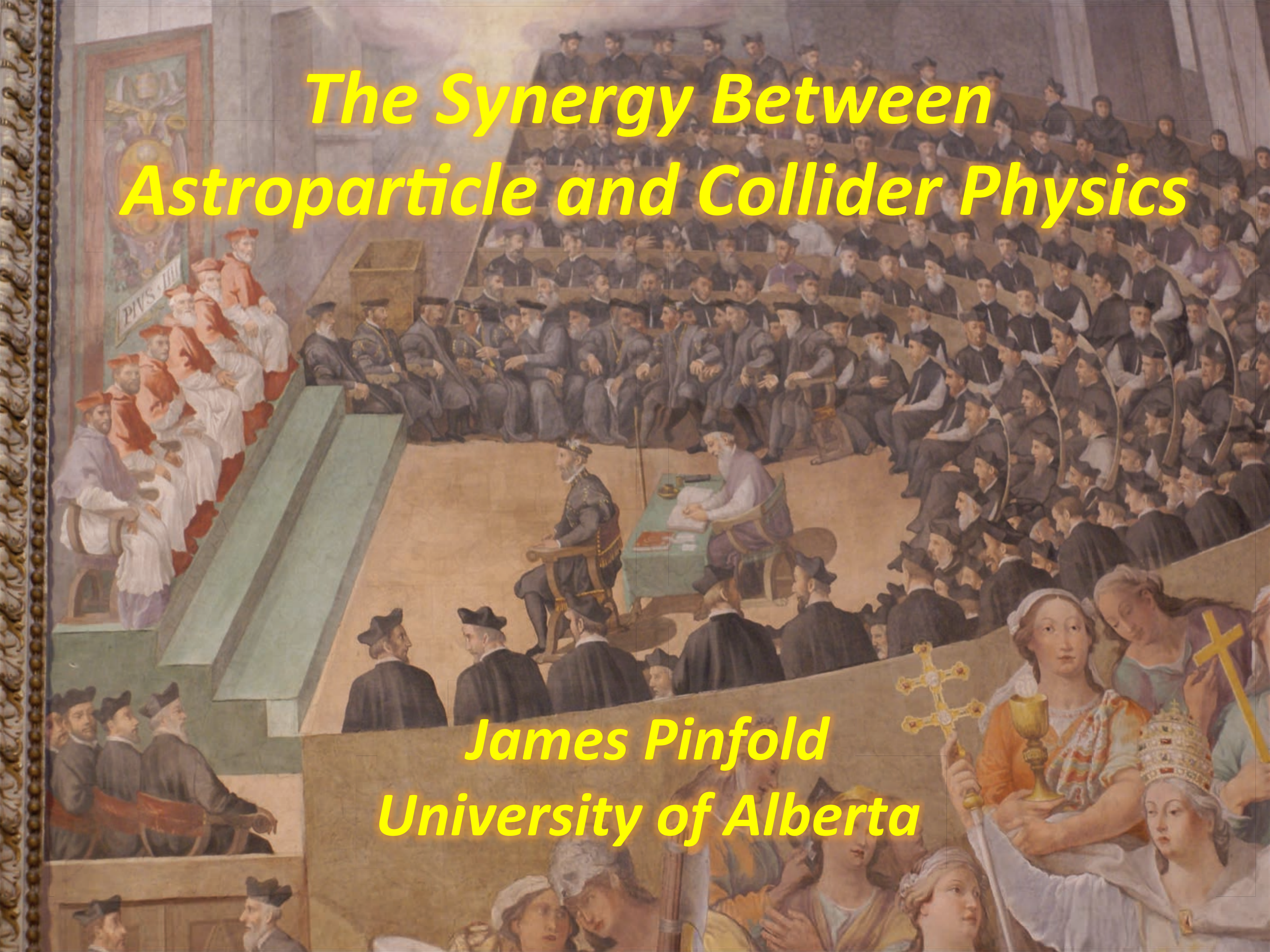
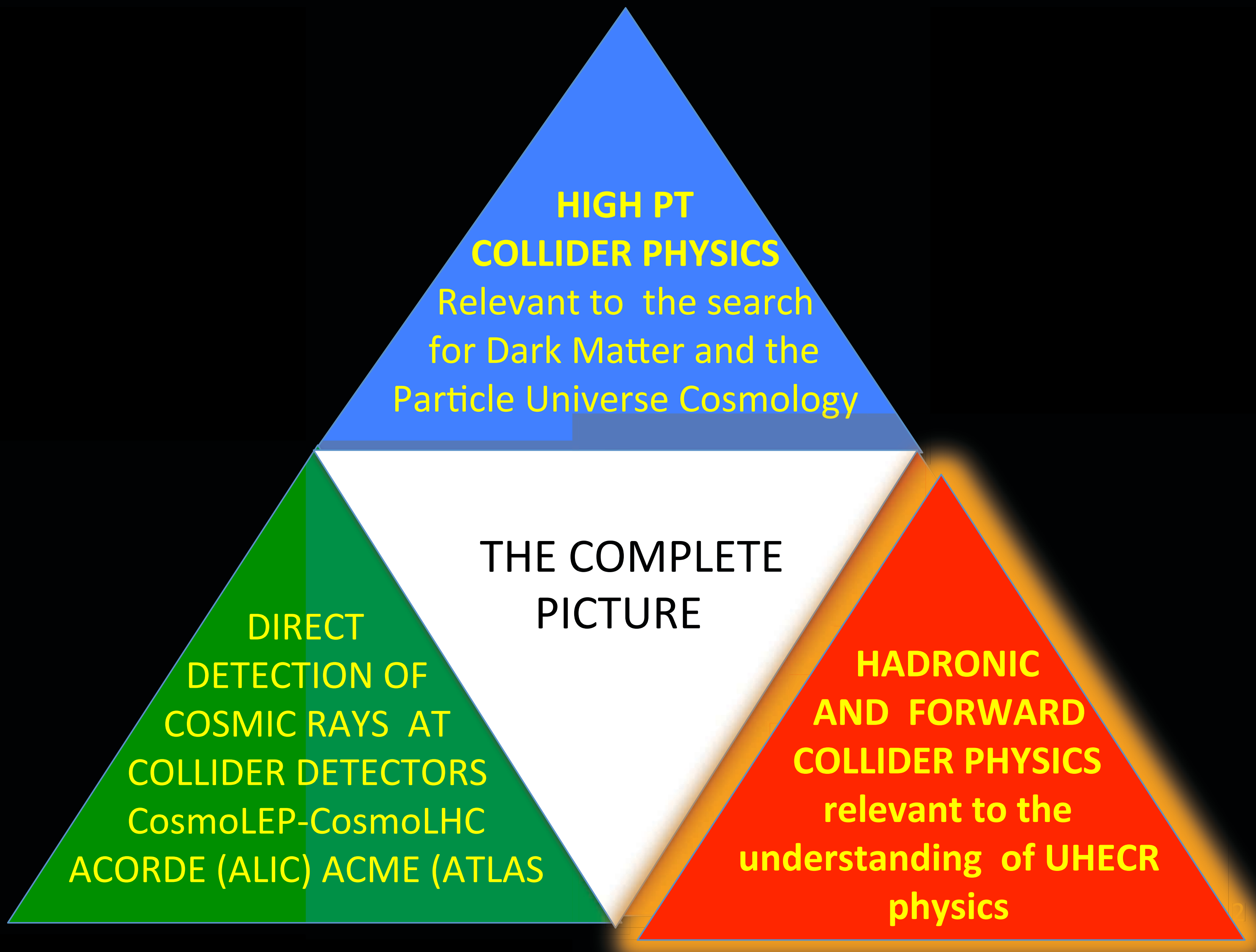


The Synergy Between Astroparticle and Collider Physics

James Pinfold
University of Alberta

The Collider - Astroparticle Physics Synergy

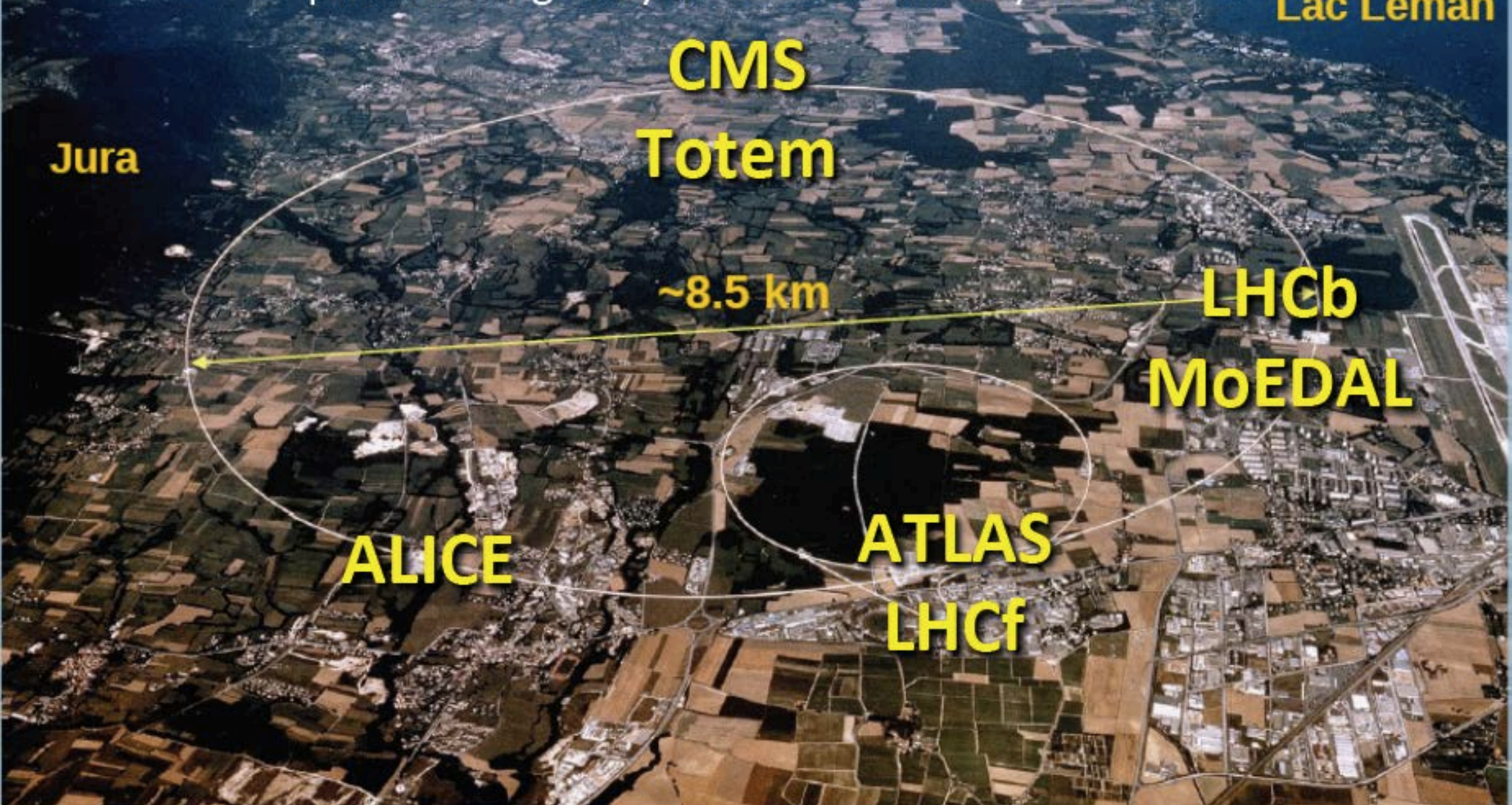


CERN Large Hadron Collider (LHC)

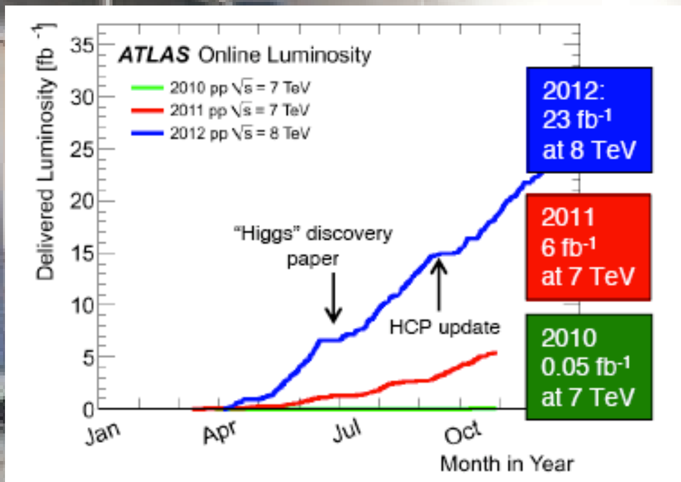
p-p collisions up to $\sqrt{s}$ = 14 TeV, $\mathcal{L}=10^{34}\ cm^{-2}s^{-1}$, 8 mo/yr

pPb,PbPb up to $\sqrt{s}$ = 8.8,5.5 TeV, $\mathcal{L}=10^{30,27}\ cm^{-2}s^{-1}$, 1 mo/yr

p-Pb running early in 2013 luminosity $10^{28}\ cm^{-2}\ s^{-1}$



The Onward March of the LHC



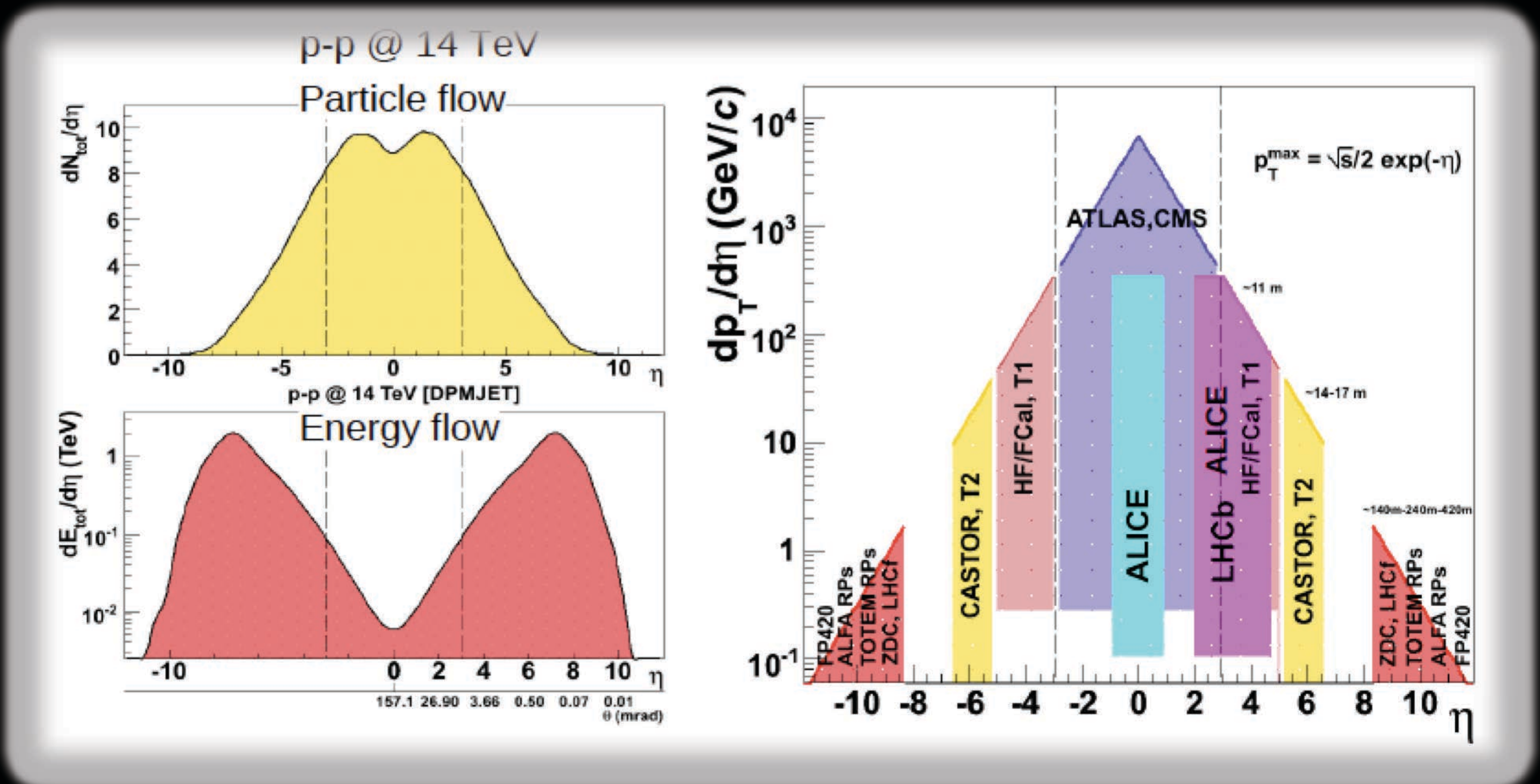
LHC
L_{peak} $7.7 \cdot 10^{33}$ $cm^{-2}s^{-1}$
L_{int} ~ 29 fb^{-1}
in 2011+2012

Year	
2013 2014	LHC-shutdown to go to the design energy and nominal energy (13-14TeV)
2015 2016 2017	**$\sqrt{s}$=13-14TeV**, ~1 x 10^{34} $cm^{-2}s^{-1}$, 25-50 fb^{-1} per year-> **~100 fb^{-1}**
2018	LHC-shutdown, upgrade to go to the full design luminosity
2019 2020 2021	**$\sqrt{s}$=13-14TeV**, ~2 x 10^{34} $cm^{-2}s^{-1}$, ~100 fb^{-1} per year -> **~400 fb^{-1}**
2022	LHC-shutdown for the high luminosity
2023 ~ 2030	**$\sqrt{s}$=13-14TeV**, ~5 x 10^{34} $cm^{-2}s^{-1}$ (pileup~140) -> take data until **>3000 fb^{-1}**

Results of 2015 will play important role for the future plans of the high energy particle physics.

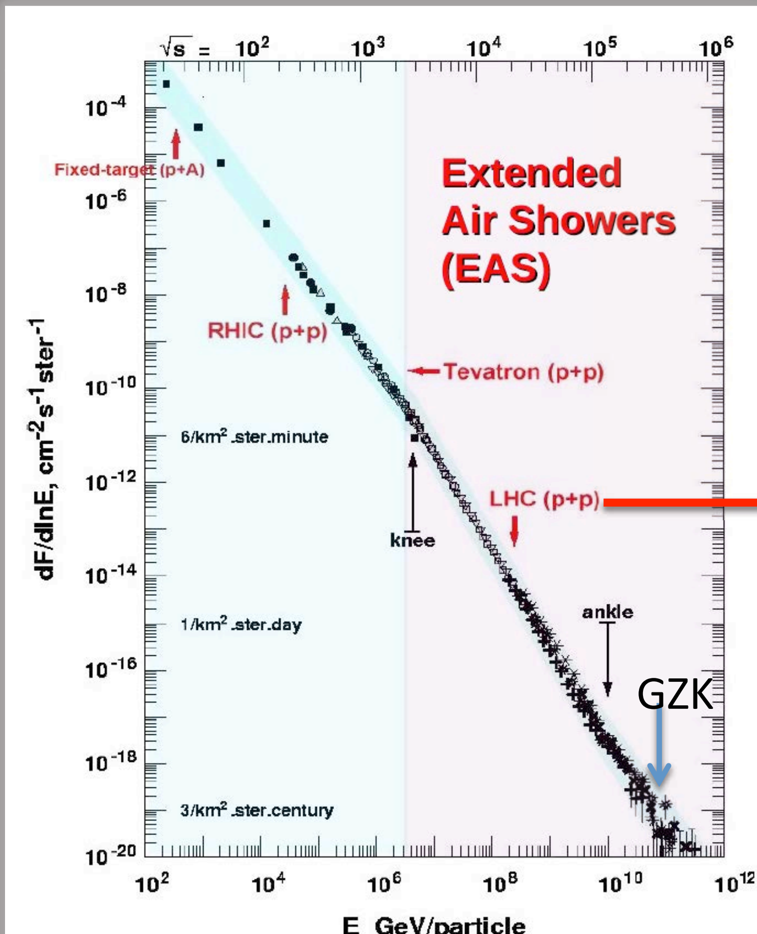
HL-LHC (2022–2030)
Not approved yet.

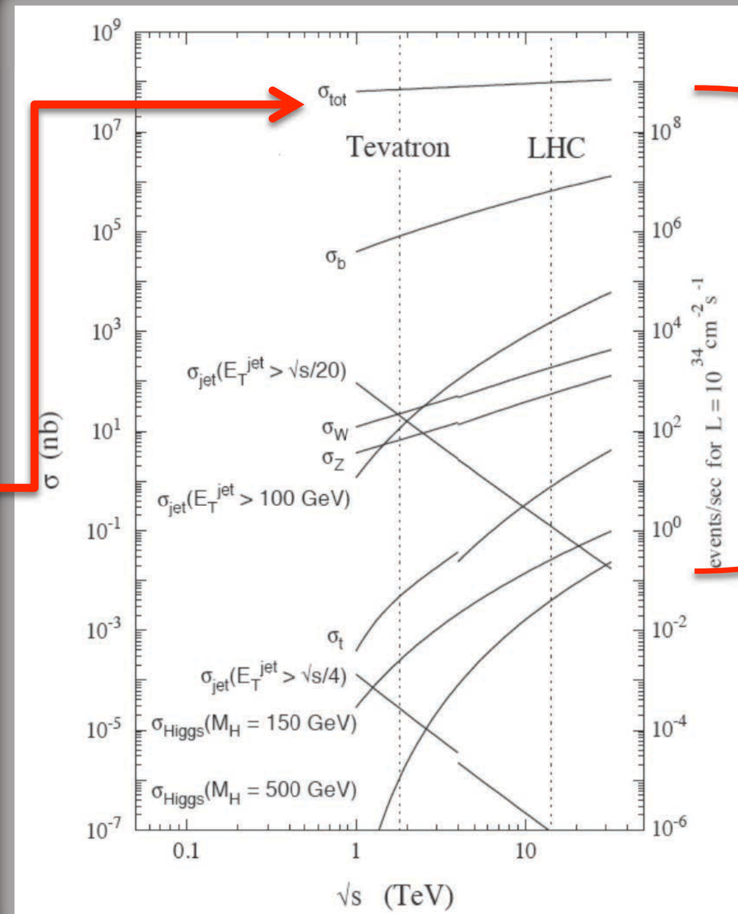
Coverage of the LHC Detectors



- *Central detector, forward calorimeters , Very forward calorimeters (Castor, ZDC), forward spectrometers (AFP, HPS)*
- *Large pseudorapidity η - coverage of detectors @ LHC!*

Cosmic Ray Flux vs LHC Cross-sections





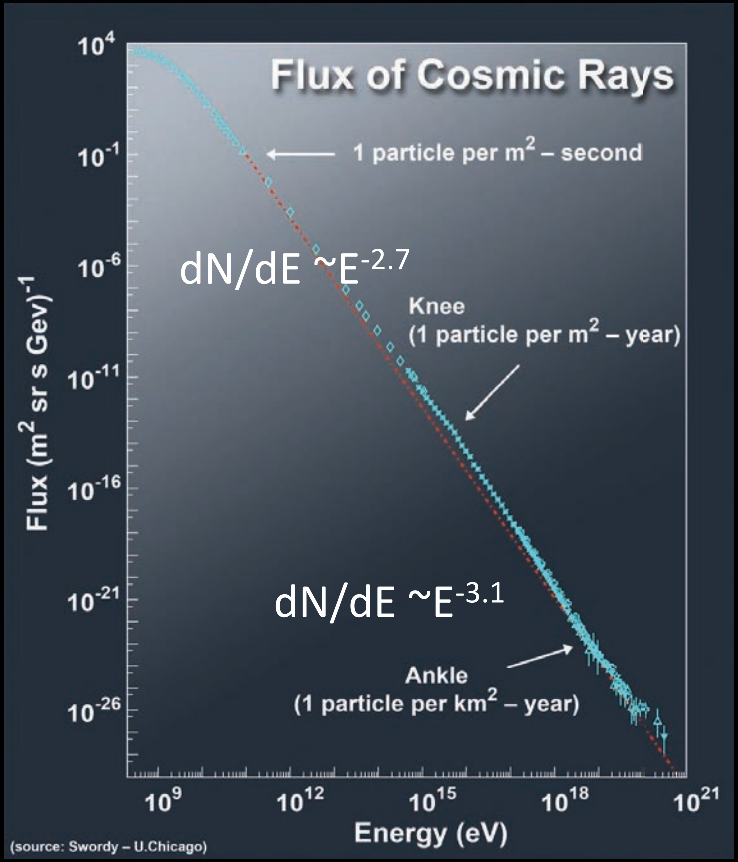
σ_{TOT} & σ_{INEL}

A factor of 10^9-10^{10}

HIGGS

- *Cosmic ray p-N collisions in the atmosphere above "knee" at ~10^8 GeV/particle can be probed in p-p collisions at the LHC*

High Energy Cosmic Ray Questions

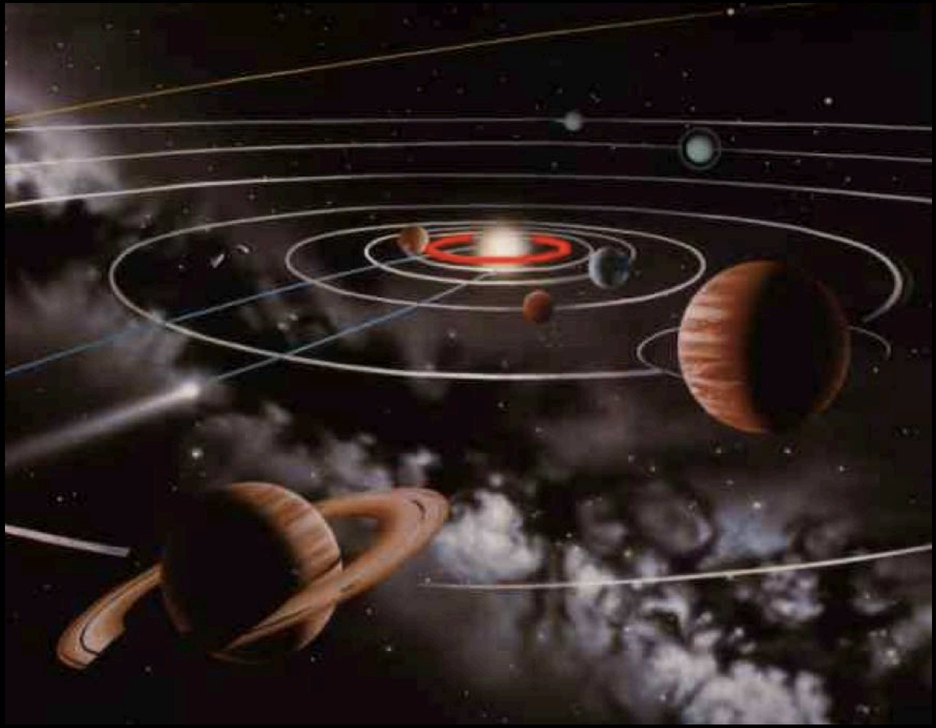


Direct detection

Detection via air showers

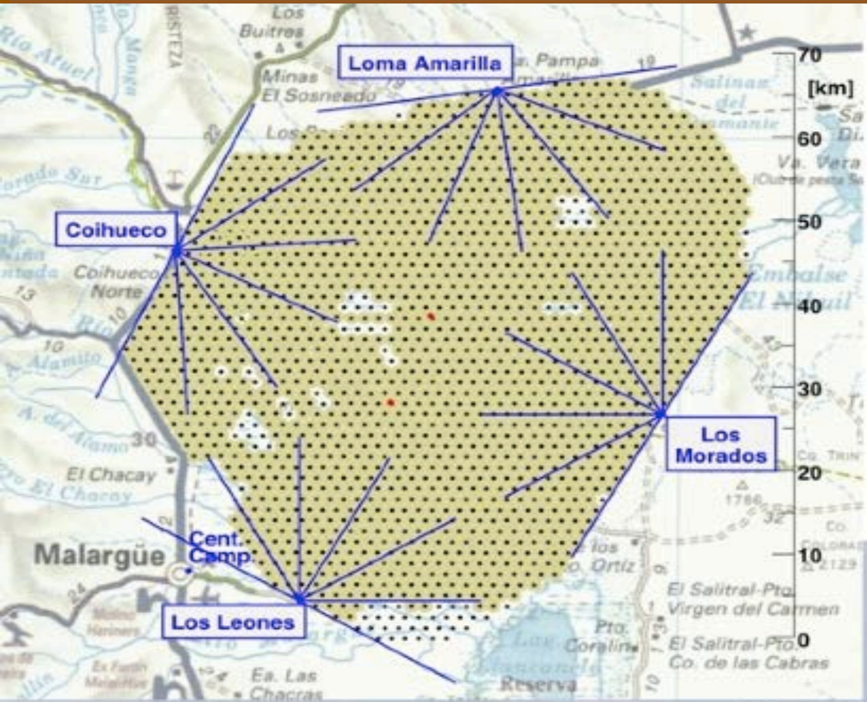
- *At >~ 10^{14} eV E_{CR} and CR ID has to be determined via hadronic MCs*
  - *p-N collisions: QCD interactions at E_{cm} up to $\sqrt{s_{GZK}}$~ 300TeV*
- *Big questions: a) What are the origins of the structures in the CR spectrum; b) What are the sources and composition of CRs*

A Ultra High Energy - 10^{20} eV - Collider



- *Ultra-high energy cosmic rays reach as high as 10^{20} eV energy*
- *Large Hadron Collider (LHC), 27 km circumference, SC magnets – in 2015 it will reach a collison energy of 14 TeV*
- *We will need a "Super-LHC" accelerator of size of Mercury´s orbit to reach 10^{20} eV with current technology*

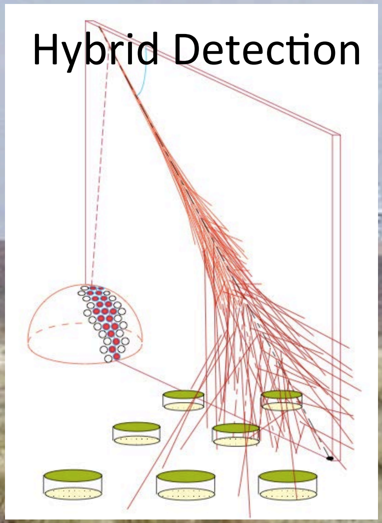
Eg Astroparticle Experiment – the PAO



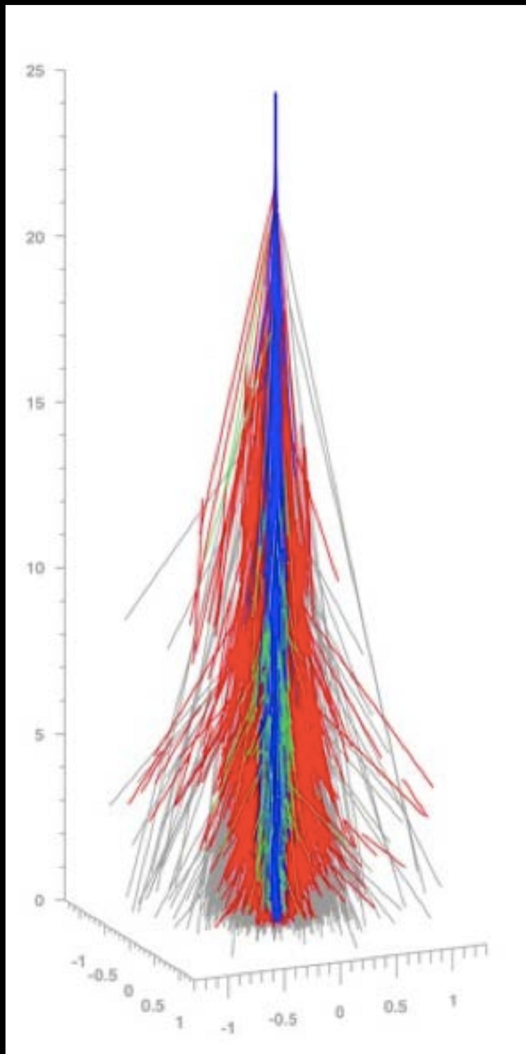
Southern Pierre Auger Observatory

Malargue, Argentina

Area ~3000 km^2,
1660 surface detectors (1.5 km grid)
24+3 fluorescence telescopes

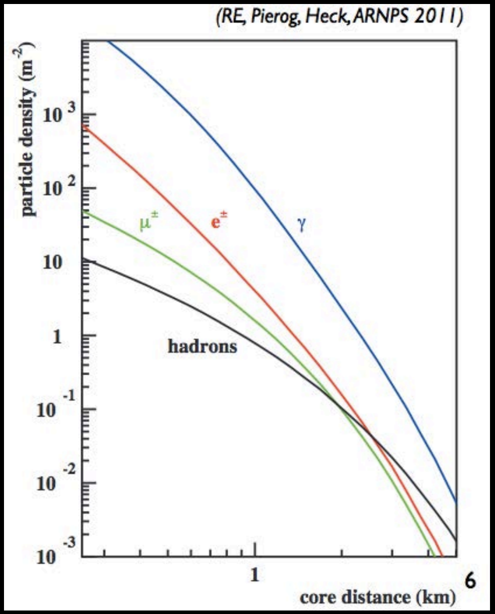


Extensive Cosmic Ray Air Showers



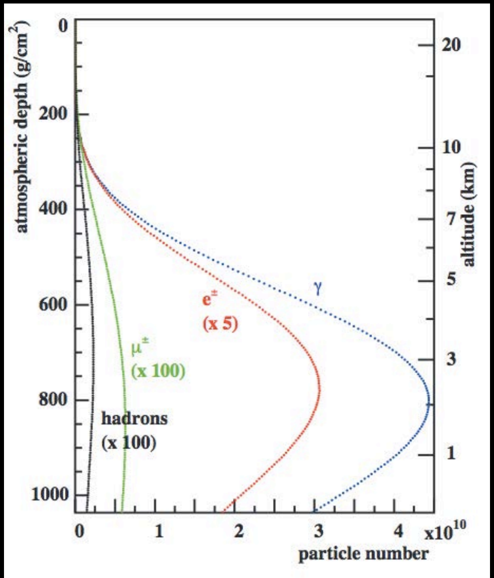
Proton induced
10^{19} eV air shower

- *LATERAL AIR SHOWER – Ground Detectors*

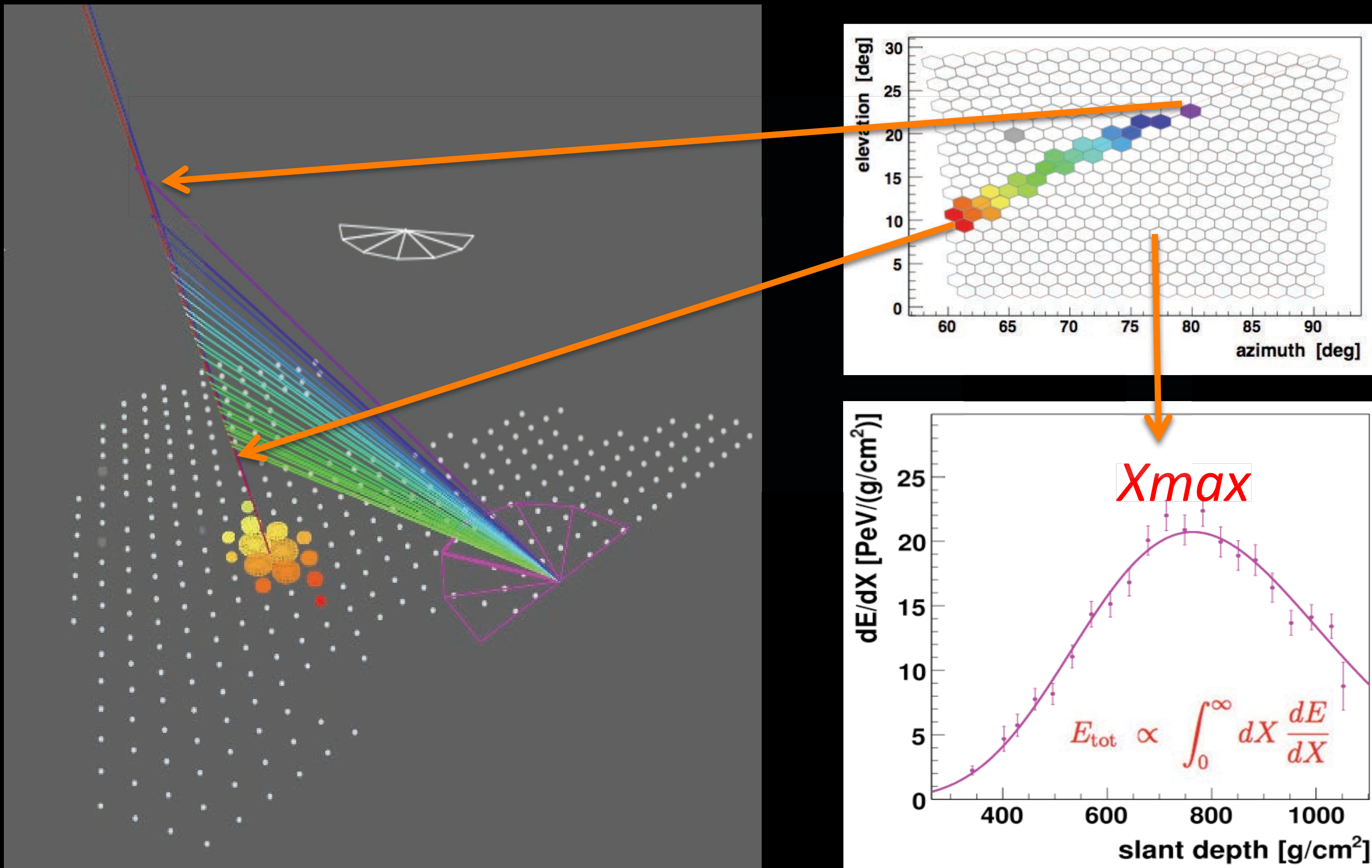


THE ATMOSPHERE AS A CALORIMETER FOR MEASURING COSMIC RAY ENERGY

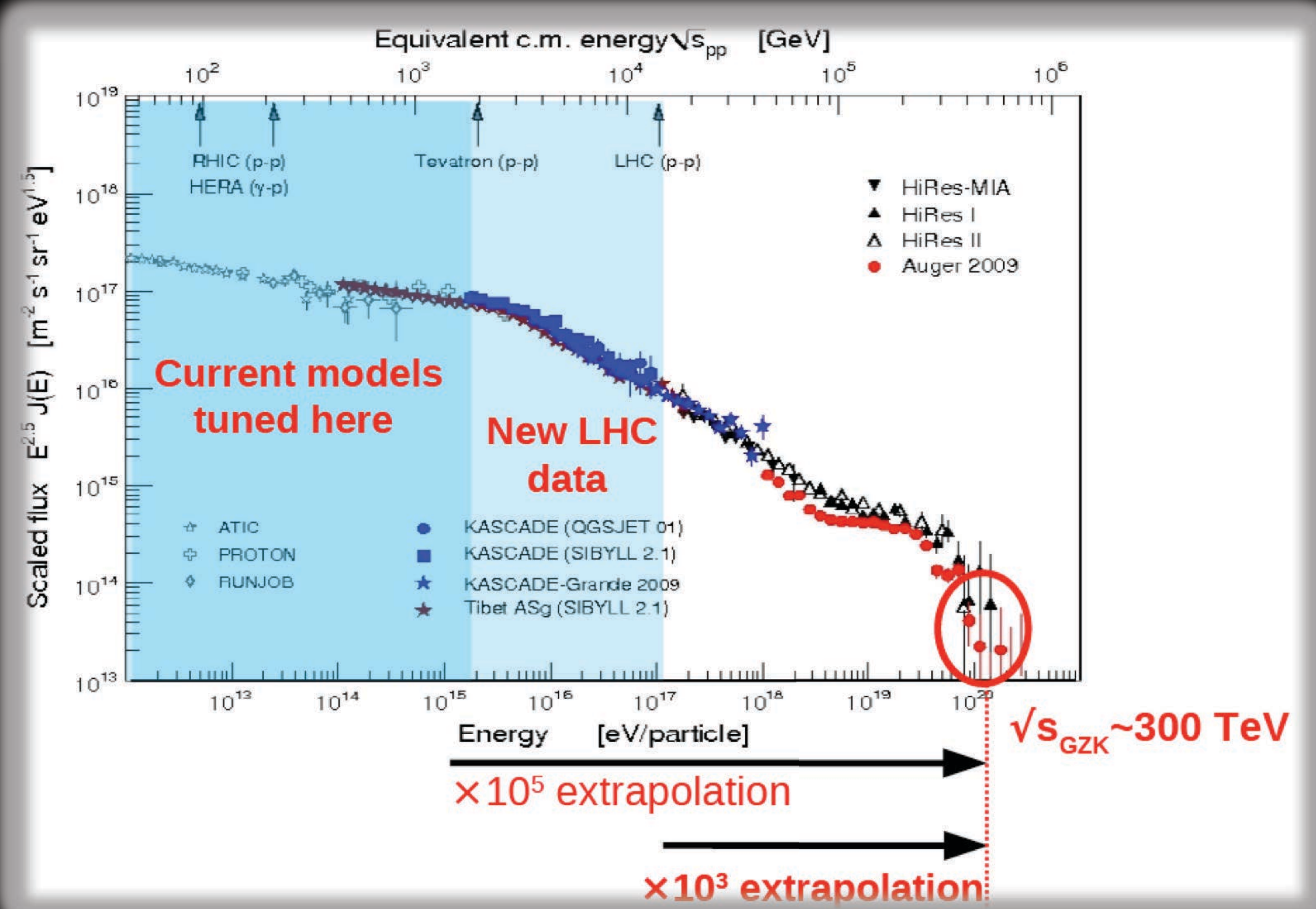
- *LONGITUDINAL AIR SHOWER: Fluorescence light from N_2*



Hybrid Observation of X_{max}

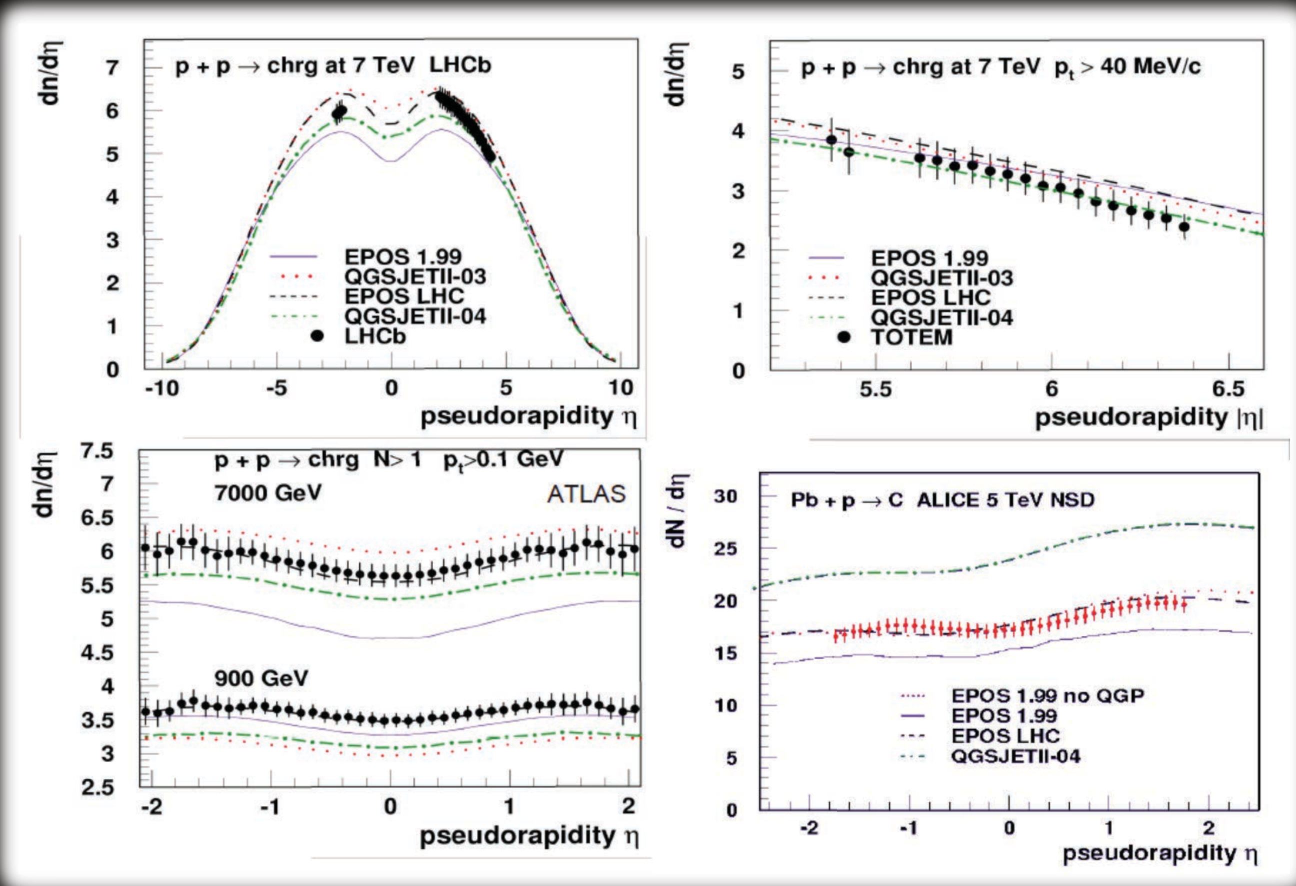


UHECR Simulations and Collider Data



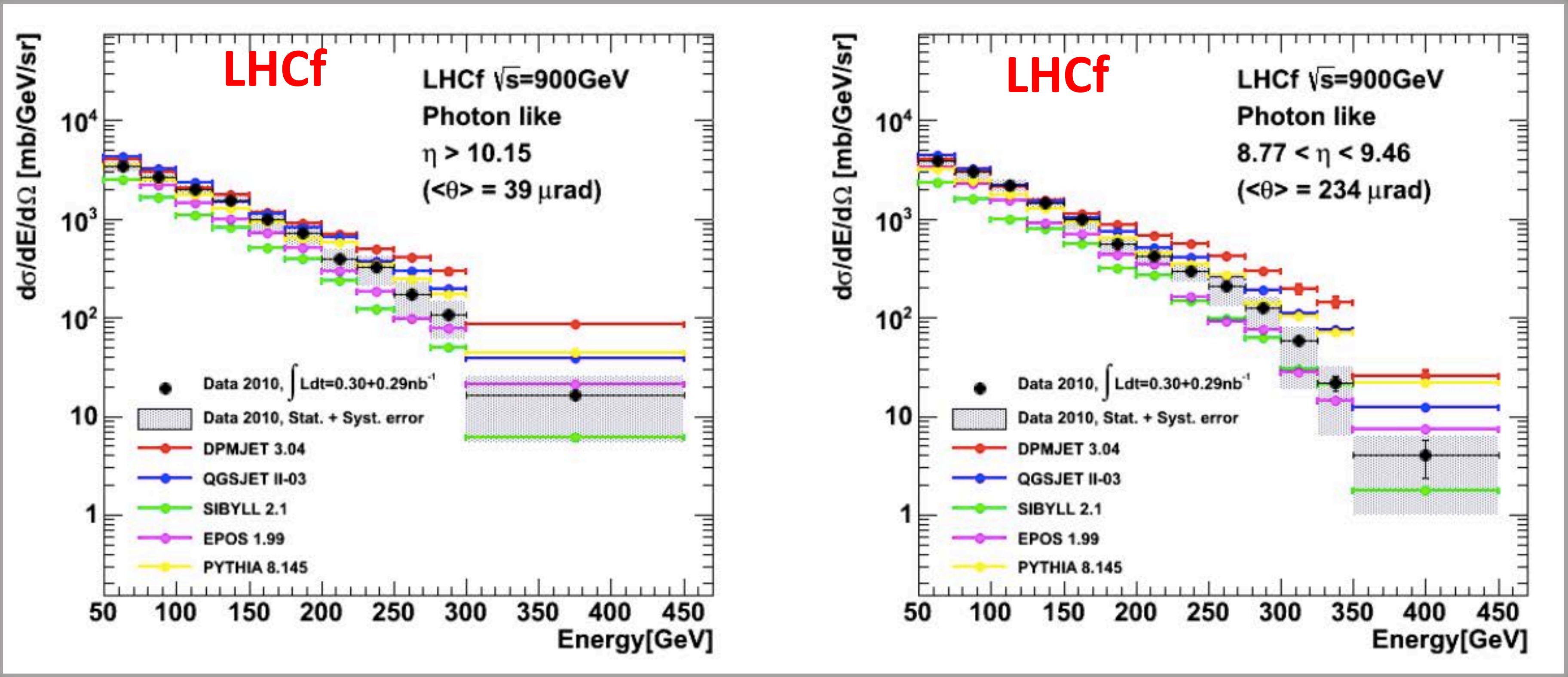
- *The LHC provides a significant lever-arm reduction in providing constraints for hadronic Monte Carlos for UHECR*

LHC: Distribution of Charged Secondary Particles



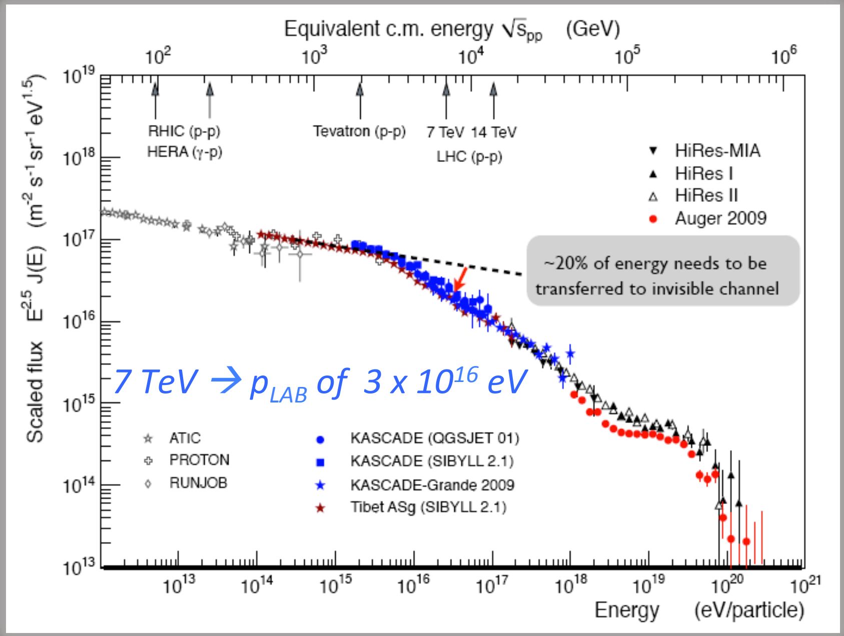
- *No model with perfect predictions but data well bracketed*
- *Similar agreement seen by ATLAS, LHCb, ALICE, ToTEM for all kinematic varaibels*

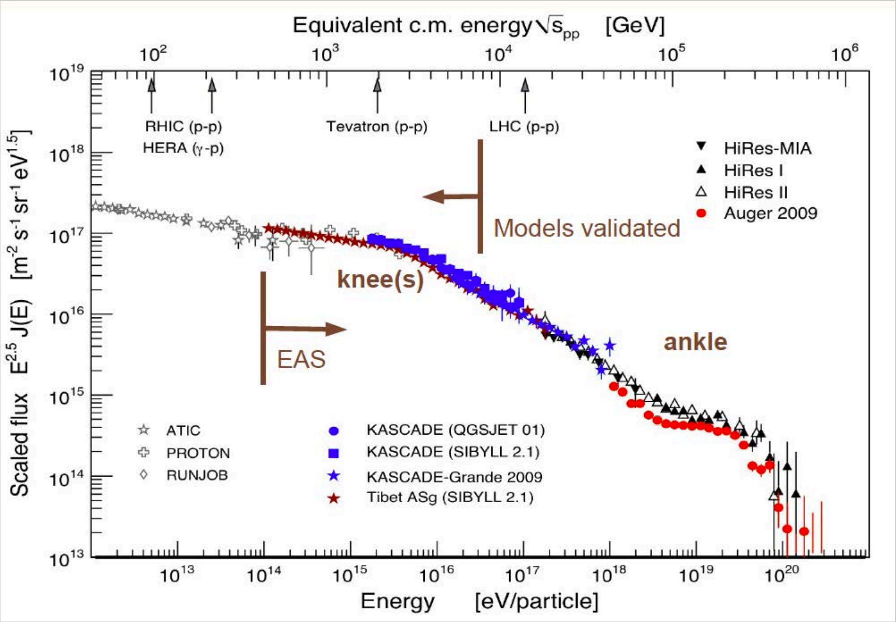
Forward Spectra



pp → γ + X   Model predictions bracket the LHC data

New Physics at the Knee?





- *Cosmic Ray models 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*
  - *Probable dependence on primary CR composition*

Was this LHC's First Discovery?

LETTERS

The LHC and cosmic rays

Very recent measurements at the LHC show that the charged-particle density in the central rapidity region is following a simple power law in energy all of the way from as low as 10 GeV up to 2.6×10^7 GeV laboratory energy (ALICE collaboration 2010, see also page 6). Specifically the power law exponent, α = 0.11, is the same as that found for laboratory energies $1.5 \times 10^3 - 1.5 \times 10^5$ GeV (Erlykin 1983) and close to α = 0.13 found at even lower energies $10 - 1.5 \times 10^3$ GeV (Wdowczyk and Wolfendale 1979).

There is immediate relevance to the nature of the famous "knee" in the primary cosmic-ray energy spectrum around 3×10^6 GeV, because it is the first time that measurements cover interactions at these and even higher energies. The preservation of that rate of rise for the charged-particle density means that drastic changes in the "nuclear-physics model" of the knee cannot be invoked. Conventional astrophysical models – with no change in interaction mechanism – suggest light nuclei (protons and helium) from a local single supernova as being responsible.

ALICE collaboration 2010 arxiv:1004.3514.

A D Erlykin 1983 *Proc. Int.Cosm. Ray Conf. Bangalore* **5** 1.

J Wdowczyk and A W Wolfendale 1979 *Nuovo Cim.* **54A** 433.

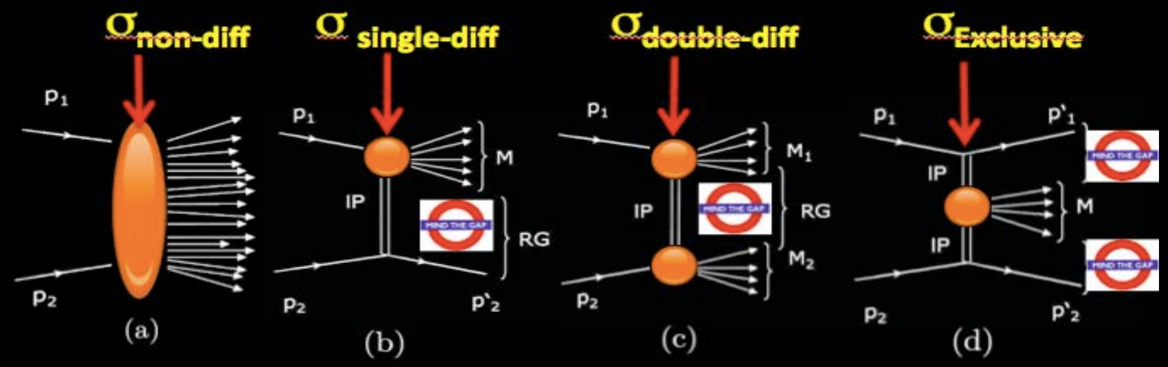
A D Erlykin and A W Wolfendale.

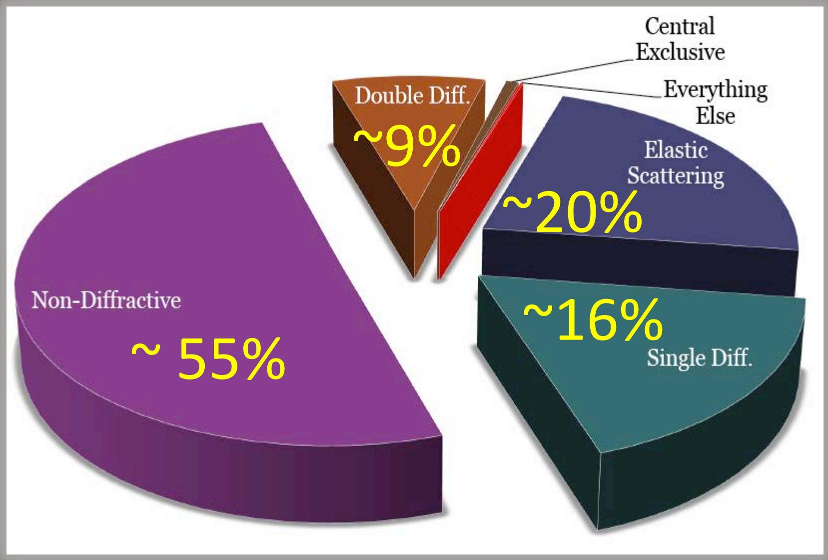
Krisch and cross-sections

I am a great admirer of Alan Krisch and I was delighted to see the article about him in the *CERN Courier* of April 2010. I think that all of those like Krisch, or, at CERN, Louis Dick, who had the courage to investigate polarization phenomena without the support of most of the theoretical community have great merits. Their surprising results remain largely unexplained, and many theoreticians say that these results are not really interesting. Indeed perturbative QCD is unable to say anything about these because the transition

CERN COURIER June 2010

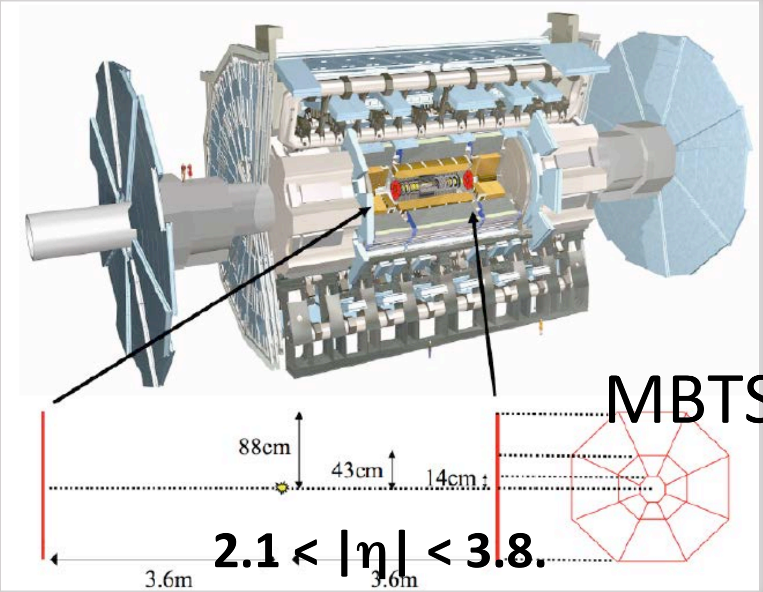
The Total p-p Cross-section

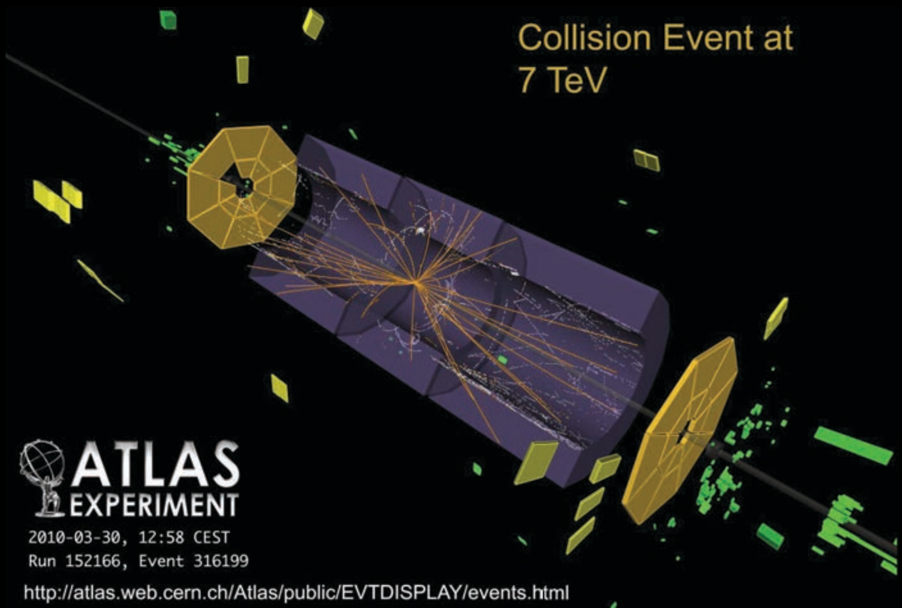




$$\sigma_{total} = \sigma_{elastic} + \underbrace{\sigma_{non\text{-}diff} + \sigma_{single\text{-}diff} + \sigma_{double\text{-}diff} + \sigma_{Exclusive} + ..}_{\text{INELASTIC}}$$

Determining the Inelastic Cross-section



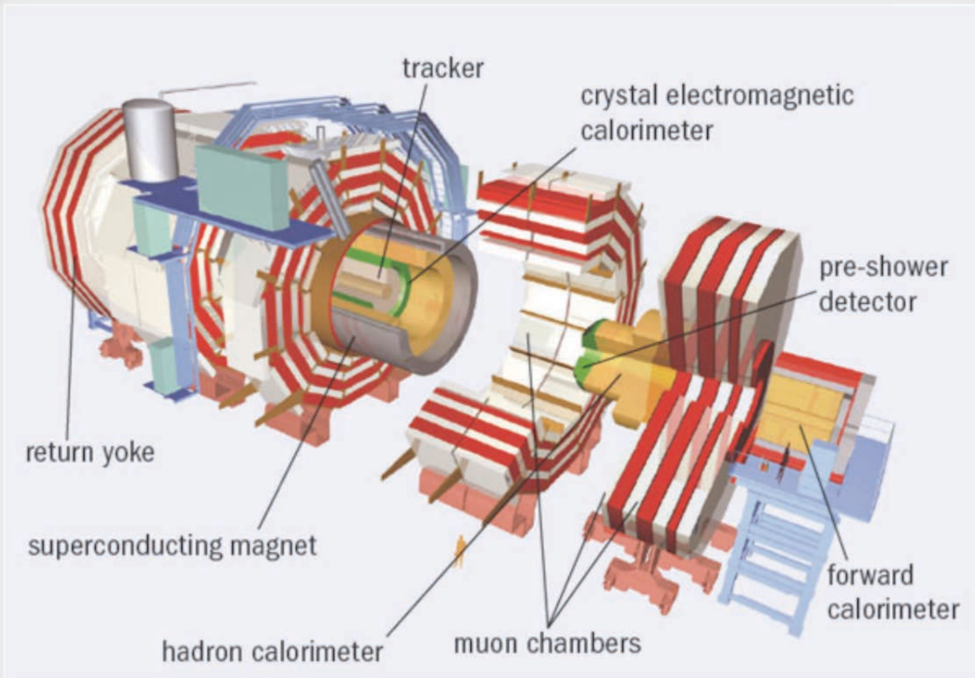


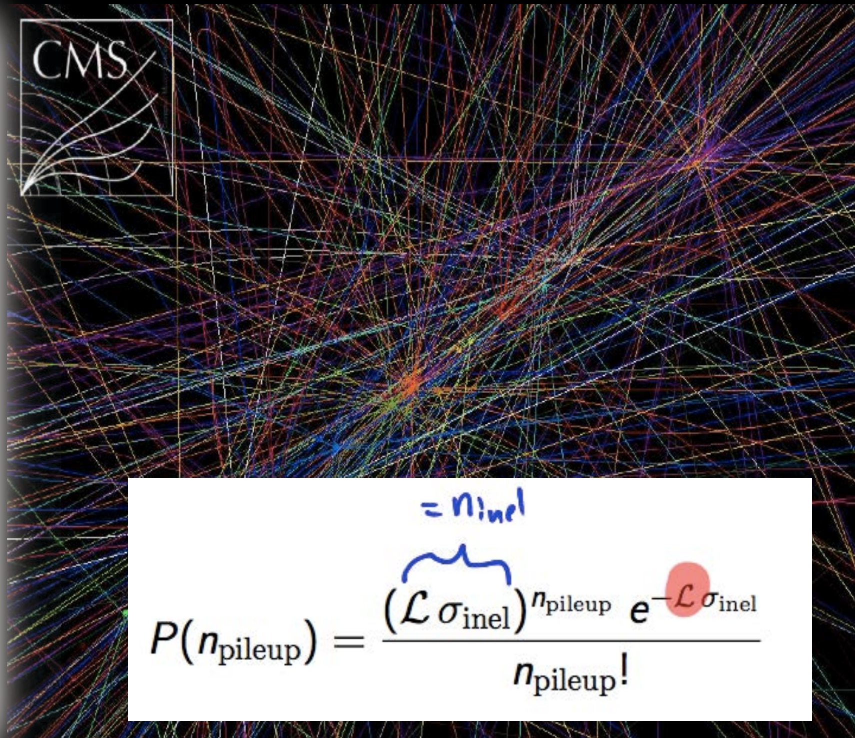
- *The ATLAS analysis uses MBTS to tag inelastic collisions.*
  - *Acceptance $\xi = M_x^2/s > 5 \times 10^{-6} \rightarrow M_x = 15.7$ GeV for $\sqrt{s} = 7$ TeV*
  - *The data collected on the 31 March 2010, corresponding to $L = 20.3 \pm 0.7\ \mu b^{-1}$ - peak instantaneous $L = 1.2\times10^{27}\ cm^{-2}\ s^{-1}$*
- *$\sigma_{inel} = 69.1 \pm 2.4(exp.) \pm 6.9(extrap.)$ mb.*

(Nature Commun. 2 463 2011)

uncertainty on the ξ-dependence

The CMS Approach – Count Vertices





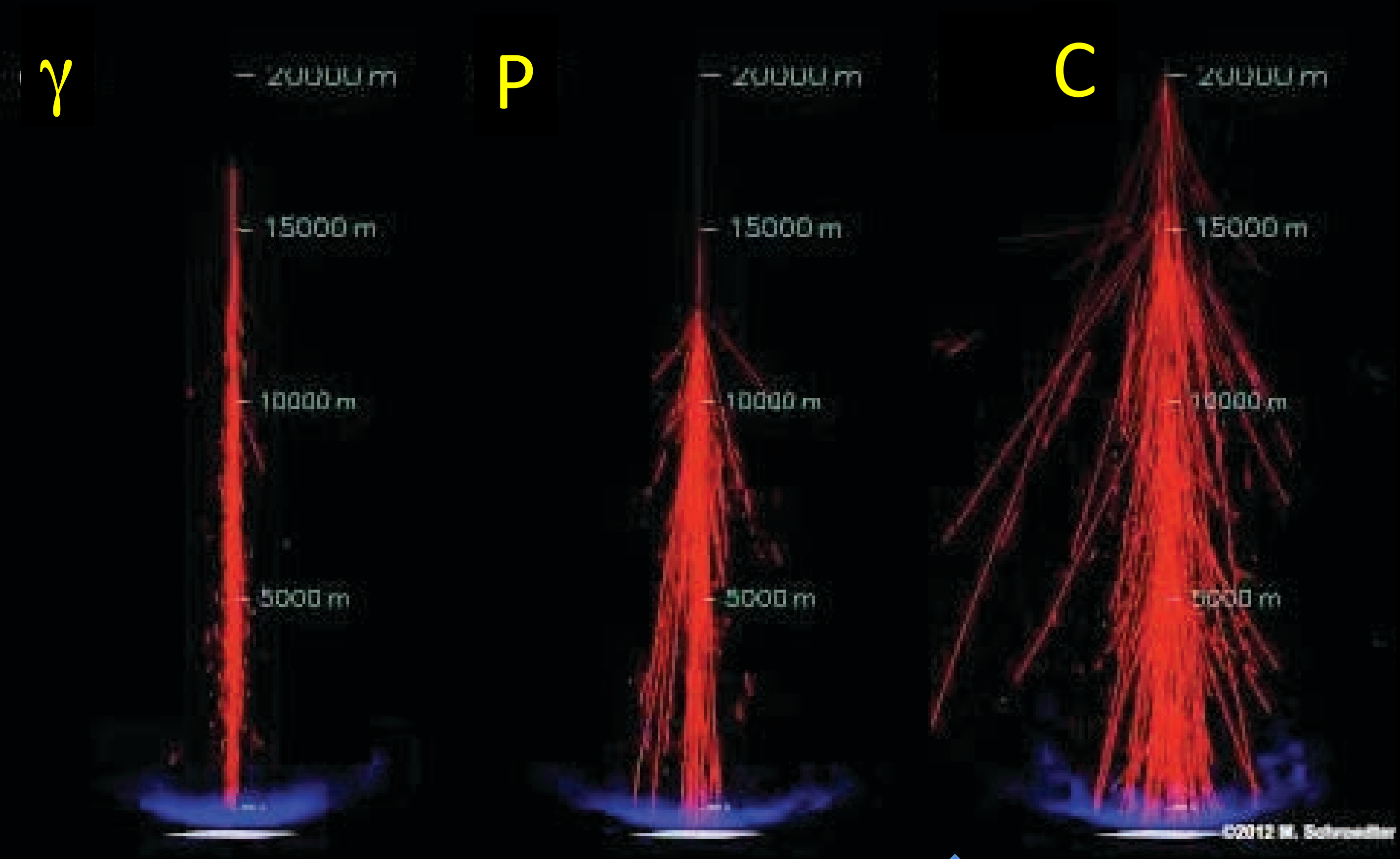
$$P(n_{\text{pileup}}) = \frac{(\mathcal{L}\,\sigma_{\text{inel}})^{n_{\text{pileup}}}\, e^{-\mathcal{L}\sigma_{\text{inel}}}}{n_{\text{pileup}}!}$$

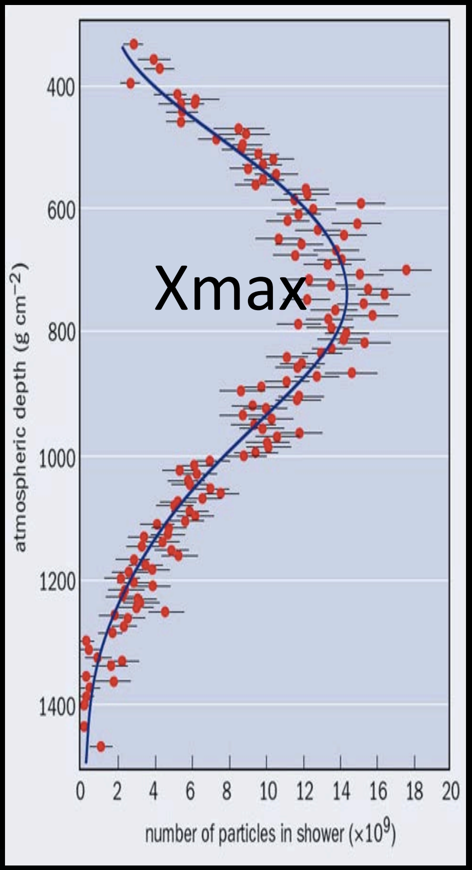
= n_{inel}

- *Count the number of pileup events*

$$\sigma_{inel} = 68.0 \pm 2(sys) \pm 2.4(lum) \pm 4(extrap.)\ mb.$$

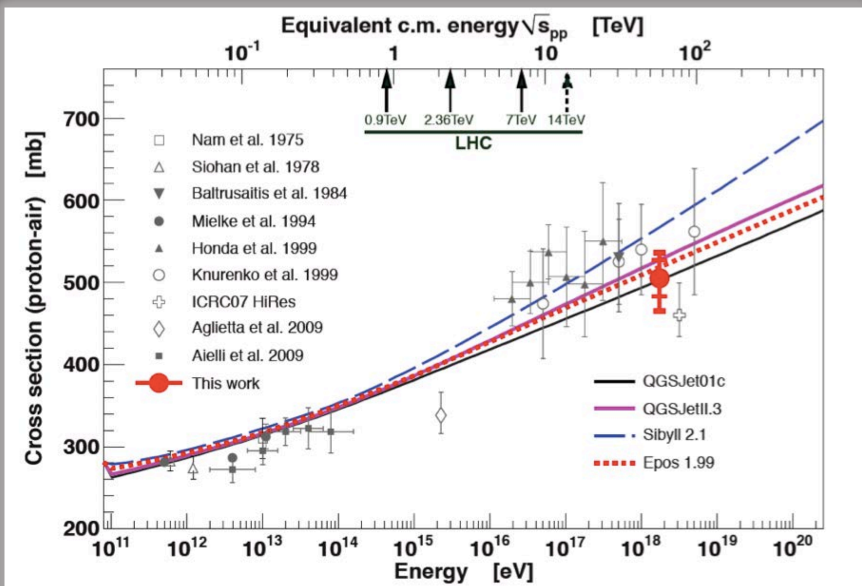
Composition Measurement Using



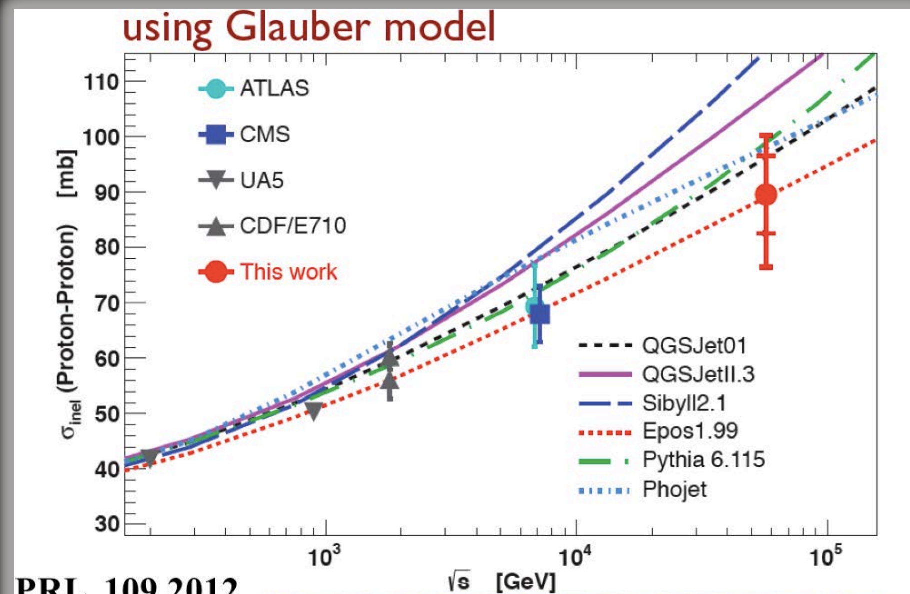


The depth of the shower maximum (X_{max}) indicates the composition of cosmic ray showers – the X_{max} distribution can be used to measure the inelastic cross-section

AUGER's Inelastic Cross-section Result



$\sigma_{p\text{-}Air} = (505 \pm 22_{stat}\,(^{+26}_{-34})_{sys})$ mb

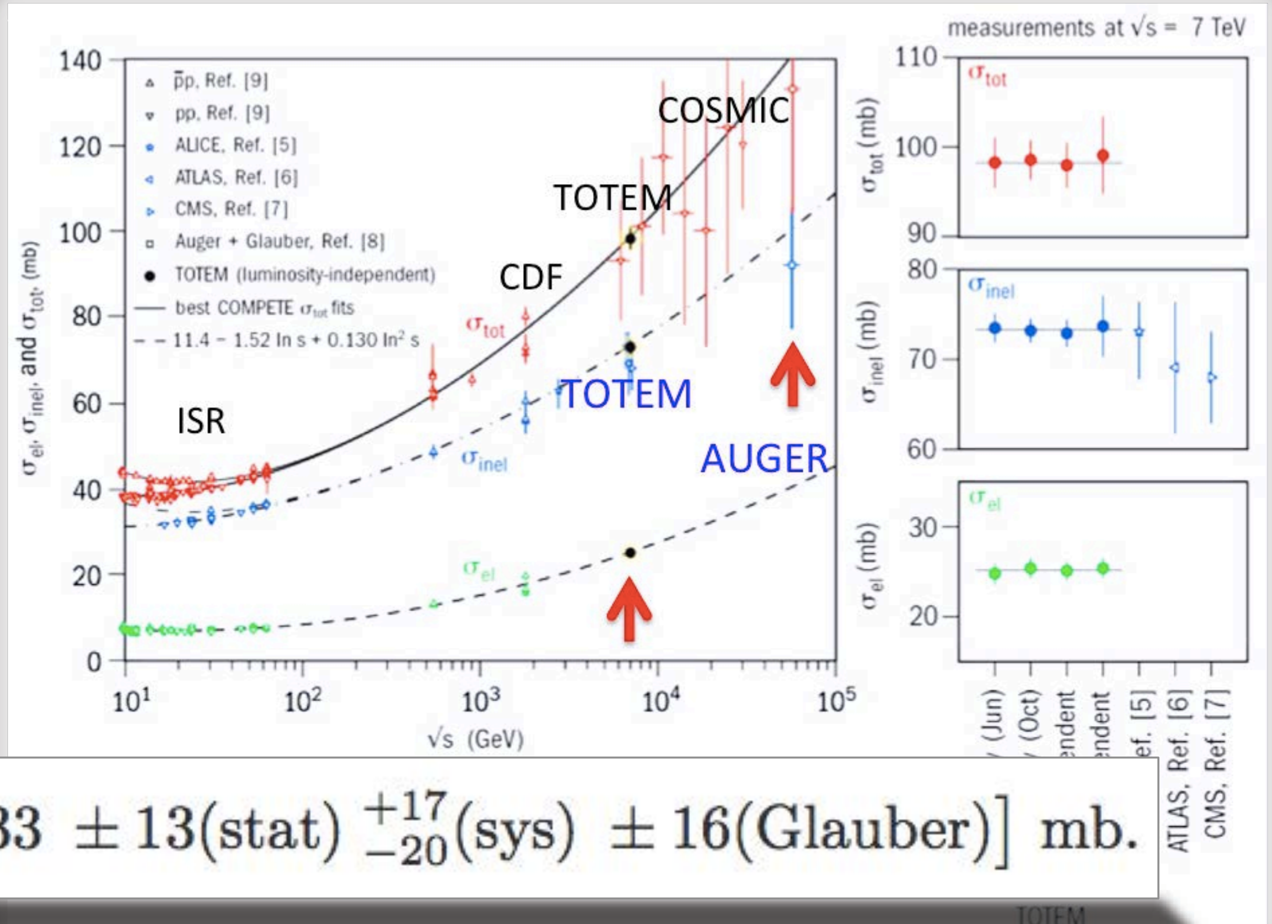


PRL 109 2012

$\sigma_{pp} = (92 \pm 8_{stat}\,(^{+8}_{-11})_{sys} \pm 7_{Glauber})$ mb

- *Auger measure p-Air using the Glauber formalism to predict the p-p cross-section at ~60 TeV*
- *The EPOS1.99 model describes well the rise in the cross-section through 7 TeV (ATLAS/CMS) to 60 TeV (Auger)*

The Total Cross-section

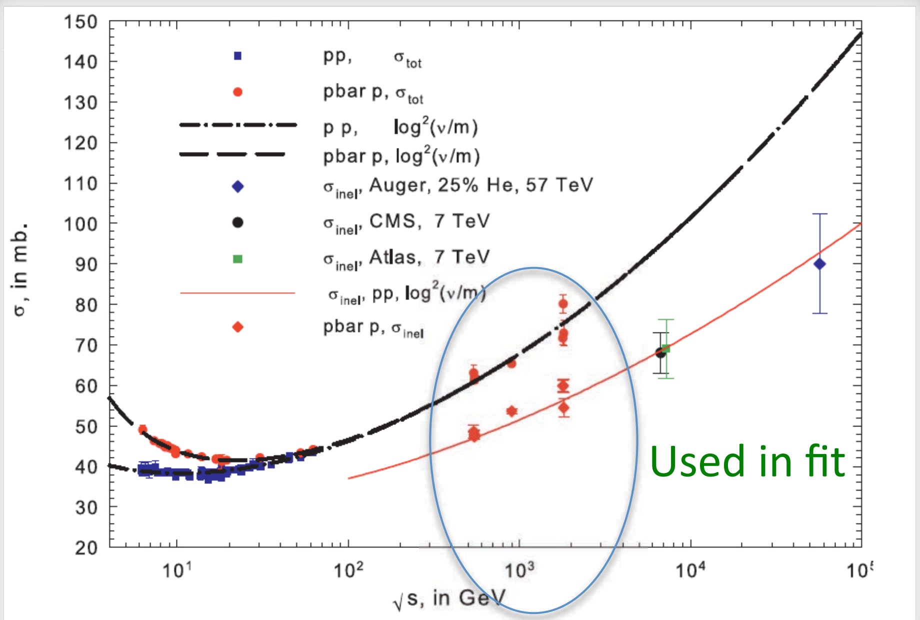


AUGER

$$\sigma_{pp}^{tot} = [133 \pm 13(\mathrm{stat})\ ^{+17}_{-20}(\mathrm{sys}) \pm 16(\mathrm{Glauber})]\ \mathrm{mb}.$$

σ_{el} =25.1±1.1 mb, σ_{inel} =72.9±1.5 mb & σ_{tot} =98.0±2.5 mb (TOTEM)

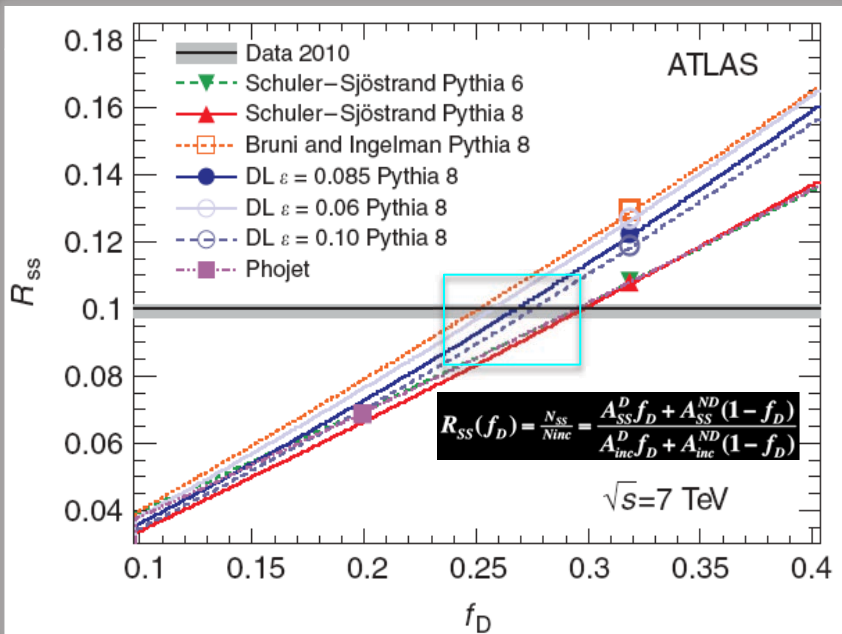
Probing Asymptopia

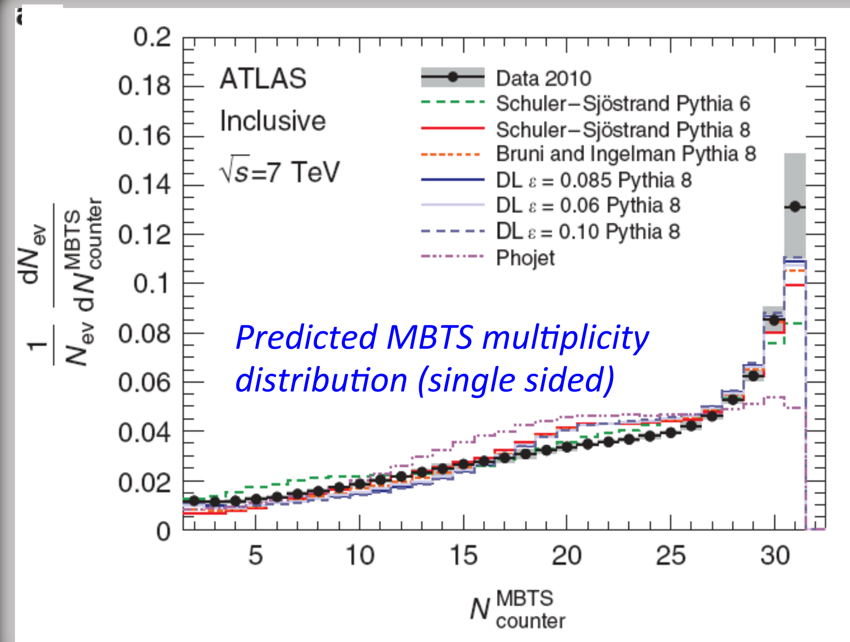


Block & F Halzen Phys.Rev. D86 (2012) 051504

- *Block & Halzen's analyticity constrained amplitude fit to lower energy data is in agreement with ATLAS,CMS & AUGER data*
- *They find σ_{inel} & σ_{tot} saturate the Froissart bound and that asymptotically $\sigma_{inel}/\sigma_{tot}$ = 0.51 ± 0.02 (if 0.5 if p is a black disc)*
- *No new high-σ hadronic physics at colliders up to ~60 TeV !*

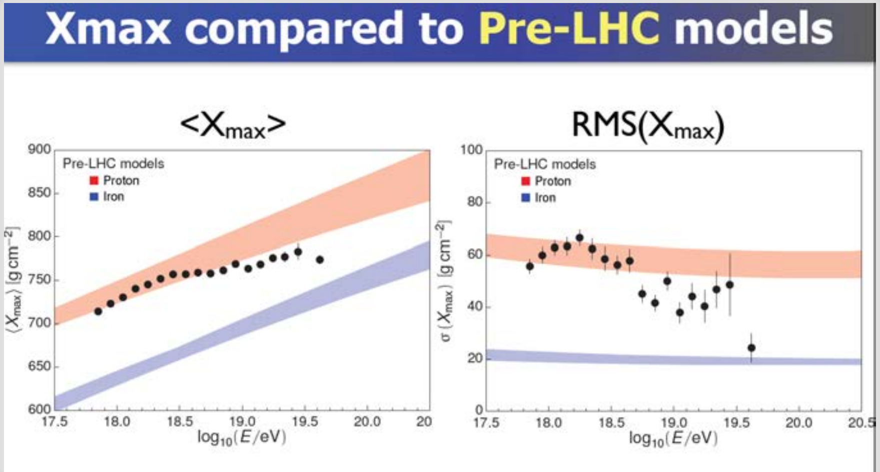
The Diffractive Fraction

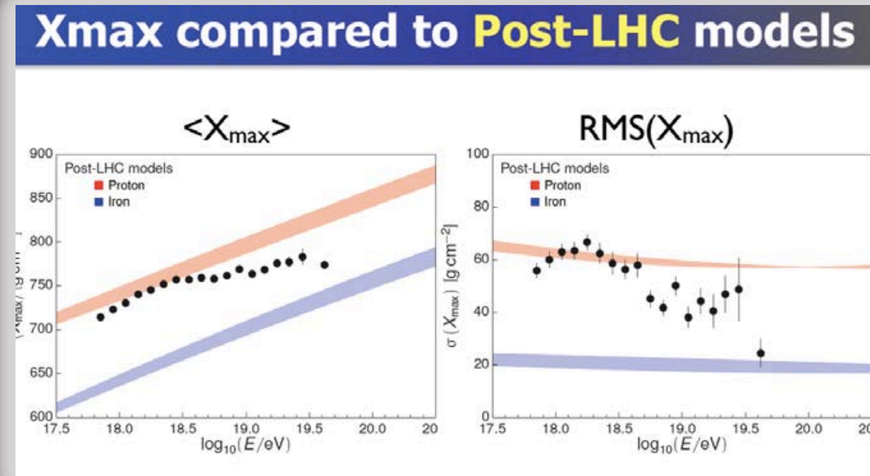




- *SD selection ≥ 2 MBTS hits on one side only → 122,490 events*
- *Default model (Pythia8 + D & L.) -*
  - *Diffractive fraction* $f_D = 26.9^{+2.5}_{-1.0}\%$
  - *Fraction of single sided events* $R_{ss} = [10.02 \pm 0.03(\text{stat.})^{+0.1}_{-0.4}(\text{syst.})]\ \%$
- *Diffractive fraction is an important quantity for EAS simulation*

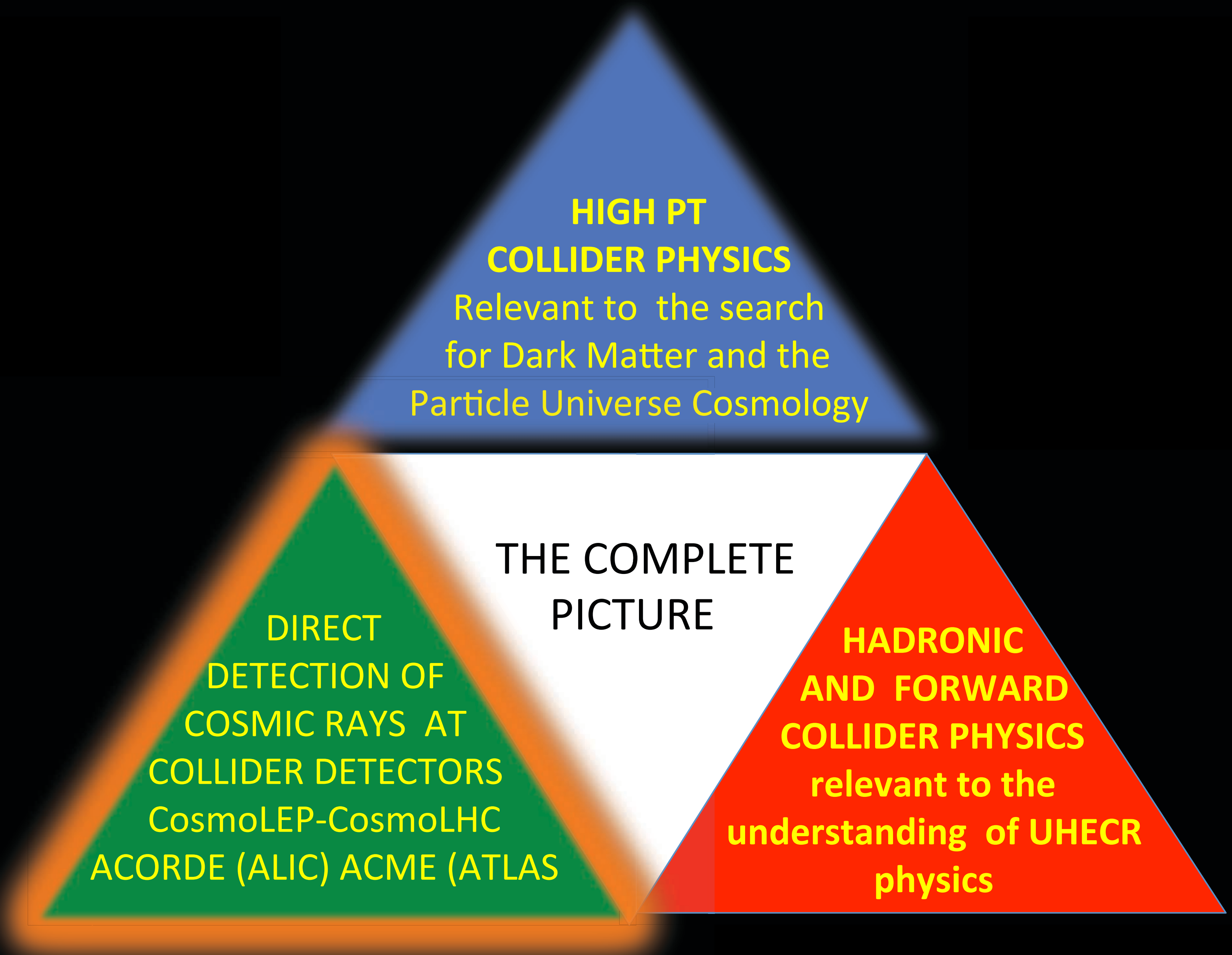
The Consequences for Cosmic Comp.





- *LHC + AUGER data indicates a slower energy rise of σ_{inel} (pp) than was previously predicted by a number of models.*
- *This leads to a reduction of the predicted proton-air cross section and on average a deeper shower max. position*
- *This clearly reveals the move to heavier (non-protonic) composition at cosmic ray energy ≥ 10^{19} eV*

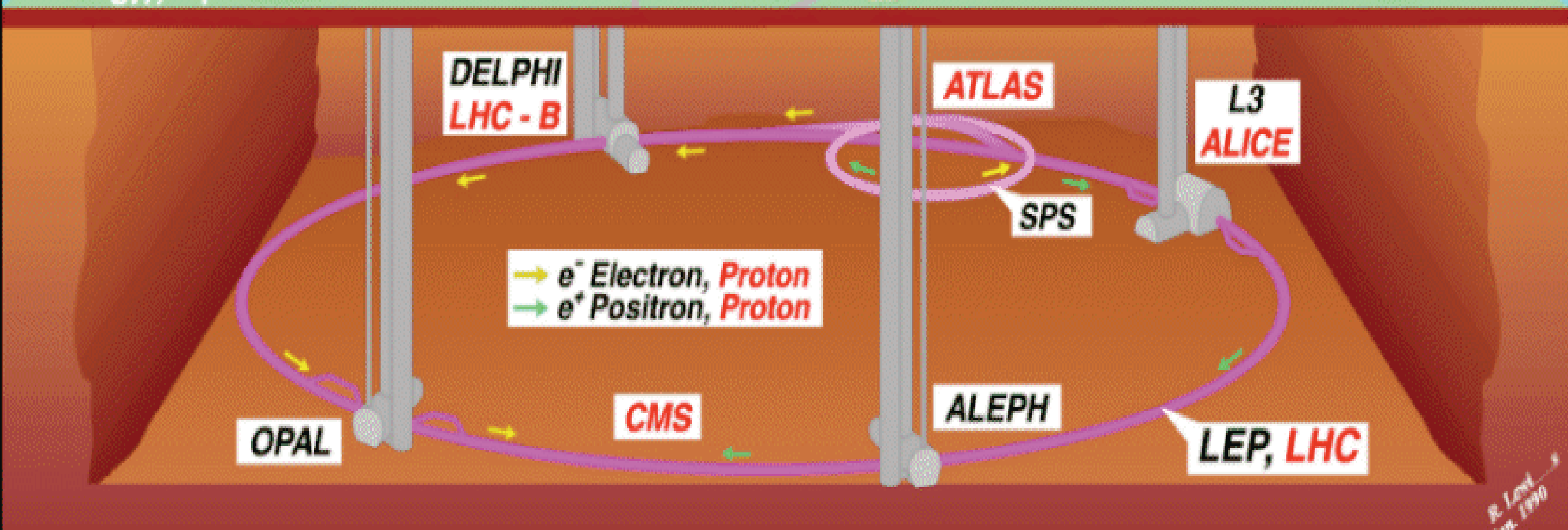
The Collider - Astroparticle Physics Synergy



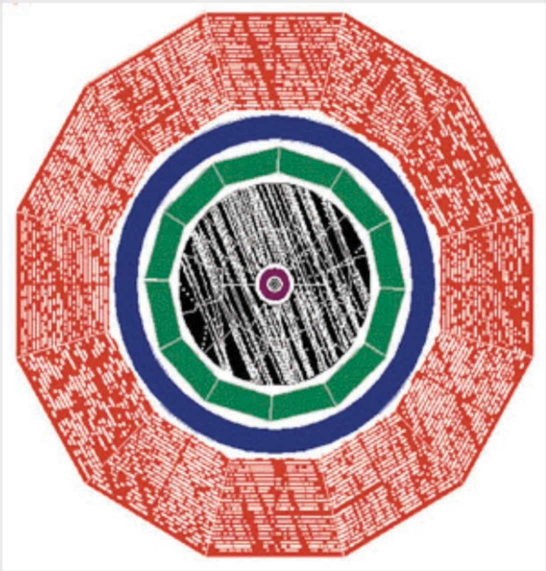
Detecting Cosmic Muons at Colliders

WHY USE LHC Detectors?

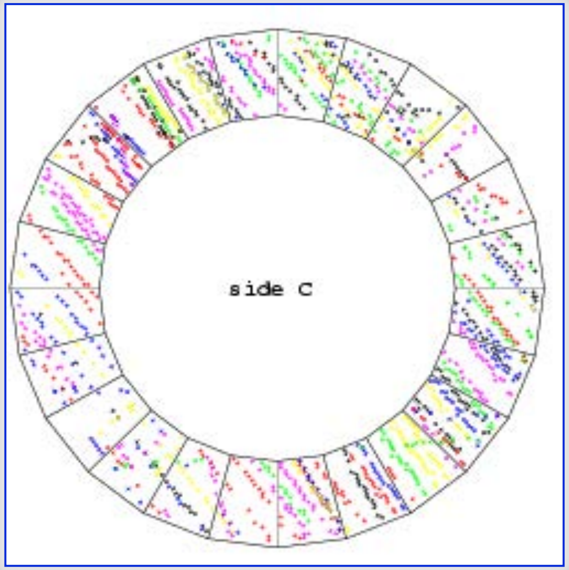
- ***Unprecedented areas of precision tracking calorimetry***
  - ***Muon momentum together with fine grained position measurement***
  - ***Superb pointing resolution***
- ***The shallow depth of the LEP/LHC colliders gives them an momentum acceptance complementary to existing CR detectors – a new possibility for cosmic ray physics***



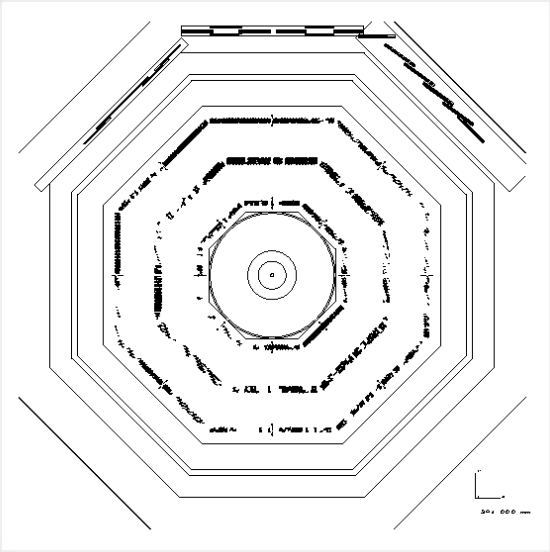
LEP Observes Muon Bundles



ALEPH



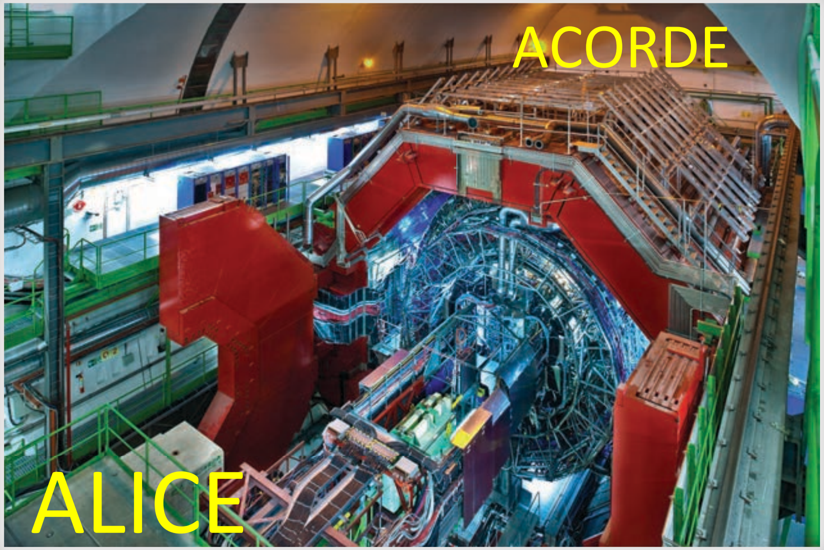
DELPHI

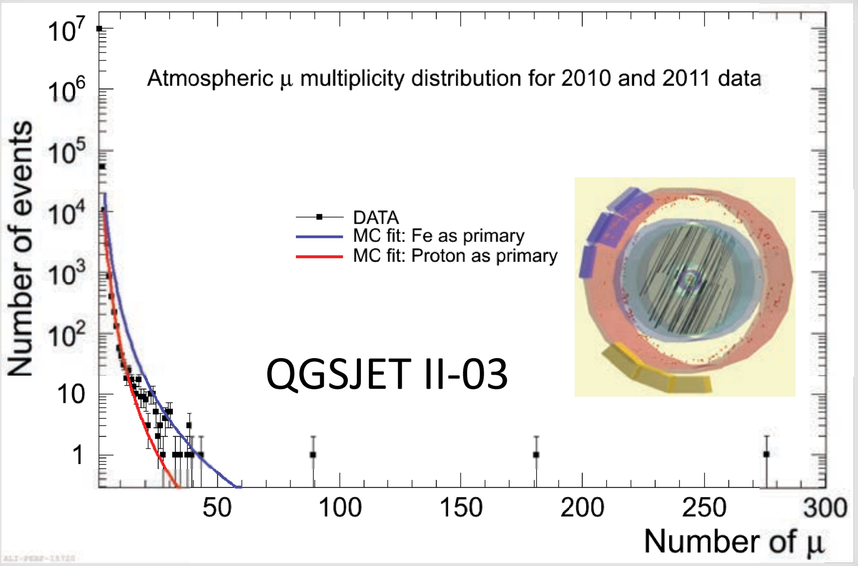


L3 + C

- *COSMOLEP observed muon bundles – numbers of quasi-parallel muons with small spatial separation*
  - *Rate depends on: primary energy, CR composition & interaction details*
  - *LEP observed "anomalously" high number of high multiplicity muon bundles*

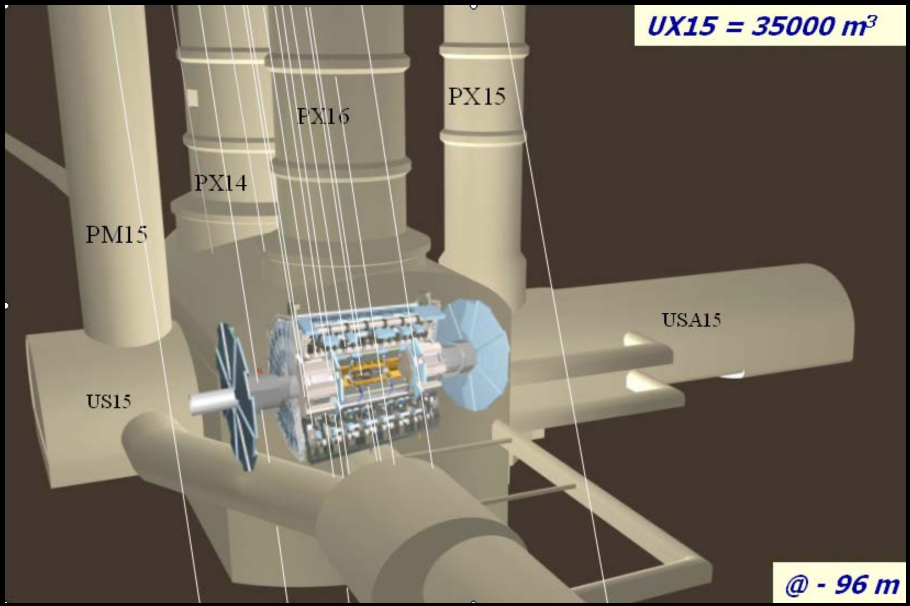
ALICE Also Observes the Same Excess





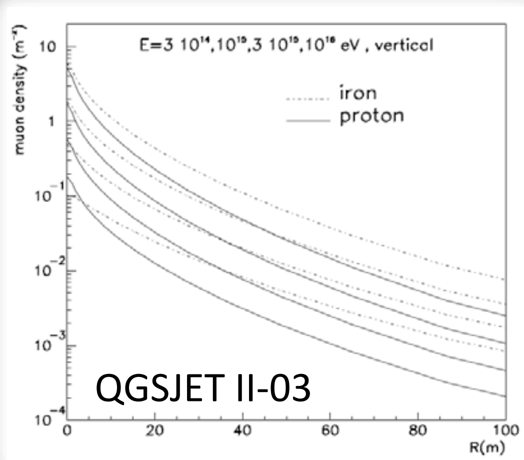
- *The ACORDE scintillator detector + TPC was used to measure cosmic muons underground (30m of rock) with E_μ > ~15 GeV*
  - *In ~ 11 days of data taking ALICE found 3 "anomalous" high muon multiplicity" events*
- *The ACME cosmic muon detector is proposed for ATLAS using the ATLAS muon system with horizontal area ~600 m²*

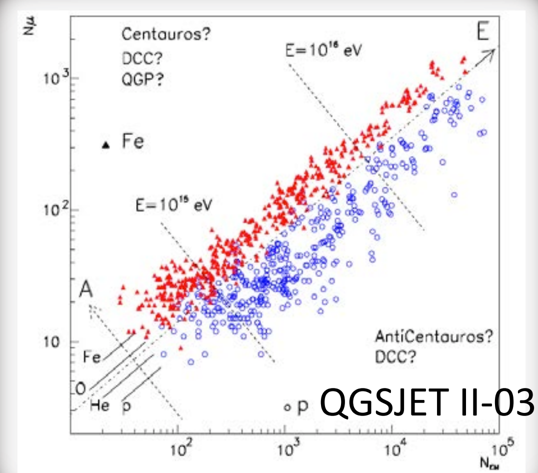
An ATLAS Cosmic Muon Experiment?



- *ATLAS would measure CR muons directly using unprecedented areas of precision μ-tracking + calorimetry ~80m underground*
  - *Muon momentum threshold ~50 GeV*
  - *12000 m^2 of ATLAS muon detector - to measure the muon content of the shower - with momentum measurement for each track*
  - *The surface array would be used to measure the EM component*
  - *ATLAS could be triggered underground of from the surface array*

Physics Possibilities





- *PRECISION COSMIC MUON PHYSICS $E_{CR} = 10^{15} \rightarrow 10^{18}$ GeV*
  - *Standard muon physics –*
  - *Muon bundle physics → the core density & lateral extent of muon bundles used to estimate the energy and composition of primaries.*
- *Other physics:*
  - *Quark-gluon-plasma formations → anomalously large muon content.*
  - *High energy γ-ray astronomy ($E_\gamma > 10^{17}$ eV) – using superior pointing resolution*
  - *New Physics: Centauros, etc*

Concluding Remarks

- *The first hadronic data from the LHC has been used to improve HECR EAS simulations (σ_{TOT}, diffractive fraction, etc.)*
- *LHC hadronic physics results have already yielded important information on the knee of the cosmic ray spectrum*
  - *Eg It is unlikely that the knee is due to new hadronic physics*
- *LHC & AUGER have together pushed the measurement of the p-p inelastic cross-section to E_{cm} ~ 60 TeV.*
  - *A prediction from Block and Halzen of no new high cross-section hadronic physics up to 60 TeV.*
  - *This measurement has enabled us to more clearly recognize the move to a heavier composition of VHECR above 10^{19} GeV*
- *ATLAS/CMS could be used as an underground, large area, precision, high granularity cosmic muon detectors – complementary to existing CR detectors*