LHC and Cosmic Rays : the Chicken or the Egg ?

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik,
Karlsruhe, Germany

Karlsruhe Institute of Technology

CPPM, Marseille, France

June the 18th 2018

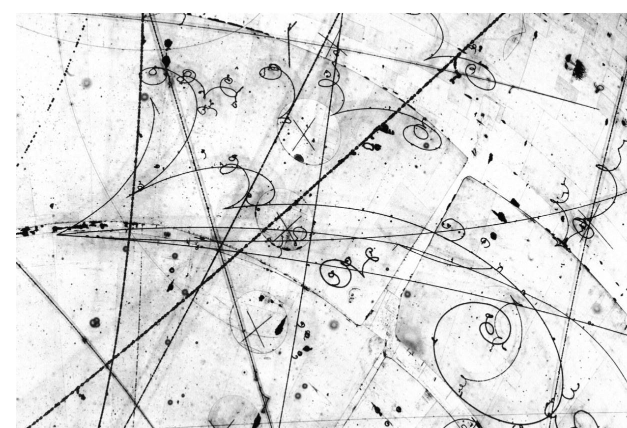
Outline

- **Introduction**
- **Monte-carlo for Cosmic Ray analysis**
  - ➔ MC comparison to accelerator data
- **input from LHC**
  - ➔ Mass composition of primary cosmic rays
- **input from CR**
  - ➔ Electromagnetic (EM) signal in extended air showers
  - ➔ Muon signal

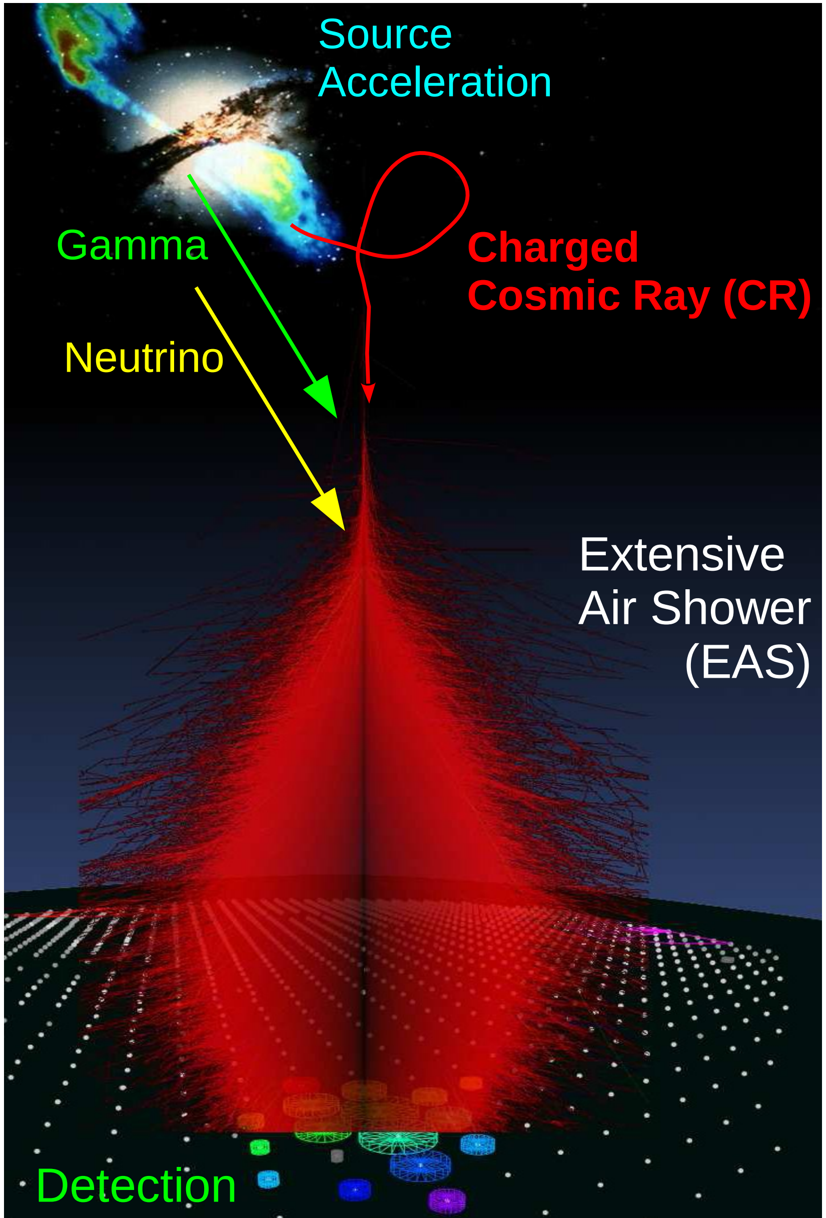
LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Good description of air showers improve model predictive power for the description of min. bias LHC data and detector simulations.

History

- **Victor Hess discovered in 1912 that natural radioactivity was increasing with height**
  - ➡ radiation from space
- **Pierre Auger discovered air showers in 1937**
  - ➡ secondary particles produced by primary cosmic rays
- **until ~1950 particle physics was studied thanks to cosmic rays**
  - ➡ all first unstable particles discovered in cosmic rays
    - muon, pion, strangeness …
  - ➡ cosmic rays could not be used for astrophysics
- **after first start of accelerators, things changed ... until now !**



Astroparticles

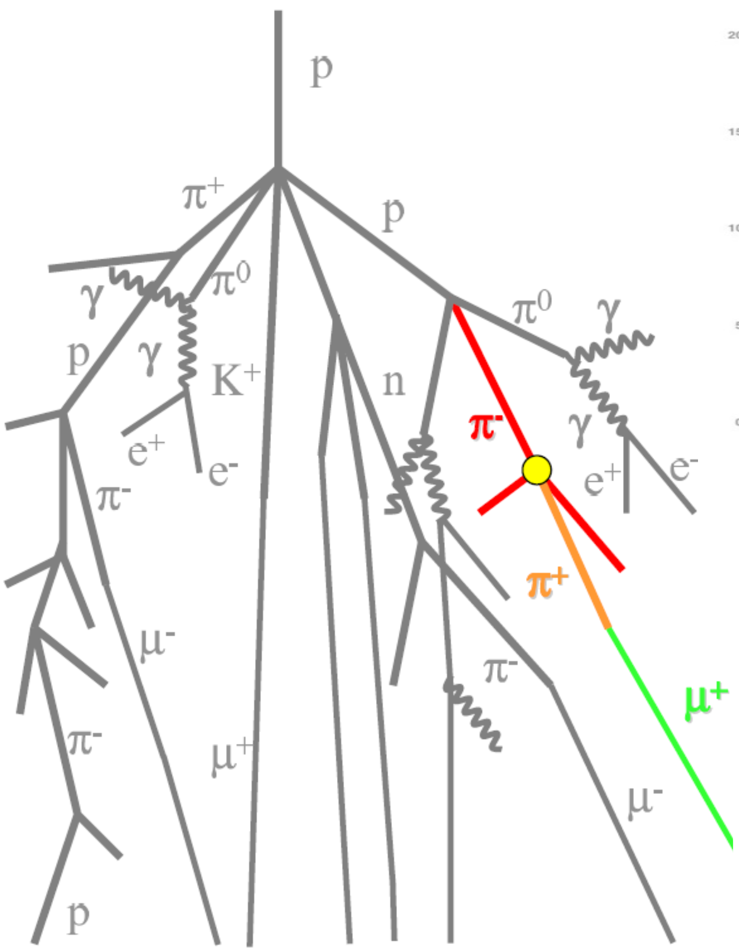


From R. Ulrich (KIT)

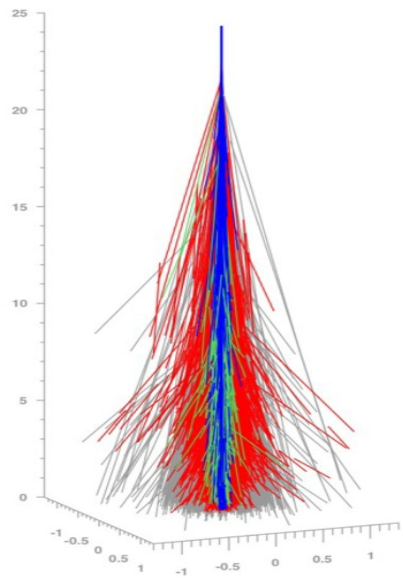
- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct

Extensive Air Shower



From R. Ulrich (KIT)



$A + air \rightarrow$ hadrons
$p + air \rightarrow$ hadrons
$\pi + air \rightarrow$ hadrons

hadronic physics

initial γ from π^0 decay

$e^{\pm} \rightarrow e^{\pm} + \gamma$
$\gamma \rightarrow e^{+} + e^{-}$

well known QED

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu / \bar{\nu_\mu}$

Cascade of particle in Earth's atmosphere

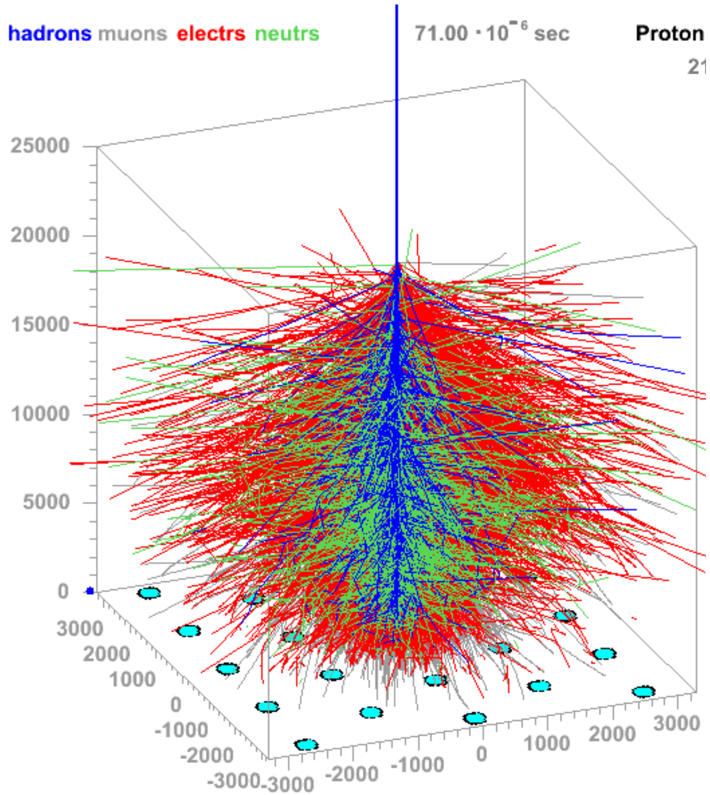
Number of particles at maximum

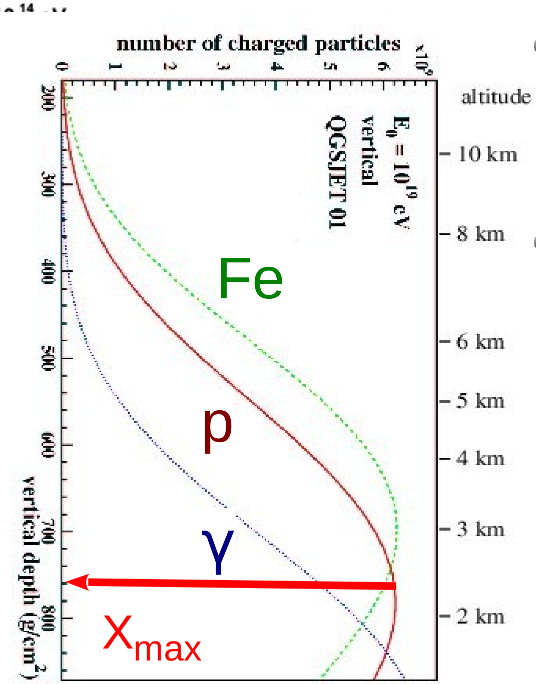
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

Extensive Air Shower Observables

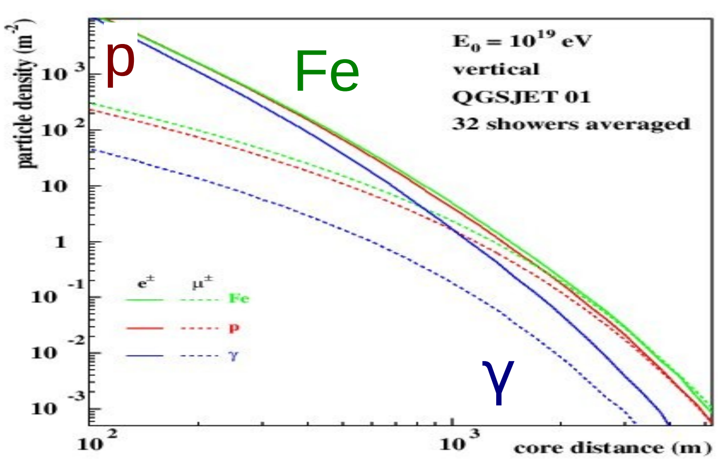




- **Longitudinal Development**
  - number of particles vs depth

$$X = \int_h^\infty dz\, \rho(z)$$

  - Larger number of particles at X_{max}
    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}
    - depends on primary mass
    - depends on Hadr. Inter.

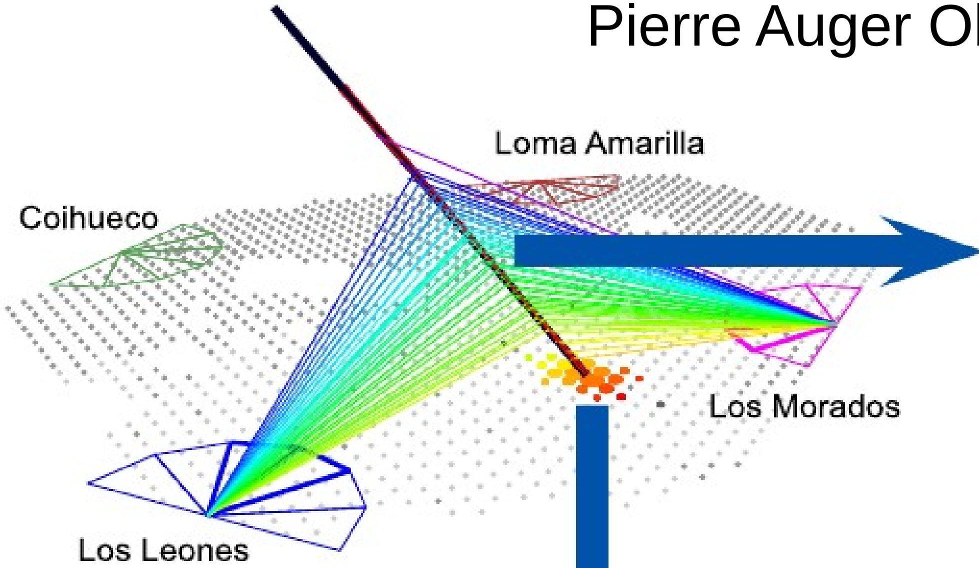


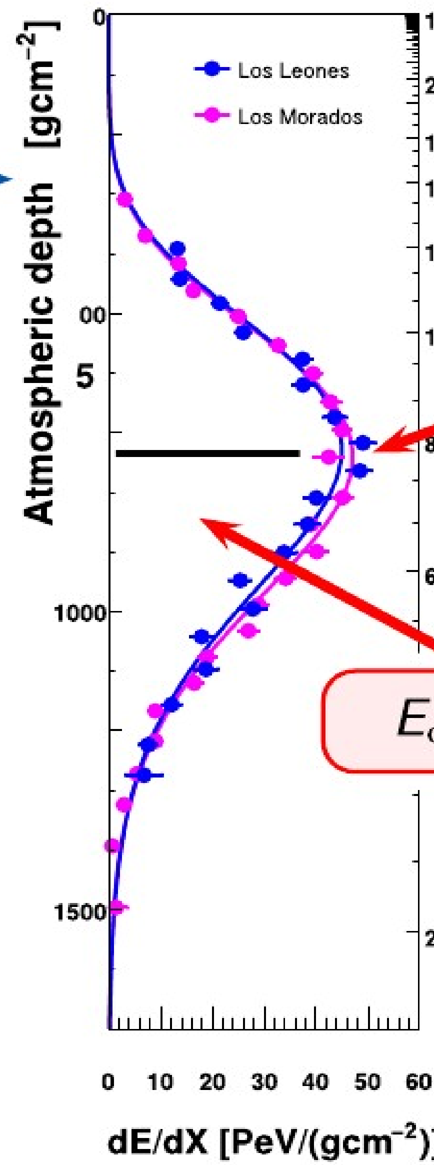
- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

- **Others: Cherenkov emissions, Radio signal**

Hybrid Detection

Pierre Auger Observatory / Telescope Array





$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

$X_{\max}$

Fluorescence detector (FD)

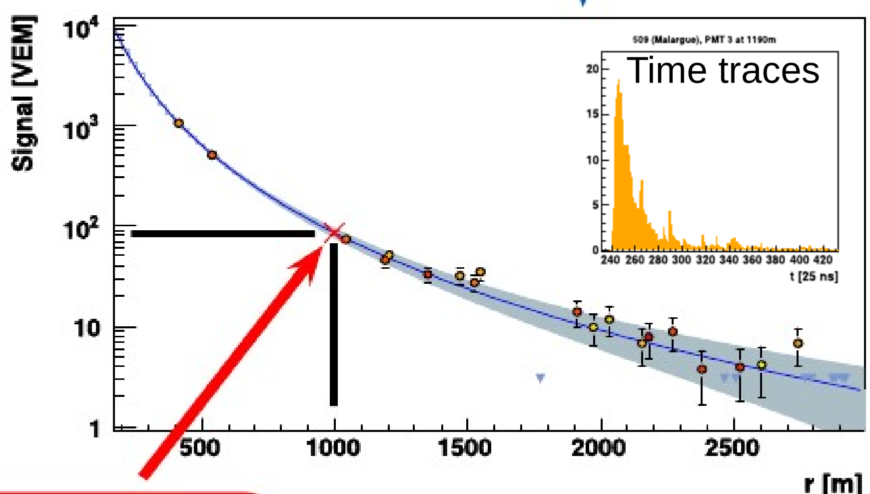
$E_{\mathrm{cal}} = \int \mathrm{d}X \; \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

Various detection technique = **energy scale independent of hadronic inter. models**

Surface detector (SD)

From R. Ulrich (KIT)

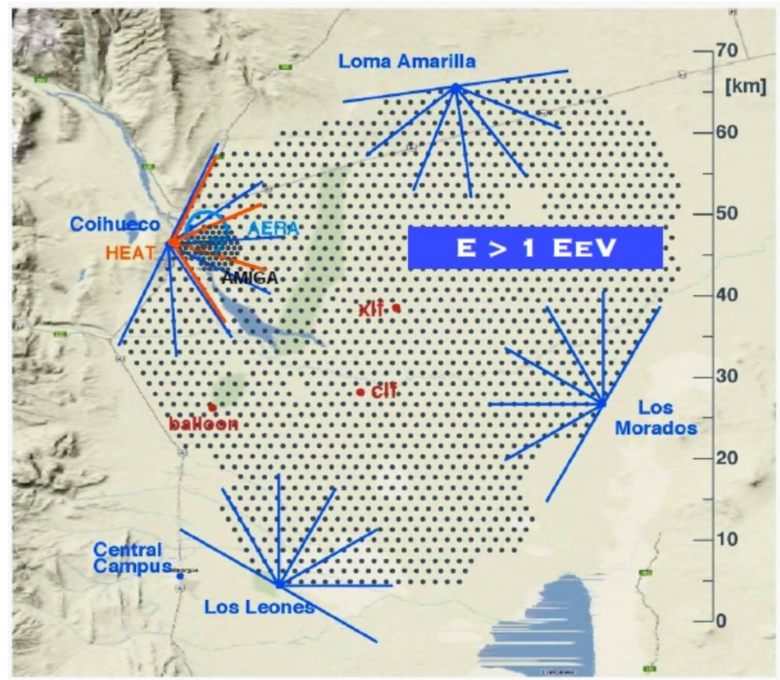


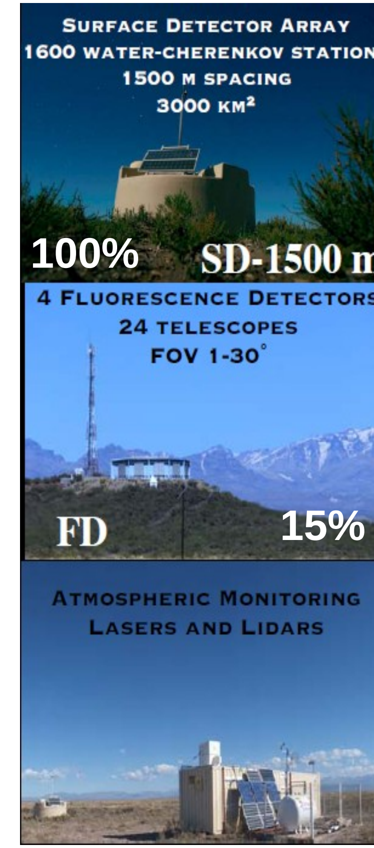
S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

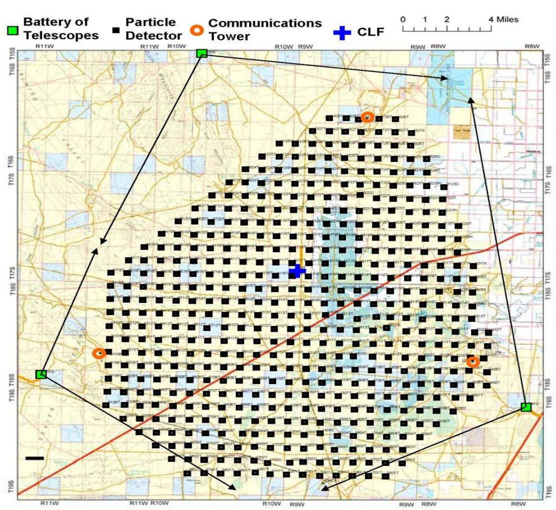
PAO/TA

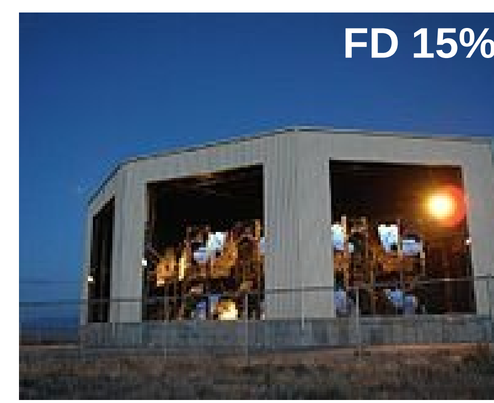
- **Pierre Auger Observatory (PAO)**
  - Mendoza, Argentina
  - Southern Hemisphere
  - 3000 km²: 32000 km²/sr/yr



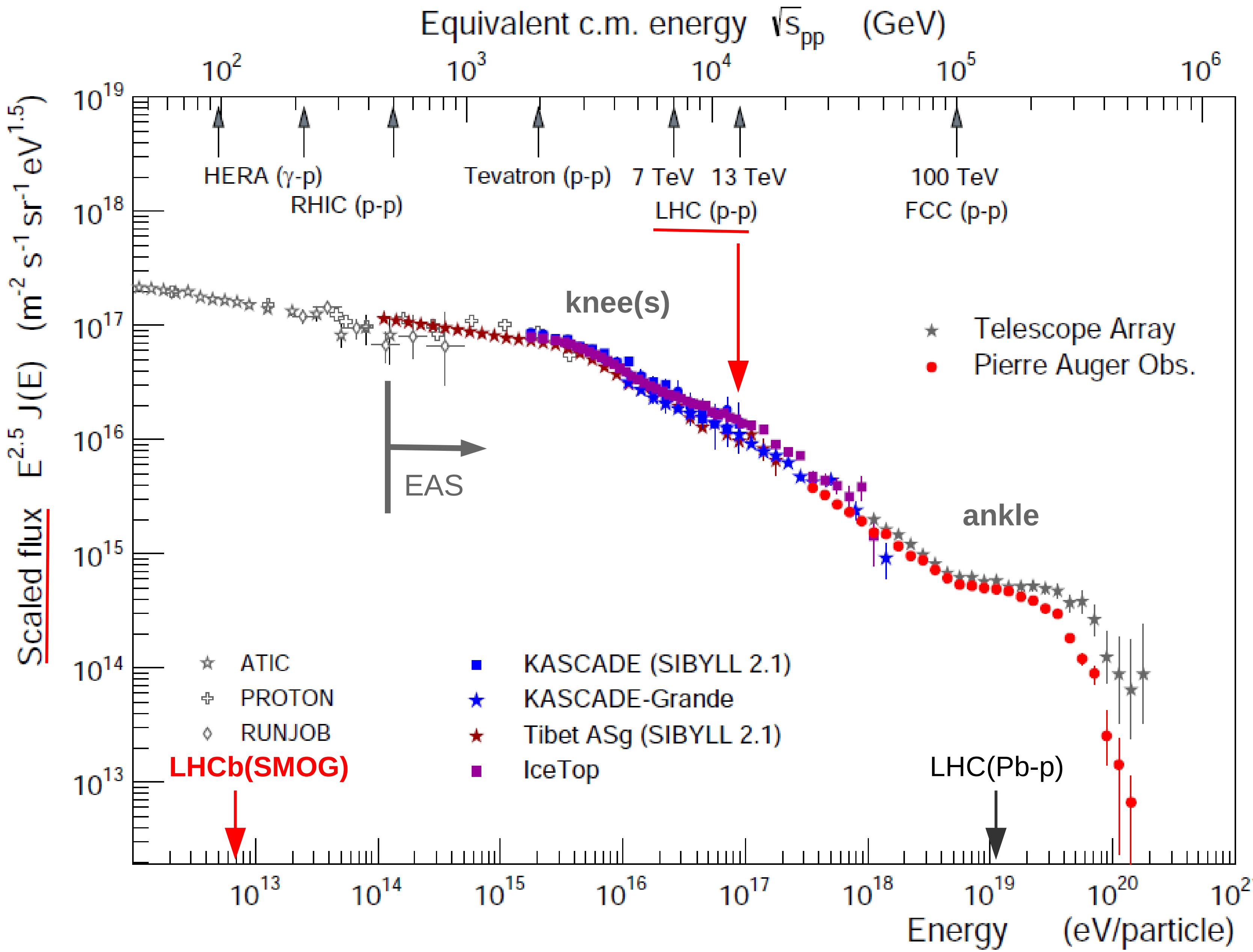


- **Telescope Array (TA)**
  - Utah, USA
  - Northern Hemisphere
  - 680 km²: 3700 km²/sr/yr



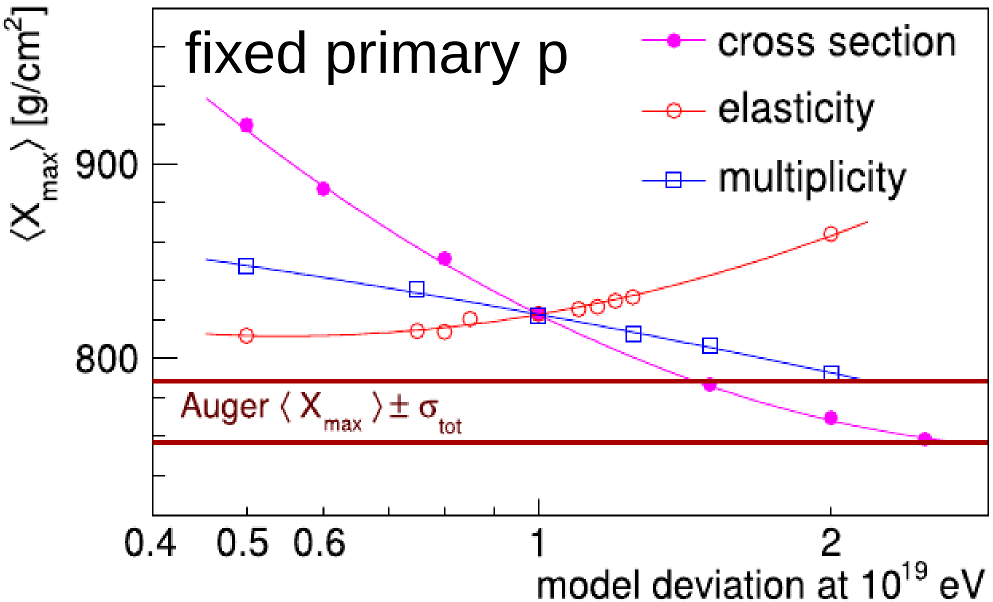


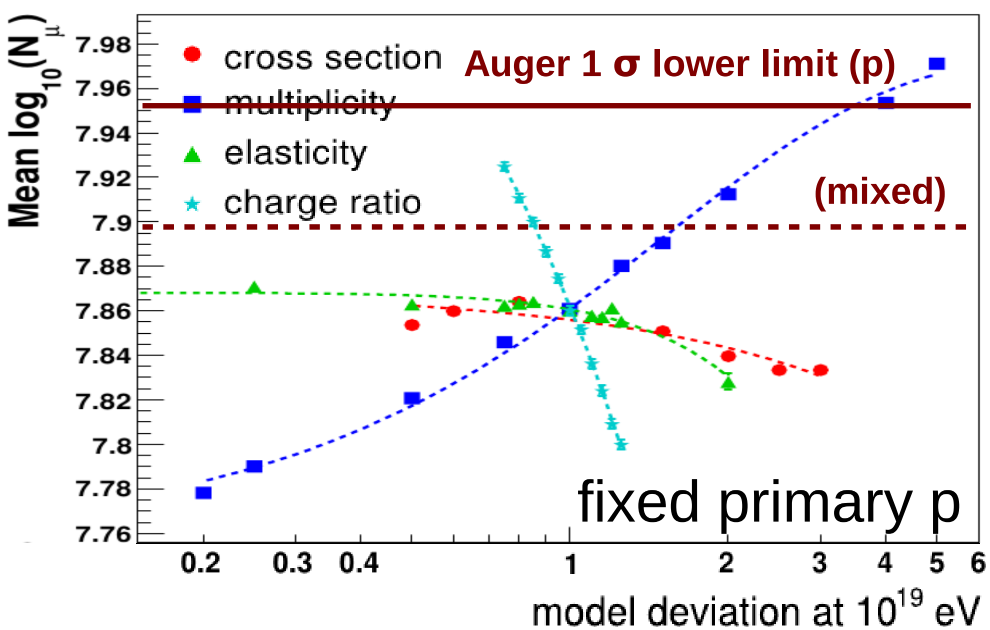
Energy Spectrum



R. Engel (KIT)

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

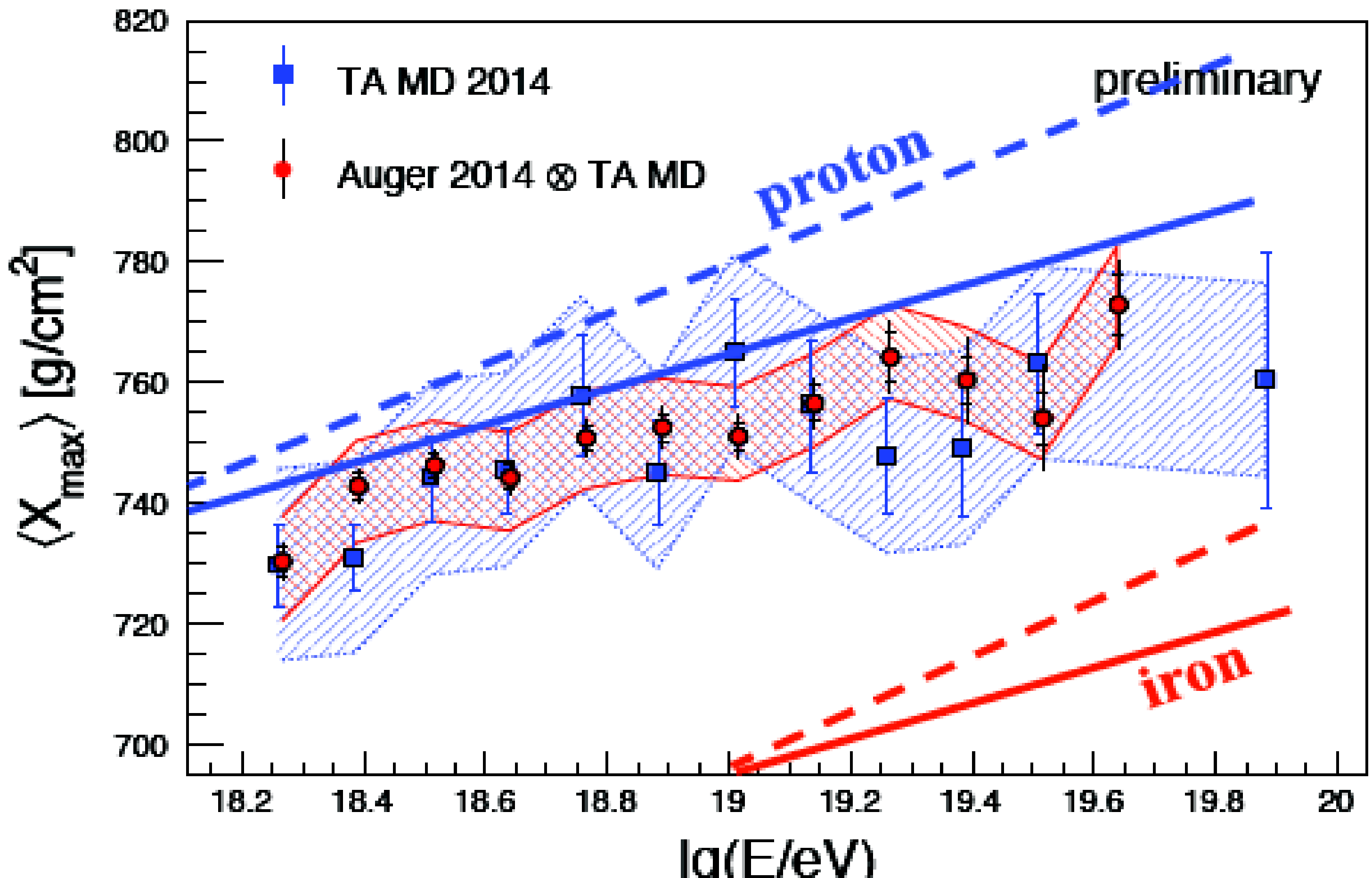
- **Air shower development dominated by few parameters**
  - mass and energy of primary CR
  - cross-sections (p-Air and (π-K)-Air)
  - (in)elasticity
  - multiplicity
  - charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - cross-section, elasticity, mult. ...

With unknown mass composition hadronic interactions can only be tested using various observables which should give consistent mass results

Pre-LHC UHECR Composition

With pre-LHC models current CR data would be difficult to interpret

- Full (QGSJET) : proton ("easy" and "old" astrophysical interpretation)
- Dashed (EPOS/SIBYLL) : mixed composition



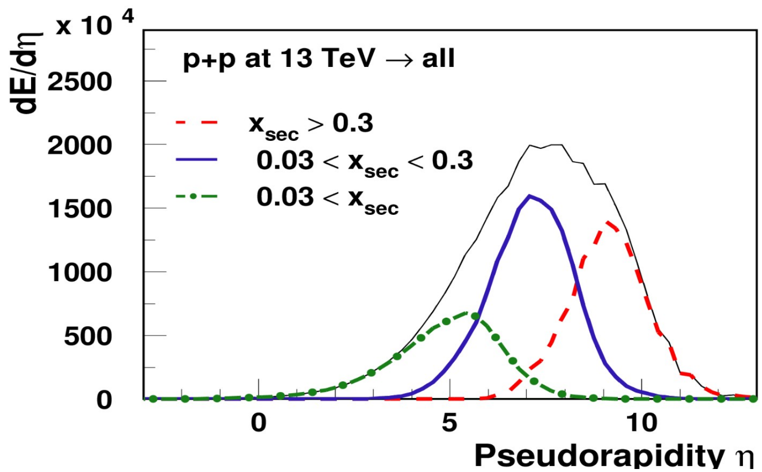
Roberto Aloiso UHECR (2015 PAO/TA working group)

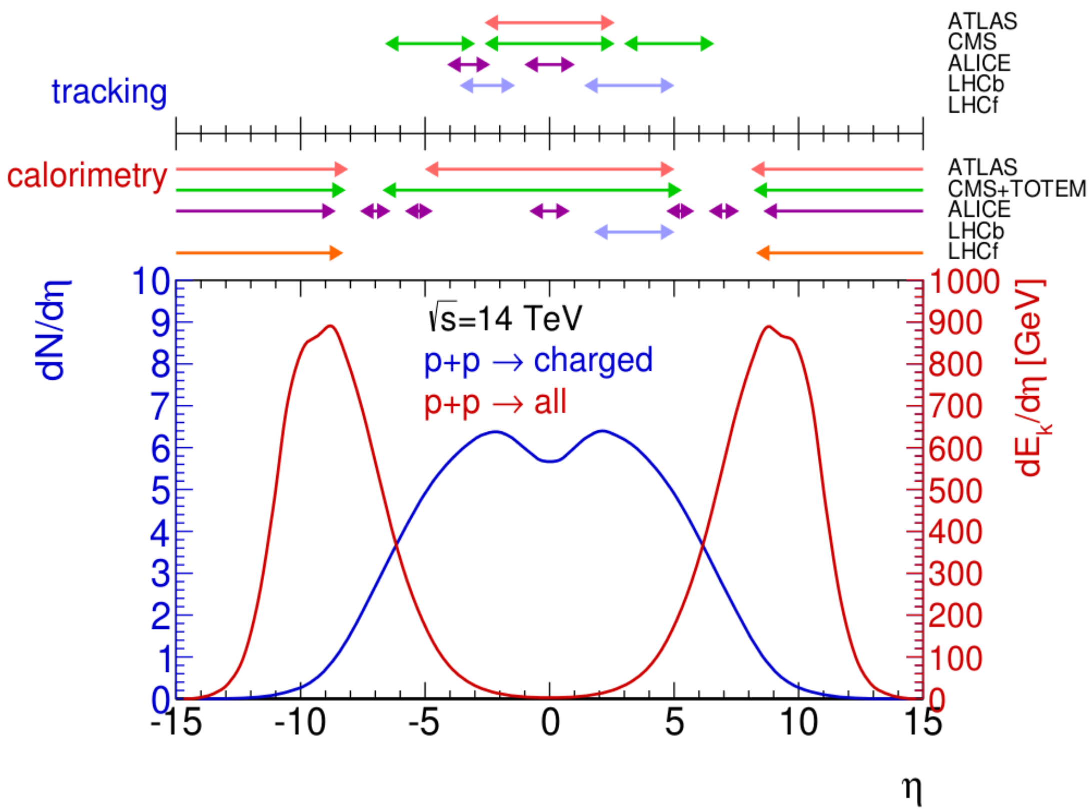
Hadronic Interaction Models

- **What are the hadronic model suppose to do ?**
  - Transfer part of the energy of a fast projectile to slower newly produced particles when a target is hit
  - excite the vacuum to produce new particles (quantum number conservation)
  - conserve the total energy of the system
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)

- **Which model for CR ? (alphabetical order)**
  - **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - **QGSJET** (01/II-03/II-04) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/2.3c)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

LHC acceptance and Phase Space





- **p-p data mainly from “central” detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward

- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers

When does a projectile interact ?

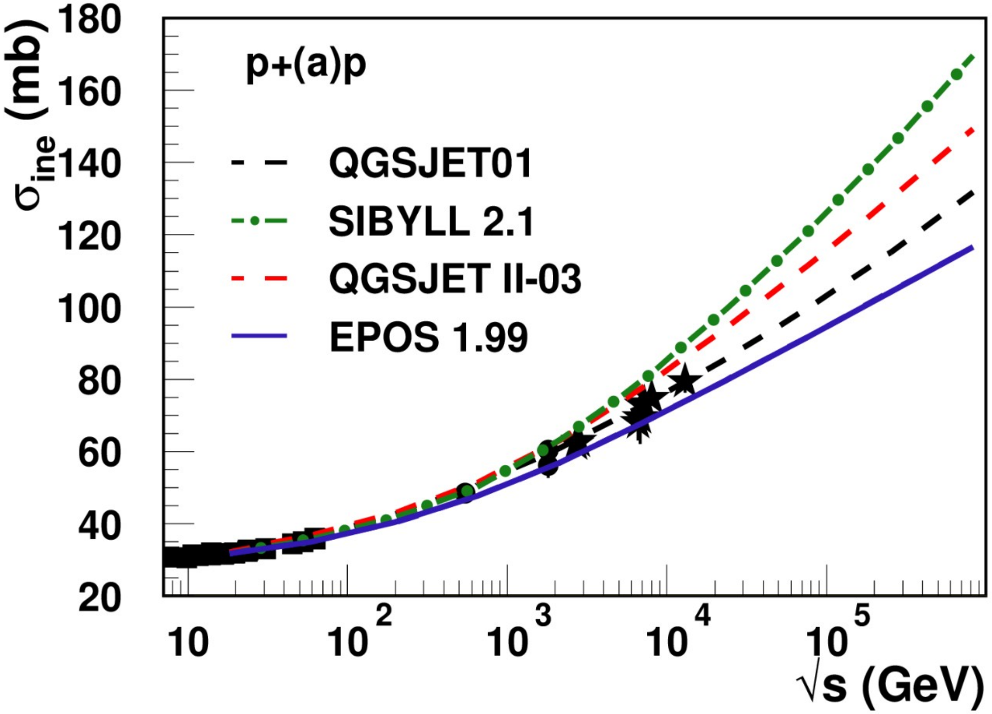
For all models cross-section calculation based on optical theorem

- total cross-section given by elastic amplitude

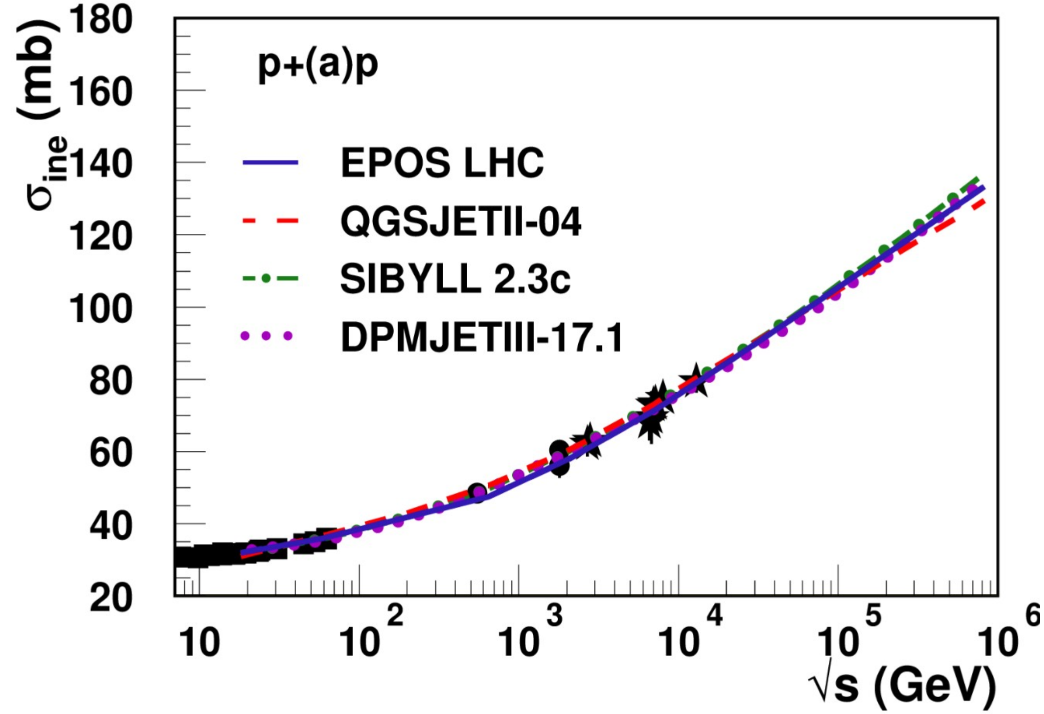
$$\sigma_{tot} = \frac{1}{s}\Im m(A(s,t \to 0))$$

- different amplitudes in the models but free parameters set to reproduce all p-p cross-sections
- basic principles + high quality LHC data = same extrapolation

Pre - LHC

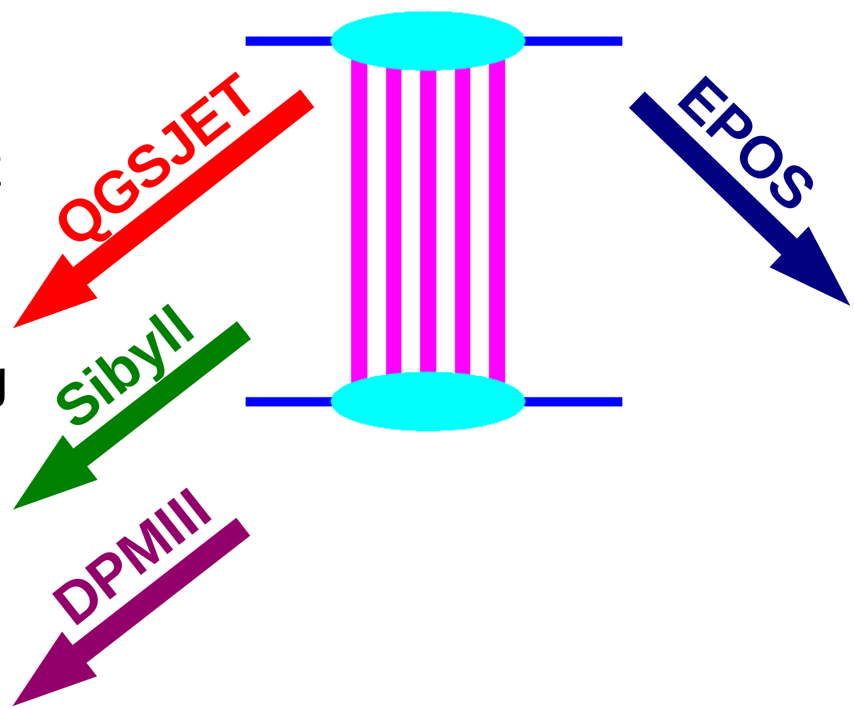


Post - LHC



How does the projectile interact ?

- **Field theory : scattering via the exchange of an excited field**
  - ➔ parton, hadron, quasi-particle (= Reggeon or Pomeron (vacuum excitation))
- **Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states**
  - ➔ different ways of dealing with energy conservation



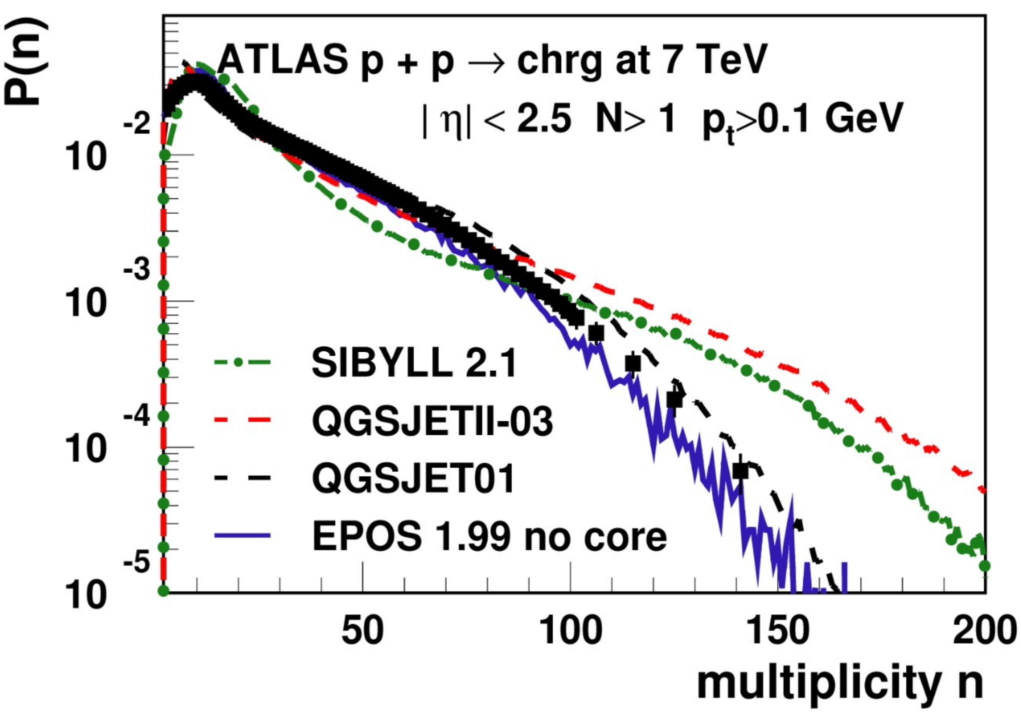
- ➔ sum all scatterings with full energy to get cross-section
- ➔ get number of elementary scattering without energy sharing (Poissonian distribution)
- ➔ share energy between scattering afterwards

- ➔ cross-section calculated with energy sharing
- ➔ get the number of scattering taking into account energy conservation
- ➔ consistent approach

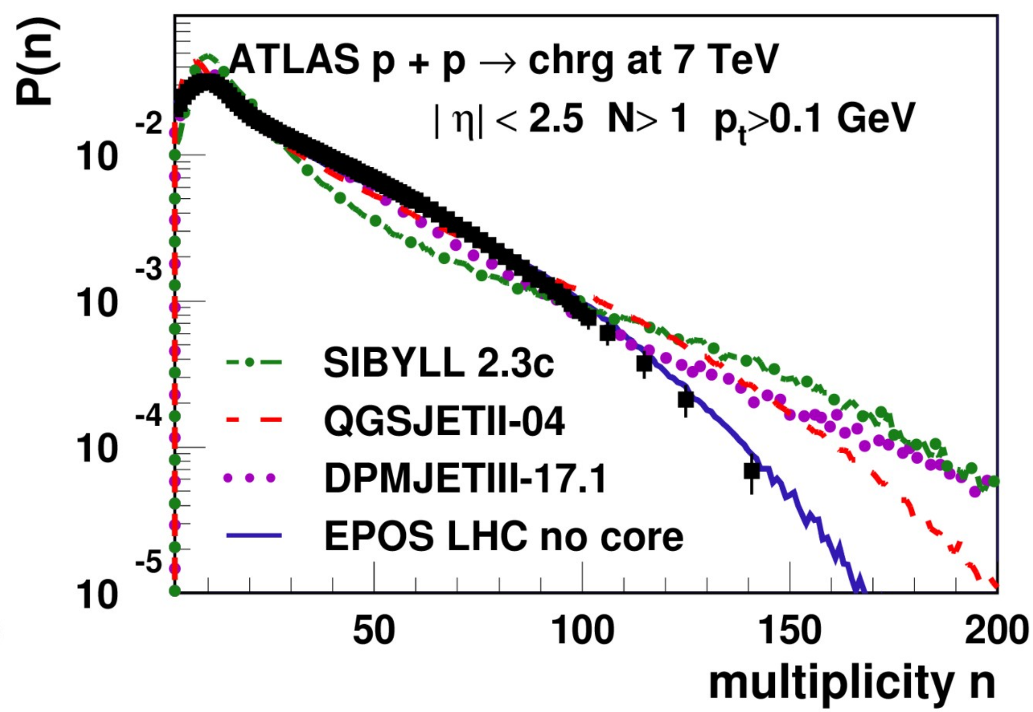
Does energy sharing order matter ?

- **Field theory : scattering via the exchange of an excited field**
  - ➜ parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states**
  - ➜ different ways of dealing with energy conservation

Pre - LHC

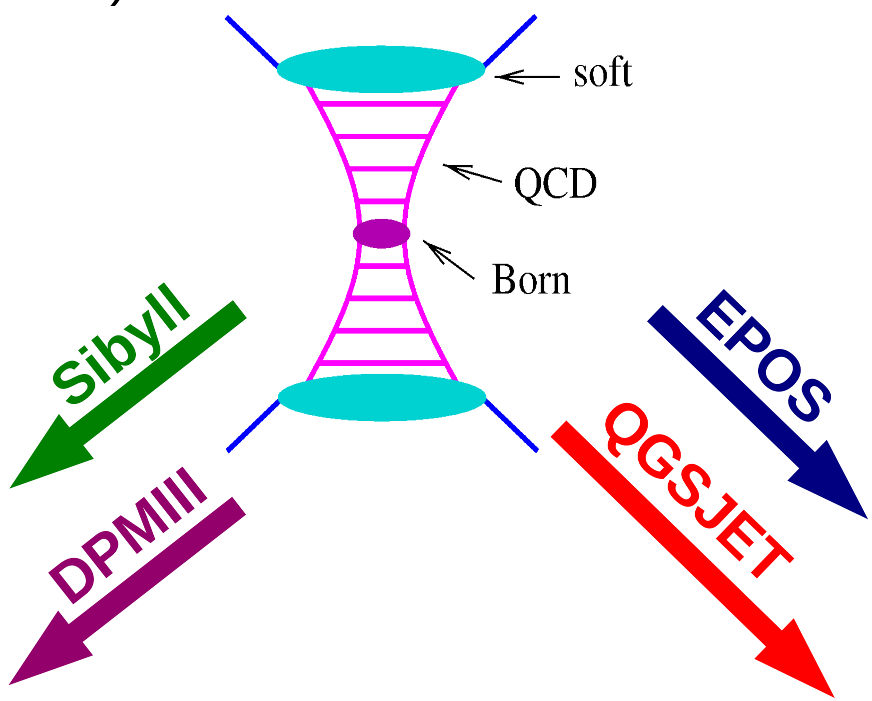


Post - LHC



How to build the amplitude ?

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
  - all minijet based (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions



- soft+hard in different components
- external parton distribution functions (**GRV98**,**cteq14**)
- connection to projectile/target with small “x”

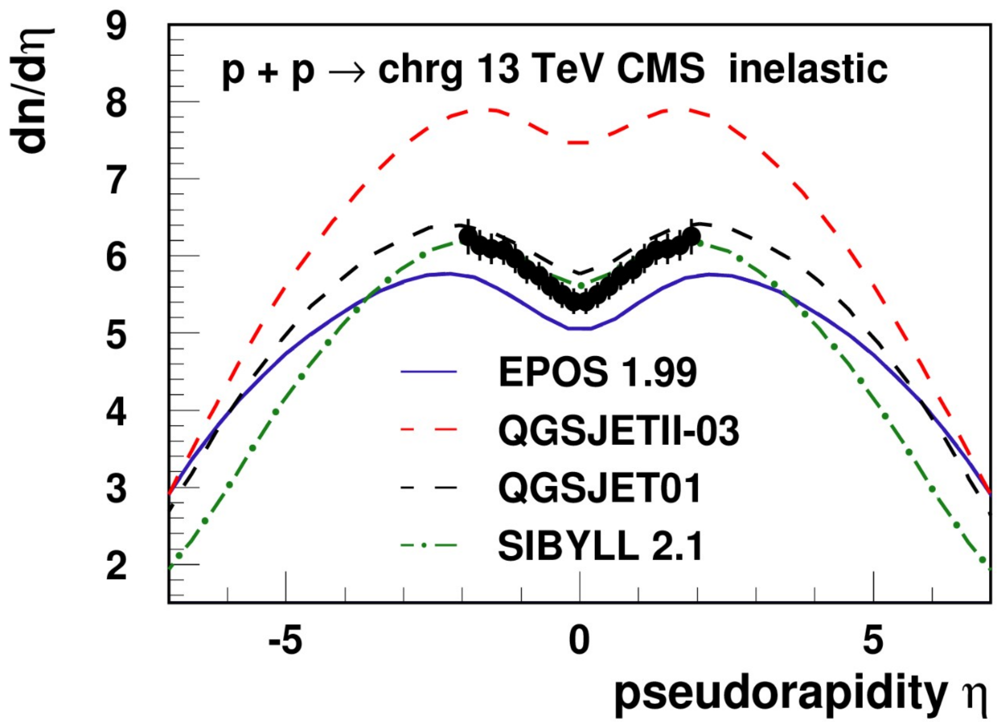
- soft+hard in the same amplitude
- own parton distribution function compatible with HERA data (<u>not for QGSJET01: pre-HERA time</u>)
- connection to projectile/target with large “x”

Ostapchenko et al. Phys.Rev. D94 (2016) no.11, 114026

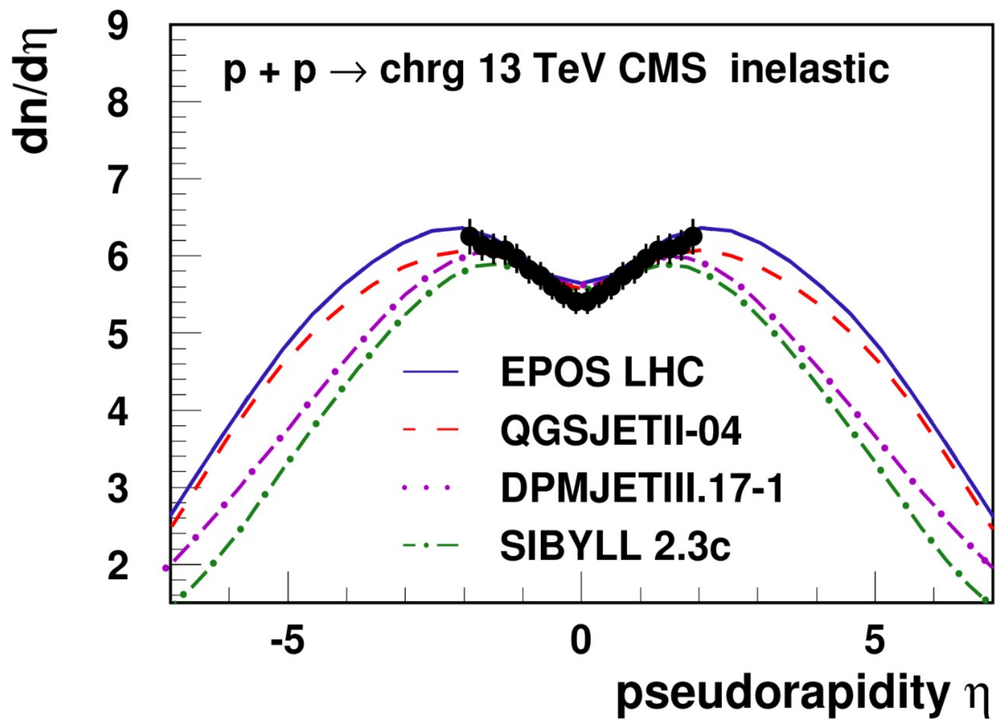
Does the minijet definition matter ?

- **Field theory : scattering via the exchange of an excited field**
  - ➜ parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
  - ➜ all minijet based (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions

Pre - LHC



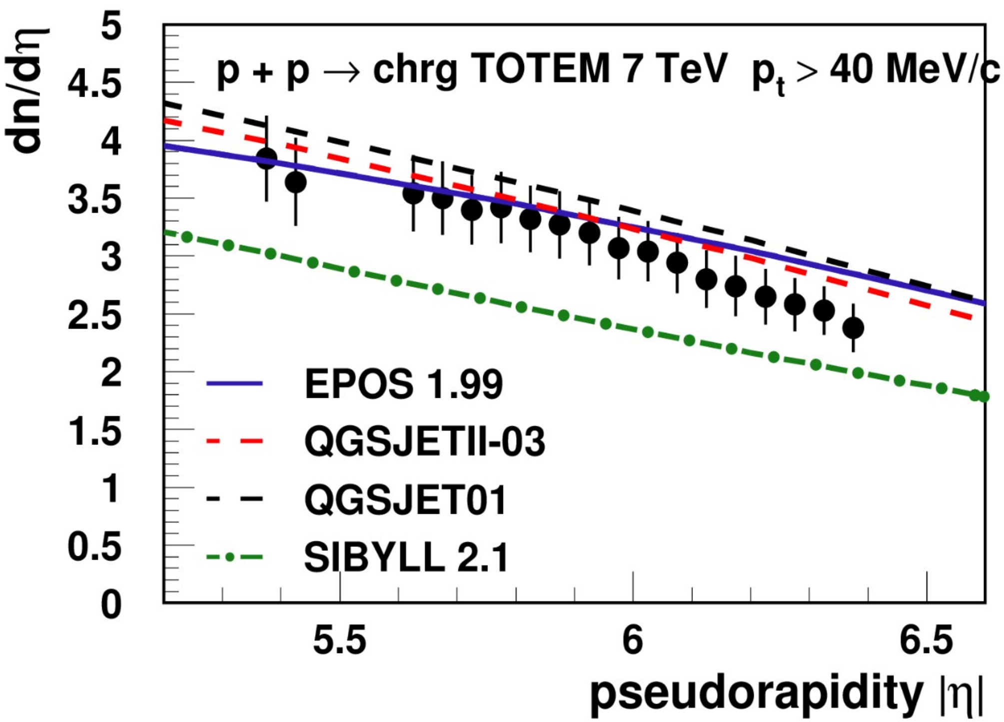
Post - LHC



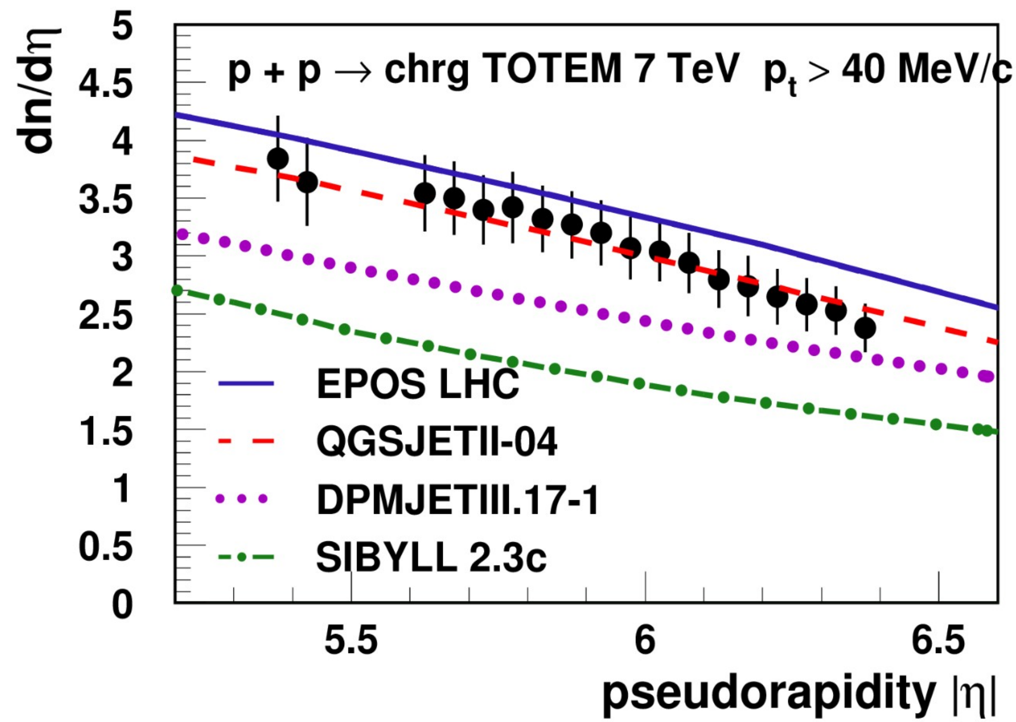
Does the minijet definition matter ?

- **Field theory : scattering via the exchange of an excited field**
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
  - all minijet based (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions

Pre - LHC

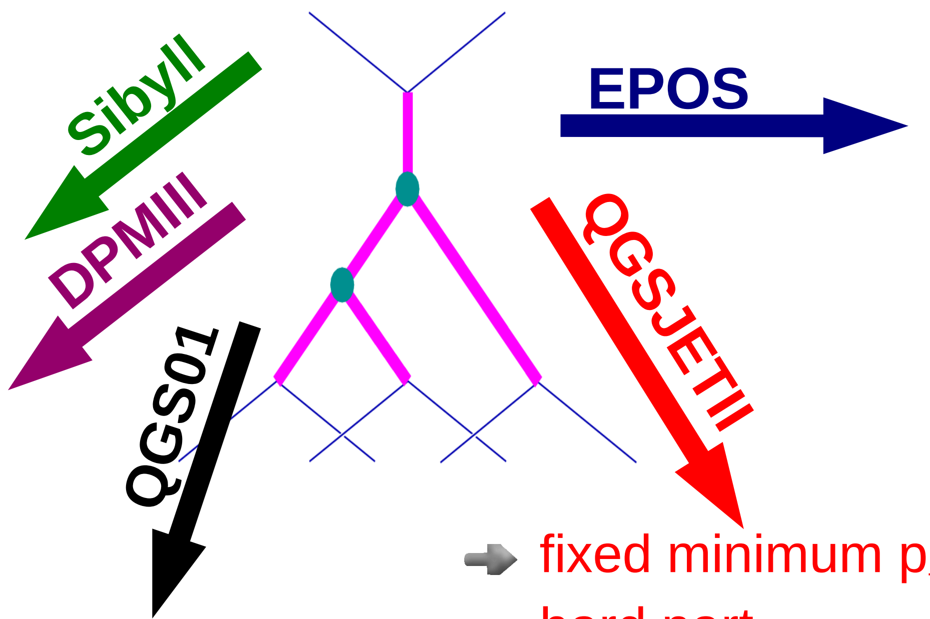


Post - LHC



How to take into account energy evolution ?

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - ➡ non-linear effects should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**



- ➡ hard amplitude depend on minimum p_t
- ➡ parametrize minimum p_t as a function of energy (and impact parameter for DPMJETIII)
- ➡ fit to data (multiplicity and cross-section)

- ➡ not needed because of wrong parton distribution function

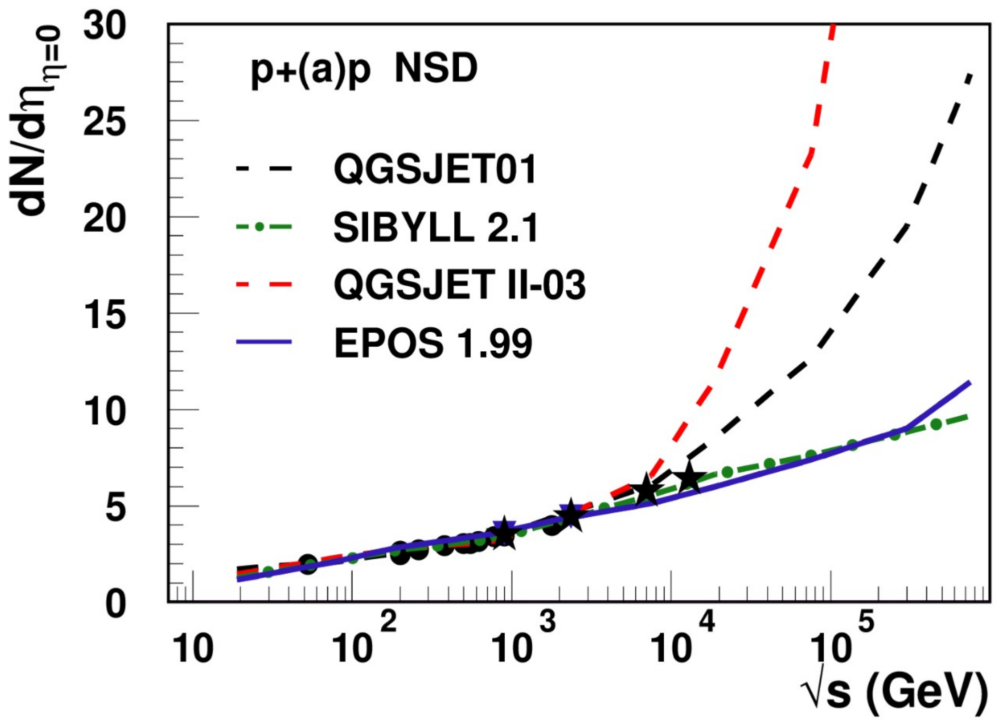
- ➡ fixed minimum p_t in hard part
- ➡ theory based "fan diagrams" resumed to infinity without energy sharing

- ➡ fixed minimum p_t in hard part
- ➡ enhanced diagrams not compatible with energy sharing
- ➡ modification of vertex function to take into account non linear effects (data driven phenomenological approach)

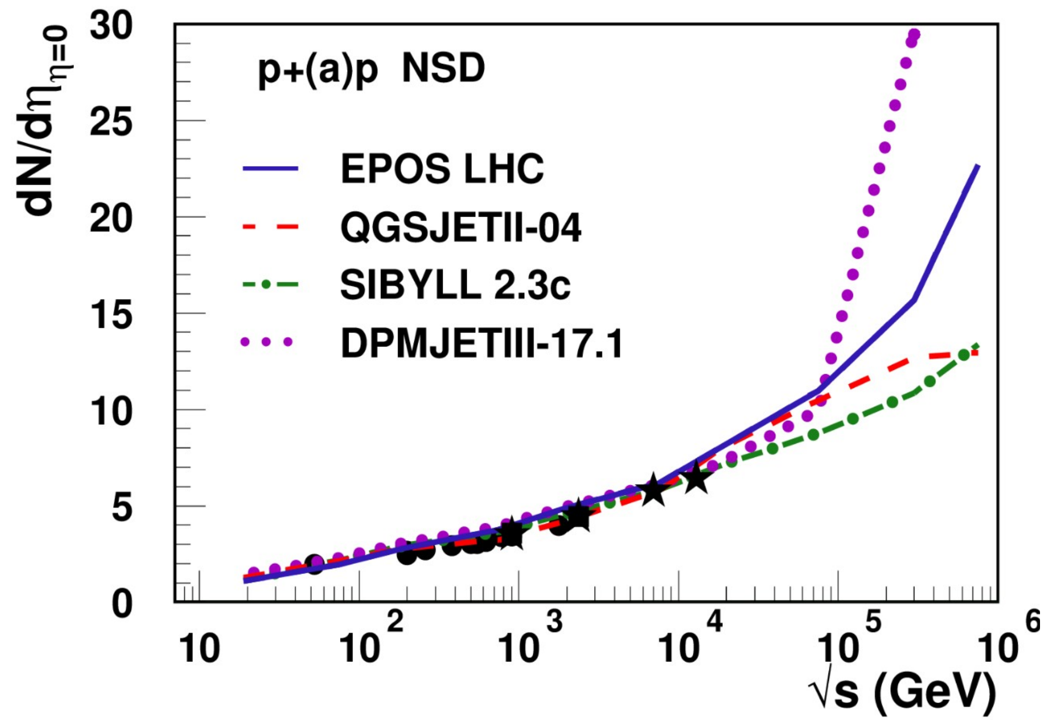
Do non linear effects matters ?

- **Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section**
  - ➡ non-linear effect should be taken into account (interaction between scatterings)
- **Solution depends on amplitude definition**
  - ➡ large uncertainties at high energy but reduced after LHC

Pre - LHC



Post - LHC

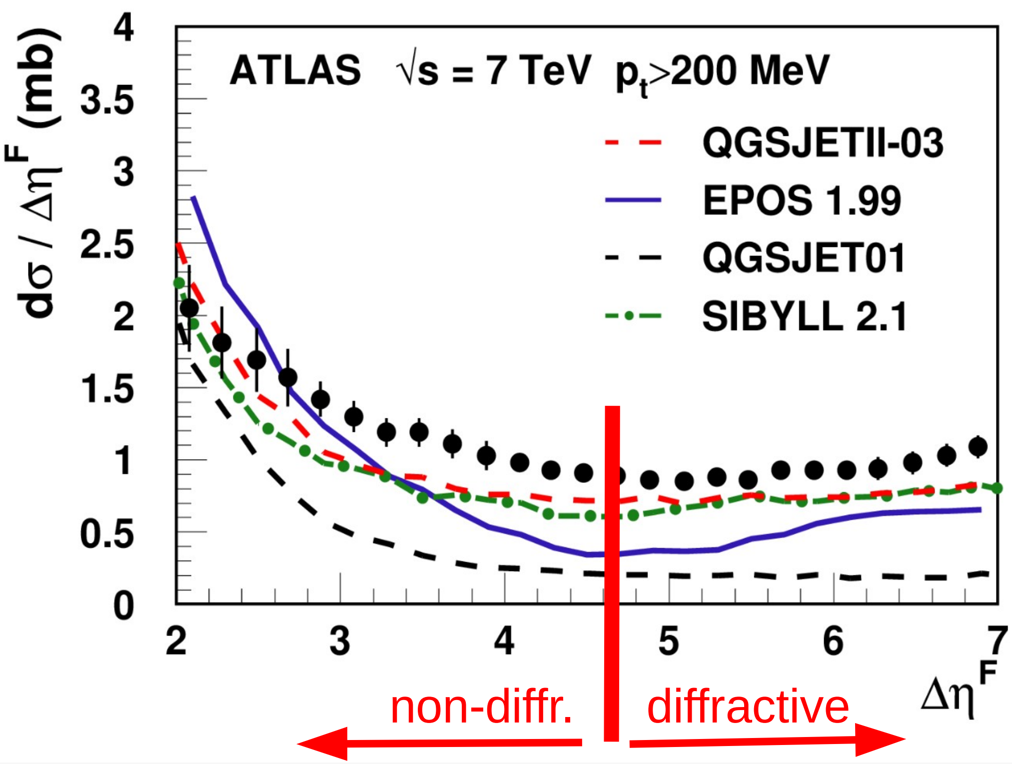


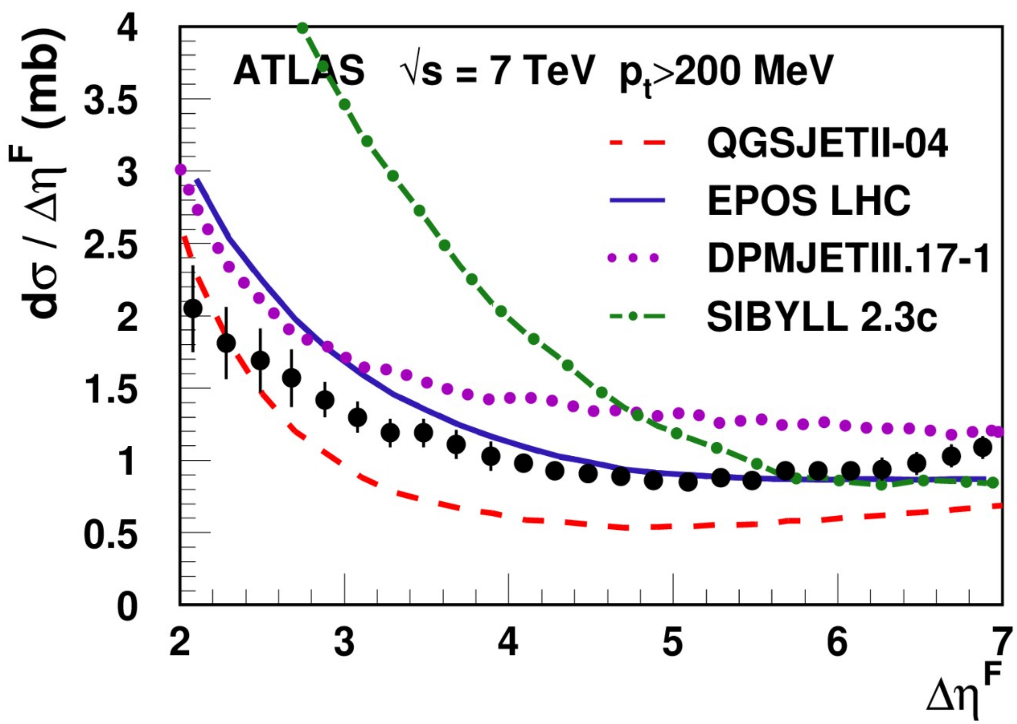
What if only energy is transferred ?

- **In most of the cases, the projectile is destroyed by the collision**
  - ➔ non-diffractive scattering : high energy loss for leading particle, high multiplicity
- **In 10-20% of the time, the projectile have a small energy loss (high elasticity) and is unchanged**
  - ➔ diffractive scattering : low energy loss, low multiplicity on target side
- **Model difference mostly at technical level (and choice of data)**

Pre - LHC

Post - LHC



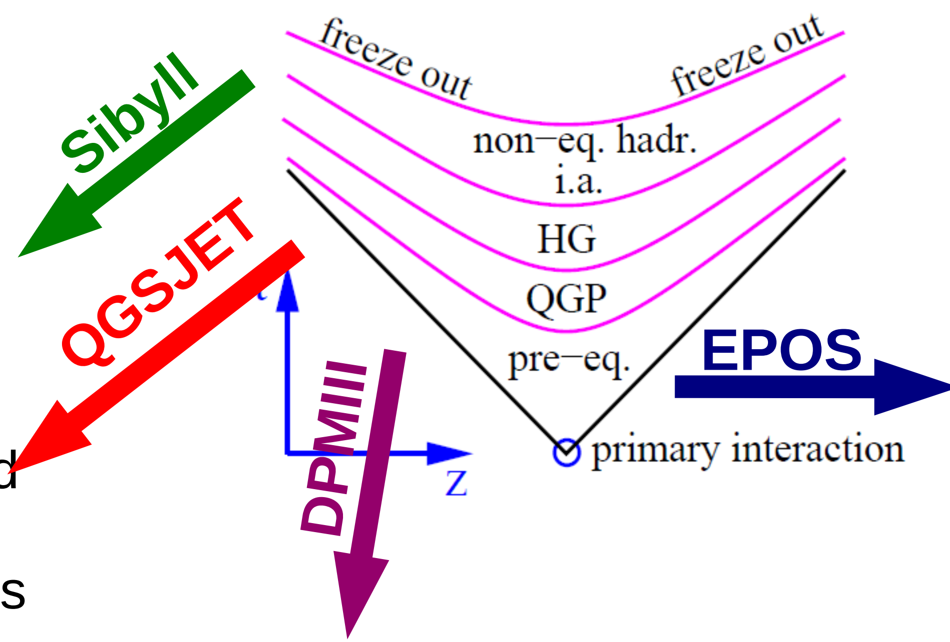


Should everything be taken into account ?

Models have different philosophies !

- number of parameters increase with data set to reproduce
- predictive power may decrease with number of parameters
- predictive power increase if we are sure NOT to neglect something

- models for CR only
- fast and not suppose to describe everything
- no detailed hard scattering or collective effects

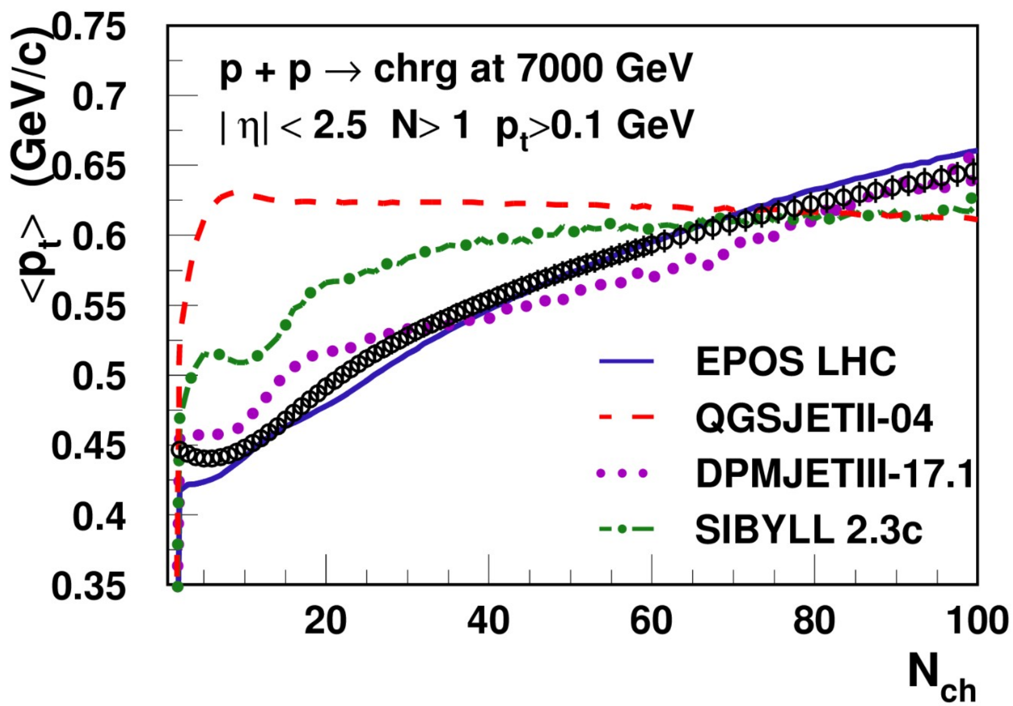


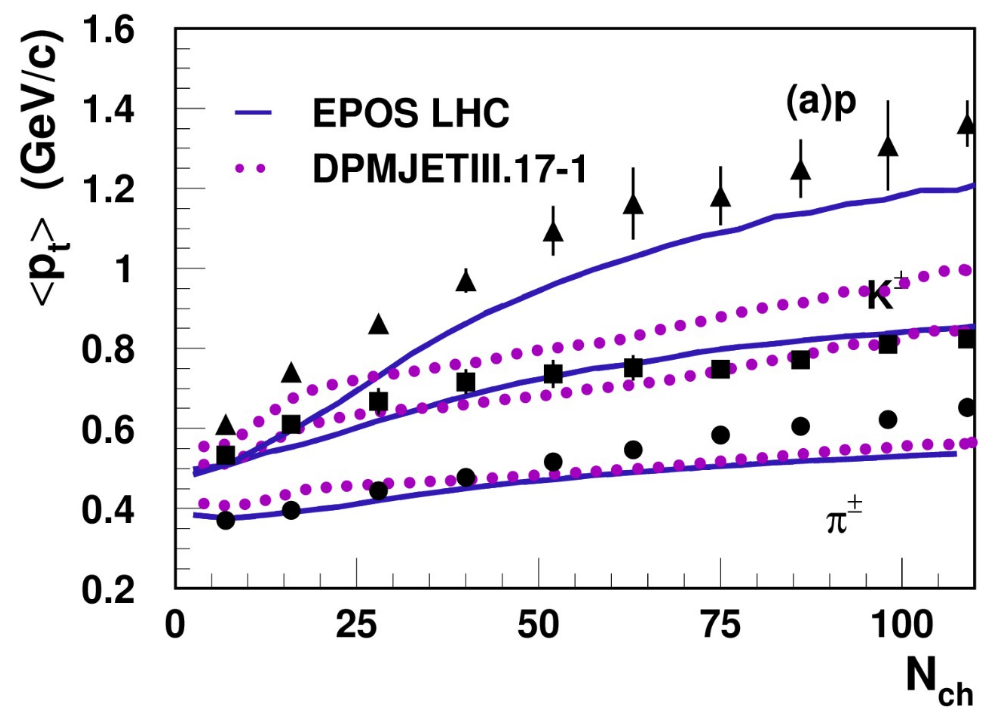
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2 and 3)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC)

- heavy ion model intended to be used for high energy physics
- limited development for collective effects but correct hard scattering

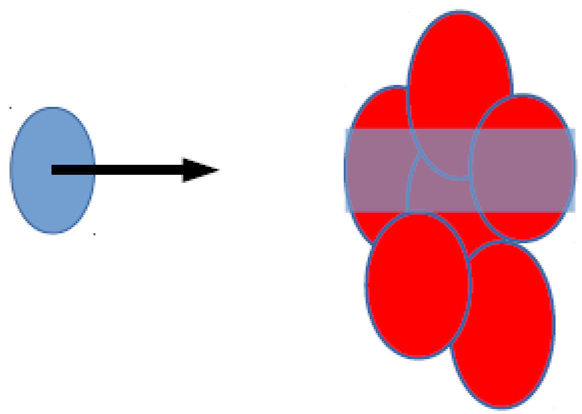
Should everything be taken into account ?

- **Models have different philosophies !**
  - ➡ number of parameters increase with data set to reproduce
  - ➡ predictive power may decrease with number of parameters
  - ➡ predictive power increase if we are sure not to neglect something
- **No direct influence on air showers but different parameters and extrapolations ?**





How to do nuclear interactions ?

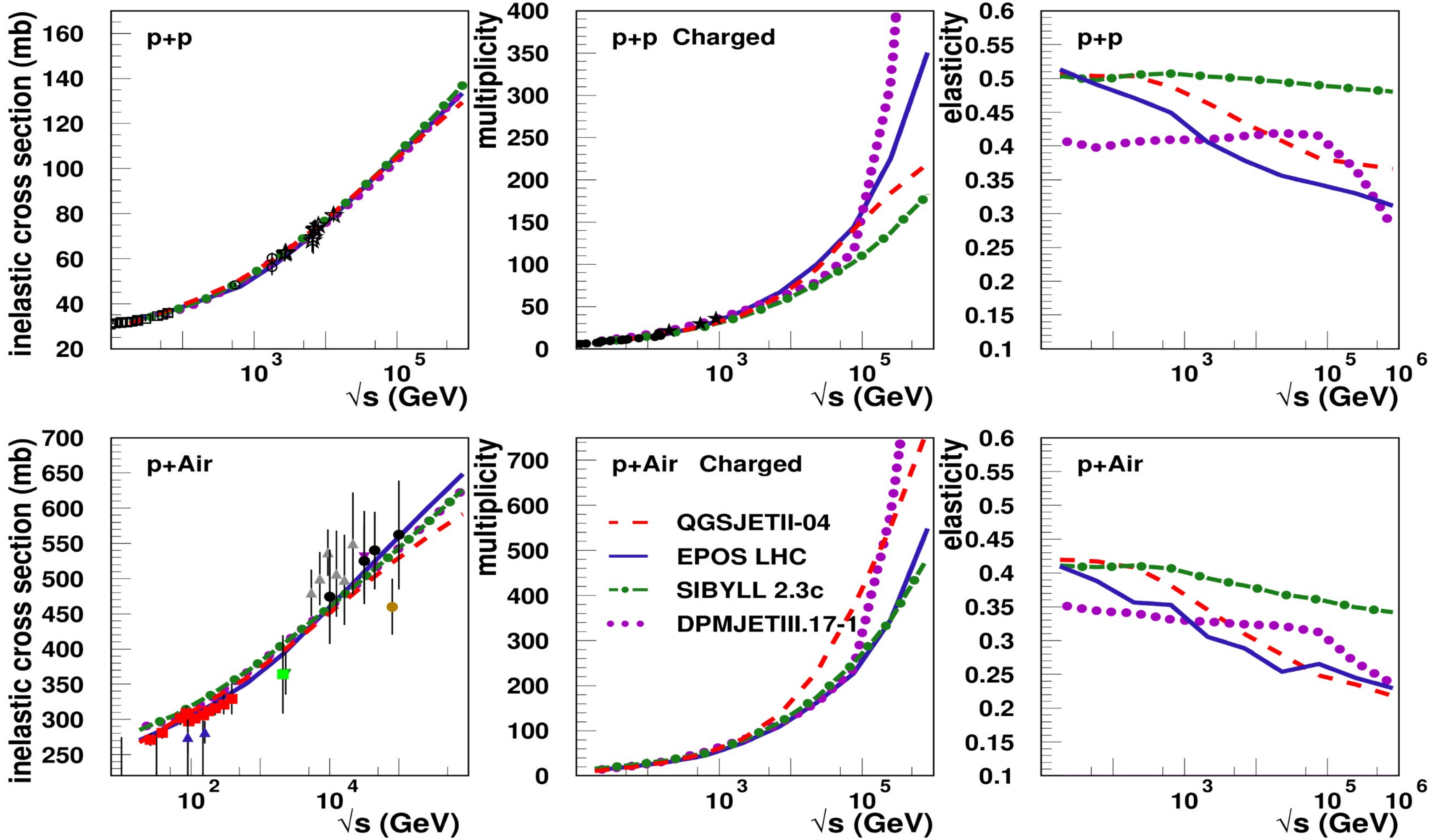


Main source of uncertainty in extrapolation :

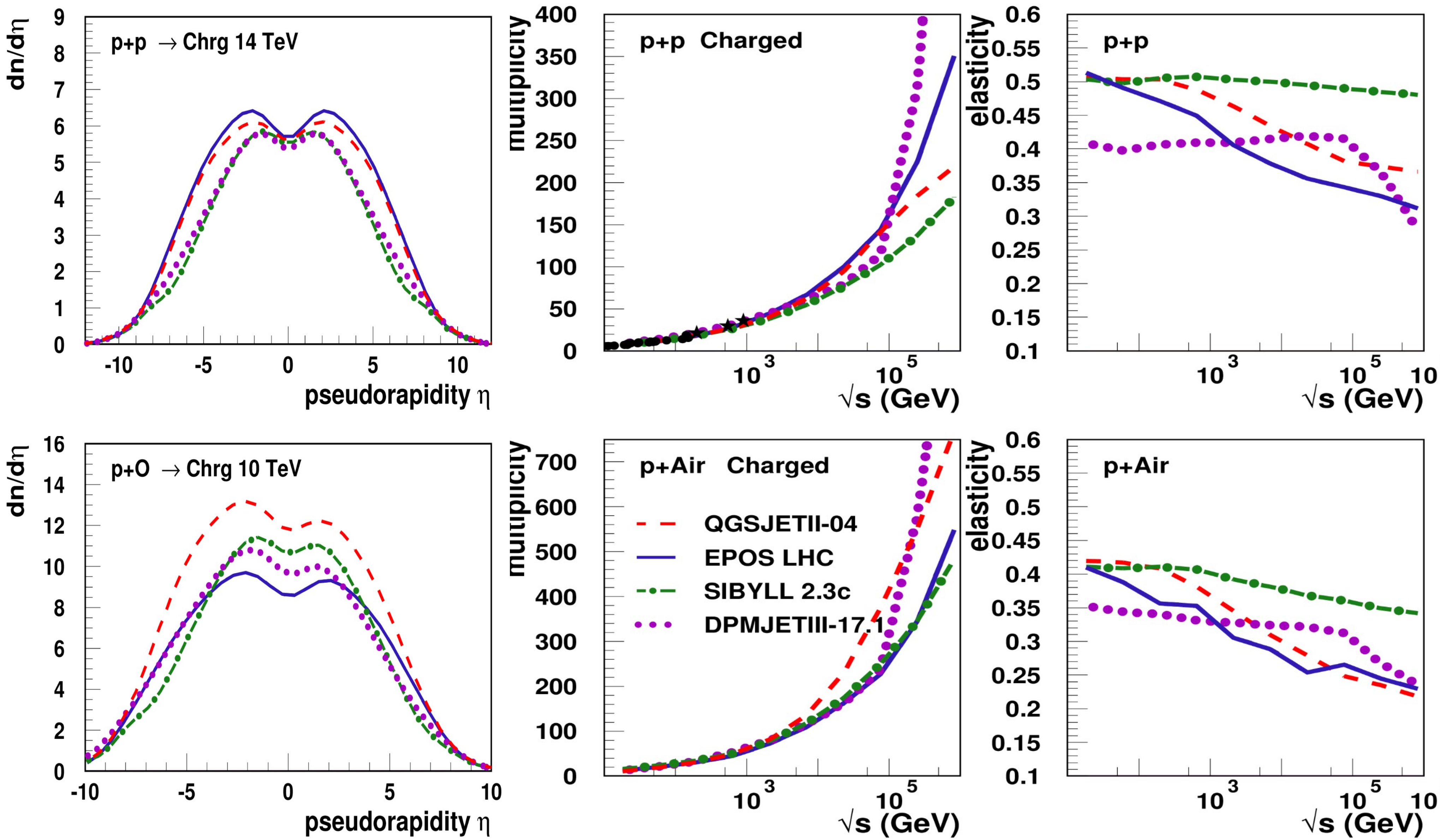
- **very different approaches**
- **limited available data set**
- **limited models capabilities**

- **Sibyll** (light ion only)
  - ➔ corrected Glauber for pA
  - ➔ superposition model for AA (A x pA)
- **QGSJETII** (all masses but not all data)
  - ➔ Scattering configuration based on A projectiles and A targets
  - ➔ Nuclear effect due to multi-leg Pomerons
- **DPMJETIII (all masses)**
  - ➔ Glauber
  - ➔ limited collective effects treatment
- **EPOS** (all masses)
  - ➔ Scattering configuration based on A projectiles and A targets
  - ➔ screening corrections depend on nuclei
  - ➔ final state interactions (core-corona approach and collective hadronization with flow for core)

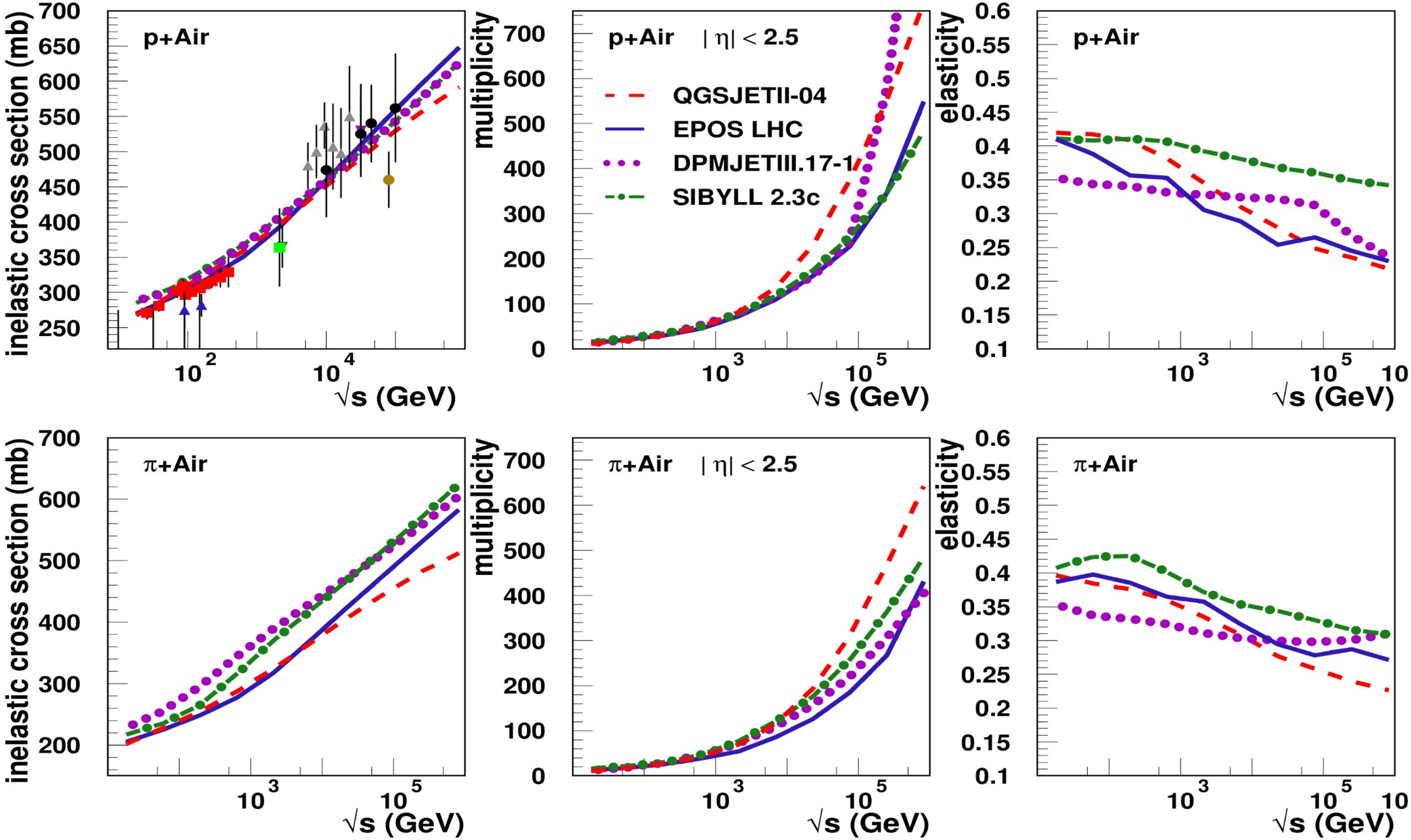
Ultra-High Energy Hadronic Model Predictions p-Air



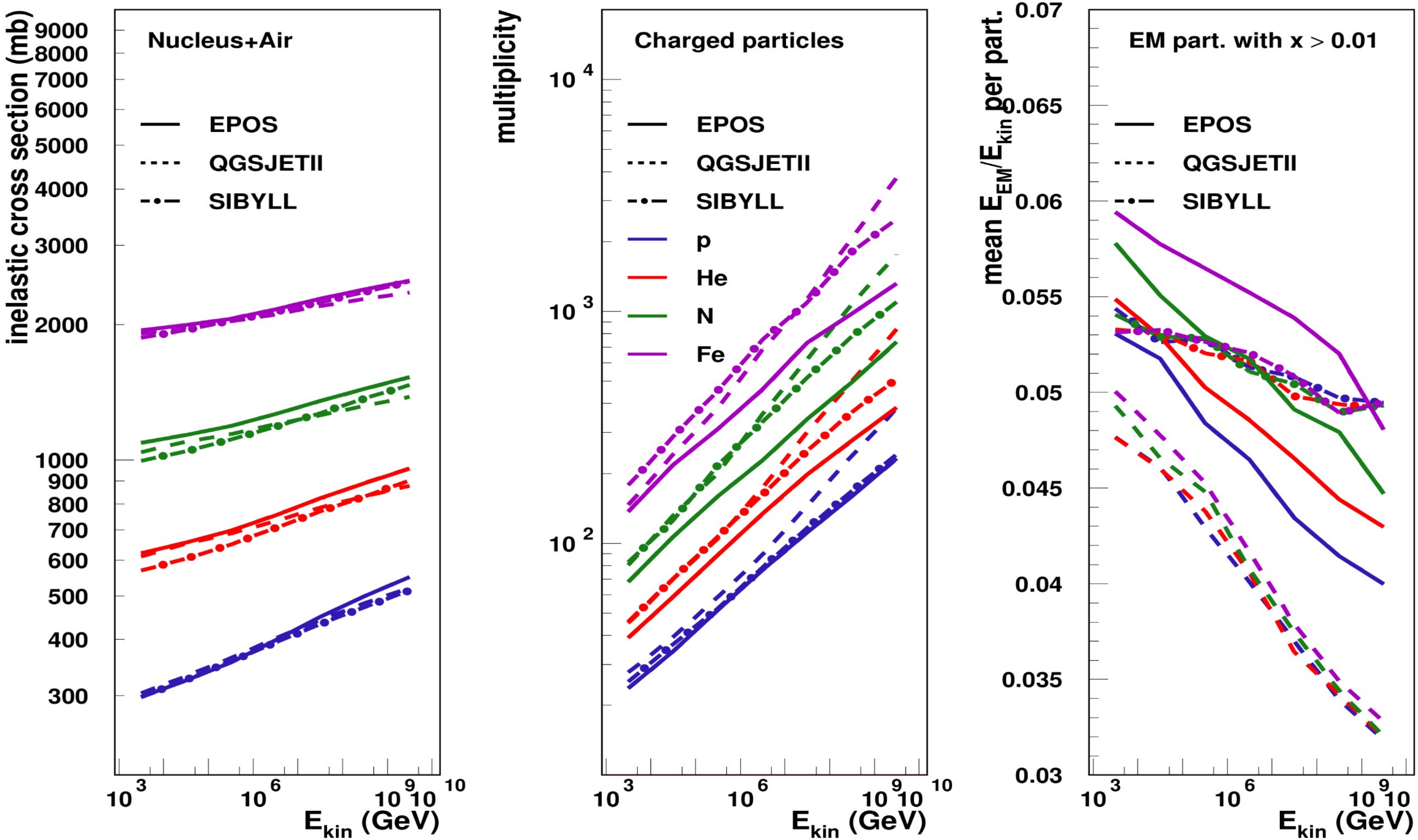
Ultra-High Energy Hadronic Model Predictions p-Air



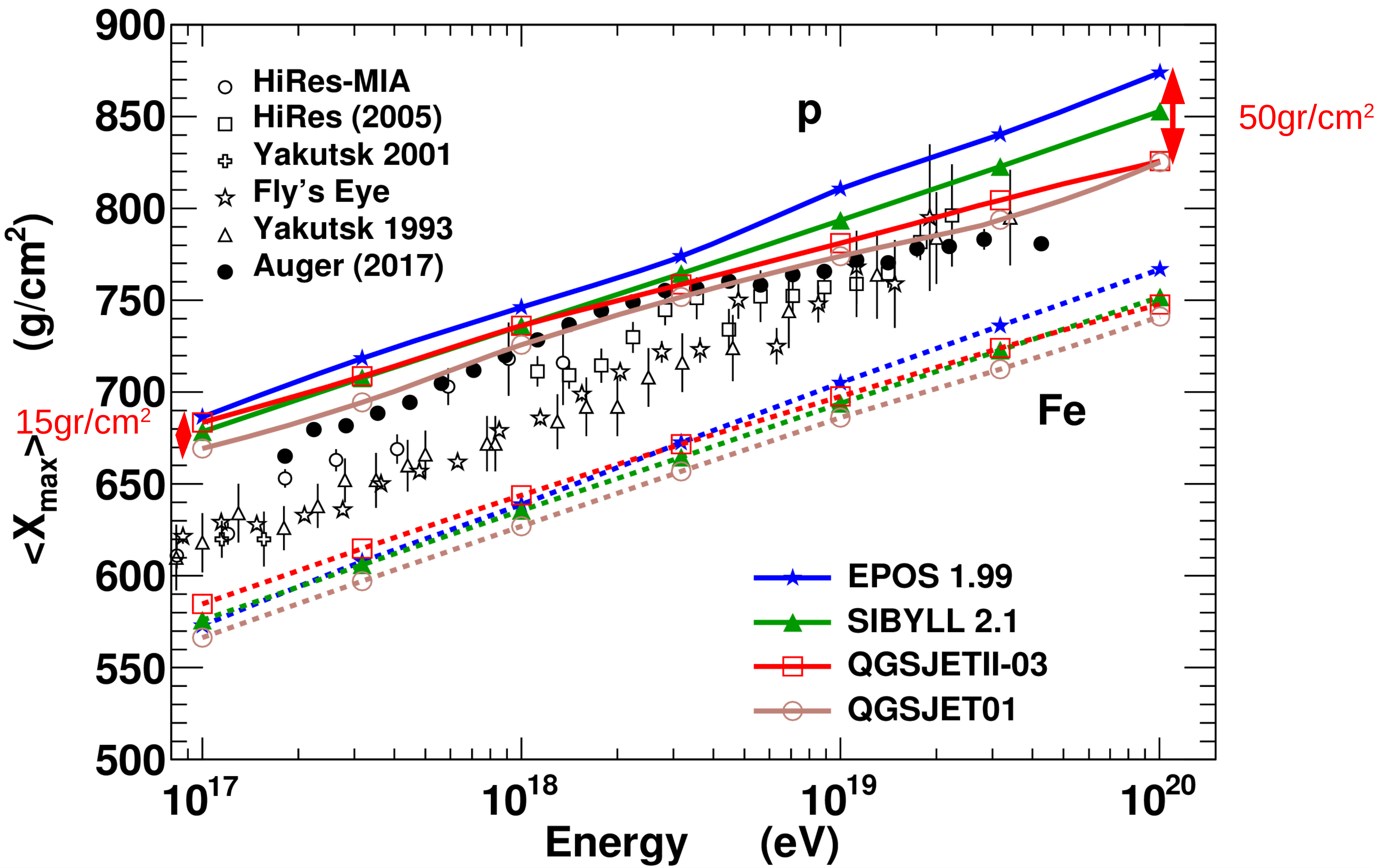
Ultra-High Energy Hadronic Model Predictions π-Air



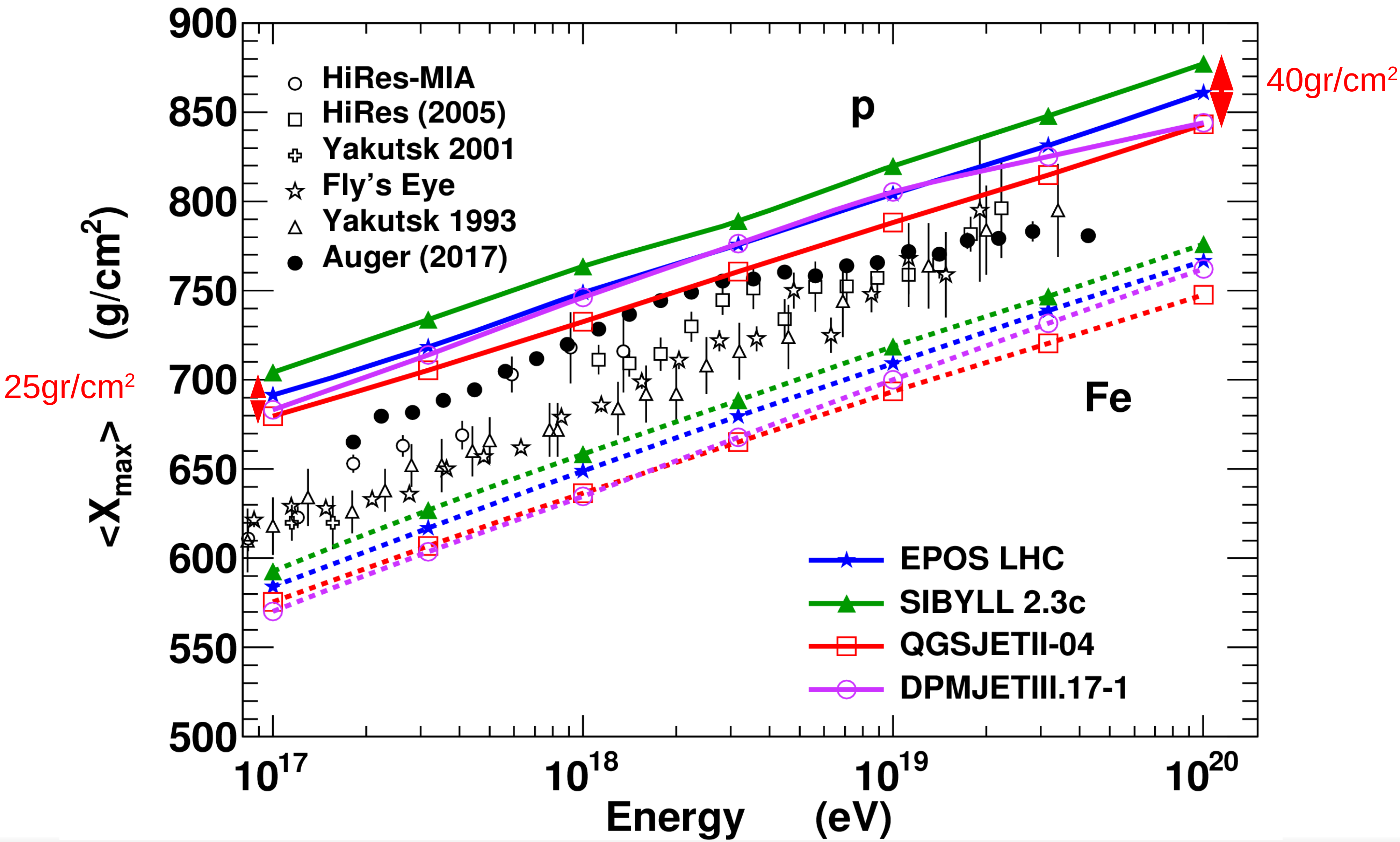
Ultra-High Energy Hadronic Model Predictions A-Air



EAS with Old CR Models : X_{max}

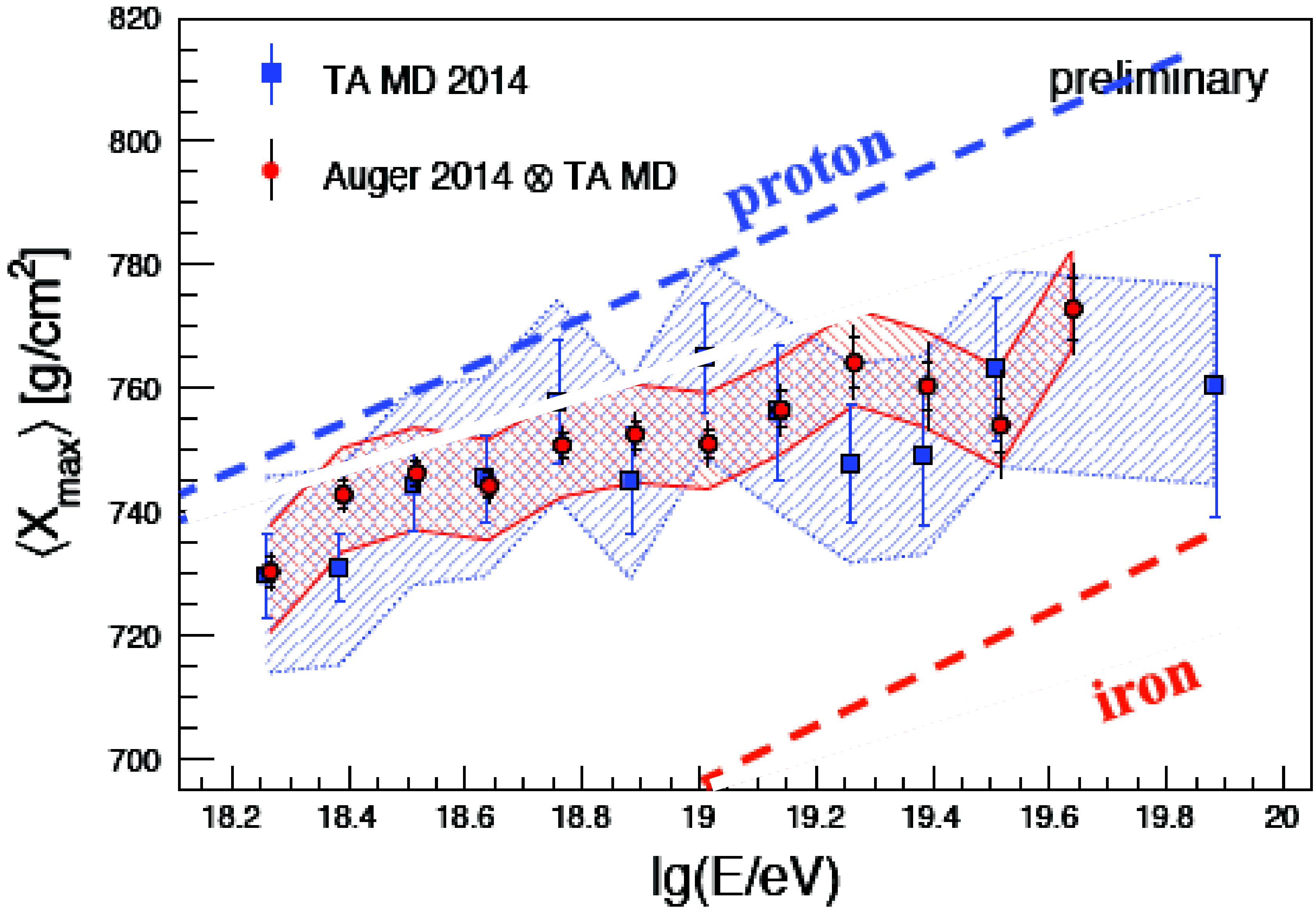


EAS with Re-tuned CR Models : X_{max}



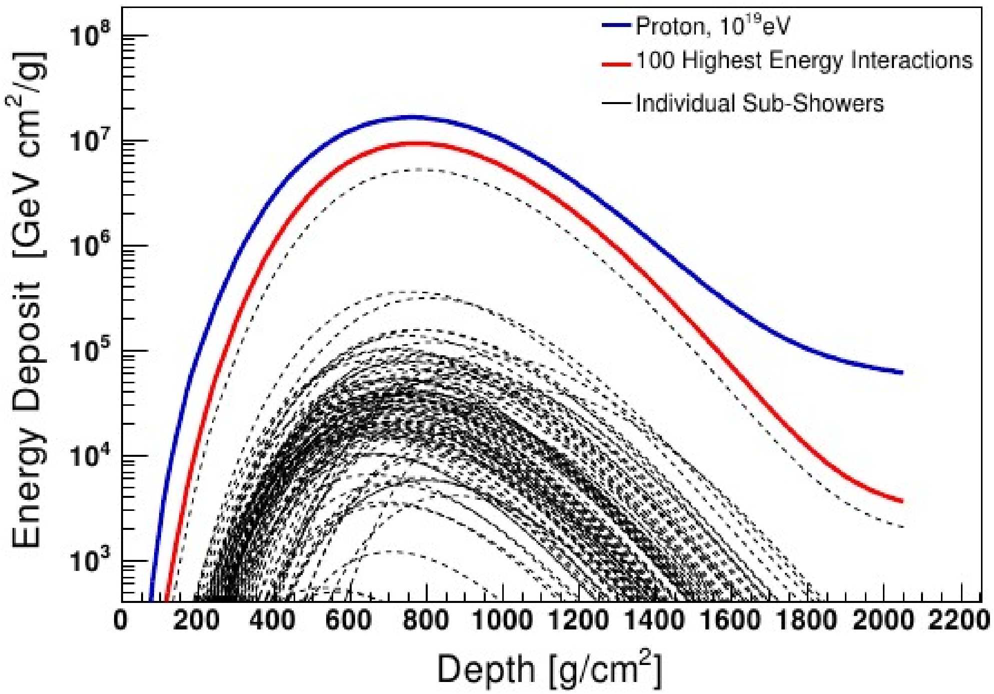
Post-LHC Composition

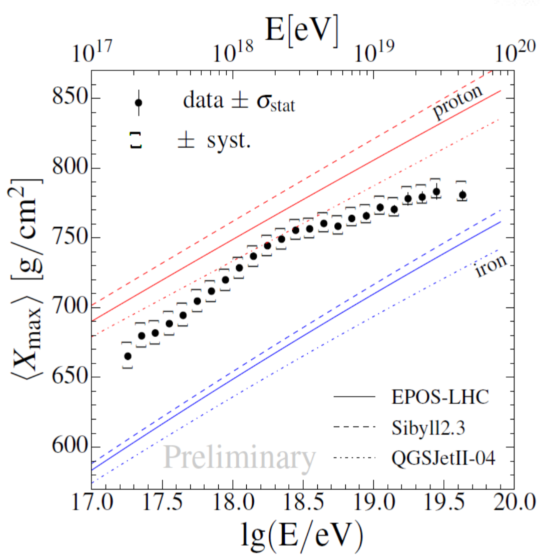
With post-LHC models there is no doubt about mixed composition

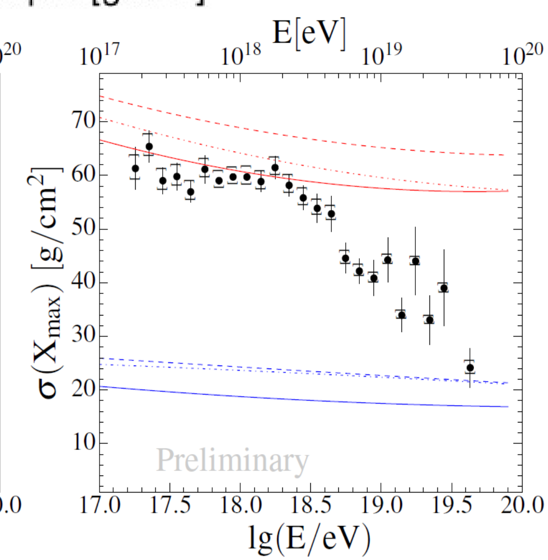


Fluorescence Detector (FD)

From R. Ulrich (KIT)





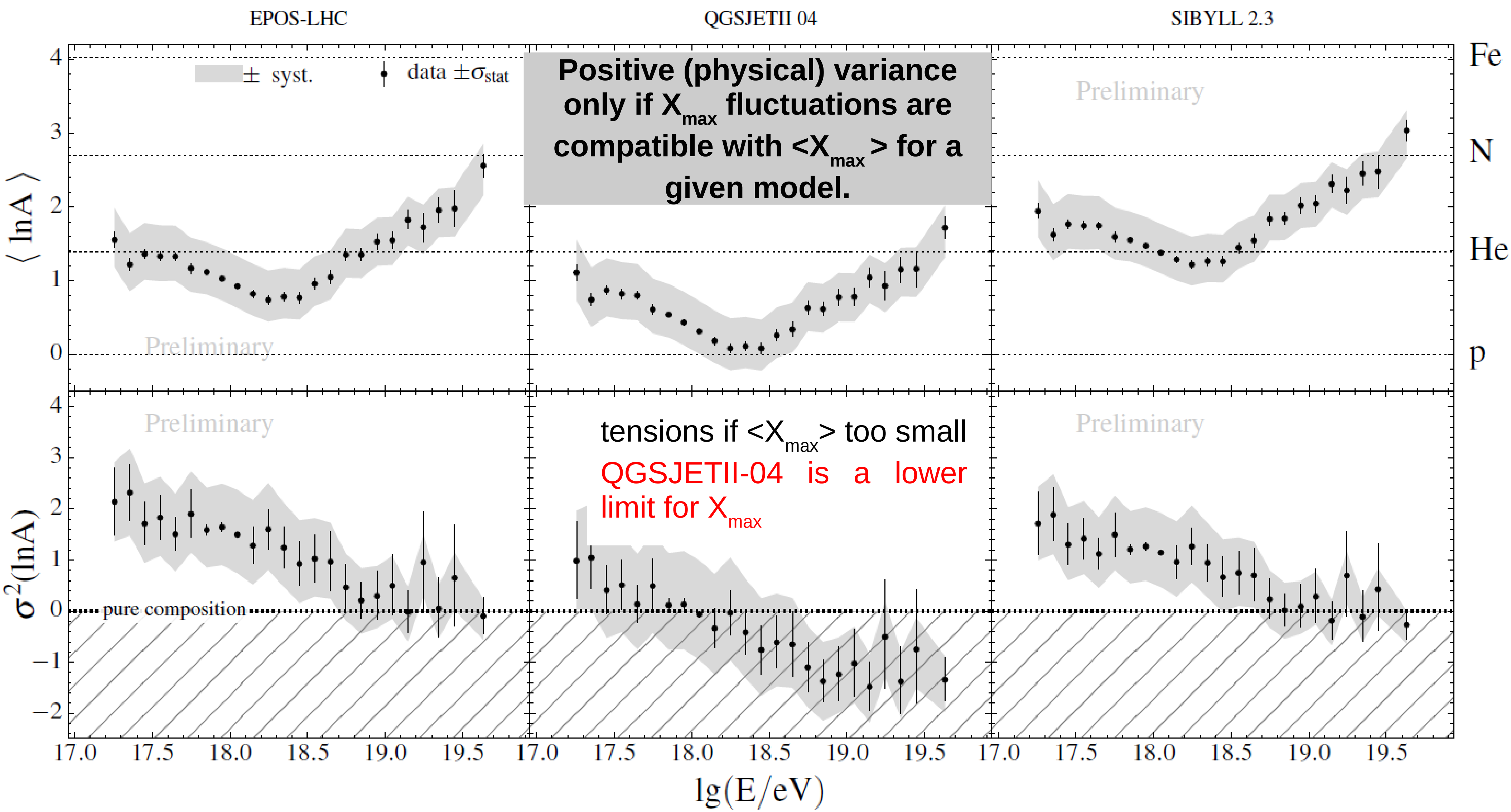


- **Most direct measurement**
  - ➡ dominated by first interaction
- **Reference mass for other analysis**
  - ➡ <lnA> from <X_{max}> and RMS
- **Possibility to use the tail of X_{max} distribution to measure p-Air inelastic cross-section.**
  - ➡ require no contamination from photon induced showers (independent check)
  - ➡ correction to “invisible” cross-section using hadronic models
  - ➡ conversion to p-p cross-section using Glauber model.

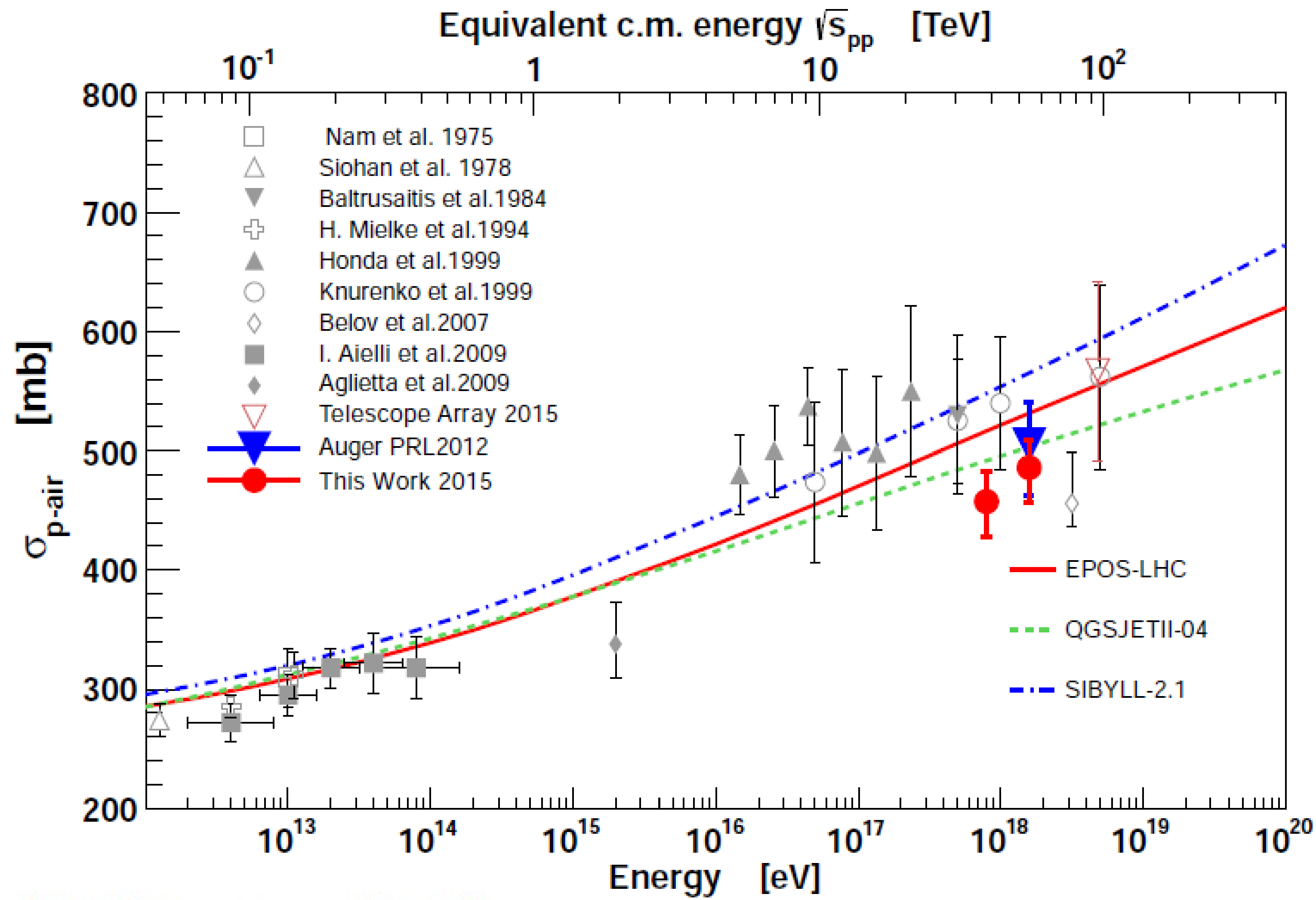
Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration (ICRC 2017)

➡ std deviation of lnA allows to test model consistency.



p-Air Production Cross Section @ 39 and 55 TeV

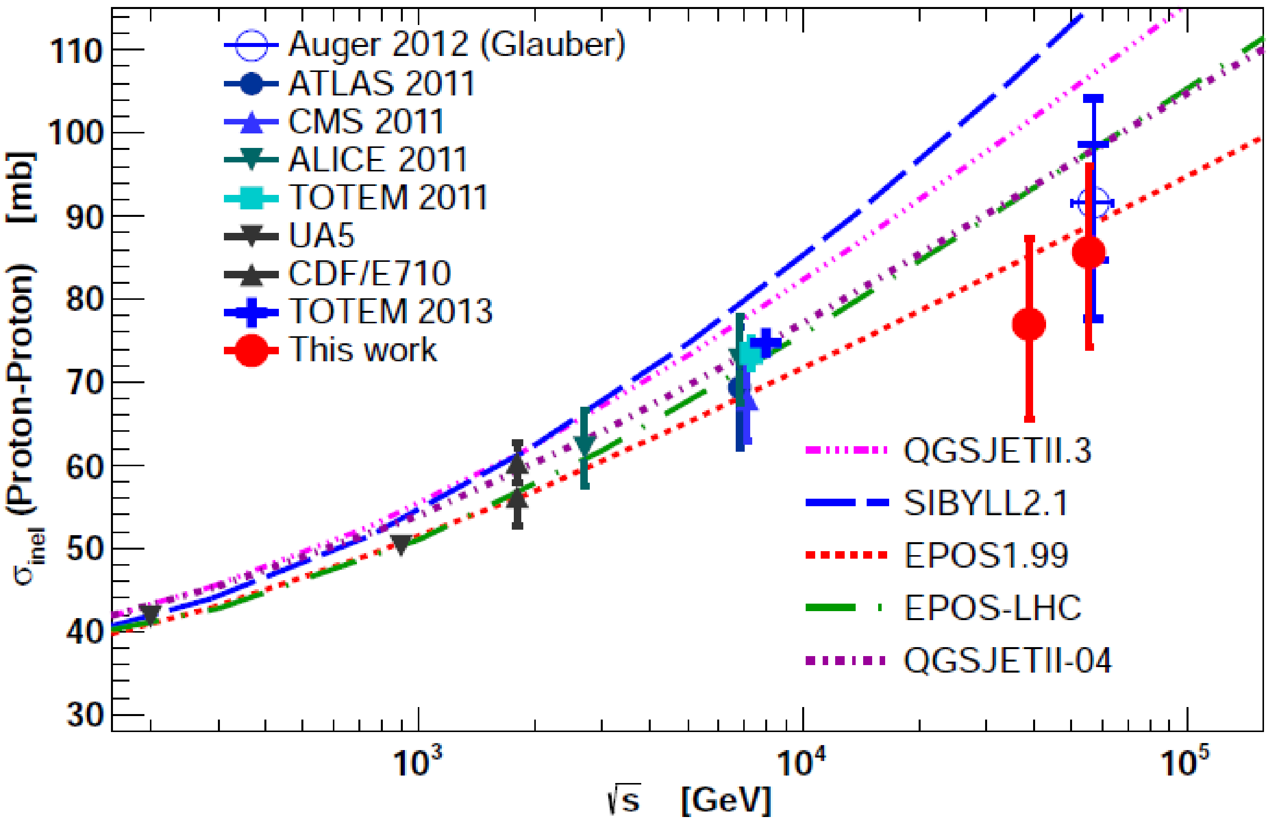


Results, σ_{p-air} in mb

Lower energy point	Higher energy point
457.5±17.8(stat)+19/-25(syst)	485.8±15.8(stat)+19/-25(syst)

p-p Inelastic Cross Section @ 39 and 55 TeV

Conversion using Glauber model: $\text{Glauber}(\sigma_{pp}^{\text{tot}}, B_{\text{el}}, \lambda, \ldots) \rightarrow \sigma_{\text{p-air}}$



- Extended Glauber conversion with inelastic screening
- propagation of modeling uncertainties
- Model uncertainties may be underestimated, since there are other theoretical models available for the conversion

Results, $\sigma_{pp}^{\text{inel}}$ in mb

Lower energy point

76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)

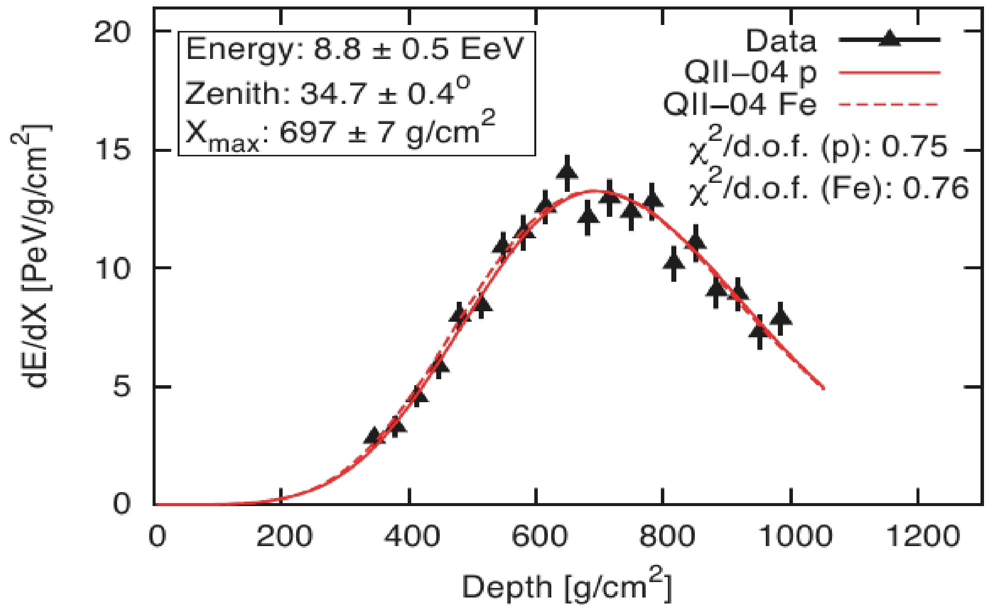
at $\sqrt{s_{\text{pp}}} = 38.7 \pm 2.5$ TeV

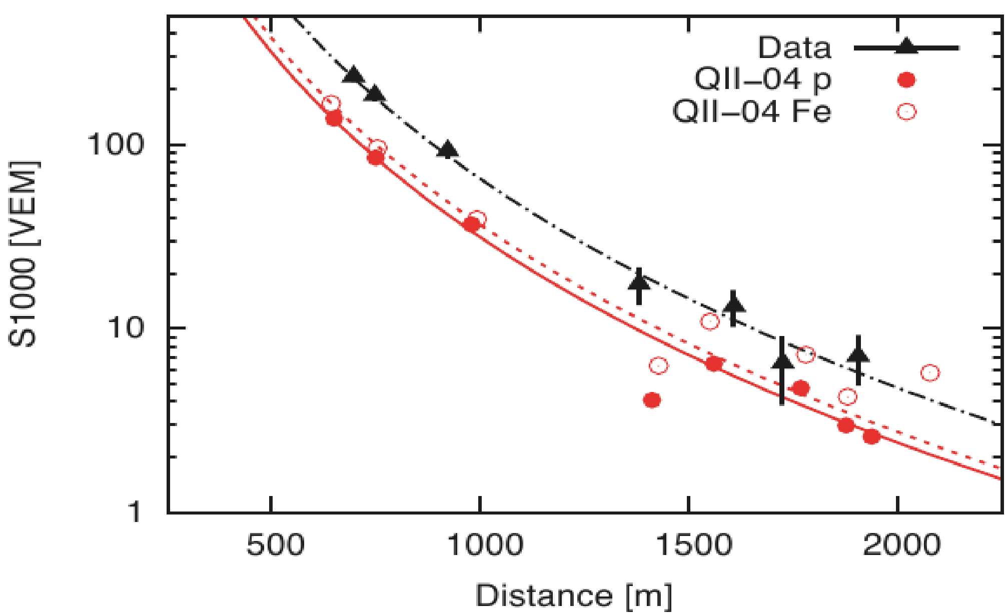
Higher energy point

85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)

at $\sqrt{s_{\text{pp}}} = 55.5 \pm 3.6$ TeV

Hybrid Analysis





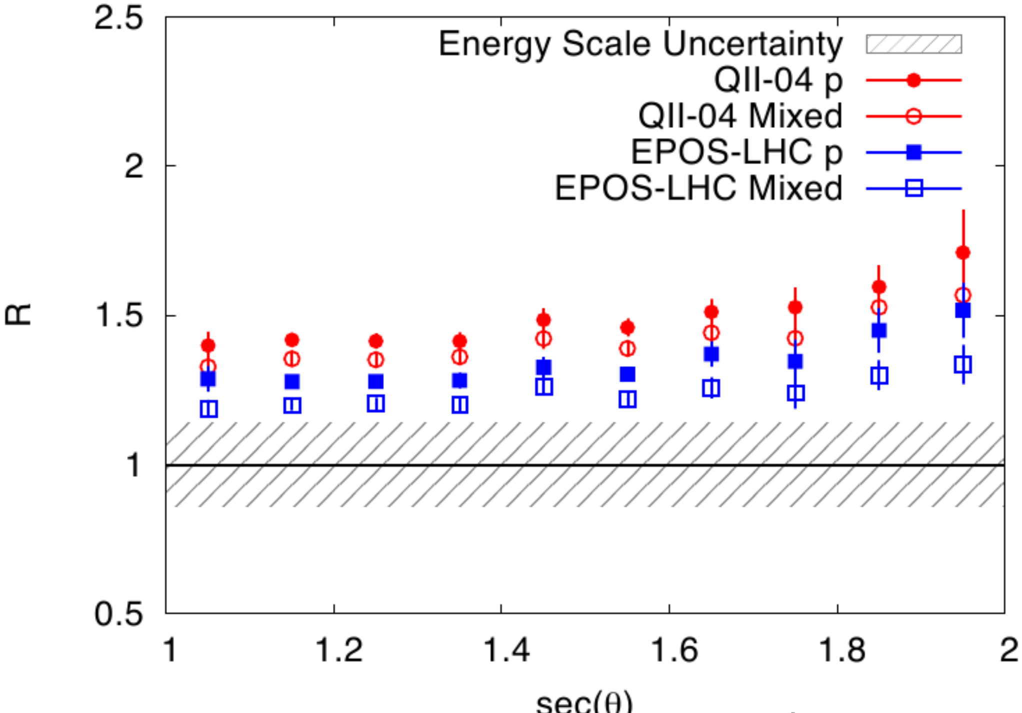
- **Analysis based on 411 Golden Hybrid Events**
  - find simulated showers reproducing each FD profile for all possible models and primary masses (p, He, N, Fe),
  - decompose ground signal into pure electromagnetic (S_{EM}) and muon dependent signal (S_μ),
  - rescale both component separately (R_E and R_μ to reproduce SD signal for each showers,

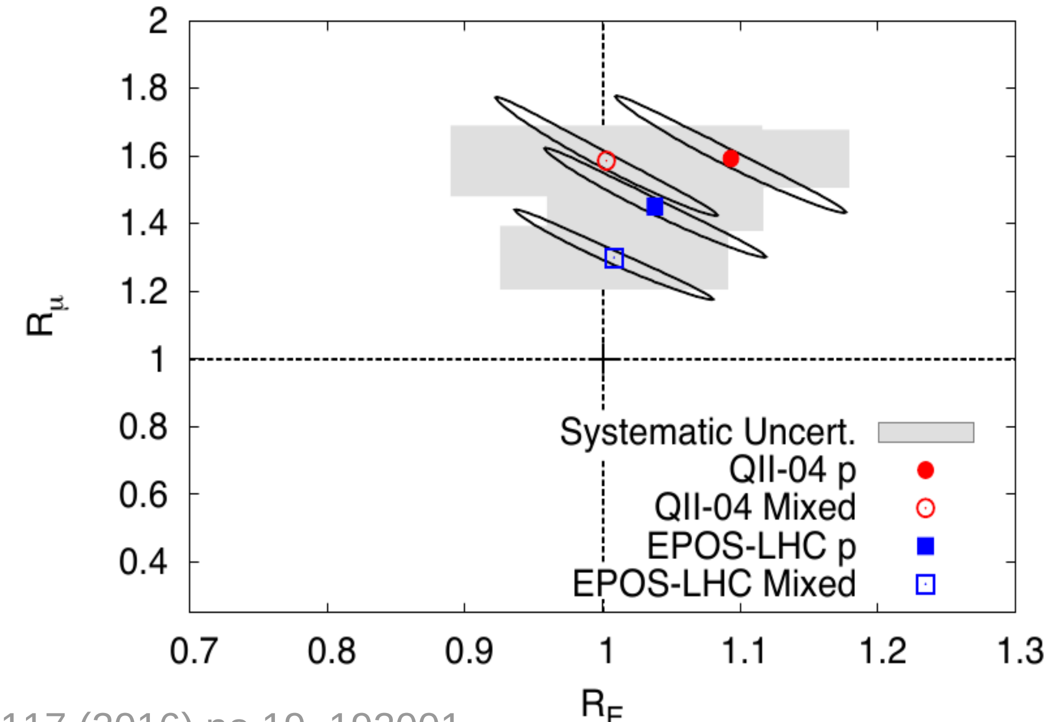
$$S_{\rm resc}(R_E, R_\mu)_{i,j} \equiv R_E\, S_{EM,i,j} + R_E^\alpha R_\mu\, S_{\mu,i,j}$$

  - for mixed composition, give weight according to X_{max} distribution.

Muon Rescaling

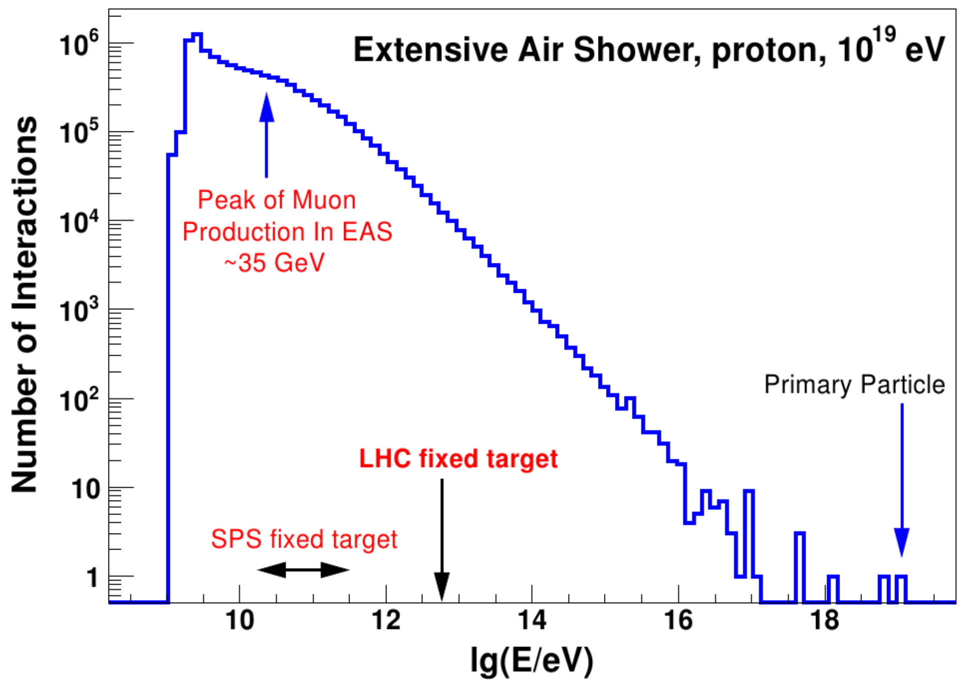
- **Simulations don't reproduce FD and SD signal consistently**
  - $R=S_{1000}^{observed}/S_{1000}^{predicted}$ increase with zenith angle
  - EPOS-LHC Iron could be (almost) compatible with data, but X_{max} data are NOT pure Iron (but mixed).
- **To reproduce data simulations have to be rescaled**
  - for mixed composition, only muon component has to be changed
    - correct energy scale
  - 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.

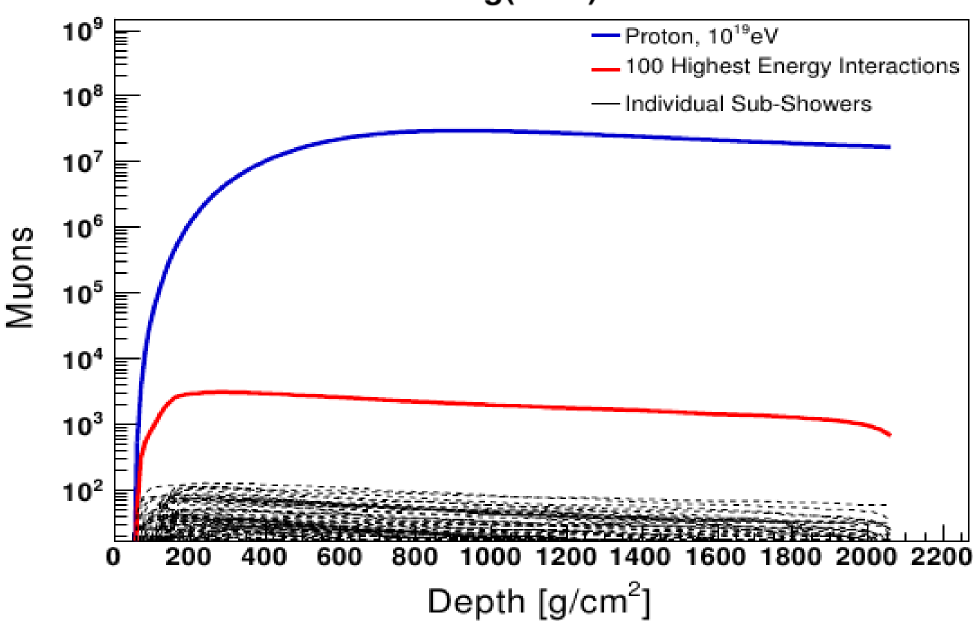




Phys.Rev.Lett. 117 (2016) no.19, 192001

Surface Detector (SD)

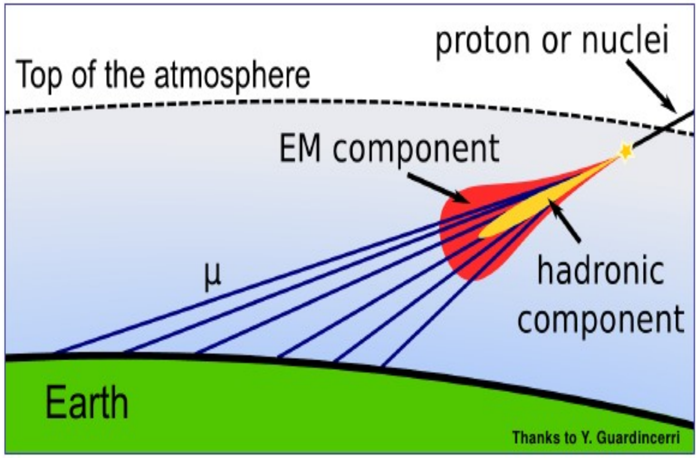


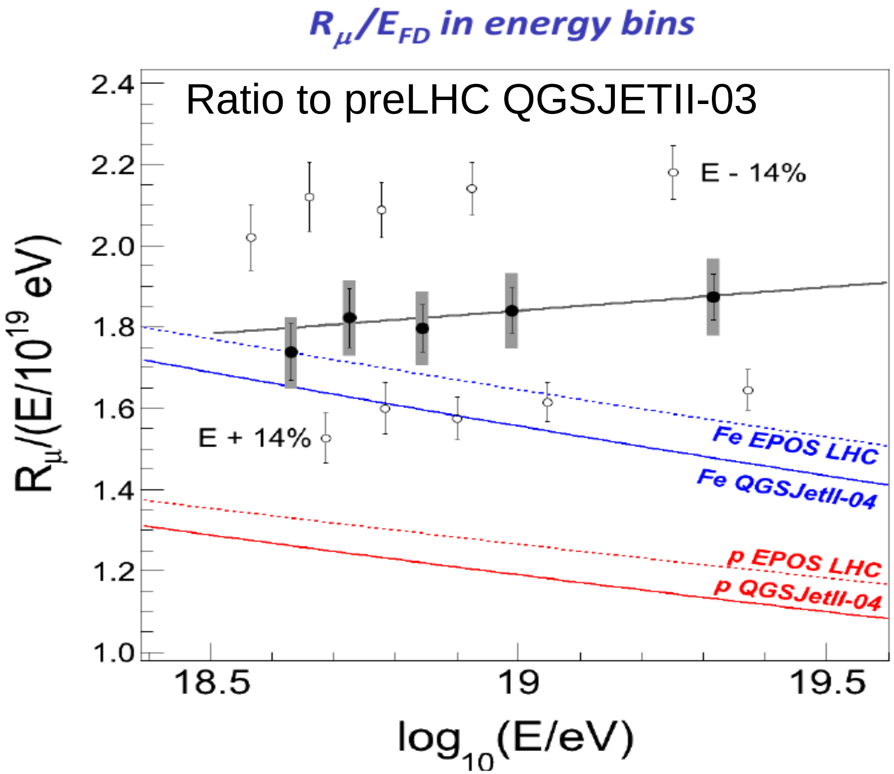


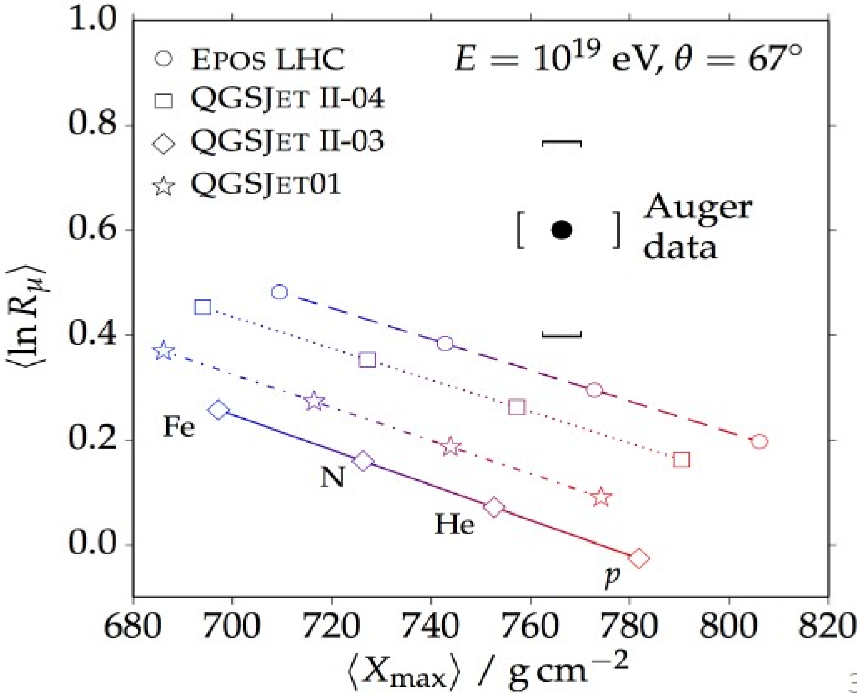
- **SD detector sensitive to**
  - electromagnetic particles (EM)
  - muons
- **Particles at ground produced after many generations of hadronic interactions**
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of hadronic cascade (depend on low energy hadronic interactions)
  - small fraction of EM (at large r) produced by last hadronic generation
- **EM and muons give different signal in Cherenkov detector.**
  - property of time traces

Direct Muon Measurement

- **Old showers contain only muon component**
  - direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)
  - EM halo accounted for
  - correction between true muon number and reconstructed one from map by MC (<5%)







Muon Production Depth

- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

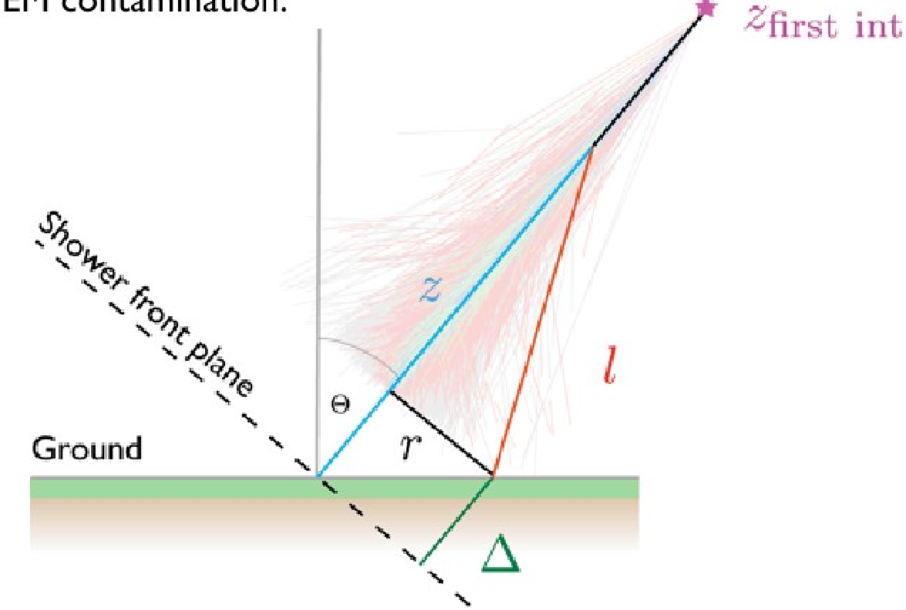
$$c \cdot t_g = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

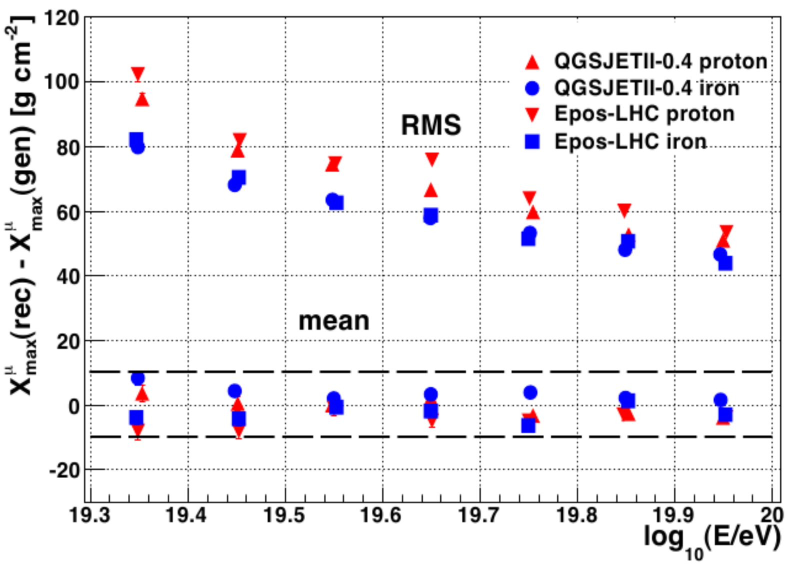
  - mapped to muon production distance

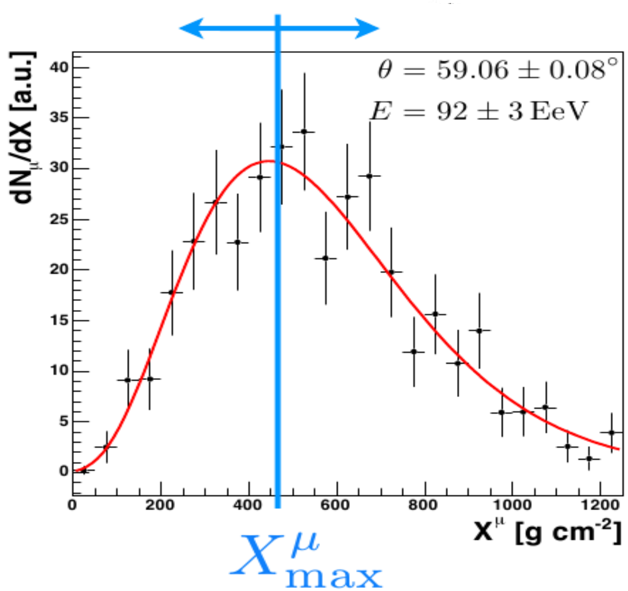
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

  - decent resolution and no bias

Inclined events to avoid EM contamination:

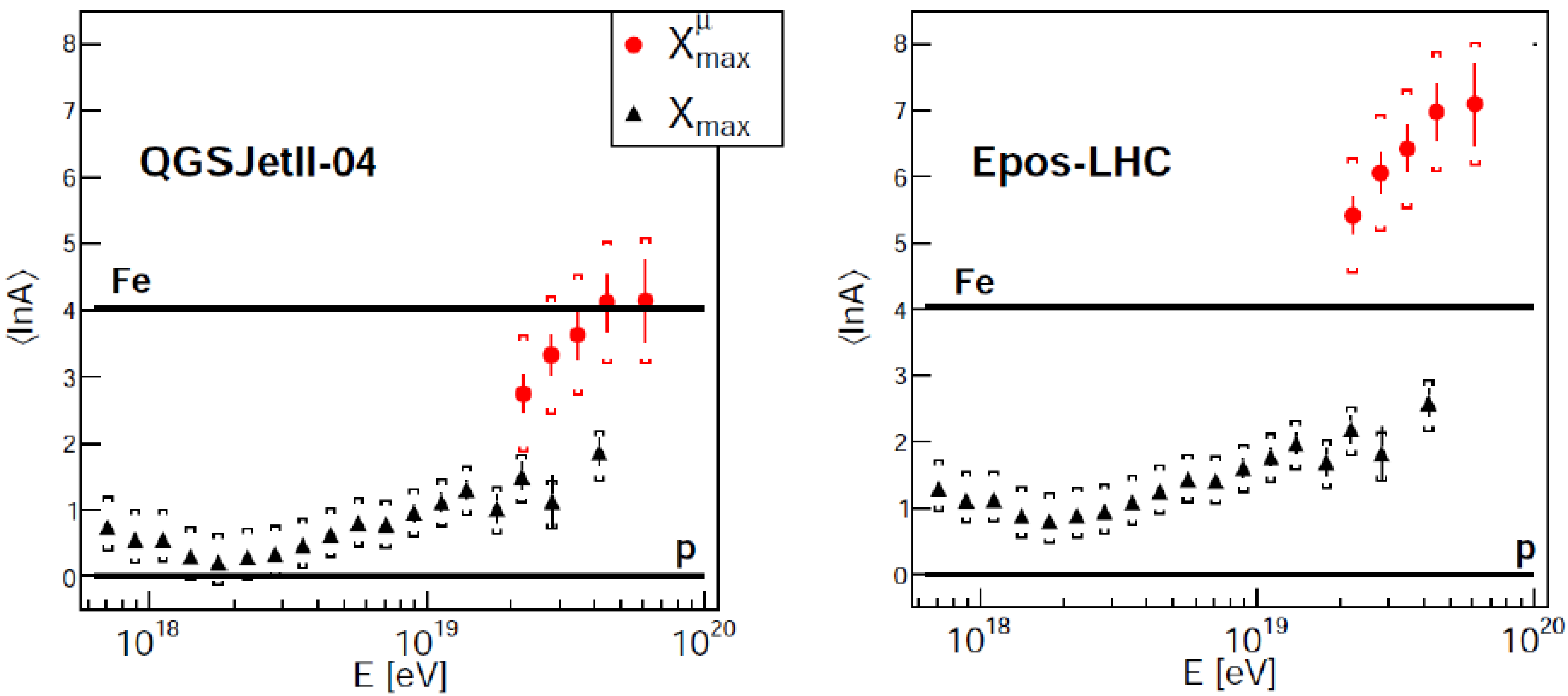






MPD and Models

- **2 independent mass composition measurements**
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data (low mass diffraction) and model consistency (forward baryon production at high energy): direct constraint on hadronic interactions.

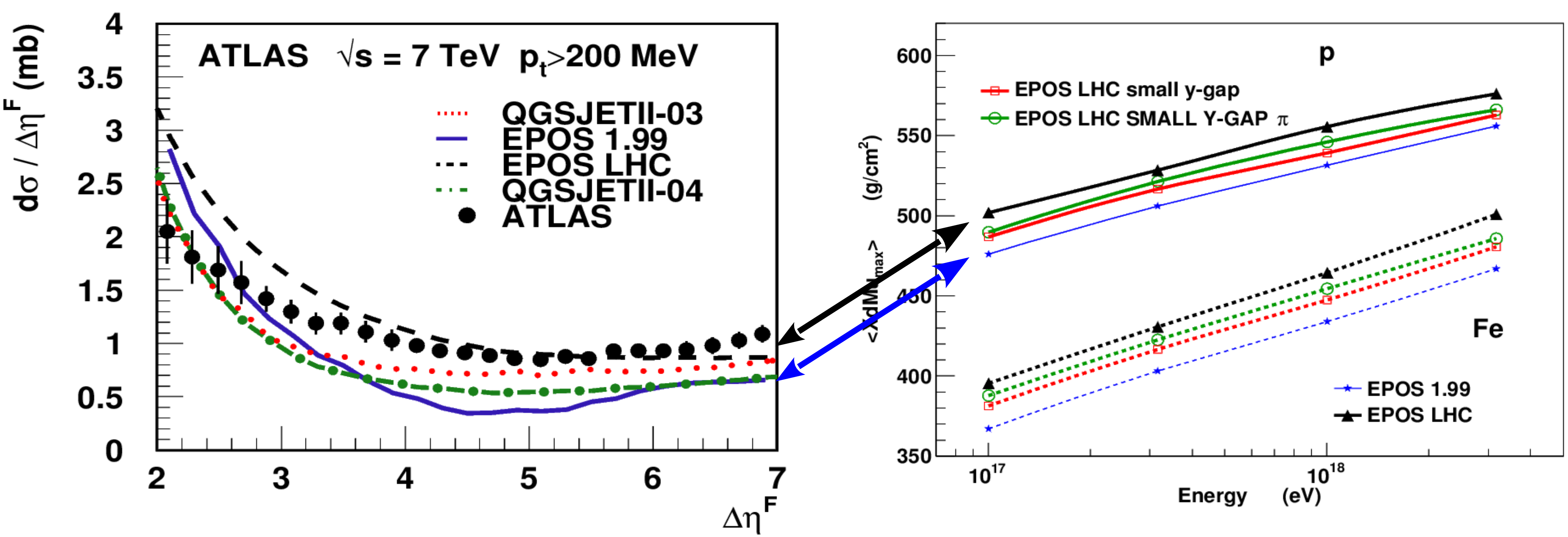


MPD and Diffraction

Inelasticity linked to diffraction (cross-section and mass distribution)

- weak influence on EM X_{max} since only 1st interaction really matters
- cumulative effect for X^{μ}_{max} since muons produced at the end of hadr. subcasc.
- rapidity-gap in p-p @ LHC not compatible with measured MPD
- harder mass spectrum for pions reduce X^{μ}_{max} and increase muon number !

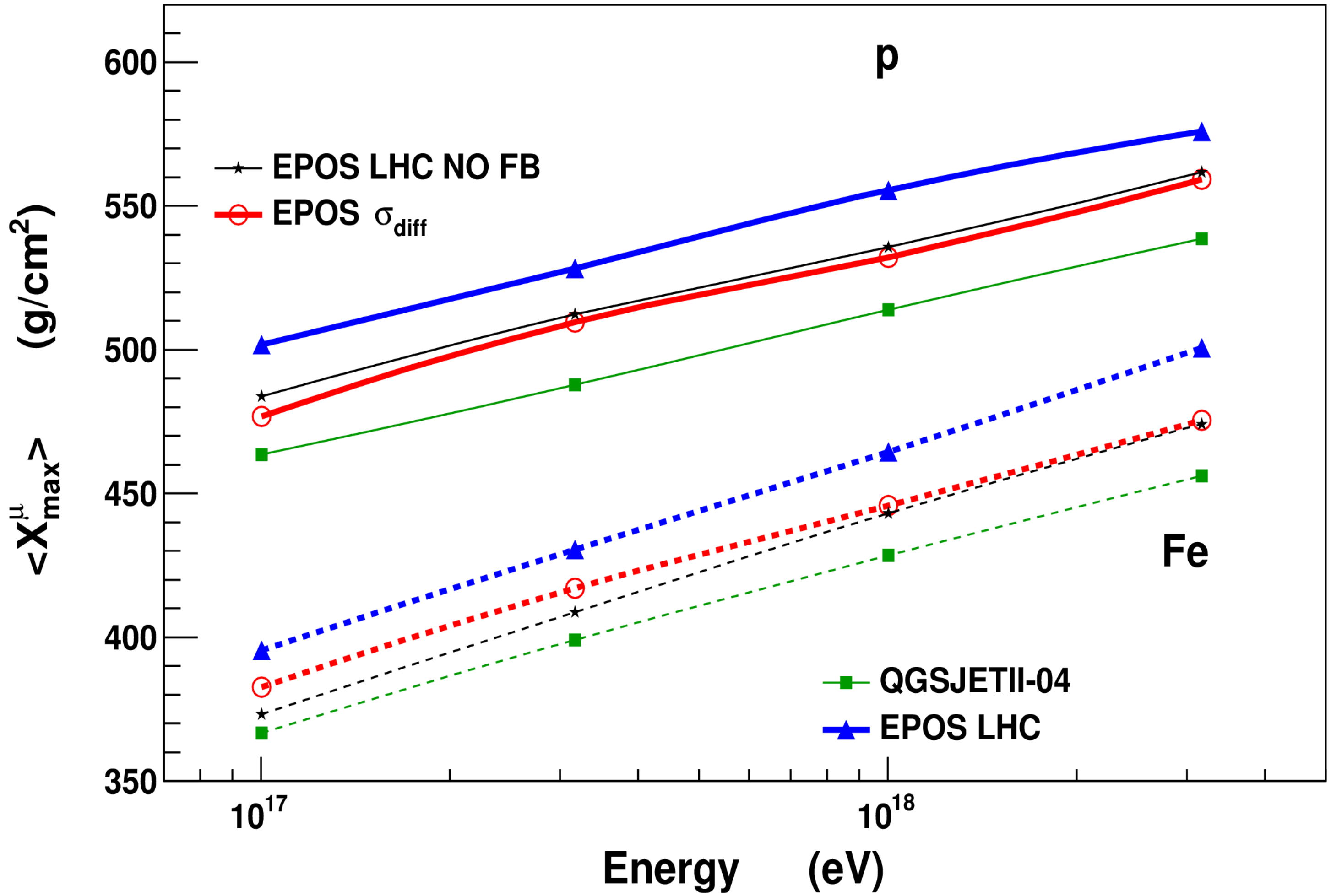
different diffractive mass distribution for mesons and baryons !



$<X^{\mu}_{max}>$ with modified EPOS LHC

Same than in mixed models

- softer meson spectra (lower elasticity) : lower X^{μ}_{max}
- less forward baryons (FB) : lower X^{μ}_{max}



-25 g/cm² for diff

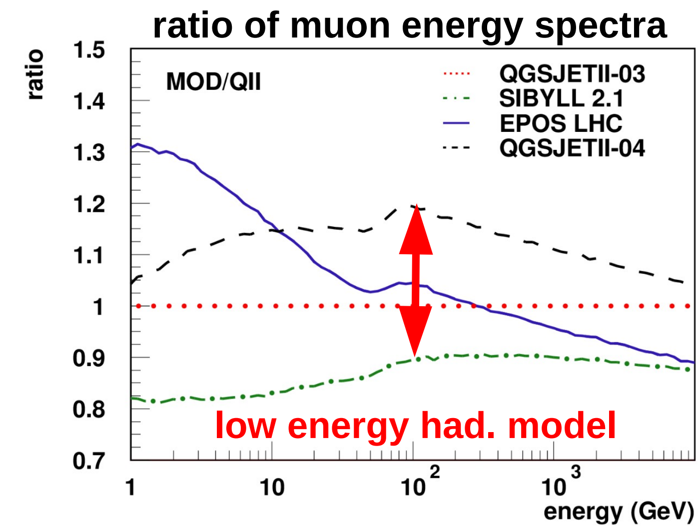
-20 g/cm² for baryons

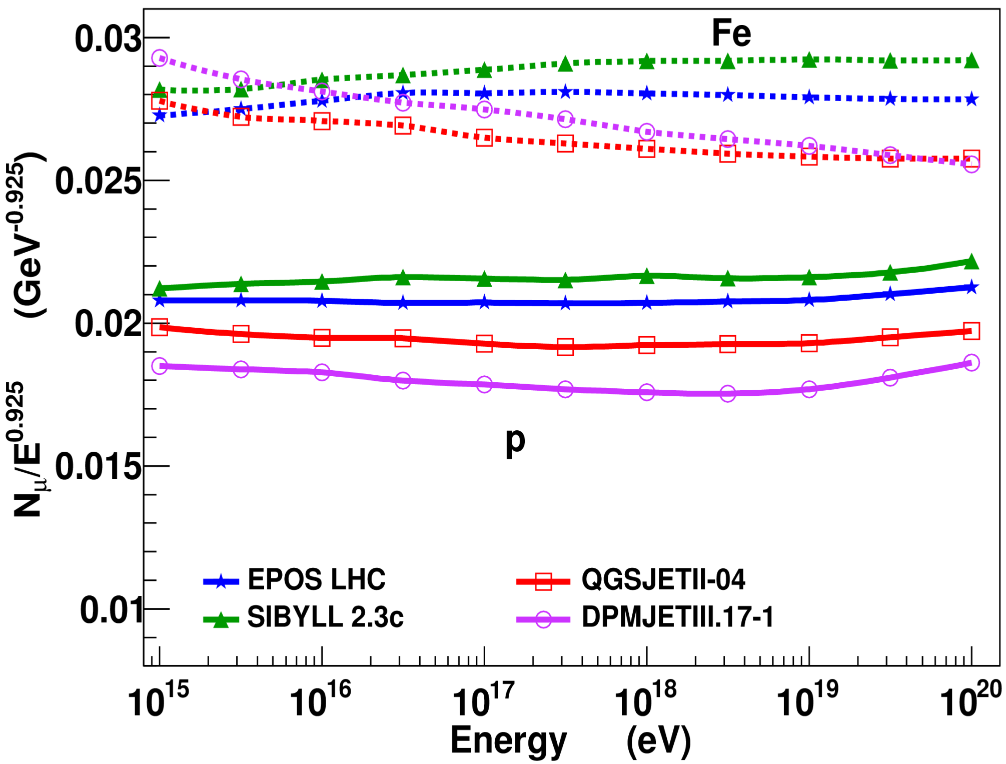
MPDs sensitive to baryon (less generation) and meson spectra in pion interactions

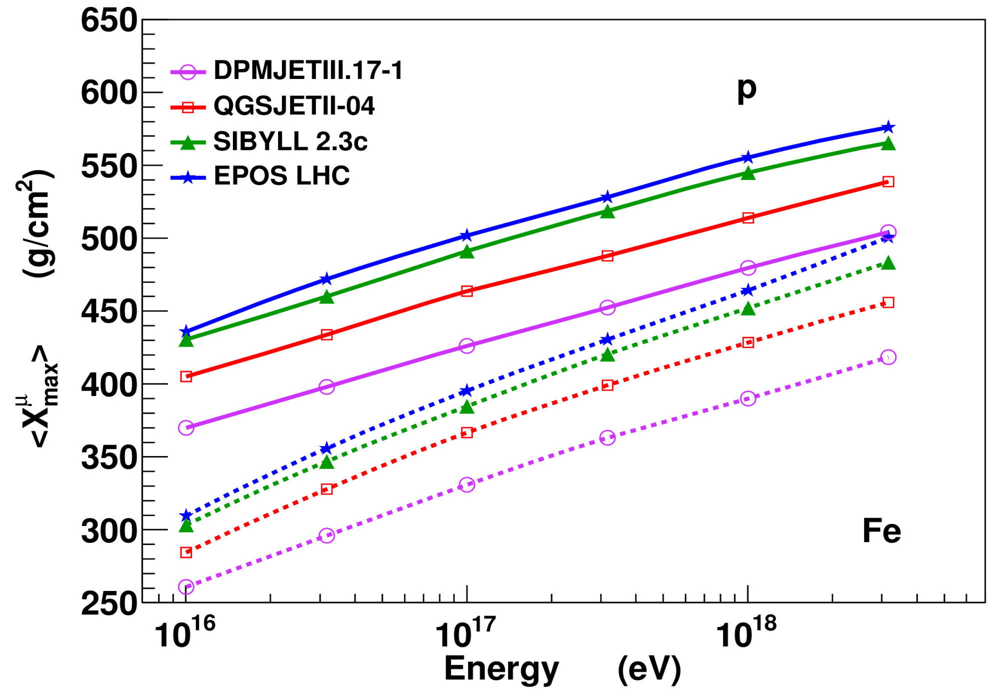
Ostapchenko et al. Phys.Rev. D93 (2016) no.5, 051501

Muons at Ground

- Muon production depends on all int. energies
- Muon production dominated by pion interactions (LHC indirectly important)
- Resonance and baryon production important
- Post-LHC Models ~ agrees on numbers but with different production height and spectra







The chicken ...

- **Hadronic interaction models very important to interpret cosmic ray data**
  - mass composition
  - LHC data used to tune and complete the models
- **Central particle production at LHC reduced model uncertainties in slope of X_{max}**
  - same energy evolution in models important for mass of primary cosmic rays
  - all pre-LHC models in contradiction with LHC data (central and forward prod.)
  - using latest model version reduce uncertainties and avoid unphysical behavior
- **Remaining 20 gr/cm^2 difference for X_{max} predictions**
  - linked to forward physics (photon spectra and diffraction measured at LHC) not yet taken into account in models used for EAS simulation (coming...)
  - effect of extrapolation to p-Air interaction
    - p-O beam necessary to check that p-p properly extrapolated
    - p-Pb measurements can be used but need change in most models (only EPOS reproduces p-Pb data for the moment)

… or the egg

- **Auger data (and other low energy cosmic ray experiments) not consistently described by hadronic interaction models (even post LHC)**
  - <X_{max}> and fluctuations, number of muons and muon production depth …
  - ➡ but it has never been so good ! only 1 to 2 sigma difference in most of the cases
- **Comparison of <lnA> from X_{max} from FD and X^{μ}_{max} from SD allows direct test of hadronic interaction models (and Physics behind !)**
  - ➡ test small effects amplified by cascade effect
  - ➡ test energy, phase space (forward) and projectile (mesons) difficult to reach with accelerators
- **Hadronic models used for cosmic ray analysis very important for LHC**
  - ➡ constraints from CR on hadronic models improve their predictive power (better energy dependence than HEP models)
  - ➡ CR models compared to minimum bias data (best description from EPOS LHC)
  - ➡ EPOS used in detector simulations (correction, reconstruction …)
  - ➡ more reliable predictions for the Future Circular Collider (100 TeV)

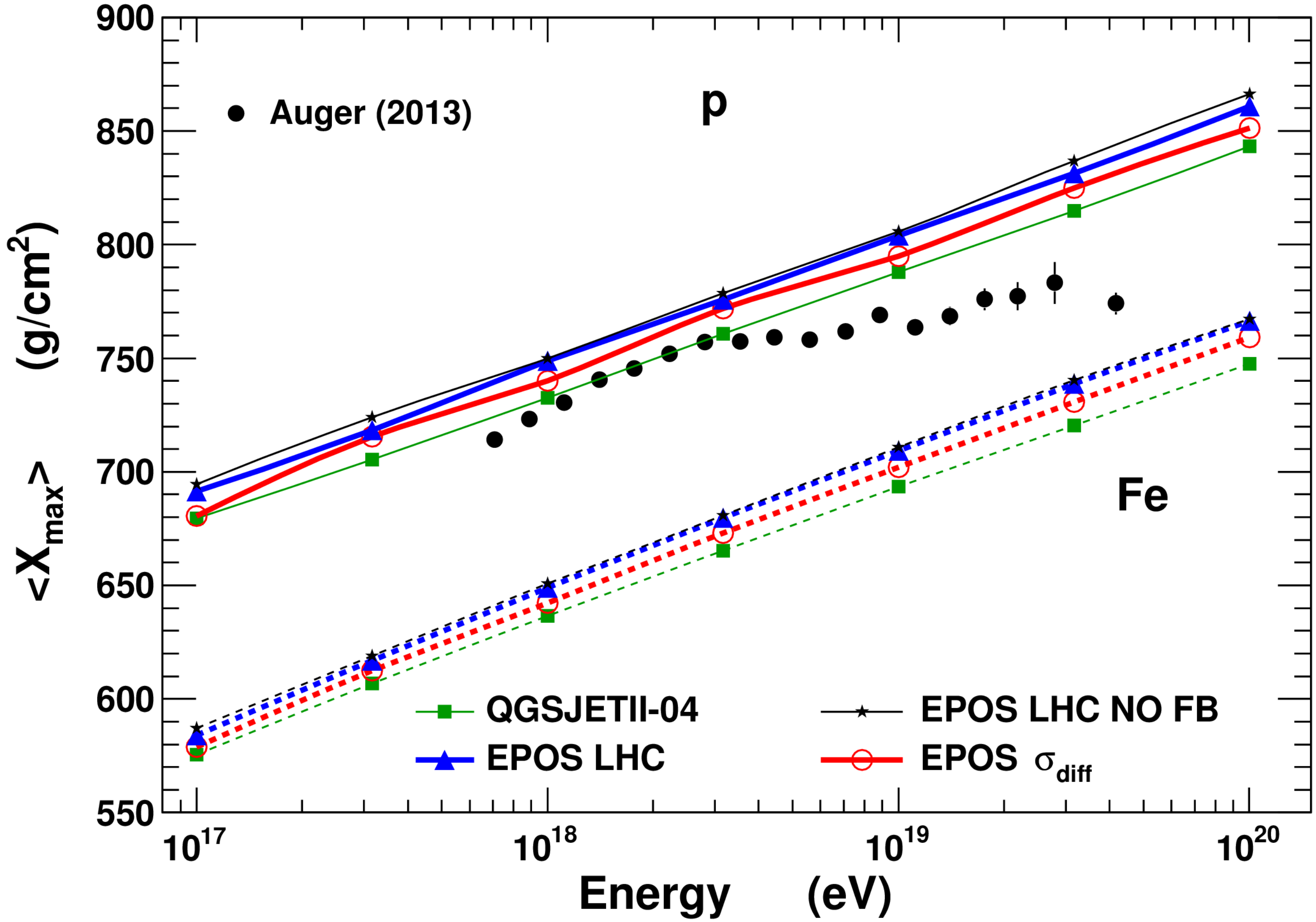
LHC data reduced the model uncertainties and exclude old models for mass composition of cosmic rays. Good description of air showers improve model predictive power for the description of min. bias LHC data and detector simulations.

Thank you !

$<X_{max}>$ with Modified EPOS

Same than in mixed models

- softer meson spectra: lower X_{max}
- forward baryons: small effect



-10 g/cm² for diff

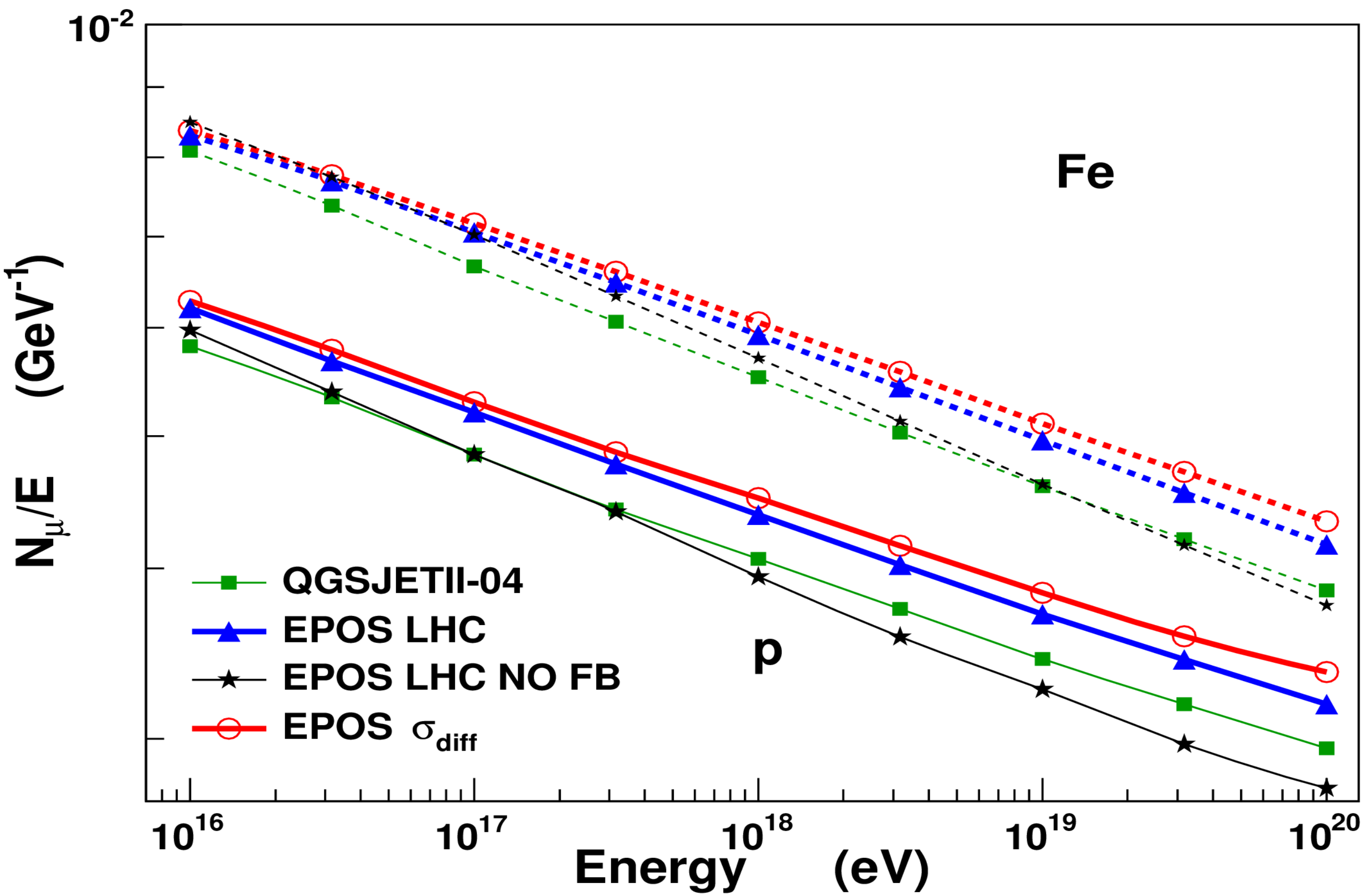
~0 g/cm² for baryons

X_{max} less sensitive to baryon spectra than to pion spectra in pion interactions

N_μ with Modified EPOS

Number of muons depends on the same parameters

- softer meson spectra: larger N_μ
- forward baryons: lower N_μ but could be compensated by ρ^0 (keep energy to produce muons but doesn't change the number of generations: lower MPD)



N_μ sensitive to baryon (less generation) and meson spectra in pion interactions

+5% for diff

-15% without forward baryons

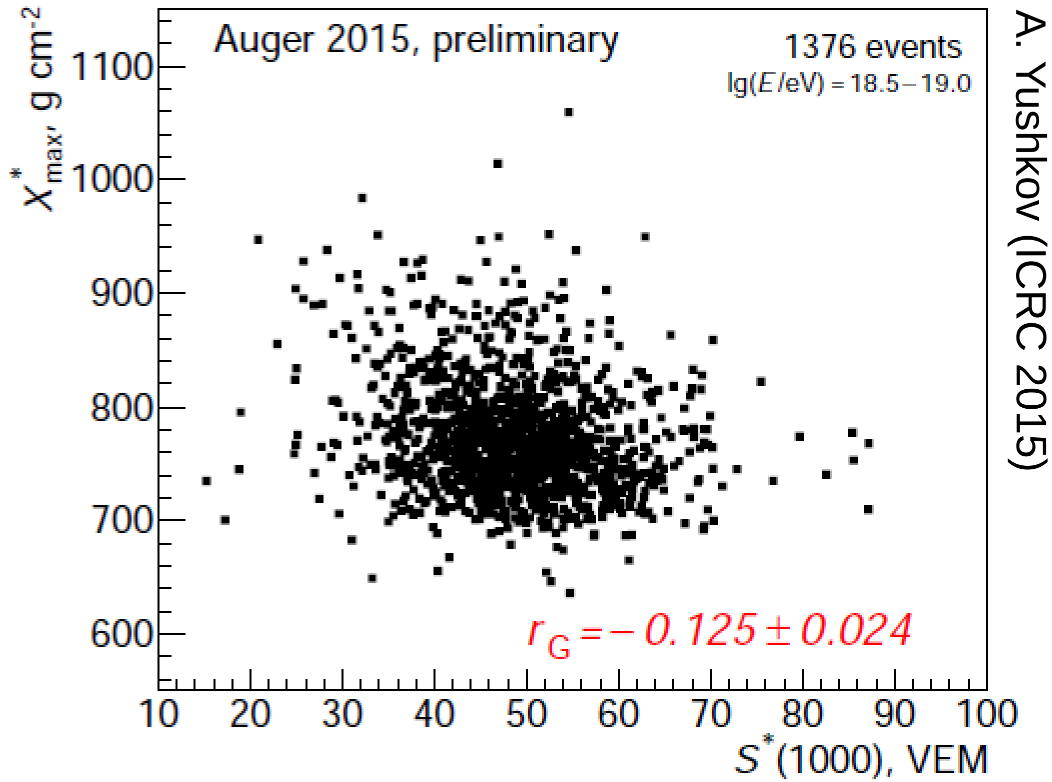
Correlation between X^*_{max} and $S^*(1000)$

- **in data correlation is significantly negative**

  ➡ $r_G = -0.125 \pm 0.024$

- **$r_G(X^*_{max}, S^*(1000))$ for p**
  - ➡ EPOS-LHC : 0.00 (5σ to data)
  - ➡ QGSJetII-04 : +0.08 (8σ to data)
  - ➡ Sibyll 2.1 : +0.07 (7.5σ to data)
- **difference is larger for other pure beams**

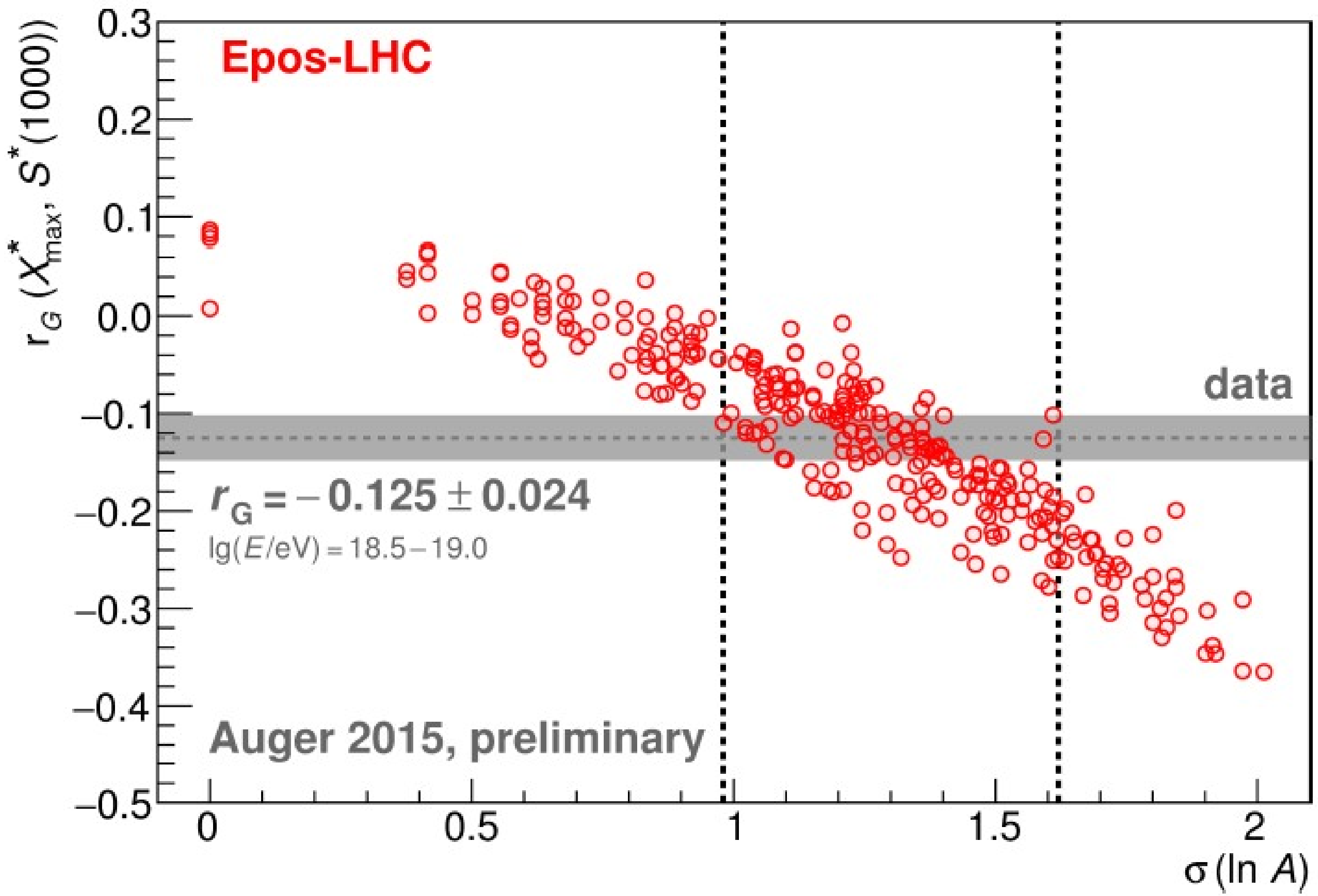
primary composition near the `ankle' is mixed



r_G - rank correlation coefficient introduced in R. Gideon, R. Hollister, JASA 82 (1987) 656

- **test of "exotic" models fails**

Dispersion of Masses in Data



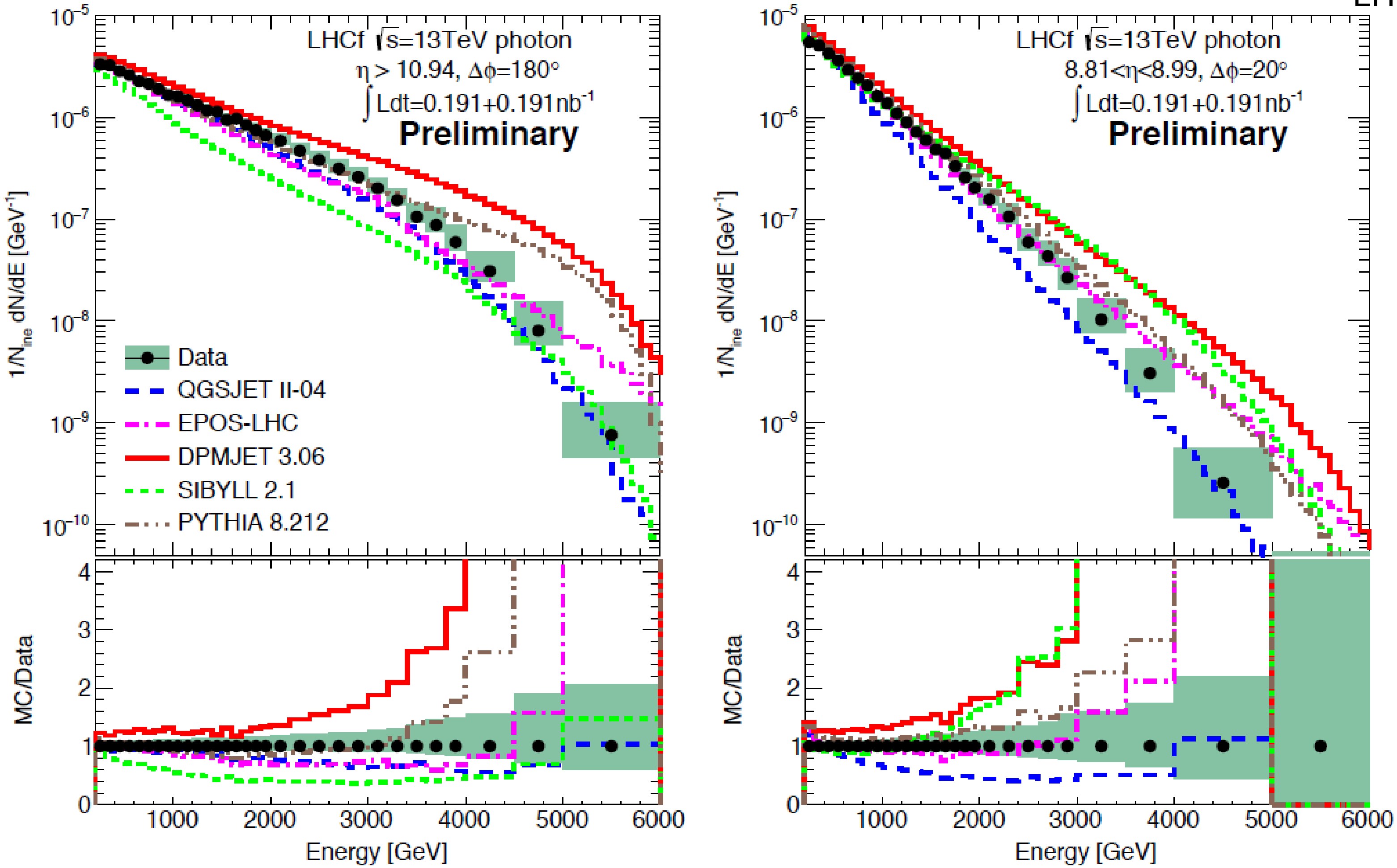
A. Yushkov (ICRC 2015)

data are compatible with 1.0 ≲ σ(ln A) ≲ 1.7

Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep X_{max}
- No model compatible with all LHCf measurements : room for improvments !
- Can p-Pb data be used to mimic light ion (Air) interactions ?

T.Sako for the LHCf collaboration



Baryons in Pion-Carbon

- **Very few data for baryon production from meson projectile, but for all :**
  - ➡ strong baryon acceleration (probability ~20% per string end)
  - ➡ proton/antiproton asymmetry (valence quark effect)
  - ➡ target mass dependence

- **New data set from NA49 (G. Veres' PhD)**
  - ➡ test π^+ and π^- interactions and productions at 158 GeV with C and Pb target
  - ➡ confirm large forward proton production in π^+ and π^- interactions but not for anti-protons
    - ◆ forward protons in pion interactions are due to strong baryon stopping (nucleons from the target are accelerated in projectile direction)
    - ◆ strong effect only at low energy

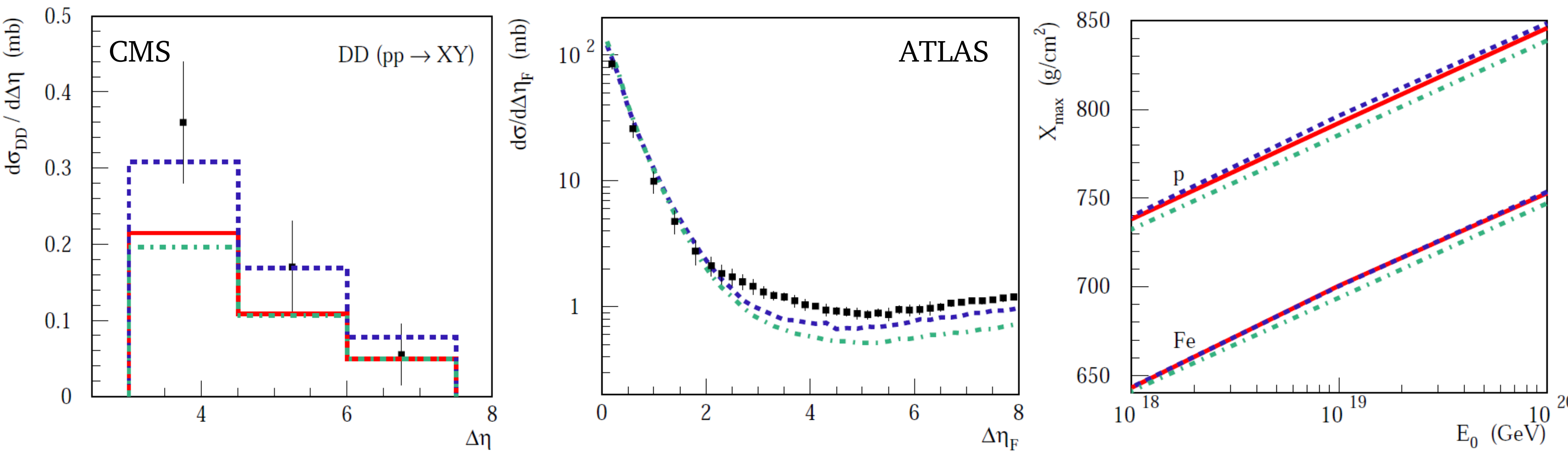
➡ EPOS overestimate forward baryon production at high energy

Diffraction measurements

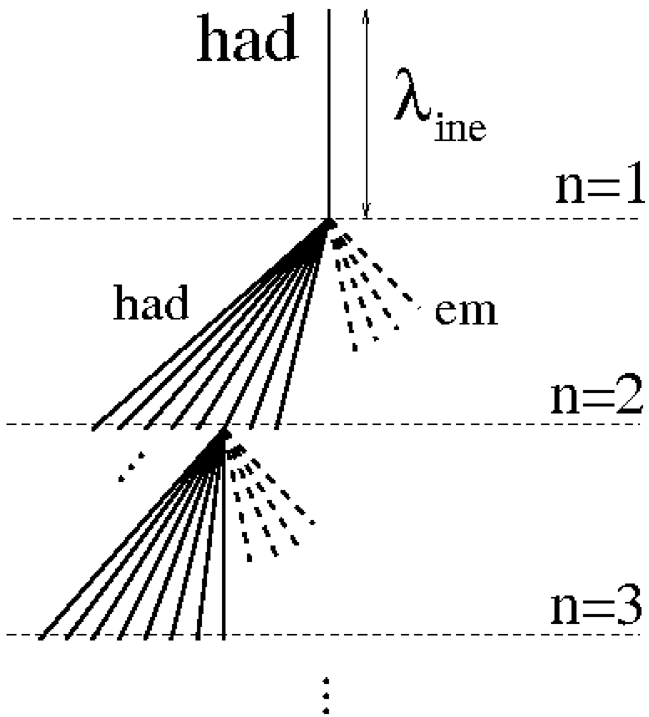
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04** **(PRD89 (2014) no.7, 074009)**
  - ➜ SD+ option compatible with CMS
  - ➜ SD- option compatible with TOTEM

M_X range	< 3.4 GeV	$3.4 - 1100$ GeV	$3.4 - 7$ GeV	$7 - 350$ GeV	$350 - 1100$ GeV
TOTEM [13, 24]	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

  - ➜ difference of ~10 gr/cm² between the 2 options



Simplified Shower Development



$$N_{tot} = N_{had} + N_{em}$$

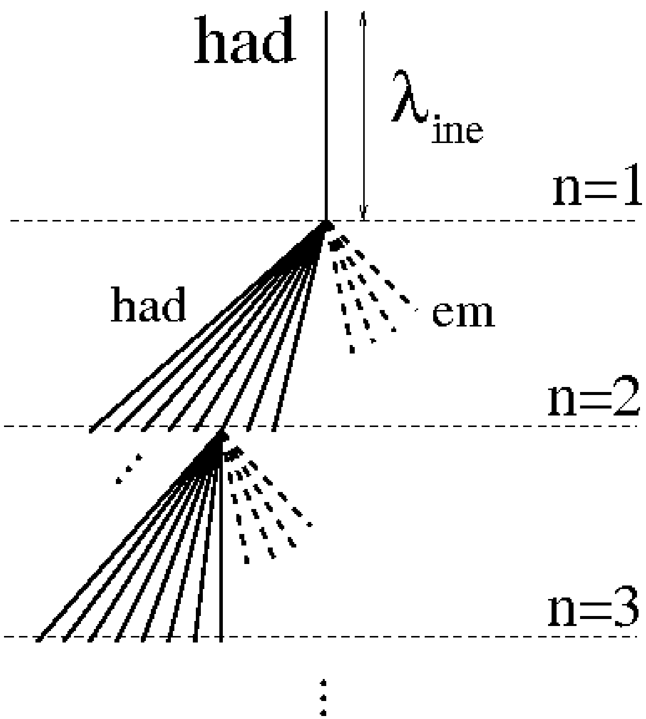
J. Matthews, Astropart.Phys. 22 (2005) 387-397

Using generalized Heitler model and superposition model :

$$X_{max} \sim \lambda_e \ln\left((1-k).E_0/(2.N_{tot}.A)\right) + \lambda_{ine}$$

- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

Toy Model for Hadronic Cascade



$$N_{tot} = N_{had} + N_{em}$$

Primary particle : hadron
Muons produced after many had. generations

N_{had}^{n} particles can produce muons after n interactions

$$N(n) = N_{had}^{n}$$

N_{tot}^{n} particles share E_0 after n interactions

$$E(n) = E_0 / N_{tot}^{n}$$

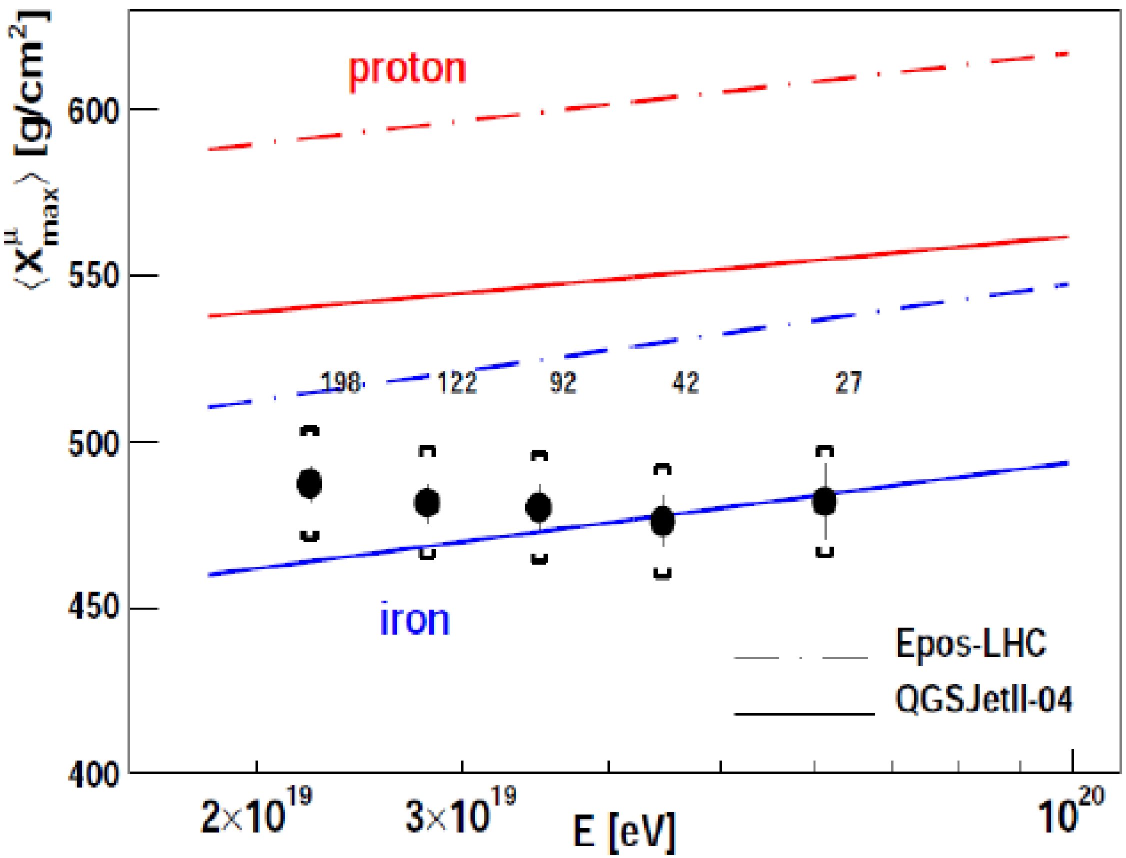
Assumption: particle decay to muon when $E = E_{dec}$ (critical energy) after n_{max} generations

$$E_{dec} = E_0 / N_{tot}^{n_{max}}$$

$$n_{max} = \frac{\ln(E_0/E_{dec})}{\ln(N_{tot})}$$

$$\ln(N_{\mu}) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

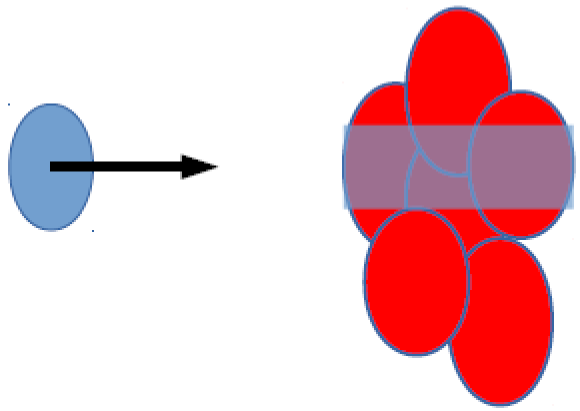
MPD and Models

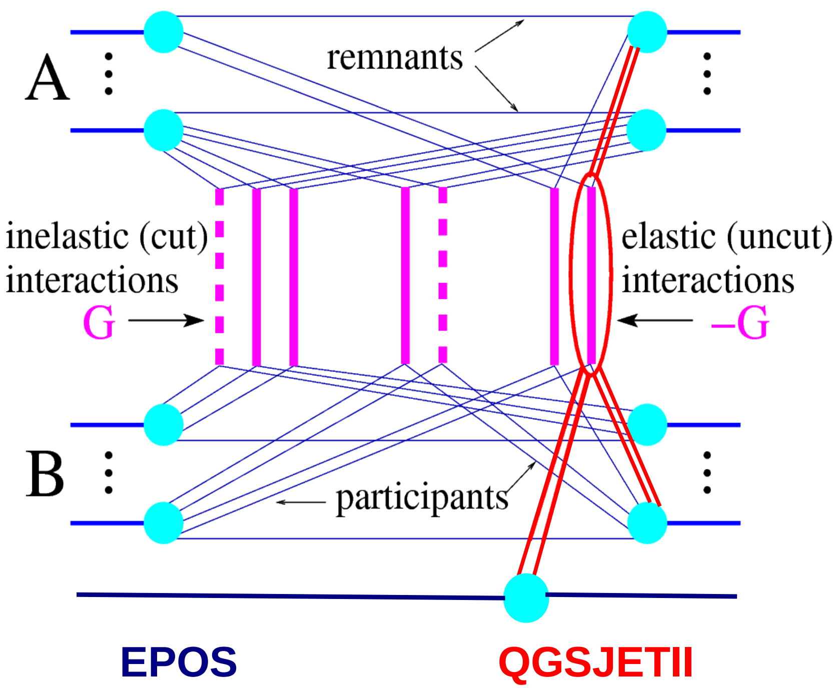


- data set: 01/2004 – 12/2012
- E > 1e19.3 eV
- zenith angles [55°,65°]
- Core distances [1700 m, 4000 m] (more muons/event)
- 481 events after quality cuts
- syst: 17 g/cm2
- Event by event resolution:
  - 100 (80) g/cm2 at $10^{19.3}$ eV for p (Fe)
  - 50 g/cm2 at 10^{20} eV

Large discrepancies between models :
EPOS LHC predictions for MPD excluded by data (outside p-Fe range)
High sensitivity of MPD to some details of hadronic interactions

Nuclear Interactions



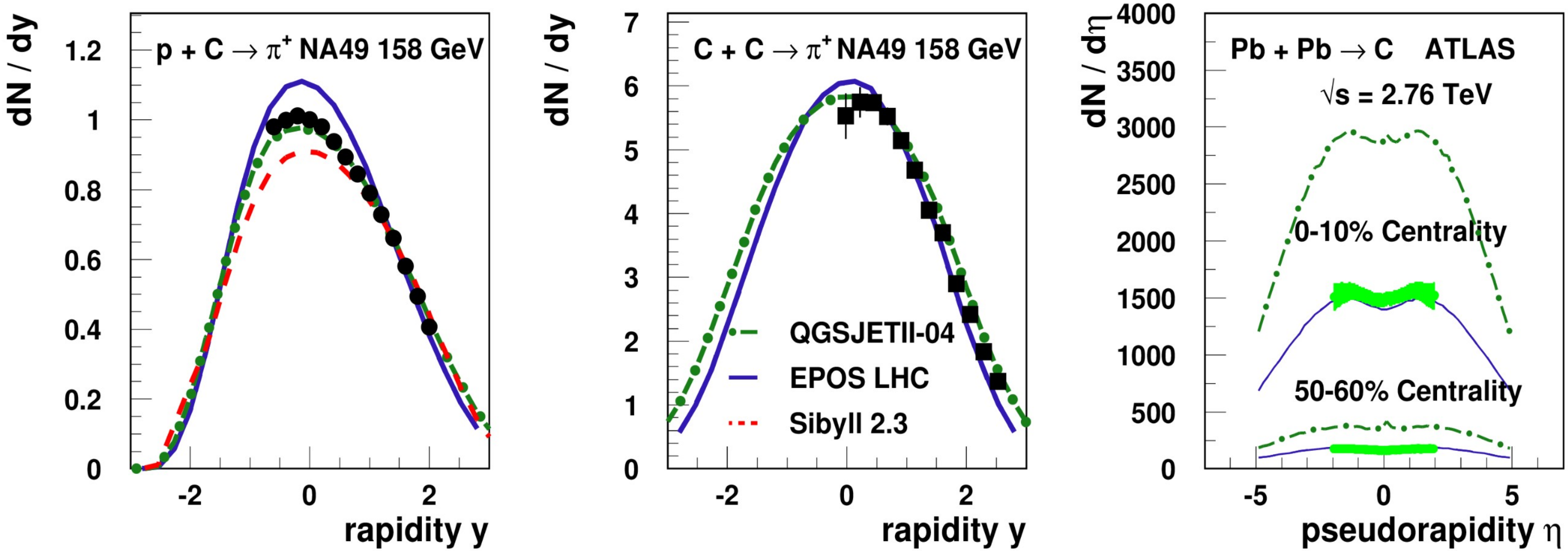


- **Sibyll**
  - Glauber for pA
    - with inelastic screening for diffraction in new Sibyll 2.3 (only nuclear effect)
  - superposition model for AA (A x pA)
- **QGSJETII**
  - Pomeron configuration based on A projectiles and A targets
  - Nuclear effect due to multi-leg Pomerons
- **EPOS**
  - Pomeron configuration based on A projectiles and A targets
  - screening corrections depend on nuclei
  - final state interactions (core-corona approach and collective hadronization with flow for core)

Light Ion Data

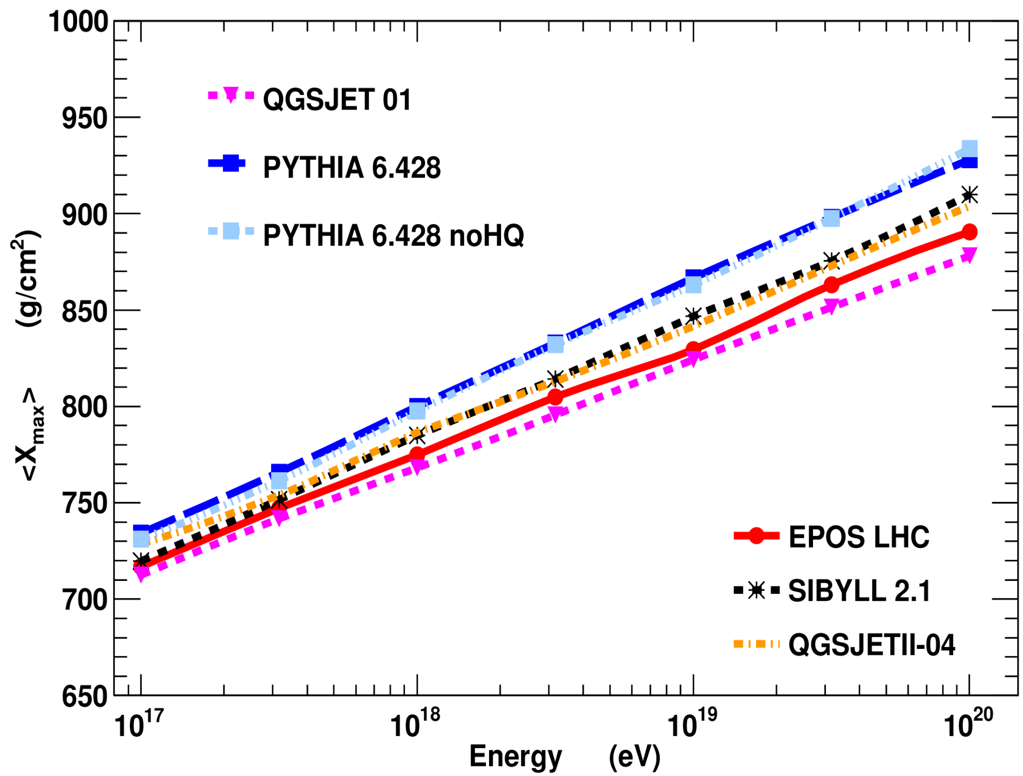
Very few data to compare with all CR models :

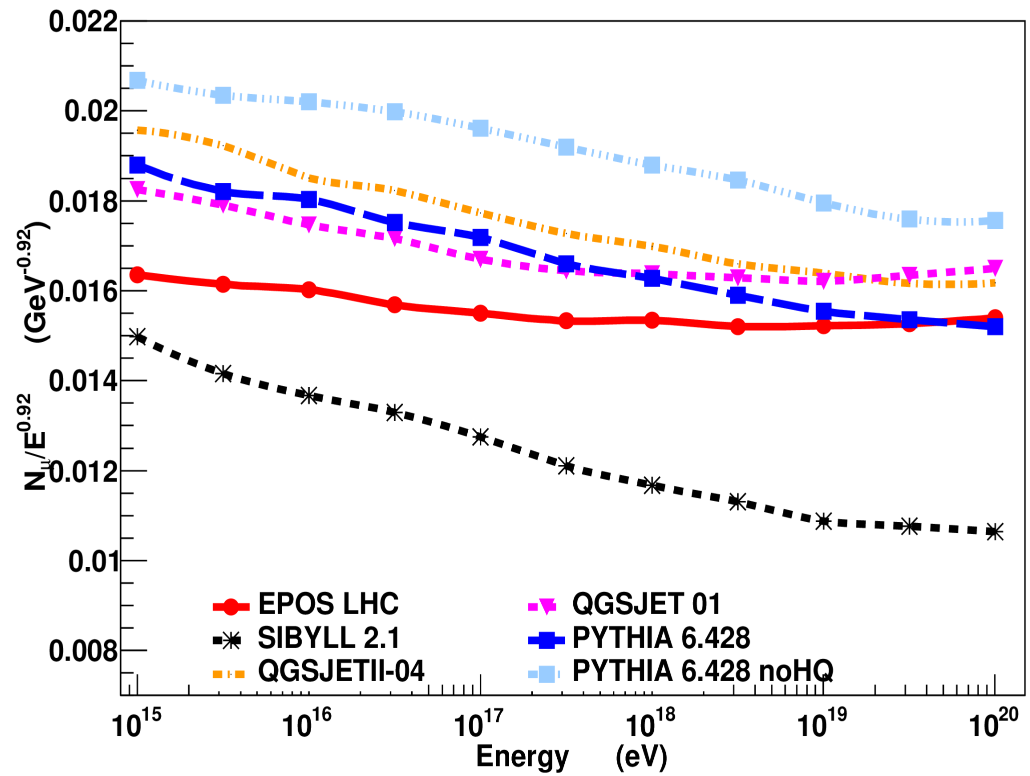
- ➡ strong limitations in Sibyll (projectile up to Fe only and target up to O !)
- ➡ no final state interactions exclude heavy nuclei for QGSJETII
- ➡ no light ion data at high energy



Tests using hydrogen atmosphere

- **Work done with David D'Enterria (CERN) and Sun Guanhao**
  - ➜ test of Pythia event generator
- **Modified air shower simulations with air target replaced by hydrogen**
  - ➜ for interactions only (no change in density)
  - ➜ no nuclear effect





Hadronic Interaction Models for EAS

(HDPM)

Old generation : (SIBYLL 2.1 QGSJET01 DPMJET 2.55 VENUS) (<2001)

All Glauber based

But differences in hard, remnants, diffraction …

Engel et al.

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New (!) generation : (QGSJET II-03) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

Ostapchenko

Pierog & Werner

Riehn & Engel

Fedinitch & Engel

LHC inspired : SIBYLL 2.3c QGSJET III (?) DPMJET III EPOS 3 (2017-)

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

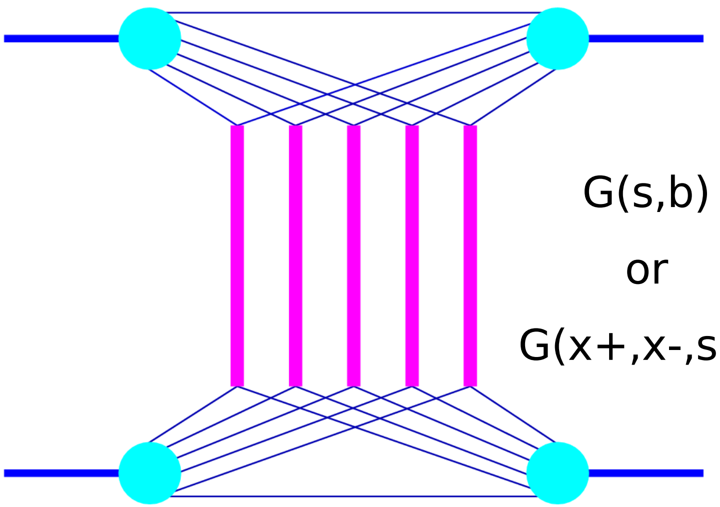
- update with LHC results

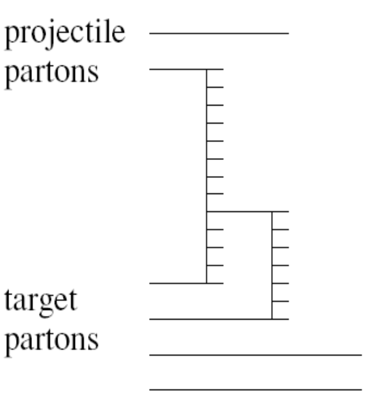
-fix high energy

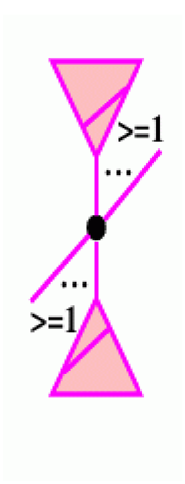
Motivation :

- binary scaling in hard probes

Cross Section and Multiplicity in Models



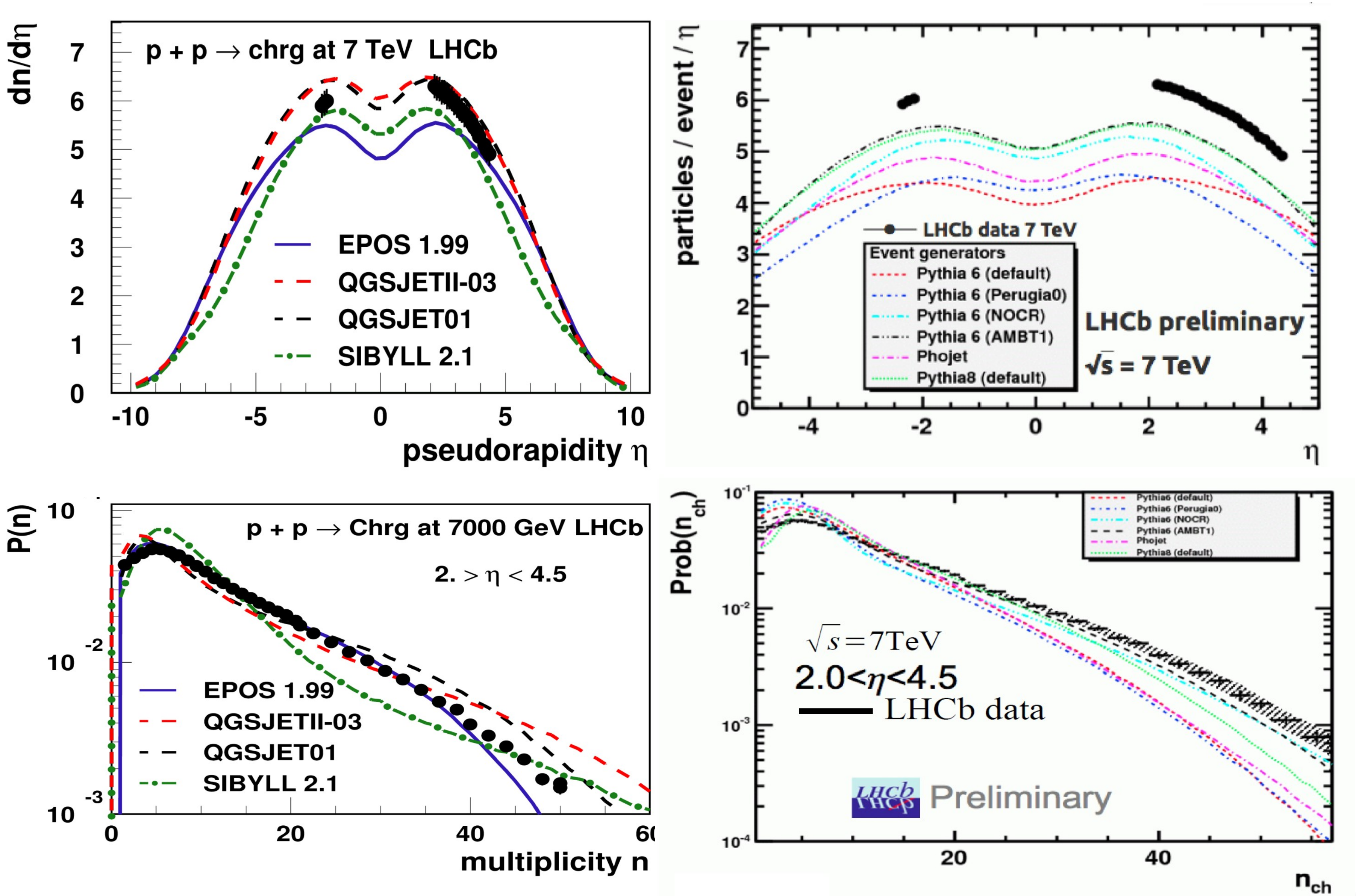




- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET, SIBYLL and DPMJET (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets with cutoff in SIBYLL and DPMJET
  - Same hard Pomeron (DGLAP convoluted with soft part : no cutoff) in QGSJET and EPOS but
    - Generalized enhanced diagram in QGSJET-II
    - Simplified non linear effect in EPOS
      - Phenomenological approach

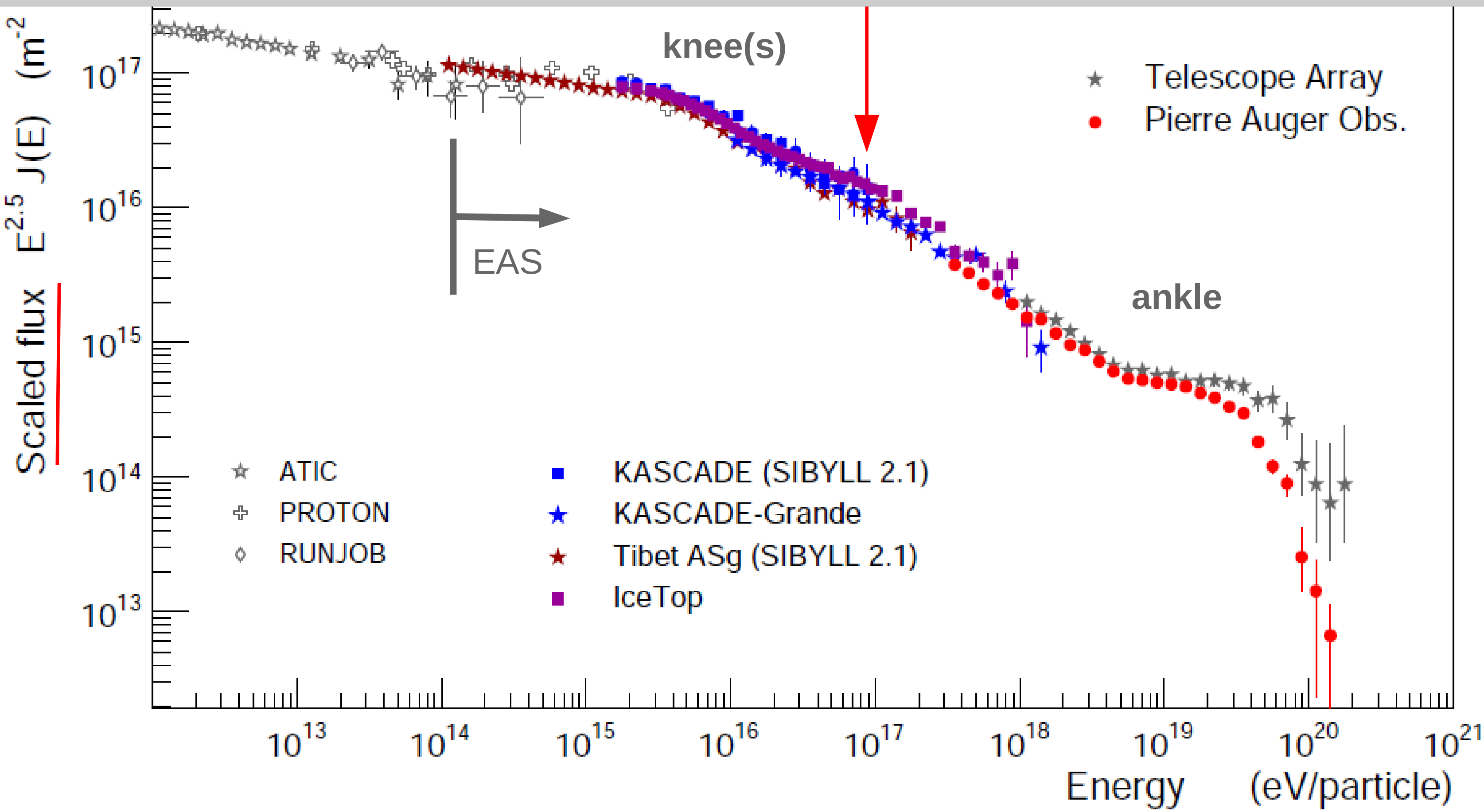
Cosmic Ray vs High Energy Physics

Models used for EAS had better LHC predictions than HEP MC



Energy Spectrum

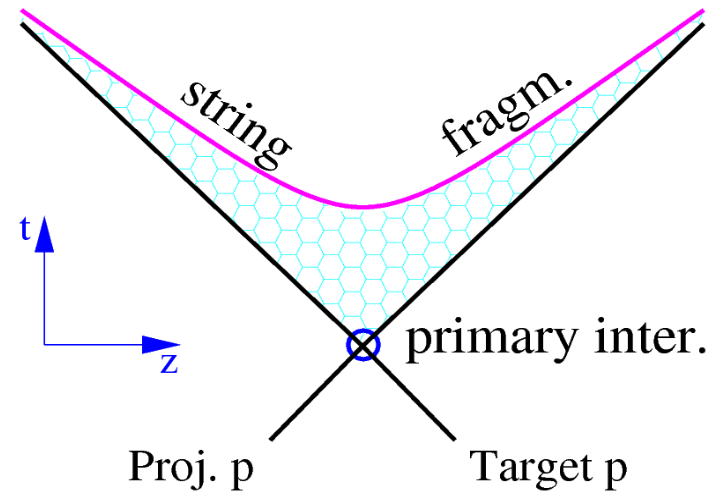
LHC data well bracketed by models used for CR analysis : reliable simulations up to LHC energy : knee energy … Spectral shape not due to a change in hadronic interactions : change in the mass composition !



R. Engel (KIT)

Post-LHC Models

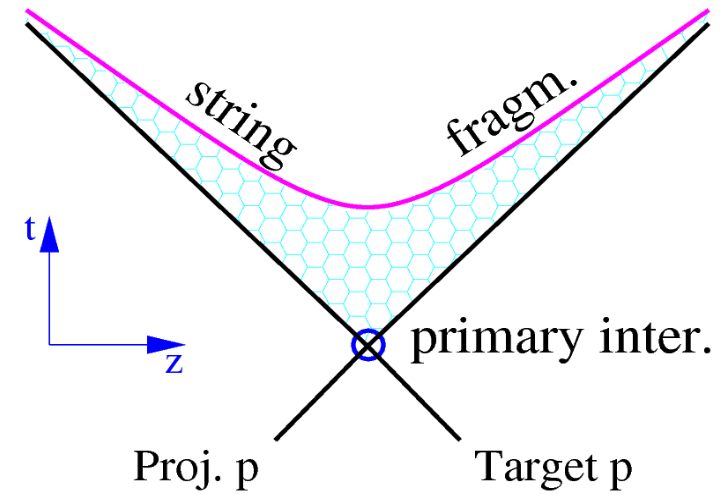
- **Sibyll 2.1 to Sibyll 2.3c :**
  - ρ^0 forward production in pion interaction
  - re-tuning some parameters for LHC and lower energies
  - improved remnants and baryon production
  - charm production



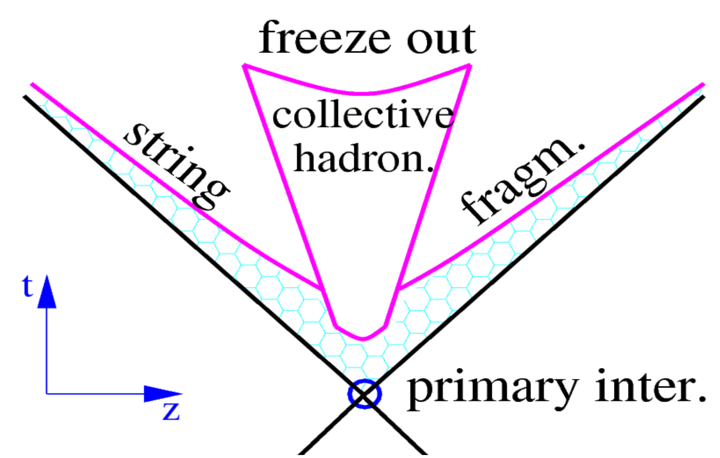
- **DPMJETIII.06 to DPMJETIII.17-1**
  - improved treatment of very high energy
  - improved baryon distributions at low energy

Post-LHC Models

- **QGSJETII-03 to QGSJETII-04 :**
  - loop diagrams
  - ρ^0 forward production in pion interaction
  - re-tuning some parameters for LHC and lower energies



- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow (collective effect) calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies

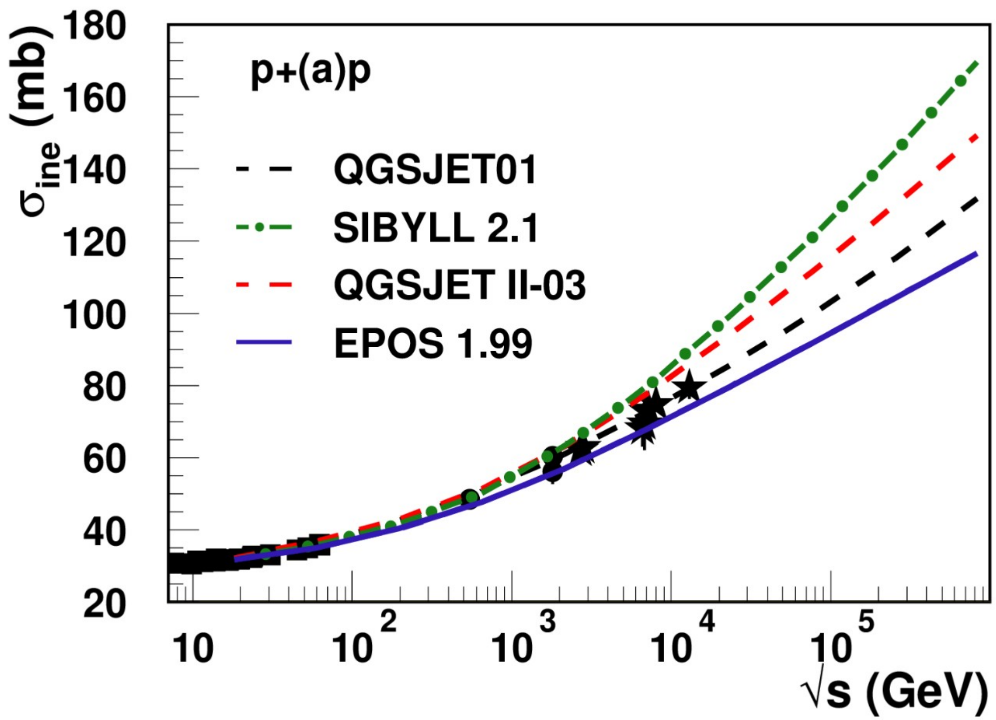


No direct influence of collective effects on EAS simulations seen but important to compare to LHC and set parameters properly (<pt>, ...).

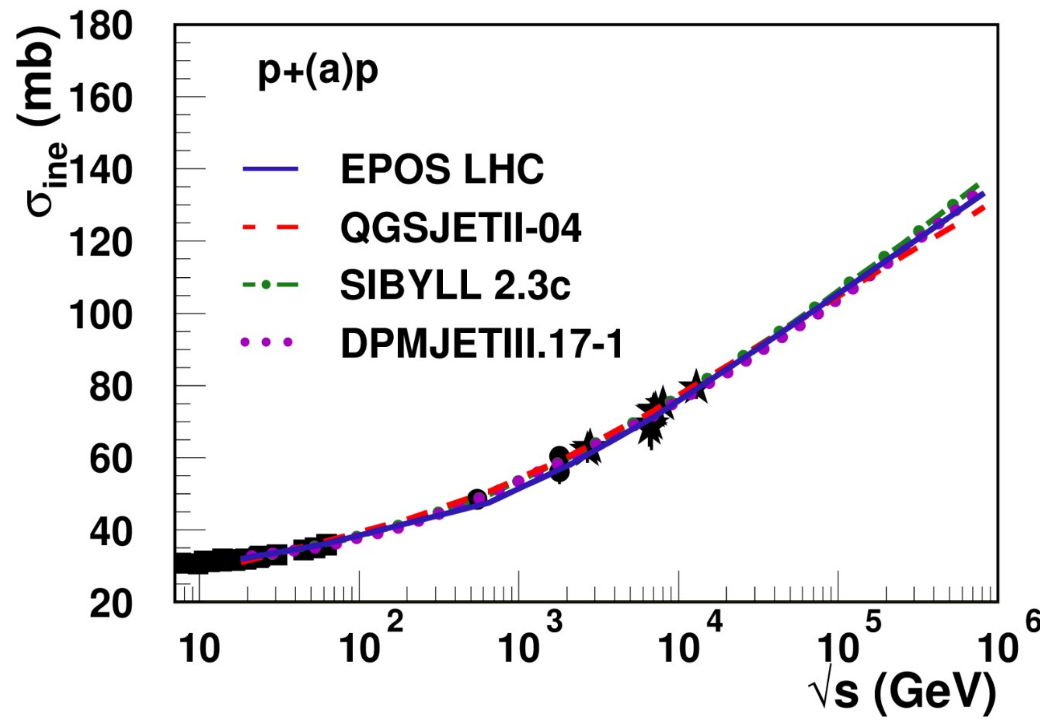
Cross Sections

- Same cross section prediction at pp level and low energy (data for tuning)
- extrapolation to high energy looks settled
  - different amplitude and scheme
    - same extrapolations

Pre - LHC



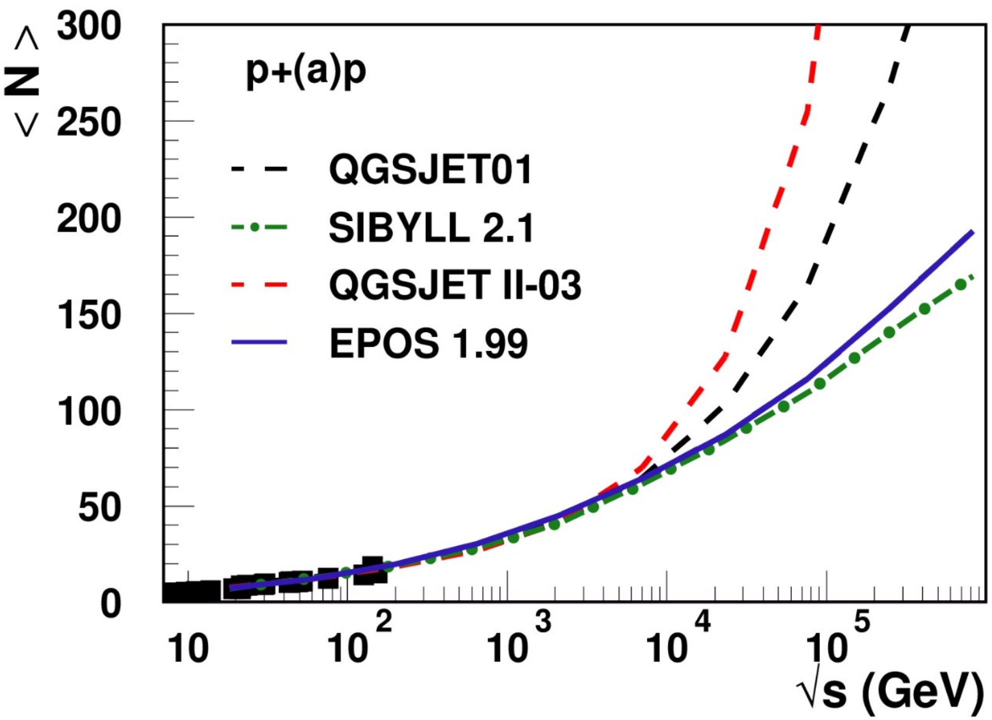
Post - LHC



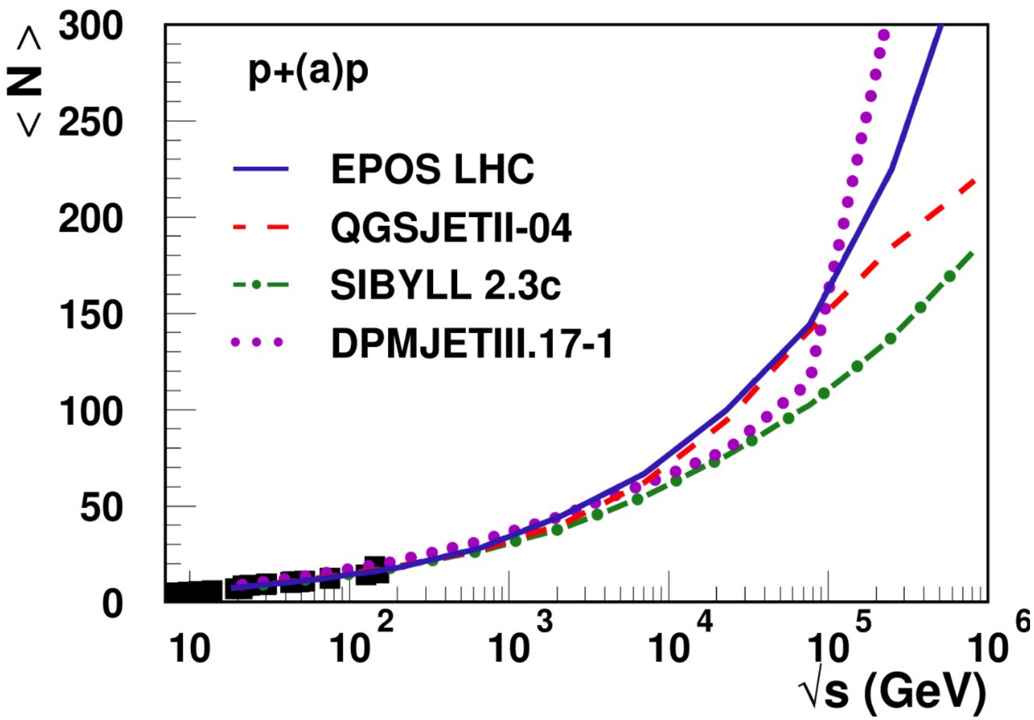
Multiplicity

- Multiplicity fixed by data up to 900 GeV
- extrapolation to high energy is still model dependent ?

Pre - LHC



Post - LHC

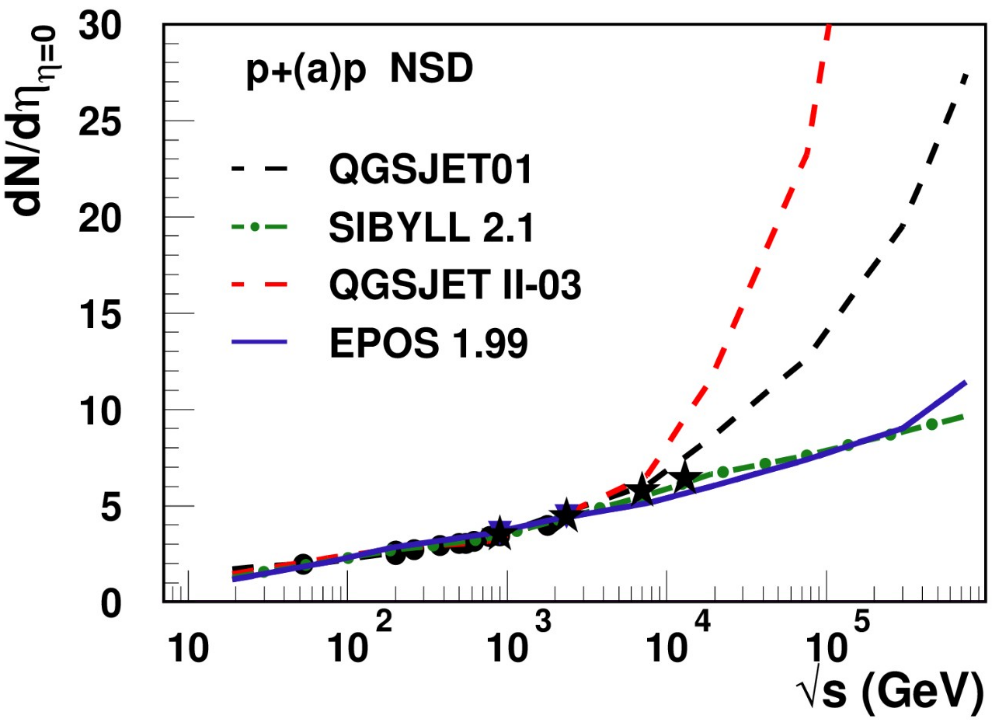


Multiplicity at mid-rapidity

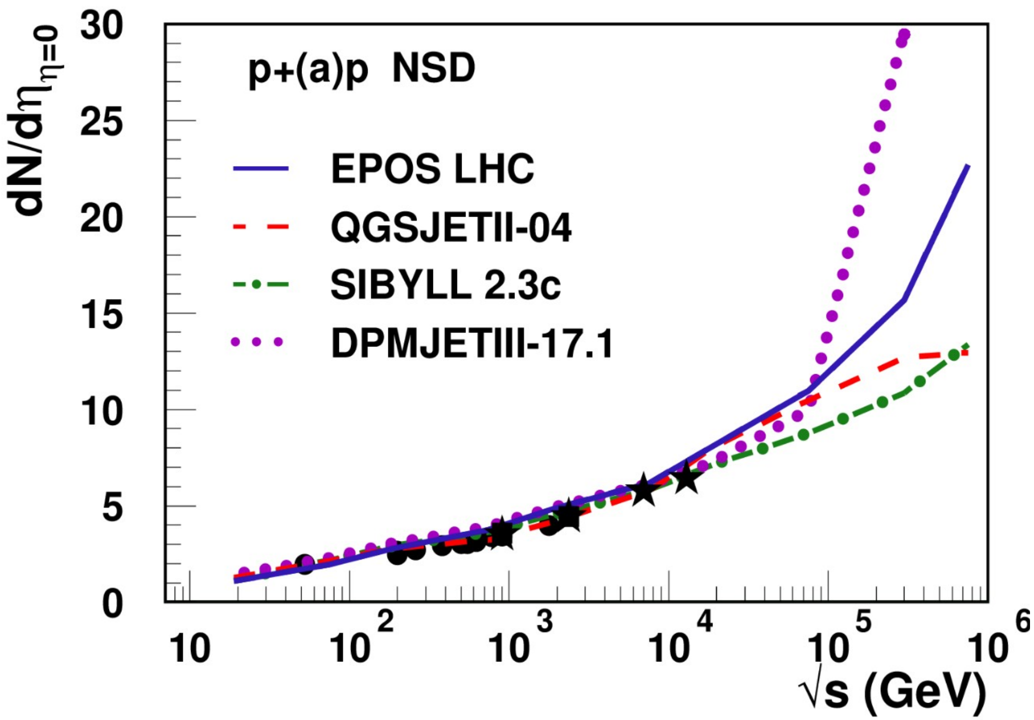
Looking at particles produced perpendicular to the beam axis :

- multiplicity fixed by data up to 13 TeV
- extrapolation to high energy less model dependent after LHC
- QGSJET01 and QGSJETII-03 extrapolation excluded

Pre - LHC



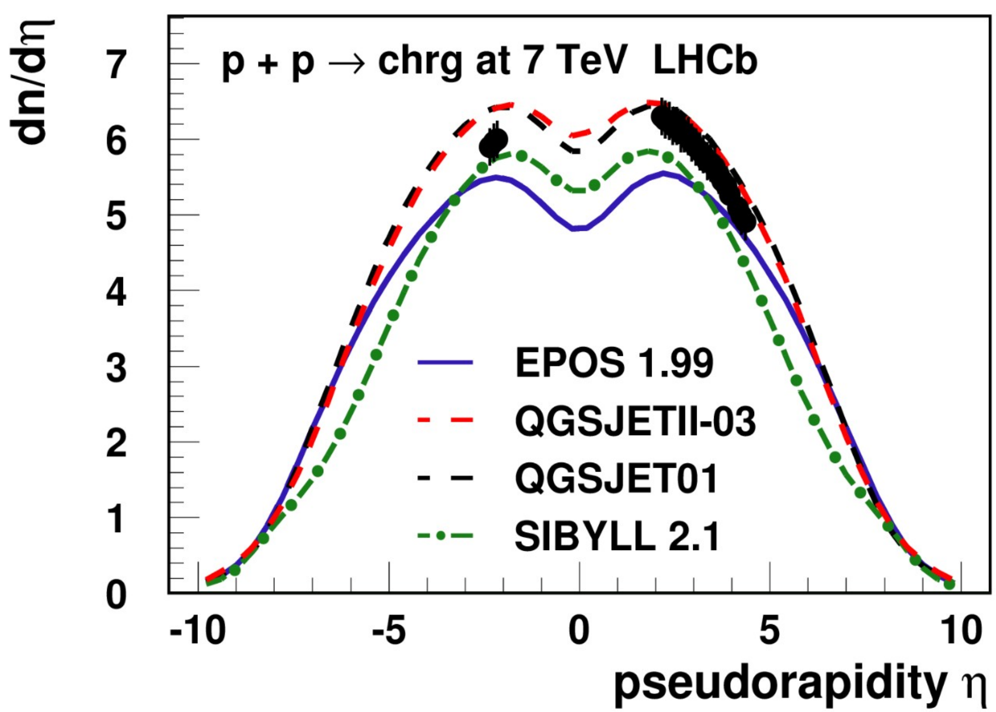
Post - LHC



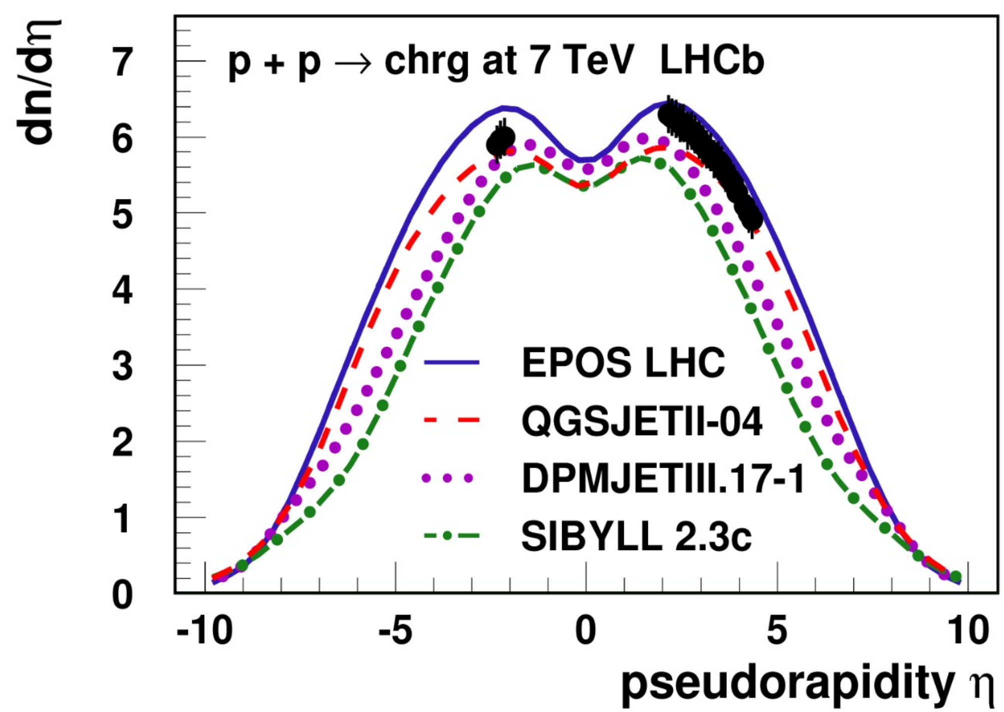
Pseudorapidity

- Difference between mid-rapidity and full multiplicity coming from the width of the pseudorapidity distributions
- From LHC data
  - DPMJETIII.17-1 and SIBYLL 2.3c too narrow
  - QGSJETII-04 ~ OK
  - EPOS LHC a bit too large

Pre - LHC



Post - LHC

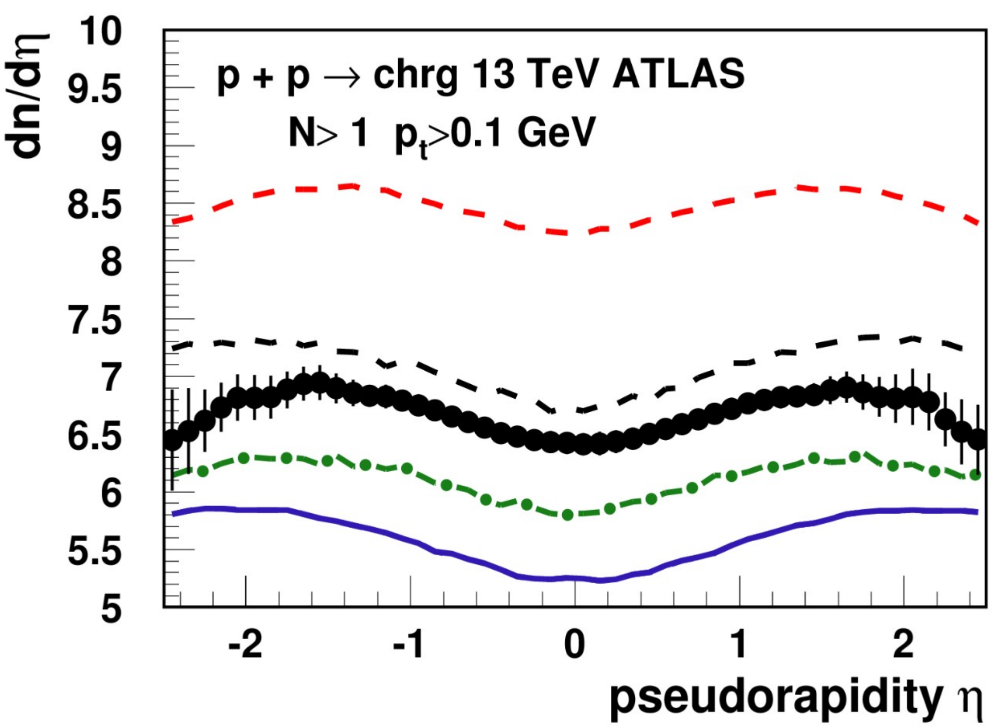


Test of Models vs Accelerator Data

- From LHC data
  - All pre-LHC models extrapolation excluded
  - DPMJETIII.17-1 and SIBYLL 2.3c underestimate multiplicity
  - QGSJETII-04 and EPOS LHC ~ OK (and similar to Pythia 8)

QGSJET01
SIBYLL 2.1
QGSJET II-03
EPOS 1.99

Pre - LHC



Post - LHC