Sibyll 2.3 - from LHC to the universe

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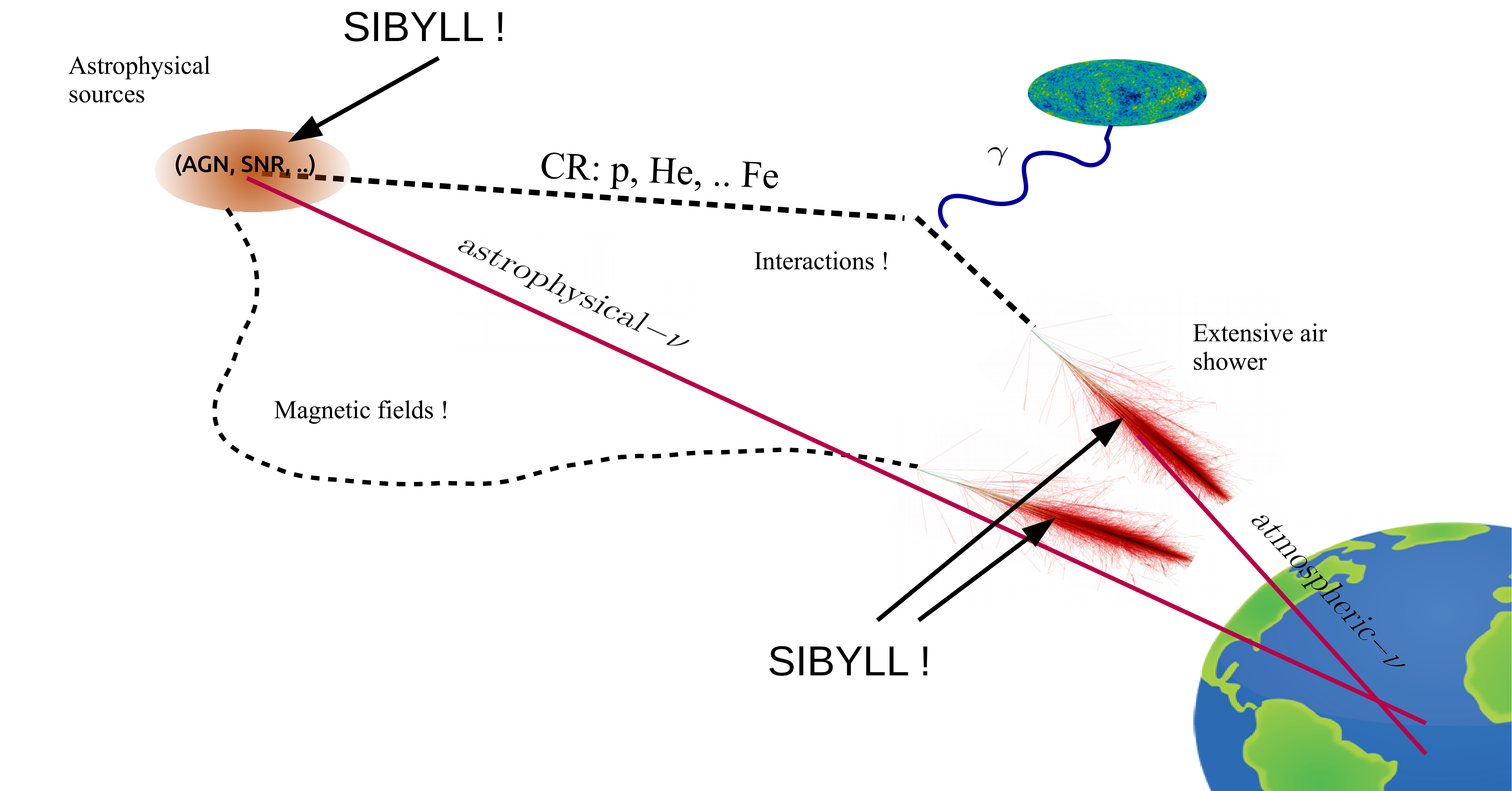
MPI at LHC 2016 – San Cristobal de las Casas, Chiapas, Mexico


SIBYLL !
Astrophysical sources
(AGN, SNR, ..)
CR: p, He, .. Fe
γ
Interactions !
astrophysical$-\nu$
Extensive air shower
Magnetic fields !
atmospheric$-\nu$
SIBYLL !

Sibyll

Designed explicitly and exclusively for air shower simulations

Air shower specific features:

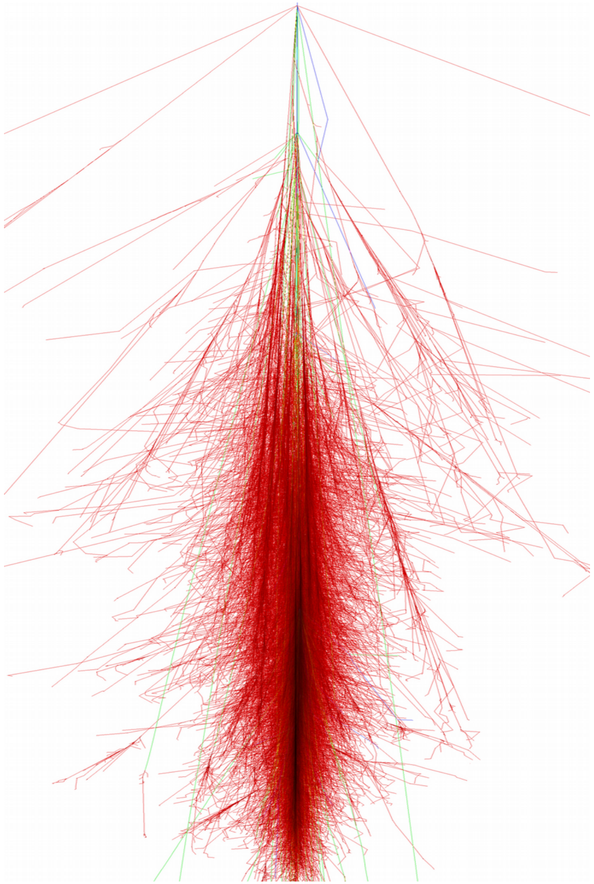
- Projectiles: p, n, π, K
- Target: nuclei (Air)

$$E_{\mathrm{Lab}} = 100\,\mathrm{GeV} \ldots 10\,\mathrm{EeV}$$

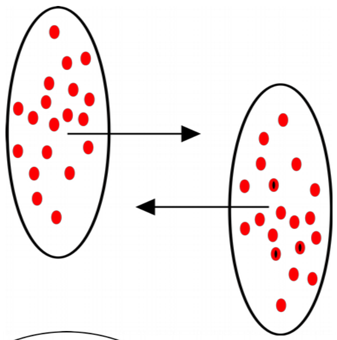
- Forward particle production, energy flow

QCD inspired:
- Minijets
- Color ‘string’ hadronization

Soft physics:
- Diffraction dissociation
- Soft exchange

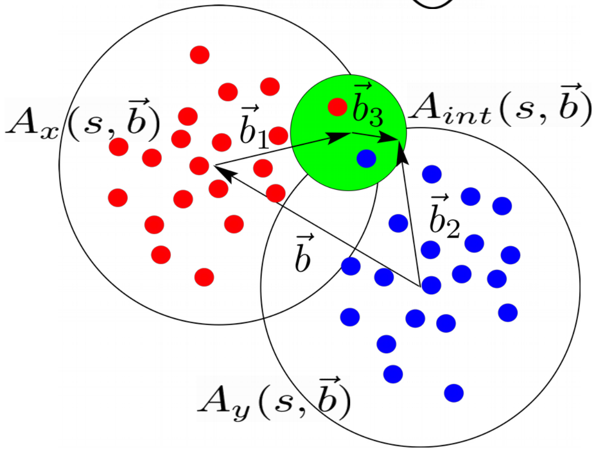


Basic interaction picture



Multiple interactions based on overlap

$$\langle n(s,\vec{b})\rangle = \sigma(s)\cdot A(s,\vec{b})$$: number of interactions



Independent parton-parton interactions

$$P_n(s,\vec{b}) = \frac{\langle n(s,\vec{b})\rangle^n}{n!}\exp\left(-\langle n(s,\vec{b})\rangle\right)$$

Hadron profile: em. form factor

Interactions have profile too
hard: point-like, soft: extended (Gaussian)

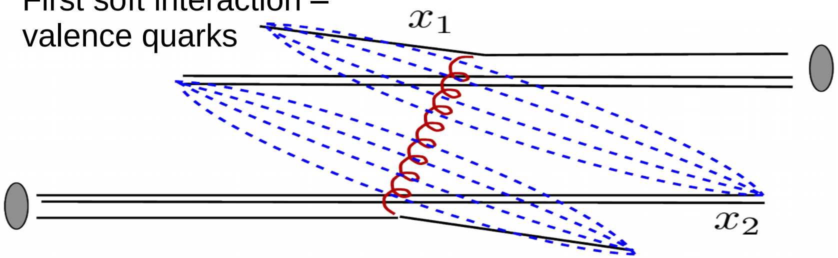
$$A(s,\vec{b}) = \int \mathrm{d}\vec{b}_1\,\mathrm{d}\vec{b}_2\,\mathrm{d}\vec{b}_3\,A_x(s,\vec{b}_1)A_y(s,\vec{b}_2)A_{int}(s,\vec{b}_3)\delta^{(2)}(\vec{b}-\vec{b}_1-\vec{b}_2-\vec{b}_3)$$

Partons to Hadrons

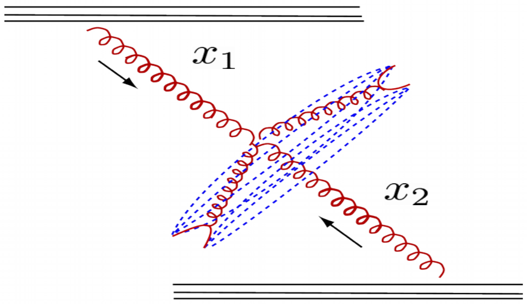
Event structure

$$P_{n_s,n_h}(s) = \int d\vec{b} \prod_{i=h,s} \frac{\langle n_i(s,\vec{b})\rangle^{n_i}}{n_i!} \exp\left(-\langle n_i(s,\vec{b})\rangle\right)$$

First soft interaction – valence quarks



$$f_{soft} \sim \frac{1}{\sqrt{x}}$$



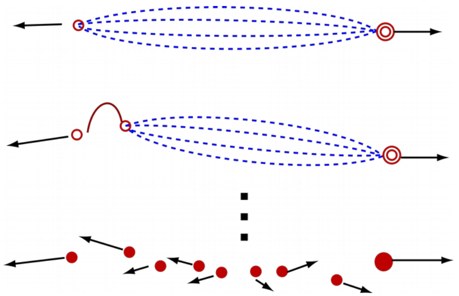
$(n_s - 1) + n_h$

minijets

$$f_{hard} = g(x) + \frac{4}{9}[q(x) + \bar{q}(x)]$$

with g(x) and q(x) from DGLAP PDF

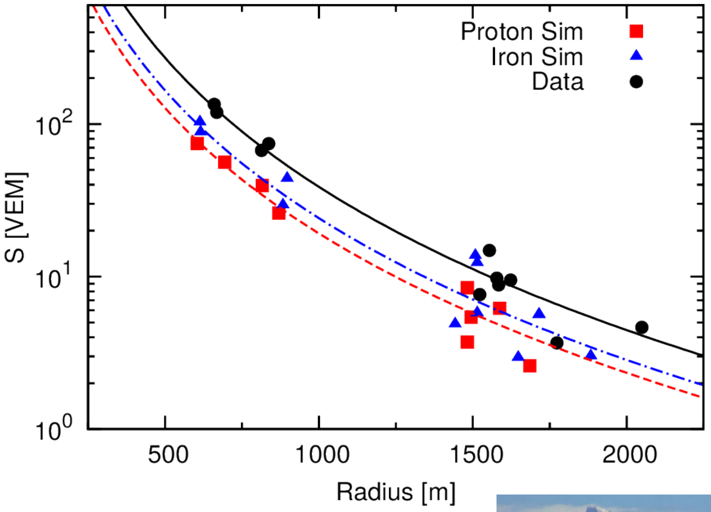
Each string:



Lund string fragmentation

Why new version?

Hadron/muon excess in air showers
at Pierre Auger Observatory
(PRL 117 (2016))



Epos-LHC : 1.33

QGSjetII-04 : 1.61

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|                                                                |
|                        S I B Y L L  2.1                        |
|                                                                |
|              HADRONIC INTERACTION MONTE CARLO                   |
|                              BY                                |
|                         Ralph ENGEL                            |
|               R.S. FLETCHER, T.K. GAISSER                      |
|                   P. LIPARI, T. STANEV                         |
|                                                                |
| Publication to be cited when using this program:               |
| R. Engel et al., Proc. 26th ICRC, 1 (1999) 415                 |
|                                                                |
| last modified:  28. Sept. 2001 by R. Engel                     |
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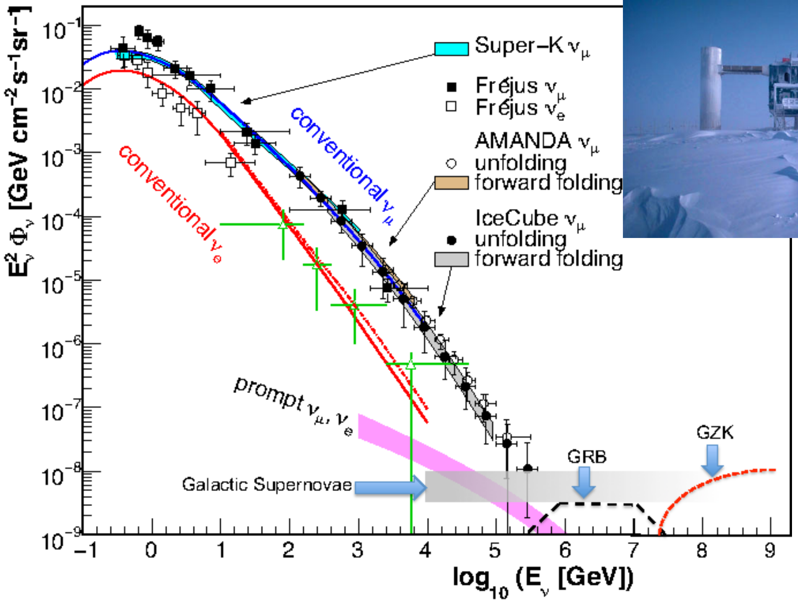
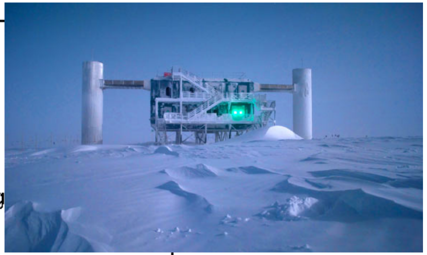
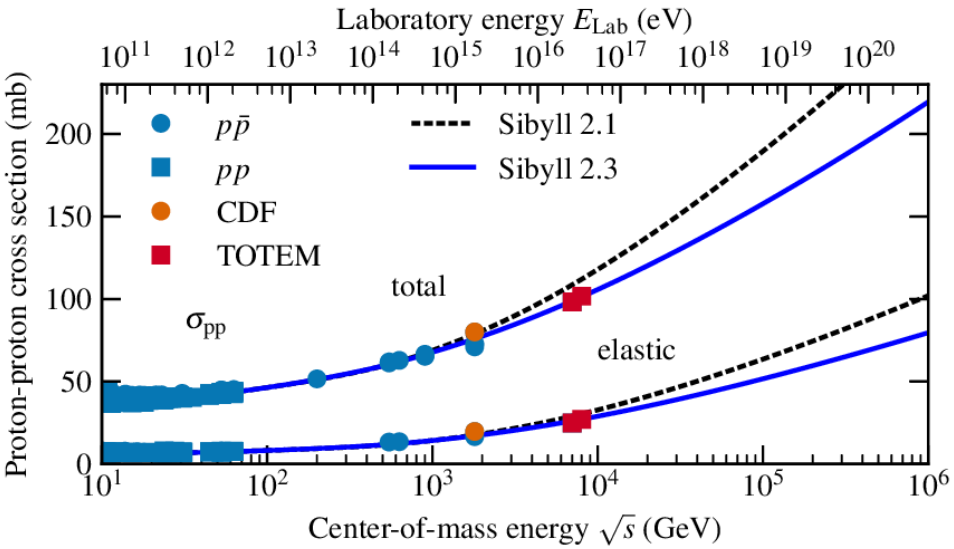
No LHC !

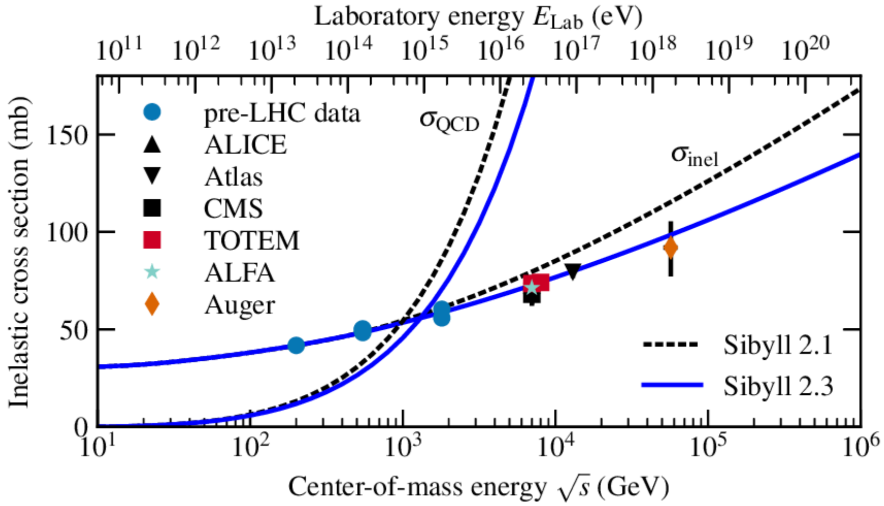




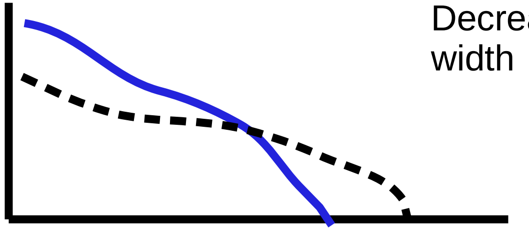
LHC input

Interaction cross section



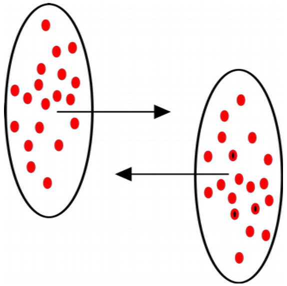


Profile



Decrease profile width

Impact parameter

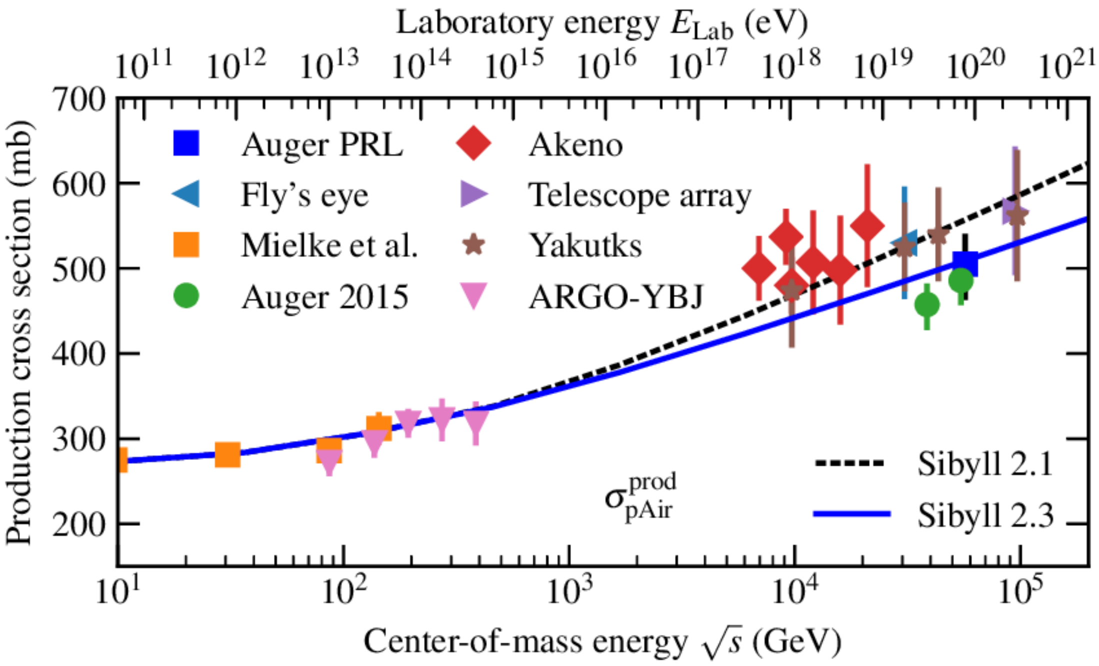


$$\langle n_{\mathrm{hard}} \rangle = \sigma_{\mathrm{QCD}}\, A(s, \vec{b})$$

p-air cross section

New p-p cross section

Inelastic screening in
Hadron-nucleus



Muon production & leading particles

Muon production in EAS

$$\pi, \mathrm{K} \to \mu + \nu_\mu$$

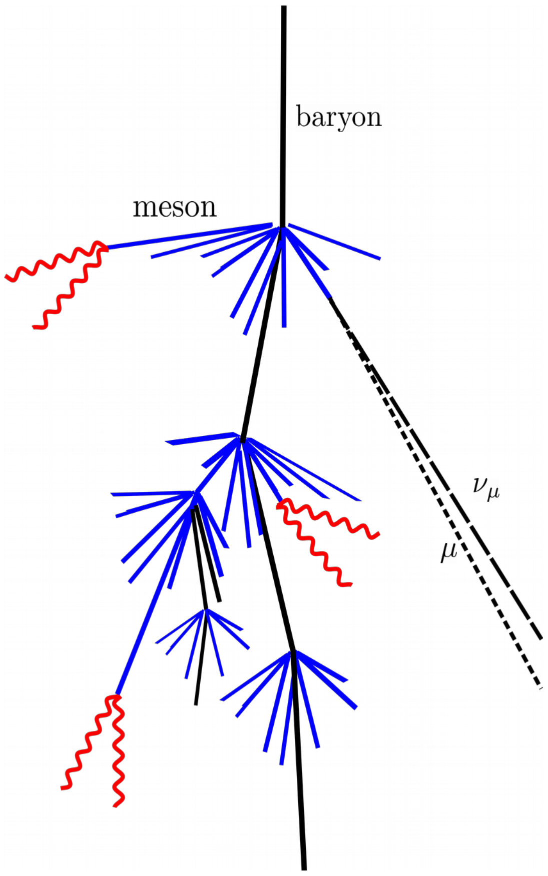
Increase mesons → increase muons

High energy, prompt decay

$$\mathrm{D} \to \mu + \nu_\mu$$

Any type of meson?

$$\pi^0 \to \gamma + \gamma$$

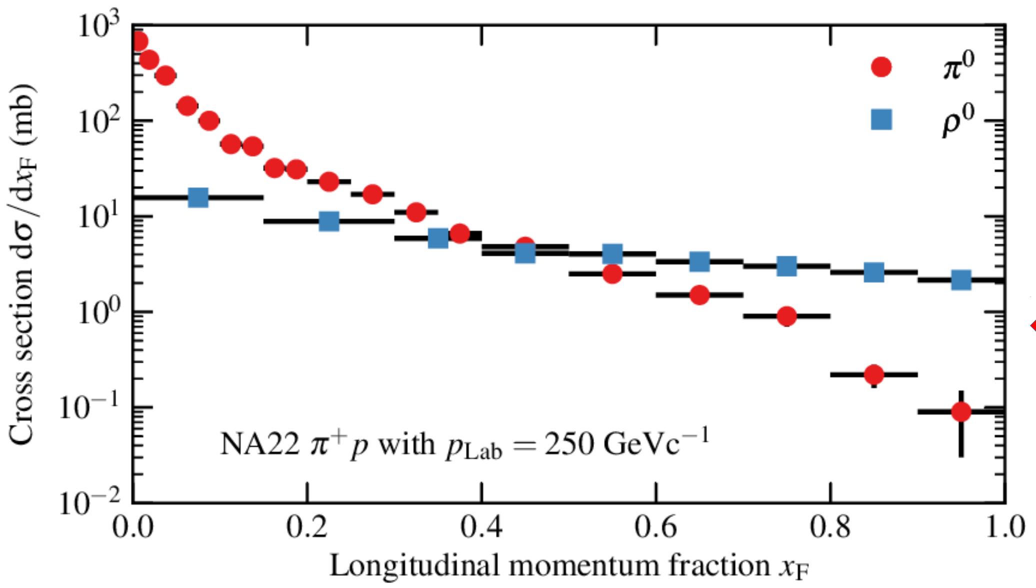


Leading particles !

$$\pi^\pm + \mathrm{Air} \to \rho^0 \to \pi^+\pi^-$$

$$\pi^\pm + \mathrm{Air} \to \pi^0 \to \gamma\gamma$$

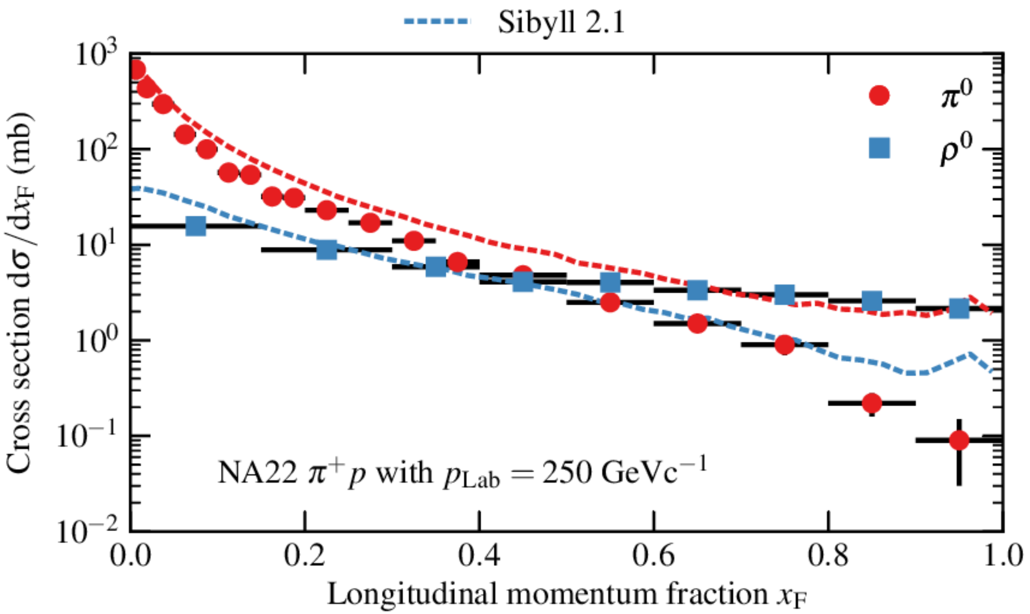
In data ?



$$\pi + \mathrm{p} \to \pi^0 , \rho^0$$

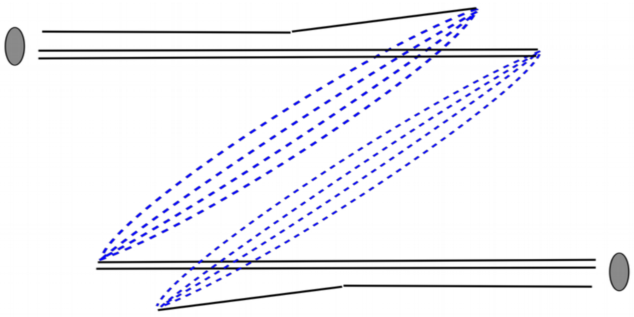
ρ^0 favored

Data & model

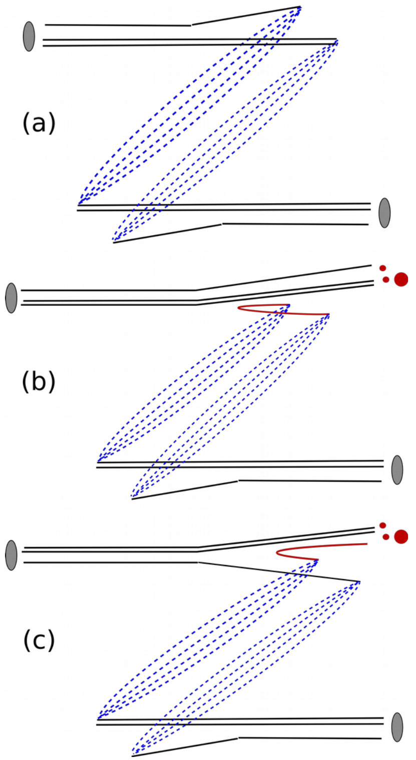


$$P_{\pi^0 \to \rho^0} = \mathrm{const}$$

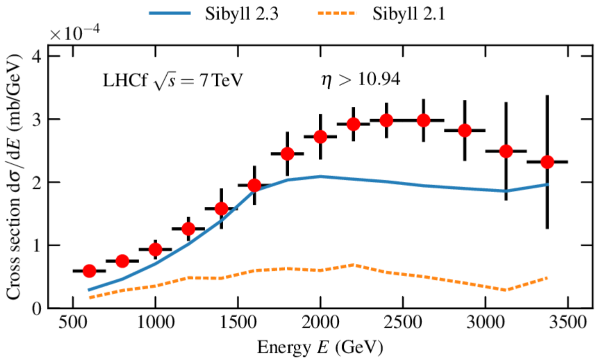
$$\pi + \mathrm{p} \to \pi^0 , \rho^0$$

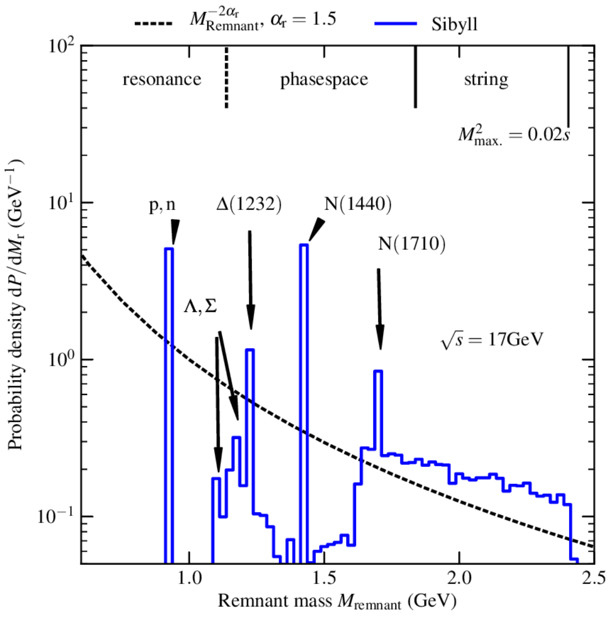


Leading particles, refined



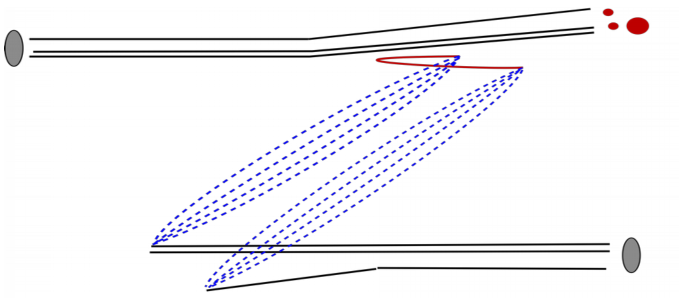
Remnant formation
Common in Pythia, Epos, QGSjet

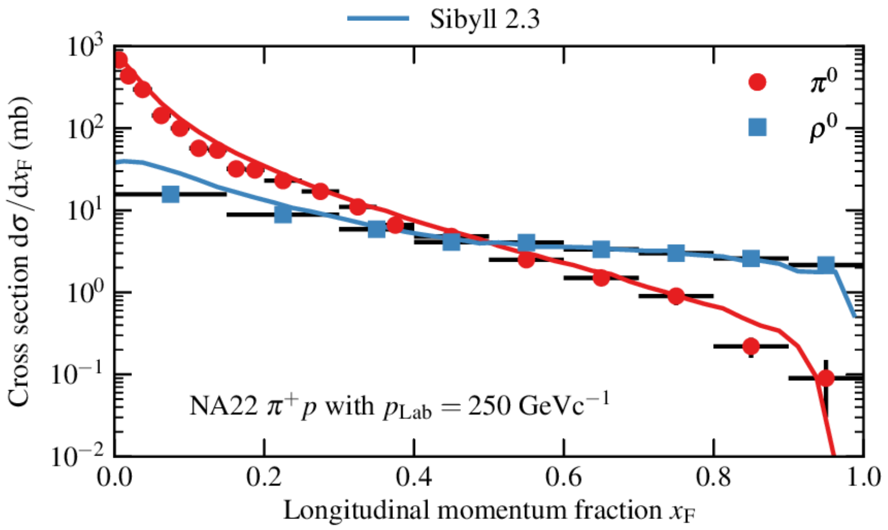




$$\pi^{\pm} + \mathrm{Air} \to \rho^0 + \mathrm{X}$$

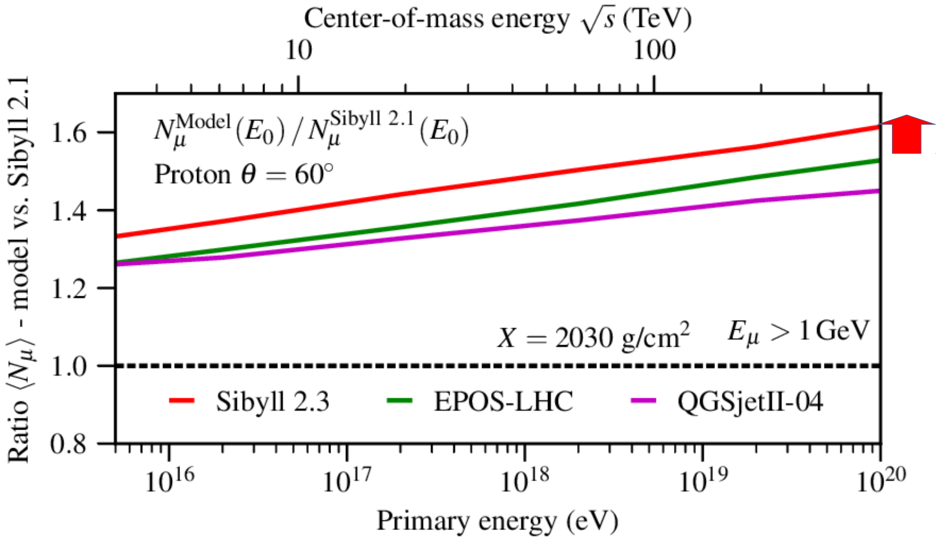
Effect on data

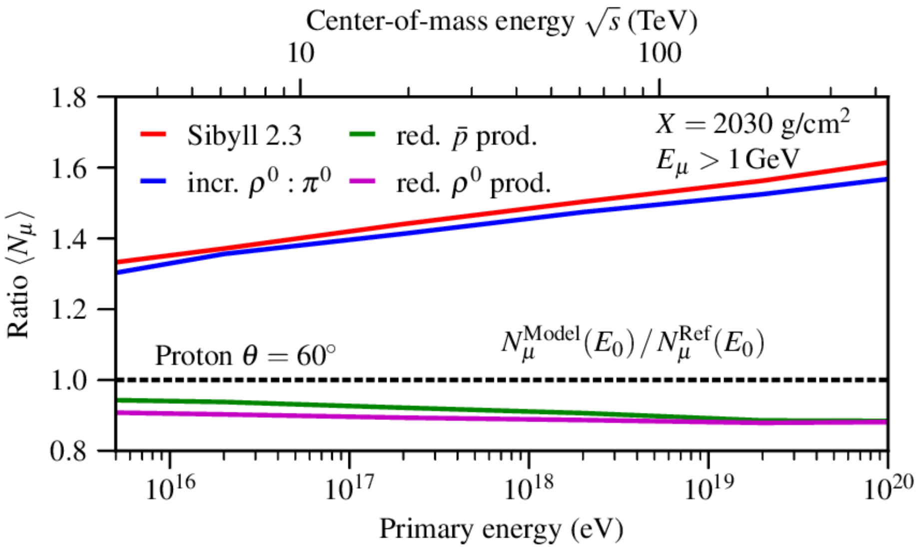




$$P_{\pi^0 \to \rho^0} = f(x_F)$$

Muon prediction for EAS





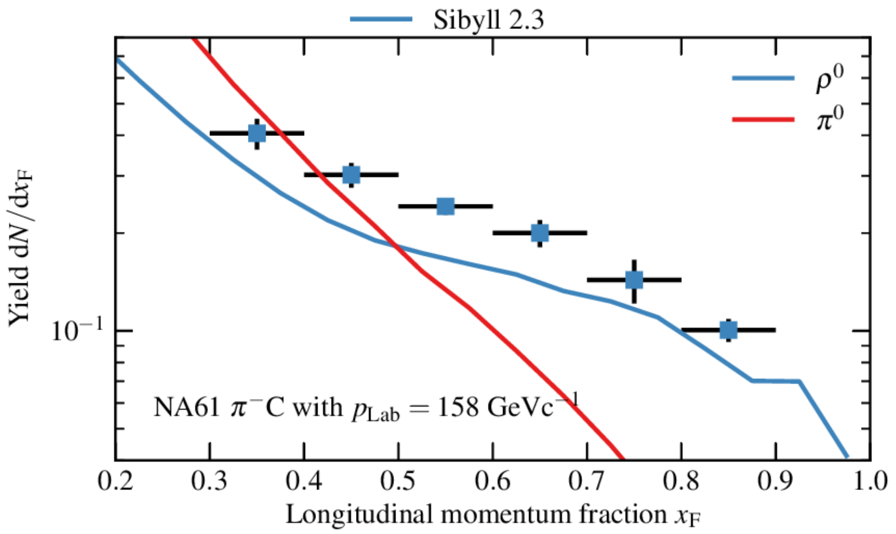
40% - 60% more muons relative to Sibyll 2.1

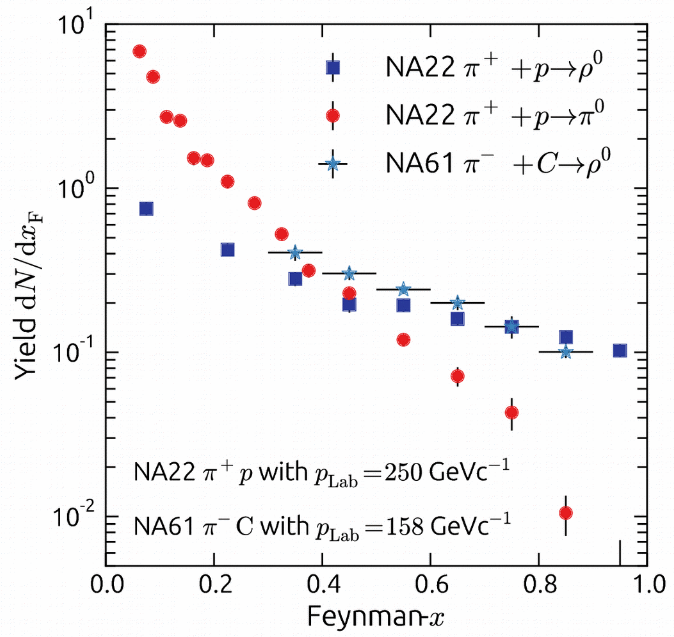
Epos-LHC : 1.33

QGSjetII-04 : 1.61

What about pion-Nuclear ?

NA61 pi-Carbon

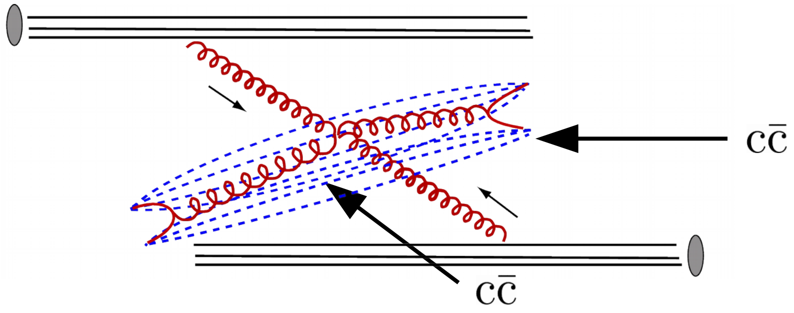




No measurement of neutral pion

Charm production

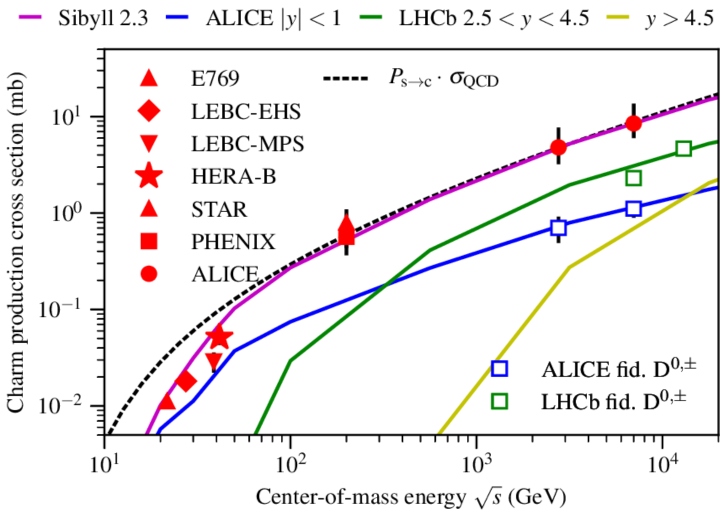
Charm model

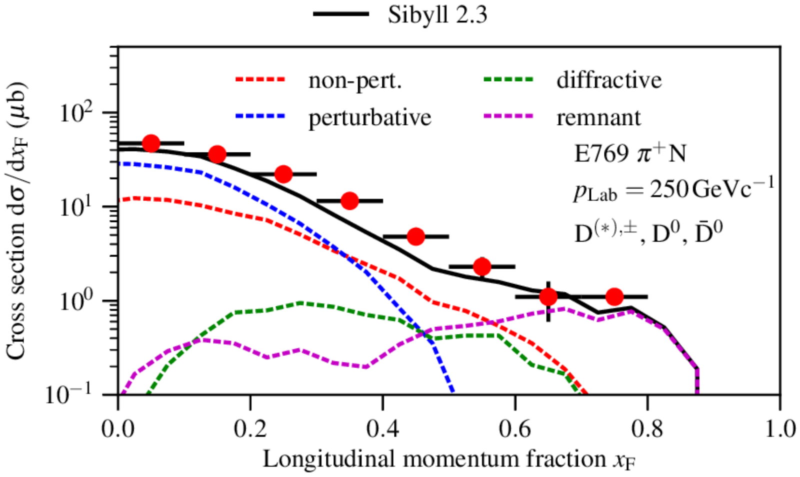


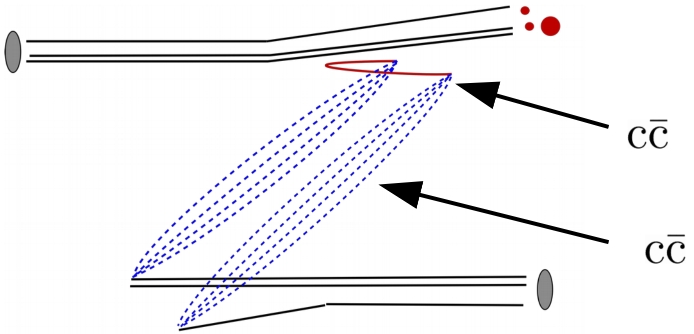
High energy: pQCD

$gg \to c\bar{c}$

$P_{s \to c}$

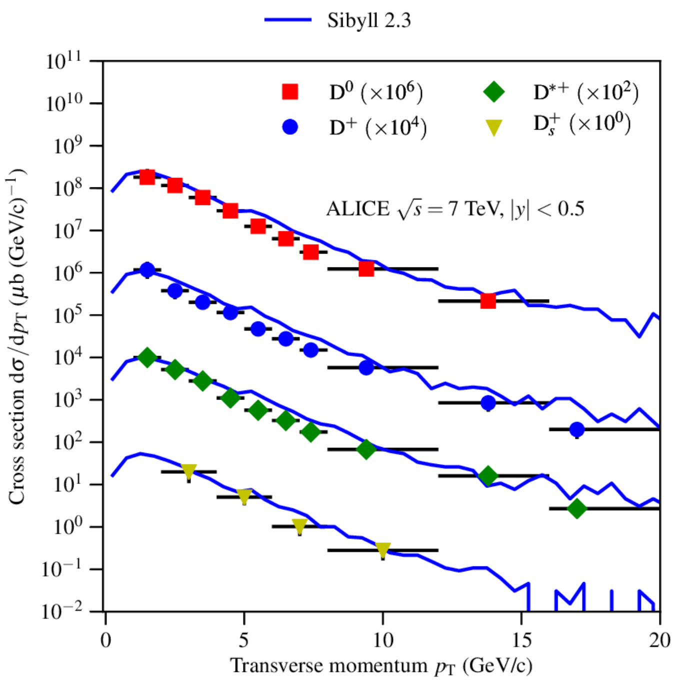


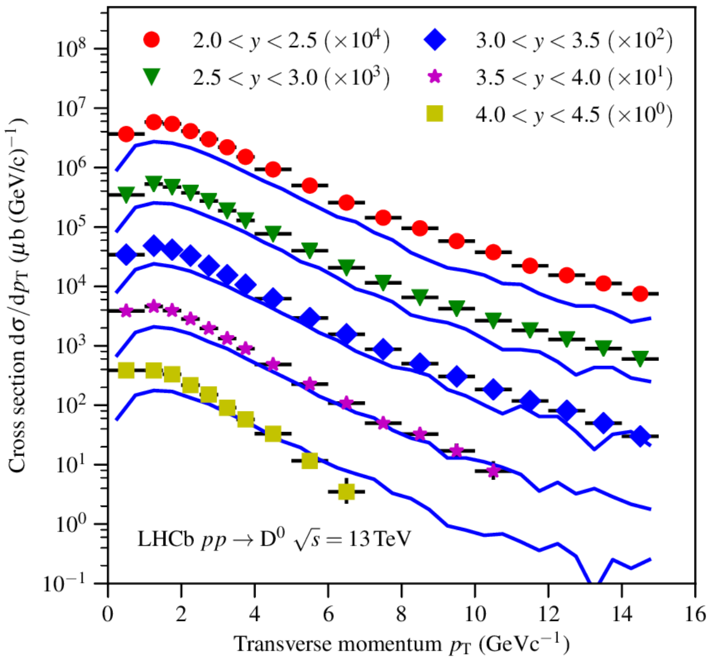




Comparing to data

Central phase space, 7TeV

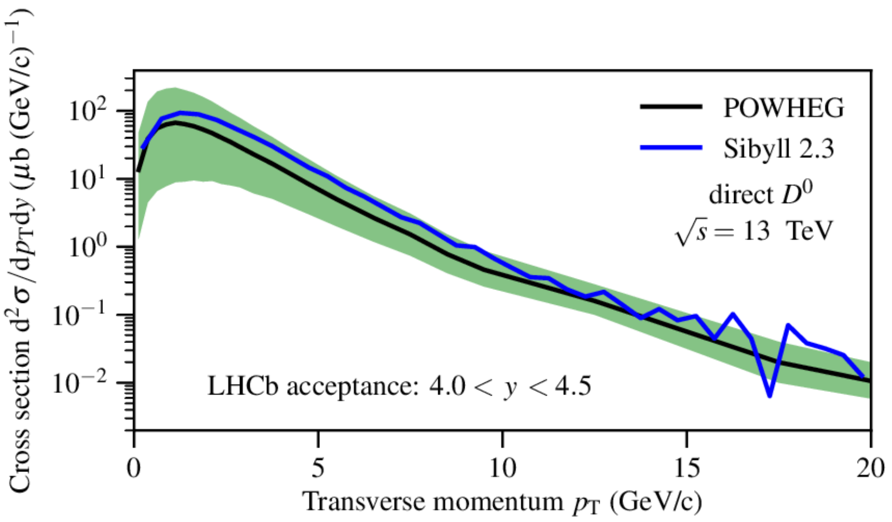




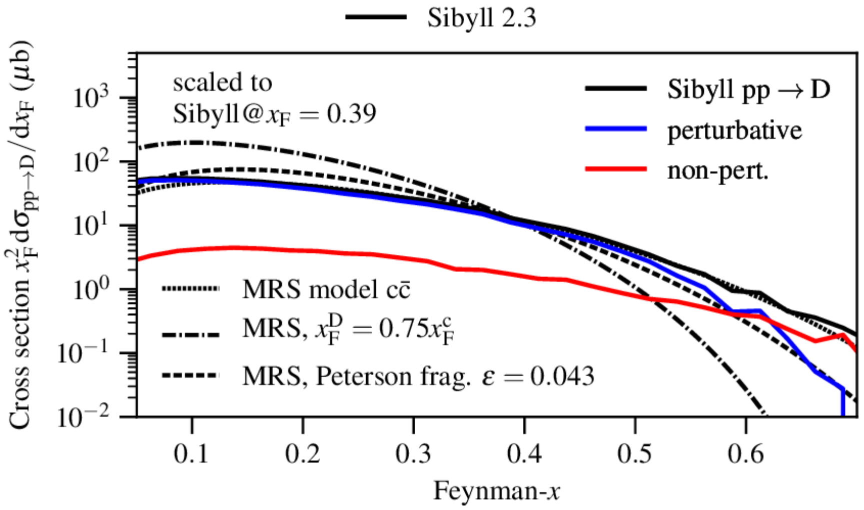
13 TeV data: model limited

Comparing 2: calculations

Central phase space



Full long. Phase space



Conclusion

New version of Sibyll 2.3 extended with

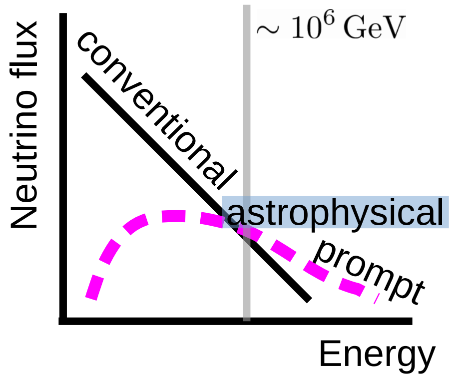
- charm production
- remnant formation
- baryon production model
- new cross section fit
- updated PDFs

Increased compatibility with EAS measurements

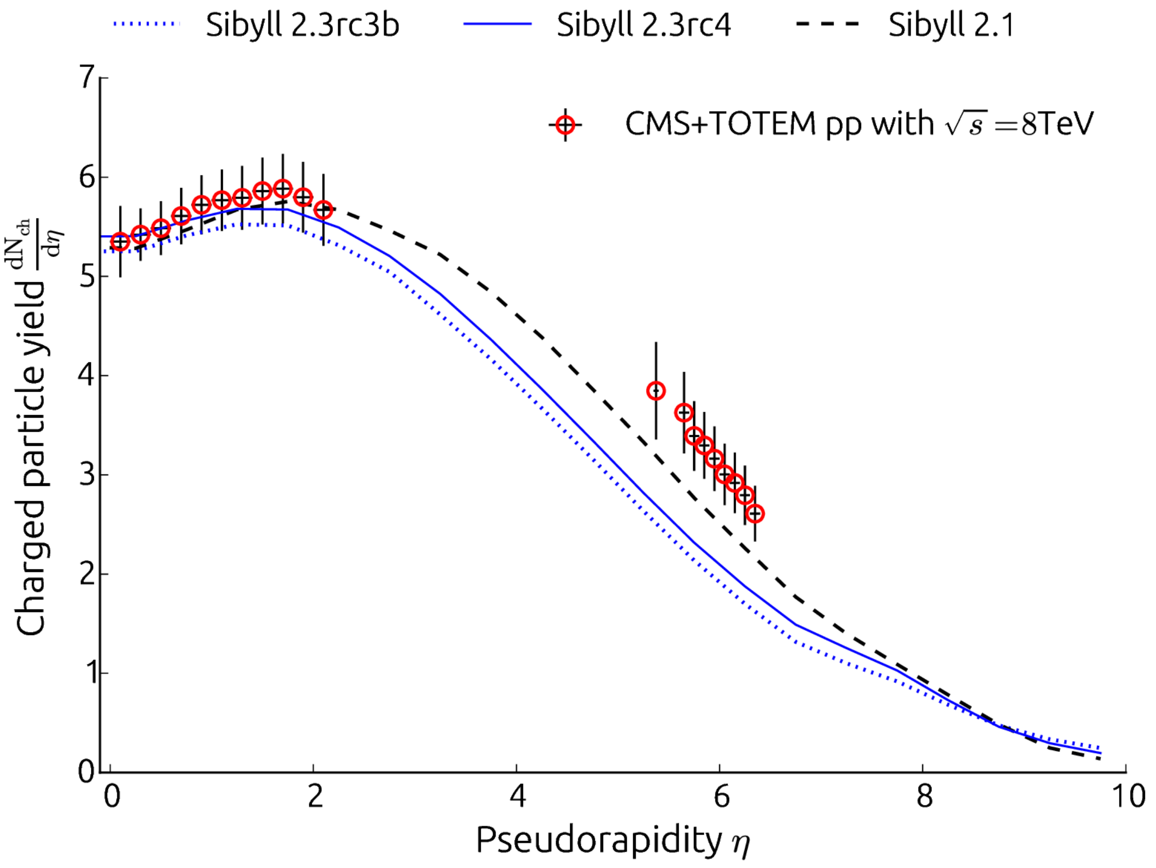
Allows calculation of atmospheric fluxes up to highest energies (IceCube)

But also:

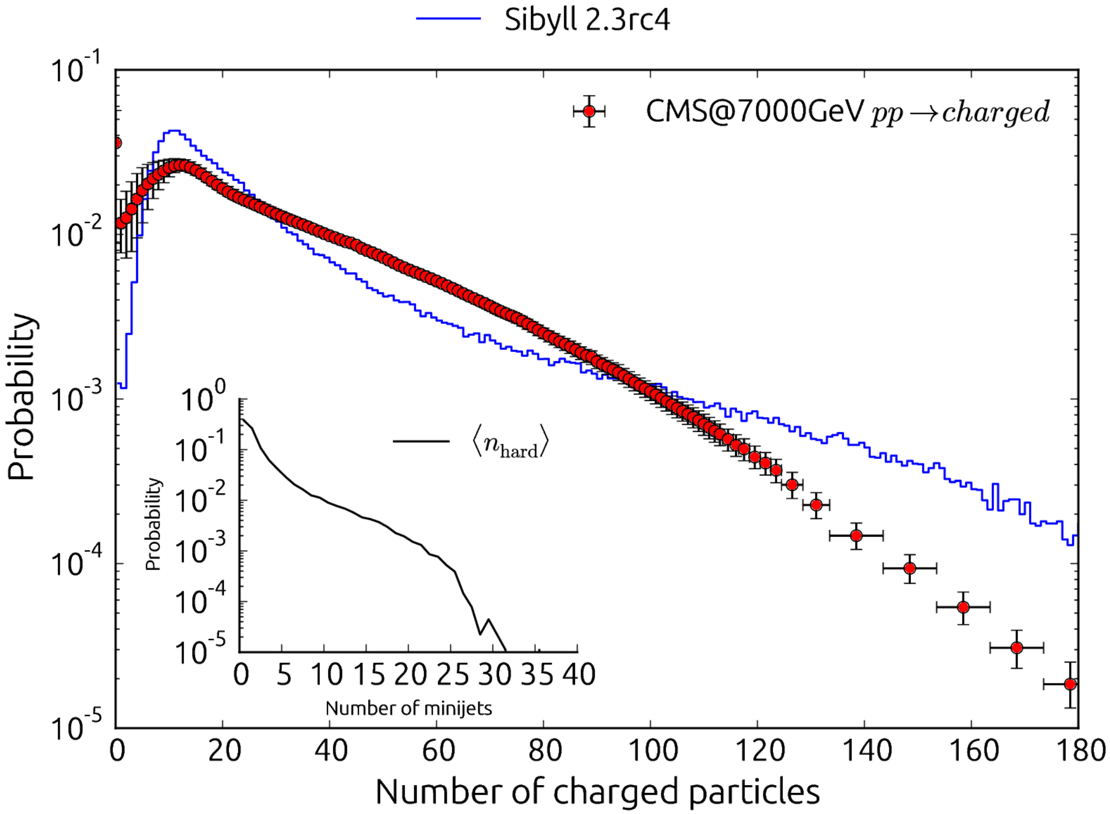
Simplified minijet model is at limit



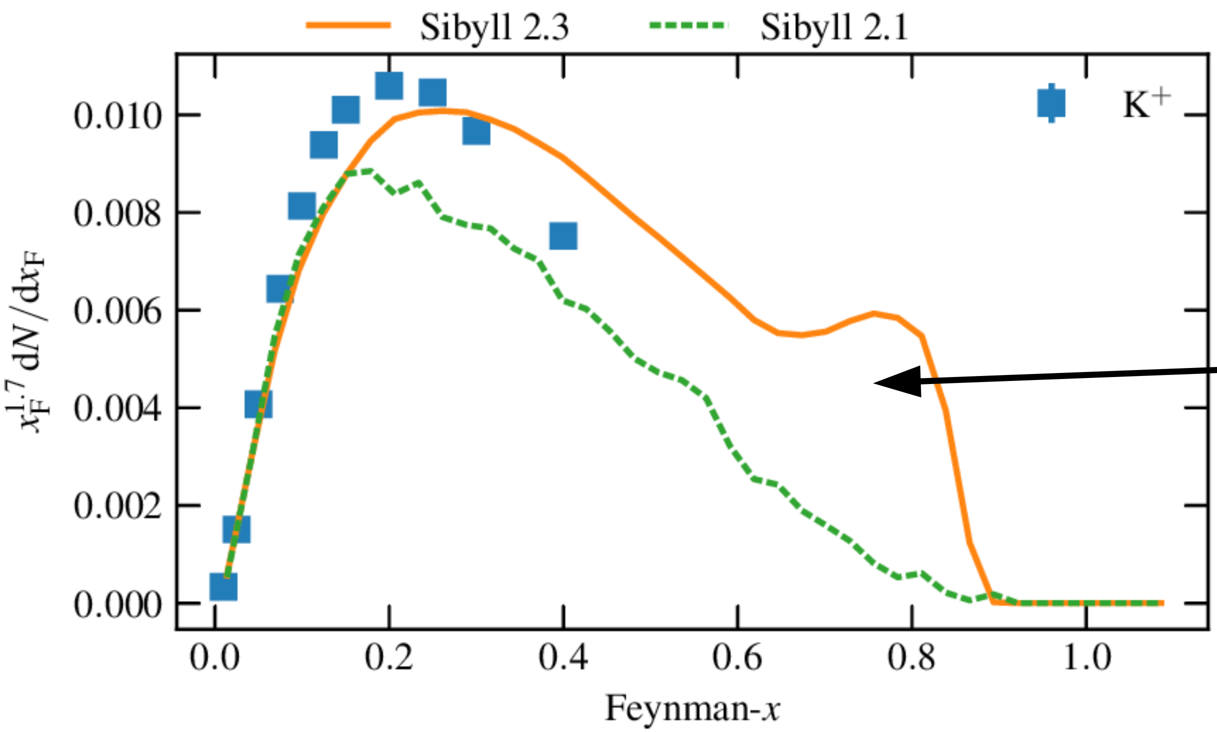
Problems: MPI & minijets



Problems: MPI

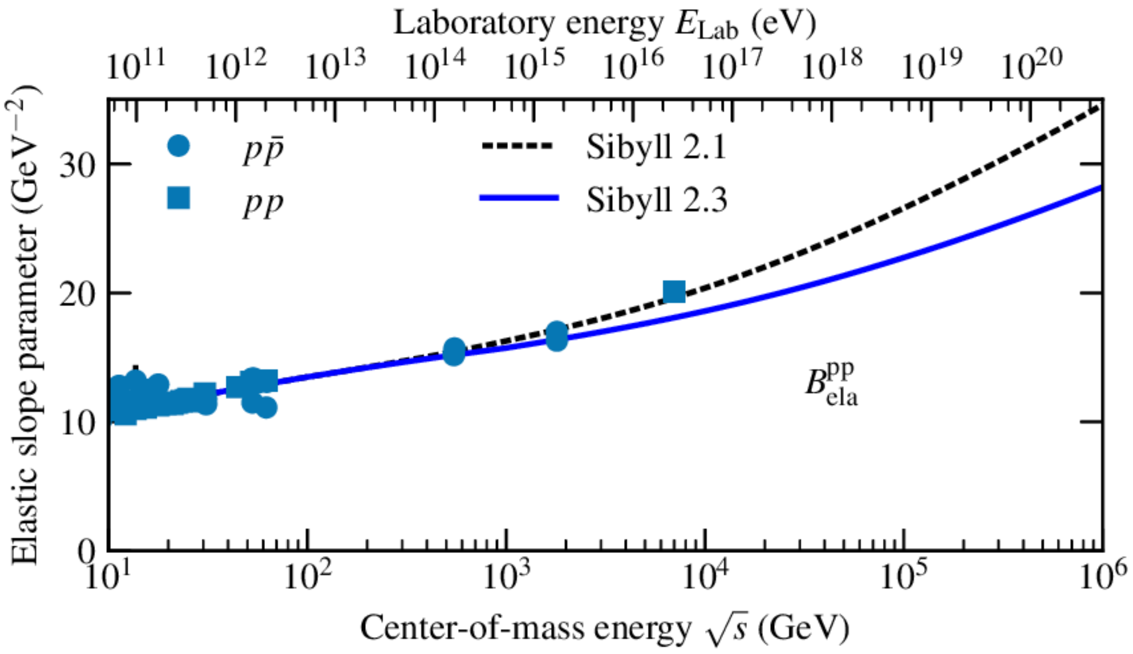


Leading kaons



?!

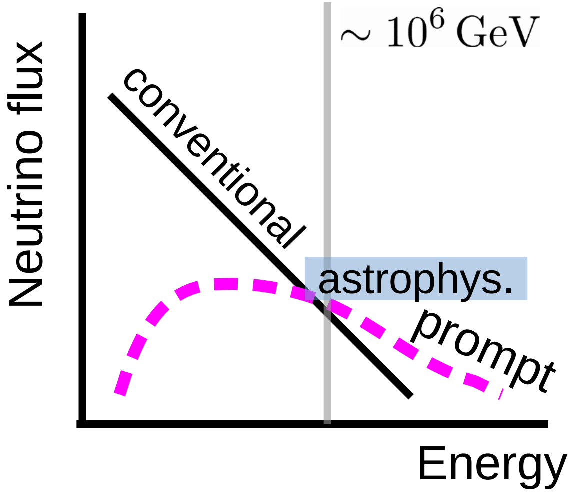
Problem: cross section



Artifact of changing profile width

$$1/B_{\mathrm{ela}} \sim R_{\mathrm{p}}$$

Can be reconciled by using latest PDFs CT14 which decrease cross section


$\sim 10^6\ \mathrm{GeV}$
Neutrino flux
conventional
astrophys.
prompt
Energy