

# ATLAS-LHC and Ultra High Energy Cosmic Ray Physics

ISVHECRI-2016 Moscow

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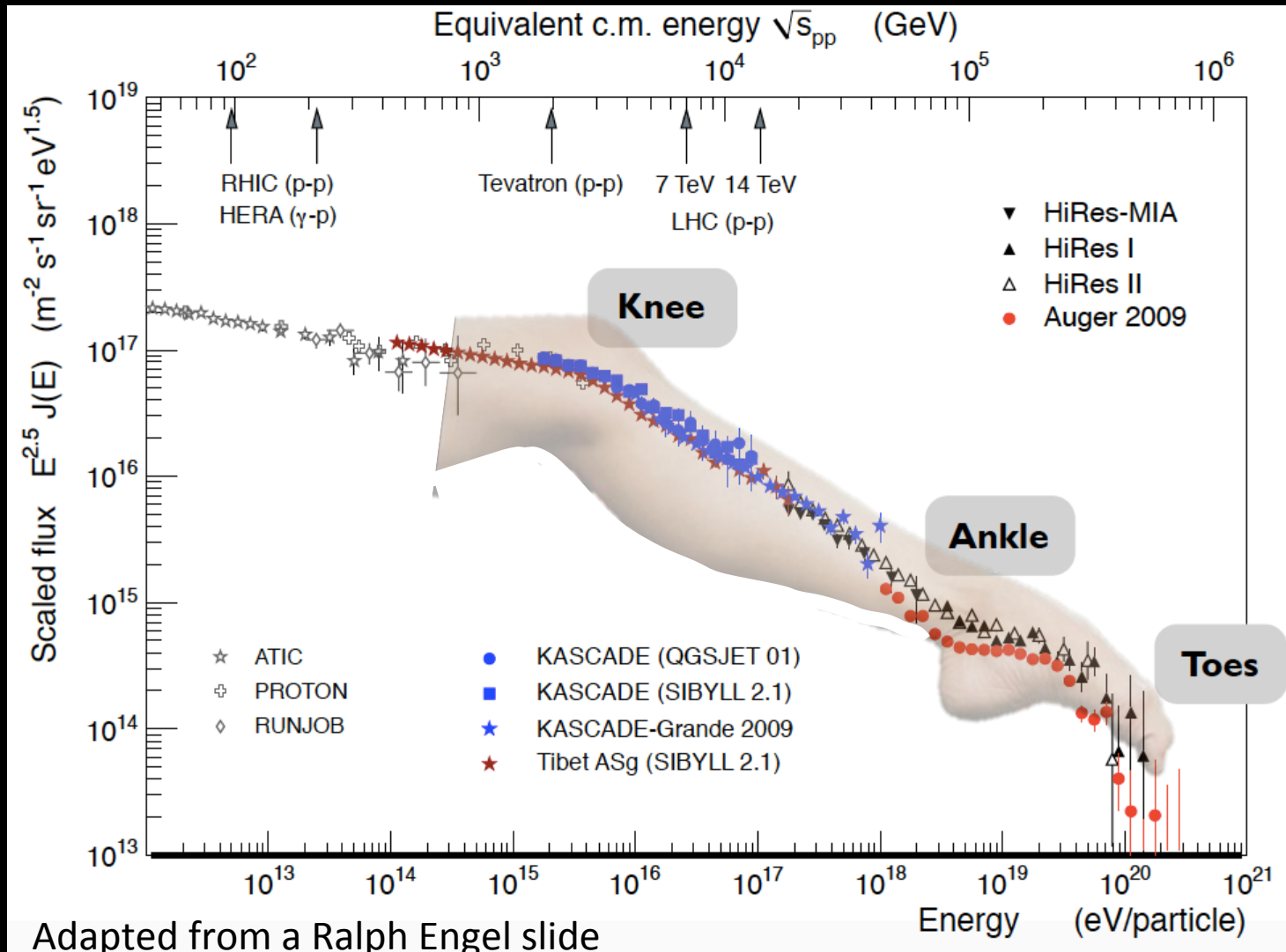
# *MENU*

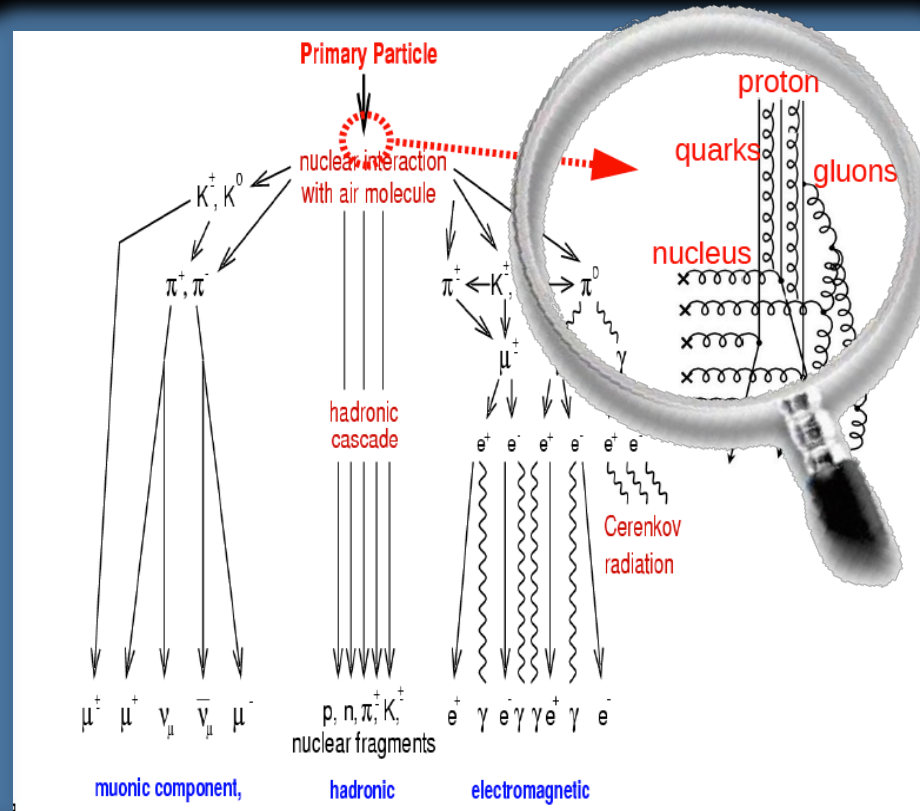
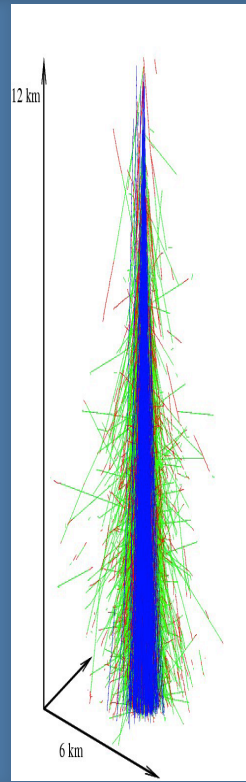
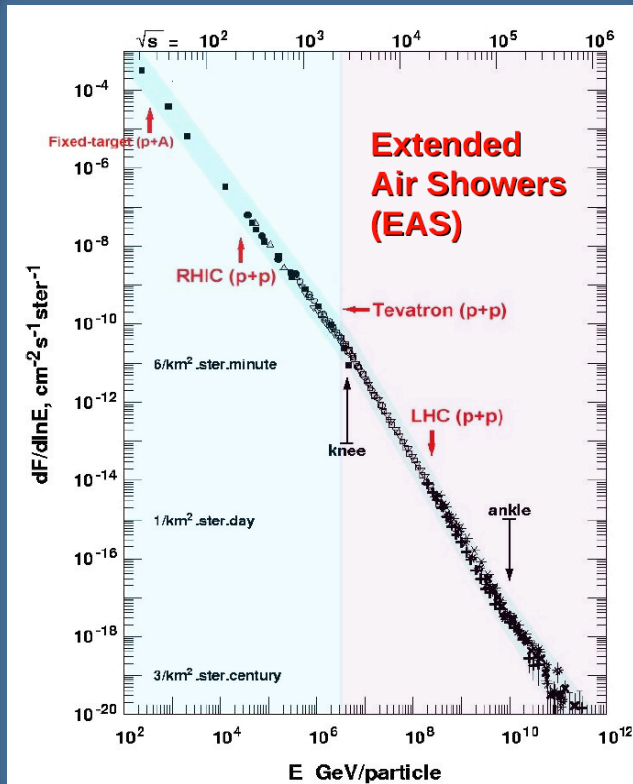
- 1. Introduction*
- 2. ATLAS and its forward detectors*
- 3. The p-p total, inelastic and elastic cross-section*
- 4. p-p charged particle distributions*

# *MENU*

- 5. Examples of Implications for High Energy Cosmic Ray physics*
- 6. New developments*
- 7. SUMMARY and conclusion*

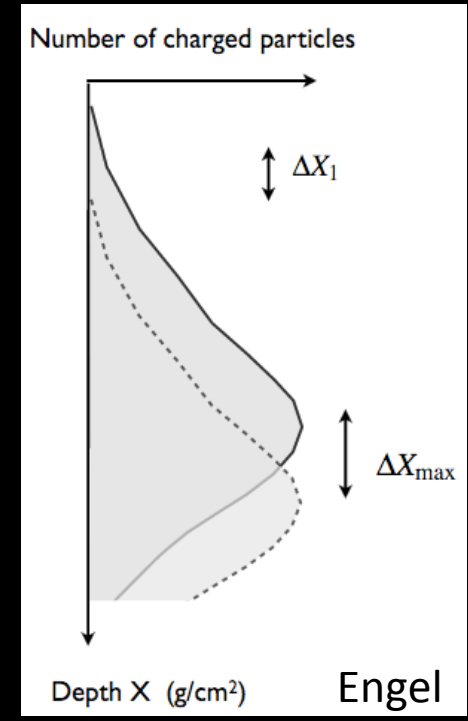
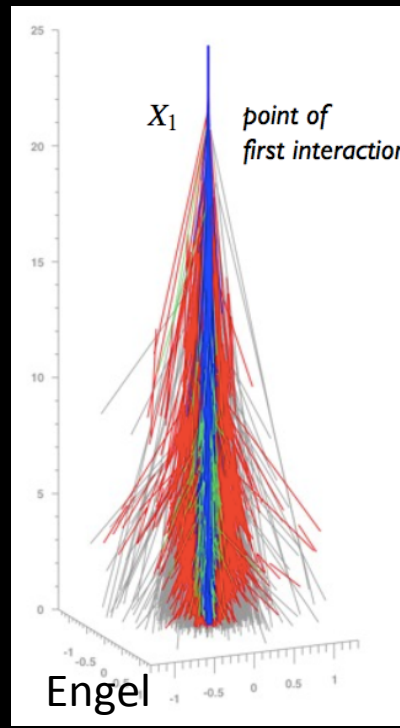
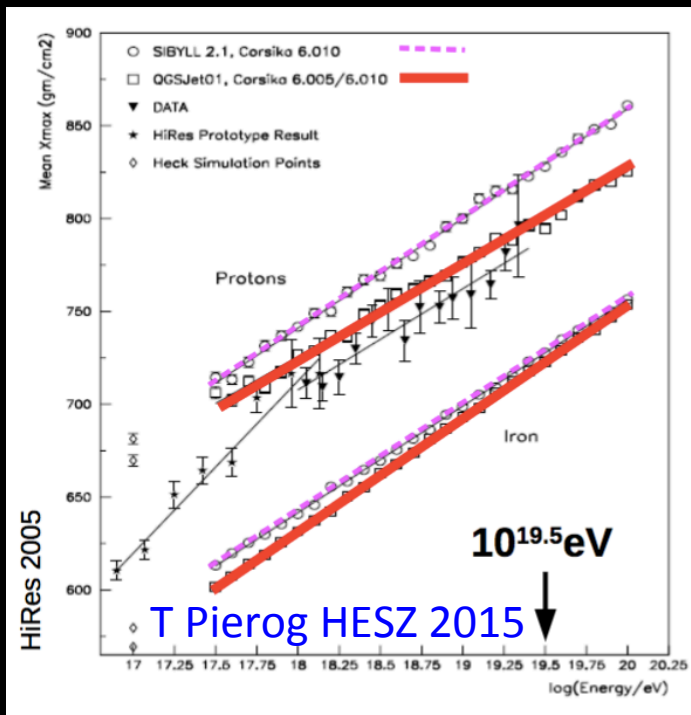
# The Cosmic Ray Spectrum





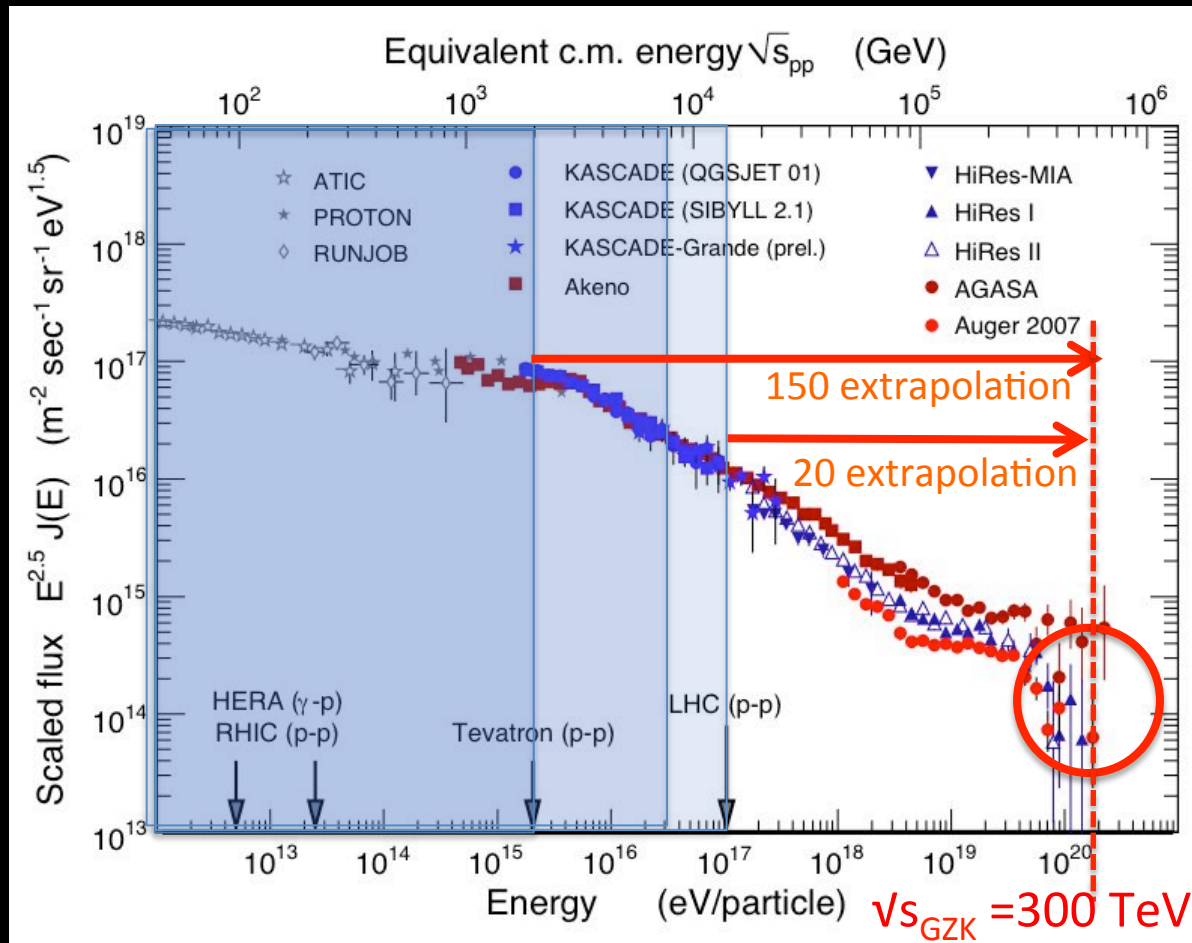
- Above  $\sim 10^{15}$  eV CR energy & ID determined via hadronic MCs
  - $p$ -N collisions: QCD interactions at  $E_{cm}$  up to  $\sqrt{s}_{GZK} \sim 300\text{TeV}$
- Many questions: origin of the structures in the energy spectrum? What is the sources & composition of UHECRs?

# UHECR Mass Composition



- Mean  $X_{max}$  can be used to determine CR composition
- In 2006 the main hadronic models utilized to understand  $X_{max}$  were: QJSJET01 – protons and SYBYLL2.1 – mixed
- The interpretation at the time was that that UHECRs (extra galactic) were protons

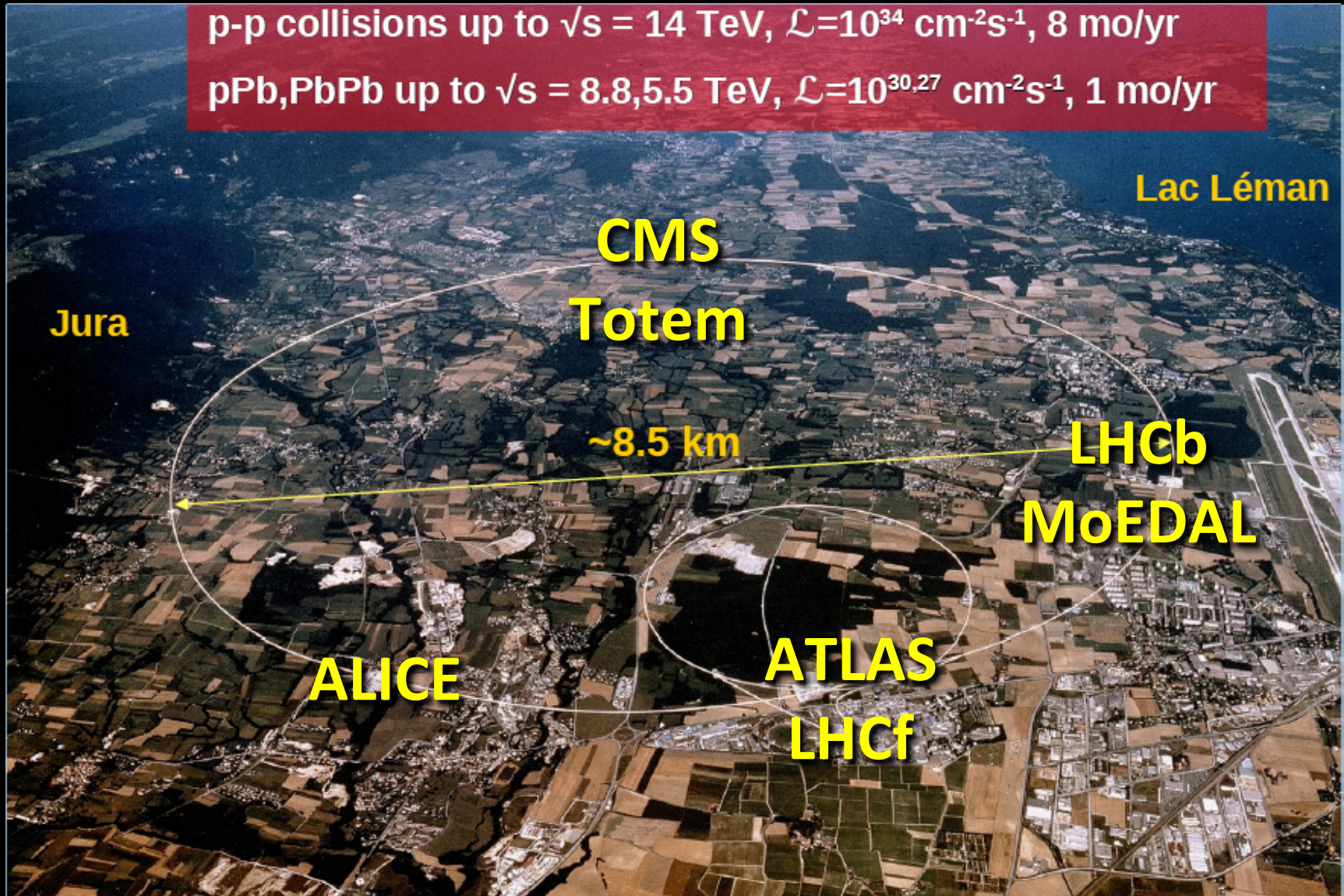
# Understanding UHECR Air Showers with LHC Data



*LHC Run-1/2 has provided a significant lever-arm to constrain & tune hadronic Monte Carlos for UHECR.*

# The Large Hadron Collider

p-p collisions up to  $\sqrt{s} = 14$  TeV,  $\mathcal{L} = 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>, 8 mo/yr  
pPb, PbPb up to  $\sqrt{s} = 8.8, 5.5$  TeV,  $\mathcal{L} = 10^{30,27}$  cm<sup>-2</sup>s<sup>-1</sup>, 1 mo/yr



LHC experiments are back in business at a new record energy 13 TeV

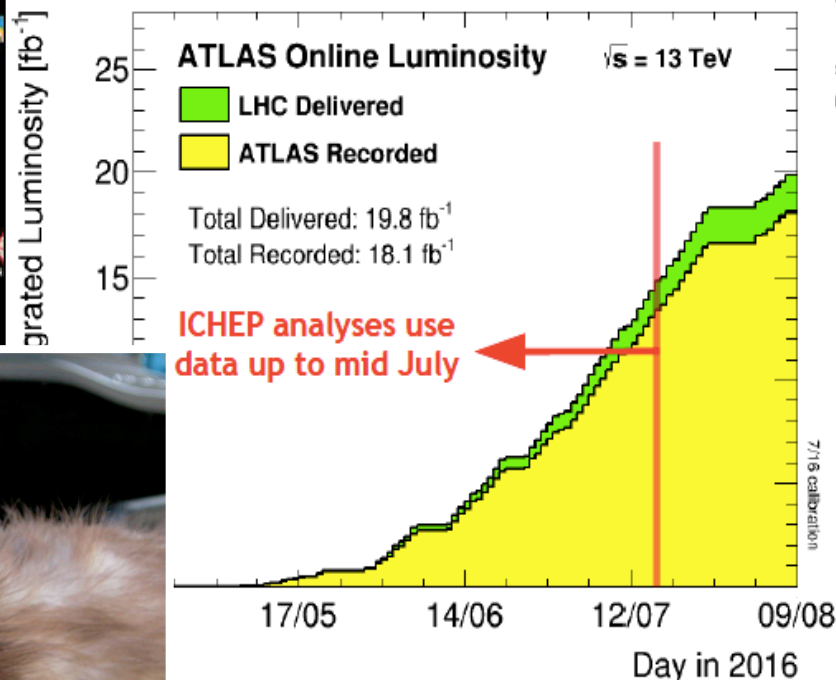
3<sup>rd</sup> June 2015



## Data Samples

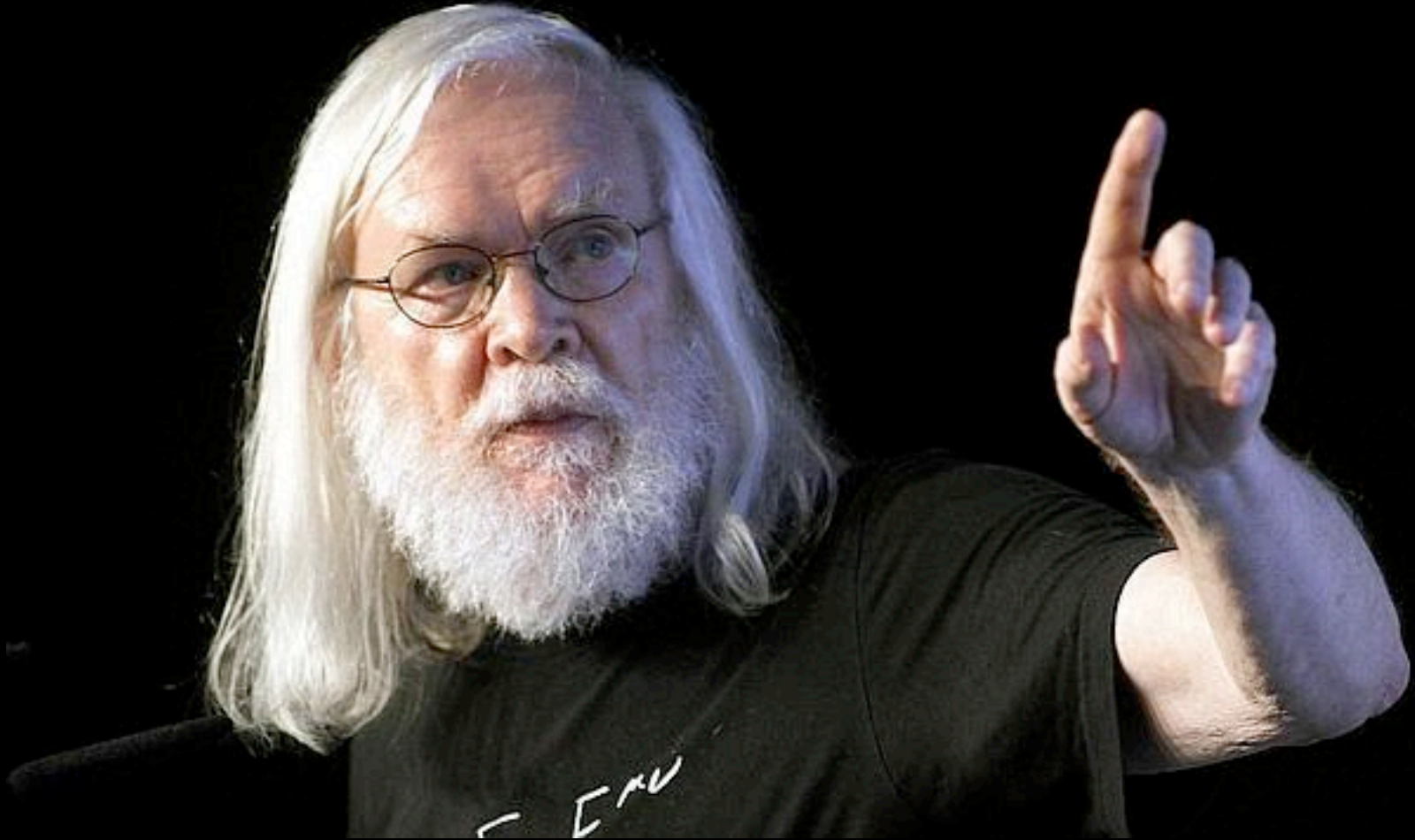
Exceptional LHC performance in 2016 following 13 TeV commissioning in 2015 (2015: 4.2 fb<sup>-1</sup> delivered, 3.9 fb<sup>-1</sup> collected)

**Results reported with 3-15 fb<sup>-1</sup>**



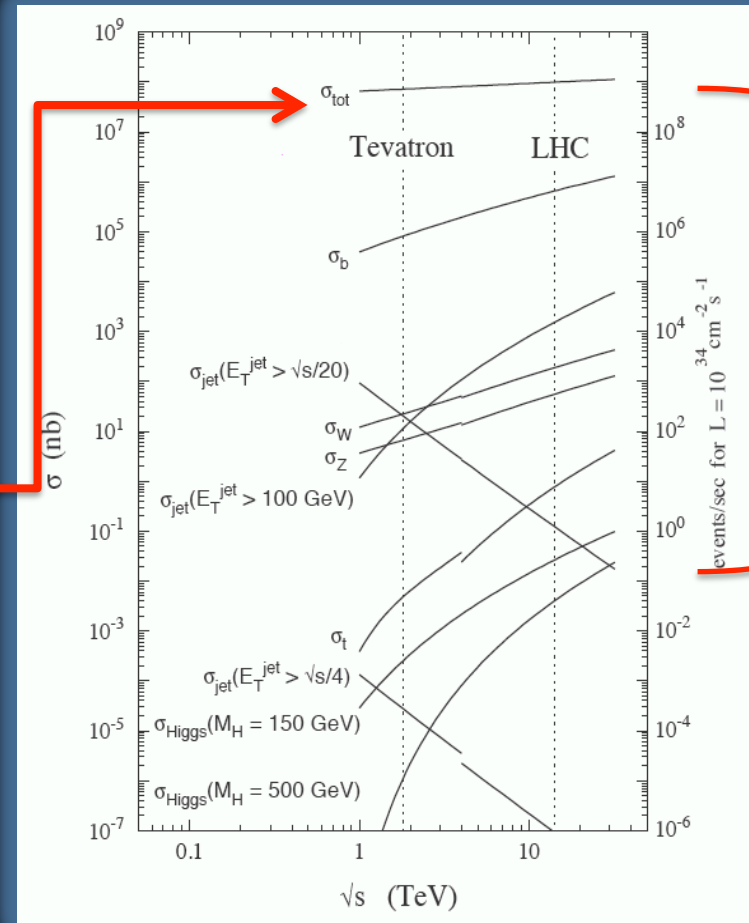
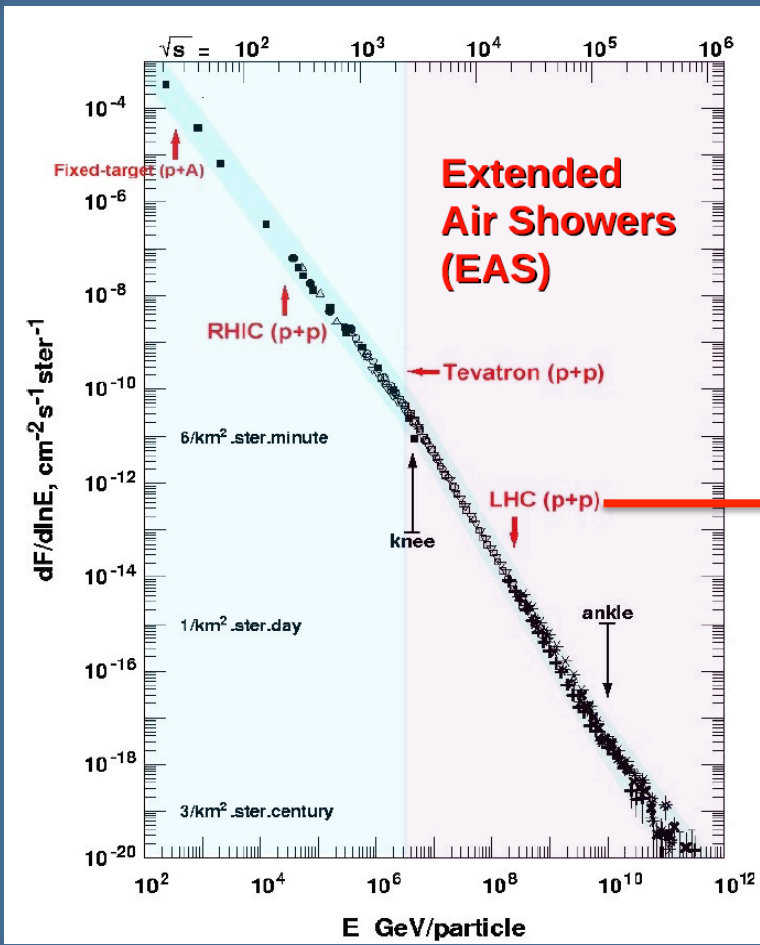
Despite “Sparky” the Field Martin - still on track for 100 fb<sup>-1</sup> In Run 2

# Summary of ATLAS New Physics Search Results



**READ MY LIPS - NO NEW PHYSICS**

# Cosmic Ray Versus LHC Energy Spectrum

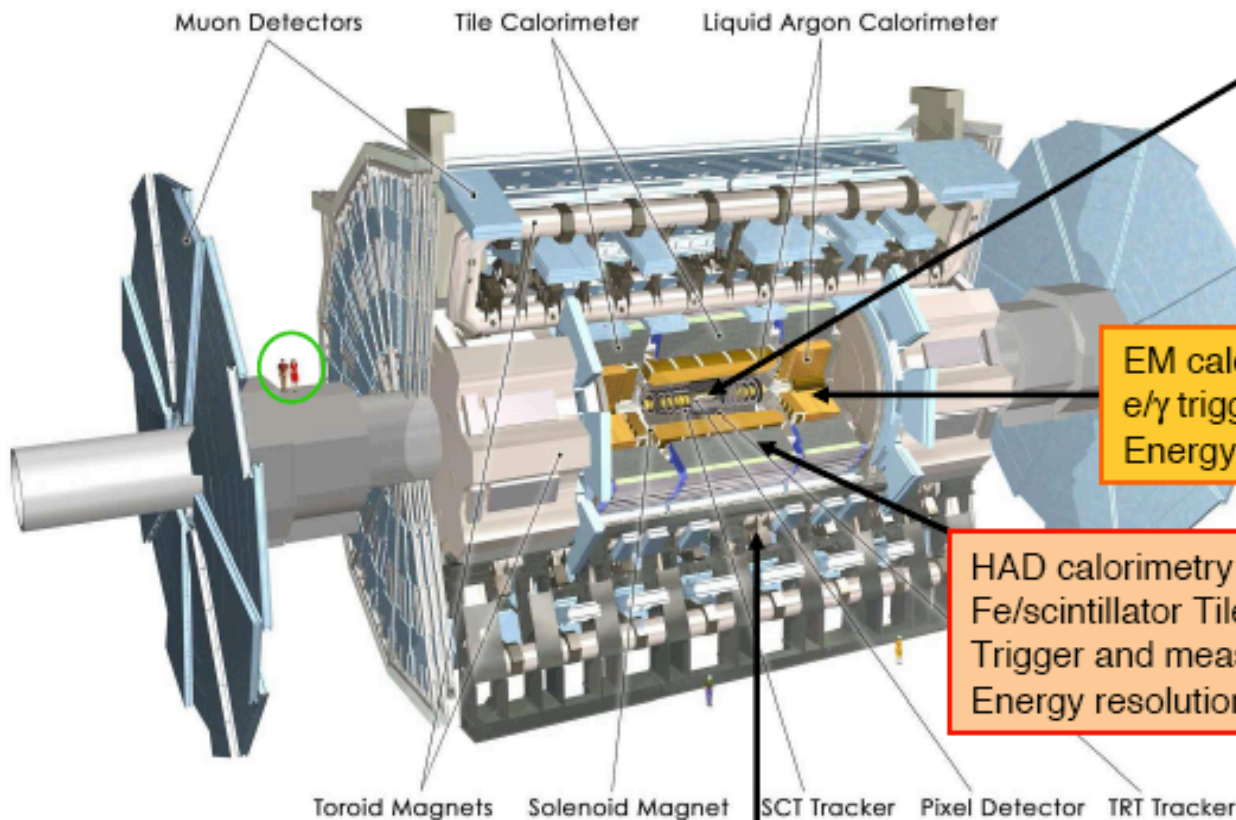


$\sigma_{TOT}$  &  
 $\sigma_{INEL}$   
 ↑  
 A factor of  
 $10^9 - 10^{10}$   
 ↑  
**HIGGS**

- Cosmic ray p-N collisions in the atmosphere above “knee” at  $\sim 10^8$  GeV/particle can be probed in p-p collisions at the LHC

# The ATLAS Detector

L ~ 46 m,  $\varnothing$  ~ 22 m, 7000 tons  
 $\sim 10^8$  electronic channels



Inner Tracker ( $|\eta| < 2.5$ , B=2T):  
 Si Pixels, Si strips, Transition  
 Radiation detector (straws).  
 Precise tracking and vertexing,  
 $e/\pi$  separation.  
 Momentum resolution:  
 $\sigma/p_T \sim 0.04\% p_T$  (GeV)  $\oplus$  1.5%

EM calorimeter: Pb-LAr Accordion.  $|\eta| < 3.2$   
 $e/\gamma$  trigger, identification and measurement  
 Energy resolution:  $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

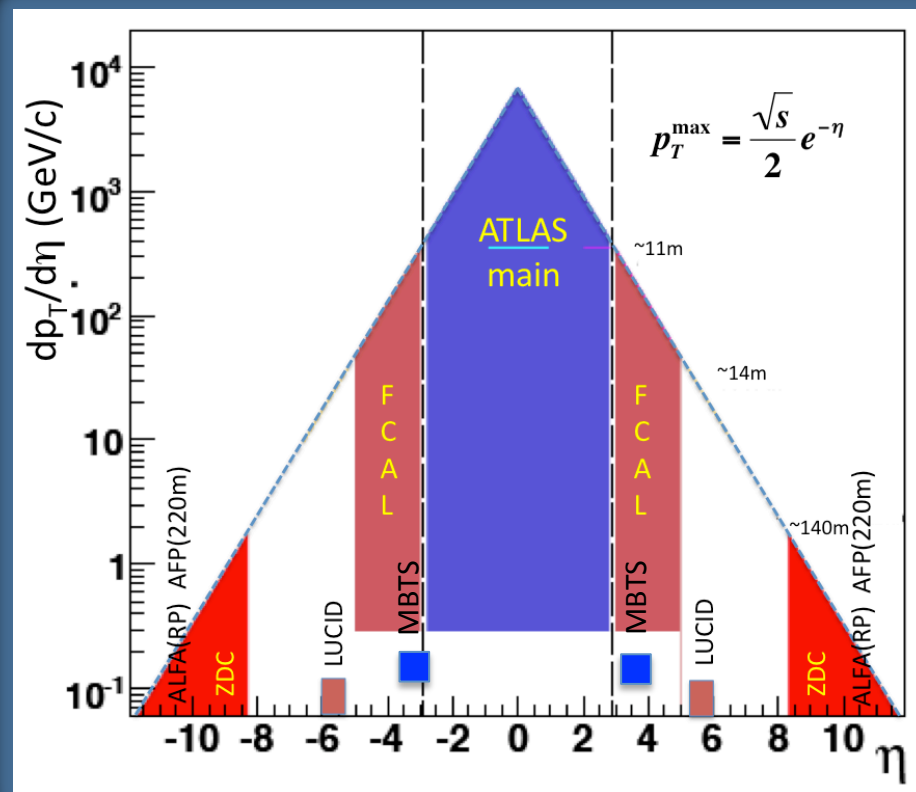
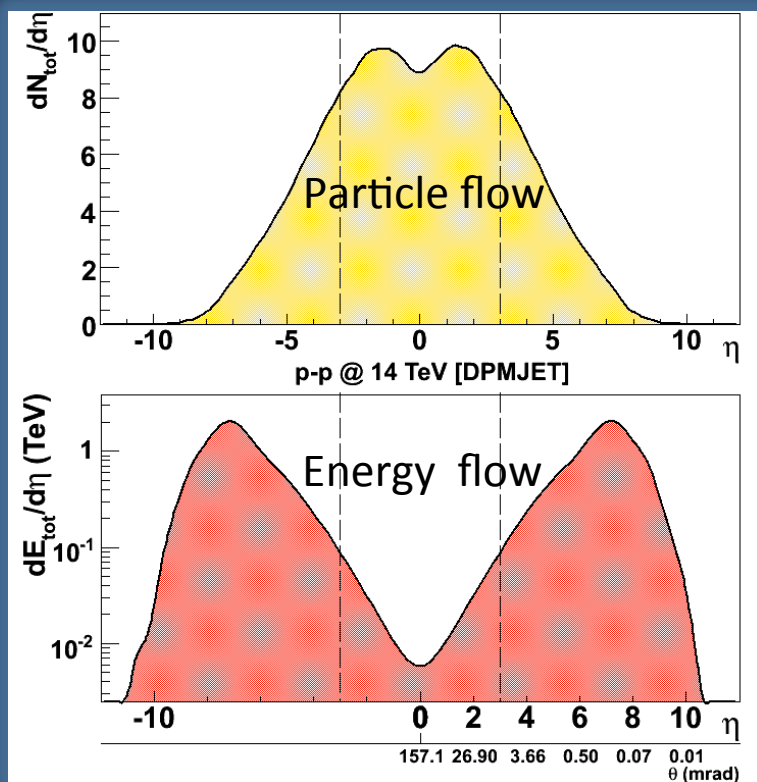
HAD calorimetry ( $|\eta| < 5$ ): segmentation, hermeticity.  
 Fe/scintillator Tiles (central), Cu/W-LAr (forward).  
 Trigger and measurement of jets and missing  $E_T$ .  
 Energy resolution:  $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

3-level trigger  
 reducing the rate  
 from 40 MHz to  
 $\sim 200$  Hz

Muon Spectrometer ( $|\eta| < 2.7$ ): air-core toroids with gas-based muon chambers.  
 Muon trigger and measurement with momentum resolution  $< 10\%$  up to  $E_\mu \sim 1$  TeV

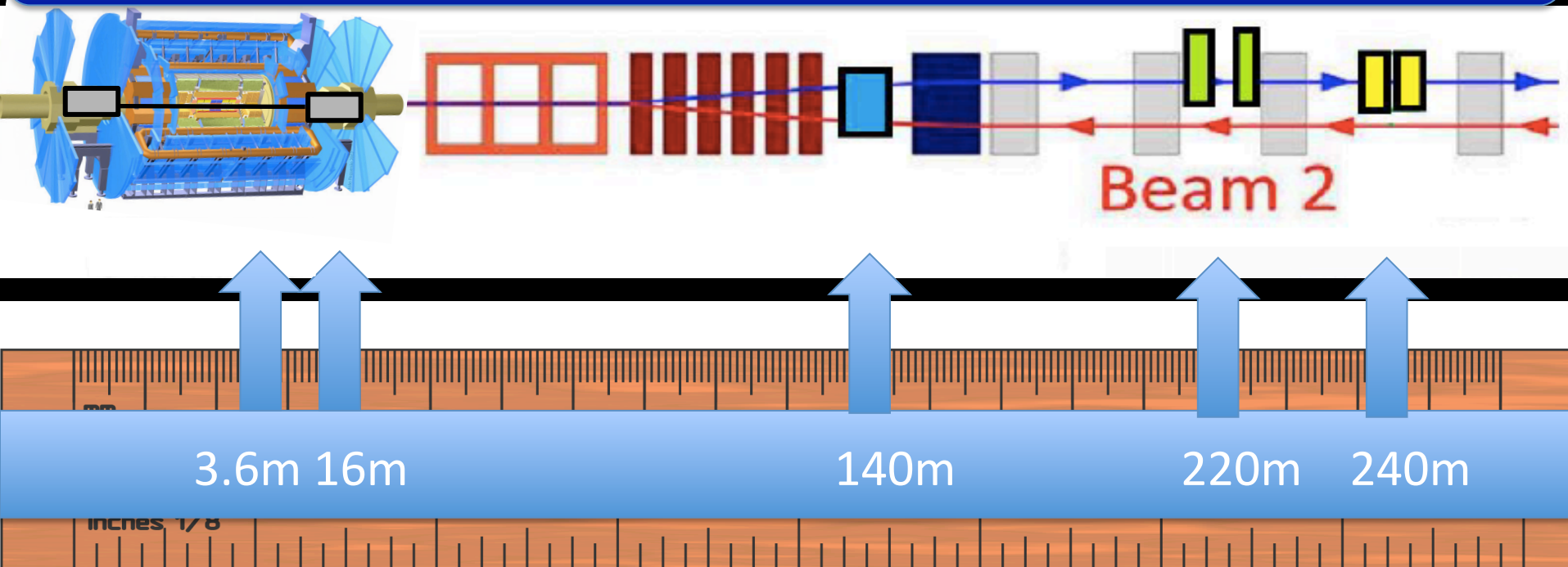
p-p @ 14 TeV

$\eta = -\ln(\tan\theta/2)$



- Forward events have less multiplicity but higher energy
- Large coverage of phase space.

# The ATLAS Forward Detectors



3.6m 16m

140m

220m

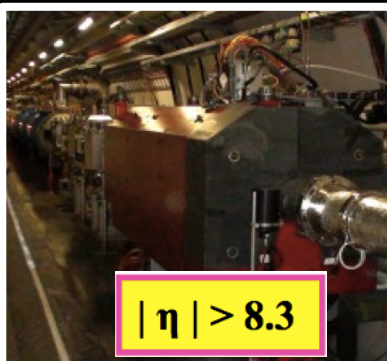
240m



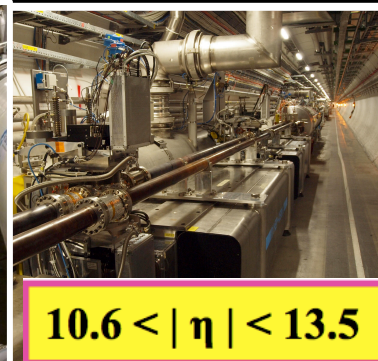
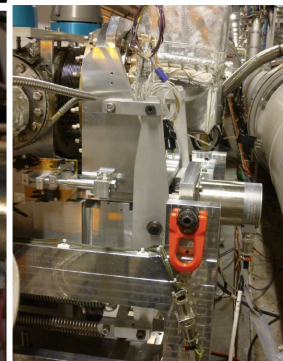
$2.07 < |\eta| < 3.86$



$5.6 < |\eta| < 5.9$



$|\eta| > 8.3$



$10.6 < |\eta| < 13.5$

**MBTS**

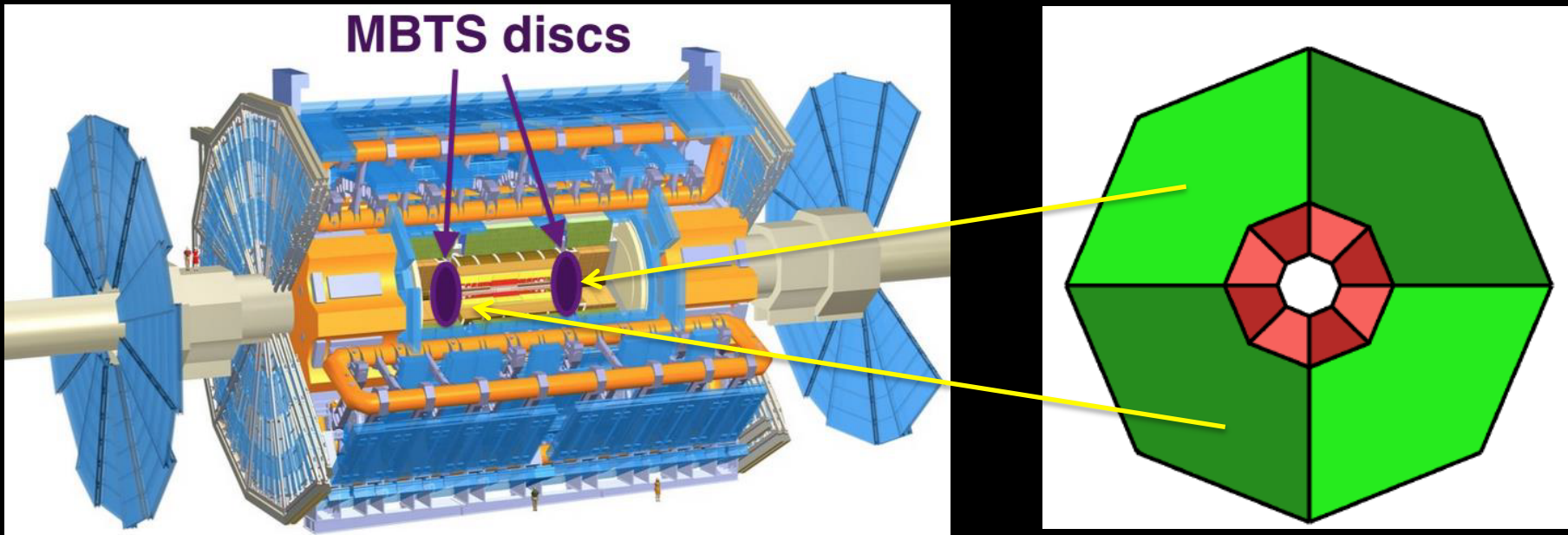
**LUCID**

**ZDC**

**AFP (2 Sts)**

**ALFA**

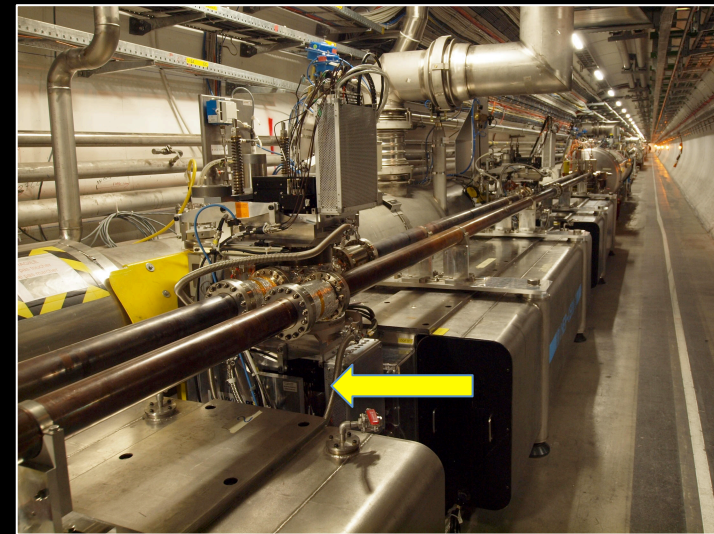
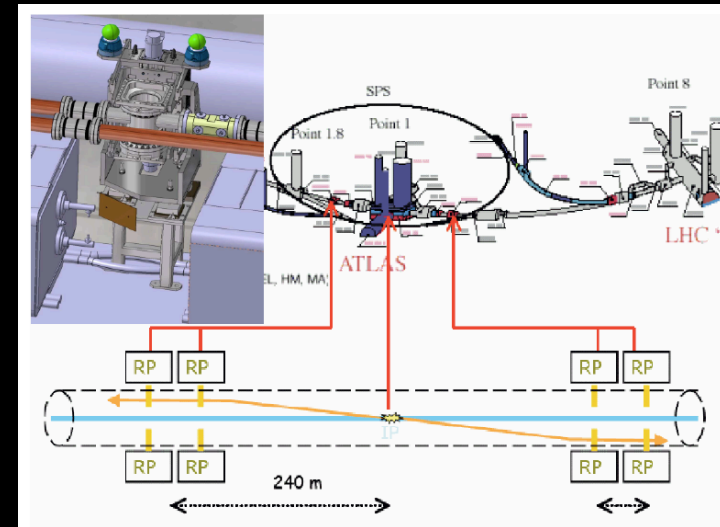
*(Scintill. Det.) (PMT-Cerenkov) (W-Quartz Cal.) (RPs-Si-ToF) (SciFi tracker)*



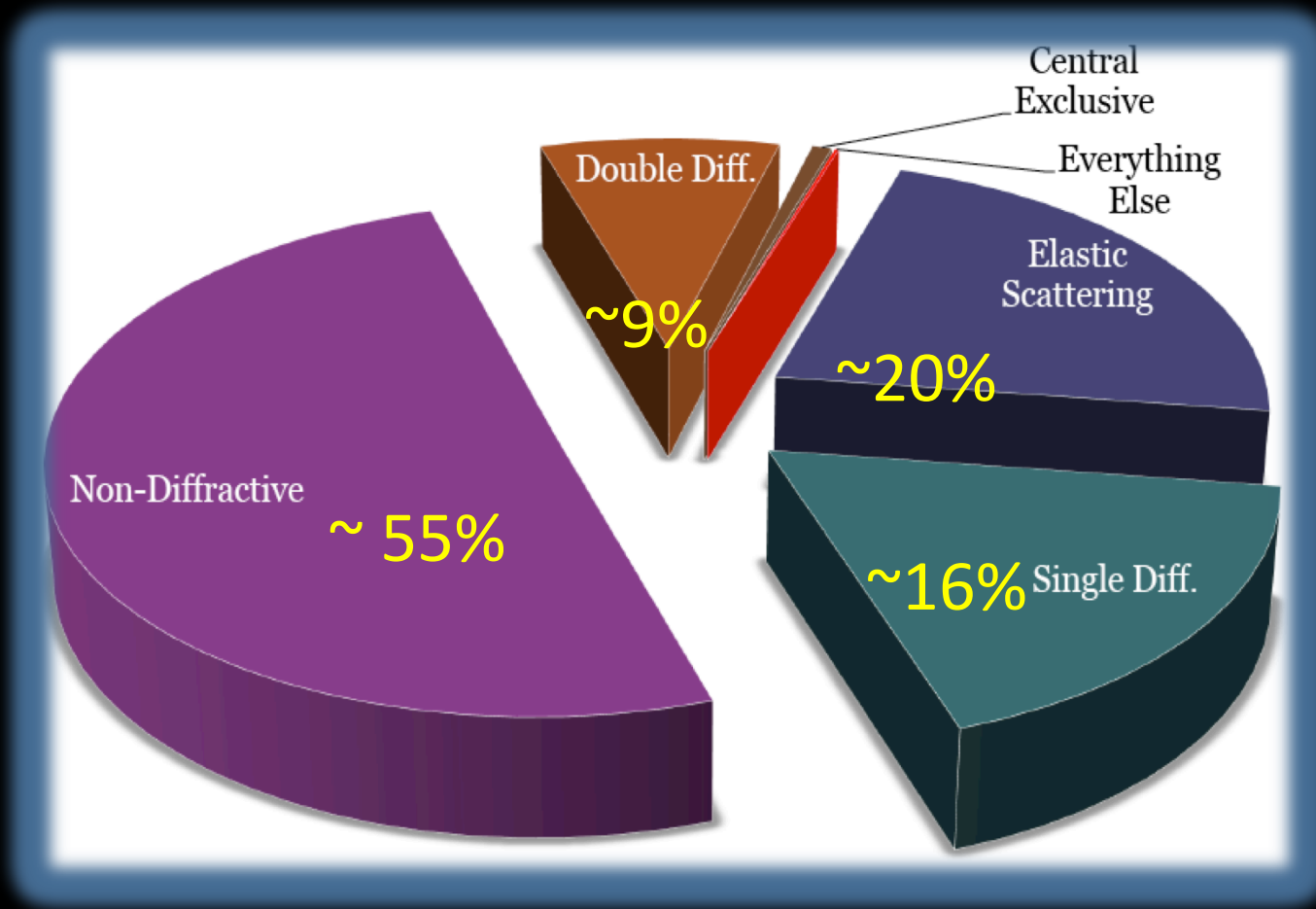
- *The new MBTS (updated for Run 2) was used in a min. bias trigger to make new measurements of the inelastic cross-section and diffraction.*
  - *The old MBTS detector ran from 2009-2014.*
- *This scintillator detector was placed at  $z = \pm 3.6\text{m}$* 
  - *2 x 8 fold segmentation near to beam pipe, 4-fold further out*
  - *It covers the range  $2.1 < |\eta| < 3.8$*

# The ALFA Detector

- *The ATLAS ALFA detector was installed in the shutdown of 2010-11*
  - *The ALFA detector consists of Scintillating Fibre (SciFi) detectors deployed in RPs at  $\pm 240\text{m}$  from IP1 (237.7m & 241.5m)*
  - *Special “high-beta” optics & low lumi ( $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ ) needed to reach the Coulomb Nuclear Interference region ( $-t \sim 6 \times 10^{-4} \text{ GeV}^2$ )*
- *The purpose of ALFA:*
  - *Absolute lumi determination for ATLAS*
  - *Measurement of  $\sigma_{\text{tot}}$  and p-p elastic scattering parameters*
  - *Proton tags for single diffraction and central diffraction*

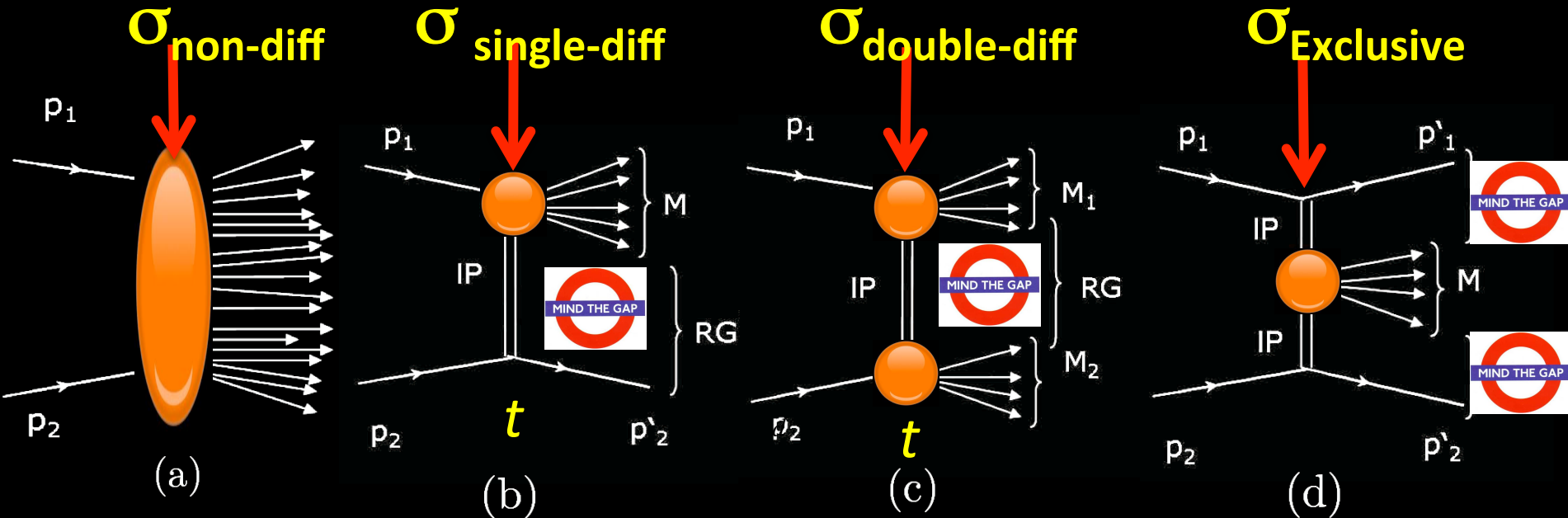


# The Total p-p Cross-section



$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \underbrace{\sigma_{\text{non-diff}} + \sigma_{\text{single-diff}} + \sigma_{\text{double-diff}} + \sigma_{\text{Exclusive}} + \dots}_{\text{INELASTIC}}$$

# The Inelastic p-p Cross-section



$\xi - xi - ksaai$

$$\Delta\eta(RG) \approx -\ln \xi$$

$$\xi = M^2/s = 1 - (E'_p/E_p)$$

- *Non-diffractive (~70% of inelastic): parton-parton interactions - described by perturbative QCD*
- *Diffractive (~30% of inelastic): colourless Pomeron exchange - described by Regge-Gribov type models.*
  - *$M$  can be as big as 1 Tev at the LHC  $\rightarrow$  jets & other hard probes*

# The p-p Total, Elastic & Inelastic Cross-section

nature  
COMMUNICATIONS

OPEN

MBTS

ARTICLE

Received 5 Apr 2011 | Accepted 4 Aug 2011 | Published 6 Sep 2011

DOI:10.1038/ncomms1472

Measurement of the inelastic proton-proton cross-section at  $\sqrt{s} = 7$  TeV with the ATLAS detector

The ATLAS Collaboration<sup>1\*</sup>

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Rev. Lett.



MBTS

CERN-EP-2016-140  
18th July 2016

Measurement of the Inelastic Proton-Proton Cross Section at  $\sqrt{s} = 13$  TeV with the ATLAS Detector at the LHC  
arXiv:1606.02625v2 [hep-ex] 15 Jul 2016

The ATLAS Collaboration



ELSEVIER

Nuclear Physics B

Volume 889, December 2014, Pages 486–548



Open Access

ALFA

Measurement of the total cross section from elastic scattering in  $pp$  collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector

ATLAS Collaboration<sup>\*</sup>,

Show more

doi:10.1016/j.nuclphysb.2014.10.019

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EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Lett. B.



ALFA

CERN-EP-2016-158  
25th July 2016

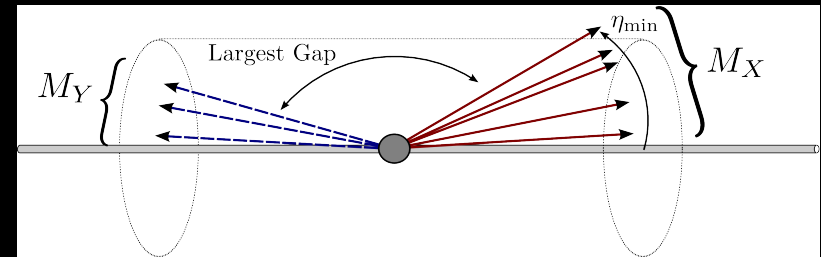
Measurement of the total cross section from elastic scattering in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector  
arXiv:1607.06605v1 [hep-ex] 22 Jul 2016

The ATLAS Collaboration

# Determining the Inelastic Cross-section @13 TeV

- The ATLAS analysis uses MBTS to tag inelastic collisions.

- Requires  $\geq 2$  MBTs hits
- Acceptance neither proton can dissociate into a system of  $M_X > 13 \text{ TeV} \rightarrow \xi = M_X^2/s > 10^{-6}$

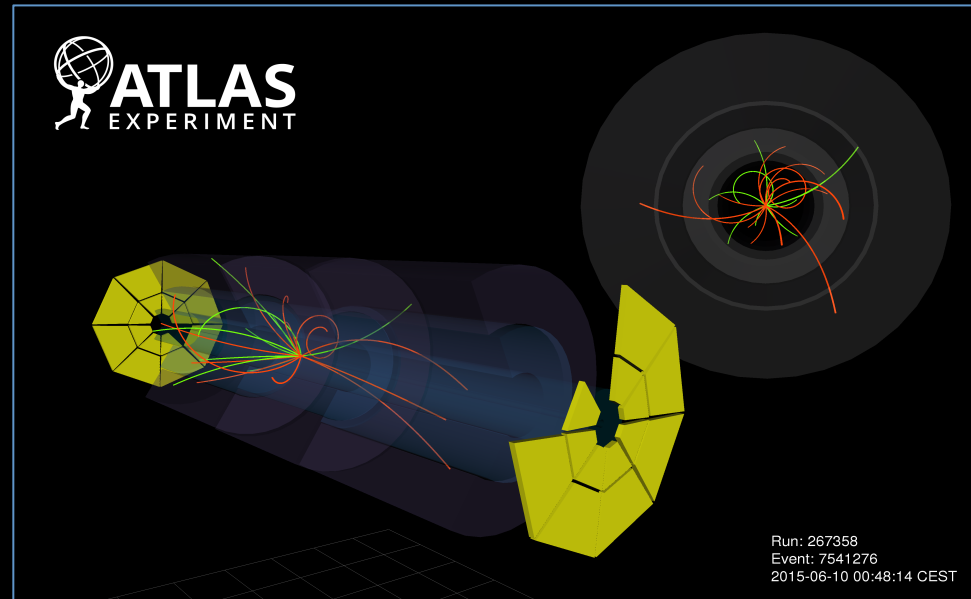
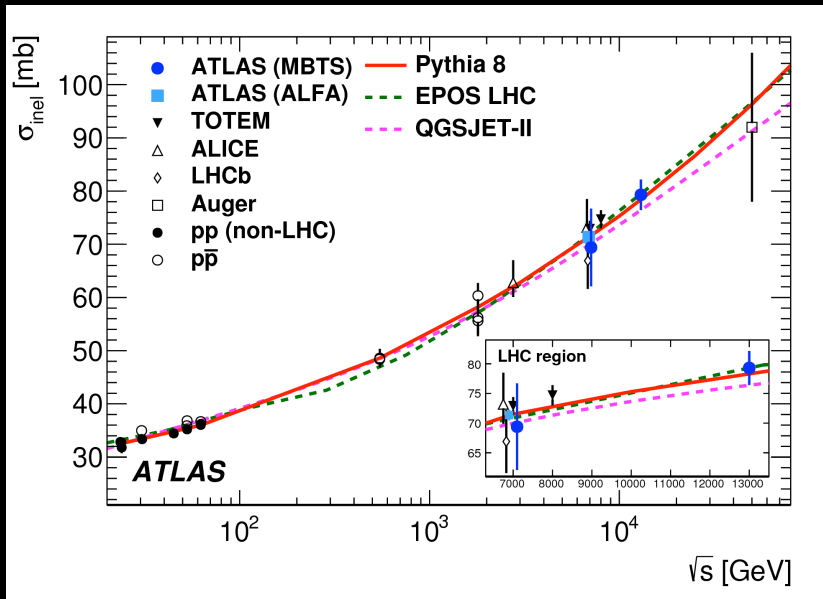


Factor	Value	Rel. uncertainty
Number of events passing the inclusive selection ( $N$ )	4159074	—
Number of background events ( $N_{BG}$ )	51187	$\pm 50\%$
Integrated luminosity [ $\mu\text{b}^{-1}$ ] ( $\mathcal{L}$ )	60.1	$\pm 1.9\%$
Trigger efficiency ( $\epsilon_{\text{trig}}$ )	99.7%	$\pm 0.3\%$
MC correction factor ( $C_{MC}$ )	99.3%	$\pm 0.5\%$

$N_{BG}$ : Small background from beam-gas, Acceptance & migration correction from MC radiation & activation (51,187 events)

$$\sigma_{\text{inel}}^{\text{fid}} (\xi > 10^{-6}) = \frac{N - N_{BG}}{\epsilon_{\text{trig}} \times \mathcal{L}} \times \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{\text{sel}}}$$

# Determining the Inelastic Cross-section @13 TeV



- **Fiducial cross-section**

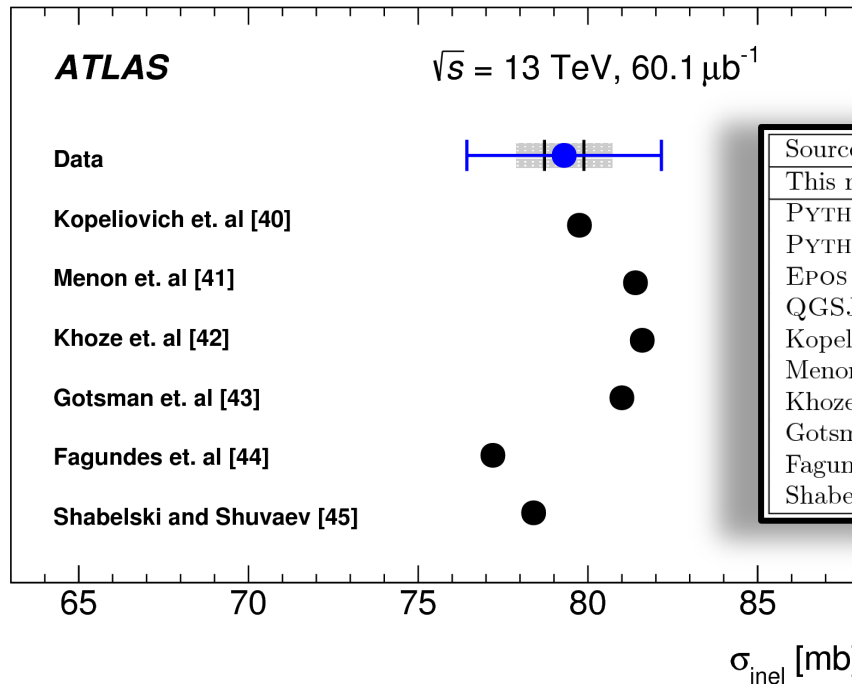
- $\sigma_{inel}^{fid} = 68.1 \pm 0.6 (exp.) \pm 1.3 (lum.) \text{ mb.}$

- **Extrapolation into region with  $\xi < 10^{-6}$  done using MC**

- $\sigma_{inel} = 79.3 \pm 0.6 (exp.) \pm 1.3 (lum.) \pm 2.5 (extrap.) \text{ mb.}$

- **Result is in good agreement with EPOS-LHC and QGSJET-II**

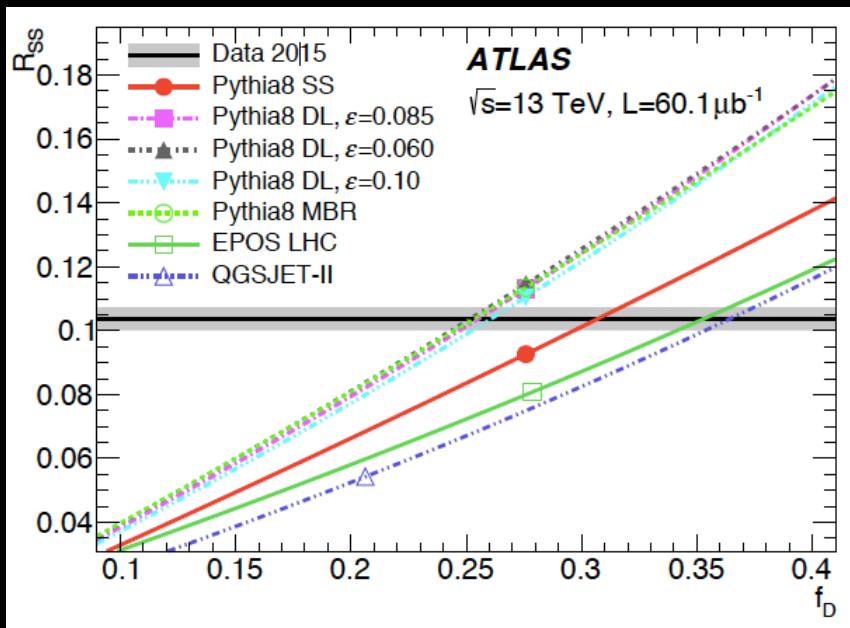
# $\sigma_{inel}$ - Comparison with Predictions



Source	Value
This measurement	$79.3 \pm 0.6$ (exp.) $\pm 1.3$ (lum.) $\pm 2.5$ (extr.) mb
PYTHIA8 SS / DL	78.4 mb
PYTHIA8 MBR	76.6 mb
EPOS LHC	79.0 mb
QGSJET-II	80.2 mb
Kopeliovich et al. [42]	79.8 mb
Menon et al. [43]	$81.4 \pm 2.0$ mb
Khoze et al. [44]	81.6 mb
Gotsman [45]	81.0 mb
Fagundes [46]	77.2 mb
Shabelski and Shuvaev [47]	78.4 mb

*The results are consistent with models based on Regge phenomenology, eikonal models and other approaches to non-perturbative QCD*

# The Diffractive Fraction



*SD selection  $\geq 2$  hits on 1 side only*

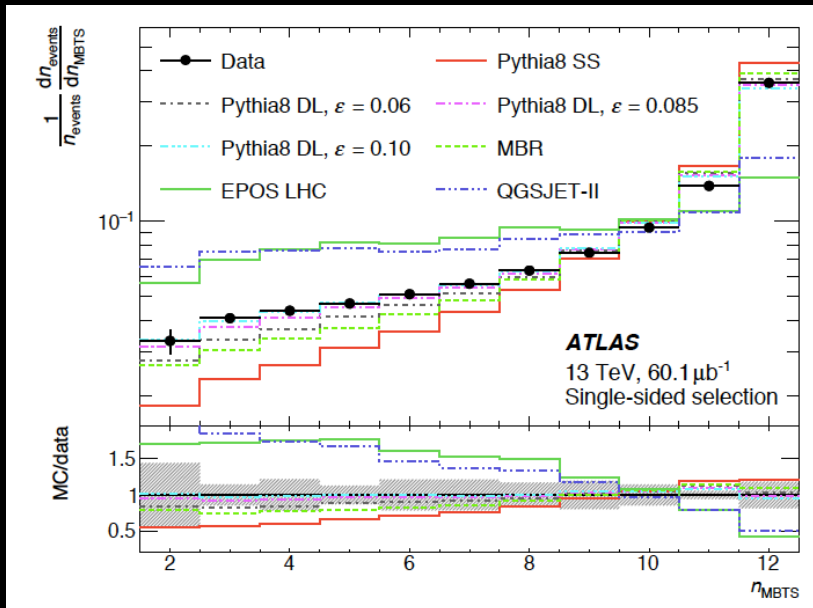
$$R_{SS}(f_D) = \frac{N_{SS}}{N_{inc}} = \frac{A_{SS}^D f_D + A_{SS}^{ND} (1 - f_D)}{A_{inc}^D f_D + A_{inc}^{ND} (1 - f_D)}$$

Diffractive fraction

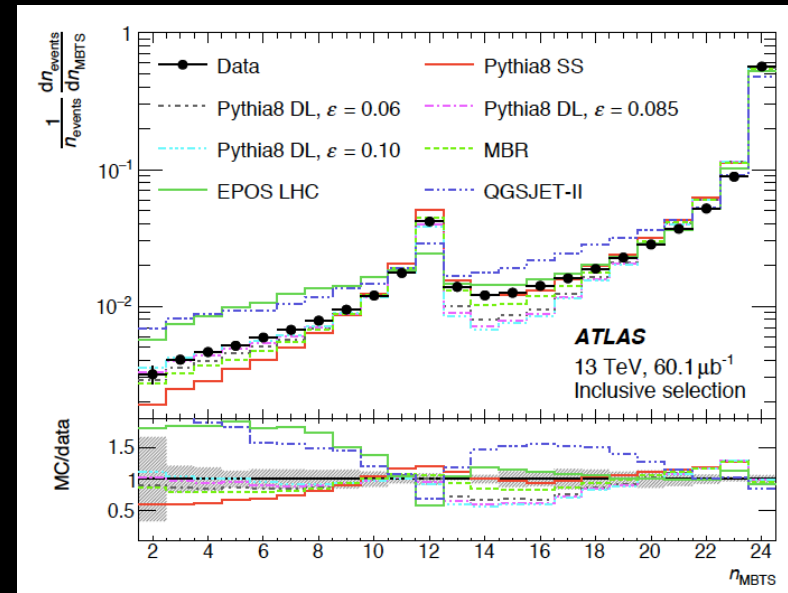
$$f_D = (\sigma_{SD} + \sigma_{DD}) / \sigma_{inel}$$

- $R_{SS}$  = Ratio of samples with one side of the MBTS firing to the inclusive sample is used to tune fractions of events considered diffractive in each MC model
- Measured value of  $R_{SS} = [10.4 \pm 0.4] \%$ 
  - $f_D$  in the Pythia8 samples is between 25% and 31%
  - $f_D$  the EPOS/QGSJET samples give 37% / 35%,

# The Diffractive Fraction



*Single sided detection*



*inclusive detection*

- *Sample with only one side of the MBTS registering activity enriched in SD events*
  - *Number of MBTS counters firing distinguishes between MC models of diffraction*
  - *Surprisingly QGSJET-II and EPOS-LHC provide a relatively poor description of the data - PHYTHIA DL  $\epsilon = 0.085$  is best*

# ALFA - the Total, Inelastic & Elastic X-section

- The quantities  $\sigma_{tot}$ ,  $\sigma_{el}$  and  $\sigma_{inel}$  can all be determined from a measurement of the differential elastic cross-section

- The  $\sigma_{tot}$  is found using the optical theorem:

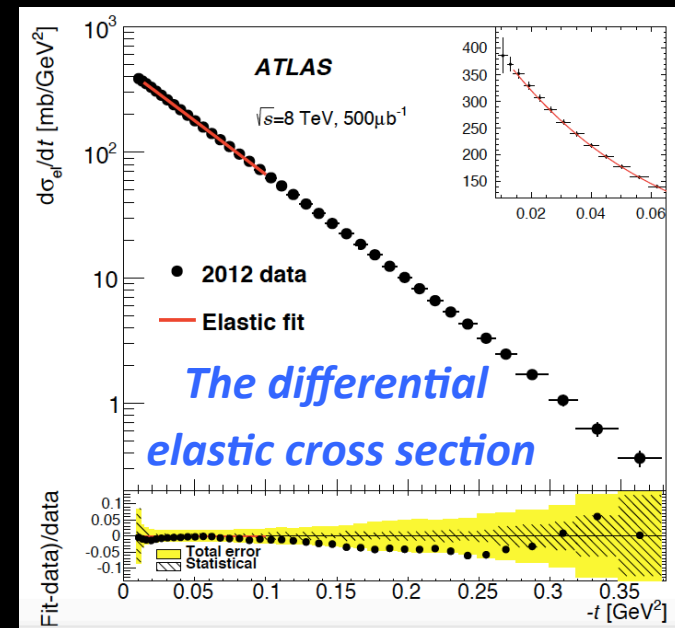
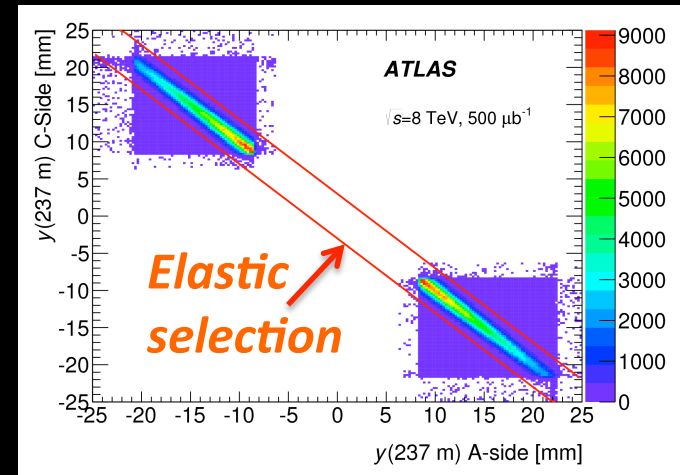
$$\sigma_{tot} \propto 4\pi \cdot \text{Im}(f_{el})_{t \rightarrow 0}$$

- The  $\sigma_{el}$  is obtained by integration:

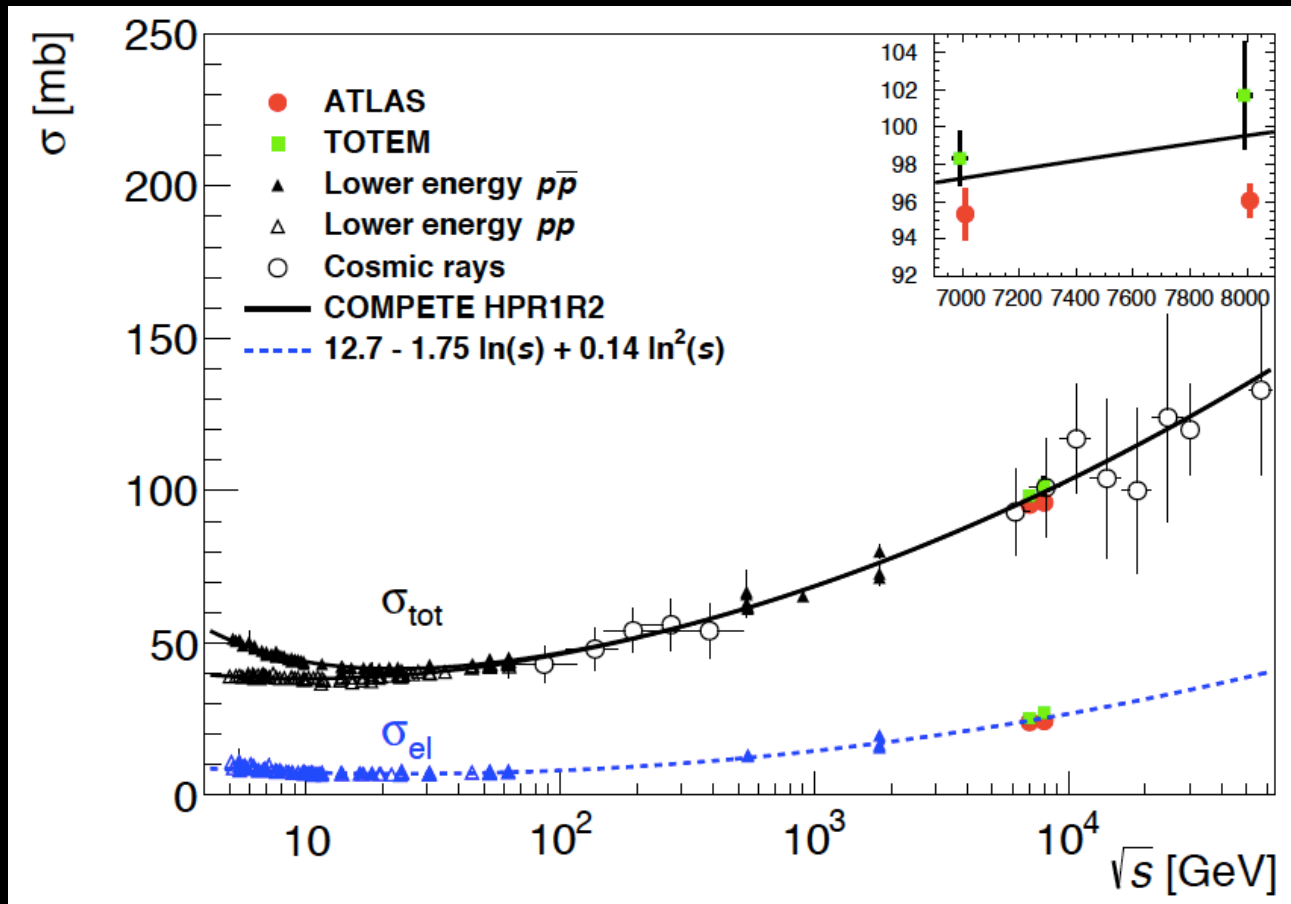
$$\sigma_{el} = \int d\sigma_{el}/dt$$

- The  $\sigma_{inel}$  is derived by subtraction

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$$

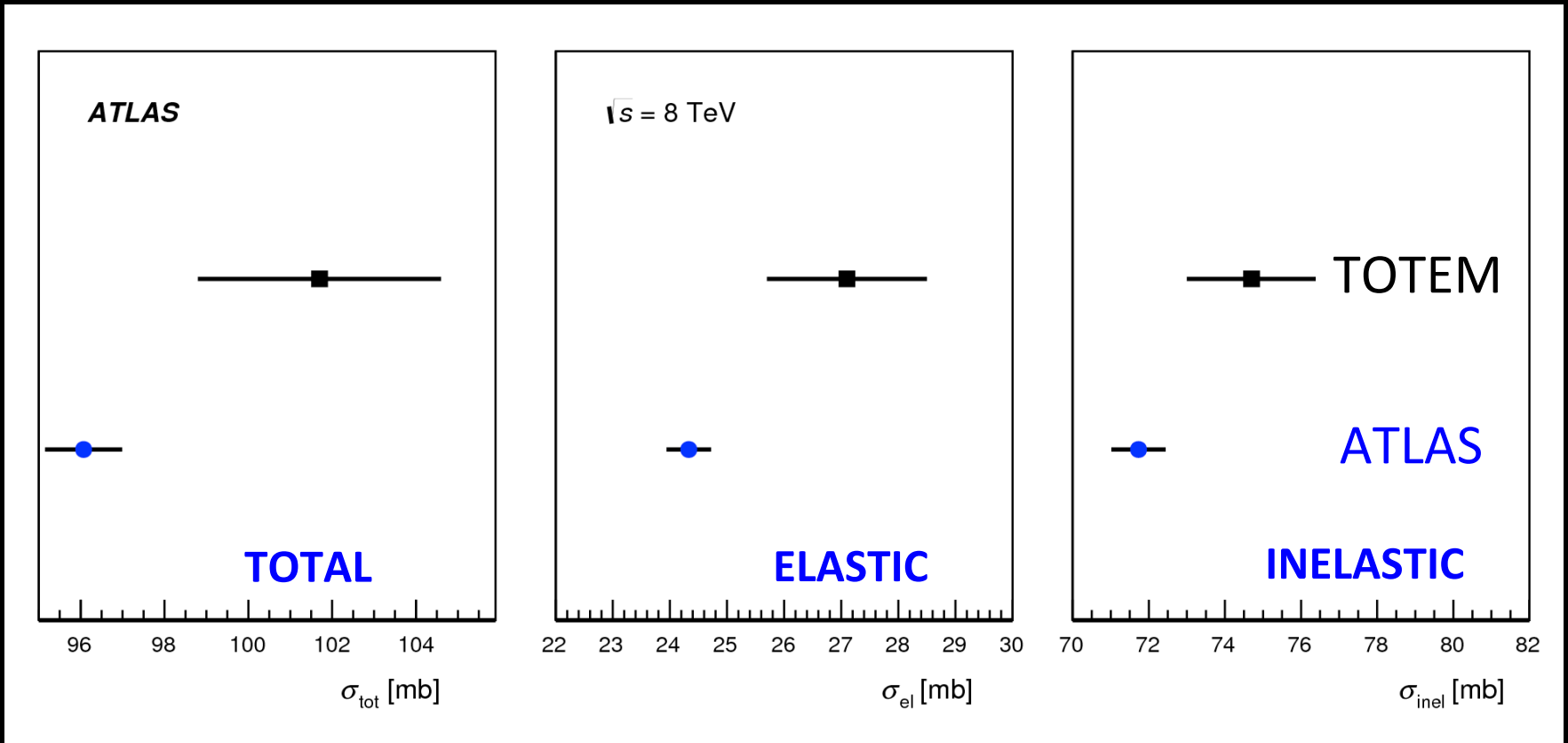


# ALFA - Cross-section Results



*Comparison of total & elastic cross-section measurements presented here with other published measurements and model predictions as a function of the centre-of-mass energy.*

# Comparison with TOTEM



*Comparison of the measurements presented here at  $\sqrt{s}=8$  TeV with the measurement published by the TOTEM Collaboration.*

# ATLAS pp Charged Particle Distributions

## New Journal of Physics

The open-access journal for physics

### Charged-particle multiplicities in $pp$ interactions measured with the ATLAS detector at the LHC

The ATLAS Collaboration

*New Journal of Physics* 13 (2011) 053033 (68pp)  
Received 22 December 2010  
Published 19 May 2011  
Online at <http://www.njp.org/>  
doi:10.1088/1367-2630/13/5/053033

Eur. Phys. J. C (2016) 76:403  
DOI 10.1140/epjc/s10052-016-4203-9

THE EUROPEAN  
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

### Charged-particle distributions in $pp$ interactions at $\sqrt{s} = 8$ TeV measured with the ATLAS detector

ATLAS Collaboration\*

CERN, 1211 Geneva 23, Switzerland

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: EPJC



CERN-EP-2016-099  
6th June 2016

### Charged-particle distributions at low transverse momentum in $\sqrt{s} = 13$ TeV $pp$ interactions measured with the ATLAS detector at the LHC

The ATLAS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



Submitted to: Phys. Lett. B.



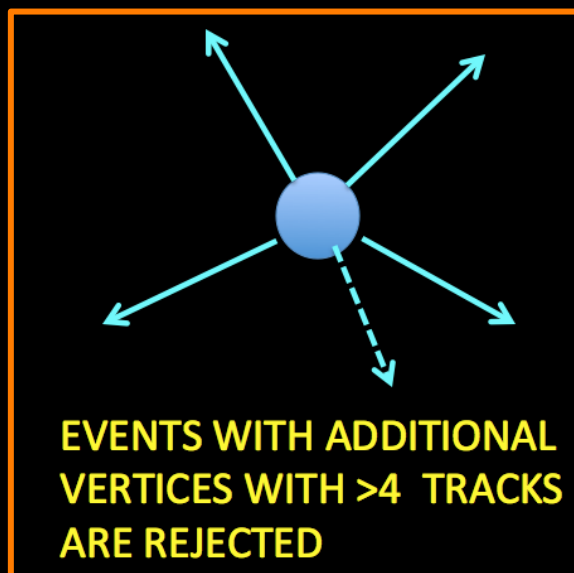
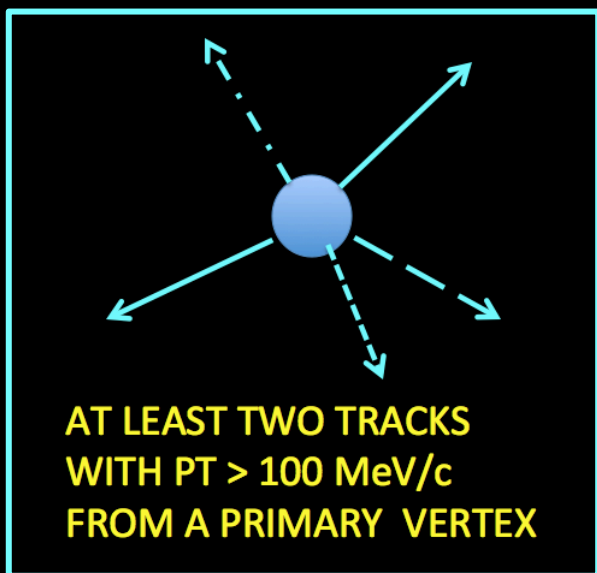
CERN-EP-2016-014  
5th February 2016

### Charged-particle distributions in $\sqrt{s} = 13$ TeV $pp$ interactions measured with the ATLAS detector at the LHC

The ATLAS Collaboration

# Event Selection

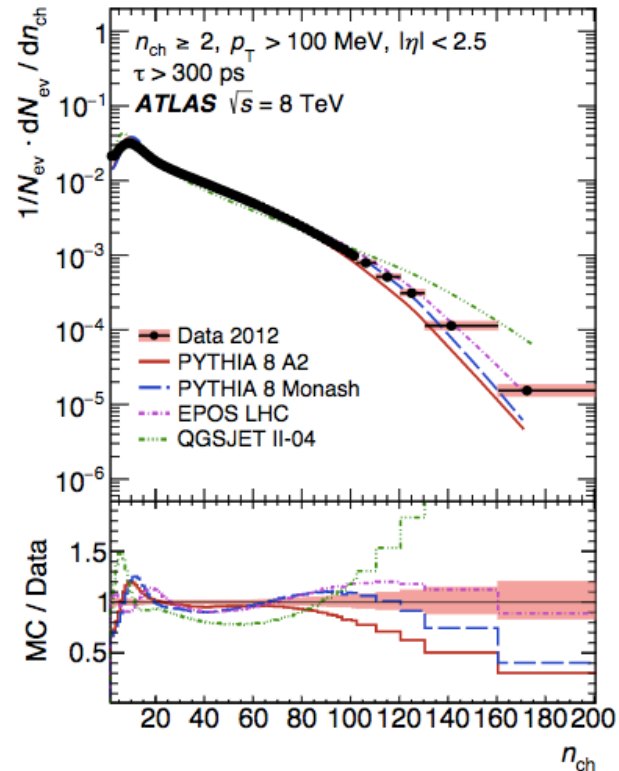
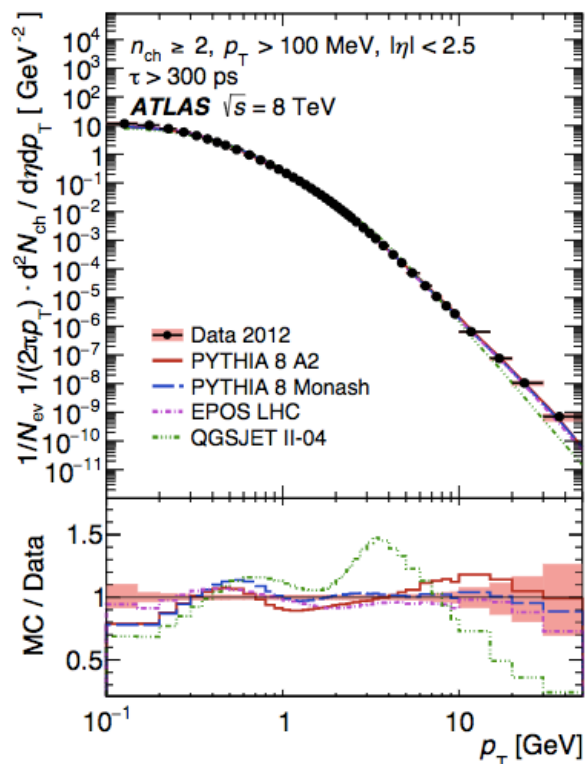
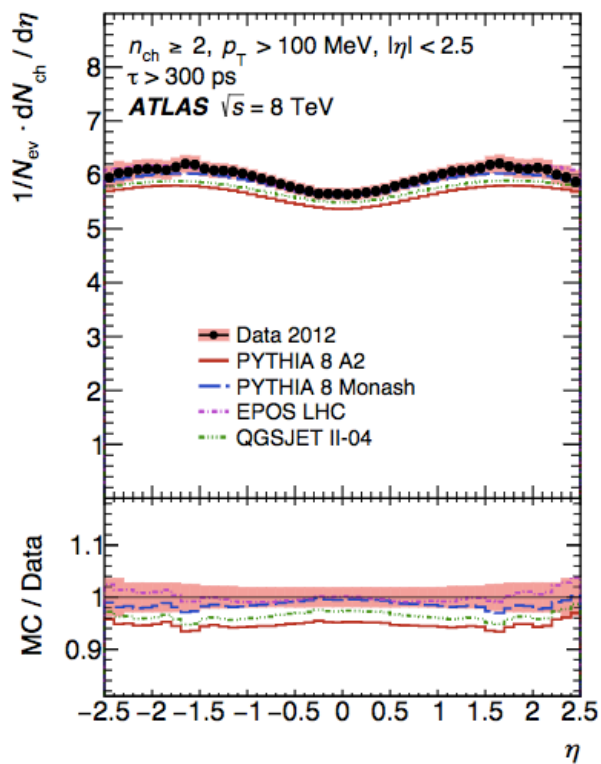
- *Trigger one or more MBTS modules above threshold on either side were considered. Data taken at very low luminosity*



ADDITIONAL SELECTIONS ARE MADE ON MULTIPLICITY AND TRACK  $p_T$

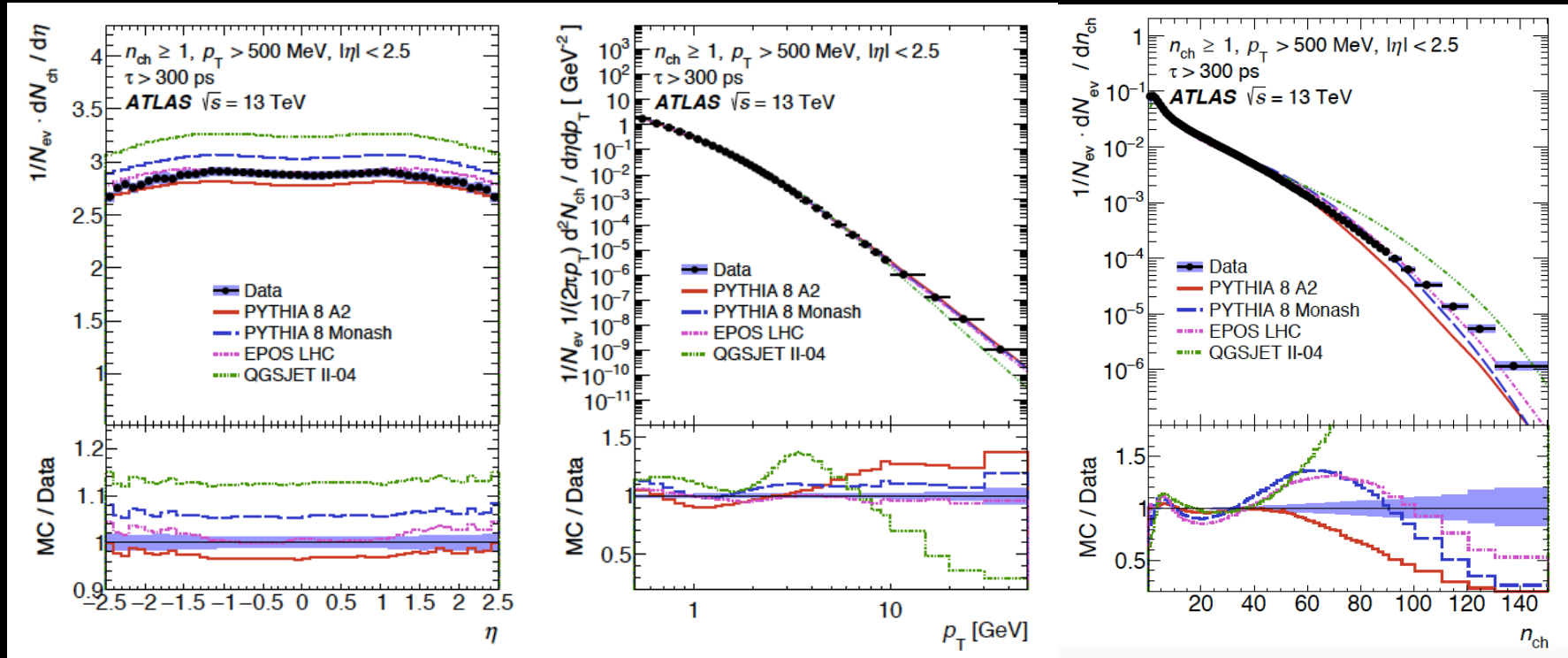
- *Following the above selections, the event yield is:*
  - $9.2 \times 10^6$  for the most inclusive phase space at  $n_{sel} \geq 2$  &  $p_T > 100$  MeV
  - The phase space with the lowest number of events ( $6.4 \times 10^4$ ) corresponds to  $n_{sel} \geq 50$  and  $p_T > 500$  MeV.

# Charged Particle Distributions @ $\sqrt{s} = 8\text{TeV}$



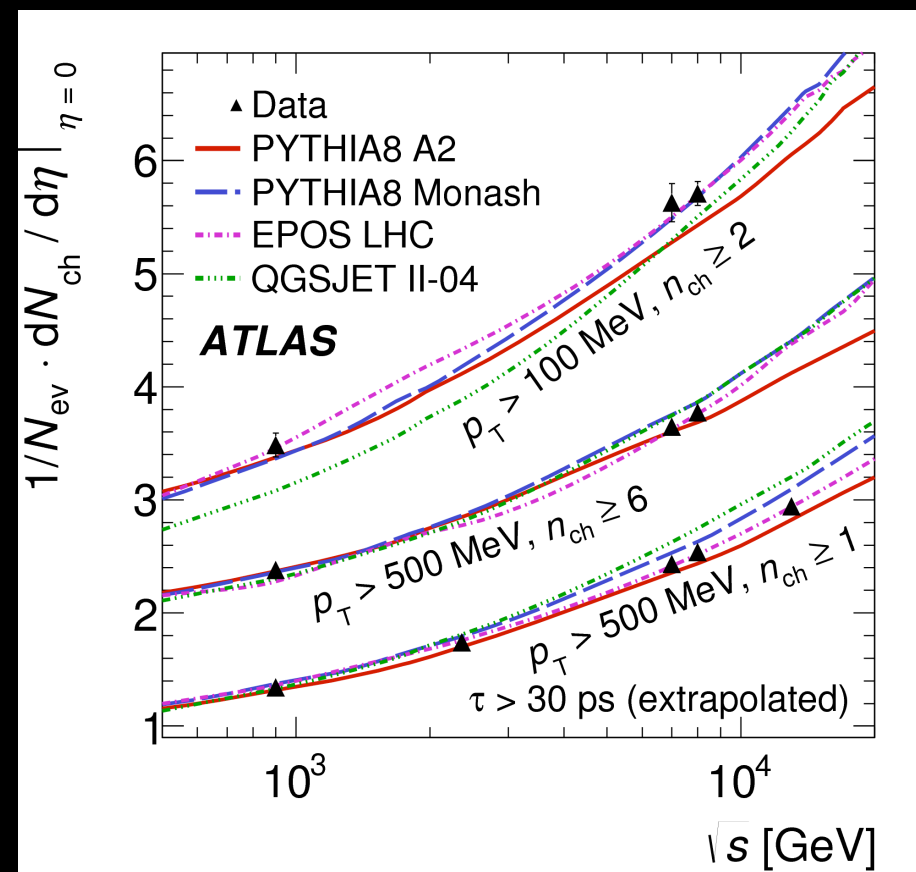
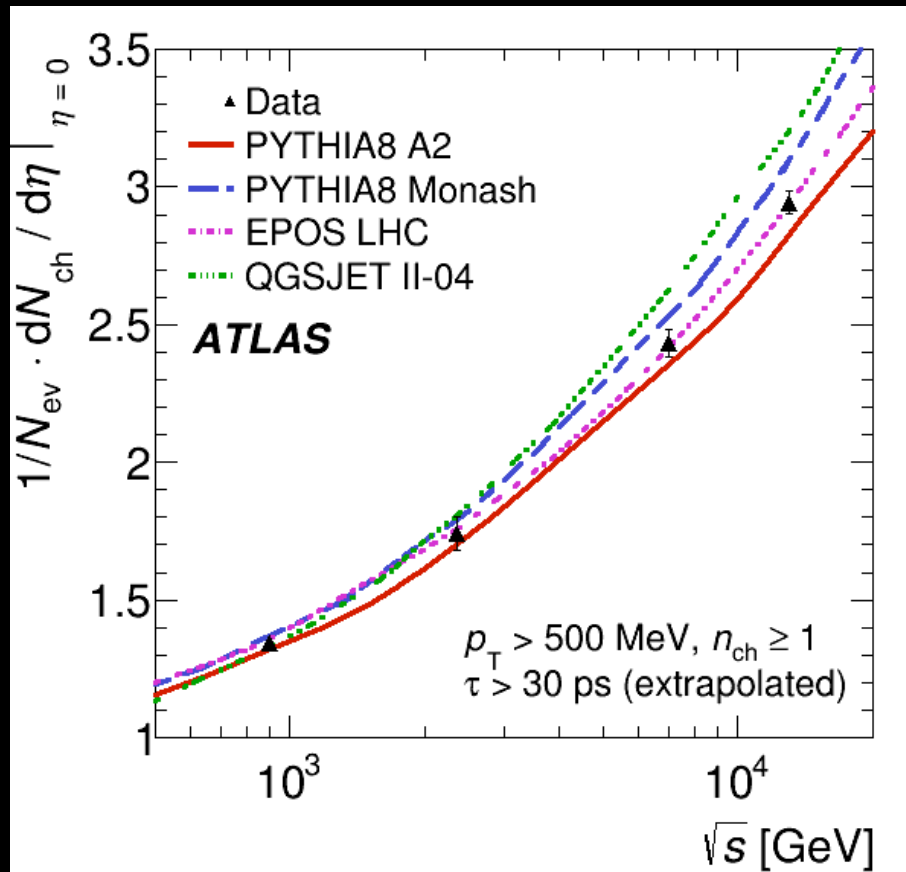
*Distribution of primary charged particles in events for which  $n_{\text{ch}} \geq 2, p_{\text{T}} > 100 \text{ MeV}$  and  $|\eta| < 2.5$  pseudorapidity (left),  $P_{\text{T}}$  (middle) and charged particle multiplicity (right)*

# Charged Particle Distributions @ $\sqrt{s}=13$ TeV

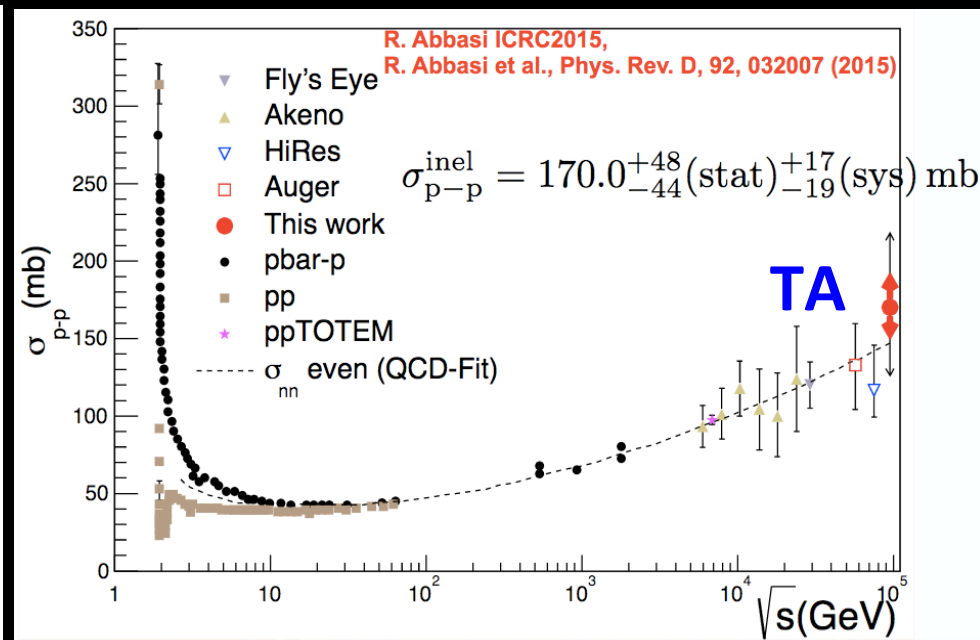
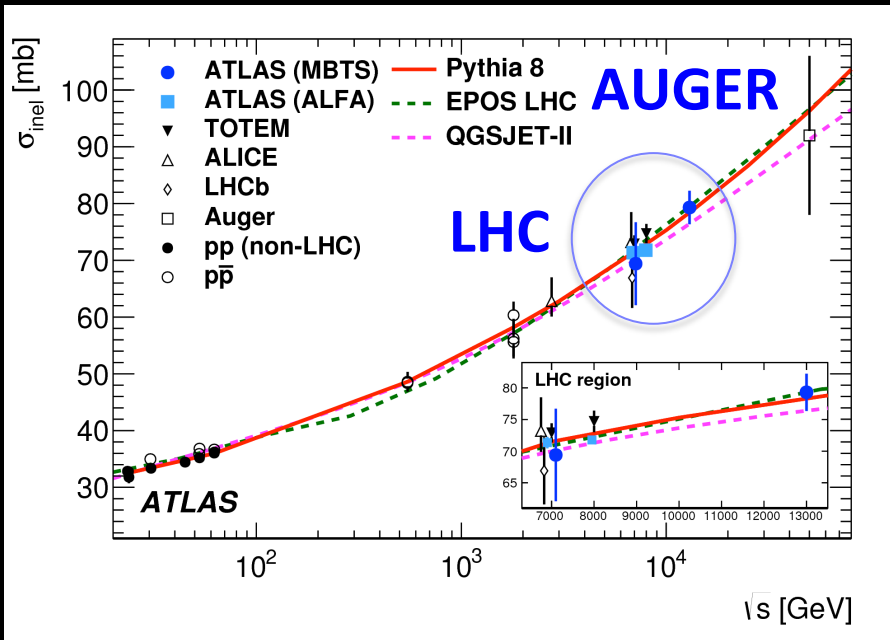


*Primary charged particle multiplicities as a function of (left) pseudorapidity,  $\eta$ , and (right) transverse momentum,  $p_T$*

# Charged Particle Distributions @ $\sqrt{s} = 8 \text{ \& } 13\text{TeV}$

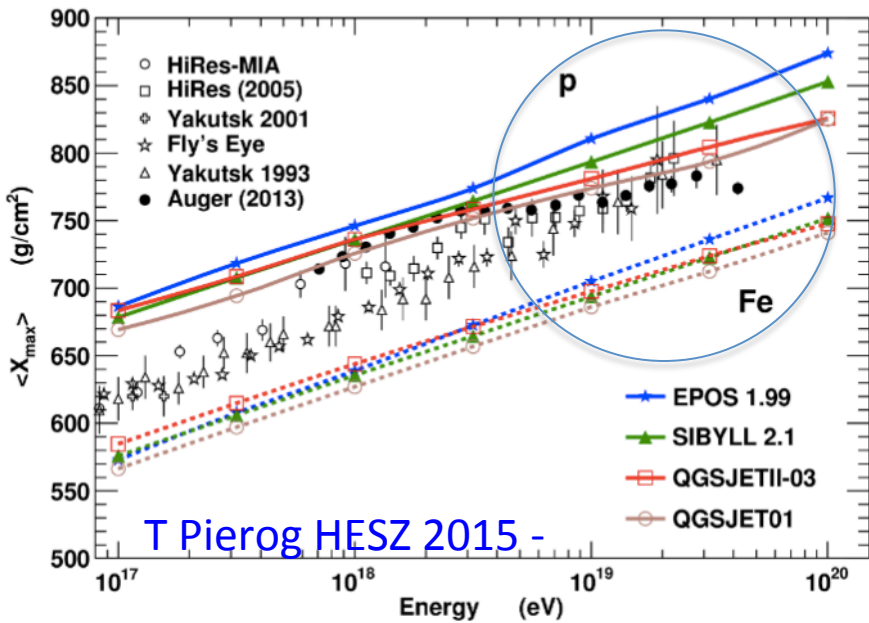


*The average primary-charged-particle multiplicity per unit of  $\eta$  at  $\eta = 0$ , as a function of the  $E_{cm}$*

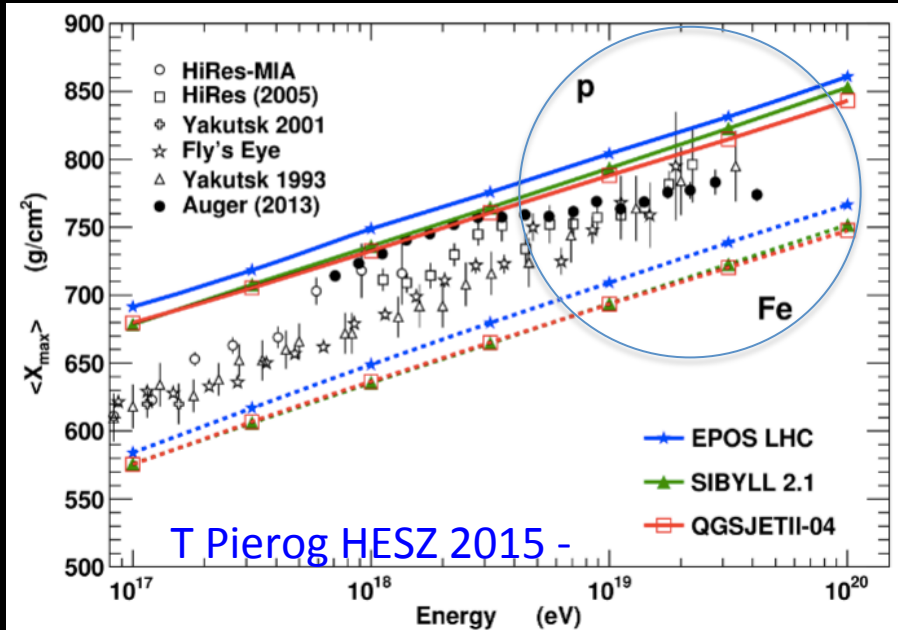


- The latest Telescope Array (TA) data takes the measurement of the p-p cross-section out to  $\sqrt{s} = 95 + 5 - 8 \text{ TeV}$  (AUGER'S is at 57 TeV)
  - The Pierre Auger Array and Telescope Array p-p cross-sections are extracted from the p-air cross-sections using the Glauber model
- Recent results from ATLAS and the TA support the EPOS-LHC description of the data taking the extrapolation to higher x-sections

# Impact of the LHC X-sec Measurement



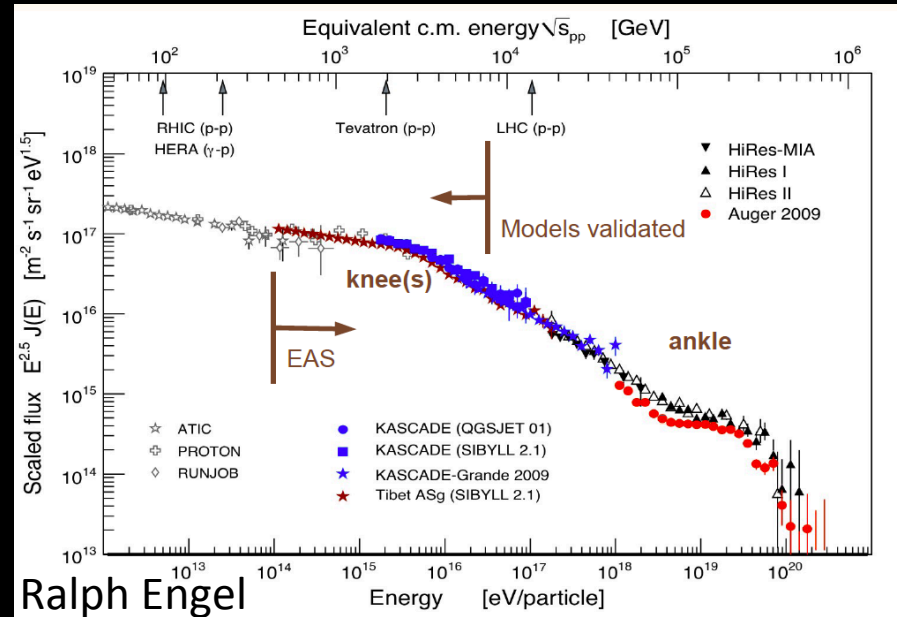
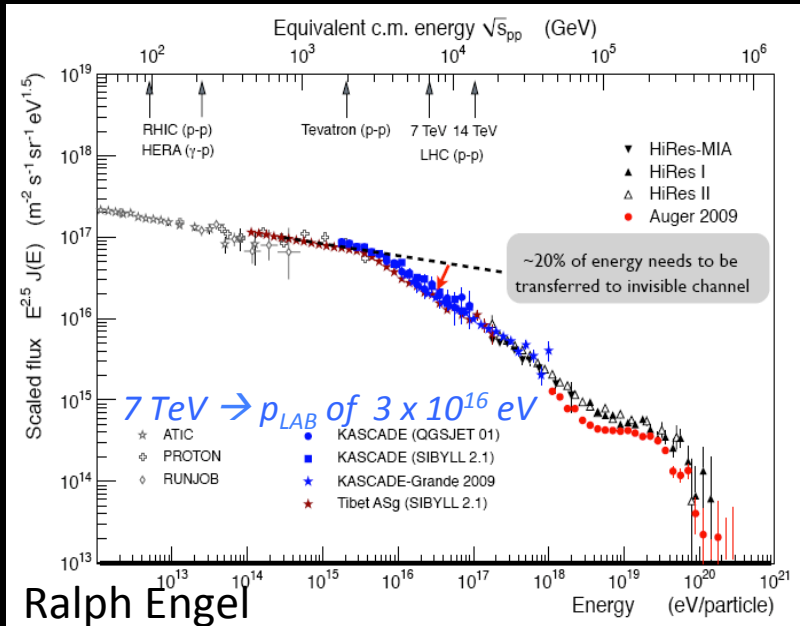
EAS with old CR models:  $X_{max}$



EAS with retuned CR models using Run 1 LHC data:  $X_{max}$

- SIBYLL2.1 predictions confirmed by EPOS-LHC and QGSJETII-04 but QGSJET01 and QGSJETII-03 disfavoured
- The interpretation of the composition of UHECR's moves from the picture that they are mostly protons to a mixed composition

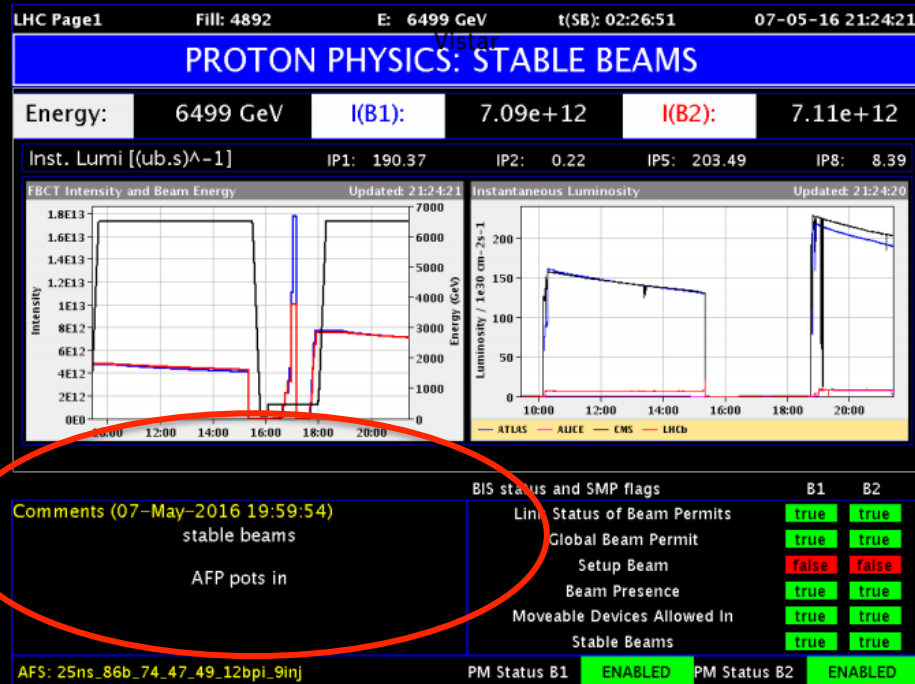
# Is the Knee Due to New Physics?



- **Cosmic ray models essentially validated by the LHC**
- Reasonable description of the main observables
- Data bracketed by CR Models
- **Origin of the Knee?**
- Most likely NOT due to exotic hadronic interactions
- A dependence on primary CR composition?
- Or a nearby supernova (Wolfendale)

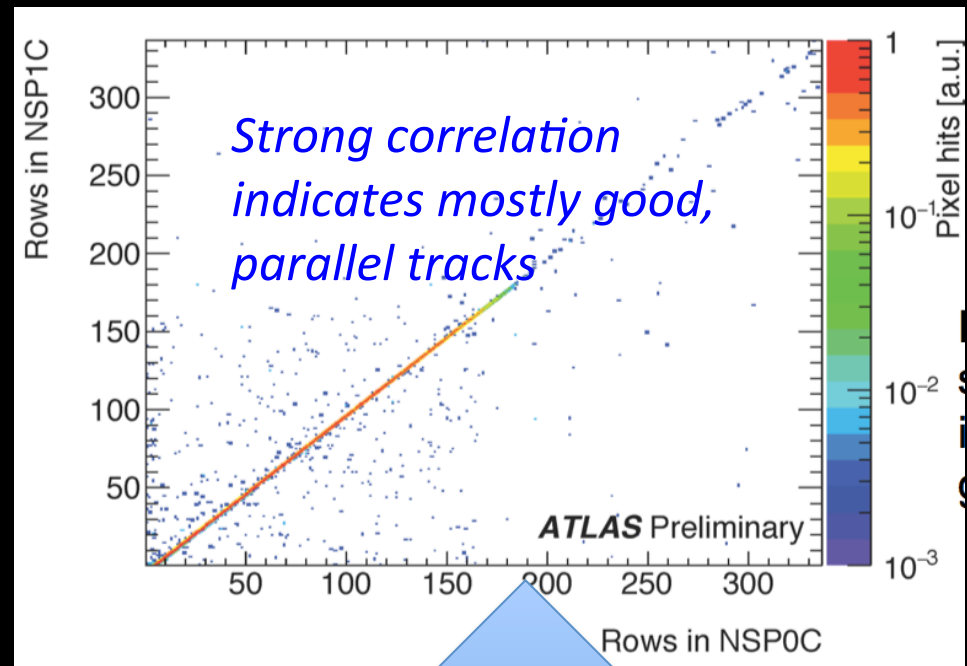
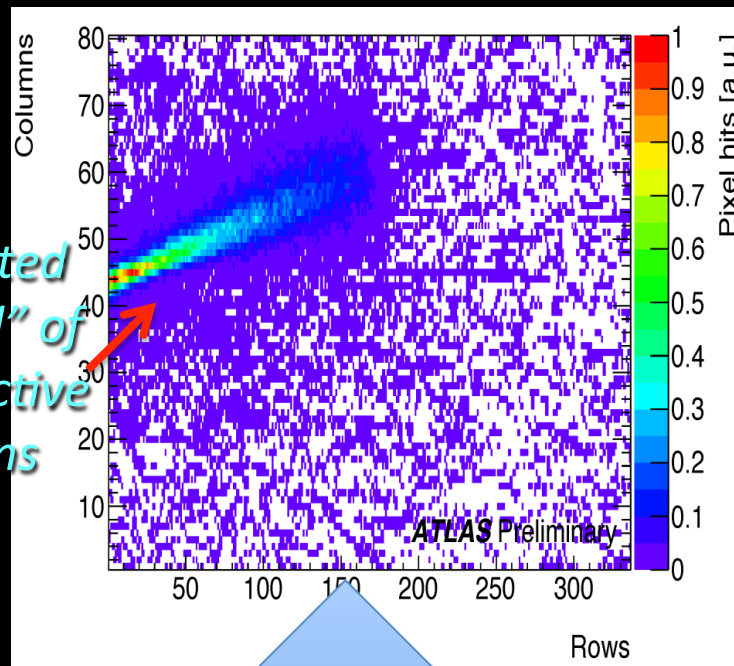


# Current Status



- 3D Pixels in (3 layers Near & 4 Far)
- Trigger (each station) in reasonable working order
- Readout chain to the ROS in place
- AFP TDAQ integration going well – AFP running smoothly in ATLAS partition – DCS integration ongoing.
- Several AFP insertions already – Low mu physics run completed

# Performance Plots



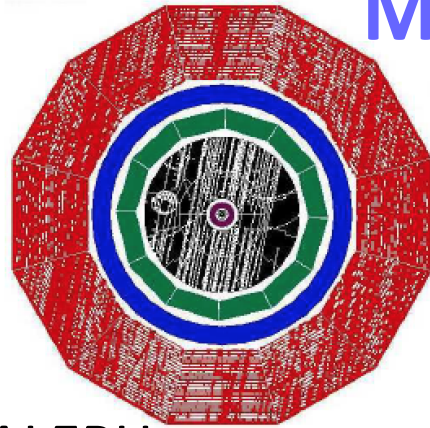
Number of raw pixel hits in arbitrary units of a tracker plane in the near station AFP was triggered by ATLAS. The diagonal line corresponds to diffracted protons

Correlation of row pixel hits between consecutive tracker planes in the near station C (205m).. AFP was triggered by ATLAS

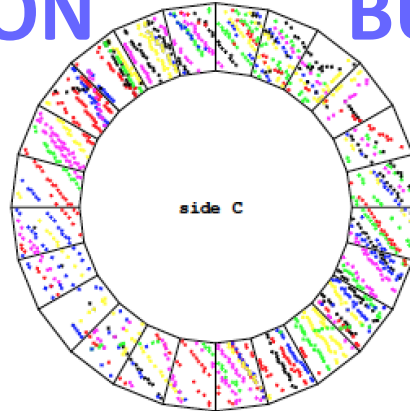
Data was taken the 300 bunches LHC intensity ramp up (10<sup>th</sup> May 2016)

# Cosmic Muon Mysteries

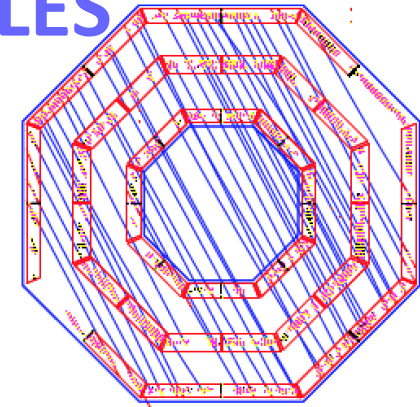
## MUON BUNDLES



ALEPH

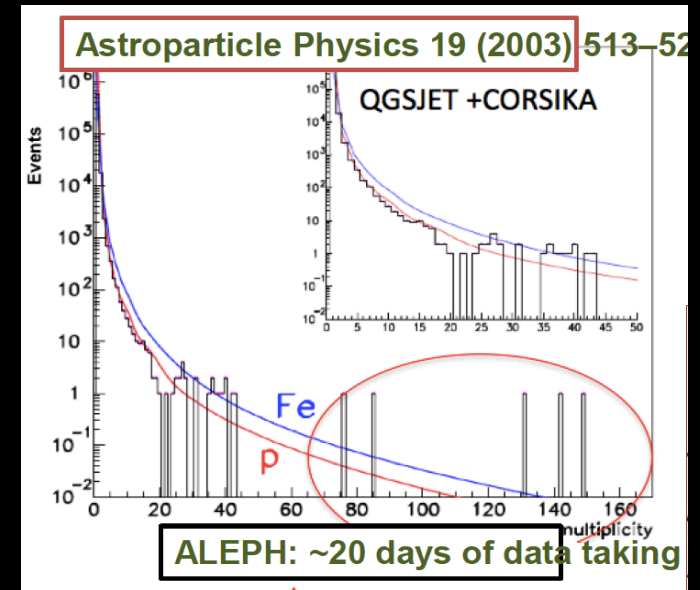


DELPHI

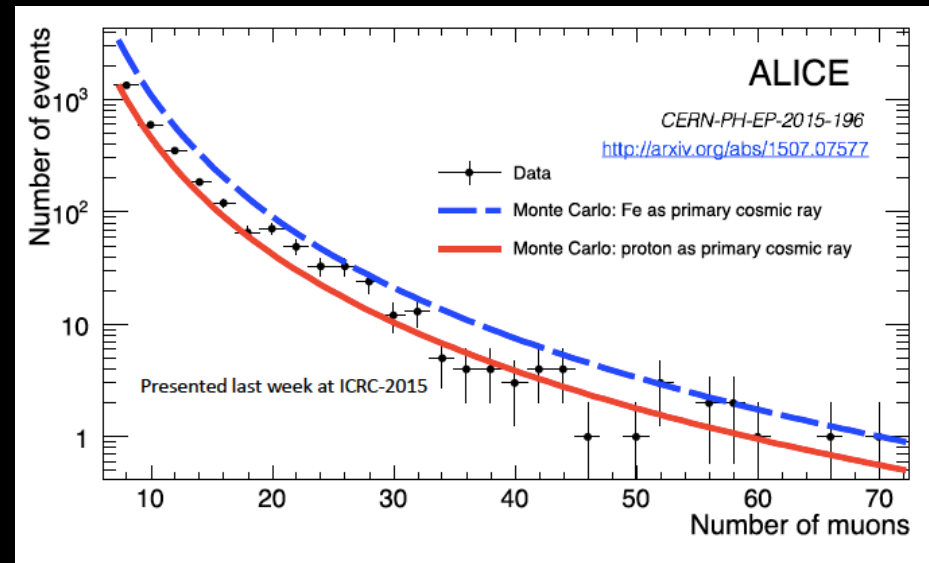
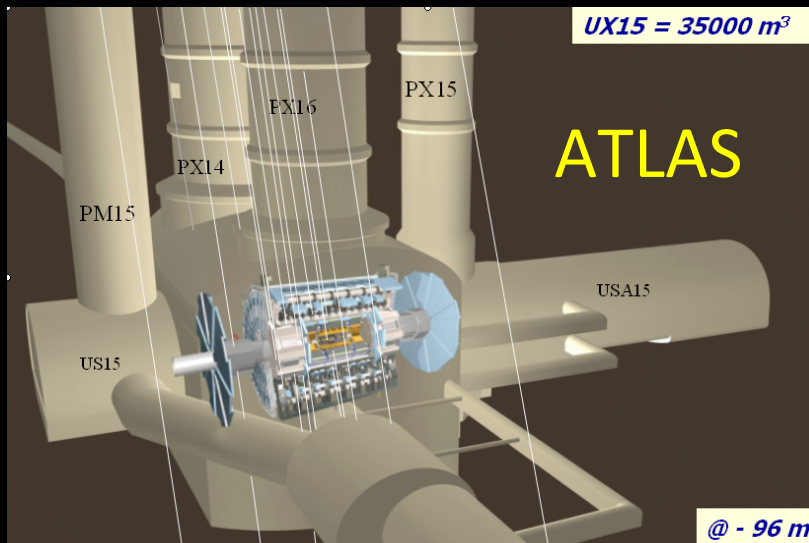


L3+C

- *Muon production in EAS data is still not being consistently reproduced even by post-LHC MC models.*
- *An old problem? At LEP existing MC's could not explain the number of high multiplicity muon bundles*



# Cosmic Muon Physics with ATLAS?



- *The muon bundle multiplicity dist. is sensitive to composition*
  - *The ALICE-ACORDE detector result on muon bundle indicates the composition gets heavier as primary energy increases*
- *ATLAS would measure CR muons directly using 12,000 m<sup>2</sup> of  $\mu$ -tracking + calorimetry  $\sim$ 70m underground with a CT trigger provided underground or from a surface array*
  - *“Horizontal area” of ATLAS muon system is  $\sim$ 50 times larger than the ALICE-ACORDE CR detector*

# Summary

- *Direct Inelastic Cross Section Measurement at  $\sqrt{s} = 13$  TeV*
  - *Agrees with all reasonable models at current level of precision*
  - *Provides valuable anchor point on extrapolation to 60 TeV (AUGER) and 95 TeV (TA)*
  - *Leads to better understanding of  $X_{max}$  distribution and the composition of UHE cosmic rays*
- *ATLAS p-p hadron data agree quite well with existing “standard” models*
  - *Indicates that the knee in the cosmic ray energy spectrum that is covered by LHC data is probably not due to new hadronic physics*
- *The AFP detector now being successfully installed (so far) gives the promise of a new handle on diffractive physics*
- *The possibility of cosmic ray muon physics (muon bundles) using the ATLAS detector is now being studied.*