UNESP UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

Minijets and cosmic ray particle production at very high energy

D. A. Fagundes

with A. Grau, G. Pancheri, Y. N. Srivastava, O. Shekhovtsova

New Trends in High-Energy Physics and QCD – Natal/RN, Brazil

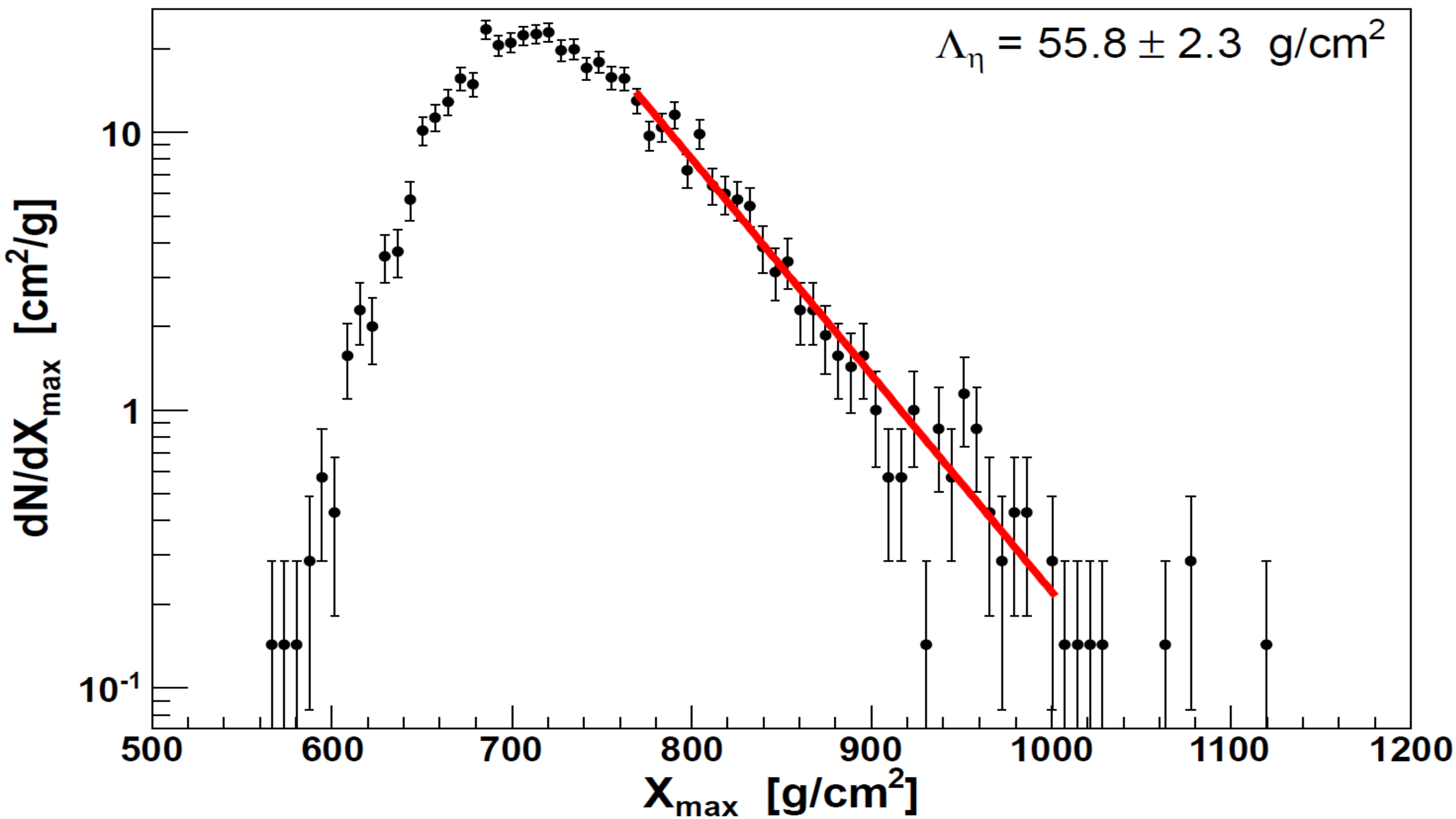
Outline

- Overview of AUGER's measurement of σ_{prod}^{p-air} at 57 TeV
- *pp & pA* scattering single channel model by Durand & Pi
- A minijet model with soft gluon resummation for σ_{tot}^{pp}
- Predictions for the inelastic cross section
- Extensions for p-air - first application of this model

Measurement of $\sigma_{p\text{-air}}^{\text{prod}}$ with the Pierre Auger Observatory

P. Abreu at el, *Phys.Rev.Lett. 109 (2012) 062002*

$X_{\max}$-distribution $\quad dN/dX_{\max} \propto \exp(-X_{\max}/\Lambda_\eta)$



$\Lambda_m = k\,\lambda_{p\text{-air}} = k\,\dfrac{14.4m}{\sigma_{p\text{-air}}^{\text{prod}}}$ → $\sigma_{p\text{-air}}^{\text{prod}}$ - for *particle emission* in the primary interaction

Measurement of $\sigma^{\text{prod}}_{p-\text{air}}$ with the Pierre Auger Observatory

P. Abreu at el, *Phys.Rev.Lett. 109 (2012) 062002*

Model dependence: extrapolation of MC interaction codes to cosmic ray energy region

$$f(E, f_{19}) = 1 + (f_{19} - 1)\,\frac{\lg\left(E/10^{15}\,\text{eV}\right)}{\lg\left(10^{19}\,\text{eV}/10^{15}\,\text{eV}\right)}$$

Predictions for p-air cross section

at 57 TeV:

QSJet01 – 523.7 mb

QSJetII – 502.9 mb

SIBYLL – 496.7 mb

EPOS – 497.7 mb

Average – 505 mb

Sta. Unc. - 22 mb

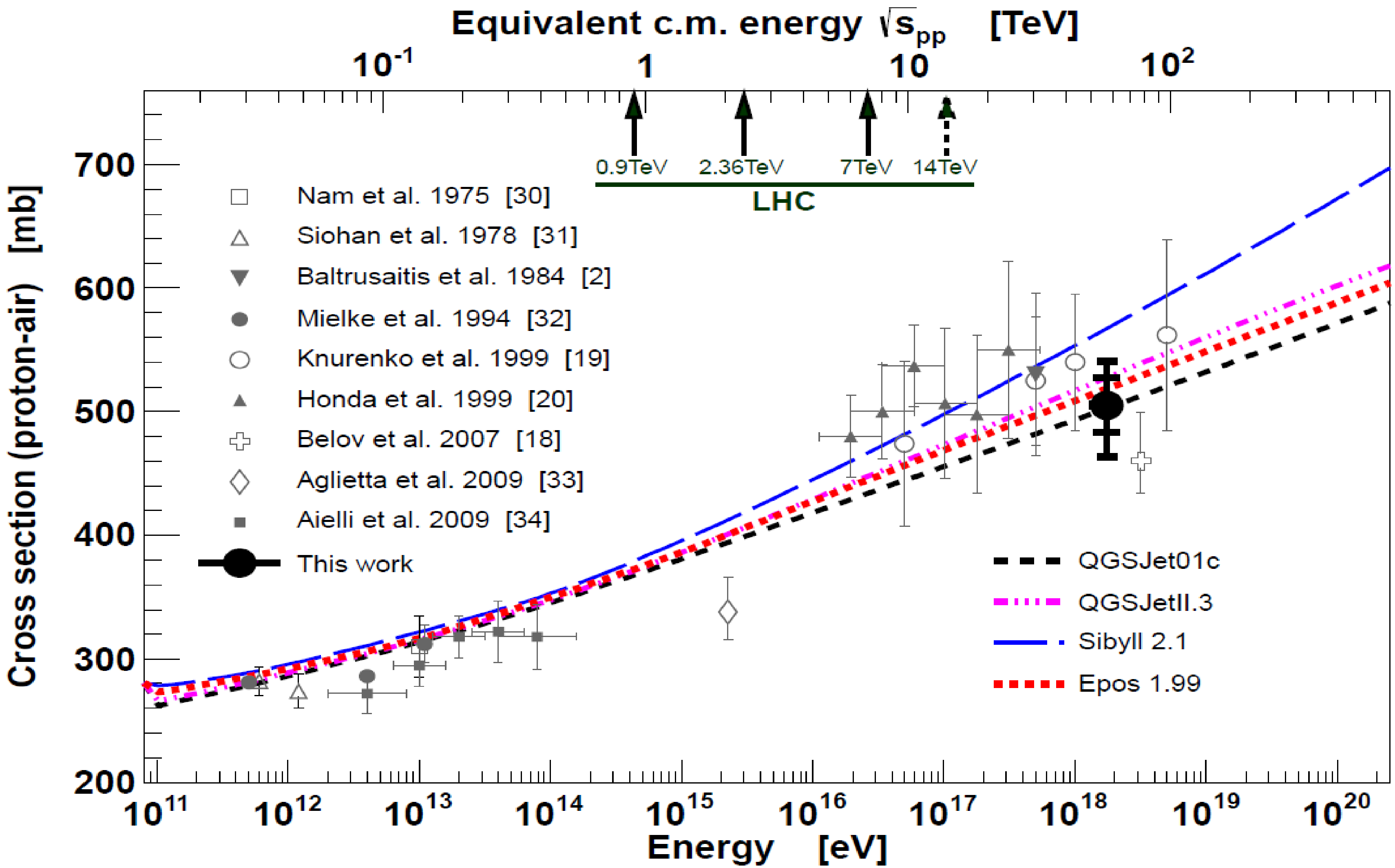
Summary of the systematic uncertainties.

Description	Impact on $\sigma^{\text{prod}}_{p\text{-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, <0.5 %	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb

uncertainty in the mass composion

Measurement of $\sigma_{p-\mathrm{air}}^{\mathrm{prod}}$ with the Pierre Auger Observatory

P. Abreu at el, *Phys.Rev.Lett. 109 (2012) 062002*



$$\sigma_{p\text{-air}}^{\mathrm{prod}} = \left[505 \pm 22(\mathrm{stat})\,^{+28}_{-36}(\mathrm{sys})\right]\ \mathrm{mb}$$

The Durand & Pi model for *pp* scattering

L. Durand and H. Pi, Phys.Rev. D38 (1988) 78-84

A single-channel eikonal model for *pp* scattering at high energies:

$$F(s,t) = i\int_0^\infty bdbJ_0(b\sqrt{-t})\Gamma(s,b)$$

$$\sigma_{\text{tot}} = 4\pi\int db\, b\,(1-e^{-\chi(b,s)})$$

$$\sigma_{\text{el}} = 2\pi\int db\, b\,(1-e^{-\chi(b,s)})^2$$

$$\sigma_{\text{inel}} = 2\pi\int db\, b\,(1-e^{-2\chi(b,s)})$$

$$\chi_{pp}(b,s) = \chi_{pp}^{\text{soft}}(b,s) + \chi_{pp}^{\text{QCD}}(b,s)$$

$$\chi_{pp}^{\text{soft}} = C_0 A(b) = \tfrac{1}{2}\sigma_0 A(b)$$

$$\chi_{pp}^{\text{QCD}}(b,s) = \tfrac{1}{2}n_{pp}(b,s) = \tfrac{1}{2}A(b)\sigma_{\text{QCD}}(s)$$

Average number of collisions *semi-hard* parton-parton collisions modelled after pQCD

$$\sigma_{\text{QCD}}(s) = 2\int_{2\nu/\sqrt{s}} dx_1 \int_{x_1}^{1} dx_2 \int_{Q^2_{\min}}^{x_1x_2s/2} d\,|\hat{t}|\, \frac{9\pi\alpha_s^2(\hat{t})}{2\hat{t}^{\,2}} F(x_1,\hat{t})F(x_2,\hat{t})$$

The Durand & Pi model for pA scattering

L. Durand and H. Pi, Phys.Rev. D38 (1988) 78-84

A single-channel eikonal model for pA scattering at high energies:

$$\sigma_{\rm abs}(pA)=2\pi\int_0^\infty db\, b\left(1-e^{-2\tilde{\chi}_{pA}(b,s)}\right)$$

$$\chi_{pA}^{\rm QCD}(b,s)=\tfrac{1}{2}\tilde{A}(b)\sigma_{\rm QCD}(s)$$

$$\tilde{A}(b)=\int d^2r_\perp dz\,\rho_A(\mathbf{r}_\perp,z)A(|\mathbf{b}-\mathbf{r}_\perp|)$$

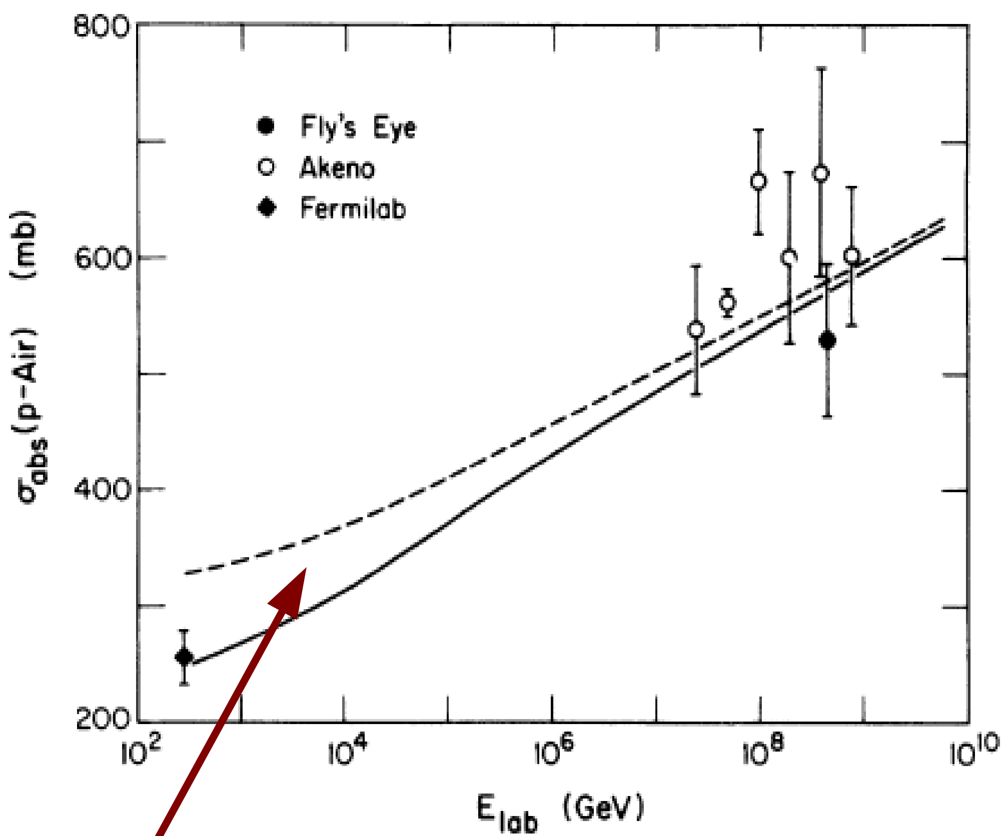
$$\tilde{\chi}_{pA}(b,s)=\tfrac{1}{2}(\sigma_0+\sigma_{\rm QCD})\tilde{A}(b)$$

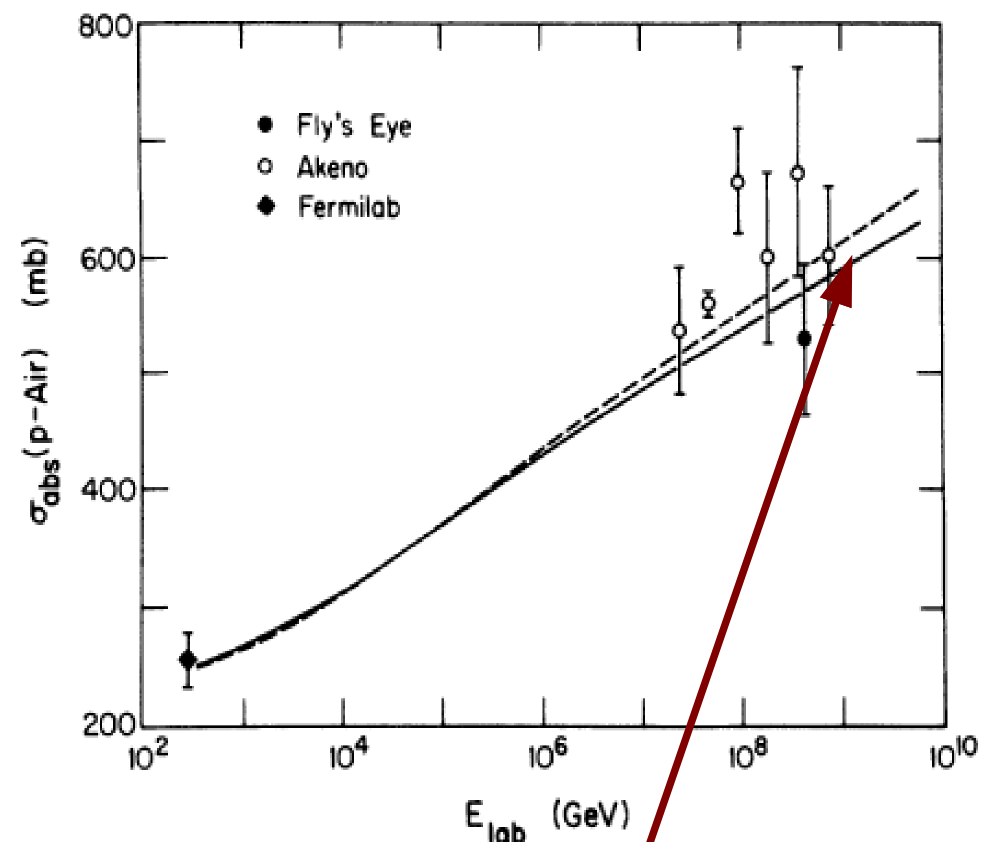
The often called "absorption" cross section gives the pA production cross section.

Instead, the inelastic pA cross section includes the quasi-elastic scattering of the incident particle from a target nucleon which breaks up the nucleus, without particle production.

QCD-inspired models – the Durand & Pi model

L. Durand and H. Pi, Phys.Rev. D38 (1988) 78-84





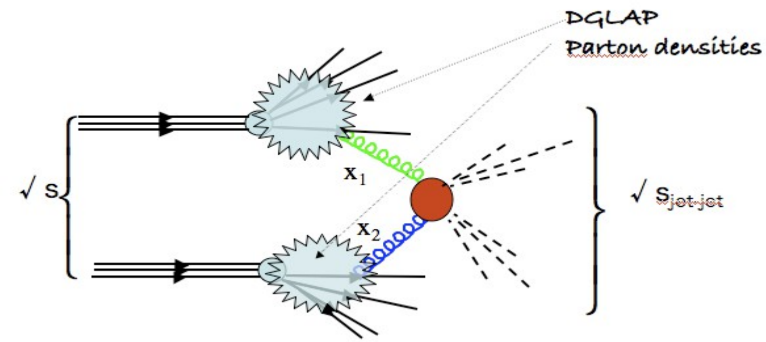
σ_0 effect at lower energies

Nuclear density effect - $\tilde{A}(b)$

Bloch-Nordsieck model for the *pp* total cross section

A.Corsetti et al., Phys.Lett. B382 (1996) 282;

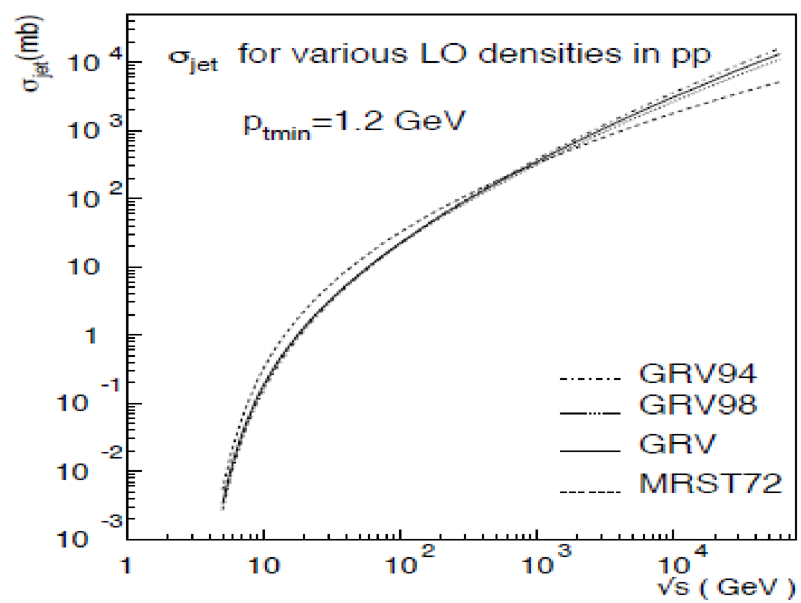
R.Godbole et al., Phys.Rev. D72 (2005) 076001



Key ingredients:

1) minijet cross section with PDFs evolved by DGLAP

$$\sigma_{jet} \sim s^{\epsilon_{PDF}}, \quad \epsilon_{PDF} \sim 0.3 - 0.4$$



Multiple semi-hard parton-parton interactions:

$$\sigma_{total} = 2\int d^2\vec{b}[1 - e^{-\chi_I(b,s)}]$$

$$\sigma_{inel} = \int d^2\mathbf{b}[1 - e^{-2\chi_I(b,s)}]$$

$$2\chi_I(b,s) = n^{pp}_{soft}(b,s) + n^{pp}_{jet}(b,s) = A_{FF}\sigma^{pp}_{soft}(s) + A^{pp}_{BN}(p, PDF; b, s)\sigma_{jet}(PDF, p_{tmin}; s)$$

Bloch-Nordsieck model for the *pp* total cross section

A.Corsetti et al., Phys.Lett. B382 (1996) 282;

R.Godbole et al., Phys.Rev. D72 (2005) 076001

2) soft kt- resummation, which tames the rise by introducing a cutoff in b-space

$$A_{\rm BN} = \frac{e^{-h(b,s)}}{\int d^2\vec{b}\, e^{-h(b,s)}}$$

Fixed by single gluon emission kinematics – energy dependent scale

$$h(b,s) = \frac{8}{3\pi}\int_0^{q_{\max}} \frac{dk}{k}\alpha_s(k^2)\ln\left(\frac{q_{\max}+\sqrt{q_{\max}^2-k^2}}{q_{\max}-\sqrt{q_{\max}^2-k^2}}\right)[1-J_0(kb)]$$

Resummation function – emission from valence quarks

Bloch-Nordsieck model for the *pp* total cross section

R.Godbole et al., Phys.Rev. D72 (2005) 076001

$$q_{\max}(s;p_{tmin}) = \sqrt{\frac{s}{2}} \frac{\sum_{i,j}\int\frac{dx_1}{x_1}\int\frac{dx_2}{x_2}\int_{z_{min}}^1 dz f_i(x_1)f_j(x_2)\sqrt{x_1x_2}(1-z)}{\sum_{i,j}\int\frac{dx_1}{x_1}\int\frac{dx_2}{x_2}\int_{z_{min}}^1 dz f_i(x_1)f_j(x_2)}$$

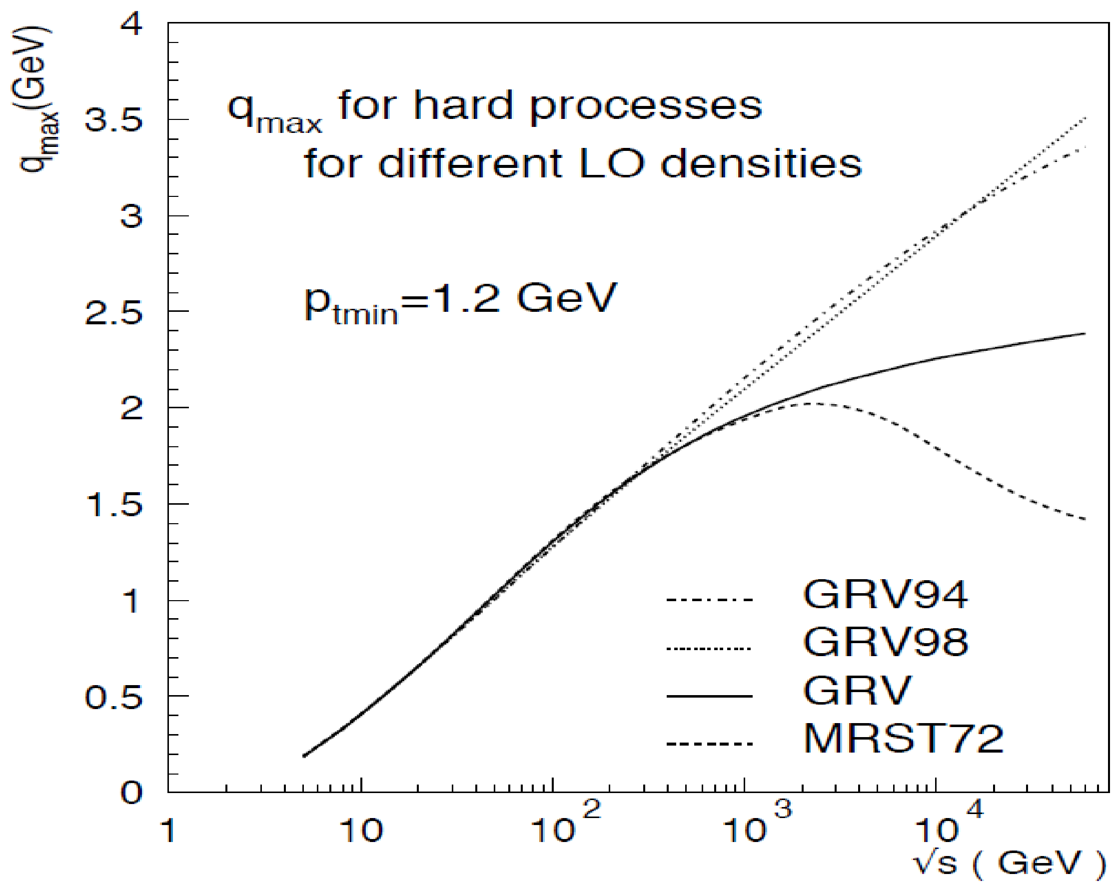
$$z_{min} = 4p_{tmin}^2/(sx_1x_2)$$

1) Maximum transverse momentum allowed to single gluon emission

2) Emissions in the initial state

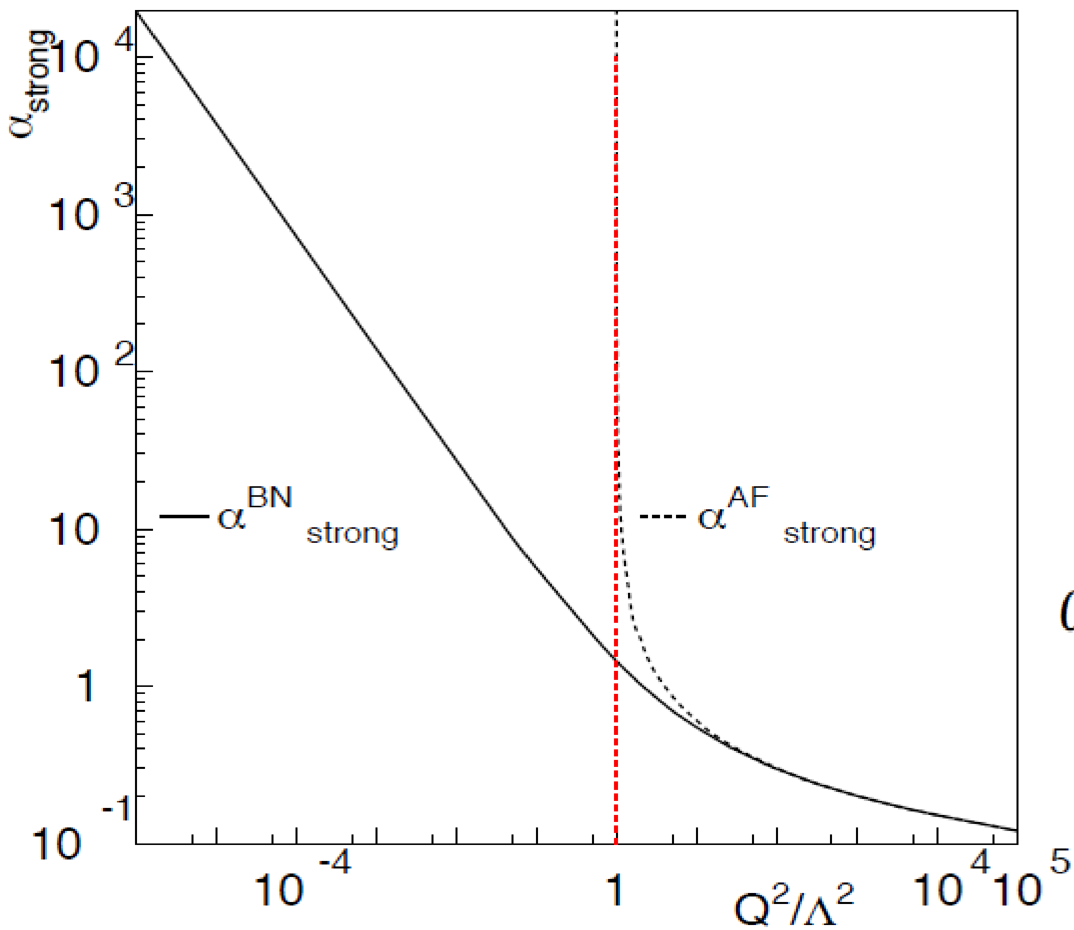
2) Average over PDFs

3) s and ptmin dependent



Bloch-Nordsieck model for the *pp* total cross section

R.Godbole et al., Phys.Rev. D72 (2005) 076001;



$$\alpha_s(k_t^2) = \frac{p}{b_0 \ln[1 + p(\frac{k_t^2}{\Lambda^2})^p]}$$

$$\alpha_s(k_t^2) \to \frac{1}{b_0}\left(\frac{k_t}{\Lambda}\right)^{-2p} \quad k_t^2 << \Lambda^2$$

$$\alpha_s(k_t^2) \to \alpha_s^{AF}(k_t^2) = \frac{1}{b_0 \ln[\frac{k_t^2}{\Lambda^2}]} \quad k_t^2 >> \Lambda^2$$

Regularizes the integrated soft gluon spectrum as long as $p < 1$.

Bloch-Nordsieck model for the *pp* total cross section

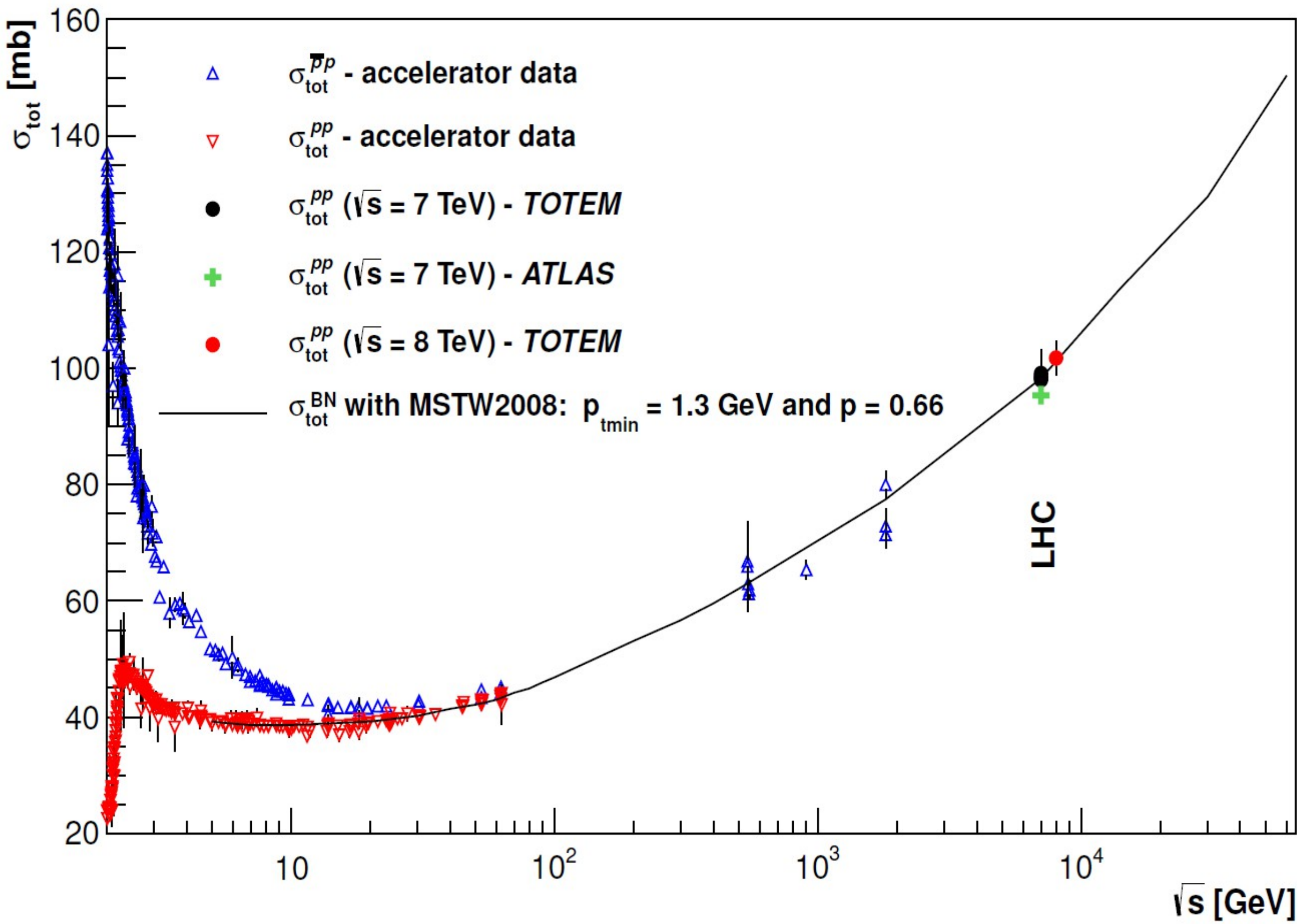
A. Achilli, Phys.Rev. D84 (2011) 094009;

D.A. Fagundes et al., arXiv:1408.2921;

For applications to $\pi p, \pi\pi, \gamma p, \gamma\gamma$:

Phys.Lett. B693 (2010) 456-461;

Phys.Lett. B435 (1998) 441-448;



Asymptotic behaviour:

$$\sigma_{tot}^{pp} \sim \frac{2\pi}{(\bar{\Lambda})^2}[\epsilon \log s]^{1/p}$$

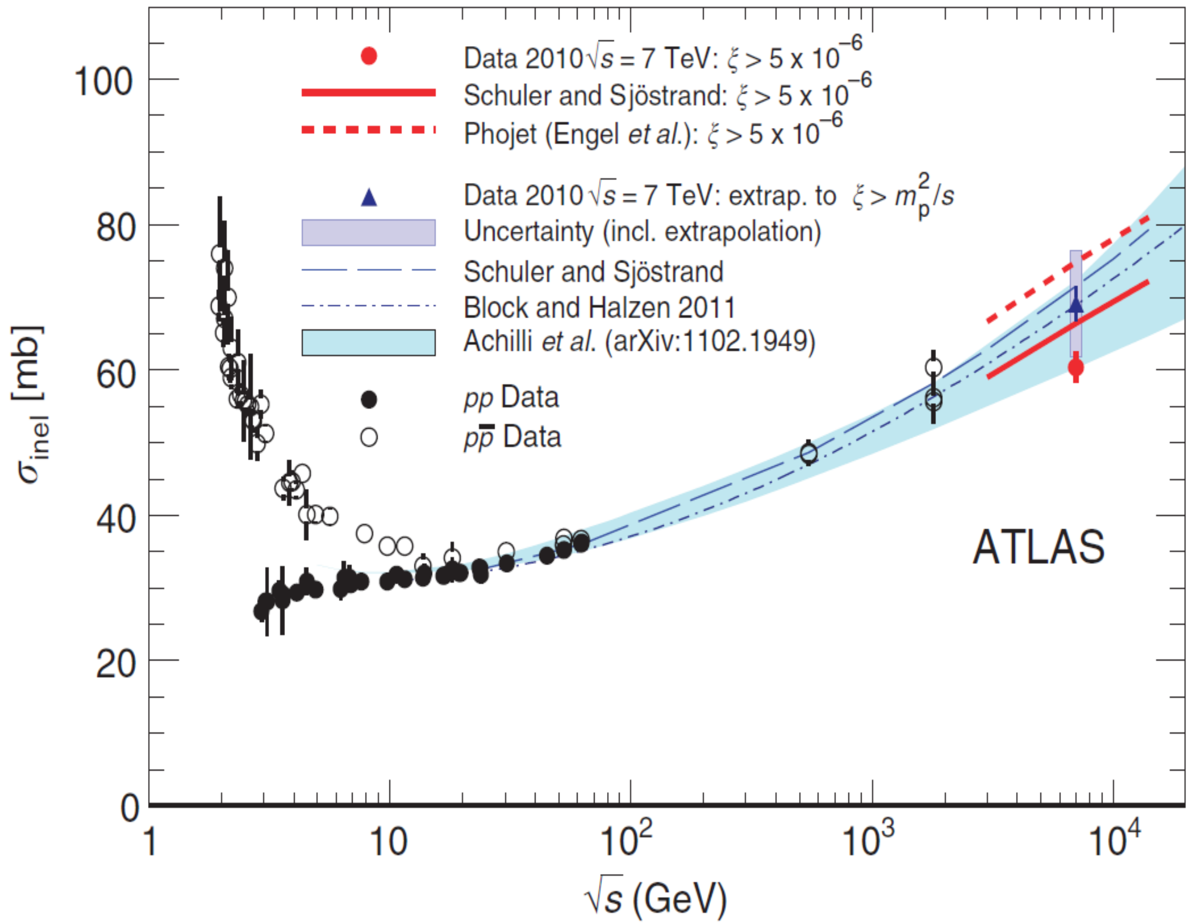
$$1/2 < p < 1$$

Parameters tunned to describe LHC7 and LHC8 data – only accelerator data is used

Predictions for the inelastic cross section - pre-LHC

G. Aad (ATLAS Collaboration), Nature Commun. 2 (2011) 463;

A. Achilli, Phys.Rev. D84 (2011) 094009



$$p = 0.66 \rightarrow \sigma_{inel} = 60mb$$

$$p = 0.5 \rightarrow \sigma_{inel} = 75mb$$

Table 2 | Comparisons of the inelastic cross-section with predictions.

	$\sigma(\xi > 5\times10^{-6})$ (mb)
ATLAS Data 2010	60.33±2.10(exp.)
Schuler and Sjöstrand	66.4
Phojet	74.2
Ryskin *et al.*	51.8-56.2
	$\sigma(\xi > m_p^2/s)$ (mb)
ATLAS Data 2010	69.1±2.4(exp)±6.9(extr.)
Schuler and Sjöstrand	71.5
Phojet	77.3
Block and Halzen	69.0±1.3
Ryskin *et al.*	65.2-67.1
Gotsman *et al.*	68
Achilli *et al.*	60-75

Measurement and theoretical predictions of the inelastic cross-section for the restricted kinematic range, $\xi > 5\times10^{-6}$, and for the full kinematic range, $\xi > m_p^2/s$. The experimental uncertainty (exp.) includes the statistical, systematic and luminosity uncertainties. The extrapolation uncertainty (extr.) only applies to the full kinematic range and is listed separately.

Bloch-Nordsiek model for the *pp* total cross section

A.Corsetti et al., Phys.Lett. B382 (1996) 282;

R.Godbole et al., Phys.Rev. D72 (2005) 076001

Yes, we can get the inelastic as well as the total. On the other hand, let us recall that in the approximation we're using only non-correlated part of the inelastic is accounted

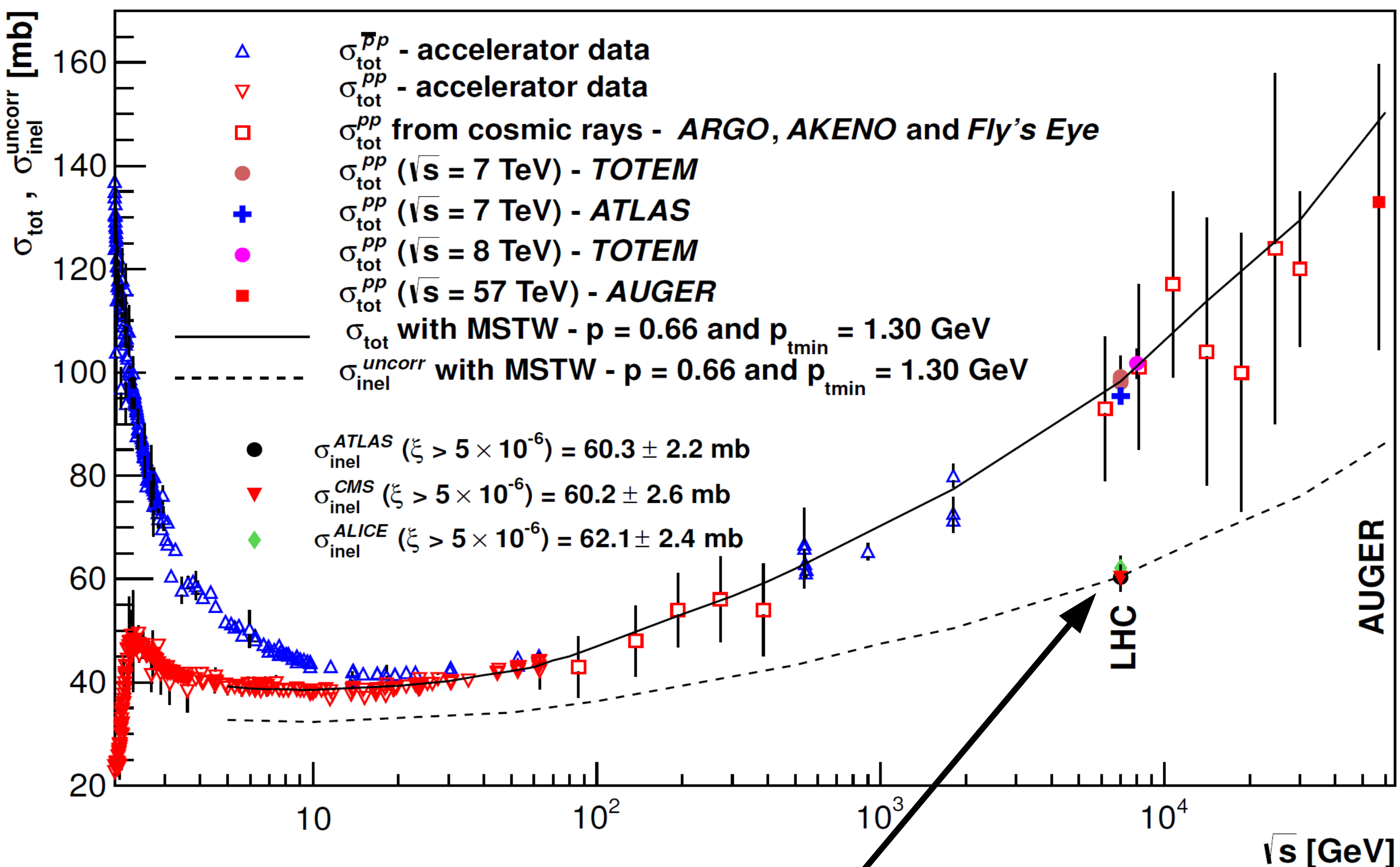
$$P_{inel}(s,b) = \sum_{1}^{\infty} \frac{(\bar{n})^n e^{-\bar{n}(b,s)}}{n!} = 1 - e^{-\bar{n}(b,s)}$$

Thus, the formalism is tied to give only the non-diffractive part of the inelastic

$$\sigma_{inel}^{uncorr} = \int d^2b[1 - e^{-\bar{n}(s,b)}]$$

Bloch-Nordsiek model for the *pp* total cross section

D.A. Fagundes et al., arXiv:1408.2921



With the same *p* that describes the total, the nondiffractive inelastic cross section is obtained

Glauber modelling of the *p-air* production cross section

N.N. Nikolaev, Phys.Rev. D48 (1993) 1904-1906;

B.Z. Kopeliovich, Phys.Rev. C68 (2003) 044906;

E. Gotsman, E. Levin, U. Maor, Phys.Rev. D88 (2013) 114027.

In the simplest Glauber formalism the production cross section can be calculated as

$$\sigma_{\rm abs}(p\text{-air})=\sigma_{\rm tot}(p\text{-air})-\sigma_{\rm el}(p\text{-air})-\sigma_{\rm Qel}(p\text{-air})=\int d^2\mathbf{b}\left\{1-\left[1-\frac{1}{A}\sigma_{\rm in}(p\text{-}p)T(b)\right]^{2A}\right\}$$

$$\approx\int d^2\mathbf{b}\{1-\exp[-\sigma_{\rm in}(p\text{-}p)T(b)]\}\ .$$

Screened cross section

$$\sigma_{\rm in}=\sigma_{\rm tot}-\sigma_{\rm el}-\sigma_{\rm dif}\longrightarrow\sigma_{inel}^{nondiff.}$$

Nuclear profile function

C.W. De Jagier, H. De Vries and C. De Vries, At. Data Nucl. Data Tables 14, 479 (1974)

Gaussian:

$$T_A(b) = \frac{A}{\pi R_N^2} e^{-b^2/R_N^2}$$

$$A = 14.5, \quad R_N = (1.1 fermi) A^{1/3}$$

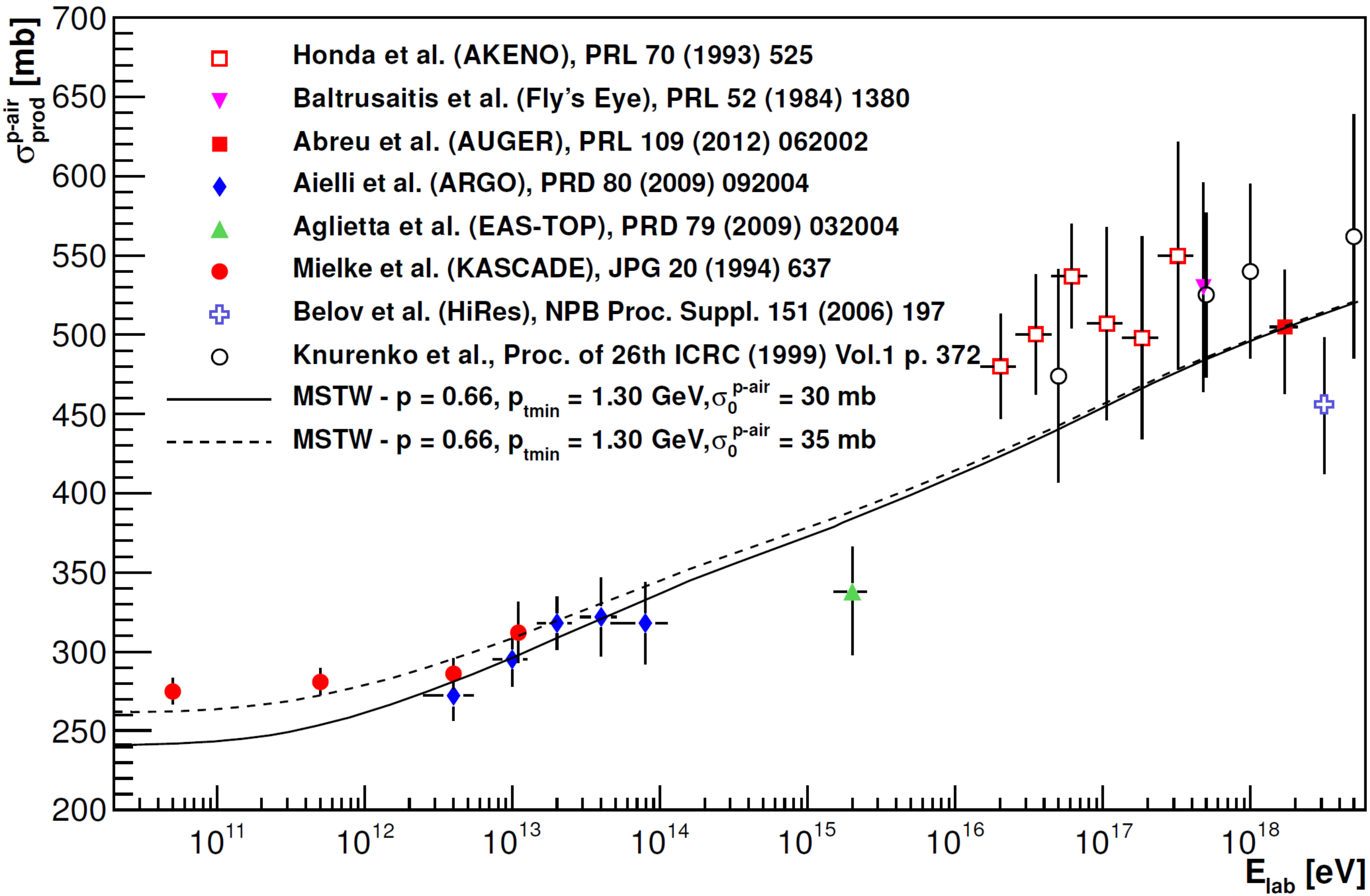
Woods-Saxon:

$$T_A(b) = \int_{-\infty}^{\infty} dz \frac{\rho_0}{1 + \exp\left(\frac{\sqrt{z^2+b^2} - R_A}{h}\right)}$$

Normalization

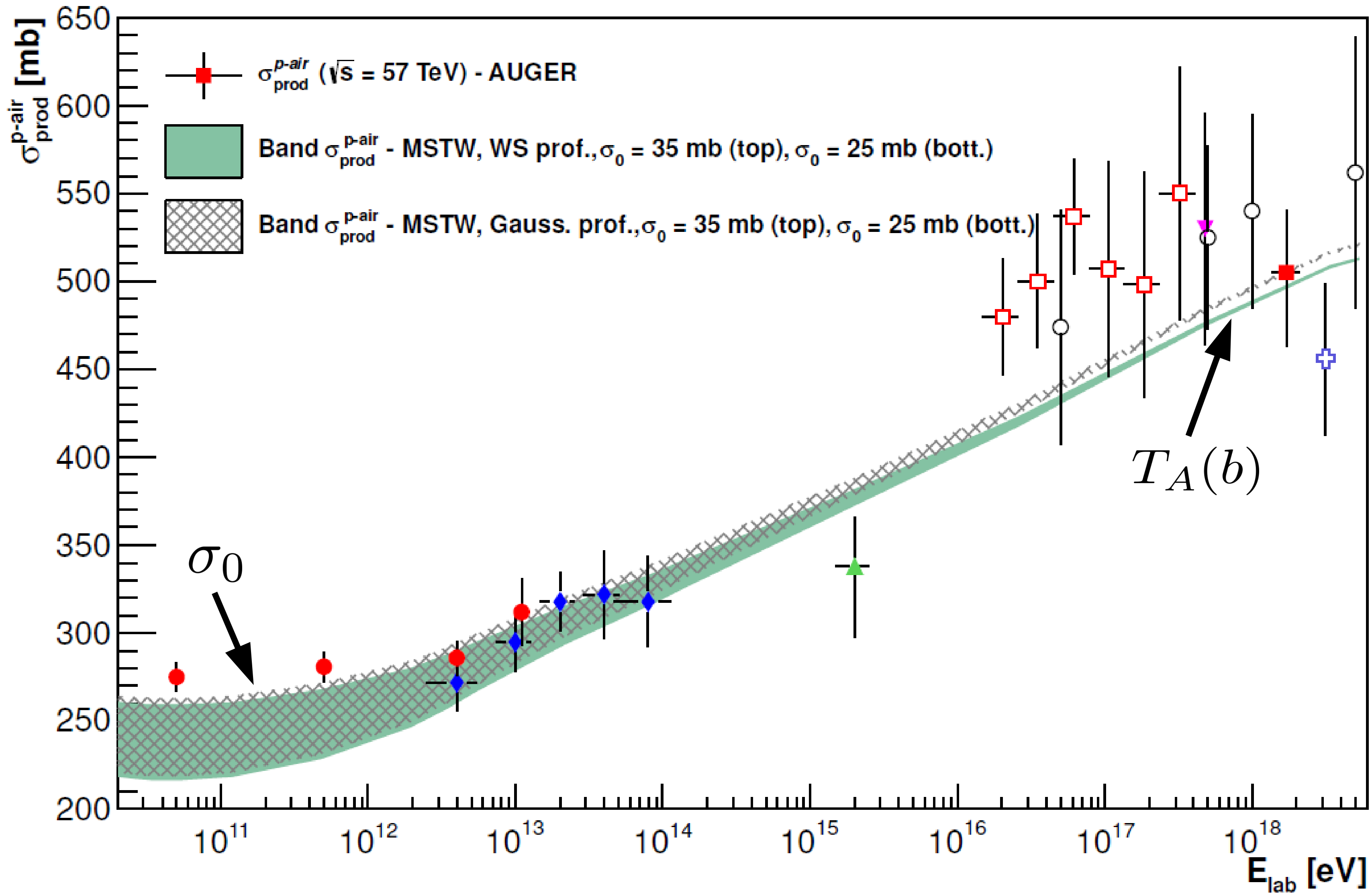
$$\int d^2\mathbf{b} T_N(b) = A$$

Glauber modelling of the *p-air* production cross section



Good description of cosmic ray data, specially Auger's

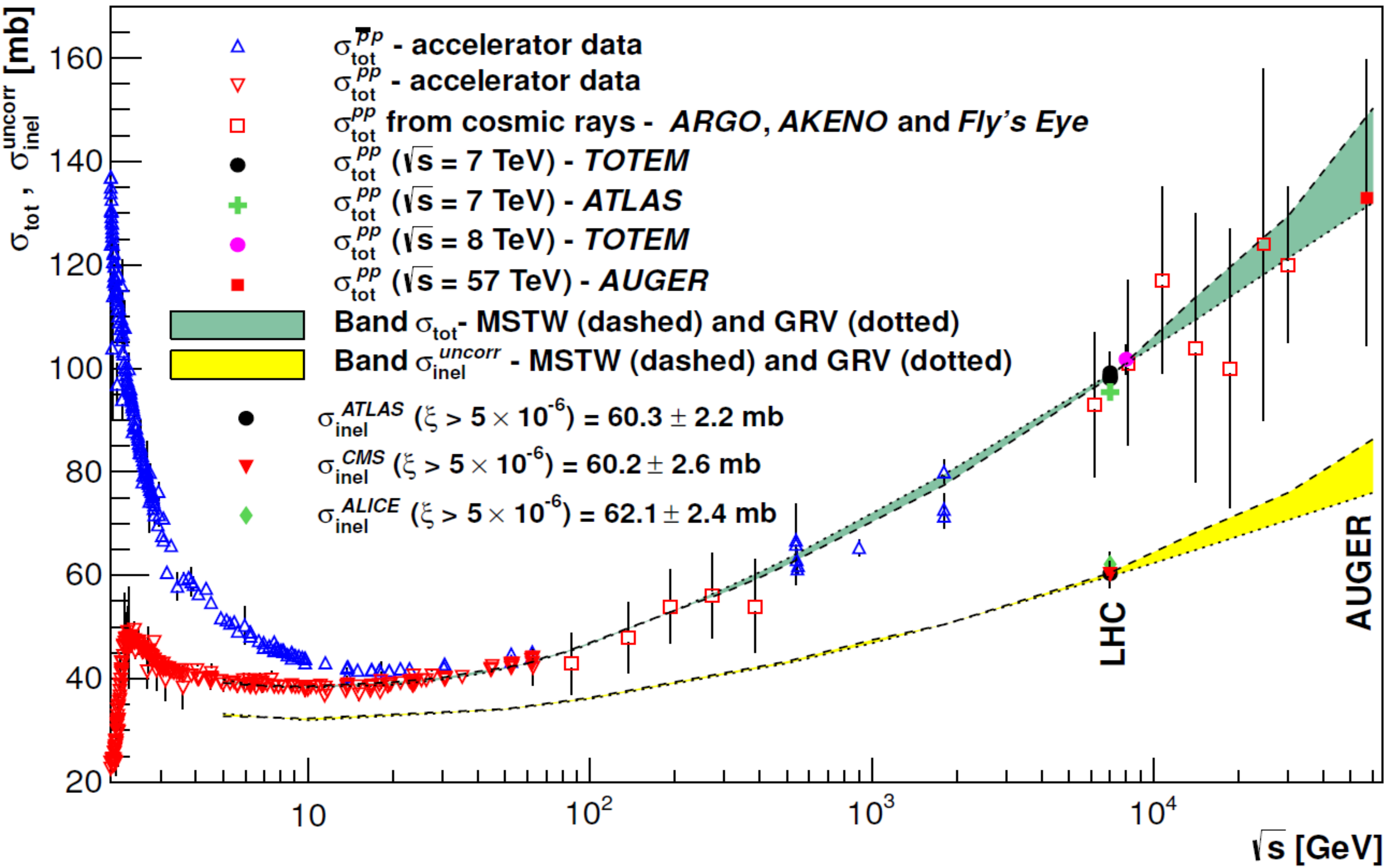
Glauber modelling of the *p-air* production cross section



At very high energy not very sensitive to the nuclear profile input

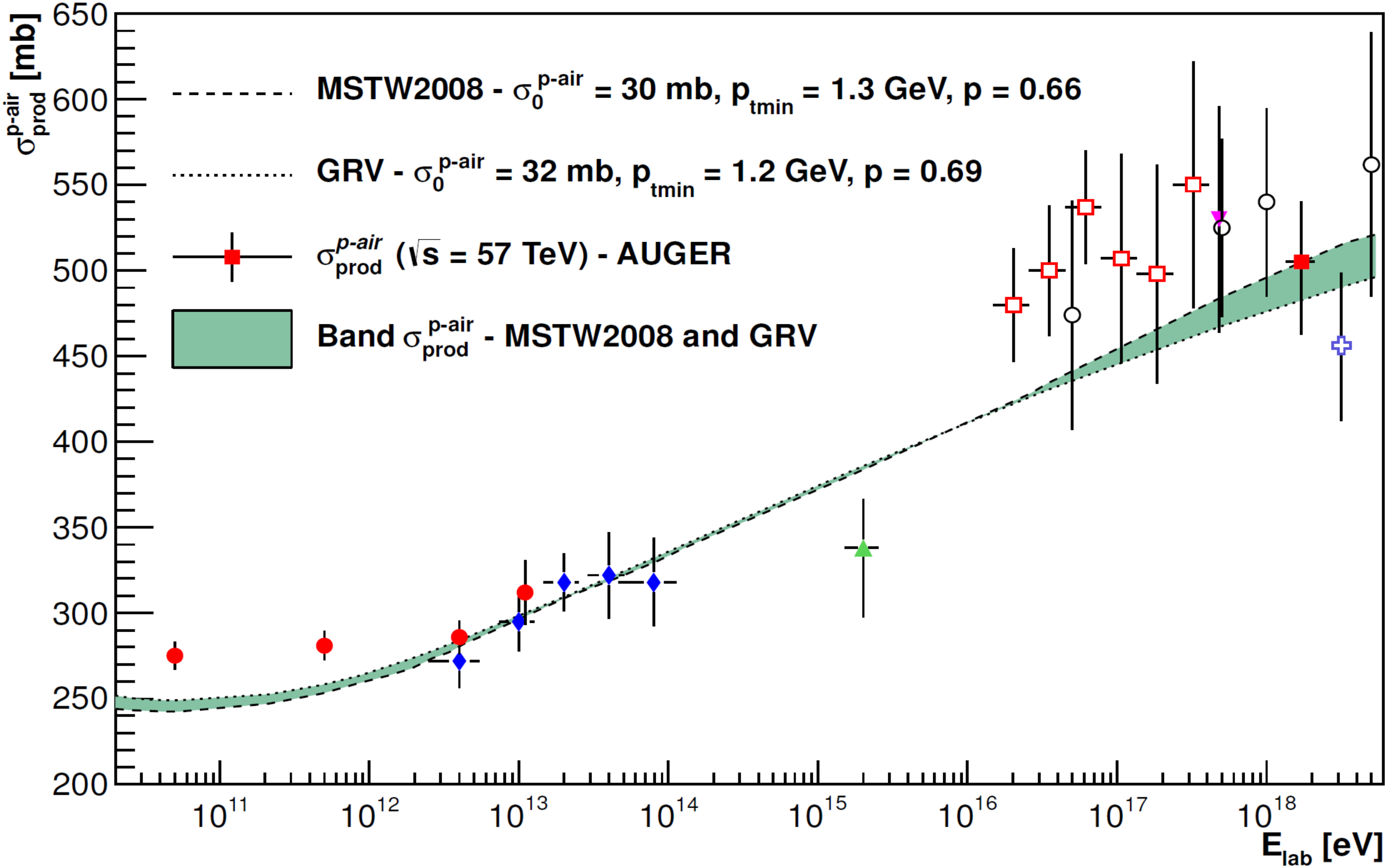
Low-x behaviour of (LO) PDFs – MSTW2008 *vs* GRV

D.A. Fagundes et al., arXiv:1408.2921;



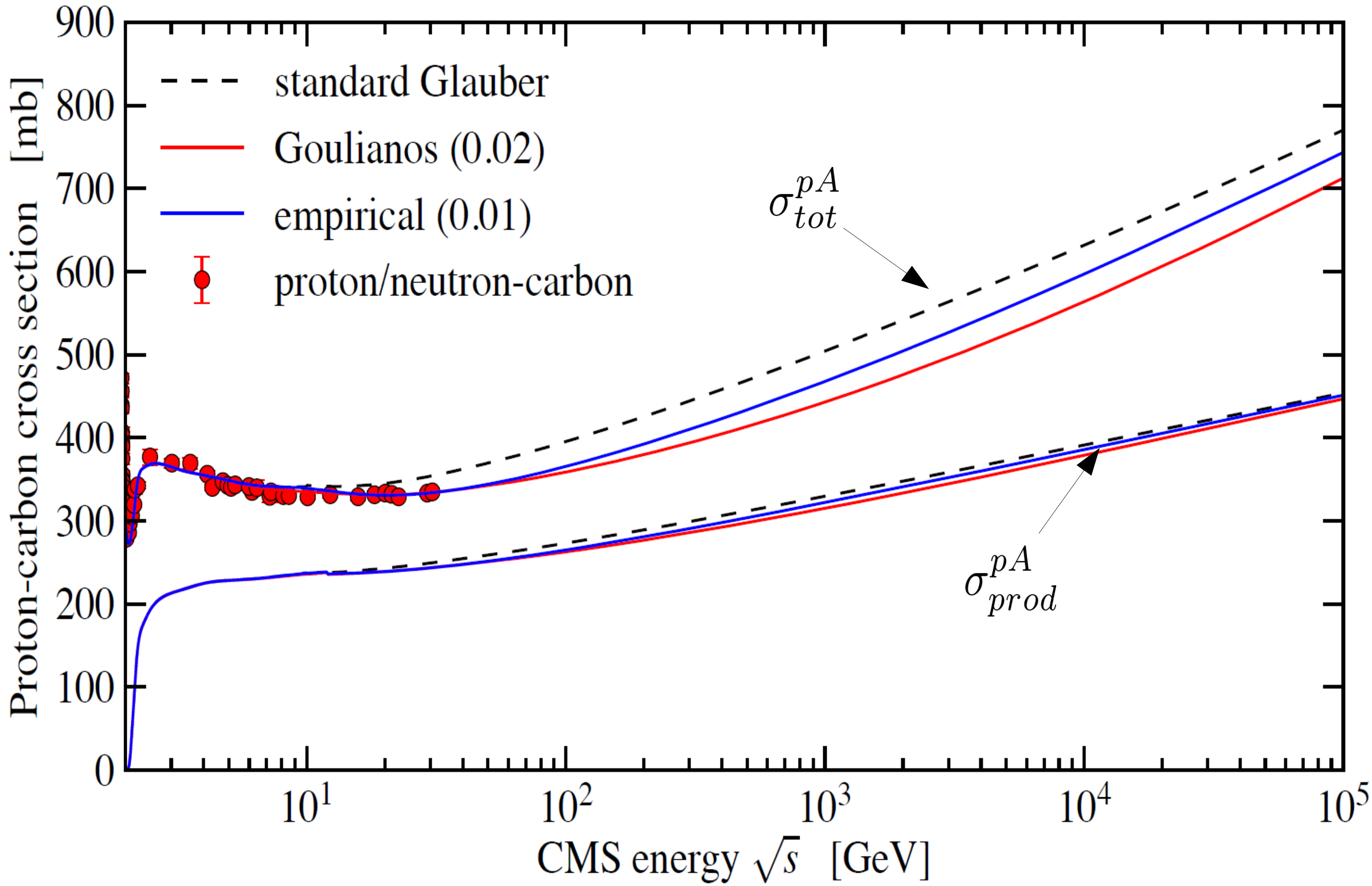
Bands at very high energy dictated by the low-x behaviour of PDFs

Uncertainties in $\sigma_{p-\mathrm{air}}^{\mathrm{prod}}$ at very high energy



Inelastic screening - total vs production cross sections

R.Engel and R.Ulrich, Pierre Auger Internal Note (unpublished), GAP-2012



Very important for the total, less so for the production one.

Summary and Outlook

- Despite the limitations of the one-channel approach there are some interesting features in this model, namely:

  (1) describes the rise of all total cross section: $pp, \pi^{\pm}p, \pi^{\pm}\pi^{\pm}, \gamma p, \gamma\gamma$

  (2) it gives the nondiffractive (uncorrelated) inelastic cross section;

  (3) in simplest Glauber picture, the p-air production cross section is obtained as long as the problem of subtracting the diffractive cross section is circumvented;

- However, several aspects deserve further investigation:

  (1) how to get the elastic differential?;

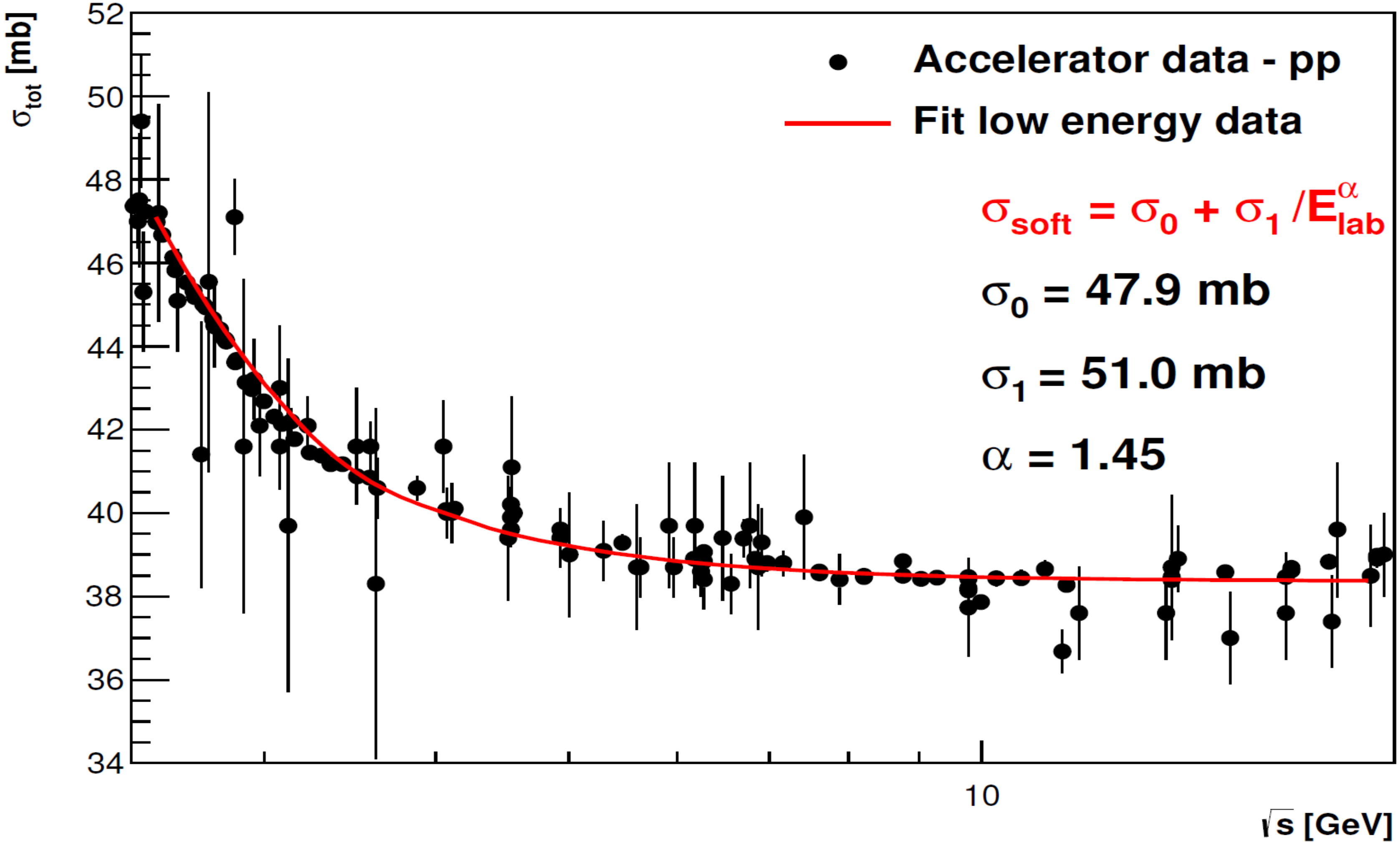
  (2) real part of the amplitude?;

  (3) GW decomposition to include low mass diffraction;

  (4) higher order correction from soft gluon emission?;

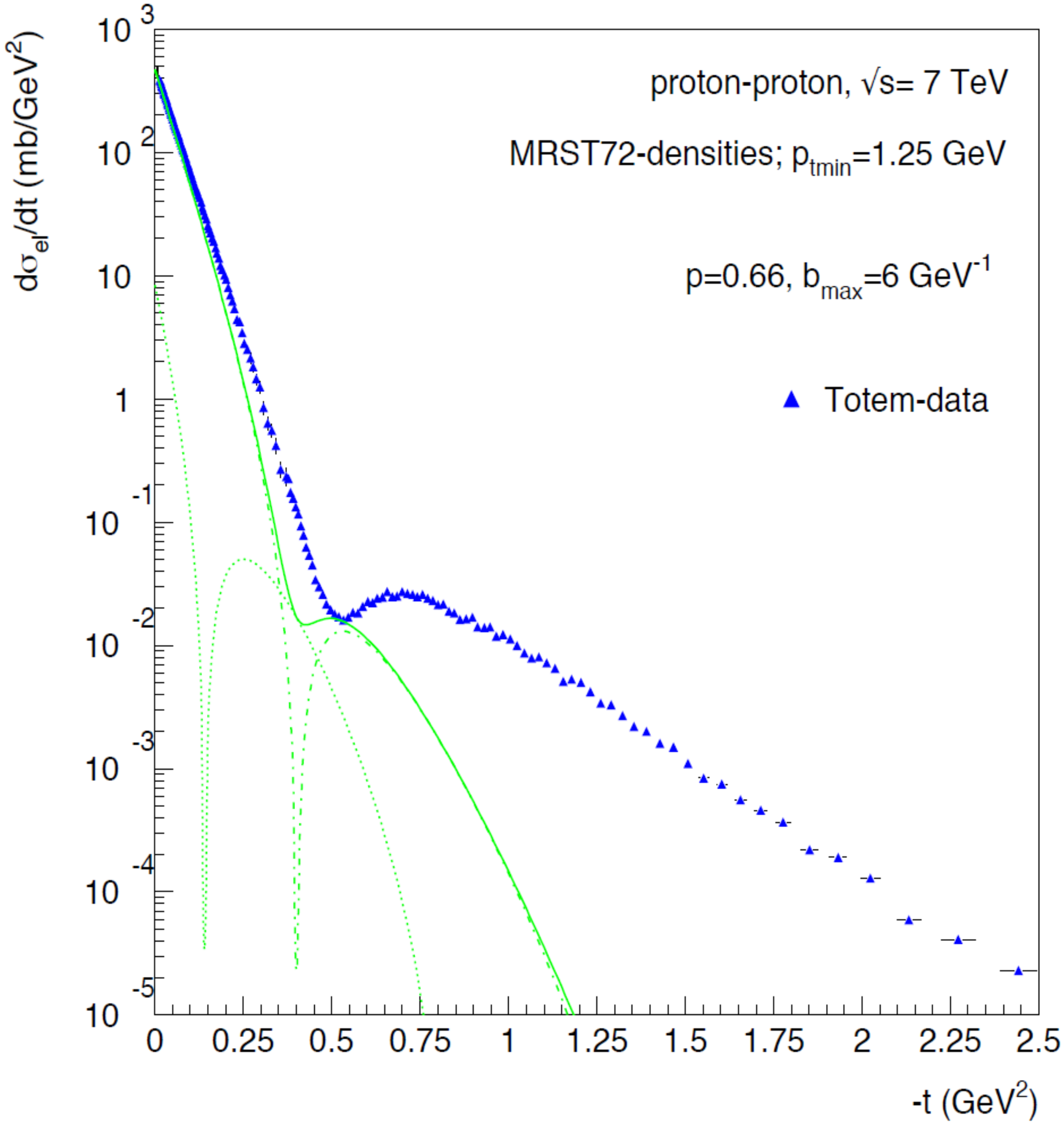
- While the model needs improvements, the fundamental problem of having a comprehensive and widely accepted formalism to treat soft diffractive interactions in terms of QCD remains open

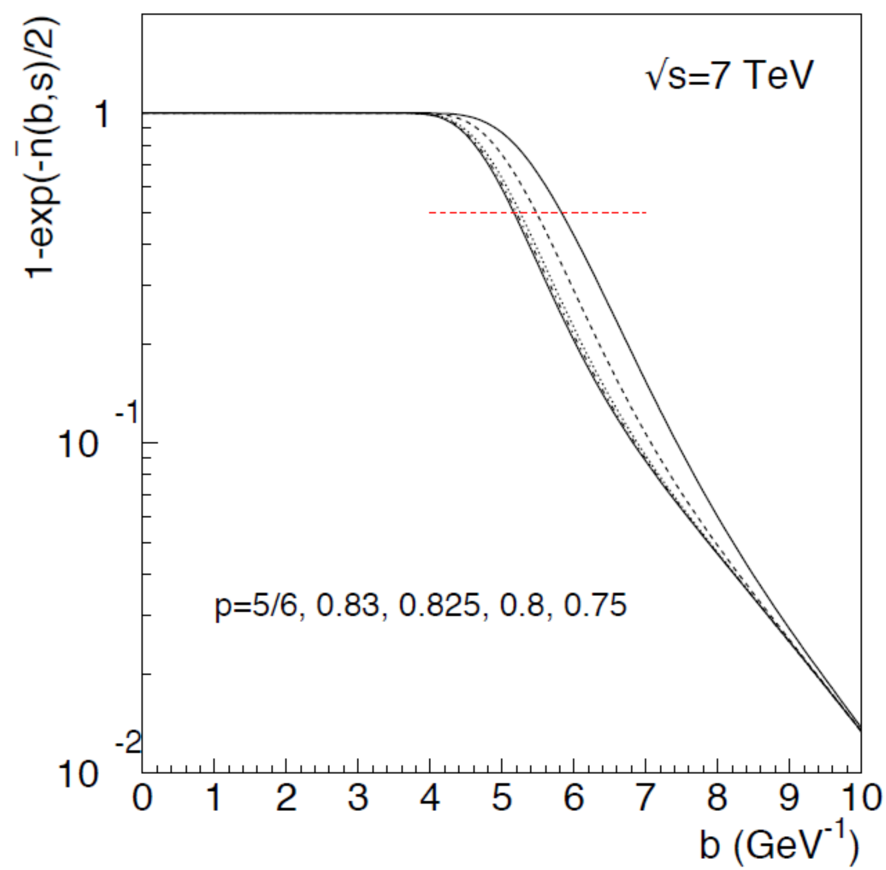
The low energy contribution



$$A_{FF}(b) = \frac{1}{(2\pi)^2} \int d^2\vec{b}\, e^{iq\cdot b} \left[\frac{\nu^2}{q^2+\nu^2}\right]^4 = \frac{\mu^2}{96\pi}(\mu b)^3 K_3(\mu b)$$

Differential elastic cross section





$$A_{el}(s,b) = 1/2 \to b_{max}$$

$$b_{max} \sim 6\ \mathrm{GeV}^{-1}$$