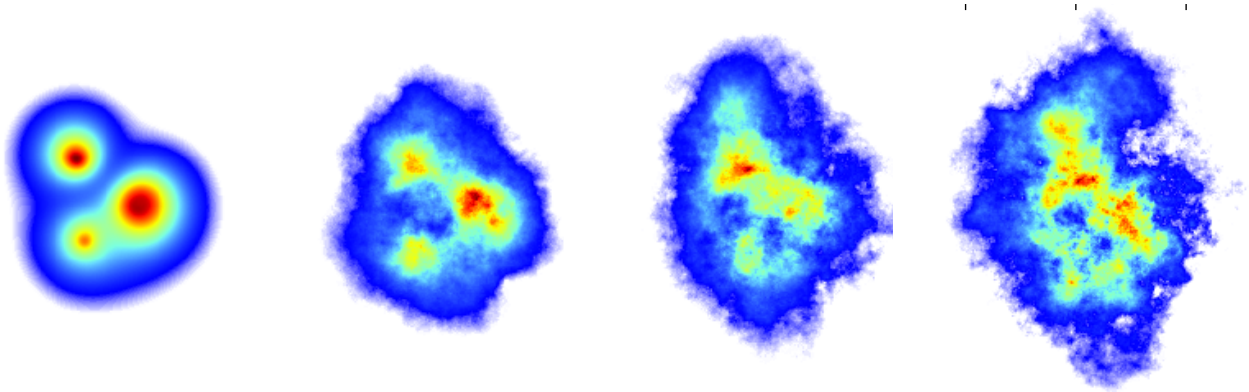
Impact parameter dependent JIMWLK evolution meets HERA data

Heikki Mäntysaari
In collaboration with B. Schenke
Based on Phys.Rev. D98 (2018), 034013 (arXiv:1806.06783)

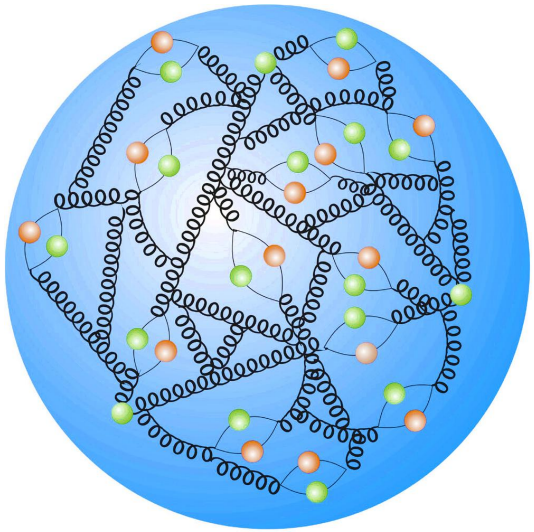
University of Jyväskylä, Department of Physics
Finland



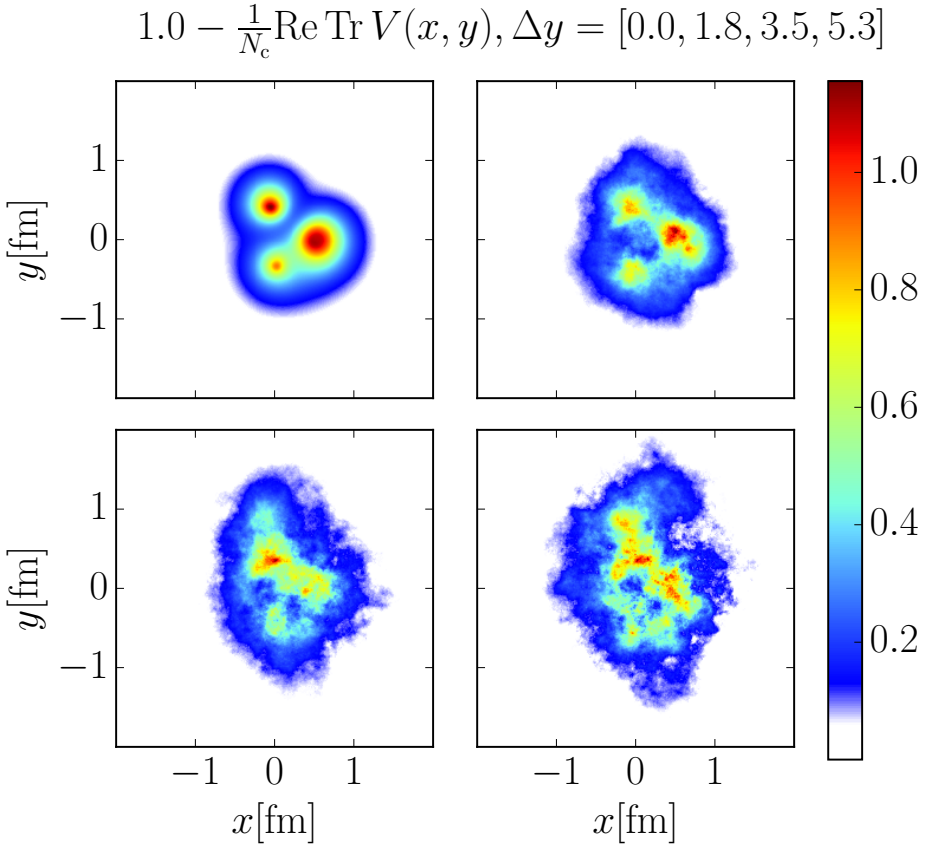
Going beyond a round proton

A fundamental question

How are small-x gluons distributed spatially inside the proton?
How do the positions fluctuate?
How do these distributions evolve in Bjorken-x?

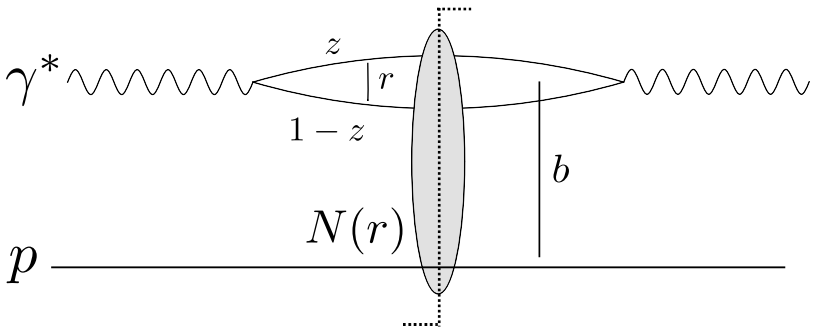


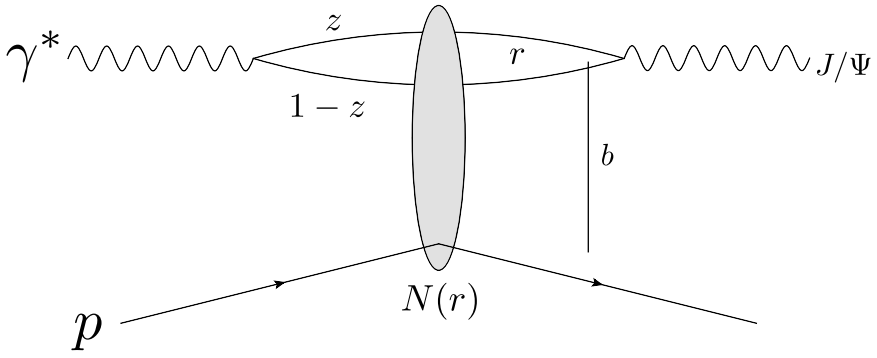
$\Rightarrow$



Deep Inelastic Scattering as a probe of the proton structure

DIS at high energy: dipole picture





Optical theorem:
$\sigma^{\gamma^* p} \sim$ dipole amplitude

$\sigma^{\gamma^* p \to V p} \sim |$dipole amplitude$|^2$

Multiple constraints

Dipole-target interaction: dipole amplitude $N \sim$ gluon density

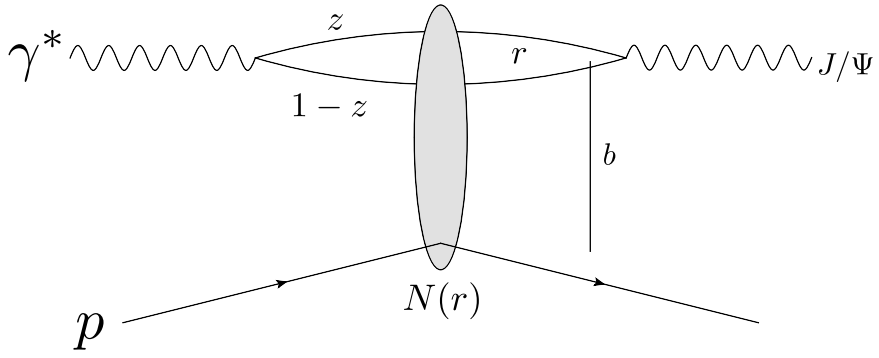
- Structure function $\sim$ **gluon density** $\times \sigma_0$
- Diffraction $\sim$ **gluon density^2** and access to the spatial structure

Energy dependence of N from JIWMLK

Probe of the geometry: exclusive J/Ψ production

High energy factorization:

1. $\gamma^* \to q\bar{q}$: $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically Amplitude N
3. $q\bar{q} \to J/\Psi$: $\Psi^V(r, Q^2, z)$



Diffractive scattering amplitude

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

- Impact parameter is the Fourier conjugate of the momentum transfer $\to$ Access to the spatial structure
- Total F_2: forward elastic scattering amplitude ($\Delta = 0$) for $V = \gamma$ (same dipole amplitude)

Average over configurations

Coherent diffraction:

Target proton remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

$\langle\,\rangle$: average over target configurations [N(r, **b**)]

Average over configurations

Coherent diffraction:

Target proton remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Incoherent/target dissociation:

Total diffractive − coherent cross section

Target breaks up

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Variance, measures the amount of fluctuations!

$\langle\,\rangle$: average over target configurations [N(r, **b**)]

Initial condition for JIMWLK

- Parametrize proton geometry, $Q_s^2 \sim T_{\text{proton}}(\mathbf{b})$
- MV-model: Sample color charges ρ, density $\sim Q_s(\mathbf{b})$
- Solve Yang-Mills equations: write color field in momentum space

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

- Here introduce a UV damping factor v, fixed by Q^2 evolution of F_2
- Wilson lines are then obtained as a Fourier transform

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

- Dipole amplitude: $N(\mathbf{x}, \mathbf{y}) = 1 - \mathrm{Tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y})/N_c$
- Energy evolution: solve JIMWLK equation to get $V(\mathbf{b})$ at small x

Schenke, Schlichting, 1407.8458

Initial condition for JIMWLK

- Parametrize proton geometry, $Q_s^2 \sim T_{\text{proton}}(\mathbf{b})$
- MV-model: Sample color charges ρ, density $\sim Q_s(\mathbf{b})$
- Solve Yang-Mills equations: write color field in momentum space

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

- Here introduce a UV damping factor v, fixed by Q^2 evolution of F_2
- Wilson lines are then obtained as a Fourier transform

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

- Dipole amplitude: $N(\mathbf{x}, \mathbf{y}) = 1 - \mathrm{Tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y}) / N_c$
- Energy evolution: solve JIMWLK equation to get $V(\mathbf{b})$ at small x

Schenke, Schlichting, 1407.8458

Initial condition for JIMWLK

- Parametrize proton geometry, $Q_s^2 \sim T_{\text{proton}}(\mathbf{b})$
- MV-model: Sample color charges ρ, density $\sim Q_s(\mathbf{b})$
- Solve Yang-Mills equations: write color field in momentum space

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

- Here introduce a UV damping factor v, fixed by Q^2 evolution of F_2
- Wilson lines are then obtained as a Fourier transform

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

- Dipole amplitude: $N(\mathbf{x}, \mathbf{y}) = 1 - \mathrm{Tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y})/N_c$
- Energy evolution: solve JIMWLK equation to get $V(\mathbf{b})$ at small x

Schenke, Schlichting, 1407.8458

Initial condition for JIMWLK

- Parametrize proton geometry, $Q_s^2 \sim T_{\text{proton}}(\mathbf{b})$
- MV-model: Sample color charges ρ, density $\sim Q_s(\mathbf{b})$
- Solve Yang-Mills equations: write color field in momentum space

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

- Here introduce a UV damping factor v, fixed by Q^2 evolution of F_2
- Wilson lines are then obtained as a Fourier transform

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

- Dipole amplitude: $N(\mathbf{x}, \mathbf{y}) = 1 - \mathrm{Tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y})/N_c$
- Energy evolution: solve JIMWLK equation to get $V(\mathbf{b})$ at small x

Schenke, Schlichting, 1407.8458

Strategy

Start with round protons, $T(\mathbf{b}) \sim \exp(-\mathbf{b}^2/(2B_p))$

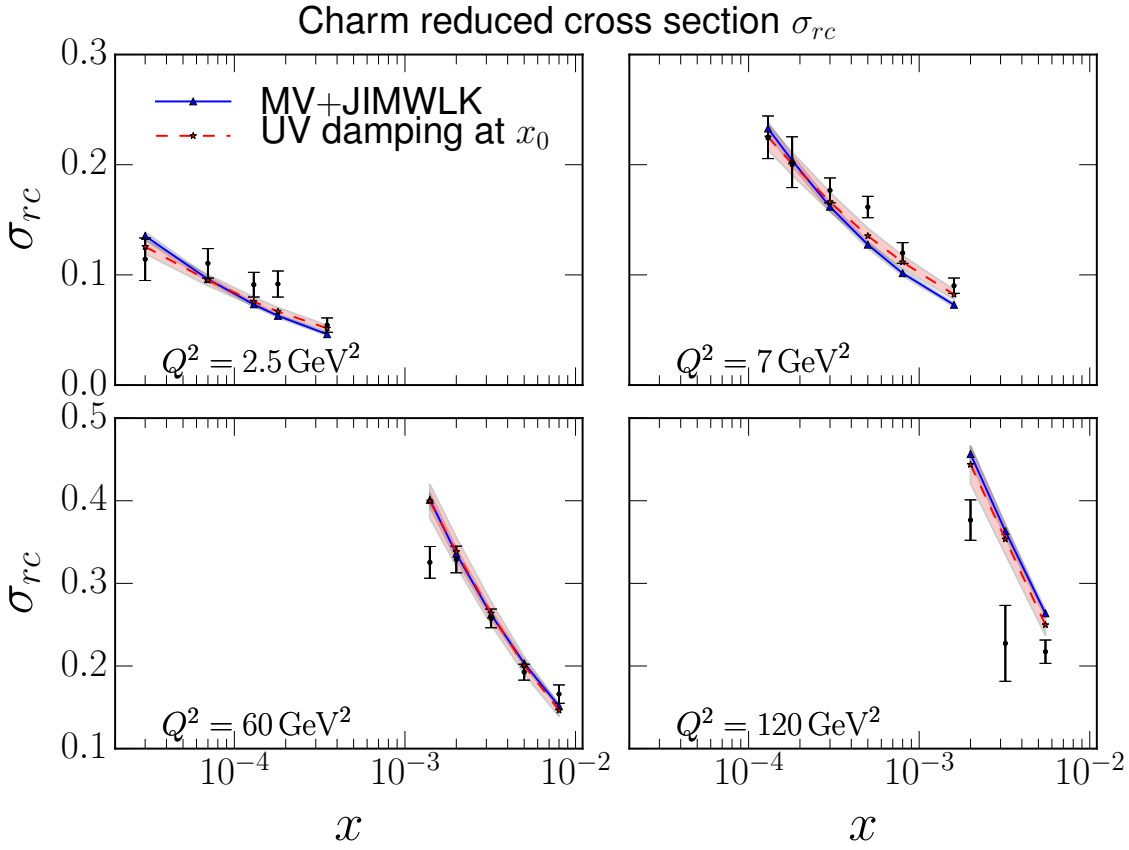
- Constrain evolution speed (α_s or $\Lambda_{\rm QCD}$) and $\langle Q^2_{s,0}\rangle$ by charm reduced cross section data
  - Avoid total F_2 as it is sensitive to large dipoles (more later)
- Proton size fixed by HERA J/Ψ data (slope of the coherent t spectra)

Introduce fluctuating geometry

- Fix proton geometry by coherent and incoherent J/Ψ data at 75 GeV
- Predict evolution of the diffractive cross sections

Initial condition for the JIMWLK evolution (round proton)

Good description of the charm production data

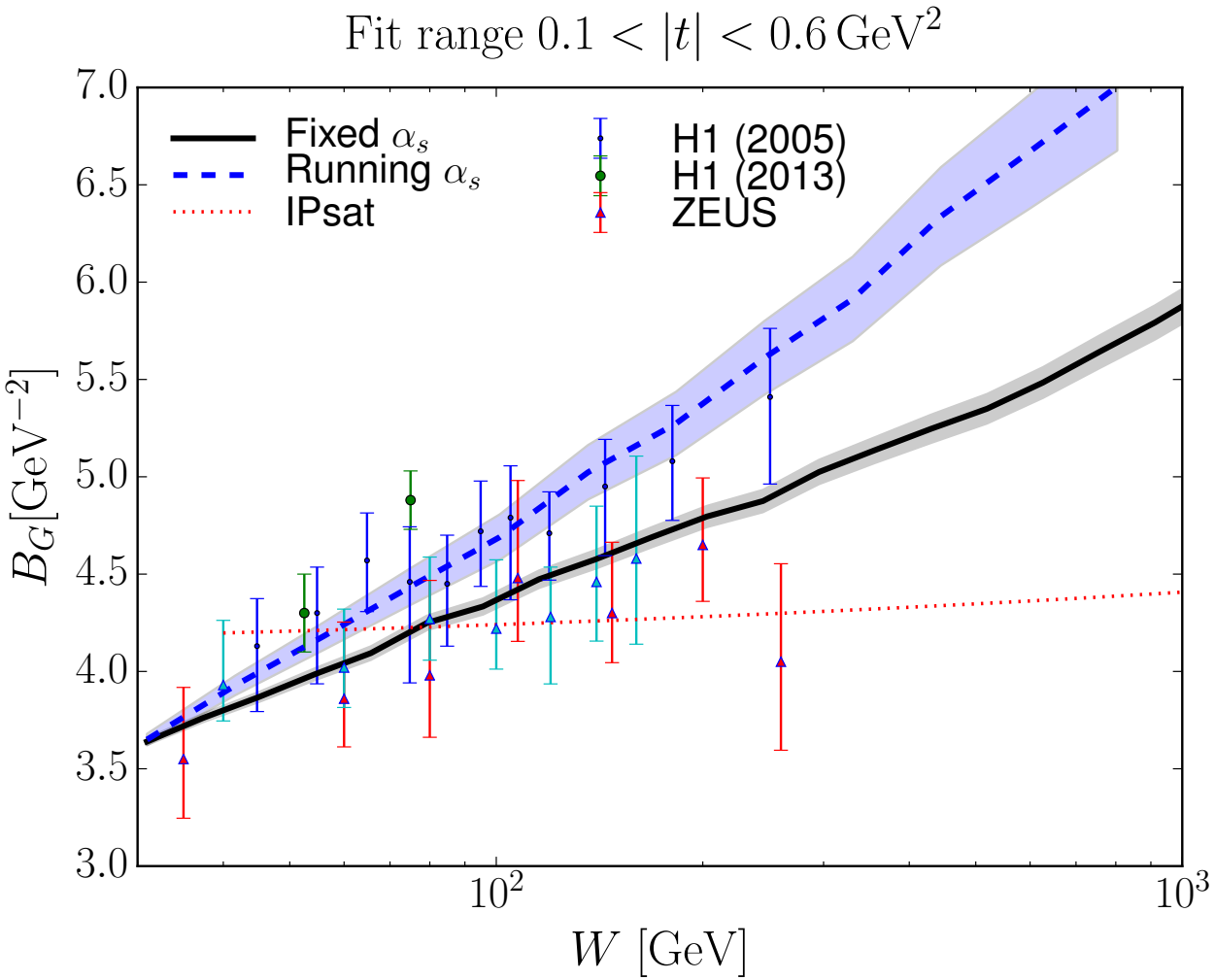


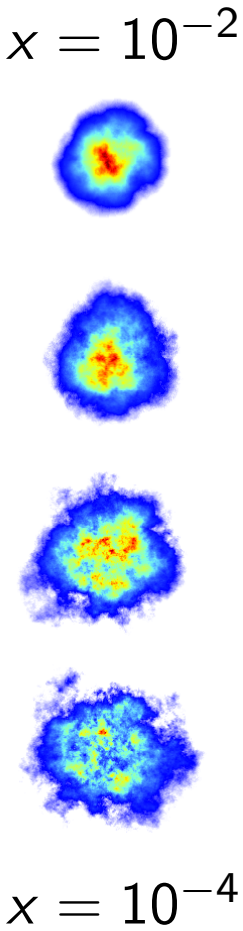
- Too fast Q^2 dependence from MV model
  Fit improves when UV modes are damped at x_0: $\chi^2/N : 4.3 \to 2.5$

H.M, B. Schenke, 1806.06783

Proton size evolution (round proton)

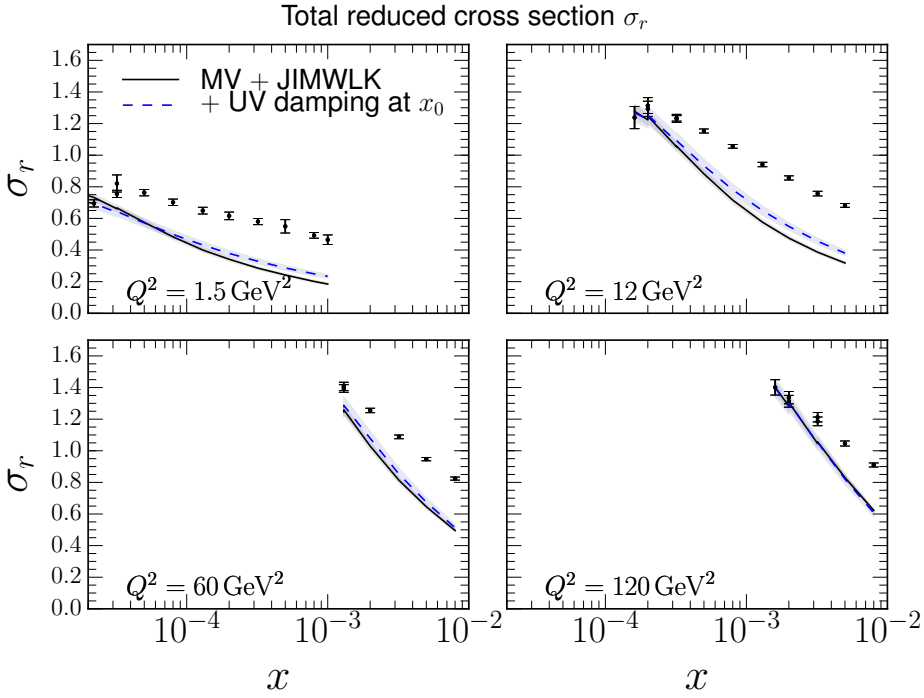
Size fixed at $W = 30$GeV, evolution speed fixed by charm-F_2

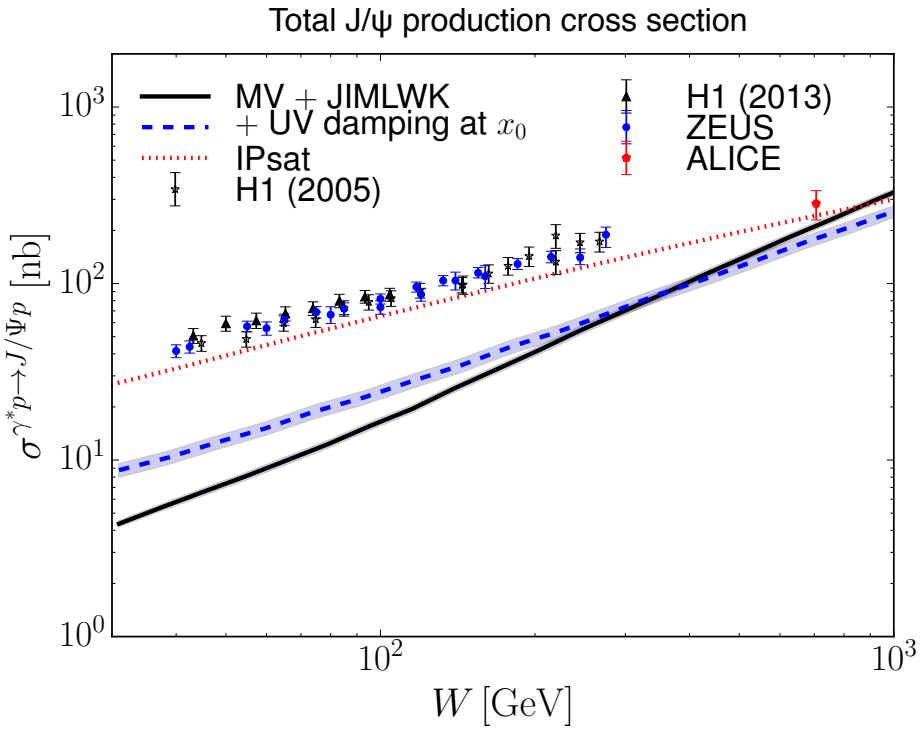




Running α_s: faster evolution at long distance scales. $r_{\mathrm{RMS}} \approx \sqrt{2B_G}$

Problem with total cross sections

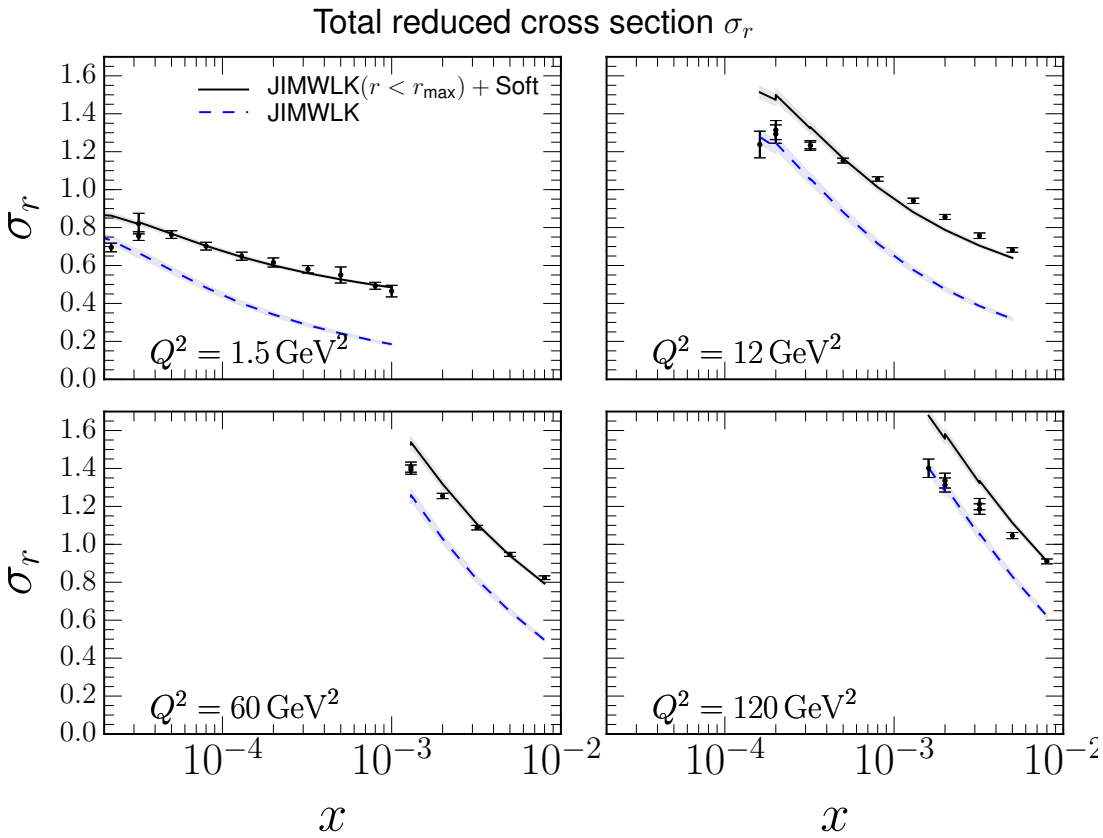


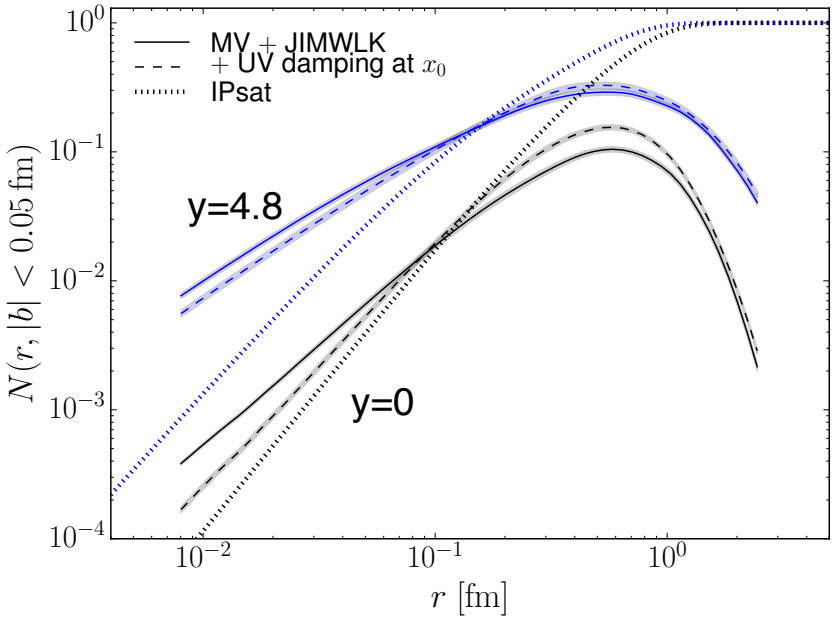


Total F_2 and exclusive cross sections underestimated

- Effect even larger on J/Ψ photoproduction, as it probes [dipole]^2

A possible explanation: missing large dipoles



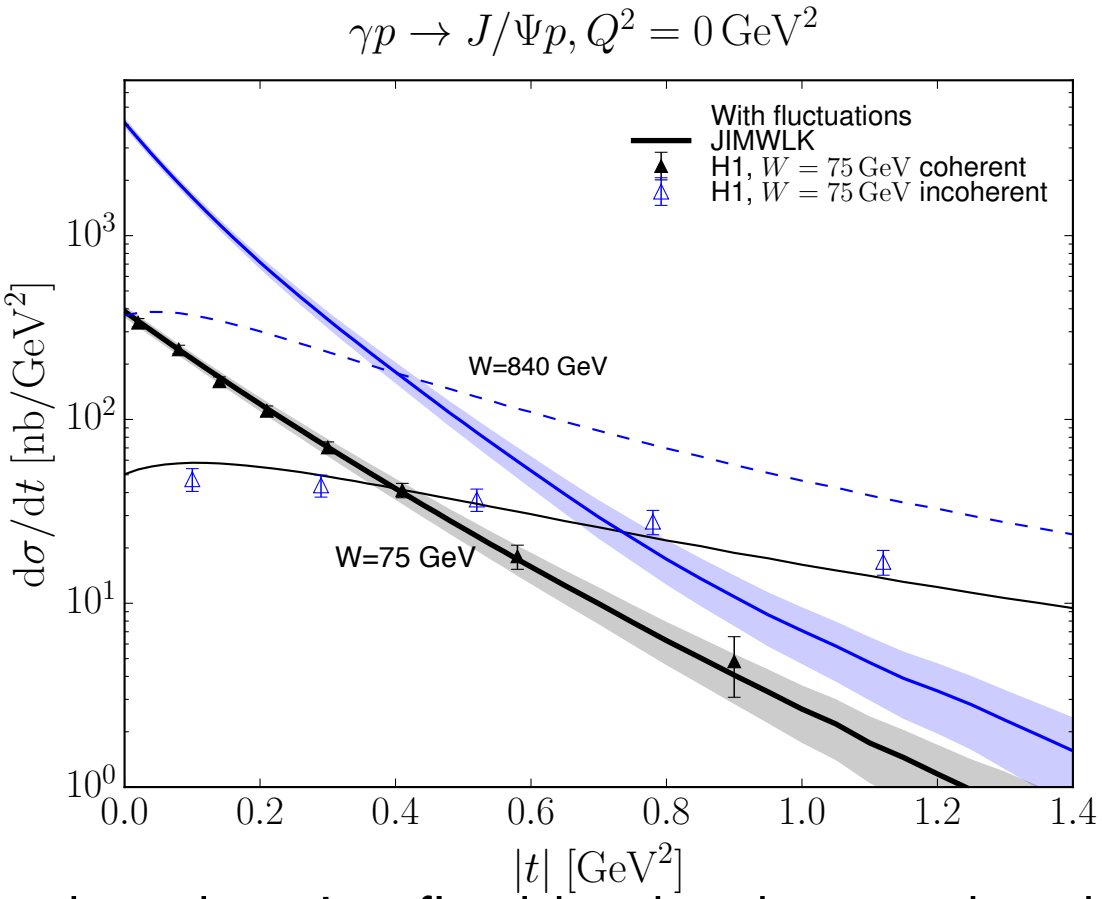


- F_2 is sensitive to large dipoles, but $N(r > R_p, b = 0) \to 0$
- Need a *non-perturbative* contribution,
  Here: $N(r > R_p) = 1$ as suggested in Berger, Stasto, 1106.5740
- Comparison to IPsat, which describes HERA F_2, $F_{2,\mathrm{charm}}$ and J/Ψ

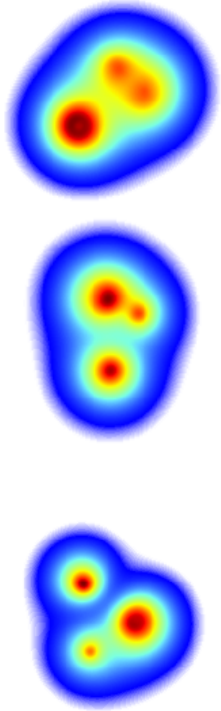
More about large dipole contributions: H.M, P. Zurita, 1804.05311 H.M, B. Schenke, 1806.06783

Fix proton geometry at $W = 75$ GeV (fluctuations)

Implement constituent quark structure $T_{\text{proton}}(\mathbf{b}) = \sum_{i=1}^{3} T_p(\mathbf{b} - \mathbf{b}_i)$



$W = 75$ GeV:

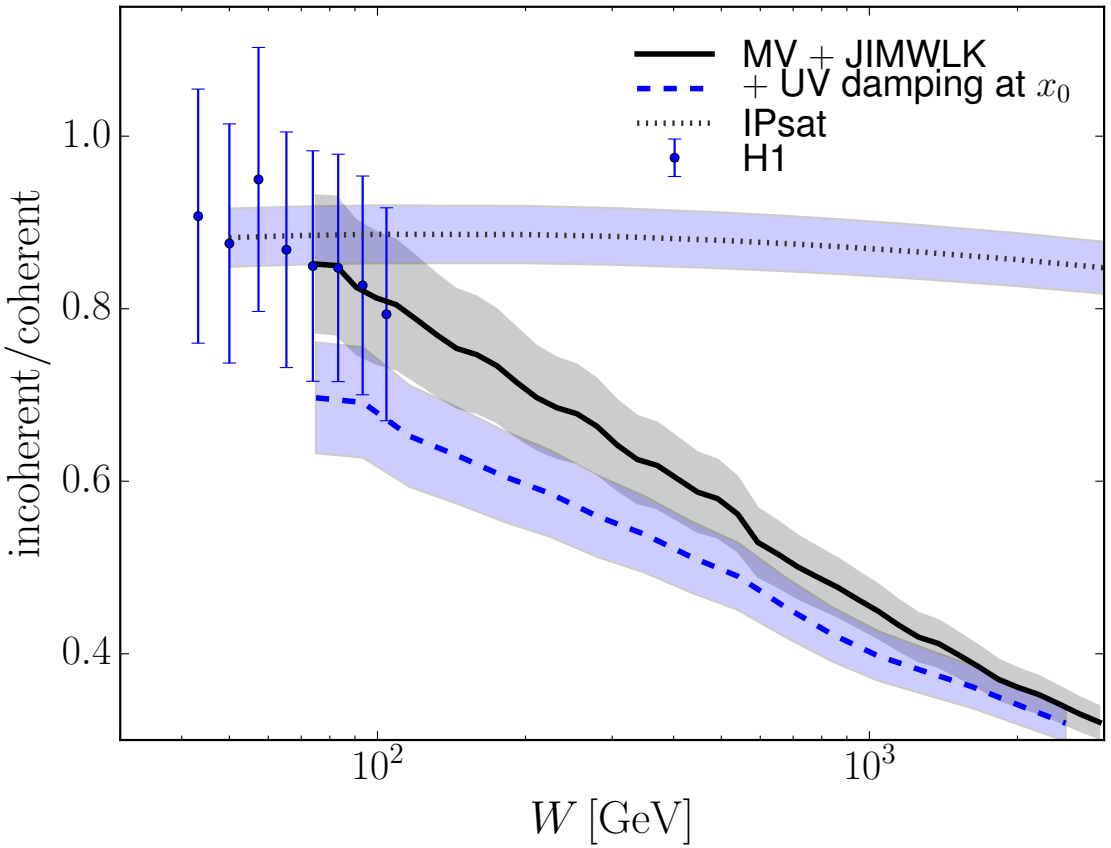


- α_s and uv damping fixed by the charm reduced cross section data
- Geometry and initial Q_s^2 fixed at $W = 75$GeV

H.M, B. Schenke, 1806.06783

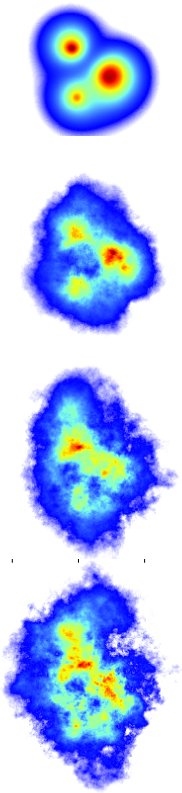
Evolution of the fluctuations: $\gamma + p \to J/\Psi + p$

Incoherent/coherent cross section ratio compatible with H1 data
Note: insensitive to contributions from large dipoles



Note: parameters fixed at $W = 75$GeV, the rest is prediction

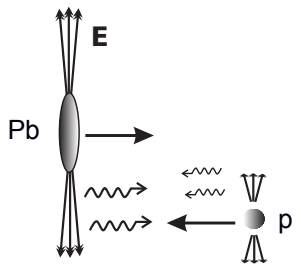
$W = 75$ GeV:

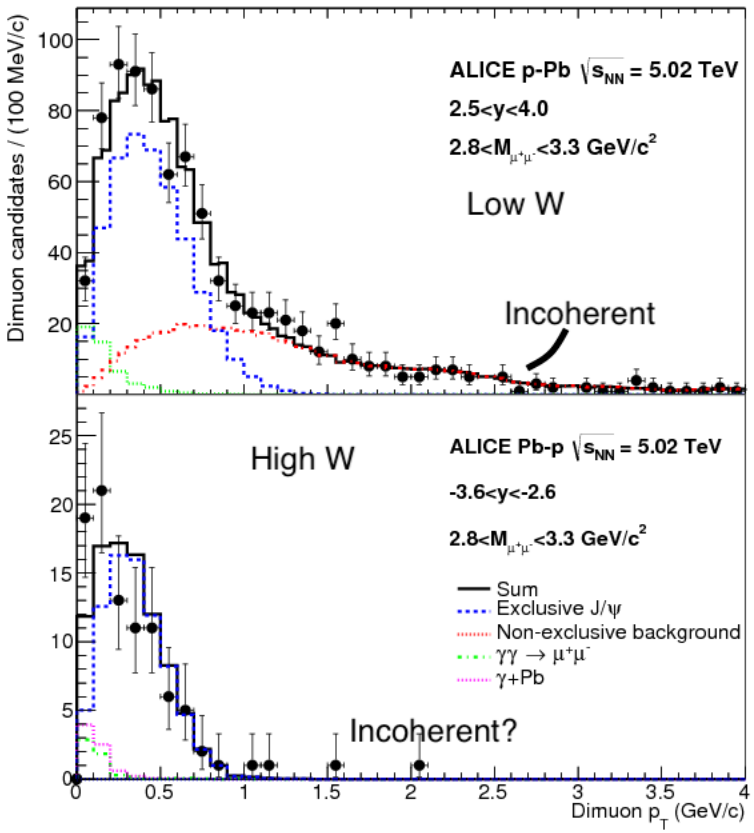


$W = 680$ GeV

High-energy J/Ψ photoproduction at the LHC

Ultraperipheral $p + A$ at the LHC:
Photon flux $\sim Z^2 \Rightarrow \gamma + p$ dominates





Forward/backward rapidity J/Ψ
High/low W

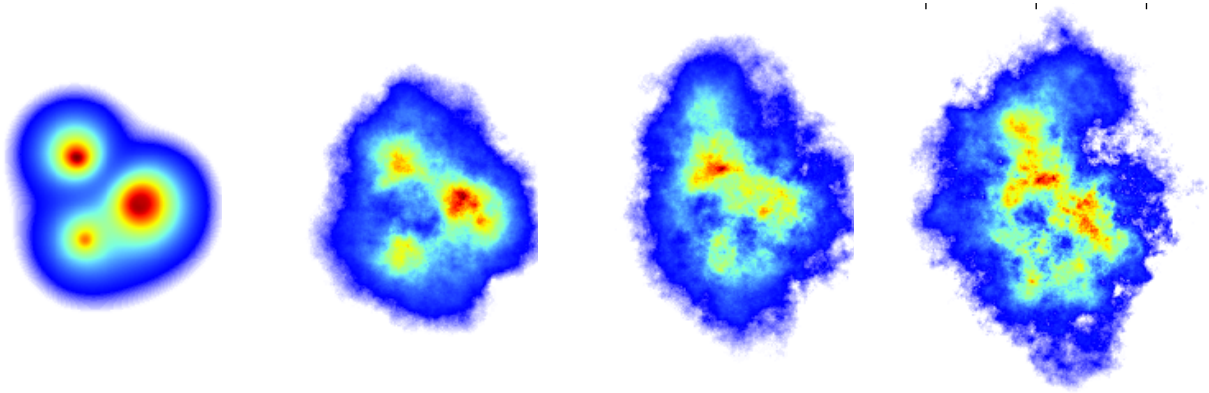
- Low W: significant coherent and incoherent contributions
- High W: no incoherent
  Qualitatively in agreement with our JIMWLK results
  Black disk limit reached?

ALICE: 1406.7819

Conclusions

Multi dimensional event-by-event picture of the proton

- Bjorken-x dependence from JIMWLK evolution equation
- Initial condition from HERA data
- Uncertainty: how to describe large dipole - proton scattering?
  - Simultaneous description of F_2, $F_{2,\mathrm{charm}}$ and diffractive data requires additional *non perturbative* contribution
  - Charm-F_2 data not sensitive to large dipoles
- Qualitatively describe disappearing incoherent contribution in ALICE

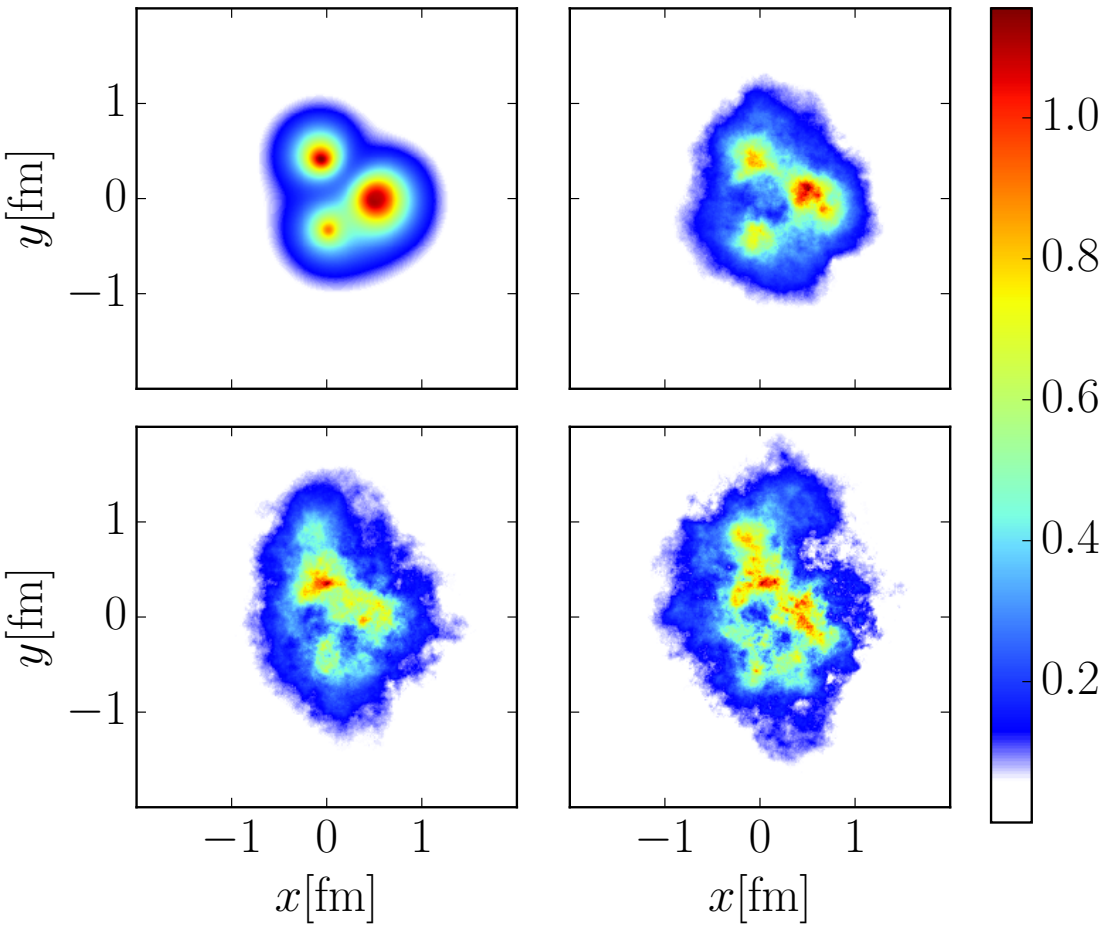


BACKUPS

What does the fluctuating proton look like

Illustration of the proton shape evolution: trace of a Wilson line

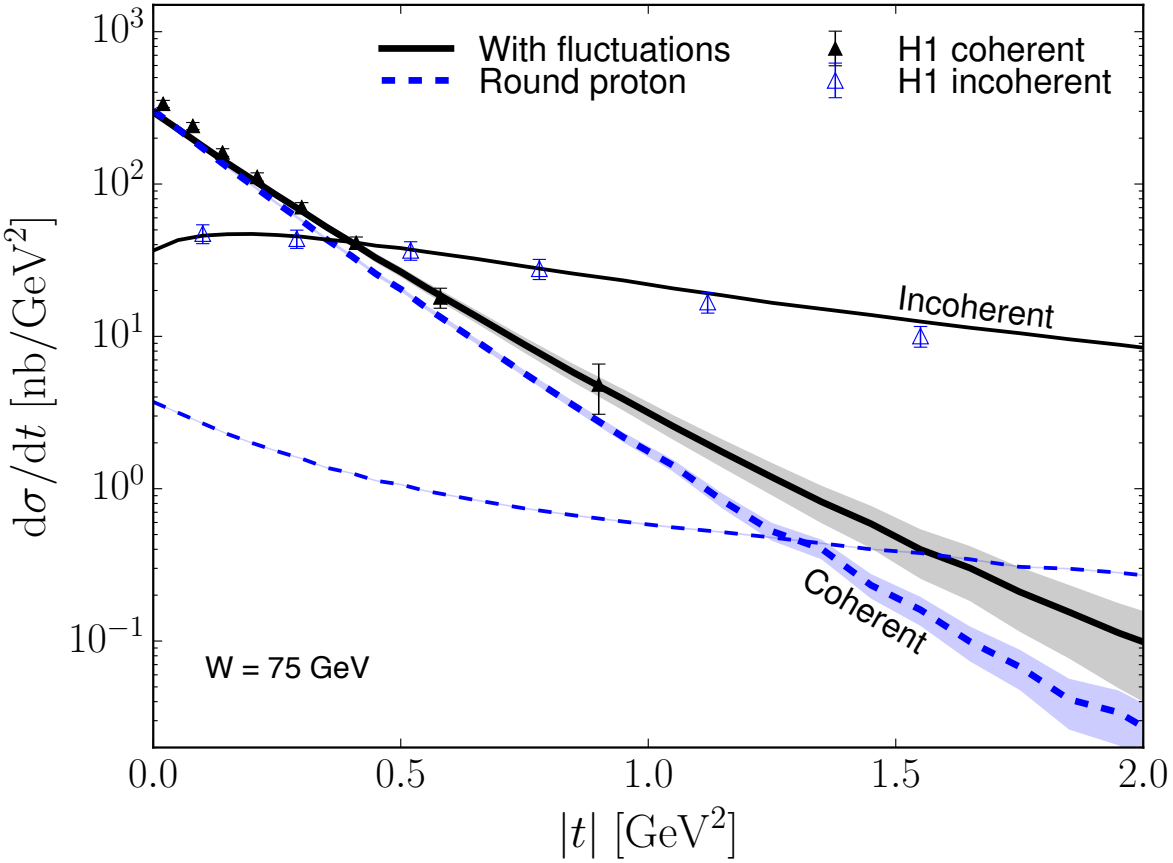
$1.0 - \mathrm{Re}\,\mathrm{Tr}\,V(x,y), \Delta y = [0.0, 1.5, 3.0, 4.5]$



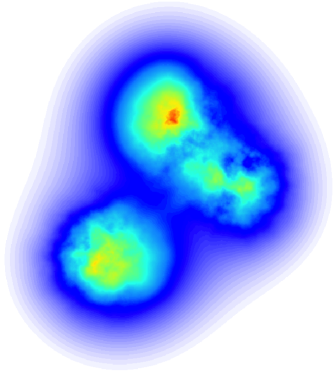
H.M, B. Schenke, in preparation. Also Schenke, Schlichting, 1407.8458

Evidence of fluctuations at HERA: $\gamma + p \to J/\Psi + p$

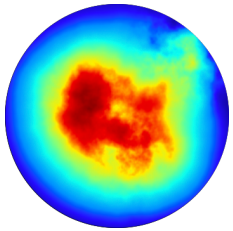
HERA data with only color charge fluctuations



Fluctuations



Round

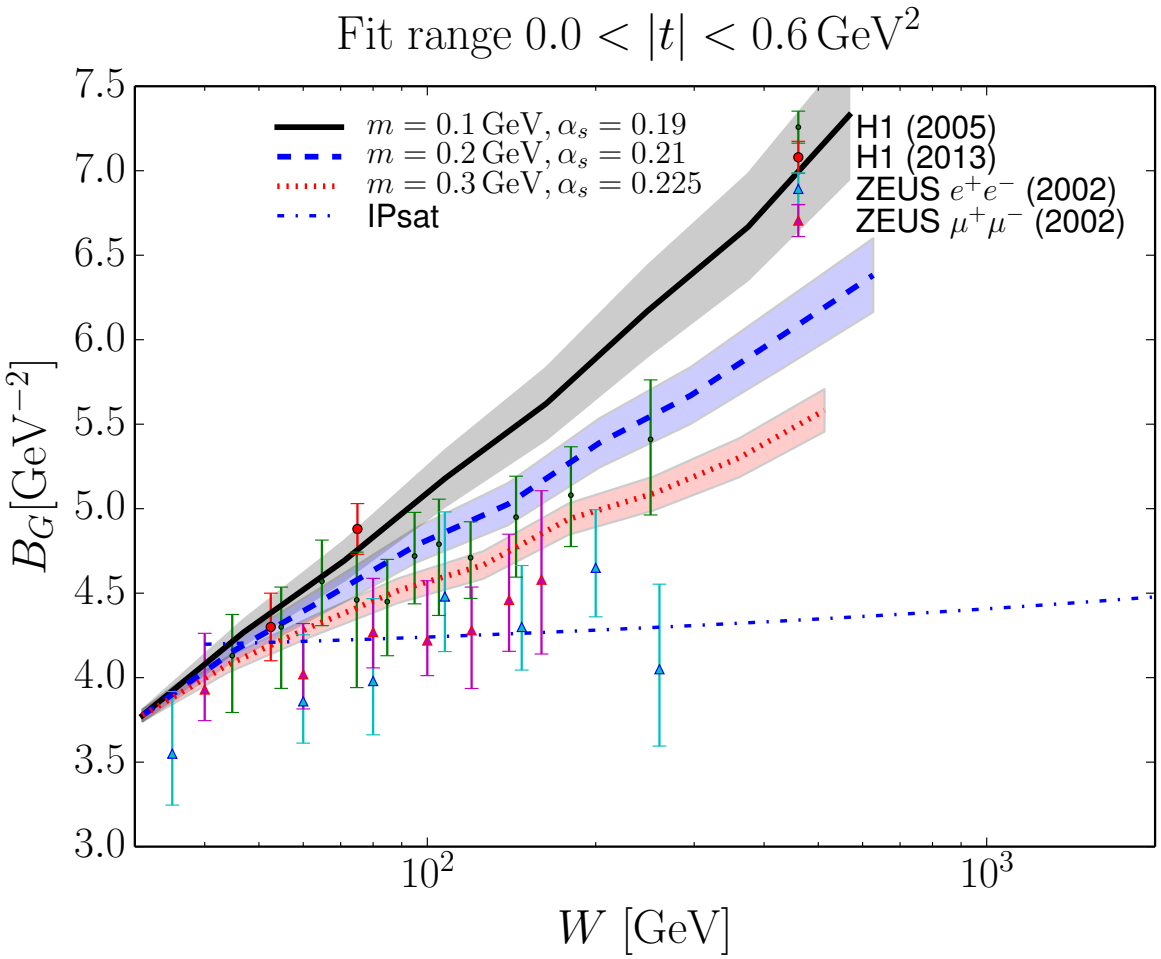


H.M, B. Schenke, 1607.01711, H1: 1304.5162

Problem with the incoherent cross section

Infrared regulator

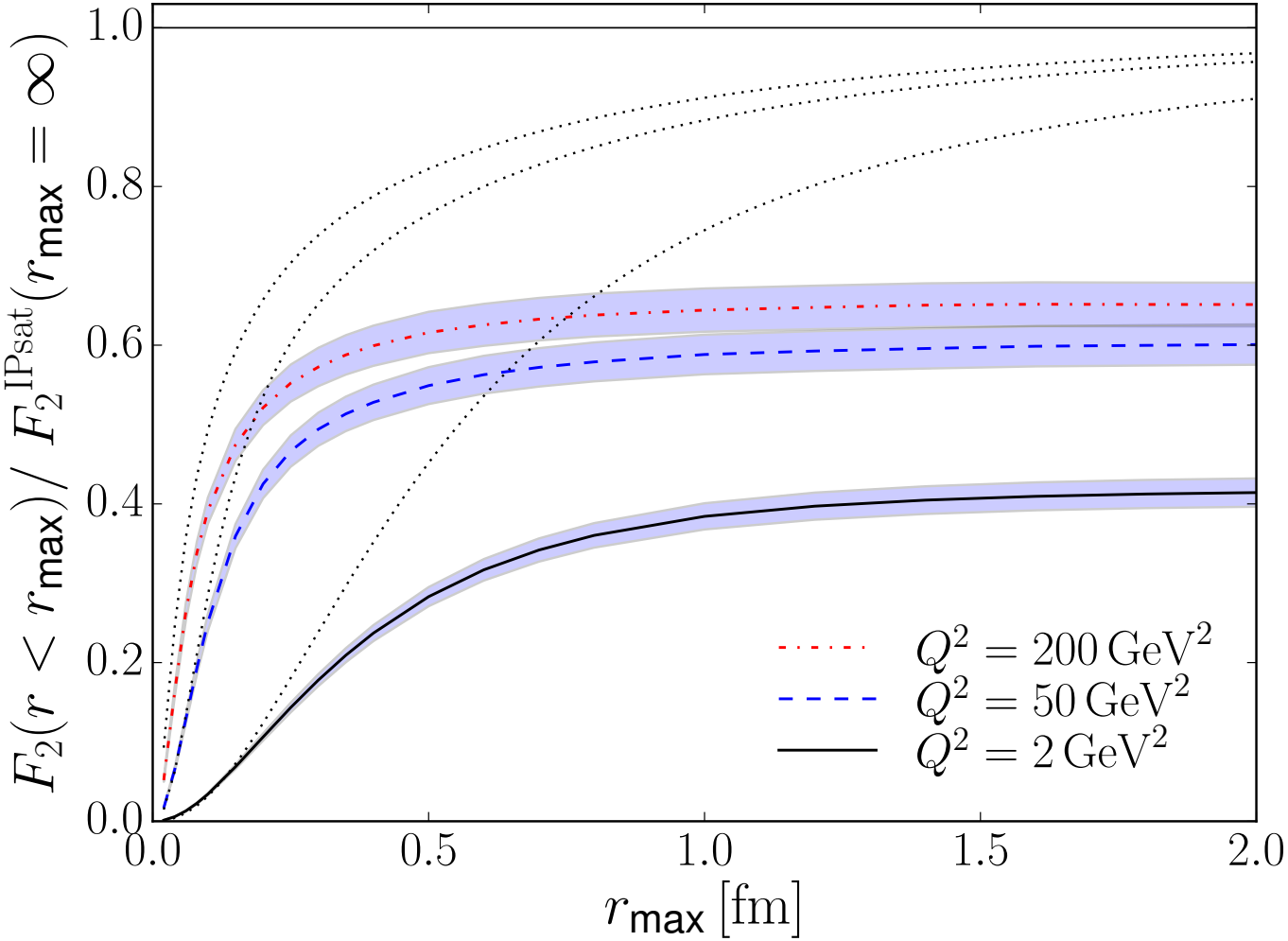
JIMWLK evolution: suppress long-distance Coulomb tails by an infrared regulator $m \sim \Lambda_{\mathrm{QCD}}$



- Small-t part of the spectra sensitive to long distance evolution $\sim m$

Contribution from large dipoles: F_2

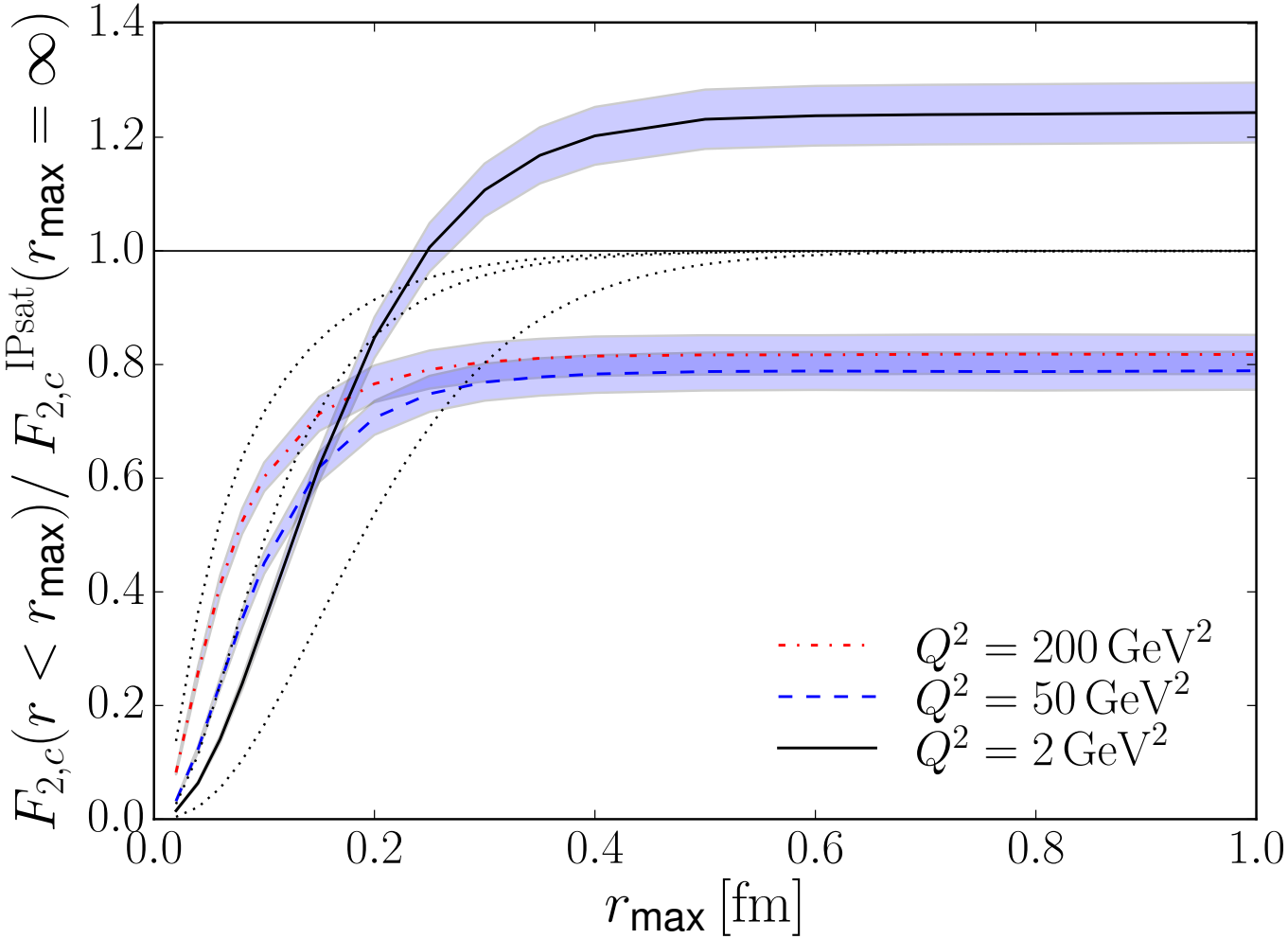
Fraction of IPsat F_2 recovered in $r < r_{\mathrm{max}}$ ($x = 0.01$)



H.M, B. Schenke, 1806.06783

Contribution from large dipoles: charm F_2

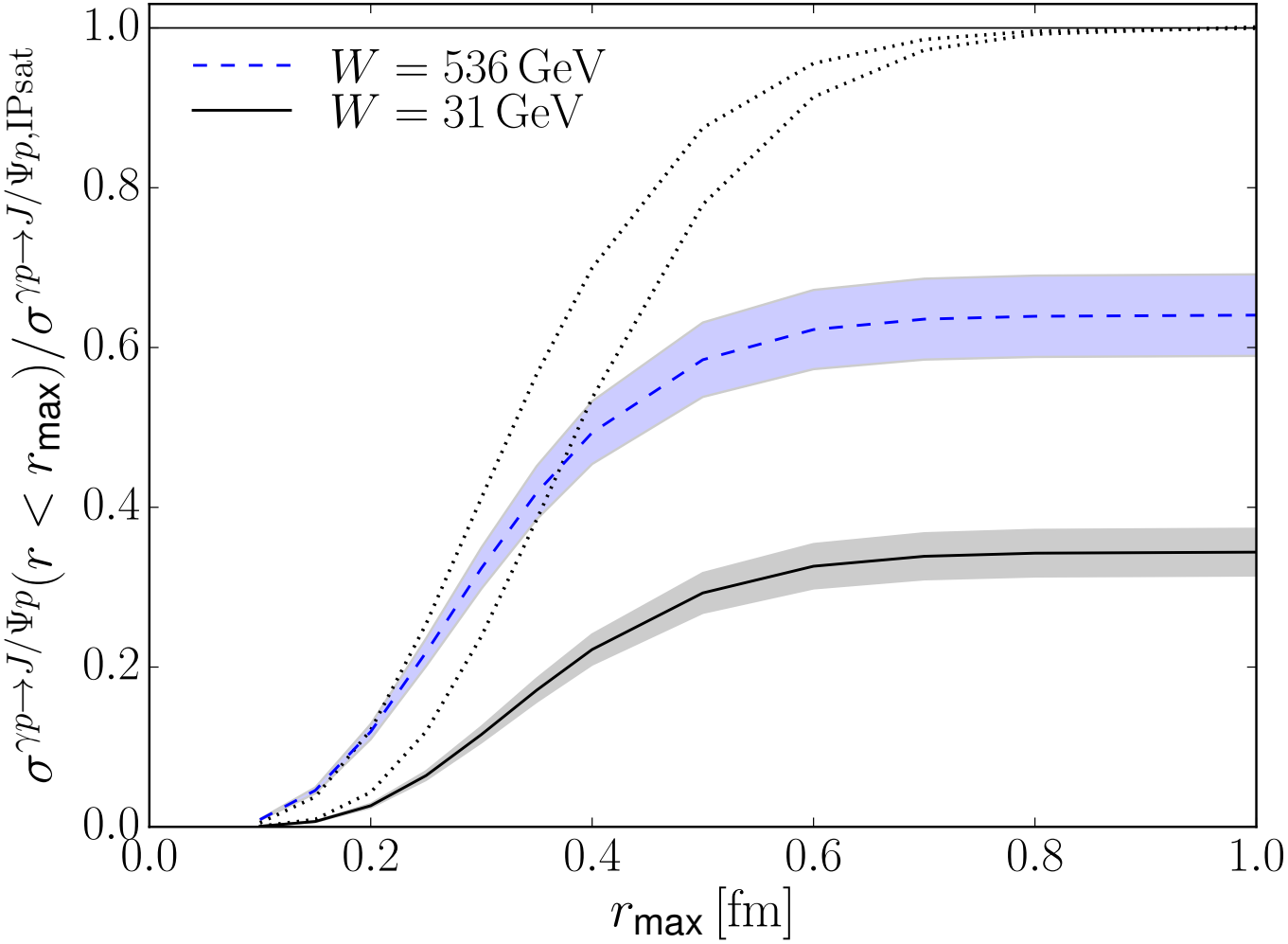
Fraction of IPsat charm-F_2 recovered in $r < r_{\text{max}}$ ($x = 0.01$)



H.M, B. Schenke, 1806.06783

Contribution from large dipoles: J/Ψ photoproduction

Fraction of IPsat J/Ψ photoproduction cross section recovered in $r < r_{\mathrm{max}}$



H.M, B. Schenke, 1806.06783