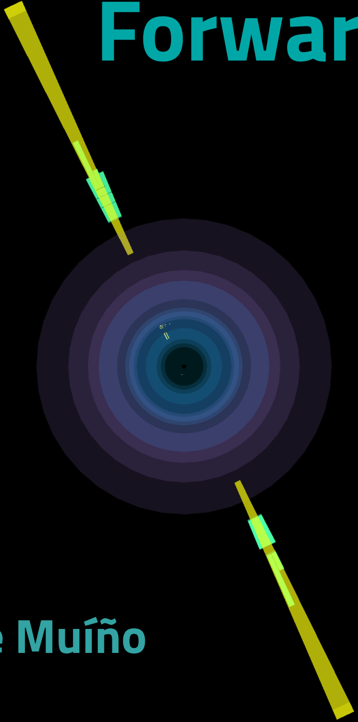
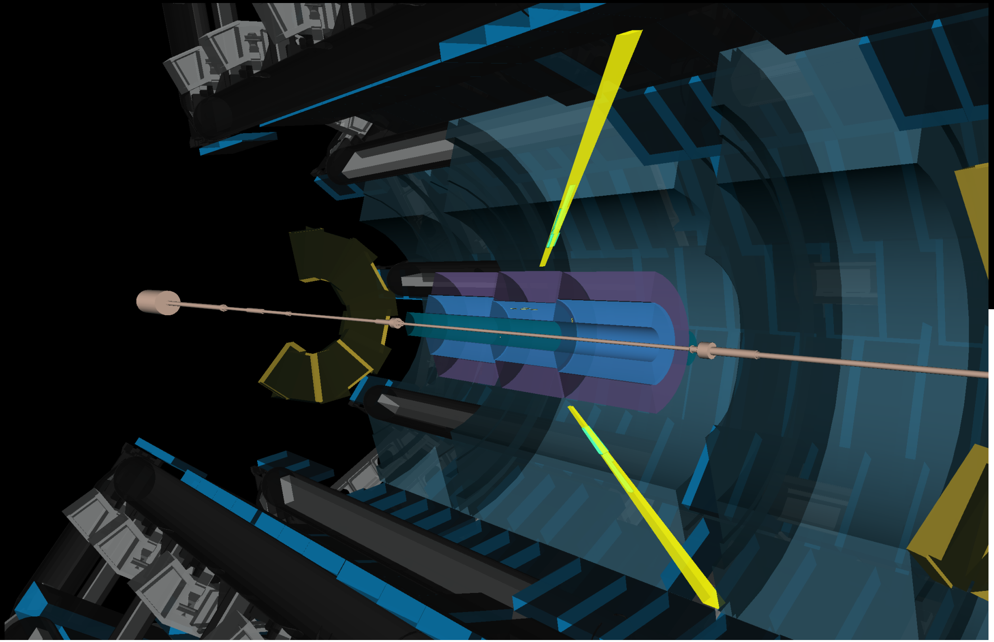
Probing the SM (and more) with Forward Proton Tagging @ ATLAS

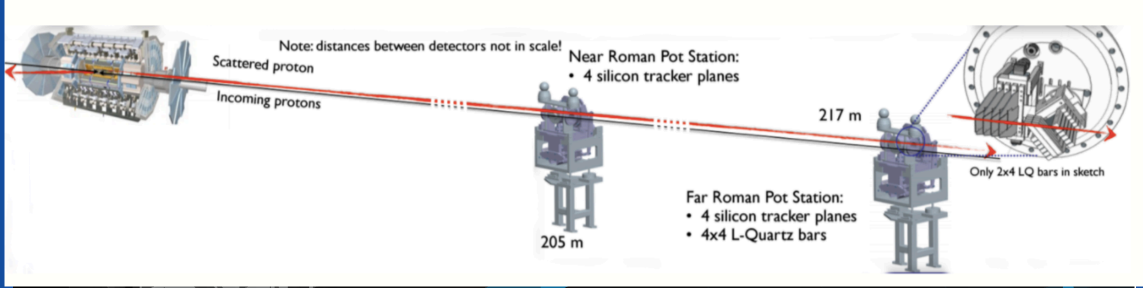


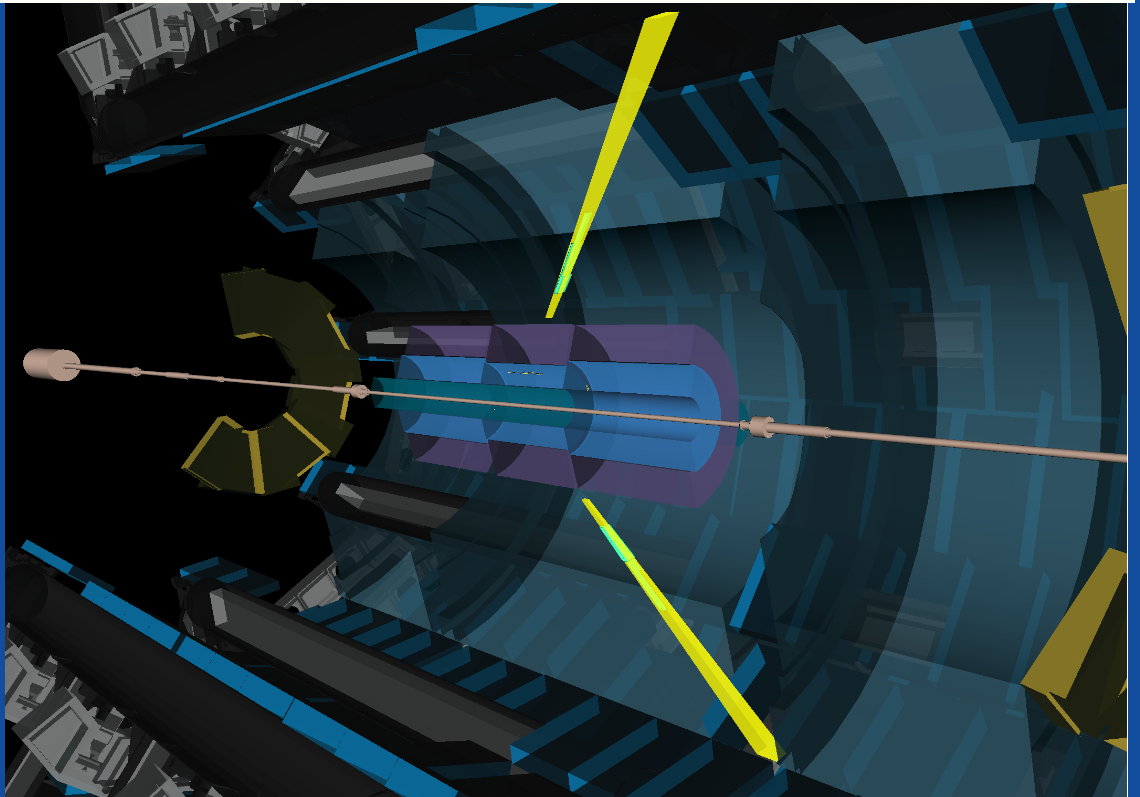


Patricia Conde Muíño
(IST & LIP)

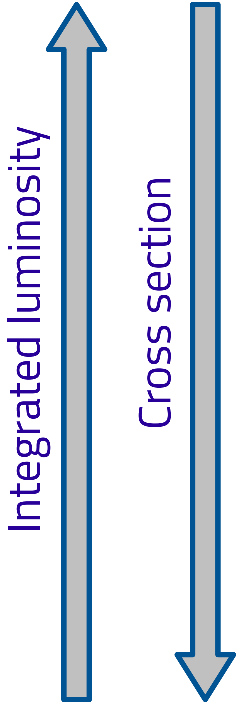
Diffracted p?

- Soft interaction between p
  - No dissociation
  - Continue moving in the beam pipe
  - Detected far away from the interaction point

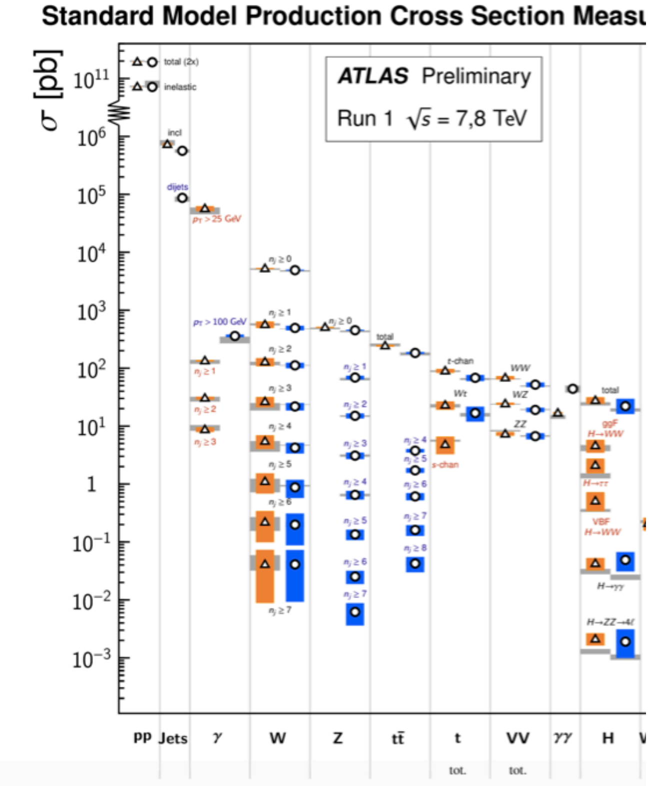




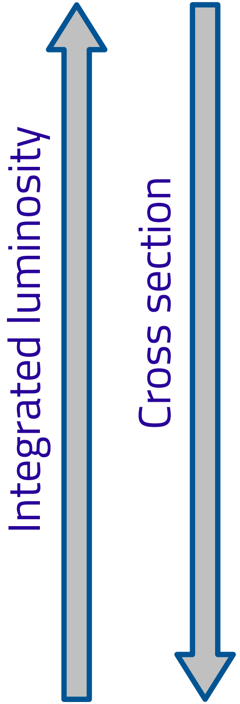
Physics with diffracted protons



- High cross section processes:
  - Total cross section with ALFA
  - Single/double diffraction (differential distributions)
  - Other processes
- Medium cross section:
  - central exclusive production
- Low cross section:
  - Quartic Gauge Boson Couplings
  - FCNC in top quark production
  - Searches: dark matter



Physics with diffracted protons



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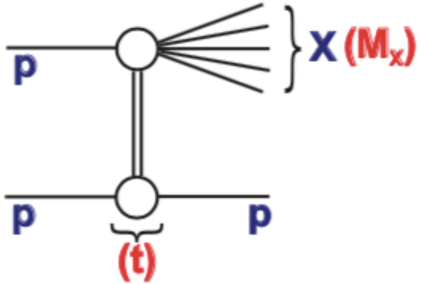
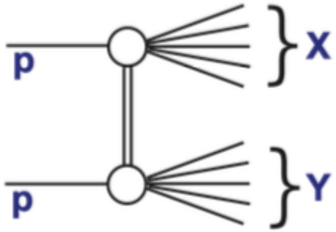
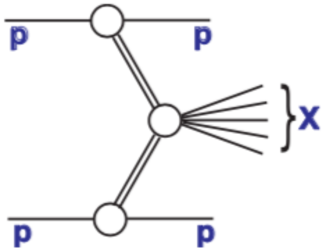
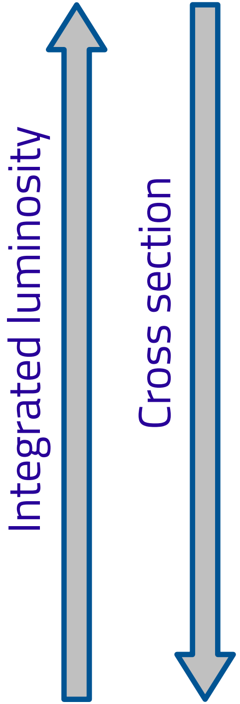






Physics with diffracted protons



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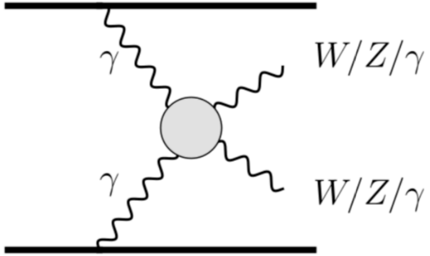
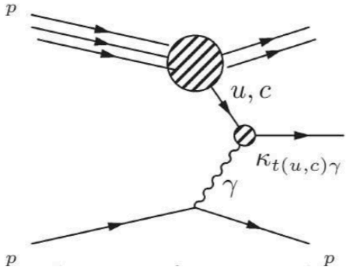
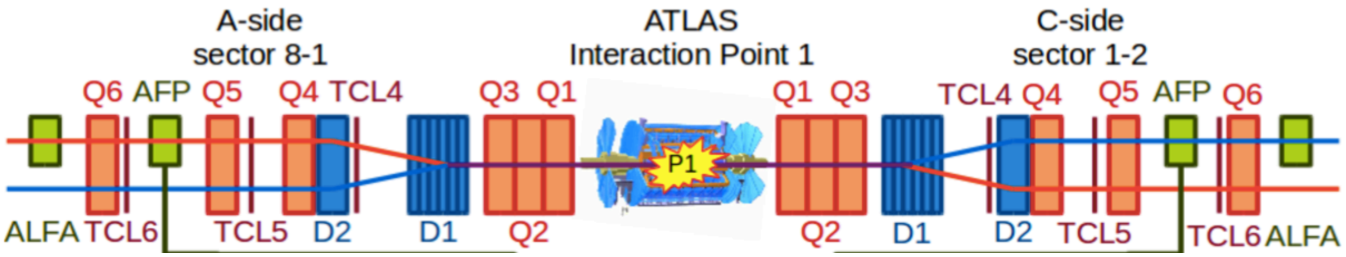




ARP Detectors

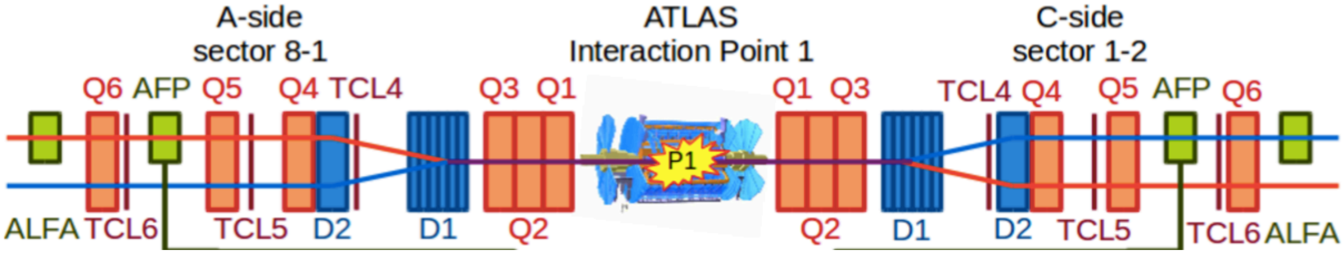


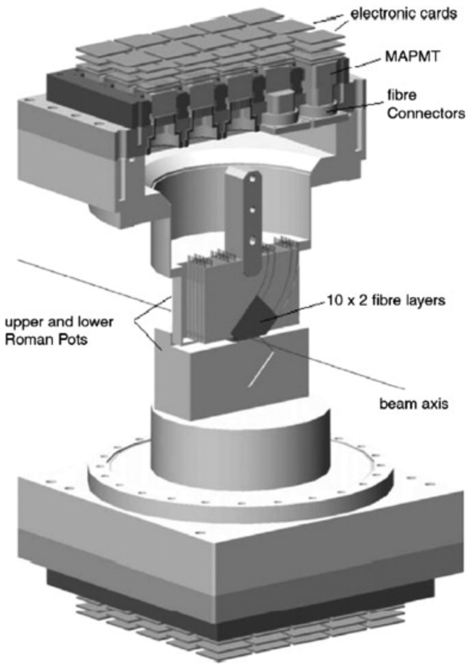
ATLAS Roman Pot Detectors

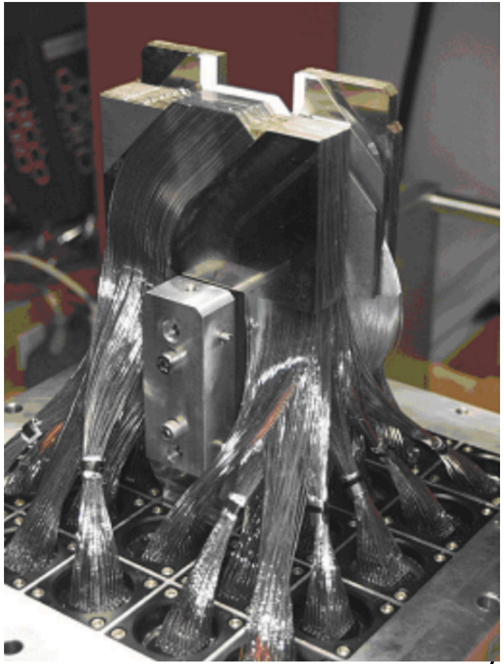
- Two sets of detectors
  - ATLAS Forward proton tagging detectors (AFP)
  - Absolute Luminosity detector (ALFA)

ATLAS Roman Pot Detectors

Luminosity detector (ALFA)

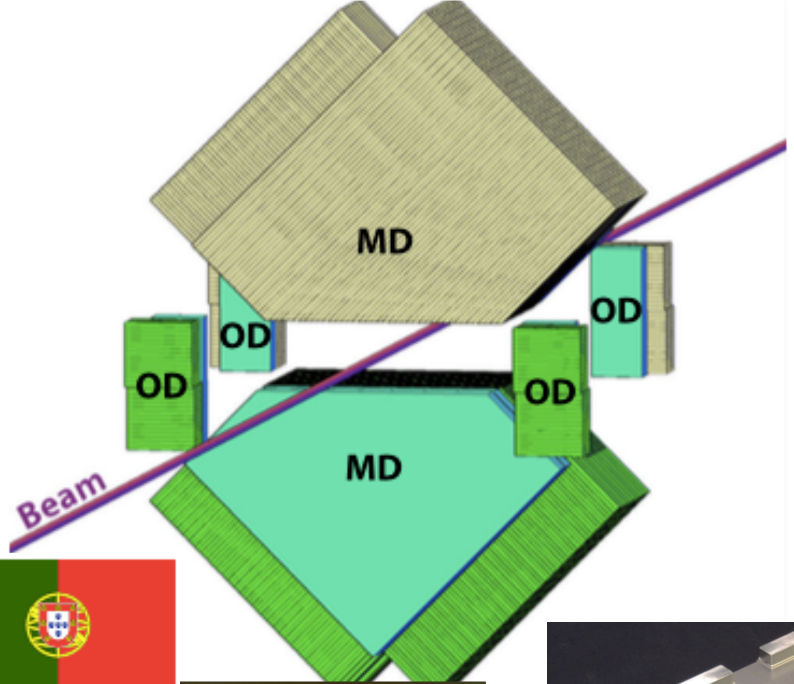


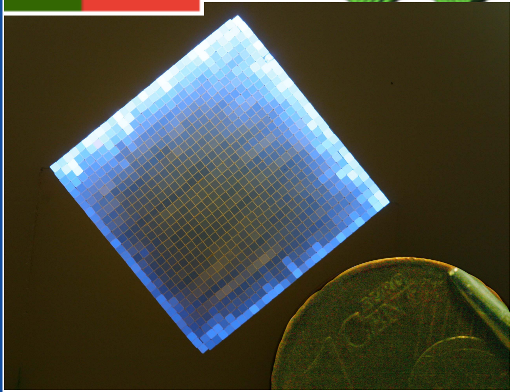


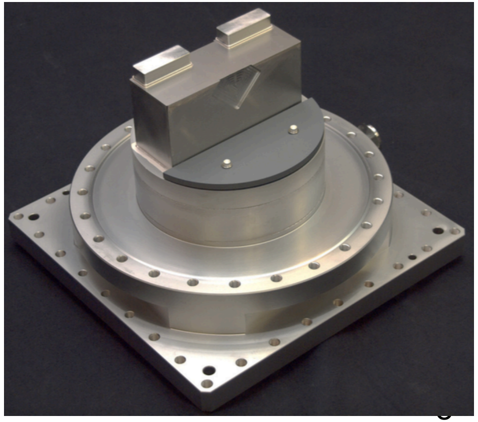


ALFA

- Measure scattered p at mm distance from beam
  - Resolution: 30 µm in x, y
  - Precise alignment
    - Overlap detector 10 µm precision
- Square scintillating fibres
  - aluminised (body, top)
  - Staggered layers
- Read out by MAPMTs

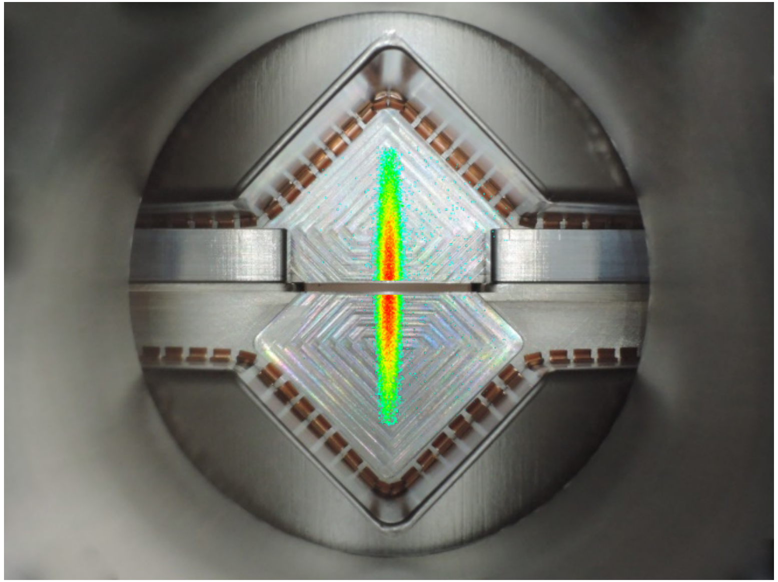




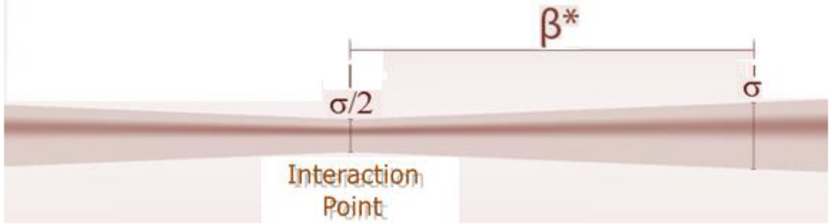


ALFA

- Housed in Roman Pots to approach the beam
- Operates at low luminosity and with special optics
  - $L = 10^{27}\ cm^{-2}s^{-1}$
  - High β^*



Luminosity: $$L = \frac{N_1 \cdot N_2 \cdot n \cdot f \cdot \gamma}{4 \cdot \pi \cdot \varepsilon \cdot \beta^*} F$$

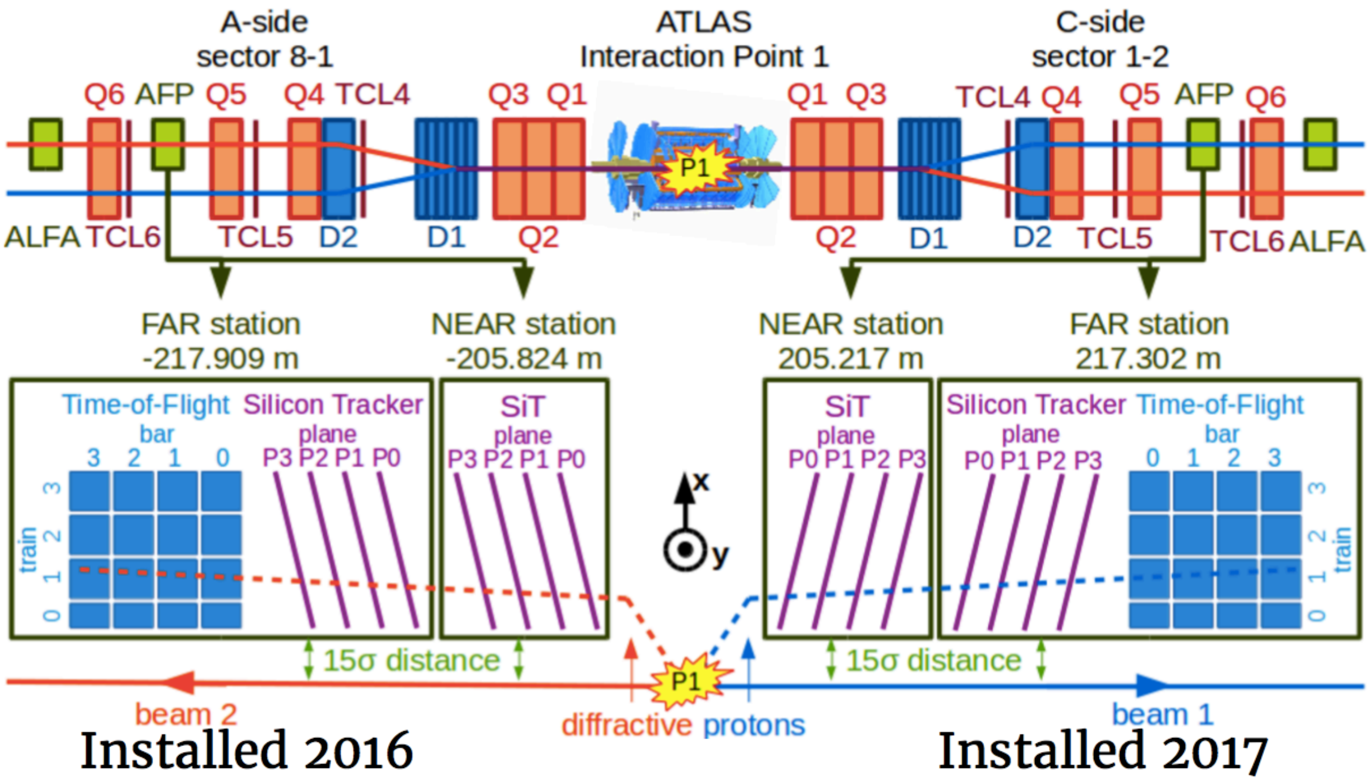


Detector Control System

- Main Portuguese responsibility for years

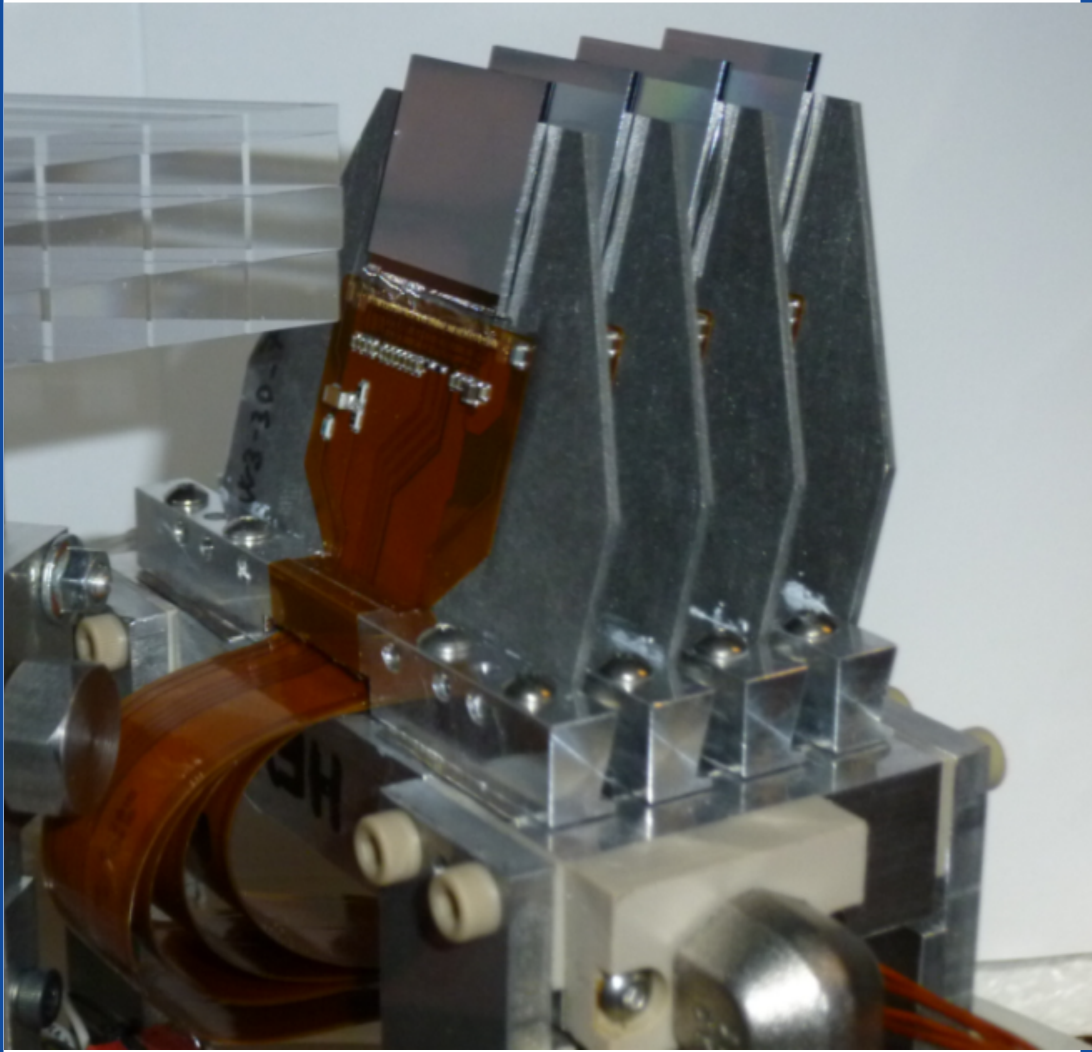
- Provides
  - Safe operation of the detector
  - Monitoring and control

ATLAS Forward Proton Tagging Detectors



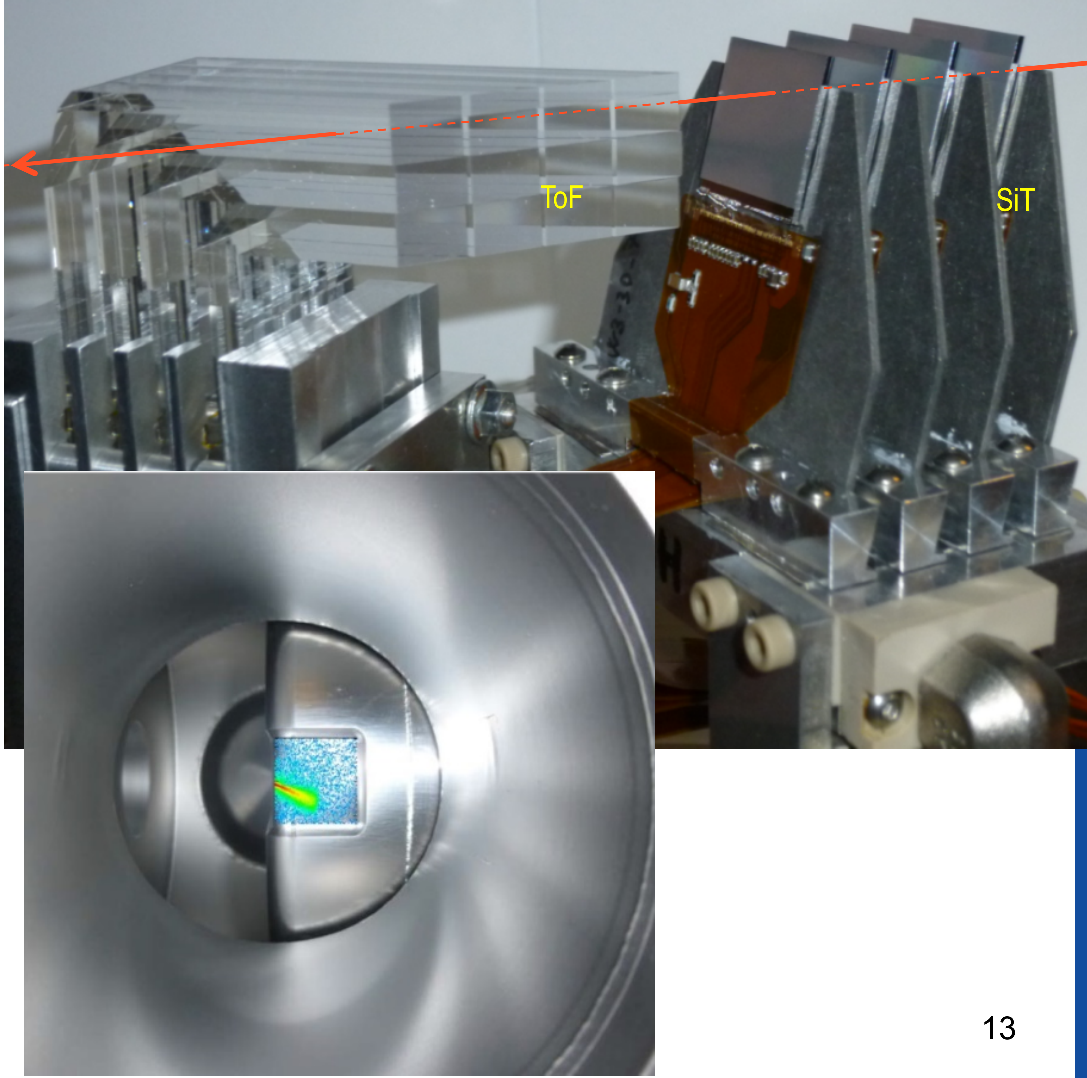
AFP

- Tracking detectors:
  - slim-edge 3D ATLAS IBL pixel sensors bonded with FE-I4 readout chips.
  - σx = 6 μm, σy = 30 μm
  - Trigger: majority vote (2 out of 3)

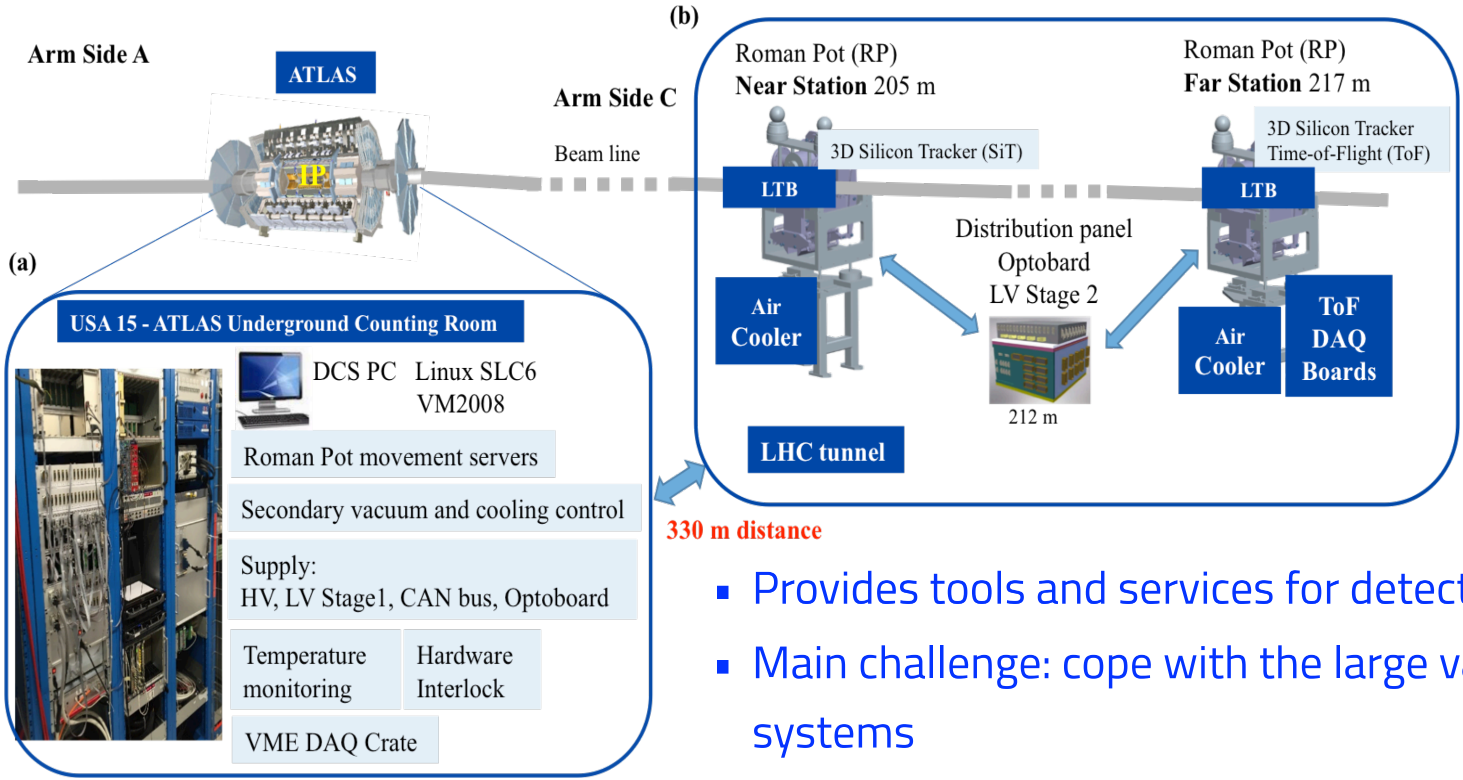


AFP

- Time of flight measurement
  - Pile-up suppression
    primary vertex z_{ID} and z_{ToF}
  - $\sigma_t \sim 20$ ps
- Quartz bars @ Cerenkov angle
- Readout by Photonis MCP-PMT
- Horizontally inserted RP



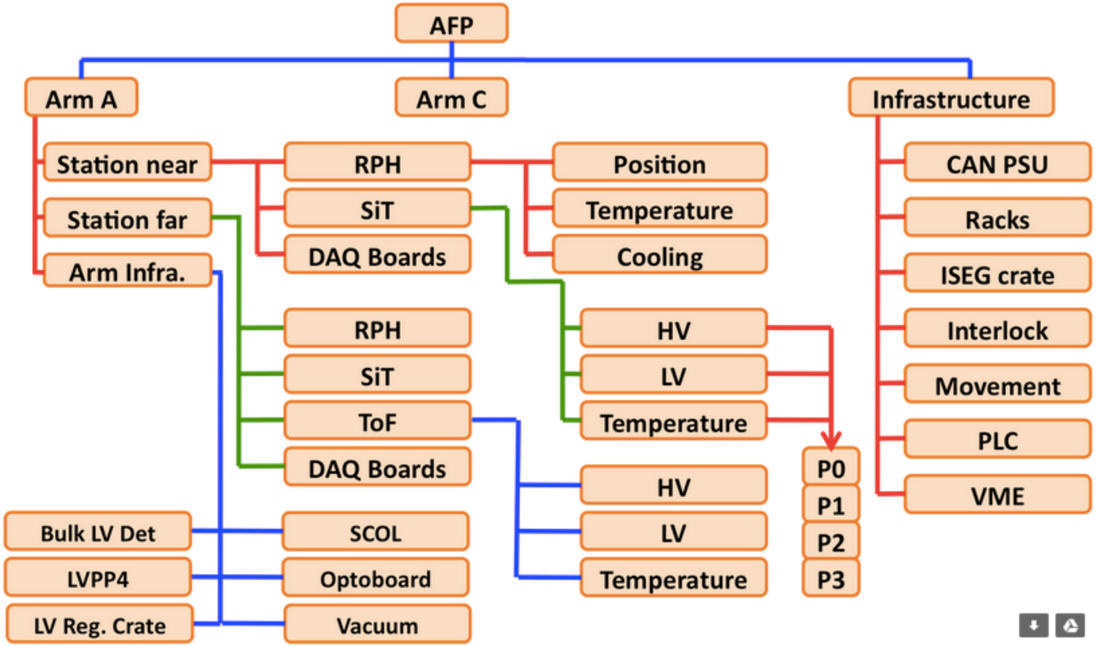
AFP Detector control system



- Provides tools and services for detector operation
- Main challenge: cope with the large variety of sub systems

AFP Detector Control System

- FiniteStateMachine
- Archiving
- Alerts
- Graphical user interfaces
-



AFP installation and data taking

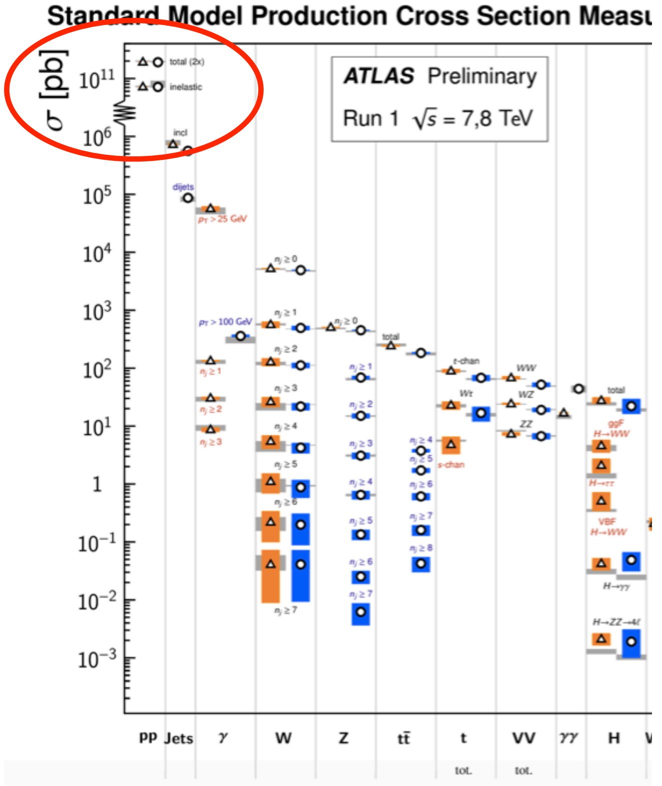
- Staggered installation
  - First arm in YETS 2016
  - Second arm and ToF detecto in YETS 2017
- Operation experience
  - No ToF measurement due to problems with MCP-PMT
    - Solutions in place for Run 3
  - Very low ToF efficiency but good timing resolution (σ_t=20-25 ps/p)
- 2017 data available for physics studies
- For Run 3:
  - New ToF detectors
  - Out-of-vacuum PMT solution —> long lifetime of the PMT
  - picoTDC: improve the timing!

Physics with diffracted protons

Integrated luminosity

Cross section

- High cross section processes:
  - Total cross section with ALFA
  - Single/double diffraction (differential distributions)
  - Other processes
- Medium cross section:
  - central exclusive production
- Low cross section:
  - Quartic Gauge Boson Couplings
  - FCNC in top quark production
  - Searches: dark matter



Total Production Cross Section Measurement

arXiv:1408.5778 arXiv:1607.06605

- Fundamental parameter of the strong interaction
- Study its evolution as $\sqrt{s}$ increases
- Measured using the optical theorem
  - Needs independent luminosity measurement
- As small t as possible
  - minimize model dependence!
  - special optics needed
    - β^* = 90 m

$$\sigma_{\text{tot}} = 4\pi \text{Im}\left[f_{\text{el}}\,(t \to 0)\right]$$

Elastic scattering amplitude
Extrapolated to zero momentum
Transfer

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|},$$

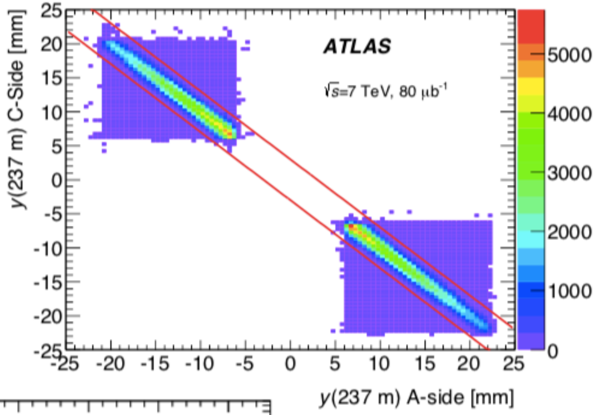
$$f_N(t) = (\rho + i)\frac{\sigma_{\text{tot}}}{\hbar c}e^{-B|t|/2}$$

Total Production Cross Section Measurement

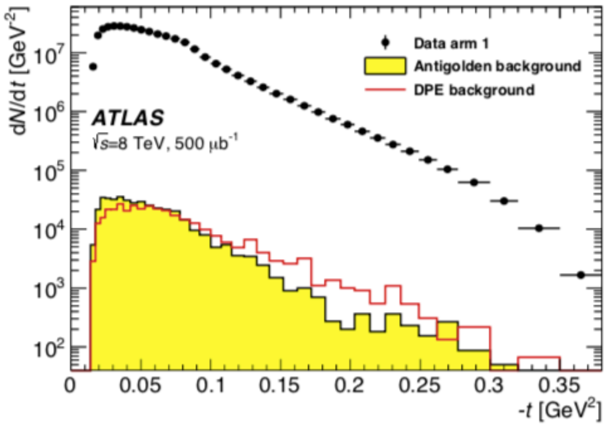
- 4-momentum transfer: $-t = \left(\theta^{\star} \times p\right)^2$
  - Use matrix method

$$\theta^{\star}_{w} = \frac{w_{\mathrm{A}} - w_{\mathrm{C}}}{M_{12,\mathrm{A}} + M_{12,\mathrm{C}}}$$

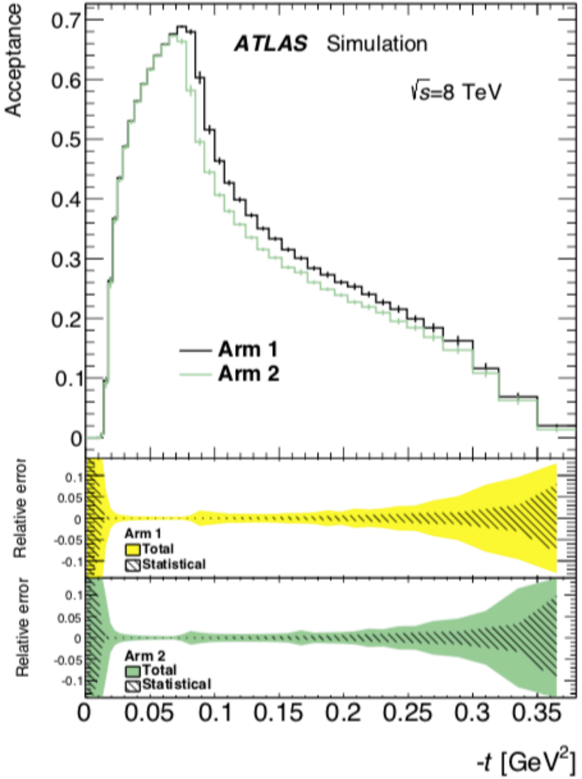
$$w = \{x, y\}$$



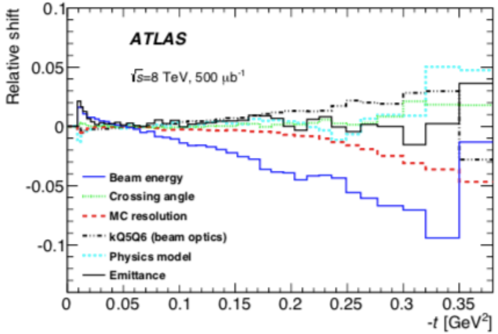
- Back-to-back p tracks
  - Reduce beam-halo backgrounds

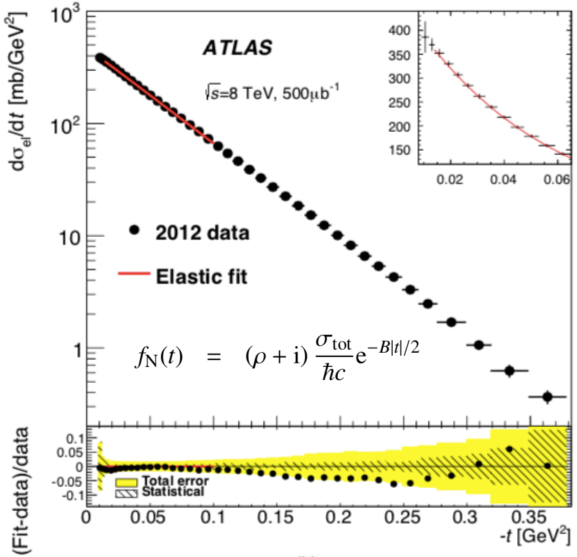


Total Production Cross Section Measurement



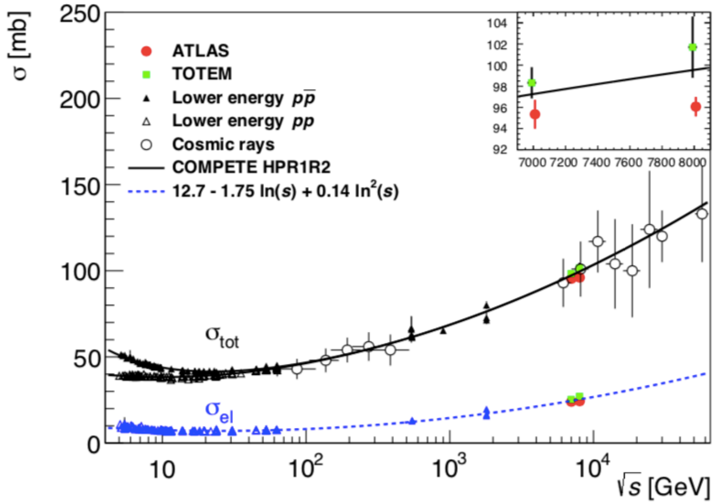
- Correct for acceptance and reconstruction efficiency
- Luminosity from Van der Meer scans calibrated at 10^{30} $cm^{-2}s^{-1}$
  - Precision 1.5%
- Dominating uncertainties:
  - beam momentum, luminosity





Total Production Cross Section Measurement

- Significant improved measurement with respect to previous ATLAS publications!

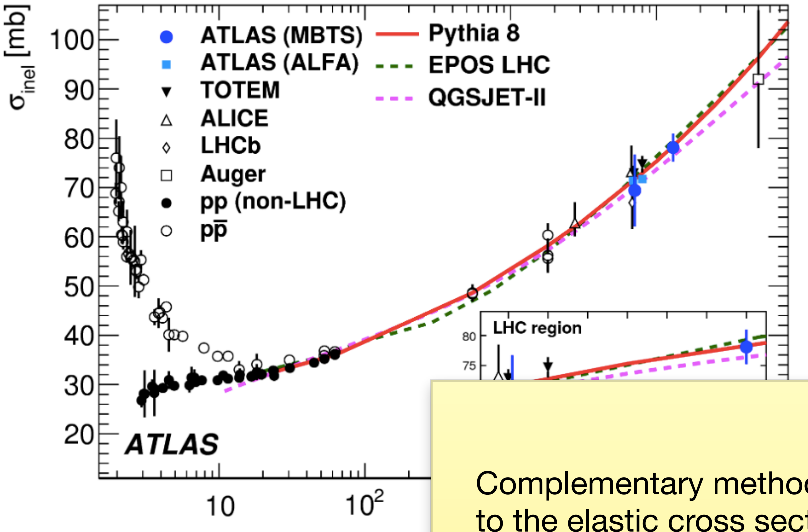


$$\sigma_{\text{tot}} = 96.07 \pm 0.18\ (\text{stat.}) \pm 0.85\ (\text{exp.}) \pm 0.31\ (\text{extr.})\ \text{mb}$$

$$\sigma_{\text{el}} = 24.33 \pm 0.04\ (\text{stat.}) \pm 0.39\ (\text{syst.})\ \text{mb}$$

$$\sigma_{\text{inel}} = 71.73 \pm 0.15\ (\text{stat.}) \pm 0.69\ (\text{syst.})\ \text{mb}$$

Inelastic cross sections measurements

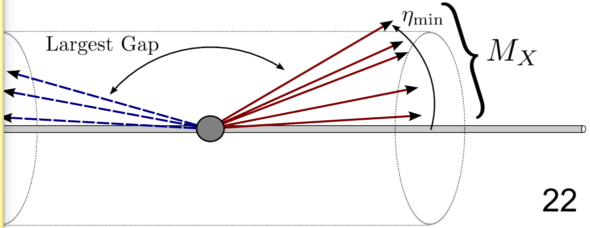


- ALFA measurements at 7 and 8 TeV
- Other measurements using MinBias scintillators and rapidity gaps
  - Sensitive to events with

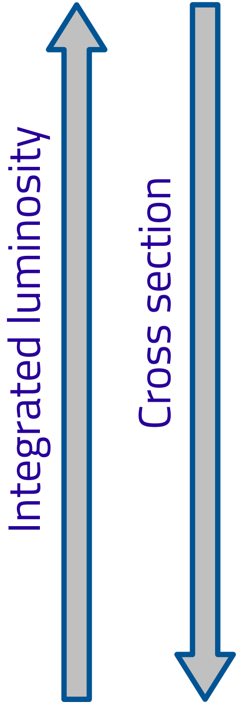
$$M_X > 13 \text{ GeV}$$

$$\xi = M_X^2/s > 10^{-6}$$

Complementary method, not sensitive to the elastic cross section
Only sensitive to inelastic events (including single diffraction)



Physics with diffracted protons



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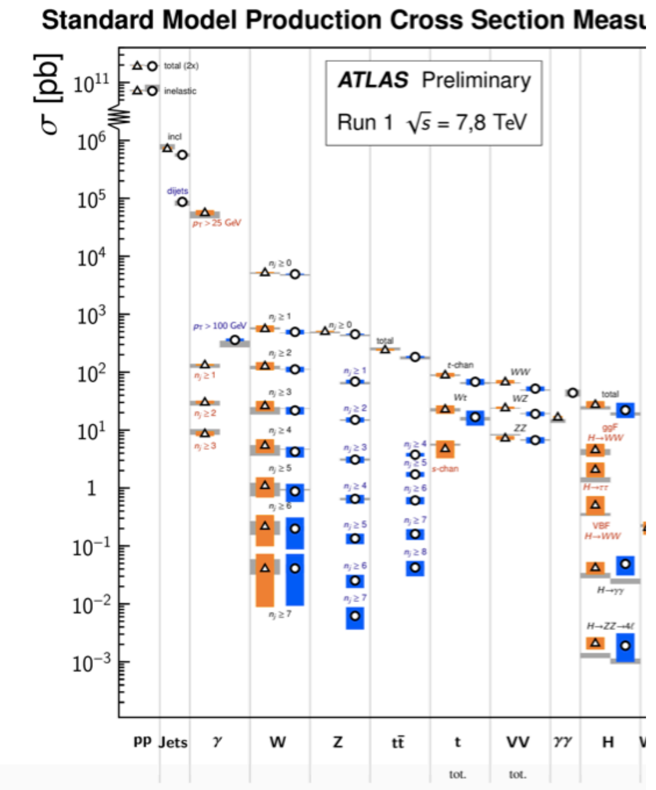
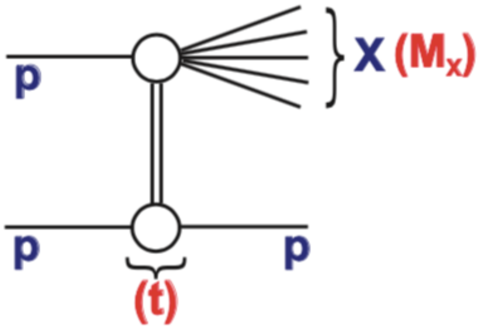
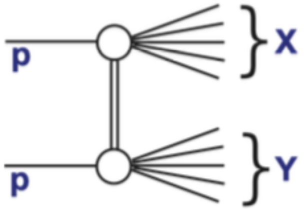


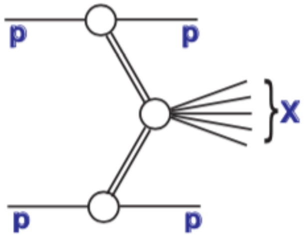
Single Diffractive Differential Cross Sections

arXiv:1911.00453

- Diffraction important to understand
  - Low-x proton structure
  - Cosmic ray air showers
  - Pile-up modelling
  - ...
- Phenomenologically described by the exchange of a pomeron
- Large uncertainties on predictions for the LHC
- Previous ATLAS measurements exploited large rapidity gaps

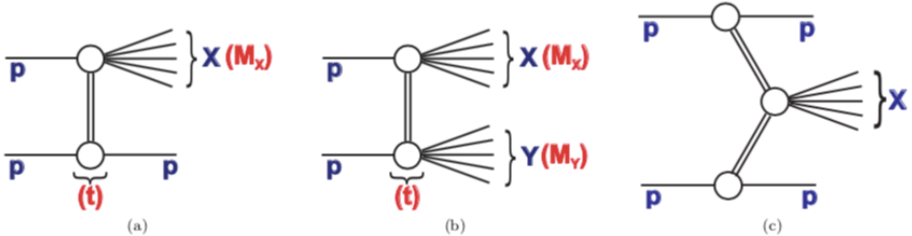


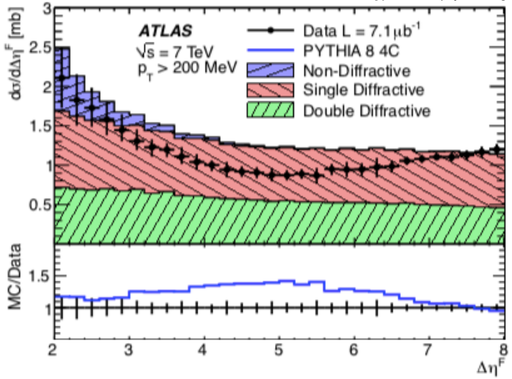


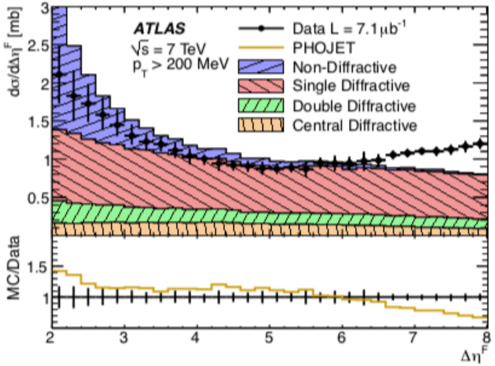


Diffractive Differential Cross Sections

arXiv:1201.2808

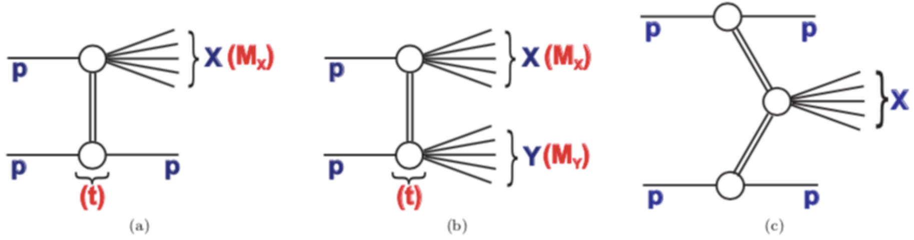






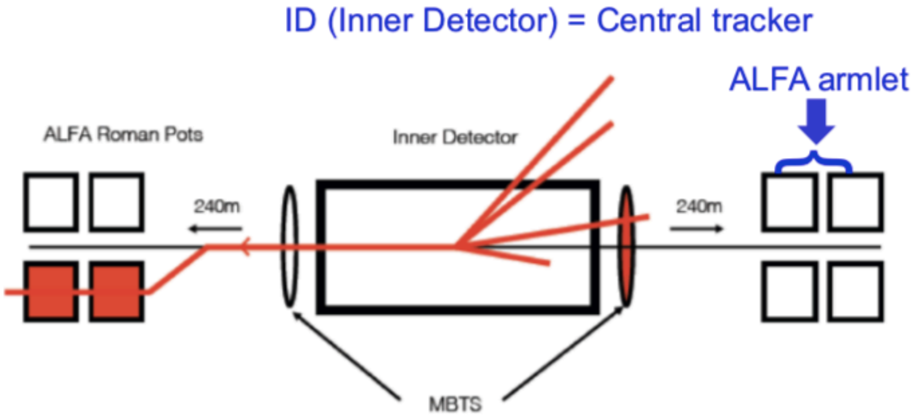
- Previous ATLAS measurements: inelastic cross section as a function of rapidity gap
  - Clearly establish the presence of diffractive component
  - Cannot distinguish between single and double diffraction
  - Large uncertainty on model predictions!!
- Forward proton tagging can see the differences!

Diffractive Differential Cross Sections @ 8 TeV



- Recent measurement of single diffraction
  - Exclude double diffraction/non-diffractive
  - Identify intact final state proton with ALFA
    - Local precision: 30 μm (x, y)
- Dedicated data taking in 2012 (high β^*)
  - ALFA measurement of 4-momentum transfer t and

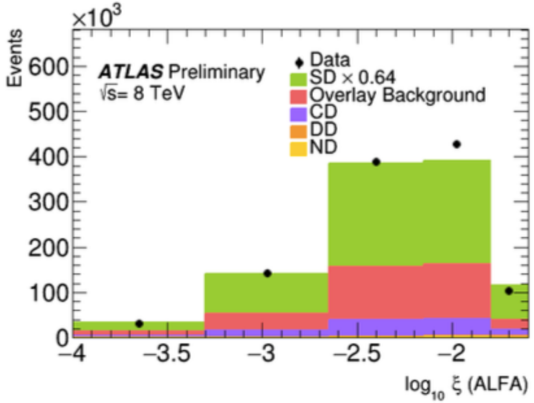
$$\xi = \frac{M_X^2}{s}$$

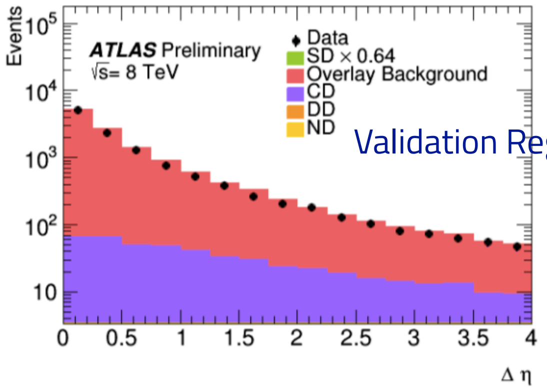


Diffractive Differential Cross Sections @ 8 TeV

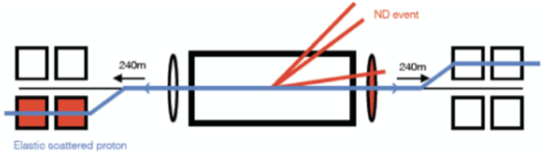
arXiv:1911.00453

- p E loss reconstructed from ID: $\xi \simeq \frac{\sum_i E^i \pm p_z^i}{\sqrt{s}}$
  - Min pT 100 MeV
  - Corrected for neutral particles
  - Cross-checked using ALFA $\xi_p = 1 - \frac{E_{p'}}{E_p}$
- Backgrounds:
  - Central diffraction: estimated from MC
  - Overlay: pile-up, beam background, ...
    - Data driven: activity in all MBTS, accidental p
  - Modelling cross checked with validation region





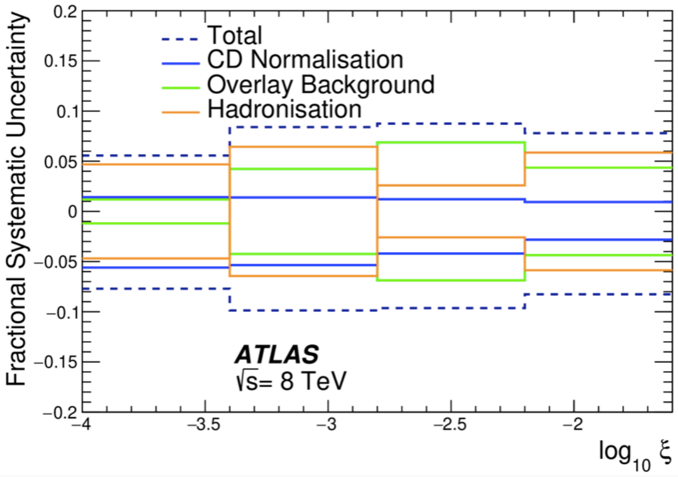
Validation Region

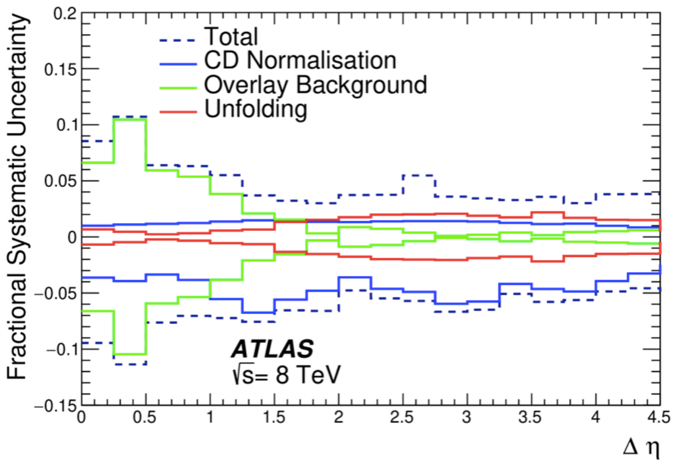


Diffractive Differential Cross Sections @ 8 TeV

arXiv:1911.00453

- Bayesian iterative unfolding
- Dominant systematics



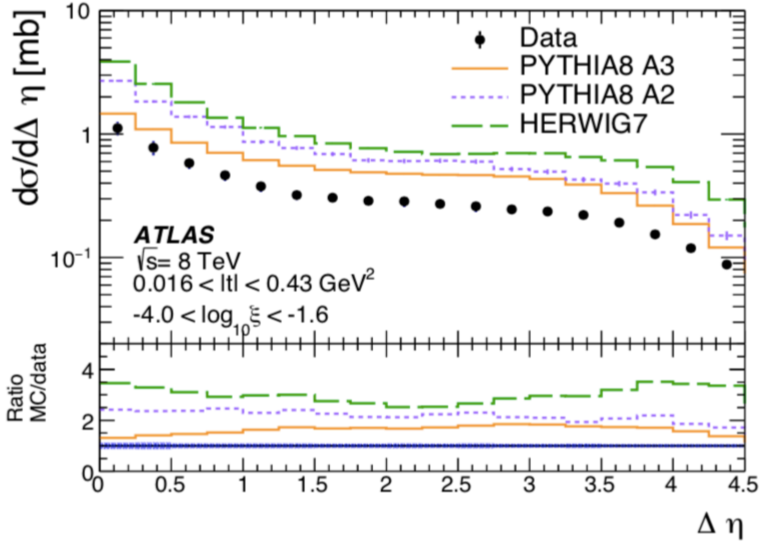


Diffractive Differential Cross Sections @ 8 TeV

arXiv:1911.00453

- Pythia 8 A3:
  - Tripple Regge formalism
  - Pomeron with trajectory $\alpha(t) = \alpha(0) + \alpha' t$
  - 'Donnachie–Landshoff' pomeron flux factor

    $\alpha(0) = 1.07$
- Pythia 8 A2:
  - Schuler–Sjöstrand pomeron flux factor $\alpha(0) = 1$
- H1 2006 Fit B diffractive pdfs
- Herwig7: similar model to Pythia A3 but final state particle dissociation according to multi-peripheral model

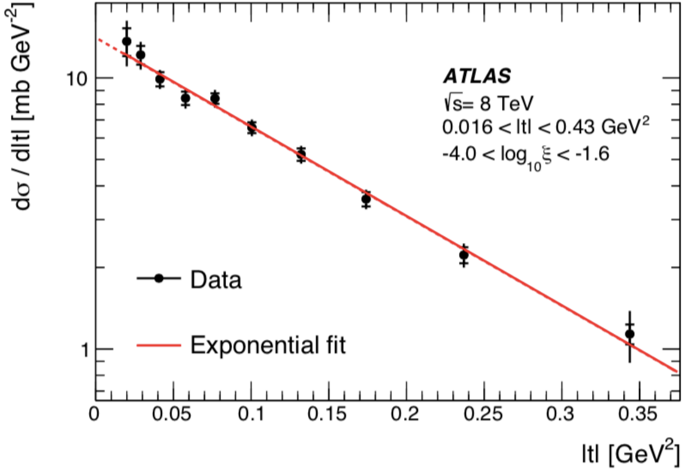


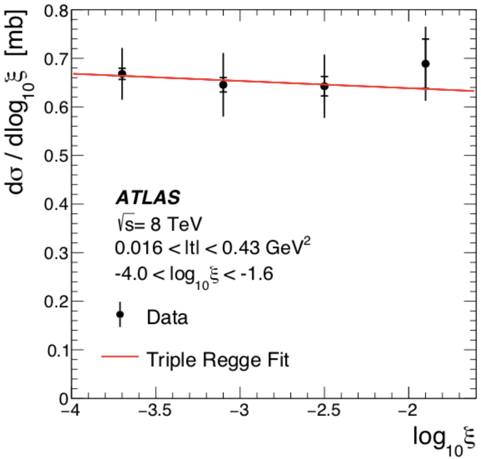
$$-4.0 < \log_{10} \xi < -1.6$$

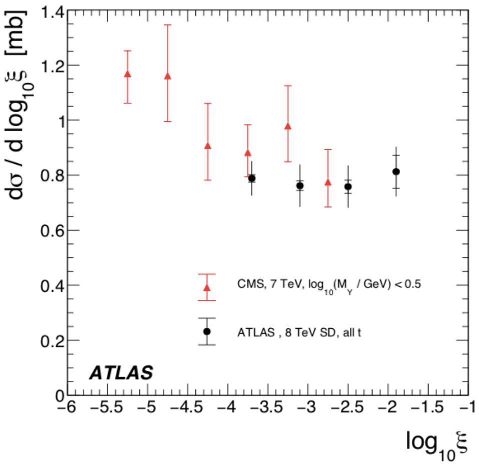
$$0.016 < |t| < 0.43 \text{ GeV}^2$$

Diffractive Differential Cross Sections @ 8 TeV

arXiv:1911.00453







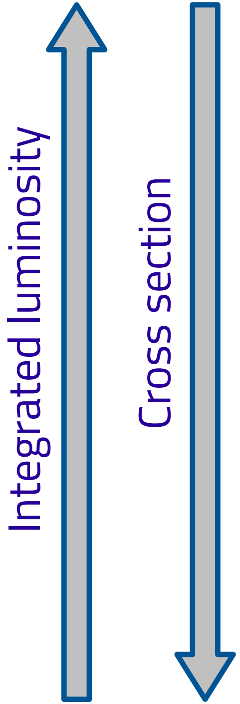
- Exponential fit:

$$B = 7.65 \pm 0.26(\text{stat.}) \pm 0.22(\text{syst.})\ \text{GeV}^{-2}$$

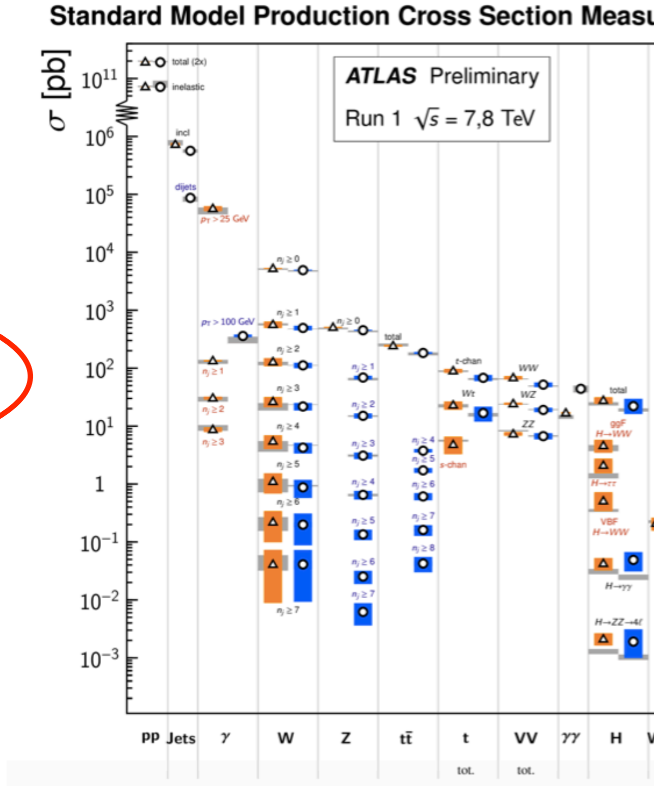
$$\frac{d^2\sigma}{d\xi dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-1} (M_X^2)^{\alpha(0)-1}\ e^{B_0 t}$$

  - Agreement with Donnachie–Landshoff/Schuler–Sjöstrand within 1.6σ/0.5σ

Physics with diffracted protons

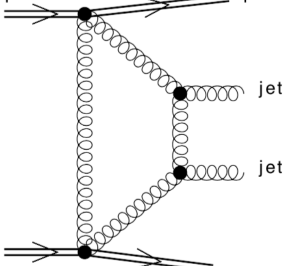


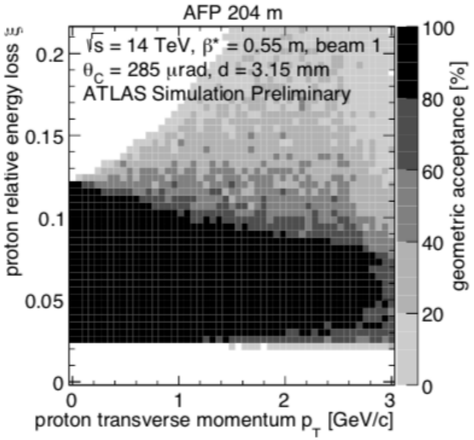
- High cross section processes:
  - Total cross section with ALFA
  - Single diffractive deferential distributions
  - Other processes
- Medium cross section:
  - central exclusive di-jet production
- Low cross section:
  - Quartic Gauge Boson Couplings
  - FCNC in top quark production
  - Searches: dark matter



Central-exclusive di-jet production

ATL-PHYS-PUB-2015-003





- Exclusive: only di-jet system produced centrally
  - No colour exchange between p
  - Central system: $J^{PC} = 0^{++}$ state
- Measurement requires AFP detector
  - High luminosity needed
  - Proton kinematics measurement
  - Proton-vertex reconstruction —> ToF
    - Background rejection

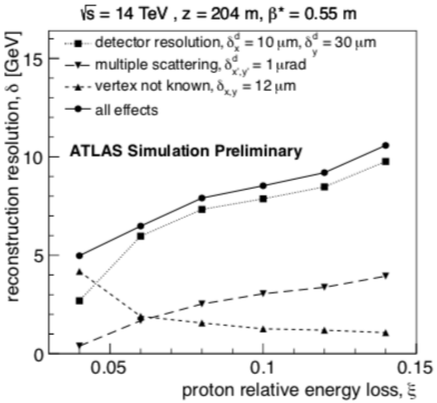
$$\xi_p = 1 - \frac{E_{p_{proton}}}{E_{p_{beam}}}$$

$$z_{vtx} = c(t_A - t_C)$$

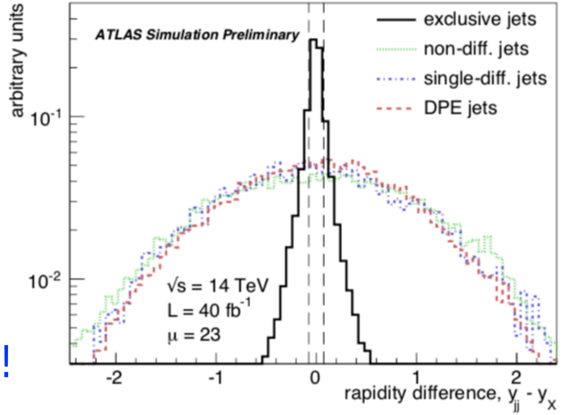
CEP dijet expectations at ATLAS

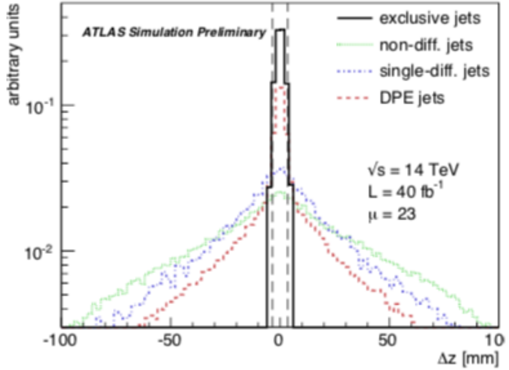
ATL-PHYS-PUB-2015-003

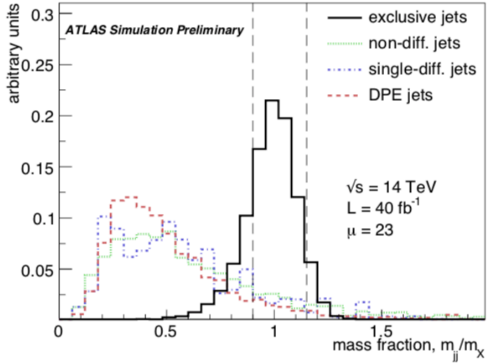
- p energy resolution:



- Event selection based on exclusivity



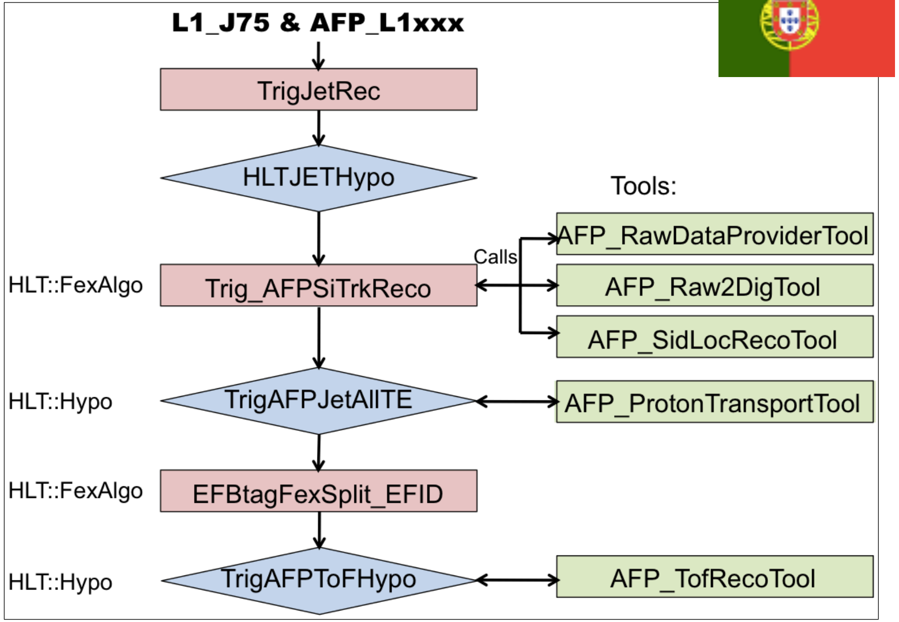




- Requires especial triggers!

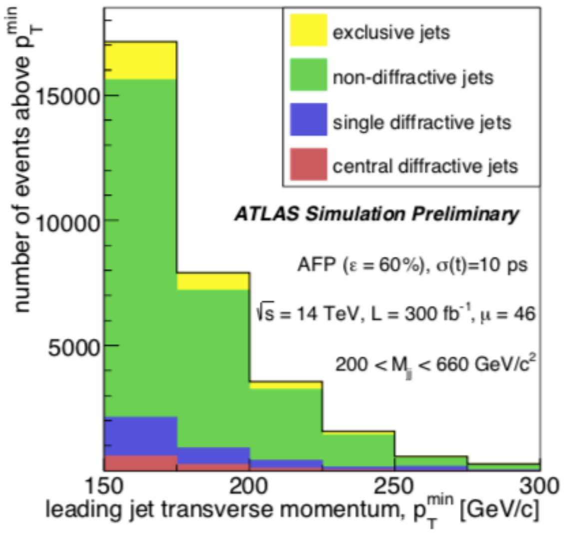
AFP Central Exclusive Production di-jet trigger

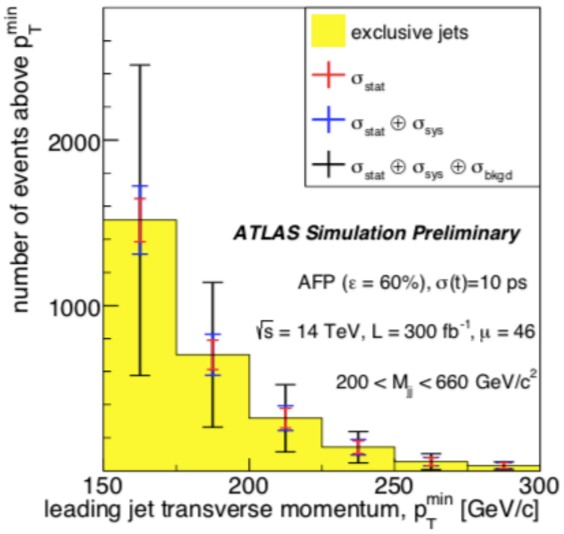
- Being developed at LIP
  - Start from coincidence L1 and AFP
  - Reconstruct HLT jets
    - pT threshold on jets
  - Reconstruct AFP tracks
    - Require two good tracks
    - Match track kinematics to di-jet system
  - Reconstruct proton vertex using ToF
    - Match to primary vertex reconstructed with ID tracks
- Can be the base for new AFP based triggers



CEP dijet expectations at ATLAS

ATL-PHYS-PUB-2015-003



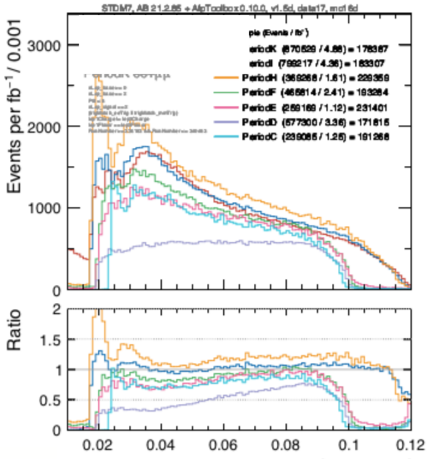


Dominant uncertainties from combinatorial background (ND events)

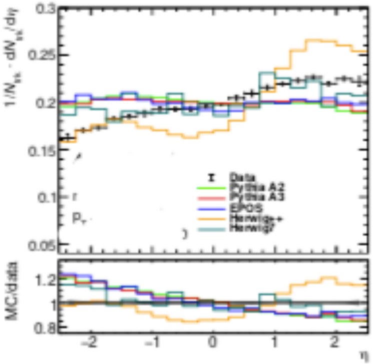
Improvements require

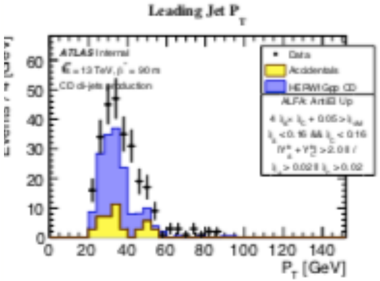
- improved background measurements
- Good timing resolution

Other physics topics

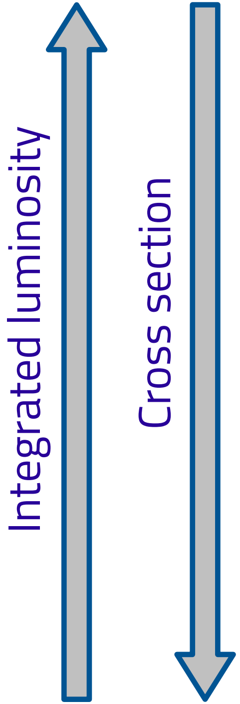


- Diffractive jets with ALFA
- Charged particle distributions in diffractive events
- Single diffraction at 13 TeV
- Exclusive dilepton production
- Exclusive pion production
- Strange production in diffractive events
- And more results to come…





Physics with diffracted protons



- High cross section processes:
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  - FCNC in top quark production
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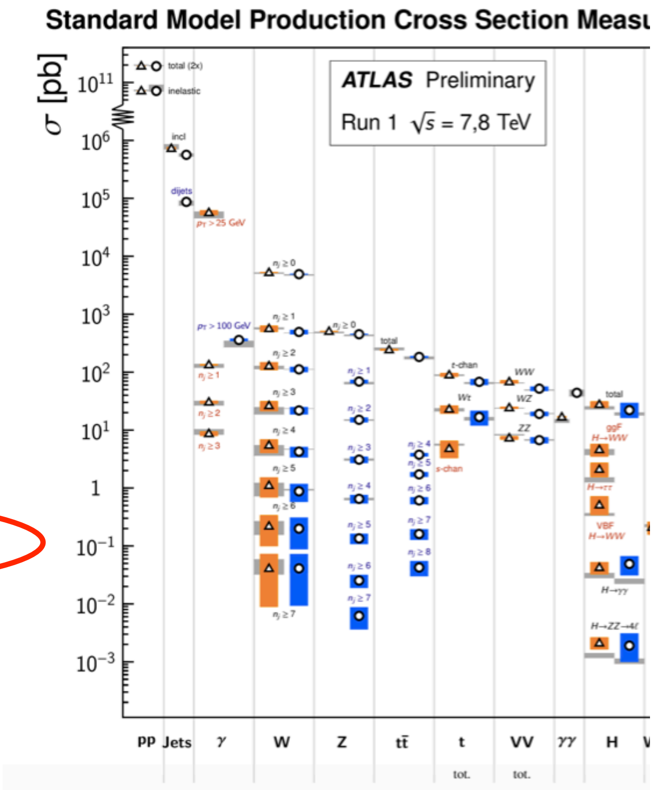
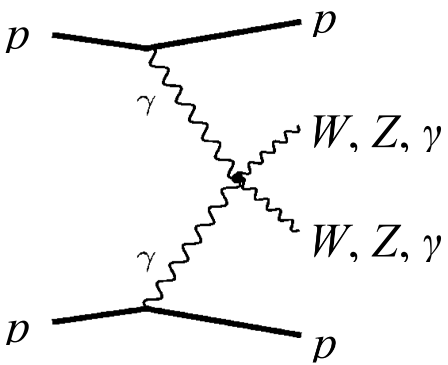
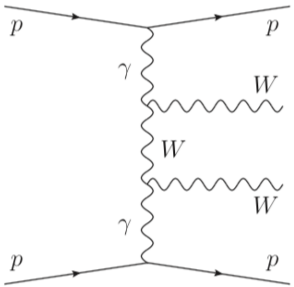


Quartic gauge boson couplings

- AFP converts the LHC in a photon-photon collider!
- Triple and Quartic Gauge Boson Couplings introduced in the SM due to the non abelian nature of the EW symmetry
- Very precise predictions:
  - WWWW, $\gamma\gamma$WW, WWZZ exist
  - ZZZZ, $\gamma\gamma$ZZ: only at loop level
  - Might be modified by BSM physics
- Exclusive production
  - Match kinematic properties of central system and in AFP
  - Timing information important for vertex reconstruction and pile-up suppression



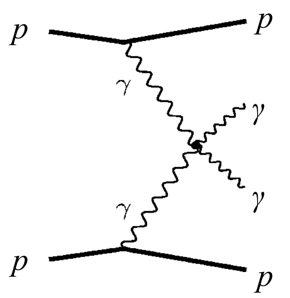


Search for $\gamma\gamma\rightarrow\gamma\gamma$ anomalous couplings

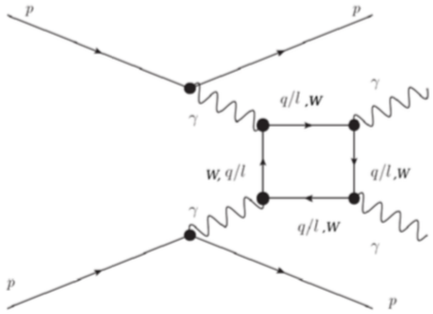
$$\mathcal{L}_{\gamma\gamma\gamma\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu}$$

- New physics at a mass scale Λ >> E accessible
  - Effective Lagrangian with new operators (dim-8 for photons)
    - Loops of heavy charged particles could contribute
    - Proporcional to (charge)^4

      Enhanced for particles with large charges (composite Higgs models)
    - Extra dimensions models, strongly coupled conformal extensions of the SM predict couplings ~10-^{13}, 10^{-14}

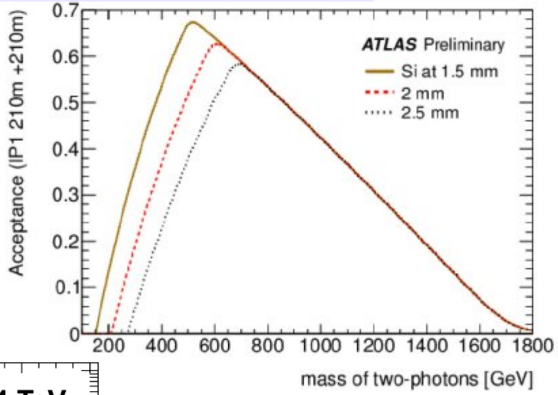


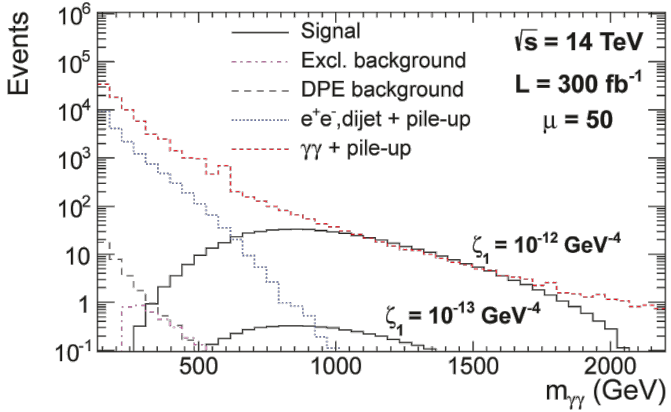
  - Backgrounds:
    - SM $\gamma\gamma\rightarrow\gamma\gamma$ produced via gluon/quark loops, $\gamma\gamma\rightarrow$ee
    - CEP $\gamma\gamma$ production
    - CEP di-jets misidentified
    - Accidental coincidence of non-diffractive $\gamma\gamma$ + diffractive proton interactions

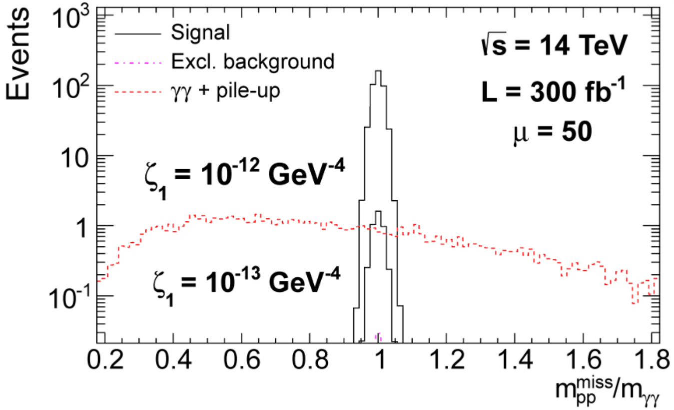


Search for $\gamma\gamma \rightarrow \gamma\gamma$ anomalous couplings

- Background rejection:
  - Large invariant di-photon mass
  - Matching pp kinematics to di-photon system
    - Rapidity, missing mass, vertex



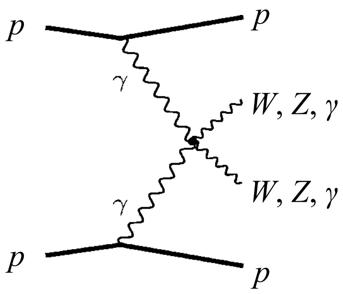




From M. Saimpert, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon; EPJ Web of Conferences **90**, 06001 (2015)

Search for $\gamma\gamma \rightarrow \gamma\gamma$ anomalous couplings

$$\mathcal{L}_{\gamma\gamma\gamma\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu}$$



- Sensitivity reaching extra-dimensions models with 300 fb^{-1} of collected luminosity!

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1. \cdot 10^{-13}$	$9. \cdot 10^{-14}$	$5. \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$7. \cdot 10^{-15}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1. \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3. \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

EPJ Web of Conferences **90**, 06001 (2015)

Quartic gauge boson couplings $\gamma\gamma$WW, $\gamma\gamma$ZZ

- Similar process
- Allow to impose limits on dim-6 operators:

$$\mathcal{L}_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

CERN-LHCC-2011-012

Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 10^{-6} (2.5 10^{-6})
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10^{-5} (2.0 10^{-5})	2.4 10^{-5} (9.2 10^{-6})

- Improve LEP sensitivity by more than 4 orders of magnitude
- AFP improves the results obtained with central detector only by 2 orders of magnitude
- Reaches the sensitivity needed for extra-dimensions models!!

Quartic gauge boson couplings $\gamma\gamma$WW, $\gamma\gamma$ZZ

- Similar process
- Allow to impose limits on dim-6 operators:

$$\mathcal{L}_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2\theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

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a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10^{-5} (2.0 10^{-5})	2.4 10^{-5} (9.2 10^{-6})

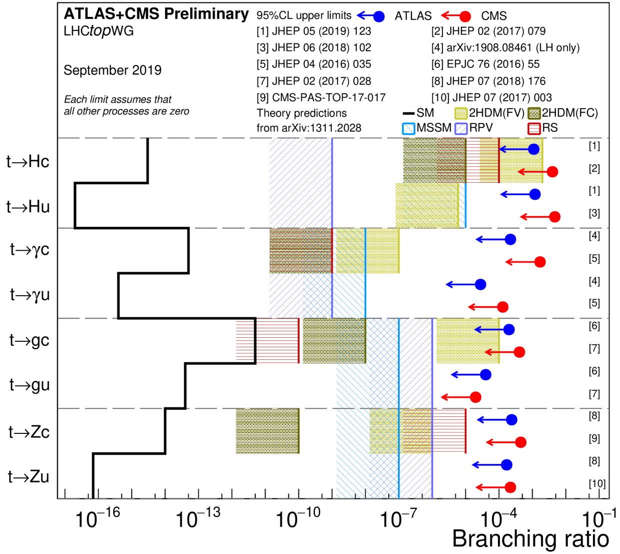
- Current CMS limits using forward p tagging

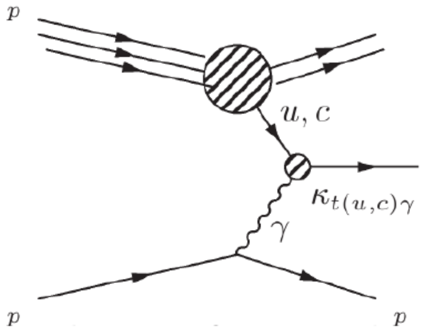
$$-0.00015 < a_0^W/\Lambda^2 < 0.00015\,\mathrm{GeV}^{-2}$$
$$-0.0005 < a_C^W/\Lambda^2 < 0.0005\,\mathrm{GeV}^{-2}$$

$$(a_C^W/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$(a_0^W/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}).$$

Flavour Changing Neutral Currents in top production

- FCNC top quark interactions strongly suppressed in the SM
  - Can be considerably enhanced in New Physics



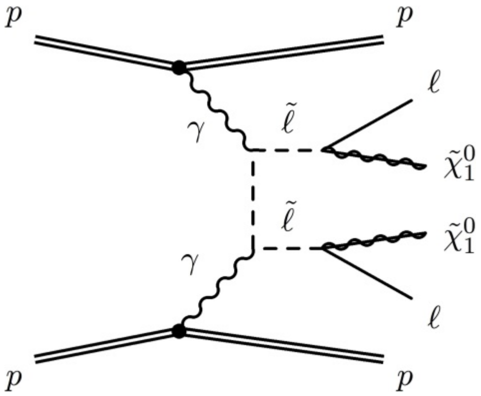


- Probing utγ and ctγ couplings
- Single diffractive mode
- Main irreducible backgrounds: γp interactions producing a W+jets
- Complements other analysis done at ATLAS

Search for dark matter

- SUSY compressed mass scenario
  - Small mass splitting between neutralino and
    - small MET, low lepton momentum
- Photo-production of electrowe
  - Well defined initial stat , precise mass measurement
  - Clear signatures!
- Truth-level study

Need dedicated triggers!



1812.04886 [hep-ph] V. Khoze, L. Harland-Lang, M. Ryskin, and M. Tasevsky

Di–lepton	$5 < p_{T,l_1,l_2} < 40$ GeV	$\lvert\eta_{l_1,l_2}\rvert < 2.5$ (4.0)
	Aco $\equiv 1 - \lvert\Delta\phi_{l_1 l_2}\rvert/\pi > 0.13$ (0.095)	$2 < m_{l_l l_2} < 40$ GeV
	$\Delta R(l_1, l_2) > 0.3$	$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 2.3$
	$\bar{\eta} \equiv \lvert\eta_{l_1} + \eta_{l_2}\rvert/2 < 1.0$	$\lvert\lvert \vec{pT}_{l_1}\rvert - \lvert \vec{pT}_{l_2}\rvert\rvert > 1.5$ GeV
	$W_{\text{miss}} > 200$ GeV	
FPD	$0.02 < \xi_{1,2} < 0.15$	$p_{T,\text{proton}} < 0.35$ GeV
No–charge	No hadronic activity	z-veto

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$ 0	10	50
Excl. sleptons	0.6—3.9	0.5—3.3	0.3—1.9
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.1(0.1)	1.8(2.4)

Conclusions

- Forward proton tagging enlarges the physics topics of ATLAS
  - Single diffraction, central diffraction, …
  - Searches for anomalous quartic gauge boson couplings, dark matter, FCNC in top quark production, …
- The Portuguese ATLAS group has contributed to
  - Fibres preparation for ALFA
  - Detector control system (ALFA, AFP)
  - Exclusive trigger implementation and performance
- Preparations for the Run 3 are going
  - Expect a wealth of data to analyse
  - Small group of people —> help is needed!

Thanks!

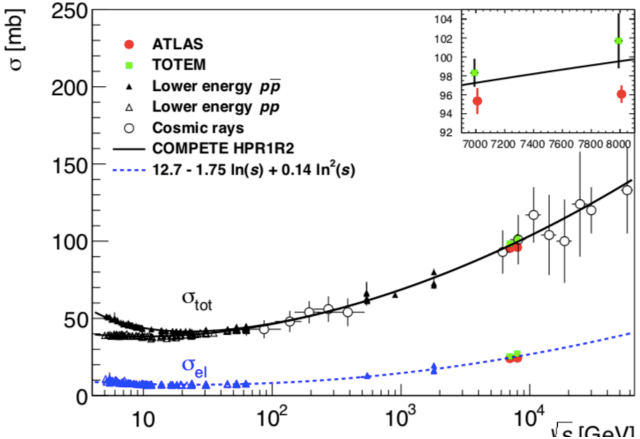
Acknowledgments

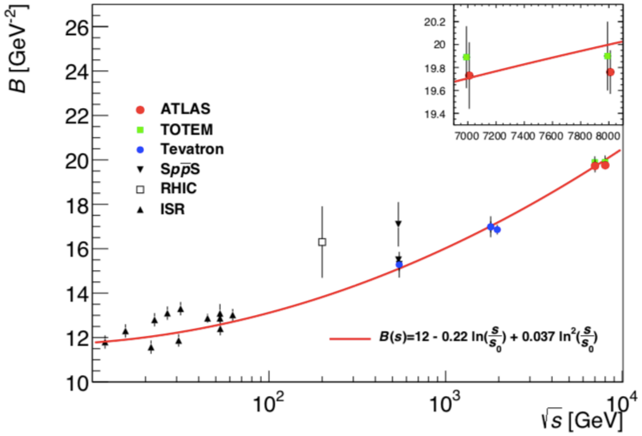
REPÚBLICA PORTUGUESA

FCT Fundação para a Ciência e a Tecnologia

Backup

Total Production Cross Section Measurement





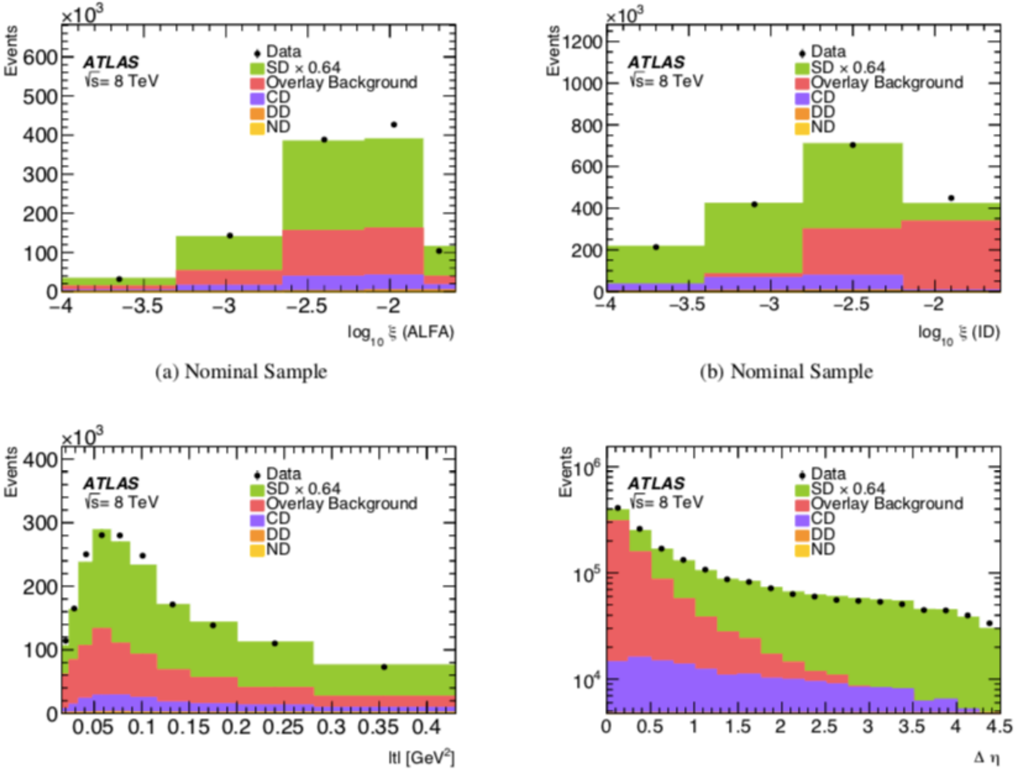
$$\sigma_{\text{tot}} = 96.07 \pm 0.18\ (\text{stat.}) \pm 0.85\ (\text{exp.}) \pm 0.31\ (\text{extr.})\ \text{mb}$$

$$\sigma_{\text{el}} = 24.33 \pm 0.04\ (\text{stat.}) \pm 0.39\ (\text{syst.})\ \text{mb}$$

$$\sigma_{\text{inel}} = 71.73 \pm 0.15\ (\text{stat.}) \pm 0.69\ (\text{syst.})\ \text{mb}$$

$$\sigma_{\text{el}} = \frac{\sigma_{\text{tot}}^2}{B} \frac{1+\rho^2}{16\pi(\hbar c)^2}$$

Difractive dissociation

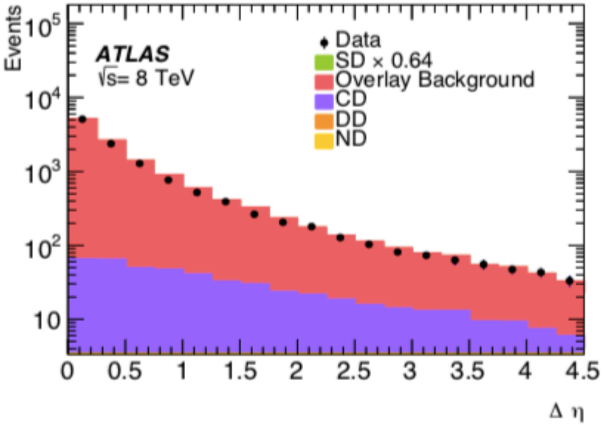


(a) Nominal Sample
(b) Nominal Sample
(c) Nominal Sample
(d) Nominal Sample

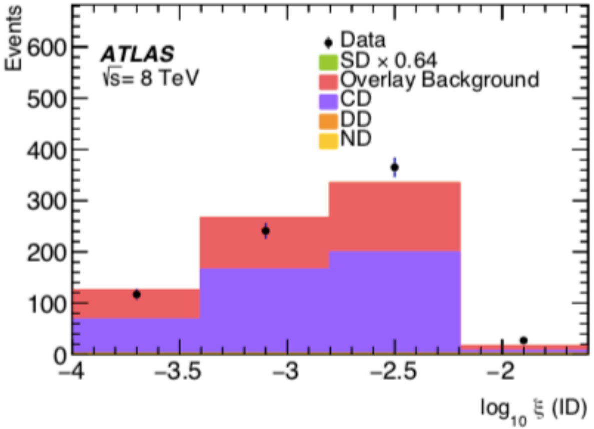
- Distributions before unfolding

Difractive dissociation

- Contro regions



(e) Control Region 1



(f) Control Region 2

CEP di-jets

Table 2: Requirements used to separate exclusive jet signal from backgrounds.

Requirement	Value
Two good quality leading jets with the transverse momentum of the leading jet.	$p_T > 150$ GeV/c
Distance between the hard interaction vertex reconstructed by ATLAS and from the one obtained from the AFP time measurement.	$\|\Delta z\| < 3.5$ mm
Azimuthal angle between two leading jets.	$2.9 < \Delta\phi < 3.3$
Difference of rapidity of the jet system and rapidity of the proton system.	$\|y_{jj} - y_X\| < 0.075$
Ratio of mass of the jet system to missing mass.	$0.9 < \frac{m_{jj}}{m_X} < 1.15$
Missing mass.	$m_X < 550$ GeV/c^2
Mass fraction which aims to reduce the effects of hard final state radiation.	$0.9 < R_j < 1.3$
Number of tracks outside of the jet system in η.	$n_{trk}^{eta} < 5$
Number of tracks perpendicular to the leading jet in ϕ.	$n_{trk}^{phi} < 2$