Karlsruhe Institute of Technology

Measurements at accelerators particularly useful for High-Energy Astroparticle Physics

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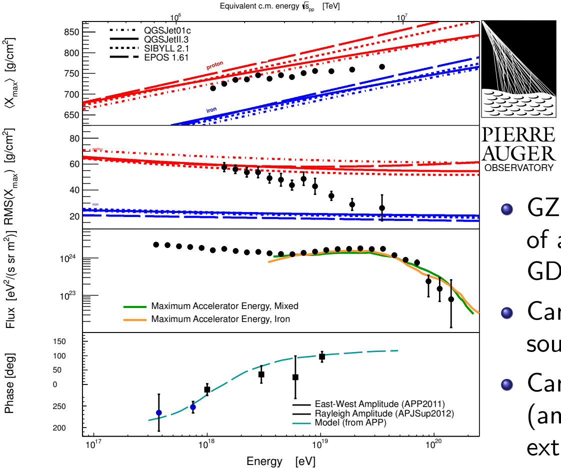
Outline

1. Ultra-high energy cosmic rays
2. Extensive air showers
3. Hadronic interactions in air showers
4. LHC data and models

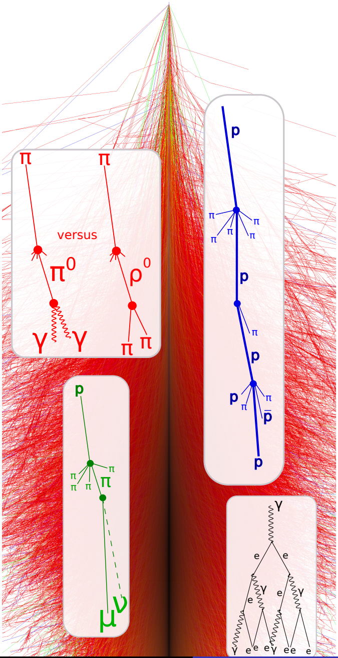
What is the nature and the sources of the highest energy particles in the universe?



- GZK cutoff? Maximum energy of accelerators? GDR/dissociation?
- Can we find individual (point) sources?
- Can we identify a transition (anisotropy) from galactic to extragalactic?

→ **Mass composition is a key measurement to resolve questions!**

Ultra-high energy cosmic ray extensive air showers



- Huge coupled cascading process
- Conversion of primary energy into
  - Electrons/ photons
  - Muons
  - Low energy hadrons
- Most relevant mass-sensitive observables are:
  - Depth of shower maximum
  - Muon content
- Precise modelling is mandatory for a cosmic ray mass measurement

Air shower cascade

Model features and parameters

Hard and soft particle production, string/remnant fragmentation:

General characteristics of hadronic multiparticle production.

$\Rightarrow$ all detectors, especially detailed central measurements

Projectile remnants, forward fragmentation, leading hadrons, inelasticity:

Most critical for energy transport in air showers!

$\Rightarrow$ LHCf, Zero Degree Calorimeters

Diffraction:

Above LHC energy, $> 40\,\%$ of interactions are diffractive.

$\Rightarrow$ Totem, CASTOR, ...

Cross sections (diffractive, elastic, inelastic and total):

Extremely important for the development and fluctuation of air shower cascades!

$\Rightarrow$ Totem

Gluon saturation, non-linear QCD:

x values down to 10^{-8} in UHECR, saturation effects studied at LHC via p_T , correlations, forward particle production, etc.

$\Rightarrow$ ATLAS, ALICE, CMS, ...

Nuclear Effects:

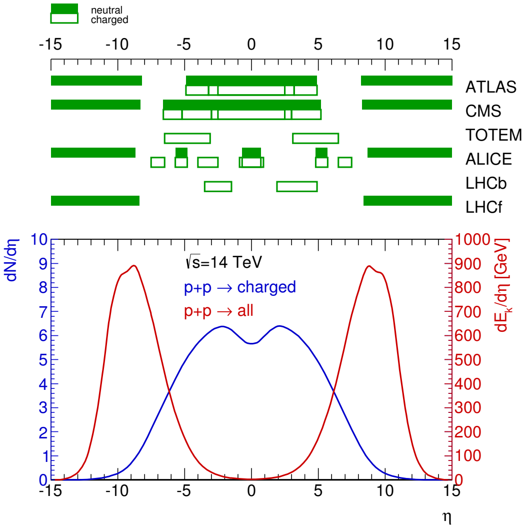
$\Rightarrow$ LHC pA and **pO**

PeV neutrinos and muon puzzle:

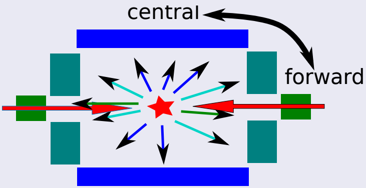
$\Rightarrow$ LHC fixed target

Angular acceptance of LHC experiments

Definition of *pseudorapidity*: $\eta = -\log\tan(\theta/2)$
where θ is the angle wrt. to the beam



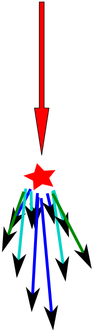
Phase-space coverage at LHC



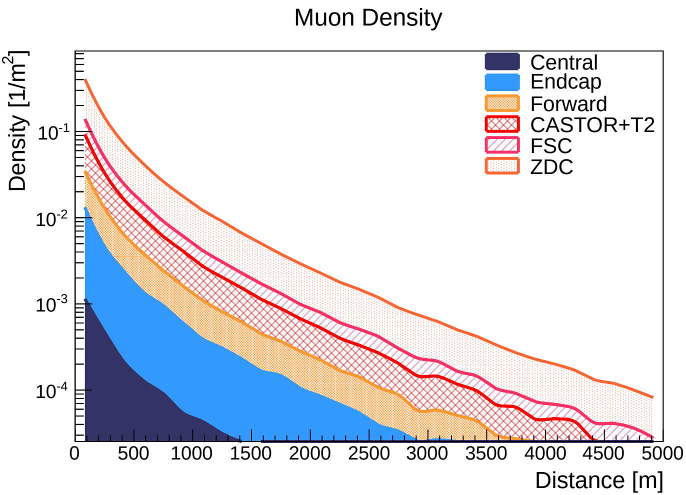
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

- How relevant are specific detectors at LHC for air showers?

$\rightarrow$ Simulate parts of shower individually.

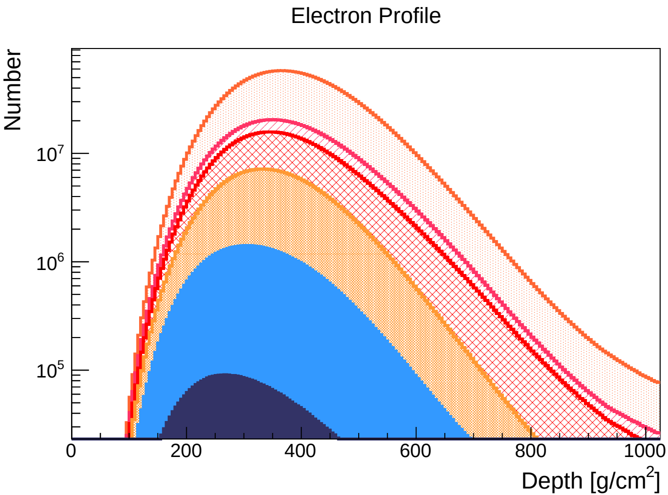


Lateral particle density on ground level



- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

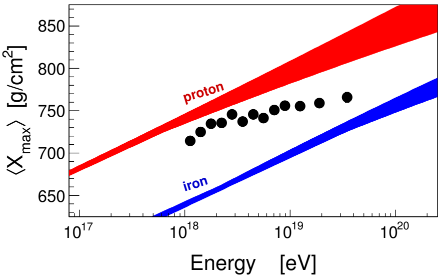
Longitudinal shower development

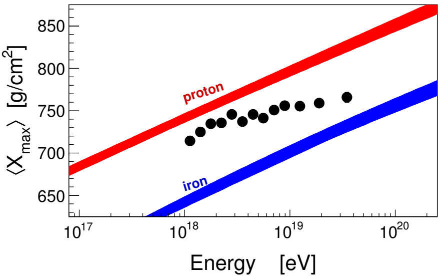


- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

Model tuning to LHC data and $\langle X_{\max} \rangle$ predictions

EPOS 1.99	$\rightarrow$	**EPOS LHC**
QGSJetII.3	$\rightarrow$	**QGSJetII.4**

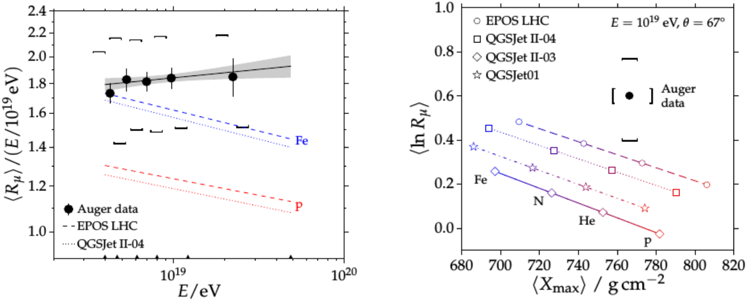




Tuning impact:

- Obvious apparent improved model predictions
- But is this really a quantitative indication of a better understanding?

Muon content of air showers at ground level

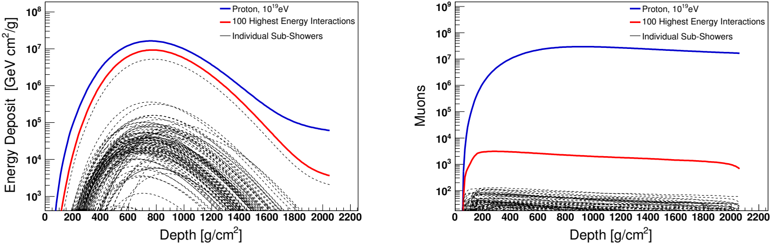


Auger, PRD 91 (2015) 032003

- More muons in air shower data than expected
- No consistency between different observables can be achieved

$\rightarrow$ Interaction physics in air shower models still not accurate

Sensitivity to interaction physics

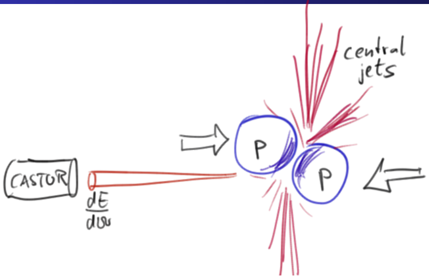


- Wide range of energies, reaching beyond accelerators
- Extrapolation into forward phase space

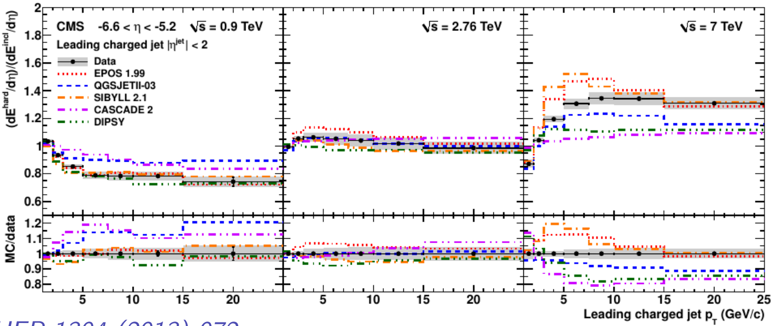
→ **Very different impact on different EAS observables:**

X_{max} Very high energy interactions
Muons Low energy interactions

Forward energy as a function of central activity (pp)



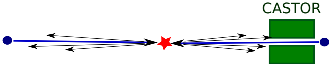
- **Forward energy** ∼ Remnant fragmentation
- **Central jets** ∼ String fragmentation
- "Underlying-Event" study in very forward direction



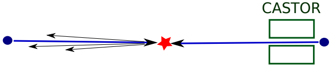
JHEP 1304 (2013) 072

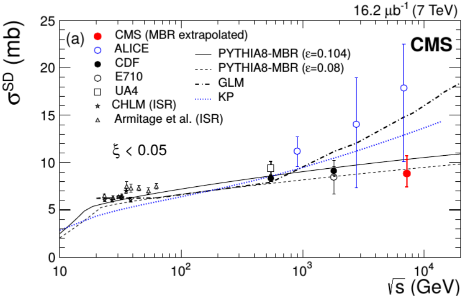
CMS/CASTOR low-mass single diffraction (pp, 7 TeV)

Double Diffraction



Single Diffraction

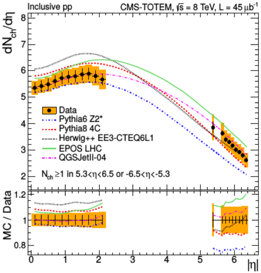


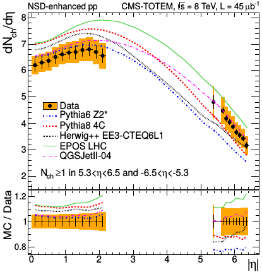


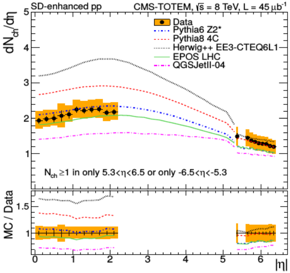
PRD 92 (2015) 012003

Separation of single- and double-diffraction possible with CASTOR detector

CMS + TOTEM combined multiplicity data (pp, 8 TeV)





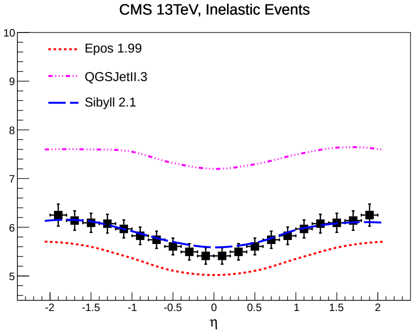


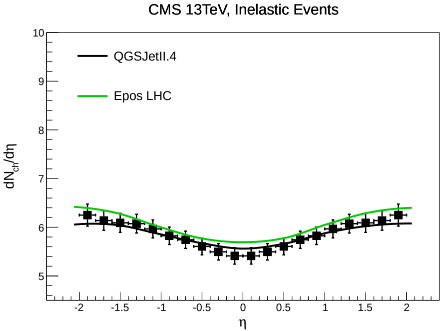
EPJ C74 (2014) 3053

1) Very wide acceptance! 2) Correlations and final state selection!

Multiplicity measurements at 13 TeV

pre-LHC models → **Models tuned at 7 TeV**

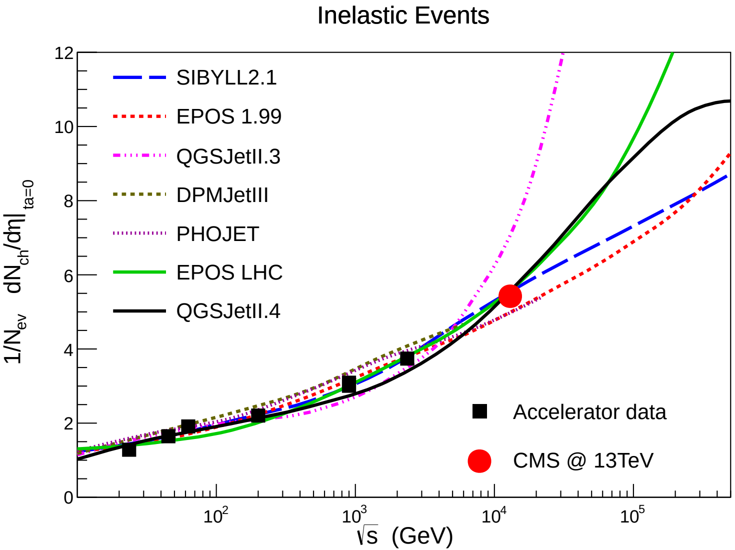




CMS: PLB 751 (2015) 143

- Good extrapolation over factor ≈2 in $\sqrt{s}$
- Poorly constraint beyond factor > 10 in $\sqrt{s}$

Extrapolation to ultra-high energies



CMS minijet measurements (pp, 8 TeV)

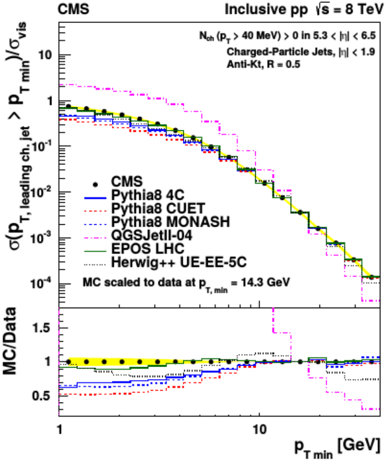
$$\sigma_{QCD}(s, p_{T,min}) = \int_{p_{T,min}}^{\sqrt{s}/2} dp_T \int_{4p_T^2/s}^{1} dx_1 \int_{4p_T^2/(x_1 s)}^{1} dx_2 \sum_{ijkl} f_{i,A}(x_1, p_T^2) f_{j,B}(x_2, p_T^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_T}$$

p_T-Cutoff

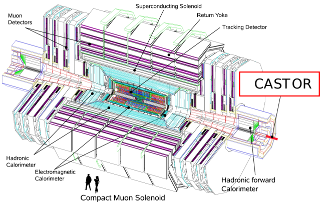
Parton distribution functions, PDFs

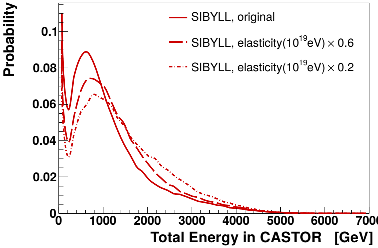
Minijet Cross section

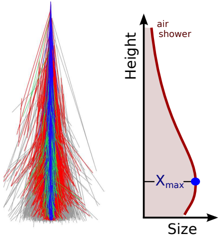
- Hadronization in string fragmentation, minijet production
- p_{T} threshold

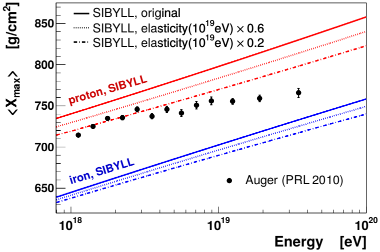


CASTOR and cosmic ray interpretation



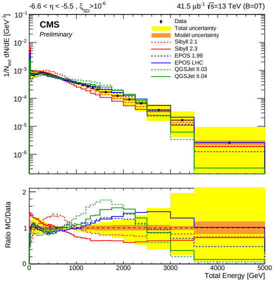




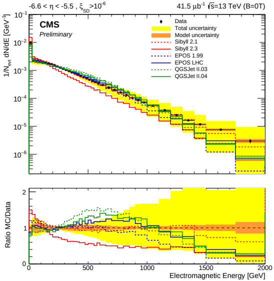


CASTOR at 13 TeV

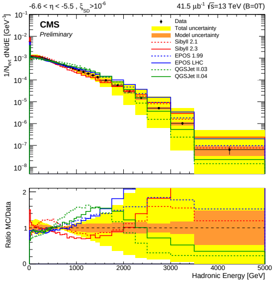
Total energy



Electromagnetic energy



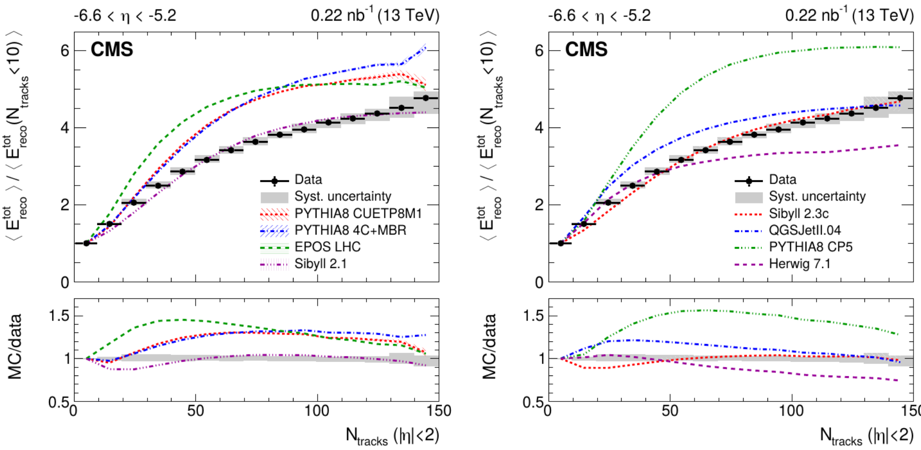
Hadronic energy



(JHEP 08 (2017) 046)

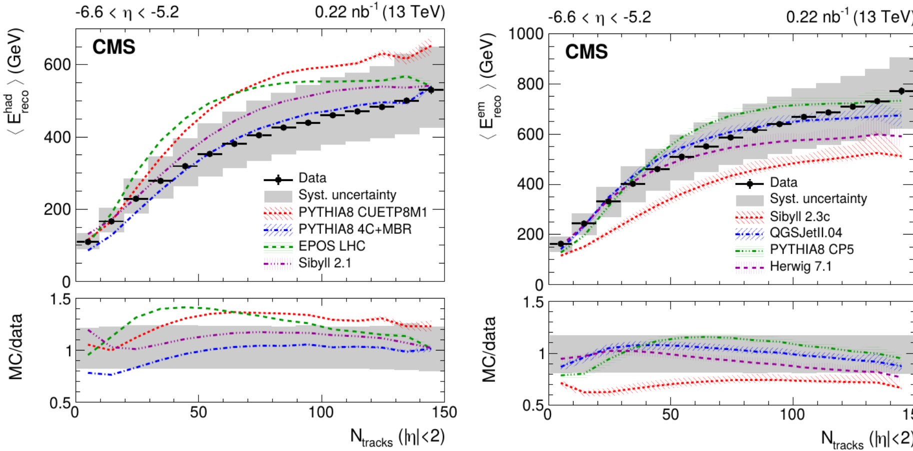
- Model performance tested in crucial phase-space domain
- Very sensitive to MPI, diffraction, low-x structure
- Represents a significant part of the overall energy-flow

Multiplicity dependence of CASTOR data



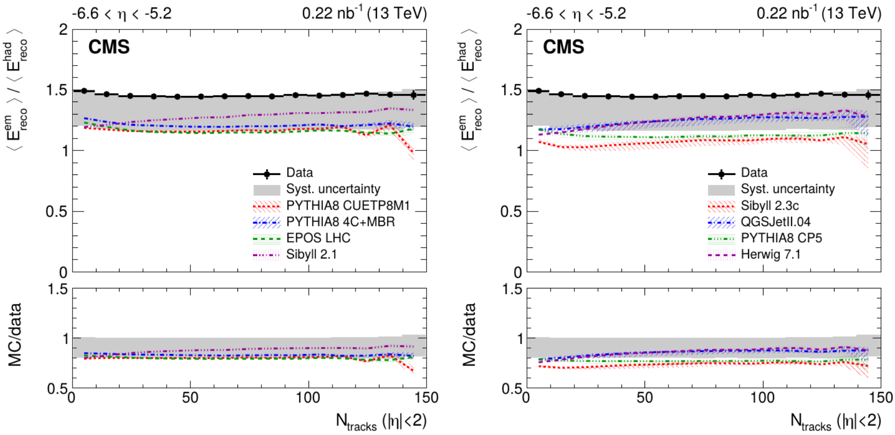
(submitted to EPJC, arXiv 1908.01750)

Multiplicity dependence of CASTOR data



(submitted to EPJC, arXiv 1908.01750)

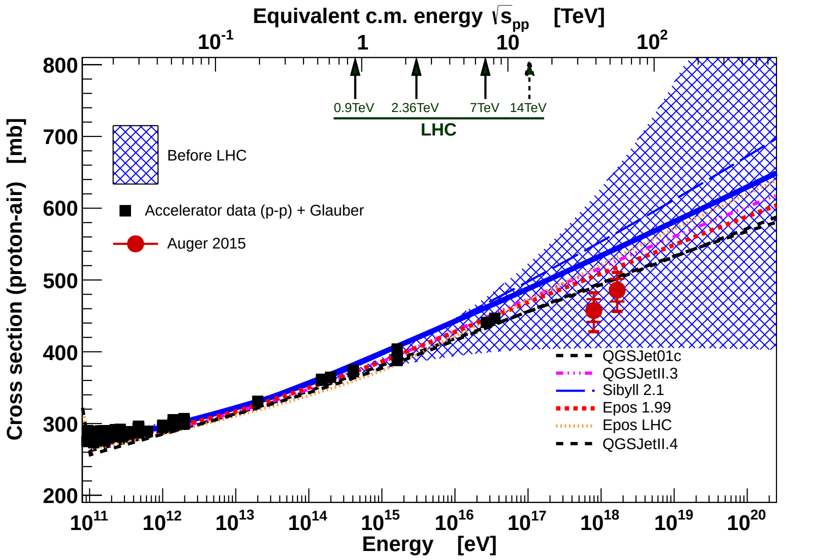
Ratio of em to had energies



(submitted to EPJC, arXiv 1908.01750)

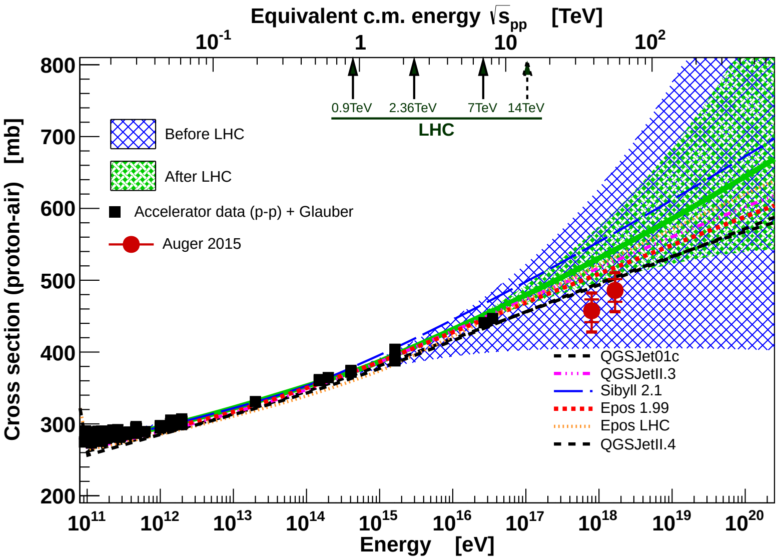
→ Hadronic energy already tend to be *maximized* by all models. Data seems to favour smaller value.

Proton-Air cross section, with Tevatron data



compare to Nucl.Phys.Proc.Suppl. 196 (2009) 335

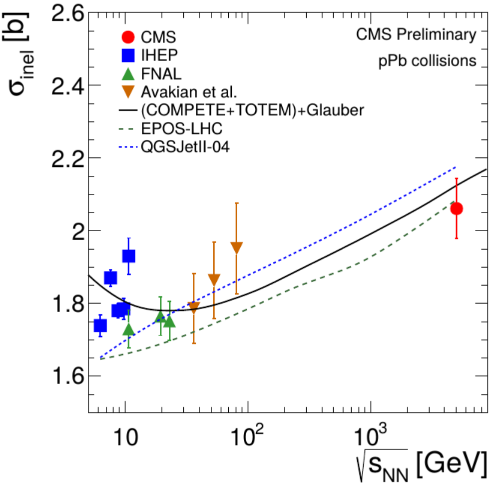
Proton-Air cross section, with LHC data



⇒ Sign of a clear relevant improvement

Large uncertainties due to nuclear effects from pp to p-air

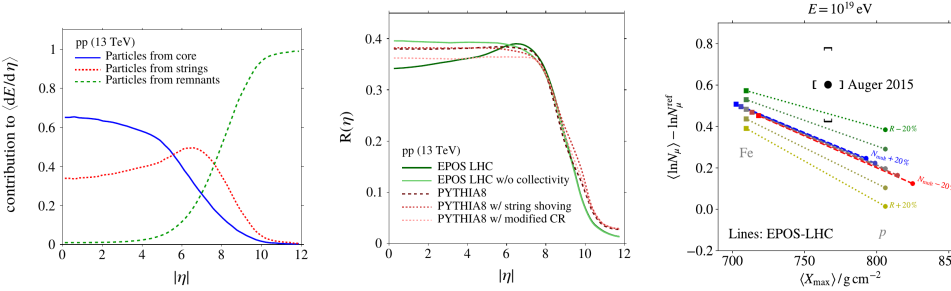
Inelastic proton-lead cross section at 5.02 TeV



PLB 759 (2016) 641

- **Direct test of Glauber model (and related physics) at LHC**

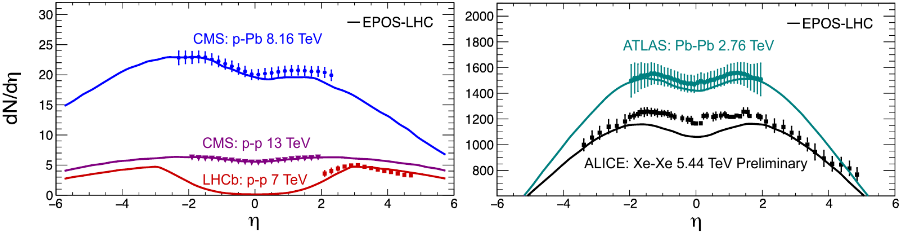
Hadronization, collective effects



arXiv: 1902.09265 [hep-ph], submitted

→ Different modes of hadronization may play a crucial role to understand muons in EAS

Nuclear effects



arXiv: 1812.06772 [hep-ph], CERN YR QCD in Run3

$\rightarrow$ "Interpolation" between pp and heavy-ion is NOT trivial
$\rightarrow$ For robust results we need **oxygen** collisions in LHC

LHC shopping list

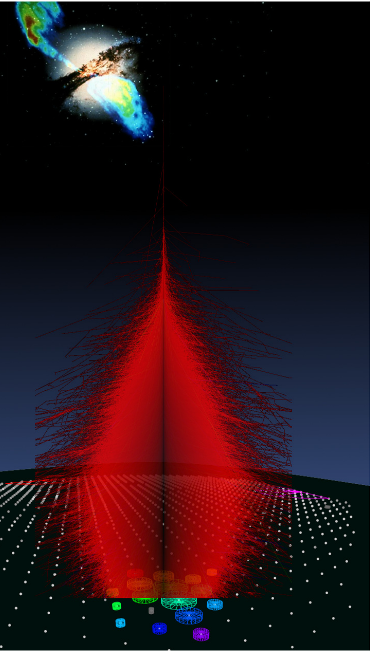
At 13 TeV

- Total and elastic cross section, elastic slope, imaginary to real part of amplitude (rho)
- Soft diffraction, rapidity gaps, characteristics of “pomeron” exchange
- Mini-jets, PID spectra, correlations
- PDF constraints ($W^{\pm}$, Z, ...)
- LHCf zero-degree π^0 and neutrons
- Underlying event with CASTOR, CMS+TOTEM $dN/d\eta$

Finally

- LHC energy scan: 0.9 GeV $\rightarrow$ large x_{F}-range
- Nuclear scan: proton-lead, proton-oxygen
- Maximum acceptance, dedicated detector components
- Pion as beam particle

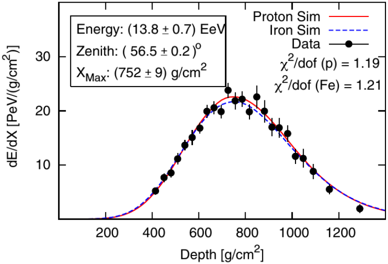
Summary

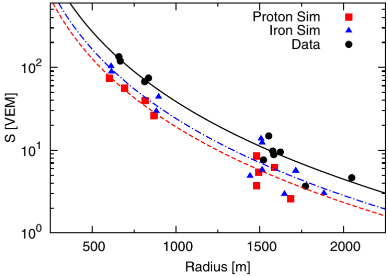


- Models already constraint and improved
- Predictions tend to converge (overall) but with important deviations
- Models so far tuned at LHC roughly to a level of about 10 %
- Forward detectors ultimately of paramount importance
- Important for air showers: energy AND phase space !

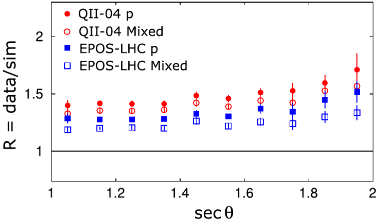
- **Need to continue to push for maximum output of LHC for cosmic ray physics**

Hadronic interactions, Auger



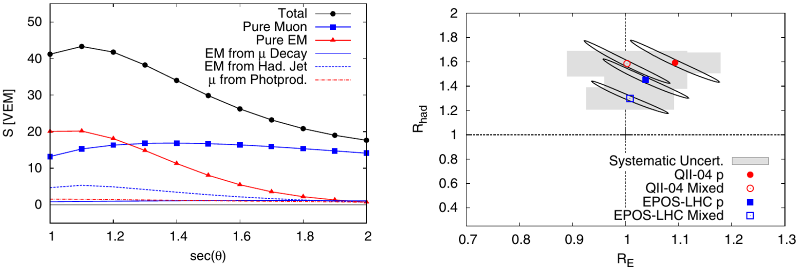


Attempt of consistent description of longitudinal and lateral shower data.



PRL 117, 192001 (2016)

Hadron/Muon component in data is too large



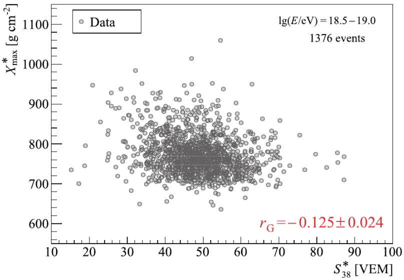
PRL 117, 192001 (2016)

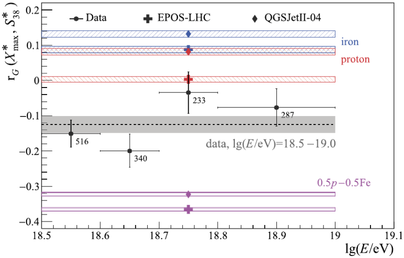
- Scale E.M. and had. part of MC showers with R_E and R_{had} to fit data:

$$S_{\mathrm{resc}}(R_{\mathrm{E}}, R_{\mathrm{had}}) = R_{\mathrm{E}} S_{\mathrm{EM}} + R_{\mathrm{had}} R_{\mathrm{E}}^{\alpha} S_{\mathrm{had}}$$

- While $R_E = 1$ is possible and mostly consistent with data
- R_{had} is significantly above 1
- None of the models/assumptions reproduces data

Evidence for mixed mass composition





PLB 762 (2016) 288

- Correlate event-by-event S_{1000} and X_{max}
- correct for "trivial" effects: $S^*_{38} = S_{1000}(38°)$ and $X^*_{\mathrm{max}} = X_{\mathrm{max}}(10\,\mathrm{EeV})$
- Measure correlation with Gideon/Holister ranking r_G
- A pure composition is ruled out by the data.
- A small admixture of heavier particles is needed.
- Helium is not sufficient, $A > 4$ is also needed.