LHC Heavy Ion Measurements and Cosmic Ray Generators

ISCRA 2019
Moscow, 25-29 June

Lev Kheyn

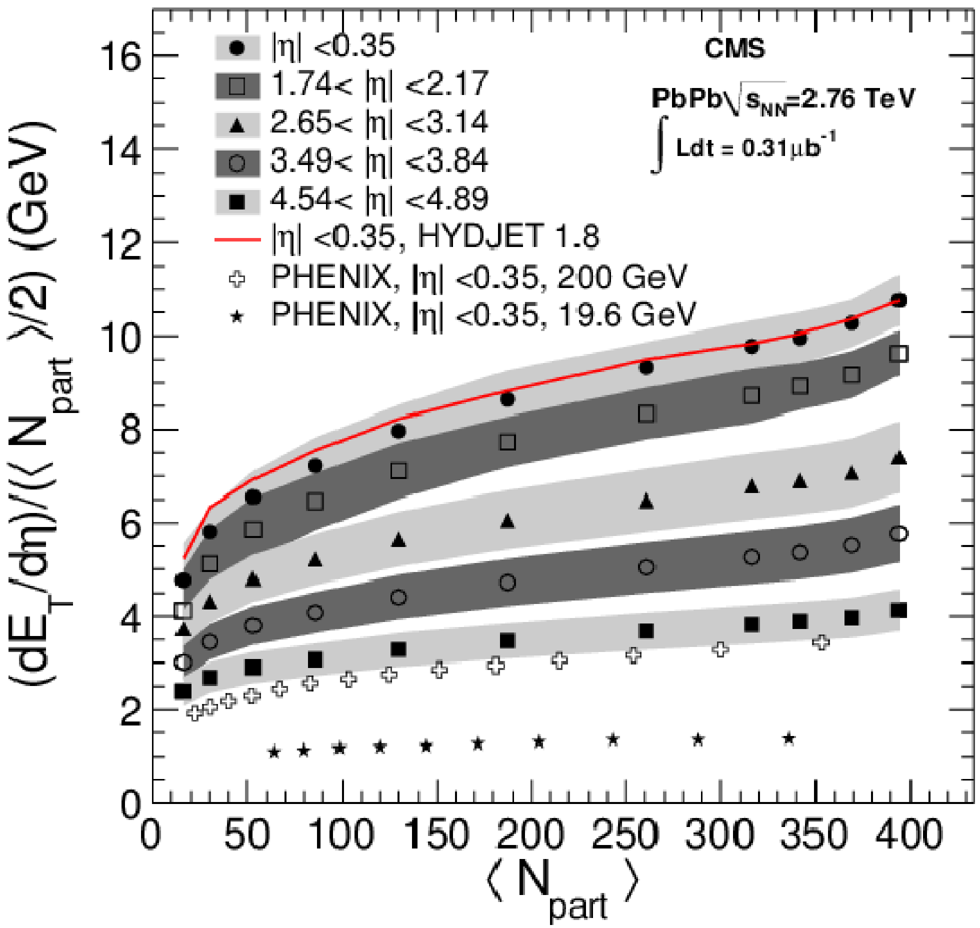
SINP MSU

LHC Heavy Ions

LHC heavy ion program is mainly pointed at study of properties of high density system produced in nuclear collisions, to what is named quark-gluon plasma. Nevertheless, several measurements provide results that are relevant to physics which realization is under discussion in generators used in cosmic rays. In particular, results on pseudorapidity dependence of particle production.
I restrict myself to review of these results.

CMS PbPb

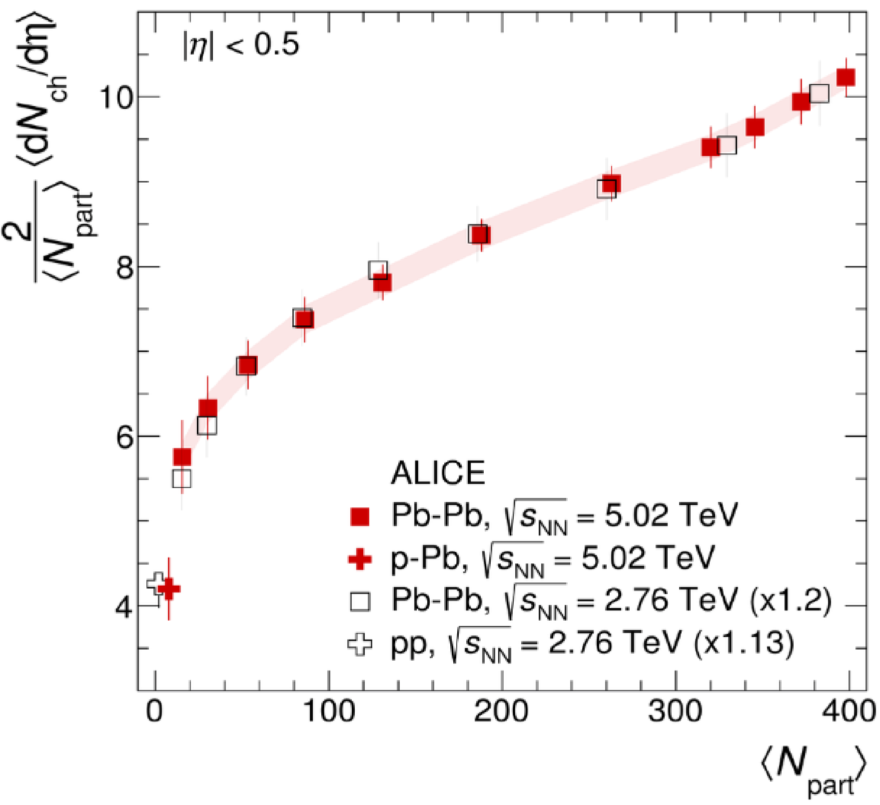
Measurement of the pseudorapidity and centrality dependence of the transverse energy density in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
CMS collaboration [*Phys. Rev. Lett. 109 (2012) 152303*]

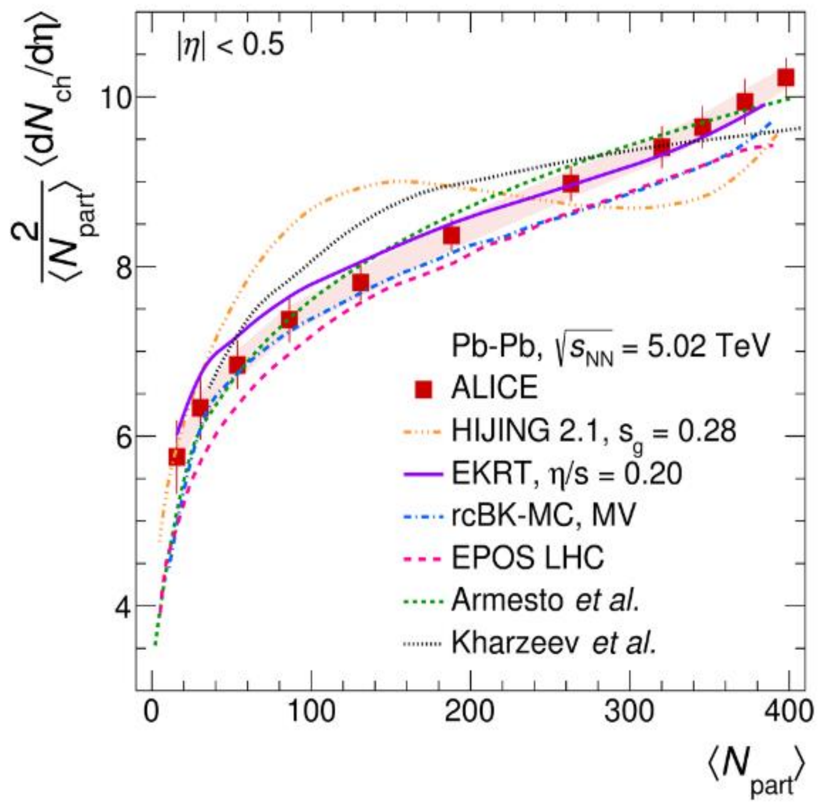


✓ No scaling on N_{part} for any η interval

ALICE PbPb

Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE collaboration [*Phys. Rev. Lett. 116 (2016) 222302*]





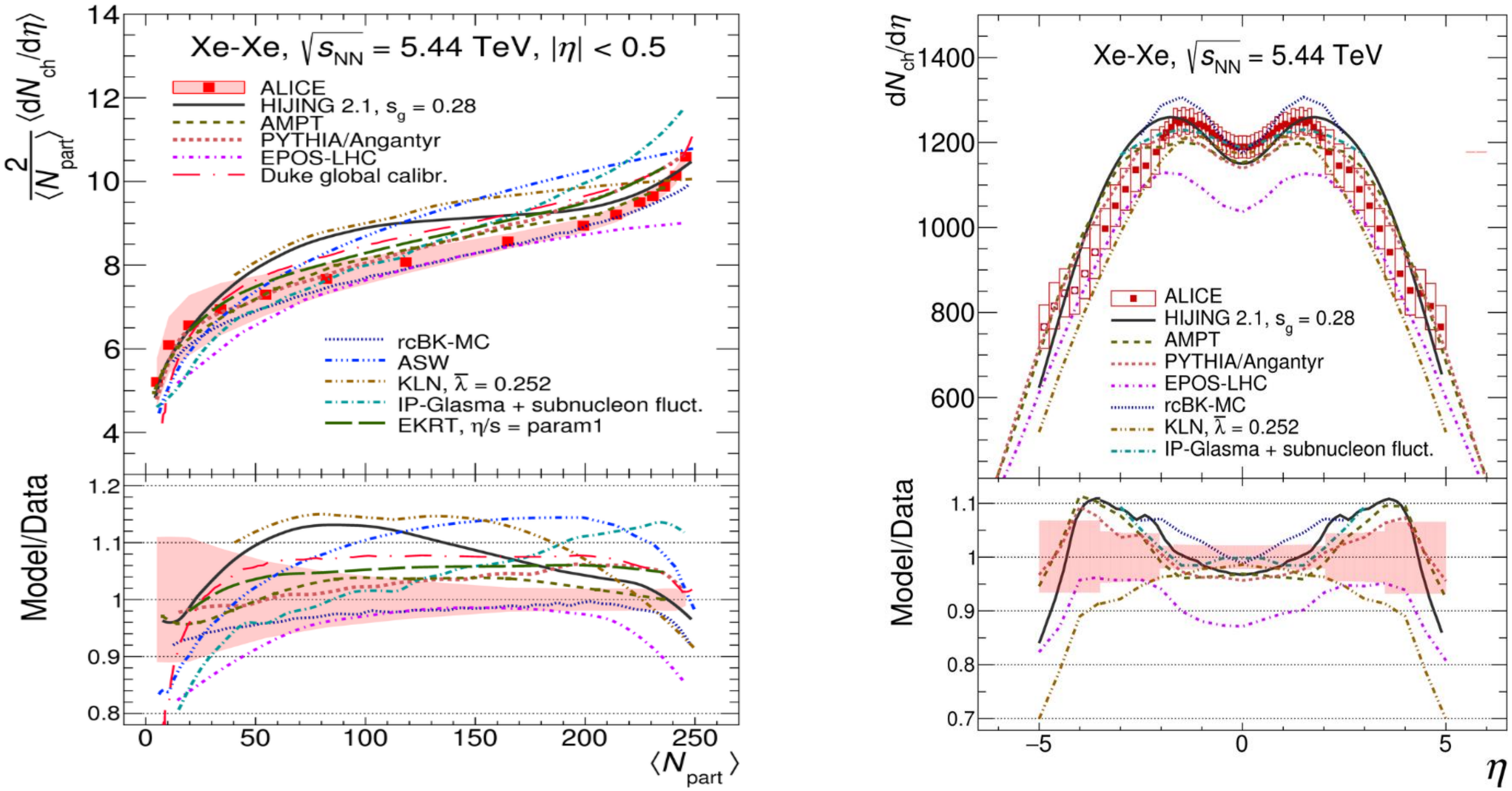
- ✓ No scaling of particle production in central region on N_{part}
- ✓ Shape same at different energies

EPOS-LHC:

- ✓ shape agrees with data,
- ✓ production rate below data by 5-7%

ALICE XeXe

Centrality and pseudorapidity dependence of the charged-particle multiplicity density in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV
ALICE Collaboration_*Phys. Lett. B 790 (2019) 35-48*

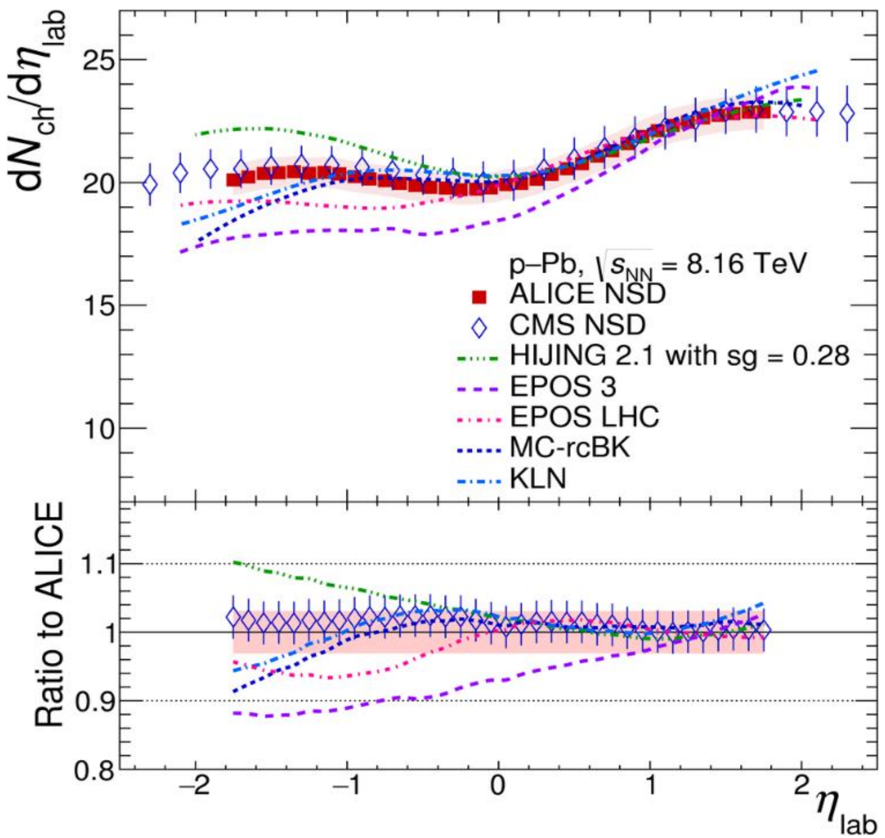


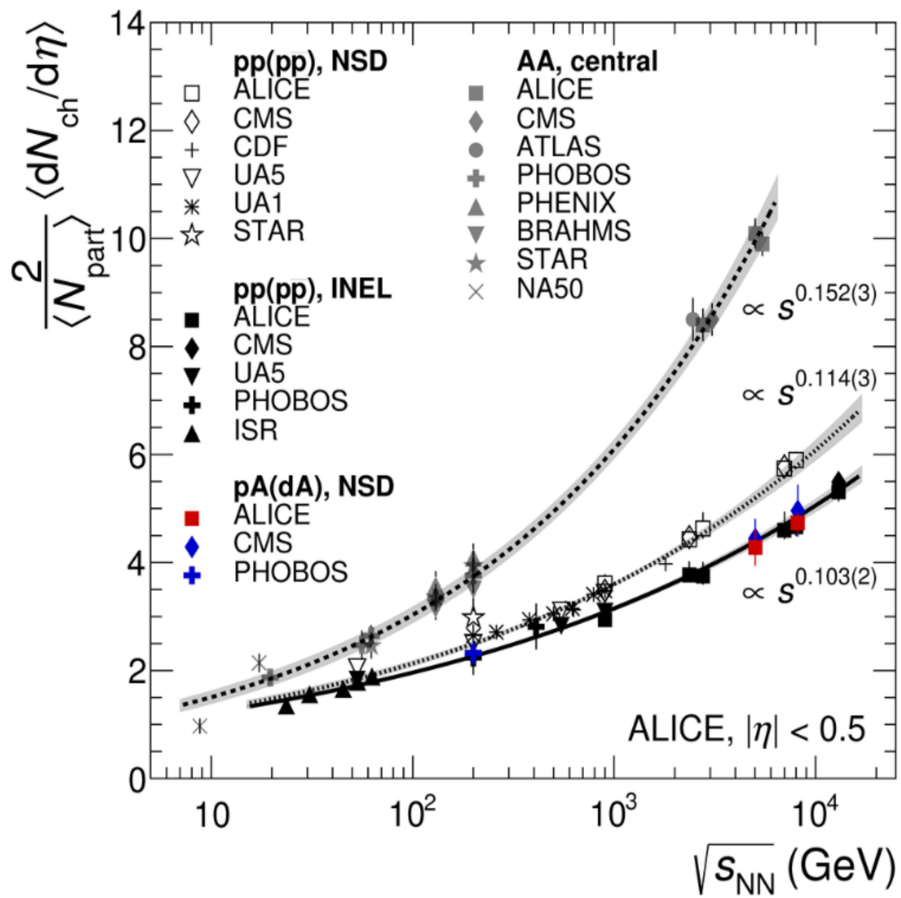
- ✓ No scaling of particle production in central region on N_{part}
- ✓ EPOS-LHC: production rate below data by ~5-10%

ALICE pPb

Charged-particle pseudorapidity density at mid-rapidity in p–Pb collisions at 8.16 TeV

ALICE Collaboration [*Eur. Phys. J. C (2019) 79: 307*]()



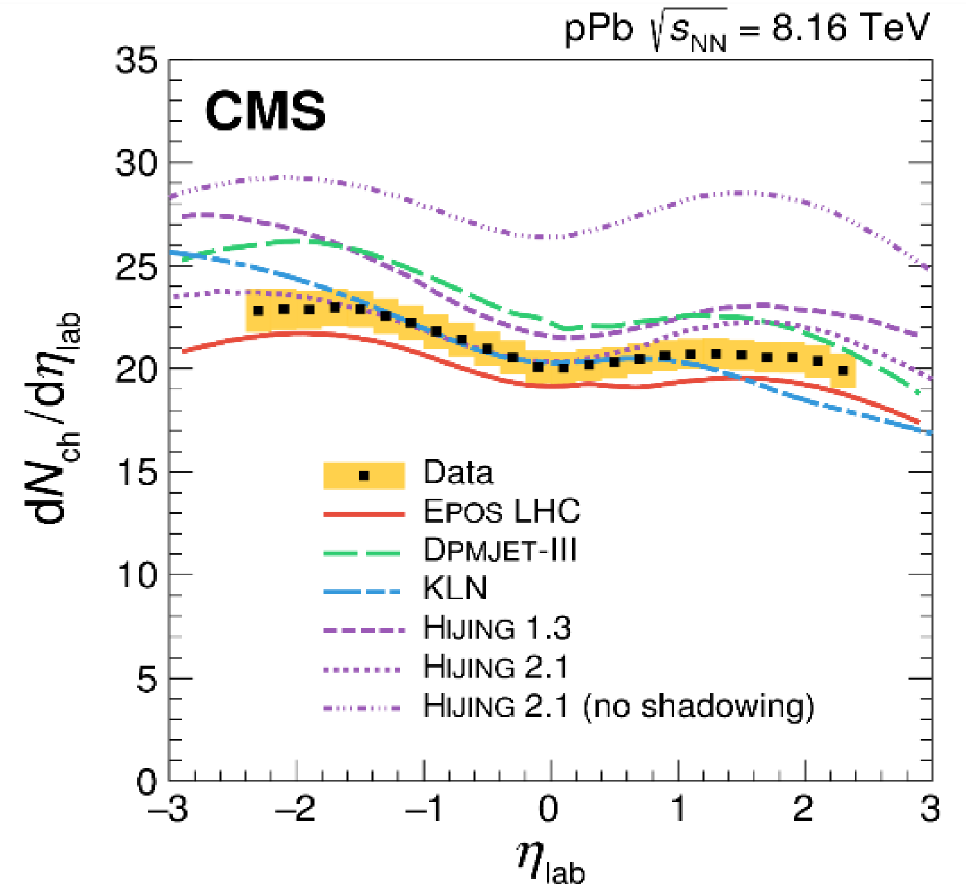


EPOS-LHC agrees with measurements in lead (plus) side and below data by ~5-7% in proton (minus) side

Agreement between CMS and ALICE

CMS pPb

Pseudorapidity distributions of charged hadrons in proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV
CMS collaboration *JHEP 01 (2018) 045*



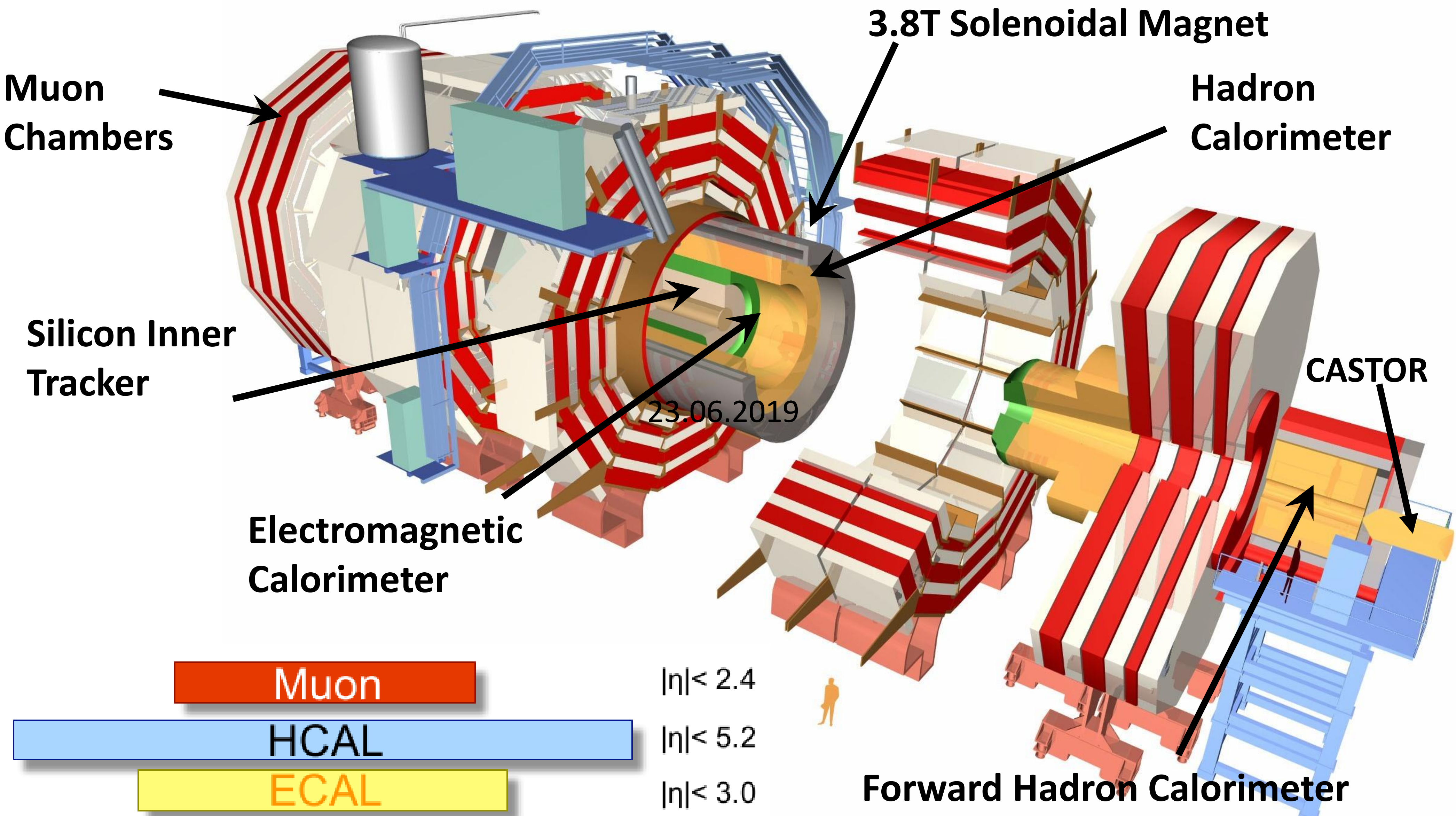
EPOS-LHC agrees with data in shape
and is below data in production rate by ~8%

CMS pPb

Centrality and pseudorapidity dependence of the transverse energy density in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS collaboration *arXiv:1810.05745*

In this study, comparison is presented of data with both EPOS-LHC and QGSJETII, which are generators most intensively used in simulations in Cosmic Rays .
I will discuss results in detail since comparison provides conclusions that could relate problems appearing in simulating by these generators of interactions with air.

The CMS detector



Muon	|η|< 2.4
HCAL	|η|< 5.2
ECAL	|η|< 3.0
Tracker	|η|< 2.5
CASTOR	-6.6<η<-5.2

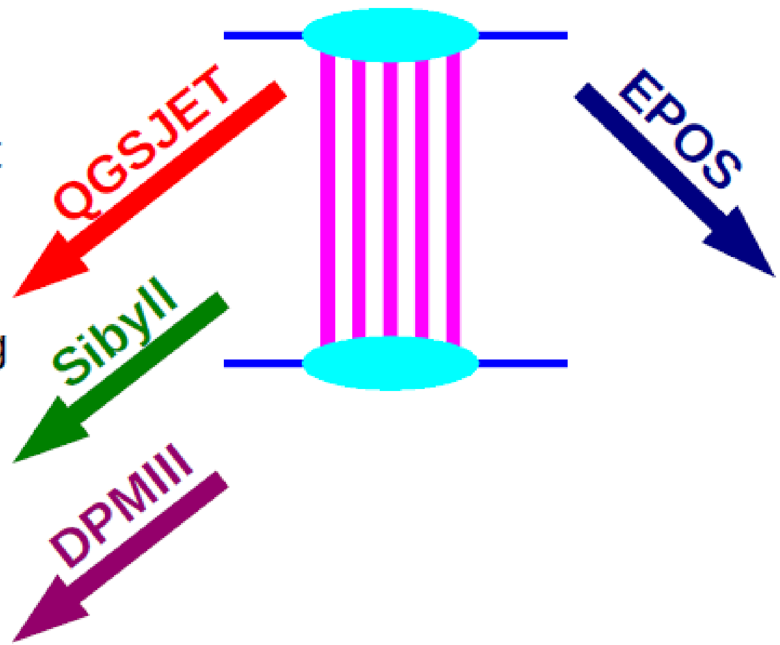
Cosmic Ray Monte Carlo

From T.Pierog

How does the projectile interact ?

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

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



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

Centrality

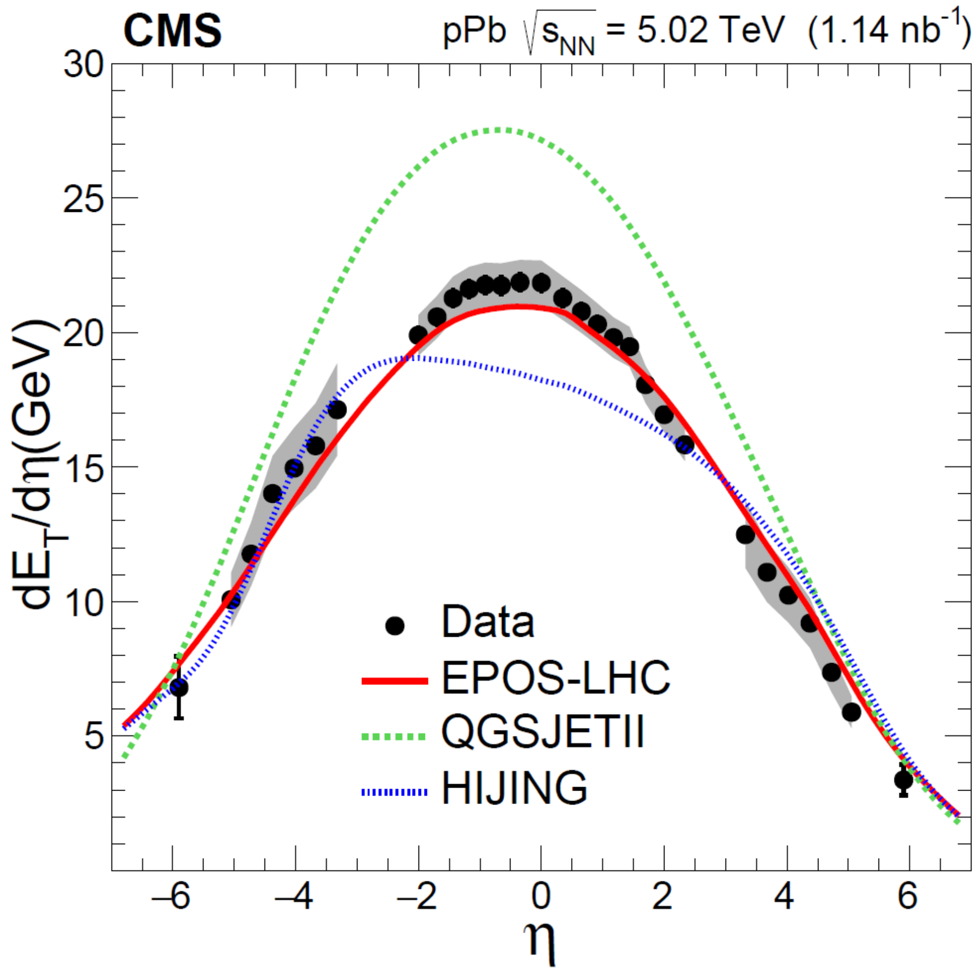
Centrality estimates impact parameter of collision and thus overlap of two nuclei and hence number of participating nucleons. Since these quantities are not measured directly, centrality in data is defined with use of some strongly correlated with them measured quantities.
We compared three estimators:

Centrality Name	Definition
HF-Double	E_T within $4 < \|\eta\| < 5$
HF-Single	E_T within $-4 > \eta > -5$
N_{Track}	Tracks within $\|\eta\| < 2.4$

Proton moves toward positive pseudorapidity, i.e. HF-Single sums up energy in lead side

The centrality is defined as percentile of events with values of the estimator within some predefined interval.
A Glauber model is used to relate the centrality to N_{part} and impact parameter.

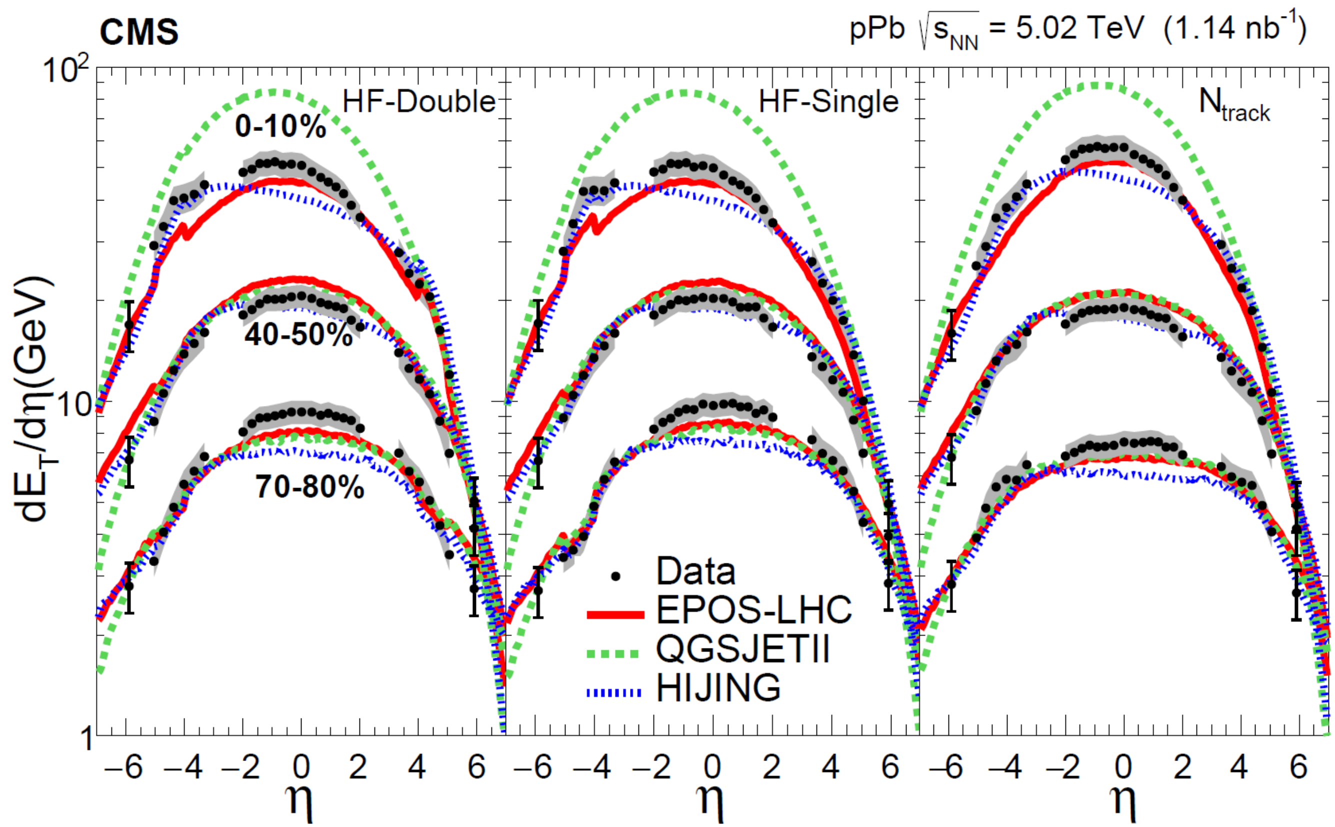
$dE_T/d\eta$ for minimum bias



- EPOS-LHC do well
- QGSJETII overestimates energy
- HIJING underestimates energy in central region

$dE_T/d\eta$ at different centralities

Three centrality estimators are used

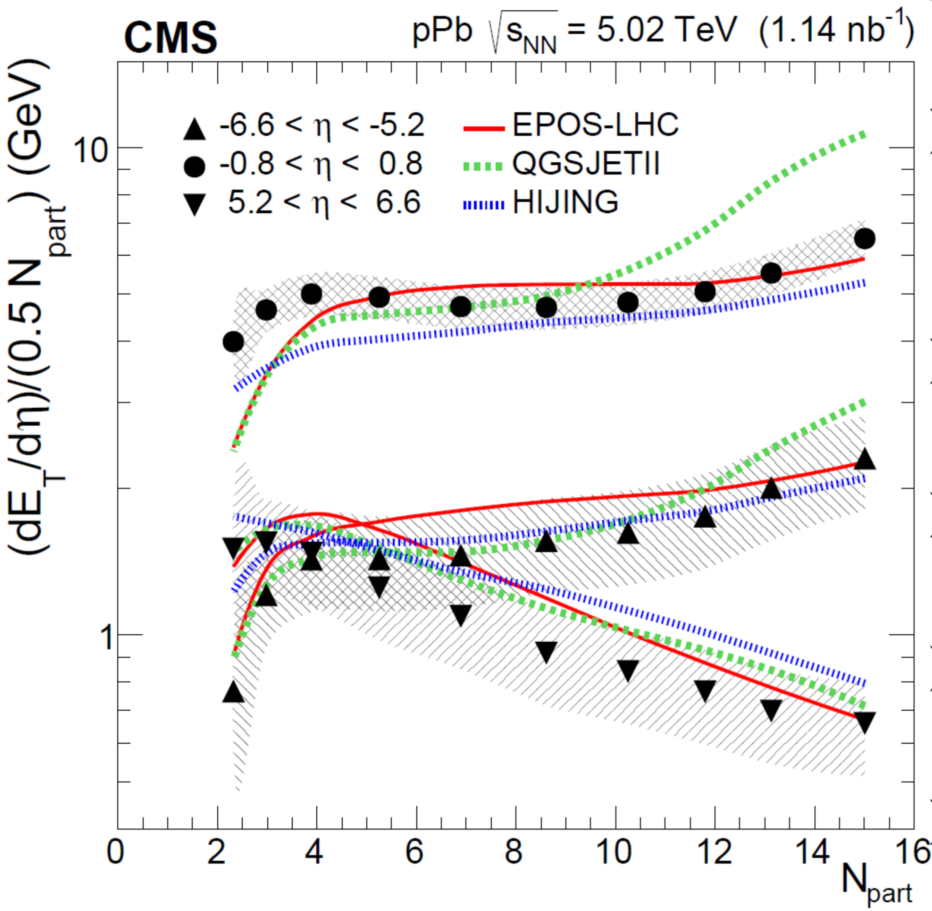


- QGSJETII largerly overpredicts production at high centrality, excess over data in minimum bias originates from that
- HIJING best in describing lead fragmentation region at high centrality
- QGSJETII and EPOS-LHC close to each other and data at medium and low centrality

$dE_T/d\eta$ divided by participant number

Three η ranges

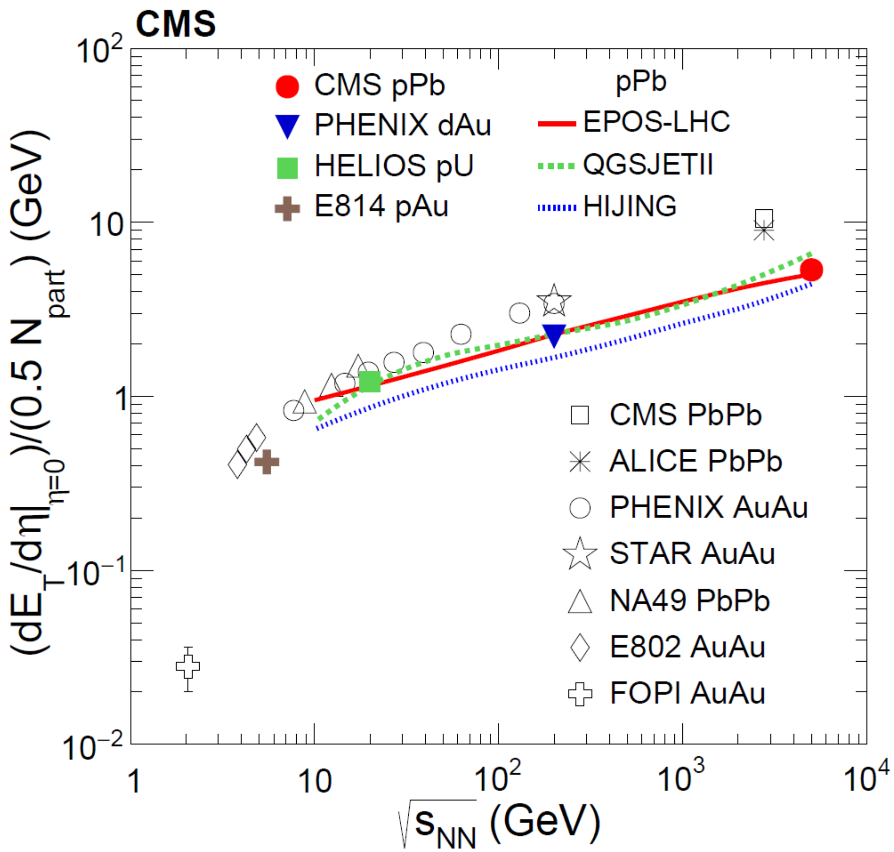
N_{part} from standard Glauber model



- $(dE_T/d\eta)/N_{part}$ is about flat at midrapidity except for smallest and largest N_{part}
- $dE_T/d\eta$, as expected, rises faster than N_{part} in lead fragmentation and slower than N_{part} in proton fragmentation region
- QGSJETII goes up from data for large N_{part} at central η
- All generators are below data for most peripheral events at central η
- QGSJETII slightly goes up from data for large N_{part} in lead fragmentation region.
- All generators are close to each other and data in proton fragmentation region

$(dE_T/d\eta)_{\eta=0}$ /N_{part} for different colliding systems

AA for central collisions, pA and dA for minimum bias



- Minimum bias pA rises with energy faster than central AA
- EPOS-LHC reproduces data at non-small energies
- QGSJETII goes up from data at highest energy
- HIJING is below data

Summary on LHC Heavy Ions

- Centrality and pseudorapidity dependences of charged-particle multiplicity density are measured for PbPb, XeXe and pPb collisions
  - No scaling over number of participating nucleons in nucleus-nucleus collisions
  - XeXe N_{part} dependence is close to that of PbPb as function of $N_{part}/2A$
  - EPOS-LHC is close to data in nucleus-nucleus collisions in shape of N_{part} dependence and below data in production rate
- Transverse energy density is measured in pPb at 5 TeV/n for broad pseudorapidity range $-6.6<\eta<6.6$

  Comparison with three generators shows that:
  - EPOS-LHC is best in describing majority of data
  - HIJING underestimates production at central η
  - QGSJETII demonstrates significant overestimation of production at high centrality that points to problem which could reveal itself in interaction with air

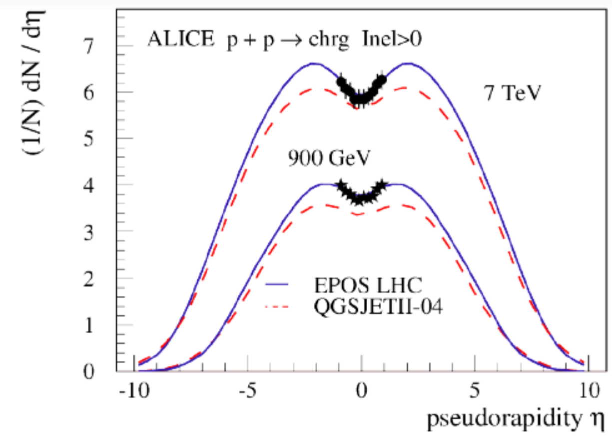
Proton-Oxygen Puzzle

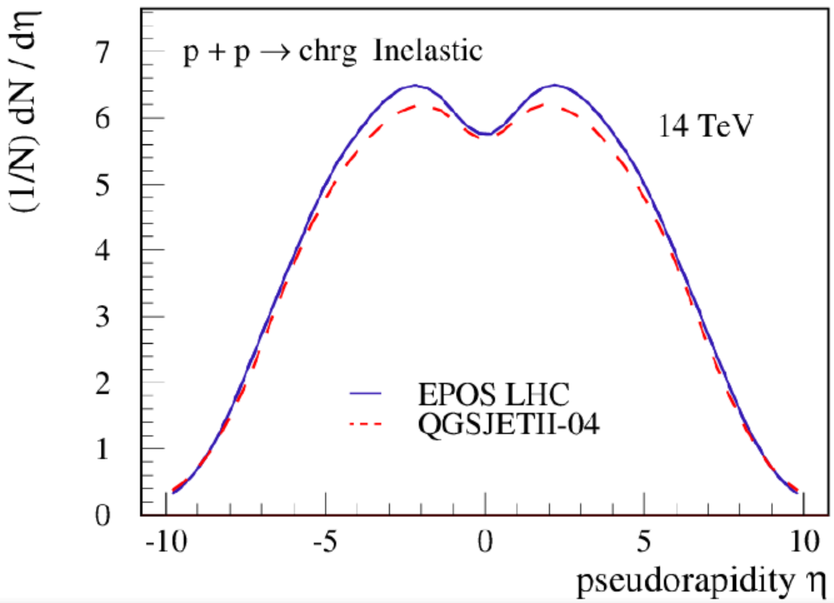
Tangie Pierog

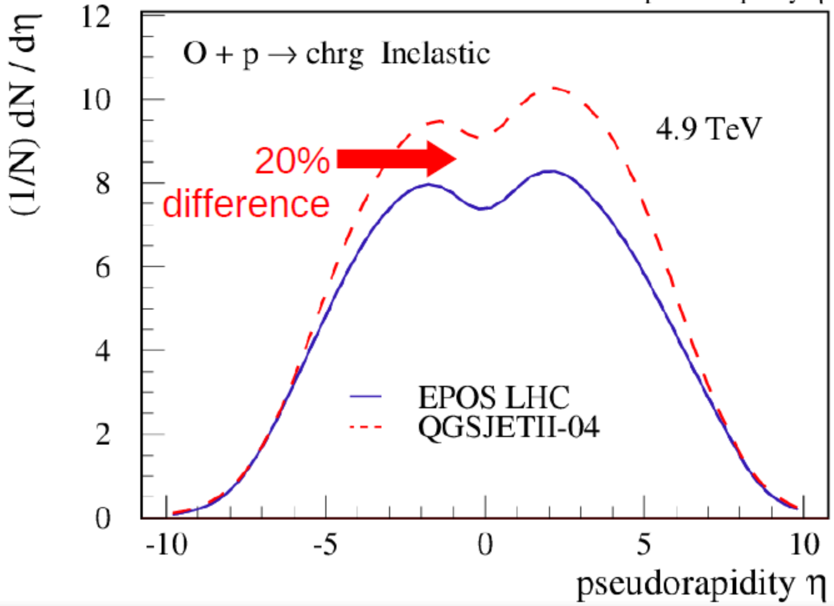
Air Showers   Current LHC Data   Needed LHC data

Interactions in Air Shower : p-Air

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air
    - current main source of uncertainty
- **Needs for new data : p-O**







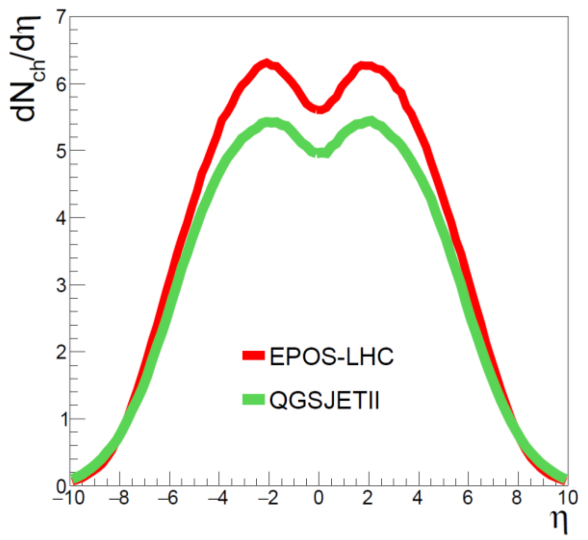
QCD and Forward Phys. – April – 2014   T. Pierog, KIT - 26/30

Proton-Oxygen Puzzle

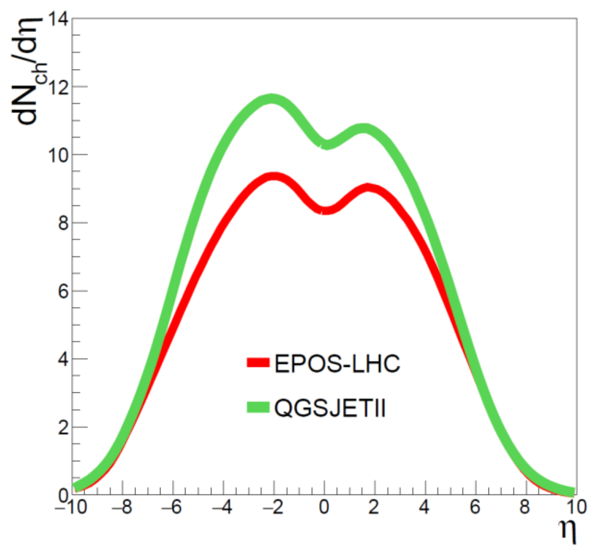
Can we use pPb data for resolving simulation pO puzzle?

Charged particle density vs η, inelastic collisions 4.9 TeV/nucleon

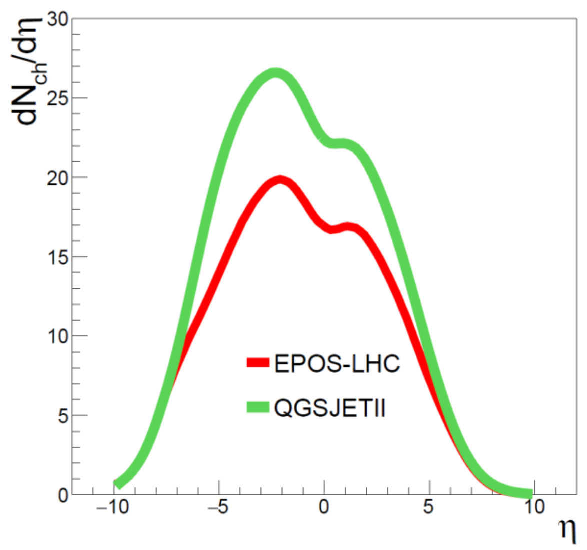
pp



pO



pPb



EPOS-LHC is above QGSJETII in central region for pp by ~10% whereas for pO, **QGSJETII is above EPOS-LHC (~20%)**. This is strange since oxygen is a light nucleus.

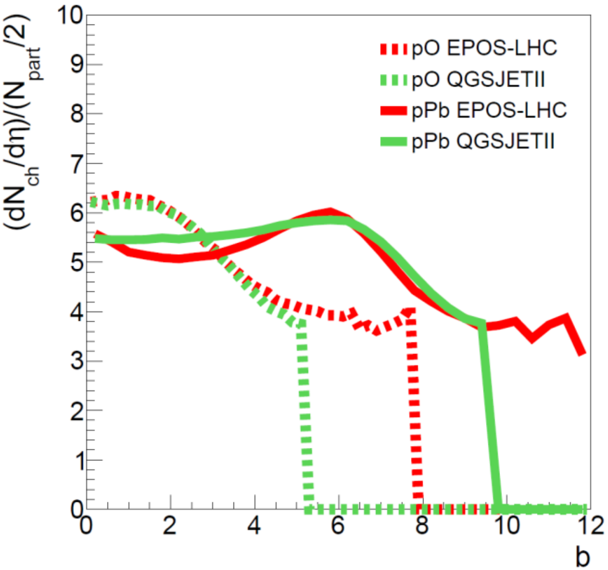
That difference between generators in pPb is only slightly bigger than in pO. It is interesting since lead is very heavy nucleus compared to oxygen.

Same mechanism for pO and pPb?

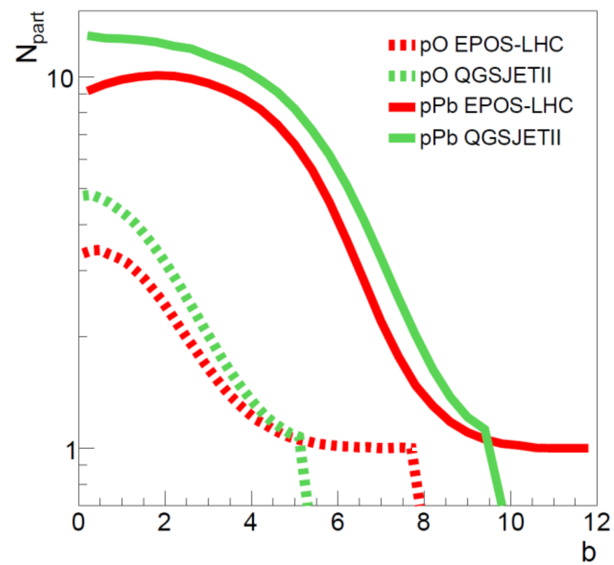
Impact parameter dependence

Central multiplicity $dN_{ch}/d\eta$ at $-0.5<\eta<0.5$

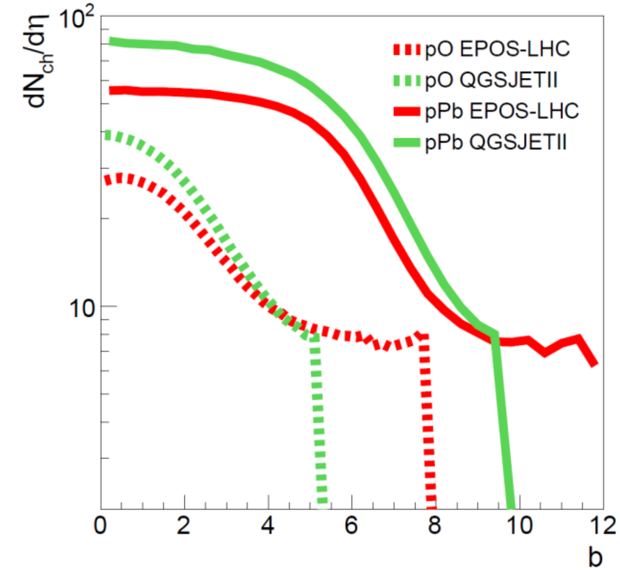
$dN_{ch}/d\eta$ normalized to N_{part}



Number of participants



$dN_{ch}/d\eta$ unnormalized to N_{part}



Multiplicity on one participant is close enough in QGSJET and EPOS

Number of participants is different: much larger N_{part} in central events in QGSJETII than in EPOS-LHC (log scale)!

Distribution of unnormalized to N_{part} charged density is accordingly different (what we see in previous slide)

But it was shown earlier that in pPb for central events (at small impact parameters) QGSJETII is much above data, whereas EPOS-LHC fits data much better.
We can assume that in this big difference in number of participants, which defines difference in production at central η both in pO and pPb, just **QGSJETII experiencies problems.**

Interactions and shower

Is that difference between generators in central region of interaction important for longitudinal shower development?

Which characteristics of particle production are considered to be important for longitudinal shower development?
Usually, these are inelasticity, multiplicity and fraction of hadron energy going to electromagnetic component.

Particle production in central region defines multiplicity. Why multiplicity matters?
Because of logarithmic dependence of electromagnetic shower depth on energy. If energy dissipation is larger (larger multiplicity) electromagnetic subshowers start at smaller energies and are shorter, and accordingly, total shower is getting shorter.

But produced particle should not contribute to shower development with equal weight, their contribution should be proportional to their energy and length of subshowers they produce, that is to logarithms of energy.

It what be good to know that certainly, that is, to look somehow at explicit connection between interaction characteristics and longitudinal shower development, e.g. shower maximum.
We have cascade theory. But shower maximum is difficult quantity for cascade theory .
Meanwhile**, shower center of gravity (CG), <x>, is suitable for treatment by cascade theory.**

1-st interaction

Consider simplest case: contribution from first interaction.

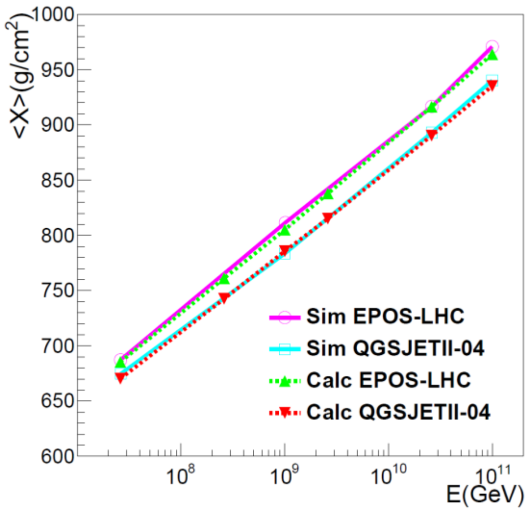
We can derive expression for the center of gravity of electromagnetic contribution from the first interaction of proton:

$$< X^{(1)}_{p\gamma}(E) >= \lambda_p + X_0 \left(\log \frac{E}{E_c} + \delta - \frac{1}{2} + \frac{\mu_{p\gamma}}{g_{p\gamma}} \right)$$

Where $g_{p\gamma} = \int_0^1 x \frac{dn_{p\to\gamma}}{dx}(x)\, dx$ and $\mu_{p\gamma} = \int_0^1 x \cdot logx \frac{dn_{p\to\gamma}}{dx}(x)\, dx$

And λ_p is interaction length, X_0 is radiation unit, E_c is critical energy, $\frac{dn_{p\to\gamma}}{dx}$ is inclusive spectrum

Let's check how it fits simulations.



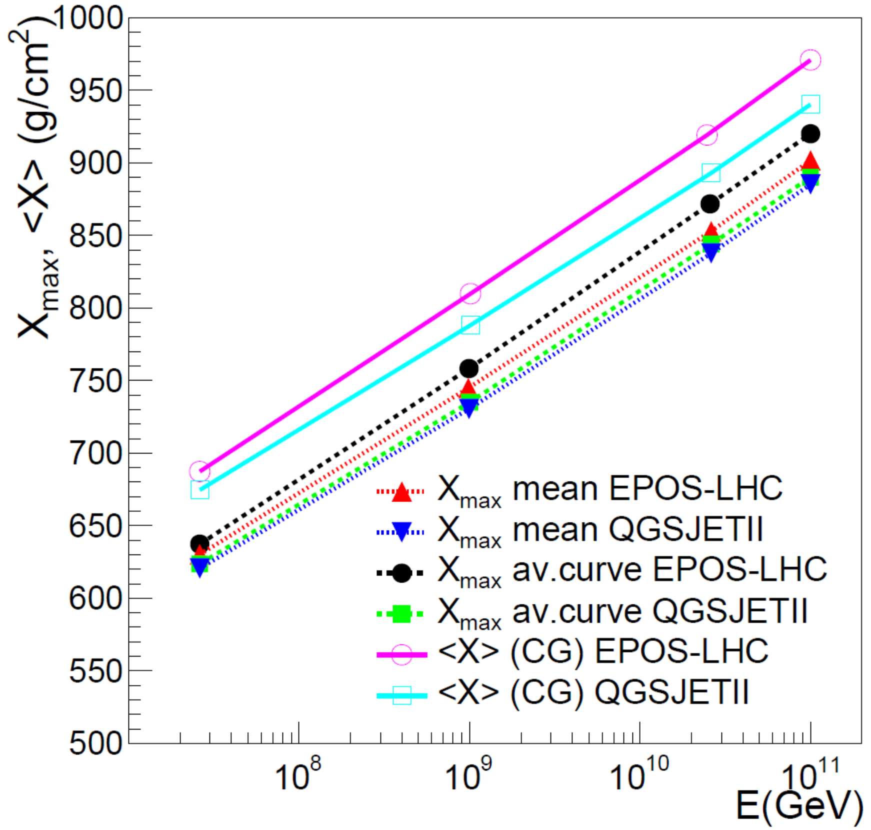
Very good agreement

Expression for $R_{p\gamma}$ is exact formulation of earlier suggestion of the way energy dissipation acts in shower development!

1-st interaction

But we are interested in shower maximum.

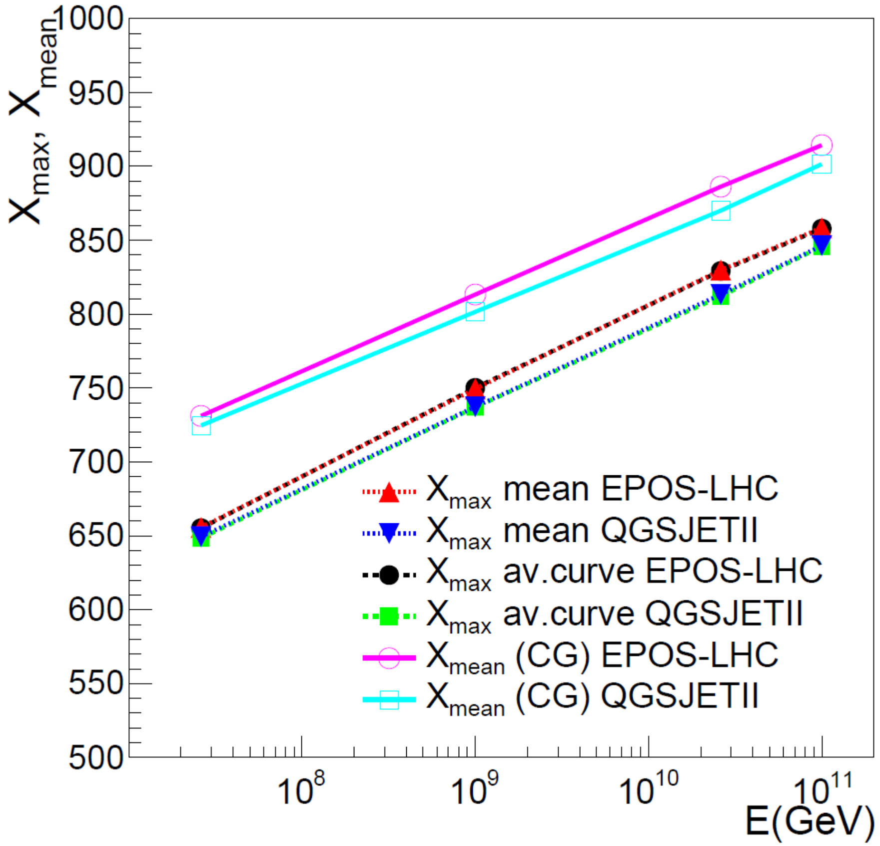
Cascade theory states that for electromagnetic showers, shift between shower maximum and center of gravity does not depend on energy. That should stay for electromagnetic contribution from the first interaction of proton.



Shower center of gravity,<x>, is compared with maximum of average shower profile and mean maximum of individual showers.
Shift between <x> and both maxima does not depend on energy.
That implies that dependence on energy and difference between generators of shower maximum can be delivered by cascade theory

Full shower

For full shower, energy dependence of X_{max} slightly steeper than of X_{mean}



Full shower

On assumption of Feinman scaling, expression for center of gravity of shower from proton (nucleon) can be obtained (*LK, Astropart. Phys.* ***92*** *(2017)7*) :

$$\overline{X_N(E)} = X_0\left(\ln\frac{E}{E_c} + \delta - \frac{1}{2}\right)$$
$$+ \frac{1}{1-g_{NN}}\left\{\lambda_N(E_N^{eff}) + X_0\cdot\mu_N + \frac{g_{N\pi}}{1-g_{\pi\pi}}\left[\lambda_\pi(E_\pi^{eff}) + X_0\cdot\mu_\pi\right]\right\}$$

Interaction lengths are taken at some effective, reduced relative to primary, energies :

$$E_N^{eff} = E\cdot exp\left(\frac{\gamma_{NN}}{1-g_{NN}}\right) \quad \text{and} \quad E_\pi^{eff} = E_N^{eff}\cdot exp\left(\frac{\gamma_{N\pi}}{g_{N\pi}} + \frac{\gamma_{\pi\pi}}{1-g_{\pi\pi}}\right)$$

For definition of μ, γ see next slide.

Master integrals

Characteristics of particle production enter two kinds of expressions.

- First kind reflects energy transition between different sorts of hadrons, i.e. from barion to charged or neutral pions or from charged pion to neutral pions (i,j below denote sort). The obtained expressions are simply mean relative energies contained in produced particles of some sort (like inelasticity):

$$g_{ij} = \frac{1}{\sigma^i_{inel}(E^{eff}_i)} \int_0^1 x \frac{d\sigma_{i\to j}}{dx}(x, E^{eff}_i)\, dx = \int_0^1 x \frac{dn_{i\to j}}{dx}(x)\, dx$$

Energy transition governs pace of shower elongation through hadron cascading and transfer of energy to electromagnetic component.
These integrals are general case of integral $K_{p\gamma}$ in expression for CG from first interaction.

- Second kind reflects rate of energy dissipation:

$$\gamma_{ij} = \int_0^1 x \cdot log(x) \frac{dn_{i\to j}}{dx}(x)\, dx$$

splitting energy of particle of type **i** into energies of produced particles of type **j**

$$\mu_i = \gamma_{iX} = \int_0^1 x \cdot log(x) \frac{dn_{i\to X}}{dx}(x)\, dx$$

splitting energy of particle of type **i** into energies of all produced particles

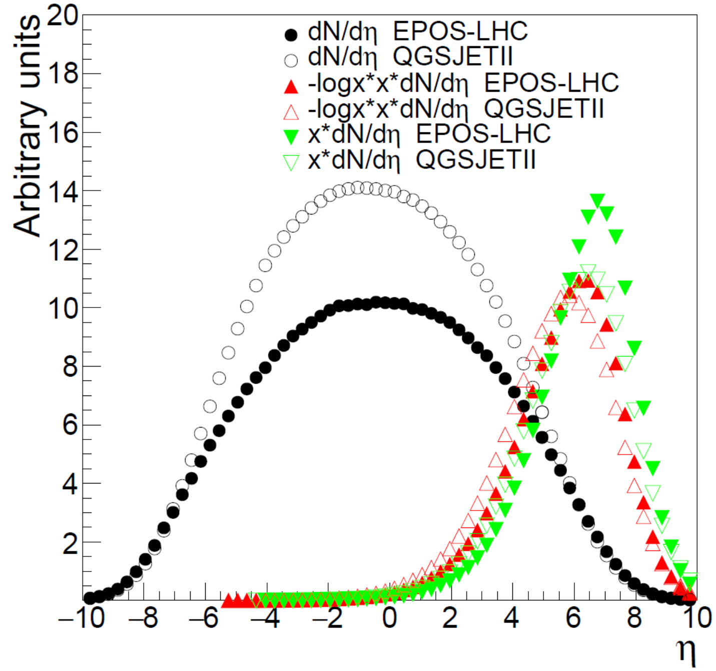
These integrals are **negative** : dissipation of energy slows down shower development. Both CG and Xmax are reduced.
They are generalization of integral $\mu_{p\gamma}$ in expression for CG from first interaction.

Integral kinematics

Which kinematic regions of interaction mostly contribute to master integrals?

Rewrite: $$\int_0^1 x \frac{dn}{dx} dx = \int_{\eta_{min}}^{\eta_{max}} x \frac{dn}{d\eta} d\eta$$ and $$\int_0^1 x \cdot \log x \frac{dn}{dx} dx = \int_{\eta_{min}}^{\eta_{max}} x \cdot \log x \frac{dn}{d\eta} d\eta$$

pO -> γ +X at E_{cm} = 4.9 TeV/nucleon



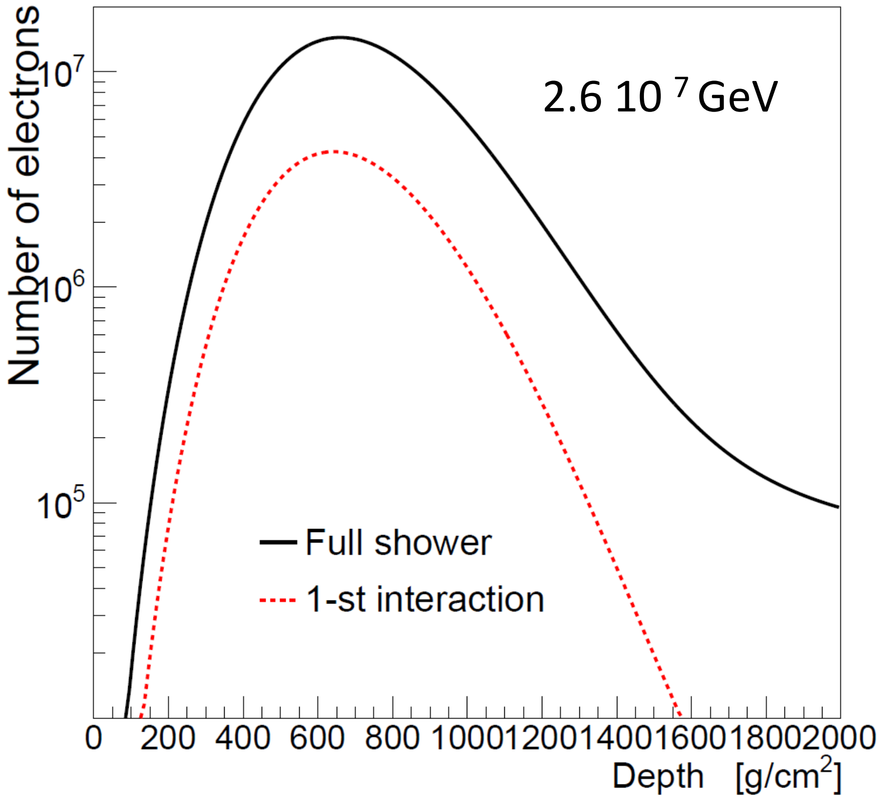
Apparently, multiplicity is collected in central region.
Important that integral which should represent instead of multiplicity energy dissipation is almost as forward as integral which defines energy transition.

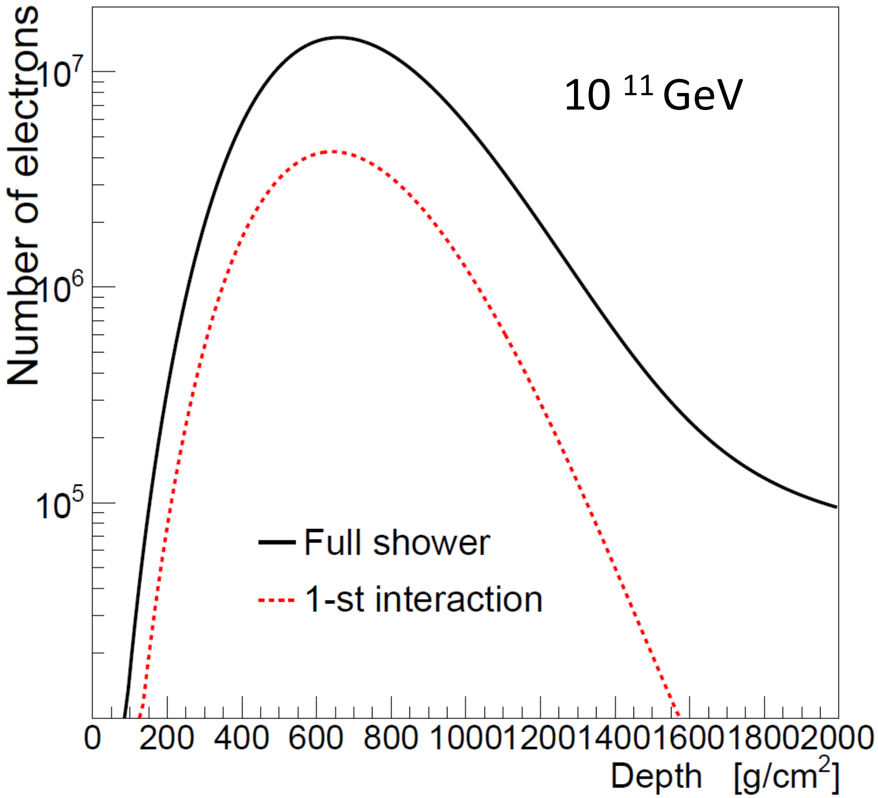
Summary on CR generators and interaction & shower

- Big difference in particle production at central pseudorapidities in pO and pPb collisions between EPOS-LHC and QGSJETII, of the same size for two target nuclei, originates in difference in number of participating nucleons for both nuclei. Data on transverse energy in pPb evidences in favor of EPOS-LHC.
- Particle production in hadronic interactions determines shower longitudinal development inclusively through integrals of two types.
  - First type is responsible for energy transitions between different components.
  - **Second type is responsible for energy dissipation. It is represented not by multiplicity of interaction but by integrals which differ from integrals of first type by weight *logx*. They are almost as forward as integrals of first type. This is the main new message.**

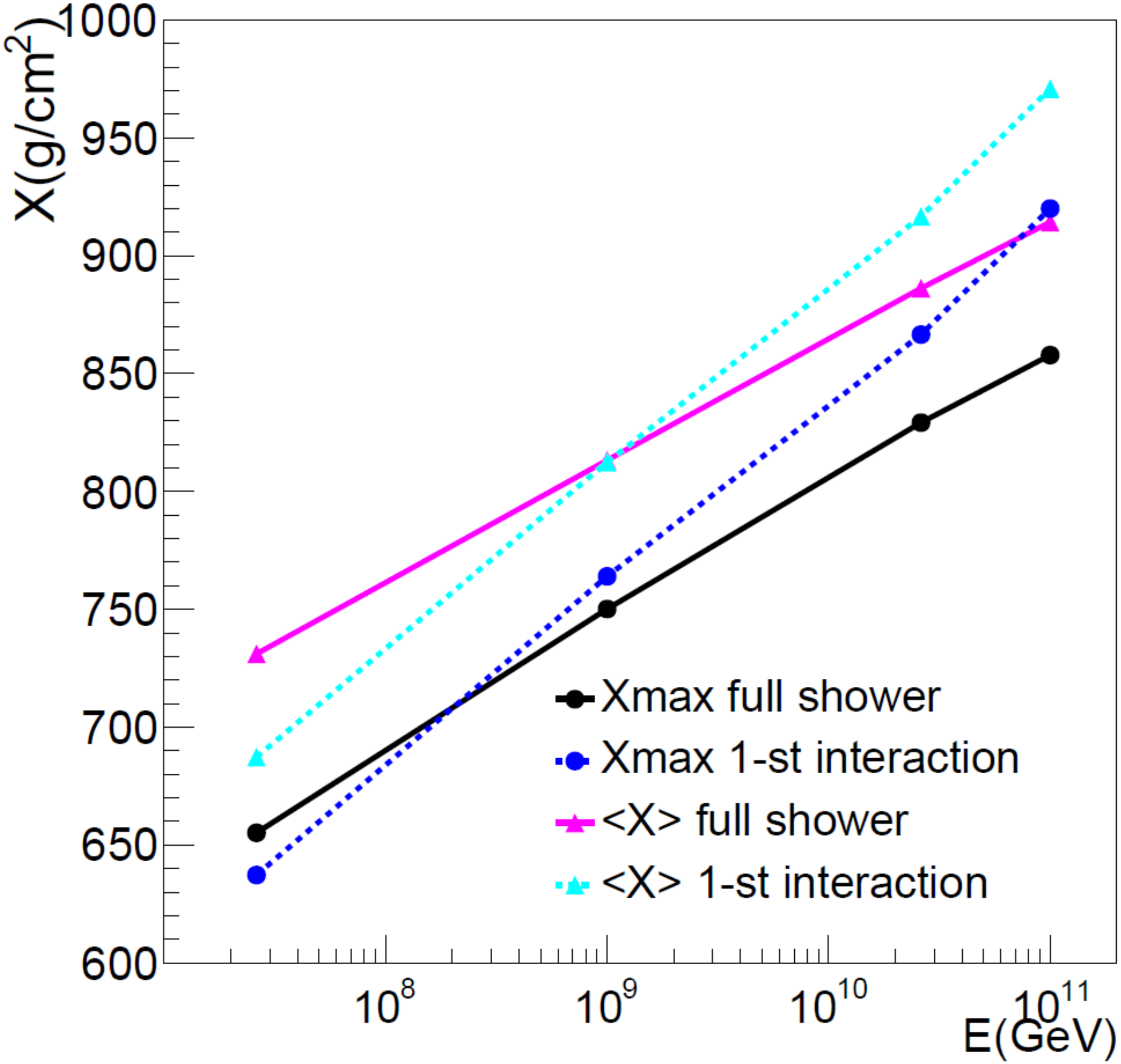
Backup slides

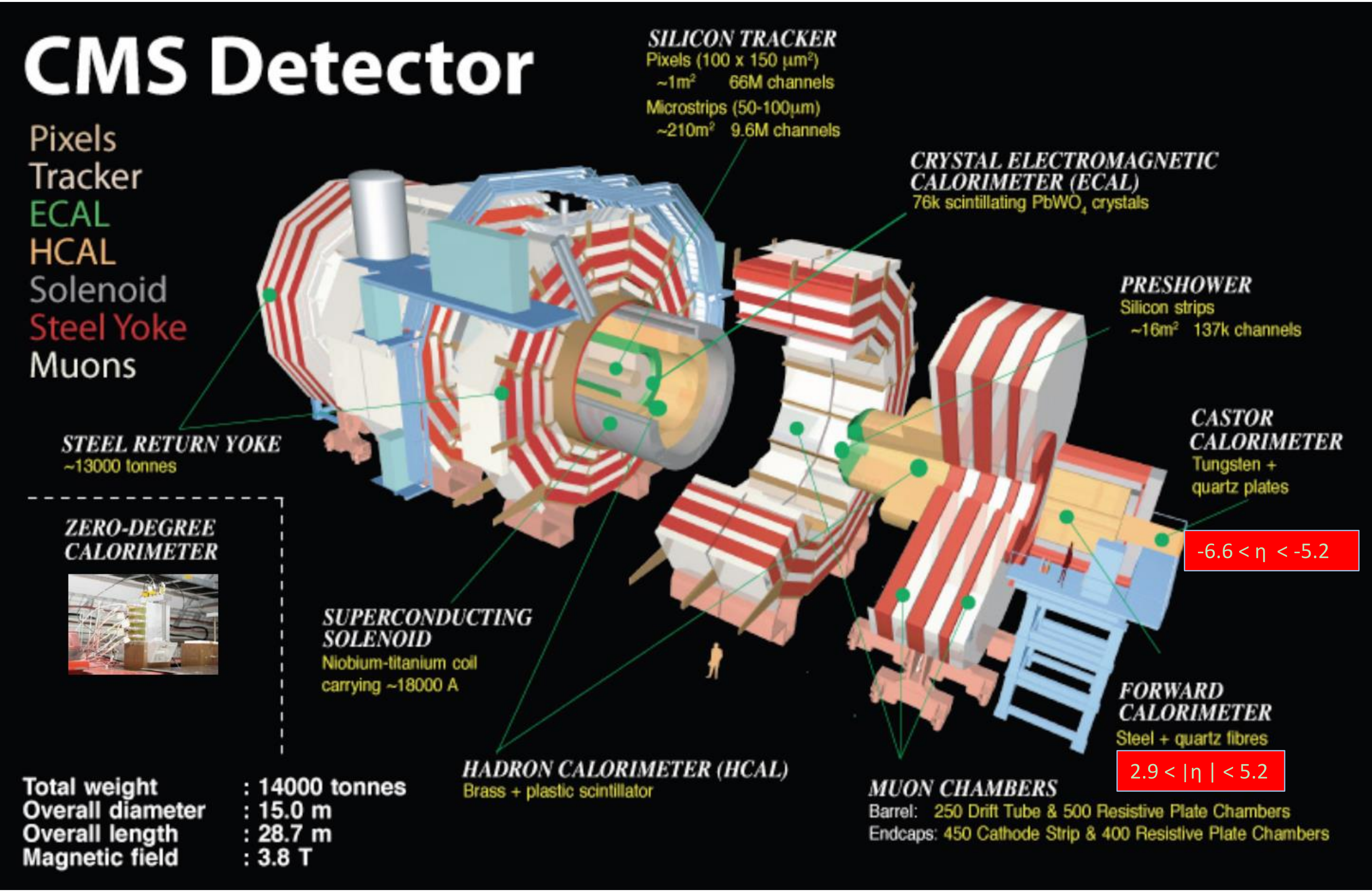
Shower profiles at different energies





Comparison of energy dependencies of X_{max} and <X>




CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
CASTOR CALORIMETER
Tungsten + quartz plates
-6.6 < η < -5.2
STEEL RETURN YOKE
~13000 tonnes
ZERO-DEGREE CALORIMETER
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
2.9 < |η | < 5.2
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T