# New title:
# Minijets for cosmic rays interactions

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A minijet model *cum* soft gluon k-t resummation applied to

1. Photoproduction models for total cross section and shower development [old title]
   with/on behalf of F. Cornet, C. Garcia Canal, A. Grau and S. Sciutto

2. p-air production cross-section and uncorrelated processes in pp scattering [poster]

   with/on behalf of D.A. Fagundes, A. Grau, Y.N. Srivastava and O. Shekhovtsova

# Total cross-sections: outline

- Our model for pp : called Bloch Nordsieck (BN) model because of resummation down to zero momenta [PLB 1996, PRD 1999, PRD 2005]

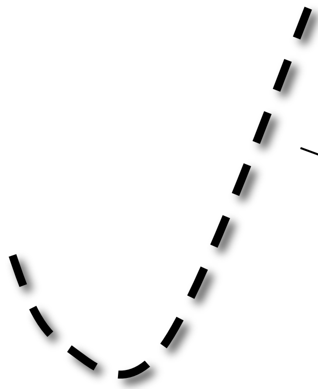
- Photoproduction and showers [under completion]

- pp and p-air cross-section model [arXiv:1408.2921]

# All total cross-sections rise… but not too much (Froissart dixit)

Cline,Halzen &Luthe 1973
Gaisser, Halzen,Stanev 1985
G.P., Y.N. Srivastava 1986
Durand,Pi 1987
Sjostrand, van Zijl 1987
…

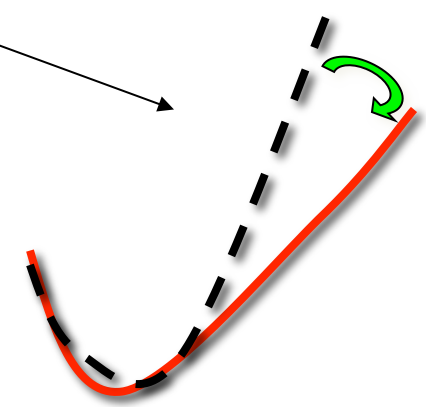
What generates the rise? Low-x parton collisions



$s^{\epsilon} \quad \epsilon \sim 0.3$

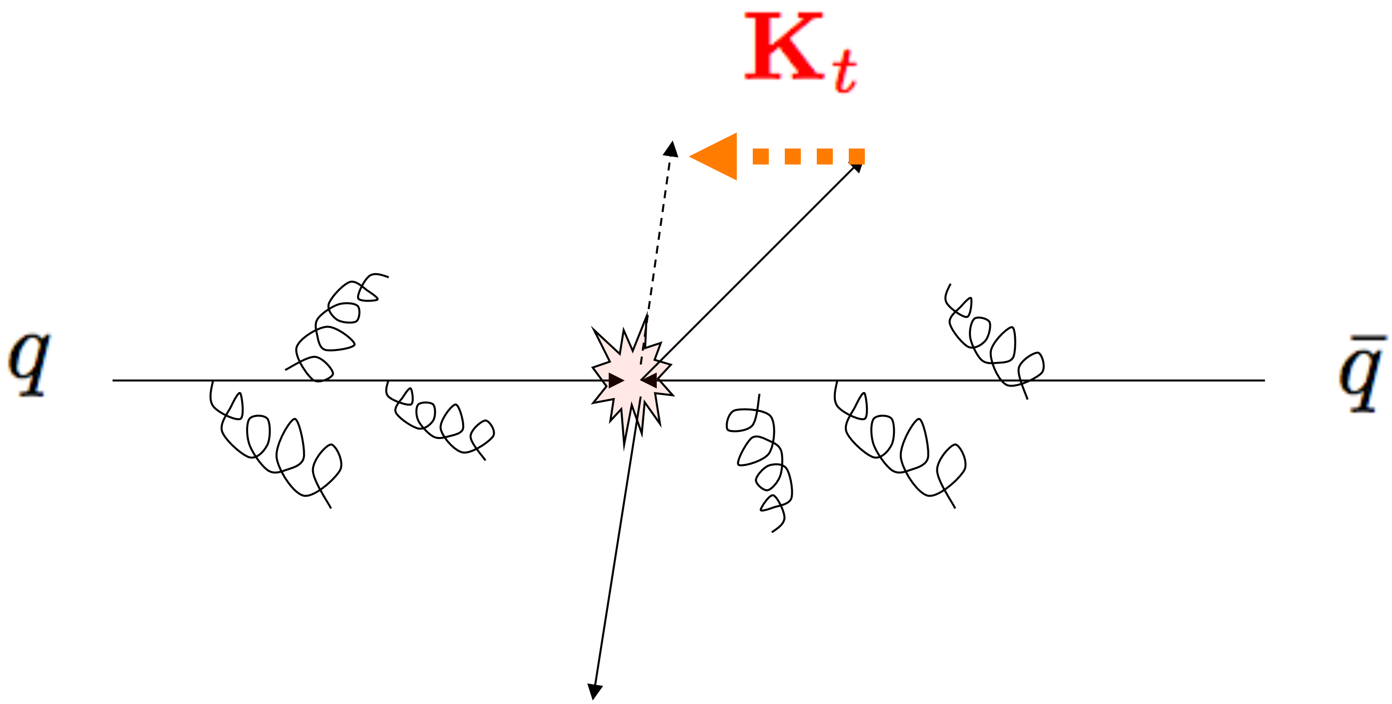
How to go from
hard to soft ?

What tames the rise into to a Froissart-like behavior?



A cut off obtained by [embedding into the eikonal]
the acollinearity induced by IR kt-emission
[our model, G.P. et al. **Phys.Lett.B382, 1996**]

# Soft gluon emission introduces acollinearity




Acollinearity reduces the collision cross-section as
partons do not scatter head-on any more, also explained as the gluon cloud
Becoming too thick for partons to see each other : gluon saturation

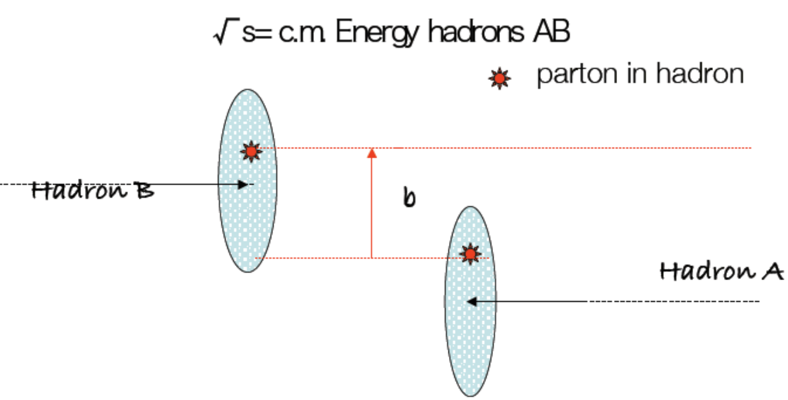
We model the impact parameter distribution as the Fourier-transform of ISR soft $k_t$ distribution and thus obtain a cut-off at large distances : Froissart bound?

$$A_{BN}(b,s) = N \int d^2\mathbf{K}_\perp \, e^{-i\mathbf{K}_\perp\cdot\mathbf{b}} \frac{d^2P(\mathbf{K}_\perp)}{d^2\mathbf{K}_\perp} = \frac{e^{-h(b,q_{max})}}{\int d^2\mathbf{b}\, e^{-h(b,q_{max})}}$$

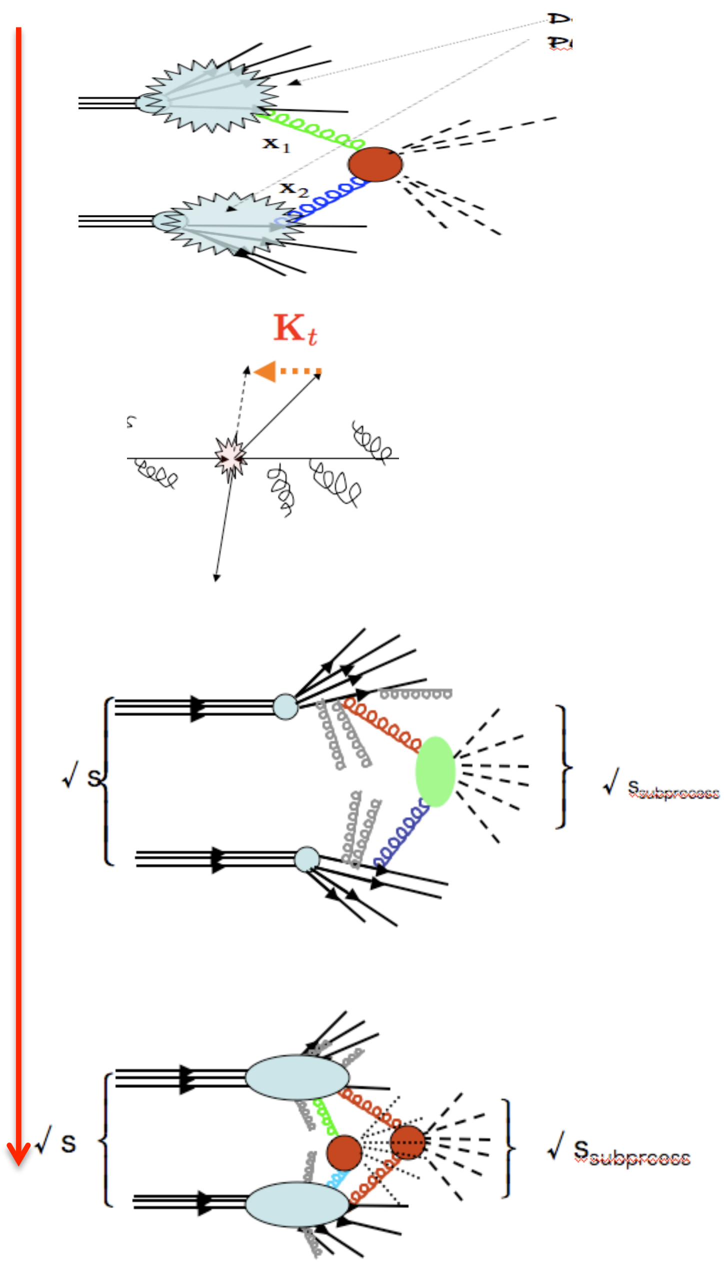
$$h(b,E) = \frac{16}{3\pi}\int_0^{qmax} \frac{dk_t}{k_t}\alpha_{eff}(k_t)\ln\left(\frac{2q_{max}}{k_t}\right)[1 - J_0(bk_t)]$$

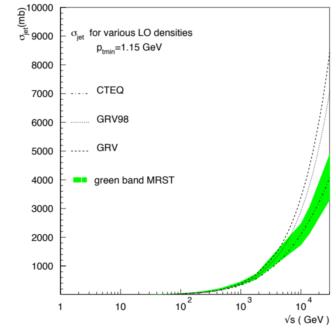
$$\alpha_{eff}(k_t \to 0) \sim k_t^{-2p}$$

$$A_{BN}(b,s) \sim e^{-(b\bar{\Lambda})^{2p}}$$



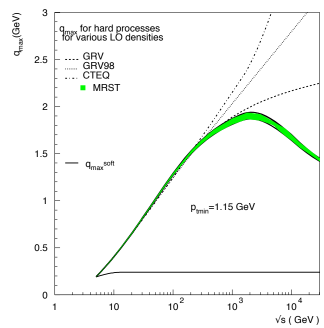

$q_{tmax}$ ? Fixed by single gluon emission kinematics



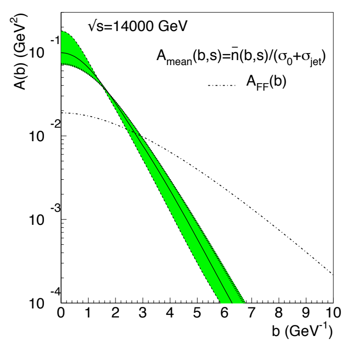

1. Calculate mini-jet cross-section Choosing densities and ptmin

$$\sigma_{mini-jet} \simeq s^{\epsilon}$$
$$\epsilon \simeq 0.3 - 0.4$$



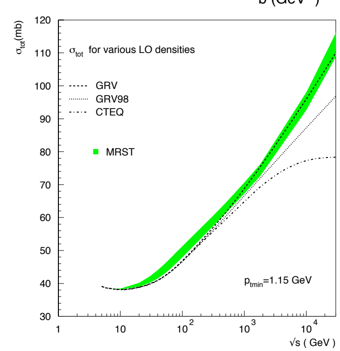

2. Calculate qmax: single soft gluon upper scale, for given PDF, ptmin

$$q_{max} \simeq p_{tmin}$$
$$\lesssim 2 - 3\ GeV$$




3. Calculate impact parameter distribution for given qmax and given infrared parameter p

$$\chi(b,s) = \chi_{low\ energy} +$$
$$+ A(b, qmax)\sigma_{jet}$$




4. Eikonalize

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

# Major traits of our model

- Energy rise from mini-jets (to be obtained from DGLAP evoluted PDF and parton-parton x-sections)

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

- Saturation comes as a large distance effect: at large distances, soft gluon emission leads to a cut-off

$$A(b,s) \sim e^{-[b\bar{\Lambda}(s)]^{2p}}$$

- Embedded into eikonal formulation

# 1. Extension of the mini-jet model to photoproduction Eur.Phys.J. C63 (2009) 69-85

$$\sigma_{tot}^{\gamma p} = 2P_{had}\int d^2b\left[1-e^{-n^{\gamma p}(b,s)/2}\right]$$

$$P_{had} = \sum_{V=\rho,\omega,\phi}\frac{4\pi\alpha}{f_V^2}$$

Mimics details of photon fluctuation into a hadron

$$n^{\gamma p}(b,s) = n_{soft}^{\gamma p}(b,s) + n_{hard}^{\gamma p}(b,s)$$

Fletcher, Gaisser, Halzen,Phys.Rev. D45 (1992) 377

$$n_{hard}^{\gamma p}(b,s) = A_{BN}(b,s)\sigma_{jet}^{\gamma p}(s)/P_{had}$$

resummation

LO current PDFs

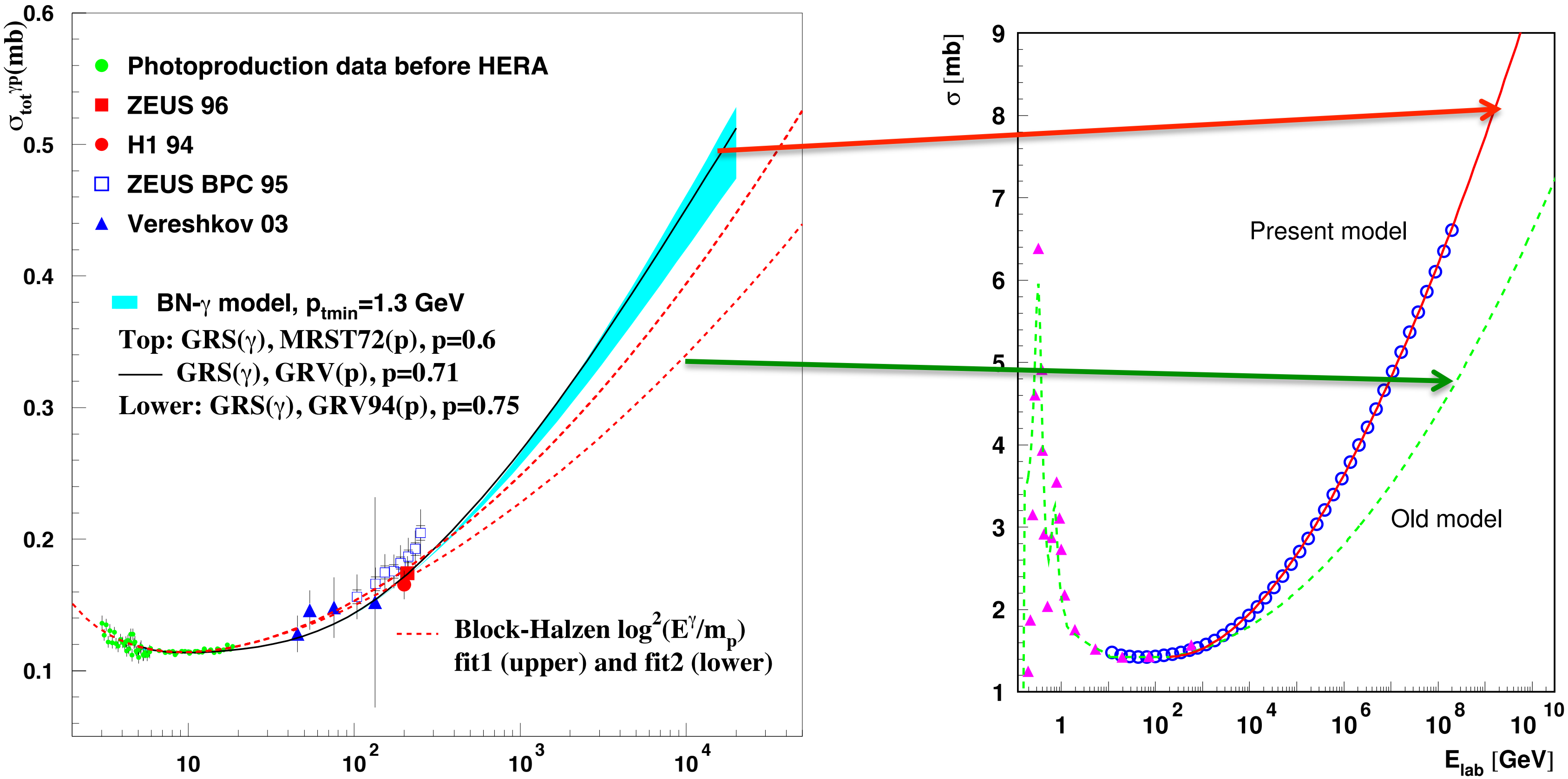
Input from our BN model

# Shapes of shower observables

With F. Cornet, C.A. Garcia Canal , A. Grau and S. Sciutto

Photon-proton

Photon-air



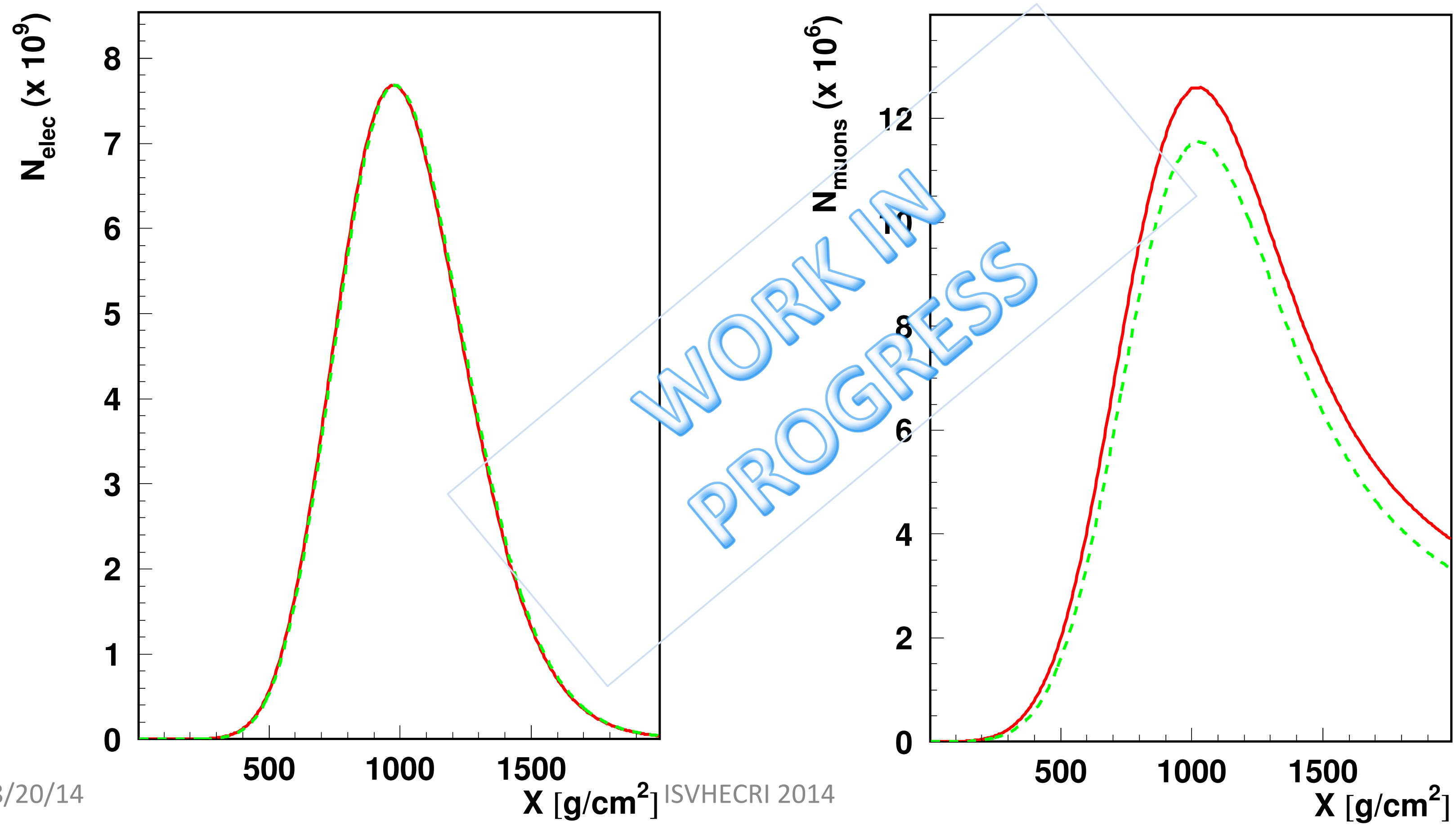

"old"= standard cross sections implemented in AIRES and other SP

# Longitudinal development from $10^{19}$ eV photon showers

---- standard cross sections implemented in AIRES

Electrons and positrons

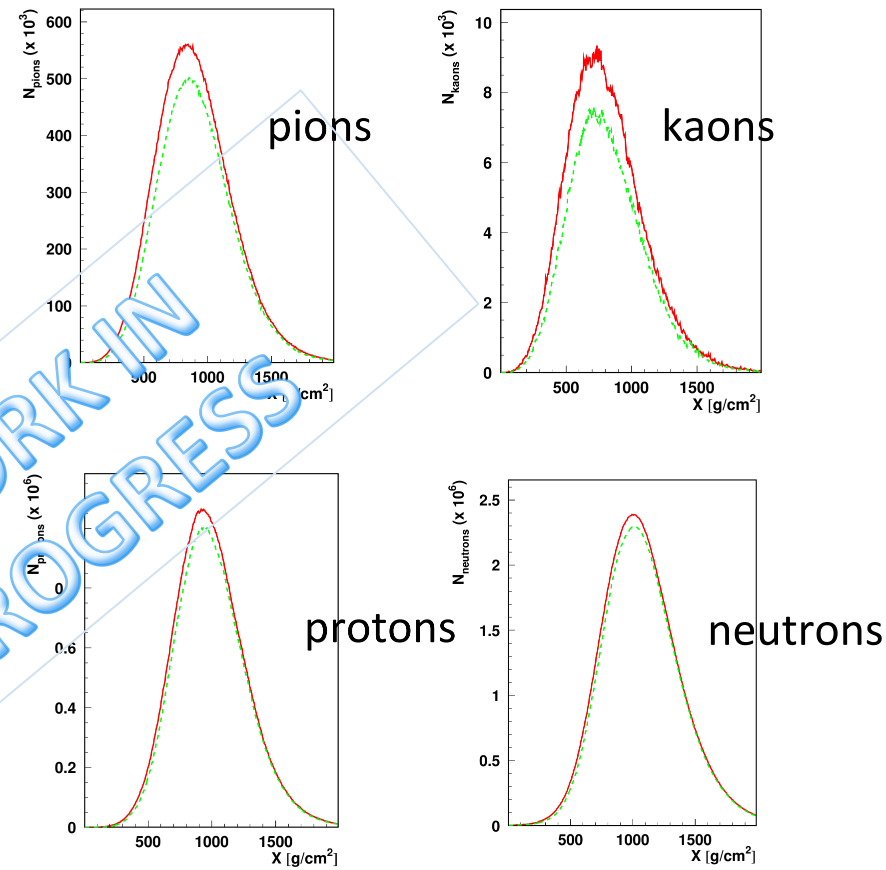
muons



# Longitudinal shower development of hadrons from BN-γ model input

Using central curve from BN model for proton - γ cross-section into AIRES simulation

[On behalf of C. Garcia Canal, F. Cornet, S. Sciutto]




---- standard cross sections implemented in AIRES

# 2. p-air production with or without diffraction?

- Usually $\sigma_{p-air}^{prod} = \sigma_{p-air}^{tot} - (\sigma_{p-air}^{el} + \sigma_{p-air}^{q-el})$
  - we need to model three terms in p-air + model diffraction in pp as well

BUT

*There is no unique definition of diffraction* (Khoze-ISVHECRI 2014)

- And then we need to take it away!

*How can you take away something you do not see?* (Katkov-ISVHECRI 2014)

Our proposal*:*

- In one-eikonal formalism

$$\sigma_{p-air}^{prod} = \int d^2\mathbf{b}[1 - e^{-2\chi_I^{p-air}}]$$

$$2\chi_I^{p-air} = n^{p-air}(b, E_{Lab})$$

Where only uncorrelated (Poisson distributed) p-air collisions are summed up in the integral

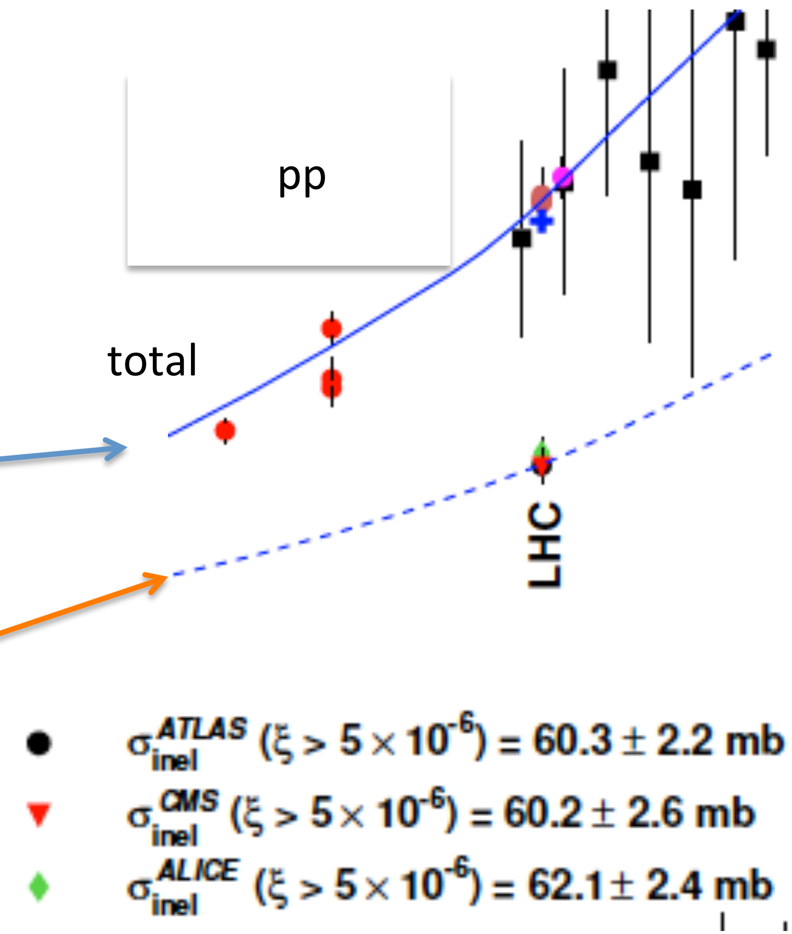
$$n^{p-air} \equiv n_{ind-coll}^{p-air} \longleftrightarrow \sigma_{inel}^{pp}$$

This quantity $\sigma^{pp}_{inel}$ should be the non-diffractive part and can be obtained

1. from multichannel formalism, subtracting elastic and diffraction from the total, thus further modeling (KMR, GLM, Ostapchenko, … see Khoze's talk)

Or

2. from one-channel eikonal formulations where a fit to the total gives the uncorrelated non-diffractive inelastic cross-section *for free*

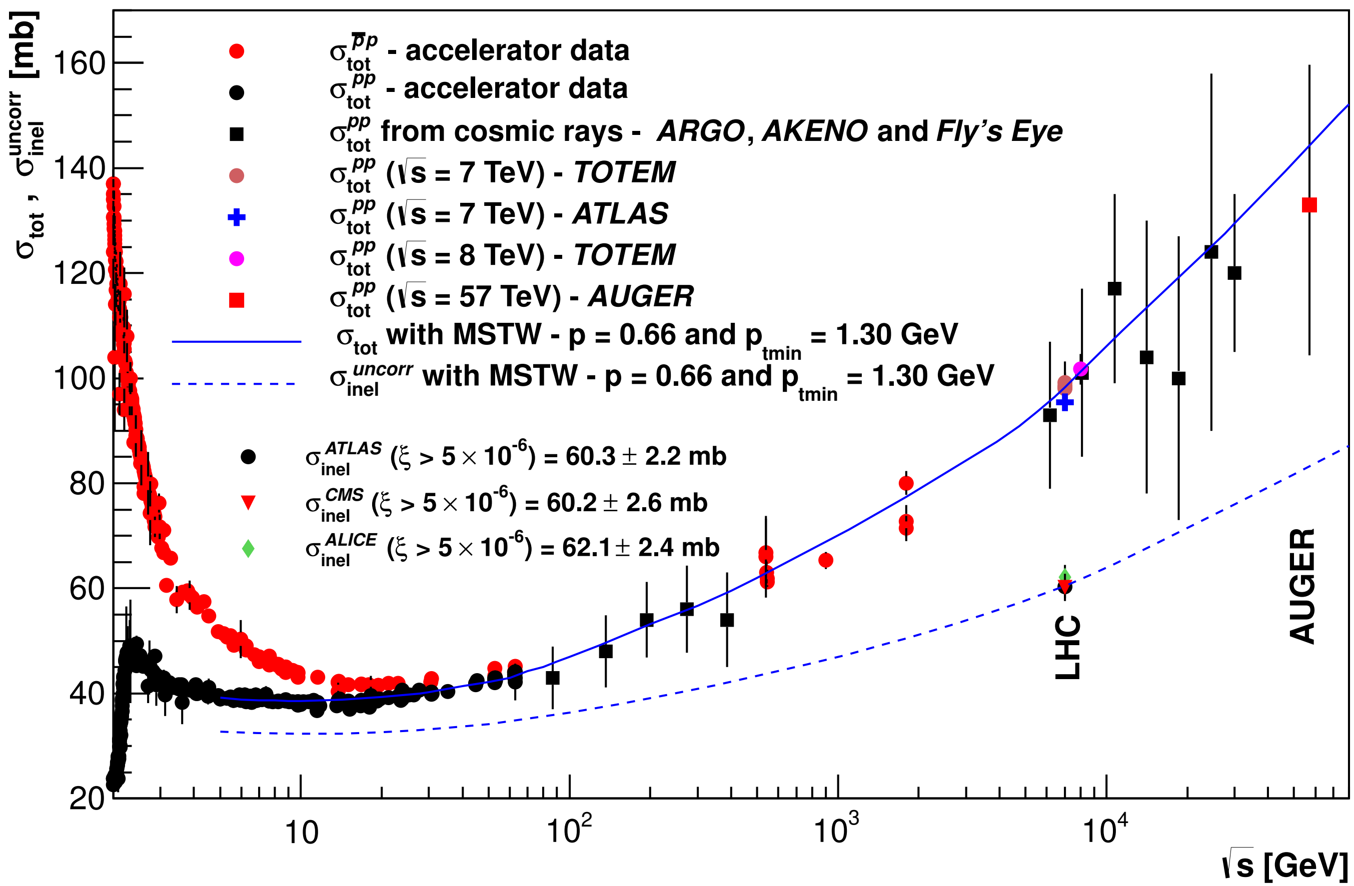



$$\sigma^{pp}_{inel} = \int d^2\mathbf{b}[1 - e^{-2\chi_I(b,s)}]$$

Achilli, Godbole, Grau, GP, Shekhovtsova, Srivastava Phys.Rev. D84 (2011) 094009,

# pp : Updated (after LHC) modeling of total and central inelastic collisions with one-channel eikonal, mini-jet with soft gluon resummation model [arXiv:1408.2921]

MSTW LO densities for mini-jet cross-sections



# Now ... to p-air

$$n_{p-air}(b,s) = T_N(\mathbf{b})\sigma^{\mathbf{pp}}_{\mathbf{inel}}(\mathbf{s})$$

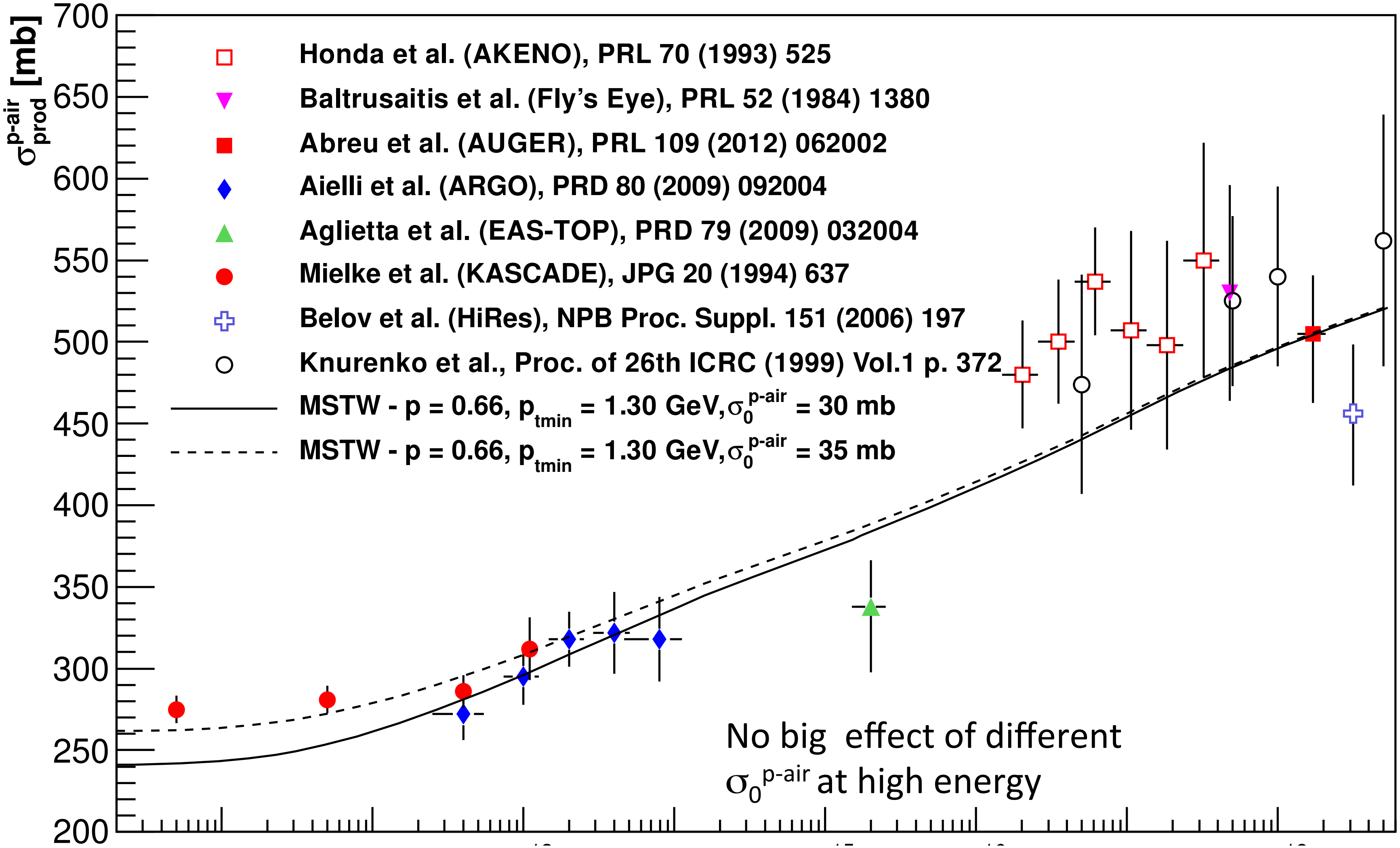
$$T_N(b) = \frac{A}{\pi R_N^2}\mathrm{e}^{-b^2/R_N^2}$$

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

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

$$\sigma^{pp}_{tot} = 2\int d^2\mathbf{b}[1 - \Re e^{i\chi(b,s)}]$$

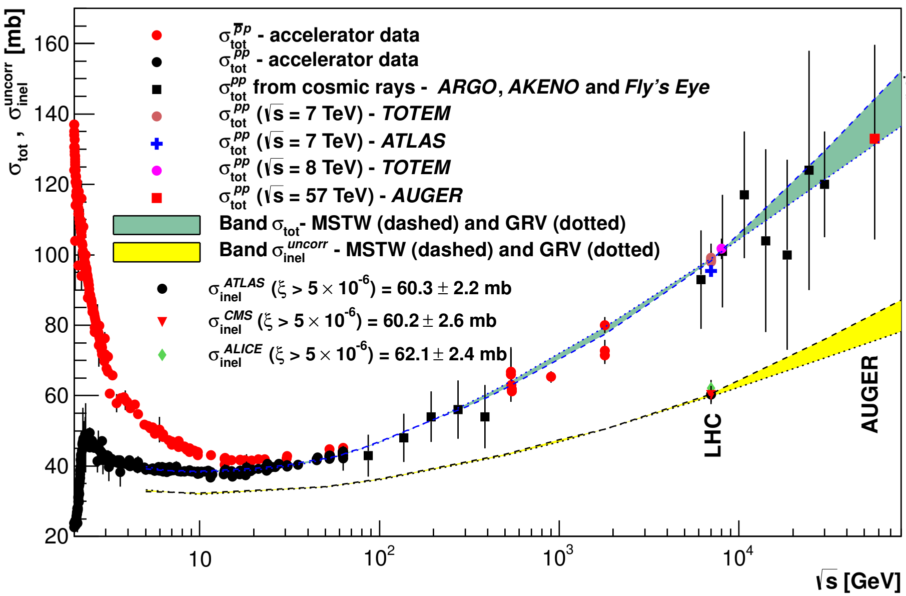
# p-air = Glauber+inelastic pp



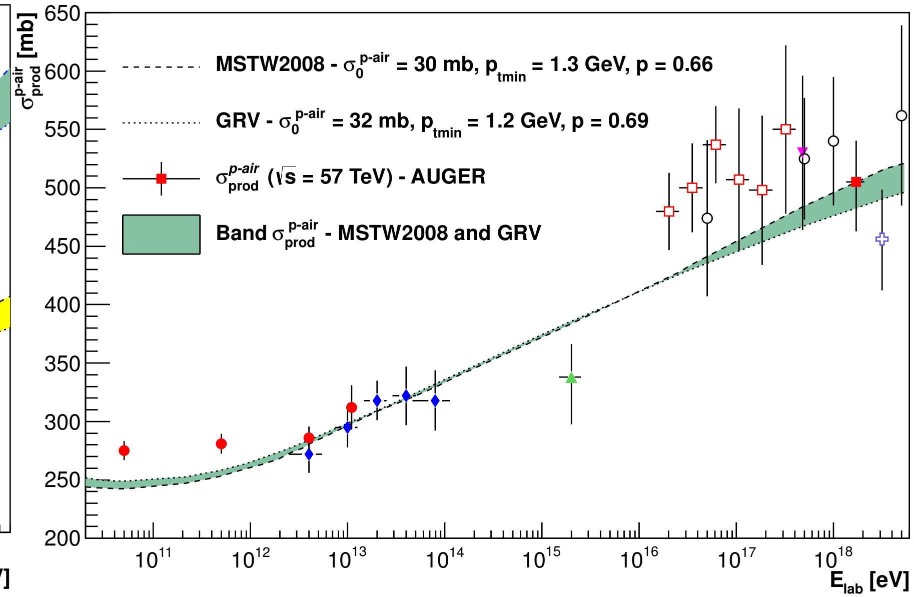

arXiv:1408.2921 with Fagundes, Grau, Srivastava, Shekhovtsova

# From pp total to p-air production: estimating the uncertainty due to PDFs

pp




p-air




Calculation with LO PDFS:

1. GRV
2. MRST72
3. MSTW

Band = uncertainty in PDFs low-x parametrization in GRV or MSTW

# Final comment (before conclusion)

Major differences with most other mini-jet models=>pQCD +explicit NPQCD

**Mini-jet cross-sections**

- We use LO parton-parton cross-sections and current DGLAP evoluted LO parton densities
  - GRV (various versions)
  - MRST72
  - MSTW (new)

- LO because model already includes all order gluon resummation (may be modified in the future)

**Zero $k_t$ gluons resummed**

- Large distance cut-off (Froissart limit-FL) is obtained from resumming very small momentum gluons
- Direct connection to confinement : FL is a manifestation of confinement
  - Need to extend resummation below pQCD cut-off
  - Ansatz for $\alpha_s(k_t)$ with link to confining potential

# Conclusions

- The BN model can be extrapolated up to $\sqrt{s}$ = 50-100 TeV with uncertainty past LHC due to to low-x behaviour of PDFs

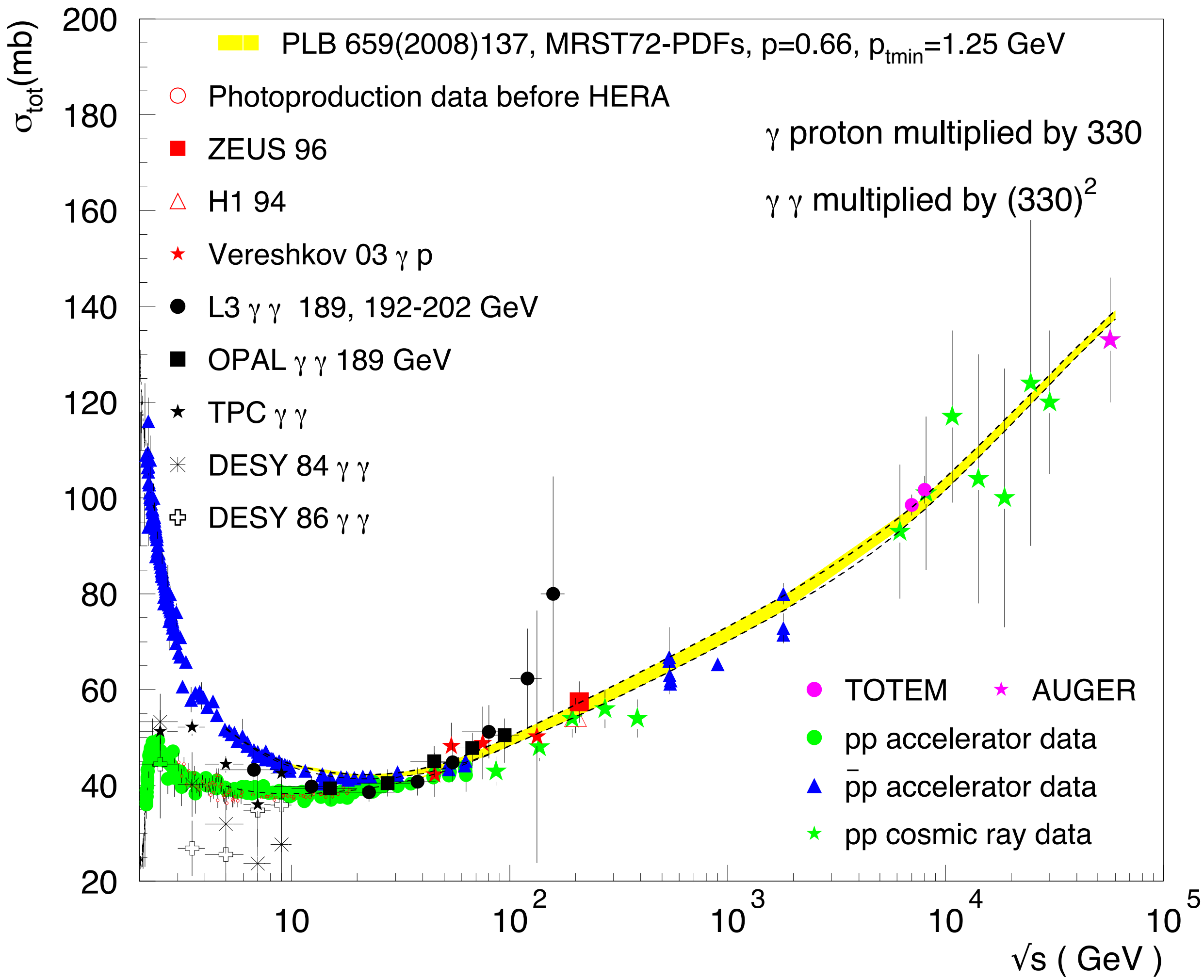
→ pp and $\gamma$p can be explored at CR energies

- The one-channel eikonal gives an inelastic cross-section without the remnants of the proton

→ If you have a single eikonal that fits the total pp cross-section, that eikonal would give the uncorrelated, non diffractive inelastic cross-section which is what is needed for cosmic rays (Bloch, Kopeliovich, etc) without having to break up the total into pieces and then reassemble.

# All total cross-sections rise

Update of EPJC 2009, GP + R.M.Godbole, A. Grau, Y. Srivastava



# All total cross-sections rise… but not too much (Froissart dixit)

OUR Model

**Rise**

Rise driven by low-x gluon-gluon collisions

minijets → $p_t$ >1 GeV

**Saturation**

Acollinearity from ISR soft gluons, $k_t$ resummed, reduces the mini-jet x-section and can lead to saturation

# Lesson from p-air: a defense of one channel eikonal formalism

- In p-air one need the non-diffractive inelastic pp cross-section
- One channel eikonals (OCE) for pp give

sigtot <->siginel-nondiff

Namely they directly give the non-diffractive inelastic input to a Glauber formalism

- Sigtot pp <-> siginel non diffractive without added parameters
- Extrapolation to full phase space is model dependent, but we dpo not need to do it for p-air calculations

Ansatz:

- The multichannel, GW or LL, eikonal formalism is needed for diffraction but at t=0 the amplitude must reduce to just one term, i.e. one-channel formalism

# Our proposal for running $\alpha_s(k_t)$ in the infrared region

$$V_{one\ gluon\ exchange} \sim r^{2p-1}$$

$$\propto k_t^{-2p} \qquad k_t << \Lambda$$

To reconcile with asymptotic Freedom

$$\propto \frac{1}{\log k_t^2/\Lambda^2} \qquad k_t >> \Lambda$$

A phenomenological interpolation

$$\alpha_{eff}(k_t) = \frac{12\pi}{11N_c - 2N_f} \frac{p}{\log[1 + p(k_t/\Lambda_{QCD})^{2p}]}$$

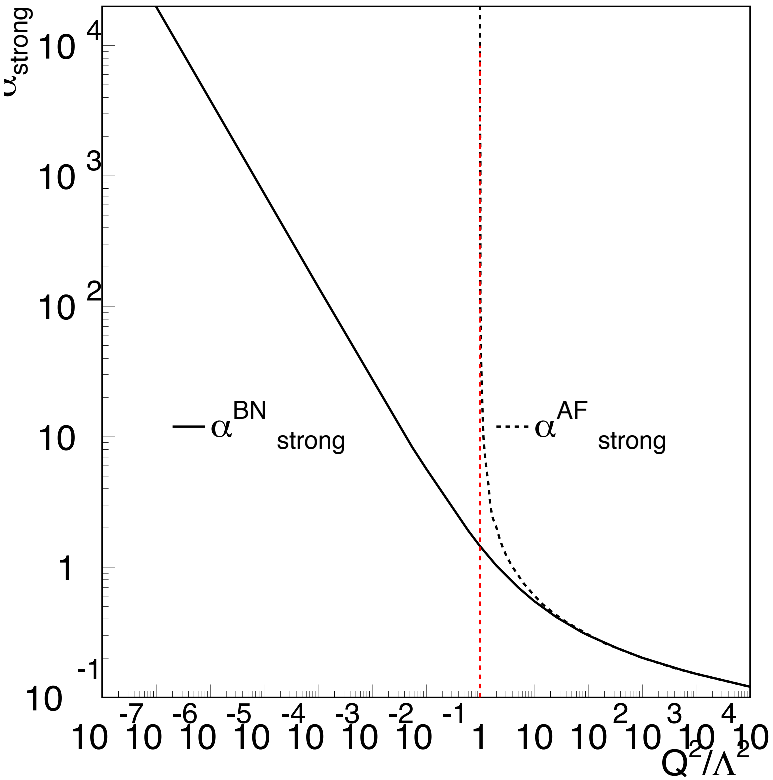
# About our ansatz for $\alpha_s$ in the infrared

- The expression we use

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

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

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



In our model, the emission of singular infrared gluons tames low-x gluon-gluon scattering ( mini-jets) and restores the Froissart bound

$s^{\varepsilon}$

$$\sigma_{tot}(s) \approx 2\pi \int_0^{\infty} db^2 [1 - e^{-C(s) e^{-(b\bar{\Lambda})^{2p}}}]$$

$$\sigma_{tot}(s) \rightarrow [\varepsilon \ln(s)]^{(1/p)}$$

$$\frac{1}{2} < p < 1$$

Grau, Godbole,GP,Srivastava,PLB682 2009

# The actual calculation

# Our QCD model for the total cross-section
## R. Godbole, A. Grau, GP, YN Srivastava

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

$$2\chi_I(b,s) = \sigma_{soft} + A(b,s)\sigma_{jet}$$

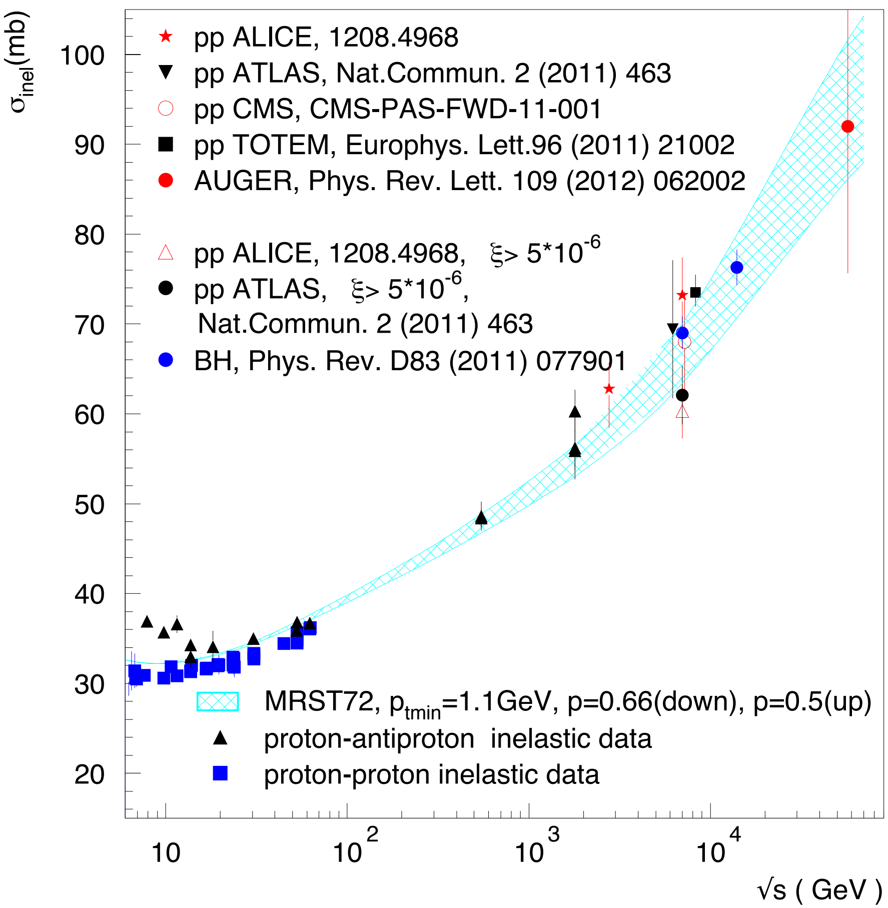
- Minijets to drive the rise
- Soft kt-resummation to tame the rise and introduce the cut-off needed to satisfy theFroissart bound

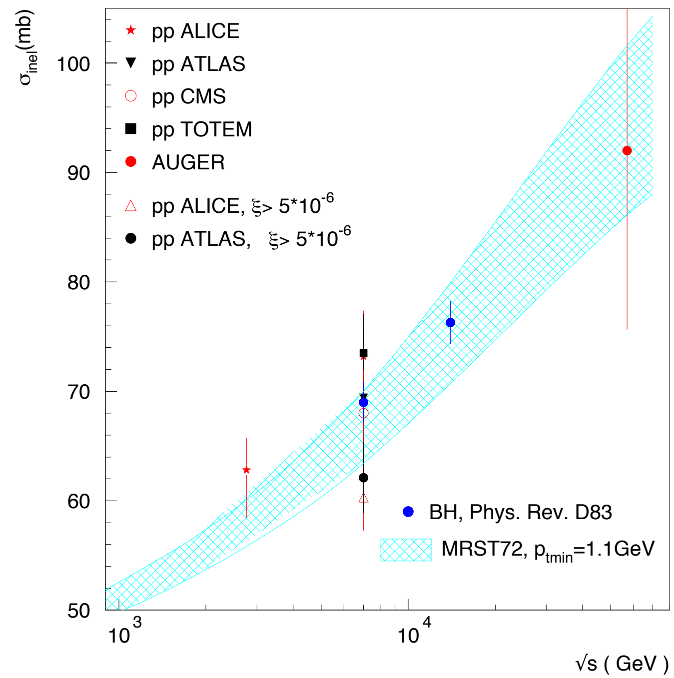
- Phenomenological singular but integrable soft gluon coupling to relate confinement with the rise
- Interpolation between soft and asymptotic freedom region

PLB1996-PRD2005

# Update of PRD2012 analysis

With Olga Shekhovtsova




Why the uncertainty in the inelastic? Models for diffraction

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$

- Elastic cross-section: *pp* amplitude $-t \neq 0$

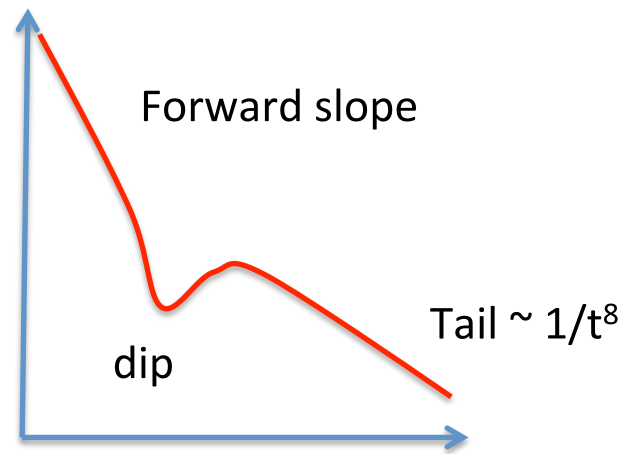
  well defined both theoretically and experimentally

$$\int_0^\infty dt\{[\Im m\mathcal{A}(s,t)]^2 + [\Re e\mathcal{A}(s,t)]^2\}$$

- Inelastic : what is not elastic!!! Yes, but not so simple, diffractive, central, large mass,small mass

# The one eikonal does not work

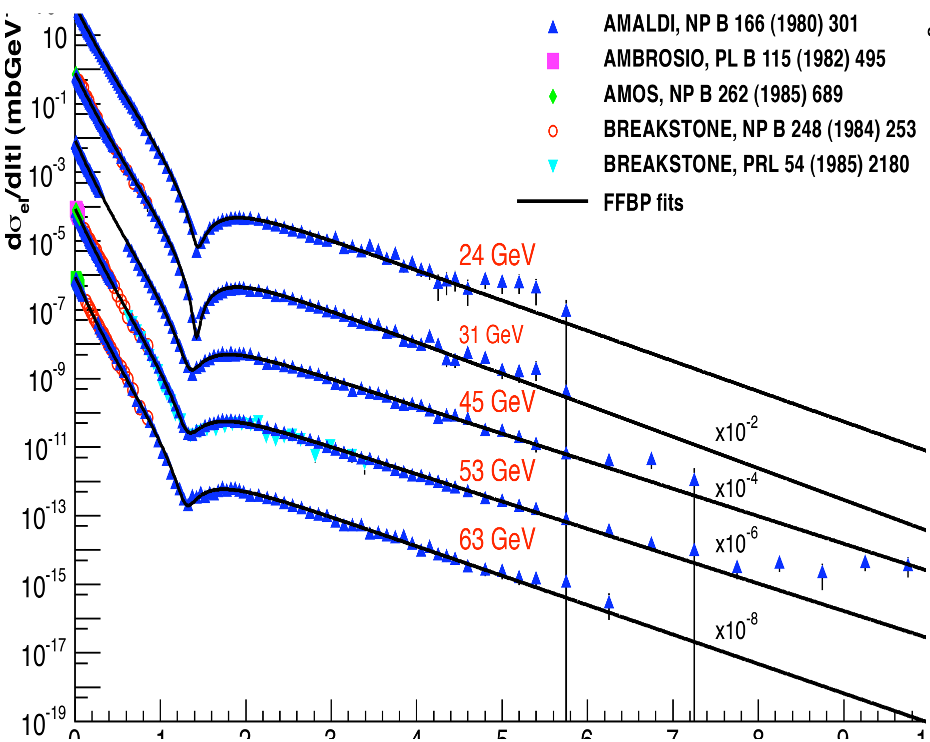
- Optical point : total cross-section
- Forward slope? Regge?
- The dip? ??
- The tail?  3 gluons perhaps



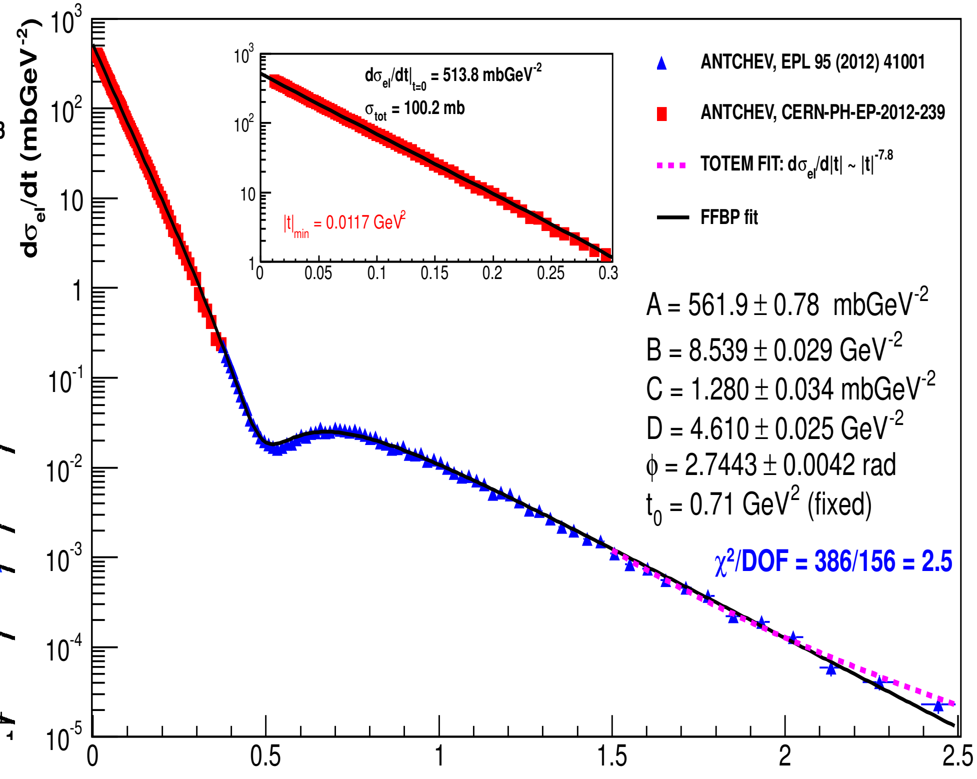

Resort to an EMPIRICAL MODEL to try to understand the building blocks

# BP model with Proton Form Factor

## ISR for pp




## TOTEM LHC7 for pp




Fagundes, Grau, GP, Srivastava PRD 2013

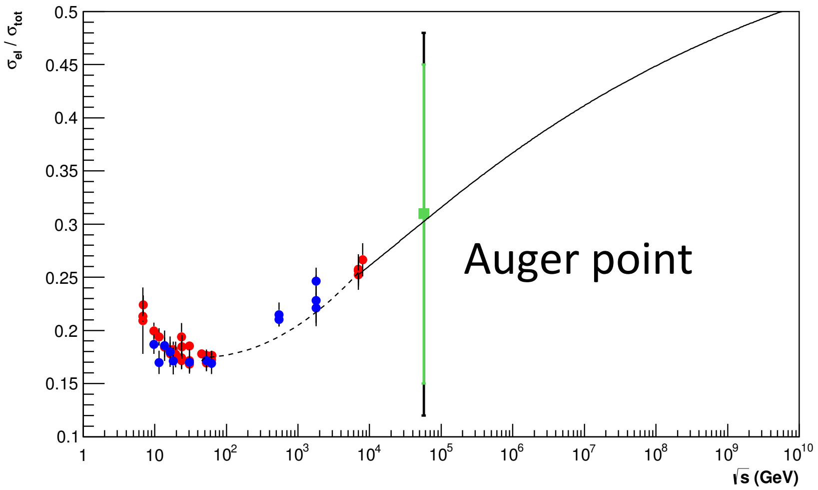
# A lesson from the empirical model

- The black disk limit is very far away

$$\sigma_{total}^{blackdisk} = 2\pi R^2(s)$$

$$\sigma_{elastic}^{blackdisk} = \pi R^2(s)$$

$$\mathcal{R}(s) = \frac{\sigma_{elastic}}{\sigma_{total}} \neq \frac{1}{2}$$



# State-of-the-art of total cross-section : before LHC and AUGER

1973
Barger

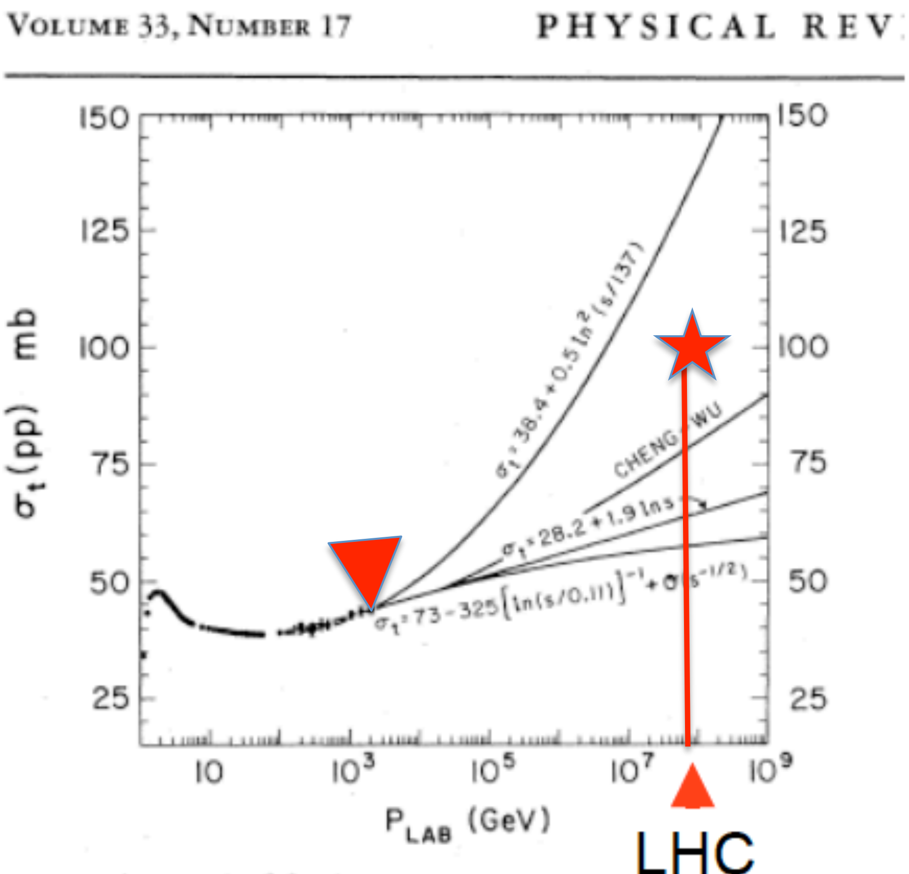
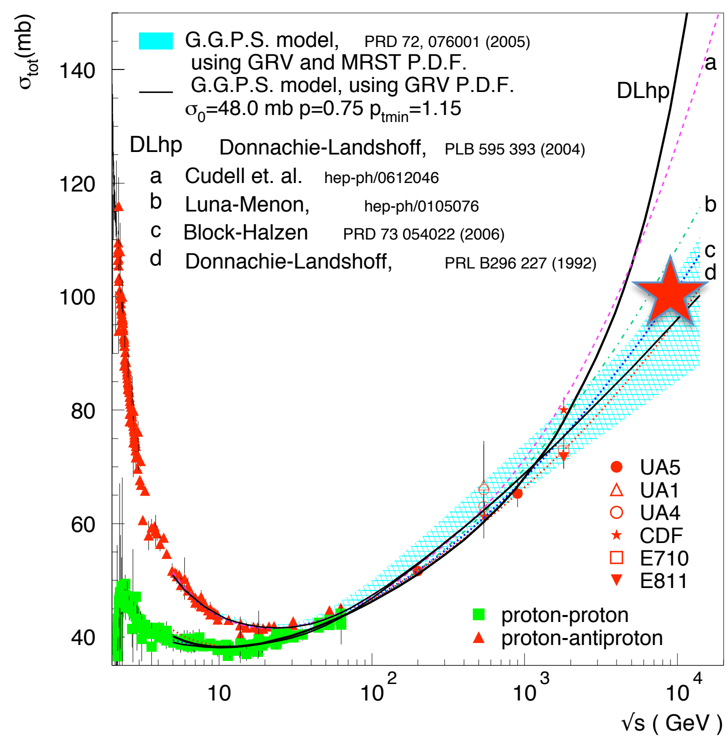



FIG. 1. Typical high-energy model extrapolations of the proton-proton total cross section to the energy range accessible to extensive-air-shower experiments.

2008, PLB, GP etc.



# About the inelastic

- Inelastic=central+diffraction
- One-channel eikonals which describe sigmatotal fail to give the full contribution including diffraction
- GW mechanism-> multichannel eikonals, continuous distributions, etc. -> diffraction can be included through more parametrs and various modeling
- For sigma p-air we do not need diffraction