High energy CR composition, interaction models, and LHC data

S. Ostapchenko

NTNU Trondheim

TeVPA-2011

Stockholm, August 1-5, 2011

Outline

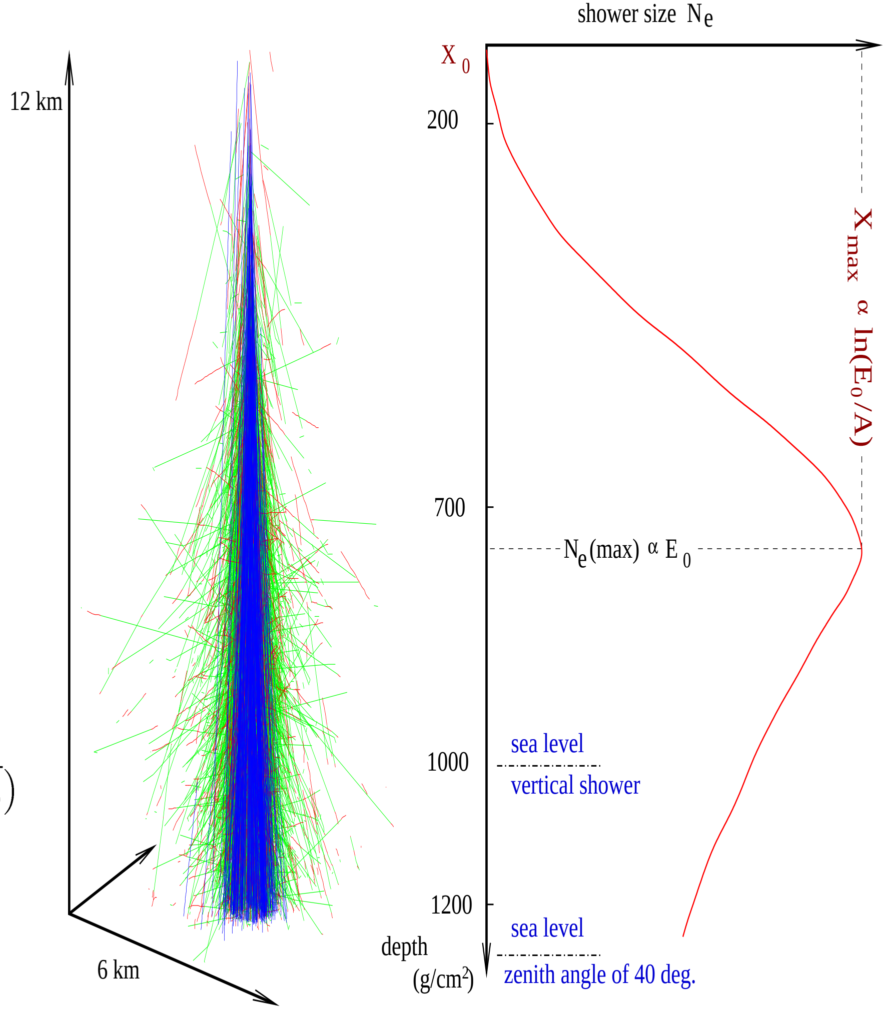
- extensive air shower physics
- CR composition sudies & superposition model
- CR interaction models and LHC data
- impact on EAS characteristics
- UHECR puzzles
- outlook

Extensive air shower physics

Studies of high energy CRs - based on extensive air shower (EAS) detection

EAS development $\Leftarrow$ high energy interactions

- backbone - hadron cascade
- guided by few interactions of initial (fastest secondary) particle
  $\Rightarrow$ main source of fluctuations
- many sub-cascades of secondaries
  $\Rightarrow$ well averaged



Most sensitive to hadronic physics:

- shower maximum position $X_{\max}$
  - mostly sensitive to $\sigma^{\rm inel}_{p-{\rm air}}$ $(\sigma^{\rm non-diffr}_{p-{\rm air}})$, $K^{\rm inel}_{p-{\rm air}}$
- number of muons at ground N_μ
  - mainly depends on $N^{\rm ch}_{\pi-{\rm air}}$ (at energies $\sim \sqrt{E_0}$)

Both observables are main tools for CR composition studies

CR composition studies & superposition model

For average (only!) EAS characteristics so-called superposition model works well: shower induced by nucleus A of energy $E_0 = A$ proton-induced cascades of energy E_0/A

- follows from the number of interacting nucleons per collision:

$$\langle \nu_A \rangle = \frac{A\, \sigma_{p-\mathrm{air}}}{\sigma_{A-\mathrm{air}}}$$

- mean free pass of the nucleus is $(\sigma_{p-\mathrm{air}}/\sigma_{A-\mathrm{air}})$ times shorter
- but each nucleon interacts with the probability

$$w_{\mathrm{int}} = \frac{\langle \nu_A \rangle}{A} = \frac{\sigma_{p-\mathrm{air}}}{\sigma_{A-\mathrm{air}}}$$

- $\Rightarrow \langle X^A_{\max}(E_0) \rangle = \langle X^p_{\max}(E_0/A) \rangle = \langle X^p_{\max}(E_0) \rangle - \mathrm{ER}\ \ln \mathrm{A}$, $\mathrm{ER} = d\langle X^p_{\max}(E_0) \rangle / d \ln E_0$
- $\Rightarrow$ can be used for CR composition studies: p-induced EAS penetrate deeper in the atmosphere than e.g. Fe-induced cascades
- similarly:

$$\begin{aligned} \langle N_e^A(E_0) \rangle &= A\, \langle N_e^p(E_0/A) \rangle \propto E_0^{\alpha_e}\ A^{1-\alpha_e};\ \ \alpha_e \simeq 1.1 \\ \langle N_\mu^A(E_0) \rangle &= A\, \langle N_\mu^p(E_0/A) \rangle \propto E_0^{\alpha_\mu}\ A^{1-\alpha_\mu};\ \ \alpha_\mu \simeq 0.9 \end{aligned}$$

$\Rightarrow$ Fe-induced showers have more muons $(\langle N_\mu^A(E_0) \rangle / \langle N_\mu^p(E_0/A) \rangle = A^{0.1})$ and less electrons $(\langle N_e^A(E_0) \rangle / \langle N_e^p(E_0/A) \rangle = A^{-0.1})$

CR interaction models

In general, interpretation of exp. results requires detailed description of EAS development

Important ingredient: CR interaction models

Representative models:

- QGSJET (Kalmykov & SO, 1993, 1997)
- SIBYLL (Ahn, Engel, Gaisser, Lipary & Stanev, 1999, 2009)
- QGSJET-II (SO, 2006, 2011)
- EPOS (Liu, Pierog & Werner,2007-2011)

All are based on similar ideas / qualitative approaches

But differ in the implementation, theoretical basis, amount of phenomenology, etc.
$\Rightarrow$ in predictions

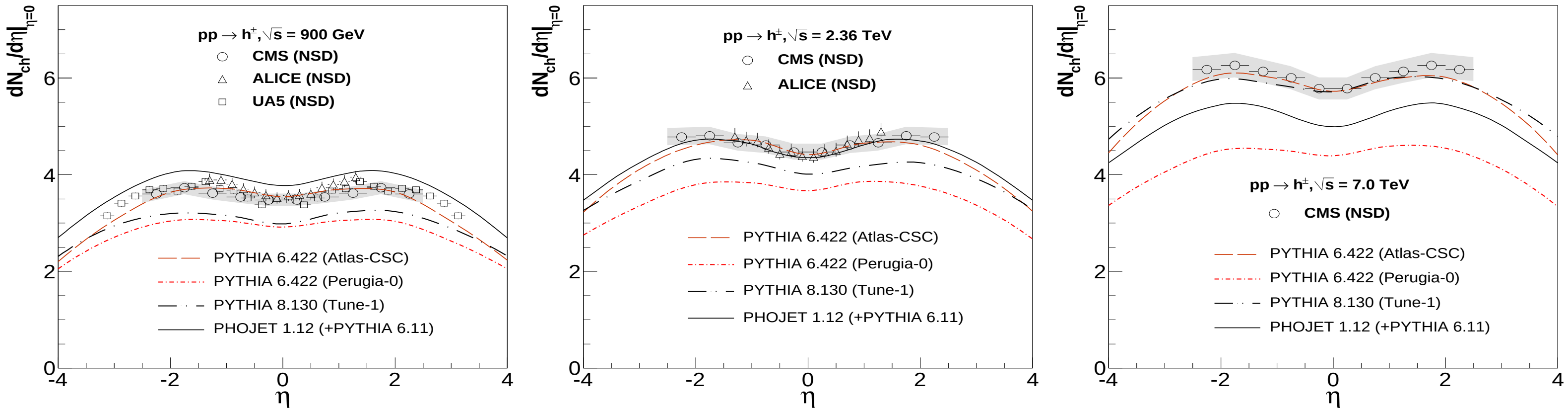
By consequence, model updates and cross checks with exp. data necessary

In the following: analysis of the impact of LHC data - based on an update of QGSJET-II (QGSJET-II-03 $\rightarrow$ QGSJET-II-04)

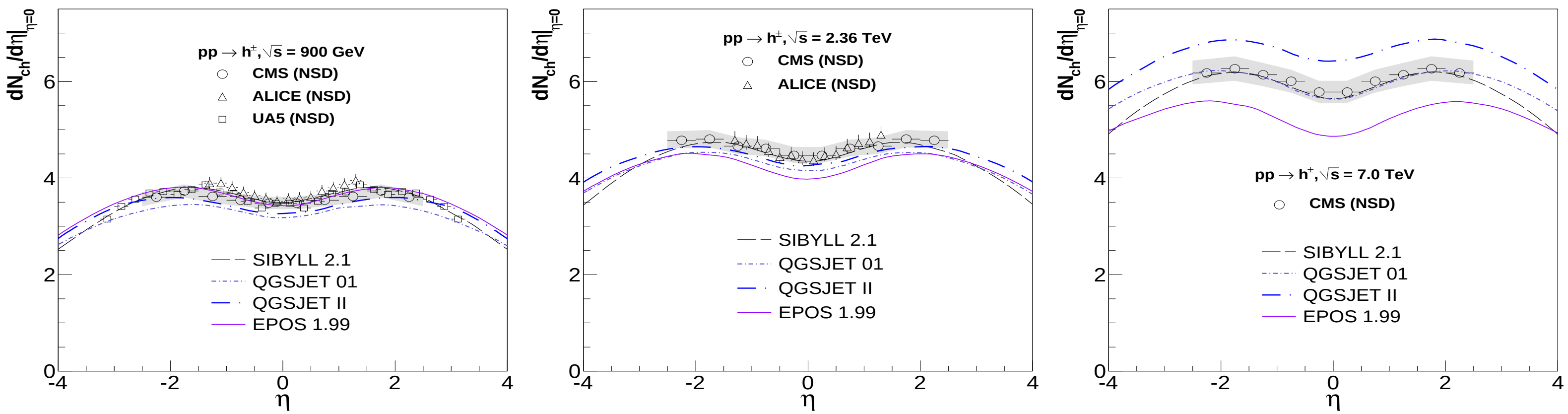
Impact of LHC data: multiplicity

CR interaction models met LHC data generally well

E.g. most collider models underestimate multiplicity:



On the contrary, most of CR interaction models agree with the data within $\sim 10\%$:



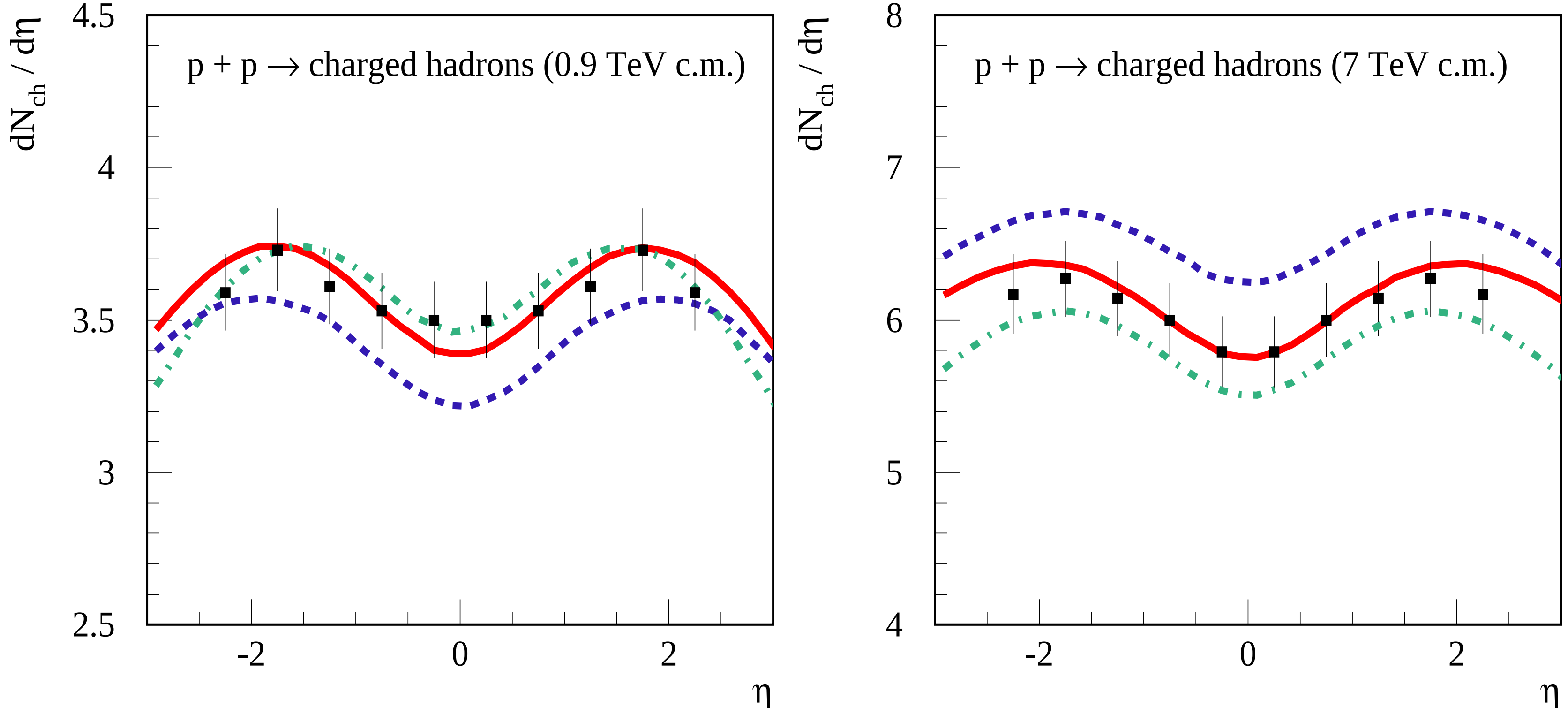
However, certain improvements desirable

- e.g., $N_{\rm ch}$ grows too fast with $\sqrt{s}$ in QGSJET-II

Multiplicity adjustment in QGSJET-II

In general, a reasonable agreement after the adjustment:

QGSJET-II-04 / QGSJET-II-03 / SIBYLL vrs. CMS data

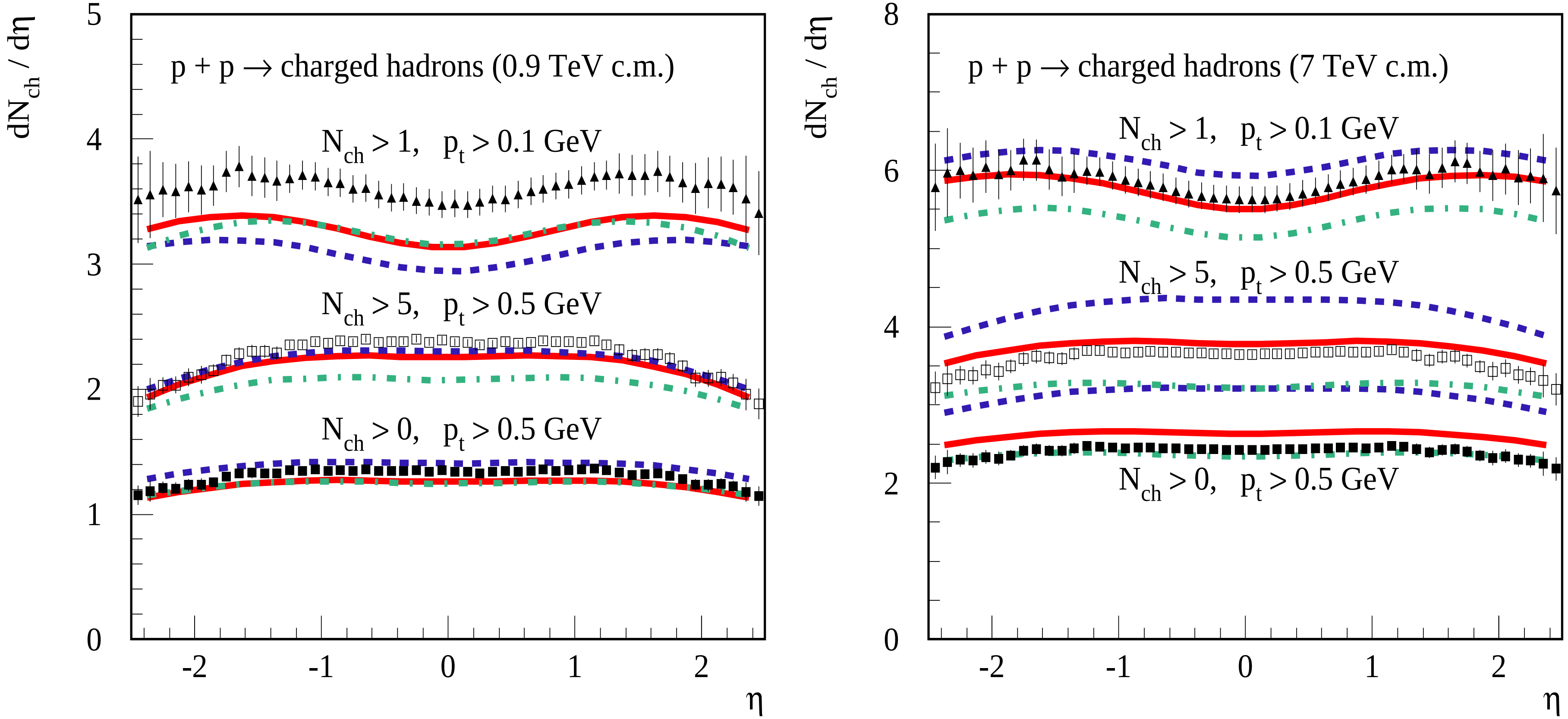


Remarks:

- some basic model parameters have been changed
- ⇒ other model predictions influenced: slower energy-rise of total and inelastic cross sections

Cross check with ATLAS data for model-independent event selections

QGSJET-II-04 / QGSJET-II-03 / SIBYLL vrs. ATLAS data



- qualitatively the same trend
- the level of (dis-)agreement varies for different event selections
- overall agreement at 10% level for QGSJET-II-04
- overall corrections of N_{ch} at 10% level compared to QGSJET-II-03
- ⇒ not important for EAS description

Production of (anti-)baryons and strange hadrons

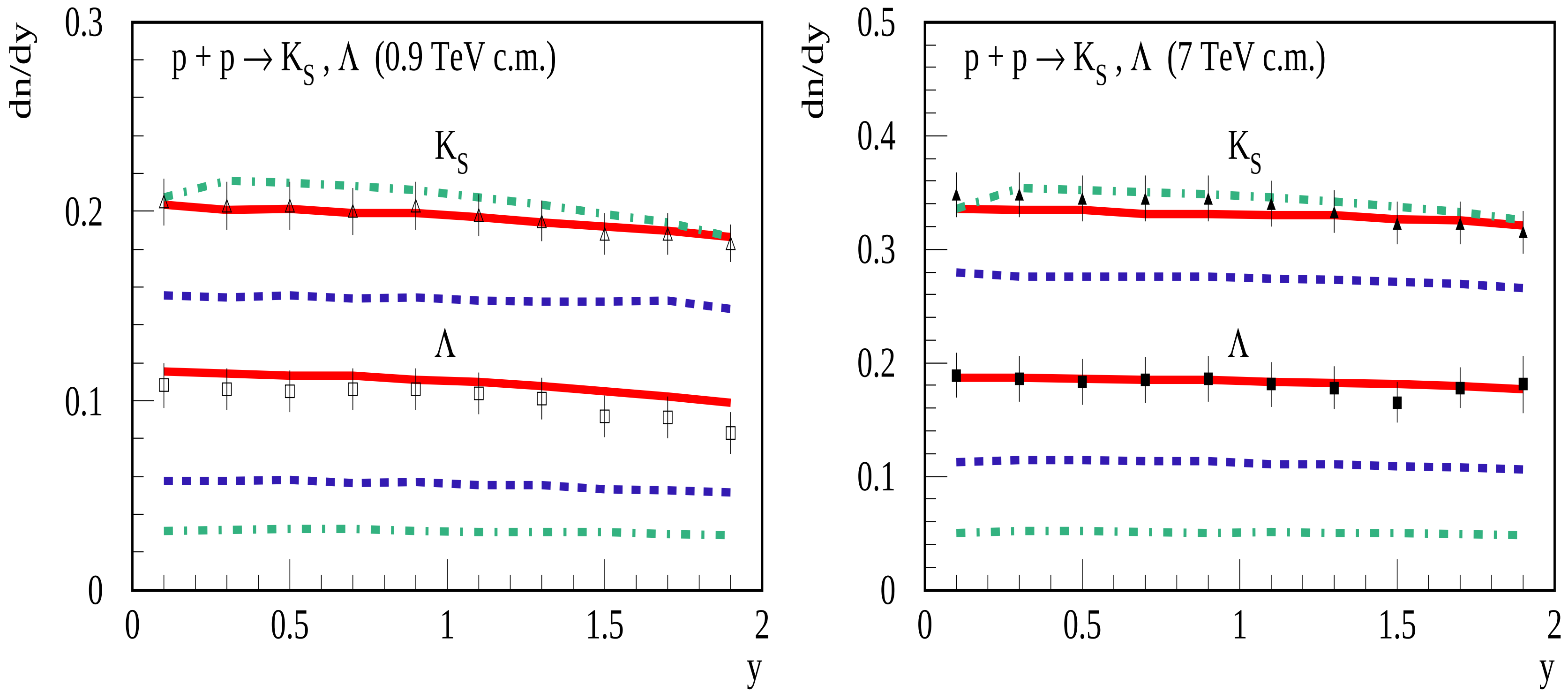
In general, enhanced production of (anti-)baryons may impact EAS muon content *[Grieder, 1973; Pierog & Werner, 2008]*:

- more energy kept in the hadronic cascade
- more hadron generations produced (nucleons don't decay) $\Rightarrow$ more muons

However: no indication on higher than predicted $\bar{p}$-multiplicity from LHC data

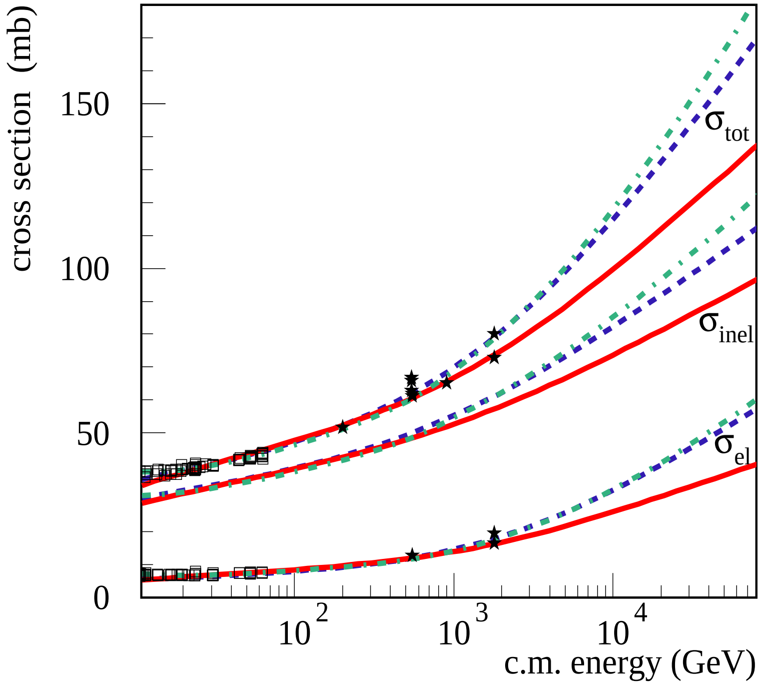
More important: enhancement of strangeness production

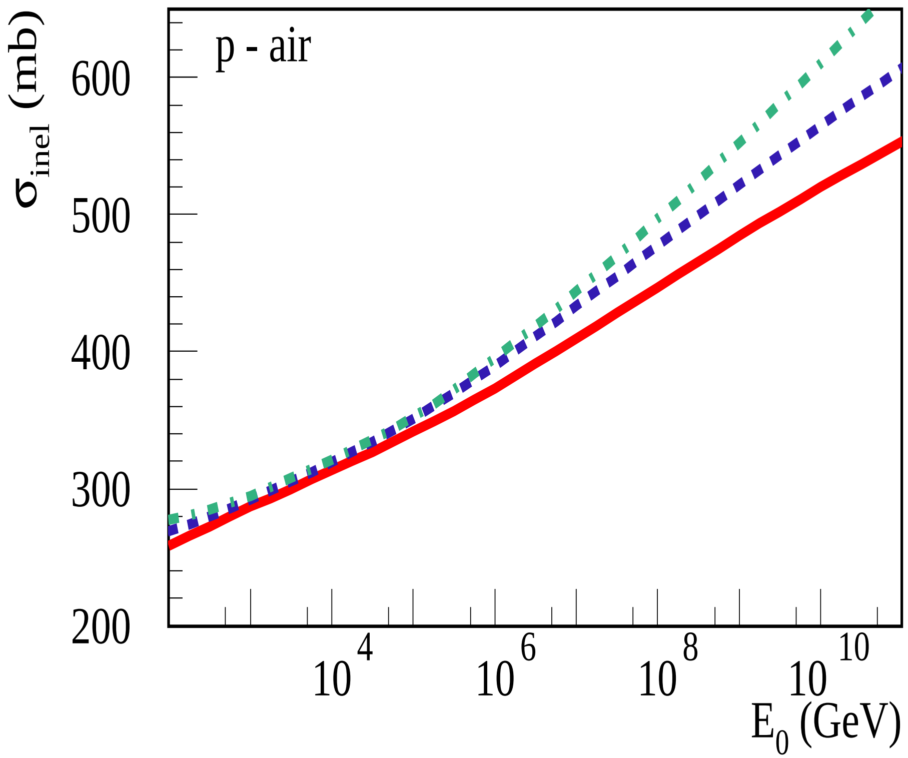
QGSJET-II-04 / QGSJET-II-03 / SIBYLL vrs. CMS data



LHC: measurements of 'visible' cross sectios for MB event selections

QGSJET-II-04 / QGSJET-II-03 / SIBYLL predictions for *pp* and *p*-air cross sections:





'Visible' cross section for different event selections by ATLAS - support smaller σ_{pp}^{inel}:

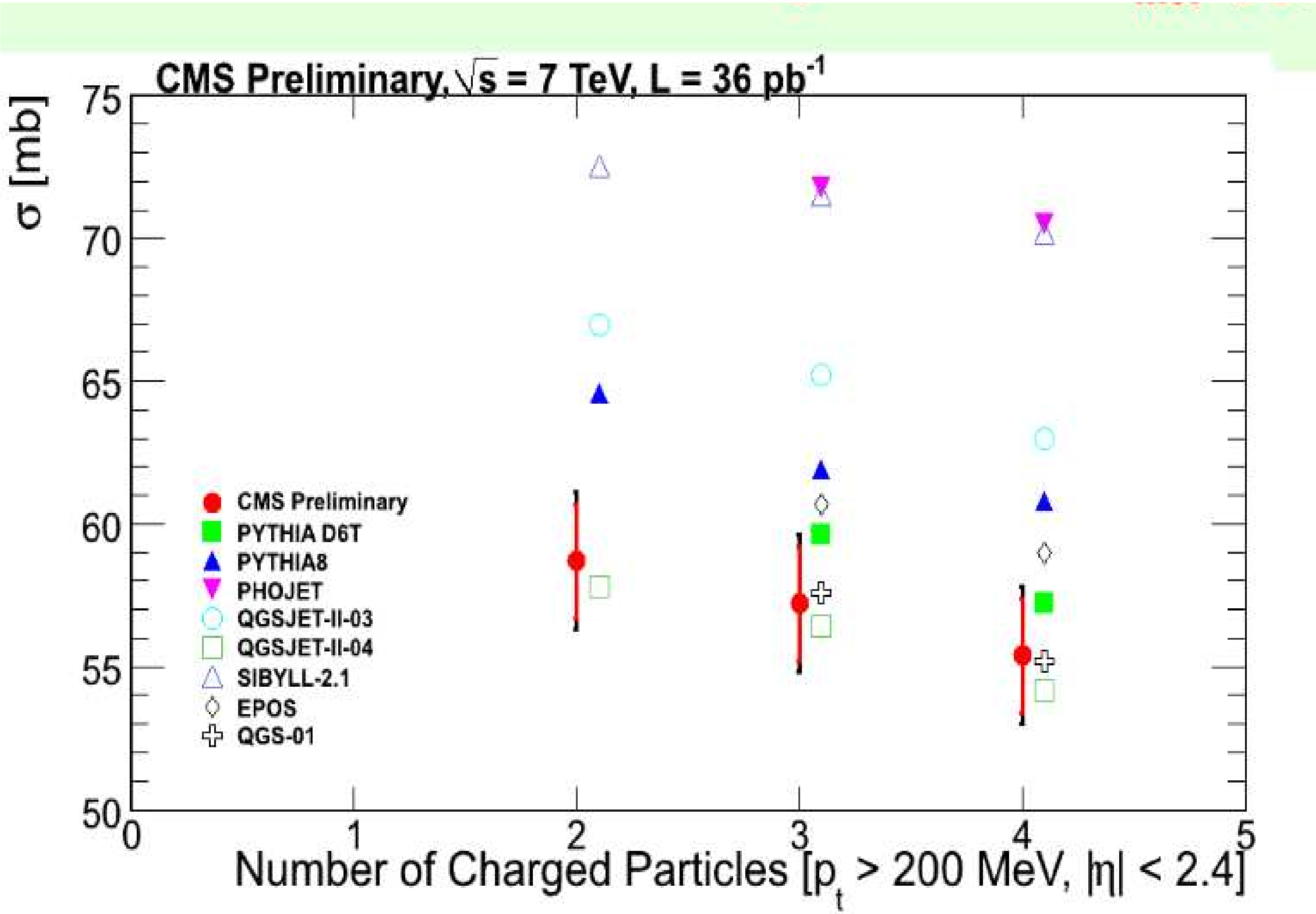
	QGSJET-II-04	QGSJET-II-03	SIBYLL	exp. (ATLAS)
MB_OR	54.1	62.3	68.4	51.9 ± 5.7
MB_AND	60.8	69.8	74.7	58.7 ± 6.5

QGSJET-II-03 and SIBYLL exceed data by 2σ and 3σ respectively

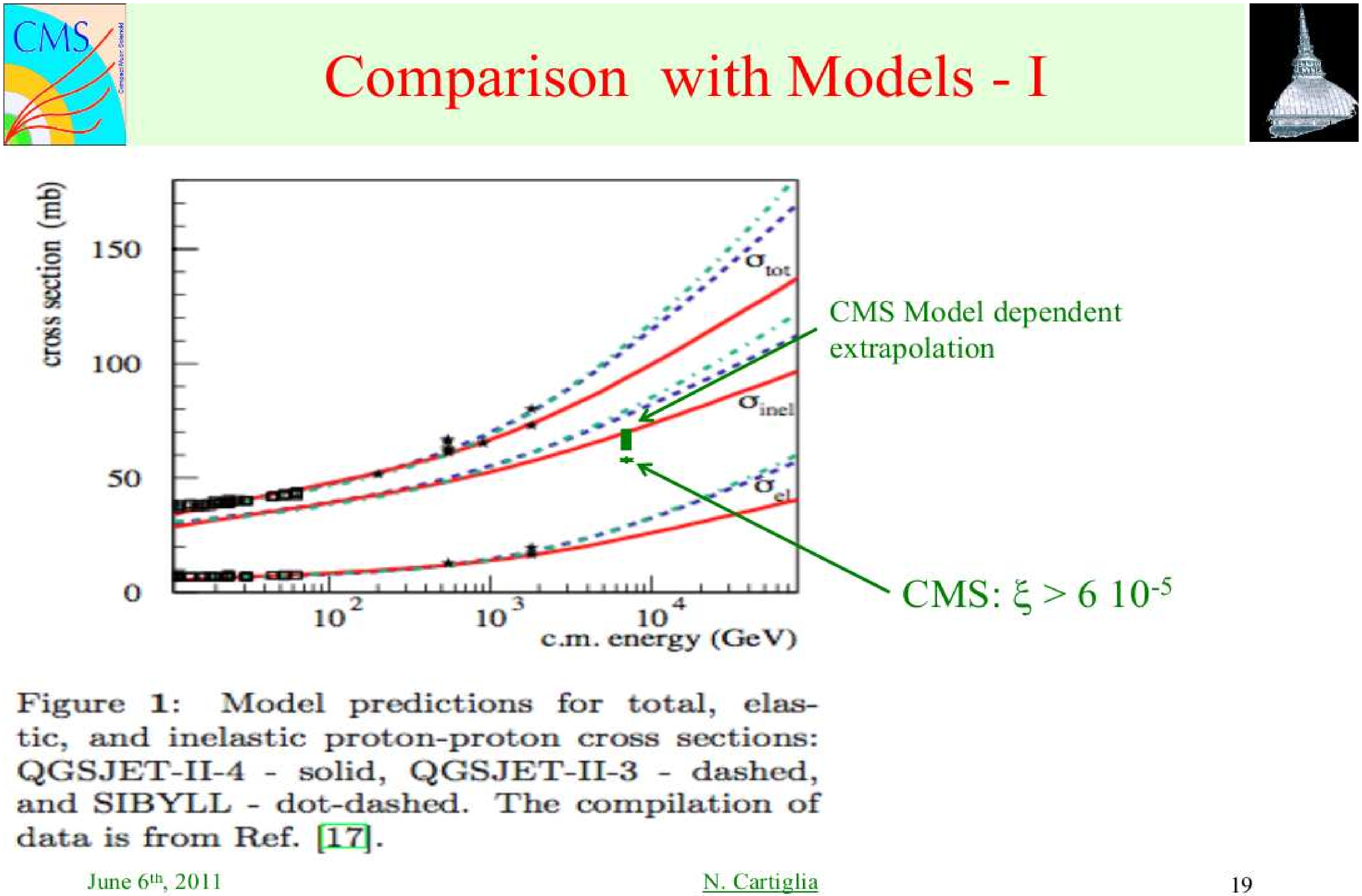
Similar results for MB_AND selection by ALICE:

$\sqrt{s}$	QGSJET-II-04	QGSJET-II-03	SIBYLL	exp. (ALICE)
2.76 TeV	47.4	52.5	56.2	47.2 ± 3.3
7 TeV	55.1	63.6	69.1	54.2 ± 3.8

And for CMS selections:



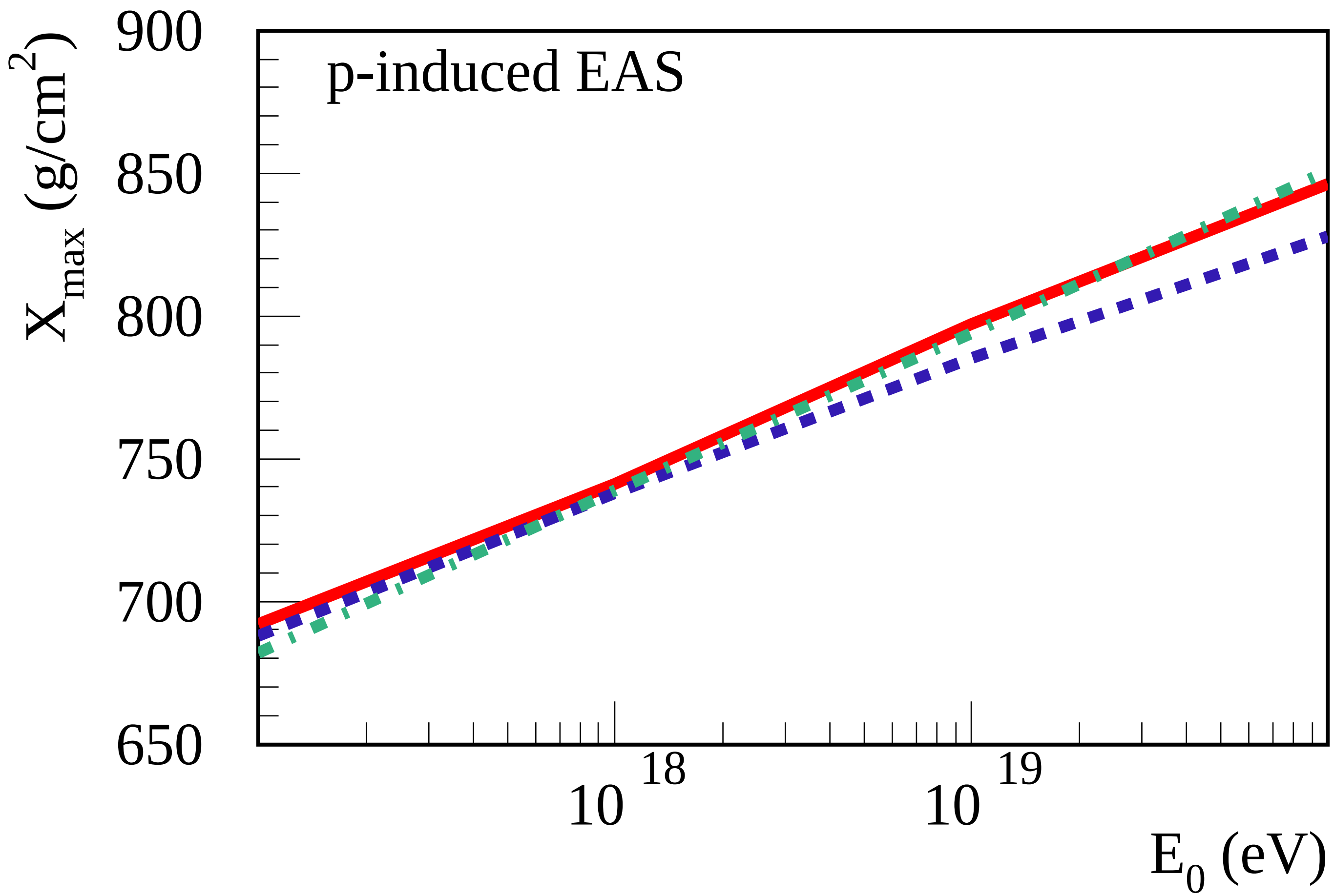
However: extrapolations for $\sigma_{pp}^{\text{inel}}$ - model-dependent



Air shower characteristics

Reduced cross sections ⇒ larger EAS elongation rate above 10^{18} eV

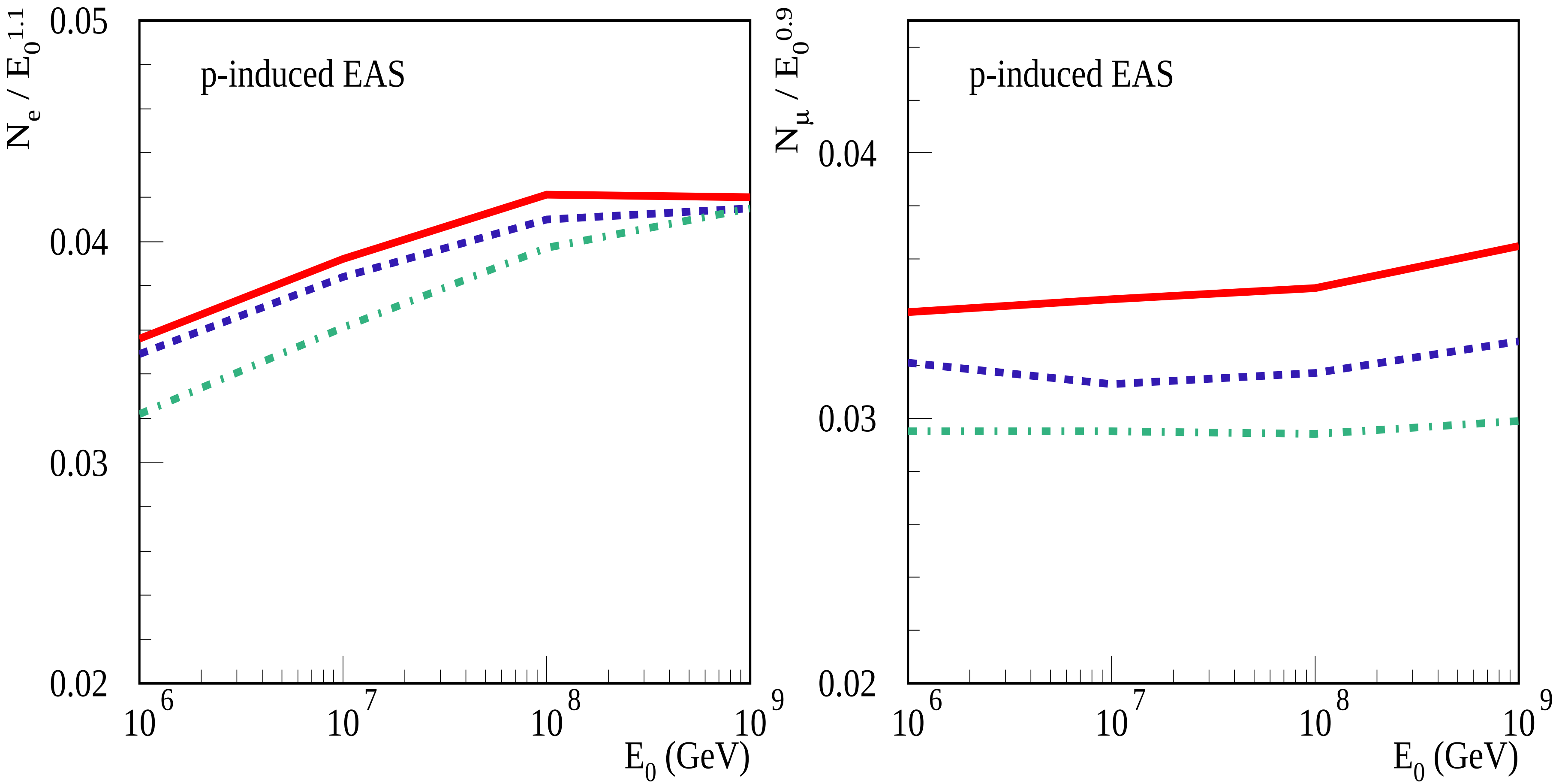
QGSJET-II-04 / QGSJET-II-03 / SIBYLL predictions for $X_{\max}$:



- even larger increase of $X_{\max}$ expected for SIBYLL - if $\sigma_{pp}^{\rm inel}$ is adjusted to LHC data

EAS characteristics in KASCADE-Grande range

QGSJET-II-04 / QGSJET-II-03 / SIBYLL predictions for $N_{e/\mu}$:



- N_e - no significant changes in the KG range
- N_μ (>1 GeV) - $\sim$ 10% rise
- $\Rightarrow$ no significant impact on composition studies

RMS of $X_{\max}$ - model-independence

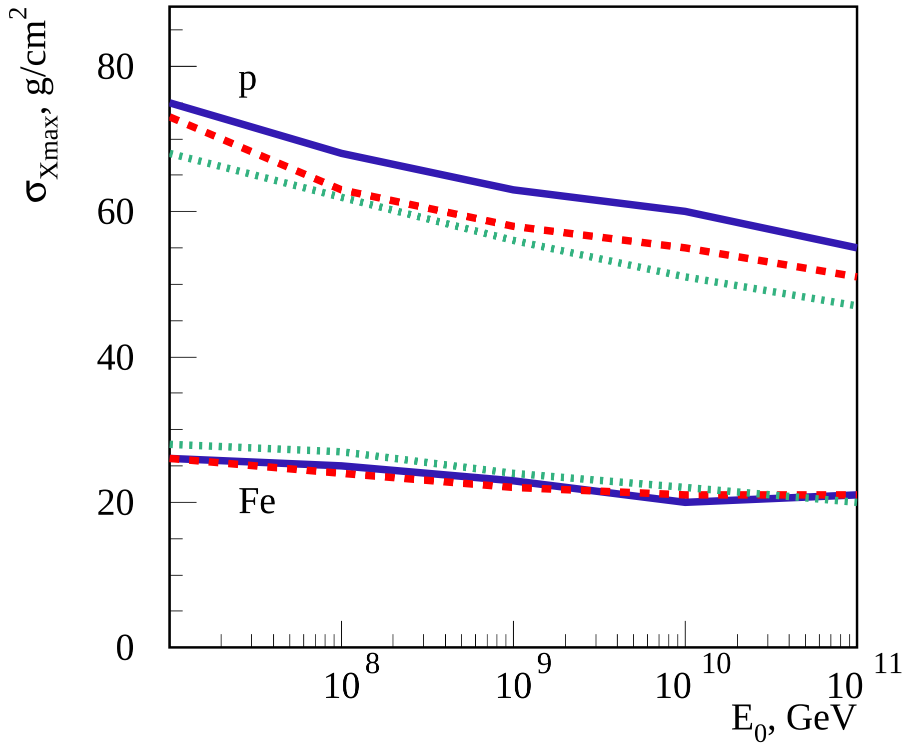
RMS of $X_{\max}$ - model-independent quantity *[Aloisio et al., 2008]*

- proton-induced EAS

  mean free pass λ_p dominates:
  $\Delta\sigma_X^p = \lambda_p \sim 1/\sigma^{\rm inel}_{p-{\rm air}}$ (~ 50 g/cm^2);

  geometry of $p-$ air collisions:
  - small $b \Rightarrow$ large $K_{\rm inel}$, $N_{\rm ch}$
  - large $b \Rightarrow$ small $K_{\rm inel}$, $N_{\rm ch}$

QGSJET / QGSJET-II-03 / SIBYLL



- A-induced EAS:
  superposition model ($\sigma_X^A = \sigma_X^p/\sqrt{A}$) - invalid
  [Kalmykov & SO, 1989, 1993]

  collision geometry dominates:
  fluctuations of multiplicity ($\sigma_{N_{\rm ch}}/N_{\rm ch} \sim 1$) and N of 'wounded' nucleons $\Rightarrow K_{\rm inel}$

  nuclear fragmentation - factor of 2 difference for $\sigma^A_{X_{\max}}$ between extreme assumptions

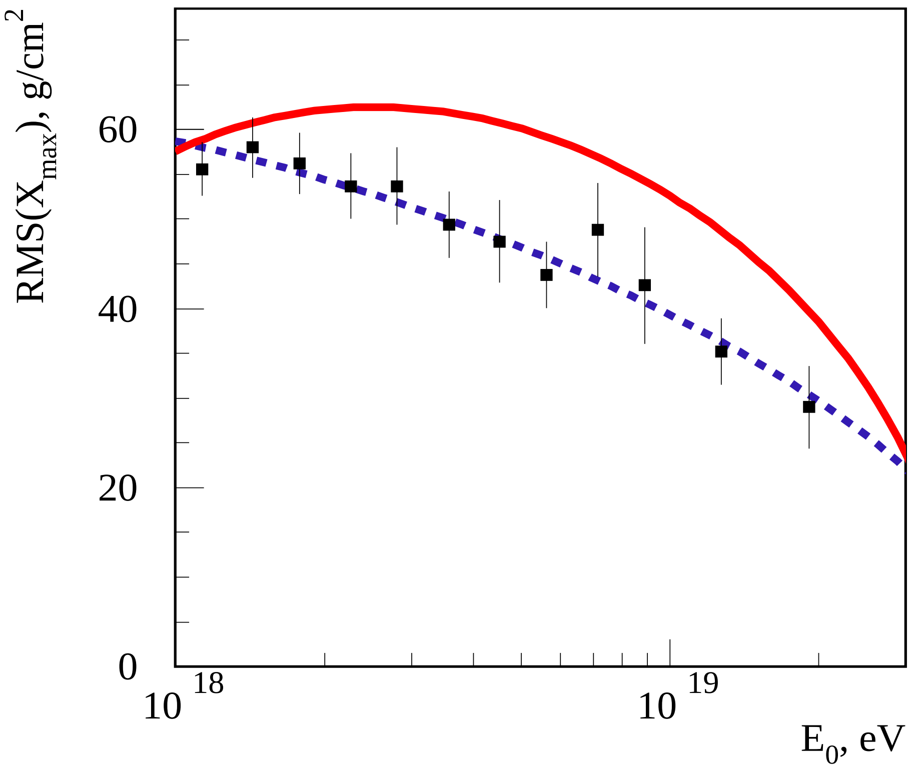
  still much smaller fluctuations than for p-induced showers

RMS of $X_{\rm max}$ - Pierre Auger data

Pierre Auger measurements of RMS of $X_{\rm max}$: change from protons to iron?

One has to check the energy-trend, e.g with a 2-component model:

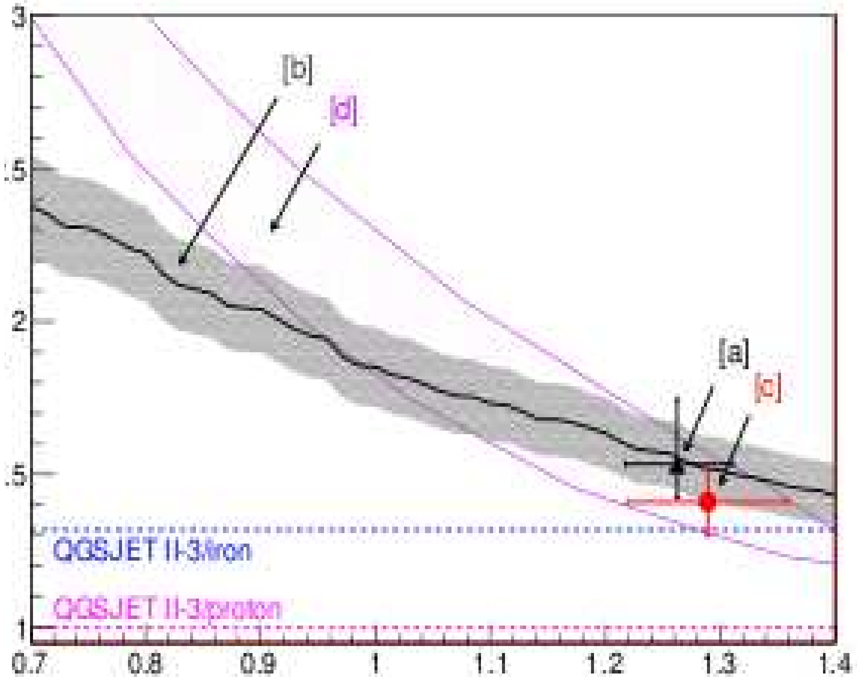
- $f_p(E) = 1 - \frac{2}{3}\,\lg(E/EeV)$, $f_{\rm Fe}(E) = 1 - f_p(E)$
- or $f_p(E) = 0.4\left[1 - \frac{2}{3}\,\lg(E/EeV)\right]$, $f_{\rm Fe}(E) = 1 - f_p(E)$



Clearly, data favor a 'heavy mix' at 1 EeV already!

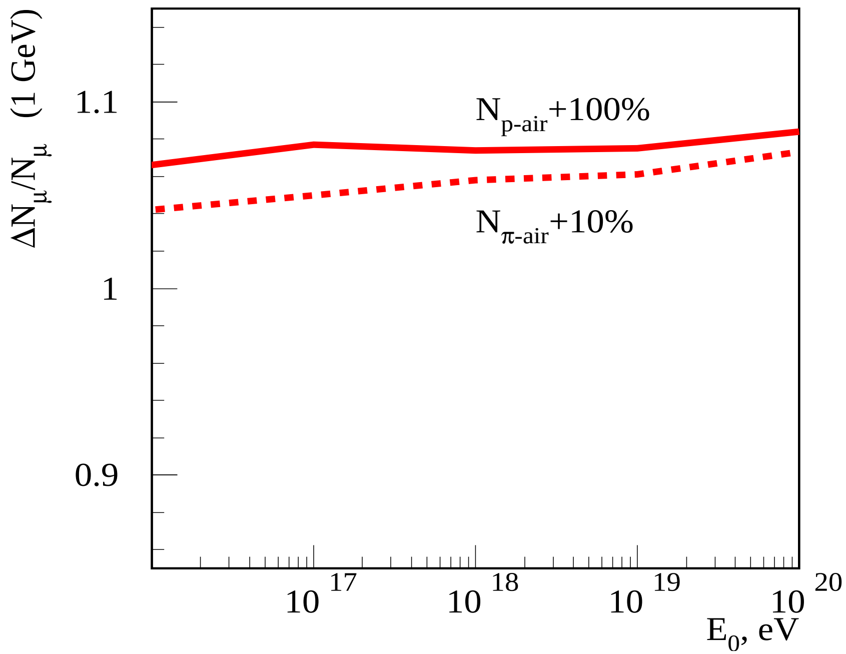
Muon puzzle

Pierre Auger collaboration - models underestimate ρ_μ by 50%:



Even larger (factor of 2) mismatch reported now

Complete mystery: requires to increase multiplicity by an order of magnitude over a wide energy range - in strong variance to LHC data



Example: increase $N^{\rm ch}_{p-{\rm air}}$ by 100% (QGSJET)

or $N^{\rm ch}_{\pi-{\rm air}}$ by 10% - nearly same effect

Conclusions (1)

Composition studies - crucial for understanding very- and ultra-HECRs:

- CR 'knee': propagation effect or acceleration cutoff
- galactic-extragalactic transition
- UHECR sources/acceleration mechanisms

Interpretation of data - depends on EAS simulation procedures / hadronic MC models

First experience at LHC:

- CR interaction models are 'not bad'
- only cosmetic improvements needed

Important exception: inelastic cross section

- data favor smaller $\sigma_{pp}^{\rm inel}$ (as extrapolated from E710 data)
- $\Rightarrow$ smaller $\sigma_{p-{\rm air}}^{\rm inel}$ $\Rightarrow$ larger elongation rate above 10^{18} eV
- decisive results to come soon from the TOTEM experiment

Conclusions (2)

CR composition - things seem so promising few years ago:

- theoretically: B-field enhancement put the 'knee' at the 'correct place'
- KASCADE experiment: rigidity-dependent 'knee' positions for p, He
- HiRes experiment: abrupt change from Fe- to p-dominance at 10^{17} eV
- Auger experiment: correlations with AGNs
- theoretically: 'dip' model for galactic-extragalactic transition

Presently one seems to be on a 'heavy track':

- KASCADE-Grande: 'iron knee' is at the place but doesn't look like a spectral cutoff (mixed composition up to 10^{18} eV?!)
- Auger: RMS($X_{\rm max}$) also seems to support a 'heavy mix' at 10^{18} eV (going to pure Fe above?)

However, puzzling contradictions:

- between $\langle X_{\rm max}\rangle$ and RMS($X_{\rm max}$)
- between Auger data on N_μ and model predictions

Most annoying is not a model-dependence of the results, rather their 'model-independence': *none of the models is able to bring them together in a coherent fashion*