Hadronic Interactions and Cosmic Rays at Ultra High Energies

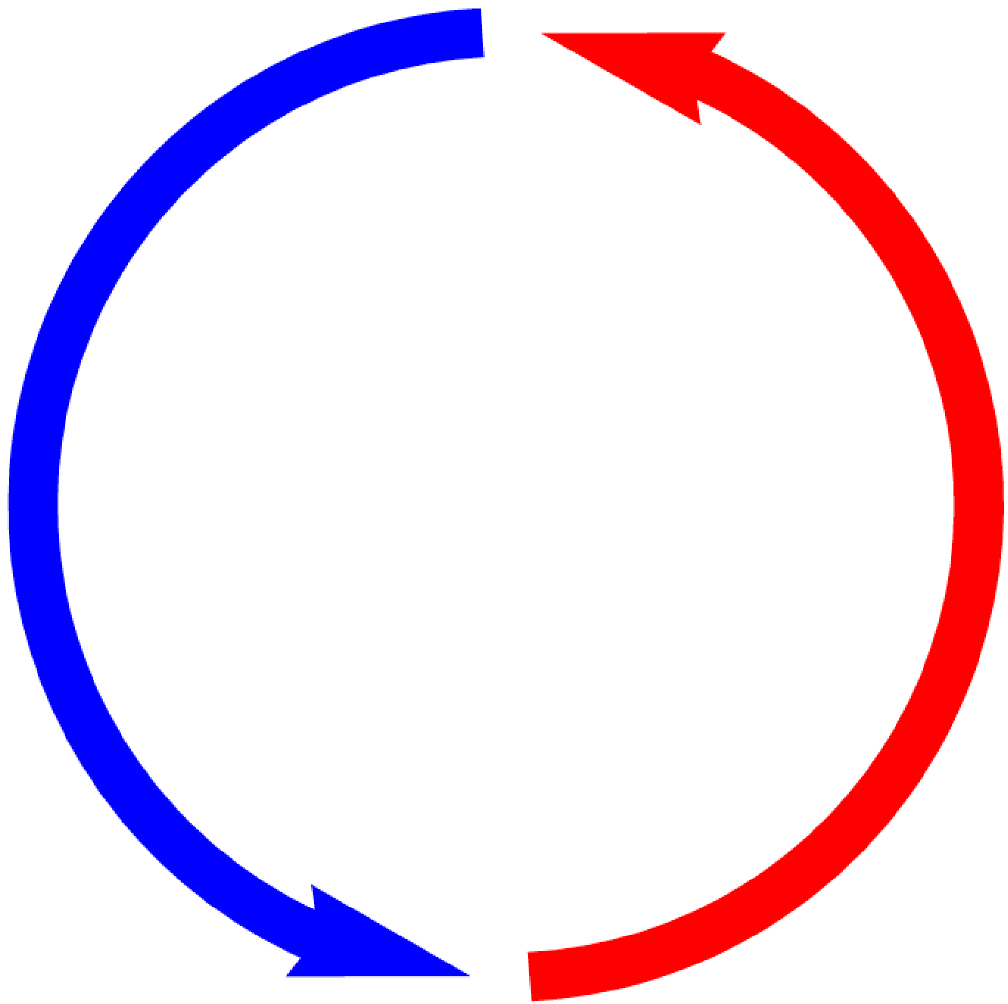
[Interplay of: cross sections,
interaction properties,
composition]

Paolo Lipari (INFN, Roma Sapienza)

Future directions in UHECR.

CERN, Geneve 14th february 2012

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

Theory (QCD) +
[Accelerator Data]

UHE Cosmic Ray
Data

"Direct Route" Program:

1. Obtain data at accelerators
   (LHC ! + others)

2. Develop a sound theoretical
   framework to extrapolate to
   high energy.

3. Interpret the CR data

Theory (QCD) +
[Accelerator Data]

UHE Cosmic Ray Data

"Direct Route" Program:

1. Obtain data at accelerators (LHC ! + others)

2. Develop a sound theoretical framework to extrapolate to high energy.

3. Interpret the CR data

Questions:

1. What new measurements are most important/possible ?

2. What are the best theoretical instruments to guide the extrapolation?

3. Where are we?
4. What can we achieve ?

LHC has been very generous !.....

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... but on can hope for more ...

(my) list of "desired" gifts from LHC.....

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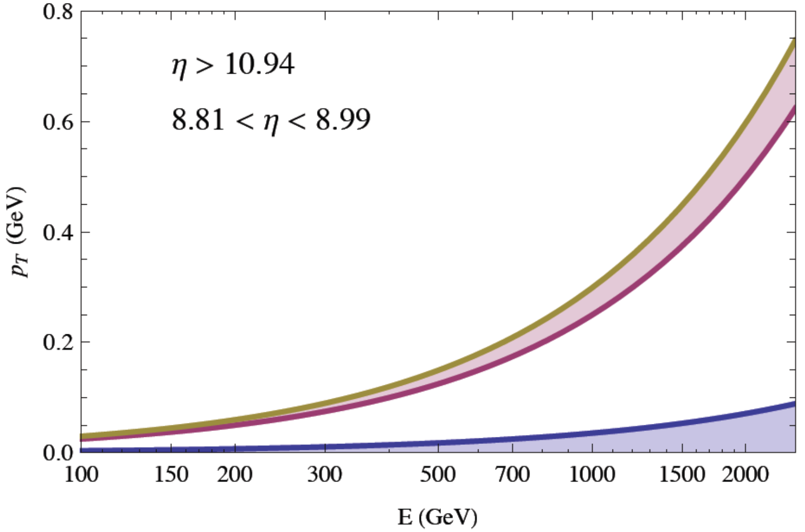
Proton – Nucleus collisions !

LHCf inclusive spectra
($p_\perp$ integrated) (photons + pi0)



Diffraction cross sections
(theoretical understanding)

Understanding of the "underlying events"
Consistent with $d\sigma_{\rm el}/dt$ (profile function)

Is it possible to obtain information about Particle Physics from the UHECR data ?

Particle Physics
[hadronic interactions, "exotica" ?]

UHE Cosmic Ray Data

Is it possible to obtain information about Particle Physics from the UHECR data ?

Particle Physics
[hadronic interactions,
"exotica" ?]

Isn't (the lack of information about) composition an "impossible obstacle" ?

1. Astrophysical composition measurements:
   * Magnetic deviations
   * Energy losses imprints on the energy spectrum

2. "Self-consistency" or "Bootstrap" ?

UHE Cosmic Ray Data

Measurement of the p-Air Interaction Length:

$$X_{\max} = X_0 + Y$$

Position 1st interaction
Shower Development

$$F(X_{\max}) \equiv \frac{dN_{\text{shower}}}{dX_{\max}}$$

$$G(Y) \equiv \frac{dN_{\text{shower}}}{dY}$$

$$F(X_{\max}) = \int_0^\infty dY \int_0^\infty dX_0 \; G(Y) \; \frac{e^{-X_0/\lambda_p}}{\lambda_p} \; \delta[X_{\max} - (X_0 + Y)]$$

$$= \frac{e^{-X_{\max}/\lambda_p}}{\lambda_p} \left[\int_0^{X_{\max}} dY \; G(Y) \; e^{Y/\lambda_p} \right]$$

$$X_{\max} \to \infty$$

$$F(X_{\max}) = \frac{e^{-X_{\max}/\lambda_p}}{\lambda_p} \underbrace{\left[\int_0^{X_{\max}} dY \; G(Y) \; e^{Y/\lambda_p}\right]}_{\text{constant}}$$

Asymptotically: Exponential Distribution

Slope = Interaction Length

$$\boxed{G(X) = F(X) + \lambda_p \, \frac{dF}{dX}}$$

$$\Lambda(X) \equiv -\left[\frac{1}{F(X)} \, \frac{dF(X)}{dX}\right]^{-1} = \lambda_p \, \left(1 - \frac{G(X)}{F(X)}\right)^{-1}$$

"Local slope"
(directly measurable)

Interaction Length

$$\boxed{\begin{array}{l} X_{\max} \to \infty \\ \\ \Lambda(X_{\max}) \to \lambda_p \end{array}}$$

$$G(X)/F(X) \to 0$$

Total Proton-Proton Cross Section at $s^{1/2} = 30$ TeV

R. M. Baltrusaitis, G. L. Cassiday, J. W. Elbert, P. R Gerhardy,
S. Ko, E. C. Loh, Y. Mizumoto, P. Sokolsky, and D. Steck
University of Utah, Salt Lake City, Utah 84112
(Received 16 January 1984)

We have measured the proton-air inelastic cross section at $s^{1/2} = 30$ TeV by observing the distribution of extensive-air-shower maxima as a function of atmospheric depth. This distribution has an exponential tail whose slope is $\lambda = 72 \pm 9$ g cm^{-2} which implies that $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} = 530 \pm 66$ mb. Using Glauber theory and assuming that the elastic-scattering slope parameter b is proportional to $\sigma_{pp}^{\mathrm{tot}}$, we infer a value of $\sigma_{pp}^{\mathrm{tot}} = 120 \pm 15$ mb which lies between a log$s$ and a log^2s extrapolation of the total pp cross section as measured at lower energies.

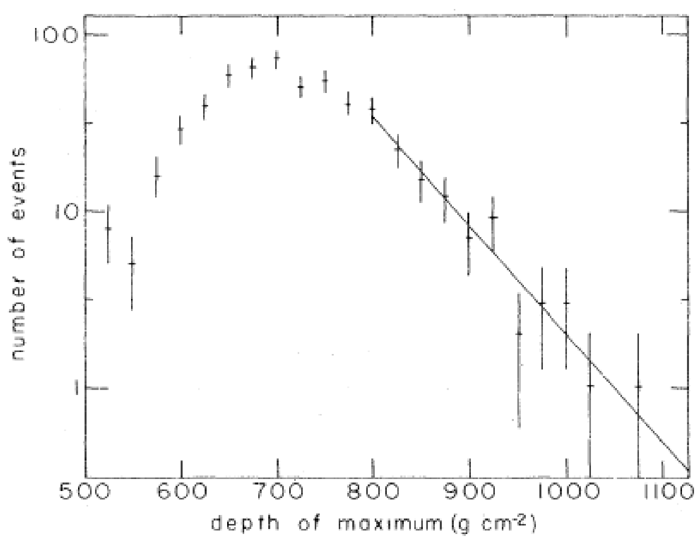
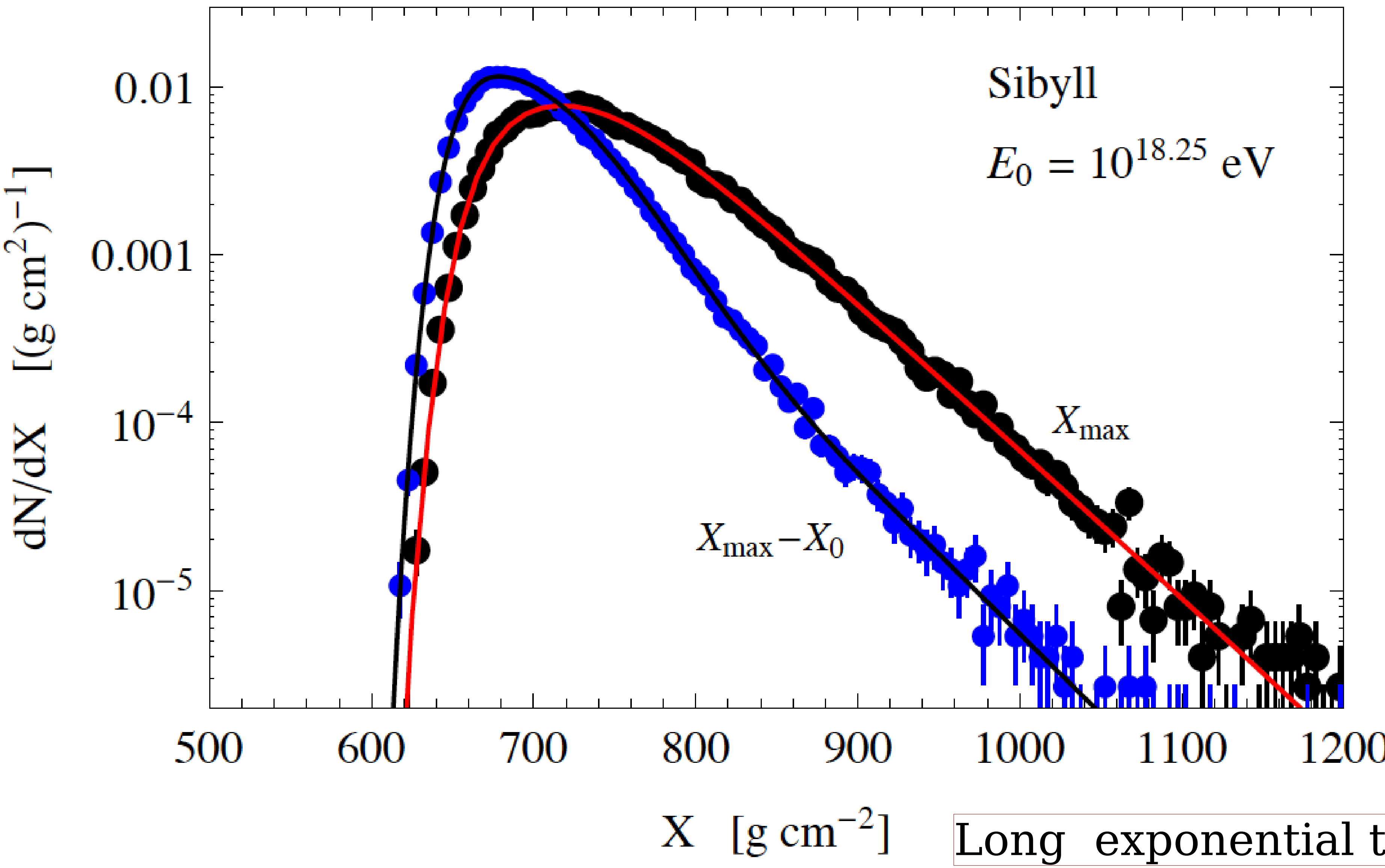


FIG. 5. Distribution of depth of maxima $X_{\max}$ for data whose fitting errors are estimated to be $\delta x < 125$ g cm^{-2}. The slope of the exponential tail is $\lambda = 73 \pm 9$ g cm^{-2}.

Pioneering work of Fly's Eye

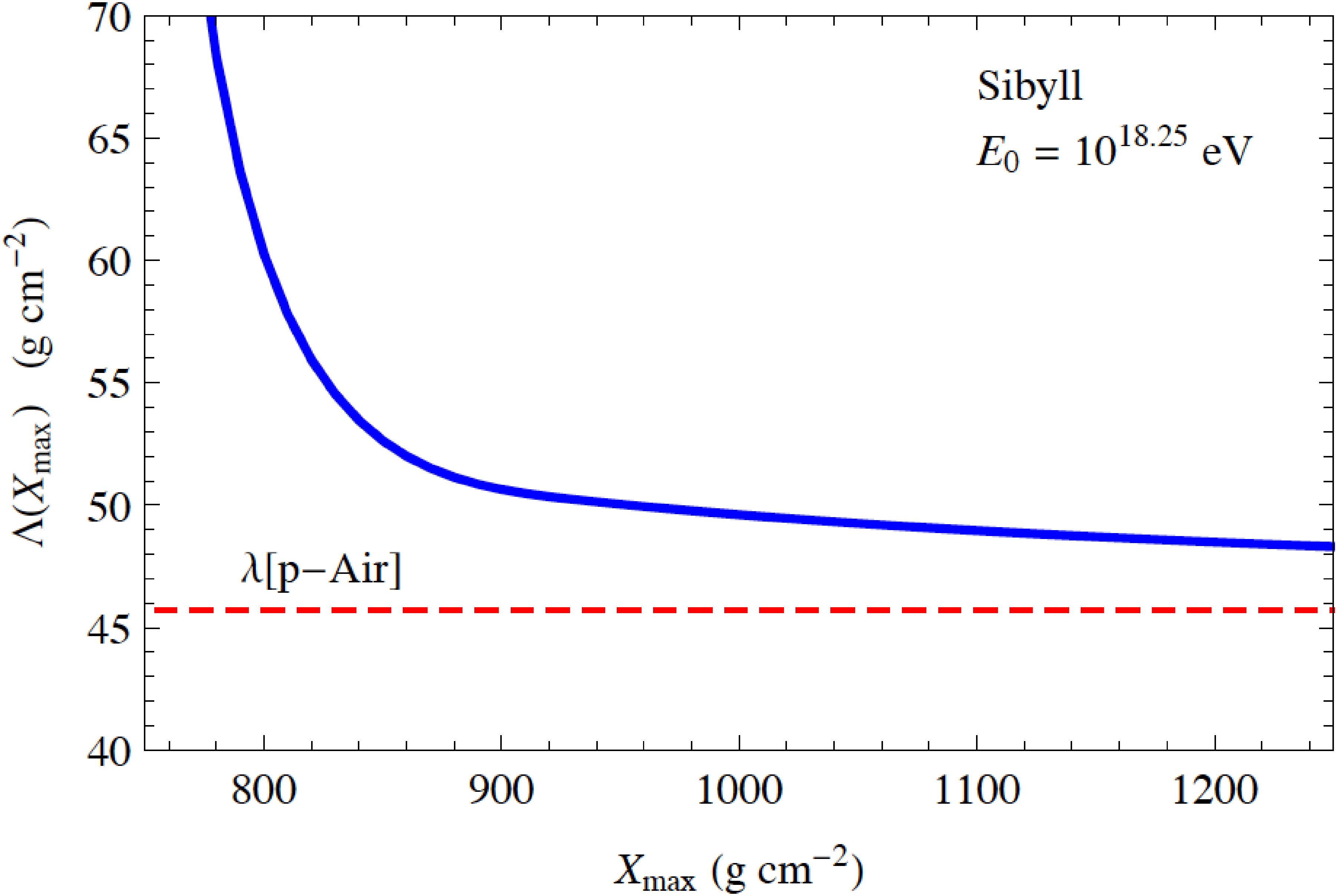
The (p-air) “Pierre” cross section

Montecarlo calculation Using Sibyll
[+PDG cross sections + original Glauber]



Long exponential tail

Slow convergence of slope the interaction Length:



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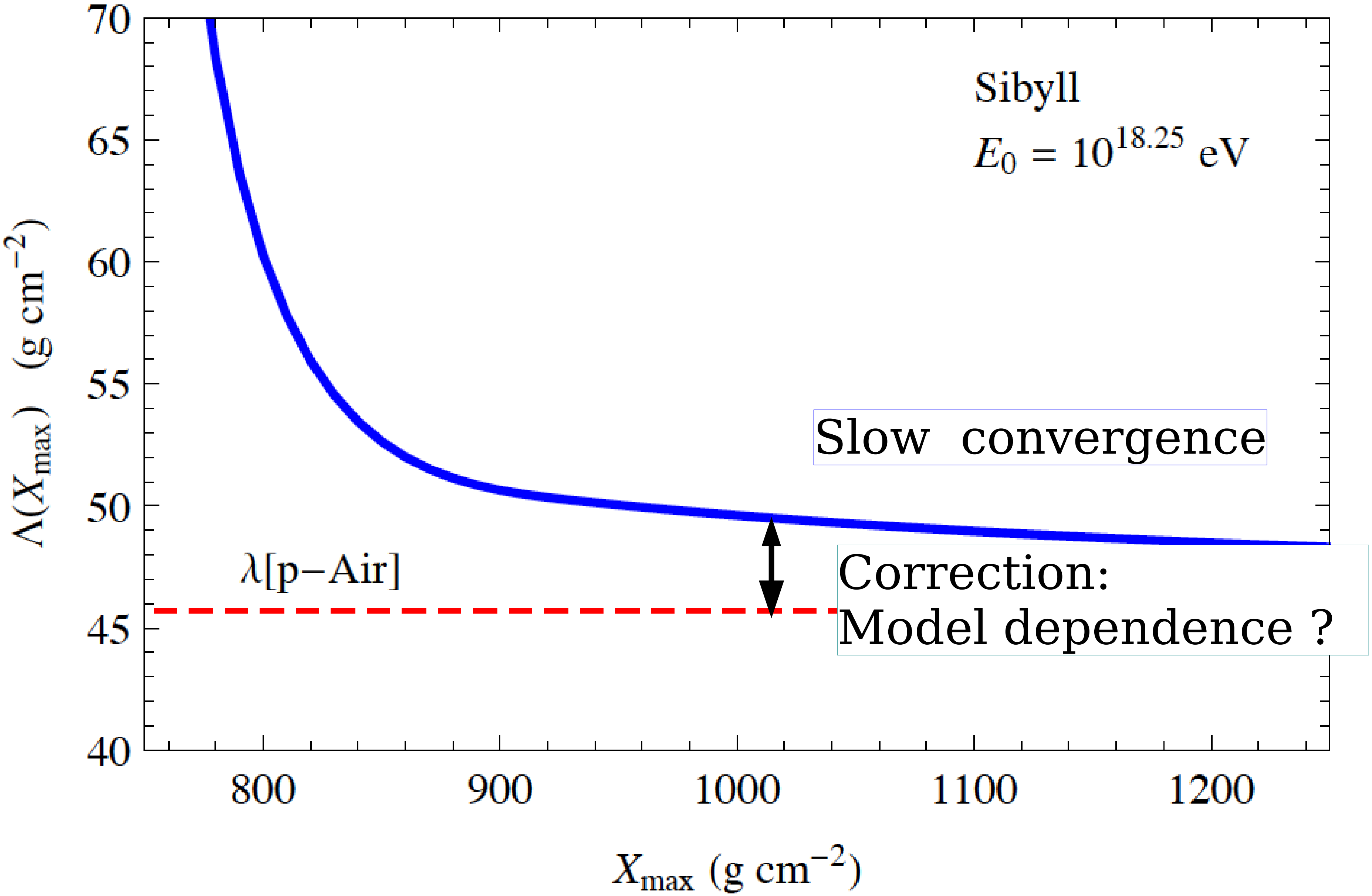
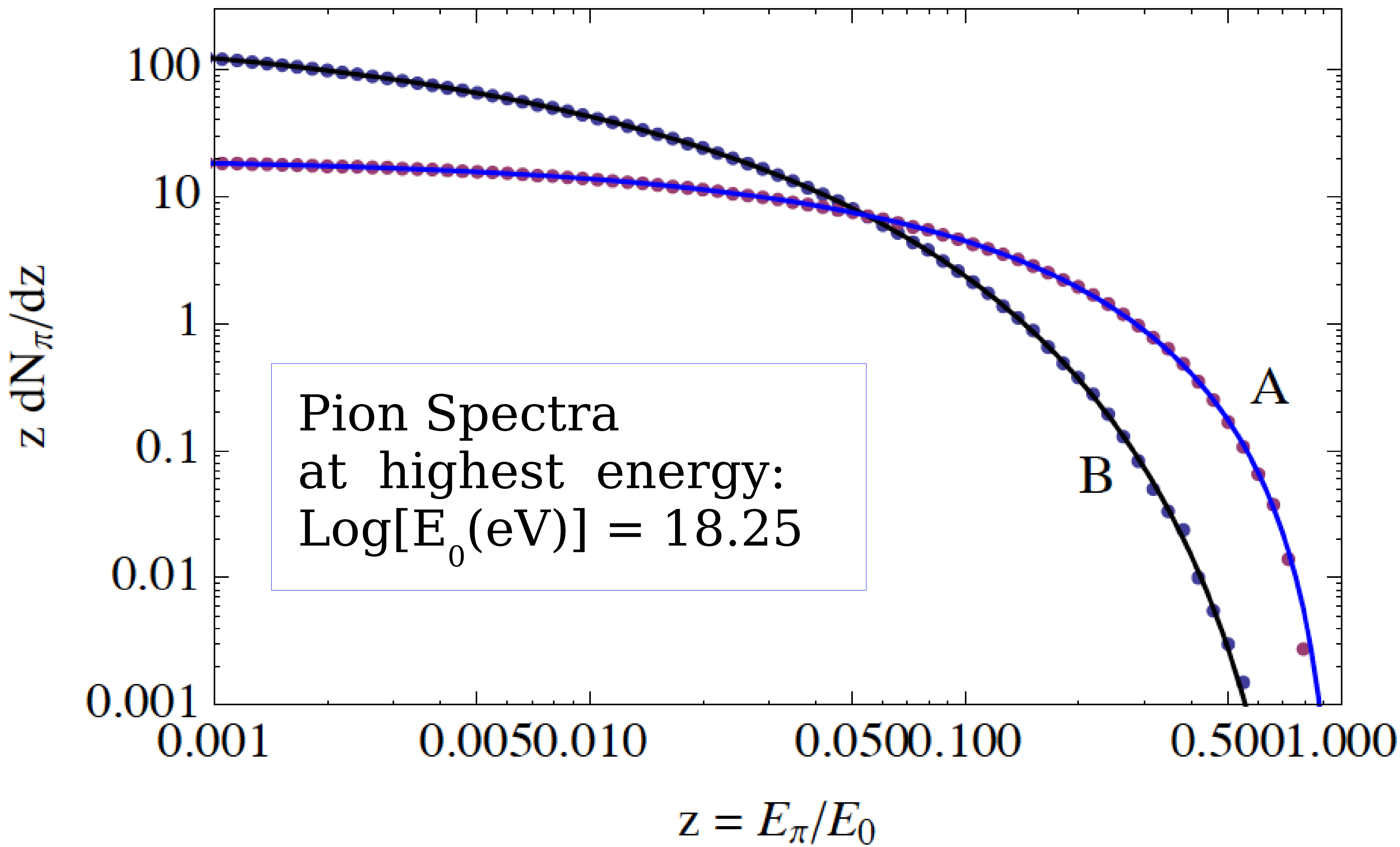
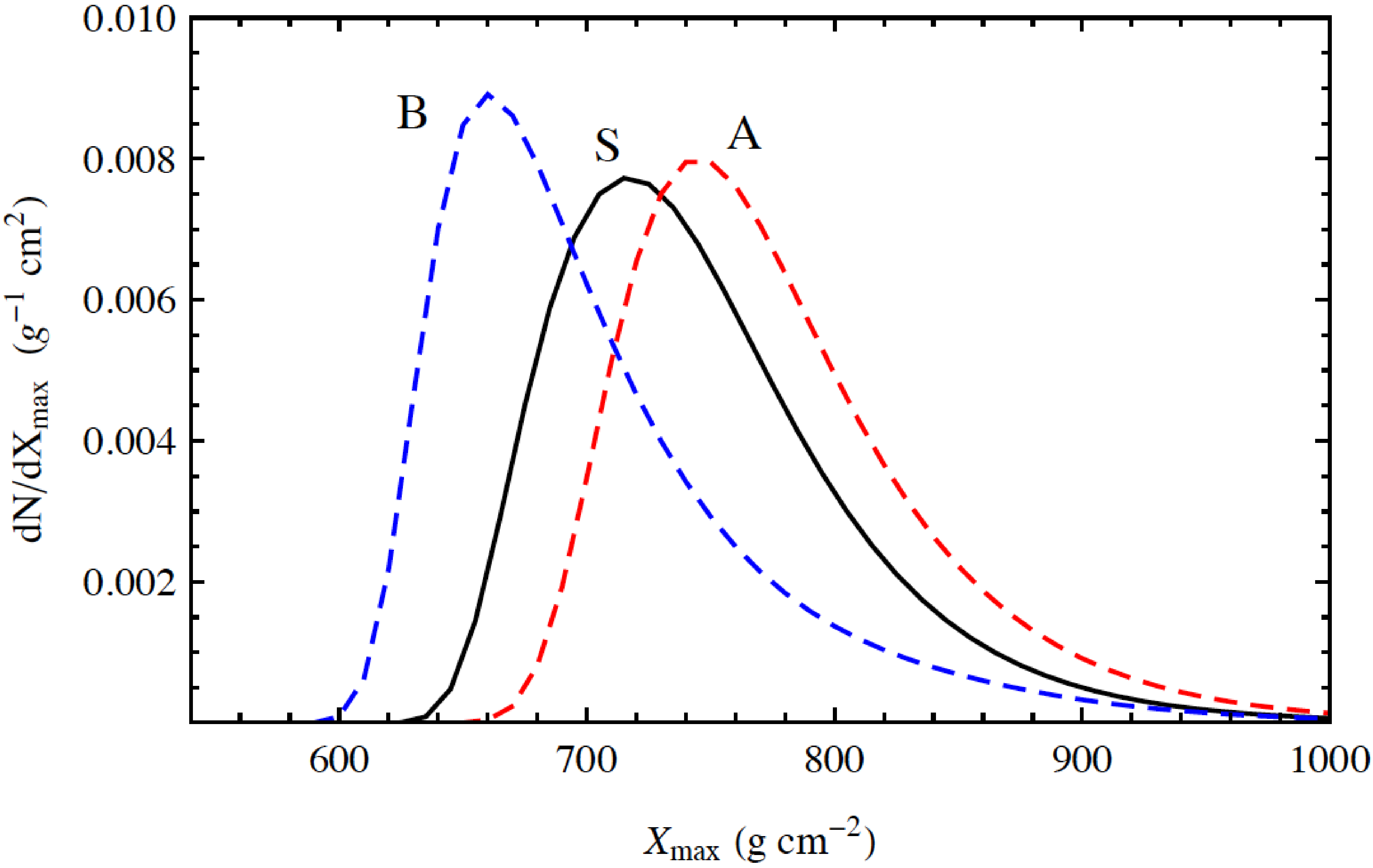


“Toy Models”
(Analytic representation of particle spectra):

Model A : Hard spectra, more penetrating showers
Model B : Soft spectra, less penetrating showers



Comparison of the 3 models



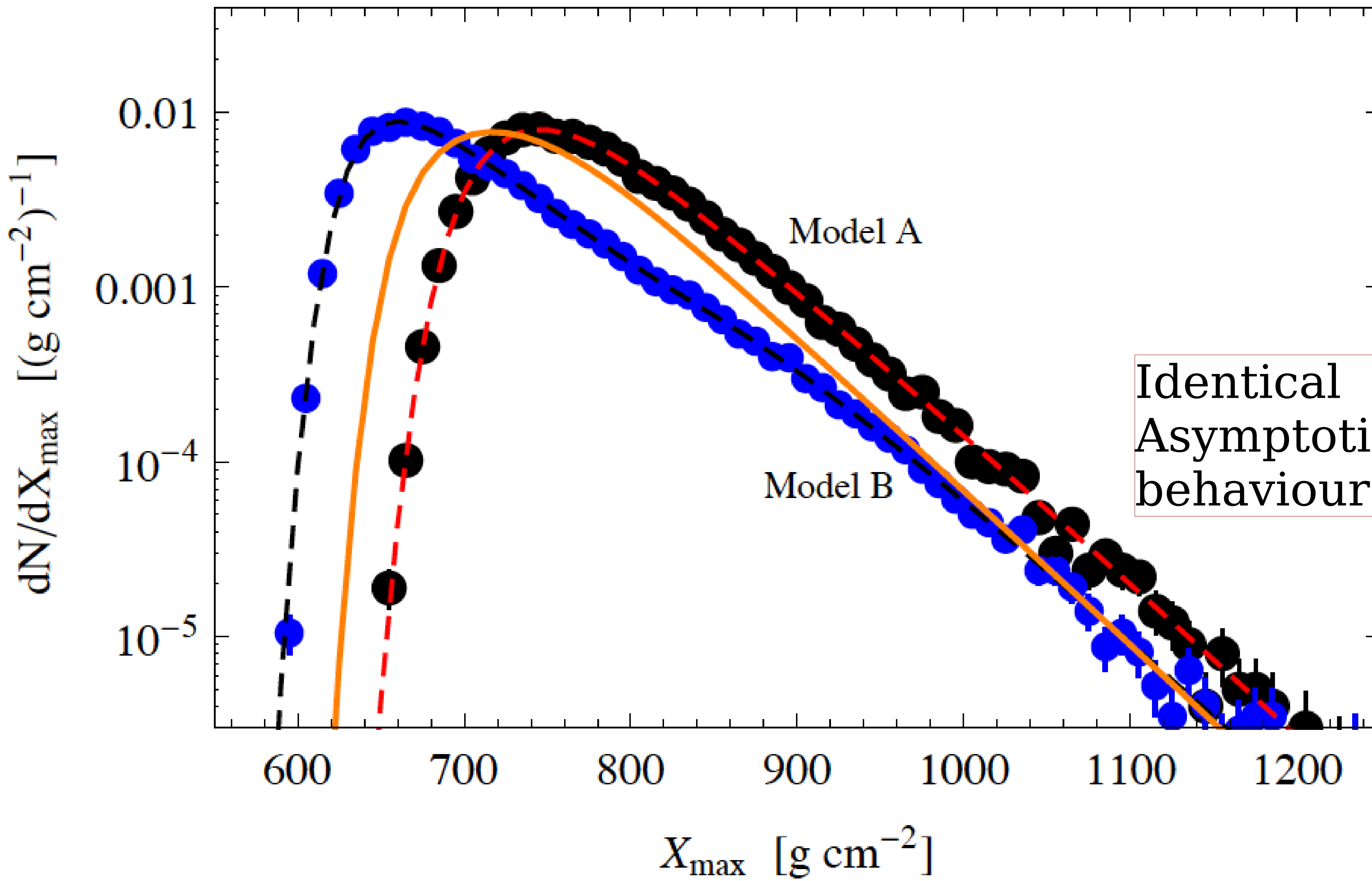
Estimate of “theoretical uncertainties”

The differences among the set of available Montecarlo codes is not necessarily a good estimate of the true uncertainty.

[I think it is an underestimate]

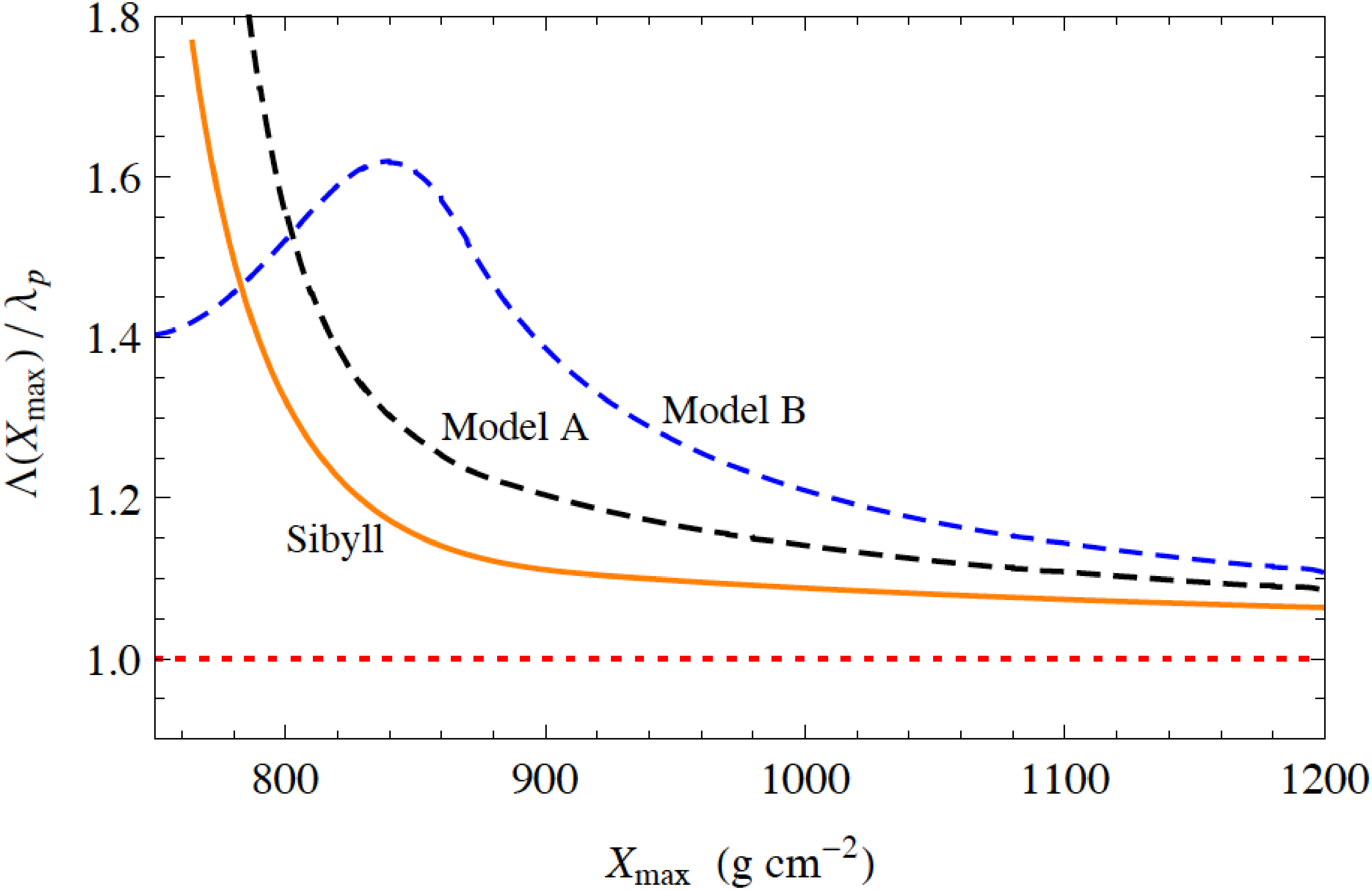
How can one have a more robust estimate of the systematic uncertainty?

Xmax Distributions:

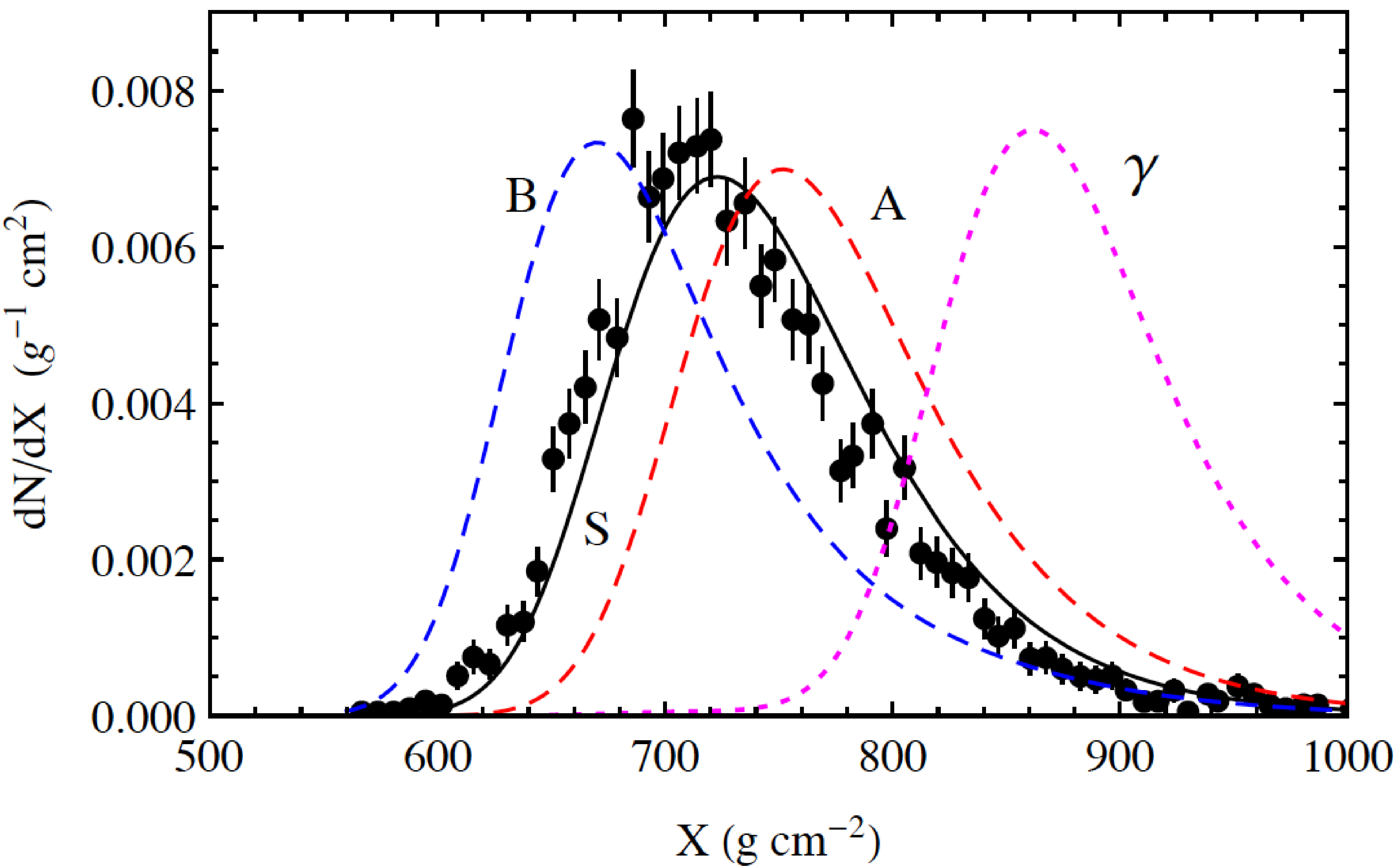


Identical
Asymptotic
behaviour

Larger corrections to obtain the interaction length.



Compare with Auger data. Normalization: equal area.



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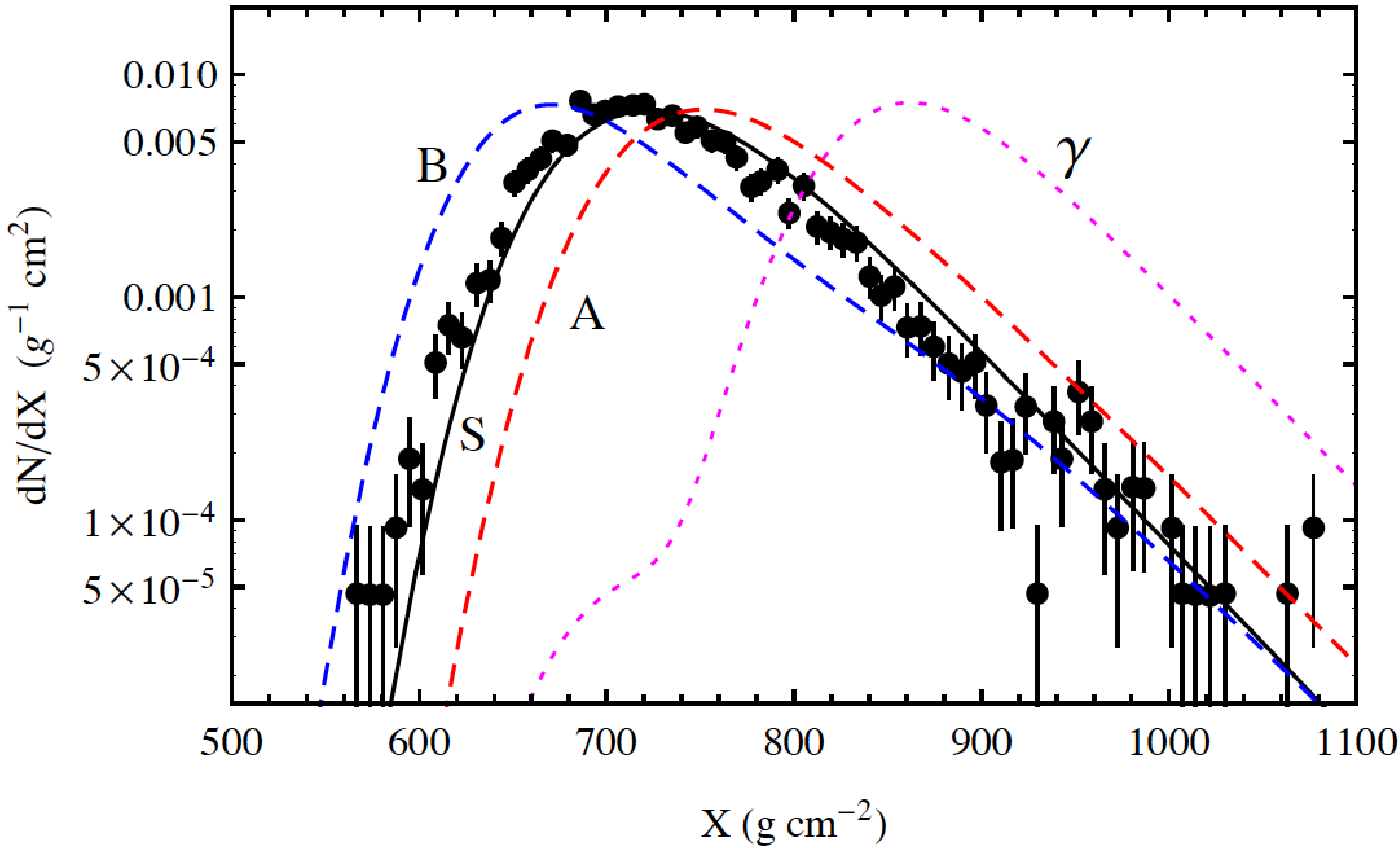
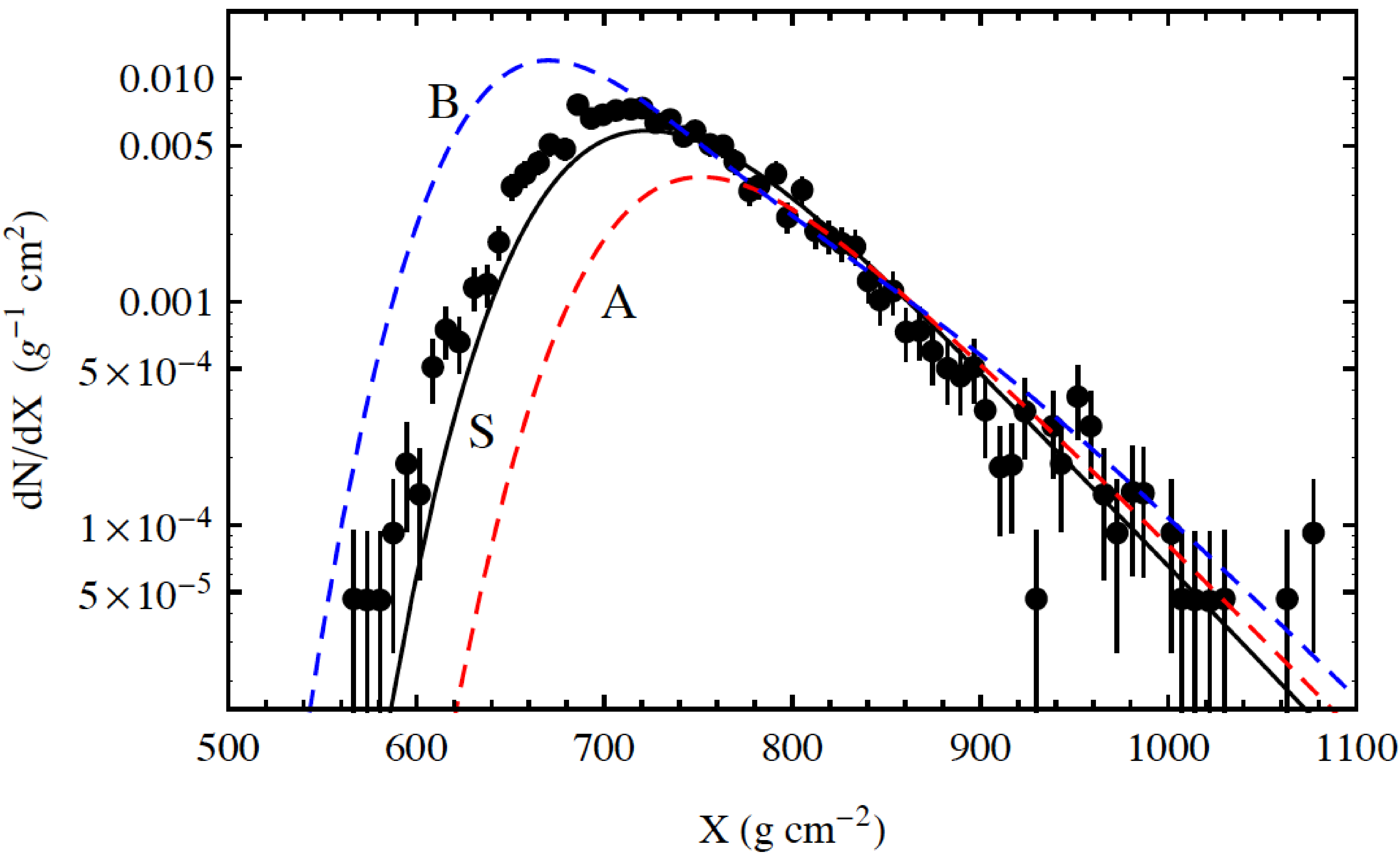


Normalization: same # of events for: $X_{\max} \geq 800\ \mathrm{g/cm^2}$



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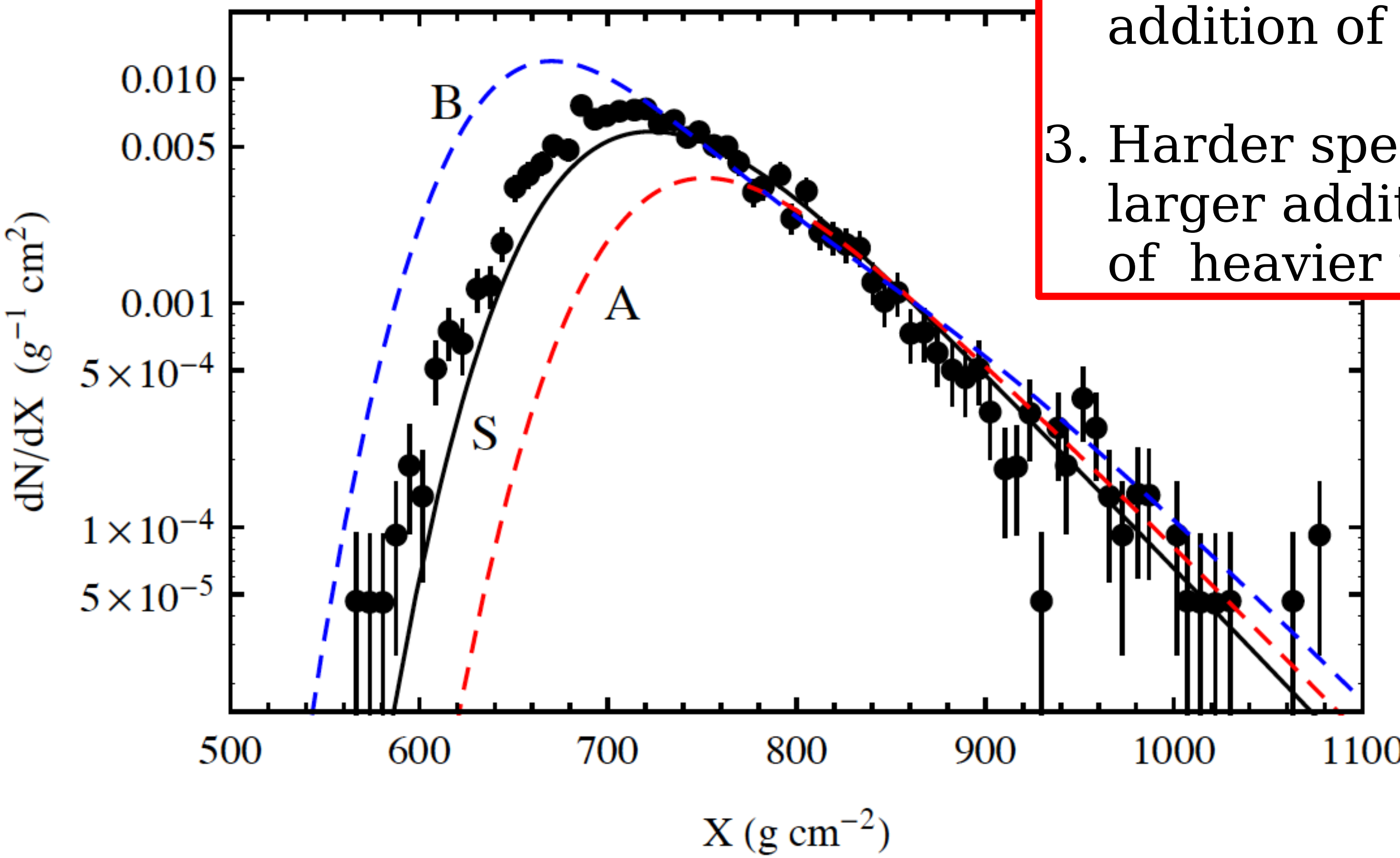


Tentative conclusions:

1. A very soft model Like "model B" is EXCLUDED by the data !
2. A Model like "Sibyll" (moderate softening with increasing energy). allows/needs only a small addition of helium + (Z>2 nuclei)
3. Harder spectra require larger additional component of heavier nuclei.

Comment:

This was an “exercise”.
[detector response modeled as gaussian smearing of 20 g/cm2]

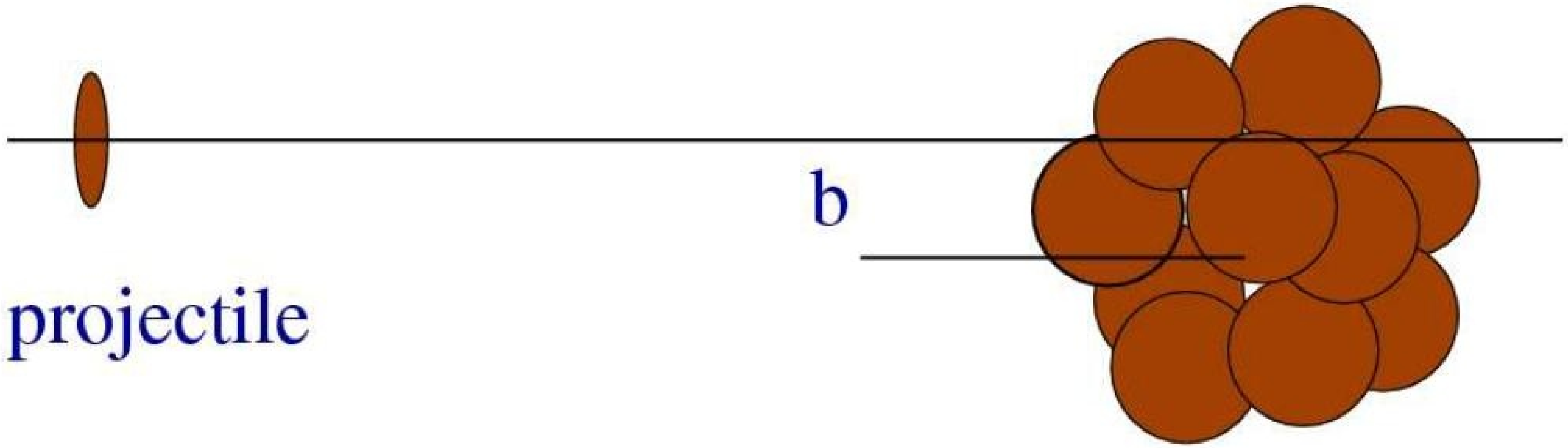
Goal here is to discuss the potential of simultaneously:

Estimating a composition, *and*
Measure the cross section, *and*
Constrain the interaction model

Potential of the study of the $X_{\max}$ distribution

From pp to pA (and viceversa)

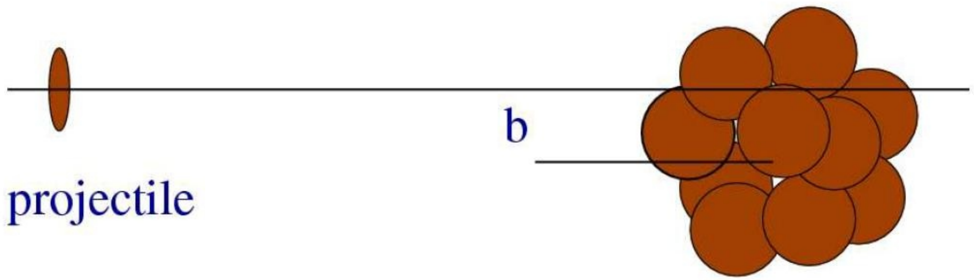
is Glauber formalism adequate?



From pp to pA (and viceversa)

is Glauber formalism adequate?

Crucial equation
of Glauber theory:



$$T(b, \{\vec{r}_j\}) = \prod_{j=1}^{A} t(|\vec{b} - \vec{r}_{\perp j}|)$$

Transmission amplitude
For a proton and a nucleus
(positions of A nucleons $\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A$)

(Quasi)-elastic scattering amplitude

$$h + A \rightarrow h + A^*$$

$$F_{fi}(q) = i \int d^2b\, e^{i\vec{q}.\vec{b}} \left\{ \int \prod_j d^3r_j\ \phi_f^*(\vec{r}_1, \vec{r}_2, \ldots \vec{r}_A)\ T\left[b, \{\vec{r}_j\}\right]\ \phi_i^*(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) \right\}$$

Completeness relation:

$$\sum_f \phi_f(\vec{r'}_1, \vec{r'}_2, \ldots, \vec{r'}_A)\ \phi_f^*(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \prod_{j=1}^{A} \delta^3\left[\vec{r}_j - \vec{r'}_j\right]$$

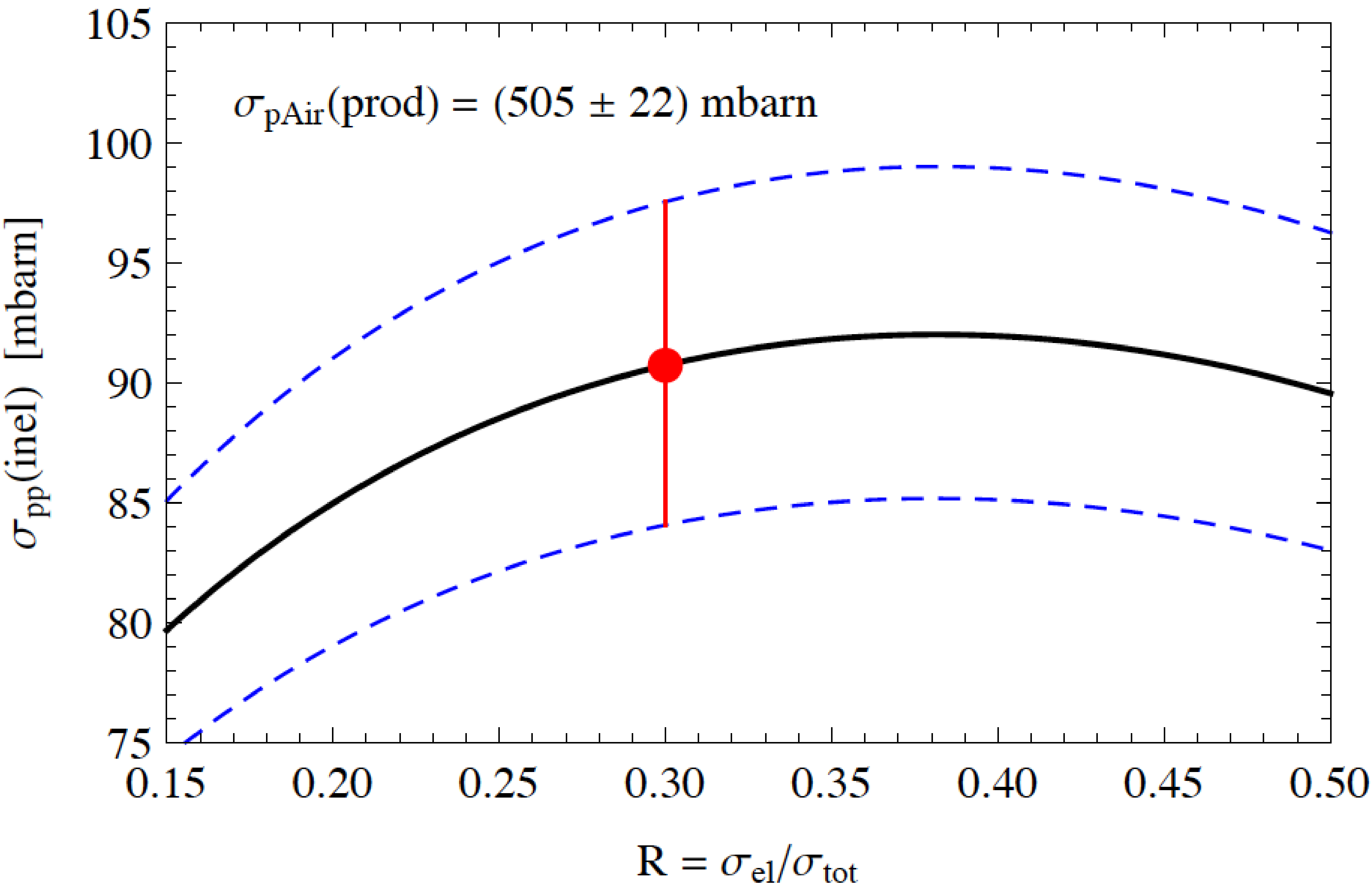
Nuclear Physics

$$|\phi_i(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)|^2 = \rho_1(\vec{r}_1)\, \rho_2(\vec{r}_2)\ \ldots\ \rho_A(\vec{r}_A)$$

$$\Gamma(b) = \frac{\sigma_{\rm tot}\,(1 - i\,\alpha)}{4\pi\, B_{\rm el}}\ \exp\left[-\frac{b^2}{2\, B_{\rm el}}\right]$$

parametrization of pp profile

Application to the AUGER result:



Problem of “INELASTIC SCREENING”

Transition: $p \longrightarrow \Delta$

$A_{p\to\Delta}(b,s)$ [Amplitude of transition for pp collisions]

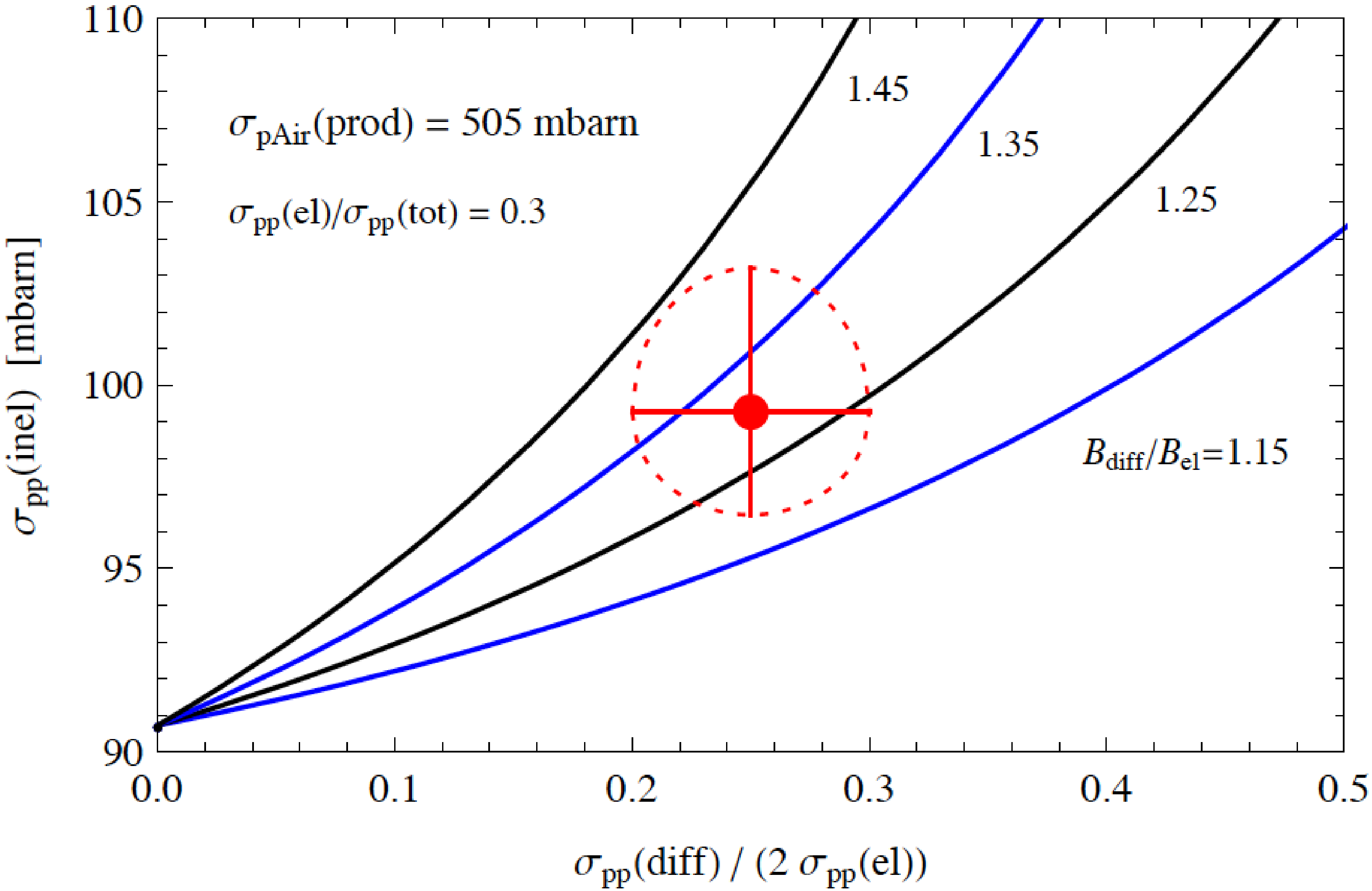
Nuclear target:

$$A(p \to \Delta) \times A(\Delta \to p)$$

Additional contribution to elastic scattering

Subtract from inelastic channels

Inelastic Screening Correction



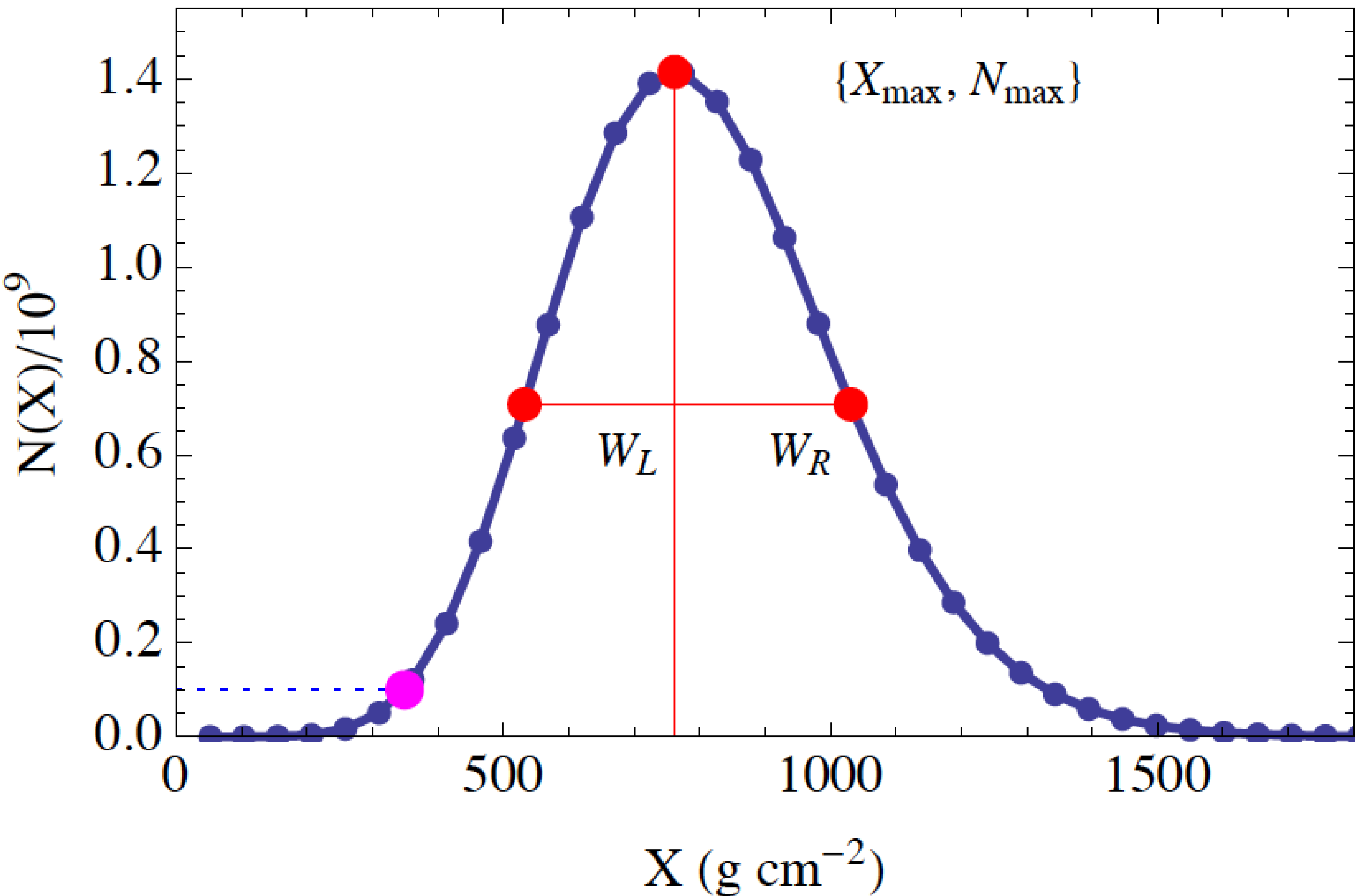
Observables to obtain information about hadronic interactions.

Longitudinal (electromagnetic) profile

Muon generation profile
[In principle VERY interesting]
[can it be measured ?]

Surface Array Information
(The “muon problem”)

One individual Montecarlo Shower [fast “CONEX-like” simulation]



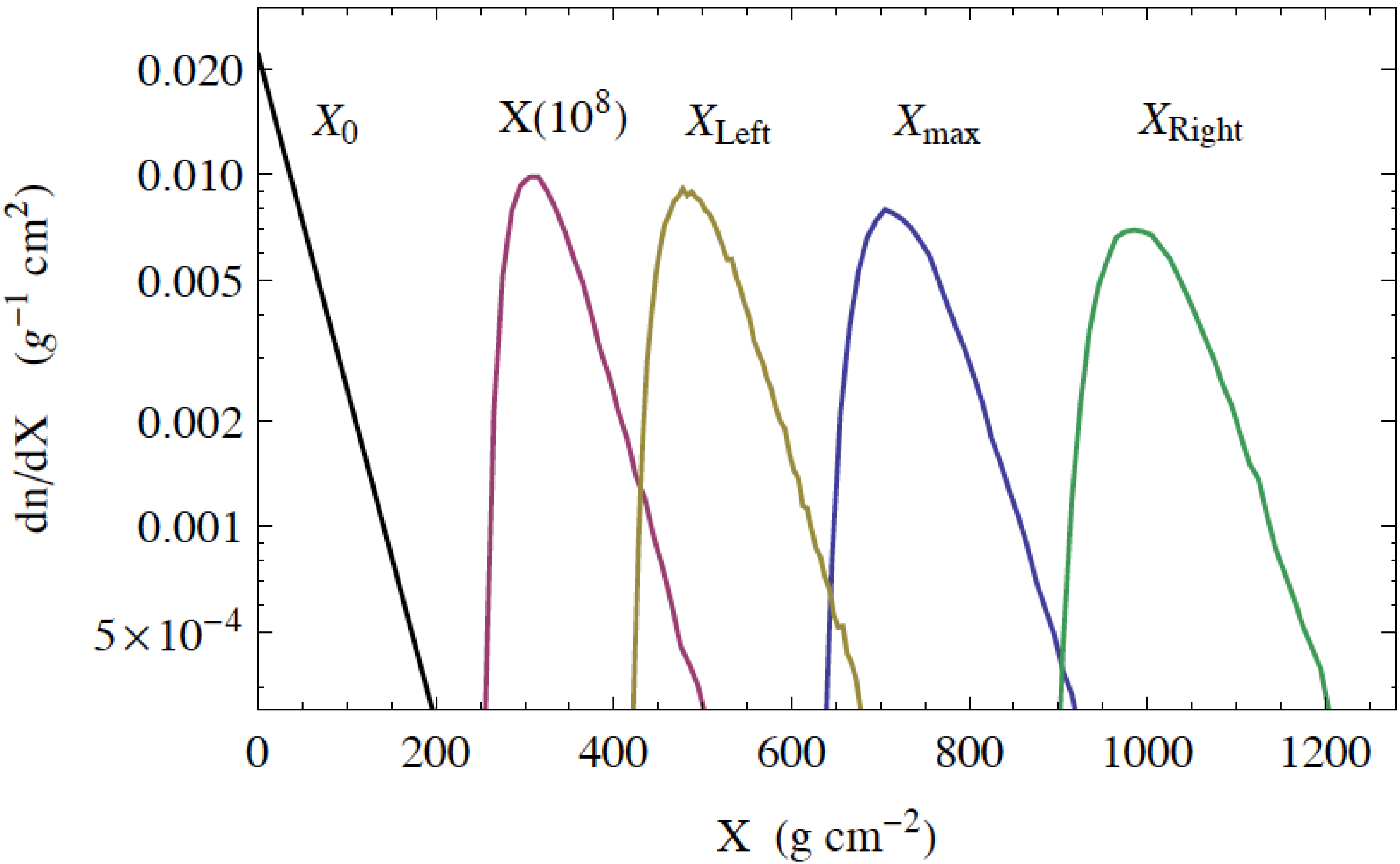
$$\{X_{\rm max}, N_{\rm max}, W_{\rm L}, W_{\rm R}\}$$

$$X_{\rm thresh} \equiv X(N = 10^8)$$

$E_0 = 10^{18.25}$ eV

[Sibyll, p Montecarlo showers]

$$\{X(10^8), X_{\rm left}, X_{\rm max}, X_{\rm right}\}$$



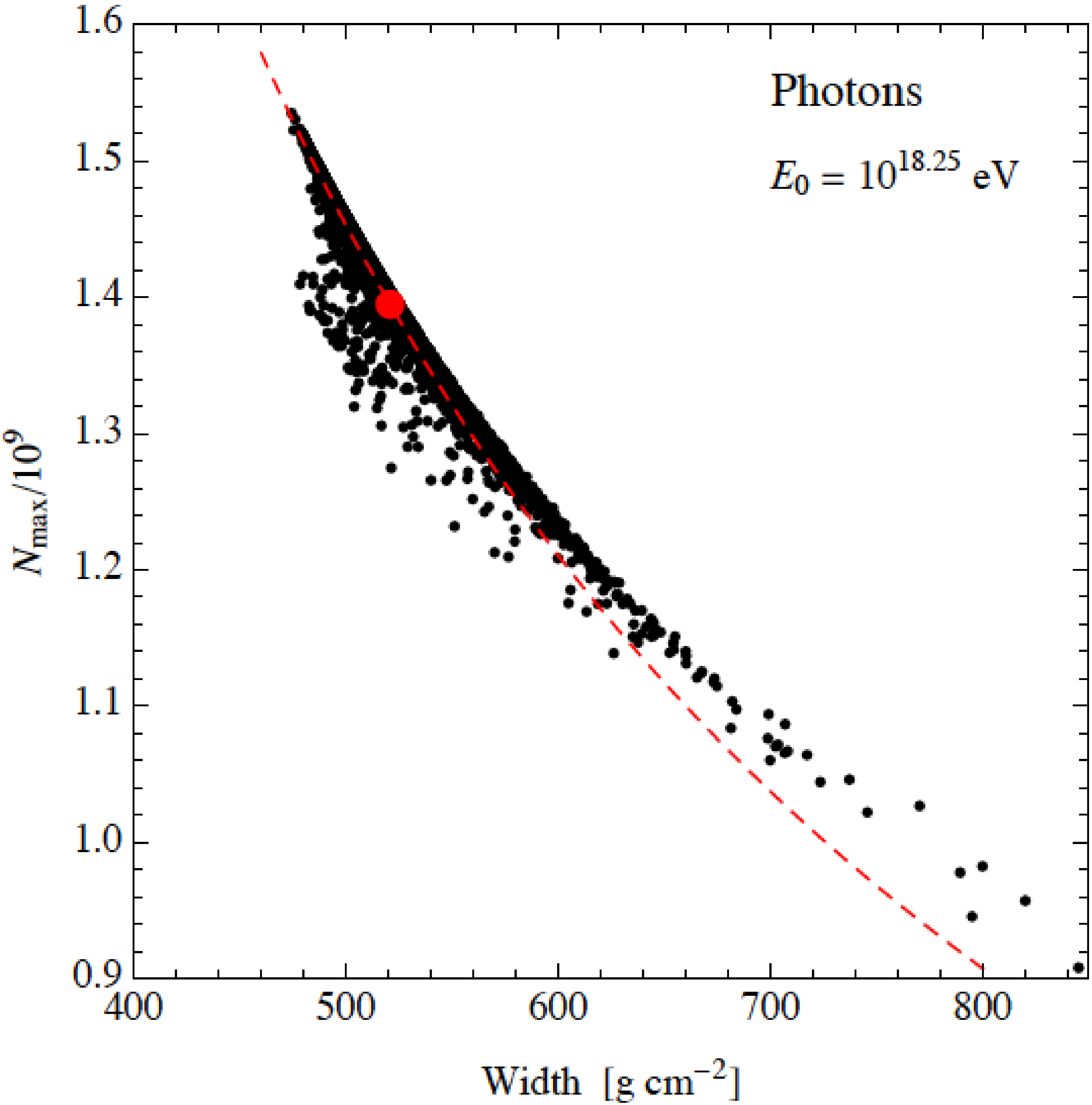
Average electromagnetic profile:

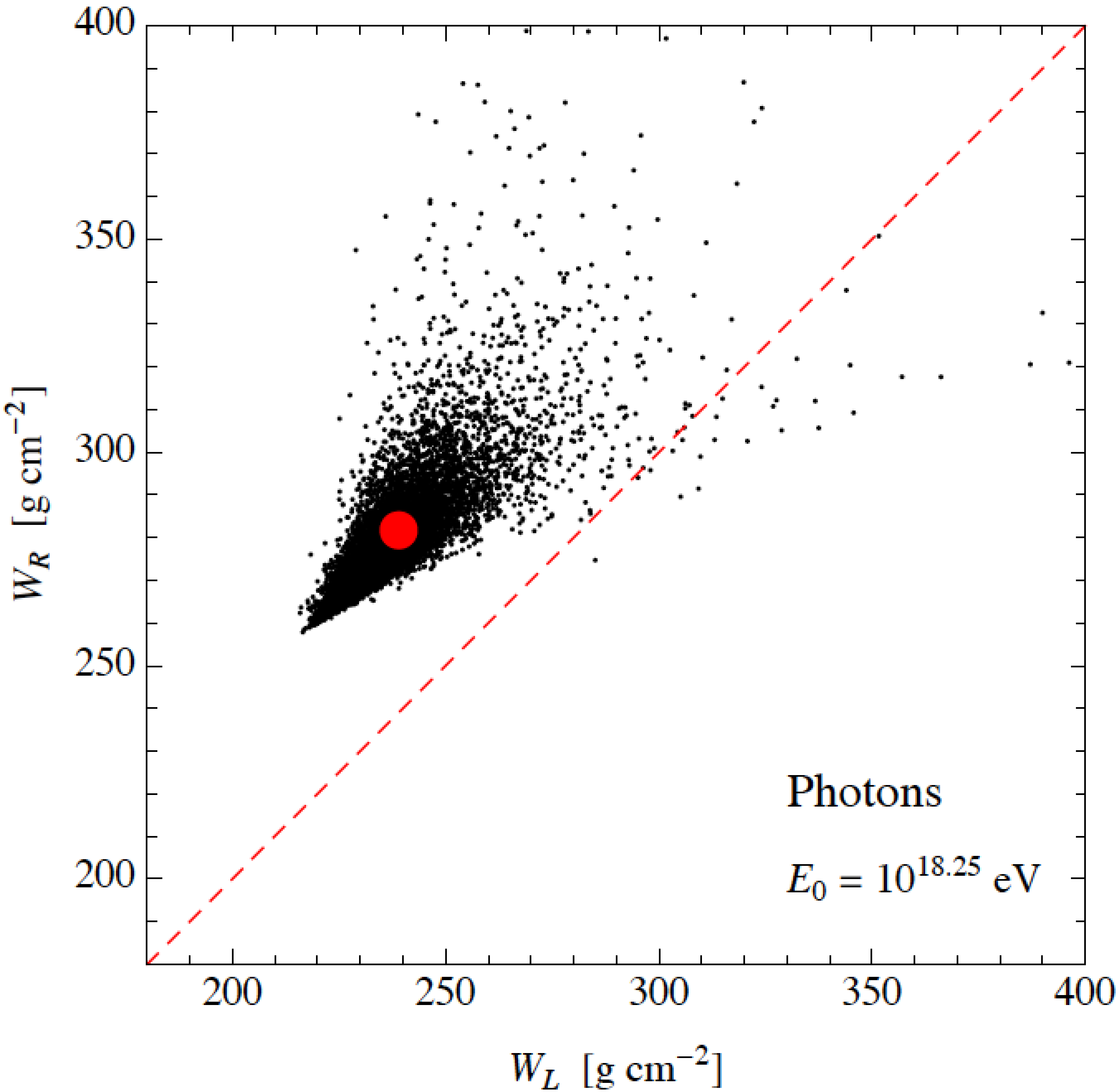
$$N_{\mathrm{Greisen}}(t, E_0) = \frac{\kappa}{\sqrt{\ln E_0}} \; \exp\left\{ t \left[1 - \frac{3}{2} \ln\left(\frac{3t}{t + 2\ \ln E_0} \right) \right] \right\}$$

$$t_{\mathrm{max}} = \ln E_0$$

$$N_{\mathrm{max}} = 0.31\ \frac{E_0}{\sqrt{\ln E_0}}$$

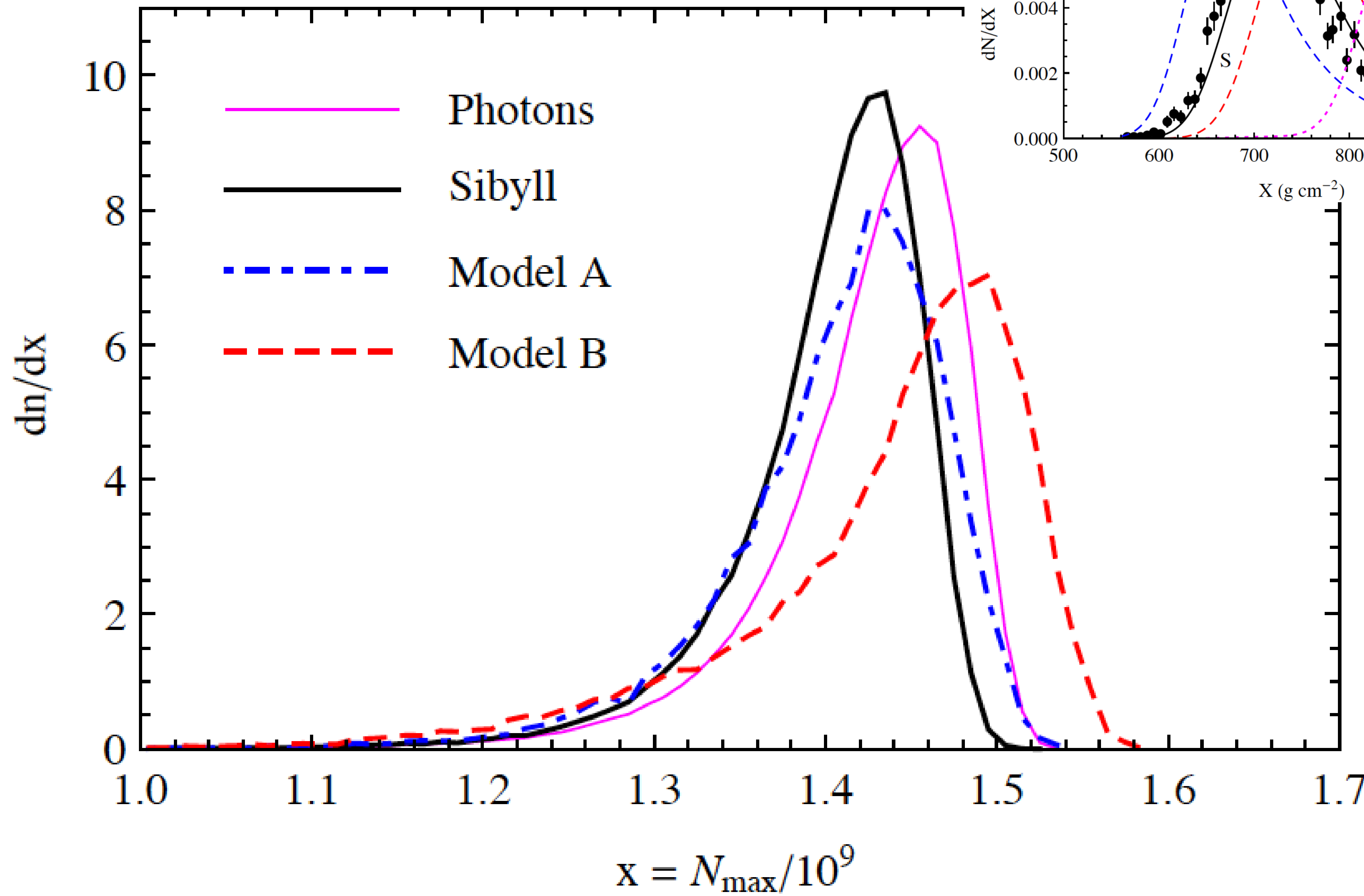
$$t_{L,R} \simeq t_{\mathrm{max}} \mp \left(\sqrt{2 \ln 2}\, \sqrt{\frac{3}{2}\ \ln E_0 \mp \frac{5}{6}\ \ln 2} \right)$$

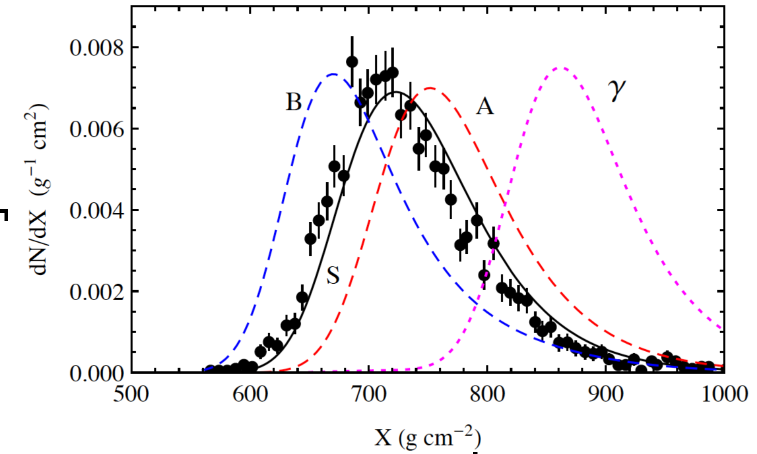

Photons
$E_0 = 10^{18.25}$ eV
$N_{\rm max}/10^9$
Width [g cm^{-2}]
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
400
500
600
700
800



Photons
$E_0 = 10^{18.25}$ eV
W_R [g cm^{-2}]
W_L [g cm^{-2}]
400
350
300
250
200
200
250
300
350
400

Showers very similar around maximum





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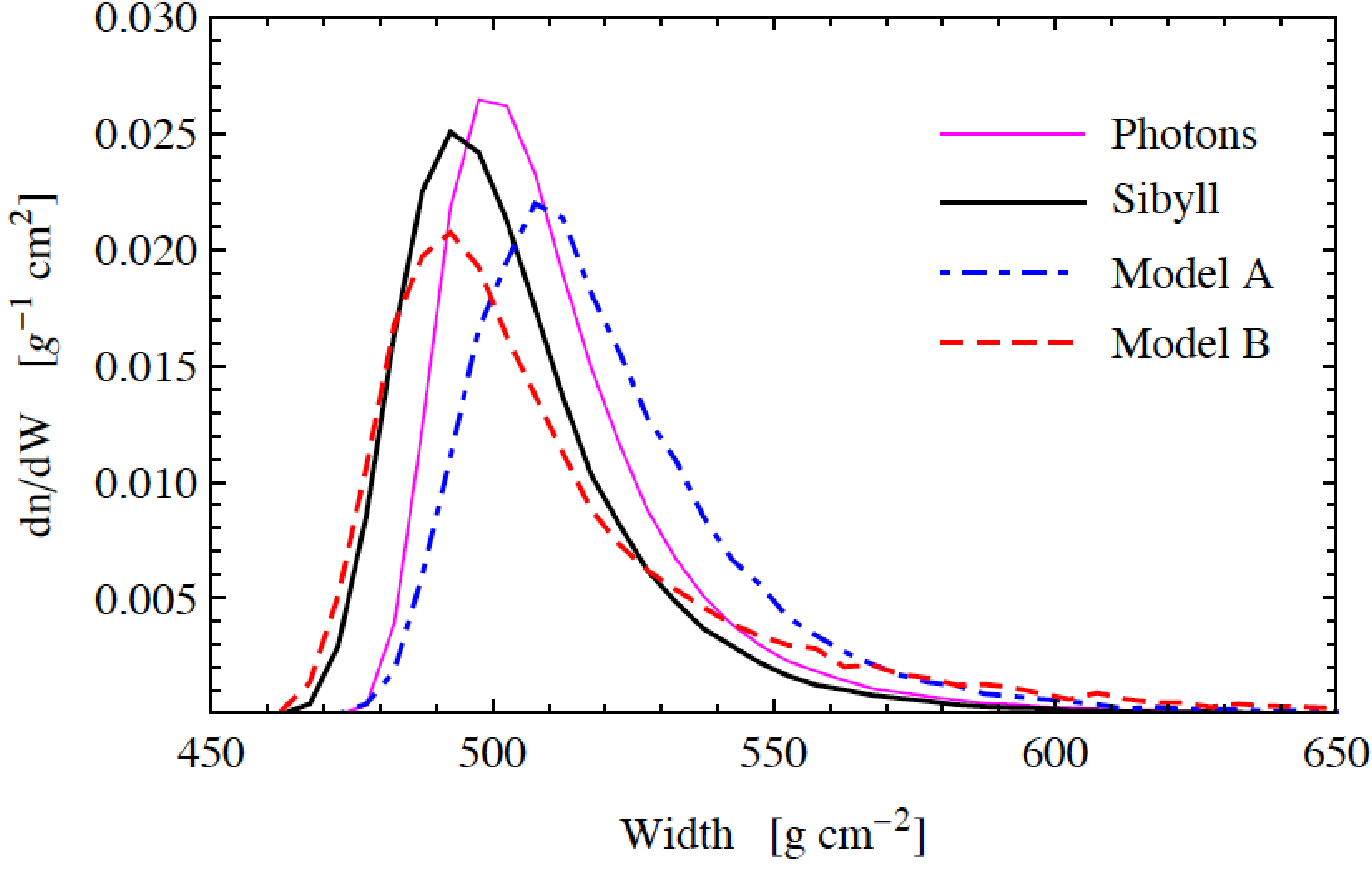

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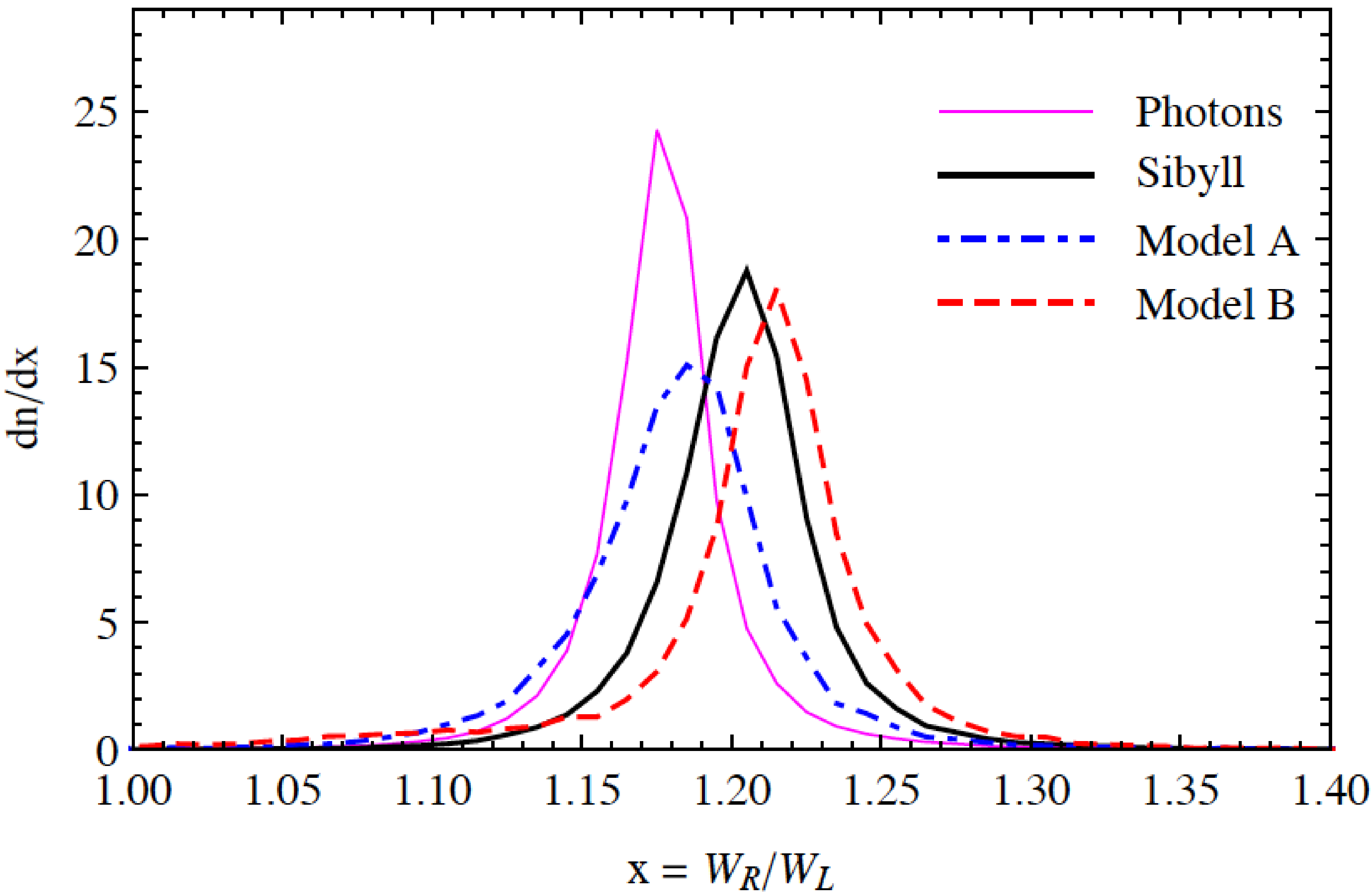
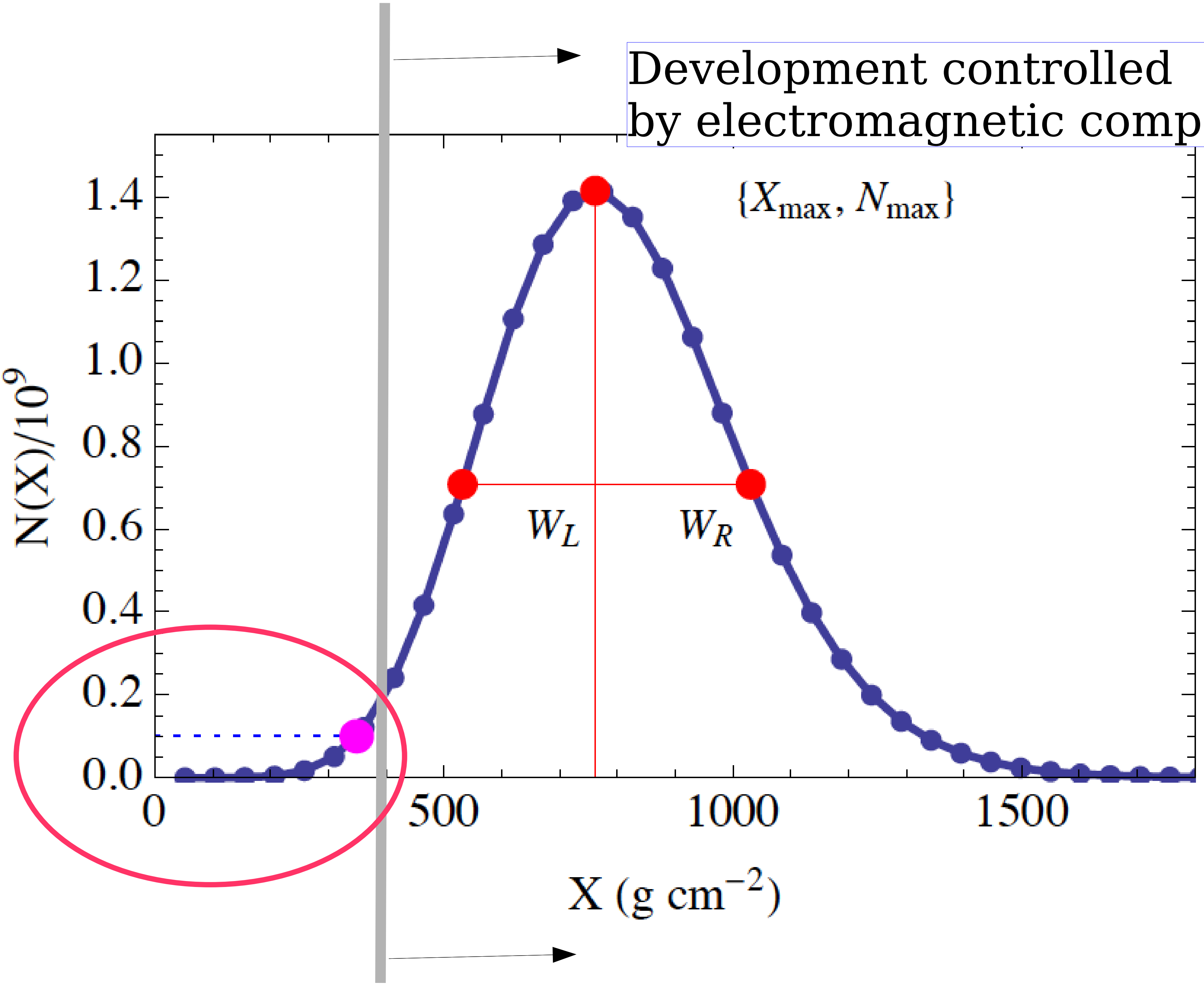
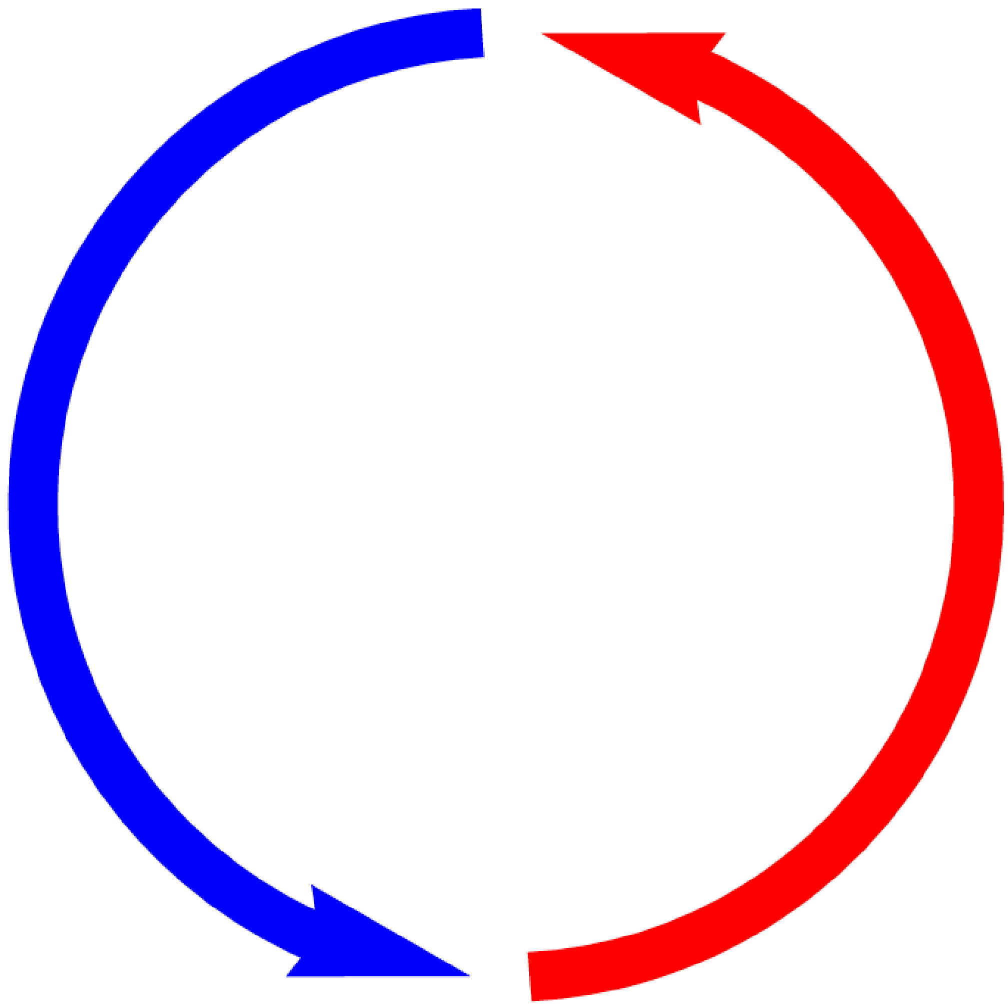


One individual Montecarlo Shower [fast “CONEX-like” simulation]

Development controlled
by electromagnetic component



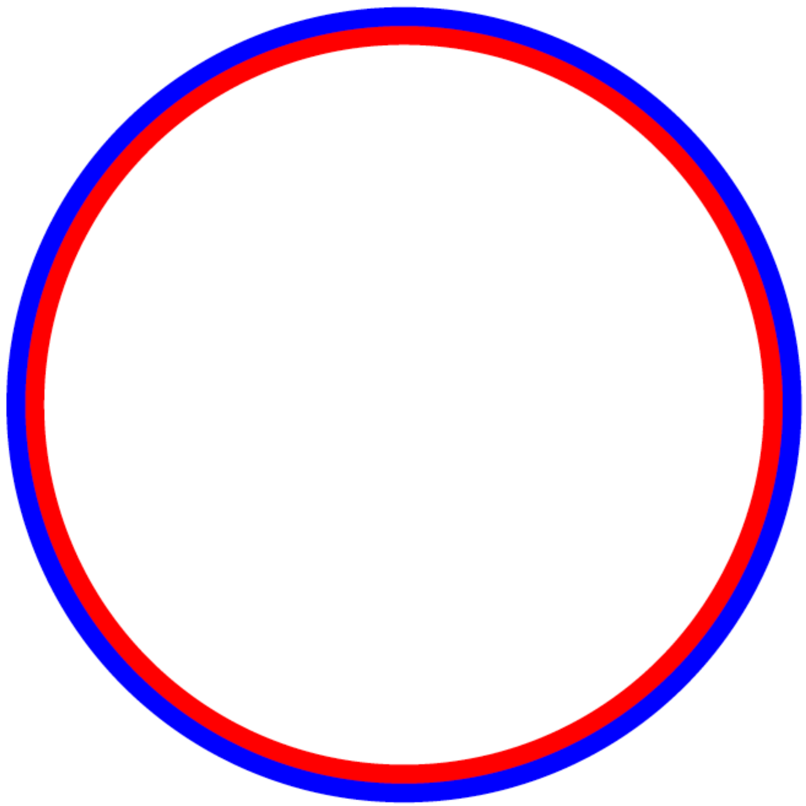
PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

(more than) a dream : closing the circle!

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS