Diffractive Physics with Forward Proton Tagging at the LHC

Maciej Trzebiński

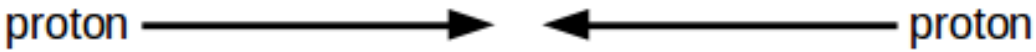
Institute of Nuclear Physics
Polish Academy of Sciences

Laboratory of Instrumentation and Experimental Particle Physics

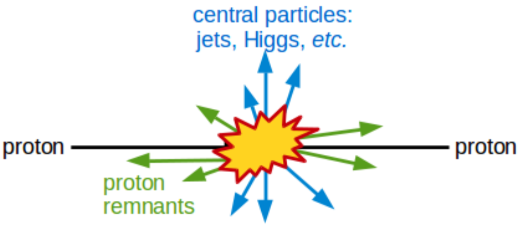
Lisbon, Portugal

17th April 2019

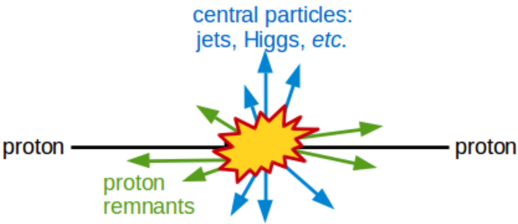
Usual situation at the LHC:

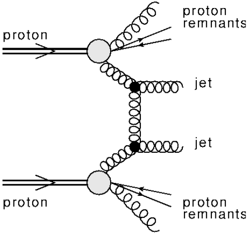


Usual situation at the LHC:

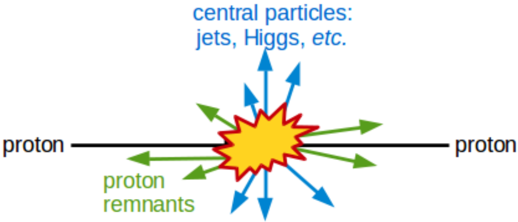


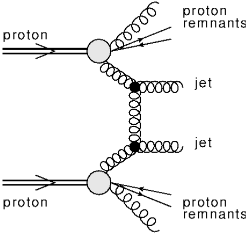
Usual situation at the LHC:





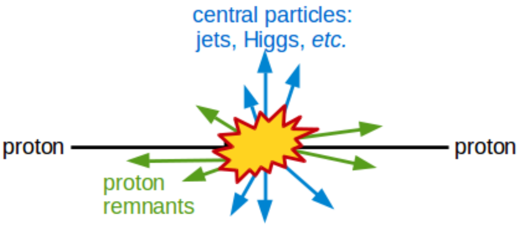
Usual situation at the LHC:

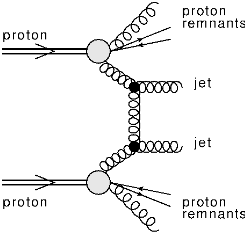




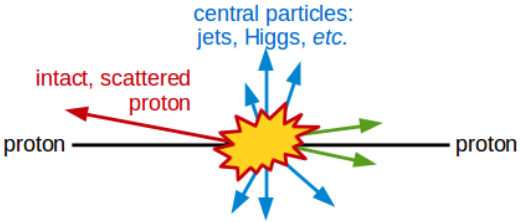
Can proton(s) remain intact?

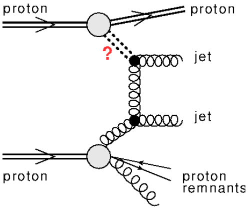
Usual situation at the LHC:



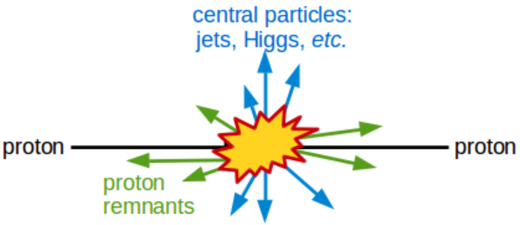


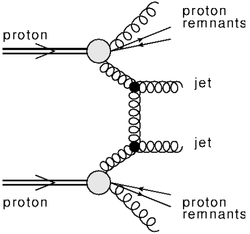
Can proton(s) remain intact?



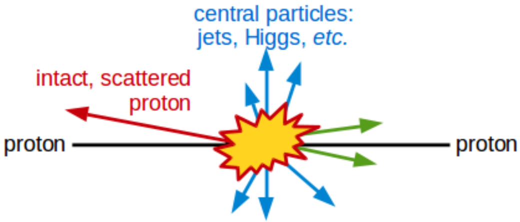


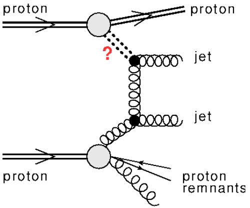
Usual situation at the LHC:





Can proton(s) remain intact?



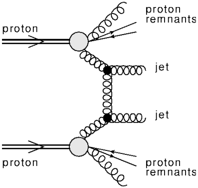


Yes! But exchanged object must not change quantum numbers of proton(s):

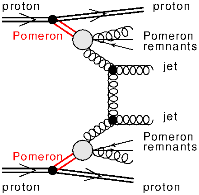
- electromagnetic force: photon,
- strong force: Pomeron (QCD = two gluons + h.o. terms).

Physics Processes

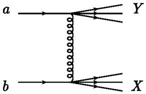
- **hard** – perturbative approach is valid; small cross-sections:
  - non-diffractive



  - diffractive

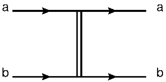


- **soft** – large cross-sections:
  - non-diffractive:

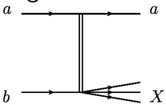


  - diffractive:

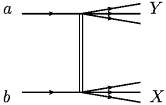
Elastic Scattering



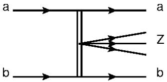
Single Diffraction



Double Diffraction



Central Diffraction



Diffraction:

- colour singlet exchanged,
- Pomeron (QCD = two gluons + ...).

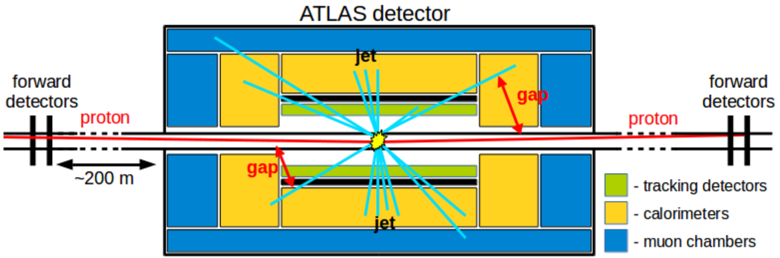
Natural ways to seek for diffraction:

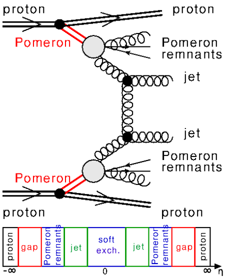
- rapidity gaps,
- **forward protons**.

Measurement Idea

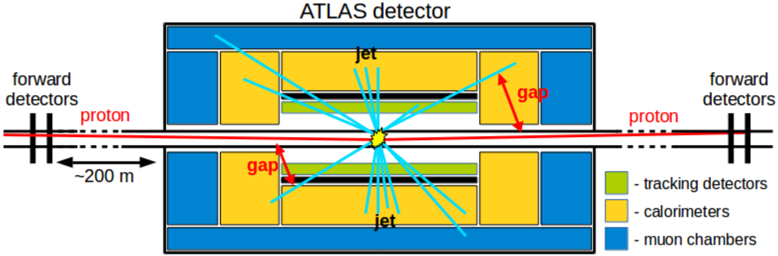
Assumption: one would like to measure diffractive interactions at the LHC.

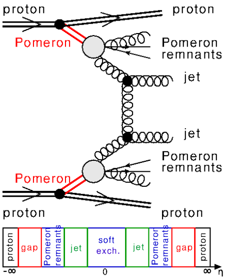
Assumption: one would like to measure diffractive interactions at the LHC.
Typical diffractive topology: a gap in rapidity is present between proton(s) and central system and one or both interacting proton stay intact.





Assumption: one would like to measure diffractive interactions at the LHC.
Typical diffractive topology: a gap in rapidity is present between proton(s) and central system and one or both interacting proton stay intact.

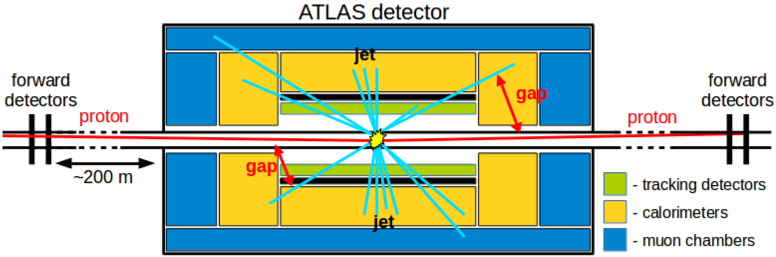


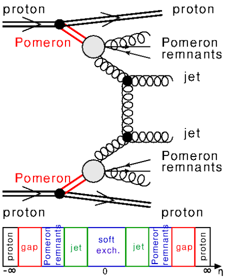


Method 1 (rapidity gap):

+ 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

Assumption: one would like to measure diffractive interactions at the LHC.
Typical diffractive topology: a gap in rapidity is present between proton(s) and central system and one or both interacting proton stay intact.





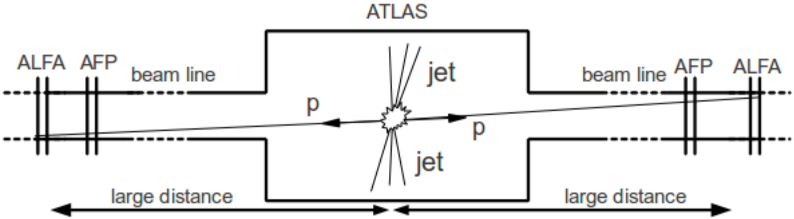
Method 1 (rapidity gap):

+ 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

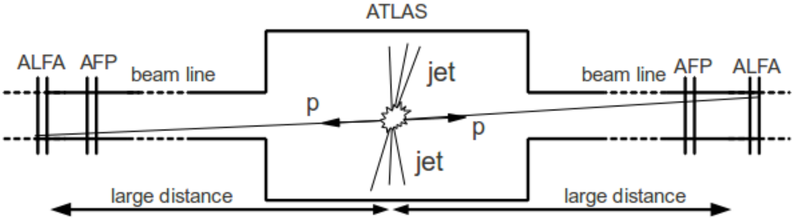
Method 2 (forward protons):

+ 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.



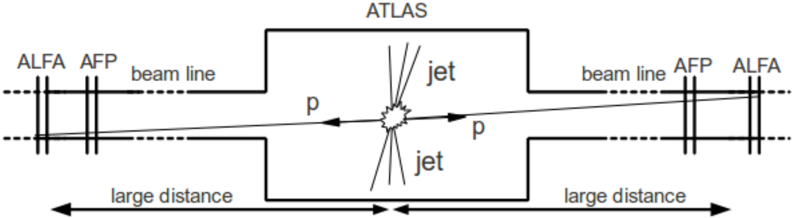
Intact protons → natural diffractive signature → usually scattered at very small angles (μrad) → detectors must be located far from the Interaction Point.



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

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



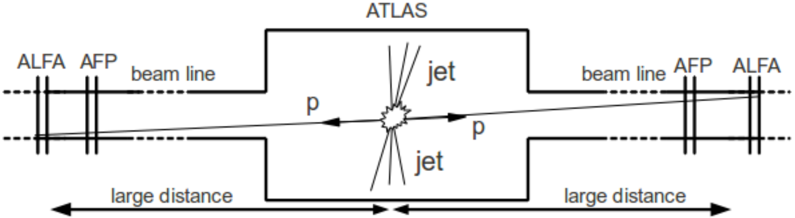
ALFA

- **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

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

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



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

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

Similar devices @ IP5: CMS-TOTEM.

Luminosity: $L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F$

- N_1 **and** N_2 **– number of protons per bunch in beam 1 and 2,**
- n **– number of bunches per beam,**
- f – revolution frequency,
- γ – beam Lorentz factor,
- ε – beam emittance,
- β^* **– betatron function at the IP,**
- F – luminosity reduction factor due to the crossing angle at the IP.

Luminosity: $L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F$

- N_1 **and** N_2 **– number of protons per bunch in beam 1 and 2,**
- n **– number of bunches per beam,**
- f – revolution frequency,
- γ – beam Lorentz factor,
- ε – beam emittance,
- β^* **– betatron function at the IP,**
- F – luminosity reduction factor due to the crossing angle at the IP.

Data collecting strategies

Luminosity: $L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F$

- N_1 **and** N_2 **– number of protons per bunch in beam 1 and 2,**
- n **– number of bunches per beam,**
- f – revolution frequency,
- γ – beam Lorentz factor,
- ε – beam emittance,
- β^* **– betatron function at the IP,**
- F – luminosity reduction factor due to the crossing angle at the IP.

Data collecting strategies

hard processes, potential discoveries

⇓

small cross sections

⇓

rare events

⇓

much luminosity needed

⇓

maximise N_1, N_2, n, $1/\beta^*$

forward protons: access to wide range
of relative energy loss (ξ)

Luminosity: $L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F$

- **N_1 and N_2 – number of protons per bunch in beam 1 and 2,**
- **n – number of bunches per beam,**
- f – revolution frequency,
- γ – beam Lorentz factor,
- ε – beam emittance,
- **β^* – betatron function at the IP,**
- F – luminosity reduction factor due to the crossing angle at the IP.

Data collecting strategies

hard processes, potential discoveries
⇓
small cross sections
⇓
rare events
⇓
much luminosity needed
⇓
maximise N_1, N_2, n, $1/\beta^*$

forward protons: access to wide range of relative energy loss (ξ)

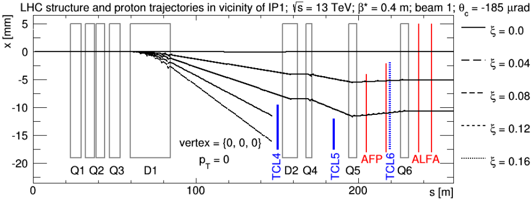
soft processes, elastic scattering
⇓
large cross sections
⇓
clean environment needed
⇓
minimise pile-up, pp interactions within a beam and beam divergence
⇓
optimise N_1, N_2, n, β^*

forward protons: access to as low $|t|$ values as possible

Proton trajectory is determined by the LHC magnetic field.

Proton trajectory is determined by the LHC magnetic field.

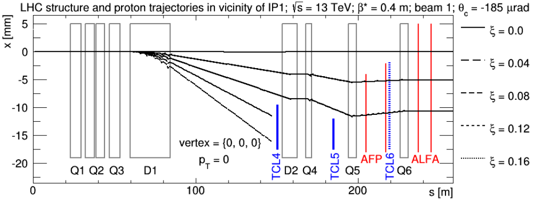
collision optics,
ALFA and **AFP**:
trajectory due to ξ
$\xi = 1 - E_{proton}/E_{beam}$



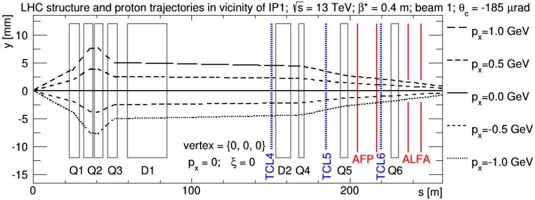
Proton trajectory is determined by the LHC magnetic field.

collision optics, **ALFA** and **AFP**: trajectory due to ξ

$\xi = 1 - E_{proton}/E_{beam}$



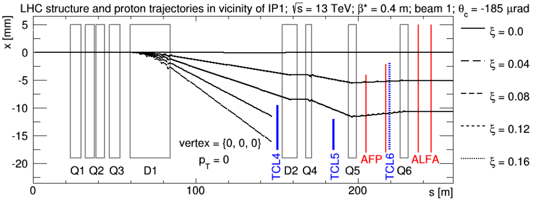
collision optics, **ALFA** and **AFP**: trajectory due to p_y



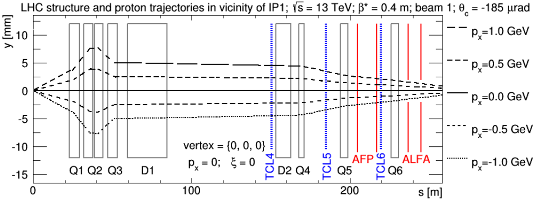
Proton trajectory is determined by the LHC magnetic field.

collision optics, **ALFA** and **AFP**: trajectory due to ξ

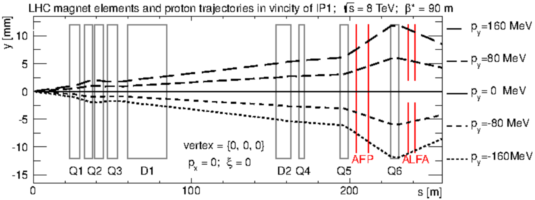
$\xi = 1 - E_{proton}/E_{beam}$



collision optics, **ALFA** and **AFP**: trajectory due to p_y



special high-β^* optics, **ALFA**: improve acceptance in $p_T = \sqrt{px^2 + py^2}$



From SPIE 9290 (2014) 929026, arXiv:1408.1836

Geometric Acceptance for Various Optics

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

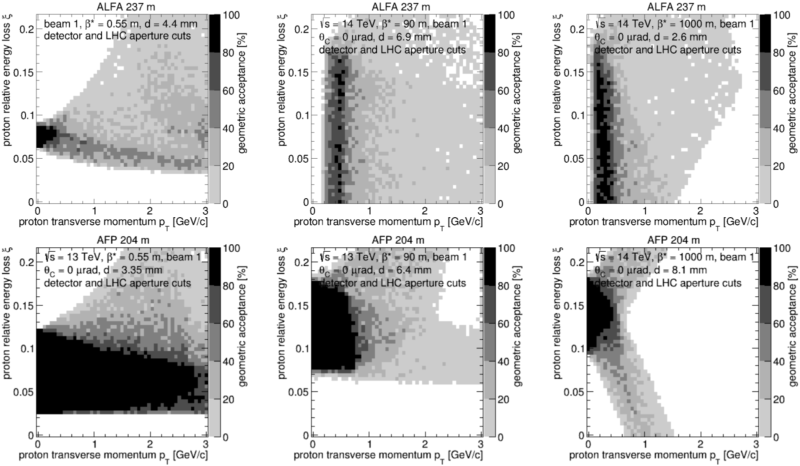
$\beta^* = 0.55$ m
nominal (*collision*)

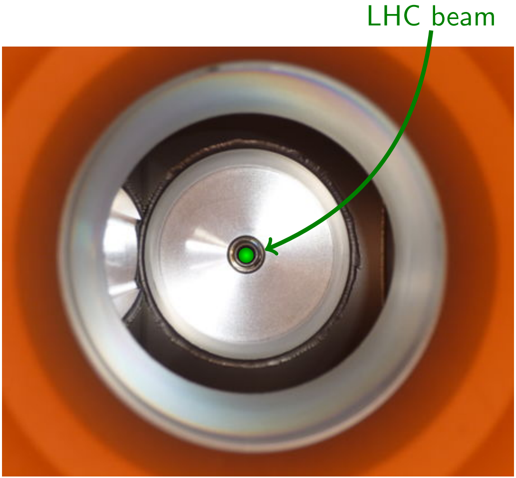
$\beta^* = 90$ m
special (*high-β^**)

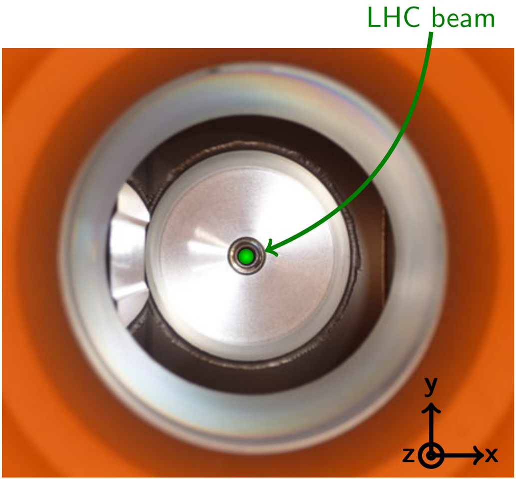
$\beta^* = 1000$ m
special (*high-β^**)

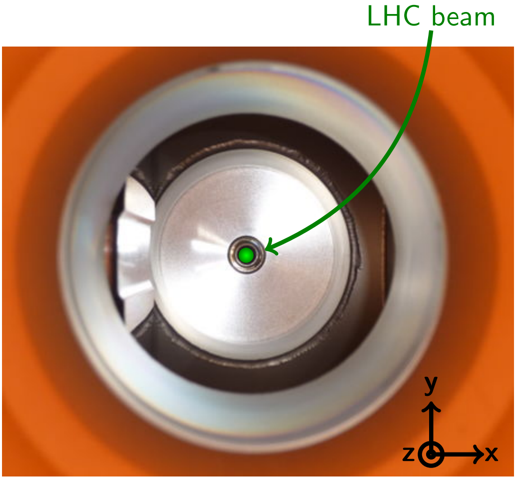
ALFA

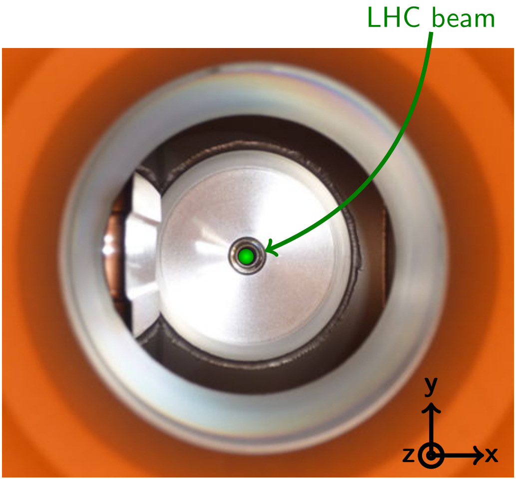
AFP

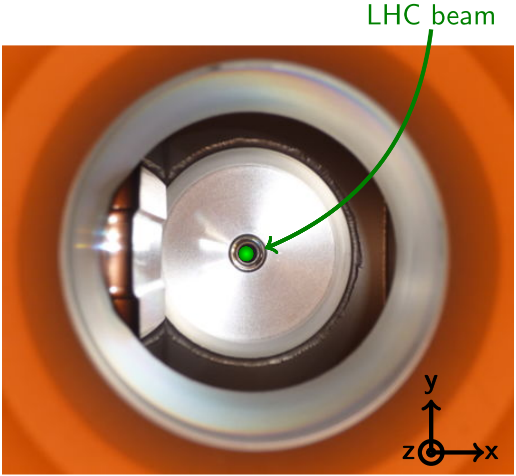


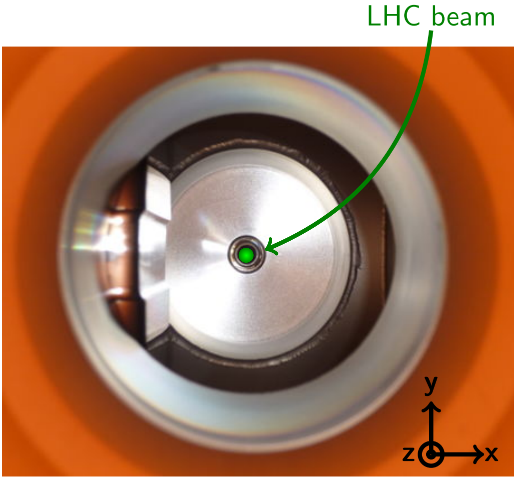

LHC beam

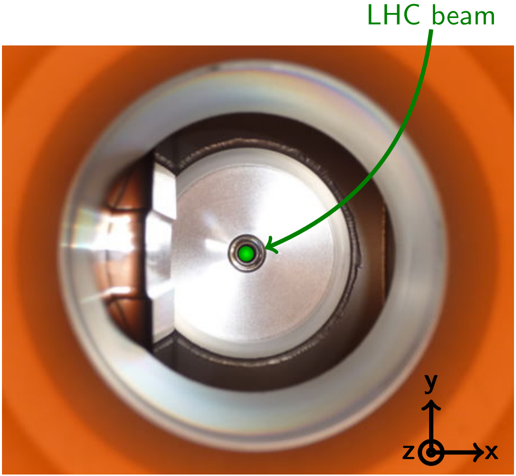

LHC beam
y
z
x


LHC beam
y
z
x

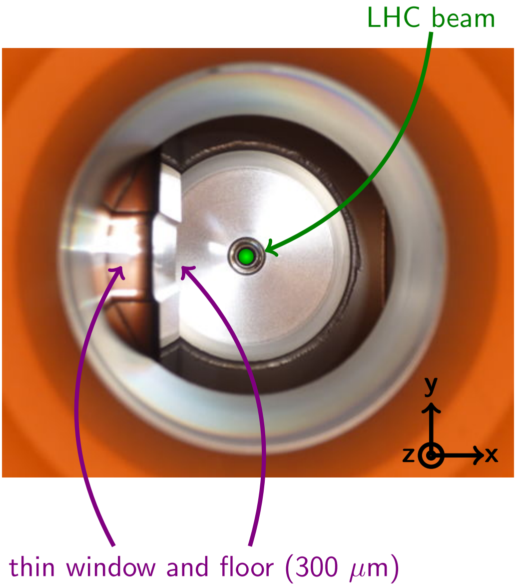

LHC beam
y
z
x


LHC beam
y
z
x

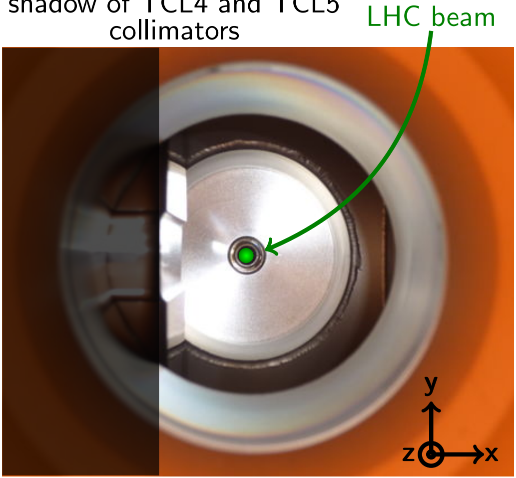

LHC beam
y
z
x


LHC beam
y
z
x

Advantages of Roman Pot Technology

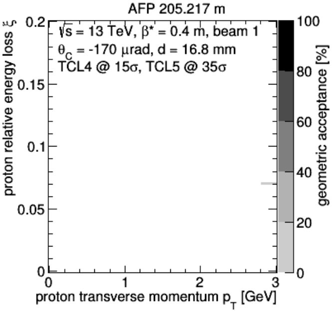


shadow of TCL4 and TCL5 collimators

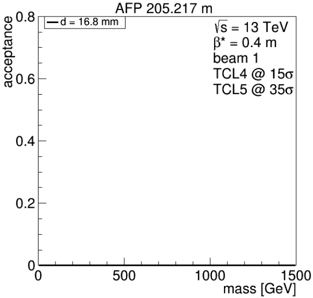


thin window and floor (300 μm)

Geometric acceptance:

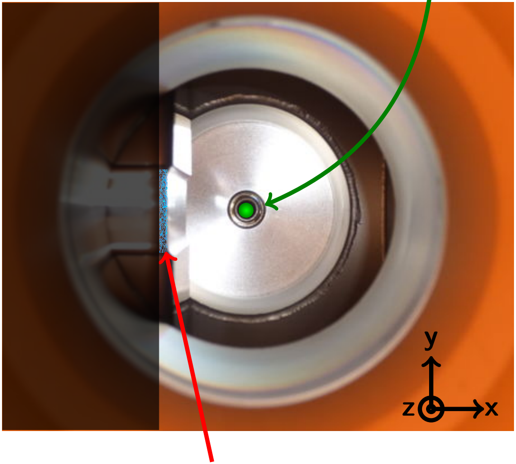


Mass acceptance:



shadow of TCL4 and TCL5 collimators

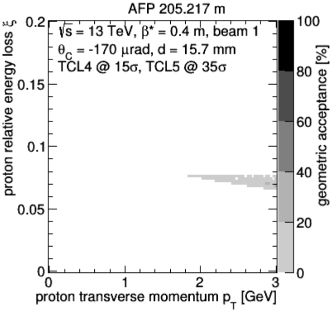
LHC beam



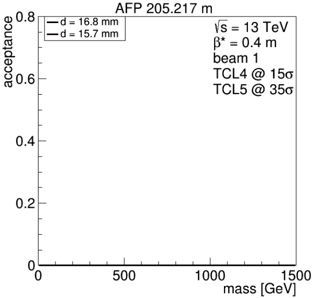
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

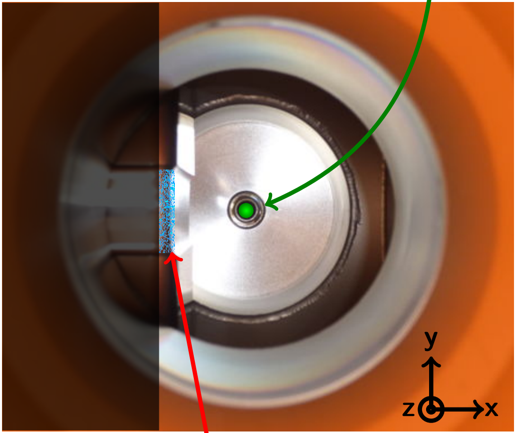


Mass acceptance:



shadow of TCL4 and TCL5 collimators

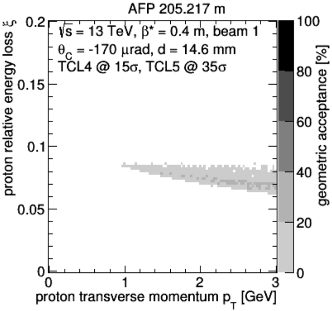
LHC beam



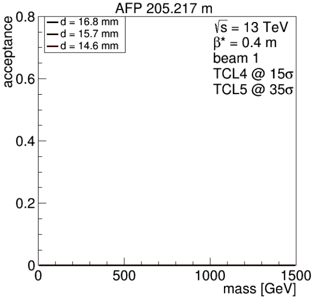
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

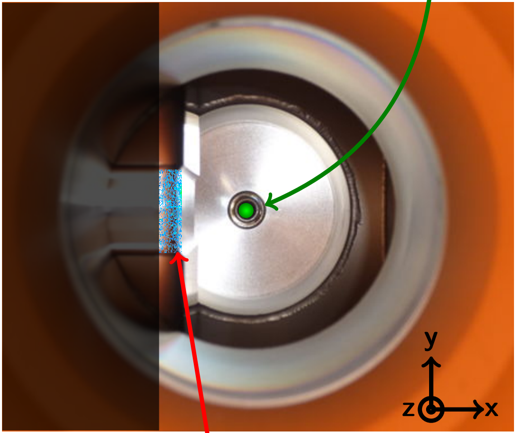


Mass acceptance:



shadow of TCL4 and TCL5 collimators

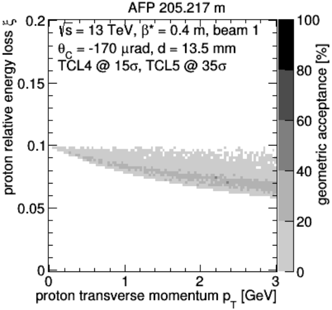
LHC beam



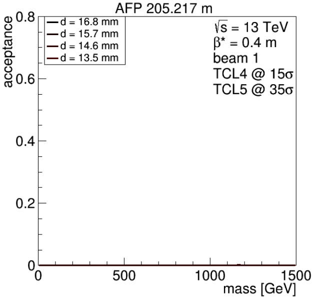
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

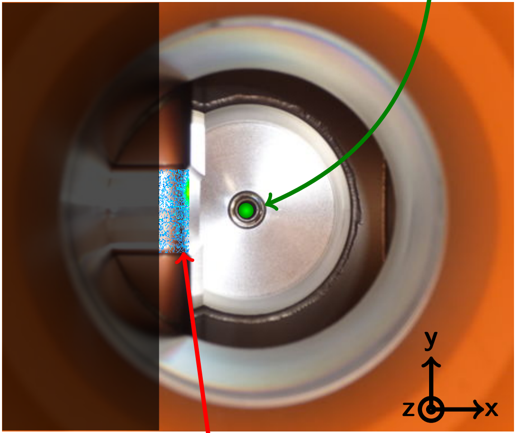


Mass acceptance:



shadow of TCL4 and TCL5 collimators

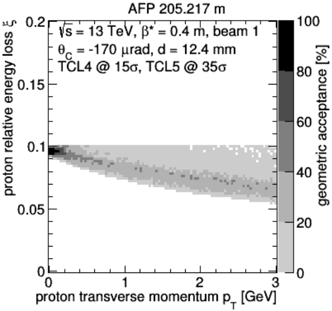
LHC beam



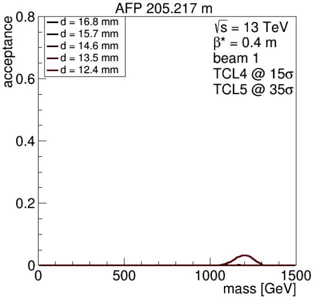
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

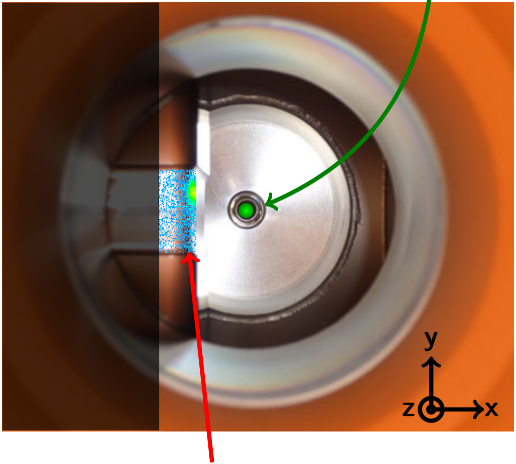


Mass acceptance:



shadow of TCL4 and TCL5 collimators

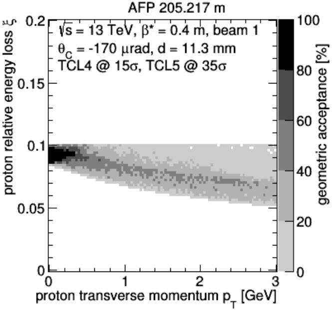
LHC beam



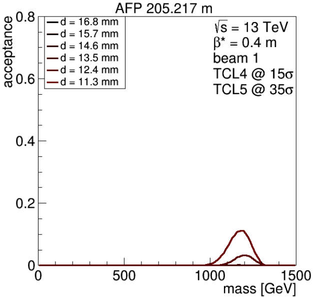
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

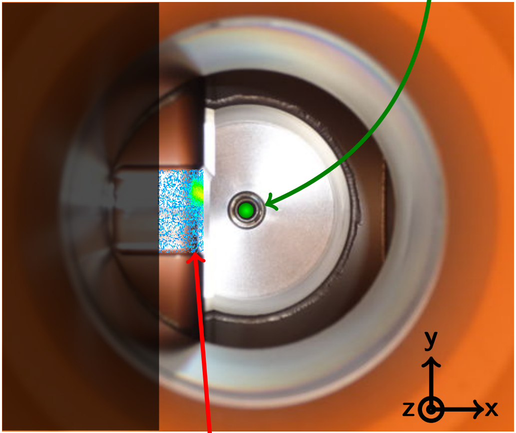


Mass acceptance:



shadow of TCL4 and TCL5 collimators

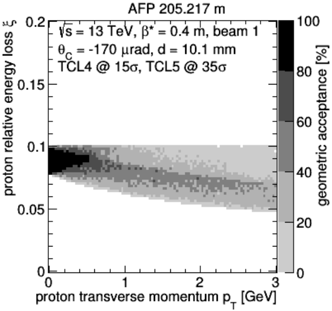
LHC beam



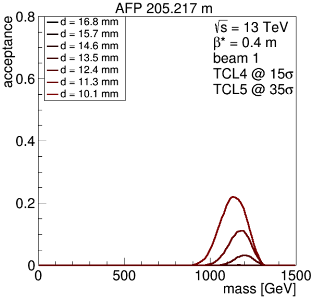
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

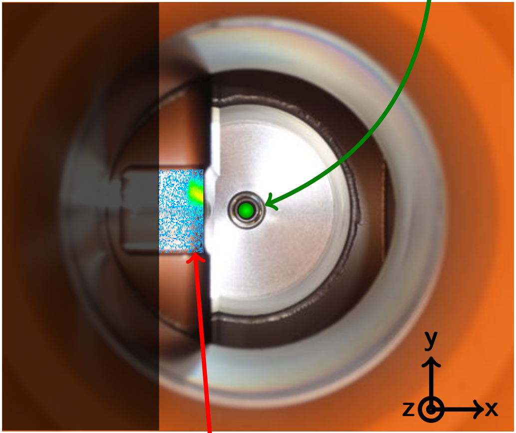


Mass acceptance:



shadow of TCL4 and TCL5 collimators

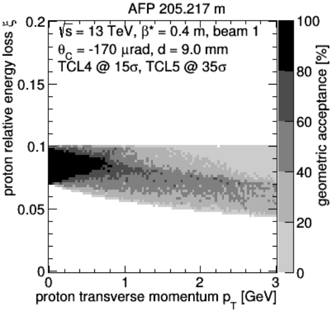
LHC beam



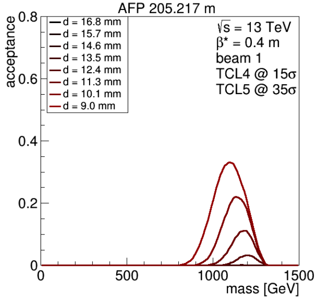
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:



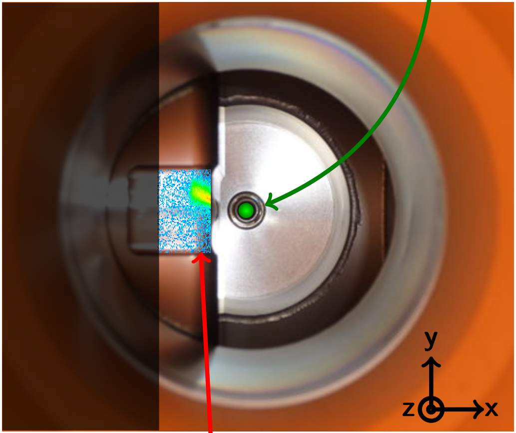
Mass acceptance:



Advantages of Roman Pot Technology

shadow of TCL4 and TCL5 collimators

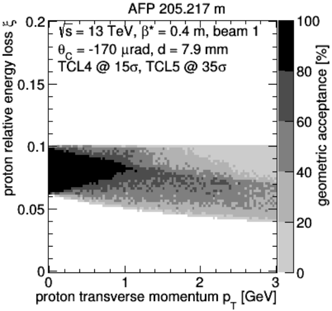
LHC beam



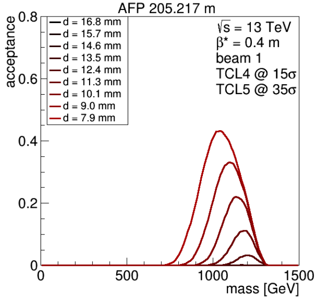
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

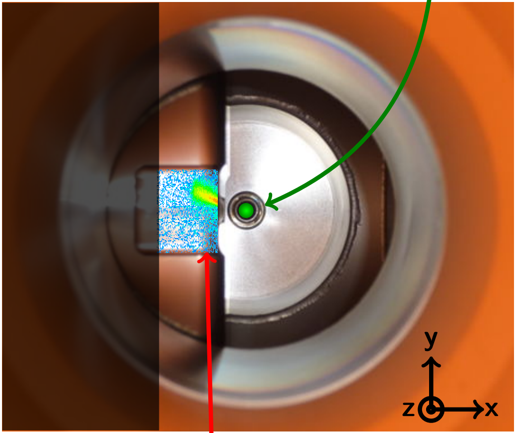


Mass acceptance:



shadow of TCL4 and TCL5 collimators

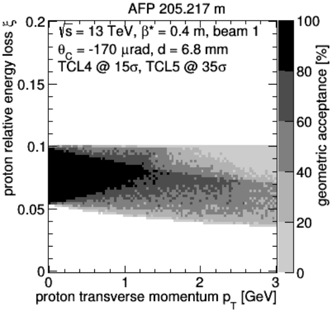
LHC beam



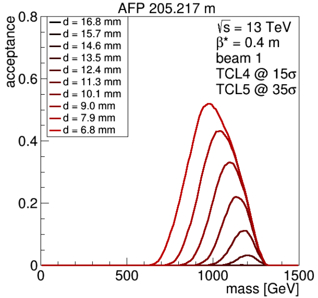
diffractive protons

thin window and floor (300 μm)

Geometric acceptance:

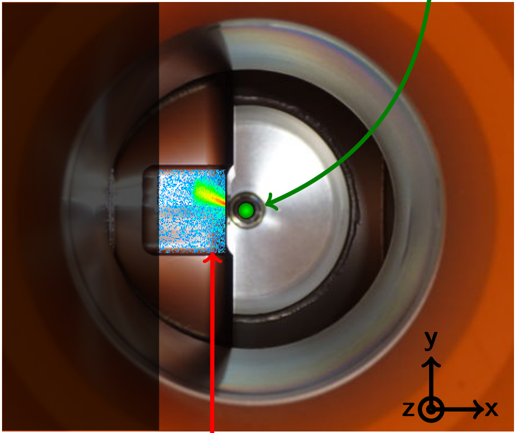


Mass acceptance:



shadow of TCL4 and TCL5 collimators

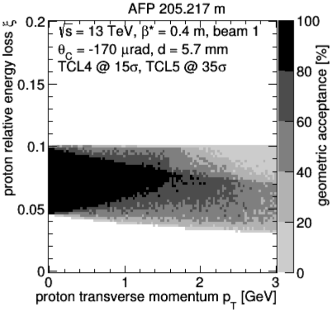
LHC beam



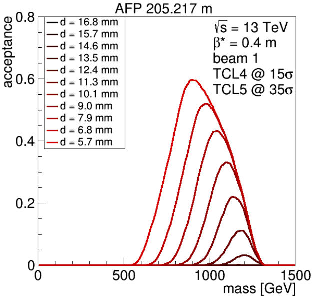
diffractive protons

thin window and floor (300 μm)

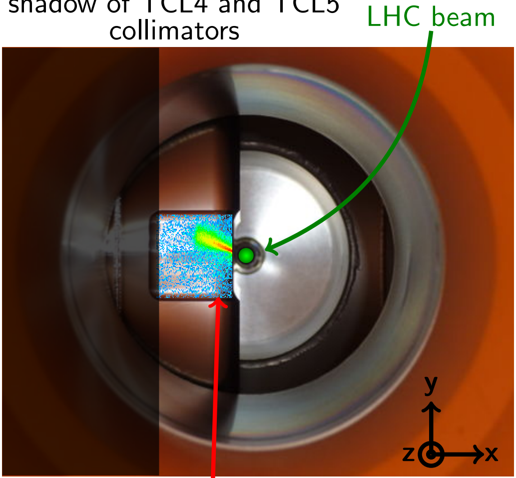
Geometric acceptance:



Mass acceptance:



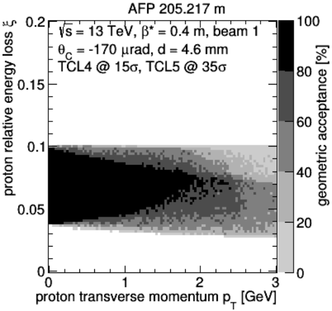
shadow of TCL4 and TCL5 collimators



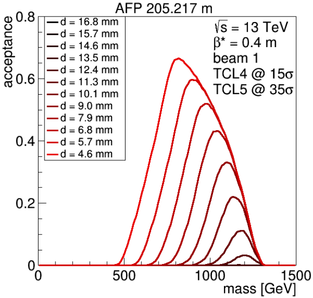
diffractive protons

thin window and floor (300 μm)

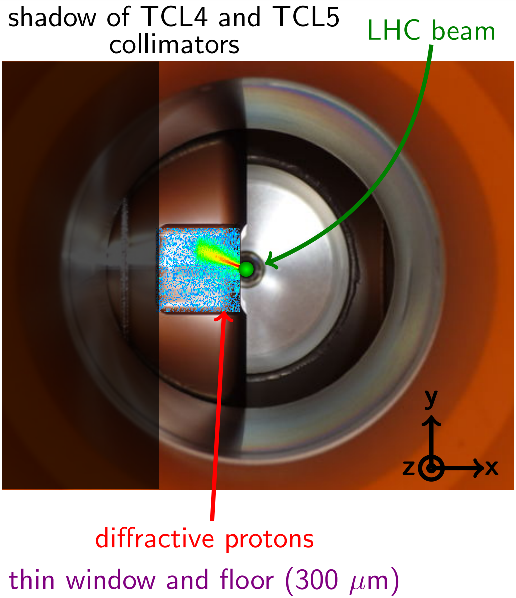
Geometric acceptance:



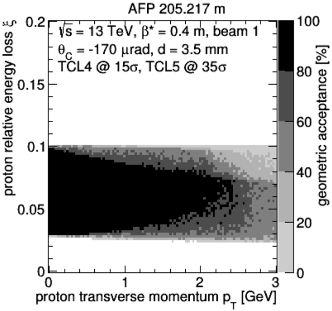
Mass acceptance:



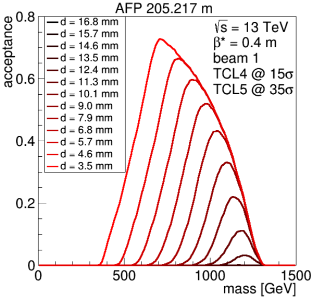
Advantages of Roman Pot Technology

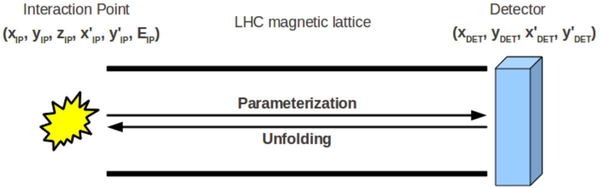


Geometric acceptance:

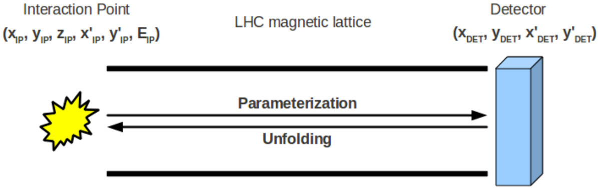


Mass acceptance:

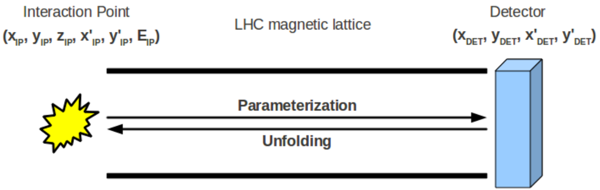




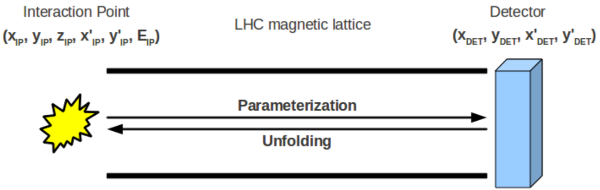
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).



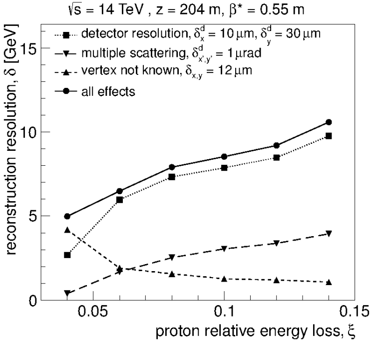
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).



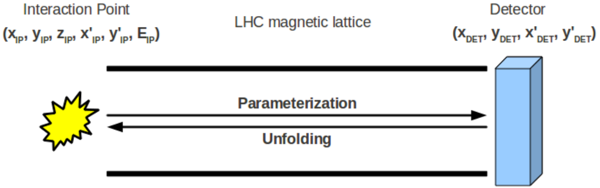
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics at the IP from their position in the AFP detector.



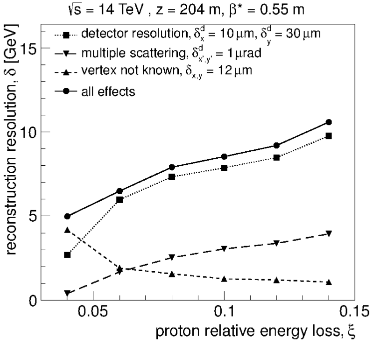
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics at the IP from their position in the AFP detector.
- Exclusivity: kinematics of scattered protons is strictly connected to kinematics of central system.



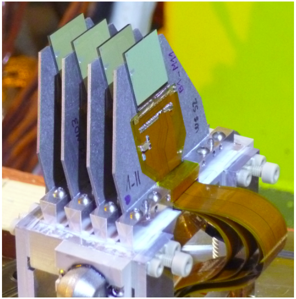
From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024

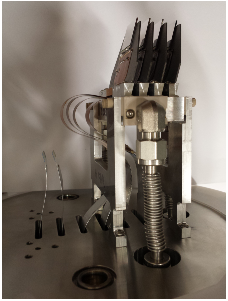


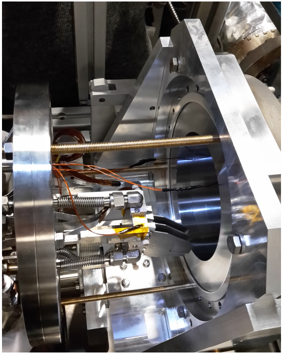
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics at the IP from their position in the AFP detector.
- Exclusivity: kinematics of scattered protons is strictly connected to kinematics of central system.
- Detector resolution play important role in precision of such method.



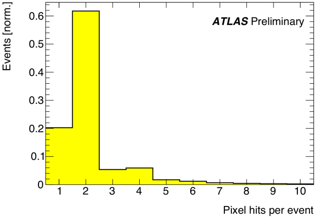
From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024



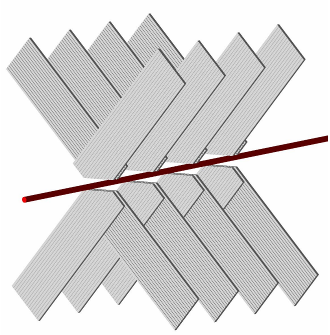


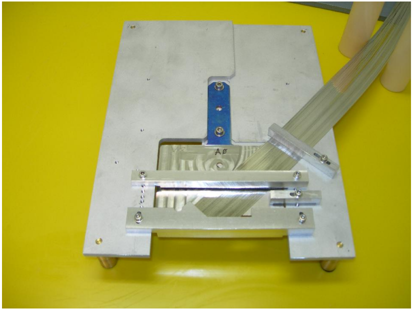


- Four detectors in each station.
- Technology: slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- Pixel size: 50x250 μm^2.
- Tilted by 14^0 to improve resolution in x.
- Resolution: $\sim$6 μm in x and $\sim$30 μm in y.
- Trigger: majority vote (2 out of 3; two chips in FAR station are paired and vote as one).



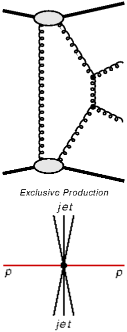
From JINST **11** (2016) P09005; JINST **12** (2017) C01086



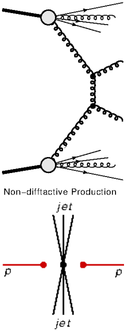


- Near stations: 237 m from ATLAS Interaction Point (IP).
- Far stations: till 2014 – 241 m, after 2014 – 245 m from ATLAS IP.
- Each station contains:
  - four outer detectors (OD) for precise alignment,
  - two main detectors (MD):
    - 10 + 10 layers of 64 fibres,
    - UV geometry,
    - trigger.
- More details in: JINST **11** (2016) P11013.

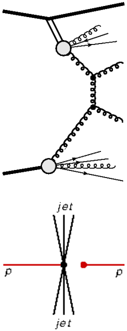
signal



background

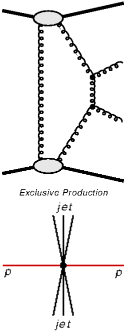


background

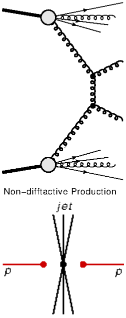


How to Reduce Physics Background?

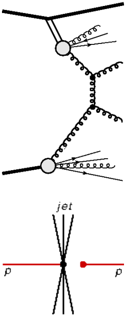
signal



background

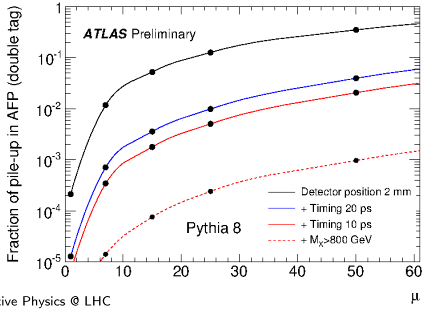


background

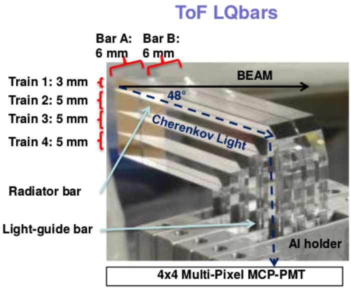


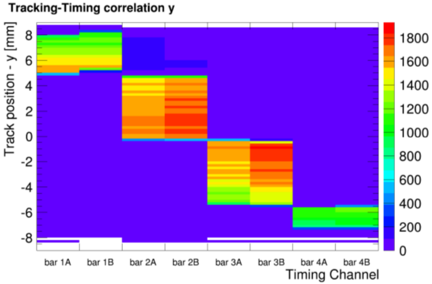
Idea:

- measure difference of time of flight of scattered protons, $(t_A - t_C)/2$
- compare to vertex reconstructed by ATLAS, $(t_A - t_C) \cdot c/2 - z_{ATLAS}$



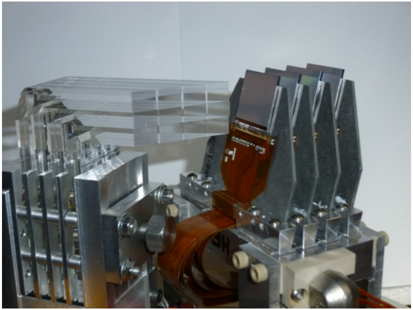
AFP: Time-of-Flight Detectors (ToF)





Setup and performance shown above are from testbeam (Opt. Express **24** (2016) 27951, JINST **11** (2016) P09005).

- 4x4 quartz bars oriented at the Cherenkov angle with respect to the beam trajectory.
- Light is directed to Photonis MCP-PMT.
- Expected resolution: ∼25 ps.
- Installed in both FAR stations.

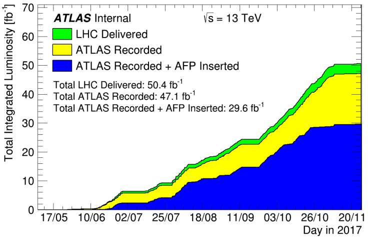


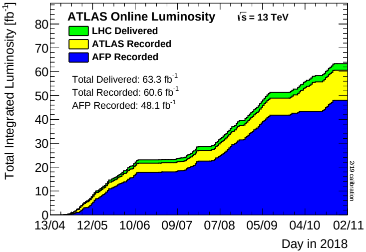
ALFA:

- data for elastic and soft diffractive analysis taken during Run 1 and Run 2,
- $\sqrt{s} = 7$, 8 and 13 TeV,
- special runs: β^* of 90, 1000 and 2500 m.

AFP:

- data taken during Run 2,
- $\sqrt{s} = 13$ TeV,
- special runs for diffraction,
- presence during standard data-taking (exclusive production and BSM).





Soft Diffraction

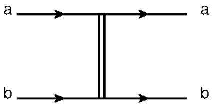
Total cross-section measurement via optical theorem

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.

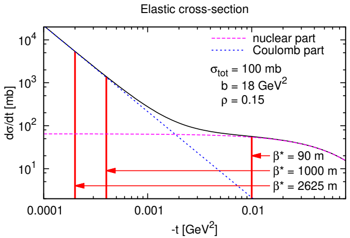


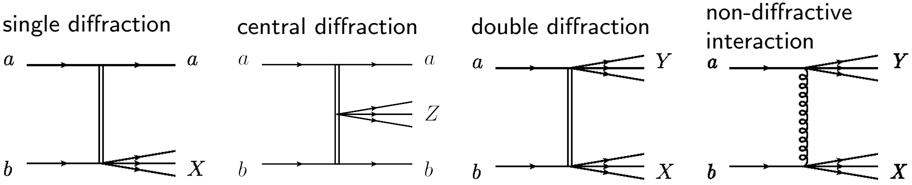
$$\left.\frac{dN}{dt}\right|_{t=0} = L\pi|f_C + f_N|^2 \approx$$

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

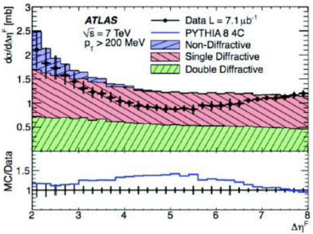
red – Coulomb part, blue – nucl. part

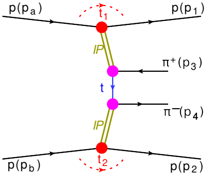
$$\rho = \left.\frac{Re\ f_{el}}{Im\ f_{el}}\right|_{t\to 0}$$

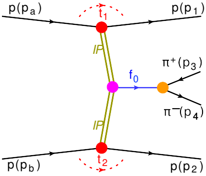




- Gap measurement in ATLAS does not distinguish SD from DD.
- Possible with the forward proton tagging.
- High cross sections → low lumi needed → low pile-up possible.
- Properties of SD – central and forward.
- Central diffraction (DPE – double Pomeron exchange).

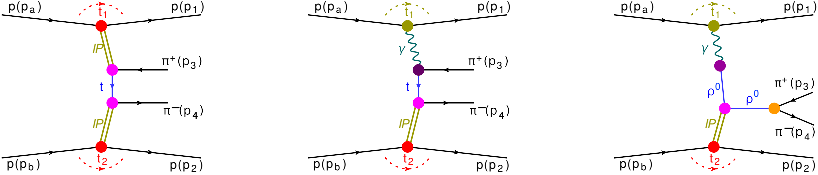






- Exclusive meson production is possible to be measured by RHIC and LHC experiments.
- Monte Carlo generator is needed in order to include detector effects (acceptance, efficiency) in theory-data comparison.
- There are few MC generators available, *e.g.* SuperCHIC, DIME.
- In Cracow, we developed a 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.

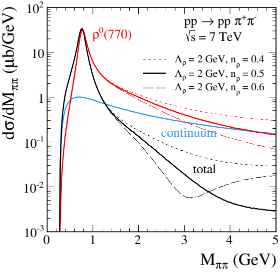
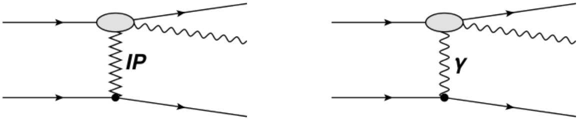
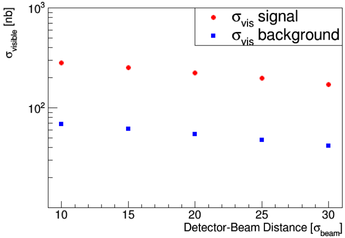


Fig. Two-pion invariant mass distributions at $\sqrt{s} = 7$ TeV. No ATLAS selection applied. From [1].



- 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.



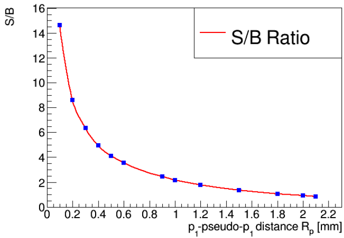
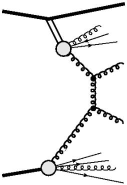


Fig. Predictions for ATLAS. **Left***: visible cross-sections for signal and background as a function of beam-detector distance.* **Right***: signal to background ratio. From [1].*

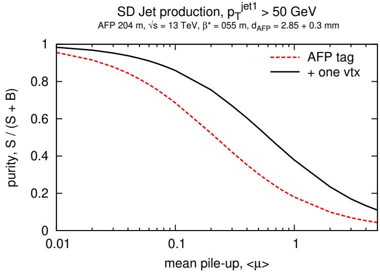
Hard Diffraction

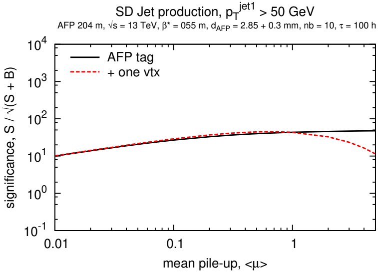


Motivation:

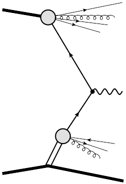
- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- check Pomeron universality between *ep* and *pp* colliders.

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





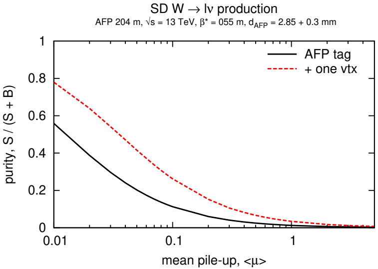
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

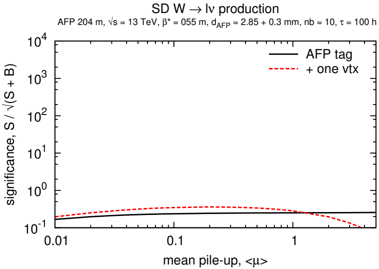


Motivation:

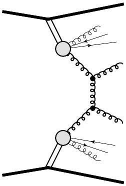
- measure cross section and gap survival probability,
- measure structure and flavour composition of Pomeron,
- search for the charge asymmetry.

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



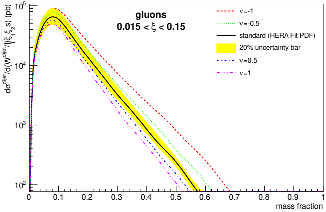


W asymmetry studies published in: Phys.Rev. D 84 (2011) 114006
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

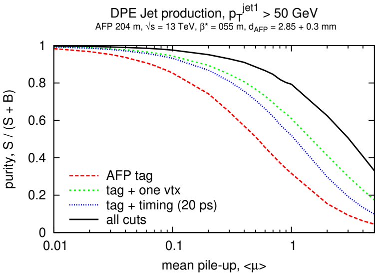


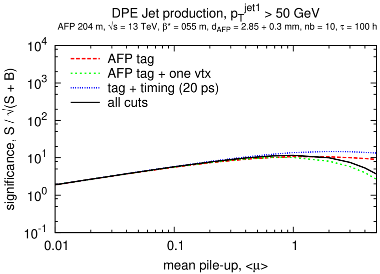
Motivation:

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

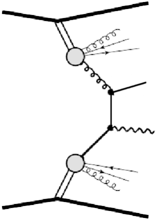


Example: purity and statistical significance for AFP and $\beta^* = 0.55$ m.



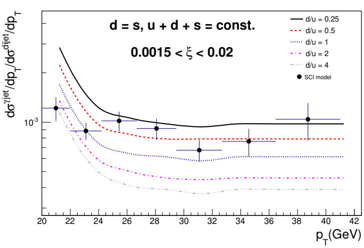


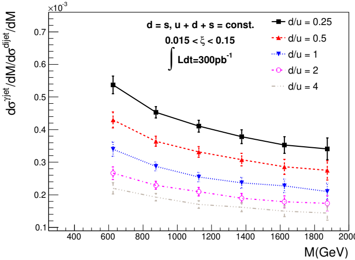
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201



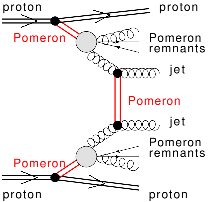
Motivation:

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



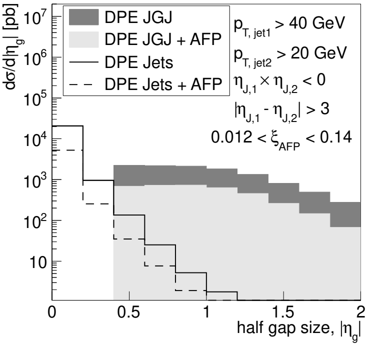


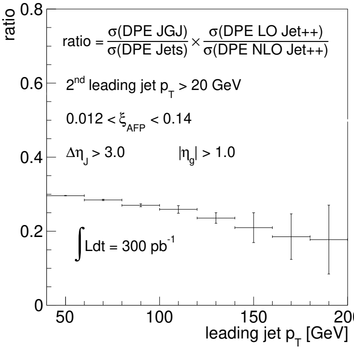
More details in: Phys.Rev. D 88 (2013) 7, 074029



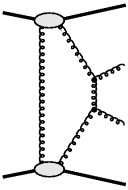
Motivation:

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



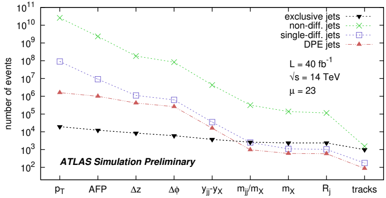


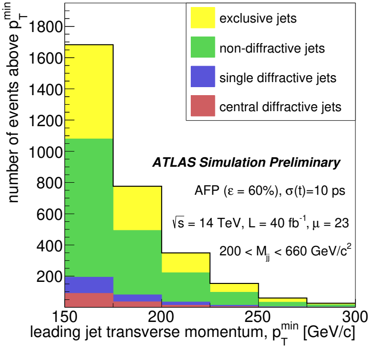
More details in: Phys.Rev. D 87 (2013) 3, 034010

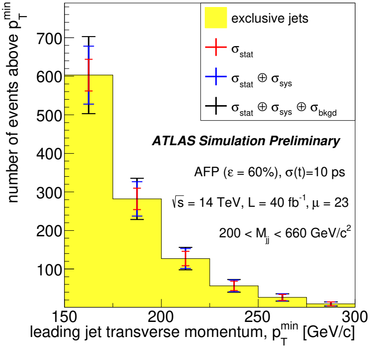


Motivation:

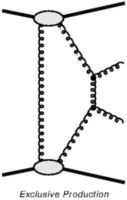
- cross section measurement for jets with $p_T > 150$ GeV,
- constrain other exclusive productions (*e.g.* Higgs).





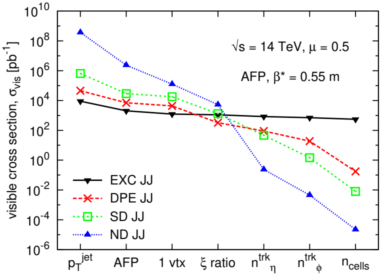


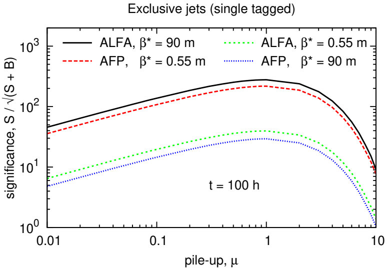
More details in: ATL-PHYS-PUB-2015-003



Motivation:

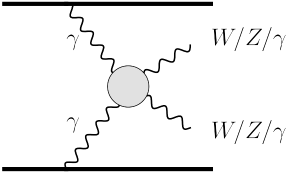
- cross section measurement for low p_T jets,
- constrain other exclusive productions (*e.g.* Higgs).





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

Anomalous couplings of gauge bosons: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$



- 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 $\gamma\gamma\gamma\gamma$).

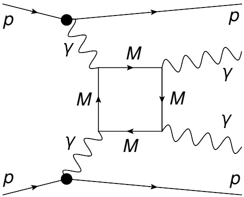
$\gamma\gamma WW$ and $\gamma\gamma ZZ$

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.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$

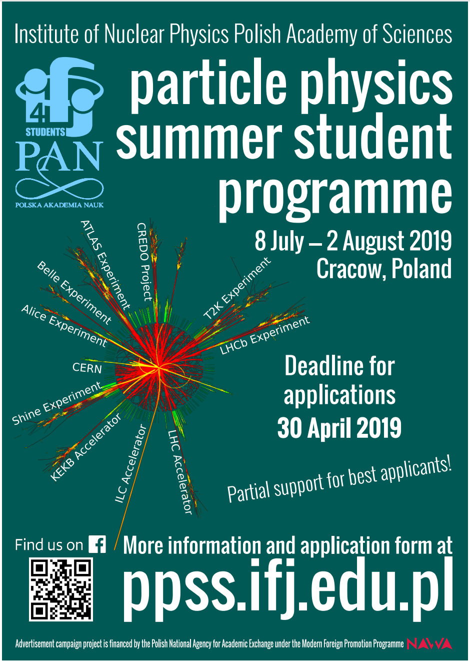
- **Main idea:** production of objects in which background can be extremely reduced by kinematic constraints coming from forward proton measurements (high mass).
- Production of magnetic monopoles:



- 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 → natural diffractive signature → usually scattered at very small angles (μrad) → 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: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$.

Advertisement campaign project is financed by the Polish National Agency for Academic Exchange under the Modern Foreign Promotion Programme NAWA


Institute of Nuclear Physics Polish Academy of Sciences
4 STUDENTS
PAN
POLSKA AKADEMIA NAUK
particle physics summer student programme
8 July – 2 August 2019
Cracow, Poland
ATLAS Experiment
CREDO Project
Belle Experiment
Alice Experiment
T2K Experiment
LHCb Experiment
CERN
Shine Experiment
KEKB Accelerator
ILC Accelerator
LHC Accelerator
Deadline for applications
30 April 2019
Partial support for best applicants!
Find us on
More information and application form at
ppss.ifj.edu.pl
Advertisement campaign project is financed by the Polish National Agency for Academic Exchange under the Modern Foreign Promotion Programme
NAWA