Hadronic multiparticle production in SIBYLL – from LHC to air showers

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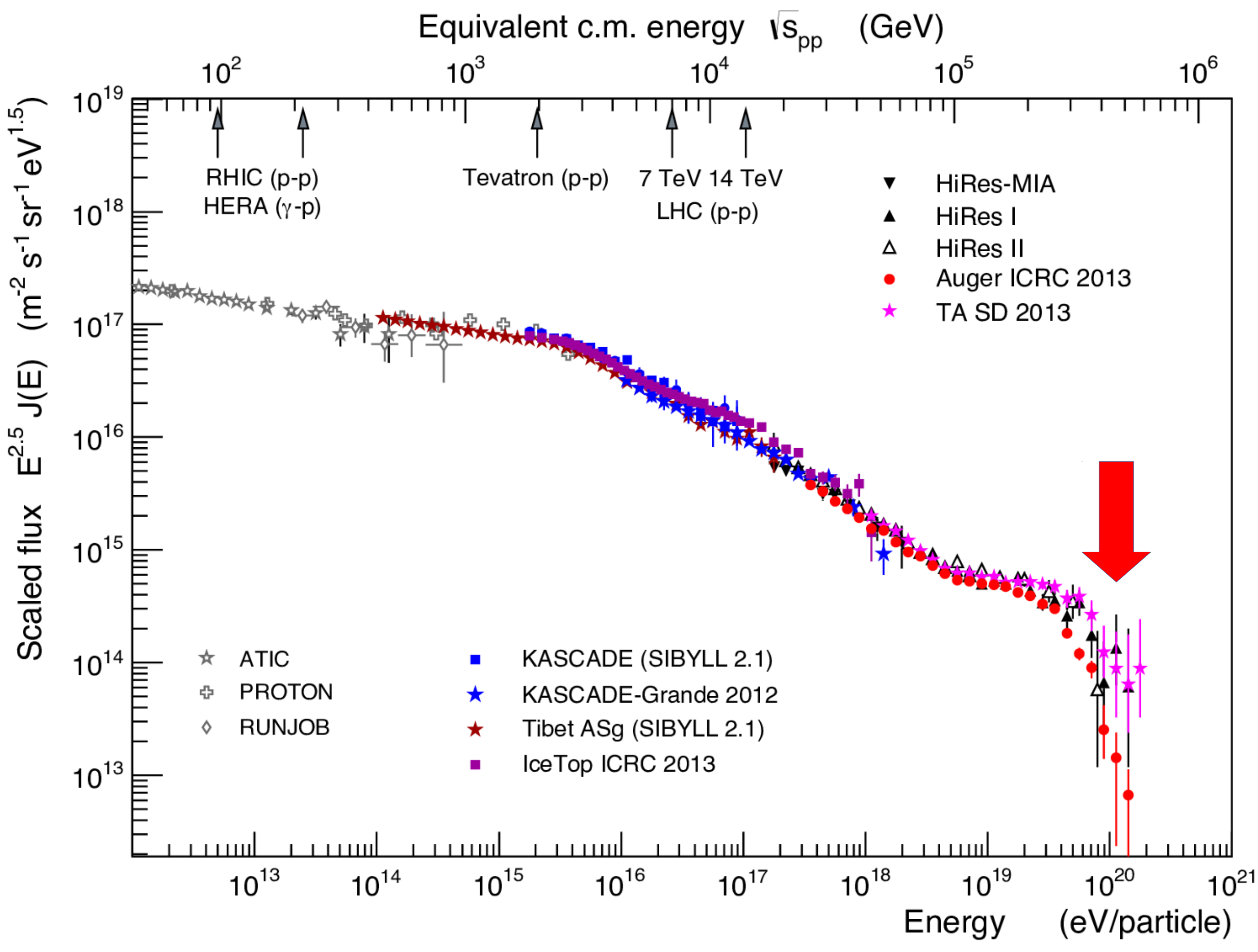
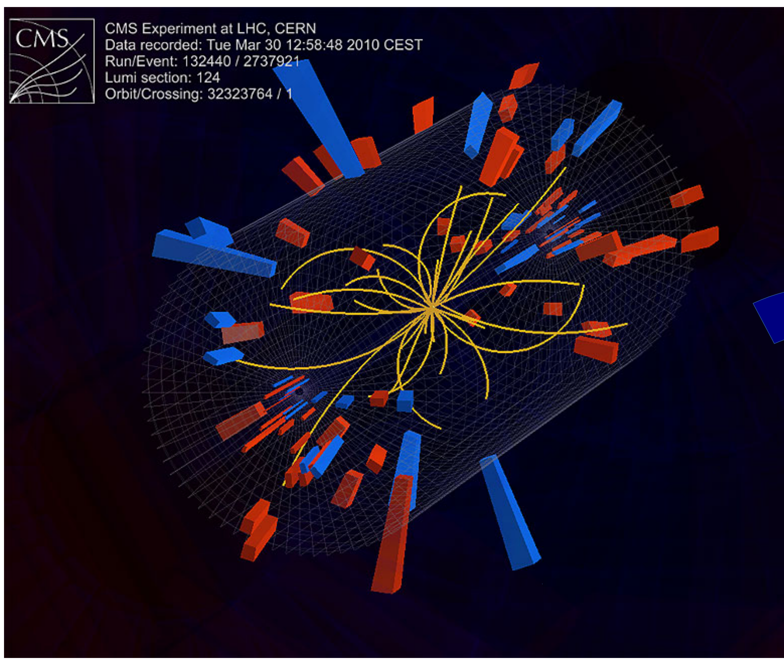
Ultra-high energy cosmic rays



Suppression

Origin ?

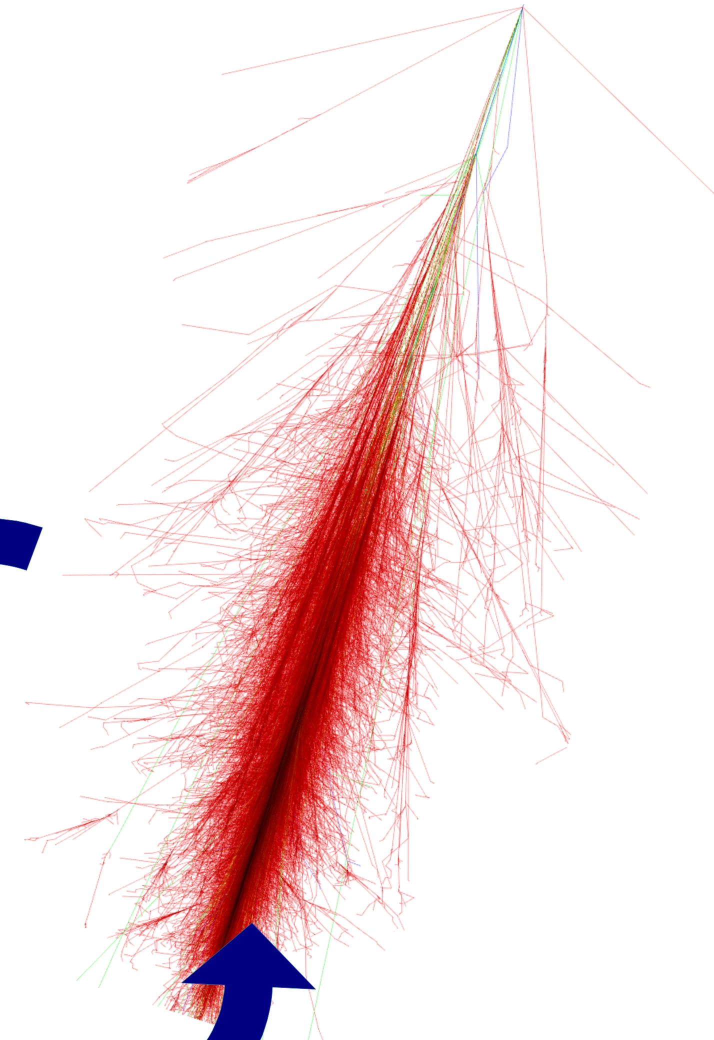
SIBYLL development



Fail again ?

SIBYLL 2.1

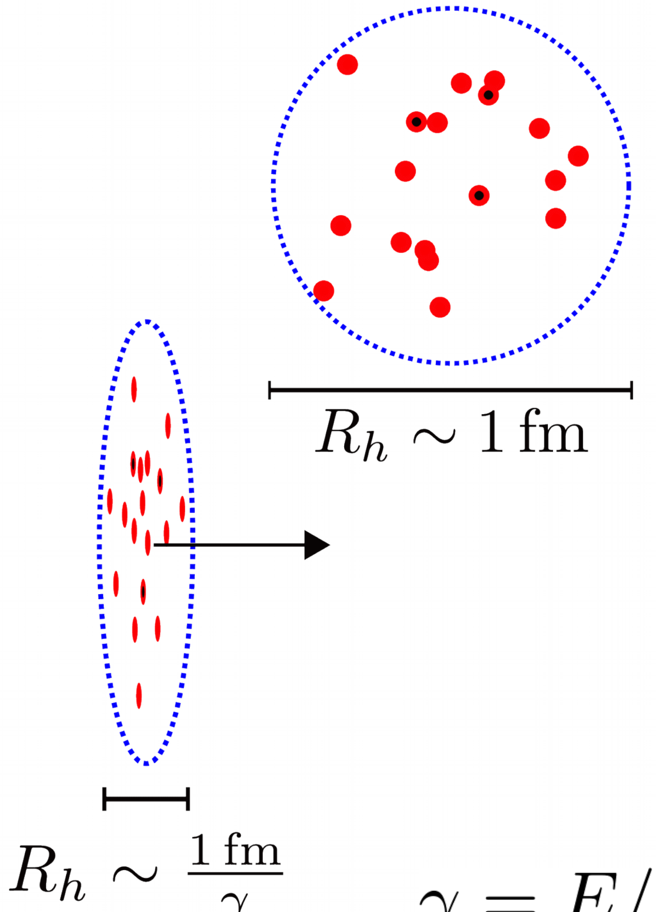
SIBYLL 2.3



Fail better !

(S. Beckett)

Hadrons



$$\gamma = E/m$$

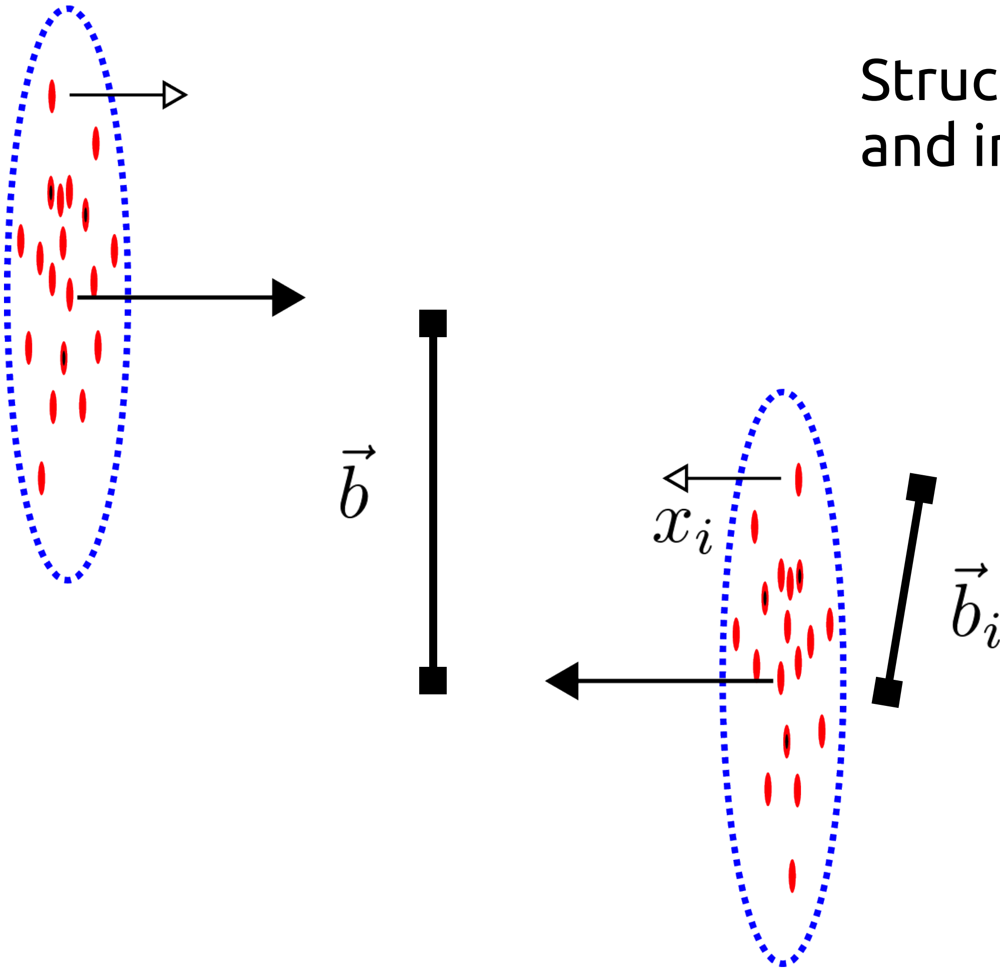
* quarks & gluons

* strong force (QCD)

* valence & sea (structured)

* Lorentz-contraction
  → disk at high energy

Hadron interactions

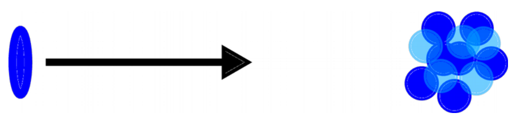


Structure in coordinate- and in momentum-space!

Multiple interactions!

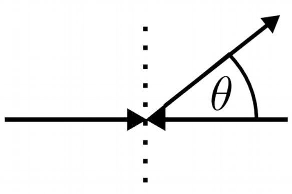
Requirements for air showers

- Energy range : GeV .. 10^6 GeV

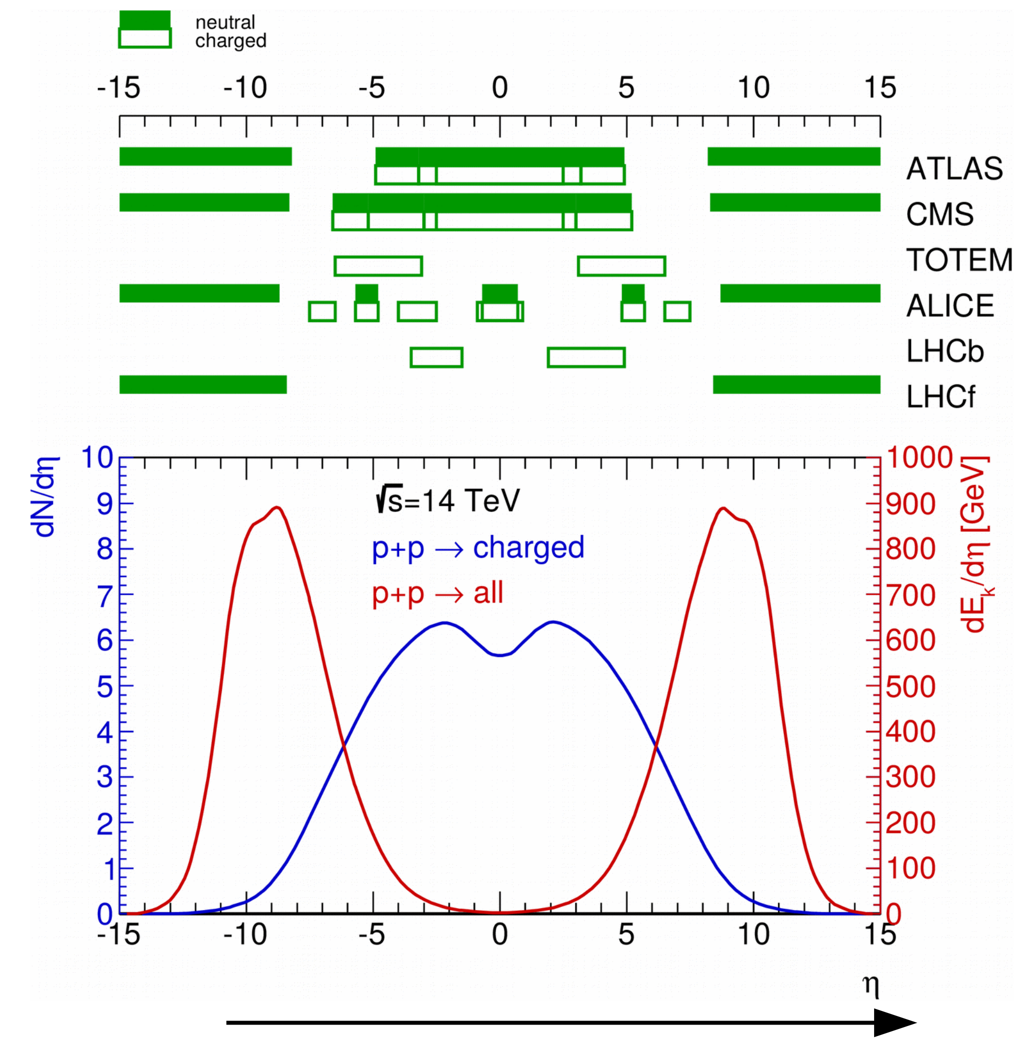


- $p, n, \pi^{\pm}, K^{\pm}, \Lambda, \Sigma$

- Forward particle production



$$\eta = -\log\tan(\frac{\theta}{2})$$



90° 1° 0.1°

HEP models ?

→ Extrapolation !

The event generator SIBYLL

* multiple interactions
* soft & hard interactions
* space & momentum structure
* diffractive interactions

Fully inclusive model

$$\sigma_{\mathrm{tot}} = 4 \int \mathrm{d}^2\vec{b}\, Im(a(s,\vec{b}))$$

Amplitude?

Eikonal approximation:

$$a(s,\vec{b}) = \frac{i}{2}(1 - e^{-\chi(s,\vec{b})}) \qquad \chi = \sum_i \chi_i = \frac{1}{2}\sigma_i(s)\, A_i(s,\vec{b})$$

σ_i Parton cross section

$A_i(s,\vec{b})$ Profile function

$\sigma_{\mathrm{inel}},\ \sigma_{N_{\mathrm{h}},\, N_{\mathrm{s}}} \cdots$

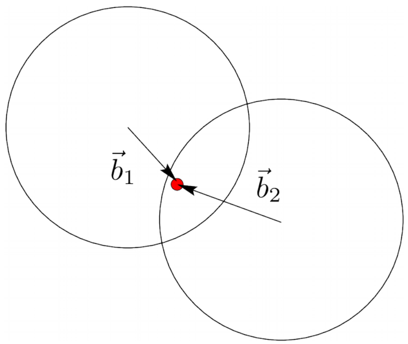
Hard & soft interactions

$$\sigma_{QCD}(s, p_T^{min}) = \int_{p_T^{min}}^{\infty} dp_T \int dx_1 \int dx_2 \sum_{i,j,k,l} f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}^{i,j\to k,l}}{dp_T}(\hat{s}, \hat{t})$$

$f_{\mathrm{i}}(x_i)$: parton distribution function

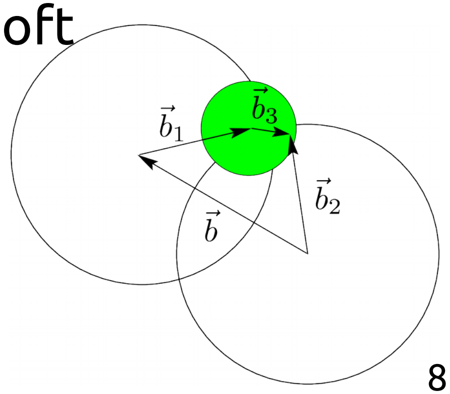
$p_{\mathrm{T}}^{\mathrm{min}}$: soft / hard

Hard



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

Soft

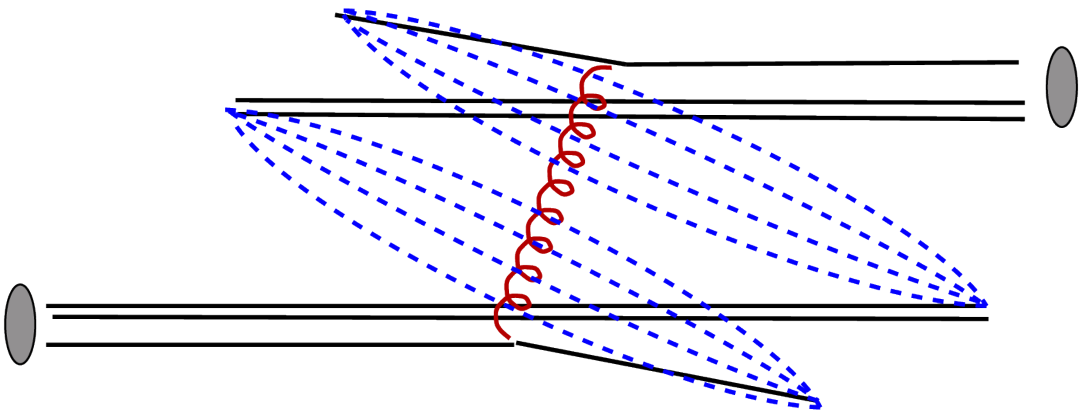


$f_{\mathrm{soft}}(x_i) \sim \left(\frac{1}{x}\right)^{\alpha}$: soft gluons

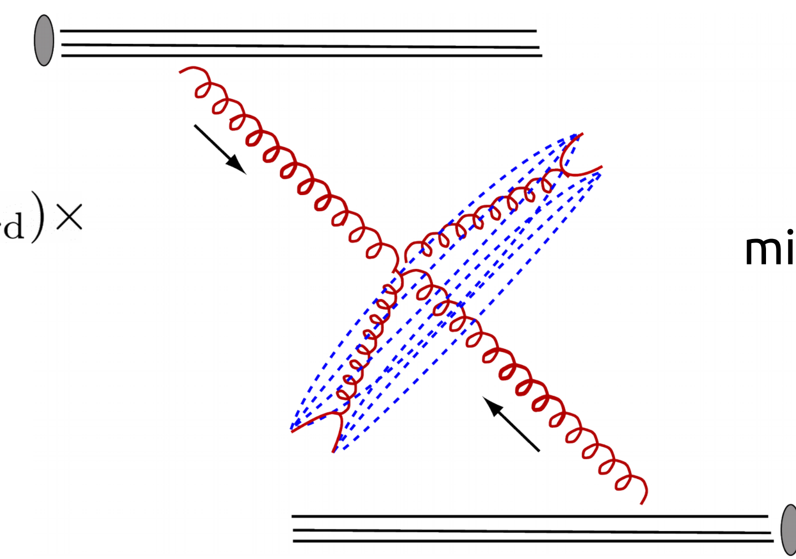
$f_{\mathrm{lead}}(x_i) \sim x^{\beta}$: valence quarks

Event in SIBYLL

Special case:
valence quarks



$$+((n_{\mathrm{soft}}-1)+n_{\mathrm{hard}})\times$$

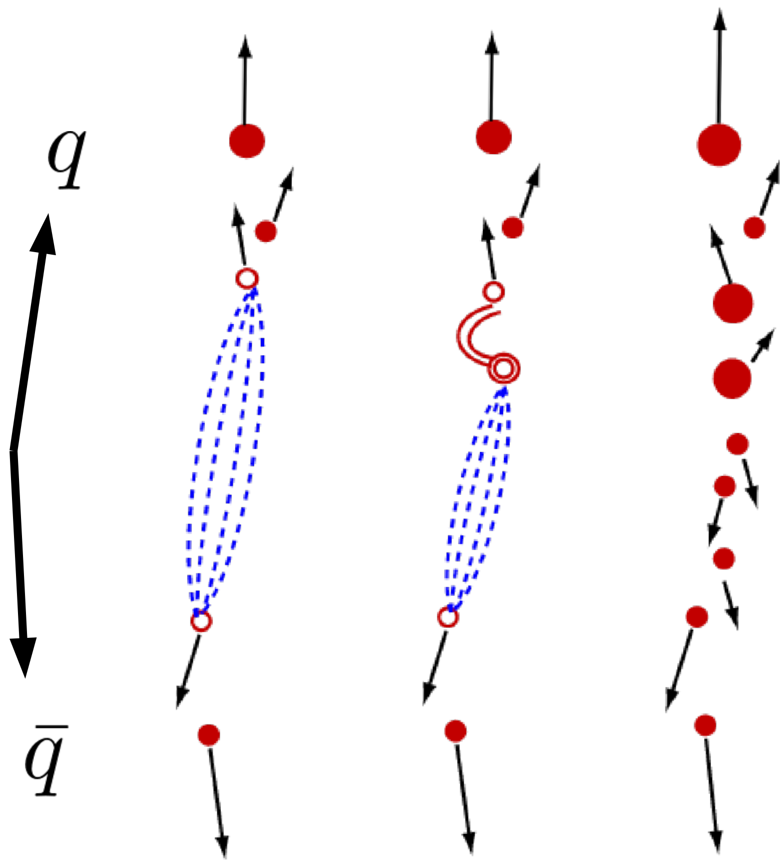


minijets

hadrons ?

Hadronization in SIBYLL

* string fragmentation



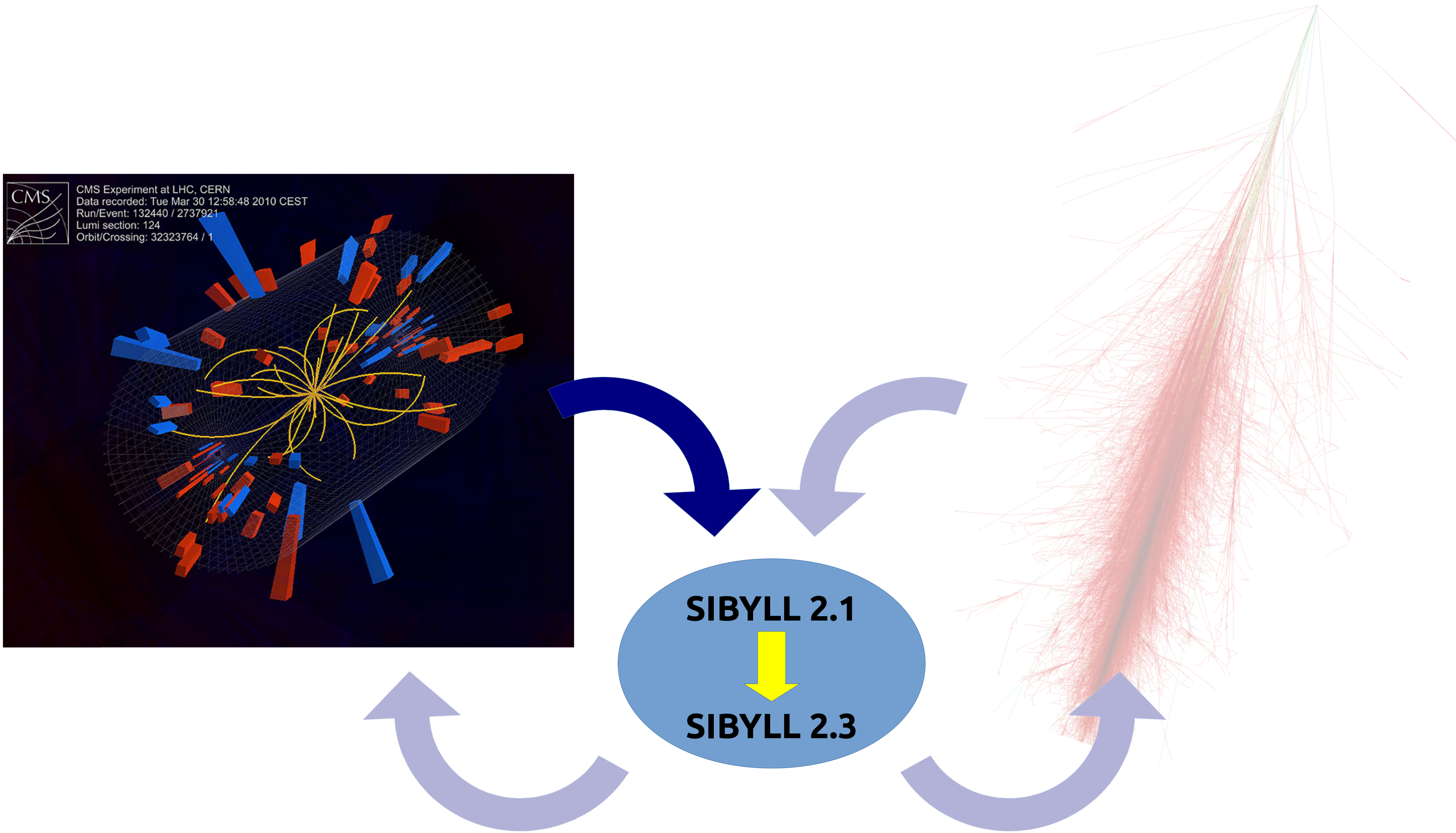
$$f(z) = \frac{(1-z)^{\alpha}}{z} e^{-b m_{\mathrm{T}}/z}$$

$$f_{\mathrm{lead}}(z) = z^{\beta}$$

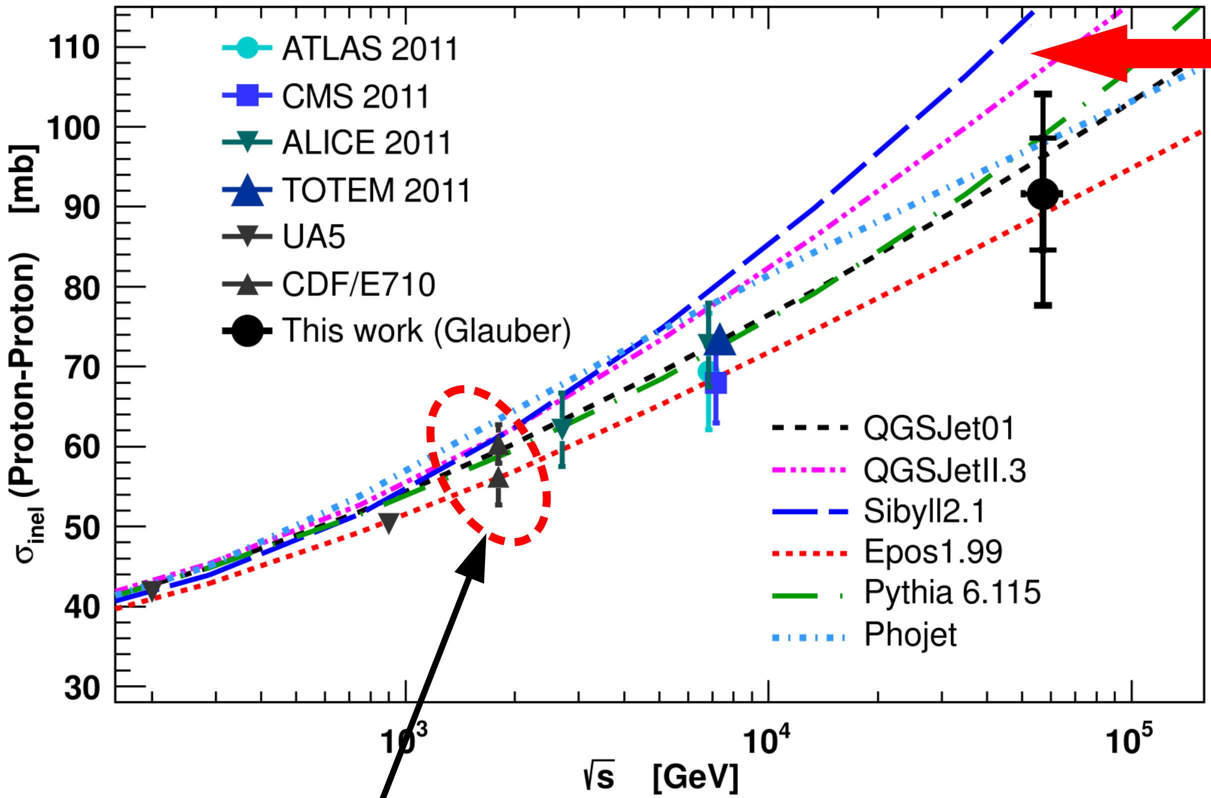
Parameters	Value
u,d : s	0.3
s : c	0.004
qq : q	0.04
Spin0 : spin1	0.3

Universal ?

LHC measurements



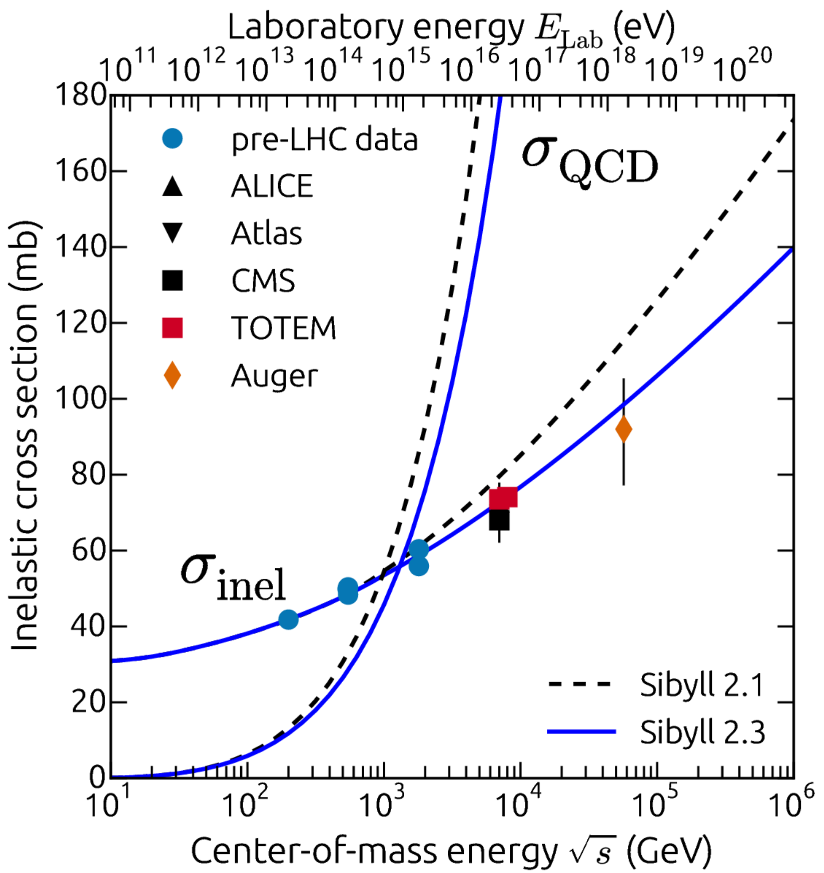
Interaction cross section

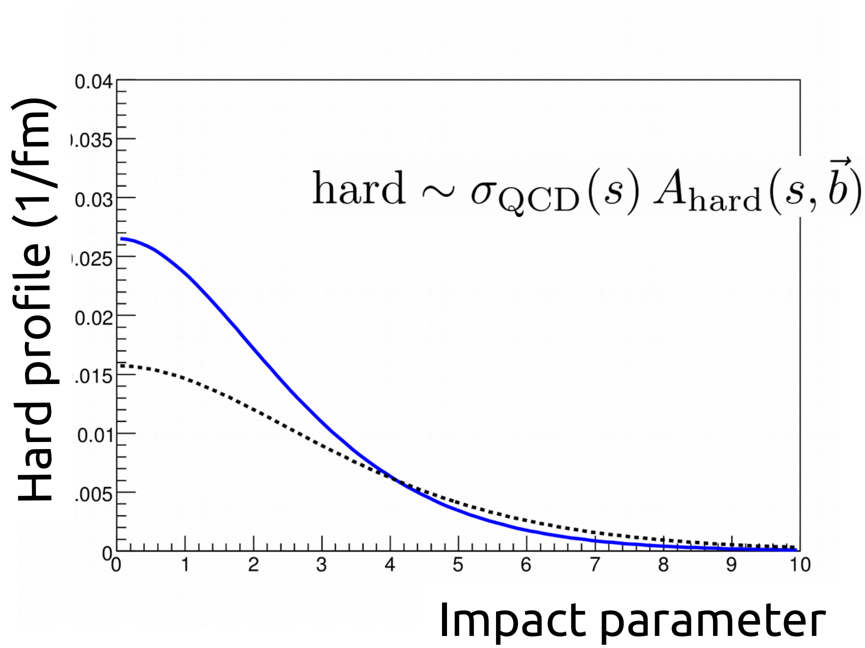


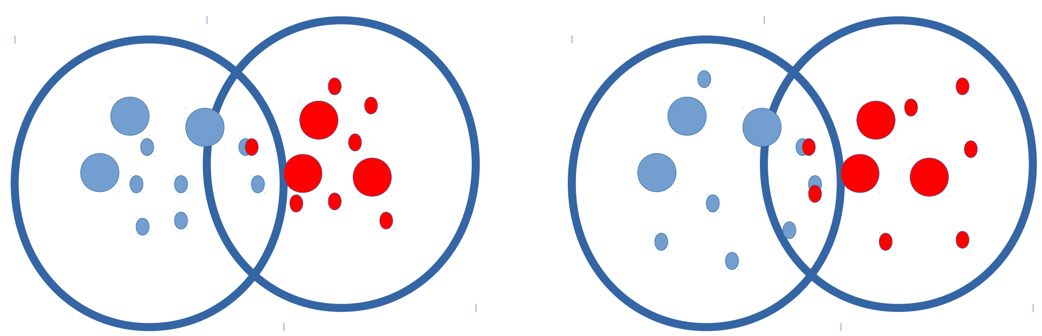
Sibyll too high

Two conflicting measurements at TeVatron!

Interaction cross section

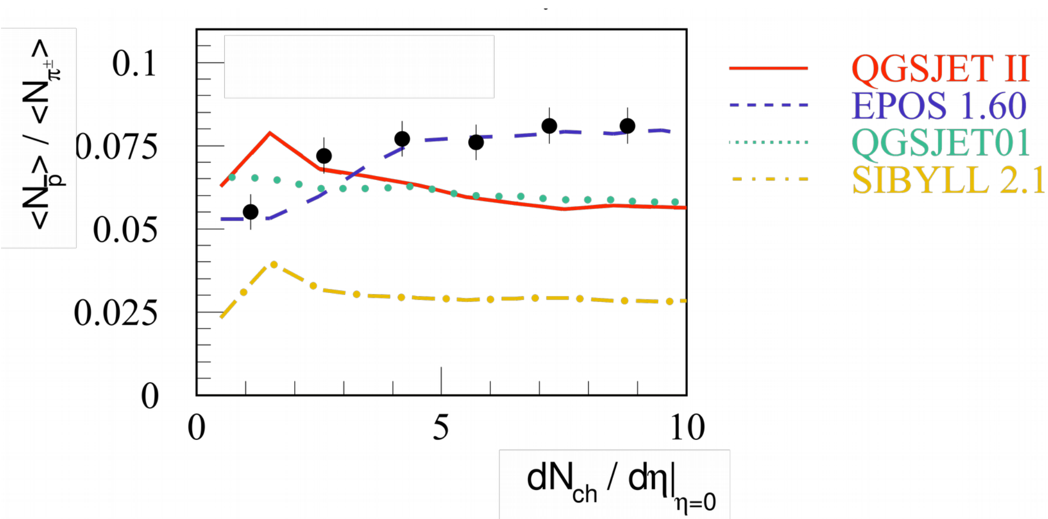




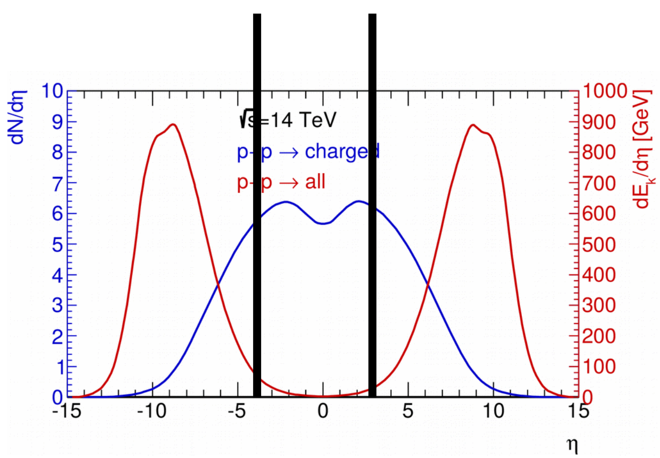


Translates into shift in Xmax

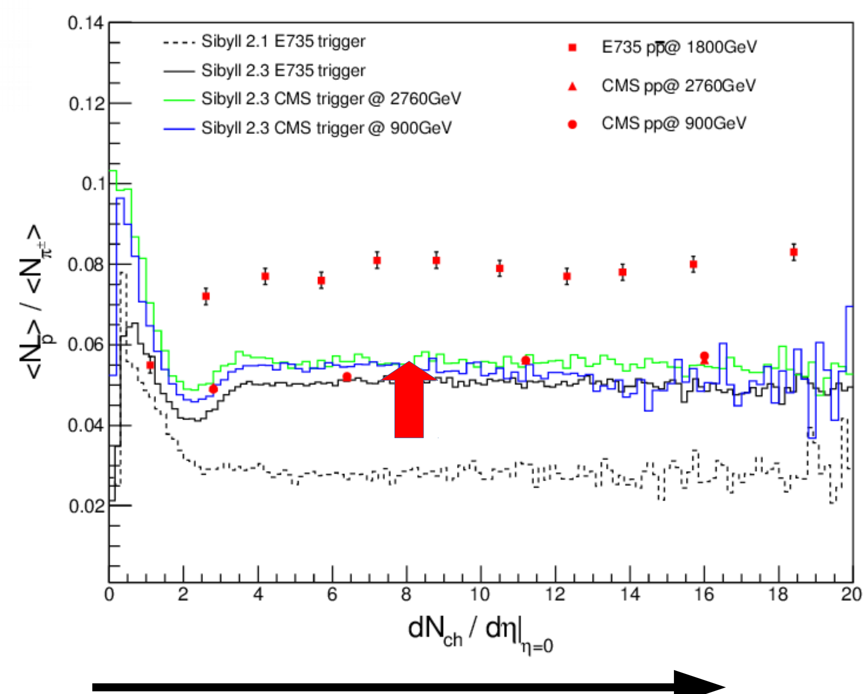
Baryon production



TeVatron measurement contradicted by CMS
→ pre-LHC models too high
→ Sibyll too low

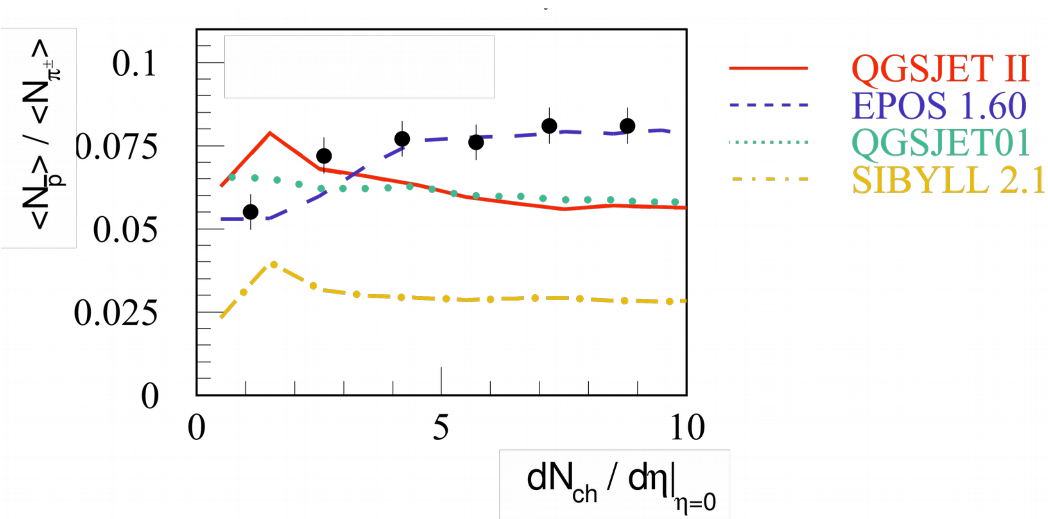


No. of tracks at 90deg



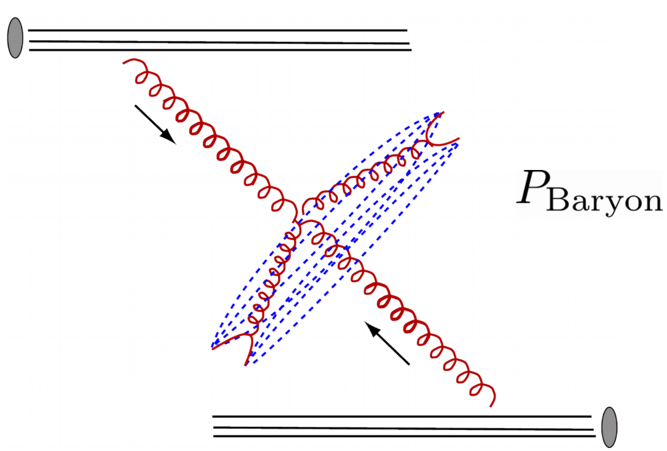
No. of minijets

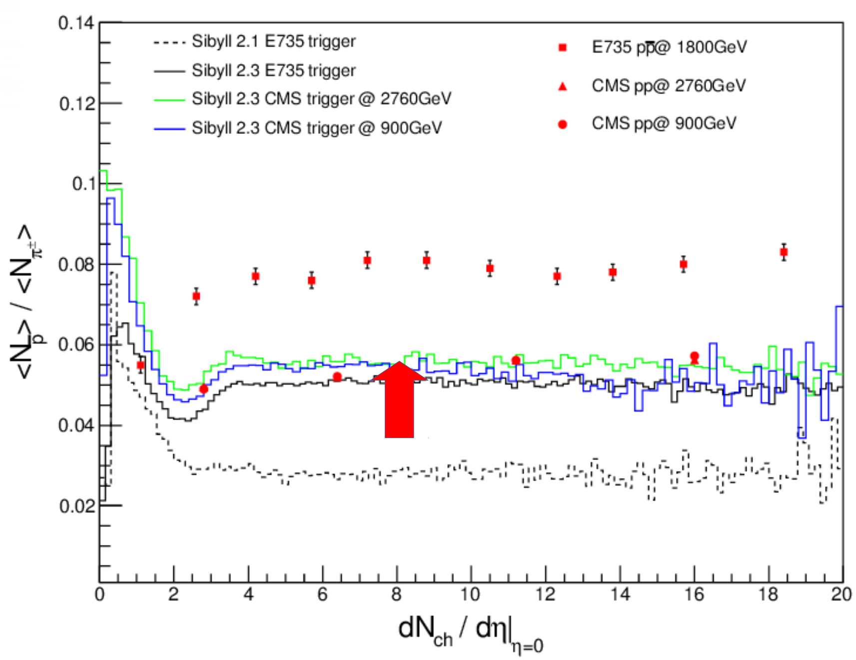
Baryon production



TeVatron measurement contradicted by CMS
→ pre-LHC models too high
→ Sibyll too low

How to improve in Sibyll ?

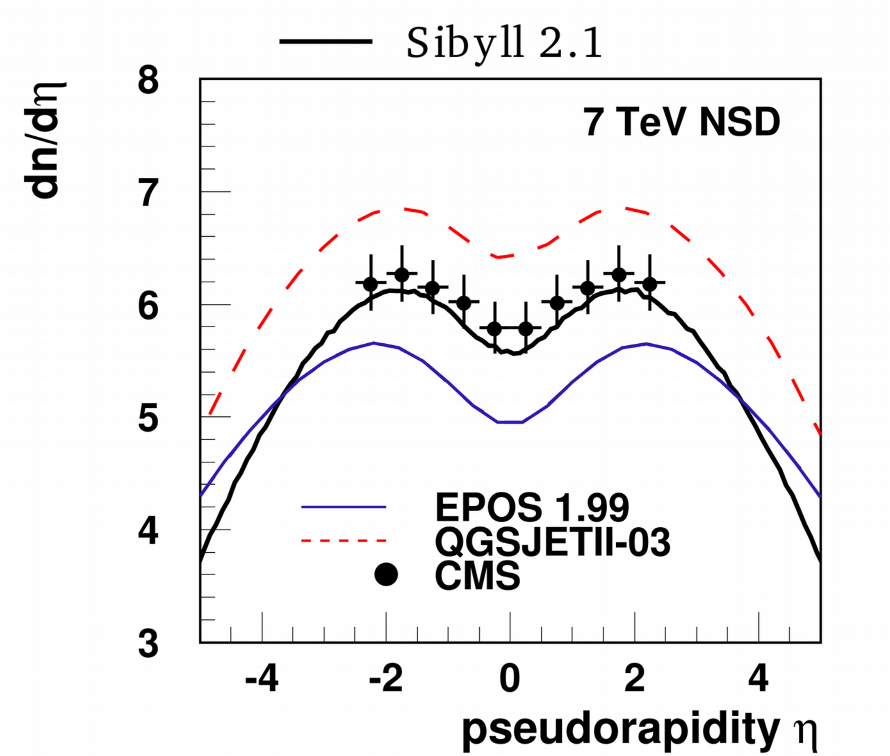


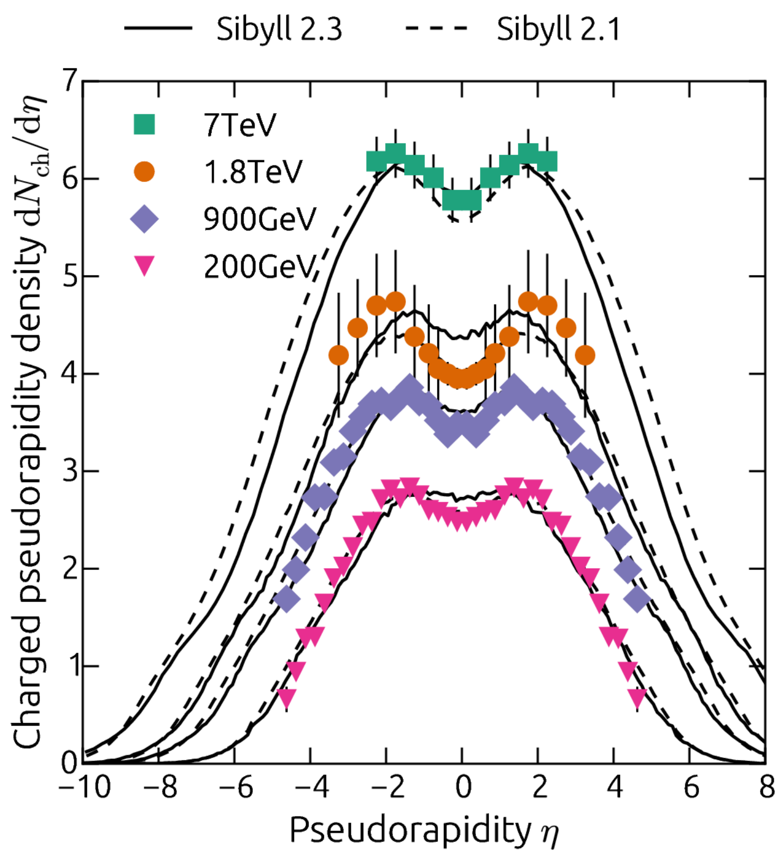


No. of minijets

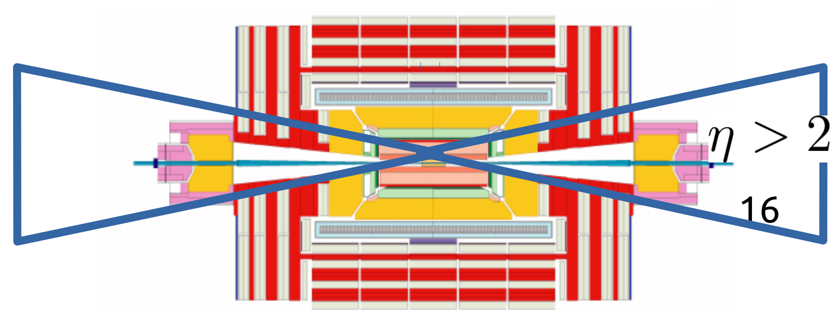
Particle production

Well described by pre-LHC models !





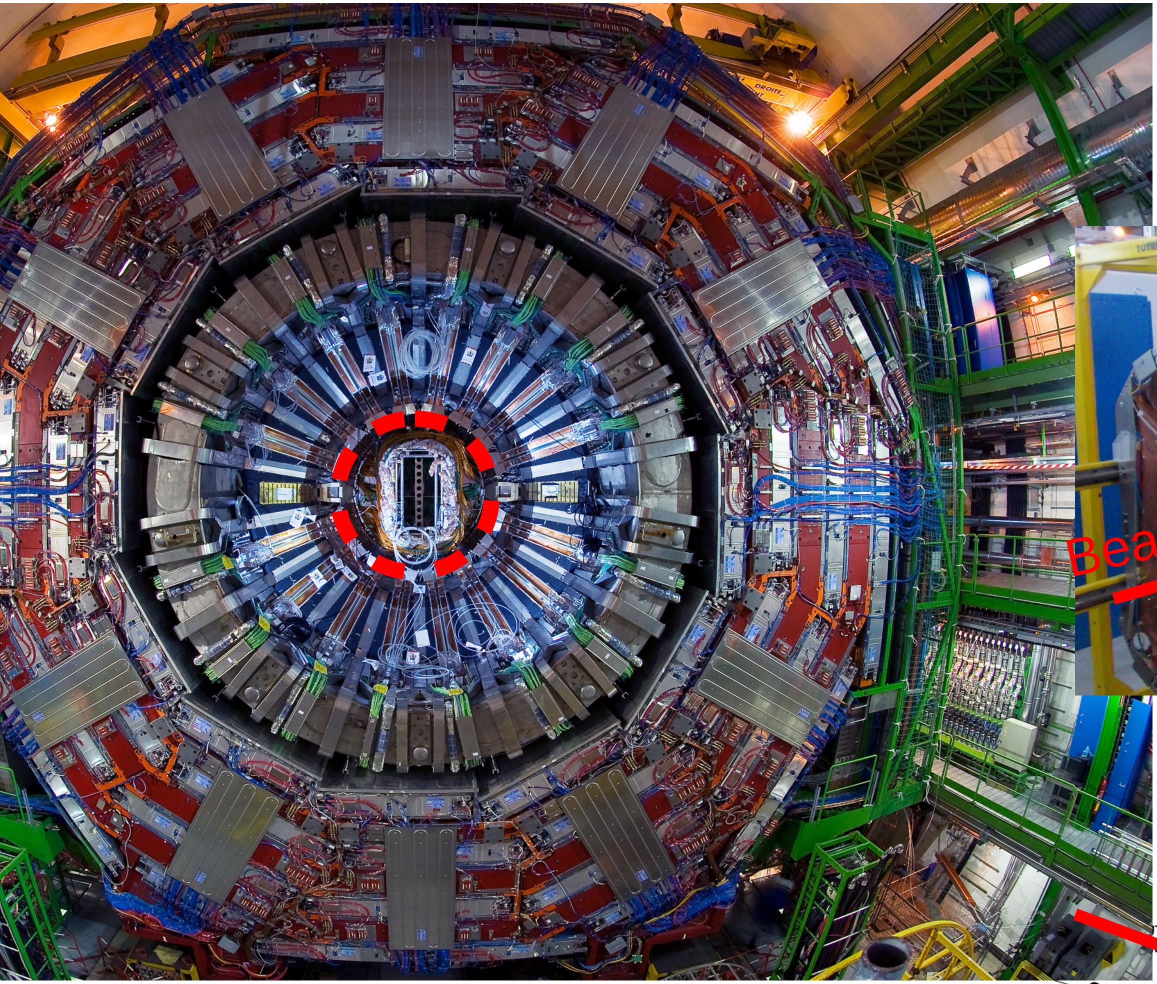
$$-2.5 < \eta < 2.5$$



In central phase space p – p interaction well understood

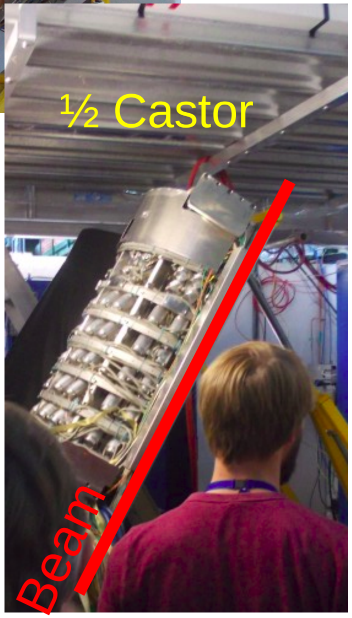
What about the rest ???

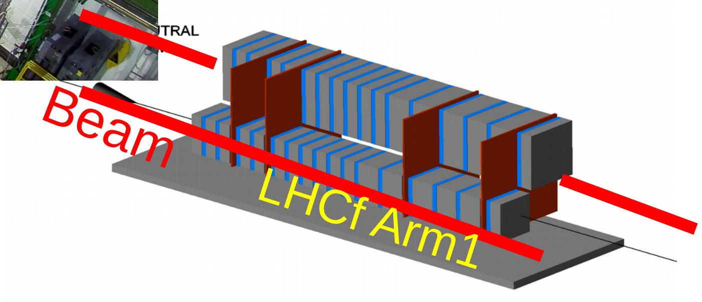
Small angle measurements



Dedicated forward experiments:

LHCf, TOTEM, Castor

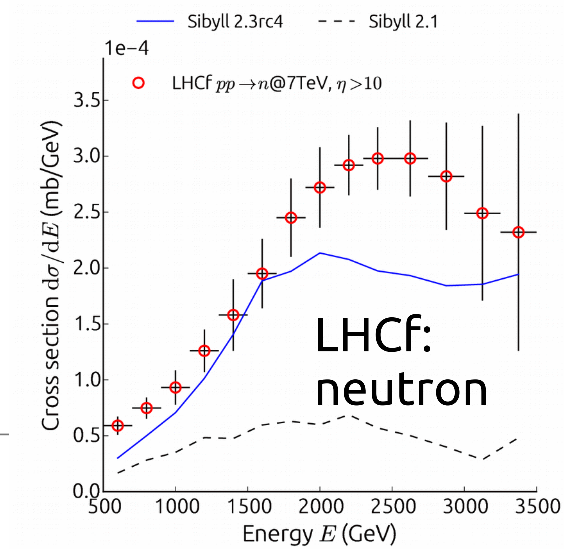


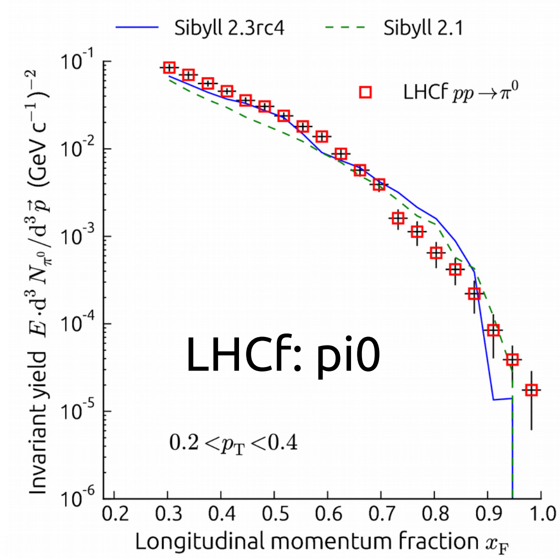


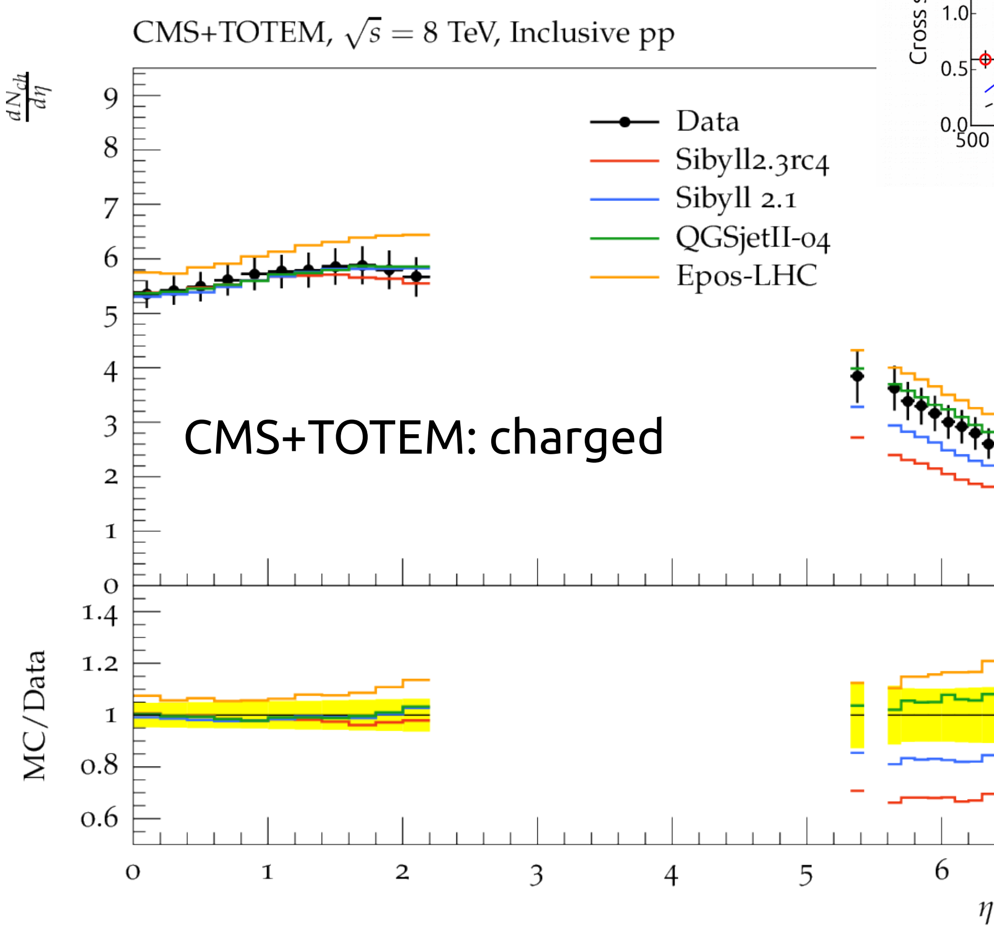
CMS is big, but there is a hole..

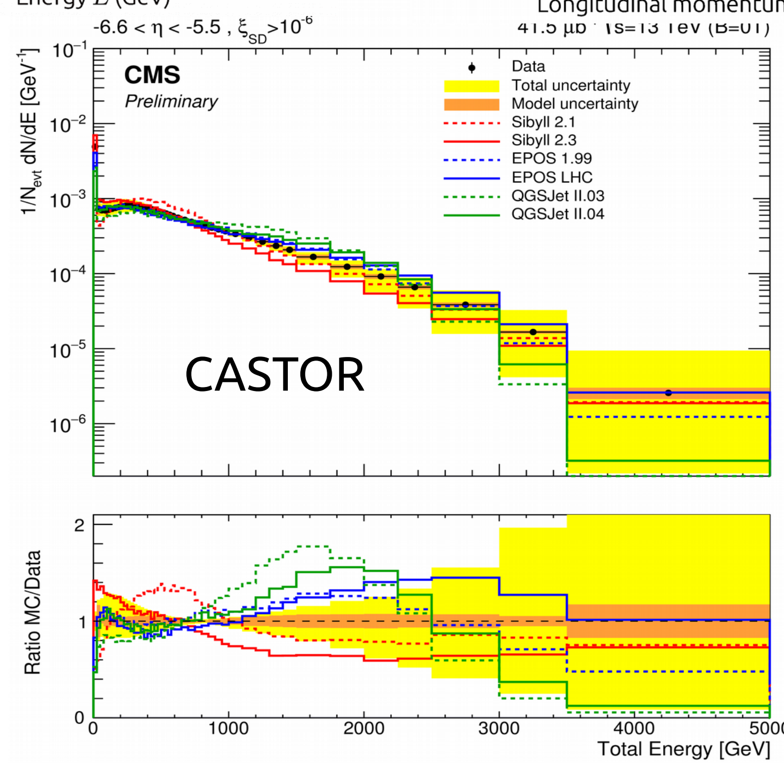
Small angle measurements

Dedicated experiments:
LHCf, TOTEM, Castor

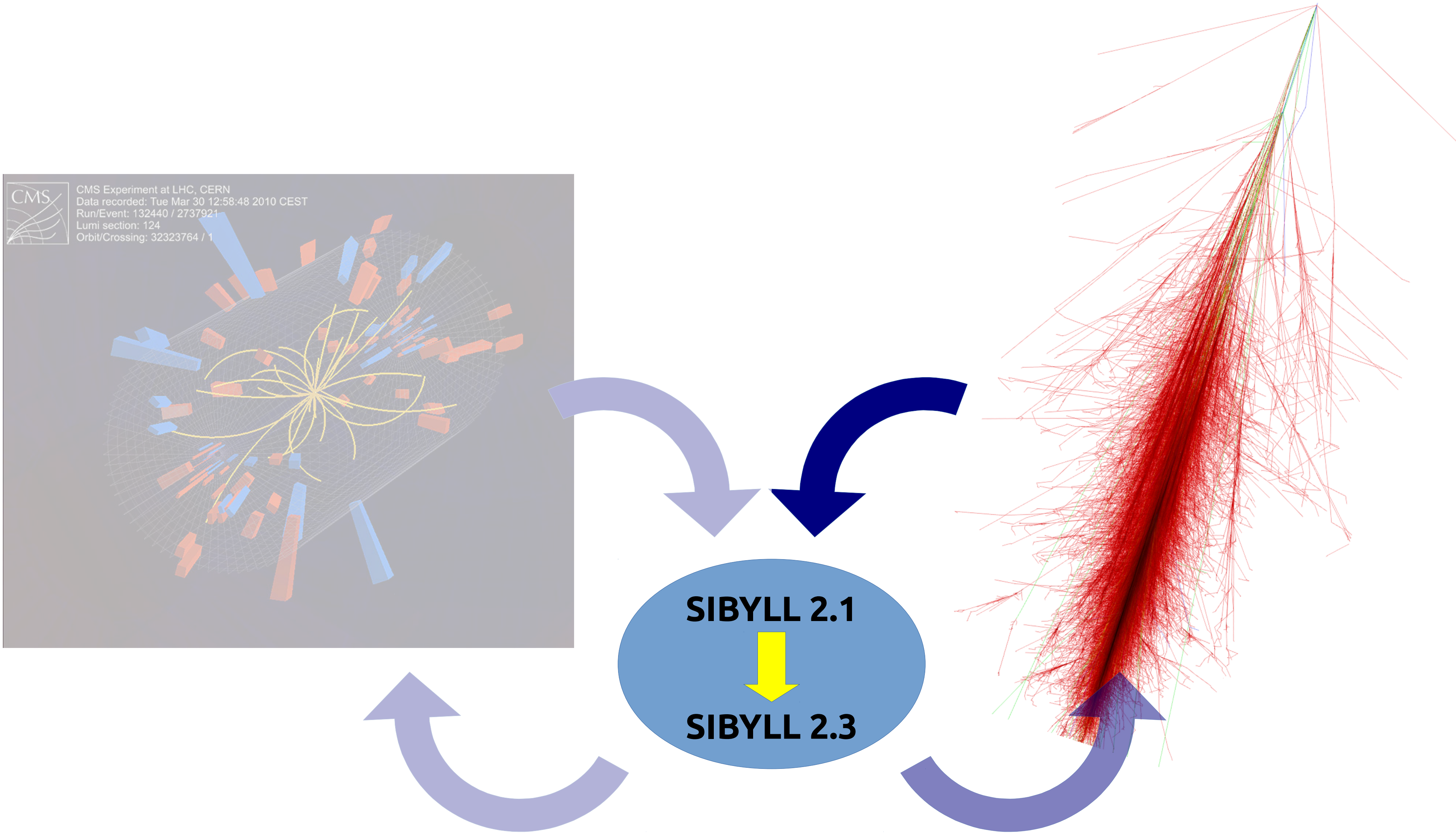






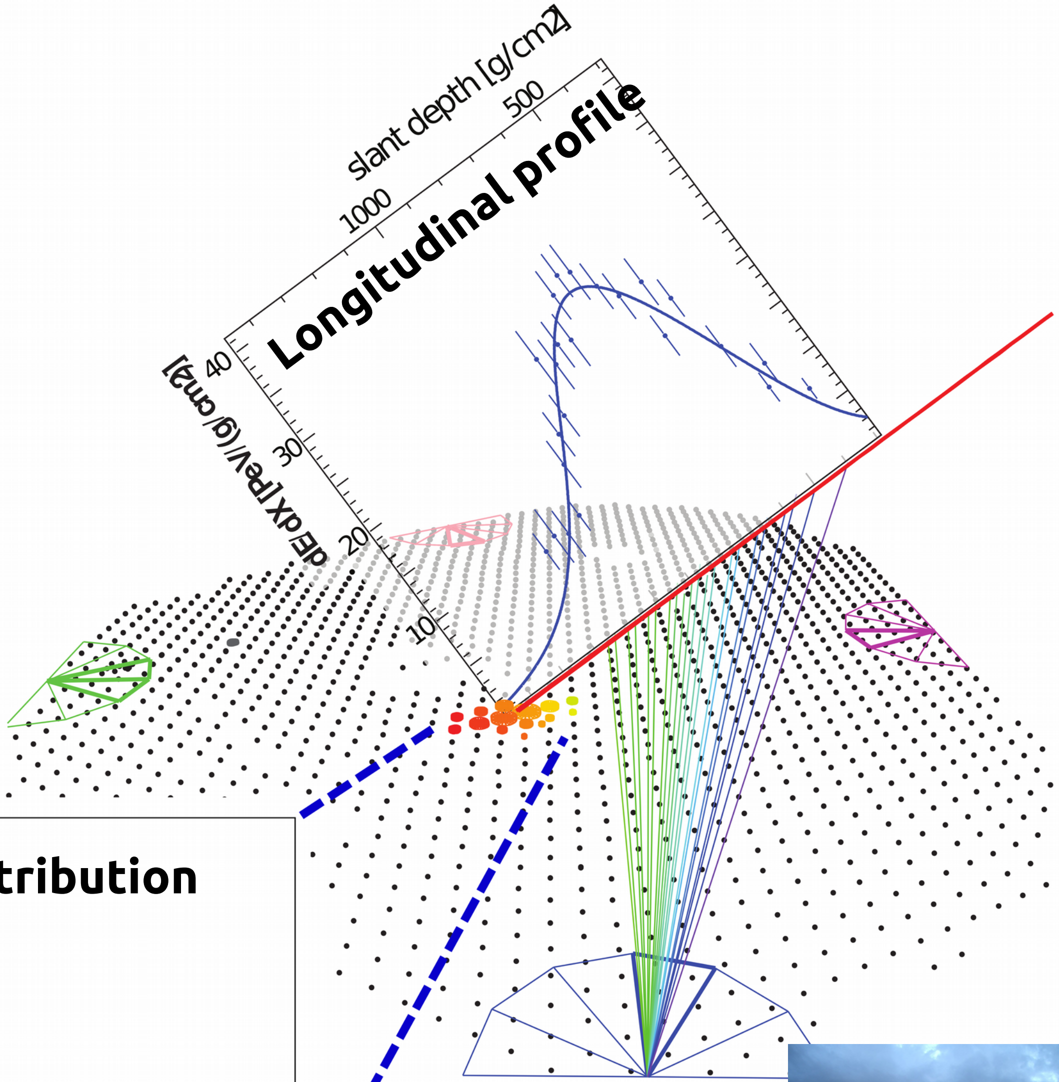


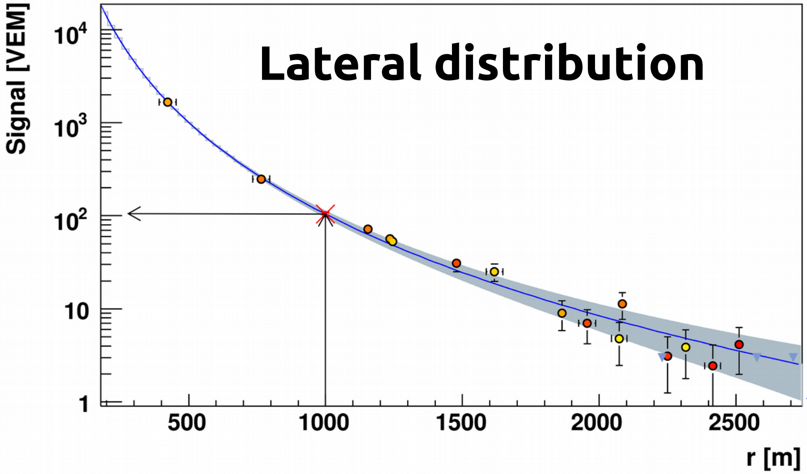
Air shower measurements



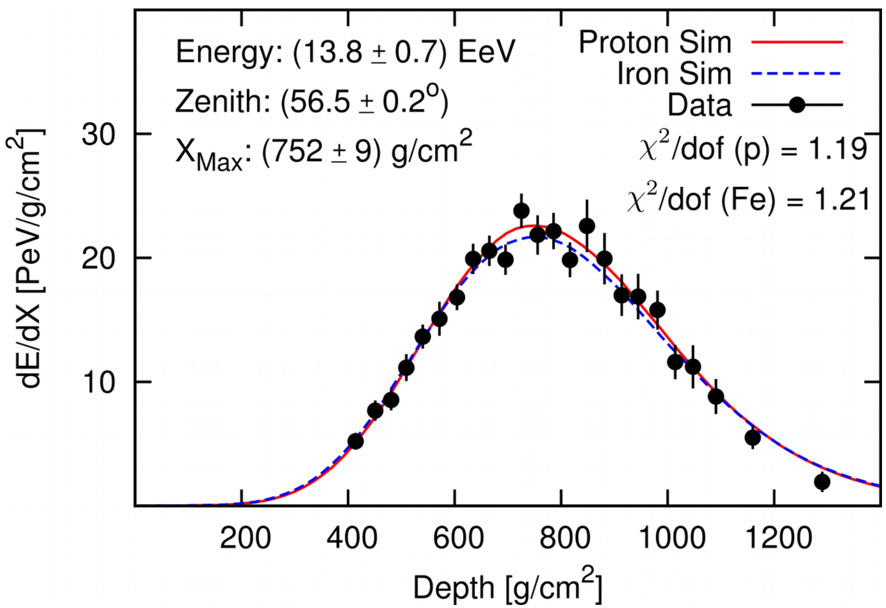
Pierre Auger Observatory

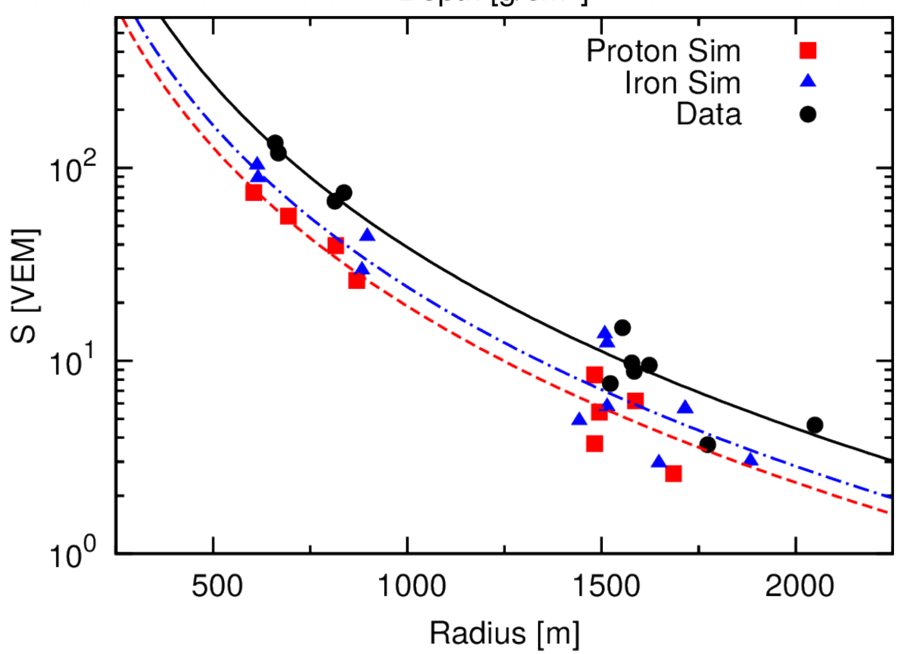
Hybrid detector





'Muon problem'





* Hybrid events

* Select longitudinal profile p & Fe

* Compare signals in surface detector

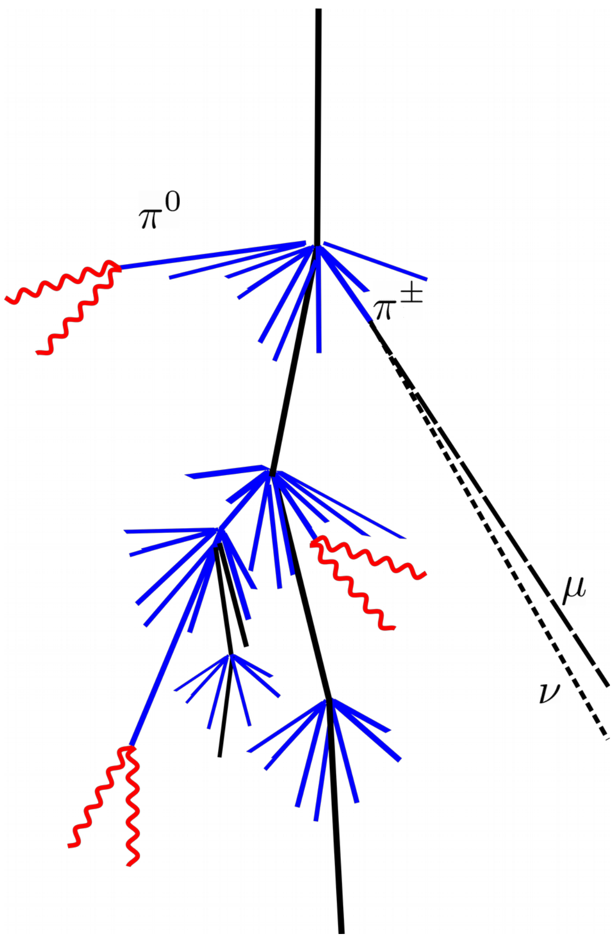
Both p and Fe simulations fail to describe signal in surface detector

Missing Muons? Models incomplete? New physics ??

$$R_\mu = 1.5 \ldots 1.6$$

How to extend the model ?

Muon production in air showers



Meson decay !

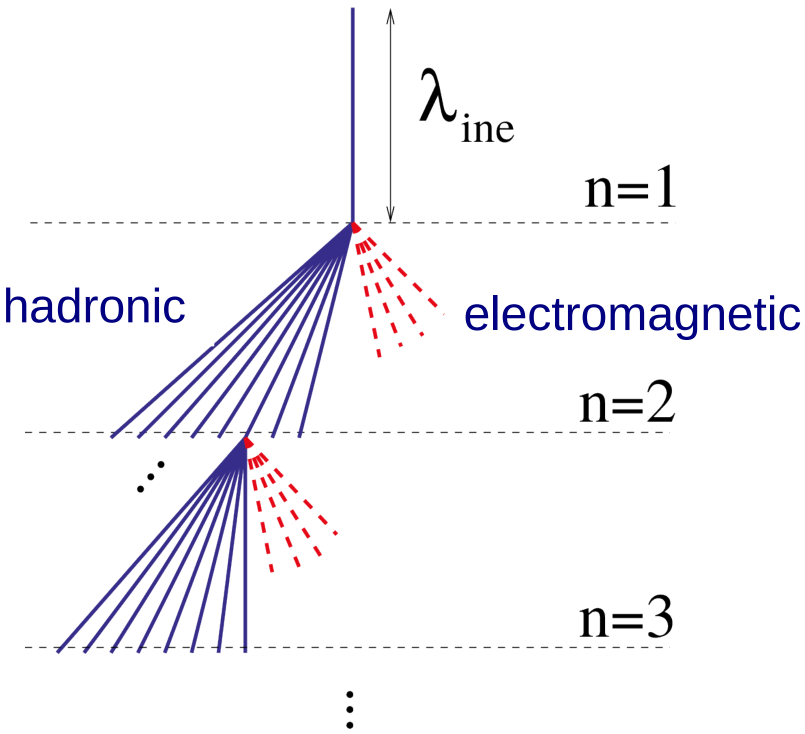
$$\pi^\pm, K^\pm \to \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

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

$$n_{\rm chd} \ : \ n_{\rm tot}$$

Muon production in air showers

Heitler-Matthews



$$n_{\mathrm{chd}} \; : \; n_{\mathrm{tot}} \to \alpha$$

Ratio: 'muon producing' to all particles

$$N_\mu = A^{1-\alpha} \left(\frac{E_0}{E_{\mathrm{crit}}} \right)^\alpha$$

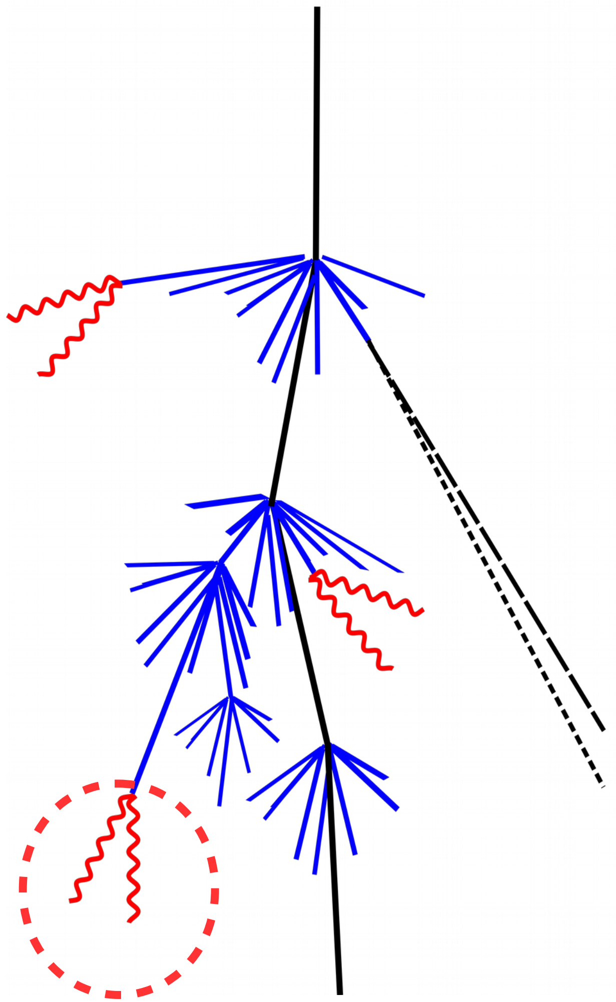
Experimentally (low-energy):

$$\alpha \approx 0.8 \ldots 0.9$$

Increase muon production

Increase ratio of 'muon producing' to electromagnetic

$$n_{\mathrm{chd}} \ : \ n_{\mathrm{tot}}$$

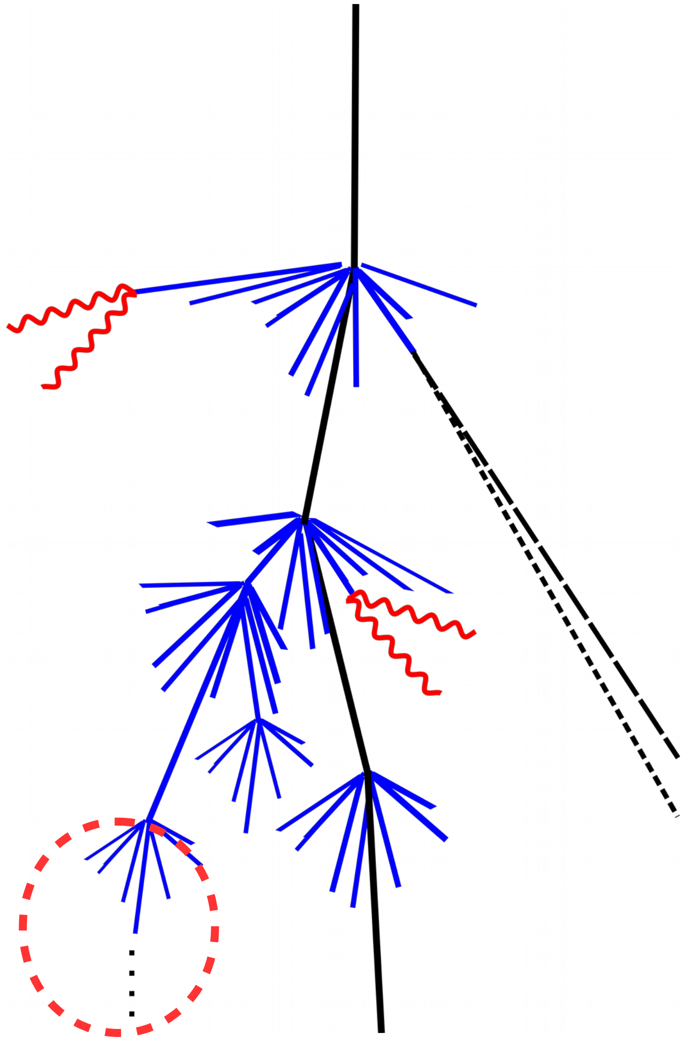


Increase muon production

Increase ratio of muon
producing to electromagnetic

$$n_{\mathrm{chd}} \ : \ n_{\mathrm{tot}}$$

Leading pions !



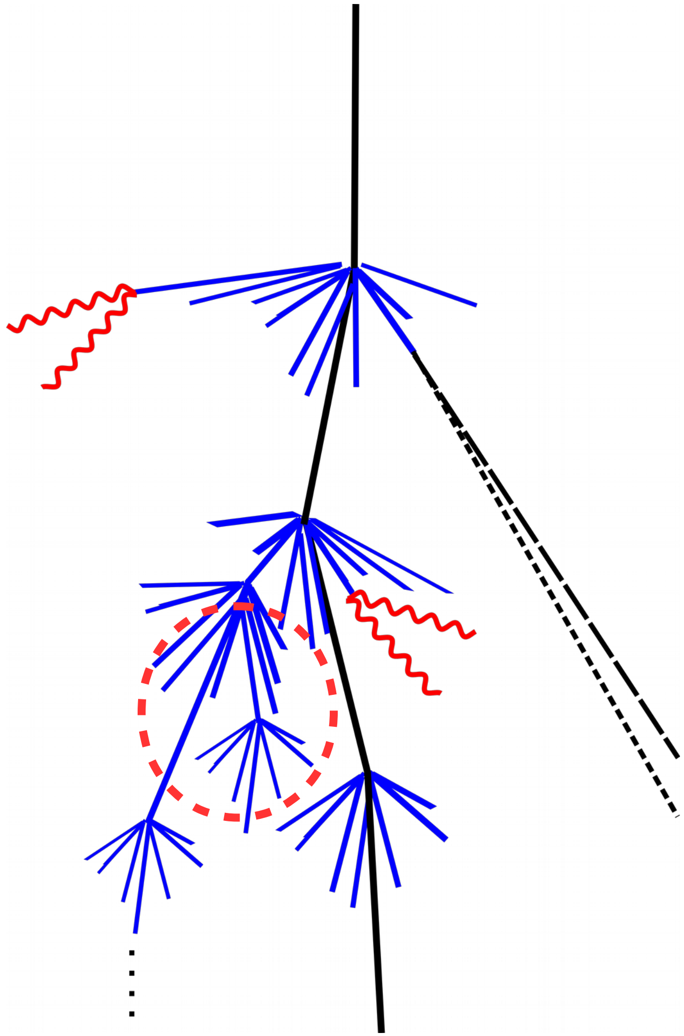
Increase muon production

Increase ratio of muon producing to electromagnetic

$$n_{\mathrm{chd}} \;:\; n_{\mathrm{tot}}$$

→ Leading pions !

→ Baryon production



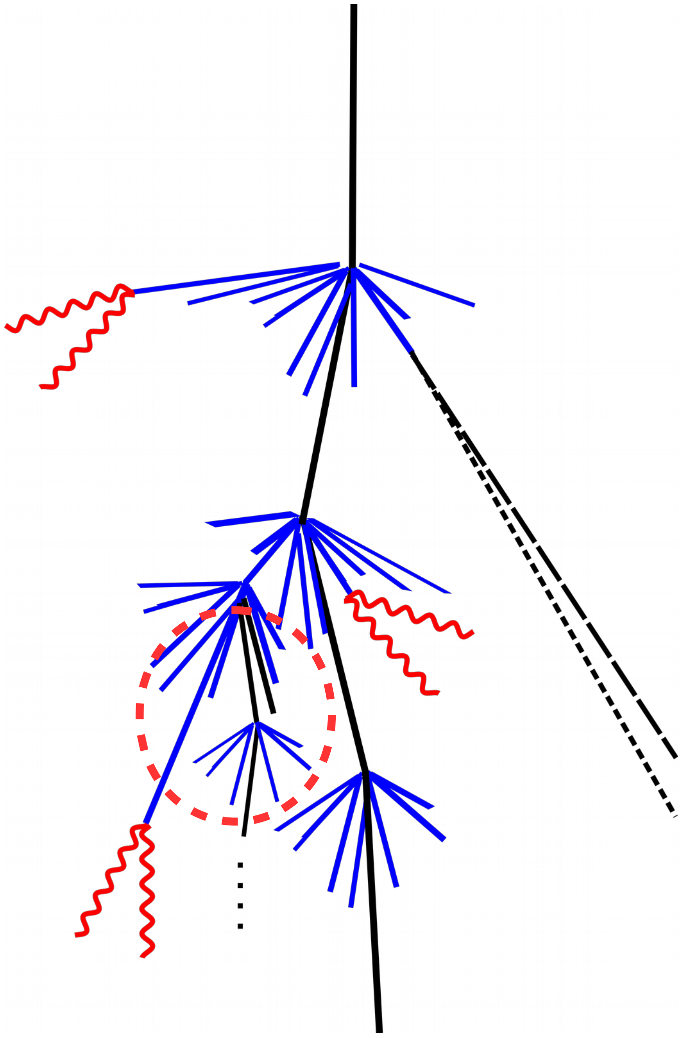
Increase muon production

Increase ratio of muon producing to electromagnetic

$$n_{\text{chd}} \ : \ n_{\text{tot}}$$

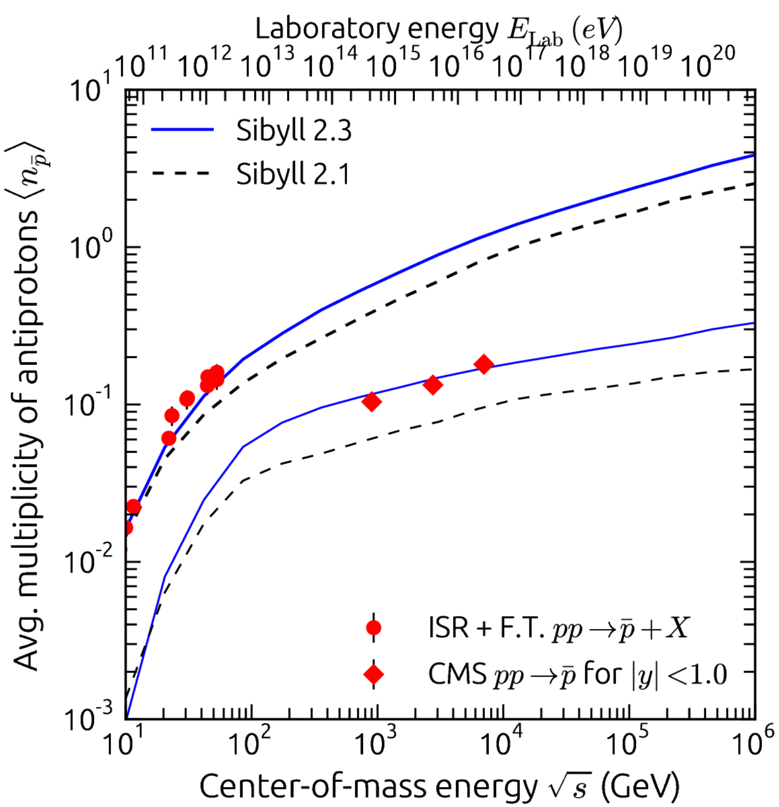
→ Leading pions !

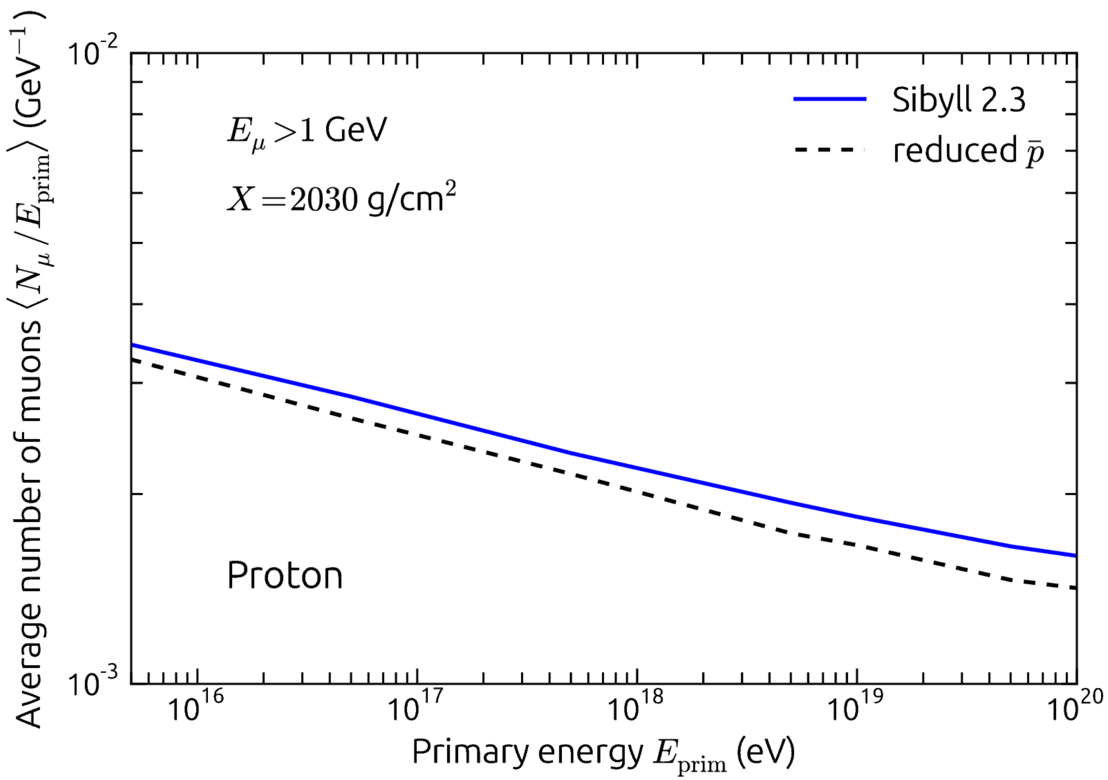
→ Baryon production



+ exotic scenarios
(new particles, pions stable ...)

Baryon production

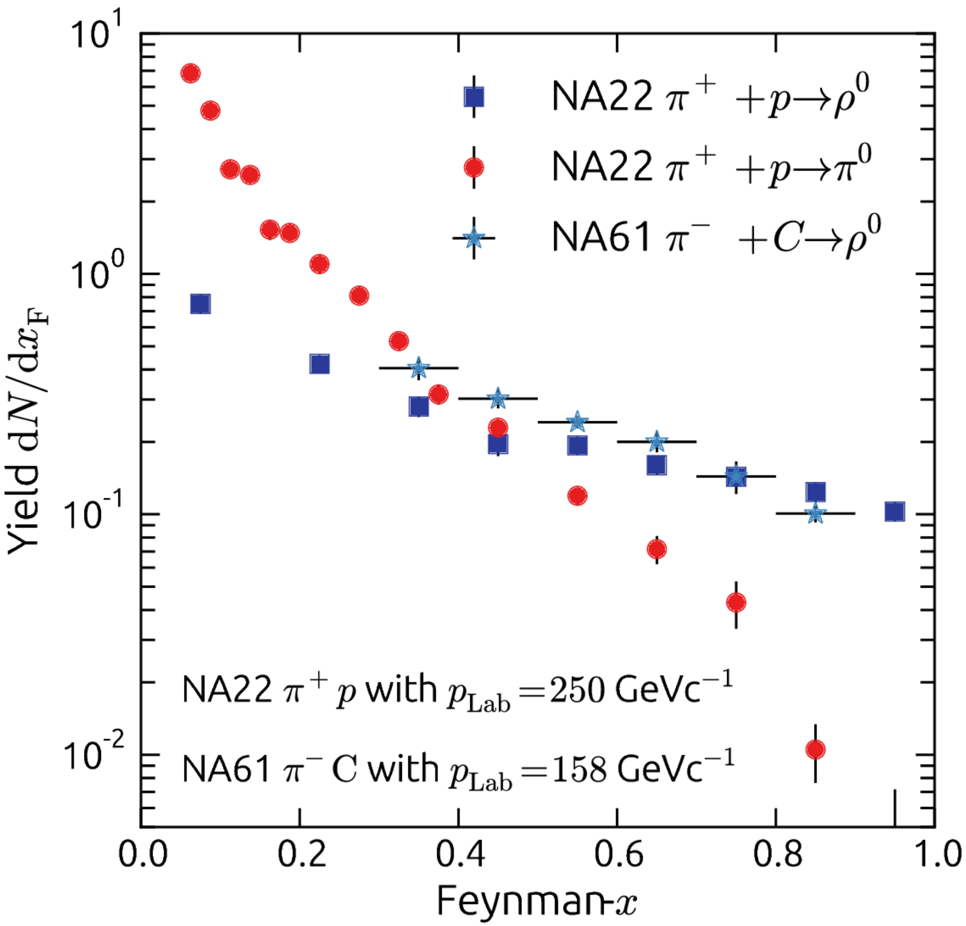




Baryon production underestimated

5-10% increase

Leading pions in data



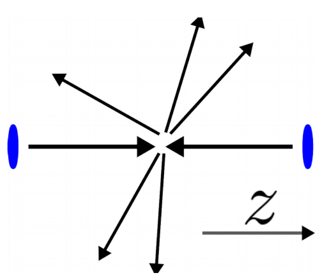
$$\pi^{\pm} + \mathrm{Air} \to \rho^0 + \mathrm{X}$$

$$\rho^0 \to \pi^+\pi^-$$

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

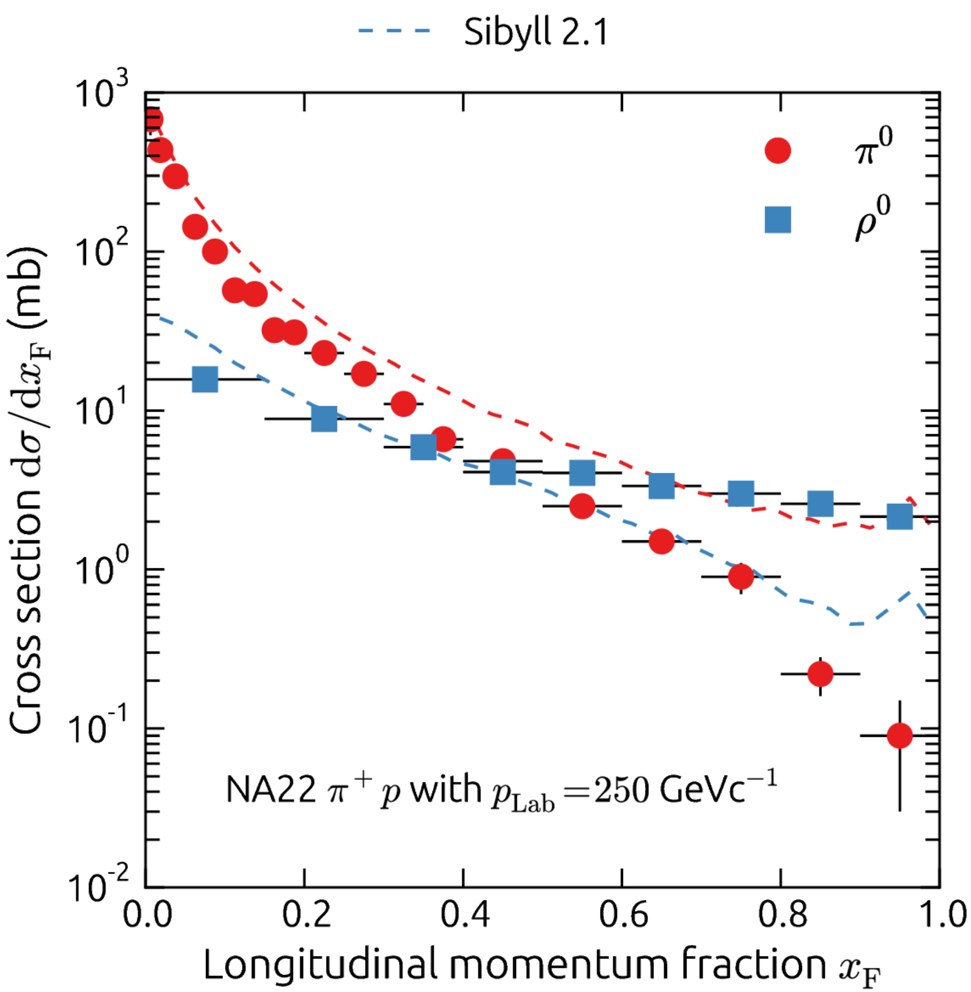
Data favors pion resonances over neutral pions

Increases α

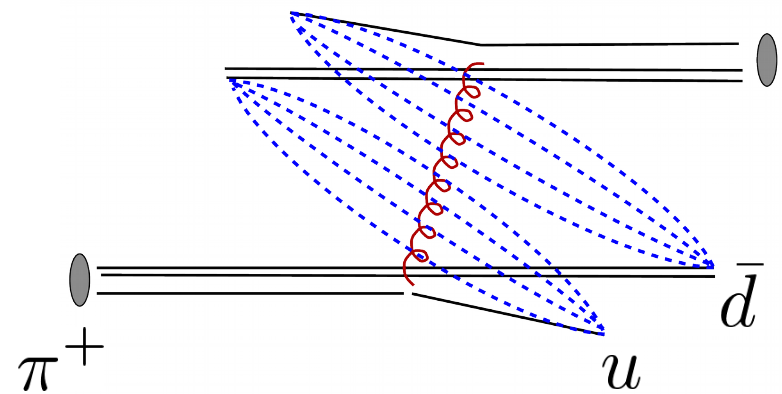


$$x_{\mathrm{F}} = p_z / p_z^{\mathrm{max}}$$

Leading pions in the model

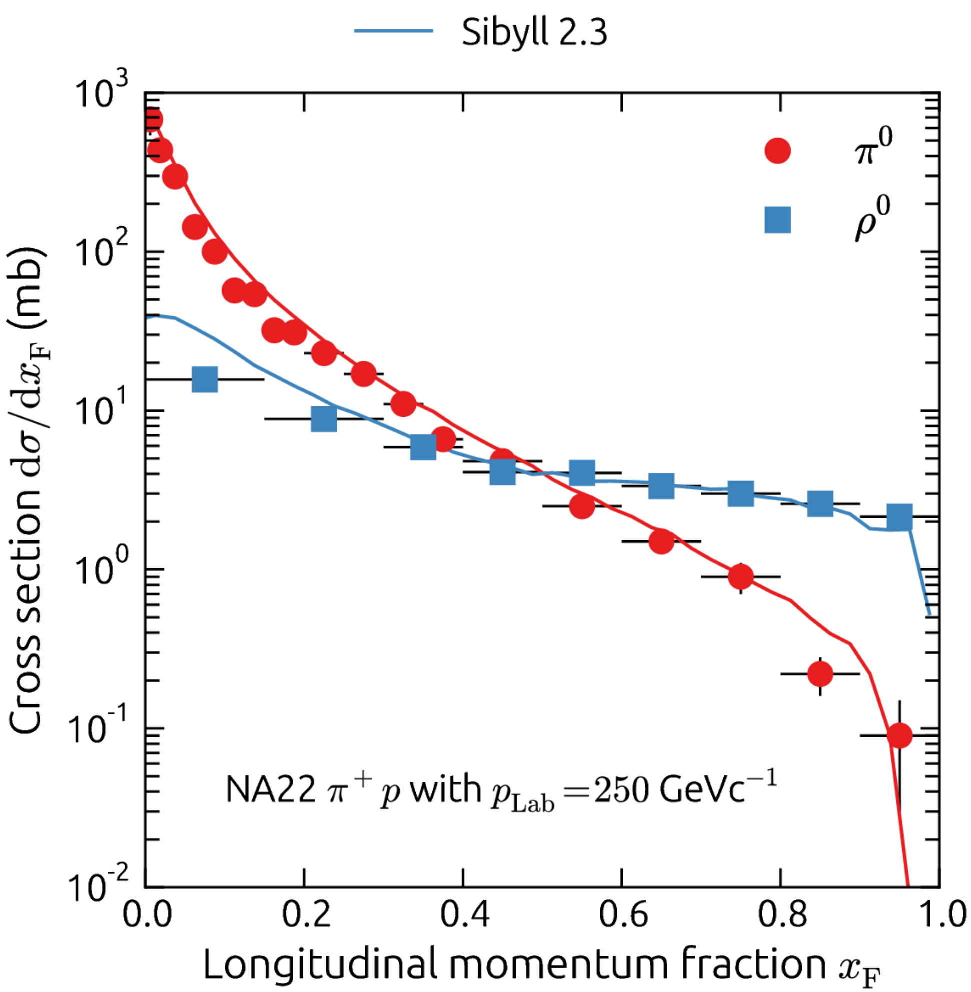


Not reproduced by model !

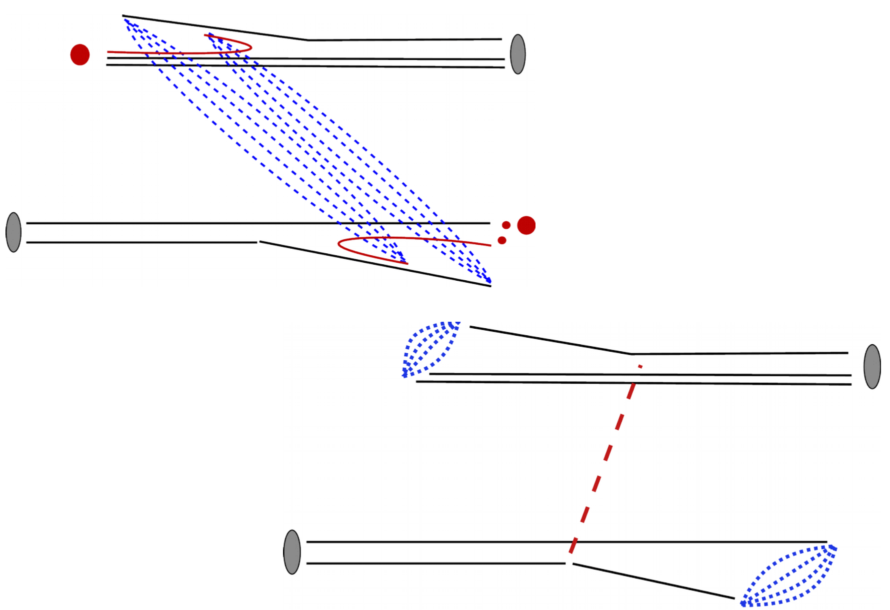


$$R_{\rho^0}/R_{\pi^0} = 0.3$$

Leading pions in the model

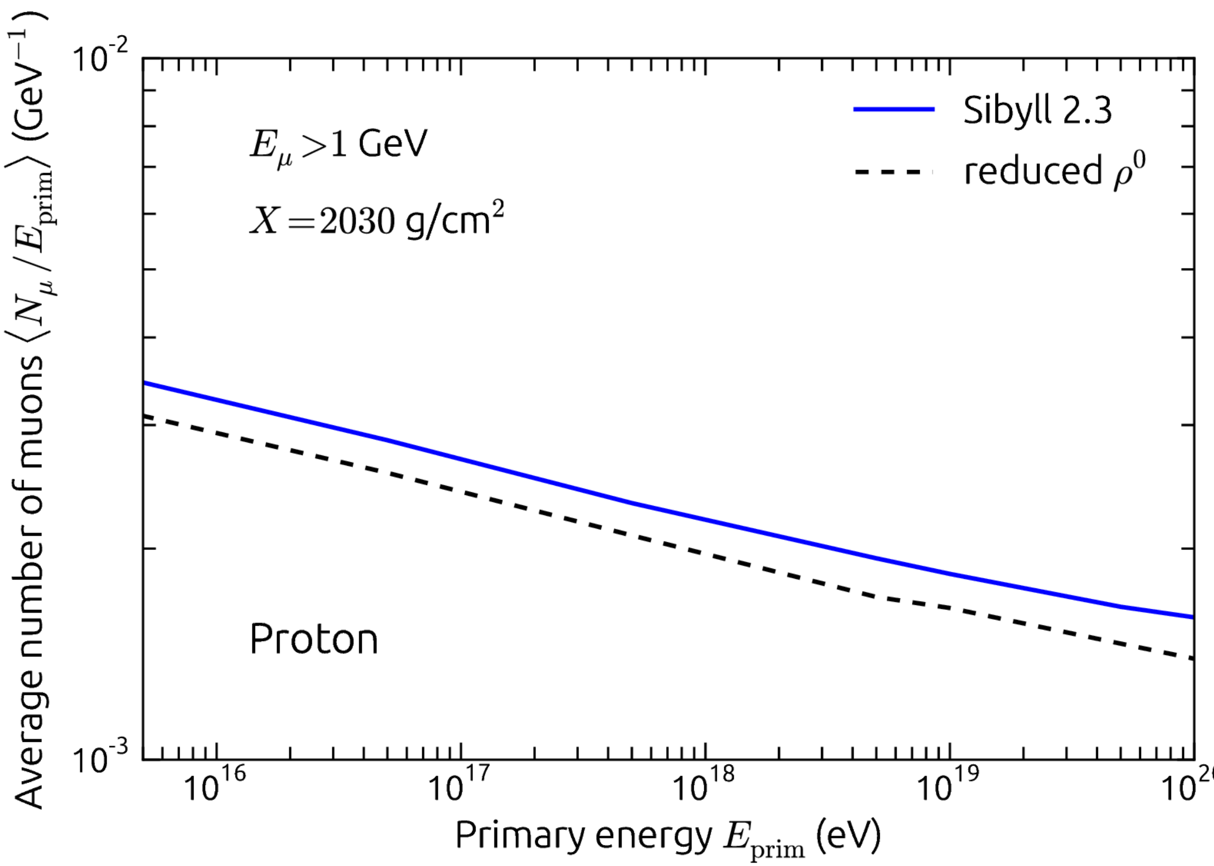


Adding new processes and exchanges



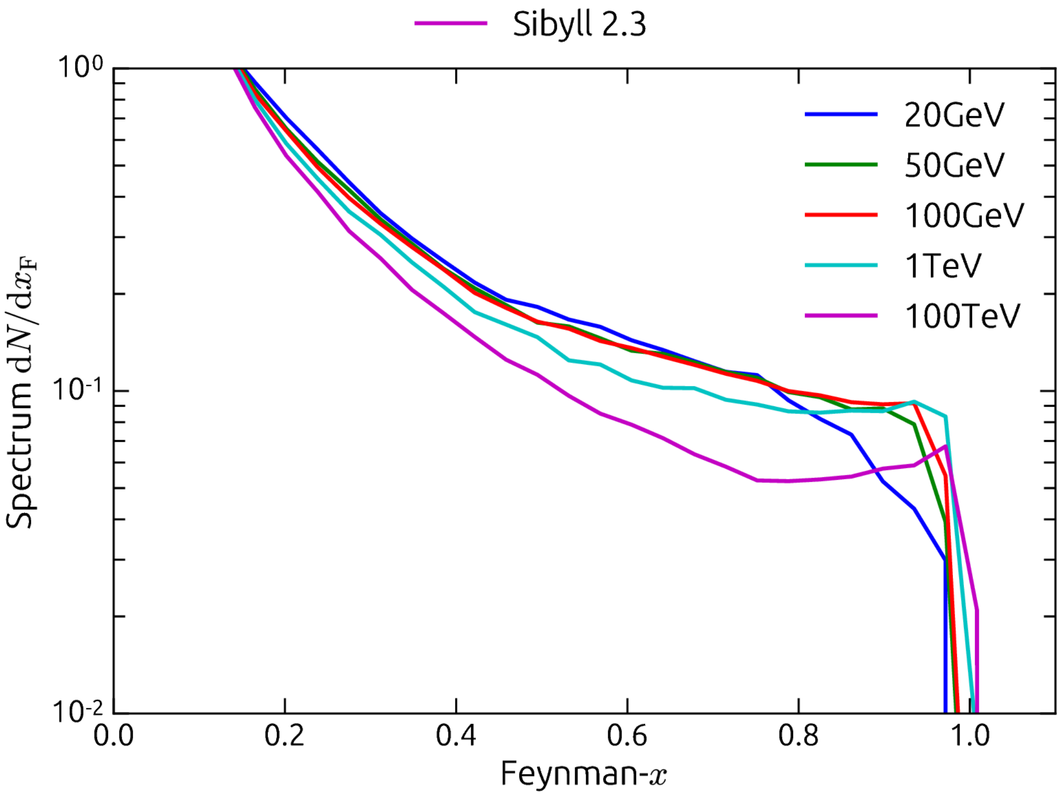
$$R_{\rho^0}/R_{\pi^0} = f(x_{\mathrm{F}})$$

Leading pions in air showers



$$\log N_\mu = \log\left(A^{1-\alpha}\right) + \alpha \log\left(\frac{E_0}{E_{\rm crit}}\right)$$

Energy dependence



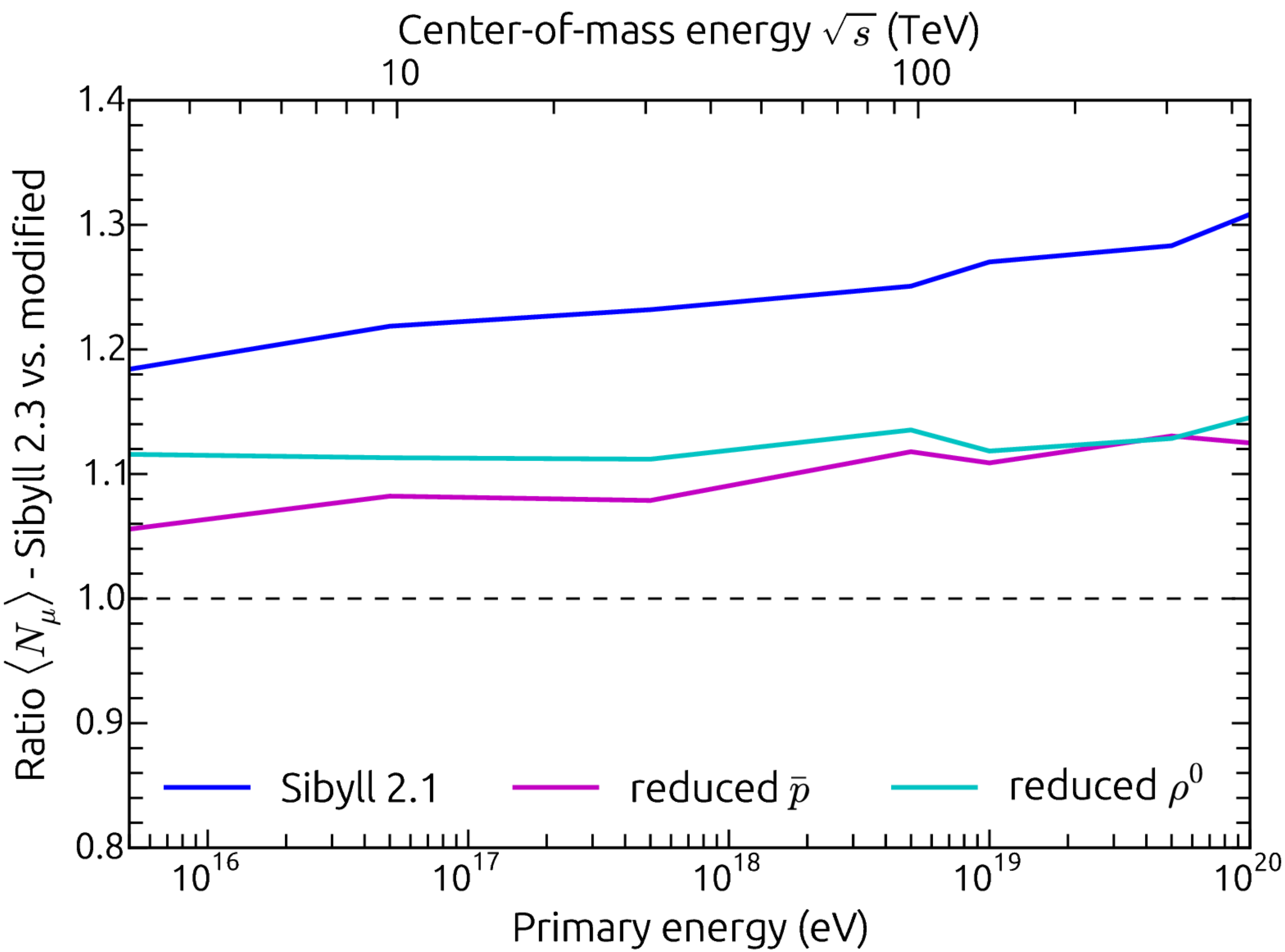
Approach entirely phenomenological

Underlying process?

→ scaling behaviour ?

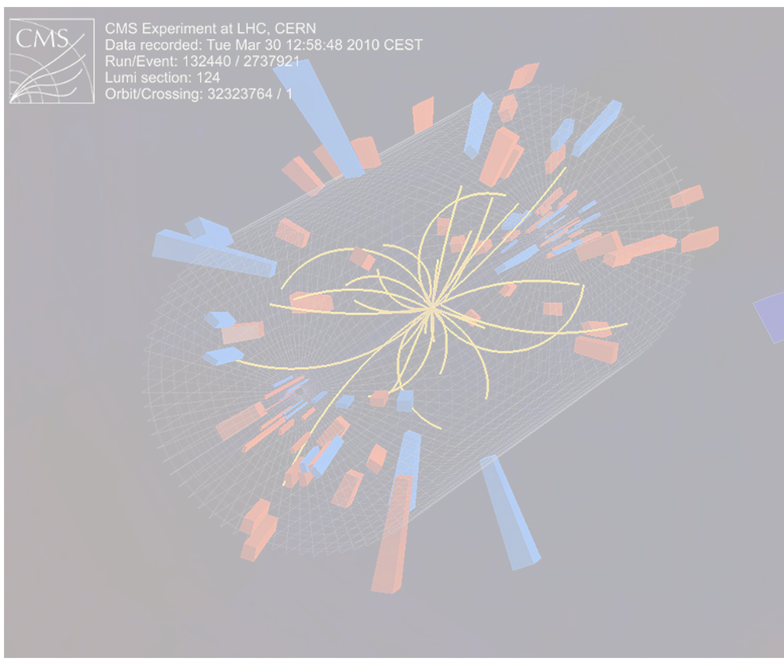
Effect on muons?

Muons in the new model



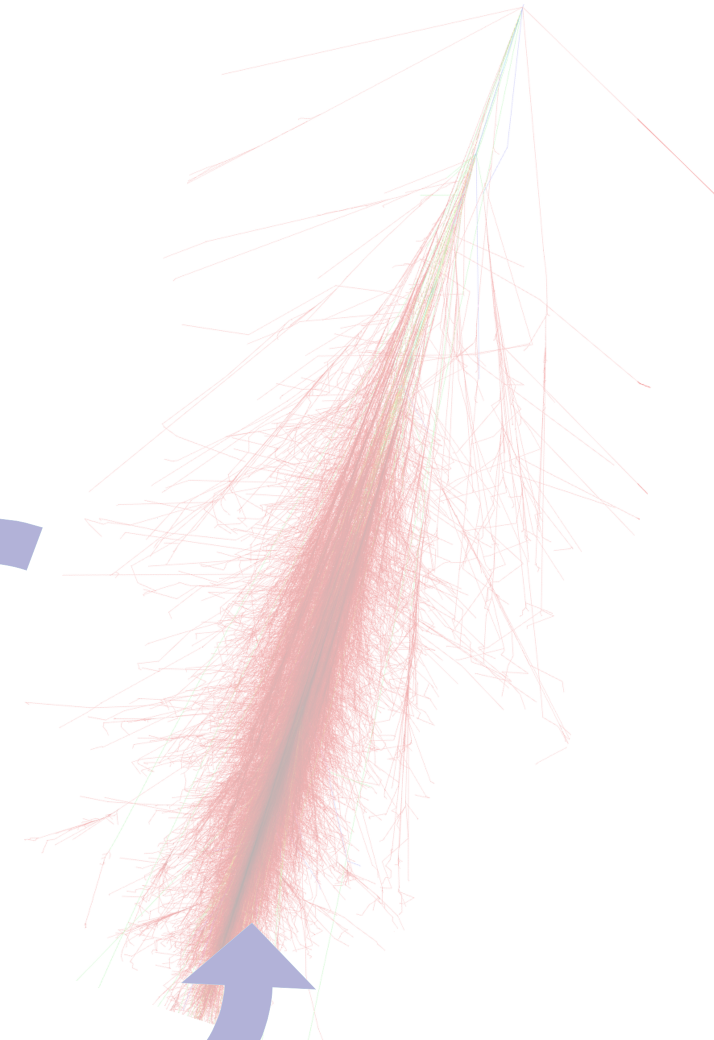
20 - 30% more muons

Input from theory



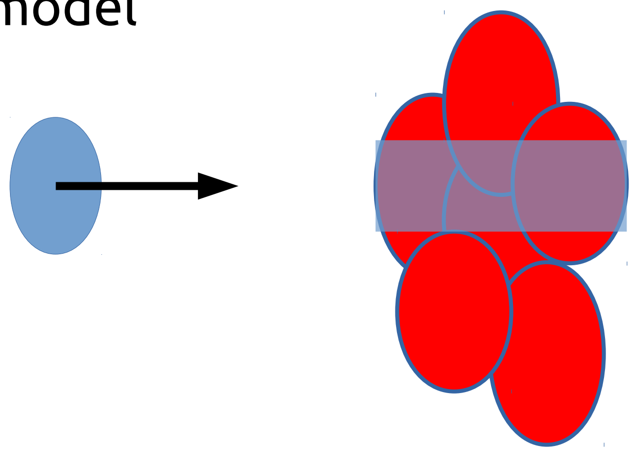
SIBYLL 2.1

SIBYLL 2.3



'Inelastic screening'

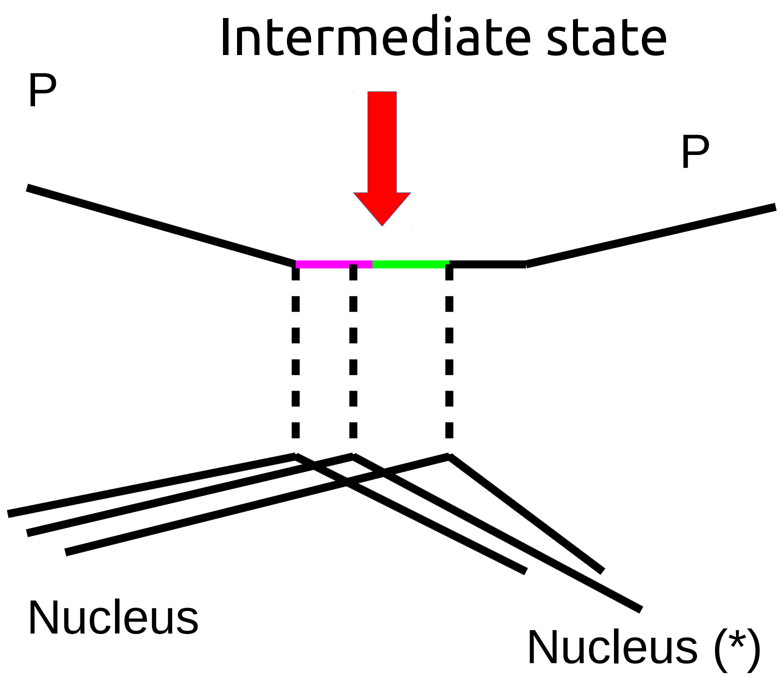
Glauber model



Inelastic contribution to elastic
p Nuc → p Nuc

AND

Diffractive
p Nuc → p* Nuc cross section



Requires coherence !

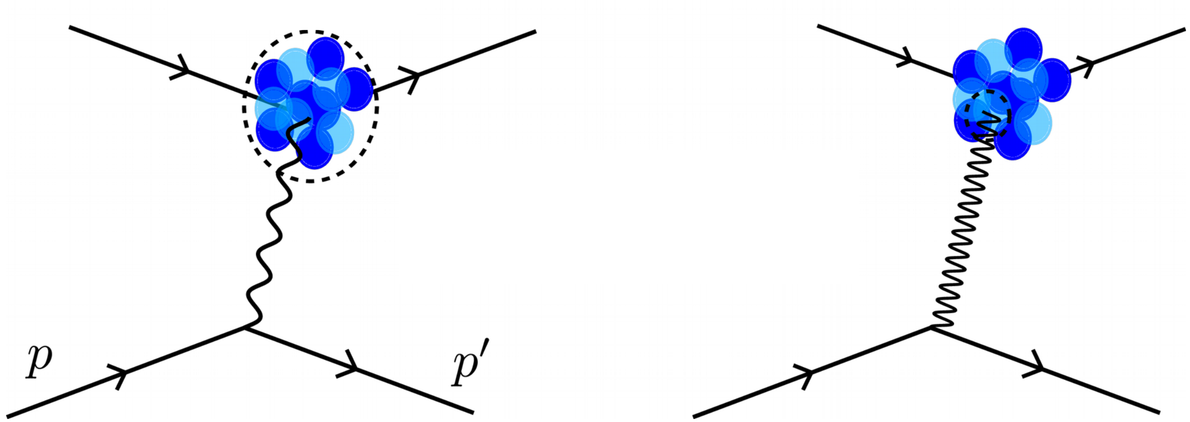
Nuclear diffraction

In Sibyll 2.1:

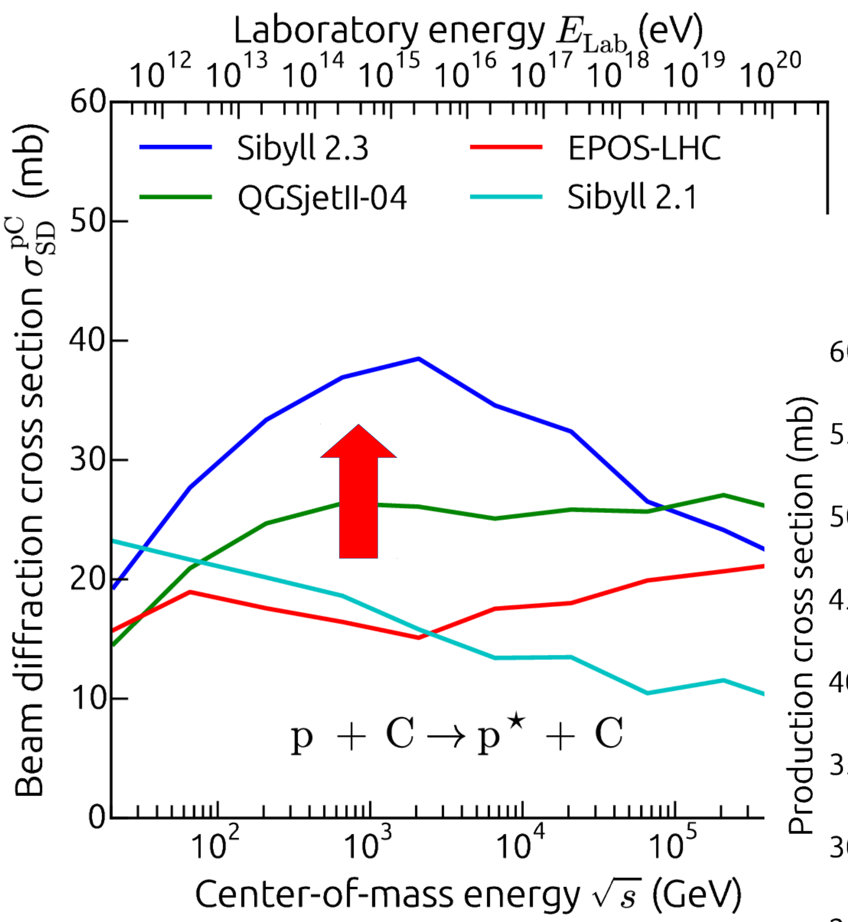
$$\sigma_{\text{diff}}^{\text{hNuc}} = \sigma_{\text{prod}} \left(\frac{\sigma_{\text{diff}}^{hp}}{\sigma_{\text{inel}}^{hp}} \right)^{N_{\text{w}}}$$

Sibyll 2.3: calculate diffractive cross section

$$\sigma_{\text{diff}}^{\text{hNuc}} = \sigma_{\text{diff}}^{\text{Glauber}} + f_{\text{incoherent}}\, \sigma_{\text{prod}} \left(\frac{\sigma_{\text{diff}}^{hp}}{\sigma_{\text{inel}}^{hp}} \right)^{N_{\text{w}}}$$

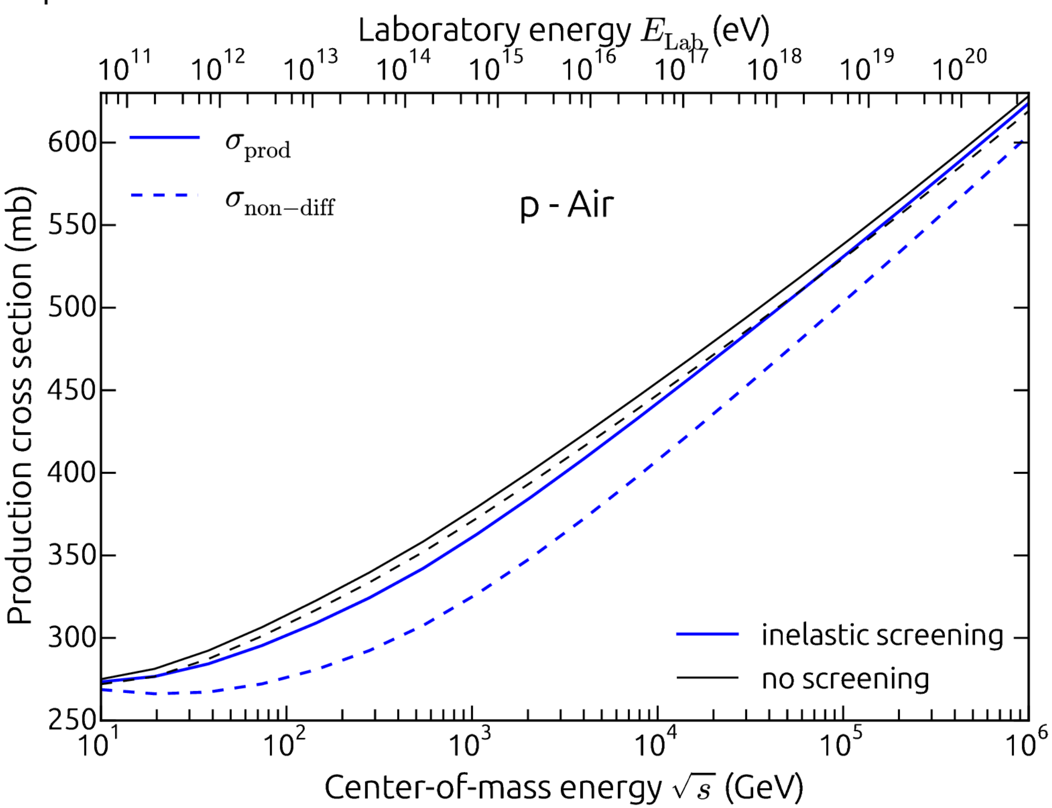


Effect of the diff. cross section

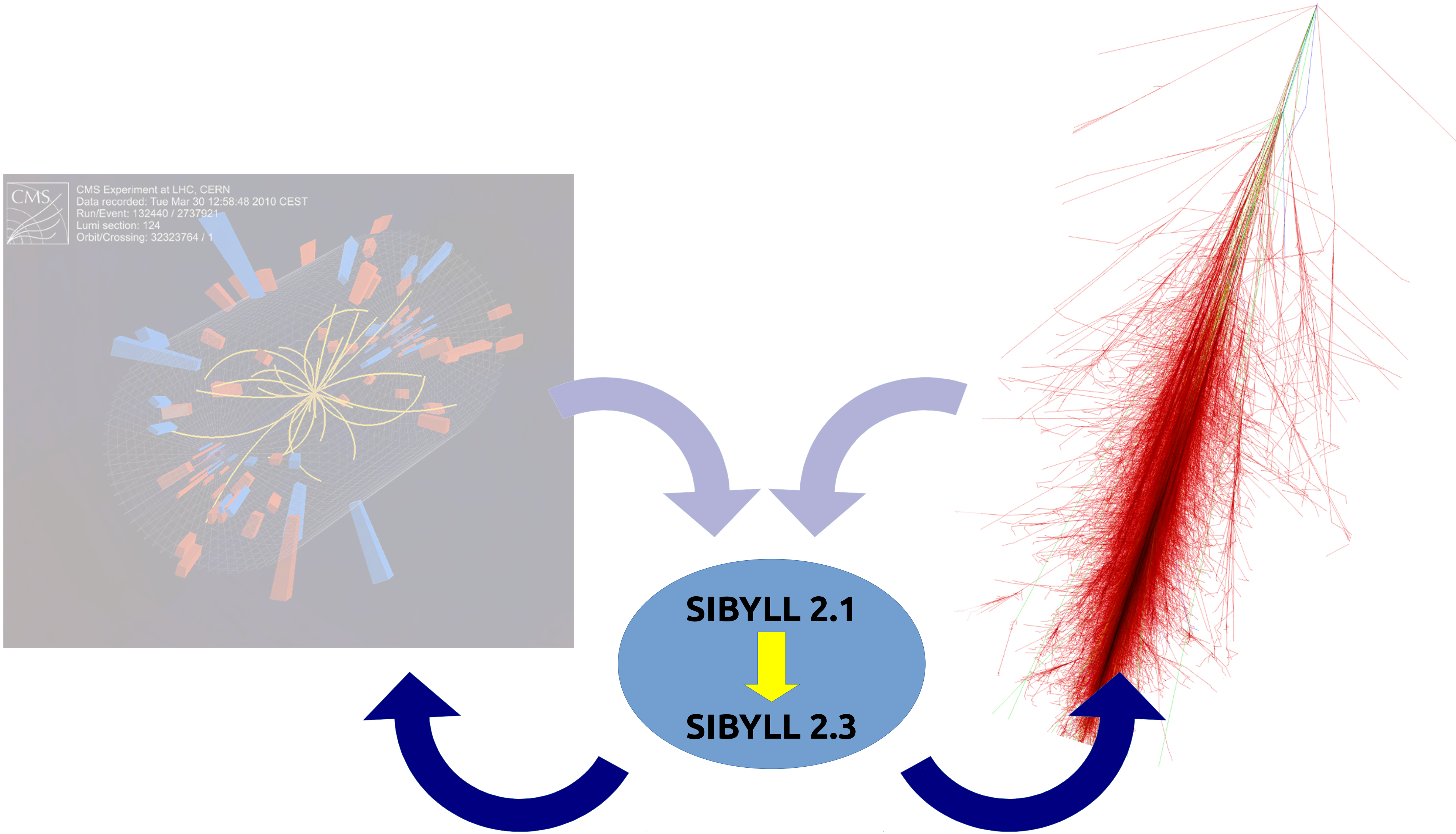


Diffraction → very elastic

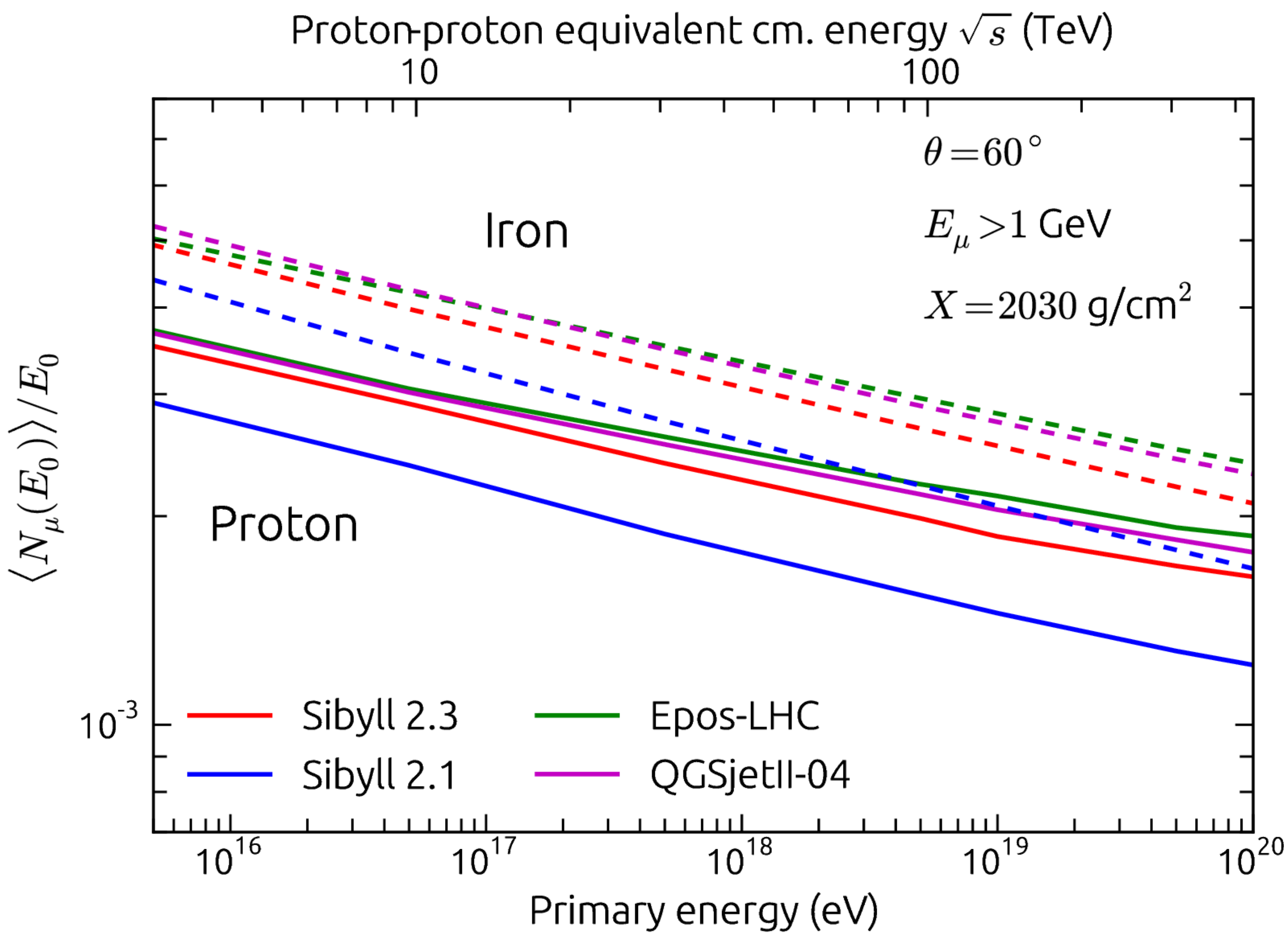
Effective interaction length increases!



Air shower predictions

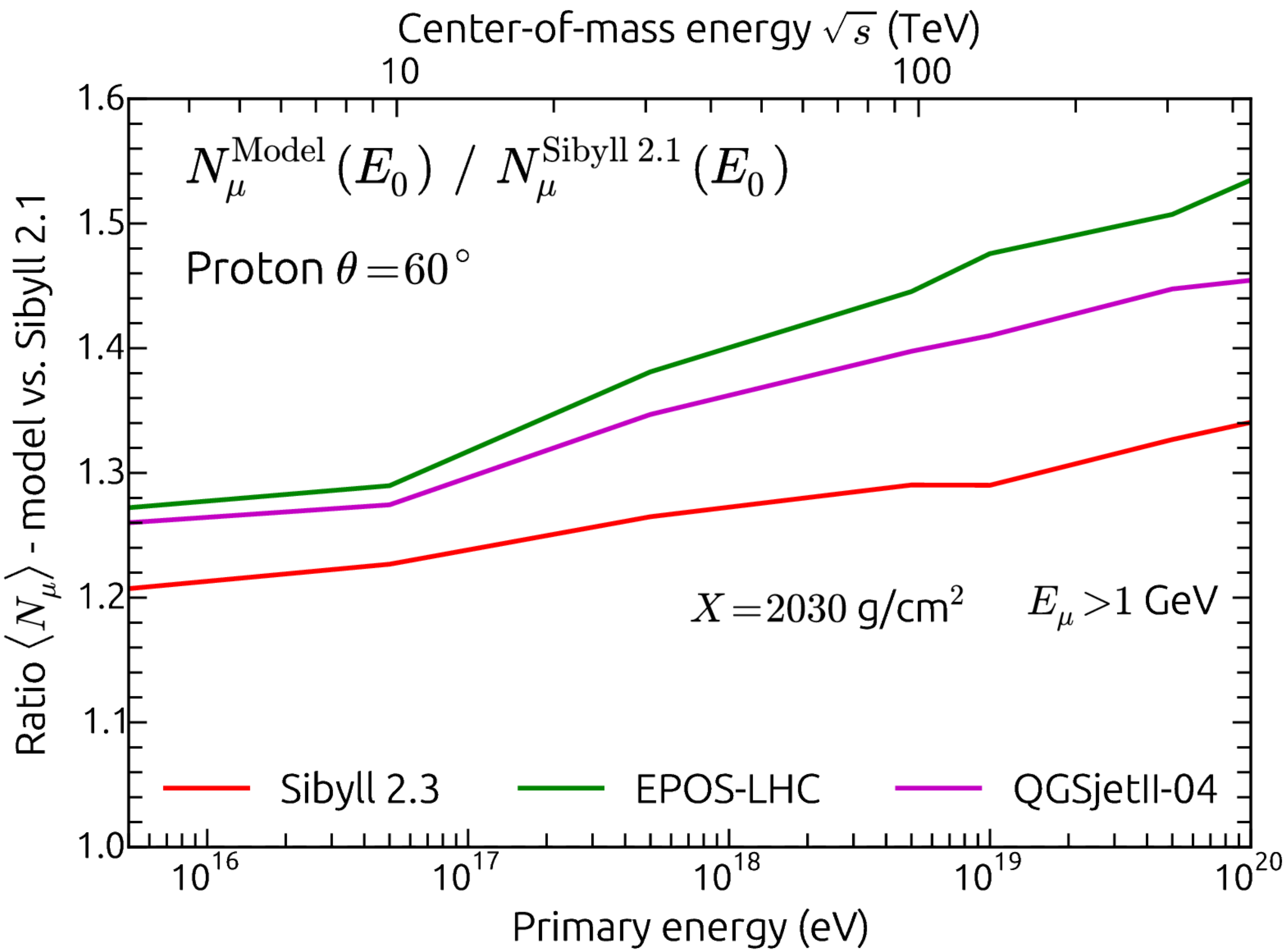


Muon number

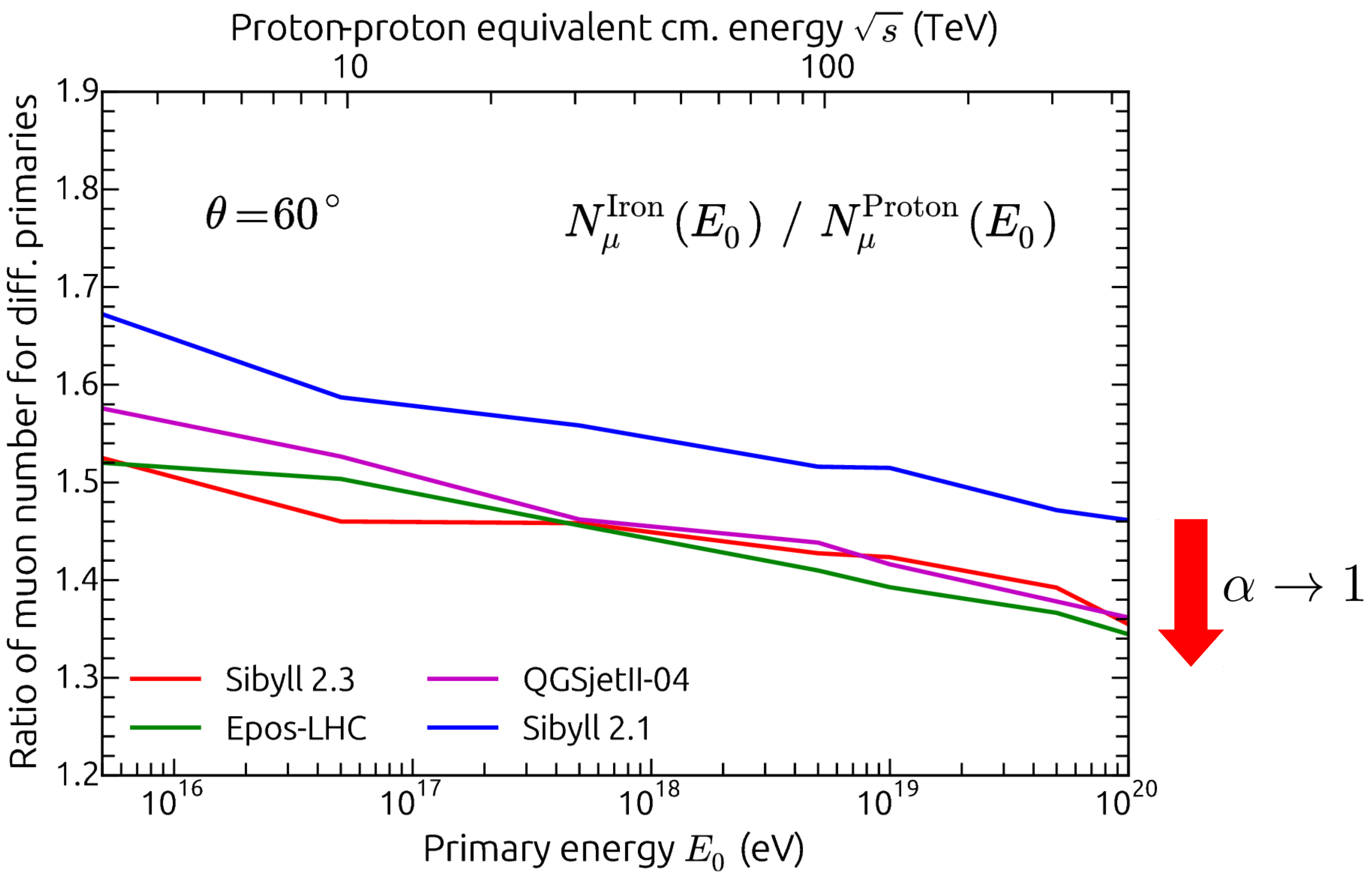


Proton-proton equivalent cm. energy $\sqrt{s}$ (TeV)
10
100
$\theta = 60^\circ$
$E_\mu > 1$ GeV
$X = 2030$ g/cm^2
Iron
Proton
$\langle N_\mu(E_0) \rangle / E_0$
10^{-3}
Sibyll 2.3
Sibyll 2.1
Epos-LHC
QGSjetII-04
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Primary energy (eV)

Relative muon number

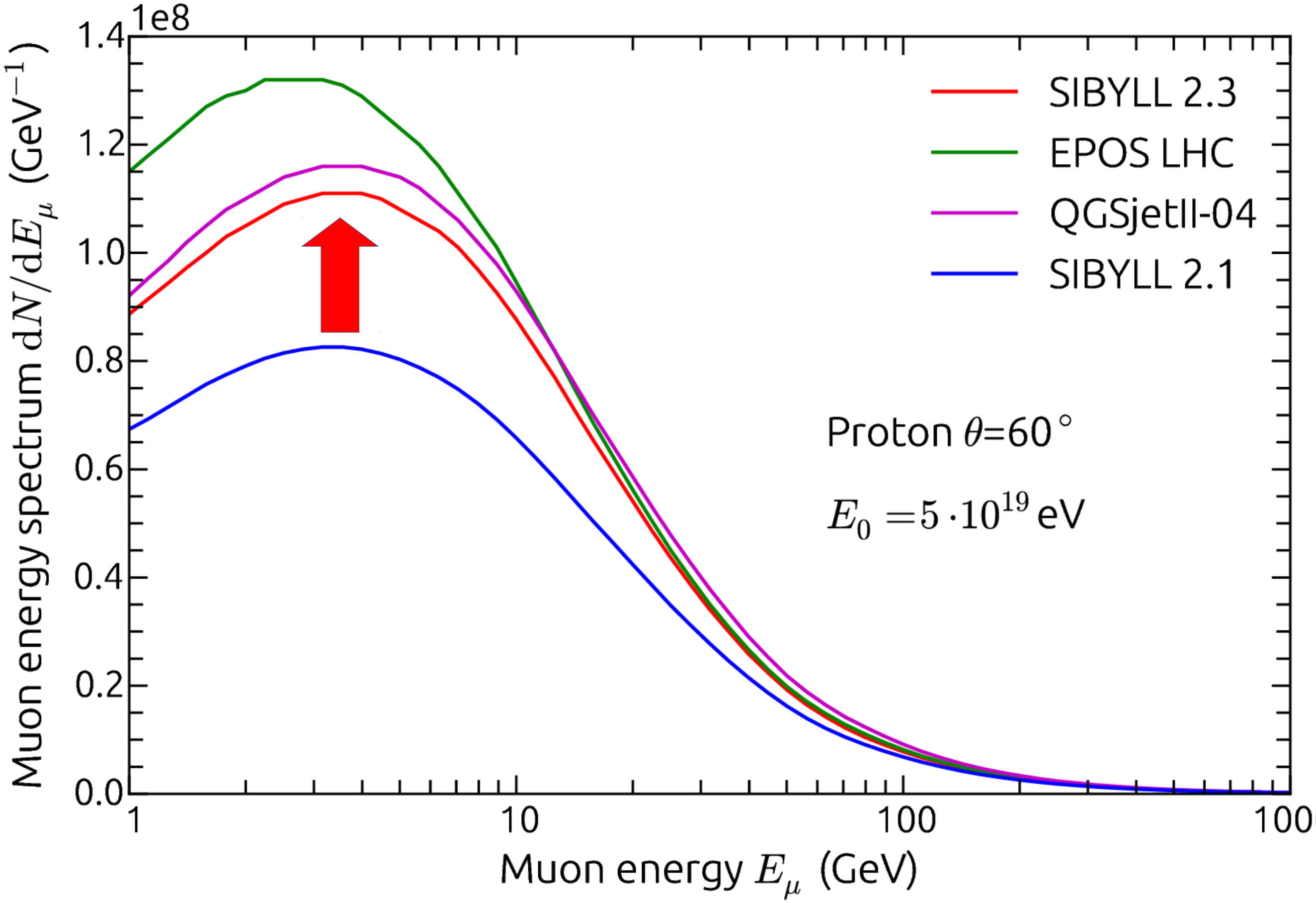


Comparing primaries



$$\log N_\mu = \log\left(A^{1-\alpha}\right) + \alpha \log\left(\frac{E_0}{E_{\mathrm{crit}}}\right)$$

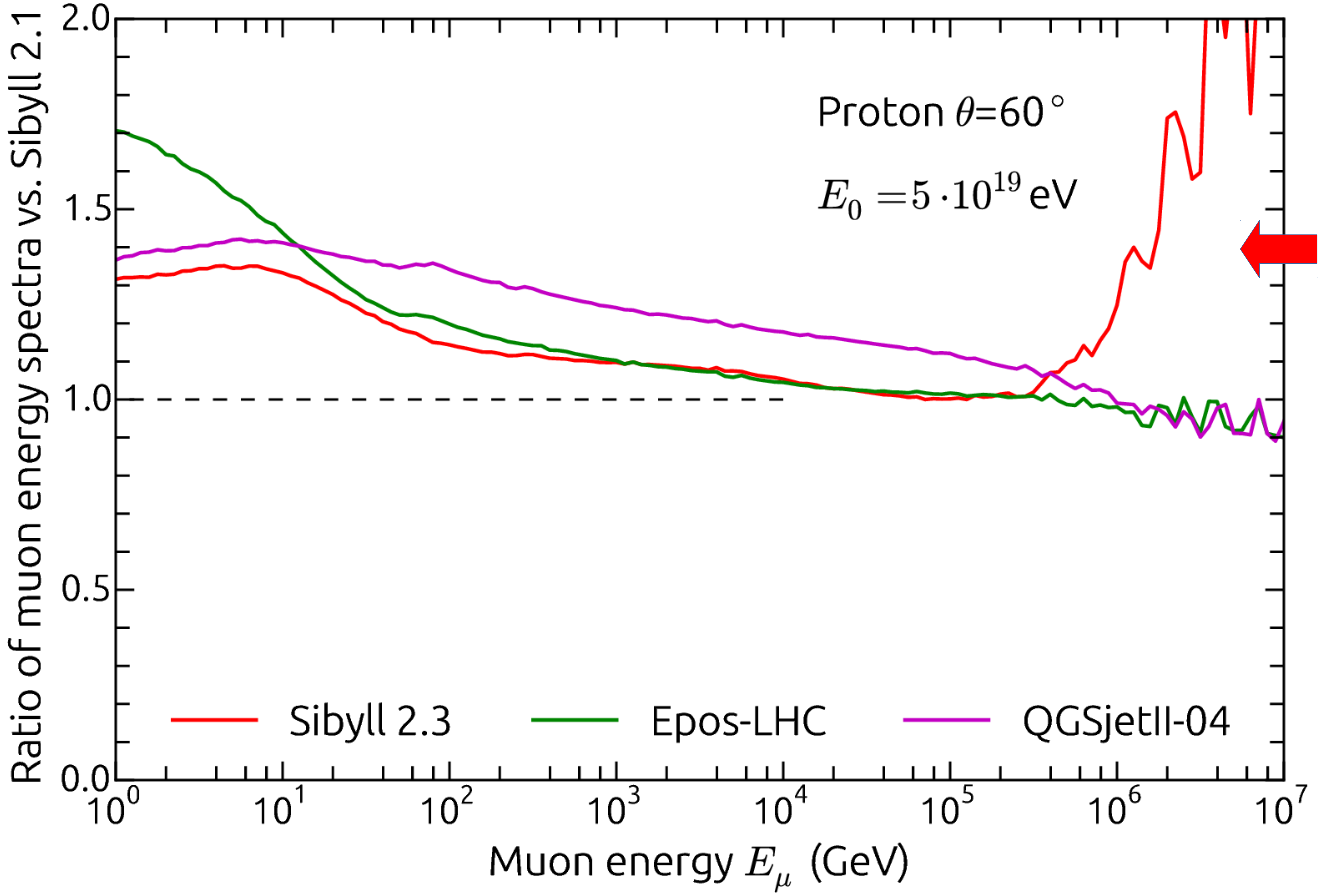
What kind of muons?



Increase in low energy muons

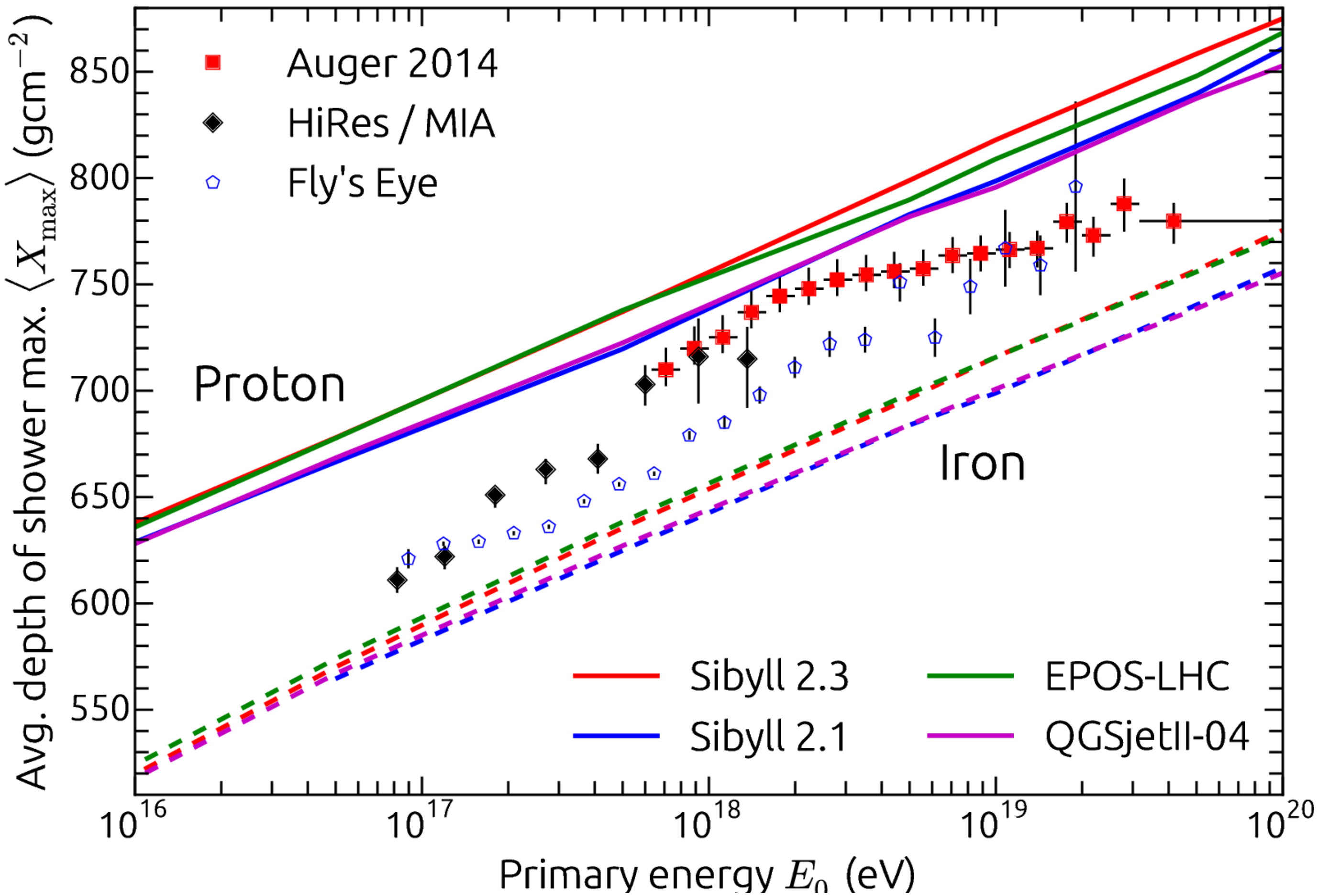
What kind of muons?

Increase in low energy muons



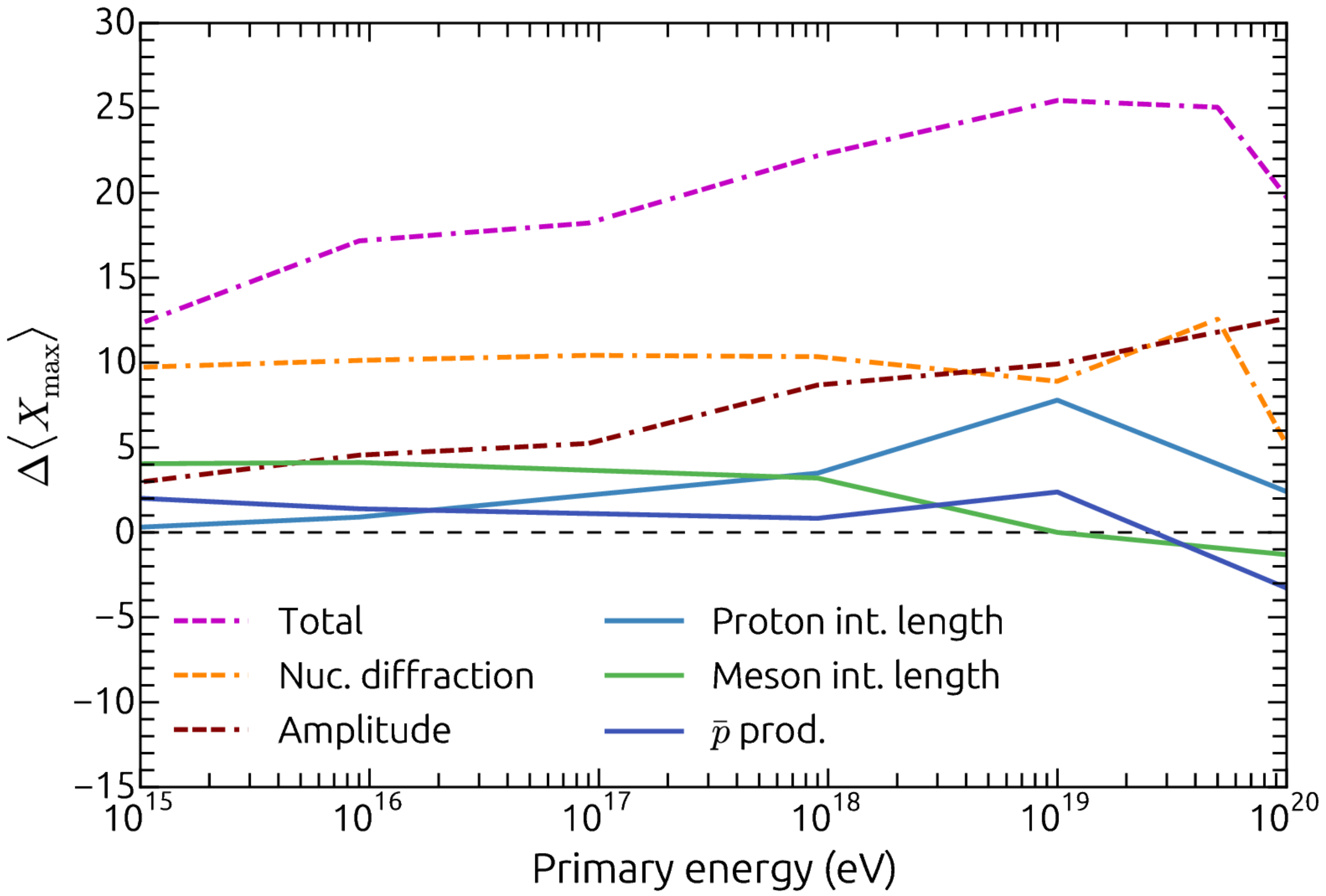
Charmed hadrons !

Xmax



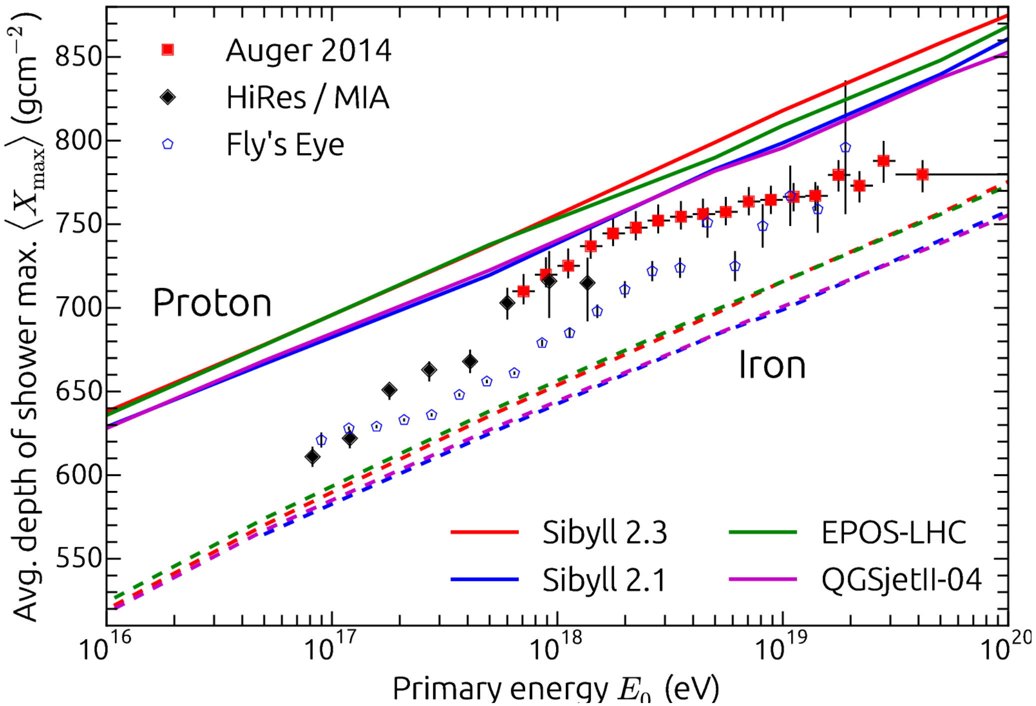
Auger 2014
HiRes / MIA
Fly's Eye
Proton
Iron
Sibyll 2.3
Sibyll 2.1
EPOS-LHC
QGSjetII-04
850
800
750
700
650
600
550
Avg. depth of shower max. $\langle X_{\max} \rangle$ (gcm^{-2})
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Primary energy E_0 (eV)

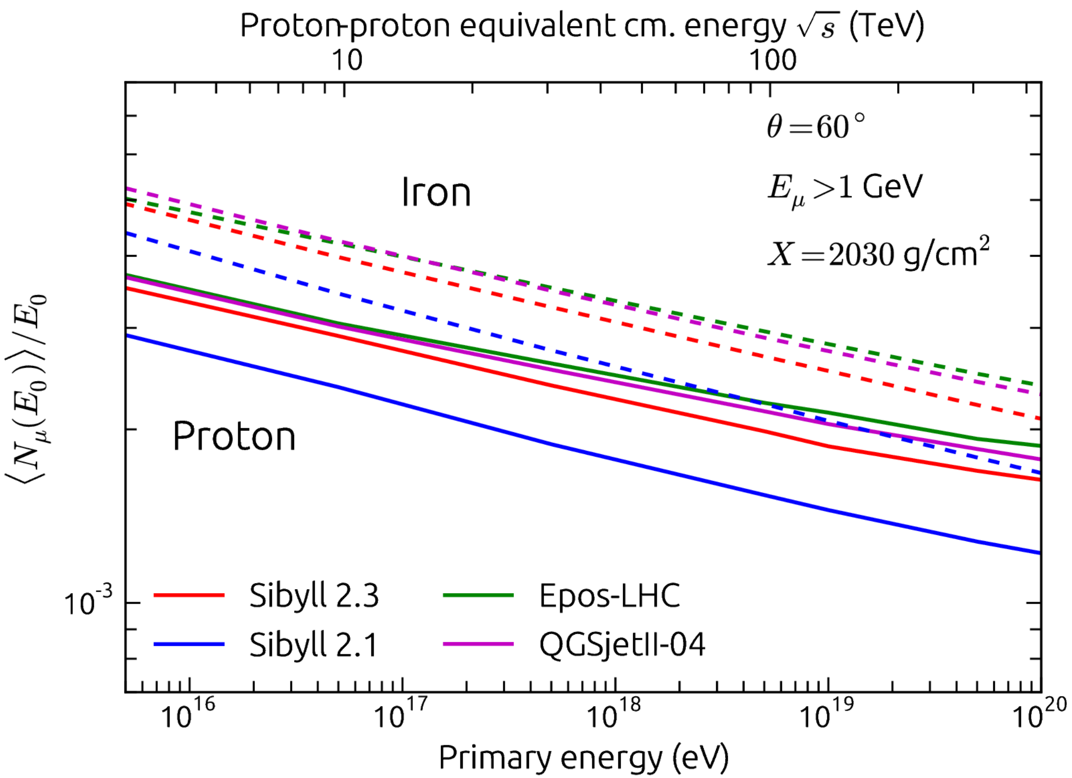
Relative changes



Xmax **not** unambigous !

Predictions summarized





Deeper Xmax → heavier composition → larger signal at ground

Increased number of muons → larger signal at ground

Enough for consistent description of Auger data?

Summary & Outlook

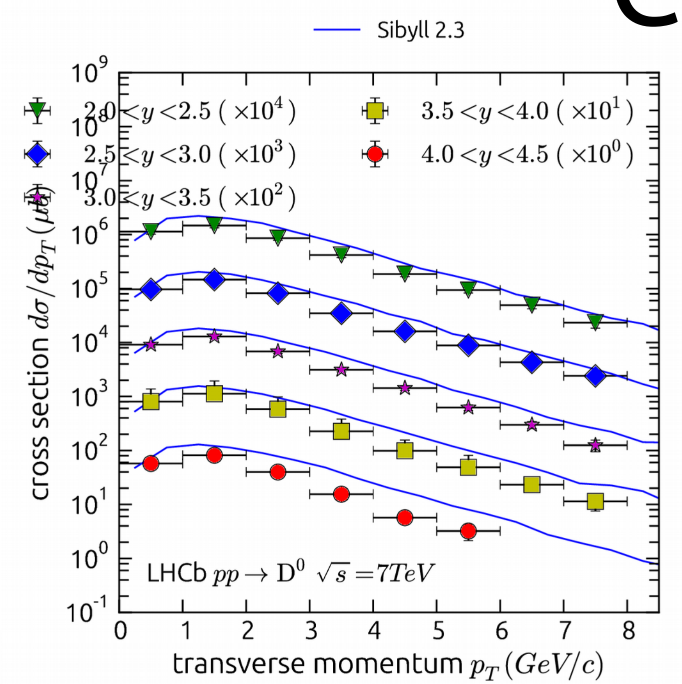
Sibyll is alive and well.

* First LHC results implemented.
* Contemporary model:
    - beam remnants, leading vector mesons, increased baryon production
* Destinct feature: charm production

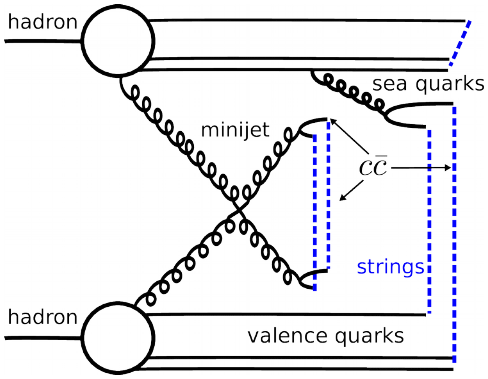
Interaction models: “the same but different”

LHC has boosted development BUT potential not exhausted.
Many forward measurements open.

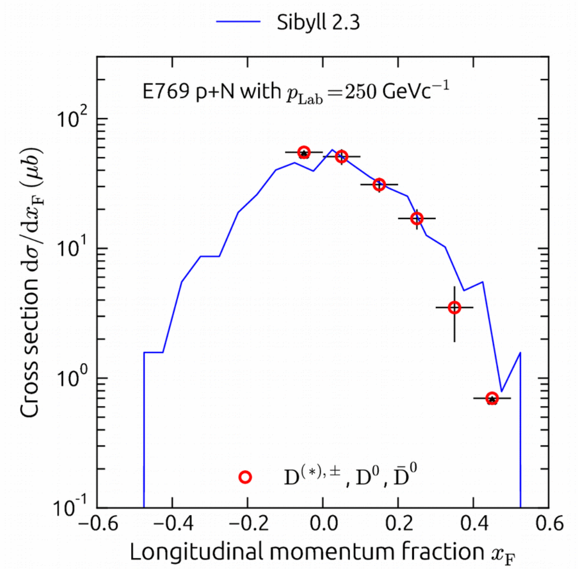
Charm model



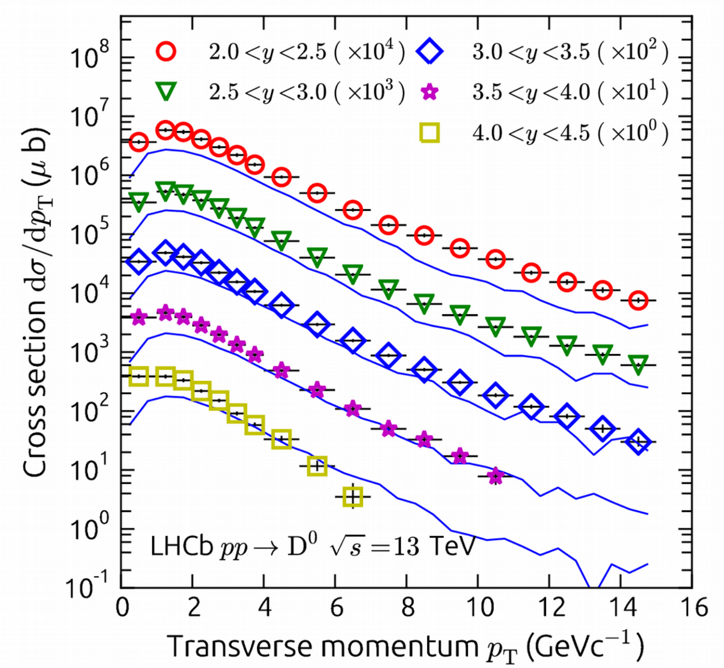
Sibyll 2.3
$2.0 < y < 2.5$ ($\times 10^4$)
$2.5 < y < 3.0$ ($\times 10^3$)
$3.0 < y < 3.5$ ($\times 10^2$)
$3.5 < y < 4.0$ ($\times 10^1$)
$4.0 < y < 4.5$ ($\times 10^0$)
cross section $d\sigma/dp_T$ (μb)
LHCb $pp \to D^0$ $\sqrt{s} = 7 TeV$
transverse momentum p_T (GeV/c)



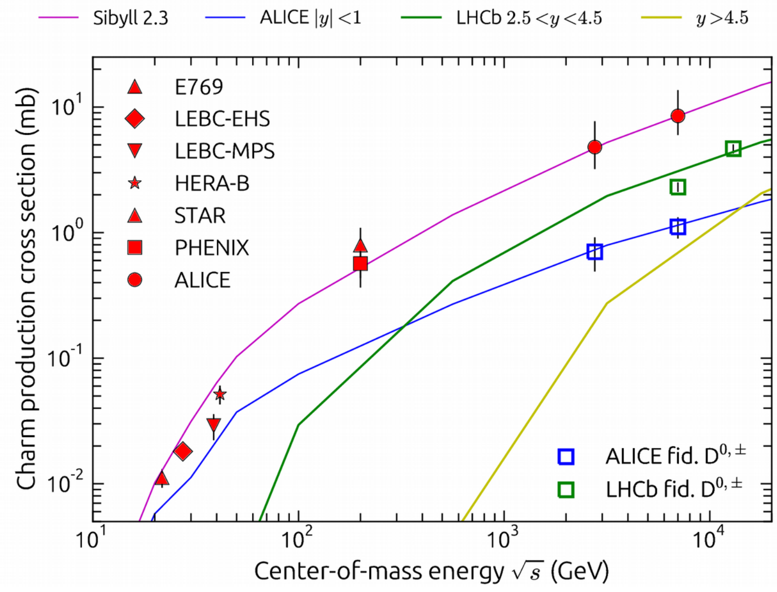
hadron
sea quarks
minijet
$c\bar{c}$
strings
hadron
valence quarks



Sibyll 2.3
E769 p+N with $p_{\rm Lab} = 250$ GeVc^{-1}
Cross section $d\sigma/dx_F$ (μb)
$D^{(*),\pm}$, D^0, $\bar{D}^0$
Longitudinal momentum fraction x_F

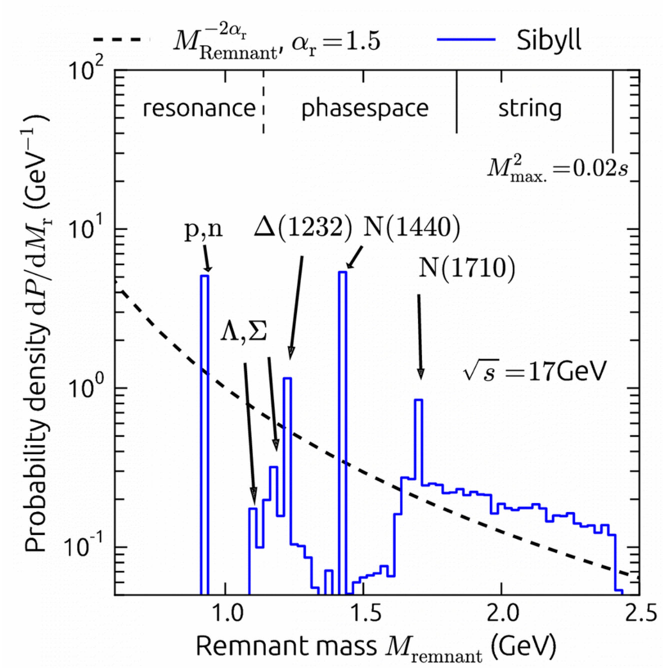


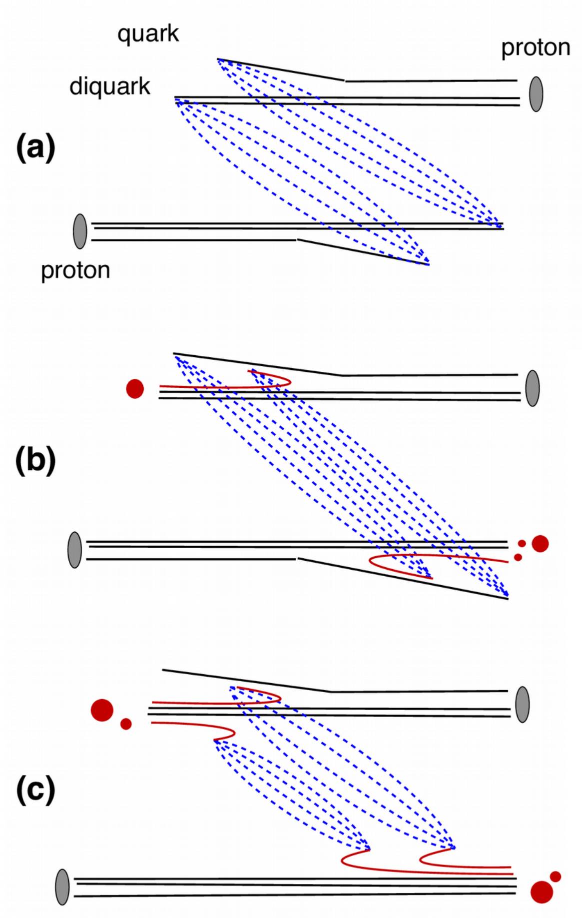
$2.0 < y < 2.5$ ($\times 10^4$)
$2.5 < y < 3.0$ ($\times 10^3$)
$3.0 < y < 3.5$ ($\times 10^2$)
$3.5 < y < 4.0$ ($\times 10^1$)
$4.0 < y < 4.5$ ($\times 10^0$)
Cross section $d\sigma/dp_T$ (μ b)
LHCb $pp \to D^0$ $\sqrt{s} = 13$ TeV
Transverse momentum p_T (GeVc^{-1})

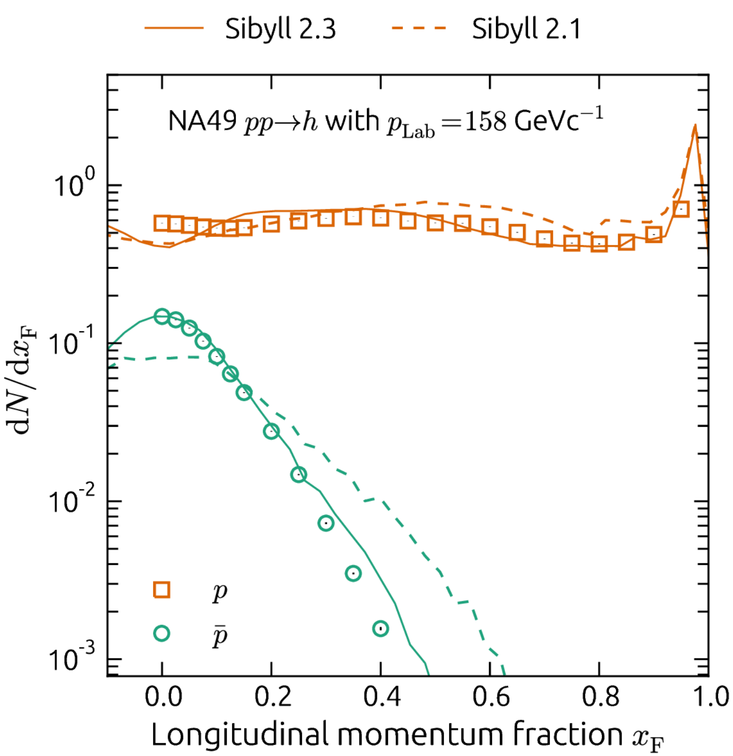


Sibyll 2.3
ALICE $|y| < 1$
LHCb $2.5 < y < 4.5$
$y > 4.5$
E769
LEBC-EHS
LEBC-MPS
HERA-B
STAR
PHENIX
ALICE
ALICE fid. $D^{0,\pm}$
LHCb fid. $D^{0,\pm}$
Charm production cross section (mb)
Center-of-mass energy $\sqrt{s}$ (GeV)

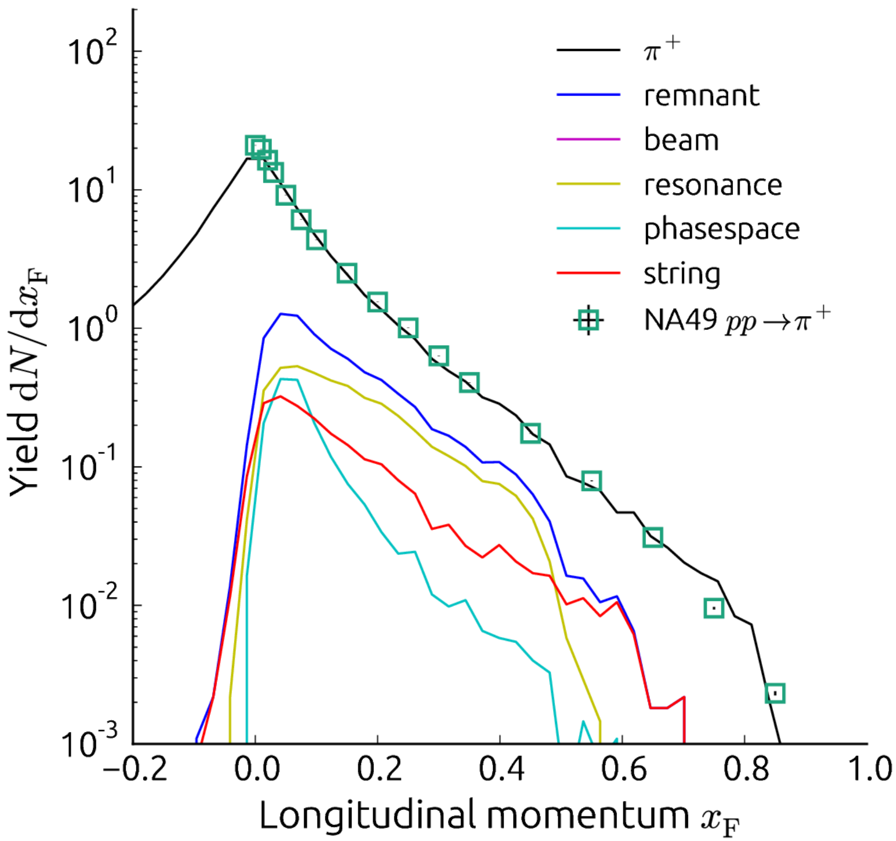
Leading particles - Remnants

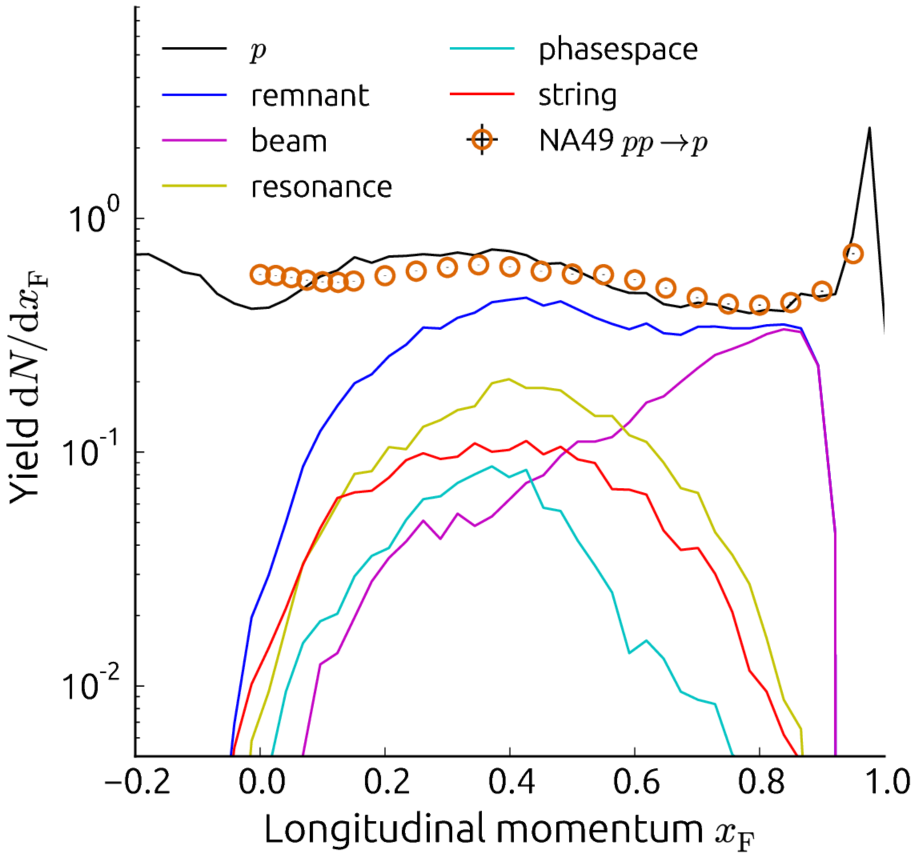




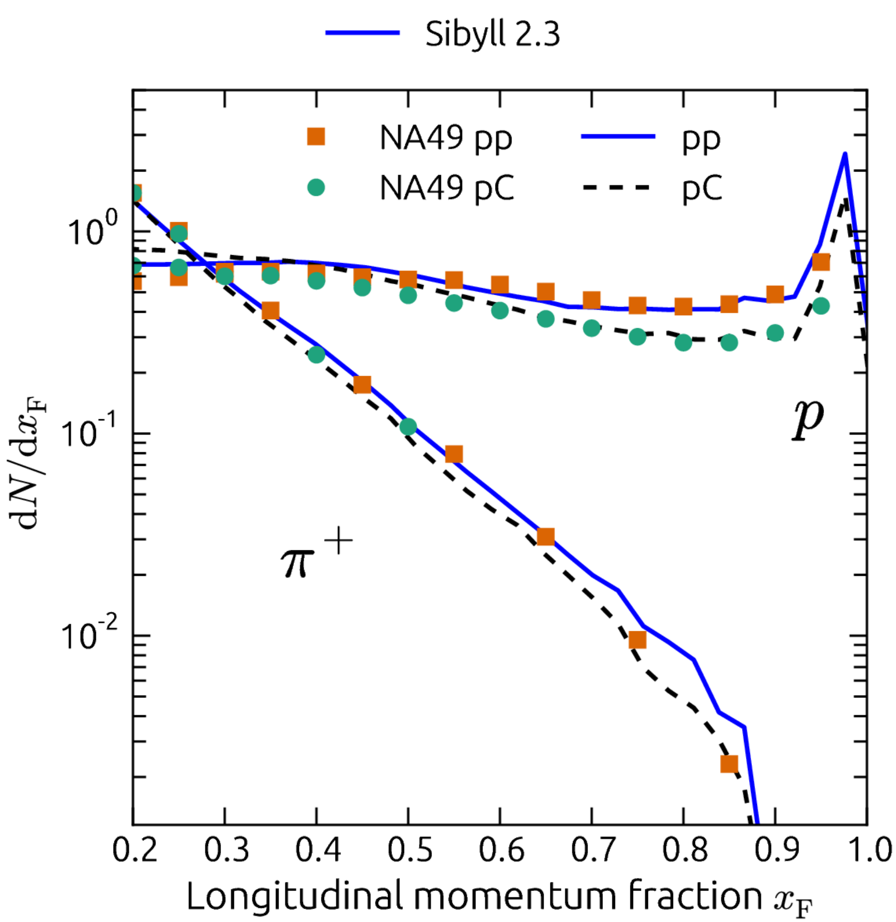


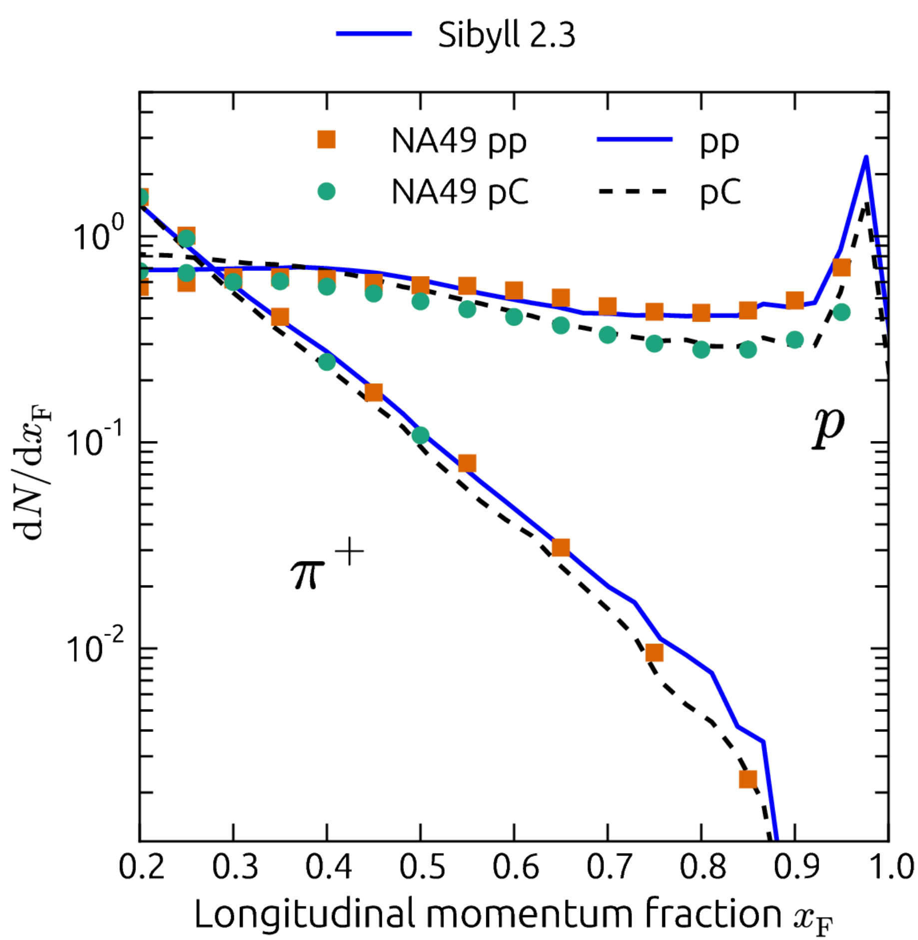
Leading particles - remnants





Leading particles - remnants





Why forward physics?

$$\Delta b \Delta p_{\mathrm{T}} \sim 1$$

Point-like partons → Q^2 small
direkt collisions (small b) are rare

$$\frac{\mathrm{d}\sigma_{\mathrm{ela}}}{\mathrm{d}Q^2} \approx e^{-B_{\mathrm{ela}} Q^2}$$

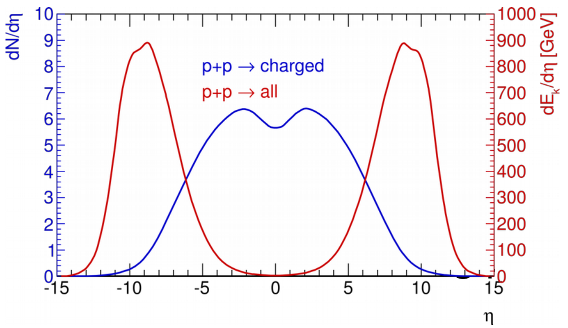
B_{ela} ~ 20 GeV^{-2} → $\langle Q^2 \rangle$ ~ 0.5 GeV^2

$$\theta = \tan(\frac{p_{\mathrm{T}}}{p_z}) \approx \frac{p_{\mathrm{T}}}{p_z}$$

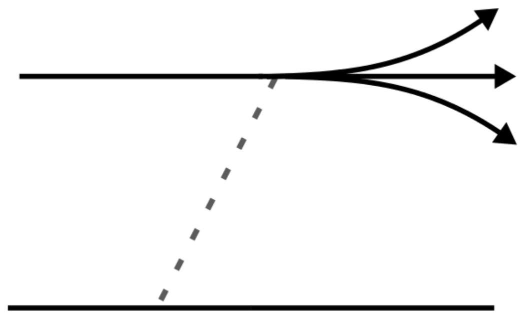
p_{T} is $\mathcal{O}(0.5\mathrm{GeV})$ with $\ln(E_{\mathrm{cm}})$

p_z is $\mathcal{O}(E_{\mathrm{cm}})$

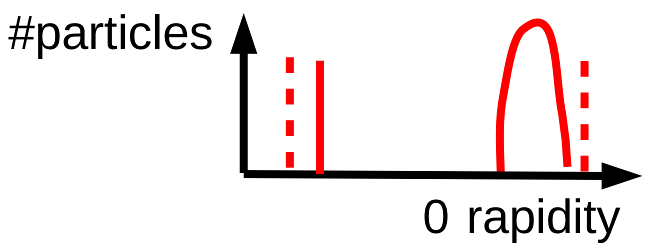
Most energy at small angles !
the larger the energy the smaller the angle

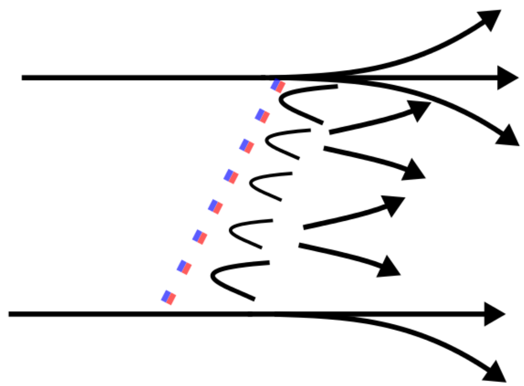


Event types

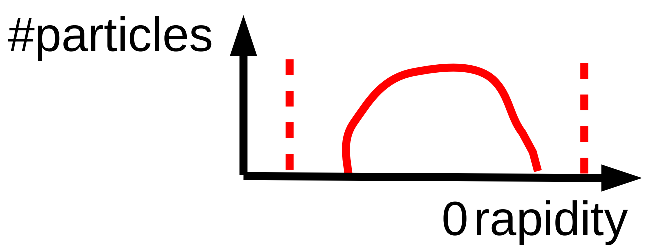


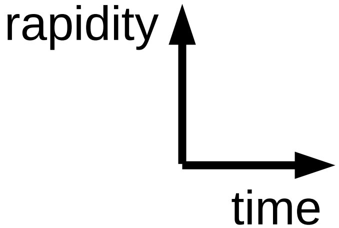
No color exchange
(diffractive)

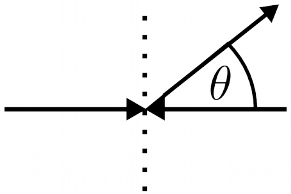




Color exchange
(non-diffractive)







$$\eta = -\log \tan(\frac{\theta}{2})$$

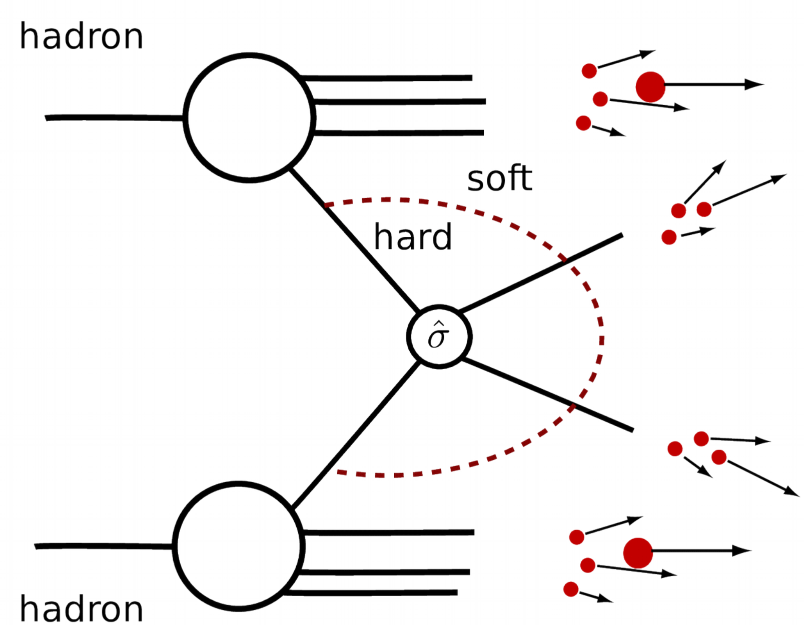
Modelling hadron interactions

$$d\sigma_{pp\to\text{final state}} = |\mathcal{M}|^2 \prod_{\text{final state}} \frac{d\vec{p}_i}{E_i}$$

Problems.. * complex final state

* Amplitude unknown

$\alpha_s \approx 1$



Approach: factorization

Hard scattering
Soft scattering
Hadronization

What are we doing?