The strong interaction at multi-TeV energies: collider & cosmic-rays data(*)

"30 years of Strong Interactions"

Spa, 7th April 2011

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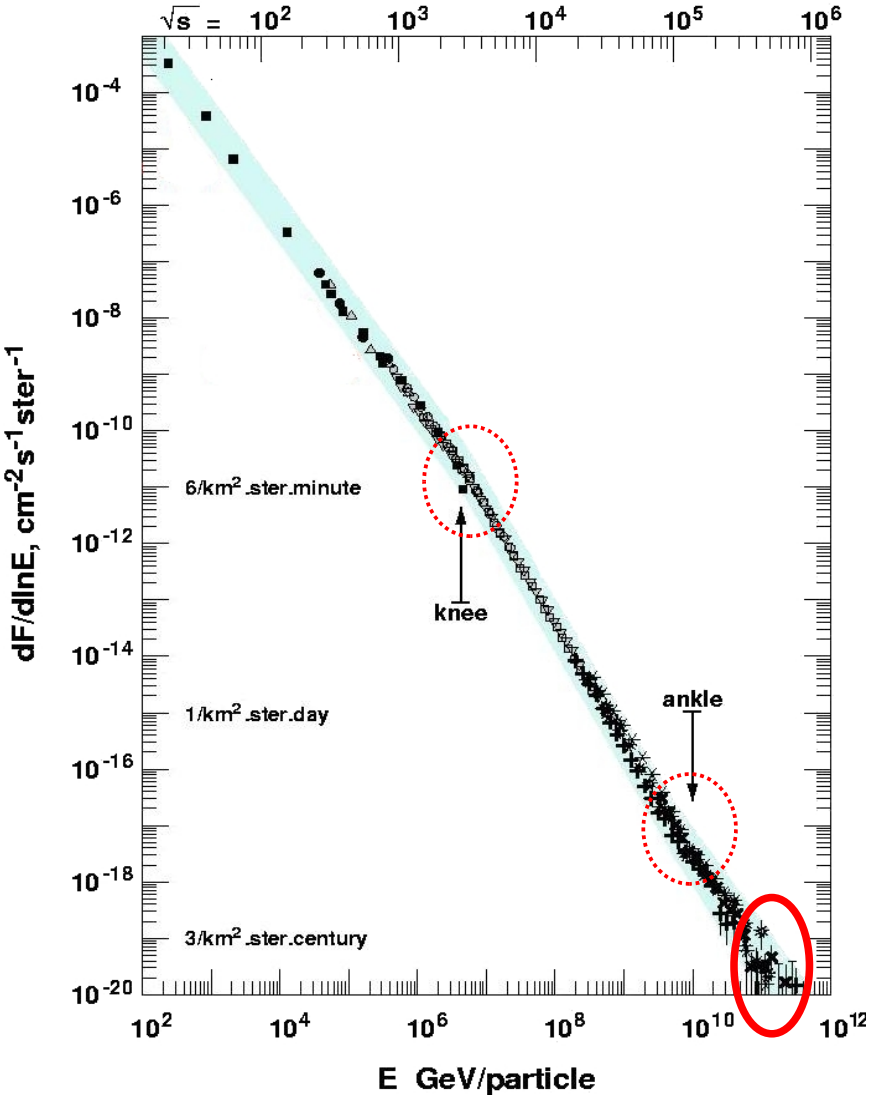
CERN

(*) DdE, R.Engel, S.Ostapchenko, T.Pierog, K. Werner, arXiv:1101.5596 [astro-ph.HE]

Ultra High Energy Cosmic-Rays (UHECRs)

- Cosmic-ray flux falls very rapidly with energy (power-law: E^{-n}):

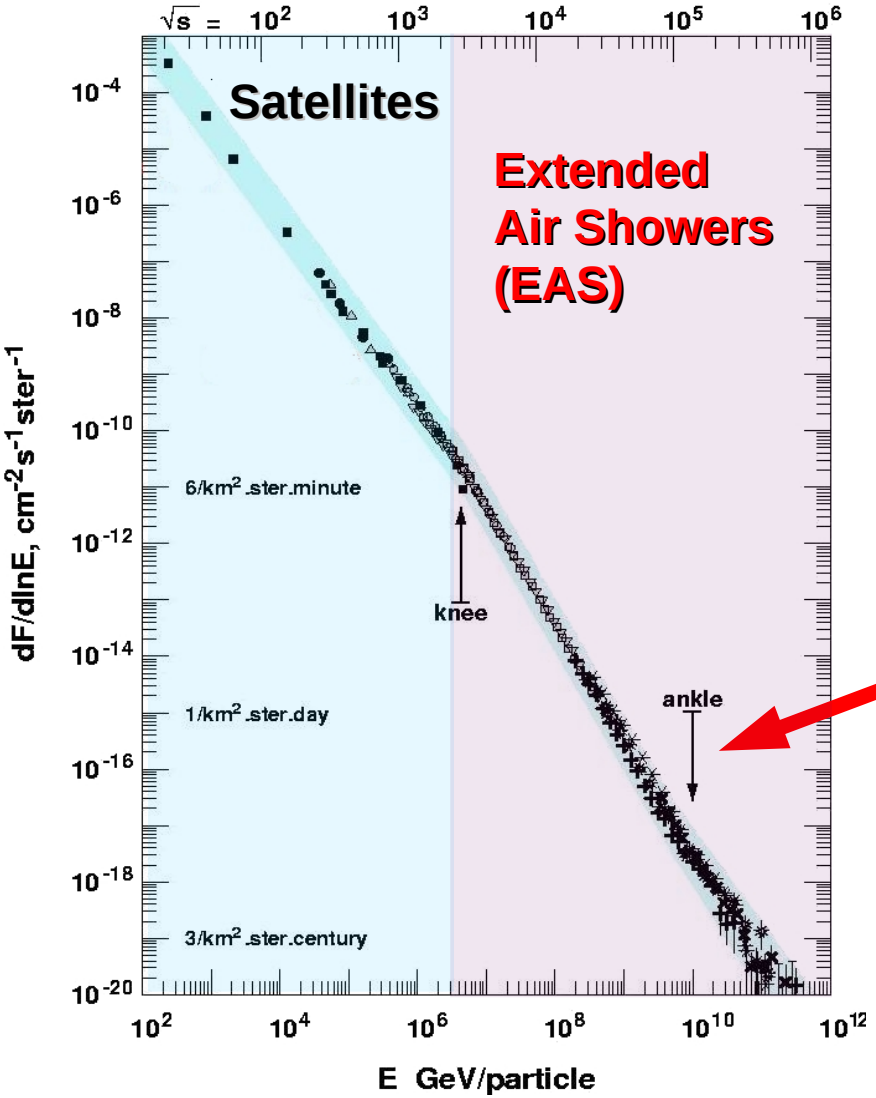


- Flux has 2 slope changes:
  "knee" at $E_{lab} \sim 10^{15}$ eV: $E^{-2.7} \rightarrow E^{-3.1}$
  "ankle" at $E_{lab} \sim 10^{18}$ eV: $E^{-3.1} \rightarrow E^{-2.6}$
- ☞ What's the origin of these structures ?
- Cosmic-rays observed up to energies $E_{lab} \sim 10^{20}$ eV (GZK-cutoff):
  - ☞ What are their sources ? What's the acceleration mechanism ?
  - ☞ What is their nature (protons, ions) ?

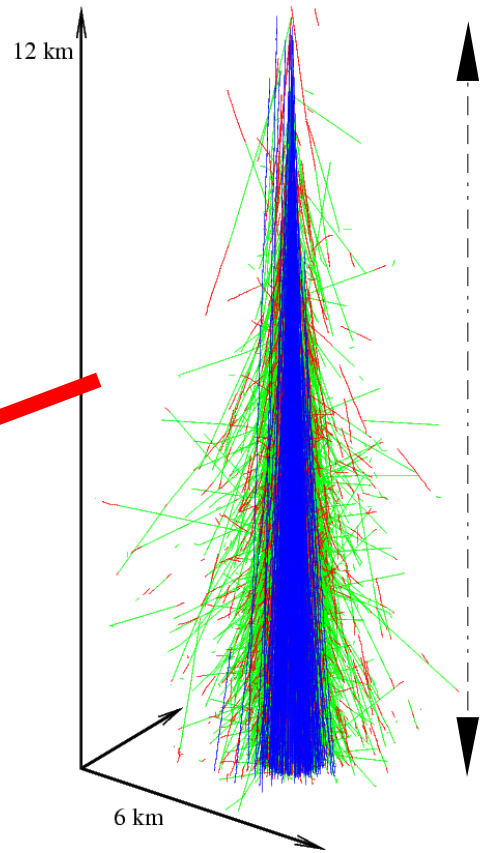
What can the LHC do to solve those open questions ?

Ultra High Energy Cosmic-Rays via EAS

- For $E_{lab} > 10^{15}$ eV flux too low for satellites/balloons (1 CR per m^2-year):



- Indirect measurements using the atmosphere as a "calorimeter":



~27 X_0

~11 λ_{int}

Ultra High Energy Cosmic-Rays via EAS

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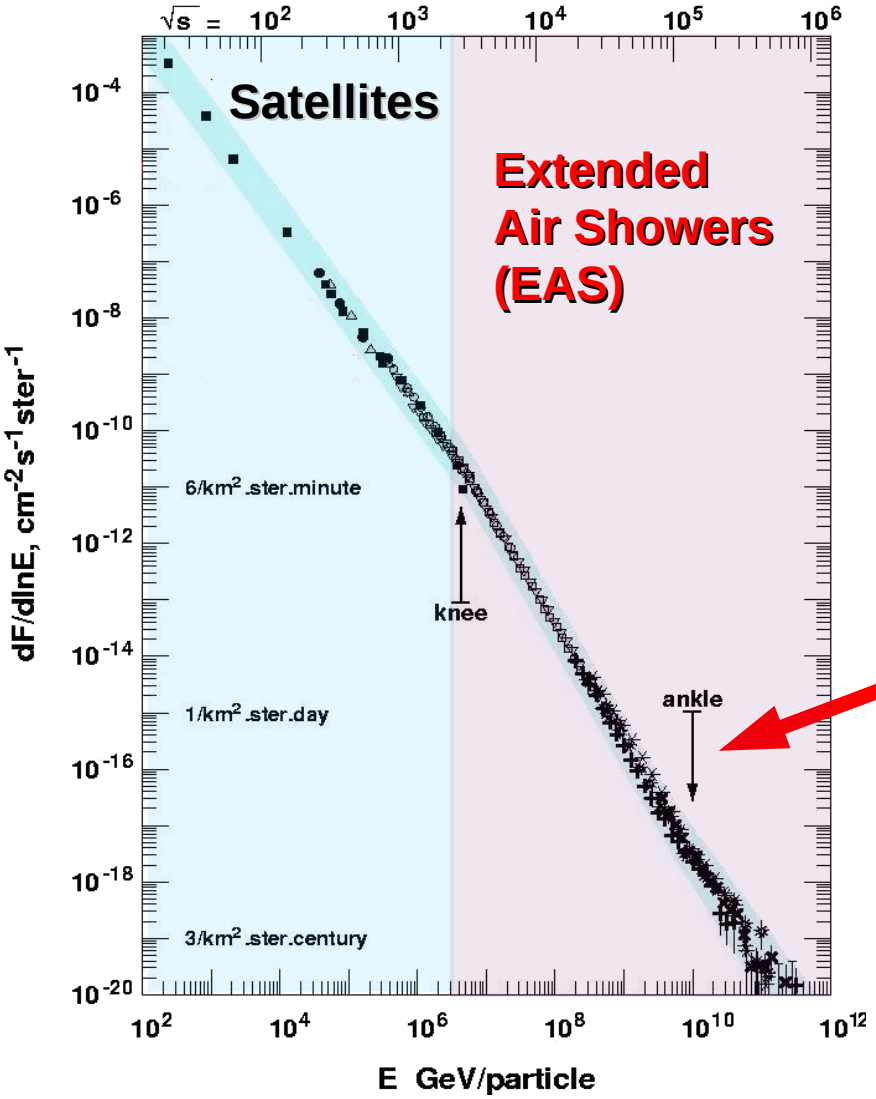
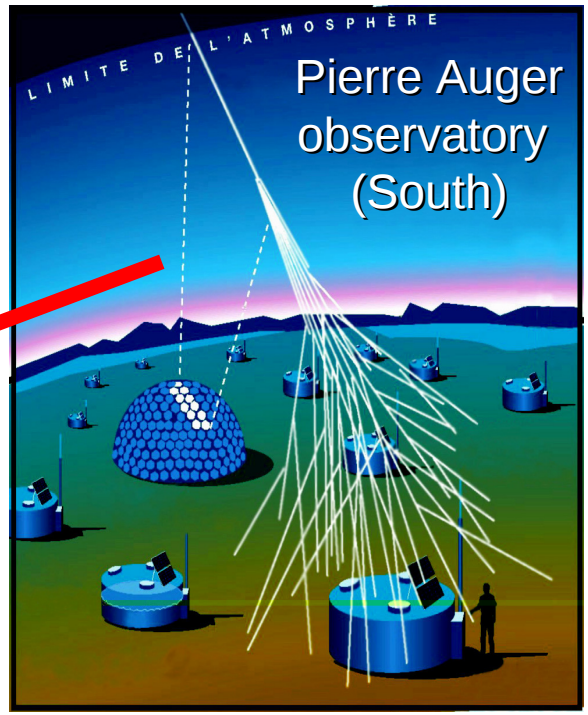


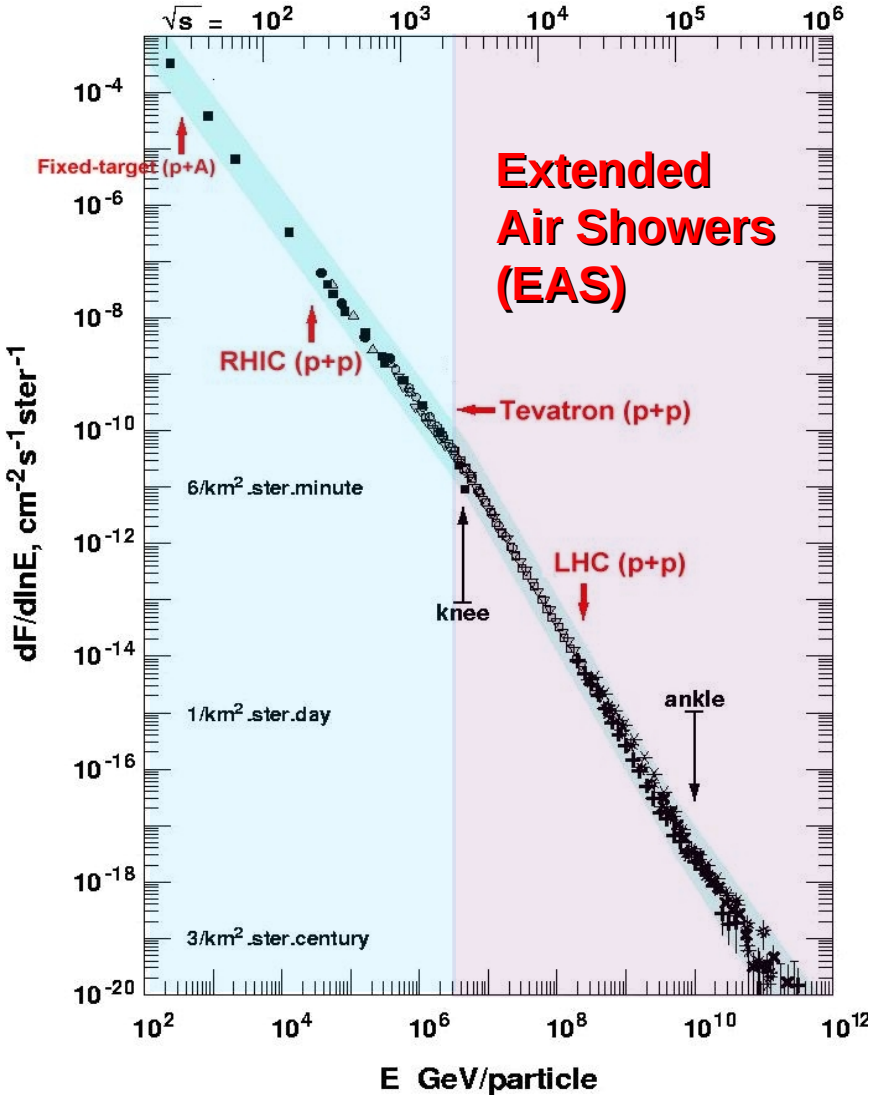
- Indirect measurements using the atmosphere as a "calorimeter":
  - UV fluorescence light in air (N*)
  - Cherenkov-light from $e^{\pm}$,$\mu^{\pm}$ at ground



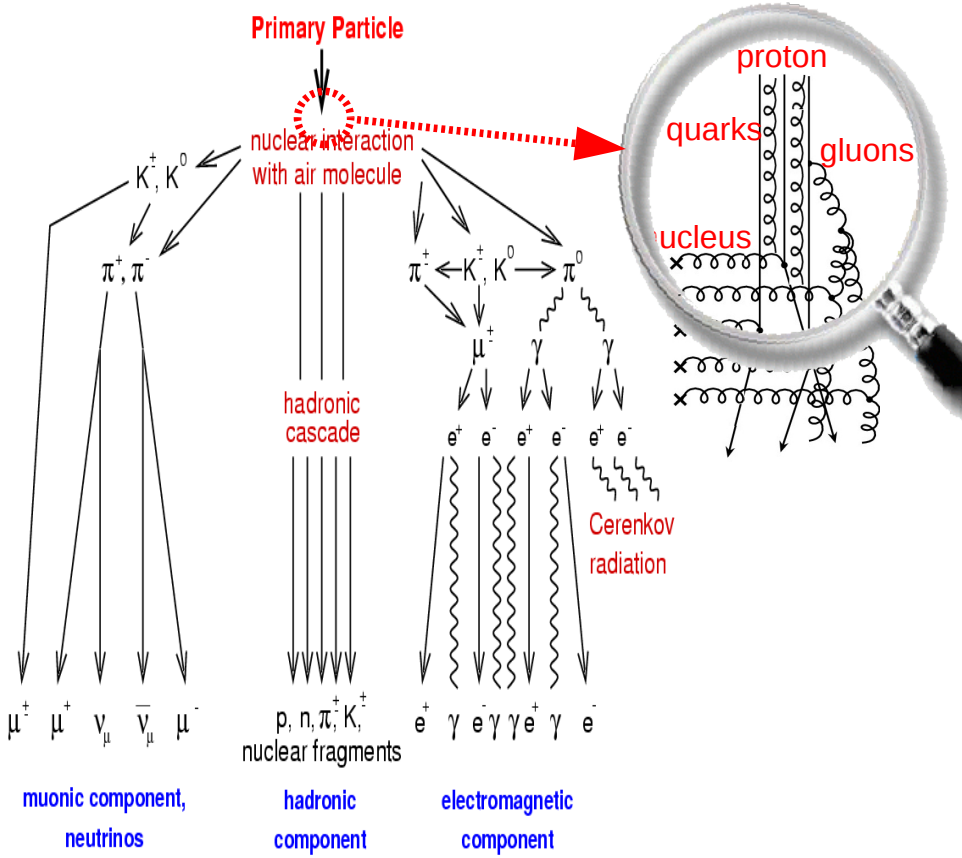
HiRes/TA observatory (North)

Ultra High Energy Cosmic-Rays via EAS

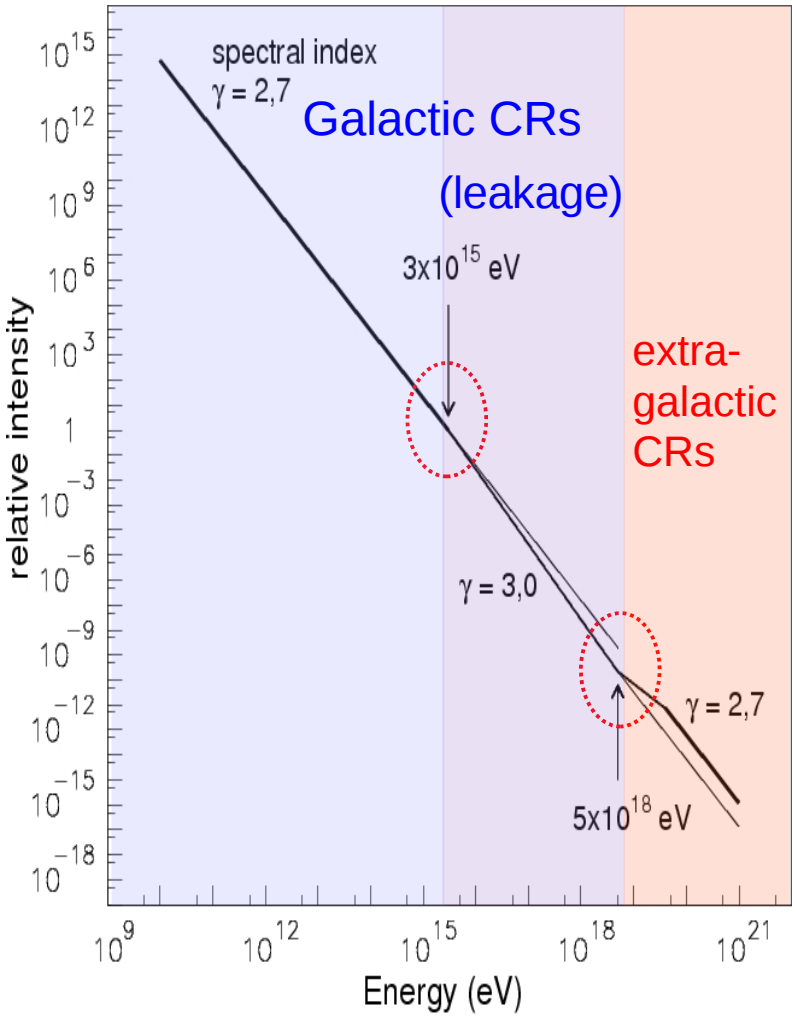
- CR energy & mass determined via hadronic+transport Monte Carlos:



- Primary collisions: QCD interactions at c.m. energies up to $\sqrt{s}_{GZK}$~300 TeV.
- MCs tuned with accelerator data.



UHECR structures: “knee” & “ankle” ?



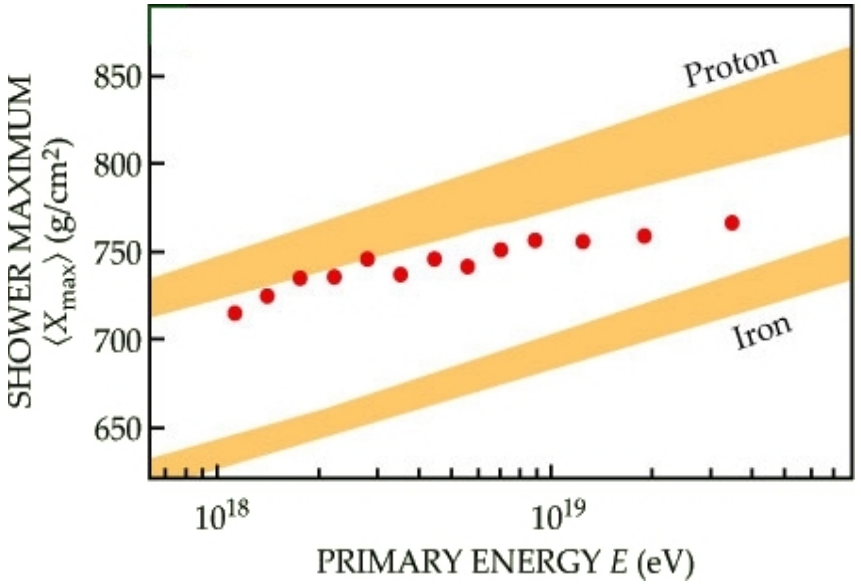
Adapted from A.Codino, F.Plouin NPB(2007)307

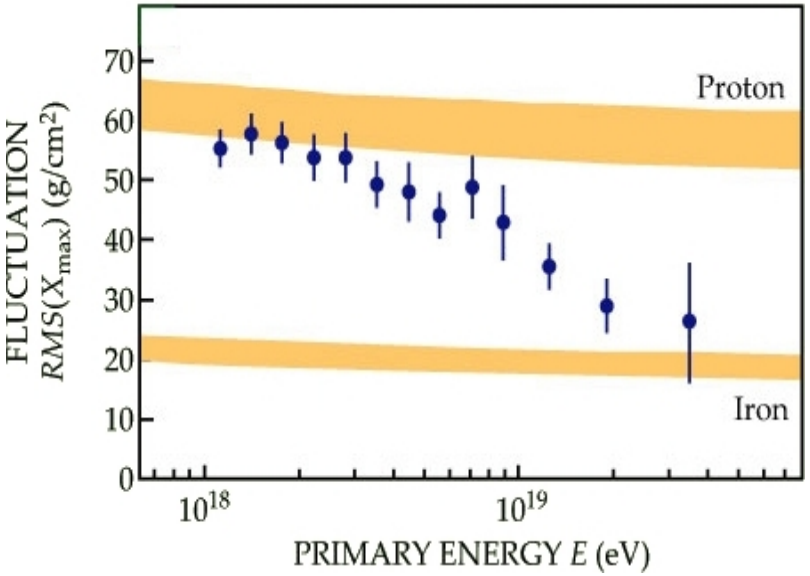
- Knee change of slope ($E_{lab} \sim 10^{15}$ eV):
  - ✓ Steeping occurring later for heavier CRs observed. Consistent with increasing leakage outside of galaxy of CRs with smaller Z-charge (Larmor radius).
  - ✓ Also $E_{max} \sim 10^{15}$ eV from Galactic SNRs
  - ✖ Changes in EAS due to the production of new (unobserved) particles excluded ?
- Ankle change of slope ($E_{lab} \sim 10^{18}$ eV):
  - ✓ Change from Galactic - Extragalactic CRs ?
  - ✖ CR identities unclear today (uncertainties shower X_{max}, N_μ-N_e, and hadronic MC)

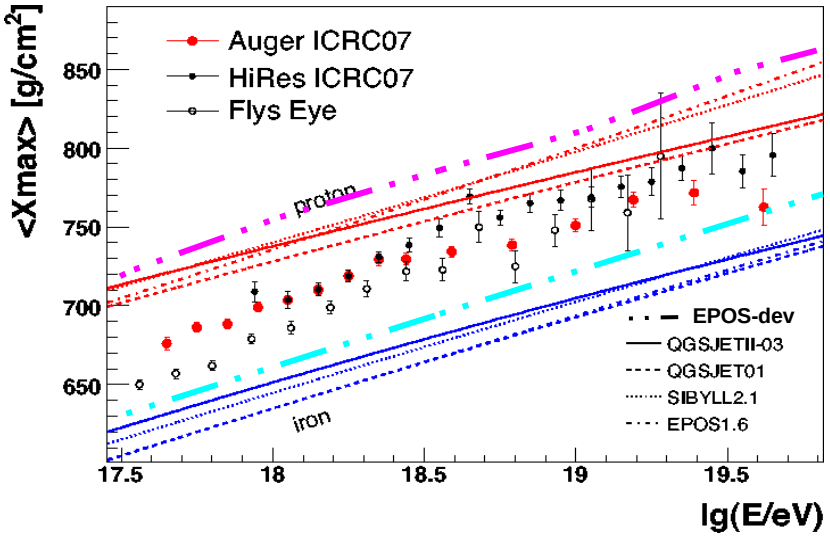
UHECR at GZK-cutoff: protons or Fe-ions ?

Auger: PRL 104 (2010) 091101

- Shower-max position & fluctuations favour heavier ions above 10^{19} eV







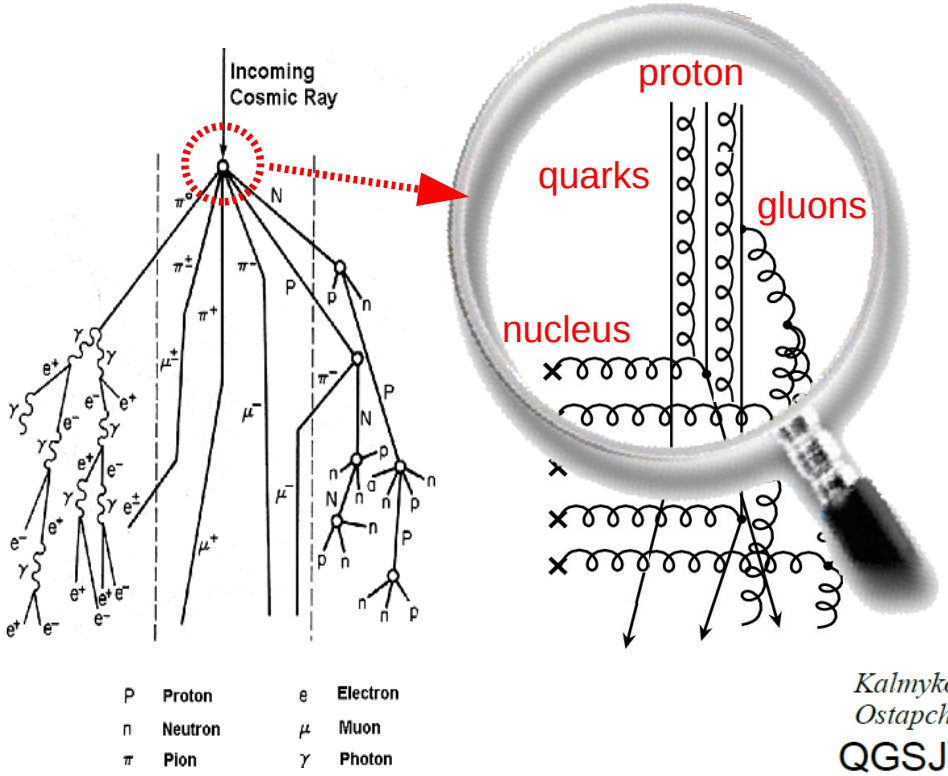
- Hadronic MC uncertainties propagate to CR mass.

QGSJET-II,SIBYLL: favour protons

EPOS-dev: favours Fe-ions

Hadronic Monte Carlos

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

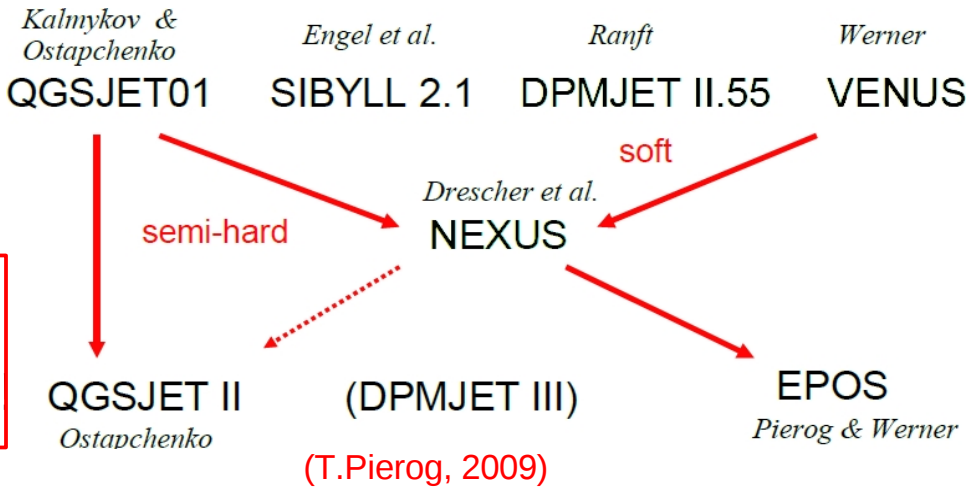


- Theoretical basis :
  Gribov-Regge (soft) + pQCD (hard)
- Lots of extra modeling:
  - Diffraction
  - Gluon saturation in PDFs
  - Multi-parton interactions
  - Parton fragmentation
  - Beam-remnants
  - ...

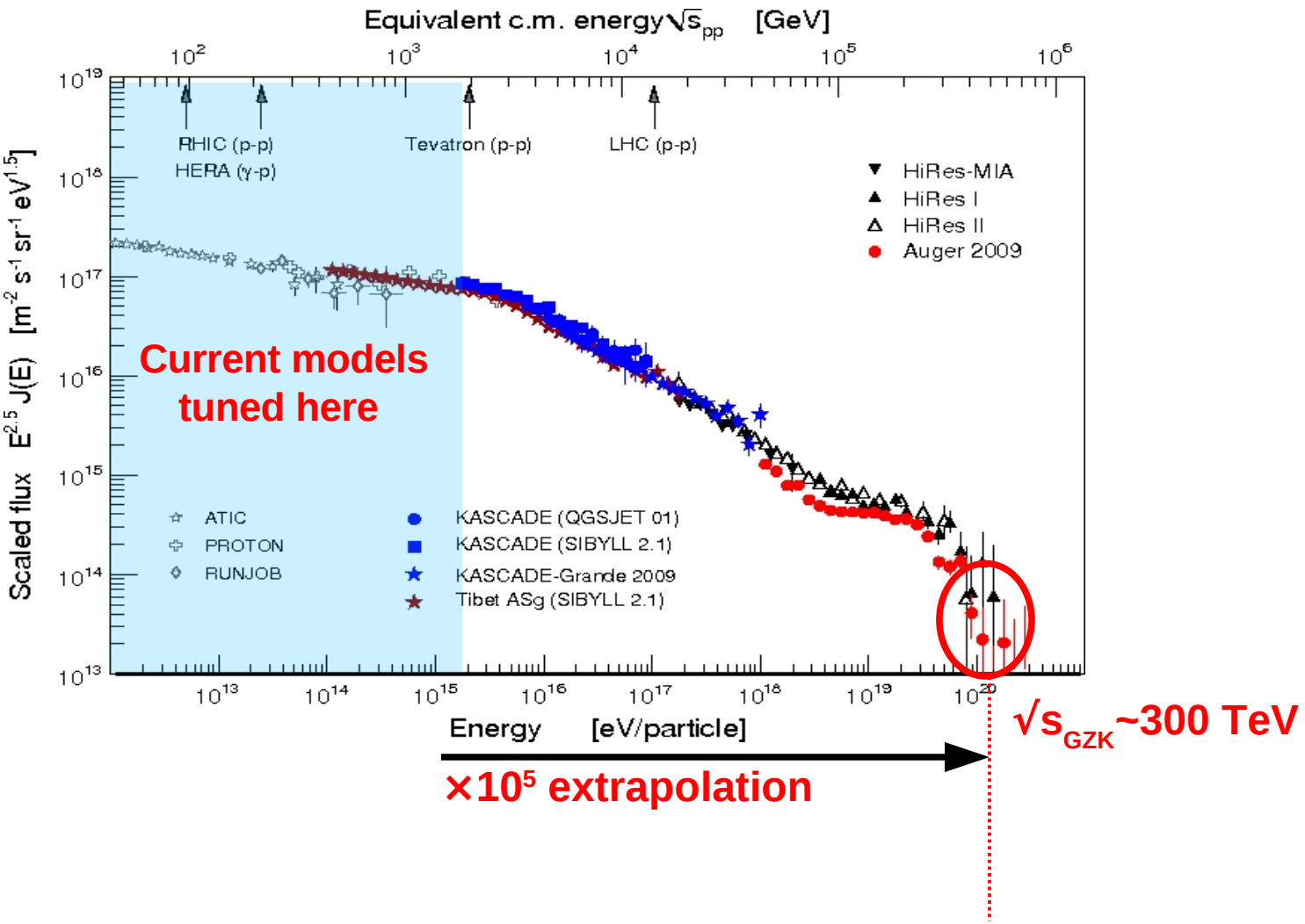
- Hadronic Monte Carlos:

Tuned with accelerator data.

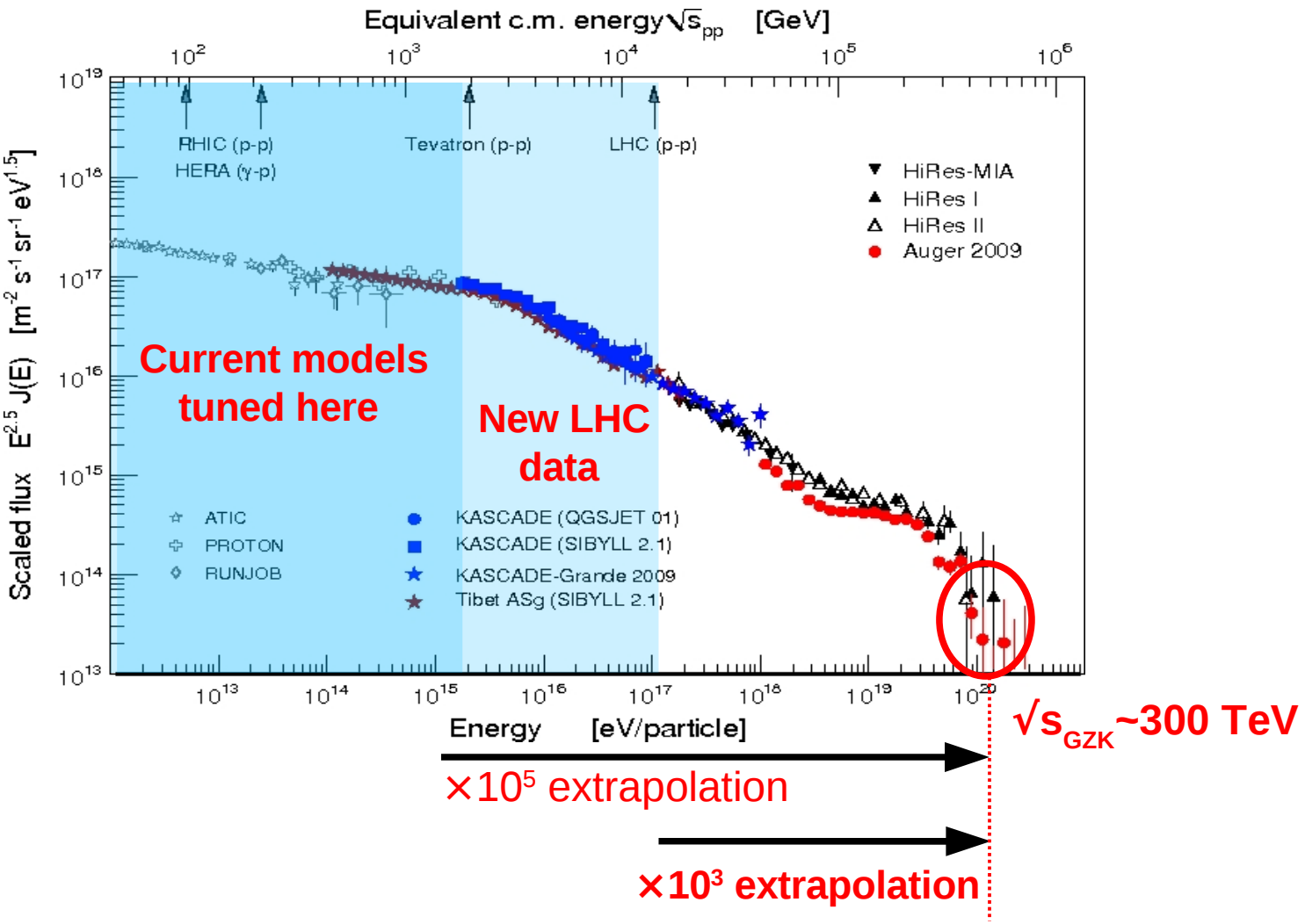
Large √s extrapolations involved



Hadronic MCs tuning with collider data

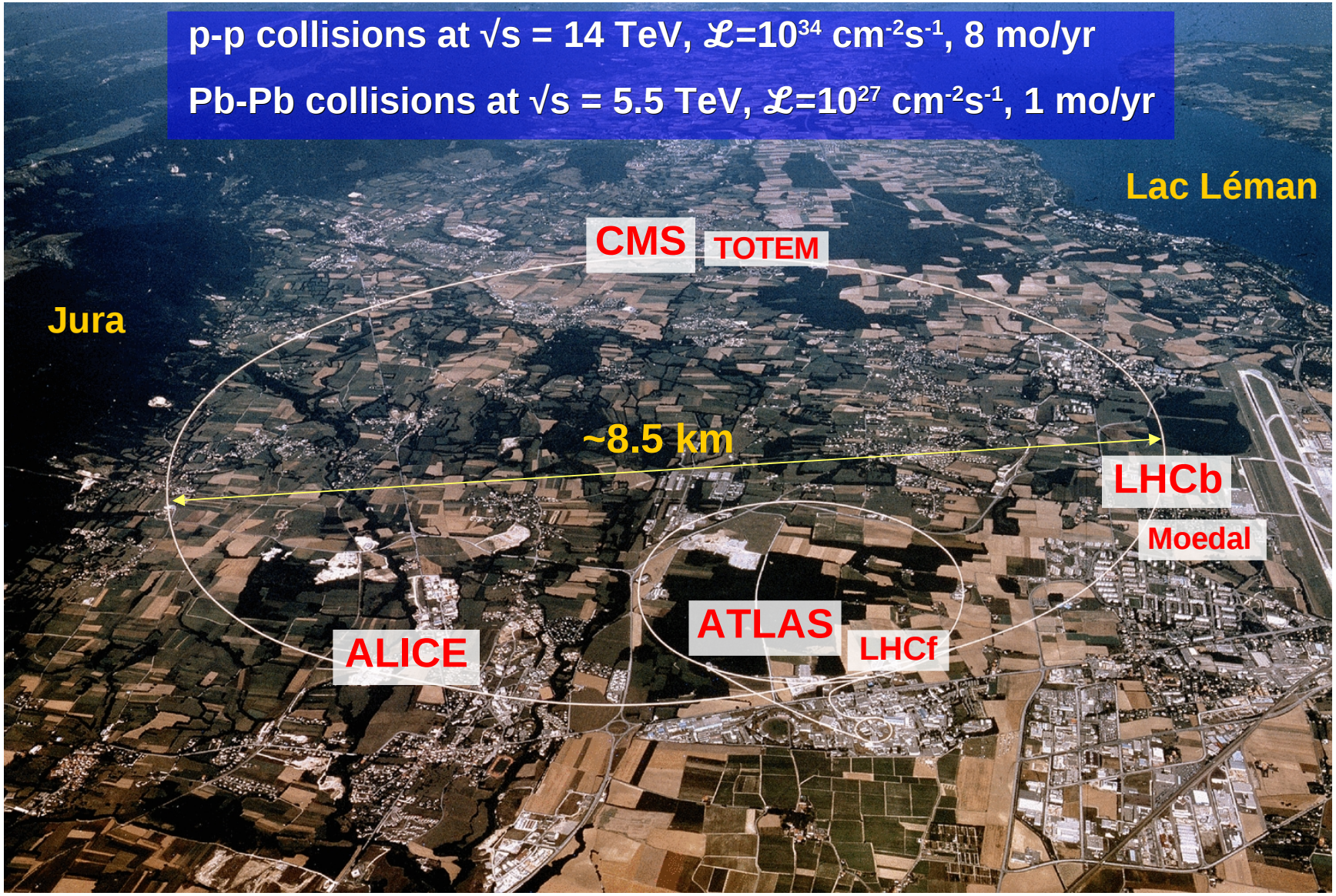


Hadronic MCs tuning with collider data

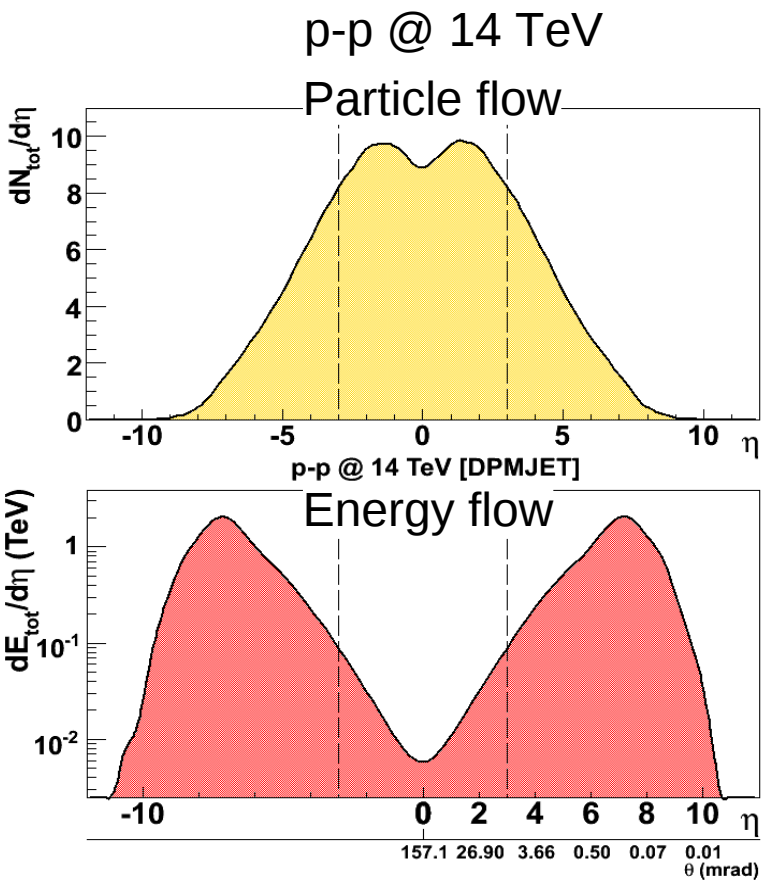


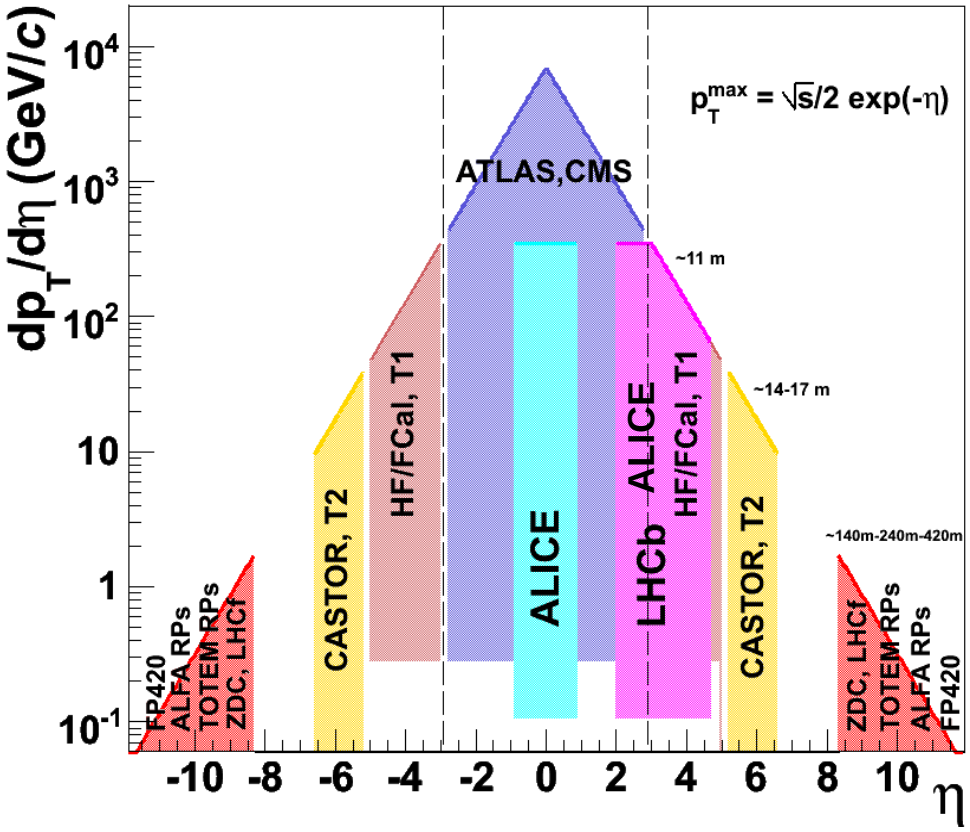
- The LHC provides a significant lever-arm in providing constrains for hadronic Monte Carlos for UHECR

CERN Large Hadron Collider (LHC)



LHC experiments: (p_T,η) acceptance

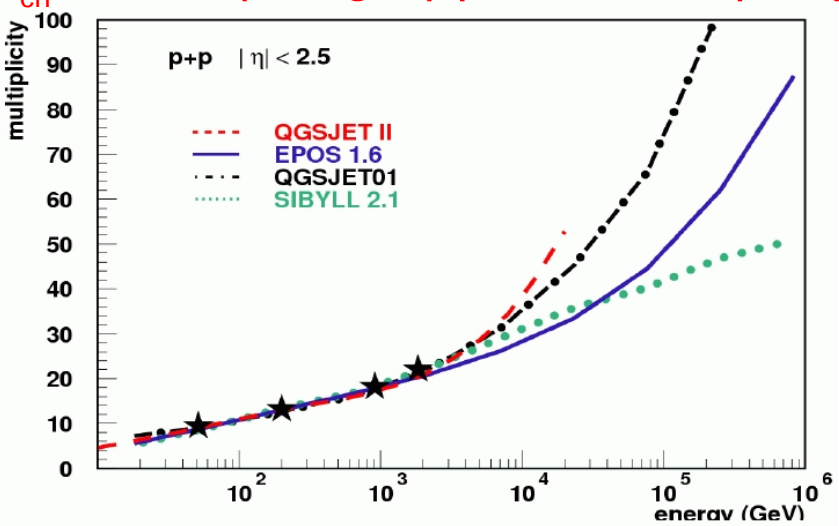




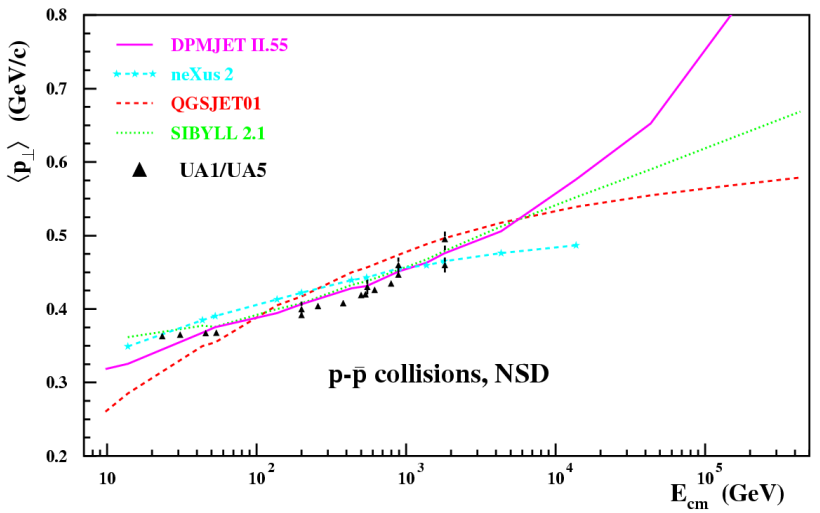
- Particle production at the LHC over $\Delta\eta \sim 2\times\ln(\sqrt{s})/m_p \sim 20$
- All phase-space virtually covered (1st time in a collider) !

UHECRs MCs: model uncertainties

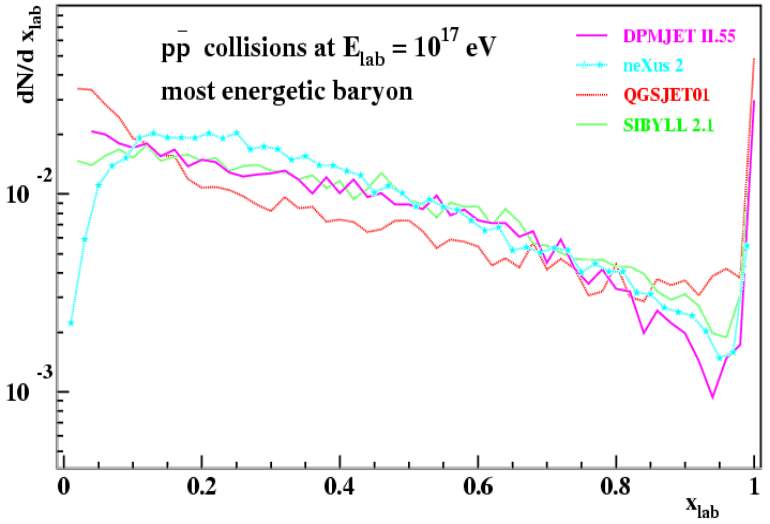
$<N_{ch}>$: Total (charged) particle multiplicity



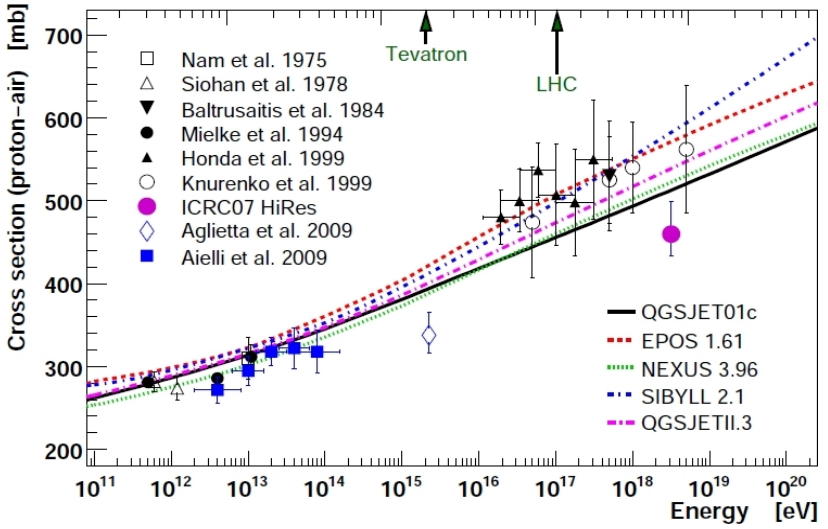
$<p_T>$: Average transverse momentum



dN/dx_F: Forward particle spectra

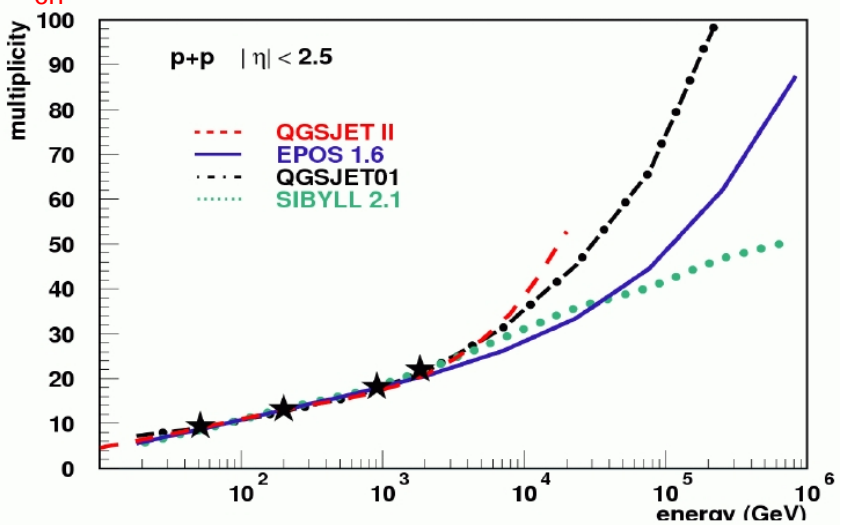


σ(p-A): proton-nucleus total cross-section



UHECRs MCs : constraints from LHC data (I)

$\langle N_{ch} \rangle$: Total (charged) particle multiplicity



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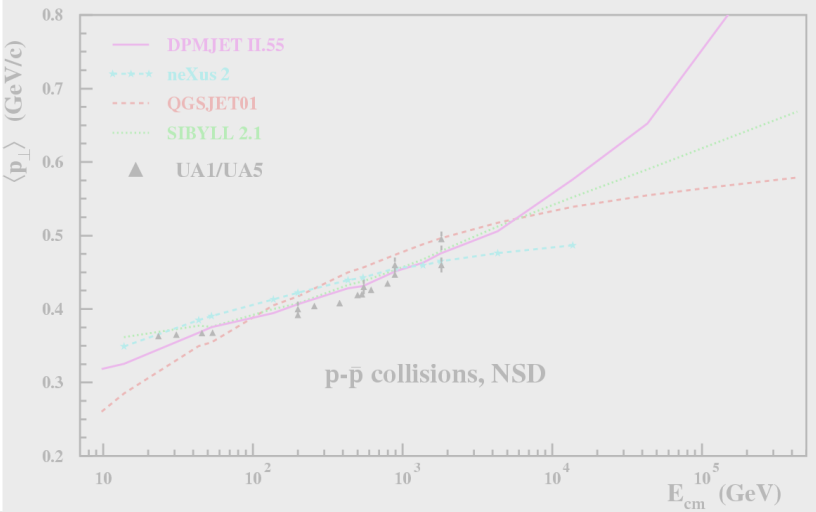

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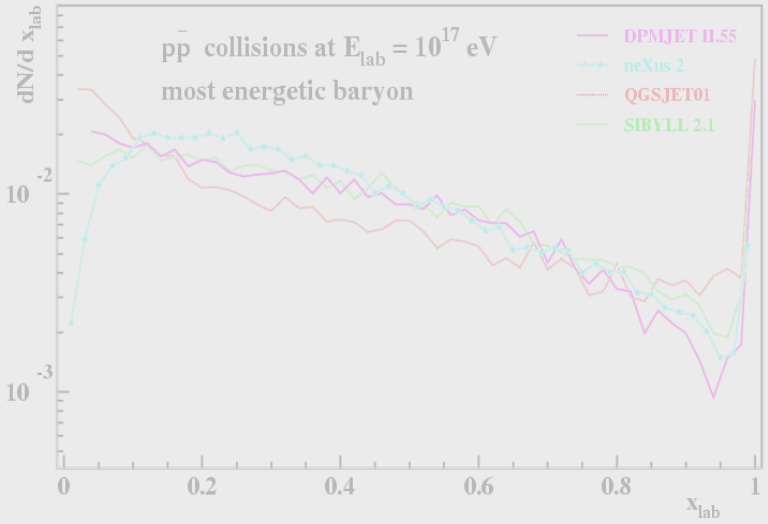

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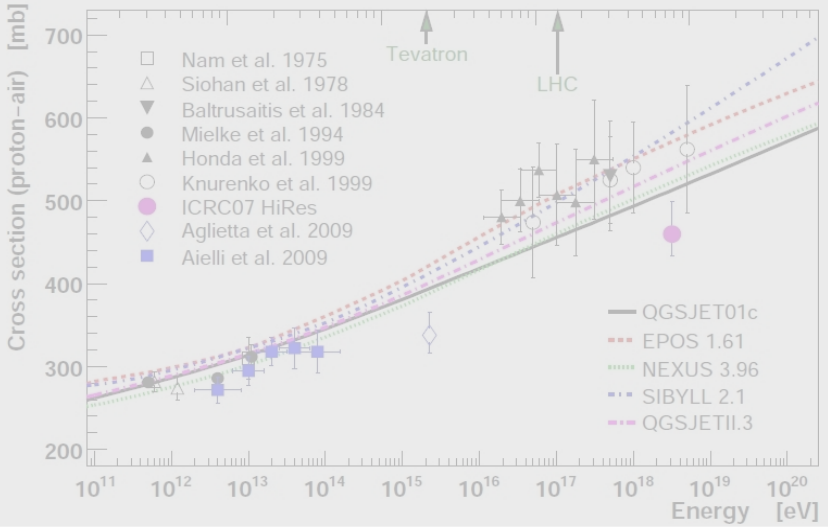
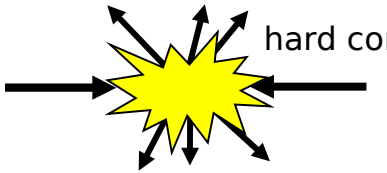


Particle production in p-p collisions

- perturbative parton-parton collisions ~60%



~40%

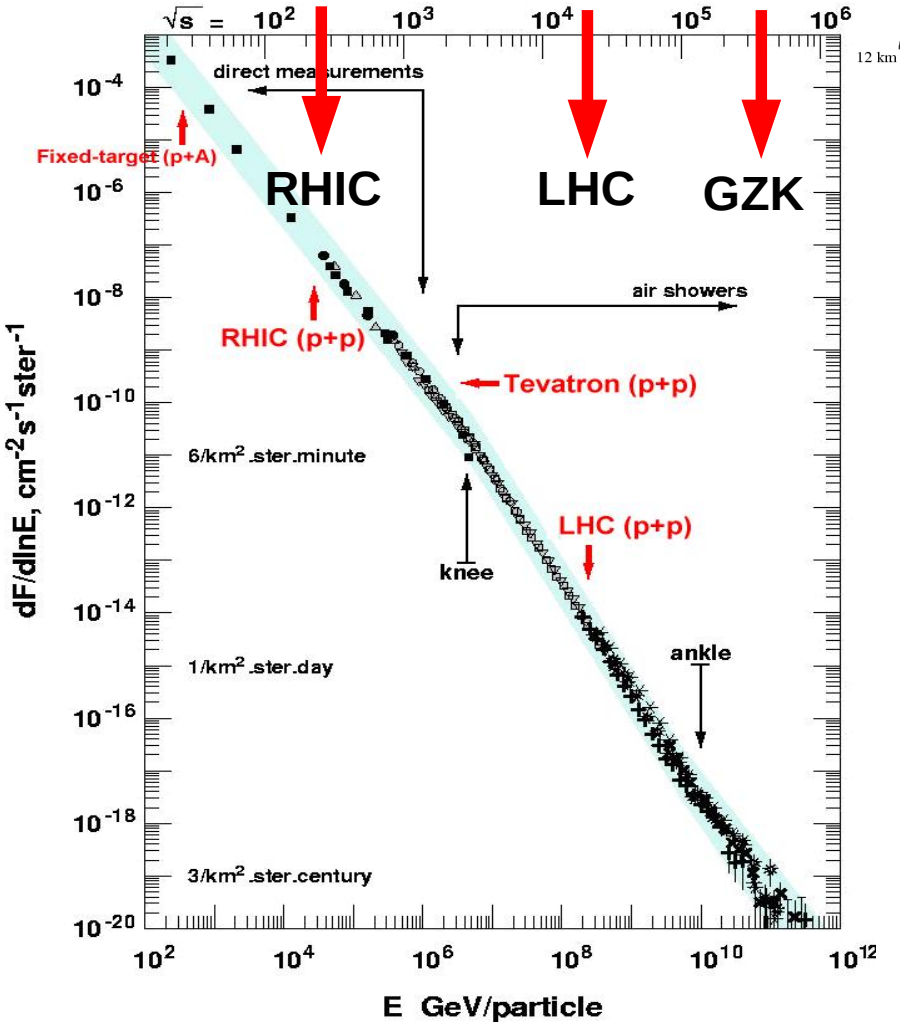
- No colour flux
- Colourless exchange with vacuum quantum-numbers: |Pomeron = (2-gluons in colour-singlet state)
- 1 or 2 protons intact.
- 1 or 2 rapidity gaps

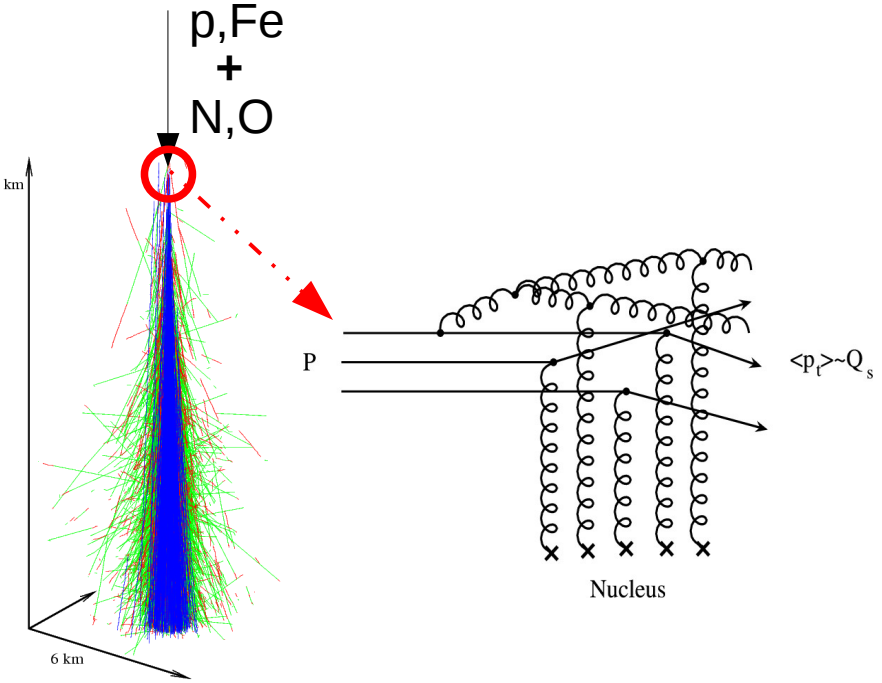
■ Diffractive/Elastic scattering is ~40% p-p σ_{tot} at the LHC

Phenomenologically modeled. Energy extrapolations ±20-30% uncertainty.

Gluon-gluon collisions in UHECRs

$x(y=0,y_{max}/2)$: 10^{-2} -10^{-3} $10^{-3.5}$ -10^{-6} 10^{-5} -10^{-8}



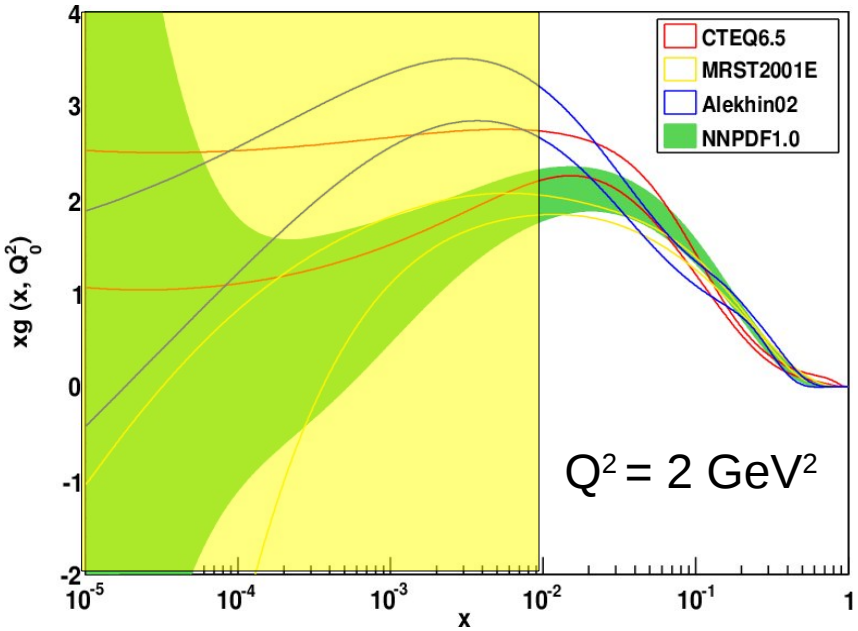


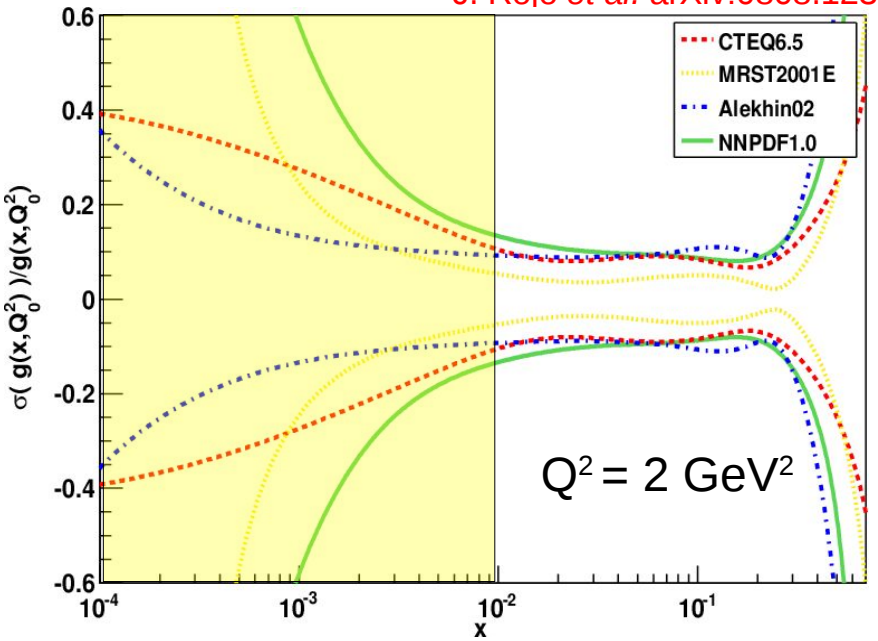
- At GZK cut-off energies, Mostly gluon-gluon interactions at $x\sim10^{-5}$-10^{-8} !

Badly known gluon density at low-x

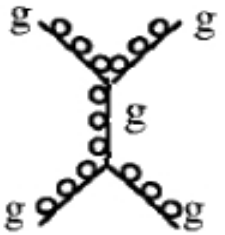
- Most of our current knowledge of gluons comes indirectly from DIS F_2 "scaling violations": $\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi} xg(x,Q^2)$
- Gluon unconstrained below x=p(parton)/p(proton)~10^{-2} at semihard Q^2 :

J. Rojo *et al.* arXiv:0808.1231





- Large uncertainties in parton-parton x-sections at low-x & moderate p_T: $x<2p_T/s\sim10^{-2}$, $Q\sim p_T\sim2$ GeV



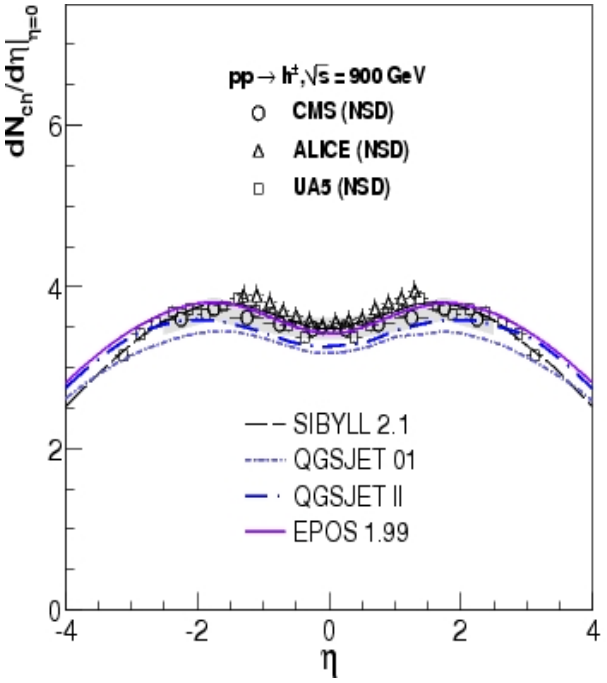
LHC data: Particle pseudorapidity density

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K.Werner, arXiv:1101.5596]

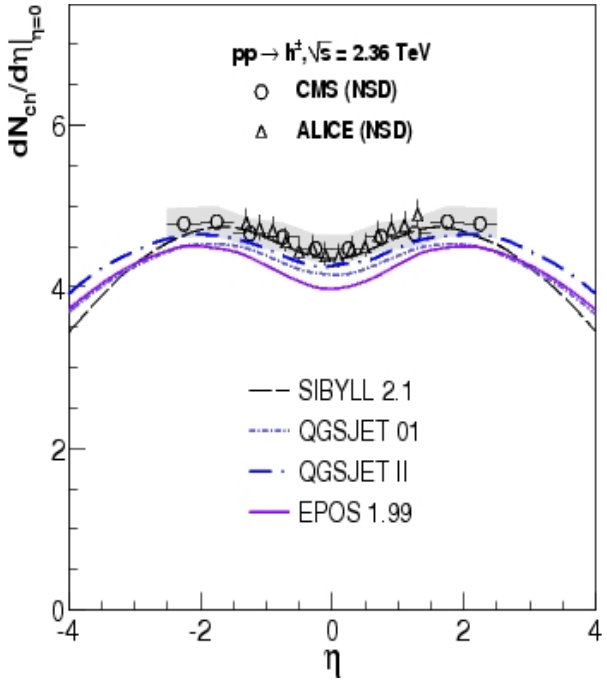
- 0.9, 2.36, 7.0 TeV charged-hadron data vs. CRs MC:

  Particle multiplicity not completely well predicted at 7.0 TeV:

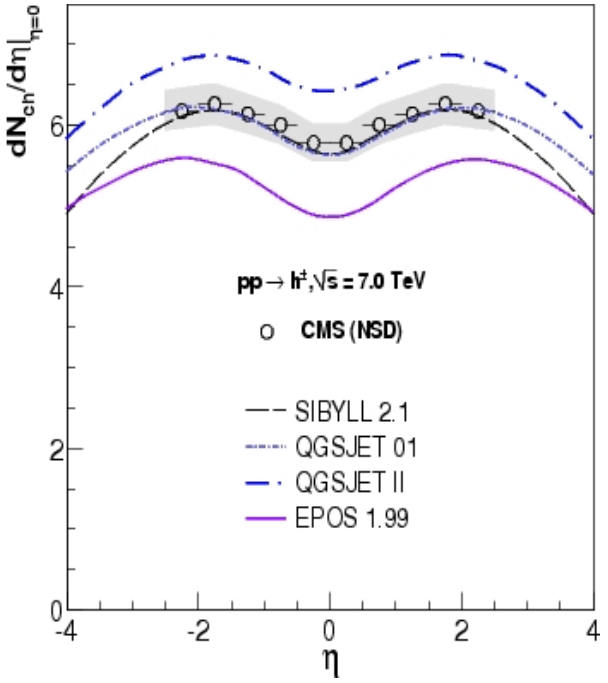
  "Simplest" models: QGSJET-01, SIBYLL 2.1 better than more complete ones



0.9 TeV



2.36 TeV



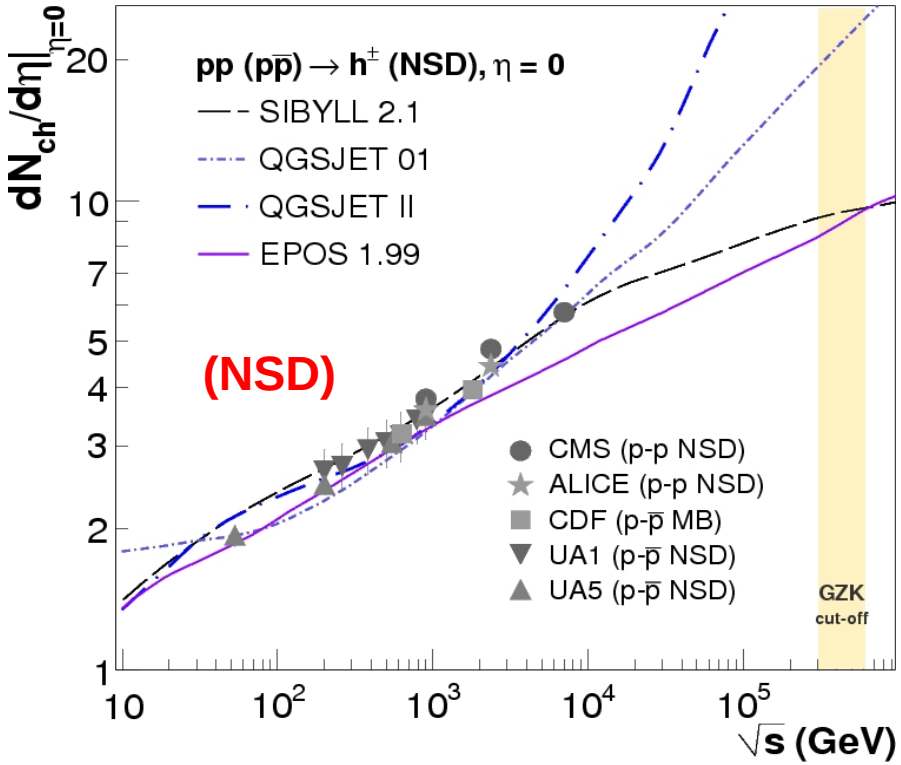
7.0 TeV

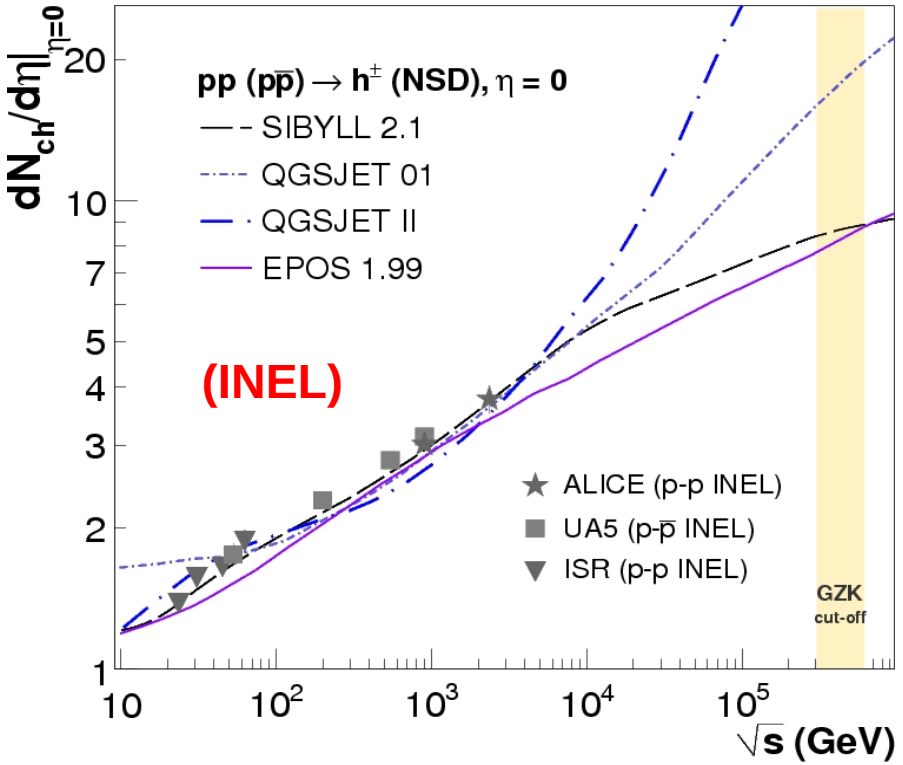
LHC data: pseudorapidity density vs. sqrt(s)

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K. Werner: in preparation]

- Very large differences predicted at $\sqrt{s}_{GZK}$~300 TeV !

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

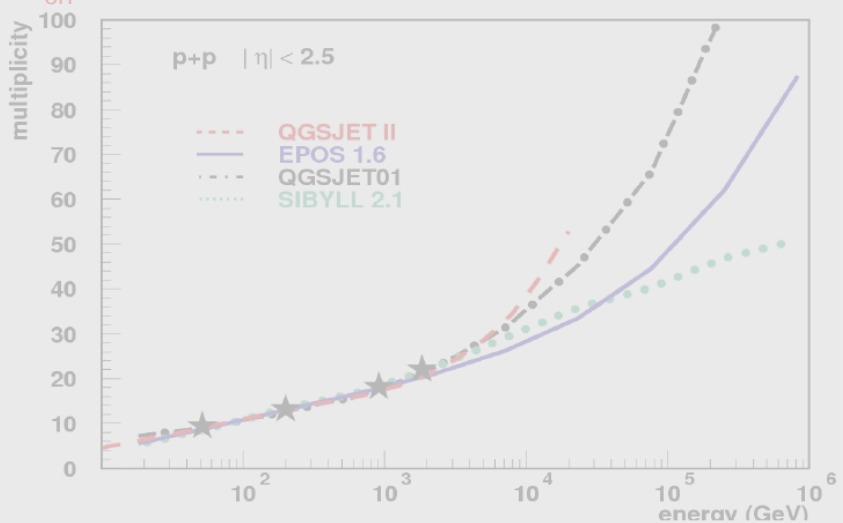




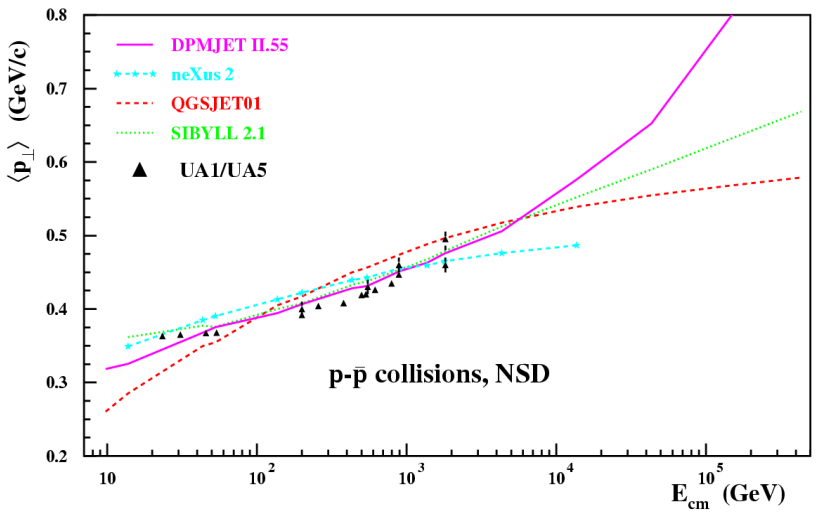
- GZK: models with $dN_{ch}/d\eta$~20 favoured (p-p data at 14-TeV needed)

UHECRs MCs : constraints from LHC data (II)

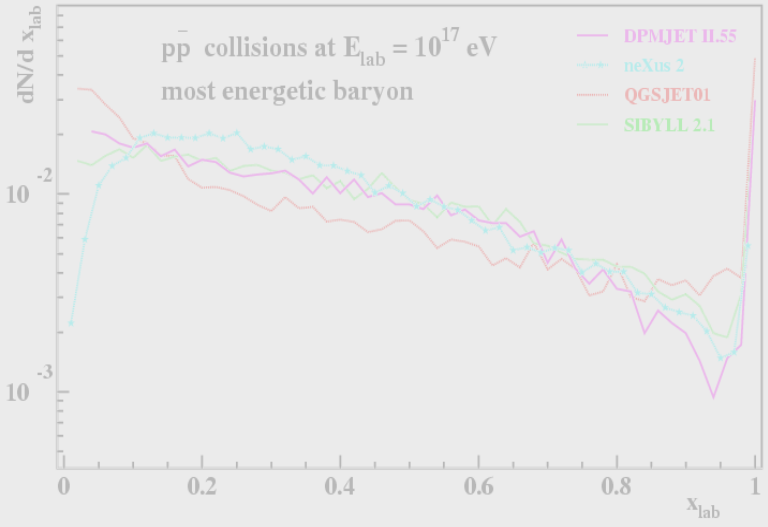
$\langle N_{ch} \rangle$: Total (charged) particle multiplicity



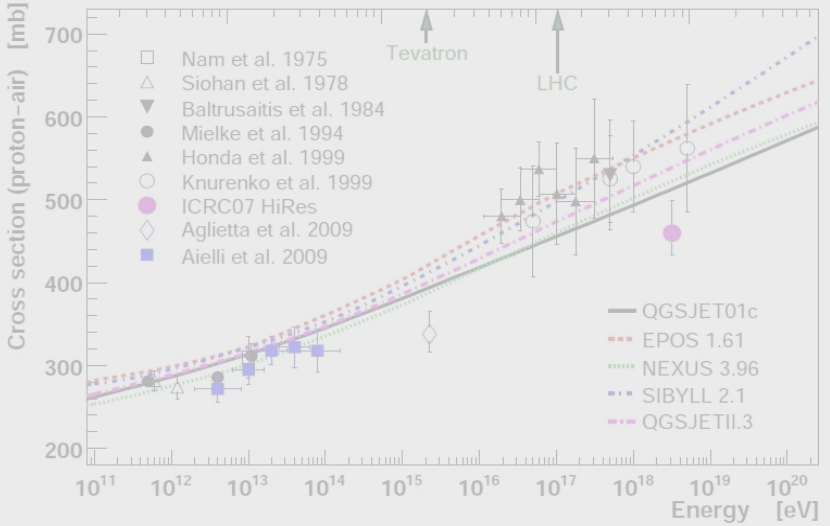
$\langle p_T \rangle$: Average transverse momentum



dN/dx_F: Forward particle spectra



σ(p-A): proton-nucleus total cross-section

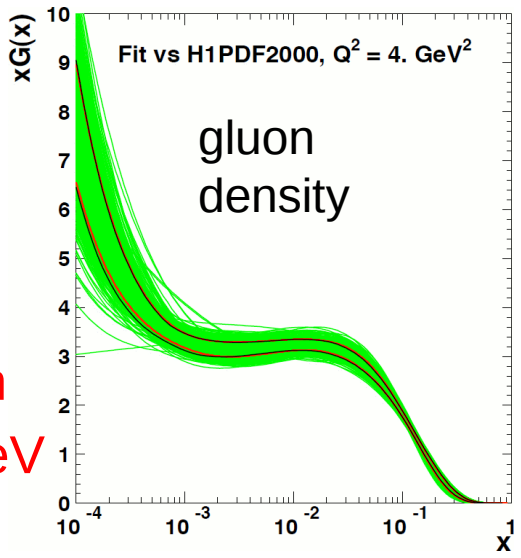


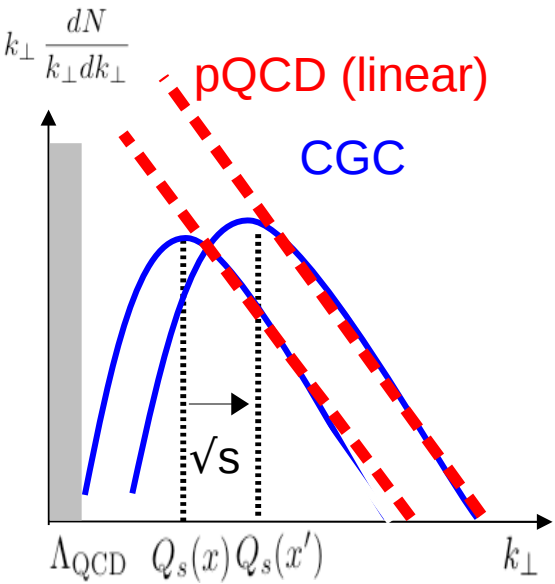
Gluon saturation (non-linear QCD)

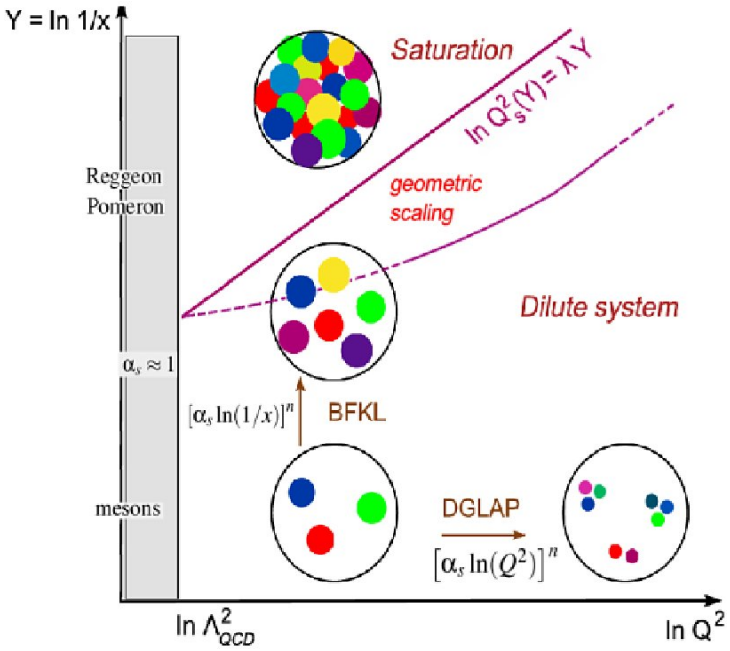
- Gluons start to overlap at "saturation scale"

$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$

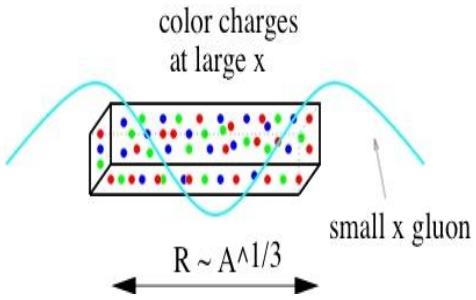
- pQCD gluon-gluon x-section peaks at $p_T \sim Q_s(\sqrt{s}) \sim$ 1-4 GeV







- Hadrons ~ "Color Glass Condensate" below Q_s
- Saturation effects enhanced in nuclei:



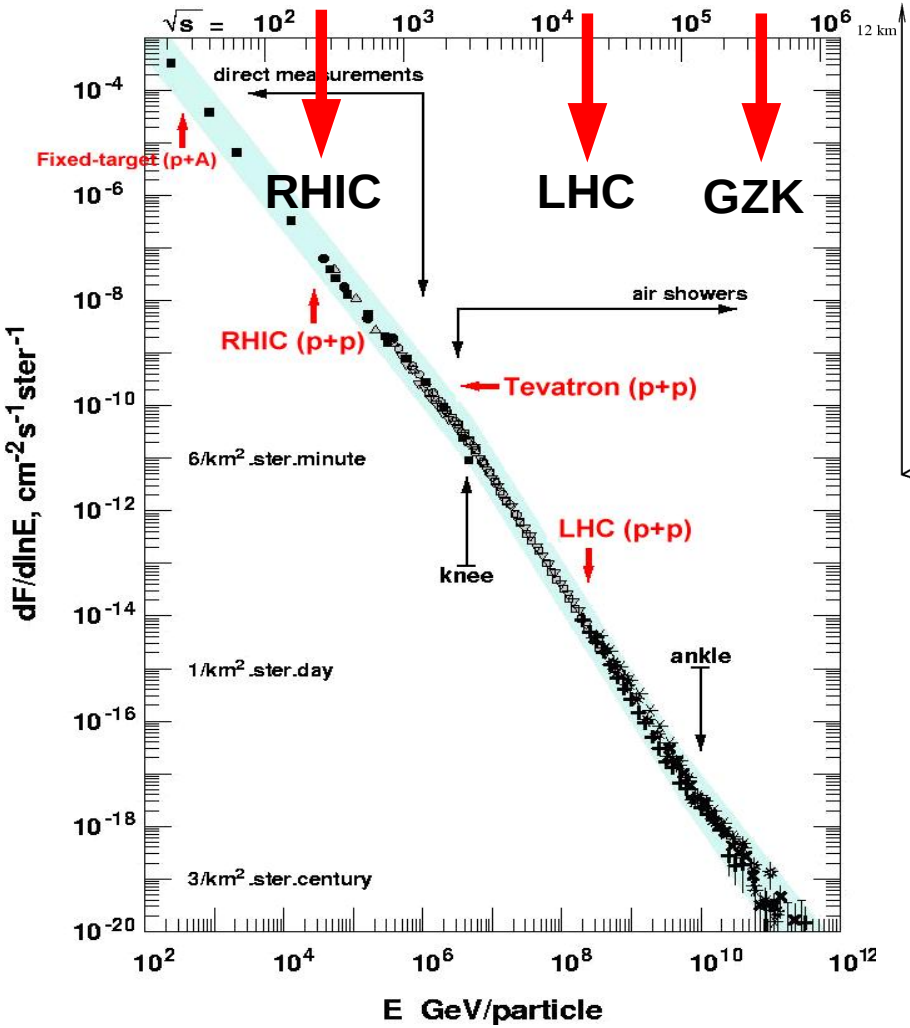
Large # of partons per transverse area

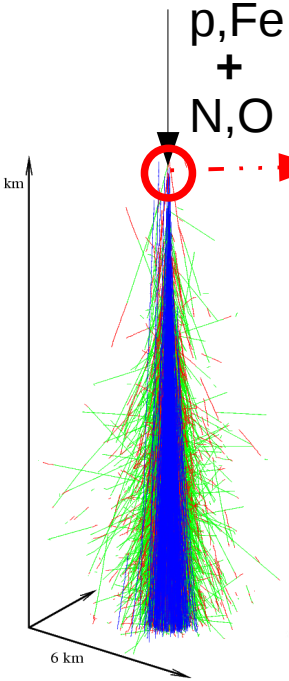
$$Q_s^2 \sim A^{1/3} \sim 6$$

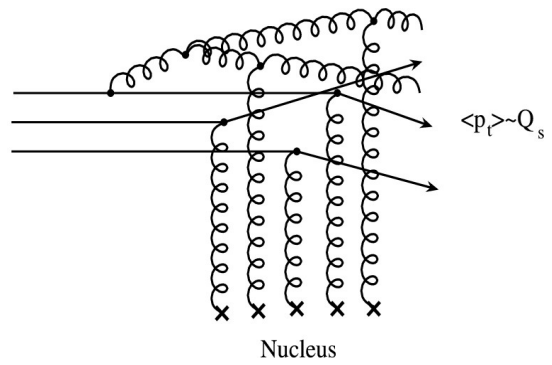
Gluon saturation in UHECRs: p-Air, Fe-Air

$x(y=0,y_{max}/2)$: 10^{-2} -10^{-3} $10^{-3.5}$ -10^{-6} 10^{-5} -10^{-8}

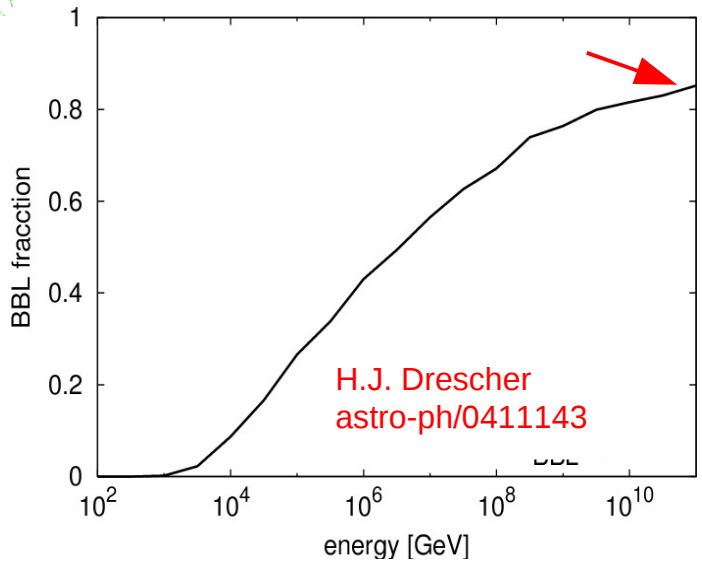
Q_s^2 :~1.5GeV^2 ~4GeV^2 ~16GeV^2







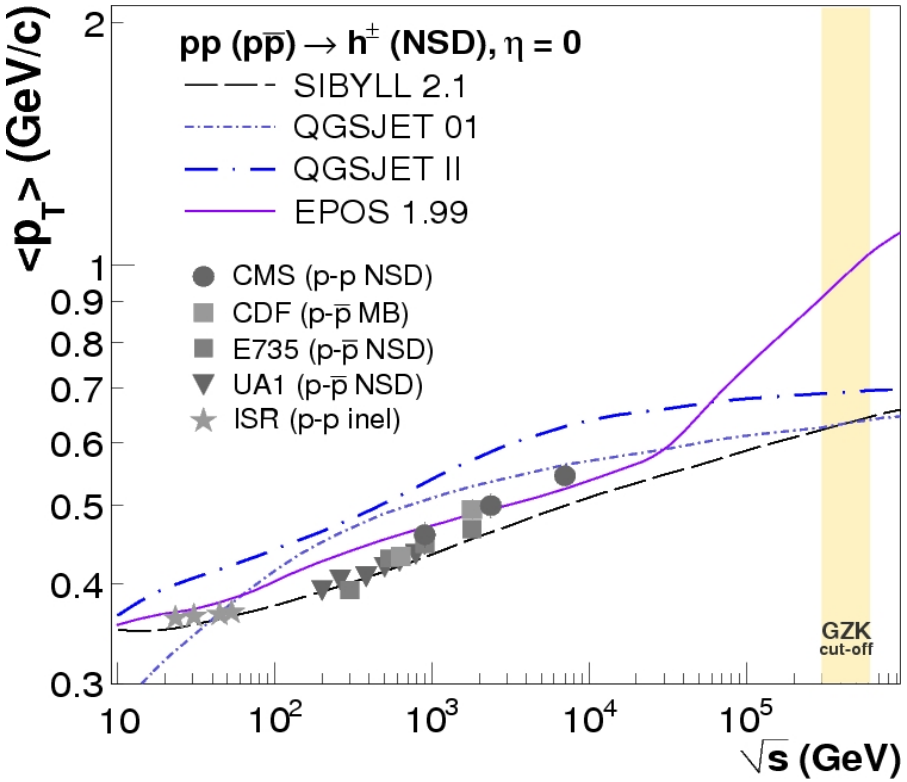
- At GZK cut-off energies, ~90% of p-A collisions in the saturation regime

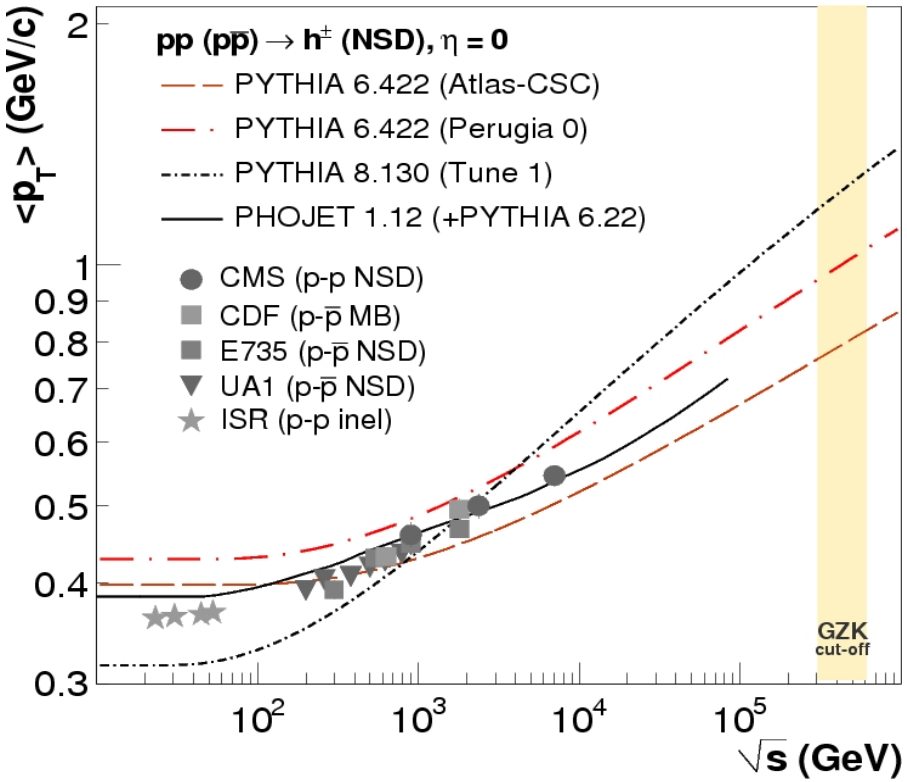


LHC data: Average p_T vs. sqrt(s)

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K. Werner: in preparation]

- $\langle p_T \rangle$: sensitive to pQCD x-sections & to gluon-saturation.
- $\langle p_T \rangle$: sqrt(s)-evolution mildly reproduced by models

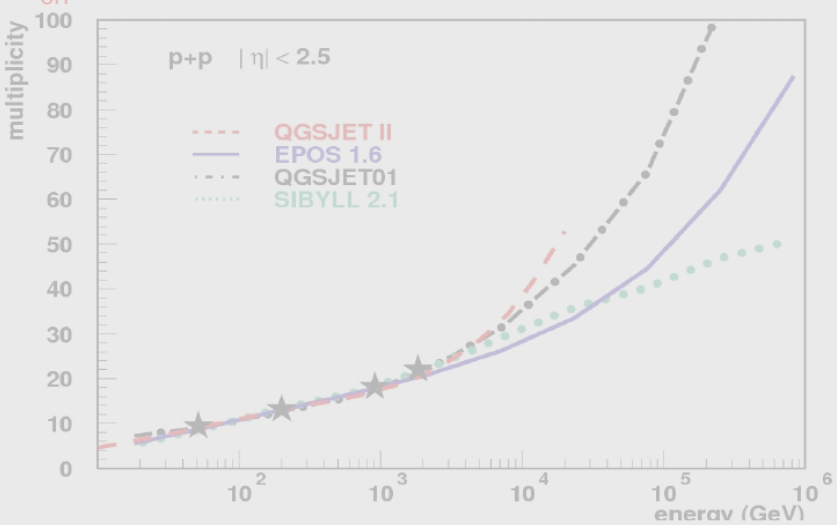




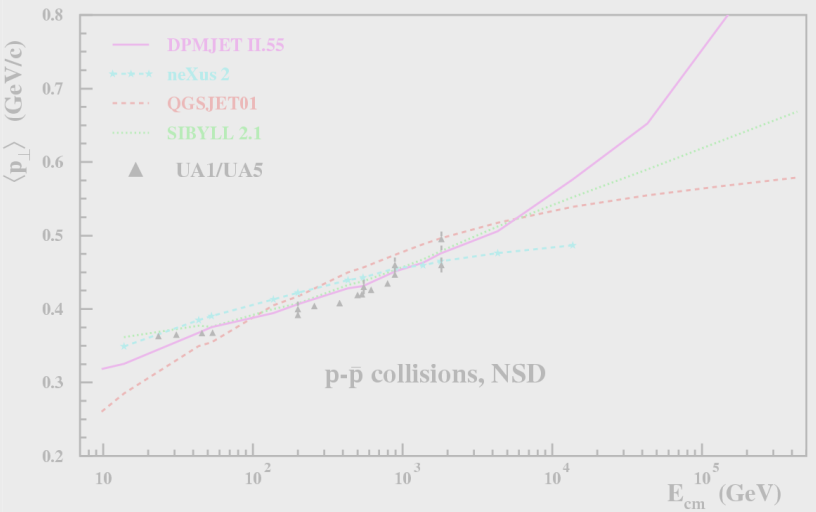
- CRs MCs predict very slow $\langle p_T \rangle$ increase
- PYTHIA: $\langle p_T \rangle$~0.7-1.5 GeV/c at GZK (except EPOS, but due to collective flow)

UHECRs MCs : constraints from LHC data (III)

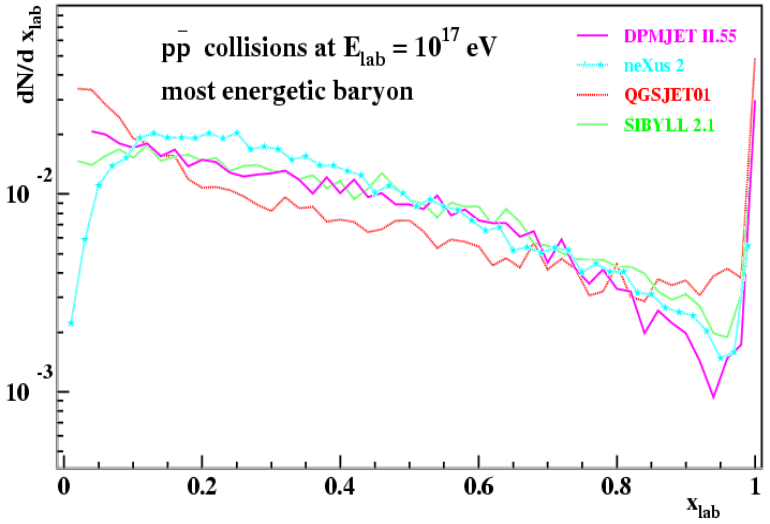
<N_{ch}>: Total (charged) particle multiplicity



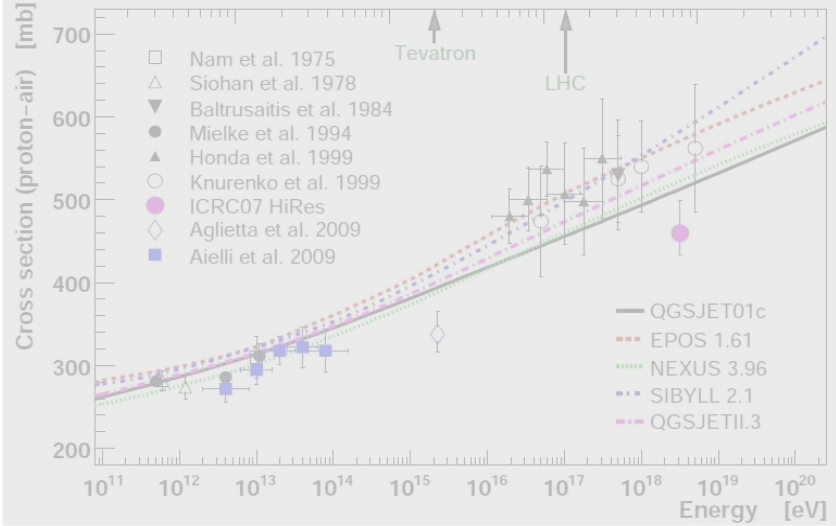
<p_T>: Average transverse momentum



dN/dx_F: Forward particle spectra

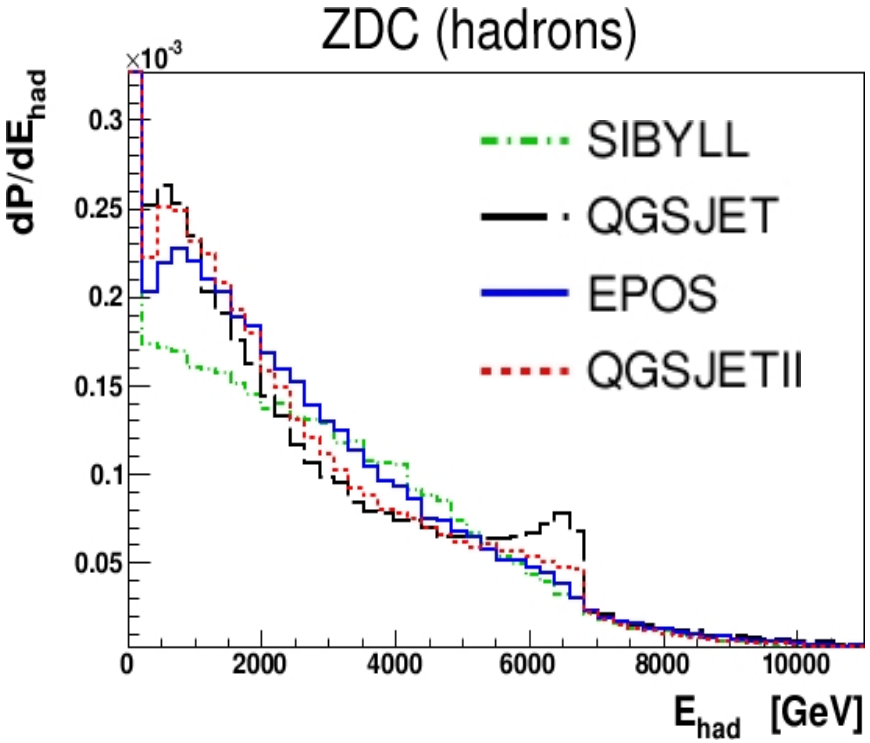


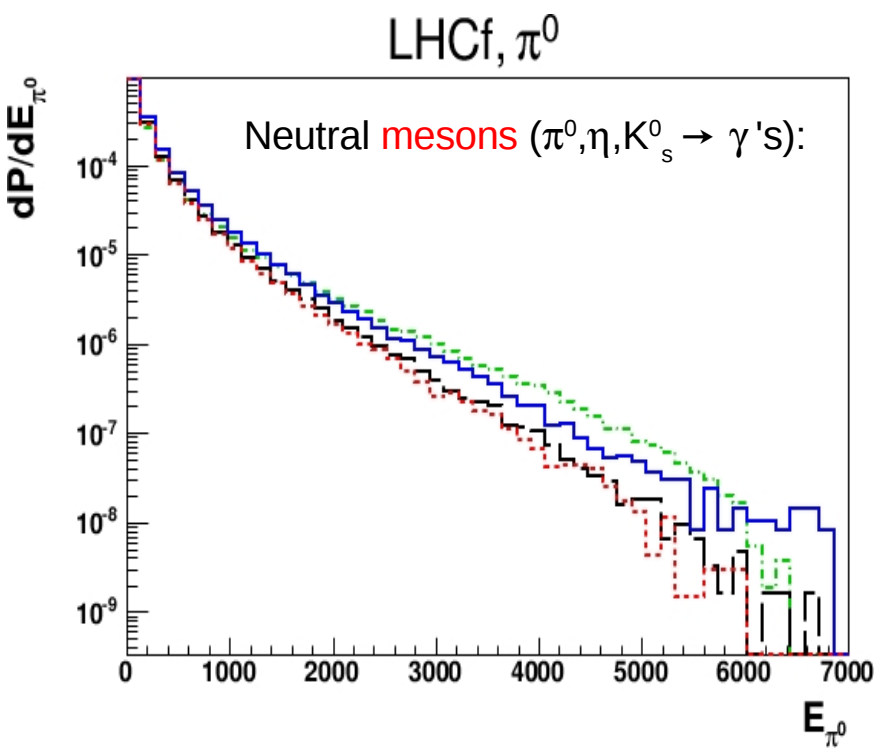
σ(p-A): proton-nucleus total cross-section



Forward hadron & leading-baryon production

- Forward multiplicity: very sensitive to primary shower development: leading baryon (inelasticity).
- LHC detectors present at zero-degrees for neutral particles:

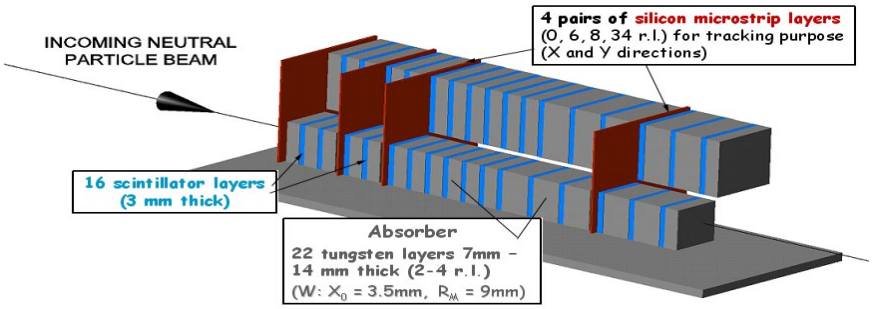


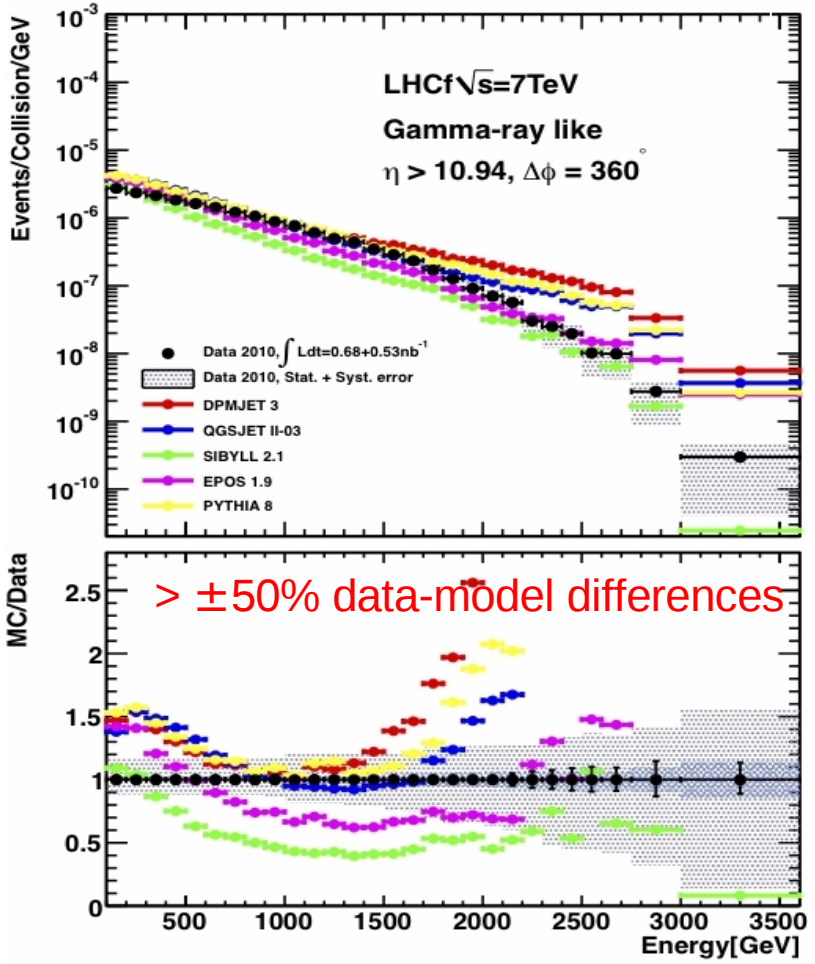


- Strong constraints on non-perturbative MC ingredients: diffractive peak, beam-remnants, fragmentation, ...

LHC data: Neutral particles at zero degrees

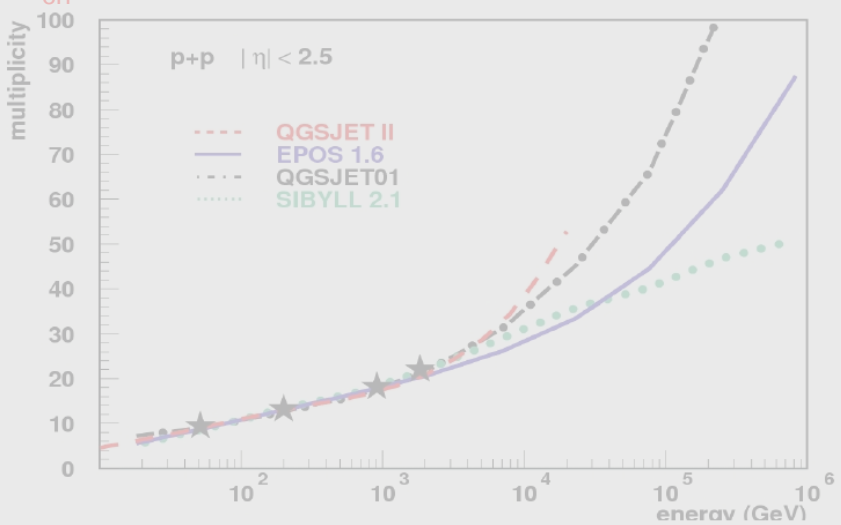
- **LHC-f** (±140m in ATLAS tunnel): n,γ detection for |η| > 8.3
- Zero-Degree-Calos also in same region.
- 1st TeV e.m..showers ever in the lab !



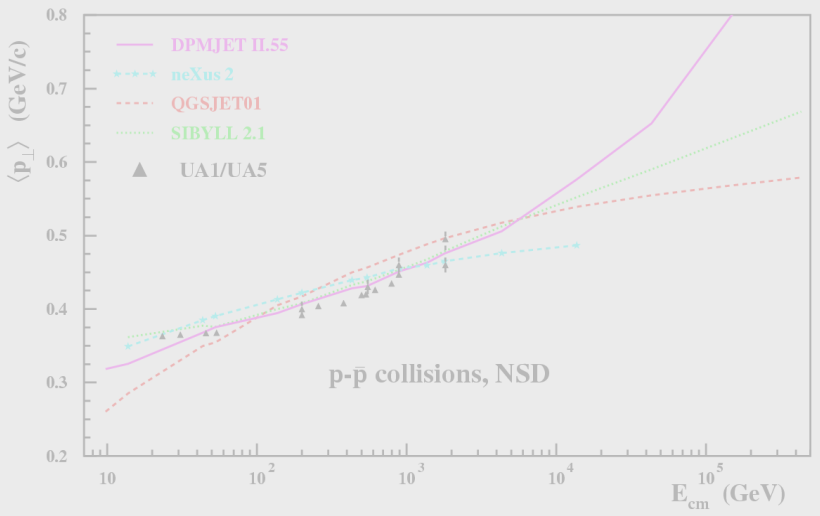


UHECRs MCs : constraints from LHC data (IV)

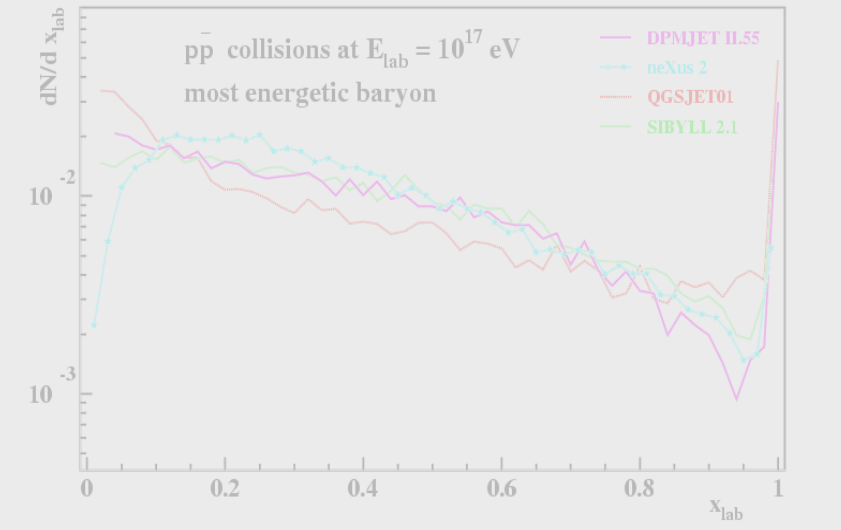
$<N_{ch}>$: Total (charged) particle multiplicity



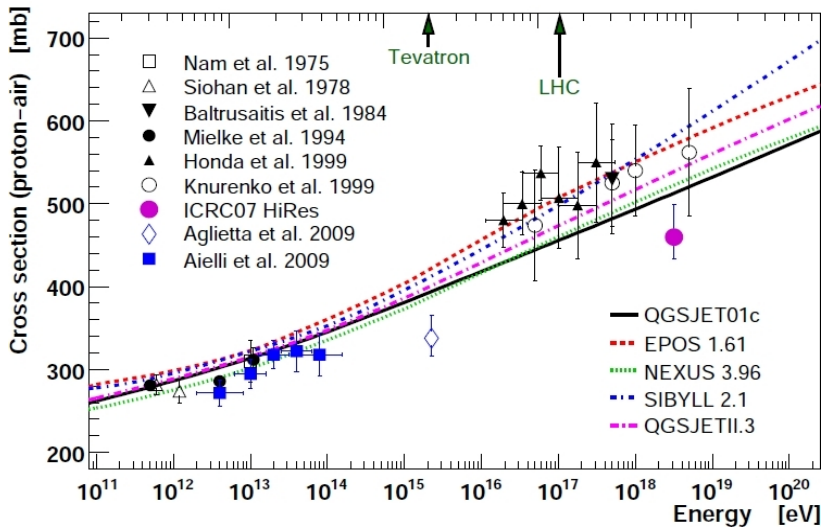
$<p_T>$: Average transverse momentum



dN/dx_F: Forward particle spectra



σ(p-A): proton-nucleus total cross-section

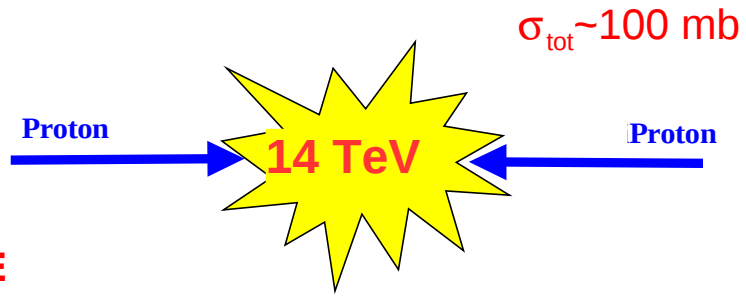


proton-proton cross sections

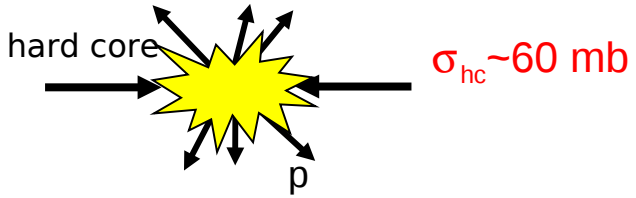
- Total cross-sections at the LHC:

$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

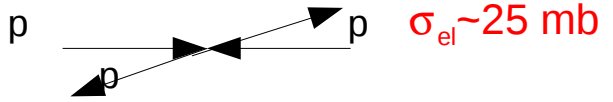
$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$



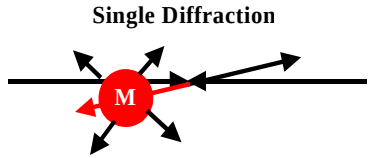
~60% of the time a "hard" collision occurs



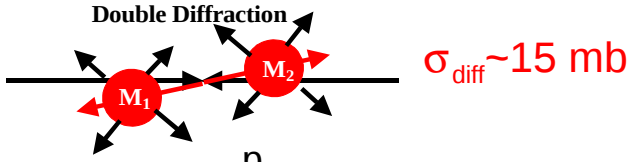
~25% of the time the protons scatter elastically



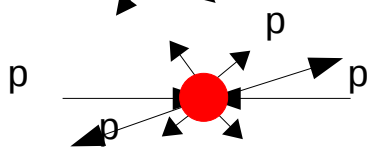
~10% of the time single diffraction occurs



~1% of the time double diffraction occurs



~1% of the time central (exclusive) diffraction occurs

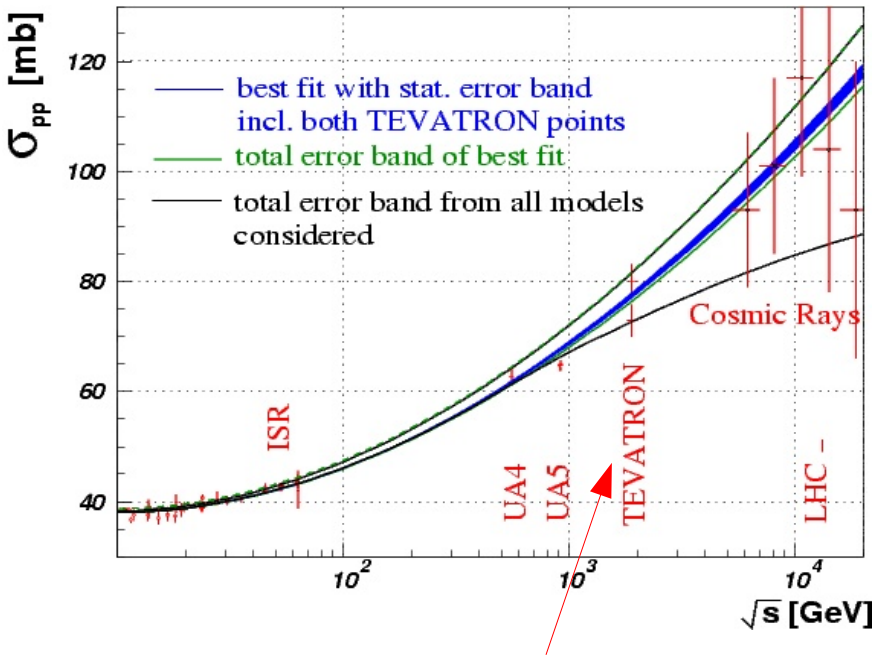


Total & elastic p-p cross sections

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

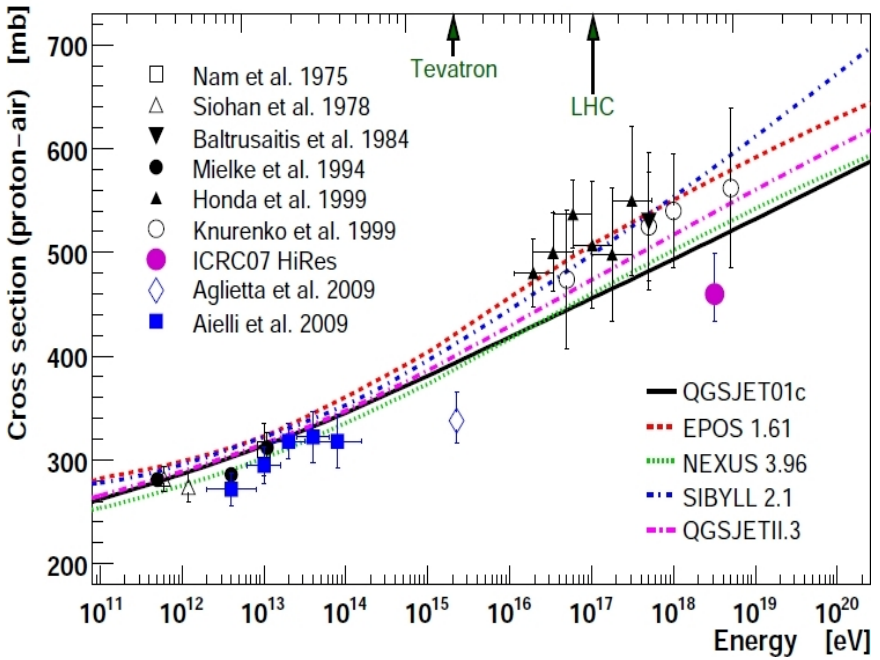
- LHC p-p x-section predictions:

σ_{tot}(LHC) = 90-120 mb $^{+10}_{-20}$ %.



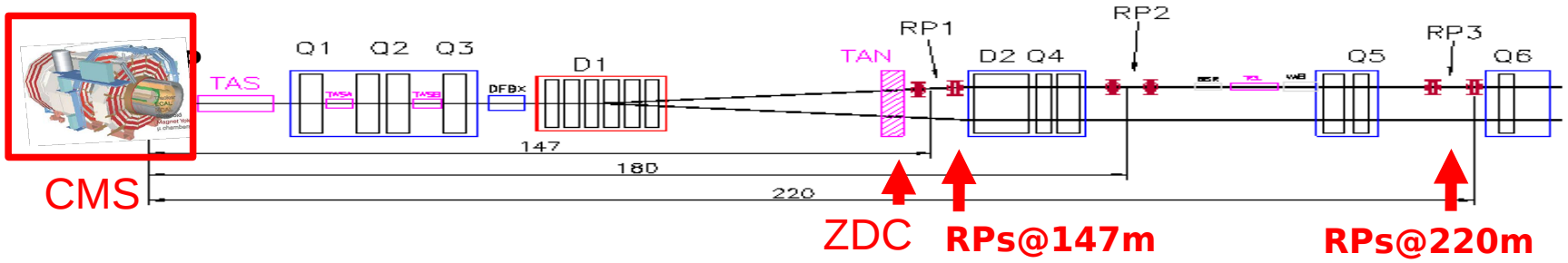
(Tevatron: E710–CDF 2.6σ disagreement)

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

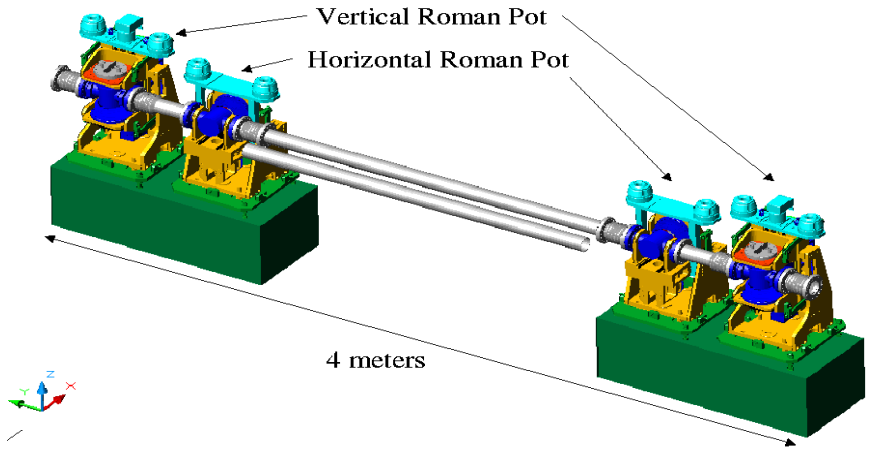


R.Ulrich, eConf C0906083 (2009)

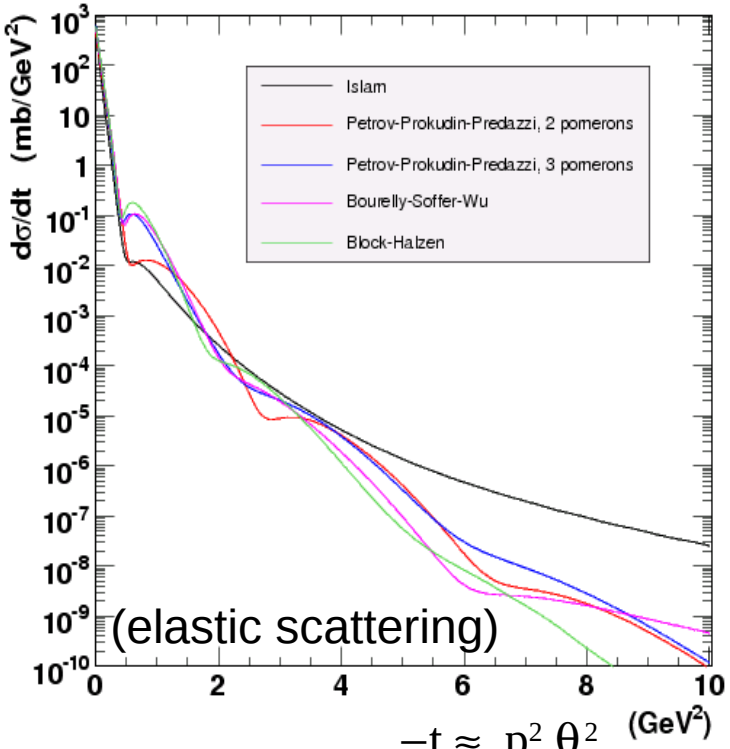
LHC data: TOTEM elastic x-section



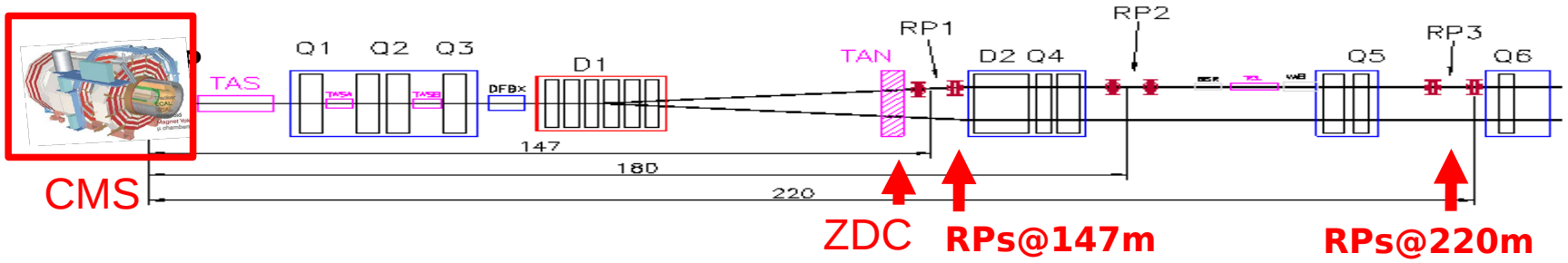
- **TOTEM** silicon Roman Pots: proton taggers inside LHC tunnel at ±147,±220 m



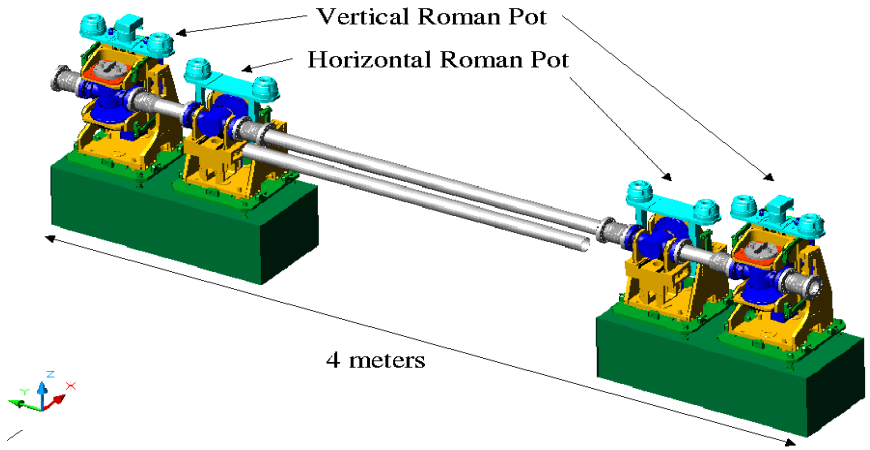
- Goal: $\sigma_{el,tot}$ with few % precision



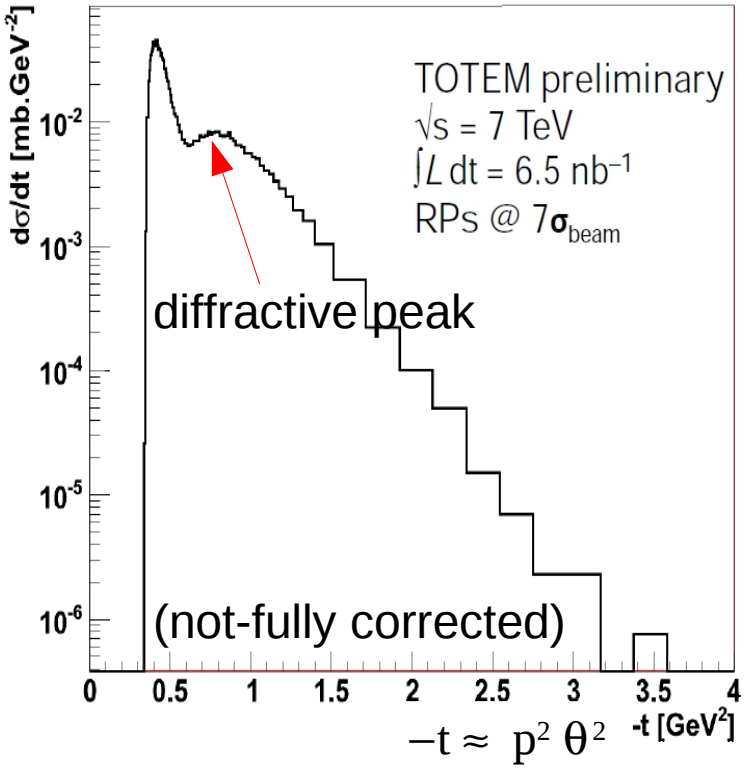
LHC data: TOTEM elastic x-section



- **TOTEM** silicon Roman Pots: proton taggers inside LHC tunnel at ±147,±220 m



- Preliminary dσ/dt:



Summary: QCD @ LHC for UHECRs

- First LHC (p-p) measurements:

(1) Monte Carlos bracket: particle multiplicity, mean transv. momentum

Model	QGSJET01			QGSJETII			SIBYLL 2.1			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
$dN_{ch}/d\eta\|_{\eta=0}$	✓	✓	✓	✓	✓	over	✓	✓	✓	✓	under	under
$\langle p_\perp \rangle$	over	over	✓	over	over	over	✓	under	under	✓	✓	✓
$P(N_{ch} < 5)$	over	over	under	over	over	over	over	over	over	✓	✓	✓
$P(N_{ch} > 30)$	✓	under	under	✓	✓	over	over	✓	over	under	under	under

though no model reproduces consistently all data (retunings needed)

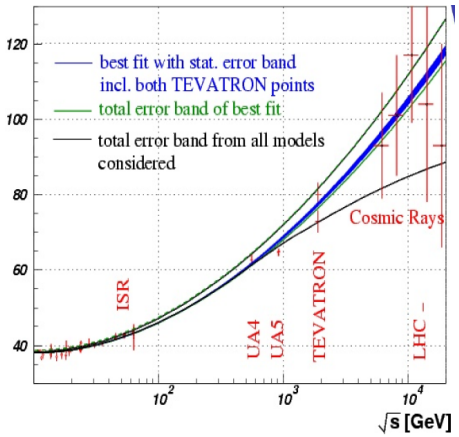
(2) Coming data to add CR MCs constraints:

total p-p x-section, baryon spectra, forward spectra, proton-nucleus

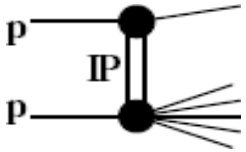
- "Knee" in CR spectrum likely not due to new (unobserved) particles

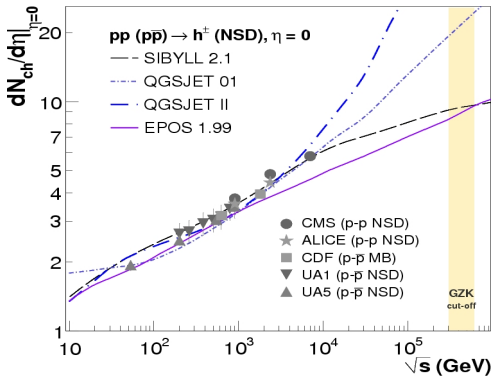
Summary: QCD @ LHC for UHECRs

σ_{tot}, elastic scatt.

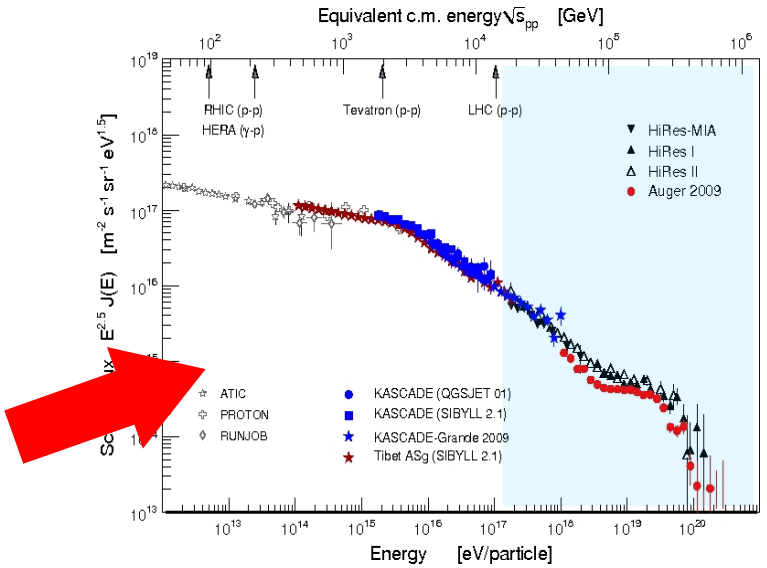


diffraction

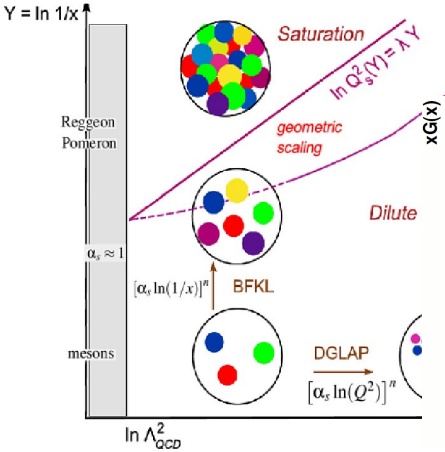




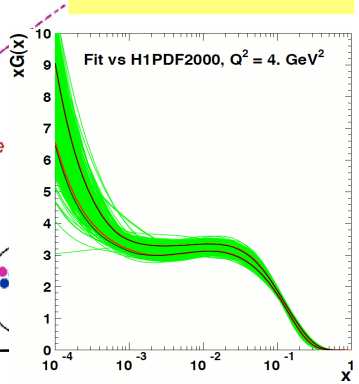
UE, MPI, MB

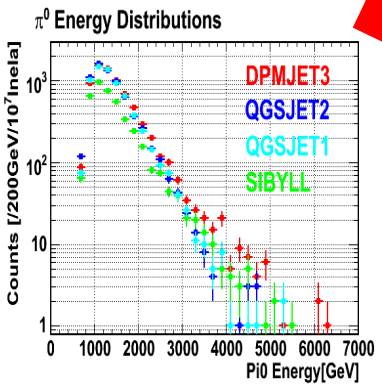


saturation/CGC

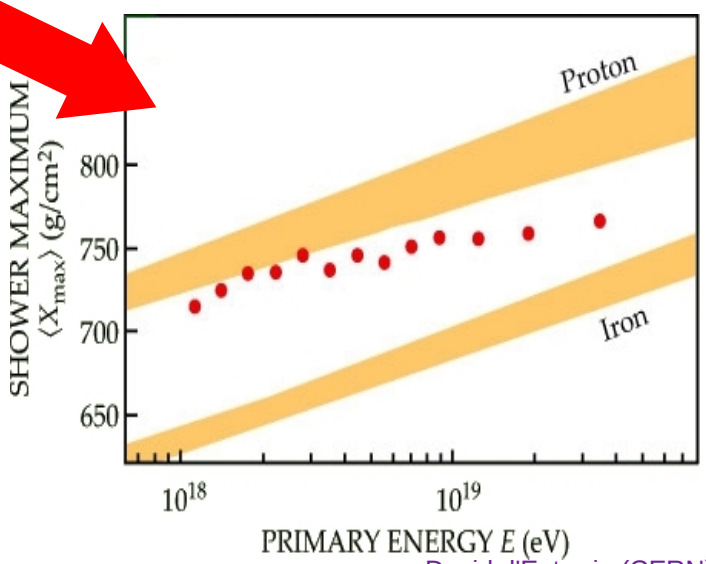


low-x PDFs





beam remnants



Backup slides

Summary: UHE cosmic-rays

- Open questions in UHECRs physics:

  (1) Structures in spectral flux slope:

  - knee – 10^{15} eV : Z-dependent leakage of galactic CRs
  - ankle – 10^{18} eV: Intergalactic component kicks-in. CRs charges ?

  (2) Sources of CRs with E~10^{20} eV:

  - No astrophysical mechanism known w/ accel. power beyond 10^{20} eV.
  - GZK cutoff observed at $3 \cdot 10^{19}$ eV, but general AGN-correlation unclear.
  - Charges of CRs (deflection in intergalactic magnetic fields) ?

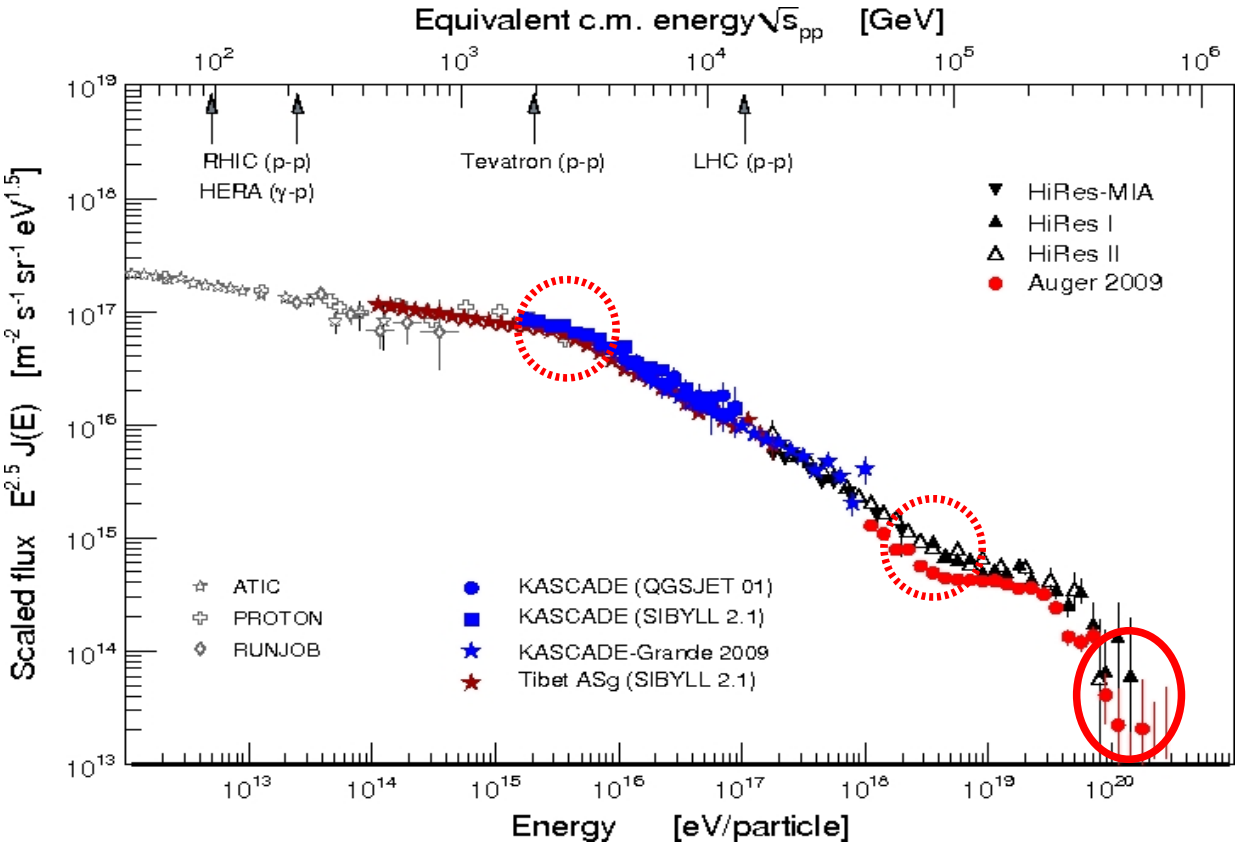
  (3) Identity of CRs with E~10^{20} eV:

  - Latest X_{max} position & fluctuations favour Fe-like ions.

- LHC p-p data halves $\sqrt{s}$-dependent hadronic MC extrapolations:

  - Diffraction fraction. Low-x PDFs. Gluon saturation. Multiparton interactions. Beam remnants. Total x-sections ...

UHECR energy spectrum: 3 open questions



1. Explanation of
"knee" at $E_{lab} \sim 10^{15}$ eV,
"ankle" at $E_{lab} \sim 10^{18}$ eV

2. Sources of CR at $E_{lab} \sim 10^{20}$ eV

3. Nature of CR at $E_{lab} \sim 10^{20}$ eV

What can the LHC do to help solving these questions ?

Overview

- Ultra-High-Energy Cosmic-rays (UHECR):

  - Measurements via extended air-showers

- 3 open questions in UHECRs physics:

  (1) Structures in spectral flux slope (knee – 10^{15} eV, ankle – 10^{18} eV) ?

  (2) Sources of CRs at E~10^{20} eV ?

  (3) Identity of CRs at E~10^{20} eV ?

- UHECR uncertainties from hadronic MCs uncertainties.

- Large Hadron Collider (LHC) constraints.

- LHC measurements:

  (1) particle multiplicity
  (2) average hadron p_T } new data vs. models

  (3) total p-p cross-section
  (4) baryon & fwd spectra } near-future data vs. models

UHECRs energy & identification

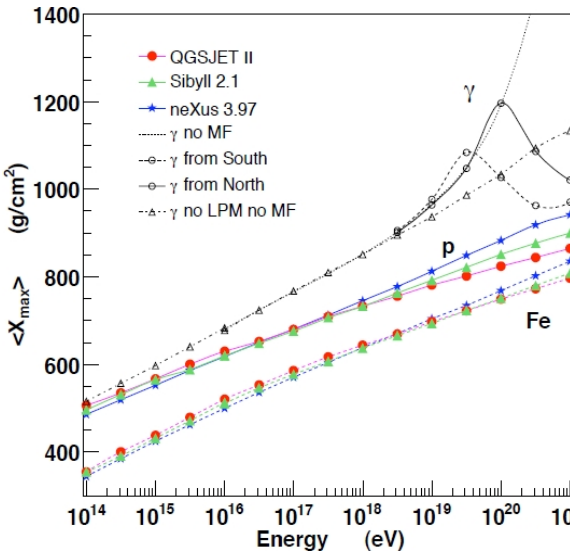
[Blumer-Engel-Horandel, PPNP 68(2009)293]

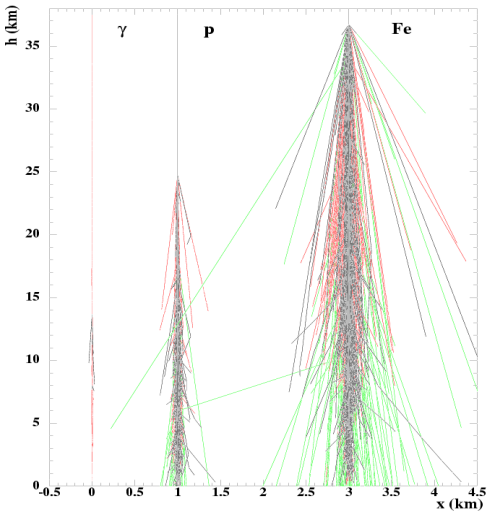
- Position & fluctuations of shower maximum:

  Depth: $\gamma > p > A$

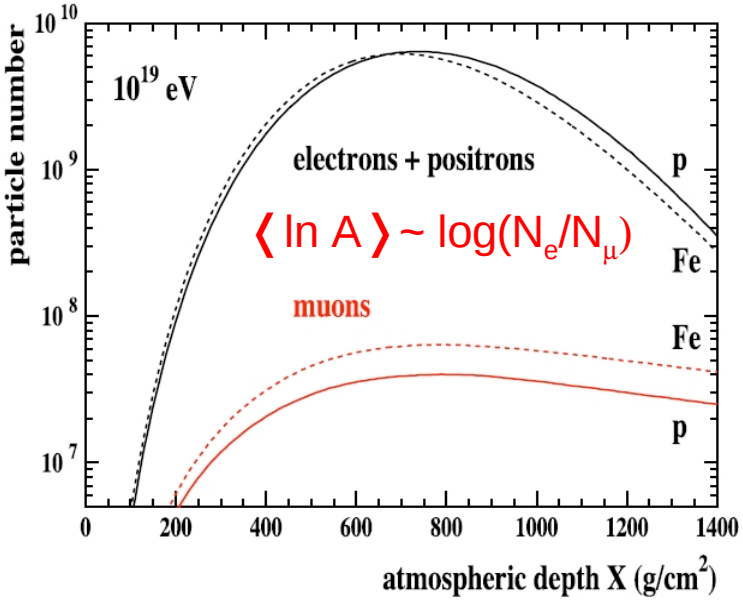
  $X_{max}(p) \sim X_{max}(Fe) + 150$ g/cm^2

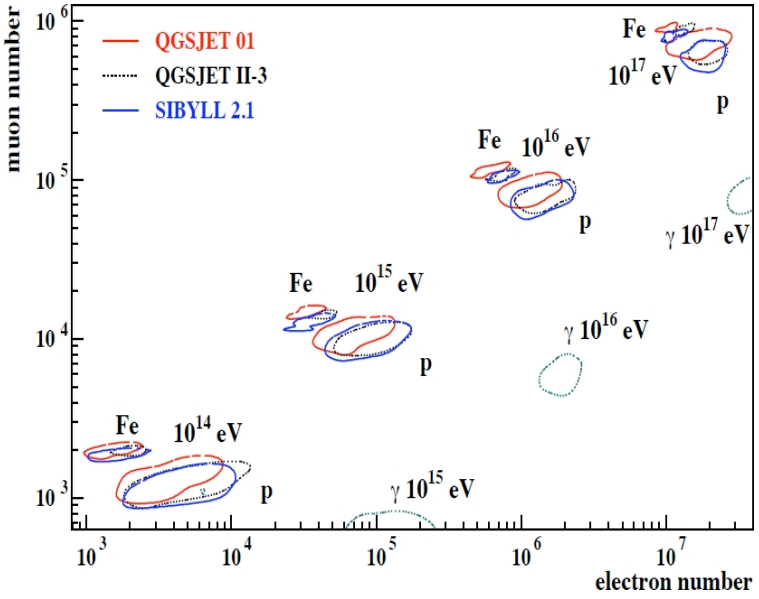
  Shower-to-shower fluctuations: smaller for ions than proton.





- Number of $e^{\pm}$ & muons:





(Q2) UHECR sources: cosmic accelerators

[Blumer-Kampert, Phys. Bl 65N3 (2000)39]

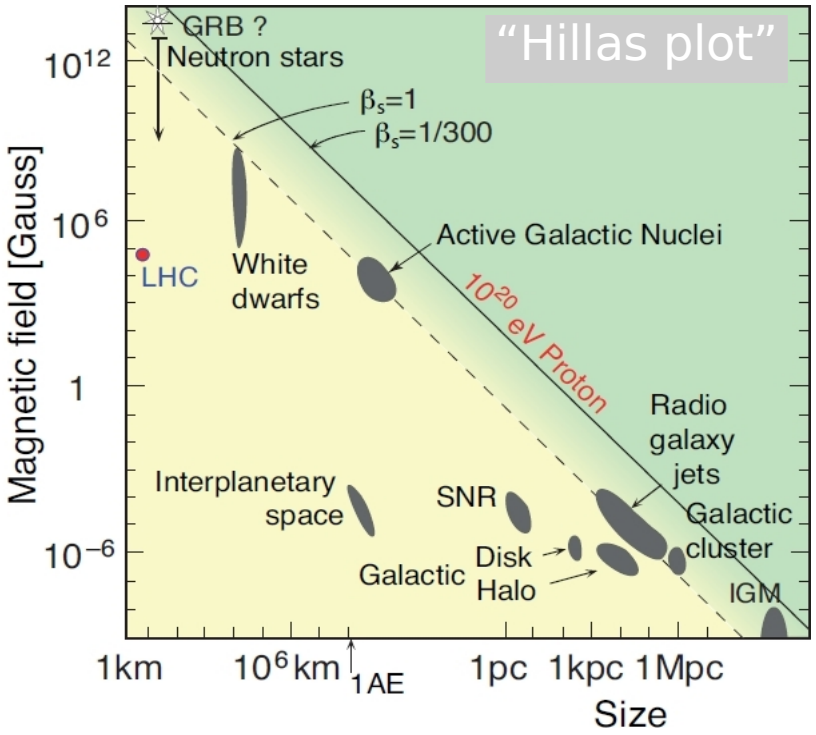
- Astrophysical objects with large B-field or large acceleration length:

$$E_{max} \sim Z_{CR} \cdot (\beta_{shock} \cdot B \cdot L)$$

Difficult to reach 10^{20} eV !

(required shock-front speeds $\beta \sim 1$)

[easier for ions, Z(Fe)=26]

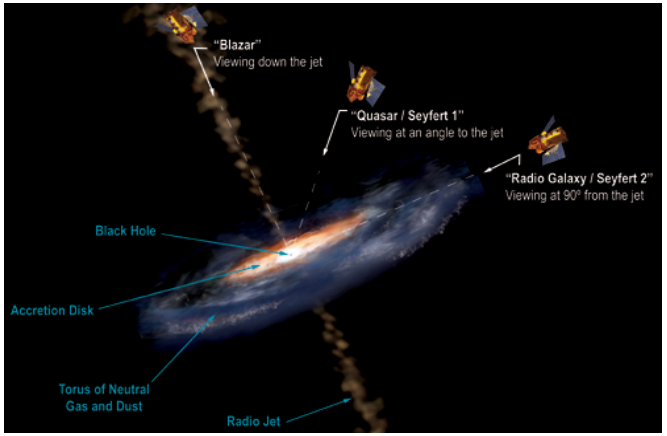


- Best candidates:

- Neutron-star: highly magnetized & spinning
- AGN/GRB: rapidly spinning giant black-holes

Supernova: shockfronts "only" $E_{max} = Z \cdot 10^{14\text{-}17}$ eV

(range: single explosion – multiple remnants)



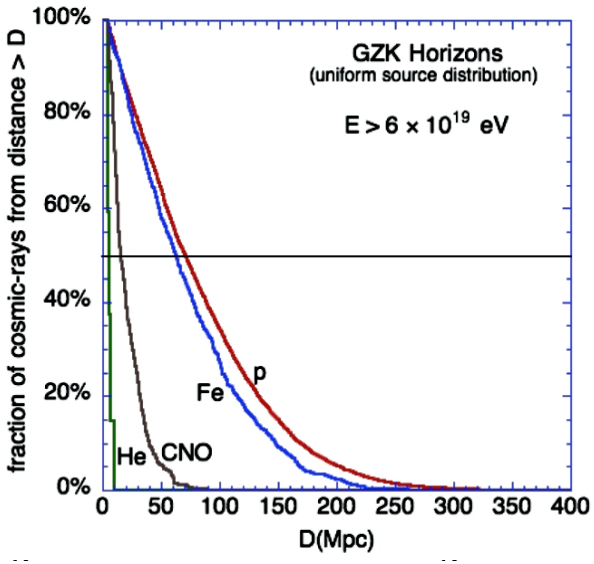
(Q2) UHECR sources: GZK cut-off ?

- Proton with $E_{GZK} > 6 \cdot 10^{19}$ eV will breakup in collisions with CMB ($E_\gamma \sim 0.35$ meV):

  Proton: $\mathbf{p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0, n + \pi^+}$

  Heavy-ion: $\mathbf{A + \gamma_{CMB} \rightarrow A^* \rightarrow A + n}$ *(lower E_{GZK} for nuclei)*

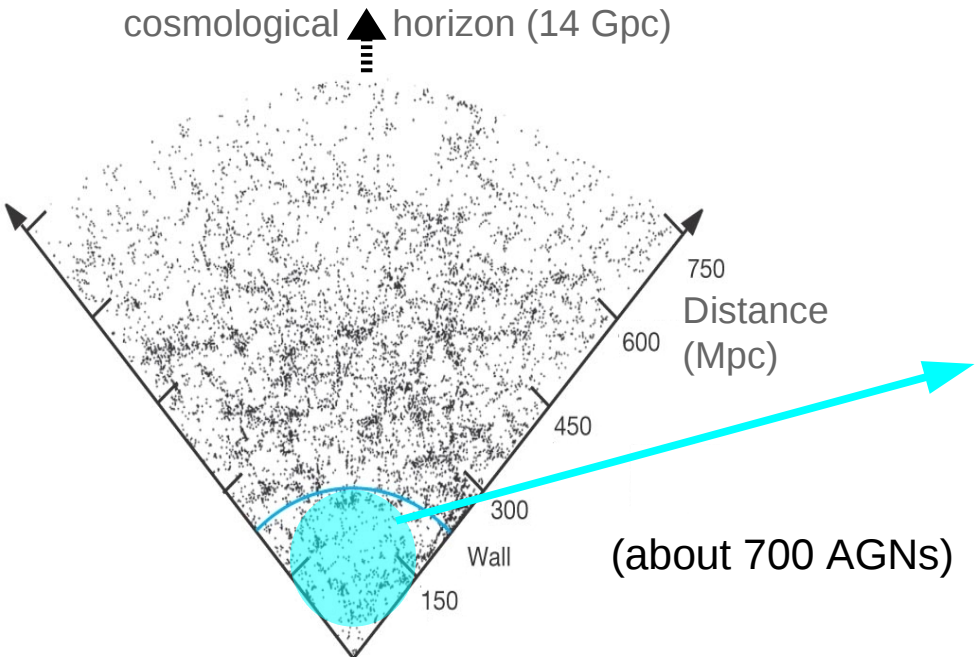
Greisen, PRL16 (1966)748, Zatsepin-Kuzmin JETP Lett. 4 (1966)78



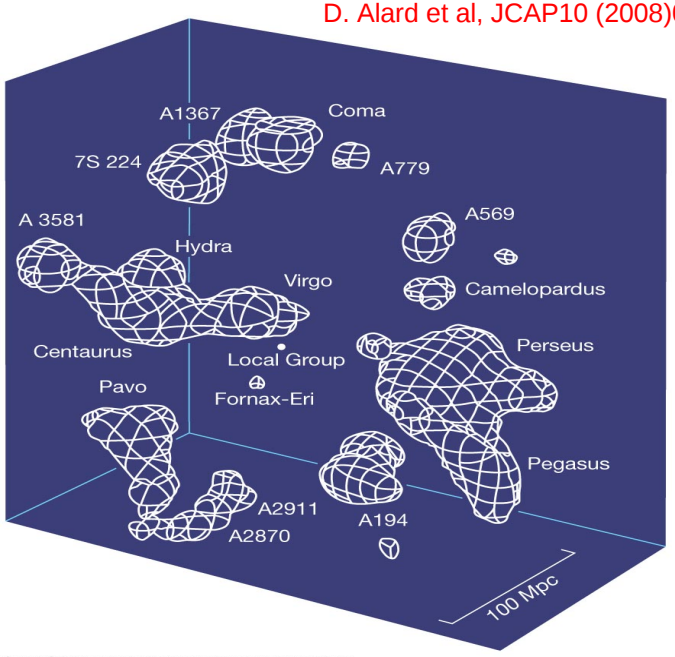
D. Alard et al, JCAP10 (2008)033]

- GZK horizon ~100-200 Mpc:

  UHECR come within our Local-Supercluster:



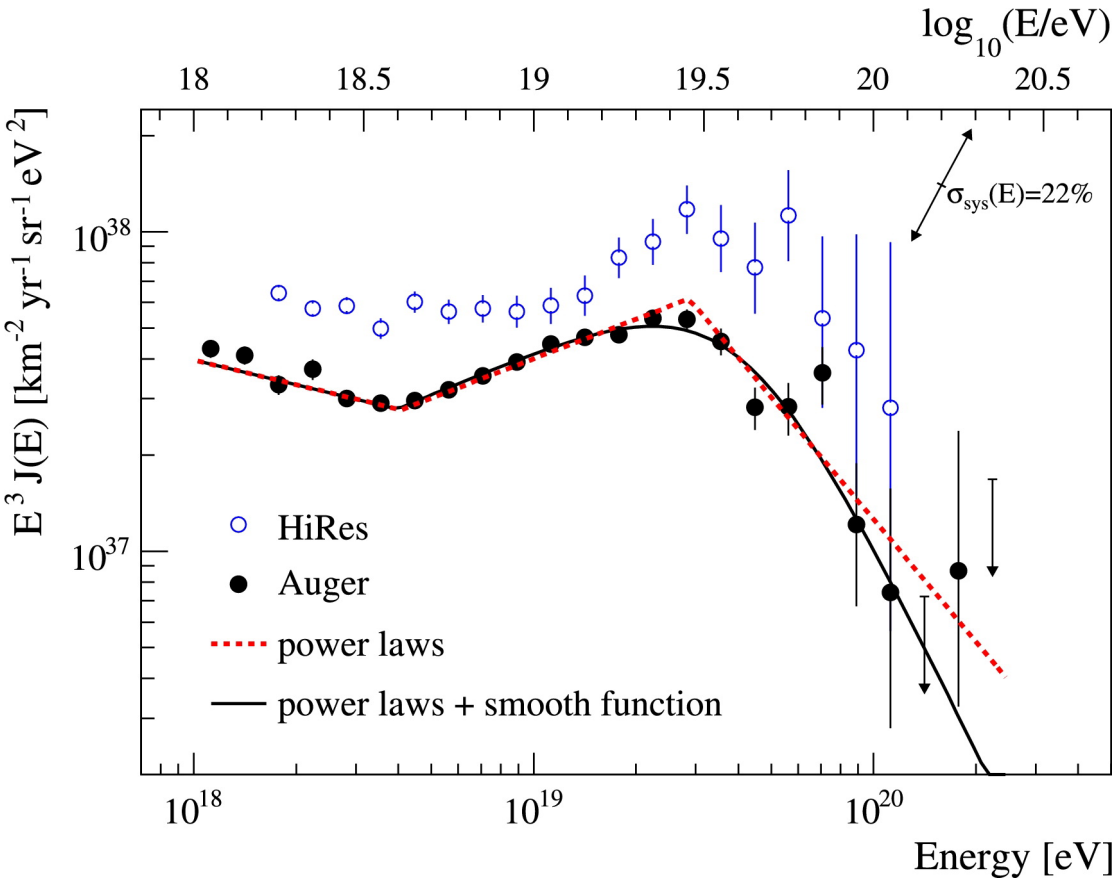
(about 700 AGNs)



(Q2) UHECR sources: Cut-off observed

- Abrupt flux suppression at $E_{CR} \sim 3 \cdot 10^{19}$ eV.

  Consistent with combined GZK for different species:



HiRes: PRL 100 (2008)101101
Auger: PLB 685 (2010)239

- GZK ? or cutoff at source ? Astrophys. accelerators running out of steam ?

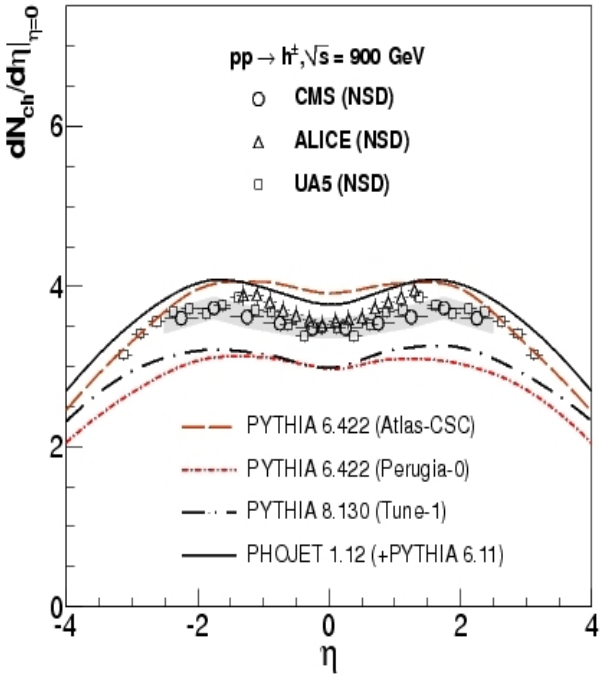
Particle pseudorapidity density (p-p, LHC)

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K.Werner, arXiv:1101.5596]

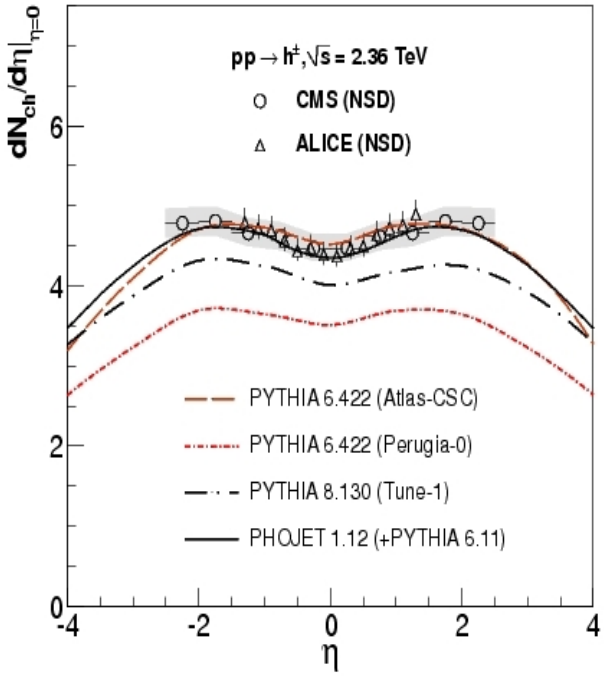
- 0.9, 2.36, 7.0 TeV charged-hadron data vs PYTHIA & PHOJET:

  Particle multiplicity not well reproduced at 2.36, 7.0 TeV by most tunings:

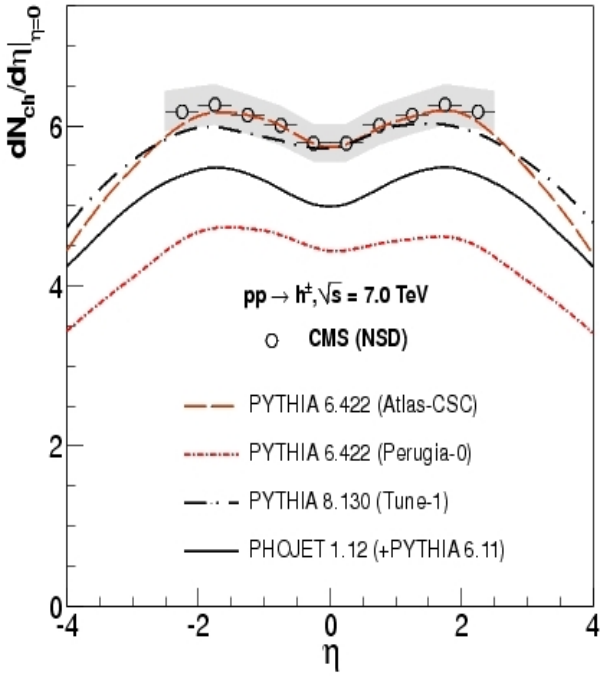
  Less particles predicted in most MCs than in real data.



0.9 TeV



2.36 TeV



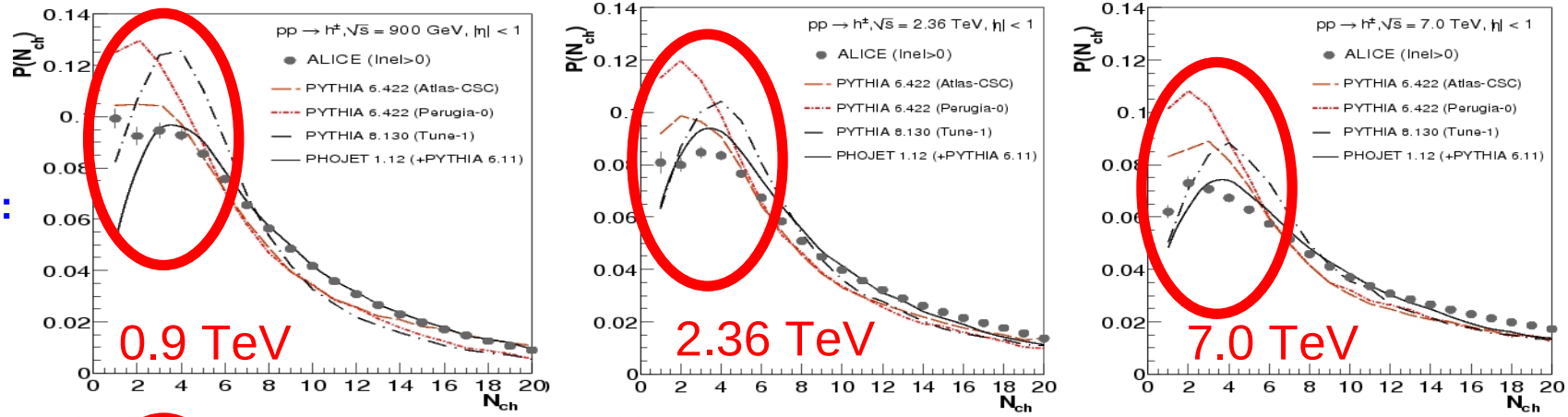
7.0 TeV

Events with low multiplicities (p-p, LHC)

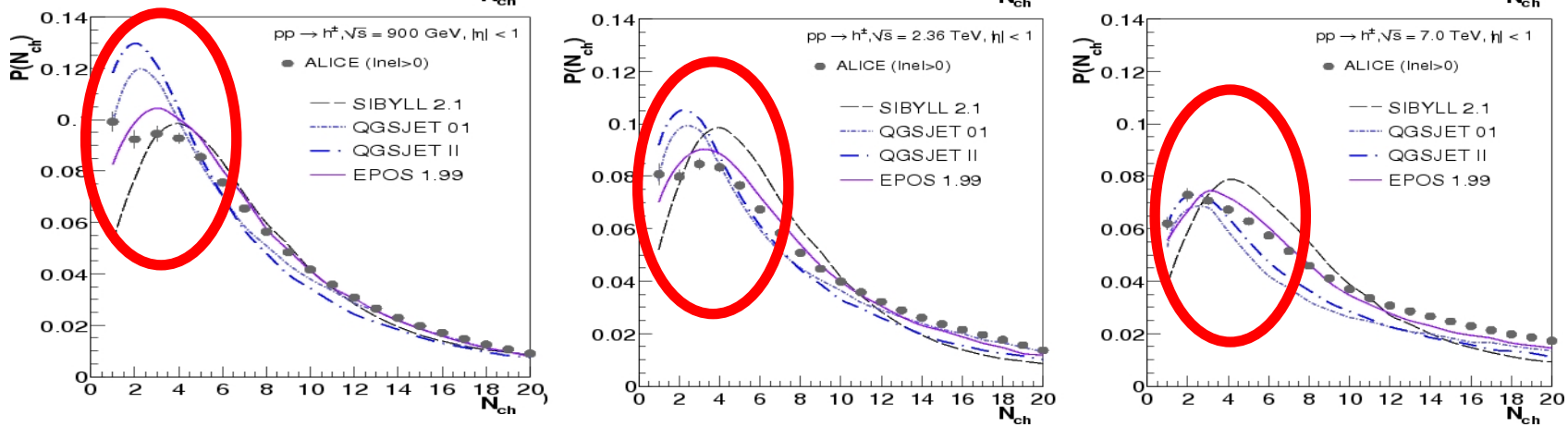
[DdE, R.Engel, S.Ostapchenko, T.Pierog, K.Werner, arXiv:1101.5596]

- 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:

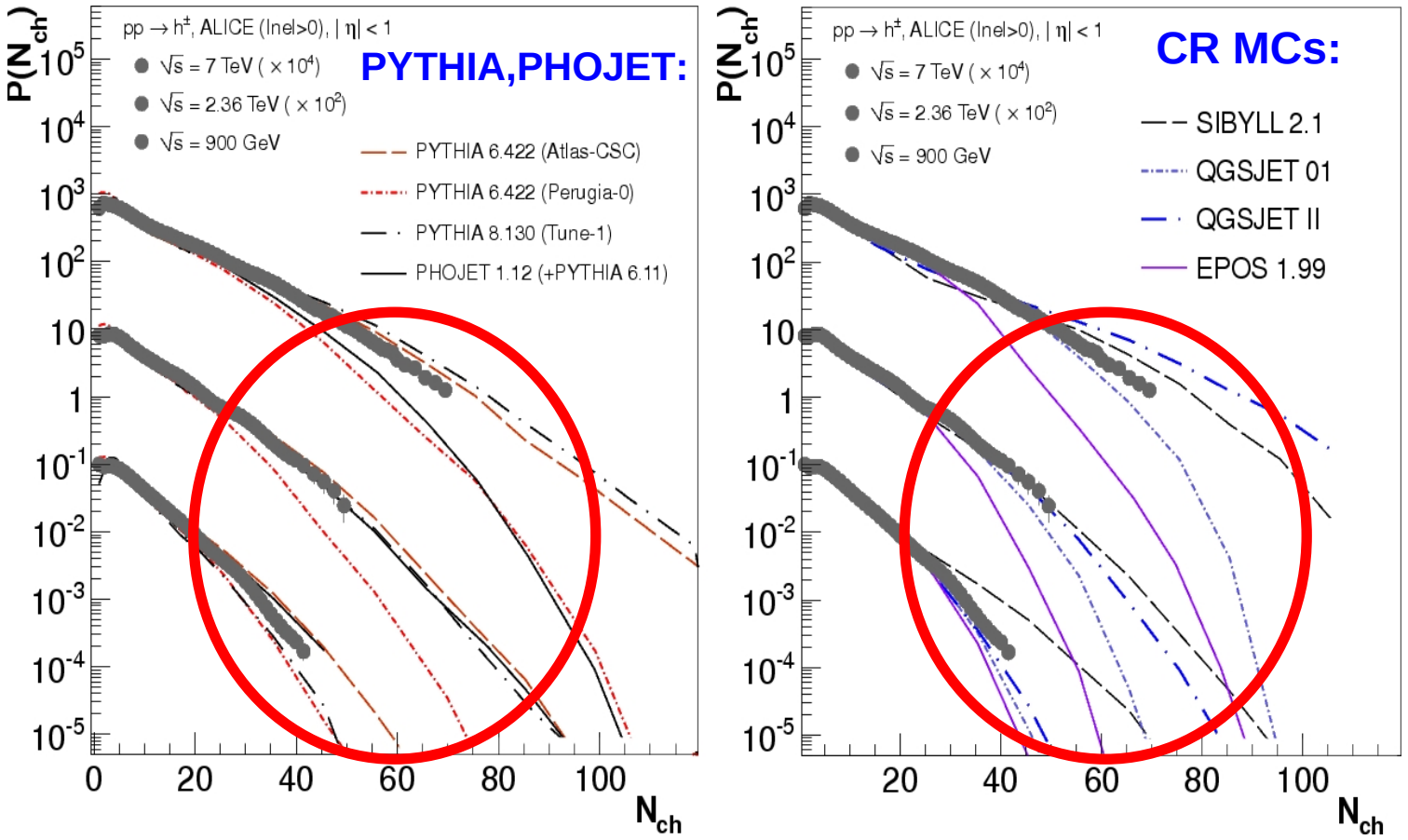


- Improvement of diffractive interactions needed.

Events with large multiplicities (p-p, LHC)

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K.Werner, arXiv:1101.5596]

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



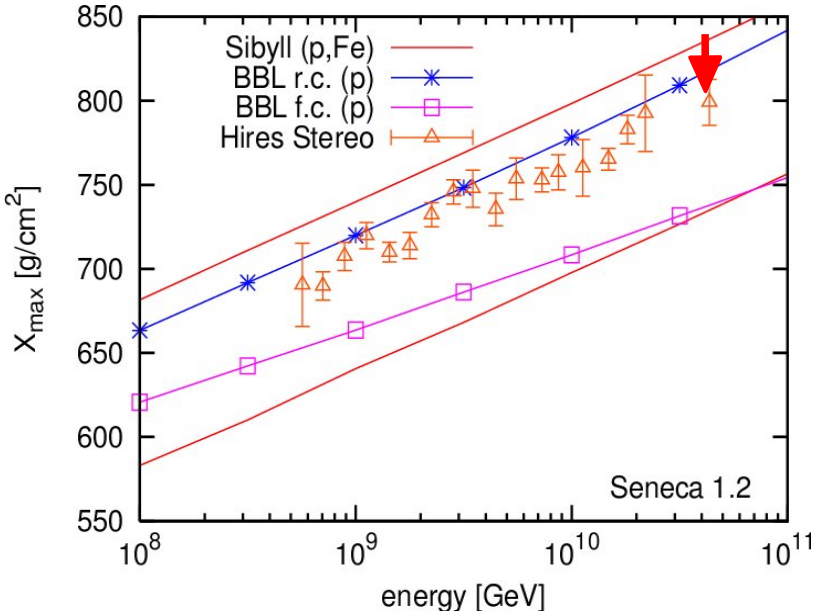
- Improvement of multi-parton interactions modeling needed.

Examples of implications for EAS

- Reduced dN/dη (esp. fwd):

  Less penetration:
  lower X_{max} (~ -30 g/cm^2)

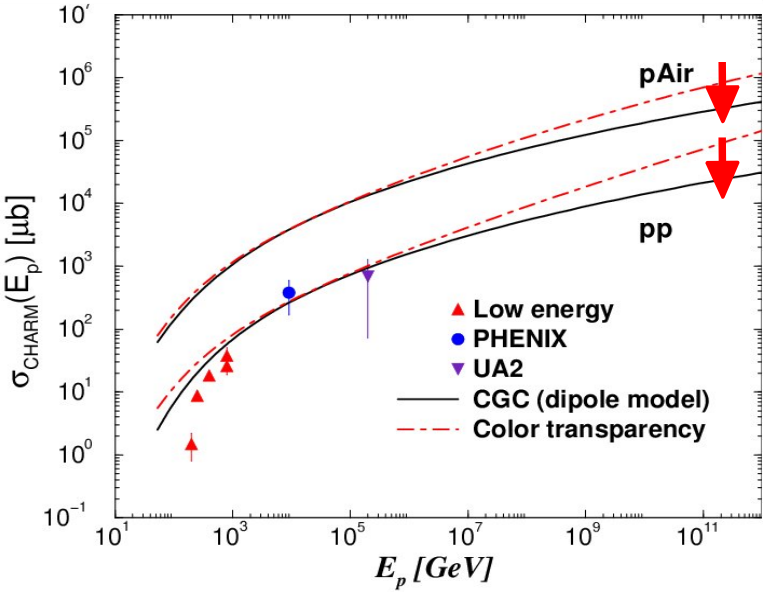
Drescher, Dumitru, Strikman
PRL 94 (2005) 231801



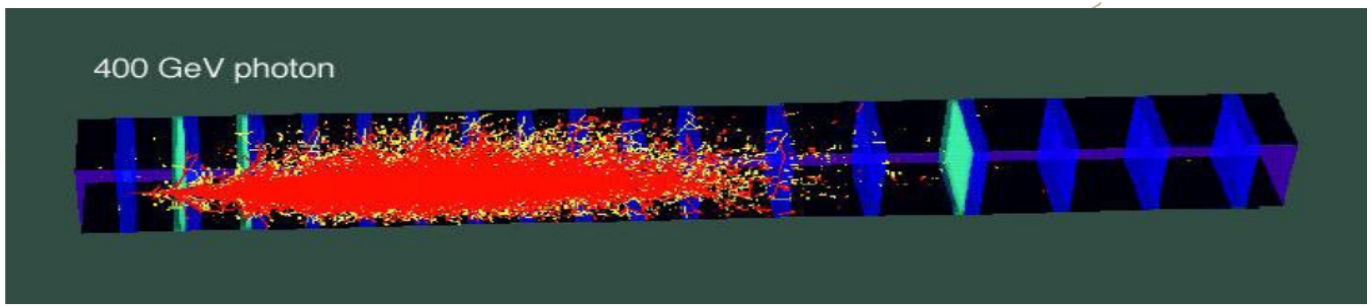
- Reduced charm cross sections:

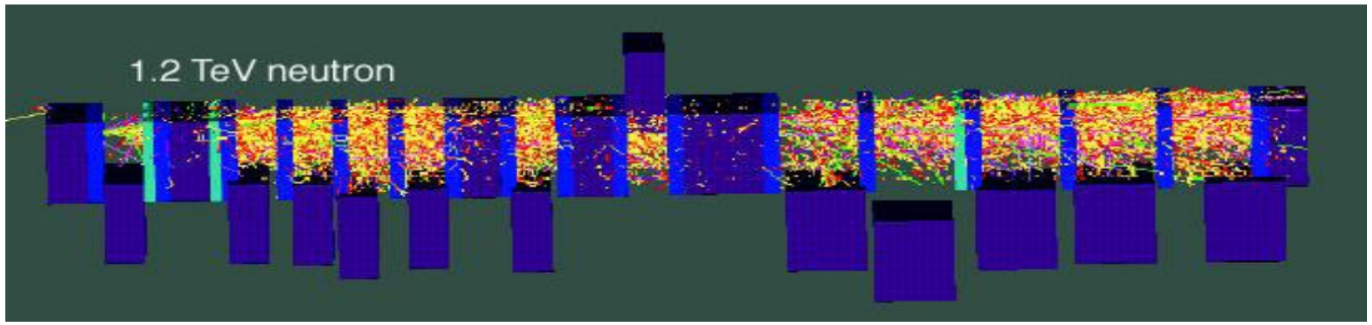
  Less muons

Machado&Goncalves
JHEP0704 (2007) 028

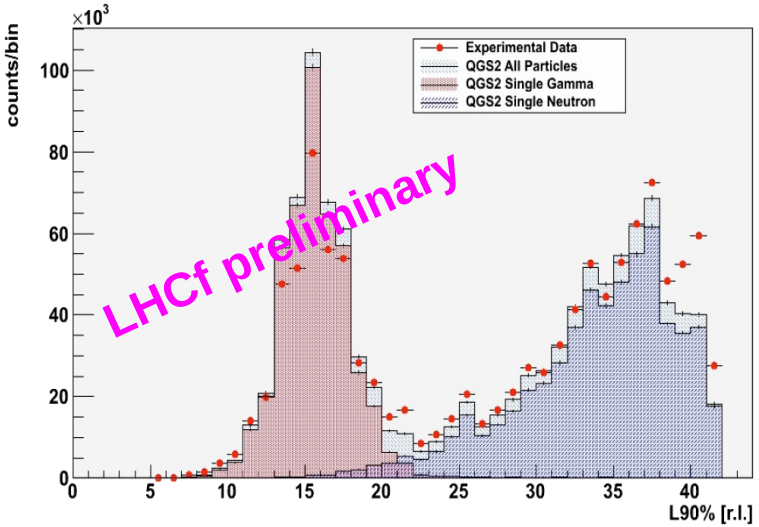


LHCf: Neutron-gamma PID





- Showers simulations

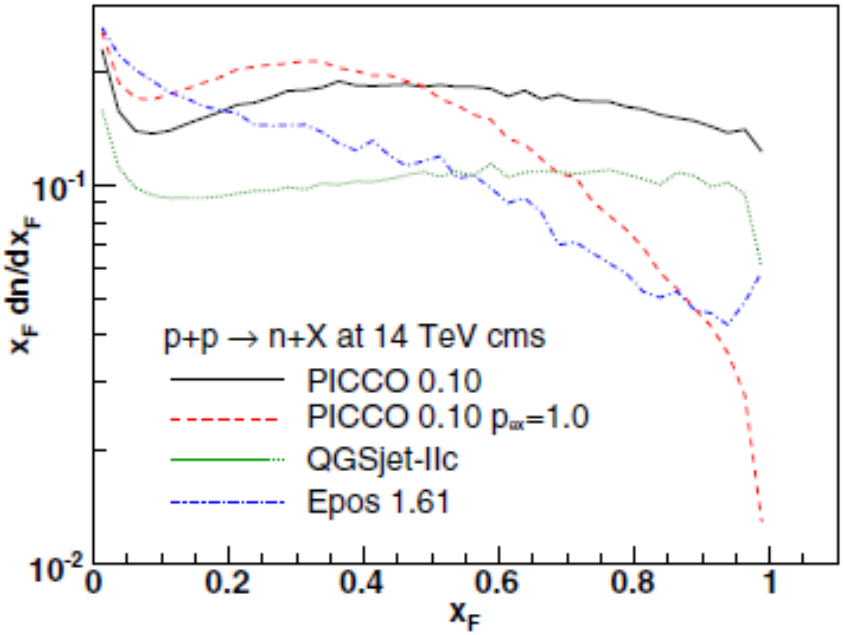


- Good agreement data with shower simulation ($L_{90\%}$)

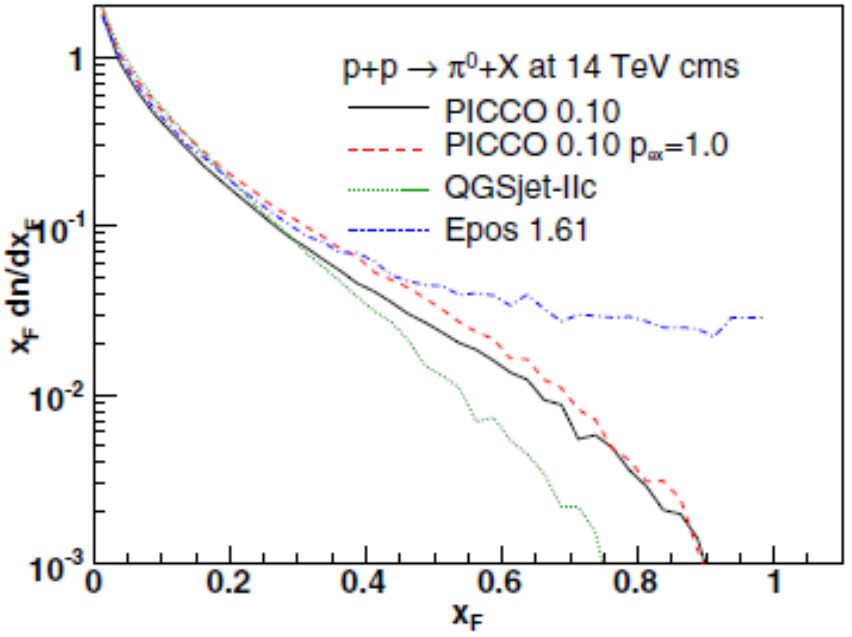
Forward hadron & leading-baryon production

- Forward multiplicity: very sensitive to primary shower development: leading baryon (inelasticity).
- LHC detectors present at zero-degrees for neutral particles:

Leading neutron:



Neutral mesons (π^0,η,$K^0_s \rightarrow \gamma$'s):



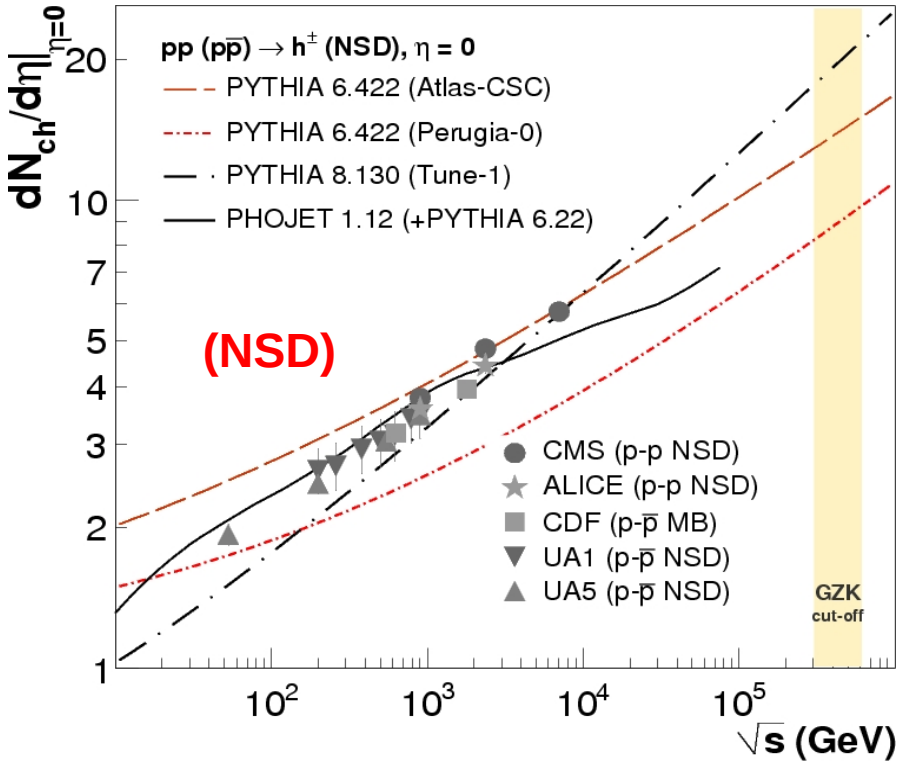
- Strong constraints on non-perturbative MC ingredients: beam-remnants, fragmentation, ...

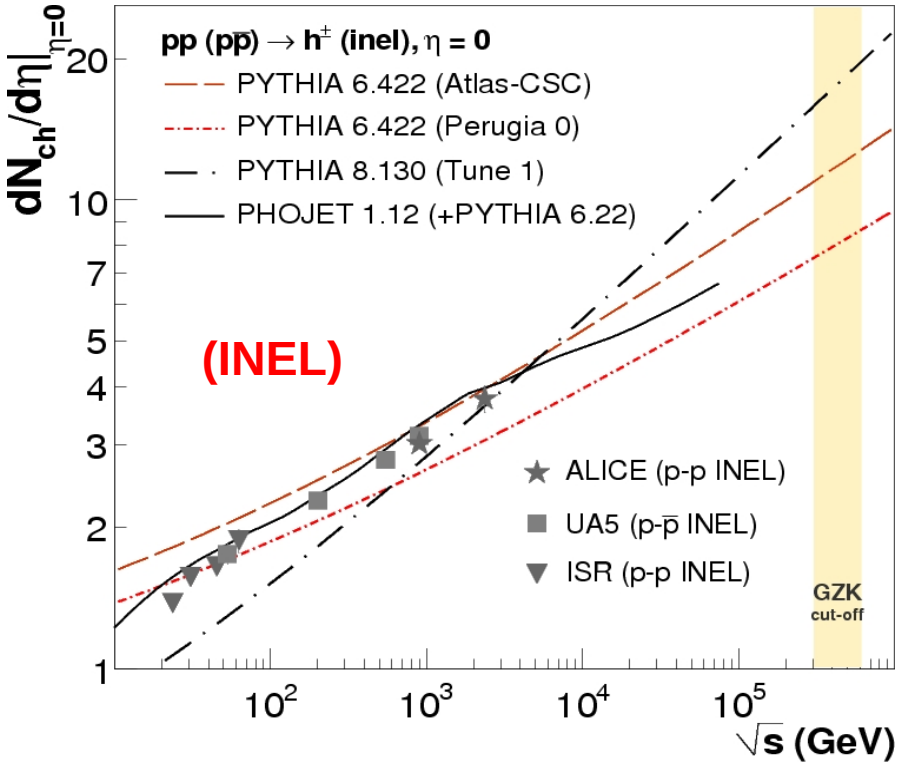
Particle pseudorapidity densities (LHC-GZK)

[DdE, R.Engel, S.Ostapchenko, T.Pierog, K.Werner, arXiv:1101.5596]

- Large differences predicted by PYTHIA-tunes at √s~300 GeV!

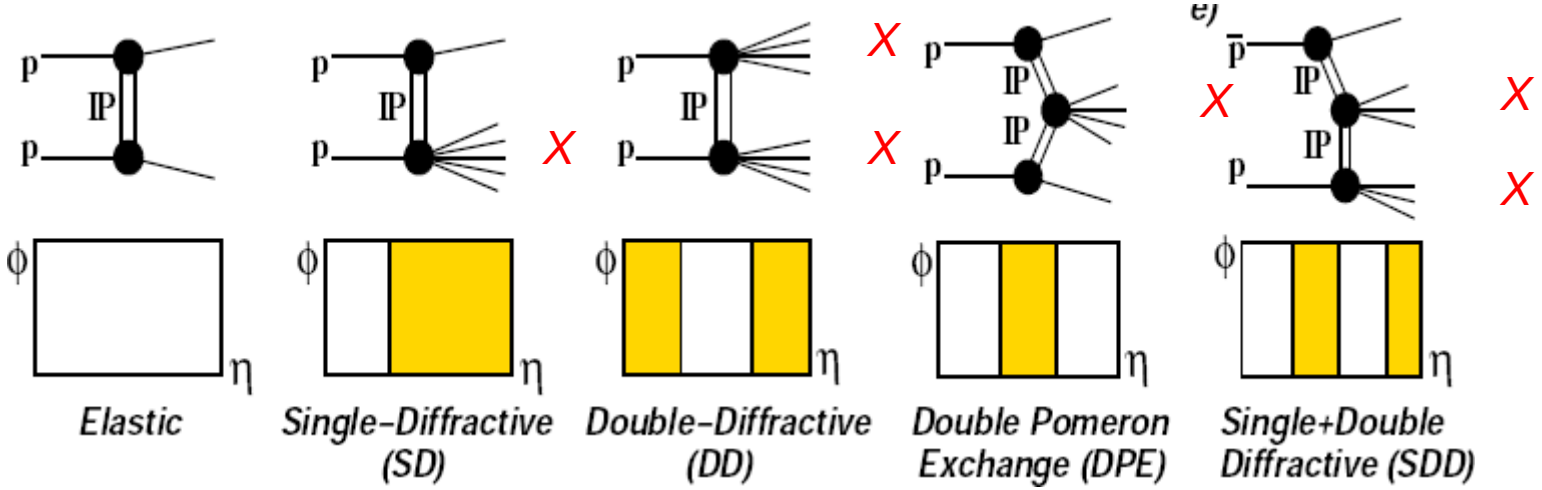
  PYTHIA 8.130 (~20) > ATLAS-CSC (~15) > Perugia-0 (discarded)





Pomeron-induced processes

- Diffract./Elastic scatt. (~40% p-p σ_{tot}): p intact (Roman Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:

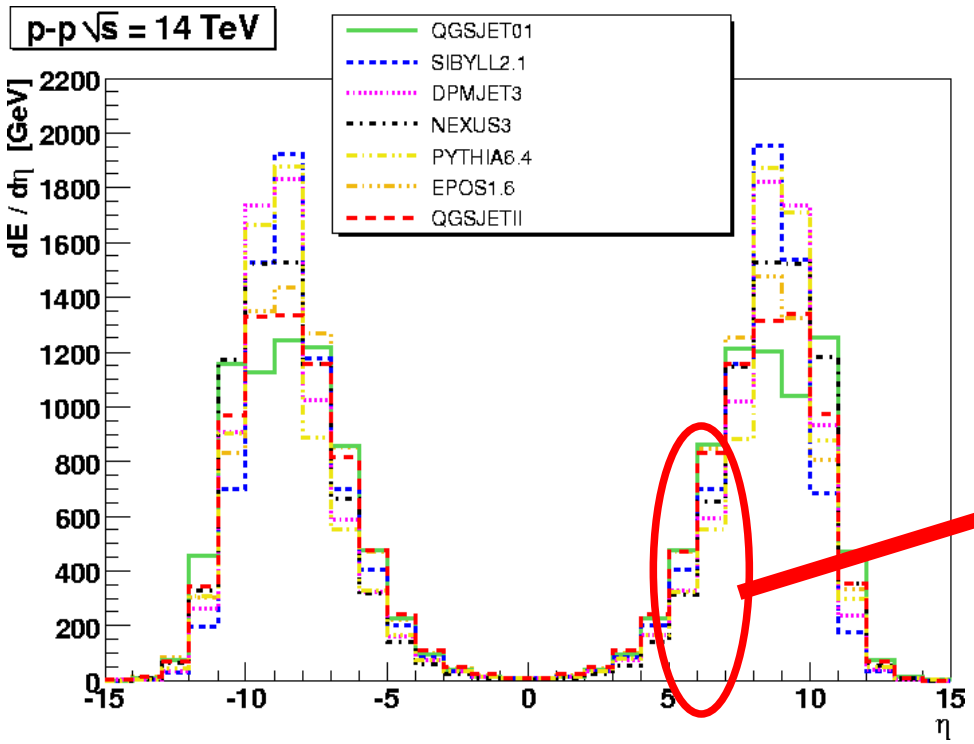


- σ_{tot},ρ: Test fundamental QM relations (Froisart bound, optical th., dispersion relat)
- Soft diffraction (*X* = anything): Dominated by soft QCD → SD, DPE vs. s, t, M_X provide valuable info of non-perturb. QCD. Contributions to pile-up p-p events.
- Hard diffraction (*X* = jets, W's, Z's ...): Calculable (in principle) in pQCD → Info on proton structure (dPDFs,GPDs), multi-parton interactions, discovery physics (DPE Higgs, beyond SM)

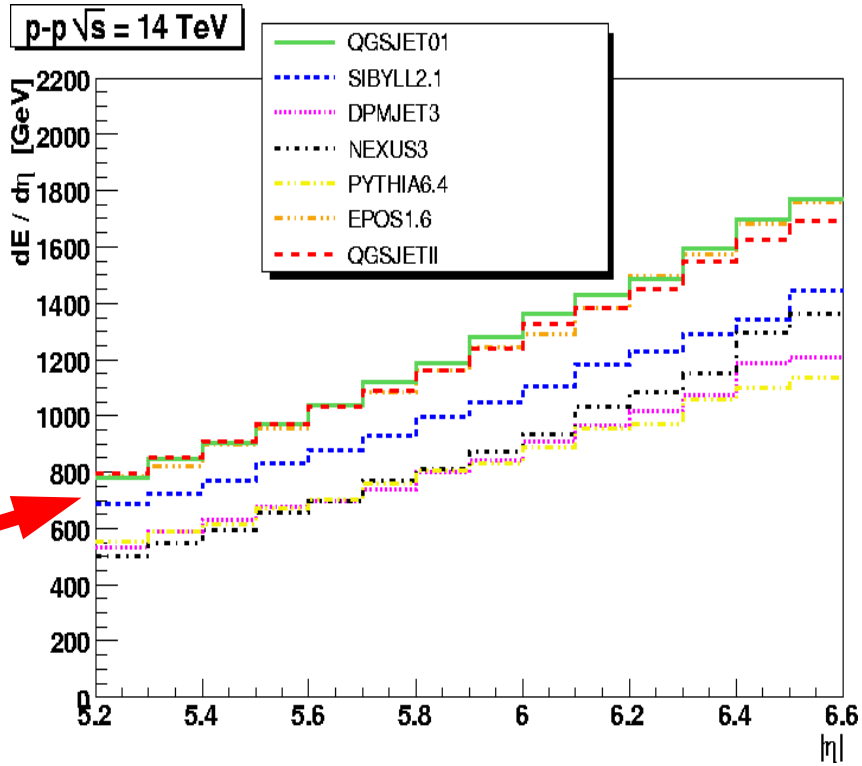
proton-proton @ √s = 14 TeV

- Energy rapidity densities (dE/dη), dominated by soft QCD: underlying event, multi-parton interactions, fragmentation, ...

[full η]



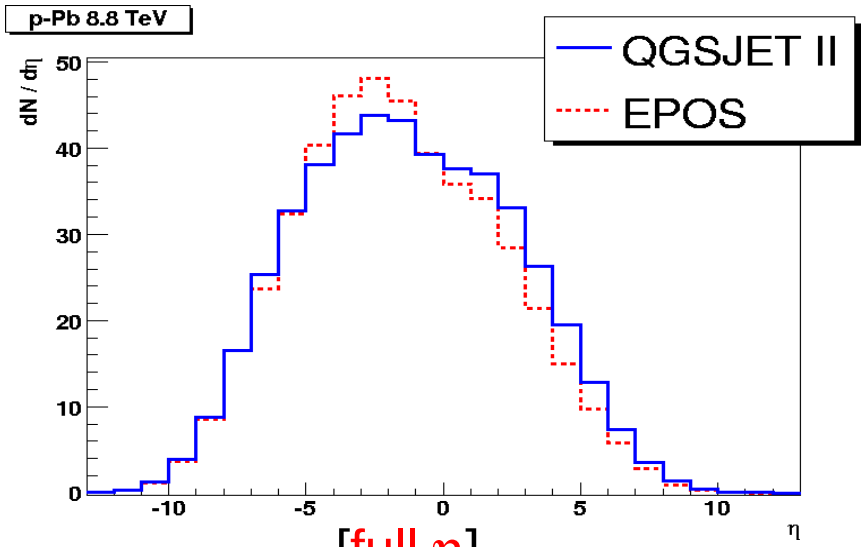
[CASTOR calorimeter region]



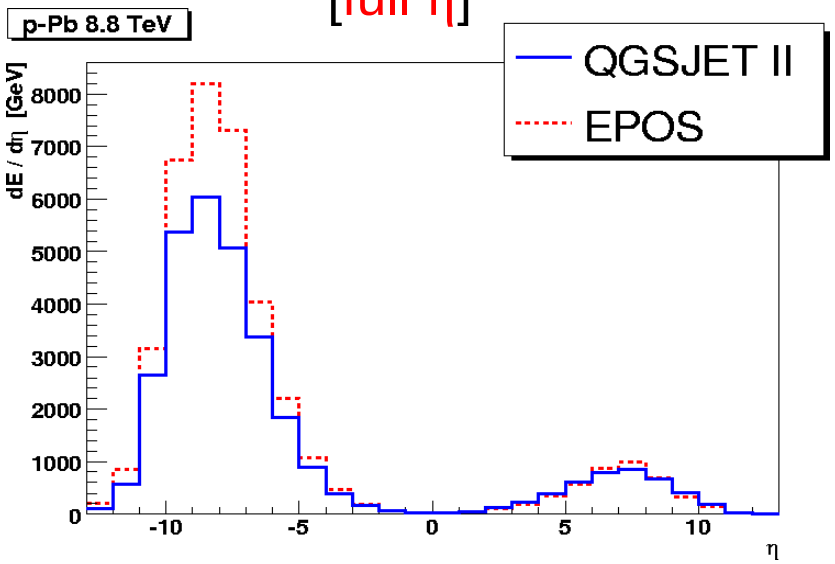
DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

proton-Pb @ √s = 8.8 TeV

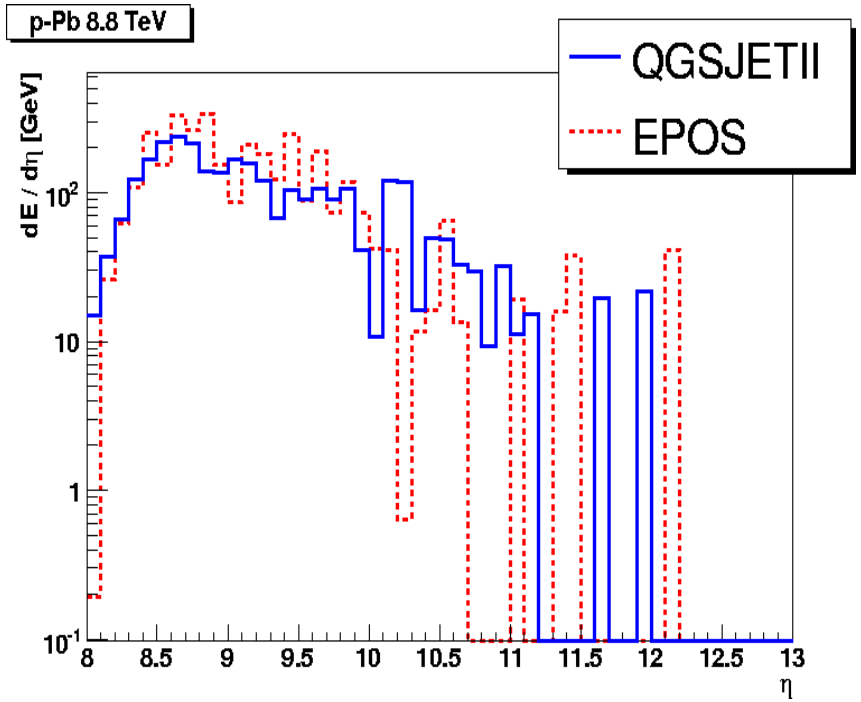
- Particle (dN/dη) & energy (dE/dη) rapidity densities:



[full η]



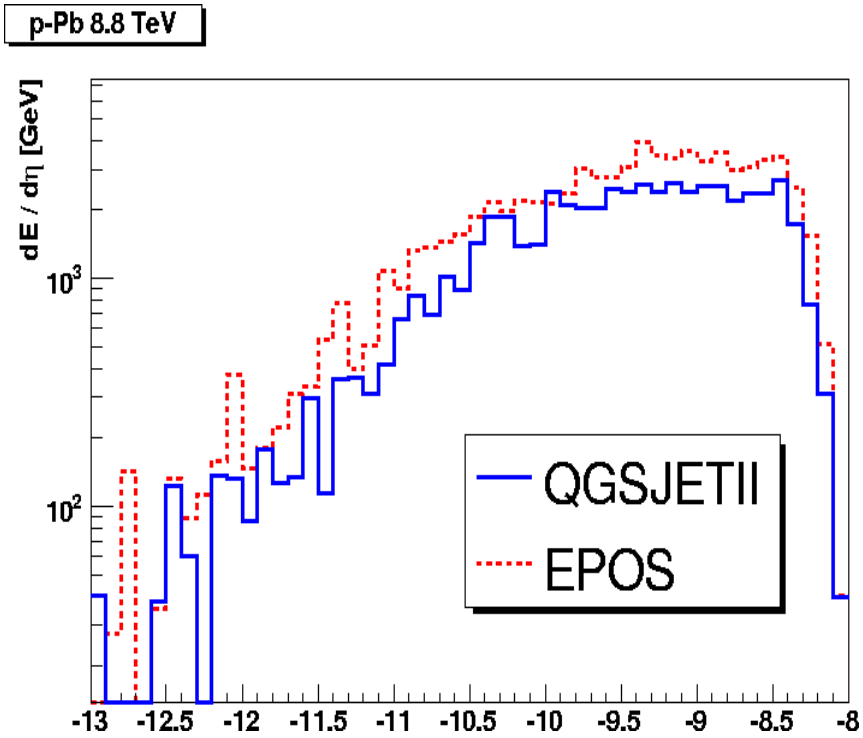
[ZDCs/LHCf calorimeter region]

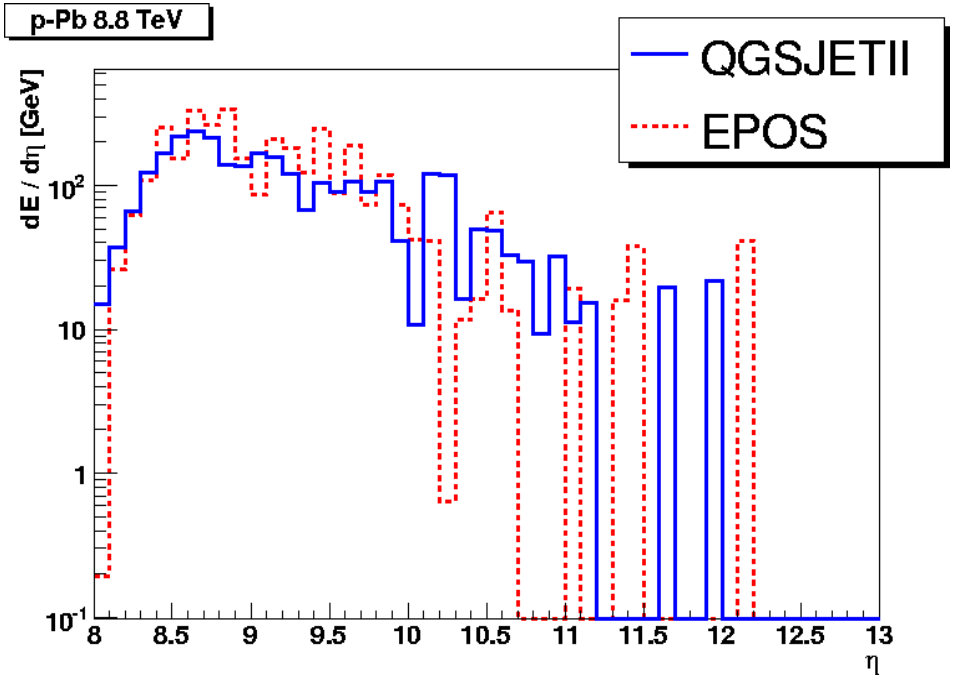


DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

proton-Pb @ √s = 8.8 TeV

- Particle (dN/dη) & energy (dE/dη) at forward rapidity :



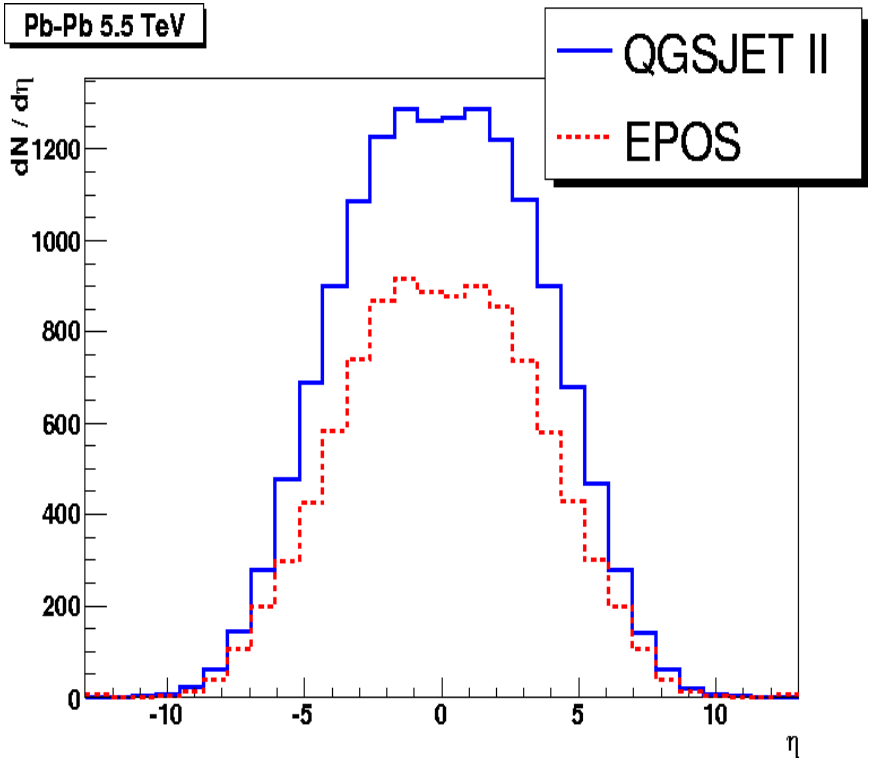


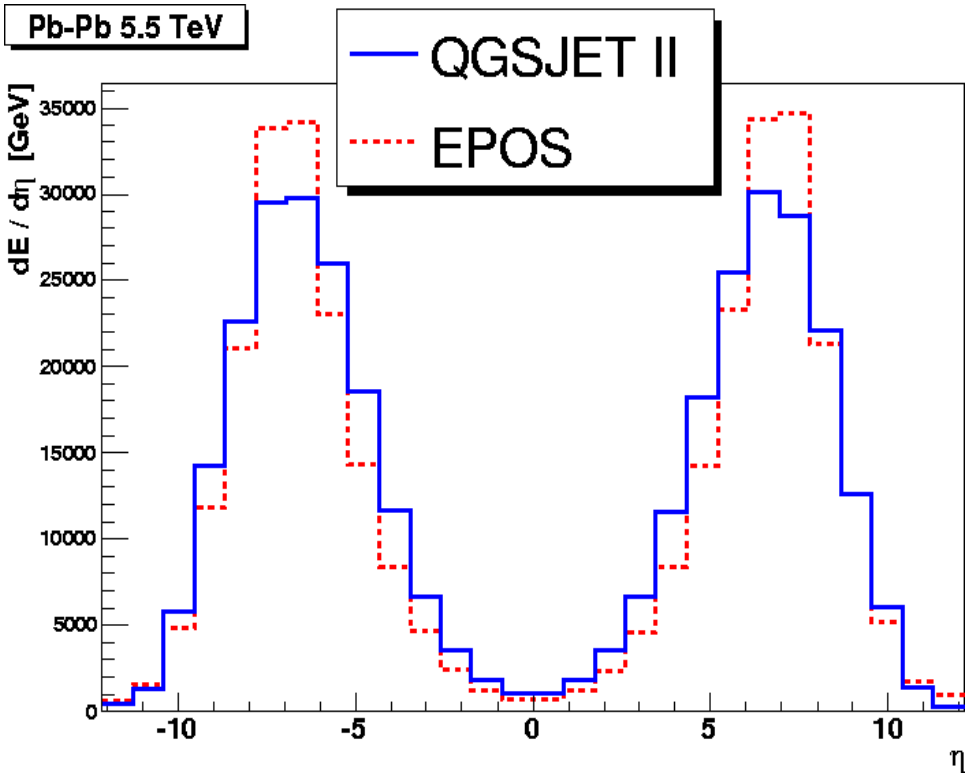
(*) DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Pb-Pb @ √s = 5.5 TeV

- Particle (dN/dη) & energy (dE/dη) rapidity densities:

[full η]



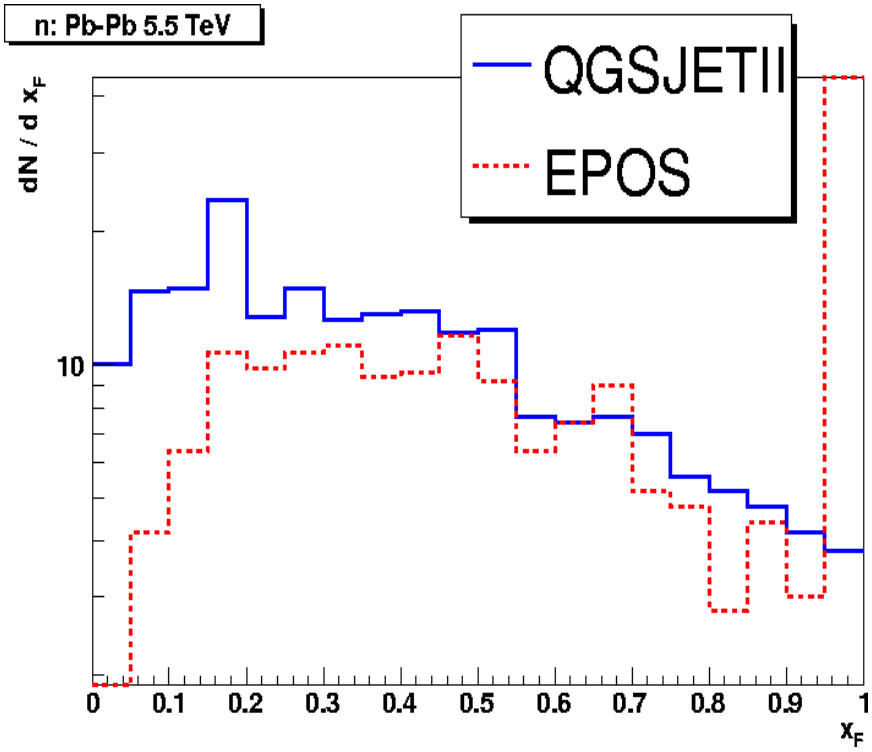


DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

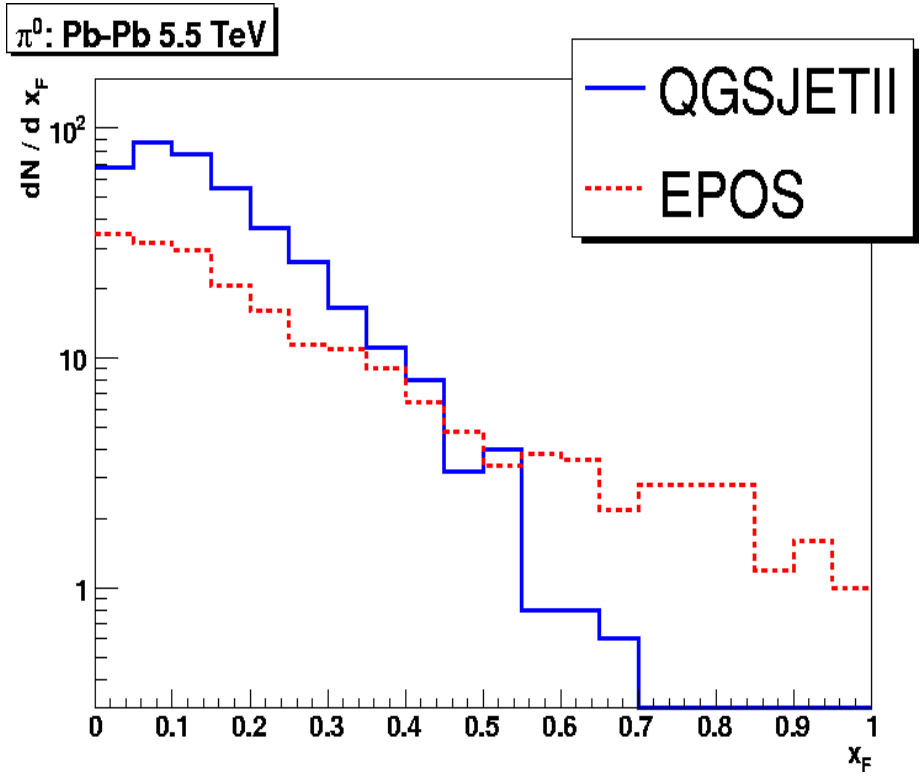
Pb-Pb @ √s = 5.5 TeV

- Leading particle (dN/dxF) in ZDCs/LHCf calorimeter region:

(neutrons)



(neutral pions: $\gamma\gamma$)



DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]