SIBYLL

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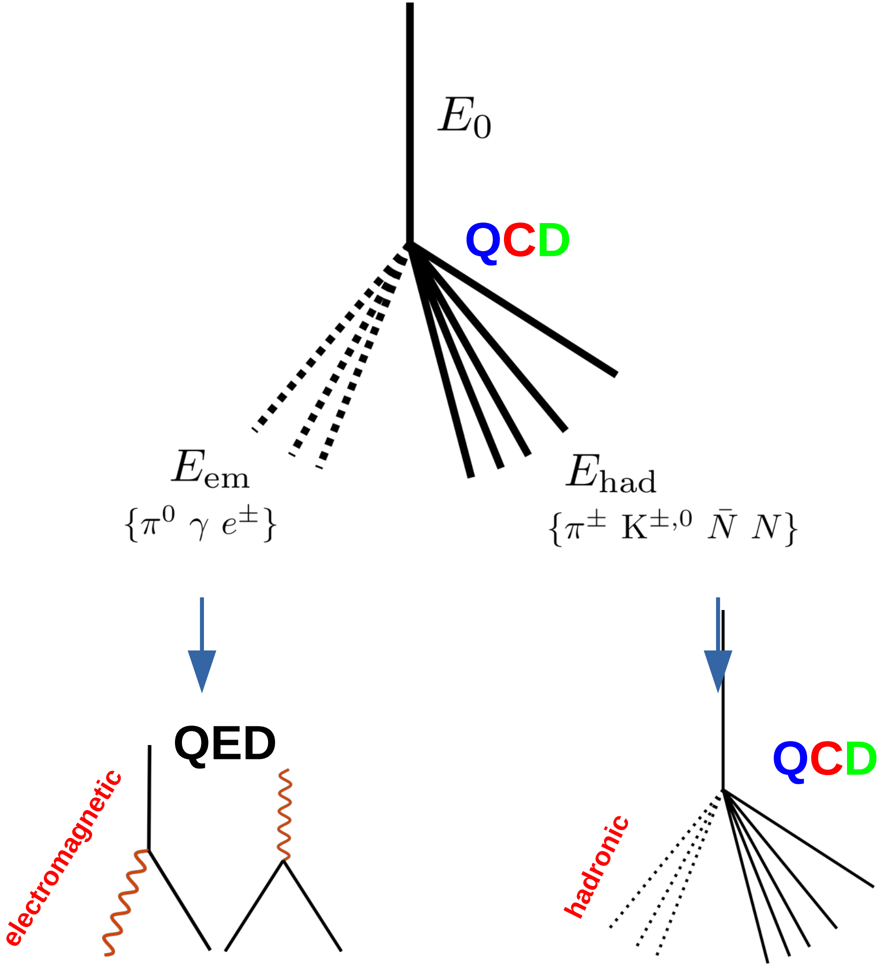
Air shower development: two cascades

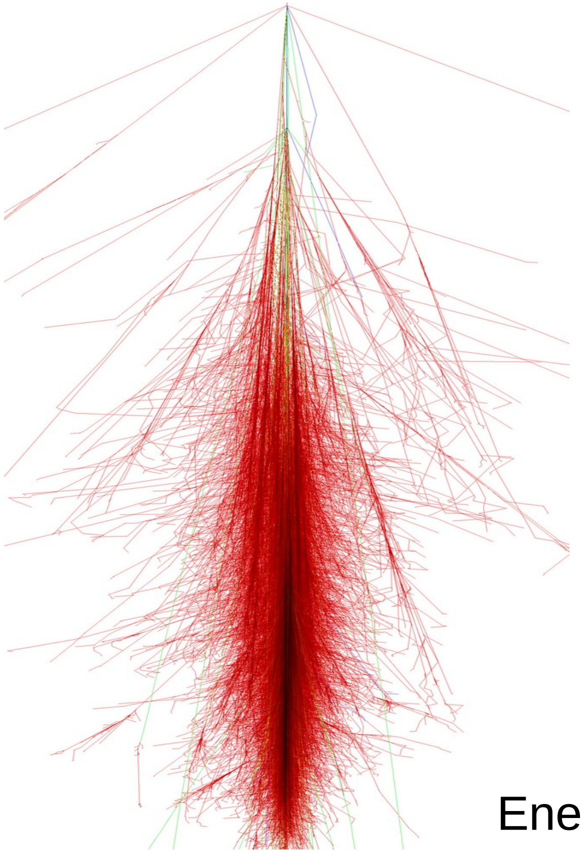
1st interaction

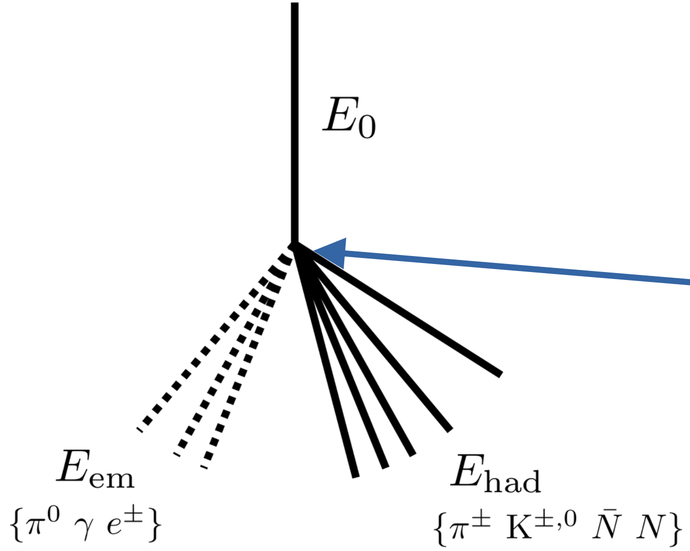
$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$
$$c\tau_{\pi^0} = 25\,\mathrm{nm} \quad \pi^0 \to \gamma\gamma$$

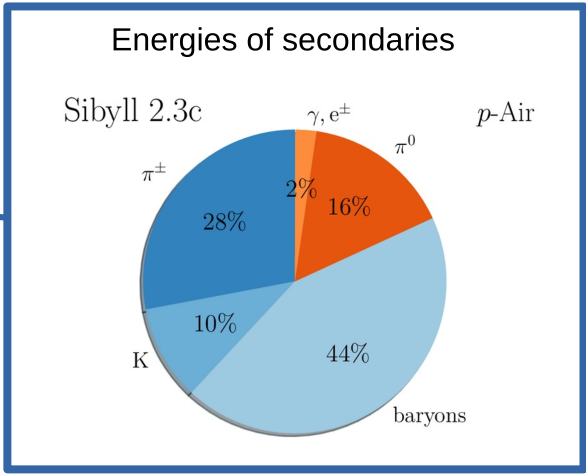
2nd interactions ..



Air shower development: energy flow







EM cascade

hadronic cascade

Energy flow

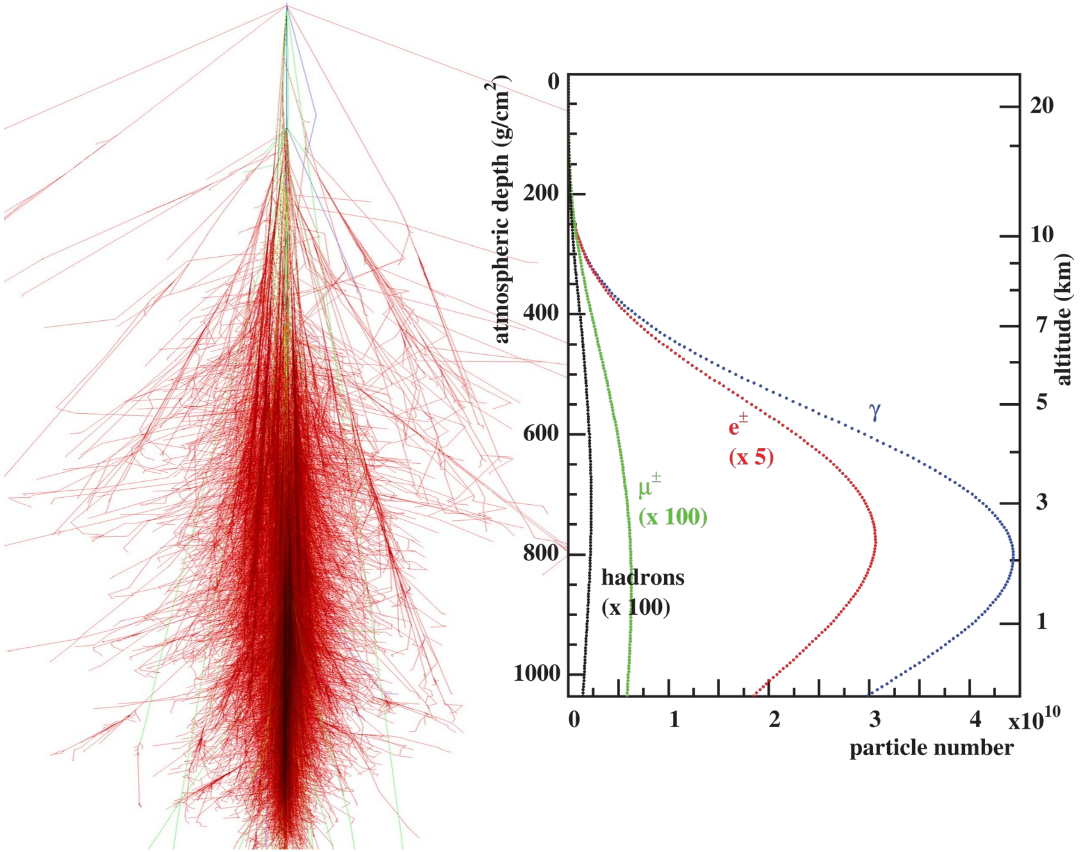
Only 80% energy remains in hadrons ..

After n steps:

$$E_n^{\rm had} = 0.8^n\, E_0$$

$$E_n^{\rm EM} = (1 - 0.8^n)\, E_0$$

Air shower development: observables



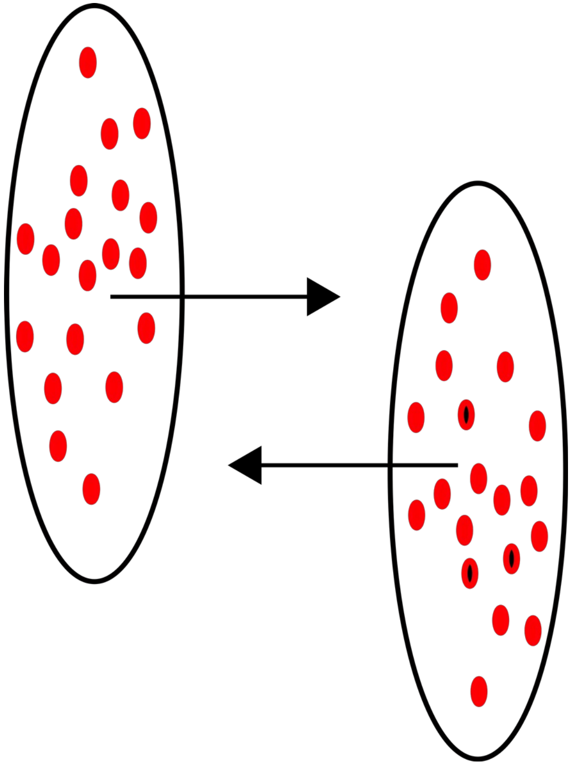
Shower profile & Xmax:
EM cascade,
first few hadronic interactions

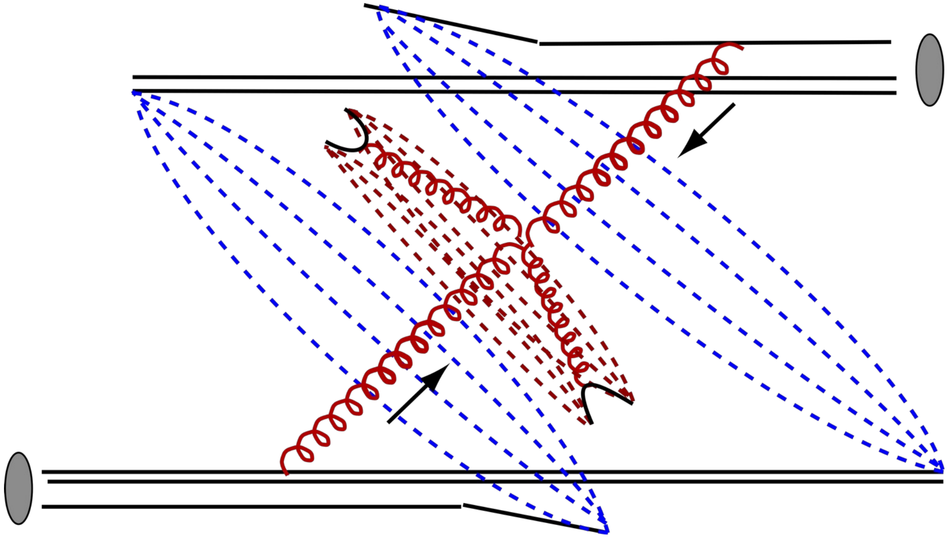
$$E_n^{\rm EM} = (1 - 0.8^n)\, E_0$$

muons: **Full** hadronic cascade
muons produced at end

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

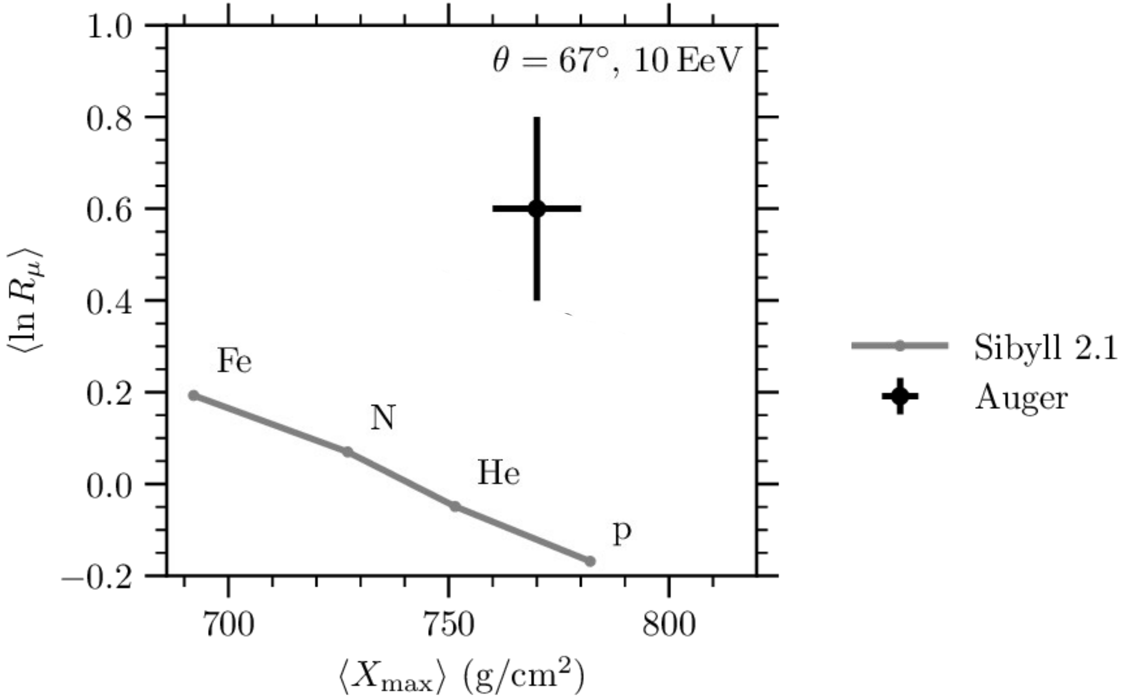
Sibyll model





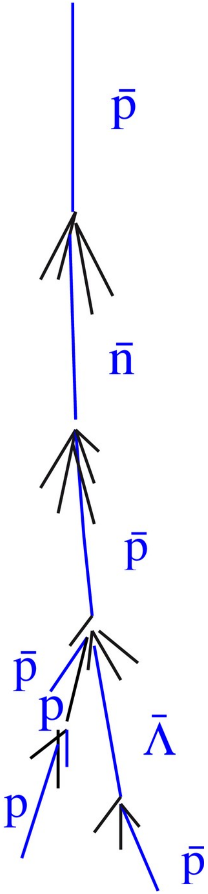
(PRD 80 (2009) 094003,
PRD 102 (2020) 6, 063002)

Muon discrepancy in Sibyll 2.1



Muon production significantly
underestimated

More muons: baryon, rho0 and strange production



Baryon number conservation !

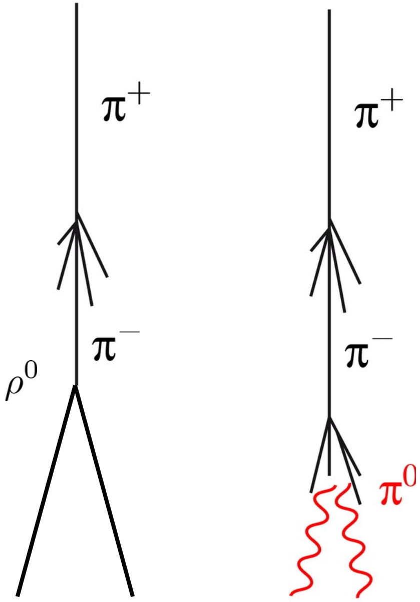
particle production until
Sub-relativistic !

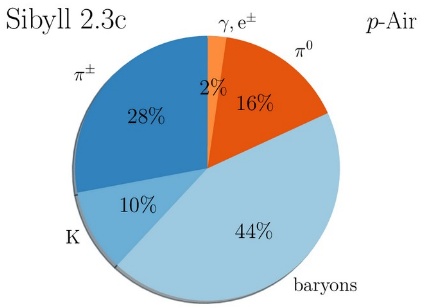
$$\pi^+ + p \rightarrow \text{leading} + X$$

$$\text{leading} : \pi(\text{spin}-0) \text{ or } \rho(\text{spin}-1)$$

$$\rho^0 \rightarrow \pi^\pm$$

$$\pi^0 \rightarrow 2\gamma$$

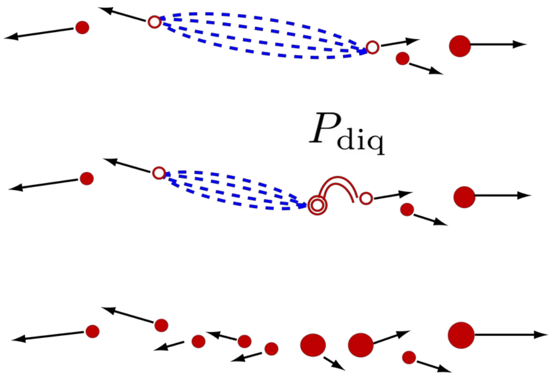


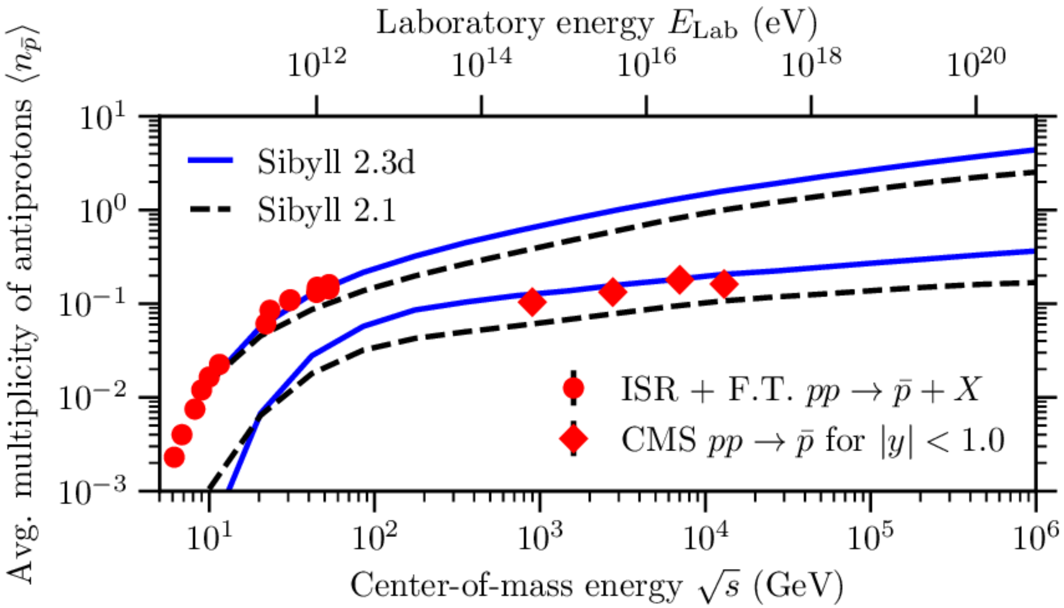


More Kaons → More Ehad

QCD conserves strangeness

Baryon production in SIBYLL



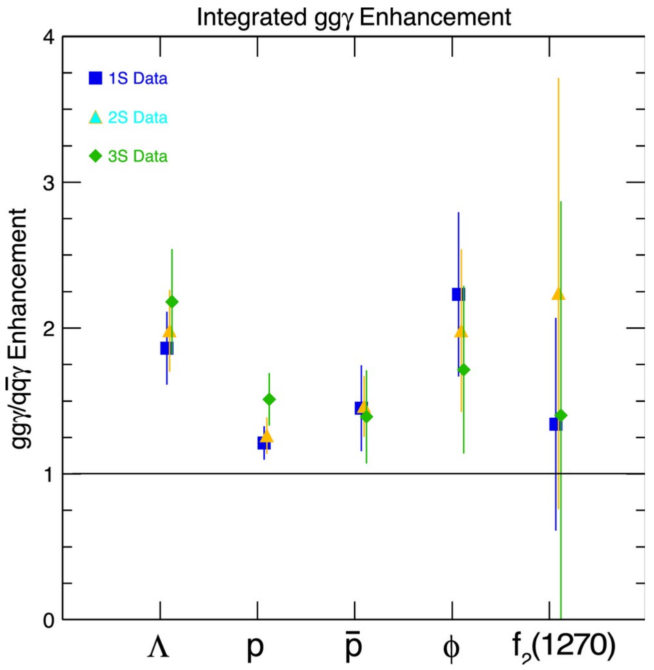


Sibyll 2.1 (from TeVatron times)

Fixed rate of baryon (diq) production

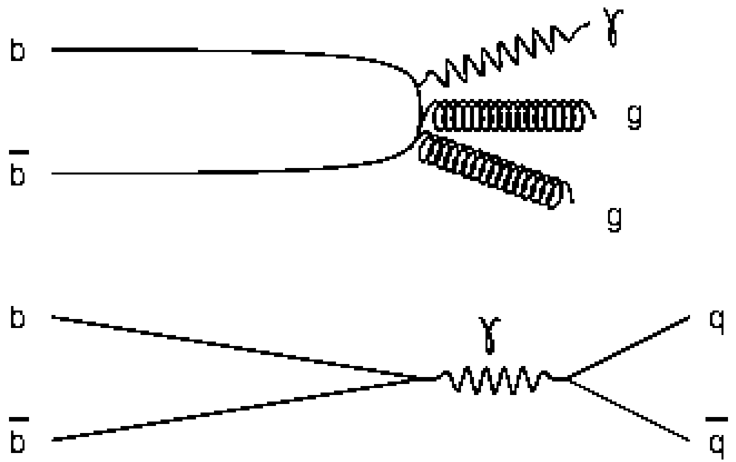
Baryon production not universal ?

(CLEO collab. R.Briere et al, Phys.Rev.D**76**,2007)



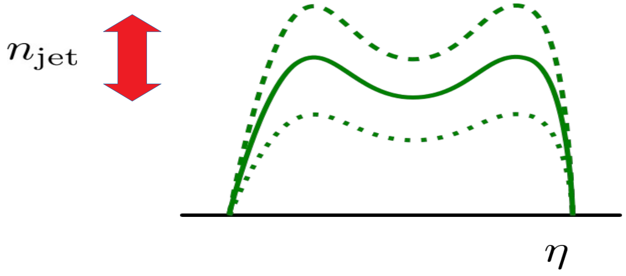
Pdiq depends on gluon density?

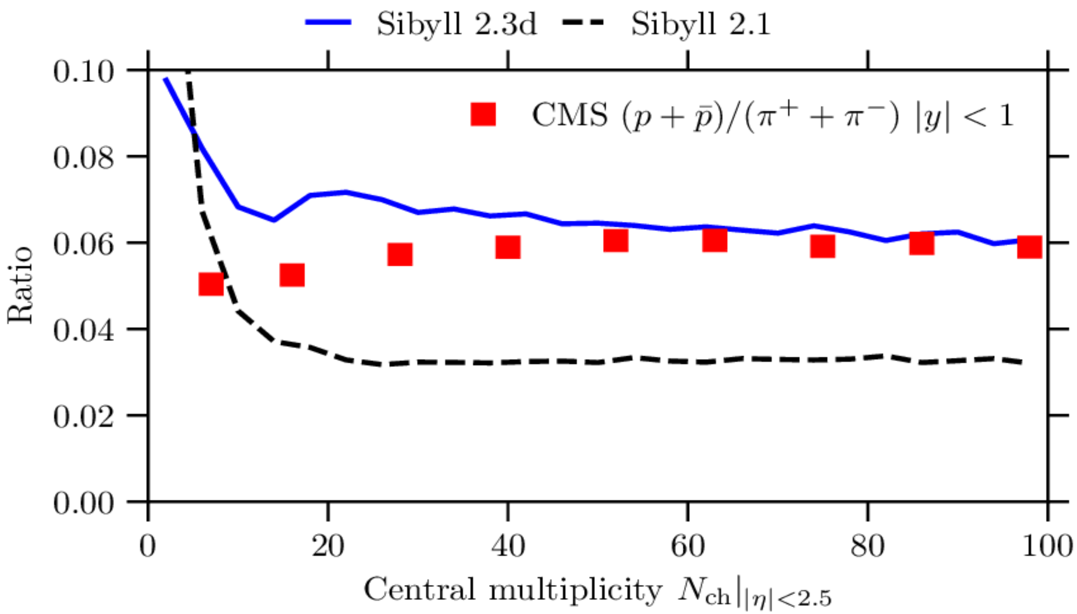
Decay of Υ(9460) resonance



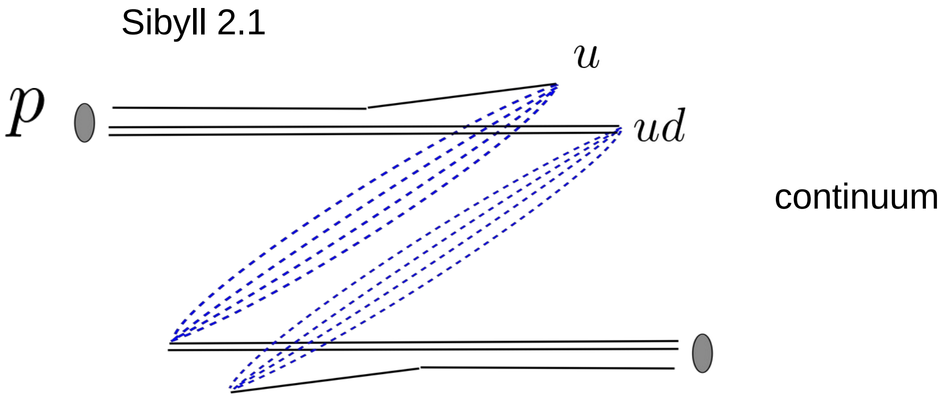
Compare with off-resonance scattering

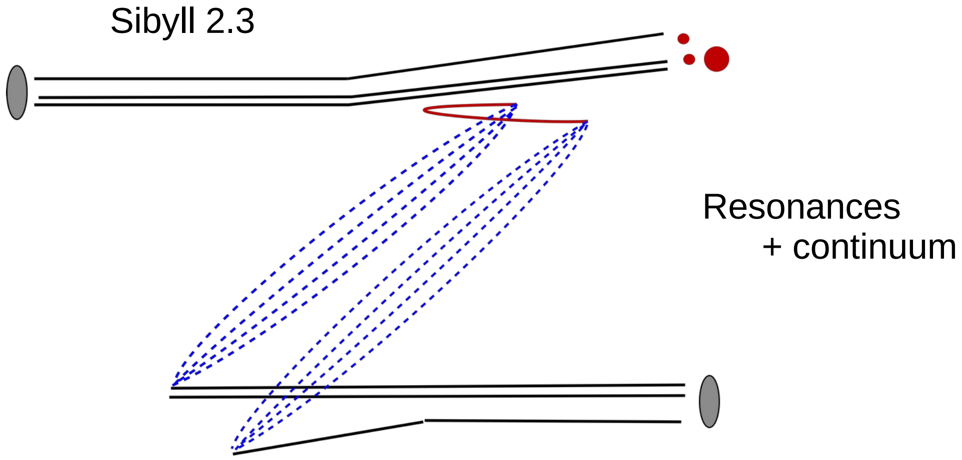
Baryon production constant in rapidity

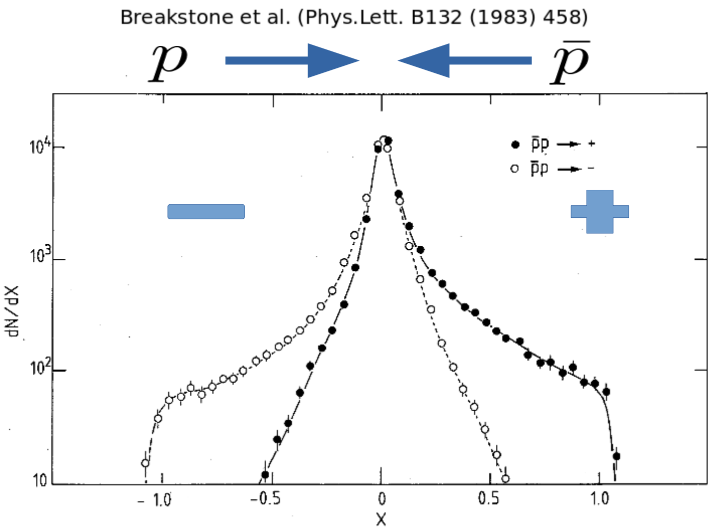


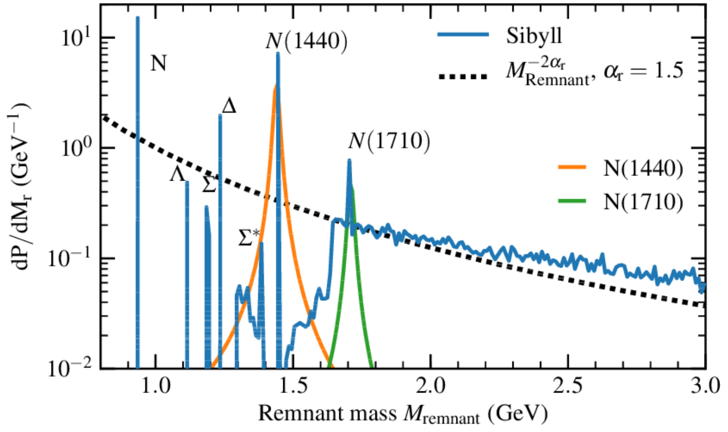


Remnants


Sibyll 2.1
p
u
ud
continuum

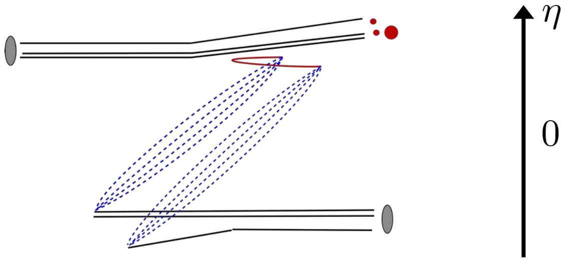

Sibyll 2.3
Resonances
+ continuum

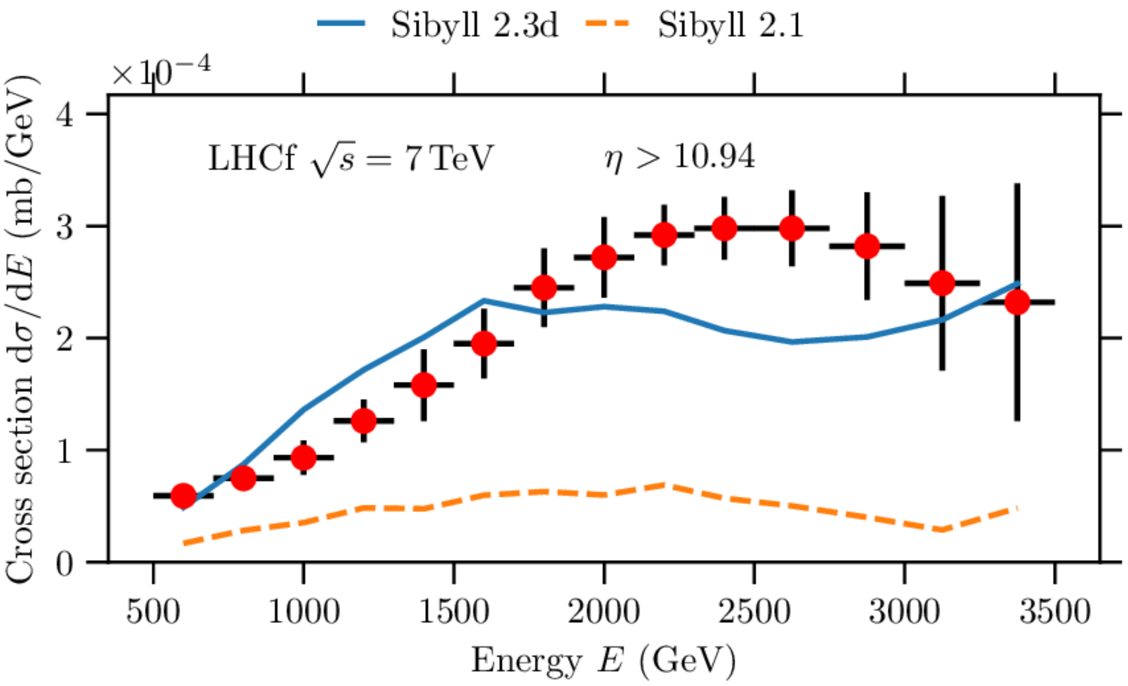

Breakstone et al. (Phys.Lett. B132 (1983) 458)
p
p̄
dN/dX
X
p̄p → +
p̄p → -


N
N(1440)
Δ
Λ
Σ
Σ*
N(1710)
Sibyll
N(1440)
N(1710)
dP/dM_r (GeV^-1)
Remnant mass M_remnant (GeV)

LHCf

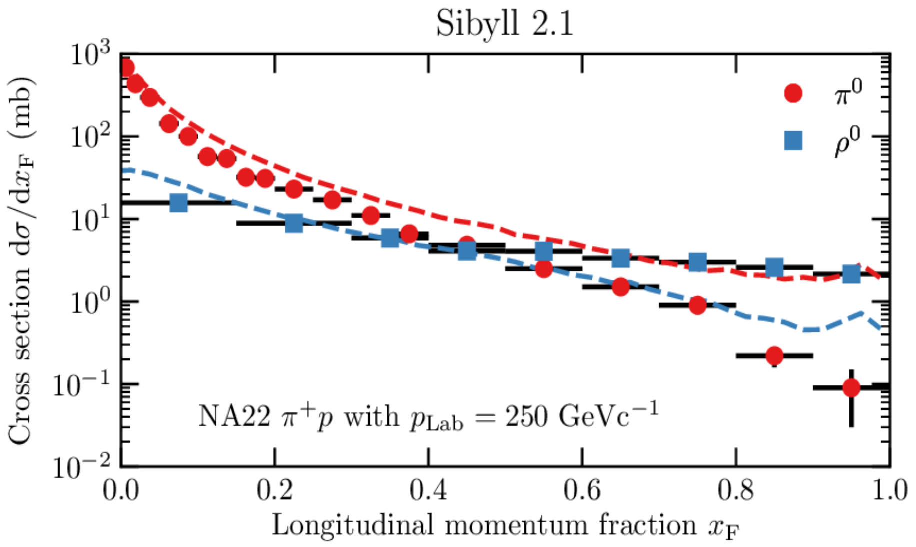
(LHCf Adriani et al 2015)

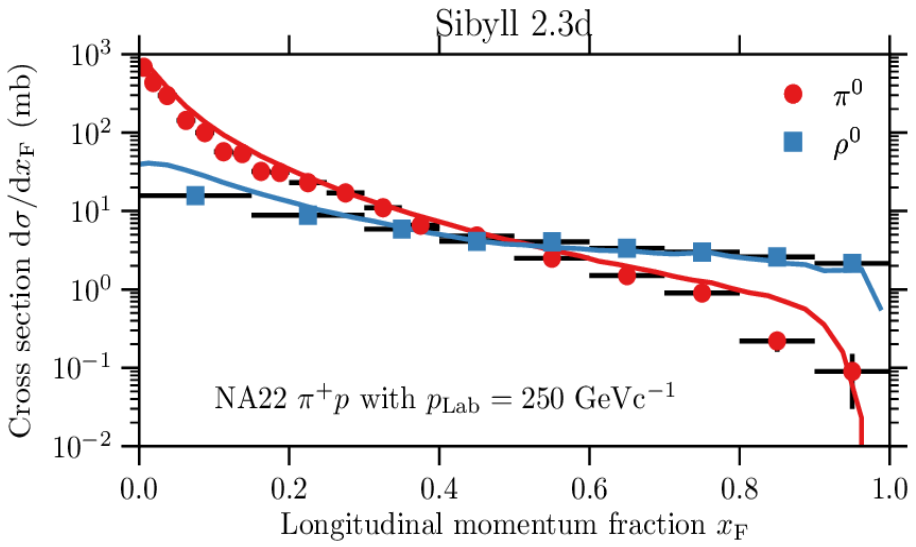




Leading rho0

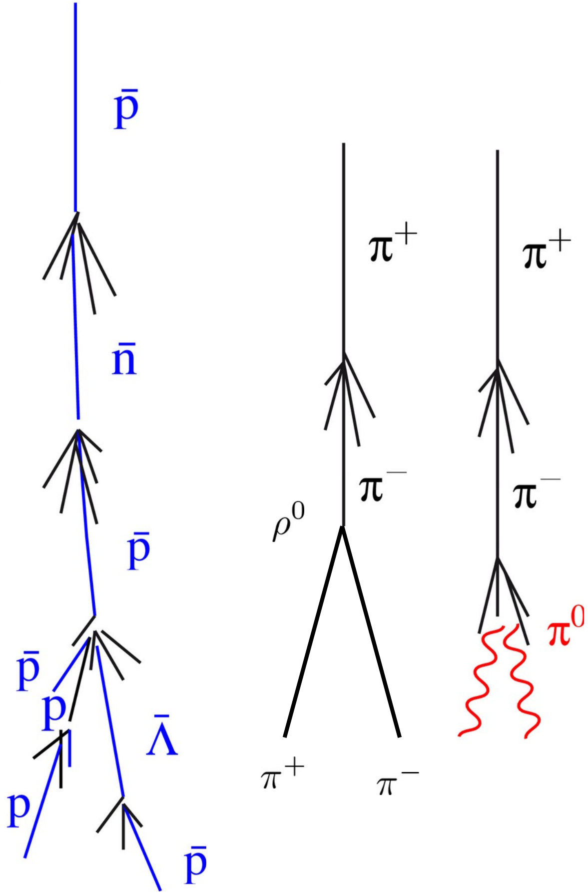
$$\pi^+ + p \;\rightarrow\; \text{leading} + X \qquad\qquad \text{leading} : \pi,\; \rho$$

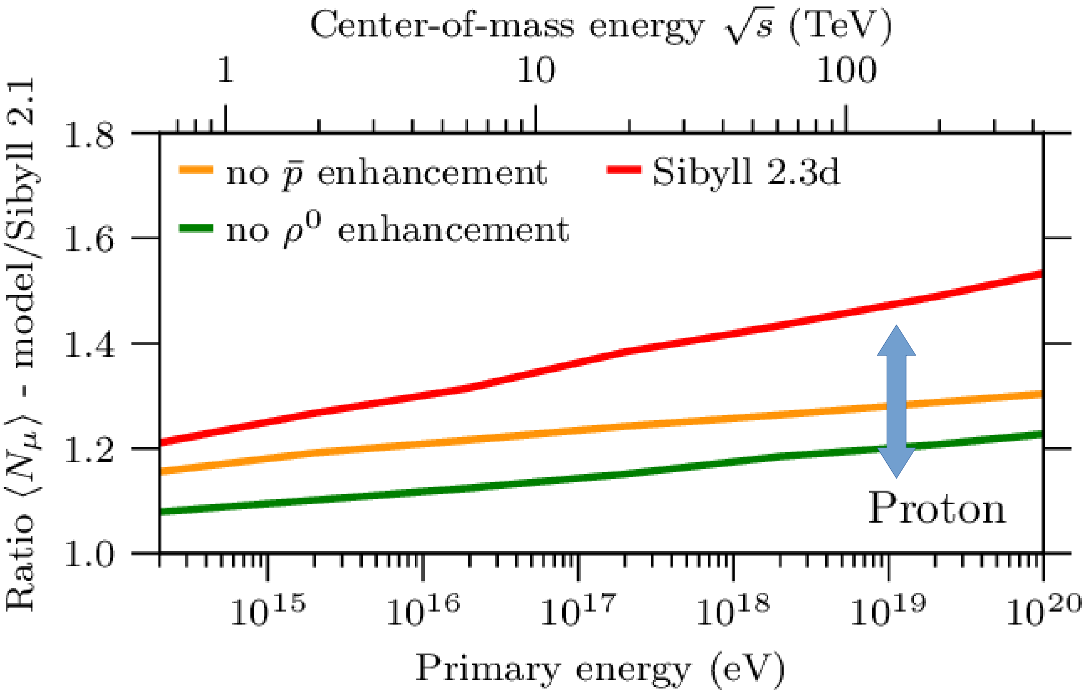




$$P_{\pi:\rho} = 1/3$$

Muons in Sibyll 2.3d





~40% increase

Muon discrepancy in Sibyll

30% enhancement in number of muons from 2.1 → 2.3d

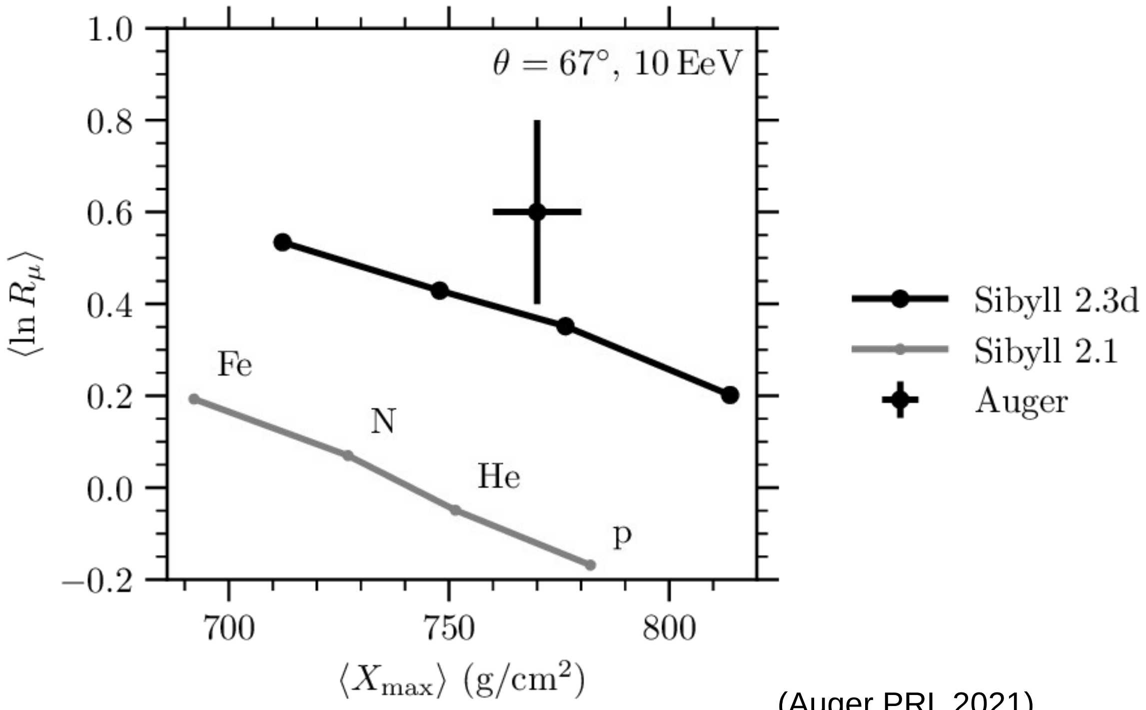
Achieved through:
- baryon production
- Forward Rho meson production

Data driven (LHC,NA22/NA61) !

NOT ENOUGH MUONS !

Is there more room within standard physics ?

→ **Sibyll***



(Auger PRL 2021)

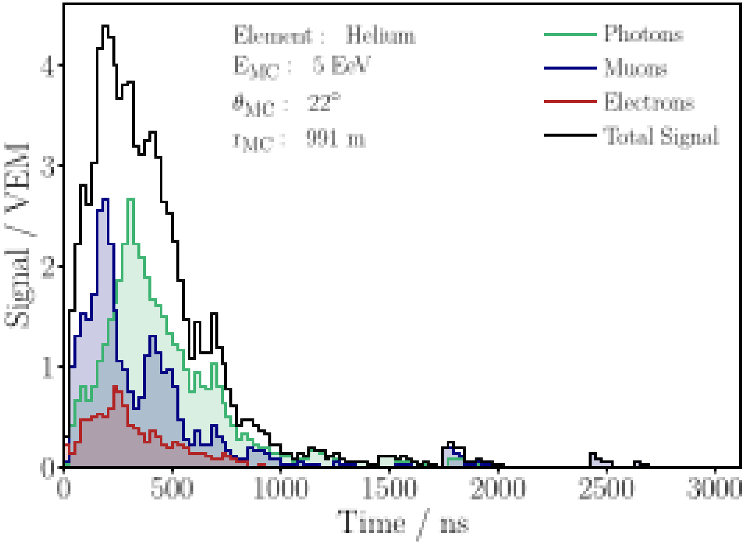
In addition, **ML** analyses require detailed simulations that are consistent with data

DNN for Xmax reconstruction

* Training DNN on simulations of surface detector signals to produce mass estimator Xmax

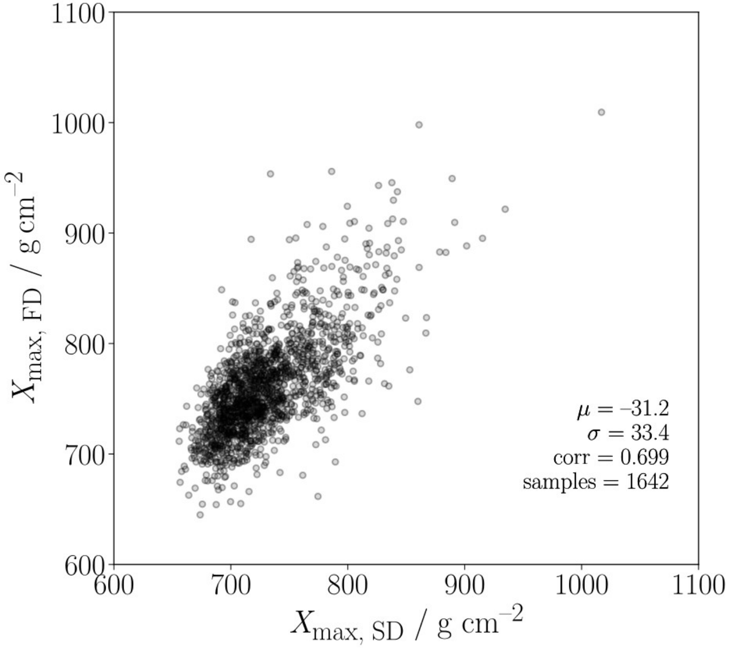
* Cross check with hybrid measurements results in **30g/cm2** bias (p – Fe ~ 100g/cm2)

Simulated signal trace of one station



2024)

measured estimator



DNN estimator

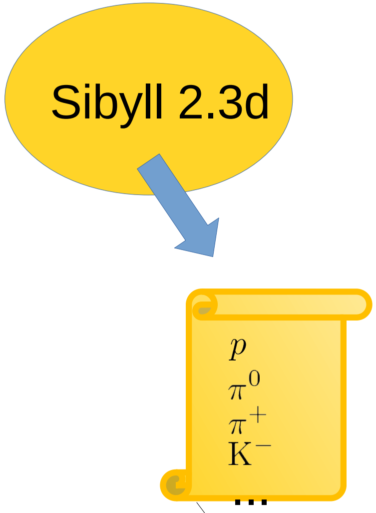
Sibyll*

We want:

* test different scenarios
* simple adjustable parameters
* physically consistent events

(energy/momentum + Q,B,S conservation)

Therefore leave Sibyll unmodified, but alter final state.



List of particle names & momenta

Post-processing

1) Replace *suitable* pairs/tripels of pions with desired hadrons at a **specific rate P**
Example: for rho-meson replace (pi0,any) with (rho0,any)

2) Recalculate momenta

Energy- and phasespace dependent modifications

Start from Sibyll 2.3d and only change events **outside** of phasespace covered by accelerator experiments

$$P_i = P_{i,0} \cdot |x_F|^{\epsilon_i} \cdot f(\sqrt{s}, E_{thr})$$

Base rate

Longitudinal phasespace dependence

Epsilon → 1 max. change in forward phasespace

Epsilon → 0 no change

Energy dependence

* linear in log(s)
* zero at thresh.
* unity at 10**19eV

Four variants

Kaon/strangeness enhancement

We test 4 scenarios:

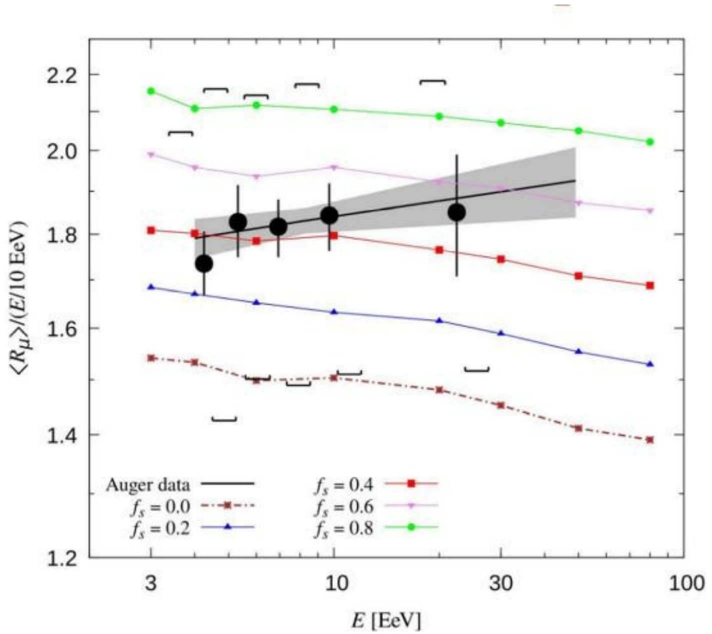
- $S^\star(\bar{p})$
- $S^\star(\rho^0)$

} Sibyll 2.3d

- $S^\star(K^{\pm,0})$
- $S^\star(\mathrm{mix})$

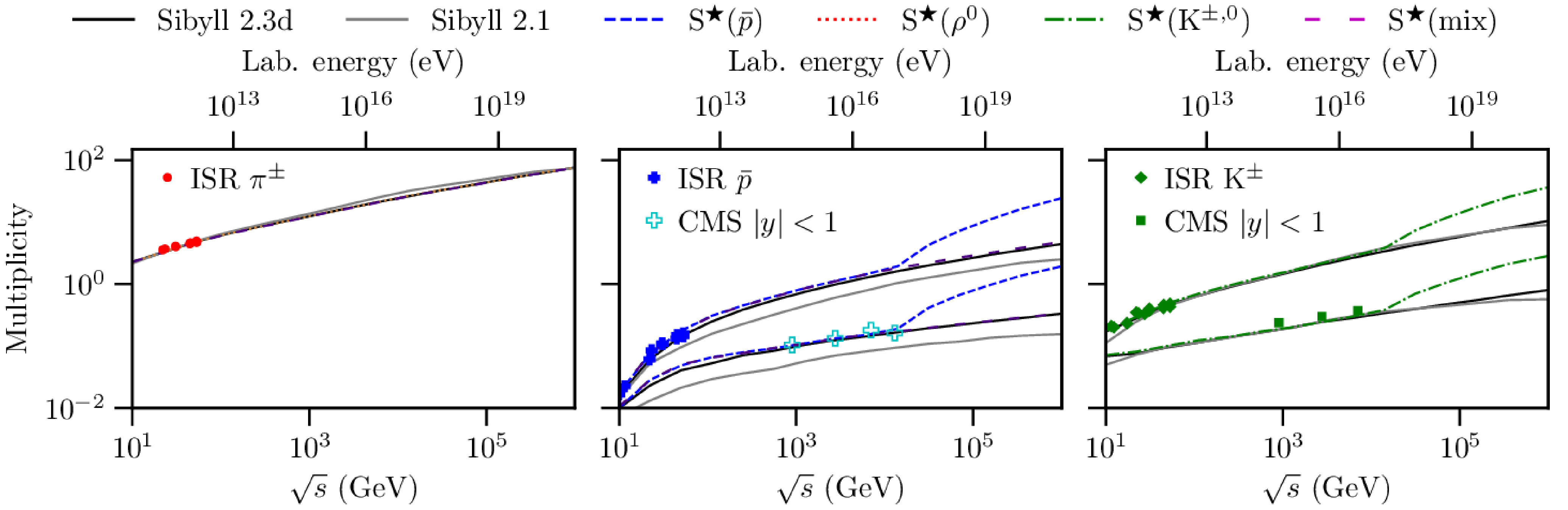
$\bar{p} + \rho^0$

Enhancements fine-tuned



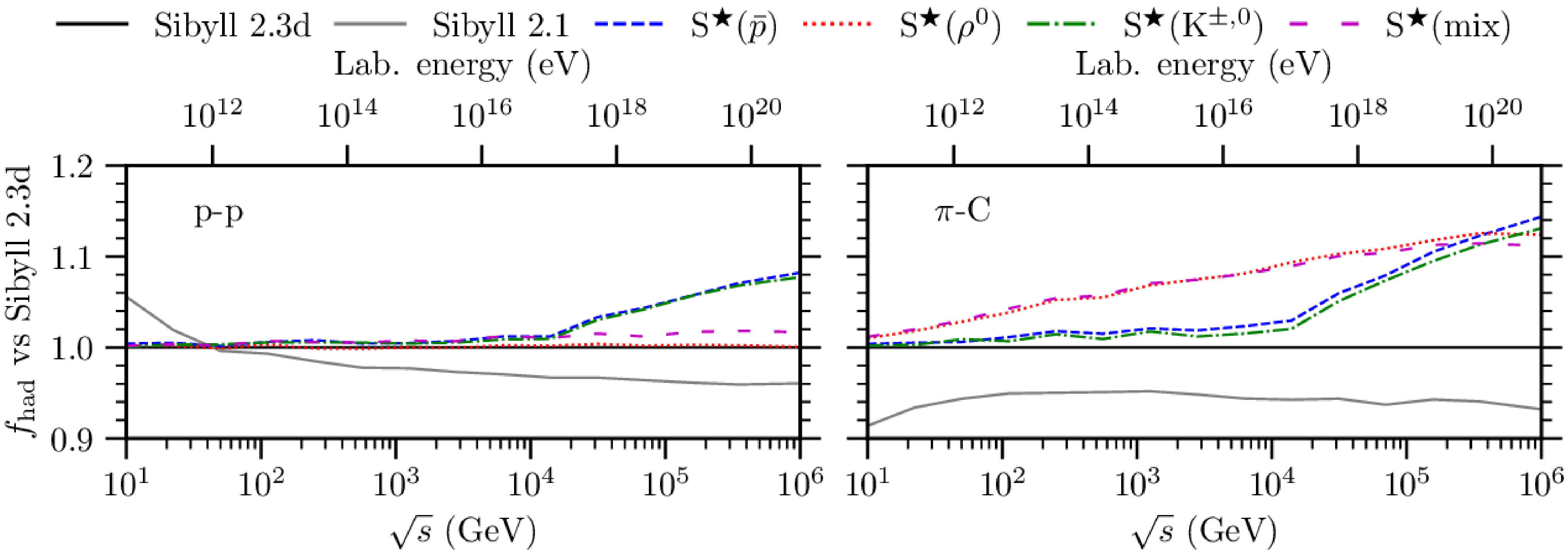
(Anchordoqui et al. 2017,
Manshanden 2022,
Sciutto et al. 2022,
Baur et al. 2023)

Sibyll* variants in proton-proton



Hadron energy fraction

Fraction of beam energy that is carried by all hadrons except *neutral pions*
= energy available in EAS to produce muons



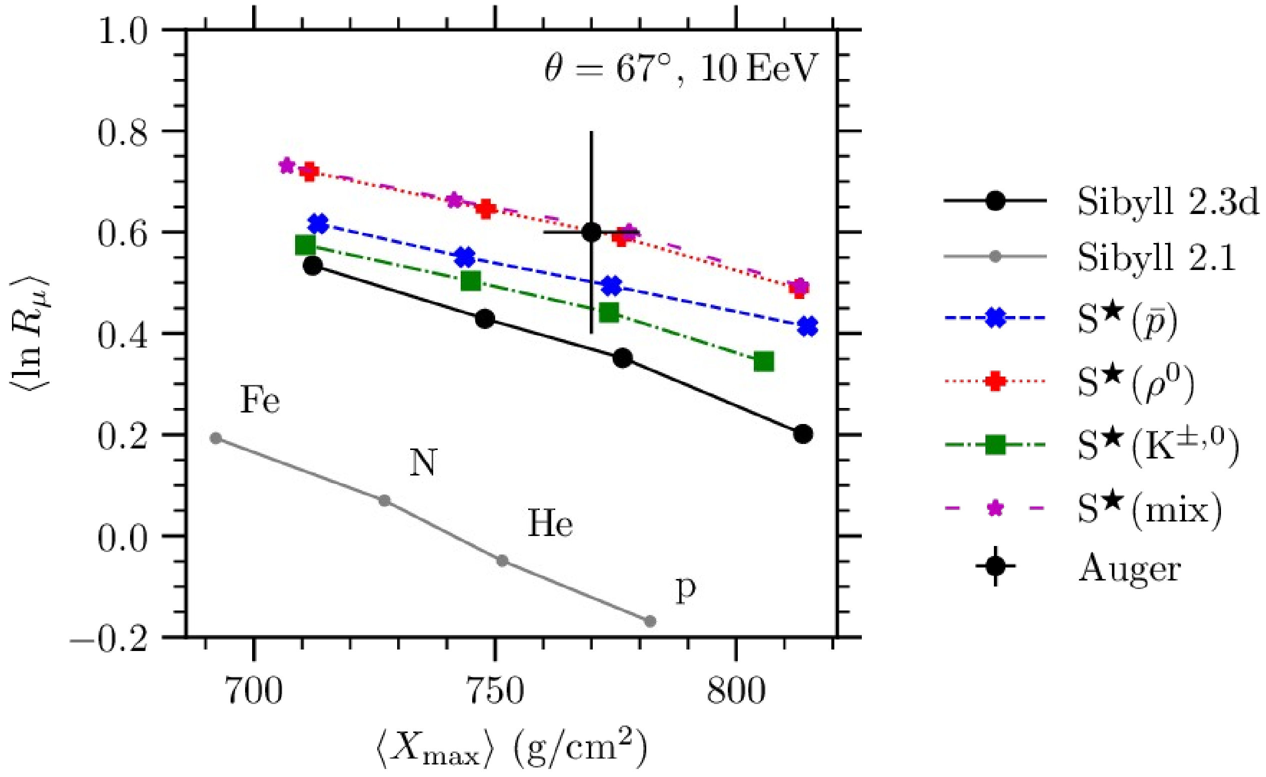
Sibyll* vs Auger inclined

(Astropart.Phys. 160 (2024) 102964)

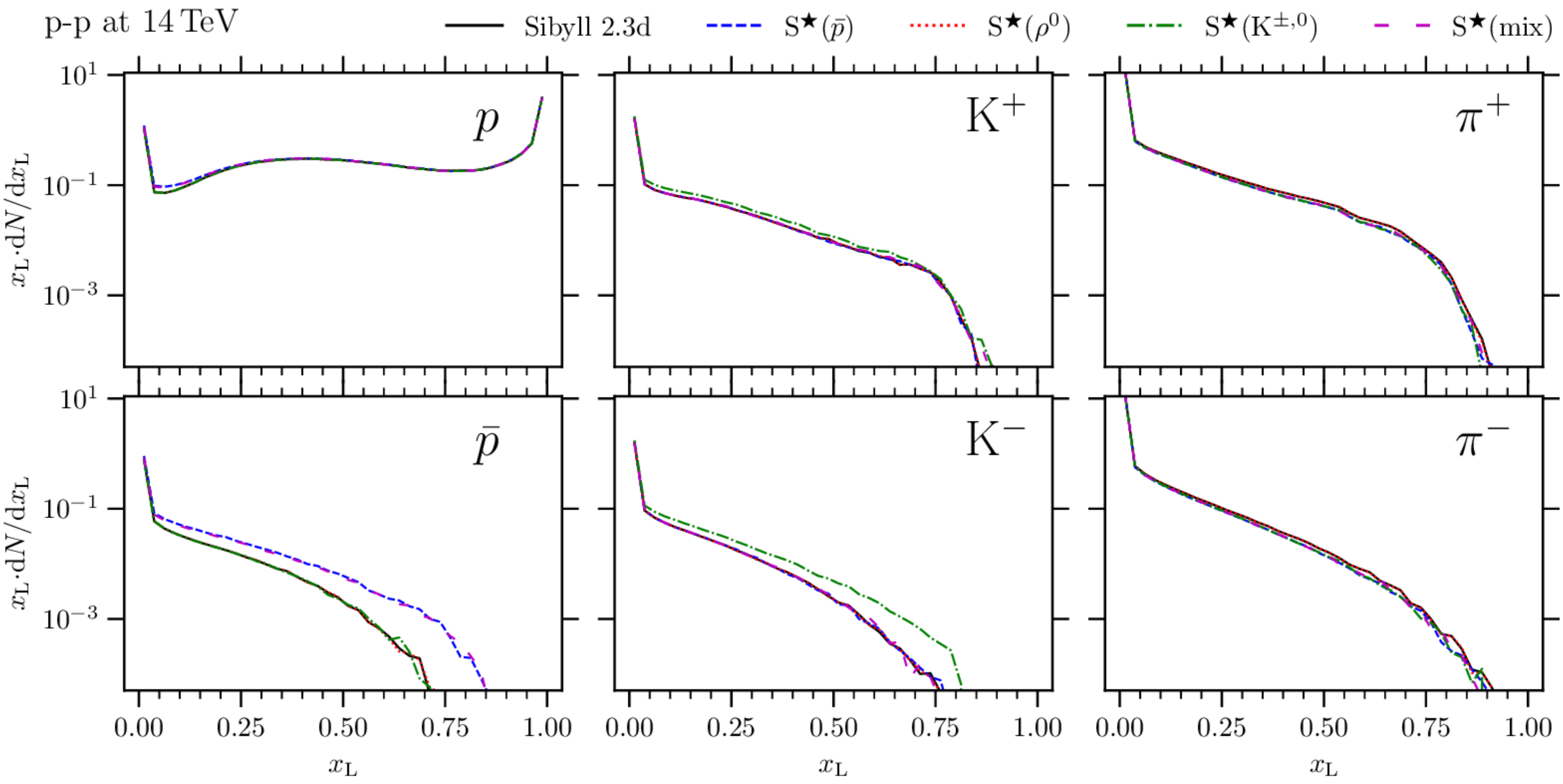
YES!

Finally sufficient muons

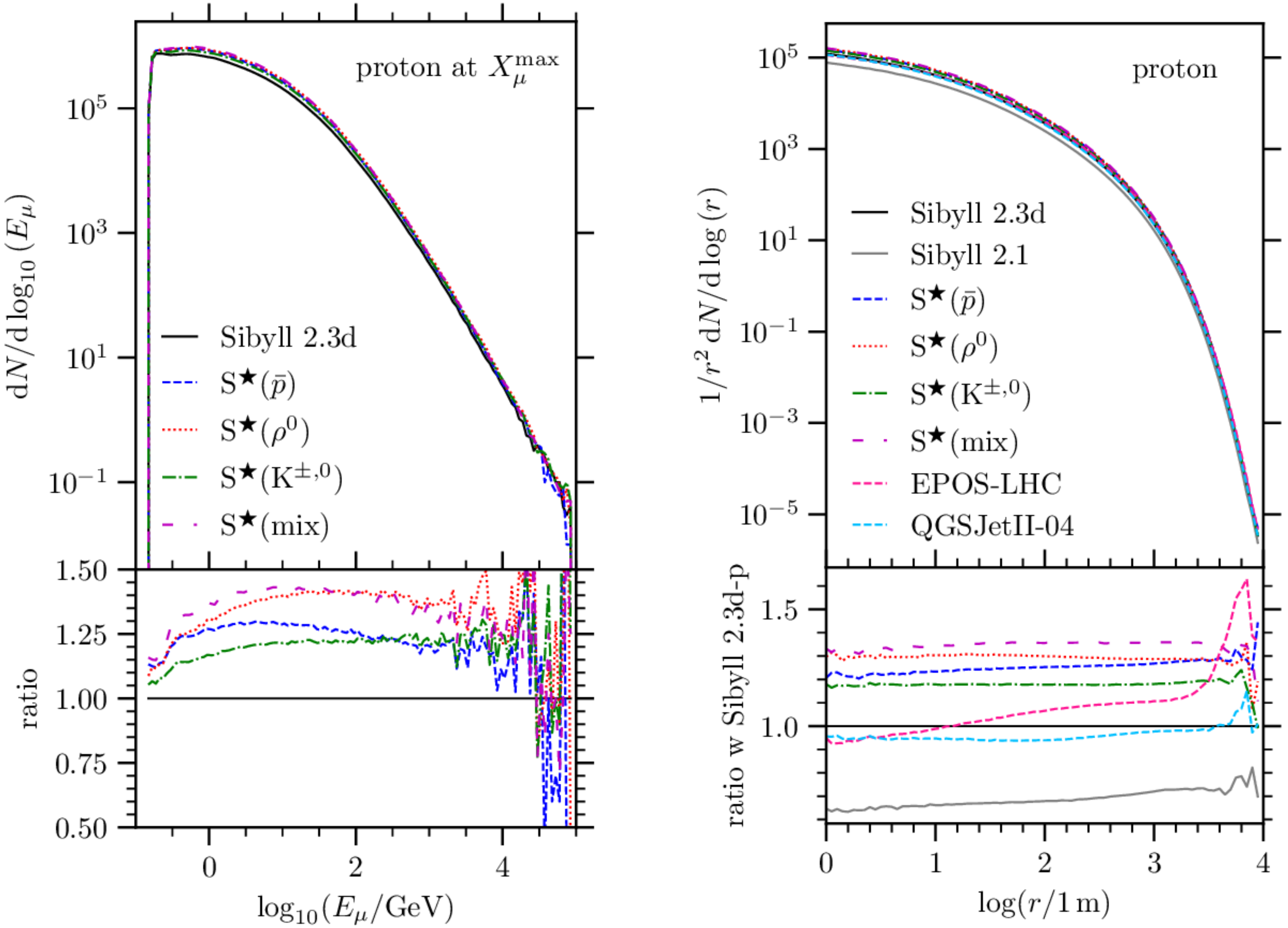
Preliminary studies suggest Sibyll* also works for machine learning



Particle spectra in Sibyll*



Shower predictions



Summary

* baryon production & rho production much improved in Sibyll 2.3d

* set of Sibyll variants with sufficient muon production (Auger inclined) → best choice: **mixed** model (Sibyll*)

* Muon puzzle is fine-tuning problem. Require precise measurement & modeling of data

Acknowledgments

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USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

XUNTA DE GALICIA

Xacobeo 21·22

UNIÓN EUROPEA

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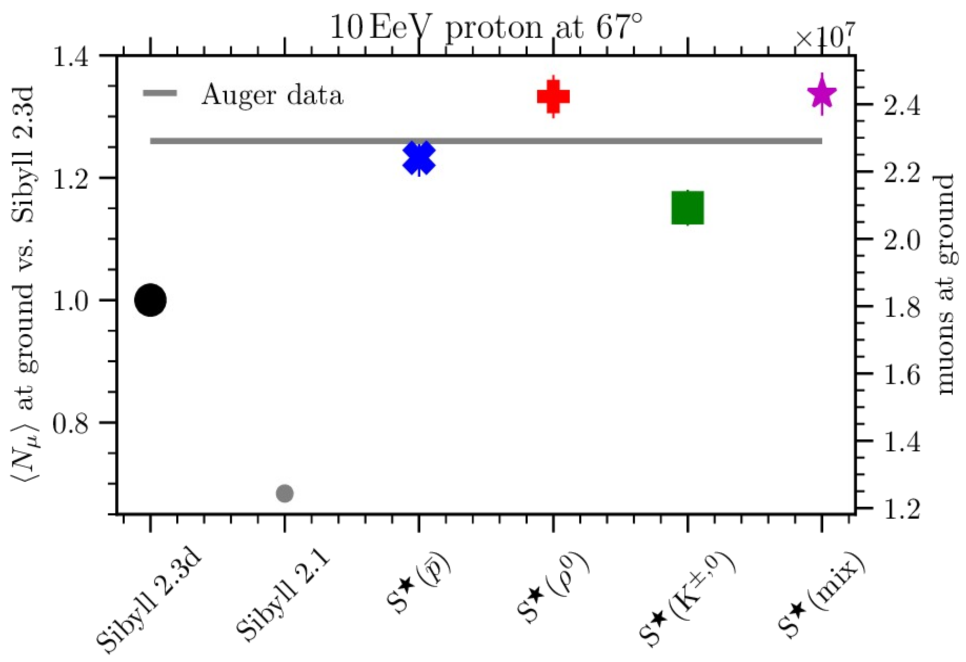
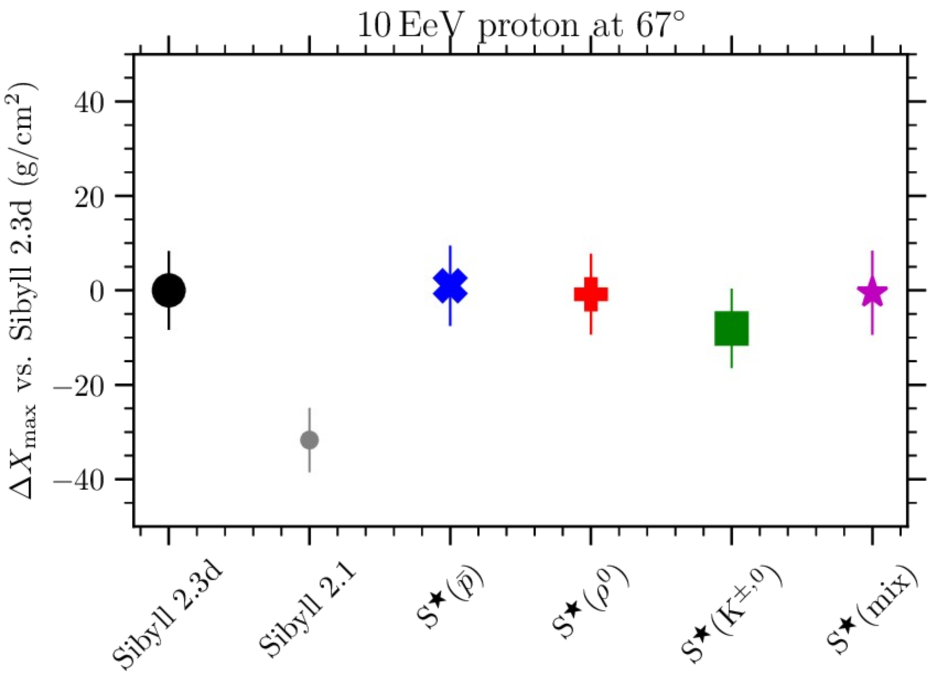
EAS predictions for protons

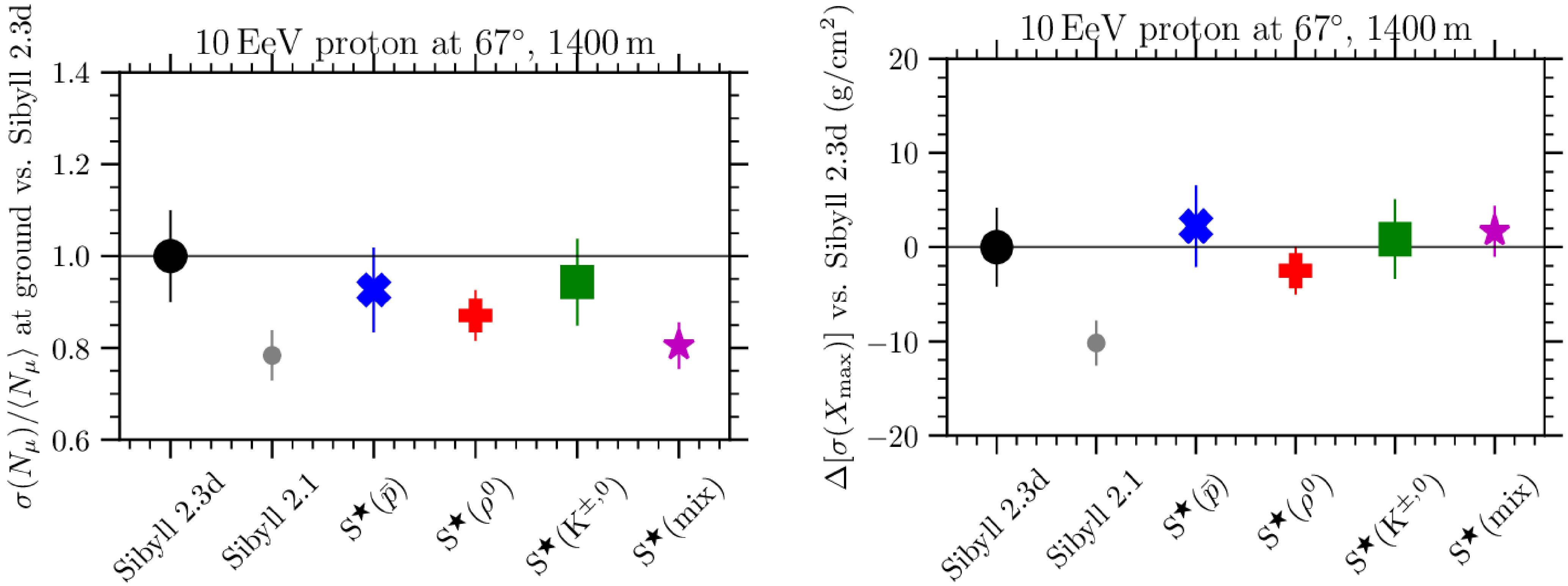
Looking good...



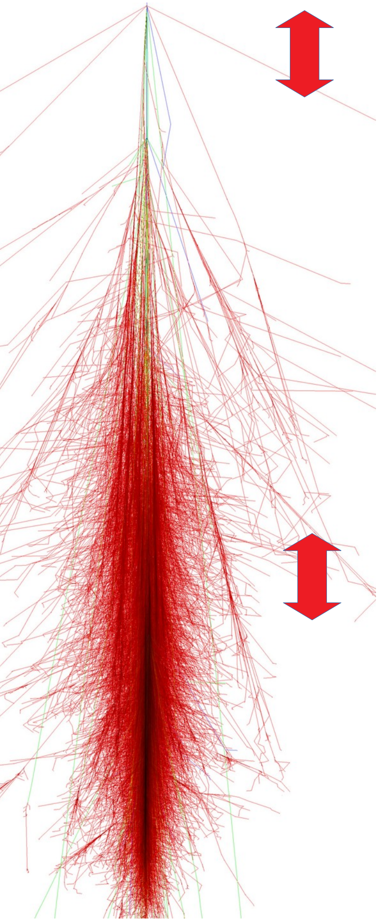


Enough for Auger data?

Fluctuations



Xmax in Sibyll 2.3d

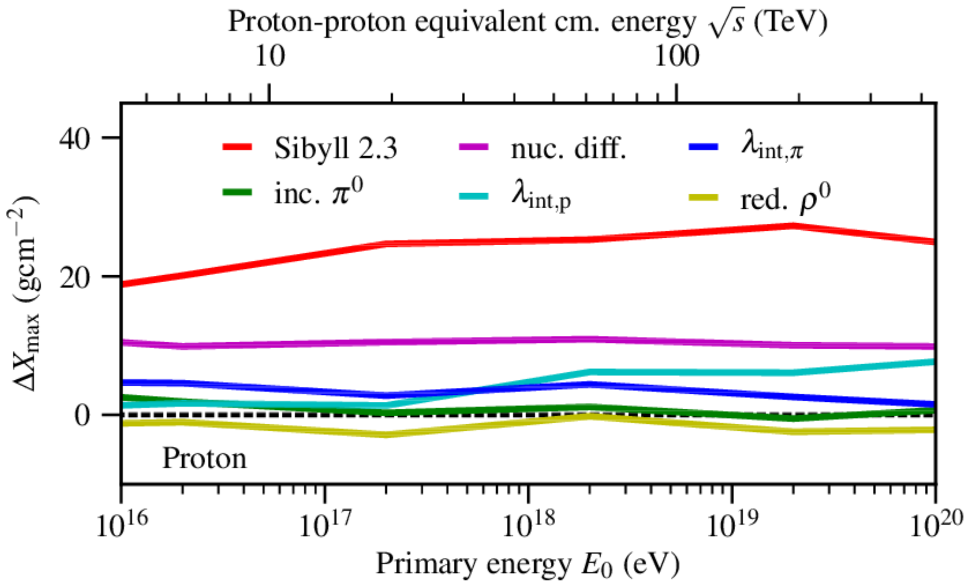


* p-p cross section reduced

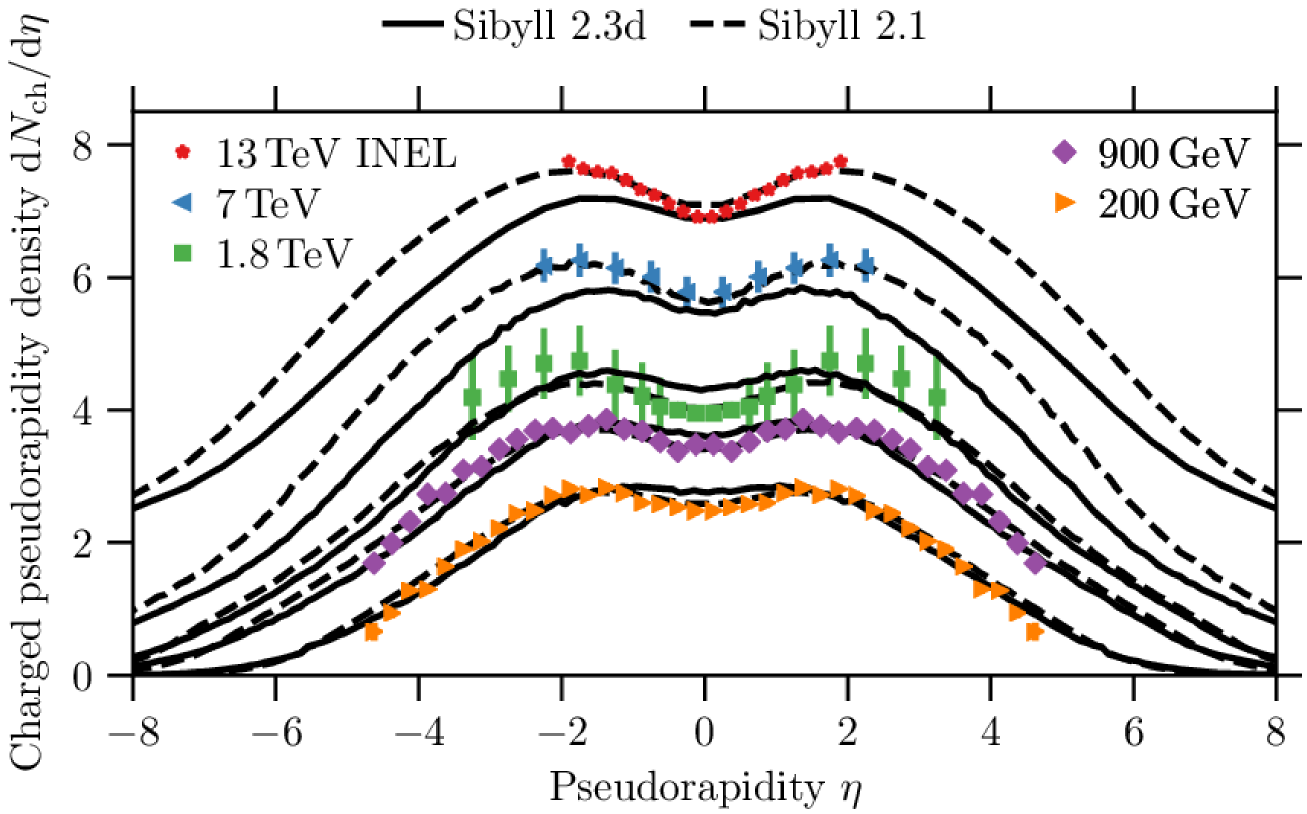
* p-air cross section reduced

* p-air diffraction increased
  (coherent diffraction)

→ 20 g/cm² deeper proton showers

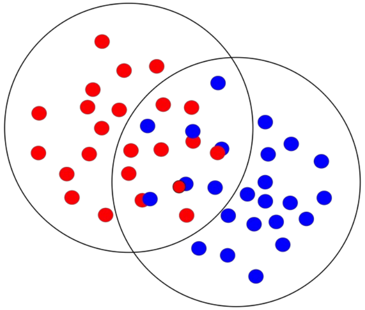


Model performance

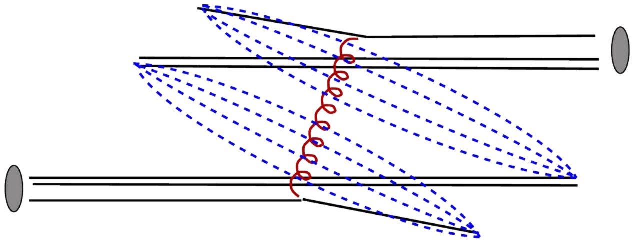


Interlude: hadron interactions in SIBYLL

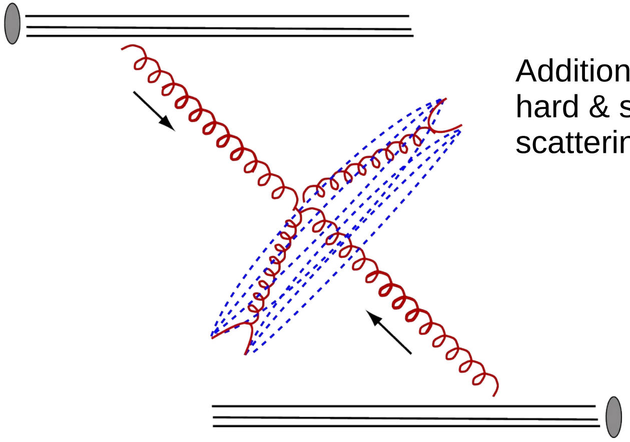
* parton picture
* LO QCD jets → minijets
* multiparticle interactions
* diffraction dissociation
* leading particles, associated production
* Lund string fragmentation



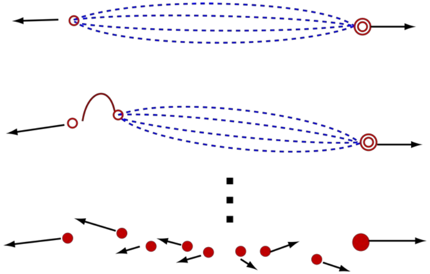
soft scattering of
valence quarks



Model for:
Pions, Kaons, Protons and
Nuclei up to 1 PeV CoM



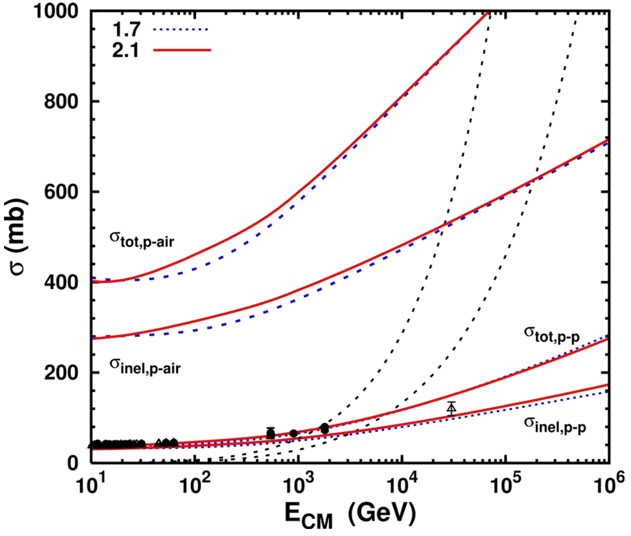
Additional
hard & soft
scattering



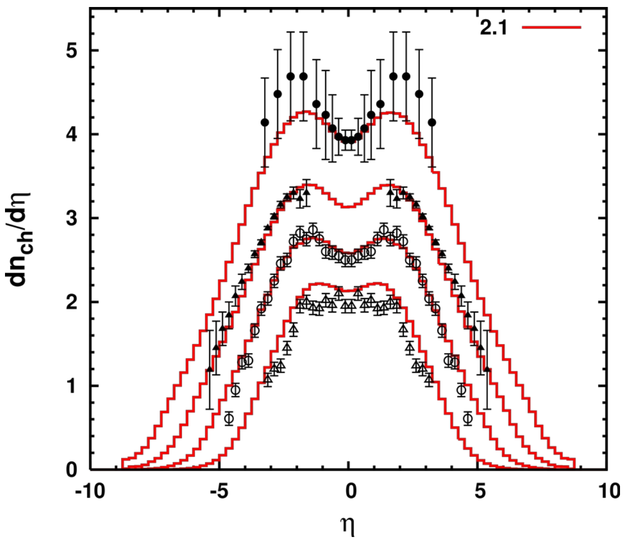
(PRD 80 (2009) 094003,
PRD 102 (2020) 6, 063002)

Model performance

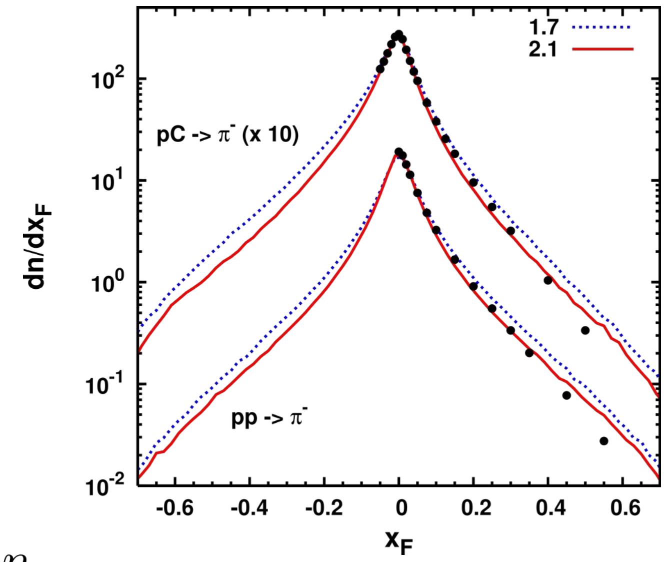
$$\sigma_{\rm inel} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_n(\vec{b}) = \int d^2\vec{b} \left(1 - \exp\{-\langle n(\vec{b})\rangle\}\right)$$

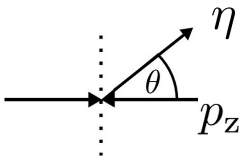


(CDF, UA5, NA22)



(NA49)





Sibyll 2.1

tuned to TeVatron