ATLAS EXPERIMENT

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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ATLAS Forward Proton: Measurements and Prospects for Exclusive Diffraction, BSM Physics and Pomeron Structure

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On behalf of the ATLAS Collaboration

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Outline

- Diffraction in pp collisions at LHC
- LHC Running Parameters and Strategies
- ATLAS up to 2015: σ_{EL} & σ_{TOT}, Diffraction Studies with Rapidity Gaps in Central Detector
- Increasing ATLAS Physics Reach: the AFP Project
  - 2016: AFP Single Arm Configuration
    - proton tag validation
  - 2017: AFP Double Arm Configuration
    - Current Status
  - Expected Physics Reach
- The (foreseeable) Future

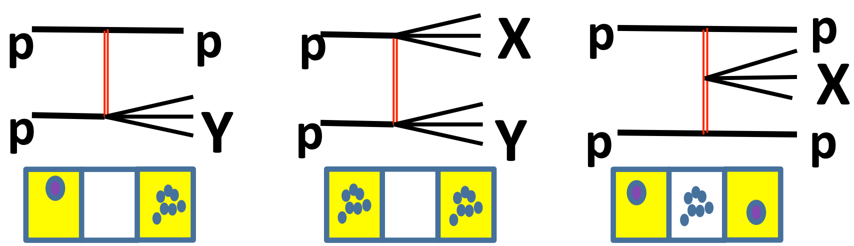
Diffraction in pp collisions at LHC

$\sigma_{tot} = \sigma_{inel}$ (≈ 75%) + σ_{EL} (≈ 25%)   Total Cross Section ≈ 100 mb …

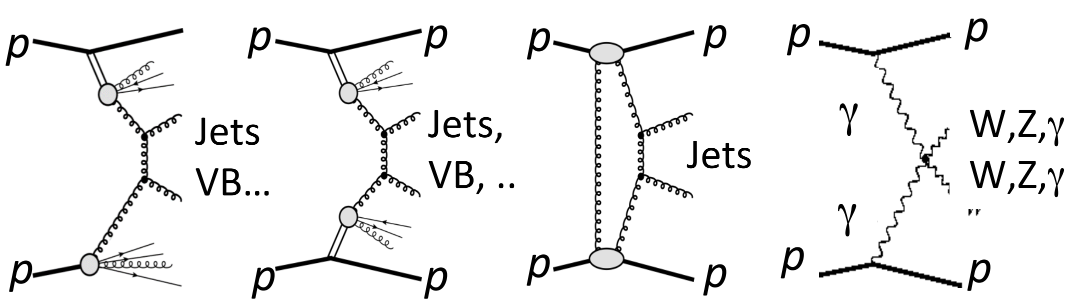
$\sigma_{inel} = \sigma_{ND} + \sigma_{SD} + \sigma_{DD} + \sigma_{CD}$ (diffractive part 25-30% of inelastic)

Diffractive events characterized by exchange of colorless objects: photons (QED) or pomerons (QCD). Pomeron constituents resolved in hard diffraction.

Experimental Signatures: rapidity gaps and very forward protons



Soft Diffraciton
SD, DD, CD
described by models



Hard Diffraction: SD, DPE with pomeron remnants; DPDF description; gap survival probability S^2; CEP; two-photon interactions

… only few fb for rarest processes

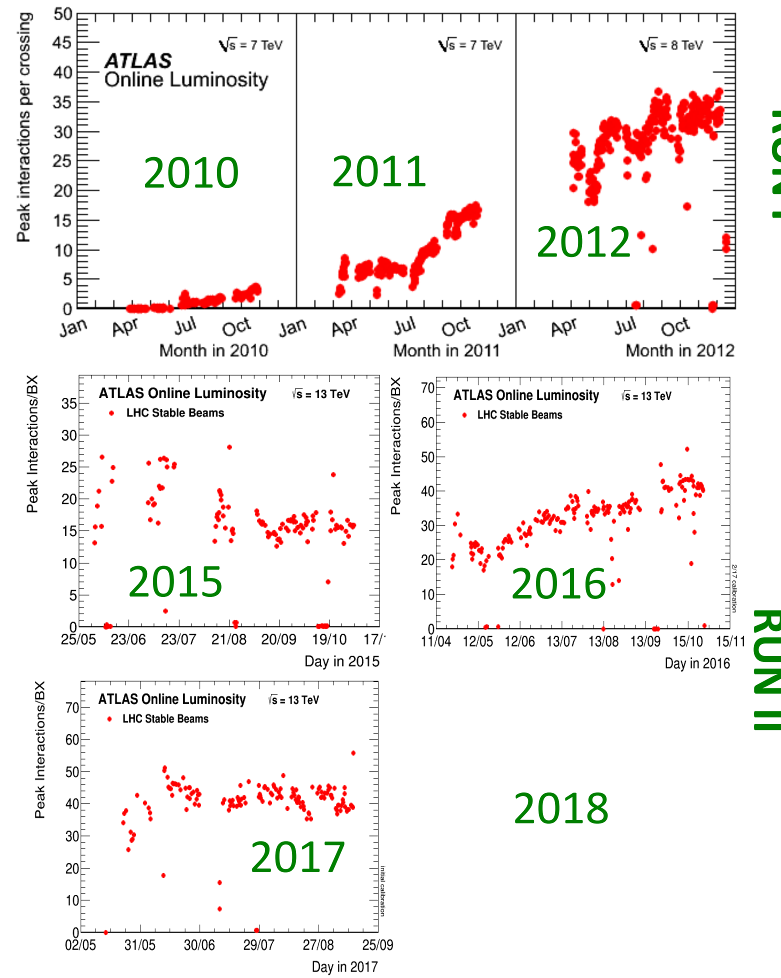
LHC Running Parameters and Strategies

Main Machine Settings:

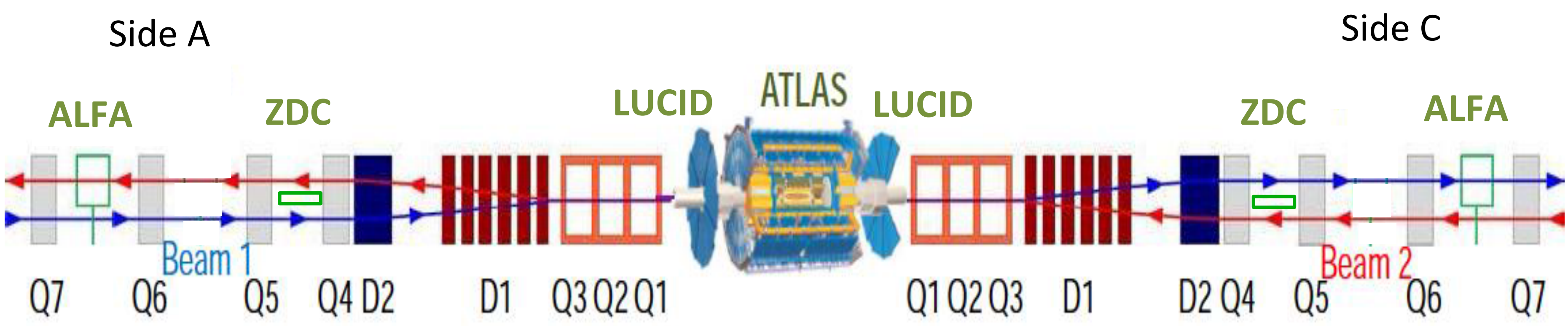
- Filling Scheme: from few to ~ 2800 bunches, isolated/ trains, beam intensity
- E_{CM}
- Beam Optics: standard (β^*<1 m), and special with β^* = 90 m, 1 km, 2.5 Km, …

Running Strategies:

- Rare processes: Maximize Luminosity → many bunches, high intensity, low β^*, large μ = pile-up of inelastic interactions
- Elastic scattering, B, ρ → Large β^* and low μ
- Pile-up modeling, Underlying Event, Diffraction without proton tags /ToF → Special low-μ at nominal β^*
- σ_{tot} , ρ evolution → Special E_{CM} (900 GeV)



ATLAS up to 2015

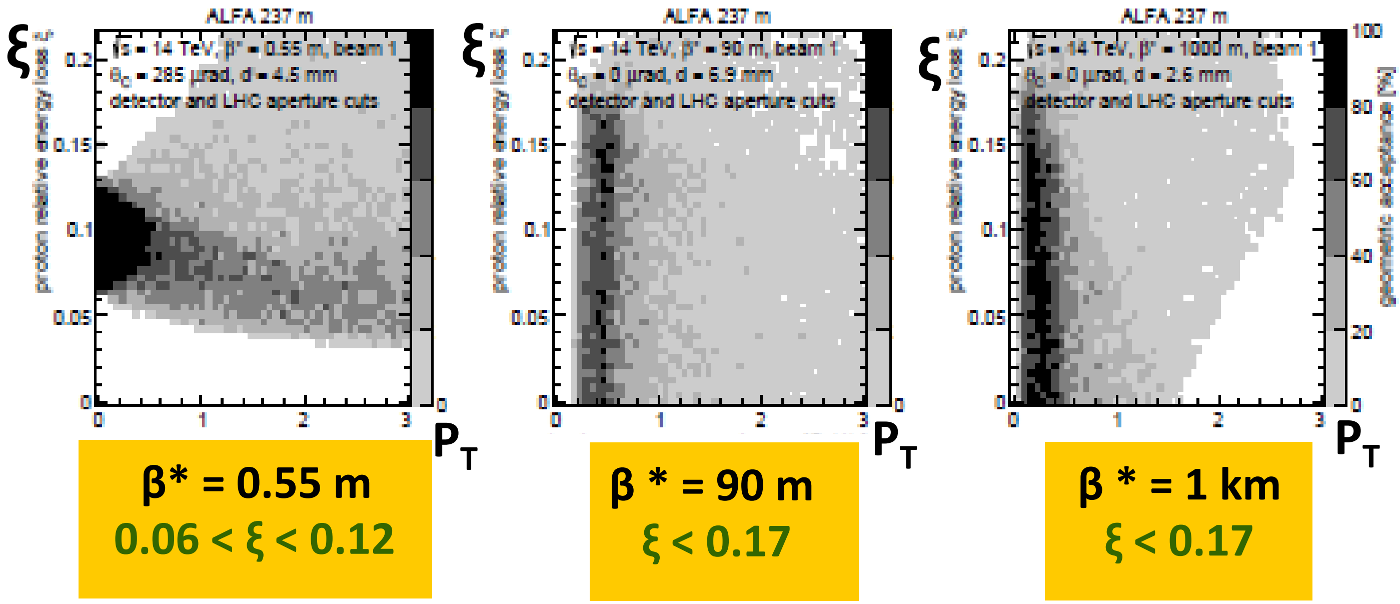


LHC Collimators, Dipoles, Qualdrupoles

- Central Detector |η|<4.9
- LUCID at 17 m from IP (luminosity monitor)
- ZDC at 140 m from IP, to detect neutrons/photons in HI collision
- ALFA: scintillating-fiber tracking detectors in vertical Roman Pots at 237-245 m from IP, optimized for elastic scattering: proton fractional momentum loss $\xi \approx 0$ and small p_T

pp Diffraction with ALFA

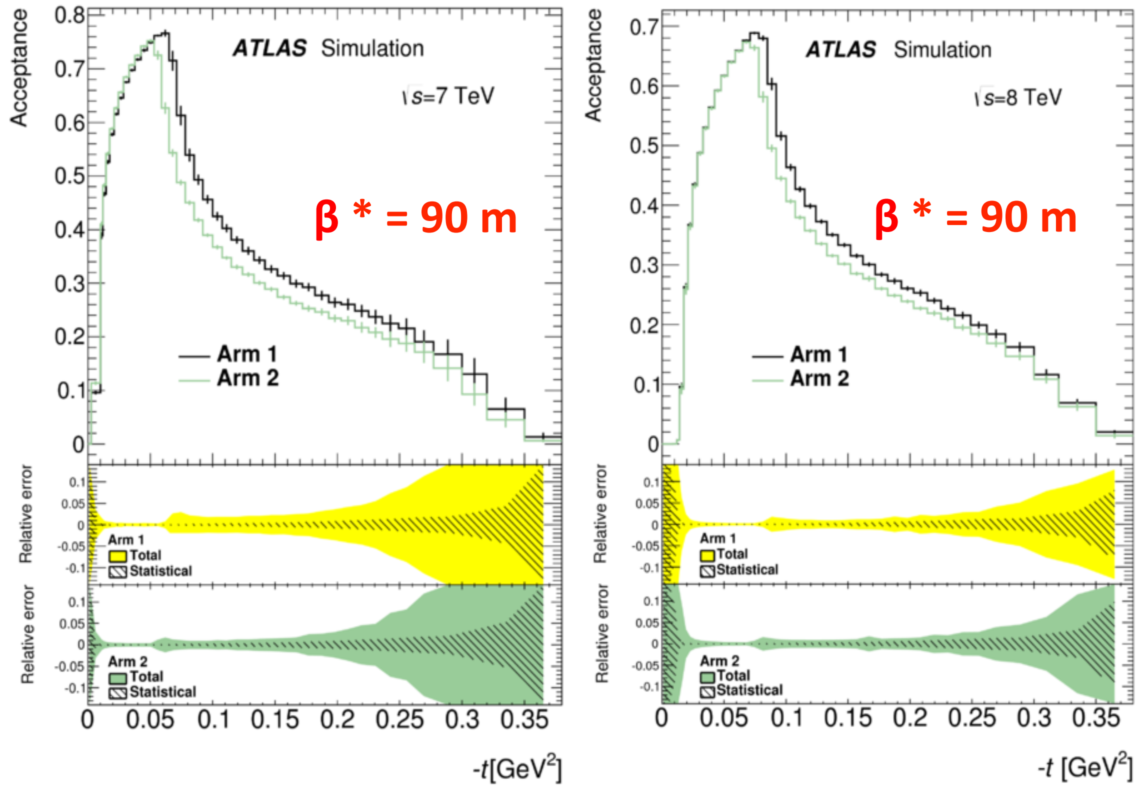
Proton $\xi = 1 - E_p/E_{beam}$ acceptance strongly dependent on beam optics:



- Standard optics (β^*<1m) with limited acceptance for diffracion, and not useful for studying Elastic Scattering
- Detectors moved close to beam (<10 σ_{beam}) in large β^*, dedicated runs only
- Studies on Diffraction with large β^* runs also possible

pp Elastic Scattering with ALFA

- Parallel-to-point-focusing in vertical plane
- Precise knowledge of LHC magnetic lattice and detector position needed to count events as a function of *t*
- Goals: σ_{TOT} , ρ, B and Absolute Luminosity via elastic pp scattering in Coulomb-Nuclear Interference region (very small *t*)



Acceptance as a function of true value of Mandelstam *t* for β * = 90 m beam optics at 7 and 8 TeV

σ_{EL} and σ_{TOT}

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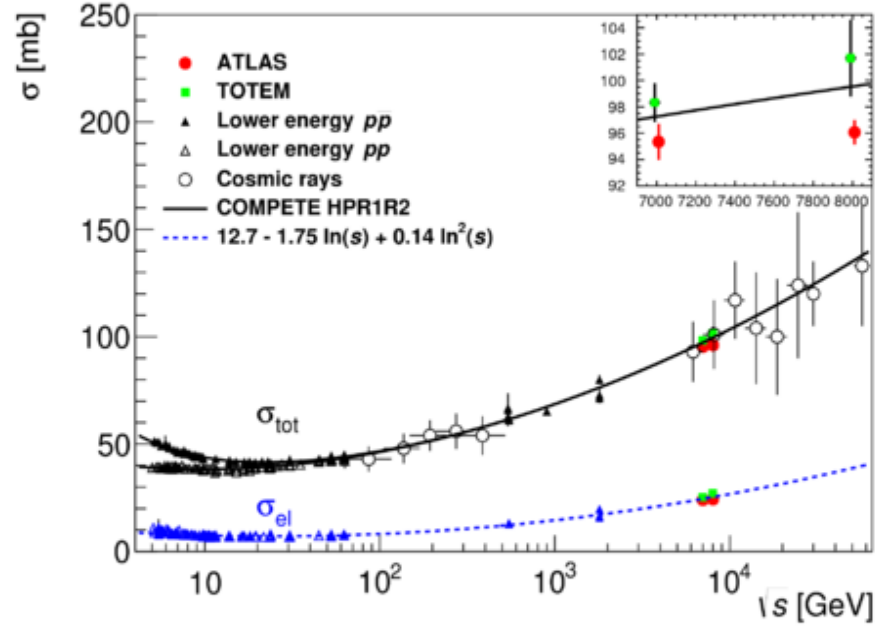
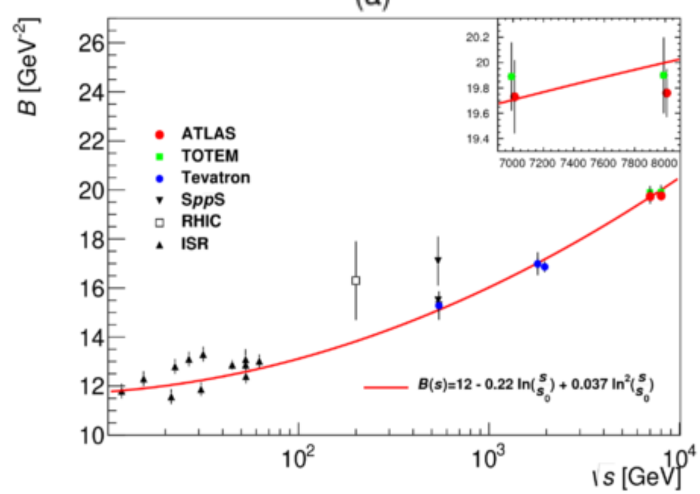
- σ_{TOT} from σ_{EL} + optical theorem in β^*= 90 m runs at 8 (and 7) TeV
- Fit range: 0.014 $GeV^2 < -t <$ 0.1 GeV^2
- Extrapolation to $t \rightarrow 0$
- Luminosity from other detectors (main syst. for σ_{TOT})
- B-slope fit (main syst. from beam momentum)



(a)

Analysis of runs taken with β^*=1 Km (8 TeV) and β^*=2.5 Km (13 TeV) coming soon (smaller $t \rightarrow \rho$ measurement)

LHC at E_{CM} = 900 GeV with β^*=100 m probably before winter TS

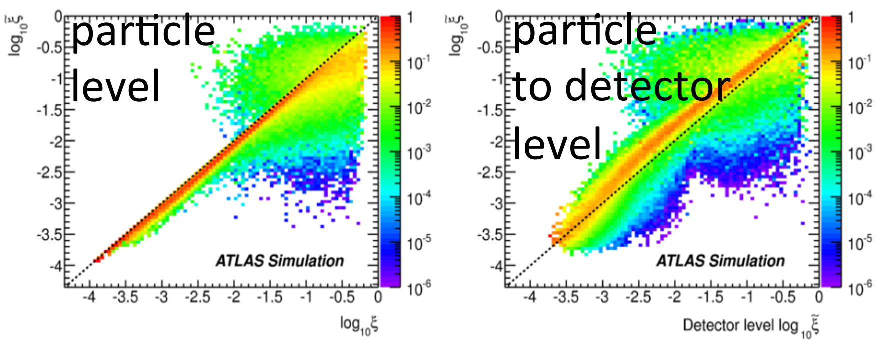


(b)

Hard Diffraction with Central Detector: Dijet + rapidity gap @ 7 TeV

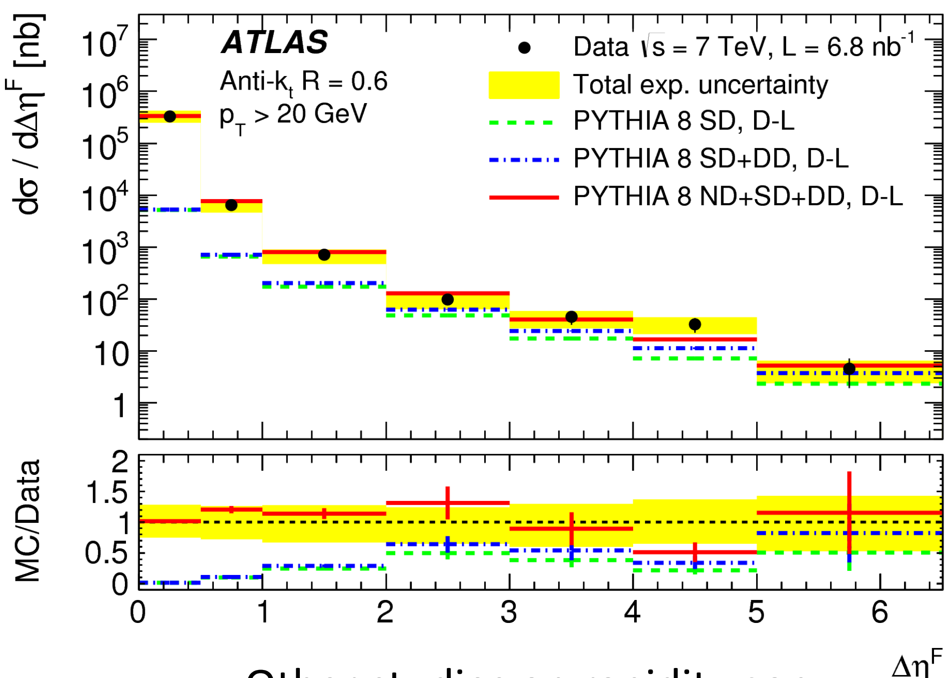
Phys. Lett. B 754(2016) 214

- Rapidity gap ($\Delta\eta^F$) → $\mu<1$ data
- Proton fractional momentum loss estimated with calorimeters ($\tilde{\xi}$)
- Diffractive component dominant at **largest $\Delta\eta^F$** and **smallest $\tilde{\xi}$** → comparisons to MC
- Overall MC description good



correlation between true fractional proton momentum loss ξ and estimation from energy deposited in Central Detector ($\tilde{\xi}$)

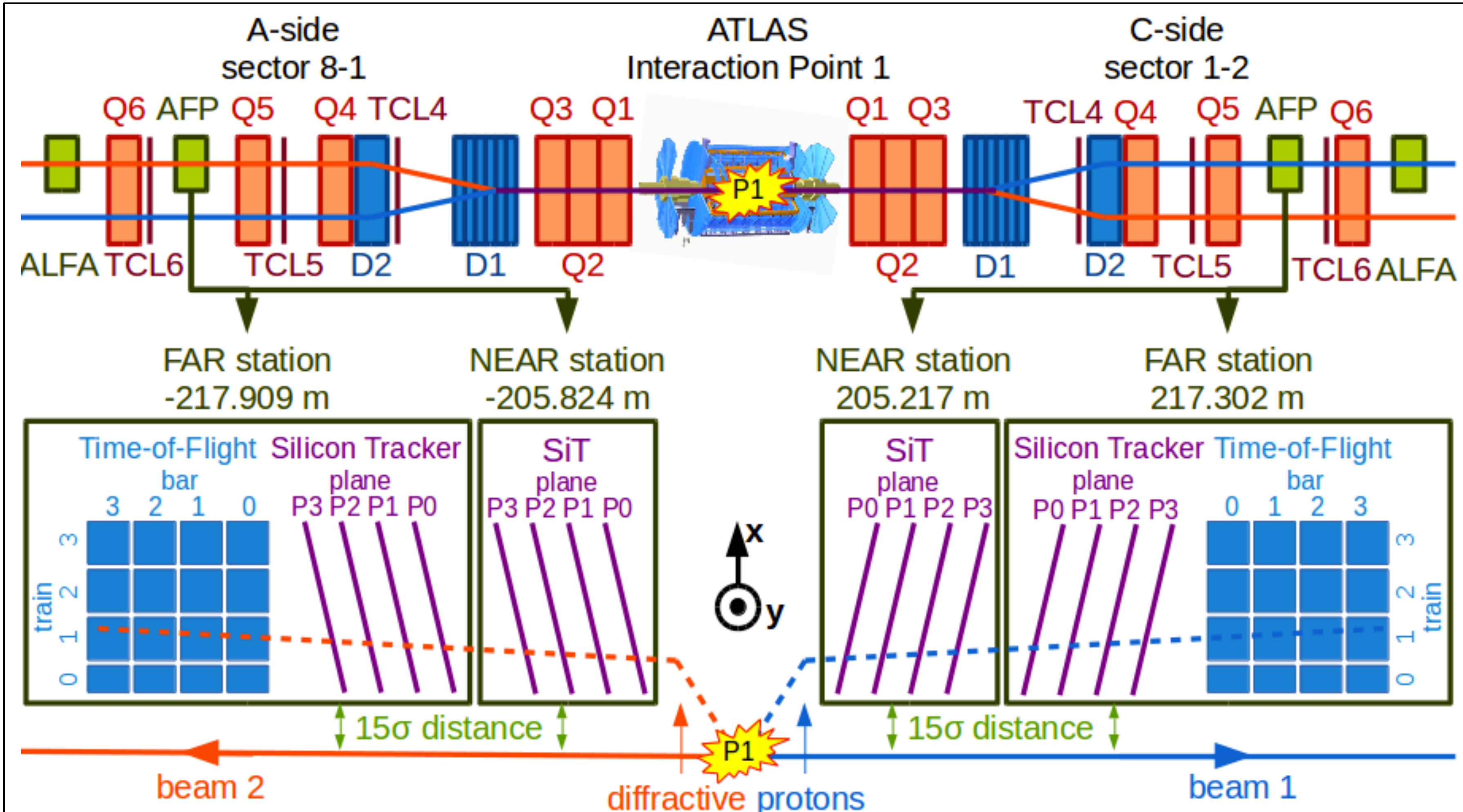
$S^2 = 0.16 \pm 0.04 \pm 0.08$ (with LO POMWIG)



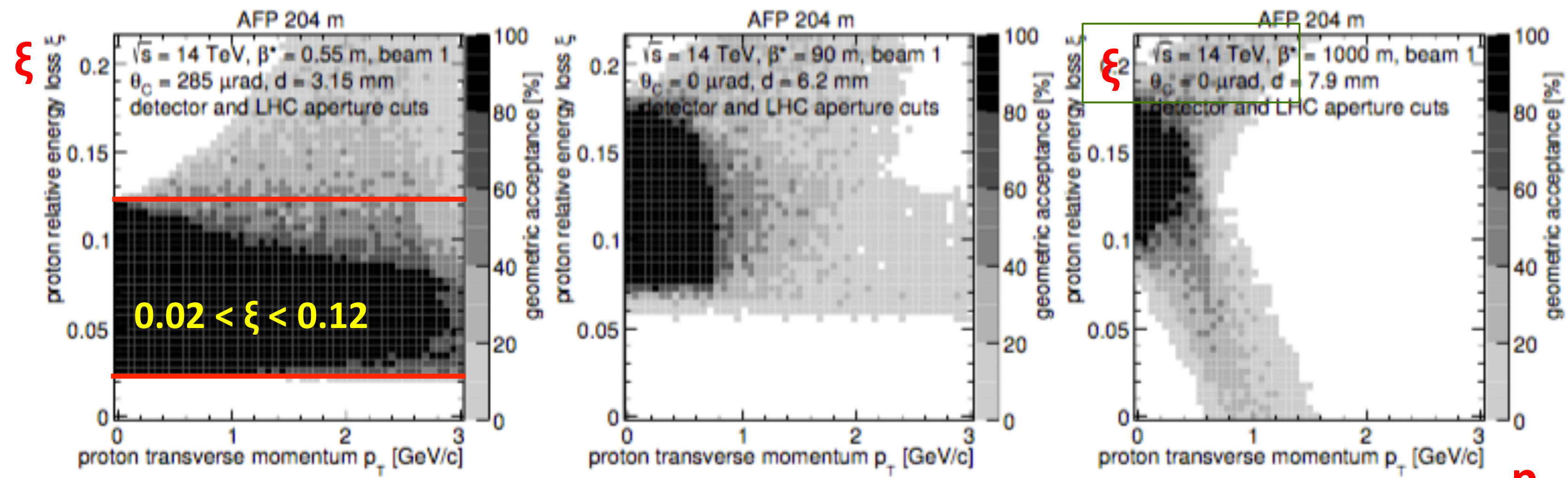
Other studies on rapidity gap survival (S^2), *forward* gap spectra, SD+DD, limited to $\mu<1$ runs (RUN I)

LoI (phase I upgrade) in 2011: *CERN-LHCC-2011-012*
Approved in 2014, TDR in 2015: *ATL-TDR-024-2015*

The AFP Project



AFP Proton Acceptance *versus* Beam Optics



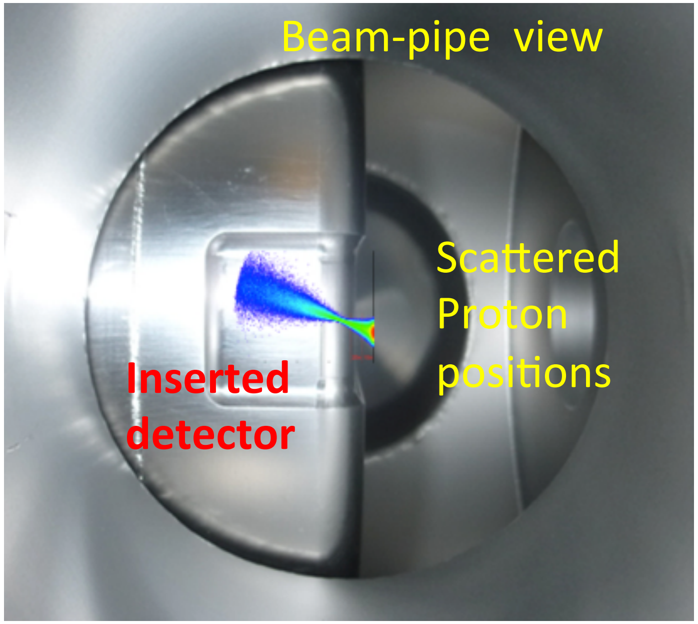
β* = 0.55 m **β* = 90 m** **β* = 1 Km**

Best acceptance in fractional momentum loss for standard, low β* optics independently of crossing angle

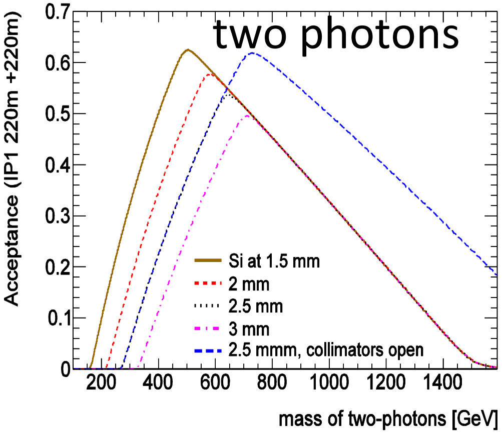
Complementary to ALFA

Tracking Detector Requirements

- $\xi = 1 - E_p/E_{beam}$ acceptance dependent on *x*-distance from beam → minimum dead area, as close to beam as possible
- Radiation hard (expect from 5×10^{12} to 3×10^{15} neq for 10 fb^{-1})
- 2-3% resolution on centrally produced mass → $\sigma_x = 10\ \mu m$, $\sigma_y = 30\ \mu m$



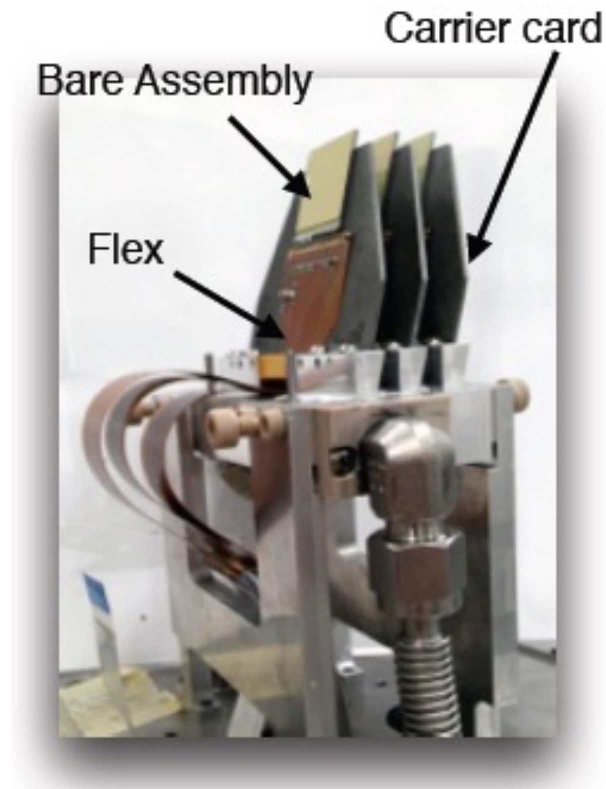
Mass of centrally Produced system X:
$M_X^2 = \xi_1 \xi_2 s$



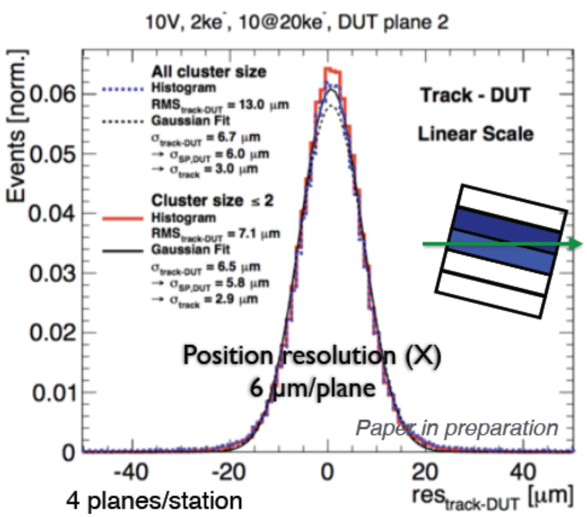
for distance ≈ 15 σ_{beam} (2 mm)
$0.02 < \xi < 0.1$
Upper limit set by position of LHC collimator

Selected Tracker

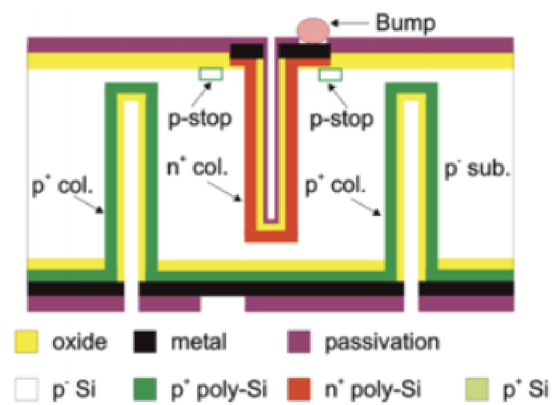
- Slim edge 3D pixel sensors (as in ATLAS-IBL + dead area cut to 150 μm)
- validated for non-uniform irradiation up to 5×10^{15} neq/cm^2
- FEI4 readout chip (4 bits for ToT)
- 4 layers of 336 x 80 pixels of size 50 x 250 μm^2
- 14^{o} tilt in x (2 pixels/cluster) $\sigma_x \approx 6$ μm/plane
- Staggered along y



Beam test 2016



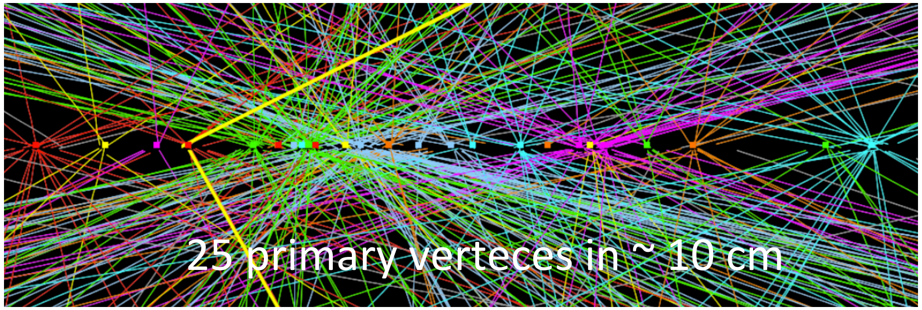
-> Tracker resolution (X) of ~3 μm/station

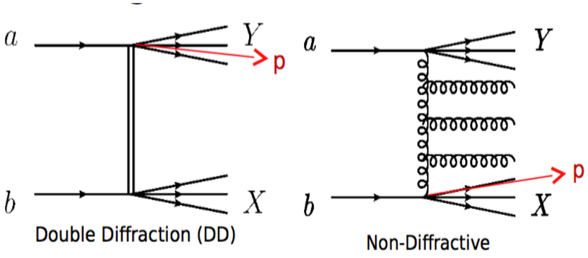


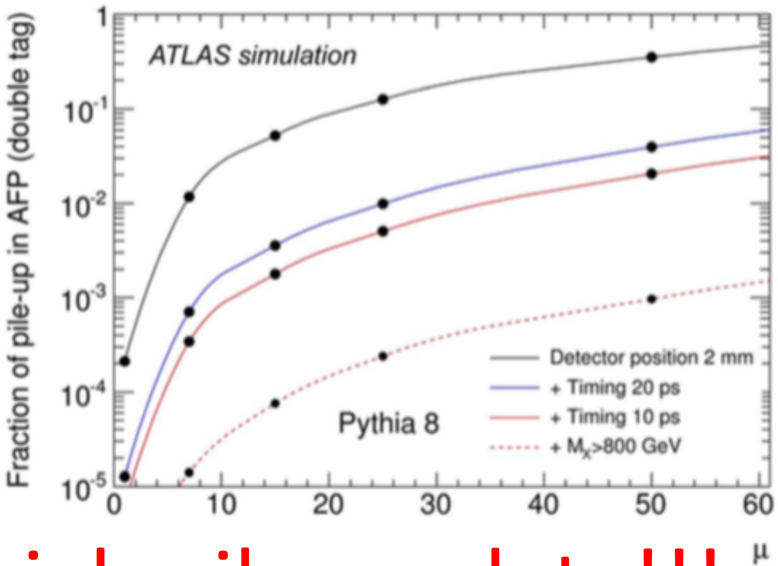
Timing Detector Requirements

- Identify primary vertex in high pile-up events (up to μ≈55) → $\sigma_t \approx 10$ ps, or $\sigma_z \approx 2$ mm
- E > 90% (trigger)
- Granularity to reject pile-up protons in AFP itself (SD + ND, DD events with protons from hadronization + beam halo, beam-gas…)

$z_{vtx} = \frac{1}{2}c(t_L - t_R)$





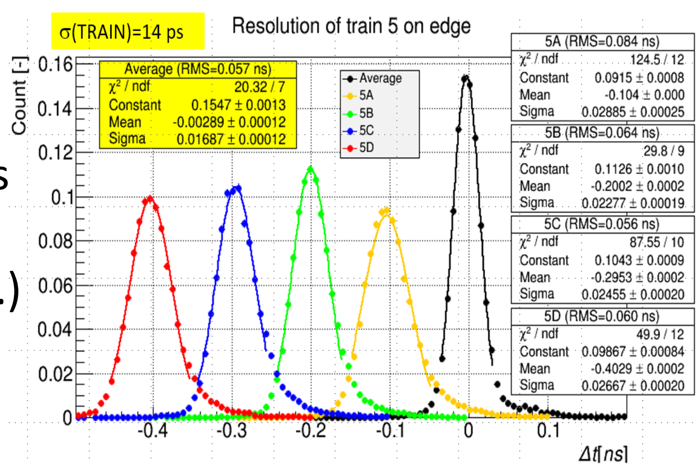


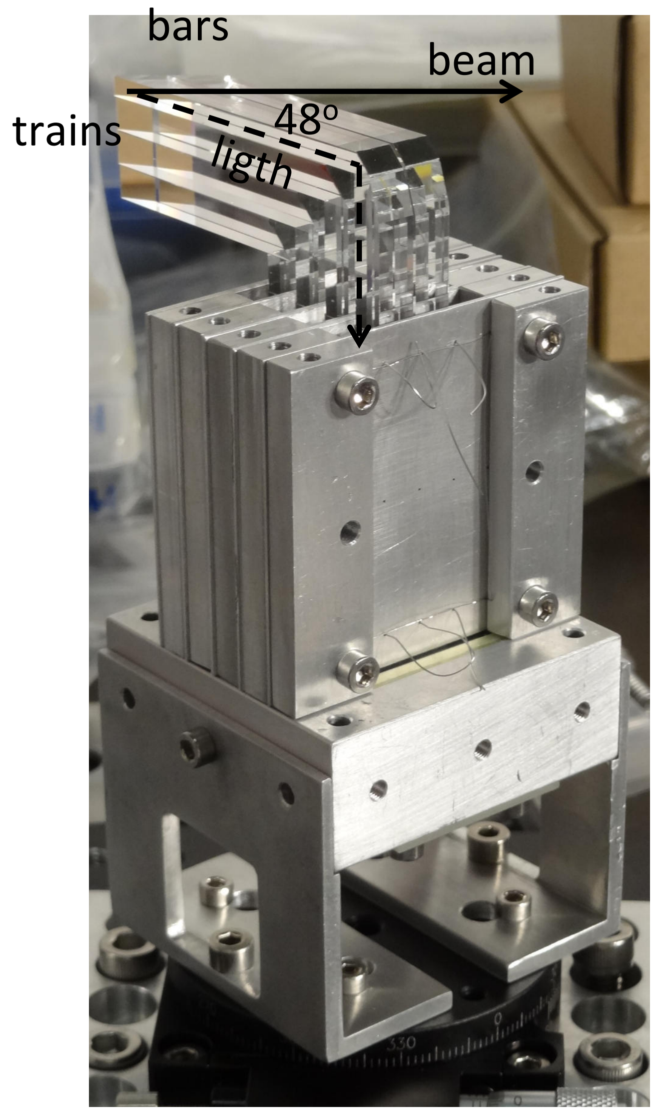
Essential to exploit high pile-up data!!!

Selected ToF

- 4 trains of 4 Quartz Lbars at Cherenkov angle with respect to impinging protons
- light readout by MCP-PMTs
- Electronics includes CFD for triggering, HPTDC for Time of Flight
- Approaching goal resolution with 4 uncorrelated measurements (beam test for R&D still on-going)

Beam tests in 2016 (June, Sept.)

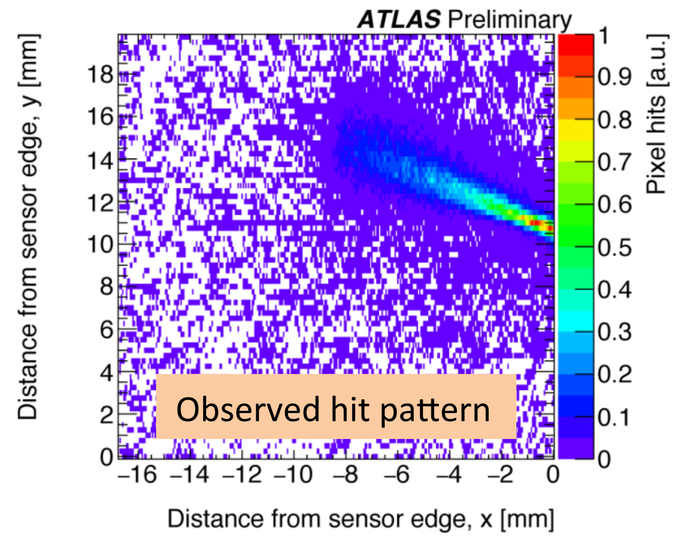


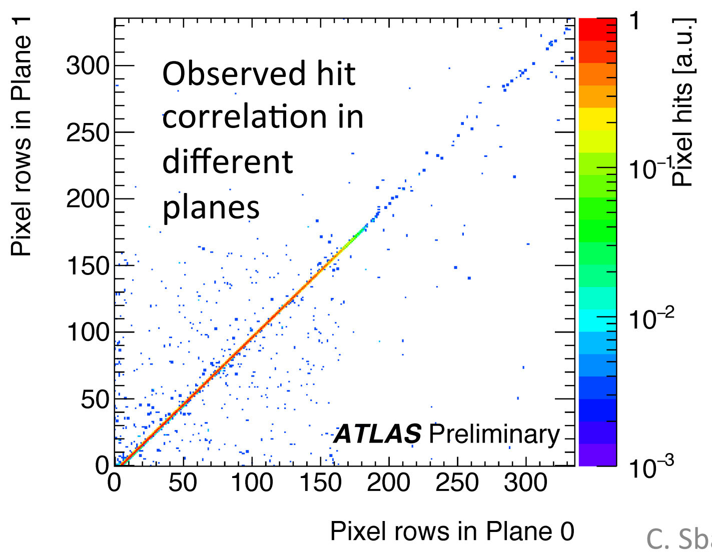


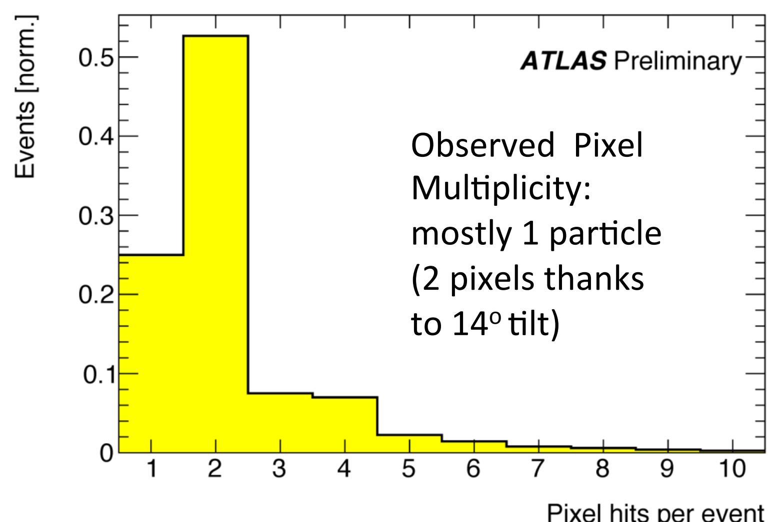
AFP 0+2 (2016): First Data

- 3(4) planes of SiT in near (far) station (side C)
- No ToF
- DAQ ready by March, insertions during LHC intensity rump-up, beam-based alignment
  - ➢ good plane alignment, signals as expected
  - ➢ Trigger (plane-majority logic) timed in

Data from 300-bunch run, μ≤26, β*=0.4 m







Events with tagged protons and jets

ATL-PHYS-PUB-2017-012

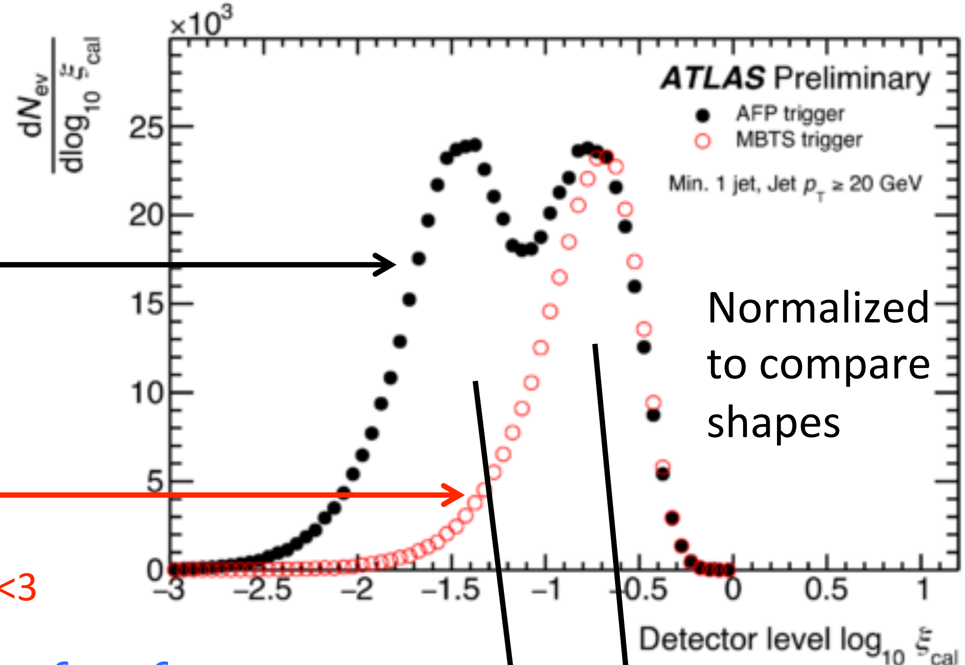
Low pile-up run: $\mu \approx 0.3$, $\beta^* = 0.4$m

AFP triggered

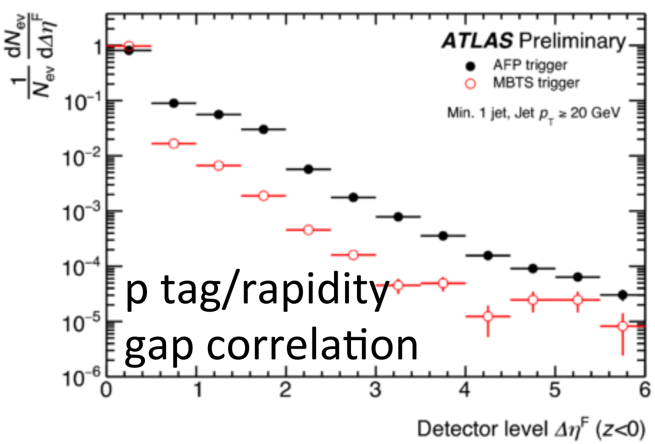
- ≥ 5 AFP tracker planes with one cluster
- at least one jet with $p_T > 20$ GeV and $|\eta| < 3$
- no more than one vertex, no pile-up

Minimum Bias triggered

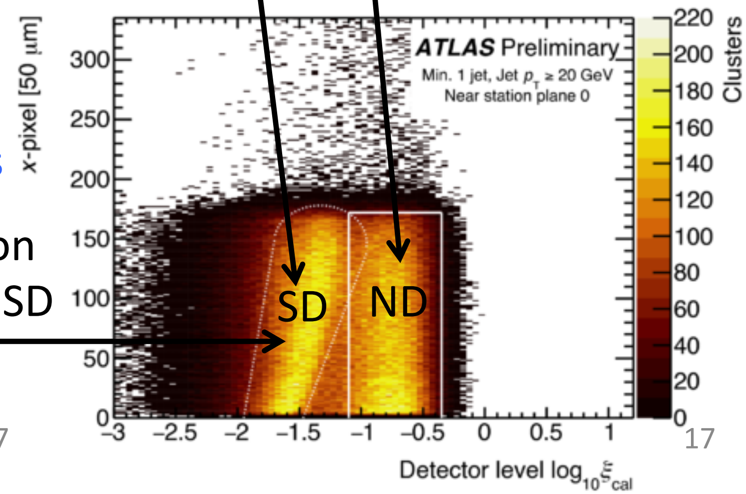
- ≥ 2 hits in MBTS
- at least one jet with $p_T > 20$ GeV and $|\eta| < 3$
- No more than one vertex, no pile-up



$\xi_{cal} = \xi$ estimation from energy in calorimeters



Energy-position correlation in SD



2016 summary

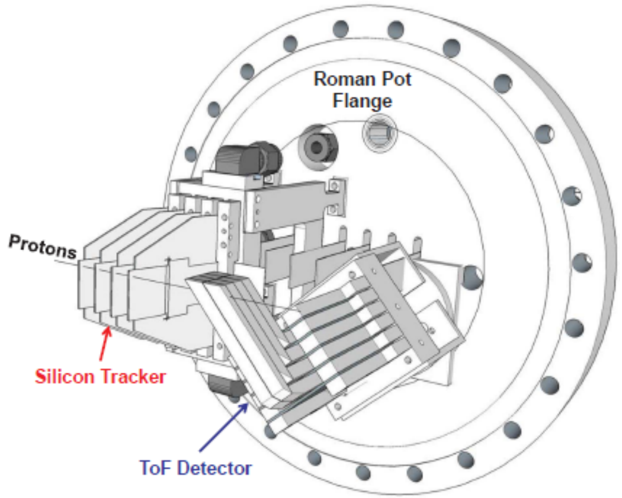
- First arm of AFP installed (2015 End of Year Technical Stop) with Si trackers in two stations and fully commissioned with 2016 beam
- AFP inserted up to 20 σ_{beam} (~3 mm)→ ξ_{min} ≈3.5%
- Various insertions in fills at high pile-up (alignment, study of beam bkg, radiation)
- hit-probability in AFP per minimum bias event: 1.5% (near station) 2.0 %(far station) → estimate of pile-up in high-μ double tagged events for 2017
- **AFP validated as proton tag** to select SD events
- Two low pile-up runs ($\mu<0.3$, $\mathcal{L} \approx 0.5\ pb^{-1}$) to be analyzed for Physics

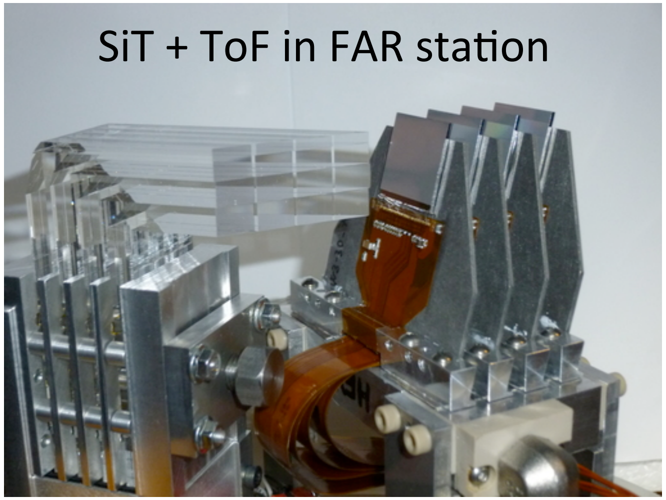
AFP 2+2 (2017): Second Arm

- Successful installation and calibration of second arm (side A)
- All detectors in: ToF in far station behind SiT on both sides
- Qualified for full insertion

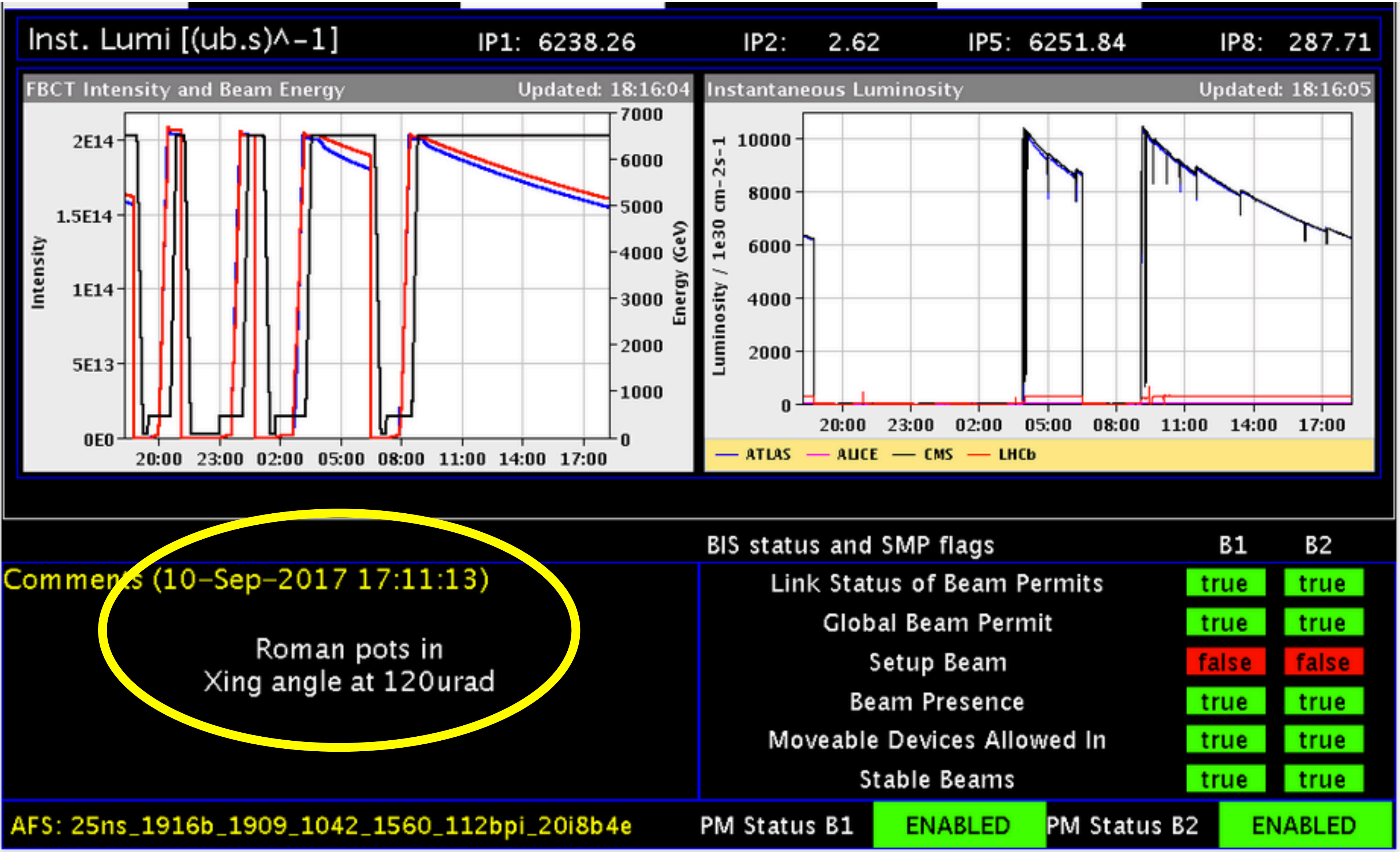
  12σ+0.3 mm (1.5-2.7 mm)
- Full integration in ATLAS DAQ
- Correlation between ToF and SiT signals observed
- Trigger signals to ATLAS timed in correct BCID (both SiT and ToF)
- ToF resolution under study with both data and beam test (understand cross-talk, efficiency, resolution, showers,bkg…)

A HUGE amount of work!





AFP now taking data all the time at high pile-up



few operational issues…

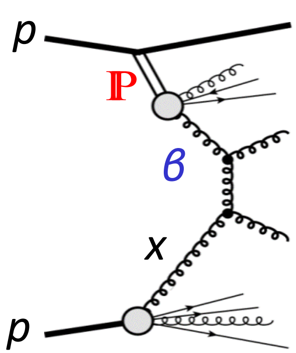
- Jitter in reference clock (one side) solved at beginning of September (no *z*-vertex reconstruction before) → focus on getting *z*-vertex distributions since then
- HV/LV cables integrity (SiT plane inefficiencies)
- Radiation effects (SiT currents, auto-recovery from SEU in electronics) are maneageble
- Ageing of DAQ fibers (monitored/under control)
- …

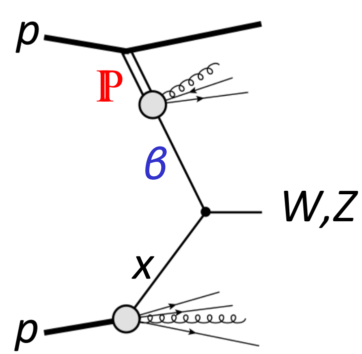
… and no show stoppers

Physics with AFP 0+2 (μ ≤ 1)

$\mathcal{L} \approx 0.5$ pb^{-1}
In 2016 at μ<0.3

Improve and **extend** ATLAS SD studies based on rapidity gaps

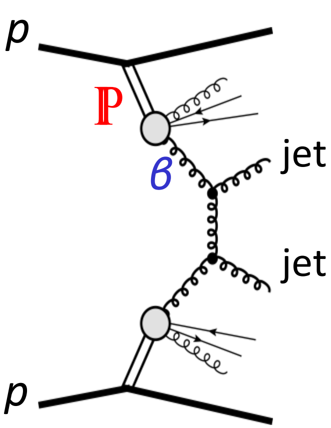


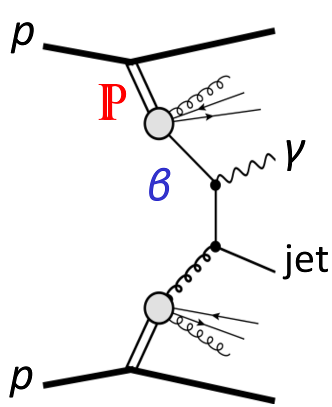


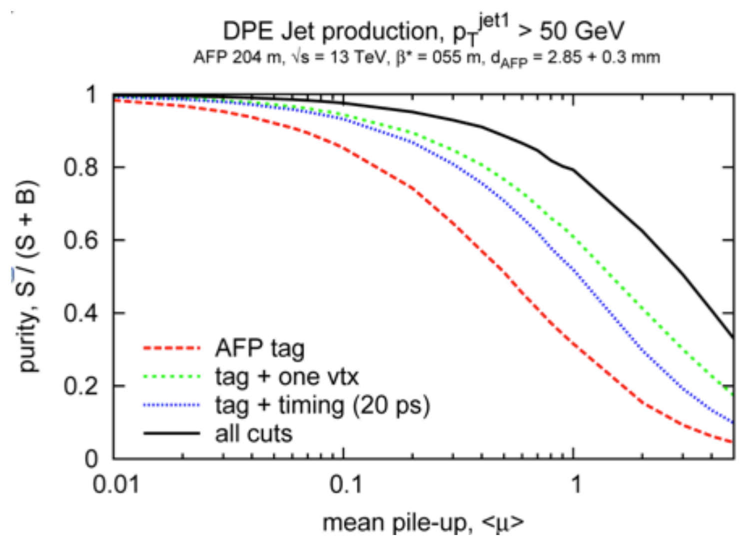
Analysis	**Motivation**	$\int Ldt$ [pb^{-1}]	**Optimal μ**
Soft Single Diffraction with AFP0+2			
$d\sigma/dt$, $d\sigma/d\xi$, t-Slope vs. ξ, $dN^{\pm}/dp_T$ vs. t and ξ	Saturation, MC tuning, Cosmic Ray physics	1	$\mu \sim 0.01$
Single Diffractive jet Production [21]			
σ, rapidity gap, Jet structure and p_T, event shape (MPI [21]); vs. t, ξ, and β	gap survival probability, Pomeron structure Pomeron flux, MC tuning	$10-100$	$\mu \sim 1$
Single Diffractive jet-gap-jet Production [22, 23, 24]			
σ, central gap distribution, Jet p_T; vs. t, ξ, and β	observation of a new process, test of BFKL dynamics	$1-100$	$\mu \sim 1$
Single Diffractive Production of γ + jet [25]			
σ, rapidity gap, Jet structure and p_T, Photon p_T, event shape (MPI); vs. t, ξ, and β	observation of a new process, mechanism of hard diffraction, gap survival probability, Pomeron structure	$10-100$	$\mu \sim 1$
Single Diffractive Z Production			
σ, rapidity gap, charge-asymmetry; vs. t, ξ, and β	gap survival probability, Pomeron structure	$10-100$	$\mu \sim 1$
Single Diffractive W Production			
σ, rapidity gap; vs. t, ξ, and β	gap survival probability, Pomeron structure and flavor composition Pomeron quark content	$10-100$	$\mu \sim 1$

Physics with AFP 2+2 (low μ)

- Soft diffraction: separation between SD/DD components, high purity samples for quantitative model testing
- All SD channels mentioned before
- DPE jet and γ+jet production (DPDF, gluon/quark content of Pomeron in clean samples)





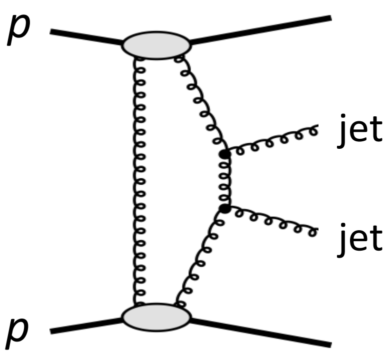


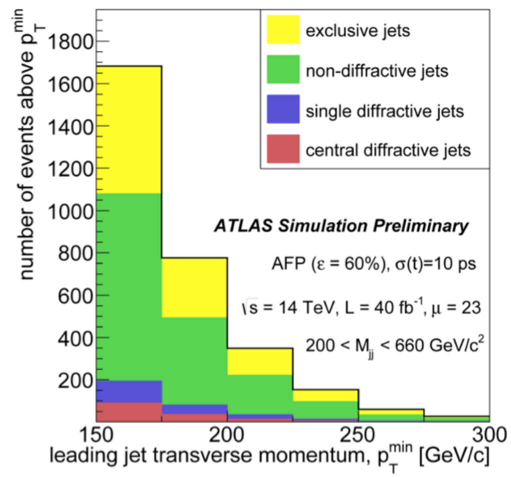
Up to 10 pb^{-1} expected in 2017-2018 runs

Physics with AFP 2+2 (high μ)

Central Exclusive Jet Production

First observed by CFD@Tevatron
Low σ → high pile-up run
→ double tag
→ ToF to control bkg

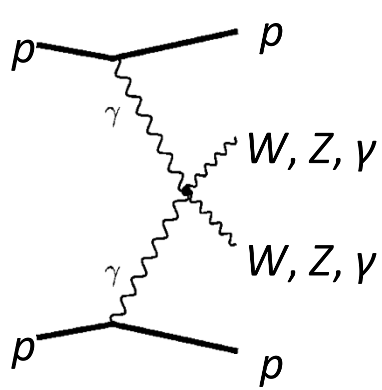


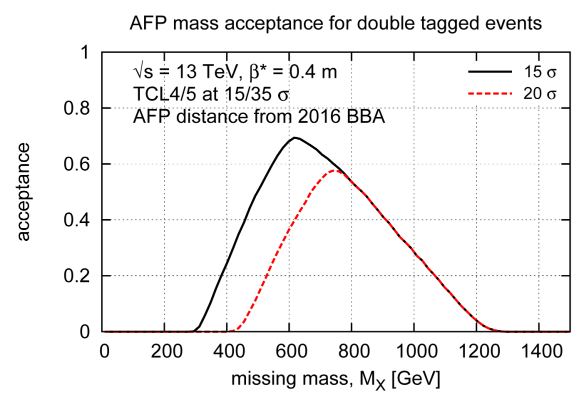


Photon-induced WW/ZZ/γγ Production

Best sensitivity to aQGC (few % missing mass resolution): factor 100 better than "standard" LHC analyses (sensitivity to higgless models, extra dimensions)

Compare mass and rapidity of central and pp systems





New Particles?

Dileptons good for calibration

The (foreseeable) future

- **Run III** (2020-2022)
  - Run with possibly improved detector (luminosity in standard runs increased mostly by leveling)
- **HL-LHC** (2025 and beyond)
  - Available space/optics?
  - Detector at 420 m for exclusive Higgs (defined spin-parity state) and $H \rightarrow bb$ (couplings)?
  - $\gamma\gamma \rightarrow WW/ZZ/\gamma\gamma$ and new high-mass resonances
  - …

Research Program will depend on LHC strategy and Previous Results

Conclusions

- ATLAS has been complemented with a new system to tag Forward Protons, complementary to ALFA (the former for standard β^* runs, the latter for large β^* ones)
- AFP is now taking data with ATLAS and is qualified for full insertion at $12\sigma + 0.3$ mm (1.5-2.7 mm)
- Work still ongoing to get z-vertex resolution
- A rich physics program including studies of pomeron structure and searches for BSM Physics is opening in RUN II
- Perspectives for RUN III and beyond under investigation