

Heavy quark pair production and parton saturation in pA collisions at the LHC

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work in collaboration with H.Fujii

Low-x Meeting, Kyoto, Japan
June 17 2014

H.Fujii and K.W, Nucl.Phys.A 915, 1 (2013),
Nucl.Phys.A 920, 78 (2013).

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$$Q_{sA}^2(x) \sim A^{1/3} \left(\frac{0.01}{x} \right)^{0.3} \Lambda_{\text{QCD}}^2 \gg \Lambda_{\text{QCD}}^2$$

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- (1) to evaluate the cold nuclear matter effects quantitatively
- (2) to probe a gluon structure in the heavy nucleus

Predictions and data

- LHC data

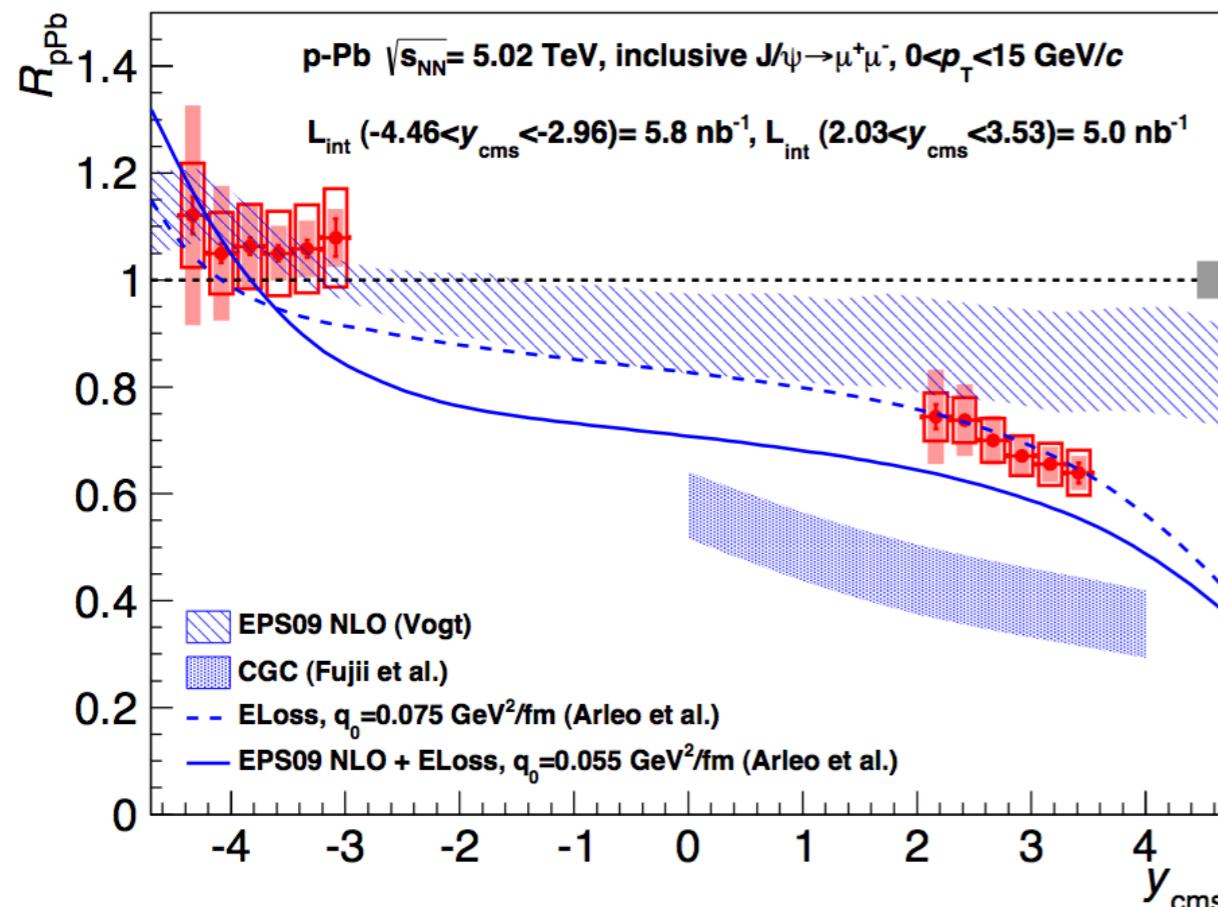


Figure from
ALICE Collab. JHEP 1402 (2014) 073.

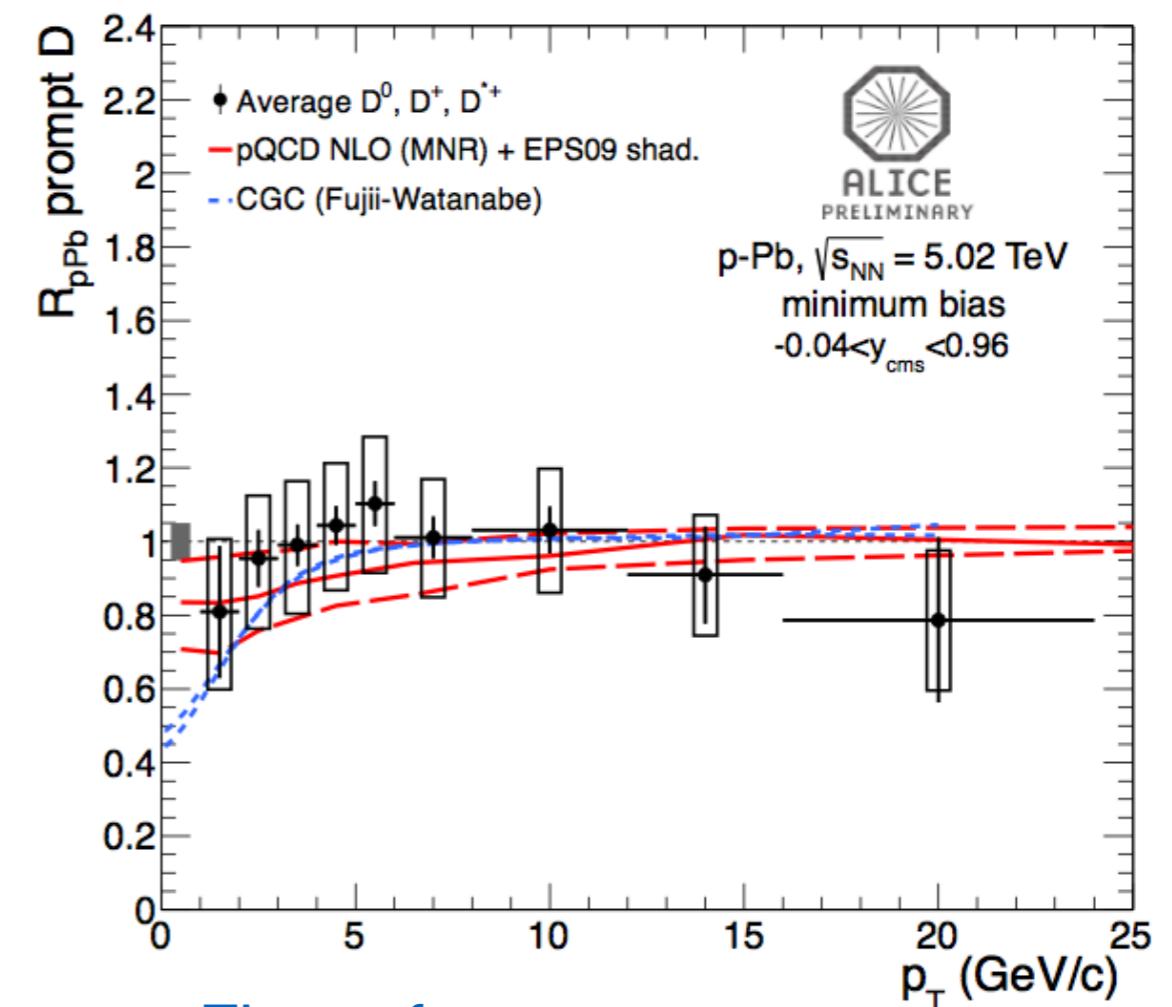


Figure from
ALICE Collab. arXiv:1310.1714

Plan

1. Gluon distribution at small-x
2. Quark pair production from the CGC
3. Results: Quarkonium and open heavy flavor

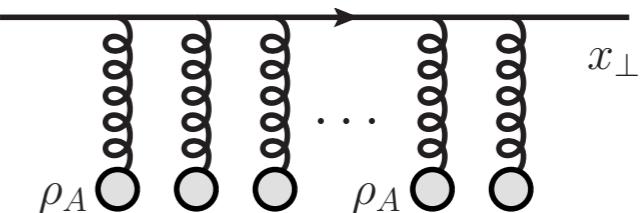
Unintegrated gluon distribution

$$\phi_{A,Y}^{g,g}(k_{2\perp}) = \frac{\pi R_A^2 N_c k_{2\perp}^2}{4\alpha_s} \int \frac{d^2 k_\perp}{(2\pi)^2} \tilde{S}_Y(k_\perp) \tilde{S}_Y(k_{2\perp} - k_\perp)$$

$$\tilde{S}_Y(k_\perp) \equiv \int d^2 x_\perp e^{-ik_\perp \cdot x_\perp} [1 - N_Y(x_\perp)]$$

- **Dipole amplitude :** $N_Y(\vec{x}_\perp - \vec{x}'_\perp) \equiv 1 - \frac{1}{N_c} \langle \text{tr}[\tilde{U}(\vec{x}_\perp) \tilde{U}^\dagger(\vec{x}'_\perp)] \rangle_Y$

$$\tilde{U}(x_\perp) = \mathcal{P}_+ \exp \left[-ig^2 \int_{-\infty}^{+\infty} dz^+ \frac{1}{\nabla_\perp^2} \rho_A(z^+, x_\perp) \cdot t \right]$$



- **BK equation : Quantum evolution in large- N_c**

I.Balitsky (1996), Y.V.Kovchegov (1999)

$$\frac{d}{dY} N_Y(\vec{r}_\perp) = \int d\vec{r}_{1\perp} \mathcal{K}(\vec{r}_\perp, \vec{r}_{1\perp}) \left[\underbrace{N_Y(\vec{r}_{1\perp}) + N_Y(\vec{r}_{2\perp}) - N_Y(\vec{r}_\perp)}_{\text{BFKL cascade}} - \underbrace{N_Y(\vec{r}_{1\perp}) N_Y(\vec{r}_{2\perp})}_{\text{Recombination}} \right]$$

- The running coupling evolution kernel I.Balistky (2007)

$$\mathcal{K}_{\text{run}}(\vec{r}_\perp, \vec{r}_{1\perp}) = \frac{\alpha_s(r^2) N_c}{2\pi^2} \left[\frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]$$

- Parametrized initial condition : MV $^\gamma$ model

J.L.Albacete et al. (AAMQS) (2011)

$$Y \equiv \ln \frac{x}{x_0}$$

$$x_0 = 0.01$$

$$N_{Y=0}(r_\perp) = 1 - \exp \left[-\frac{(r^2 Q_{s0,p}^2)^\gamma}{4} \ln \left(\frac{1}{\Lambda r} + e \right) \right] \quad (*\Lambda = 0.241 \text{ GeV})$$

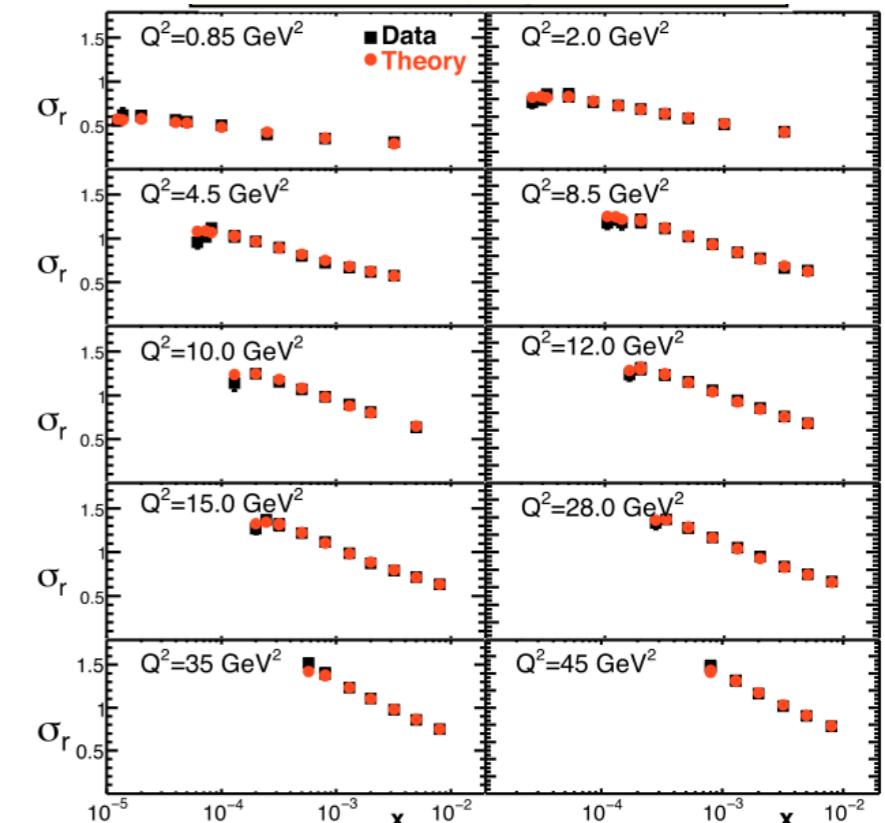
$$\alpha_s(r^2) = \left[b_0 \ln \left(\frac{4C^2}{r^2 \Lambda^2} + a \right) \right]^{-1}$$

$$\alpha_s(r \rightarrow \infty) = \alpha_{fr}$$

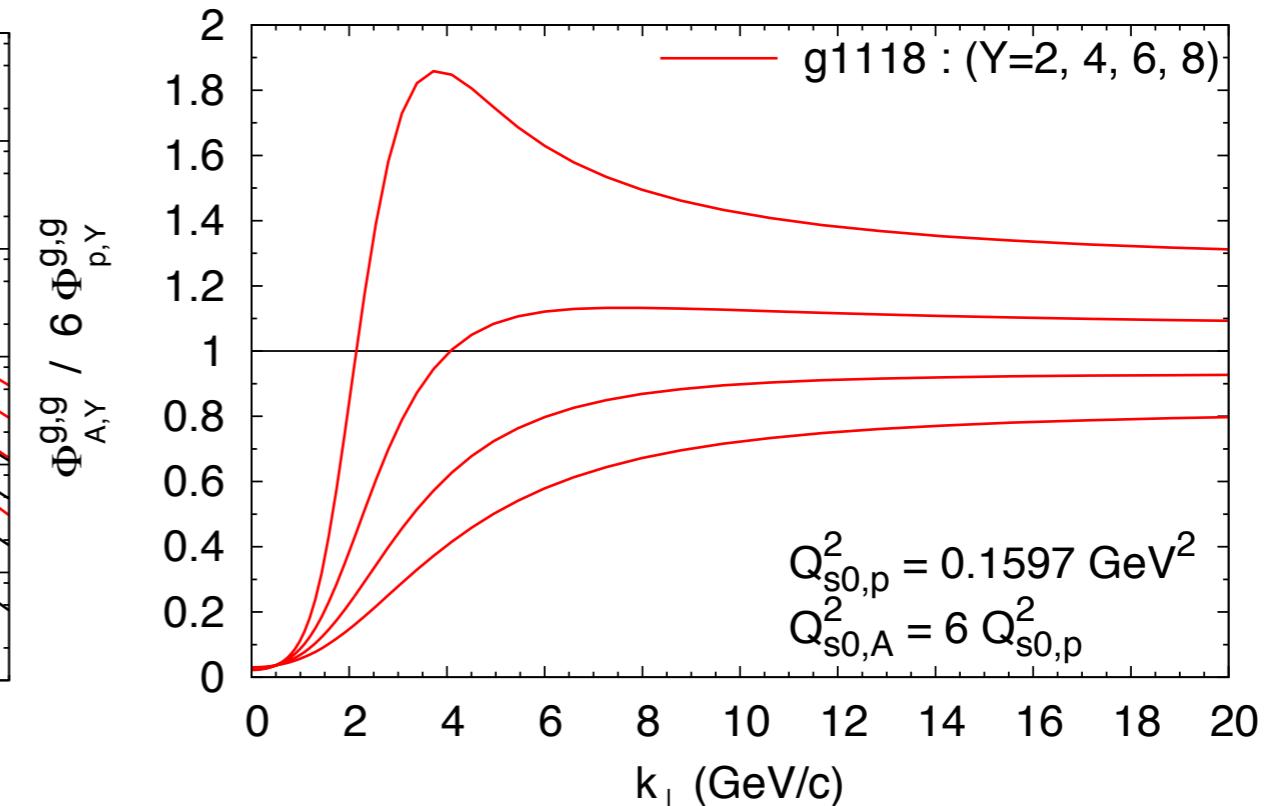
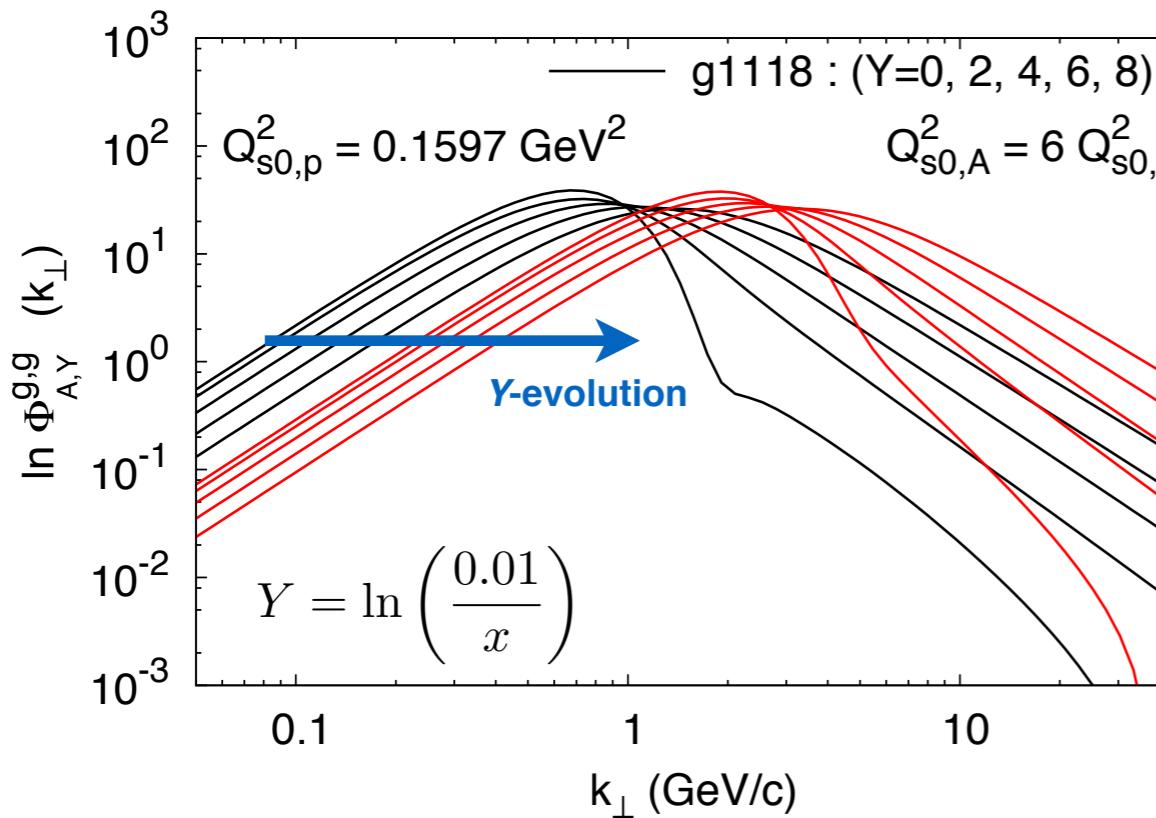
Global fits to DIS data

set	$Q_{s0,p}^2/\text{GeV}^2$	γ	α_{fr}	C	$\chi^2/\text{d.o.f.}$
MV $^\gamma$	0.1597	1.118	1.0	2.47	≈ 1.1

γ controls the steepness of the gluon distribution at higher momentum $k_\perp > Q_{s0,p}$



Quantum evolution of uGDF



$$Q_{s0,A}^2 = A^{1/3} Q_{s0,p}^2$$

- The number of net gluons increases with decreasing in Bjorken'x.
- Low- k_\perp distribution is suppressed by gluon saturation.
- High- k_\perp region is enhanced by gluon radiations.

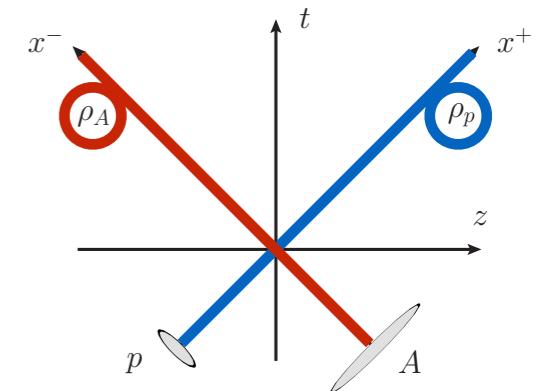
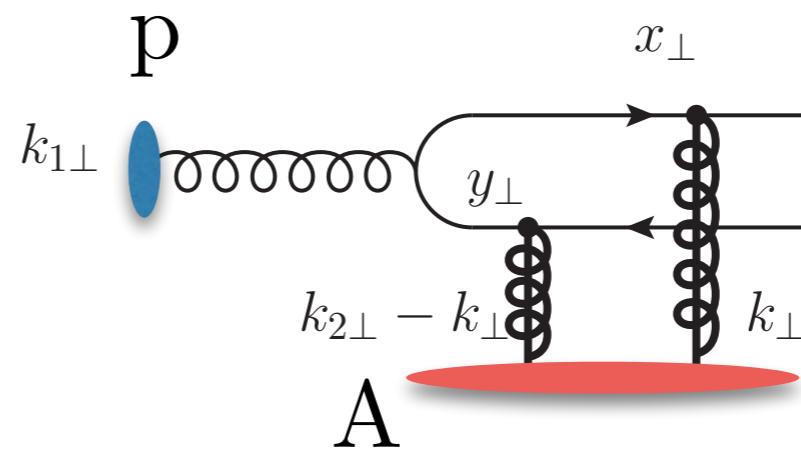
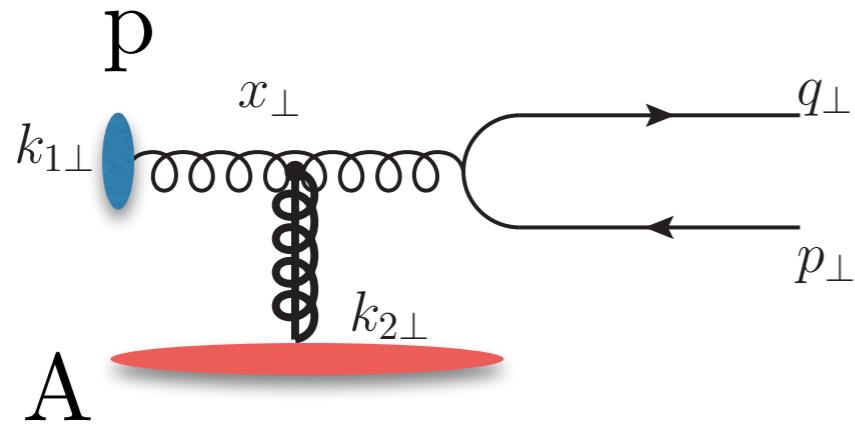
Plan

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Quark pair production

- Production from classical background field at the order $\mathcal{O}(\rho_p^1 \rho_A^\infty)$

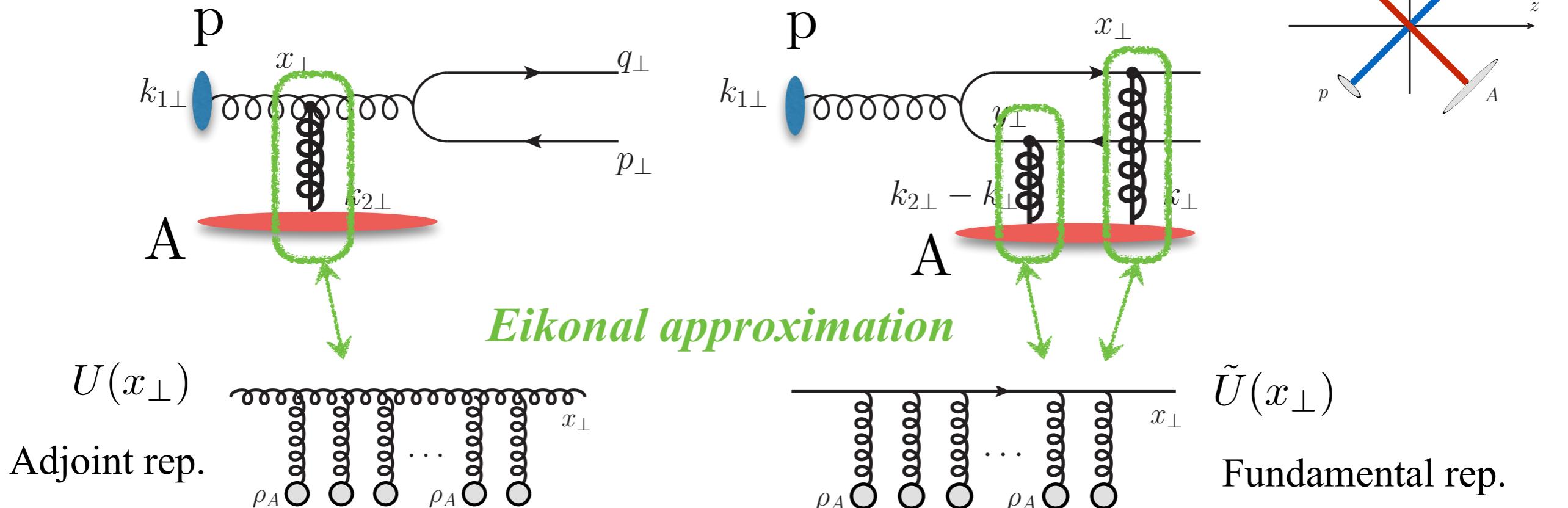
J-P.Blaizot, F.Gelis, R.Venugopalan (2004)



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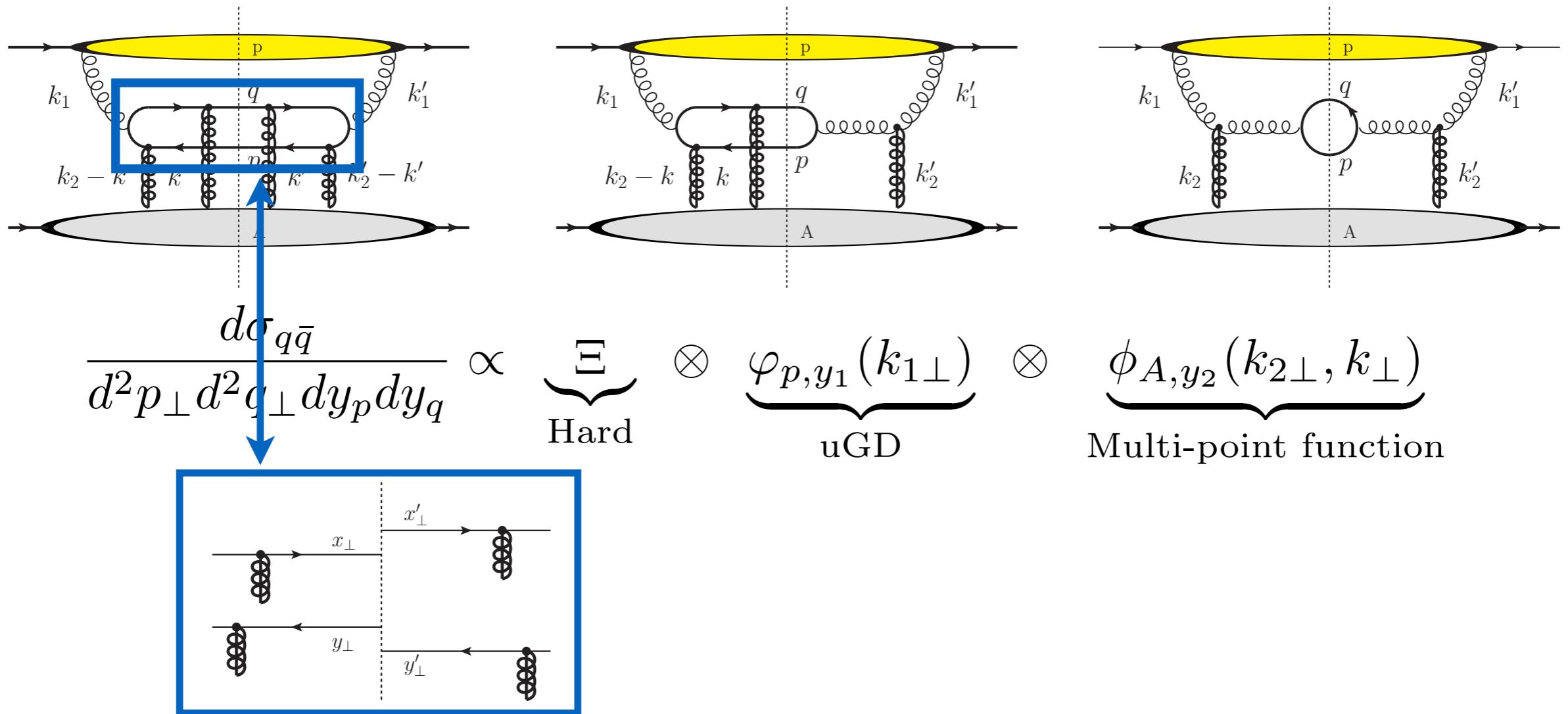
- Multiple scattering before and after the quark pair production.

Multi-point function

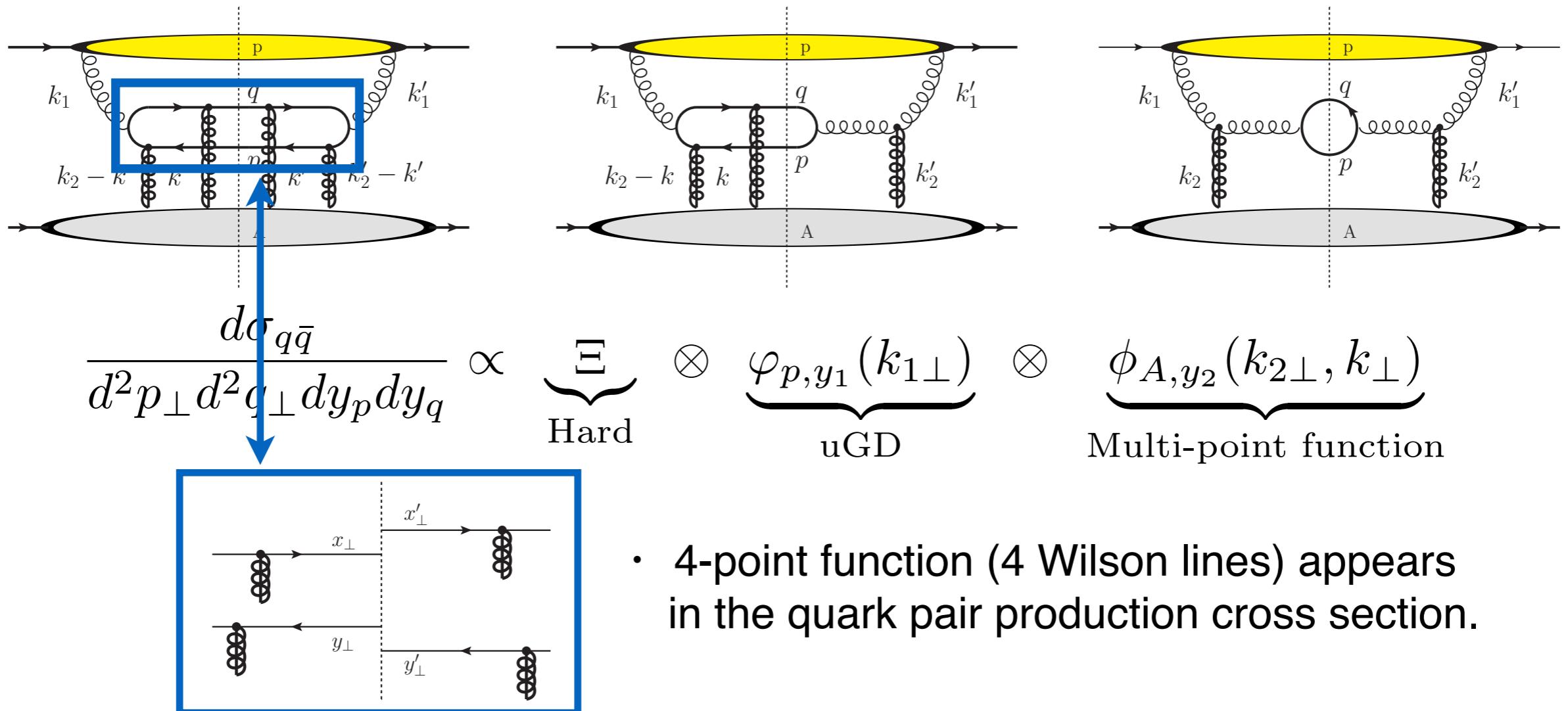
The figure shows three Feynman diagrams illustrating the decomposition of a multi-point function. Each diagram consists of two horizontal lines representing incoming particles and two horizontal lines representing outgoing particles. A central vertical dashed line represents the interaction point. The top diagram is yellow and labeled 'p'. The bottom diagram is grey and labeled 'A'. The left diagram shows a quark-gluon vertex with momenta k_1 , $k_2 - k$, and k . The right diagram shows a gluon-gluon vertex with momenta k_1' , k_2' , and $k'_2 - k'$. The middle diagram shows a quark-gluon vertex with momenta q , p , and k . The bottom diagram shows a gluon-gluon vertex with momenta k_1' , k_2' , and k'_2 .

$$\frac{d\sigma_{q\bar{q}}}{d^2 p_\perp d^2 q_\perp dy_p dy_q} \propto \underbrace{[E]}_{\text{Hard}} \otimes \underbrace{\varphi_{p,y_1}(k_{1\perp})}_{\text{uGD}} \otimes \underbrace{\phi_{A,y_2}(k_{2\perp}, k_\perp)}_{\text{Multi-point function}}$$

Multi-point function

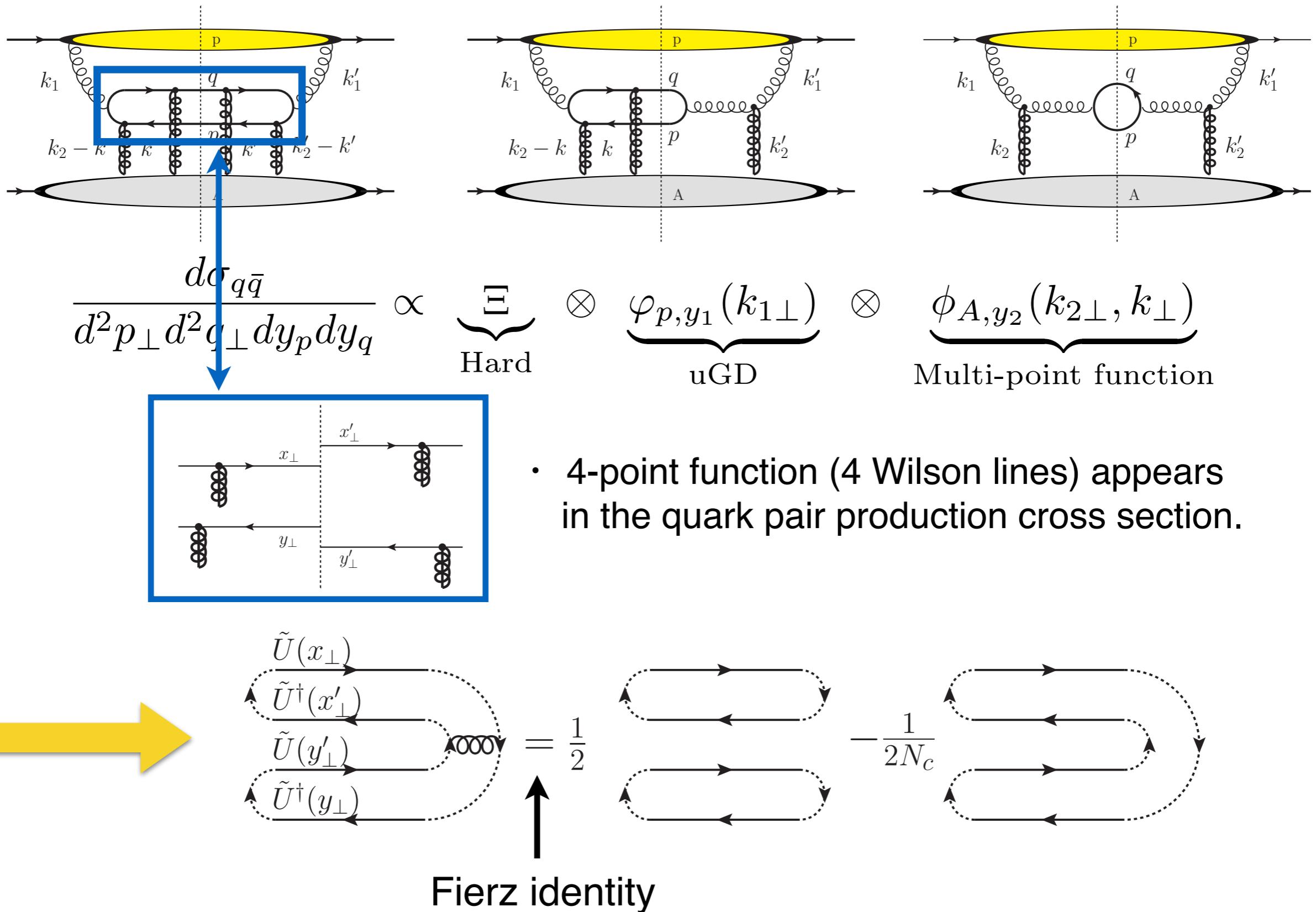


Multi-point function

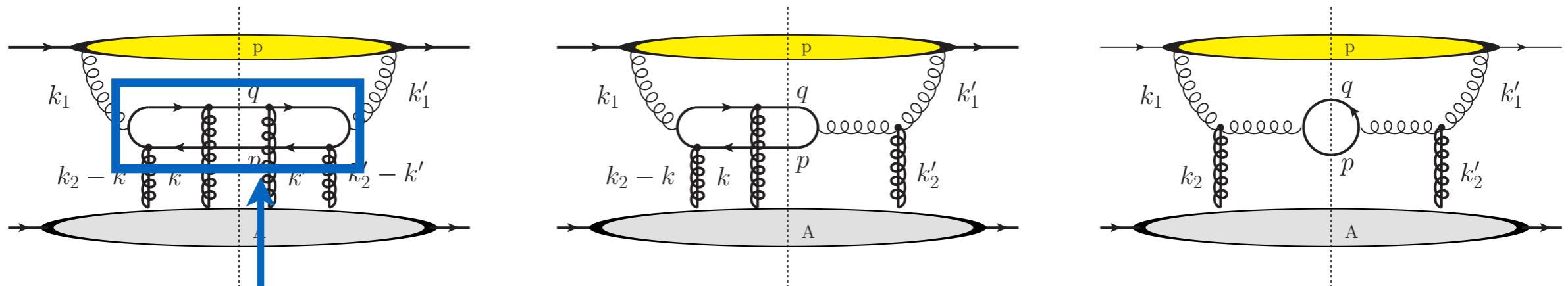


- 4-point function (4 Wilson lines) appears in the quark pair production cross section.

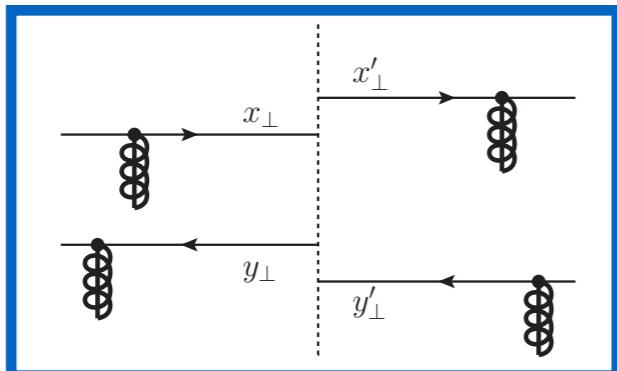
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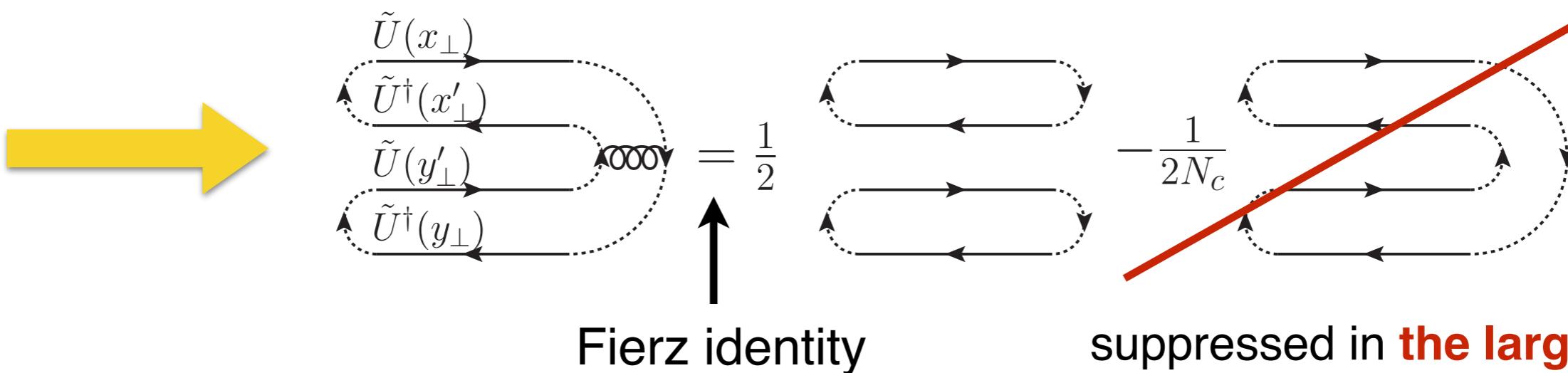
Multi-point function



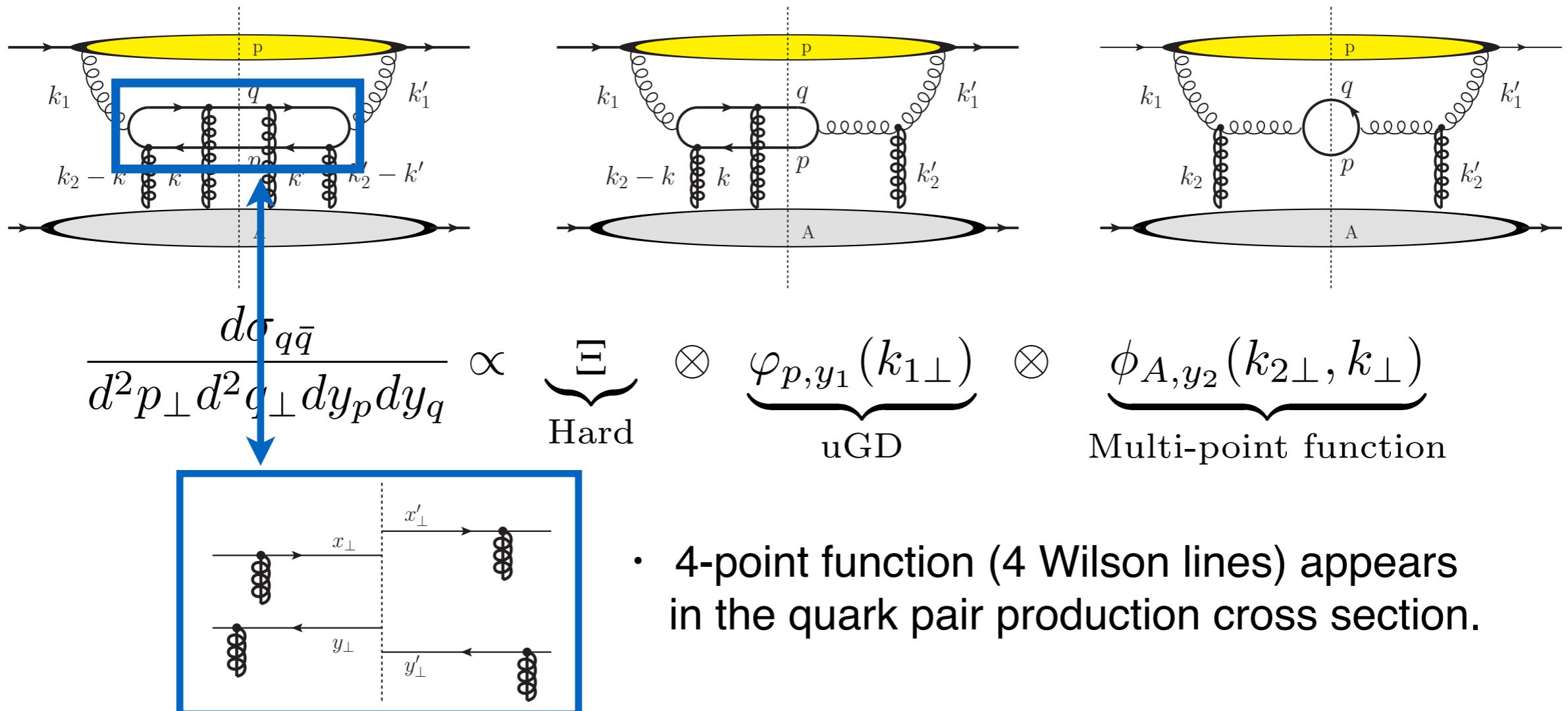
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Multi-point function



Dipole amplitude

A yellow arrow points to the left, indicating the direction of the Fierz identity. The equation is:

$$\tilde{U}(x_\perp) \tilde{U}^\dagger(x'_\perp) \tilde{U}(y'_\perp) \tilde{U}^\dagger(y_\perp) = \frac{1}{2} \left(\text{diagram A} - \frac{1}{2N_c} \text{diagram B} \right)$$

Diagram A is shown with two blue boxes around the gluon lines. Diagram B is shown with a red diagonal line through the gluon loop.

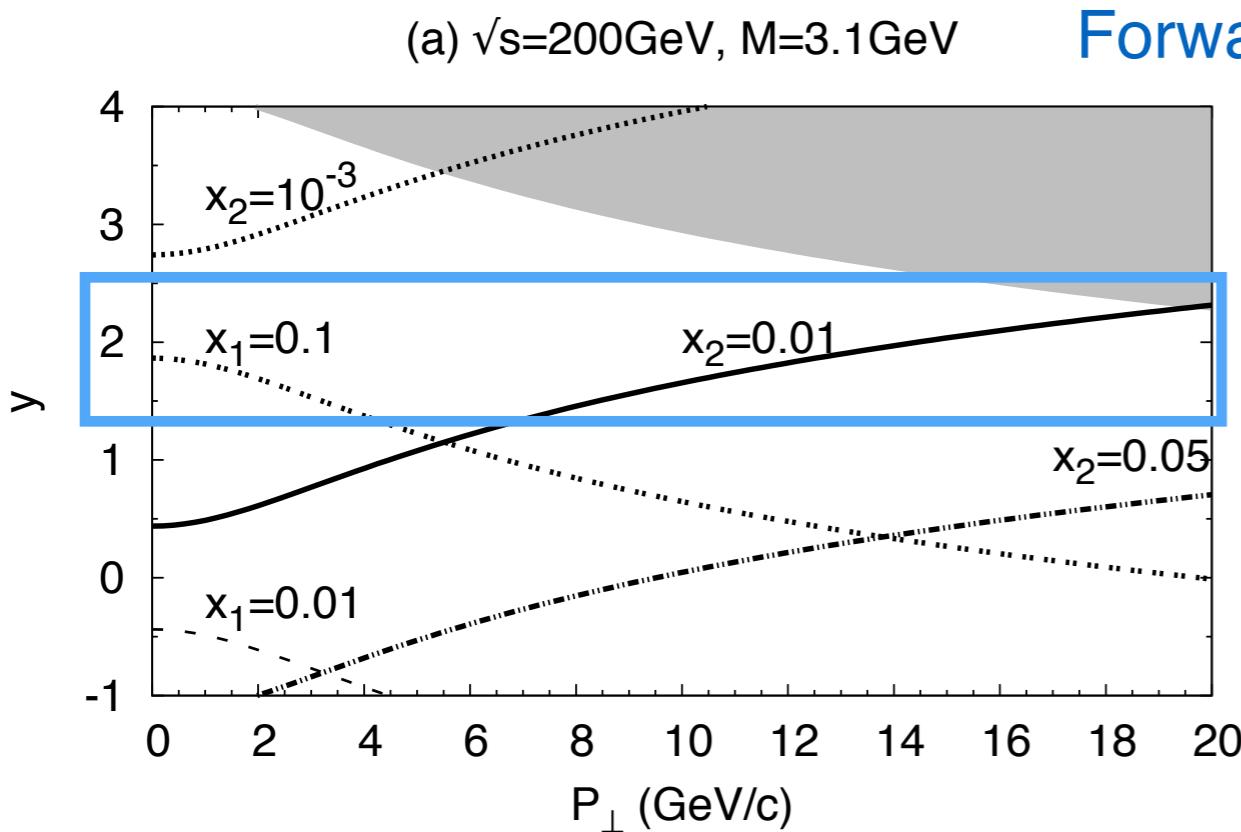
Fierz identity

suppressed in **the large- N_c limit**

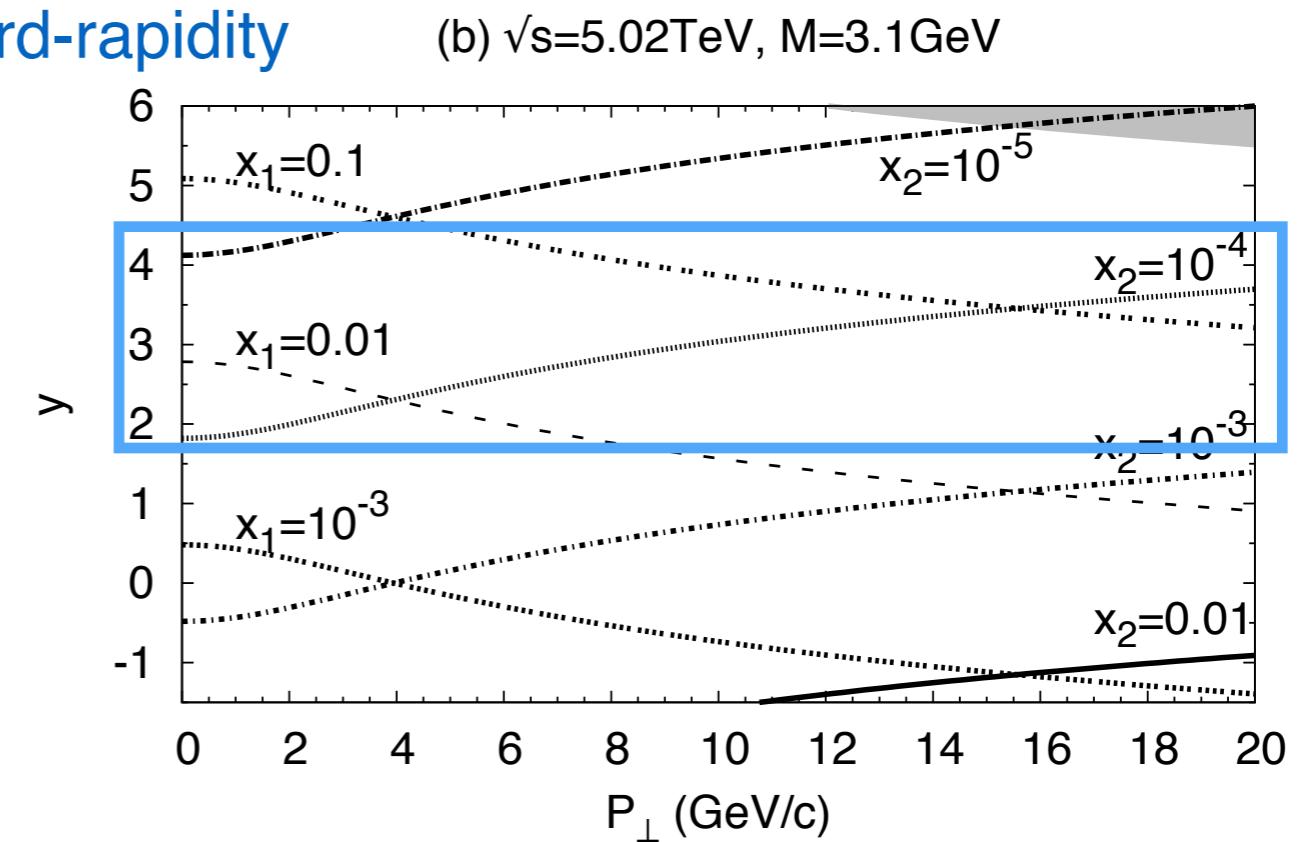
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How low-x?

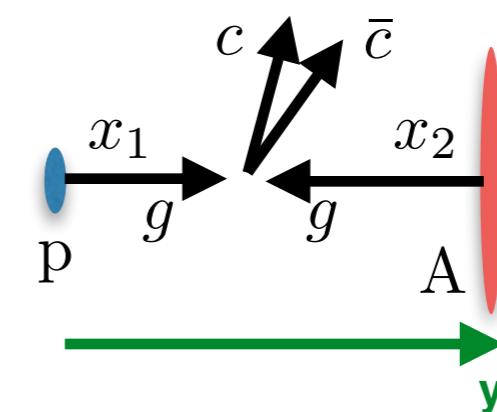


Forward-rapidity



$$x_{1,2} = \sqrt{\frac{M^2 + P_{\perp}^2}{s}} e^{\pm y}$$

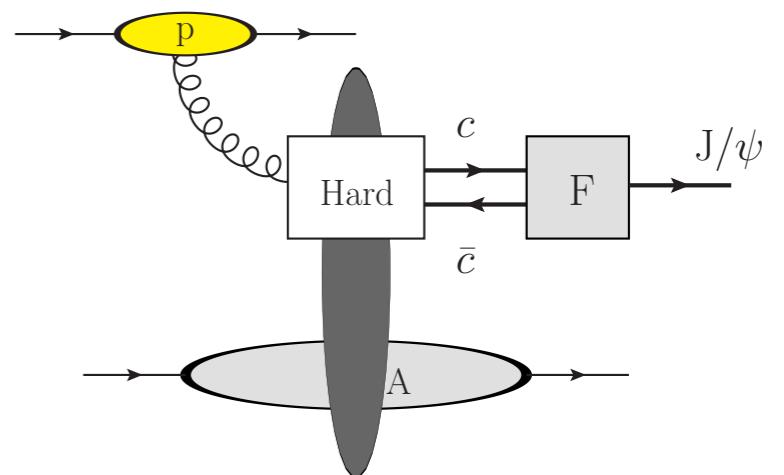
(M : invariant mass of the quark pair)



Quarkonium

- Color evaporation model

$$\frac{d\sigma_{J/\psi}}{d^2 P_\perp dy} = F_{J/\psi} \int_{4m_c^2}^{4M_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{d^2 P_\perp dM^2 dy}$$

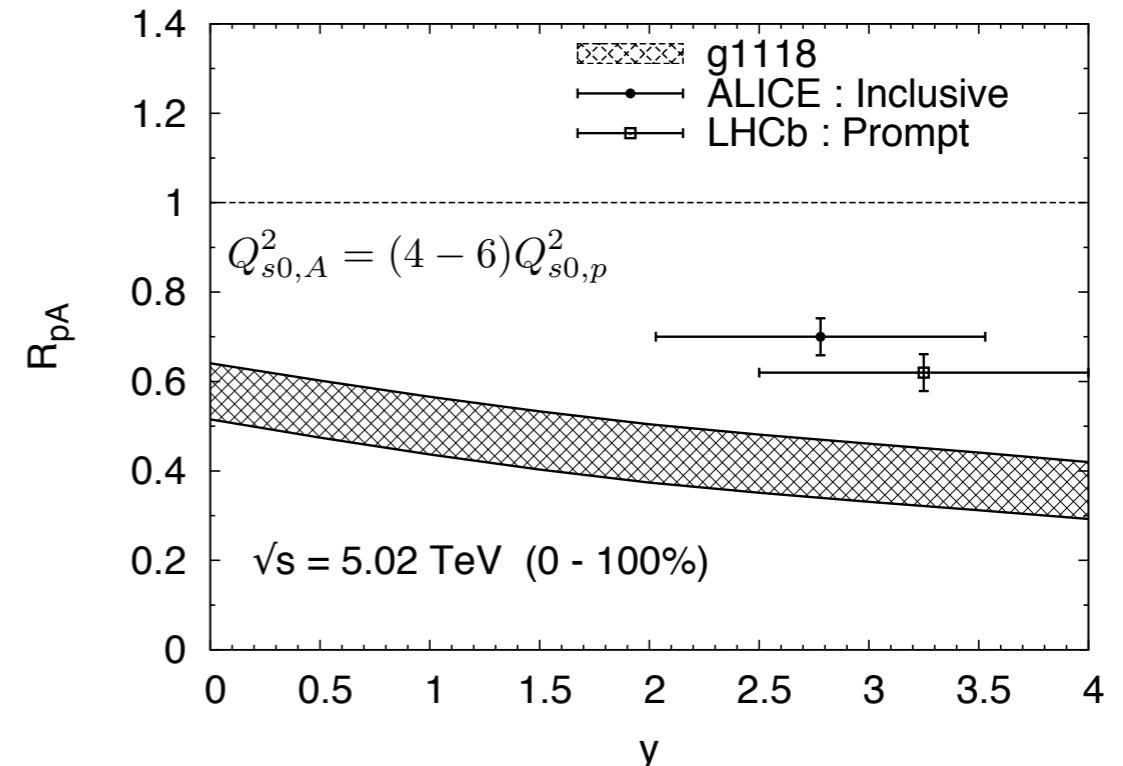
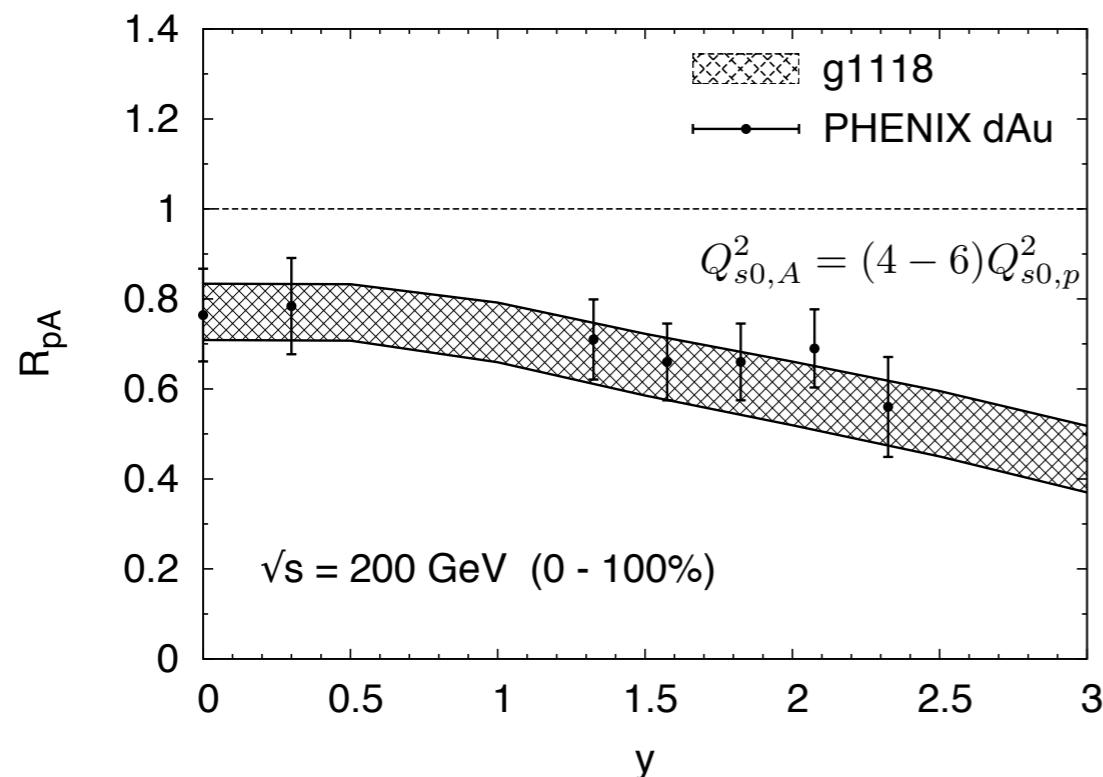


- We assume that the produced quark pair hadronizes outside the nucleus.
- All the quark pair - singlet and octet - makes bound state with constant probability.
- No feed down from excited states in this calculation .

Quarkonium

- Nuclear modification factor

$$R_{pA} = \frac{\frac{dN_{pA}}{d^2 P_\perp dy}}{N_{\text{coll}} \frac{dN_{pp}}{d^2 P_\perp dy}}$$
$$N_{\text{coll}} = A^{\gamma/3}$$

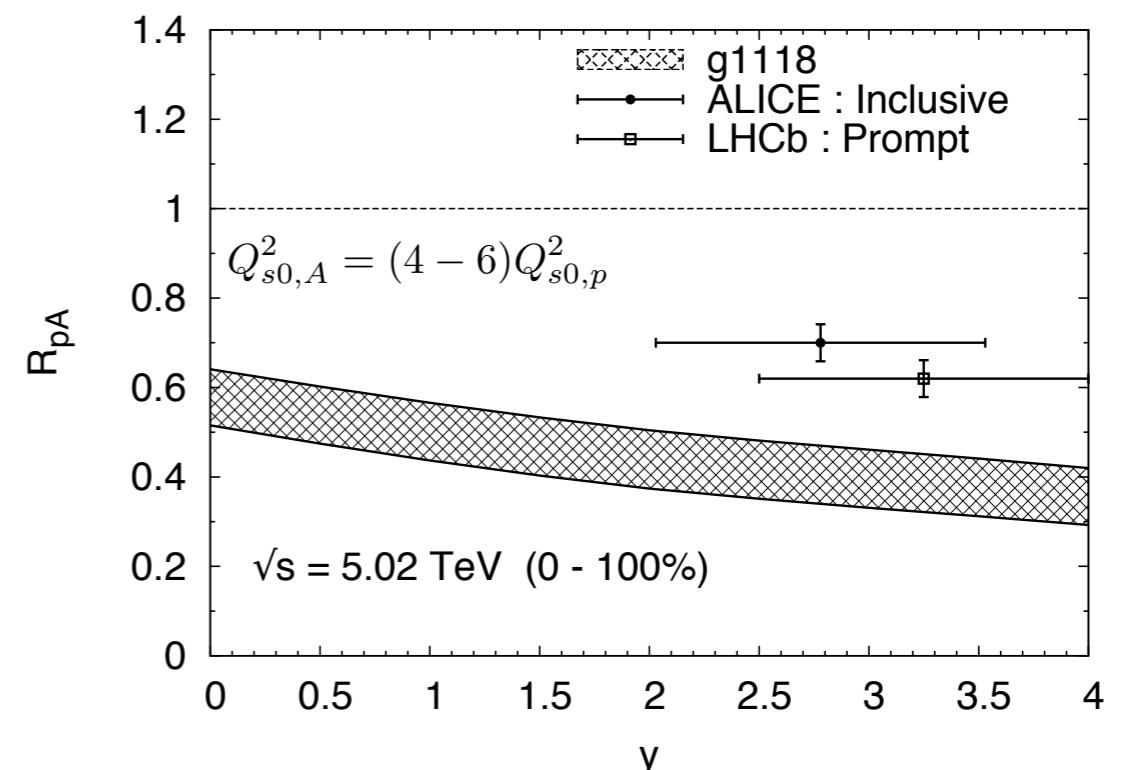
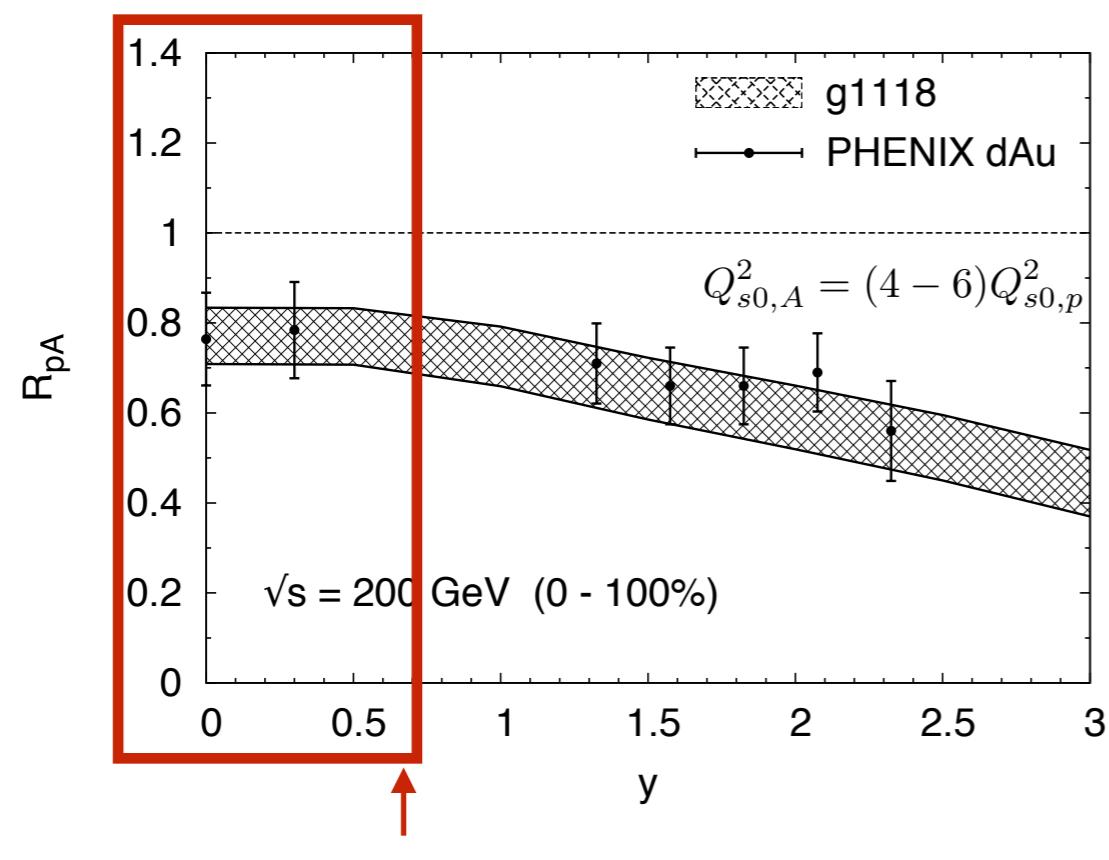


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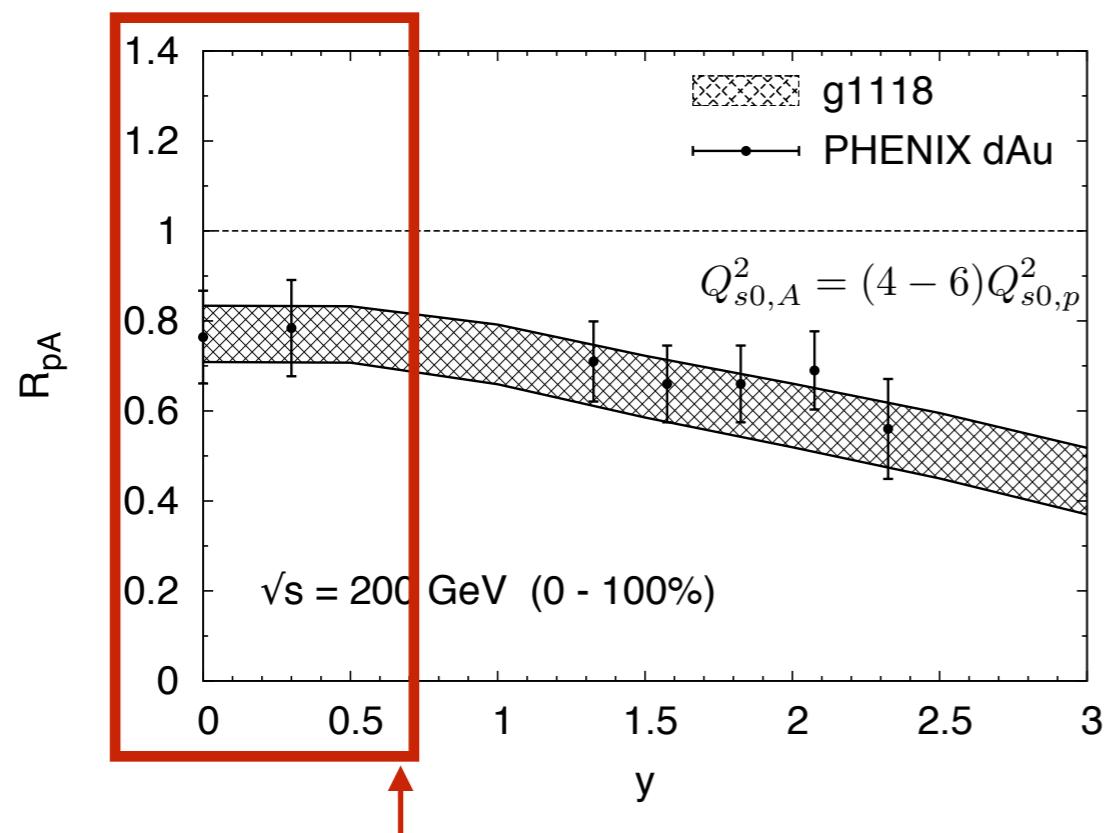
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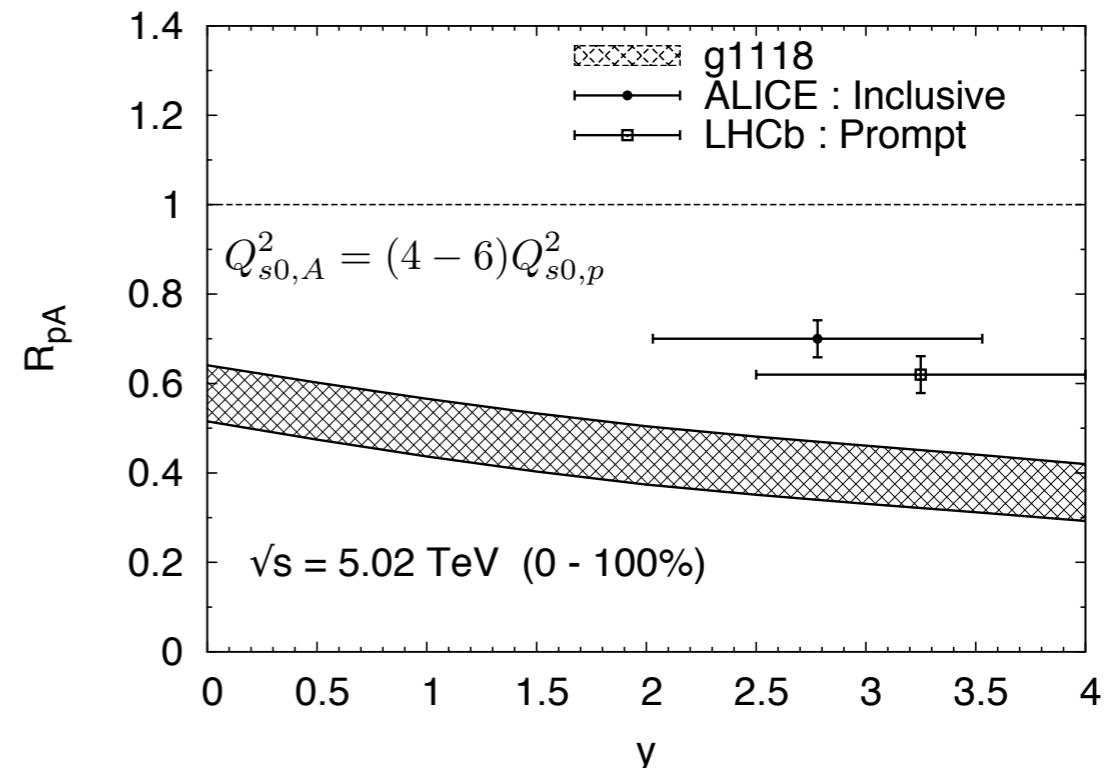
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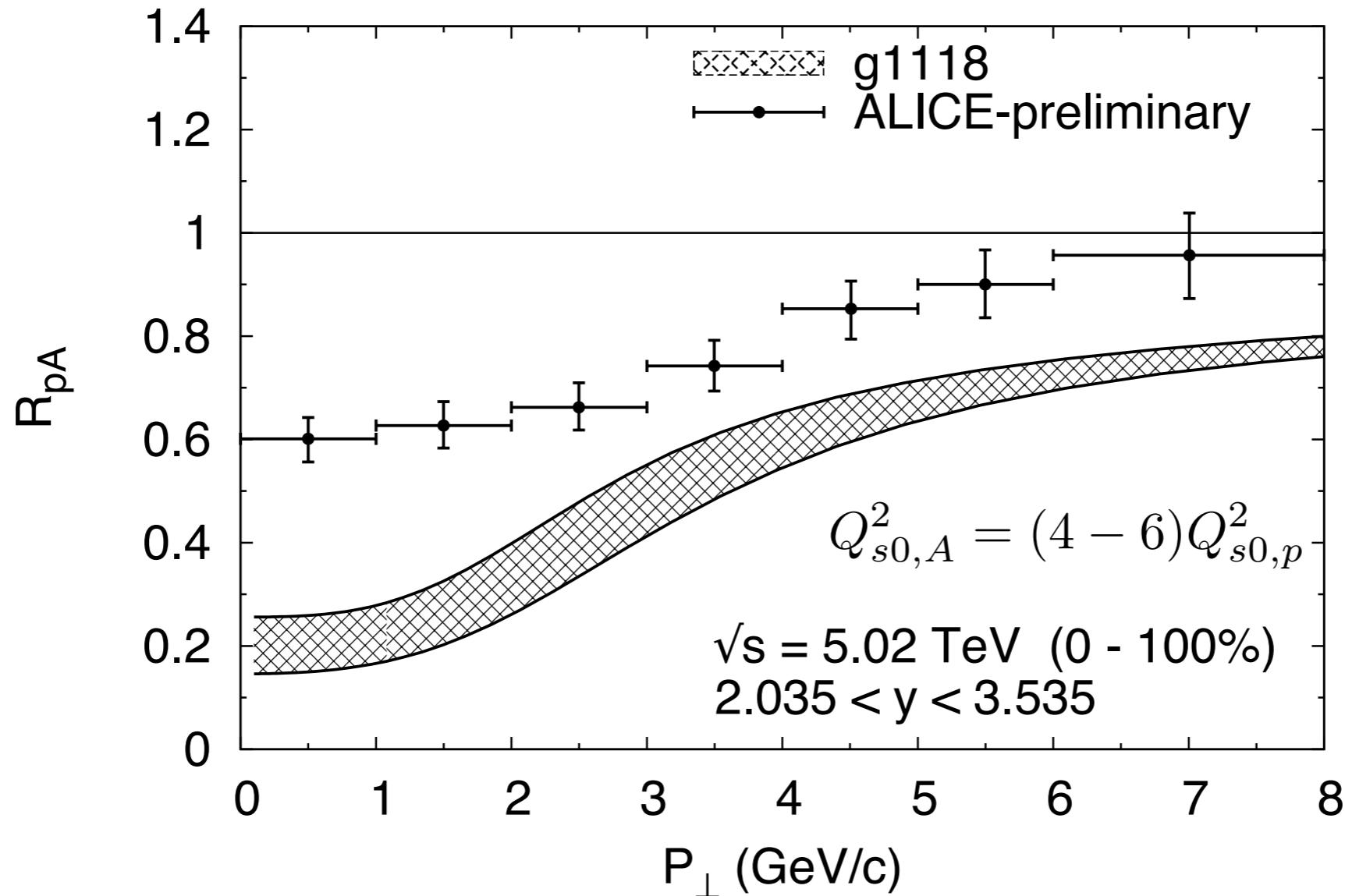


No saturation



- Strong suppression of R_{pA} at the LHC is a naturally result of the quantum evolution.

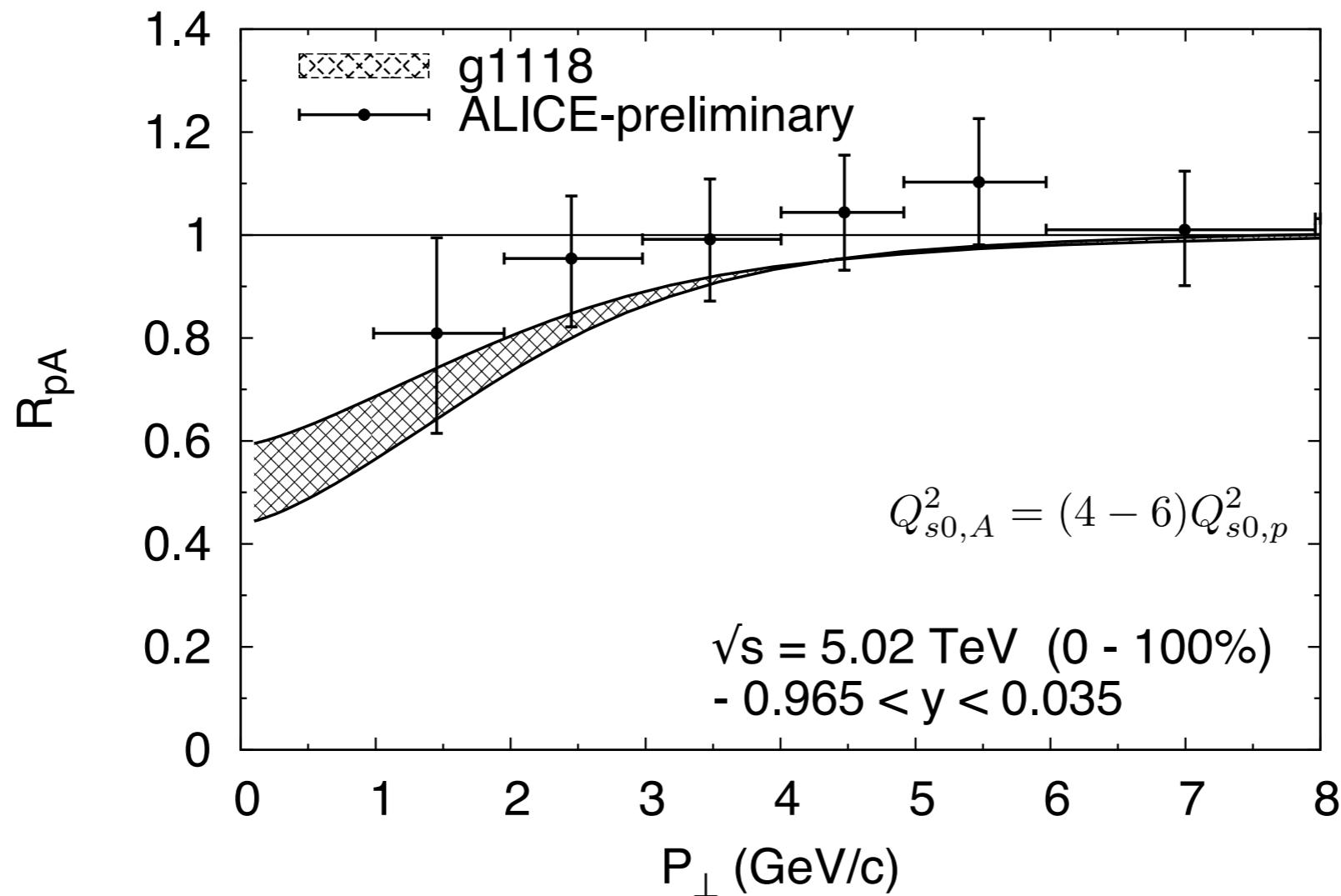
Quarkonium



- Strong suppression due to multiple scattering and saturation is found at small P_{\perp} ; overestimated

Open heavy flavor

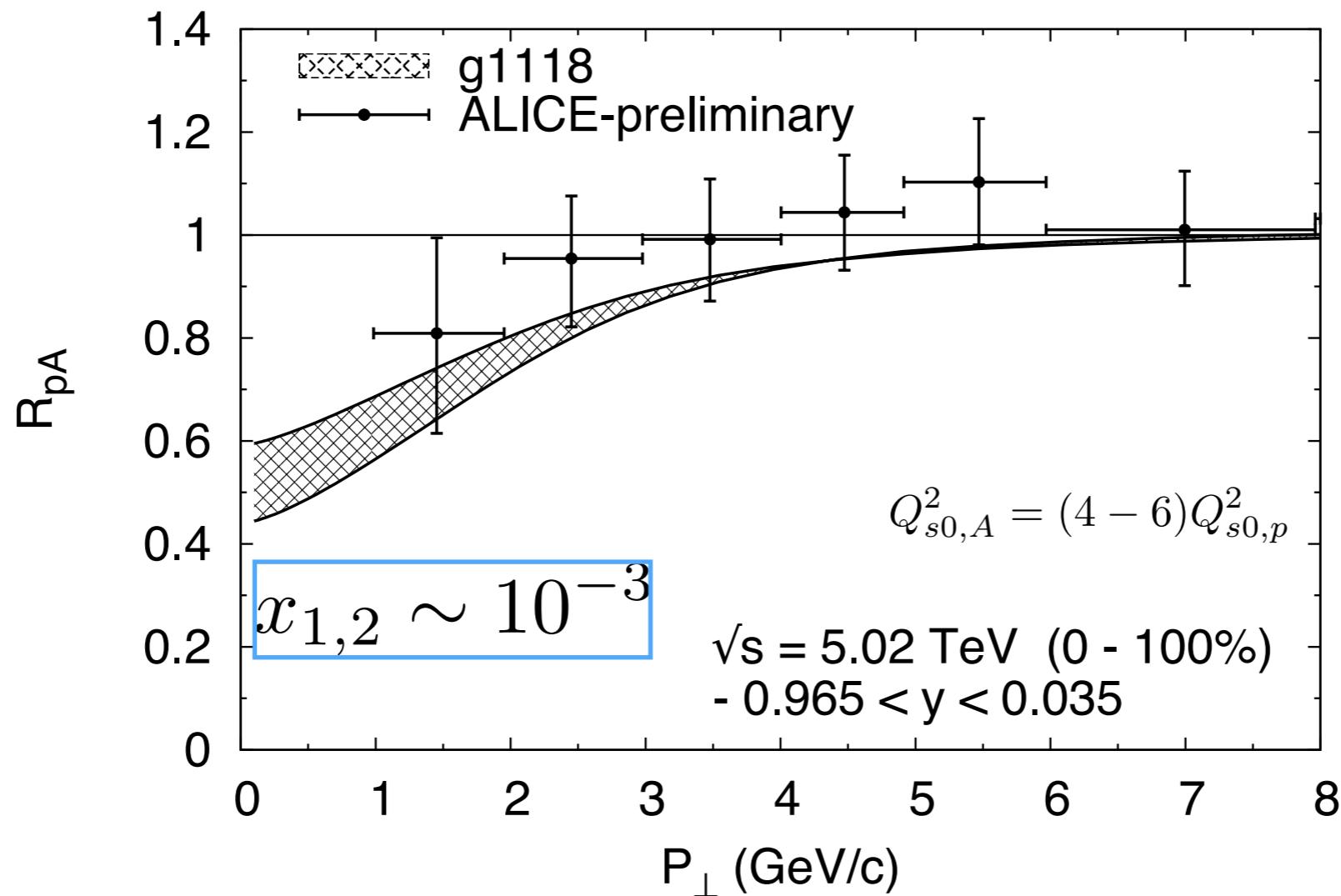
$$\frac{d\sigma_D}{d^2 p_{D\perp} dy} = \int dz \frac{D_c^D(z)}{z^2} \frac{d\sigma_c}{d^2 q_\perp dy} \quad p_{D\perp} = z q_\perp$$



- Suppression due to multiple scattering and saturation: reproduce the data.

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- In this CGC calculation with large- N_c approximation, we have shown that R_{pA} of J/Ψ and D meson productions are strongly suppressed in the low- p_\perp region at forward rapidity due to the multiple scattering and saturation effects in the target nucleus.
- J/Ψ and D meson productions largely reflect the behavior of multi point function in the target nucleus.

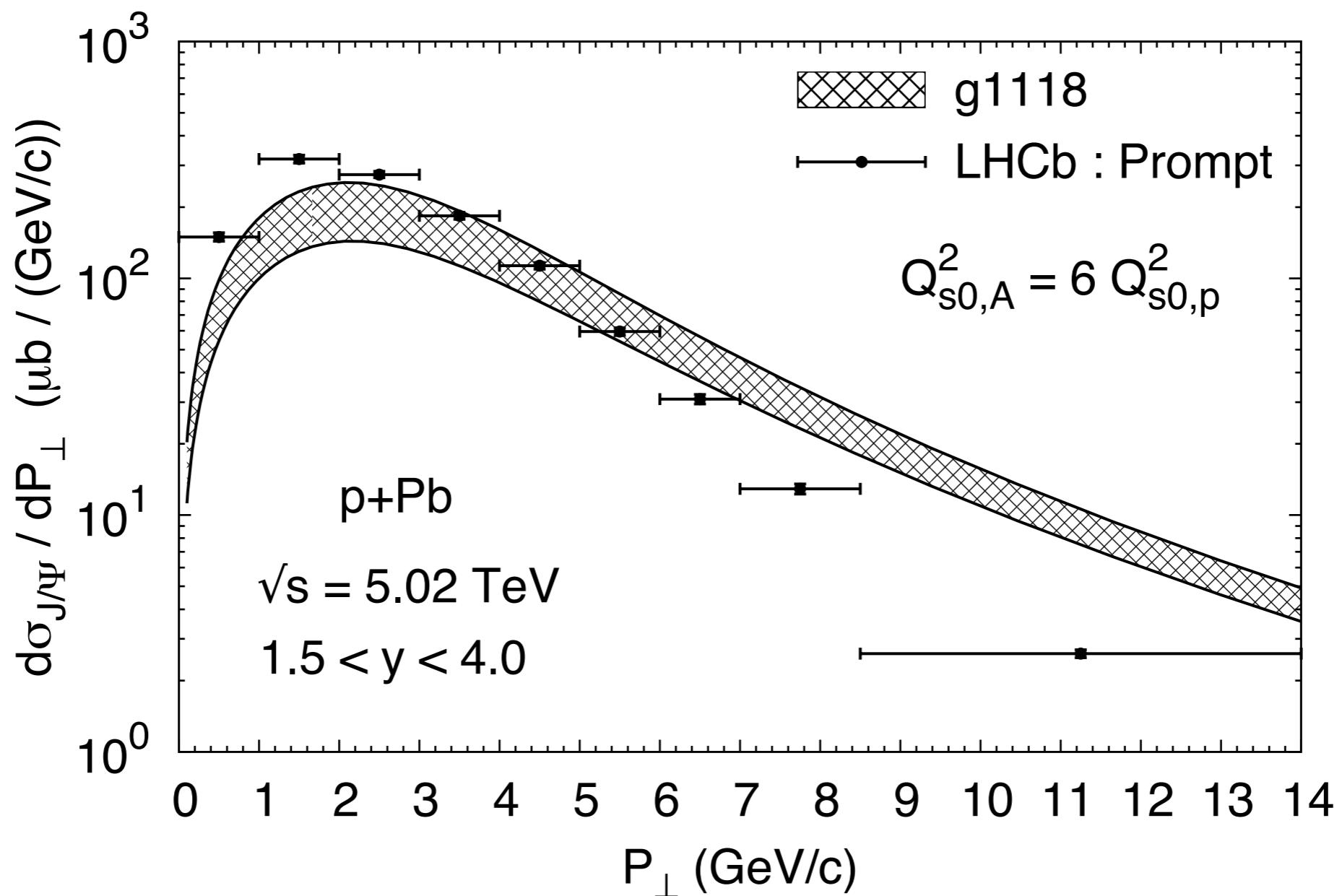
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Outlook

- NLO corrections (e.g. Sudakov factor) [Mueller, Xiao, Yuan (2013)]
- Hadronization : NRQCD matching [Kang, Ma, Venugopalan (2013)], [Qiu, Sun, Xiao, Yuan (2013)]

P_\perp spectrum of J/ ψ



Azimuthal angle correlation

$$CP[\Delta\Phi] = \frac{2\pi}{N_{\text{tot}}} \int \frac{dp_{D\perp}^2}{2} \frac{dp_{\bar{D}\perp}^2}{2} \frac{dN_{D\bar{D}}}{d^2 p_{D\perp} d^2 p_{\bar{D}\perp}}$$

Q_{s0}^2 : pp collision
 $(4 - 6)Q_{s0}^2$: pA collision

