Diffractive di-jet production in the CGC

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SEMINAIRE de PHYSIQUE des PARTICULES, Ecole Polytechnique, CPHT, Sep 22, 2016

Outline:

- Introduction, motivation.
- Exclusive dijet production in coherent diffractive processes in DIS, and real (and virtual) photon-hadron collisions.
- Phenomenology at the LHC.
- Summary.

This talk is partly based on:

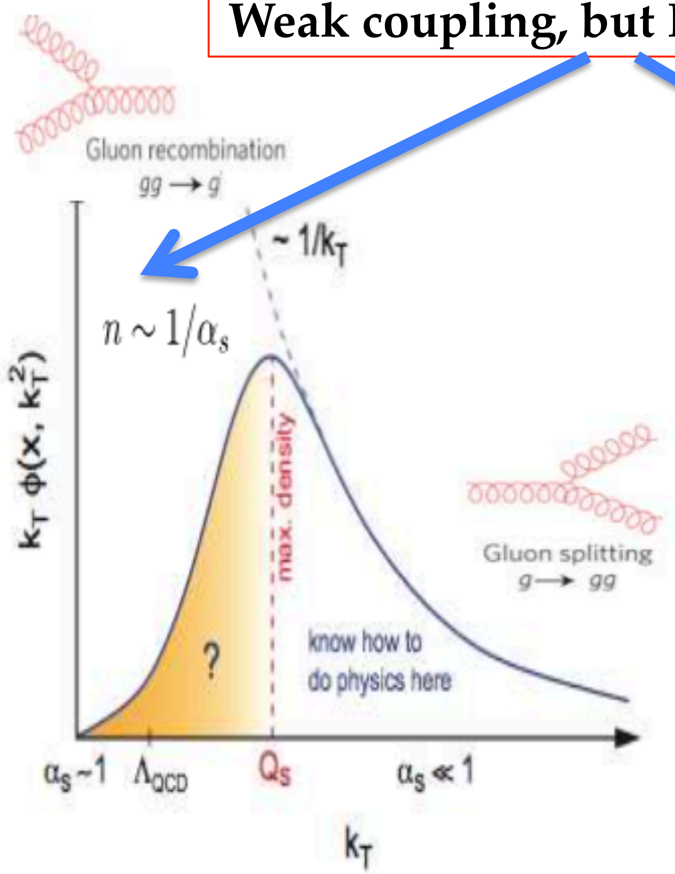
1) Altinoluk, Armesto, Beuf and Rezaeian, arXiv:1511.07452.
2) Armesto and Rezaeian, arXiv:1402.4831.

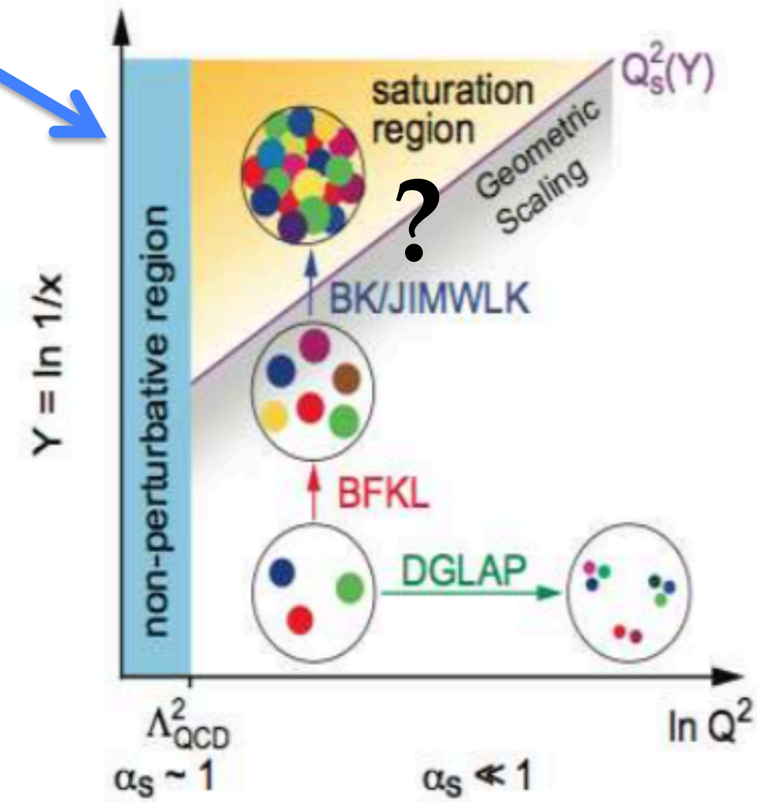
See also recent related paper:

1) Boussarie, Grabovsky, Szymanowski and Wallon, arXiv:1606.00419.
2) Hatta, Xiao and Yuan, arXiv:1601.01585.

Road map of strong interaction

Weak coupling, but Non-perturbative (small α_s, large $A\mu A\mu \sim 1/\alpha_s$)





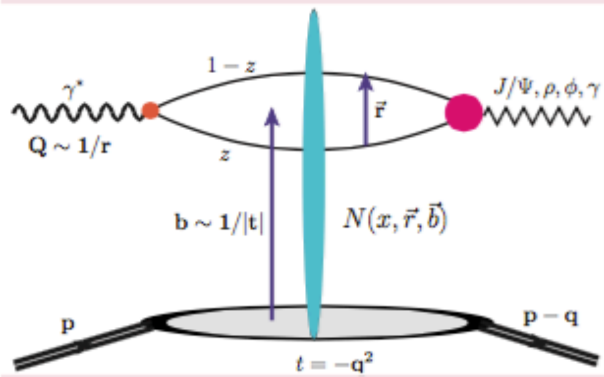
- Is the CGC perturbative approach reliable & systematic at the small-x?

  True when the saturation scale $Q_s \gg \Lambda_{QCD}$ ⟶ Is Q_s large enough?

- **What are the signatures of the gluon saturation phenomenon at HERA, RHIC, LHC, LHeC, EIC and FCC?**

Unified description of inclusive & exclusive processes in color-dipole factorization

Exclusive diffractive process: $\psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N} \otimes \phi^{V}_{q\bar{q}}$

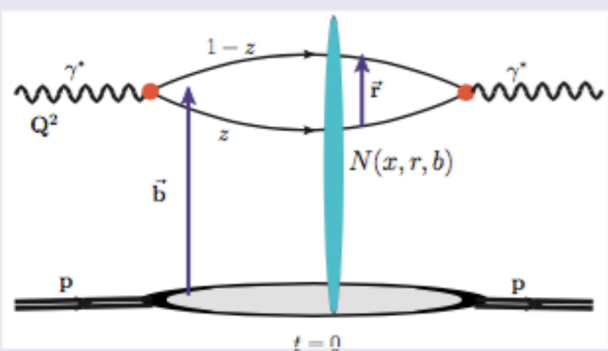


$$\mathcal{A}^{\gamma^* p \to Vp}_{T,L}(x, Q, \Delta) = 2i \int d^2\vec{r} \int_0^1 dz (\Psi_E^* \Psi)_{T,L} \int d^2\vec{b}\, e^{-i[\vec{b}-(1-z)\vec{r}]\cdot\vec{\Delta}} N(x, r, b)$$

$$\frac{d\sigma^{\gamma^* p \to Ep}_{T,L}}{dt} = \frac{1}{16\pi} \left| \mathcal{A}^{\gamma^* p \to Ep}_{T,L} \right|^2 \qquad t = -\Delta^2$$

- With corrections from the real part of the amplitude and skewedness effect $x \neq x'$
- $(b \to 1/|t|)$: t-distributions access impact-parameter distribution of interactions

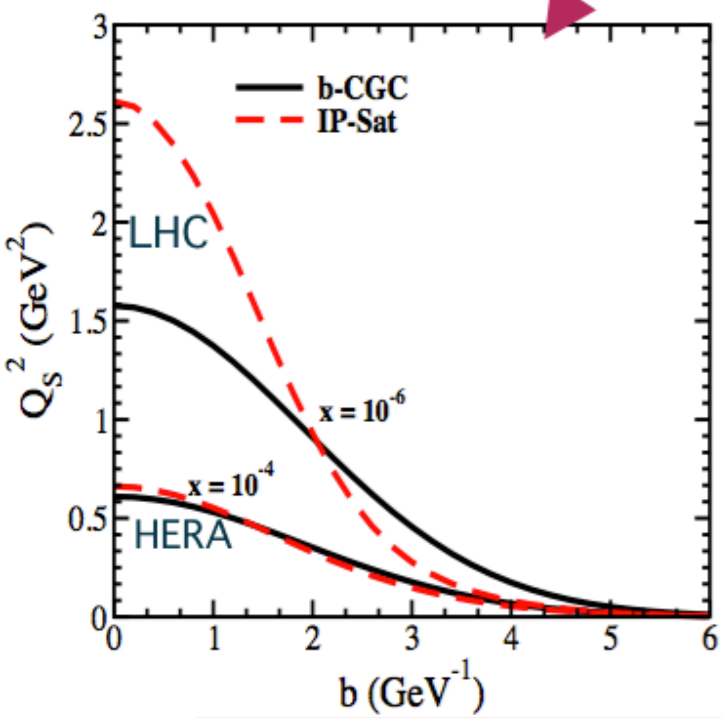
Inclusive deep-inelastic scattering (DIS): $\psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N} \otimes \psi^{\gamma}_{q\bar{q}}$

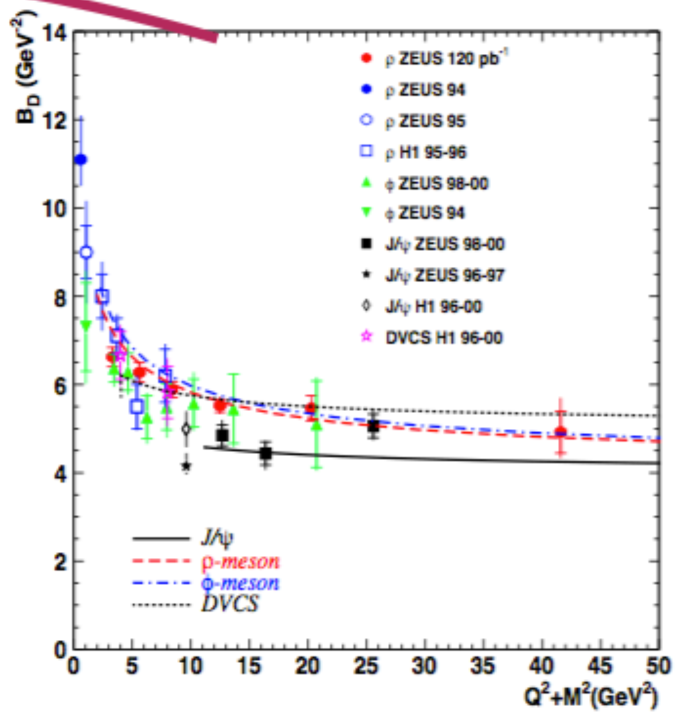


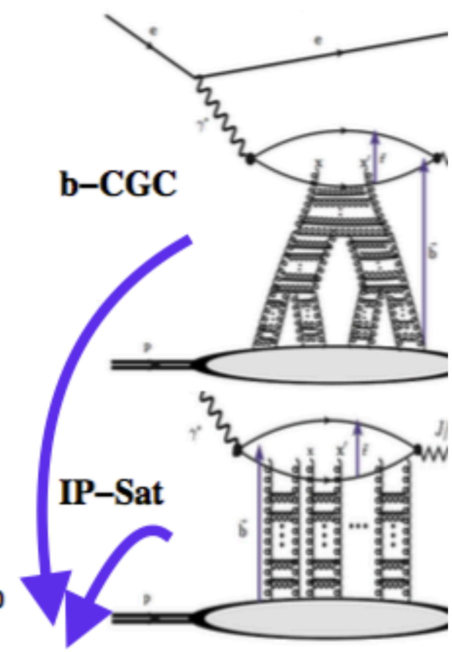
$$\sigma^{\gamma^* p}_{L,T}(Q^2, x) = Im\, \mathcal{A}^{\gamma^* p \to \gamma^* p}_{T,L}(x, Q, \Delta = 0)$$
$$= 2 \int d^2\vec{r} \int_0^1 dz\, |\Psi_{L,T}(r, z; Q^2)|^2 \int d^2\vec{b}\, N(x, r, b)$$

- DIS is less sensitive to the b-dependence compared to exclusive diffractive process

and **does not** probe $b \approx 0$, but $b \approx 2 \div 3\ \text{GeV}^{-1}$.







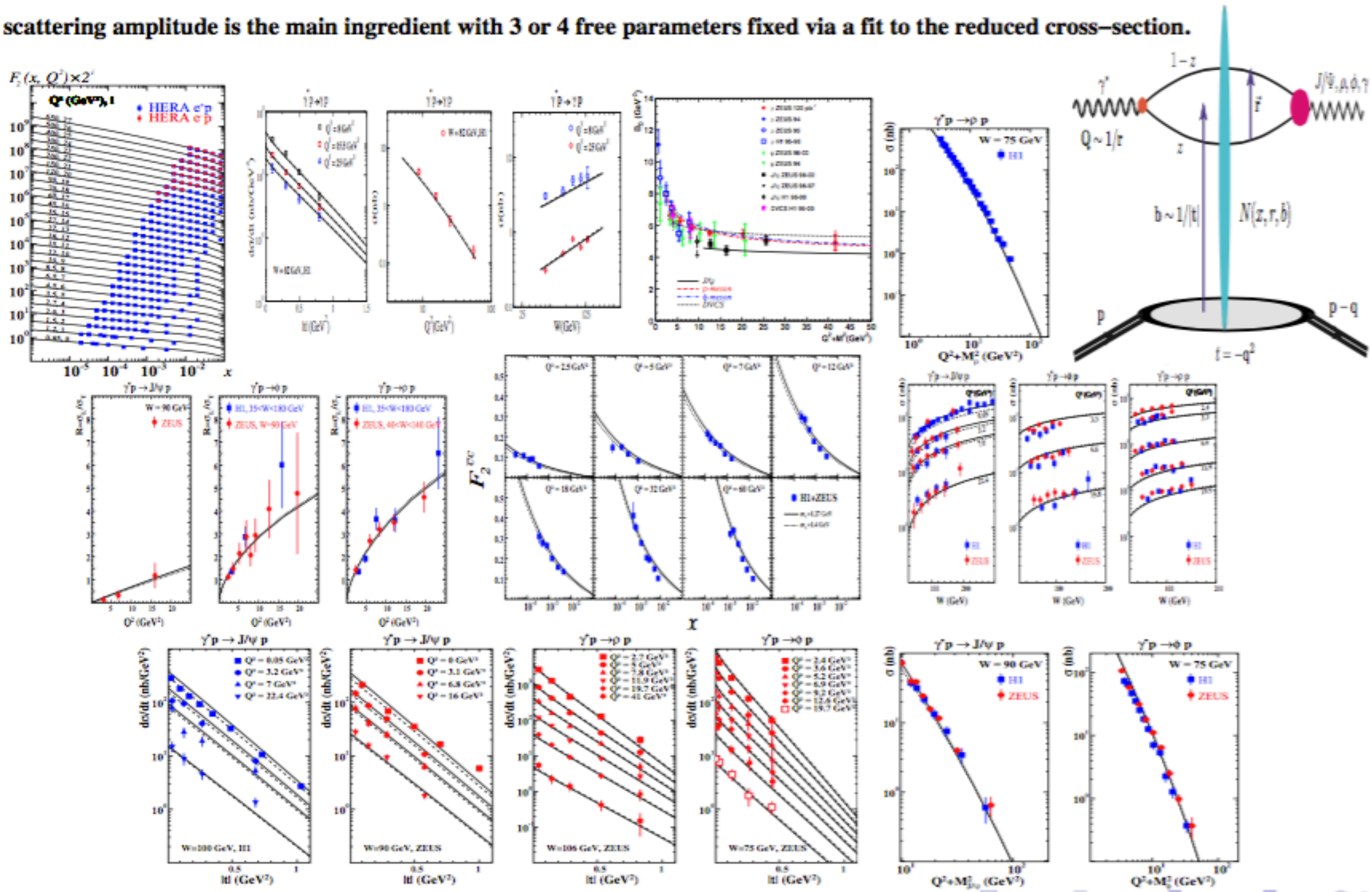
$$\frac{d\sigma^{\gamma^* p \to Ep}_{T,L}}{dt} \approx e^{-B_D|t|} \text{ (large } Q^2) \Longleftrightarrow Q_s^2(x,b) \approx Q_s^2(x) e^{-b^2/2B_D}$$

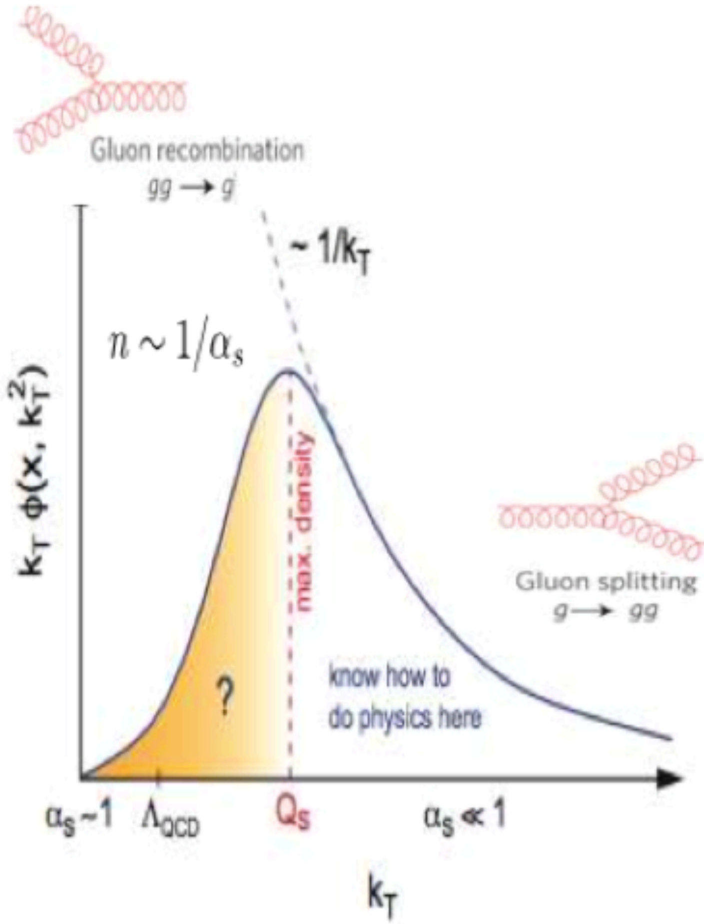
- At a fixed Q^2, the typical dipole size is bigger for lighter vector meson $\Longrightarrow$ validity of the above asymptotic expression is postponed to a higher Q^2.
- t-slope B_D **gives the width of saturation scale distribution in proton.**

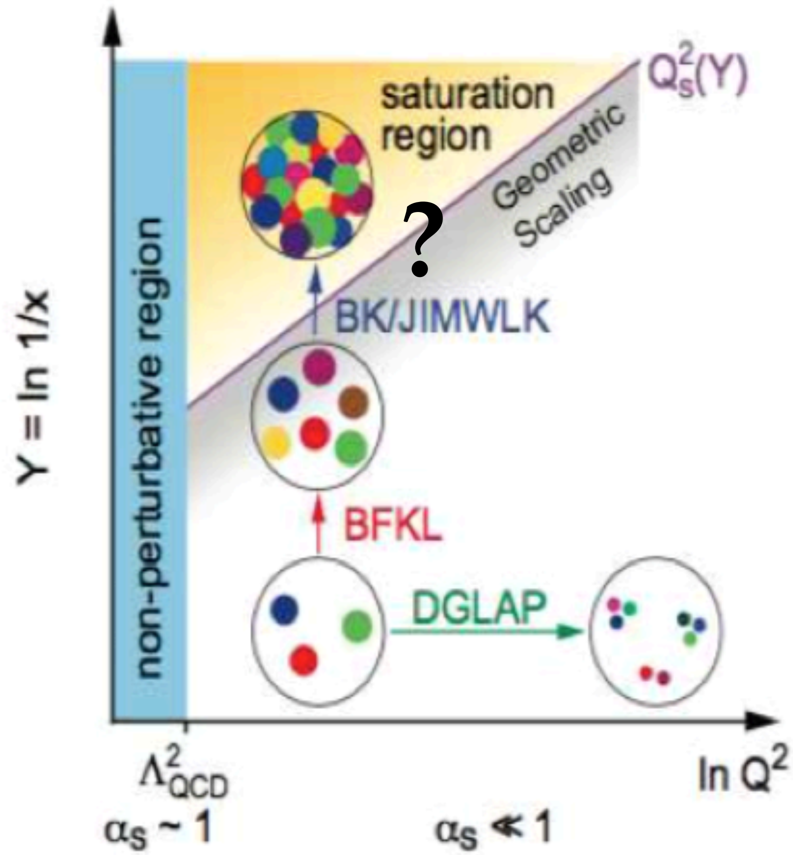
A unified description of combined inclusive HERA data & diffractive data in CGC

Rezaeian, Siddikov, Van de Klundert, Venugopalan, arXiv:1212.2974; Rezaeian, Schmidt, arXiv:1307.0825

The dipole scattering amplitude is the main ingredient with 3 or 4 free parameters fixed via a fit to the reduced cross–section.



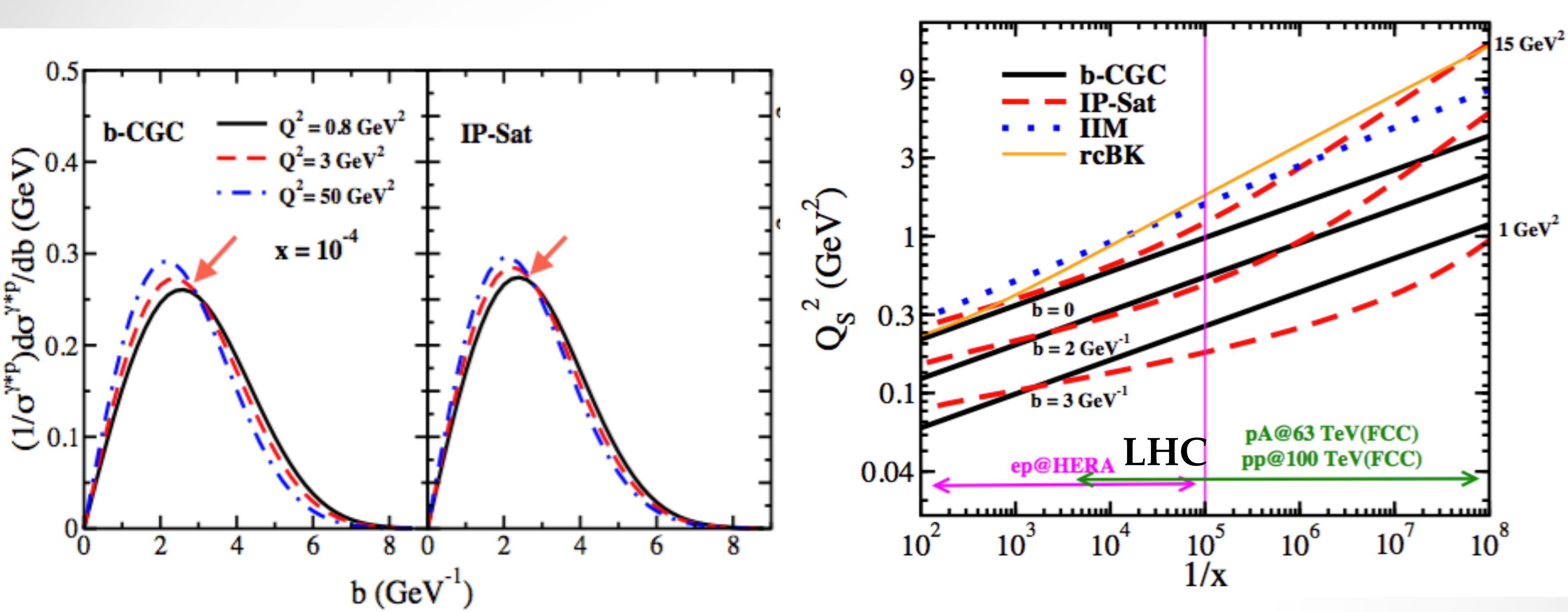




- Is the CGC perturbative approach reliable & systematic at the small-x?

Is the saturation scale large enough?

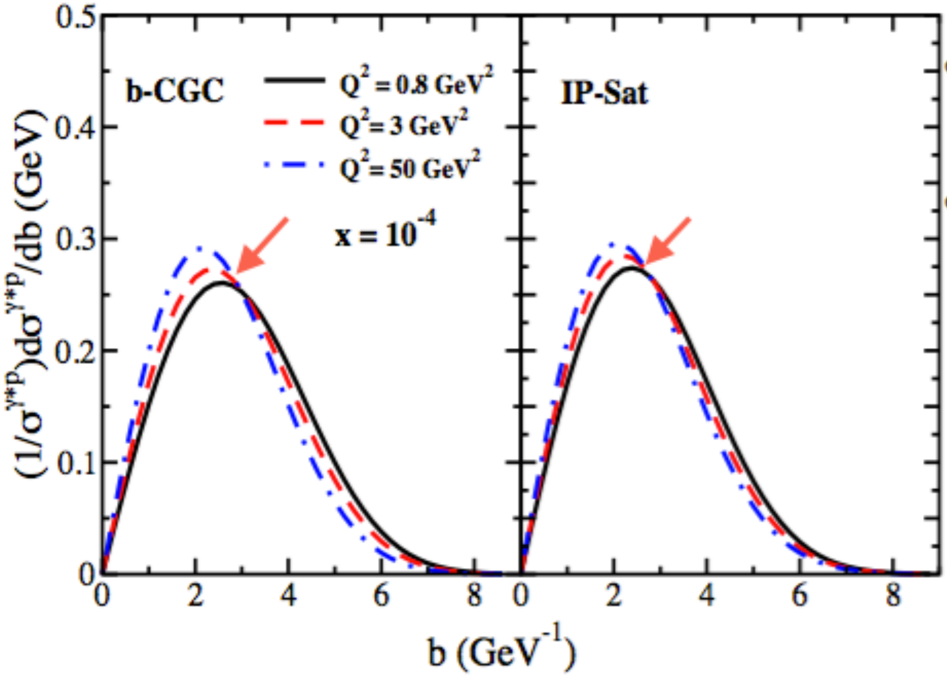
The impact-parameter b and x- dependence of the saturation scale for proton

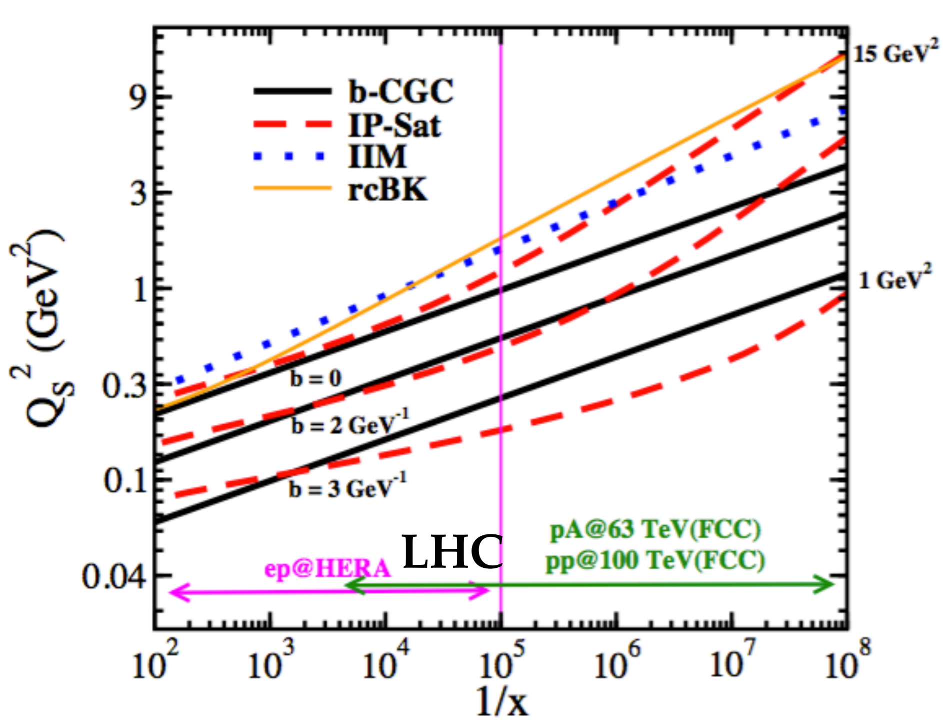


- The typical impact-parameter probed in the total $\gamma^* p$ cross-section is about $b \approx 2 \div 3\,\text{GeV}^{-1} \Longrightarrow$ less constrain for $b \approx 0 \Longrightarrow$ large $|t|$ diffractive data are needed (data are not yet available).

Impact *independent* saturation models significantly overestimate Q_s.

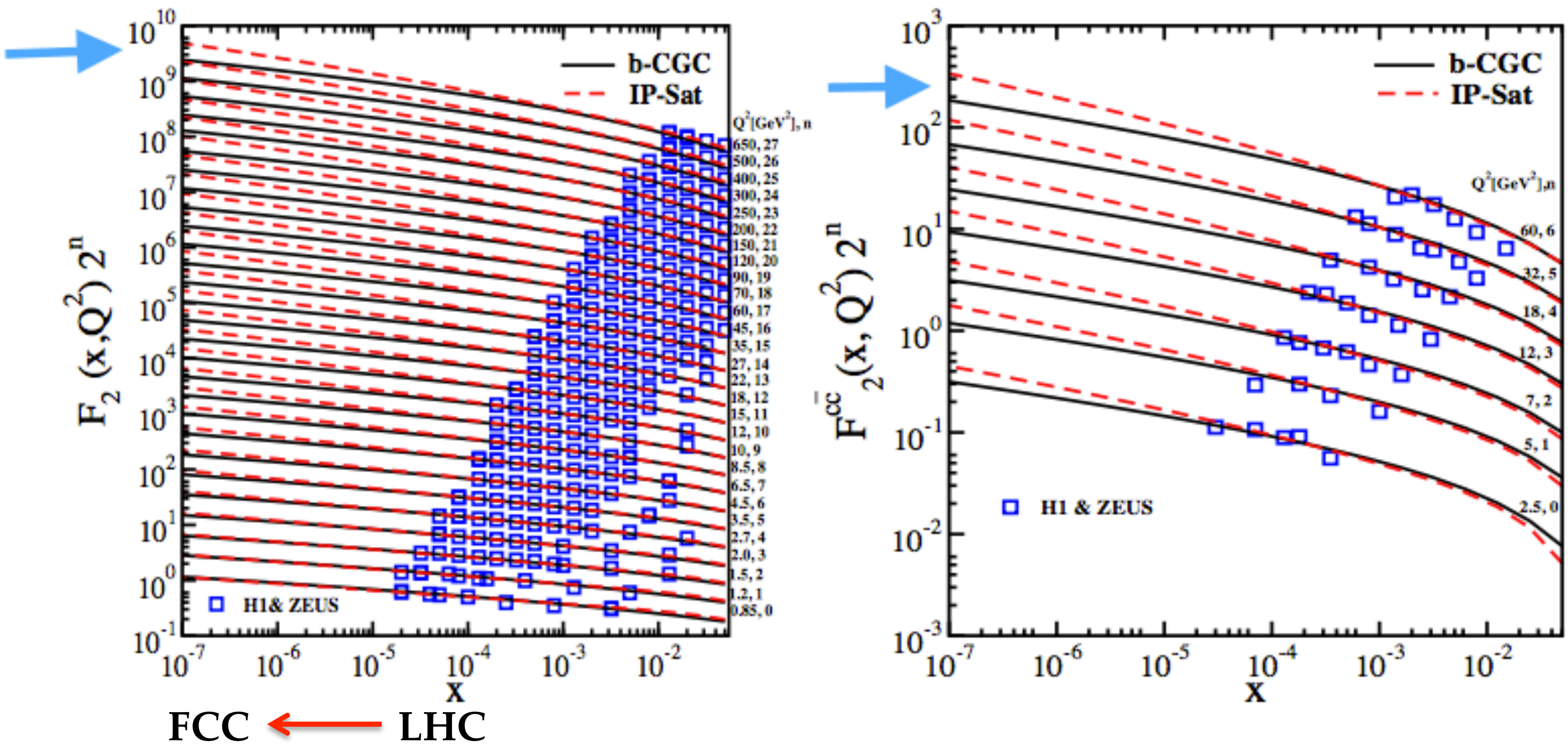
The impact-parameter b and x- dependence of the saturation scale for proton





- The typical impact-parameter probed in the total $\gamma^* p$ cross-section is about $b \approx 2 \div 3\,\mathrm{GeV}^{-1} \Longrightarrow$ less constrain for $b \approx 0 \Longrightarrow$ large $|t|$ diffractive data are needed (data are not yet available).
- The proton saturation scale at HERA: $Q_s(x, b) < 1$ GeV, at the LHC: $Q_s^2(x, b) < 1.5 \div 3\,\mathrm{GeV}^2$ and at the FCC: $Q_s^2(x, b) \leq 4 \div 15\,\mathrm{GeV}^2$.

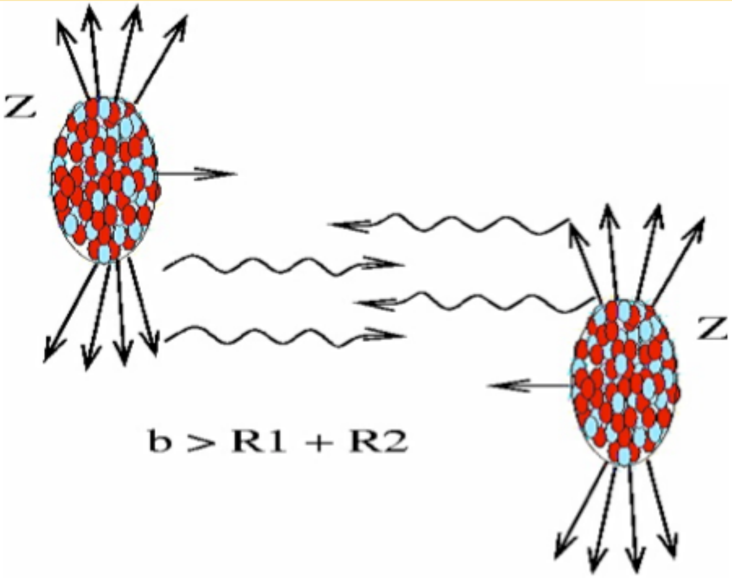
CGC (IP-Sat v. b-CGC) description of combined HERA data

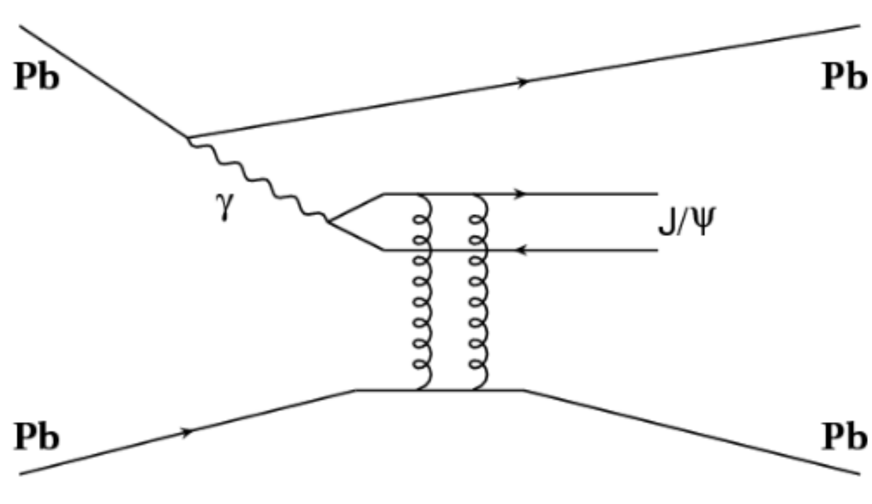


- $F_{c\bar{c}}$, F_2 data were not included in the fit. → *No biased, No over-fitted.*
- The difference among models can be considered as our current theoretical uncertainties $\Longrightarrow$ significant uncertainties at small-x $\Longrightarrow$ Future exps with $x_B < 10^{-5}$ (LHeC, EIC) can constrain saturation models.

Photo-vector-meson production in ultra-peripheral collisions at LHC

▸ Ultra-Peripheral Collision: limit $Q^2 = 0$





UPC's give a strong constraint on gluons at small x (10^{-3}-10^{-5}), but . . .

❑ pQCD:

No factorization theorem for exclusive cross section $\sim xg(x,Q^2)^2$.

No full NLO calculation, pdf scheme, scale…?

❑ CGC:

✓ Proven factorization.

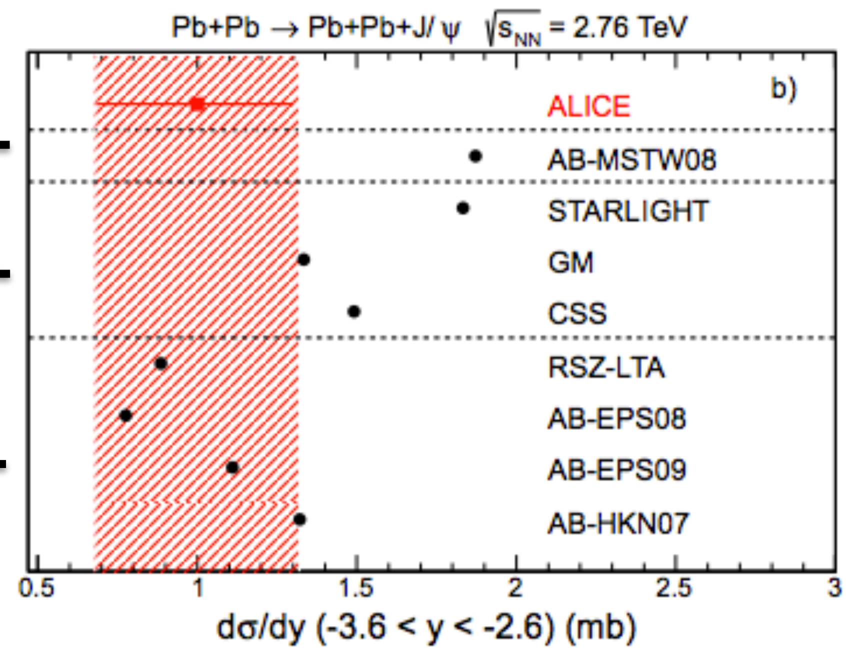
Nuclear saturation scale needs to be modeled & unconstrained.

Photonuclear vector meson production in ultra-peripheral collisions at LHC

Without nuclear effects

Color dipole models
(modeling nuclear Q_s?)

With nuclear gluon shadowing



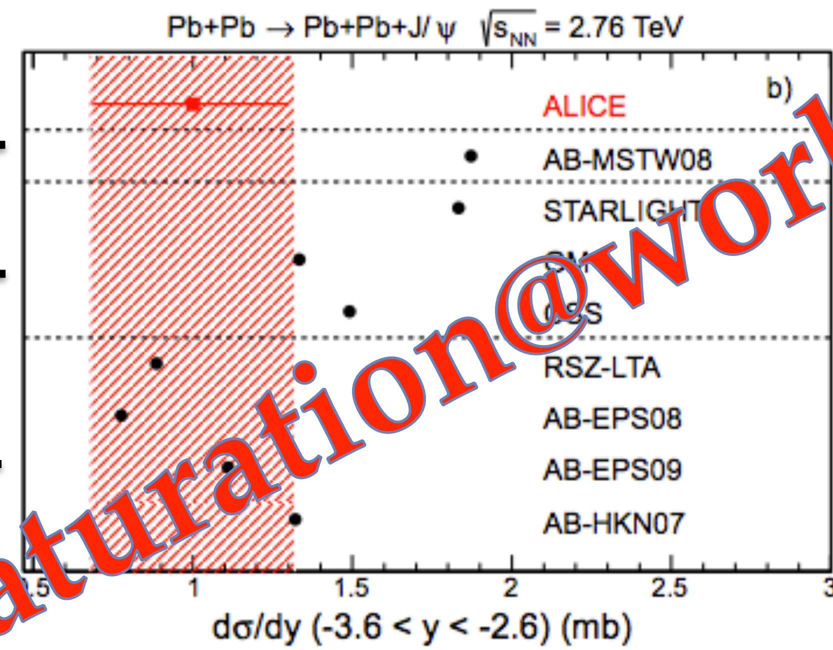
➢ ALICE conclusión (arXiv:1303.2009):

The cross section cannot be understood from a simple scaling of the nucleon cross section neglecting nuclear effects. Best agreement is seen with models which include nuclear gluon shadowing.

Without nuclear effects ←

Color dipole models (modeling nuclear Q_s?) ←

With nuclear gluon shadowing ←



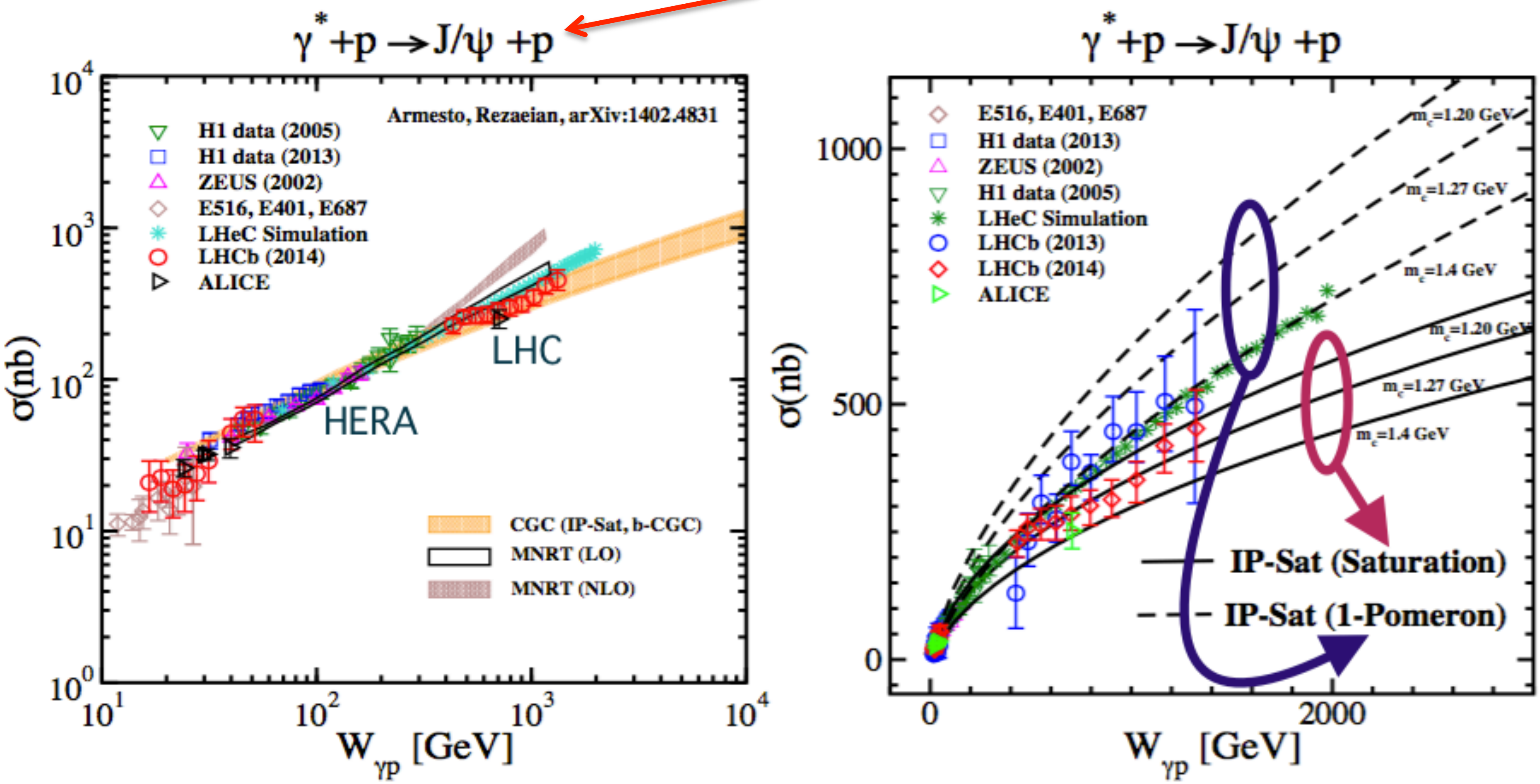
Shadowing or saturation@work

- **ALICE conclusión (arXiv:1303.2009):**

The cross section cannot be understood from a simple scaling of the nucleon cross section neglecting nuclear effects. Best agreement is seen with models which include nuclear gluon shadowing.

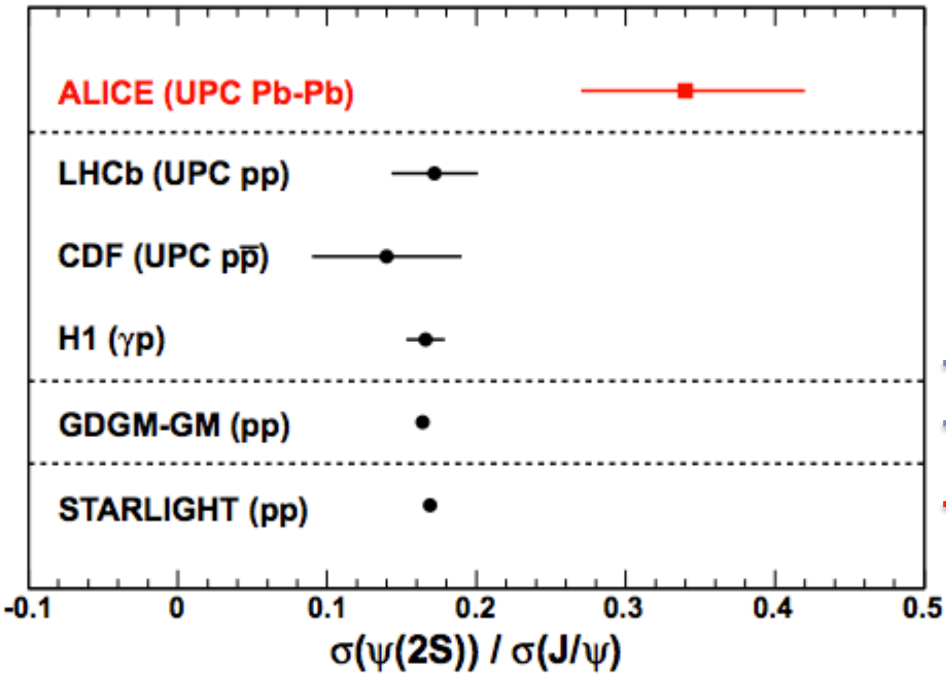
Photo-production of J/ψ from HERA to the LHC

Proton Q_s constrained from HERA. Zero free parameters!

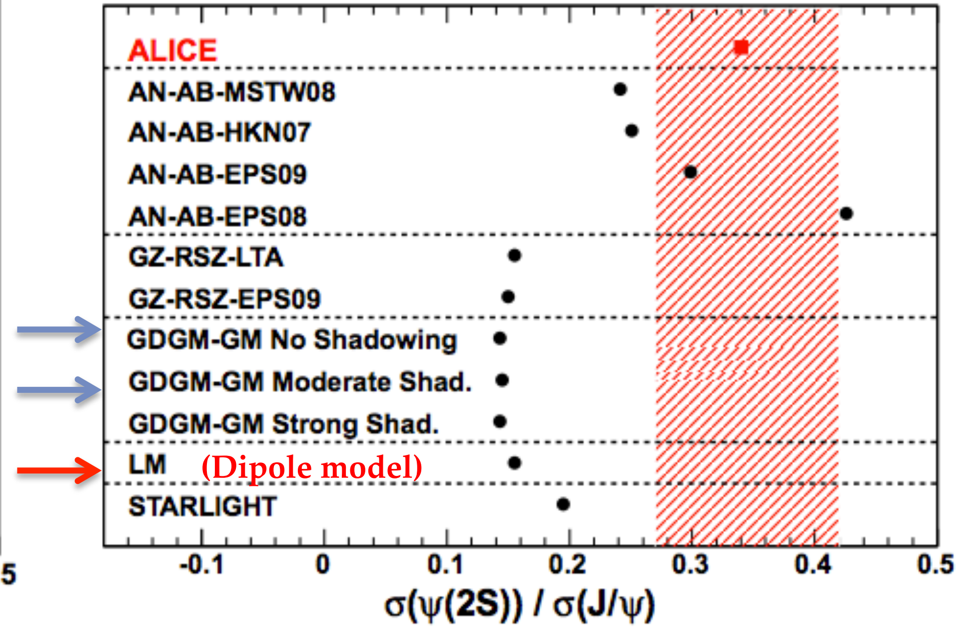


- The LHCb and ALICE data seem to favor the CGC/Saturation predictions.
- The uncertainties related to the charm mass is very large.

Photonuclear Ψ(2S) production in ultra-peripheral collisions at LHC



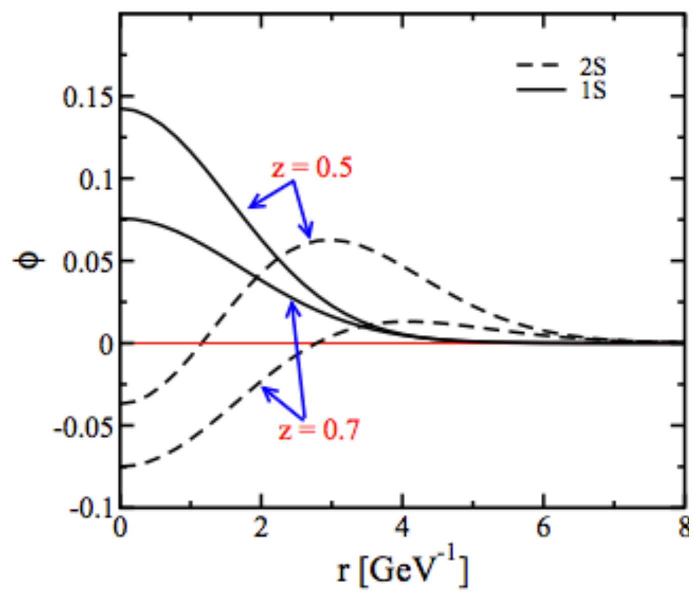
arXiv:1508.05076



Ψ(2S) wave function has a node and is heaver than J/Ψ

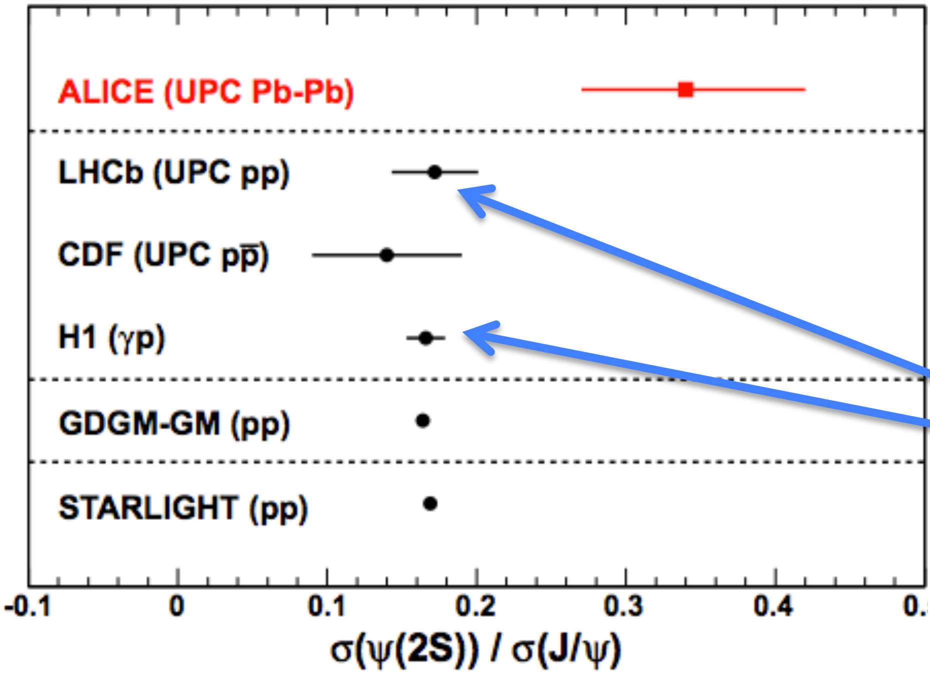
→ Large suppression compared to J/Ψ.

Data remain to be understood? Stay tuned!

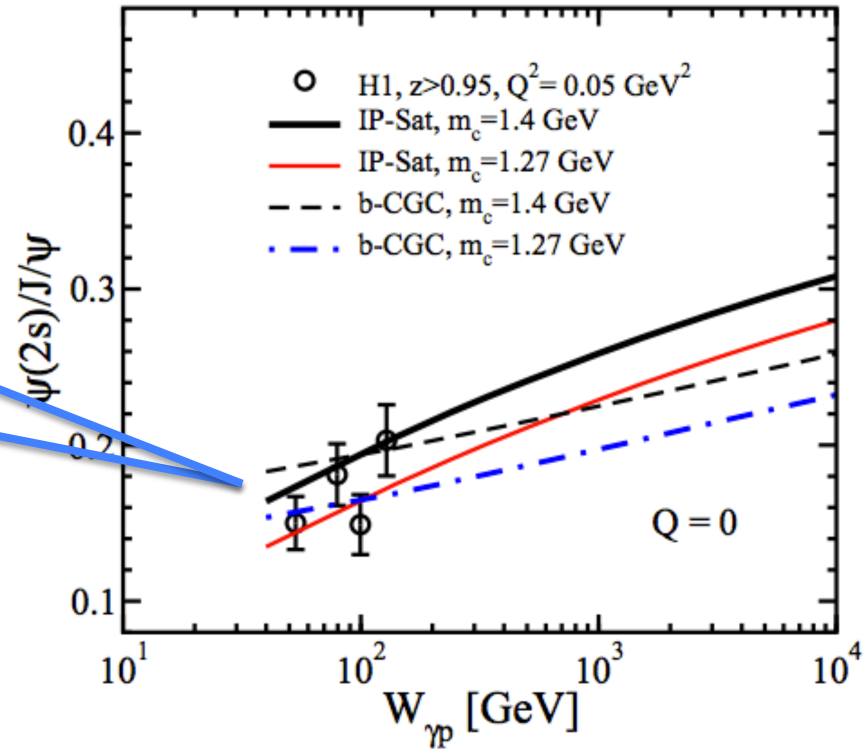


Photonuclear Ψ(2S) production in ultra-peripheral collisions at LHC

ALICE, arXiv:1508.05076



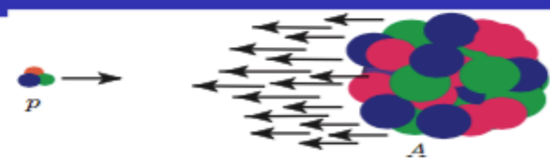
Armesto, AR, arXiv:1402.4831



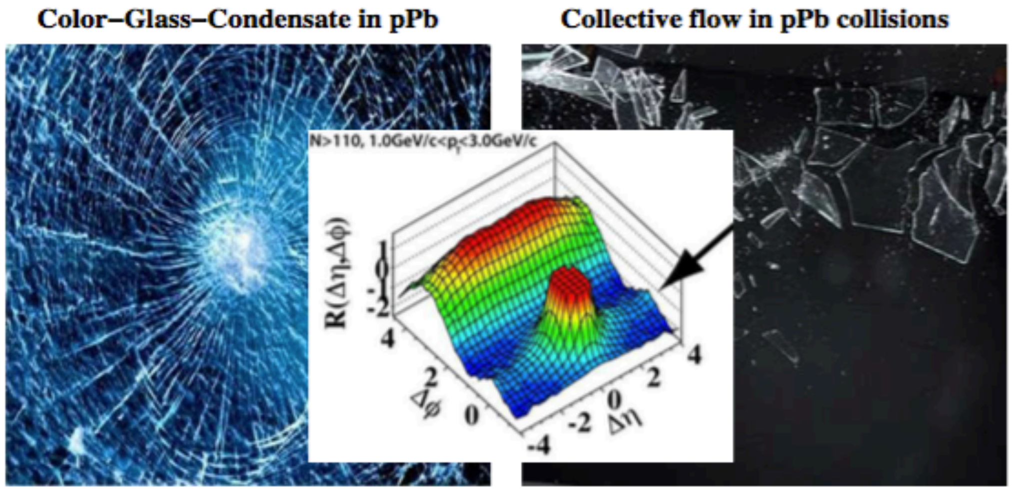
- The ratio is certainly energy-dependent!.
- The energy-dependence of the ratio can be a good test of the color-dipole picture!.

Why diffractive dijet in DIS?

What is origin of the observed Ridge phenomenon in p+p(A) collisions?



Motivation:



- Does the ridge phenomenon in p+p(A) collisions mainly come from initial-state or final-state effects?
- Is the "ridge" universal phenomenon, for all different two-particle productions in p+p(A) collisions?

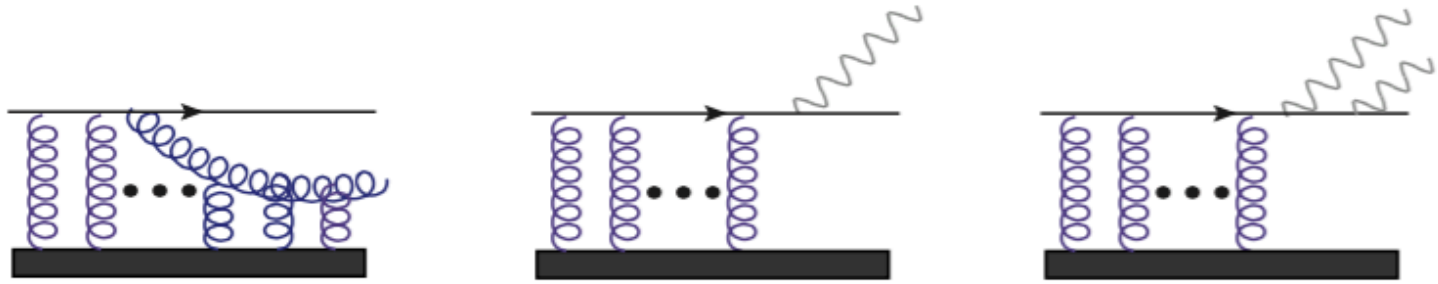
❑ **Is there a ridge-like phenomenon for diffractive production?**

❑ **Is there a ridge-like structure in DIS dijet production in the saturation regime?**
A system with a large saturation scale ⟺ a dense system.
NO QGP in DIS on proton target (and EIC!).

Back-to-back decorrelations in inclusive production in the CGC

Motivation:

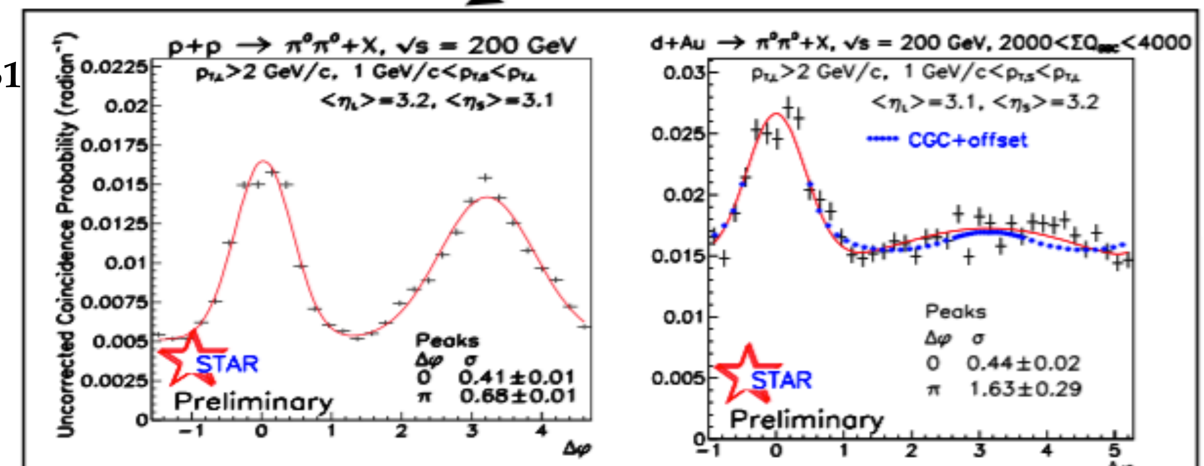
Dihadron | **Photon–hadron** | **Diphoton**



Measured at RHIC
PHENIX & STAR (2011)

Not yet measured | **Not yet measured**

Marquet, arXiv:0708.0231



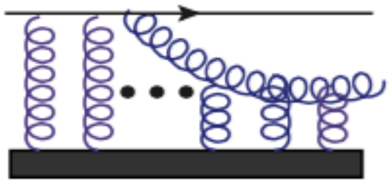
Braidot,arXiv:1008.3989

Gelis, Jalilian-Marian, hep-ph/0205037.
Kovner, AR
arXiv:1508.02412

- Back-to-back correlation gets suppressed due to the saturation scale. This is universal to all **inclusive** two-particle production shown above.

Back-to-back decorrelations in inclusive production in the CGC

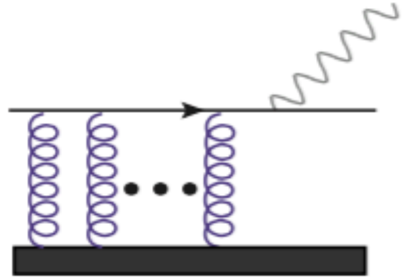
Dihadron



Measured at RHIC

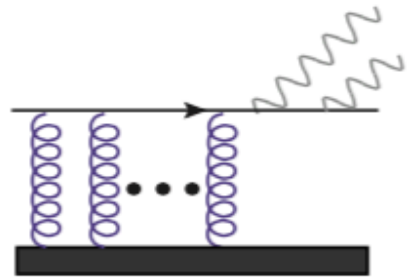
PHENIX & STAR (2011)

Photon–hadron

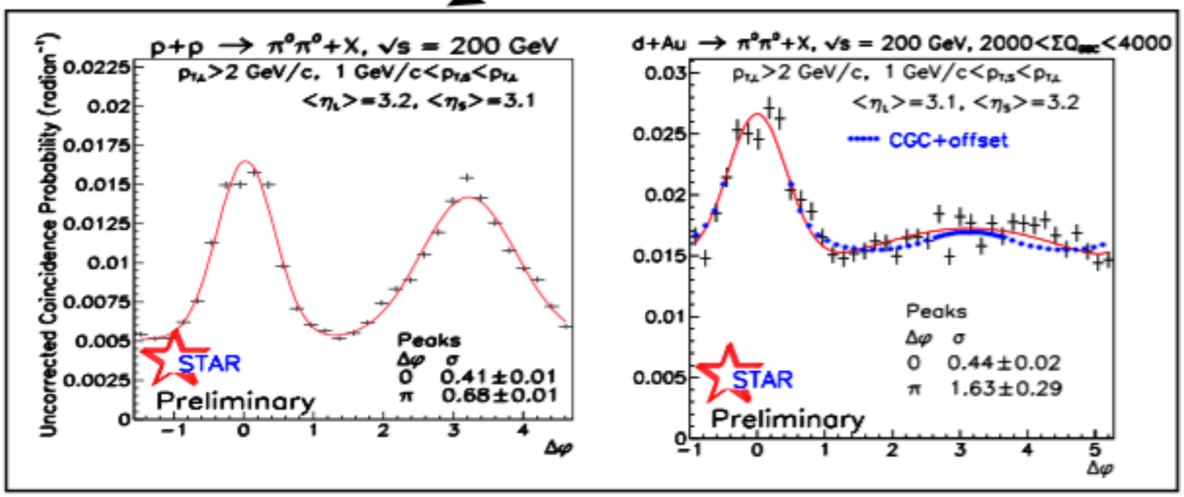


Not yet measured

Diphoton



Not yet measured



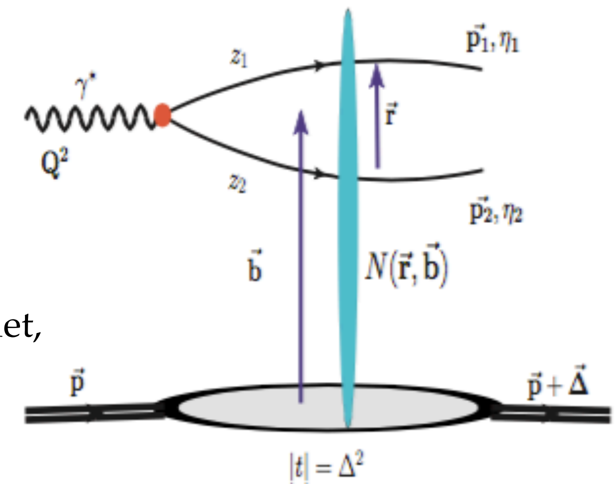
- Back-to-back correlation gets suppressed due to the saturation scale. This is universal to all **inclusive** two-particle production shown above.

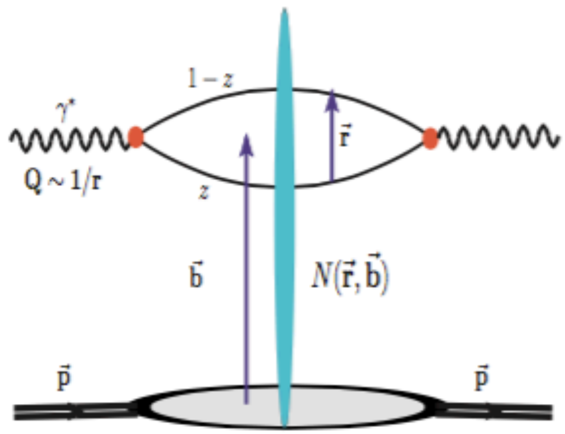
What about diffractive production?, suppression or enhancement?.

Diffractive dijet in DIS v. Inclusive DIS and Inclusive dijet

Diffractive (averaging over color at amplitude level): $\sigma \propto |\langle \mathcal{M} \rangle_\rho|^2$
Inclusive (averaging over color at cross-section level): $\sigma \propto \langle |\mathcal{M}|^2 \rangle_\rho$

Dominguez, Marquet, Xiao, Yuan, arXiv:1101.0715





Altinoluk, Armesto, Beuf, Rezaeian, arXiv:1511.07452

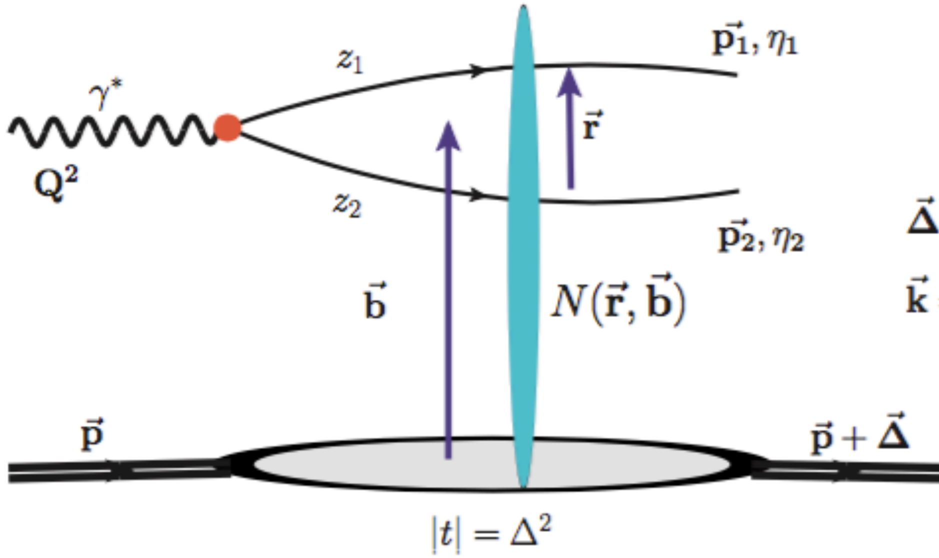
$$\sigma^{\text{Diffractive dijet}} \propto \psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N}(\vec{r}, \vec{b}) \otimes \mathcal{N}(\vec{r'}, \vec{b'}) \neq \psi^{\gamma}_{q\bar{q}} \otimes [\mathcal{N}(r, b)]^2$$

$$\sigma^{\text{Inclusive dijet}} \propto \psi^{\gamma}_{q\bar{q}} \otimes [\mathcal{N}(\vec{r}, \vec{b}) + S^{\text{Quadrupole}}(\vec{r}, \vec{r\prime}, \vec{b}, \vec{b'})]$$

$$\sigma^{\text{Inclusive DIS}} \propto \psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N}(\vec{r}, \vec{b}) \otimes \psi^{\gamma}_{q\bar{q}}$$

- In contrast to inclusive dijet production, diffractive dijet production only depends on the dipole amplitude (not WW gluon distribution) at LO.

Diffractive Dijet production in the CGC: $\gamma^* + p(A) \to q\bar{q} + p(A)$



$\vec{\Delta} = \vec{p}_1 + \vec{p}_2$

$\vec{k} = \frac{1}{2}(\vec{p}_1 - \vec{p}_2)$

$$\sigma = \psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N}(\vec{r}, \vec{b}) \otimes \mathcal{N}(\vec{r'}, \vec{b'}) \neq \psi^{\gamma}_{q\bar{q}} \otimes [\mathcal{N}(r, b)]^2$$

$$\left(\frac{d\sigma_{\mathrm{T}}^{\mathrm{dijet}}}{dz_1 \, dz_2 \, d^2\mathbf{p}_1 \, d^2\mathbf{p}_2} \right) = (2\pi)^2 \delta(z_1 + z_2 - 1) N_c \alpha_{em} \sum_f e_f^2 \int \frac{d^2\mathbf{r}}{(2\pi)^2} \int \frac{d^2\mathbf{r}'}{(2\pi)^2} \int \frac{d^2\mathbf{b}}{(2\pi)^2} \int \frac{d^2\mathbf{b}'}{(2\pi)^2}$$

$$\times \, \mathbf{e}^{-i(\mathbf{b}-\mathbf{b}')\cdot(\mathbf{p}_1+\mathbf{p}_2)} \mathbf{e}^{-i(\mathbf{r}-\mathbf{r}')\cdot(\mathbf{p}_1-\mathbf{p}_2)/2} \mathcal{N}(\mathbf{r}, \mathbf{b}) \, \mathcal{N}(\mathbf{r}', \mathbf{b}') \, 2[z_1^2 + z_2^2] \, \frac{\mathbf{r} \cdot \mathbf{r}'}{\mathbf{r}^2 \mathbf{r}'^2} \, [\varepsilon|\mathbf{r}| K_1(\varepsilon|\mathbf{r}|)] \, \left[\varepsilon|\mathbf{r}'| K_1(\varepsilon|\mathbf{r}'|)\right]$$

- **Diffractive dijet production is a sensitive probe of the color-dipole orientation.**

Diffractive dijet production as a probe of color-dipole orientation

Let's assume:

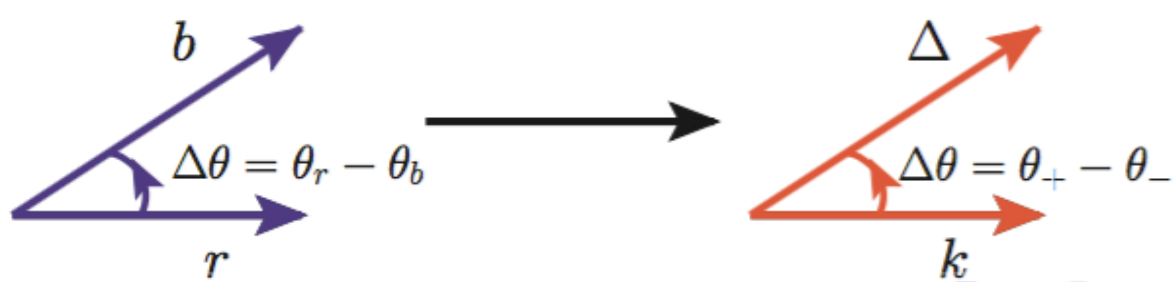
$$\mathcal{N}(\mathbf{r},\mathbf{b}) = \mathcal{N}(r, b, \theta_r - \theta_b) = 1 - e^{-\frac{Q_s^2(b)}{4} r^2 \left(1 + \mathbf{A} \cos^2(\theta_r - \theta_b)\right)}$$

θ_r, θ_b are the angles of vectors $\vec{r}$, $\vec{b}$ with respect to a reference vector, respectively. Assuming $Q_s^2 r^2 A/4 \ll 1$:

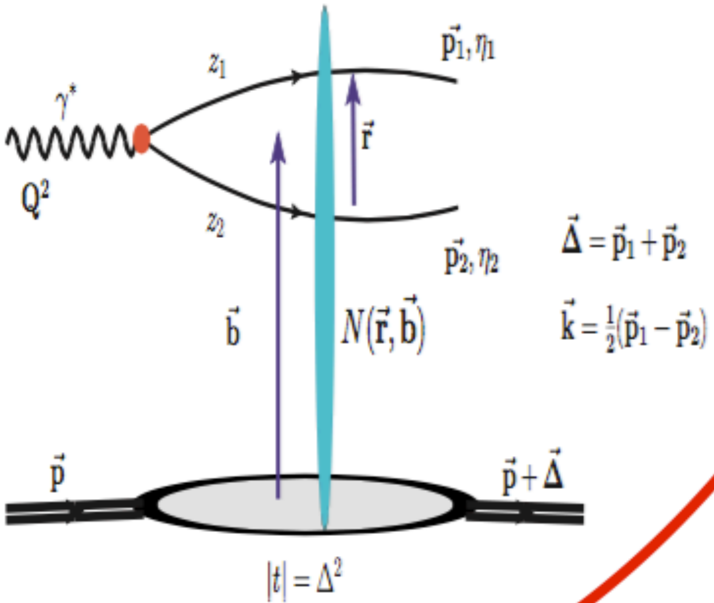
$$\int \frac{d^2\mathbf{r}}{(2\pi)^2} \int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{-i\mathbf{b}\cdot(\mathbf{p}_0+\mathbf{p}_1)} e^{-i\mathbf{r}\cdot(\mathbf{p}_0-\mathbf{p}_1)/2} \mathcal{N}(\mathbf{r},\mathbf{b}) K_0(\varepsilon|\mathbf{r}|) \simeq \int_0^{+\infty} \frac{dr}{2\pi} r \int_0^{+\infty} \frac{db}{2\pi} b \, J_0\left(b|\mathbf{p}_0 + \mathbf{p}_1|\right) \times J_0\left(r\frac{|\mathbf{p}_0 - \mathbf{p}_1|}{2}\right) \mathcal{N}(r, b, \theta_- - \theta_+) K_0(\varepsilon r)$$

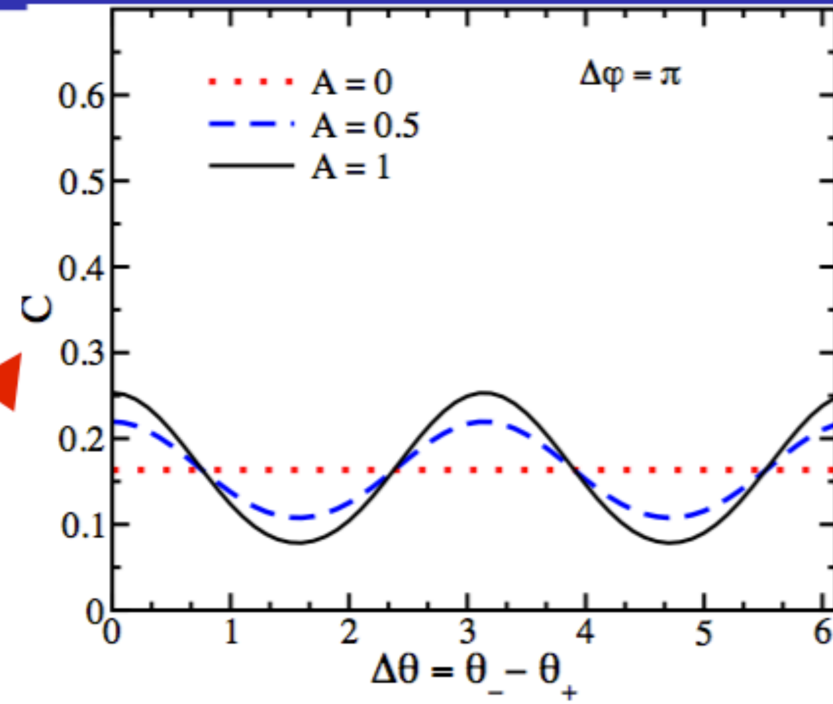
θ_+, θ_- denote the angles of vectors $\vec{\Delta} = \vec{p}_0 + \vec{p}_1$ and $\vec{k} = \frac{1}{2}(\vec{p}_0 - \vec{p}_1)$ with respect to a reference vector, respectively.

- **A nonzero A corresponding to the existence of $\vec{r} - \vec{b}$ correlations in the color dipole amplitude, induces azimuthal correlations between $\vec{\Delta}$ and $\vec{k}$.**



Diffractive dijet production as a probe of color-dipole orientation

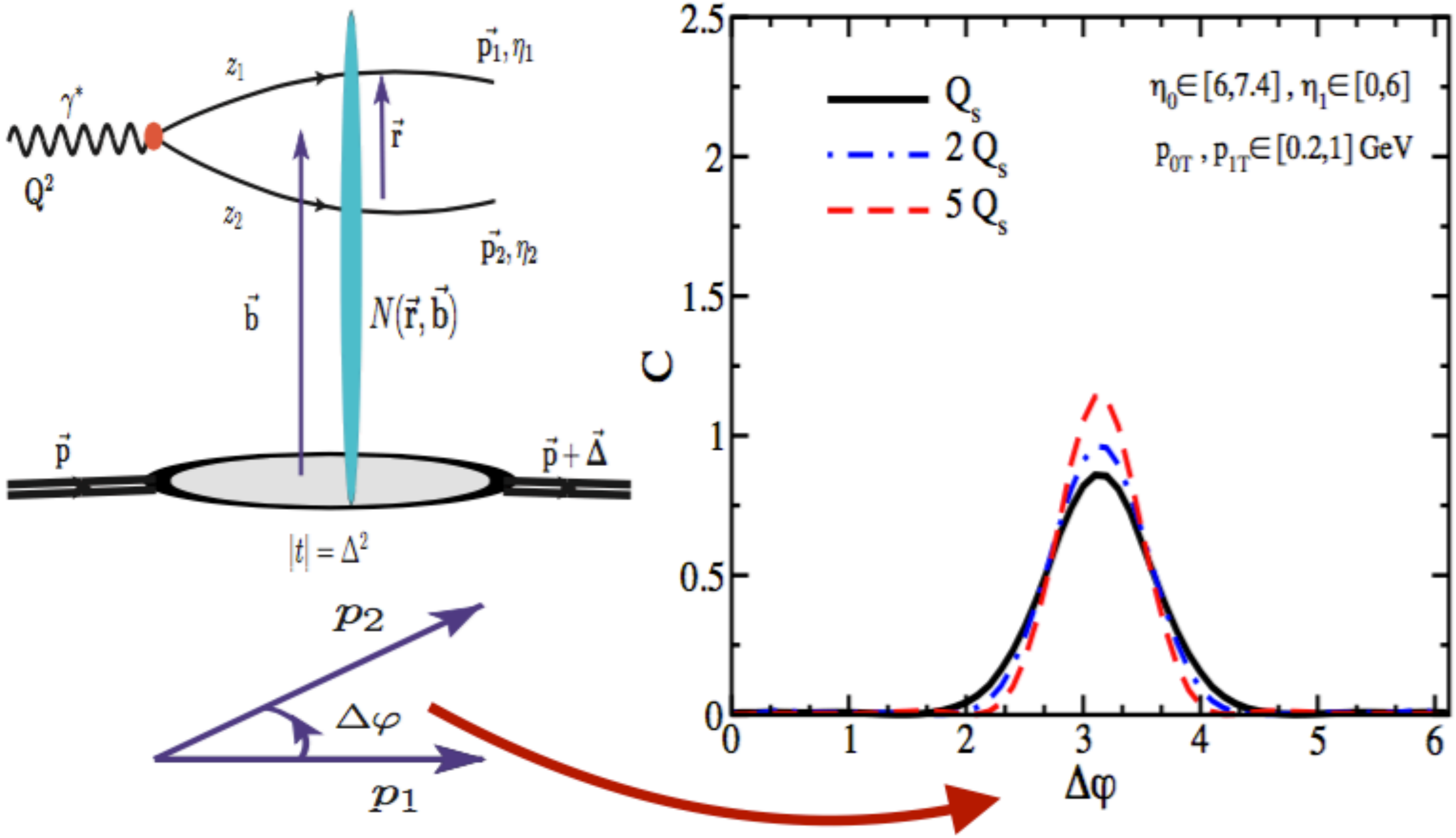




$$C(\Delta\theta) = \frac{d\sigma^{\gamma^* p \to q\bar{q}p}}{d\mathbf{p}_0\, \mathbf{p}_1 d\Delta\theta} \Bigg/ \int_0^{2\pi} d\Delta\theta \frac{d\sigma^{\gamma^* p \to q\bar{q}p}}{d\mathbf{p}_0\, \mathbf{p}_1 d\Delta\theta}$$

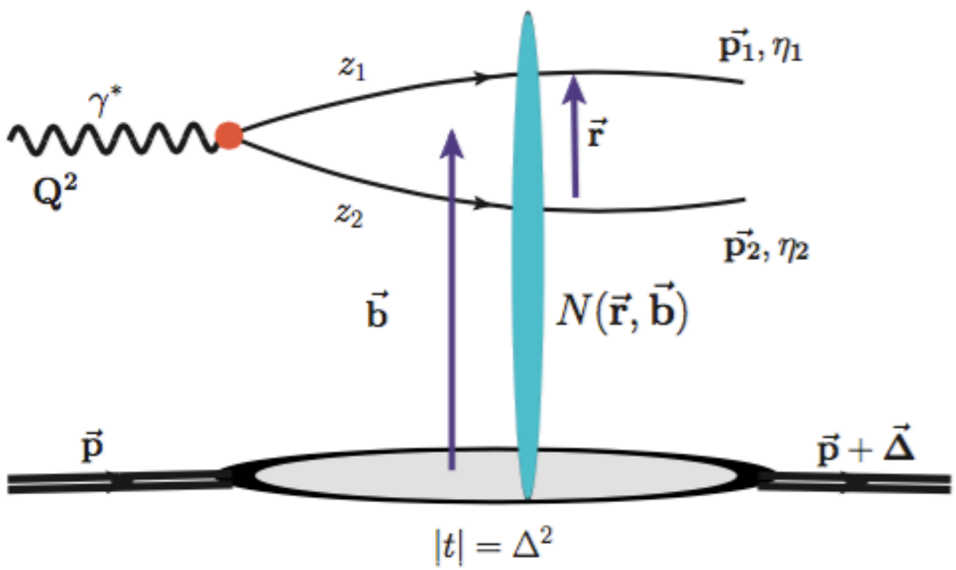
- **A nonzero A corresponding to the existence of $\vec{r} - \vec{b}$ correlations in the color dipole amplitude, induces sizeable azimuthal correlations for dijet between $\vec{\Delta}$ and $\vec{k}$.**

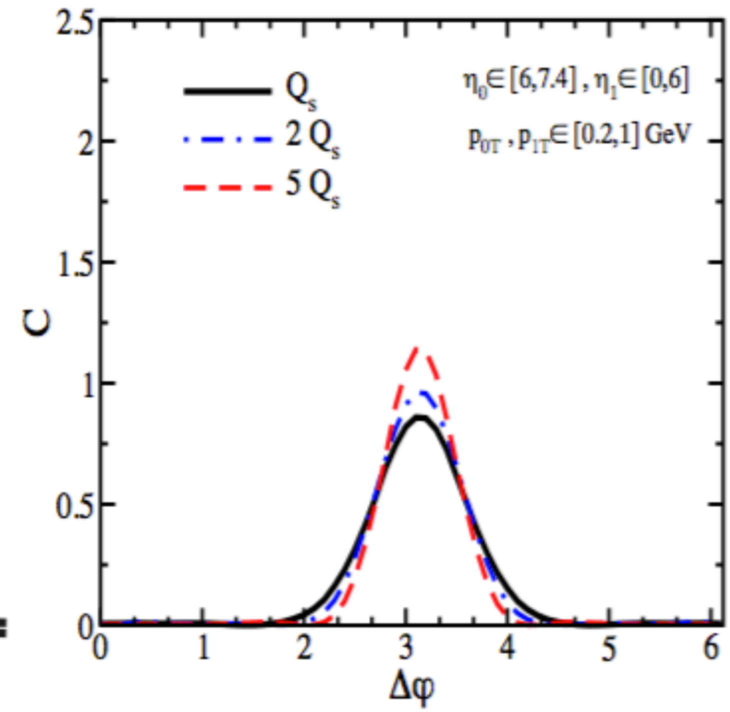
Correlations v. decorrelations



- In order to keep the color neutrality of the dijet system, required by its diffractive nature, the production becomes dominated by $q\bar{q}$ pairs of smaller transverse size with increasing saturation momentum.

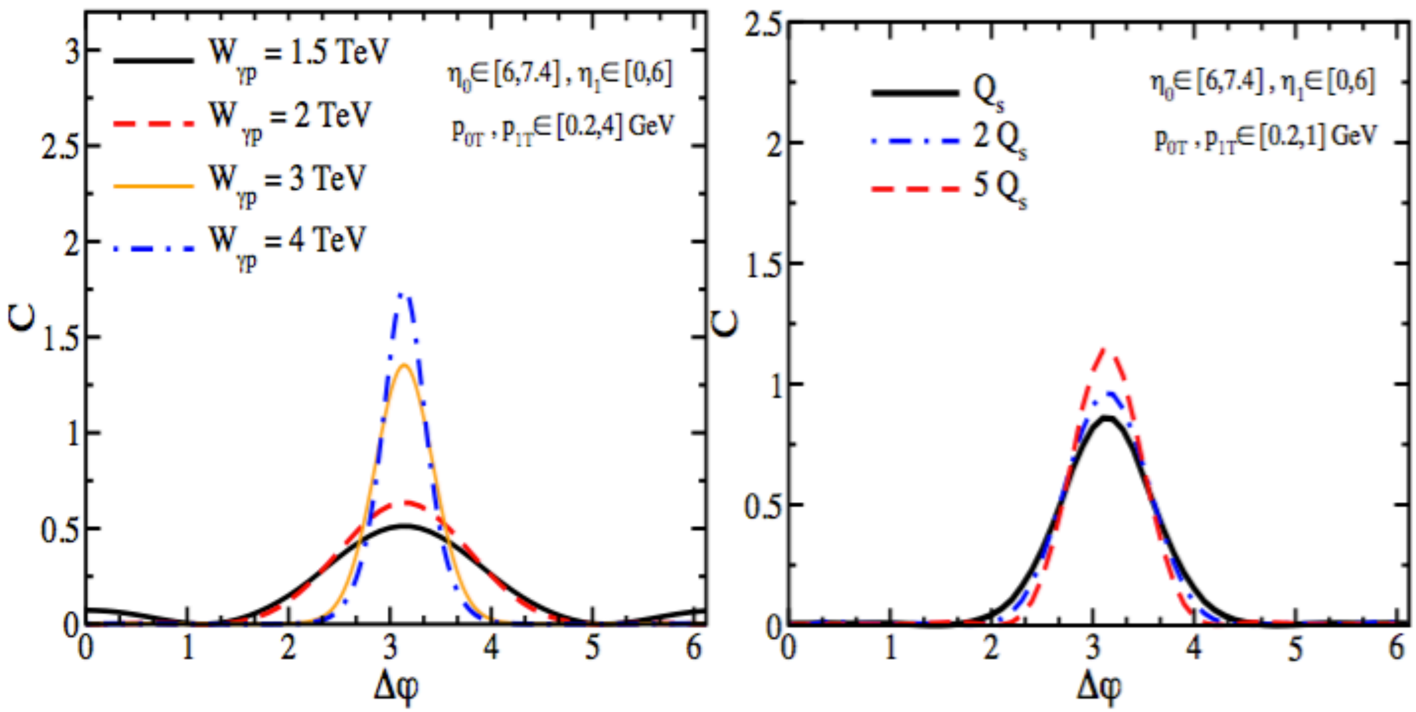
Inclusive v. diffractive two-particle production





- **Diffractive** dijet photoproduction:
  Back-to-back correlation gets **enhanced** due to the saturation scale.
  Balance between: $p_{1T}, p_{2T}, \vec{\Delta}, Q_s$
- **Inclusive** dijet:
  Back-to-back correlation gets **suppressed** due to the saturation scale.
  Balance between: p_{1T}, p_{2T}, Q_s

Inclusive v. diffractive two-particle production



- **Diffractive** dijet photoproduction:
  Back-to-back correlation gets **enhanced** due to the saturation scale.
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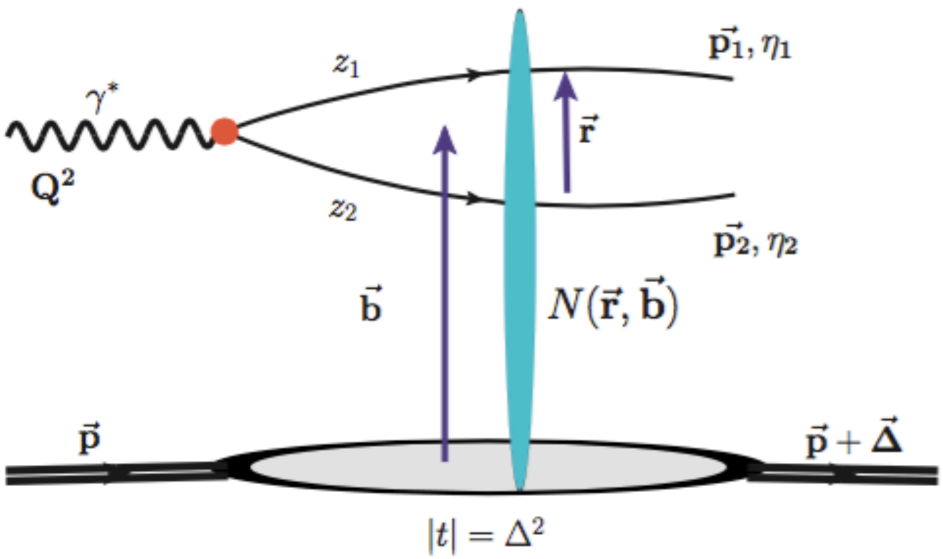
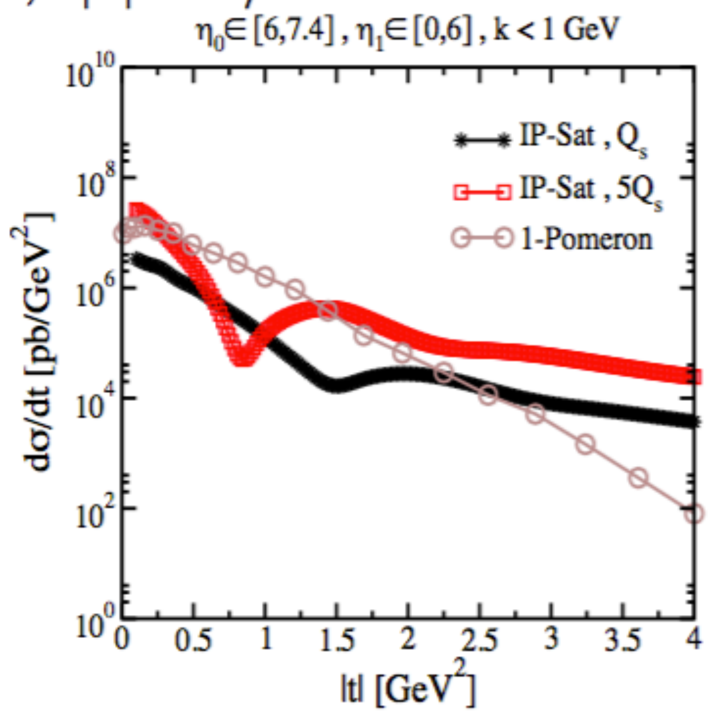
  Back-to-back correlation gets **suppressed** due to the saturation scale.
  Balance between: p_{1T}, p_{2T}, Q_s

t-distribution of diffractive dijet photo-production at the LHC

$$\vec{\Delta} = \vec{p_1} + \vec{p_2}, \quad \vec{k} = \tfrac{1}{2}(\vec{p_1} - \vec{p_2}), \quad |t| = \Delta^2, \quad |t| \propto 1/b$$

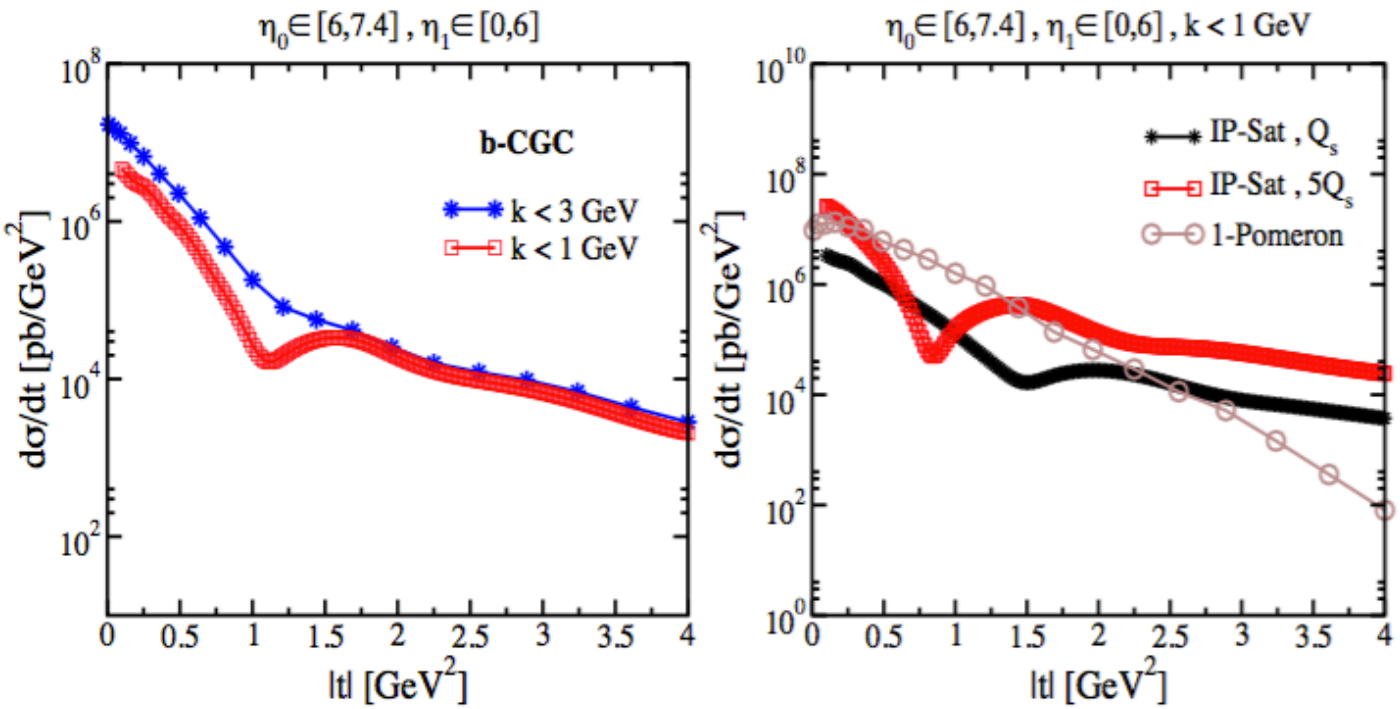




Diffractive dijet photoproduction:

- $|t|$ distribution exhibits dips for the saturation models, similar to diffractive vector mesons.
- There is NO dips for the non-saturation models (i.e. 1-Pomeron).
- The dips become stronger by increasing the saturation scale.

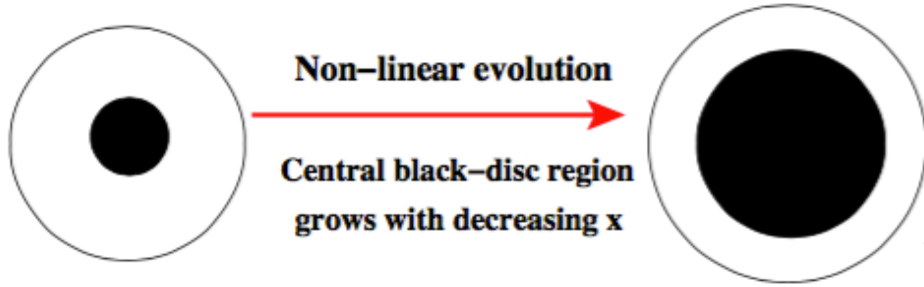
t-distribution of diffractive dijet photo-production at the LHC

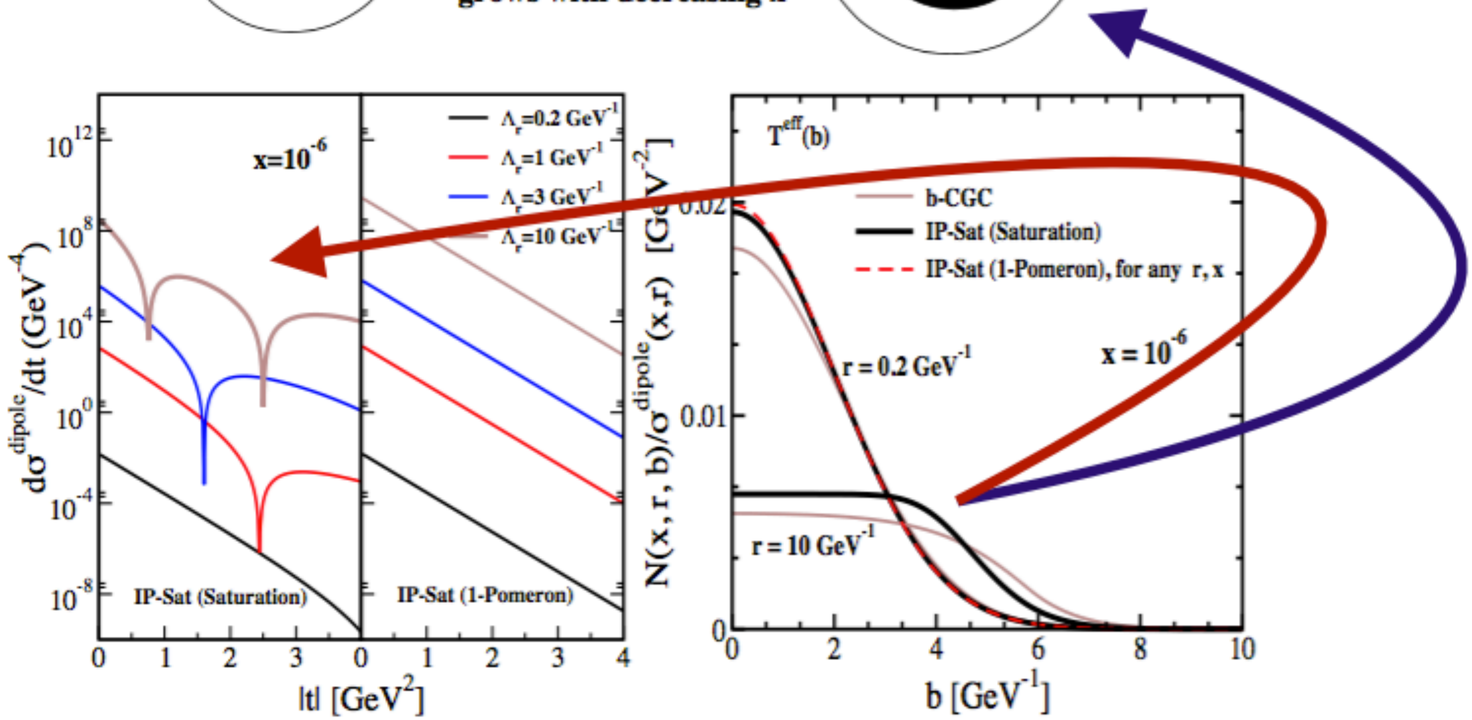


Diffractive dijet photoproduction:

- The dips become stronger by increasing the saturation scale: lowering x, decreasing k and increasing energy.

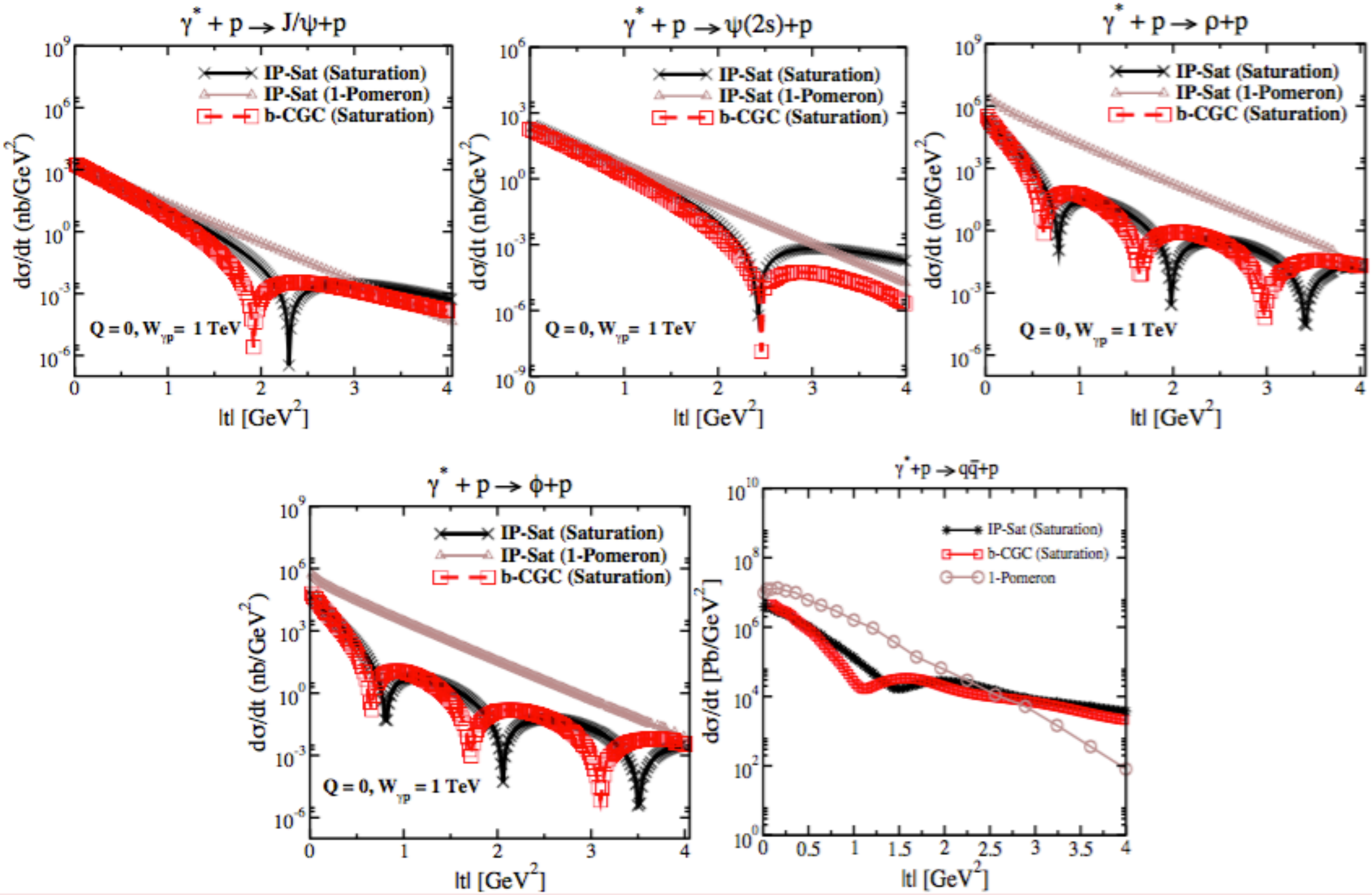
The origin of diffractive dips: Non-linear evolution of black-disc region





- Non-linear evolution $\Longrightarrow$ evolves any realistic profile in b, like a Gaussian or Woods-Saxon distribution, and makes it closer to a step-like function in the b-space at black-disc limit.

The universality of the diffractive dip at small-x



- The emergence of dip structure in the diffractive *t*-distribution is universal and does not depend on the details of the final-state particle wave functions.

Conclusion:

- Away-side correlations are enhanced in coherent diffractive processes in DIS and real (and virtual) photon-hadron ($\gamma^{(*)}$-h) collisions due to the saturation effects.
- Saturation and non-saturation models are very different at very small x and large $|t|$ ($x < 10^{-5}$ and $|t| > 1$):
  - Emergence of dips in the t-distribution of diffractive photoproduction of vector mesons and dijet in $\gamma^{\star}p$ collisions at large $|t|$ in the saturation models.
  - The t-distribution of diffractive production unambiguously discriminate among saturation and non-saturation models.
- **Diffractive dijet production** in dilute-dense scatterings is a sensitive probe of the color-dipole orientation:
  - Dipole orientation generates v_2: (Kopeliovich, Rezaeian and Schmidt, arXiv:0809.4327). **Edmond Iancu, AR, in progress.**