ATLAS Forward Proton Detectors
Status, performance and new physics results

EMMI Workshop
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on behalf of ATLAS Forward Detectors

HELMHOLTZ

Outline

- **Physics Motivation**

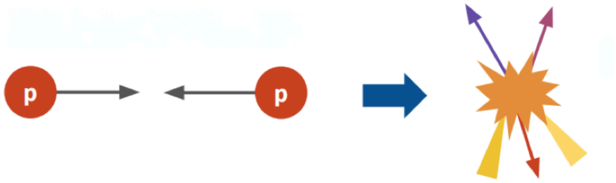
- **ATLAS Forward Proton Detectors**
    - Layout
    - SiT and ToF

- **Status and performance**
    - Datasets
    - Alignment
    - ToF Performance
    - AFP in Light/Heavy Ion campaigns

- **Latest Physics results**

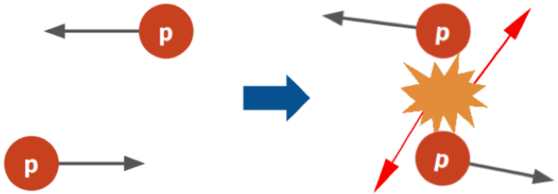
Physics Motivation

Non-diffractive collisions



- Most common type of collisions
- **Protons break up**
- Colour exchange
- High hadronic activity
- Collision product emitted in the central region

Diffractive collisions



- **Proton(s) remain intact**
- Scatter by a small angle
- Central system + forward proton(s) observed

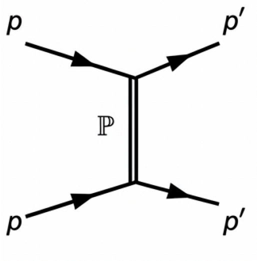
- Characteristic topology: rapidity gaps

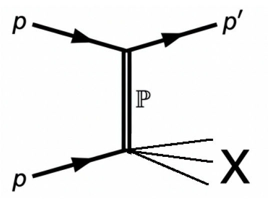
Slide inspired by [T.Mroz talk]

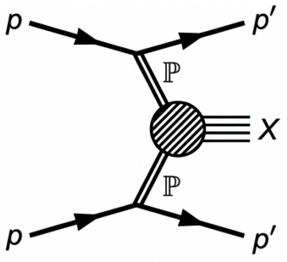
Physics accessible by tagging forward protons

Diffractive processes

- Elastic scattering
- Single/Double Diffractive Dissociation
- Central Exclusive Production (CEP)
- Protons exchange Pomeron

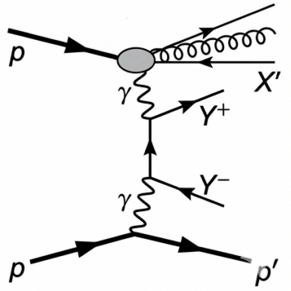


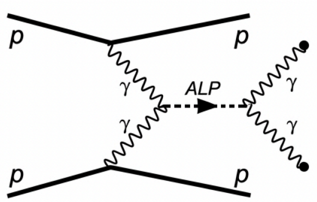


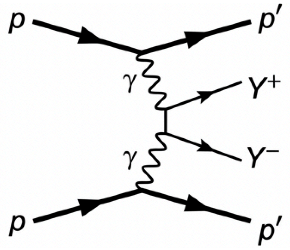


Photon-induced processes

- Exclusive/semi-exclusive pair production: $\gamma\gamma \rightarrow ll, WW$
- BSM Searches (ALPs, missing mass searches etc.)
- Clean final states, precise kinematics



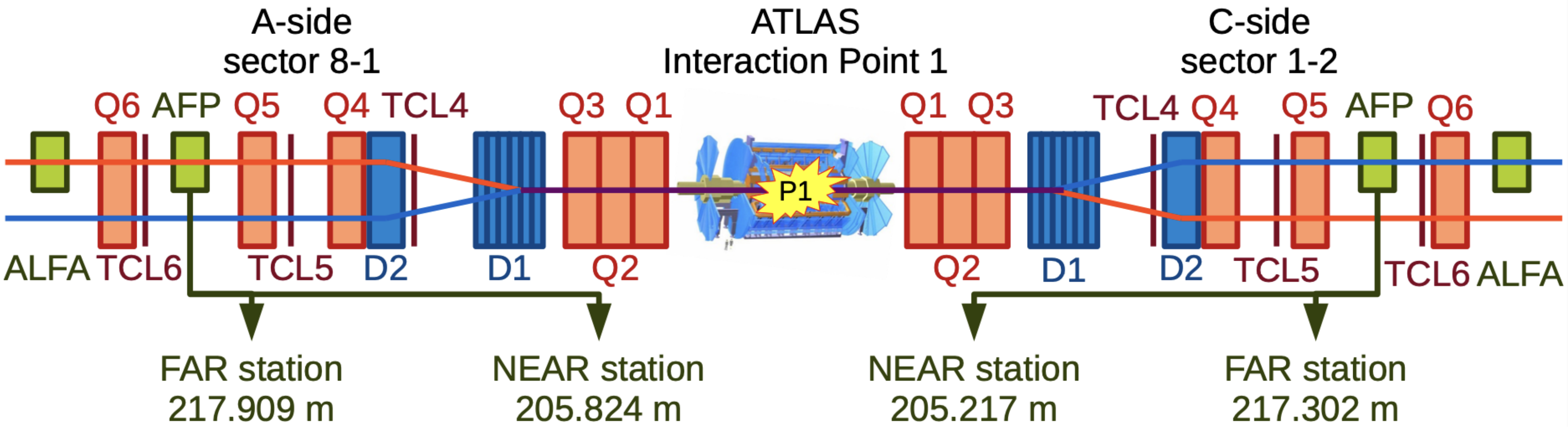




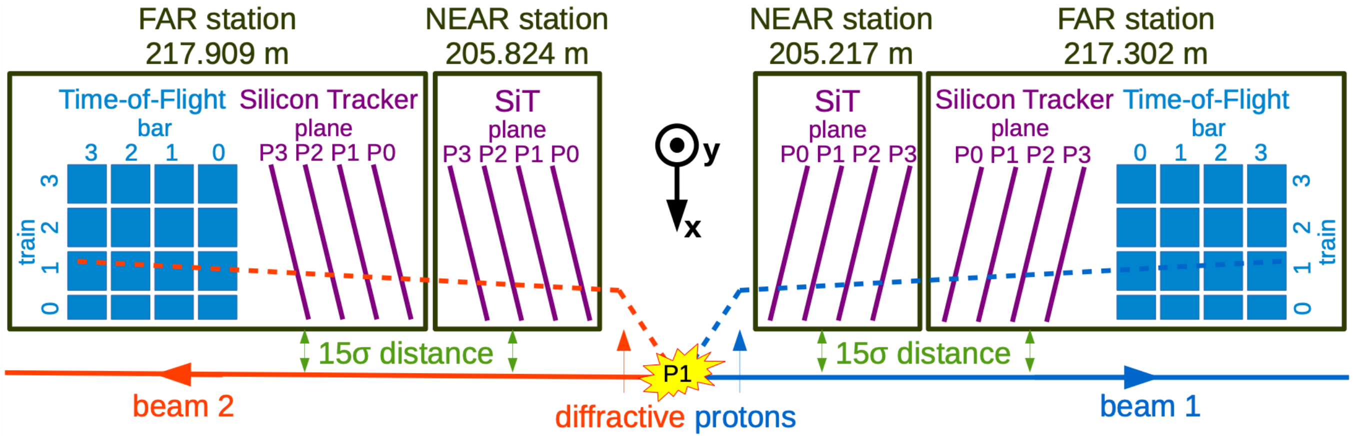
Slide inspired by T.Mroz talk

What is the ATLAS Forward Proton (AFP) Detector?

- Designed to measure **diffractive** and **photon-fusion** processes in which one or both scattered **protons remain intact** and continue moving **forward**
- Placed symmetrically with respect to the ATLAS IP at ~200 m
- **FAR** and **NEAR** stations on each side

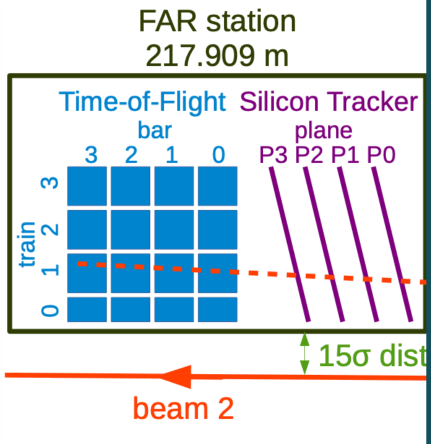


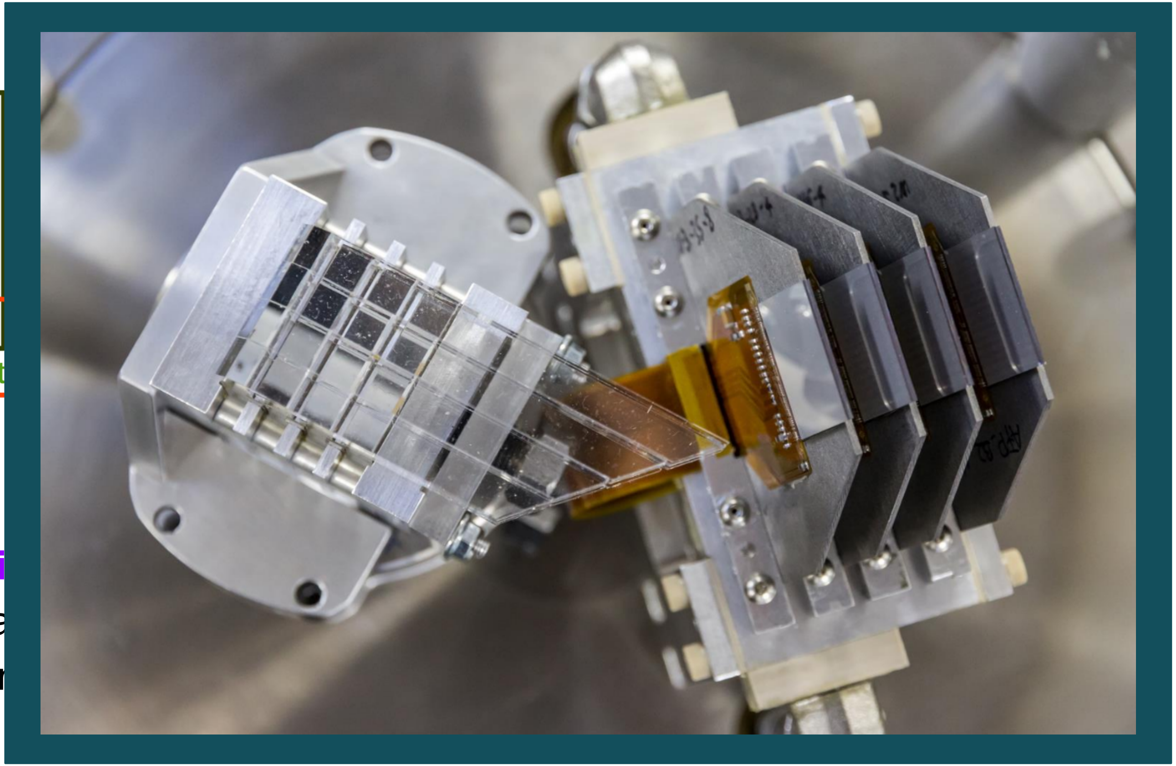
What is the ATLAS Forward Proton (AFP) Detector?



- NEAR stations consist of **Silicon Tracker Planes**
- FAR stations additionally have **Time-of-Flight detectors**
- Housed in Roman Pots: ~2mm from the beam during operation

What is the ATLAS Forward Proton (AFP) Detector?

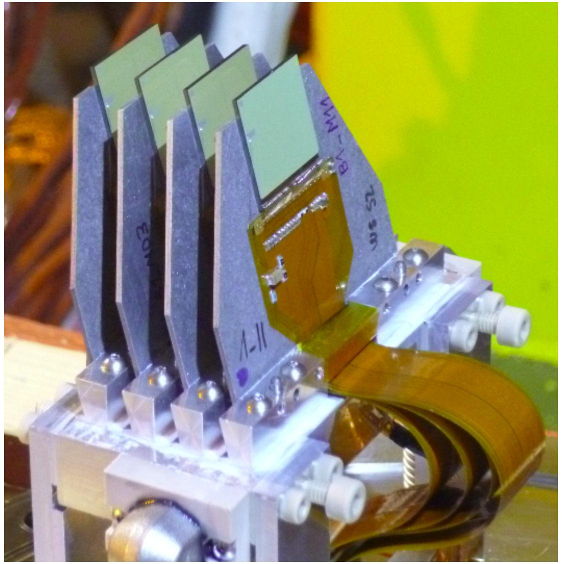




- NEAR stations consist of **Si**
- FAR stations additionally ha
- Housed in Roman Pots: ~2r

Silicon Tracker (SiT)

- 4 planes of **336 × 80** 3D silicon pixels
- 3D pixel size: **50 µm x 250 µm x 230 µm**
- Inclined by 14° with respect to the beam to improve x-resolution



- **Main observable:**

$$\boxed{\xi_{\mathrm{AFP}}^{A,C} = 1 - \frac{E_{\mathrm{reco}}}{E_{\mathrm{beam}}}}$$

- Related to the position in which the proton hits the SiT planes:

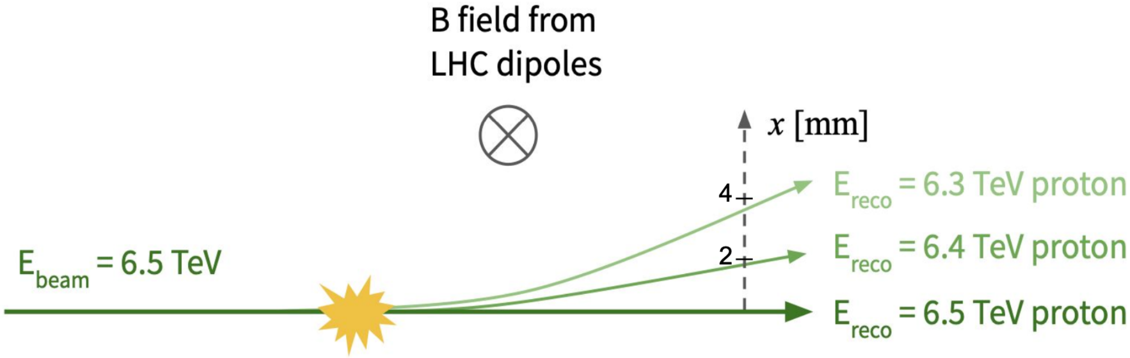
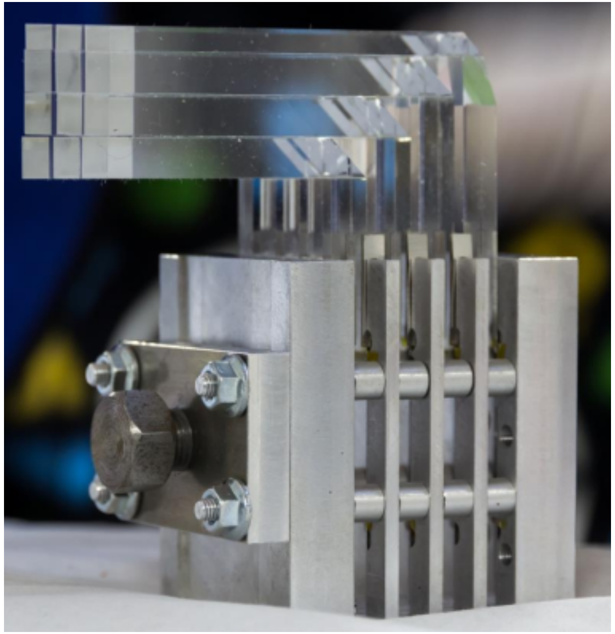


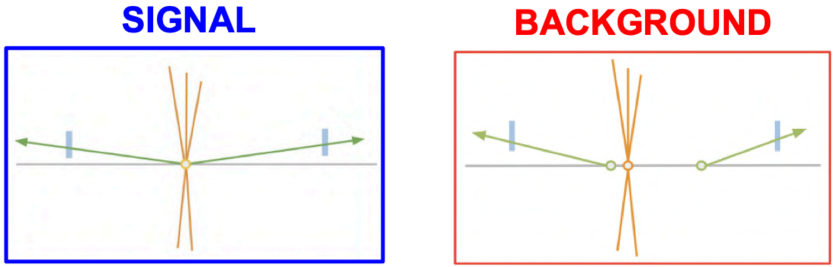
Figure adapted from J. Liu

Time of Flight (ToF)

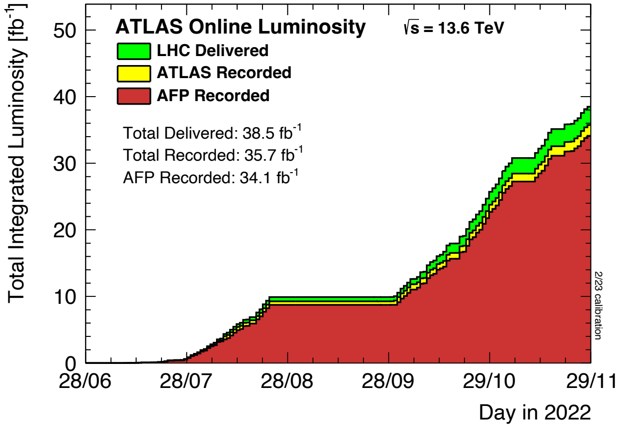
- 4x4 grid of L-shaped quartz bars
- L-shaped Quartz bar (LQ-bar) sends Cherenkov signal to a microchannel plate photomultiplier tube (MCP-PMT)
- Signal is amplified and processed by fast electronics
- Trigger is possible

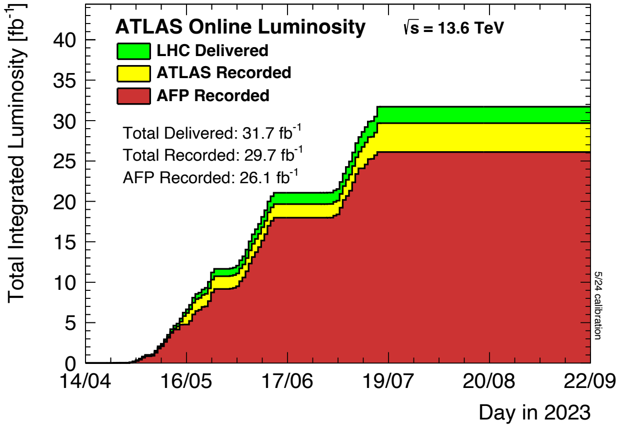
- Difference in time-of-flight used to **calculate interaction vertex position** and compare to reconstructed primary vertex in central ATLAS detector

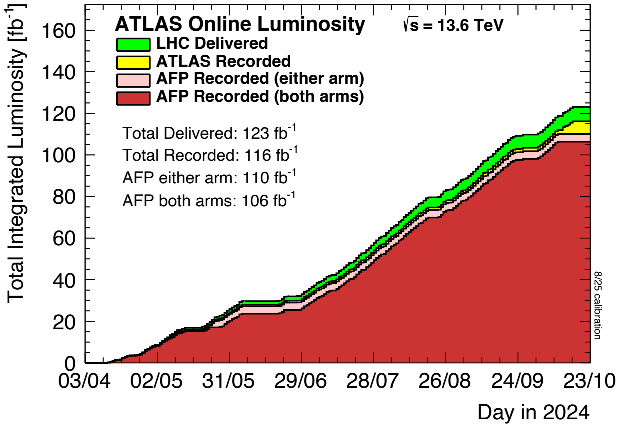


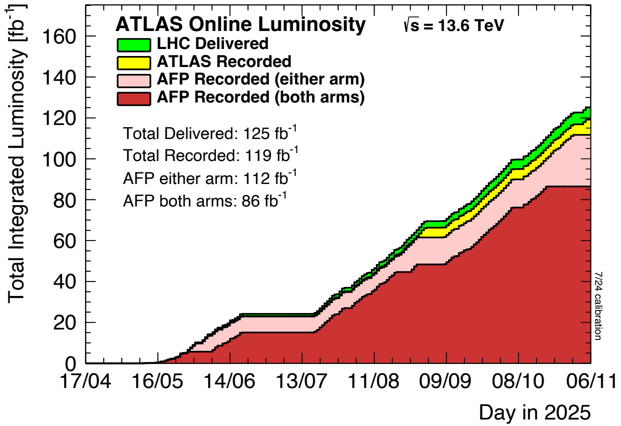


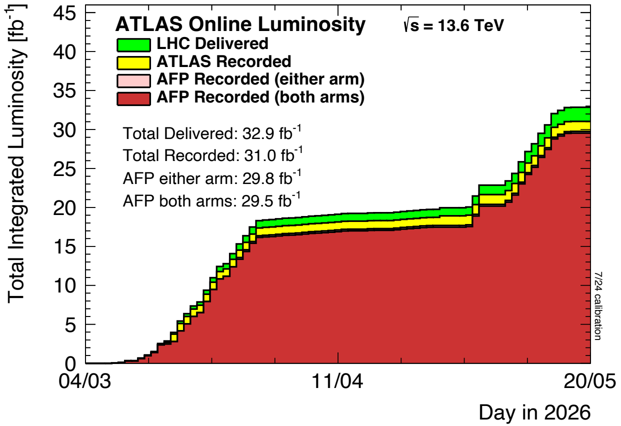
Available Data











282 fb^{-1} in Run 3 p+p

+ AFP recorded data in OO, pO, NeNe and PbPb collisions

AFP Alignment

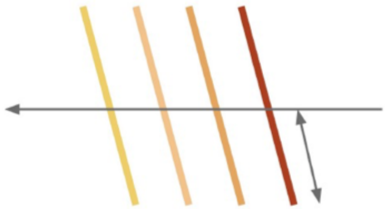
Local Alignment

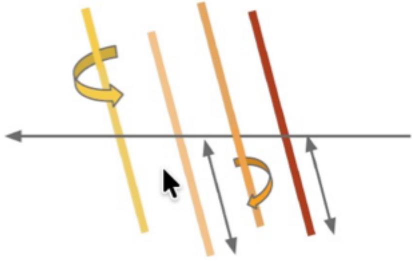
- Relative position of **individual silicon tracker** planes wrt each other
- Impacts track reconstruction

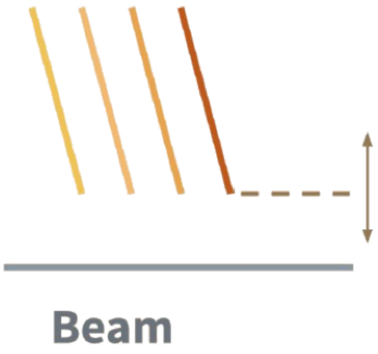
Global Alignment

- Relative position of **AFP station** wrt to the beam
- Impacts precision of proton reconstruction

Ideal alignment







Global alignment of the AFP

$$x(r,s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s) + \delta x_{\text{corr}}(s)$$

x - track position
r - run
s - station

Global alignment of the AFP

given track without alignment

$$x(r,s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s) + \delta x_{\text{corr}}(s)$$

x - track position
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Global alignment of the AFP

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x - track position
r - run
s - station

tracker position: -0.5mm

Global alignment of the AFP

given track without alignment

beam position: from Beam Based Alignment

$$x(r,s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s) + \delta x_{\text{corr}}(s)$$

tracker position: -0.5mm

x - track position
r - run
s - station

Global alignment of the AFP

given track without alignment

beam position: from Beam Based Alignment

$$x(r,s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s) + \delta x_{\text{corr}}(s)$$

x - track position
r - run
s - station

tracker position: -0.5mm

Roman Pot position

Global alignment of the AFP

given track without alignment

beam position: from Beam Based Alignment

in-situ global alignment correction

$$x(r,s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s) + \delta x_{\text{corr}}(s)$$

tracker position: -0.5mm

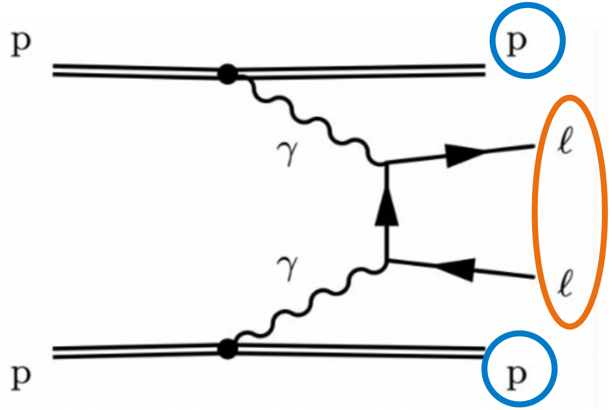
Roman Pot position

x - track position
r - run
s - station

Global alignment of the AFP

$$x(r, s) = x_{\text{pre-align}} + x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r, s) + \boxed{\delta x_{\text{corr}}(s)}$$

- Final in-situ global alignment correction: **use Run 3 exclusive di-muon events**



ATLAS central detector:

- calculate predicted position

$\boxed{\xi_{\mu\mu} = (m_{\mu\mu}/\sqrt{s})\, e^{\pm y_{\mu\mu}}}$ mapped to $\boxed{x_{\mu\mu}}$

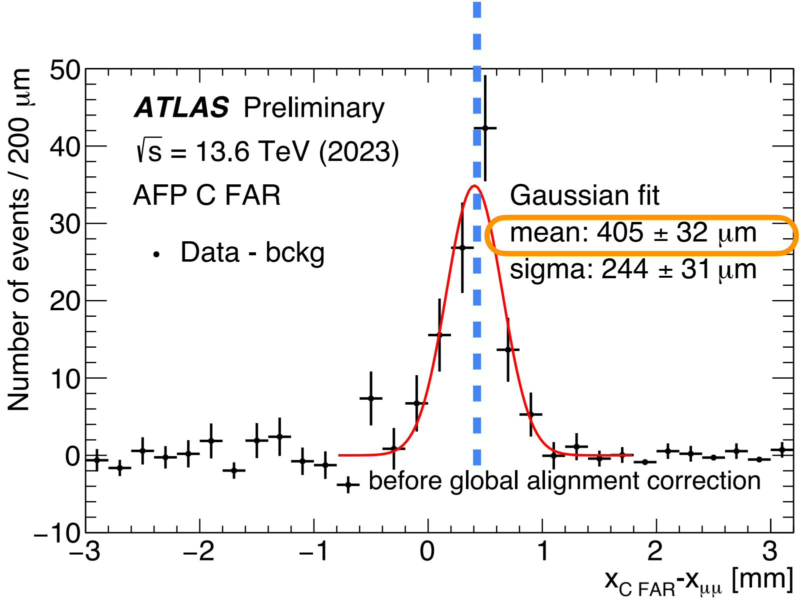
AFP:

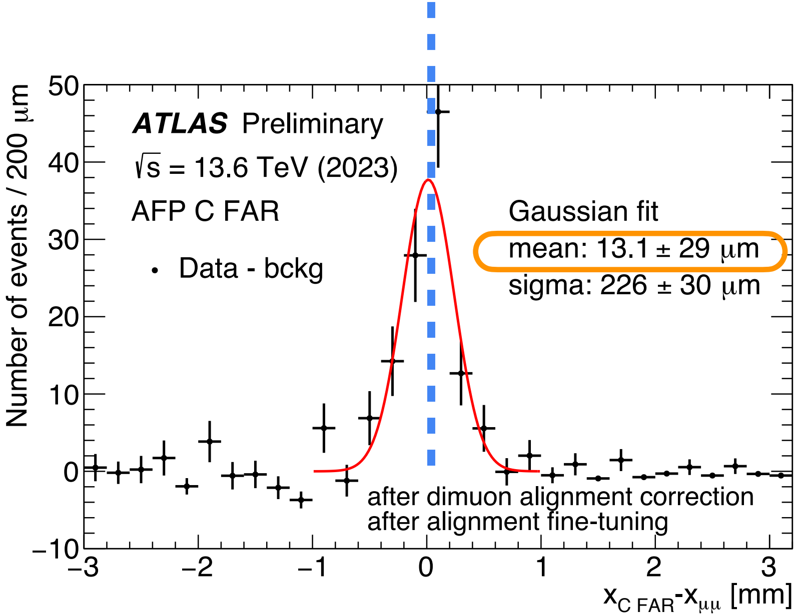
- measured proton position

$\boxed{x_{\text{AFP}}}$

Global alignment of the AFP

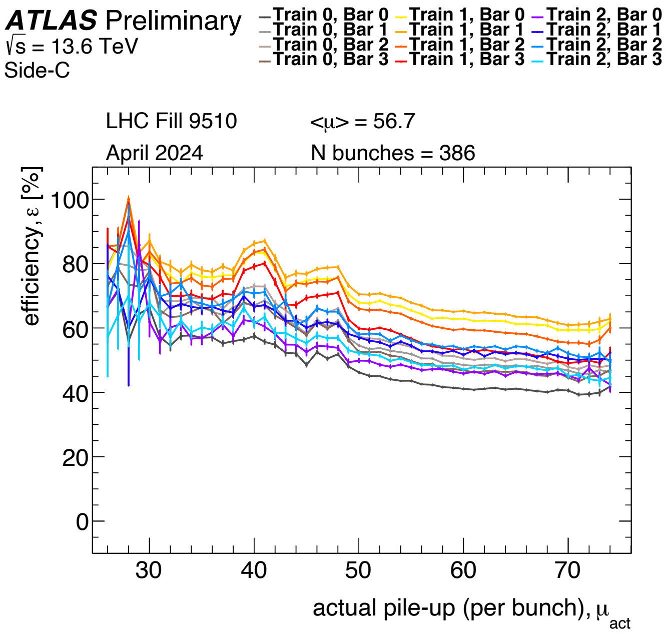
- fit $\boxed{x_{\mathrm{AFP}}}$ - $\boxed{x_{\mu\mu}}$ and shift residuals
- alignment correction: **mean value** of the fitted gaussian

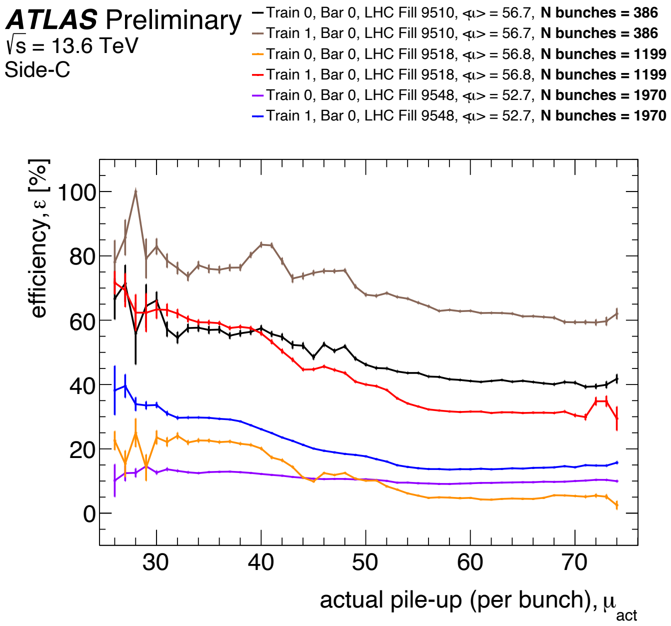




ToF Performance

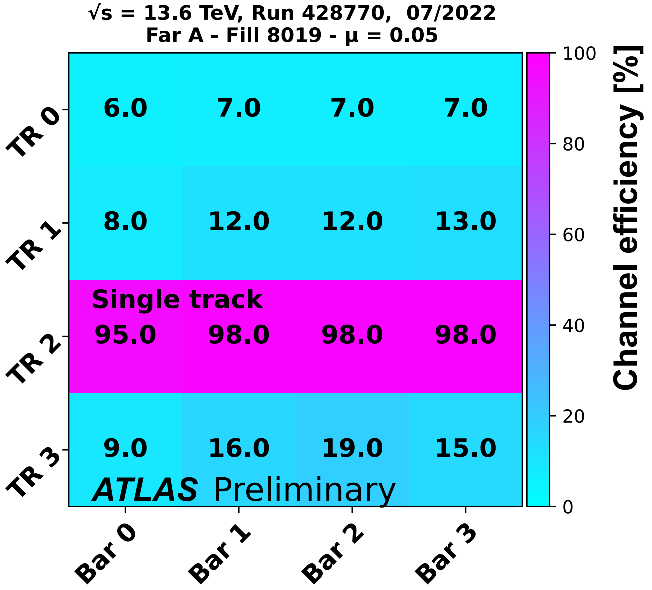
- AFP ToF was installed in **2022** and operated until **2024**
- Performance strongly depends on **particle rate**: pileup and number of bunches
- ToF reinstalled in **2026** with **new readout electronics** (pico-TDC): data analysis in progress



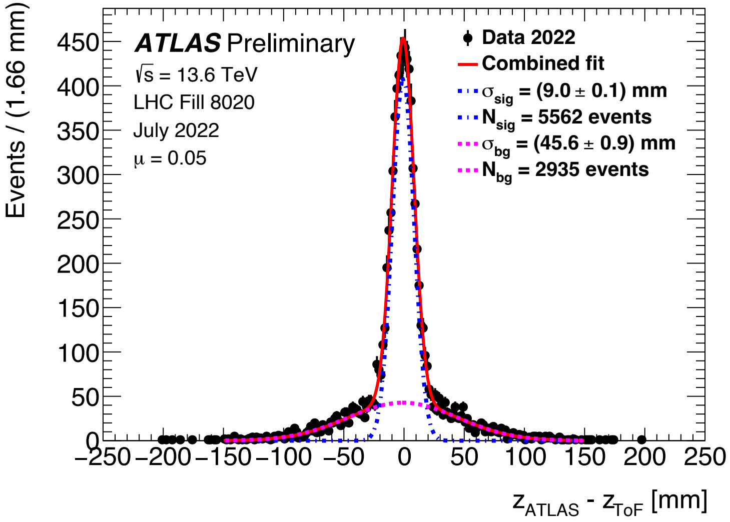


ToF Performance during special runs

- Much higher efficiency of ToF during **low pileup runs**
- Very good precision of vertex reconstruction
- Time resolution of **30 ps** (9 mm) for μ = 0.05 in 2022



Vertex matching



- Difference in primary **vertex z-position** measured by ATLAS and by ToF
- Observe narrow peak: protons originating from primary vertex

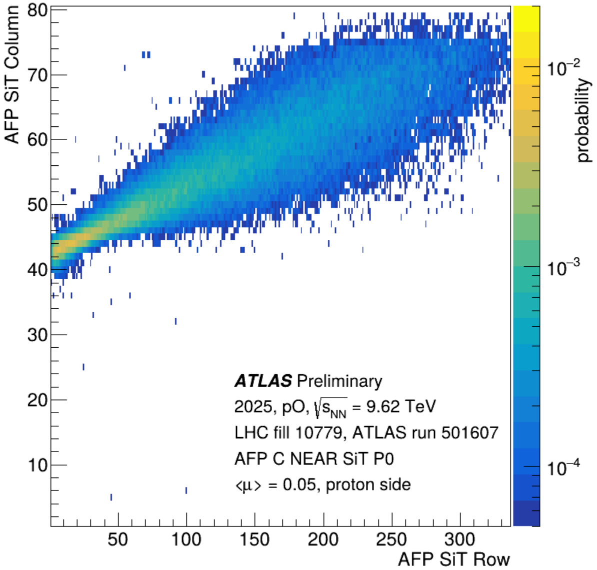
$$z_{ToF} = \frac{c}{2}(t_C - t_A)$$

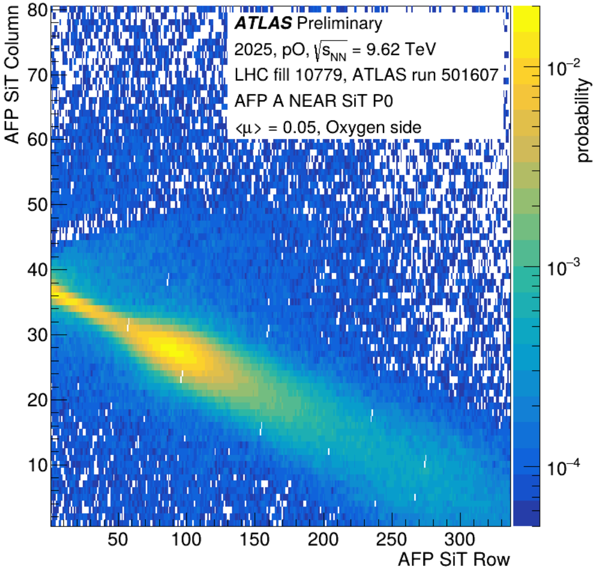
AFP in Light/Heavy Ion campaigns

AFP included in ion runs in 2025 (pO, OO, NeNe) and 2026 (PbPb)

Motivation

- **Unique Physics Phase Space**
- **Cosmic Ray Physics:** input for cosmic ray hadronic interaction models.
- **Last opportunity** to capture forward-tagged heavy-ion data at ATLAS!





Collected a unique dataset
BUT offline analysis/reconstruction may have to be developed from scratch

Latest Physics Results

Missing-mass search in forward-proton-tagged dilepton events with the ATLAS detector

arXiv:2603.20837

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

JHEP 07 (2023) 234

Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS

PRL 125 (2020) 261801

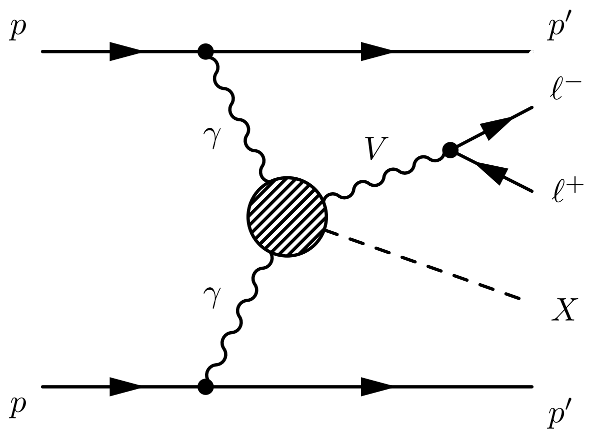
Missing-mass search in forward-proton-tagged dilepton events

- Search for any undetected particle X produced alongside visible dileptons
- Forward proton tagging - access to full kinematic information

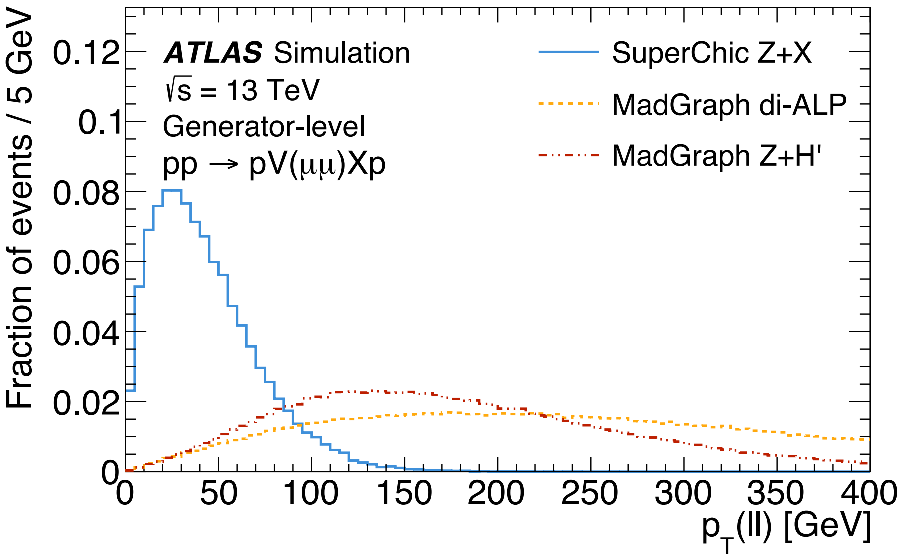
arXiv:2603.20837

Consider three BSM scenarios:

- **Z + X**: Z-boson with invisible particle X
- **Di-ALP**: two axion-like particles produced
- **Z + H′**: Z boson with a generic invisible scalar H′



Access to wide kinematic range



Missing-mass search in forward-proton-tagged dilepton events

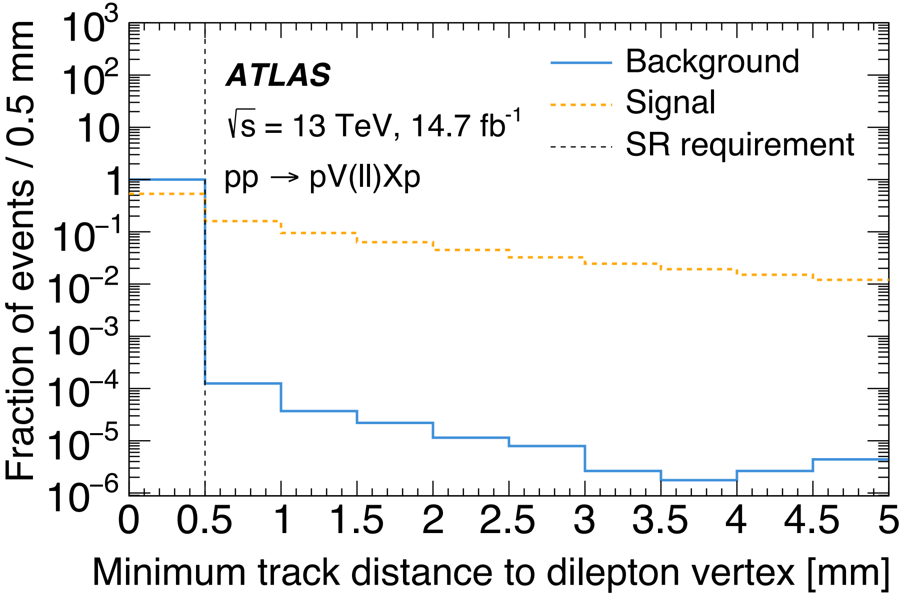
arXiv:2603.20837

- Run 2 (2017) **14.7 fb^{-1}** of pp data
- Channels: **ee** and **μμ**
- **Combinatorial background dominant**
- Data-driven background modeling via **event mixing**
- Search for a narrow resonance in missing mass:

$$100 < m_X < 900\ [GeV]$$

Track-veto:

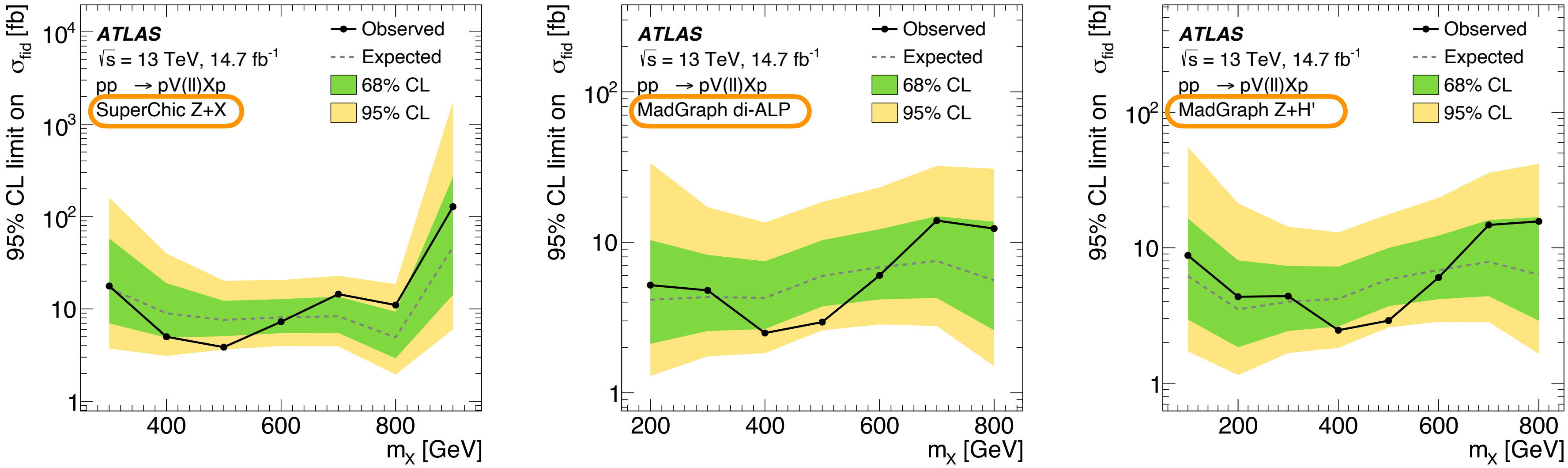
- **Reject events with tracks within 0.5 mm in z of the dilepton vertex**
- **Substantially reduce quark-induced backgrounds**



Missing-mass search in forward-proton-tagged dilepton events

arXiv:2603.20837

- Set 95% CL upper limits on fiducial cross section: **~125 fb^{-1} - 2.5 fb^{-1}**
- No excess observed over SM predictions



Conclusions

- AFP designed to measure diffractive and photon-induced processes by tagging forward protons
- Deinstallation after Run 3 → **no forward proton program in Run 4**
- Recent missing-mass searches in dilepton final states provide a **powerful proof-of-principle for BSM searches**
- **Multiple analyses** are underway using Run 2 and Run 3 data across both low- and high-pileup regimes
- **Unlocking Ions**: The unique light/heavy-ion dataset ready to understand and to analyse - more results coming soon!

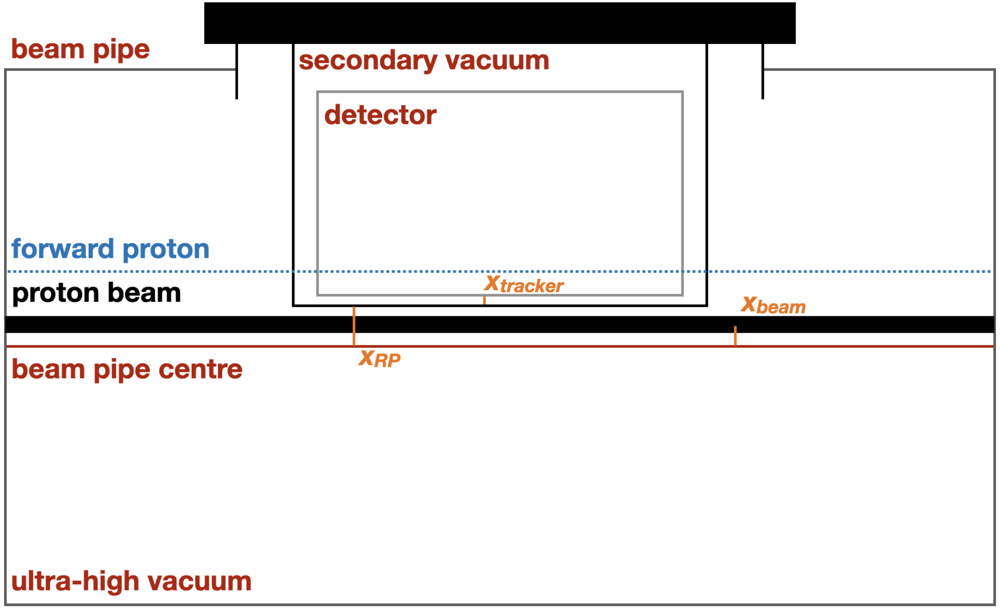
Thank you!

Backup

Introduction

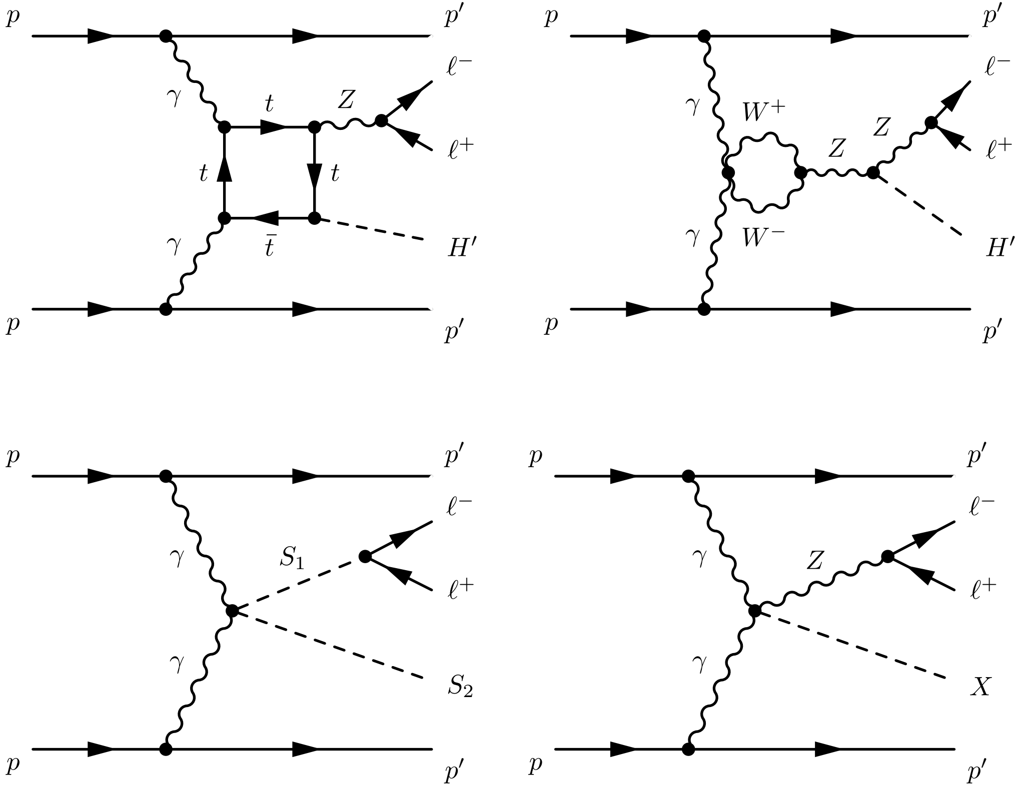
Alignment corrections

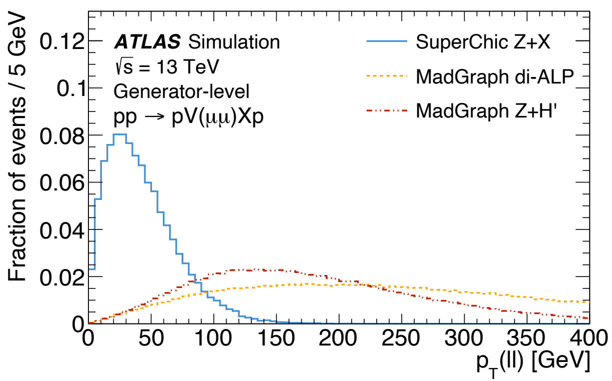
$$x(r,s) = x_{\text{pre-align}} + \boxed{x_{\text{tracker}} - x_{\text{beam}}(s) + x_{\text{RP}}(r,s)} + \delta x_{\text{corr}}(s)$$

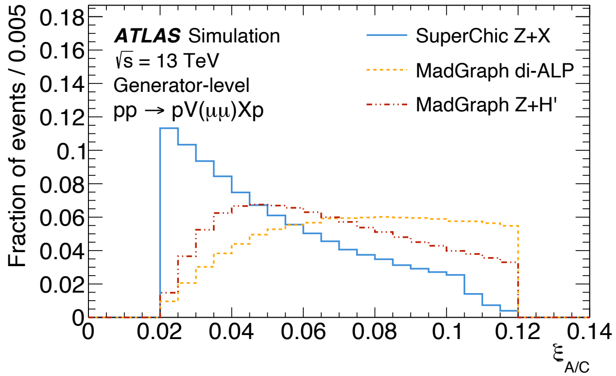


Missing-mass search in forward-proton-tagged dilepton events

[arXiv:2603.20837](https://arxiv.org/abs/2603.20837)



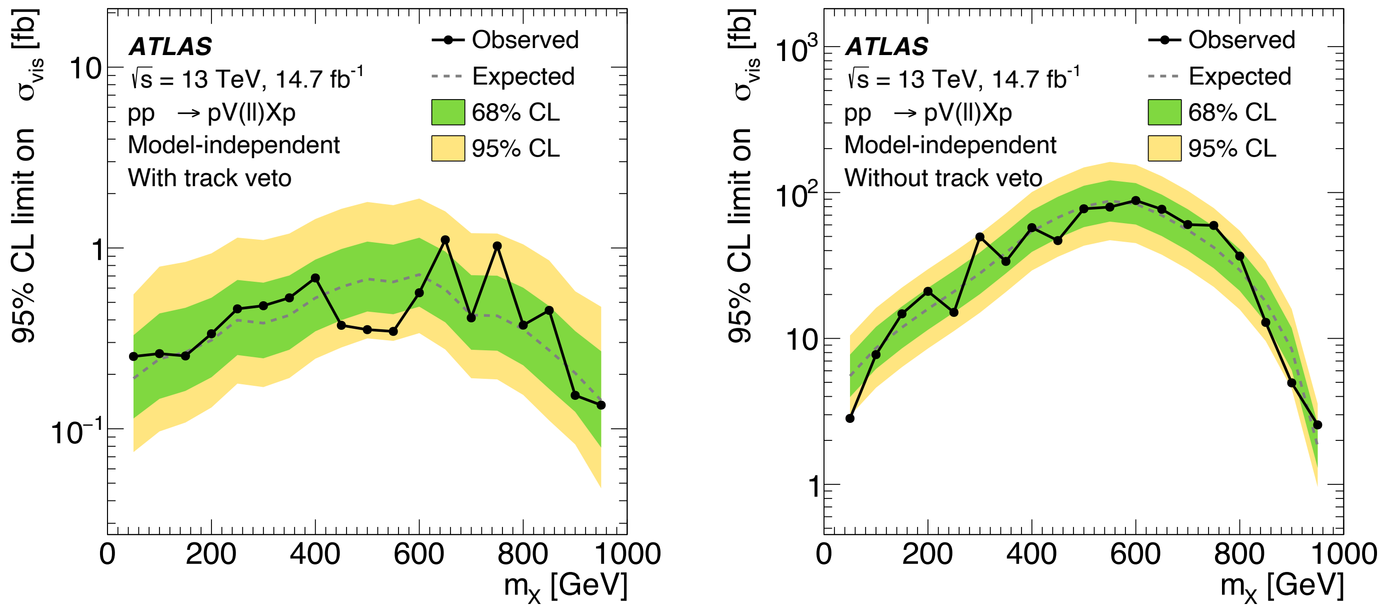




Missing-mass search in forward-proton-tagged dilepton events

arXiv:2603.20837

model-independent limits on the visible cross-section (σ × acceptance × efficiency)



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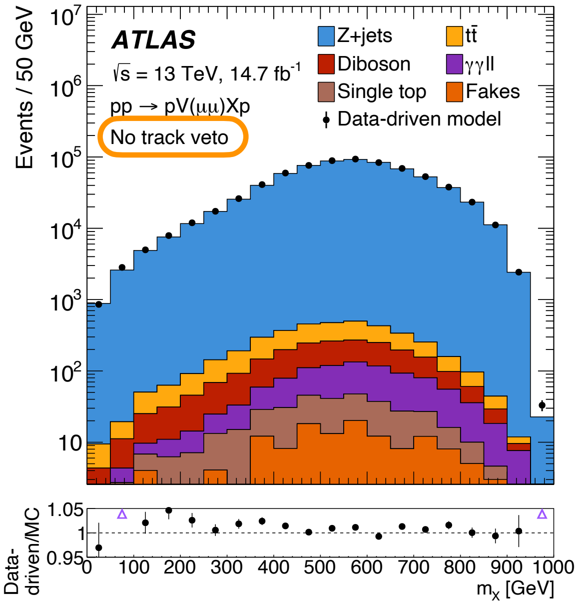
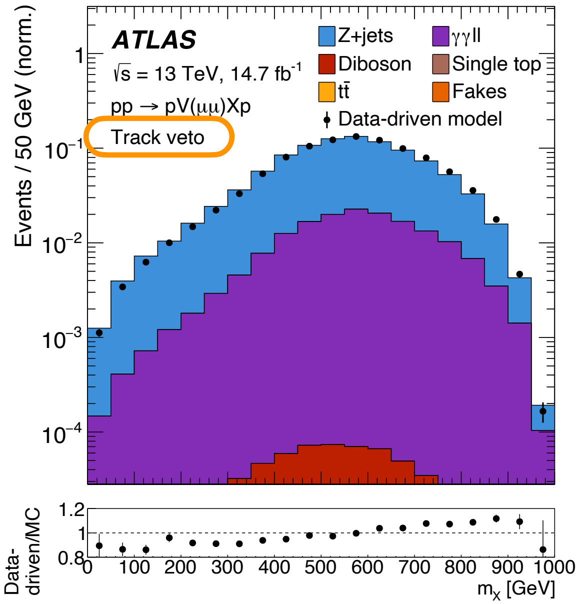
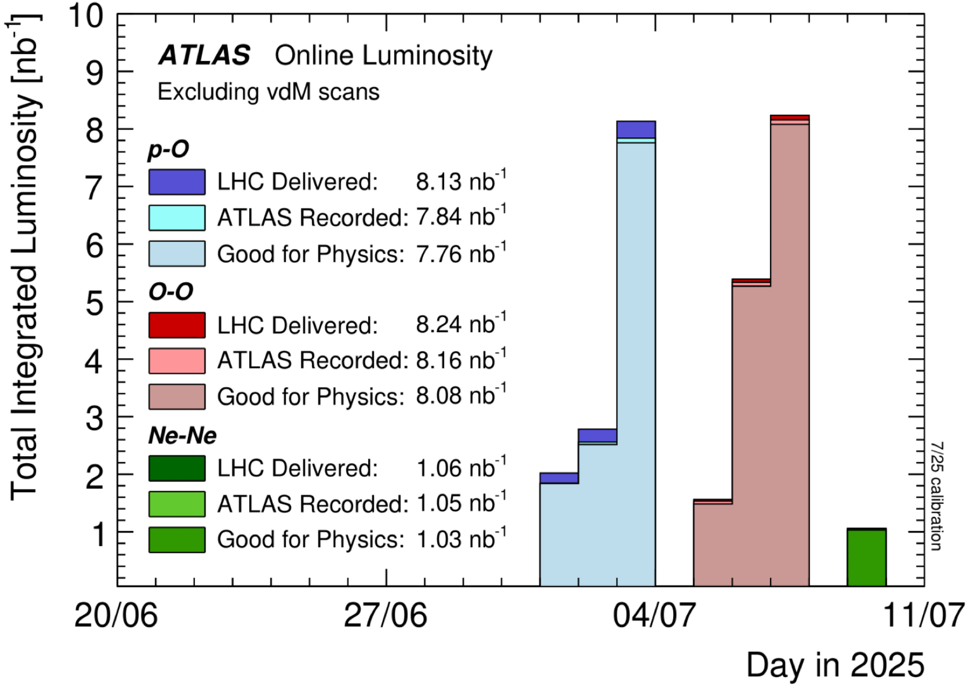




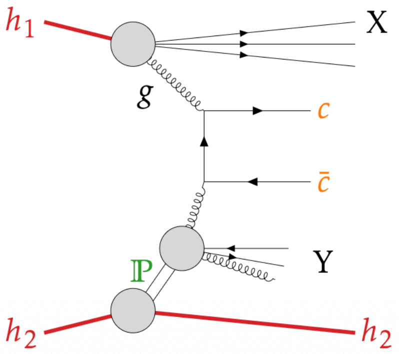
AFP in Light Ion campaigns



Diffractive processes and AFP

Heavy-quarks

- $c\bar{c}$ production - lowest-mass process involving hard-scale
- Probing the nature of Pomeron, testing competing models: Resolved Pomeron, Dipole, Soft Color Interaction
- Testing the factorization theorem and measurement of gap survival probability



Diffractive jets

- Single Diffractive Jet Production
- Double Pomeron Exchange (DPE) Jet production
- Jet-gap-jet (Mueller-Tang jets)
- Exclusive Jet Production