

Exclusive Production at the LHC

Maciej Trzebiński

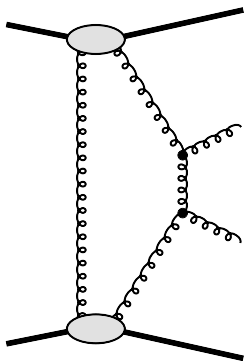
Institute of Nuclear Physics
Polish Academy of Sciences



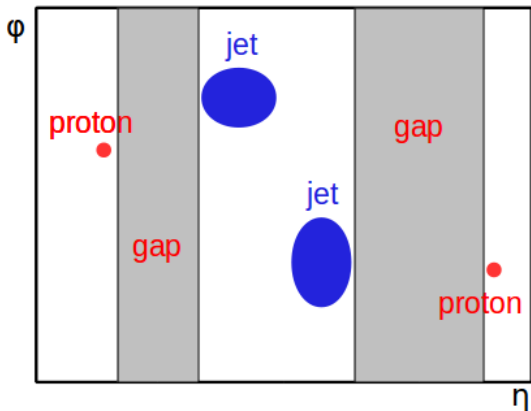
QCD at LHC: forward physics and UPC collisions of heavy ions

28th September 2016

Exclusivity Criterion



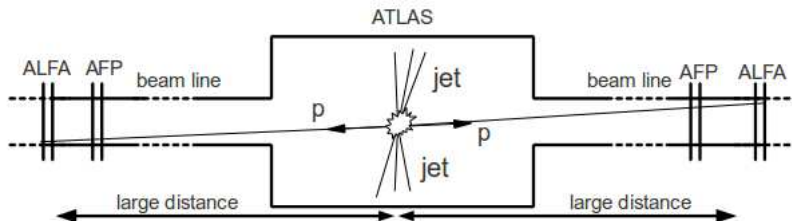
Exclusive Production



All particles produced within detector acceptance.

Forward Detectors

Intact protons – natural diffractive signature.



ALFA

- 240 m from ATLAS IP
- elastic scattering
- special runs (high β^* optics)
- position detectors
- vertically inserted Roman Pots

AFP

- 210 m from ATLAS IP
- hard diffraction
- nominal runs (collision optics)
- position and timing detectors
- horizontally inserted RP

- **soft events**, **pile-up background**

- **proton detector for hard events**

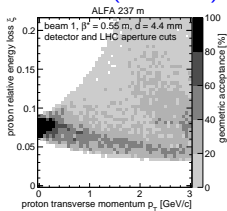
ATLAS was taken as an example, but the conclusions are similar for CMS/TOTEM

Geometric Acceptance

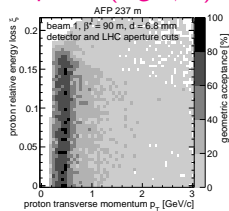
optics

ALFA

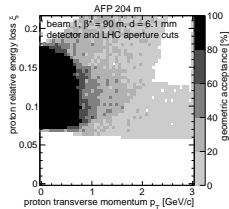
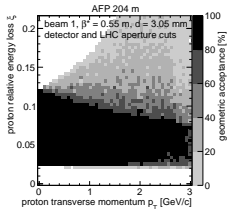
$\beta^* = 0.55$ m
nominal (*collision*)



$\beta^* = 90$ m
special (*high- β^**)



AFP



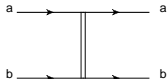
Exclusive Pion Production

Exclusive Pion Production with Forward Proton Tagging

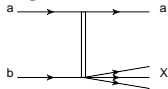
R. Staszewski, P. Lebiedowicz, M. Trzebinski, J. Chwastowski,
A. Szczurek, Acta Physica Polonica B **42** (2011) 1861

Soft Diffractive Production

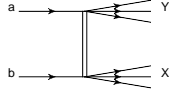
Elastic Scattering



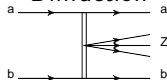
Single Diffraction



Double Diffraction



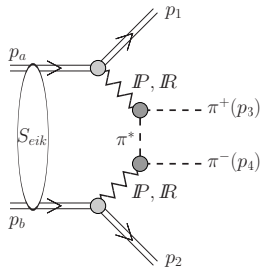
Central
Diffraction



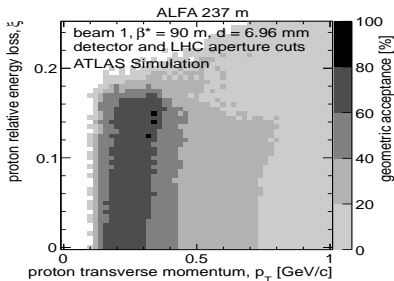
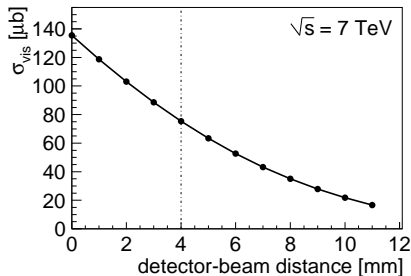
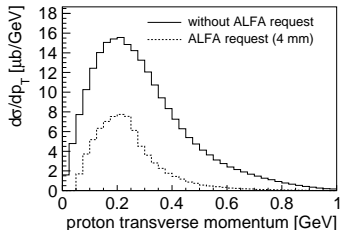
Exclusive $\pi^+\pi^-$ Production

- both outgoing protons tagged in ALFA,
- pions measured in ATLAS detector.

soft process \rightarrow relatively large cross-section:
 $\sigma(pp \rightarrow p\pi^+\pi^-p) \approx 230 \mu\text{b}$



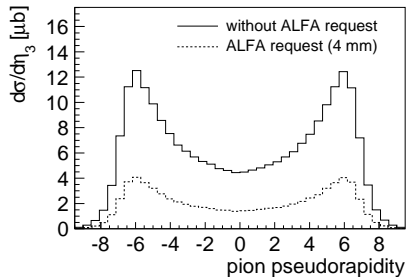
Forward Protons



Cross section visible in the ALFA detectors (both protons tagged) as a function of the distance between the detectors and the beam centre.

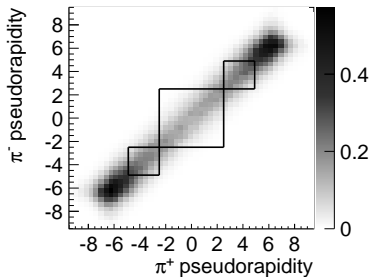
Majority of outgoing protons are in ALFA acceptance region!

Central Pions



Total cross section as a function of pion pseudorapidity.

Distribution peaked around $|\eta| \sim 6$.

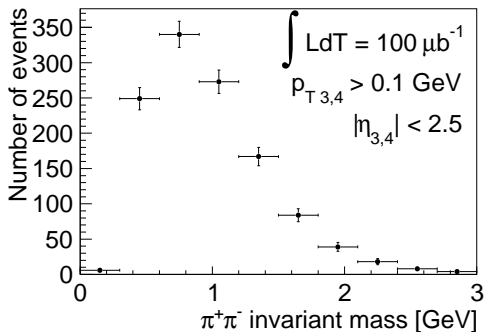


Large correlation between pions pseudorapidity.

Measurements possible in:

- tracker,
- FCAL.

Possible Measurement



Possible measurement of the $\pi^+\pi^-$ invariant mass distribution for $L = 100 \mu\text{b}^{-1}$ (luminosity: $10^{27} \text{ cm}^{-2}\text{s}^{-1}$, data collecting time: 30 h.).

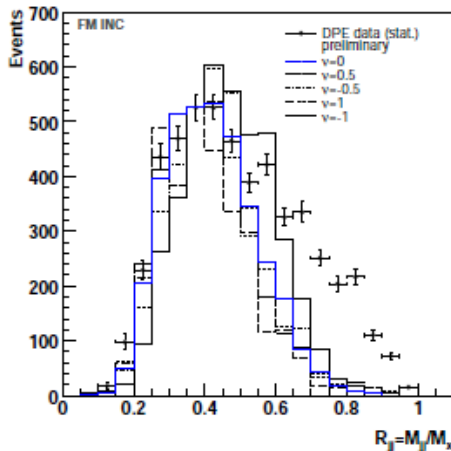
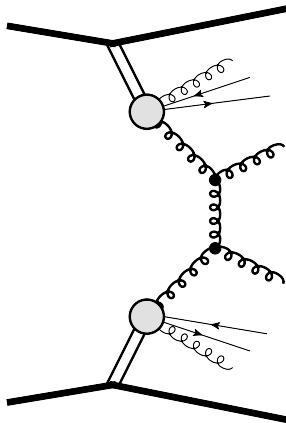
- Measurement of Exclusive $\pi^+\pi^-$ is possible using ALFA data.
- Motivated joint ALFA-ATLAS data taking.
- It requires ALFA trigger and low- p_T tracking.
- Measurements at LHC are on the way. So far the only measurements were performed at:
 - $\sqrt{s} = 62$ GeV and $\sqrt{s} = 63$ GeV by the ABCDHW Collaboration,
 - $\sqrt{s} = 200$ GeV STAR,
 - $\sqrt{s} = 1.96$ TeV Tevatron.
- GenEx – exclusive meson generator – see talk by Paula.

Exclusive Jets

Tevatron – Analysis of the DPE Jet Production

DPE – Double Pomeron Exchange

Signature: two jets in central region + two intact protons.



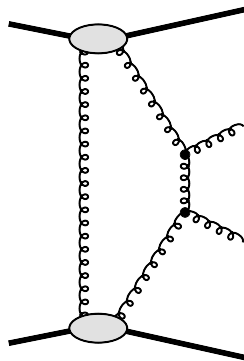
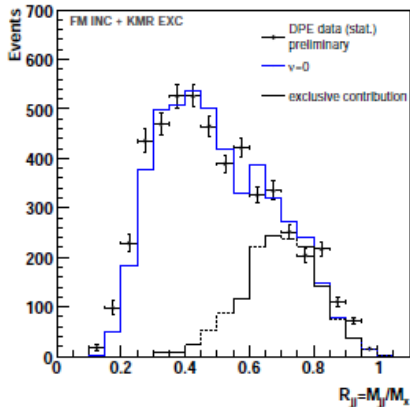
Goal: to probe the Pomeron Density Function.

Too much events in the high mass ratio (M_{jj}) region.

Mass ratio is defined as the ratio of mass of the dijet system to missing mass.

Exclusive Jet Production at the Tevatron

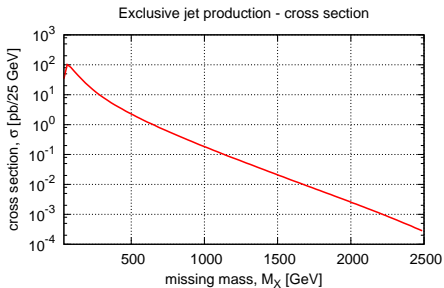
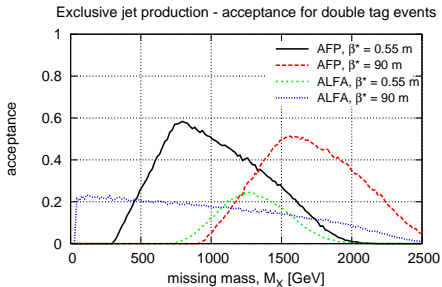
Signature: two jets in central region + two intact protons
+ **gap in rapidity between jet and proton** (no remnants).



Exclusive Production

KMR model explains additional contribution in high mass ratio region. In such process there are no Pomeron remnants (in theory ratio = 1, smearing due to the detector effects).

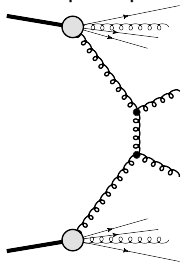
Mass Acceptance



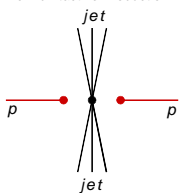
Background

Pile-up – multiple collisions during one bunch crossing (mostly min-bias).

Non-diffractive jets
+ pile-up.

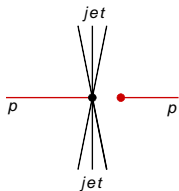
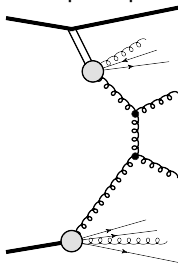


Non-diffractive Production



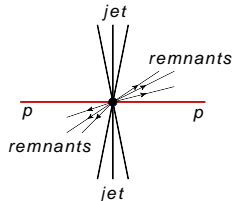
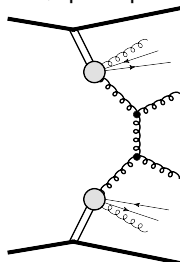
CS ($p_T > 150$ GeV):
645 nb

Single-diffractive jets
+ pile-up.



CS ($p_T > 150$ GeV):
2.26 nb

DPE jets
+ pile-up.

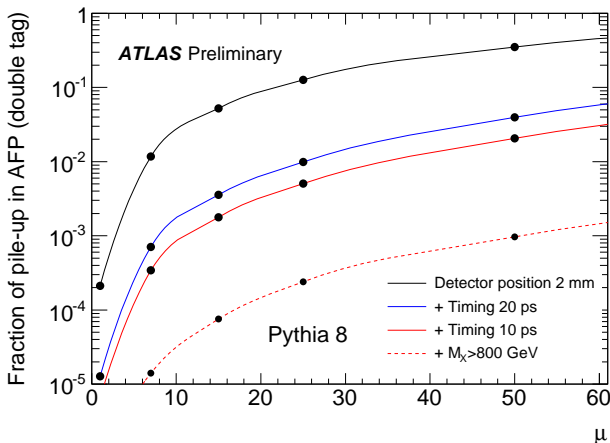


CS ($p_T > 150$ GeV):
40 pb

Double Tagged Events

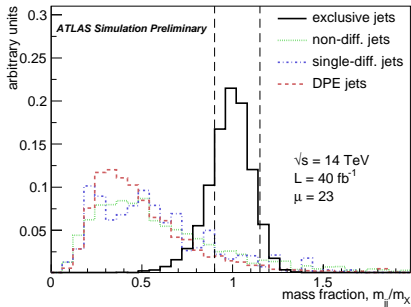
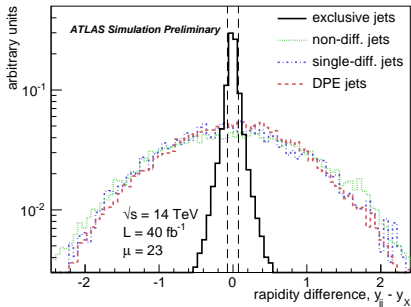
Exclusive Jet Production with Forward Proton Tagging
ATL-PHYS-PUB-2015-003

Cuts – AFP Acceptance



Fraction of pile-up events in AFP (double tagged events) as a function of the average number of interactions with a timing resolution of 20, 10 ps, and for a diffractive mass greater than 800 GeV.
Exclusive jet studies for pile-up $\mu = 23$ end $\mu = 46$.

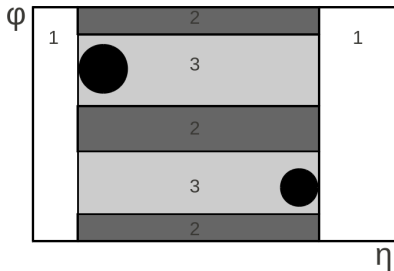
Cuts – Rapidity Difference



Left: Difference, $y_{jj} - y_X$, of the rapidity of the jet system (y_{jj}) and the rapidity of the proton system $y_X = 0.5 \cdot \ln \left(\frac{\xi_1}{\xi_2} \right)$, where ξ_1 and ξ_2 are relative energy losses of the tagged in the AFP C and A stations.

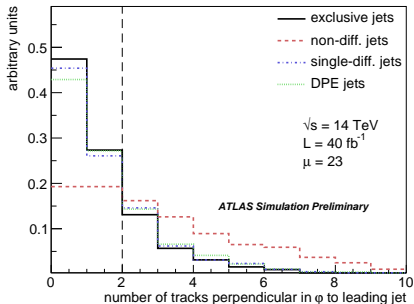
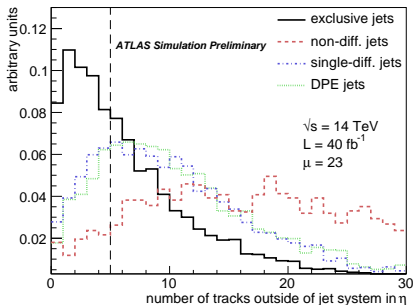
Right: The ratio of the jet system mass to the missing mass $M_X = \sqrt{s \cdot \xi_1 \cdot \xi_2}$.

Cuts – Tracks Outside Jets

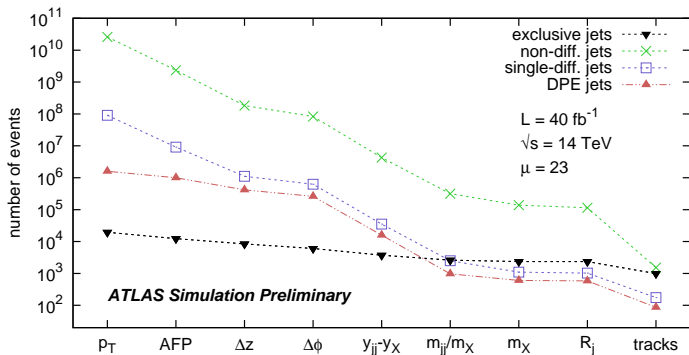


The number of tracks (fitted to the primary vertex) outside the jet system in η (region 1, top) and the number of tracks perpendicular to the leading jet in ϕ (region 2, bottom) for the signal and background events at pile-up $\mu = 23$.

The dashed line represents the value of the applied cut.

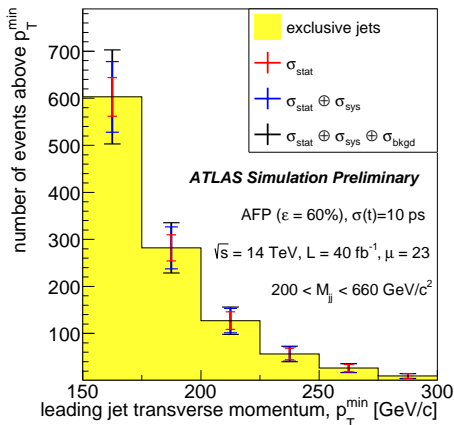
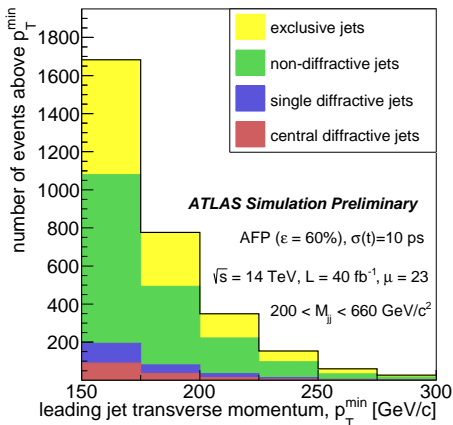


Discriminating Power



The number of events accepted after a particular cut for signal and background processes for the integrated luminosity of 40 fb^{-1} at pile-up $\mu = 23$ as a function of the applied consecutive cuts.

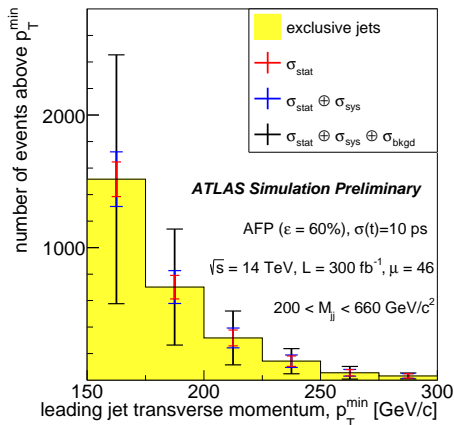
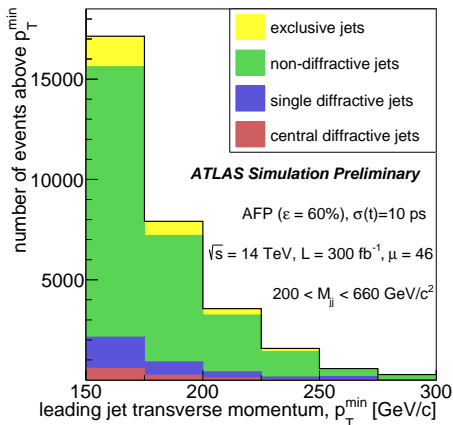
Number of Events ($\mu = 23$)



Left: The number of accepted events as a function of the leading jet p_T threshold for the integrated luminosity $L = 40$ fb $^{-1}$ and average number of interactions of $\mu = 23$.

Right: the number of signal events, marked as yellow bar, with statistical (σ_{stat}), systematic (σ_{sys}) and background (σ_{bkgd}) uncertainties. The \oplus sign means that given errors are added in quadrature.

Number of Events ($\mu = 46$)



Left: The number of accepted events as a function of the leading jet p_T threshold for the integrated luminosity $L = 300 \text{ fb}^{-1}$ and average number of interactions of $\mu = 46$.

Right: the number of signal events, marked as yellow bar, with statistical (σ_{stat}), systematic (σ_{sys}) and background (σ_{bkgd}) uncertainties. The \oplus sign means that given errors are added in quadrature.

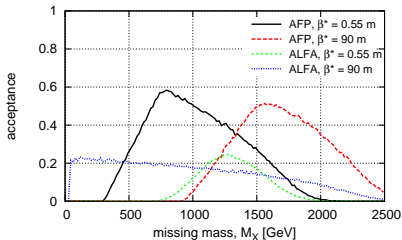
Single Tagged Events

*On the Possibility of Measuring the Single-tagged Exclusive Jets at the
LHC*

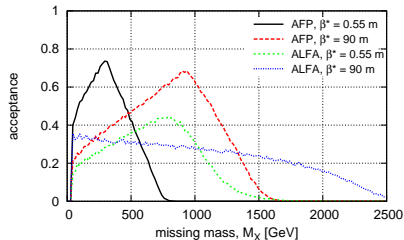
Eur. Phys. J. C **75** (2015) 320, arXiv:1503.00699

Motivation

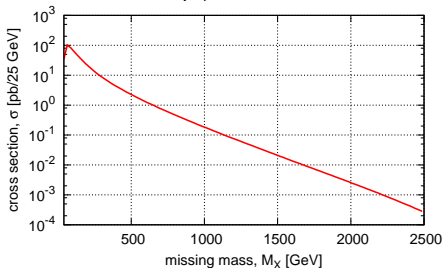
Exclusive jet production - acceptance for double tag events



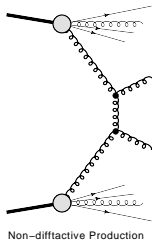
Exclusive jet production - acceptance for single tag events



Exclusive jet production - cross section



Non-diffractive jets
+ pile-up

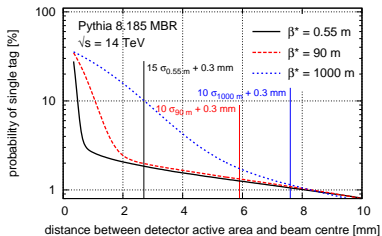


Cuts:

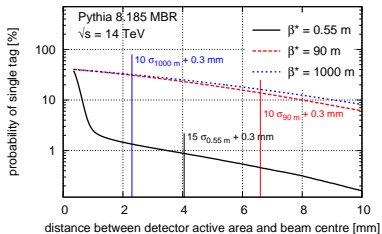
- proton in AFP/ALFA,
- one reconstructed vertex.

Soft single tag probability

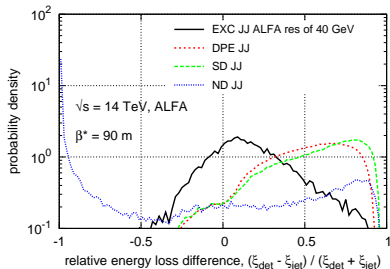
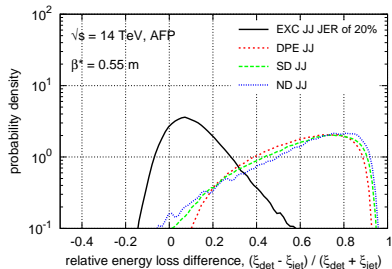
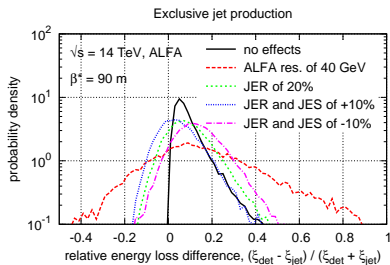
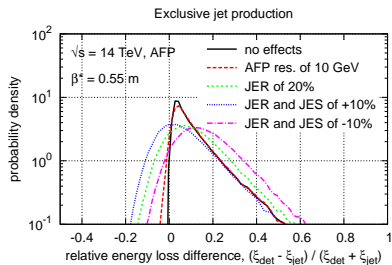
Minimum-bias and elastic protons in AFP station at 204 m



Minimum-bias and elastic protons in ALFA station at 237 m

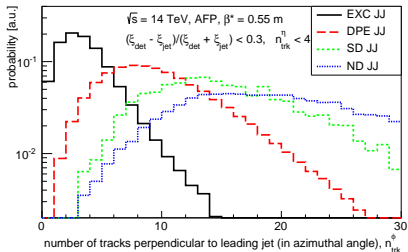
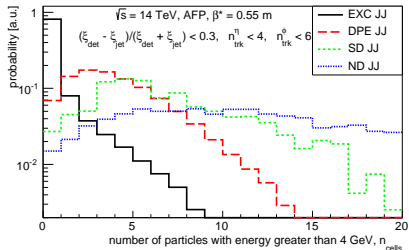
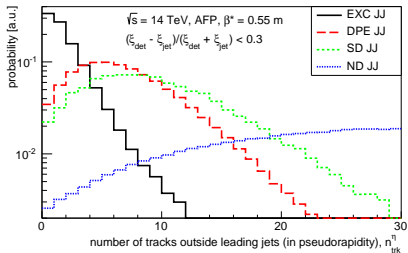


Relative Energy Loss Difference



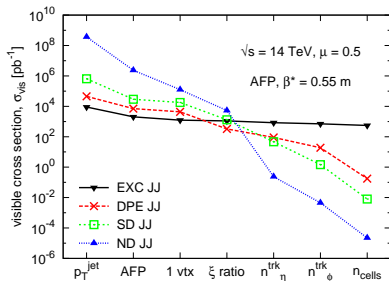
$$\xi^{\text{jet}} = \exp(\pm y_{ij}) \frac{M_{ij}}{\sqrt{s}}$$

Veto on Additional Activity

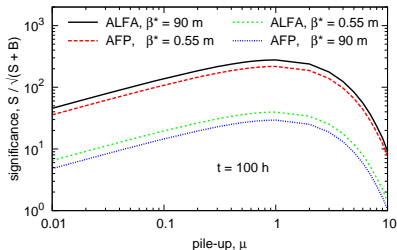
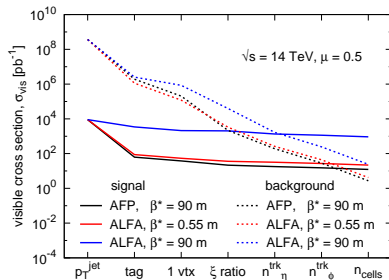


- number of tracks outside jet system (in η): $n_{\text{trk}} < 4$,
- number of tracks perpendicular to the leading jet (in ϕ): $n_{\text{phi}} < 6$,
- number of particles with energy greater than 4 GeV, $n_{\text{cells}} < 2$.

Veto on Additional Activity



Exclusive jets (single tagged)



- Top: cutflow.
- Bottom: statistical significance ($\frac{S}{\sqrt{S+B}}$) for 100 hours.

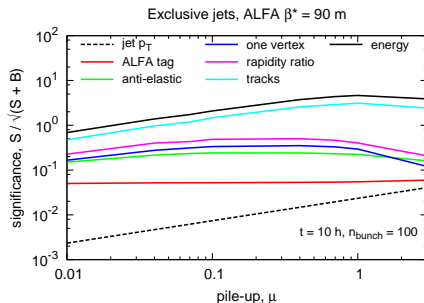
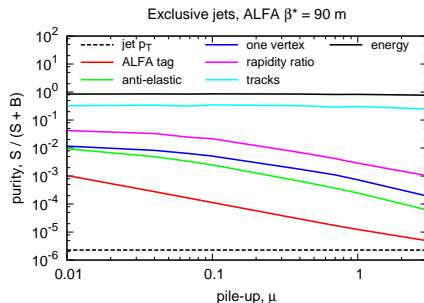
Double Tagged Events

Exclusive Jet Measurement in Special LHC Runs – Feasibility Studies
Acta Phys. Pol. B **47** (2016) 1745, arXiv:1604.03855

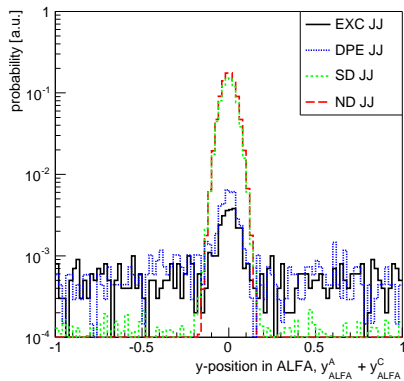
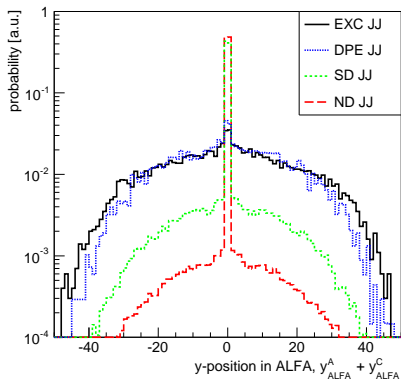
Results

- low- p_T jets,
- double tag in ALFA,
- anti-elastic cut,
- one reconstructed vertex,
- proton-jet correlation: relative energy loss,
- number of tracks outside the jet system,
- amount of energy in forward calorimeters.

Pure ($> 90\%$) and statistically significant measurement should be feasible with data collected by ALFA during Run II.



Anti-elastic Cut



High- p_T jets (double tag)

- Measurement of the exclusive jet production will be possible in the ATLAS detector during normal runs (low beta, high pile-up) using the AFP detectors.
- Very challenging measurement – difference of six orders of magnitude between signal and background cross-sections (impossible to measure without AFP)!
- Results published in: ATL-PHY-PUB-2015-003

Low- p_T jets (single tag)

- Smaller masses \rightarrow larger cross-sections \rightarrow smaller pile-up \rightarrow cleaner events.
- High signal-to-background ratio.
- High statistical significance.
- Results published in: Eur. Phys. J. C **75** (2015) 320.

Low- p_T jets (double tag)

- Pure ($> 90\%$) and statistically significant measurement should be feasible with data collected by ALFA during Run II.
- Results published in: Acta Phys. Pol. B **47** (2016) 1745.

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