

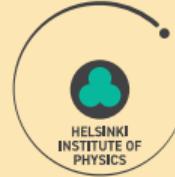
# Hot spots in a proton

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# Outline

- ▶ Simple model for gluonic hot spots
- ▶ Initial eccentricity for proton-nucleus collision
- ▶ Exclusive vector mesons

Based on PhD work of S. Demirci:

- ▶ S. Demirci, T. Lappi and S. Schlichting, "Hot spots and gluon field fluctuations as causes of eccentricity in small systems," Phys. Rev. D **103** (2021) no.9, 094025, [[arXiv:2101.03791 \[hep-ph\]](https://arxiv.org/abs/2101.03791)].
- ▶ S. Demirci, T. Lappi and S. Schlichting, "Proton hot spots and exclusive vector meson production," Phys. Rev. D **106** (2022) no.7, 074025 [[arXiv:2206.05207 \[hep-ph\]](https://arxiv.org/abs/2206.05207)].

See also:

- ▶ S. Demirci and P. Guerrero-Rodríguez, "Evolution of eccentricities induced by geometrical and quantum fluctuations in proton-nucleus collisions," Phys. Rev. D **107** (2023) no.9, 094004 [[arXiv:2302.02236 \[hep-ph\]](https://arxiv.org/abs/2302.02236)].

Goal: analytically tractable model for gluonic hot spots

# Hot spot models

- ▶ Energy dependent hot spot model

Cepila et al 1711.01855 [hep-ph]

- ▶ IPglasma Mäntysaari, Schenke 1603.04349 [hep-ph]

- ▶ p+p collisions, “hollowness”

Soto-Ontoso et al. 1605.09176 [hep-ph] ...

- ▶ Quark model approach

Traini, Blaizot 1804.06110 [hep-ph],

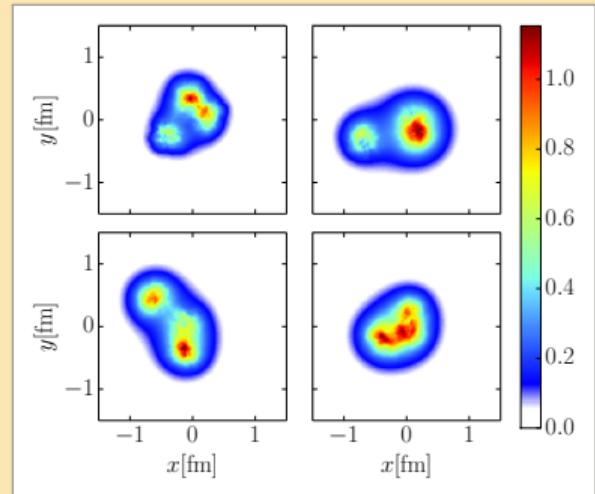
Dumitru, Paatelainen 2010.11245 [hep-ph]

- ▶ Hot spots within hot spots

Kumar, Toll 2106.12855 [hep-ph]

- ▶ Bayesian fits of flow etc.

Moreland et al 1808.02106 [nucl-th]



H. Mäntysaari and B. Schenke,

[arXiv:1607.01711 [hep-ph]]

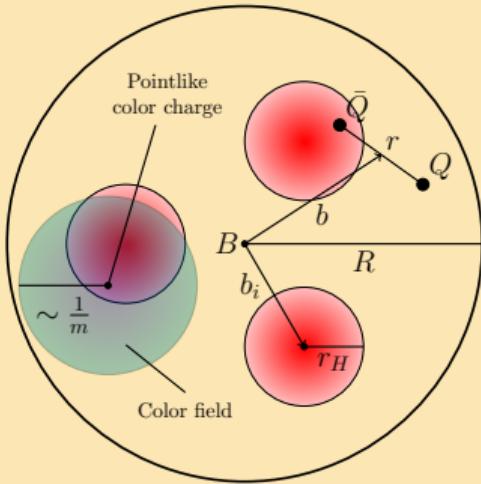
## Our goal

- ▶ No attempt to put in all bells & whistles to fit data

- ▶ Rather: analytically tractable model to understand physics

# Simple model for hot spots

# Simple model

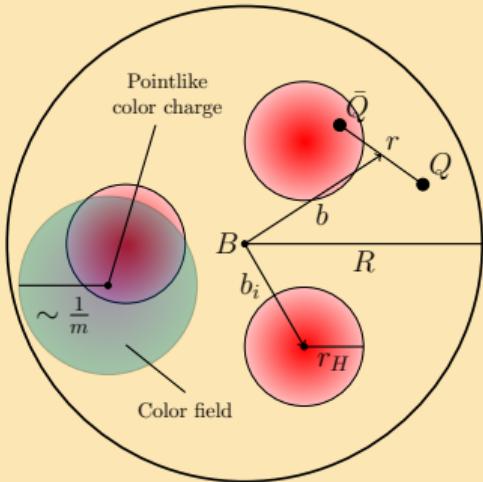


Parameters:

- ▶ Proton radius  $R$
- ▶ Hot spot radius  $r_H$
- ▶ Number of hot spots  $N_q$
- ▶ IR regulator in color charge vs field  $m$

- ▶ Color field average
- ▶ Hot spot average

# Simple model



- ▶ Color field average
- ▶ Hot spot average

$$\left\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y}) \right\rangle_c = \sum_{i=1}^{N_q} \mu^2 \left( \frac{\mathbf{x} + \mathbf{y}}{2} - \mathbf{b}_i \right) \delta^{(2)}(\mathbf{x} - \mathbf{y}) \delta^{ab},$$

$$\mu^2(\mathbf{x}) = \frac{\mu_0^2}{2\pi r_H^2} \exp \left[ -\frac{\mathbf{x}^2}{2r_H^2} \right] \quad T(\mathbf{b}) = \frac{1}{2\pi R^2} \exp \left[ -\frac{\mathbf{b}^2}{2R^2} \right].$$

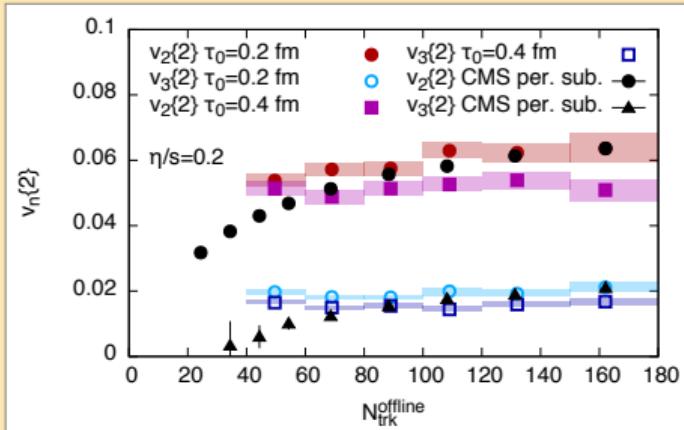
$$\langle\langle \mathcal{O} \rangle\rangle = \left( \frac{2\pi R^2}{N_q} \right) \int \prod_{i=1}^{N_q} \left[ d^2 \mathbf{b}_i T(\mathbf{b}_i - \mathbf{B}) \right] \delta^{(2)} \left( \frac{1}{N_q} \sum_{i=1}^{N_q} \mathbf{b}_i - \mathbf{B} \right) \langle \mathcal{O} \rangle_c$$

$$(-\nabla^2 + m^2) A_{\text{cov}}^+ = \rho \quad V(\mathbf{x}) = \exp \{ ig A_{\text{cov}}^+ \} \quad \Rightarrow \quad \text{color field}$$

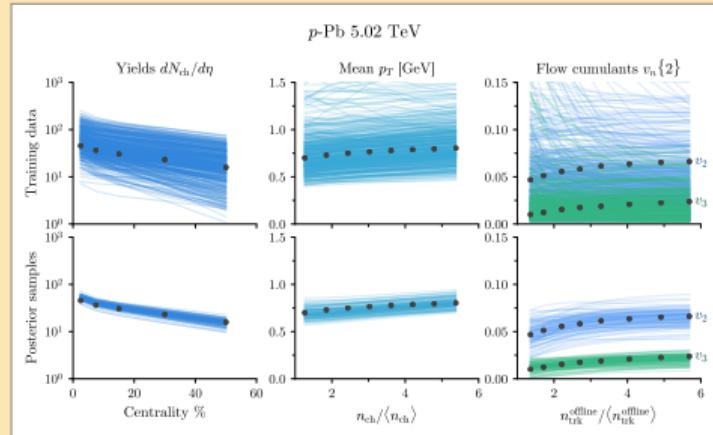
- ▶ Explicit  $\mathbf{x}, \mathbf{y}$ -dependence;  $\mathbf{b}$  not factorized
- ▶ Note centering at hot spot center of mass
- ▶ Here: linearize in  $\rho$

# Eccentricity

# Substructure and flow in pA



Mäntysaari, Schenke, Shen, Tribedy 1705.03177 [nucl-th]

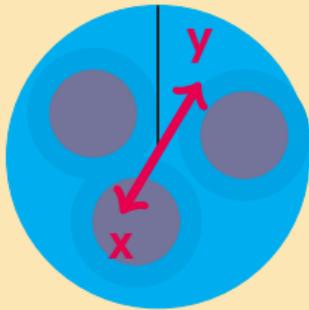


Moreland, Bernhard, Bass, 1808.02106 [nucl-th]

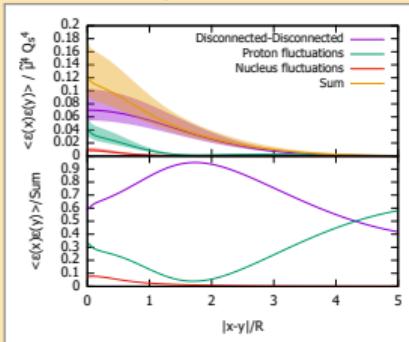
- ▶ High-multiplicity proton-nucleus collisions: signs of hydrodynamical flow
- ▶ Hydro requires proton substructure to explain this
  - ➡ calculate eccentricities in pA our hot spot model
- ▶ Use  $\varepsilon(\tau = 0, \mathbf{x})$ , which is analytically calculable
- ▶ Proton: color charge and hot spot fluctuations, linearize
- ▶ Infinite smooth nucleus: only color charge fluctuations, nonlinear

# Energy density correlations

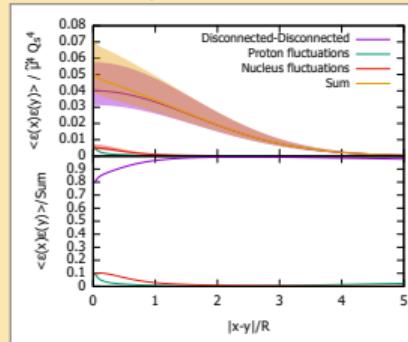
$\langle \varepsilon(\mathbf{x})\varepsilon(\mathbf{y}) \rangle$  vs  $|\mathbf{x} - \mathbf{y}|/R$



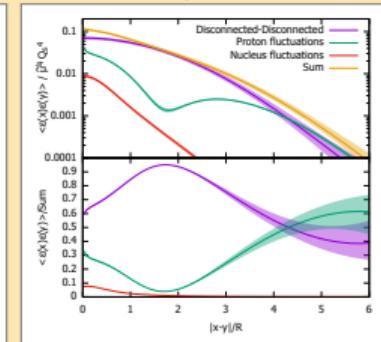
$N_q = 3$



$N_q = 100$



$N_q = 3$



Bands: vary

UV-reg.

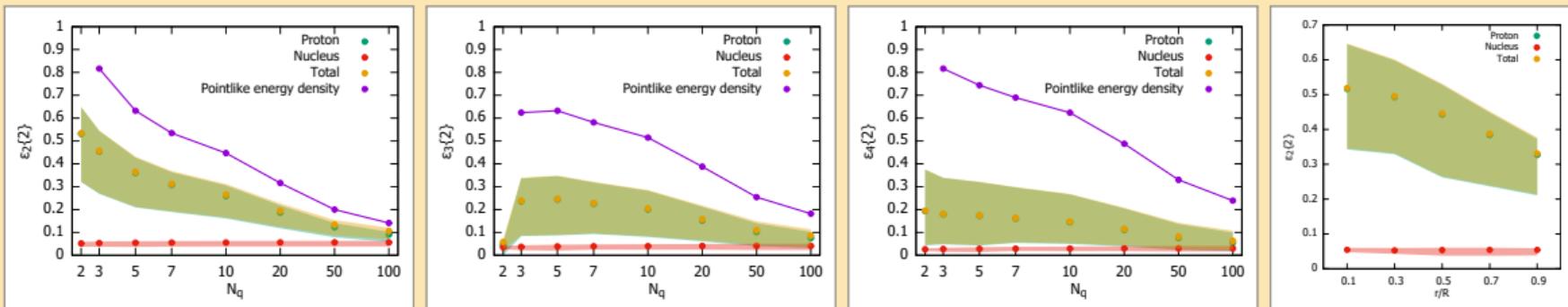
UV-reg.

IR-reg. ( $m$ )

- ▶ Proton hot spots dominate correlation structure (except for large  $N_q$ )
- ▶ Energy density fluctuation (short distance,  $\tau = 0$ ) very sensitive to UV cutoff
- ▶ Long distance: dependence on IR-regulator  $m$

# Eccentricities in hot spot model

$$(\varepsilon_n\{2\})^2 = \frac{\int d^2\mathbf{x} d^2\mathbf{y} |\mathbf{x}|^n |\mathbf{y}|^n e^{in(\theta_{\mathbf{x}} - \theta_{\mathbf{y}})} \langle \varepsilon(\mathbf{x}) \varepsilon(\mathbf{y}) \rangle}{\int d^2\mathbf{x} d^2\mathbf{y} |\mathbf{x}|^n |\mathbf{y}|^n \langle \varepsilon(\mathbf{x}) \varepsilon(\mathbf{y}) \rangle}$$



- ▶ Hot spots more important than color charge fluctuations
- ▶ Big dependence on IR regulator  $m$  (green band is varying by  $\pm 50\%$ )
- ▶ Significant dependence on number of hot spots  $N_q$  and hot spot radius  $r_H/R$

Could we constrain these with vector meson data?

# Exclusive vector mesons

# Good-Walker

Fluctuations in hadron/nucleus, e.g.

1. Nucleons in nucleus
2. Hot spots in nucleon
3. Color charges  
(as in MV model)
4. Different size dipoles

Related to cross sections:

- ▶ Elastic: outgoing target in same state

$$\sigma \sim |\langle \Omega | \mathcal{N} | \Omega \rangle|^2$$

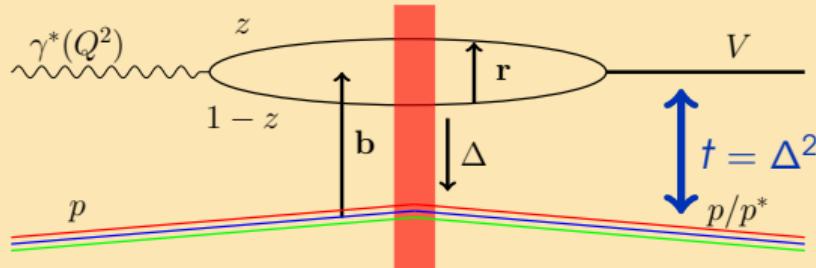
- ▶ Quasielastic: allow (limited) dissociation

$$\sigma \sim \sum_{\Omega'} |\langle \Omega' | \mathcal{N} | \Omega \rangle|^2$$

- ▶ Incoherent (diffractive dissociation) : variance

$$\sigma \sim \sum_{\Omega'} |\langle \Omega' | \mathcal{N} | \Omega \rangle|^2 - |\langle \Omega | \mathcal{N} | \Omega \rangle|^2$$

# Exclusive vector mesons in dipole picture



$$\mathcal{A}^{\gamma^* p \rightarrow V p}(Q^2, \Delta) = i2 \int d^2 \mathbf{r} \int d^2 \mathbf{b} \int \frac{dz}{4\pi} \exp \{-i\mathbf{b} \cdot \Delta\} \Psi_{\gamma^*}^* \Psi_V \frac{1}{N_c} (1 - V(\mathbf{x})V^\dagger(\mathbf{y}))$$

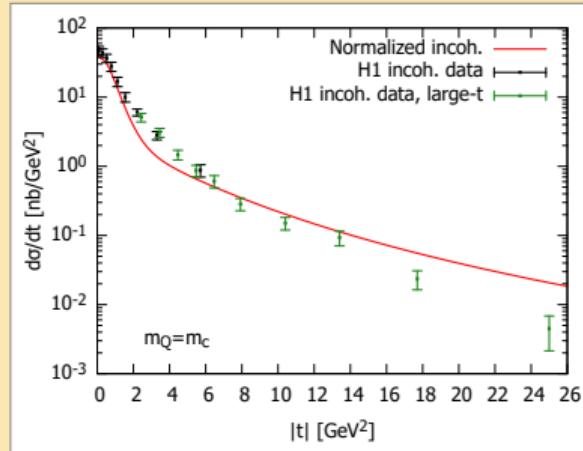
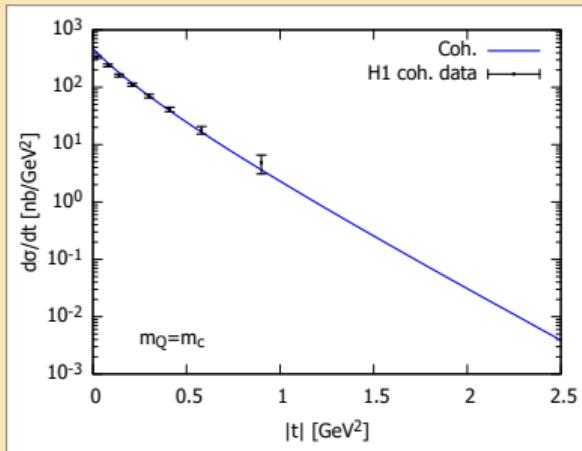
Simple in the **nonrelativistic limit** for the meson

$$\Psi_V(z, |\mathbf{r}|) \propto \delta \left( z - \frac{1}{2} \right)$$

Still have  $\mathbf{r}$ -dependence from  $\gamma^*$  wavefunction

- ▶ Averages over color charges, hot spots calculated analytically
- ▶ Remains: integrals over  $\mathbf{r}$ , Laplace  $\rho \rightarrow V(\mathbf{x})$ : analytical in limiting cases

# HERA data



- With natural (cf. other studies) parameters  $t$ -dependence  $\sim$  agrees with HERA
- But: we have to artificially adjust up the incoherent normalization  
    → We are missing a source of fluctuations active up to very high  $t$   
( For Mäntysaari& Schenke this is "Q<sub>s</sub> fluctuations".  
Maybe more natural would be to have  $N_q$  fluctuate)

# Ideal case: “top” quark

Heavy quark  $\gamma^*$ -wavefunction  $\Rightarrow$  dipole point-like

Characteristic ranges in  $t$ :

Coherent: small  $|t|$

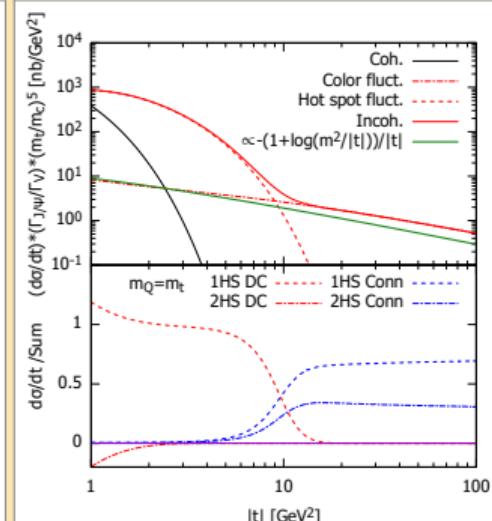
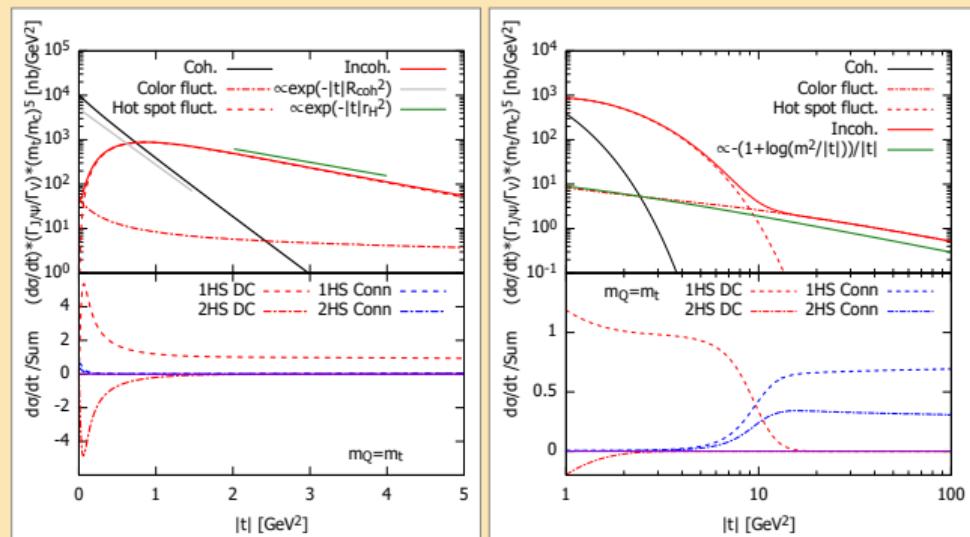
- Slope not quite

$$R_c^2 \equiv \frac{N_q - 1}{N_q} R^2 + r_H^2 \text{ but}$$

broader, by  $\sim 1/m$   
(Measure field, not charge)

Incoherent/dissociative:

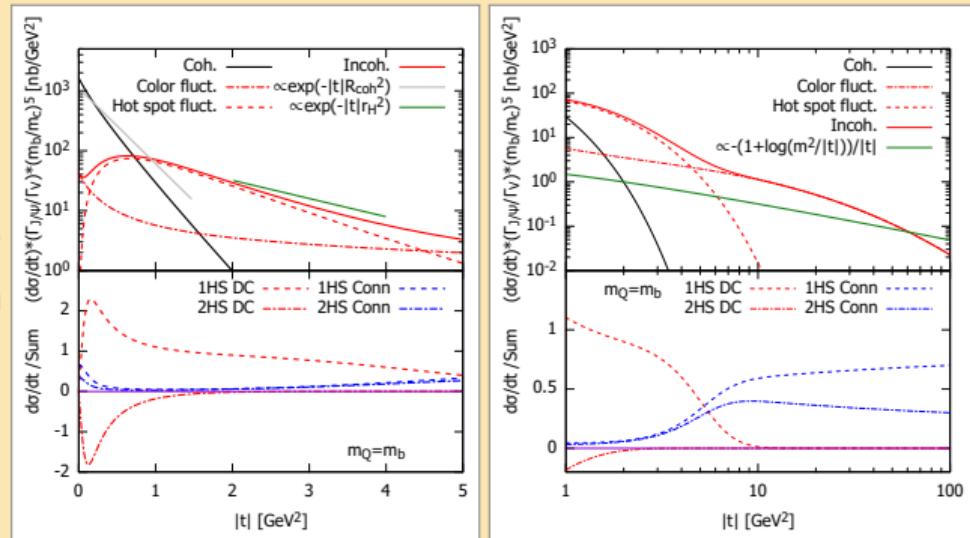
- Intermediate  $-t \sim 1/r_H^2$ : hot spot size
- High  $|t| \gtrsim 10$  power law: color charge fluctuations



# More realistic: bottom quark

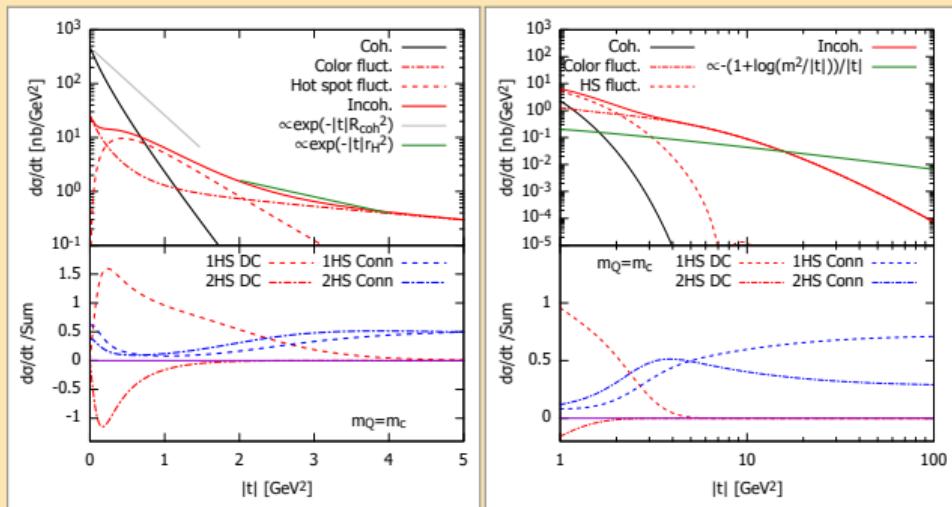
Already for bottom significant deviations

- ▶ Dipole size spoils interpretation  
slope  $\leftrightarrow$  target size
- ▶ Intermediate  $-t \sim 1/r_H^2$   
dissociative: still hot spot size
- ▶ Also large- $t$  color fluctuation regime different from ideal  
( $m_Q \rightarrow \infty$ )



# Charm

- ▶ Coherent slope far from target size
- ▶ Intermediate  $-t \sim 1/r_H^2$  still gives  $r_H$
- ▶ Large- $t$  far from ideal ( $m_Q \rightarrow \infty$ ) limit



# Conclusions

- ▶ Emerging consensus: “gluonic hot spot” structure in the nucleon
  - ▶ Matters for proton-nucleus (even nucleus-nucleus) collisions
  - ▶ Can be probed by incoherent exclusive vector mesons in DIS and UPC’s
- ▶ Simple hot spot model  $\implies$  **averages over fluctuations analytically**
- ▶ Eccentricities from energy density correlation function
- ▶ Exclusive vector meson  $t$ -spectrum:
  - ▶ Small  $-t \lesssim 1\text{GeV}^2$ : coherent
  - ▶ Intermediate  $1\text{GeV}^2 \gtrsim -t \sim 10\text{GeV}^2$ : hot spot structure
  - ▶ Larger  $-t$ : color charges
- ▶ Realistic quark mass:  $t$ -distribution convolution of probe and target structure
- ▶ HERA data: Additional source of fluctuations needed