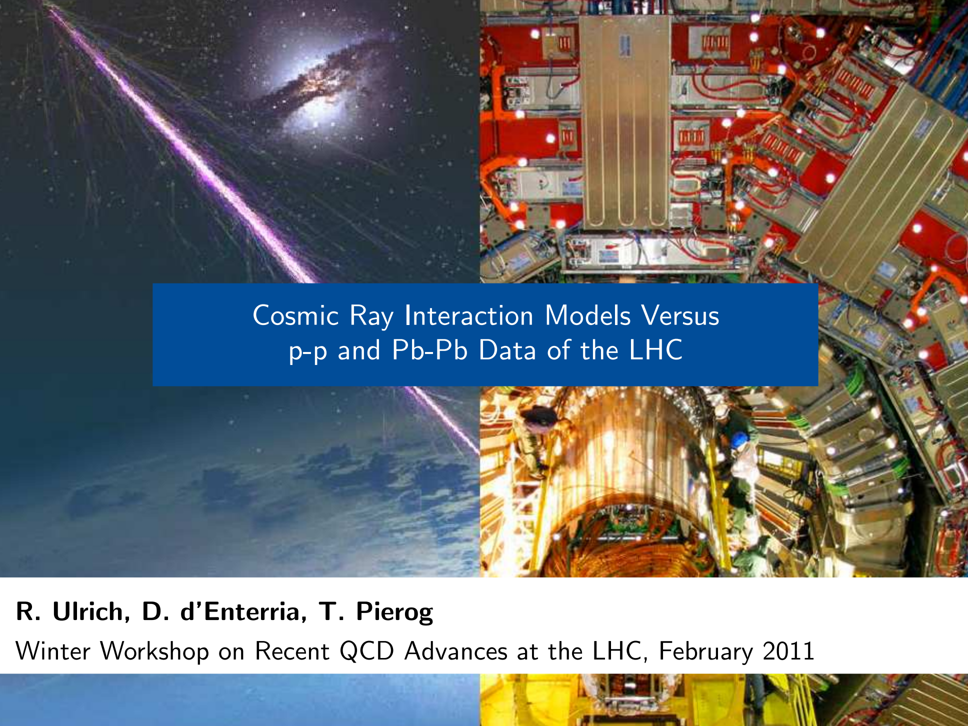
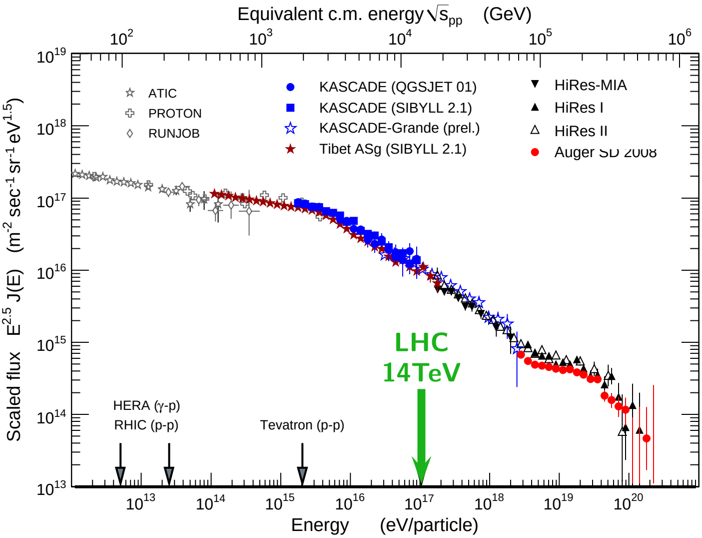


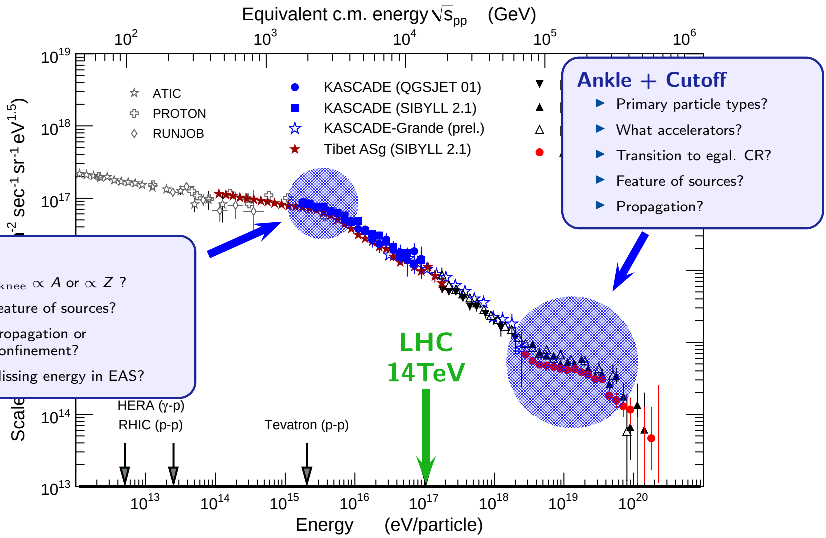
Cosmic Ray Interaction Models Versus p-p and Pb-Pb Data of the LHC

R. Ulrich, D. d'Enterria, T. Pierog

Winter Workshop on Recent QCD Advances at the LHC, February 2011


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2 10^3 10^4 10^5 10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19} 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)
HiRes-MIA
HiRes I
HiRes II
Auger SD 2008
LHC
14TeV
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV/particle)

Cosmic Ray Overview and Open Questions



Knee

- $E_{\mathrm{knee}} \propto A$ or $\propto Z$?
- Feature of sources?
- Propagation or Confinement?
- Missing energy in EAS?

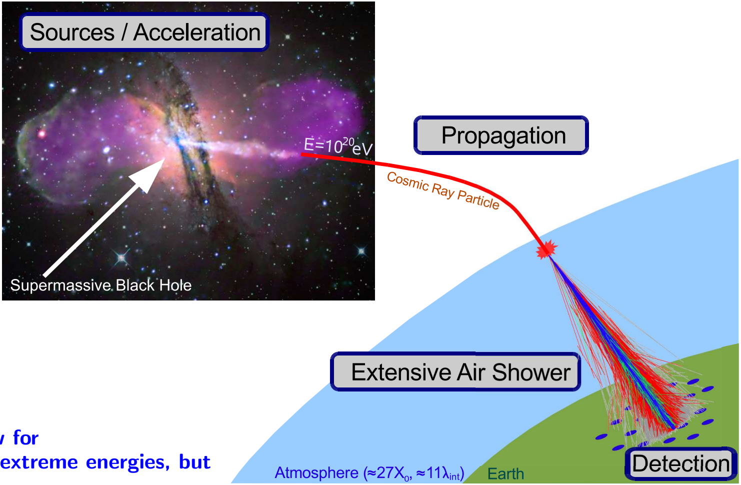
Ankle + Cutoff

- Primary particle types?
- What accelerators?
- Transition to egal. CR?
- Feature of sources?
- Propagation?

→ LHC first accelerators above the knee !

→ LHC only factor of < 10 in $\sqrt{s}$ away from ankle !

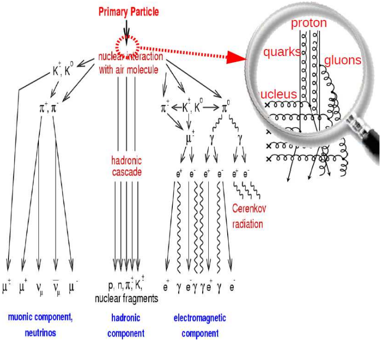
Cosmic Rays and Extensive Air Showers



Observational window for astrophysics at most extreme energies, but

- No direct detection of cosmic rays
- Extensive Air Showers (EAS)
- Need to understand ground based EAS observables
- **Very good EAS models required!** **⇒ Interactions up to $\sqrt{s}$ ∼500 TeV**

Modelling Interactions in Extensive Air Showers



Requirements and Problems:

- Interactions up to $\sqrt{s} \sim 500$ TeV
  $\rightarrow$ Far beyond accelerator energies...
- Mainly soft physics + diffraction: **forward region**
  $\rightarrow$ Difficult to instrument...
  $\rightarrow$ Only fixed target at lower energies...
- Target is **air**: p-air, π-air, K-air, A-air, ...
  $\rightarrow$ Typical target very different from **air**:
  Nuclear effects must be considered...

Ingredients:

- Theory: pQCD (hard) + Gribov-Regge (soft)
- A lot of phenomenology: Diffraction, String fragmentation, Saturation, Remnants, Nuclear effects, ...

Older models:

Glauber based, different mostly in remnants+diffraction, for example:
QGSJet01 *(Kalmykov, Ostapchenko)*
SIBYLL *(Engel, Gaisser, Lipari, Stanev)*

Recent models:

QGSJetII *(Ostapchenko)*
Theory++, Optimized for cosmic rays

EPOS *(Werner, Pierog)*
Phenomenology++
Optimized for LHC, RHIC (and cosmic rays)

Cosmic Ray Models and LHC Data

we can only show here a very small subset of all data of
ALICE, ATLAS, CMS, LHCb

read
arXiv:1101.5596v2 [astro-ph.HE] or also
arXiv:1101.1852v1 [hep-ex]
for more details and references

Overview and Prospects

Hard and soft particle production, string/remnant fragmentation: General characteristics of hadronic multiparticle production.
⇒ all detectors, especially detailed central measurements

Projectile remnants, forward fragmentation, leading hadrons, inelasticity
Most critical for energy transport in air showers!
⇒ LHCf, Zero Degree Calorimeters

Diffraction: Above LHC energy, $> 40\,\%$ of interactions are diffractive.
⇒ Totem, CASTOR, ...

Cross sections (diffractive, elastic, inelastic and total): Extremely important for the development and fluctuation of air shower cascades!
⇒ Totem

Gluon saturation, non-linear QCD: x values down to 10^{-8} in UHECR, saturation effects studied at LHC via $\langle p_{\mathrm{T}} \rangle$, correlations, forward particle production, etc.
⇒ ATLAS, ALICE, CMS, ...

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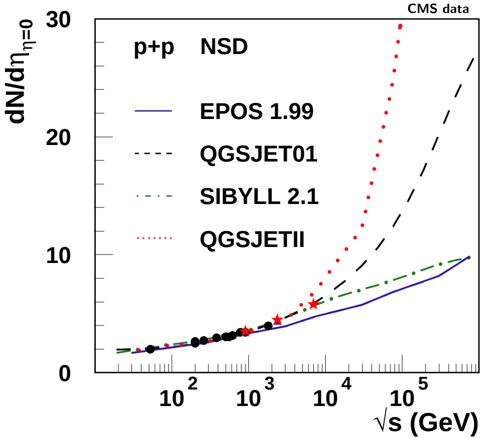
So far only central detectors published data up to 7 TeV

Charged Hadron Density at Midrapidity

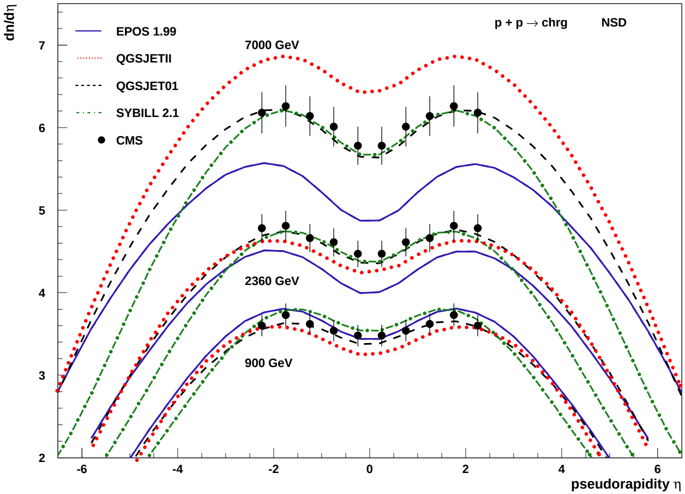
- Good and fast cross-check for overall data-MC agreement



- Models describe LHC data well
- The older models (QGSJet/SIBYLL) perform better
- Divergence starts at ~ 7 TeV

$\Rightarrow$ Data at 14 TeV very important!

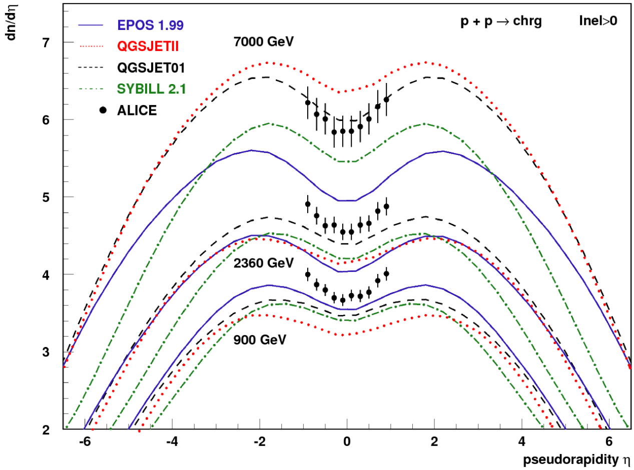
Hadron Pseudorapidity Densities, NSD



- The non single diffractive data is well reproduced by SIBYLL/QGSJet01 for $|\eta| < 2.5$
- Model differences increase towards higher pseudorapidities

$\Rightarrow$ Forward tracking data important!

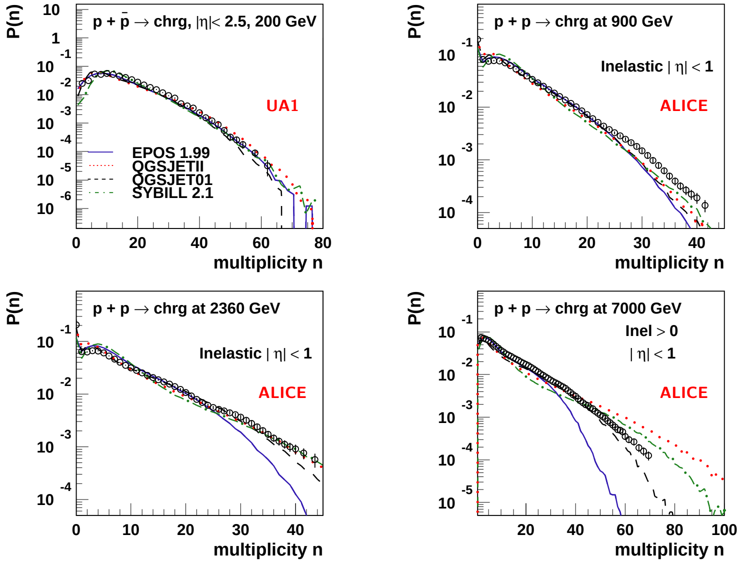
Hadron Pseudorapidity Densities, INEL



- The inelastic event selection is less well reproduced by models
- Agreement of models with data not perfect...

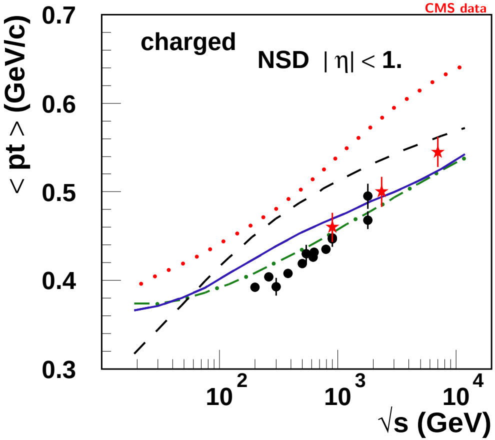
→ Clear that models have to be improved

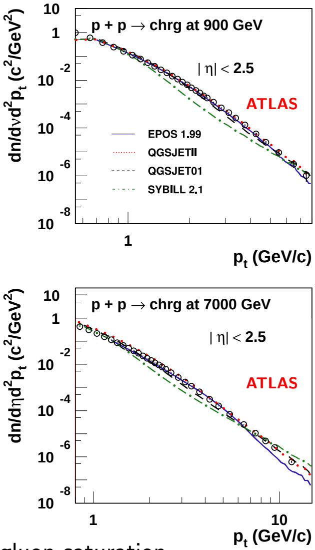
Multiplicity Distributions



- Sensitive to diffraction (low N_{ch}) and multiparton interactions (high N_{ch}) modeling
- Worse data-models agreement ($\rightarrow$ all models are tuned to low energy data)

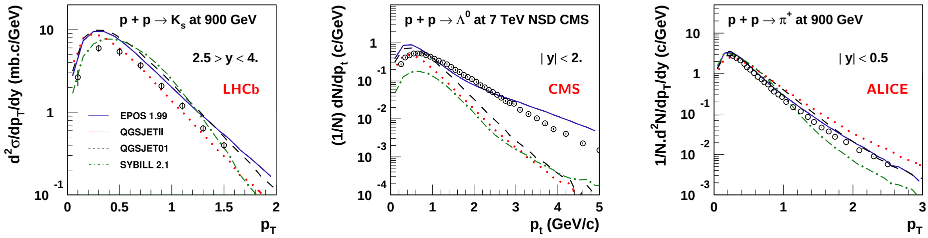
Transverse Momentum





- $\langle p_{\mathrm{T}} \rangle$ is sensitive to pQCD x-sections and to gluon-saturation
- Data shows slow and smooth rise, which is similar in the models
- No important new effects yet visible (saturation, collective effects)

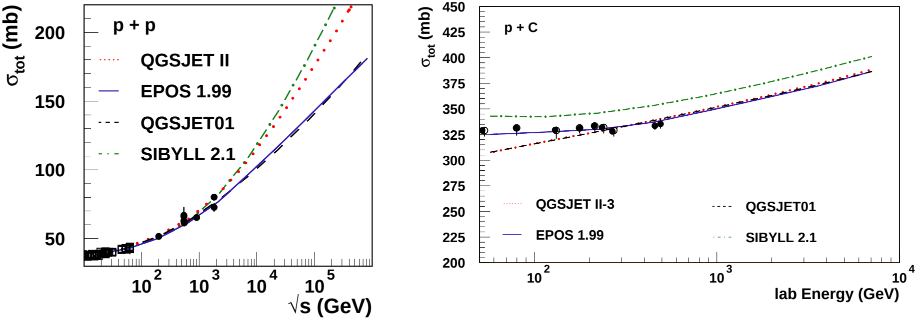
Transverse Momentum (Identified) Spectra



- Models have trouble to describe details of the production of mesons and baryons. EPOS is acceptable.

⇒ Relevant for the muon content of air showers

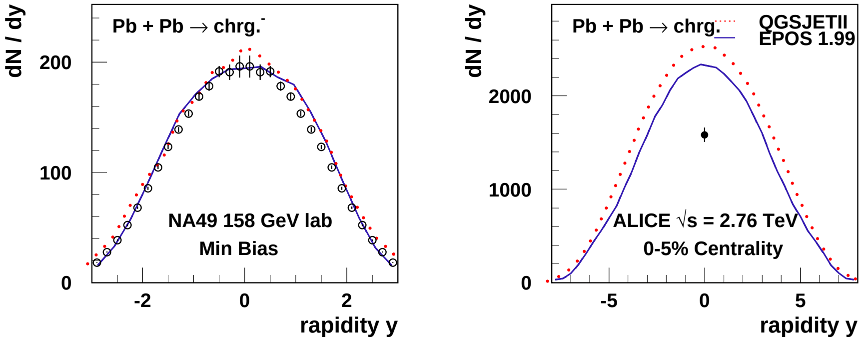
- Total p-p cross section (including elastic & diffractive contributions) measurable by TOTEM and ATLAS-ALFA



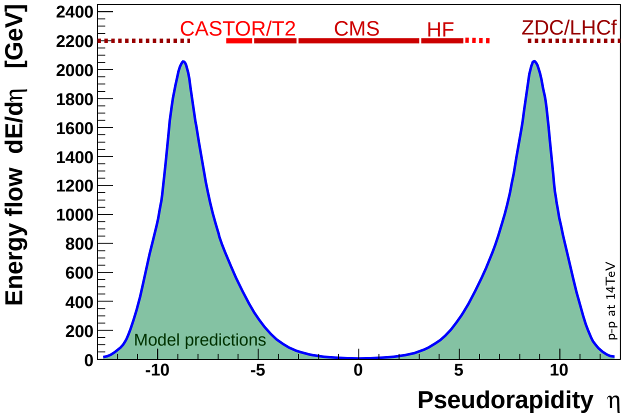
Extensive Air Showers: p-Air, A-Air, π-Air, ...

⇒ Important to study not only p-p, but p-A and A-A collisions at the LHC

Pb-Pb Hadron Pseudorapidity Density



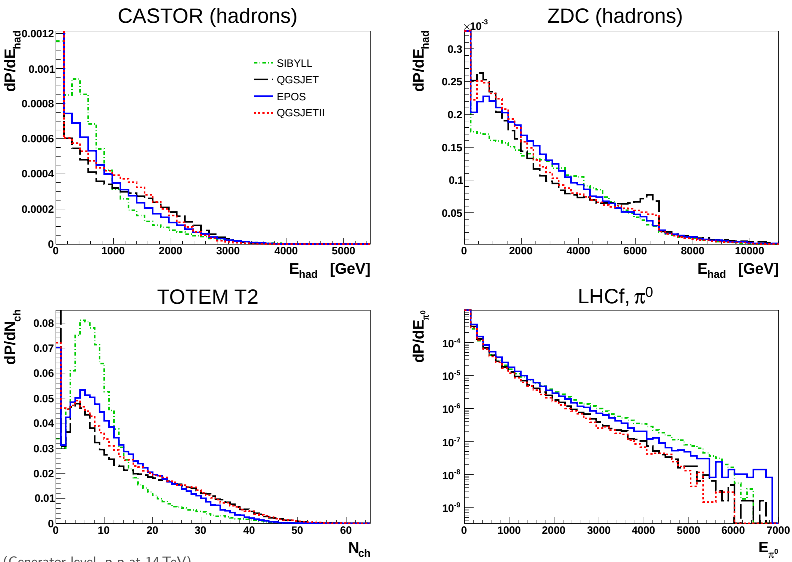
⇒ Models overpredict particle multiplicity at 2.76TeV:
Coherence, gluon saturation effects well implemented ?



- Most primary energy is transported into the very forward direction

⇒ Crucial for air showers is particle production in **forward direction**!
TOTEM, LHCf, CASTOR, ZDCs, HF, FCal, ... detectors

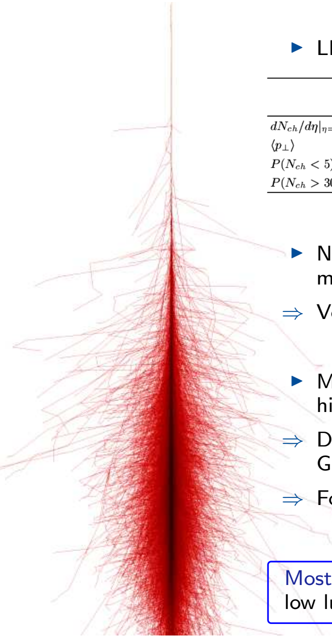
Particle Production in Forward Direction



(Generator level, p-p at 14 TeV)

- Models differ significantly where it matters most for air showers
- Model differences measurable with current forward detectors

Summary



- LHC minimum-bias data so far mostly bracketed by CR models

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

- No *surprising* features or changes found in data with respect to model predictions

⇒ Very unlikely that the *knee* is caused by interaction physics

- Models diverge rather rapidly towards higher energies and higher pseudorapidities

⇒ Data at $\sqrt{s}$ =14 TeV crucial for model tuning up to GZK-cutoff energies

⇒ Forward detectors most relevant

Most important for cosmic ray applications are:
low luminosity runs, high energy, p-p, p-A (light)