Total cross-sections at LHC and cosmic ray energies

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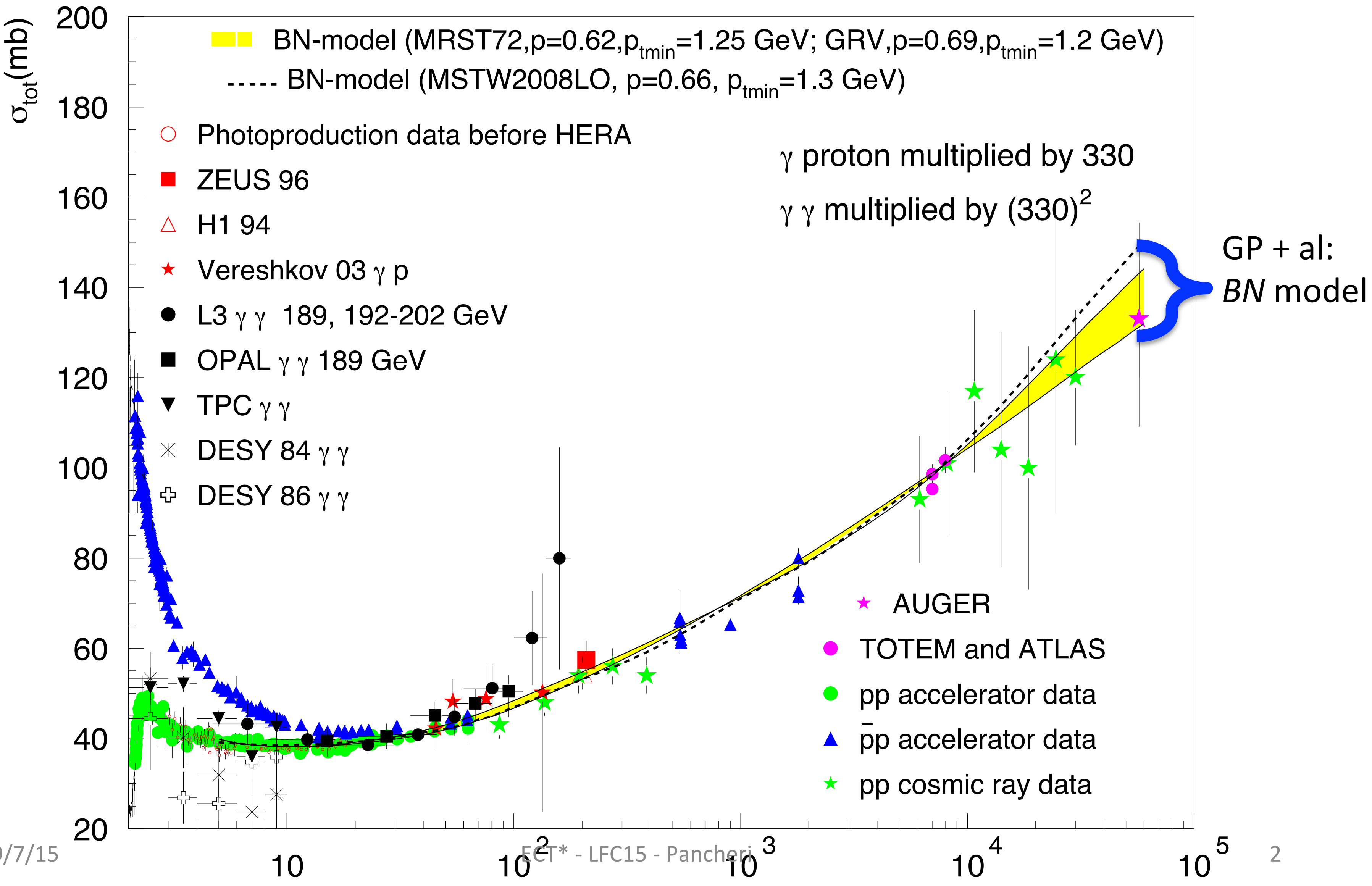
Present status of total cross-section data

EPJH2009, updated by A. Grau, 2015



Of notice

- In pp and $p\bar{p}$
  - The shape with an apparent minimum
  - The rise
  - The softening of the rise
- In γp and $\gamma\gamma$
  - Lack of high energy data
  - Apparent stronger rise, especially in gamma gamma

Questions to address:

1. What does one learn from
   - Present models

   vs

   - Accelerator data : most models accommodate new data just by changing the parameters (a little bit…)
   - Cosmic ray data : large uncertainties on pp from data extraction

2. Which machines and experiments can give new information to move ahead with models and get understanding of the underlying dynamics?

A long history of Models

- Heisenberg with pion cloud – 1952 $constant \quad or \quad [\ln s]^2$

Optical theorem + Regge behaviour

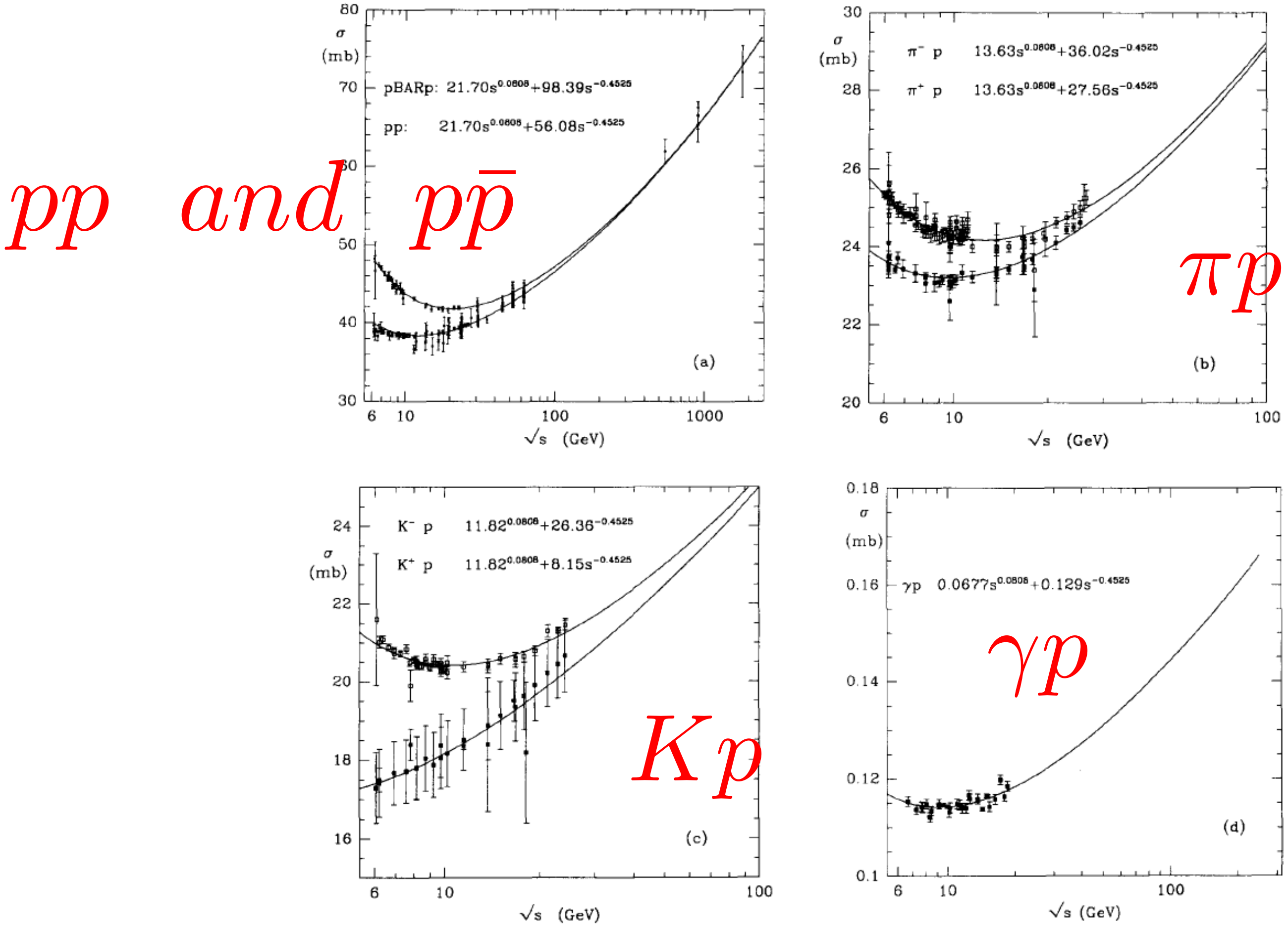
- Regge exchanges -> $s^{-\eta}$ $\quad -\eta = \alpha_R(t=0) - 1 < 0$
  decreasing before ISR (1972) $\quad for \;\; Regge \; poles$

- Pomeron exchange -> $s^{+\epsilon}$ $\quad \epsilon = \alpha_P(t=0) - 1 \geq 0$
  constant or rising after ISR $\quad for \;\; Pomeron$
  (and cosmic rays ~ 1970)

- Regge + Pomeron for everybody - in 1992 $\quad X s^{-\eta} + Y s^{+\epsilon}$

Regge+Pomeron and common early rise of all total cross - sections :

$$X s^{-\eta} + Y s^{+\epsilon}$$ Donnachie and Landshoff 1992



But a power law contraddicts the Froissart bound

If the cross-section rises, it cannot rise too much

WHY?

- Because of the asymptotics of the Froissart bound

i.e.

- Because of confinement....

Basic fact: All total cross-sections rise… but not too much (Froissart dixit in 1961 + Martin 1962+Lukaszuk 1967)

Asymptotically

$$\sigma_{tot} \lesssim \sum_{0,L} \simeq L^2_{max}$$

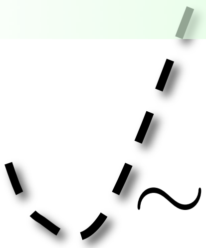
$$L_{max} = q b_{max} \sim \log s$$

$$\longrightarrow \sigma_{total} \lesssim [\log s]^2$$

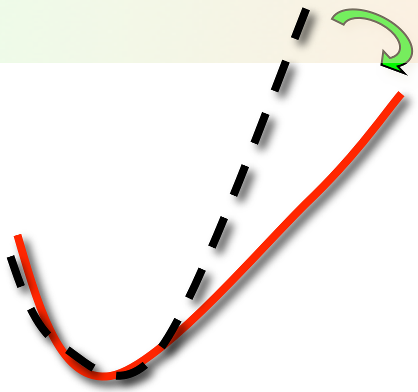
What generates the rise, which is very fast at the start (ISR)?

What tames the rise into a Froissart-like behavior?

How to go from a power-law to log s ?



$\sim s^{0.1}$



Minijets and the **rise** for √s ≈ 20 GeV

pQCD

- asymptotic freedom regime

$$\alpha_s(p_t) \to \alpha_{AF} = \frac{b_0}{\ln[p_t^2/\Lambda_{QCD}^2]}$$

$p_t >> \Lambda_{QCD} \qquad p_t \simeq 1\ GeV$

$p_t \geq p_{tmin}$

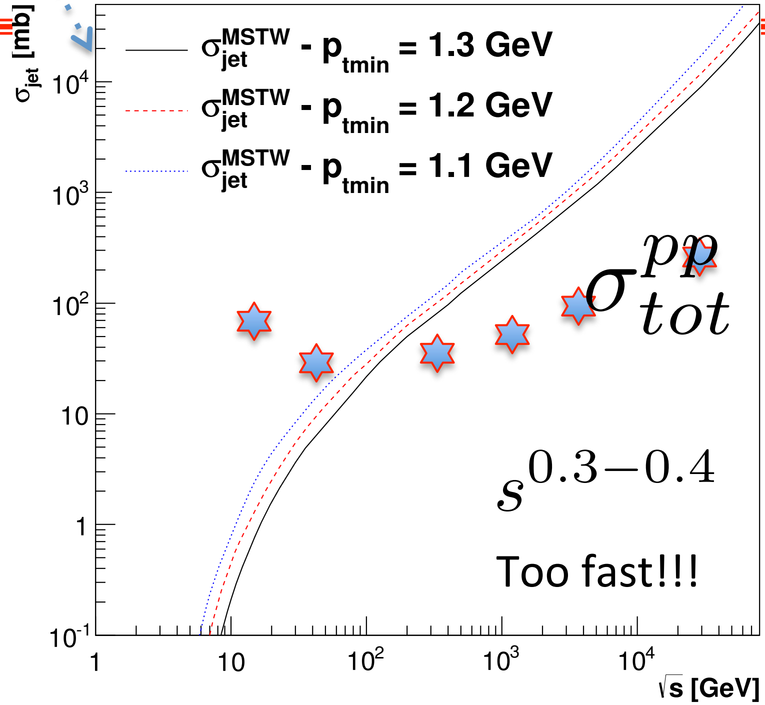
- parton-parton scattering with final parton

$f(x) \sim 1/x \qquad x \geq 2p_{tmin}/\sqrt{s}$

$x \leq 0.1 - 0.2 \quad and \quad \downarrow \quad \sigma_{mini-jet} \uparrow$

$$\sqrt{s} \gtrsim 10 - 20\ GeV$$

$$\sigma_{\rm jet}^{AB} = \int_{ptmin}^{\sqrt{s}/2} dp_t \int_{4p_t^2/s}^{1} dx_1 \int_{4p_t^2/(x_1 s)}^{1} dx_2 \sum_{i,j,k,l} f_{i|A}(x_1, p_t^2) f_{j|B}(x_2, p_t^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_t}$$



GP et al. , 1504.04890, PRD91 (2015)

How to generate a cut-off in b-space, asa confinement?

- Heisenberg 1952 shock wave model, cut off in b-space determined by the extension of the pion cloud

$$\sigma_{total} \simeq \frac{\pi}{m_\pi^2}(\ln \frac{\sqrt{s}}{< E_0 >})^2$$

$$< E_0 >\simeq constant \quad \sigma_{tot} \sim [\ln s]^2$$
$$< E_0 >\simeq \ln s \quad \sigma \simeq constant$$

- Form factors (most commonly used, early mini-jet models 1984-85), soft Pomeron models, etc.

- Resummation with singularity confinement in a eikonalized minijet model (GP et al. model, *Bloch-Nordsieck(BN model*)

Eikonal Formulation implements unitarity and impact parameter space

One-channel eikonal
$$\sigma_{total}(s) = 2\int d^2b[1 - \Re e^{i\chi(b,s)}]$$
$$\simeq \int d^2b[1 - e^{-\Im m\chi(b,s)}]$$
$$\sigma_{elastic}(s) = \int d^2b|1 - e^{i\chi(b,s)}|^2$$
$$\sigma_{inel} = \sigma_{total} - \sigma_{elastic} = \int d^2b[1 - e^{-2\Im m\chi(b,s)}]$$

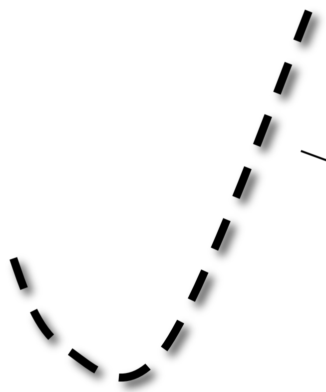
Two channel eikonals : $|p> = c_1|p_1> + c_2|p_2>$

Or also 3 states, continuous distributions, etc.

Mini-jet models : All total cross-sections rise… but not too much (Froissart dixit)

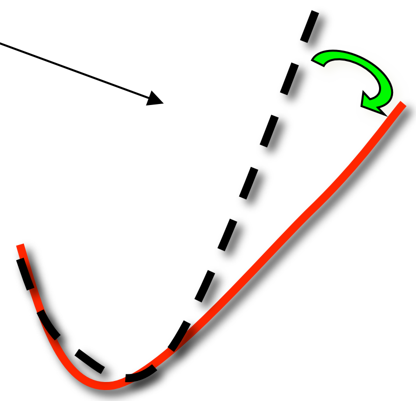
What generates the rise? Low-x parton collisions

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



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

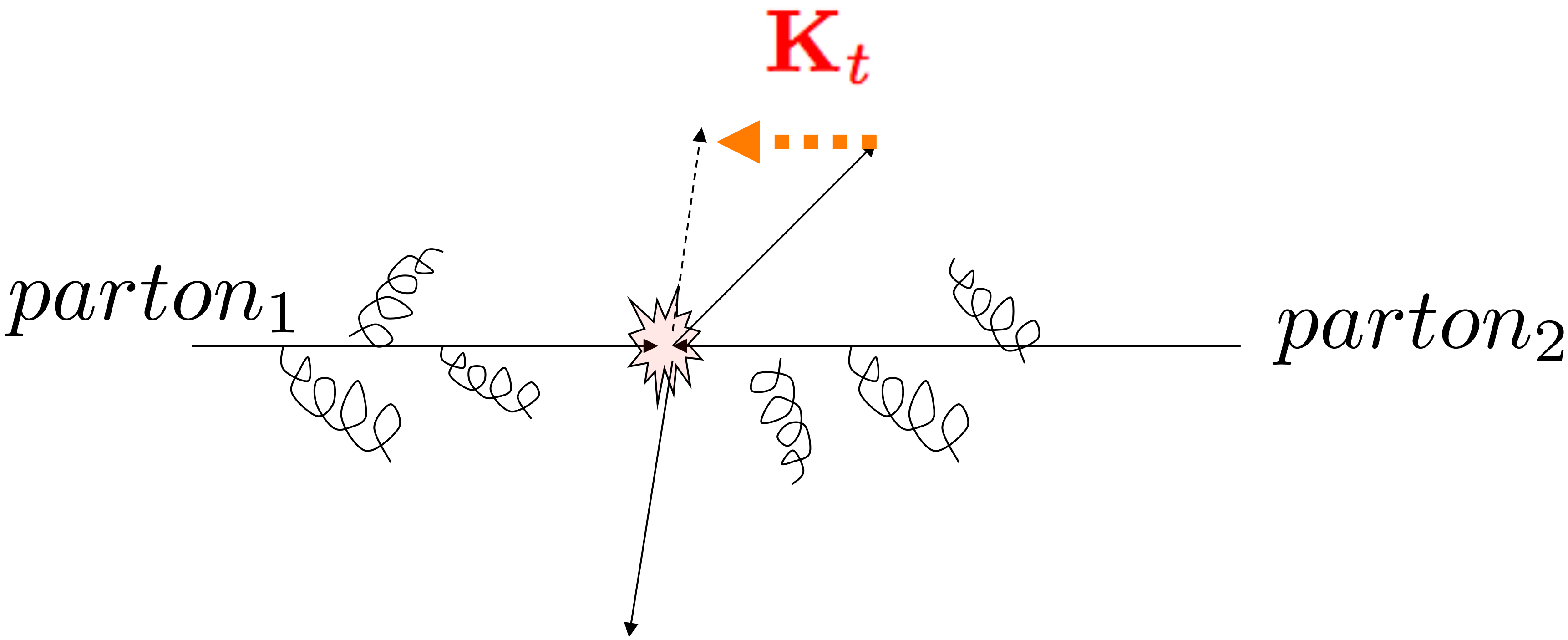
How to go from
hard to soft ?



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, PRD1999, PRD2005**]

Mini-jets alone rise too fast: we introduce soft gluon emission to induce acollinearity and soften the rise



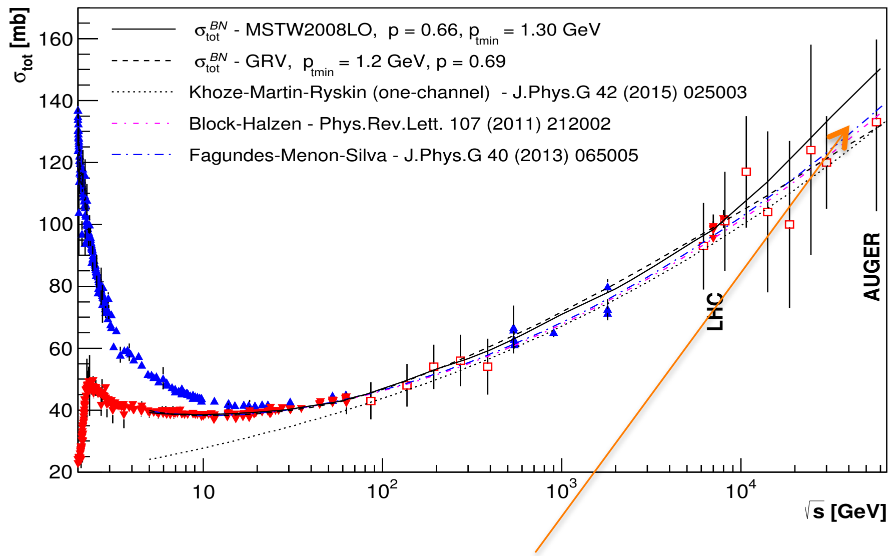
- Acollinearity reduces the collision cross-section as
- partons do not scatter head-on any more, also explained as the gluon cloud

Is becoming too thick for partons to see each other : gluon saturation

Models which include unitarity

ALL MODELS HAVE SOME FREE PARAMETERS – also by fitting the elastic x-section

- Eikonal + black disk ~ 1967
- Eikonal + Pomeron(s) ~ 1980->
- QCD Mini-jets ~1985
- Eikonal + QCD minijets ~1987
- Eikonal+minijets+resummation (ours) 1996->
- Two, three or more channels eikonals (to deal with diffraction) , i.e
  - Khoze, Martin,Ryskin
  - Gotsman,Levin,Maor,
  - Ostapchenko…



There are also FITS, i.e. Block and Halzen, up to $[\ln s]^2$

Parameters are also needed for other components $pp \to X$

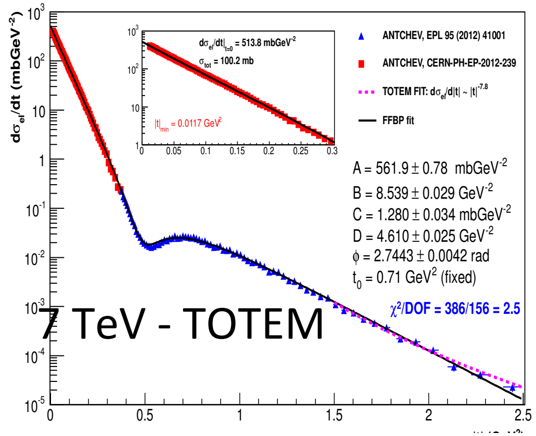
$$\sigma_{elastic} = \int_{-\infty}^{0} dt \frac{d\sigma_{el}}{dt}$$

Elastic pp-> pp

- Differential elastic
  - Optical point: $[\Im m\mathcal{A}(s,t=0)]^2 \propto [\sigma_{tot}]^2$
  - Forward peak:

    $e^{B(s,t=0)t} \quad for \quad -t \sim 0$
  - Dip and bump: diffractive spectrum? pQCD components

1. Large |t| tail : only a tail or other kinks?



- Inelastic *pp->X*
  - Exp. Definition complicated by cuts
  - Theoretical calculation still under clouds

HIC SUNT LEONES...

Eikonal + Regge: an example from Khoze, Martin, Ryskin(KMR)

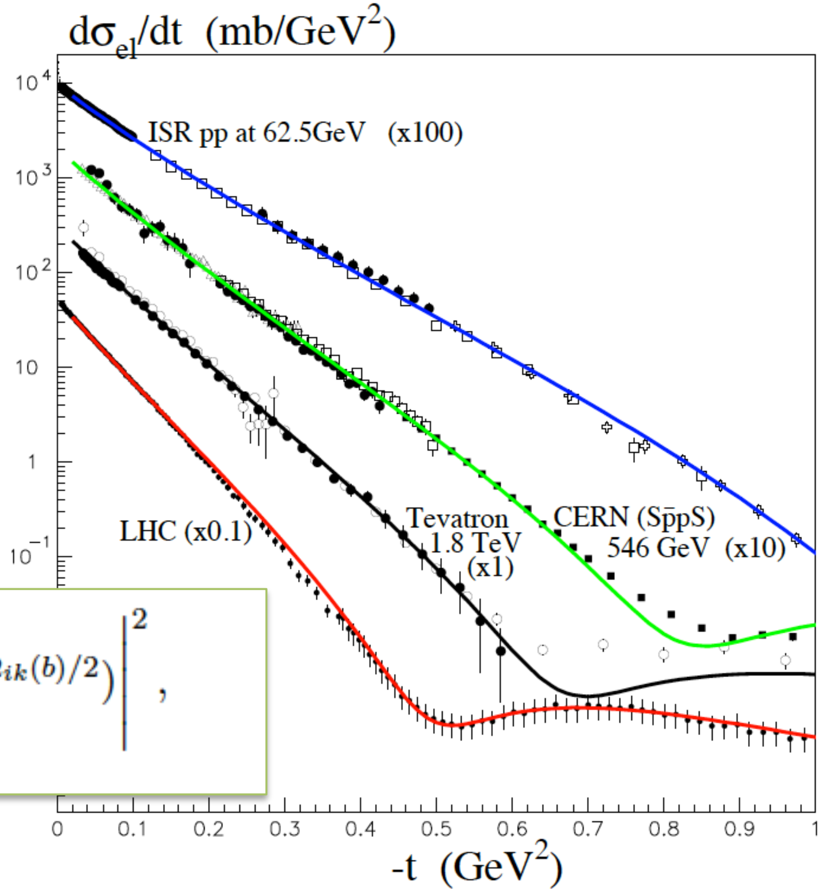
One channel

$$T_{el}(b,s) = i[1 - e^{-\Omega(b,s)/2}]$$

$$\Omega(b,s) = \int \frac{d^2 q_t}{4\pi^2} \sigma_0 F^2(q_t) [s/s_0]^{\alpha_P(t)-1}$$

Two or more channels, a' la Good and Walker

$$\frac{d\sigma_{\rm el}}{dt} = \frac{1}{4\pi} \left| \int d^2b \; e^{i\boldsymbol{q_t}\cdot\boldsymbol{b}} \sum_{i,k} |a_i|^2 |a_k|^2 \; (1 - e^{-\Omega_{ik}(b)/2}) \right|^2 ,$$



Eur.Phys.J. C74, 2756 (2014), arXiv:1312.3851

Eikonal models

- Eikonal function built through Regge and Pomeron exchanges allows good overall phenomenological description of
  - Total, elastic, differential , Diffractive

  BUT connection to phenomenology of pQCD (PDFs) not fully evident nor to confinement (usually avoiding the infrared)

- Mini-jet exchanges have clear pQCD origin, which can
  - drive the high energy behaviour of the eikonal, include resummation in a natural way (as QCD radiative corrections to parton-parton scattering), an be used in MC's or analytical calculations using parton standard PDFs,

  BUT have problems with good description of differential elastic and diffraction (need extens. to more channels)

The inelastic cross-section shows the limitations of the one-channel eikonals

- Basic definition

$$\sigma_{total} = \sigma_{elastic} + everything\ else$$

$$\sigma_{inelastic}$$

- Experimentally : since forward (-t≈0), one needs to make cuts => measurement depends on cuts and extrapolations from central regions

- Theoretically : consensus on there being different regimes in central region and “diffraction “region, but separation is ill defined

The inelastic pp cross-section

One channel eikonal models split elastic and inelastic in the wrong way

$$\sigma_{inel}^{one-channel} = \int d^2\mathbf{b}[1 - e^{-\Im m\chi(b,s)}]$$

And sum only uncorrelated events

The uncorrelated part of the inelastic

[Achilli et al., G.P., … PRD 2011, D.A. Fagundes, A. Grau, G. Pancheri, Y.N. Srivastava and O. Shekhovtsova, Phys. Rev., D91, 114011 (2015).

Uncorrelated independent events Poisson distributed in b-space

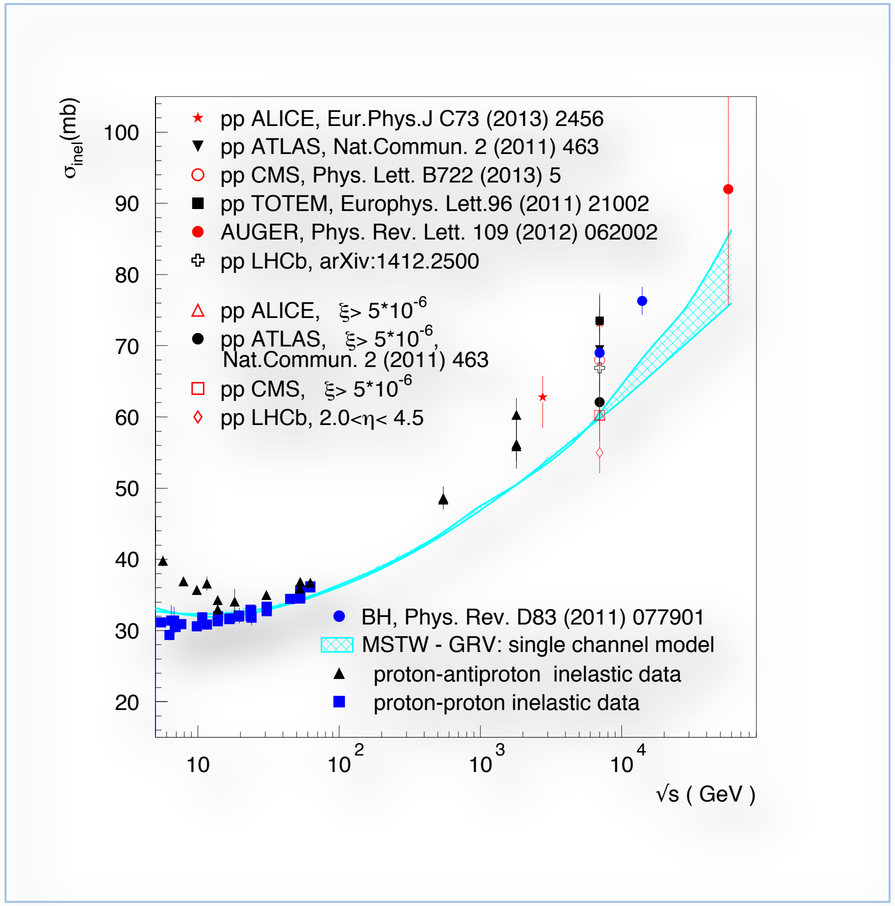
$$\Pi_n(\bar{n}) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

$$\sum_{1,\infty} \Pi_n = 1 - e^{-\bar{n}(b,s)}$$

$$\sigma_{inel}^{uncorrelated}(s) =$$

$$\int d^2b\ \Pi_n(\bar{n}) =$$

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

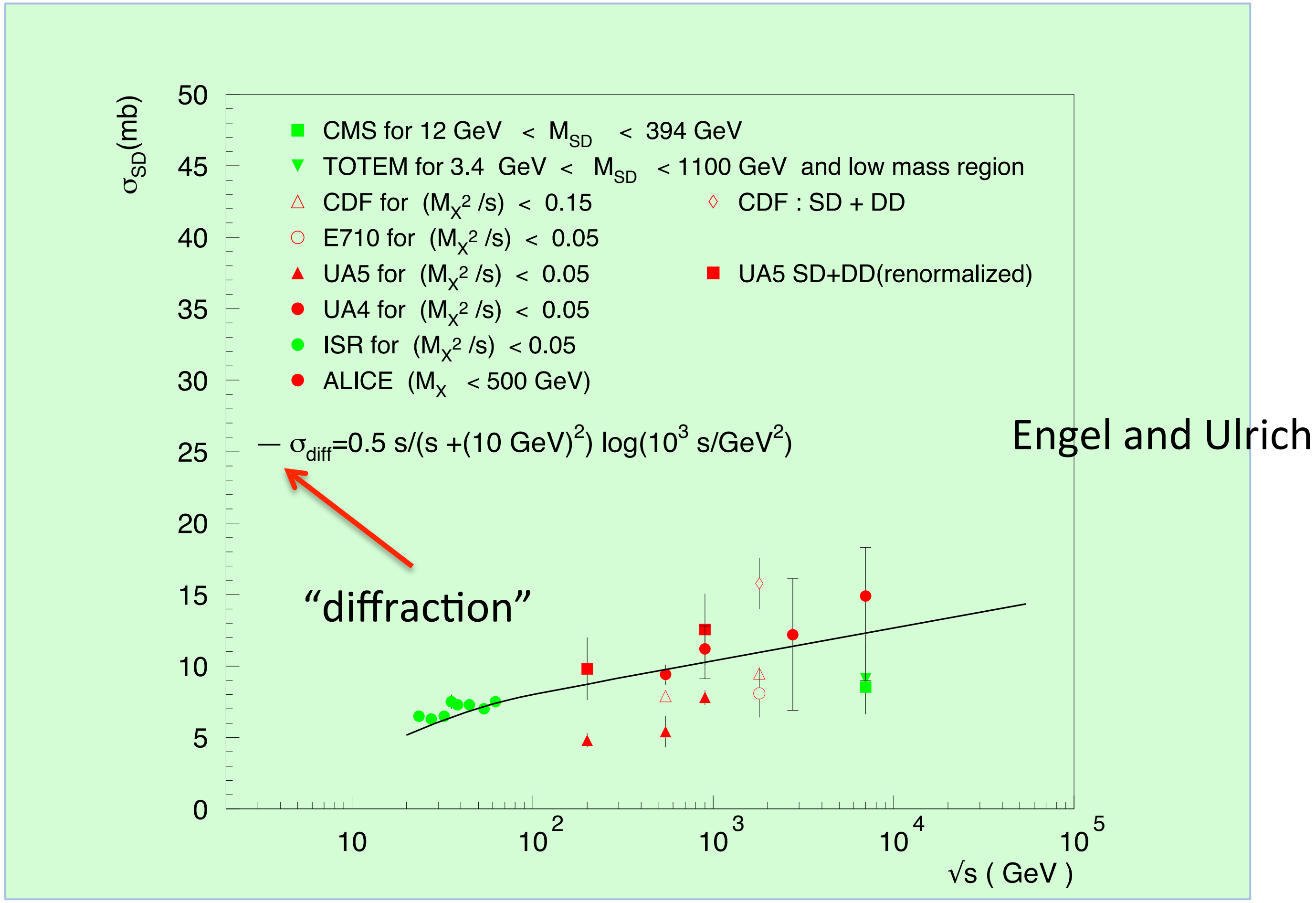


$$\bar{n}(b,s) \to \chi_I(b,s)/2$$

A check that one-channel eikonals give only uncorrelated processes:

1. Parametrize diffraction at high energy from

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

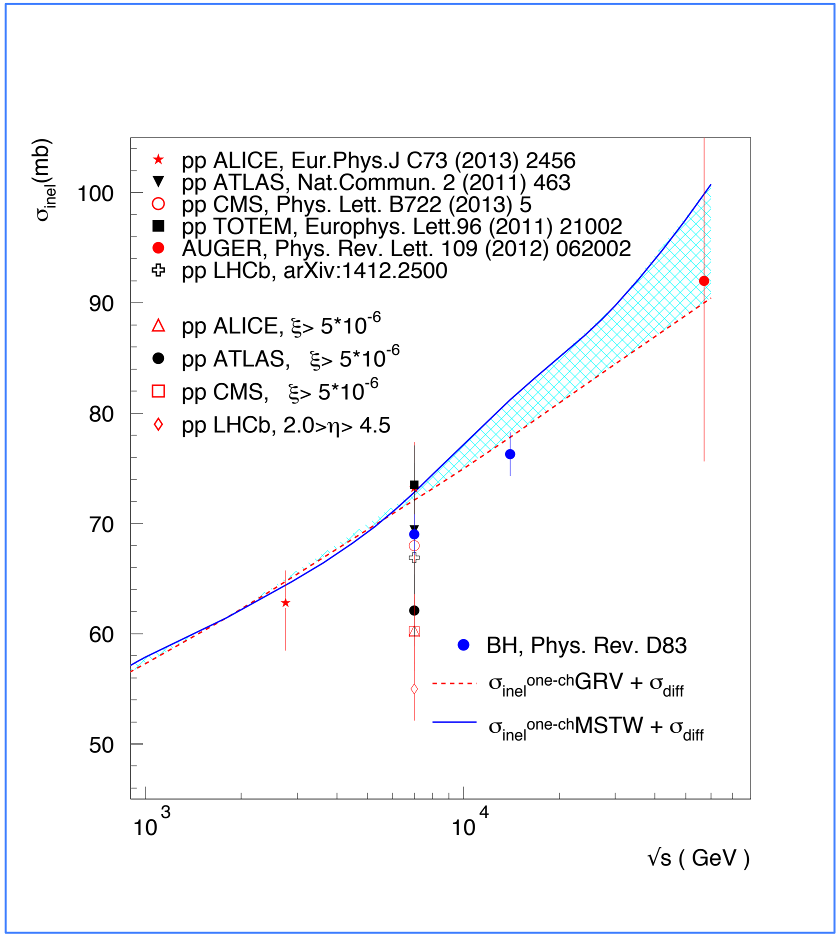


A check that one-channel eikonals give only uncorrelated processes:

2. uncorrelated (one channel) + "diffraction"

The high energy part
Now ok with data

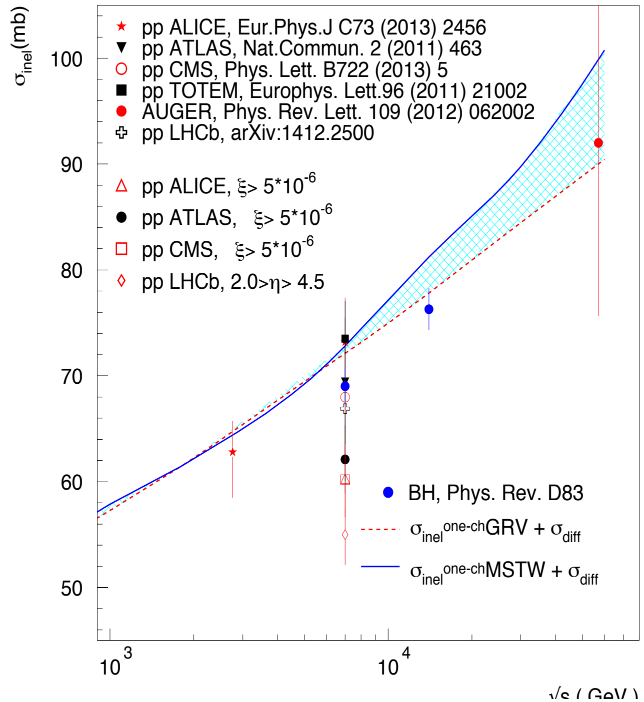
(Problems still at low energy)



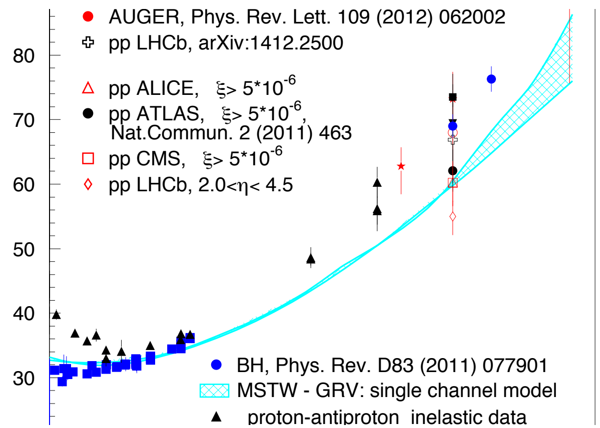
What are learning from this exercise?

Parametrizing diffraction (as shown) + one-channel for uncorrelated Poisson distributed collisions

=> Constructs total inelastic at high energy



⇒ identifies the non-diffractive high energy component in inelastic cross-section



⇒ It can be used for cosmic ray extraction of pp x-section

Where to go to see whether aymptotia has been reached…?

- LHC at higher cm energies

- pp extracted from

  p-air

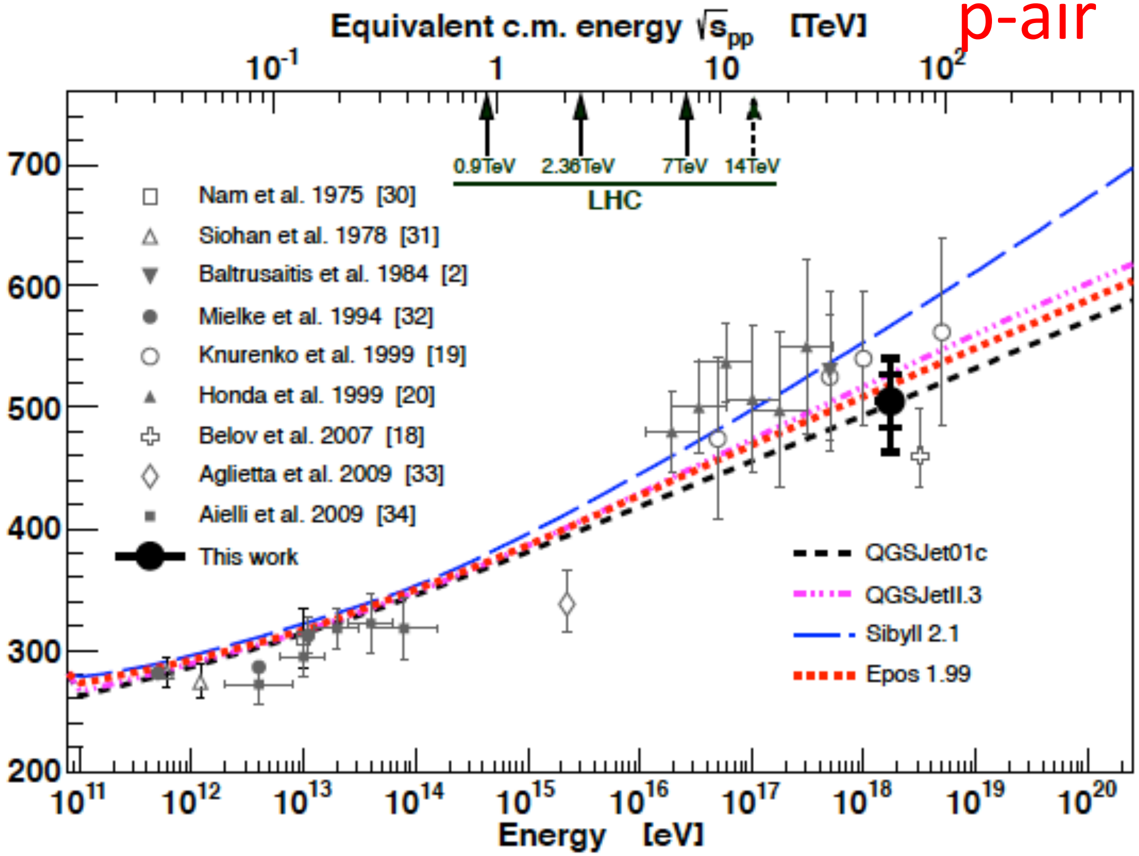
  – Presently AUGER

$$\sqrt{s} = 57\ GeV$$

  – Possibly

$$\sqrt{s} \to 100\ GeV$$

p-air



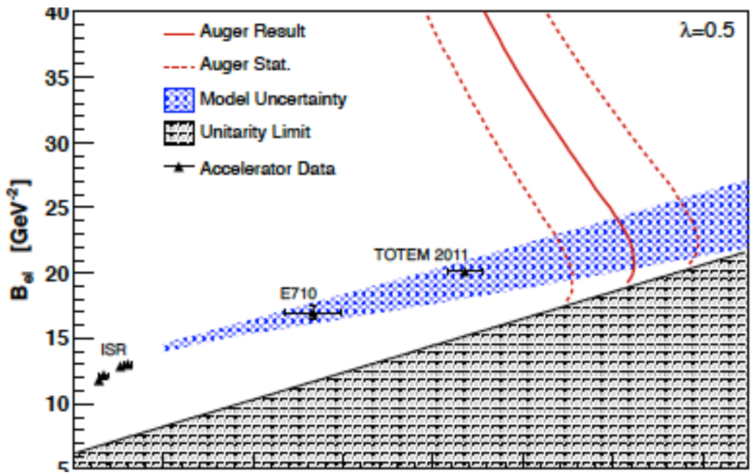
AUGER 2012

Higher energies: cosmic rays

Extraction of pp has large systematic errors

$$\sigma_{inel}^{pp} = [92 \pm 7stat^{+9}_{-11}(sys) \pm 7(Glauber)]mb$$

$$\sigma_{tot}^{pp} = [133 \pm 13stat^{+17}_{-20}(sys) \pm 16(Glauber)]mb$$

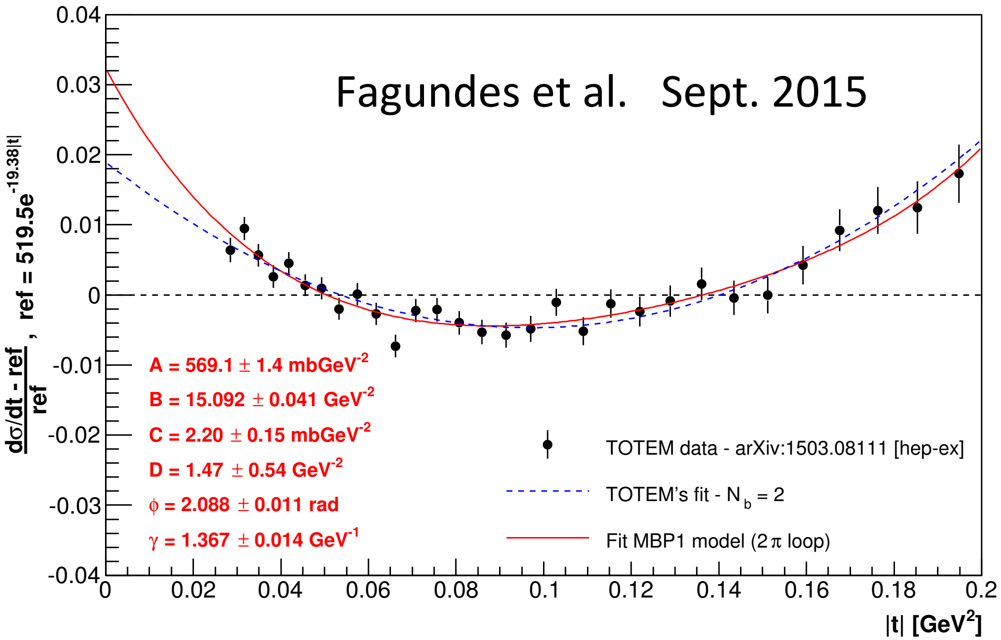


p-air- > pp sigma inelastic
-> total for pp is obtained
using correlations between

- The forward slope B(s,t=0)
- sigma total

2015 Totem results on the forward slope cast more errors on cosmic extraction of pp total

$$\frac{d\sigma_{el}}{dt} = \frac{\sigma_{tot}^2}{16\pi} e^{B(s,t=0)t} \qquad -t \simeq 0$$



DOUBTS on forward slope…

TOTEM Nucl. Phys. B 899 (2015)

Comparison of data – with expression with one slope

The slope changes even below –t=0.2 GeV^2

Gamma p

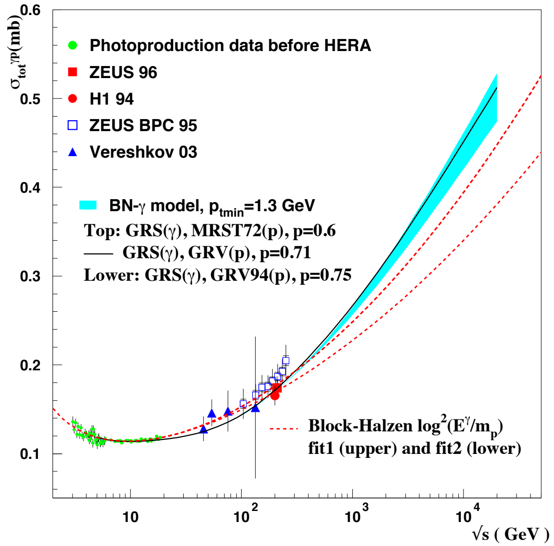
- Data only up to 200 GeV cm

But it is an important process

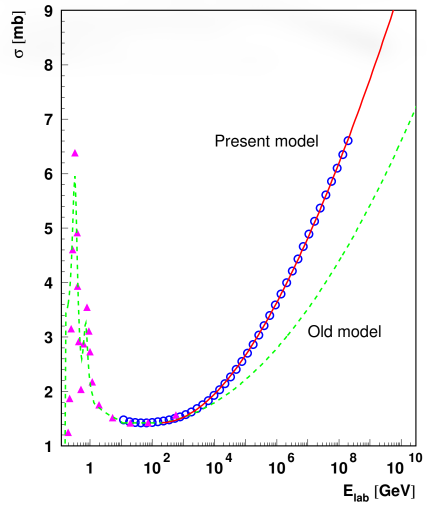
- to check different models (R-P, multichannel, dipole, Froissart analytic amplitude models)

- Theoretically to explore small-x in hadronic part of the photon through minijet models

- for simulations in photo-nuclear processes in cosmic rays

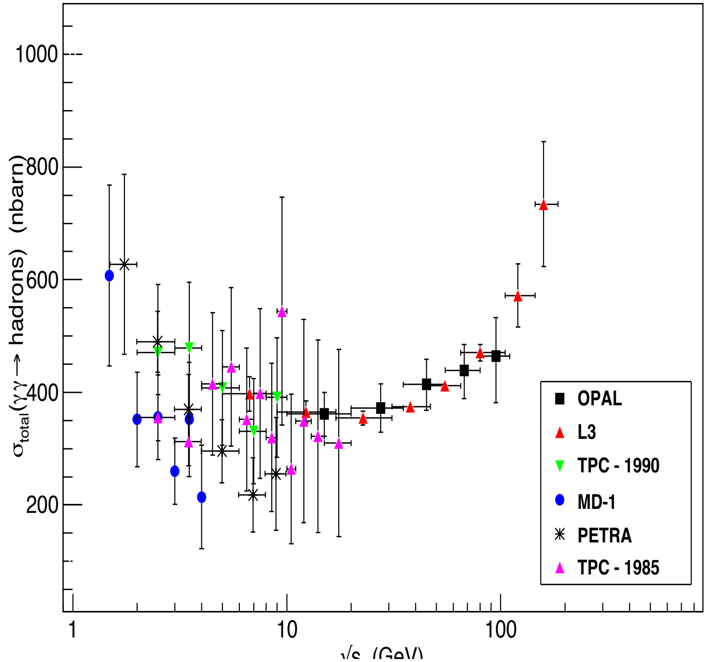


GP et al., arXiv:1411.5158



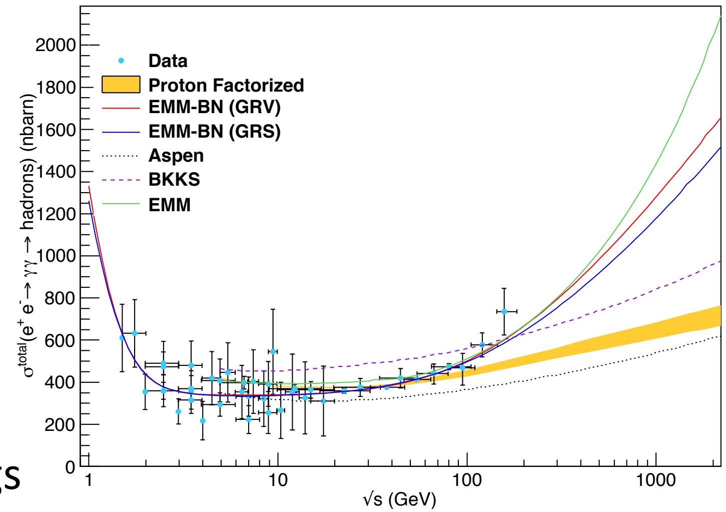
Additional info?: $\gamma\gamma$

- Data from e+e- only up to 189 GeV



- Available densities for mini-jet models: old

- Check of models at high energy: difficult



- Can pp =>$\gamma\gamma + X$ help at LHC?

With R. Godbole, LC2011 Proceedings

Finale: for total cross-section studies

- γp from LHC and e-p possibly?
- $\gamma\gamma$ from LHC, e-p and electron colliders
- => pp
  - higher energy data from LHC upgrade

$$\sigma_{tot} \qquad \frac{d\sigma_{el}}{dt}$$

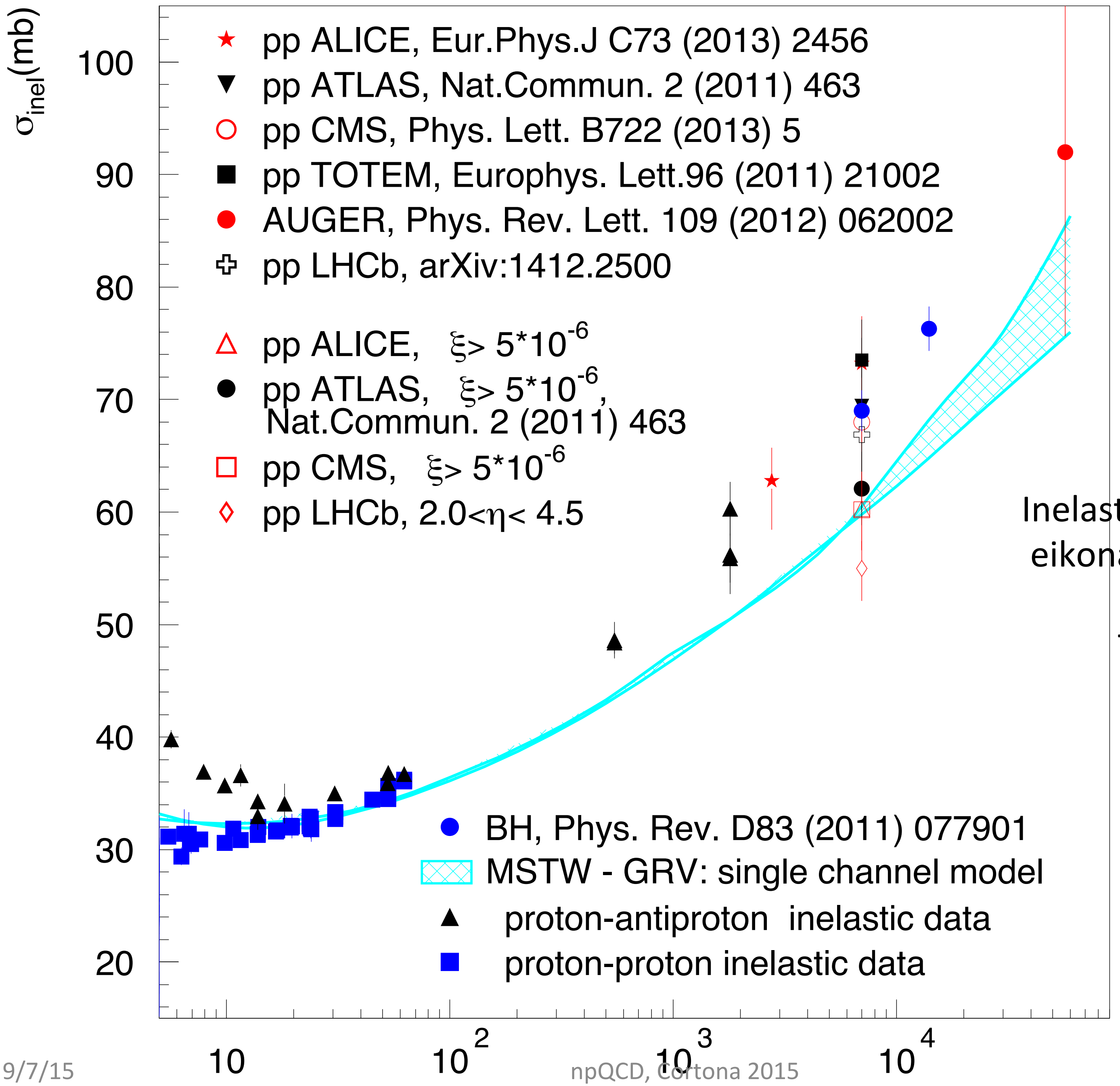
  - from cosmic rays: but it needs better understanding of
    - Glauber method for pp extraction
    - elastic pp cross-sections

Extras on BN model

- BN model by Grau, Godbole, Pancheri, Srivastava (1999-2005) + Corsetti, Achilli, Hedge, Shekhovtsova, Fagundes
- Latest on inelastic :

D.A. Fagundes, A. Grau, G. Pancheri, Y.N. Srivastava and O. Shekhovtsova, Phys. Rev., D91, 114011 (2015).

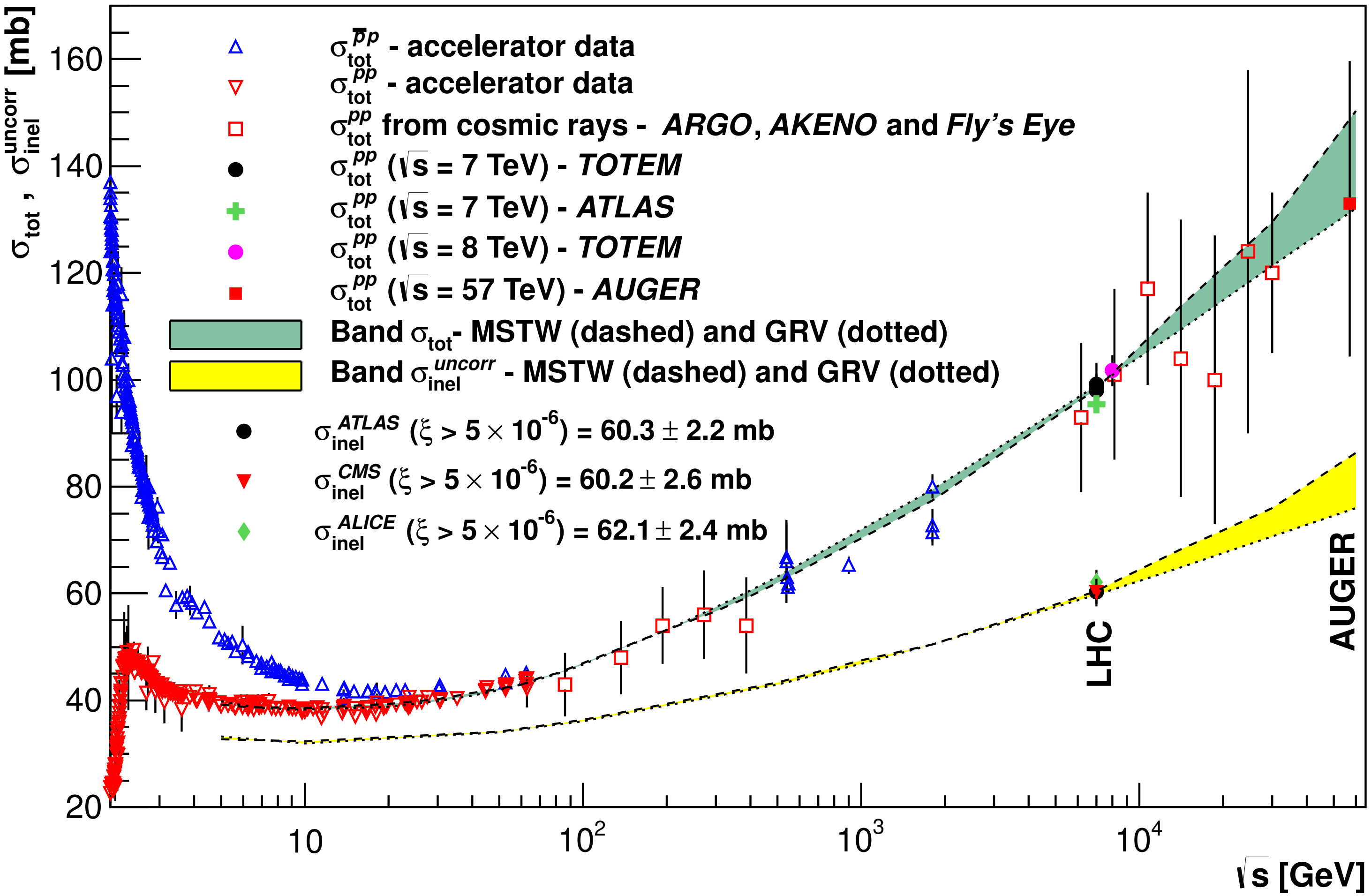
- BN for Bloch and Nordsieck because of resummation of ALL momenta



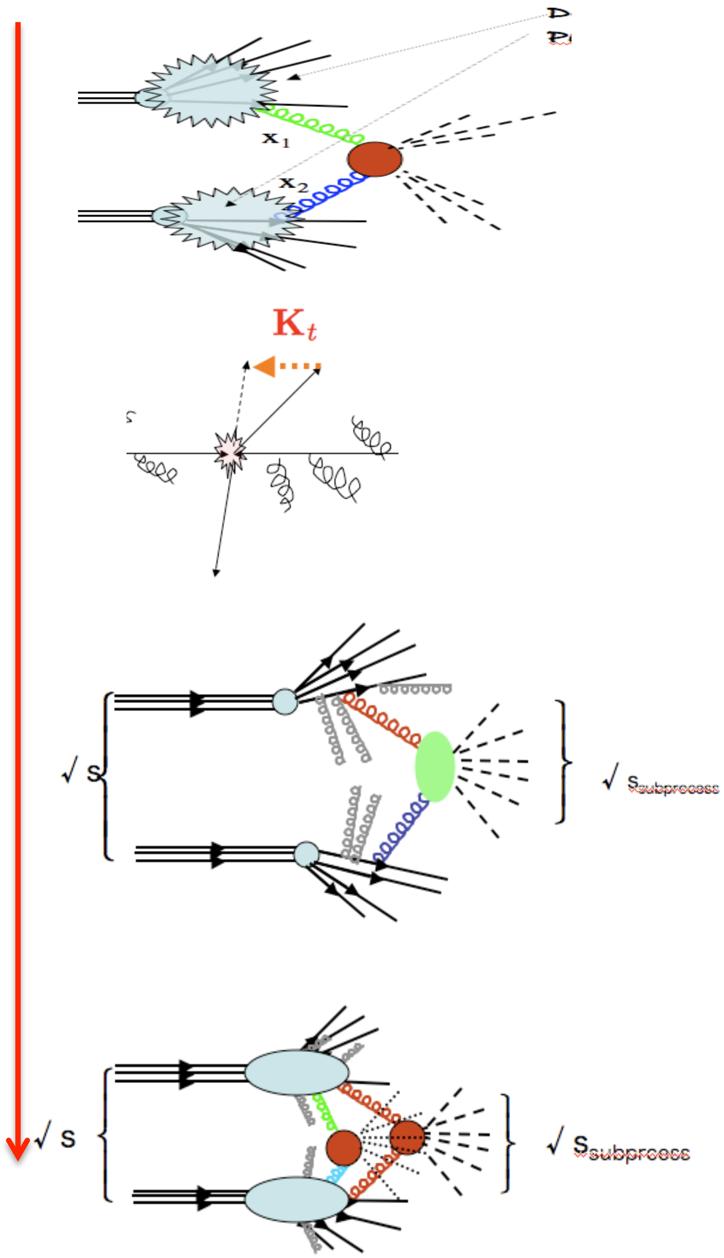
Inelastic in one channel eikonal with minijets

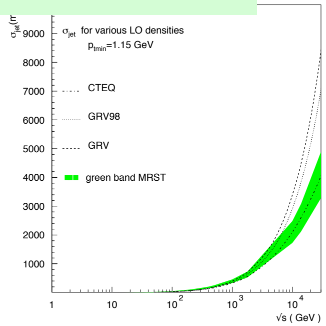
Too low

Inelastic uncorrelated and total pp x-section



GP et al model, aka *BN model*

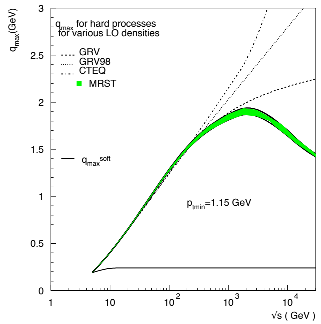




1. Calculate mini-jet cross-section Choosing densities and ptmin

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

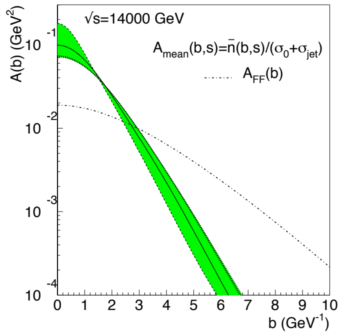
$$\epsilon \simeq 0.3 - 0.4$$



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

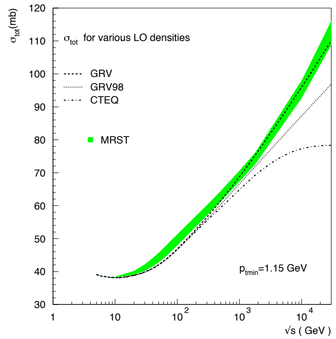
$$q_{max} \simeq p_{tmin}$$

$$\lesssim 2 - 3\ GeV$$



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

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

Resummation: a semi-classical treatment

- photons= classical (Poisson distributions constrained by overall Energy momentum conservation)+ QED (single photon emission spectrum)

$$d^2P(\vec{K}_t) = \sum P(n_k, \bar{n}_k)\delta^2(\vec{K}_t - \sum \vec{k}_t n_{k_t}) d^2\vec{K}_t$$

$$\rightarrow \frac{d^2\vec{K}_t}{(2\pi)^2}\int d^2\vec{b}\; e^{i\vec{K}_t\cdot\vec{b} - h_{QED}(b)}$$

- B. Touschek et al., Nuovo Cimento 1967

- Gluons=classical +QCD≠

Same as in QED

$$k_t \rightarrow 0$$

$$\alpha_{q\rightarrow q+\ gluon}$$

In full resummation it is not possible to use AF, i.e.

NO!

$$\alpha_{\cancel{AF}}(k_t) = \frac{b_0}{\ln[k_t^2/\Lambda^2_{QCD}]}$$

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

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

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

To reconcile with asymptotic Freedom

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

A phenomenological interpolation

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

Our QCD model for the total cross-section

R. Godbole, A. Grau, GP, YN Srivastava

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

$$\boxed{\begin{aligned} 2\chi_I(b,s) = A_{FormFactor}(b,s)\sigma_{soft}(p_t < p_{tmin}) + \\ + A_{Resum}(b,s)\sigma_{mini-jet}(p_t > p_{tmin}) \end{aligned}}$$

- Minijets to drive the rise
- Soft kt-resummation to tame the rise and introduce the cut-off in b-space needed to satisfy the Froissart bound

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

PLB1996-PRD2005

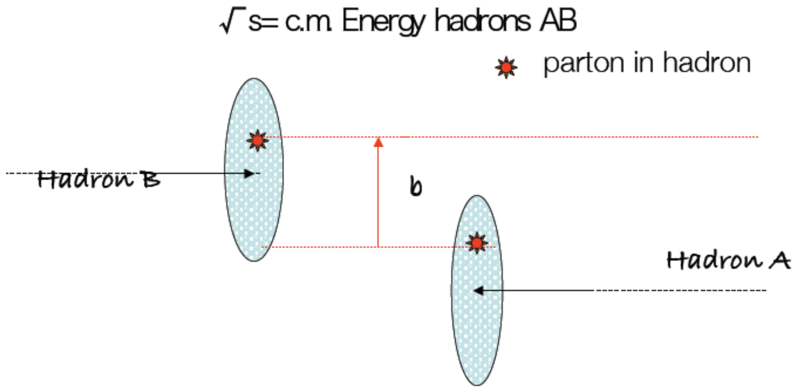
We model the impact parameter distribution as the Fourier-transform of ISR soft k_t distribution and thus obtain a cut-off at large distances : Froissart bound?

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

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

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

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

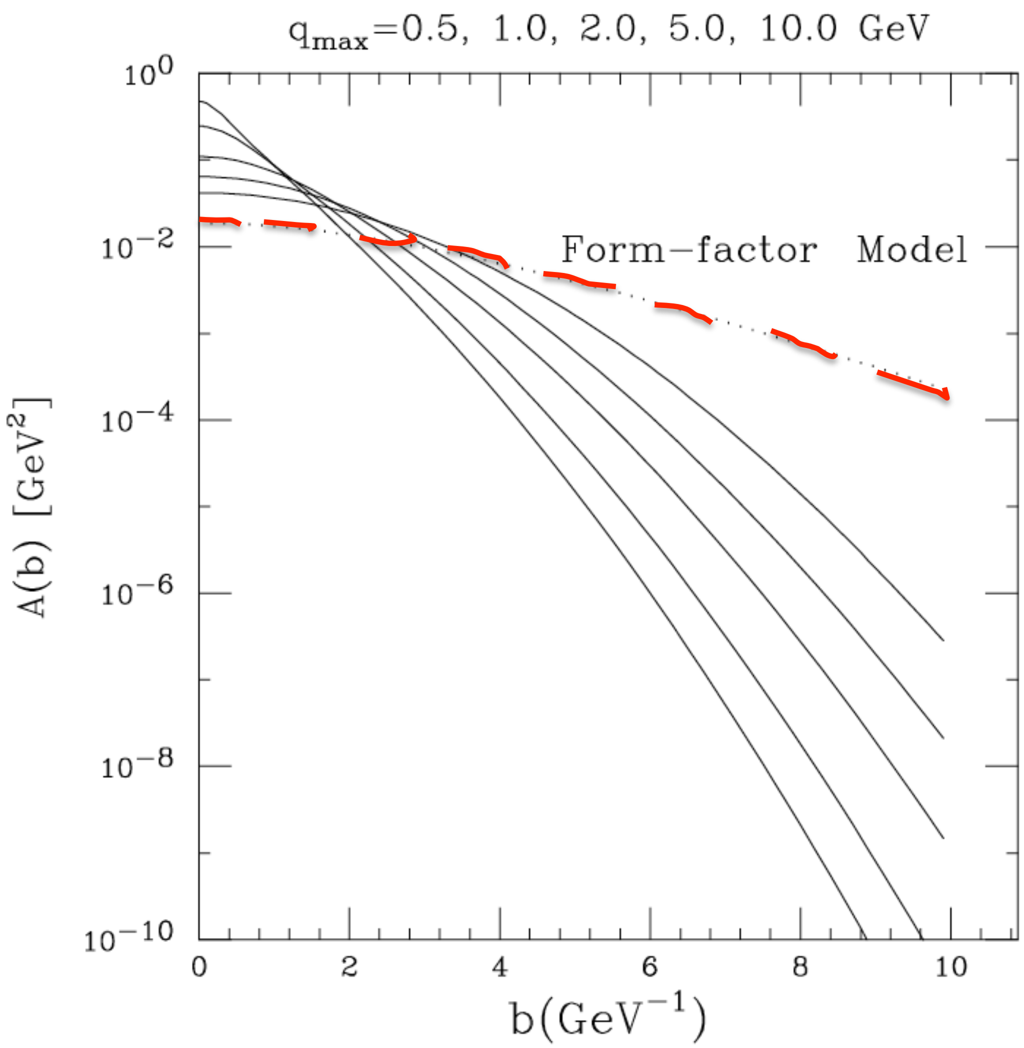


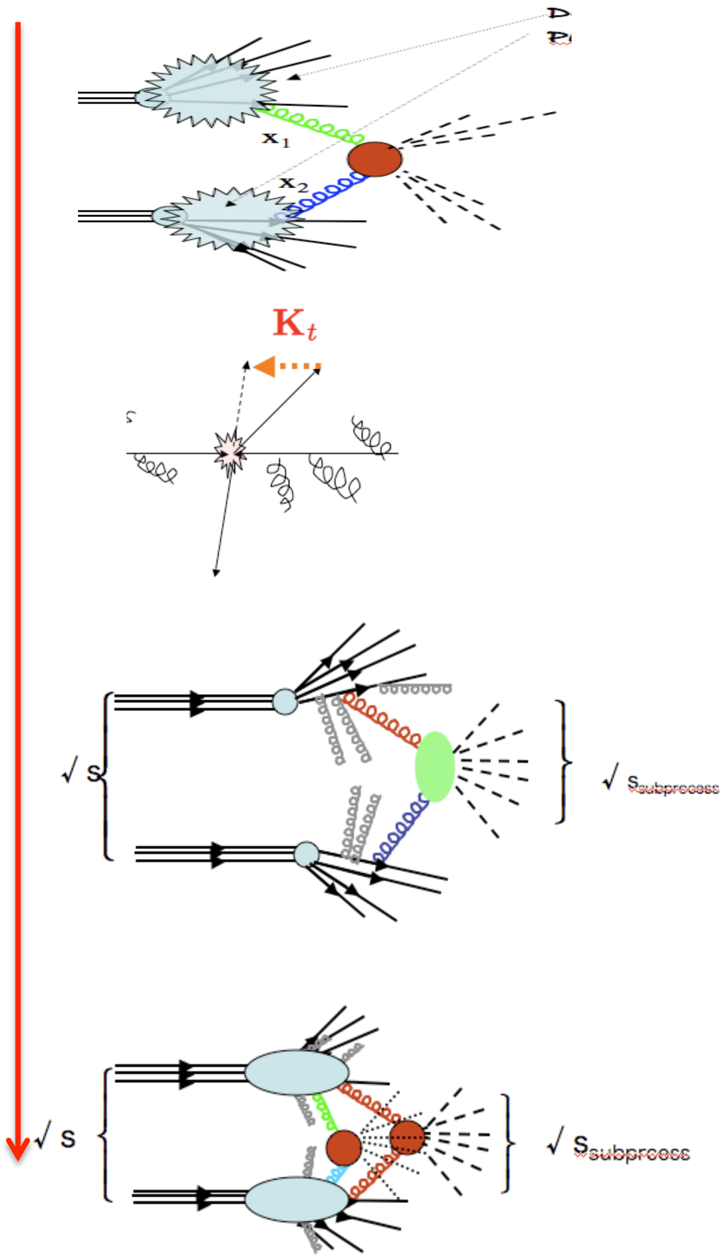
$\boxed{q_{tmax}}$ **?**

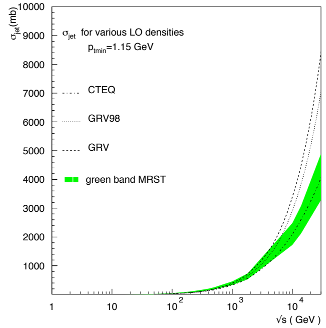
Fuzzy factorization (as in QED)
Fixed by single
gluon emission kinematics

Parton b-distribution from form factor models vs resummation models

Corsetti, Grau, Pancheri, Srivastava, PLB 1996

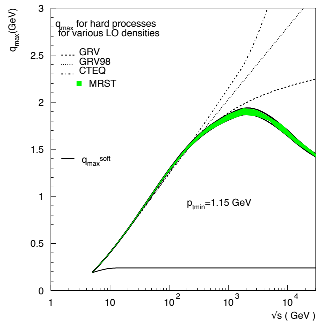






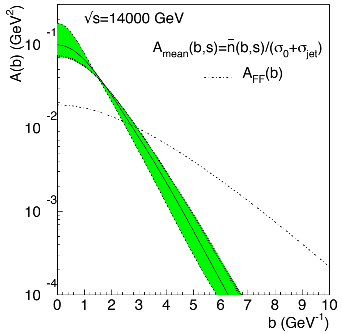
1. Calculate mini-jet cross-section Choosing densities and ptmin

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



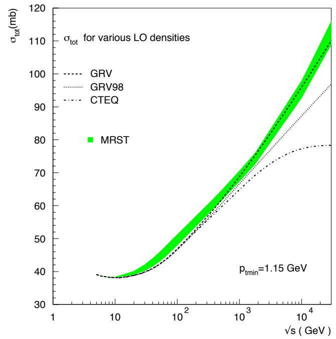
2. Calculate qmax: single soft gluon upper scale, for given PDF, ptmin

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



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

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

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

s^{ε}

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

$$\sigma_{tot}(s) \to [\varepsilon \ln(s)]^{(1/p)} \qquad \frac{1}{2} < p < 1$$

Grau, Godbole,GP,Srivastava,PLB682 2009