Overview of ATLAS Forward Proton Detectors

Status, Performance and New Physics Results

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Various faces of QCD
Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society
27/04/2024

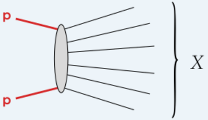
Usual proton-proton collisions at the LHC

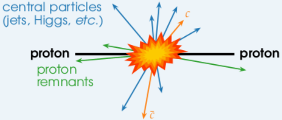
→ protons collide head-on

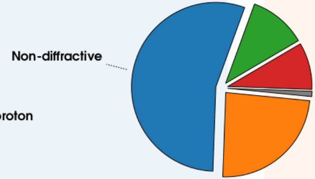
→ both protons break up

→ collision products are emitted in the central region

→ proton remnants may be found in the forward regions







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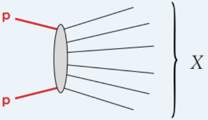

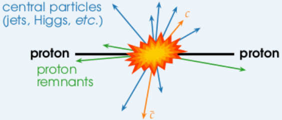

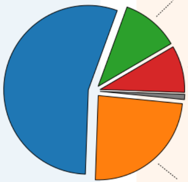

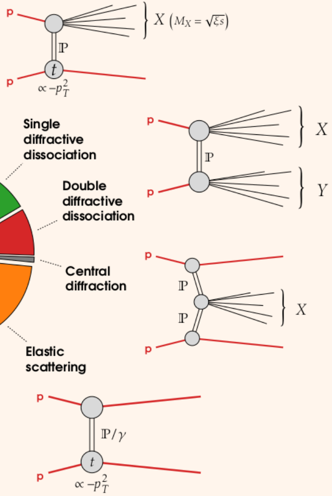

Usual proton-proton collisions at the LHC

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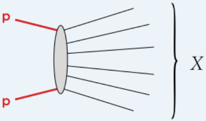
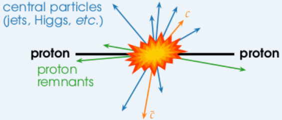
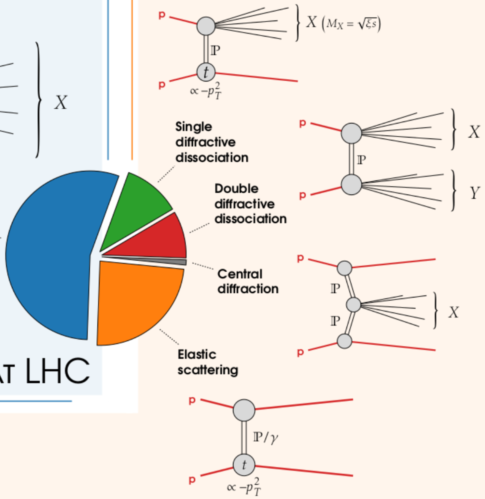
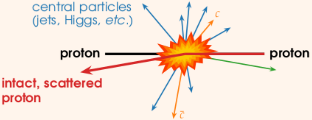




Collisions at LHC



How can proton(s) remain intact?

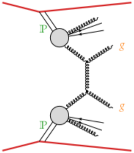


Proton can exchange objects that do not change its quantum numbers:

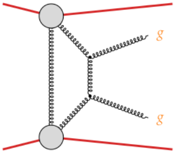
- → photon (γ) – via electromagnetic interactions
- → Pomeron ($\mathbb{P}$) – via strong nuclear force

Physics Processes

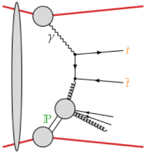
- In addition to soft processes listed on previous slide, a wide range of hard processes results in a presence of **scattered forward proton(s)**:



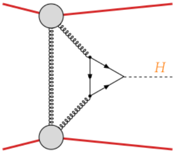
Diffractive jets



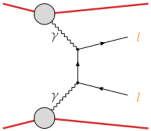
Exclusive jets



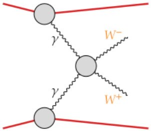
Top quarks



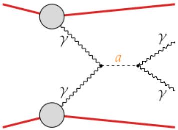
Higgs boson



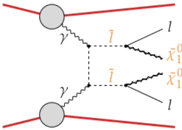
Leptons



W bosons



Axion-like particles

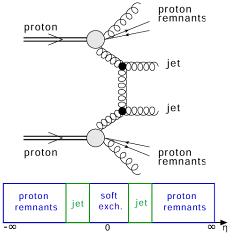


SUSY dark matter

- At the LHC high pile-up environment the main focus would be on **photon induced processes** and **Beyond Standard Model searches**.
- There are also dedicated, low-μ campaigns to study **diffractive processes**.

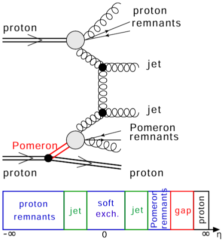
Example: Diffractive Jet Production

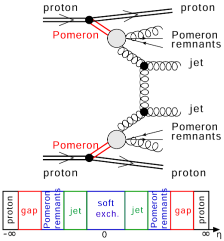
Non-Diffractive Jets



- Interacting protons are destroyed and two jets are produced.
- $gg \to gg$ production is shown, but other types of exchange (*e.g.* qg or qq) are also possible (although expected to be of lower cross sections at the LHC).
- Both interacting protons are "destroyed", remnants expected in full (η, ϕ) phase-space.

Diffractive Jets

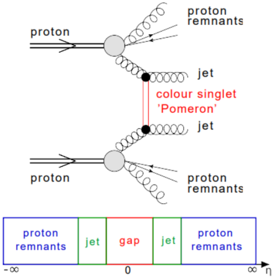




- **Left:** Single Diffractive Jet production: one interacting proton stays intact, the second one is destroyed and two jets are produced.
- **Right:** Double Pomeron Exchange Jet production: both interacting protons stay intact and two jets are produced.
- In both cases a rapidity gap between proton and Pomeron remnants is present.

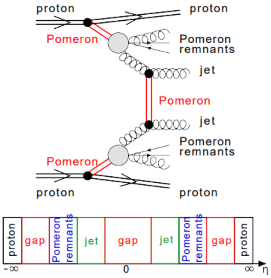
Example: Jet-Gap-Jet (JGJ) Studies (my PhD topic)

Non-Diffractive Jet-Gap-Jet



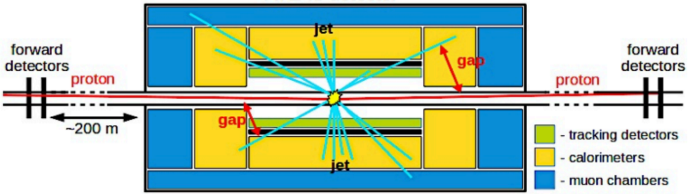
- Two jets separated by a gap in rapidity are produced, but interacting protons are destroyed.
- **Gap** in theory/experiment: space in rapidity devoid of particles/reconstructed objects (tracks, calorimeter clusters).

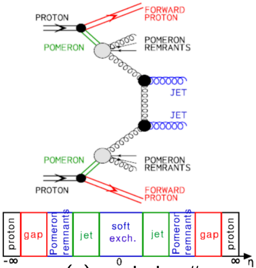
Diffractive Jet-Gap-Jet



- Protons survive and gap is present between jets → three Pomerons are exchanged:
  - between protons and the "central" system,
  - between jets in the t channel.
- Ratio of Double Pomeron Exchange (DPE) JGJ to DPE di-jet events should shed light on gluonic nature of Pomeron.

Measurement Method





- Characteristic diffractive topology: presence of rapidity gap between the proton(s) and the "central" system; one or both interacting proton(s) remain intact.
- Intact protons are scattered at very small angles ($\mathcal{O}(100\ \mu\text{rad})$) $\rightarrow$ after the interaction they are very close to the beam $\rightarrow$ detectors must be located far from the Interaction Point (IP).

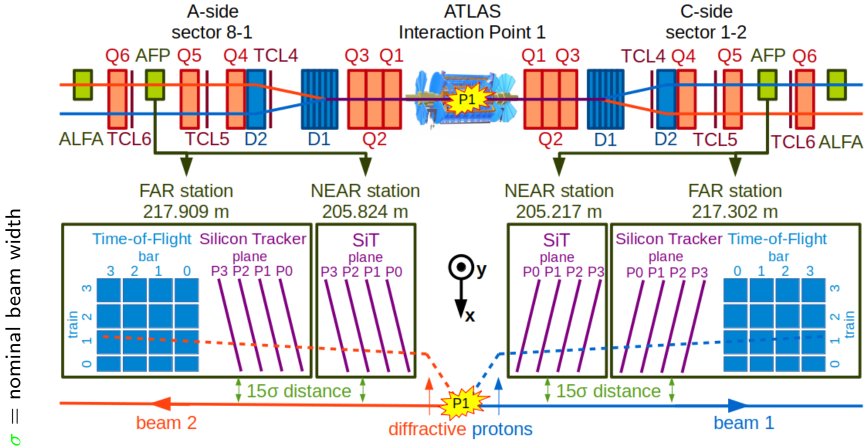
Measuring rapidity gap:

+ "classically" used for diffractive pattern identification
+ no need for additional detectors
– gap is frequently destroyed due to pile-up background
– gap may be out of acceptance of "central" detector

Measuring forward protons:

+ protons measured directly
+ suitable for pile-up environment
– protons are scattered at very small angles
– additional detectors required far downstream

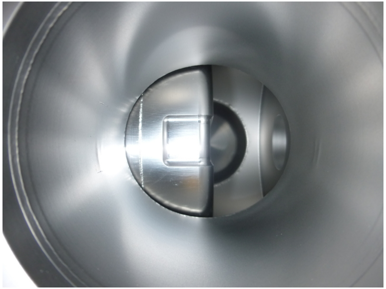
ATLAS Forward Proton Detectors



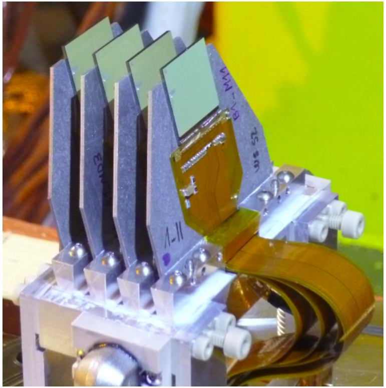
- Four Roman pot stations placed symmetrically around ATLAS, around 210 m from collision point.
- All stations host 4 layers of Silicon Trackers to measure (x, y) position of scattered proton.
  - Proton position is used to unfold the kinematics (energy and p_T) of scattered proton.
- Far stations host Time-of-Flight detectors dedicated to reduce combinatorial backgrounds.

AFP: Silicon Tracker

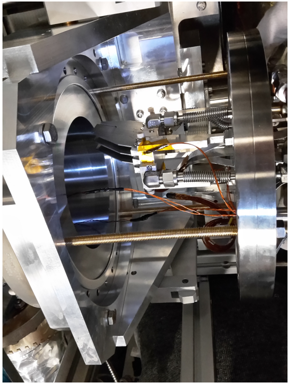
Roman pot as "seen" by proton beam, thin window of RP is visible:



4 layers of SiT modules mounted on heat exchanger:



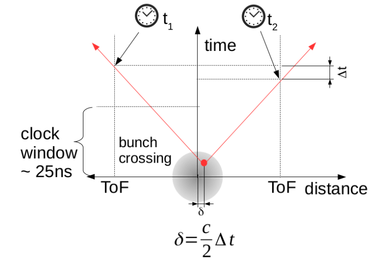
Installation of detector package:



- **4 Silicon Tracker (SiT) planes** are present in each RP station to measure proton position.
- Slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- 336×80 array of 50×250 μm^2 pixels per plane.
- 14° **tilt** to improve resolution in x, staggering of layers to improve resolution in y.
- Resolution (measured): 5.5 ± 0.5 μm in x and ≈ 30 μm in y [JINST 11 (2016) P09005].

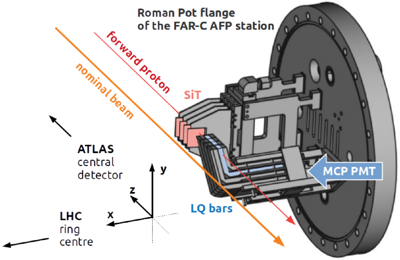
AFP: Time-of-Flight Detectors

Concept of ToF measurement:

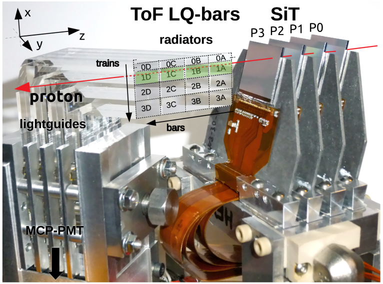


$$\delta = \frac{c}{2}\Delta t$$

Sketch of mounting SiT and ToF (Run 2 design):

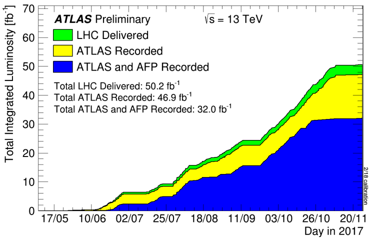


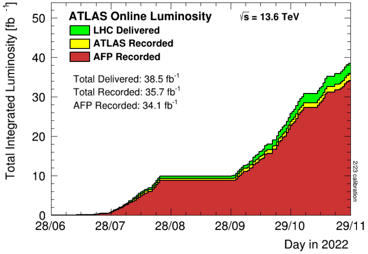
Detector package before installation (Run 2 design):

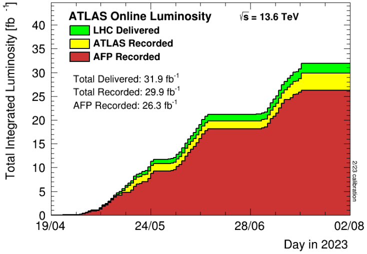


- **Purpose:** Assign protons to individual collisions in IP1 (reducing background due to pile-up).
- **Concept:**
  - measure ToF difference: $\Delta t = (t_A - t_C)/2$,
  - calculate vertex position: $z_{ToF} = c\Delta t$,
  - compare vertex z position reconstructed by ATLAS and AFP ToF.
- Detectors: 4×4 matrix of quartz bars, L-shaped and rotated 48° w.r.t. LHC beam (Cherenkov angle).
- **Timing:** aim for 20 ps [Opt. Express] resolution for Run 3, 30 ps at the beginning (in Run 2) [JINST 11 (2016) P09005].

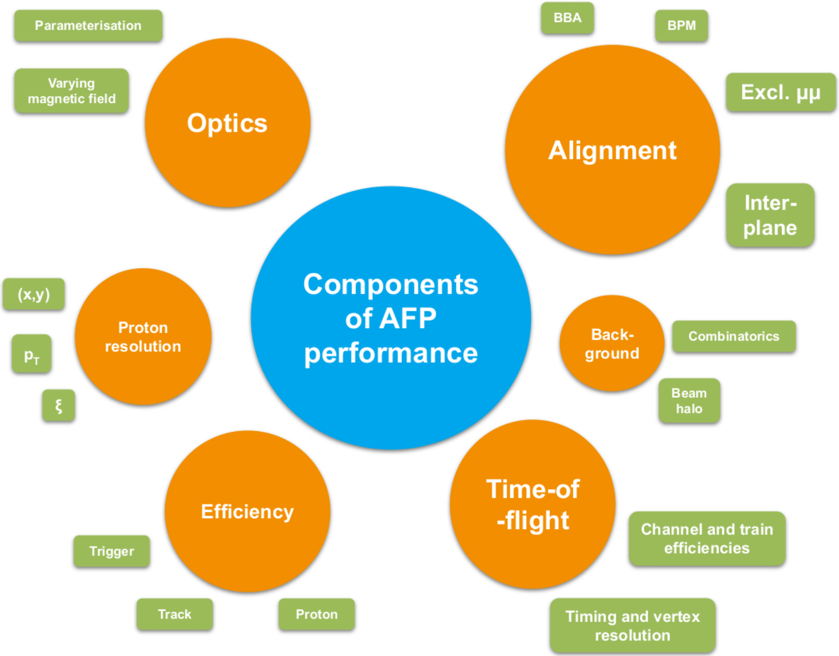
Data-taking Campaigns



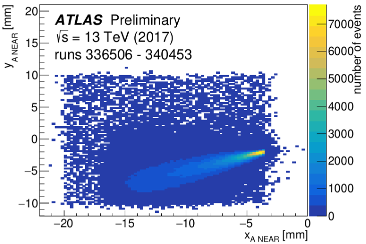




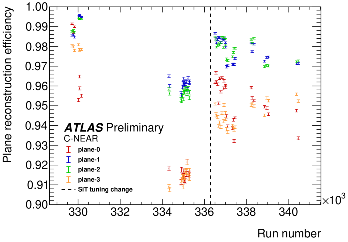
- AFP detectors were installed in 2016 on C-side of ATLAS.
- Since 2017, a full detector setup (both arms; SiT+ToF) is present and collects data on a daily basis, together with the rest of ATLAS sub-detectors:
  - these data-sets are used for studies of photon-induced processes and BSM physics.
- In addition to the high pile-up data-taking, a couple of low-μ campaigns were organized to collect data needed for the diffractive analyses.
- AFP intends to continue data taking until the end of LHC Run 3.


Components of AFP performance
Optics
Parameterisation
Varying magnetic field
Alignment
BBA
BPM
Excl. μμ
Inter-plane
Proton resolution
(x,y)
p_T
ξ
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution

SiT Performance (ATL-FWD-PUB-2024-001) – Examples



Occupancy of the AFP stations in terms of the (x, y) coordinates of track segments reconstructed from the loose dilepton selection for cases where there is exactly one segment reconstructed in a station. The colour-coded scale corresponds to the number of reconstructed track segments per bin.



Efficiencies for each SiT plane in the C NEAR station, determined separately for each ATLAS run number. The step change in the vicinity of Run number 336000 corresponds to an adjustment of thresholds.

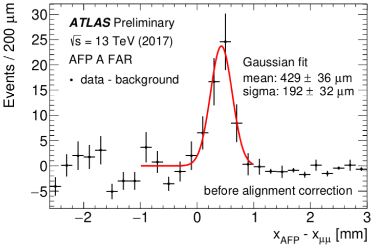
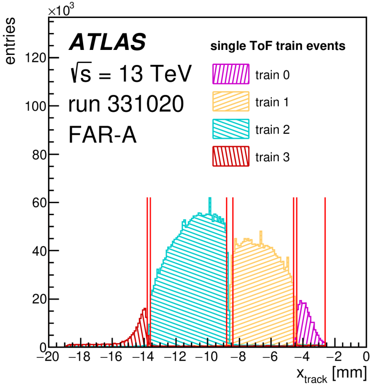
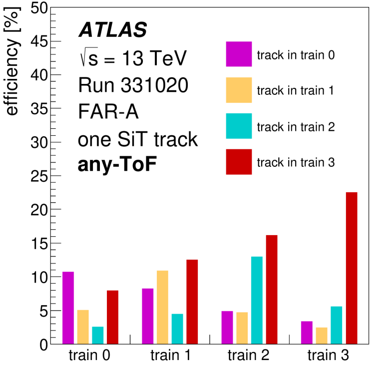


Illustration of the data-driven AFP global alignment method based on exclusive dimuon events: $x_{AFP} - x_{\mu\mu}$ distribution after subtracting the background bin-by-bin. This distribution is attributed to signal events and is fitted to a Gaussian, the mean of which is taken to be the alignment off-set constant.

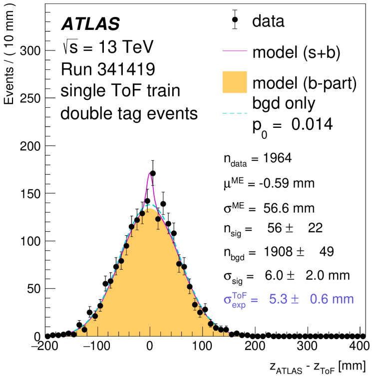
ToF Performance (arxiv:2402.06438) – Examples



Distributions of local track x-coordinates in the AFP FAR station after applying the single-ToF-train selection in the AFP calibration stream run 331020. The red vertical lines indicate the chosen cuts that are used to define the acceptance of the trains.



Efficiencies of ToF trains for the ATLAS run 331020 in the A-FAR AFP station. The data are required to contain exactly one reconstructed SiT track with no further constraints applied in the ToF.



The $z_{ATLAS} - z_{ToF}$ distributions measured in run 341419 (dots) using double-tagged events with the single-ToF-train condition. The fits of the sum of signal and background components are represented by solid lines. The background component is indicated by the filled area.

Glimpse on the Latest AFP Result

Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS

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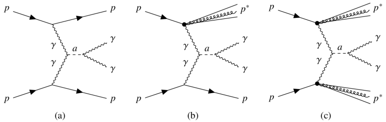
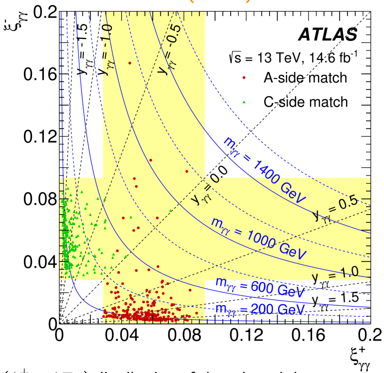
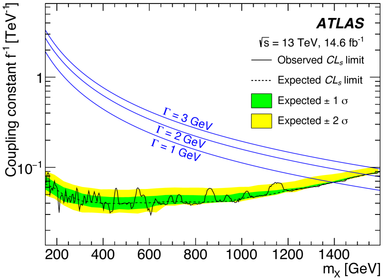


A search for forward proton scattering in association with light-by-light scattering mediated by an axion-like particle (...) Proton-proton collision data recorded in 2017 at a centre-of-mass energy of $\sqrt{s}$=13 TeV were analysed, corresponding to an integrated luminosity of 14.6 fb^{-1}. A total of 441 candidate signal events were selected. A search was made for a narrow resonance in the diphoton mass distribution, corresponding to an axion-like particle (ALP) with mass in the range 150–1600 GeV. No excess is observed above a smooth background.



$(\xi^{+}_{\gamma\gamma}, \xi^{-}_{\gamma\gamma})$ distribution of the selected data candidates after the full event selection in $m_{\gamma\gamma}$ in [150,1600] GeV with $m_{\gamma\gamma}$ contours (blue) and $y_{\gamma\gamma}$ contours (black). The range of $\xi_{\gamma\gamma}$ in which forward-proton matching is possible is indicated by the yellow rectangle for each side. Events passing the matching requirement on the A(C)-side are represented by the red dots (green triangles).



Expected and observed 95 CL upper limits on the ALP coupling constant, assuming 100% branching ratio for ALP decay into two photons, as functions of the hypothetical ALP mass m_X. The 1σ and 2σ confidence intervals are shown by the coloured bands. Contours of the ALP natural width Γ are illustrated by the smooth blue solid lines.

Summary

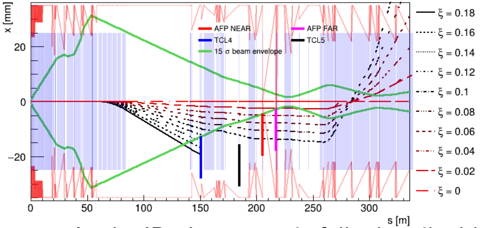
- Various physics processes result in intact protons present in the final state.
- ATLAS is equipped with dedicated devices to measure scattered protons -– Roman pot detectors:
  - low-mass events $\rightarrow$ dedicated settings of the LHC machine $\rightarrow$ special runs,
  - medium- and high-mass events $\rightarrow$ data taken with usual configuration of LHC magnets.
- Performance studies and analyses of data collected during LHC Run 2 and Run 3 are ongoing.
  - Some very interesting results were already published!
  - My interest: non-diffractive and diffractive jet-gap-jet production.
- AFP will continue taking data during regular and special runs until the end of LHC Run 3.

This work was partially supported by the Polish National Science Centre grant: 2019/34/E/ST2/00393.

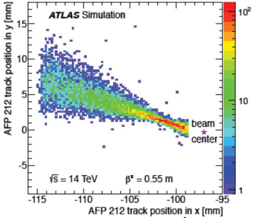
Backup

Unfolding Proton Kinematics

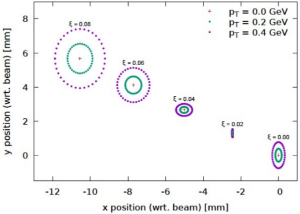
Proton trajectories along LHC beamline in vicinity of ATLAS IP; protons which lost more energy are diverged further from the beam:



"Diffractive pattern" visible in the detectors; shape is due to LHC magnetic field:



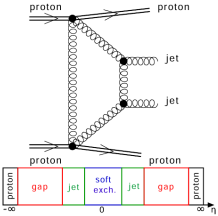
Positions of protons with given ξ and p_T; depends on settings of LHC magnets:

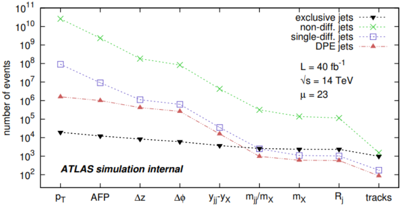


- At the IP, the proton is fully described by 6 variables: position (x_{IP}, y_{IP}, z_{IP}), angle: (x'_{IP}, y'_{IP}) and energy (E). They translate to a unique position at the AFP: $x_{AFP}, y_{AFP}, x'_{AFP}, y'_{AFP}$
- Knowledge of LHC magnetic field (*transport matrix*) allows unfolding of proton kinematics (x'_{IP}, y'_{IP}, E) from position measured in the detectors.
- **Kinematics of scattered protons is correlated to kinematics of central system.** In case of exclusive processes this correlation is very strong (exact in ideal cases) thus it provides a powerful constraints for signal recognition (background reduction).
- **Challenges:** non-uniform high radiation environment, background from showers, high pile-up
- **Note:** detector resolution and uncertainties in knowledge of magnetic fields affects precision of measuring proton kinematics.

Example: Exclusive Jet Production

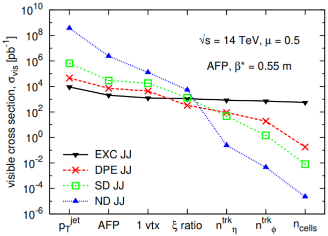
Double Tag





- **Exclusive Jet Production**: two jets are produced and both interacting protons stay intact.
- No remnants in the system: jets and protons kinematics match → very powerful constraints for background rejection.
- Feasibility studies for ATLAS: ATL-PHYS-PUB-2015-003

Single Tag (aka semi-exclusive)



- **Semi-Exclusive Jet Production**: two jets are produced and both interacting protons stay intact, but **one of them is not measured**.
- This allows to measure jets of lower p_T, see Eur. Phys. J. C 75 (2015) 320.