Colour dipole approach to Drell-Yan and heavy quarkonia production at RHIC and LHC

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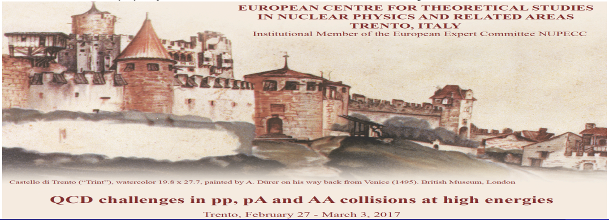

Outline

1. Motivation and Brief Introduction to Color Dipoles in DIS
2. Color Dipole Description of Drell-Yan process
   - $pp \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - $pA \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - Dilepton - hadron correlations
3. Color Dipole Description of Quarkonium Production
4. Conclusions and Outlook

Introduction

Drell-Yan and heavy quarkonia studies

- Drell-Yan (DY) in $pp/pA/AA$ collisions is an excellent tool for the investigations of strong interaction dynamics in an extended kinematical range of energies and rapidities.
- DY in *pp*@LHC allows to test the Standard Model (SM) and search for New Physics beyond the SM.
  DY in *pA* could be used to investigate the onset of initial-state effects.
- Quarkonia production in pp/pA, as well as high-p_T forward particle production in pA, are traditionally very important probes of QCD dynamics e.g. QCD factorisation, gluon resummation, higher order PT and non-PT effects, medium properties, CGC etc.
- In *pp* heavy quark masses provide hard scale to study quarkonia production mechanisms in pQCD (factorisation breaking, CS vs. CO,...)
  $c\bar{c}$ are special - m_c is at the boundary between pQCD and soft QCD.

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pQCD description of Drell-Yan: problems and solutions

- Fixed-order pQCD description of DY process is not reliable when two or more different hard scales are present [1-3].
  Examples: $p_T^{\ell\ell} \ll M_{\ell\ell}$ or at $s \gg M_{\ell\ell}^2$ when potentially large terms $\propto \alpha_s^n \ln^n(s/M^2)$ should also be resummed.
- One of the phenomenological approaches which effectively takes into account the higher-order QCD corrections is color dipole formalism [4].
- At high energies, color dipoles with a definite transverse separation are eigenstates of interaction
  $\Rightarrow$ main ingredient is universal and process-independent dipole-target scattering cross section which can be determined phenomenologically, for example using GBW approach, from DIS data [5].

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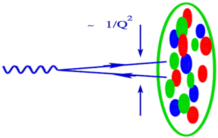
Color Dipole Description of Deep Inelastic Scattering



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$$\sigma_{T,L}(x, Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(r, z, Q^2)|^2 \hat{\sigma}(r, x)$$

where $\Psi_{T,L}$ is wave function for splitting of transverse (T) or longitudinal (L) polarized virtual photon into a $q\bar{q}$ pair (dipole) and $\hat{\sigma}$ is the dipole-proton cross section.

- The standard DIS proton structure functions $F_2 = F_T + F_L$ are related to $\sigma_{T,L}$ via $F_{T,L}(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{T,L}(x, Q^2)$
- The main assumption of the GBW model is geometric scaling of dipole-proton cross section $\hat{\sigma}(r, x) = \sigma_0 g(\frac{r}{R_0(x)})$
  Function $R_0(x)$ called saturation radius, decreases with decreasing x.
- When $\hat{r} = r/R_0(x) \to \infty$ the function $g(\hat{r})$ saturates to 1, so that $\hat{\sigma}(r, x) \to \sigma_0$
- The fact that the dipole cross section $\hat{\sigma}(r, x)$ is limited by the energy independent cross section σ_0 may be regarded as a unitarity bound.

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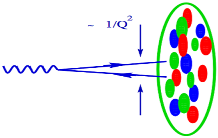

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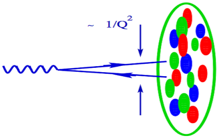

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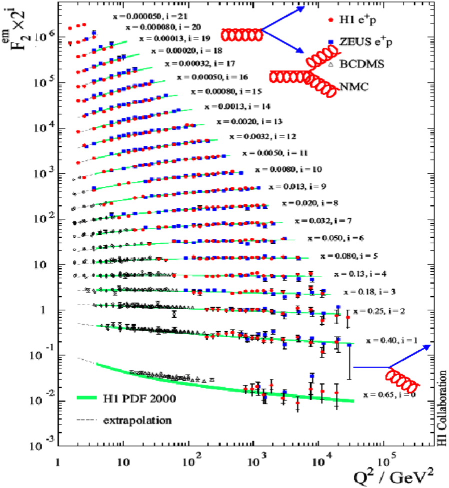
- The ep DIS data at low x can be very economically described with the help of the saturation model K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1999); 60, 114023 (1999); PRL 86, 596 (2001).



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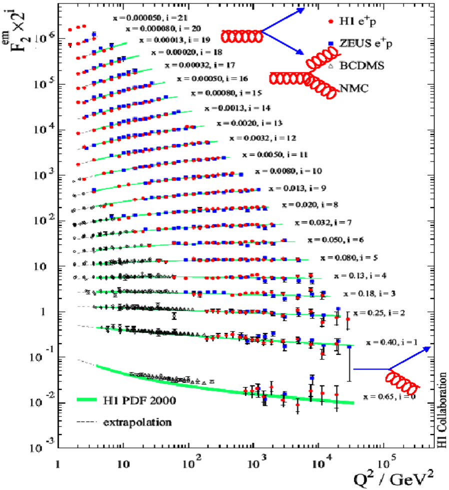

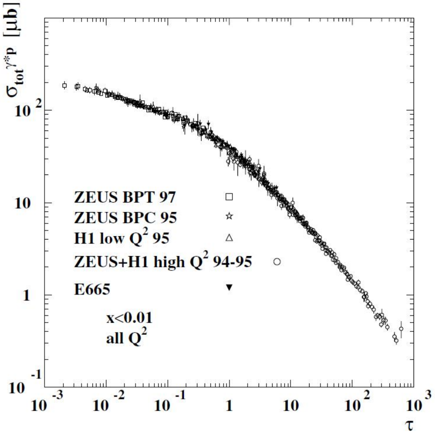

Experimental data on $\sigma_{\gamma^* p}$ from the region $x < 0.01$ plotted versus the scaling variable $\tau = Q^2 R_0^2(x)$.

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- The unknown function $Q_s(x) = R_0^{-1}(x)$ is called saturation scale.
- Original GBW ansatz for the saturation radius was $R_0(x) = 1/Q_0(x/x_0)^\lambda$ with $Q_0 = 1 GeV$. The parameters x_0, λ and σ_0 were determined from a fit to DIS data at small x.
- The observation of geometric scaling in DIS at HERA was interpreted as evidence for parton recombination and saturation.
- Dramatic consequences: Available PDF fits do not include these effects and would thus fail to provide reliable predictions at the LHC.
- However, for $Q^2 \gtrsim 10 GeV^2$ standard LO DGLAP pQCD evolution explains GS of $\sigma_{\gamma^* p}$ and in fact predicts the value λ characterizing the saturation. F. Caola and S. Forte, PRL 101, 022001 (2008)

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Color dipole description of Drell-Yan process

Frame-dependent description of Drell-Yan process

B. Kopeliovich, hep-ph/9609385: *(in DY) . . . statement that the annihilating quark and antiquark belong to the beam and to the target respectively . . . is not Lorentz invariant.*

- In the centre of mass frame, the DY process looks like $q\bar{q}$ annihilation

- In the target rest frame, the DY process looks like fragmentation of a projectile quark into a dilepton via bremsstrahlung of a heavy photon

  - Partonic fluctuation lifetime is enhanced: $\Delta\tau_{lab} \approx \sqrt{s}/m_p \times \Delta\tau_{cms}$.
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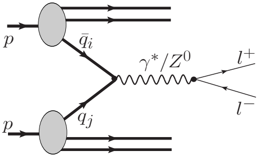

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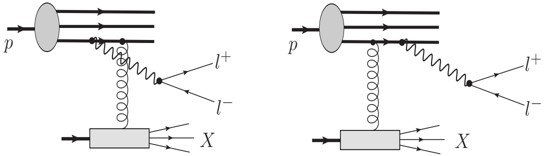

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Color dipole description of DY process

J. Raufeisen *et al.*, Phys. Rev. D **66**, 034024 (2002):

- *In the kinematical region where $\sqrt{s} \gg$ all other scales (e.g. m_c, m_b), the DY process can be formulated in the target rest frame in terms of the same color dipole cross section which is used in low-x DIS [1]:*

$$\frac{d\sigma(qN\to\gamma^* X)}{d\ln\alpha} = \int d^2\rho \, |\Psi_{\gamma^* q}(\alpha,\rho)|^2 \, \sigma^N_{q\bar{q}}(\alpha\rho, x)$$

$\Psi_{\gamma^* q}(\alpha,\rho)$ – LC wave function. Gives rate of $q\to\gamma^* q$ EM radiation, is PT calculable.
$\sigma^N_{q\bar{q}}$ – dipole cross section. Has NP origin, comes from phenomenology (GBW [2] *etc.*)
α – LC momentum fraction of parent quark taken away by γ^*.
ρ – transverse separation between γ^* and final quark.

$$\frac{d^2\sigma(pN\to\ell^+\ell^- X)}{dM^2 dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f} Z_f^2\left[q_f\left(\frac{x_1}{\alpha},\mu^2\right)+\bar{q}_f\left(\frac{x_1}{\alpha},\mu^2\right)\right]\frac{d\sigma(qN\to\gamma^* X)}{d\ln\alpha}$$

$x_1 = \frac{2P_2\cdot p}{s}$, $x_2 = \frac{2P_1\cdot p}{s}$, $s=(P_1+P_2)^2$, $p^2 = M^2 \equiv M^2_{\ell\bar{\ell}}$, $x_F = x_1 - x_2 = 2p_L/\sqrt{s}$
$\mu^2 = (1-x_1)M^2$ – hard (factorization) scale at which the projectile PDF q_f is probed.

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$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$: Color dipole approach @ large M

- Quark bremsstrahlung of a virtual gauge boson G^* ($G = \gamma, Z^0$)

$$\frac{d\sigma(pp \to [G^* \to \ell^+\ell^-]X)}{d^2p_T dM^2 d\eta} = \mathcal{F}_G(M)\, \frac{d\sigma(pp \to G^* X)}{d^2p_T d\eta}\,, \qquad G = \gamma^*/Z^0$$

where
$$\mathcal{F}_\gamma(M) = \frac{\alpha_{em}}{3\pi M^2}\,, \qquad \mathcal{F}_Z(M) = \mathrm{Br}(Z^0 \to \ell^+\ell^-)\rho_Z(M)$$

and

$$\rho_Z(M) = \frac{1}{\pi}\, \frac{M\Gamma_Z(M)}{(M^2 - m_Z^2)^2 + [M\Gamma_Z(M)]^2}\,, \qquad \Gamma_Z(M)/M \ll 1\,,$$

with

$$\Gamma_Z(M) = \frac{\alpha_{em} M}{6\sin^2 2\theta_W}\left(\frac{160}{3}\sin^4\theta_W - 40\sin^2\theta_W + 21\right),$$

- In calculations we take m_u=m_d=m_s=0.14GeV, m_c=1.4 GeV, m_b=4.5 GeV, and use the CT10 NLO parametrization* for the projectile quark PDFs with the factorization scale μ_F=M.

*) H. L. Lai *et al.*, Phys. Rev. D **82**, 074024 (2010).

Color dipole cross section parametrizations

- Dipole cross section parametrizations used: GBW, BGBK, IP-sat.

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001)

$$\sigma_{q\bar{q}}(\rho,x) = \sigma_0 \left[1 - \exp(-\frac{\rho^2 Q_s^2(x)}{4})\right], \; Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$$

BGBK: J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D **66**, 014001 (2002)

$$\sigma_{q\bar{q}}(\rho,x)=\sigma_0 \left[1 - \exp\left(-\frac{\pi^2}{\sigma_0 N_c}\rho^2 \alpha_s(\mu^2) xg(x,\mu^2)\right)\right], \; \frac{\partial xg(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 dz P_{gg}(z) \frac{x}{z} g(\frac{x}{z},\mu^2)$$

IP-sat: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, ibid D **78**, 014016 (2008)

$$\sigma_{q\bar{q}}(\rho,x)=2\int d^2b \left[1 - \exp\left(-\frac{\pi^2}{2N_c}\rho^2 \alpha_s(\mu^2) xg(x,\mu^2) T_G(\mathbf{b})\right)\right], \; T_G(\mathbf{b})=(1/2\pi B_G)\exp(-b^2/2B_G)$$

- $\sigma(pp \to Z^0)$ is sensitive to dipole cross section parametrizations:

$\sqrt{s}$ (TeV)	GBW	BGBK	IP-SAT	DATA [nb]
7	0.950	1.208	0.986	0.937 ± 0.037 [1] 0.974 ± 0.044 [2]
8	1.083	1.427	1.183	1.15 ± 0.37 [3]
14 (13)	1.852	2.797	2.514	(1.98 ± 0.39) [4]

[1] ATLAS: G. Aad *et al.* (ATLAS Collaboration), JHEP **12**, 060 (2010).
[2] CMS: V. Khachatryan *et al*. (CMS Collaboration), JHEP **10**, 132 (2011).
[3] CMS: V. Khachatryan *et al*. (CMS Collaboration), Phys. Rev. Lett. **112**, 191802 (2014).
[4] ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **759**, 601 (2016).

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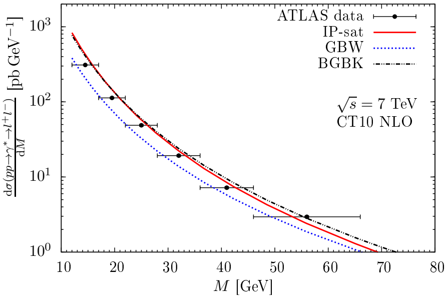
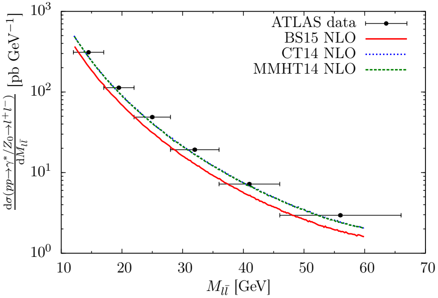
[4] ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **759**, 601 (2016).

DY: Color dipole approach vs. NLO pQCD calculations

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



E. Basso *et. al.*, Nucl. Phys. A **948**, 63 (2016)

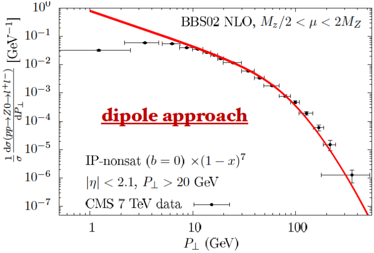


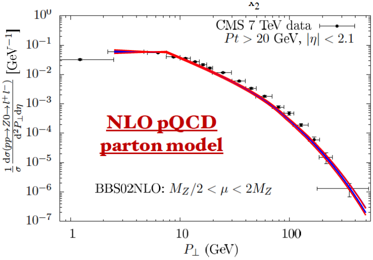
ATLAS data: G. Aad *et al.*, JHEP **1406**, 112 (2014)

- Confirms previous observation[1,2] that dipole approach effectively accounts for higher order pQCD corrections
- Theoretical uncertainties between different dipole cross sections parametrizations are similar to uncertainties in the PDFs.

DY: Color dipole approach vs. NLO pQCD calculations

- CMS data on $pp \to Z^0 \to \ell^+\ell^-$





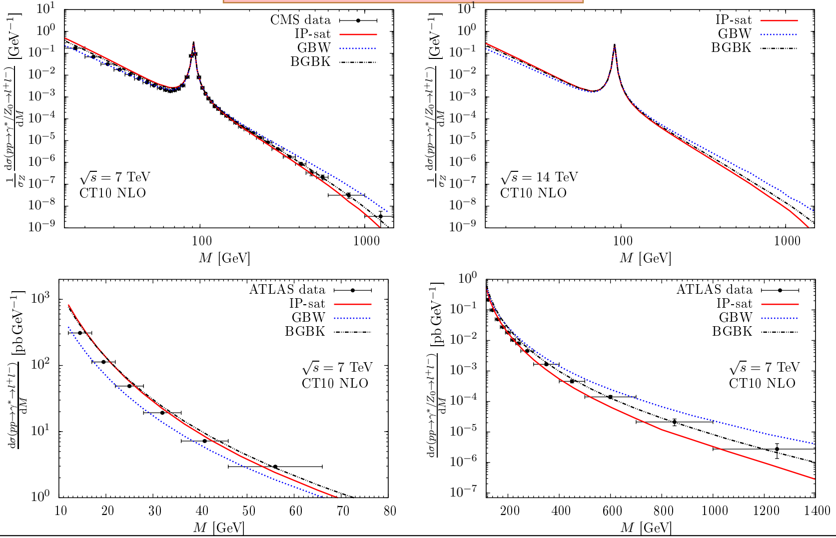
- Confirms previous observation[1,2] that
  dipole approach effectively accounts for higher order pQCD corrections
- Fails outside the region of dipole description validity (*i.e.* at low p_T)*.

[1] J. Raufeisen, J.-C. Peng and G. C. Nayak, Phys. Rev. D **66**, 034024 (2002);
[2] M. B. Johnson *et al.* Phys. Rev. C **75**, 035206 (2007); M. B. Johnson *et al.* ibid C **75**, 064905 (2007).

*) Intrinsic primordial transverse momentum of the projectile quark is neglected. Important at $p_T \lesssim 5$ GeV at the LHC.

$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ @ LHC

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

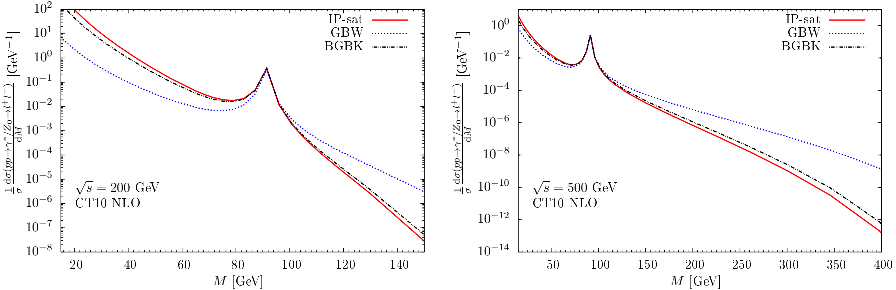


ATLAS: G. Aad *et al.* (ATLAS Collaboration), JHEP **1406**, 112 (2014), Phys. Lett. B **725** 223 (2013).

CMS: V. Khachatryan *et al*. (CMS Collaboration), Eur. Phys. J. **75**, 147 (2015).

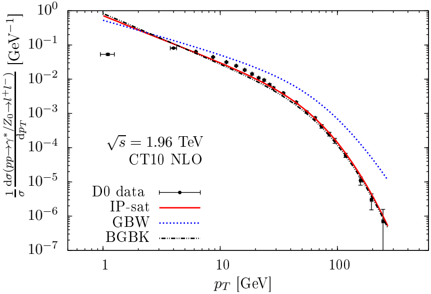
$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ at large M @ RHIC

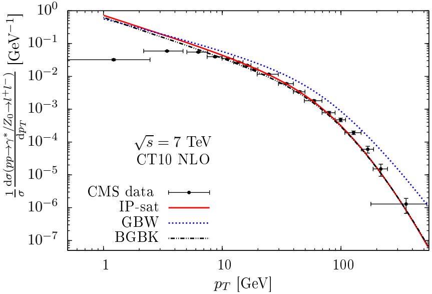
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

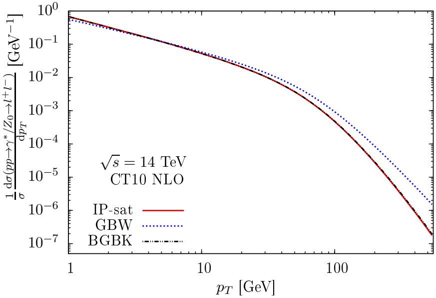


- Dilepton invariant mass spectra at large M are sensitive to different dipole cross section $\sigma_{q\bar{q}}^N$ parametrizations.

DY: Color dipole approach @ Tevatron and LHC







E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

Three different parametrizations of dipole cross section used:

IP-sat: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, Phys. Rev. D **78**, 014016 (2008).

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001).

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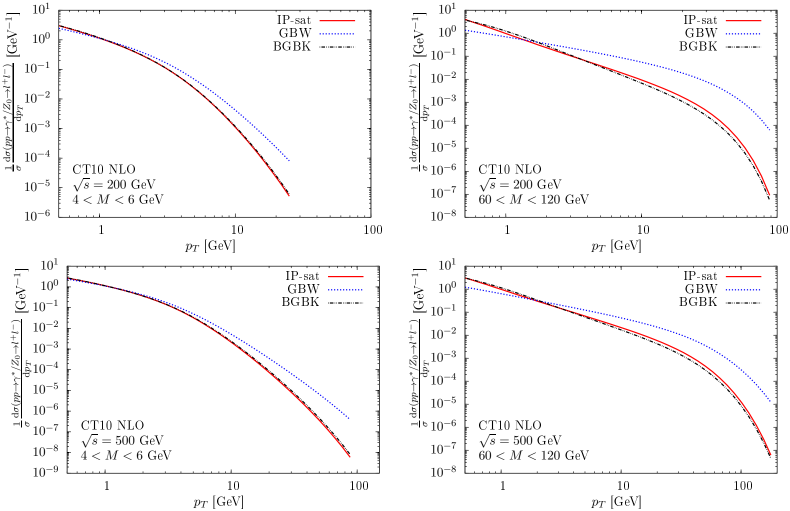
Color dipole predictions for DY@RHIC

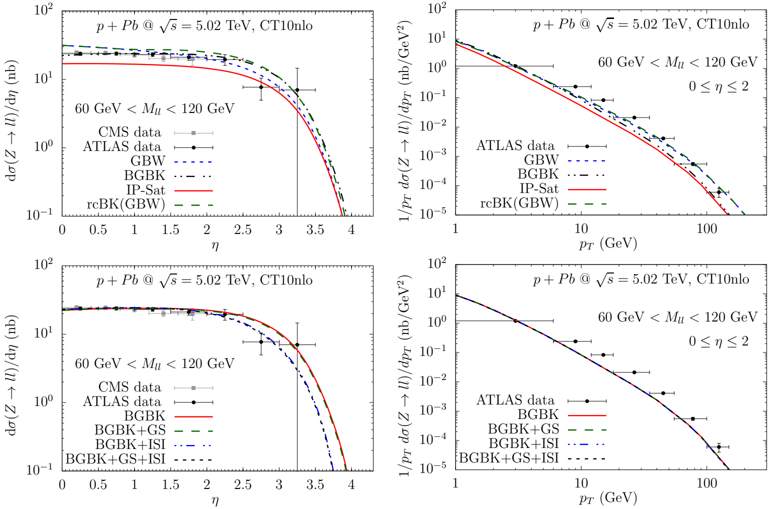
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



- Sensitive to different parametrizations of dipole cross section $\sigma^N_{q\bar{q}}$

Color dipole approach @ LHC: $pPb \to \gamma^*/Z^0 \to \ell\bar{\ell}$

E. Basso *et. al.*, Phys. Rev. D **93**, 094027 (2016)



ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. C**92**, 044915 (2015).

CMS: V. Khachatryan *et al*. (CMS Collaboration), arXiv:1512.06461 [hep-ex].

Dilepton - hadron correlations

- In both pA and pp collisions DY production is accompanied by hadron production from fragments of the quark which radiated γ^*.

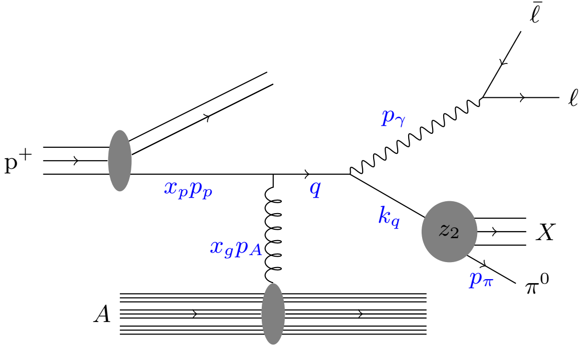


Figure from A. Staśto *et al.*, Phys. Rev. D **86**, 014009 (2012).

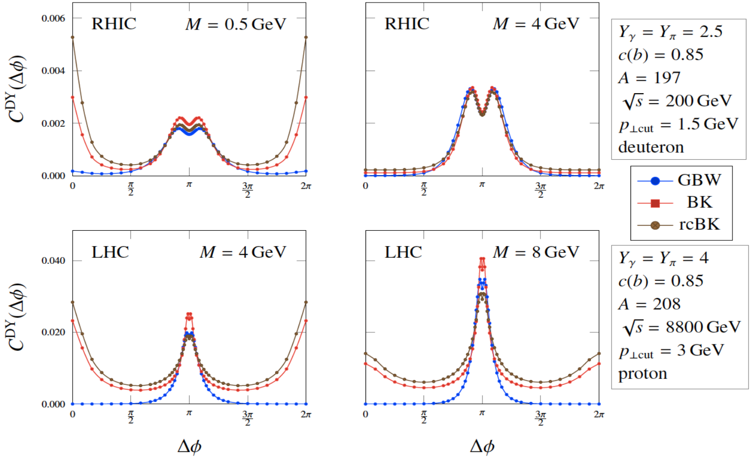
$\Rightarrow$ Study γ^*-h azimuthal correlations*

$\star$) For γ-h correlations see: A. H. Rezaeian, Phys. Rev. D **86**, 094016 (2012),

J. Jalilian-Marian and A. H. Rezaeian, Phys. Rev. D **86**, 034016 (2012).

γ^*-π azimuthal correlations in pA

A. Staśto *et al.*, Nucl. Phys. A **904-905**, 837c (2013)



In pA dipole gluon distribution at small-x as well as the cross section vanish for $p_T^g \to 0$
$\Rightarrow$ quark, in order to radiate photon, acquires its p_T via multiple scattering with gluons instead
$\Rightarrow$ double peak structure on the away side $\Delta\phi = \pi$ appears

[A. Staśto *et al.*, Phys. Rev.D **86**, 014009 (2012)].

G^*-h azimuthal correlation function $C(\Delta\phi)$

- Azimuthal correlations between dilepton and hadron are investigated using coincidence probability per trigger particle G^*:

$$C(\Delta\phi) = \frac{2\pi \int_{p_T, p_T^h > p_T^{\rm cut}} dp_T p_T \; dp_T^h p_T^h \; \frac{d\sigma(pp \to hG^* X)}{dY dy_h d^2 p_T d^2 p_T^h}}{\int_{p_T > p_T^{\rm cut}} dp_T p_T \; \frac{d\sigma(pp \to G^* X)}{dY d^2 p_T}}$$

  where $p_T^{\rm cut}$ is the experimental lower cut-off on transverse momenta of dilepton G^* and hadron h and $\Delta\phi$ is the angle between them.

- To describe interactions of the incoming quark with the target color field we employ unintegrated gluon distribution function

  $F(x_g, k_T^g) = [\pi Q_s^2(x_g)]^{-1} \, exp(-k_T^{g\,2}/Q_s^2(x_g))\, , Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$ [1]

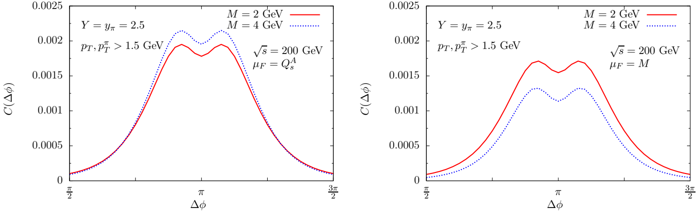
- KKP fragmentation function $D_{h/f}(z_h, \mu_F^2)$ of a quark with a flavor f into a neutral pion $h = \pi^0$ was used [2].

[1] $Q_0^2 = 1$ GeV^2, $x_0 = 3.04 \times 10^{-4}$, $\lambda = 0.288$ and $\sigma_0 = 23.03$ mb were obtained from the fit to the DIS data.

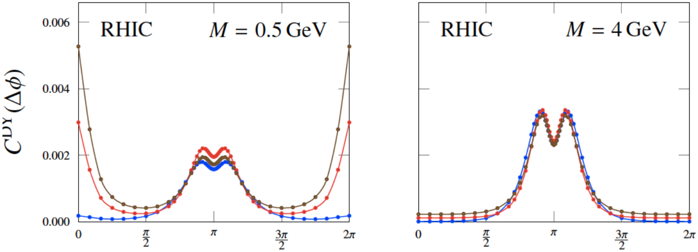
[2] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, 514 (2000).

γ^*-π azimuthal correlations in dAu @ RHIC

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



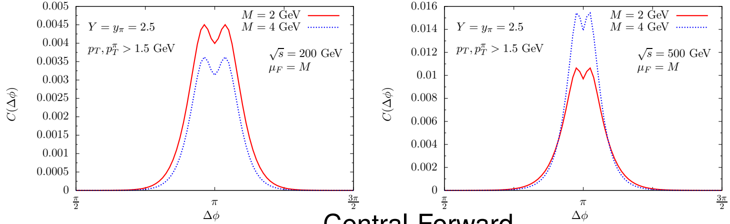
A. Staśto et al., Nucl. Phys. A 904-905, 837c (2013)



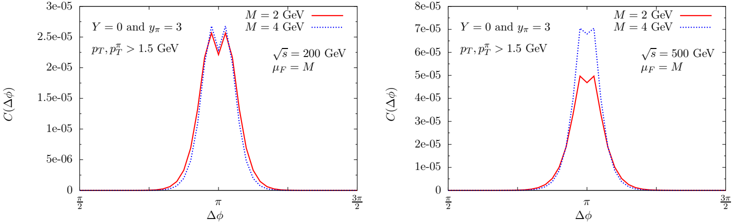
- Similarly to Staśto *et al.* the away-side double-peak structure shows up in dAu.
- Independently of the factorization scale μ_F choice $\Rightarrow$ it is expected also for pp.

γ^*-π azimuthal correlations in pp @ RHIC energies

Forward-Forward



Central-Forward

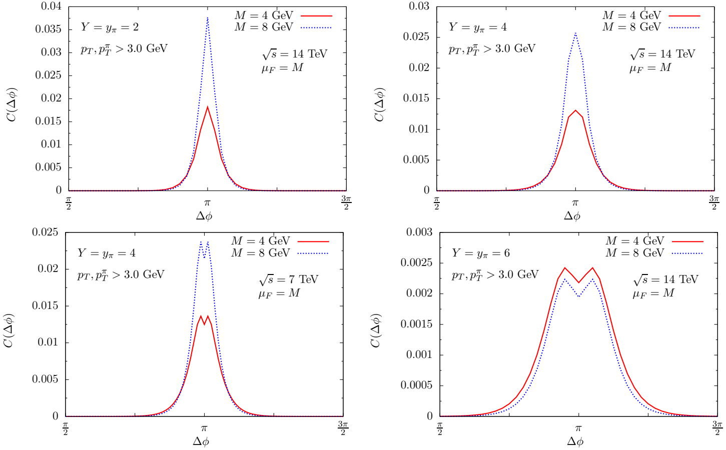


E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

- Away-side double-peak present also in pp collisions at RHIC.
- Shows up both in Fwd-Fwd and Centr-Fwd correlations $\Rightarrow$ measurable!
- Centr-Fwd correlations are by two orders in magnitude smaller than Fwd-Fwd.

γ^*-π azimuthal correlations in pp @ LHC energies

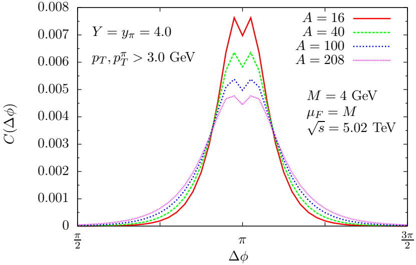
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



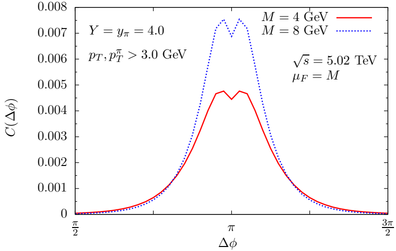
For γ^* and π close to the phase space limit double peak emerges also in *pp* @ LHC.

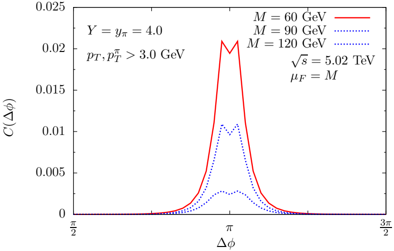
γ^*-π azimuthal correlations in pA @ LHC energies

E. Basso *et. al.*, Phys. Rev. D **93**, 094027 (2016)



With increasing *A* the away-side peak is suppressed.





In pPb a double-peak structure shows up also for the large invariant masses.

Dipole Color Singlet Model of Quarkonium Production*

*) For color dipole description of open heavy flavor production see J. Raufeisen and J.-C. Peng Phys. Rev. D **67**, 054008 (2003)

Heavy quark pair production in the dipole framework

- Replacing virtual photon with gluon one can try to describe process $G_a + p\ (A) \to q\bar{q}$, $(q = c, b, t;\ a = 1, \ldots, 8)$ as a splitting $G \to q\bar{q}$ into dipole in the color background field of the target proton (nucleus).
- In Born approximation dominant contribution to inclusive production, both in open charm and P-wave quarkonia production channels, are:

$$\frac{d\sigma(Gp \to q\bar{q}+X)}{d\ln\alpha} = \int d^2\rho\ |\Psi_{q\bar{q}}(\alpha,\rho)|^2\ \sigma^p_{q\bar{q}}(\alpha\rho, x)$$

$\Psi_{q\bar{q}}(\alpha,\rho)$ – LC wavefunction giving rate of $G \to q\bar{q}$, can be calculated perturbativelly:

$$|\Psi_{q\bar{q}}(\alpha,\rho)|^2 = \frac{\alpha_s}{2\pi^2}\left[m_q^2 K_0^2(m_q\rho) + (\alpha^2 + (1-\alpha)^2) K_1^2(m_q\rho)\right]$$

$\sigma^p_{q\bar{q}}$ – dipole cross section for inclusive (singlet + octet) $q\bar{q}$ production (GBW form):

$$\sigma^p_{q\bar{q}} = \sum_{S=1^-,8^\pm} \sigma_3^S = \frac{9}{8}\left[(\sigma_{q\bar{q}}(\alpha\rho) + \sigma_{q\bar{q}}((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(\rho)$$

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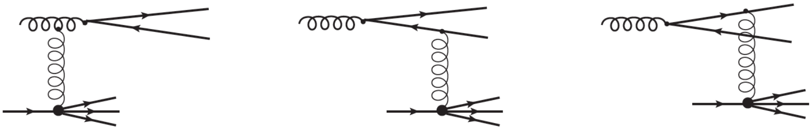

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Dipole Color Singlet Model of $pp \to \{q\bar{q}\}_{1^+} + X$

- In the dipole picture incoming gluon moves along the z-axis.
  $\Rightarrow$ use collinear gluon PDF $xg(x, \mu^2)$ with $k_\perp$-distribution of projectile gluon implicitly integrated out (B. Kopeliovich *et al.*, Nucl. Phys. A **696**, 669 (2001)):

$$\frac{d\sigma^{pp}_{incl}}{dYd\alpha} = x_1 g(x_1, \mu^2) \frac{d\sigma(Gp \to q\bar{q} + X)}{d\alpha}, \ \mu^2 \approx M^2_{q\bar{q}} = \frac{m_q^2 + k_{12}^2}{\alpha(1-\alpha)}$$

  $\Rightarrow$ p_T-distribution of heavy quarkonia is generated by ISR and FSR only.

- LO contribution to C-odd S-wave quarkonium production is due to extra gluon emission off the produced heavy quark $q\bar{q}$ pair state (to produce $\{q\bar{q}\}_{1^+}$ state at least 3 gluons need to be coupled to the quark line).

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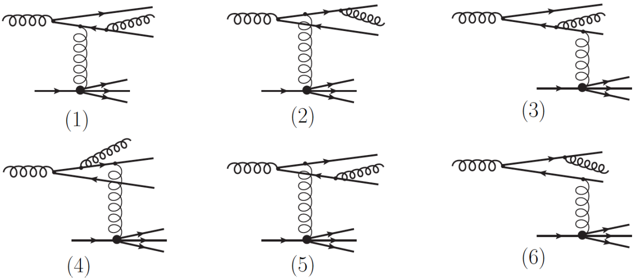
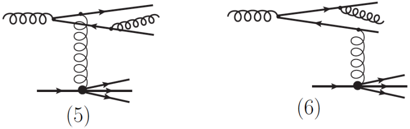


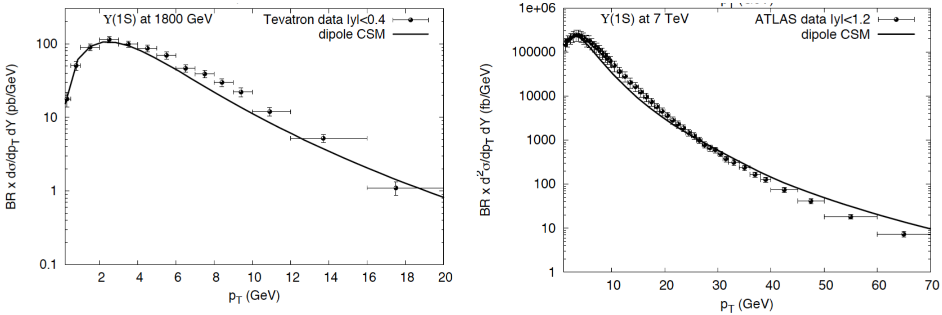
Color-singlet production in association with a gluon

- For S-wave quarkonia (e.g. J/ψ, $\psi(2S)$ and Υ) higher Fock states, e.g. $G + G \to q\bar{q} + G$ need to be included.
- Diagrams (5) and (6) with real gluon emission off a quark different from that coupled to the t-channel gluon are suppressed:



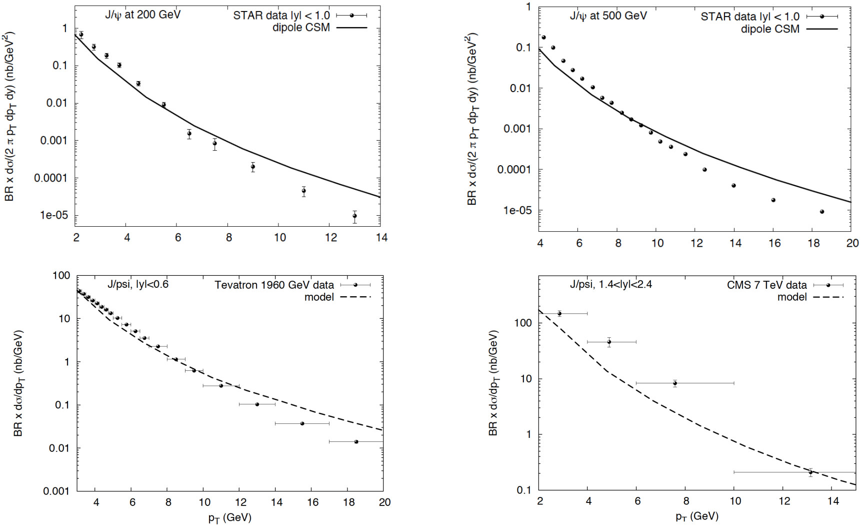
- Momentum transferred by color background field of the target proton to collinearly moving gluon with $k_{1\perp} = 0$ is predominantly longitudinal one (exchanged gluons have typically soft transverse momenta $k_{2\perp} \sim m_g$).
  $\Rightarrow$ in the perturbative limit, by momentum conservation J/ψ transverse momentum $\vec{p}_T \approx -\vec{k}_3$ is close to that of the radiated gluon $k_3 \gg m_g$.

$\Rightarrow$ Transverse momentum correlation between S-wave quarkonium and (semi-hard) hadron from the fragmentation of the third gluon.



$d\sigma/dp_T dY$ - spectra of $\Upsilon(1s)$ at mid-rapidity, from Tevatron (left) and LHC (right).
CDF: Phys.Rev.Lett. 88 (2002) 161802, ATLAS: arXiv:1211.7255 [hep-ex]

J/ψ production in pp collisions (preliminary results)



Transverse momentum spectra of J/ψ at mid-rapidity, from RHIC (top), Tevatron (bottom left) and LHC (bottom right).
CDF: Phys. Rev. Lett. 79, 572 (1997), CMS:arXiv:1111.1557 [hep-ex], STAR: arXiv:1208.2736 [nucl-ex]

Conclusions and Outlook

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- The color dipole description of DY production of gauge bosons and quarkonia was presented and its sensitivity to different parametrizations of $\sigma_{q\bar{q}}(\rho, x)$ was studied.

- Dilepton - hadron azimuthal correlation reveals a double peak structure on the away side $\Delta\phi = \pi$ in both pA and pp collisions at the LHC as well as at RHIC.

- Parameter-free calculations of J/ψ and Υ differential transverse momentum cross section performed within dipole CSM approach provide substantial improvement over previous CS NLO calculations.

- Further test of the model will come from expected quarkonim–(semi-hard) hadron correlation.

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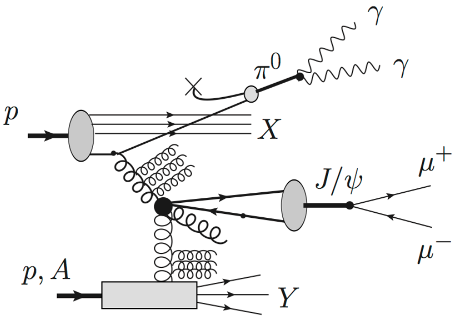
Outlook

- Color dipole approach was also used to study high-p_T suppression of forward hadrons at RHIC: J. Nemchik, *et al.*, Phys. Rev.C 78, 025213(2008) J. Nemchik, M. Š., Nucl. Phys. A 830, 611C (2009), PoS ICHEP2010 (2010) 354

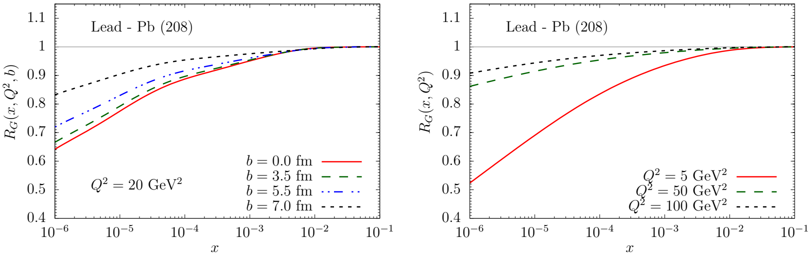


- Joining forward hadron with mid-rapidity quarkonium production $\Rightarrow$ forward-central correlations in pp and pA – feasible at RHIC
- New class of measurements will reduce backgrounds and uncertainties in quarkonium production in pp/pA; allows to test h.o. effects in pQCD and disentangle them from e.g. CGC and other multi-particle effects.

Back up slides

Color dipole description of pA collisions

- $\sigma^N_{q\bar{q}}(\rho, x) \to \sigma^A_{q\bar{q}}(\rho, x) = 2 \int d^2b \left[1 - \exp\left(-\frac{1}{2} T_A(\mathbf{b}) \sigma^N_{q\bar{q}}(\rho, x)\right)\right]$
- Gluon shadowing: $\sigma^N_{q\bar{q}}(\rho, x) \to \sigma^N_{q\bar{q}}(\rho, x)\, R_G(x, Q^2, \mathbf{b})$ leads to additional nuclear suppression in production of DY pairs at small x in the target. R_G - ratio of the gluon densities in nuclei and nucleon - was derived in [1]



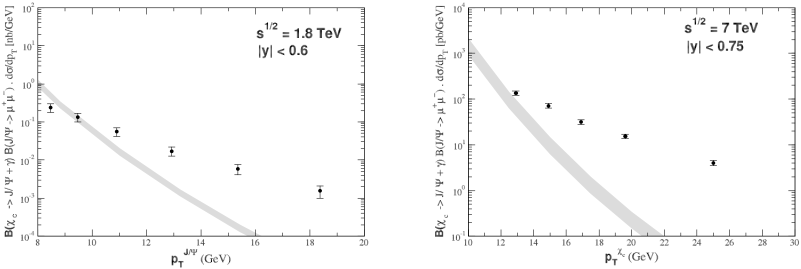
- Initial-state energy loss suppression of nuclear PDFs at the kinematical limits [2]:

$$q_f(x, Q^2) \to q_f^A(x, Q^2, b) = C_v\, q_f(x, Q^2)\, \frac{e^{-\xi \sigma_{\rm eff} T_A(b)} - e^{-\sigma_{\rm eff} T_A(b)}}{(1-\xi)(1 - e^{-\sigma_{\rm eff} T_A(b)})}$$

[1] B.Z. Kopeliovich *et al.* Phys. Rev. **D62**, 054022 (2000); ibid C**65**, 035201 (2002), J. Phys. G**35**, 115010 (2008).

[2] B.Z. Kopeliovich *et al.* Phys. Rev. C**72**, 054066 (2005); Int. J. Mod. Phys. E**23**, 1430006 (2014).

$pp \to \chi_c \to J/\psi$ (preliminary results)



Transverse momentum spectra of J/ψ at mid-rapidity, Tevatron (left) and LHC (right).
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p+A Collisions in Short and Long Coherence Limits

B.Z.Kopeliovich, J. Nemchik, A. Schäffer and A.V. Tarasov, Phys.Rev.Lett. 88,232303(2002)

$\ell_c \equiv \sqrt{s}/(m_N k_T)$ k_T – transverse momentum of produced parton

Short coherence length ($\ell_c \ll R_A$): multiple soft rescatterings of the projectile parton inside A accompanied by the gluon radiation.

$$\sigma_{pA}^{\ell_c \ll R_A}(p_T) = \sum_{i,j,k,l} \tilde{F}_{i/p} \otimes F_{j/A} \otimes \hat{\sigma}_{ij\to kl} \otimes D_{h/k}$$

$F_{i/p}(x_1, k_T)$, $F_{j/A}(x_2, k_T)$ – PDF of p,A. The tilde stands for PDF modification due to (non-factorizable) momentum broadening and energy loss.

Long coherence length ($\ell_c \gg R_A$): hard fluctuation in the incident proton containing a high-p_T parton propagates through the whole nucleus and is freed by the interaction.

$$\sigma_{pA}^{\ell_c \gg R_A}(p_T) = F_{G/p} \otimes \sigma(GA \to G_1 G_2 X) \otimes D_{h/G_1}$$

The high-p_T hadrons originate mainly from radiated gluons.

Kinematical variables of the DY process

- In the target rest frame, the DY process looks like fragmentation of a projectile quark into a dilepton via bremsstrahlung of a heavy photon.
- Standard kinematic variables are $x_1 = \frac{2\,P_2 \cdot p}{s}$, $x_2 = \frac{2\,P_1 \cdot p}{s}$ where P_1, P_2 and p are the four-momenta of the beam, target and the photon, respectively, $s = (P_1 + P_2)^2$ and $p^2 = M^2 \equiv M^2_{\ell\bar{\ell}}$.
- Using: $\tau \equiv x_1\,x_2 = \frac{p_T^2 + M^2}{s}$ and $x_F = x_1 - x_2 = 2\,p_L/\sqrt{s}$, where p_L is the longitudinal momentum of the photon, one can express kinematic variables x_1 and x_2:

$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\,\tau} + x_F\right) \qquad x_2 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\,\tau} - x_F\right)$$

$\Rightarrow$ at fixed p_T, x_1 rises with x_F.

Coherence length of the DY process

$$\ell_c \equiv \frac{1}{q_L} = \frac{2E_q\alpha(1-\alpha)}{p_T^2+(1-\alpha)M_{\bar{\ell}\ell}^2+\alpha^2 m_q^2} \approx \frac{s(1-\alpha)x_1}{m_N[p_T^2+(1-\alpha)M_{\bar{\ell}\ell}^2]}$$

where

- p_T and α are transverse momentum and the fraction of the light-cone momentum of the quark carried our by the dilepton
- $M_{\bar{\ell}\ell}$ is dilepton invariant mass
- $E_q = \frac{s}{2m_N}x_q$ and m_q are the energy and mass of the projectile valence quark
- x_q is fraction of the proton momentum carried out by the valence quark: $\alpha x_q = x_1$
- $q_L = \frac{M_{q\bar{\ell}\ell}^2 - m_q^2}{2E_q}$ is the longitudinal momentum transfer.