Overview of heavy quark production in heavy ion collisions at the LHC

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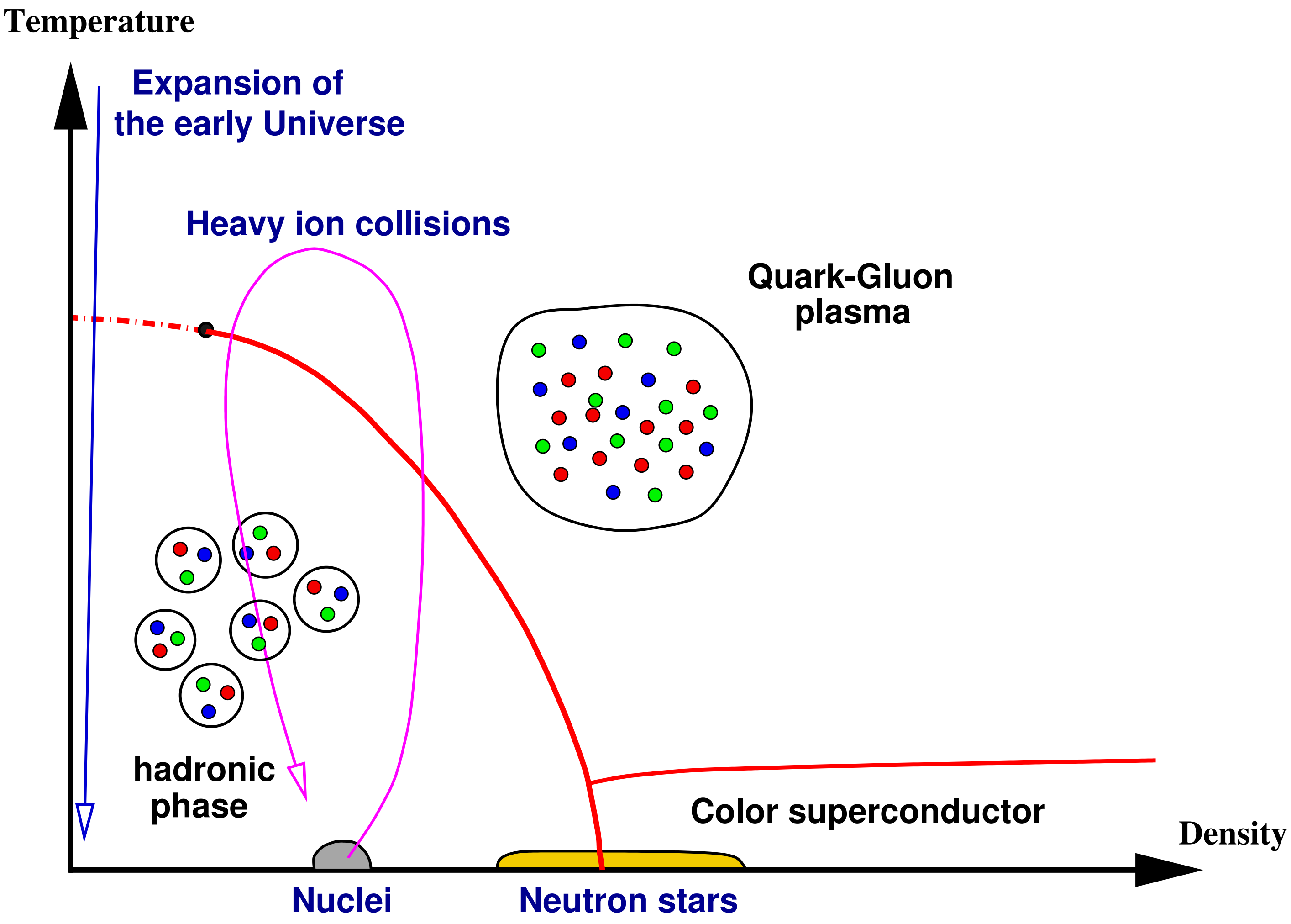
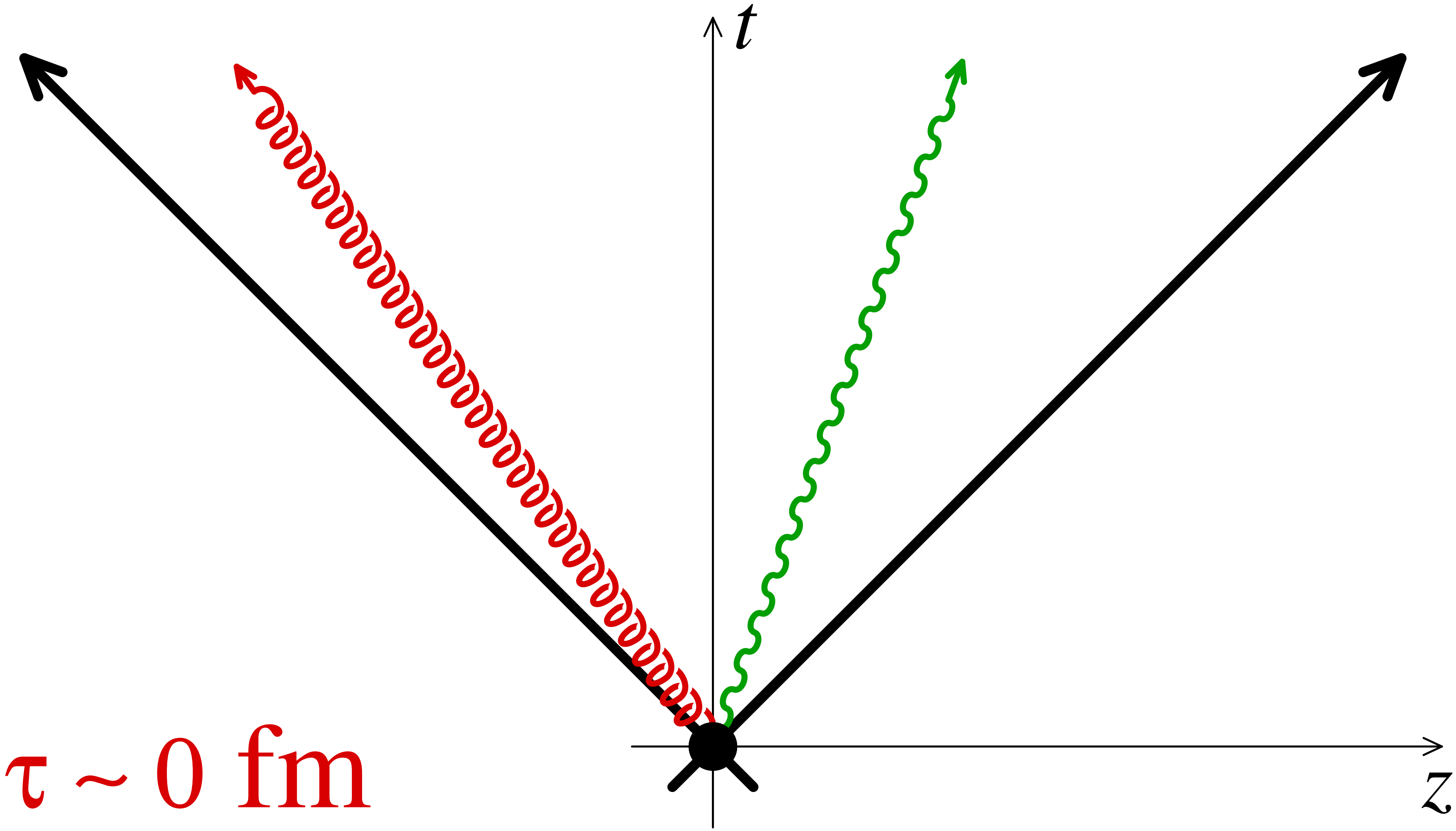
Outline

- Introduction
- pp collisions
  - Reference when looking for “anomalous” effects in pA or AA
  - **Note:** things we do not understand in pp collisions are unlikely to get better with nuclei...
- pA collisions
  - Reference for “normal” nuclear suppression
  - Interesting by itself for the physics of saturation
- AA collisions
  - Quarkonium states are a probe of the surrounding medium
  - Recent lattice results on quarkonia
- Conclusions

QCD phase diagram

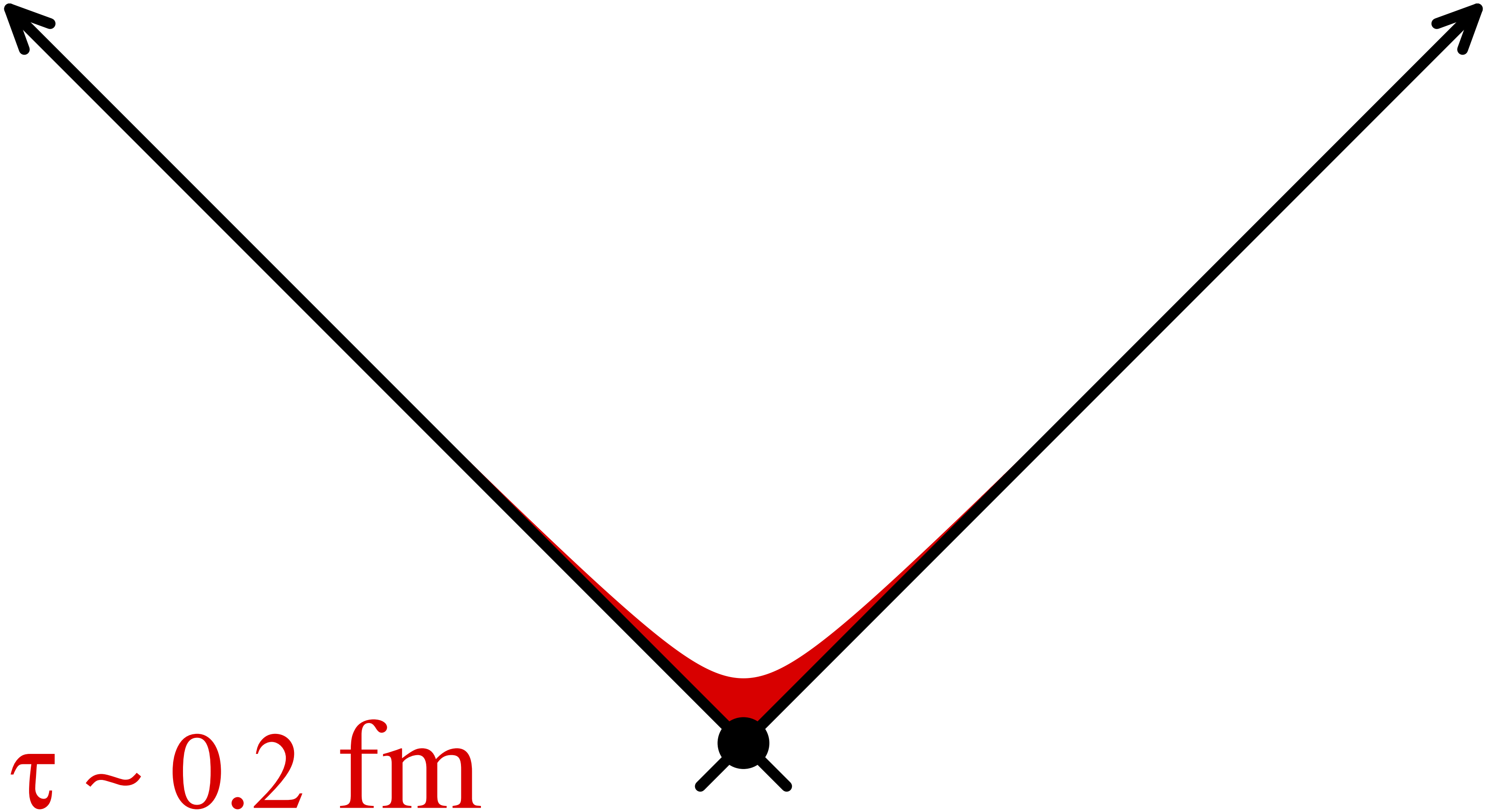


Initial impact



- Prompt particle production (jets, heavy quarks, photons) high $p_\perp$, large x physics, calculable in pQCD

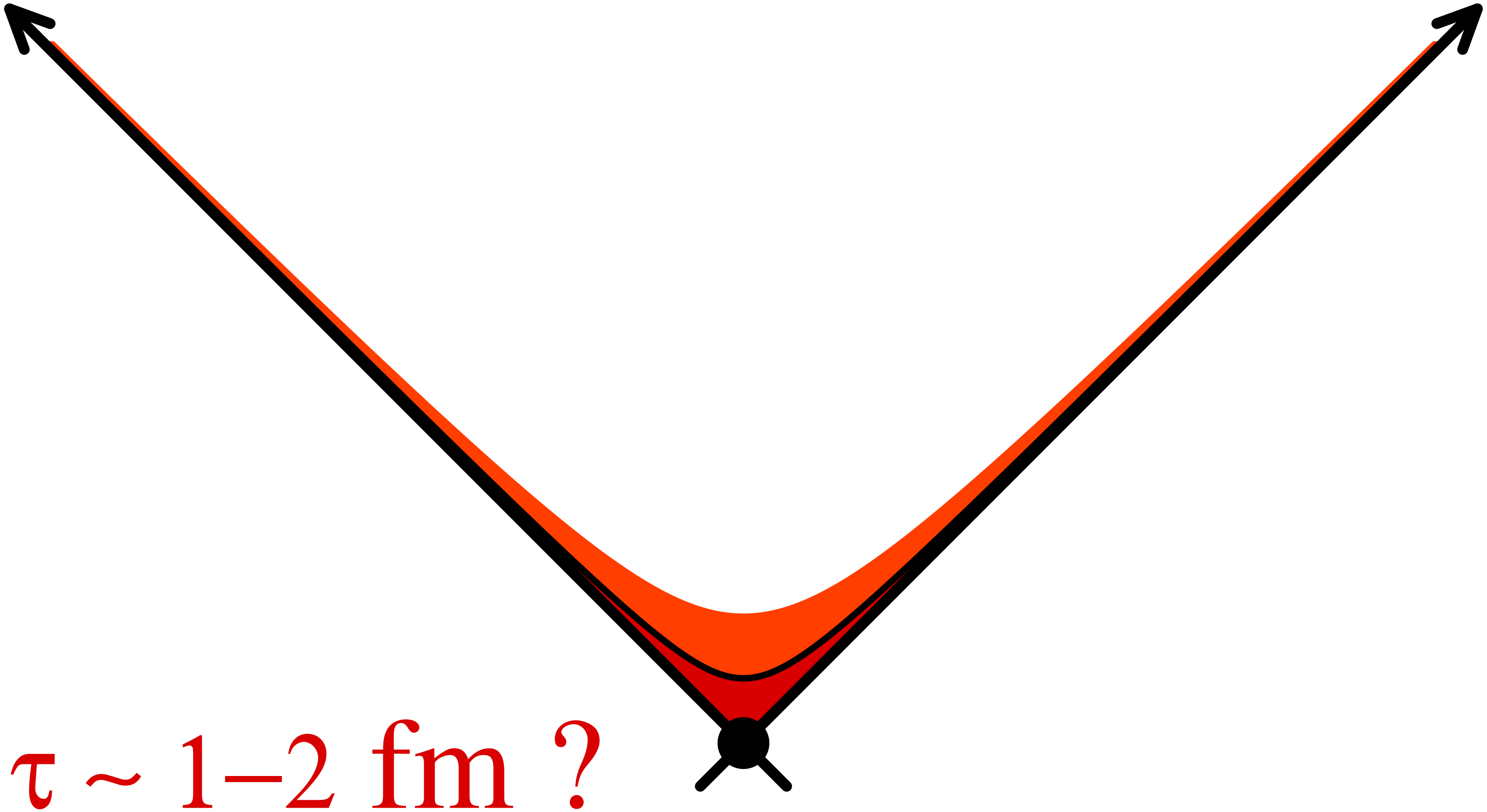
Soft glue liberation



$\tau \sim 0.2$ fm

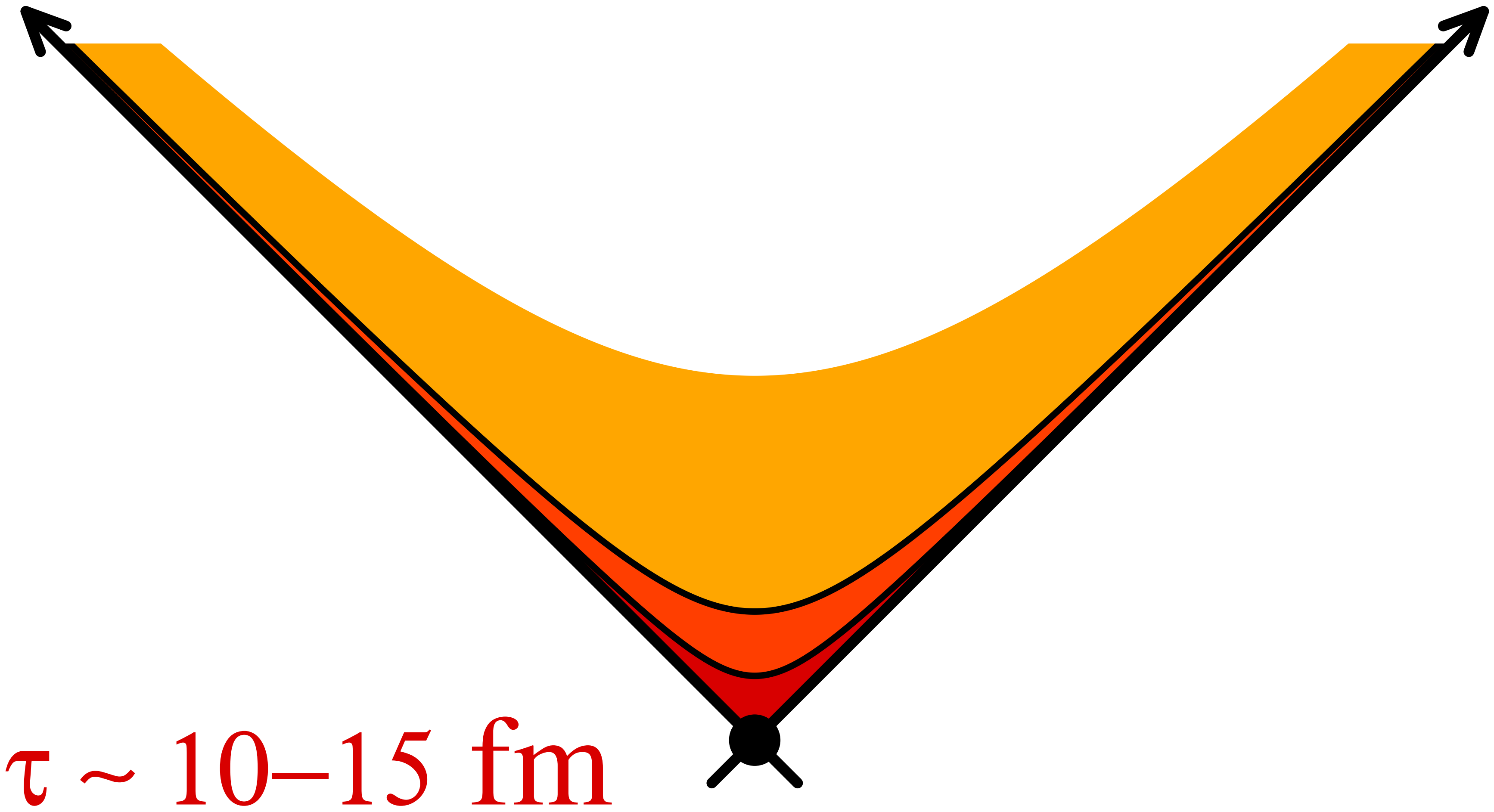
- Soft gluon production : small $p_\perp$; requires to know the small-x component of the hadron wave function

Thermalization



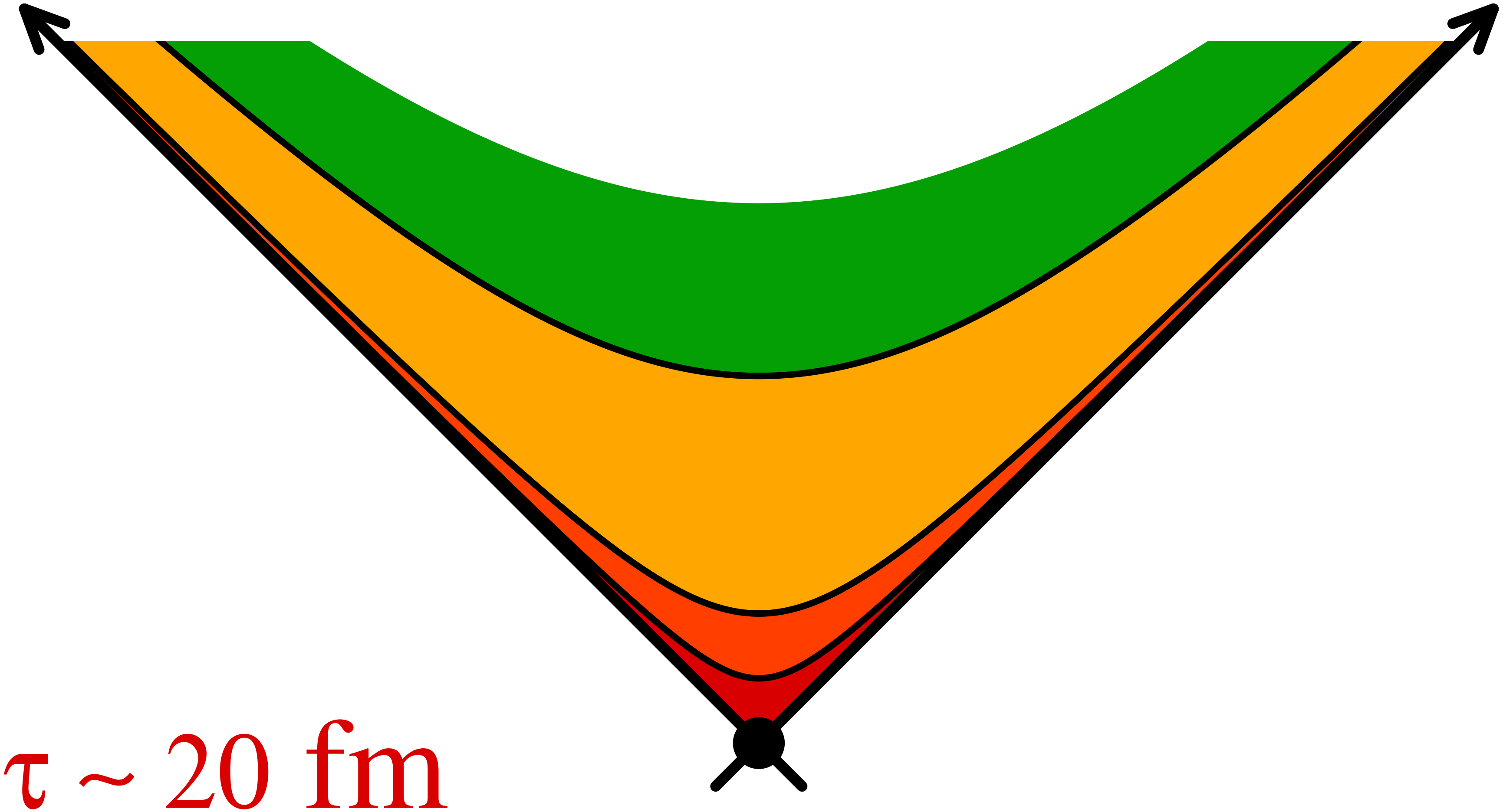
$\tau \sim 1\text{–}2$ fm ?

Quark-Gluon plasma



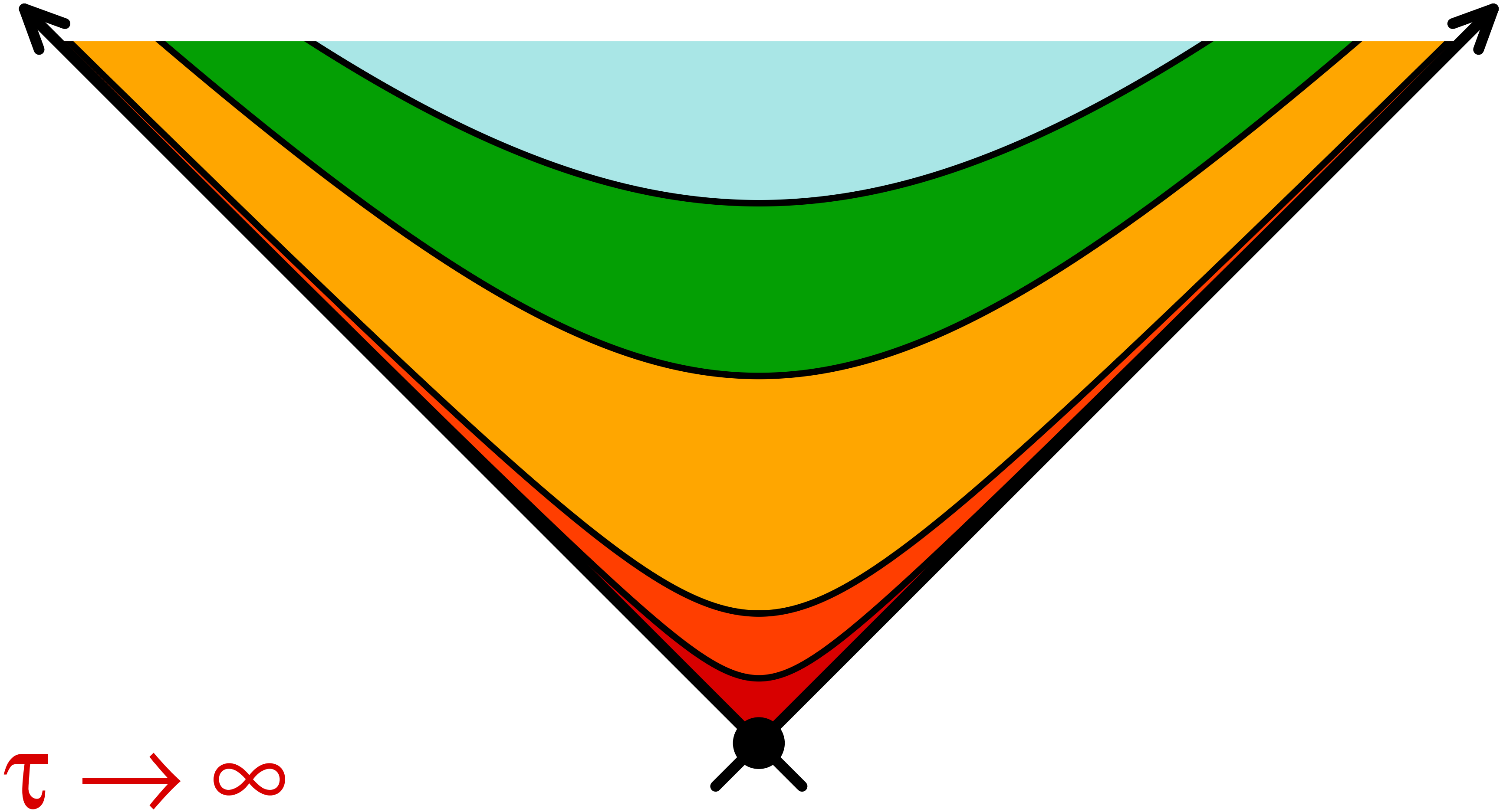
$\tau \sim 10\text{–}15\ \mathrm{fm}$

Hadron gas



$\tau \sim 20$ fm

Freeze-out and free streaming

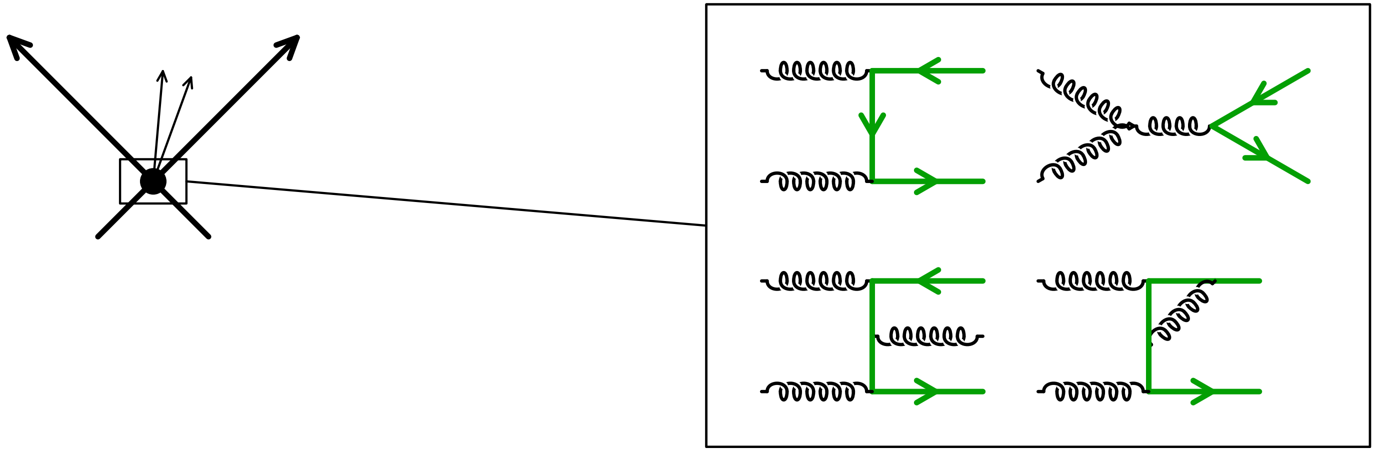


$\tau \longrightarrow \infty$

- Easy, not much happens after freeze-out...
- Unstable hadrons decay

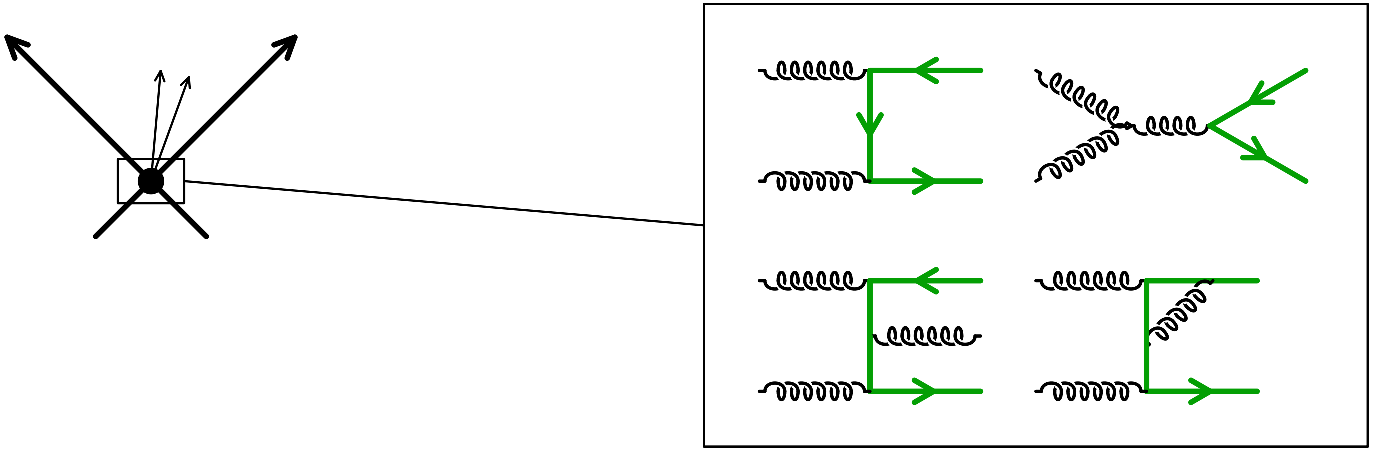
Heavy quark production

- Standard collinear factorization

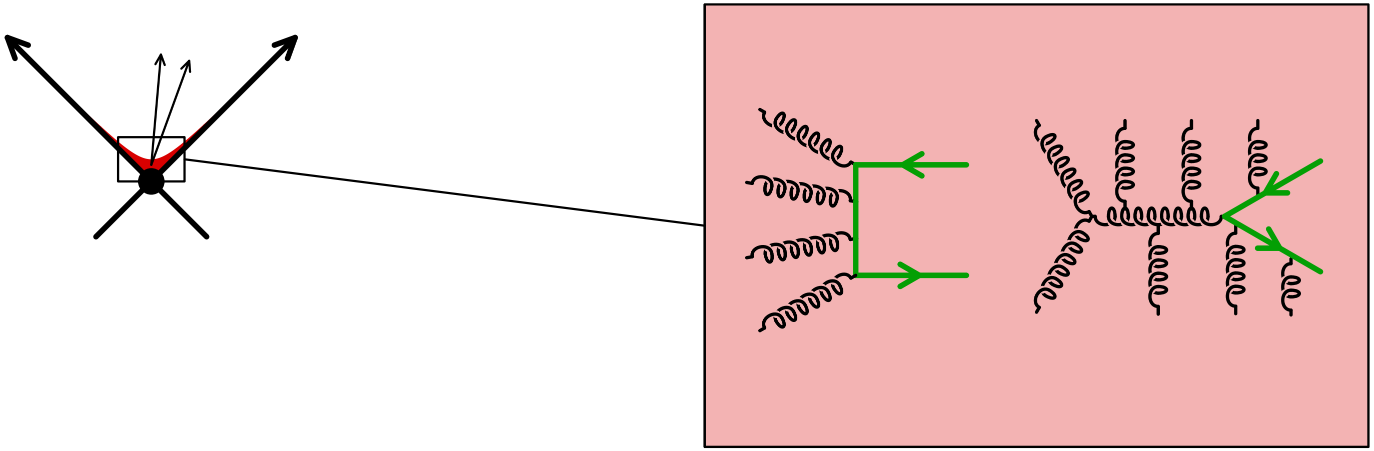


Heavy quark production

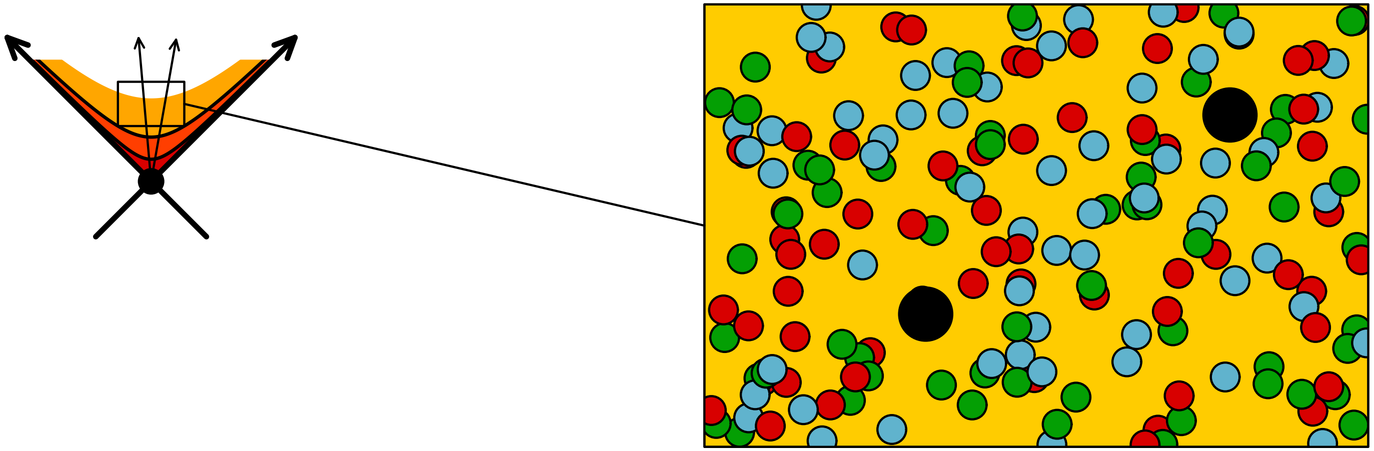
- Standard collinear factorization



- ...or higher twist effects ?



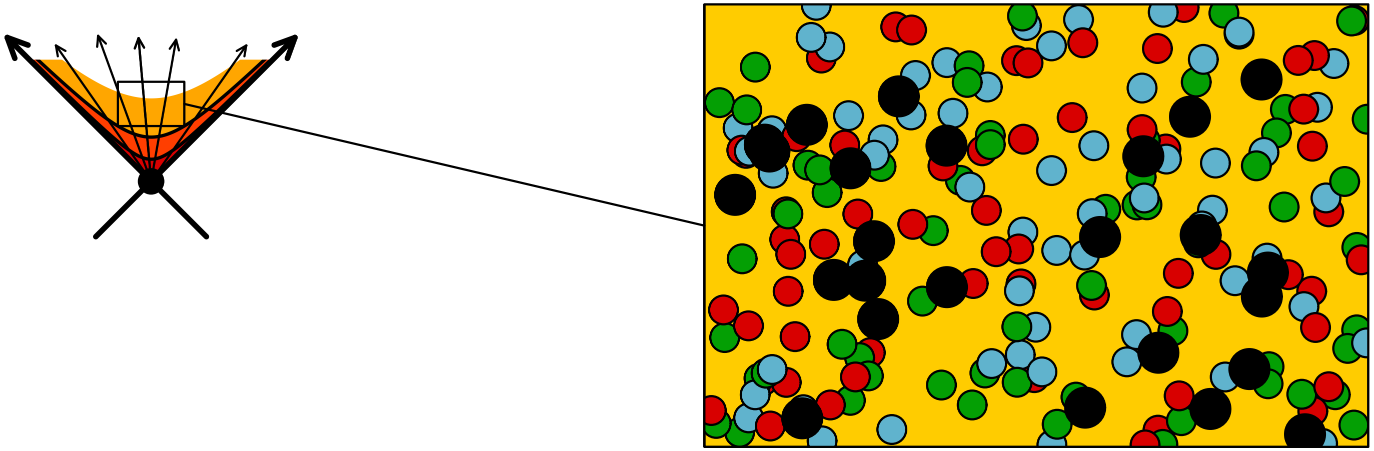
In-medium J/psi suppression



- Debye screening prevents the formation of quarkonium states Matsui, Satz (1986)
  - the heavy quarks pick a light quark instead and form a D meson
- Heavy quark potential, screening masses, and spectral functions calculable on the lattice
- Relevant observable :

$$[J/\psi] \ / \ [\text{Open charm}]$$

...or QQbar recombination ?



- Many $Q\overline{Q}$ pairs are produced in each AA collision
  Braun-Munzinger, Stachel (2000)
  Thews, Schroedter, Rafelski (2001)
  - A Q from one pair can recombine with a $\overline{Q}$ from another pair
- Avoids the conclusion of the Matsui-Satz scenario, provided that the average distance between heavy quarks is smaller than the Debye screening length
- Leads to an enhancement of J/ψ formation

1 - pp

Collinear factorization

- Common wisdom: $m_Q \gg \Lambda_{QCD}$, so that $\alpha_s(m_Q^2) \ll 1$
- Factorization formula for open charm production :

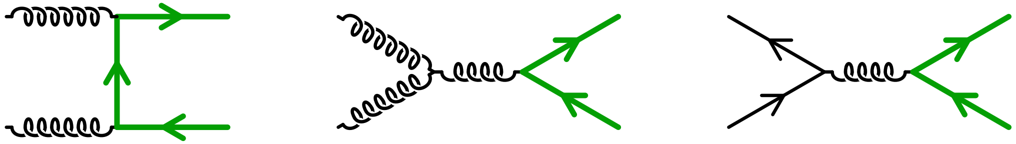
$$\frac{d\sigma_{pp\to H+X}}{d\Phi_H} = \sum_{ij} \int f_{i/p}(x_1) f_{j/p}(x_2) \frac{d\sigma_{ij\to Q\overline{Q}}}{d\Phi_Q d\Phi_{\overline{Q}}} D_{Q\to H}(z)$$

  - $f_{i/p}(x)$: distribution of parton i in the proton, known at NLO from fits of DIS data
  - $D_{Q\to H}(z)$: fragmentation function of quark Q into hadron H
  - $d\sigma_{ij\to Q\overline{Q}}/d\Phi_Q d\Phi_{\overline{Q}}$: perturbative cross-section for the production of heavy quarks, known up to NLO

- Remarks :
  - NLO results depend on renormalization and factorization scales
  - Factorization is broken by corrections that are power suppressed, e.g. $(Q_0^2/Q^2)^n$ where Q_0 is some non-perturbative hadronic scale and Q the large momentum scale in the process

Fixed order calculations

- LO $[\mathcal{O}(\alpha_s^2)]$:



Fixed order calculations

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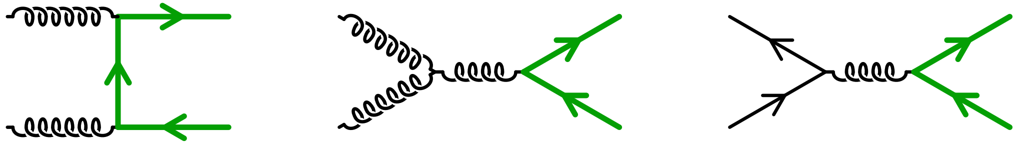
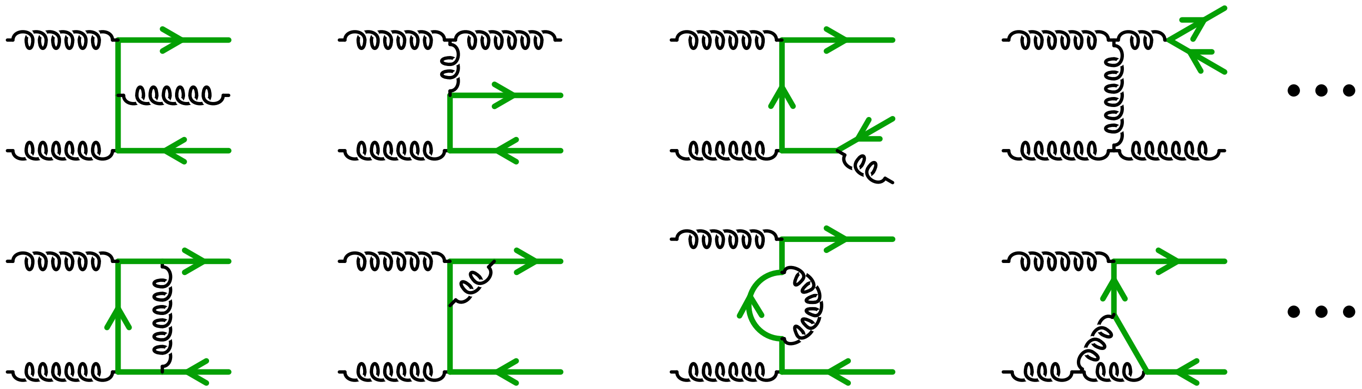


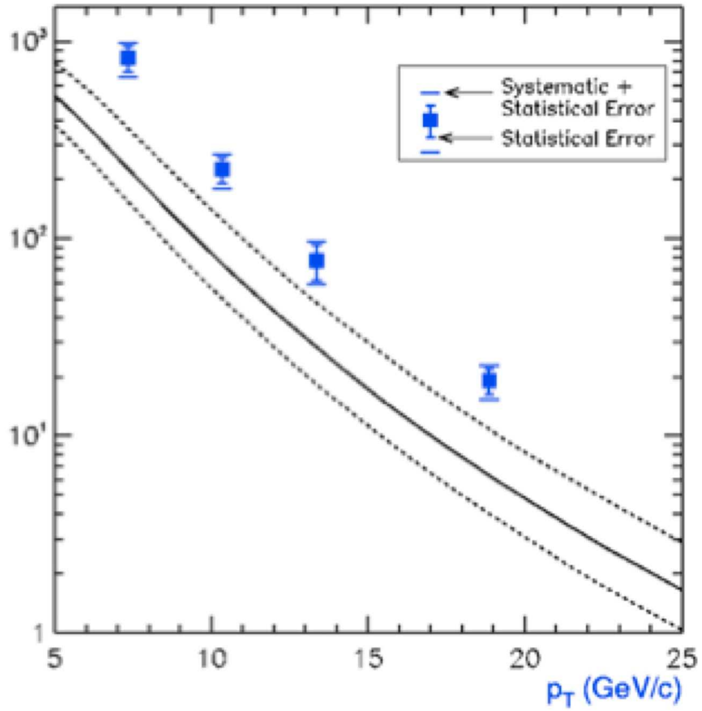
- NLO $[\mathcal{O}(\alpha_s^3)]$: Nason, Dawson, Ellis (1988)



- NLO almost as large as LO + rather large scale dependence
- NNLO not known yet for this process

Fixed order calculations

- Plain LO+NLO has been problematic for a long time:
  B production at CDF vs NLO-pQCD, as of 2001



▷ data / theory ~ 2.9... somewhat embarassing for pQCD...

Resummation of logarithms

- The coefficients of the perturbative expansion may be enhanced by logarithms

$$d\sigma_{ij\to Q\overline{Q}} = \sum_{n=2}^{\infty} c_n \alpha_s^n \quad , \quad c_n = \sum_{k=0}^{n-2} c_n^{(n-2-k)} \left[\ln \mathcal{Q}\right]^{n-2-k}$$

where $\mathcal{Q}$ might be large enough so that $\alpha_s \ln \mathcal{Q} \geq 1$

- Logs that are independent of the observable :
  - Threshold logs: $\mathcal{Q} = \widehat{s}/4m_Q^2 - 1$
  - Small-x logs: $\mathcal{Q} = \widehat{s}/m_Q^2$
- Logs that depend on the details of the observable :
  - Single Q spectrum at large momentum: $\mathcal{Q} = p_\perp(Q)/m_Q$
  - $Q\overline{Q}$ spectrum at low pair momentum: $\mathcal{Q} = m_Q/p_\perp(Q\overline{Q})$
  - $Q\overline{Q}$ spectrum in a back-to-back configuration: $\mathcal{Q} = 1 - \phi_{Q\overline{Q}}/\pi$

Resummation of logarithms

- Including these logarithms amounts to taking into account extra radiation in the final state
- Rearrangement of the perturbative expansion:

$$d\sigma = \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \sum_{i=0}^{\infty} r_i^{(n)} \left[\alpha_s \ln \mathcal{Q}\right]^i + \mathcal{O}\left(\mathcal{Q}^{-1}\right)$$

  - $n = 0$: Leading Log (LL)
  - $n = 1$: Next-to-Leading Log (NLL)
- Two different implementations :
  - FONLL : NLO fixed order + analytic resummation of leading logs Cacciari, Greco, Nason (1998)
  - MC@NLO : NLO fixed order + resummation of logs via a “parton shower” Frixione, Webber (2002)

Present data vs theory situation

introduction

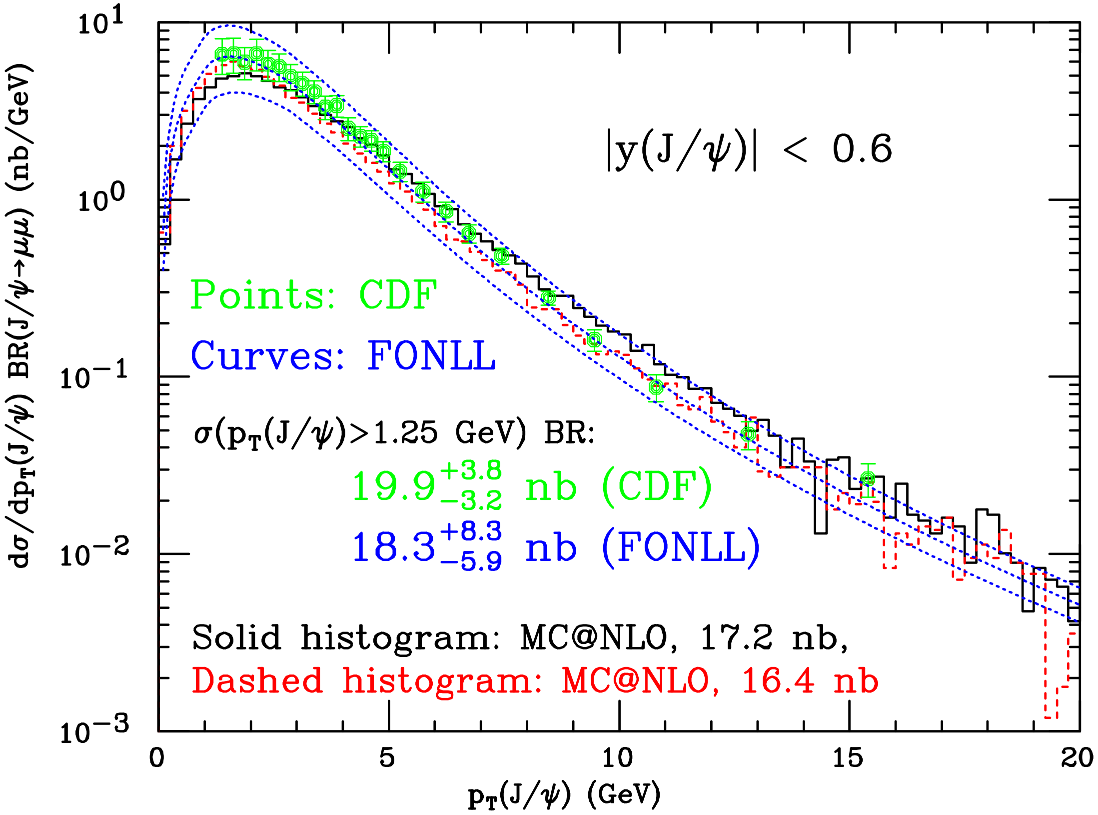
proton-proton
- perturbative expansion
- log resummations
- Kt-factorization
- quarkonium production

proton-nucleus

nucleus-nucleus

conclusions

- Resummations + better fragmentation functions: better agreement with data : B production at Tevatron II



▷ **Note :** the data has gone down as well...

Azimuthal correlations

introduction

proton-proton
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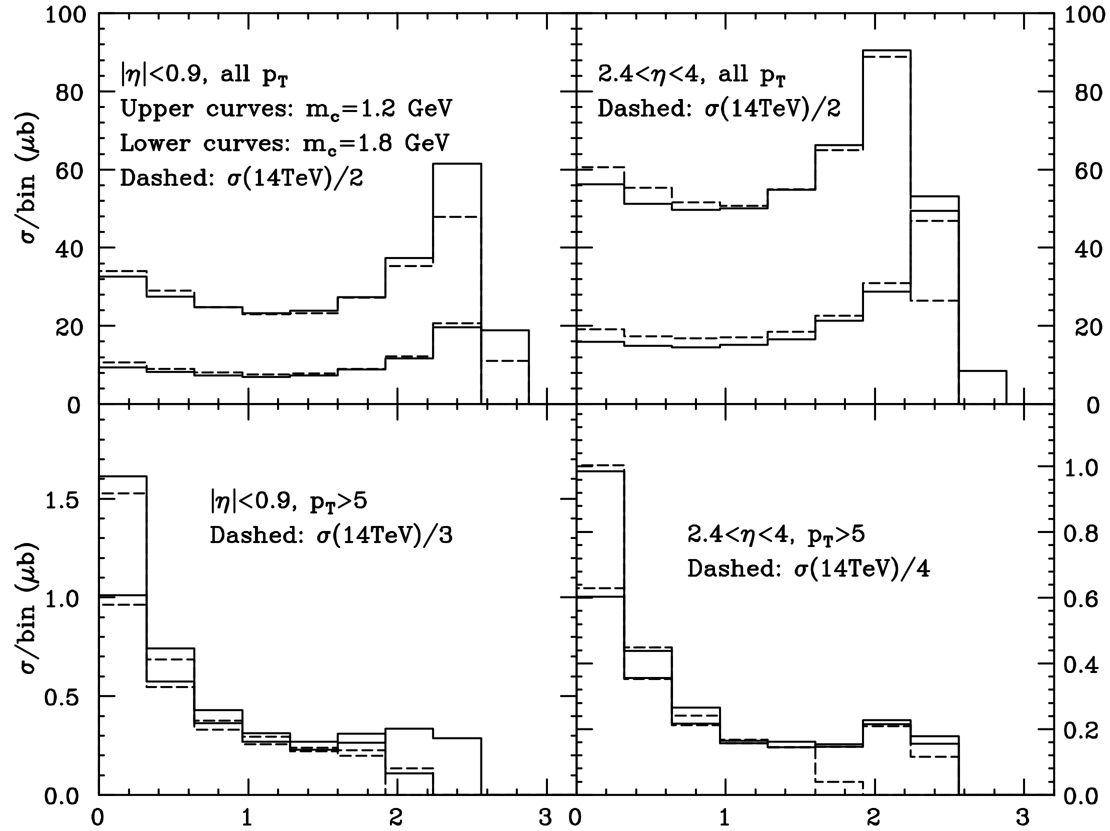
conclusions

- $c\bar{c}$ angular correlation



▷ loss of the back-to-back correlation when a $p_\perp$ cut is applied (high-$p_\perp$ production dominated by gluon splitting)

Azimuthal correlations

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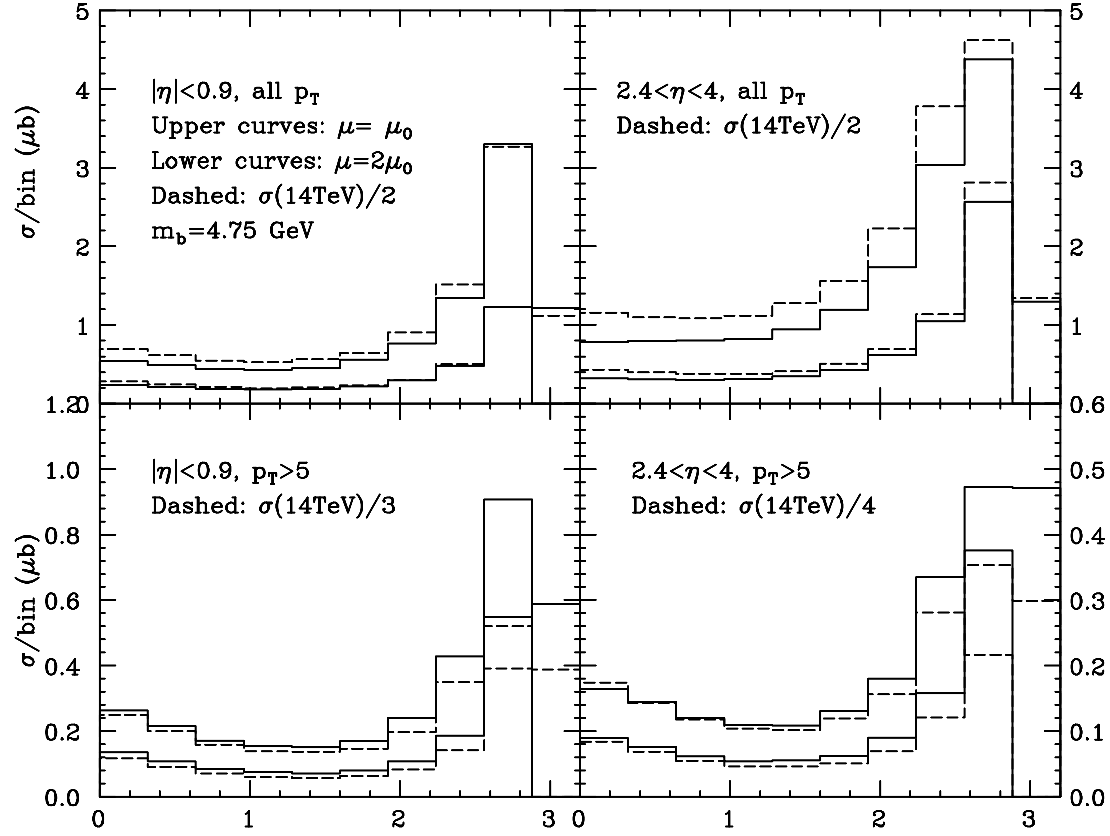
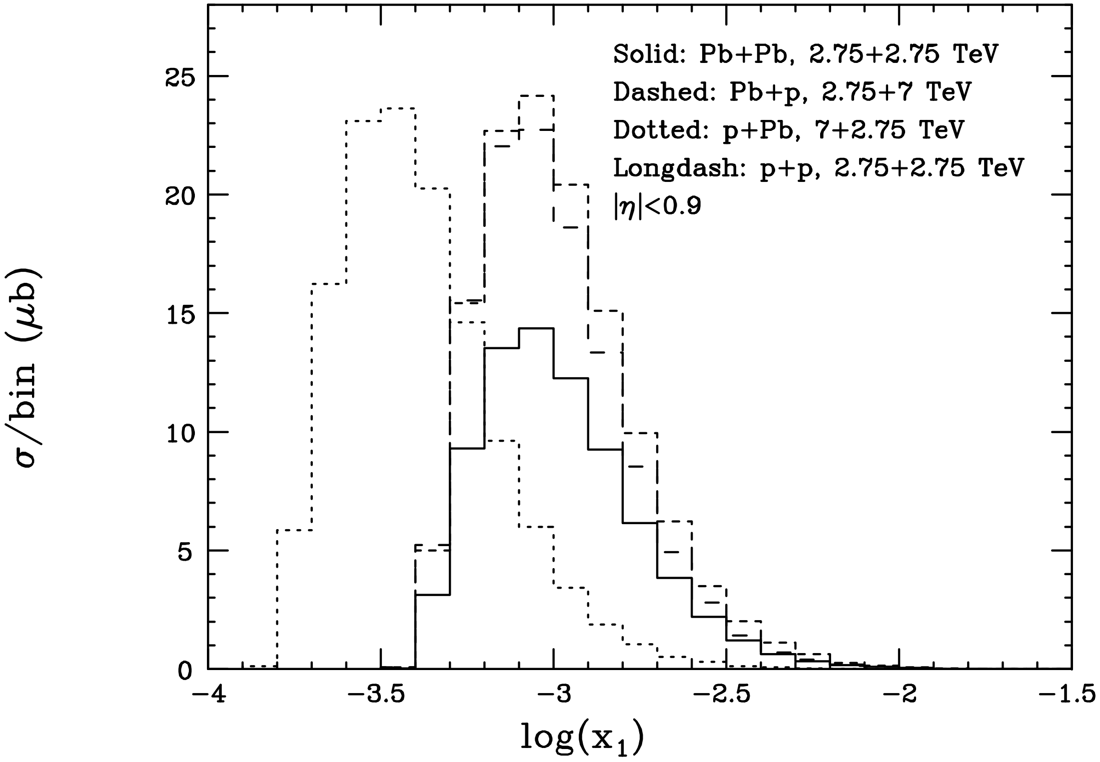
- $b\bar{b}$ angular correlation



Kt-factorization

- x coverage for $c\bar{c}$ production at the LHC : central rapidity



Kt-factorization

introduction

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- perturbative expansion
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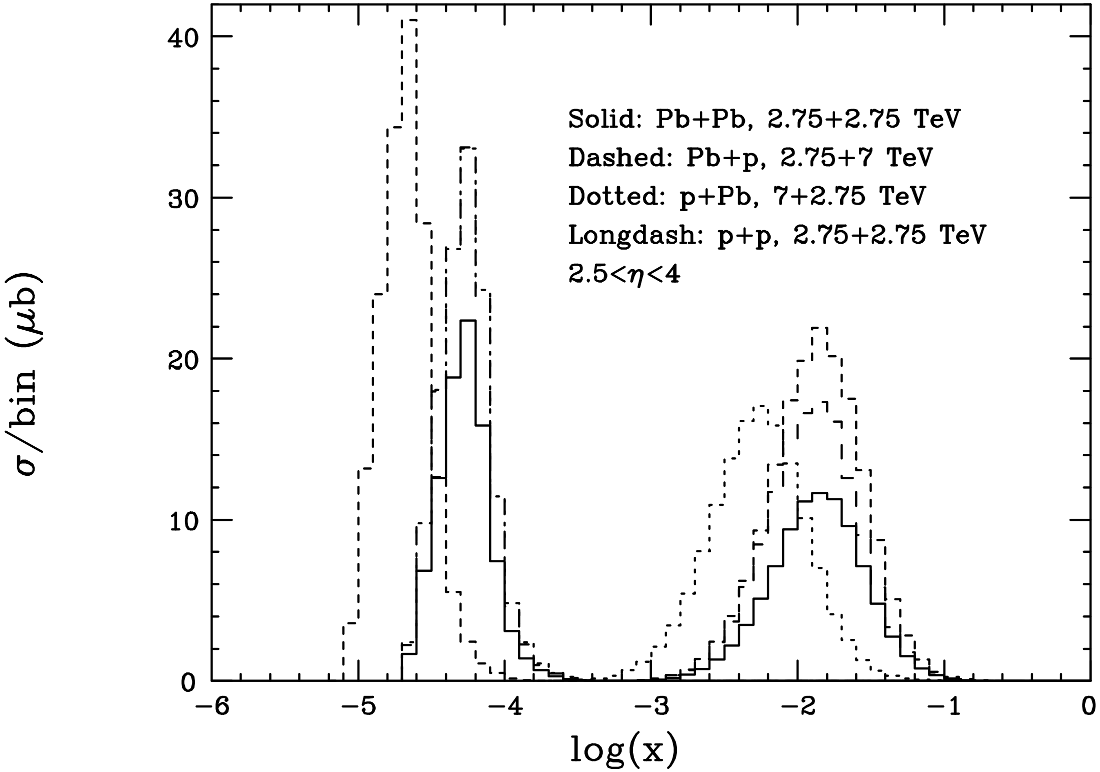
conclusions

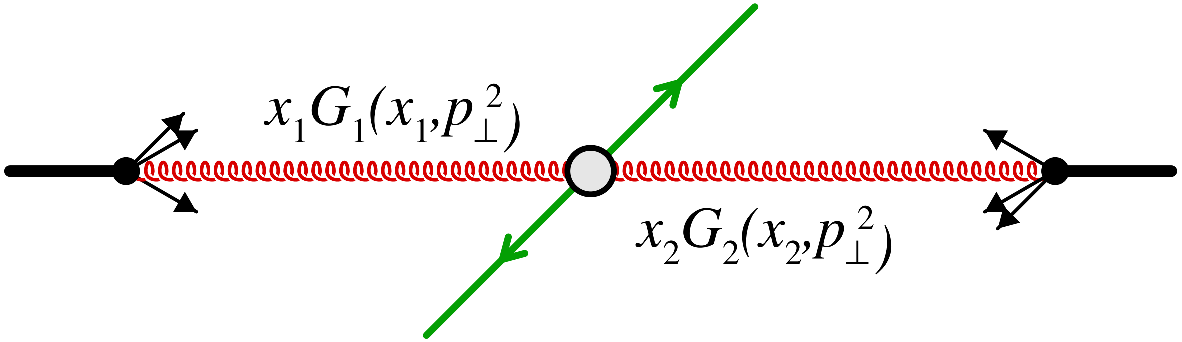
- x coverage for $c\bar{c}$ production at the LHC : forward rapidity



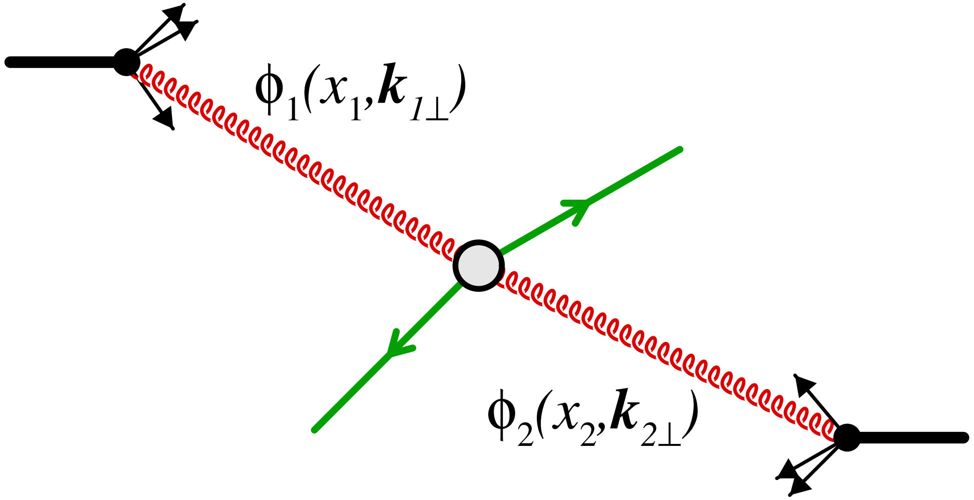
▷ very small values of x reached in one of the projectiles. Small-x effects may be important, especially for Pb.

Kt-factorization

- Collinear factorization : $s \sim p_\perp^2 \gg \Lambda_{QCD}^2$



- $\boldsymbol{k}_\perp$-factorization : $s \gg p_\perp^2 \gg \Lambda_{QCD}^2$
  Collins, Ellis (1991), Catani, Ciafaloni, Hautmann (1991)



Kt-factorization

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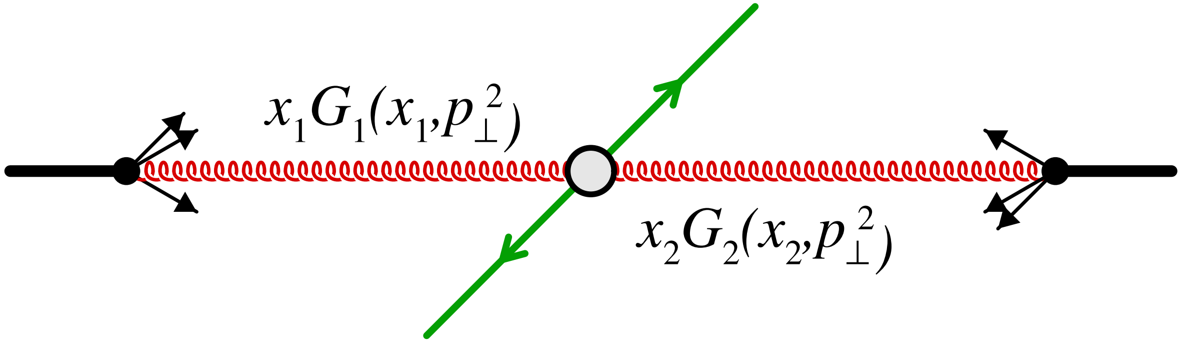
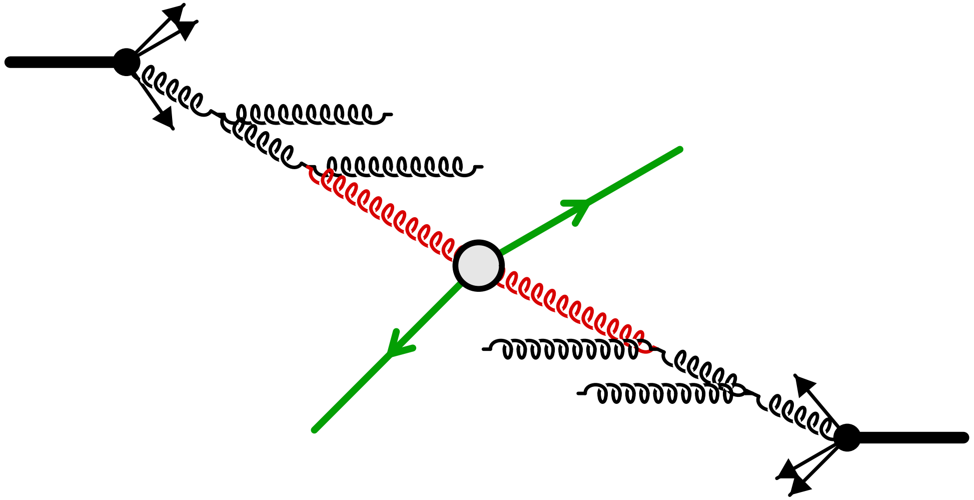
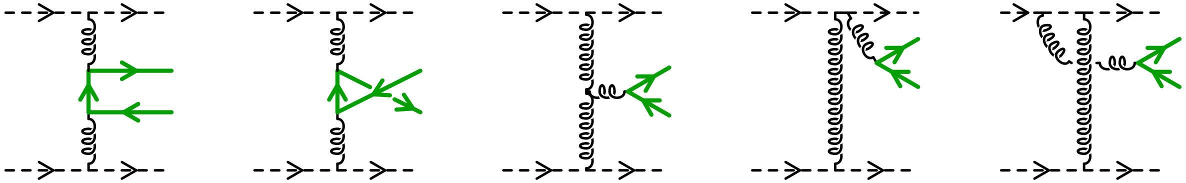


- $\boldsymbol{k}_\perp$-factorization + BFKL: resum $\left[\alpha_s \ln(s/p_\perp^2)\right]^n$
  Collins, Ellis (1991), Catani, Ciafaloni, Hautmann (1991)



Kt-factorization

- Included diagrams :



- $Q\overline{Q}$ cross-section in $k_\perp$-factorized form :

$$\frac{d\sigma_{pp\to Q\overline{Q}}}{d\Phi_Q d\Phi_{\overline{Q}}} = \int \frac{\delta(\vec{\boldsymbol{k}}_{1\perp} + \vec{\boldsymbol{k}}_{2\perp} - \vec{\boldsymbol{p}}_\perp(Q\overline{Q}))}{\boldsymbol{k}_{1\perp}^2 \boldsymbol{k}_{2\perp}^2} \varphi_p(x_1, k_{1\perp})\varphi_p(x_2, k_{2\perp})|\mathcal{M}|^2$$

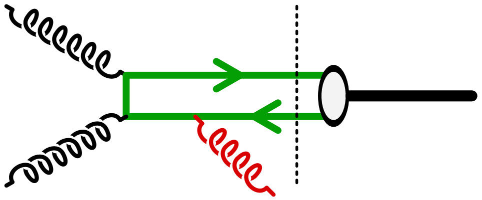
- Pros :
  - Proper way of including intrinsic $k_\perp$
  - Some NLO and NNLO diagrams are already included
  - This formalism can be generalized to include higher twist effects
- Cons :
  - The incoming gluons are off-shell $\Rightarrow$ difficult calculations
  - Only a subset of the NLO terms is included
  - No formal “factorization theorem”...

Quarkonium production

- More difficult than the inclusive fragmentation $c \longrightarrow D + X$
- LO is clearly insufficient in order to get the $p_\perp$ distribution of J/ψ or Υ, since by construction $p_\perp(Q\overline{Q}) = 0$ at this order
- Several approaches :
  - Color Singlet Model (CSM)
  - Non-Relativistic QCD (NRQCD) [aka Color Octet Model]
  - Color Evaporation Model (CEM)
  - Comover Enhancement Scenario (CES)

Quarkonium production

- Color Singlet Model :
  - The $Q\overline{Q}$ pair is assumed to be produced with the proper quantum numbers by the hard sub-process
    ▷ No further interactions are required
  - The $Q\overline{Q}$ pair is simply projected on the non-relativistic wave-function of the bound state

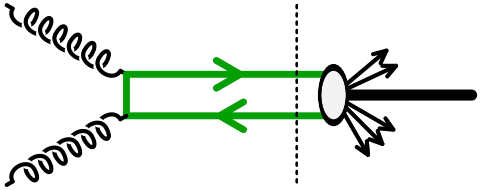


  - Not too bad for J/ψ photoproduction
  - undershoots by more than an order of magnitude for $J/\psi, \psi'$ (even Υ) hadroproduction...
  - Problem : in this model, the gluon emission is controlled by a hard scale ▷ suppressed by $\alpha_s(4m_Q^2) \ll 1$

Quarkonium production

- Non-Relativistic QCD :
  - Based on a double expansion in α_s and v^2 $(v^2(c,b) \sim 0.3, 0.1)$
  - Provides a factorization formula:

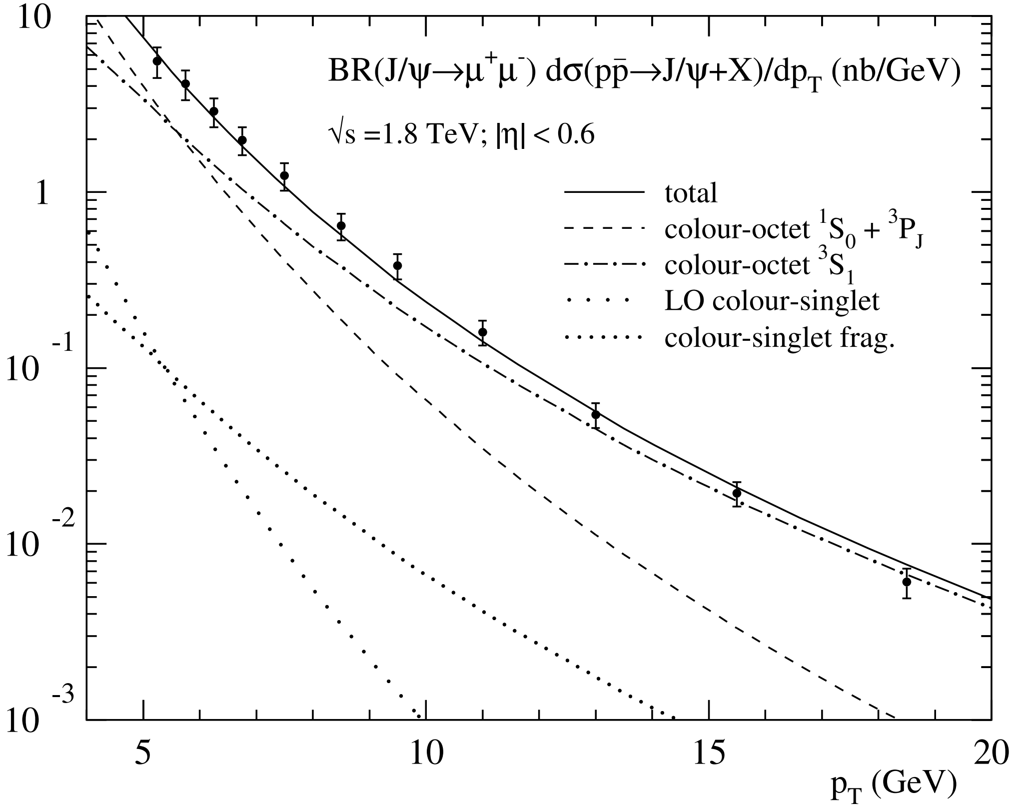
$$d\sigma_{ij\to H+X} = \sum_n \left\langle \widehat{\mathcal{O}}_H[n] \right\rangle d\sigma_{ij\to Q\overline{Q}[n]} \; , \; n = \{c{=}(1,8), {}^{2s+1}L_J\}$$



  - The matrix elements $\left\langle \widehat{\mathcal{O}}_H(n) \right\rangle$ play the same role as fragmentation functions ▷ non-perturbative, but universal.
  - The extra emissions occur at a soft non-perturbative scale ▷ no penalty associated to them
  - Problem : the sum over the states n is infinite. It can be truncated since higher states are of higher order in v.

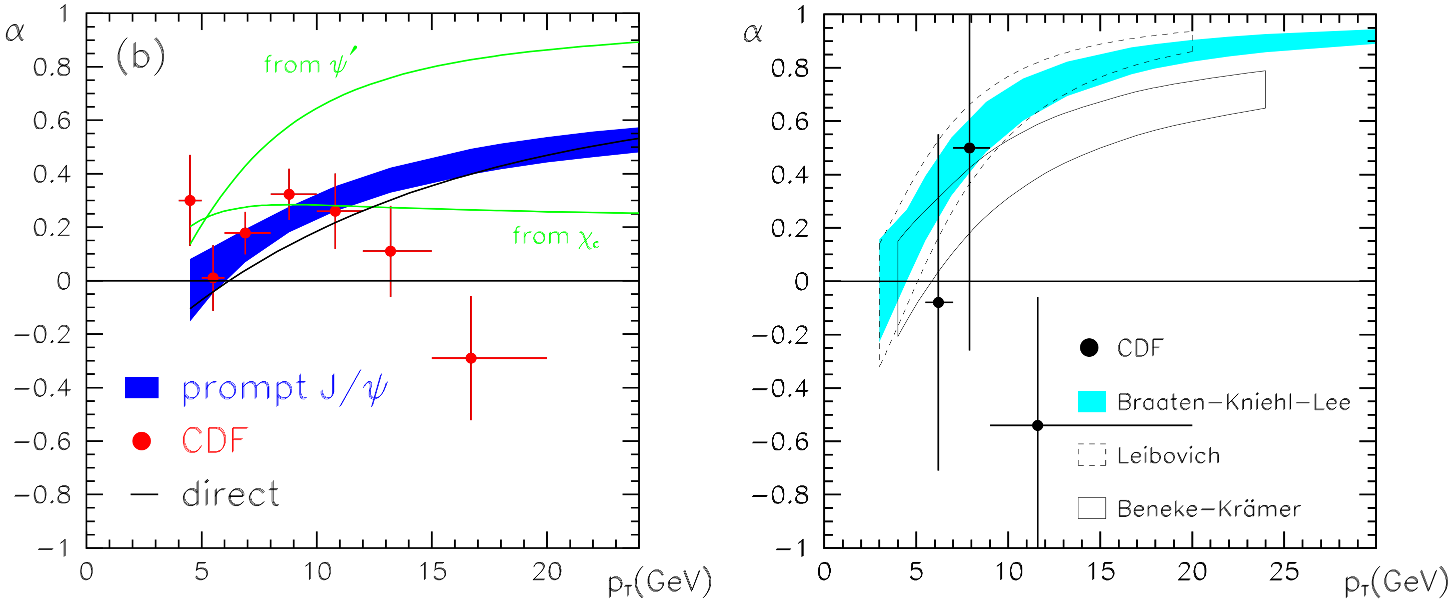
Quarkonium production

- Non-Relativistic QCD : comparison with CDF



Quarkonium production

- Non-Relativistic QCD : polarization



▷ according to the literature : "theory is in good agreement with data"... nothing to see here...

Quarkonium production

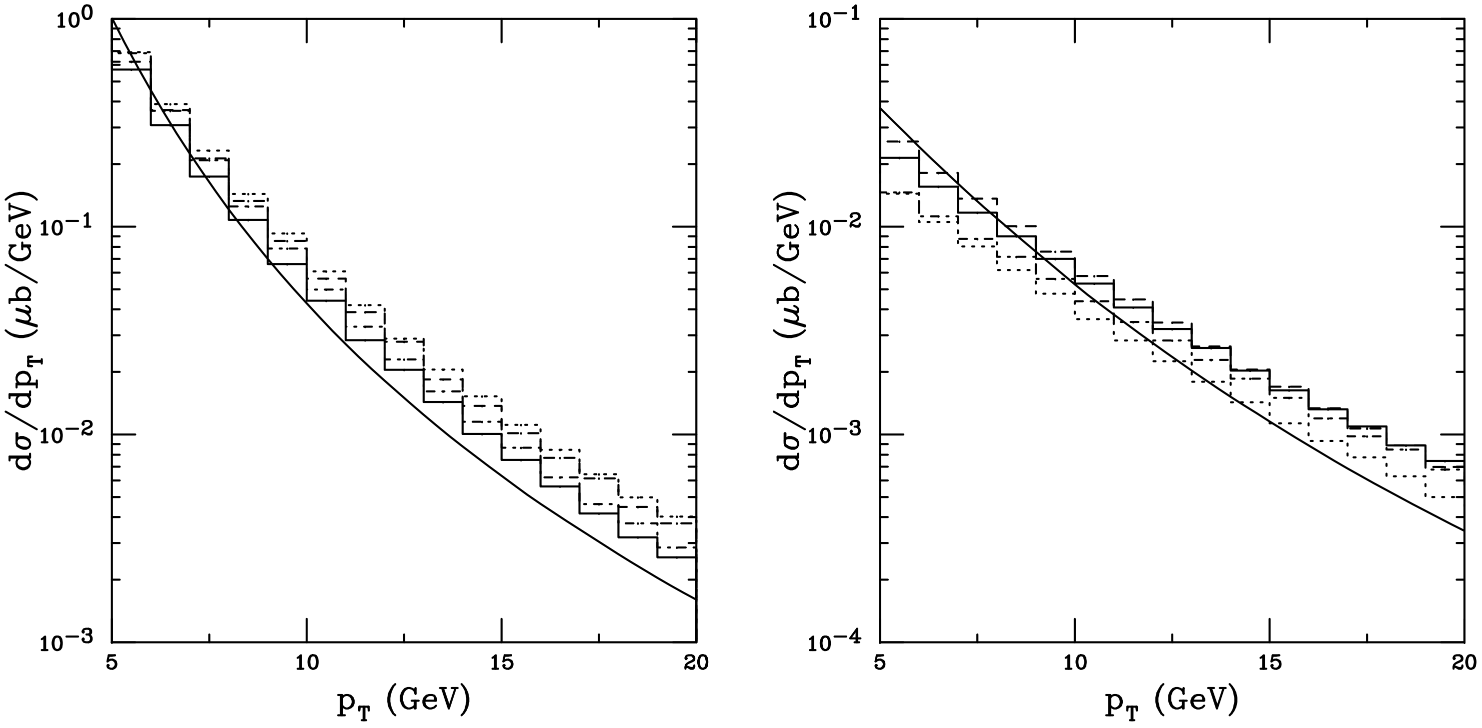
- Color Evaporation Model :
  - Based on the idea that (unspecified) soft non-perturbative interactions will bring the quantum numbers of the $Q\overline{Q}$ pair to those of the hadron
  - Assumes that all the $Q\overline{Q}$ pairs produced in a certain range of invariant mass become quarkonium states with a certain probability

$$\sigma_{ij\to H+X} = F_{_H} \int_{4m_Q^2}^{4m_{D,B}^2} d\widehat{s}\;\; \sigma_{ij\to Q\overline{Q}}(\widehat{s})$$

  - The constants $F_{_H}$ depend only on the quarkonium state being produced, but not on $p_\perp$, s, y, or on the state in which the $Q\overline{Q}$ pair is produced
  - The upper limit in the integral is the threshold for the production of a pair of D or B mesons

Quarkonium production

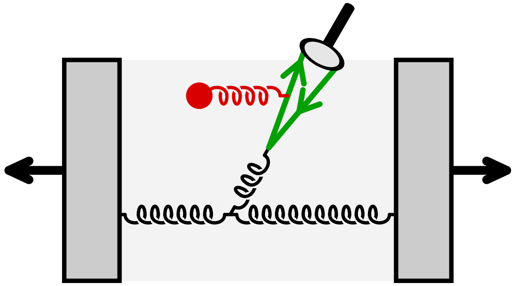
- Comparison between NRQCD and CEM :



Left : J/ψ Right : Υ

Quarkonium production

- Comover Enhancement Scenario :
  - Assumes that the quarkonia states are formed within a comoving color field (produced by spectator partons), through gluon absorption (rather than emission, as assumed in in the CSM or in NRQCD)



  - May lead to an enhancement over the CSM predictions
  - May explain why the CSM works for photoproduction (no comoving field in that case), but not for hadroproduction
  - This physics is included in approaches that contain rescatterings (see pA collisions)

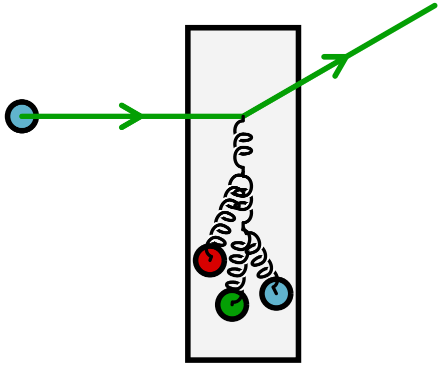
2 - pA

Nuclear effects

- pA collisions are useful as a reference in which no QGP is expected while there are some high density effects
- Saturation, shadowing
  - Saturation effects are more pronounced for a large projectile
  - Usually included within collinear factorization by using special parton distribution functions (e.g. EKS98, HKM)
- Rescattering effects
  - Strong color field produced in the collision
  - Models of Comovers
- All these effects can be addressed simultaneously in the Color Glass Condensate framework
- Heavy quark production in pA collisions is also interesting per se as a means of studying the physics of saturation

Leading twist shadowing

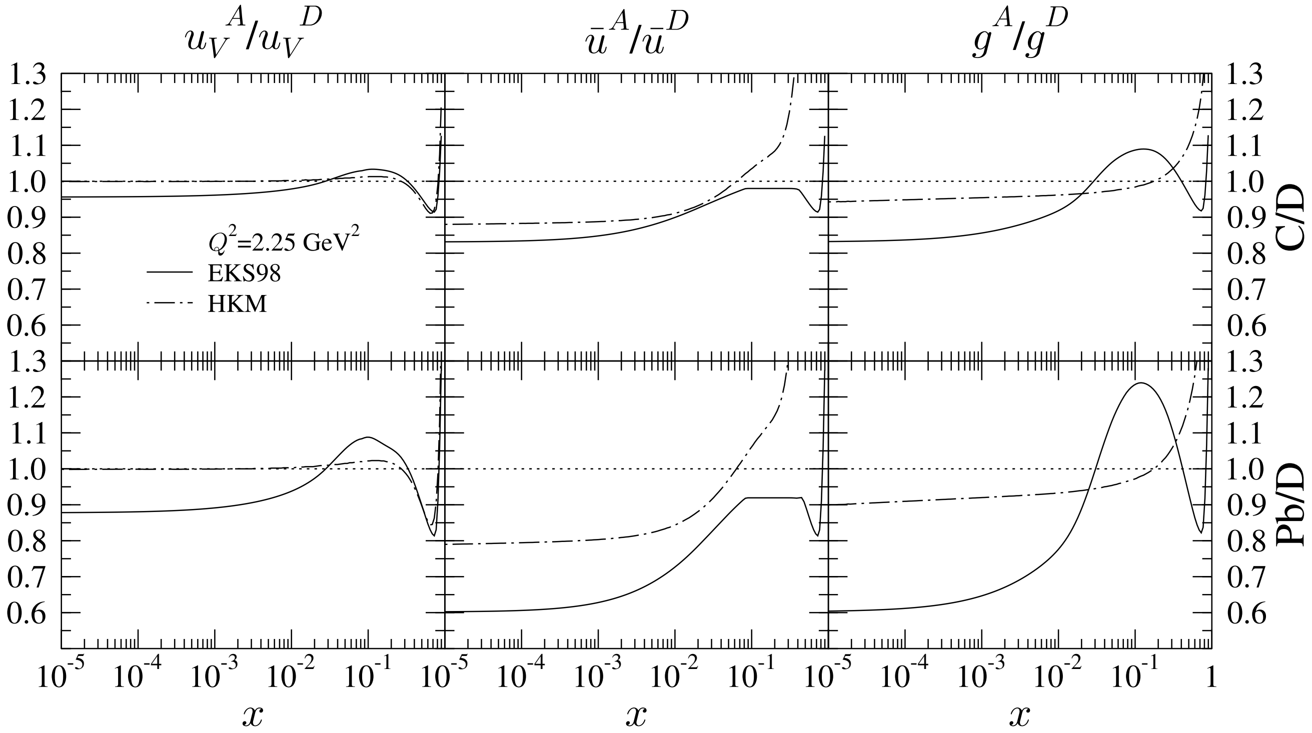
- Interactions among the partons in the nuclear target :



  - Non-perturbative modification of the expectation value of twist-2 operators due to the nucleus
  - Collinear factorization can accomodate these effects
  - The PDFs of a nucleus differ from $A\ f_p(x, Q^2)$

Parametrizations of nuclear PDFs

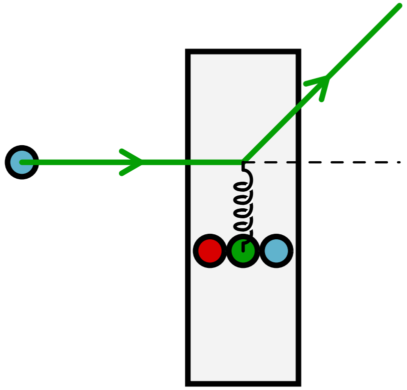
- Eskola, Kolhinen, Salgado (1998)
  Hirai, Kumano, Miyama (2001)



- ◆ The discrepancy is mostly due to the scarcity of data
  ▷ importance of doing a pA run at the LHC...

Shadowing and rescatterings

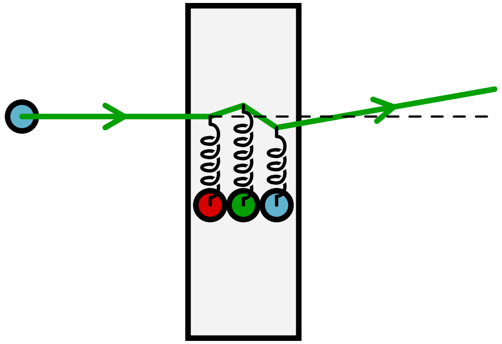
- Single scattering at high $p_\perp$ (large x) :



  - In the absence of leading twist shadowing, differential cross-sections at high $p_\perp$ scale like A (volume scaling)
  - Single scattering dominates ▷ leading twist formalism
  - As seen previously, the PDFs may be modified by intra-nuclear effects

Shadowing and rescatterings

- Multiple scatterings at low $p_\perp$ (small x) :



  - One of the scatterings “produces” the final state, while the others just change its momentum
  - Each extra scattering corresponds to a correction $\alpha_s A^{1/3}\Lambda^2/p_\perp^2$
  - If there is no leading twist shadowing, differential cross-sections at low $p_\perp$ scale like $A^{2/3}$ (area scaling)
  - Cannot be included in the leading twist formalism of collinear factorization

Wrapping it all in colored glass...

- Rescattering effects are important in collisions involving nuclei, but cannot be included in a natural way by using collinear factorization
- The Color Glass Condensate framework can address this problem. It incorporates :
    - Interactions between partons inside the projectiles
    - Non-linear effects in the evolution with energy
    - Multiple scatterings of the incoming/outgoing particles (equivalent to the color field present in hard comover scenarios)
- Drawbacks :
    - Exists only at LO so far
    - More difficult implementation
    - PDFs are replaced by correlators of Wilson lines (universal, but one may need different correlators for different final states)

Color glass condensate

McLerran, Venugopalan (1994)
Iancu, Leonidov, McLerran (2001)

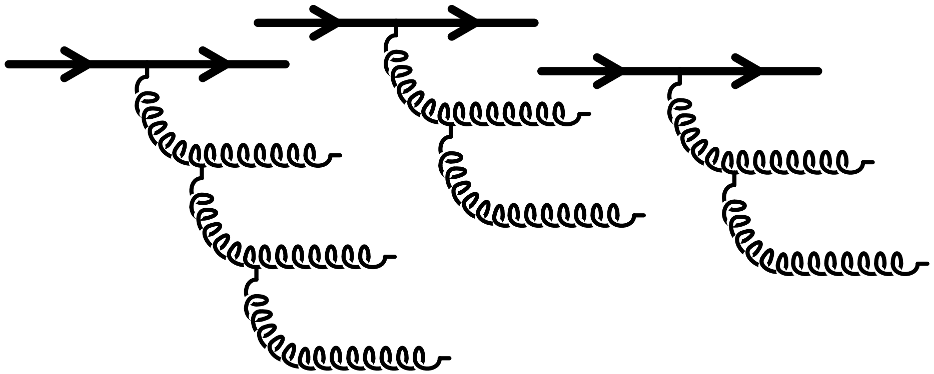
- Small x modes have a large occupation number
  - ▷ they are described by a classical color field
- Large x modes are described by “frozen” color sources ρ_a
- The classical field obeys Yang-Mills equations:

$$\left[D_\nu, F^{\nu\mu}\right]_a = \delta^{\mu +}\delta(x^-)\rho_a(\vec{\boldsymbol{x}}_\perp)$$

- The color sources ρ_a are random, and their distribution is described by a functional $W_{x_0}[\rho]$, where x_0 is the separation between “small x” et “large x”. $W_{x_0}[\rho]$ changes with x_0 according to the JIMWLK equation.
- Observables are calculated in the presence of the classical field, and then averaged over the configurations of the sources ρ_a:

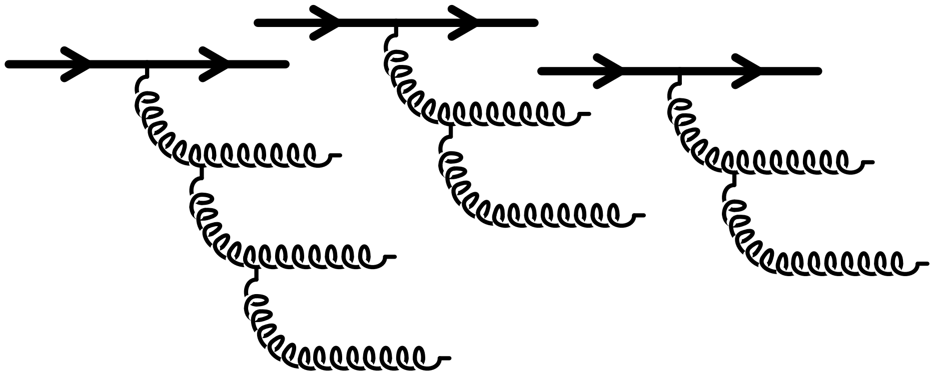
$$\langle\mathcal{O}\rangle = \int [D\rho_a]\, W_{x_0}[\rho_a]\, \mathcal{O}[\rho_a]$$

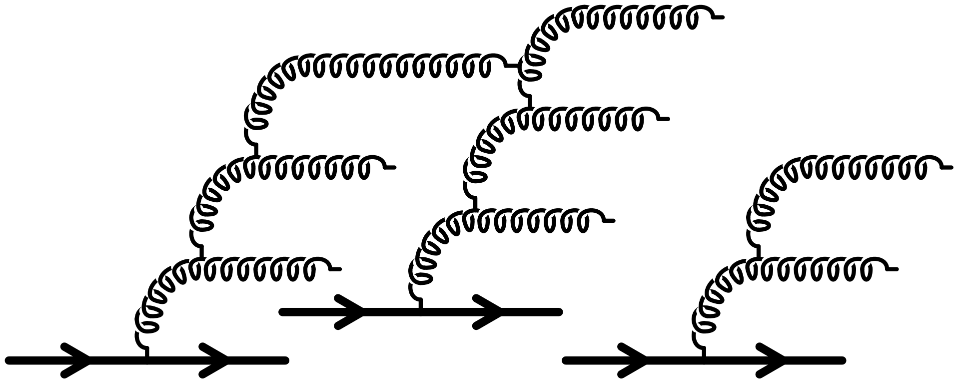
Quark production in the CGC



▷ get $W_{x_1}[\rho_1]$ for the first projectile

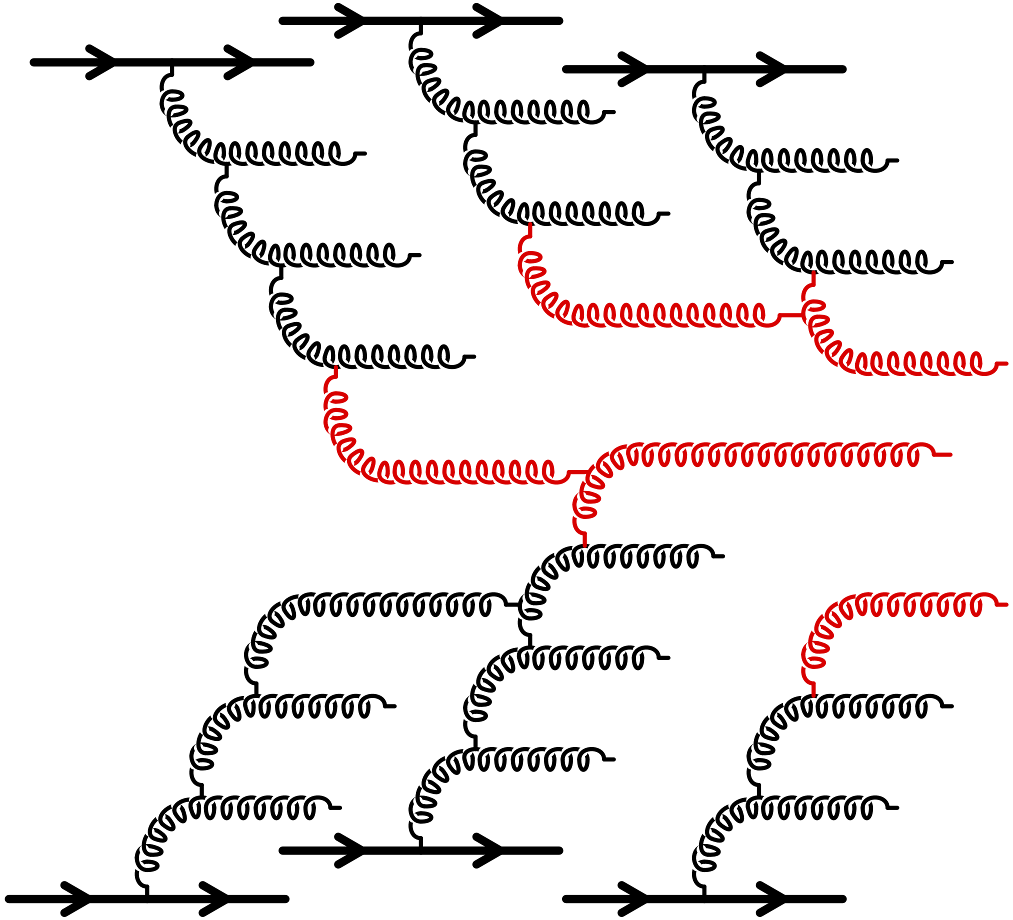
Quark production in the CGC





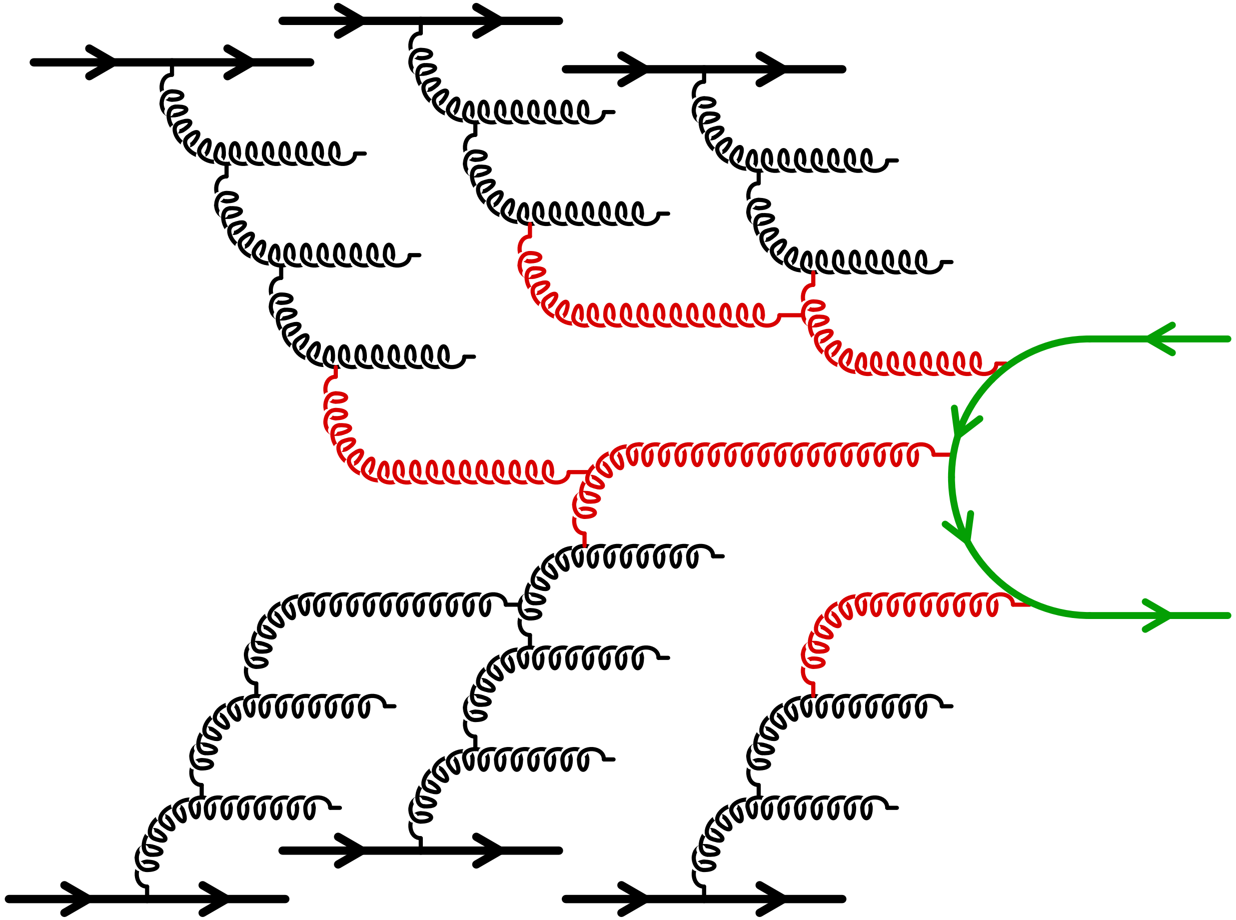
▷ get $W_{x_2}[\rho_2]$ for the second projectile

Quark production in the CGC



▷ solve the Yang-Mills equations for the sources ρ_1, ρ_2

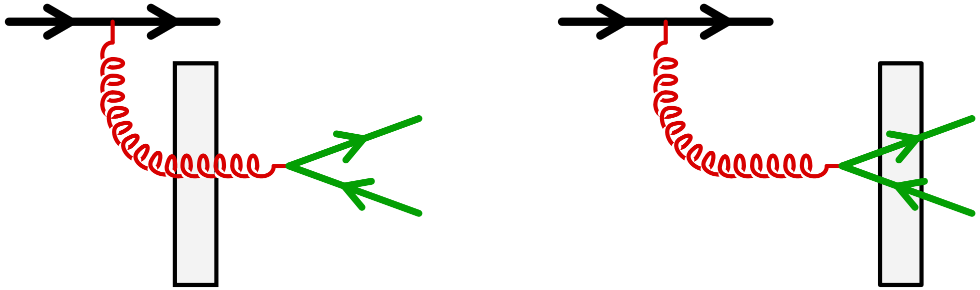
Quark production in the CGC



▷ compute the quark propagator in the classical field

Quark production in the CGC

- The program outlined above cannot be completed analytically in general
- For pA collisions, one may assume that the proton is a dilute object while the nucleus is dense
  ▷ keep all orders in ρ_A, but only the first order in ρ_p
  Blaizot, FG, Venugopalan (2004)
- (Very sketchy) diagrammatic content :



- In this approximation, all the steps can be carried out analytically

Quark production in the CGC

- Pair production cross-section :

$$
\begin{aligned}
\frac{d\sigma}{d\Phi_Q\, d\Phi_{\overline{Q}}} = \int \frac{\delta(\vec{\boldsymbol{k}}_{1\perp}+\vec{\boldsymbol{k}}_{2\perp}-\vec{\boldsymbol{p}}_\perp(Q\overline{Q}))}{\boldsymbol{k}_{1\perp}^2\,\boldsymbol{k}_{2\perp}^2}\,\varphi_p(x_1,\vec{\boldsymbol{k}}_{1\perp})\\
\times\Big\{\int_{\vec{\boldsymbol{k}}_\perp,\vec{\boldsymbol{k}}'_\perp} \mathcal{M}_{q\bar q}(\vec{\boldsymbol{k}}_\perp)\mathcal{M}^*_{q\bar q}(\vec{\boldsymbol{k}}'_\perp)\,\phi_A^{(4)}(x_2,\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp,\vec{\boldsymbol{k}}'_\perp)\\
+\int_{\vec{\boldsymbol{k}}_\perp}\Big[\mathcal{M}_{q\bar q}(\vec{\boldsymbol{k}}_\perp)\mathcal{M}_g^*+\text{h.c.}\Big]\,\phi_A^{(3)}(x_2,\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp)\\
+\mathcal{M}_g\mathcal{M}_g^*\,\phi_A^{(2)}(x_2,\vec{\boldsymbol{k}}_{2\perp})\Big\}
\end{aligned}
$$

- $k_\perp$-factorization valid on the proton side, but not for the nucleus: one needs three different “distributions” to describe the nucleus
- $\phi_A^{(2,3,4)}$ are correlators of 2,3 and 4 Wilson lines
- Reduces to the $k_\perp$-factorized formula of Collins & Ellis in some approximations

Quark production in the CGC

- Single quark production cross-section :

$$\frac{d\sigma}{d\Phi_Q} = \int \frac{1}{\boldsymbol{k}_{1\perp}^2 \boldsymbol{k}_{2\perp}^2} \varphi_p(x_1, \vec{\boldsymbol{k}}_{1\perp})$$
$$\times \left\{ 8 + \int_{\vec{\boldsymbol{k}}_\perp} I_3(\vec{\boldsymbol{k}}_\perp)\, \phi_A^{(3)}(x_2, \vec{\boldsymbol{k}}_{2\perp} | \vec{\boldsymbol{k}}_\perp) + I_2\, \phi_A^{(2)}(x_2, \vec{\boldsymbol{k}}_{2\perp}) \right\}$$

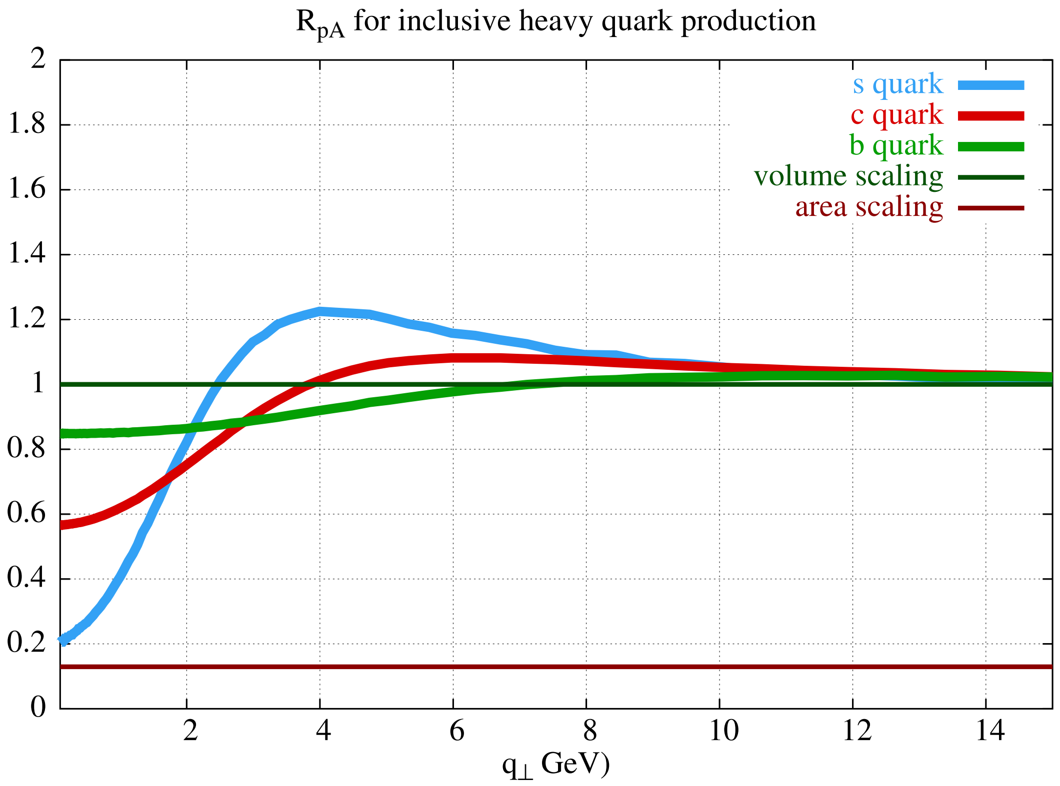
  - still no $k_\perp$-factorization on the nucleus side
  - contains only 2-point and 3-point correlators
  - The functions I_2 and I_3 are known in closed form
  - This formula (as well as the previous one) includes leading-twist shadowing and multiple scatterings (hard “comovers”) for pA collisions

Quark production in the CGC

- Take the McLerran-Venugopalan model (gaussian $W_{x_0}[\rho]$)
- Then assume for simplicity that :

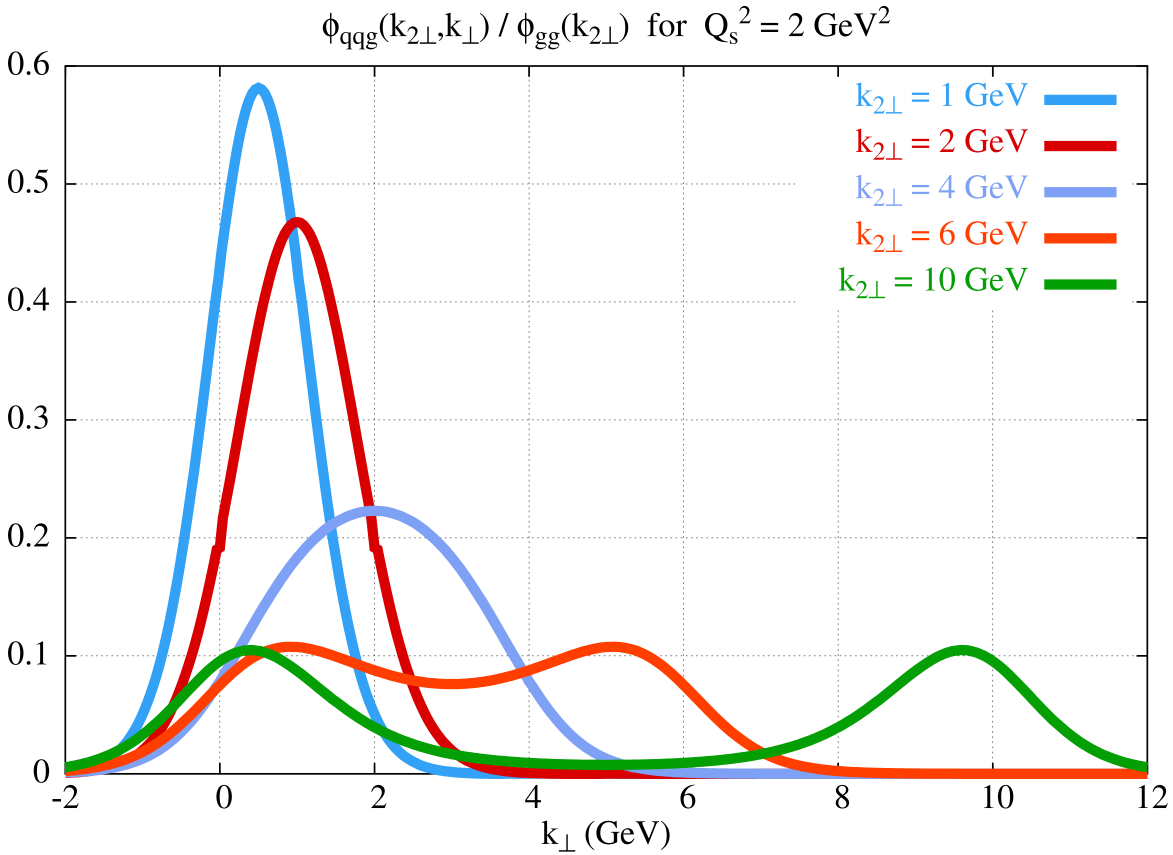
$$\phi_A^{(3)}(x_2,\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp) \approx (2\pi)^2 \frac{1}{2}\left[\delta(\vec{\boldsymbol{k}}_\perp)+\delta(\vec{\boldsymbol{k}}_\perp-\vec{\boldsymbol{k}}_{2\perp})\right]\phi_A^{(2)}(x_2,\vec{\boldsymbol{k}}_{2\perp})$$

(this is the condition to have $k_\perp$-factorization)



Quark production in the CGC

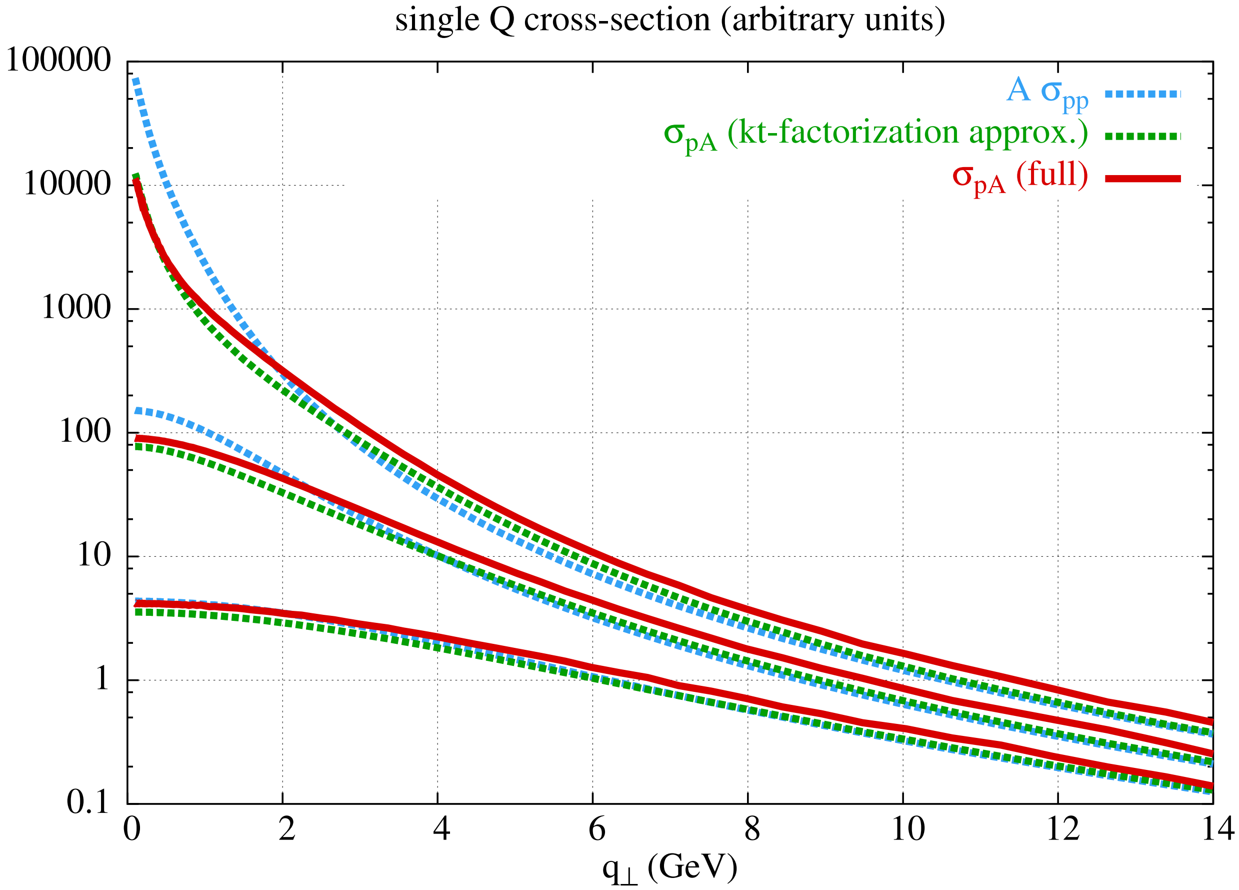
- How good is the assumption of $k_\perp$-factorization?



▷ far from a sum of two δ functions, strong broadening

Quark production in the CGC

- Full single quark cross-section: (preliminary)



▷ the breaking of $\boldsymbol{k}_\perp$-factorization has a moderate effect ($\sim 20\%$ increase for charm)

3 - AA

Charmonium suppression in the QGP

Matsui, Satz (1986), Kharzeev, Satz (1994), and many others...

- If the Debye screening radius is smaller than the size of quarkonium state, the binding of the Q and $\overline{Q}$ is destroyed by the surrounding light quarks and gluons
- The Q and $\overline{Q}$ drift in the QGP, and cannot find each other again
- At hadronization time, they pick up a light quark and form D or B mesons
- A suppression of the ratio $[J/\psi]$ / [Open charm] could be a signature of the QGP
- Not as simple though : there is also a suppression in pA collisions. One should therefore look for “anomalous” suppression effects

Normal nuclear suppression

- Parameterization of the J/ψ absorption in cold nuclear matter :

$$\sigma_{\rm abs}(\sqrt{s}) = \sigma_{\rm abs}(\sqrt{s_0}) \left(\frac{s}{s_0}\right)^{\Delta/2}$$

$$\sigma_{\rm abs}(\sqrt{s_0} = 17.3\ {\rm GeV}) = 5 \pm 0.5\ {\rm mb} \quad , \ \Delta \approx 0.125$$

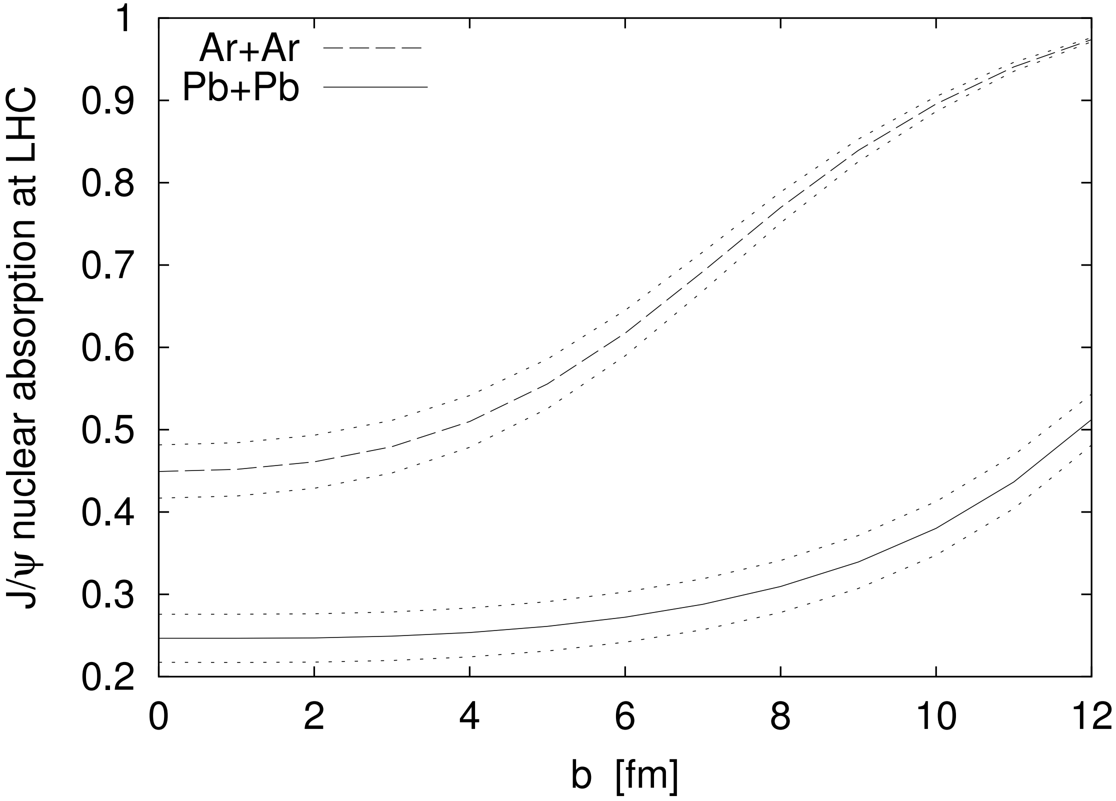
- Quarkonium survival probability in an AB collision :

$$S(\vec{\boldsymbol{b}}) = \int d^2\vec{\boldsymbol{s}}\, dz_{{}_A} dz_{{}_B}\ \rho_{{}_A}(\vec{\boldsymbol{s}}, z_{{}_A})\rho_{{}_B}(\vec{\boldsymbol{b}} - \vec{\boldsymbol{s}}, z_{{}_B})$$

$$\times \exp\left[-(A-1)\int_{z_A}^{\infty} dz \rho_{{}_A} \sigma_{\rm abs}\right] \exp\left[-(B-1)\int_{z_B}^{\infty} dz \rho_{{}_B} \sigma_{\rm abs}\right]$$

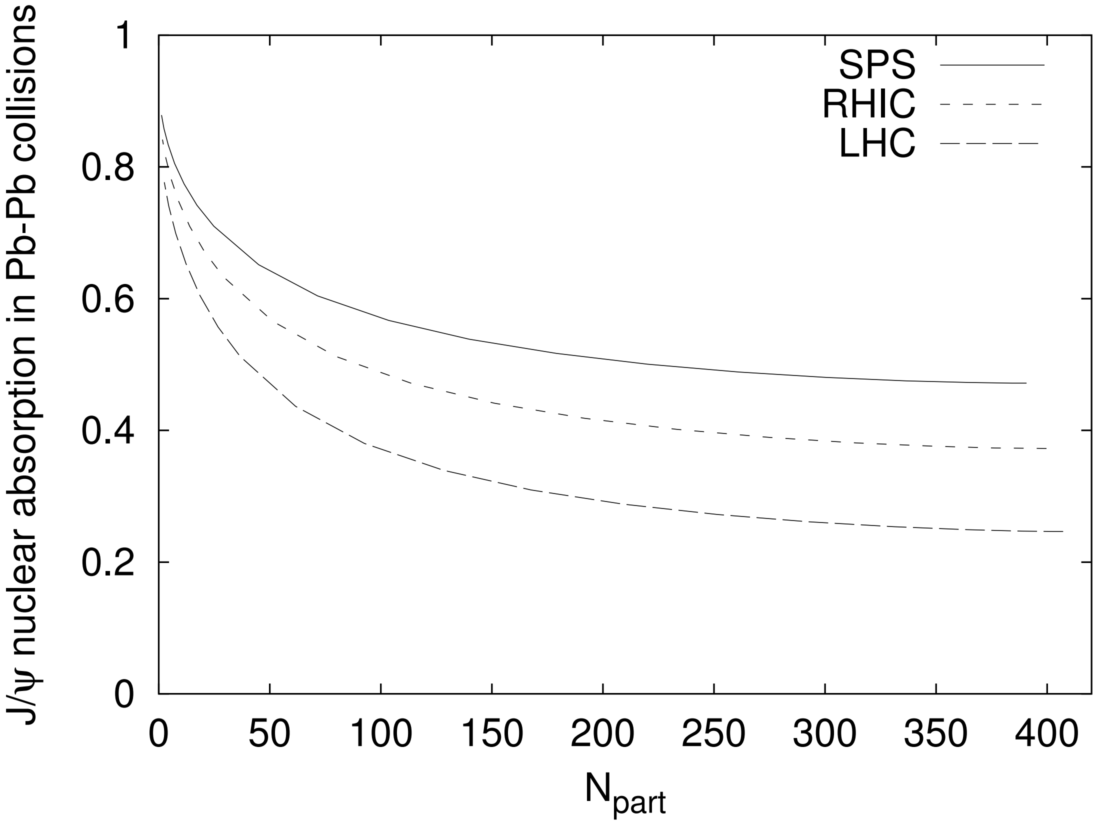
Normal nuclear suppression

- Impact parameter dependence of the survival probability :



Normal nuclear suppression

- $N_{\rm part}$ dependence of the survival probability :



Lattice results

- Reminder : only Euclidean quantities can be calculated directly in lattice Monte-Carlo simulations :

$$\text{Minkowkian} \;:\; e^{iS[A^\mu]} \quad\longrightarrow\quad \text{Euclidean} \;:\; e^{-S[A^\mu]}$$

- Potential between pairs of heavy quarks in a QGP
  - Can be fed into a non-relativistic Shöedinger equation in order to compute the binding energy of the bound states
- Extraction of the $Q\overline{Q}$ spectral functions from lattice data
  - Fairly new method, still in developement
  - Results in qualitative agreement with the previous one
- These issues are totally unexplored at finite μ_B

Heavy quark potential

- The “averaged” free-energy is obtained from Polyakov loops :

$$e^{-F(r,T)/T} = \frac{1}{9}\Big\langle \mathrm{tr}L(\vec{\boldsymbol{r}})\,\mathrm{tr}L^\dagger(\vec{0})\Big\rangle \quad , \quad L(\vec{\boldsymbol{r}}) = \prod_{i=1}^{N_\tau} U_0(\vec{\boldsymbol{r}},\tau)$$

- It can be divided into a color singlet and a color octet parts :

$$e^{-F(r,T)/T} = \frac{1}{9}e^{-F_1(r,T)/T} + \frac{8}{9}e^{-F_8(r,T)/T}$$

$$e^{-F_1(r,T)/T} = \frac{1}{3}\Big\langle \mathrm{tr}L(\vec{\boldsymbol{r}})L^\dagger(\vec{0})\Big\rangle$$

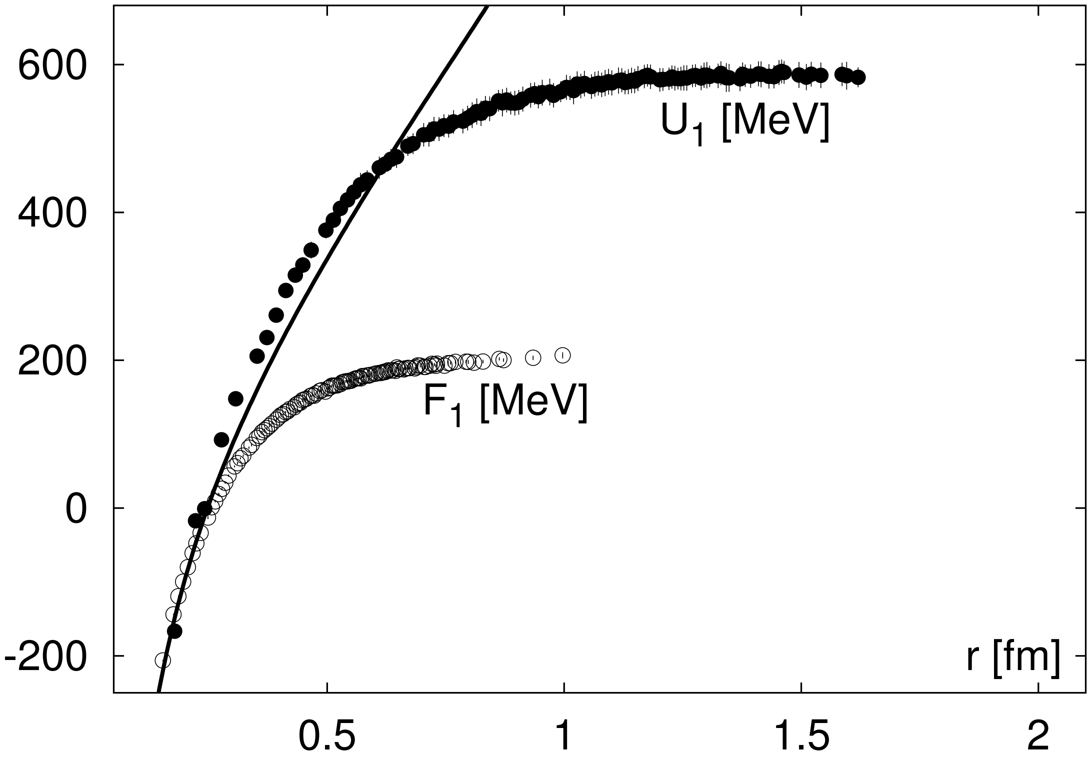
$$e^{-F_8(r,T)/T} = \frac{1}{8}\Big\langle \mathrm{tr}L(\vec{\boldsymbol{r}})\,\mathrm{tr}L^\dagger(\vec{0})\Big\rangle - \frac{1}{24}\Big\langle \mathrm{tr}L(\vec{\boldsymbol{r}})L^\dagger(\vec{0})\Big\rangle$$

- In principle, one needs to transform that into the potential energy U :

$$F = U - TS \quad , \quad S = -\frac{\partial F}{\partial T}$$

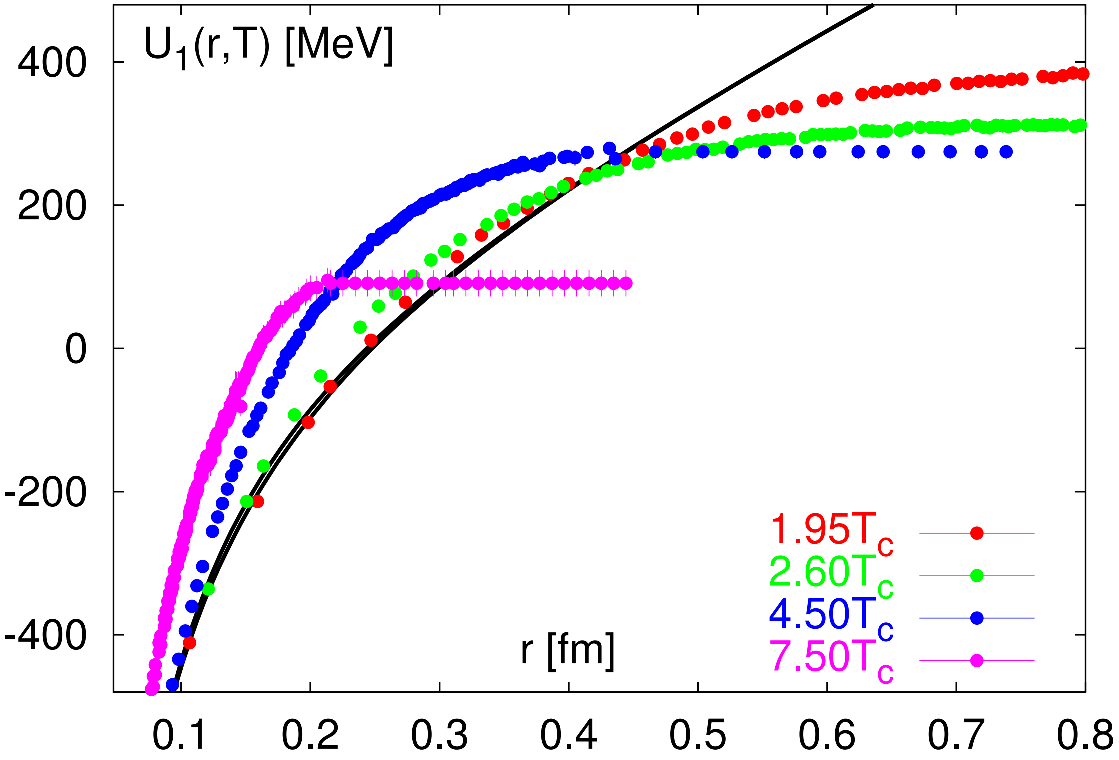
Heavy quark potential

- Results for $T/T_c = 1.5$:



Heavy quark potential

- T-dependence of the potential above T_c :



Heavy quark potential

- What do we do with that?
  - Shröedinger equation for $Q\overline{Q}$ bound states :

$$\left[2m_Q + \frac{1}{m_Q}\vec{\nabla}^2 + U_1(r,T)\right]\psi_i = M_i(T)\psi_i$$

  - Non-relativistic
  - Assumes 2-body interactions only
- Dissociation temperatures :

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'
T_d/T_c	2.0	1.1	1.1	4.5	2.0	2.0

▷ the quarkonium states do not get immediately dissolved above the critical temperature

Heavy quark spectral functions

- Method for extracting spectral functions :

$$G_H(\tau,\vec{\boldsymbol{p}}) = \int_0^\infty d\omega\ \rho_H(\omega,\vec{\boldsymbol{p}}|T)\ \frac{\cosh(\omega(\tau-1/2T))}{\sinh(\omega/2T)}$$

$$G_H(\tau,\vec{\boldsymbol{p}}) = \int d^3\vec{\boldsymbol{x}}\ e^{i\vec{\boldsymbol{p}}\cdot\vec{\boldsymbol{x}}}\left\langle J_H(\tau,\vec{\boldsymbol{x}})J_H(0,\vec{0})\right\rangle \quad , \quad J_H = \overline{\psi}\,\Gamma_H\,\psi$$

state	χ_c^0	η_c	J/ψ	χ_c^1
Γ_H	1	γ_5	γ_μ	$\gamma_\mu\gamma_5$

- $\rho_H(\omega,\boldsymbol{p})$ has a sharp peak for stable states in the corresponding channel (broad peak for an unstable state)
- Main problem : $G_H(\tau,\vec{\boldsymbol{p}})$ is known at a finite number of τ's
  ▷ the inversion of the spectral integral in order to obtain the function ρ_H is a mathematically ill-defined problem

Heavy quark spectral functions

- Maximum Entropy Method :
  - Many more degrees of freedom in $\rho_H(\omega,\vec{\boldsymbol{p}})$ than data points
    ▷ a χ^2-fit would have flat directions...
  - Most of the multiple solutions would have unphysical features: non-positivity, not smooth, incorrect large ω behavior
  - Idea : add a convex term F to the χ^2 so that there is a unique minimum

$$\chi^2 \longrightarrow \chi^2 + \alpha F[\rho_H]$$

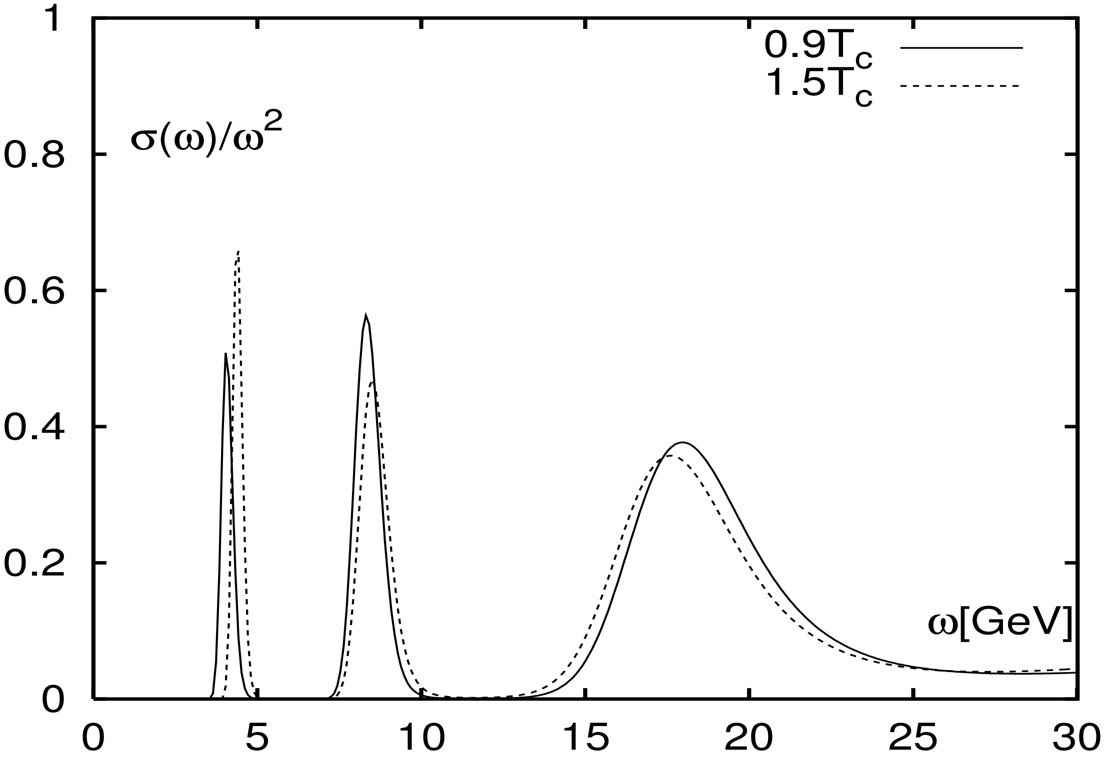
  - MEM :

$$F[\rho_H] = \int_0^\infty d\omega\,\left[\rho_H(\omega) - \rho_0(\omega) - \rho_H(\omega)\ln(\rho_H(\omega)/\rho_0(\omega))\right]$$

▷ ensures the positivity of ρ_H
▷ for $\alpha \to \infty$, the solution wants to be identical to the “prior” ρ_0
▷ use with extreme caution because you may only get what you bring...

Heavy quark spectral function

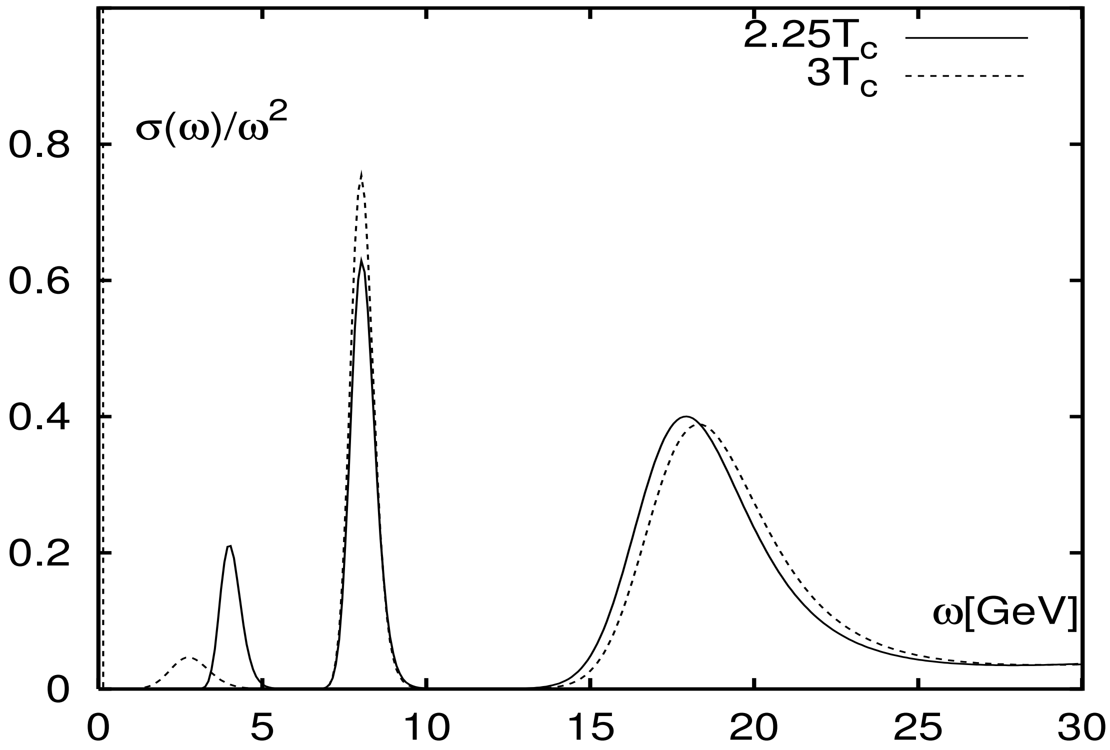
- J/ψ spectral function below T_c :



- The second and third peaks (the fat ones...) are lattice artifacts. Shouldn't we worry about them contaminating the physical peak?

Heavy quark spectral function

- J/ψ spectral function above T_c :



- The J/ψ peak starts going down for T above $2T_c$
  ▷ good qualitative agreement with the method based on the heavy quark potential

QQbar recombination

- What has been said so far is correct if there is only a few $Q\overline{Q}$ pairs in the system
- At LHC energies, pQCD predicts that hundreds of $c\bar{c}$ pairs are being produced in a central PbPb collision
- Q and $\overline{Q}$ that have been produced uncorrelated may encounter and form a quarkonium state
- Model independent estimates :
    - $\mathrm{Prob}(J/\psi) \sim N_c/N_{u,d,s} \sim N_{c\bar{c}}/N_{\mathrm{ch}}$
    - $N_{J/\psi} \sim N_{c\bar{c}}^2/N_{\mathrm{ch}}$
    - Since $N_{c\bar{c}}^2$ grows faster with energy than N_{ch}, this mechanism of J/ψ production will eventually be dominant
- Two different implementations :
    - Statistical hadronization
    - Kinetic models

Statistical hadronization

Braun-Munzinger, Stachel (2000)

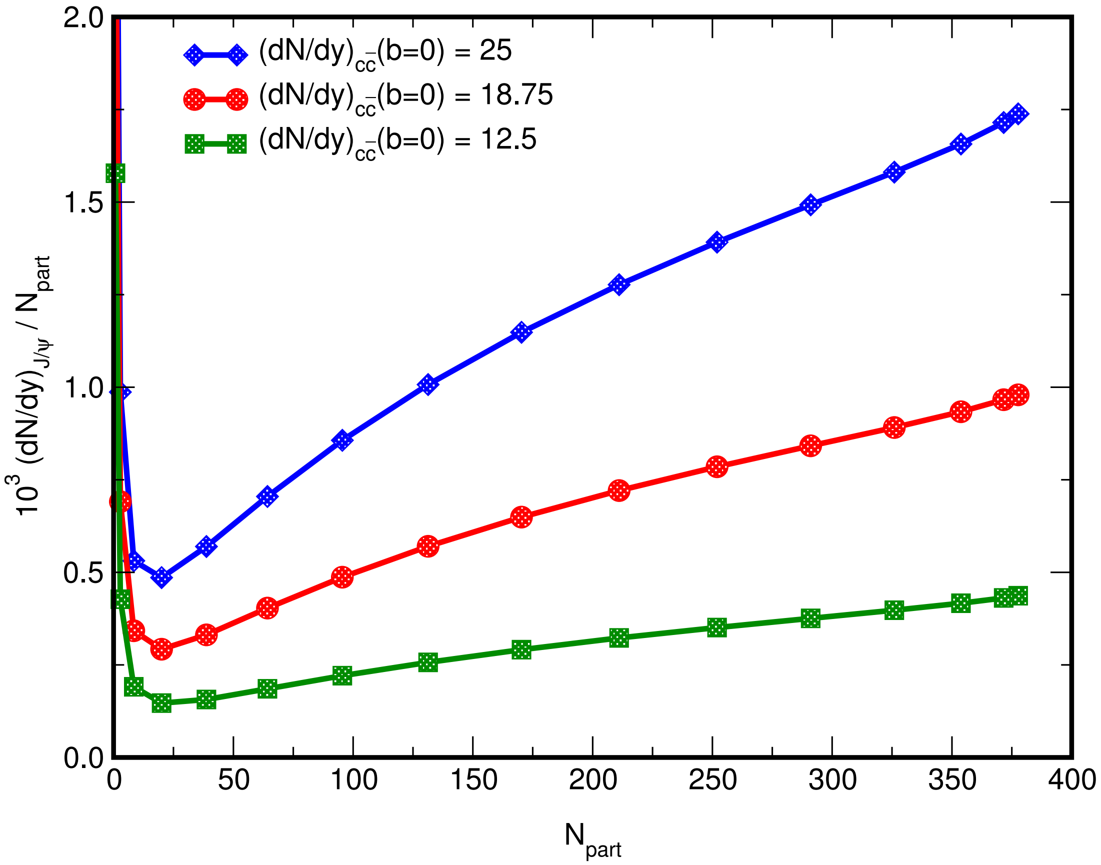
- Early attemps to include charm in thermal fits underpredicted the yield of charmed hadrons
- However, the ratio $\sigma_{\psi'}/\sigma_{J/\psi}$ measured at SPS goes to its thermal value when $N_{\rm part}$ is large
- One assumes that the number of $c, \bar{c}$ quarks is determined by early hard collisions (no thermal production/annihilation)
- Hadronization is assumed to follow thermal distributions, modified by an "enhancement factor" γ_c (one power of γ_c per c or $\bar{c}$ quark in the hadron). Conservation of charm :

$$N_{c\bar{c}}^{\rm direct} = \frac{1}{2}\gamma_c V \sum_i \left(n_{\rm th}(D_i) + n_{\rm th}(\Lambda_i)\right) + \gamma_c^2 V \sum_i n_{\rm th}(\psi_i) + \cdots$$

- Then : $N_{_D} = \gamma_c V n_{\rm th}(D)$ and $N_{J/\psi} = \gamma_c^2 V n_{\rm th}(J/\psi)$

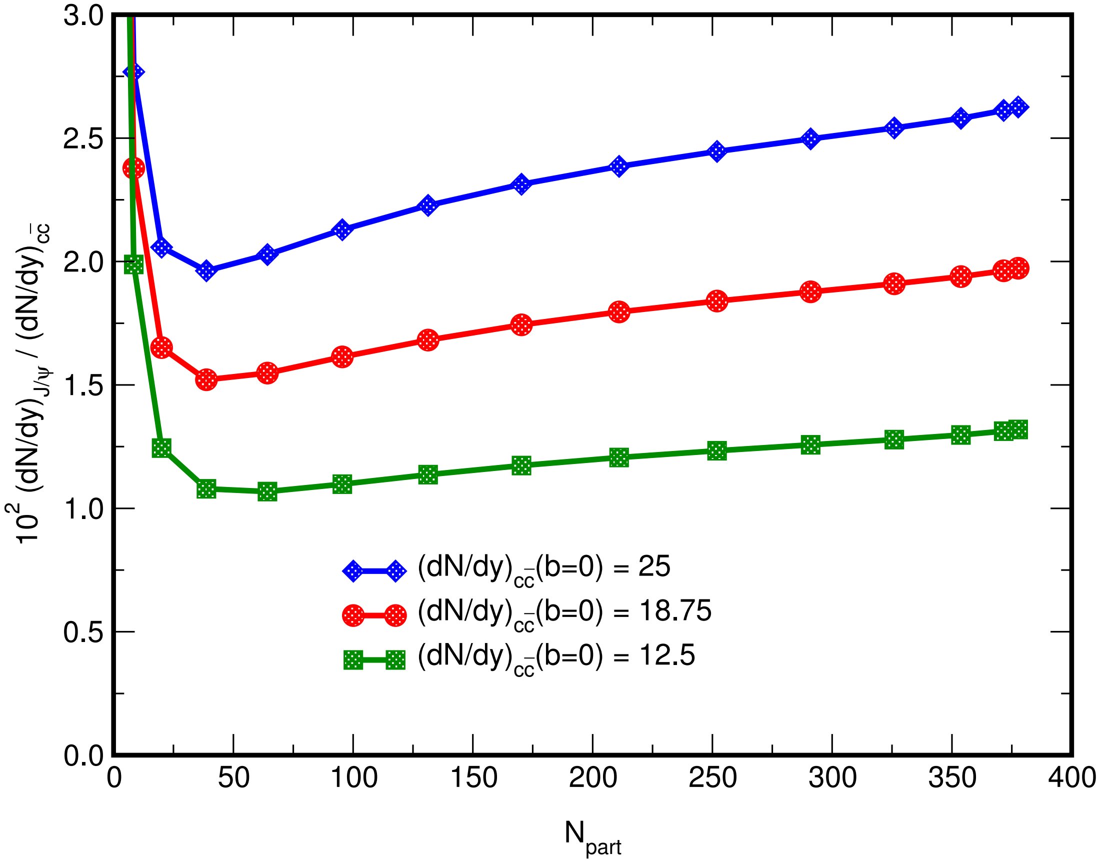
Statistical hadronization

- LHC : J/ψ yield per participant



Statistical hadronization

- LHC : J/ψ yield per $c\bar{c}$ pair



▷ this behavior with centrality is the opposite of what one expects in the Matsui-Satz scenario

Kinetic formation

Thews, Schroedter, Rafelski (2001)

- Dominant in-medium J/ψ breakup process : $g + J/\psi \to c\bar{c}$
- The reverse process $c\bar{c} \to J/\psi + g$ should also occur, with a probability that increases like the square of the density of charmed quarks
- Kinetic equation :

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F \frac{N_c N_{\bar{c}}}{V(\tau)} - \lambda_D \rho_{\rm g} N_{J/\psi}$$

  - $V(\tau)$: τ-dependent volume (expansion plays against recombination)
  - $\rho_{\rm g}$: gluon density
  - $\lambda_{F,D}$: formation and dissociation rates ($\lambda = \overline{\sigma v_{\rm rel}}$)

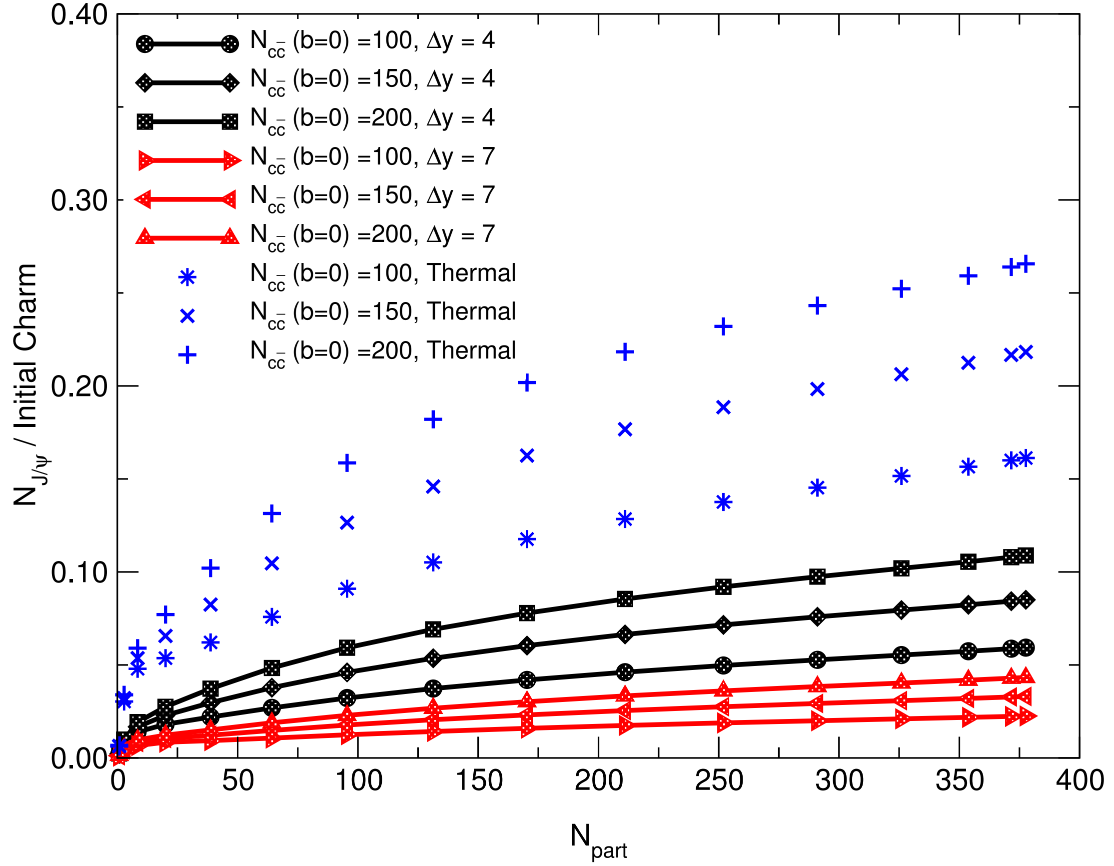
- Solution : $N_{J/\psi}(\tau) = \epsilon(\tau)\left[N_{J/\psi}(\tau_i) + N_{c\bar{c}}^2 \int_{\tau_i}^{\tau} d\tau \frac{\lambda_F}{V(\tau)\epsilon(\tau)}\right]$

with $\epsilon(\tau) = \exp(-\int_{\tau_i}^{\tau} d\tau\, \rho_{\rm g} \lambda_D)$

Kinetic formation

- introduction
- proton-proton
- proton-nucleus
- nucleus-nucleus
  - in-medium suppression
  - lattice results
  - QQbar recombination
- conclusions

- LHC : J/ψ yield per $c\bar{c}$ pair



- very sensitive to the distribution of initial charm

  See Gossiaux, Guiho, Aichelin (2004) for a Fokker-Plank description of the time evolution of the $c, \bar{c}$ distributions

Conclusions

- pp collisions :
  - Well under theoretical control for inclusive observables
  - J/ψ production still has some rough edges, especially spin
- pA collisions :
  - Shadowing corrections
  - Rescattering corrections (breaking of $k_\perp$-factorization fairly small for c quarks or heavier)
  - Forward measurements are very useful in order to probe saturation physics
  - A pA run at LHC energy would bring very valuable informations on all these issues
- AA collisions :
  - Lattice news : the J/ψ may survive in a QGP up to $T \sim 2T_c$
  - Quarkonium suppression if few $Q\overline{Q}$ pairs are produced
  - Quarkonium enhancement due to $Q\overline{Q}$ recombination if many heavy quarks are produced (although no hint of this at RHIC)