Soft physics at ATLAS and CMS

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On behalf of the ATLAS and CMS Collaborations

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Soft physics

Soft domain of the strong interaction

- Soft interactions: interactions with low transverse momentum exchange where perturbative approach is not applicable
- Soft phenomena approached with phenomenological methods
- Total and inelastic *pp* cross sections dominated by soft interactions

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{inel}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{Diffractive}} + \sigma_{\mathrm{nonDiffractive}}$$

- Area includes:
  - Total & inelastic *pp* cross sections
  - Diffraction (indicated by rapidity gaps)

  } This talk
  - Underlying event
  - Multi-parton interactions
  - Hadronization

  } Talks by S. Martin-Haugh, E. Kryshen
- Source of crucial information for Monte Carlo tunes needed to properly simulate ~all processes studied at LHC

@7 TeV:
σ_{inel} : ~75% of σ_{tot}
$\sigma_{\mathrm{Diffractive}}$: ~30% of σ_{inel}
$\sigma_{\mathrm{nonDiffractive}}$ has soft and hard components

CERN-EP-2018-004

CMS: Inelastic *pp* cross section

- $\sqrt{s} = 13$ TeV, using 2015 low-pileup LHC runs with average pileup between 0.05 and 0.54
- Trigger on filled bunch crossings (empty/single bunch triggers to collect background events)
- Offline selection: energy deposits above 5 GeV in a forward calorimeter, |η| > 3.0
  - Noise-subtracted fraction of events above 98.5%
  - Central exclusive production negligible
  - Two data sets with different phase space coverage and detector configuration

	Forward detector	Pseudorapidity	M_X , M_Y	$\xi = M^2/s$	Magnetic field	Lumi
1	Forward hadron (HF)	3.0<|η|<5.2	$M_{X,Y}$>13 GeV	$\xi > 10^{-6}$	B = 3.8 T	41 μb^{-1}
2	HF and CASTOR	3.0<|η|<5.2 and -6.6<η<-5.2	M_x>4.1 GeV, M_Y>13 GeV	$\xi_X > 10^{-7}$, $\xi_Y > 10^{-6}$	B = 0 T	28 μb^{-1}

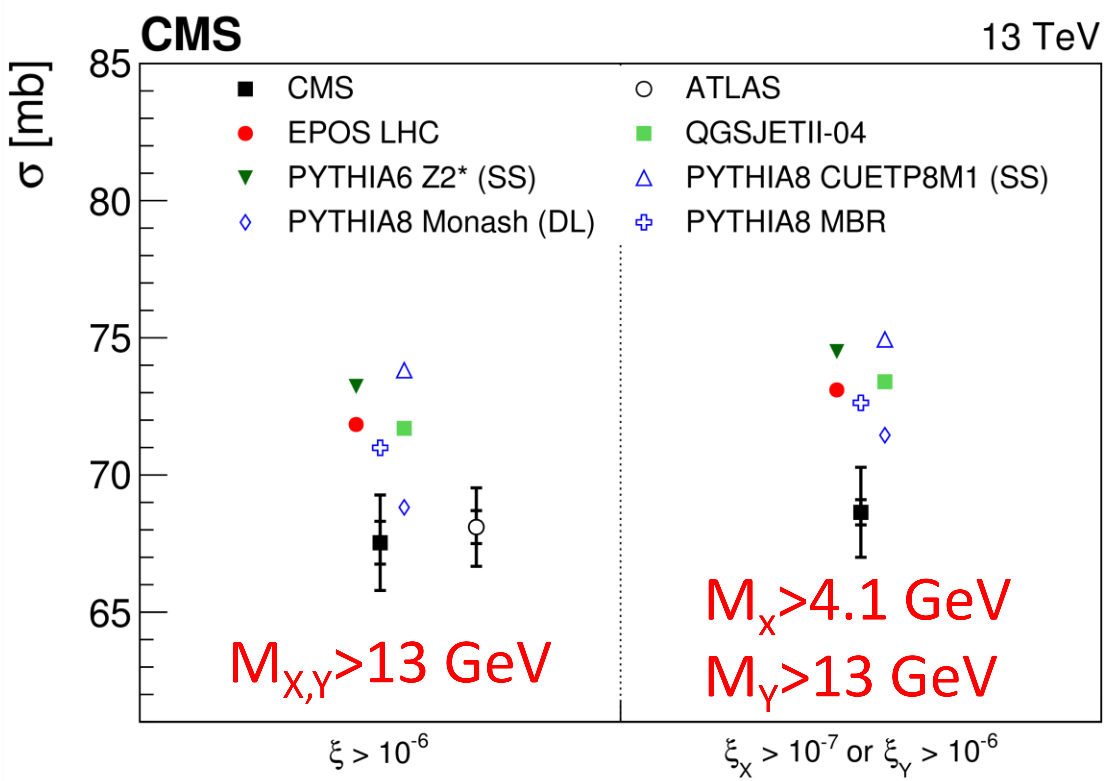
- Uncertainty dominated by systematics of the integrated luminosity measurement

	$\sigma(\xi > 10^{-6})$ (mb)	$\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ (mb)
Model dependence	0.68	0.39
HF energy scale uncertainty	0.35	0.14
CASTOR energy scale uncertainty	—	0.04
Run-to-run variation	0.15	0.14
Total	0.78	0.45
Integrated luminosity uncertainty	1.55	1.58

CERN-EP-2018-004

CMS: Inelastic *pp* cross section

- Fiducial cross sections compared between two phase space regions
- Region $10^{-7} < \xi < 10^{-6}$ ($4.1 < M_X < 13$ GeV) probed for the first time
- Compatible results for ATLAS and CMS, predictions overshoot the data



Relative cross section increase in %	
Data	1.64 ± 0.53
EPOS LHC	1.76
QGSJETII-04	2.36
PYTHIA 6 Z2* (SS)	1.74
PYTHIA 8 CUETP8M1 (SS)	1.52
PYTHIA 8 Monash (DL)	3.83
PYTHIA 8 MBR	2.32

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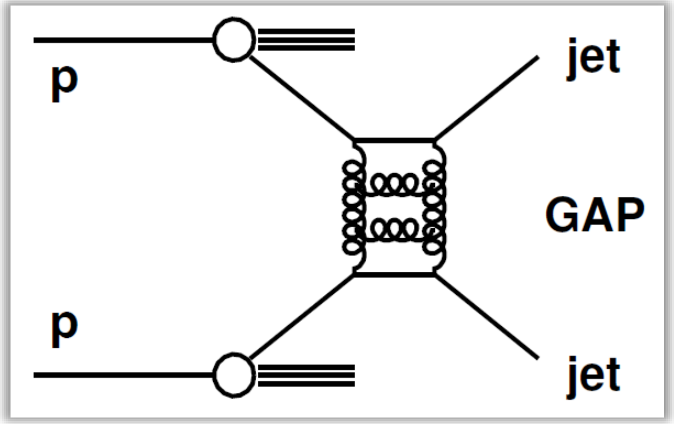
CMS: dijets with a large rapidity gap

- Data collected in 2010 at $\sqrt{s} = 7$ TeV, with low pileup <μ> = 1.16 … 1.6, L=8 pb^{-1}
- Anti-k_T jets with $p_T^{jet} > 40$ GeV, $1.5 < |\eta^{jet}| < 4.7$, two leading-p_T jets on opposite sides of the detector: $\eta^{jet1}\eta^{jet2} < 0$
- Charged particle multiplicity N_{tracks} is studied for $p_T^{track} > 0.2$ GeV in the range $|\eta^{track}| < 1.0$



- Mechanisms to generate gap topology (N_{tracks}=0 or 1 or 2):
  - Color singlet exchange (CSE) between colliding partons (gluon ladder); modeled with HERWIG
    - Tracks may be produced by radiation/interaction of spectator partons – defines gap survival probability
  - Fluctuation in the radiation and hadronization in inclusive dijet production (excluding CSE); modeled with Pythia6

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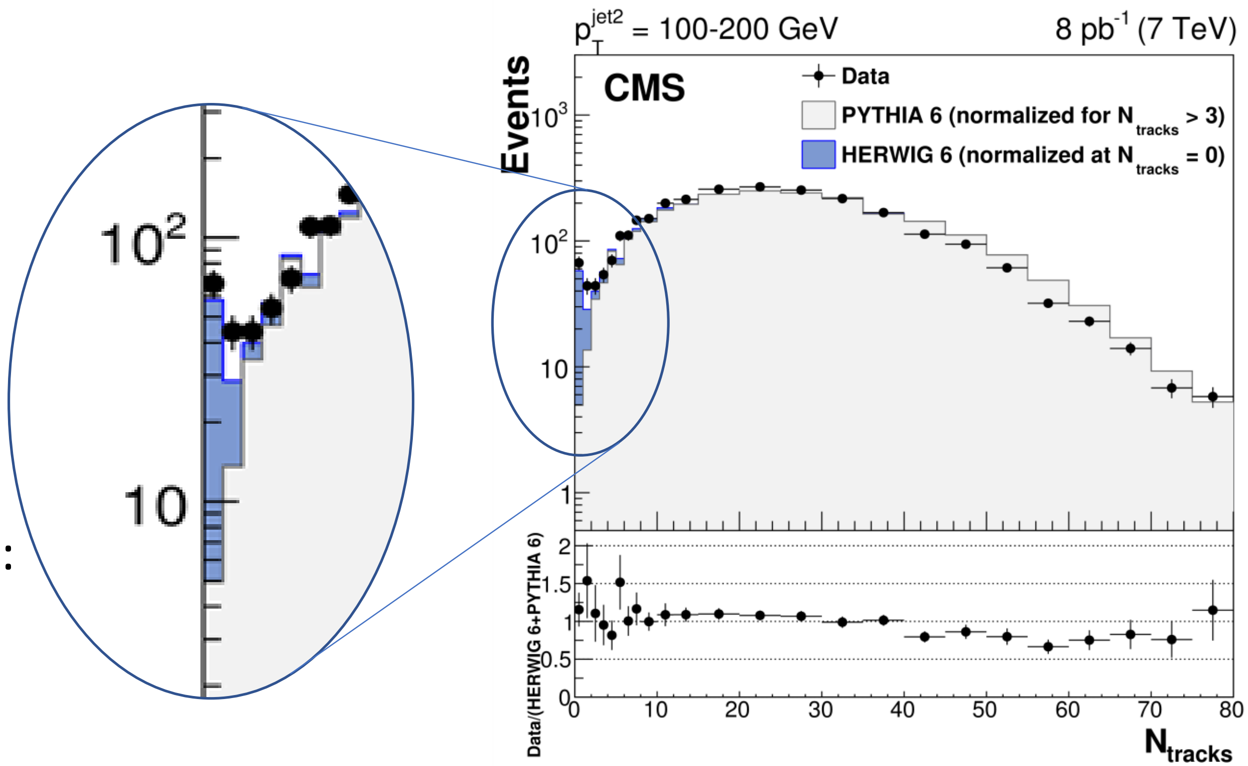
CMS: dijets with a large rapidity gap

- PYTHIA6 (no CSE) normalized to data in the region N_{tracks}>3
- HERWIG6 (includes CSE) normalized to data in the region N_{tracks}=0
- HERWIG6 agrees with the data N_{tracks} distribution
- The relative amount of CSE-initiated events is quantified:

$$f_{\mathrm{CSE}} = \frac{N^{\mathrm{F}}_{\mathrm{events}} - N^{\mathrm{F}}_{\mathrm{non\text{-}CSE}}}{N_{\mathrm{events}}}$$



N^{F}_{events} - number of events in the first multiplicity bins (N_{tracks}< 2 or N_{tracks}< 3)
$N^{F}_{non-CSE}$ - number of events originated from non-CSE mechanism (estimated with data-driven methods)
N_{events} - total number of events

Uncertainties of f_{CSE} in %

Source	40–60 GeV	60–100 GeV	100–200 GeV
Jet energy scale	±5.1	±6.7	±2.1
Tracks quality	±0.3	±1.3	±0.4
Background subtraction	±14.1	±0.9	±1.9
Total systematic	±15.0	±6.9	±2.8
Statistical	±23	±22	±15

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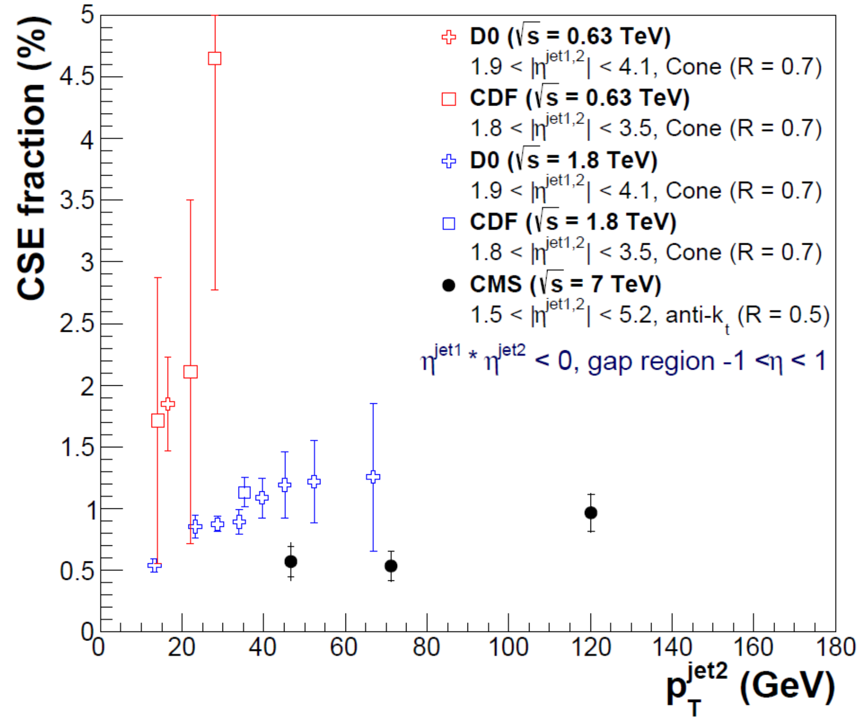
CMS: dijets with a large rapidity gap

- Extracted f_{CSE} as a function of second-leading jet p_T was compared to D0 and CDF results
  - ➢ Decrease of f_{CSE} with the increasing center-of-mass energy is observed
- f_{CSE} also measured for different rapidity differences between two leading jets
  - ➢ Increases with increasing $<\Delta\eta_{jj}>$

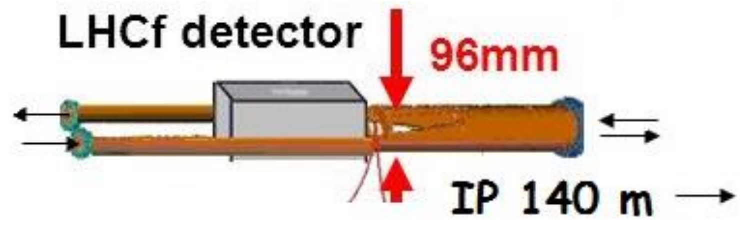


p_T^{jet2} (GeV)	40–60		60–100		100–200	
$\Delta\eta_{jj}$ range	$\langle\Delta\eta_{jj}\rangle$	f_{CSE} (%)	$\langle\Delta\eta_{jj}\rangle$	f_{CSE} (%)	$\langle\Delta\eta_{jj}\rangle$	f_{CSE} (%)
3–4	3.63	$0.25 \pm 0.20 \pm 0.04$	3.62	$0.47 \pm 0.19 \pm 0.05$	3.61	$0.78 \pm 0.21 \pm 0.06$
4–5	4.46	$0.41 \pm 0.16 \pm 0.14$	4.45	$0.47 \pm 0.16 \pm 0.08$	4.41	$0.99 \pm 0.23 \pm 0.06$
5–7	5.60	$1.24 \pm 0.32 \pm 0.10$	5.49	$0.91 \pm 0.32 \pm 0.21$	5.37	$1.95 \pm 0.69 \pm 0.44$

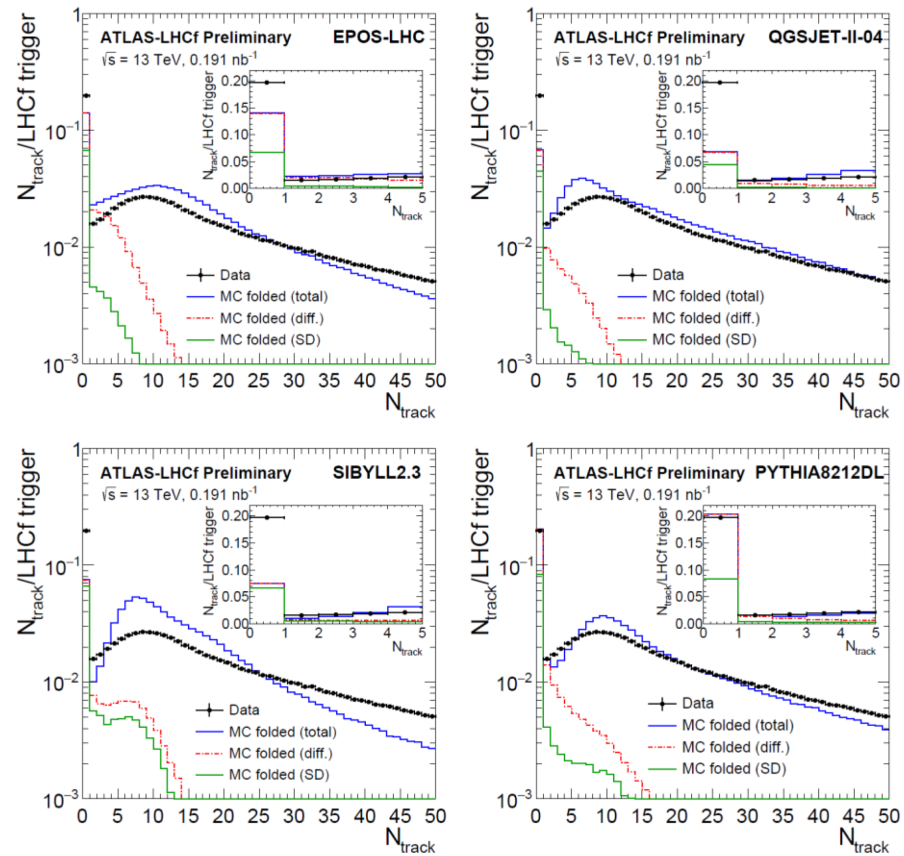
ATLAS-CONF-2017-075

ATLAS: Diffractive Processes in Forward Photon Spectra

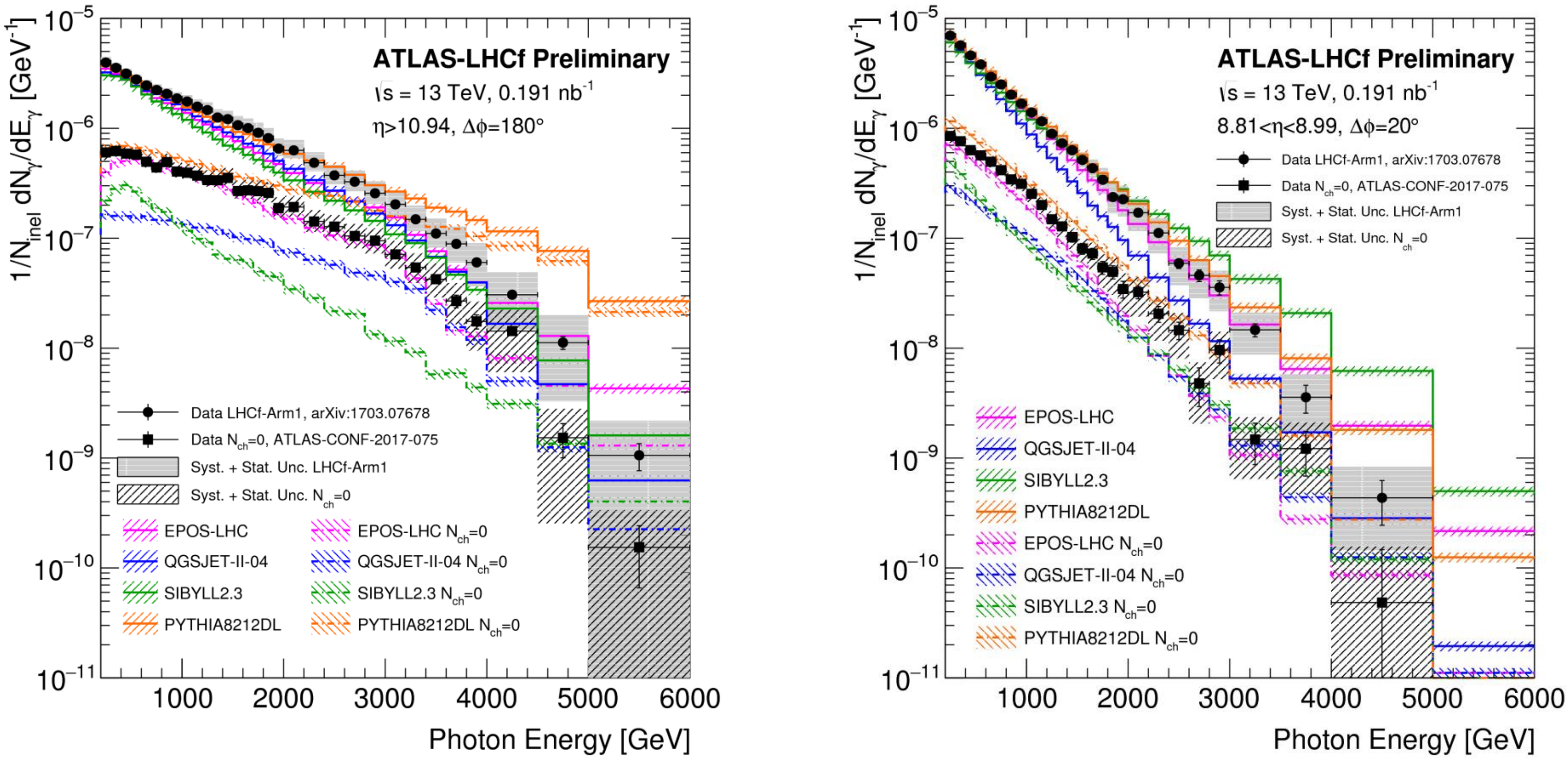
- 13 TeV, 0.191 nb^{-1}, 2015 data, <μ> = 0.01
- First joint analysis of ATLAS and LHCf
  - ➢ LHCf: designed for precision measurement of neutral particles; covers 0 polar angle limit



- ATLAS inner tracker used to reject events with tracks ($p_{\mathrm{T}}^{\mathrm{track}} > 0.1$ GeV) within |η|<2.5 to suppress non-diffractive events; purity of diffractive events > 99%
- LHCf measured photon spectra in two regions: 8.81 < η < 8.99 and η > 10.94
  - ➢ Strictly one photon with E > 200 GeV required
- MC models reproduce main features of N_{track} distribution, but far from agreement

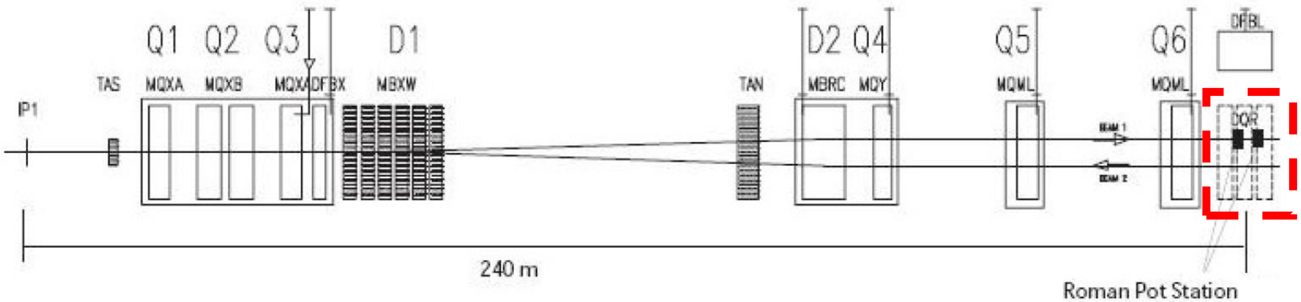


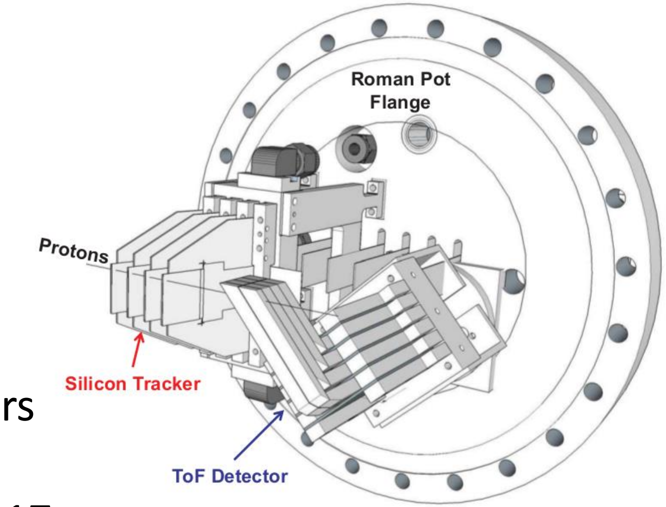
ATLAS: Diffractive Processes in Forward Photon Spectra



- Photon spectra unfolded to particle level and compared to various MC models
- Presented inclusively and for diffractive events with $N_{\text{charged particles}}$=0
- EPOS gives a better overall description compared to other models

ATLAS: Proton tagging with AFP

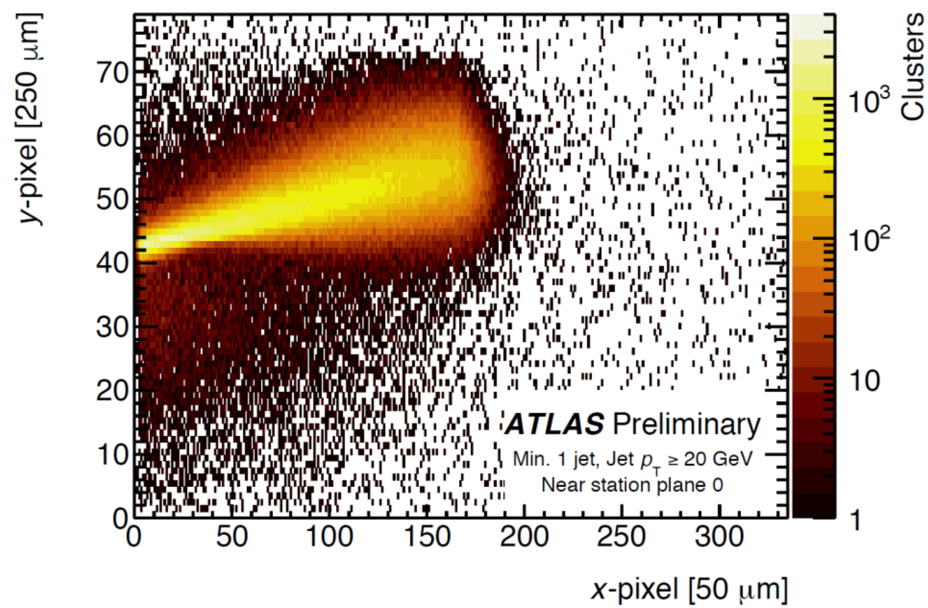




- ATLAS Forward Proton (AFP) detector
  - 2+2 Roman Pots with 4 silicon tracking planes + ToF detectors
  - ±205 and ±217 m from IP1, up to 3 mm from the LHC beam
  - Negative-*z* arm installed in 2016, both arms completed in 2017

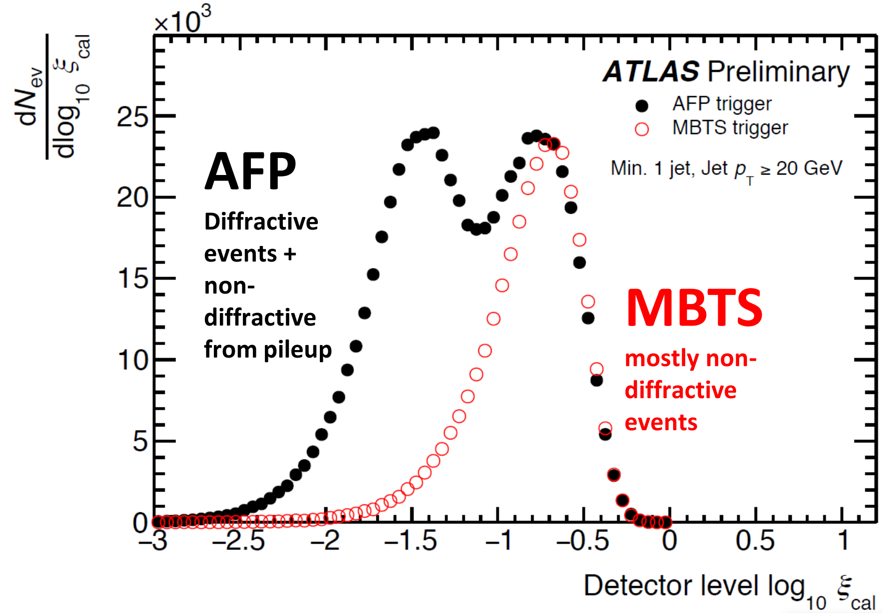
- Protons transported from IP by the LHC optic system
- After loosing a fraction ξ of the initial energy in a diffractive scattering, the proton is deflected differently by LHC magnets -> spatial distribution of proton hits in the AFP tracker plane
- Estimated sensitivity: $0.02 < \xi < 0.1$

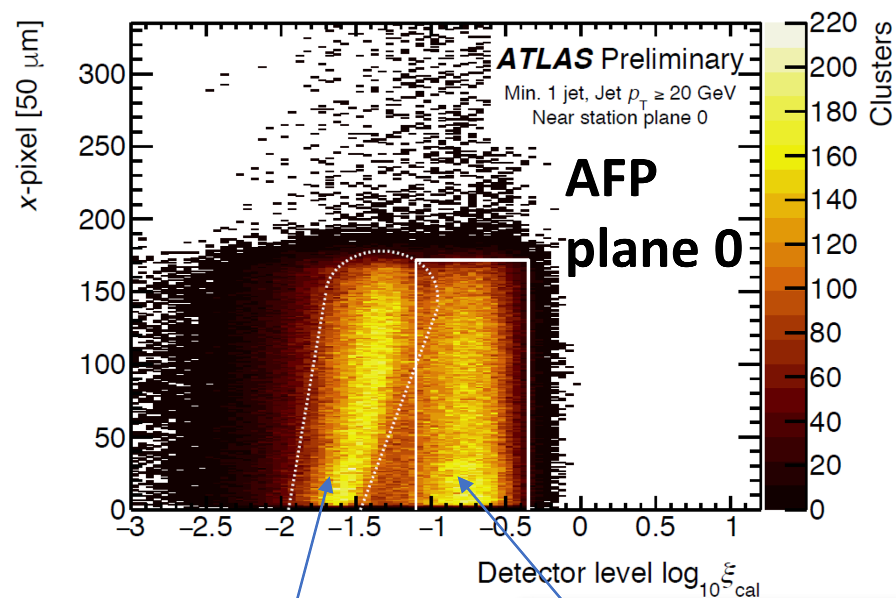
- Diffraction dissociation: correlate AFP signals with the activity in ATLAS calorimeter



ATLAS: Proton tagging with AFP

- 2016 data (negative-*z* arm only), <μ> = 0.3, β* = 0.4 m. AFP + J10 trigger
- Require single cluster of hits in at least 5 out of 7 AFP tracker planes
- At least one jet with p_T > 20 GeV and |η| < 3.0 reconstructed from calorimeter cells, one primary vertex (PV), jets compatible with the PV
- In total $6.3 \cdot 10^5$ events selected; detector level distributions studied
- Compare to a sample of $2.4 \cdot 10^5$ jet events with MBTS + J10 trigger (MBTS: 2 hits 2.08<|η|<3.86)





$$\xi_{\mathrm{cal}} = \frac{1}{\sqrt{s}} \sum_i p_{\mathrm{T}}^i e^{-\eta_i}$$

AFP hit position correlated with the proton energy loss ξ_{cal}.
AFP sees diffractive events!

Hit position uncorrelated to ξ_{cal}: pileup and beam halo

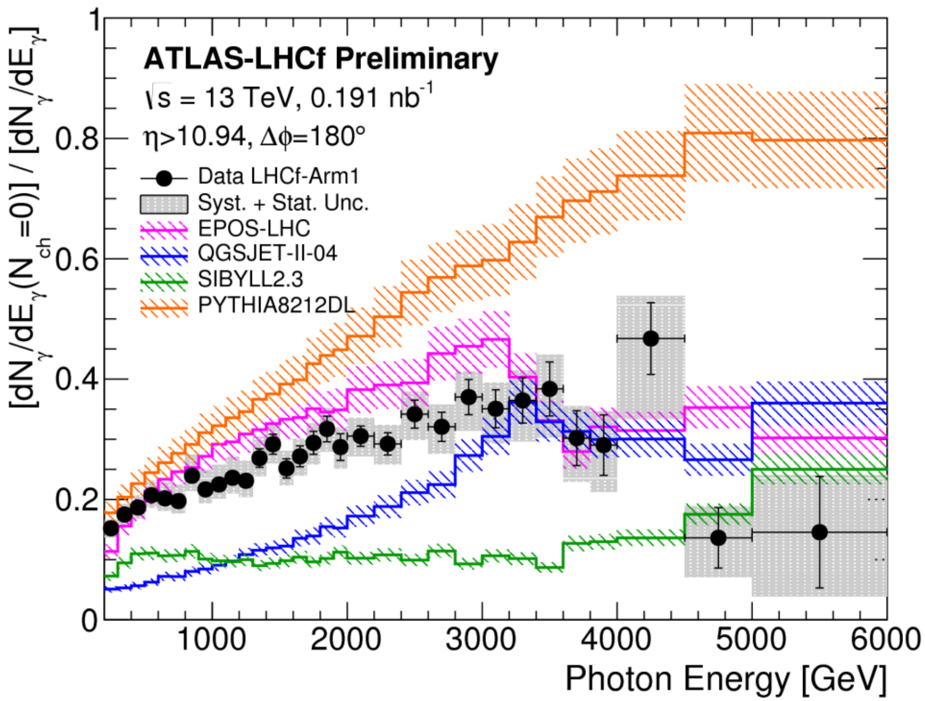
Summary

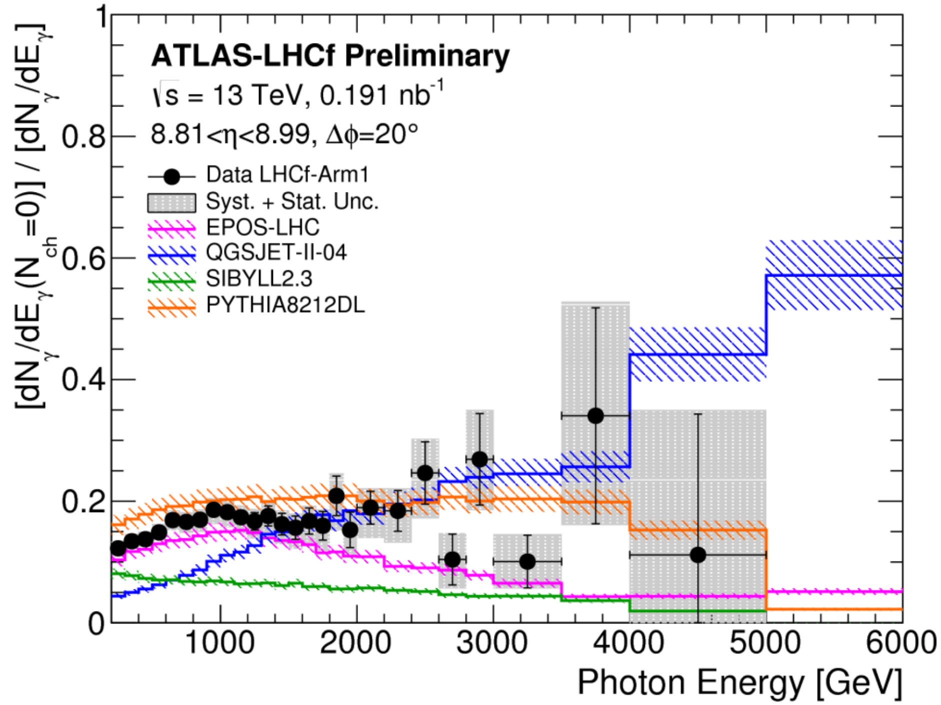
- Soft physics
  - ➢ Studies a major part of *pp* collisions phenomena
  - ➢ Source of valuable input for Monte Carlo tunes
- Presented:
  - ➢ CMS measurement of inelastic *pp* cross section at 13 TeV
  - ➢ CMS measurement of dijet production with a large rapidity gap at 8 TeV
  - ➢ First joint ATLAS and LHCf measurement of the forward photon spectra, inclusively, and within diffractive events at 13 TeV
  - ➢ Detector level distributions with one-arm ATLAS Forward Proton detector

Backup

ATLAS-CONF-2017-075

ATLAS: Diffractive Processes in Forward Photon Spectra

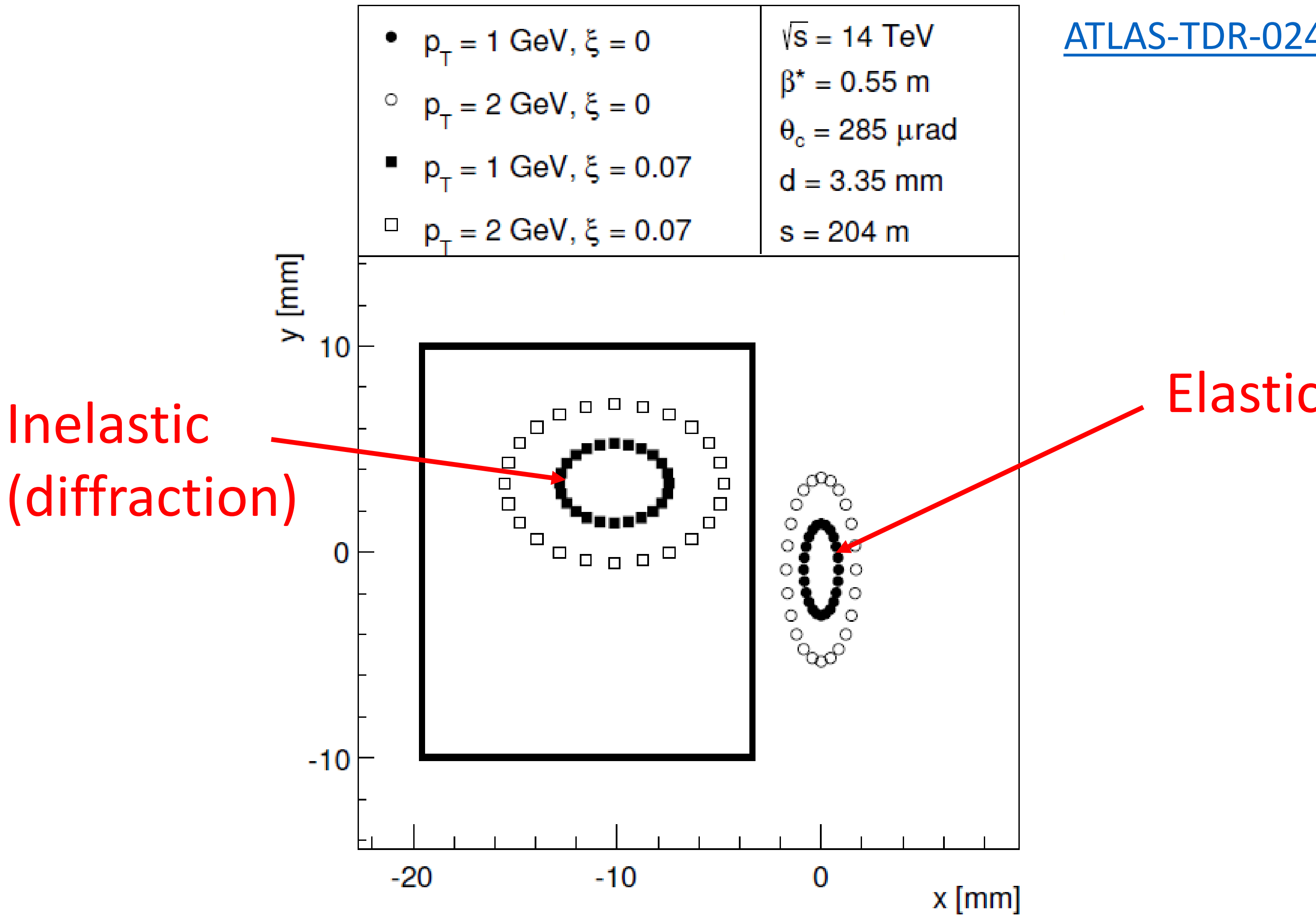




- Ratio of yields: diffractive to inclusive as a function of photon energy
- EPOS gives a better overall description compared to other models
- Pythia8 overshoots data at very forward rapidities

AFP geometrical acceptance

ATLAS-TDR-024-2015



(a) $\beta^* = 0.55$ m, $\theta_c = 285$ μrad