Status of the AFP Project in ATLAS

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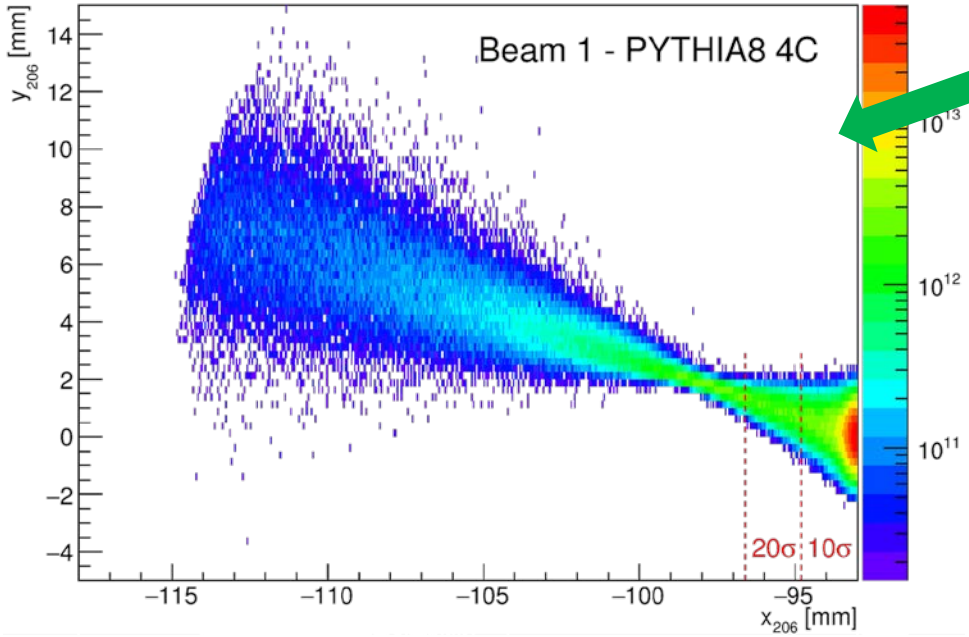
On behalf of the ATLAS AFP collaboration

Diffraction 2016, Acireale-Sicily, Italy - Sept 3-7 2016

1) Concept
2) Status
3) First data
4) Plans

Concept of AFP = ATLAS Forward Proton

Proton leaves the interaction intact, travels through LHC optics and is detected at ~210 m



(x,y)-distribution of protons at ~210 m from IP1 using all processes in Pythia 8
[upward deflection due to vertical crossing angle in IP1]

Diffractive protons deflect horizontally (given by LHC beam optics)

Only horizontal pots needed

Good acceptance for diffractive protons is close to the beam

Put detectors in Roman Pots and insert in LHC aperture (ample experience in Totem and ALFA)

Detector acceptance covers ξ of 0.02-0.15, where ξ=proton fractional energy loss

What is AFP?

1) **Array of radiation-hard near-beam** Silicon detectors **with resolution ~10 μm, 1μrad**

2) Timing detectors **with up to ~10 ps resolution for overlap background rejection (SD+JJ+SD)**

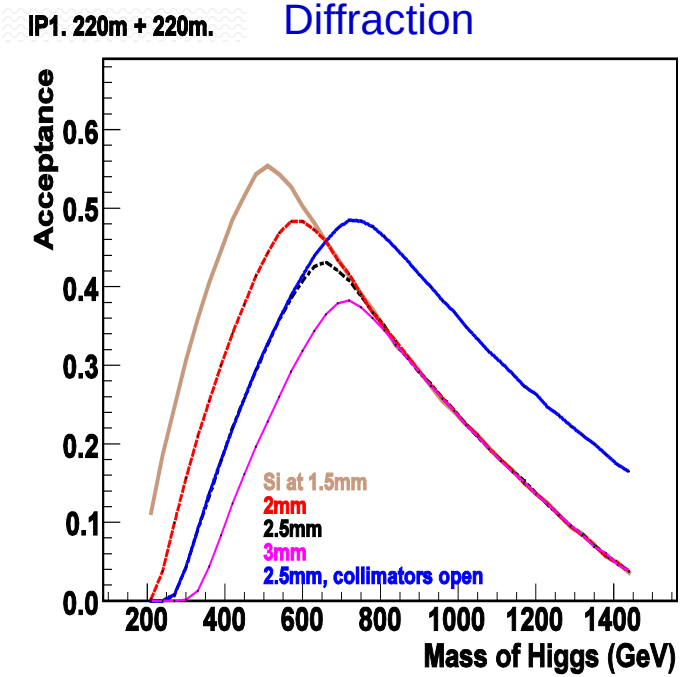
3) Roman Pots

Currently AFP approved with 2 arms for low pile-up
Ultimate goal for AFP: 2 stations on each side of IP1 with tracking detectors at 205 and 217m and timing (ToF detectors at 217m – to run continuously at nominal lumi

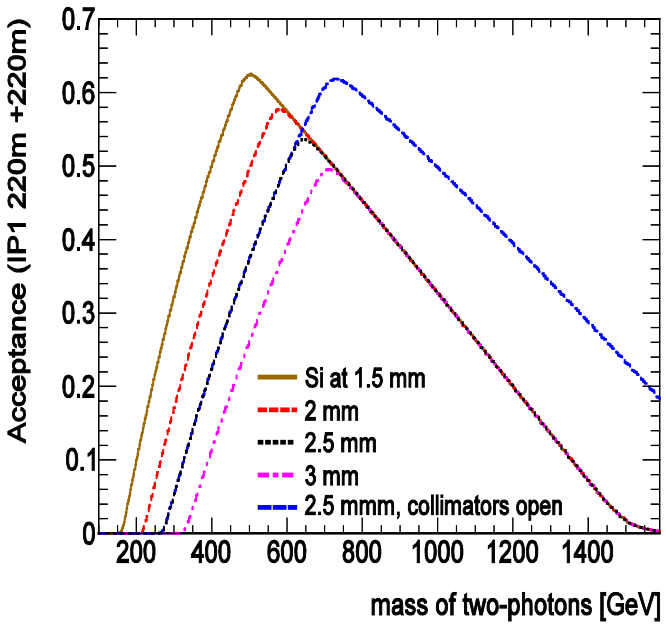
What does AFP Provide?

210+210 at IP 1

Diffraction



Two-photon



Acceptance >40% for wide range of produced mass

- Mass and rapidity of centrally produced system

$$M = \sqrt{\xi_1 \xi_2} * \sqrt{s}$$

$$y = \frac{1}{2}\ln(\xi_1 / \xi_2)$$

where $\xi_{1,2}$ are the fractional momentum loss of the protons

- Mass resolution of 5-10 GeV *per event*

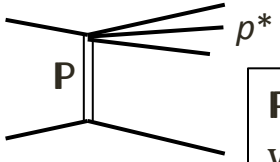
Allows ATLAS to use LHC as a tunable √s Pomeron-Pomeron or γγ collider while simultaneously pursuing standard physics program

Primary goals of AFP (low & medium μ)

In a fraction of Forward Physics: one or both protons stay intact: measure them with AFP and provide ξ & t *(these make up around 20% of total pp x-section)*

Single-tag: Single Diffraction

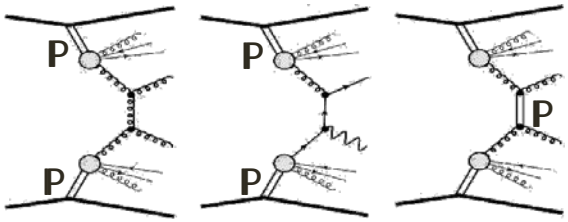
- Jets, W, Z: Soft survival prob. S^2
- Particle spectra, Gap spectra: SD vs. DD



P:= 'Pomeron', a **color-less** object with *quantum* numbers of the vacuum

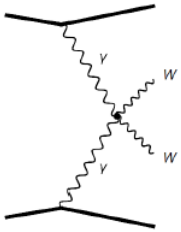
Double-tag: Double-Pomeron Exchange

- Dijet: constrain gluon content of Pomeron
- γ+Jet: constrain quark content of Pomeron
- Jet-gap-jet: test BFKL IP



Double-Photon Exchange

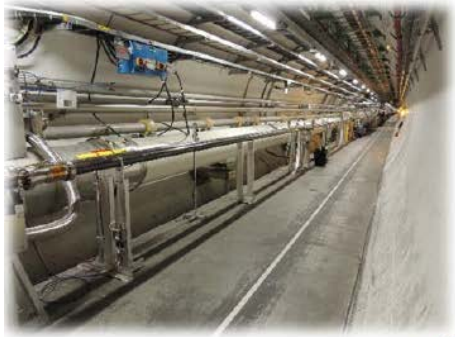
- $\gamma\gamma \rightarrow$ **WW/ZZ/γγ**: Anomalous quartic couplings → sens. 30-100x better than only central det.
- $\gamma\gamma \rightarrow$ **μμ**: calibration/alignment of AFP

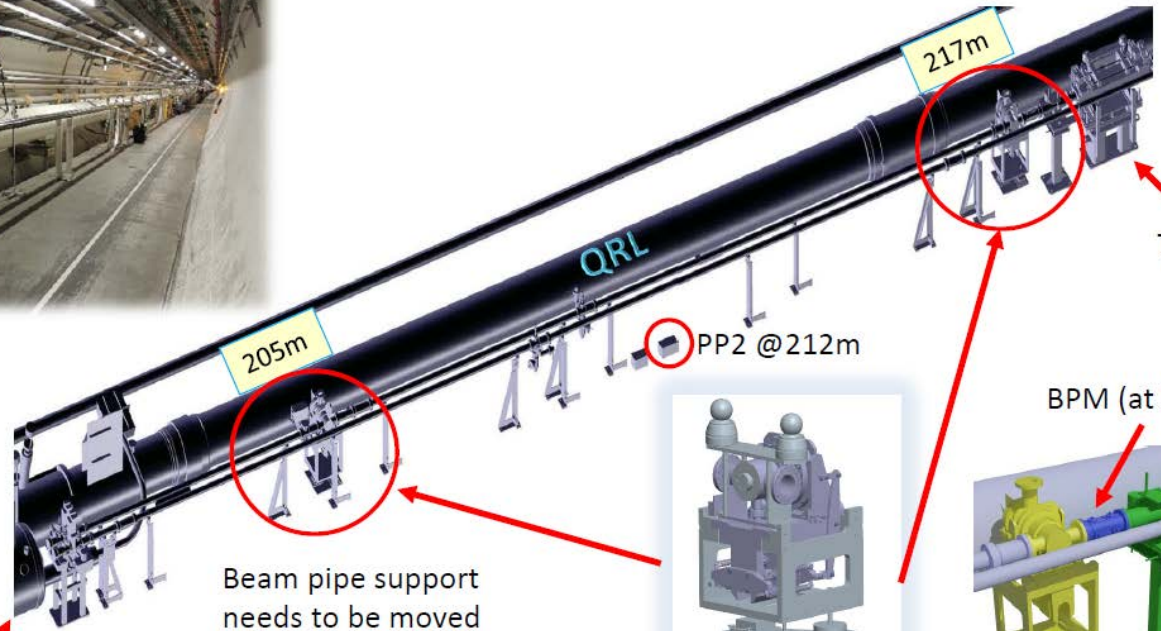


Central Exclusive Production

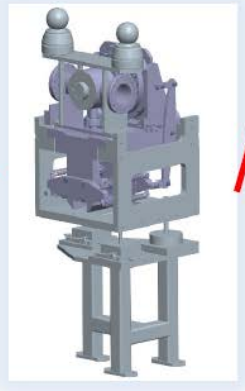
- Dijets, Trijets: constrain predictions to CEP of Higgs (S^2, Sudakov suppr., unintegr. f_g)

January-March 2016: AFP2+0 INSTALLED !!!

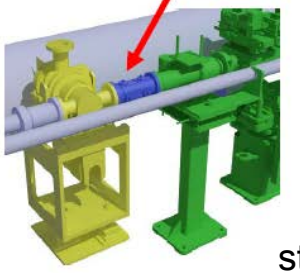


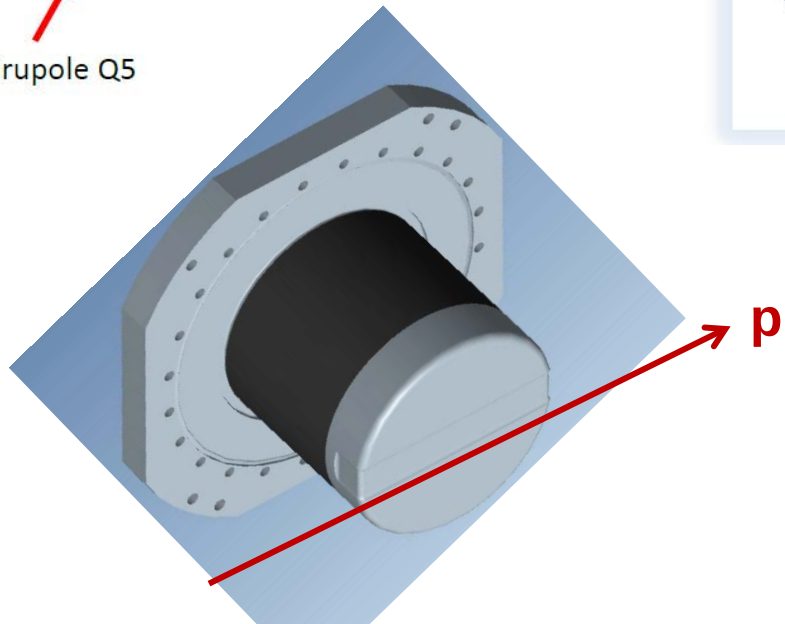


The C-side (6R1) fully installed and operational

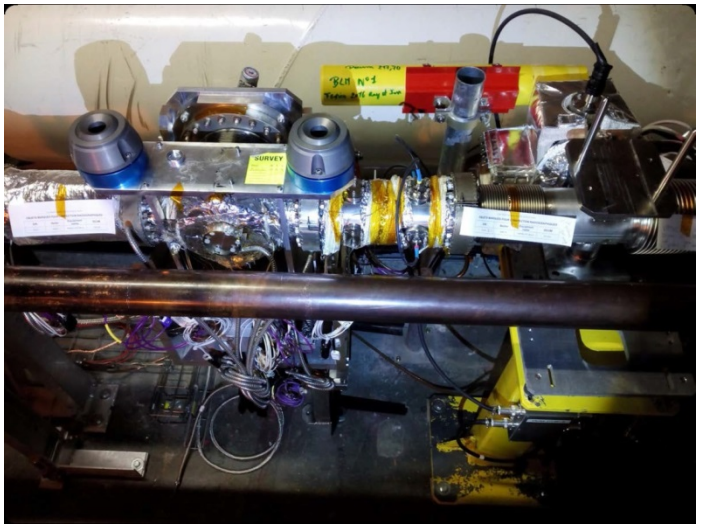


BPM (at 217m)





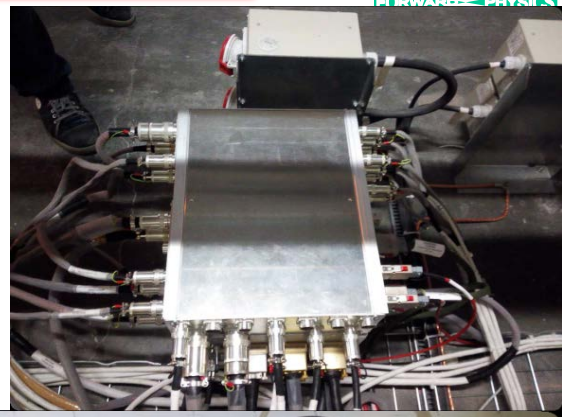
station at 217 m, BPM, BLM, TCL6



Roman Pot Installation

- Two stations validated and installed on ATLAS C-side
- **Cabling:**
  - Fast Cabling finished for both arms
  - Control cables finished for both arms
  - All C-side cables connectorized and tested
- **Services:**
  - Compressed air for Cooling (CZ)
  - Secondary Vacuum (EP-DT)
  - BPM, BLMs connected
- Installation done, connected to Beam Pipe, pump-down and bake-out done …
- Pot Motion calibrated in tunnel:
  - Survey of slide vs motor position, vs switches and LVDT 20 Feb'16

Patch Panels & LV Regulators (Milano) at 211 m



station at 217 m, BPM, BLM, TCL6

Tracking Detectors

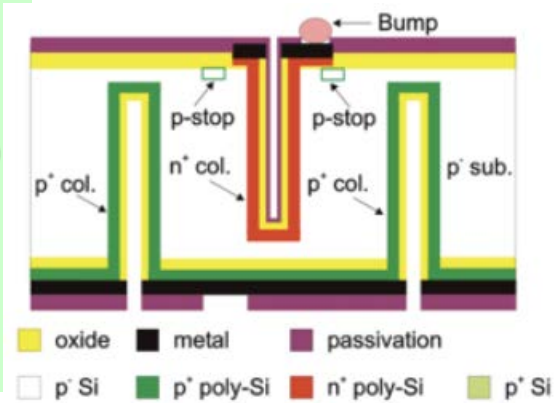
Tracker requirements:

- Close to the beam → detectors with slim edges
  dead area < 150 μm already reached
- High lumi operation → non-uniform radiation hard
  From $5x10^{12}$ up to $3x10^{15}$ neq for 10 fb^{-1} in beam position
- Resolution
  2-3% in M → ~ 10μm in X, ~10% in pT → ~ 30μm in Y
- Suppress pile-up → add ToF detector
  10 ps gives a suppression ~ 19/18/16/15 at lumi of 1/2/5/10 x 10^{33} $cm^{-2}s^{-1}$

Silicon detectors

AFP 3D Si detectors:

- Column-like electrodes: inter-electrode distance 67μm, detector thickness 230μm
  Lower voltage (~10V) for full depletion (before irradiation) At 1V & 14° tilt: >99% efficient
  Shorter drift distance -> lower trapping prob. -> radiation hard
- FE-I4 readout chip
  Tunable down to 1.5 ke threshold, 4-bit charge measrmnt (Time-over-threshold, TOT)
  HitOR (at least one hit per plane) signal used for L1 trigger
- Sensors
  (x,y)=(40μm,250μm) pixels, 336x80 pixels
- Validated in IBL to be hard to uniform irradiation of 10^{15} neq/cm²



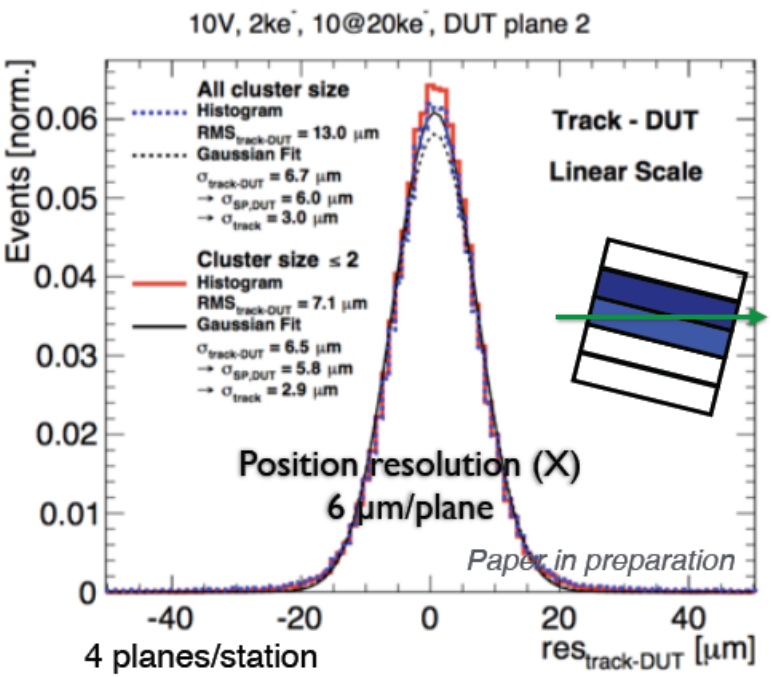
3D Si detectors successfully used in IBL (and AFP)

Tracker resolutions and installation

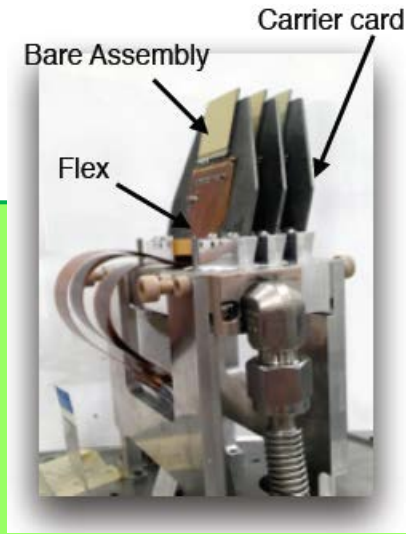
Resolution in X:
- Digital resolution ~ 14 μm (50μm/√12)
- But: FE-I4 has a 4-bit TOT measurement (Q collected)
- Maximize statistics of 2-hit events by tilting detectors by 14° along z-axis

Resolution in Y:
- Digital resolution ~ 72 μm (250μm/√12)
- Staggering necessary: resolution 19-72 μm (depending on the staggering achieved)

Results from TB 2016



4 planes/station
-> Tracker resolution (X) of ~3 μm/station



Installation:

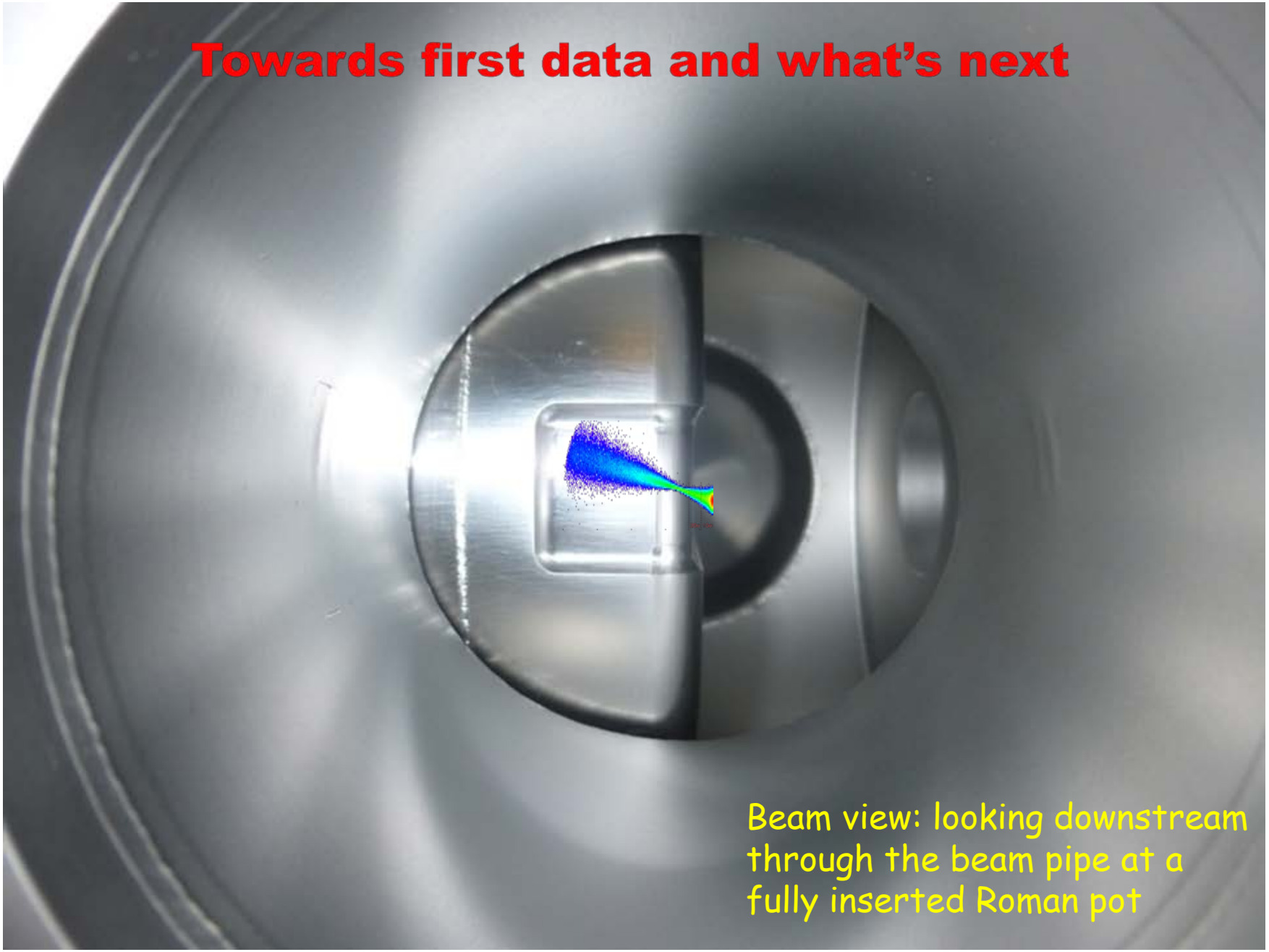
- NEAR station: 3 planes
- FAR station: 4 planes (one module short in HV line, cannot be biased but still usable at 0V – still 95% eff.)

- Trigger (each station): 2-out-of-3 layers with HitOR ON
- Local Trigger Board (HitBUS chip) ➔ Air-core Cables ➔ CTP
- AFP is within the (last BX of the) ATLAS latency !

- Readout:
- Tunnel (FE-I4➔HitBUS chip➔Optoboard) ➔ USA15 (HSIO2/RCE system) ➔ ROS

A new batch of 3D Si sensors with better characteristics is being produced and will replace the existing ones during EYETS2016

Towards first data and what's next



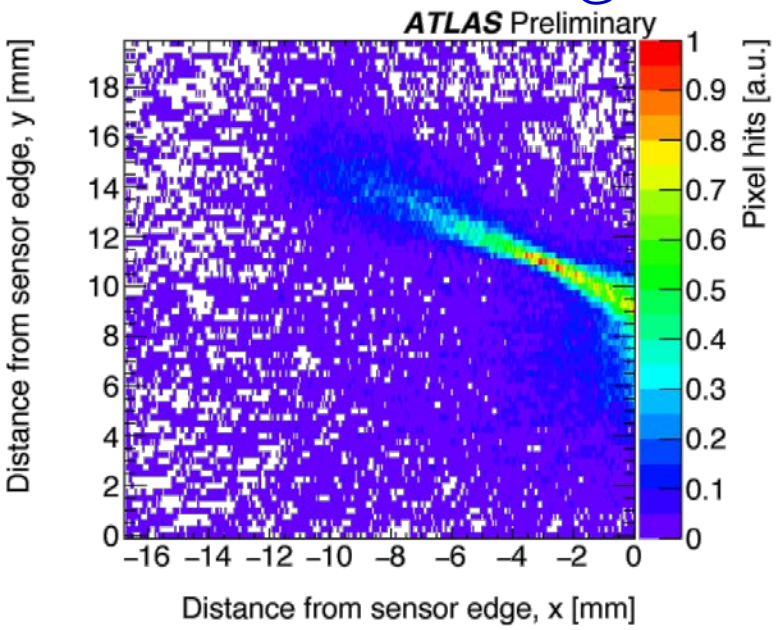
Beam view: looking downstream through the beam pipe at a fully inserted Roman pot

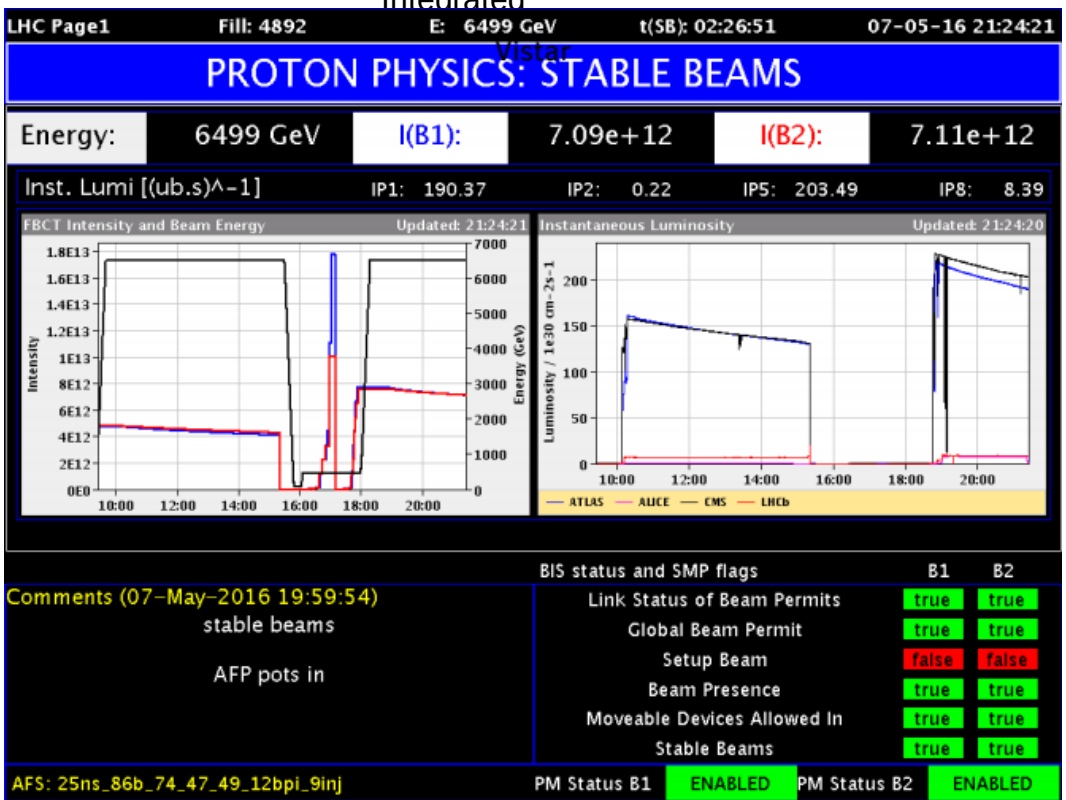
AFP Insertions

Date	Fills	TDAQ Mode
19-22 April	**B**eam-**B**ased **A**lignment and Loss Maps (6 & 3 hrs)	Stand-alone
23 April	3b: 2nd fill (no 3rd fill)	Stand-alone
24-25 April	12b: 2nd + 3rd fill	Stand-alone
29 April – 5 May	Weasel break ➔ TDAQ integration	
7 May	49/86b: 2nd + 3rd fill; 8.1pb^{-1}	Integrated
9 May	300b: 4th fill (2nd+3rd ended before AFP in); 7.9pb^{-1}	Integrated
13 May	600b: 2nd fill (1:14h); 9.3pb^{-1}	Integrated
10 June	2b: Totem loss maps	Integrated
11 June	7b: collimator test	Integrated
01 August	3b (0.023 pb^{-1})	Integrated

- **Total (TCL6 and/or AFP in):**
  - 42 h, 34 pb^{-1}

BBA @5.5σ





Performance at 300 bunches and $\mu \leq 26$

- AFP inserted during several fills with different intensities up to 600 bunches (meanwhile working on AFP TDAQ integration)

Aim was to study:

- Detector performance and alignment
- Beam background and AFP triggers
- Time-in detector to read 1BC and send triggers within ATLAS latency

At the last step of intensity ramp-up (600 b),

➢ AFP TDAQ fully integrated.

However, only high-μ available (~26)

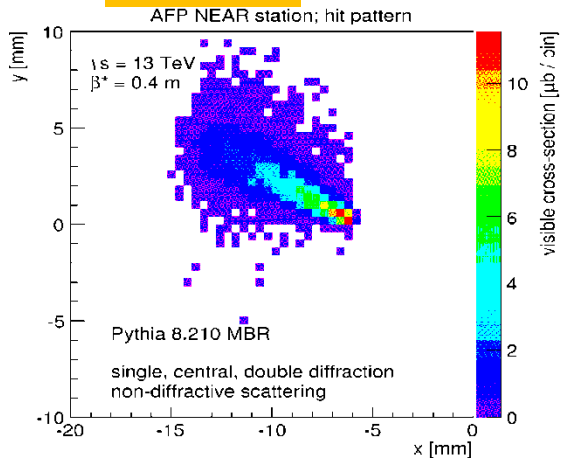
→ not useful for AFP2+0 physics (one arm, no ToF)

➢ DCS : full integration done during TS1

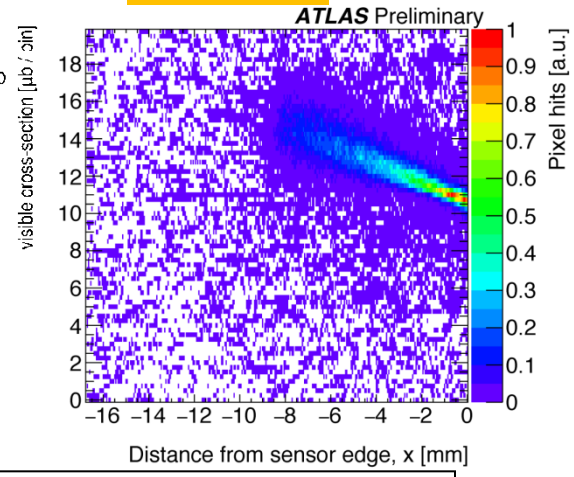
Fill 4906: 300 bunches, AFP read out but triggered by ATLAS, β*=0.4m, √s=13 TeV, L~9.3 pb^{-1}

Hit pattern, 1st plane at NEAR station

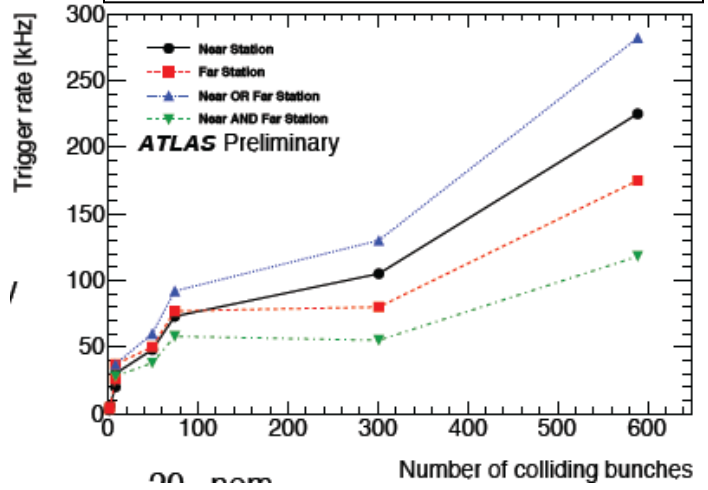
Expected



Observed

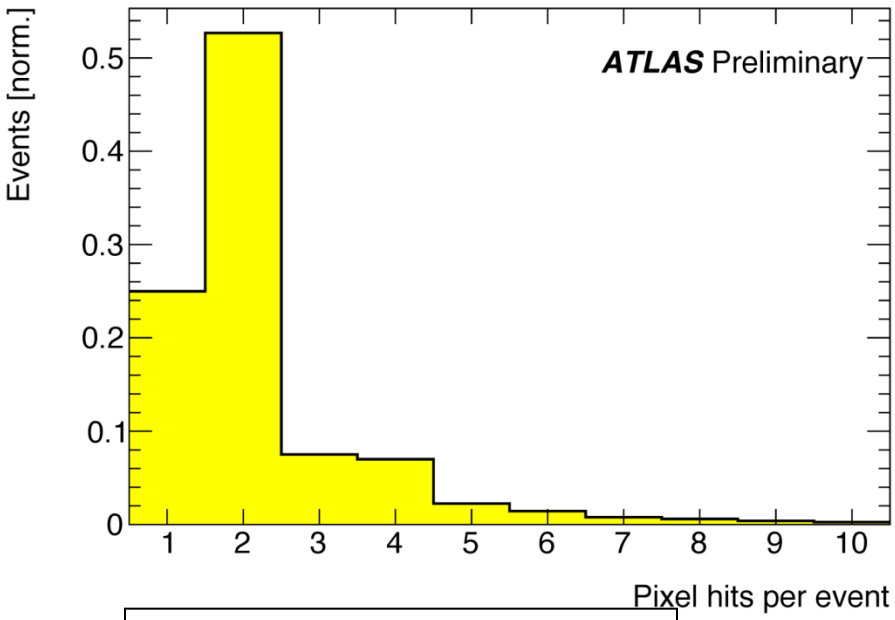


Measured AFP trigger rates

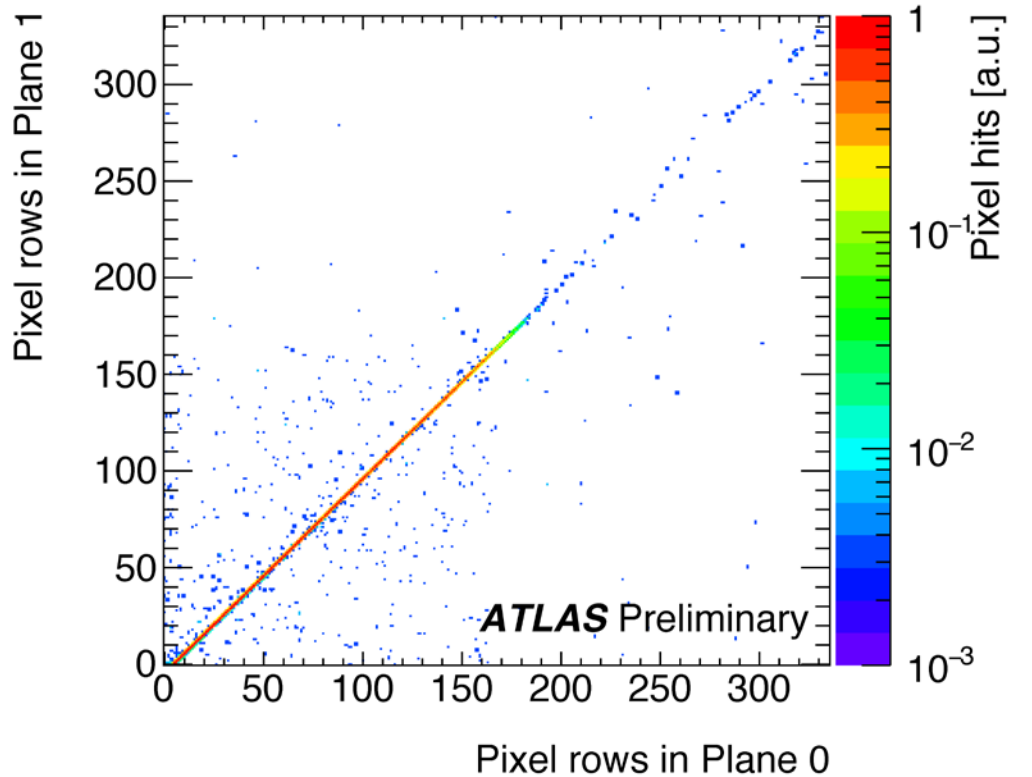


Performance at 300 bunches and $\mu \leq 26$

Fill 4906: 300 bunches, AFP read out but triggered by ATLAS, β^*=0.4m, $\sqrt{s}$=13 TeV, L~9.3 pb^{-1}



Nr. of pixel hits per event



Hit pixel row in Plane 0 vs. Hit pixel row in Plane 1

- 88% of events have no hits

hit = 2 pixels because of tilt 14° of 3D sensors

- most of events have just one track (i.e. proton)

- Good correlation means tracks parallel to z-axis and mostly single track events
- Non-correlation may mean additional tracks

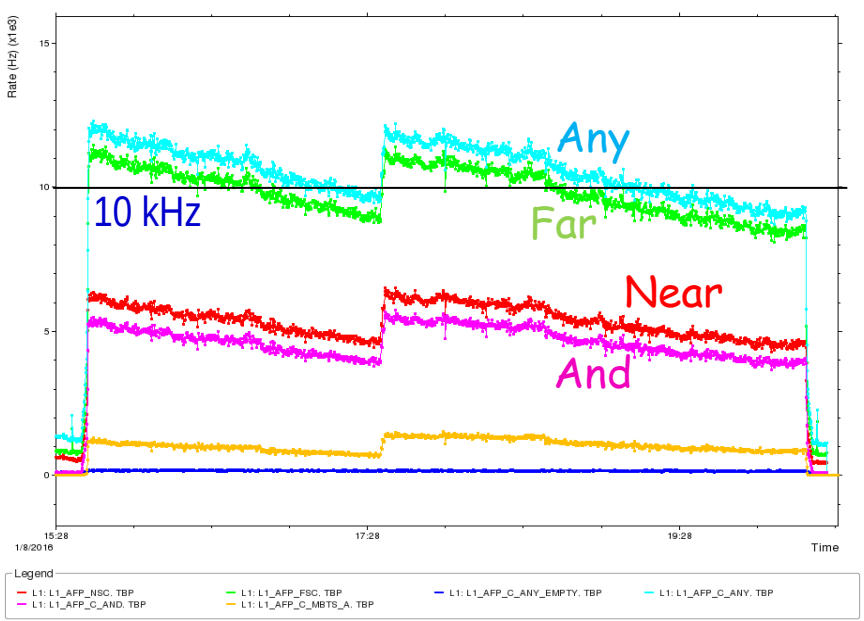
First physics AFP special run (low μ)

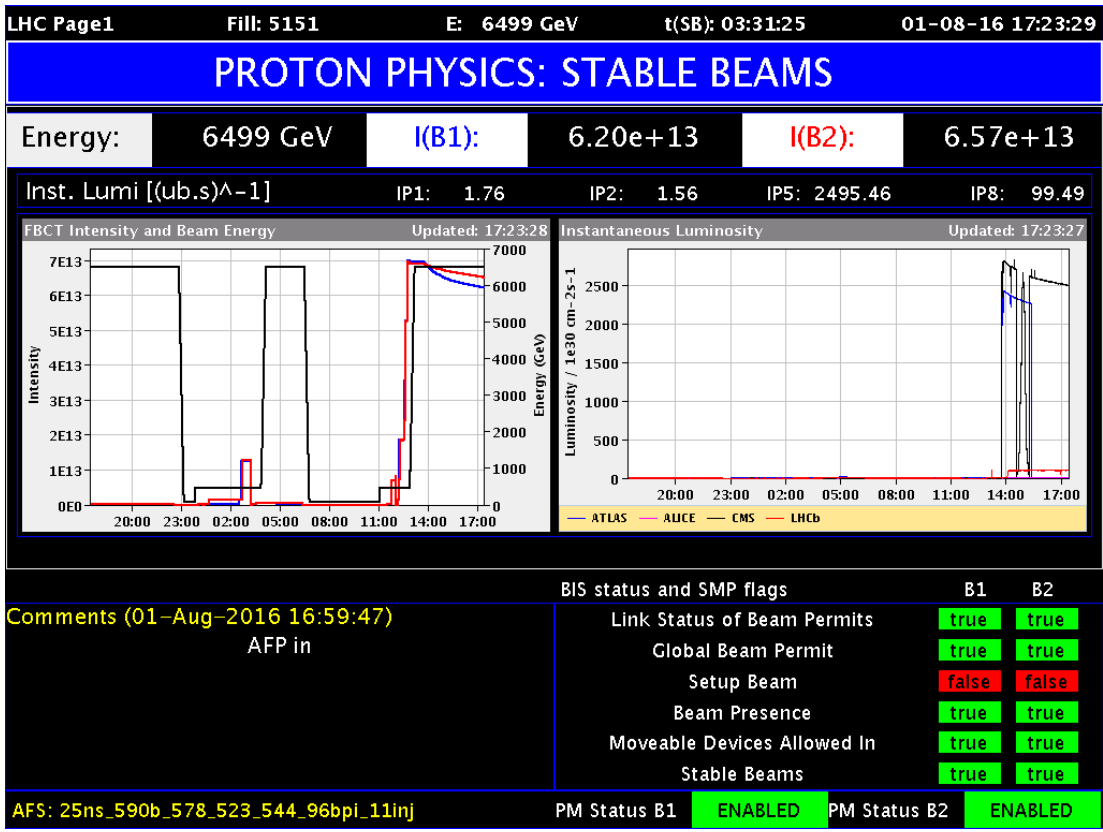
01.08.2016: Fill 5151 (run 305359): 600 bunches, AFP triggers at work, β*=0.4m, √s=13 TeV, L=0.033 pb^{-1}

- Filling scheme: 25ns_590b_578_523_544_96bpi_11inj
- 15:20: start to separate beams
- 15:24: beams at $5\sigma_H$ separation → μ_{peak} = 0.26
- 15:30: beams adjusted to $5\sigma_H$ and $2.5\sigma_V$ separation → μ_{peak} = 0.13, **<μ>=0.03**, L=2.7E30
- 15:35: start to insert AFP
- 15:42: AFP inserted!

- AFP at 20σ, TCL4/5/6 at 15/35/20 σ
- Total time in beam: 4h37m (3h58 –presc. corr)

- Next Low-μ run: after TS2 (Sept 23-24)





AFP irradiates ALFA

- **AFP aims to take data regularly in standard conditions (high μ).** High μ requires:
  - TCL4 & TCL5 must be opened to give large-ξ acceptance
  - TCL6 (behind AFP) must be closed to 20σ to protect Q6 and downstream
- This increases radiation levels to ALFA by a factor ~10
- ALFA does not have radiation hard electronics
- ALFA is still eager to take the β^*=2.5km data (Sept.2016) and possibly follow-up early 2017

- Agreement: AFP limits its insertions to 0.25 fb^{-1} in 2016
- Meanwhile: AFP+ALFA working together on a shielding to protect ALFA in 2017 and beyond
  - Studies by FLUKA team encouraging: already a factor of 3-4 reduction
  - Studies ongoing, proposal (+ECR) expected in Sept 2016

FILL 4919			BLMMI.07R1	BLMMI.07R1	BLMMI.07R1	BLMMI.07R1
start	end	type	ALF NEAR	ALF FAR	ALF NEAR2	ALF FAR2
5/12/16 20:30	5/12/16 20:40	Pedestal	2.13E-07	2.03E-07	1.90E-07	1.78E-07
	NDF= 11	rms	3.66E-09	2.02E-09	2.27E-09	1.69E-09
5/12/16 23:30	5/13/16 0:07	Stable Beam	4.94E-07	4.79E-07	2.82E-07	2.49E-07
	NDF= 38	rms	5.43E-09	6.90E-09	3.89E-09	3.59E-09
5/13/16 0:09	5/13/16 0:28	TCL6 in	1.19E-06	2.25E-06	5.59E-07	5.65E-07
	NDF= 20	rms	7.28E-09	7.28E-09	4.03E-09	4.89E-09
5/13/16 0:32	5/13/16 0:52	AFP in	1.56E-06	3.26E-06	6.36E-07	7.33E-07
	NDF= 21	rms	9.84E-09	2.13E-08	4.05E-09	5.38E-09
5/13/16 1:30	5/13/16 1:42	AFP in 2	1.51E-06	3.13E-06	6.17E-07	7.08E-07
	NDF= 13	rms	6.26E-09	1.87E-08	5.00E-09	3.50E-09
5/13/16 1:44	5/13/16 2:10	TCL6 in 2	1.12E-06	2.10E-06	5.30E-07	5.34E-07
	NDF= 27	rms	7.18E-09	1.23E-08	3.66E-09	5.75E-09
5/13/16 2:13	5/13/16 2:30	Stable Beam 2	3.67E-07	4.48E-07	2.41E-07	2.24E-07
	NDF= 18	rms	4.09E-09	8.17E-09	2.64E-09	2.36E-09
5/13/16 7:12	5/13/16 7:40	Pedestal 2	1.59E-07	1.64E-07	1.68E-07	1.46E-07
	NDF= 29	rms	2.00E-09	2.43E-09	2.23E-09	2.77E-09
Start Edge						
Standard dose with 600b		SB'=SB - Pedestal	2.81E-07	2.76E-07	9.15E-08	7.06E-08
Increase with TCL6		(TCL6-SB)/SB'	2.49E+00	6.40E+00	3.03E+00	4.48E+00
Increase with TCL6 & AFP		(TCL6&AFP-SB)/SB'	**3.82E+00**	**1.01E+01**	**3.87E+00**	**6.87E+00**
End Edge						
Standard dose with 600b		SB'=SB - Pedestal	2.08E-07	2.84E-07	7.24E-08	7.78E-08
Increase with TCL6		(TCL6-SB)/SB'	3.60E+00	5.82E+00	4.00E+00	3.99E+00
Increase with TCL6 & AFP		(TCL6&AFP-SB)/SB'	**5.48E+00**	**9.46E+00**	**5.20E+00**	**6.22E+00**

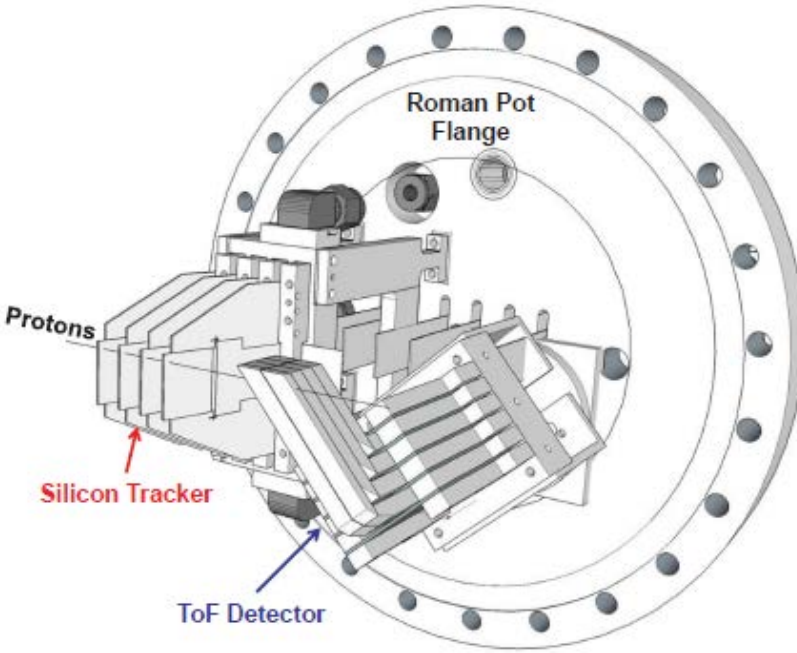
Expected 2016 LumInt	25	fb-1
Allowed ALFA dose increase	10.00%	
worst case AFP LumInt	0.26	fb-1
avg case AFP Lumint	0.39	fb-1

So far total (high-μ equivalent) lumi this year by AFP: 67 pb^{-1} << 250 pb^{-1}.
Still Run2 in Sept planned (~4h), then maybe insertions during Heavy Ion run.

Preparing for the 2nd arm

- **The ultimate goal of AFP is a two-arm system**

- **Installation of 2nd arm during EYETS**
(12 Dec 2016 – 30 Apr 2017 (BE-OP: 14 Apr 2017))



- Crucial component: ToF detectors in both arms
  - design of the prototype holder ready
  - beam tests in 2016 (June, Sept) important: R&D not finished yet
  - electronics is crucial: CFD, HPTDC, Trigger, Clock

- Status of preparation:

- ECR for 2nd arm in circulation:
  - TE-VSC-BVO started the production of the beam pipe elements
  - BPM ready, BLM group notified
- Cabling:
  - tunnel cabling is all done
  - still must complete cabling in USA15
- Cooling:
  - complete compressed air for cooling with regulators, pressure sensors
  - 2+1 more air coolers ordered
- Secondary vacuum:
  - pump system available – must be installed in RR13

Beam tests & ToF results

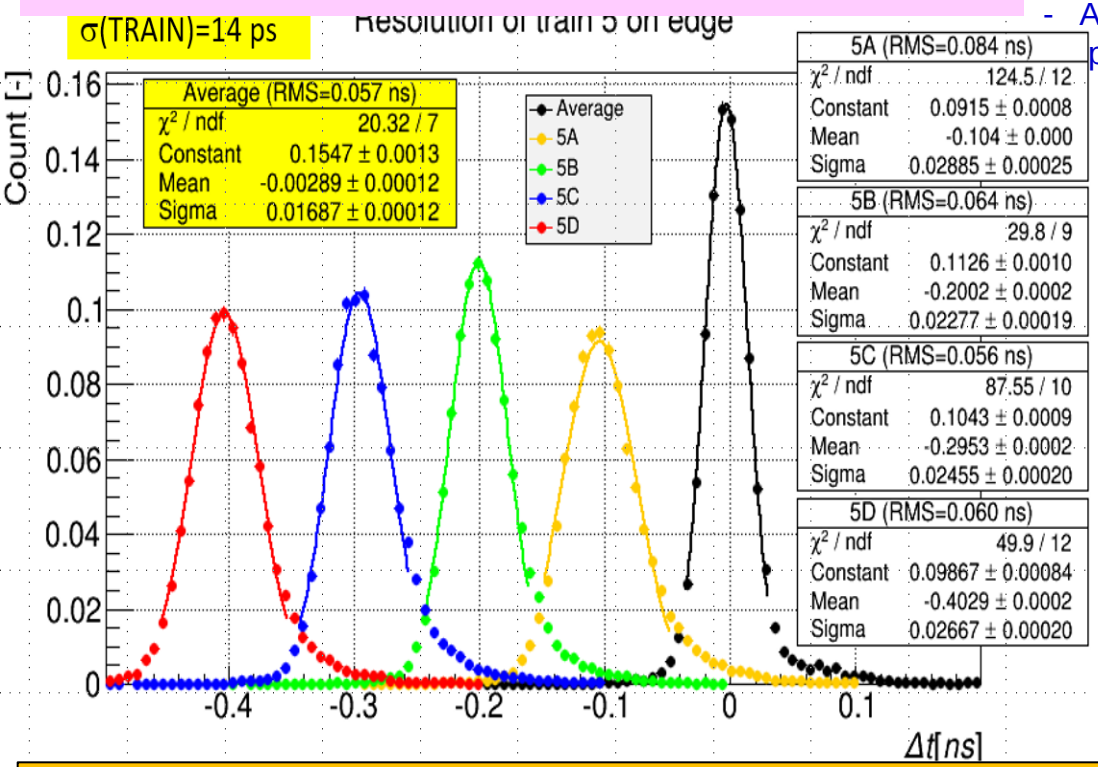
AFP is very active in TB campaigns: several in 2014-2015, and 3 in 2016!

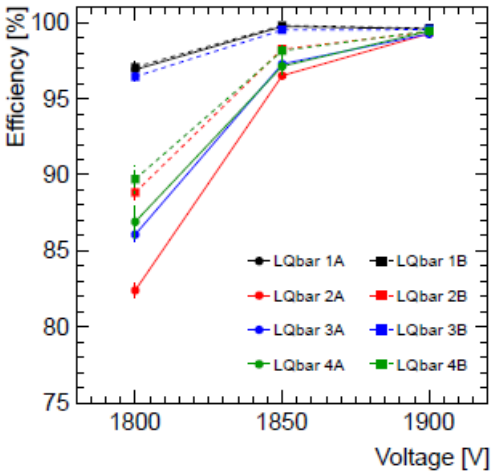
✓ TB 2014-2015: excellent spatial resolution: σ_X(track)~3μm

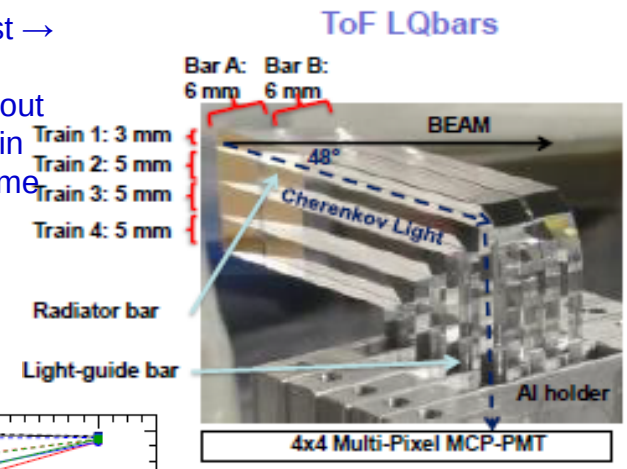
J. Lange et al., JINST10 (2015) C0303

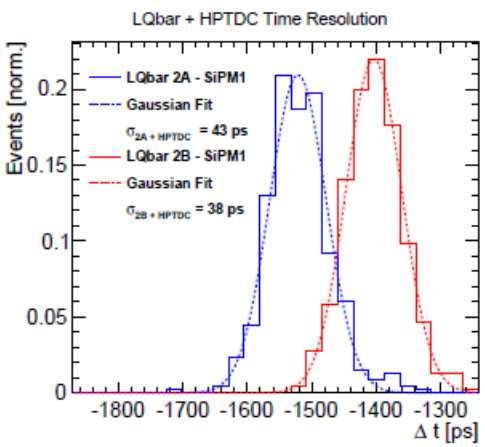
❑ TB 2016 June: ToF: full (4 bars) trains, characterization and optimization of ToF front-end: radiator bars, cross talk, MCP-PMT, CFD delay and threshold

Excellent performance of new 6 μm pore MCP-PMT (Photonis):
- Reduced MCP-Anode dist → improves cross-talk
- 6 μm pores -> faster read-out
- Atomic Layer Deposition in pores -> 10x longer lifetime









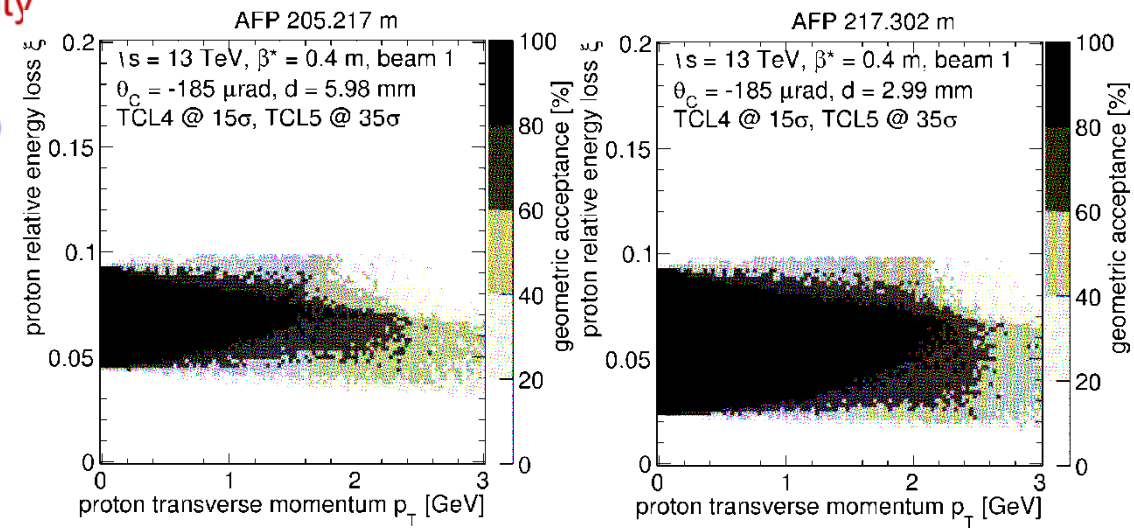
J. Lange et al., arXiv: 1608.01485 [physics-ins.det], subm. to JINST

❑ TB 2016 Sept: optimize ToF back-end electronics (HPTDC, Trigger), full integration on RP flange

Physics with low-μ and 2017 and beyond

- Pythia and AFP acceptance predict (per hour):
- β*=0.55m, μ=0.1, nb=300, stand. bunch density

Acceptance in ξ and p_T:



- 7M Soft SD events (proton rate in AFP 2 kHz)
- 15k SDjj evts with p_T>20 GeV
- 0.5k SDjj evts with p_T>50 GeV
- 3 SD+W evts

Running plans:

- Run 2 goal: 15pb^{-1} (4h @ 600b, μ~0.5-1 → ~1.3pb^{-1}), aim is 15σ approach
- Dec. 2016: HI run: ongoing discussions if AFP can be put in for Pb+p runs
- Ultimate goal of AFP: regular data taking with whatever β* and μ (concentrate on high-μ):
  - must work out the shielding to protect ALFA from irradiation
  - of course: must install the 2nd arm and ToF
  - aim is 15σ approach, AFP in ATLAS TDAQ permanently, probably L1 AFP+Calo/mu, AFP in HLT
- Special (low-μ ~ 1) runs: clean environment to study diffraction
- Plans to run after LS2:
- Currently under discussion in AFP
- Will depend on the outcome from runs before LS2
- Must be reviewed by ATLAS before going to TDR and LHCC (review planned for 2nd half of Oct 2016)

Summary

1) One arm of AFP (6R1) is installed and fully operational

2) AFP has taken data in fills with various intensity and high μ during which many checks were done (Detector performance and alignment, Beam background and AFP trigger rates, sending AFP triggers to ATLAS CTU) plus AFP TDAQ (DCS) integration into ATLAS TDAQ (DCS)

✓ Backgrounds seem to be under control

3) AFP has recently taken data with low μ (0.03). They look promising and analysis is ongoing (enough statistics for SD jets). Another low-μ run (0.5-1.0) expected in Sept 2016

4) ALFA and AFP teams work on the shielding to protect ALFA from irradiation caused by AFP

5) AFP is preparing for the 2nd arm (to be installed beg. 2017):

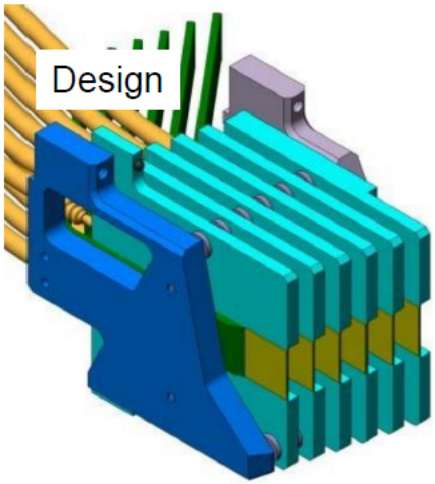
- ✓ ECR recently approved
- ✓ ToF detector most critical item (two Beam tests in 2016)
- ✓ Production of other critical items is well underway

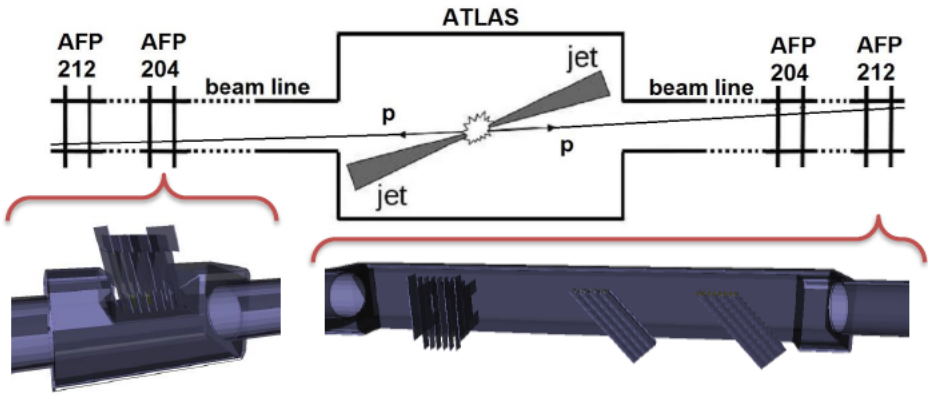
6) AFP is preparing for running after LS2:
- ultimate goal is to be in beams permanently
- this still has to be approved by ATLAS

B A C K U P S L I D E S

AFP in ATLAS simulation (1): SiD hits

- Actual SiD setup:
  - 2 AFP stations with Si detectors per ATLAS side (**SiD 0 - 1** <– **IP** –> **SiD 2 - 3**)
  - 6 Si layers/station separated by 10 mm (13 deg tilt in the x-z plane)
  - No staggering of the layers (yet)
  - 336 x 80 array of **50 x 250** μm^2 pixels per layer
  - **Kalman filter** is used for the tracking reconstruction

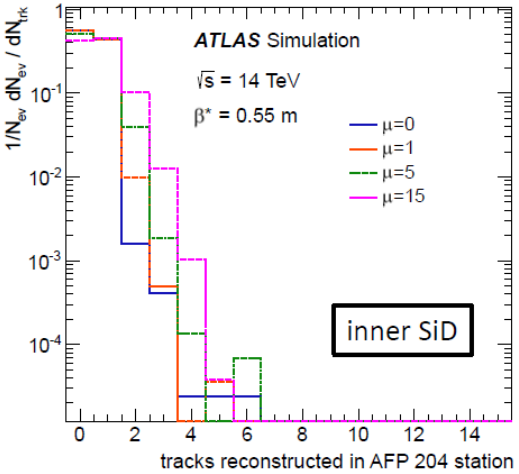


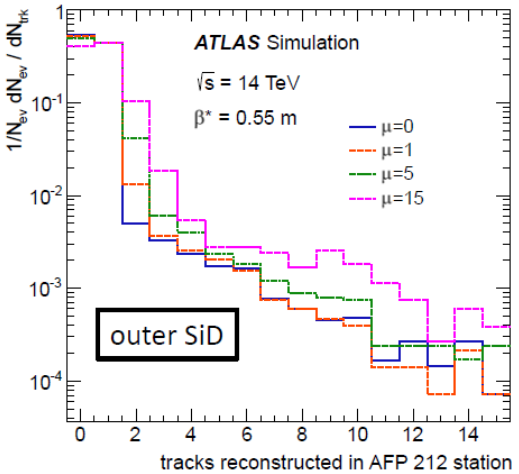


Geant4 AFP GeoModels

- **Reconstructed track multiplicity** with $|x_{slope}| < 0.003$ and $|y_{slope}| < 0.003$ cut (per station) to separate proton tracks from showers
- Events are generated without any cut on the proton kinematics (i.e. $\xi < 1$)
- Approximately **50%** of protons in the sample **do not enter** the AFP acceptance region (**$0.015 < \xi < 0.15$**) which results in no reconstructed tracks

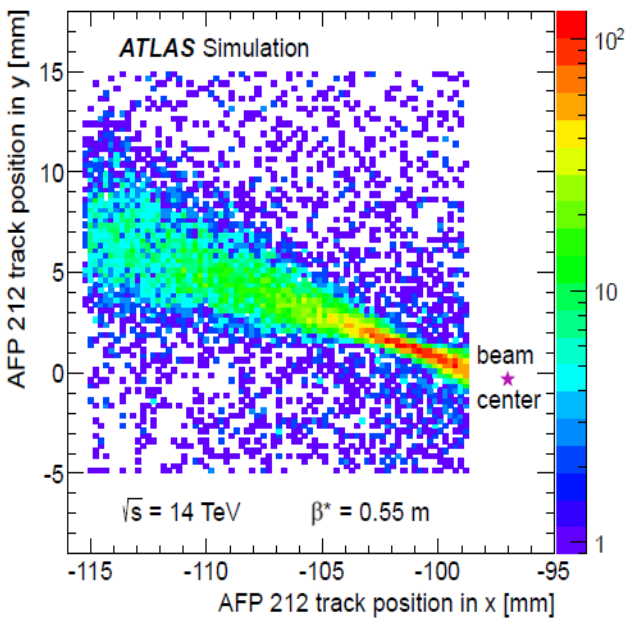
- Expected tracking resolution wrt 4 staggered layers: 8 µm in x, 20 µm in y

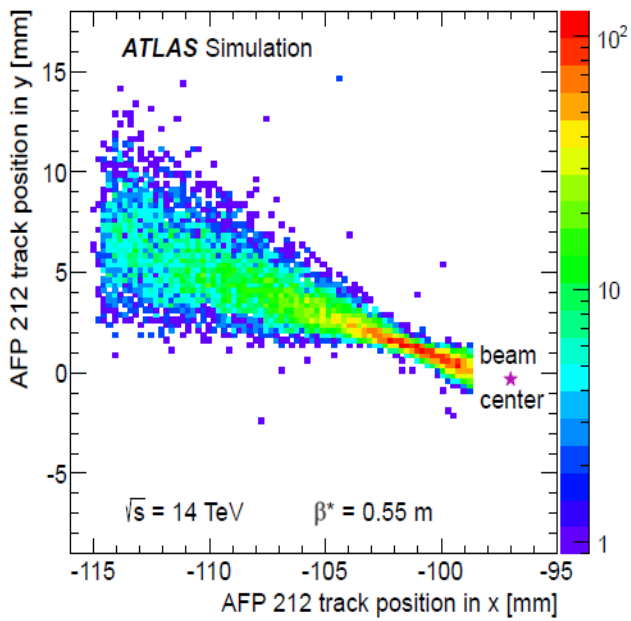


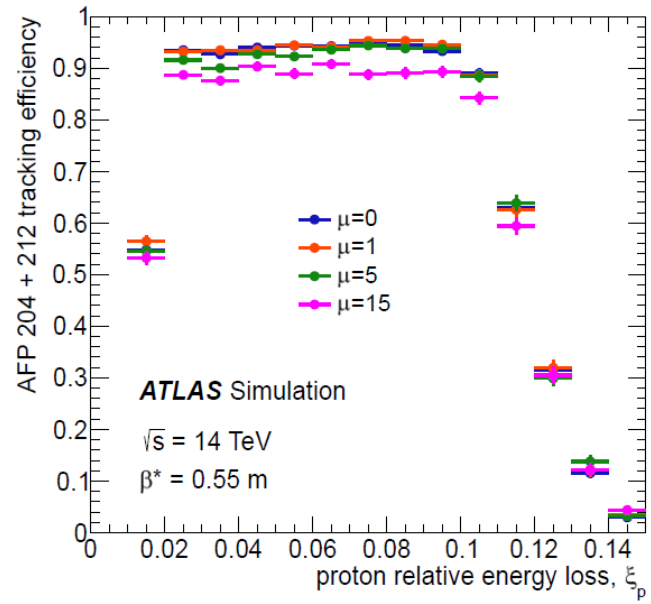


AFP in ATLAS simulation (2): SiD efficiency

- **x-y track positions hitmap** for outer SiD station before (left) and after (right) track matching included for outer (AFP 212) station
- Tracks matched between inner and outer SiD stations are considered
- Positions are calculated in the ATLAS Coordinate System – beam center at x = -97mm







AFP proton track reconstruction efficiency for different pile-up conditions:

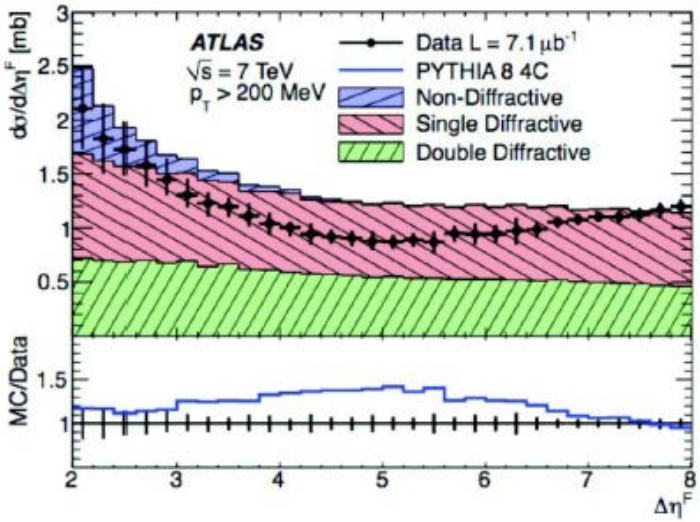
≈ 95% in **0.02 < ξ < 0.11** and **μ = 0/1**

- matching between tracks in inner and outer stations included
- cuts suppressing showers applied (ntr_inner <=2, ntr_outer <=5)
- improvement expected, subject of further cut optimization

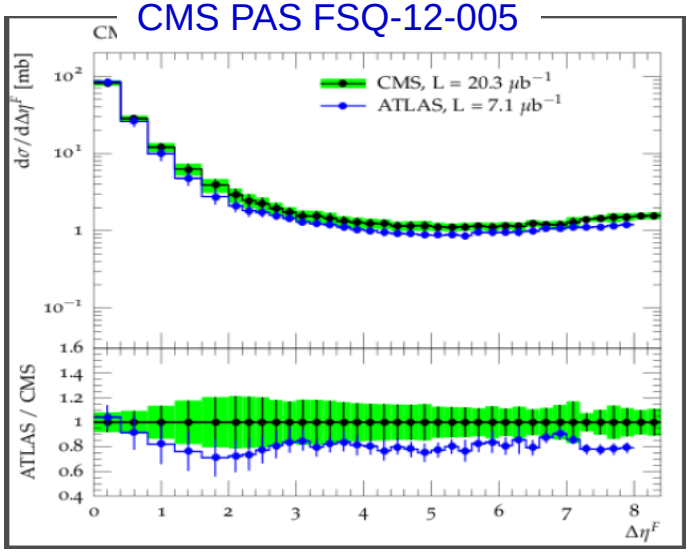
Example for low luminosity: Gap spectra

ATLAS and CMS measurements without proton tags:

ATLAS EPJ C72 (2012) 1926



CMS PAS FSQ-12-005



ATLAS and CMS agree within systematic uncertainties (hadron |eta|<4.7 vs. |eta|<4.9: 5% diff. model for unfolding: 10%)

1) CMS systematically above ATLAS !
2) Pythia8 predicts SD~DD !

Could proton-tagging shed light on 1) and 2) ?

- AFP: wide t-range, ξ-acceptance depends on beam optics
- ALFA: whole ξ-range, limited t-acceptance Suitable for high- β* optics
- AFP & ALFA complement each other

β*=0.55m, √s = 14TeV, d=3mm

- AFP210 provides limited range of gaps: $0 < \Delta\eta \sim -\ln\xi < 2.5$
- Gap on the side of the detected proton in AFP
- DD shows very different gap spectrum

Running scenarios:
- Statistics not a problem
- Very low μ necessary
- β *=90m: ALFA + AFP common run
- β *=0.55m: larger (xi,t)-acceptance with AFP
- Single-tag or Double-tag AFP Trigger

Example for medium luminosity: Pomeron structure

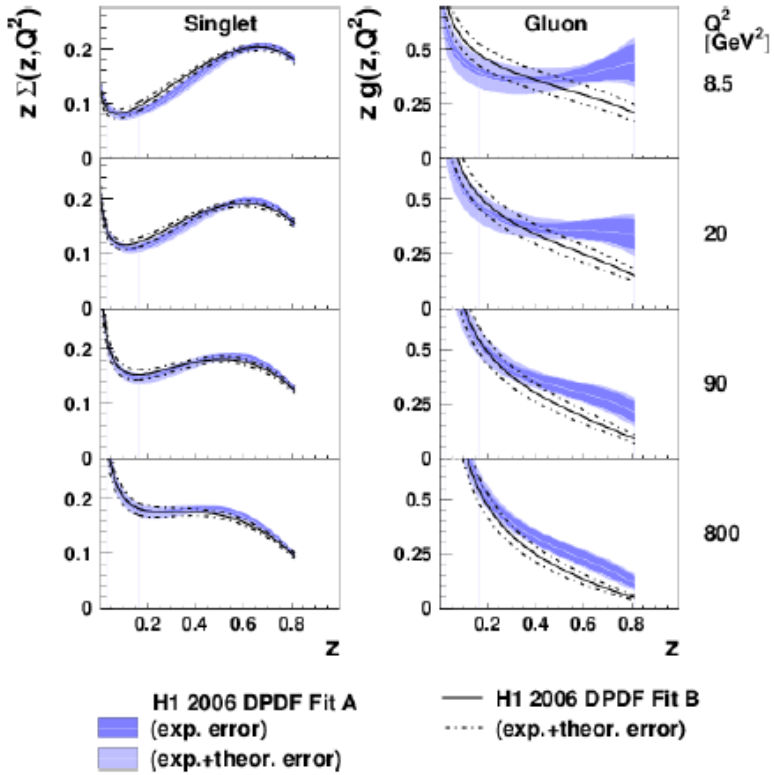
Pomeron structure (dPDFs) measured at HERA

1) Not well constrained at high β (= z = x_{Bj}/ξ)

2) Assumptions in H1Fit of dPDFs measured at HERA:

u=d=s=ubar=dbar=sbar -> F2D ~ 4/9u + 1/9d + 1/9s

- Two degrees of freedom: R_{ud} = u/d, R_{sd} = s/d
  - $u = q^* 6 * R_{ud}/(1+R_{sd} + 4R_{ud})$
  - $s = q^* 6 * R_{sd}/(1+R_{sd} + 4R_{ud})$
  - $d = q^* 6 / (1+R_{sd} + 4R_{ud})$
- Result: different Pomeron flavour structures consistent with HERA



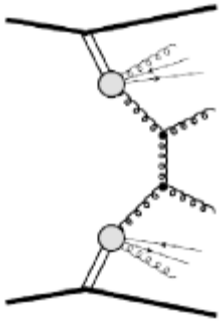
AFP has potential to complement the HERA measurements

SD W production
- Sensitive to quark content of dPDFs
- Measure charge asymmetry

DPE gamma+jet
- Sensitive to quark content of dPDFs and to Soft Color Interaction model

DPE dijet
- Sensitive to gluon content of dPDFs and to Soft Color Interaction model

Pomeron structure: DPE dijet



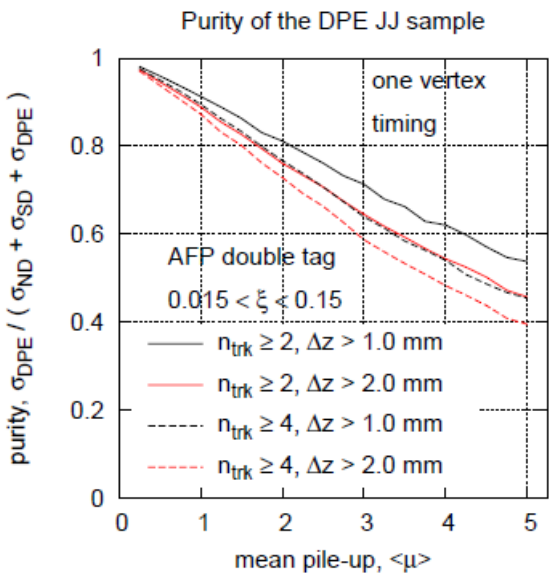
Cross-section after cuts ~ 10nb
- Dominantly g+g

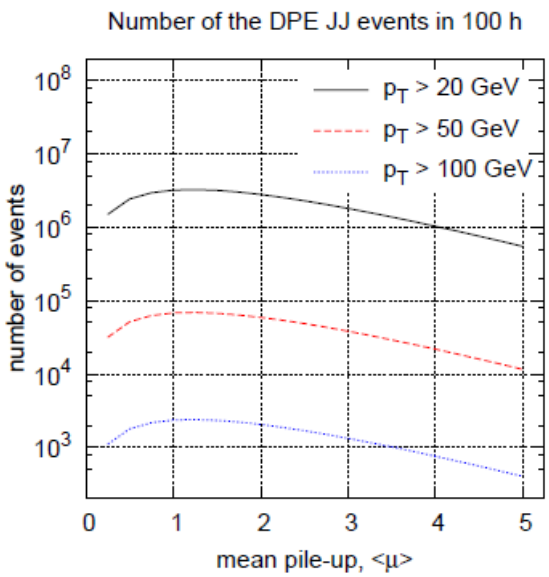
MAD-X + MC generator-level:
- 2 jets Et>20 GeV + AFP acceptance

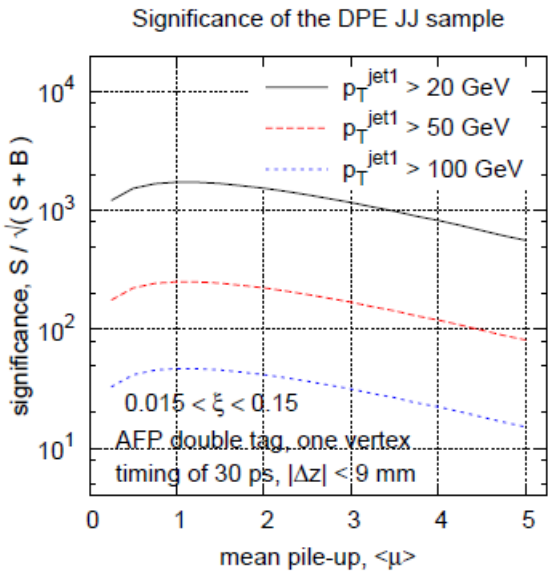
Effect of PU studied:
- Single-tag as well as double-tag
- Two models (Py8 default, Py8 MBR)
- Fast timing det. necessary

β^*=0.55m, $\sqrt{s}$ = 14TeV, d=3mm

Assuming conservatively resolution of only 30ps for Run II







With moderate timing resolution 30ps and one-vertex requirement:
1) Excellent purity up to μ~3
2) Event yield and significance optimal at μ~1 but still manageable up to μ~5

Running scenarios:
- Effective x-section ~ 10 nb -> medium lumi needed
- μ~1 optimal but μ up to 5 && Etjet up to 100 GeV manageable
- Run of 100h with μ<5
- May be measured with both β^*=0.55m and 90m (0.55m preferred due to larger statistics and larger AFP acceptance)
- Double-tag AFP210 + Jet trigger gives sufficiently low rate

Physics program for Run II

Analysis	Lumi req. $[pb^{-1}]$	Optimal μ range	β* scenario	L1 trigger
Particle spectra	1	< 0.05	90m(ALFA+AFP) 0.55m	AFP-ST AFP-DT
Gap spectra	1	< 0.05	90m(ALFA+AFP) 0.55m	AFP-ST AFP-DT
SD jj	10-100	0.01-1.0	90m **0.55m**	AFP-ST && Jet
DPE jj	10-100	0.5-5.0	90m **0.55m**	AFP-DT && Jet
SD W	10-100	0.1-1.0	90m **0.55m**	AFP-ST && Lepton (&& MET)
DPE γ+j/jj	> 200	1.0-2.0	0.55m	AFP-DT && Jet/Photon
DPE j-g-j	> 100	0.1-2.0	0.55m	AFP-DT && Jet

1 week of 100h:
μ = 0.1: ~10 pb^{-1}
μ = 1 : ~100 pb^{-1}

Alignment

Hardware:

- **BPM (Beam Position Monitor):** measures the AFP position w.r.t. the actual beam
  - Sub-um precision expected with dedicated electronics
  - BPM→RP→detector calibration less accurate (100µm?) – possible improvement with a quartic window
- **LVDT (Linear Variable Differential Transformer):**
  - Fixed reference frame
  - ALFA experience: 35 µm precision, 250 µm for calibration

Software (Methods):

1) **Kinematic peak**: **measure the t-distr. and compare with MC for several detector positions**
   - used in CDF experiment
   - at LHC sensitive to the relative alignment (between stations)
   - 100k SD events: 30µm precision in x (preliminary), worse in y (due to worse resolution in y)

2) **Hot spot**: **make use of the characteristic dense area (hot spot) in the (x,y)-distribution of AFP hits**
   - hot spot is found as a minimum in the distr. of rms of y-position in bins of x-position
   - 100k events: 8µm precision (preliminary)
   - small sensitivity to physics models and optics changes

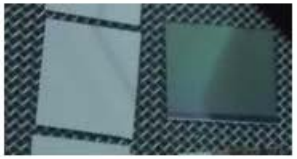
3) **Distribution shift**: **comparing distributions of the x-position of protons from two runs (time periods) using the Wilcoxon-Mann-Whitney statistical test**
   - search for translation that equalizes distributions shapes. Precision: 13/25/100 µm for 1M/100k/10k evts

4) **Exclusive γγ→µµ**: **compare ξ-distributions measured by AFP and by muon pair in central detector**
   - Cross section small (40 fb) but precision 10 µm with 100 events only.

AFP tracker module production: Overview

Chip

Sensor



Carrier card

Flex

Flip-Chip