Impact of LHC data on UHECR physics

UHECR 2018

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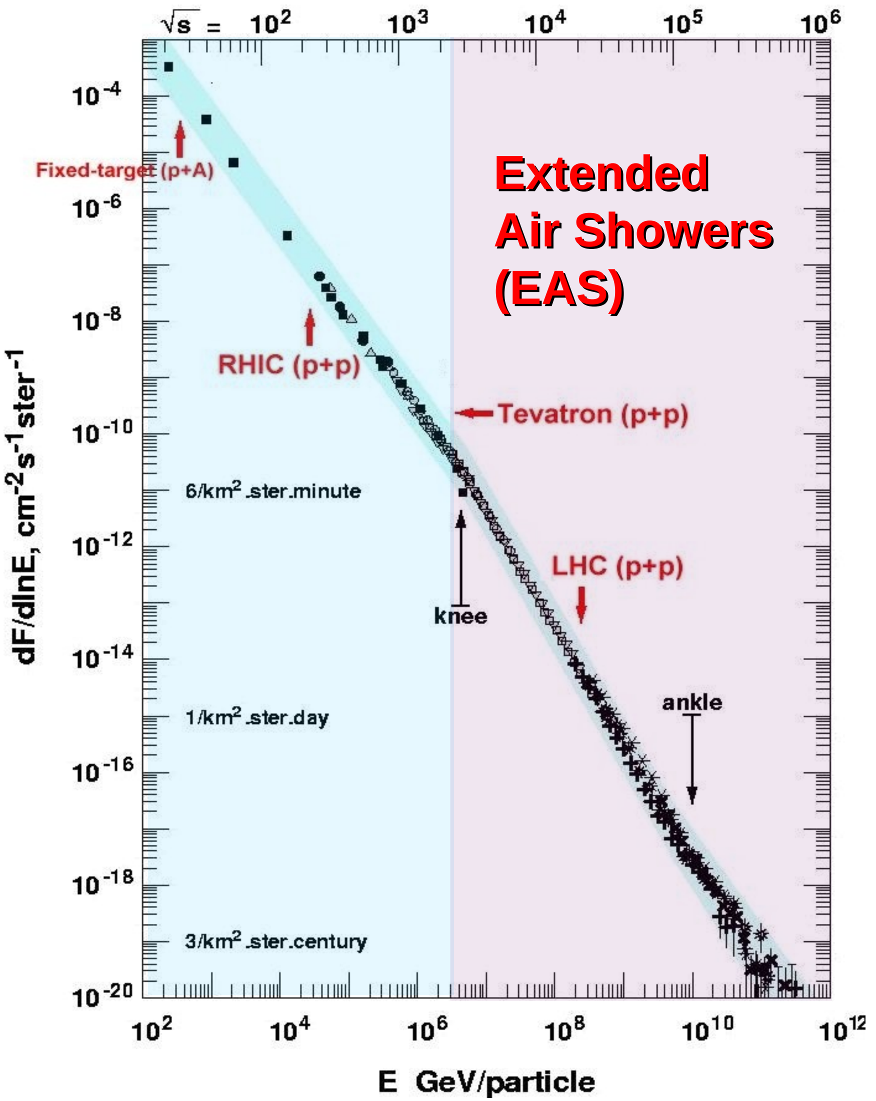
CERN

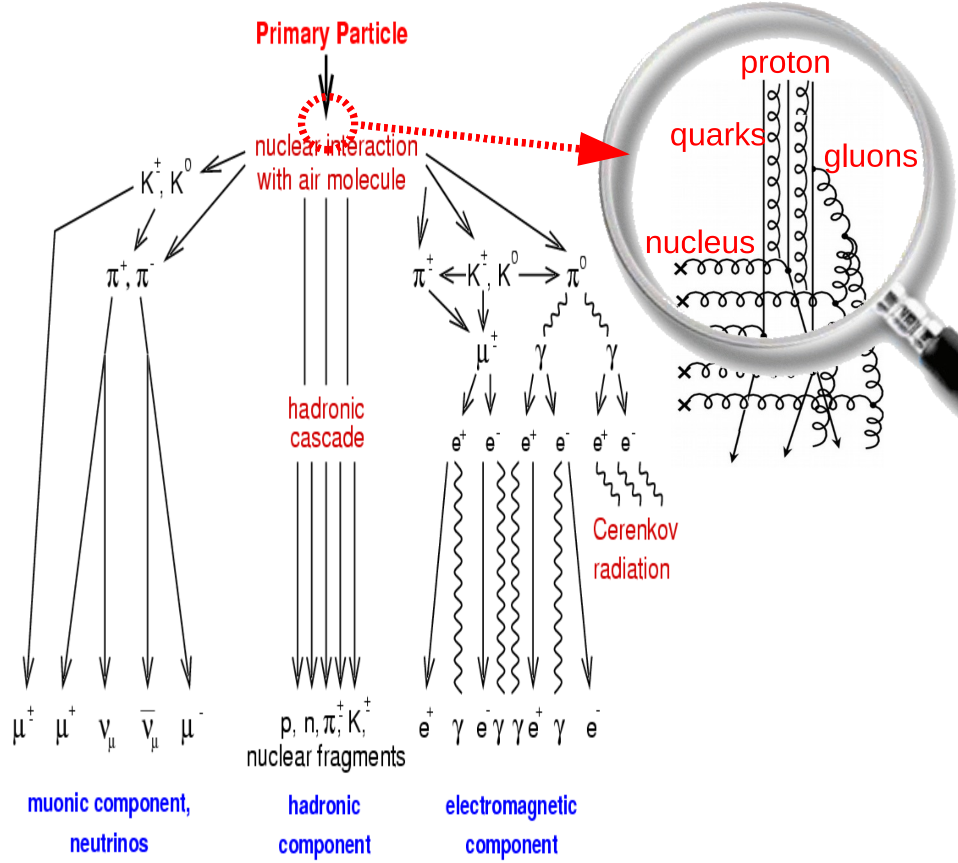
Mostly based on: D. d'E, Engel, Pierog, Ostapchenko, Werner, Astropart. Phys. 35 (2011) 98
D. d'E, T. Pierog, G. Sun, arXiv:1809.06406

Ultra High Energy Cosmic-Rays via EAS

- CR energy & identity for $E_{CR}=10^{15}$–10^{21} eV determined using earth atmosphere as a "calorimeter" & comparing shower to hadronic MCs:

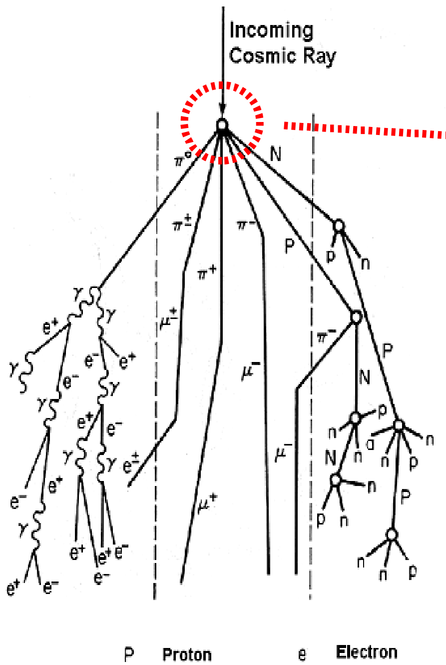


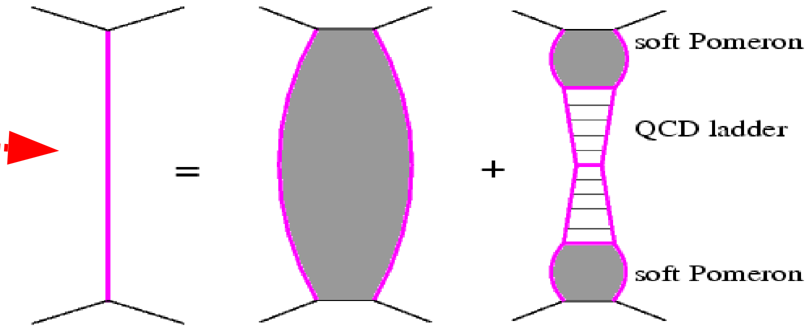
- CR+Air collisions: QCD interactions at c.m. energies up to $\sqrt{s}_{GZK}$~400 TeV



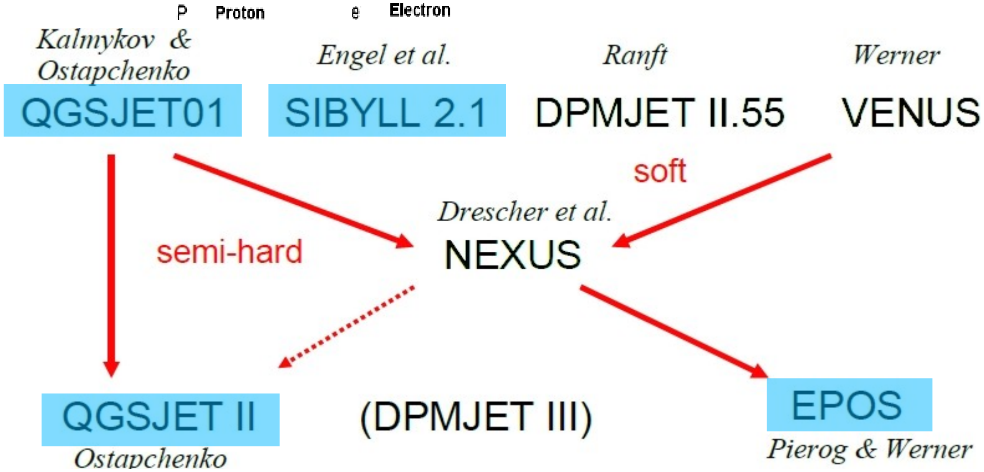
Hadronic Monte Carlos for UHECR

- Primary hadronic collisions (p-p, p-A) = Complex QCD interactions:





- Theoretical basis :
  - Reggeon Field Theory: soft, diffraction, eikonal (multi)parton ladders (pA, AA)
  - pQCD LO: “(cut) hard Pomerons”
  - Parton saturation in PDFs.



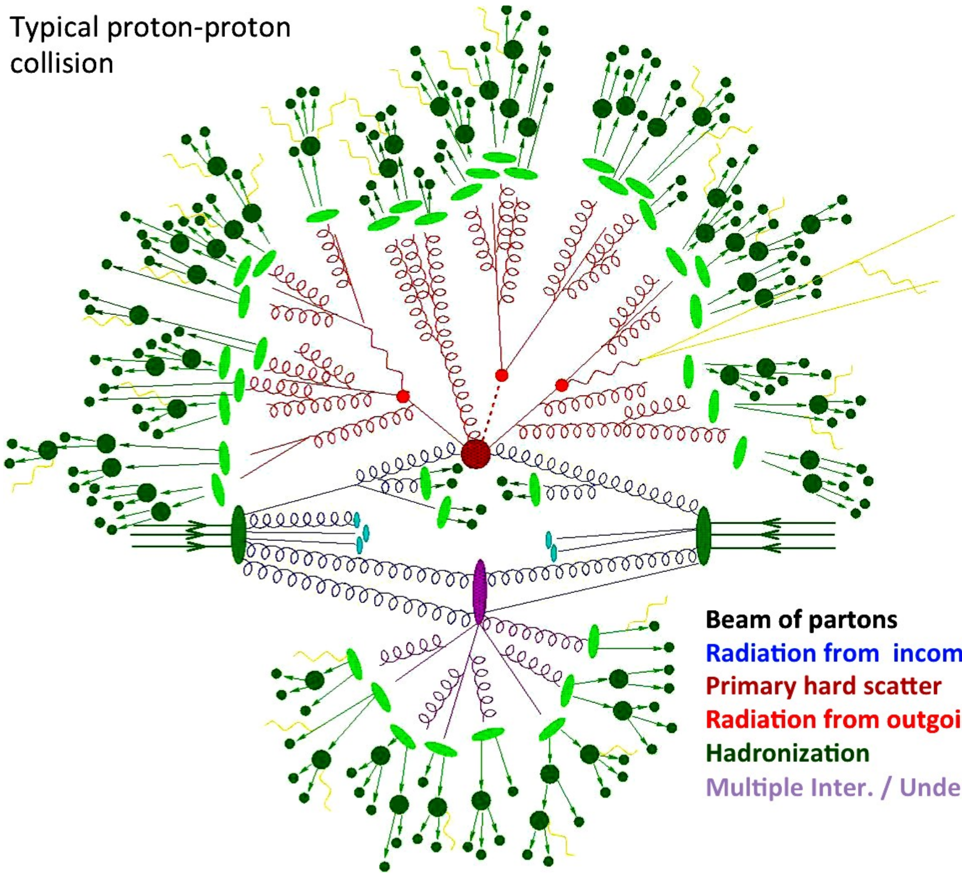
(T.Pierog, 2009)

- Non-pQCD modeling:
  - String hadronization.
  - Beam-remnants.
- Model parameters:
  - O(20-100) parameters tuned to multiple accelerator/ collider data.

Hadronic Monte Carlos for LHC collisions

- Proton-proton collisions in PYTHIA, HERWIG,...

Typical proton-proton collision



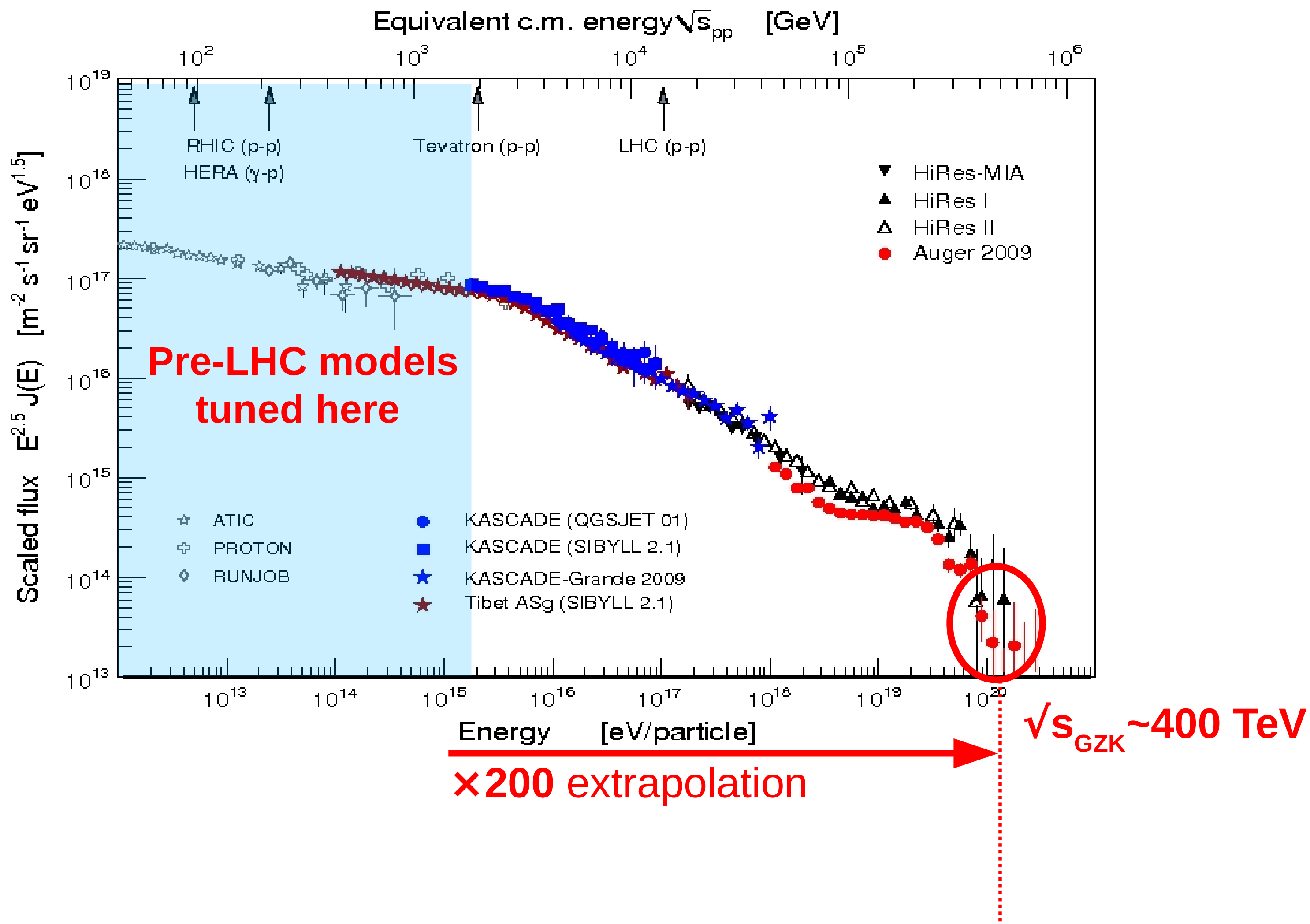
- Theoretical basis:
  - Perturbative QCD (LO + K-factor): PDFs, matrix-elements.
  - Leading-log parton shower.
  - Multiparton interactions.
  - Saturation-based infrared p_T cut-off

- Non-pQCD modeling:
  - String fragmentation (Lund model).
  - Beam-remnants.
  - Diffraction.

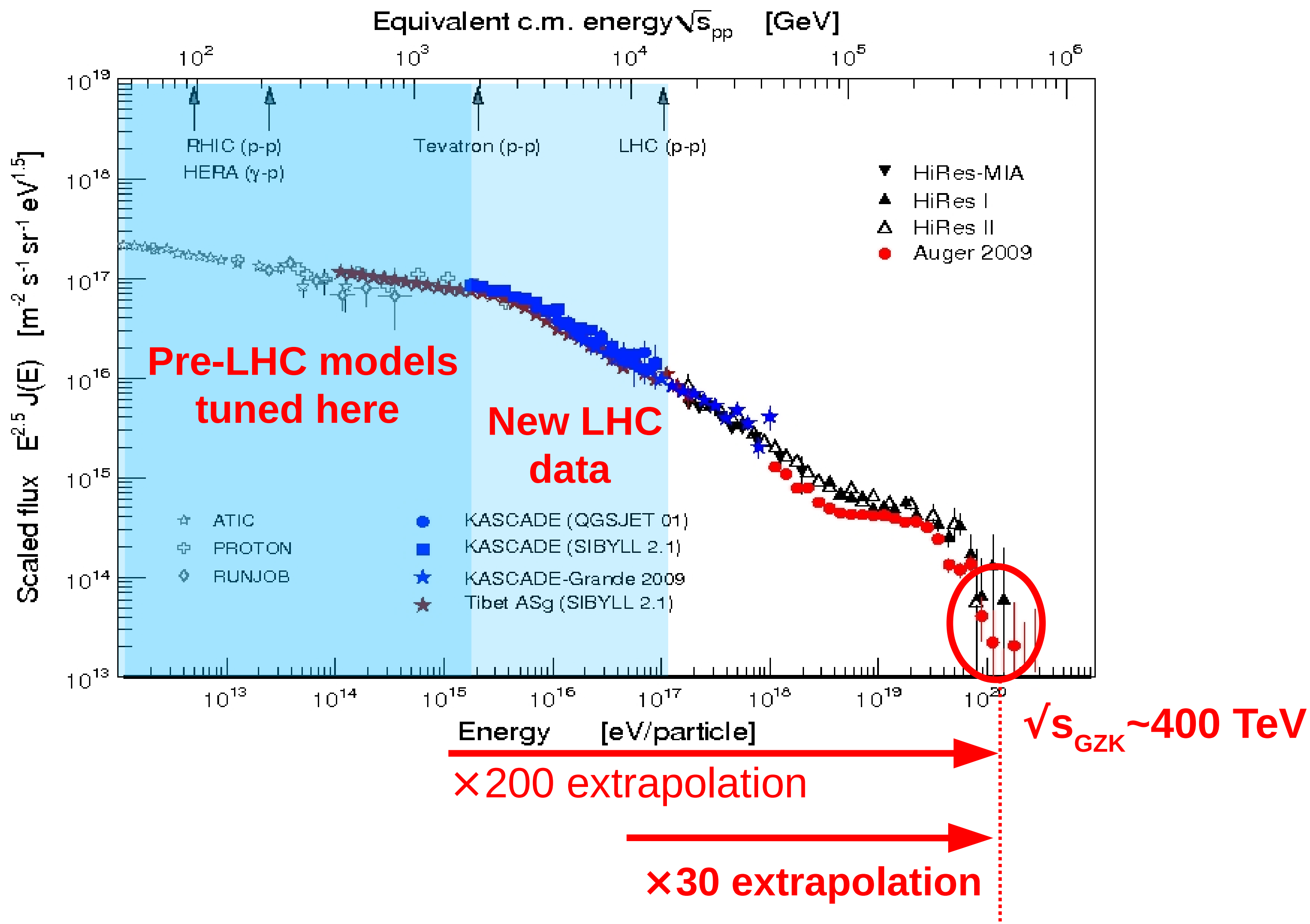
- Model parameters:
  - *O*(100) parameters
  - Multiples tunes to many collider measurements.

- No p-A, A-A available (yet). But PYTHIA comparable to EPOS/QGSJET via:
  - Constructing a CONEX hydrogen atmosphere with same density as air.
  - Running PYTHIA-6 proton-hydrogen with varying MC tunes to LHC data.

Hadronic MCs tuning with (pre-LHC) collider data



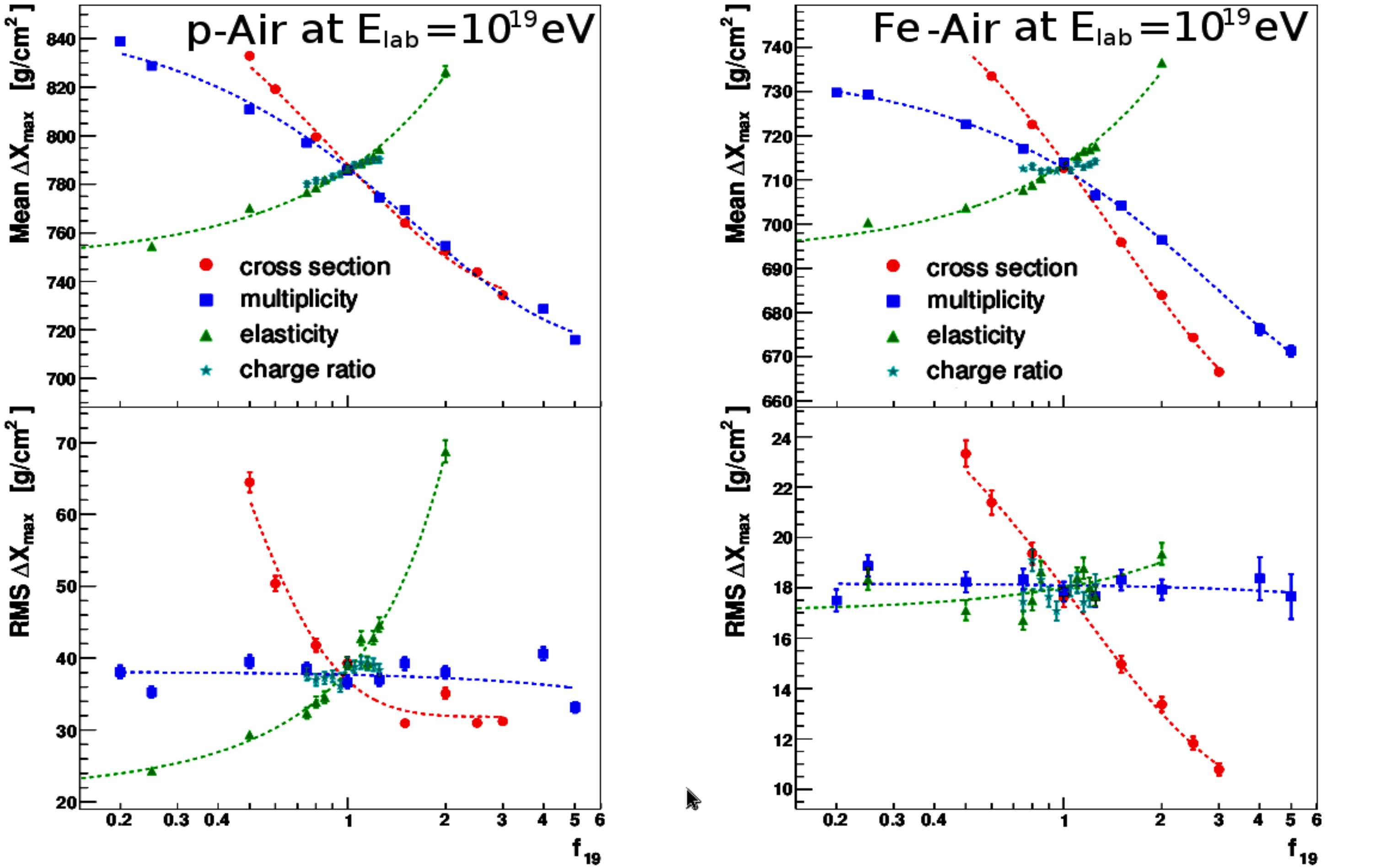
Hadronic MCs tuning with LHC data



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

Key MC parameters for EAS development

- Average shower max. depth (X_{max}) & its fluctuations (RMS–X_{max}) are key observables to determine primary CR energy & identity (p, Fe)
- Chiefly depend on the p-p inel. cross section, multiplicity, elasticity in the MC:

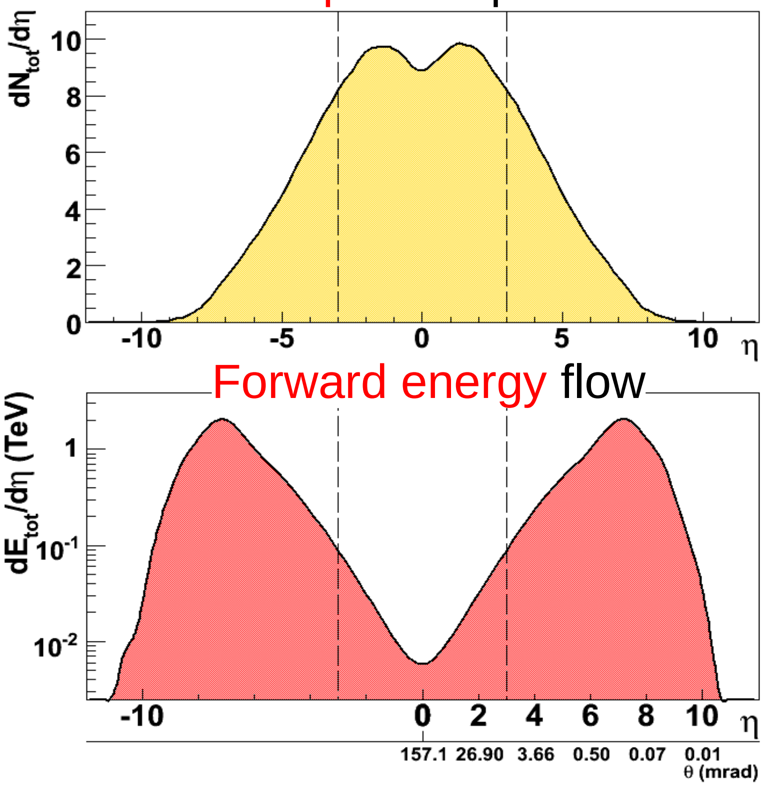


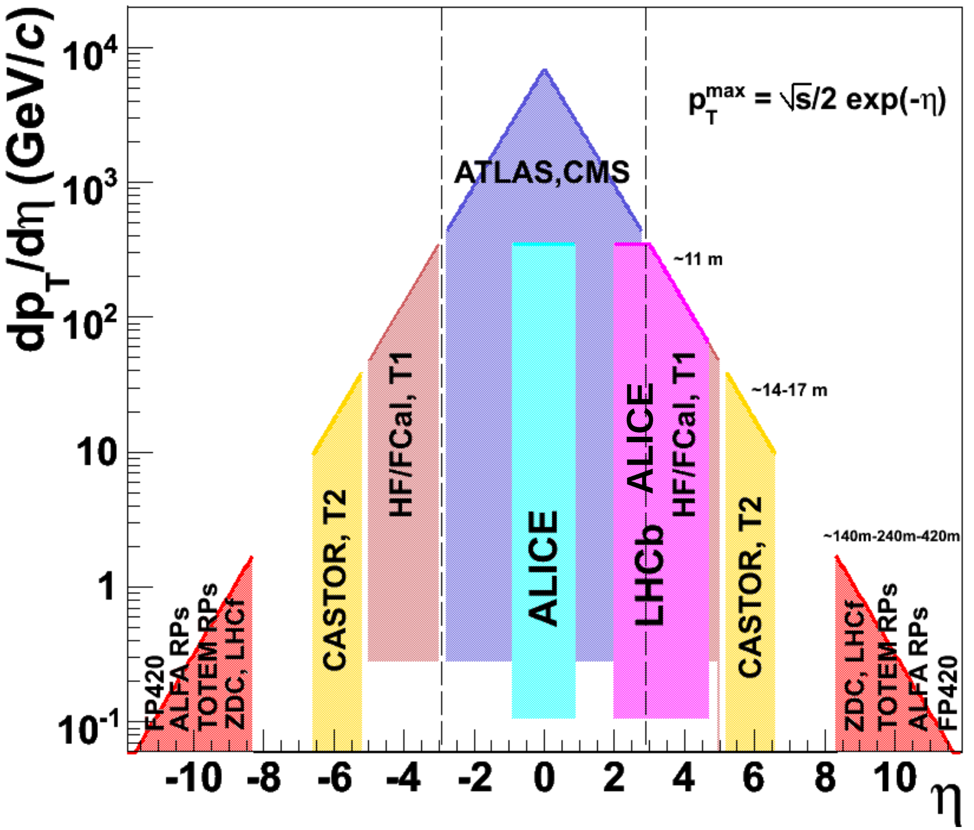
[Ulrich, Engel, Unger, Phys.Rev. D83 (2011) 054026]

LHC experiments: (p_T,η) acceptance

p-p @ 14 TeV

Central particle production

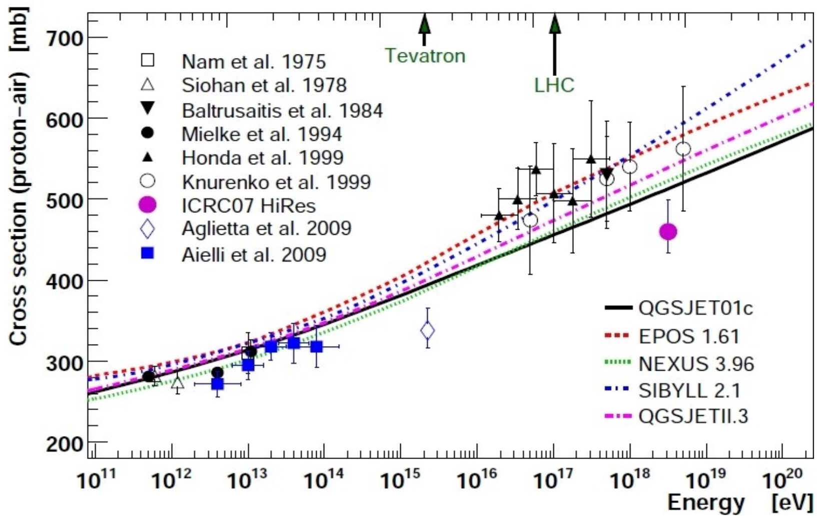




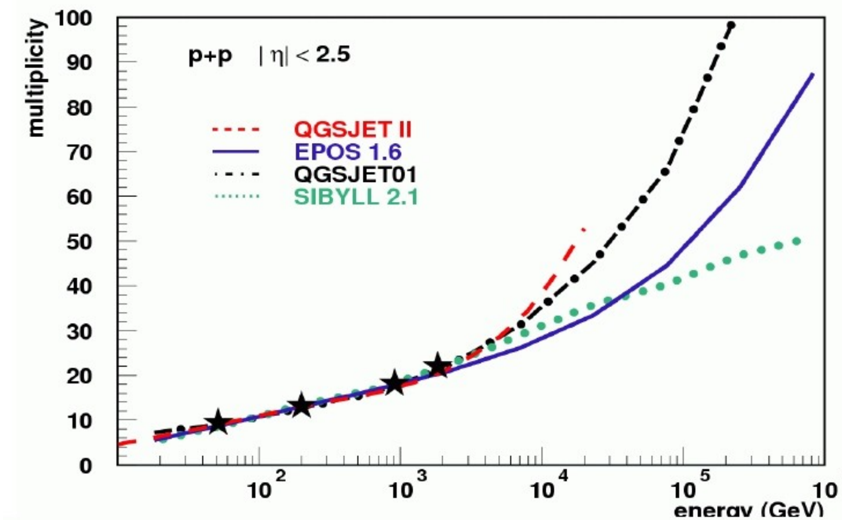
- Particle production in p-p, p-A, A-A up to $\Delta\eta \sim 2\times\ln(\sqrt{s})/m_p \sim 20$ units
- Dedicated detectors at forward rapidities: TOTEM,LHCf,Alfa,CASTOR...
- All phase-space virtually covered: 1st time in a collider !

Cosmic-ray MCs (pre-LHC) vs. LHC data

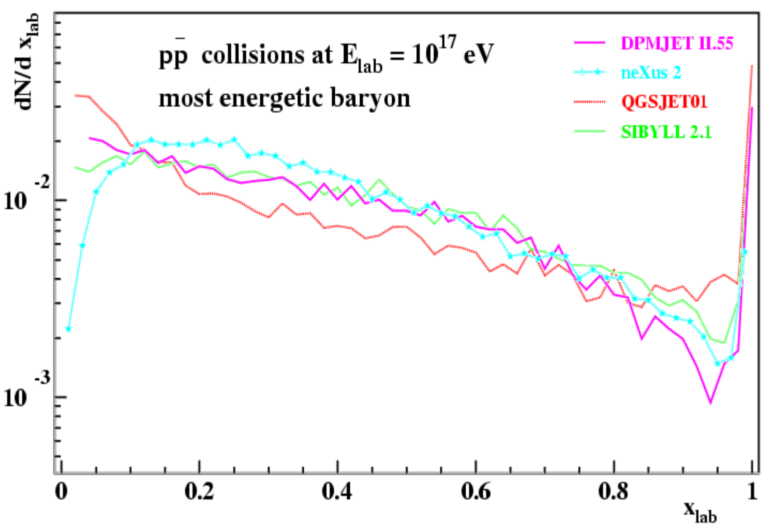
Hadronic inelastic cross-section



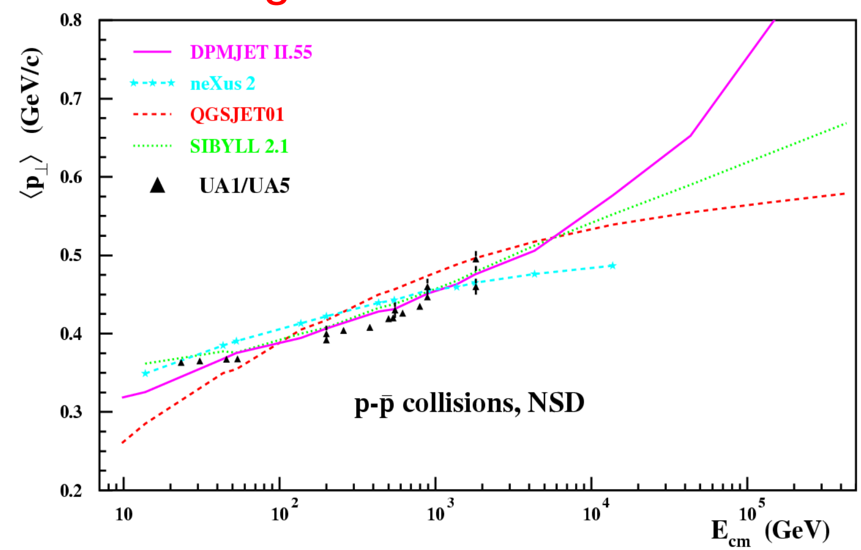
Hadron multiplicity



Forward particle production

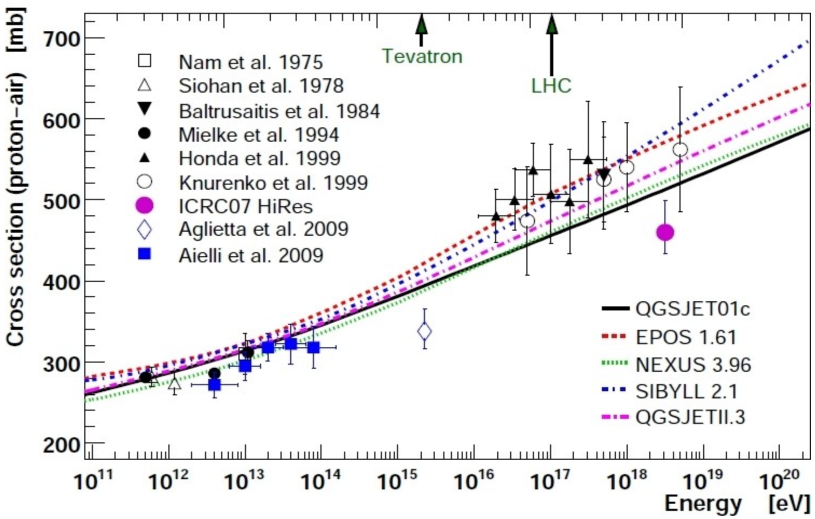


Average transverse momentum

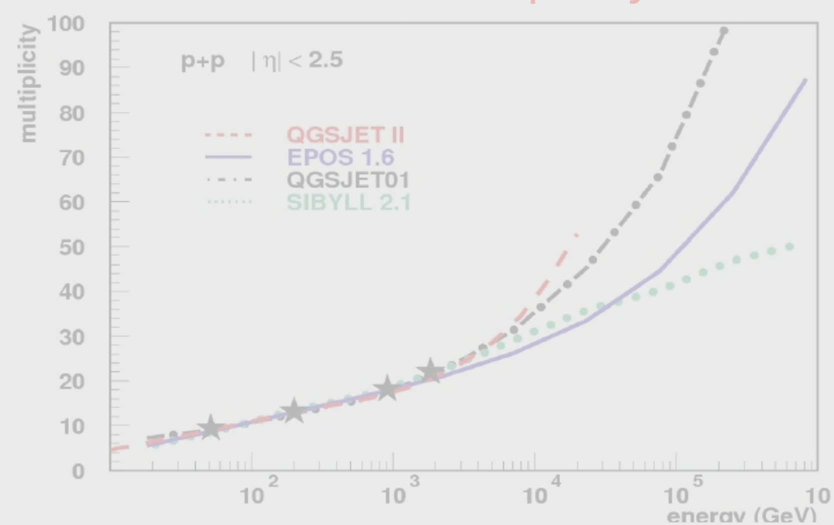


Cosmic-ray MCs vs. LHC data (I)

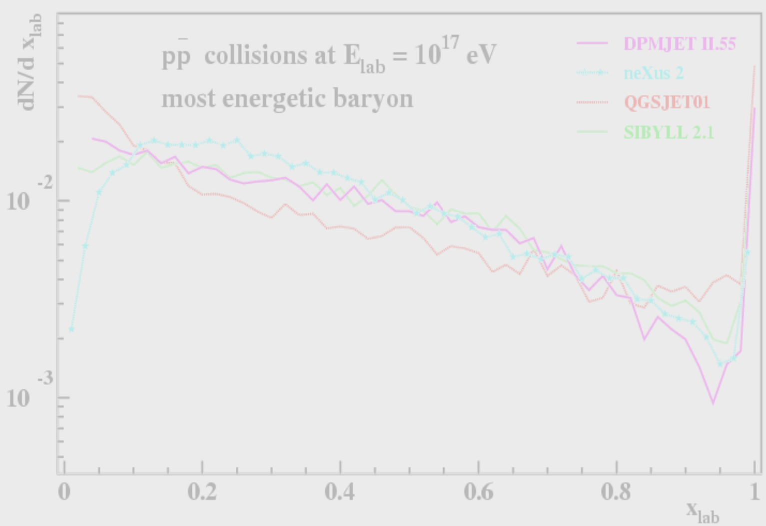
Hadronic inelastic cross-section



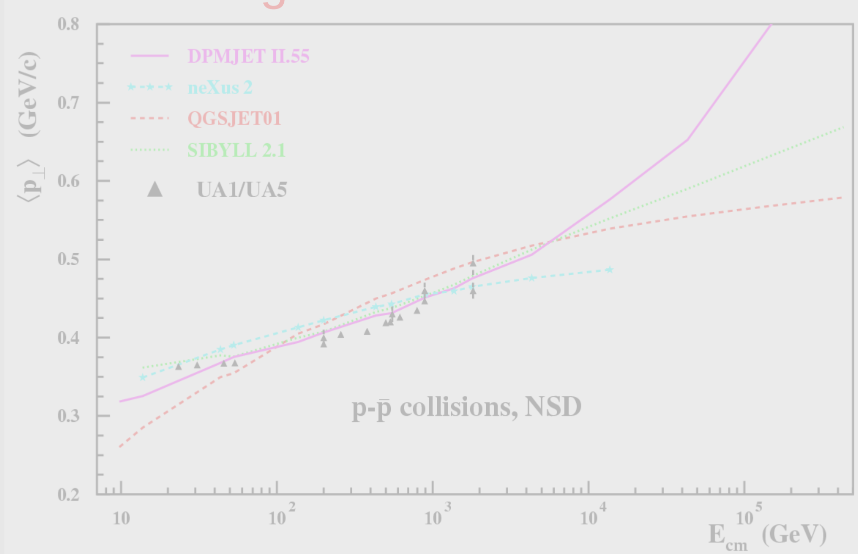
Hadron multiplicity



Forward particle production



Average transverse momentum

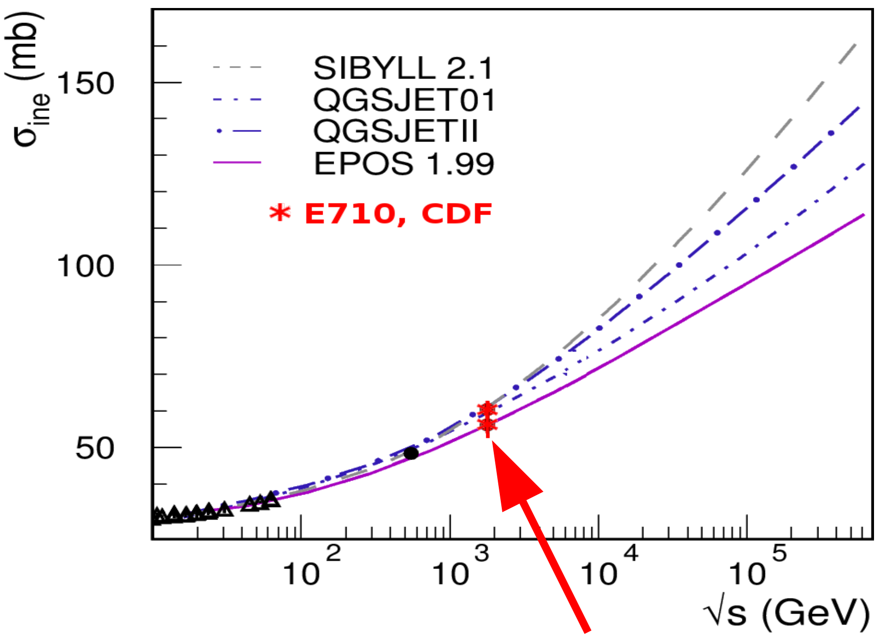


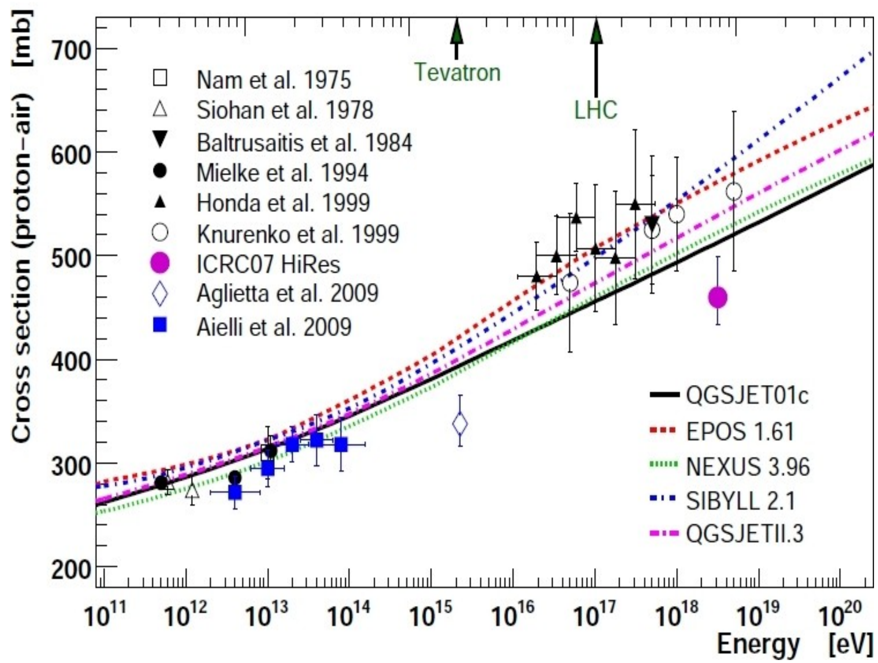
Total & (in)elastic p-p cross sections (pre-LHC)

- Non-computable from QCD Lagrangian (maybe lattice?), but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.

- LHC p-p total x-section predictions:
  σ_{tot}(LHC) = 90–120 mb $^{+10}_{-20}$ %.

- p-Air x-sections even more uncertain (Glauber model):



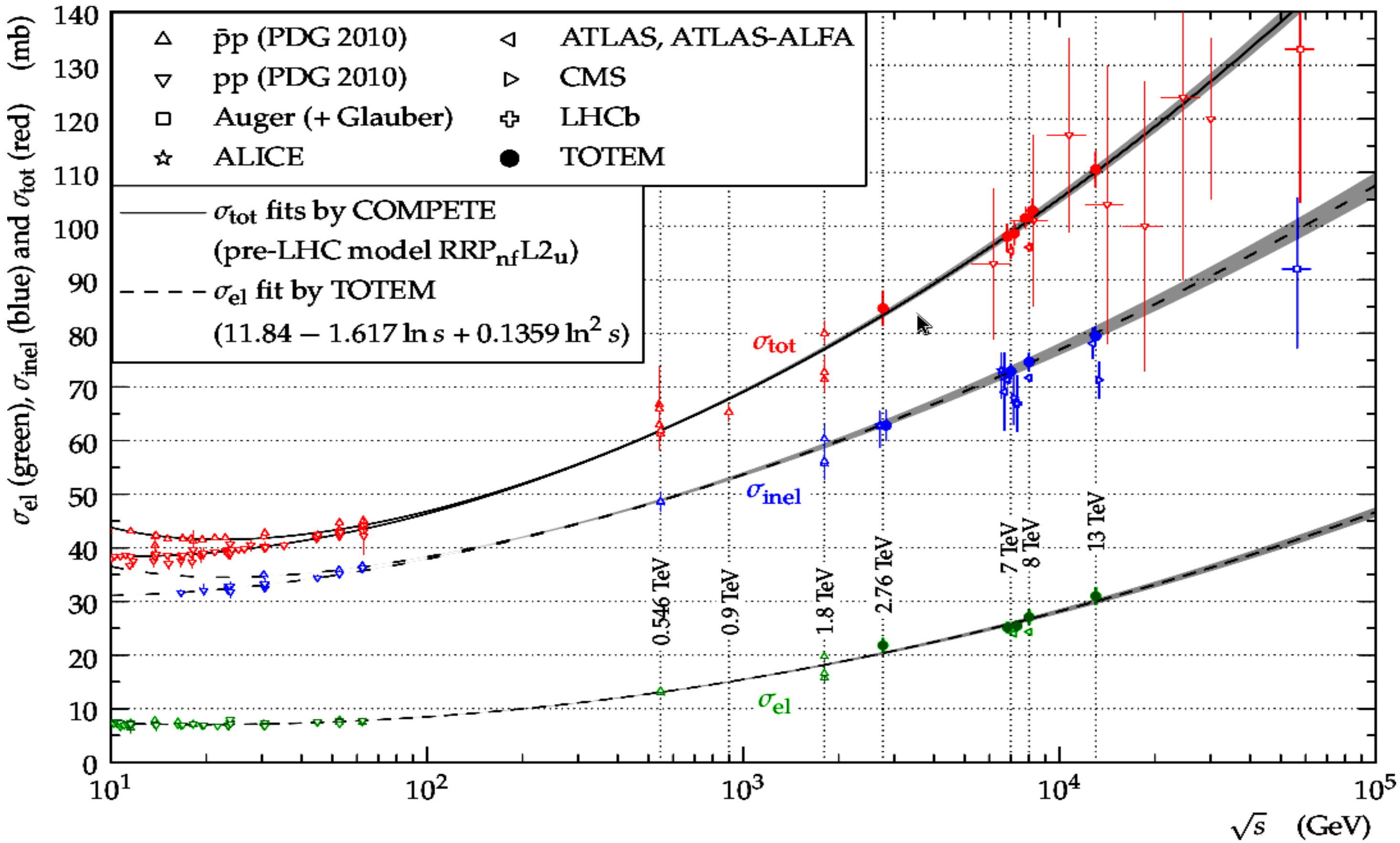


R.Ulrich, eConf C0906083 (2009)

- Pre-LHC σ(inel) uncertainties driven by E710–CDF 2.6σ disagreement

Total & (in)elastic p-p cross sections (LHC)

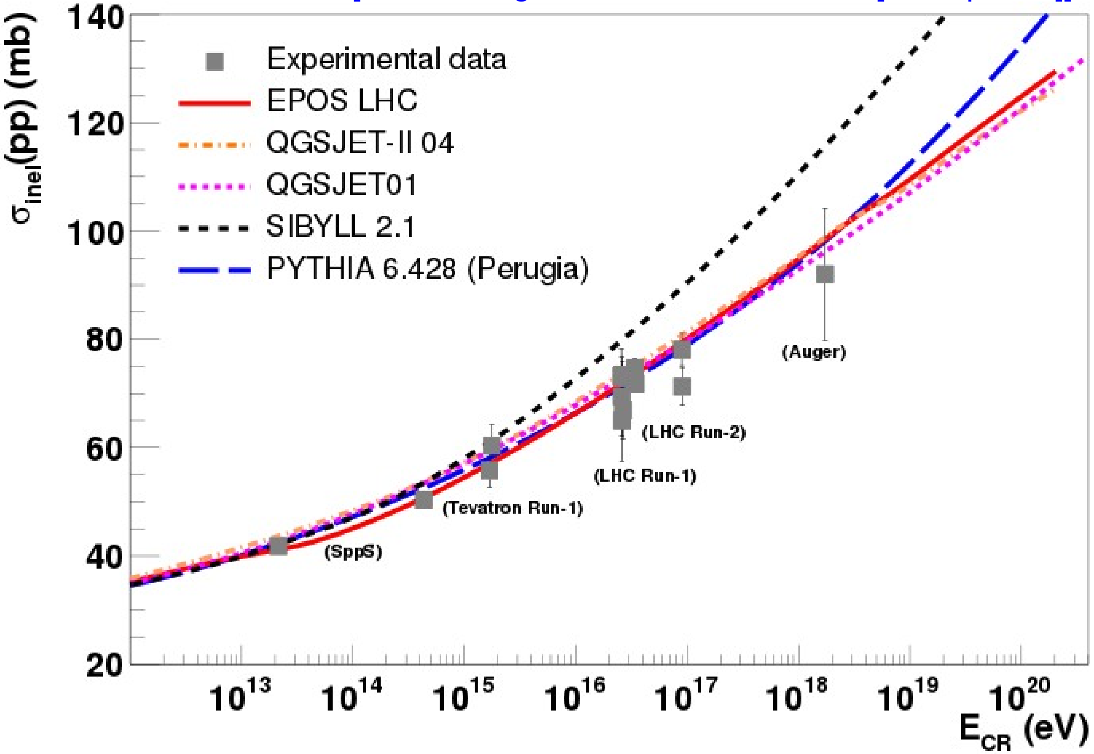
- Many measurements (TOTEM, ALFA, CMS, ATLAS, ALICE, LHCb):
  At $\sqrt{s}$=13 TeV: σ_{tot} = 110.6 ± 3.4 mb (σ_{inel} ~72%, σ_{el} ~28%).

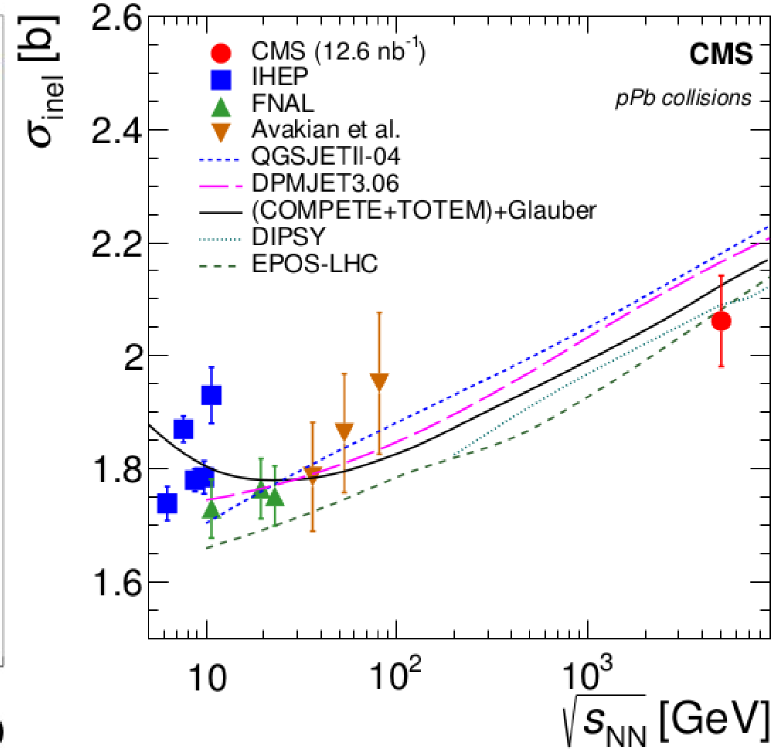


- Inelastic cross section mostly overestimated by MCs.
- Most MCs over- (under)estimate high- (low-)mass diffraction.

Inelastic p-p, p-Pb cross sections (LHC)

[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]

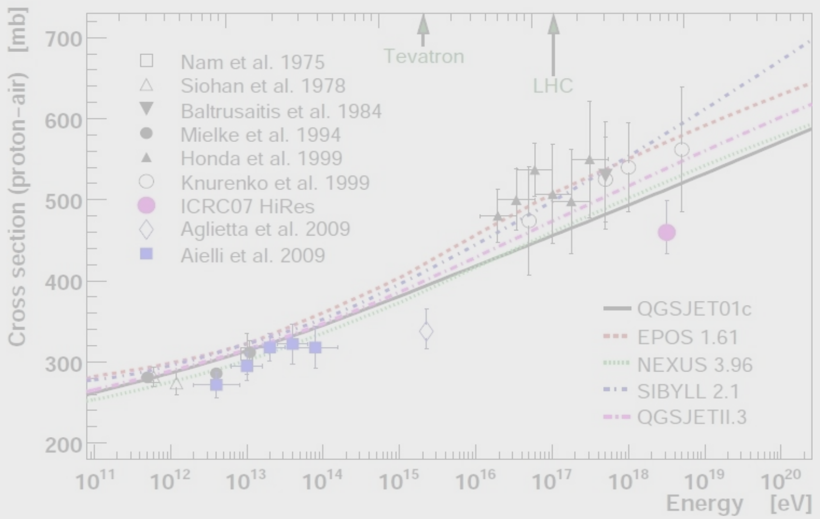




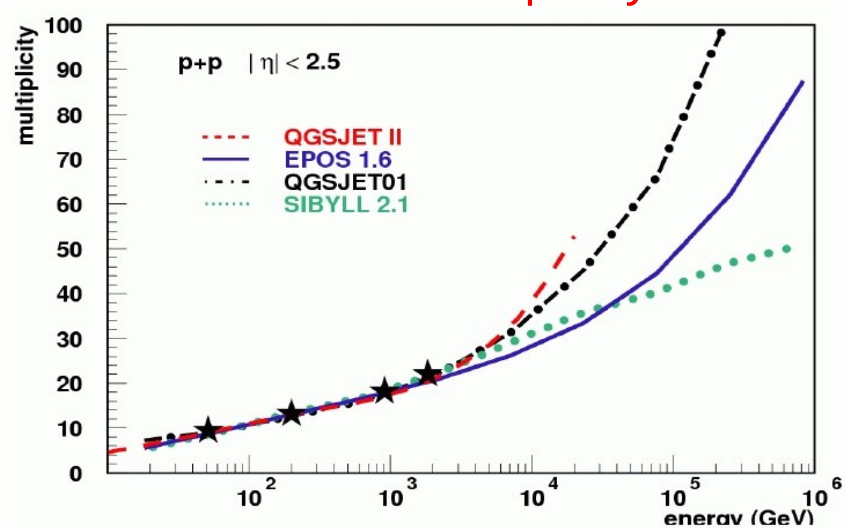
- All retuned MCs predictions are now ~consistent up to GZK cutoff.
- Measured σ(p-Pb) at 5.16 TeV confirms Glauber-scaling of σ(p-p) to σ(p-Air)
- Measured σ(p-p) at LHC, slightly below pre-LHC MC predictions, leads to reduced σ(p-Air): Deeper shower X_{max} position.

Cosmic-ray MCs vs. LHC data (II)

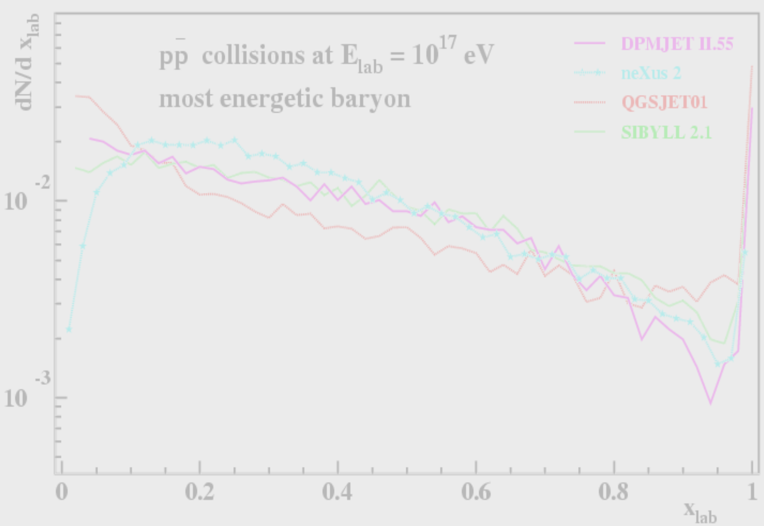
Hadronic inelastic cross-section



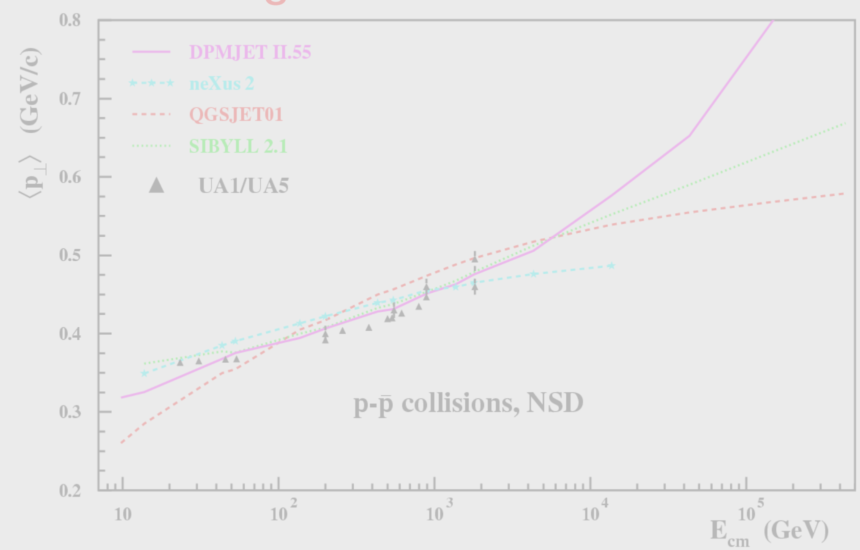
Hadron multiplicity



Forward particle production

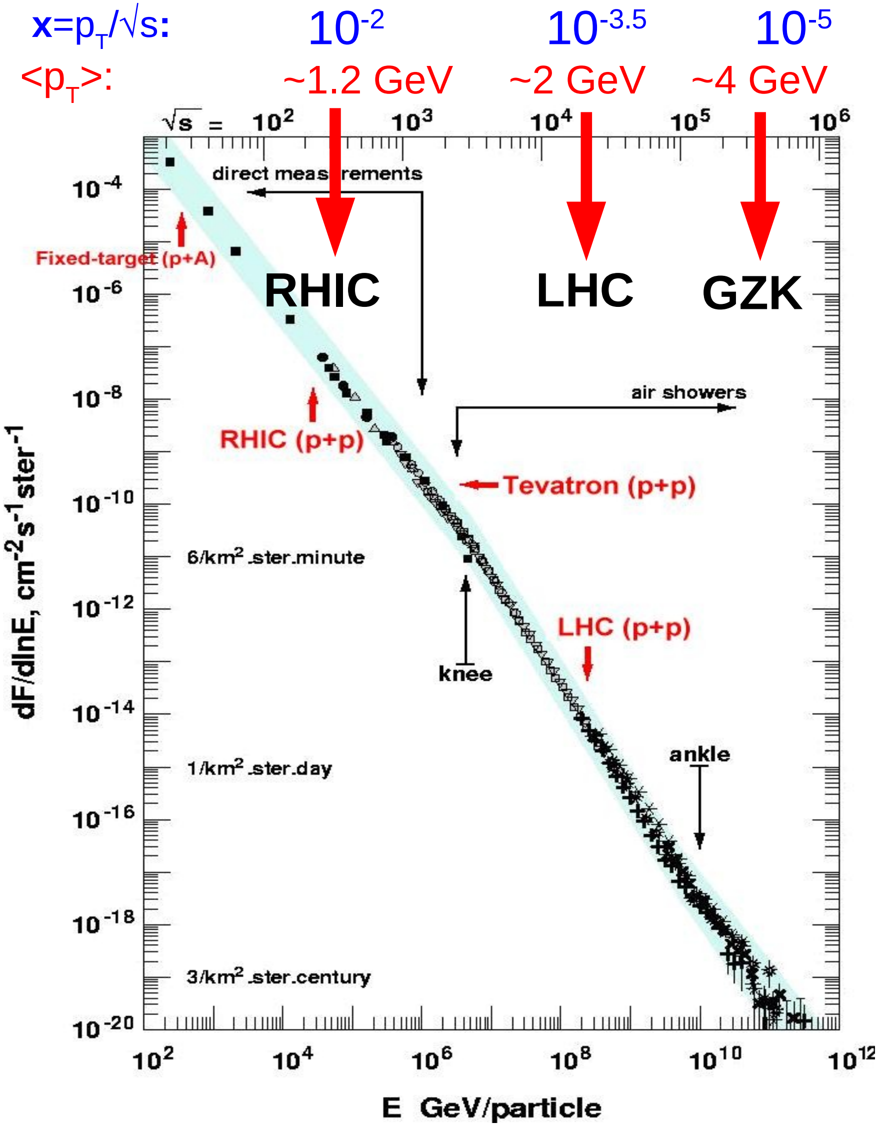


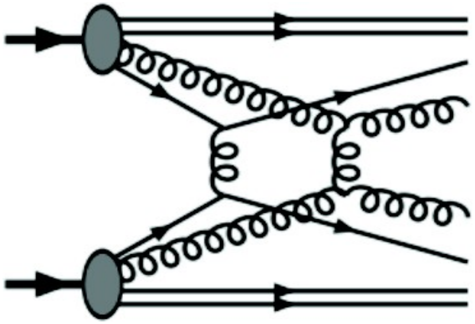
Average transverse momentum



Particle production from multi-gluon collisions

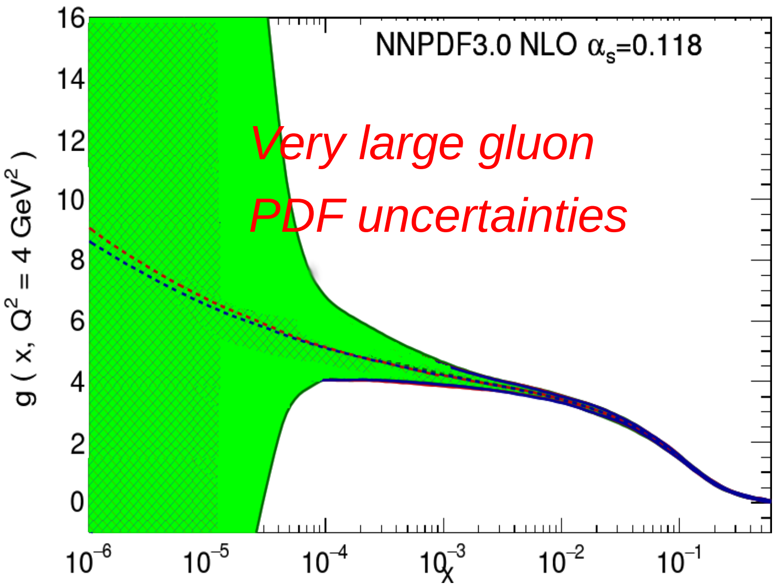
- Most (~70%) of hadrons from gluon fragmentation in multiple low-x scatterings





- Steeply rising ($x^{-0.3}$) gluon density:

At GZK multi g-g collisions at $x<10^{-5}$

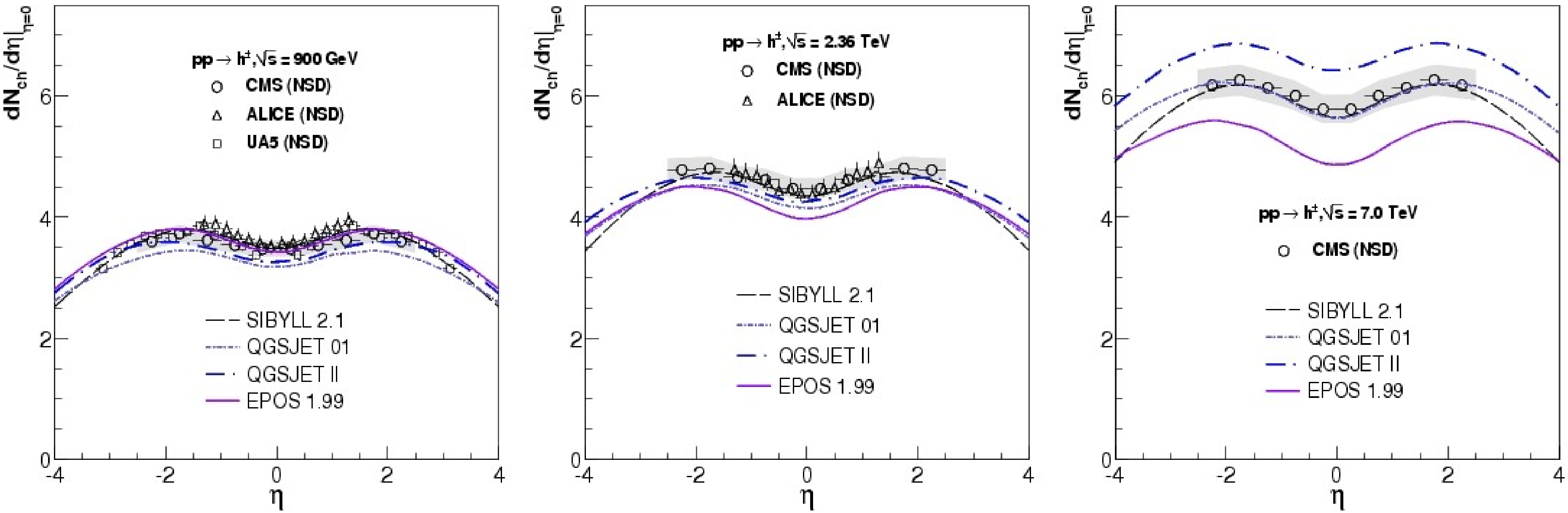


Central particle production: Data vs. pre-LHC MCs

[Dd'E et al., Astr.Phys. 35 (2011) 98]

- First LHC pseudorapidity distributions data vs. CR models:

0.9 TeV | 2.36 TeV | 7.0 TeV



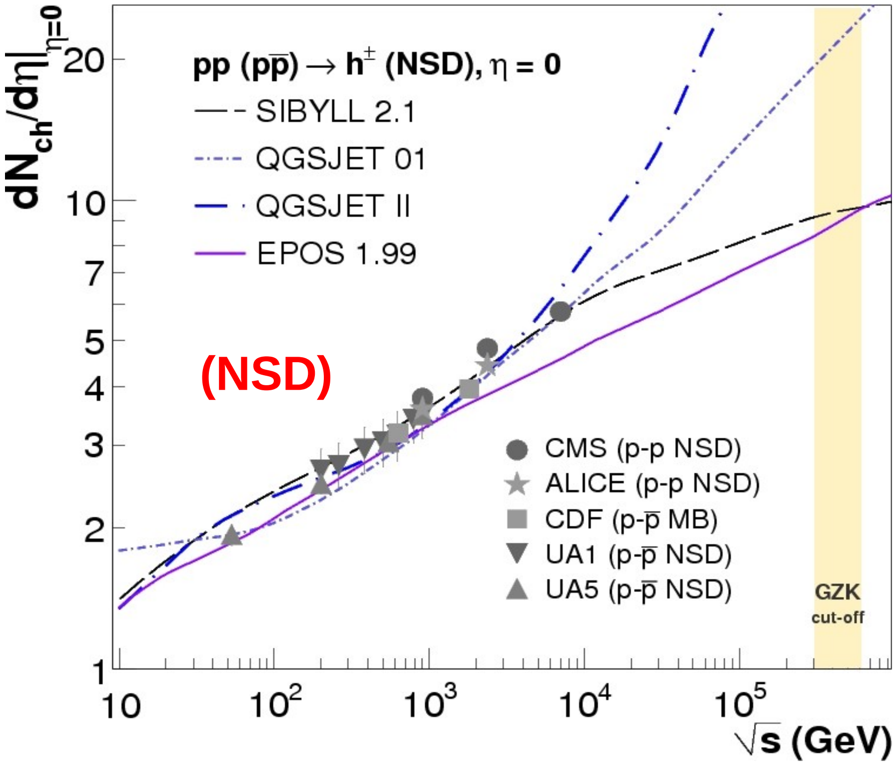
- 900-GeV data well reproduced (MCs were tuned to SppS, Tevatron).
- Particle multiplicity less well predicted at 7.0 TeV but all CR models "bracket" the experimental distributions.

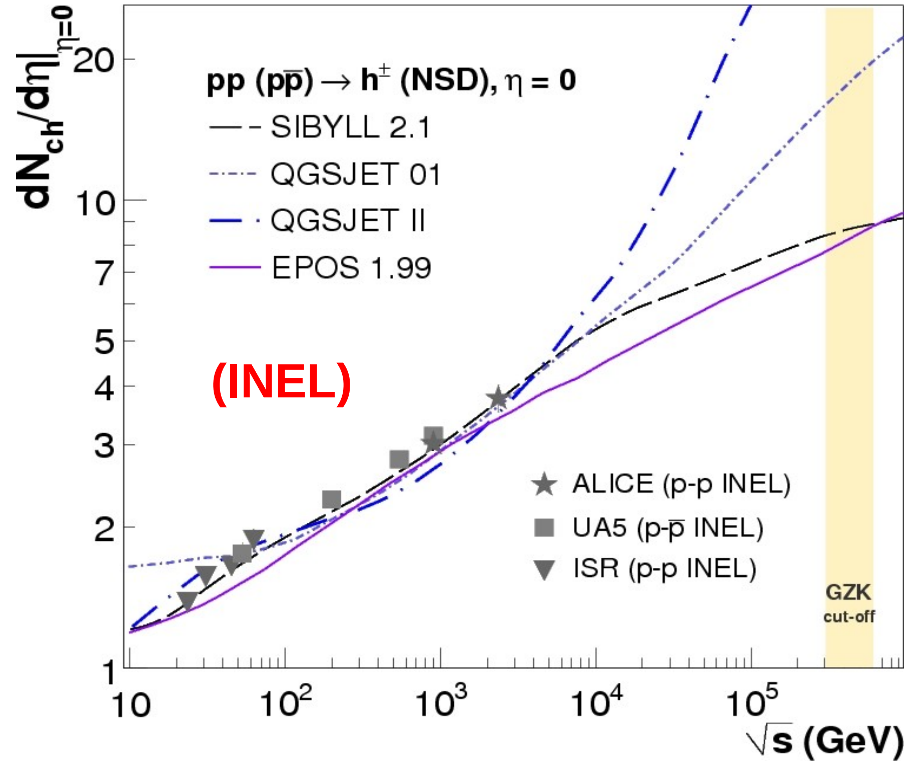
Central particle production: Data vs. pre-LHC MCs

[Dd'E et al., Astr.Phys. 35 (2011) 98]

- Power-law s^{ε}, $\varepsilon \sim 0.1$ controlled by soft-hard p_T-cutoff (sat. scale) evolution
- Very large differences predicted at $\sqrt{s}_{GZK} \sim$ 400 TeV !

  QGSJET-II (~40) > QGSJET01 (~20) > SIBYLL 2.1,EPOS 1.99 (~8)

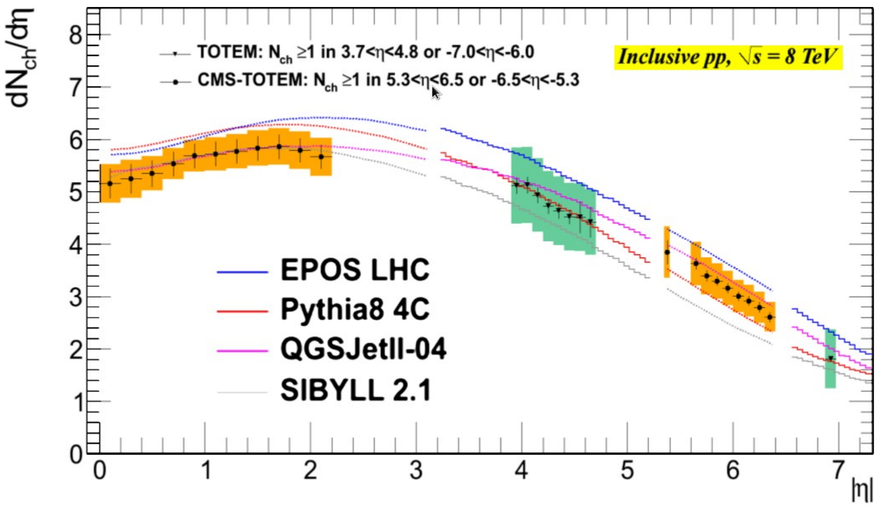


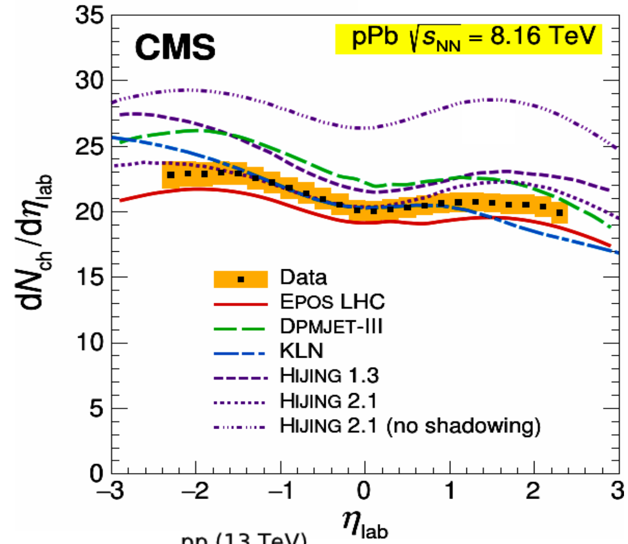


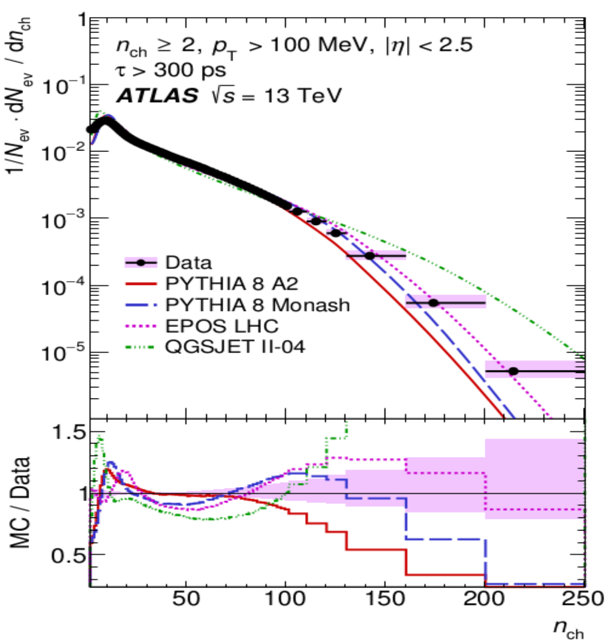
- EPOS (1.99→LHC), QGSJETII-04, SIBYLL (2.1→2.3) retuned based on these (and other) data. $dN_{ch}/d\eta \sim 15 \pm 5$ at GZK now.

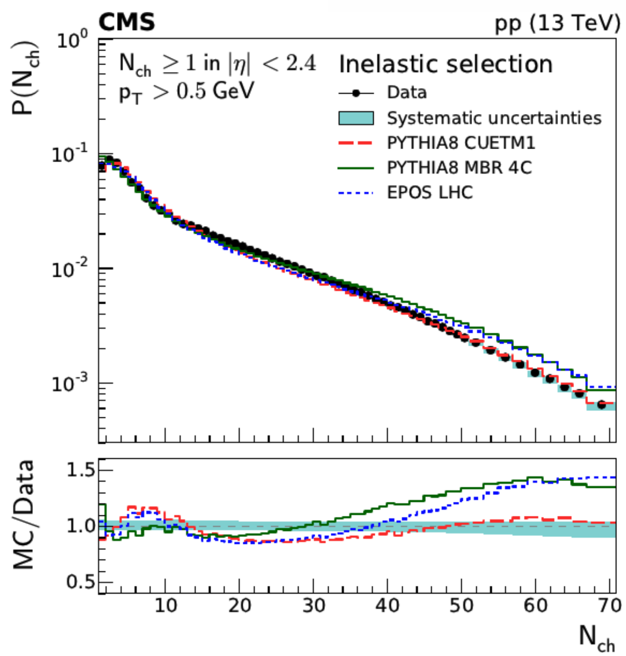
Central particle production: Data vs. post-LHC MCs

- Charged particle pseudorapidity density & multiplicity distributions:





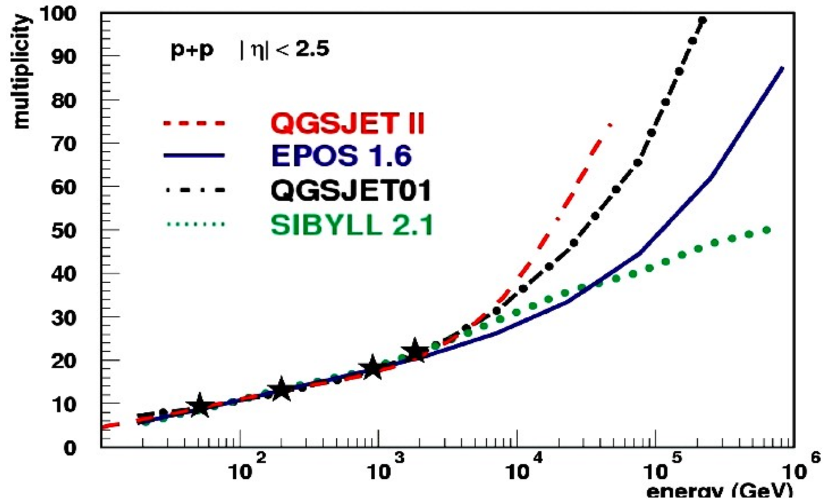




- Retuned UHECR hadronic MCs "bracket" well all p-p, p-A distributions up to 13 TeV.
- Improvements needed in tails of distributions (small impact on UHECR).

Central particle production: Data vs. MCs

- Central charged particle multiplicity vs. CR energy:

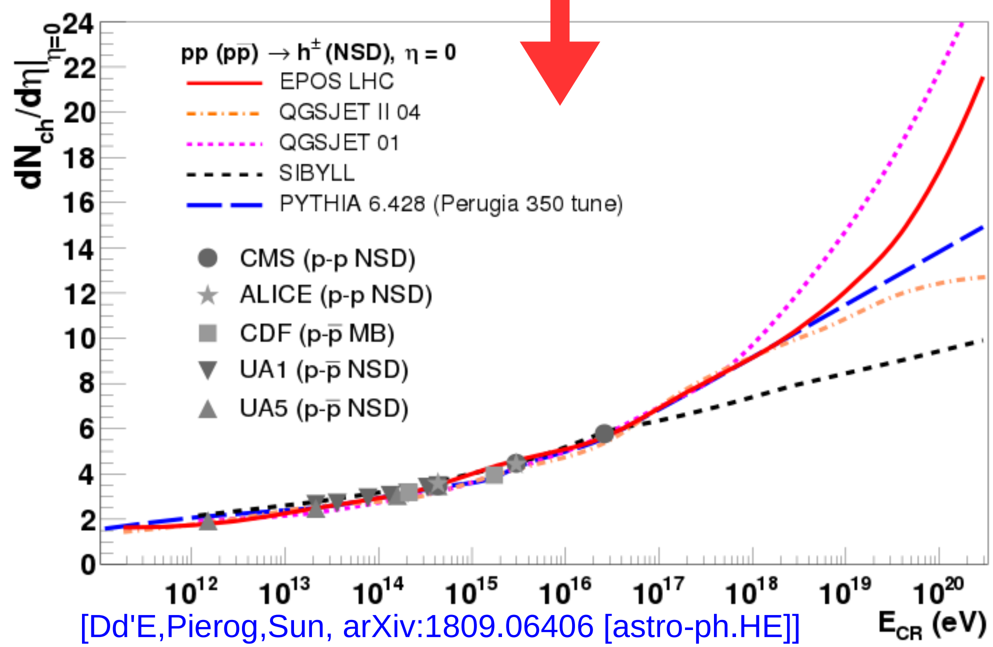


Pre-LHC MCs:
Factors of ~2 differences
on predicted LHC particle multiplicities.

Post-LHC MCs:

- Much better agreement among LHC-retuned models compared to pre-LHC versions up to E_{CR}~$10^{18.5}$ eV.

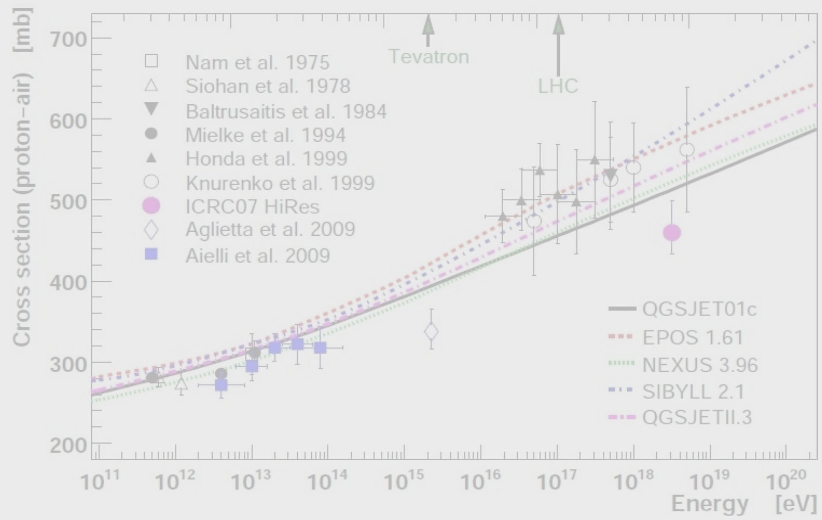
- $dN_{ch}/d\eta$~15±5 with ~30% differences at GZK-cutoff among EPOS, QGSJET-II, PYTHIA 6.



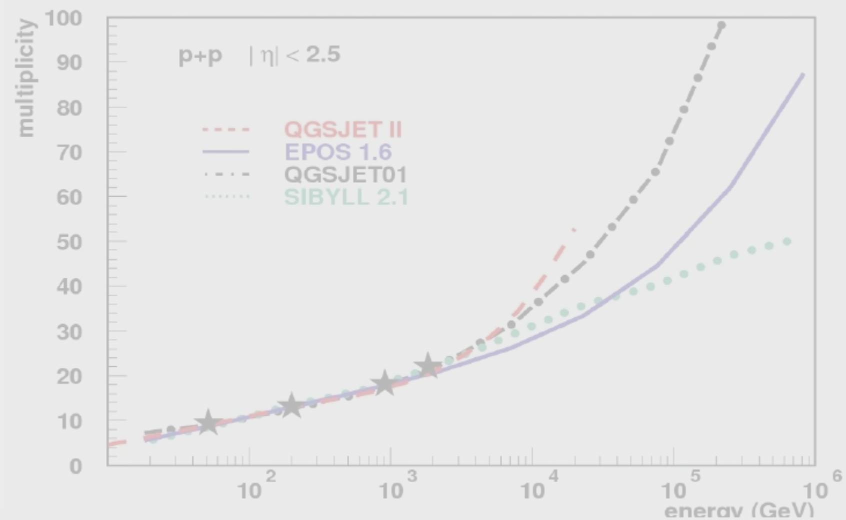
[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]

Cosmic-ray MCs vs. LHC data (III)

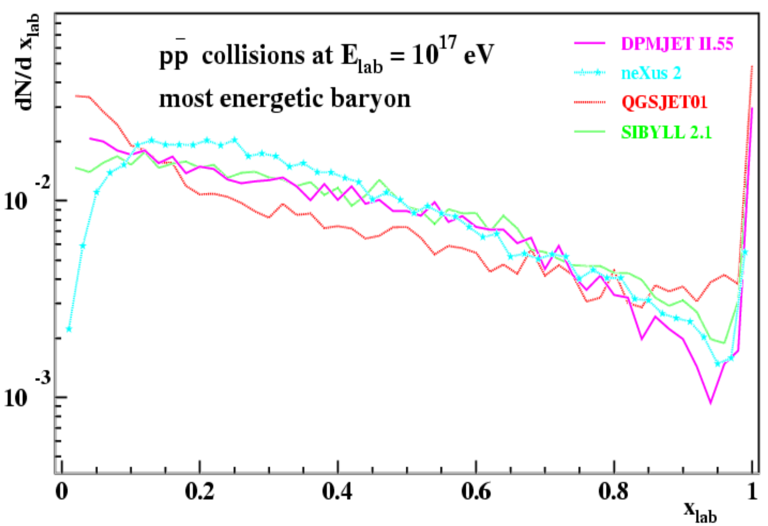
Hadronic inelastic cross-section



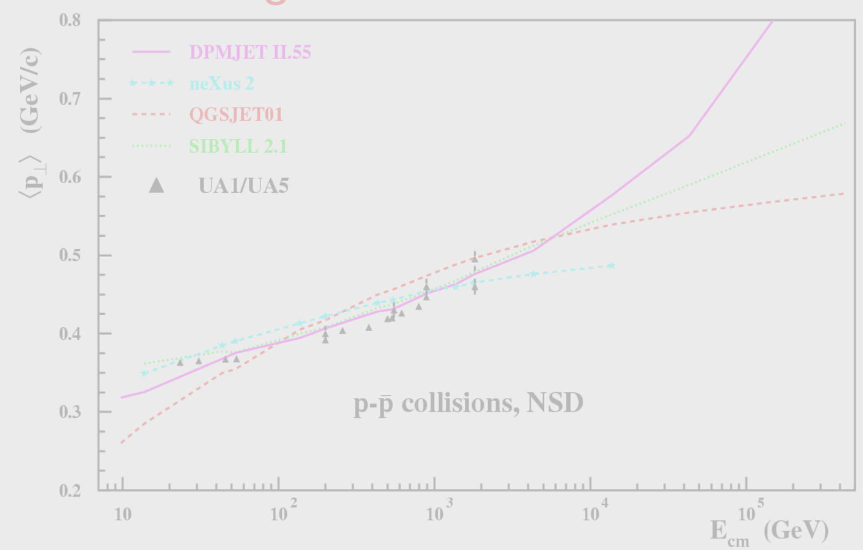
Hadron multiplicity



Forward particle production

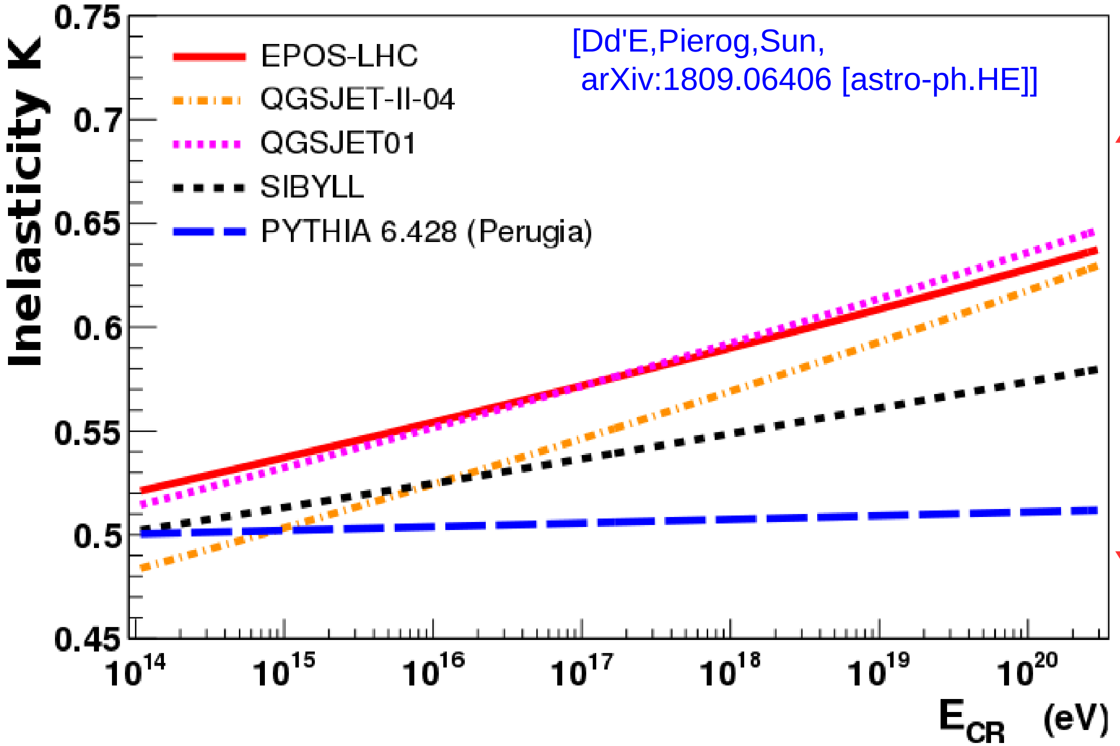


Average transverse momentum



Very forward particle production

- The inelasticity $K=1-E_{lead}/E_{CR}$ (fraction of primary particle energy transferred to secondary particles after removing the most energetic “leading” hadron emitted at very forward rapidities) has an important influence on cosmic-ray EAS development.
- EPOS, QGSJET have an increased inelasticity with increasing CR energy, but SIBYLL (and PYTHIA) show a flatter behaviour:

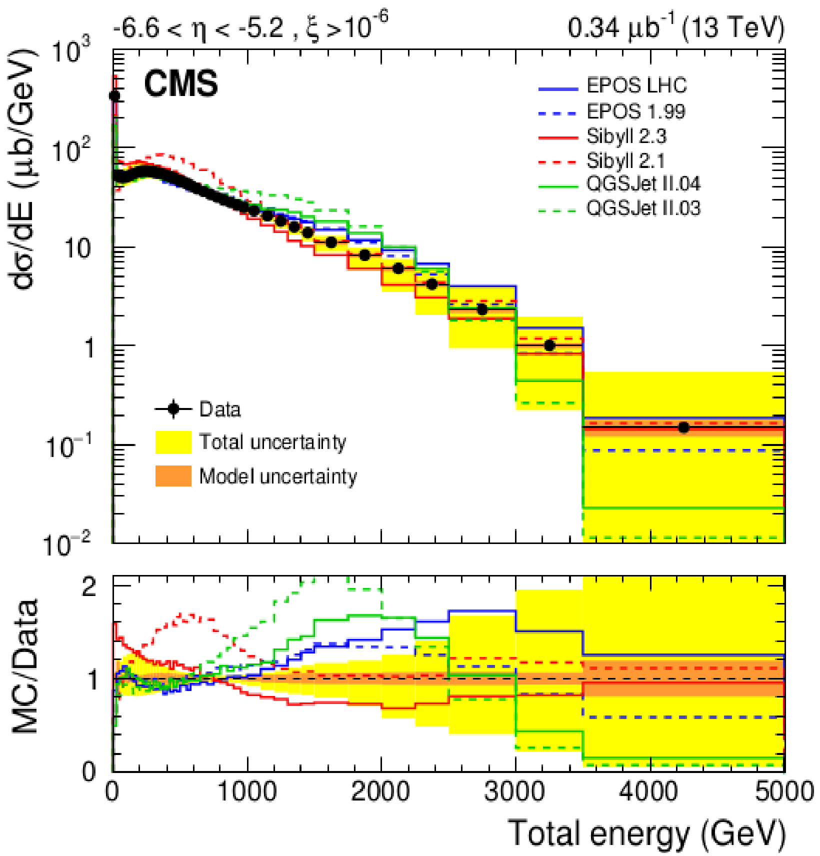


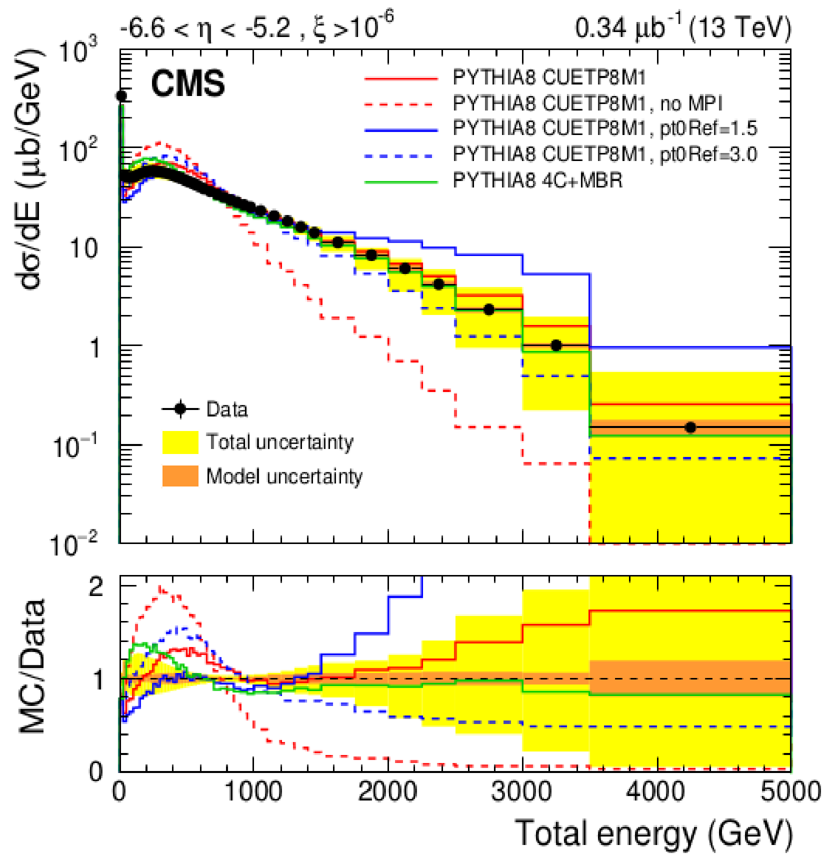
Less energy goes to very forward particle production
(Faster shower development: Smaller X_{max})

More energy goes to very forward particle production.
(Slower shower development: Larger X_{max})

Forward particle production: |η| ~ 5.–7.

- Forward energy flow in pp at LHC moderately controlled theoretically (but CR MCs better than collider MCs).
  Sensitive to multiparton interactions and beam-remnants.

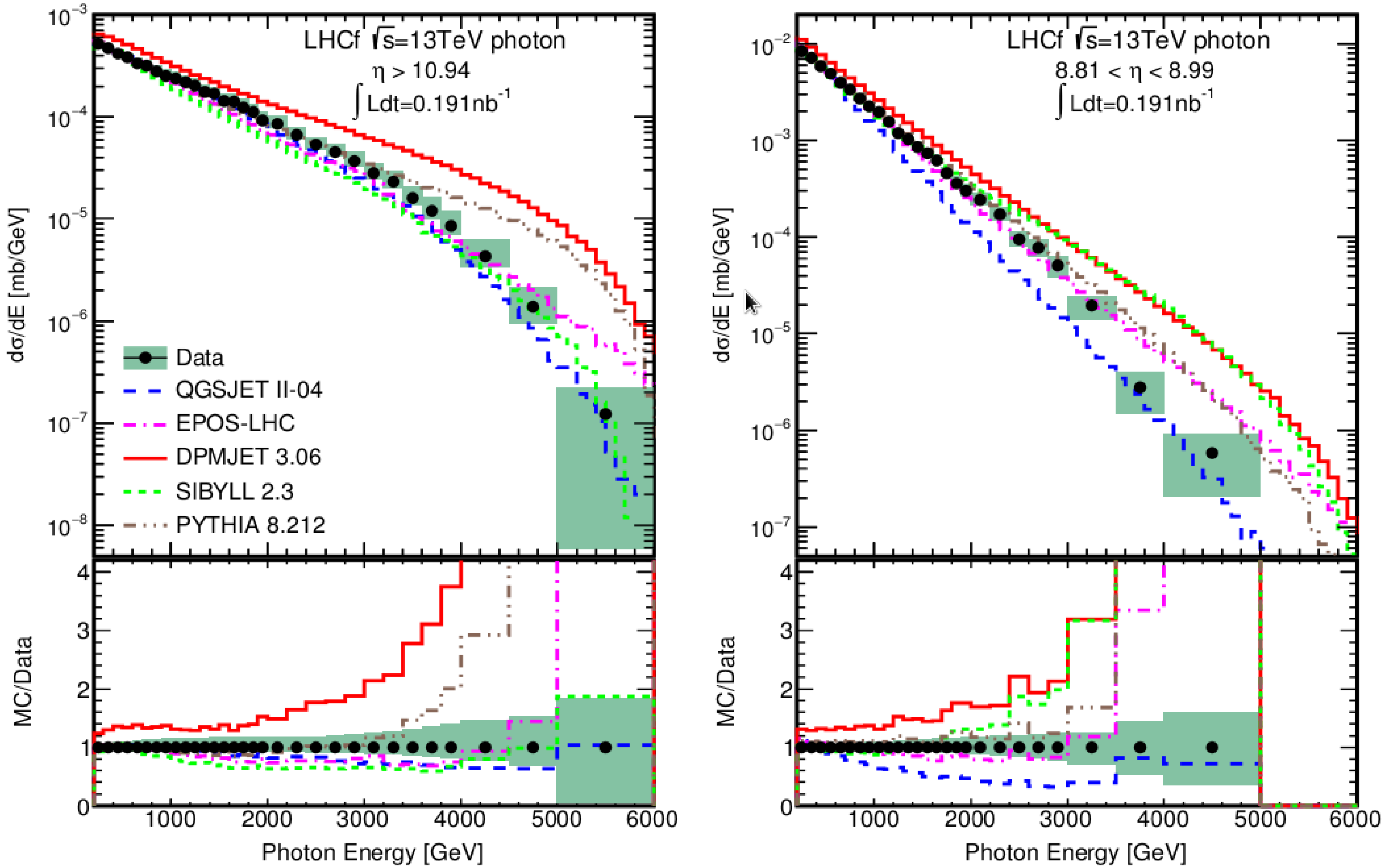




- Some forward particle retuning needed by all MCs.

Very forward photons (LHCf): |η| ~ 8.–11.

- Leading baryon (inelasticity) & had-to-e.m. energy transfer ($\pi^0 \to \gamma\gamma$) moderately controlled theoretically (but CR MCs better than collider MCs).

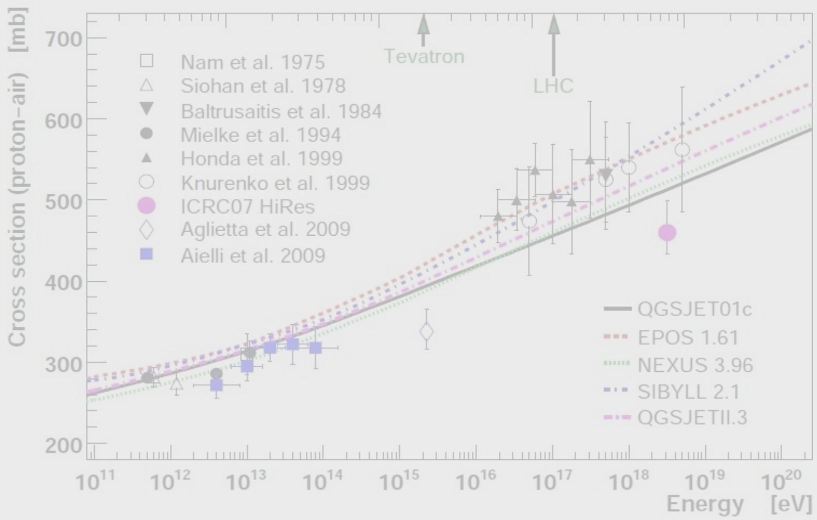


- Some forward particle retuning needed by all MCs.

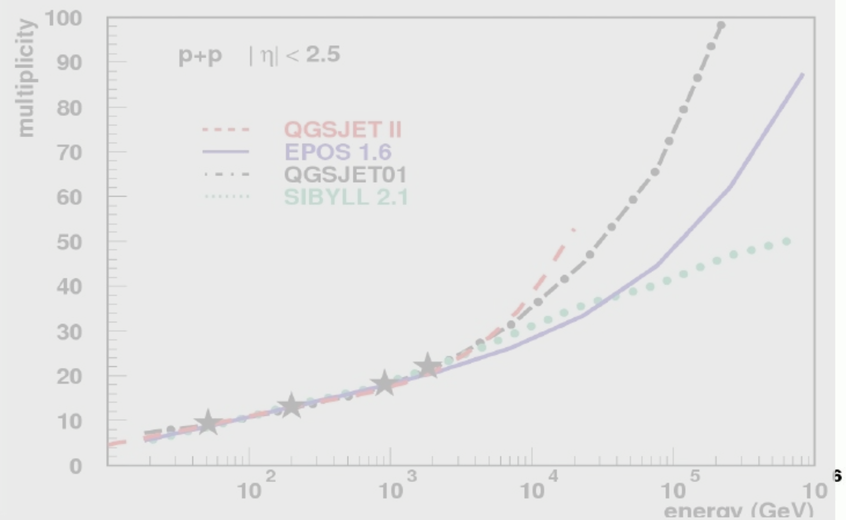
(See H. Menjo later)

Cosmic-ray MCs vs. LHC data (IV)

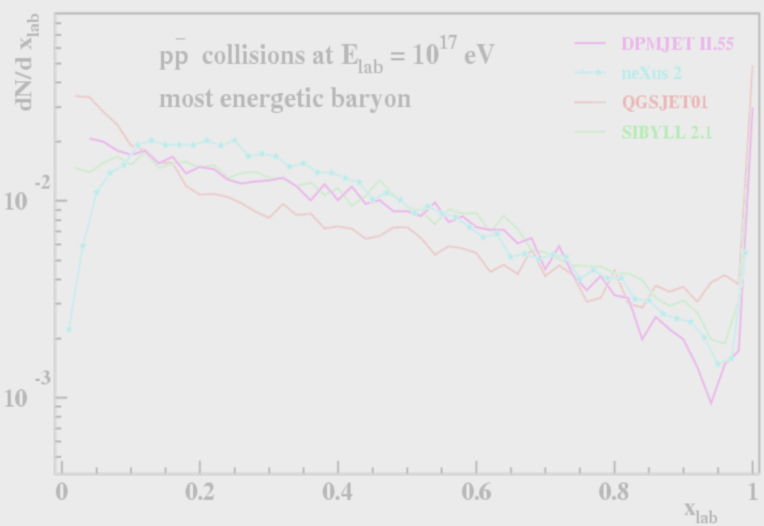
Hadronic inelastic cross-section



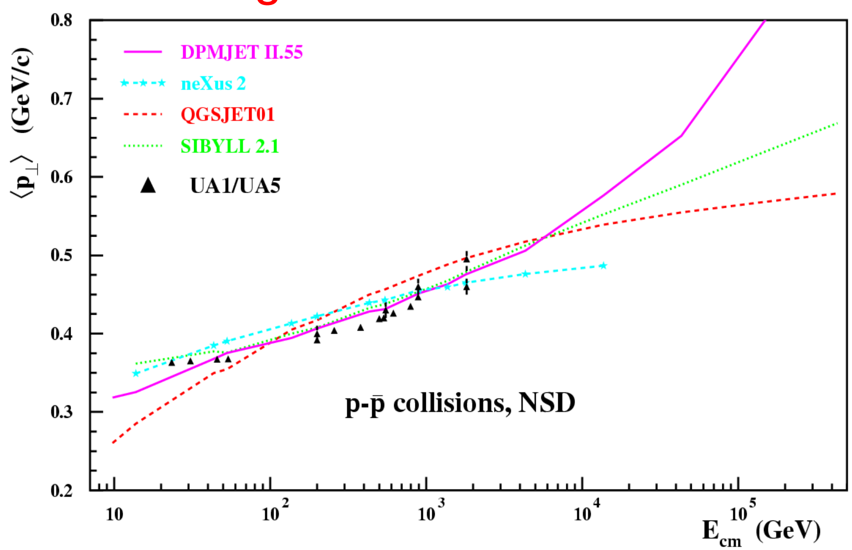
Hadron multiplicity



Forward particle production

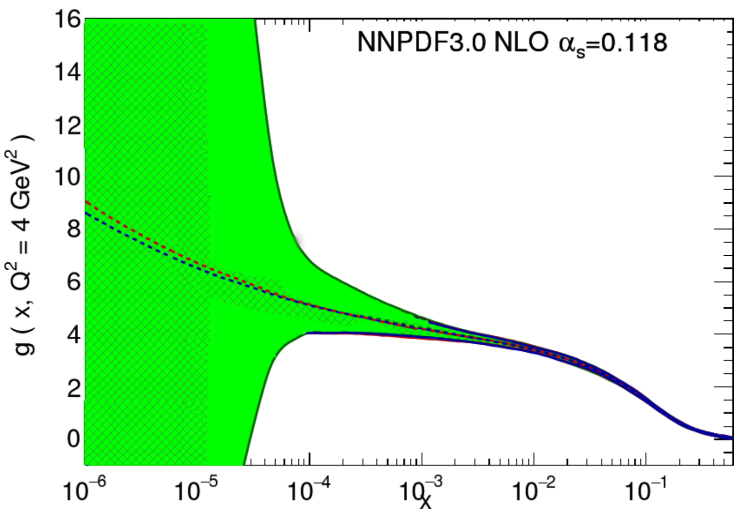


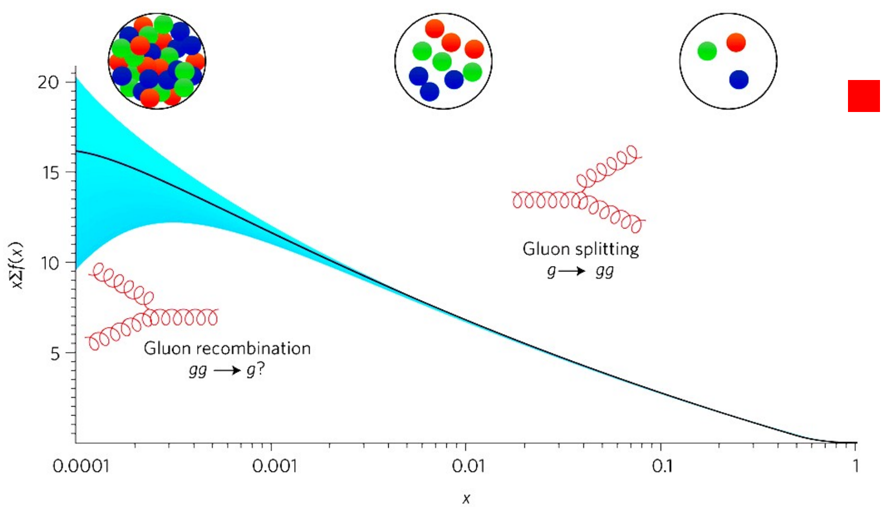
Average transverse momentum



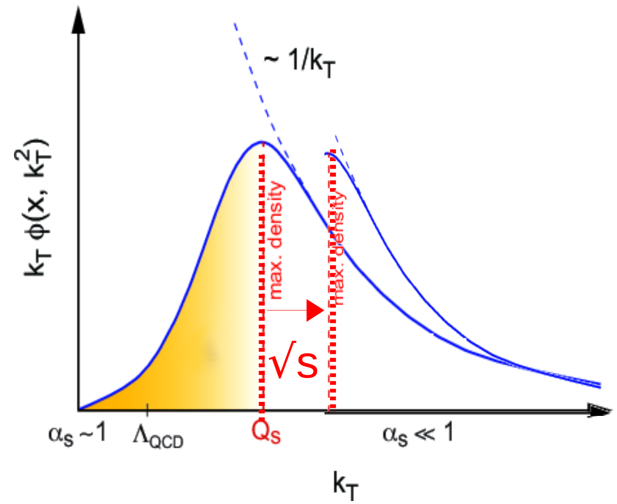
Mean p_T driven by minijet saturation dynamics

- Low-x gluons start to overlap at "saturation scale" Q_{sat}





- pQCD minijet x-section peaks at running $p_T \sim Q_{sat} \sim s^{0.15} \sim$ 1–4 GeV



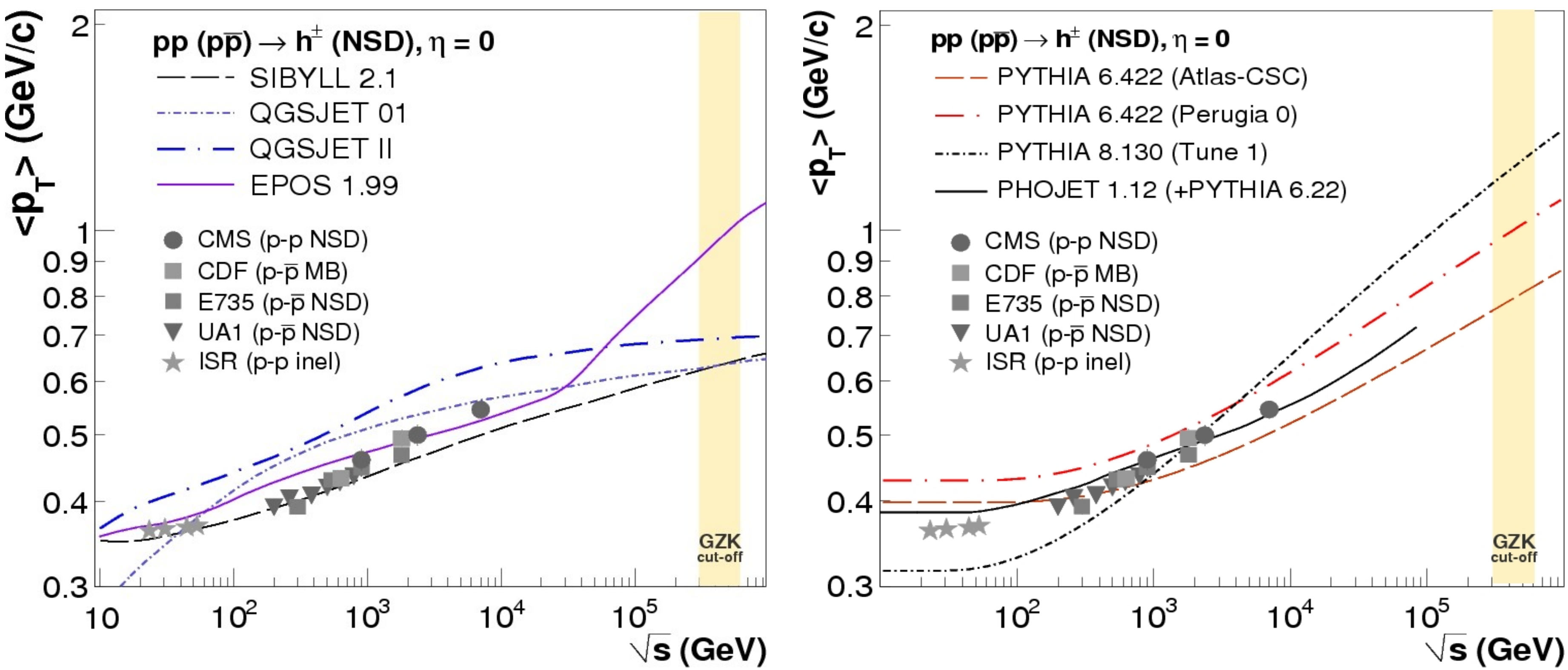
➡ Less soft minijets. Harder pQCD activity.

- Saturation effects enhanced in nuclear interactions (p-Air): Larger number of partons per unit transverse area. $\langle p_T \rangle$ increase by $A^{1/6} \sim 1.5$ (for oxygen, nitrogen).

Mean p_T vs. energy: Data vs. pre-LHC MCs

[Dd'E et al., Astr.Phys. 35 (2011) 98]

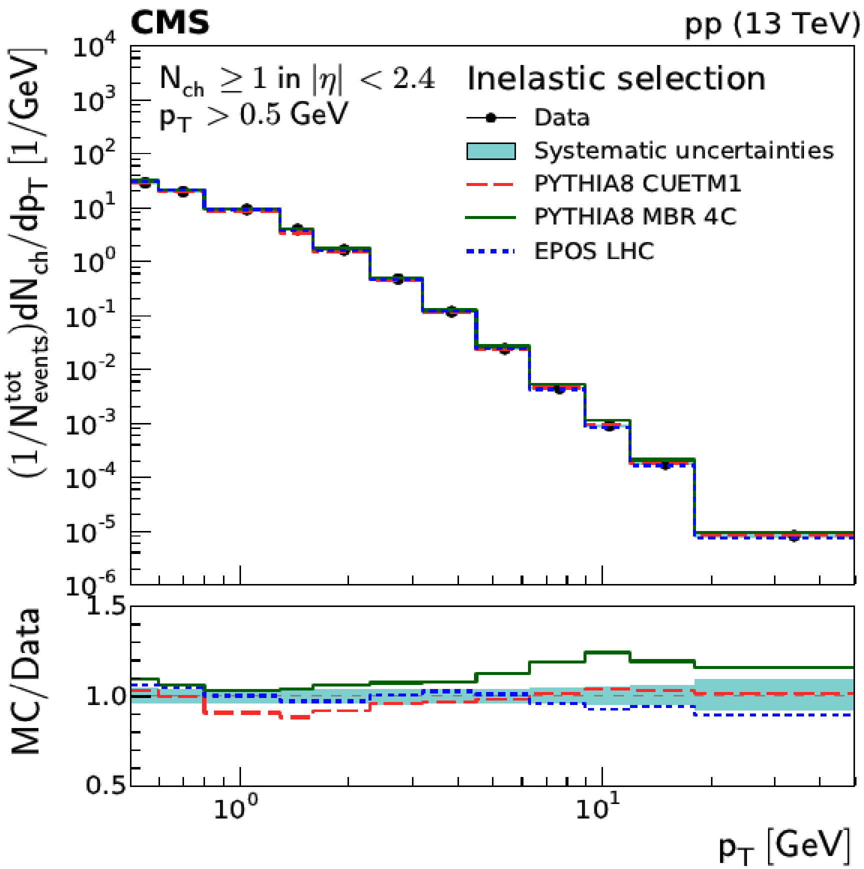
- $\langle p_T \rangle$ is sensitive to pQCD x-sections & gluon-saturation
- $\langle p_T \rangle$ should follow the saturation scale evolution: $Q_{sat} \sim s^{0.15}$



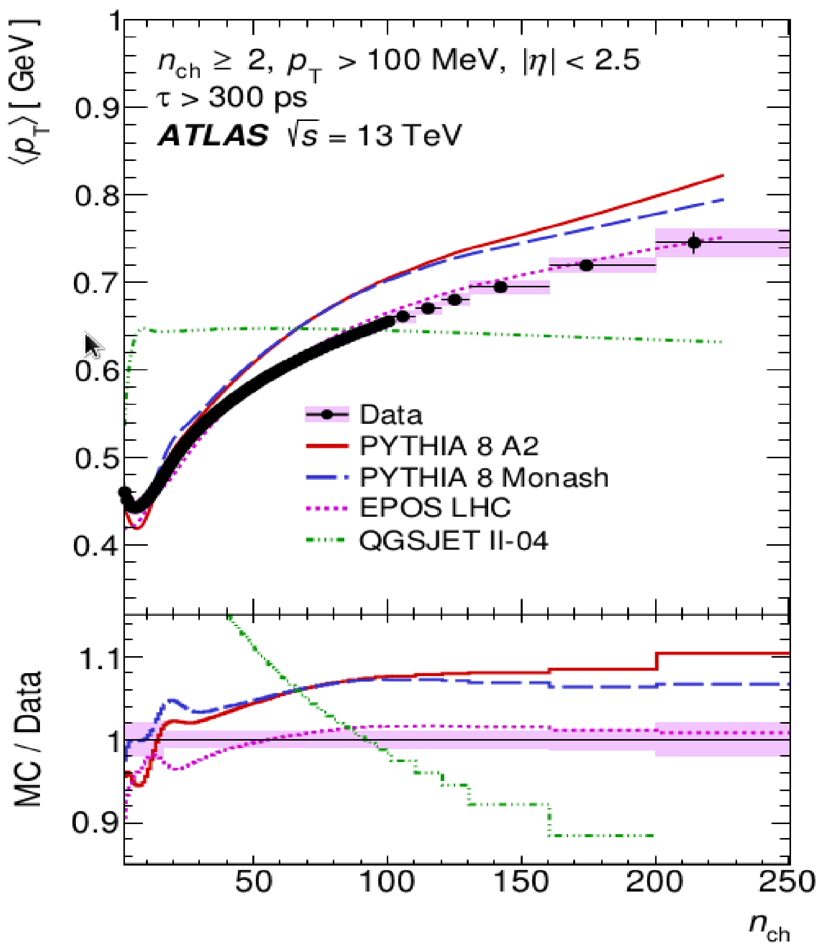
- CRs MCs predict very slow $\langle p_T \rangle$ increase (but EPOS, due to collective flow)
- At GZK: $\langle p_T \rangle \sim$ 0.6–1.0 GeV (PYTHIA: $\langle p_T \rangle \sim$ 0.7–1.5 GeV)

Transverse momentum spectra: Data vs. MCs

- In general, CR MCs have softer tails than data & pQCD-based MCs (PYTHIA).



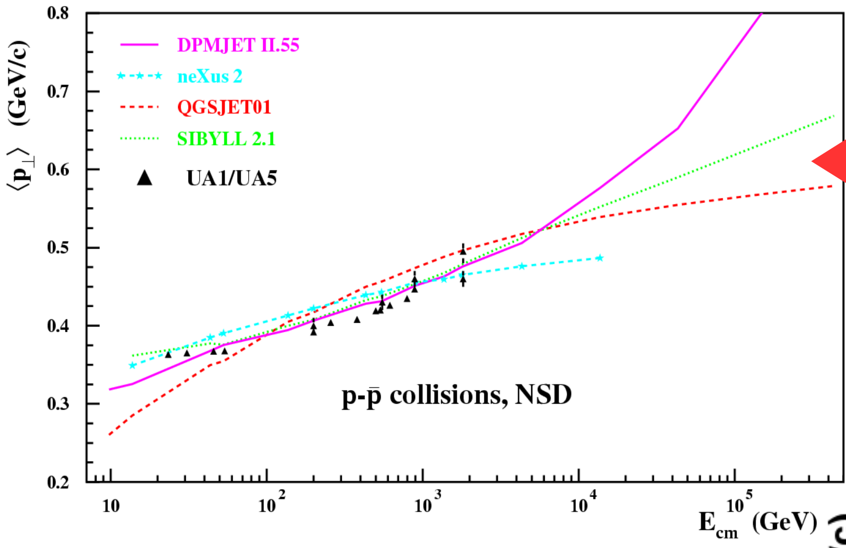
- EPOS with final-state collective flow reaches good agreement with density-dependent $<p_T>$ activity.



- CR MCs need to improve pQCD minijets evolution (also for muons, see later)

Mean p_T vs. energy: Data vs. MCs

- Average transverse momentum vs. collision energy:

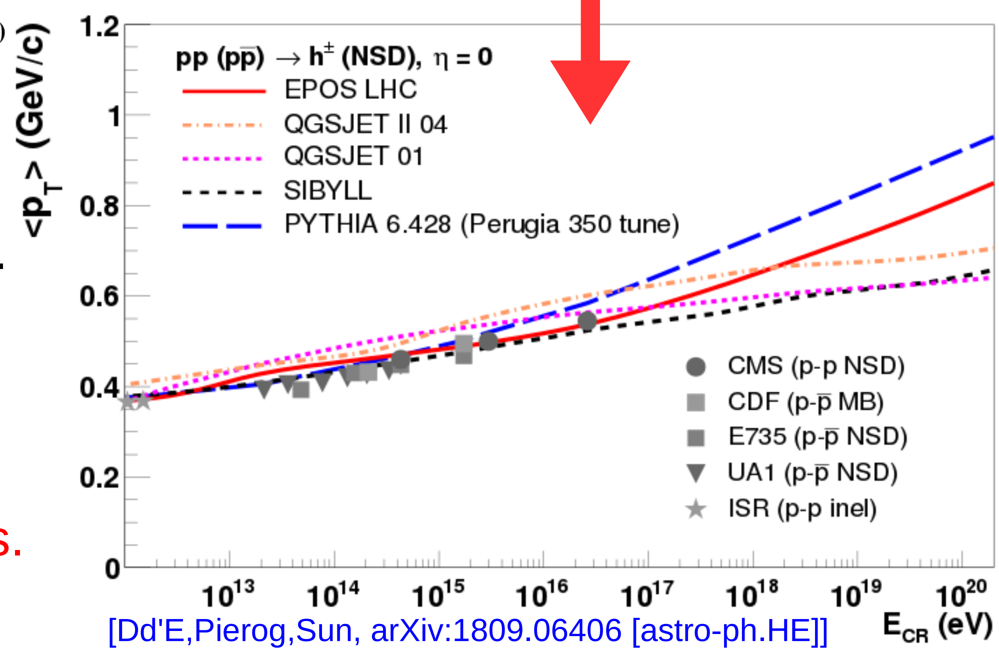


Pre-LHC MCs:

Soft particle production.

$<p_T>$ at GZK only around 0.6 GeV

Post-LHC MCs:

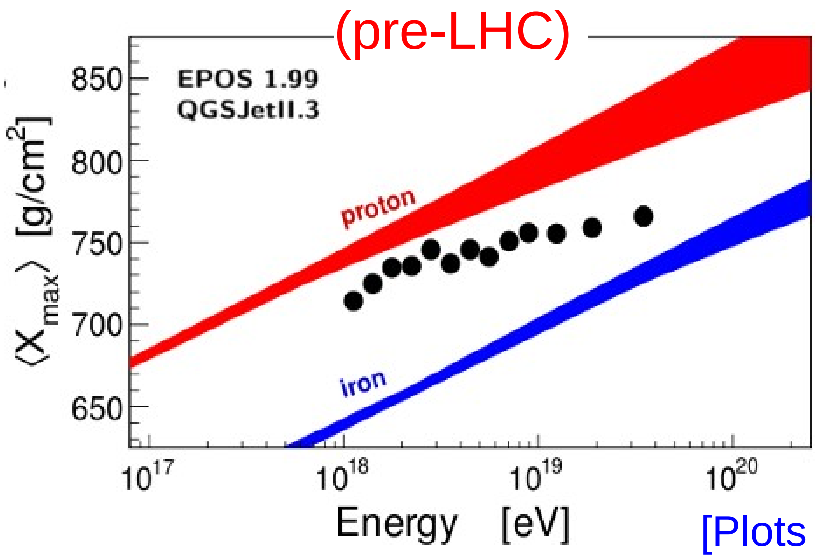


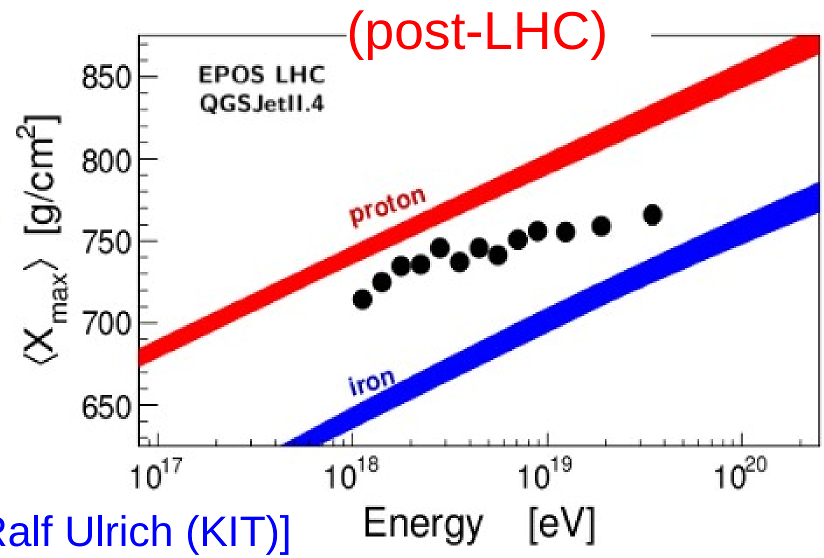
[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]

- EPOS with final-state collective flow leads to faster $<p_T>$ evolution. But still below PYTHIA 6 with $<p_T>$~1 GeV at GZK-cutoff.

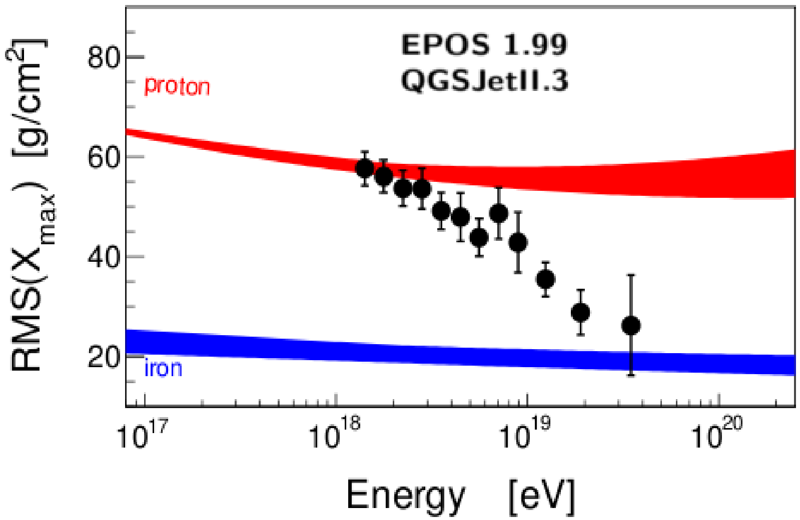
- Harder activity needed in CR MCs.

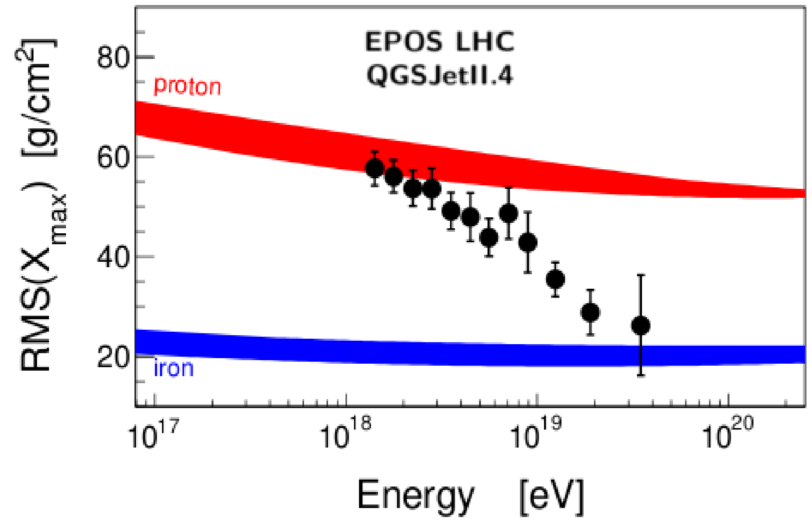
Impact on UHECR after LHC MC retuning





[Plots by Ralf Ulrich (KIT)]





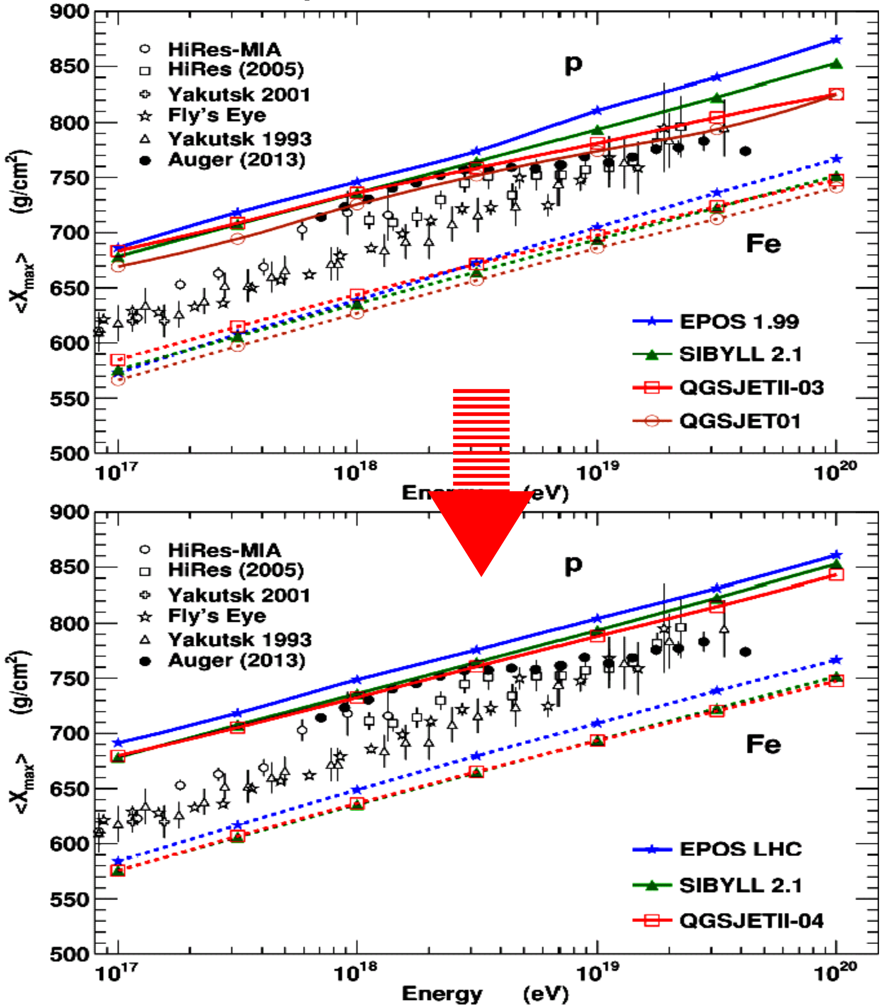
- All models consistent now with increasing CR-mass approaching GZK.
- Reduced p-Air (less so for Fe-Air) uncertainties w/ LHC-retuned Mcs.

Impact on UHECR after LHC MC retuning

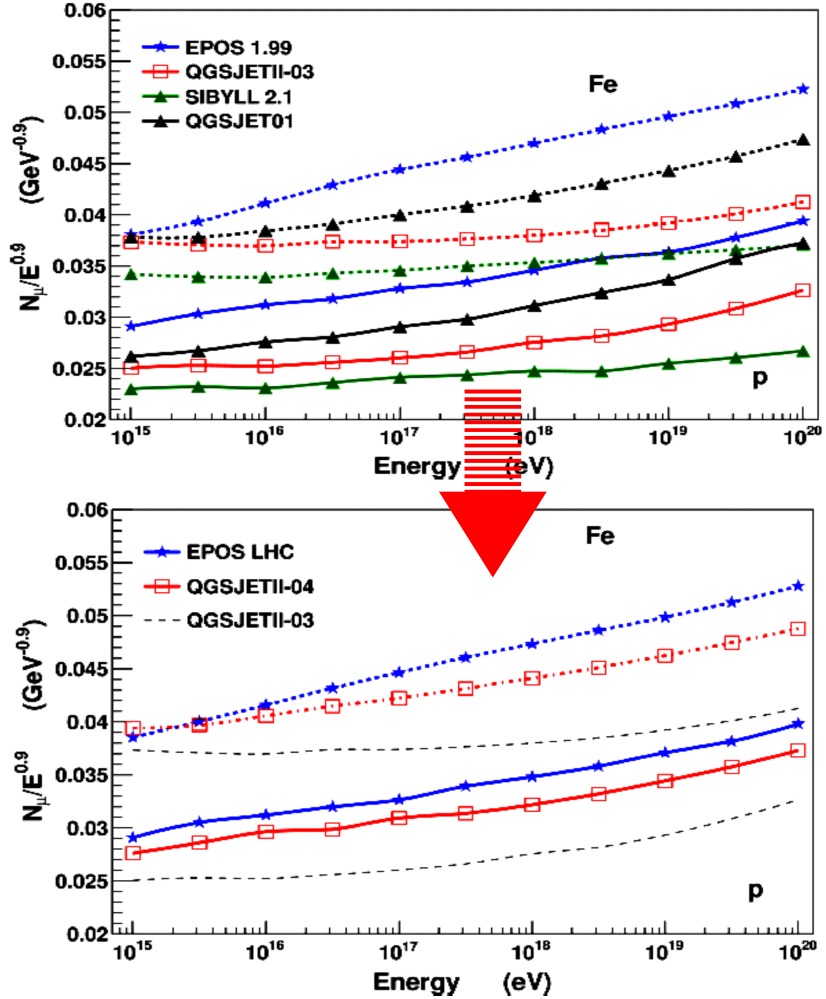
(pre-LHC)

(post-LHC)

Mean depth of shower maximum:



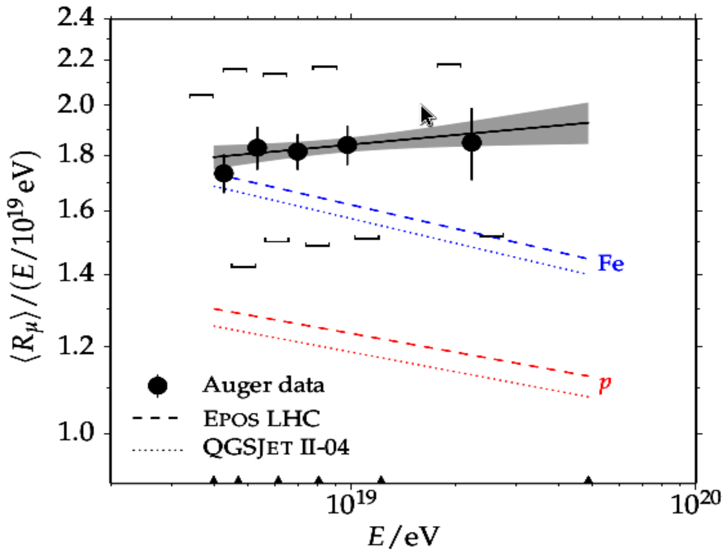
Number of muons on ground:

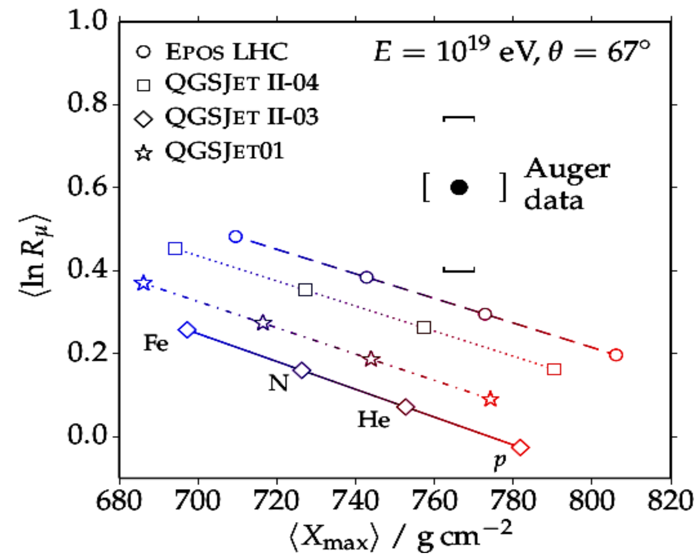


- Overall X_{max} increase. Improved MC agreement (but still ~40 gcm^{-2} inter-MC differences)
- N_{μ} increase but still ~30% deficit compared to data (heavy-quarks?)

Solving the "muon anomaly" with a collider MC?

- UHECR show μ excess (esp. at large axis distance) than predicted by MC:



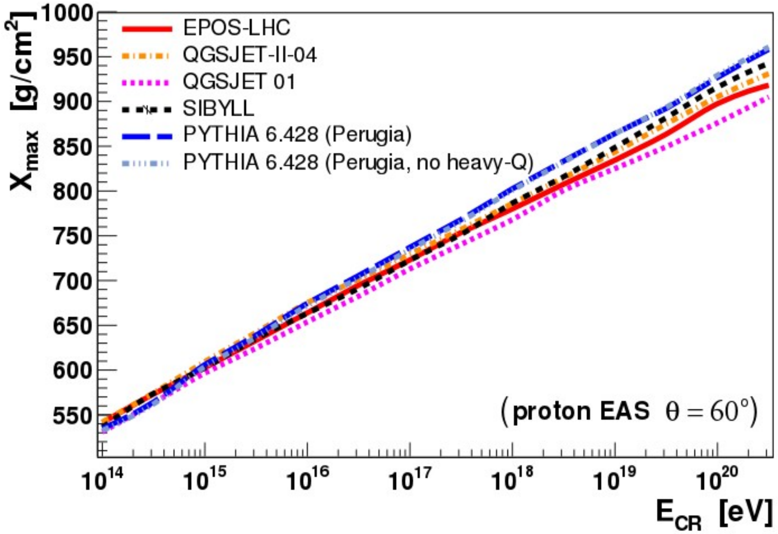


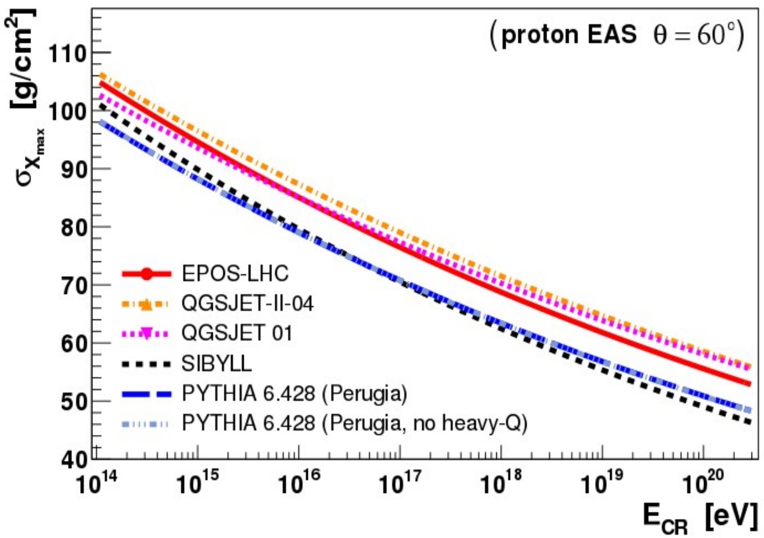
- Due to missing pQCD processes? Hard π,k→μ or D,B→μ decays?
- Impact of heavy-Q & pQCD minijet production on the μ excess studied with PYTHIA-6 (tuned to LHC data) in proton-H CONEX atmosphere.

PYTHIA 6.428 Perugia tune PYTUNES number (main features)	PDF	Q_0 cutoff at $\sqrt{s_0}$ = 7 TeV	Q_0 scaling power ϵ	ISR/FSR scale $\alpha_s(k \cdot p_T)$	Hadronization
350 (central tune 2011)	CTEQ5L1	2.93 GeV	0.265	$k = 1$	$s\bar{s}, \eta, \eta'$ suppr. = 95,63,12%
350, noHQ (central 2011; no c-,b-quarks)	CTEQ5L1	2.93 GeV	0.265	$k = 1$	$s\bar{s}, \eta, \eta'$ suppr. = 95,63,12%
371 (var. 2012, high rad.)	CTEQ6L1	2.72 GeV	0.25	$k = 1/2$	$s\bar{s}, \eta, \eta'$ suppr. = 92,70,13.5%; softer baryons
372 (var. 2012, low rad.)	CTEQ6L1	2.60 GeV	0.23	$k = 2$	$s\bar{s}, \eta, \eta'$ suppr. = 92,70,13.5%; softer baryons
380 (var. 2012, gg only at low-p_T)	CTEQ6L1	2.65 GeV	0.245	$k = 1$	$s\bar{s}, \eta, \eta'$ suppr. = 92,70,13.5%; softer baryons
381 (var. 2012, higher UE)	CTEQ6L1	2.46 GeV	0.23	$k = 1$	$s\bar{s}, \eta, \eta'$ suppr. = 92,70,13.5%; softer baryons
382 (var. 2012, lower UE)	CTEQ6L1	2.92 GeV	0.26	$k = 1$	$s\bar{s}, \eta, \eta'$ suppr. = 92,70,13.5%; softer baryons

Proton EAS properties: PYTHIA-6 vs. UHECR MCs

- PYTHIA-6 tuned to LHC data shows similar EAS as std. UHECR MCs





[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]

Proton EAS properties: PYTHIA-6 vs. UHECR MCs

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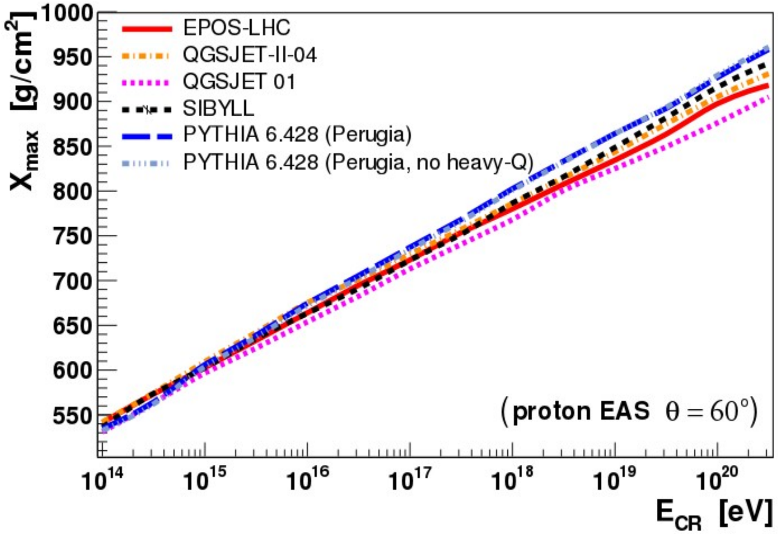
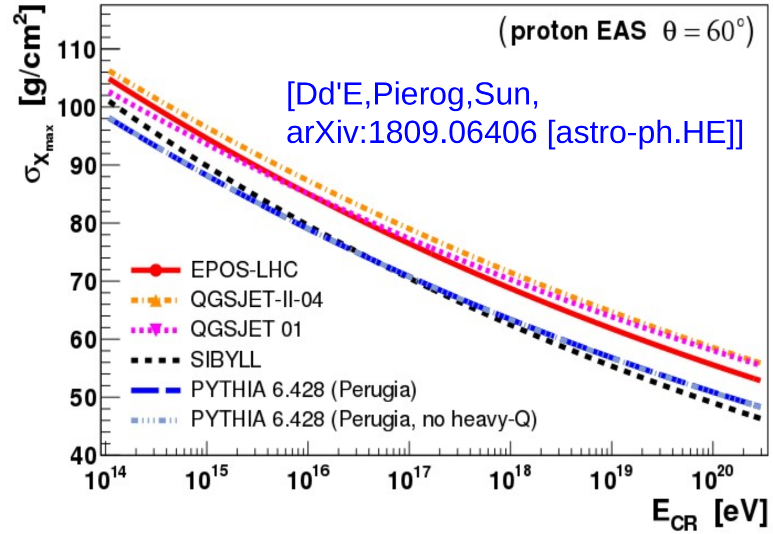
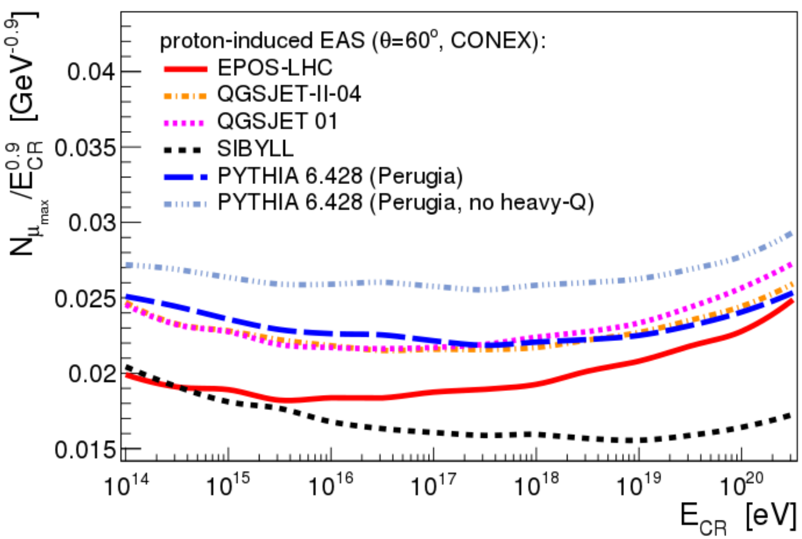
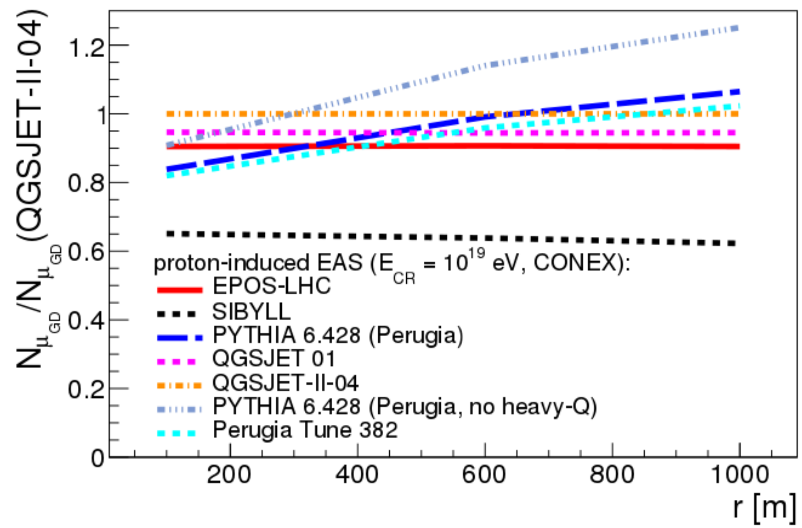




- PYTHIA-6 (esp. *without* heavy-Q) produces more μ's (and at larger axis distances) than UHECR MCs. But EPOS–QGSJET p-H, p-Air diffs. point to nuclear effects





Summary: UHECR MCs vs. LHC data

- Reasonable agreement of all pre-LHC MCs and Run-1 LHC. They "bracket" data, though no model reproduced consistently all results:

Model	SIBYLL 2.1			QGSJET01			QGSJETII			EPOS 1.99		
$\sqrt{s}$ (TeV)	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7
σ_{inel}	✓	⇑	⇑	✓	✓	✓	✓	⇑	⇑	✓	✓	✓
$dN_{ch}/d\eta\|_{\eta=0}$	✓	✓	✓	✓	✓	✓	✓	✓	⇑	✓	⇓	⇓
$P(N_{ch} < 5)$	⇑	⇑	⇑	⇑	⇑	⇓	⇑	⇑	⇑	✓	✓	✓
$P(N_{ch} > 30)$	⇑	✓	⇑	✓	⇓	⇓	✓	✓	⇑	⇓	⇓	⇓
$\langle p_\perp \rangle$	✓	⇓	⇓	⇑	⇑	✓	⇑	⇑	⇑	✓	✓	✓

- No significant change of multiparticle production at the LHC (~10^{16} eV): "CR knee" at ~$10^{15.5}$ eV not due to new (unobserved) particles.

- EPOS-LHC, QGSJET-II-4, SIBYLL2.3 updates: Retuning of diffraction, multiparton colls., saturation, proton-nucleus effects (based on p-Pb at 5 TeV, 2015). Improved reproduction of newest LHC data.
- Still further improvements needed in:
  - Very forward particle production.
  - Semi-hard MPIs. Perturbative QCD dynamics (harder minijets).
- Solution of UHECR μ deficit requires pQCD minijet + nuclear effects combined (not missing heavy-quark production). Enough or new physics?

Backup slides

High-energy proton-proton collisions

- Hadrons are extended composite objects: even at asymptotically large c.m. energies, only ~60% of x-section is “computable” within pQCD

MINI-JET pQCD

(1) Perturbative parton-parton collisions

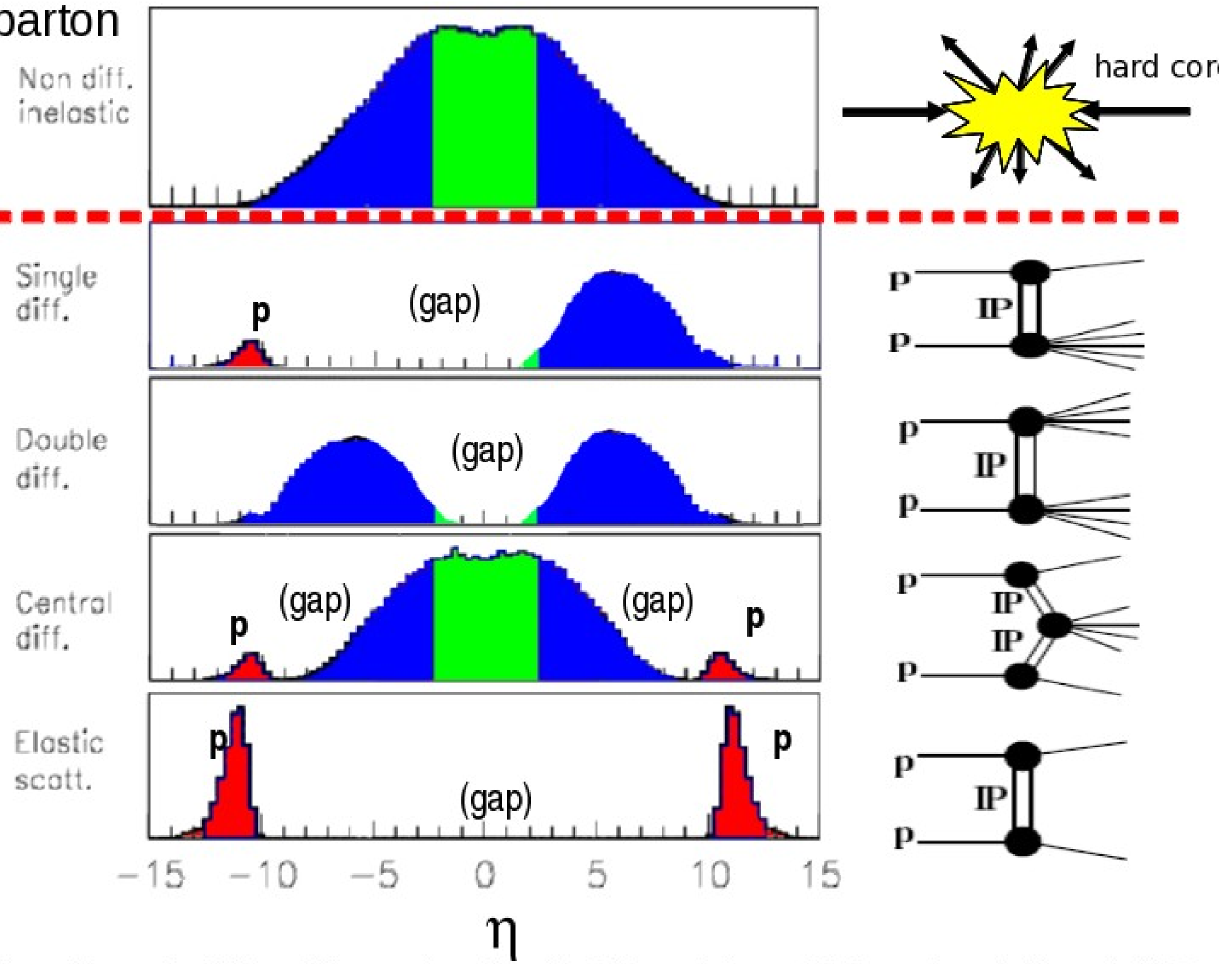
~60%

(2) Diffractive + elastic

~40%

- 1 or 2 protons intact. + 1 or 2 rapidity gaps:
- No colour flux.
- Colourless exchange with vacuum $J^{PC}=0^{++}$ quantum-numbers: |Pomeron = 2-gluons in colour-singlet state.

Regge-Gribov

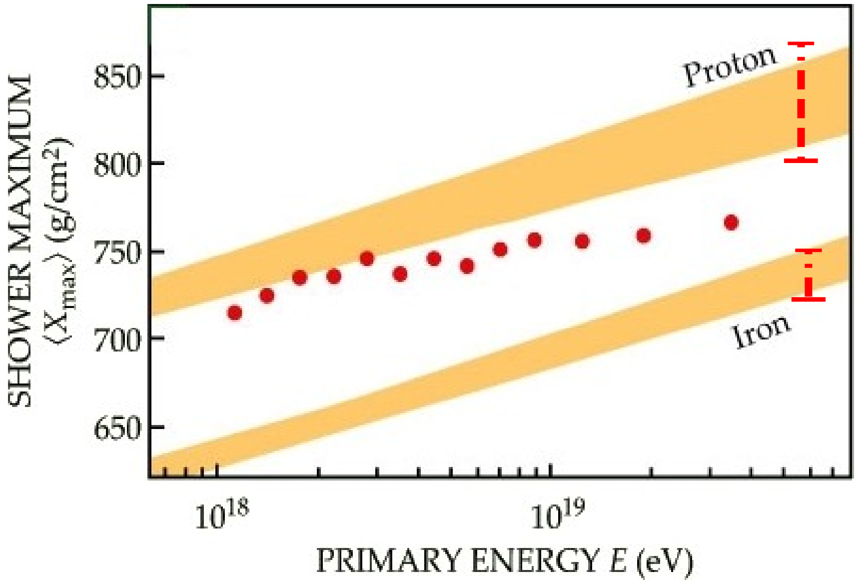


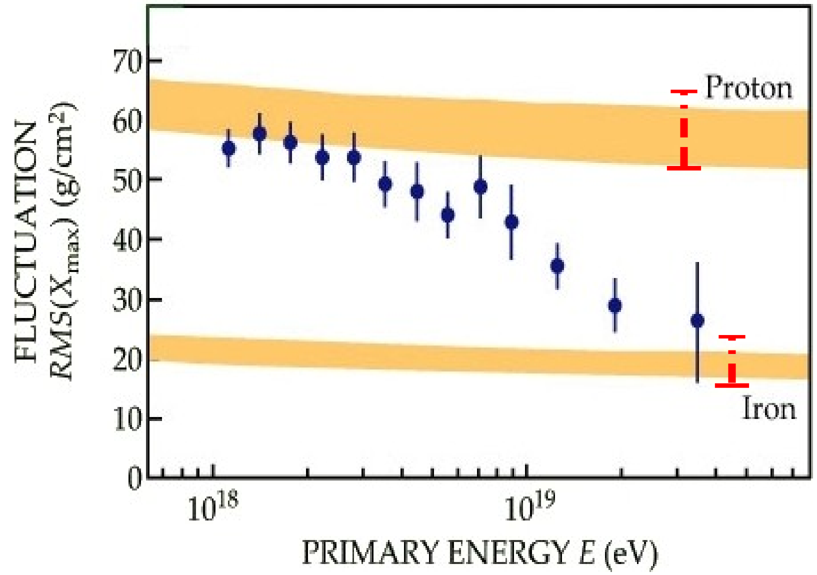
- pQCD (~60 mb) + diffractive (~15mb) + elastic (~25 mb) ~ 100 mb at the LHC.

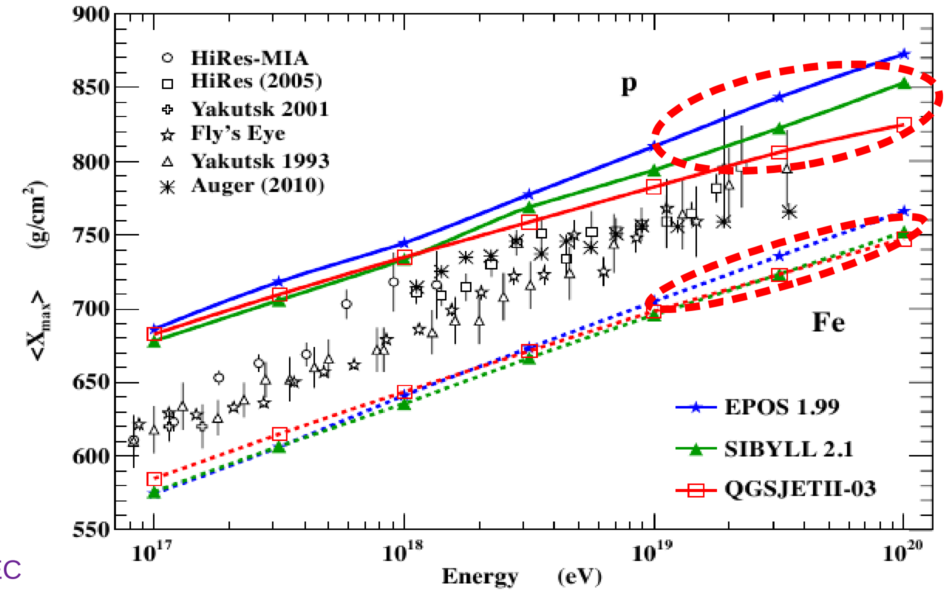
UHECR at GZK-cutoff: p or Fe-ions ? (pre-LHC)

Auger: PRL 104 (2010) 091101

- Auger shower-max position & fluctuations favour heavy-ions for $>10^{19}$ eV







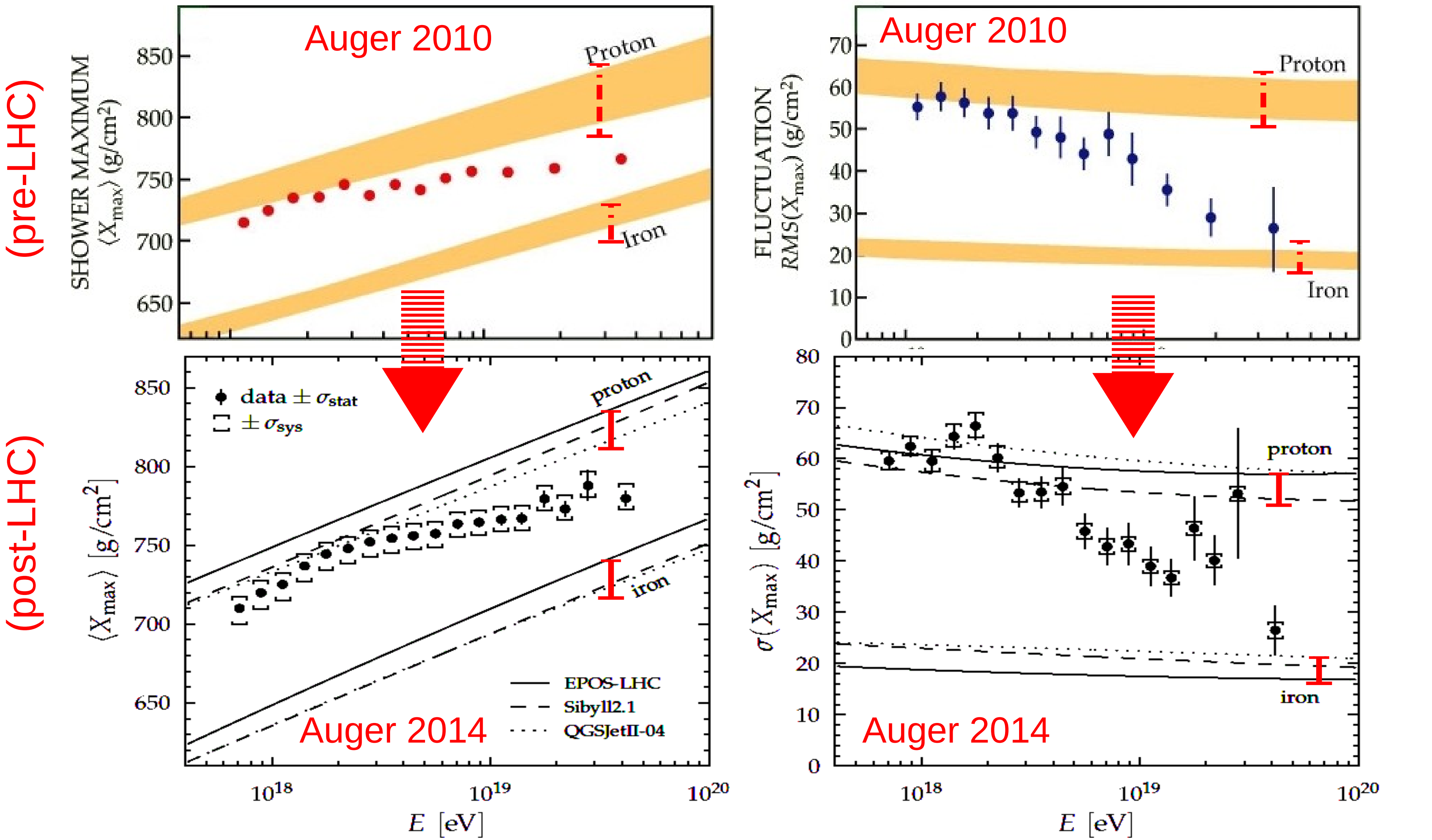
- Hadronic MC uncertainties propagate to CR mass.

QGSJET-II,SIBYLL: favour protons

EPOS: favours mixture protons+Fe-ions

Impact of LHC data on UHE CRs (Auger)

Mean depth of shower maximum: Fluctuations of shower max:

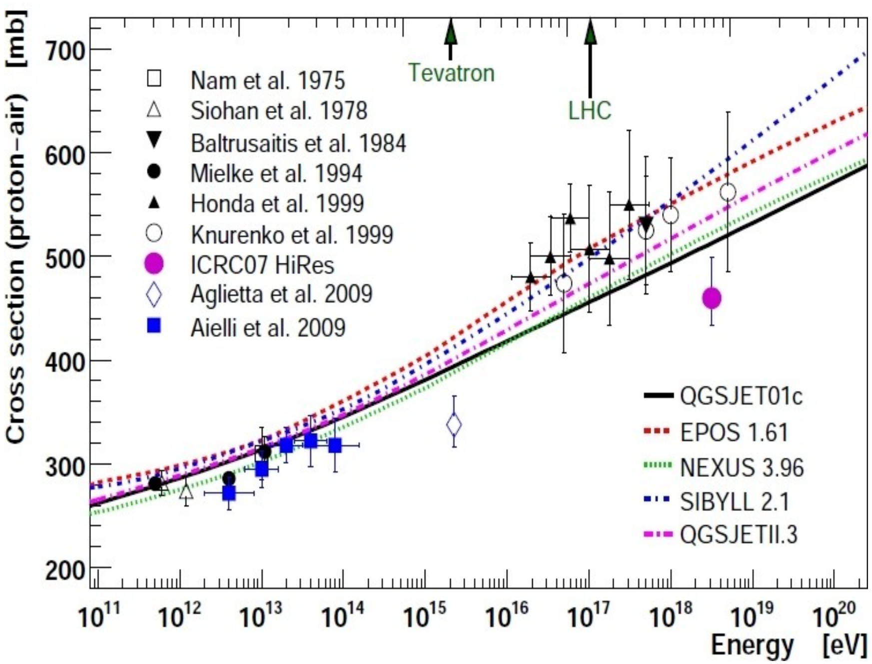


- Data prefer average p-Fe composition, w/ reduced model uncertainties.

Total & elastic p-p cross sections

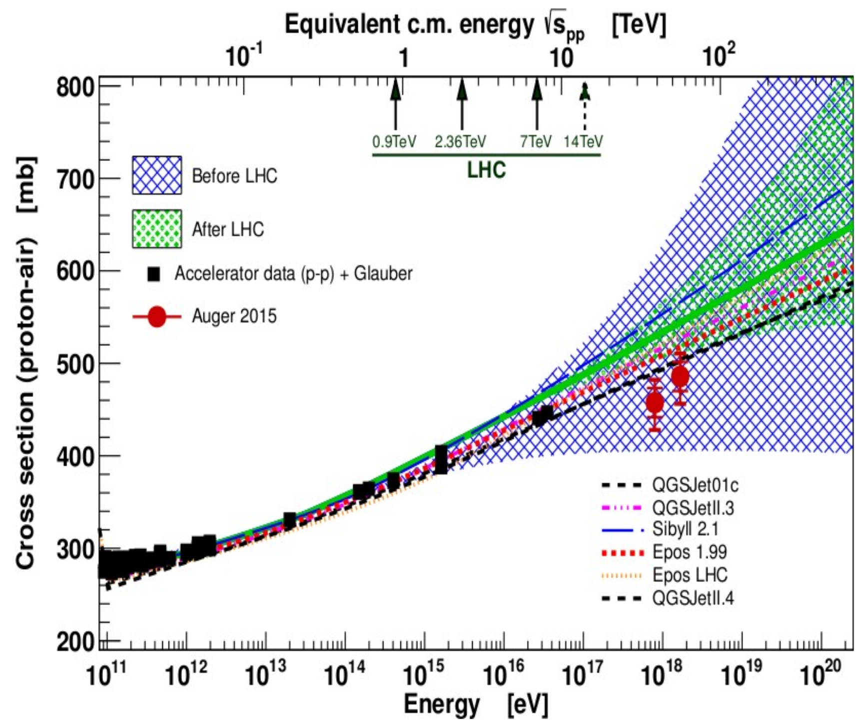
- Non-computable from QCD Lagrangian, but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.

- p-Air x-sections even more uncertain (Glauber model):



R.Ulrich, eConf C0906083 (2009)

Reduced uncertainties post-LHC1

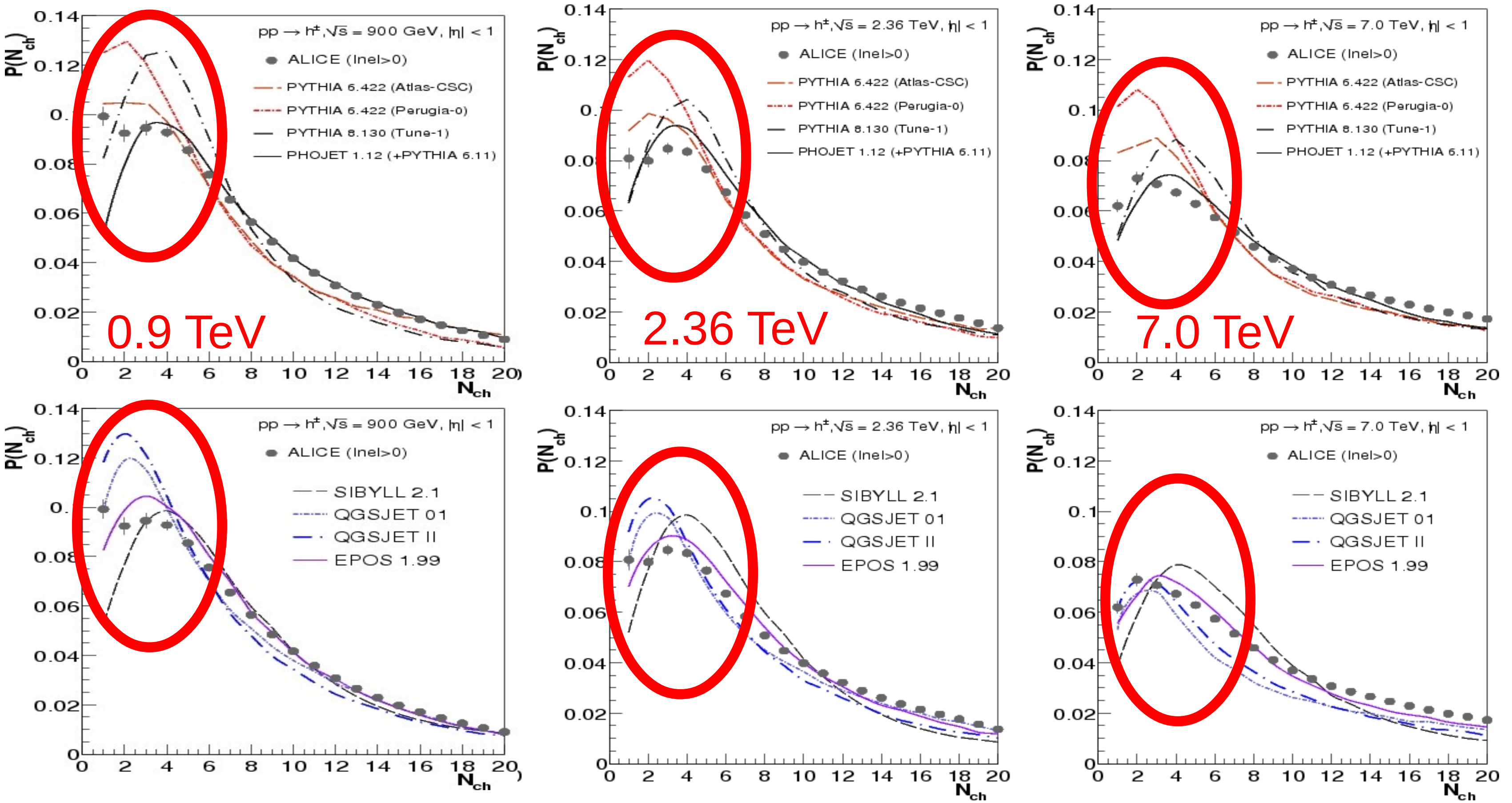


LHC low multiplicity probabilities

- Models ~OK with average multiplicity/event, may miss the event-by-event multiplicity probability at low N_{ch} in the data:

PYTHIA, PHOJET:

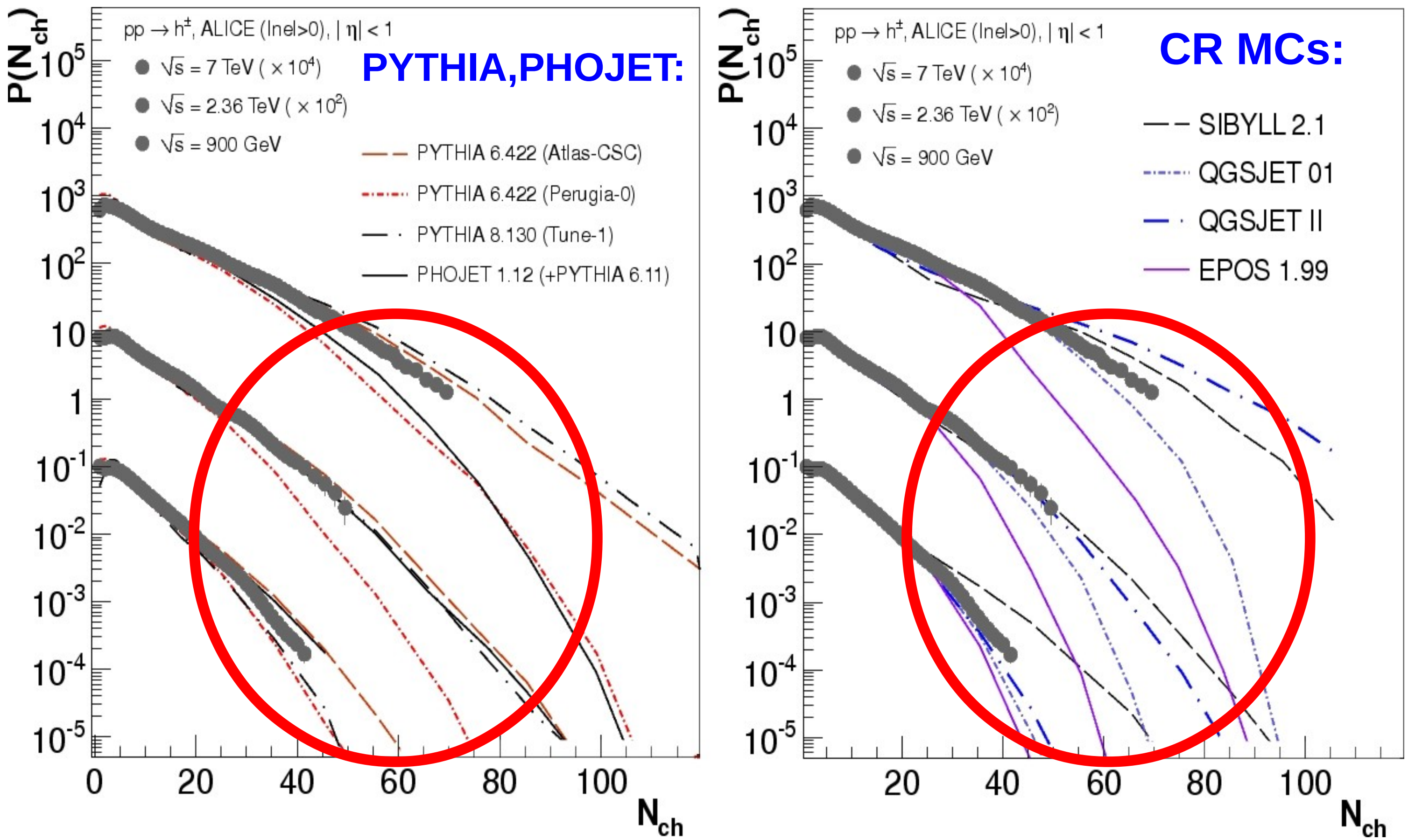
CRs MCs:



- Improvement of diffractive interactions needed.

LHC large multiplicity probabilities

- Models ~OK with average multiplicity/event, may miss the event-by-event multiplicity probability at high N_{ch} in the data:



- Improvement of multi-parton interactions modeling needed.

UHECRs energy & identification

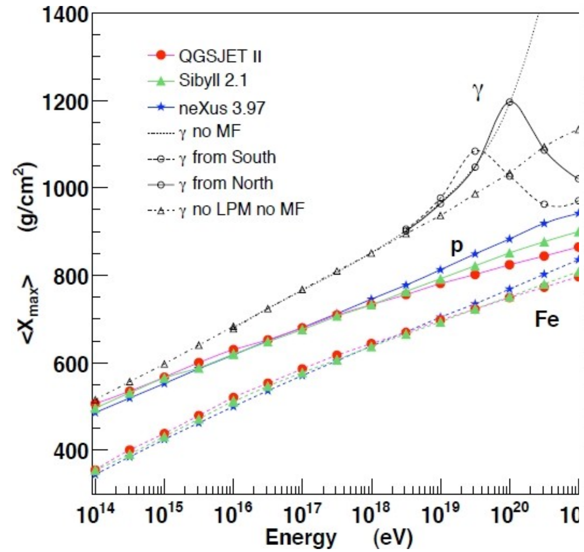
[Blumer-Engel-Horandel, PPNP 68(2009)293]

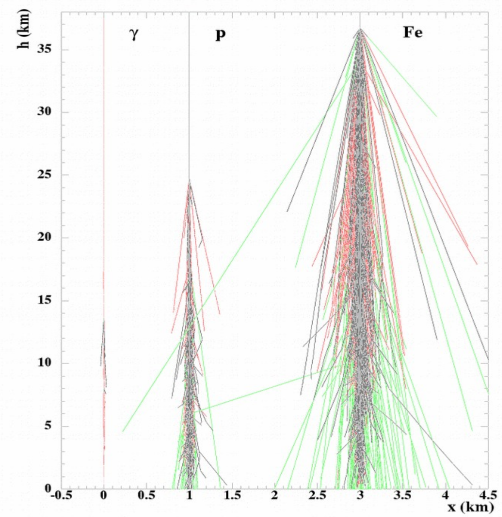
- Position & fluctuations of shower maximum:

  Depth: γ > p > A

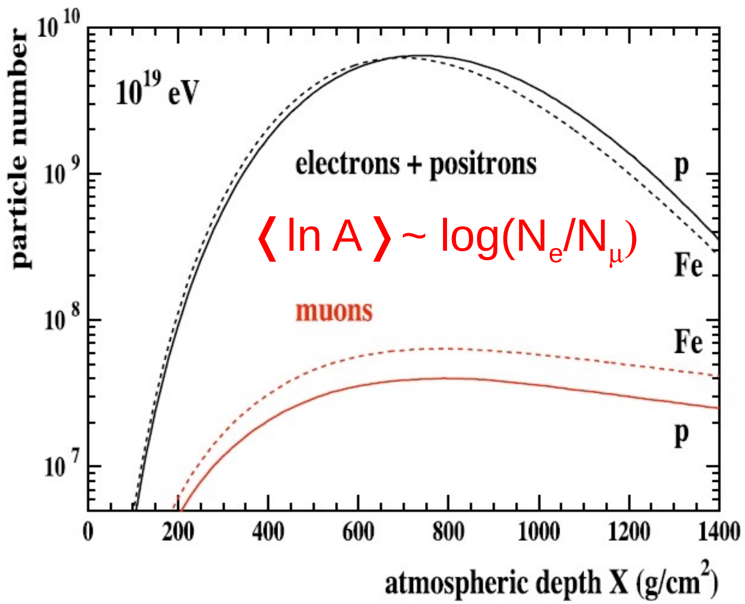
  $X_{max}(p) \sim X_{max}(Fe) + 150\ g/cm^2$

  Shower-to-shower fluctuations: smaller for ions than proton.

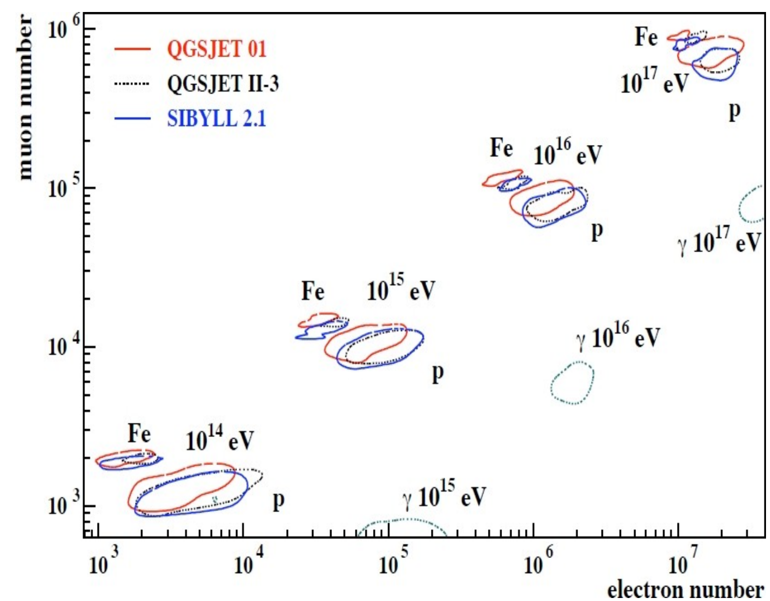




- Number of e± & muons:



$\langle \ln A \rangle \sim \log(N_e/N_\mu)$

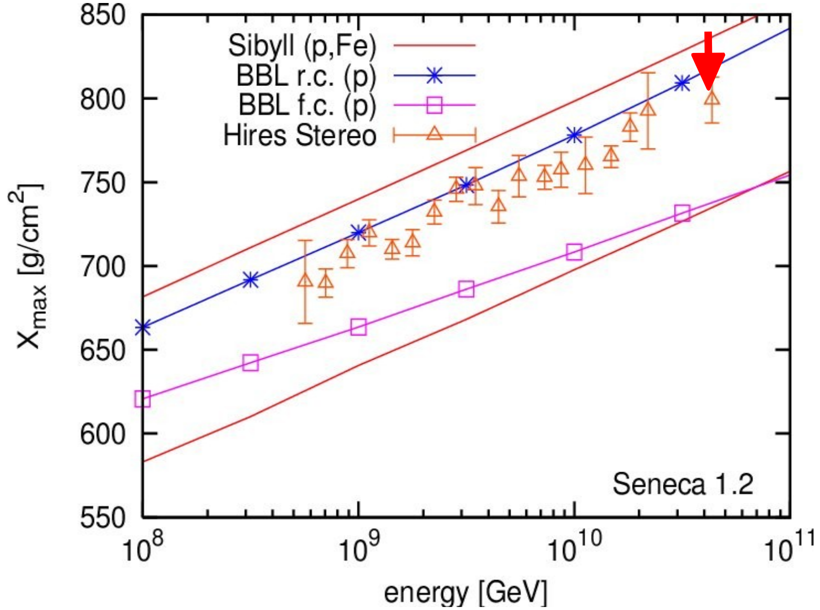


Examples of implications for EAS

- Reduced dN/dη (esp. fwd):

  Less penetration:
  lower X_{max} (~ -30 g/cm²)

Drescher, Dumitru, Strikman
PRL 94 (2005) 231801



- Reduced charm cross sections:

  Less muons

Machado&Goncalves
JHEP0704 (2007) 028