Models for exclusive vector meson production in heavy-ion collisions

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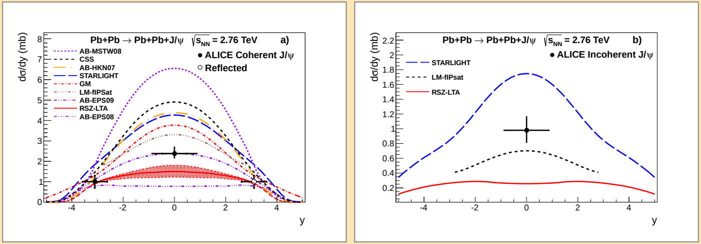
Outline

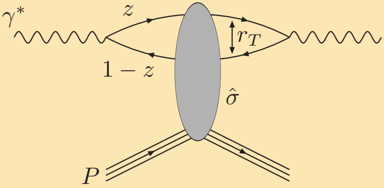
- Dipole picture of high energy DIS
- IPsat dipole-proton/nucleus cross section
- Coherent & incoherent exclusive J/Ψ

  Together with H. Mäntysaari, 2010 & 2013; "LM"
  - Interpretation in the dipole model
  - Results for LHC kinematics
  - Similarities and differences with other approaches



ALICE, arXiv:1305.1467

Dipole cross section



DIS at high energy/small x:

dipole cross section.

- CGC: Wilson line correlator:

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

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

- Dilute limit $r \ll 1/Q_s$:

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

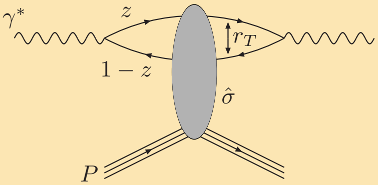
- High energy: BK/JIMWLK equation

Universality of the dipole cross section

$$\sigma_{\text{dip}}(x, \mathbf{r}_T) = \int d^2\mathbf{b}_T \frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}_T}$$

$$\sigma_{\text{dip}}(x, \mathbf{r}_T, \mathbf{\Delta}_T) = \int d^2\mathbf{b}_T \frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}_T} e^{i\mathbf{b}_T\cdot\mathbf{\Delta}_T}$$

$$\mathbf{\Delta}_T{}^2 = -t$$



From same dipole cross section calculate DIS

- Total $\gamma^* p$: $\sigma^{\gamma^* p}_{L,T} = \int d^2\mathbf{r}_T \int dz \left|\Psi^{\gamma}_{L,T}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma_{\text{dip}}(x, \mathbf{r}_T)$
- Total diff.: $\frac{\sigma^D_{L,T}}{dt} = \frac{1}{16\pi} \int d^2\mathbf{r}_T \int dz \left|\Psi^{\gamma}_{L,T}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma^2_{\text{dip}}(x, \mathbf{r}_T, \mathbf{\Delta}_T)$
- X-cl. diff.: $\frac{\sigma^D_{L,T}}{dt} = \frac{1}{16\pi} \left|\int d^2\mathbf{r}_T \int dz \left(\Psi^{\gamma}\Psi^{*V}\right)_{L,T} \sigma_{\text{dip}}(x, \mathbf{r}_T, \mathbf{\Delta}_T)\right|^2$

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

IPsat model: protons

Dipole cross section should not exceed black disk: $\frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}_T} < 2$

Starting point GBW: Golec-Biernat, Wusthoff 1998 $\sigma_{\text{dip}} = \sigma_0 \left(1 - e^{-\frac{\mathbf{r}_T{}^2}{4Q_s(x)^2}}\right)$

1 possible improvement: **Kowalski & Teaney 2003** **IPsat model**

- DGLAP evolution: improves description large Q^2 / small r
- Consistent $\mathbf{b}_T$ dependence for all observables

$$\sigma_{\text{dip}}(x, \mathbf{r}_T) = 2 \int d^2\mathbf{b}_T \left(1 - \exp\left\{-\frac{\pi^2}{2N_c}\alpha_s(\mu^2) xg(x, \mu^2) T_p(\mathbf{b}_T) \mathbf{r}_T{}^2\right\}\right),$$

- $\mu^2 = \frac{C}{\mathbf{r}_T{}^2} + \mu_0^2$, Gaussian $T_p(\mathbf{b}_T)$
- $xg(x, \mu^2)$ evolved with DGLAP, initial condition $\sim x^{\sim 0}$!
  - Restricts growth of $\mathbf{b}_T$-profile at large $\mathbf{r}_T$: feature or bug?
  - Consistent with what we expect from small x evolution?
  - BFKL/BK evolution difficult to combine with similar $\mathbf{b}_T$-dependence.

IPsat: nuclei

Straightforward generalization to nuclei:

$$\frac{\mathrm{d}\sigma^A_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T} = 2\left(1 - \exp\left\{-\frac{\pi^2}{2N_\mathrm{c}}\alpha_\mathrm{s}(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A} T_p(\mathbf{b}_T - \mathbf{b}_{T\,i})\mathbf{r}_T{}^2\right\}\right),$$

- $\mathbf{b}_{T\,i}$: nucleon positions, from Woods-Saxon, average $\langle\cdot\rangle_\mathrm{N}$
- Proton radius $\sim 0.6\mathrm{fm}$, much less than the nucleon-nucleon distance. $\Longrightarrow$ **lumpy** nucleus $\Longrightarrow$ visible in **incoherent** diffraction

"Glauber" limit $A \to \infty$, $R_p \ll R_A$

$$\left\langle \frac{\mathrm{d}\sigma^A_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T} \right\rangle_\mathrm{N} \approx_{A\to\infty} 2\left[1 - e^{-\frac{AT_A(\mathbf{b}_T)}{2}\sigma^p_{\mathrm{dip}}}\right]$$

($\int \mathrm{d}^2\mathbf{b}_T T_A(\mathbf{b}_T) = 1 \Longrightarrow T_A(\mathbf{0}_T) \sim A^{-2/3}$)

Coherent and incoherent, interpretation

Denote average over nucleon positions as

$$\langle \mathcal{O}(\{\mathbf{b}_{Ti}\})\rangle_{\mathrm{N}} \equiv \int \prod_{i=1}^{A} \left[\mathrm{d}^2\mathbf{b}_{Ti} T_A(\mathbf{b}_{Ti}) \right] \mathcal{O}(\{\mathbf{b}_{Ti}\}).$$

Quasielastic = coherent + incoherent
$\int$ final state nucleon $\mathbf{q}_{Ti}$: $\Longrightarrow$ $\mathbf{b}_{Ti}$ same in amplitude and cc.

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA^*/A}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle |\mathcal{A}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}_T)|^2 \right\rangle_{\mathrm{N}}$$

Coherent: amplitude is $\langle\rangle$ in same nucleus $\mathbf{b}_{Ti}$ state; then square

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}_T) \right\rangle_{\mathrm{N}} \right|^2$$

Incoherent is fluctuations — this dominates at large $-t$

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA^*}}{\mathrm{d}t} \sim \left\langle |\mathcal{A}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}_T)|^2 \right\rangle_{\mathrm{N}} - \left| \left\langle \mathcal{A}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}_T) \right\rangle_{\mathrm{N}} \right|^2$$

(Interpretation mean/fluctuations explicit in SARTRE event generator, by Ullrich & Toll)

Quasielastic J/Ψ production

Approximations used in T.L.& Mäntysaari, 2010, 2013

- Factorized b-dependence: **Note** $\sigma_0 = 4\pi B_p$ for gaussian $T_p(\mathbf{b}_T)$.

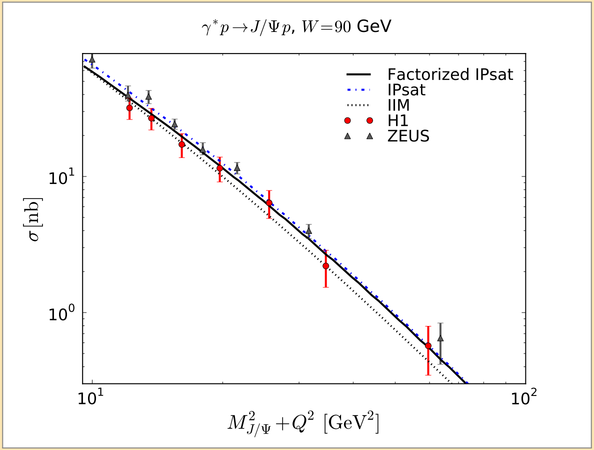
$$\frac{\mathrm{d}\sigma^{\mathrm{p}}_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T}(\mathbf{r}_T, \mathbf{b}_T, x) = 2T_p(\mathbf{b}_T)\mathcal{N}(\mathbf{r}_T, x)$$

- "fIPsat" $\mathcal{N}(\mathbf{r}_T, x) = 1 - \exp\left(-r^2 \frac{1}{2\pi B_p} \frac{\pi^2}{2N_c} \alpha_s\left(\mu(r^2)\right) xg\left(x, \mu(r^2)\right)\right)$
  Really Bartels, Golec-Biernat, Kowalski 2002
- Also compare to IIM Iancu, Itakura, Munier 2003 for proton
- As in IPsat, generalize to nuclei with:

$$S_A(\mathbf{r}_T, \mathbf{b}_T, x) = \prod_{i=1}^{A} S_p(\mathbf{r}_T, \mathbf{b}_T - \mathbf{b}_{T\,i}, x).$$

- Real part $1+\beta^2$ and skewness corrections R_g Shuvaev et al as in Kowalski, Motyka, Watt 2006, depend on $\lambda \equiv \frac{\mathrm{d}\mathcal{A}}{\mathrm{d}\ln 1/x}$

Check HERA



Works, skewness and real part correction $R_g^2(1+\beta^2)$ essential.

(Assume constant t-slope $\Longrightarrow$ finer details of t-dependence not reproduced.)

Coherent amplitude for J/Ψ

$$\left\langle \mathcal{A}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}_T) \right\rangle_{\text{N}} = \int \frac{\mathrm{d}z}{4\pi} \mathrm{d}^2\mathbf{r}_T \, \mathrm{d}^2\mathbf{b}_T e^{-i\mathbf{b}_T \cdot \mathbf{\Delta}_T} [\Psi_V^* \Psi](r, Q^2) \times 2\left[1 - \exp\left\{-2\pi B_p A T_A(b) \mathcal{N}(r, x_{\mathbb{P}})\right\}\right].$$

Essential ingredient: dipole-proton amplitude $\mathcal{N}(r, x_{\mathbb{P}})$;
($4\pi B_p \mathcal{N}(r, x_{\mathbb{P}})$ is dipole-proton cross section)

Dipole model vs. leading twist shadowing

MSoD = Multiple Scattering of Dipole	Rebyakova, Strikman, Zhalov
▸ Shadowing in F_2 from MSoD (related to DDIS)	▸ Shadowed $xg_A(x, \mu^2)$ from diffractive DIS (related to MSoD)
▸ Nuclear suppression of elastic J/Ψ from MSoD	▸ Nuclear suppression of elastic J/Ψ from $xg_A(x, \mu^2)$
▸ Common $\sigma_{\text{dip}}^{\text{p}}$, no $xg_A(x, \mu^2)$	▸ Common $xg_A(x, \mu^2)$
▸ Different r:s shadowed differently	▸ All r shadowed similarly

Incoherent amplitude

Notation:

$$\frac{d\sigma^{\gamma^* A \to V A^*}}{dt} = \frac{R_g^2(1+\beta^2)}{16\pi} \int \frac{dz}{4\pi} \frac{dz'}{4\pi} \, d^2\mathbf{r}_T \, d^2\mathbf{r}_T{}' \, [\Psi_V^* \Psi] \, [\Psi_V^* \Psi]$$
$$\times A \, (4\pi B_p)^2 \, e^{-B_p \boldsymbol{\Delta}_T{}^2} \mathcal{N}(r) \mathcal{N}(r') \int d^2\mathbf{b}_T \, T_A(b)$$
$$\times \exp\left\{-2\pi B_p (A-1) T_A(b) \left[\mathcal{N}(r) + \mathcal{N}(r')\right]\right\}$$

Interpretation:

- $\sim A\times$ squared amplitude for proton
- Nuclear attenuation factor: must *not* scatter inelastically off the other $A-1$ nucleons (survival probability of the dipole) .
- Functional form of nuclear attenuation different from coherent:
  $1-\exp(-\sigma)$ vs. $\sigma \exp(-\sigma)$

See e.g. Kopeliovich, Nemchik, Schaefer, Tarasov 2001

Incoherent amplitude

Notation:

$$\frac{d\sigma^{\gamma^* A \to VA^*}}{dt} = \frac{R_g^2(1+\beta^2)}{16\pi} \int \frac{dz}{4\pi}\frac{dz'}{4\pi}\, d^2\mathbf{r}_T\, d^2\mathbf{r}_T{}'\, [\Psi_V^*\Psi]\, [\Psi_V^*\Psi]$$

$$\times\, A\,(4\pi B_p)^2\, e^{-B_p \boldsymbol{\Delta}_T{}^2} \mathcal{N}(r)\mathcal{N}(r') \int d^2\mathbf{b}_T\, T_A(b)$$

$$\times\, \exp\left\{-2\pi B_p (A-1)\, T_A(b)\, [\mathcal{N}(r) + \mathcal{N}(r')]\right\}$$

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Incoherent amplitude

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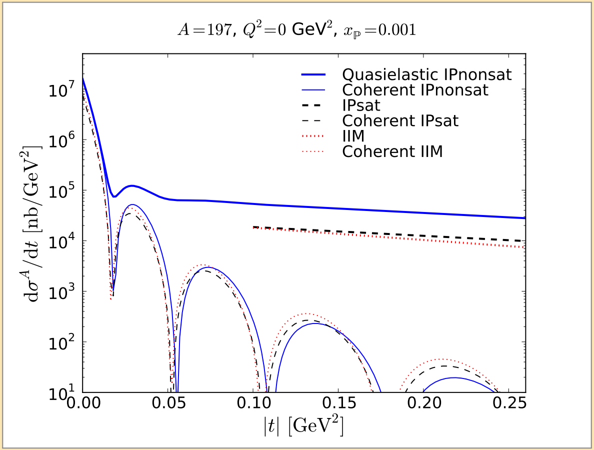
Coherent and incoherent cross sections

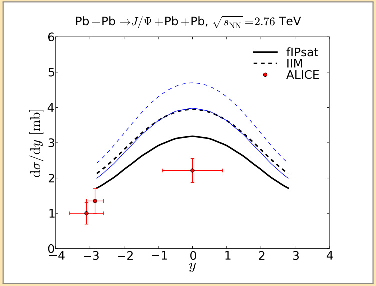


IPnonsat: linearized in r, [Caldwell, Kowalski 2009] , explicitly $A \times \sigma_p$.
Incoherent: factor of 3 suppression from $A\sigma_p$.

Coherent, comparison to LHC

T.L., Mäntysaari 2013

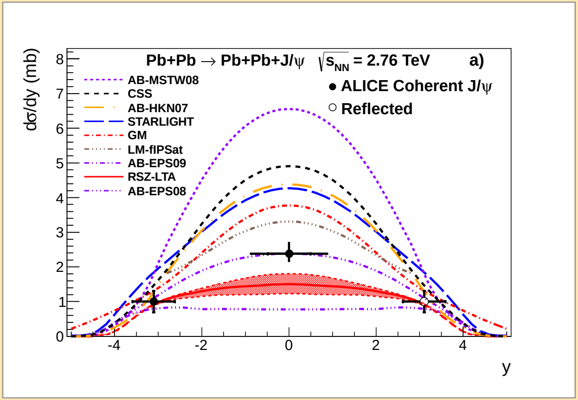
Different J/ψ wavefunctions, σ_{dip},



- Wavefunction differences significant for $Q^2 = 0$
- Dipole cross section differences also important, mainly via different σ_0/B_p
- R_g^2 is **large**; $1 + \beta^2$ also.
  - ep data requires (?) these
  - γA would work better without

PHENIX $y = 0$ UPC J/Ψ: measurement $76 \pm 35\mu$b,
Our calculation 108μb.
(Compare 119μb SARTRE with 116% correction $R_g^2(1 + \beta^2)$)

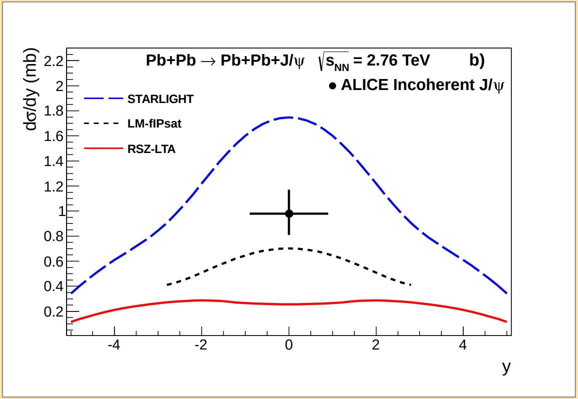
Coherent: model comparisons

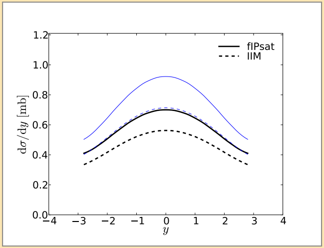


- Unshadowed AB-MSTW08 fails miserably
  $\Longrightarrow$ **ALICE result sign of saturation/shadowing**
- AB-EPS08 too shadowed (driven by PHENIX dAu data)
  $\Longrightarrow$ together pA and UPC overconstrain models.

Incoherent: model comparisons

Very few predictions for no good reason, good constraint!





- Big difference vs. STARLIGHT (shadowed $xg_A(x, \mu)$, no survival prob) (ALICE reference: "incoherent will not be further considered here")
- Suppression vs $A \times \sigma_{\gamma p}$ clear prediction of dipole picture.
- LT: different dipole & scattered nucleon reinteraction

Conclusion

- Universality of dipole picture: lot of predictive power.
- Elastic photoproduction important constraint of nuclear pdf/dipole cross section: measure and calculate **both coherent and incoherent**
- "This was solved 20 year ago"
  Brodsky, Frankfurt, Gunion, Mueller, Strikman -94
  $\Longrightarrow$ but factor $\sim$ 5 differences remain in treatments of shadowing/saturation, wavefunctions and in skewness etc. corrections.