Overview of ATLAS forward proton detectors for LHC Run 3 and plans for the HL-LHC

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International workshop on Deep Inelastic Scattering and related subjects
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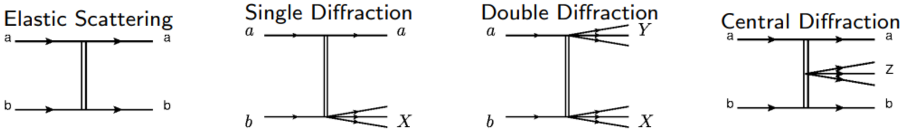
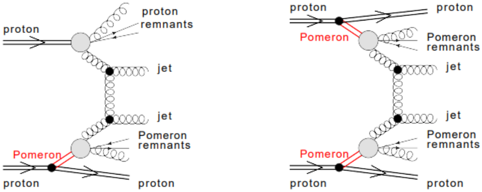
Diffractive Physics

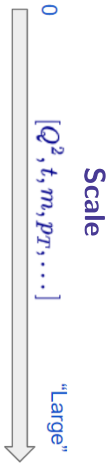
- **Soft diffractive processes**: large cross sections, non-perturbative computations:



- **Hard diffractive processes**: small cross sections, perturbative QCD, examples:

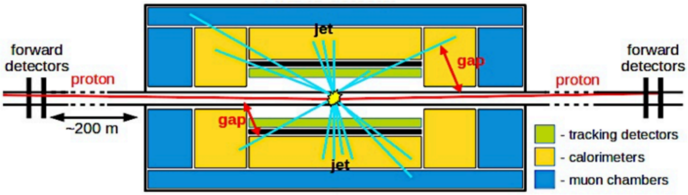
Single Diffractive Jet Production   Double Pomeron Exchange Jet Production

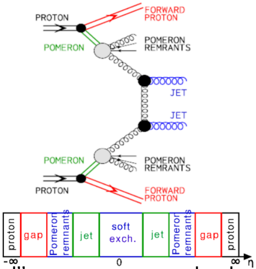




Proton survival due to colour singlet exchange (quantum numbers of the vacuum): photon (QED) or **Pomeron** (strong interactions).

Measurement method





- 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 ($\mathcal{O}(100\ \mu\text{rad})$) $\rightarrow$ very close to the beam $\rightarrow$ detectors must be located far from the Interaction Point (IP).

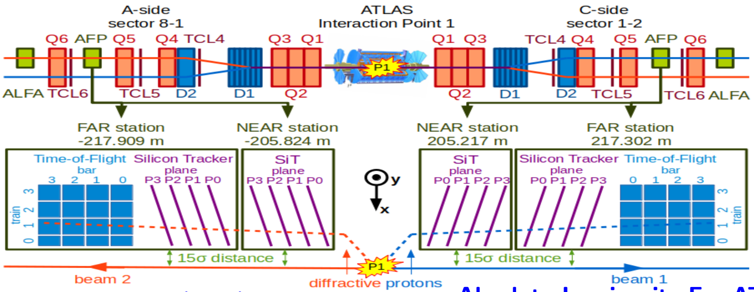
Measuring rapidity gap:

+ "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

Forward Detectors in ATLAS



ATLAS Forward Proton (AFP)

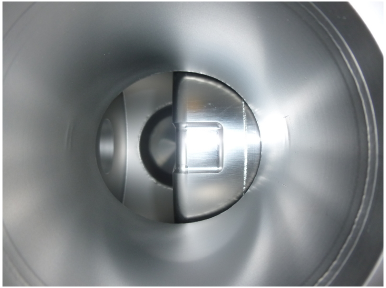
- purpose: soft and hard diffraction (limited acceptance for low masses), BSM searches
- NEAR (205 m) and FAR (217 m) stations
- horizontally inserted Roman Pots
- taking data during nominal (high pile-up, low β^*) and special (low pile-up, low β^*) runs

Absolute Luminosity For ATLAS (ALFA)

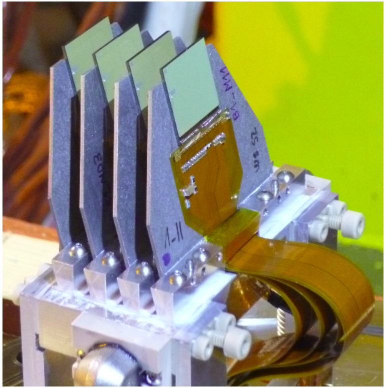
- purpose: soft diffraction, especially elastic scattering (CNI region, dip, Odderon searches)
- NEAR (237 m) and FAR (241→245 m) stations
- vertically inserted Roman Pots
- taking data during special runs: very low pile-up, (very) high β^* optics

AFP: Silicon Tracker (SiT)

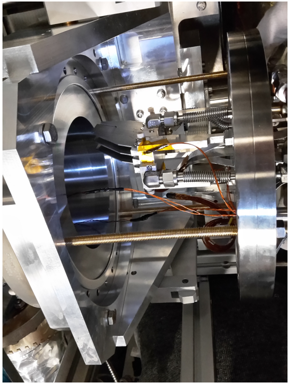
Roman pot as "seen" by proton beam, thin window of RP is visible:



4 layers of SiT modules mounted on heat exchanger:



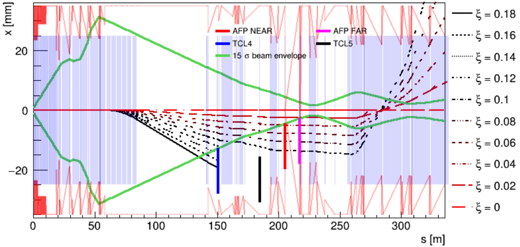
installation of detector package:



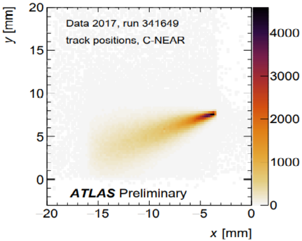
- **4 Silicon Tracker (SiT) planes** are present in each RP station to measure proton position.
- $50 \times 250\ \mu m^2$ pixel size
- 14° **tilt** to improve resolution in x, staggering of layers to improve resolution in y
- Resolution (measured): $= 5.5 \pm 0.5 \mu m$ per pixel plane, $2.8 \pm 0.5 \mu m$ for all plane in x [JINST 11 (2016) P09005] and $\approx 30\ \mu m$ in y

Unfolding Proton Kinematics

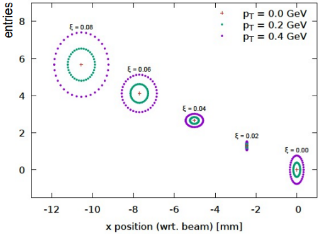
proton trajectories along LHC beamline in vicinity of ATLAS IP; protons which lost more energy are diverged further from the beam:



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



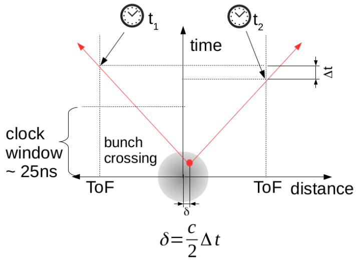
positions of protons with given ξ and p_T; depends on settings of LHC magnets:



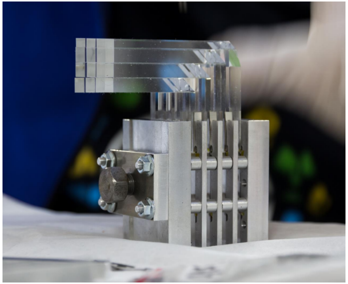
- At the IP, the proton is fully described by 6 variables: position (x_{IP}, y_{IP}, z_{IP}), angle: (x'_{IP}, y'_{IP}) and energy (E). They translate to a unique position at the AFP: $x_{AFP}, y_{AFP}, x'_{AFP}, y'_{AFP}$
- Knowledge of LHC magnetic field (*transport matrix*) allows unfolding of proton kinematics (x'_{IP}, y'_{IP}, E) from position measured in the detectors.
- **Kinematics of scattered protons is strongly correlated to kinematics of central system.**
- **Challenges:** non-uniform high radiation environment, background from showers, high pile-up

Time-of-Flight Detectors (ToF)

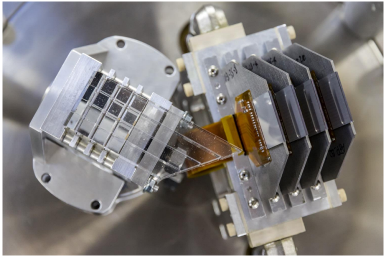
concept of ToF measurement:



sketch of ToF showing 4×4 matrix of quartz bar



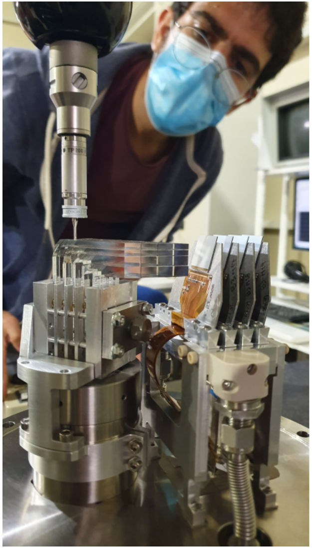
detector package before installation :

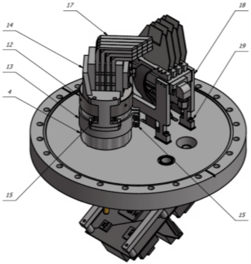


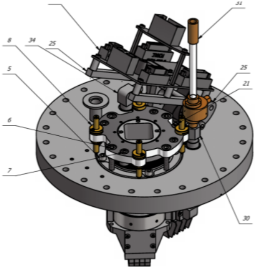
- **Purpose:** Assign protons to individual collisions in IP1 (reducing background due to pile-up)
- **Concept:**
  - Measure ToF difference: $\Delta t = (t_A - t_C)/2$
  - Calculate vertex position: $z_{ToF} = c\Delta t$
  - Compare vertex z position reconstructed by ATLAS and AFP ToF
- Detectors: 4×4 matrix of quartz bars, L-shaped and rotated 48° w.r.t. LHC beam (Cherenkov angle)
- **Timing:** 20 ± 4 ps (side A) and 26 ± 5 ps (side C) [ATL-FWD-PUB-2021-002]
  20 ps → spatial resolution of 4.24 mm.

AFP upgrades for RUN 3

- Improvement in silicon detector cooling (new heat exchangers).
- Production of new tracking modules.
- New design of detector flange: Out-of-Vacuum solution for ToF detectors
- New trigger module: possibility to trigger on single train.
- New photo-multipliers: address inefficiency issues from Run2 data-taking.
- Above items were successfully tested at DESY in 2020.
- Both NEAR and FAR station have been successfully installed:
  - laser survey (positioning wrt. LHC) done,
  - interlock validation done → Roman pots qualified to be inserted to take data,
  - commissioning of readout and trigger ongoing (validation with 900 GeV collisions).







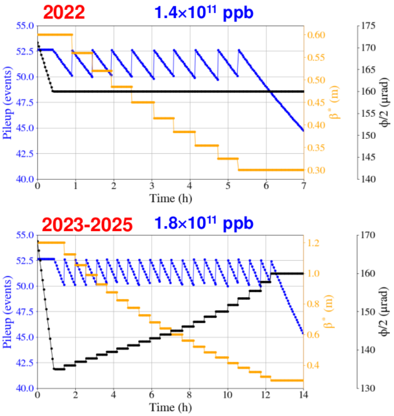
Run 3 Optics – Luminosity Levelling

2022:

- 10 steps in β^*: 60 cm $\to$ 30 cm after 5h,
- change of crossing angle only at the beginning of run from 170 $\to$ 160 μrad (afterwards constant)
- Achromatic Telescopic Squeezing (ATS) will be used $\to$ magnetic field will not change around IP1 during levelling $\to$ less complicated unfolding of proton kinematics.

2023-2025:

- 21 steps in β^*: 120 cm $\to$ 25 cm after 12 h,
- change of crossing angle only at the beginning of run from 170 to 135 μrad; afterward 135 $\to$ 160 μrad for each β^*,
- due to ATS change of β^* would not have impact of transport, but change of crossing angle will make a difference $\to$ to be addressed in the proton reconstruction procedure.



2023-2025: indicative, details may vary !

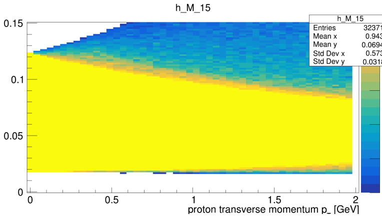
Roman Pot Position During Levelling

- Scenario 1: constant TCT position (2022):
  - jaw of the main "trimming" collimator (TCT) **kept constant in mm**, the minimal XRP distance:

$$d_{XRP}(\beta^*) = MAX[(8.5\frac{\sigma_{TCT}(\beta_0^*)}{\sigma_{TCT}(\beta^*)} + 3)\sigma_{XRP} + 0.3\ mm, 1.5\ mm]$$

  - nominal opening of collimators is defined at $\beta_0^* = 30cm$: TCT/TCL4/TCL5 $= 8.5\sigma/15\sigma/40\sigma$.
- Scenario 2: minimum RP distance (considered for 2023+):
  - if possible, **all Roman Pots at the closest distance of 1.5 mm**,
  - Setting is not possible for AFP NEAR station $\rightarrow$ TCT being close than 8.5σ limit $\rightarrow$ detectors must be further away.
  - Fixed TCT half gap at 8.5σ at all β^* to allow pots to go as close as possible and pot distance is given by $d_{XRP}[mm] = MAX(11.5 \cdot \sigma_{XRP} + 0.3\ mm, 1.\ 5mm)$

Example of AFP NEAR station acceptance for scenario 1:



Run 3 Data-taking Plans

AFP

- standard (high-μ) runs; integrated luminosity collected with AFP is expected to match the one collected by ATLAS "central" detectors,
- Dedicated low-μ ($\mathcal{O}(0.5)$, to be determined) run during 1^{st} LHC ramp-up, at 600b step:
  - purpose: soft diffraction, low p_T hard diffraction, ToF commissioning in "clean" experimental environment,
- joining very low-μ ($\mathcal{O}(0.005)$) run requested by ATLAS for min-bias studies,
- interest in joining "LHCf run": diffractive studies, connection to cosmic ray physics,
- low-μ Run during 2^{nd} ramp-up, at 600b step,
- low-μ 'electroweak' runs ($\mu \sim 1 - 2$):
  - $\sim$1/fb of data planned to be collected $\rightarrow$ excellent sample to study medium/high p_T hard diffractive processes,
- $pp \rightarrow PbPb$ reference run: sample for diffracive studies at lower energy

ALFA

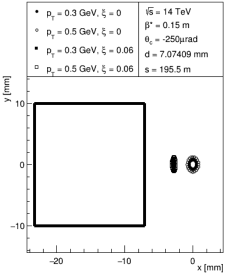
- join $\beta^* = 90$ m run in 2022,
- key interest: take data during $\beta^* = 3/6$ km run with $\sqrt{s} = 13.6$ TeV (planned early in 2023) $\rightarrow$ measurement of elastic scattering at new energy.

HL-LHC

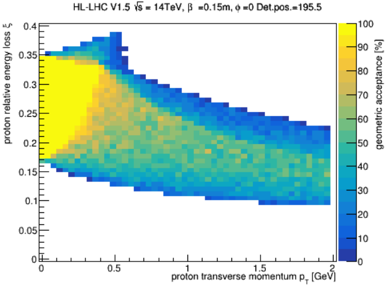
- There is an ongoing internal discussion within ATLAS community on the presence of Roman pots at HL-LHC. Especially studies of gain wrt. to "standard" ATLAS measurement possibilities.
- At HL-LHC high pile-up and low β^* environment the main focus would be on photon induced processes and Beyond Standard Model searches:
  - exclusive $\gamma\gamma \to WW/ZZ$,
  - exclusive $t\bar{t}$,
  - ALP searches,
  - Dark Matter searches,
  - ...
- Preliminary studies of possible detector acceptance were done with HL-LHC optics ver. 1.5, $\sqrt{s} = 14$ TeV, $\beta^* = 15$ cm and horizontal/vertical crossing angle.
- Following locations of pots were considered:
  - **RP1**(A/B): 195.5, 198 m,
  - **RP2**(A/B): 217, 219.5 m,
  - **RP3**(A/B/C): 234, 237, 245 m,
- Roman pots were assumed to be inserted at $11\sigma + 0.3$ mm from the beam.
- Default setting of collimators (TCL4,5,6) is 14.2σ (with possibility of opening up more, *e.g.* to 16.4 σ).

HL-LHC Acceptance – Horizontal Crossing Angle

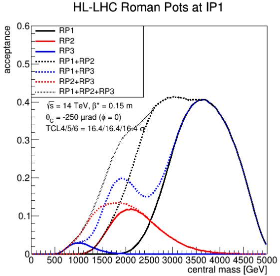
positions of protons with certain kinematics:



geometric acceptance for RP1A and horizontal crossing angle:



mass acceptance for considered sets of stations:



- Plane of crossing angle, θ_C, must be opposite at IP1 and IP5: vertical θ_C at IP5 means horizontal at IP1.
- Mass acceptance depends on pot location – stations closer to IP have acceptance towards higher masses (continues lines on right plot).
- Combination of stations (*e.g.* RP1+RP2) assumes installation of more pots (cost to be considered) to provide "enchanced" acceptance (dashed and dotted lines on right plot):

Summary

Run 2:

- Ongoing elastic, diffractive, and (semi-)exclusive analysis based on Run 2 data!

Run 3:

- All AFP stations installed and qualified to be inserted! $\rightarrow$ Commissioning ongoing.
- AFP ToF system: new PMTs, new design - Out-of-Vacuum solution. $\rightarrow$ Successful test beams at DESY and SPS.
- Plan to take data during regular (high pile-up) and special (low-pile-up) runs for BSM searches and studies exclusive processes and soft/hard diffraction.
- ALFA refurbished and qualified to be inserted! $\rightarrow$ Commissioning ongoing.
- Request to take in Run 3 with very high β^* $\rightarrow$ properties of elastic scattering at new energy.

Run 4:

- Physics programme being discussed within ATLAS.
- Output will set the constraints on preferred detector localization and technology (position and timing resolutions),
- Optimization of Run 4 optics to enhance acceptance is considered.

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BACK-UP

HL-LHC

- Pot Locations:
  - **RP1A at 195.5 m**
  - **RP1B at 198.0 m**
  - **RP2A at 217.0 m**
  - **RP2B at 219.5 m**
  - **RP3A at 234.0 m**
  - **RP3B at 237.0 m**
  - **RP3C at 245.0 m**
- RP1 means combination two stations RP1A and RP1B on both sides of IP: proton measured in all of them.
- RP1+RP2 means:
  [(RP1A & RP1B on side A) | (RP2A & RP2B on side A)] & [(RP1A & RP1B on side C) | (RP2A & RP2B on side C)].

ATS

- The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet.
- change of β^* is by acting only on the insertions on either side of IR1 and IR5 (*i.e.* IR8/2 for IR1 and IR4/6 for IR5),
- magnet settings between IP1 and AFP do not change during β^*-levelling