Exclusive vector meson (photo)production and low x dynamics

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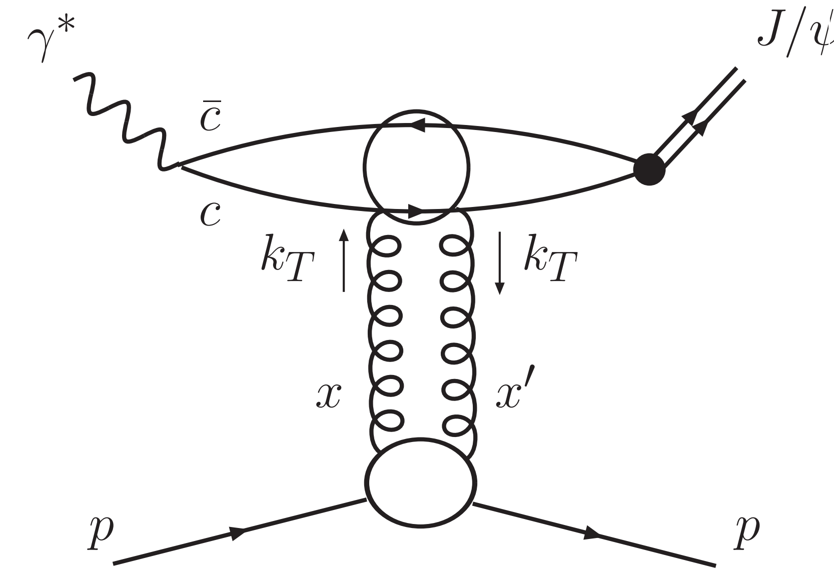
Photon 2017, CERN, May 22-26, 2017

Why exclusive diffractive VM (photo)production?

- Unique sensitivity to gluon distribution of the target: gluon density squared.
- Semi-hard scale: can treat perturbatively even in photo-production for heavier mesons.
- In ep DIS possibility to control the scale through the photon virtuality.
- Test the universality of dynamics between different VM.
- Momentum transfer dependence allows to access the impact parameter profile of the interaction radius.

Low x/dipole - type approaches to exclusive VM production

Ryskin;
Marti,Ryskin,Teubner;
Jones, Martin, Ryskin,Teubner



In the proton rest frame: the formation time of dipole is much longer than the interaction time with the target. Allows to factorize the process.

Lowest order: non-relativistic approximation to J/ψ wave function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4\,, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2+Q^2)$$

In principle need to take into account skewed gluon distribution.

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+\frac{5}{2})}{\Gamma(\lambda+4)} \quad \textbf{with} \quad \lambda(Q^2) = \partial\left[\ln(xg)\right]/\partial\ln(1/x)$$

Shuvaev,Golec-Biernat,Martin,Ryskin

Effectively, multiplicative factor taken into account

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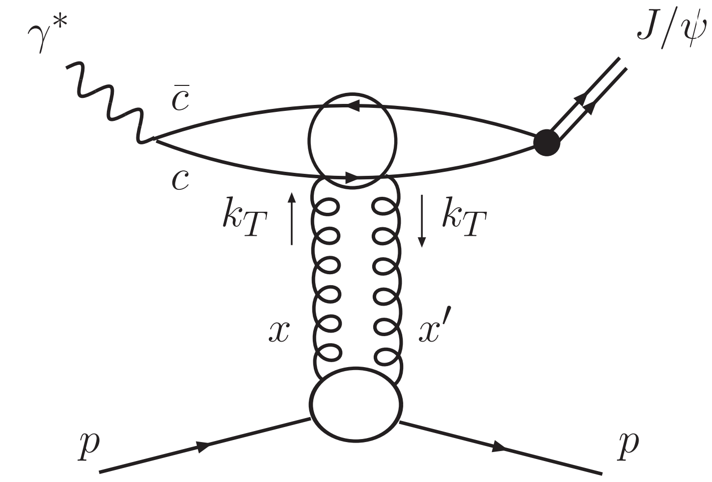
Jones, Martin, Ryskin, Teubner



'NLO' improvement:
including transverse momentum dependence in the gluon distribution integrated with the hard factor

$$\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right] \longrightarrow \int_{Q_0^2}^{(W^2-M_\psi^2)/4} \frac{dk_T^2\,\alpha_s(\mu^2)}{\bar{Q}^2(\bar{Q}^2+k_T^2)} \frac{\partial\left[xg(x,k_T^2)\sqrt{T(k_T^2,\mu^2)}\right]}{\partial k_T^2} + \ln\left(\frac{\bar{Q}^2+Q_0^2}{\bar{Q}^2}\right)\frac{\alpha_s(\mu_{\rm IR}^2)}{\bar{Q}^2 Q_0^2}\, xg(x,Q_0^2)\sqrt{T(Q_0^2,\mu_{\rm IR}^2)}\,.$$

Sudakov form factor:

$$T(k_T^2,\mu^2) \;=\; \exp\left[\frac{-C_A\alpha_s(\mu^2)}{4\pi}\ln^2\left(\frac{\mu^2}{k_T^2}\right)\right]$$

$$T=1 \quad \text{for} \quad k_T^2 \geq \mu^2$$

No additional gluons with transverse momenta larger than k_T are emitted in the process

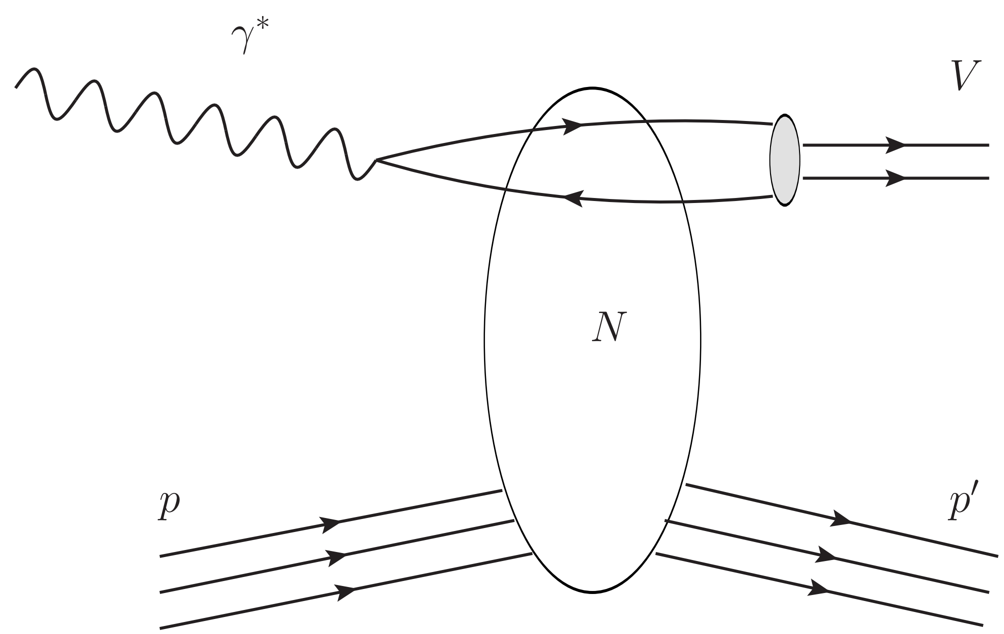
t- distribution modeled in this approach: $\sigma \sim \exp(-Bt)$

$$B(W) = (4.9 + 4\alpha' \ln(W/W_0))\ \text{GeV}^{-2}$$

Exclusive production of vector mesons in the dipole approach

Nikolaev,Zkharov;
Strikman,Frankfurt,Rogers;
Levin et al;
Munier,Mueller,AS;
Motyka,Kowalski,Watt;
Berger,AS;
Armesto,Rezeaian;
Lappi,Mantysaari,Schenke;...

ρ,Φ,J/ψ,Υ production



cross section

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|A(x,\Delta,Q)|^2$$

amplitude

$$A(x,\Delta,Q) = \sum_{h,\bar{h}} \int d^2\mathbf{r} \int dz\, \Psi_{h,h^*}(\mathbf{r},z,Q^2)\, \mathcal{N}(x,\mathbf{r},\Delta)\, \Psi^V_{h,h^*}(\mathbf{r},z)$$

dipole cross section

$$\sigma_{\rm dip}(x,\mathbf{r}) = {\rm Im}\, i\mathcal{N}(x,\mathbf{r},\Delta=0)$$

dipole amplitude

$$\mathcal{N}(x,\mathbf{r},\Delta) = 2\int d^2\mathbf{b}\, N(x,\mathbf{r},\mathbf{b})\, e^{i\Delta\cdot\mathbf{b}}$$

$\mathbf{r}$ dipole size

$\mathbf{b}$ impact parameter

Δ momentum transfer

$z,(1-z)$ fraction of the longitudinal momentum of the photon carried by the quark(anti-quark)

Low x - type approaches to exclusive VM production

Bautista,Fernandez Tellez, Hentschinski

$$\Im\mathrm{m}\mathcal{A}_T^{\gamma^* p\to Vp}(W,0) = \alpha_s(\overline{M}\cdot Q_0)\int\limits_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty}\frac{d\gamma}{2\pi i}\int\limits_0^1\frac{dz}{4\pi}\;\hat{g}\left(x,\frac{M^2}{Q_0^2},\frac{\overline{M}^2}{M^2},Q_0,\gamma\right)\cdot\Phi_{V,T}(\gamma,z,M)\cdot\left(\frac{M^2}{Q_0^2}\right)^\gamma$$

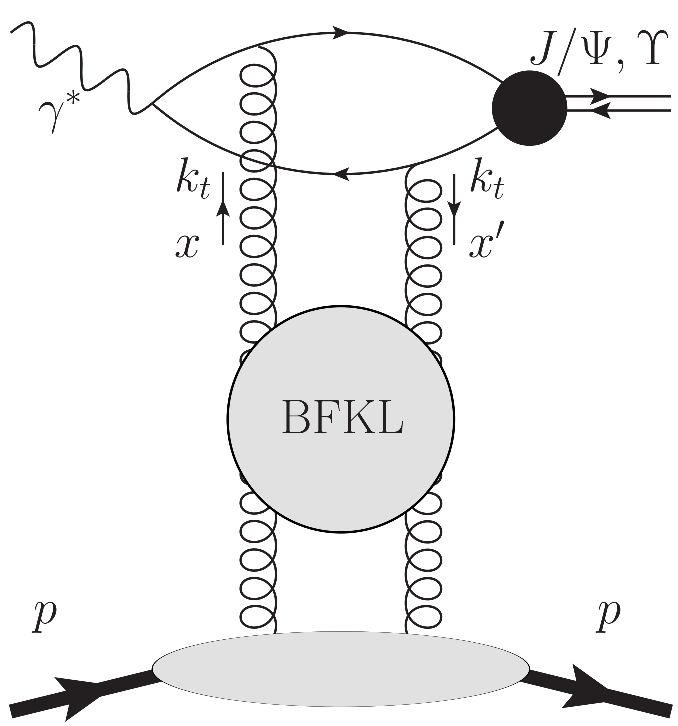
Dipole amplitude obtained from the BFKL unintegrated gluon distribution

$$G\left(x,\boldsymbol{k}^2,M\right) = \frac{1}{\boldsymbol{k}^2}\int\limits_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty}\frac{d\gamma}{2\pi i}\;\hat{g}\left(x,\frac{M^2}{Q_0^2},\frac{\overline{M}^2}{M^2},\gamma\right)\left(\frac{\boldsymbol{k}^2}{Q_0^2}\right)^\gamma$$

$$\sigma_0 N(\boldsymbol{r},x) = \frac{4\pi}{N_c}\int\frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2}\left(1-e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\right)\alpha_s G(x,\boldsymbol{k}^2)$$

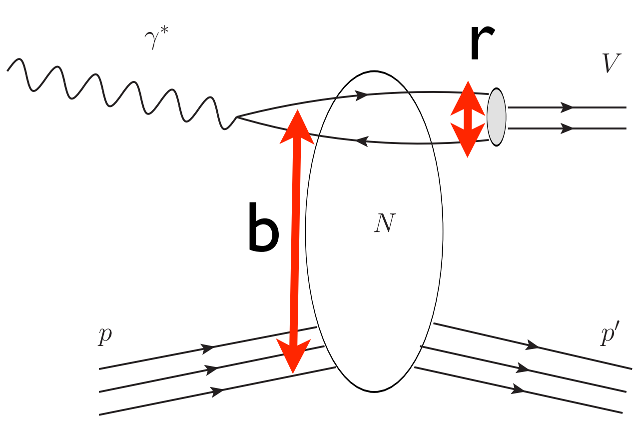
Vector meson photoproduction impact factor obtained from the dipole model in coordinate space

$$\Phi_{V,T}(\gamma,z,M) = \frac{4\pi}{N_c}\int d^2\boldsymbol{r}\int\frac{d^2\boldsymbol{k}}{(\boldsymbol{k}^2)^2}\left(1-e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\right)\left(\frac{\boldsymbol{k}^2}{M^2}\right)^\gamma(\Psi_V^*\Psi)_T(r)$$



t- distribution modeled in this approach

Low x dipole amplitude: including saturation



Glauber-Mueller parameterization often used; includes nonlinear effects

Motyka,Kowalski,Watt; 'b-Sat model'

$$N_{\rm GM}(r,b;Y=\ln 1/x) \;=\; 1-\exp\left(-\frac{\pi^2}{2N_c}r^2xg(x,\eta^2)T(b)\right)$$

$$T(b) \;=\; \frac{1}{8\pi}e^{\frac{-b^2}{2B_G}}$$

Can be obtained from low x nonlinear equation: Balitsky - Kovchegov equation

Berger,AS

$$\frac{dN(\mathbf{r}_{01},\mathbf{b}_{01},Y)}{dY} = \frac{\alpha_s N_c}{\pi}\int\frac{d^2\mathbf{r}_2\mathbf{r}_{01}^2}{\mathbf{r}_{20}^2\mathbf{r}_{12}^2}\Big[N(\mathbf{r}_{20},\mathbf{b}_{01}+\frac{\mathbf{r}_{12}}{2},Y)+N(\mathbf{r}_{12},\mathbf{b}_{01}-\frac{\mathbf{r}_{20}}{2},Y)$$
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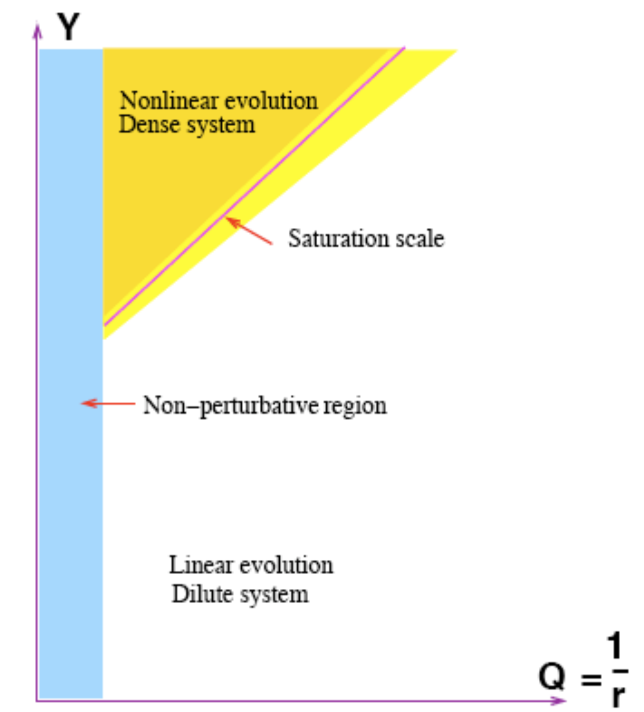
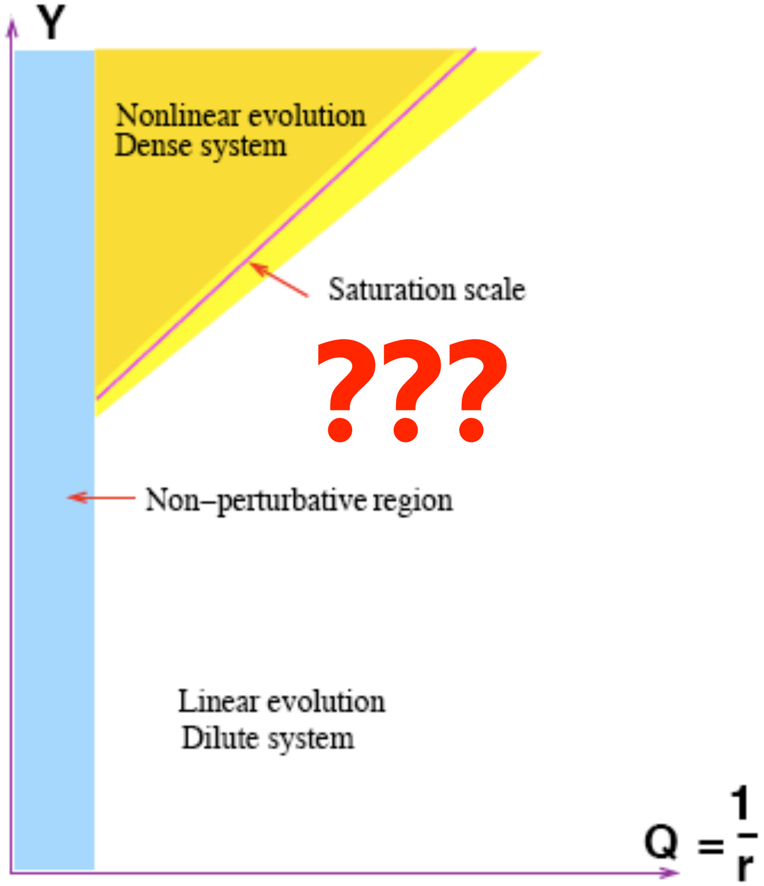
- Typically BK solved in a local approximation: without impact parameter dependence. Successful description of variety of data.
- Can be solved (at least numerically) relatively easily.
- Generates the saturation scale that divides the dense and dilute regime.



What about spatial distribution?



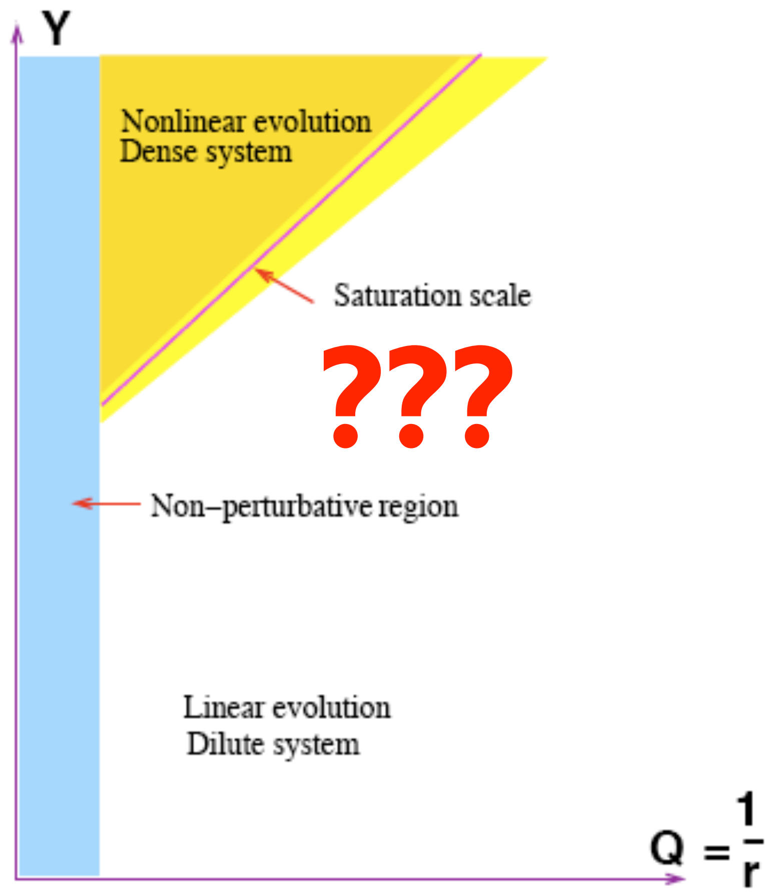
Usual approximation:

$$N(\mathbf{r}, \mathbf{b}, Y) = N(\mathbf{r}, Y)$$

- The target has infinite size.
- Local approximation suggests that the system becomes more perturbative as the energy grows.
- But this cannot be true everywhere (IR in QCD)

Impact parameter profile

What about spatial distribution?



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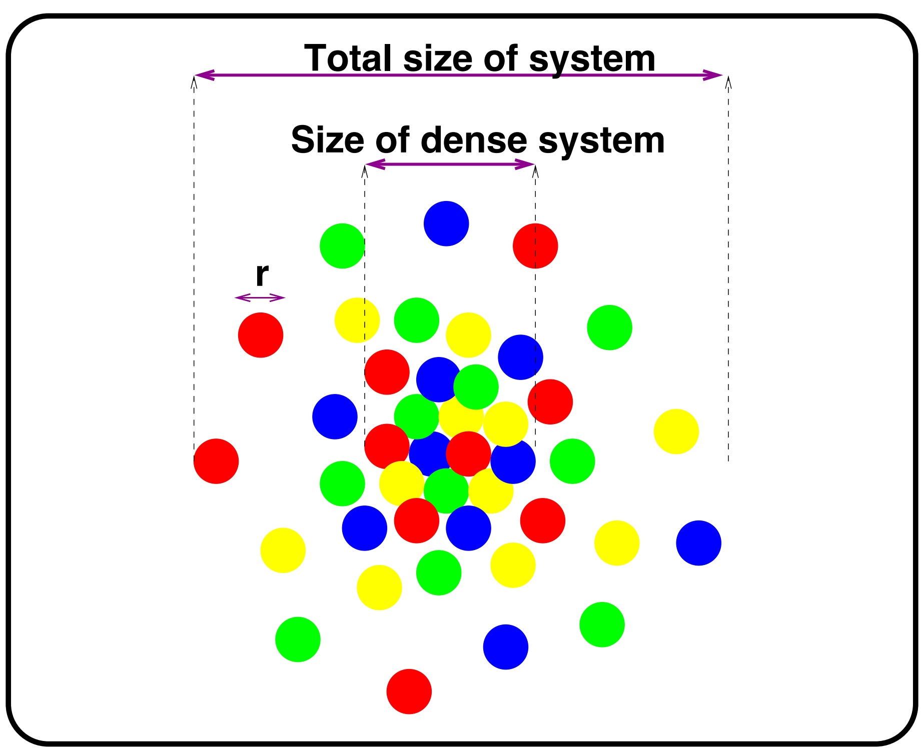
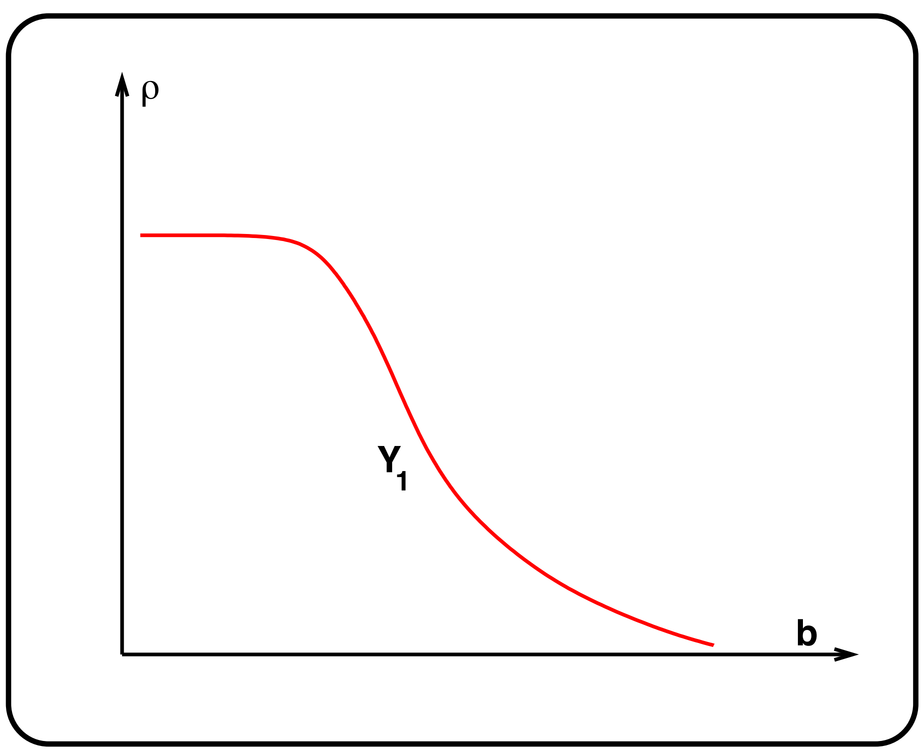


Impact parameter profile



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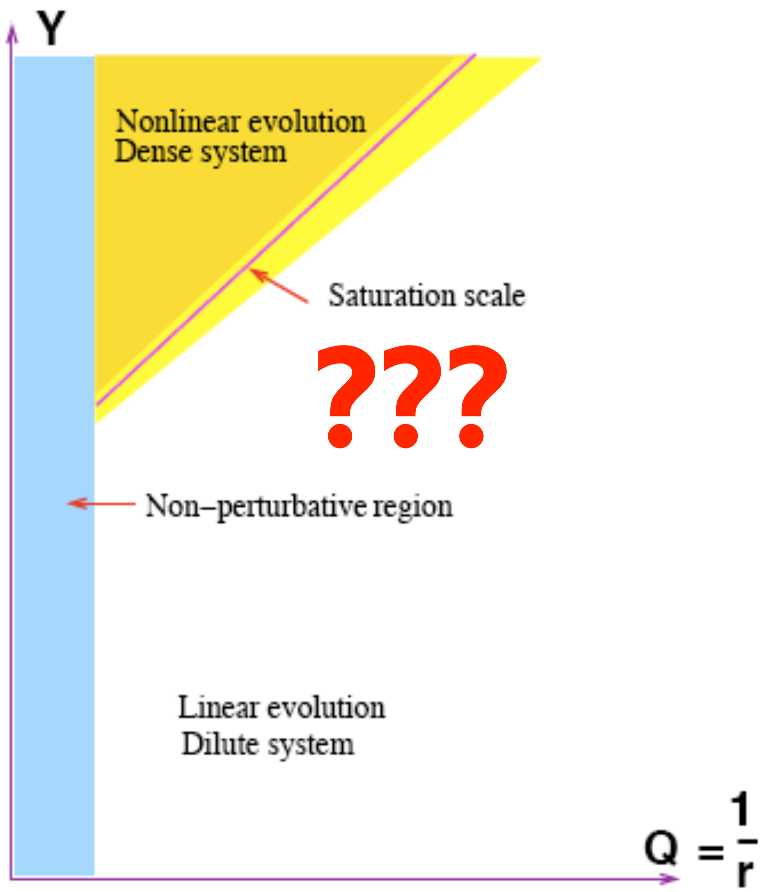

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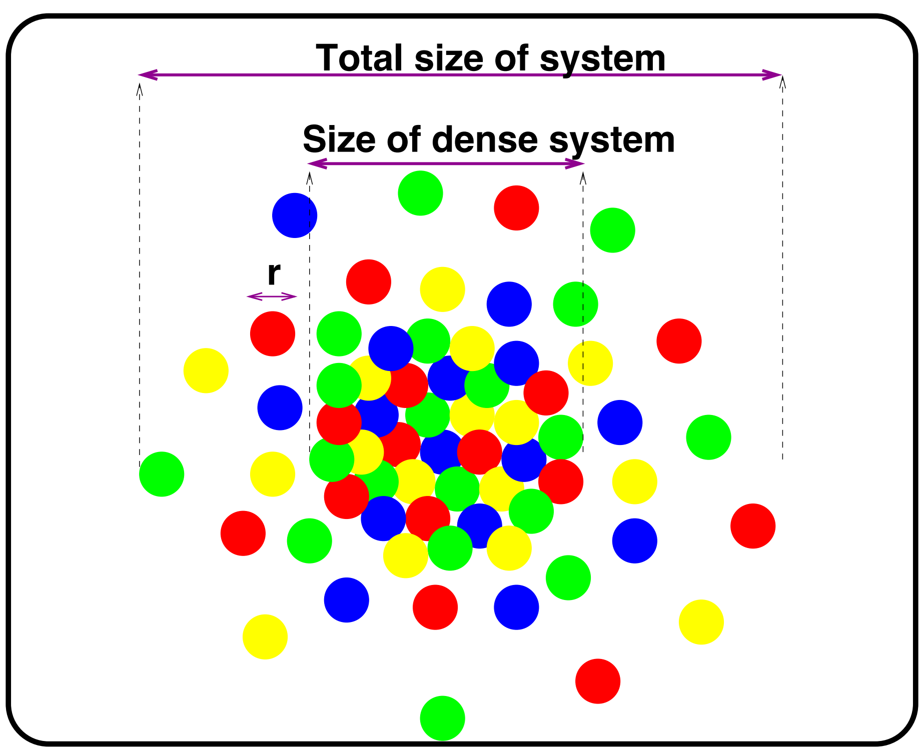

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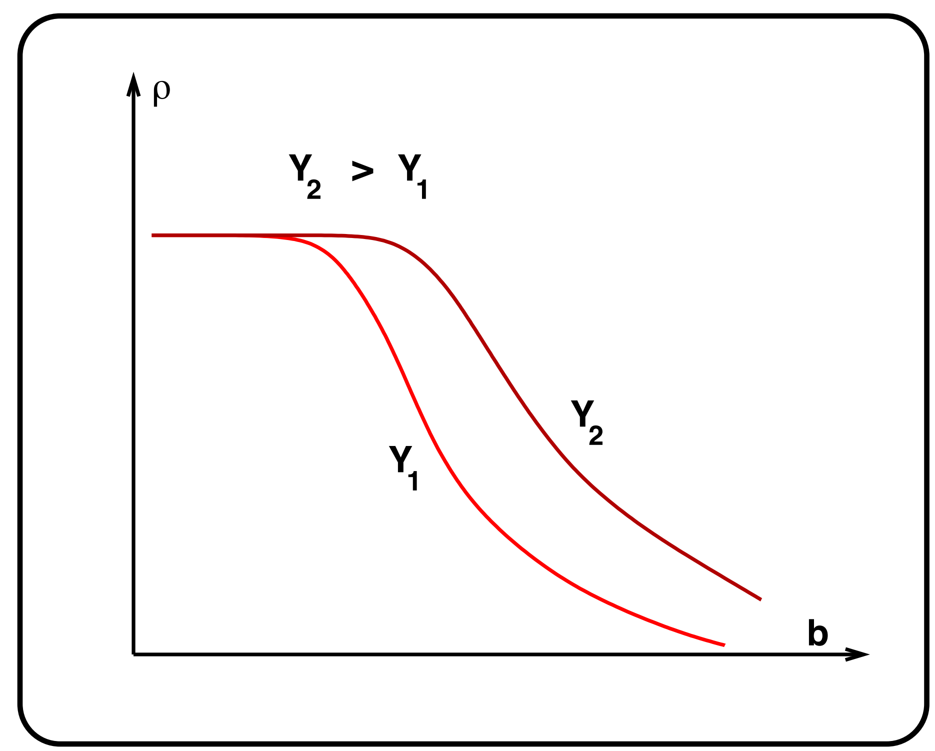

Solving impact parameter dependent BK equation

$$\frac{dN(\mathbf{r}_{01},\mathbf{b}_{01},Y)}{dY} = \frac{\alpha_s N_c}{\pi}\int \frac{d^2\mathbf{r}_2\mathbf{r}_{01}^2}{\mathbf{r}_{20}^2\mathbf{r}_{12}^2}\Big[N(\mathbf{r}_{20},\mathbf{b}_{01}+\frac{\mathbf{r}_{12}}{2},Y)+N(\mathbf{r}_{12},\mathbf{b}_{01}-\frac{\mathbf{r}_{20}}{2},Y)$$
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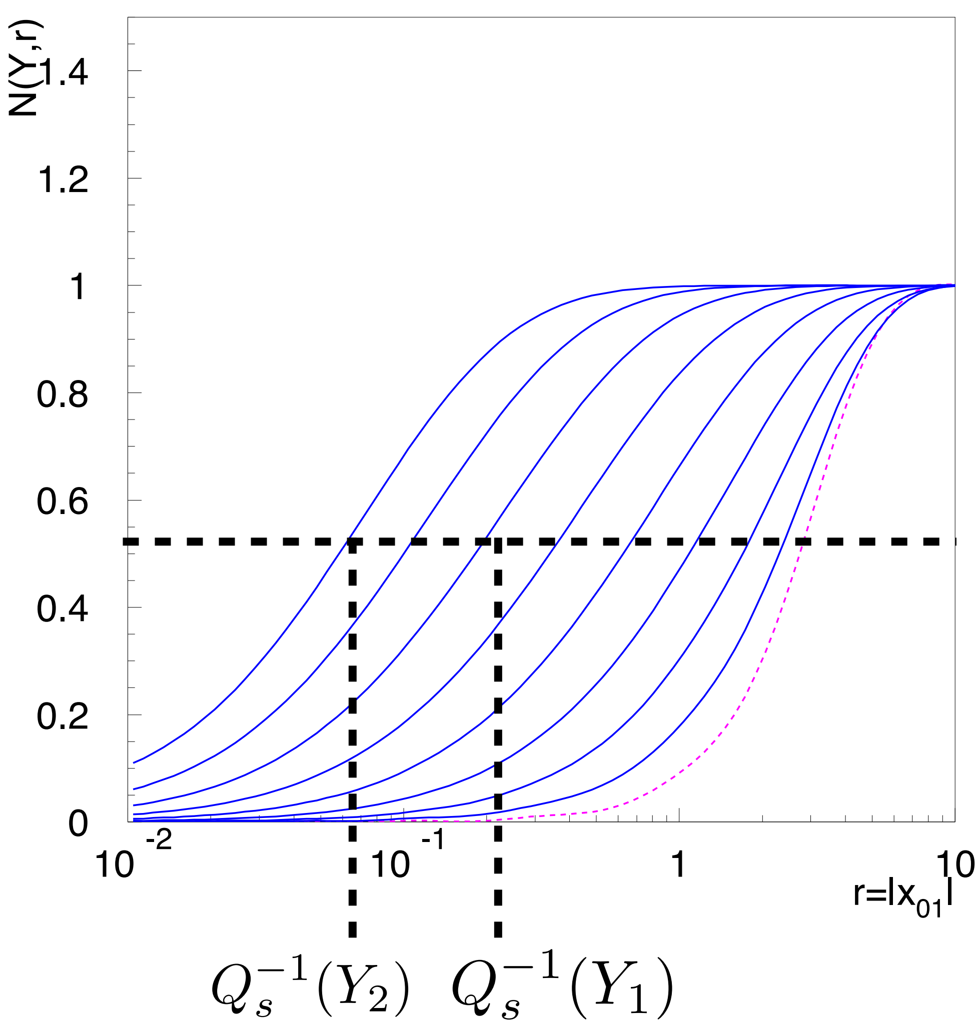
Golec-Biernat,AS; Berger,AS;

Initial condition Glauber-Mueller type: $N^{(0)} = 1 - \exp(-c_r r^2 \exp(-c_b b^2))$

Without impact parameter dependence

Dipole amplitude as a function of dipole size(arbitrary units)



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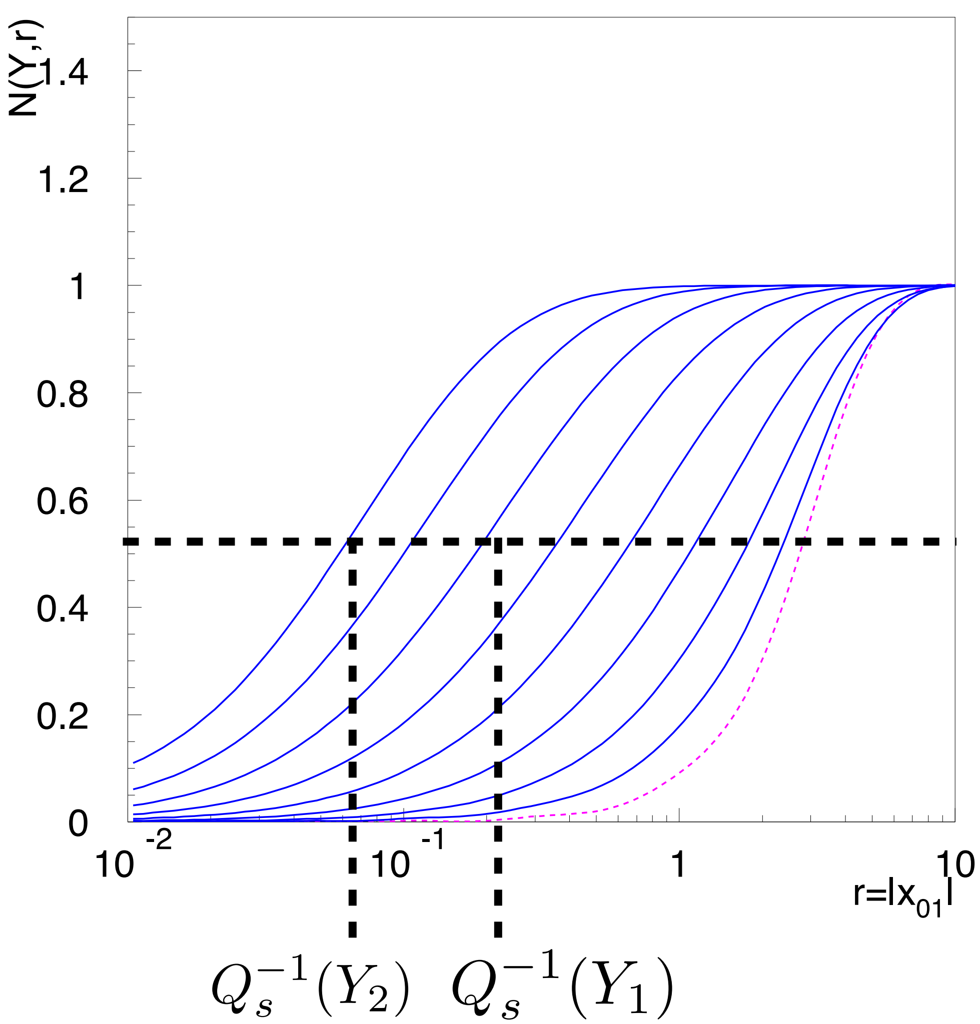
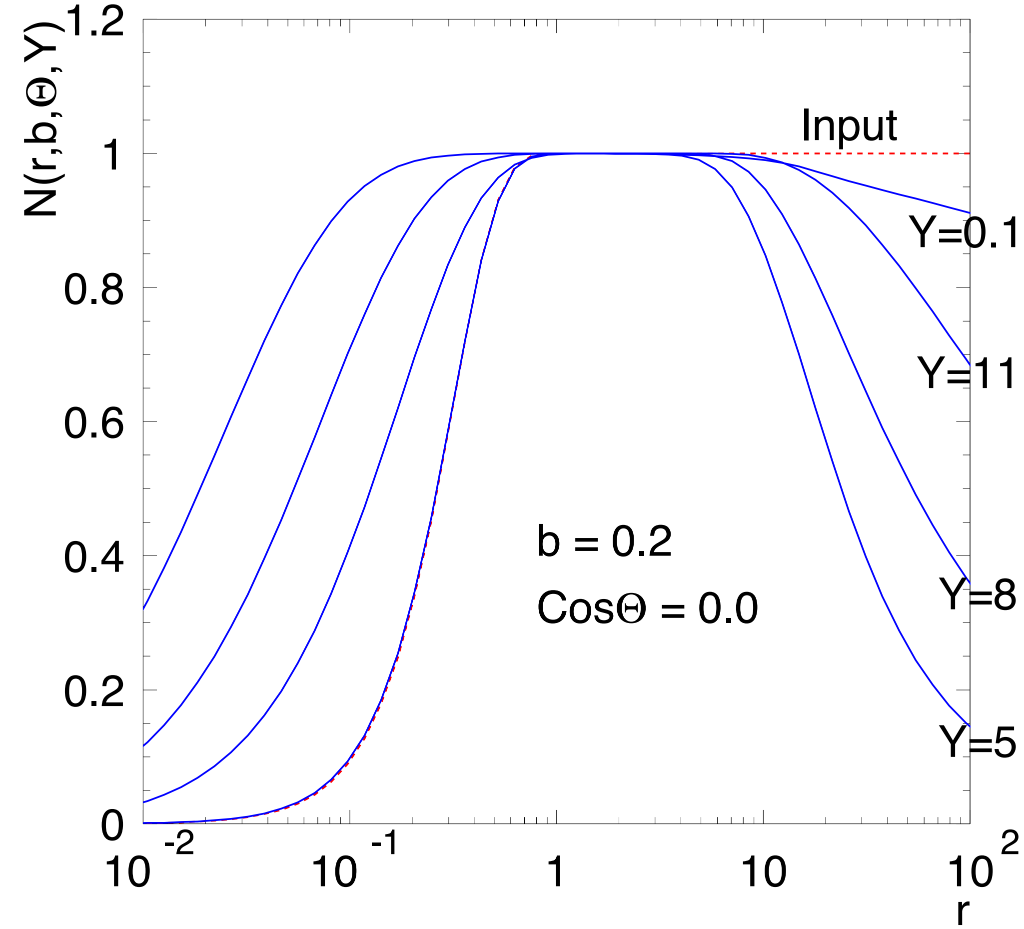


With impact parameter dependence



Solving impact parameter dependent BK equation

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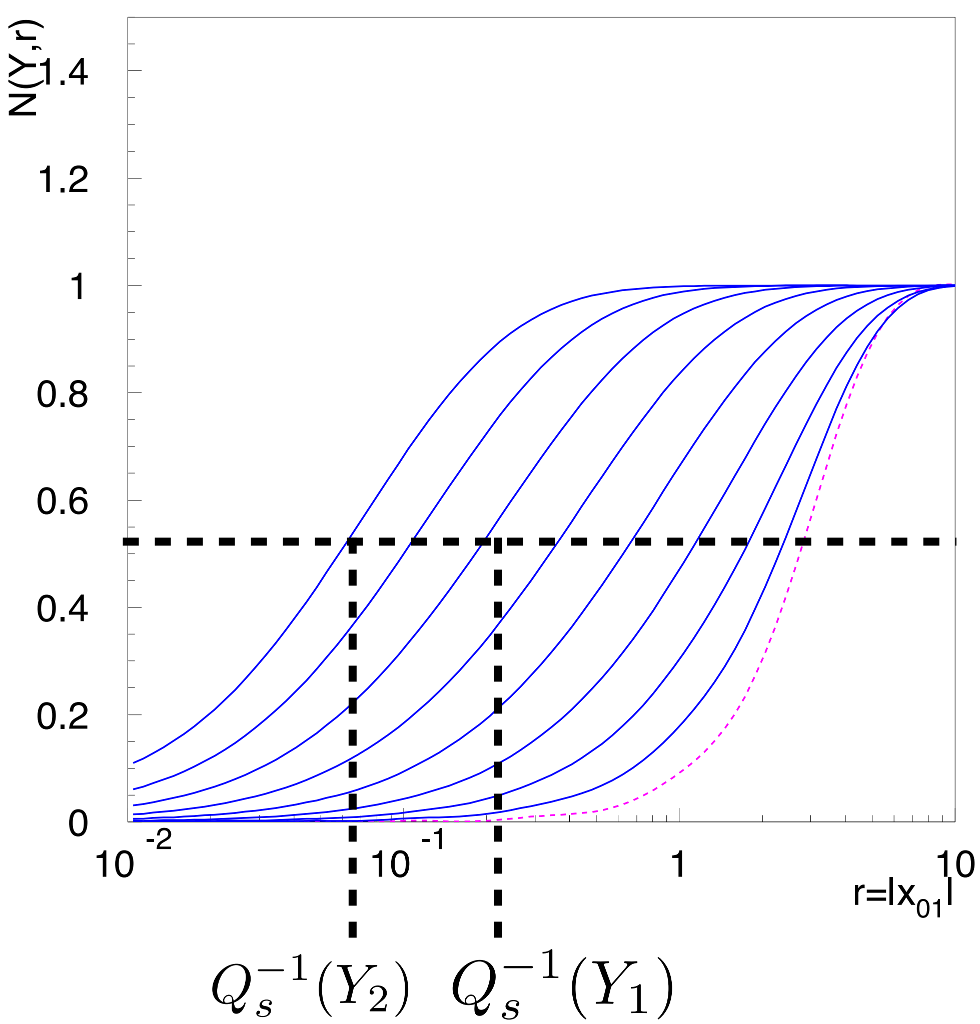

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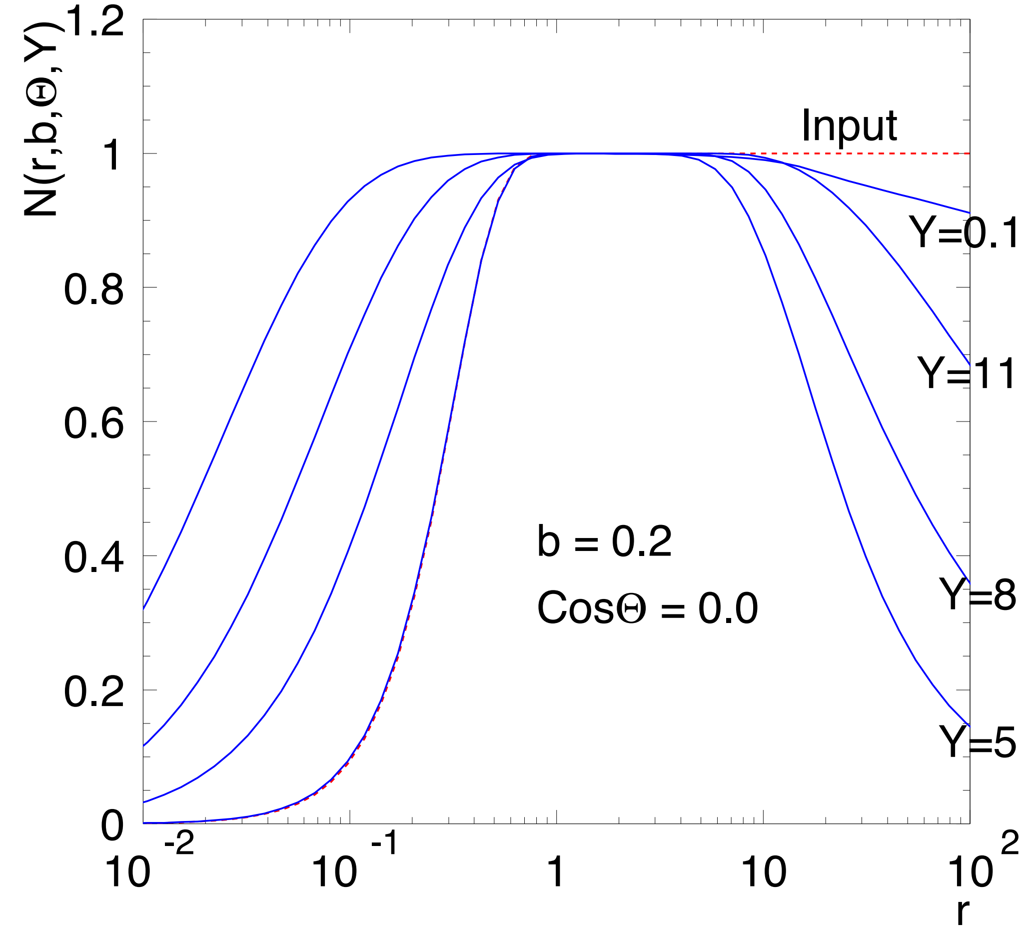
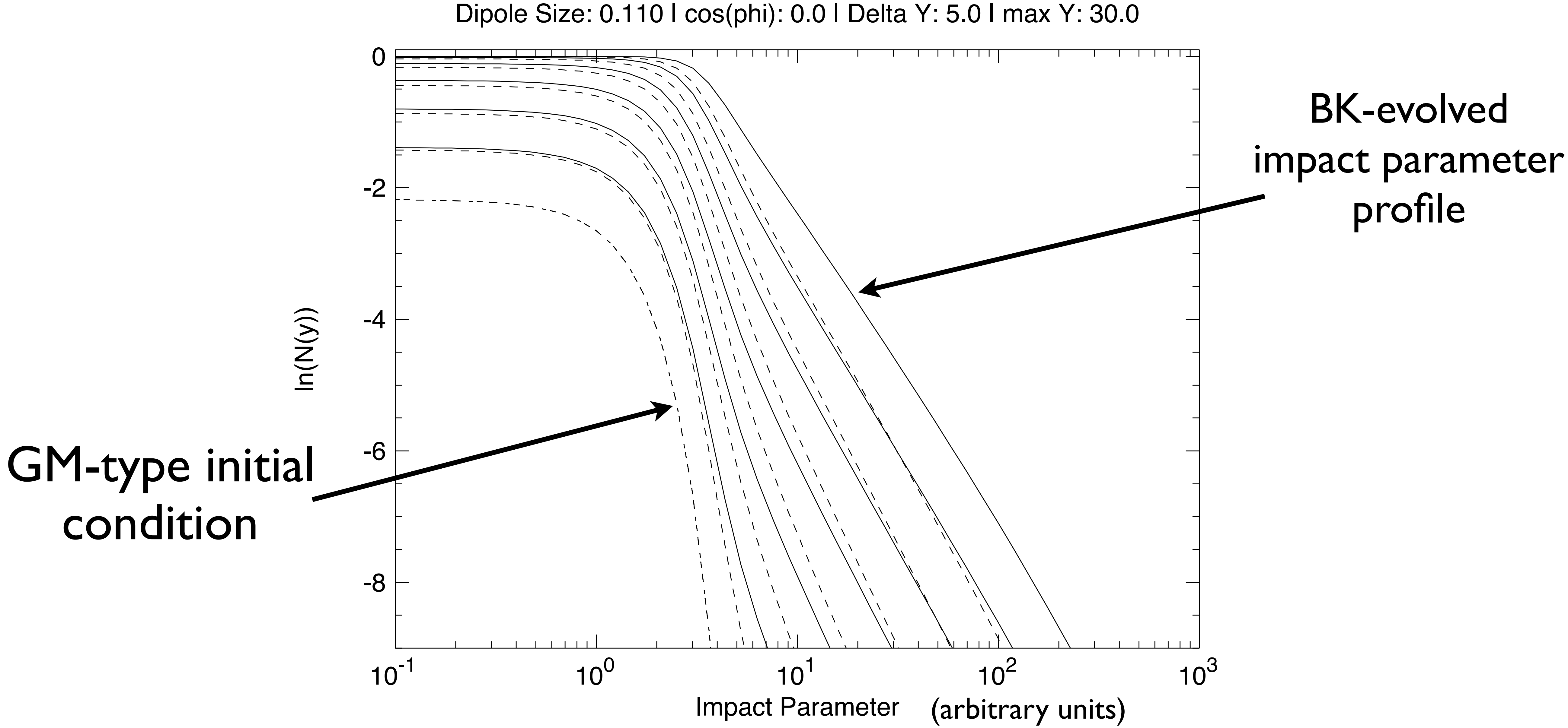


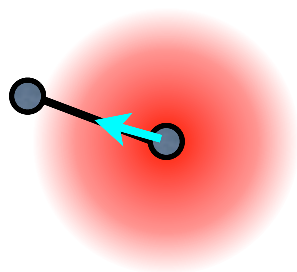
Glauber-Mueller form is not conserved under low x evolution

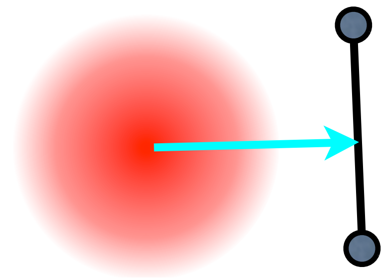
Impact parameter profile of the interaction region

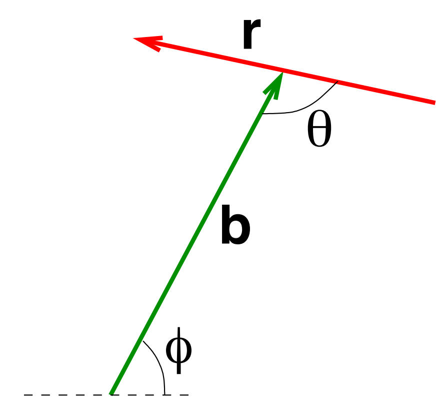


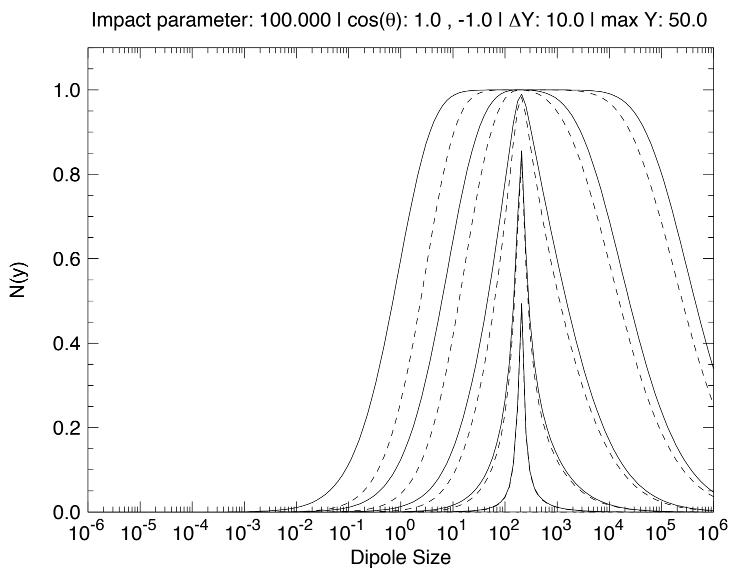
- Saturation for small impact parameters
- No saturation for large impact parameters (system is still dilute)
- Initial impact parameter profile is not preserved
- Power tail in b is generated, this is due to perturbative evolution and lack of confinement effect.

Angular correlations

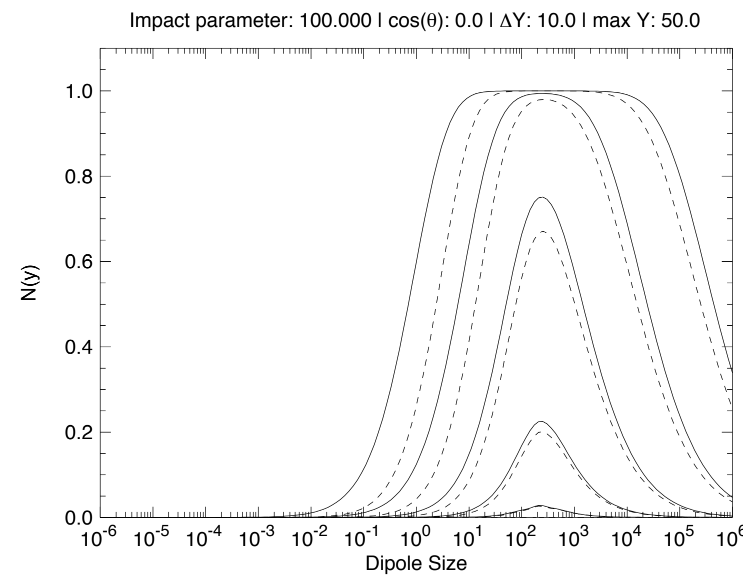




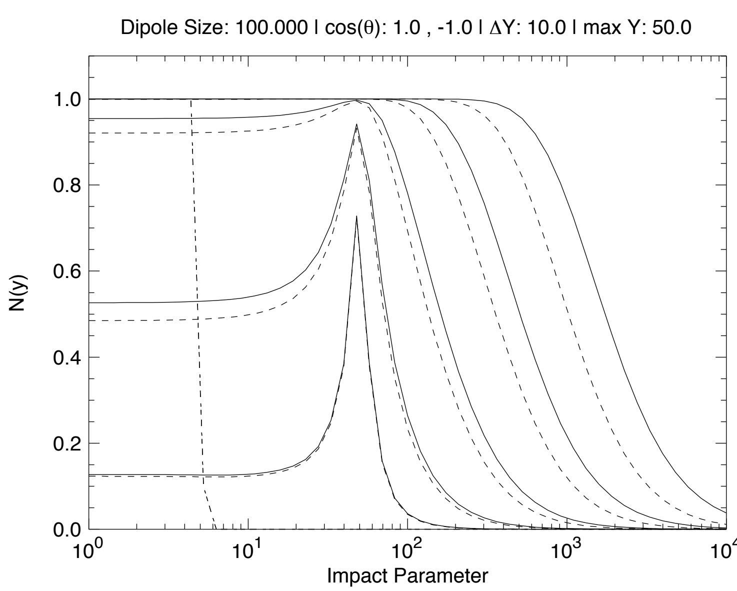




(a) $\cos(\theta) = 1.0, -1.0$



(b) $\cos(\theta) = 0.0$



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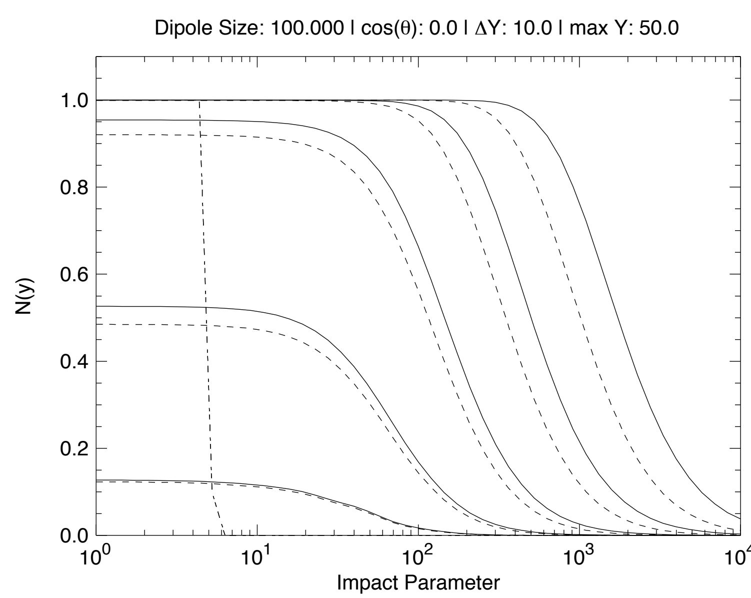


(b)$cos(\theta) = 0.0$

Angular correlations present in the solution

Amplitude larger for aligned configurations of the dipole

Could be relevant for the angular sensitive observables

Sensitivity through diffractive dijet in photoproduction/DIS

Hatta,Xiao,Yuan;
Altinoluk,Armesto,Beuf,Rezaeian;

Initial condition and cutoff for large dipoles

At x_0=0.01 use Glauber-Mueller formula:

$$N(r,b,Y_0 = \ln 1/x_0) = \quad 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 x g(x,\eta^2) T(b)\right)$$

$$T(b) \;=\; \frac{1}{8\pi} e^{\frac{-b^2}{2B_G}}$$

with parameters from Kowalski, Motyka, Watt $B_G = 4\ \mathrm{GeV}^{-2}$ $\langle b^2 \rangle = 2B_G$

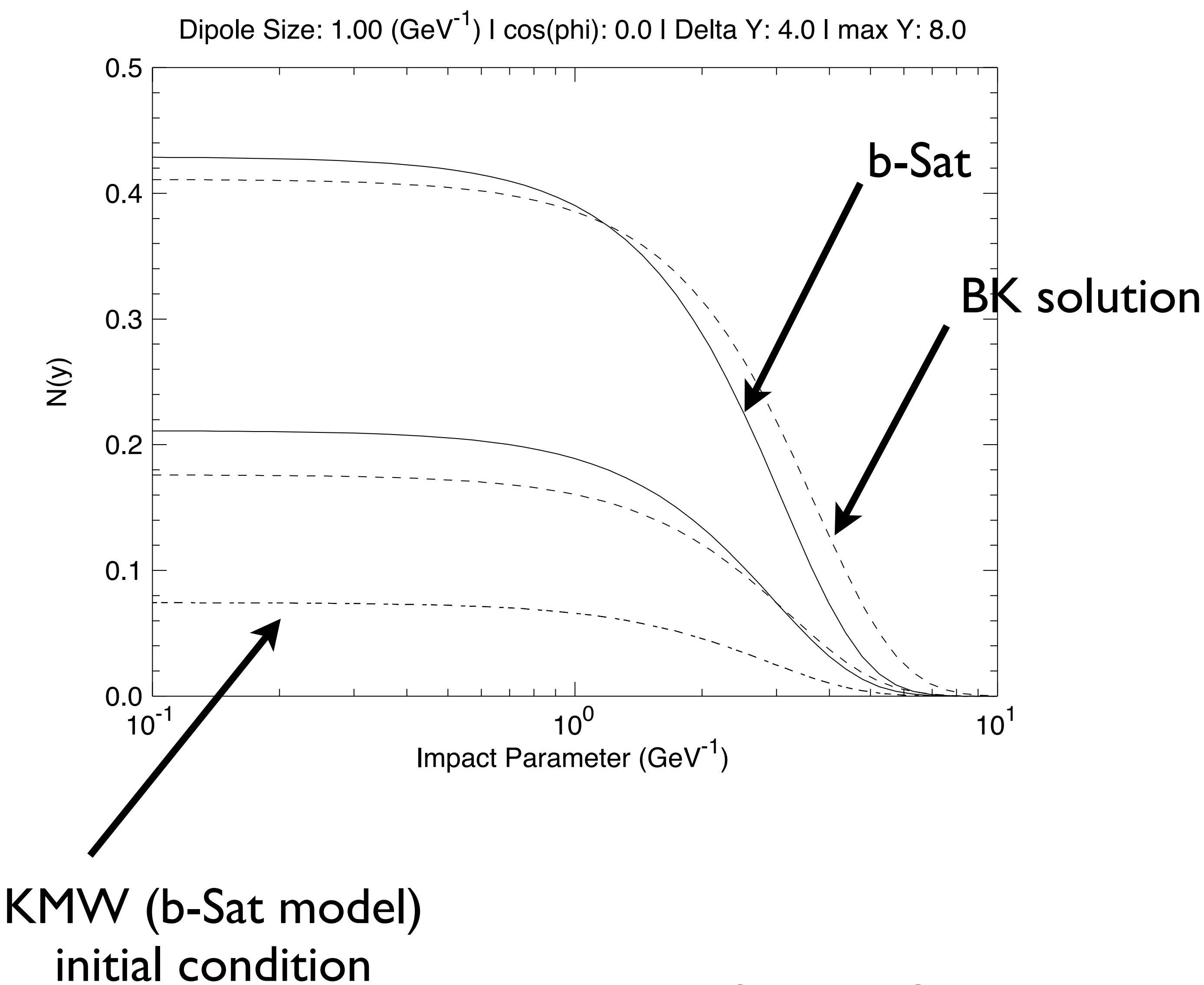
Need to implement the cutoff to regulate large dipole sizes, mimic confinement:

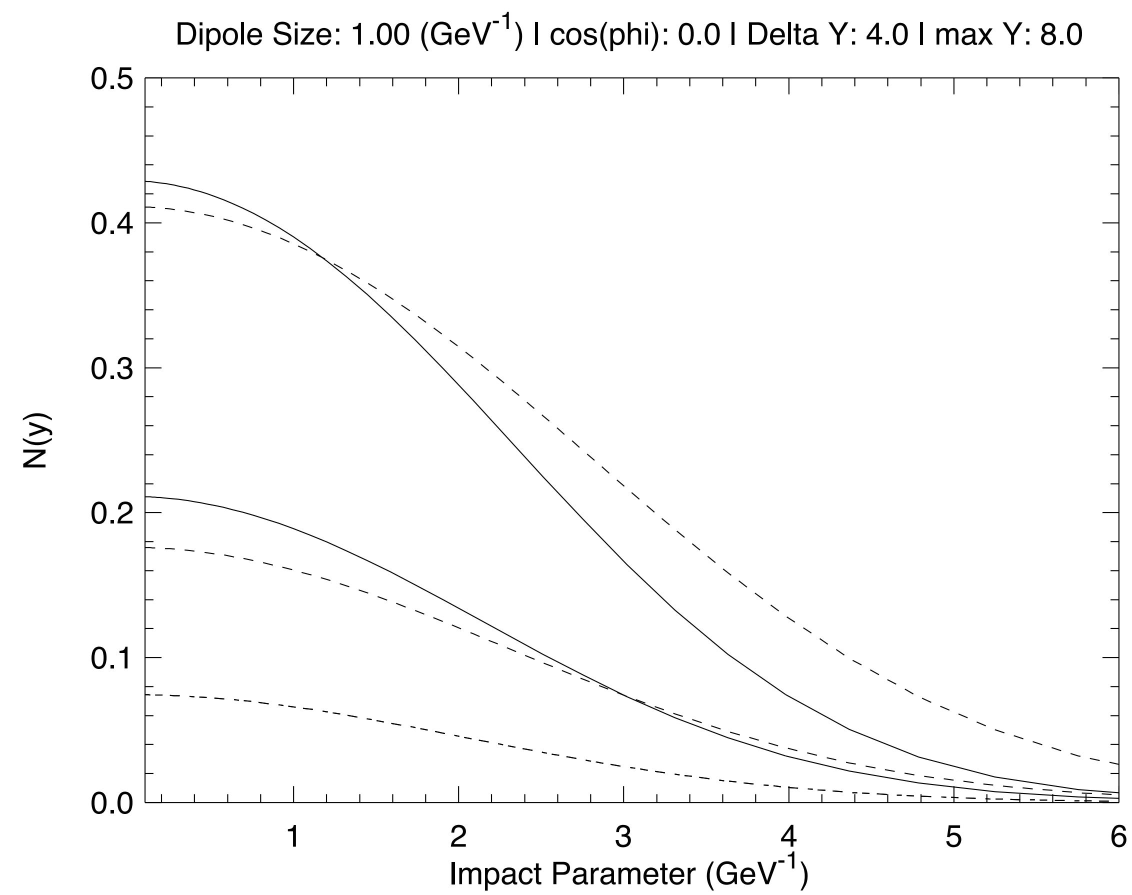
$$K = dx_{02}^2 \bar{\alpha}_s \frac{x_{01}^2}{x_{02}^2 x_{12}^2} \Theta\left(\frac{1}{m^2} - x_{02}^2\right) \Theta\left(\frac{1}{m^2} - x_{12}^2\right)$$

Cutoff: $m \simeq 1/\sqrt{2B_G} \sim 350\ \mathrm{MeV}$ $\sqrt{2B_G} \simeq 2.83\ \mathrm{GeV}^{-1}$

Cutoff included both in the evolution kernel and in the GM initial condition.
Refit the inclusive HERA data for F_2

Evolved solution for the dipole amplitude



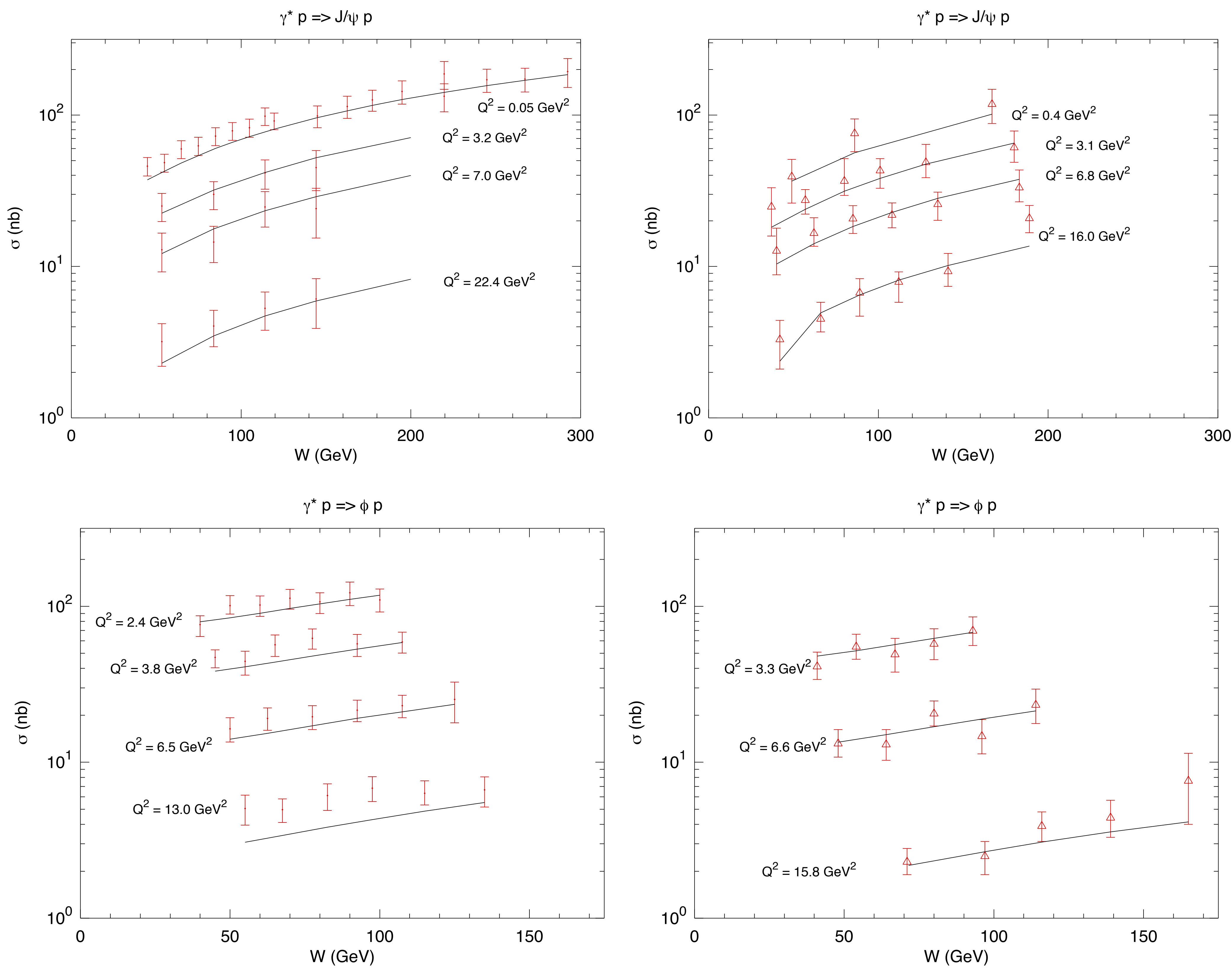


Profile in b: Solid line KMW, dashed lines BK with running coupling and cuts
Small x evolution leads to the broader distribution in impact parameter
Change of shape with decreasing x

Exclusive process: photo(production) and DIS

$J/\Psi, \phi$

exclusive production; comparison with HERA data

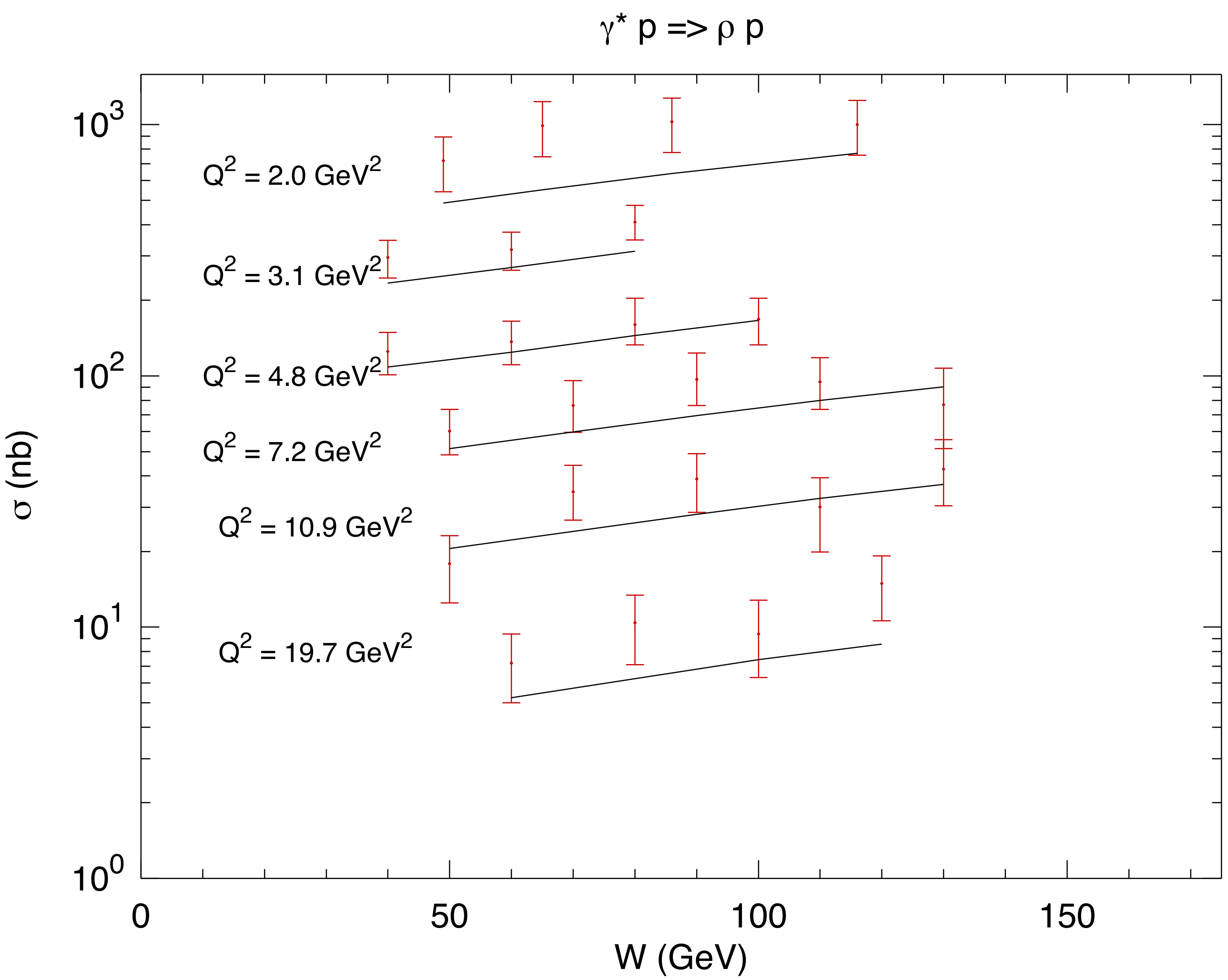


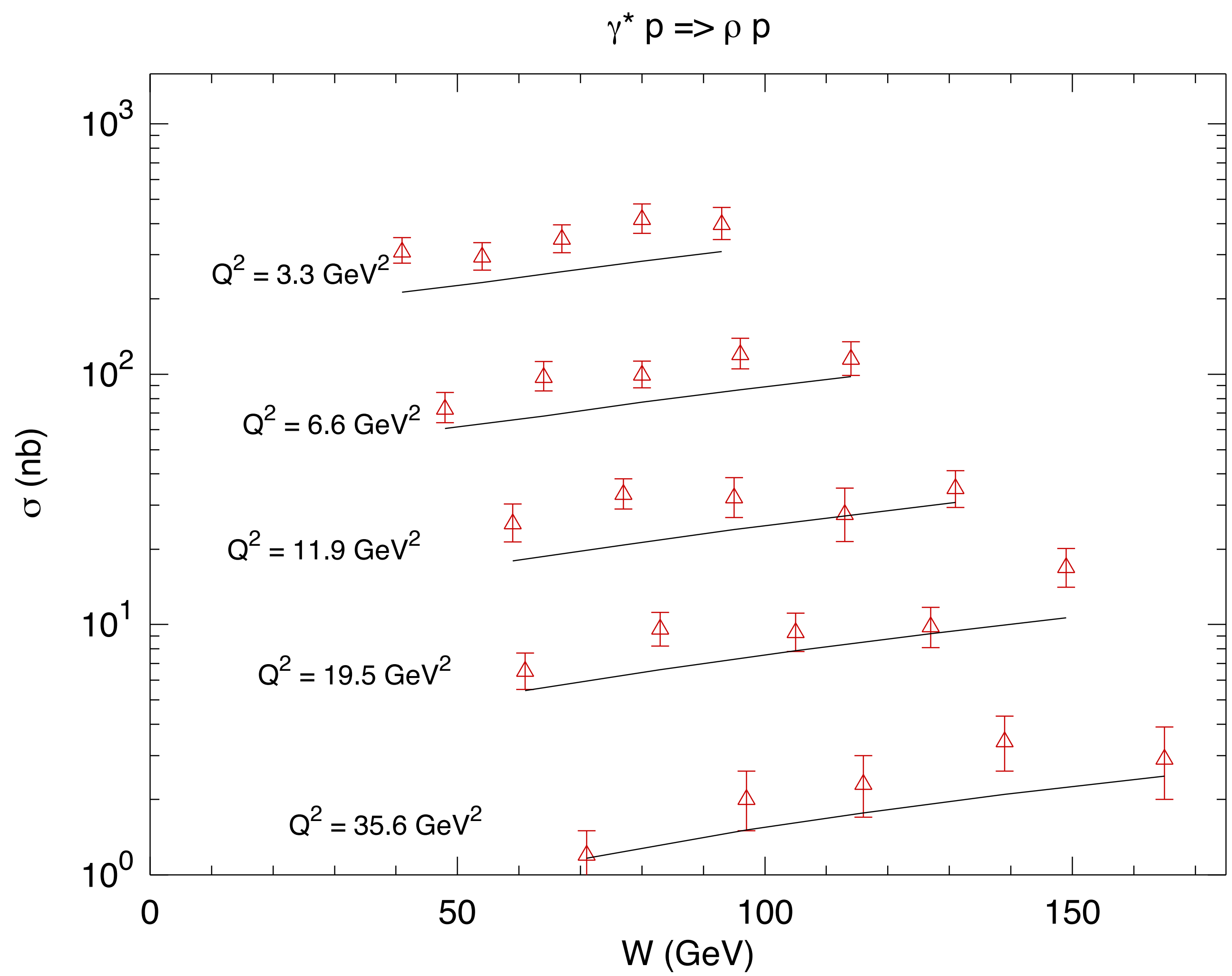
Integrated(over t): good description of the energy dependence

Anna Stasto: Exclusive VM (photo)production and low x dynamics

Exclusive diffraction

Integrated cross section





ρ production: normalization systematically underestimated especially at low scales
energy dependence is reasonably described

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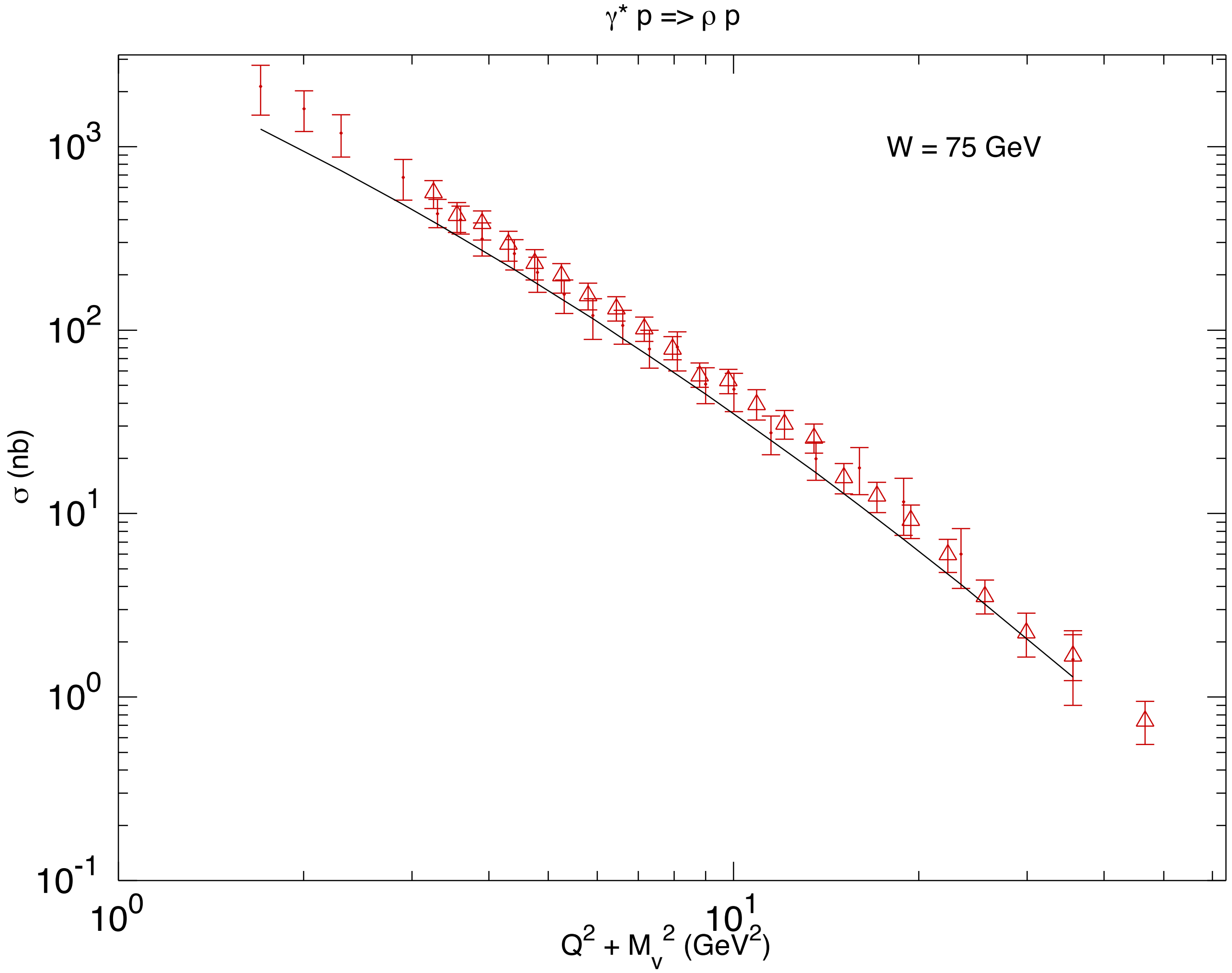
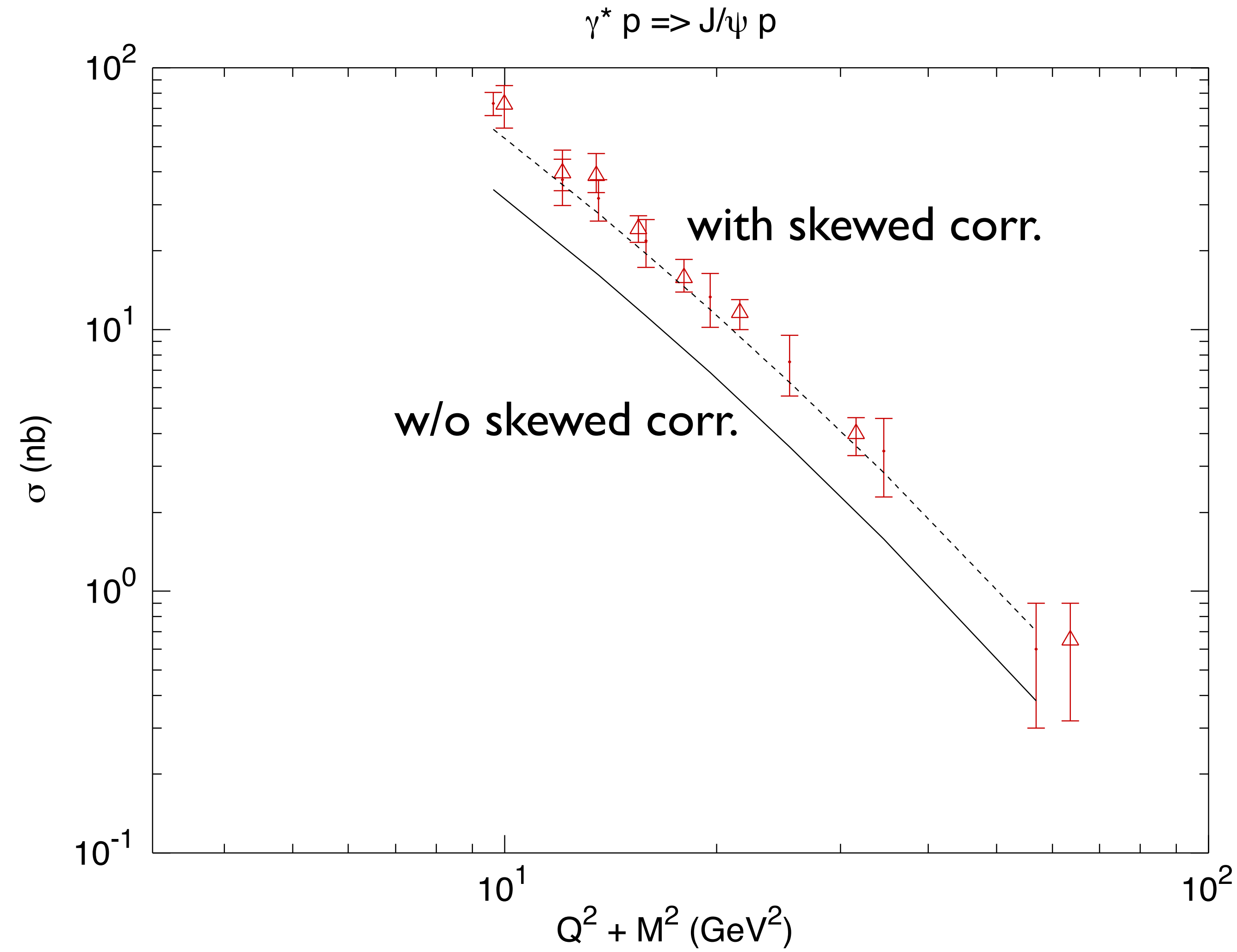
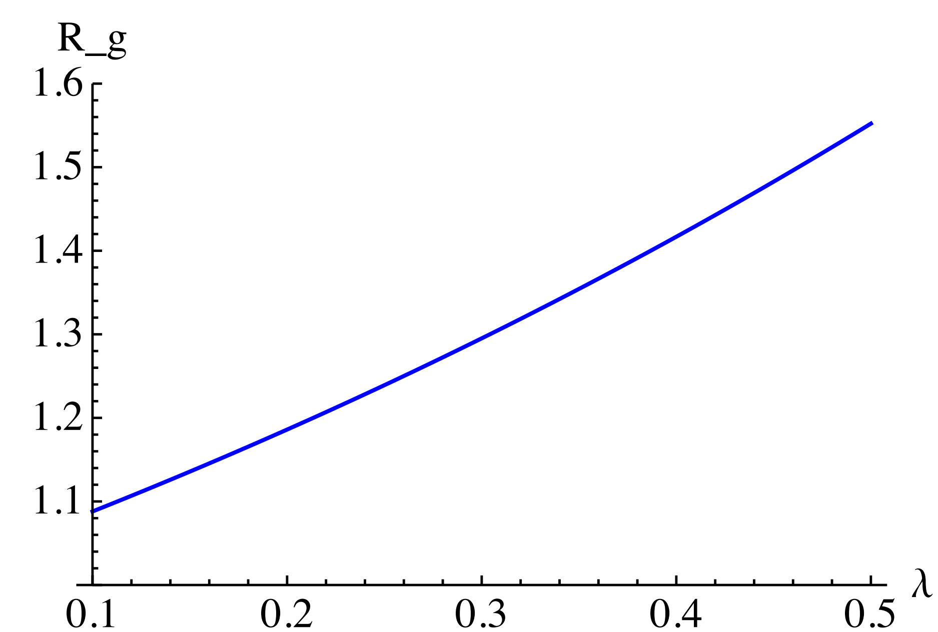
Correction from skewedness



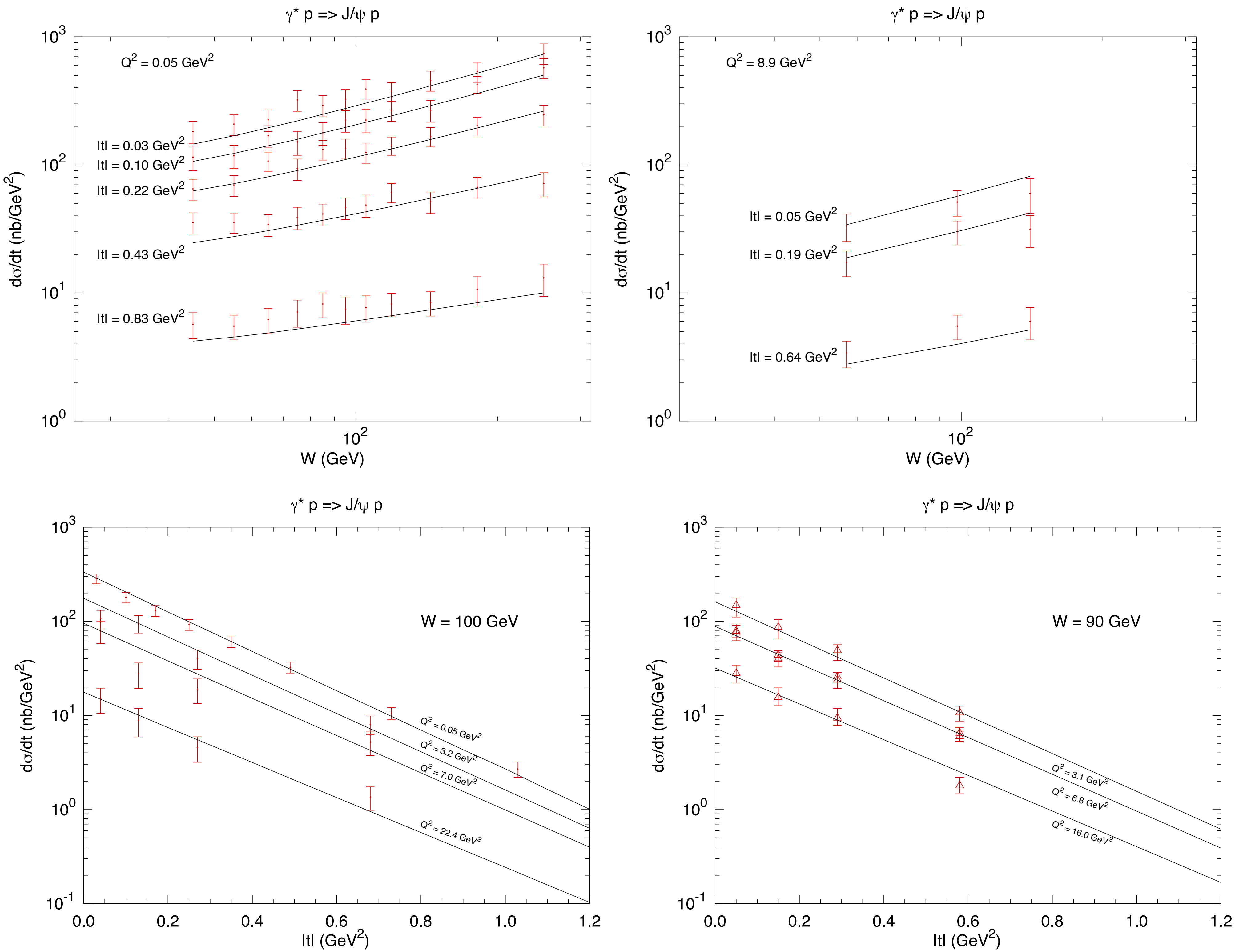


Effect of correction from skewed gluon distribution non-negligible

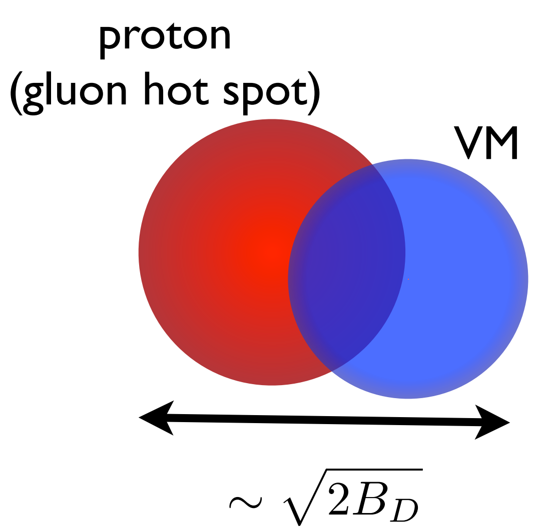
$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+\frac{5}{2})}{\Gamma(\lambda+4)}$$



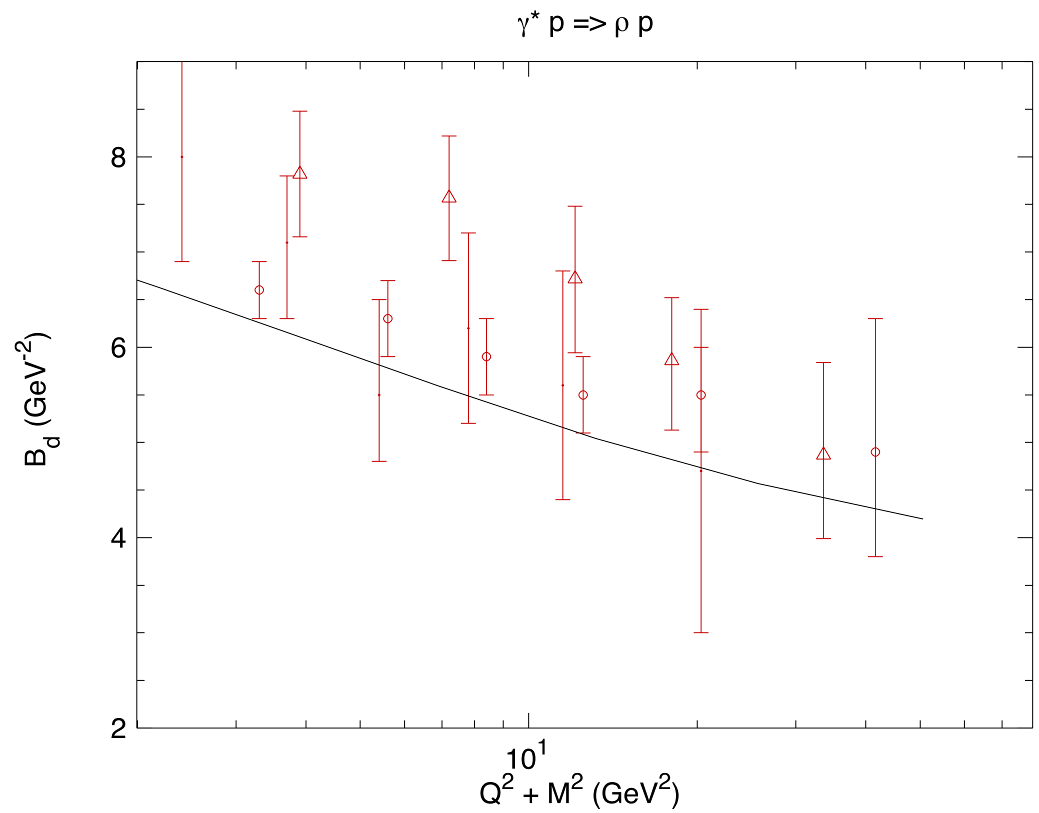
Differential cross section

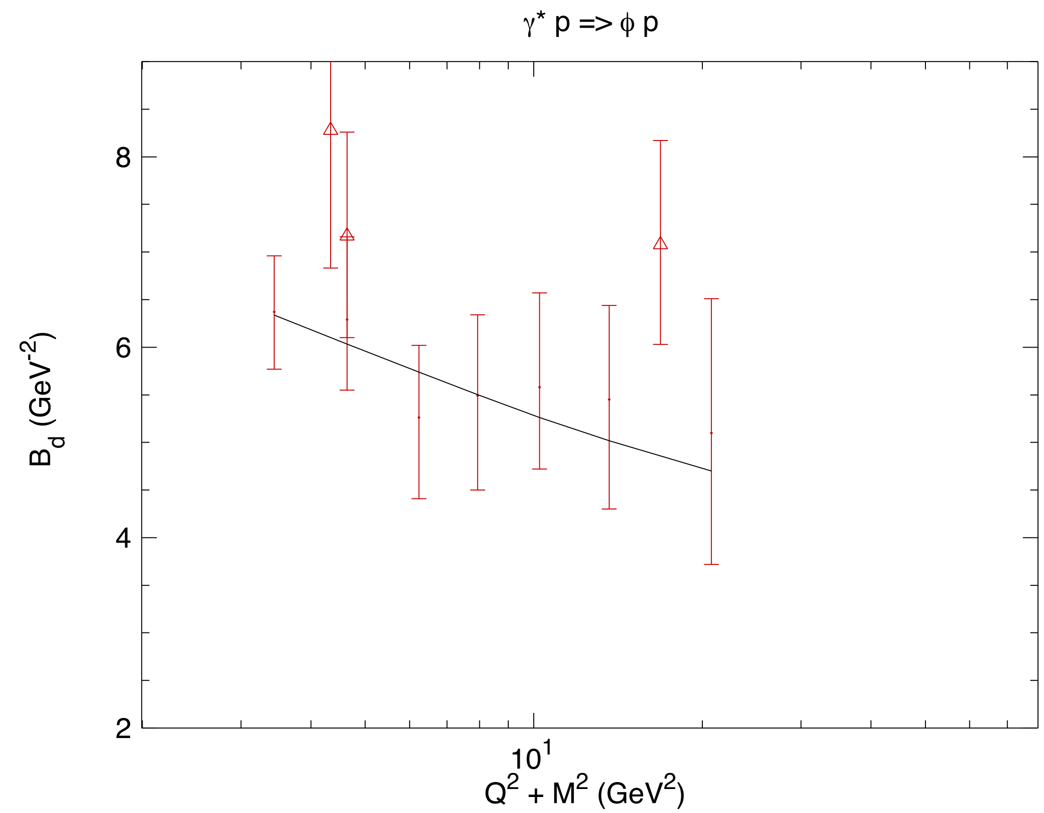


Diffractive slope

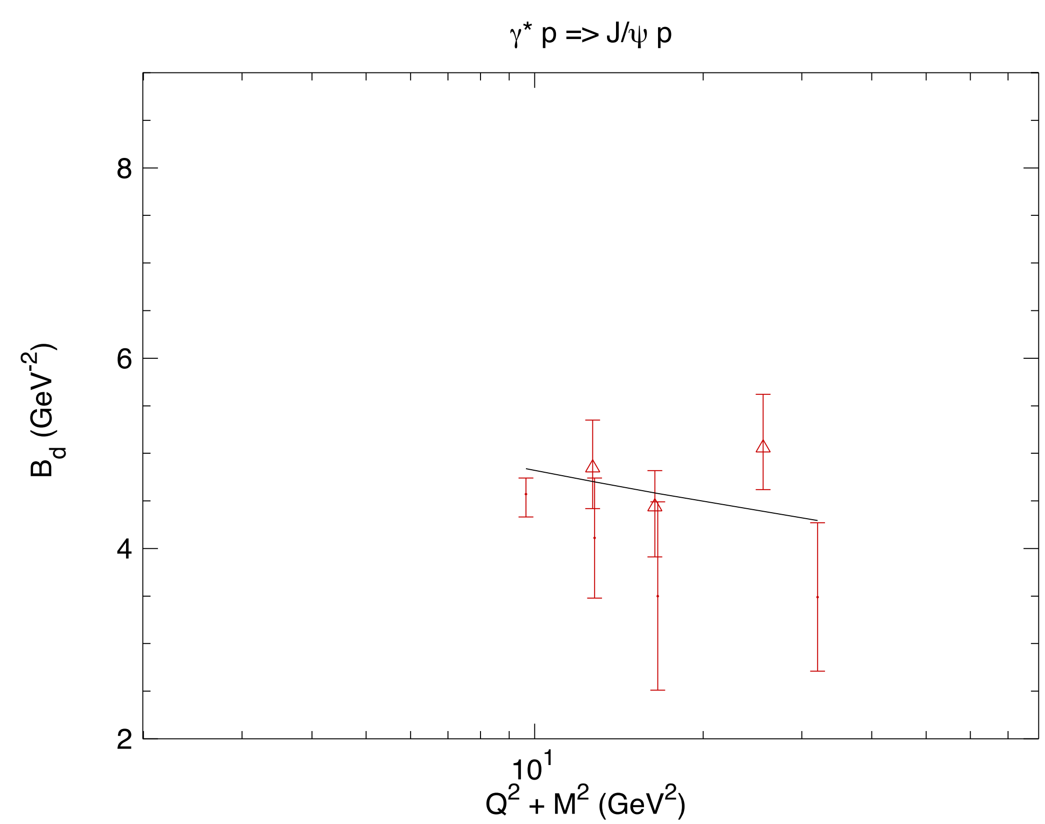


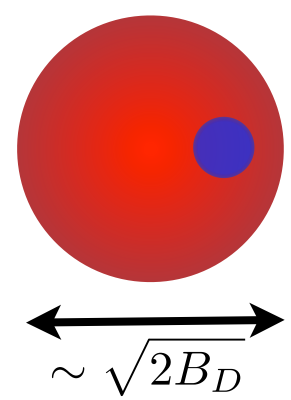
$$\frac{d\sigma}{dt} \sim e^{-B_D|t|}$$





- The value of B_D is closely related to the transverse size of the interaction region which is a combination of the size of the VM and the size of the gluon hot-spot in the proton.
- In the case of the lighter mesons it is the first one which prevails.
- For heavier mesons, it is the larger size of the gluon distribution in the proton. Thus it does not depend on Q^2 that much.

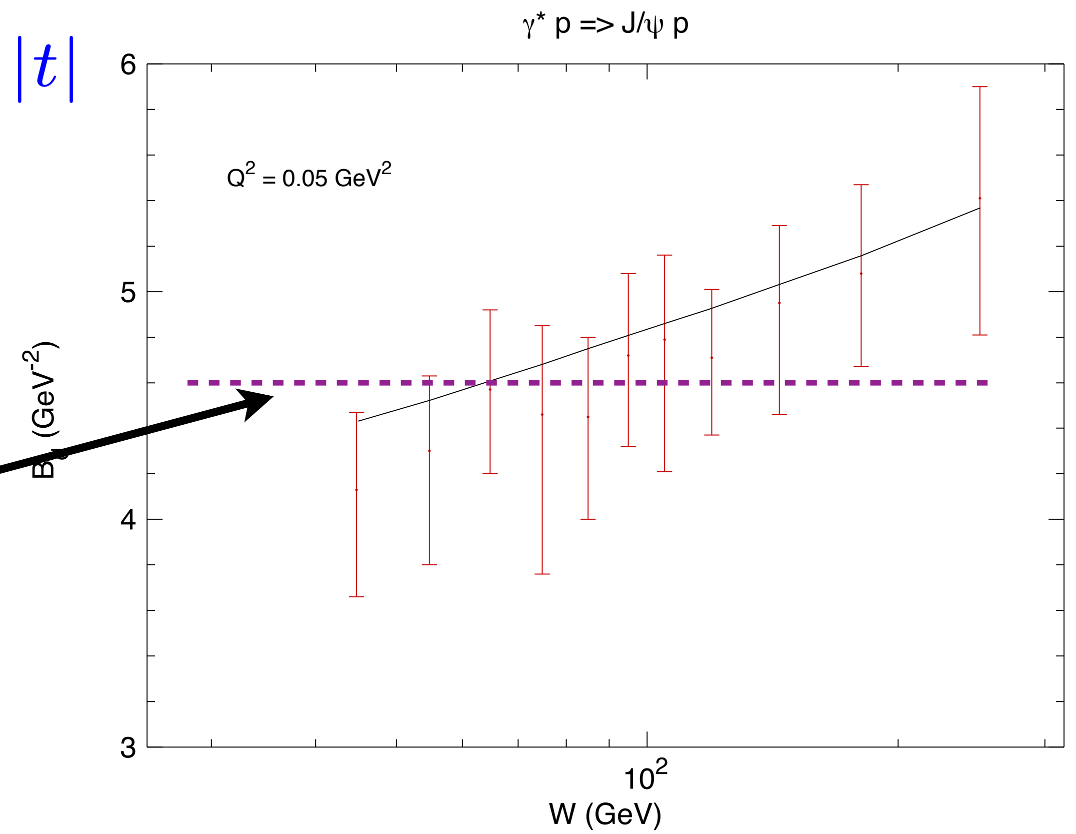


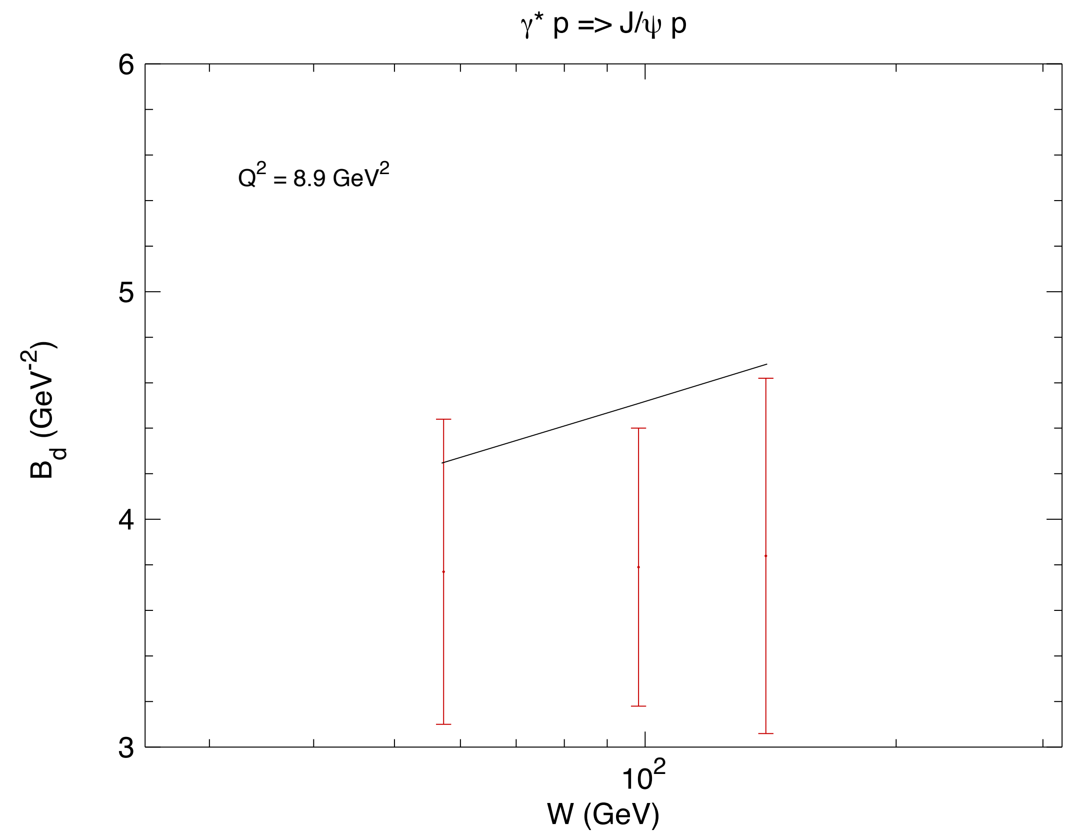


Slope vs energy

$$\frac{d\sigma}{dt} \sim e^{-B_D|t|}$$

Original b-Sat model has flat dependence

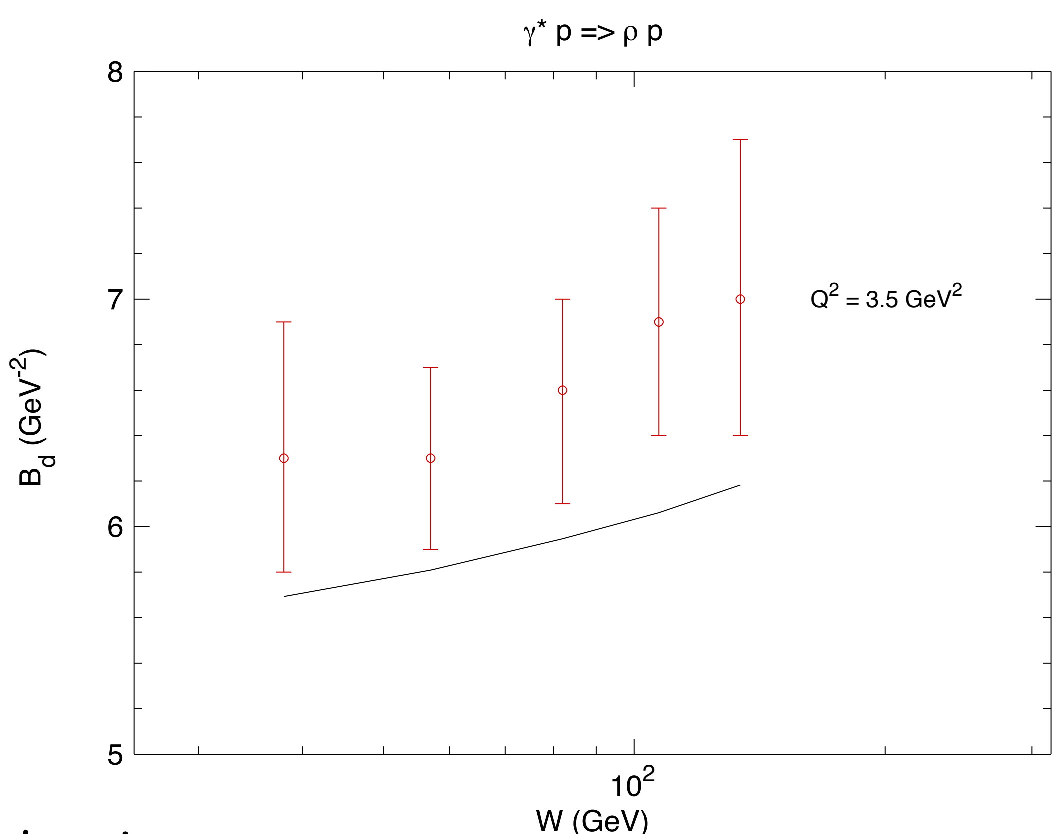




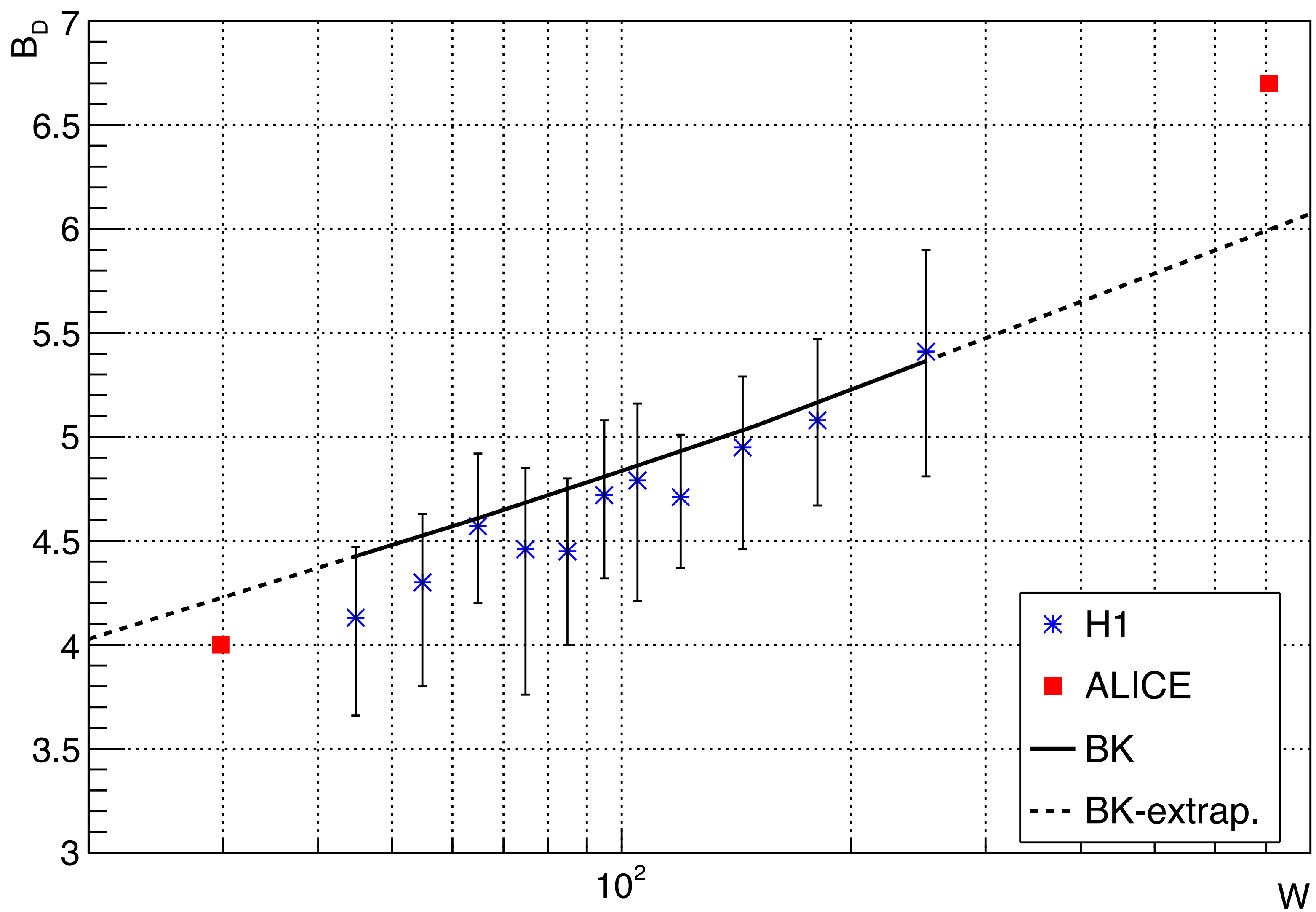
Intercept controlled by the initial profile in b, slope controlled by the mass regulator in the kernel.

Trend of the data nicely reproduced.

ρ on the lower side : more non-perturbative corrections



Slope vs energy



ALICE

$$B_D(W = 29.8\ \text{GeV}) = 4\ \text{GeV}^{-2}$$

$$B_D(W = 706\ \text{GeV}) = 6.7\ \text{GeV}^{-2}$$

- Reasonable description of the diffractive slope from dynamical prediction based on BK evolution with cutoff
- By making mass regulator smaller, the slope can be increased
- Functional dependence on energy could help determine type of cutoff: sharp or exponential

Summary and outlook

- Exclusive diffractive VM production using solution to the impact parameter dependent BK equation
- Coupling no longer regularized by saturation only. Need cuts on large dipoles. Large sensitivity to this regularization.
- Extra corrections: skewed gluon distribution, non-perturbative modification to the photon wave function.
- Exclusive diffraction of vector mesons, good description of data, in bins of t,W,Q, especially for heavier vector mesons. Lighter VM overall shape is reproduced, normalization is not well reproduced.
- Energy dependence of the diffractive slope generated by the model, depends on the phenomenological parameters, mainly set by the cutoff on the large dipoles.
- Looking forward to the more measurements of the energy dependence of t-distribution for J/ψ from LHC.