Exclusive Jet production using ATLAS and AFP data

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Forward Physics in ALICE 3

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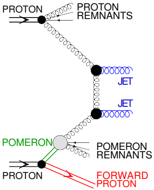
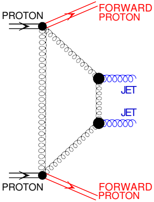
Considered Processes



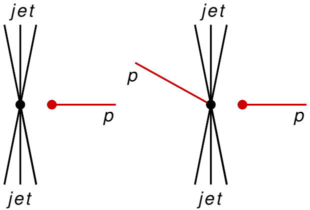
Single Diffractive Jet Production: only one forward proton accompanied by a large rapidity gap (space devoid of particles between proton and central system) + di-jet.
Motivation: measure cross-section; shed light on gluonic structure of Pomeron (if enough clean data).



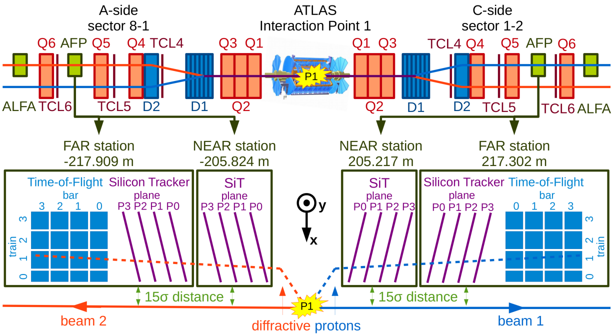
Exclusive Production: two protons on opposite sides, each accompanied by a large rapidity gap; no remnants in the final state system.
Semi-Exclusive Production: as above, but only one proton tagged due to detector acceptance.
Motivation: measure cross-section → very rare, poorly known process.

Background:

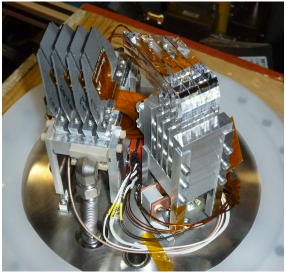
- for SD JJ: Non-Diffractive Jet production + proton in AFP (from *e.g.* pile-up),
- for semi-exclusive jet production: ND JJ + proton, SD JJ with non-recognized (not reconstructed, not within acceptance) remnants.

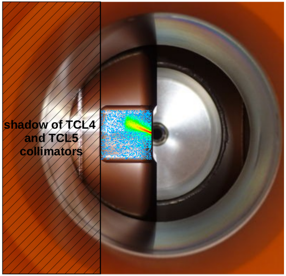


Experimental Setup – AFP and ATLAS Detectors



- Two Roman pot stations on each side of ATLAS (around 210 m from the ATLAS IP).
- Horizontally inserted into the LHC beam pipe up to few mm from the beam.
- Each station contains four Silicon Pixel planes for the track position measurement.
  - From the position reconstructed in AFP, proton kinematics at the collision point can be unfolded.
- Far stations host Time of Flight (ToF) detectors (not used in this analysis).

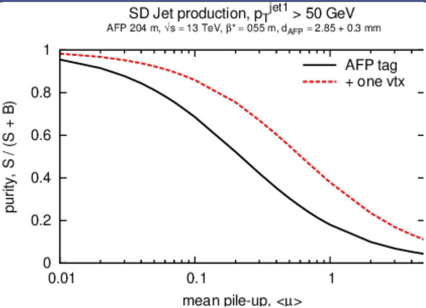




Data Samples
&
Trigger Selection

Data Samples and Triggers of Interest

1. Due to expected signal and background cross-sections, the measurement must be done in the low-μ environment to obtain reasonable purity of the sample.
2. In 2017 data was gathered with various low-μ:
   - $0.04 \sim 100$ nb^{-1},
   - $1.0 - \sim 650$ nb^{-1},
   - $2.0 - \sim 150 \cdot 10^3$ nb^{-1}.

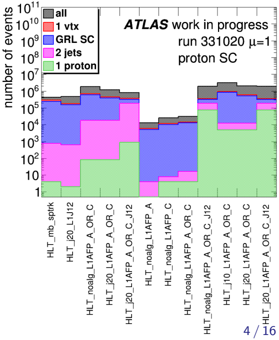


Trigger suitable for SD JJ and EXC JJ analyses must save events with:

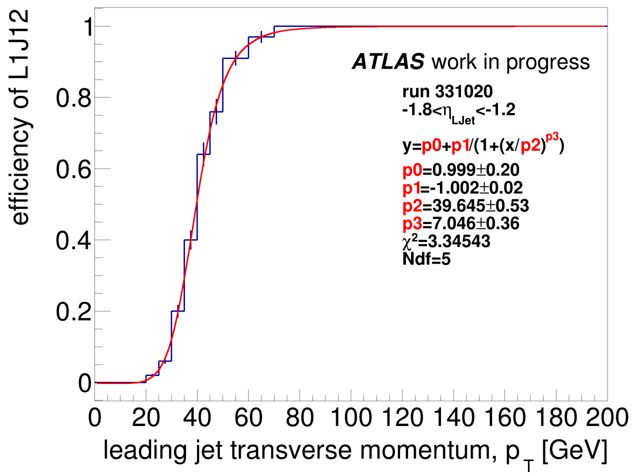
- two jets in the central detector,
- one proton registered in the AFP station.

First data-taking $\rightarrow$ various triggers present in the menu.

After detailed analysis of their efficiencies, the **HLT_j20_L1AFP_A_OR_C_J12** was selected as the best main trigger.

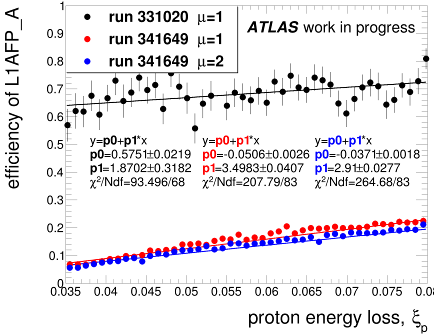


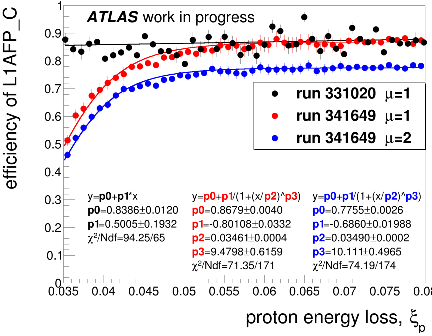
Jet Trigger Efficiency



- Depends on the transverse momentum (p_T^{LJ}) and pseudorapidity of the leading jet.
- 12 regions in pseudorapidity were considered; for each the efficiency of the L1J12 as a function of p_T^{LJ} was estimated.
- To each such distribution an effective function $y = p0 + p1/(1 + (x/p2)^{p3})$ was fitted in order to have a continuous description of a "turnover region".

AFP Trigger Efficiency



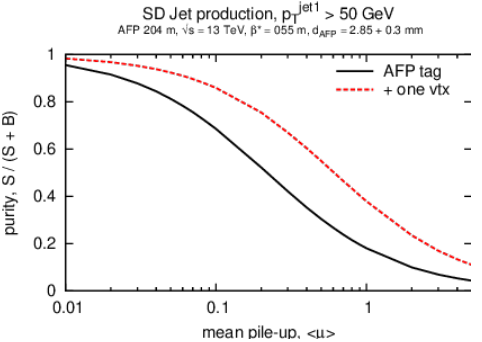


- Independent of the jet trigger performance. Depends on the relative energy loss of a proton: $\xi_p = 1 - \frac{E_{proton}}{E_{beam}}$.
- Non-trivial contribution of beam-related backgrounds effectively considered by using data-driven methods (instead of MC simulation).
- Linear fit provides a good description ($\chi^2/NDF \sim 1$) for side A in all runs and side C in runs 331020 and 336505.
- The efficiency on side C in runs with $\mu \gtrsim 1$ had to be described by function: $y = p_0 + p_1/(1+(x/p_2)^{p_3})$ to reproduce the observations in the lower ξ_p range. The effect may be due to burn-out of SiT tracker (not mitigated by compensatory increase High-Voltage).

Studies of
Single Diffractive Production

Event Selection for Single Diffractive Processes

- Initial feasibility studies were done within the *LHC Forward Physics Working Group*.
- With $\mu \gg 1$, the purity of the sample is expected to be very small $\rightarrow$ extremely challenging measurement.
- The purity can be increased by adding a single vertex is required in ATLAS.



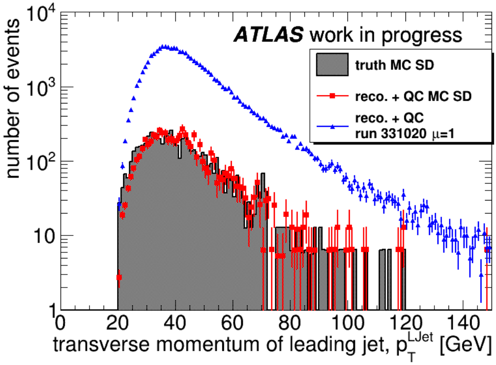
Event selection included the following requirements:

- **one interaction vertex** reconstructed in ATLAS $\rightarrow$ more vertices indicate presence of background,
- minimum **2 jets** of good quality,
- good quality **AFP proton** with no additional forward proton reconstructed.

SD JJ Selection

Monte Carlo Samples:

- produced using Pythia 8 tune A3 (suitable for soft diffraction),
- single diffractive events (MC SD) with $\sigma_{gen} = 12.83$ mb,
- filtered at the generator level requiring forward proton (with $0 < \xi_p < 0.2$) and di-jet (with $p_T > 12$ GeV);
  filter efficiency: 0.000853,
- weighted to take into account: luminosity, pile-up conditions, trigger efficiency etc. effects for used data-samples.

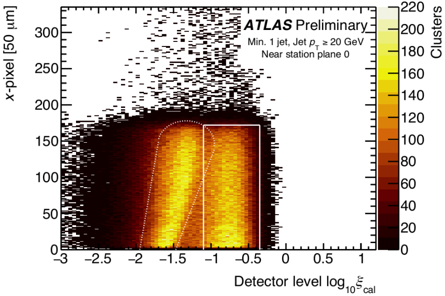


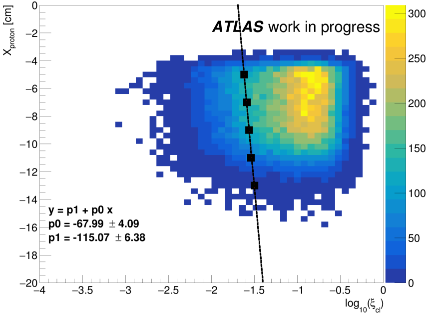
Data and MC after selection:

- As seen from the plot, the applied selection results in a larger number of events visible in the data than expected from the MC.
- It is worth noting that the shapes of the data and MC distributions are similar.

Signal Visibility

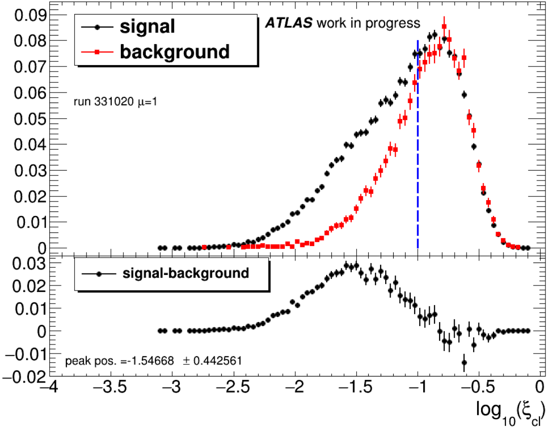
- Despite the presence of the Pomeron remnants in the event, a correlation between the central system and forward protons is expected.
- Such correlation was demonstrated in the initial studies of the 2016 pilot runs (only side C of the AFP was installed – see **left plot**):
  - central system: $\xi_{cal} = \frac{1}{\sqrt{s}} \sum_{cluster/particle} p_T \exp(\pm\eta)$,
  - forward proton: x-pixel ID (**left plot**) or reconstructed x_{proton}-position (**right plot**).





- A diffractive pattern (tilted area marked by the white dotted line on the **left plot**), is not evident in the 2017 data (run 331020, **right plot**).
- Lack of evident diffractive pattern together with observation of the MC/data difference in the number of expected events indicates surprisingly high background contribution.

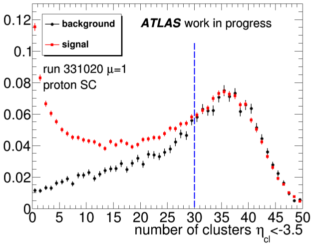
Determination of the Signal Enriched Region



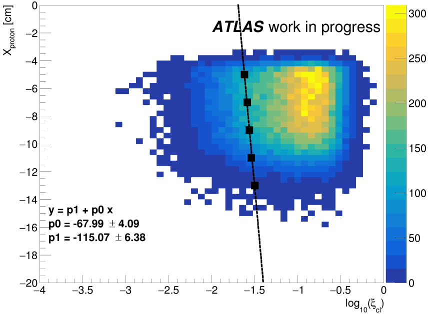
- **Signal-like** signature: AFP+jet trigger and SD JJ selection.
- **Background-like** signature: any trigger and SD JJ selection but without proton in AFP.
- ξ distributions (see plot):
  - normalization to the integral over the last bins (marked with blue line),
  - **different regions of x$_{proton}$** were considered,
  - difference of shapes of the **signal-like** and **background-like** samples is visible (here within $-2.5 < \log_{10}(\xi_{cl}) < -1.2$).

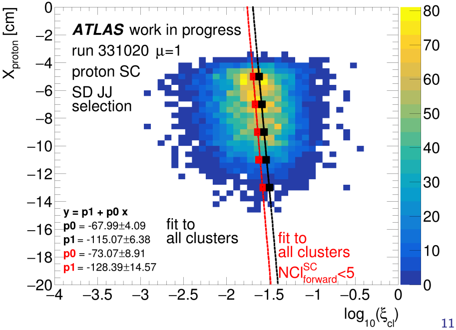
- The mean values of the distributions of the difference between the signal and background were plotted for each considered region of x_{proton}.
- Such "background-subtracted" method revealed presence of the diffractive pattern:
  - on the $\log_{10}(\xi_{cl})$ vs x_{proton} plots the maximum of background-subtracted distribution for a given x_{proton} range is indicated by red points – see right plot on a previous slide.

Background Subtraction with Forward Clusters



- **Signal**-enriched region is also visible in the multiplicity distribution of forward clusters (see top right plot) → possibility of additional selection.
- Additional selection seems to significantly reduce the background (by a factor of 10):
  - **bottom left plot**: before selection; black points indicate the maxima of the background subtracted sample,
  - **bottom right plot**: **after selection**:
    - black points correspond to black ones on the bottom left plot (*i.e.* are obtained with "background-subtracted" method),
    - red points are the mean values of distributions after selection on cluster multiplicity,





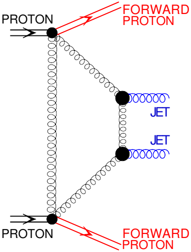
Visible Cross-Section for Single Diffractive Production

Sample	Side	visible cross-section [nb]		
		basic selection	+10>NFcl	+5>NFcl
331020	A	265.4±7.0	67.4±3.6	42.6±2.7
	C	671.1±3.6	155.1±1.7	92.0±1.3
336505	A	93.2±3.3	-	-
	C	90.1±1.2	-	-
341294	A	284±14	172±12	102.0±8.4
	C	194.1±9.3	106.5±6.3	60.6±4.3
341312	A	317±11	177.8±7.0	99.1±4.5
	C	244.7±3.2	139.7±2.4	80.9±1.8
341419	A	301.6±7.3	178.5±5.8	105.3±4.2
	C	235.8±2.3	137.5±1.8	78.2±1.3
341534	A	238.7±4.6	113.3±2.8	60.5±2.0
	C	281.3±1.9	135.4±1.3	70.97±0.95
341615	A	292.2±7.1	173.5±5.7	98.1±4.2
	C	237.2±2.3	136.3±1.7	77.5±1.3
341649	A	383±16	231±11	151.0±8.5
$\mu \sim 1.0$	C	353.3±6.2	209.7±4.5	134.5±3.6
341649	A	314±15	177±11	104.2±8.9
$\mu \sim 2.0$	C	236.8±5.4	136.3±4.1	77.1±3.0

- In table: visible cross-section for a given run and side of proton tag for:
  - basic selection: trigger, minimum 2 good quality jets, single vertex in ATLAS and exactly one proton,
  - additional selection of at most 10 and 5 clusters in the forward region on the proton side.
- Considered effects:
  - collected luminosity (after "Good Run List"),
  - trigger prescale and efficiency.
- Uncertainties are statistical.

Exclusive Jet Production

Exclusive Production of Two Jets

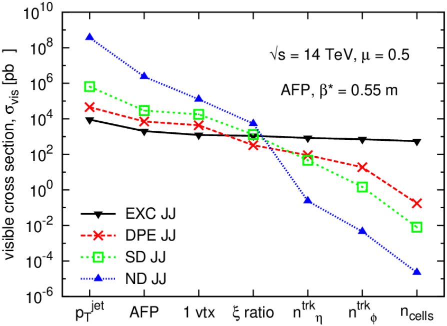


Signal features:

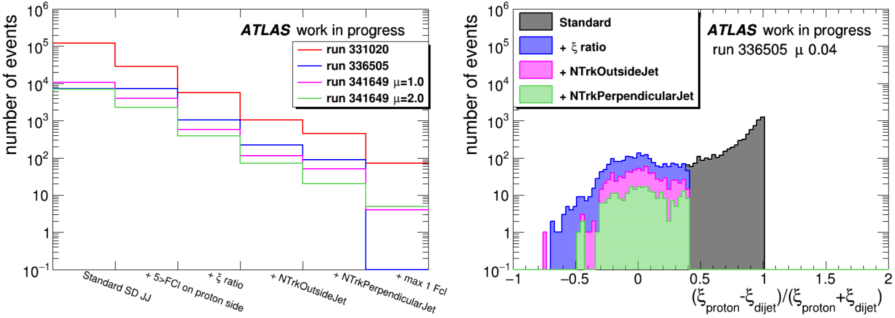
- two jets in the central region,
- two protons scattered into the LHC beam pipe at very small angles, potentially registered in AFP,
  - **semi-exclusive**: exactly one proton registered in AFP,
- no other particles present in the event in “regions outside jets”.

Event selection:

- SD JJ requirements
- difference between the proton relative energy loss ξ_p and that calculated from the di-jet system
  $\xi_{di-jet} = \exp(\pm\eta_{di-jet}) \frac{M_{di-jet}}{2E_{beam}}$
  within a specific range,
- **no large activity in regions outside the jets**: a limited number of tracks perpendicular to jets and outside jets, a limited number of forward clusters.

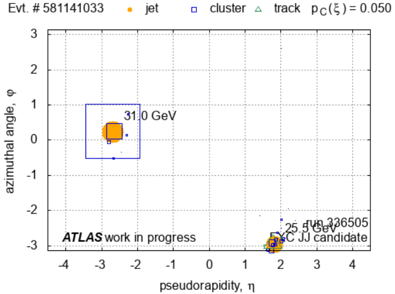


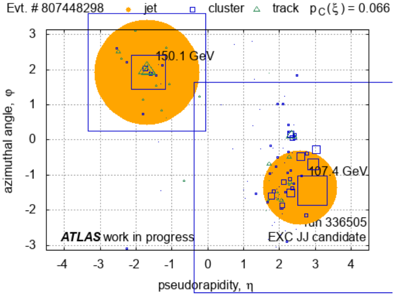
Events After Selection

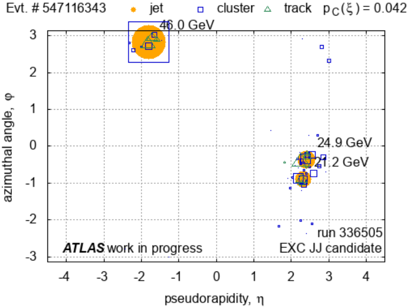


- **Expectation:** there should be asymptotic background reduction (*cf.* slide 14).
  - Note: run 336505 (blue) had some problems in forward calorimeter thus it was not taken into account (last cut/bin results in 0 events).
- **Conclusion:** no such behaviour visible → more background events than expected!
- **Expectation for signal events:** peak at 0 in ξ_{ratio} distribution visible.
- Local maximum around 0 present only for a run with the smallest pile-up (right plot).

Results







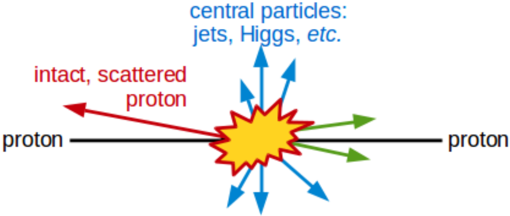
- 101 events in run with smallest μ considered as signal candidates.
- The visible cross-section is
  1.56 $\pm$ **0.47** nb (side A) and
  1.90 $\pm$ **0.20** nb (side C)
  (only statistical uncertaities).
- The numbers are in reasonable agreement with the predictions of the feasibility analysis.
- For a full analysis of the systematic effects much larger statistics is needed.

Summary

◦ Analyses of Single Diffractive and Exclusive Jets processes were carried out using 2017 ATLAS and AFP low-μ data.
◦ Jets and forward protons were measured by ATLAS and AFP detectors, respectively.
◦ One of the first analyses of such type – many dedicated, detailed studies had to be done, like AFP SiT efficiency and trigger efficiency.
◦ Unexpectedly high background contribution and incorrect hardware settings had to be considered.
◦ **Measured visible cross-section for SD JJ production: 74.4±9.0/81.1±3.8 nb**; Issue: small signal purity of 10-20%.
◦ An evidence of Exclusive Di-Jet production in a run with smallest pile-up: 101 candidates.
◦ **Estimated visible cross-section for EXC JJ: 1.56±0.47 and 1.90±0.20 nb** (side A and C, only statistical errors)

Backup

Energy Loss in ATLAS and AFP



Various **energy loss** methods can be studied:

- from **proton** energy: $\xi_{\pm} = 1 - \frac{E_{proton}}{E_{beam}}$;
- from **clusters/particles**: $\xi_{\pm} = \frac{1}{\sqrt{s}} \sum_{cluster/particle} p_T \exp(\pm\eta)$;
- from **dijet**: $\xi_{\pm} = \exp(\pm\eta_{DiJet}) M_{DiJet} \frac{1}{2E_{beam}}$;

Correlation between **central system** and **forward proton** can be indication of **signal** in data.

- **protons** ξ is limited by detector acceptance,
- **clusters** ξ expected to be similar to protons,
- **tracks** ξ expected to be smaller to protons due to central detector acceptance,
- **jets** ξ expected to be smaller than protons since only a part of produced system is taken,

Quality Cuts

Cuts affecting the number of events:

- only 1 (primary) vertex,
- exactly 2 good quality jets,
- min. 1 reconstructed proton in AFP station,

Good quality **jet** must:

- $|\eta_{jet}|$ <4.5 – whole jet must be within the acceptance of the detector,
- $p_T^{jet} > 20$ GeV – recommendations of ATLAS for PFlow jets,
- $|timing_{jet}| < 12.5$ ns – exclusion of the so-called "out-of-time" jets,
- if $|\eta_{jet}|$ <2.4 then JVT>0.5 – Jet Vertex Tagger (JVT) is the variable telling how probable is that a jet comes from the primary vertex.

Reconstructed **proton** must:

- $0.02 < \xi < 0.2$

Good quality **cluster** must:

- $|\text{cl}_t| < 10$ ns,
- $\text{cl}_{EngFracMax} < 0.8$ and $\text{cl}_{MAG} < 5500$,
- $\text{cl}_E^{raw} < 250$ MeV,
- not be on edge $|\eta| < 4.8$,
- individual hot clusters on $\eta \times \phi$ map were cut out.

Good quality **track** must:

- track $p_T > 200$ MeV and $|\eta| < 2.5$,
- minimum 1 hit from the Pixel layer, including the B-layer,
- if track $p_T > 200$ MeV, then 4 hits in SCT layer were required,
- if track $p_T > 300$ MeV, then 6 hits in SCT layer were required,
- $|d_0| \leqslant 1.5$ mm,
- $|z_0 - z_{beam}| \sin(\theta_0) \leqslant 1.5$ mm, where z_{beam} is reconstructed z position of primary vertex.

MC Weight

The Monte Carlo was weighted in the following way:

$$W_{MC} = \frac{L \cdot \sigma_{gen} \cdot \varepsilon_{gen} \cdot vtx_{frac} \cdot PS \cdot \varepsilon_{jet}(p_T, \eta) \cdot \varepsilon_p(\xi)}{N_{gen}^{MC}},$$

where:

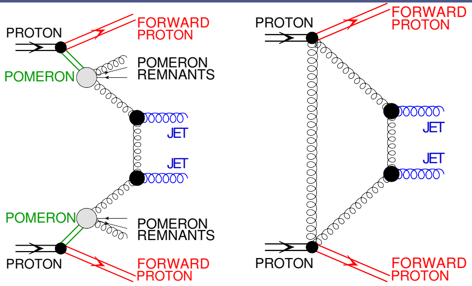
- N_{gen}^{MC} is the number of events in the MC generated sample,
- L is the luminosity collected during a given run after consideration of GRL; the distinction is made for the AFP proton on sides A and C,
- σ_{gen} is the cross-section reported by the generator,
- ε_{gen} is the generation efficiency,
- vtx_{frac} is the correction reflecting the fact that the MC was generated w/o pile-up which makes a rejection due to the single vertex requirement different for the data and MC:

$$vtx_{frac} = \frac{N_{data}^{1vtx}/N_{data}^{all}}{N_{MC}^{1vtx}/N_{MC}^{all}}$$

,

- PS is the correction due to the trigger prescale,
- $\varepsilon_{jet}(p_T, \eta)$ is a correction due to the trigger efficiency (the jet p_T and η dependent),
- $\varepsilon_p(\xi)$ reflects the "proton part" of the trigger efficiency (ξ_p dependent).

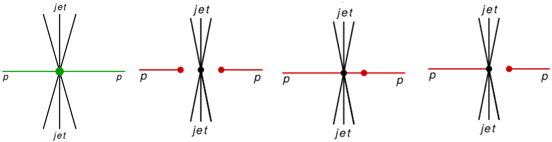
Theoretical Formalism



Double Pomeron Exchange

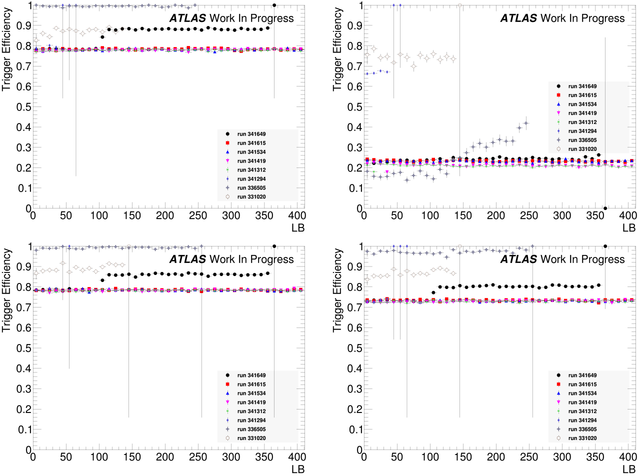
Exclusive DiJet Production

- In both cases in final state we have 2 jets and protons. Rapidity gaps are expected.
- Exclusive DiJet Production: no other particle present, for protons to stay intact screening of gluons must take place.
- Double Pomeron Exchange: Pomeron remnants are expected.
- Experimentally, one is limited by the detector acceptance and efficiency.
- The “experimental” definition of exclusivity (selection criteria) was based on the MC studies and assume “margins” in $(\eta - \phi)$ plane.



The definition of signal and background is in a sense of “experimental nature” $\rightarrow$ we considered what was visible in the detector. As shown above: the signal (2 jets and 2 protons; leftmost) will be mimicked by any of the configurations shown on other plots.

Difference in Performance of A and C Side of AFP Stations



- The efficiency of side A (**top**) is result of poor performance of A Far (**top right**) station:
  - this Station had lower number of planes (2 in run 331020, 3 in other runs).
- No such difference is observed in the case of side C (**bottom**).
- More details concerning the trigger efficiencies are given in Appendix C.

Data Samples

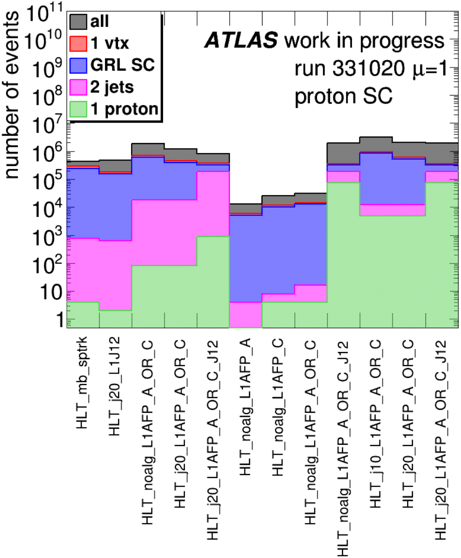
2017 low-μ data:

ATLAS Run Number	LHC Fill	Pile-up μ	Int. Luminosity [nb^{-1}] for proton on side A	Int. Luminosity [nb^{-1}] for proton on side C
331020	6019	$\sim$1.0	56.866	510.841
336505	6238	$\sim$0.04	44.751	60.2411
341294	6404	$\sim$2.0	709.542	709.542
341312	6405	$\sim$2.0	18245.492	18234.639
341419	6411	$\sim$2.0	31636.072	31593.050
341534	6413	$\sim$2.0	47663.701	52680.387
341615	6349	$\sim$2.0	31772.631	31772.631
341649	6417	$\sim$2.0	6543.940	6449.680
		$\sim$1.0	3325.167	3325.167

Run 3 low-μ data:

Run 2 (2017) Lumi $[nb^{-1}]$	μ	Run 3 (2022) Lumi $[nb^{-1}]$	μ	Run 3 (2023) Lumi $[nb^{-1}]$	μ
100	$\sim$0.05	0.46	$\sim$0.005	61	$\sim$0.05
650	$\sim$1	170	$\sim$0.02	29	$\sim$0.2
$150 \cdot 10^3$	$\sim$2	34.6	$\sim$0.05	175	$\sim$1

Number of Events Saved by the Triggers



- **Gray:** all events saved by given trigger.
- **Red:** events passing requirement for only one vertex.
- **Blue:** events passing previous requirements + cut on Good Run List on proton side (effectively cut on Lumi Blocks).
- **Magenta:** events passing previous requirements + min. two jets of “good" quality.
- **Green:** events passing previous requirements + exactly one proton of “good" quality and no other protons of bad quality.

Various triggers were considered and the detailed analysis of their efficiencies was done. At the end trigger providing best statistics was chosen.

Comparison of EXC JJ Results to the Theoretical Predictions

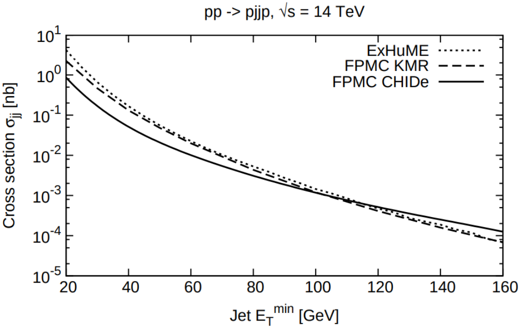


FIG. 4. Cross section for exclusive jet production at the LHC as a function of of the minimum jet E_T. Predictions of CHIDe and KMR are presented. For comparison the results of the ExHuME generator are given.

- The ExHuME, FPMC KMR and CHIDe predictions are in a good agreement with received estimations from ATLAS/AFP data.
- A. Dechambre, O. Kepka, C. Royon and R. Staszewski, *"Uncertainties on exclusive diffractive Higgs and jets production at the LHC"*, Phys. Rev. D **83** (2011), 054013