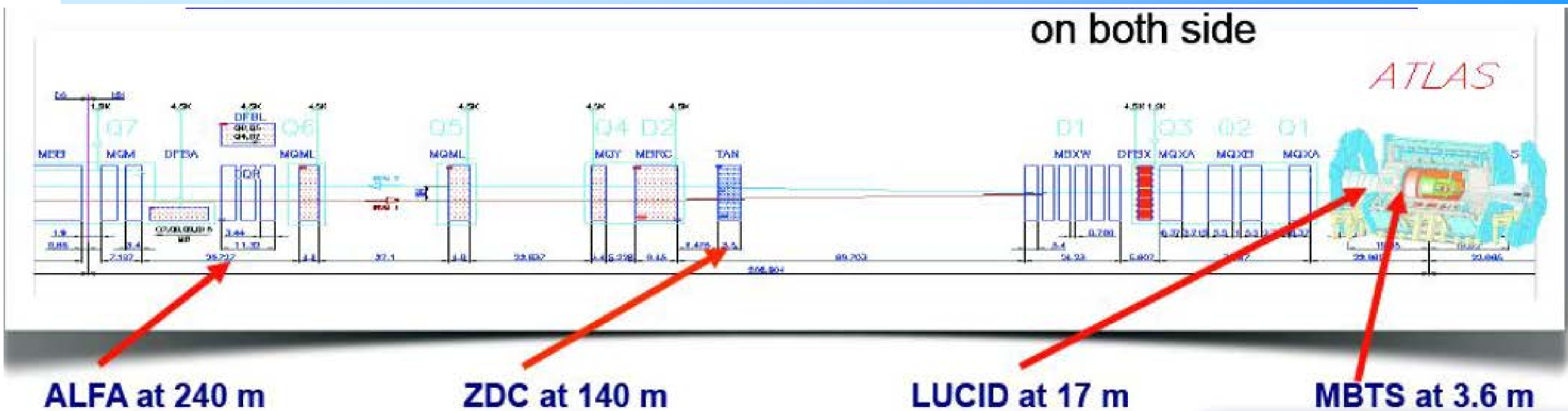
❑ Exclusive (Photon-induced) processes:

➢ $\gamma\gamma\rightarrow l^+l^-$:
 - Cross sections measured and the necessity of absorptive corrections (~20%) to EPA calculations confirmed

➢ $\gamma\gamma\rightarrow W^+W^-$:
 - Evidence (significance of 3.0) of SM $\gamma\gamma\rightarrow W^+W^-$ process obtained
 - Anomalous quartic gauge couplings: no excess seen but limits improved
 - Exclusive Higgs$\rightarrow W^+W^-$: first observed upper limits for the total x-section of Higgs prod.

B A C K U P S L I D E S

ATLAS Forward detectors

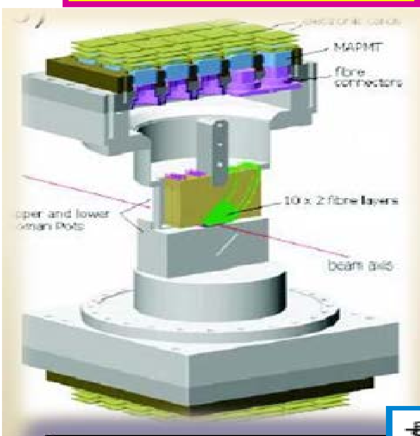


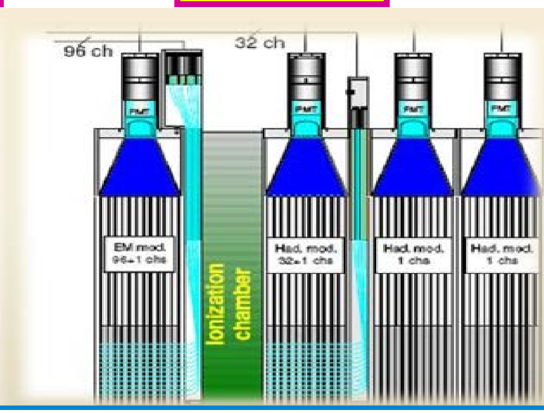
10.6 < | η | < 13.5

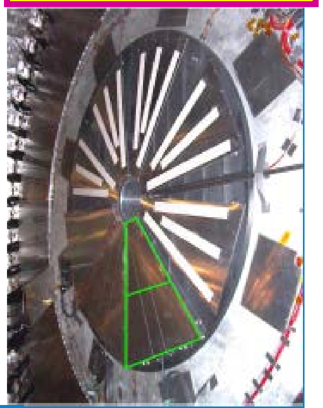
| η | > 8.3

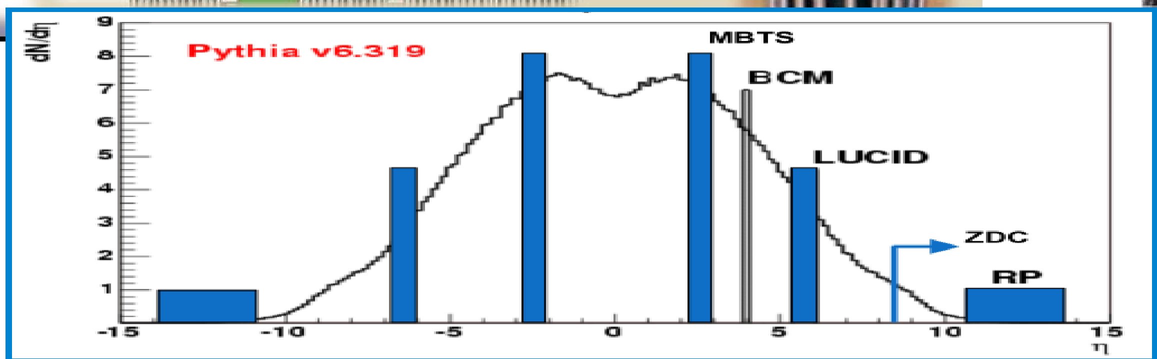
5.6 < | η | < 5.9

2.1 < | η | < 3.8

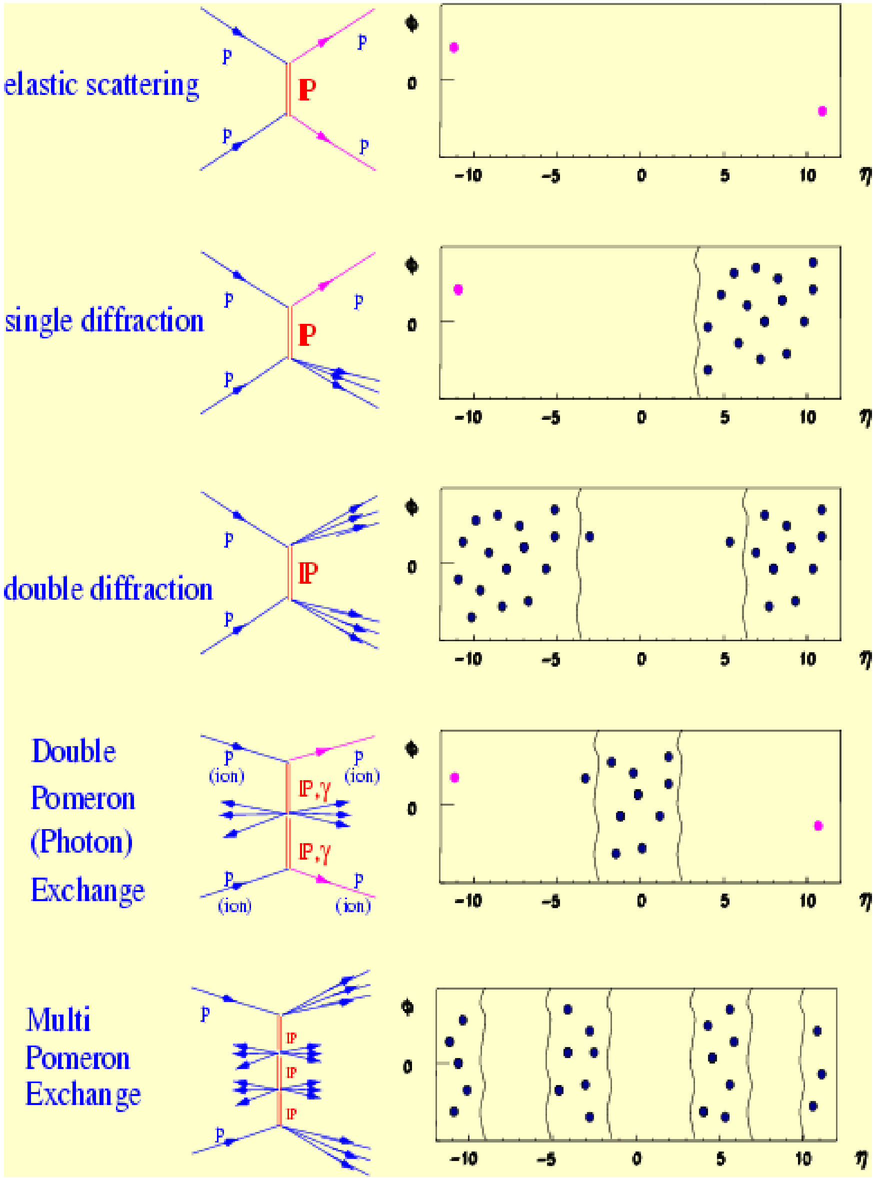








Diffraction at LHC:



- Forward proton tagging in special runs with ALFA

- Combined tag of proton in ALFA on one side (accompanied by large gap) and remnants of dissociated proton in LUCID on the other side.

In the world w/o ALFA: rely on gaps

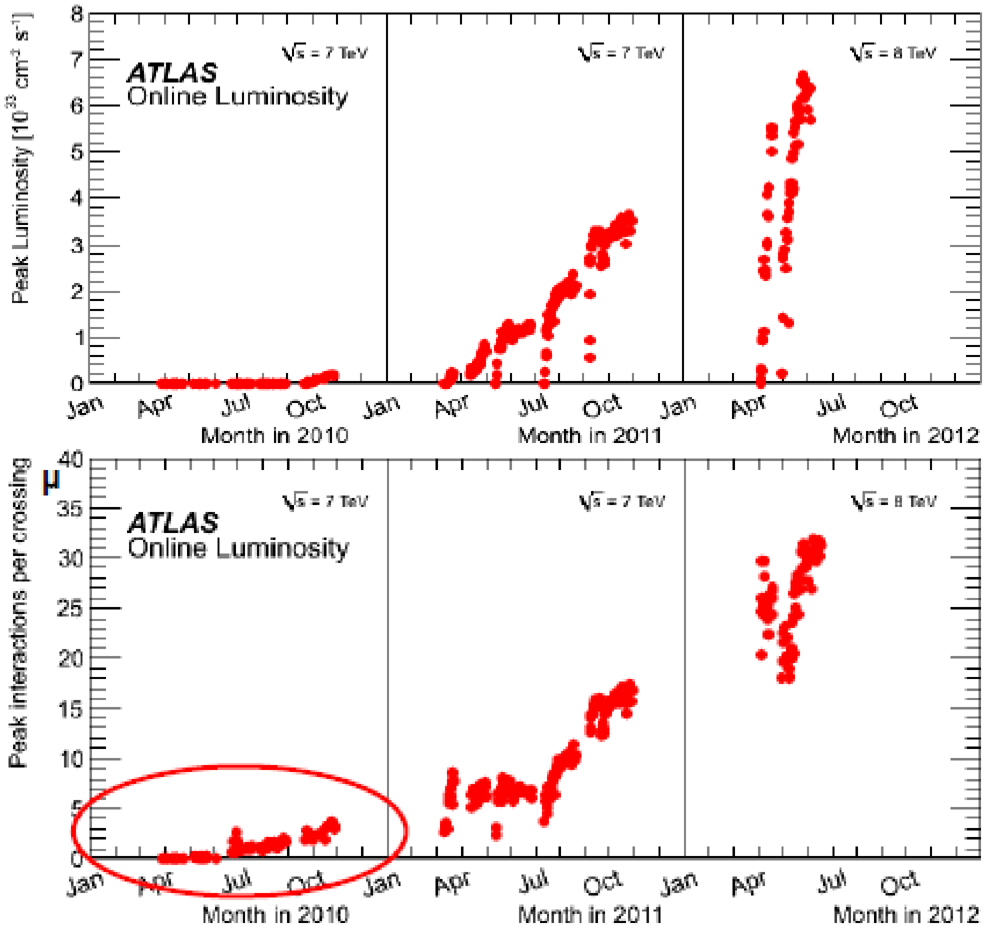
- Central rapidity gap in EM/HAD calorimeters ($|\eta|<3.2$) and inner detector ($|\eta|<2.5$)

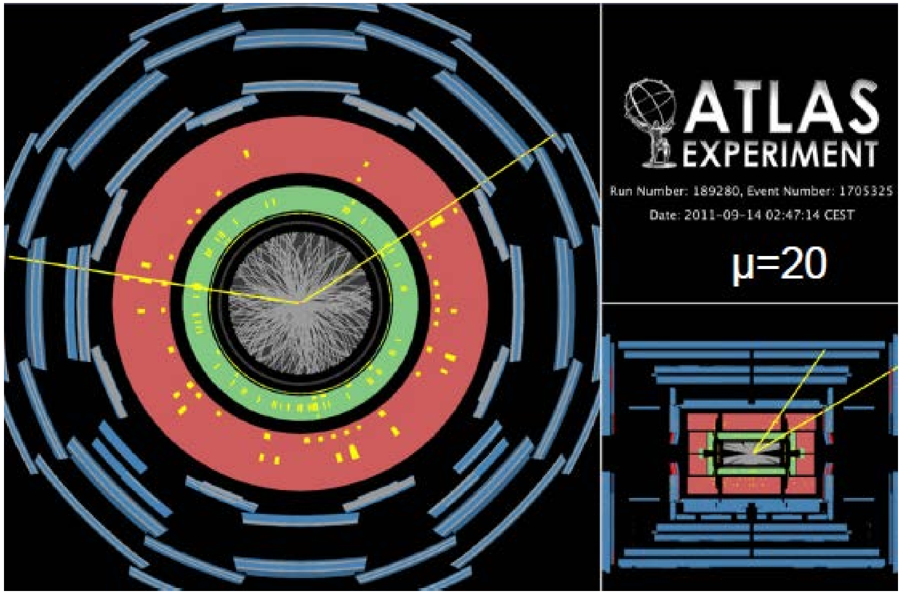
- Rapidity gaps on both sides of IP:

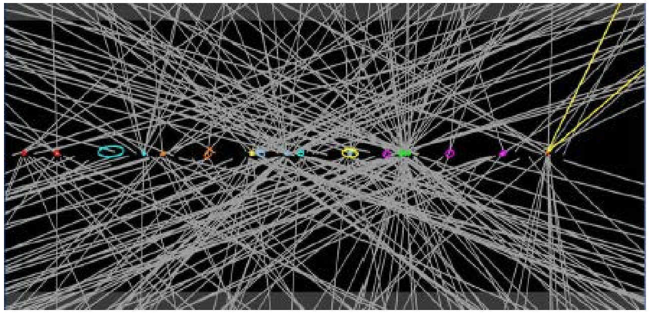
Double Pomeron Exchange: parton from Pomeron brings a fraction β out of ξ into the hard subprocess → Pomeron remnants spoil the gaps

Central exclusive production: $\beta = 1$ → no Pomeron remnants

Diffraction needs very low Pile-up







Pile-up = soft particles sitting on top of the hard-scale event, influencing efficiencies of various finding algorithms (Primary vertex, triggers, jets and other usual objects).

Gap Survival Probability

S^2 = [(Data – ND) * SD/(SD+DD)] / (Pomwig/1.23)

ND from PYTHIA8
Ratio SD/(SD+DD)
from PYTHIA8

$S^2 = 0.16 \pm 0.04(\text{stat}) \pm 0.08(\text{syst.})$
(using anti-k_T R=0.6)

Factor 1.23
removes DD
contrib. to
x-sec in Pomwig

- S^2 estimated from the lowest $\tilde{\xi}$ bin: $-3.2 < \log_{10}\tilde{\xi} < -2.5$
  - $\Delta\eta^F$ distribution not used because of larger stat. unc. and worse Data/ND suppression
  - Very model dependent number
- Systematic uncertainties for S^2:
  - Based on systematics seen in data
  - Other models? ND: Powheg NLO ND instead of Pythia8 LO ND : **S^2 = 0.15 ± 0.04**

    - HERWIG++ ND produces bumps and too large gaps

    SD,DD: Phojet does not contain hard diffraction

    - PYTHIA8 the only to model hard diffraction and separating SD from DD
- Result for anti-k_t $R = 0.6$ is regarded as the best estimate of S^2
  - Smaller statistical uncertainties
  - Smaller dependence on ND prediction (0.6: Data/ND ~ 5;   0.4: Data/ND ~3)
  - Compatible with result from the CMS Collaboration: **S^2 = 0.12 ± 0.04**

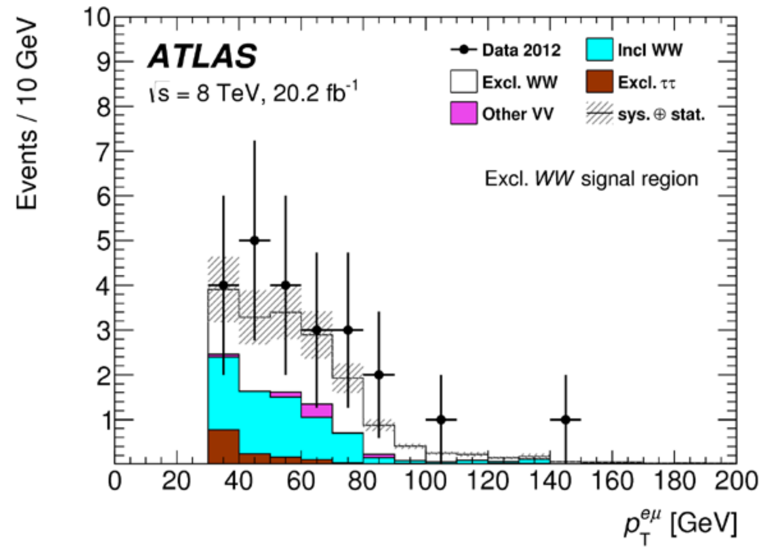
Results: SM exclusive $\gamma\gamma \to W^+W^-$

❑ $\gamma\gamma \to W^+W^-$ cross section

1) Exclusive event yields:

Data = 23, Signal = 9.3 ± 1.2, Background = 8.3 ± 2.6

[Signal = elastic + QED SD & DD events, obtained using factor f_γ=3.3]



2) Measured cross section extrapolated to the full $W^+W^- \to e\mu X$ phase space

σ = (Data-Background)/(LεA), L=20.2 fb^{-1}, εfficiency=0.37, Acceptance=0.28

σ = 6.9 ± 2.2(stat) ± 1.4(syst) fb

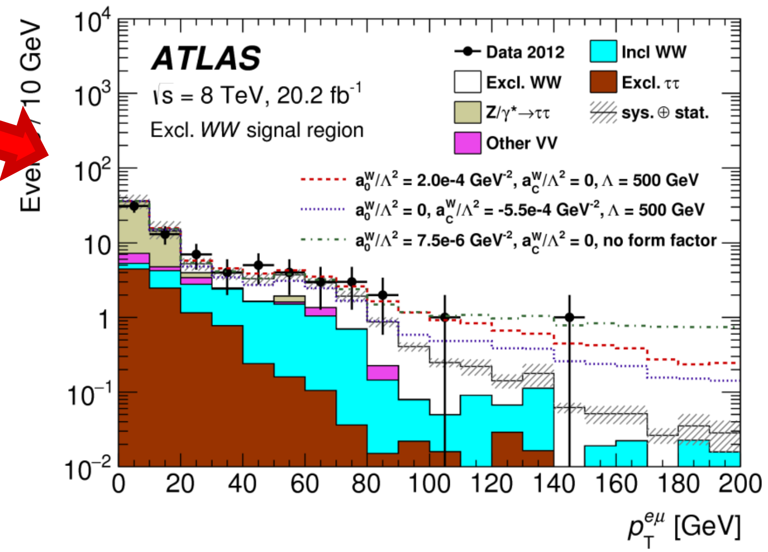
The background-only hypothesis corresponds to significance of 3.0

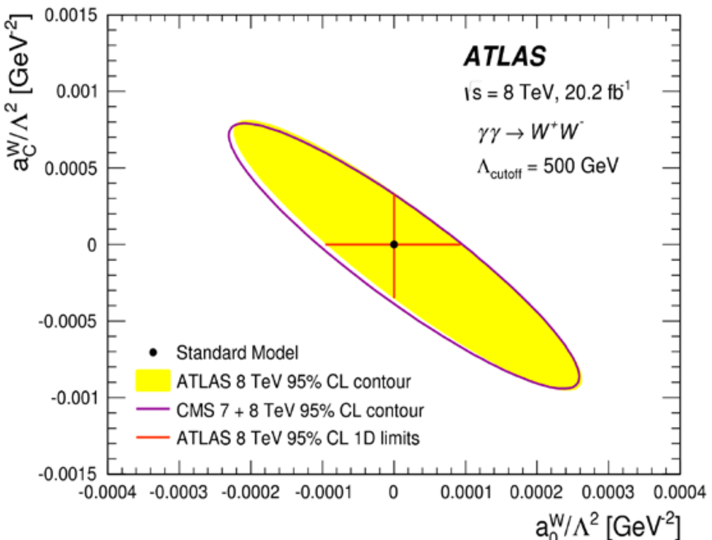
3) **Predicted cross section [by Herwig++] = 4.4 ± 0.3 fb**

❑ Limits on anomalous quartic gauge couplings aQGC

1) Event yields for $p_T(e\mu)$ > 120 GeV:

Data = 1.0, SM Signal = 0.37 ± 0.04, Background = 0.37 ± 0.13





2) Limits on aQGC more stringent than published results from OPAL, D0 and CMS.

Compatibility with CMS limits