Diffractive Physics at the LHC

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New Trends in High Energy Physics

Odessa, Ukraine

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Usual situation at the LHC:

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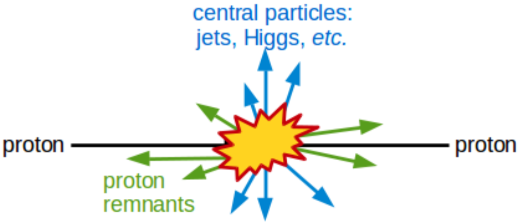

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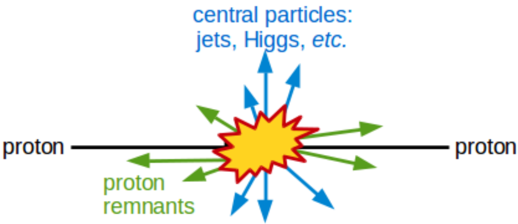

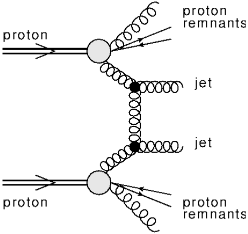

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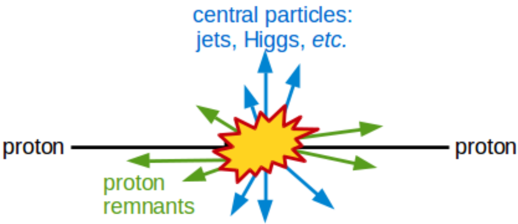

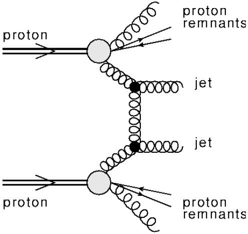

Can proton(s) remain intact?

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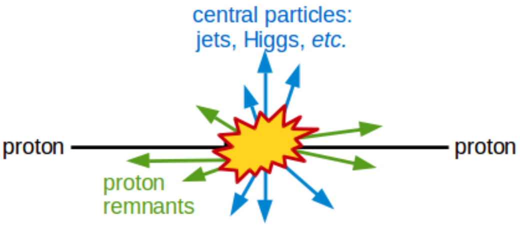

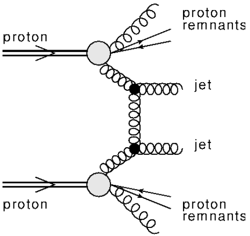

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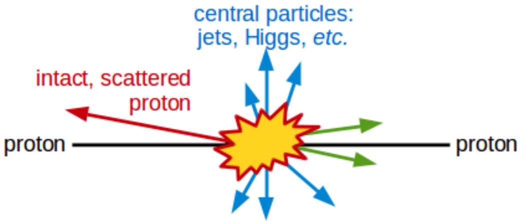

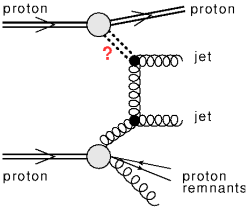

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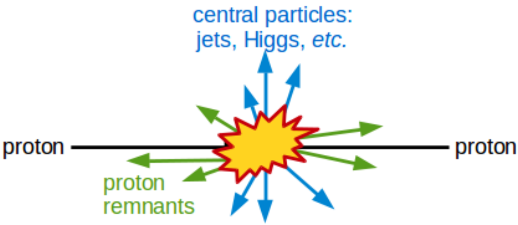

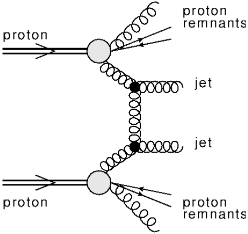

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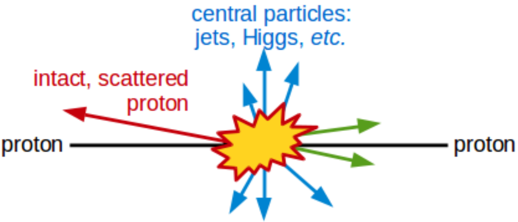

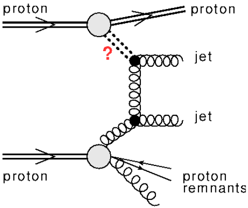

Yes! But exchanged object must not change quantum numbers of proton(s):

- electromagnetic force: photon,
- strong force: Pomeron (QCD = two gluons + h.o. terms).

Measurement Idea

Assumption: one would like to measure diffractive interactions at the LHC.

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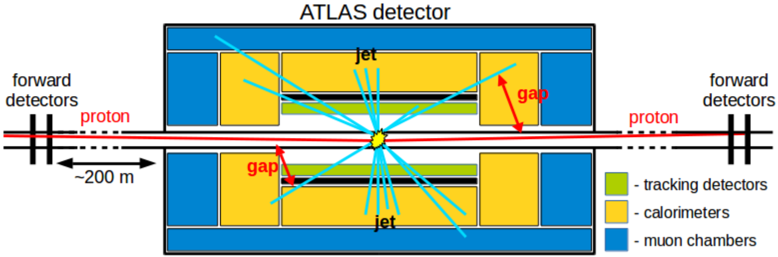
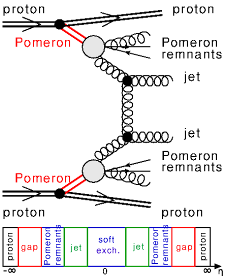
Typical diffractive topology: a gap in rapidity is present between proton(s) and central system and one or both interacting proton stay intact.





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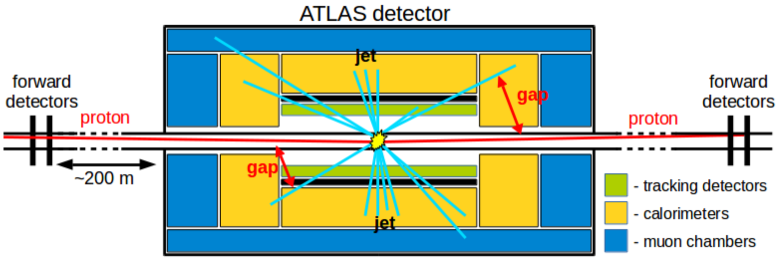

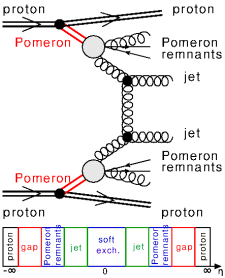

Method 1 (rapidity gap):

+ usual method of diffractive pattern recognition
+ no need to install additional detectors
– gap may be killed by *e.g.* particles from pile-up
– gap may be outside acceptance of central detector

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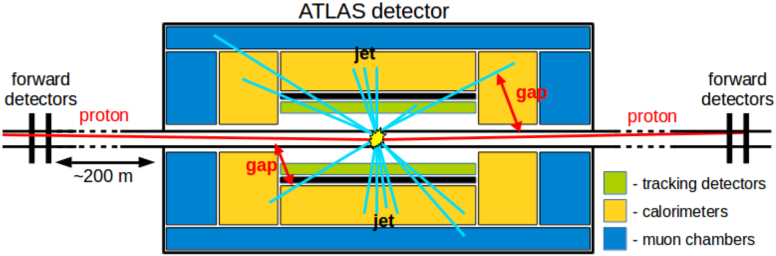

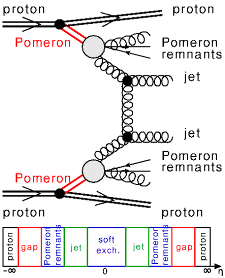

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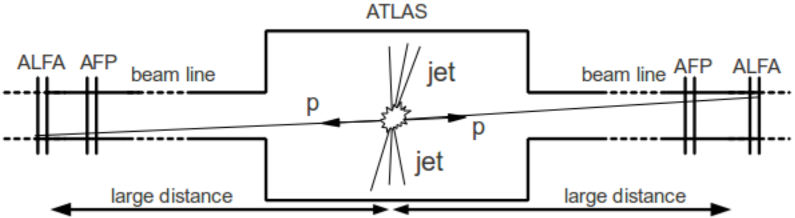
Method 2 (forward protons):

+ protons are directly measured
+ can be used in pile-up environment
– protons are scattered at small angles (few μrad)
– additional "forward" detectors are needed far away from the interaction point

Intact protons → natural diffractive signature → usually scattered at very small angles (μrad) → detectors must be located far from the Interaction Point.



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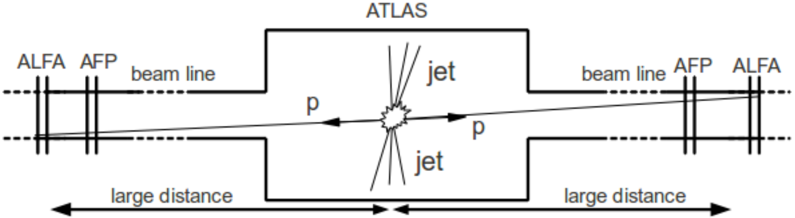

ALFA

- **A**bsolute **L**uminosity **F**or **A**TLAS
- 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high β^* optics)
- vertically inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = \sigma_y = 30\ \mu$m

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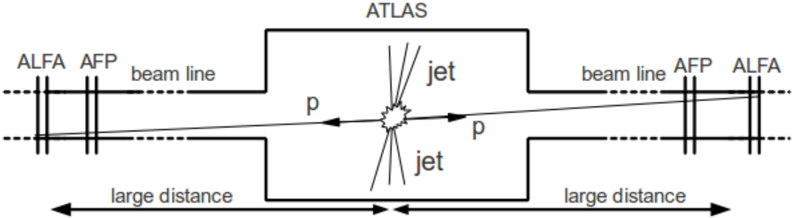

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AFP

- **A**TLAS **F**orward **P**roton
- 210 m from ATLAS IP
- hard diffraction
- nominal runs (collision optics)
- horizontally inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = 6\ \mu$m, $\sigma_y = 30\ \mu$m
- timing detectors, resolution: $\sigma_t \sim 20$ ps

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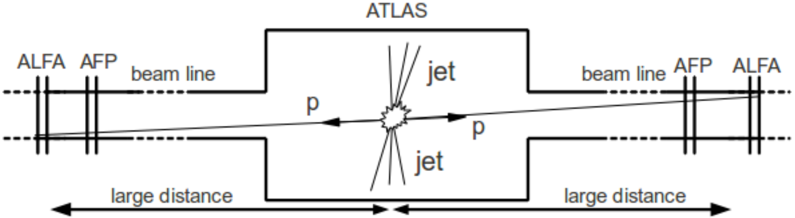

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Similar devices @ IP5: CMS-TOTEM.

Ratio of the number of protons with a given relative energy loss (ξ) and transverse momentum (p_T) that crossed the active detector area to the total number of the scattered protons having ξ and p_T.

optics

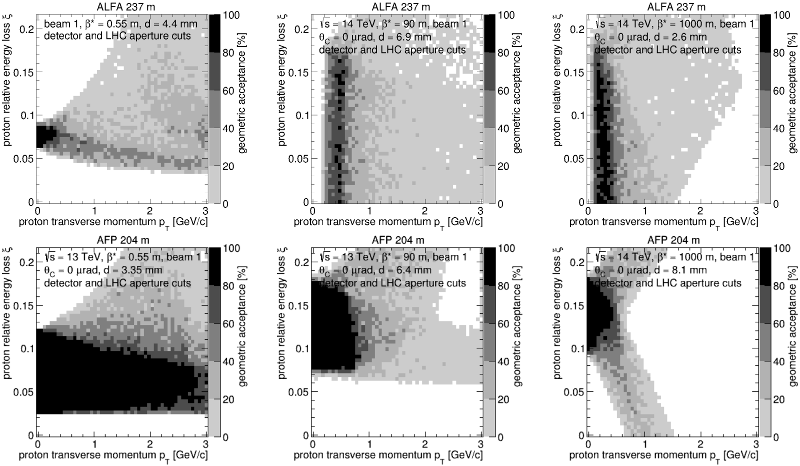
$\beta^* = 0.55$ m
nominal (*collision*)

$\beta^* = 90$ m
special (*high*-β^*)

$\beta^* = 1000$ m
special (*high*-β^*)

ALFA

AFP



Soft Diffraction

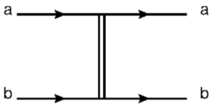
Total cross-section measurement via optical theorem

Total cross section is directly proportional to the imaginary part of the forward **elastic scattering** *amplitude extrapolated to* **zero momentum transfer***:*

$$\sigma_{tot} = 4\pi \cdot Im[f_{el}(t = 0)]$$

Elastic scattering:

- both protons stay intact,
- described by the four momentum transfer, t,
- protons are scattered at very small angles.

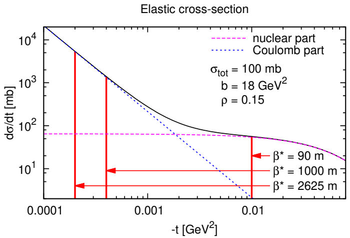


$$\left.\frac{dN}{dt}\right|_{t=0} = L\pi|f_C + f_N|^2 \approx$$

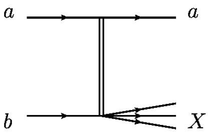
$$\approx L\pi \left| -\frac{2\alpha_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)\exp\left(\frac{-b|t|}{2}\right)\right|^2$$

red – Coulomb part, blue – nucl. part

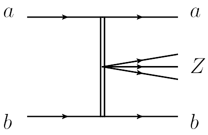
$$\rho = \left.\frac{Re\ f_{el}}{Im\ f_{el}}\right|_{t\to 0}$$



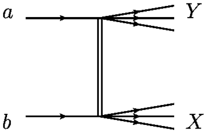
single diffraction



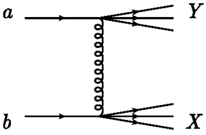
central diffraction



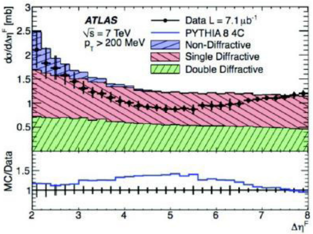
double diffraction

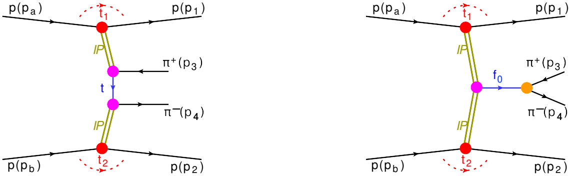


non-diffractive interaction



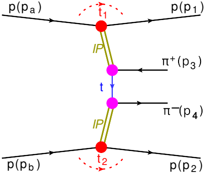
- Gap measurement in ATLAS does not distinguish SD from DD.
- Possible with the forward proton tagging.
- High cross sections → low lumi needed → low pile-up possible.
- Properties of SD – central and forward.
- Central diffraction (DPE – double Pomeron exchange).

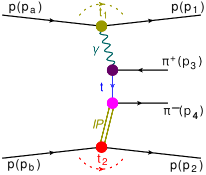


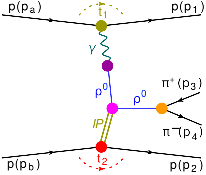


- Exclusive meson production is possible to be measured by RHIC and LHC experiments.
- Monte Carlo generator is needed in order to include detector effects (acceptance, efficiency) in theory-data comparison.
- There are few MC generators available, *e.g.* SuperCHIC, DIME.
- In Cracow, we developed a tool complementary to the existing ones in terms of implemented processes and calculation methods.
- GenEx MC generator:
  - For now, implemented models are based mainly on work of P. Lebiedowicz, A. Szczurek & co. (*e.g.* Phys. Rev. D **93** (2016) 054015),
  - non-resonant (continuum) pion and kaon pair production,
  - $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_2(1270)$, $f_2'(1520)$ and ρ_0 particles and their decays into two pions or kaons.
- Left: $pp \to p\pi^+\pi^- p$ (continuum),
- Right: $pp \to p(f_0 \to \pi^+\pi^-)p$.

Dominant diagram: Pomeron induced continuum (left).
However, photon induced continuum (centre) with ρ^0 photoproduction (right) on top of it are also possible.







- Theoretical model: Lebiedowicz-Nachtmann-Szczurek, [1] Phys. Rev. D **91** (2015) 074023.
- Processes will be added to GenEx MC generator.
- Feasibility studies of the ρ^0 photoproduction for ATLAS to be done.
- Exclusive pion measurements at 7 and 8 TeV with ALFA@ATLAS are under way.

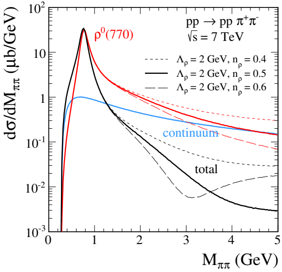
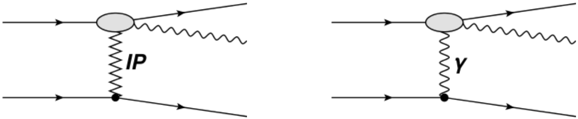
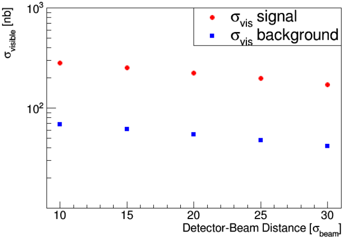


Fig. Two-pion invariant mass distributions at $\sqrt{s}$ = 7 TeV. No ATLAS selection applied. From [1].



- Pomeron or photon induced process.
- Production described by models of *e.g.*:
  - Khoze-Lamsa-Orava-Ryskin, JINST **6** (2011) P01005,
  - Lebiedowicz-Szczurek, Phys. Rev. D **87** (2013) 114013.
- Implemented in *e.g.* GENEX MC generator (Comm. in Comp. Phys. **24** 860).
- Measurement idea:
  - measure protons in ALFA and photon in ZDC,
  - described in: [1] Eur. Phys. J. C **77** (2017) 216.



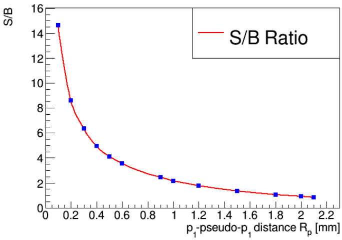
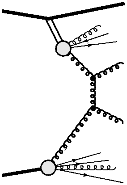


Fig. Predictions for ATLAS. **Left**: *visible cross-sections for signal and background as a function of beam-detector distance.* **Right**: *signal to background ratio. From [1].*

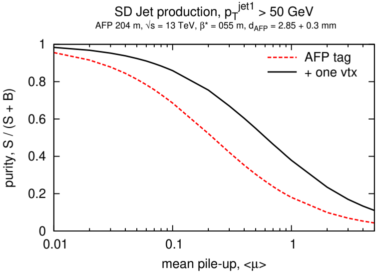
Hard Diffraction

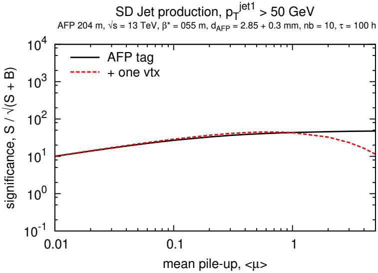


Motivation:

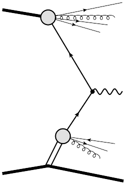
- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- check Pomeron universality between *ep* and *pp* colliders.

Example: purity and statistical significance for AFP and $\beta^* = 0.55$ m.





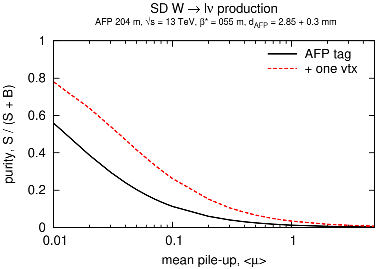
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

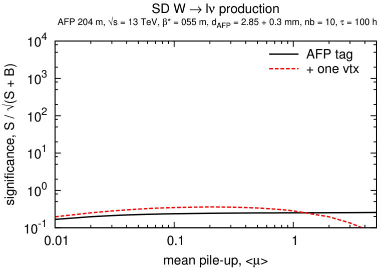


Motivation:

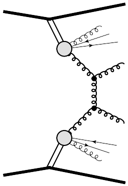
- measure cross section and gap survival probability,
- measure structure and flavour composition of Pomeron,
- search for the charge asymmetry.

Example: $W \to l\nu$ – purity and stat. significance for AFP and $\beta^* = 0.55$ m.



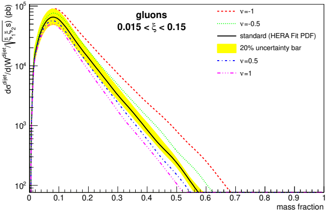


W asymmetry studies published in: Phys.Rev. D 84 (2011) 114006
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

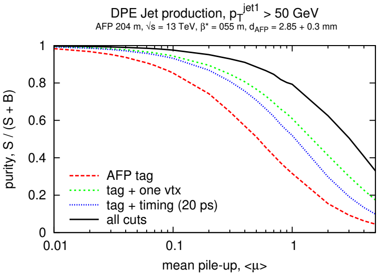


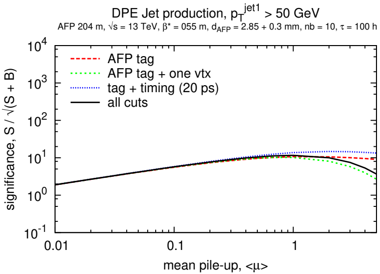
Motivation:

- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- investigate gluon structure of the Pomeron.



Example: purity and statistical significance for AFP and $\beta^* = 0.55$ m.





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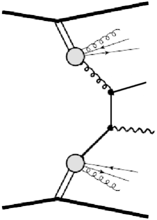
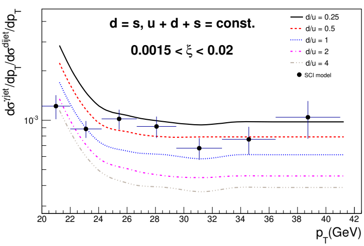
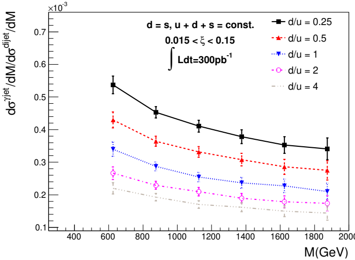


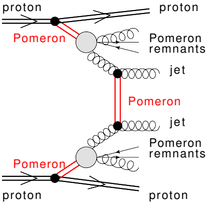
Motivation:

- measure cross section and gap survival probability,
- sensitive to the quark content in Pomeron (at HERA it was assumed that $u = d = s = \bar{u} = \bar{d} = \bar{s}$).



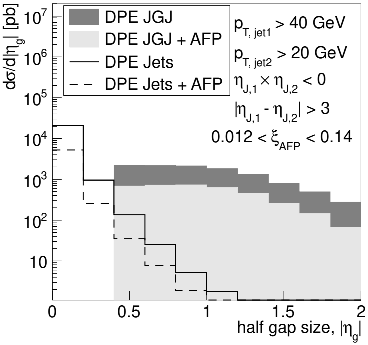


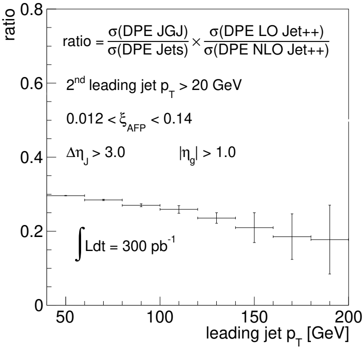
More details in: Phys.Rev. D 88 (2013) 7, 074029



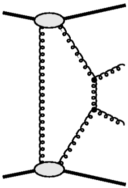
Motivation:

- measure cross section and gap survival probability,
- test the BFKL model.





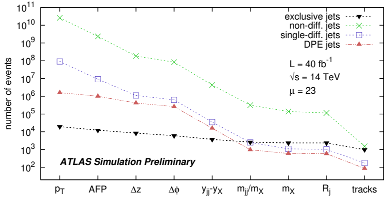
More details in: Phys.Rev. D 87 (2013) 3, 034010

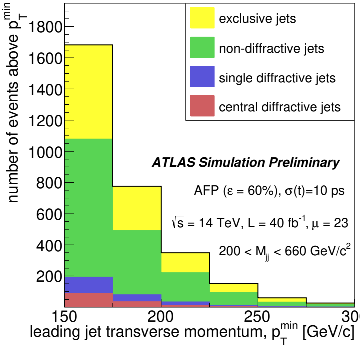


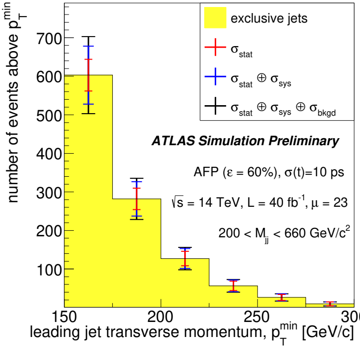
Exclusive Production

Motivation:

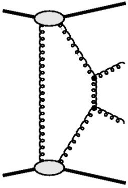
- cross section measurement for jets with $p_T > 150$ GeV,
- constrain other exclusive productions (*e.g.* Higgs).





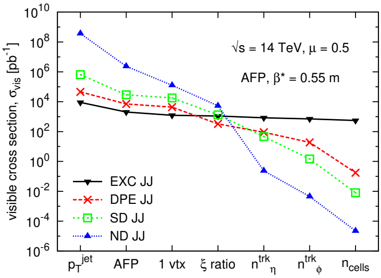


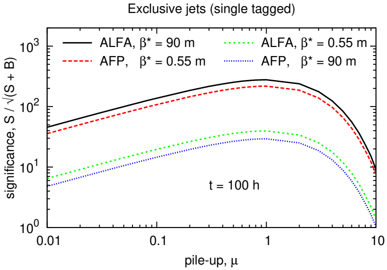
More details in: ATL-PHYS-PUB-2015-003



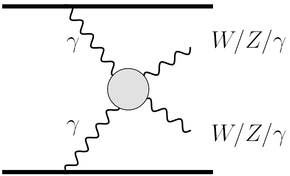
Motivation:

- cross section measurement for low p_T jets,
- constrain other exclusive productions (*e.g.* Higgs).





More details in: Eur. Phys. J. C **75** (2015) 320 and Acta Phys. Pol. B **47** (2016) 1745



- Quartic Gauge Couplings – testing BSM models.
- Constrained kinematics $\rightarrow$ low background.
- Reaching limits predicted by string theory and grand unification models (10^{-14} – 10^{-13} for $\gamma\gamma\gamma\gamma$).

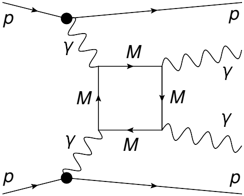
$\gamma\gamma WW$ and $\gamma\gamma ZZ$

Coupling	OPAL limits [GeV2]	Sensitivity for 200 fb1 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	$2.7 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
a_C^W/Λ^2	[-0.052, 0.037]	$9.6 \cdot 10^{-6}$	$5.2 \cdot 10^{-6}$
a_0^Z/Λ^2	[-0.007, 0.023]	$5.5 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$
a_C^Z/Λ^2	[-0.029, 0.029]	$2.0 \cdot 10^{-5}$	$9.2 \cdot 10^{-6}$

$\gamma\gamma\gamma\gamma$

Coupling (GeV^{-4})	1 conv. γ 5σ	1 conv. γ 95% CL	all 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$7 \cdot 10^{-14}$	$4 \cdot 10^{-14}$
ζ_1 no f.f.	$3 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$
ζ_2 f.f.	$3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8 \cdot 10^{-14}$
ζ_2 no f.f.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$

- **Main idea:** production of objects in which background can be extremely reduced by kinematic constraints coming from forward proton measurements (high mass).
- Production of magnetic monopoles:



- Invisible objects: central system escape (or is not measurable), but scattered protons can be measured.
- SUSY sparticle production: precise mass and quantum numbers measurement.
- Any production of new objects (with mass up to 2 TeV) *via* photon or gluon exchanges.

- Intact protons $\rightarrow$ natural diffractive signature $\rightarrow$ usually scattered at very small angles (μrad) $\rightarrow$ detectors must be located far form the IP.

- Two forward detectors systems in ATLAS (similar situation in CMS):
  - ALFA – existing vertical RPs located 240 m from IP1,
  - AFP – planned horizontal RPs located 210 m from IP1.

- **Many interesting results shall be published soon as ATLAS (and CMS) took interesting data at:**
  - very low pile-up ($\mu \sim 0.05$):
    - detectors: ALFA or AFP,
    - optics: collision or high β^*, few very low intensity bunches,
    - measure total cross section and properties of soft diffraction,
  - low pile-up ($\mu \sim 1$):
    - detectors: ALFA or AFP,
    - optics: collision or high β^*, low intensity bunches,
    - measure properties of hard diffraction:
      SD JJ, SD JGJ, SD W, SD Z, DPE JJ, DPE JGJ, DPE γ+jet, exclusive jets (single tag),
  - high pile-up ($\mu \sim 50$):
    - detectors: AFP,
    - optics: collision, join all ATLAS runs,
    - measure exclusive production and discovery physics:
      exclusive jets, anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$.

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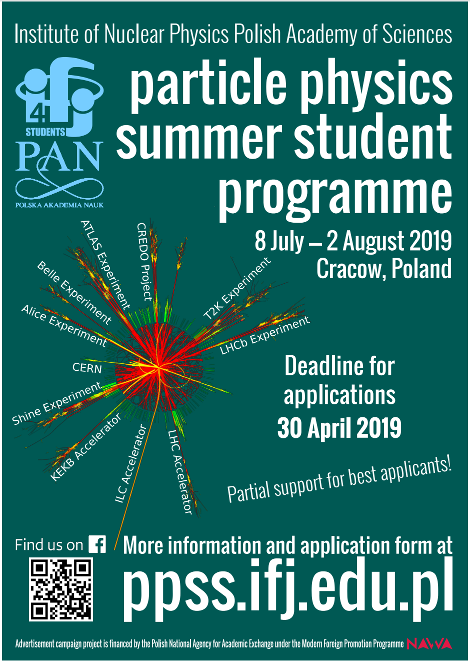
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