Hadronic interaction model SIBYLL

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ISAPP school “LHC meets CRs” 2018

CERN

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SIBYLL history

1992
- ‘early days’
- SIBYLL
- (PRD 50, 9 (1994))

2001
- ‘TeVatron’ era
- SIBYLL 2.1
- (PRD 80, 094003 (2009))

2017
- ‘post-LHC’
- SIBYLL 2.3c
- (PoS ICRC2017, 301 (2017))

E-J. Ahn, J. Engel, R. Engel,

A. Fedynitch, R. Fletcher,

T. K. Gaisser, P. Lipari, F. Riehn,

T. Stanev

More history:
“Sibyll – past, present and future”

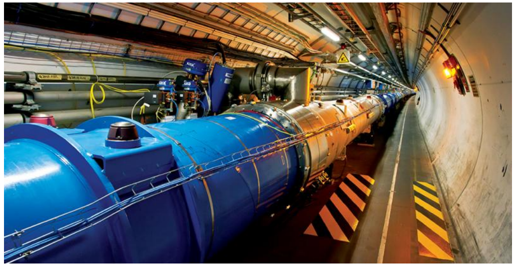
(EPJ Web Conf. 145 (2017) 08001)

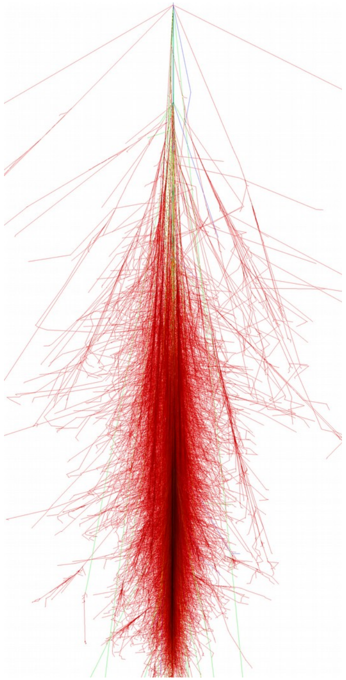
Origin of SIBYLL

First version ~1992

“Slow computers, fast programs”

(IBM)





Minimal requirements:

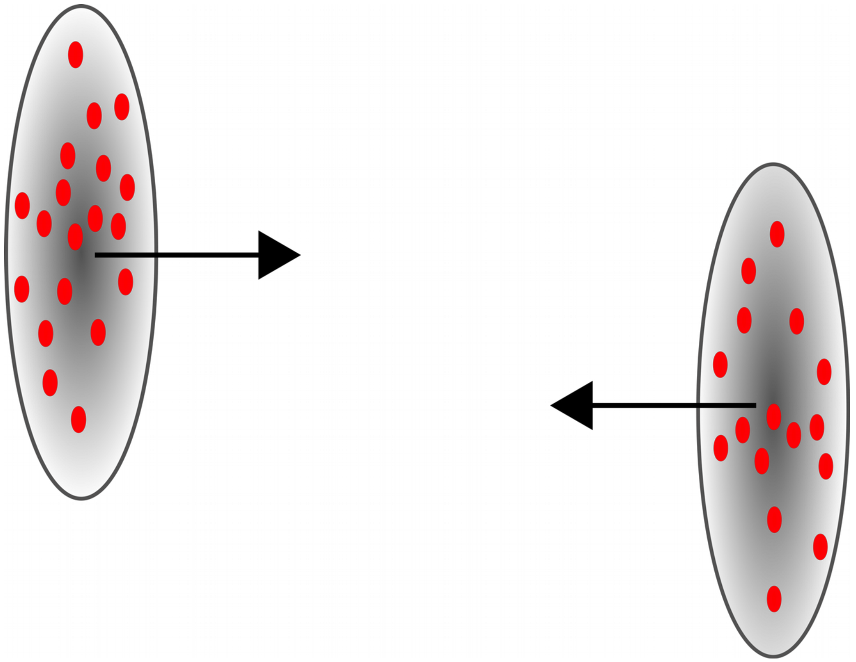
* QCD
* fast program
* Projectiles: p, pi, K and nuclei up to Fe
* ultra-high energies, 150 TeV cm
* Forward phase space

SIBYLL characteristics

QCD inspired

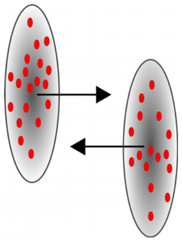
* multiple interactions
* soft & hard scattering
* saturation effects

* diffraction dissociation
* beam remnants
* Glauber picture of nuclear interactions
* string fragmentation



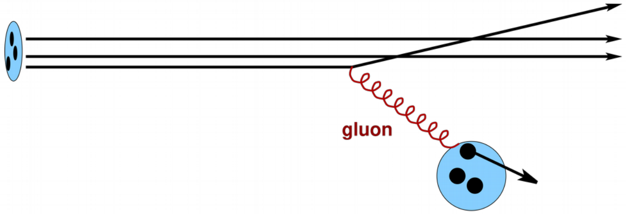
Hadron interactions

non-diffractive

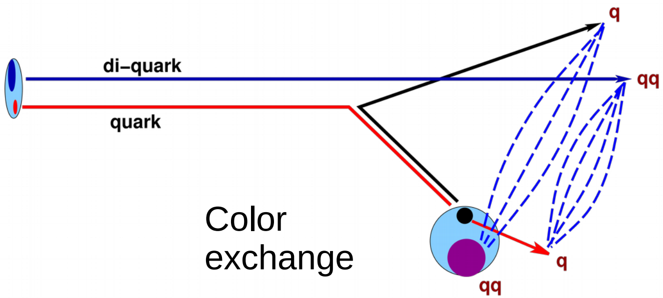


diffractive

Partonic view:

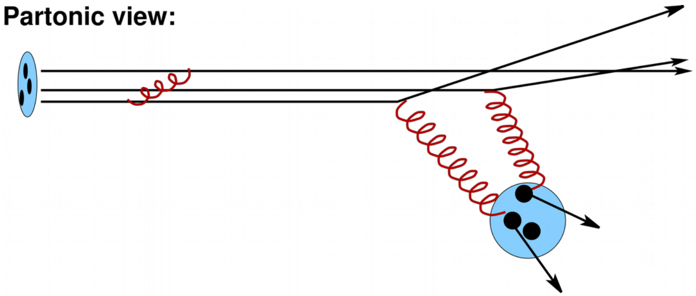


Color flow:

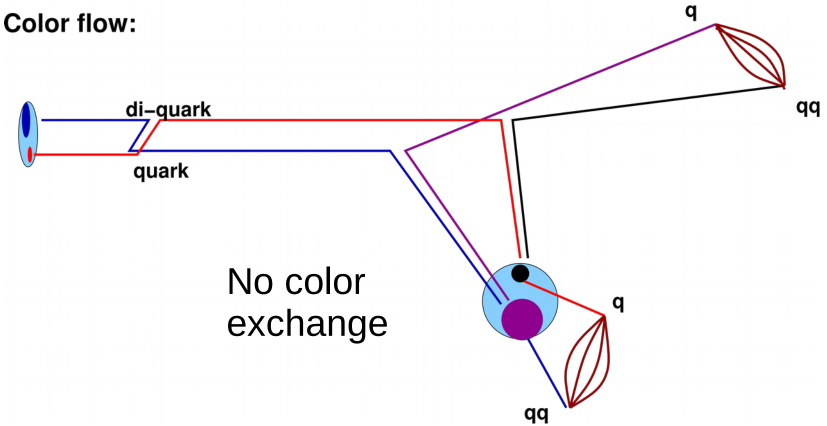


Color exchange

Partonic view:

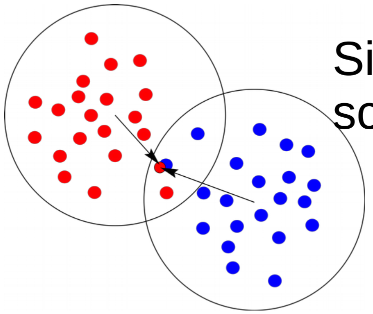


Color flow:

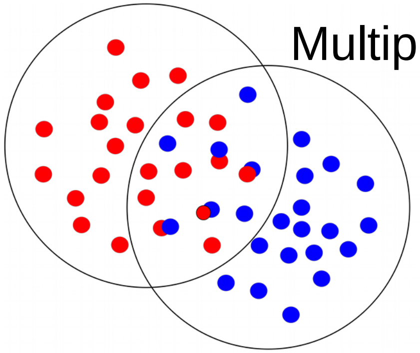


No color exchange

Non-diffractive interactions



Single
scattering

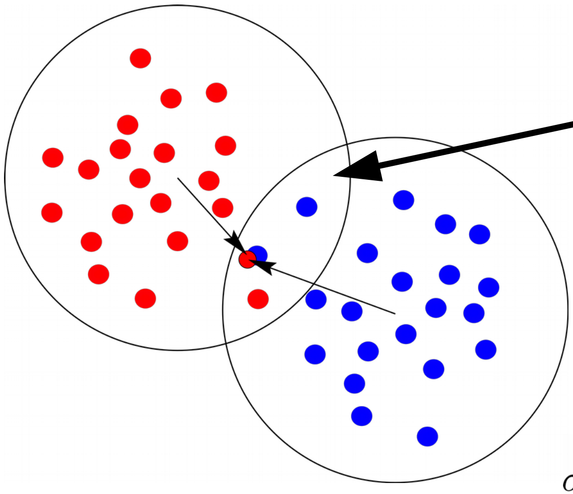


Multiple scattering

Event creation

1. number of parton interactions
2. parton momenta & color flow
3. hadronize

1. Number of interactions



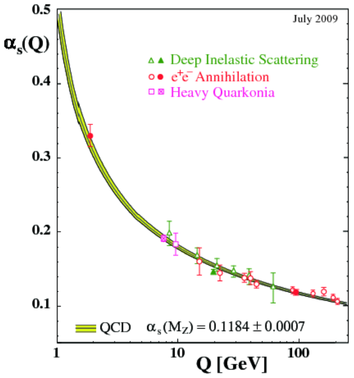
Overlap region

Parton-parton interaction probability

$$n(\vec{b}, s) = A(\vec{b}, s)\, \sigma_{\mathrm{QCD}}(s)$$

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

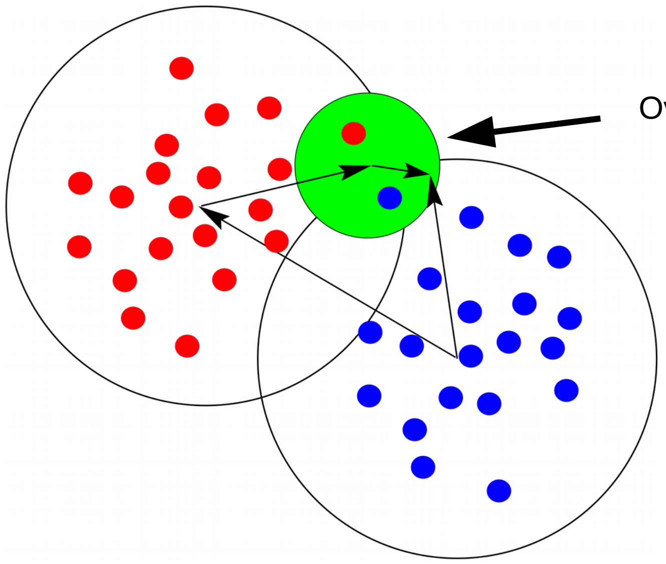
Parameters: $K, p_{\mathrm{T}}^{\mathrm{min}}, \nu_{\mathrm{h}}$



Problem!

non-perturbative

1. Number of interactions



Overlap region

Parton-parton interaction probability

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

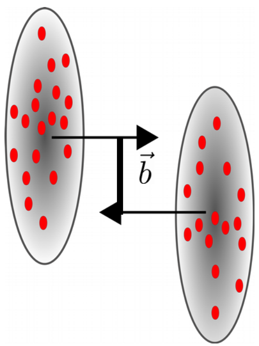
soft interaction, extended!

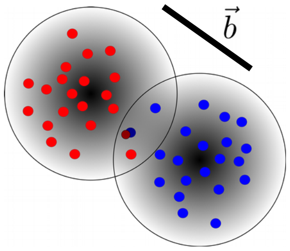
$$\sigma_{\rm soft}(s) = \mathcal{A}\left(\frac{s}{s_0}\right)^{-\epsilon} + \mathcal{B}\left(\frac{s}{s_0}\right)^{\Delta}$$

(Donnachie, Landshoff)

Parameters: 4 sigma + 3 profile

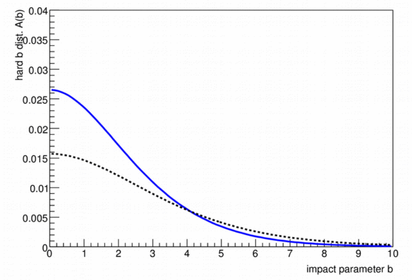
1. number of interactions





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

Take nucleon shape from experiment

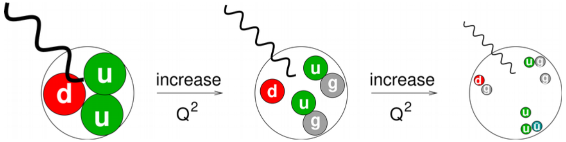


$$\langle n(\vec{b}, s)\rangle = n_{\mathrm{soft}} + n_{\mathrm{hard}}$$

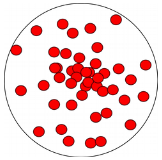
Independent scatterings → Poisson

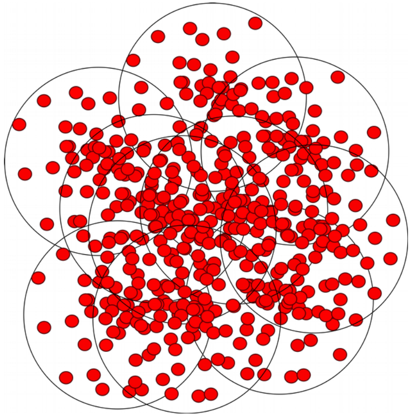
$$P_n(\vec{b}) = \frac{\langle n(\vec{b})\rangle^n}{n!} \exp\left(-\langle n(\vec{b})\rangle\right)$$

High parton densities



(Salam)





→ saturation of binary scattering !

$$\pi r_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

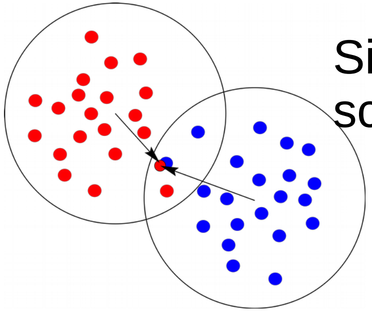
Gluon-gluon cross section

Gluon number density

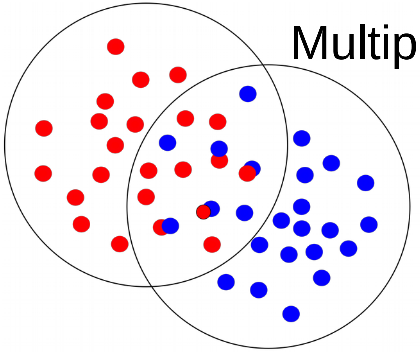
$$Q_s^2 \approx p_{\mathrm{T}}^2$$

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

Non-diffractive interactions



Single
scattering



Multiple scattering

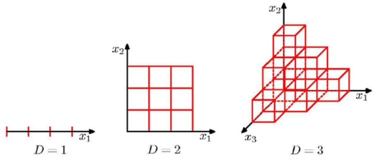
Event creation

1. number of parton interactions
   → soft & hard
   → saturation
2. parton momenta & color flow
3. hadronize

2. Parton momenta

$$P_n(\vec{b}) \to \frac{\mathrm{d}^{2n} P(\vec{b})}{\mathrm{d}x_1^1 \mathrm{d}x_2^1 \dots \mathrm{d}x_2^n}$$

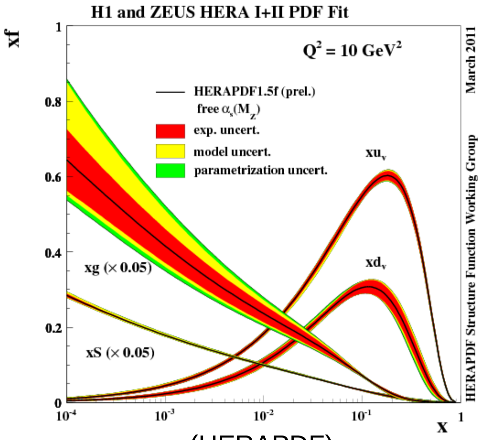
2n+1
dimensional p.d.f



→ factorize! drop correlations x ↔ b ↔ n

$$P_n(\vec{b}) \to P_n = \int \mathrm{d}^2\vec{b}\, P_n(\vec{b})$$

→ sample n → sample x



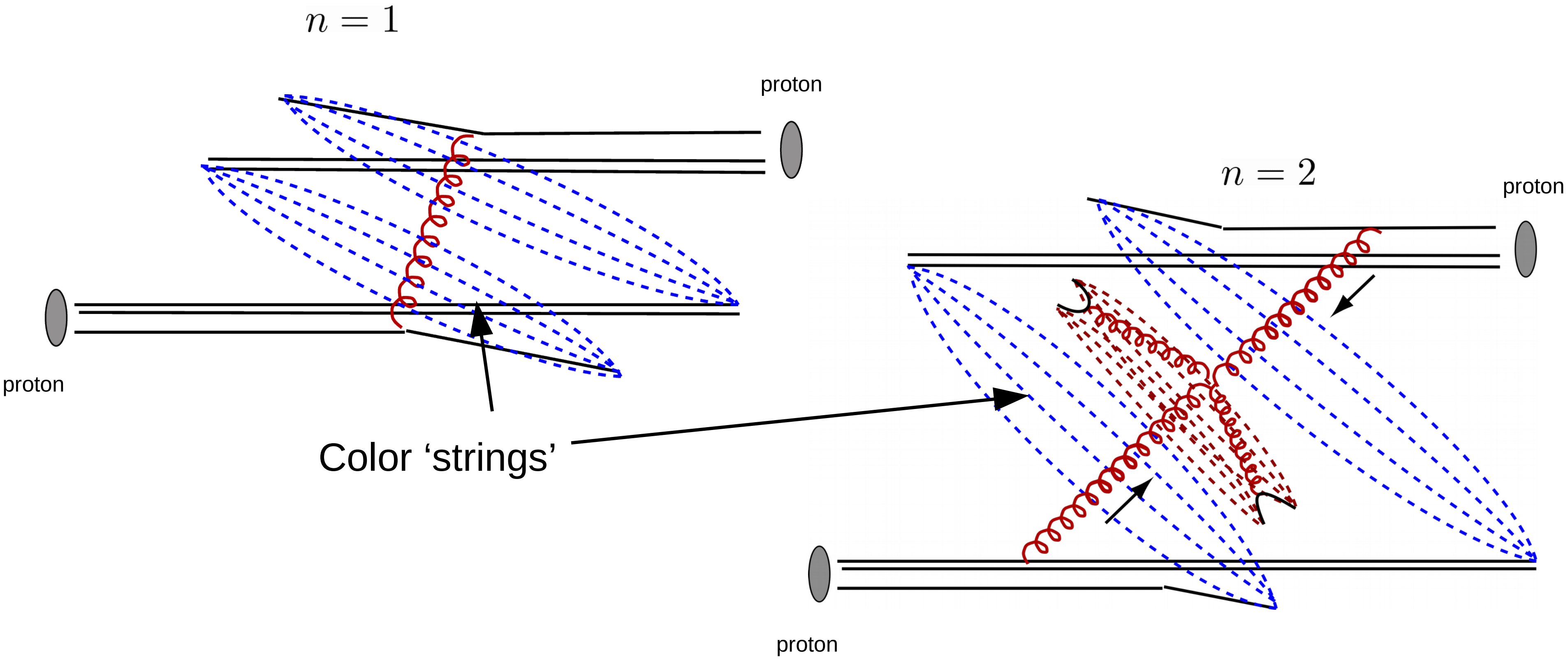
(HERAPDF)

QCD features of interest: rise of cross section, multiplicity, pT → jets

→combine u:d:s:c:g → partons

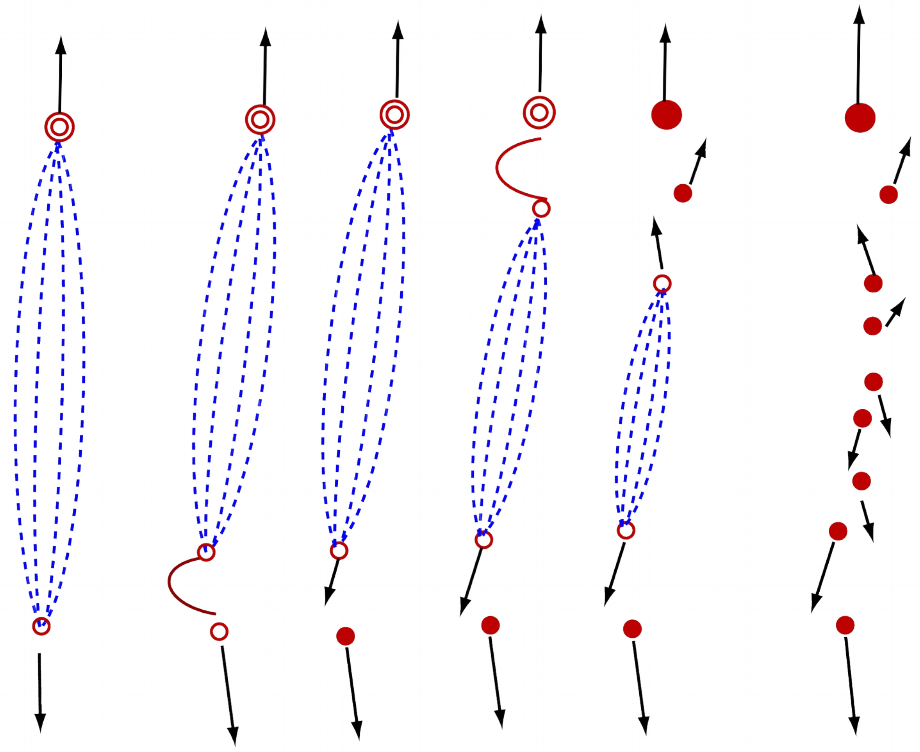
$$f(x) = g(x) + \frac{4}{9}[q(x) + \bar{q}(x)]$$

2. simplified color flow



etc.

3. hadronization



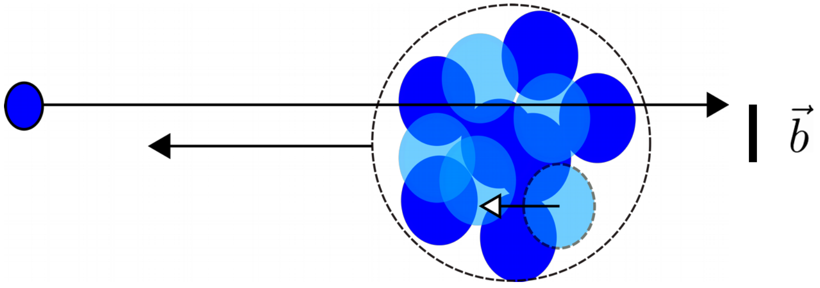
String fragmentation

$$f(z) = \frac{(1-z)^{\alpha}}{z} e^{-b m_{\mathrm{T}}/z}$$

flavors: u,d,s

+ Flavor parameters

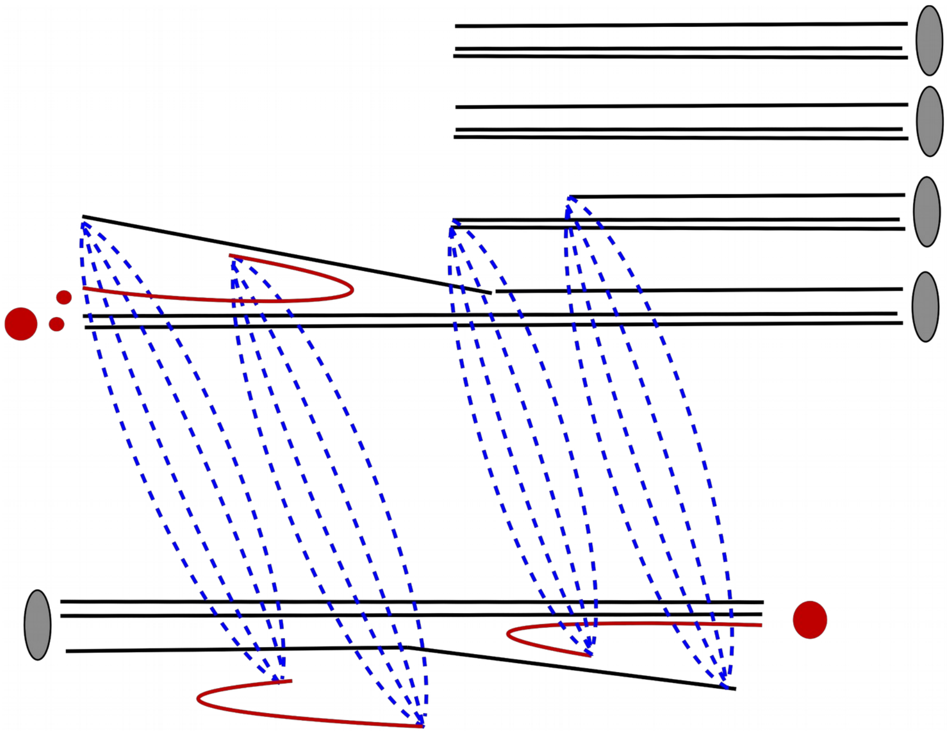
Nuclear interactions



(Glauber)

$$\sigma_{\rm prod} \approx \int {\rm d}\vec{b} \left[1 - \exp\left\{-\sigma_{\rm tot}^{NN} T(\vec{b})\right\}\right]$$

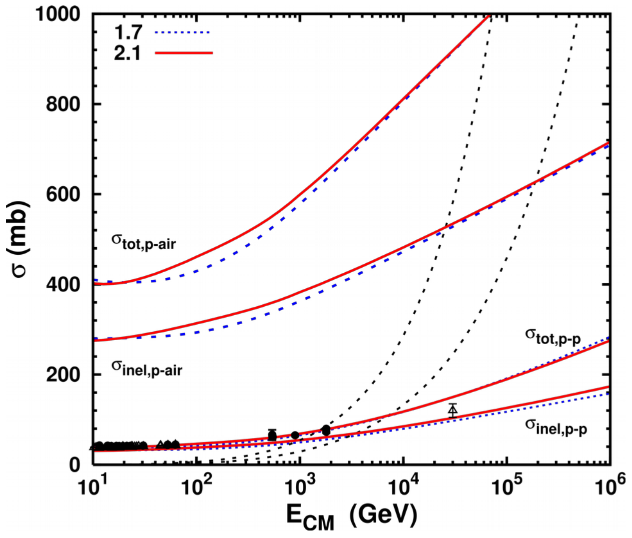
Nucleus profile function



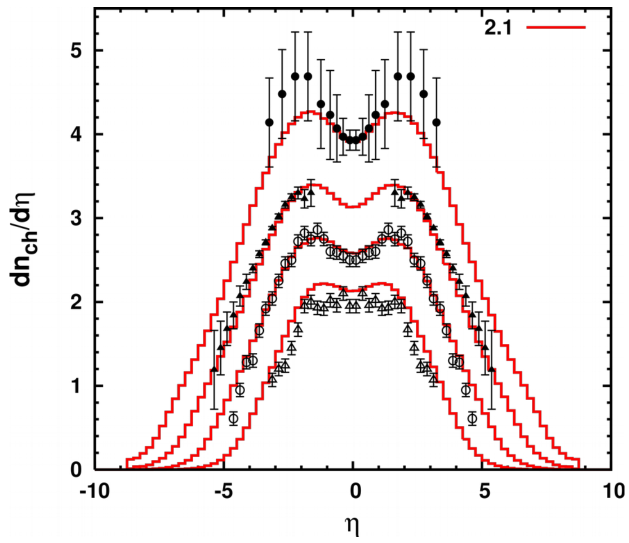
$+n_{\rm hard}, n_{\rm soft}$

Model performance

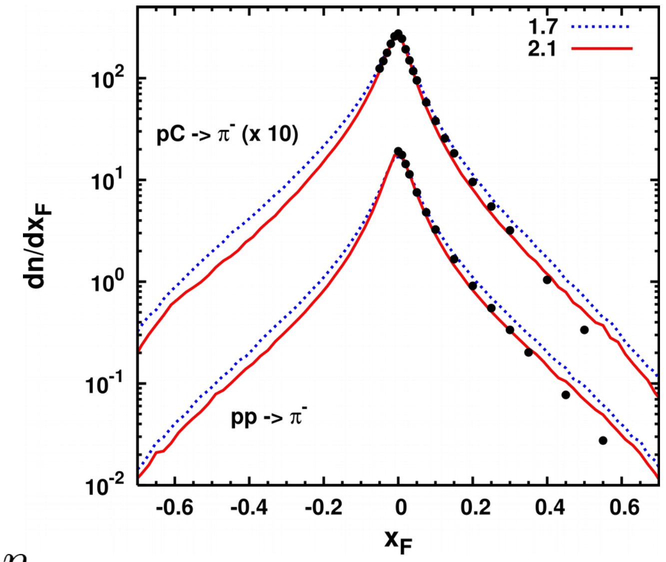
$$\sigma_{\text{inel}} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_n(\vec{b}) = \int d^2\vec{b} \left(1 - \exp\{-\langle n(\vec{b})\rangle\}\right)$$

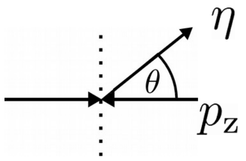


(CDF, UA5, NA22)



(NA49)





Sibyll 2.1

tuned to TeVatron

Sibyll 2.1 → Sibyll 2.3c

* LHC measurements

* baryon pair production

* beam remnants

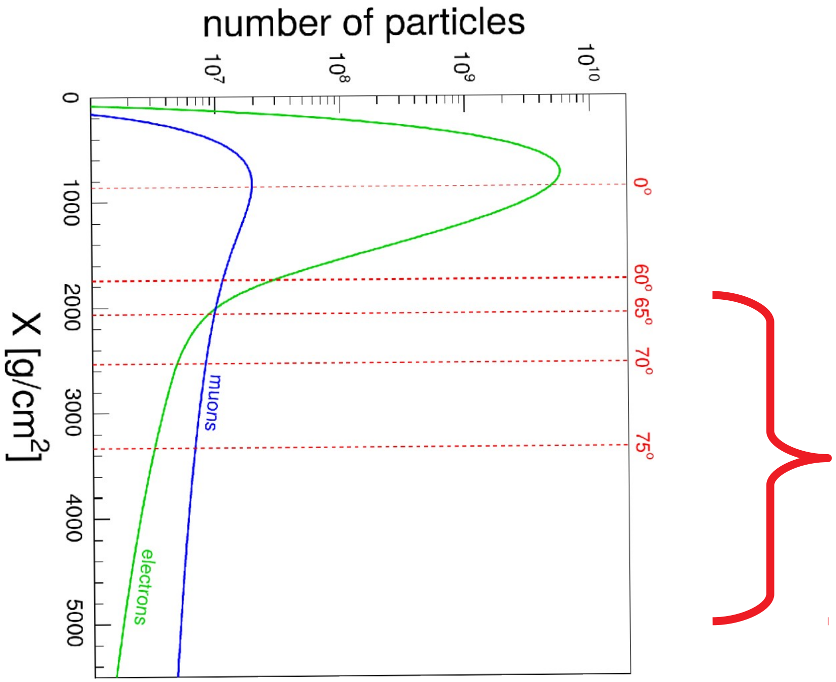
* charm production

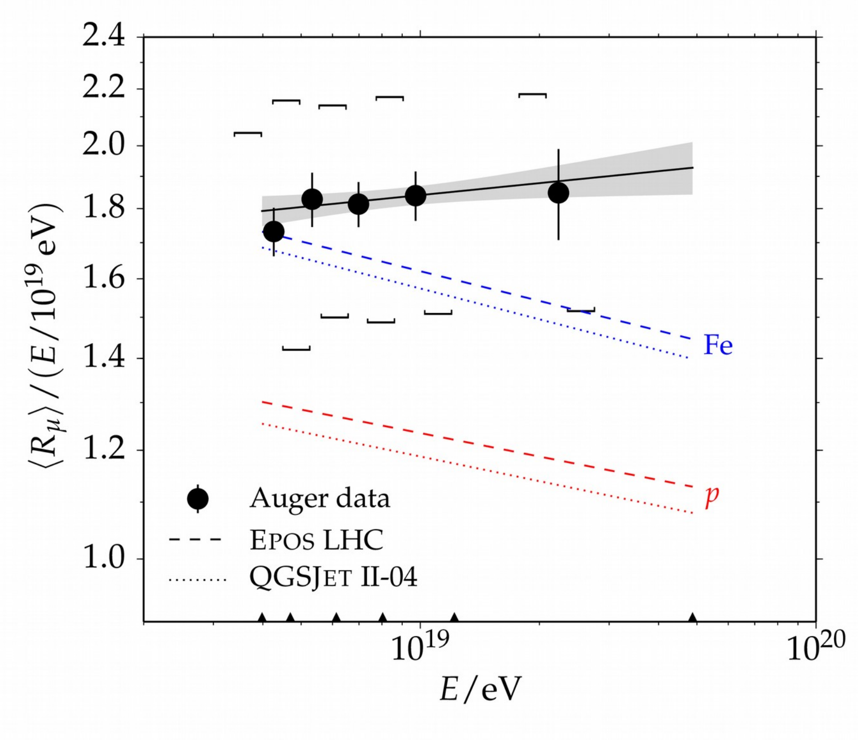
Why bother ?

EPOS-LHC & QGSjet surely cover all physics in more detail !

→ All models have problems describing extensive air showers consistently !

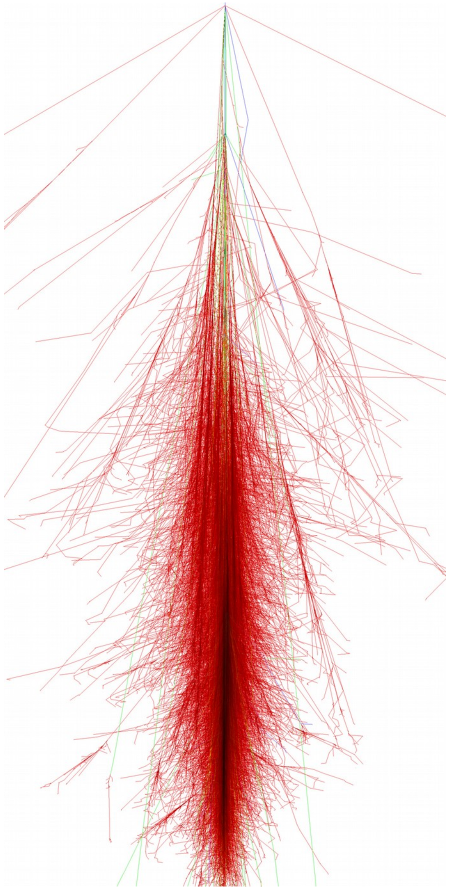
EAS performance: muons





(Auger, Phys. Rev. D, 91, 032003 (2015))

Muons in EAS



Cascade of
hadron interactions

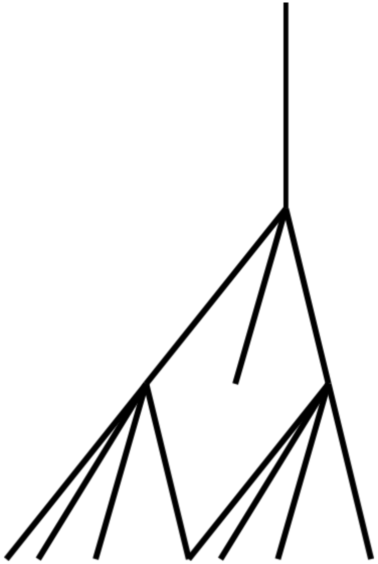
⬇

Meson decays

⬇

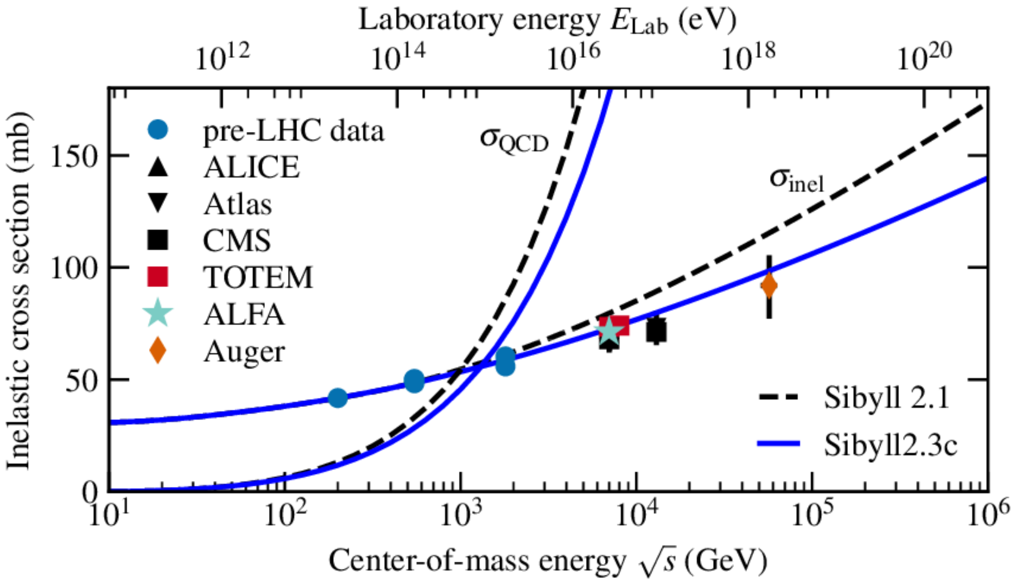
Muons

$$\langle N_\mu \rangle \sim E^\beta$$

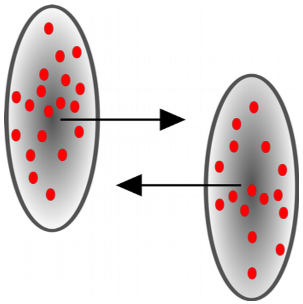


(Astro. Part.Ph 22, 387, 2005)

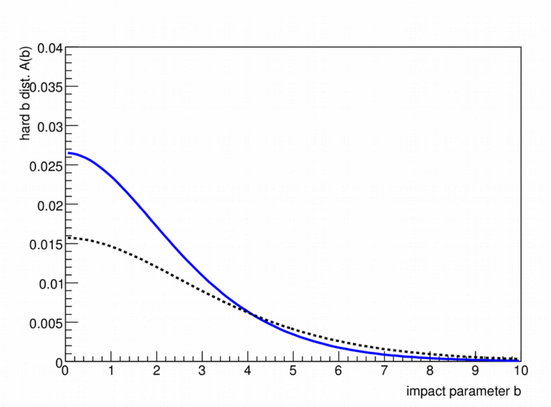
Cross section: p-p



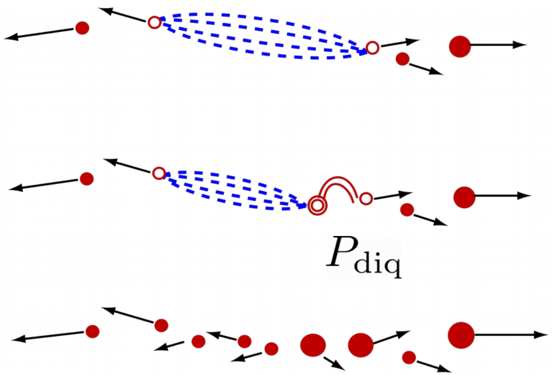
Sibyll 2.1 from 2001
(TeVatron)

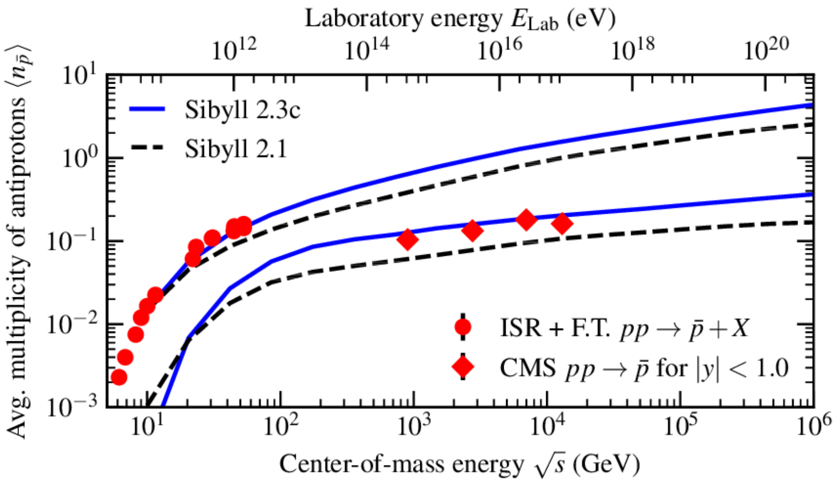


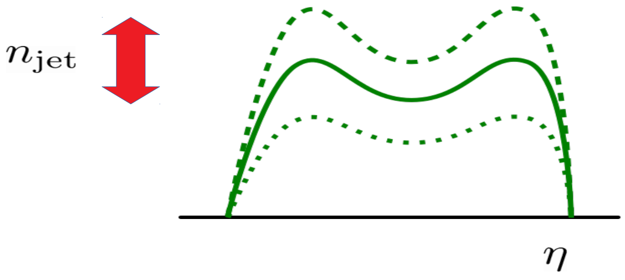
- narrow hadron profile
- increase soft-hard threshold

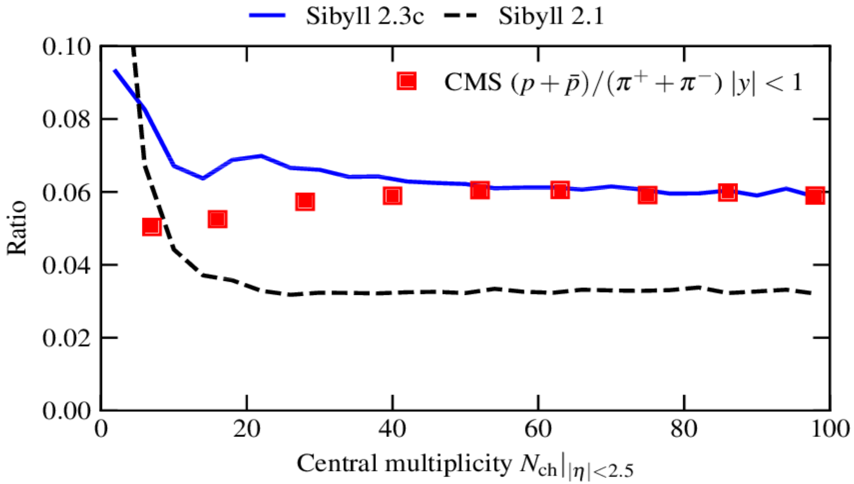


Baryon production

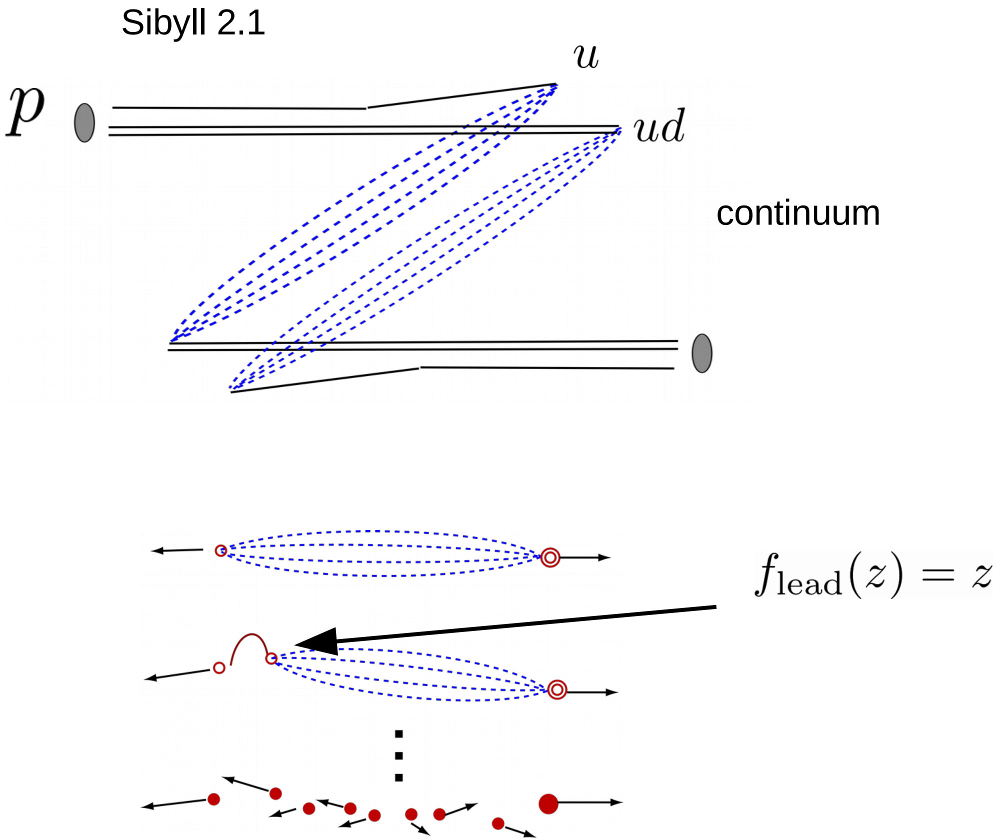


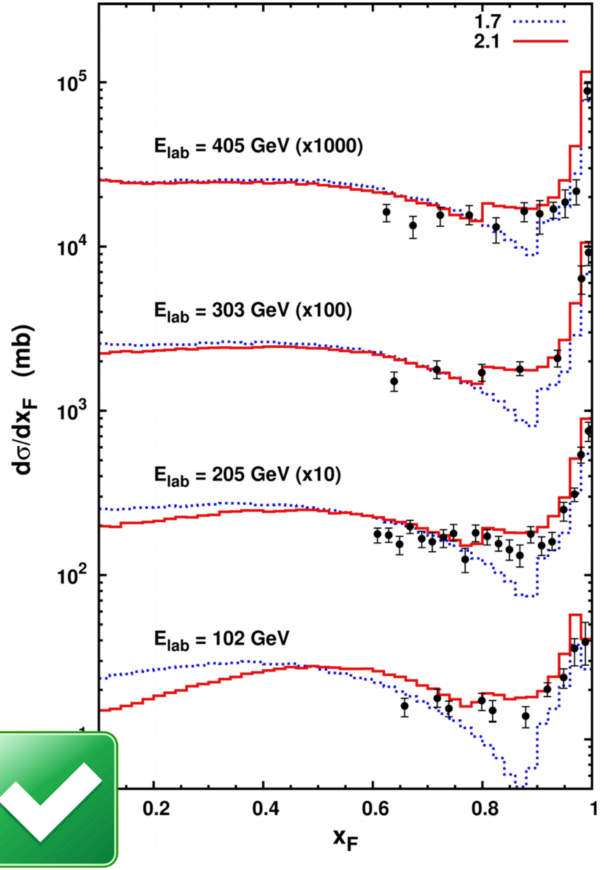




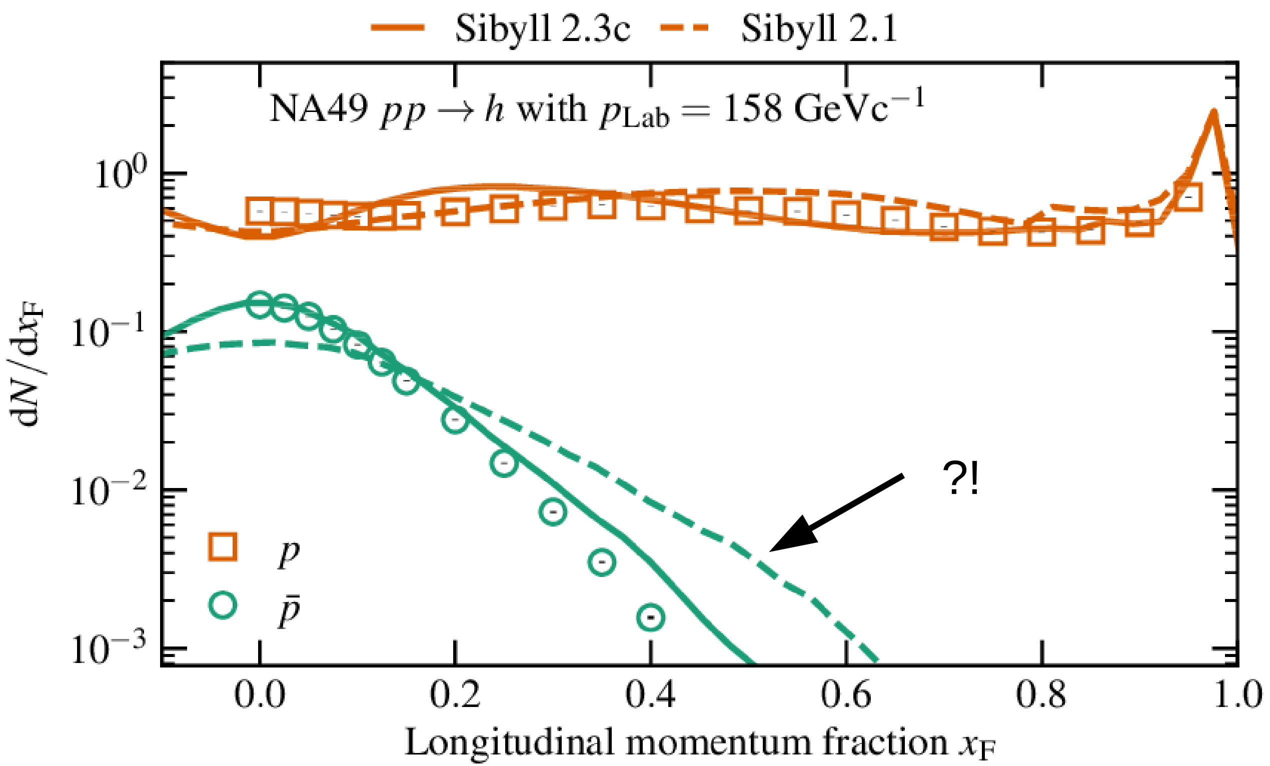


Leading particles





Leading particles I

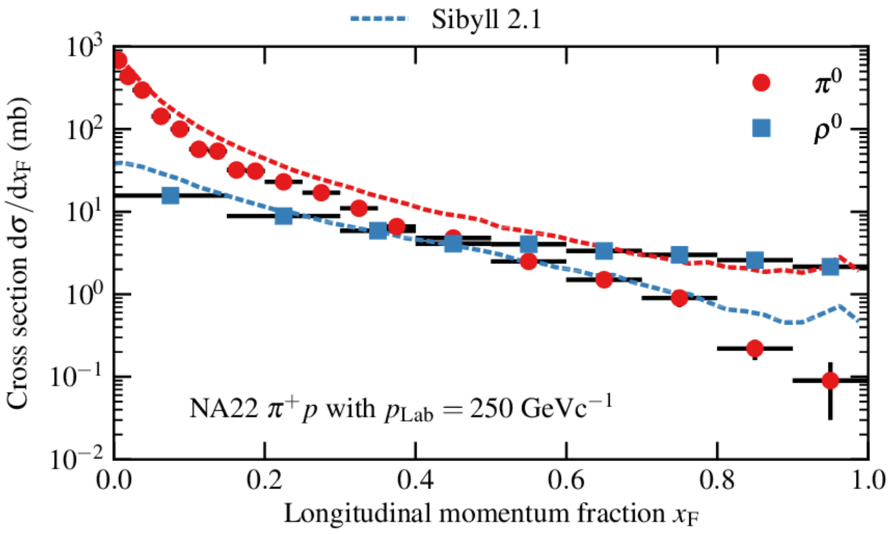


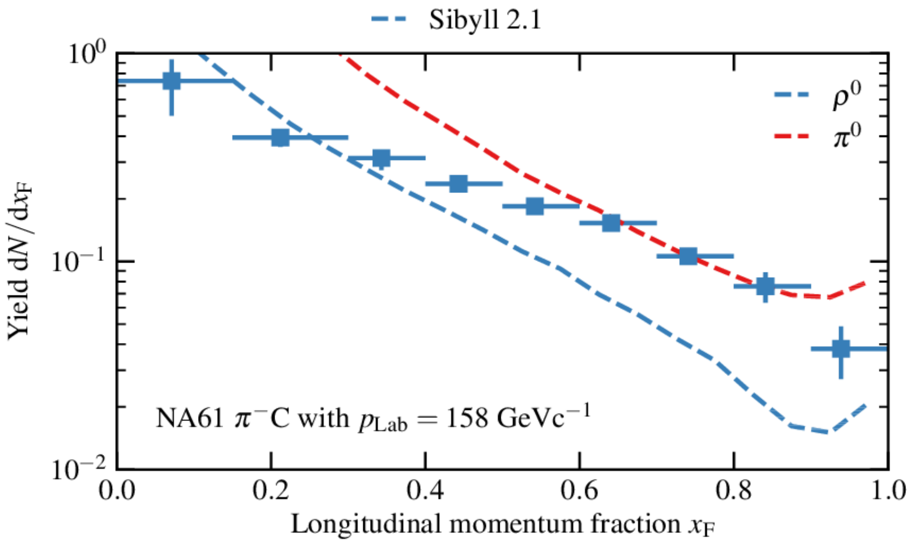
Leading particles II

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

$\text{leading} : \pi, \ \rho$

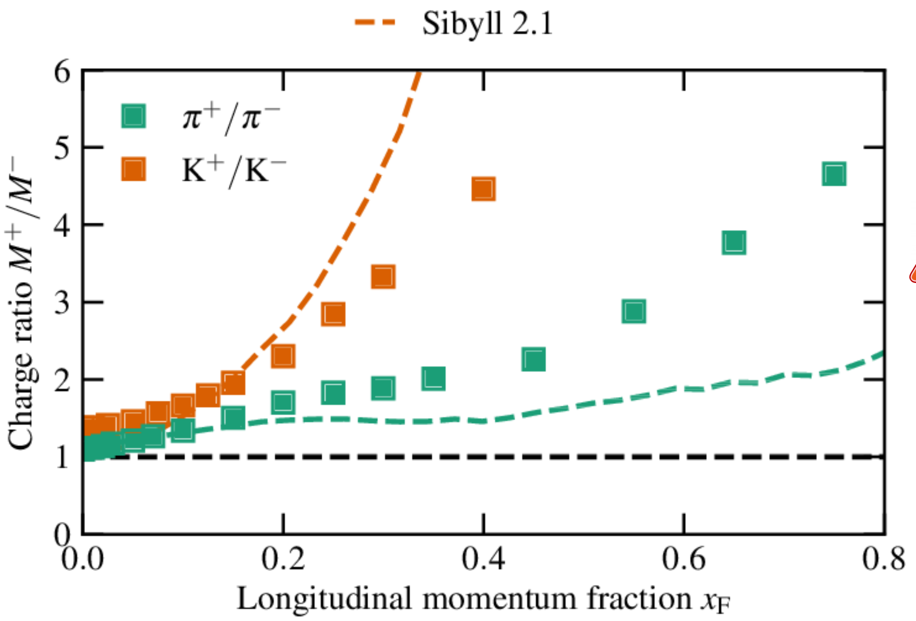
$\pi \text{Air?}$





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

Leading particles III



Directly affects muon charge ratio in atmosphere

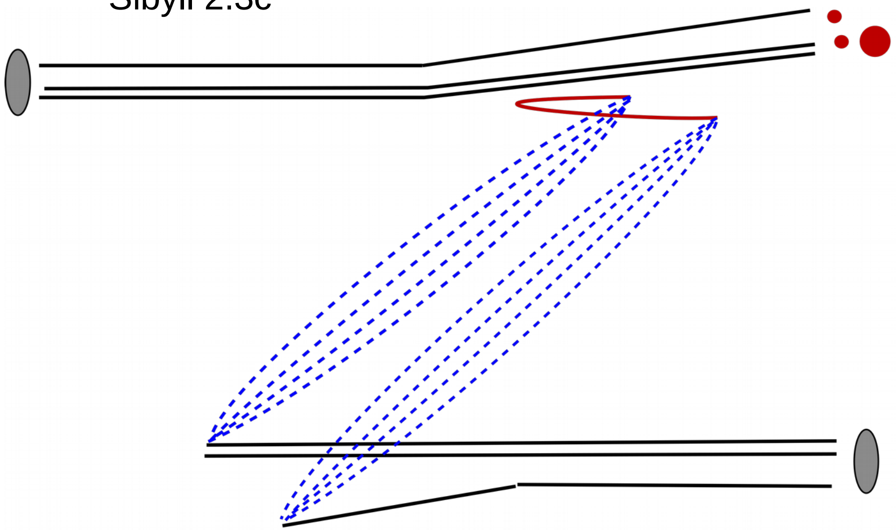
See lecture by A. Fedynitch on Thursday

Need more freedom for leading

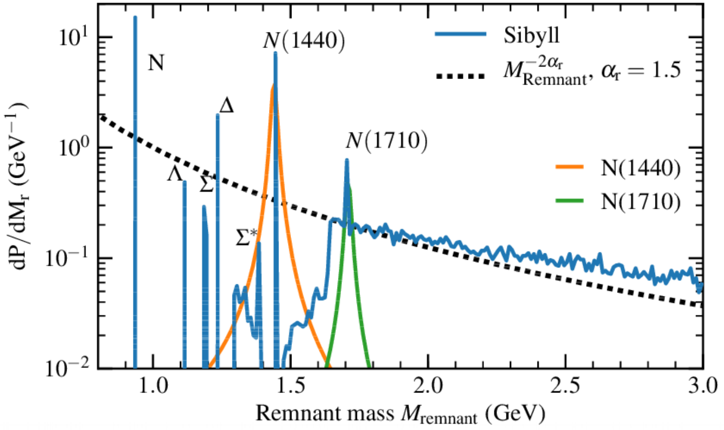
Beam remnants

Continuum + discrete excitations

Sibyll 2.3c

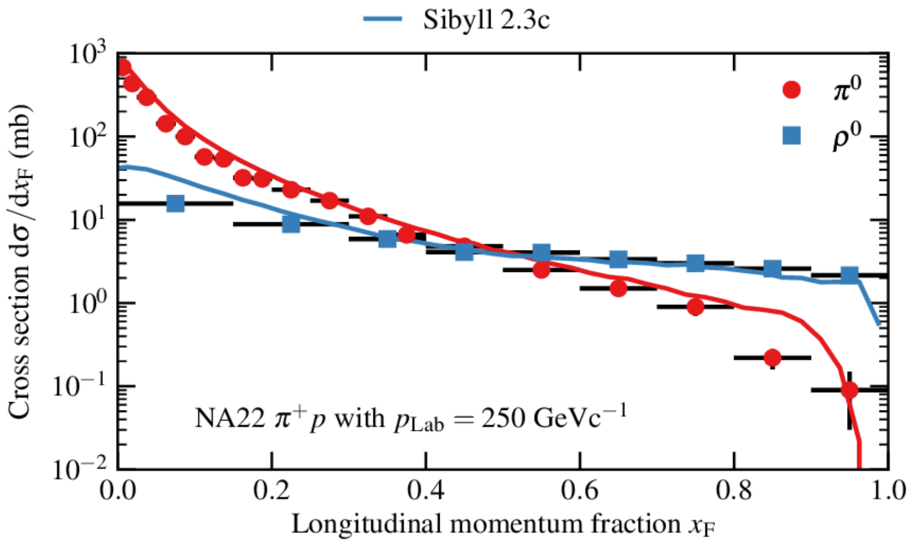


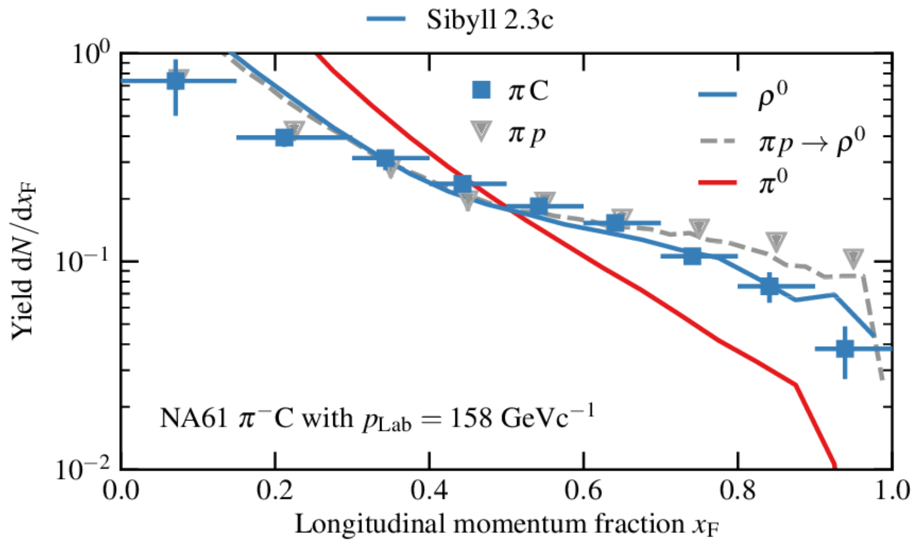
(Drescher et al., Werner et al.)



	Δ^{++}	Δ^{+}	N^{+}	Δ^{0}	N^{0}	Δ^{-}
$\pi^+ p$	1					
$\pi^+ n$		1/3	2/3			
$\pi^0 p$		2/3	-1/3			
$\pi^0 n$				2/3	1/3	
$\pi^- p$				1/3	-2/3	
$\pi^- n$						1

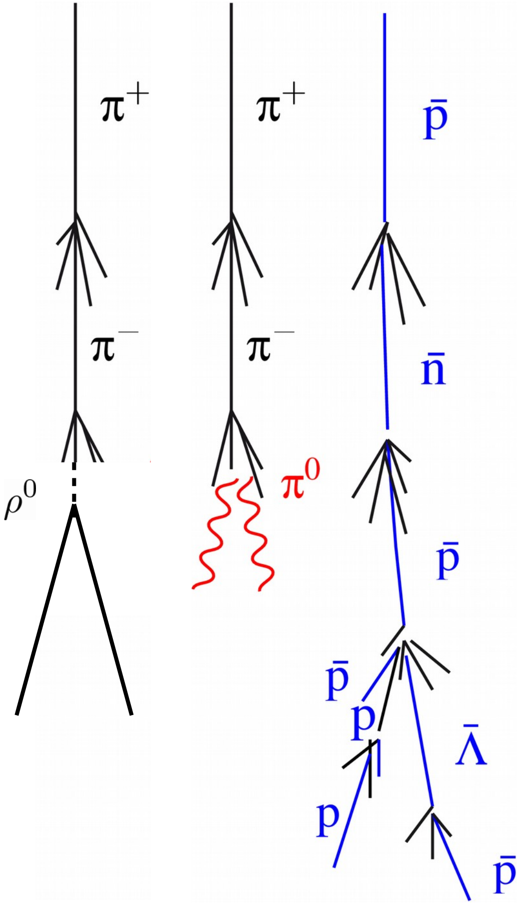
Leading Rho



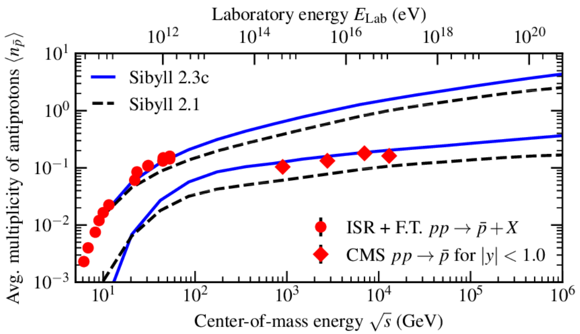


p → C

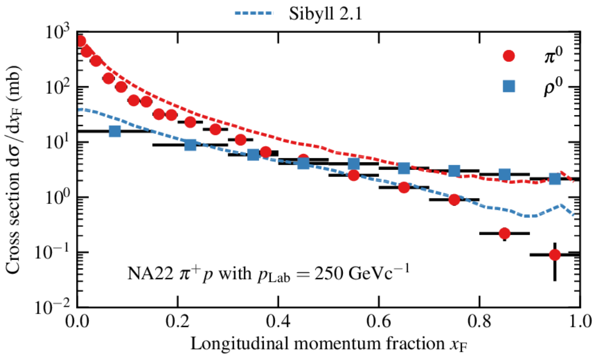
Air shower model? Leading important?

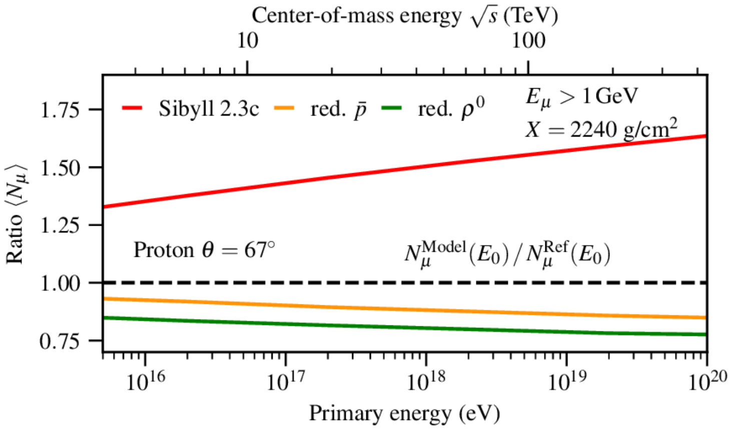


* Baryon production



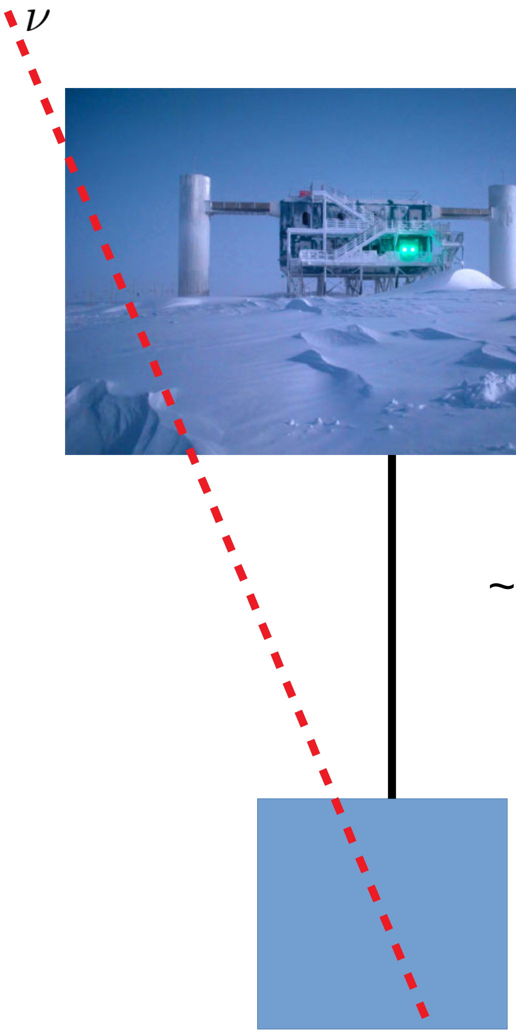
* leading rho0





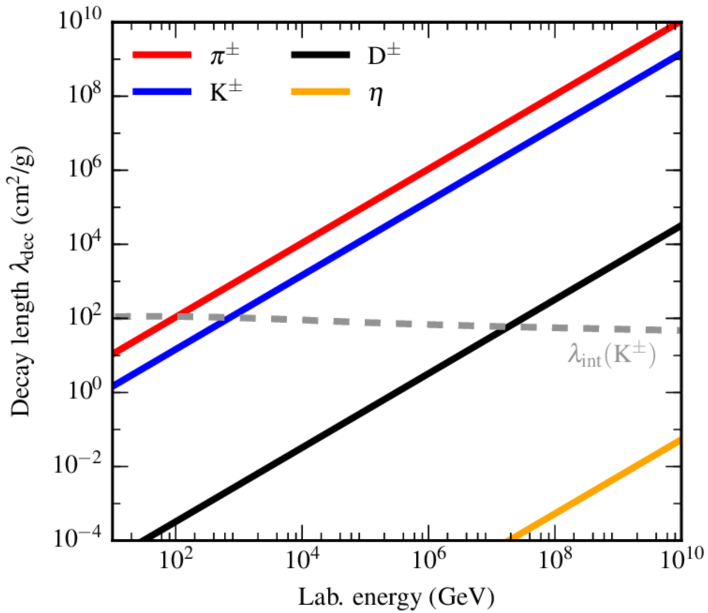
Charm production

Why charm ?



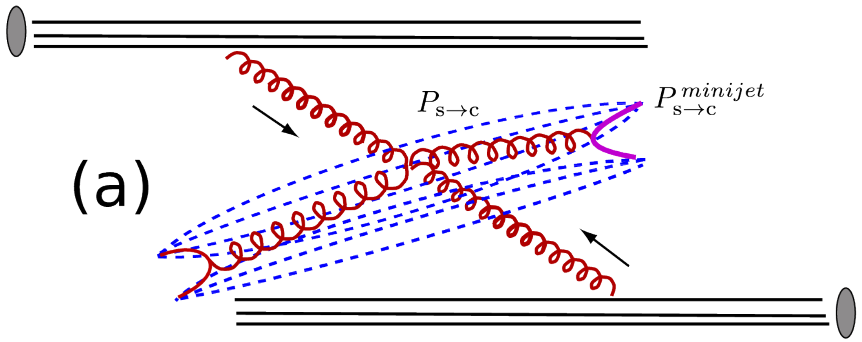
→ high energy muon/neutrinos ~ PeV

~2km → E_thr !



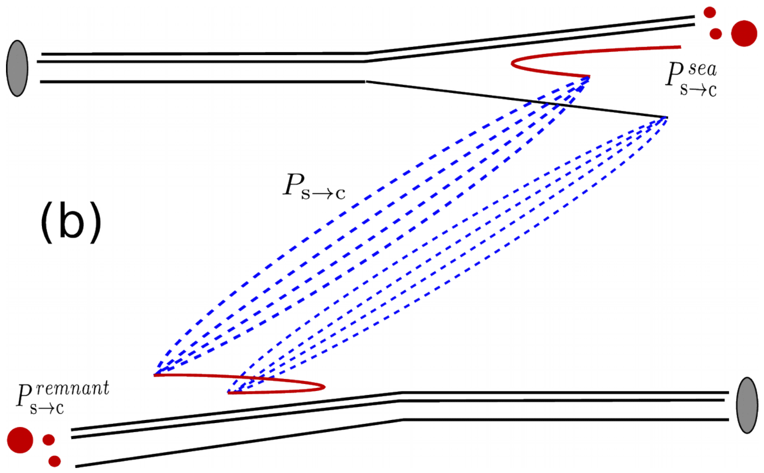
Dominant source → charm! (or astro)

Charm production



$m_c \approx 2\,\mathrm{GeV} \;\rightarrow\; \mathrm{pQCD} \;\rightarrow\; \mathrm{minijets}$

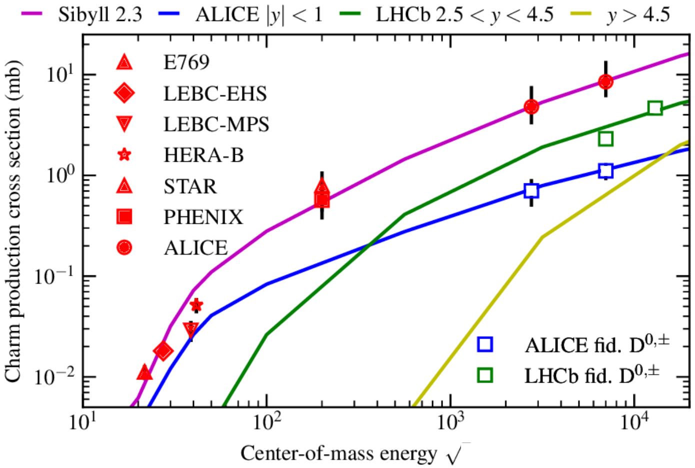
Evidence for leading,
soft charm

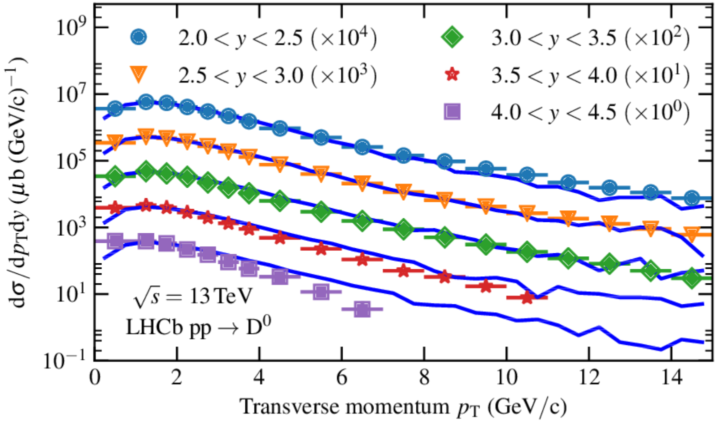


Mechanism:
Replace strange → charm

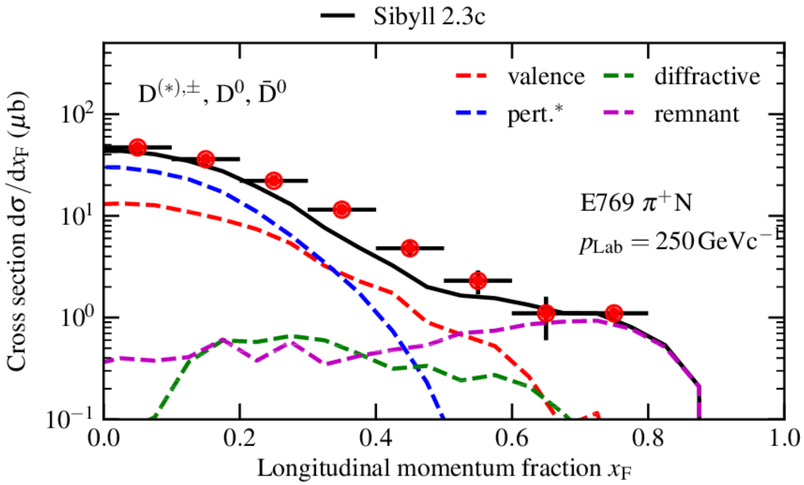
$P_{s\to c}$

Charm tuning





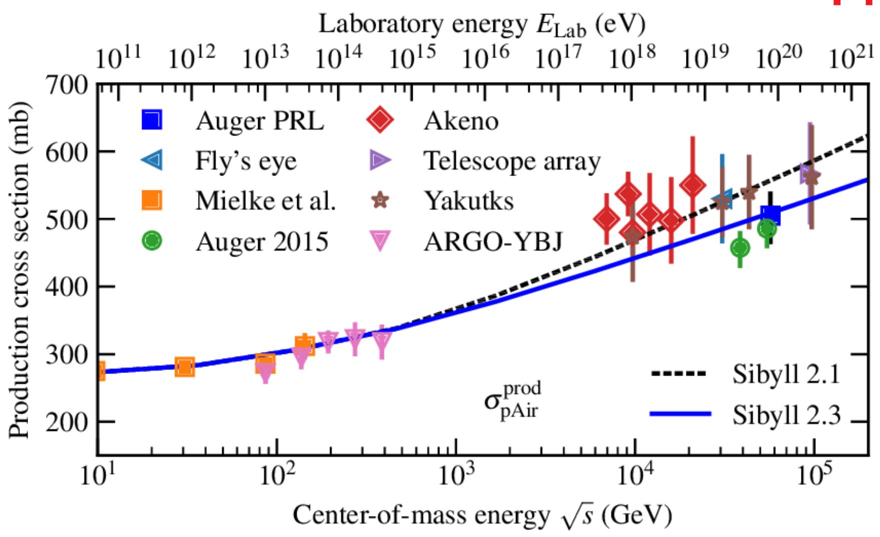
parameter	value
perturbative	
$P^{\mathrm{minijet}}_{\mathrm{s}\to\mathrm{c}}$	0.08
non-perturbative	
$P^{\mathrm{soft}}_{\mathrm{s}\to\mathrm{c}}$	0.004
$P^{\mathrm{sea}}_{\mathrm{s}\to\mathrm{c}}$	0.002
$P^{\mathrm{remnant}}_{\mathrm{s}\to\mathrm{c}}$	0.0
$P^{\mathrm{string}}_{\mathrm{s}\to\mathrm{c}}$	0.004



Fixed target
Determine spectral shape!

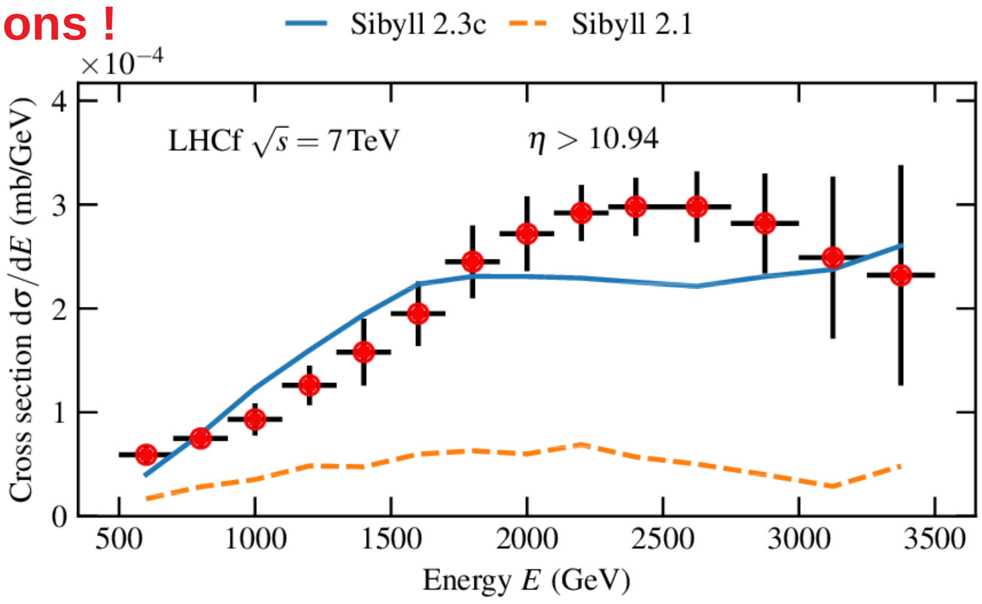
Performance tests

p-air cross section



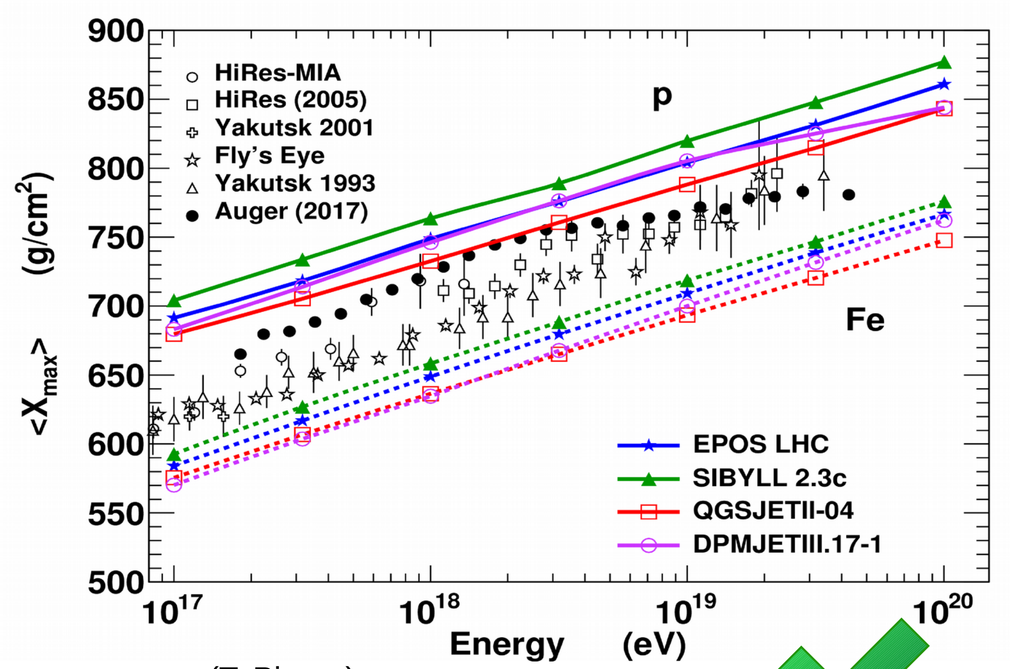
Predictions !

Leading neutrons



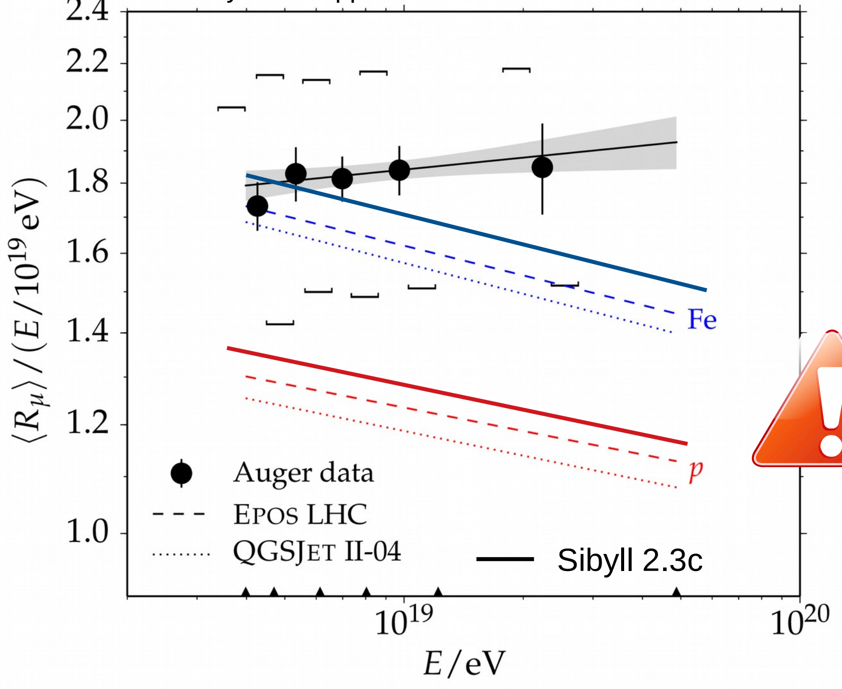
Nice ! Perfect model for air showers?

Predictions for EAS ?



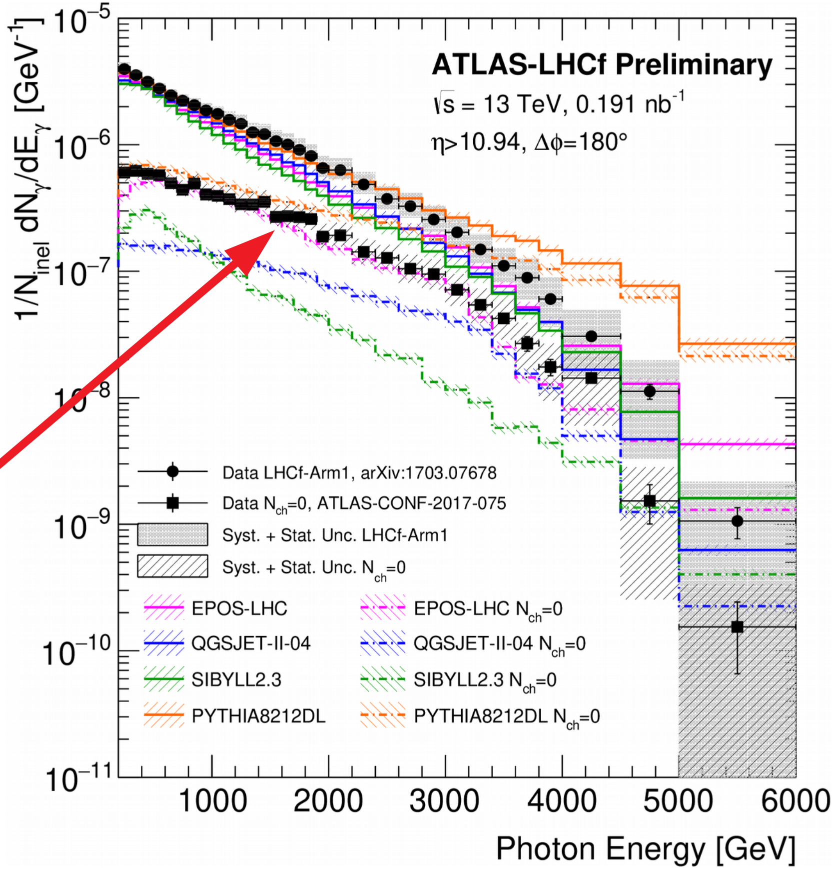
(T. Pierog)

Sibyll lines approx: S.Sciuto



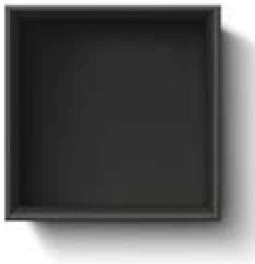
(Auger, Phys. Rev. D, 91, 032003 (2015))

Opportunities for improvements



Selection of Diffraction !

Summary



SIBYLL is a fast event generator for hadronic interactions

* LO QCD jets
* saturation
* string fragmentation
* beam remnant model

→ describes overall features of hadronic particle production

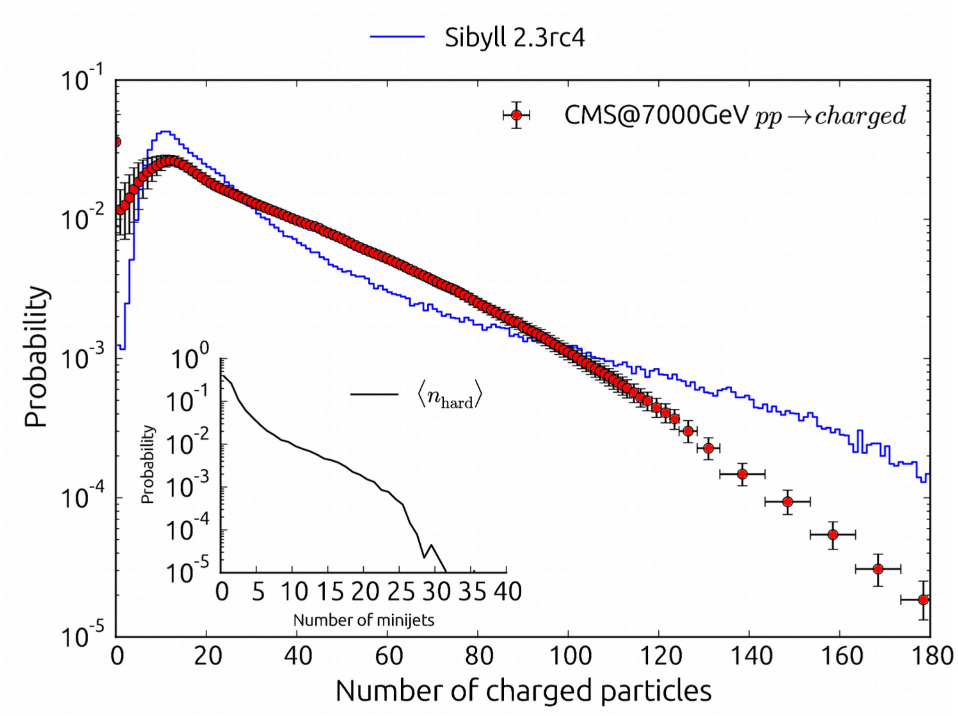
Special feature for CR models: * charm production

* Prediction of shower maximum consistent
* Muon production still problematic

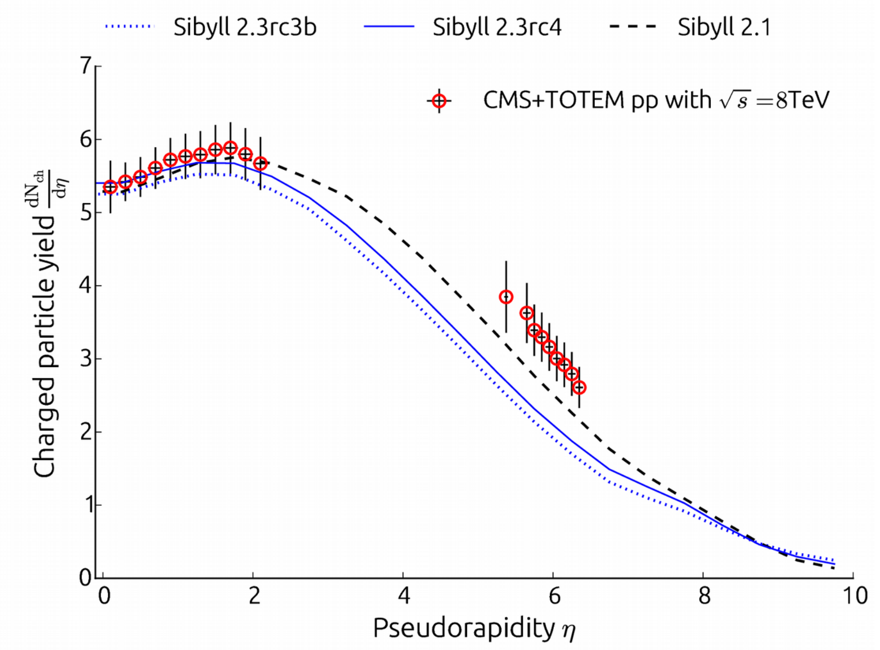
==> no strong evidence that SIBYLL is NOT sufficient to describe EAS

Opportunities for improvements (problems)

Structural → revision of interaction picture (b-dependent saturation)

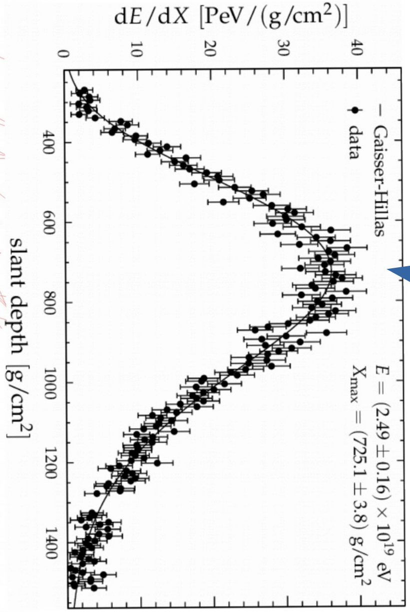


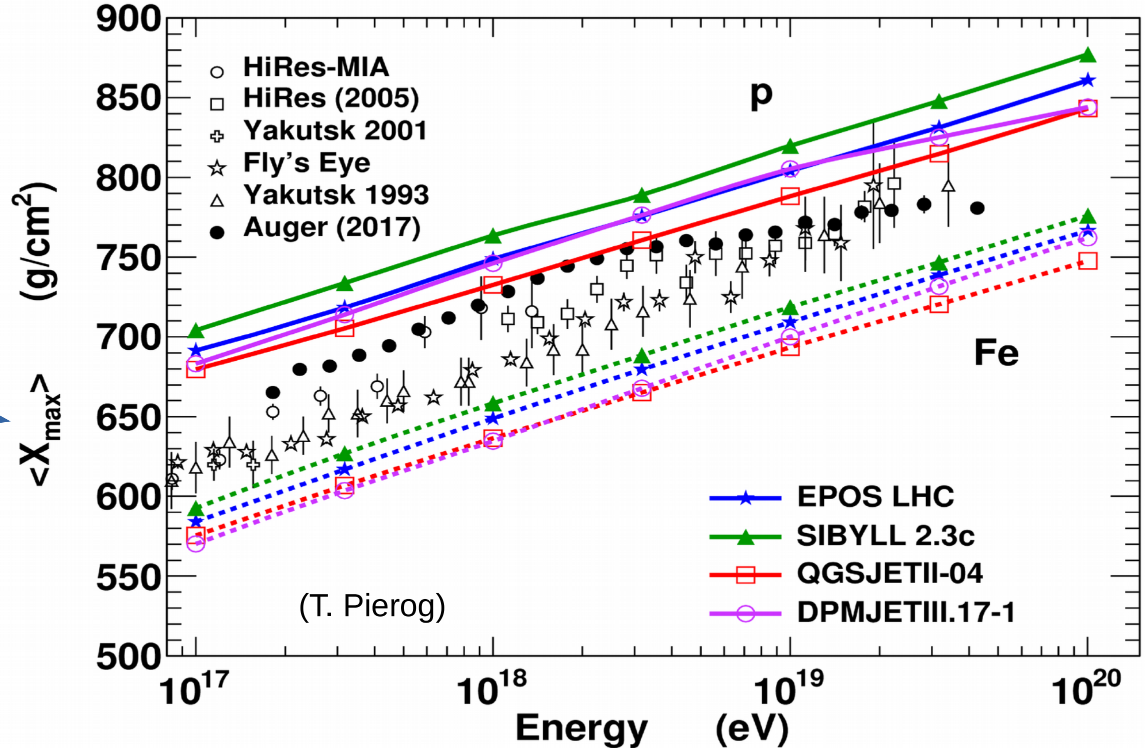
Structural → no DGLAP, extreme factorization ↔ inconsistent with modern (LHC) PDFs



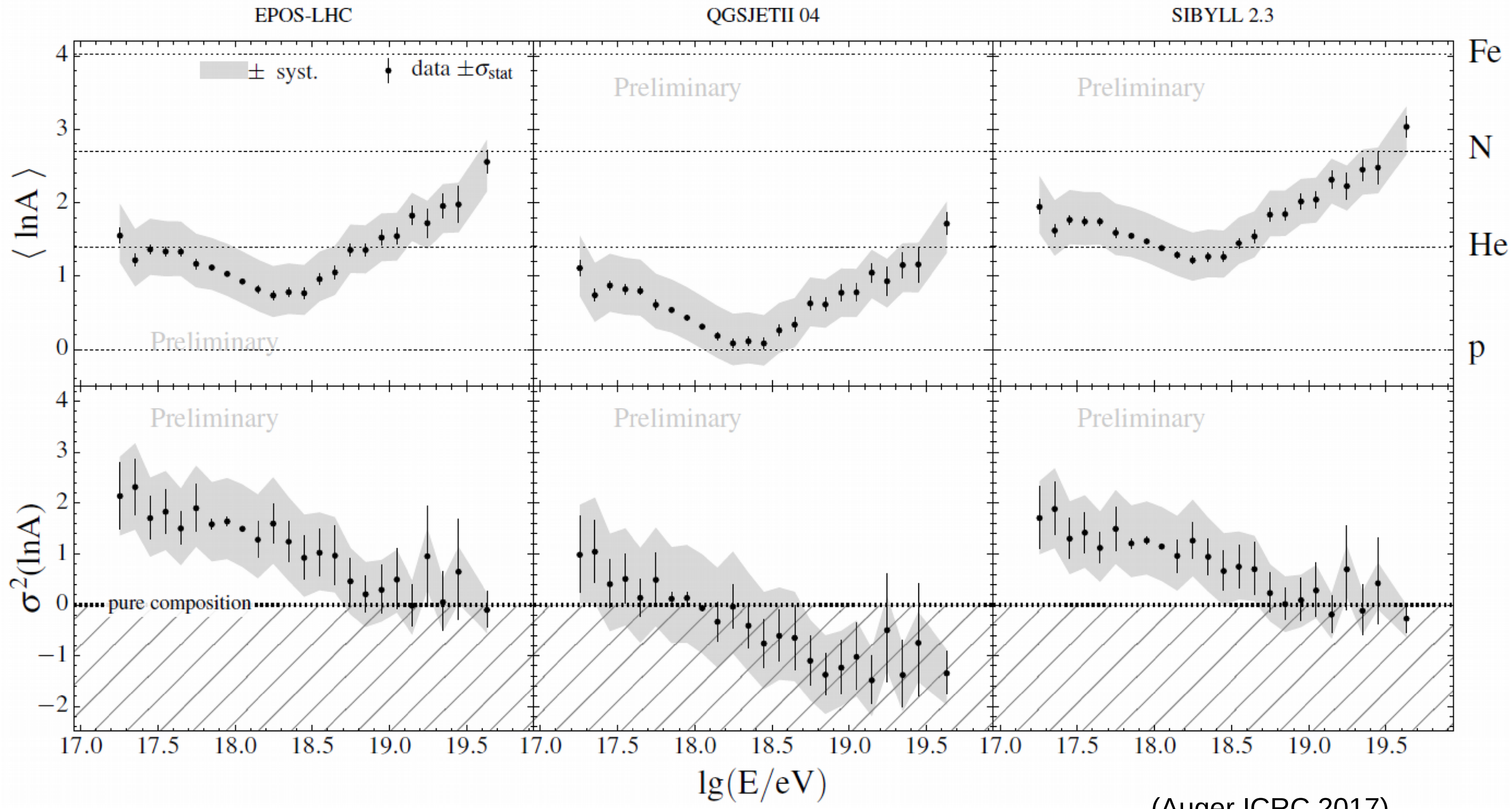
Does it matter? EAS performance

See P. Lipari talk





EAS performance: consistency



(Auger ICRC 2017)