UHE hadronic interactions in SIBYLL

C8 workshop 2022

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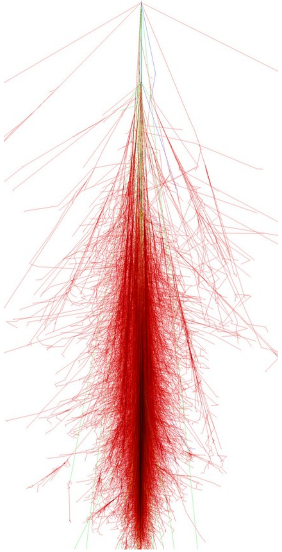
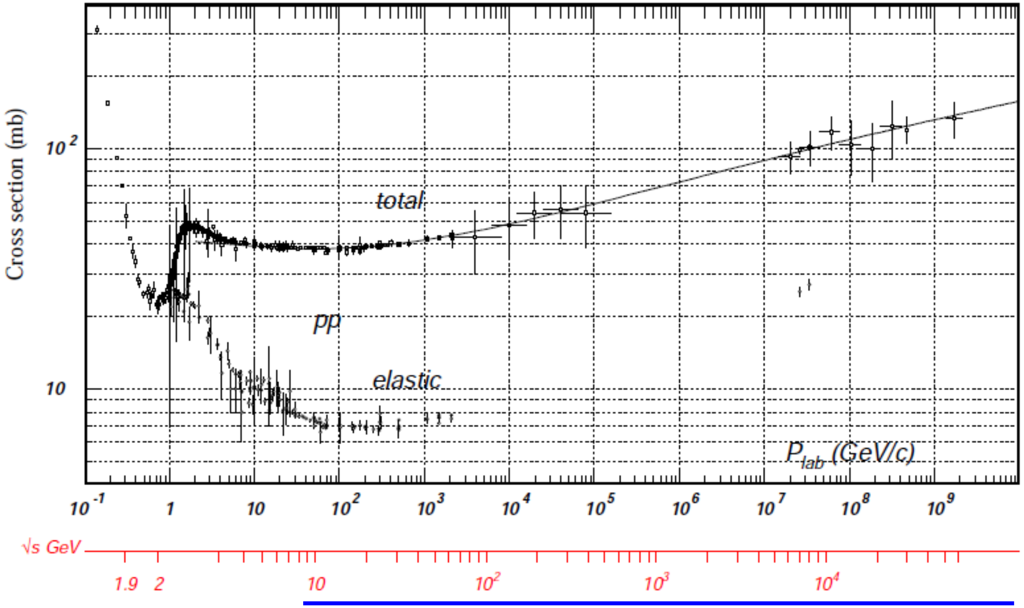
14. 07. 2022

Hadron interactions in SIBYLL



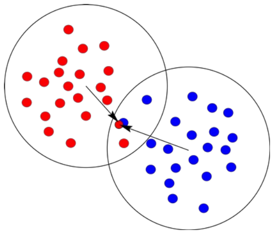


Model for
pion, kaon and proton interactions with nuclei
from 10 GeV to 10^6 GeV CoM energy

(PRD 80 (2009) 094003,
PRD 100 (2019) 10, 103018,
PRD 102 (2020) 6, 063002)

SIBYLL 101: h-h

Hard scattering:



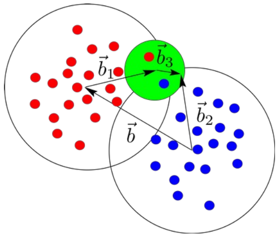
$$\sigma_{\mathrm{QCD}}(s, p_{\mathrm{T}}^{\mathrm{min}}) = K \int_{p_{\mathrm{T}}^{\mathrm{min}}}^{\infty} \mathrm{d}p_T \int \mathrm{d}x_1 \int \mathrm{d}x_2 \sum_{i,j,k,l} f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{\mathrm{d}\hat{\sigma}^{i,j\to k,l}}{\mathrm{d}p_{\mathrm{T}}}(\hat{s}, \hat{t})$$

Geom. Saturation: $\pi r_0^2 \approx \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot x g(x, Q_s^2)$

Definition of hard energy dependent: $p_{\mathrm{T}}^{\mathrm{min}}(s) = p_{\mathrm{T},0} + 0.065\,\mathrm{GeV}\ \exp\left(0.9\sqrt{\ln(s/\mathrm{GeV}^2)}\right)$

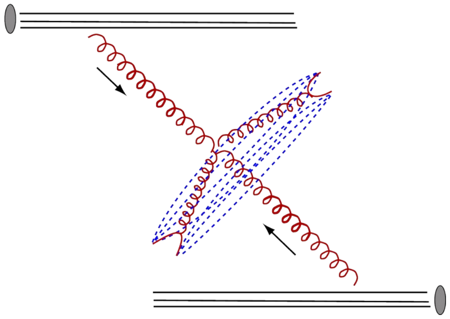
$$n(s, \vec{b}) \;=\; A(s, \vec{b})\sigma(s)$$

Soft scattering:

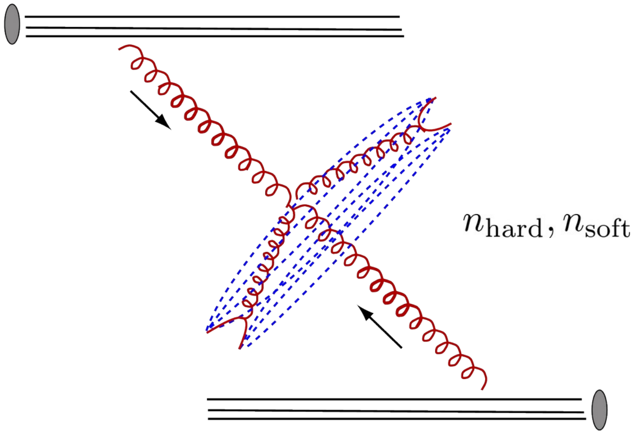


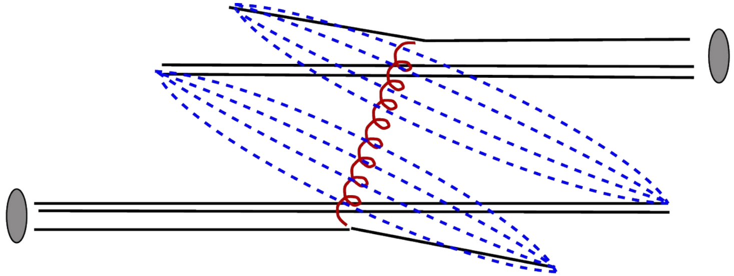
$$\sigma_{\mathrm{soft}}(s) \;=\; \mathcal{A}\left(\frac{s}{s_0}\right)^{-\epsilon} + \mathcal{B}\left(\frac{s}{s_0}\right)^{\Delta}$$

(Donnachie, Landshoff)

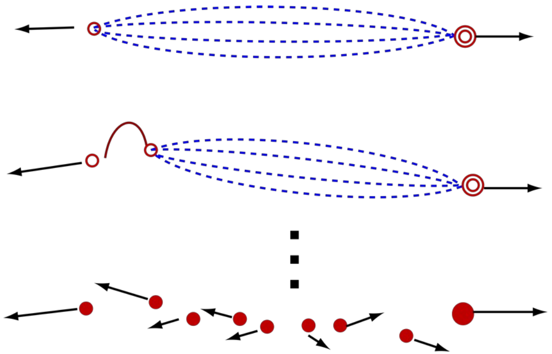


SIBYLL 102



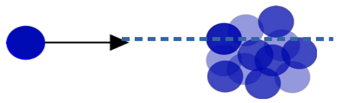


Lund string fragmentation



Nuclear interaction

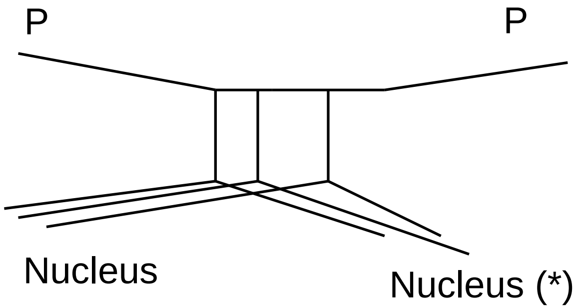
How many nucleons interacting?



$$\Gamma_{hA}(\vec{b}) \;=\; 1 - \prod_{j=1}^{A}\left[\int \Gamma_{hN}(\vec{b}-\vec{s}_j)\rho_j(\vec{r}_j)\mathrm{d}^3\vec{r}_j\right]$$

(Glauber 1970)

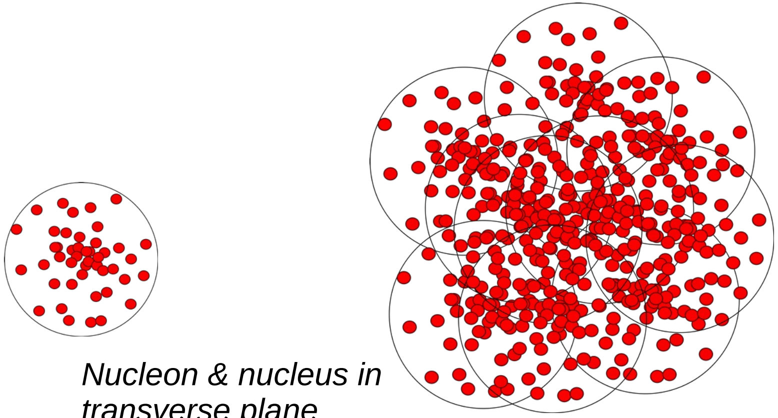
Nucleon density inside nucleus
SIBYLL: A=4-18



$$\sigma_{hA}^{\mathrm{ela}} \;=\; \int \left|\Gamma_{hA}(\vec{b})\right|^2 \mathrm{d}^2\vec{b}$$

In SIBYLL nucleon interactions are *independent* of impact parameter!

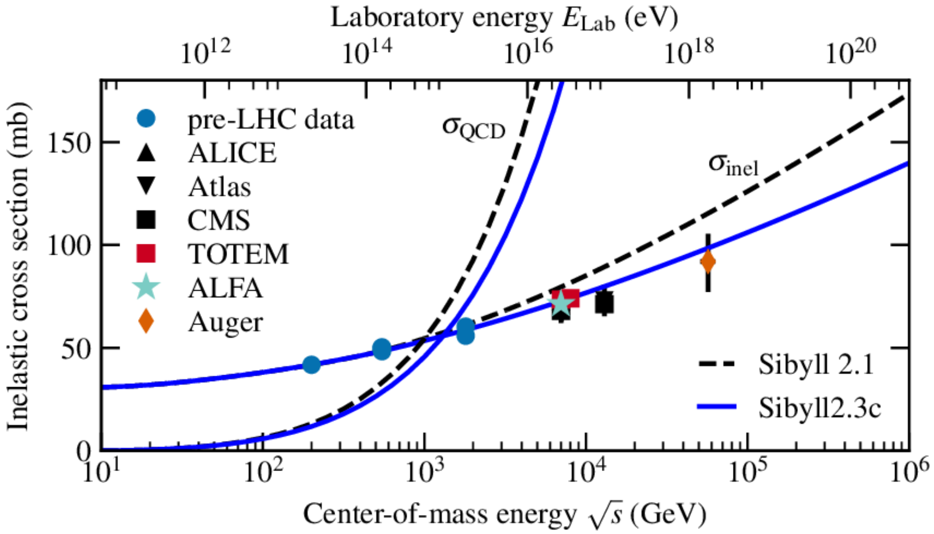
→ pO@LHC will challenge experimentally!

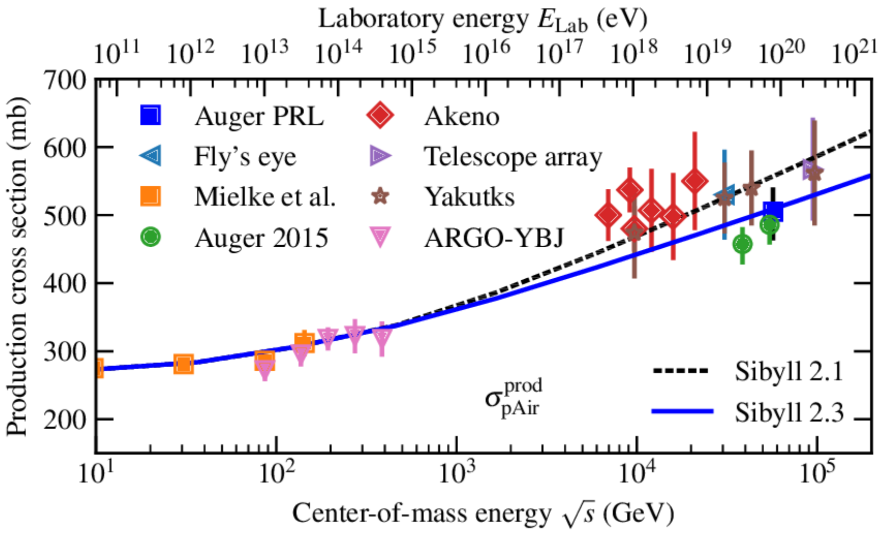


Nucleon & nucleus in transverse plane

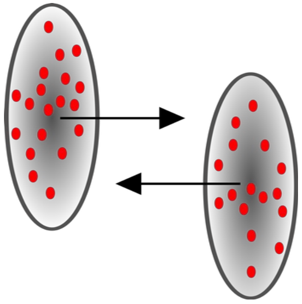
New in Sibyll 2.3

Cross section: p-p



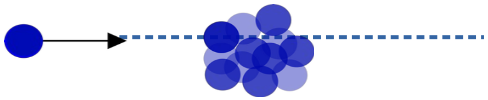


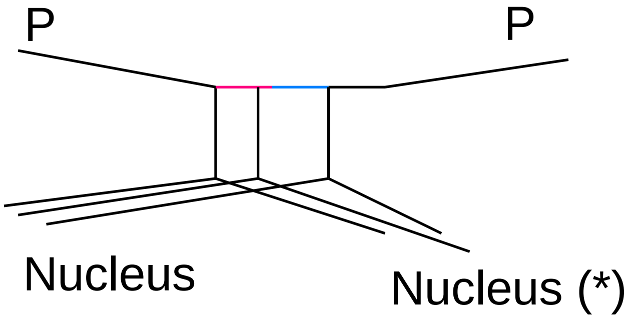
Sibyll 2.1 from 2001 (Tevatron)



Sibyll 2.3:
- narrower hadron profile
- increase soft-hard threshold

h-A: Inelastic screening





Allow inelastic intermediate states
→ 2-channel approx: p, p* with coupling $\lambda(s)$

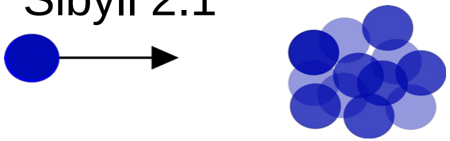
$$\sigma_{hA}^{\mathrm{ela}} = \int \left|\Gamma_{hA}(\vec{b})\right|^2 \mathrm{d}^2\vec{b} \to \int \left|\langle p|\hat{\Gamma}_{hA}^{(2x2)}(\vec{b})|p\rangle\right|^2 \mathrm{d}^2\vec{b}$$

$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{ela}} - \sigma_{\mathrm{q.ela}}$$

→ reduced production cross section

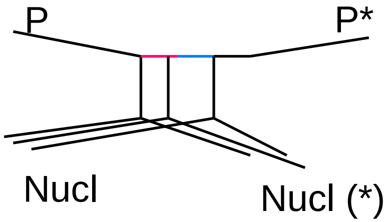
h-A: coherent & incoherent diffraction

Sibyll 2.1



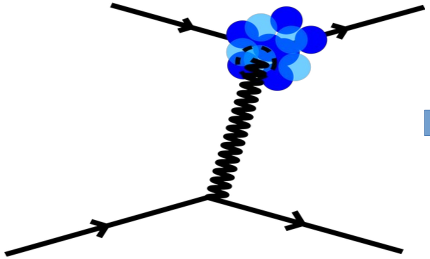
N_w Independent hadron-nucleon interactions (“incoherent”)

$$\sigma_{\text{diff}}^{pA} = (\sigma_{\text{diff}}^{pp})^{N_w}$$

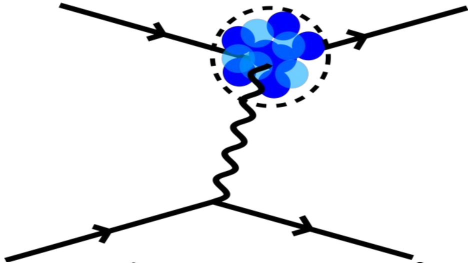


Sibyll 2.3

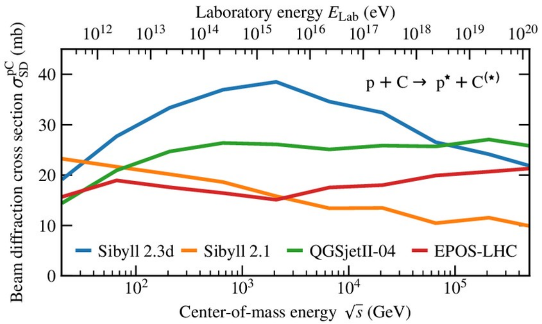
incoherent



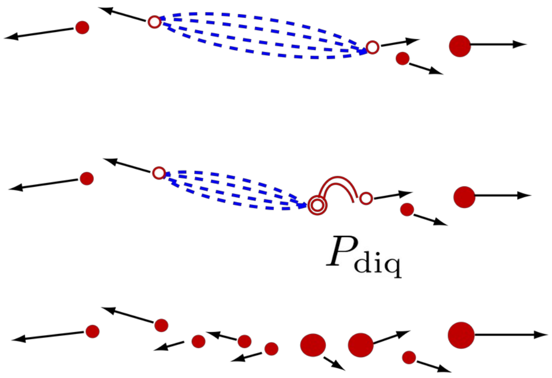
coherent

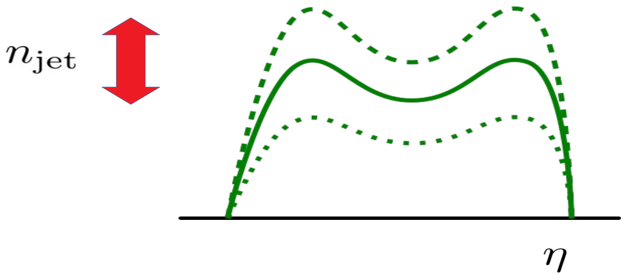


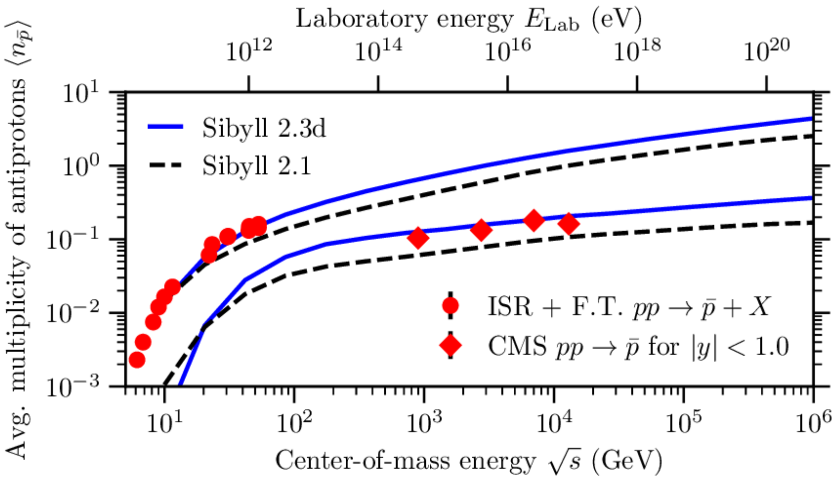
$$\sigma_{hA}^{\text{dif}} = \int \left| \langle p^* | \hat{\Gamma}_{hA}^{(2x2)}(\vec{b}) | p \rangle \right|^2 \mathrm{d}^2\vec{b}$$

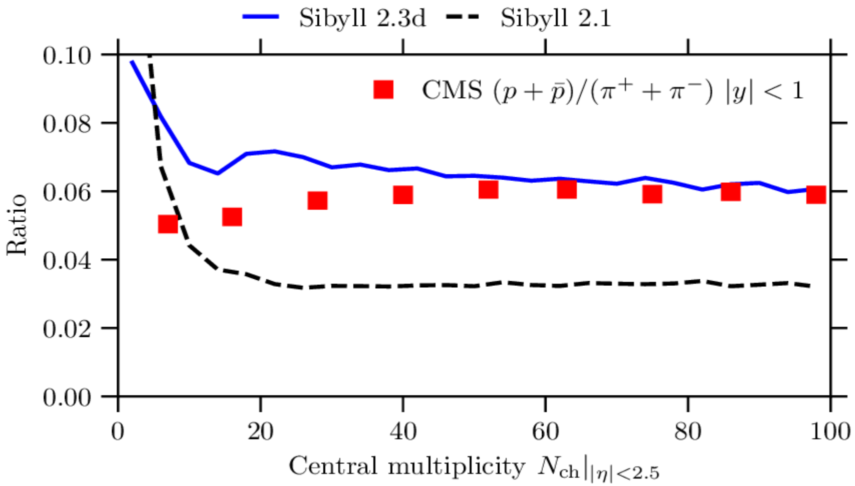


Baryon production



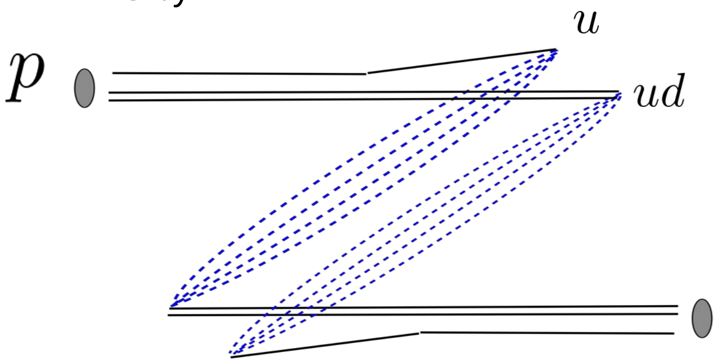






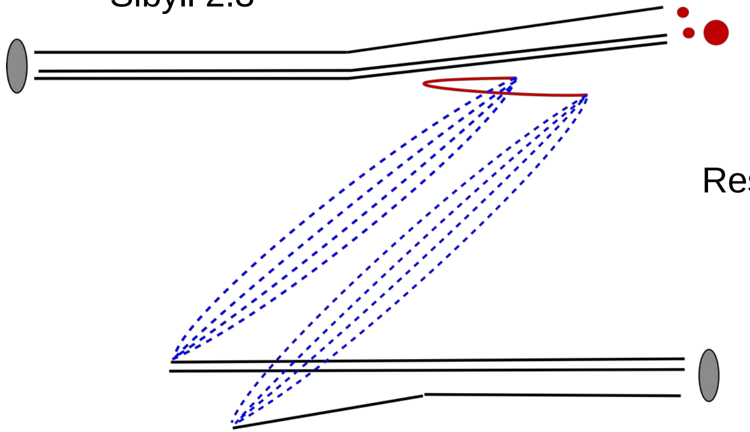
Remnants

Sibyll 2.1



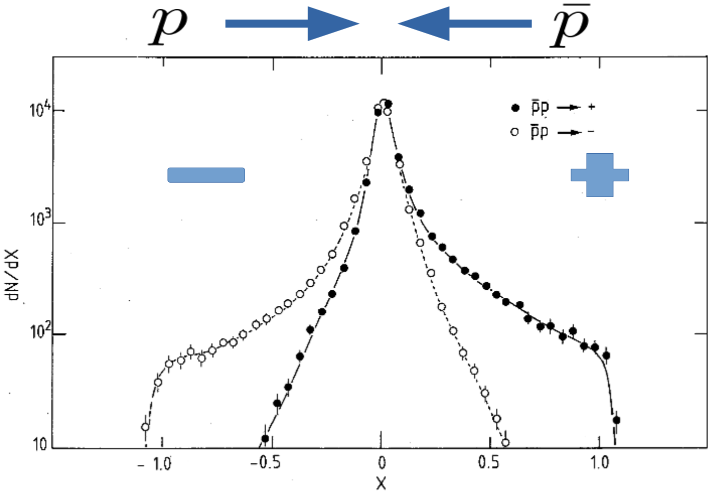
continuum

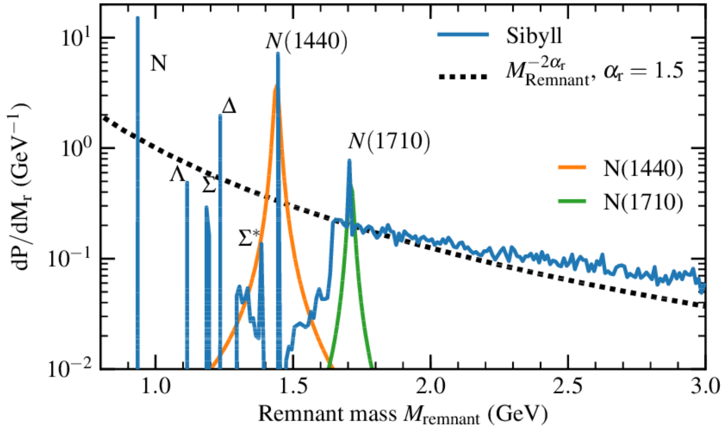
Sibyll 2.3



Resonances
+ continuum

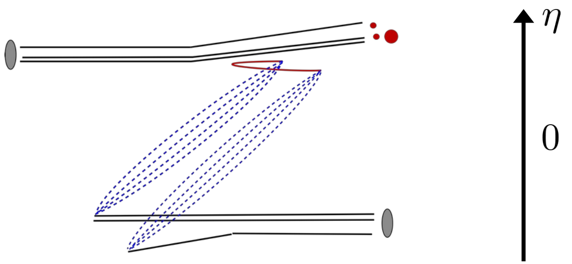
Breakstone et al. (Phys.Lett. B132 (1983) 458)

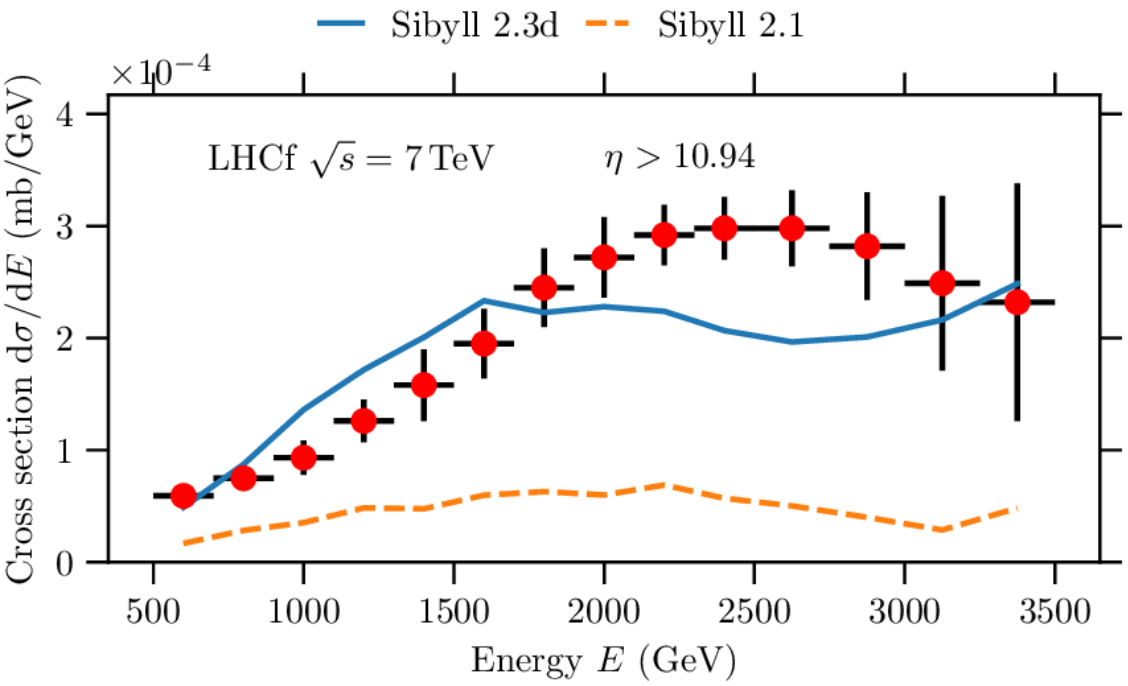




LHCf

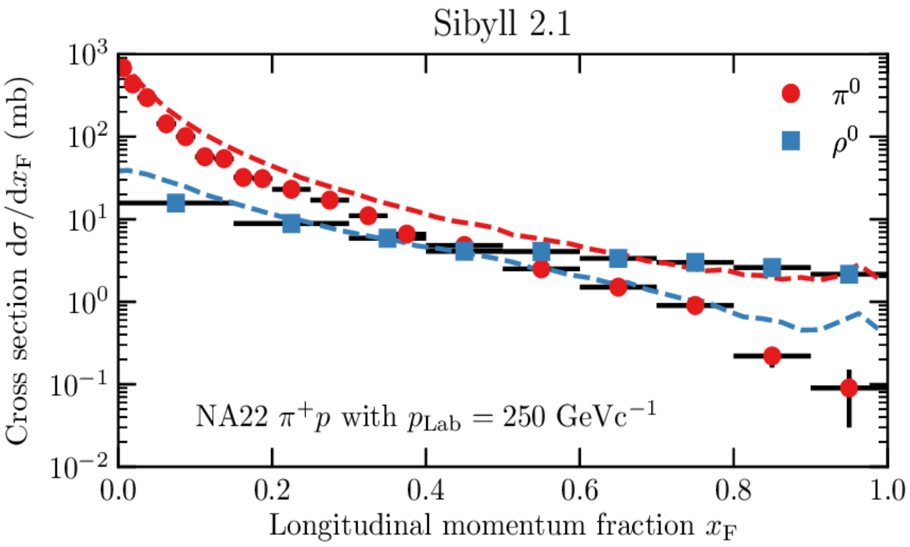
(LHCf Adriani et al 2015)

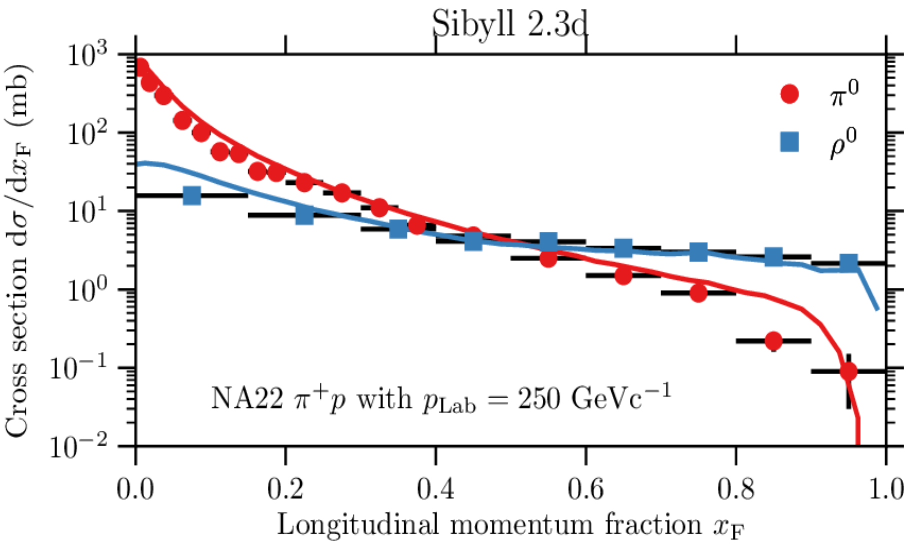




Leading rho0

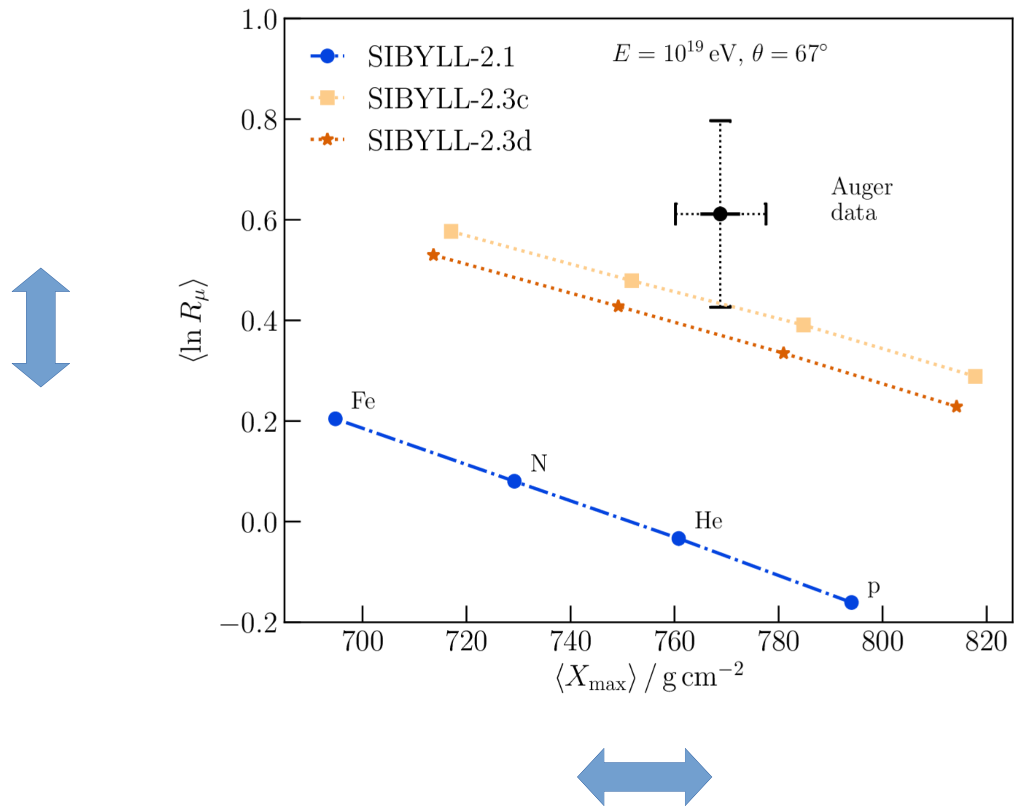
$\pi^+ + p \;\rightarrow\; \text{leading} + X$ $\text{leading} : \pi,\;\rho$





$$P_{\pi:\rho} = 1/3$$

Muon puzzle & SIBYLL

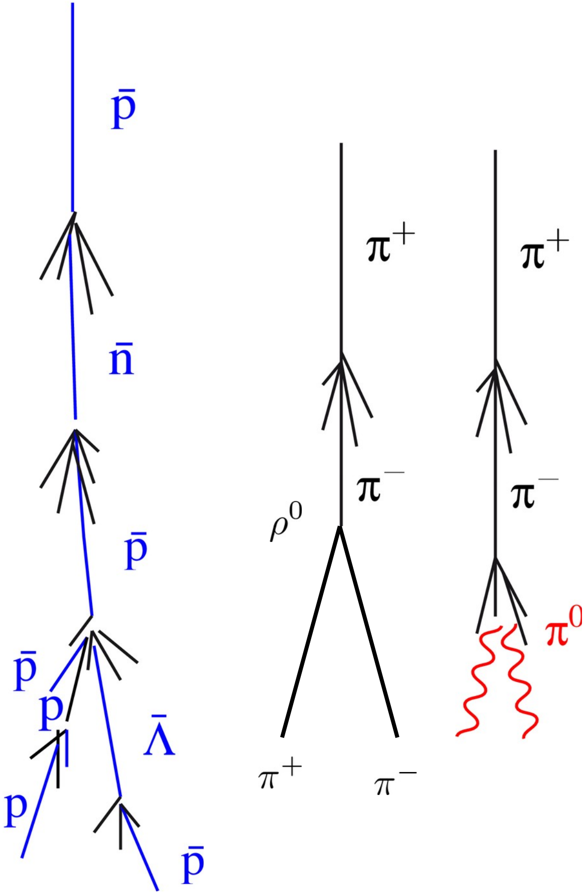


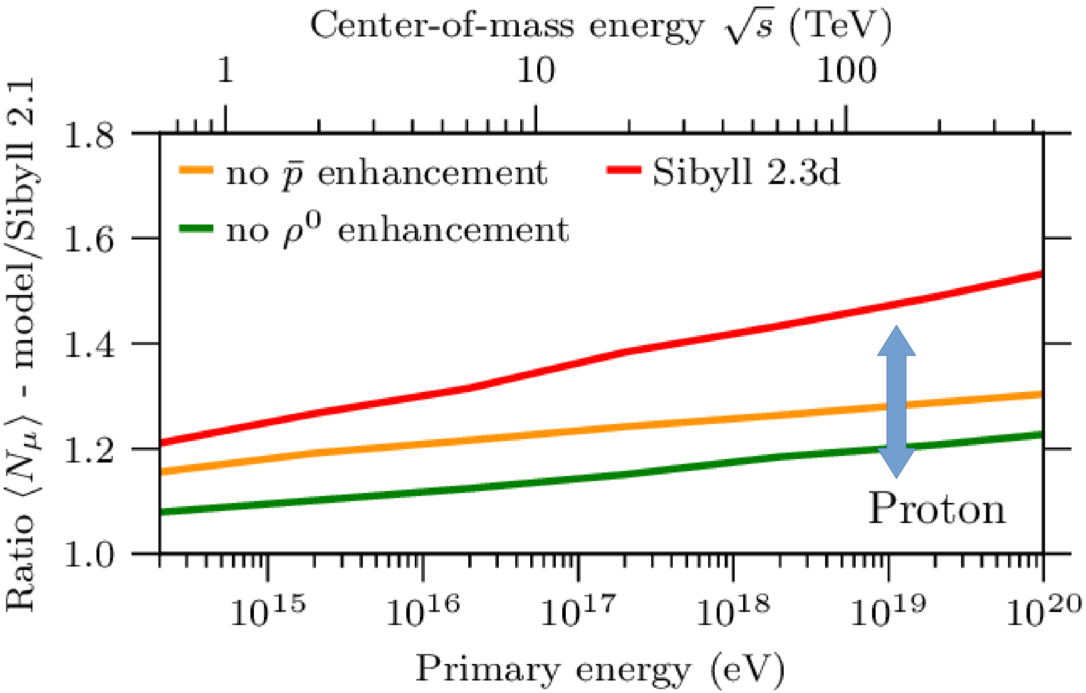
(Pierre Auger Collab.
PRL 126, 152002 (2021))

Transition
2.1 → 2.3d

“Xmax- and muon-based observables of extensive air showers when compared with simulations give inconsistent interpretations for the cosmic ray mass”

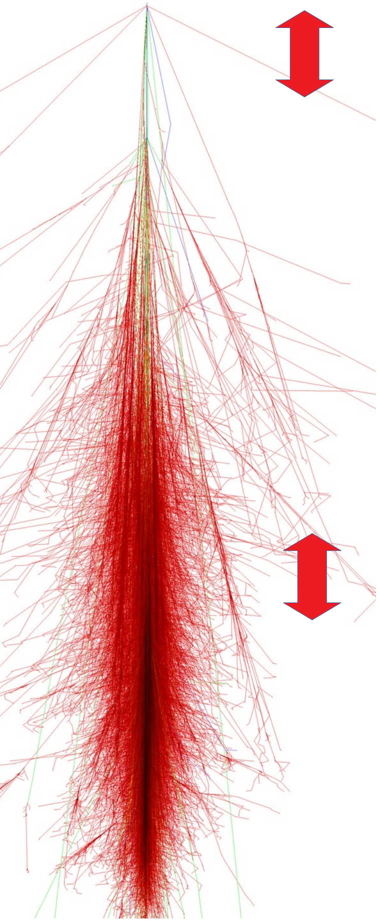
Muons in Sibyll 2.3d





~40% increase

Xmax in Sibyll 2.3d

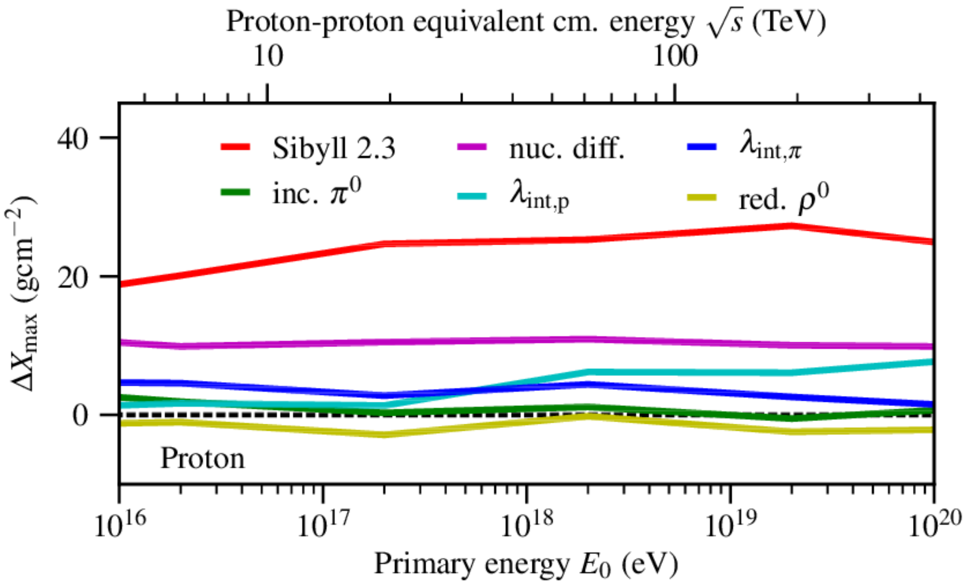


* p-p cross section reduced

* p-air cross section reduced

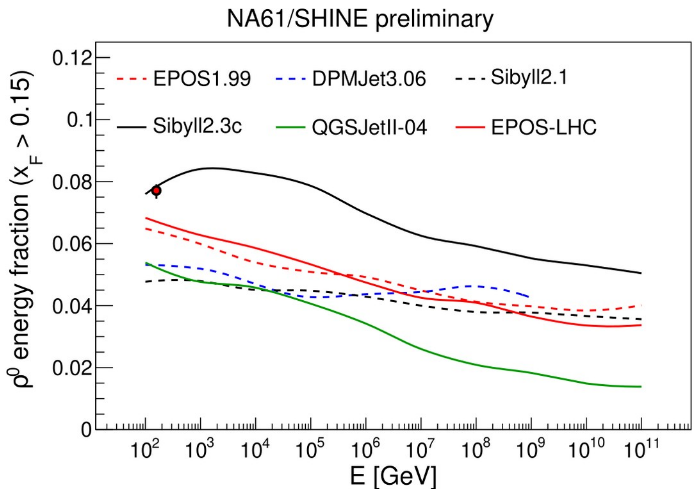
* p-air diffraction increased
  (coherent diffraction)

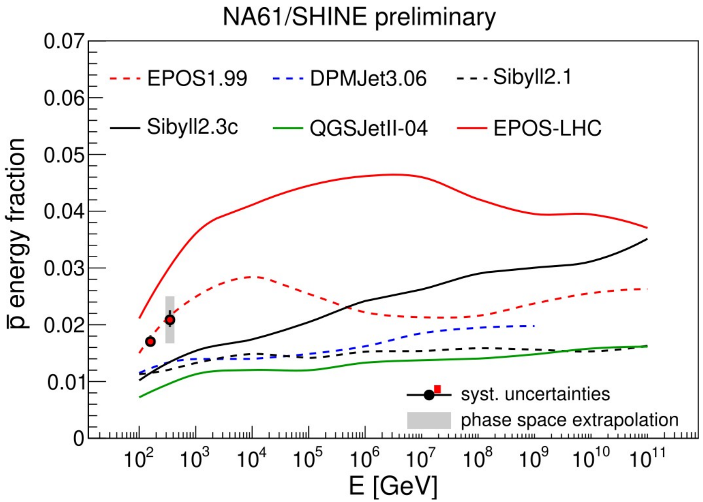
→ 20 g/cm² deeper proton showers



Energy in rho0 and baryons

$\pi^- + \mathrm{C} \to X$



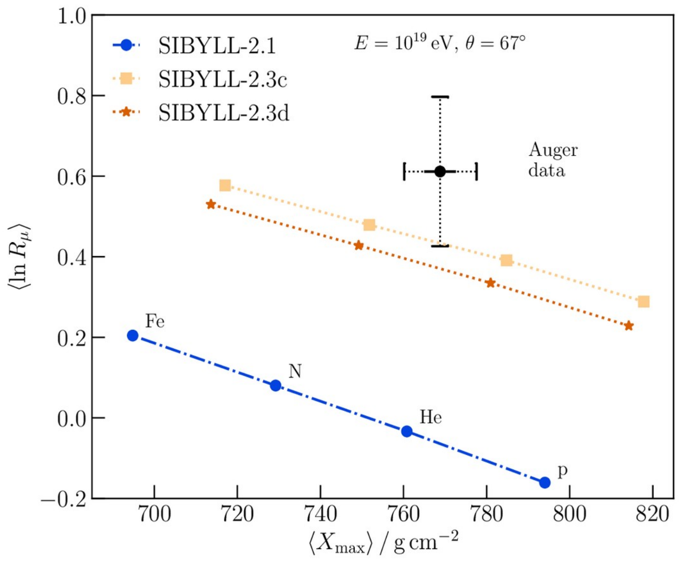


* some fine-tuning left
* new HE data from pO ?

Summary

* SIBYLL
  - minijet based model
  - Lund string fragmentation
  - Glauber for nuclei

* version 2.3d
  - enhanced baryon production
  - beam remnants, leading rho0
  - "post-LHC-RUN-1" model

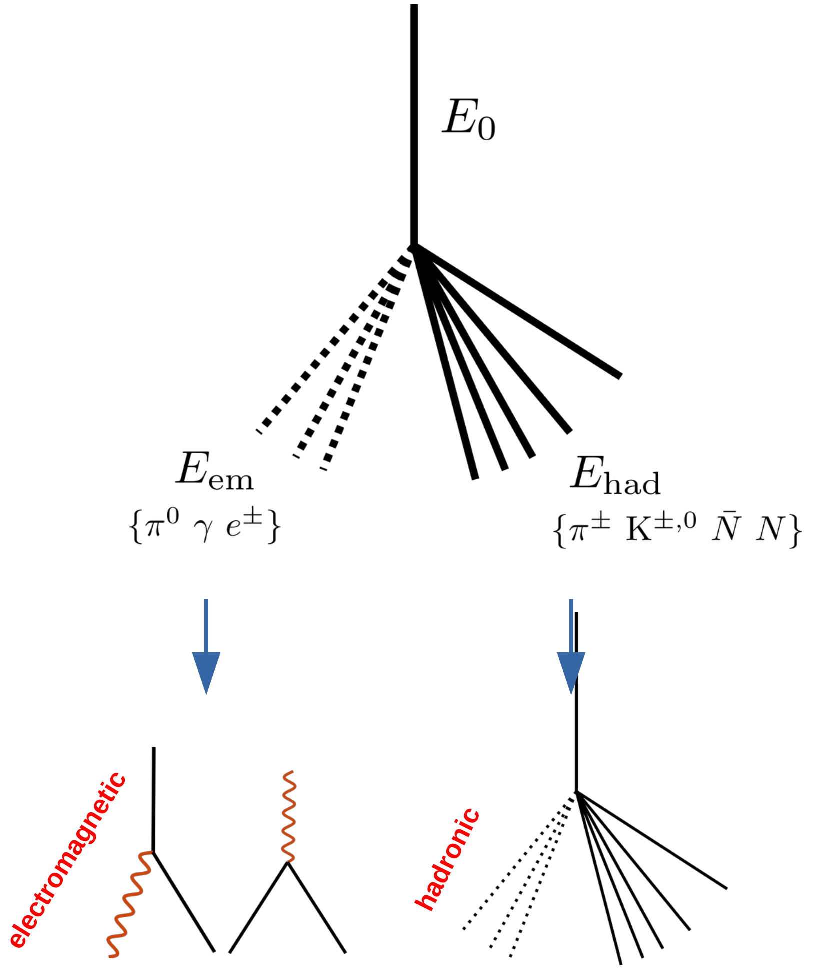


* description of LHCf/NA61 data could still improve
* expect to be challenged by pO@LHC

What next? (for muon puzzle?) (for SIBYLL?)

What matters for muons in EAS

1st interaction

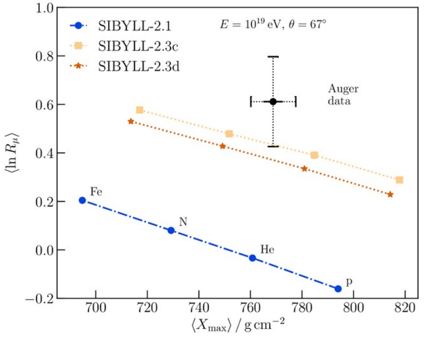


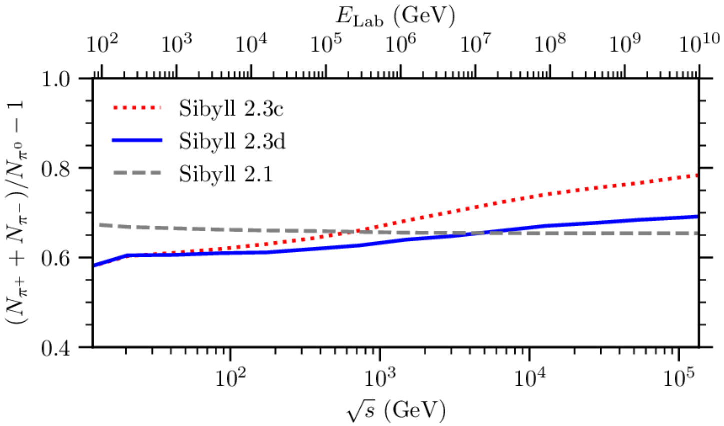
$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$

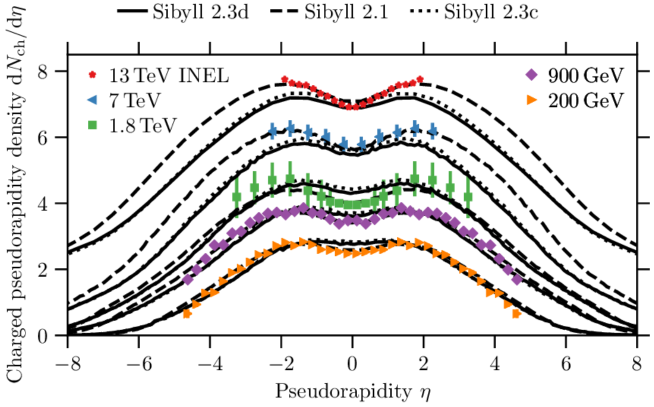
$$c\tau_{\pi^0} = 25\,\mathrm{nm} \qquad \pi^0 \to \gamma\gamma$$

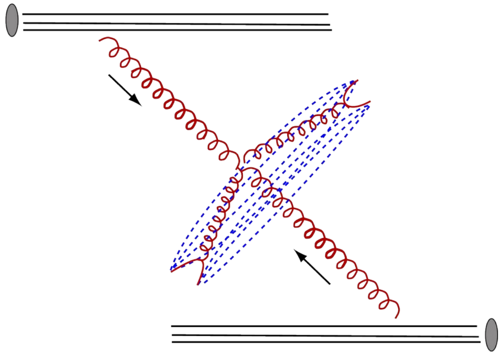
2nd interactions ..

What about Sibyll 2.3c?

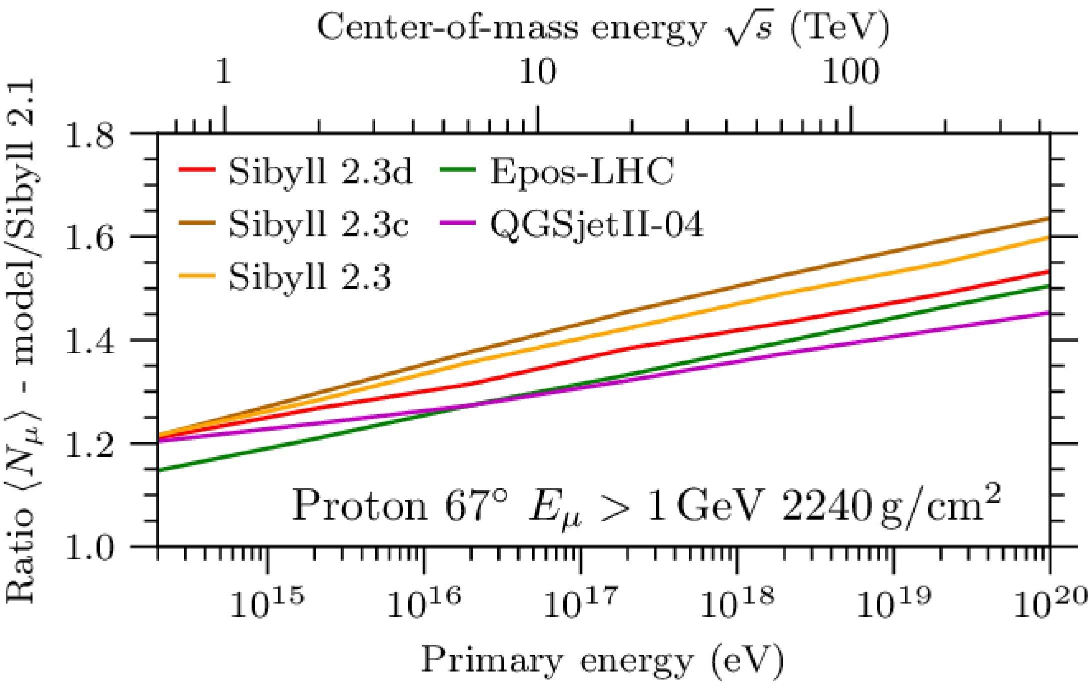






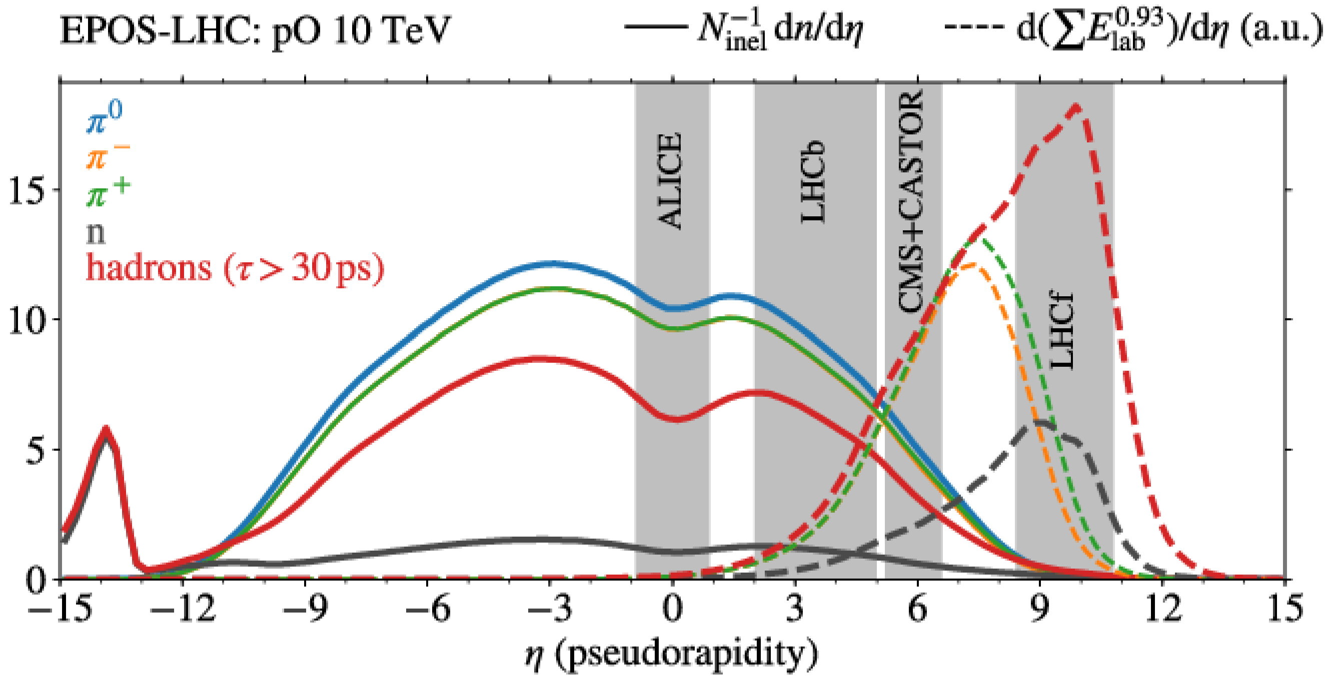


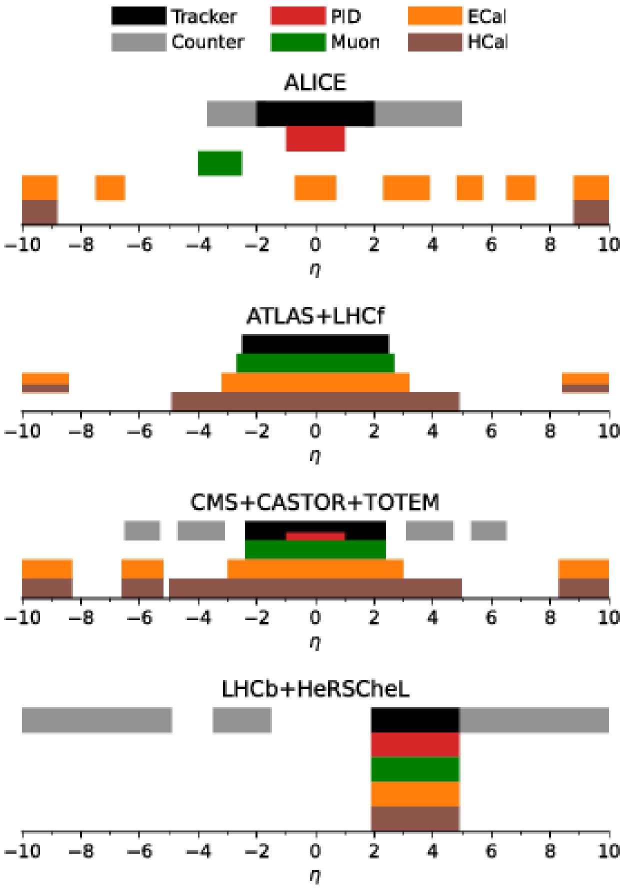
large charge to neutral ratio for pions by
accidentally applying pi0 ↔ rho0 exchange in **all** minijets



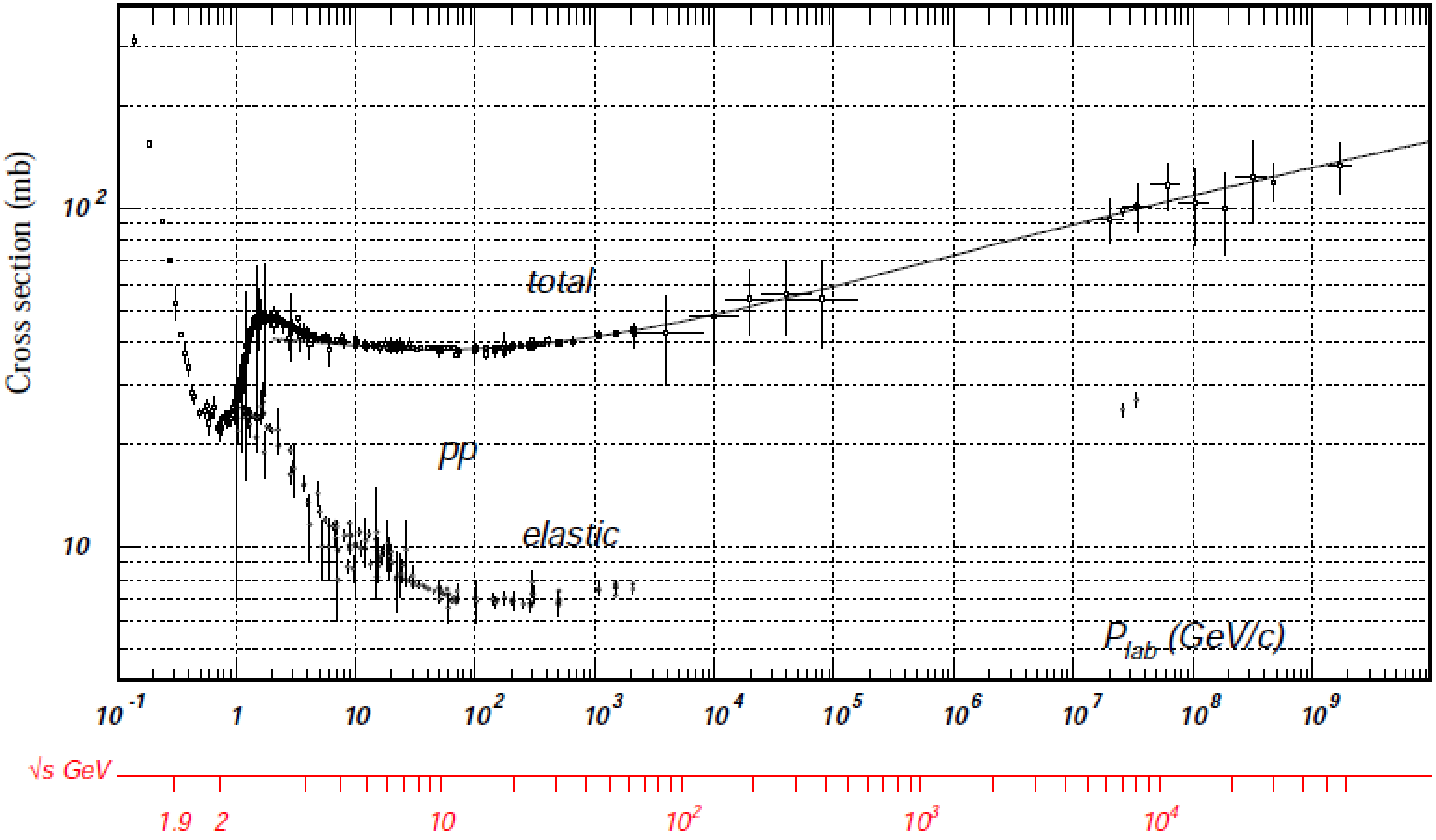
More muons yet. Increased slope

(Albrecht et al, Astrophys.Space Sci. 367 (2022) 3, 27')



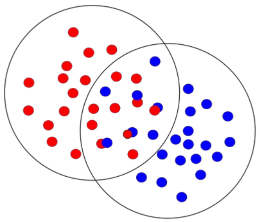


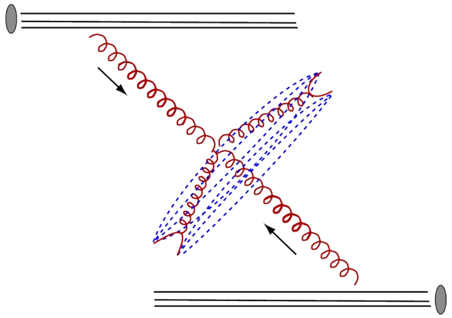
(Albrecht et al, Astrophys.Space Sci. 367 (2022) 3, 27’)


Cross section (mb)
10 2
10
total
pp
elastic
Plab (GeV/c)
10 -1
1
10
10 2
10 3
10 4
10 5
10 6
10 7
10 8
10 9
√s GeV
1.9
2
10
10 2
10 3
10 4

Hadron interactions in SIBYLL

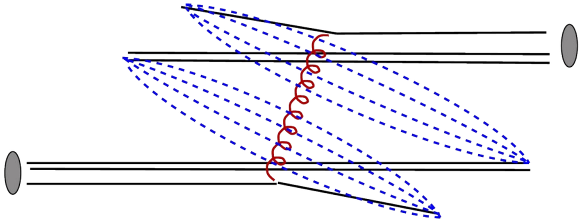
* parton picture
* LO QCD jets → minijets
* separation soft & hard:
  energy dependent pt threshold
* diffraction dissociation
* leading particles, associated production
* string fragmentation



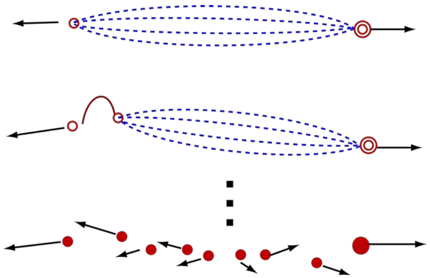


$n_{\mathrm{hard}}, n_{\mathrm{soft}}$

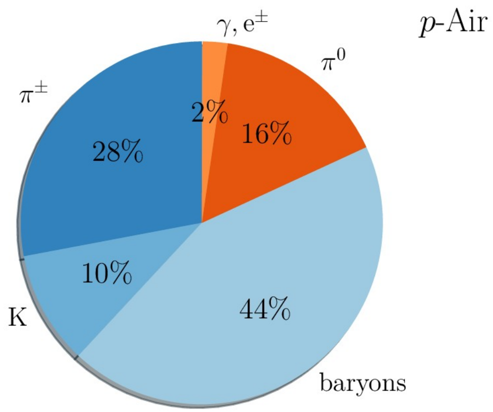
Model for:
Pions, Kaons, Protons and Nuclei
From 10 GeV to 10^6 GeV CoM energy



(PRD 80 (2009) 094003,
PRD 100 (2019) 10, 103018,
PRD 102 (2020) 6, 063002)



Energy share



Multiplicity share