# ATLAS Roman Pots

## General Experimental Overview

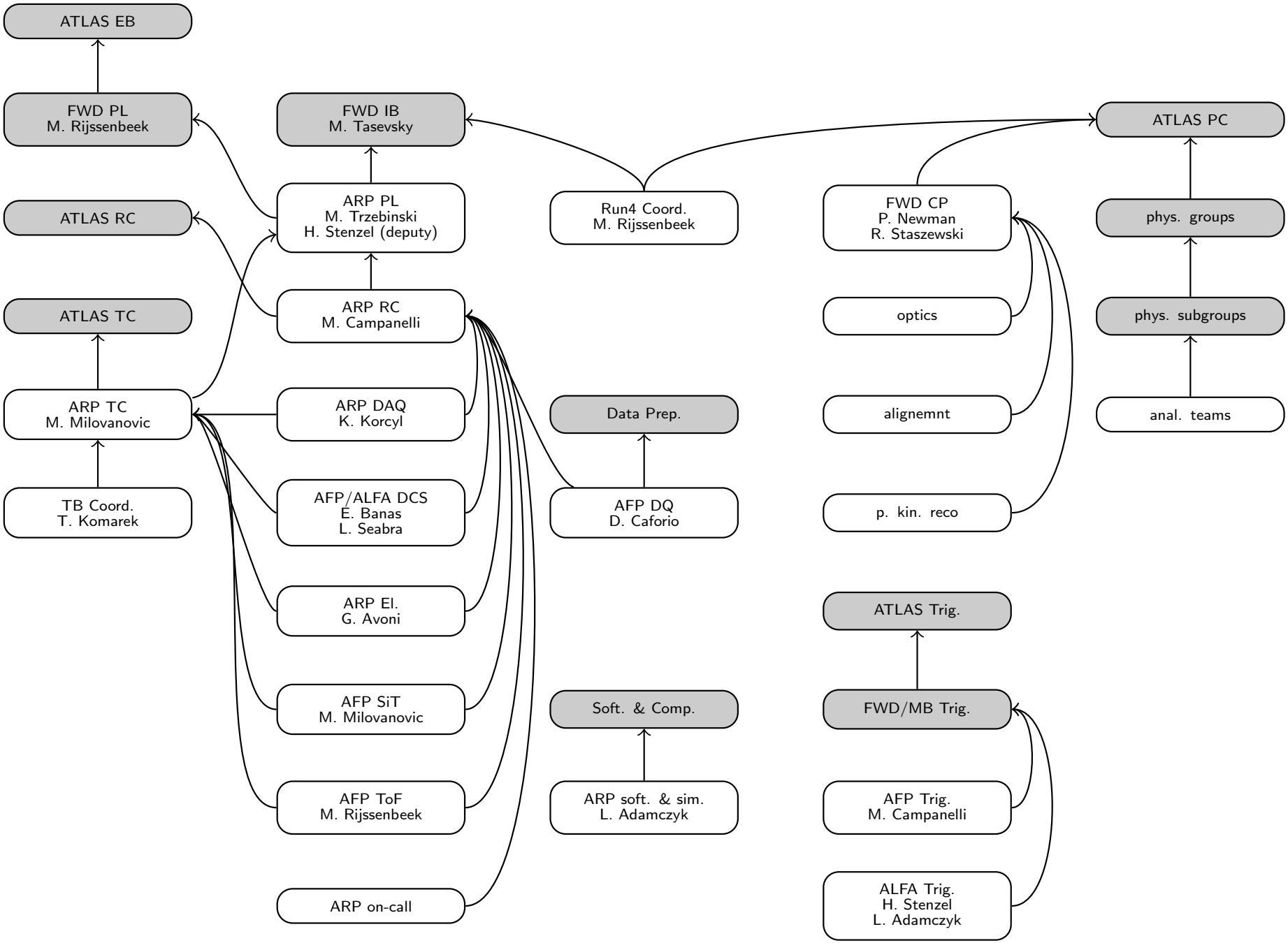
Maciej Trzebiński

Institute of Nuclear Physics
Polish Academy of Sciences

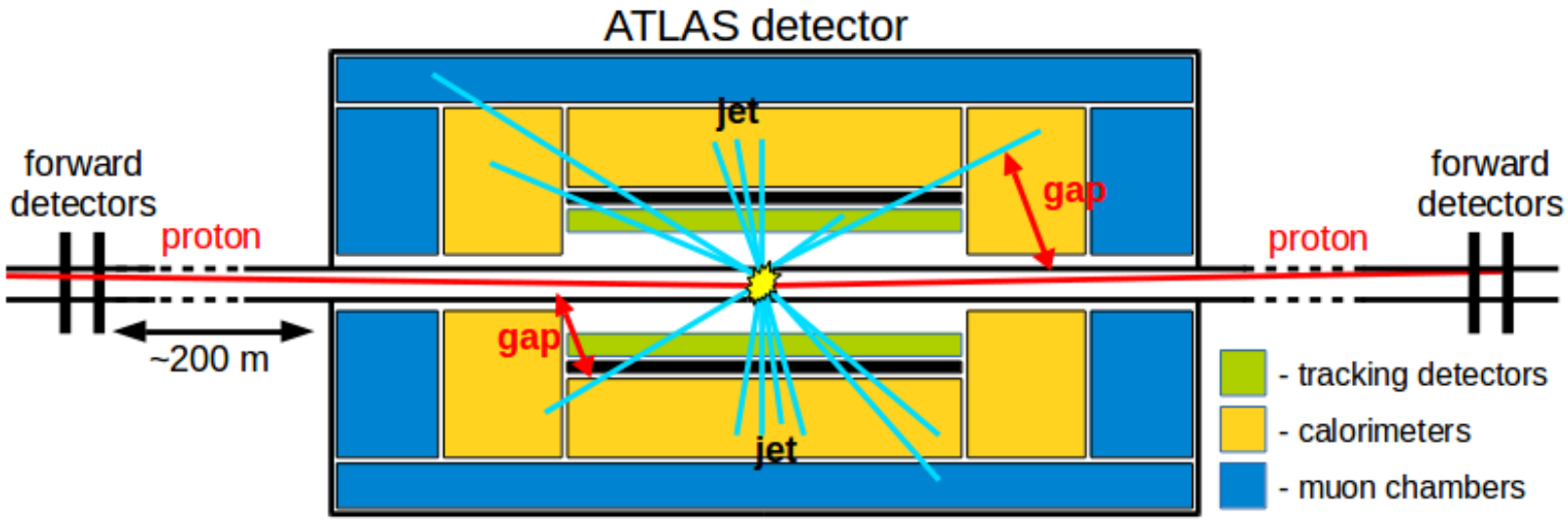
**Photon-induced processes**

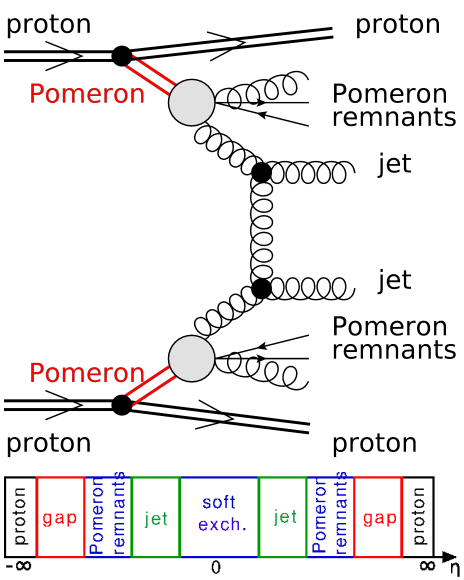
**IPPP Durham, 3rd November 2022**

# View of ATLAS Roman Pots Organization



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.



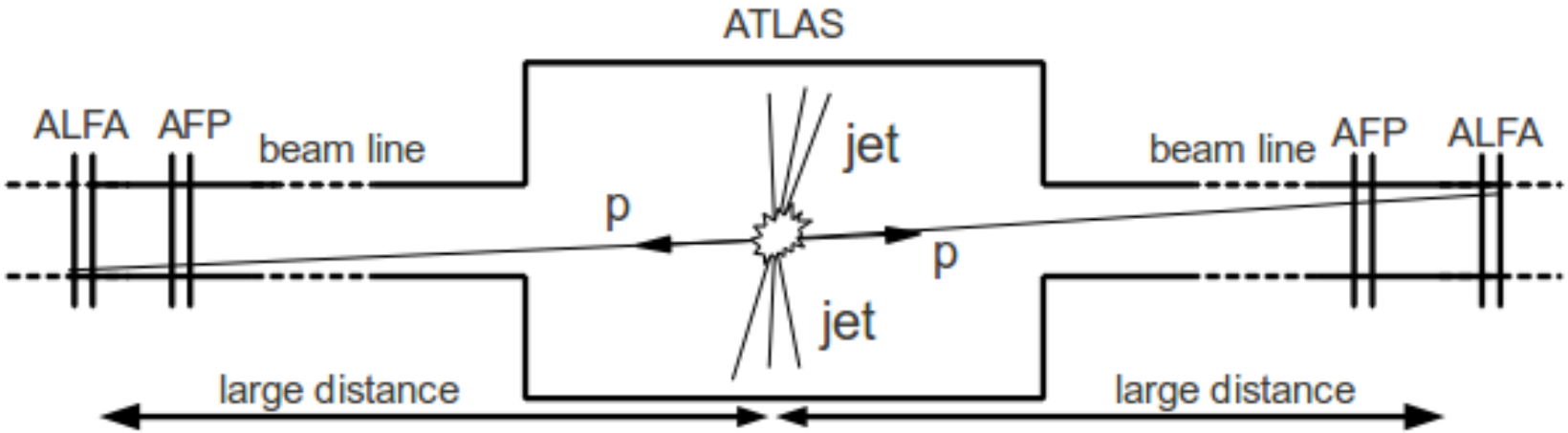

## Method 1 (rapidity gap):

+ 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 $\mu$rad)
– additional "forward" detectors are needed far away from the interaction point

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



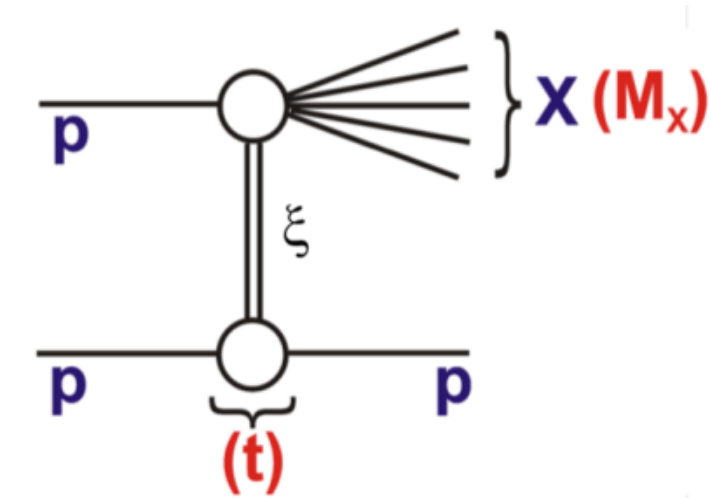

## ALFA

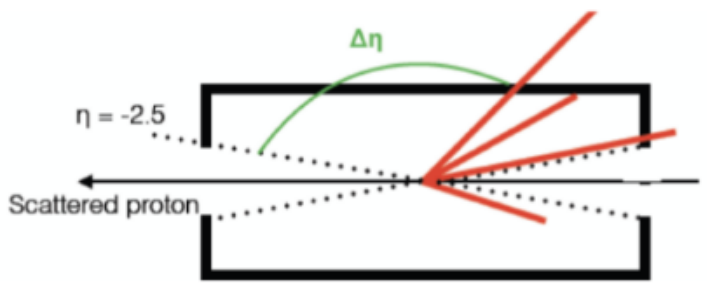
- **A**bsolute **L**uminosity **F**or **A**TLAS
- 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high $\beta^*$ optics)
- vertically inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = \sigma_y = 30$ $\mu$m

## 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

# Kinematic Variables




- $t$ – squared four-momentum transferred from the proton:
$$t \approx -p_T^2$$
- $p_T$ – proton transverse momentum
- $\xi$ – 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

# Optics

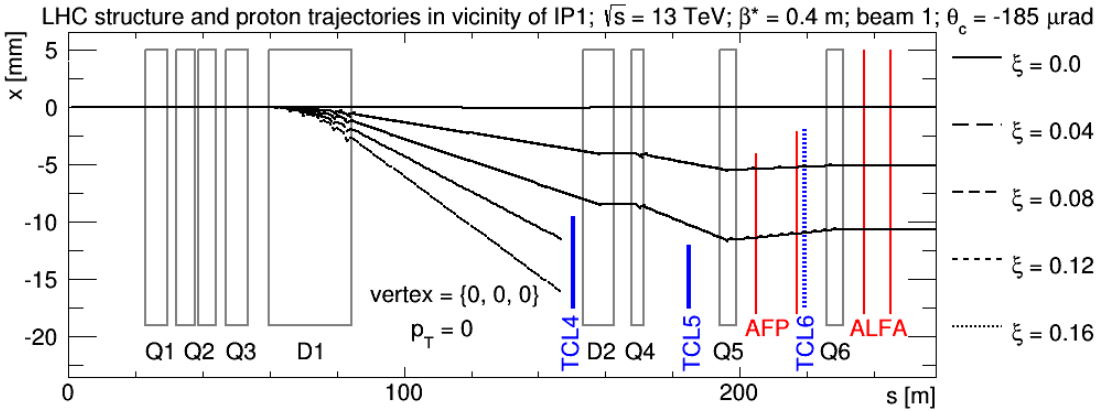
# Forward Proton Trajectories

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 $\xi$

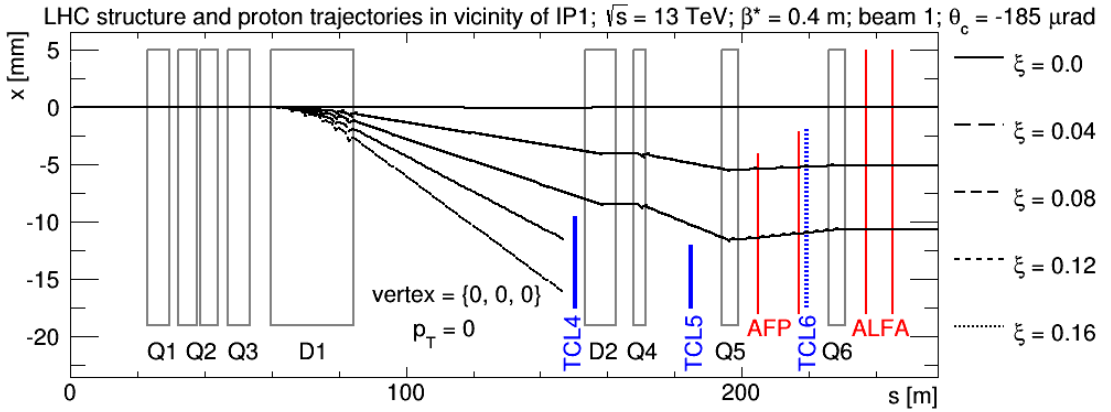
$\xi = 1 - E_{proton}/E_{beam}$



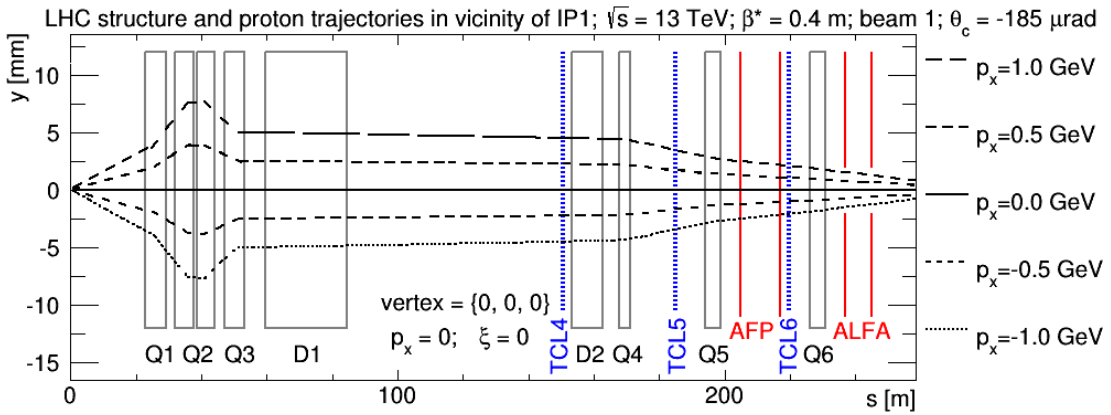
Proton trajectory is determined by the LHC magnetic field.

**collision optics**, **ALFA** and **AFP**: trajectory due to $\xi$

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



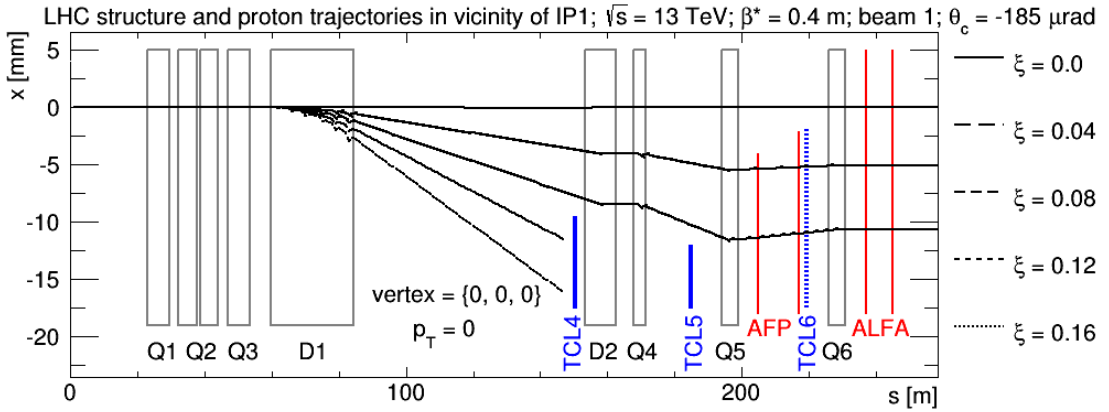

**collision optics**, **ALFA** and **AFP**: trajectory due to $p_y$



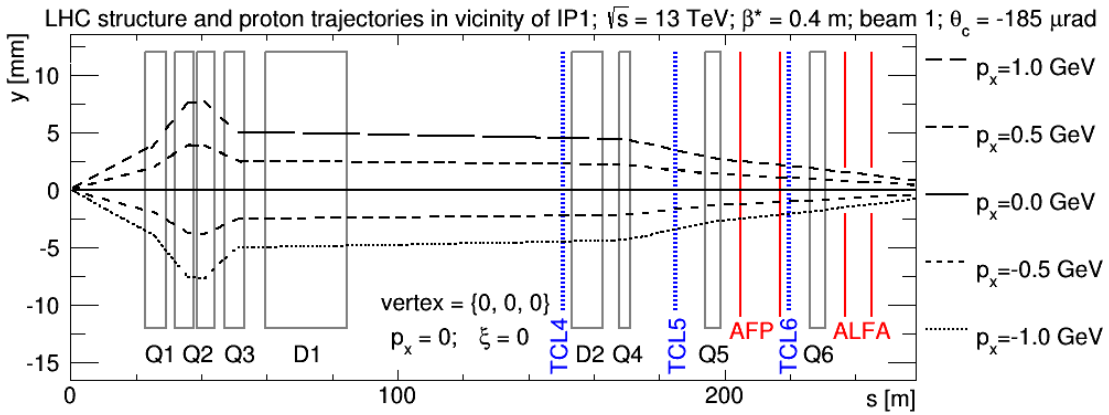
Proton trajectory is determined by the LHC magnetic field.

**collision optics**, **ALFA** and **AFP**: trajectory due to $\xi$

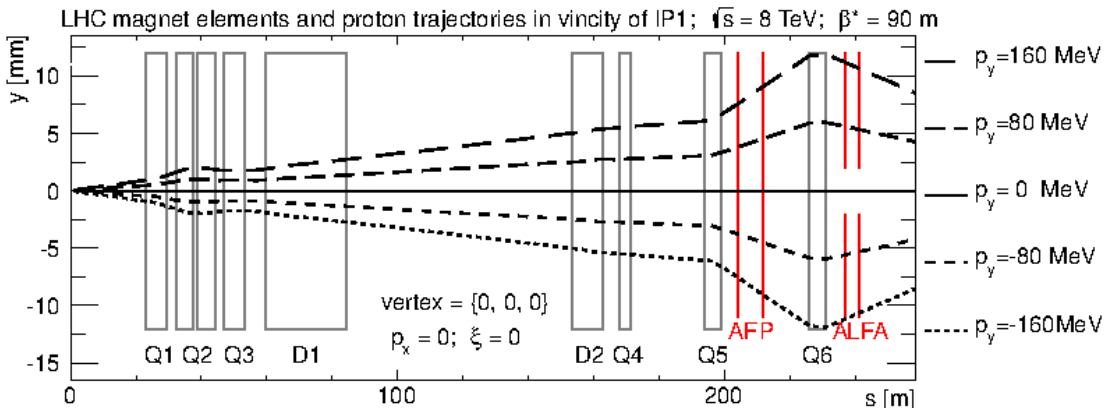
$\xi = 1 - E_{proton}/E_{beam}$




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



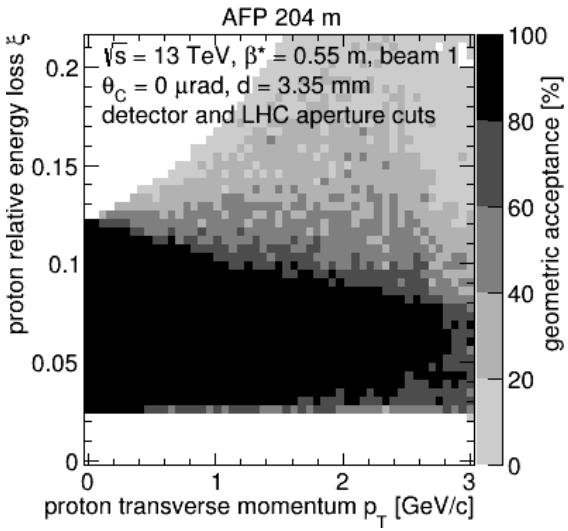

**special high-$\beta^*$ optics**, **ALFA**: improve acceptance in $p_T = \sqrt{px^2 + py^2}$

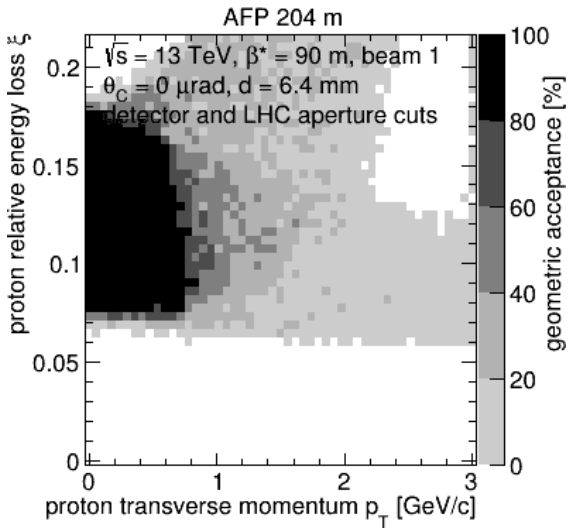


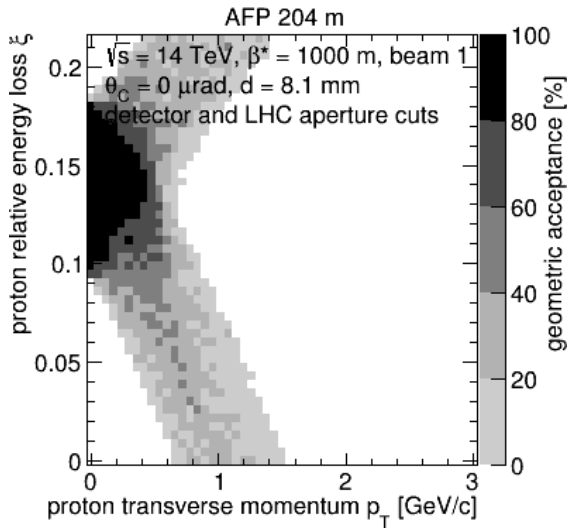

From SPIE 9290 (2014) 929026, arXiv:1408.1836

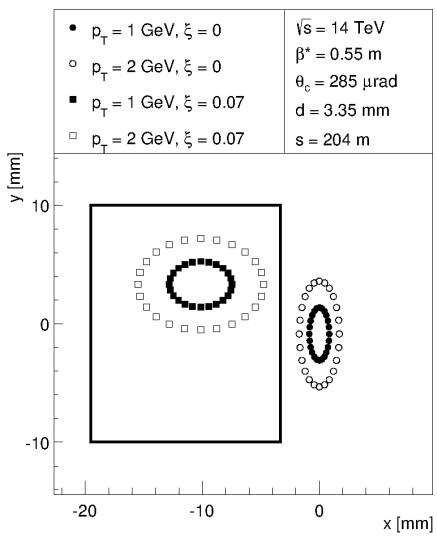
# Geometric Acceptance for Various Optics

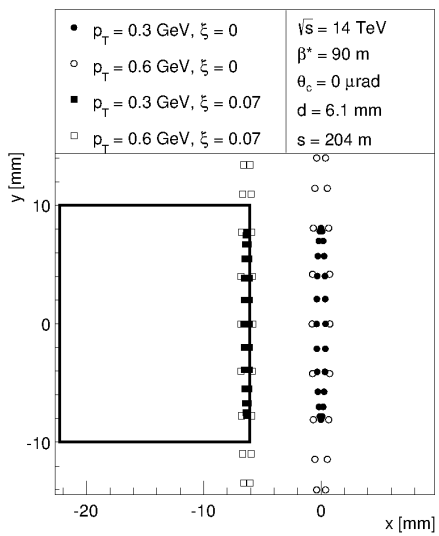
| $\beta^* = 0.55$ m | $\beta^* = 90$ m | $\beta^* = 1000$ m |
|---|---|---|
| nominal (*collision*) | special (*high-$\beta^*$*) | special (*high-$\beta^*$*) |

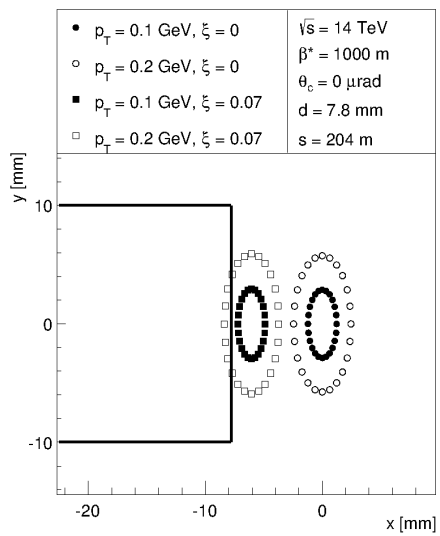


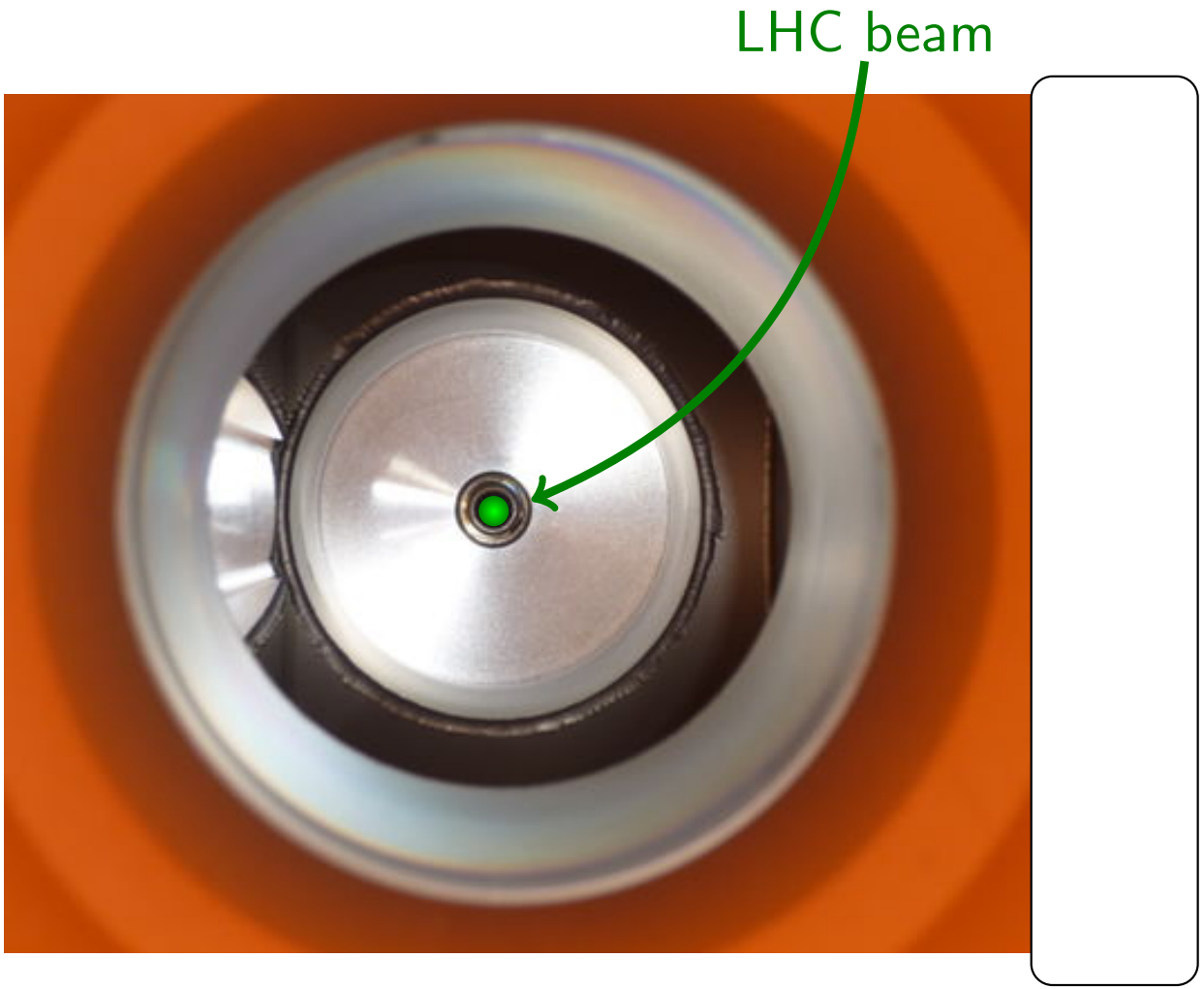




Simulation: distance from the beam was set to $10\sigma$ ($\beta^* = 0.55$ m) or $15\sigma$ ($\beta^* = 90$ and 1000 m).

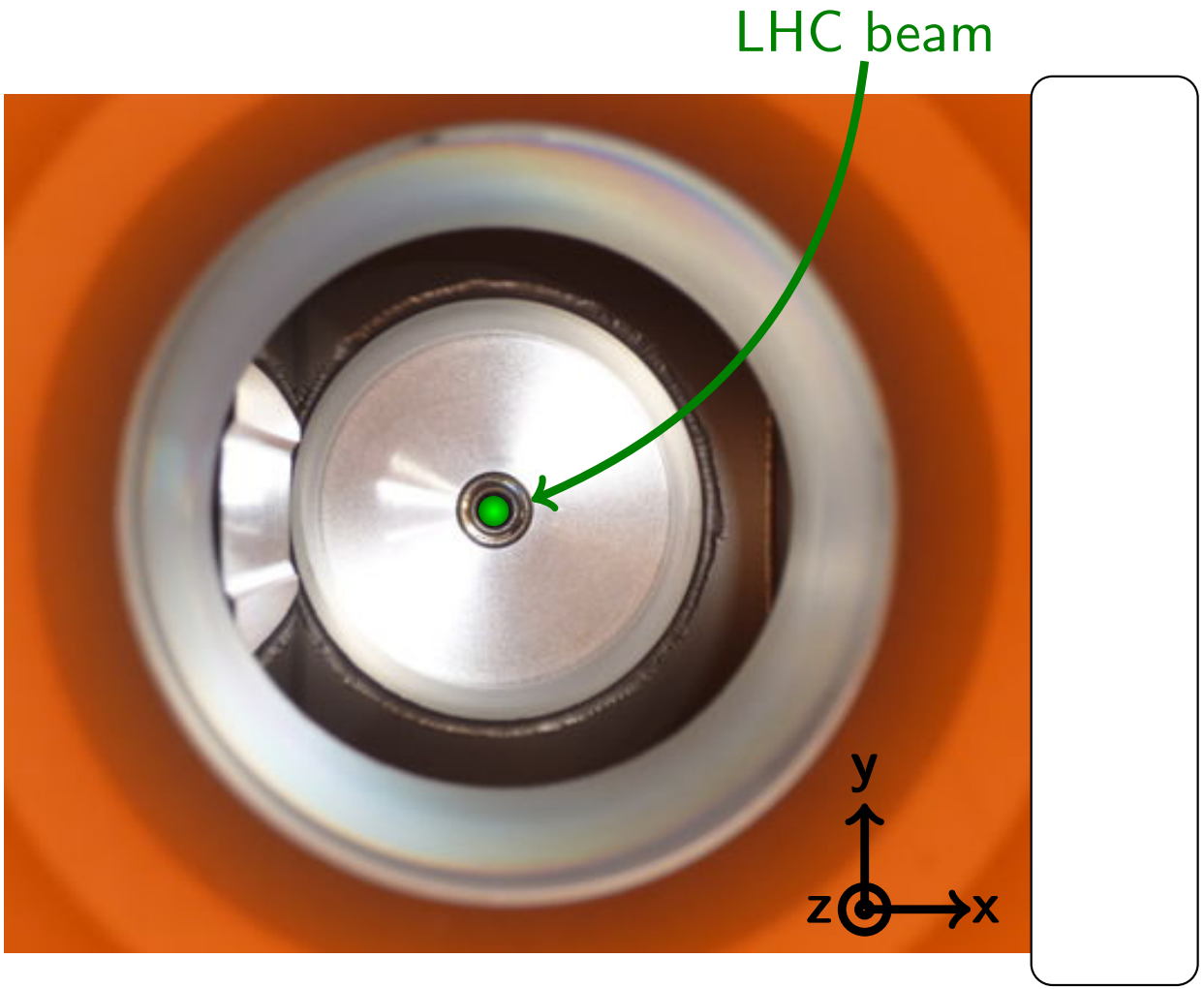
From SPIE 9290 (2014) 929026, arXiv:1408.1836

# Advantages of Roman Pot Technology

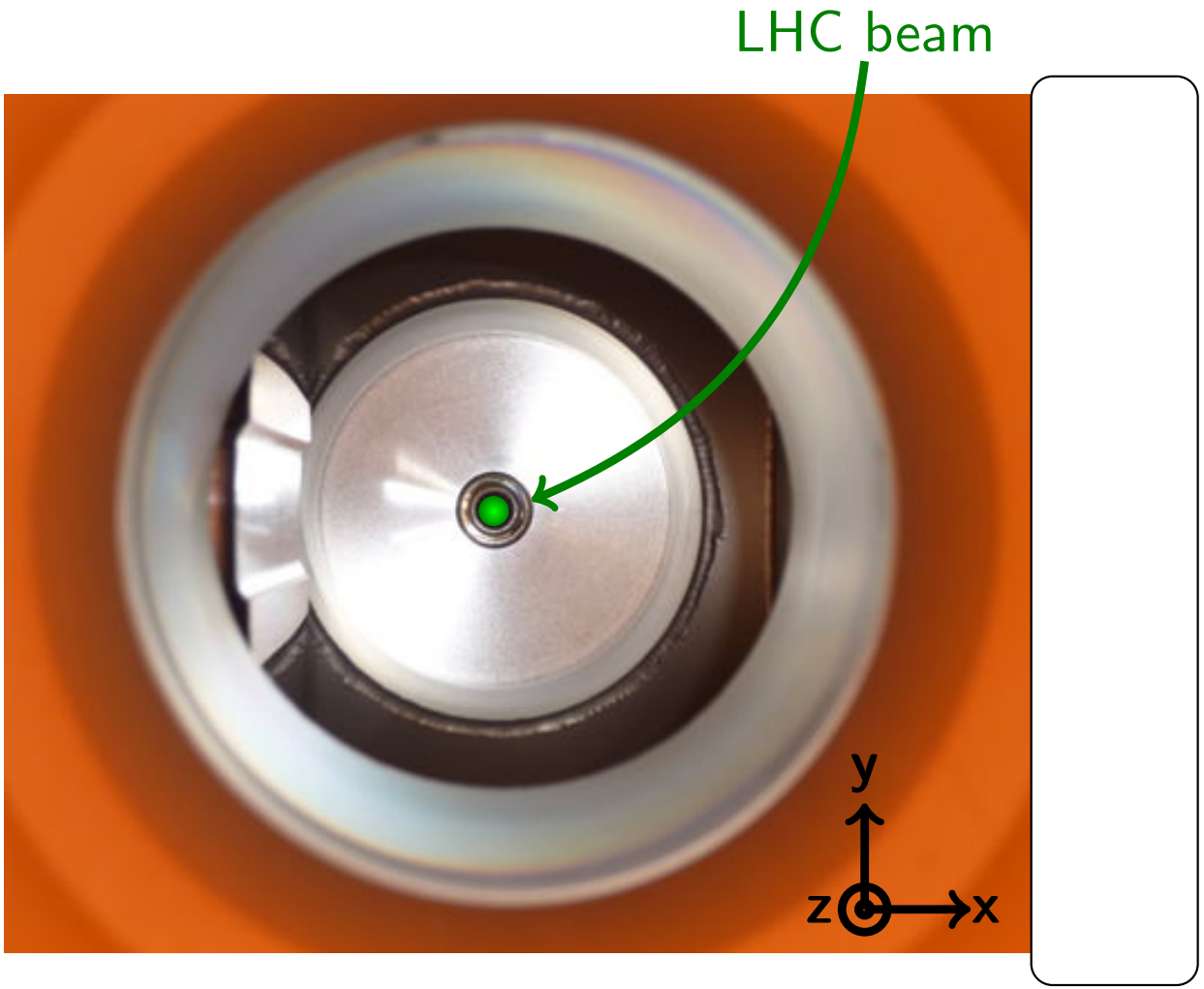
# Advantages of Roman Pot Technology



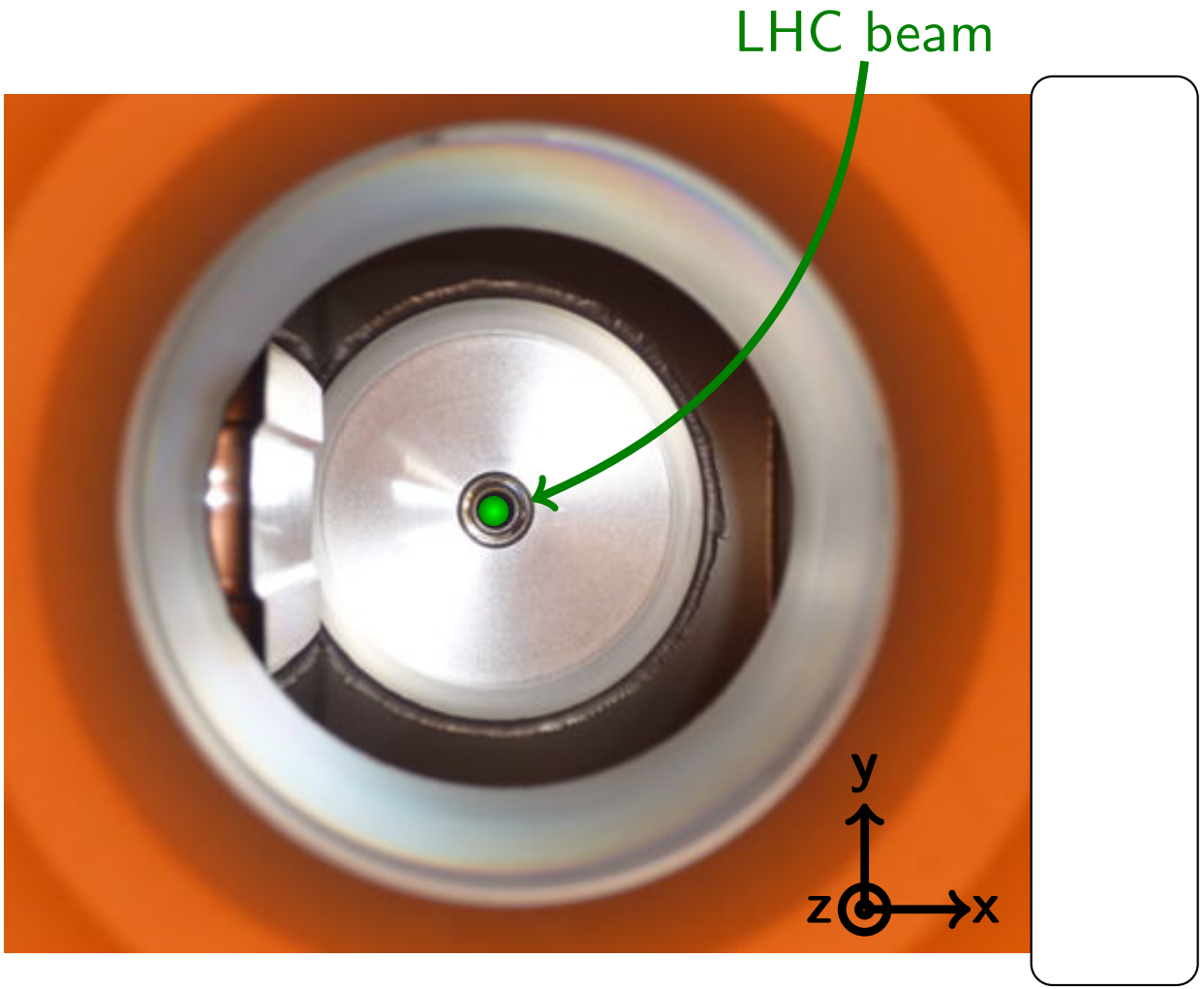
# Advantages of Roman Pot Technology



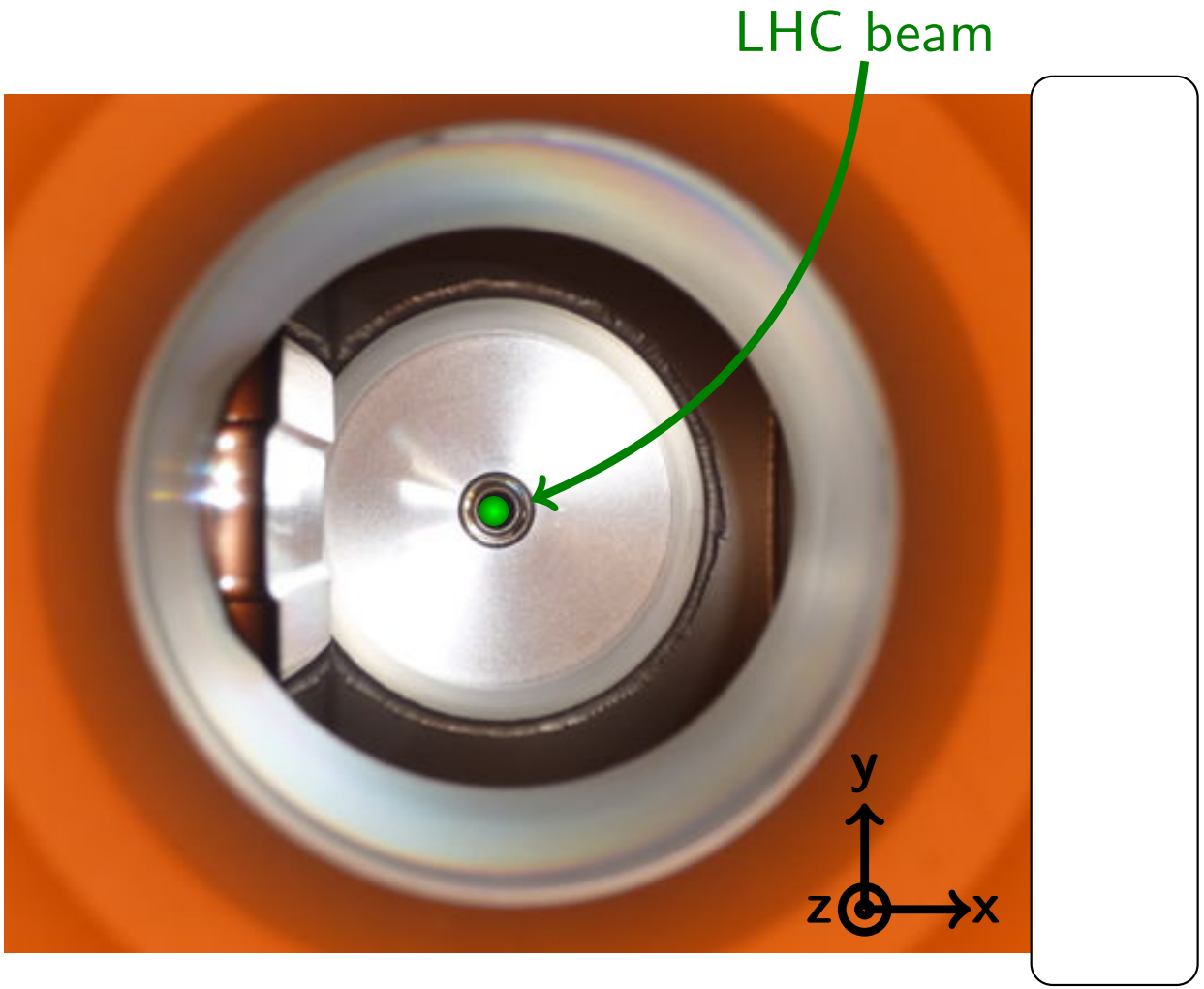
# Advantages of Roman Pot Technology



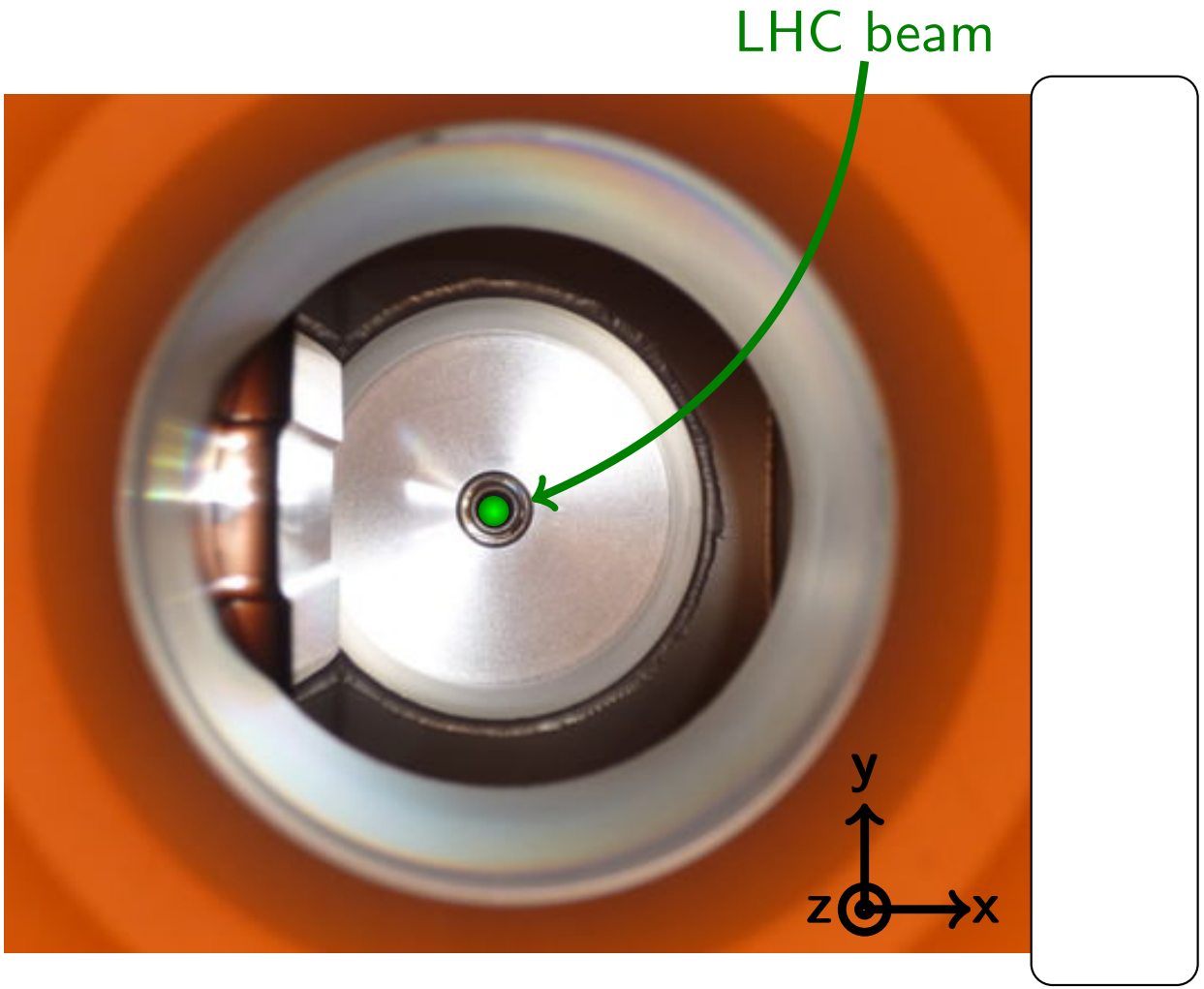
# Advantages of Roman Pot Technology



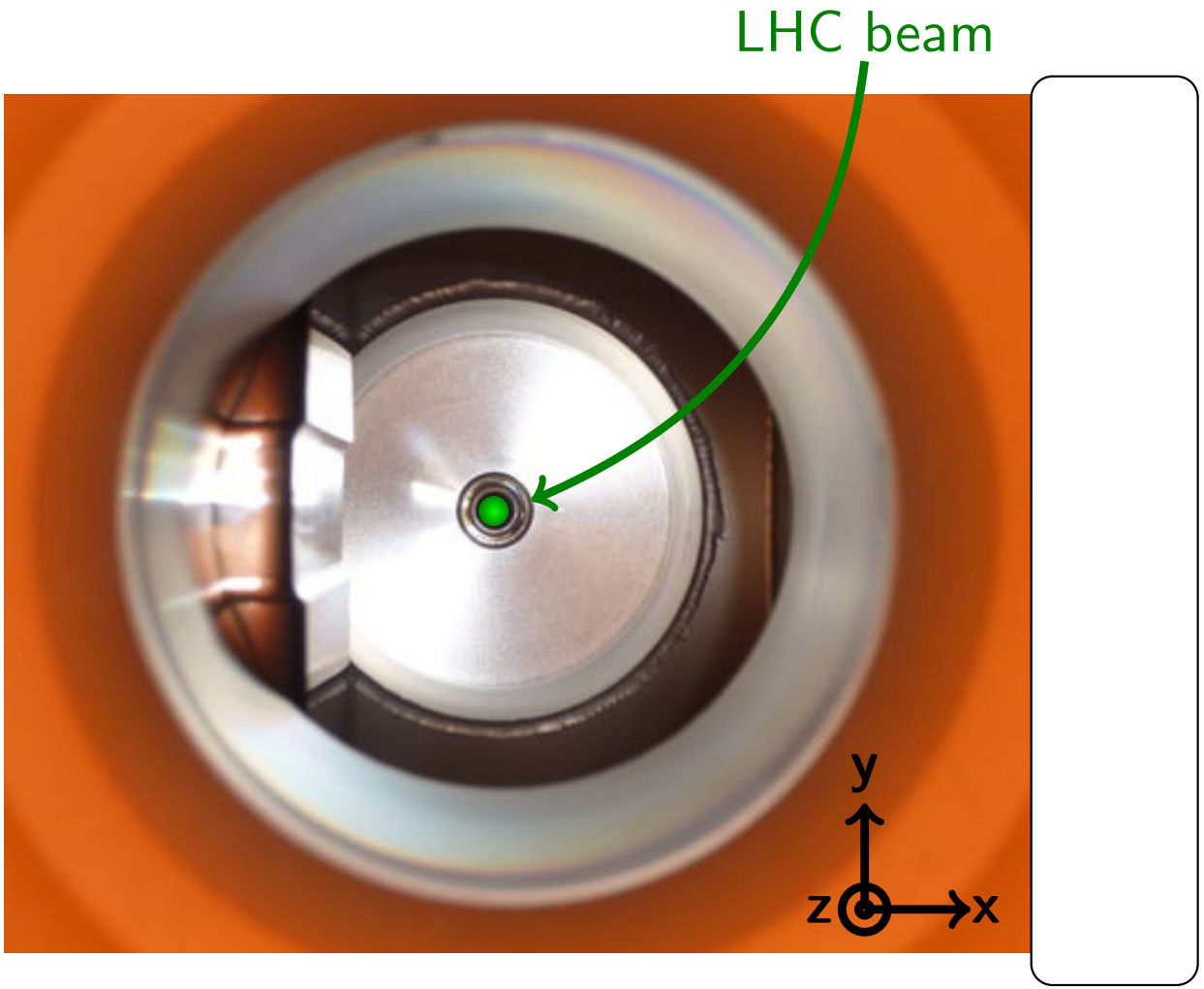
# Advantages of Roman Pot Technology



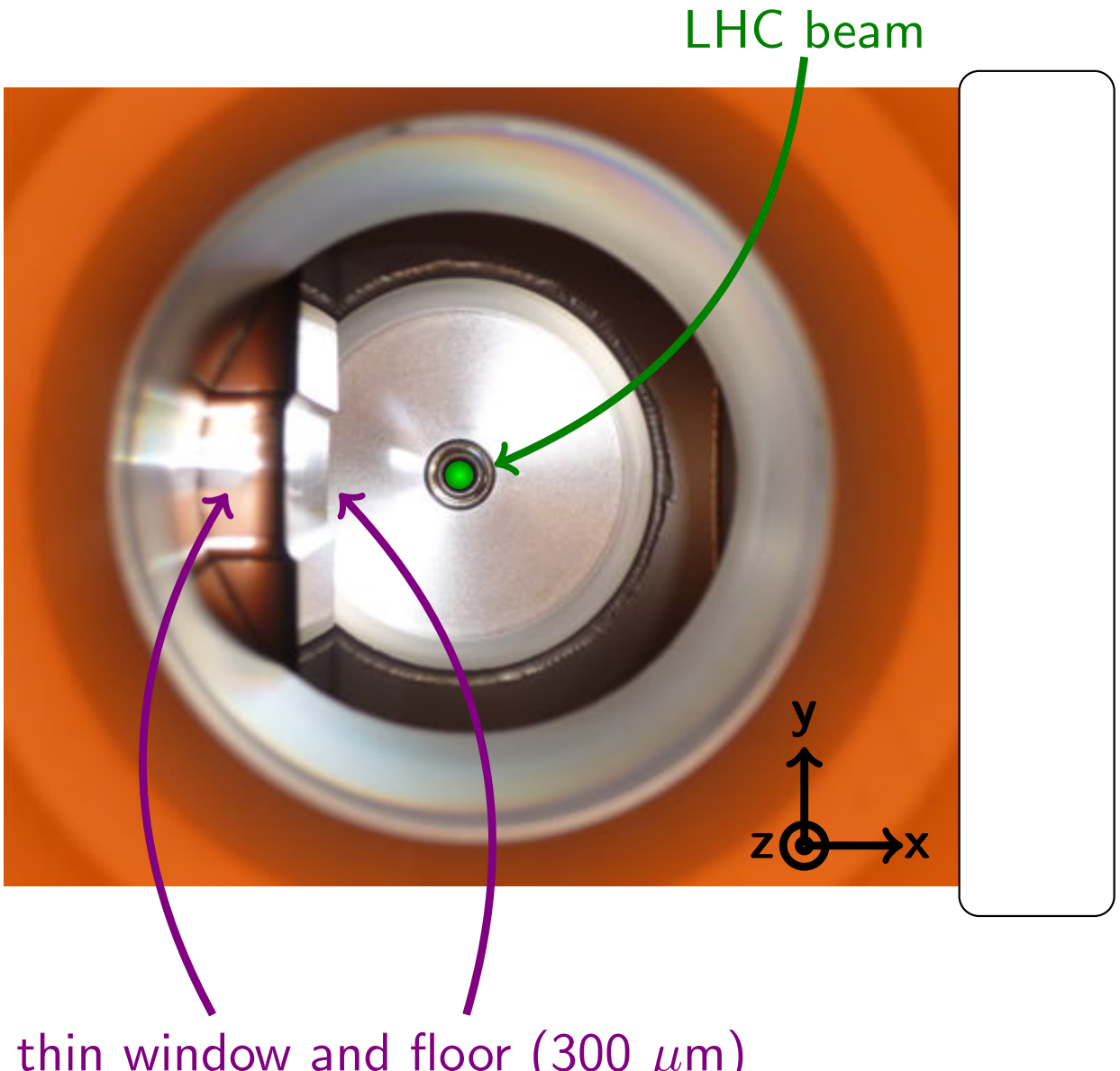
# Advantages of Roman Pot Technology



# Advantages of Roman Pot Technology

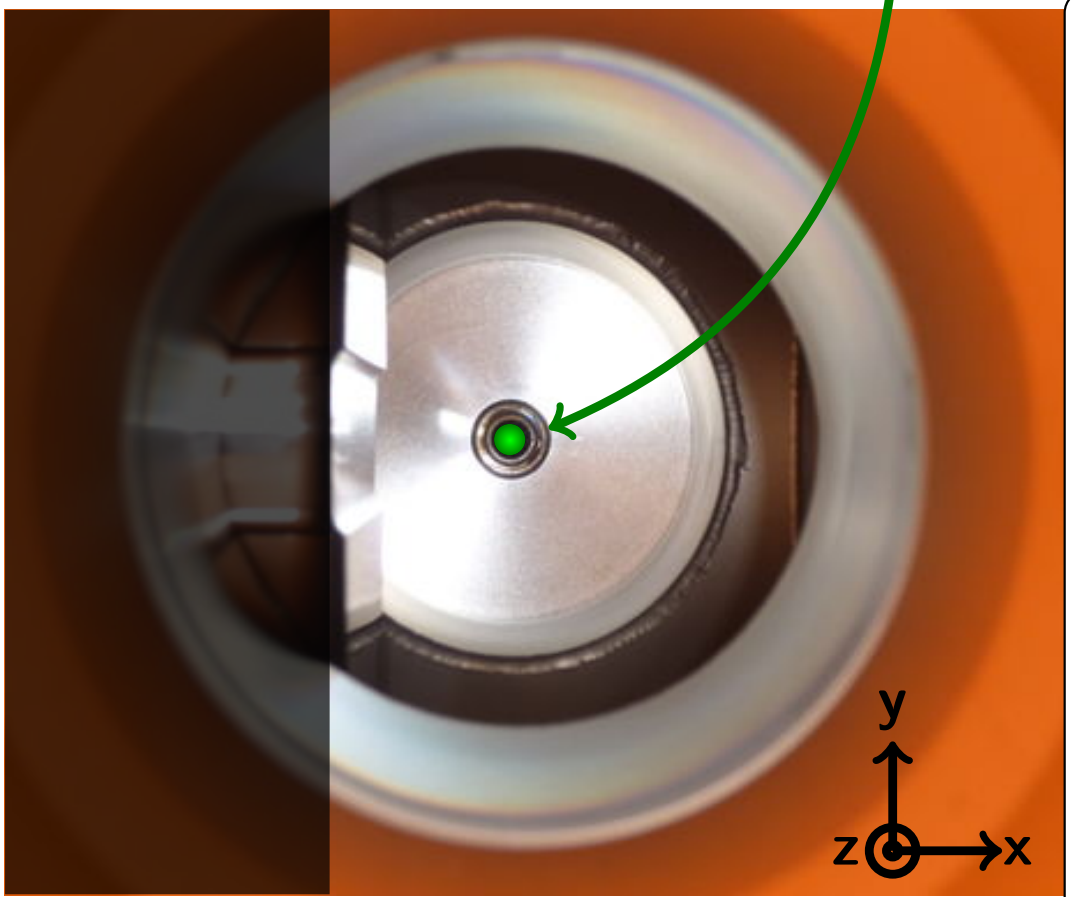


# Advantages of Roman Pot Technology

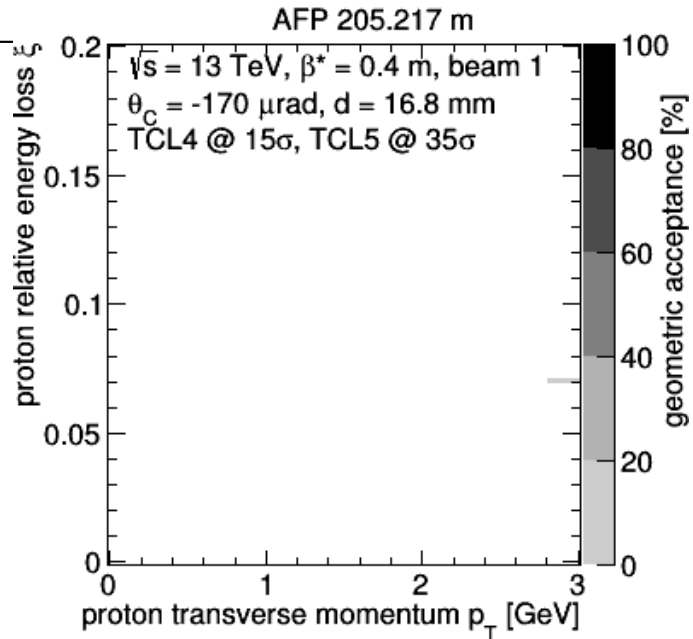


shadow of TCL4 and TCL5 collimators

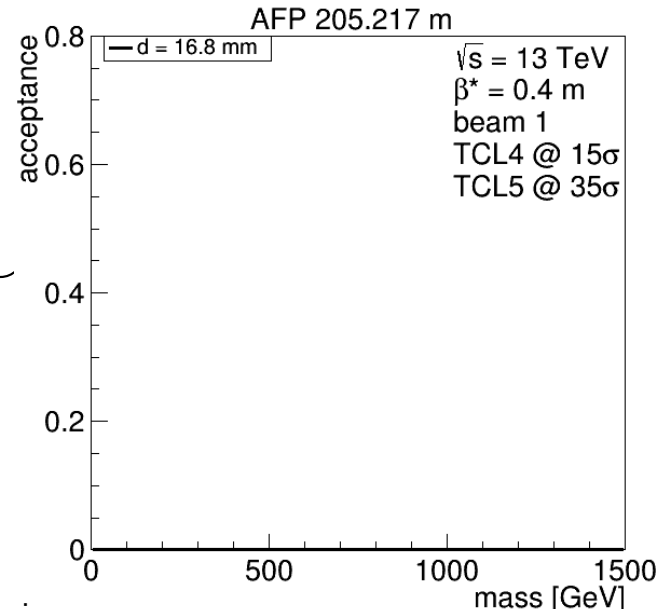
LHC beam




Geometric acceptance:



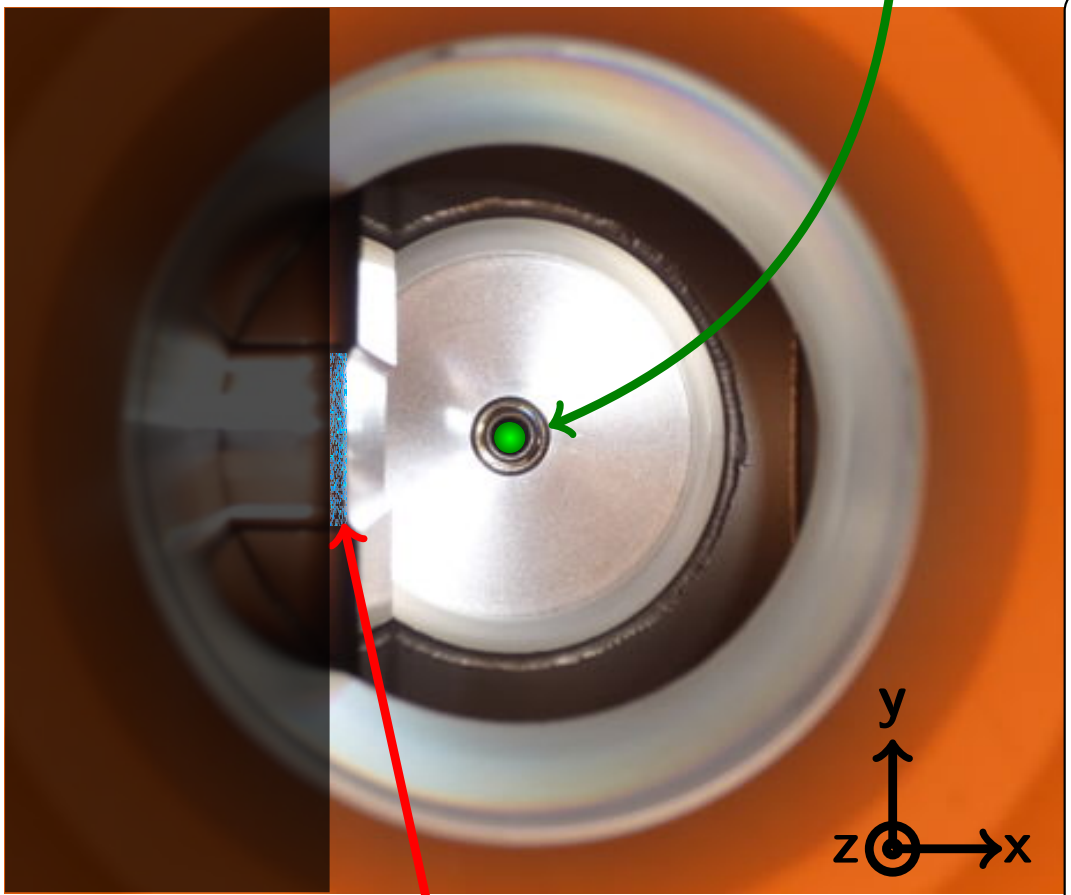

Mass acceptance:




thin window and floor (300 $\mu$m)

shadow of TCL4 and TCL5 collimators

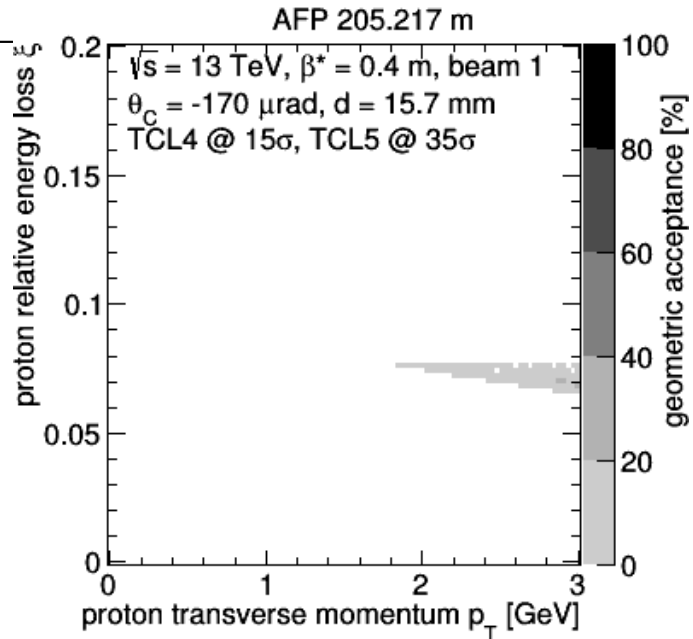
LHC beam



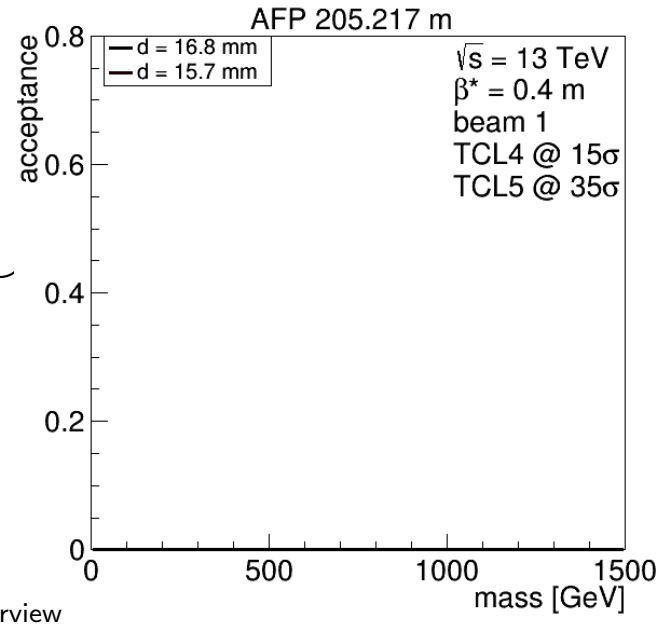

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

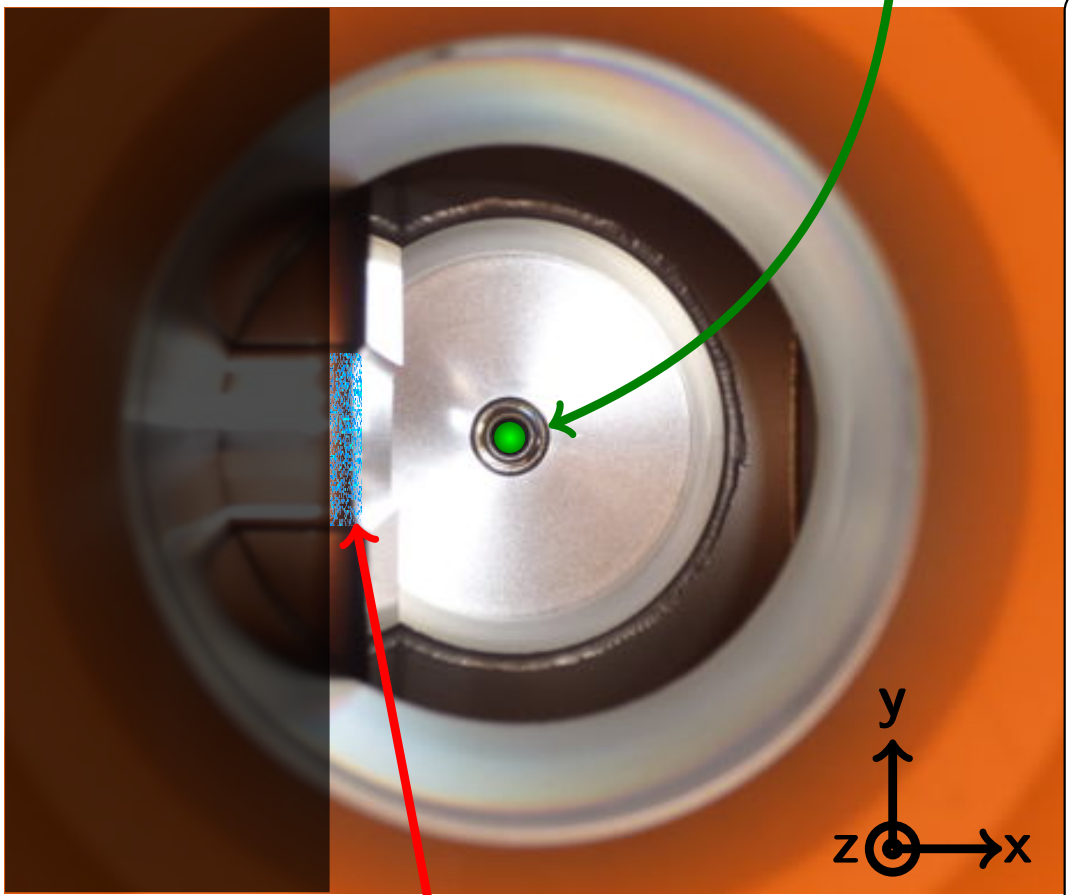



Mass acceptance:



shadow of TCL4 and TCL5 collimators

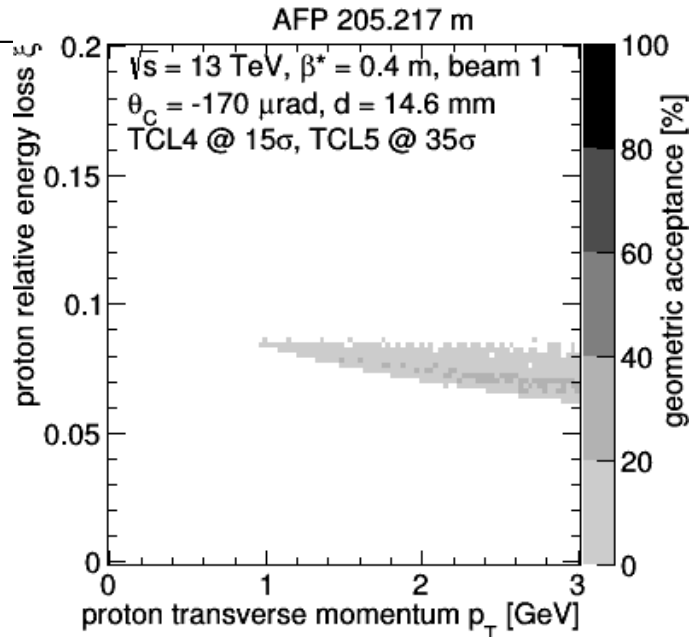
LHC beam



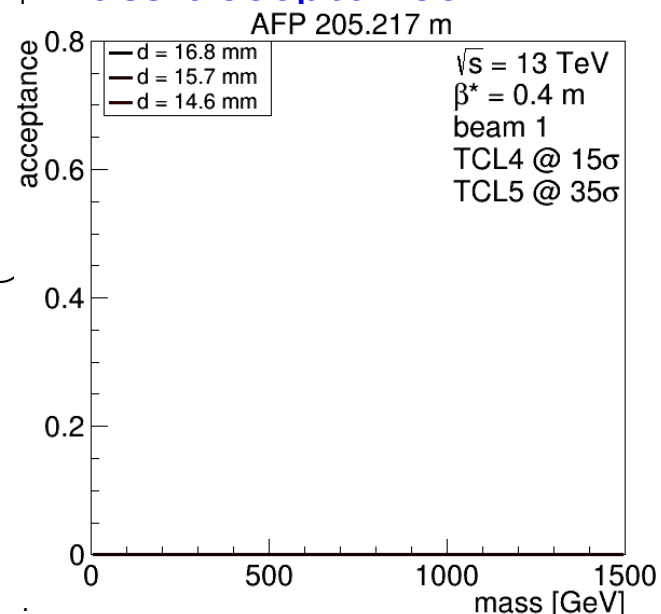

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

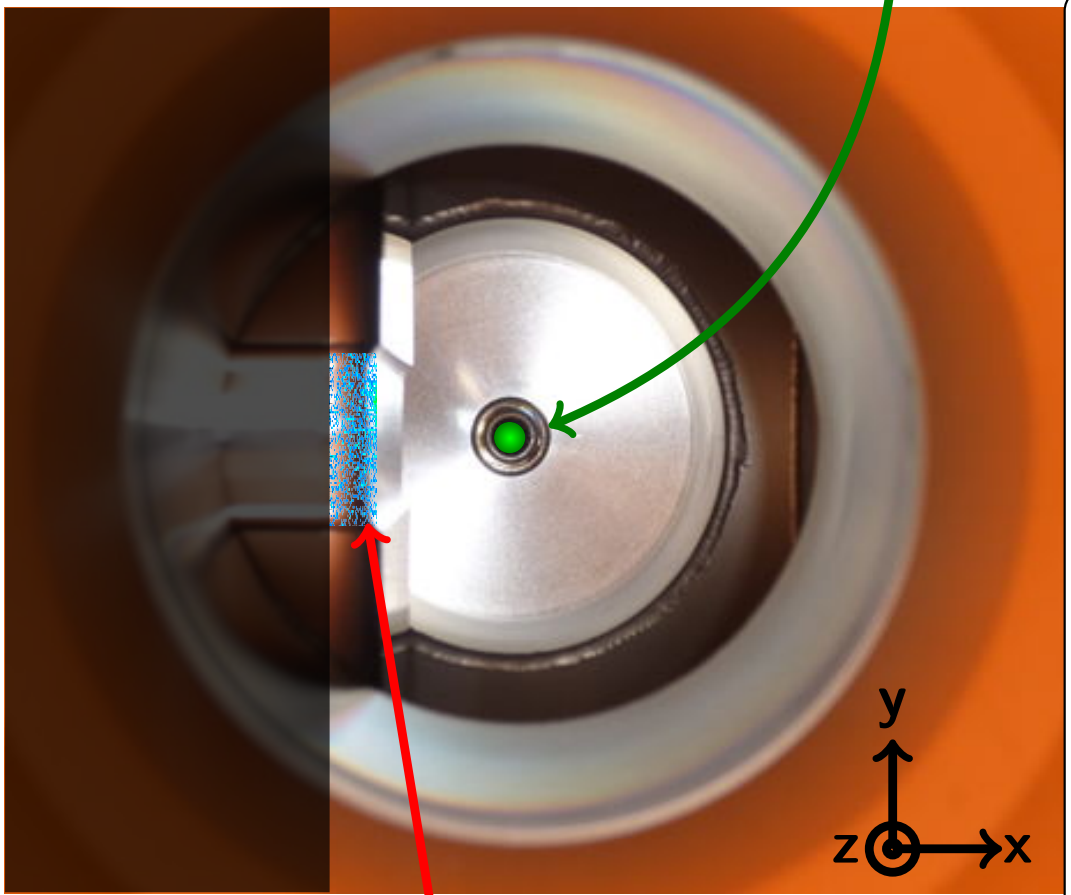



Mass acceptance:



shadow of TCL4 and TCL5 collimators

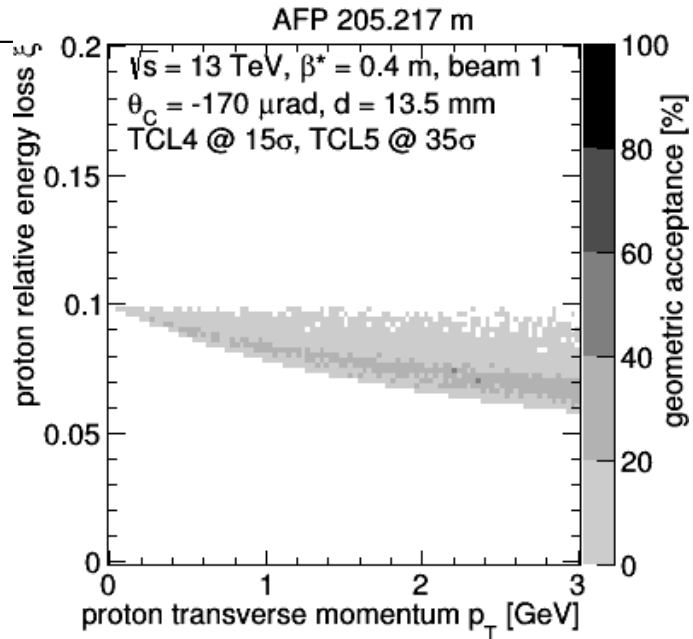
LHC beam



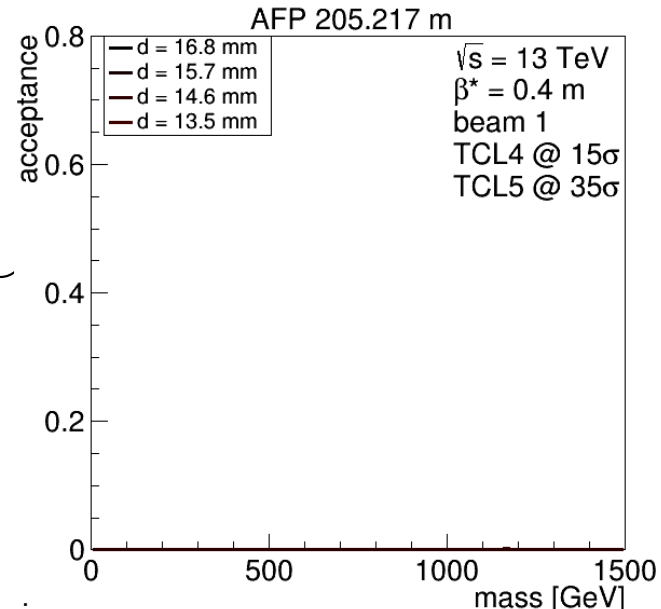

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

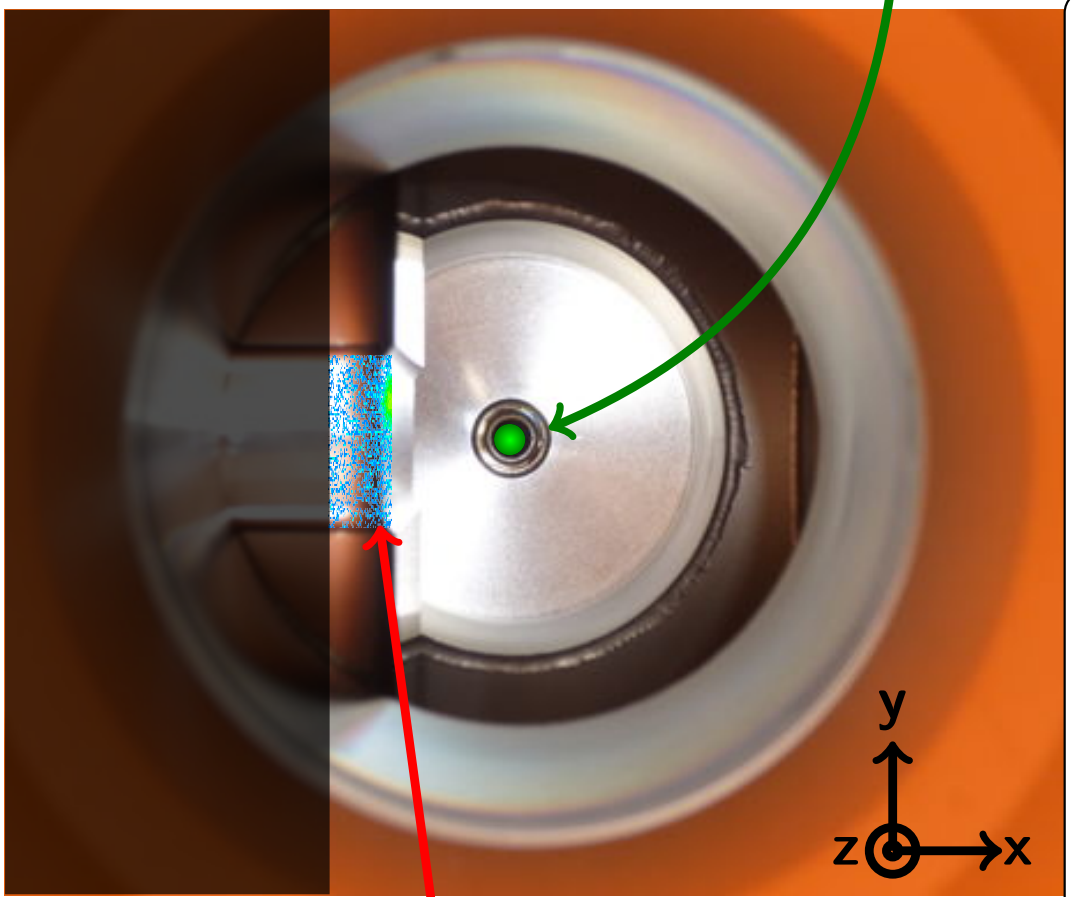



Mass acceptance:



shadow of TCL4 and TCL5 collimators

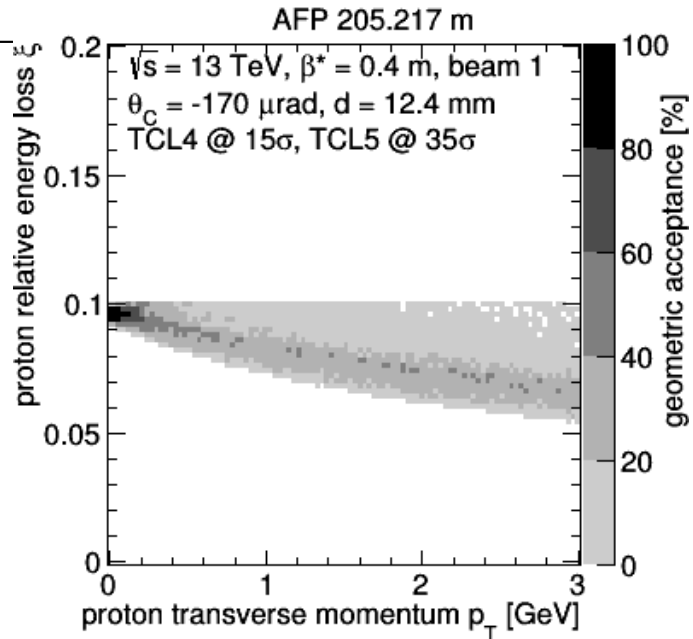
LHC beam



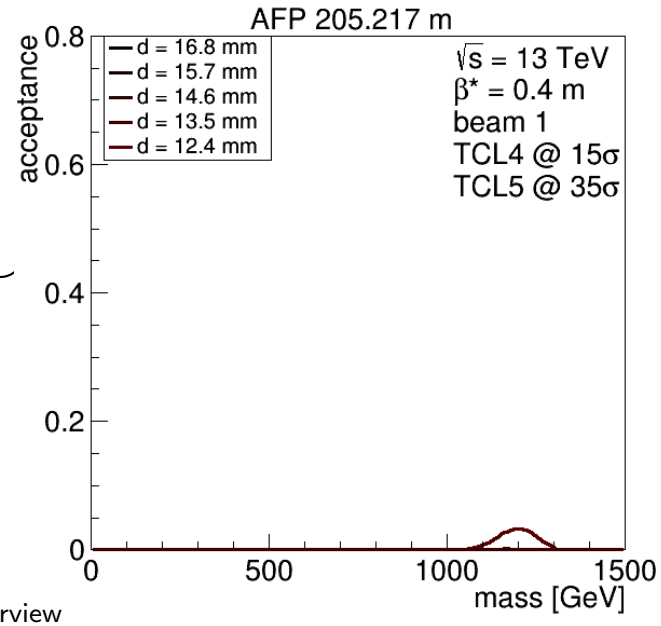

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

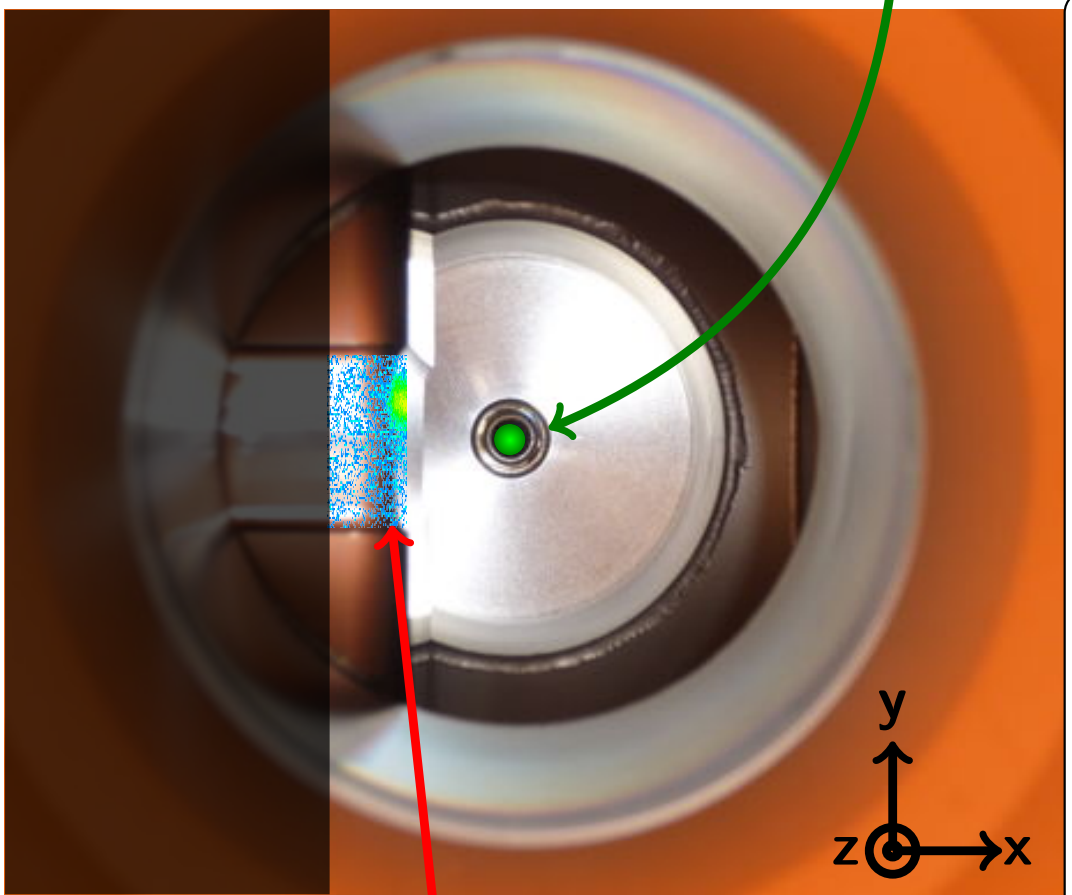



Mass acceptance:



shadow of TCL4 and TCL5 collimators

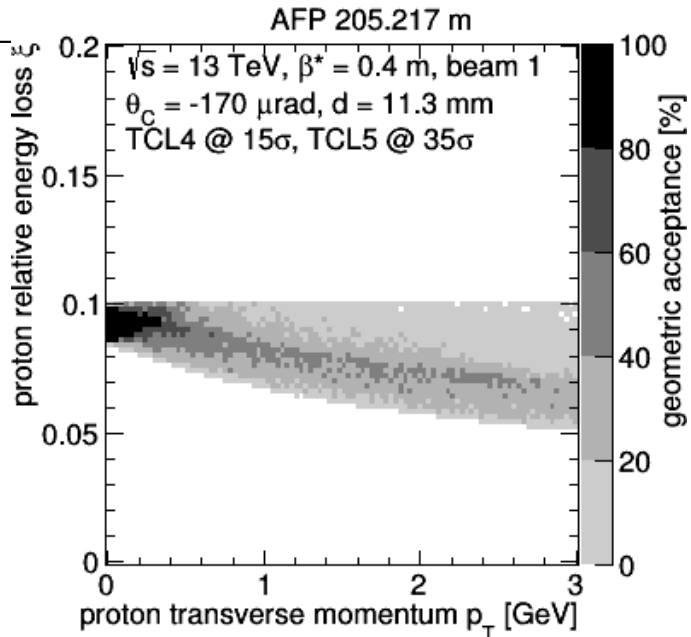
LHC beam



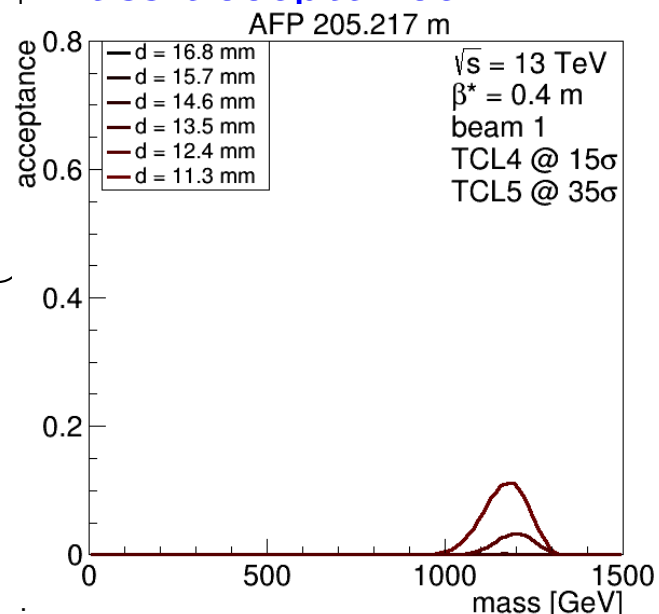

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

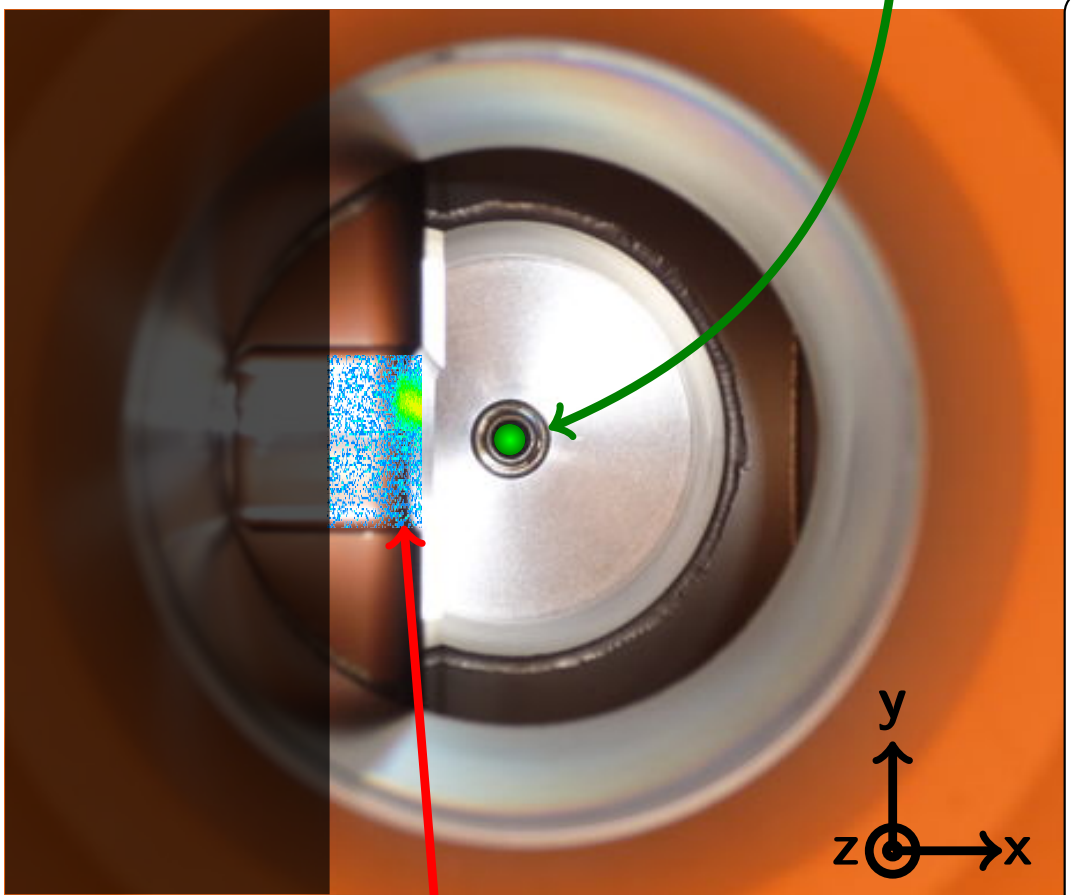



Mass acceptance:



shadow of TCL4 and TCL5 collimators

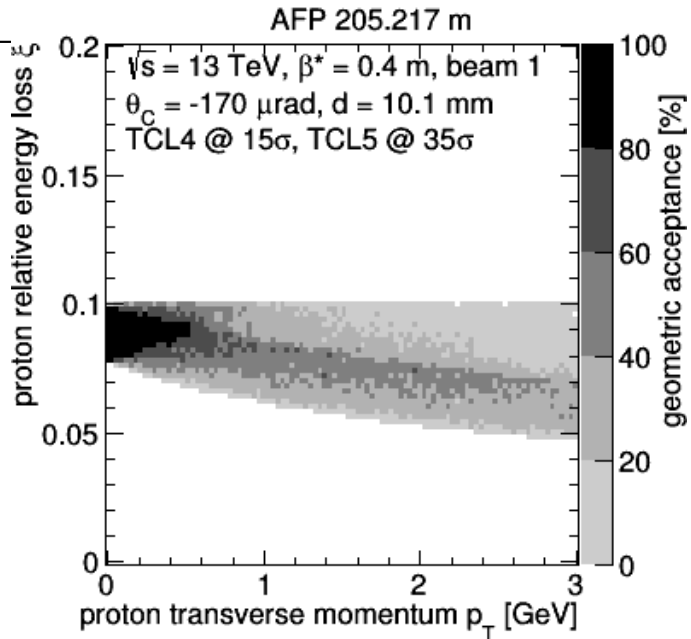
LHC beam



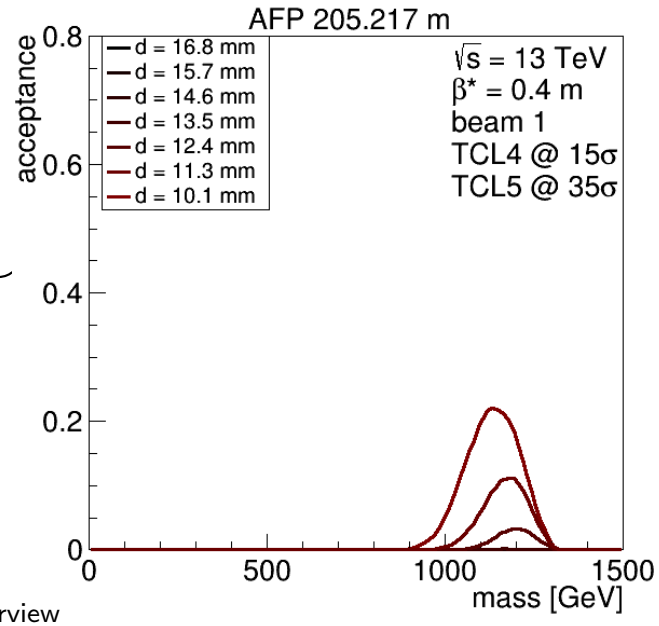

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

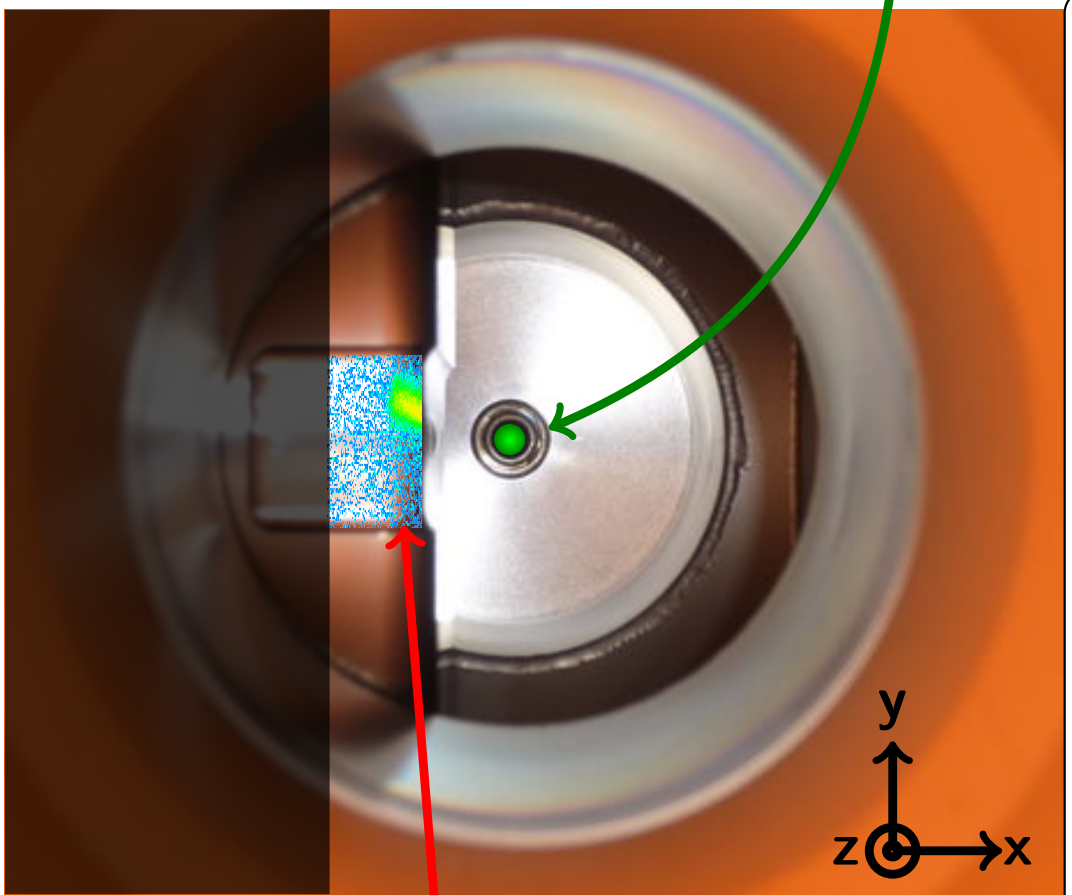



Mass acceptance:



shadow of TCL4 and TCL5 collimators

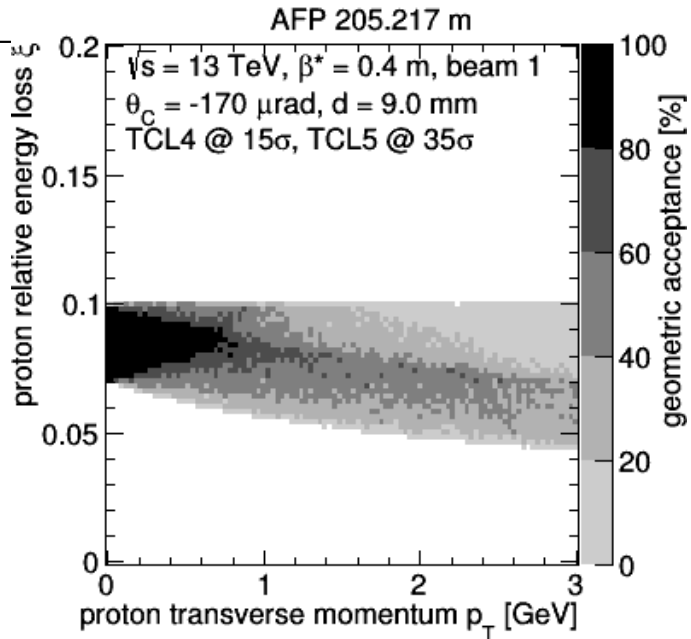
LHC beam



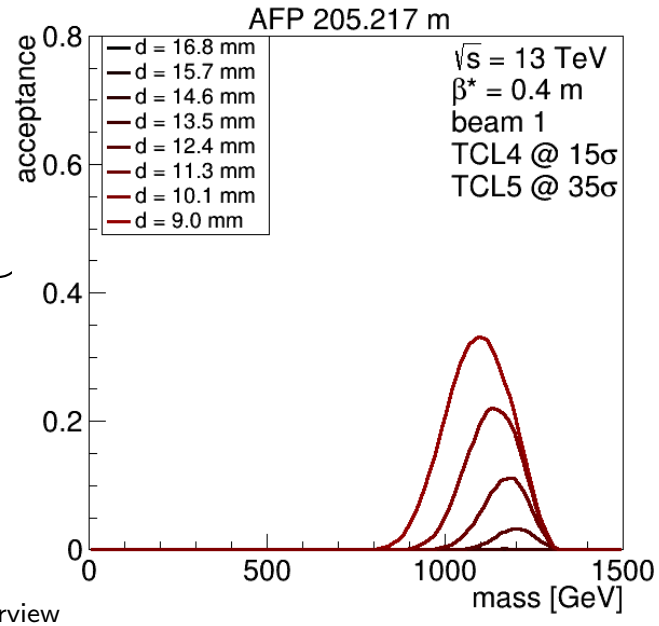

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

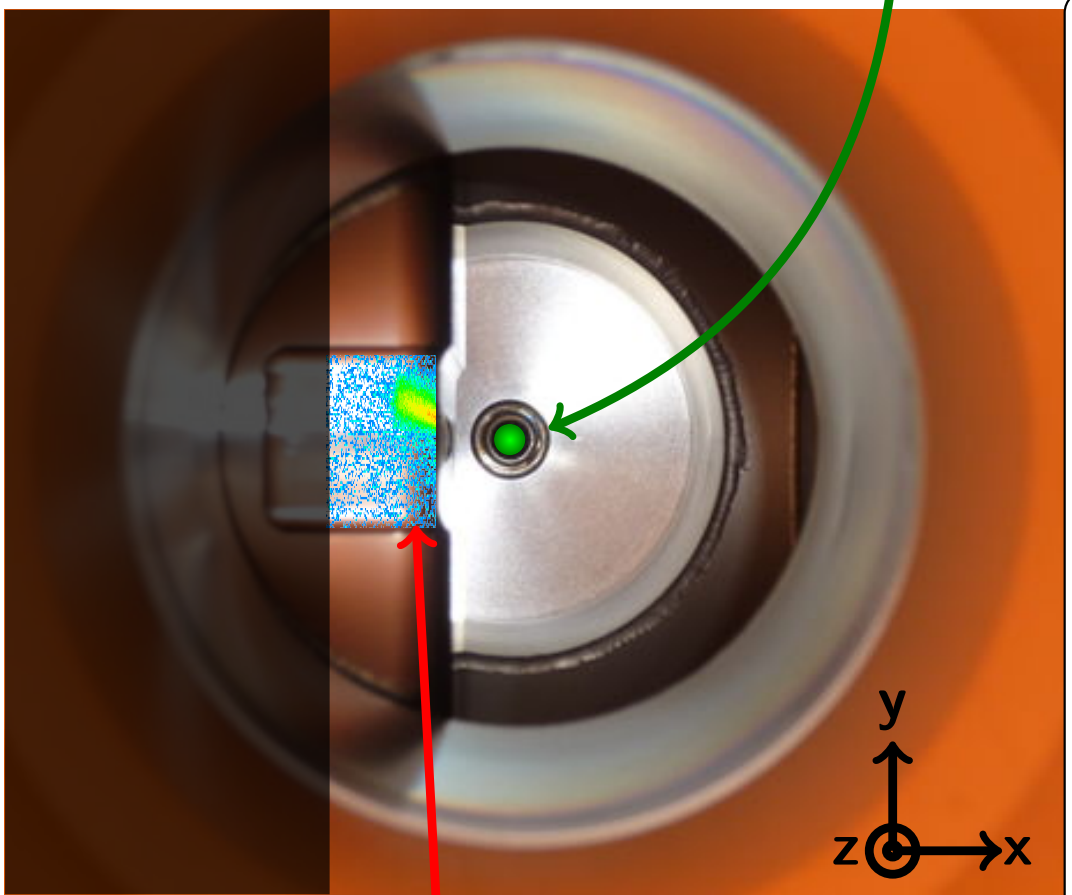



Mass acceptance:



shadow of TCL4 and TCL5 collimators

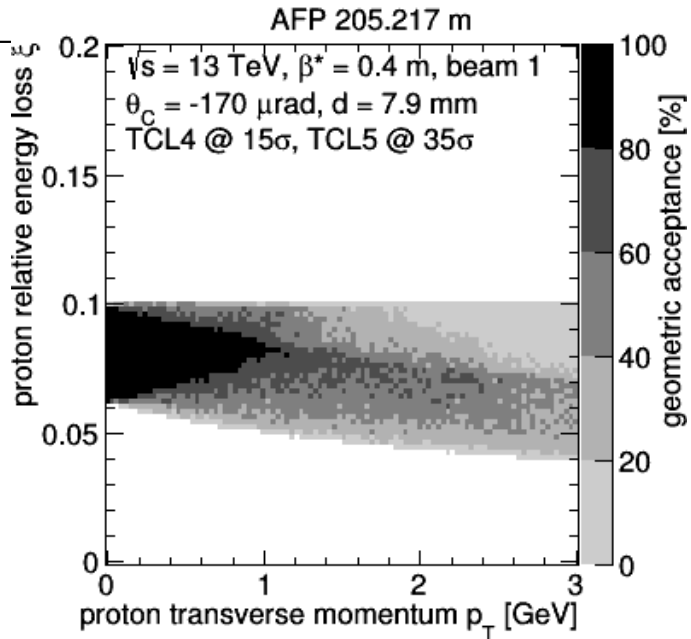
LHC beam



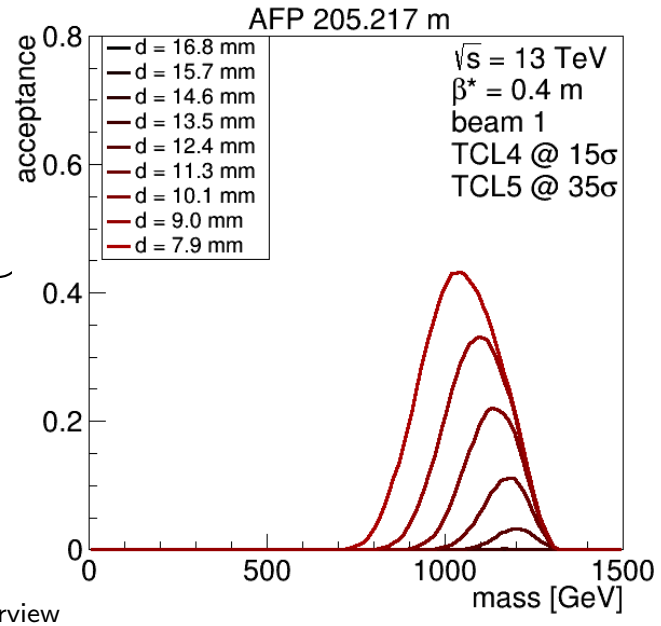

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

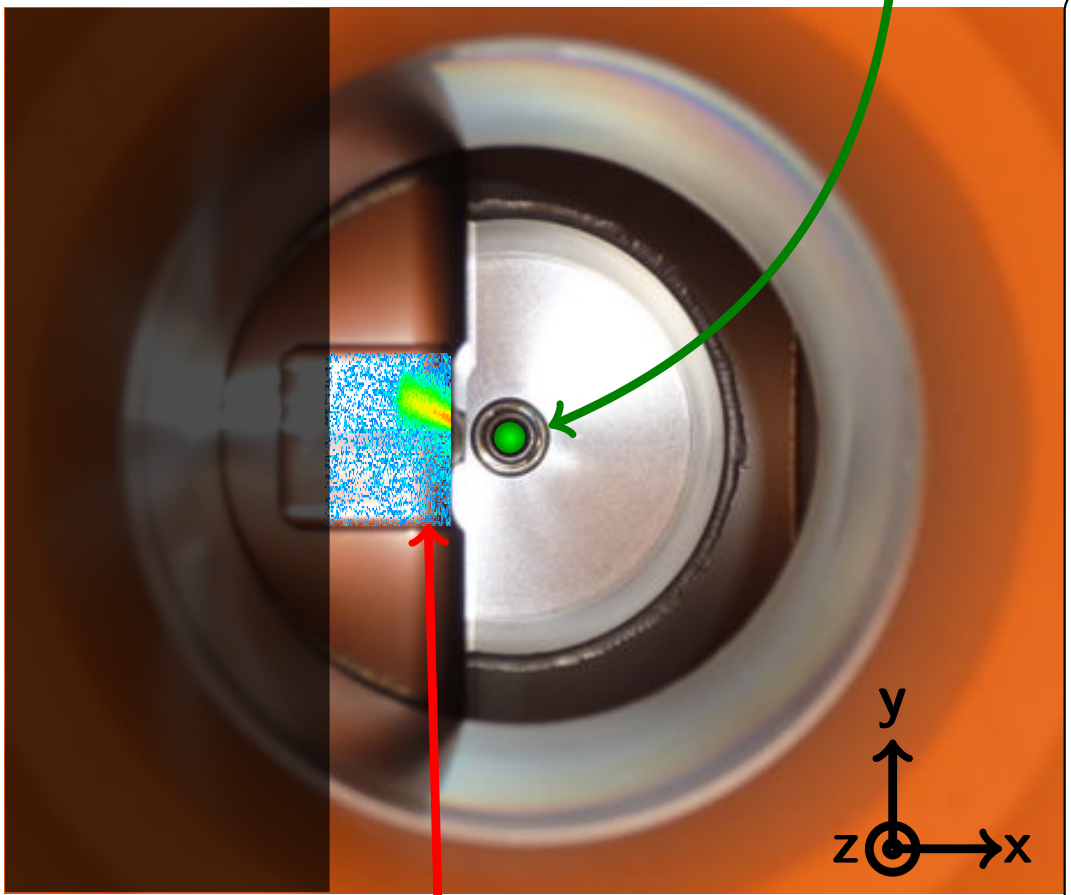



Mass acceptance:



shadow of TCL4 and TCL5 collimators

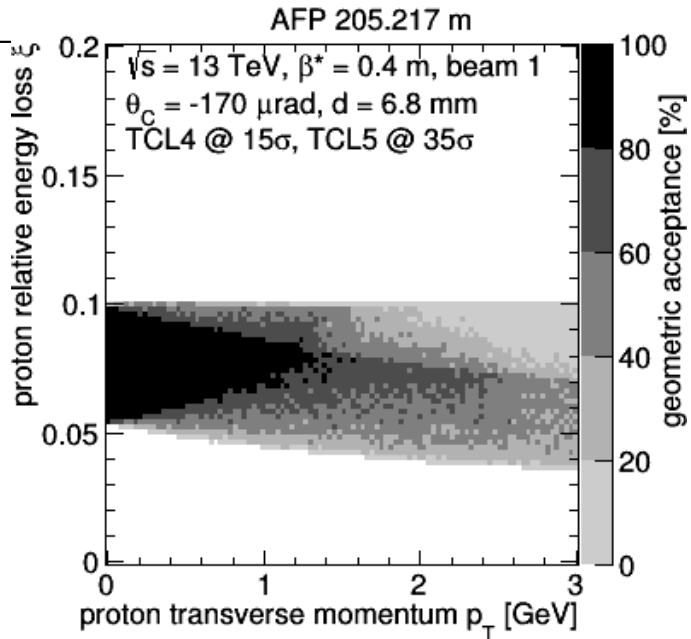
LHC beam



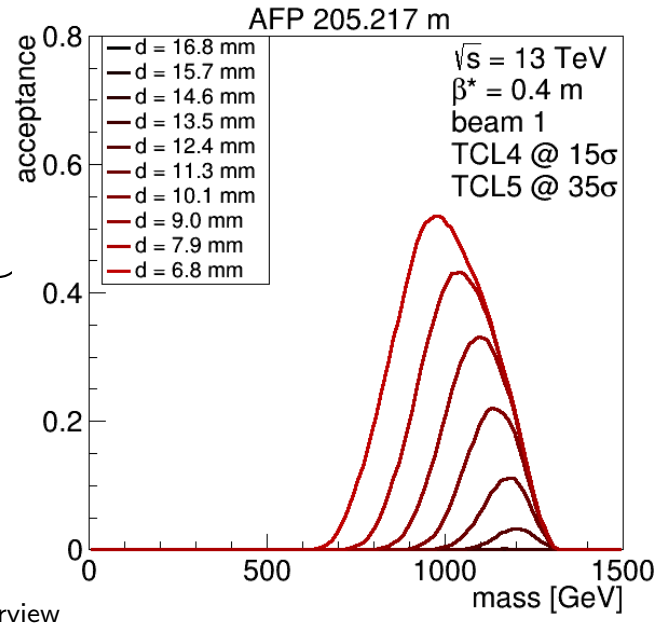

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

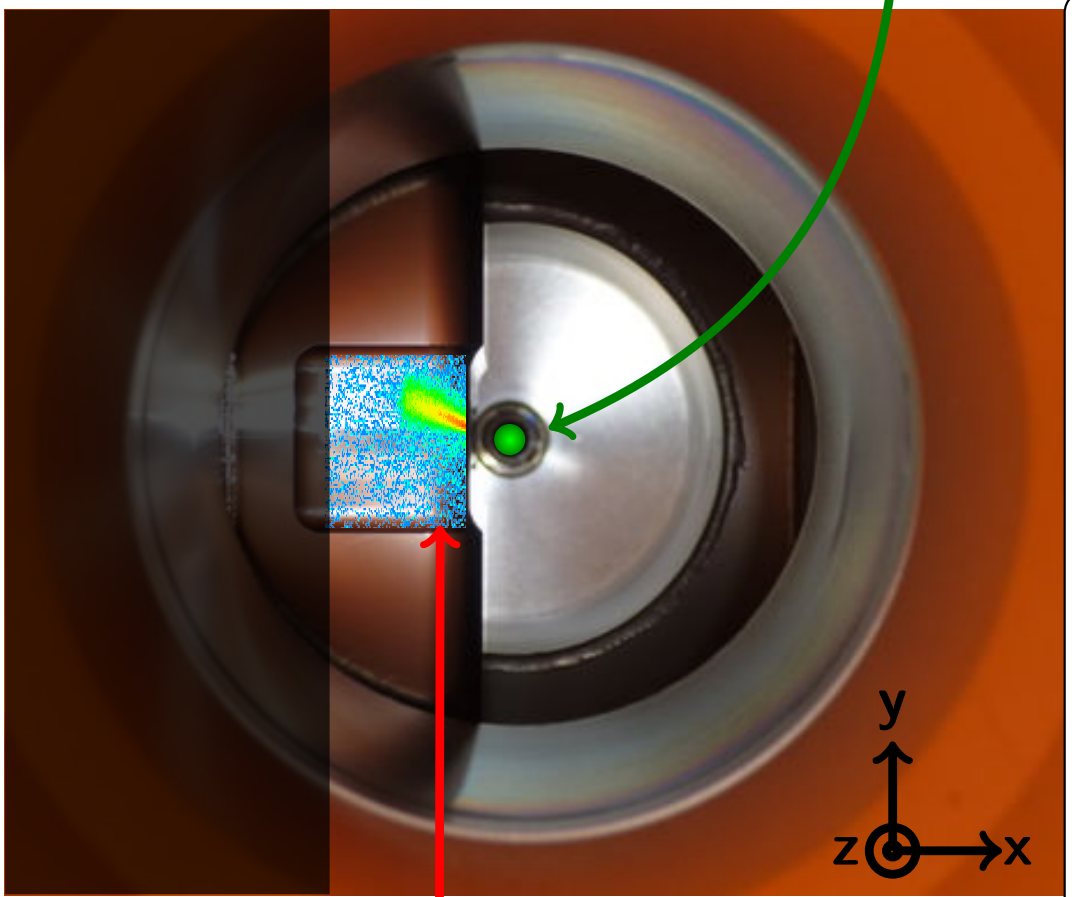



Mass acceptance:



shadow of TCL4 and TCL5 collimators

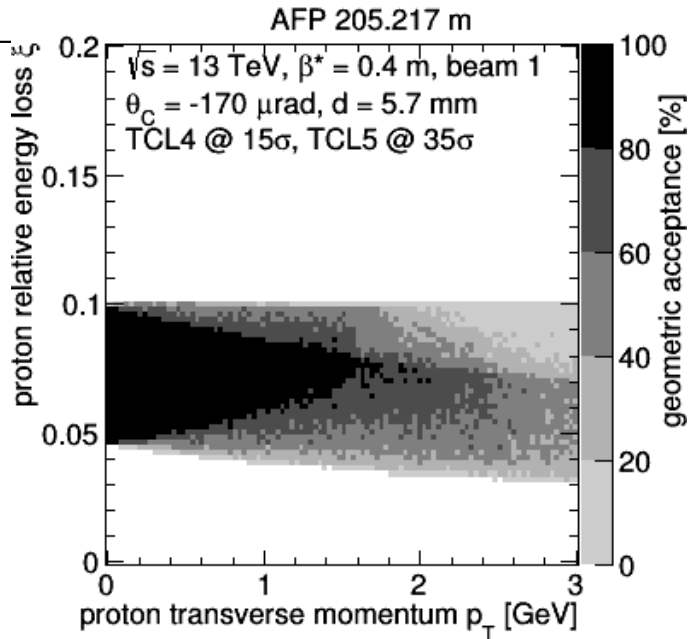
LHC beam



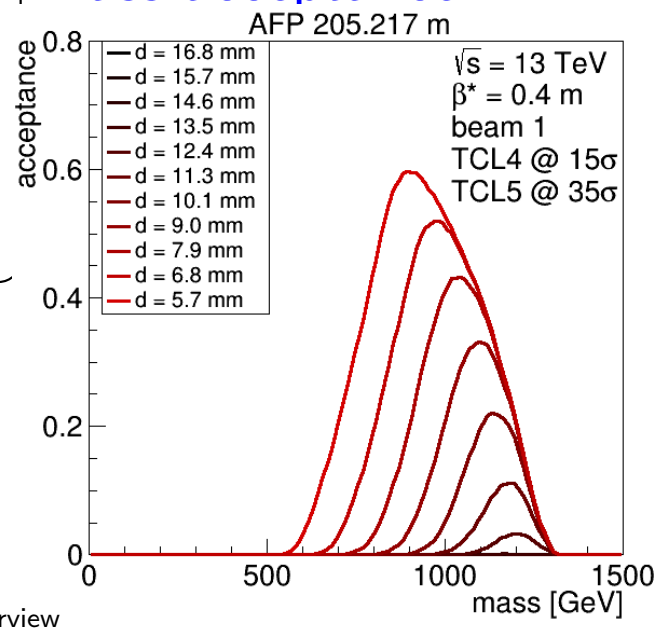

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

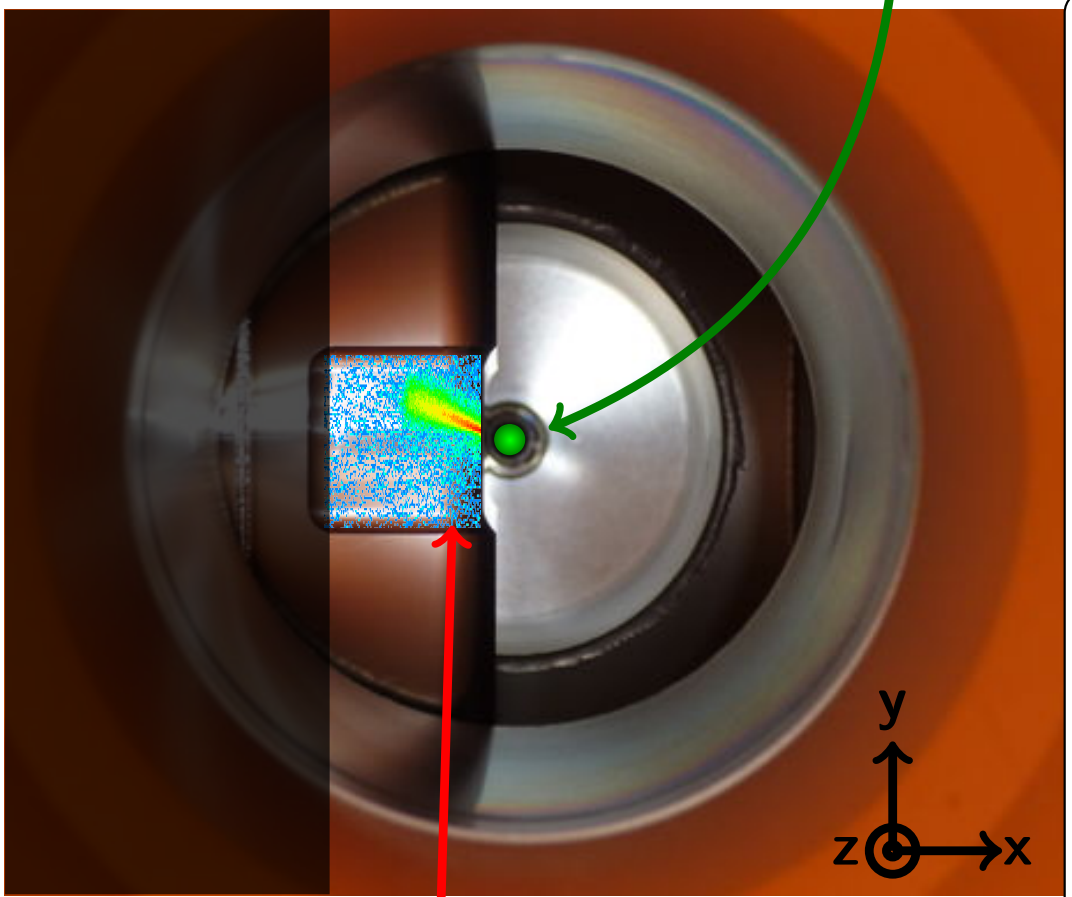



Mass acceptance:



shadow of TCL4 and TCL5 collimators

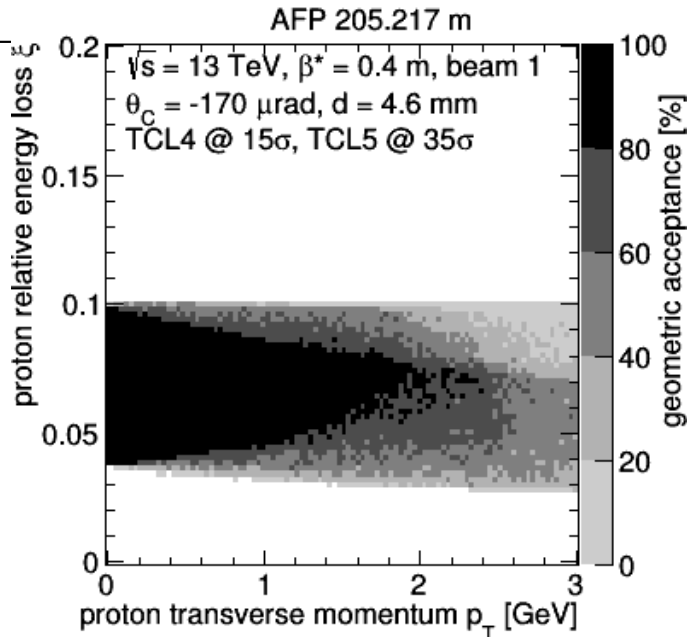
LHC beam



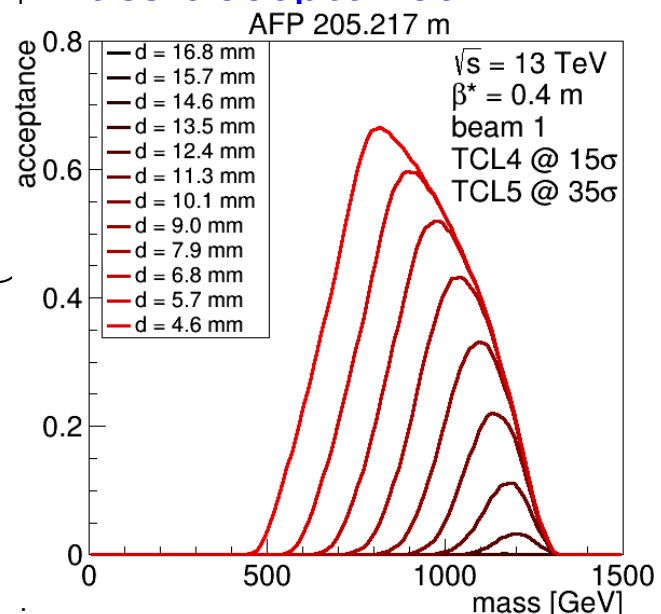

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

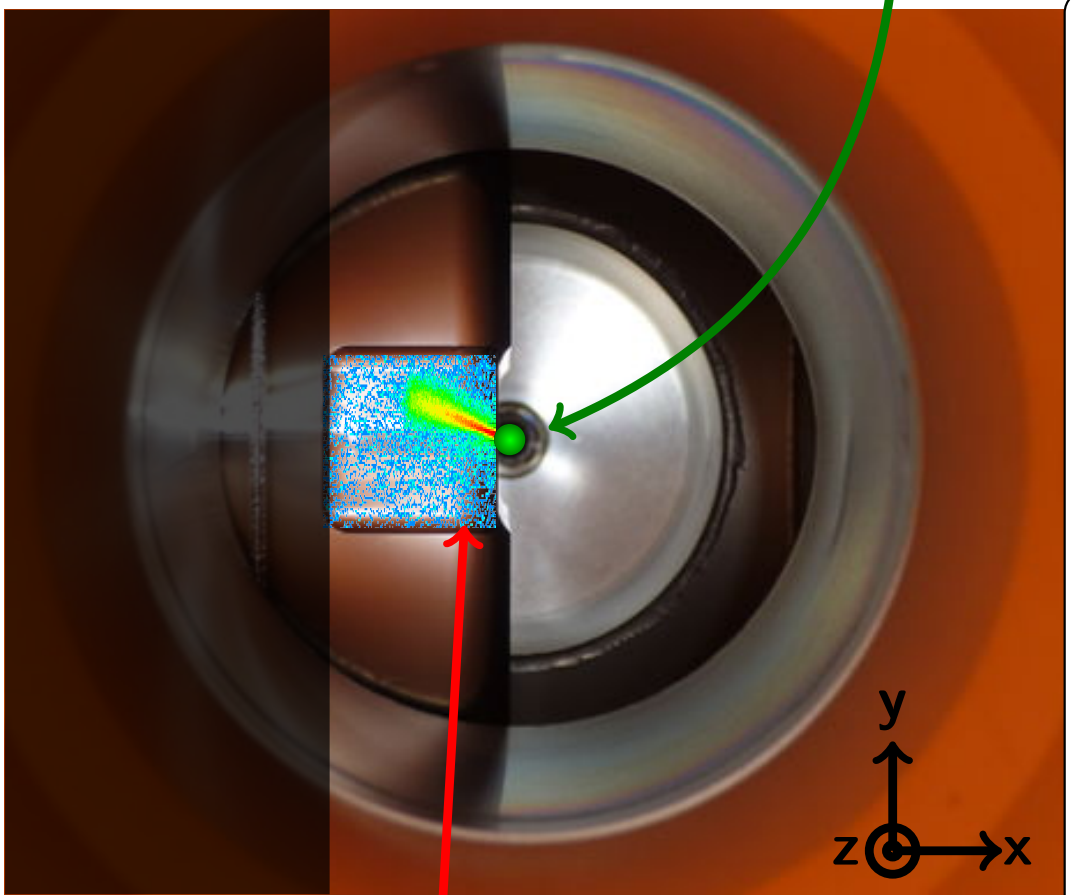



Mass acceptance:



shadow of TCL4 and TCL5 collimators

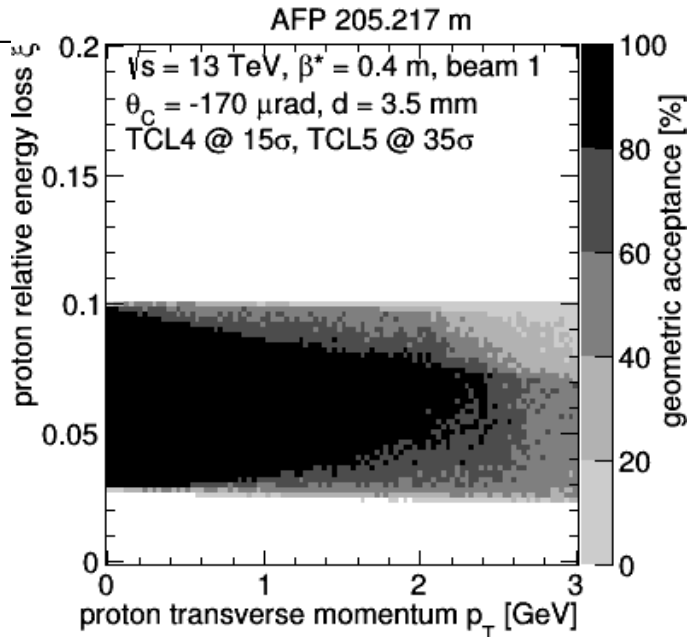
LHC beam



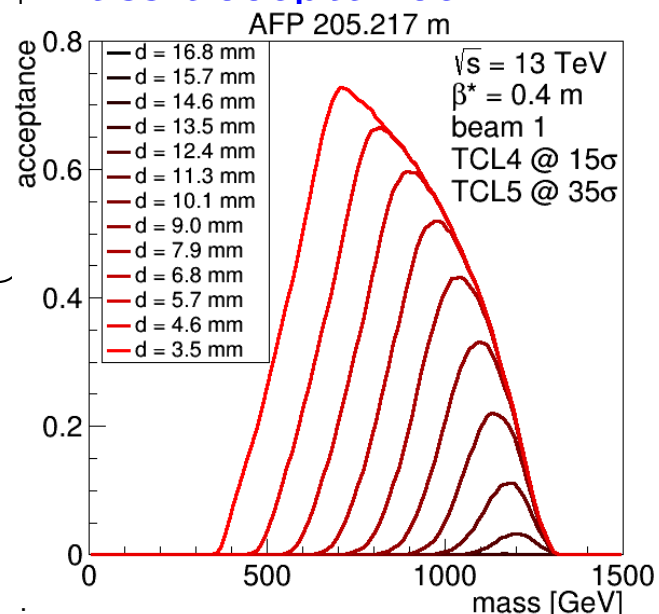

diffractive protons

thin window and floor (300 $\mu$m)

Geometric acceptance:

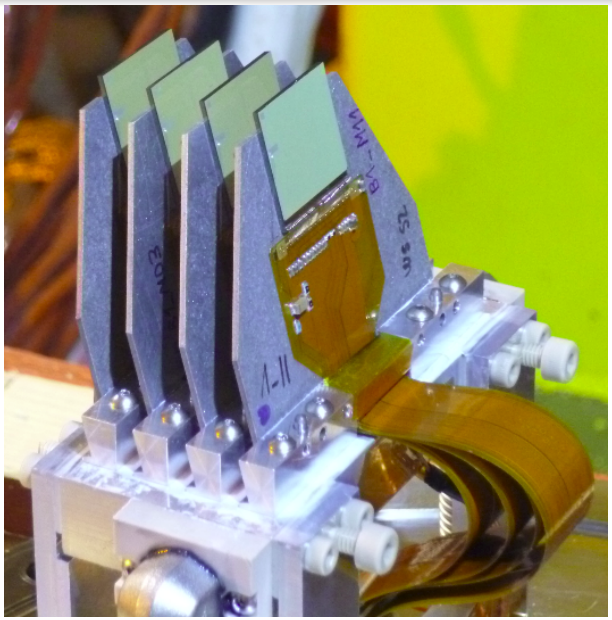


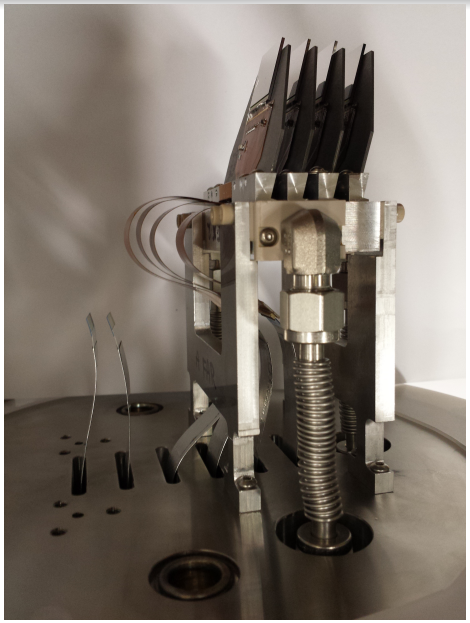

Mass acceptance:

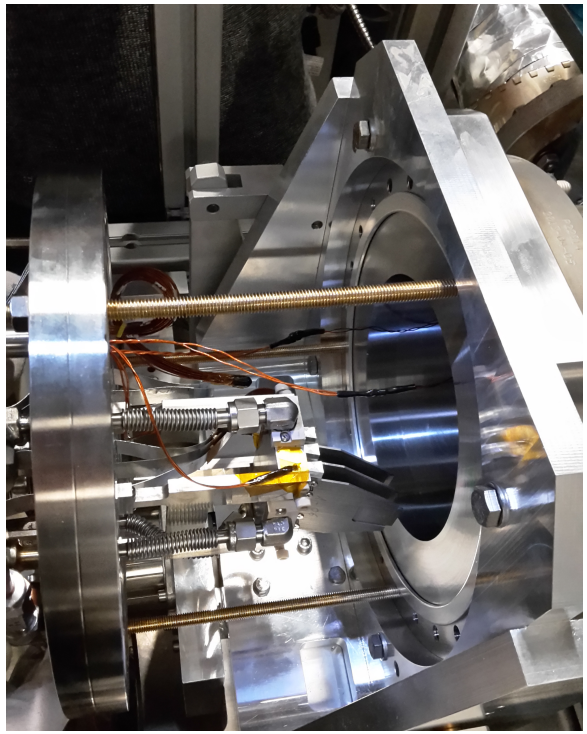


# Detectors

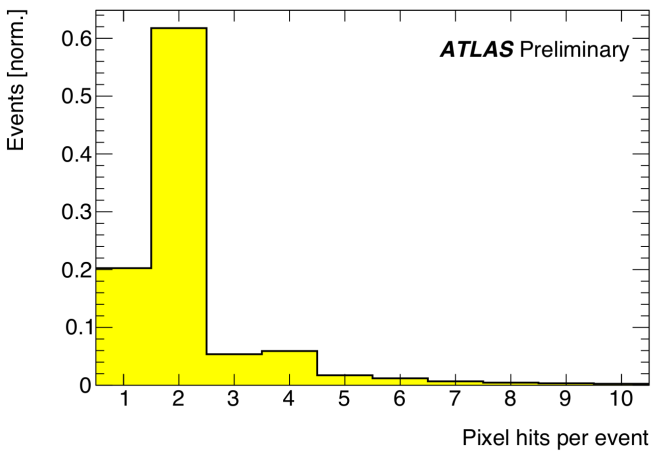
# AFP: Silicon Trackers (SiT)





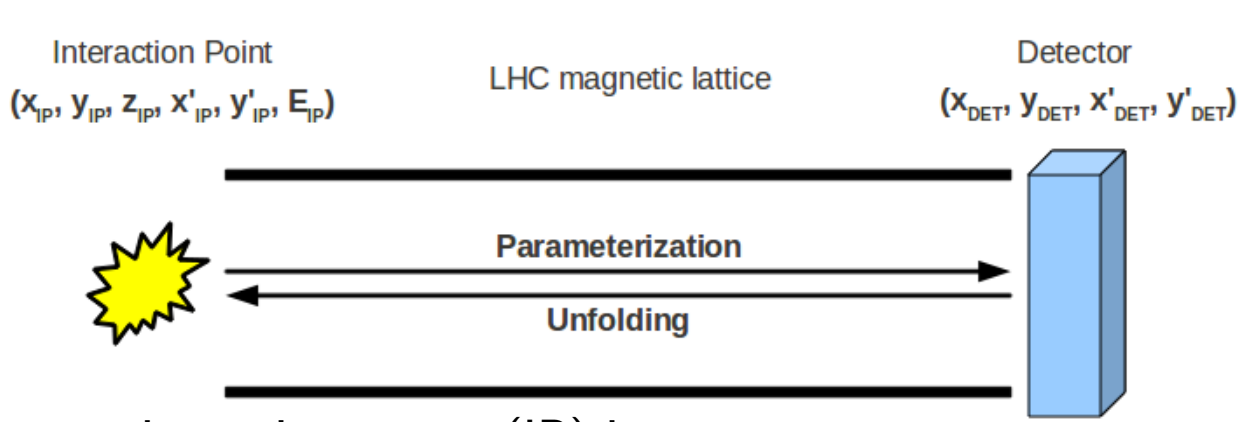


- Four detectors in each station.
- Technology: slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
- Pixel size: $50x250\ \mu m^2$.
- Tilted by $14^0$ to improve resolution in $x$.
- Resolution: $\sim$6 $\mu$m in $x$ and $\sim$30 $\mu$m in $y$.
- Trigger: majority vote (2 out of 3; two chips in FAR station are paired and vote as one).
- **No major changes between Run 2 and Run 3 detector setups.**

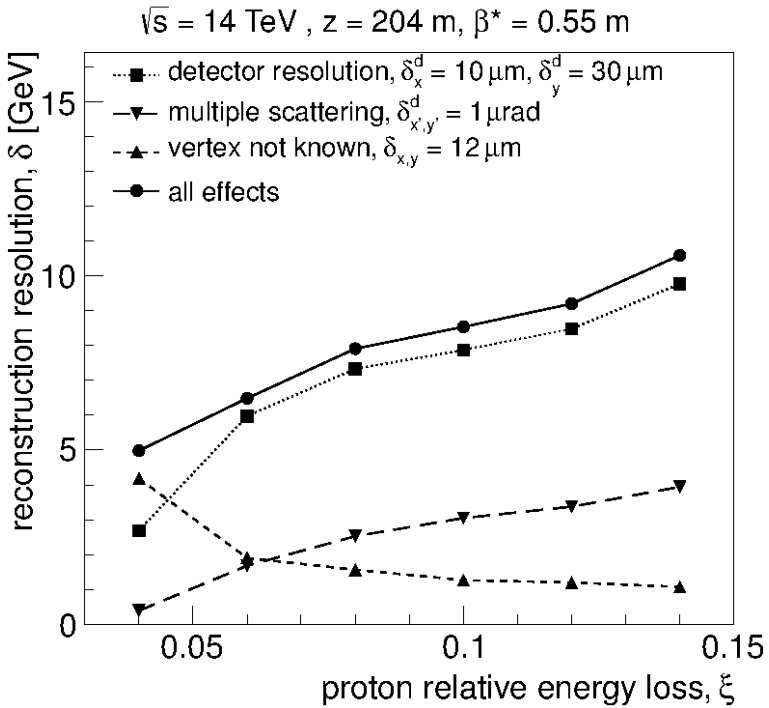



From JINST **11** (2016) P09005; JINST **12** (2017) C01086

# Proton Tagging or Position Measurement?

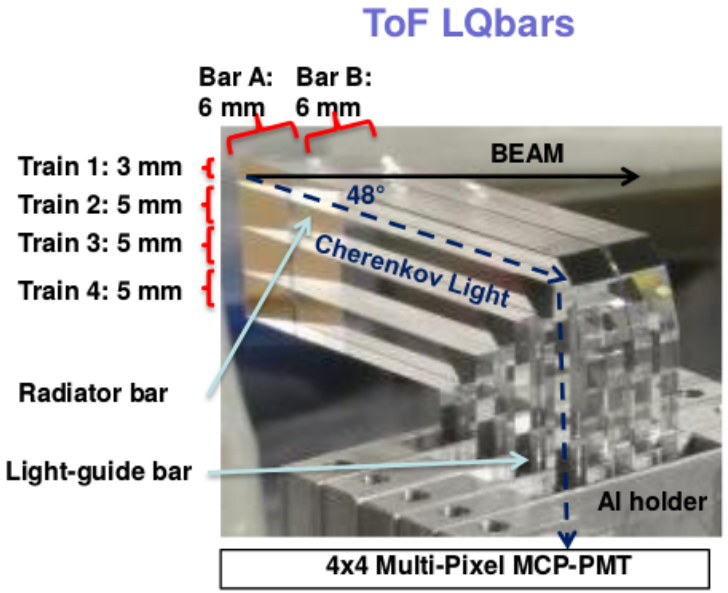


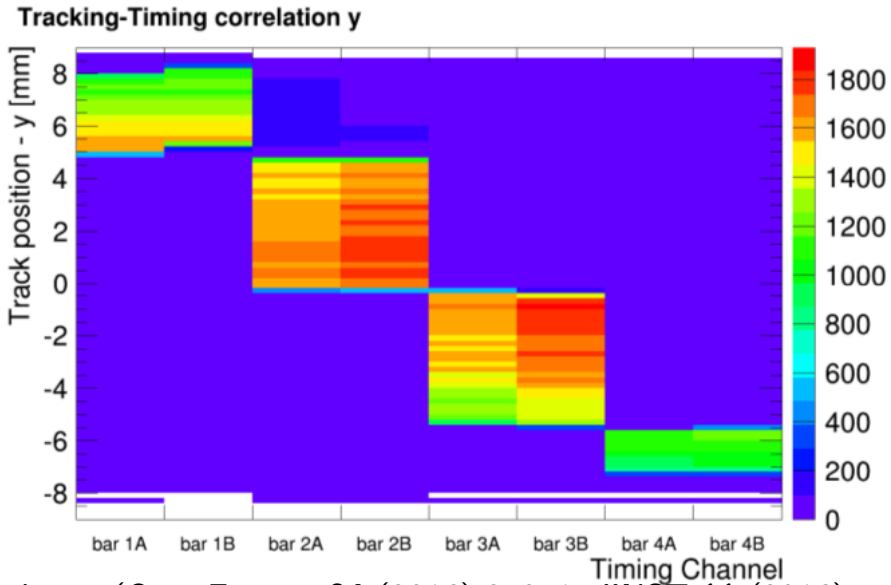

- At the interaction point proton (IP) is fully described by six variables: position ($x_{IP}$, $y_{IP}$, $z_{IP}$), angles ($x'_{IP}$, $y'_{IP}$) and energy ($E_{IP}$).
- They translate to unique position at the forward detector ($x_{DET}$, $y_{DET}$, $x'_{DET}$, $y'_{DET}$).
- Idea: get information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

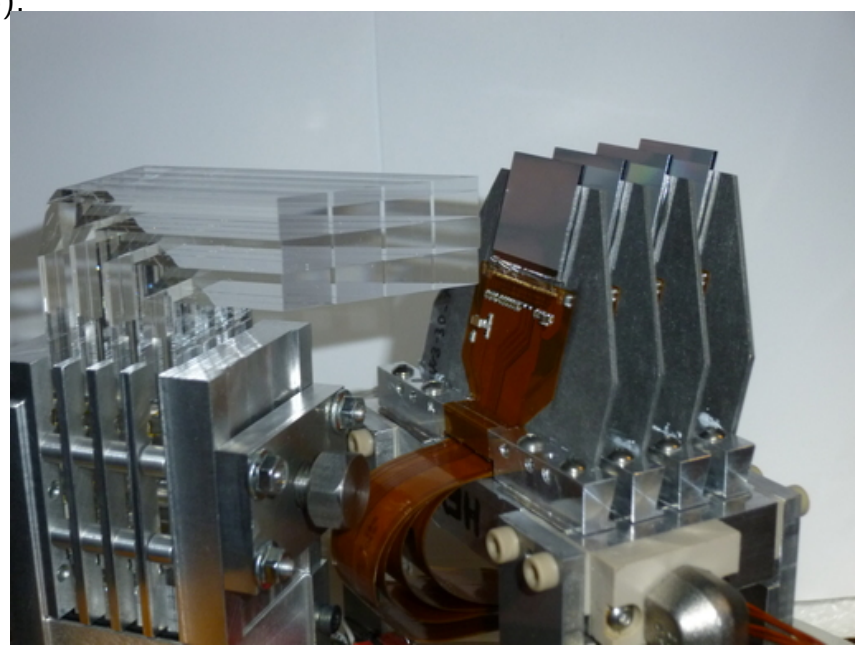
# Time-of-Flight Detectors (ToF) in 2017



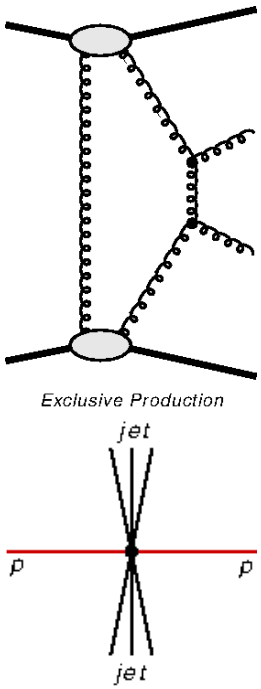

Setup and performance shown above are from test-beam (Opt. Express **24** (2016) 27951, JINST **11** (2016) P09005).

- 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.

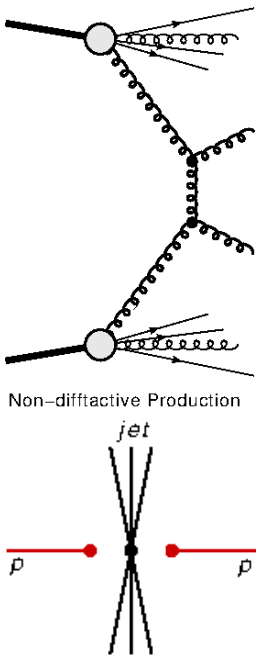


# Pile-up Background Reduction

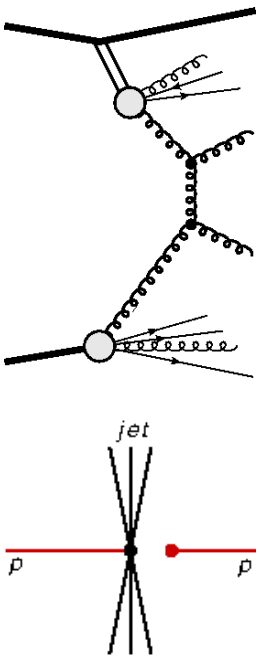
signal




background

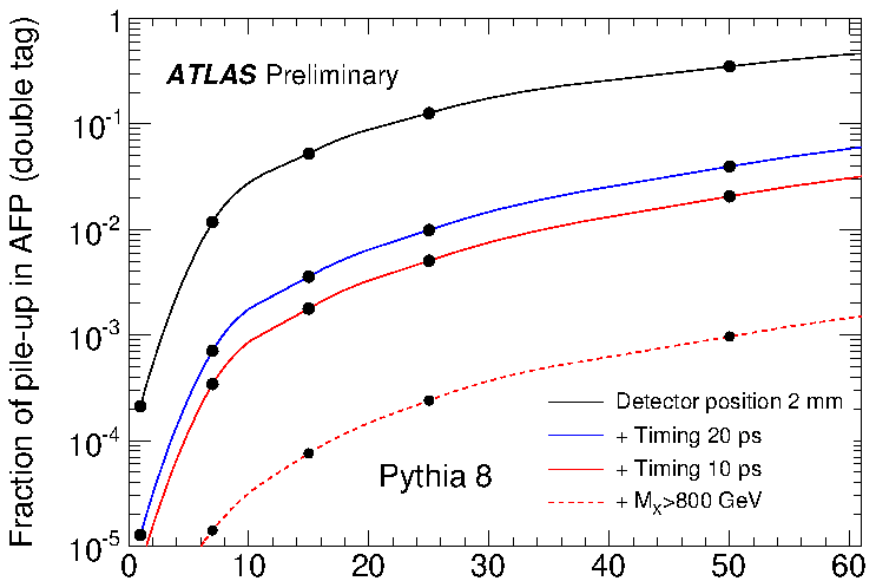



background

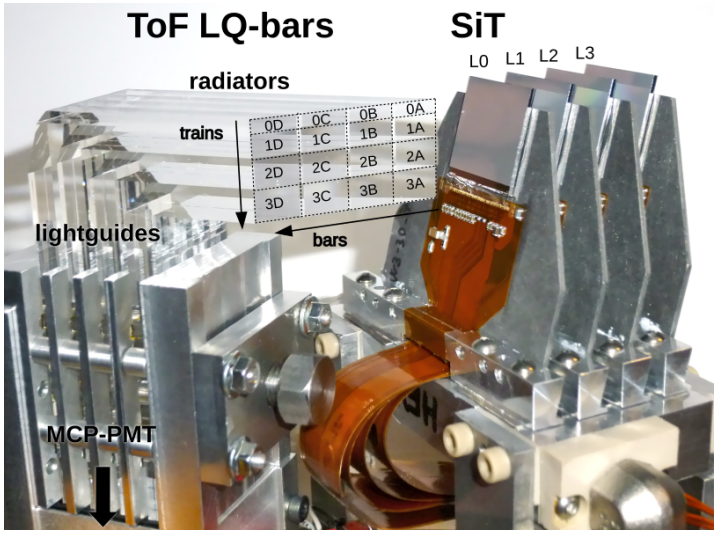


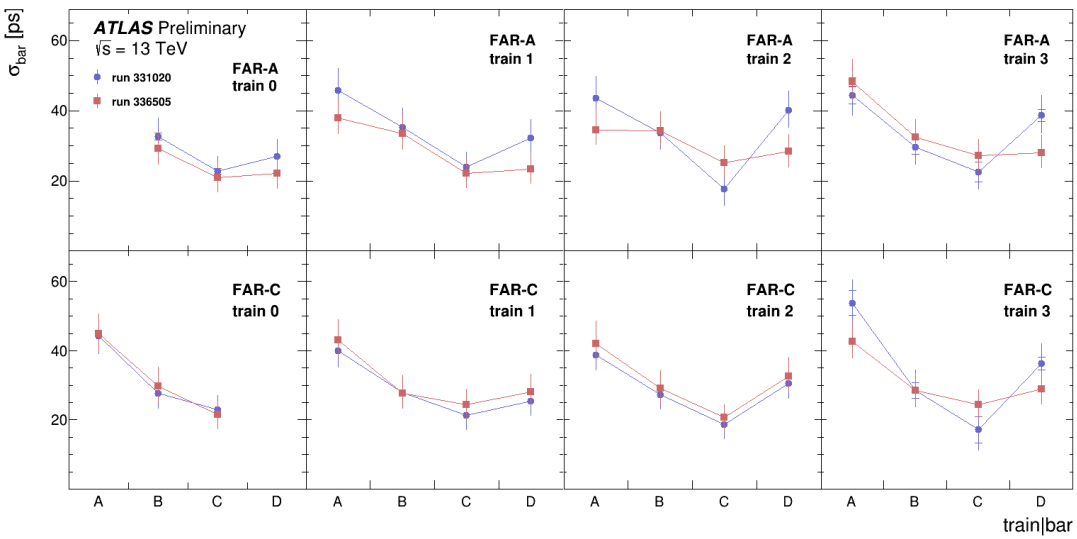

Idea:

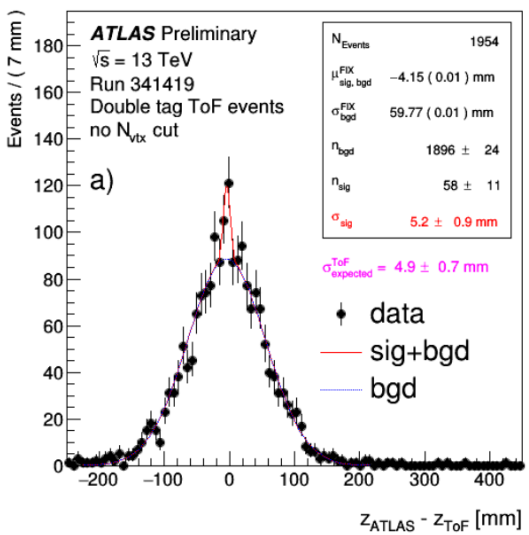
- measure difference of time of flight of scattered protons, $(t_A - t_C)/2$
- compare to vertex reconstructed by central detector, $(t_A - t_C) \cdot c/2 - z_{central}$



- Performance analysis based on 2017 data (taken with $\mu \approx 2$): ATL-FWD-PUB-2021-002.
- Poor efficiency of few percent due to fast PMT degradation; effect not expected during Run 3 due to new PMTs.
- Very good timing resolution: 20 – 50 ps for single bar.
- Overall time resolution of each ToF detector:
  - $20 \pm 4$ ps for side A,
  - $26 \pm 5$ ps for side C,
  - note: systematic uncertainties dominate.

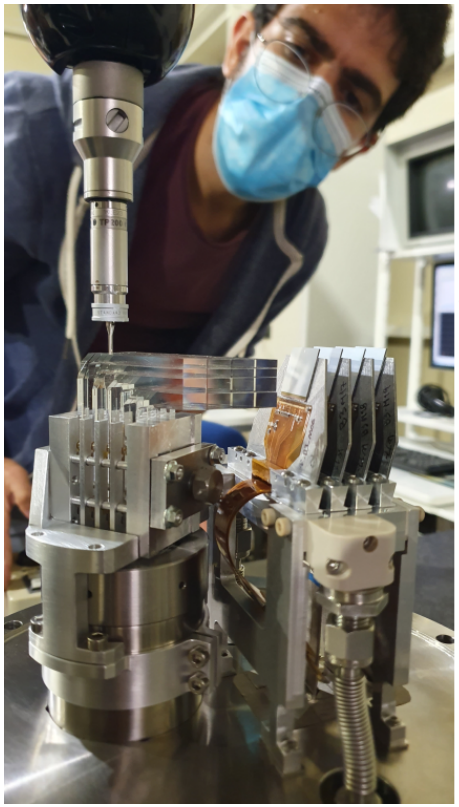


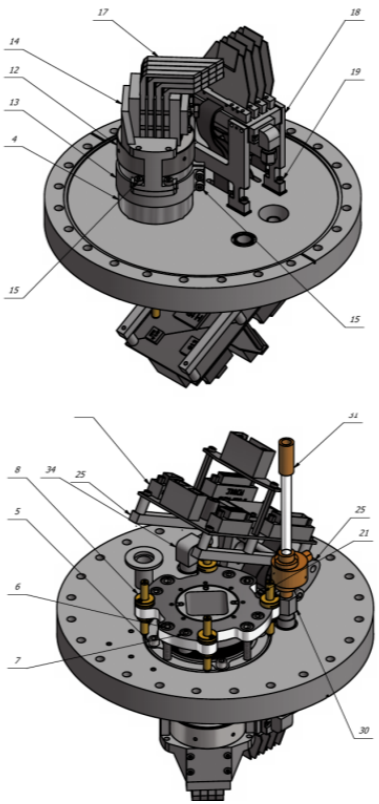



# AFP upgrades for RUN 3

- 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.





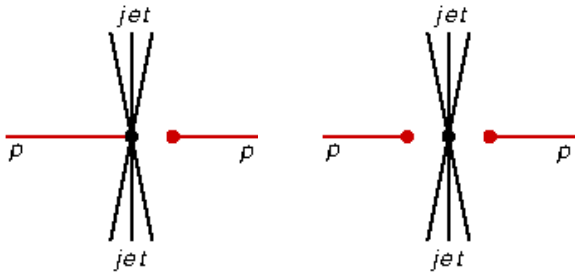
Both NEAR and FAR station have been successfully installed:

- laser survey (positioning wrt. LHC) done,
- interlock validation done $\rightarrow$ Roman pots qualified to be inserted to take data,
- SiT readout and trigger commissioned,
- ToF commissioning ongoing,
- successful data-taking during high- and low-$\mu$ runs in 2022.

# Backgrounds

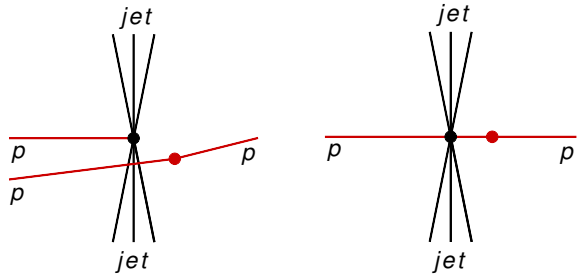
# Probability of Single and Double Tag

Single Tagged Soft Interaction(ST)




SD JJ ND JJ

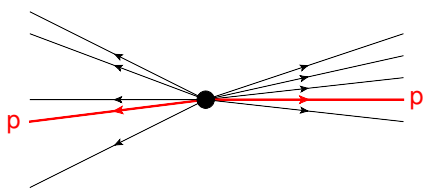
Double Tagged Soft Interaction(DT)

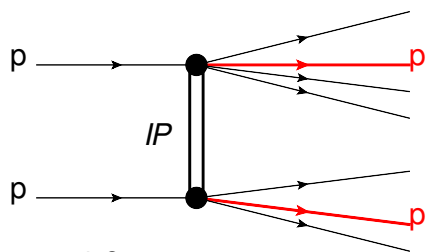


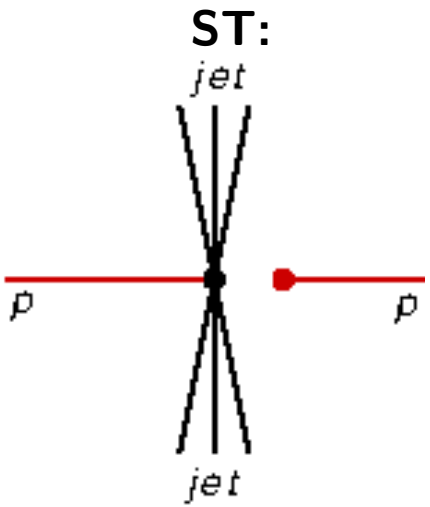

SD JJ ND JJ

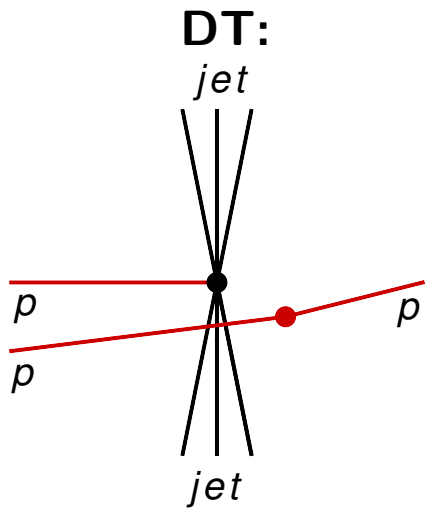
| Process (PYTHIA8) | Single Tag probability | Single Tag cross-section [mb] | Double Tag probability | Double Tag cross-section [$\mu$b] |
|---|---|---|---|---|
| SD | 0.18 | 2.32 | $4.5 \cdot 10^{-4}$ | 5.8 |
| DD | 0.051 | 0.45 | $4.3 \cdot 10^{-4}$ | 3.8 |
| ND | 0.0054 | 0.31 | $1.4 \cdot 10^{-5}$ | 0.8 |
| MB | 0.039 | 3.10 | $1.4 \cdot 10^{-4}$ | 10.4 |

Note: Double Diffractive Dissociation with protons from hadronisation propagating in forward direction.

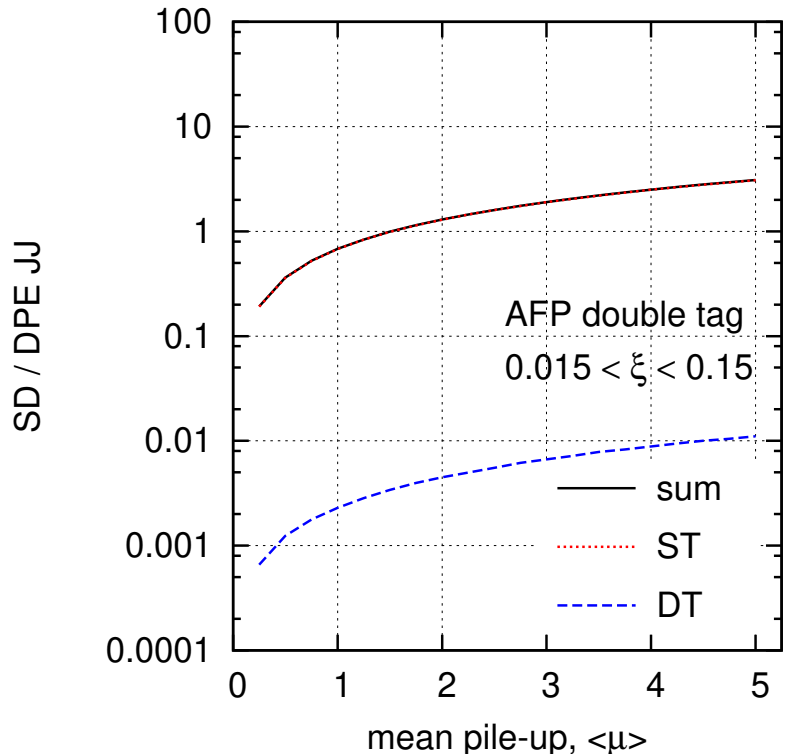


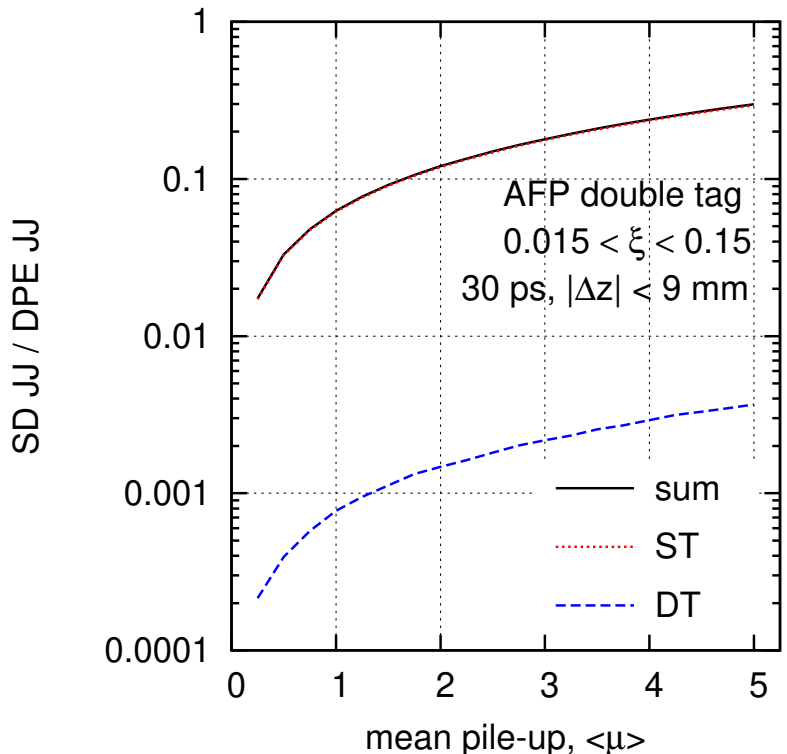



Single Diffractive contribution

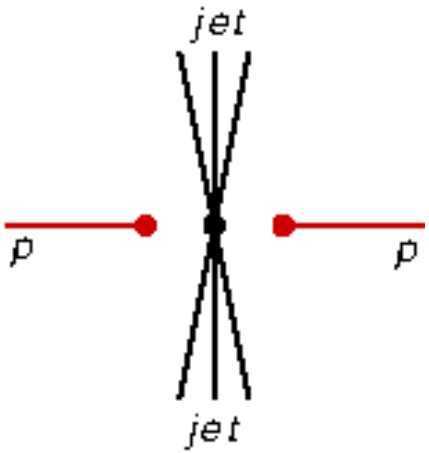



Single Diffractive contribution timing cut

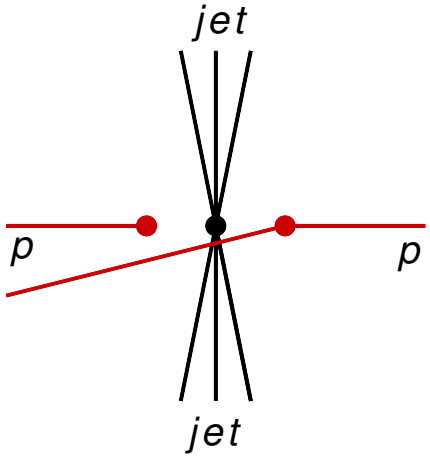


# ND Jet Background

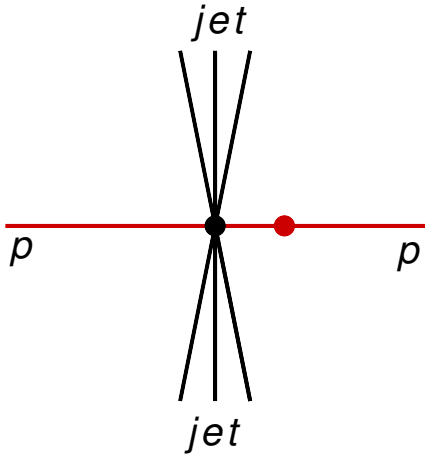
**ST + ST:**



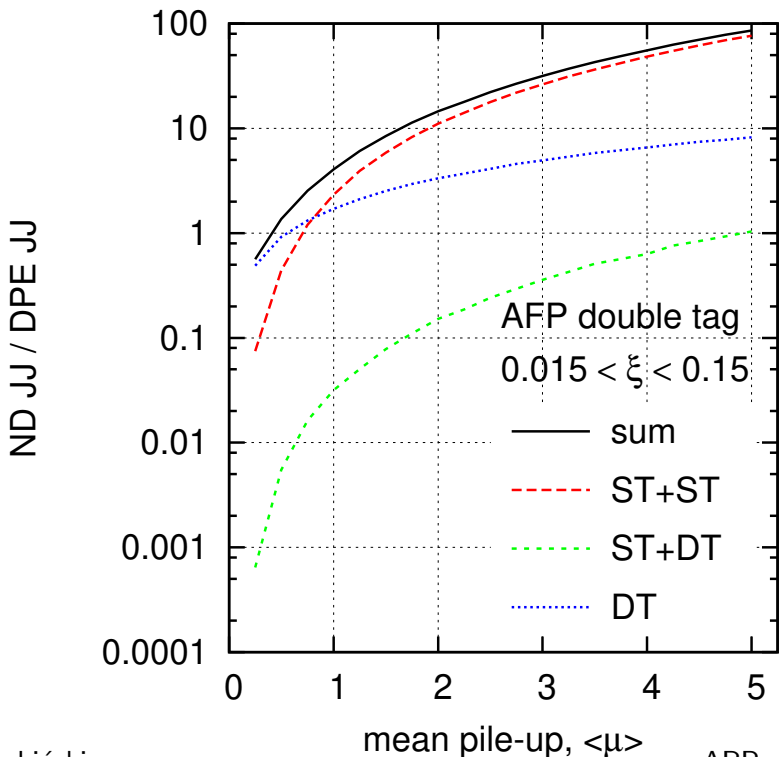

**ST + DT:**



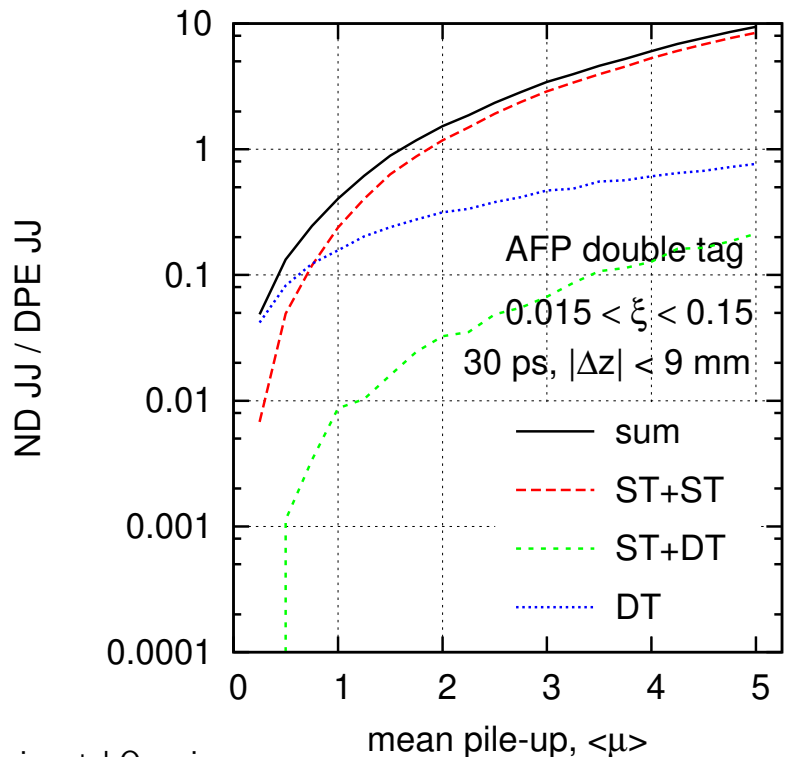

**DT:**




Non-Diffractive contribution

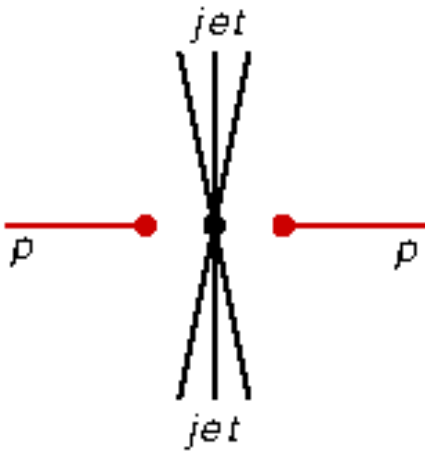



Non-Diffractive contribution timing cut

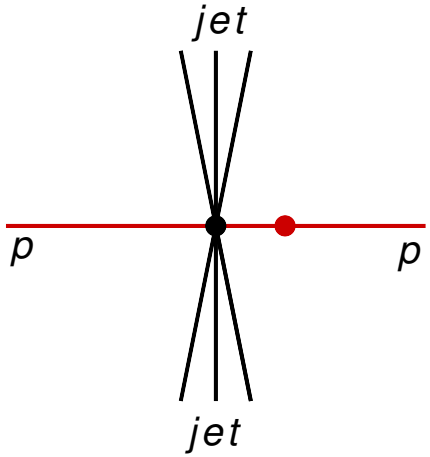


# SD + ND Jet Background

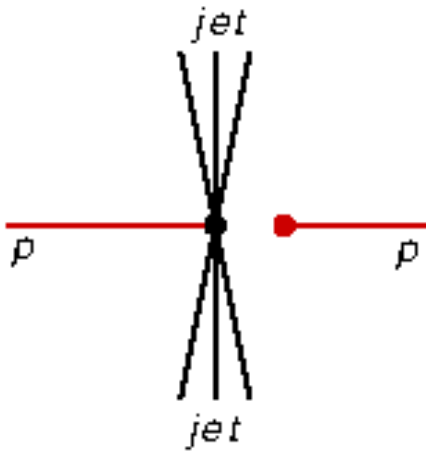
**ST + ST:**



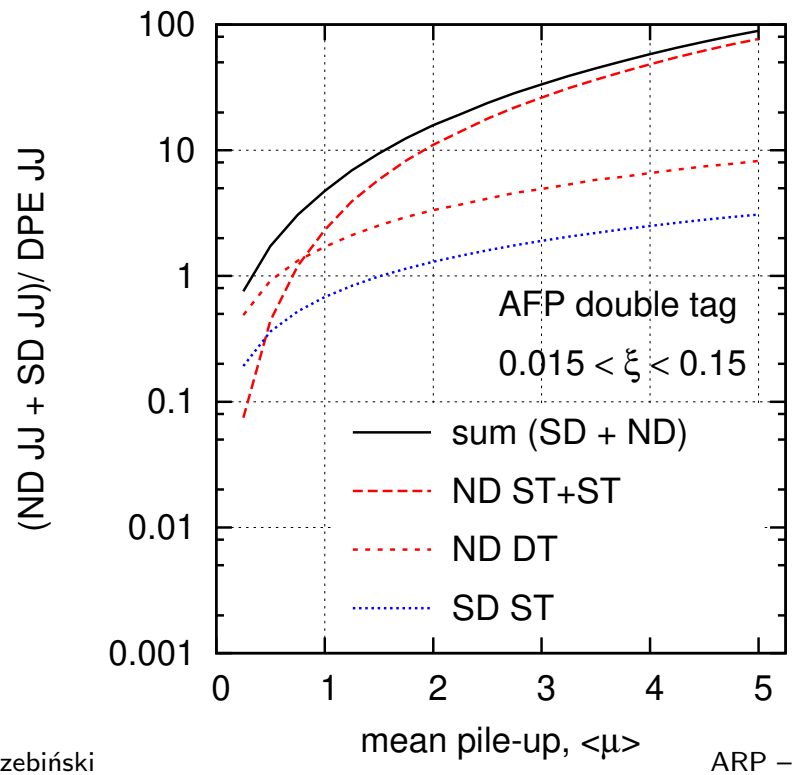

**DT:**



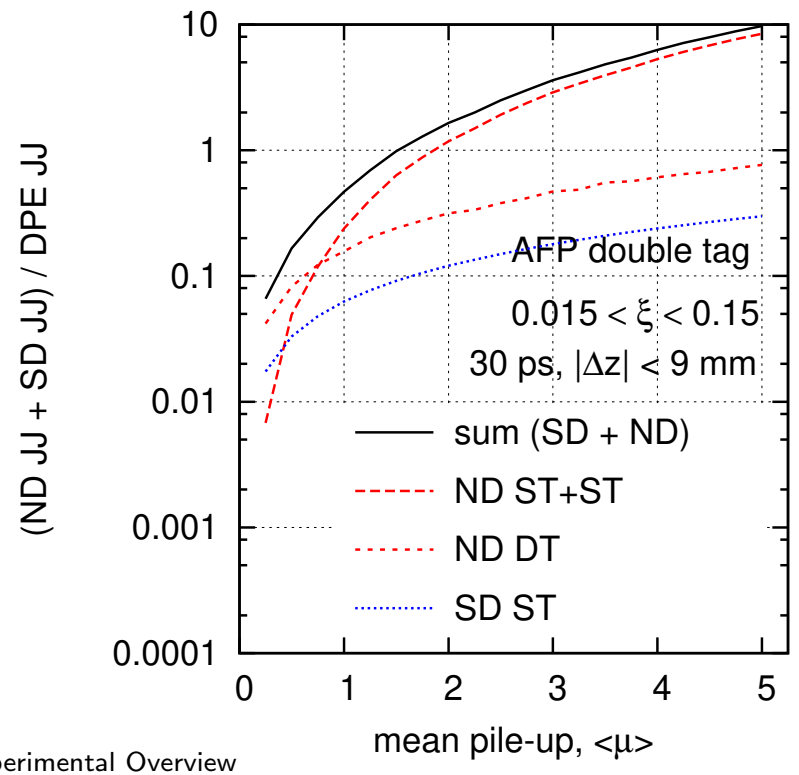

**ST:**




ND + SD contribution

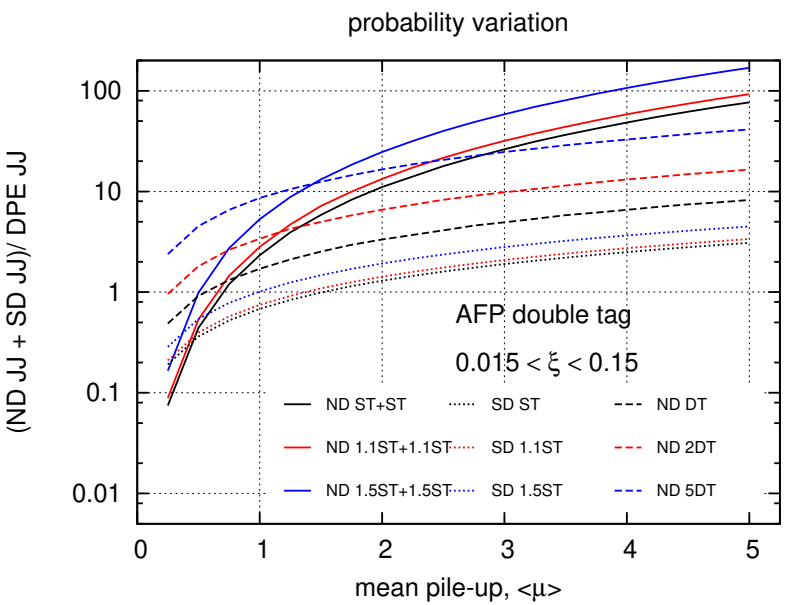


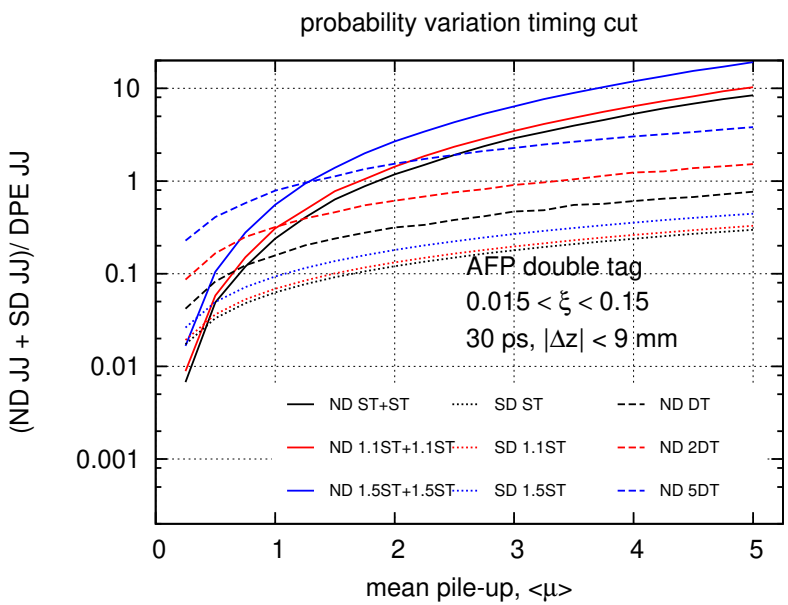

SD+ND contribution timing cut



What happens if the Single and Double Tag Probabilities are higher than predicted by MC generators?

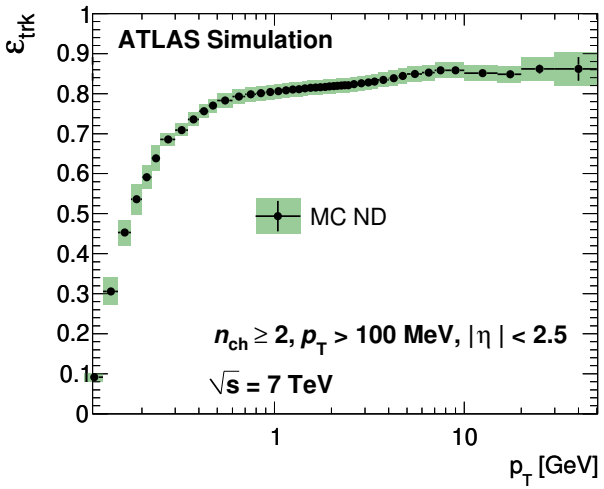
| Probability | |
|---|---|
| Single Tag | Double Tag |
| 0.039 | $1.4 \cdot 10^{-4}$ |
| **1.1** $\cdot$0.039 | **2** $\cdot 1.4 \cdot 10^{-4}$ |
| **1.5** $\cdot$0.039 | **5** $\cdot 1.4 \cdot 10^{-4}$ |



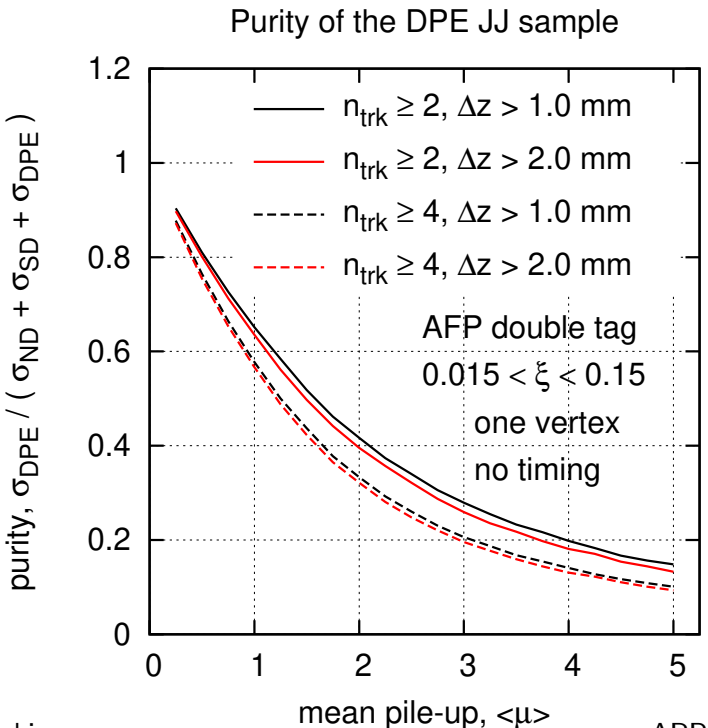



Two inefficiency sources:

- soft vertex is merged with a hard one ($\Delta z = 1$ mm, $\Delta z = 2$ mm),
- not enough reconstructed tracks pointing to the soft vertex ($n_{trk} = 2$, $n_{trk} = 4$).




| Min. number of tracks | Probability SD | DD | ND | min-bias |
|---|---|---|---|---|
| 2 | 0.532 | 0.601 | 0.995 | 0.876 |
| 3 | 0.494 | 0.540 | 0.985 | 0.855 |
| 4 | 0.457 | 0.483 | 0.968 | 0.831 |
| 5 | 0.419 | 0.429 | 0.944 | 0.801 |



# Data Samples

# Data Taken in 2016 and 2017

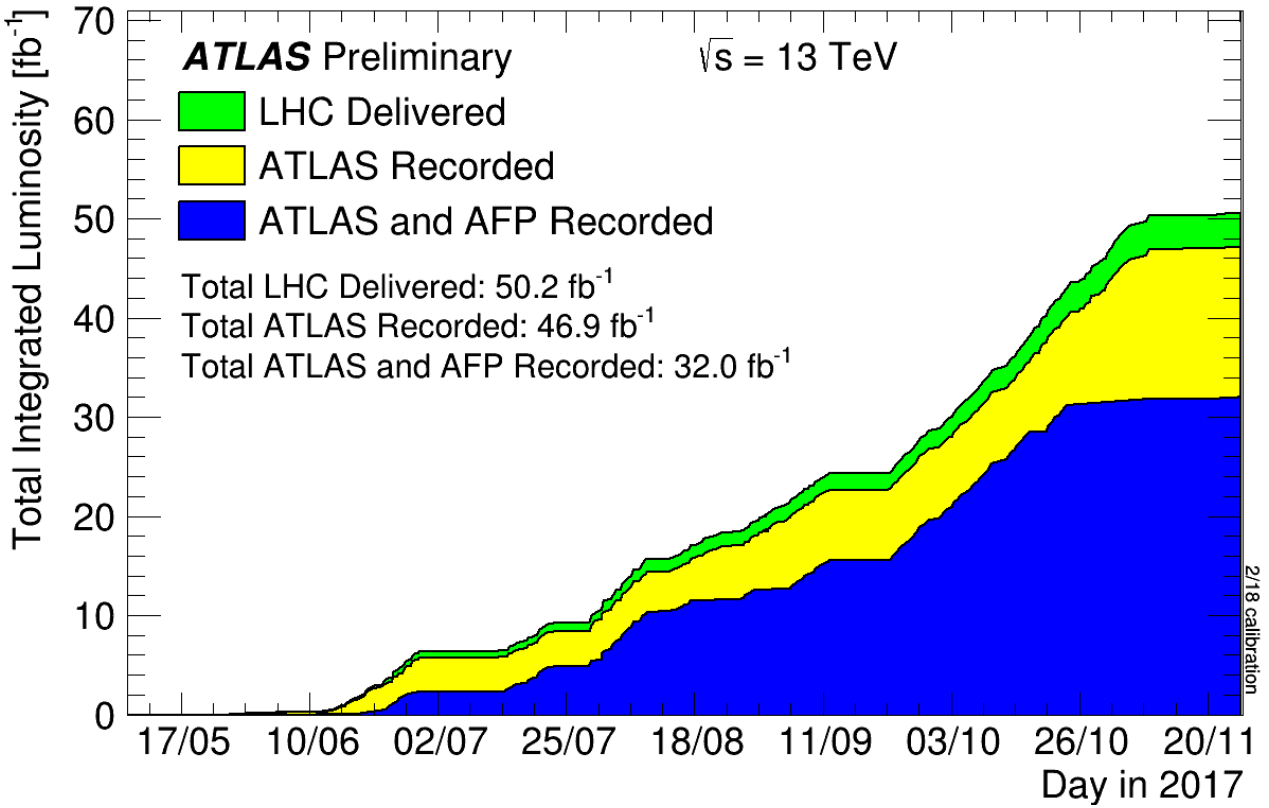
## 2016

- Conditions: $\sqrt{s} = 13$ TeV, $\beta^* = 0.4$ m
- Only two stations installed (ATLAS side C).
- Only single tagged events.
- Data taken during BBA:
  - two runs,
  - closer to the beam than during standard collisions,
  - very useful for alignment and optics studies.
- Data taken during special runs:
  - $\mu \sim 0.03$:
    - int. lumi.:$\sim$40 nb$^{-1}$,
    - AFP triggers: $\sim$2 kHz stored,
    - main goal: soft diffraction.
  - $\mu \sim 0.3$:
    - int. lumi.:$\sim$500 nb$^{-1}$,
    - AFP triggers: $\sim$2 kHz stored,
    - main goal: low-$p_T$ jets.
- Data taken during standard runs:
  - AFP was inserted only when number of bunches was not greater than 600 (ramp-up).

## 2017

- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ and 0.4 m
- Full system ready.
- Single and double tagged events.
- Data taken during BBA:
  - two runs.
- Data taken during special runs:
  - $\mu \sim 0.05$:
    - int. lumi.:$\sim$65 nb$^{-1}$,
    - AFP triggers: $\sim$2 kHz stored,
    - main goal: soft diffraction.
  - $\mu \sim 1$:
    - int. lumi.:$\sim$640 nb$^{-1}$,
    - AFP triggers: $\sim$2 kHz stored,
    - main goal: low-$p_T$ jets.
  - $\mu \sim 2$:
    - int. lumi.:$\sim$150 pb$^{-1}$,
    - AFP triggers: $\sim$300 Hz stored,
    - goals: medium-$p_T$ jets, $W/Z$.
- Data taken during standard runs:
  - AFP was inserted on regular basis, usually few minutes after stable beams.

# Data Collected in 2017




- This is only ATLAS and AFP recorded – there are no corrections due to efficiency of subsystems, *etc.*
- ToF trigger and detector were suffered very low efficiency $\rightarrow$ analysis should base on proton tagging rather than on ToF background reduction.

# Glance on Analysis: Exclusive Di-lepton Measurement with AFP Tag

PHYSICAL REVIEW LETTERS **125,** 261801 (2020)

**Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS**

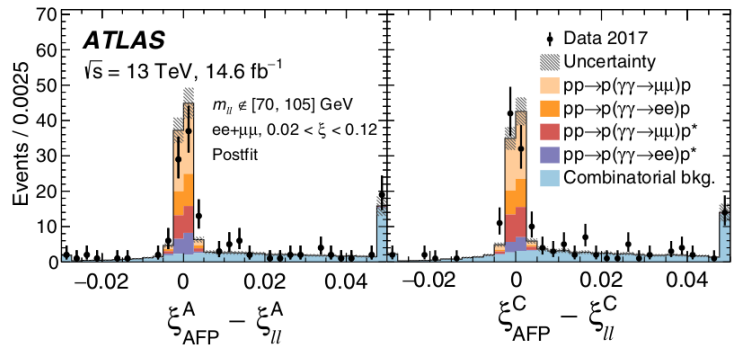
G. Aad *et al.*[*]
(ATLAS Collaboration)

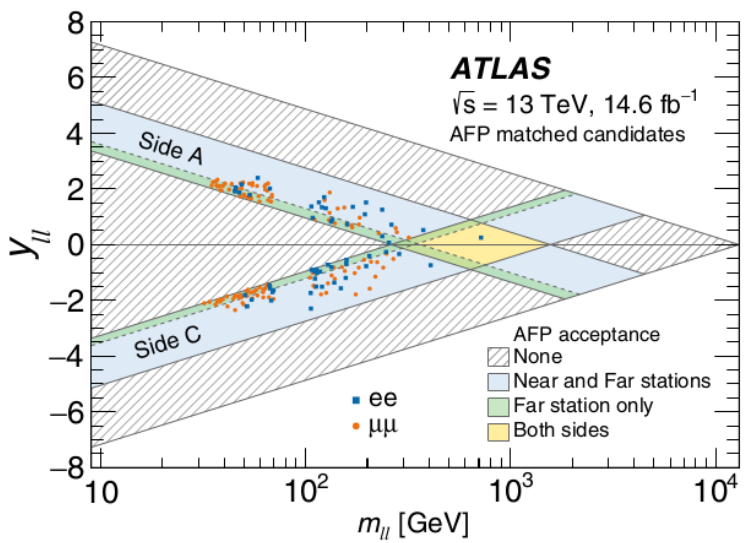
(Received 2 October 2020; revised 30 October 2020; accepted 23 November 2020; published 23 December 2020)

- Exclusive di-muons, $pp \to pl^-l^+p$:
  - proton(s) measured in AFP,
  - leptons ($\mu^+\mu^-$ or $e^+e^-$) measured in ATLAS.
- 2017 data; $\sqrt{s} = 13$; $L = 14.6$ fb$^{-1}$.
- Powerful background rejection due to AFP:
  - proton tagging,
  - kinematics match: proton vs lepton system.
- 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state.
- Background-only hypothesis rejected with a significance exceeding $5\sigma$ in each channel.
- Measured cross sections:

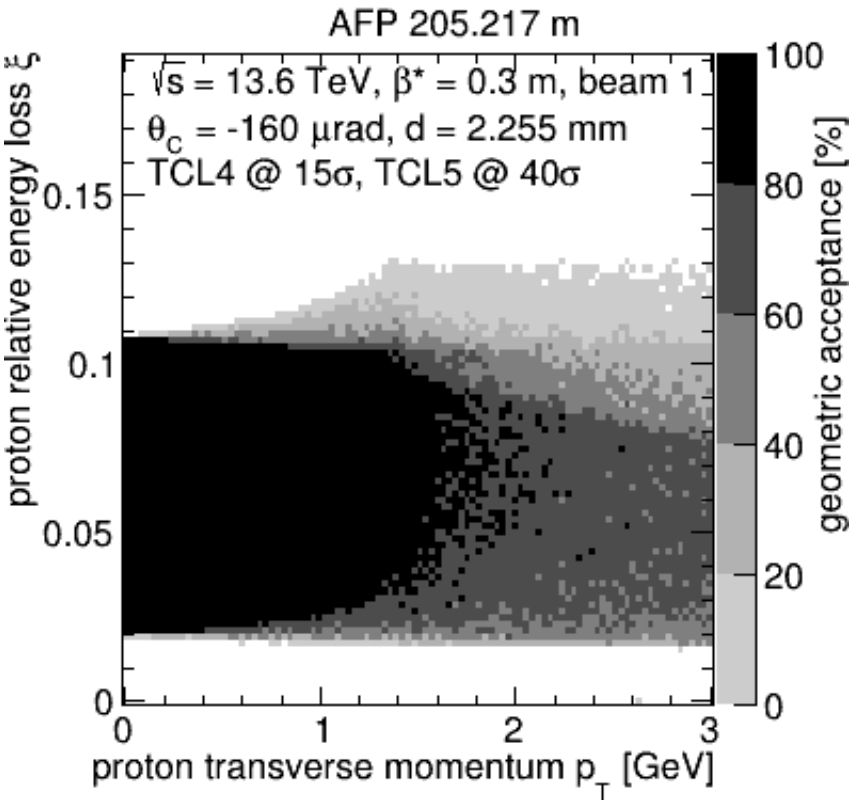
  $\sigma_{ee+p} = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi}),$

  $\sigma_{\mu\mu+p} = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi}).$

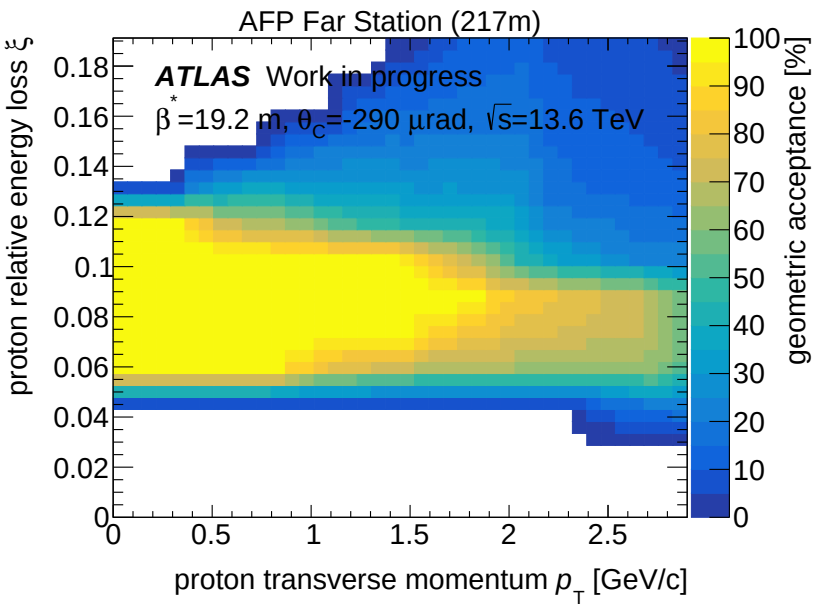


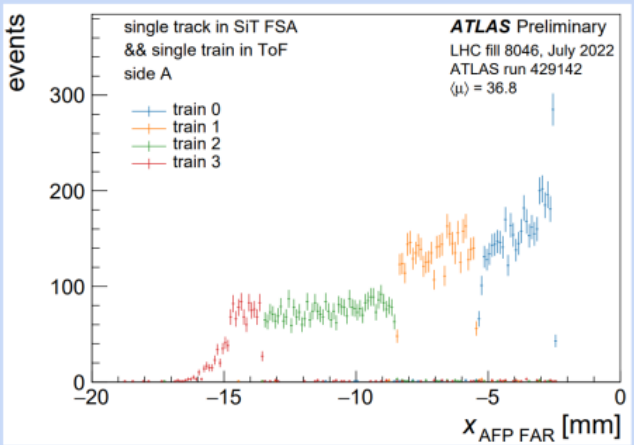



## Low-$\beta^*$ Runs

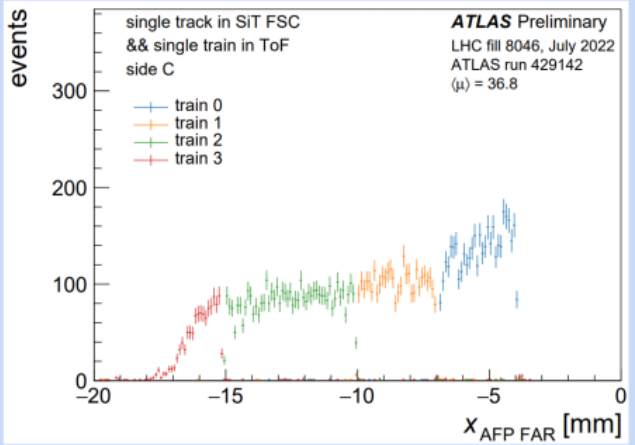


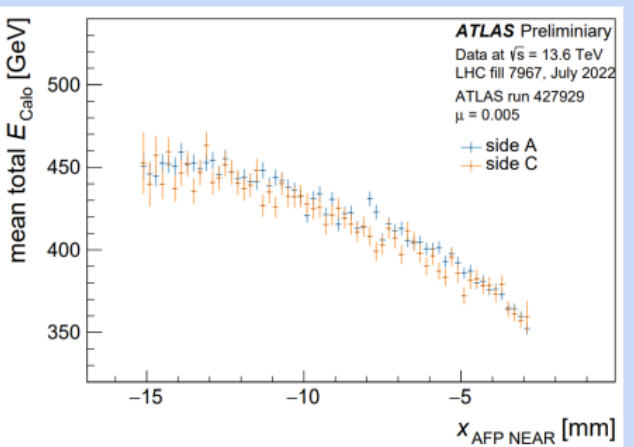

## LHCf Runs



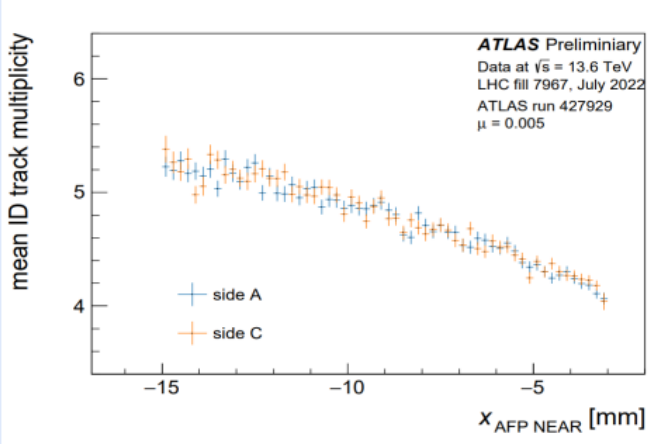



The x position of the track reconstructed in AFP SiT (FAR station) in events in which a single-train signal in ToF detector was observed for side A (left plot) and side C (right plot). The differences in the $x_{AFP\ FAR}$ between sides are due to global alignment corrections not being applied).

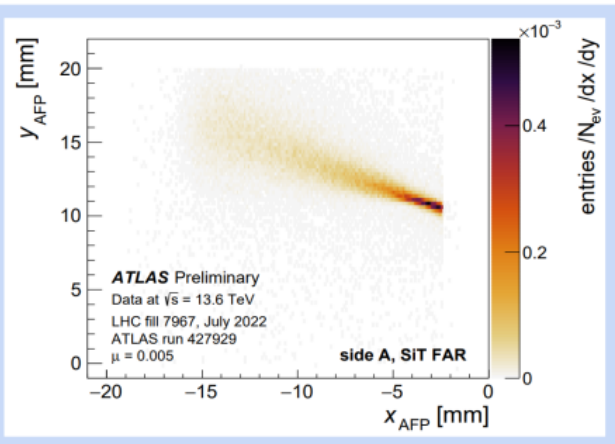



Correlation between the x position of reconstructed tracks in AFP NEAR stations and the total energy measured by the ATLAS Calorimeters for side A and C.

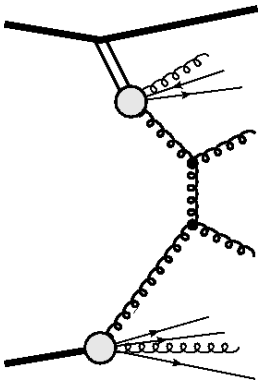



Correlation between the x position of reconstructed tracks in AFP NEAR stations and the charged track multiplicity in the ATLAS Inner Detector for Side A and C.




Positions of tracks reconstructed in AFP. Coordinate system: center of the beampipe at (x, y) = (0, 10 mm)

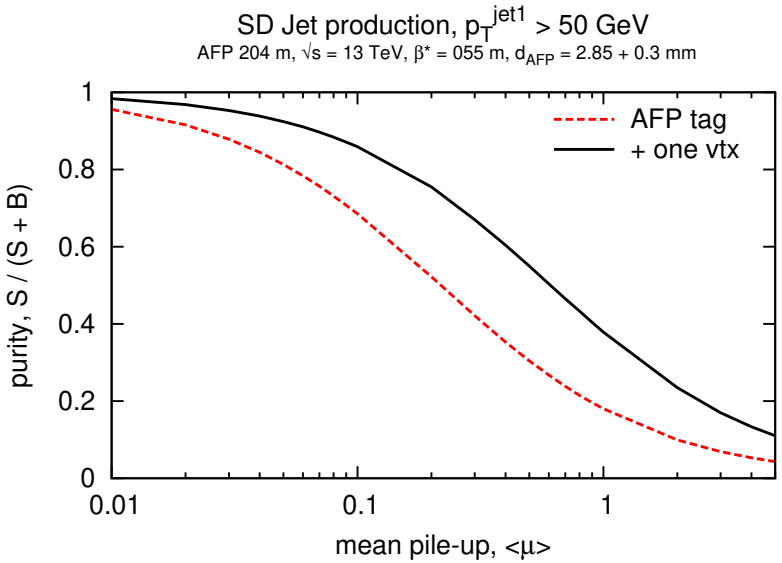
# Hard Diffractive Processes

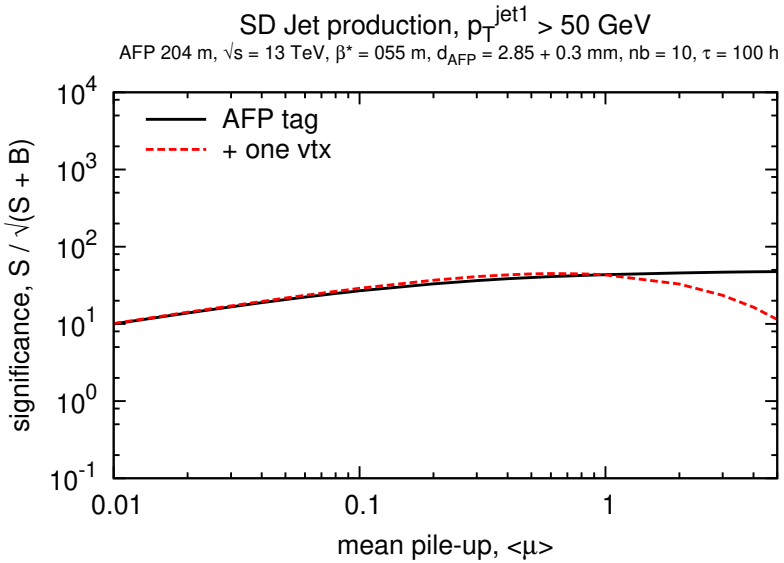


**Motivation:**

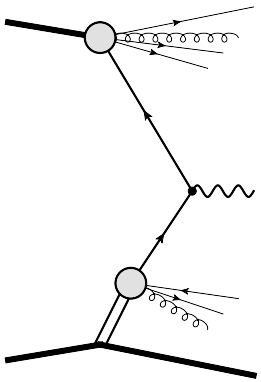
- measure cross section and gap survival probability,
- search for the presence of an additional contribution from Reggeon exchange,
- check Pomeron universality between *ep* and *pp* colliders.

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



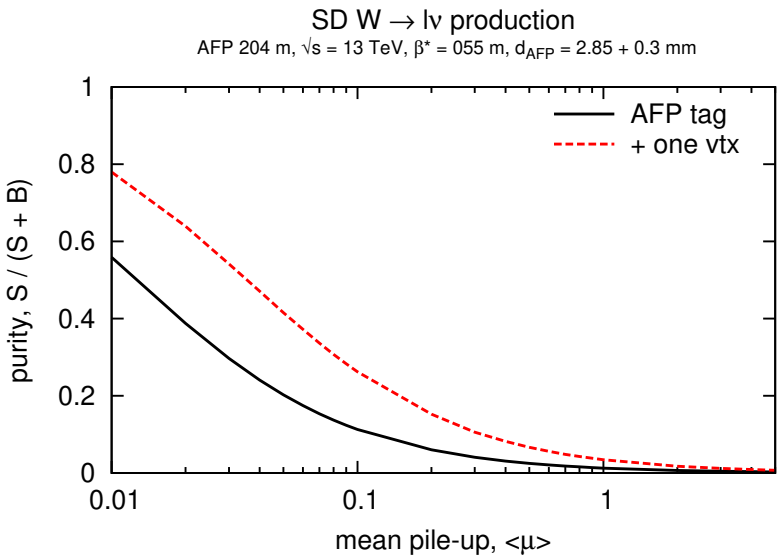

**More details in**: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

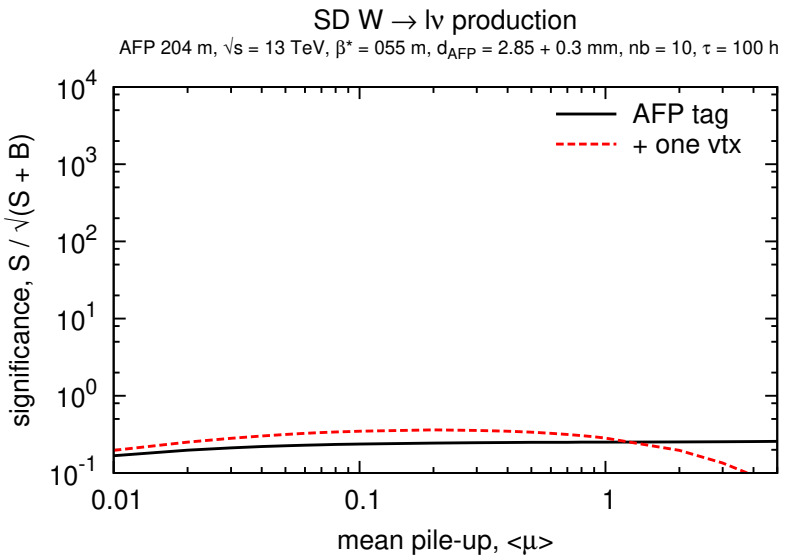


**Motivation:**

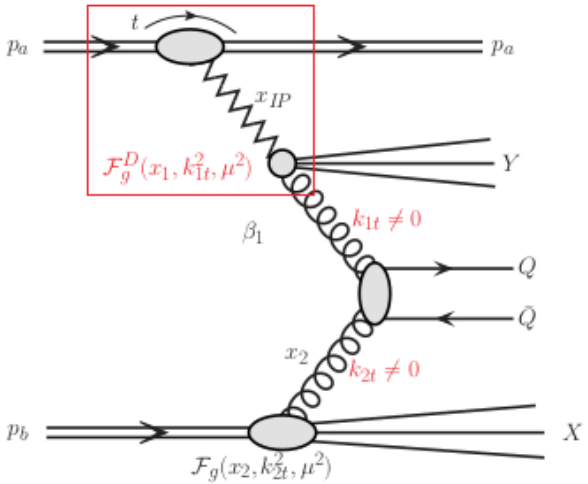
- measure cross section and gap survival probability,
- measure Pomeron structure and flavor composition,
- search for charge-asymmetry.

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



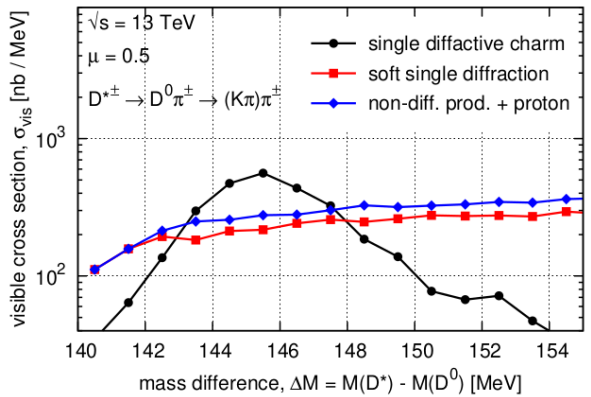




**W asymmetry studies published in:** Phys.Rev. D **84** (2011) 114006
**More details in**: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201

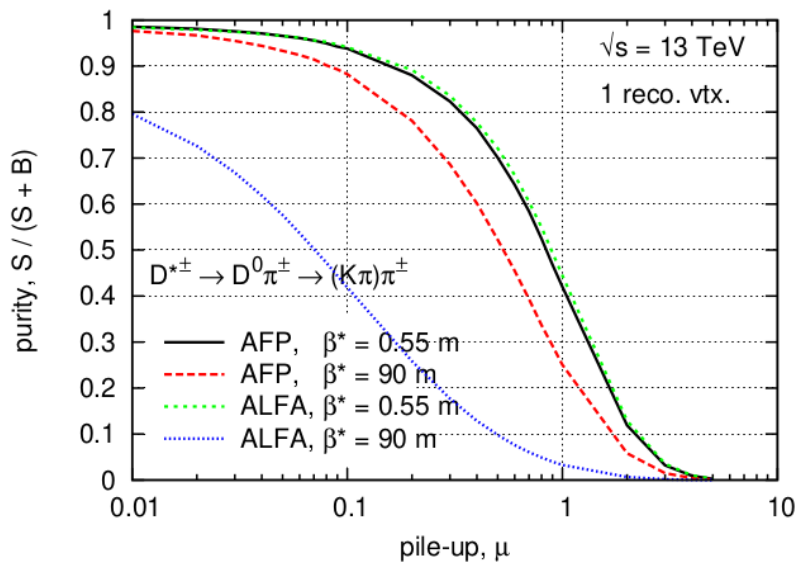


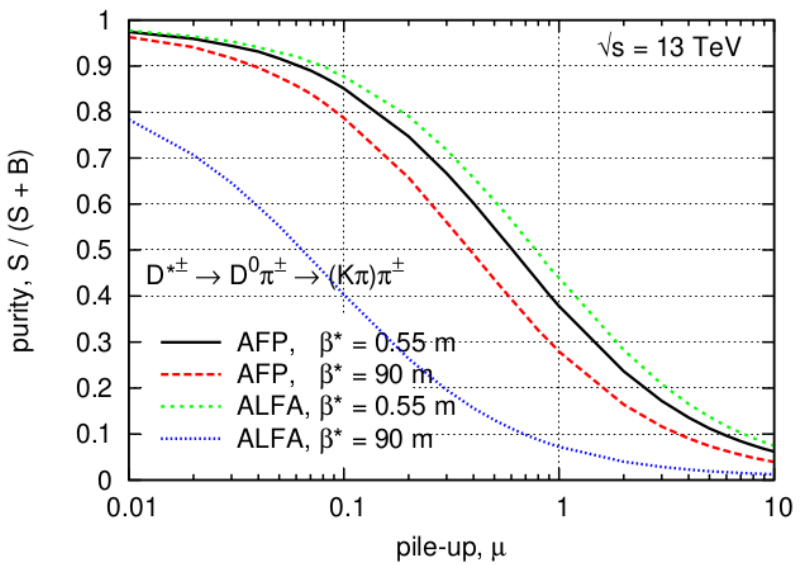

**Motivation:**

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

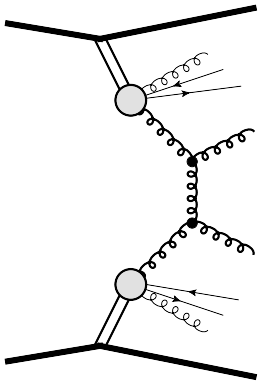



Example: purity ALFA and AFP for $\beta^* = 0.55$ and 90 m with and without 1 vertex requirement.



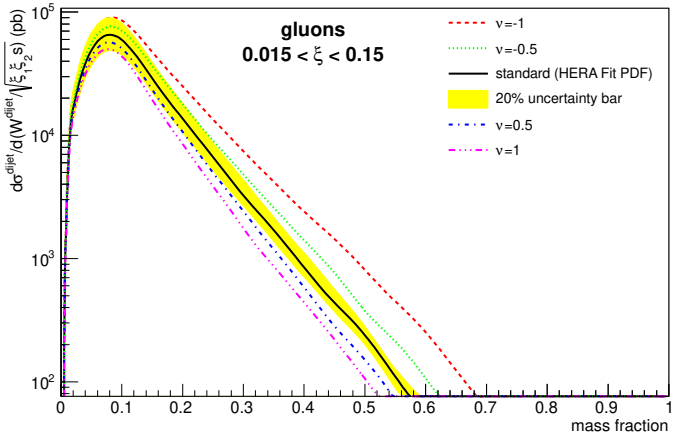




**More details in**: J. High Energ. Phys. **2017** (2017) 89

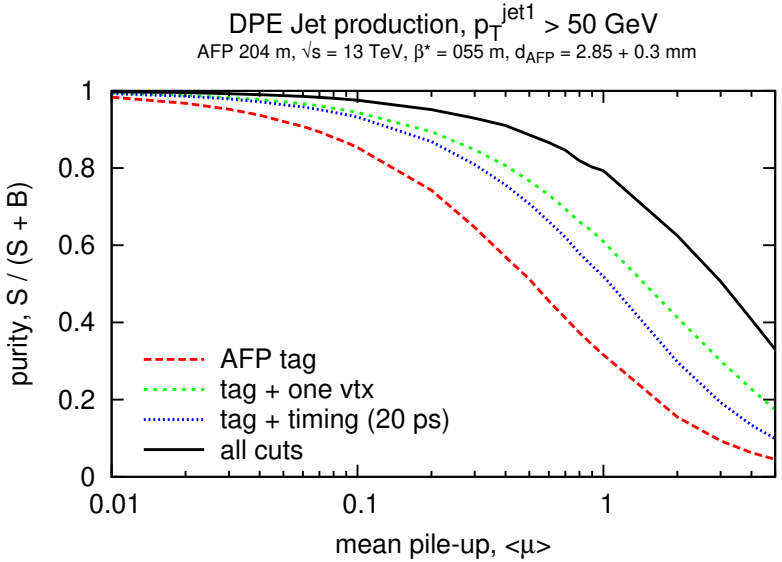


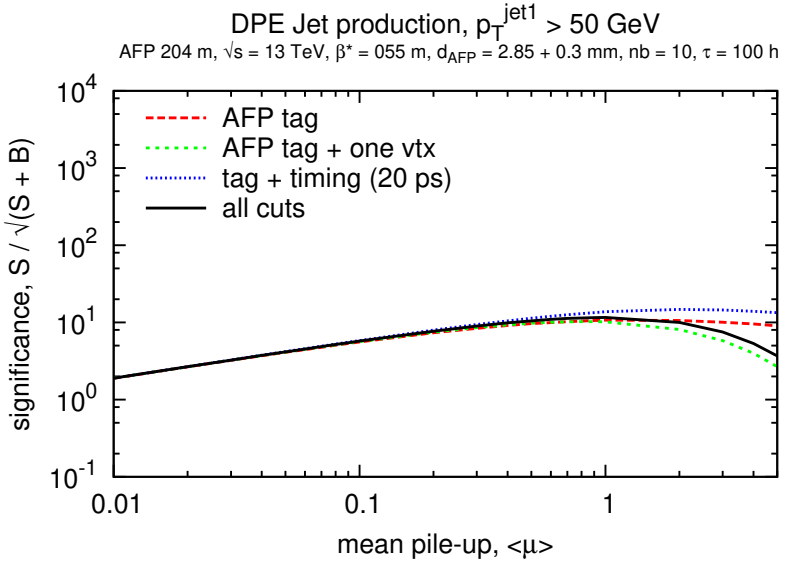
**Motivation:**

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

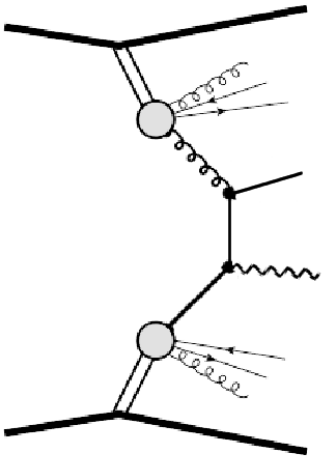



Example: purity and statistical significance for AFP and $\beta^* = 0.55$ m.



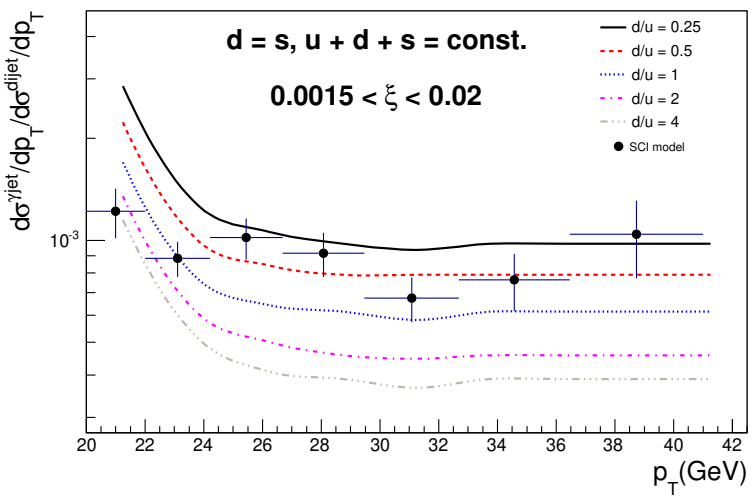



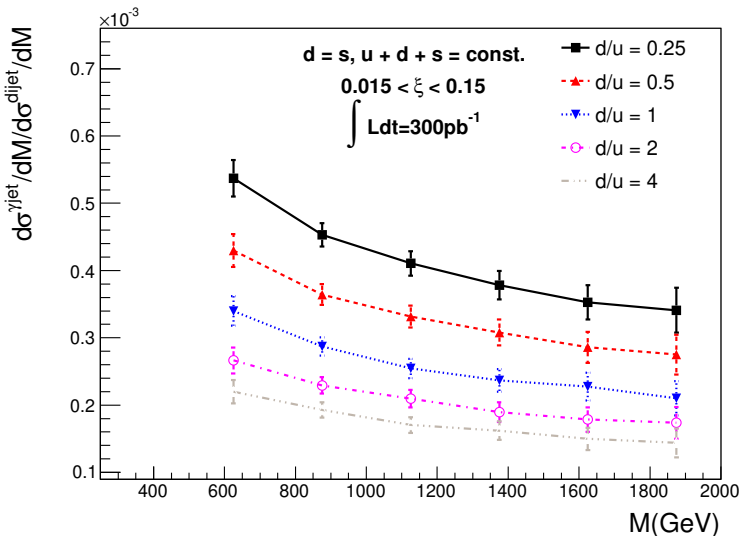

**More details in**: J. Phys. G: Nucl. Part. Phys. **43** (2016) 110201



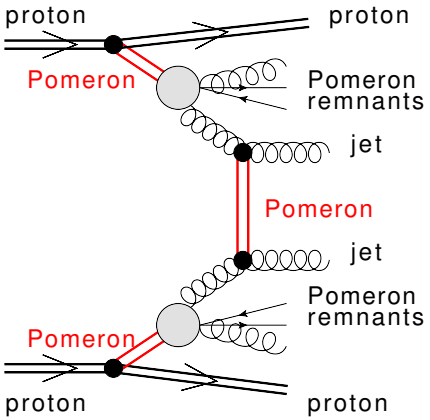
**Motivation:**

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



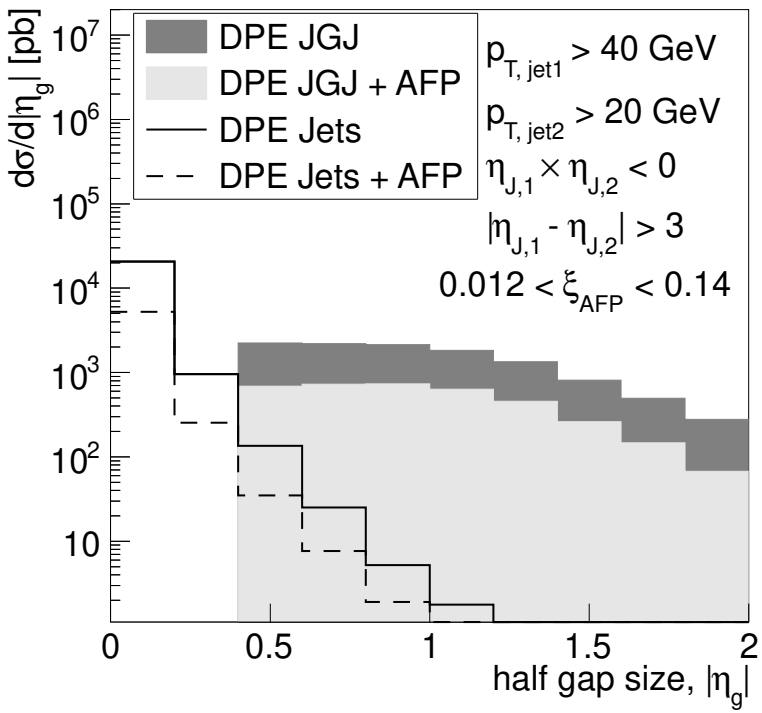



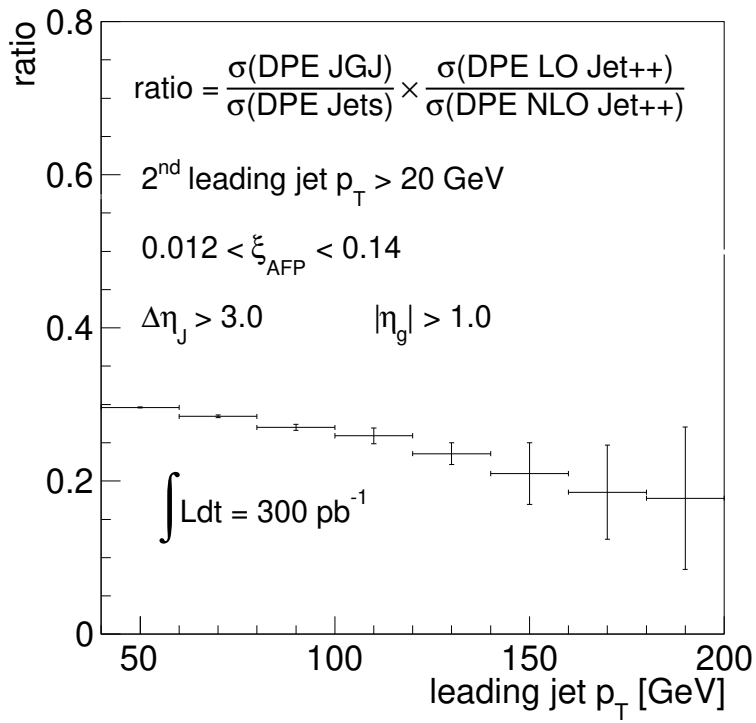

**More details in:** Phys.Rev. D **88** (2013) 7, 074029



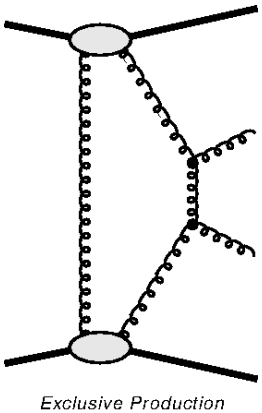

**Motivation:**

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



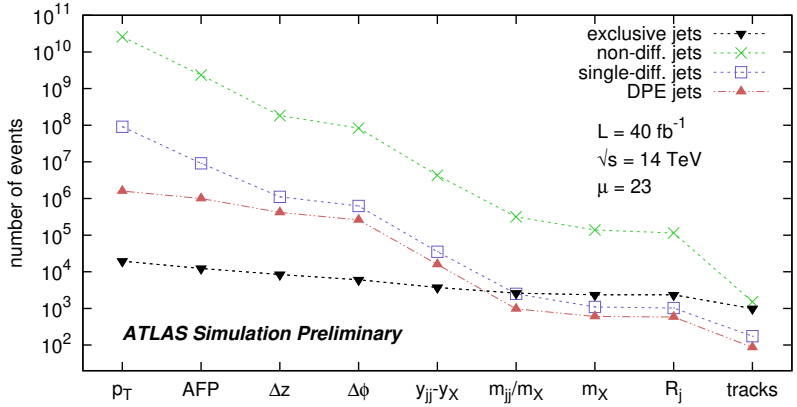



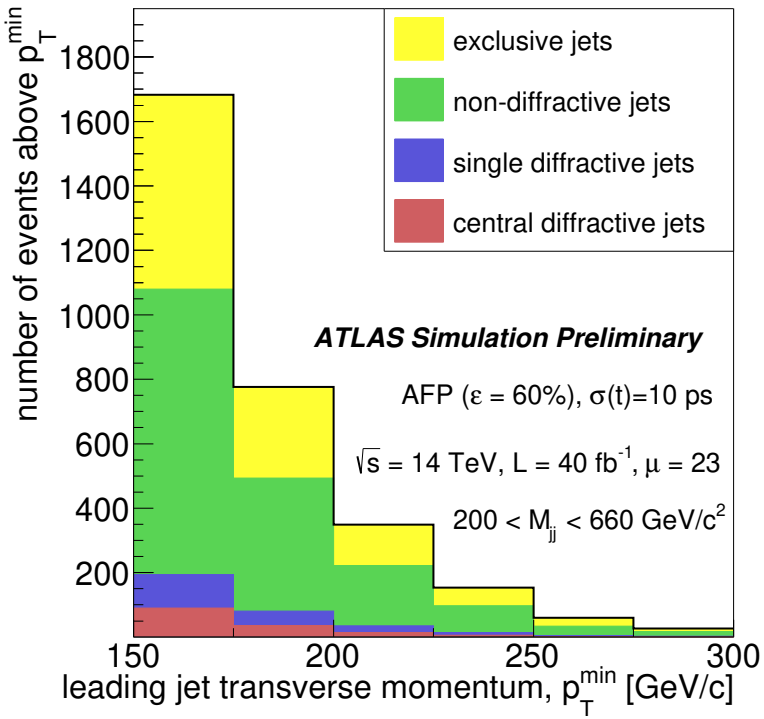

**More details in:** Phys.Rev. D **87** (2013) 3, 034010

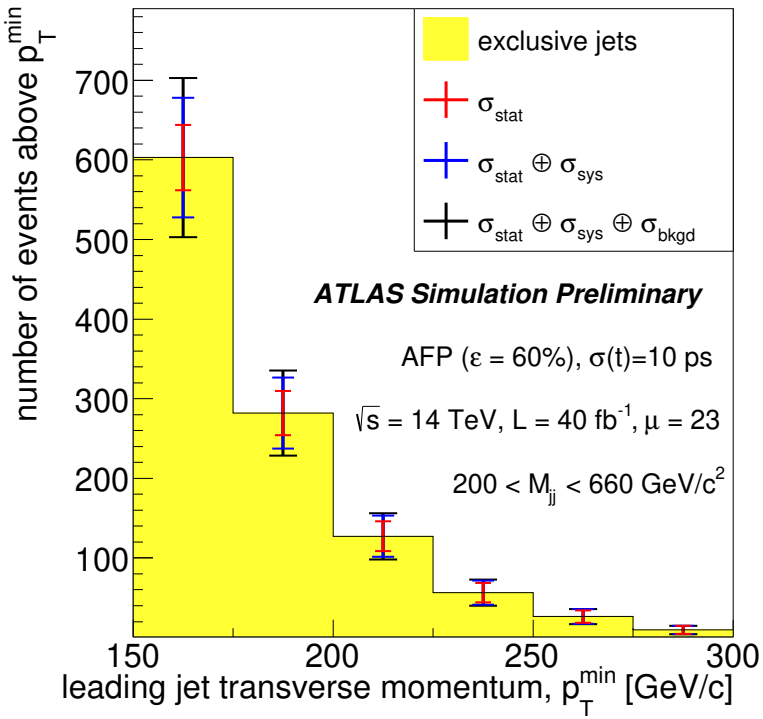



## Motivation:

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

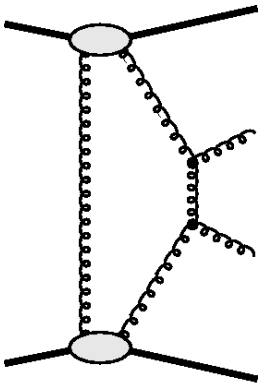



**Public ATLAS note:** ATL-PHYS-PUB-2015-003

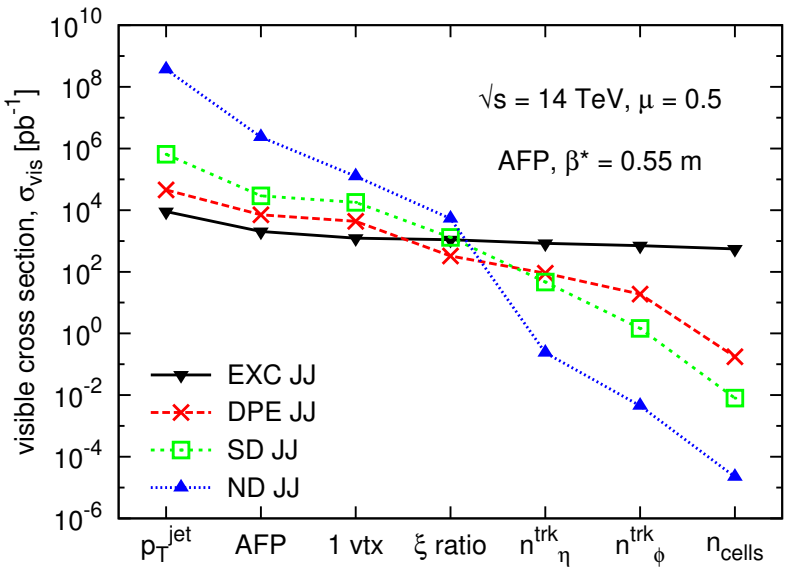
# Exclusive Jet Production (Single Tag)

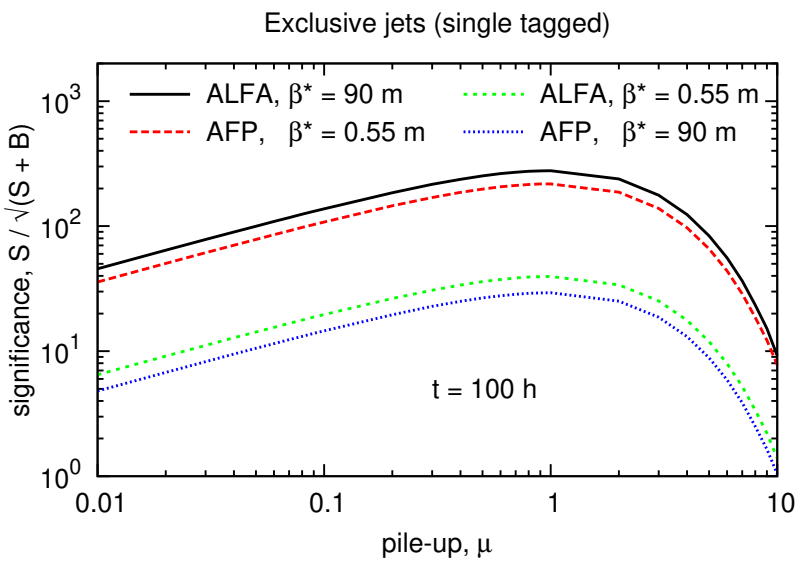


*Exclusive Production*

**Motivation:**

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

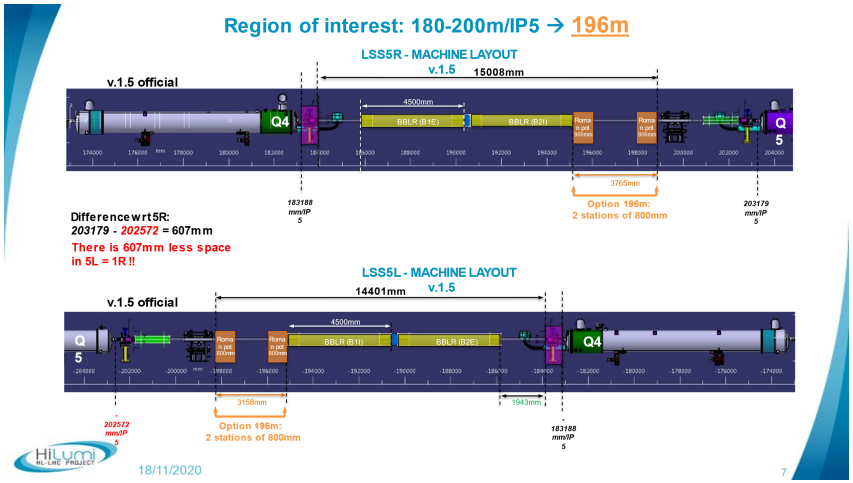


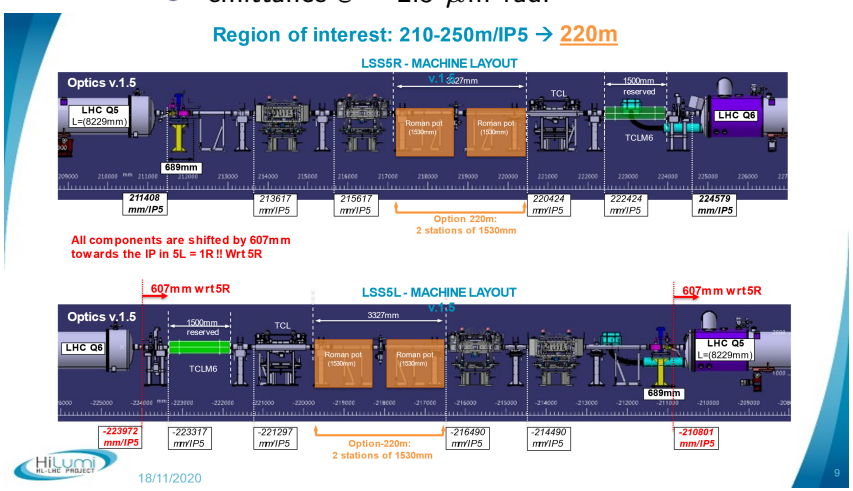



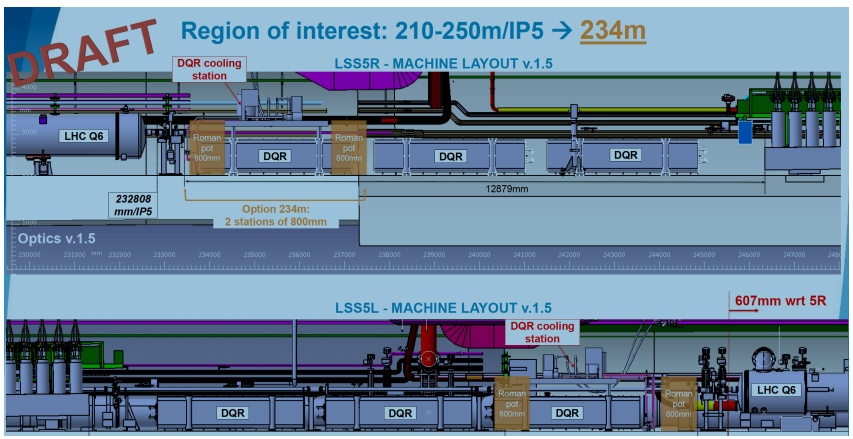

**More details in:** Eur. Phys. J. C **75** (2015) 320
and Acta Phys. Pol. B **47** (2016) 1745

# HL-LHC: Situation in Tunnel after LS3

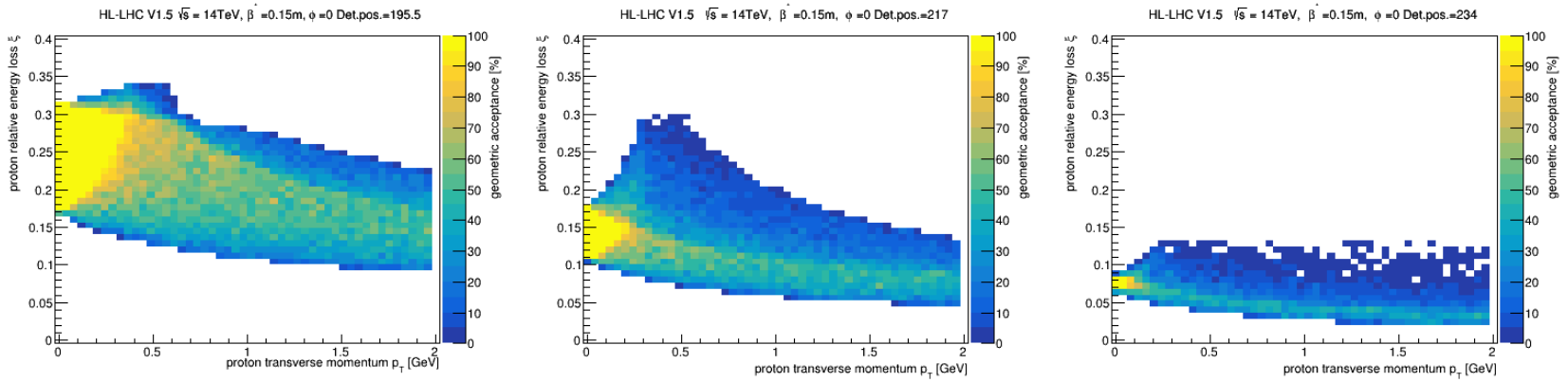
- According to HL-LHC machine layout only few locations are possible:
  - RP1A at 195.5 m
  - RP1B at 198.0 m
  - RP2A at 217.0 m
  - RP2B at 219.5 m
  - RP3A at 234.0 m
  - RP3B at 237.0 m
  - RP3C at 245.0 m
- Collimators are also relocated:
  - TCLPX4 at 136 m
  - TCL5 at 199 m
  - TCL6 at 221 m
- Studies were done using newest available HL-LHC optics.
- Assumption:
  - $\sqrt{s} = 14$ TeV, $\beta^* = 15$ cm,
  - crossing angle of 250 $\mu$rad with phase: $\phi = 0$,
  - emittance $\varepsilon = 2.5$ $\mu$m·rad.



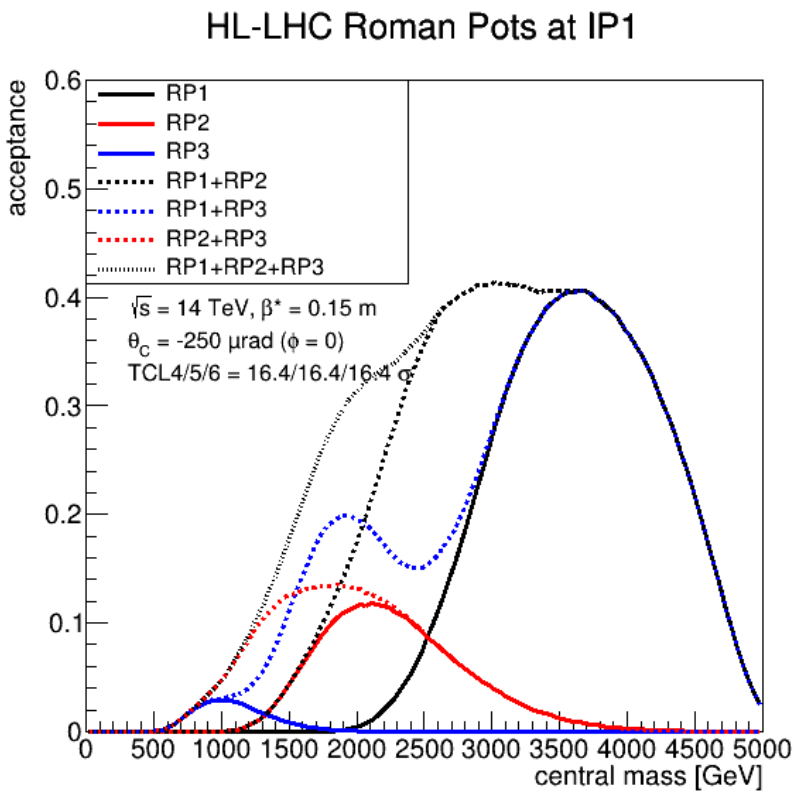
# HL-LHC: Key Factor – Detector Acceptance




- Proton relative energy loss: $\xi = 1 - \frac{E_{proton}}{E_{beam}}$.
- High-$\xi$ limit on acceptance is due to beampipe elements and TCL collimators between collision point and Roman pot.
- Low-$\xi$ limit is due to detector-beam distance, which depends on settings of collimators ("hierarchy"; machine protection rules).
- Yellow area corresponds to $> 90\%$ of proton tag chance.
- Scattered protons usually (distribution is process-dependent) have $p_T$ around 0.2 GeV.
- Left: detectors located around 195 m: $0.17 \lesssim \xi \lesssim 0.31$.
- Center: detectors located around 217 m: $0.1 \lesssim \xi \lesssim 0.19$.
- Right: detectors located around 234 m: $0.06 \lesssim \xi \lesssim 0.09$.

# HL-LHC: Mass Acceptance

- Acceptance in $\xi$ translates into the acceptance in mass (note: process dependent as integral sensitive to $p_T$).
- Figure: mass acceptance of all pots and all pots combinations for the case of horizontal crossing angle ($\phi$=0):
  - "RP1" indicates that both the protons are tagged at the pot RP1A and RP1B (similarly for RP2 and RP3),
  - "RP1+RP2" means both protons are tagged at any two of the four pot locations RP1A, RP1B, RP2A and RP2B (similarly "RP1+RP3" and "RP2+RP3"),
  - "RP1+RP2+RP3" indicates that protons are tagged at any two stations on each side.



# HL-LHC: Physics Case (Very Briefly)

- I was asked to 'squeeze' physics case and focus on other topics in this presentation.
- For the real overview, please take a look at Physics opportunities of ATLAS Forward Proton at the High-Luminosity LHC [47 pages, on CDS]:
  - detailed ATLAS simulations:
    - WW (fully leptonic) + EFT study, WW (semi-leptonic), ZZ,
    - various $\xi$ ranges; ToF of 10 and 20 ps,
  - based on ongoing Run 2 analyses: ALP searches ($0.035 < \xi < 0.08$; single-tag),
  - phenomenological studies:
    - semi-exclusive $t\bar{t}$: $0.015 < \xi < 0.15$, 10ps,
    - DM searches: $0.015 < \xi < 0.15$, 10ps,
    - exclusive Higgs in SM and BSM: $0.002 < \xi < 0.20$ (420 station considered), 10ps,
    - exclusive dijets: $0.02 < \xi < 0.12$, 10 ps.
- AFP is an asset to the ATLAS physics programme by providing additional handles for kinematic reconstruction and background rejection.
- From detailed simulations for single-tag AFP + ITk + HGTD configurations:
  - comparable significances observed to those based on central detector only,
  - higher S/B $\rightarrow$ may indicate lower background modelling uncertainties.
- RP1 + RP3 is optimum if only eight stations can be installed.

An *Initial Design Report for ATLAS Forward Proton Detectors at the High-Luminosity LHC* was sent to a Review Panel called by the ATLAS Upgrade Coordinator on 22 Sep 2022:

- The main review meeting took place on 26/27 September.
- The Review Panel report with recommendations was issued on 10 October: **the main recommendation to ATLAS is not to approve the development of an AFP upgrade program for HL-LHC for Run 4, but to reserve the space for possible Run 5 or beyond projects if this is possible for the machine w/o constraints or additional cost**.
- The USC endorsed the Review Panel report and its recommendations at its meeting on 13 October 2022.
- The Executive Board approved the Review Panel report and its recommendations at its meeting on 17 October 2022.
- The result has been reported to and accepted by the HL-LHC Coordination Group (HLCG) on 18 October 2022.

# Summary

- AFP was upgraded during LS2:
  - production of new tracking modules,
  - new design of detector flange: Out-of-Vacuum solution for ToF detectors,
  - new photo-multipliers: address inefficiency issues from Run2 data-taking,
- High and low-$\mu$ datasets collected in 2016 (one arm), 2017 and 2022:
  - performance studies close to be finalized,
  - analyses ongoing.
- No Roman Pots in ATLAS during Run 4.