UPC's and nucleon and nuclear structure

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Outline

UPC measurements and theory issues

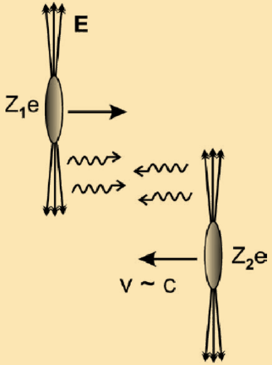
- Exclusive vector mesons: cross sections
  - Nuclear gluon distribution?
  - Species dependence: meson wavefunctions
- Geometry: t-dependence, coherent vs incoherent
- Inclusive: dijets

What can be done at EIC, but not with UPC

- Nucleon/nucleus imaging
- Access to saturation physics
- More processes and kinematics, examples
  - Inclusive hard diffraction
  - Q^2 dependence in exclusive processes
  - Measure intrinsic k_T ($\sim Q_s$)

What is an UPC?

- Range of strong interaction $\sim 1/m_\pi \sim 1\text{fm}$
- Range of e. mag. force ∞
- AA collision with impact parameter $b > 2R_A$
  $\Longrightarrow$ **photon-nucleus** collision
  $\Longrightarrow$ Just like DIS, only $Q^2 = 0$
- Look for **exclusive** events: at least one A intact



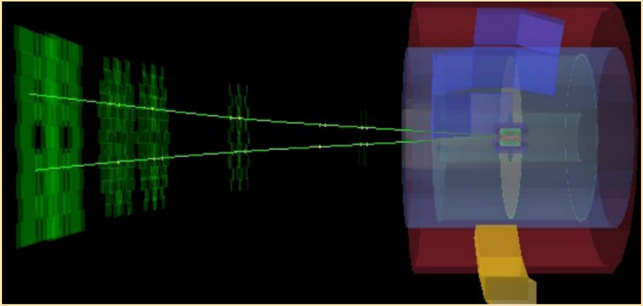
Weak coupling QCD?

- In DIS: Q^2 provides hard scale $\Longrightarrow$ QCD perturbation theory
- In UPC: hard scale e.g. from heavy quark, jets

Many measurements of "soft" observables: not covered here

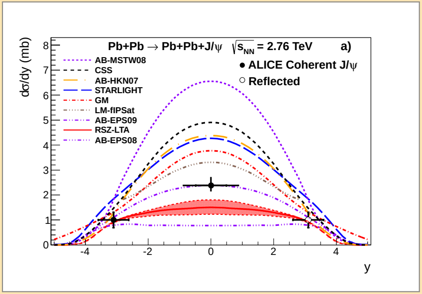
Exclusive processes

- UPC's small part of cross section in hadron colliders: need to trigger to find them
- Easiest (?) for fully exclusive, e.g. vector meson $\gamma + A \to V + A$
- "two muons in an otherwise empty detector"

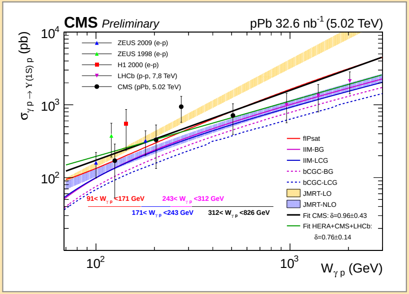


ALICE event display, $J/\Psi \to \mu^+\mu^-$

UPC results so far, vector mesons



ALICE



CMS

$\gamma + A \to J/\Psi + A$, rapidity

+ photon flux:
extract W^2 dependence,
here $\gamma + p \to \Upsilon + p$

UPC: highest energy γ-scattering data we have: very valuable!

Counting color: normalization

Measure gluon distribution?

Formula often quoted by UPC experimentalists

$$\frac{\mathrm{d}\sigma^{\gamma^* H \to VH}}{\mathrm{d}t} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{\mathrm{em}} M_V^5} \left[xg(x, Q^2) \right]^2$$

Certainly XVMP constrains gluons at small x,

but (as people here know well)

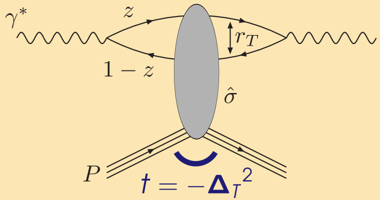
- Measurement is GPD,

  relation to $\left[xg(x, Q^2) \right]^2$ model dependent

  $\Longrightarrow$ UPC's cannot be included in **rigorous** pdf fit
- But since $\nexists$ other data for small x nuclear gluon, still try:
  - Fit normalization to HERA exclusive data (AB,RSZ)

    $\Longrightarrow$ Access **gluon shadowing** in nucleus
  - Separate pdf set (JMRT)

Dipole picture: universality



$\mathcal{N}(\mathbf{b}_T, \mathbf{r}_T)$ = elastic forward scattering amplitude of $q\bar{q}$ dipole.
(Optical theorem: $\sim$ total cross section)

From same $\mathcal{N}$ calculate different processes in DIS:

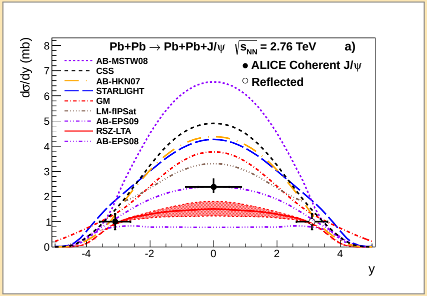
- Total $\gamma^* p/\gamma^* A$: $\sigma_{\text{tot}}^{\gamma^* H} = 2\,|\Psi(\gamma^* \to q\bar{q})|^2 \otimes \int \mathrm{d}^2\mathbf{b}_T \mathcal{N}$
- Total diffraction: $\frac{\mathrm{d}\sigma^{\gamma^* H \to X+H}}{\mathrm{d}t} = \frac{1}{4\pi}\,|\Psi(\gamma^* \to q\bar{q})|^2 \otimes |\mathcal{N}(\boldsymbol{\Delta}_T)|^2,$
- **Exclusive vector mesons:**

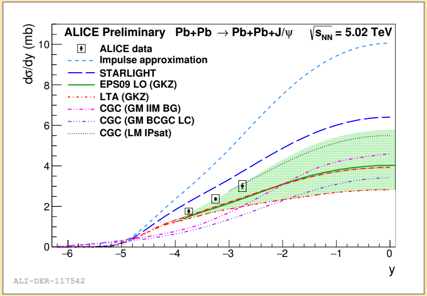
$$\frac{\mathrm{d}\sigma^{\gamma^* H \to VH}}{\mathrm{d}t} = \frac{1}{4\pi}\,|\Psi(\gamma^* \to q\bar{q}) \otimes \mathcal{N}(\boldsymbol{\Delta}_T) \otimes \Psi^*(q\bar{q} \to V)|^2$$

- + particle production and correlations in pp, pA, AA **!**

$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \sim (xg(x,Q^2))^2$ is hard limit $\mathcal{N} \sim \alpha_s(\mu^2) xg(x,\mu^2) \mathbf{r}_T{}^2$

Lessons from ALICE data so far





Run 1:

- Certainly there is gluon shadowing (MSTW08 outruled)
- Cross section smaller than dipole models generically predict (LM,GM)
- But not as much as indicated by RHIC fwd π^0 data (EPS08)

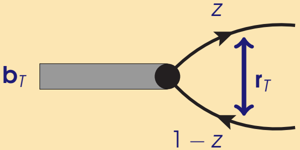
Run 2:

- Dipole models working even better

Dipole $\Longrightarrow$ vector meson transition

QCD bound state systematics

Also need transition between
$q\bar{q}$ pair and vector meson:
Meson light cone wave function

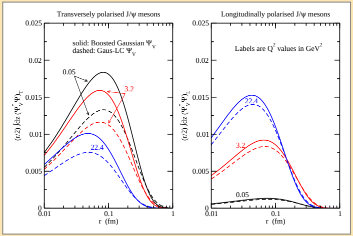


$$|V\rangle = \int \mathrm{d}z\, \mathrm{d}^2\mathbf{r}_T \psi_V(\mathbf{r}_T, z) \left| q\left(z, \mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) \bar{q}\left(1-z, \mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right)\right\rangle + \ldots$$

- NR bound state . . .
- Phenomenological parametrizations, e.g. "BG" & "Gaus-LC"

  Figure: Kowalski, Motyka, Watt
- AdS/CFT LF potential models

  Sandapen et al., Yang Li et al.

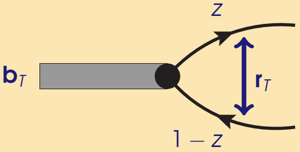


UPC ($Q^2 = 0$) much more sensitive to wave function than DIS

Dipole $\Longrightarrow$ vector meson transition

QCD bound state systematics

Also need transition between $q\bar{q}$ pair and vector meson:
Meson light cone wave function



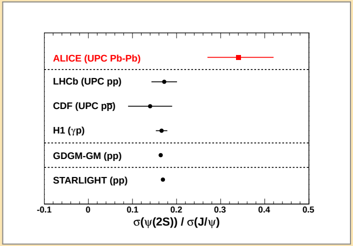
$$|V\rangle = \int \mathrm{d}z\, \mathrm{d}^2\mathbf{r}_T \Psi_V(\mathbf{r}_T, z) \left| q\left(z, \mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) \bar{q}\left(1-z, \mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right)\right\rangle + \dots$$

Small update on experimental status:

ALICE Run 1 reported **very** large

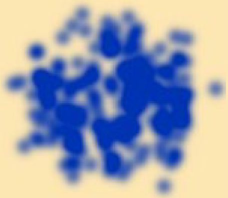
$$\frac{\sigma(\Psi(2S))}{\sigma(J/\Psi)}$$

$\Longrightarrow$ This seems (???) now to go down to HERA values in Run 2

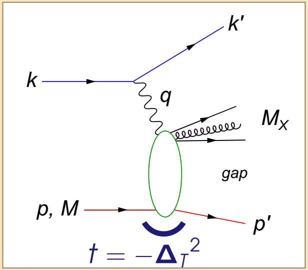


Imaging transverse geometry of gluons

Elastic scattering: Fourier transform of gluon distribution



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



Coherent target intact; total gluons integrated over $\perp$ plane

Incoherent target breaks without color exchange: spatial structure at $\sim$ nucleon radius

+ Same hierarchy repeated at higher $|t|$ for nucleon breakup

- Average **&** fluctuations: important for heavy ions
- Black disk: no R_p-scale structure $\Longrightarrow$ no incoherent
- Saturation/shadowing changes t-distribution (p and A)

Coherent & incoherent in Glauber model

$$\mathcal{N}_{\rm coh} = \int_{z,\mathbf{r}_T,\mathbf{b}_T} e^{-i\mathbf{b}_T\cdot\mathbf{\Delta}_T} [\Psi_V^*\Psi] \quad 2\left[1 - \exp\left\{-AT_A(b)\sigma_p(r)/2\right\}\right]$$

$$\frac{\mathrm{d}\sigma_{\rm incoh}}{\mathrm{d}t} = A\int \mathrm{d}^2\mathbf{b}_T T_A(\mathbf{b}_T) \left|\int_{z,\mathbf{r}_T} [\Psi_V^*\Psi]\,\mathcal{N}_p(r)\exp\left\{-AT_A(b)\sigma_p(r)/2\right\}\right|^2$$

Coherent $1 - \exp(-\sigma A T_A)$, amplitude reduces to $A\times$ proton in dilute limit $\sigma \to 0$.

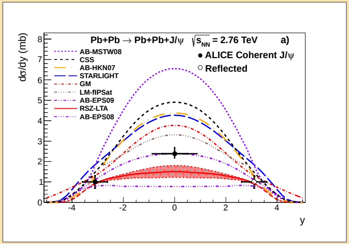
Incoherent $\sim A\times\ \sigma$ for proton, times nuclear attenuation factor (must *not* scatter inelastically off the other $A-1$ nucleons)

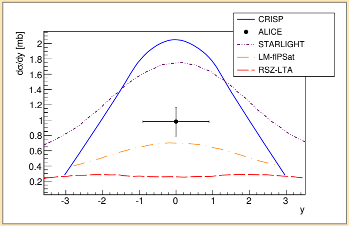
Form of nuclear attenuation different

$$1 - \exp(-\sigma) \quad \text{vs.} \quad \sigma\exp(-\sigma)$$

UPC geometry/imaging results so far

ALICE: coherent & incoherent

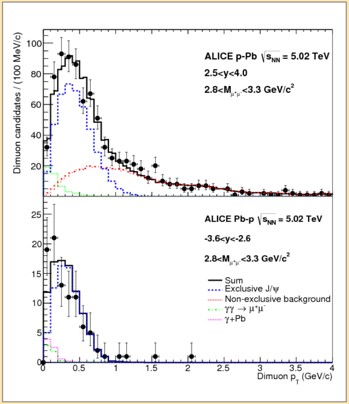




Nuclear effects very different

$\Longrightarrow$ Important constraint

LHC $\gamma + p$ with proton breakup: No cross section at small x



Here ALICE, also CMS similar

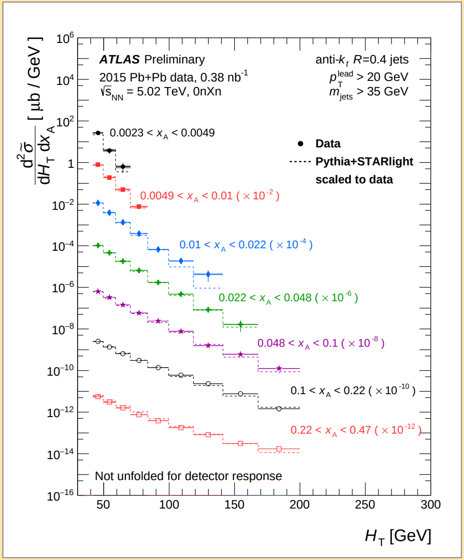
Effect bigger than expected

Inclusive γA

- At Quark Matter 2017, ATLAS reported measurement of UPC $\gamma + A \to 2j + X$
- Still preliminary; how accurate will this be (expt situation not as clean as DIS)?

First inclusive $\gamma + A$ with UPC!

But what exactly can be triggered?
Does one get access to semihard $\sim$ saturation scales?

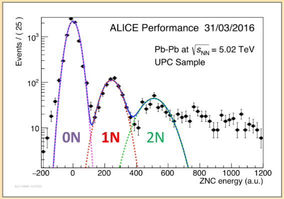


ATLAS-CONF-2017-011

UPC's and EIC

EIC vs UPCs: Imaging

- t-distribution $\Longrightarrow$ geometry
  - In photoproduction easy (?) because get t from VM p_T
  - But certainly EIC detector designed for imaging can do better (?)
- Nuclear breakup: connect to nuclear structure theory
  - Already ALICE measures "nuclear breakup after coherent process"
  - For EIC definition of coherent/incoherent is not t-distribution, but what, and how to calculate?



$\Longrightarrow$ Challenge for theorists

- UPC's limited by what can be triggered:
  - Much broader range of measurements at EIC
  - With few data points, UPC's used to validate models (collinear, dipole) in stead of parametrizing & fitting GPD's

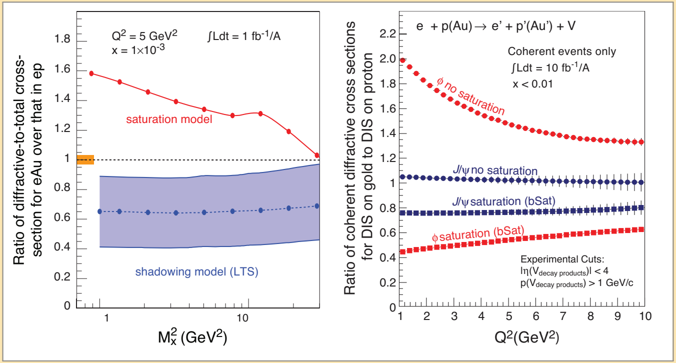
EIC vs UPCs: Gluon saturation & nonlinearity

What to look for experimentally?

- Characteristic transverse momentum scale Q_s which is **semihard** $\Longrightarrow$ can understand in weak coupling
- One consequence: evolution equations (BK, JIMWLK); **calculate** energy (x) dependence of cross sections **in weak coupling**, from first principles
  - Verifying requires $\gtrsim$ LHC energy, not with EIC
  - But can probably always fit energy dependence with DGLAP, conclusive?
- Broader view:
  Existence of Q_s $\Longrightarrow$ classical color field picture,
  allows **consistent description of several processes**
  as long as x is small enough (EIC)
  - Look for intrinsic transverse momentum: Q_s is p_T scale!
  - Vary Q^2 to turn nonlinearities off/on
  - Look for 2d phase space: x- and Q^2 dependence
    $\Longrightarrow$ verify Q_s grows with energy, not constant as Λ_{QCD}

Signals of saturation? Inclusive diffraction

Sat vs nonsat: differences much more drastic in diffractive DIS

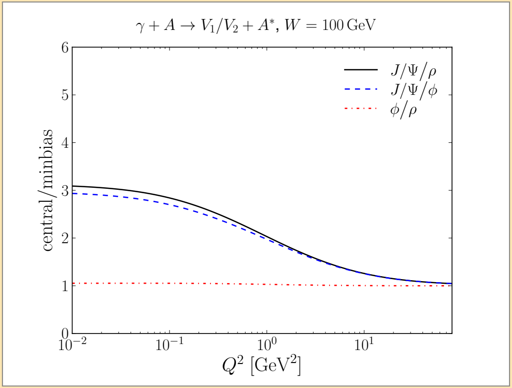


EIC white paper arXiv:1212.1701 : *eA*/*ep* ratios

- Generically: $\sigma_{\rm diff}^{\gamma^* h}/\sigma_{\rm tot}^{\gamma^* h}$ maximal at unitarity limit.
  Lots of diffraction at high Q^2 $\Longrightarrow$ saturation
  IHMO: closest thing to "smoking gun".
- Caveat: "nonsat" calculations easily unrealistic straw men.

Dependence on Q^2

An example in diffractive vector meson production



T.L., H. Mäntysaari, R. Venugopalan PRL 2015:

Central/minimum bias double ratio

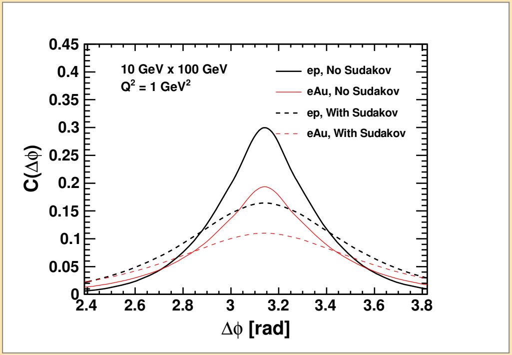
for vector mesons in incoherent diffractive nuclear DIS

Saturation turning off with increasing Q^2

Signals of saturation? Dihadron correlations

Q_s is intrinsic transverse momentum scale:

- Measure in correlations of few GeV particles: can you trigger on this in UPC? (in principle maybe yes)
- Need to understand both x and Q^2 dependence of effects



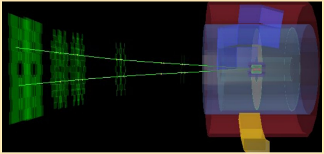
Aschenauer et al arXiv:1403:2413

DIS dihadron angular correlation

Summary UPC's are precursor to EIC

- Active program in 4 LHC experiments, and RHIC
  - So far moistly exclusive vector mesons
  - Other processes becoming available
- Advantages:
  - High collision energy
  - Happening now
- Disadvantages:
  - More limited kinematics: Q^2, t resolution
  - More limited set of processes accessible

  $\Longrightarrow$ but program expanding!



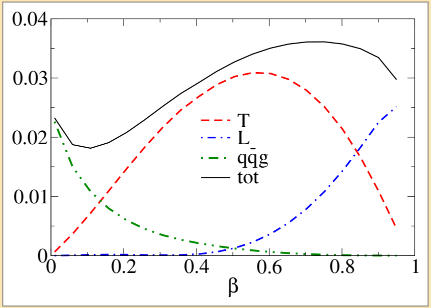
Backups

Diffractive structure function

$$F_2^D(x = x_{\mathbb{P}}\beta, \beta, Q^2) \quad ; \quad \int dt$$

In dipole picture: $\beta \sim 1/M_X^2$

- Small $\beta \ll 1$: dominated by higher Fock ($q\bar{q}g$ etc.)
- Medium $\beta \sim 0.5$: dominated by transverse $q\bar{q}$
- Large $\beta \to 1$: longitudinal $q\bar{q}$.



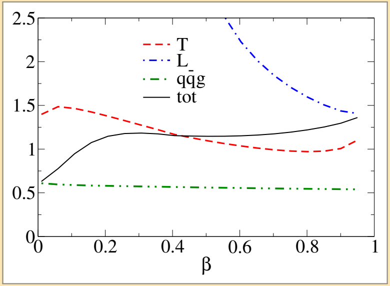
Proton, $Q^2 = 5\text{GeV}^2$, $x_{\mathbb{P}} = 10^{-3}$

Inclusive diffraction, nuclear suppression

Kowalski, T.L., Marquet, Venugopalan 2008

Essential regimes:

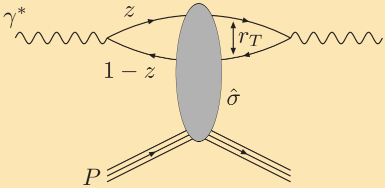
- Small $\beta \ll 1$: $q\bar{q}g$ strongly suppressed (black disk limit)
- Medium $\beta \sim 0.5$: transverse $q\bar{q}$ enhanced.
- Large $\beta \to 1$: longitudinal $q\bar{q}$ very much enhanced.



Au at $Q^2 = 5\mathrm{GeV}^2$ and $x_{\mathbb{P}} = 10^{-3}$

Note: plotting $\frac{F^D_{2A,(x)}}{AF^D_{2\ ,(x)}}$ with $x = L, T, q\bar{q}g,\ \mathrm{tot}.$

Dipole cross section in CGC



High energy/small x:
quark interacts with target via eikonal Wilson line in strong color field

- CGC: dipole cross section is Wilson line correlator

$$\sigma_{q\bar{q}}(\mathbf{r}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{1}{N_c} \mathrm{Tr} \left\langle 1 - U^\dagger\left(\mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) U\left(\mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right)\right\rangle$$

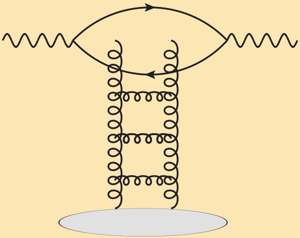
$$U(\mathbf{x}_T) = P\exp\left\{ig\int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-)\right\}$$

- High energy: energy dependence from JIMWLK (for U) or BK (for $\sigma_{q\bar{q}}$) equations

Dipole cross section in the dilute limit

Connection to pdf's

- $\sigma_{q\bar{q}}$: **elastic** scattering amplitude: color neutral state out
  $\Longrightarrow$ Exchange vacuum quantum numbers; "pomeron"
- Simplest color neutral QCD state:
- 2-gluon exchange in amplitude
  $\sim$ 1-gluon cross section
  $\Longrightarrow$ gluon distribution



Perturbative estimate; valid for small dipoles

$$\sigma_{q\bar{q}}(\mathbf{r}_T) = \frac{\pi^2}{N_c}\alpha_s(\mu^2)xg(x,\mu^2)\mathbf{r}_T{}^2$$

Dipole model hard limit

$$\frac{d\sigma^{\gamma^* H \to VH}}{dt} = \frac{1}{4\pi} \left| \int_0^1 dz\, d^2\mathbf{r}_T \Psi(\gamma^* \to q\bar{q}) \otimes \Psi^*(q\bar{q} \to V) \otimes \mathcal{N} \right|^2$$

- Heavy meson small $\Longrightarrow r \sim 1/M_V$
- $\Psi(q\bar{q} \to V)$ at $r = 0$ is related to $V \to e^+e^-$ decay width Γ_{ee}

$$f_V = \frac{e_f N_c}{\pi} \int_0^1 dz \Psi_V(\mathbf{r}_T, z) \Big|_{\mathbf{r}_T \to 0} \qquad \Gamma_{ee} = \frac{4\pi\alpha_{\mathrm{e.m.}} f_V^2}{3M_V}$$

(This simple form for longitudinal polarization, similar relation for transverse)

- With $r \ll 1/Q_s \Longrightarrow \mathcal{N} \sim \frac{\pi^2}{2N_c} \alpha_s xg(x, \mu^2) \mathbf{r}_T{}^2$ get famous formula:

$$\frac{d\sigma^{\gamma^* H \to VH}}{dt} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{em} M_V^5} \left[xg(x, Q^2) \right]^2$$ this is a dipole model result!

Derived by Ryskin; Brodsky, Frankfurt, Gunion, Mueller, Strikman

Used e.g. by Adeluyi, Bertulani, Nguyen (AB/AN) & Rebyakova, Strikman, Zhalov (RSZ)

- All r shadowed similarly, scale dependence only $xg(x, Q^2)$
- In practice usually fit normalization, e.g. to HERA