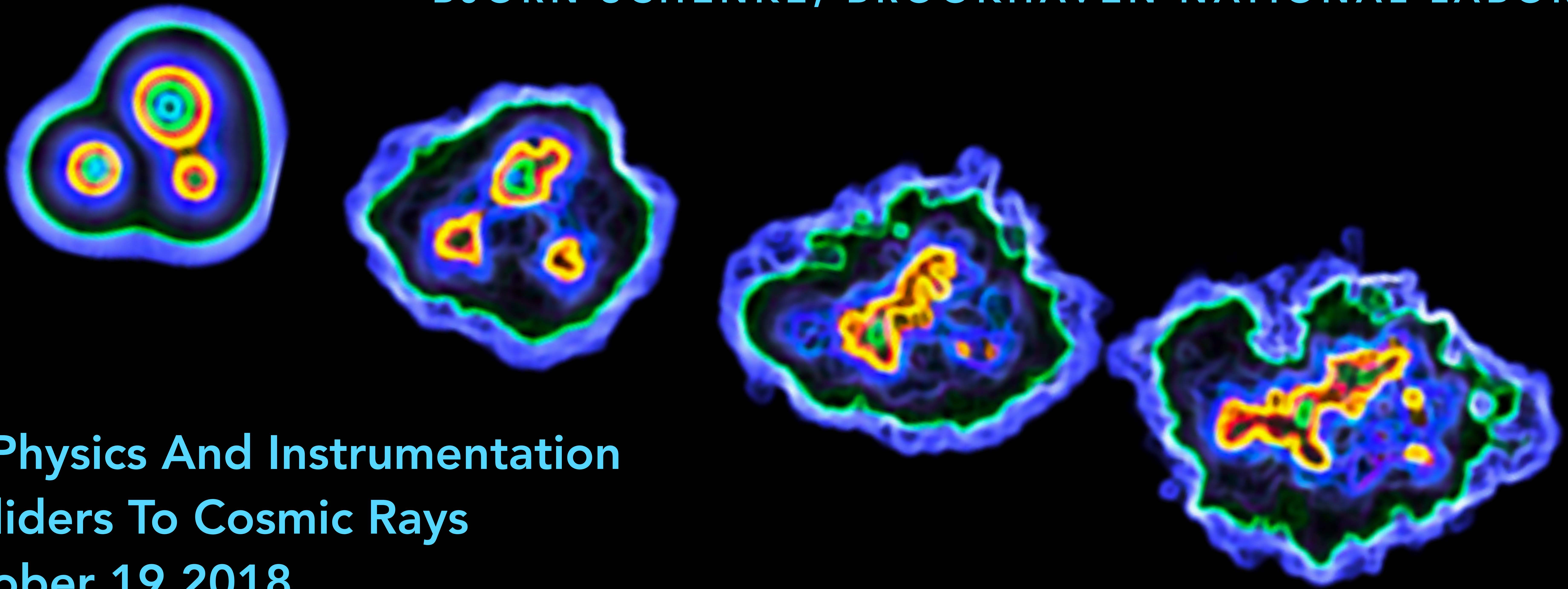
U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

# JIMWLK EVOLUTION AND APPLICATIONS TO OBSERVABLES

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

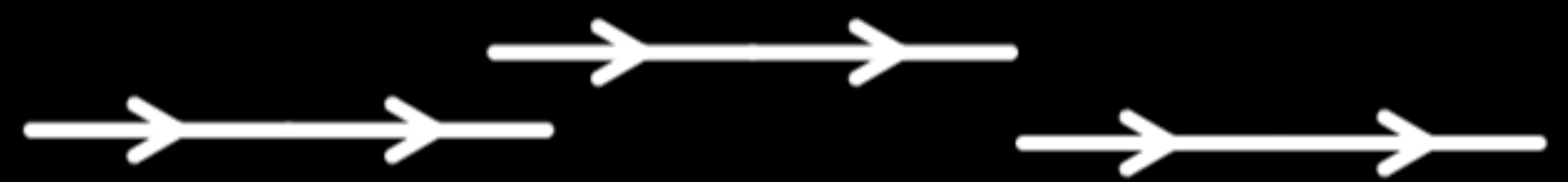


Forward Physics And Instrumentation
From Colliders To Cosmic Rays
SBU, October 19 2018

First a few words on

# Low x, Saturation, and Heavy Nuclei

# Parton Saturation



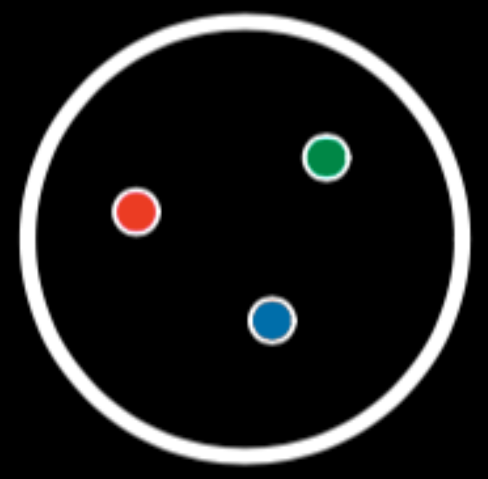


Figure from F. Gelis

At low energy, only valence quarks in the hadron wave function

# Parton Saturation

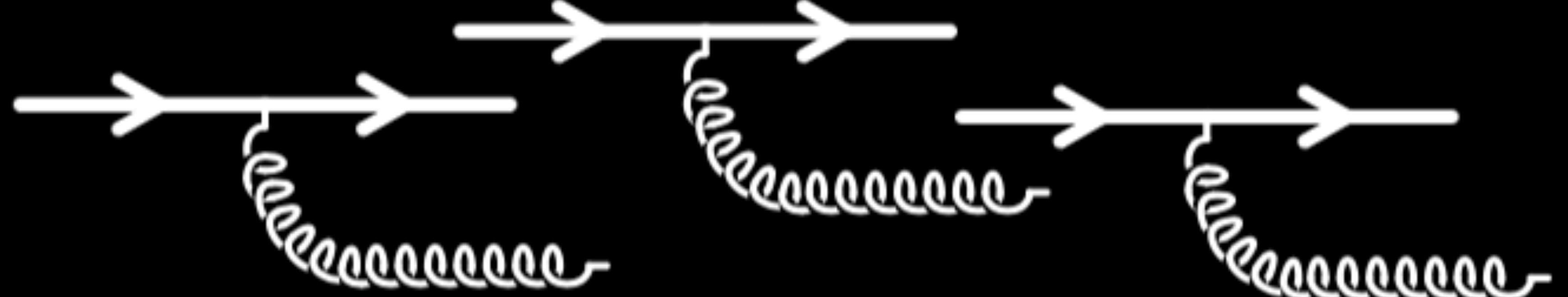


Figure from F. Gelis

- When energy increases, new partons are emitted
- The emission probability is $\alpha_s \int \frac{dx}{x} \sim \alpha_s \ln(1/x)$ with $x$ the longitudinal momentum fraction of the gluon
- At small $x$ (i.e. high energy), these logs need to be resummed

# Parton Saturation

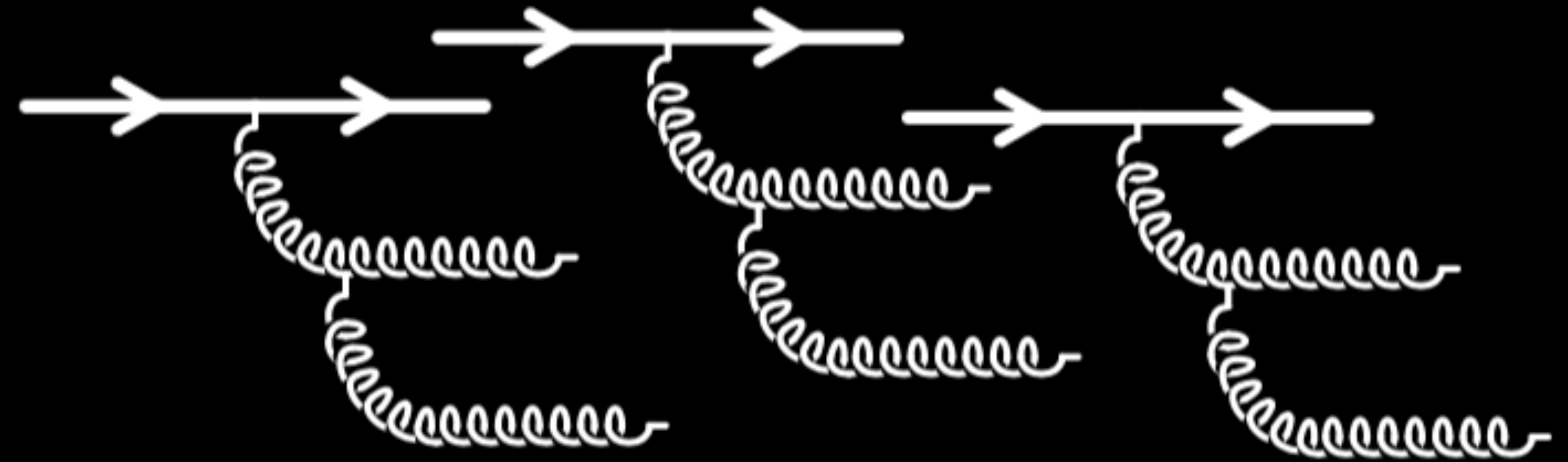


Figure from F. Gelis

- As long as the density of constituents remains small, the evolution is linear:
  The number of partons produced at a given step is proportional to the number of partons at the previous step (BFKL)

Balitsky-Fadin-Kuraev-Lipatov: L. N. Lipatov, Sov. J. Nucl. Phys. 23 (1976) 642;
V. S. Fadin, E. A. Kuraev and L. N. Lipatov, Phys. Lett. B60 (1975) 50;
Sov. Phys. JETP 44 (1976) 443; 45 (1977) 199;
Ya. Ya. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822

# Parton Saturation

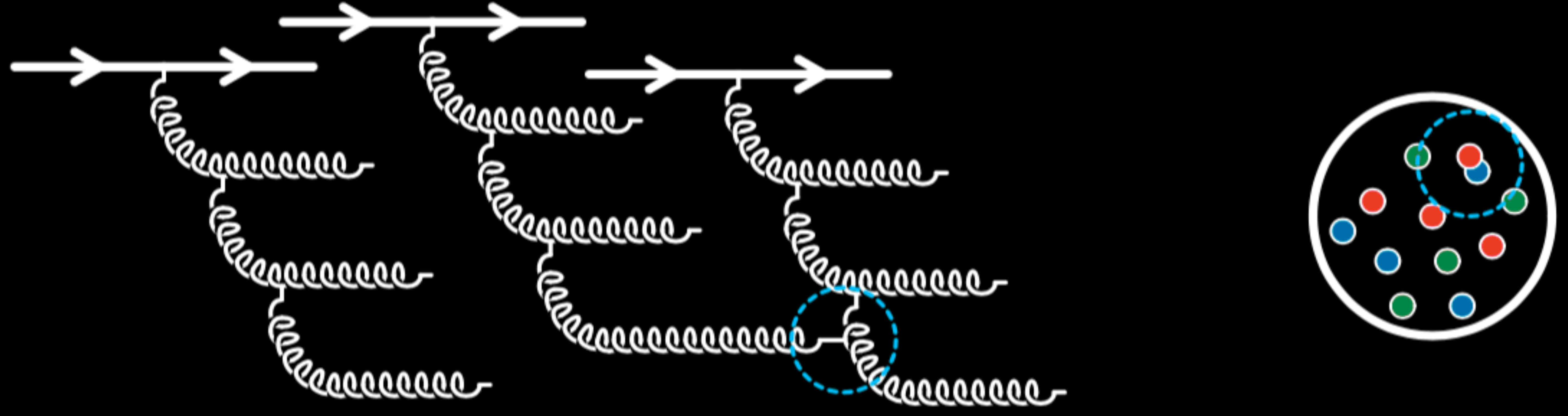


Figure from F. Gelis

- Eventually, the partons start overlapping in phase-space
  → parton recombination occurs

- Then the evolution becomes non-linear:
  The number of partons created at a given step depends non-linearly on the number of partons present previously

**Balitsky (1996), Kovchegov (1996,2000)**
**Jalilian-Marian, Kovner, Leonidov, Weigert (1997,1999)**
**Iancu, Leonidov, McLerran (2001)**

# Saturation Criterion

L.V. Gribov, E.M. Levin and M.G. Ryskin, Physics Reports 100, Nos. 1 & 2 (1983) 1—150

- Number of gluons per area:

$$\rho \sim \frac{xG(x, Q^2)}{\pi R^2}$$

- Recombination cross section:

$$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$

- Recombination important when $\rho\sigma_{gg\to g} \gtrsim 1, \text{i.e. } Q^2 \lesssim Q_s^2$

$$\text{with } Q_s^2 \sim \frac{\alpha_s xG(x, Q_s^2)}{\pi R^2} \sim A^{1/3}x^{-0.3}$$

- At saturation the phase-space density is:

$$\frac{dN_g}{d^2x_\perp d^2p_\perp} \sim \frac{\rho}{Q_s^2} \sim \frac{1}{\alpha_s}$$

# SATURATION CRITERION

L.V. Gribov, E.M. Levin and M.G. Ryskin, Physics Reports 100, Nos. 1 & 2 (1983) 1—150

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$$\text{with } Q_s^2 \sim \frac{\alpha_s xG(x, Q_s^2)}{\pi R^2} \sim A^{1/3}x^{-0.3}$$

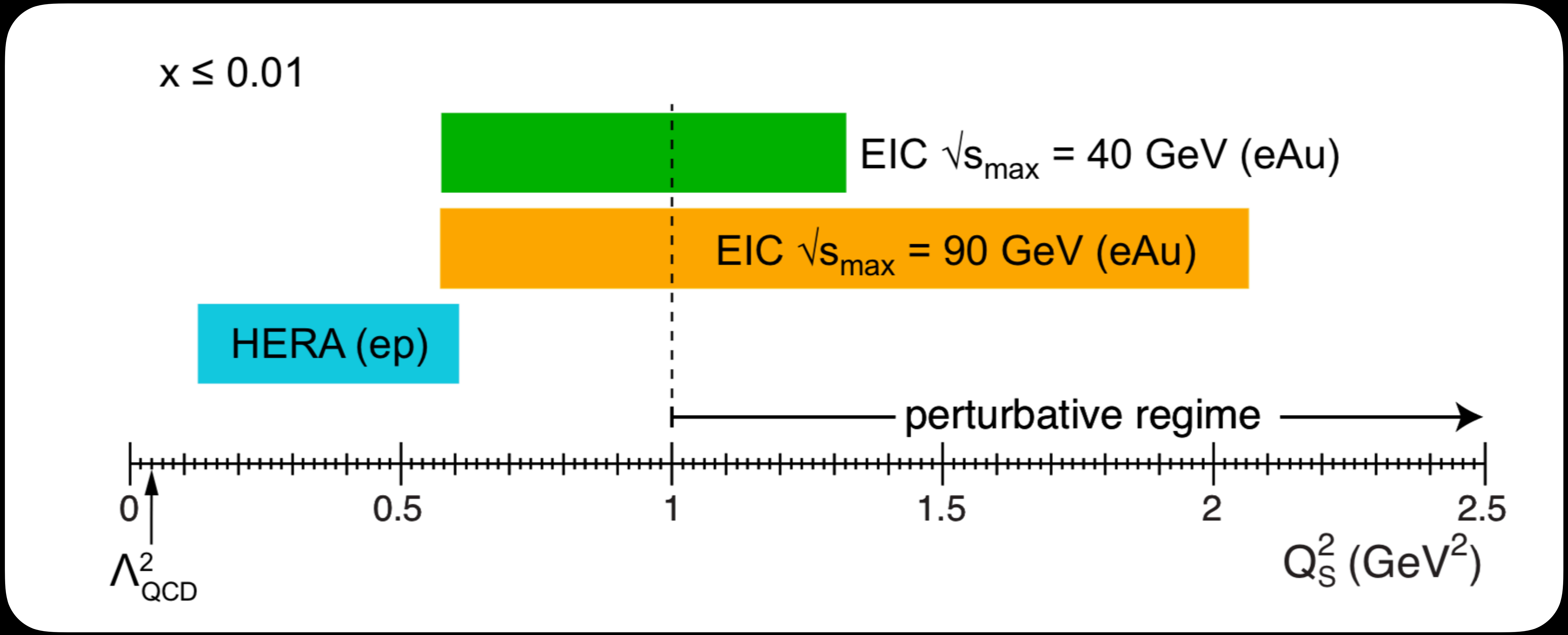
want to go forward

want large A

- At saturation the phase-space density is:

$$\frac{dN_g}{d^2x_\perp d^2p_\perp} \sim \frac{\rho}{Q_s^2} \sim \frac{1}{\alpha_s}$$

# Accessing the saturation regime



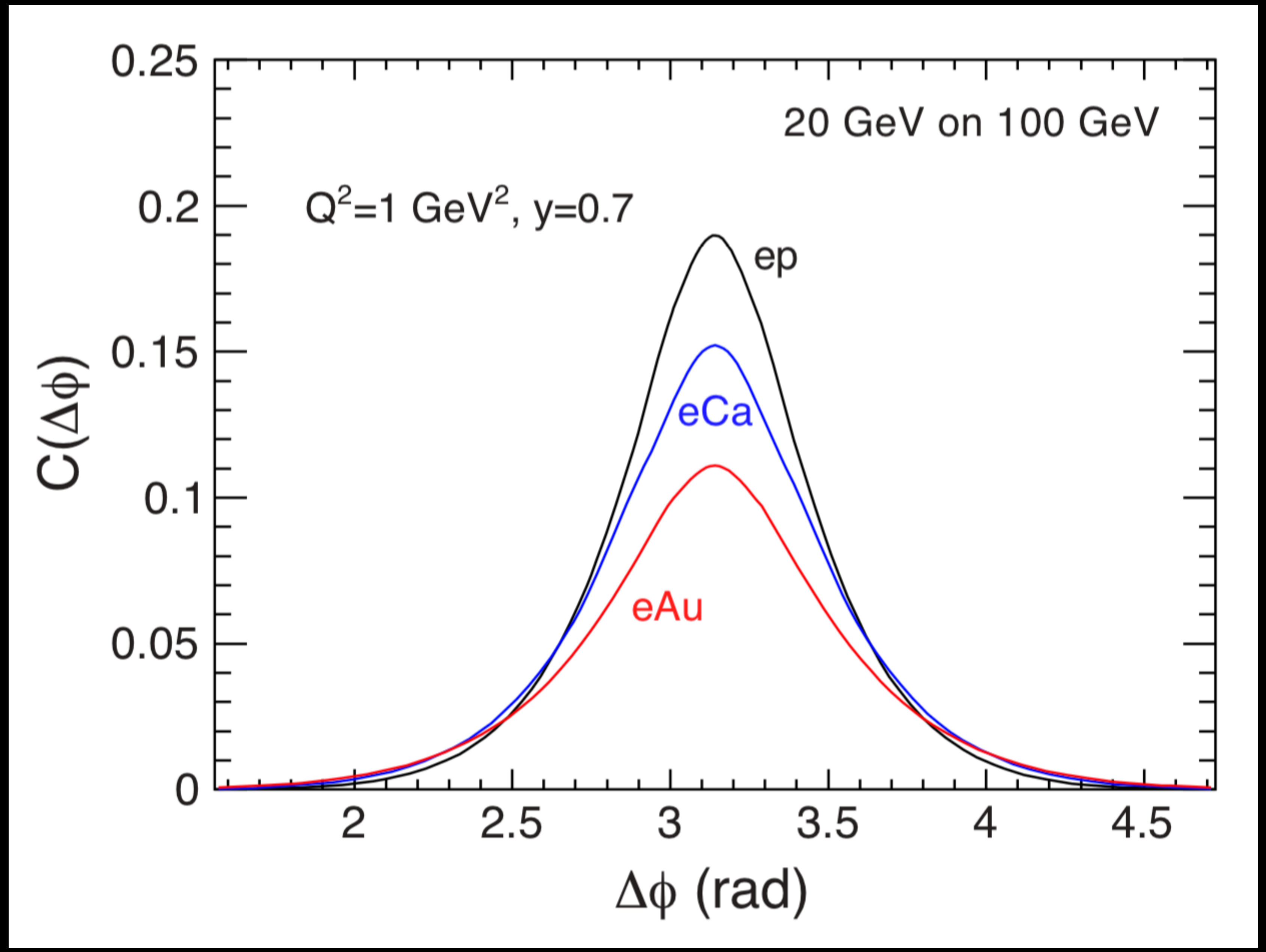

- Accessible values of the saturation scale $Q_s^2$ at an EIC in e+A collisions assuming two different maximal center-of-mass energies. Reach in $Q_s^2$ for e+p at HERA for comparison.

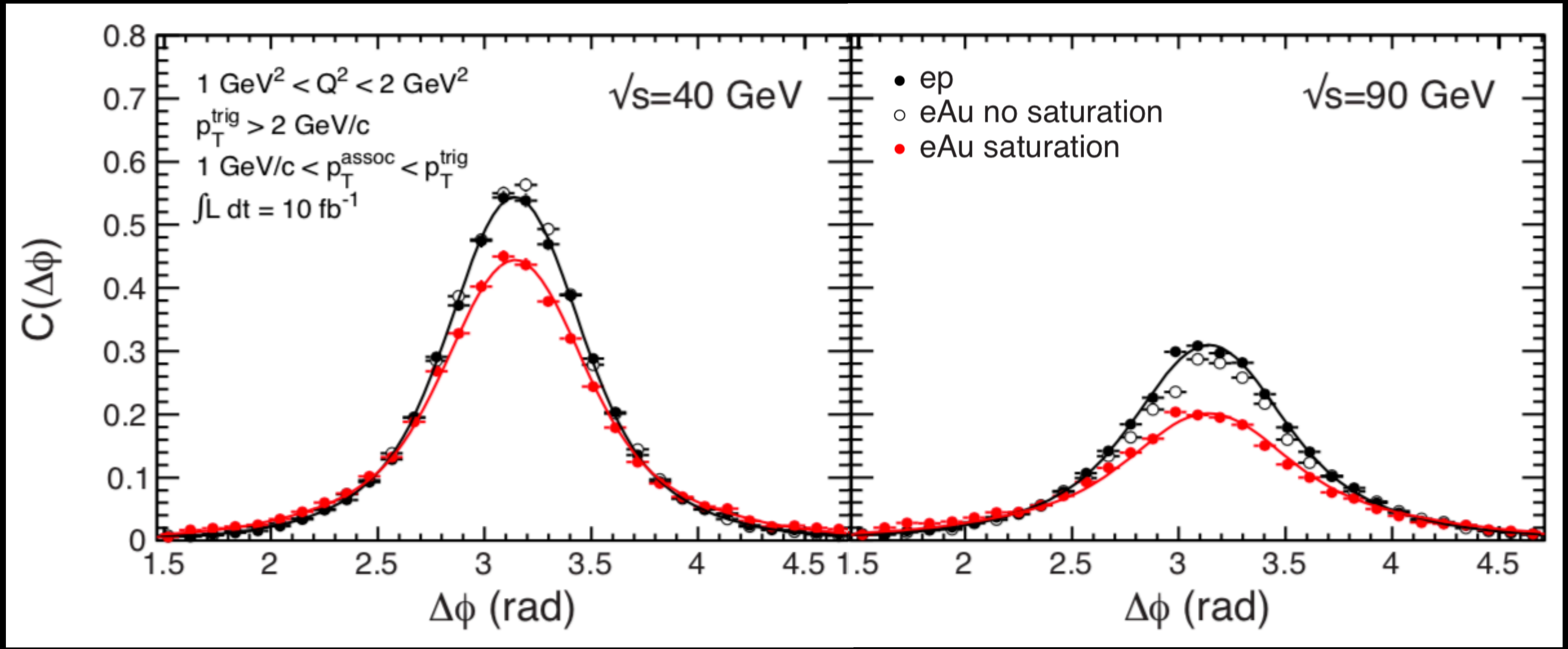
- The oomph factor $Q_s^2 \sim A^{1/3}$ makes a big difference

- Can experimentally reach the regime that is theoretically under control (weak coupling)

# Di-hadron Suppression

arXiv:
1212.1701, 1403.2413, 1708.01527

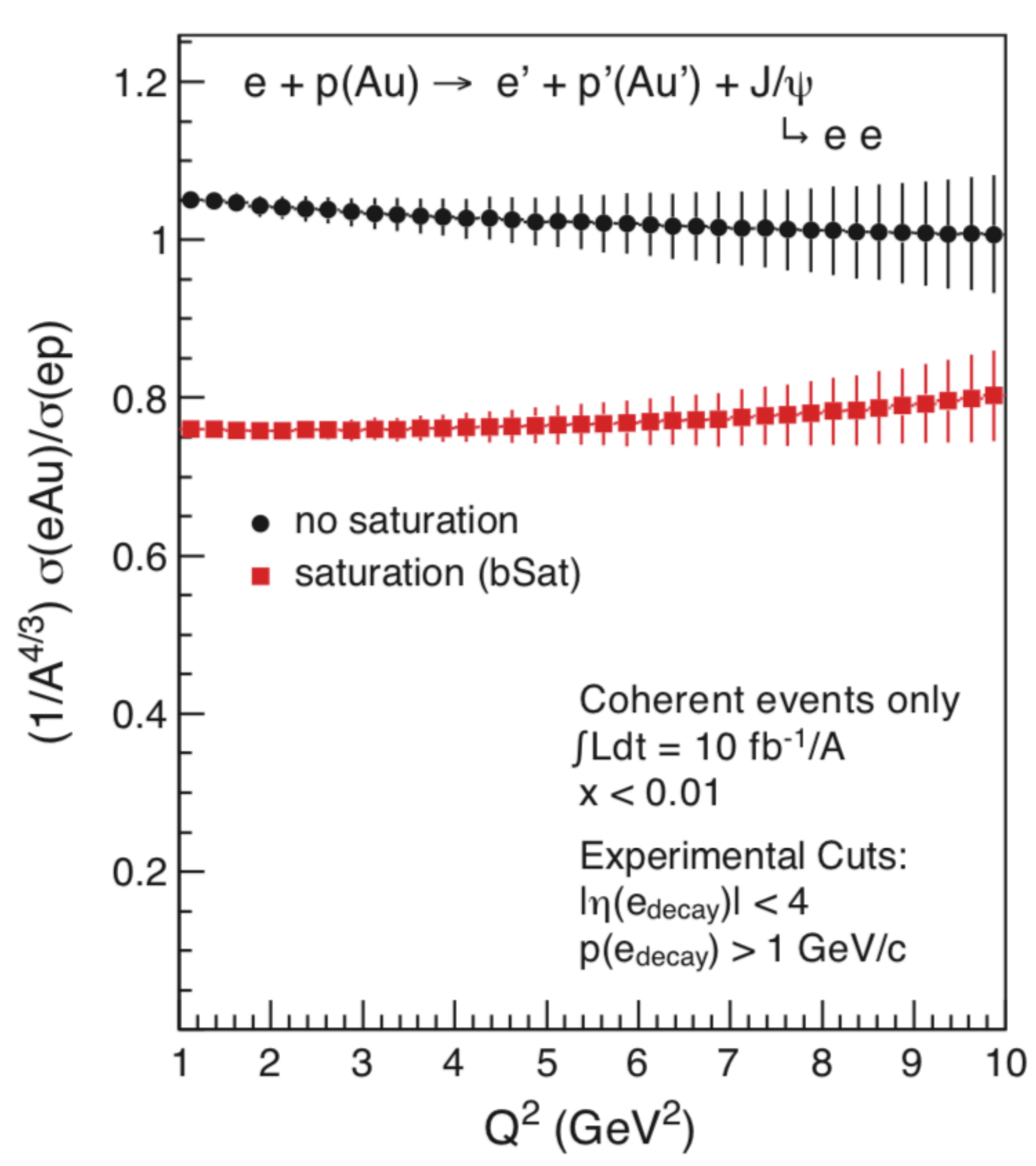


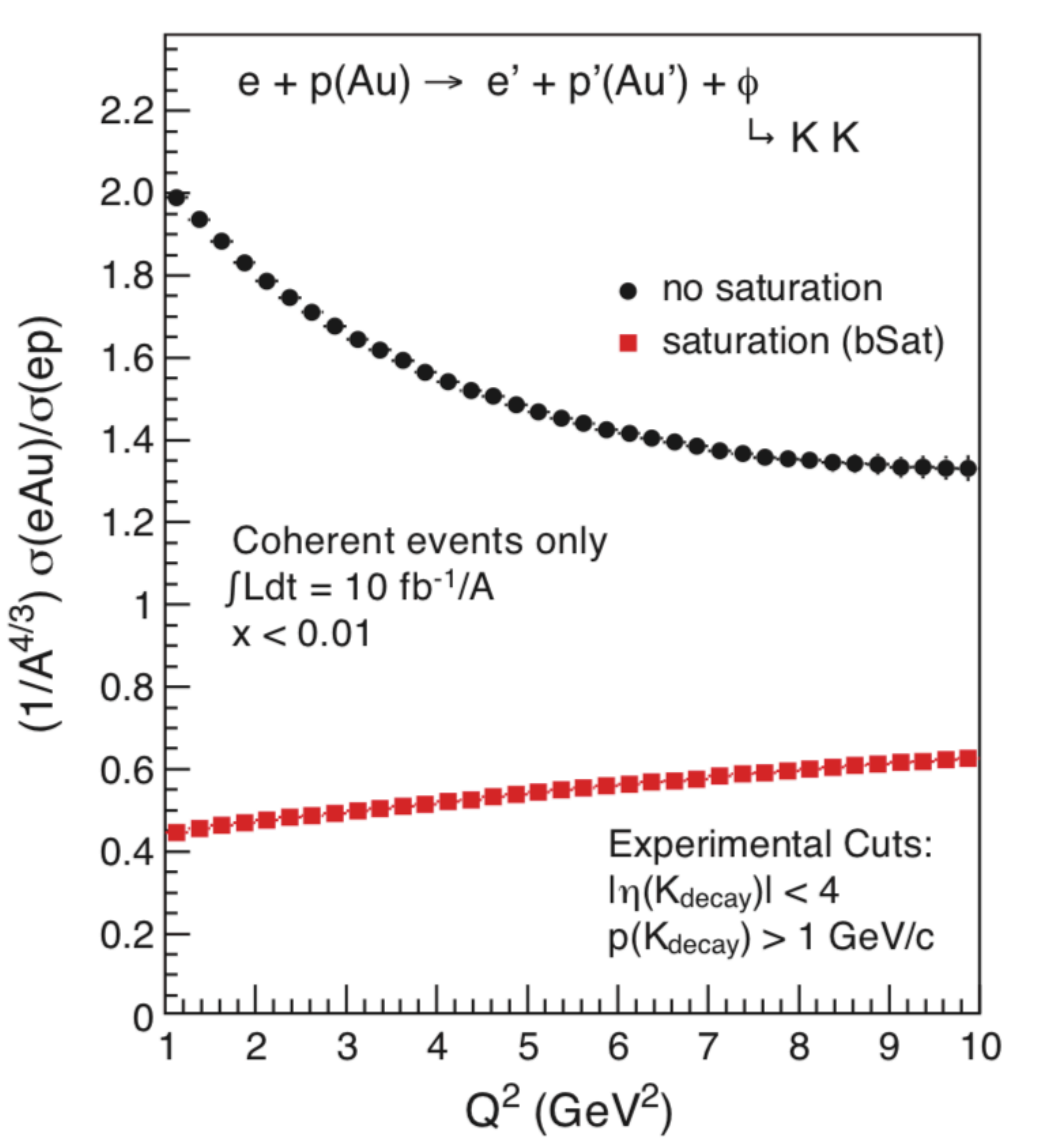



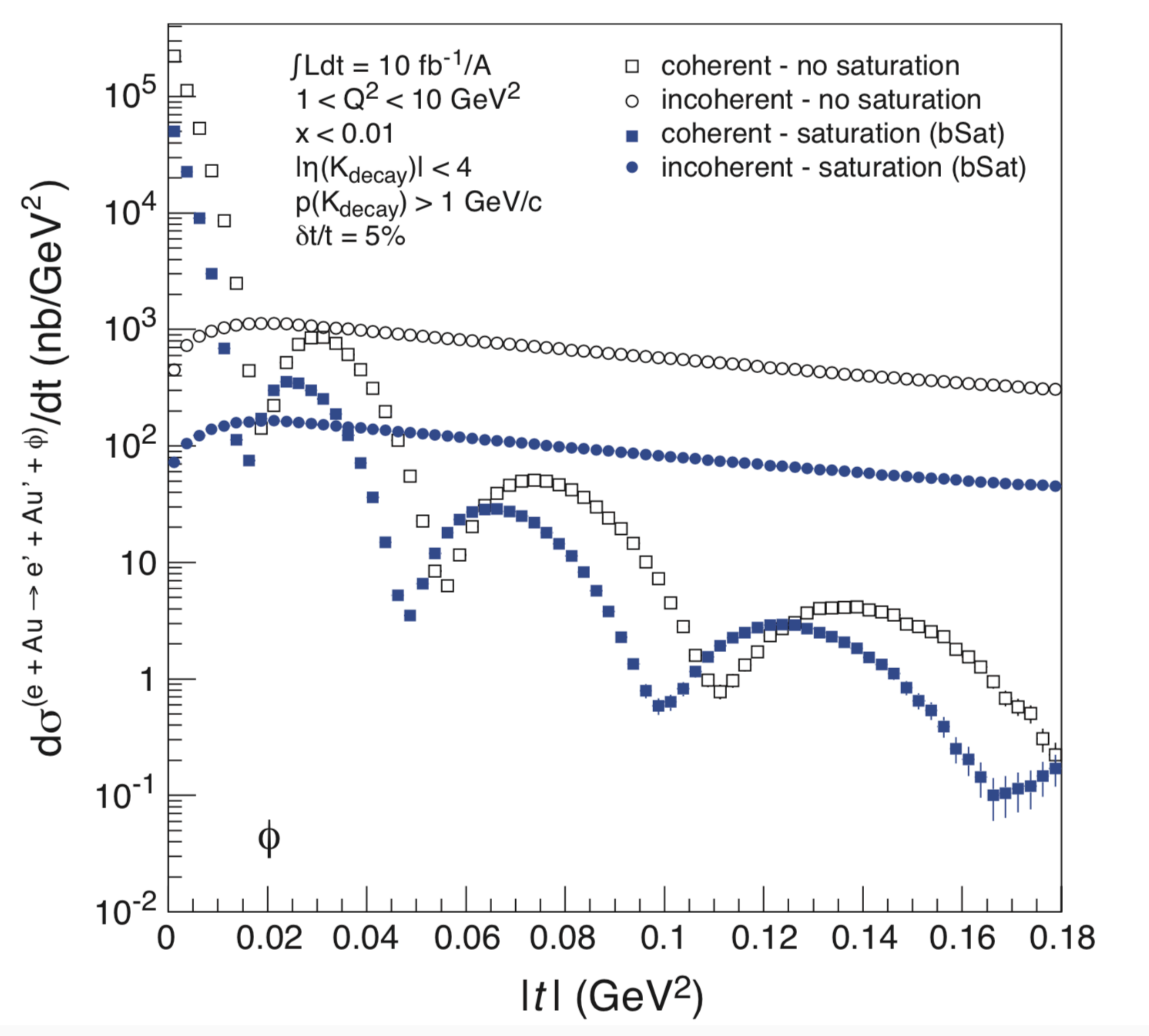

- Di-hadron correlation at an EIC for different nuclei (left) vs. relative angle
- Dihadron correlation at different cm-energies ep vs. eAu (non-sat) vs. eAu (sat) (right)
- Saturation effects (multiple re-scatterings and gluon emissions) lead to a progressive disappearance of the back-to-back correlations with increasing atomic number
- Comparison of the dihadron azimuthal distributions in e+p and e+A collisions could provide a clear experimental signature of the effect
-

# Diffractive vector meson production

arXiv: 1212.1701



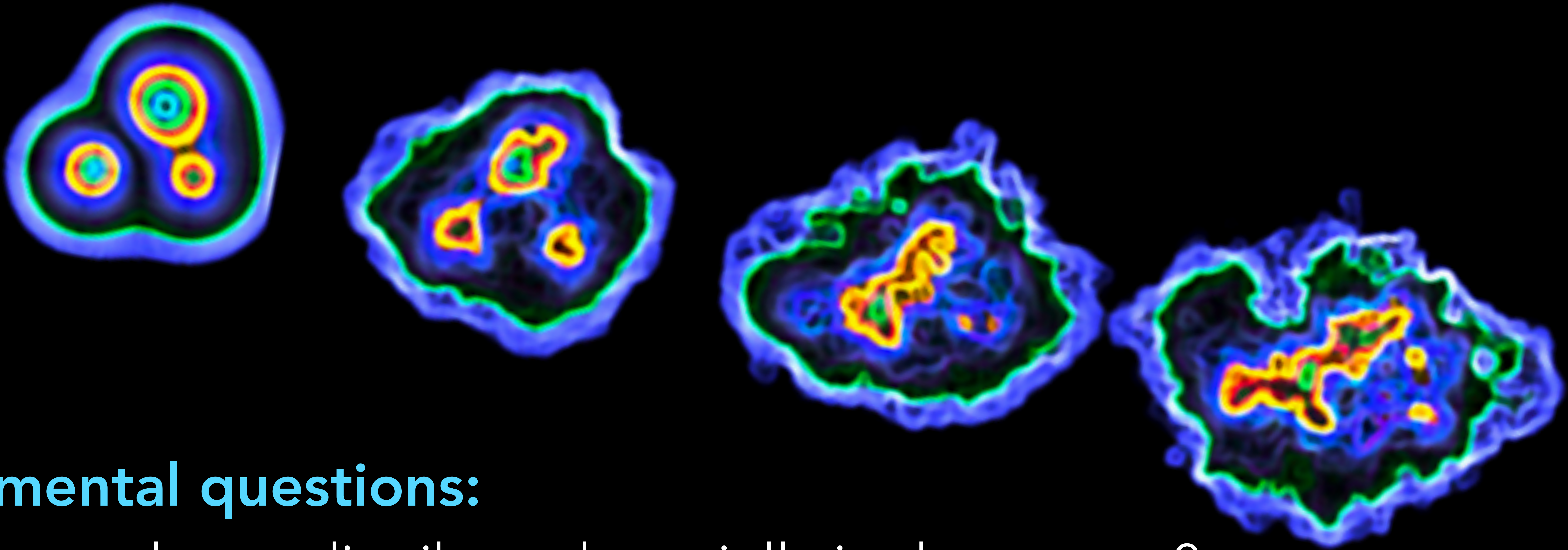




- Ratios of the cross-sections for exclusive J/ψ (left panel) and Φ (right panel) meson production in coherent diffractive e+A and e+p collisions as a function of $Q^2$ at an EIC with 20 GeV on 100 GeV beam energies (left)
- |t| spectrum encodes information on the spatial gluon distribution in the nucleus

a little more detail later, in my talk…

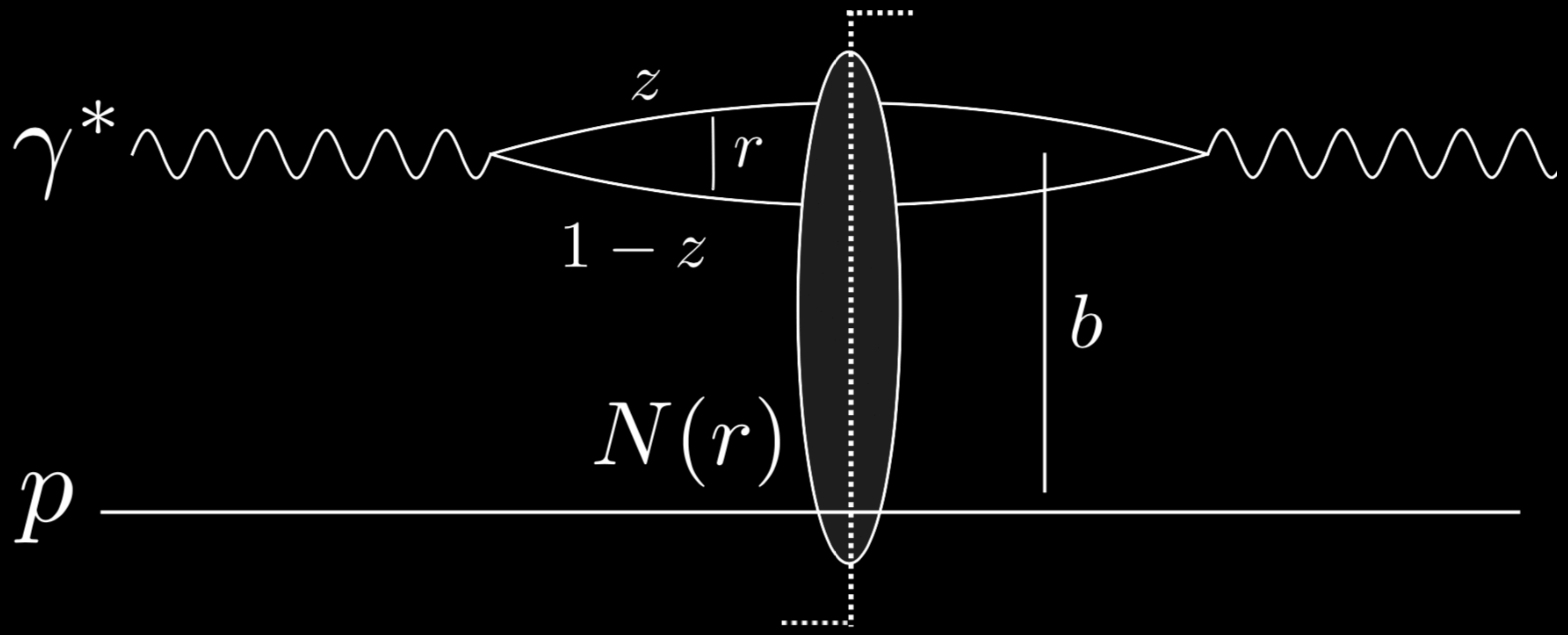
# JIMWLK EVOLUTION AND APPLICATIONS TO OBSERVABLES

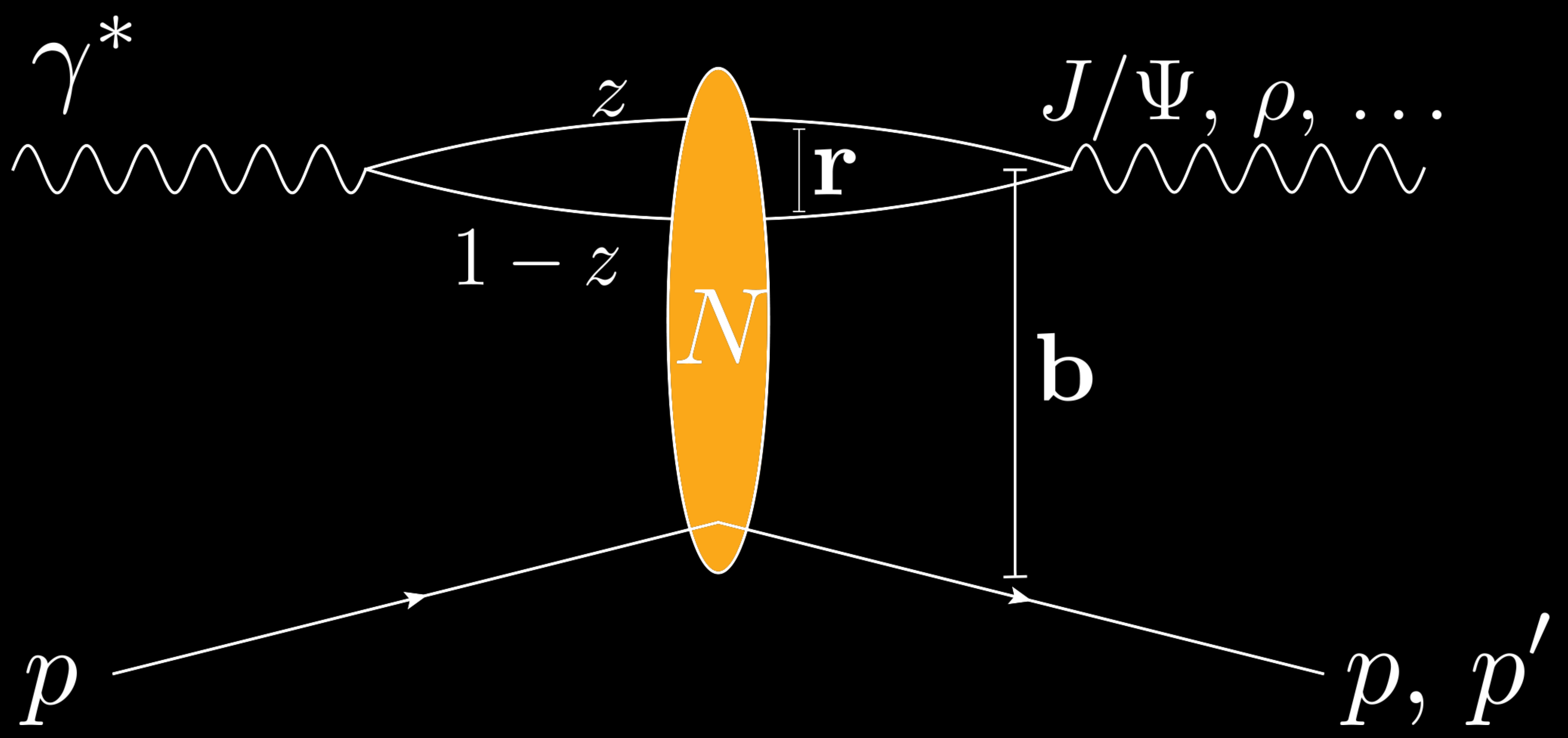


**Fundamental questions:**

- How are gluons distributed spatially in the proton?
- Do we have access to the (fluctuating) shape of the proton?
- How do the distributions evolve in Bjorken-x?

# DIS at high energy: Dipole picture



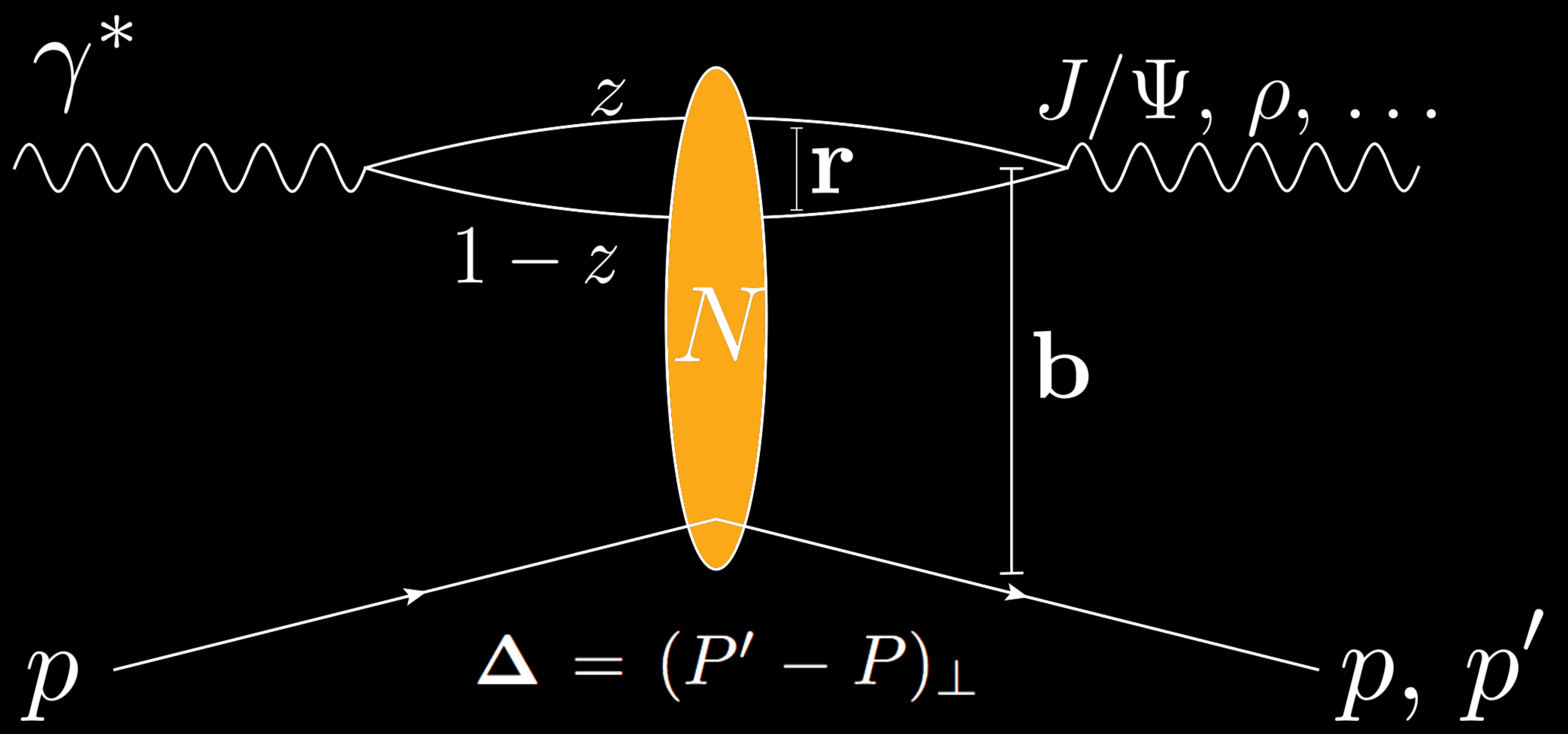

Inclusive DIS:
optical theorem:
$\sigma^{\gamma^* p} \sim$ dipole amplitude

Exclusive (diffractive) vector meson production:
$\sigma^{\gamma^* p} \sim |\text{dipole amplitude}|^2$

# CGC Framework: Scattering amplitude

High energy factorization:

- $\gamma^* \to q\bar{q} : \psi^\gamma(r, Q^2 m, z)$
- $q\bar{q}$ dipole scatters with amplitude N
- $q\bar{q} \to V : \psi^V(r, Q^2, z)$




$$\mathcal{A} \sim \int \mathrm{d}^2 b\,\mathrm{d}z\,\mathrm{d}^2 r\, \Psi^* \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Impact parameter ***b*** is the Fourier conjugate of transverse momentum transfer ***Δ*** → Access spatial structure
- Total $F_2$: forward scattering amplitude (**Δ**=0) for V=γ (same N)

# Averaging over the target

**Coherent diffraction:**

Target stays intact

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \boldsymbol{\Delta})\rangle\right|^2$$

**Incoherent diffraction:**

Target breaks up

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Vp^*}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle\left|\mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \boldsymbol{\Delta})\right|^2\right\rangle - \left|\langle \mathcal{A}^{\gamma^* p\to Vp}(x_{\mathbb{P}}, Q^2, \boldsymbol{\Delta})\rangle\right|^2\right)$$

Variance: Sensitive to fluctuations!


M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857
H. I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696
Y. V. Kovchegov and L. D. McLerran, Phys. Rev. D60 (1999) 054025
A. Kovner and U. A. Wiedemann, Phys. Rev. D64 (2001) 114002

# Strategy H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

- Determine dipole amplitude from McLerran-Venugopalan model at a given $x \sim 10^{-2}$
- Determine $x$-dependence from JIMWLK evolution
- Constrain evolution speed ($\alpha_s$ or $\Lambda_{QCD}$) and initial average $Q^2_{s,0}$ by fits to the charm reduced cross section data
- Constrain the average proton size with HERA diffractive J/Ψ data (slope of the coherent $|t|$-spectra)
- Fix parameters for fluctuating geometry using HERA incoherent diffractive J/Ψ data
- Predict energy evolution of the diffractive cross section and proton size

# Initial condition for JIMWLK evolution

H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

- Parametrize proton geometry $Q_s^2 \sim T_{\mathrm{proton}}(\vec{b})$
- MV-model: Sample local Gaussian color charges ρ, with density $\sim Q_s(\vec{b})$
- Solve Yang-Mills equations to get gluon fields:

$$A^+(x^-, \vec{k}) = -\frac{\rho(x^-, \vec{k})}{\vec{k}^2 + \tilde{m}^2}$$

- Wilson lines in coordinate space follow as

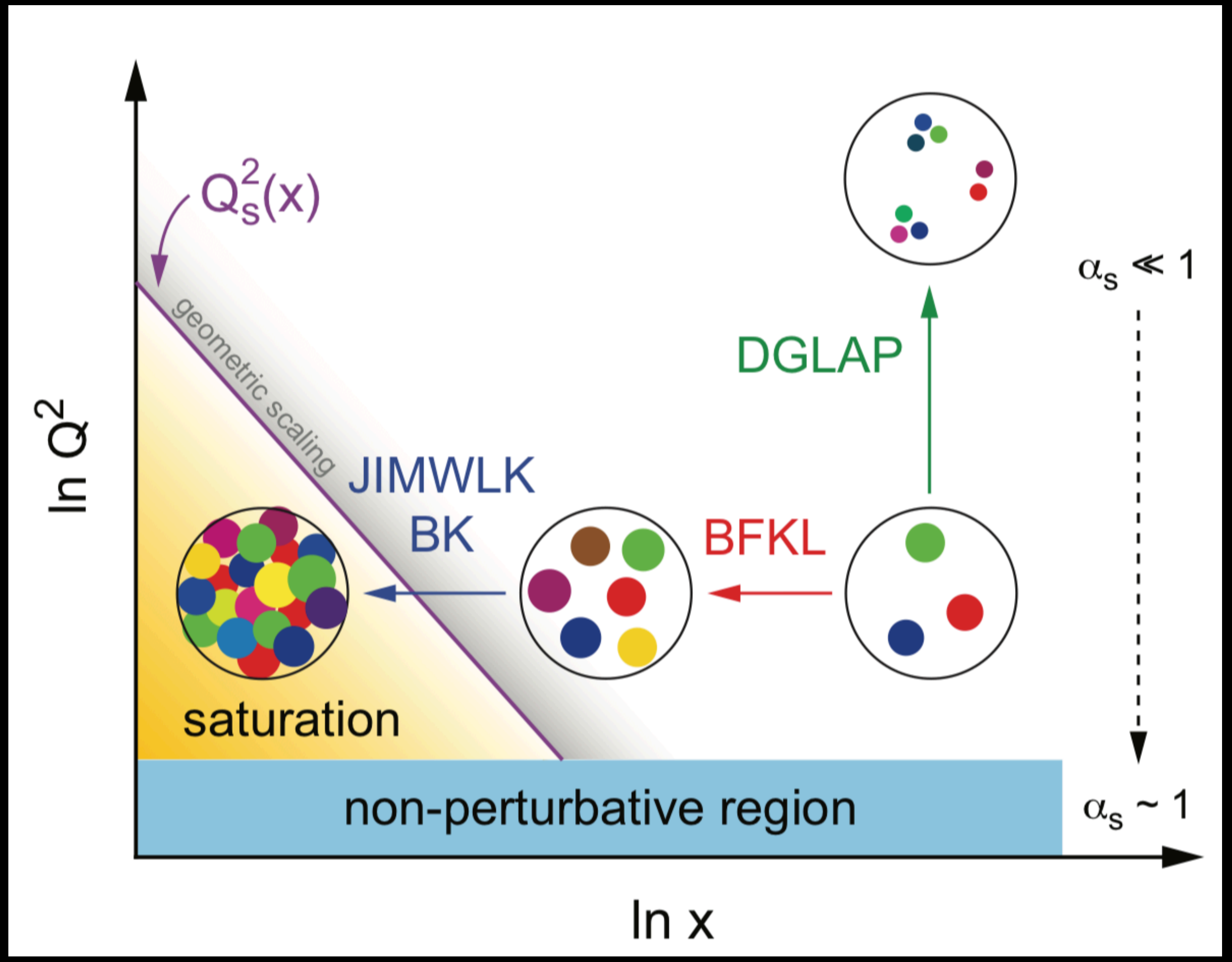
$$V(\vec{b}) = P\exp\left(\int dx^- A^+(x^-, \vec{b})\right)$$

- Dipole amplitude:

$$N(\vec{x}, \vec{y}) = 1 - \mathrm{tr}V(\vec{x})V^\dagger(\vec{y})/N_c$$

# JIMWLK

J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert,
Nucl. Phys. B504, 415 (1997), Phys. Rev. D59, 014014 (1999)
E. Iancu, A. Leonidov, and L. D. McLerran, Nucl. Phys. A692, 583 (2001)
E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A703, 489 (2002)
A. H. Mueller, Phys. Lett. B523, 243 (2001)




arXiv:1212.1701

Rapidity evolution of Wilson lines in Langevin form:

$$V_{\mathbf{x}}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot(V_{\mathbf{z}}\boldsymbol{\xi}_{\mathbf{z}}V_{\mathbf{z}}^\dagger)\right\}$$
$$\times V_{\mathbf{x}}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot\boldsymbol{\xi}_{\mathbf{z}}\right\}$$

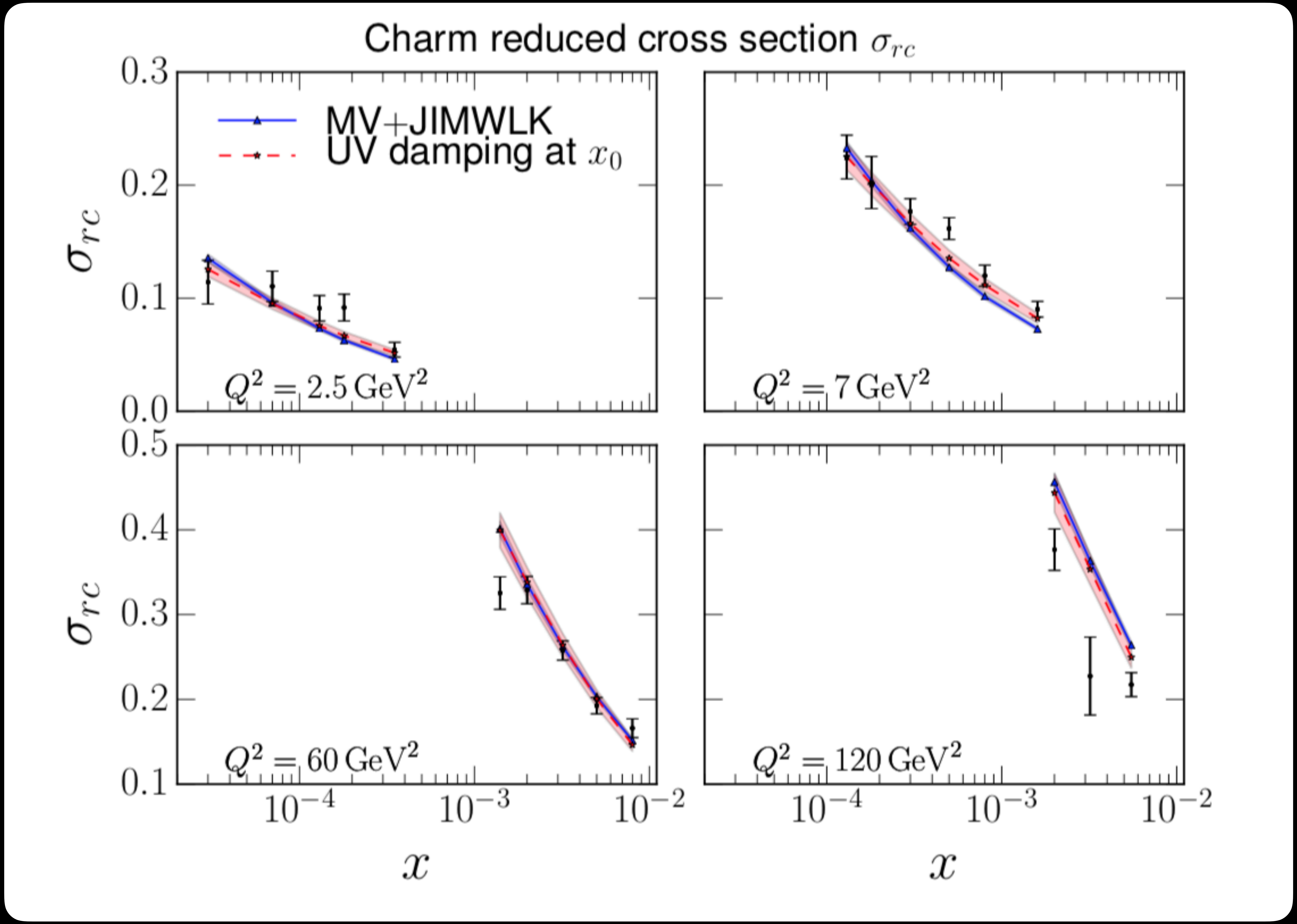
$\xi$ is Gaussian noise with zero average and $\langle \xi^a_{\mathbf{x},i}(Y)\xi^b_{\mathbf{y},j}(Y')\rangle = \delta^{ab}\delta^{ij}\delta^{(2)}_{\mathbf{xy}}\delta(Y-Y')$

The JIMWLK Kernel is modified to avoid infrared tails:

$$K^{\mathrm{mod}}_{\mathbf{x}-\mathbf{z}} = m|\mathbf{x}-\mathbf{z}|K_1(m|\mathbf{x}-\mathbf{z}|)\frac{\mathbf{x}-\mathbf{z}}{(\mathbf{x}-\mathbf{z})^2}$$

H. Weigert, Nucl. Phys. A 703, 823 (2002)
T. Lappi and H. Mäntysaari, Eur. Phys. J. C 73, 2307 (2013)
B. Schenke, S. Schlichting, PRC94, 044907 (2016)

# Charm reduced cross section




$Q^2$ evolution using MV model is too fast

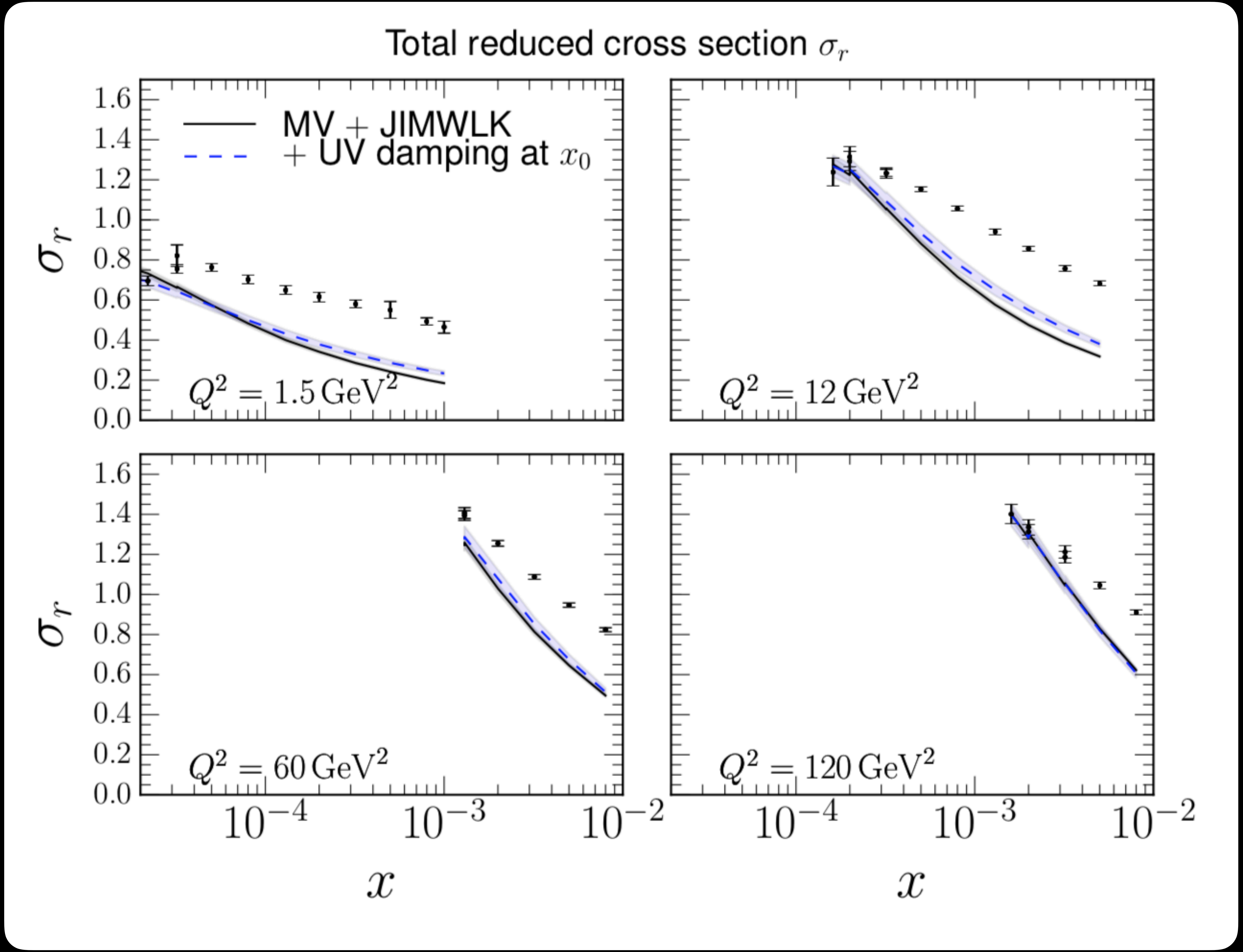
Improvement of fit when introducing UV damping

$$A^+(x^-, \vec{k}) = -\frac{\rho(x^-, \vec{k})}{\vec{k}^2 + \tilde{m}^2} e^{-|\vec{k}|v}$$

$$\chi^2/N : 4.3 \rightarrow 2.5$$

H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

# A problem



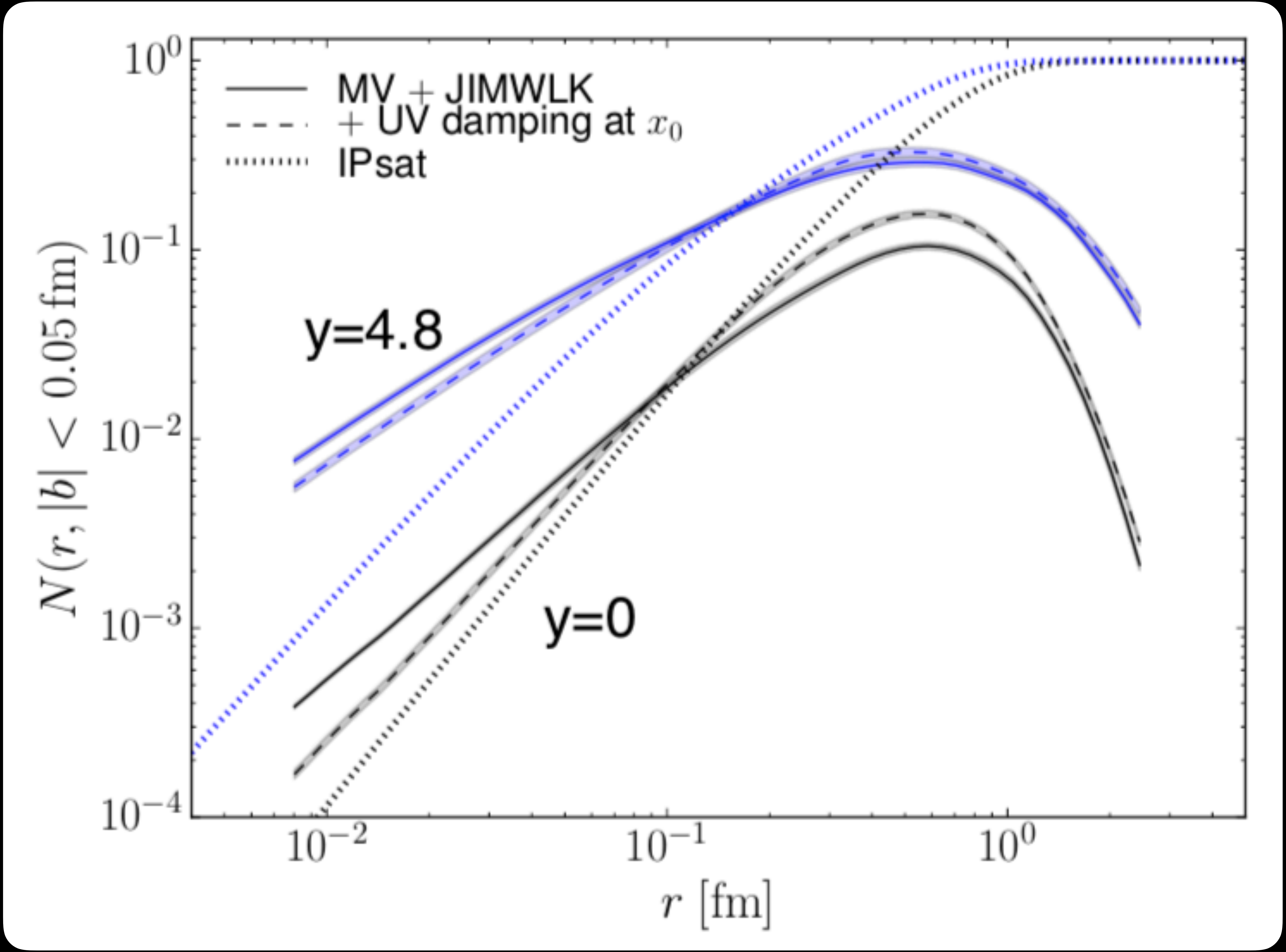

H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

Fitting parameters to the charm reduced cross section and then predicting total reduced cross section underestimates experimental data

We also underestimate J/Ψ production x-sec

Why?

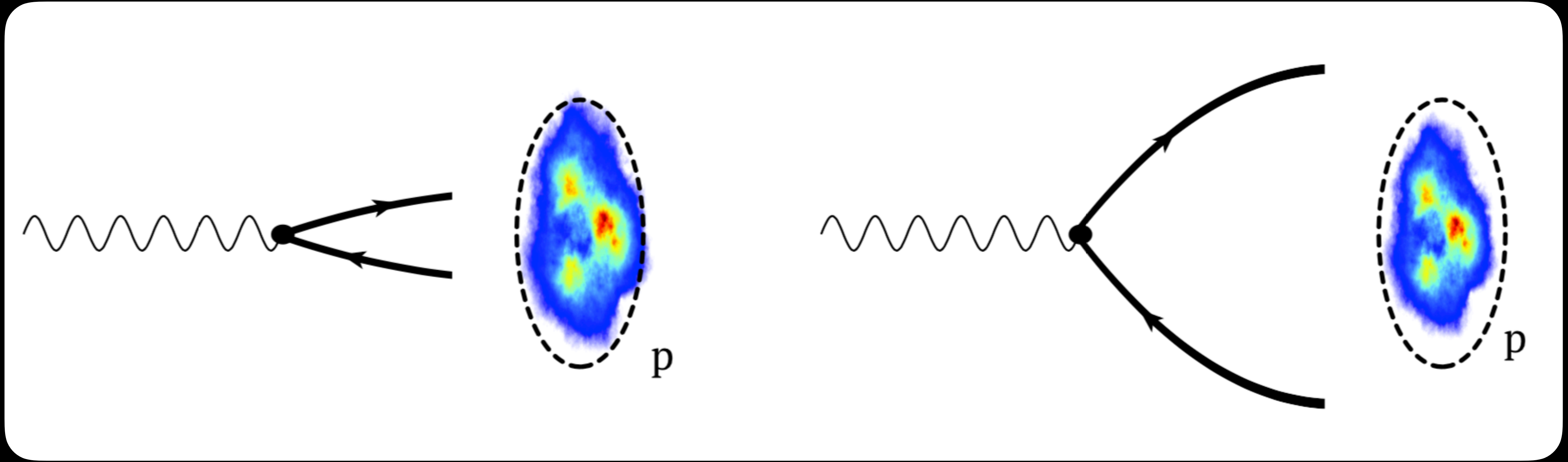
# A problem form large dipole contributions




$F_2$ has contributions from large dipoles (no hard scale to put weight to small *r* as for charm)

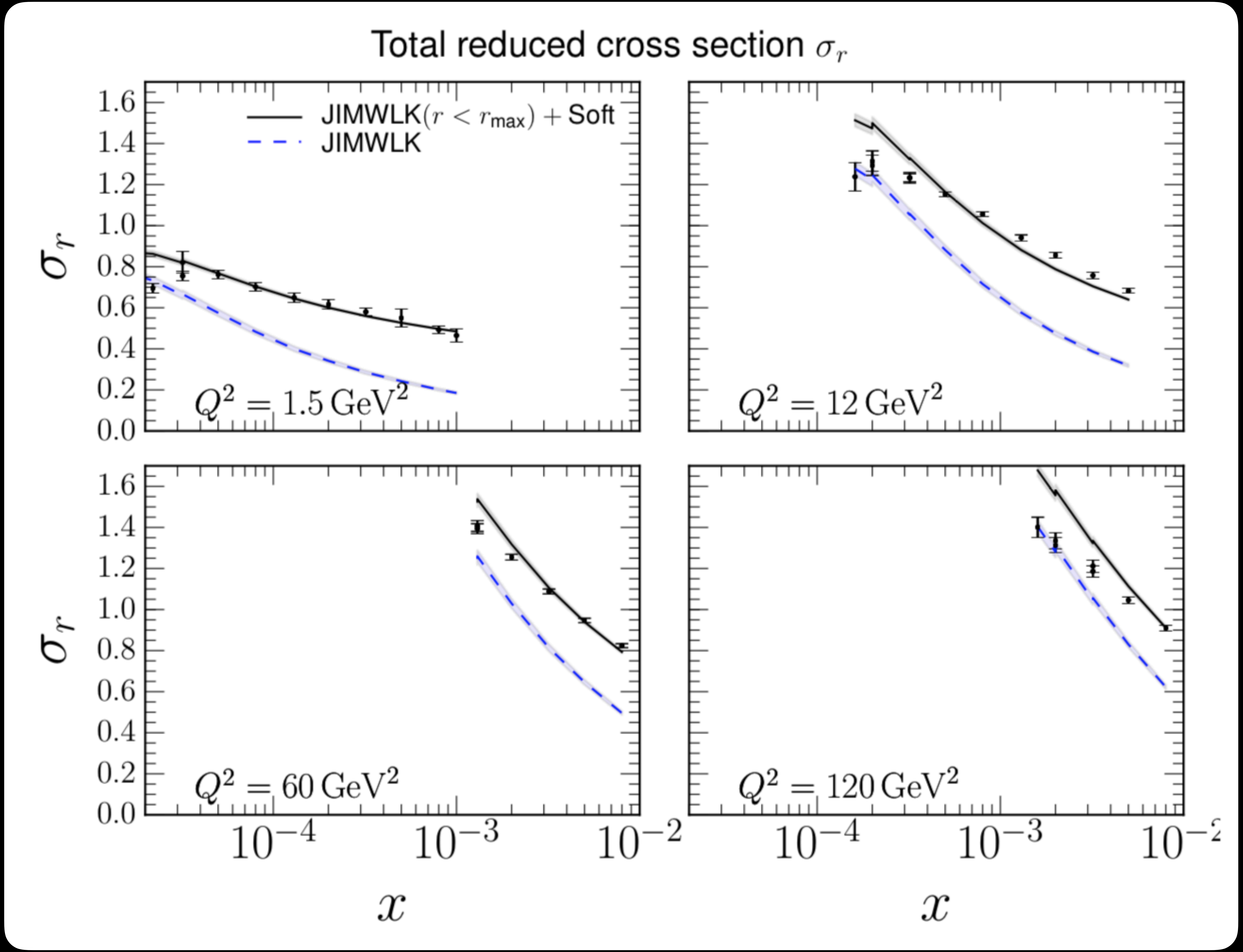
IP-Sat model has $N \to 1$ at large *r*, describes all observables

Our $N \to 0$ because of finite size




H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

# Adding non-perturbative contribution

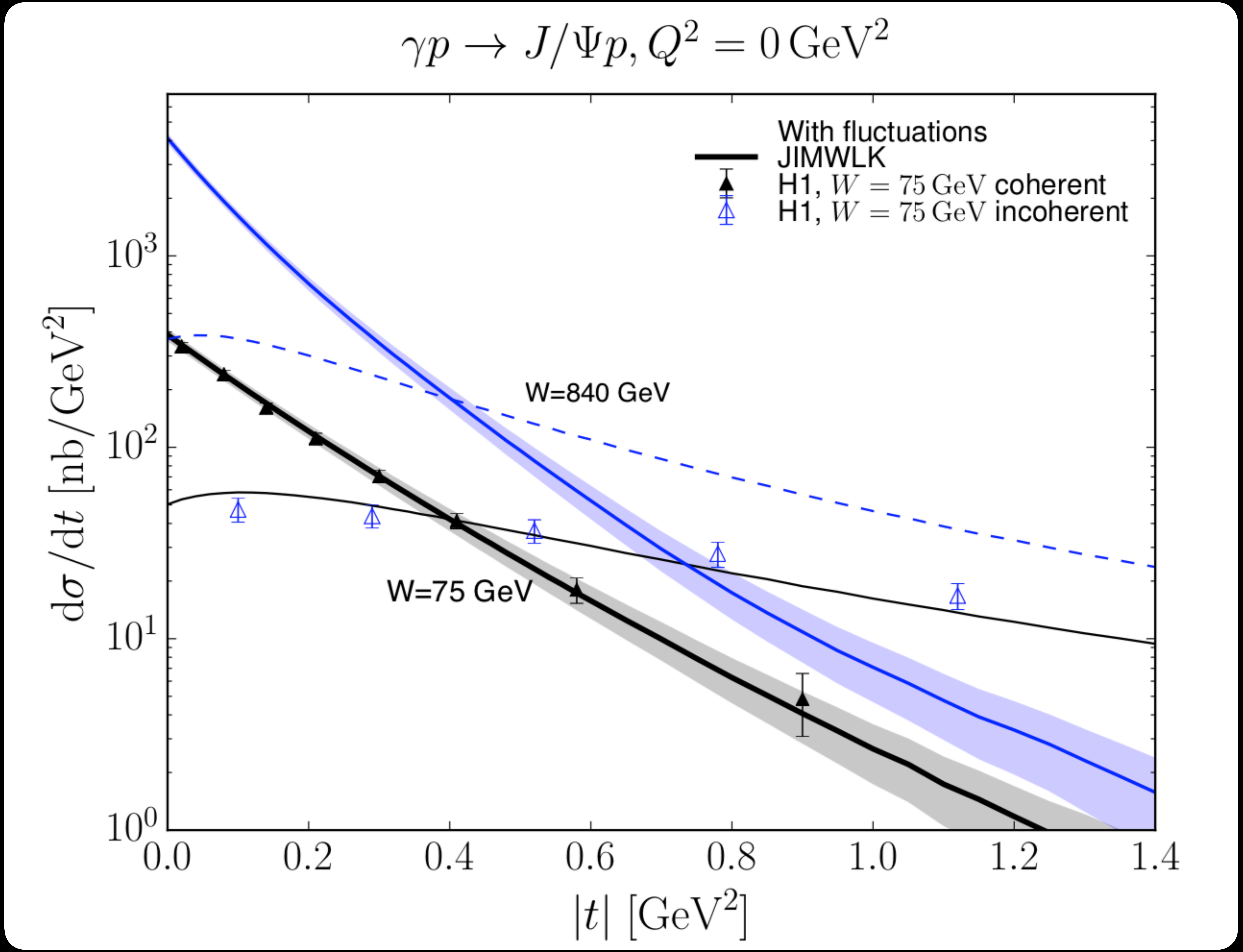



H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

Introducing a non-perturbative contribution that replaces the large $r$ result of our perturbative calculation above a given $r_{max}$ decent agreement can be found

Soft contribution as in
J. Berger and A. Stasto
Phys.Rev. D84 (2011) 094022

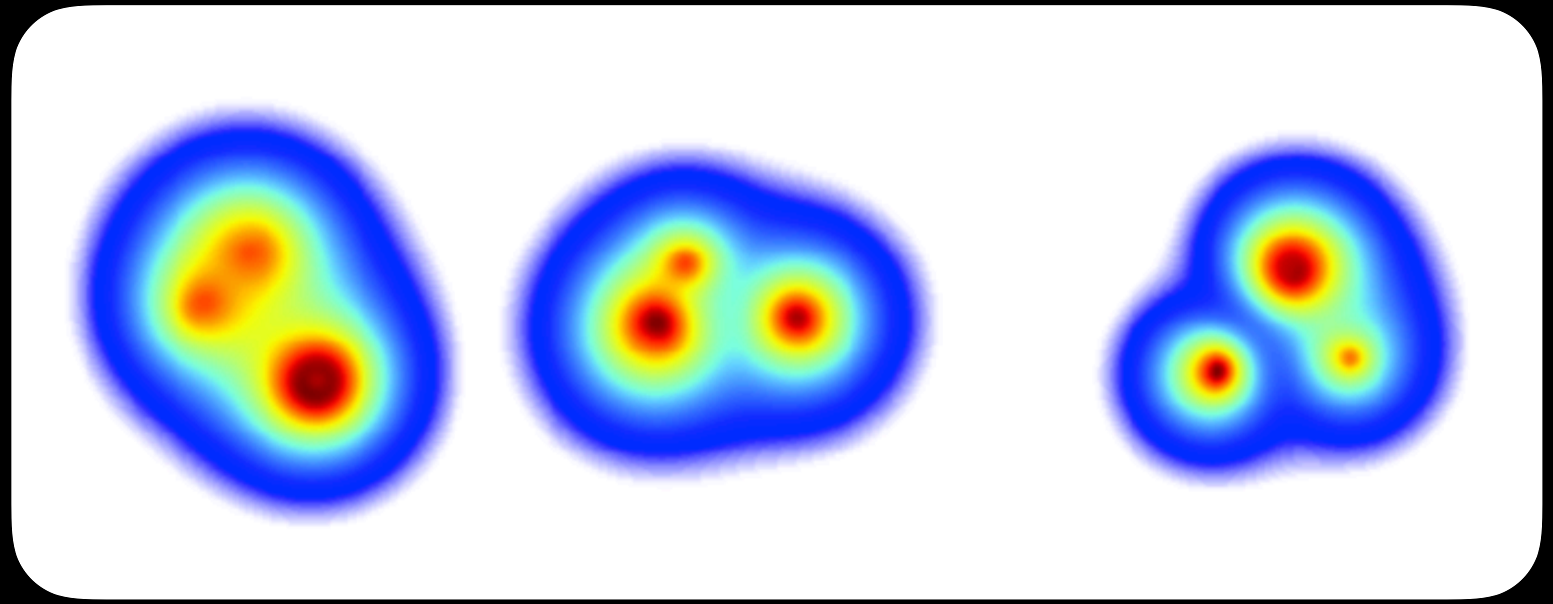
# Evolution of coherent and incoherent J/Ψ production




H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

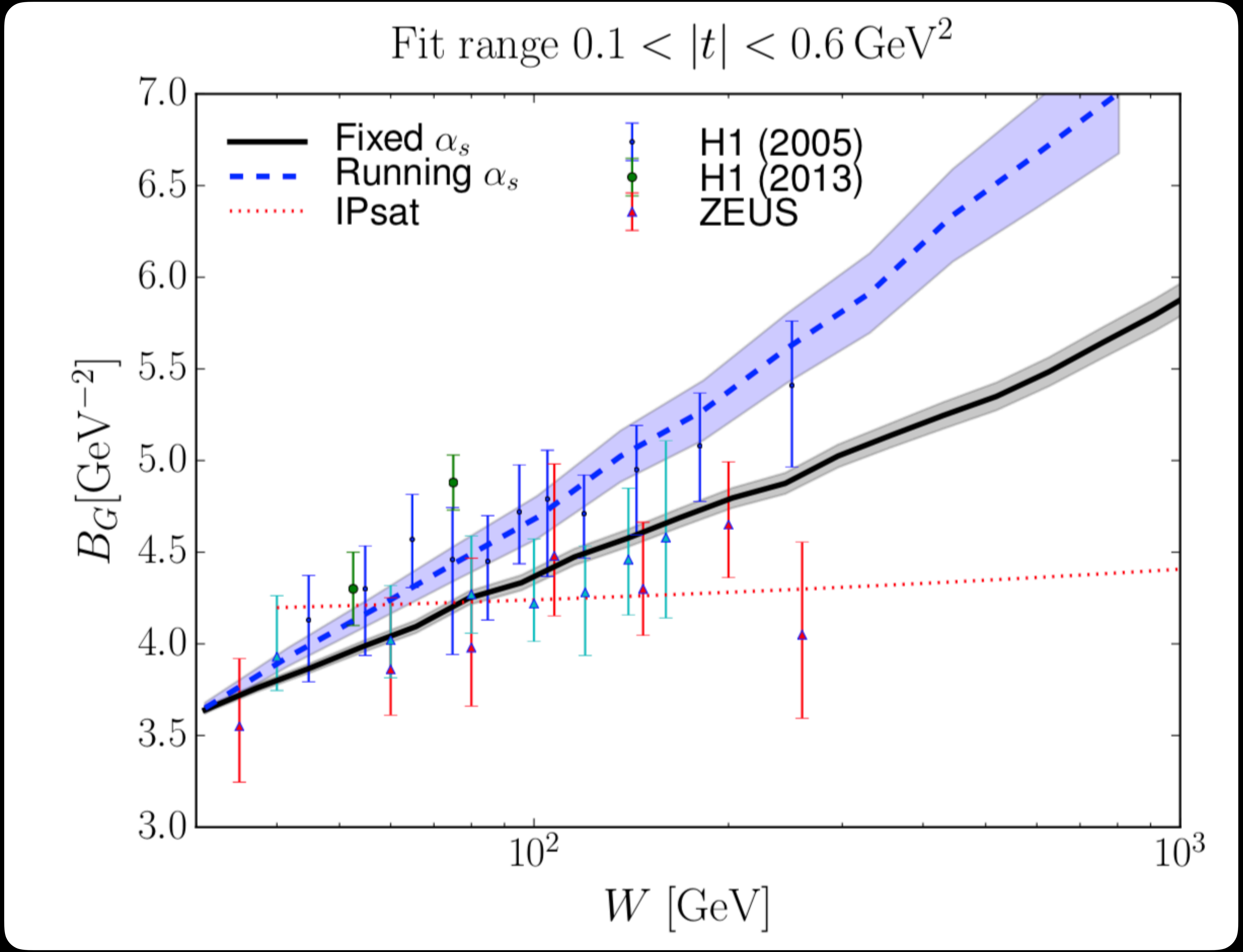
Refit normalization to describe J/Ψ production at *W*=75 GeV with fluctuating protons

Predict cross sections at larger energies



*W*=75 GeV

# Proton size evolution



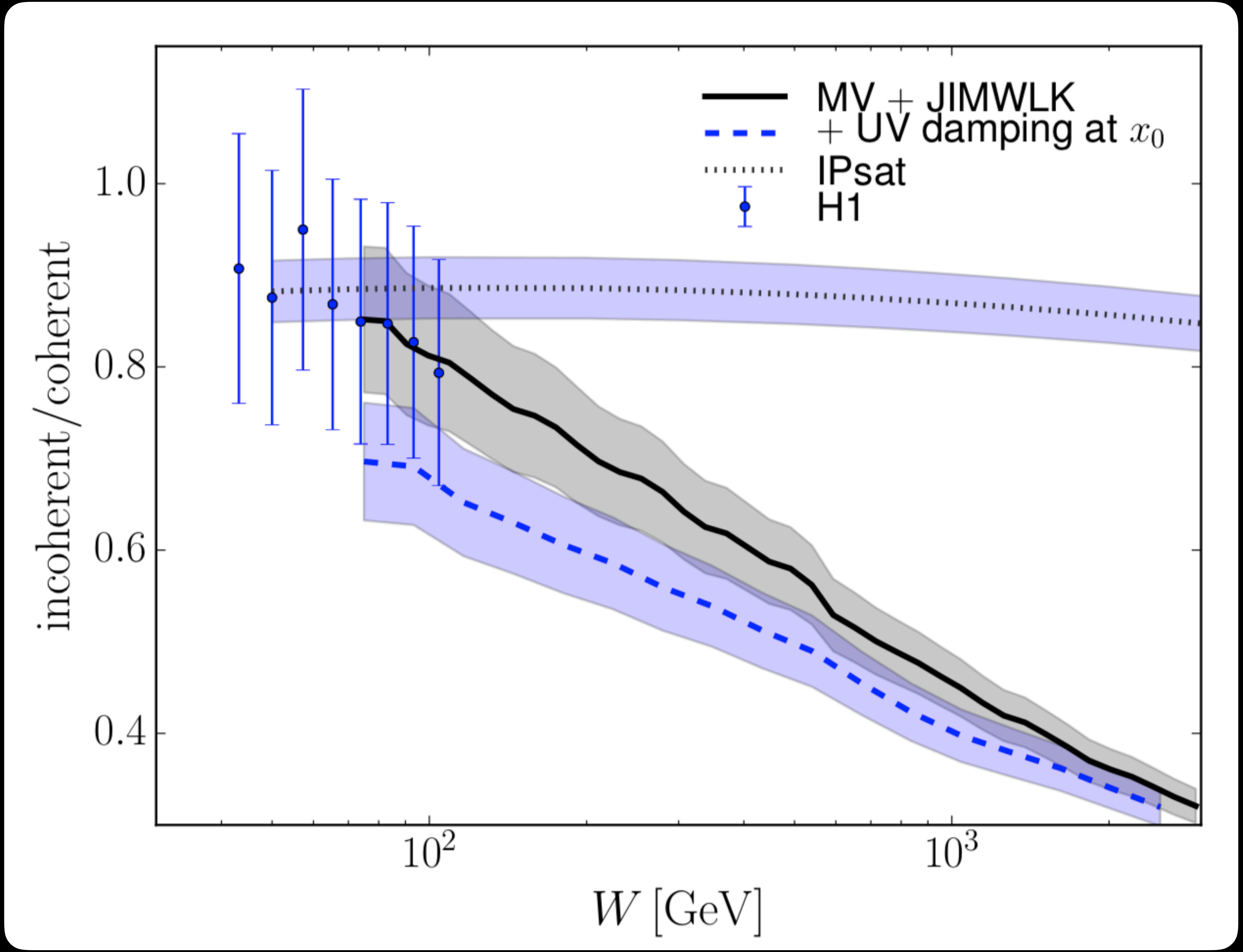

H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

$B_G$: |t|-slope of coherent J/Ψ production x-sec

Size fixed at $W$=30 GeV
Evolution speed fixed from charm-$F_2$

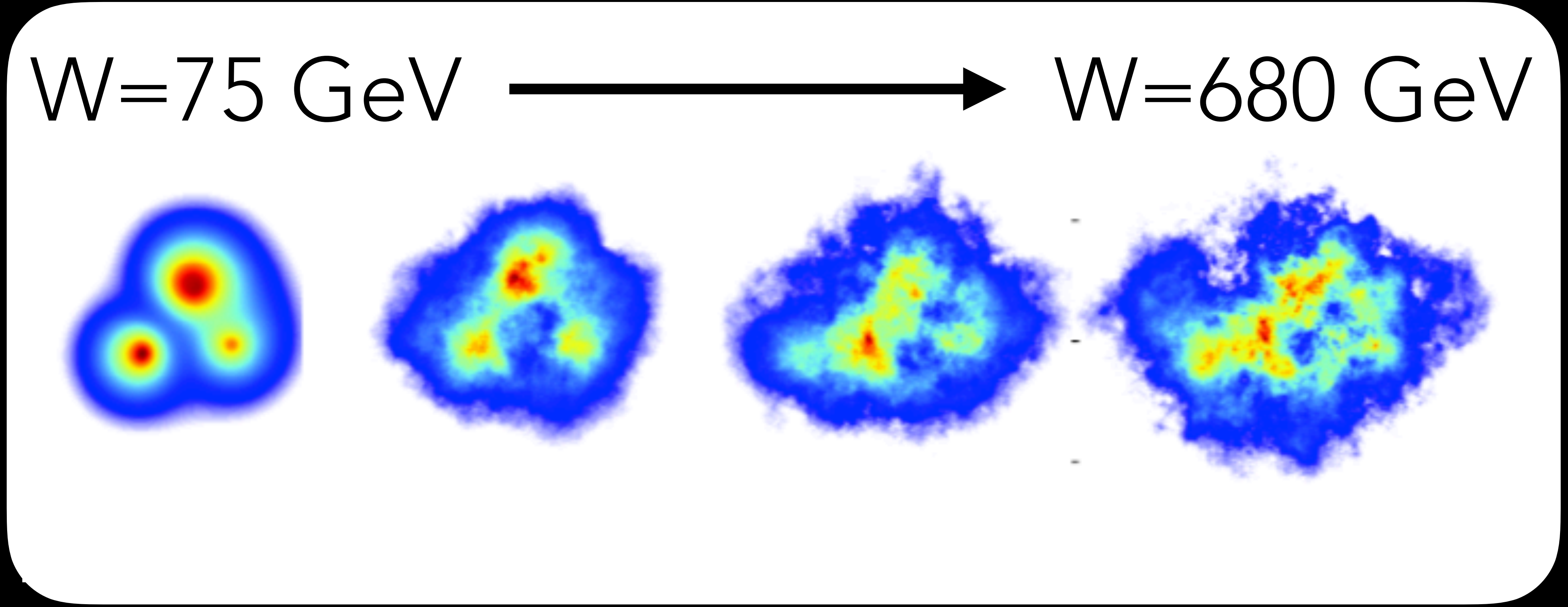
Running $\alpha_s$:
faster evolution at long distance scales, which dominate size $B_G$

# Evolution of the fluctuations



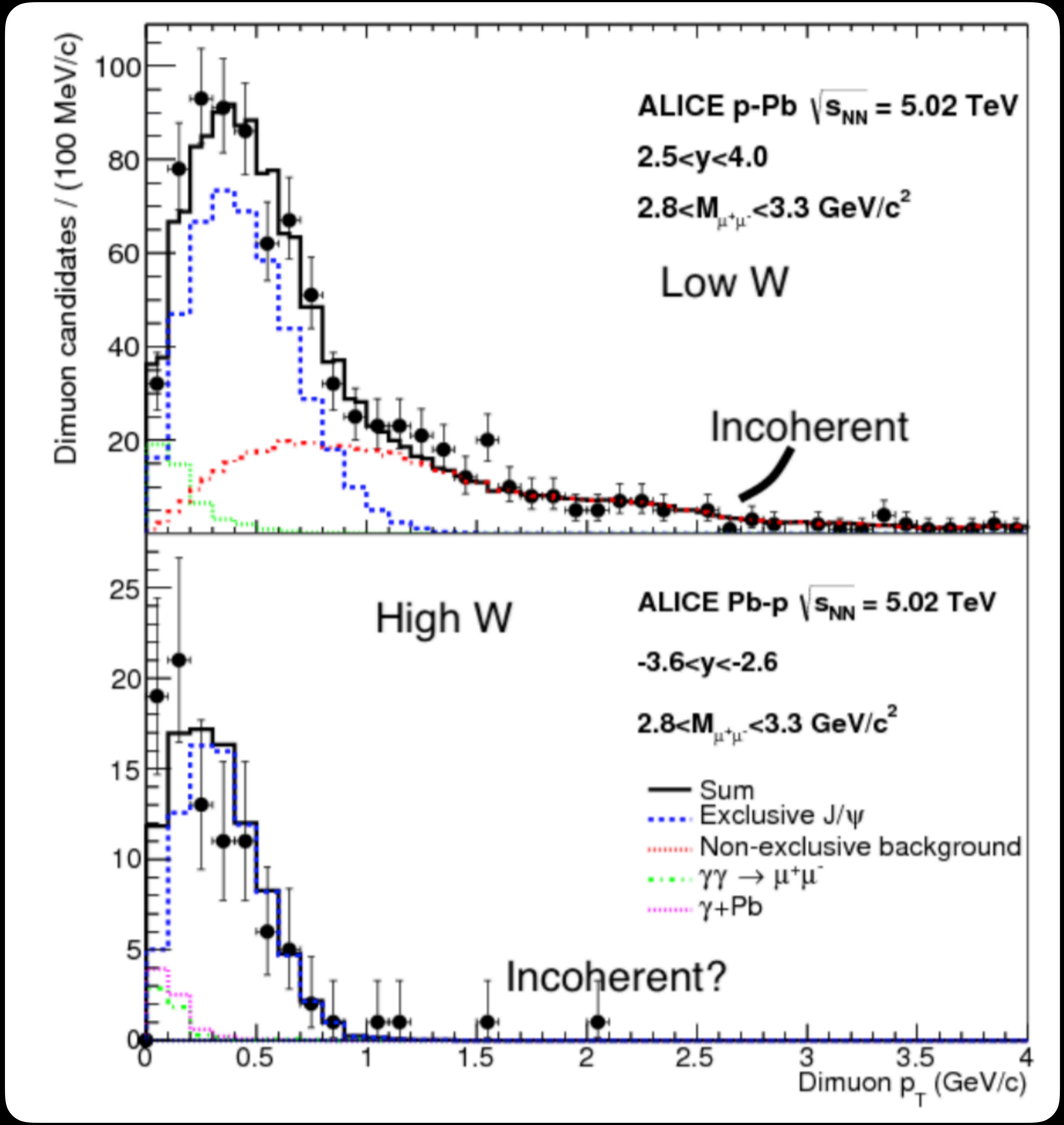

Cross section ratio compatible with H1 data

Checked that not sensitive to large dipole contribution




H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013

# Ultraperipheral p + A at the LHC




Photon flux ~ $Z^2$

→ γ + p dominates

Forward/backward rapidity J/Ψ

→ high/low W

Low W: significant coherent and incoherent contributions

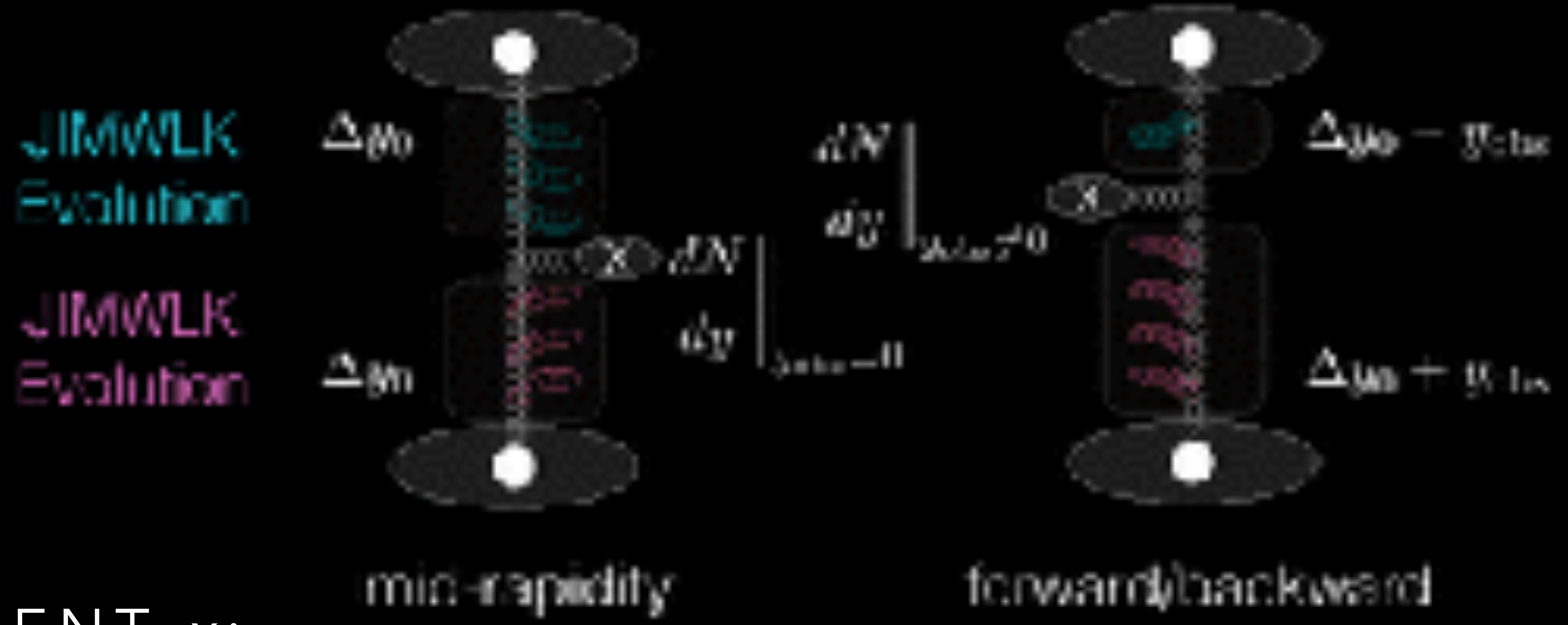
High W: no/small incoherent

Qualitative agreement with our results

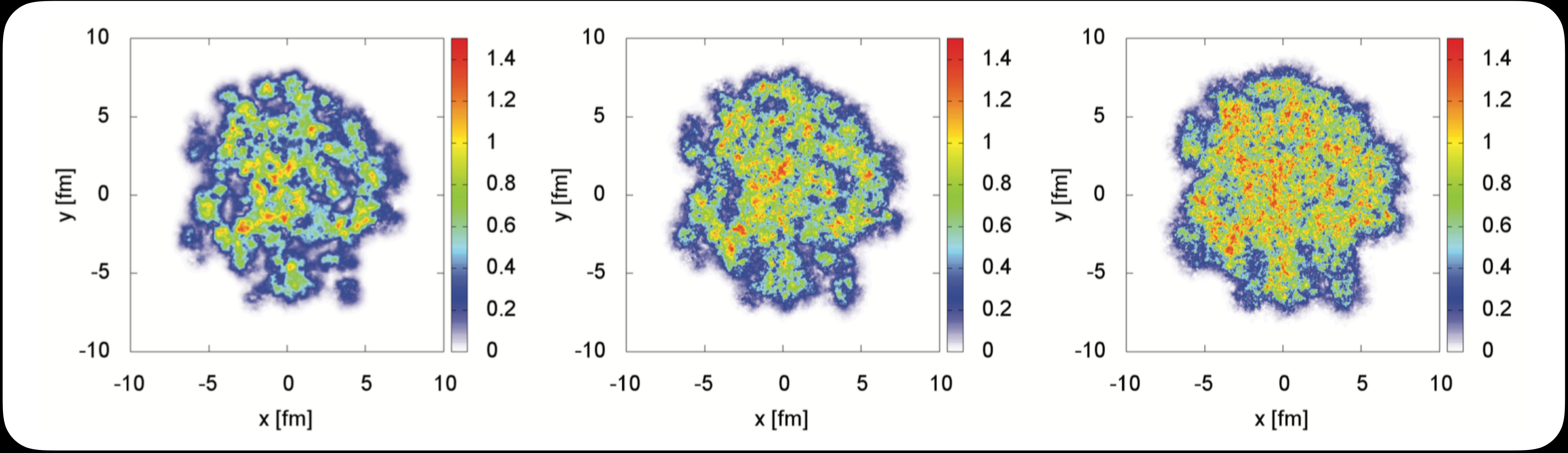
Experimenta data: ALICE Collaboration, Phys.Rev.Lett. 113 (2014) no.23, 232504

# Other applications: Rapidity dependence in A+A collisions

B. Schenke, S. Schlichting, PRC94, 044907 (2016)




GLUON FIELDS IN A NUCLEUS AT DIFFERENT *x*:

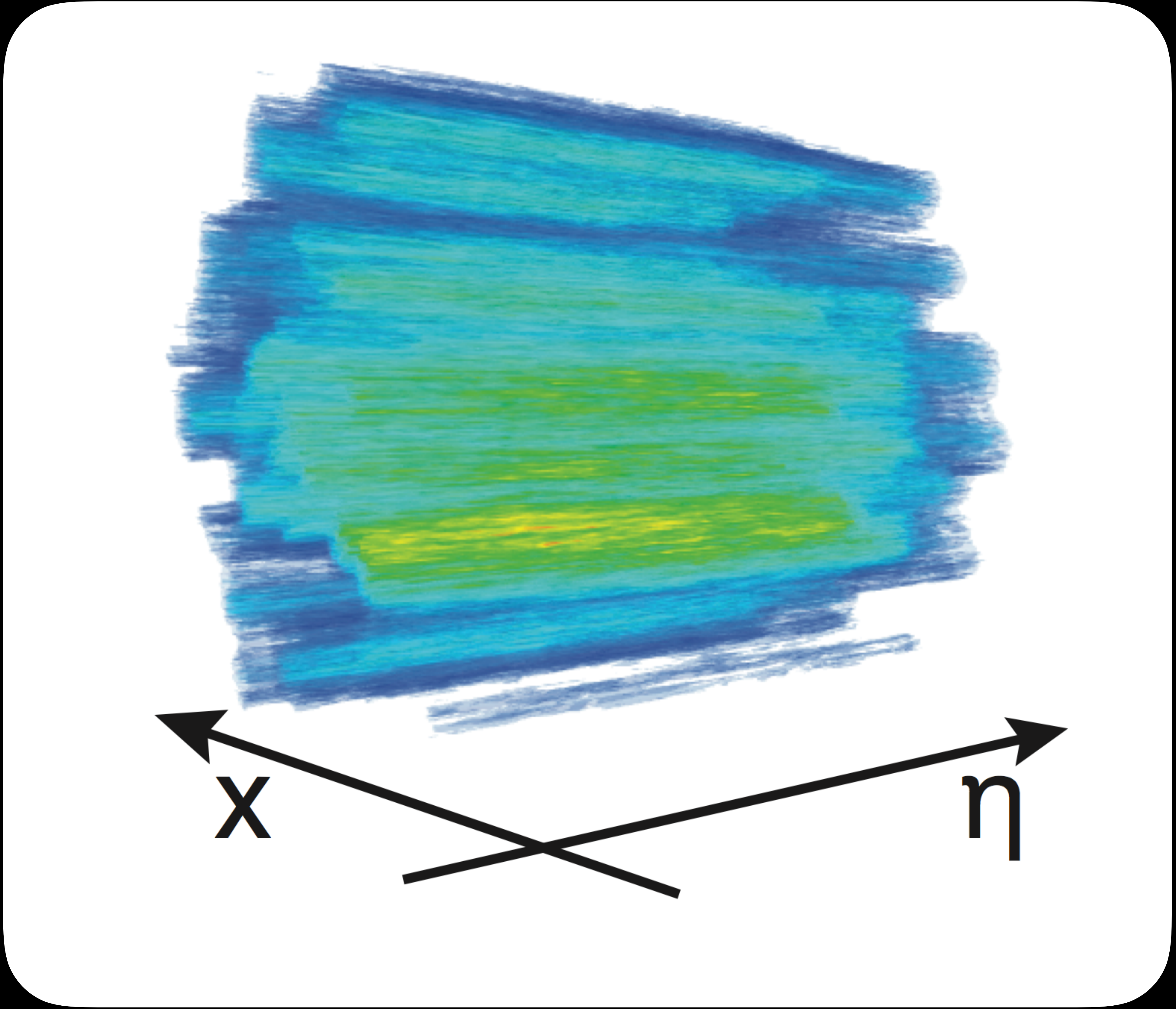



$Y = -2.4$ ($x \approx 2\times10^{-3}$) $Y = 0$ ($x \approx 2\times10^{-4}$) $Y = 2.4$ ($x \approx 1.6\times10^{-5}$)

# 3D Glasma initial state for A+A collisions

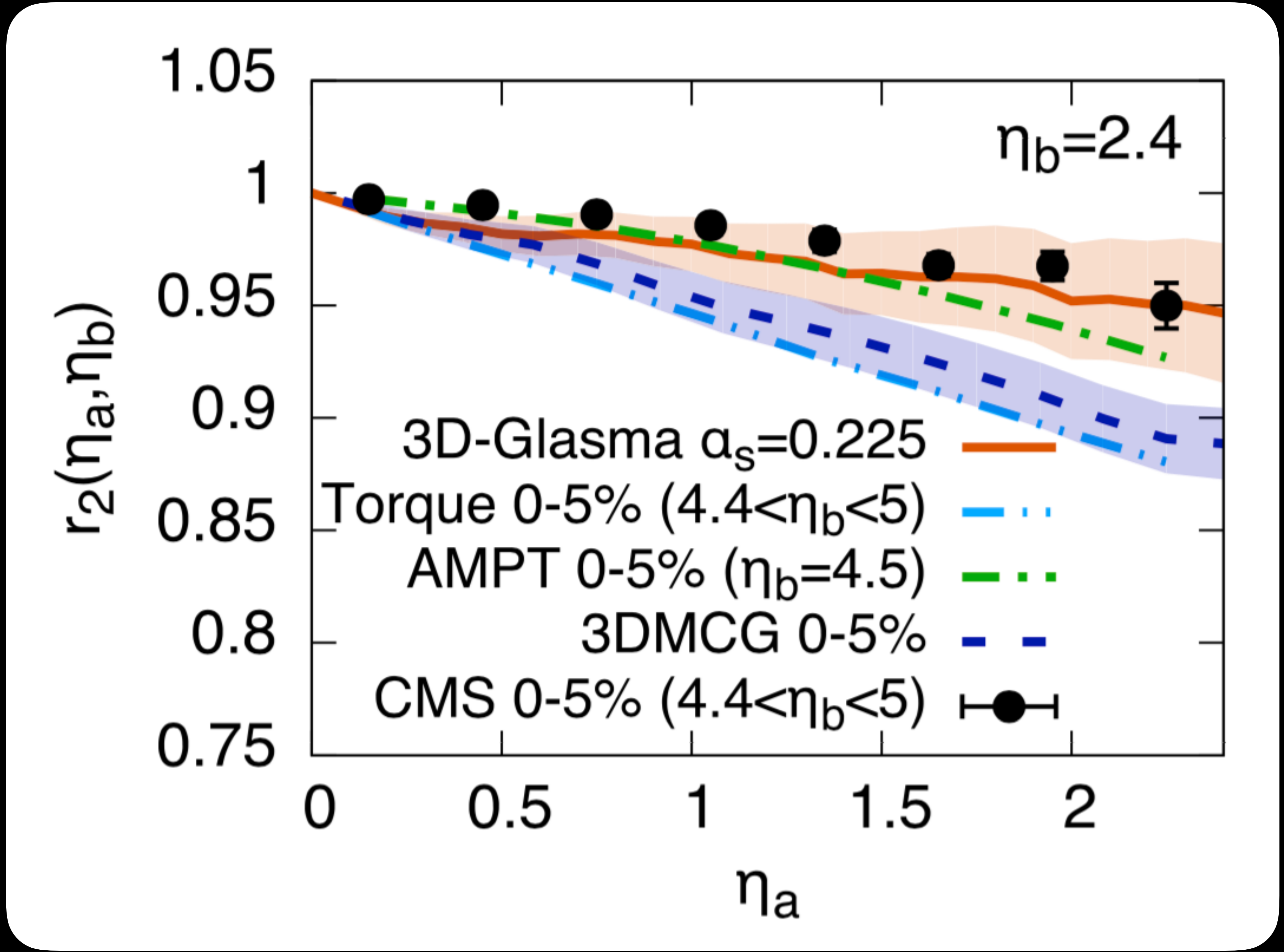
B. Schenke, S. Schlichting, PRC94, 044907 (2016)

- Collide two JIMWLK evolved Nuclei




ENERGY DENSITY

- Decorrelation measure




TORQUE: P. BOZEK AND W. BRONIOWSKI, PHYS. LETT. B 752, 206 (2016)
AMPT: L.G. PANG, H. PETERSEN, G.Y. QIN, V. ROY, AND X.N. WANG, EUR.PHYS.J.A52, 97
3DMCG: A. MONNAI AND B. SCHENKE, PHYS. LETT. B 752, 317 (2016)
EXPERIMENTAL DATA: CMS COLLABORATION, PHYS. REV. C 92, 034911 (2015)

# Conclusions

- Numerically solve JIMWLK equation for protons on a lattice
- Initial condition fit to HERA data
- Evolution speed tuned to describe $F_{2,charm}$
- *Predict* W dependence of proton size
  and incoherent/coherent cross section ratio
- Uncertainty: how to describe large dipole - proton scattering?
  - Simultaneous description of $F_2$, $F_{2,charm}$ and diffractive data require additional non perturbative contribution
  - Charm-$F_2$ not sensitive to large dipoles
- Qualitatively describe disappearing incoherent contribution in ALICE

# Backup

# COLOR GLASS CONDENSATE

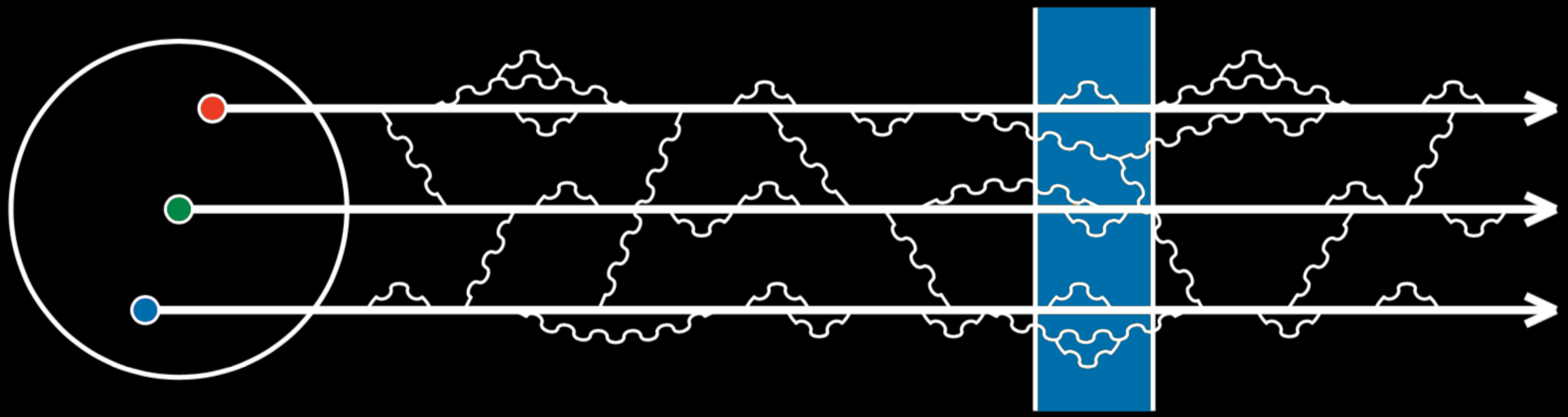


Figure from F. Gelis

Nucleon at rest:

- Complicated non-perturbative object
- Contains fluctuations at all scales smaller than its own size
- Only the fluctuations that are longer lived than the external probe participate in the interaction process
- The only role of short lived fluctuations is to renormalize the masses and couplings
- Interactions are very complicated if the constituents of the nucleon have a non trivial dynamics over time-scales comparable to those of the probe

# COLOR GLASS CONDENSATE

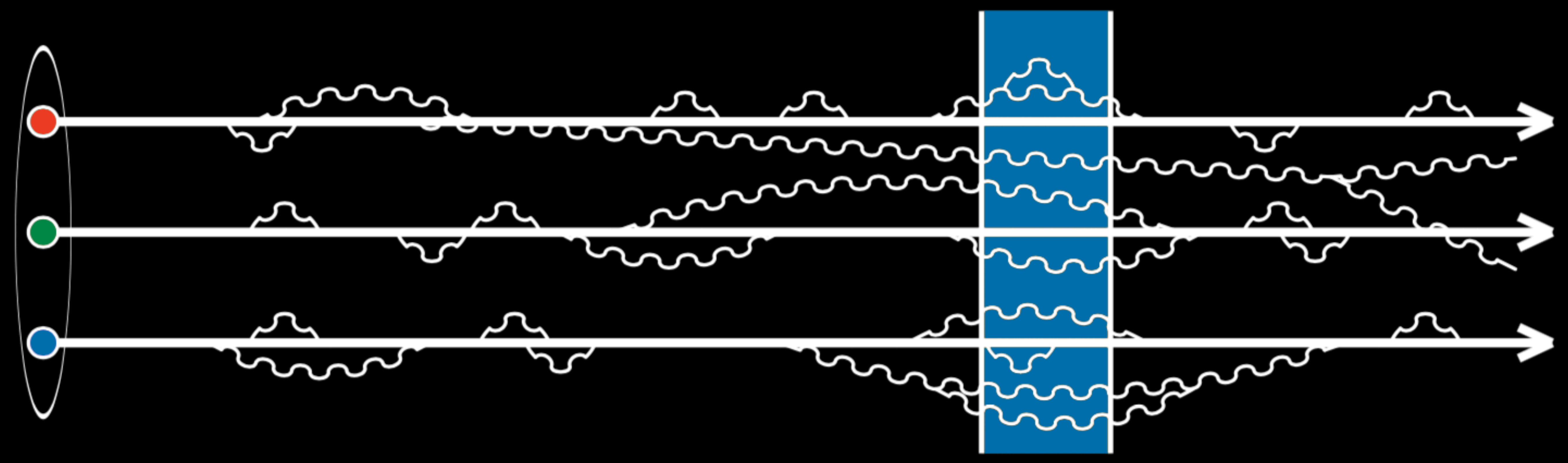


Figure from F. Gelis

Nucleon at high energy:

- Dilation of all internal time-scales of the nucleon
- Interactions among constituents now take place over time-scales longer than the characteristic time-scale of the probe → The constituents behave as if they were free
- Many fluctuations live long enough to be seen by the probe. Nucleon appears denser at high energy (contains more gluons)
- Pre-existing fluctuations are totally frozen over the time-scale of the probe, and act as static sources of new partons

# Geometric fluctuations in the IPsat model

Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

All parameters are fit to HERA DIS data

Thickness function $T_p(\vec{b})$ normally assumed to be Gaussian

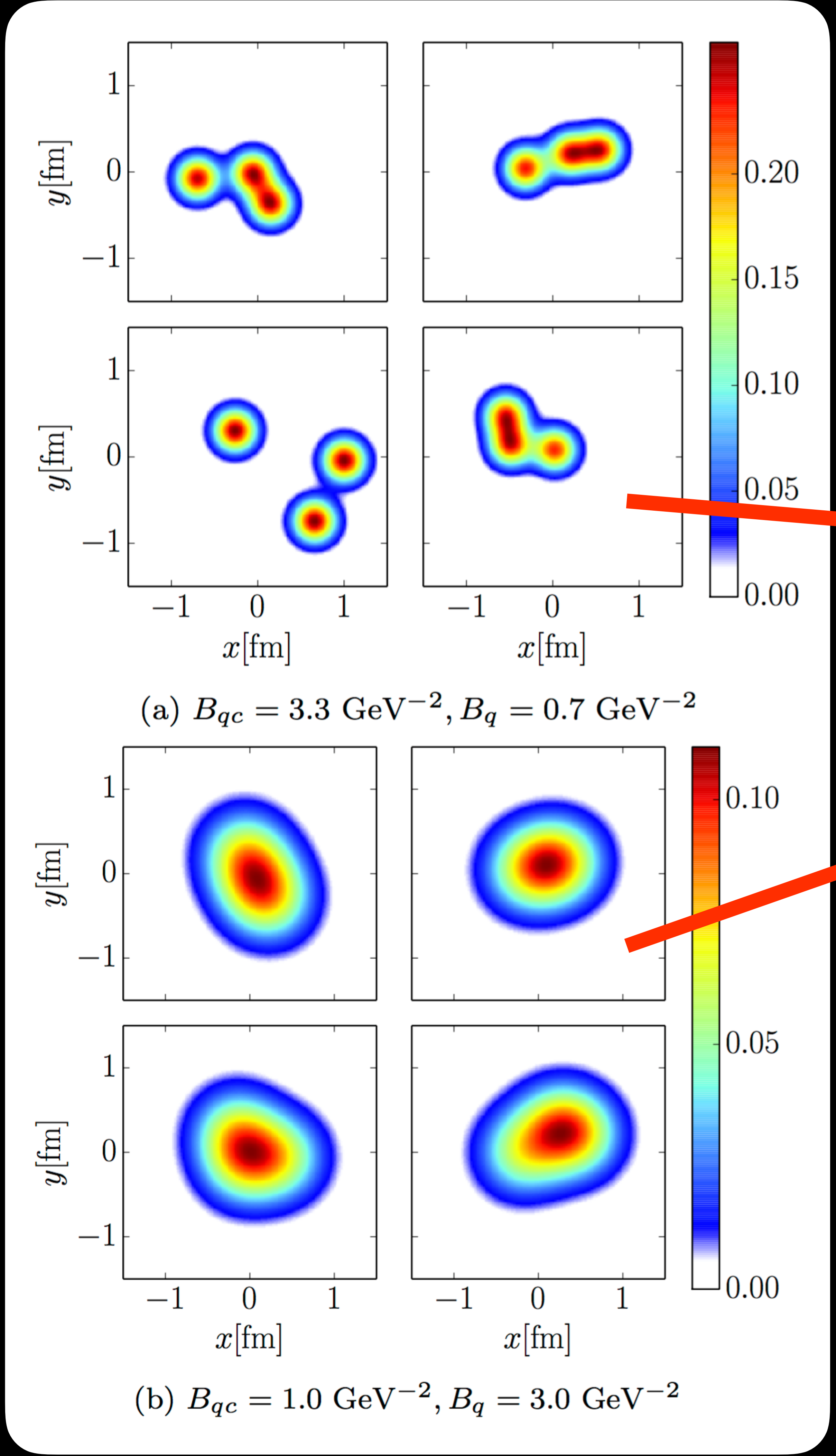
Here we introduce a substructure to the proton by defining:

$$T_p(\vec{b}) = \sum_{i=1}^{3} T_q(\vec{b} - \vec{b}_i)$$

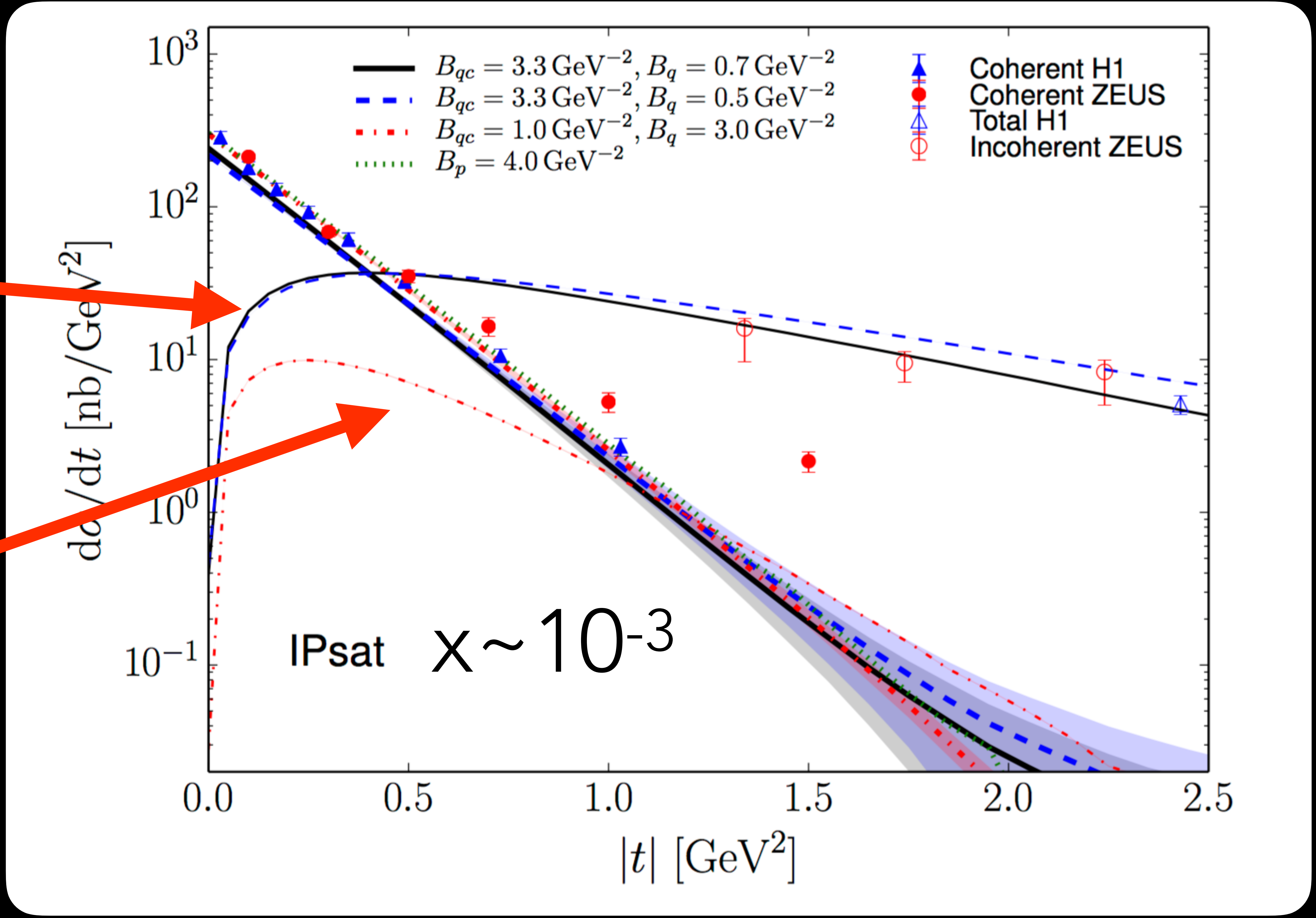
with $T_q(\vec{b}) \sim e^{-b^2/2B_q}$

where the positions $\vec{b}_i$ are sampled from a Gaussian with width $B_{qc}$

# J/Ψ production from fluctuating proton




H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042

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