Hard Diffraction at the LHC
Feasibility Studies and Experimental Aspects

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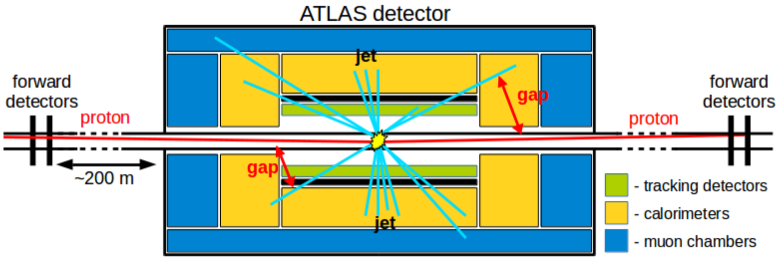
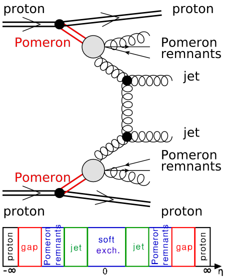
Assumption: one would like to measure diffractive interactions at the LHC.
Typical diffractive topology: a gap in rapidity is present between proton(s) and central system and one or both interacting proton stay intact.





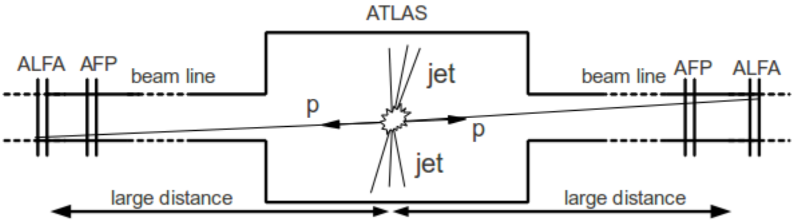
Method 1 (rapidity gap):

+ 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.



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: $\sigma_t \sim 25$ ps

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

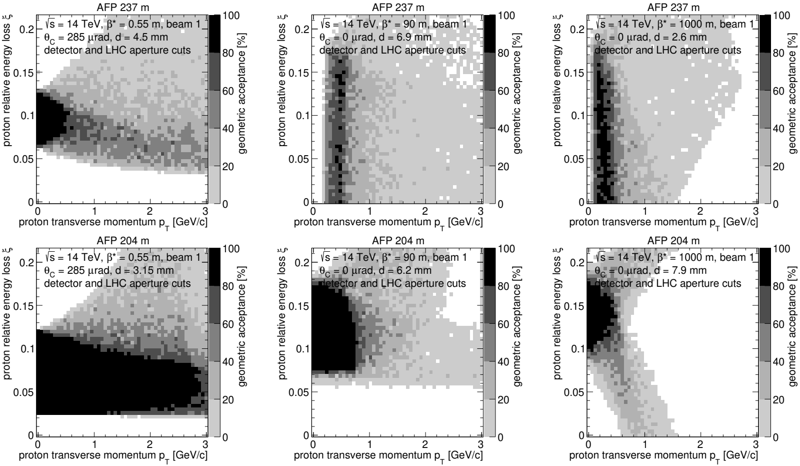
$\beta^* = 0.55$ m nominal (*collision*)

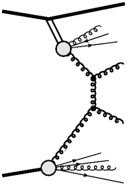
$\beta^* = 90$ m special (*high-β^**)

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

ALFA

AFP

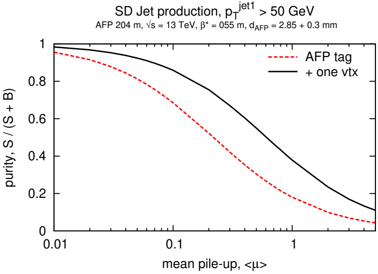


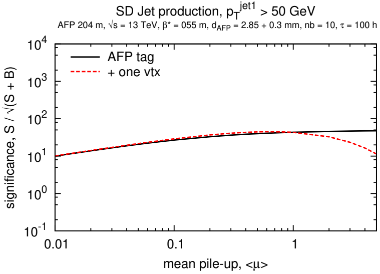


Motivation:

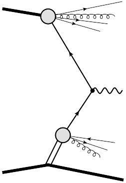
- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- check Pomeron universality between *ep* and *pp* colliders.

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





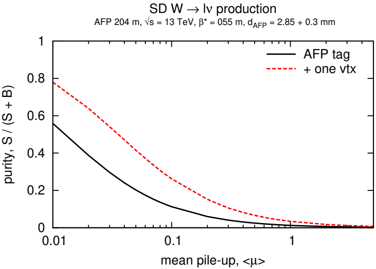
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

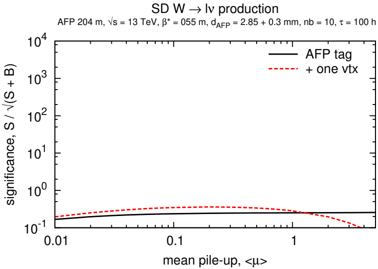


Motivation:

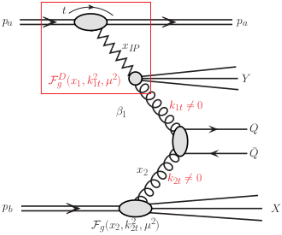
- measure cross section and gap survival probability,
- measure Pomeron structure and flavor composition,
- search for charge-asymmetry.

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



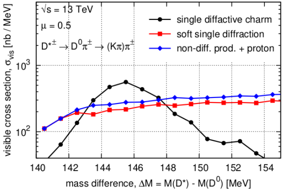


W asymmetry studies published in: Phys.Rev. D **84** (2011) 114006
More details in: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

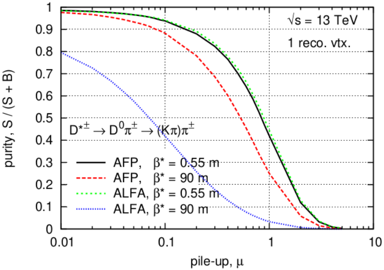


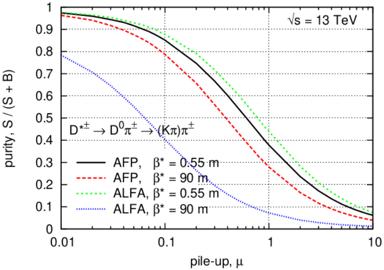
Motivation:

- measure cross section and gap survival probability,
- test the k_t-factorization approach.

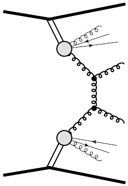


Example: purity ALFA and AFP for $\beta^* = 0.55$ and 90 m with and without 1 vertex requirement.



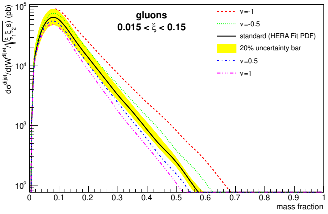


More details in: J. High Energ. Phys. **2017** (2017) 89

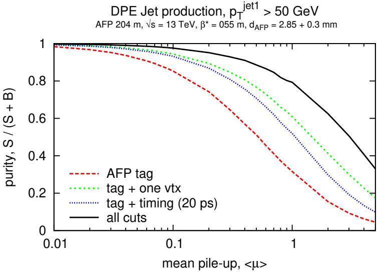


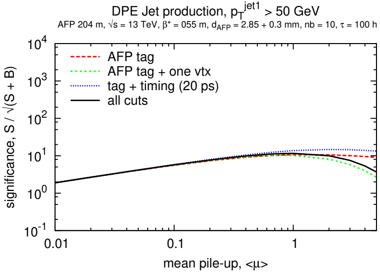
Motivation:

- 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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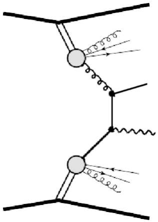
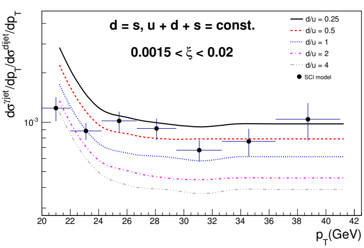
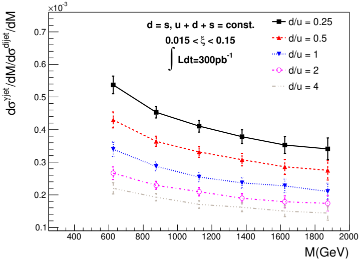


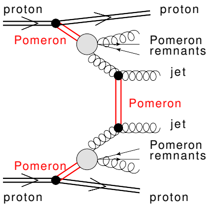
Motivation:

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



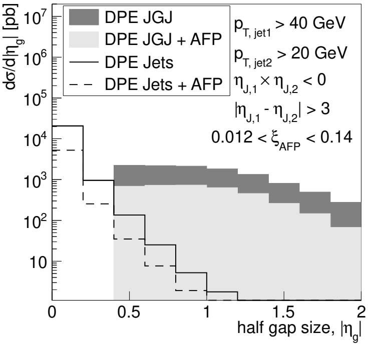


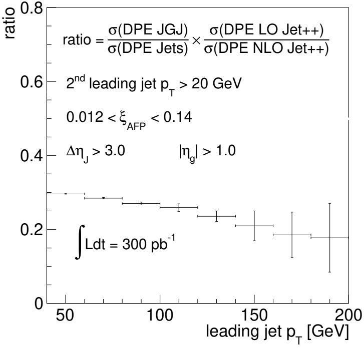
More details in: Phys.Rev. D **88** (2013) 7, 074029



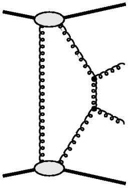
Motivation:

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



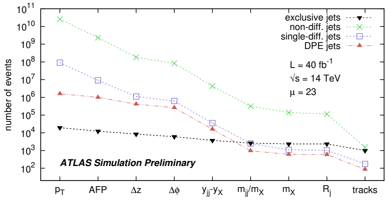


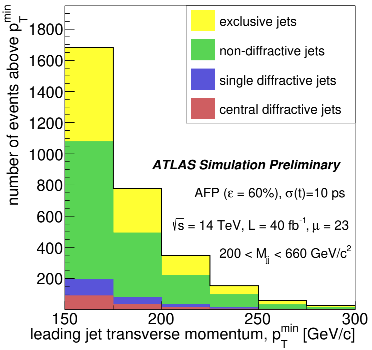
More details in: Phys.Rev. D **87** (2013) 3, 034010

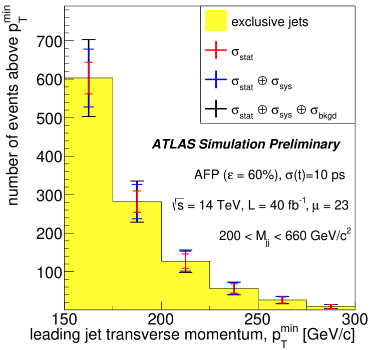


Motivation:

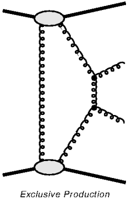
- cross section measurement,
- constrain other exclusive productions (*e.g.* Higgs).







Public ATLAS note: ATL-PHYS-PUB-2015-003



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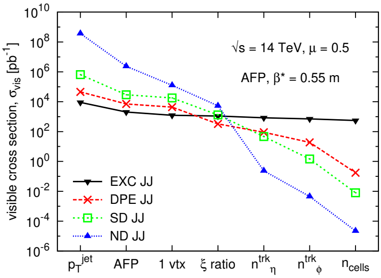
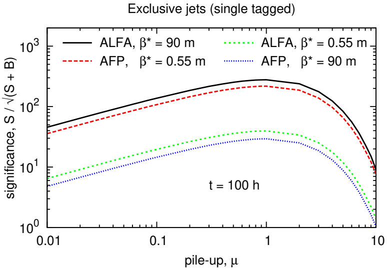




More details in: Eur. Phys. J. C **75** (2015) 320 and Acta Phys. Pol. B **47** (2016) 1745

- ATLAS with ALFA and AFP and TOTEM+CT-PPS for should deliver deliver many interesting results coming from hard diffractive and exclusive analyses based on LHC Run 2 and Run 3 data.
- What about HL-LHC?
  - The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest (CERN-CMS-NOTE-2020-008)

The Compact Muon Solenoid Experiment

CMS Note

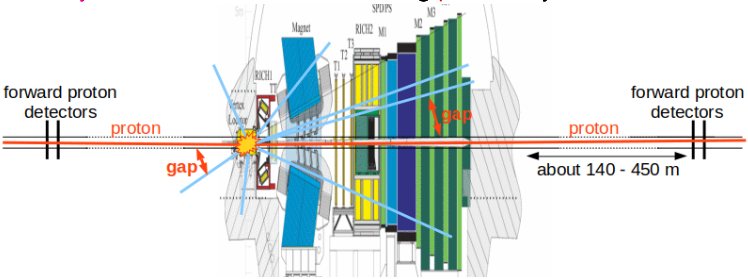
Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

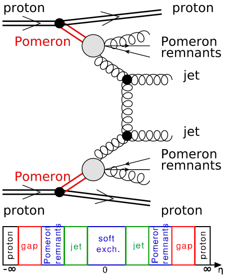
26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

  - Direct BSM Searches at High Masses
  - Quartic Gauge Couplings with W Bosons
  - All Neutral Anomalous Quartic Gauge Couplings
  - Anomalous Effects in the τ-Lepton Sector
  - QCD Physics
  - Electroweak Physics
  - Higgs Physics
  - Top Physics
  - Photoproduction
  - ATLAS Collaboration also investigates the possibility of having Roman pots.
- Are IP1 and IP5 the only options?

Assumption: one would like to measure diffractive interactions at the LHCb.
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
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Method 2 (forward protons):

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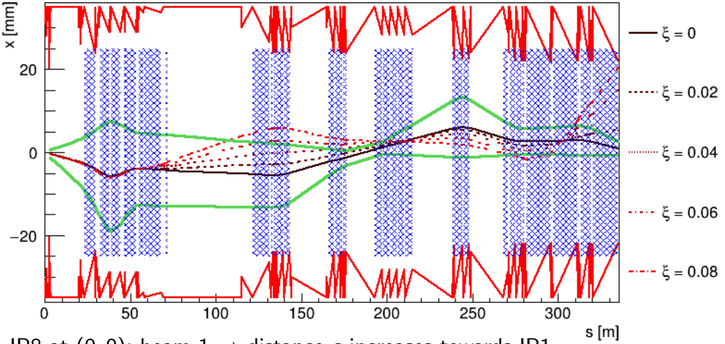
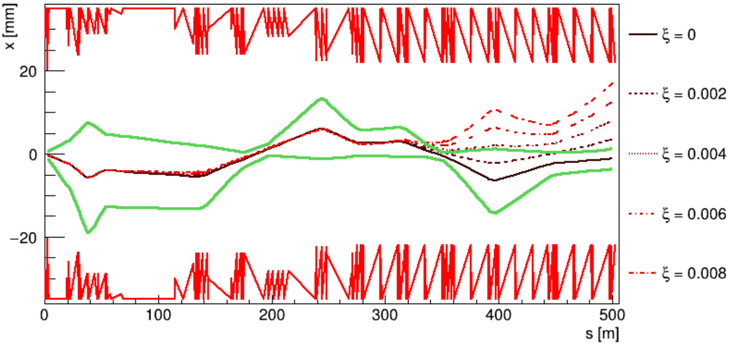
− additional “forward” detectors are needed far away from the interaction point

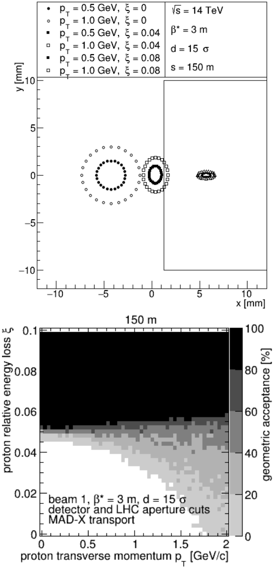
Proton Trajectories (I)



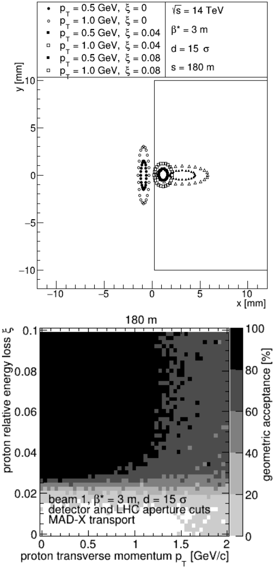
- IP8 at $(0,0)$; beam 1 $\rightarrow$ distance s increases towards IP1.
- Positive x towards LHC ring center.
- Reference frame of nominal orbit, *i.e.* 7 TeV beam w/o crossing angle will make a straight line with intercept $x = 0$.
- Solid black line – nominal proton trajectory (*i.e.* beam of 7 TeV) with crossing angle of -115 μrad ($p_X^{nom} = -0.805$ GeV).
- Solid green lines – $15 \cdot \sigma_{beam}$ (rough limit of pot insertion).
- Solid red lines – beam aperture (note: collimators not considered!).
- Blue area – LHC elements (magnets, BPMs, ...).
- Dashed red lines – trajectories of scattered protons ($p_T = 0$, various energy loss).
- Possible pot positions: outside blue areas, in a place trajectories are leaving area between green lines.



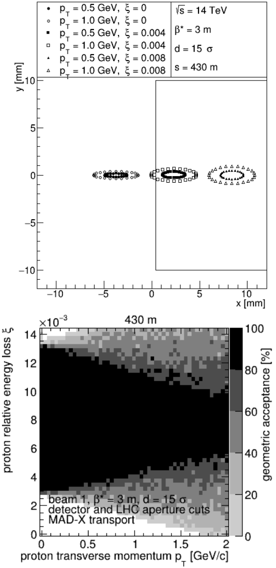
- Detectors in cold region → movable beam-pipe technology → LHC elements not drawn.
- From around 360 m access to much lower acceptance ($\xi \sim 0.004$ around 400 m and ~ 0.001 around 500 m.
- Presence of higher order magnets (sixtupoles).
- Diffractive protons going towards inside of rings → desirable from installation and operation point of view!
- 0.004 means central mass of about 55 GeV.



150 m :
$0.05 < \xi <$??



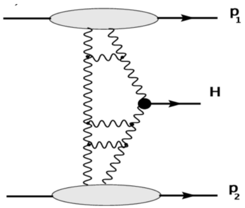
180 m :
$0.025 < \xi <$??



430 m :
$0.003 < \xi < 0.013$

Exclusive production = two protons + central system:

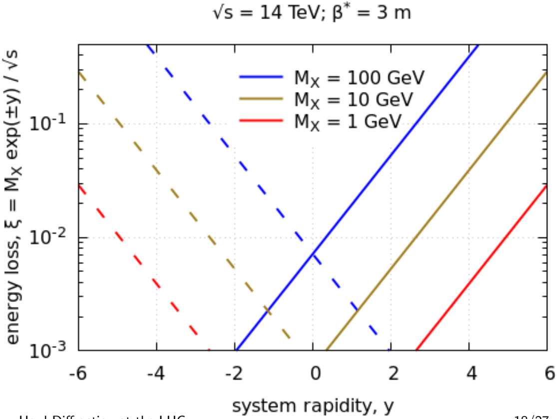
- no proton nor Pomeron remnants,
- energy of protons is precisely correlated with energy of central system: $\xi = M_X \cdot \exp(\pm y)/\sqrt{s}$, where M_X is mass and y is rapidity of central system,
- example of diagram – exclusive Higgs production.



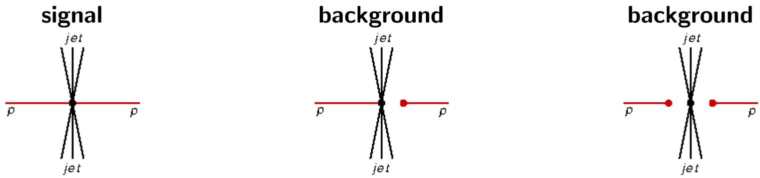
- Acceptance of LHCb:

  $$2 < \eta < 5$$
  $$\downarrow$$

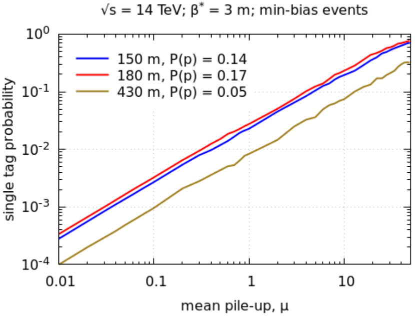
  a semi-exclusive (one proton tag) measurement should be possible.
- Also diffractive events, where fraction of proton energy goes to the Pomeron remnants, with one or both protons tagged should be measurable.

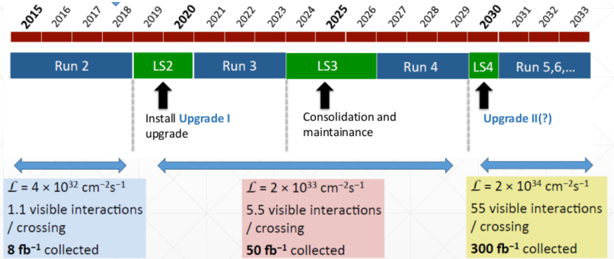


- Usually, in non-zero pile-up environment the main background for exclusive and diffractive events is due to non-diffractive production overlaid with protons from min-bias events.
- Example – double Pomeron exchange di-jet production:



- Information about proton tagging can reduce non-diffractive background.
- Efficiency depends on pile-up.
- For $\mu \sim 5$ it is about 10 for pots in hot region and 20 for cold region.
- In cold region beam-background (halo) may play an important role (effect not simulated on plot).





- Slight modifications (LS2 extended be few months, Run 3 extended by a year, *etc.*) do not change the overall picture.
- If there is a wish to bring forward protons detectors at LHCb starting from Run 4 to reality, procedures should start now:
  - definition of solid physics programme
    - hopefully triggered by this talk,
    - formulation of work-group gathering scientists interested in the diffractive, exclusive and BSM analyses / searches with forward proton or HI spectators tagging at LHCb,
  - discussion about optics, optimal detector placement and technology (vertical/horizontal pots / Hamburg beampipe),
  - gathering interests from detector groups – discussion about potential detector technology (tracking & time-of-flight) taking into account timely production capability and short-/long- term support,
  - Letter of Intent / Memorandum of Understanding, Technical Design Report, Engineering Change Request (ECR), *etc.*

Summary

- Diffractive and exclusive processes are being investigated by all major LHC experiments with Run 1 and Run 2 data.

- ATLAS and CMS/TOTEM Collaborations are equipped with dedicated devices to measure scattered protons – **Roman pot detectors**:
  - low-mass events → dedicated settings of the LHC machine → special runs,
  - medium- and high-mass events → data taken with usual configuration of LHC magnets.

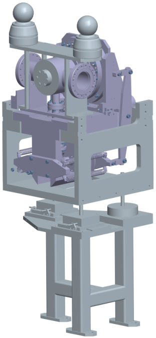
- ATLAS and CMS/TOTEM plan to continue taking data with Roman pots devices in Run 3.

- The presence of Roman pots at High Luminosity LHC (HL-LHC) is not yet decided → harsh pile-up conditions (μ around 200) significantly limits the physics programme.

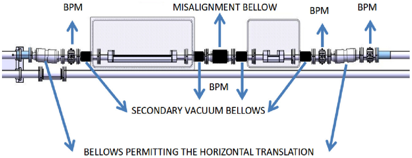
- Pile-up at **LHCb (IP8)** will increase only from about 1 to about 5 in Run4:
  – diffractive and exclusive measurements very challenging w/o proton tagging,
  + **very good conditions to operate forward proton detectors!**

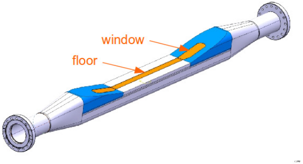
Backup

Roman Pots



Hamburg Beampime

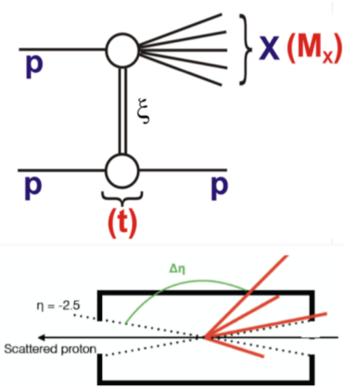




- Technology already applied at LHC (CMS/TOTEM, ATLAS).
- To be used in warm sector (straight section, up to 250 m).
- For standard optics horizontal pots should be considered.

- Not used at LHC, but machine people may be interested to test it.
- To be used in cold sector (arc, around 420 m).
- Standard optics should be considered.

Pots and movable beampipes hosts detector packages.



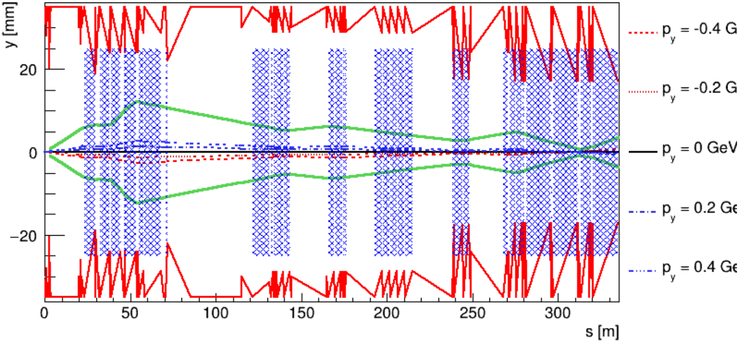
- t – squared four-momentum transferred from the proton:

$$t \approx -p_T^2$$

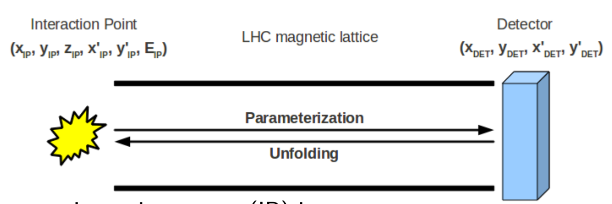
- p_T – proton transverse momentum
- ξ – momentum fraction of the proton carried by the Pomeron:

$$\xi = 1 - E/E_{beam}$$
$$\xi \approx \sum_i (E^i \pm p_z^i)/\sqrt{s}$$

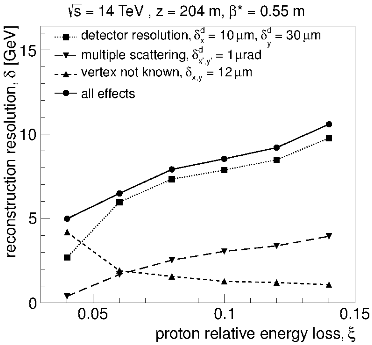
- $\Delta\eta$ – pseudorapidity gap – space in which no particles are produced / detected



- No acceptance for diffracitve protons.
- Dedicated optics will be needed → not clear if will comply to desired, 'standard' working conditions for LHCb.
- In case of interest, further investigation (discussion with LHC optics experts) is needed → development of dedicated optics.



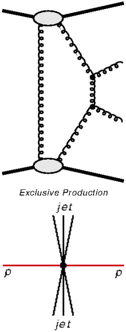
- At the interaction point proton (IP) is fully described by six variables: position (x_{IP}, y_{IP}, z_{IP}), angles (x'_{IP}, y'_{IP}) and energy (E_{IP}).
- They translate to unique position at the forward detector (x_{DET}, y_{DET}, x'_{DET}, y'_{DET}).
- Idea: get information about proton kinematics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



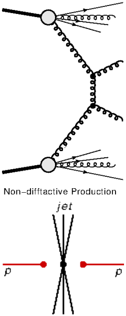
From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024

Pile-up Background Reduction

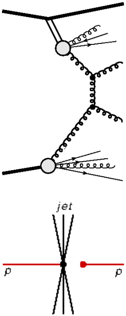
signal



background



background



Idea:

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