Charm production in AA collisions

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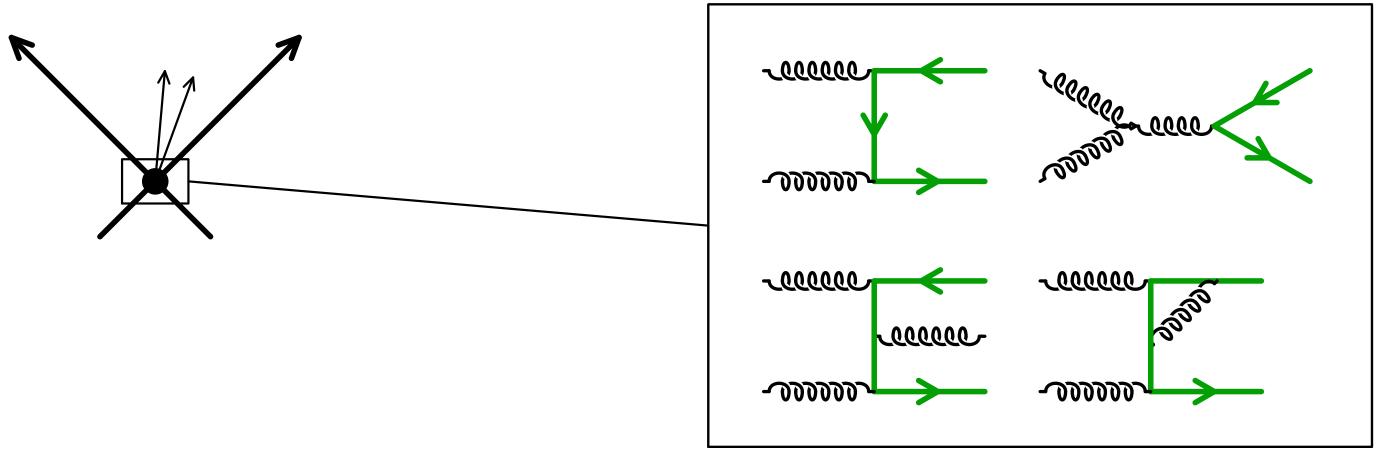
CERN and CEA/Saclay

Introduction
Collinear factorization
QQbar production at small x

Introduction

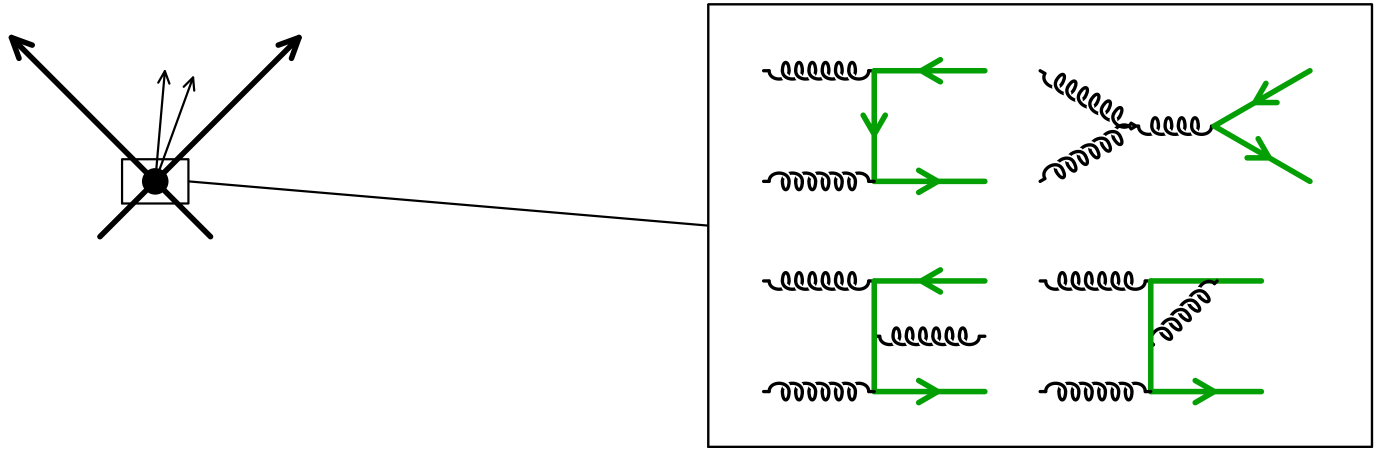
Heavy quark production

- Standard collinear factorization

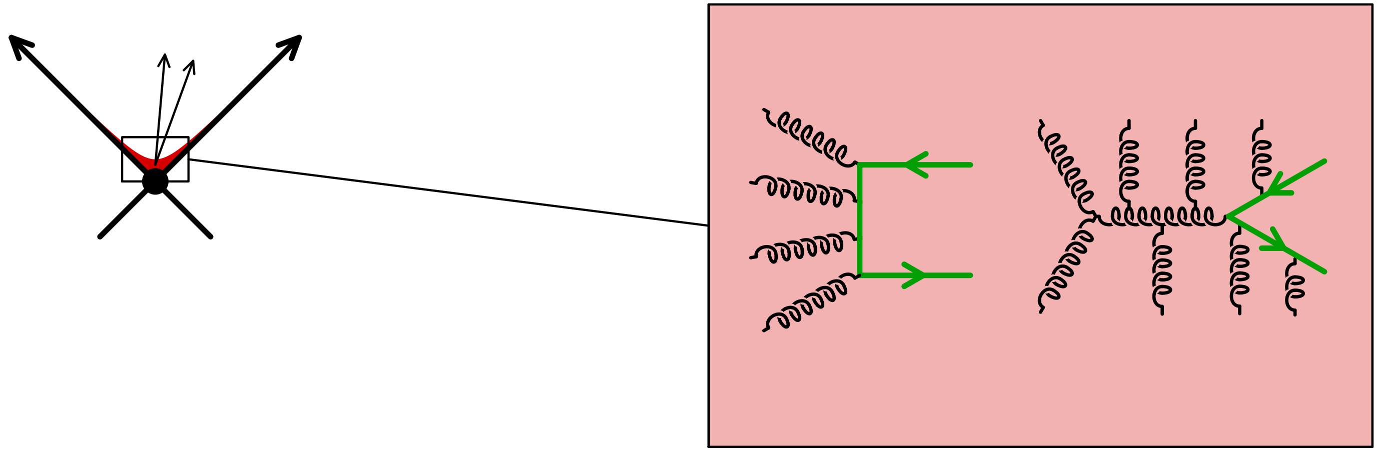


Heavy quark production

- Standard collinear factorization



- ...or higher twist effects ?



In-medium J/psi suppression

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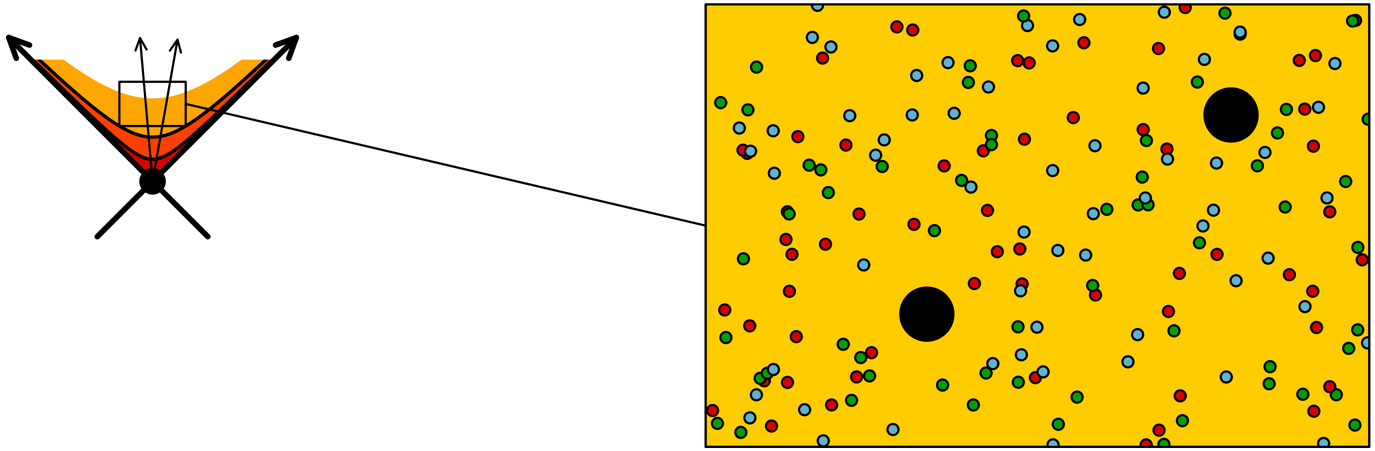
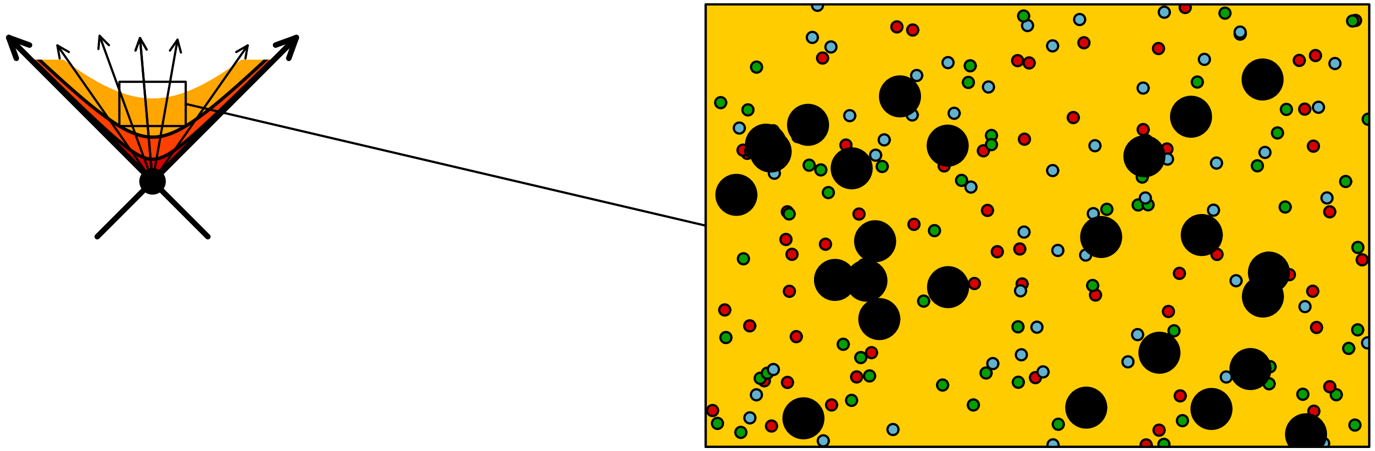


- Debye screening prevents the formation of quarkonium states Matsui, Satz (1986)
  - the heavy quarks pick a light quark instead and form a D meson
- Heavy quark potential, screening masses, and spectral functions (?) calculable on the lattice
- Relevant observable :

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

...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

Outline

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Collinear factorization

QQbar production at small x

- Collinear factorization
- $Q\overline{Q}$ production at small x

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Collinear factorization
- Fixed order
- Resummations

QQbar production at small x

Collinear factorization

Fixed order calculations

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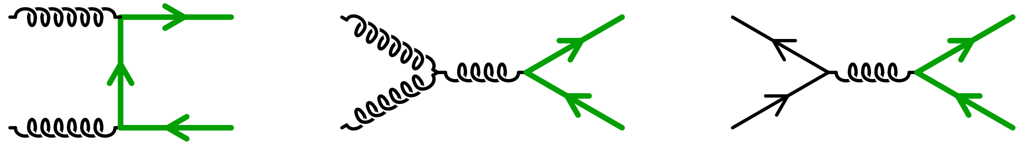
- LO $[\mathcal{O}(\alpha_s^2)]$:



Fixed order calculations

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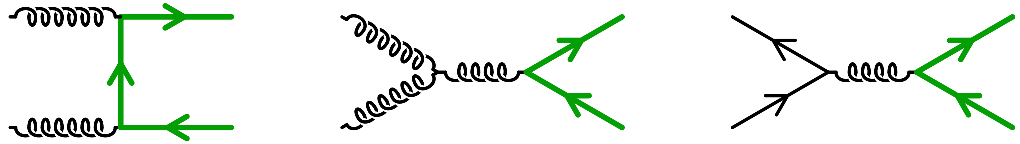
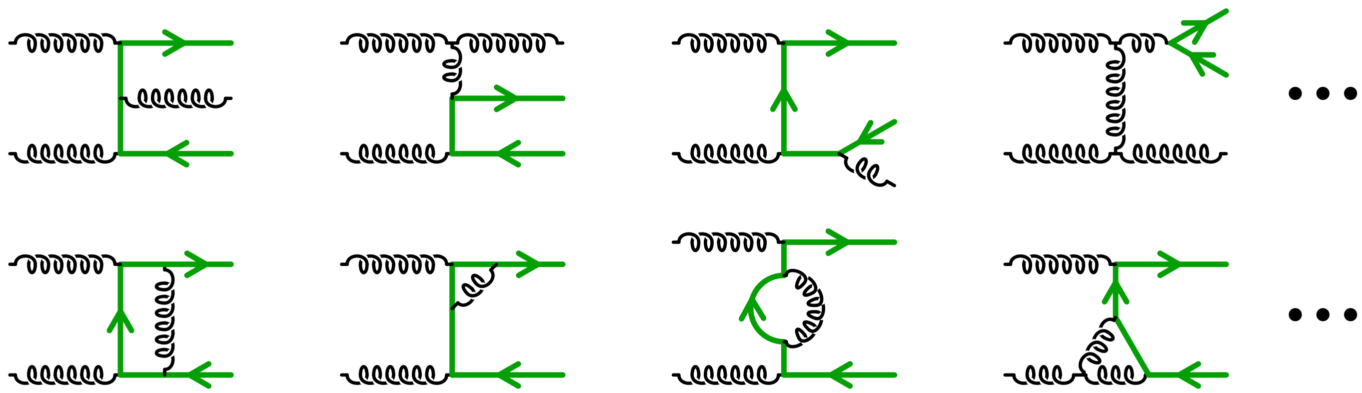
- LO $[\mathcal{O}(\alpha_s^2)]$:



- 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

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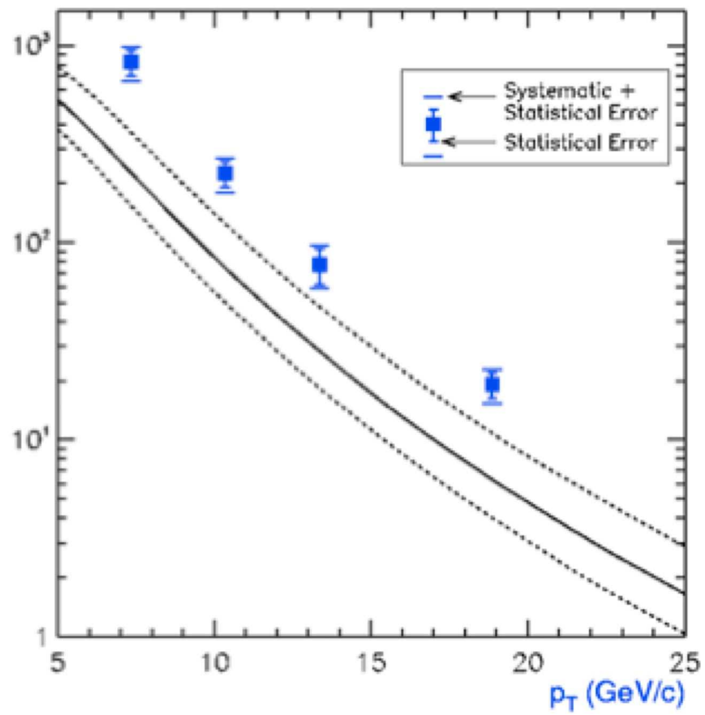
QQbar production at small x

- 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: $\mathcal{Q} = 1 - \phi_{Q\overline{Q}}/\pi$

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Resummation of logarithms

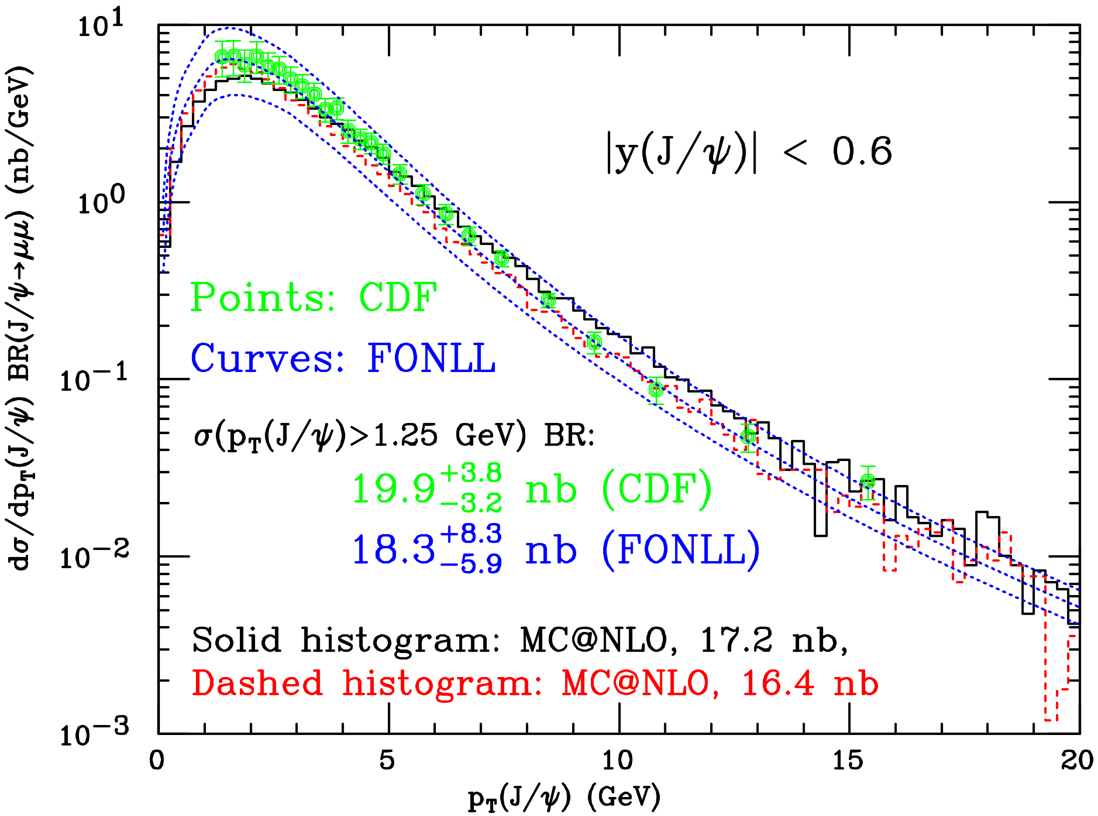
- Including these logarithms amounts to taking into account extra radiation in the final state
- Rearrangement of the perturbative expansion:

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

  - $n = 0$: 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

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



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

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- Relevant x range
- Kt-factorization
- Color glass condensate
- High density effects for pA
- AA collisions

QQbar production at small x

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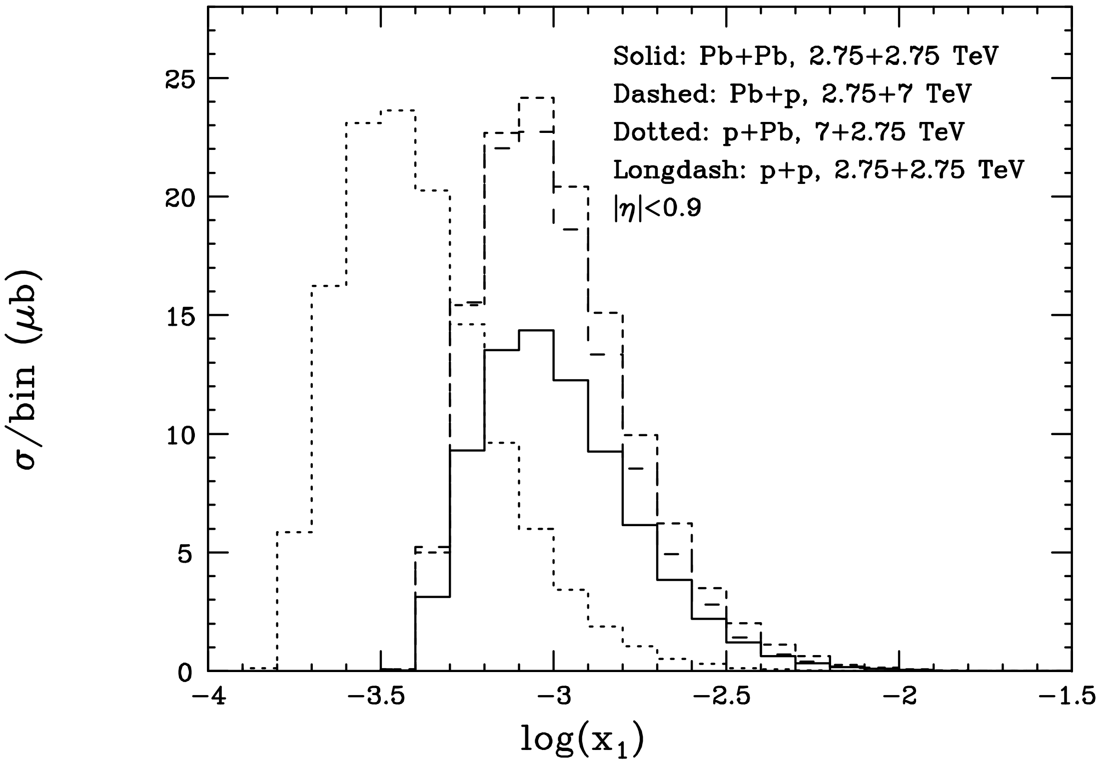
- x coverage for $c\bar{c}$ production at the LHC : central rapidity



Relevant x range at the LHC

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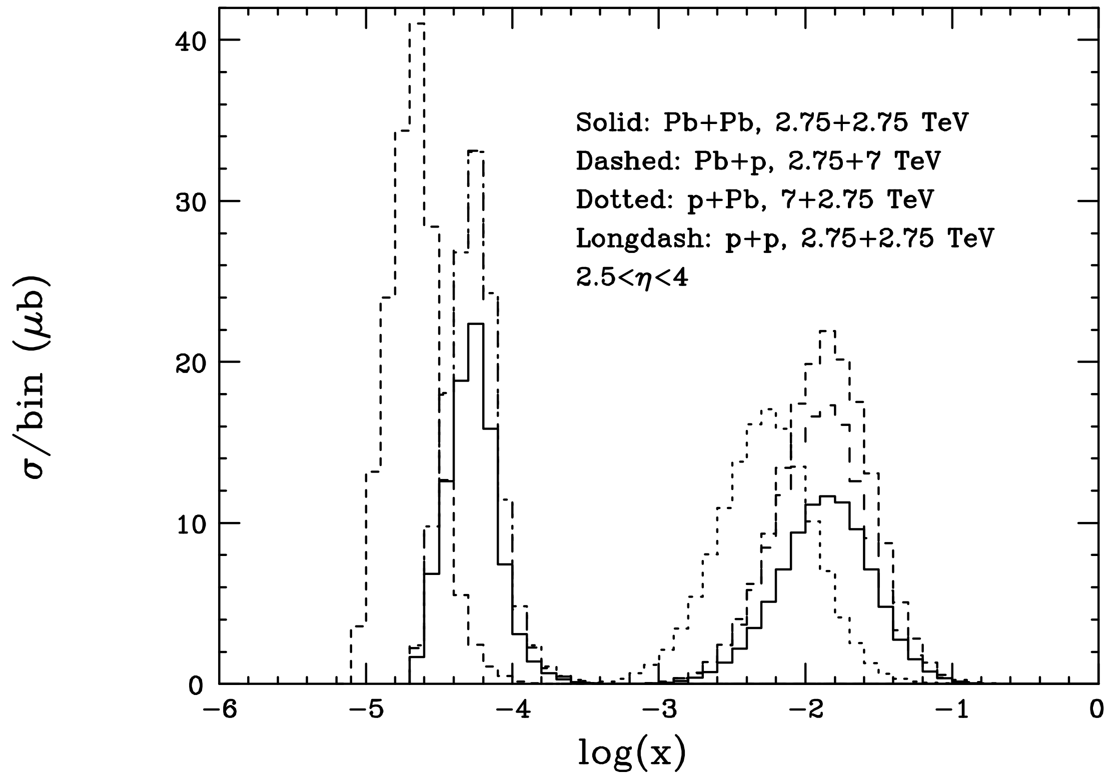
- x coverage for $c\bar{c}$ production at the LHC : forward rapidity



▷ very small values of x reached in one of the projectiles

Kt-factorization

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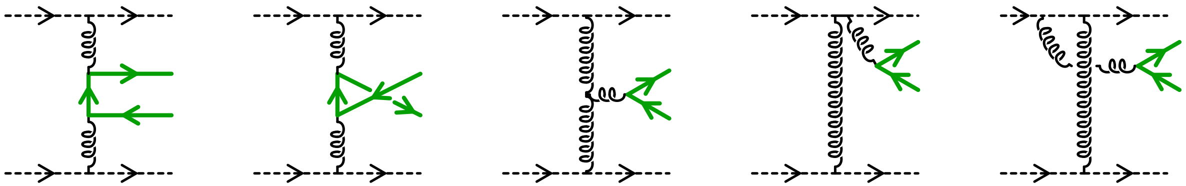
- Included diagrams :



- $Q\overline{Q}$ 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 :
  - Includes intrinsic $k_\perp$ and of resums logs of $1/x$
  - Some NLO and NNLO diagrams are already included
  - This formalism can be generalized to include saturation
- Cons :
  - The incoming gluons are off-shell $\Rightarrow$ difficult calculations
  - Only a subset of the NLO terms is included
  - Factorization proven only to Leading Log

Color glass condensate

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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

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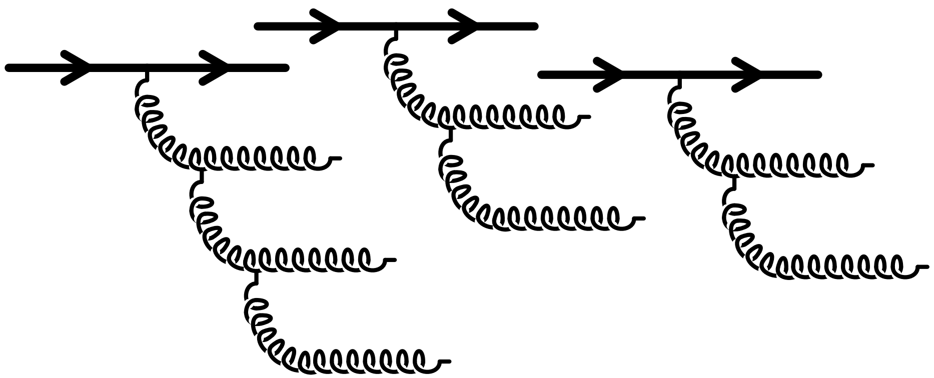
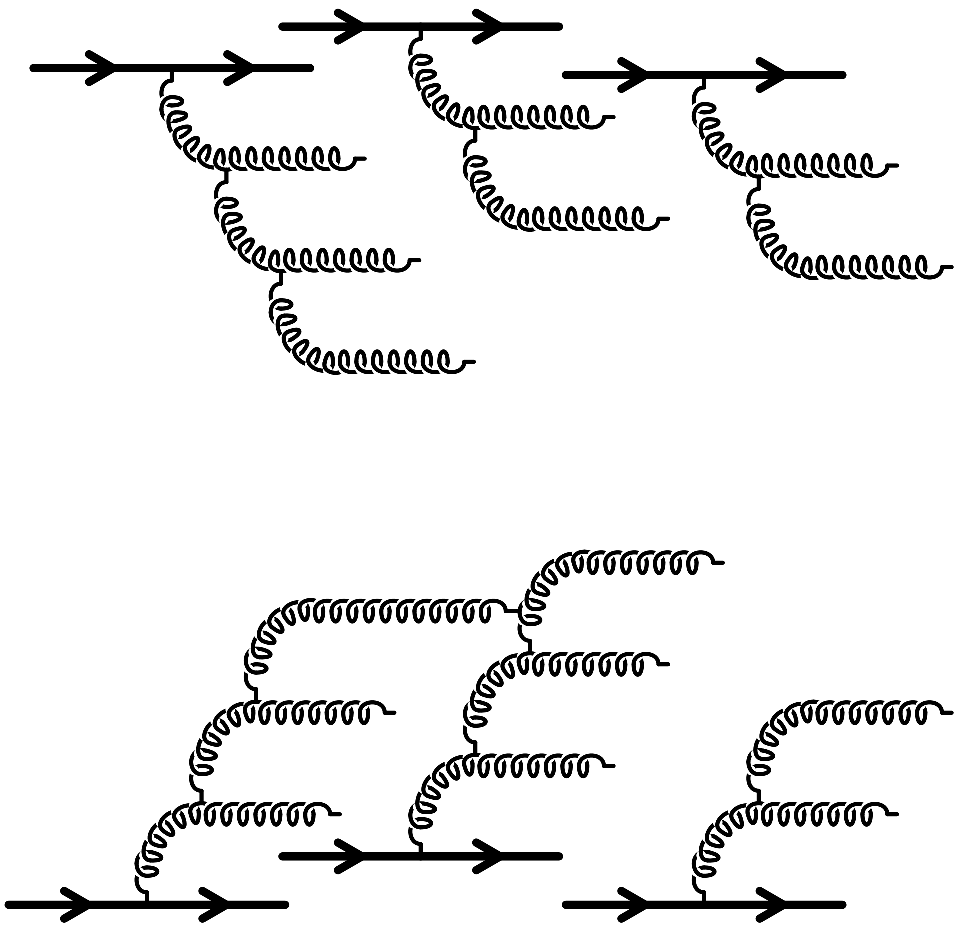


▷ get $W_{x_1}[\rho_1]$ for the first projectile

Quark production in the CGC



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

Quark production in the CGC

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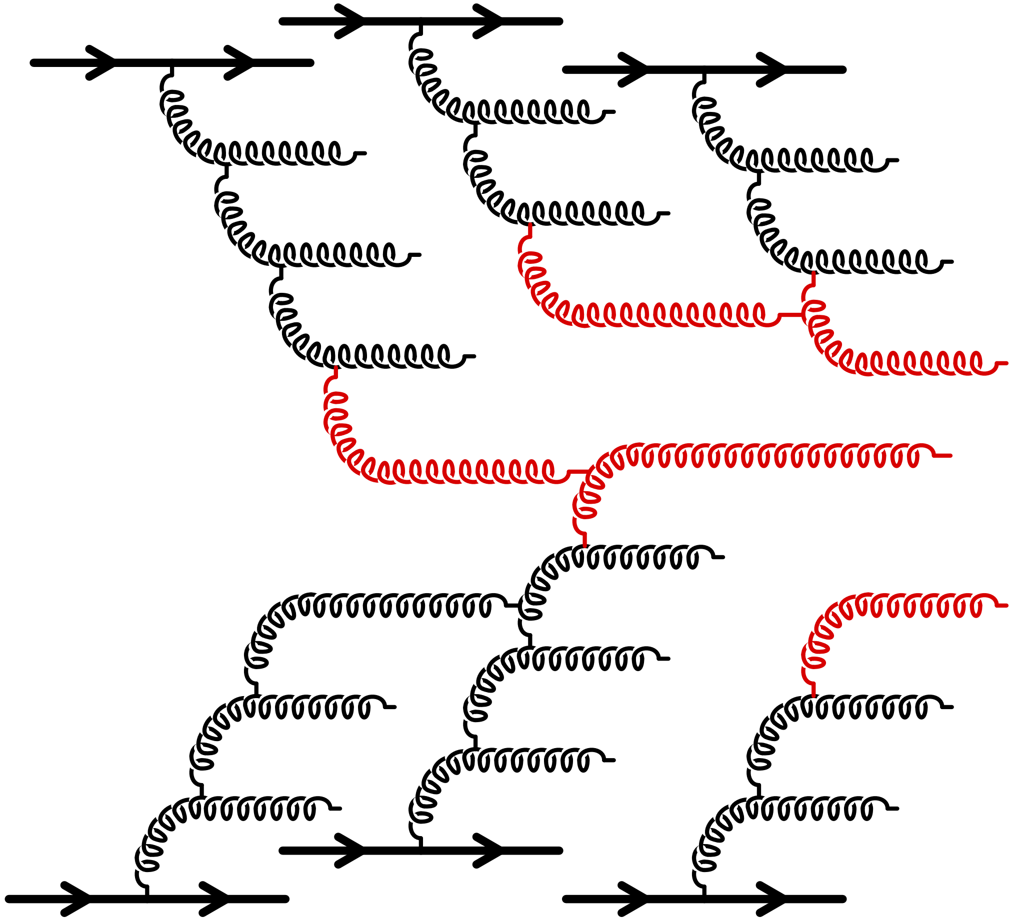

▷ solve the Yang-Mills equations for the sources ρ_1, ρ_2

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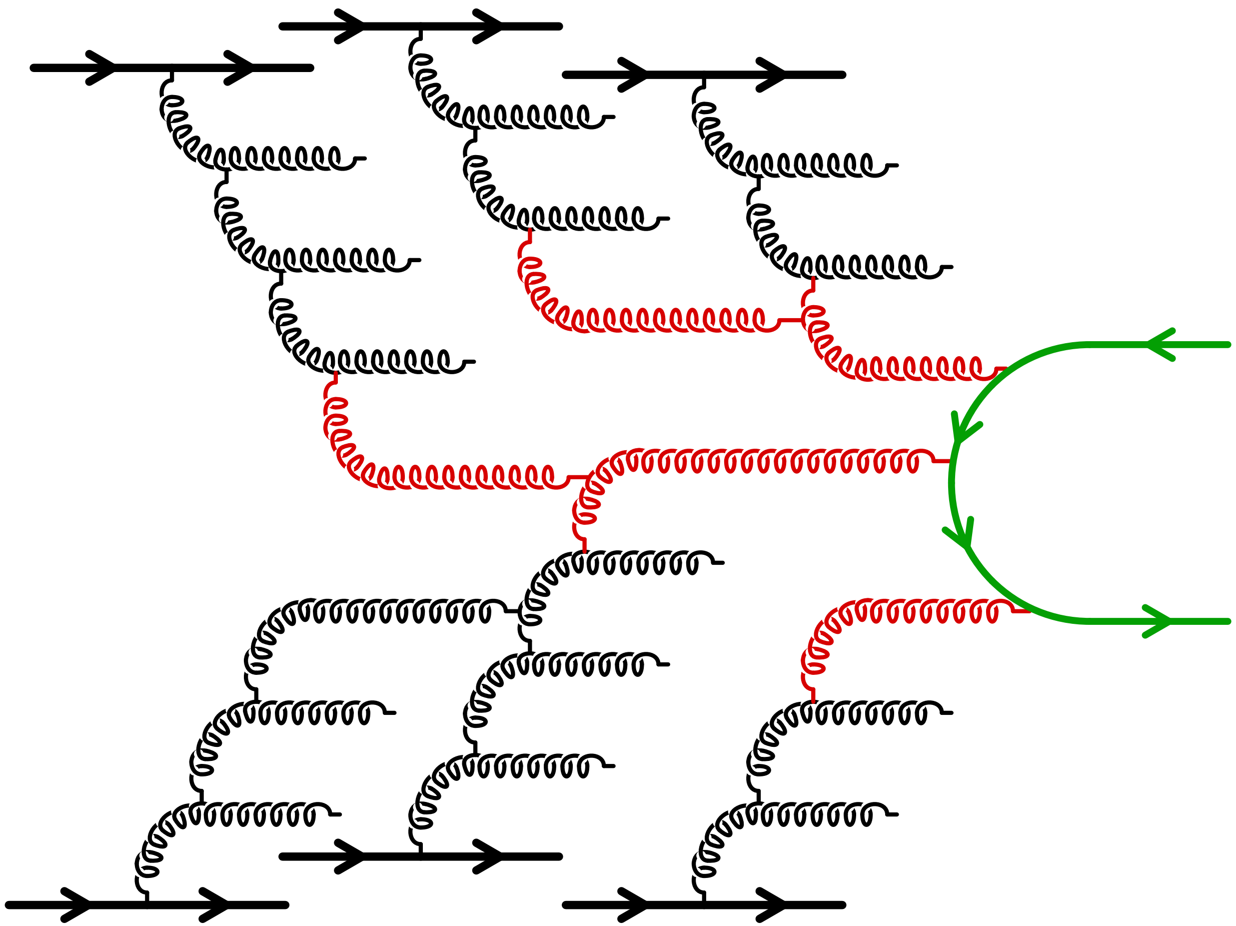

▷ compute the quark propagator in the classical field

Quark production in the CGC

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Baltz, FG, McLerran, Peshier (2001)
FG, Venugopalan (2003)
Blaizot, FG, Venugopalan (2004)

- The single inclusive quark spectrum can be expressed in terms of the retarded quark propagator :

$$E_p \frac{dN_Q}{d^3\vec{\boldsymbol{p}}} \sim \int \frac{d^3\vec{\boldsymbol{q}}}{(2\pi)^3 2E_q} \left|\overline{u}(\vec{\boldsymbol{p}}) T_R(p,-q) v(\vec{\boldsymbol{q}})\right|^2$$

- The calculation can be carried out analytically only at lowest order in one of the two sources
  i.e. $\rho_1 \sim g^{-1} \quad \rho_2 \to 0$

Cronin effect for single quarks

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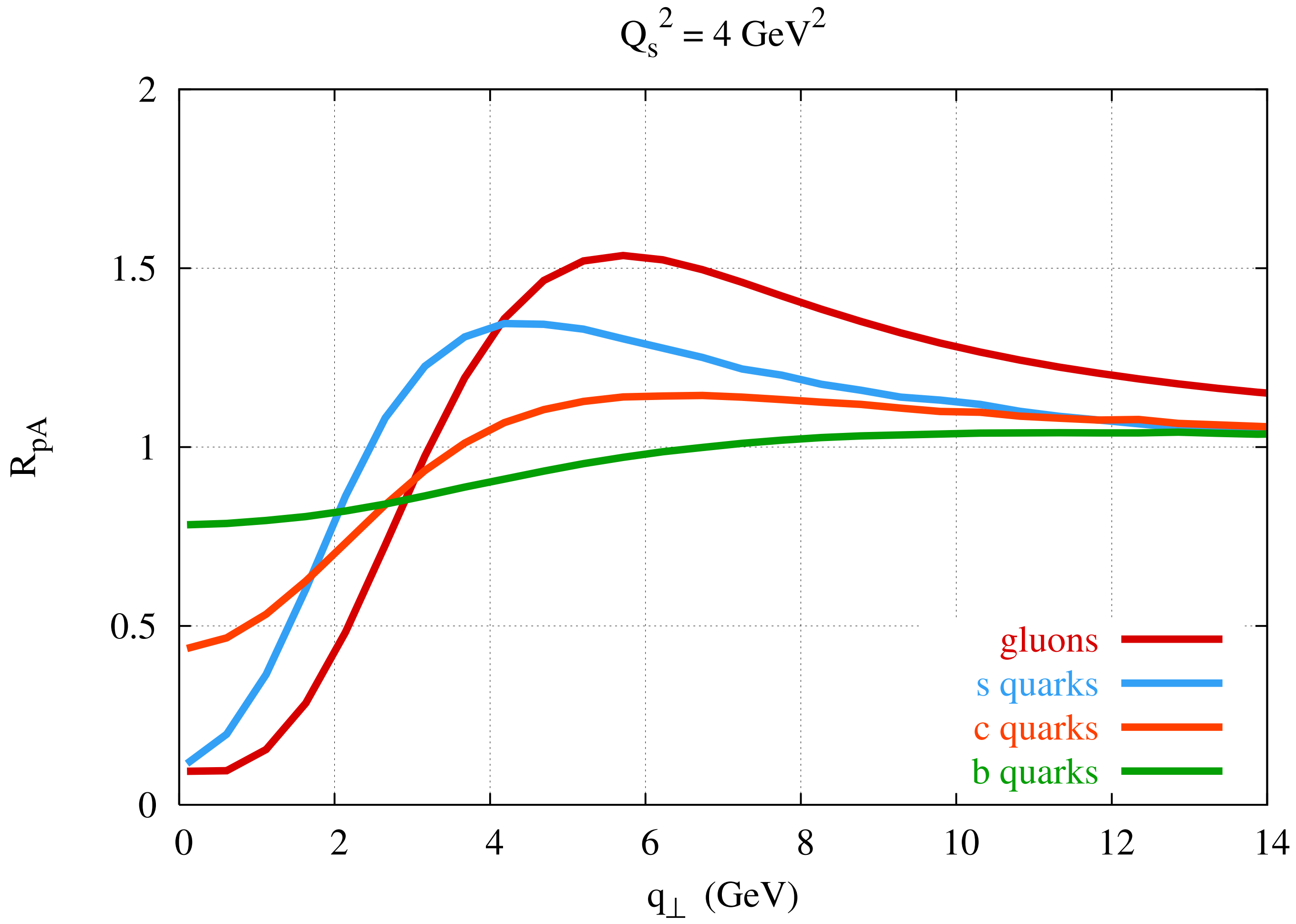
- RpA at moderate x :



Cronin effect for single quarks

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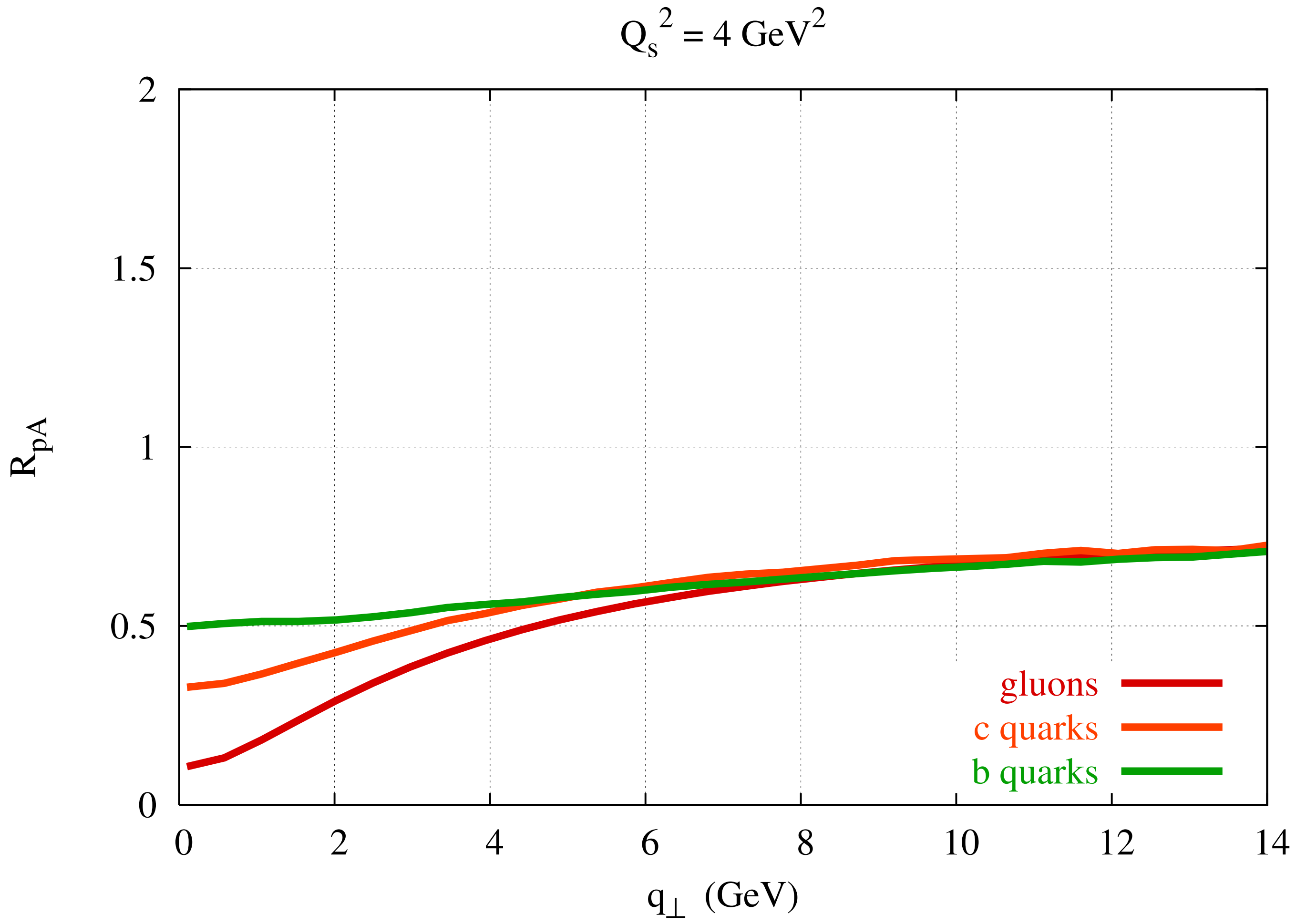
- RpA at small x :



Formulation for AA collisions

FG, Kajantie, Lappi (2004, 2005)

- To all orders in both sources, the gauge field is known only numerically. It is possible to reformulate the problem of quark production in a way which is suitable for a numerical approach
- Alternate representation of the retarded amplitude:

$$\overline{u}(\vec{\boldsymbol{q}})T_R(p,-q)v(\vec{\boldsymbol{p}}) = \lim_{\tau\to+\infty} \tau \int d\eta d^2\vec{\boldsymbol{x}}_\perp \; e^{ip\cdot x}\, u^\dagger(\vec{\boldsymbol{p}})\, e^{-\eta\gamma^0\gamma^3} \psi_{\boldsymbol{q}}(t,\vec{\boldsymbol{x}})$$

where $\psi_{\boldsymbol{q}}(t,\vec{\boldsymbol{x}})$ obeys Dirac's equation with retarded boundary conditions :

$$(i\partial\!\!\!/_x - gA\!\!\!/(x) - m)\psi_{\boldsymbol{q}}(x) = 0\ ,\ \ \psi_{\boldsymbol{q}}(t,\vec{\boldsymbol{x}}) \underset{t\to-\infty}{\longrightarrow} v(\vec{\boldsymbol{q}})e^{iq\cdot x}$$

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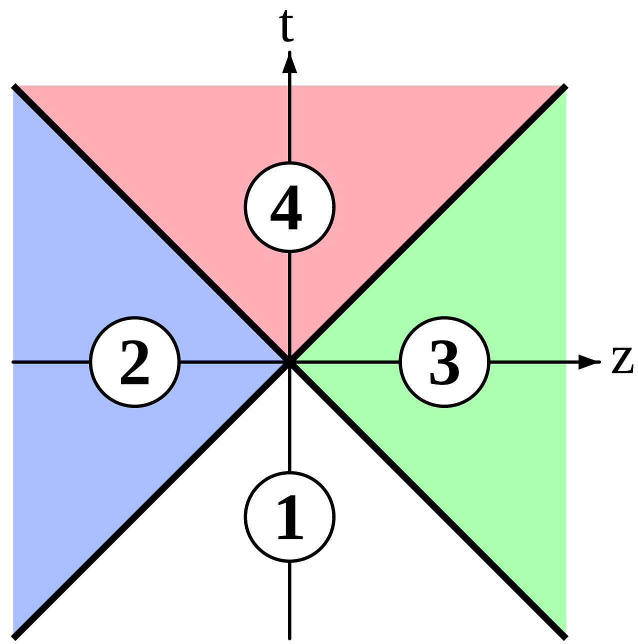
Classical color field

- Space-time structure of the classical color field:



- Region 1: $A^\mu = 0$
- Region 2: $A^\pm = 0$, $A^i = \frac{i}{g} U_1 \nabla_\perp^i U_1^\dagger$
- Region 3: $A^\pm = 0$, $A^i = \frac{i}{g} U_2 \nabla_\perp^i U_2^\dagger$
- Region 4: $A^\mu \neq 0$

- **Notes:**
  - $U_{1,2}(\vec{\boldsymbol{x}}_\perp) = \exp(-ig \frac{1}{\nabla_\perp^2} \rho_{1,2})$
  - In the region 4, A^μ is known only numerically
    Krasnitz, Venugopalan (2000,2001), Lappi (2003)

Quark propagation

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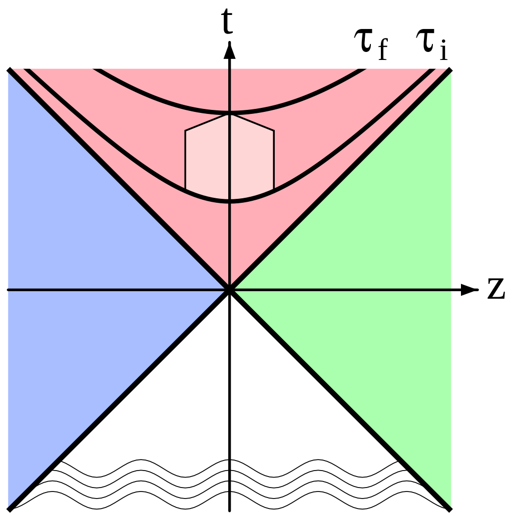
- Propagation through region 4:

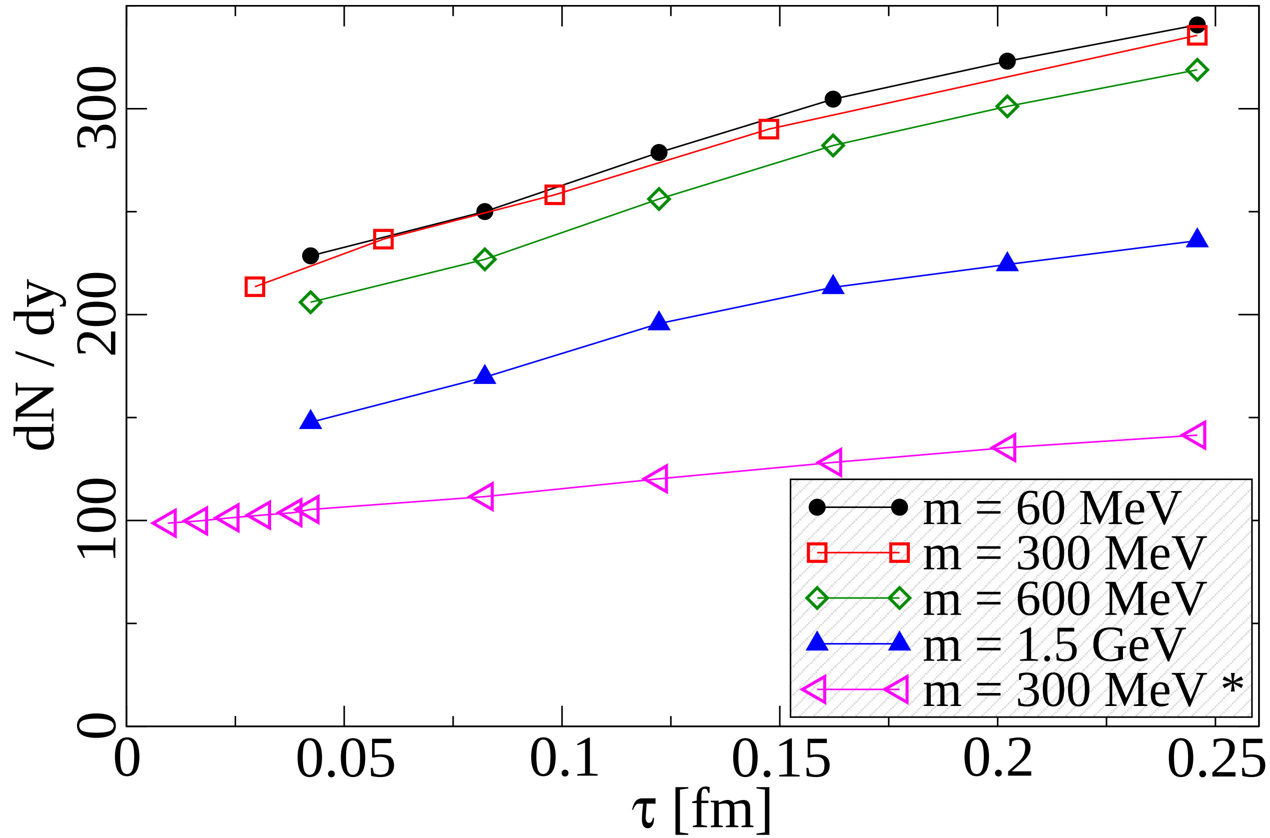


$$\partial_\tau \psi_{\boldsymbol{p}}(\tau,\eta,\vec{\boldsymbol{x}}_\perp) = \Big[-\frac{1}{2\tau} - \frac{\gamma^0\gamma^3}{\tau}(\partial_\eta + igA_\eta) + \gamma^0\vec{\gamma}_\perp \cdot (\vec{\boldsymbol{\nabla}}_\perp + ig\vec{\boldsymbol{A}}_\perp) - i\gamma^0 m \Big] \psi_{\boldsymbol{p}}(\tau,\eta,\vec{\boldsymbol{x}}_\perp)$$

- The initial condition is known analytically at $\tau_i \to 0^+$

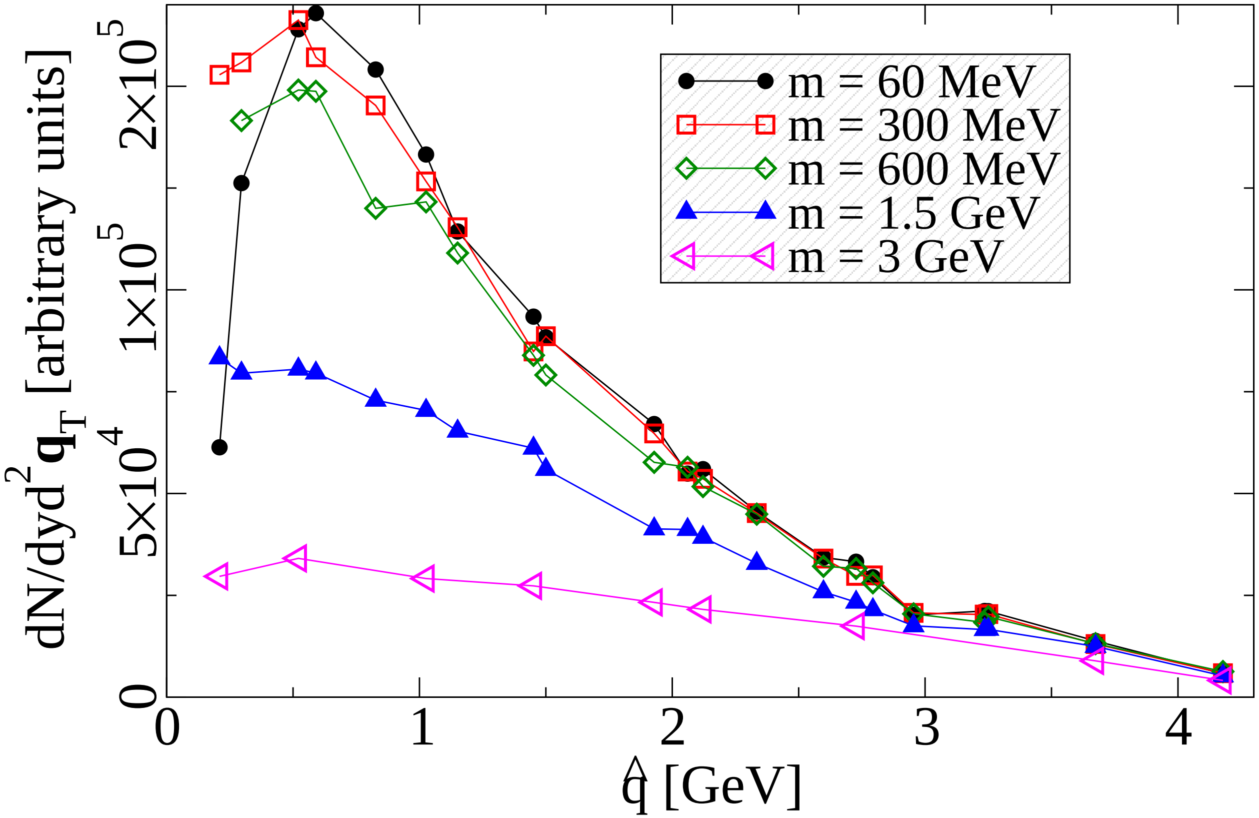
Time dependence

- $g^2\mu = 2$ GeV , (*) $g^2\mu = 1$ GeV :



Spectra for various quark masses

- $g^2\mu = 2$ GeV , $\tau = 0.25$ fm :



Qs dependence of dN/dy

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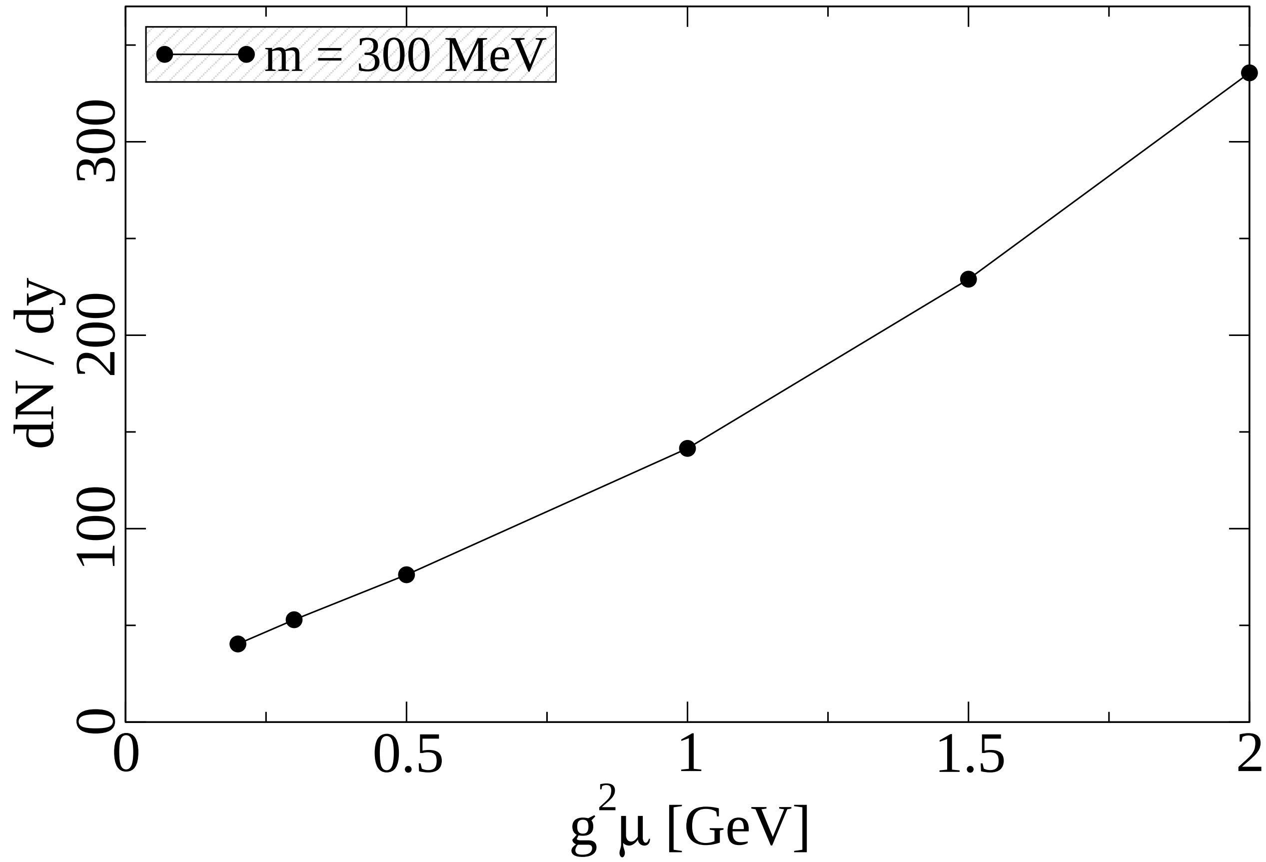
- Number of quarks at $\tau = 0.25$ fm :



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Shortcomings

- Factorization of logs of $1/x$ plausible not proven
- Numerical evaluation done on a coarse lattice due to limited computational ressources
  - ▷ large lattice artifacts at large momentum/mass
- Instead of $dN_Q/d^3\vec{\boldsymbol{p}}$, one should calculate $f_Q(t,\vec{\boldsymbol{x}},\vec{\boldsymbol{p}})$

  (easy to fix)

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Dynamical evolution
● QQbar recombination

Dynamical evolution

QQbar recombination

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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

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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

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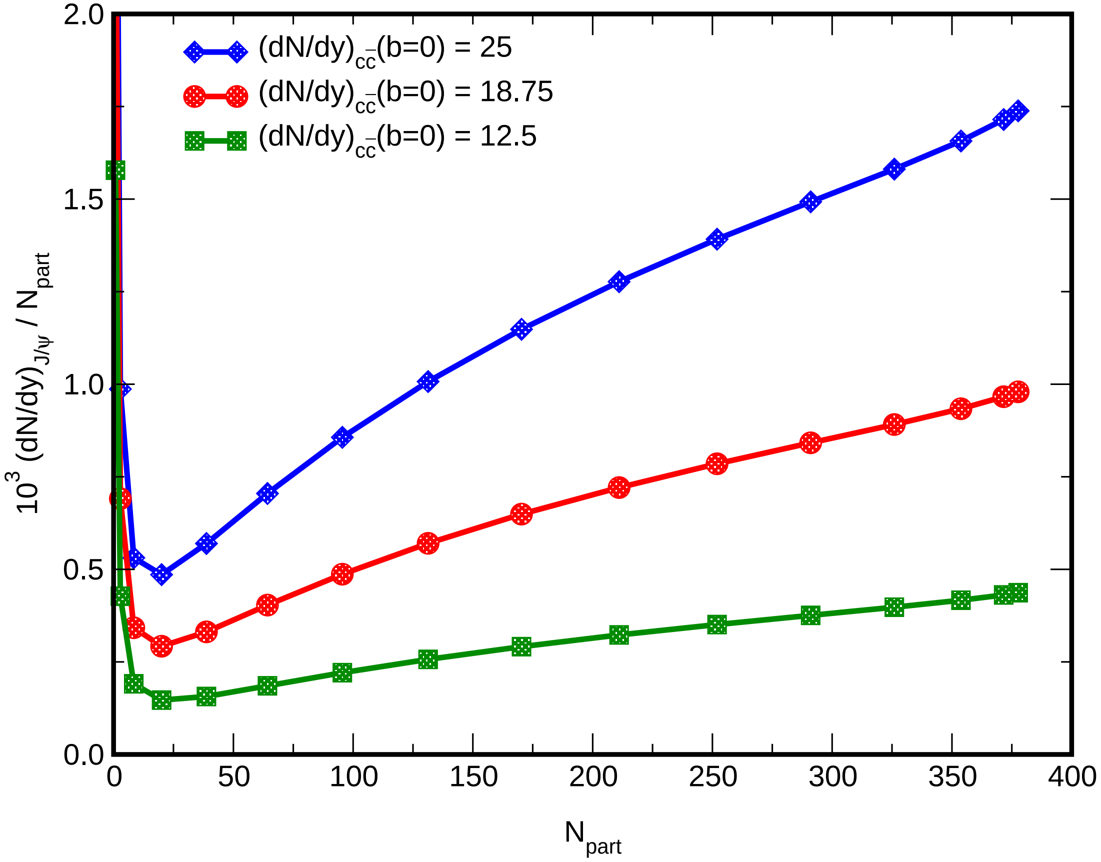
- LHC : J/ψ yield per participant



Statistical hadronization

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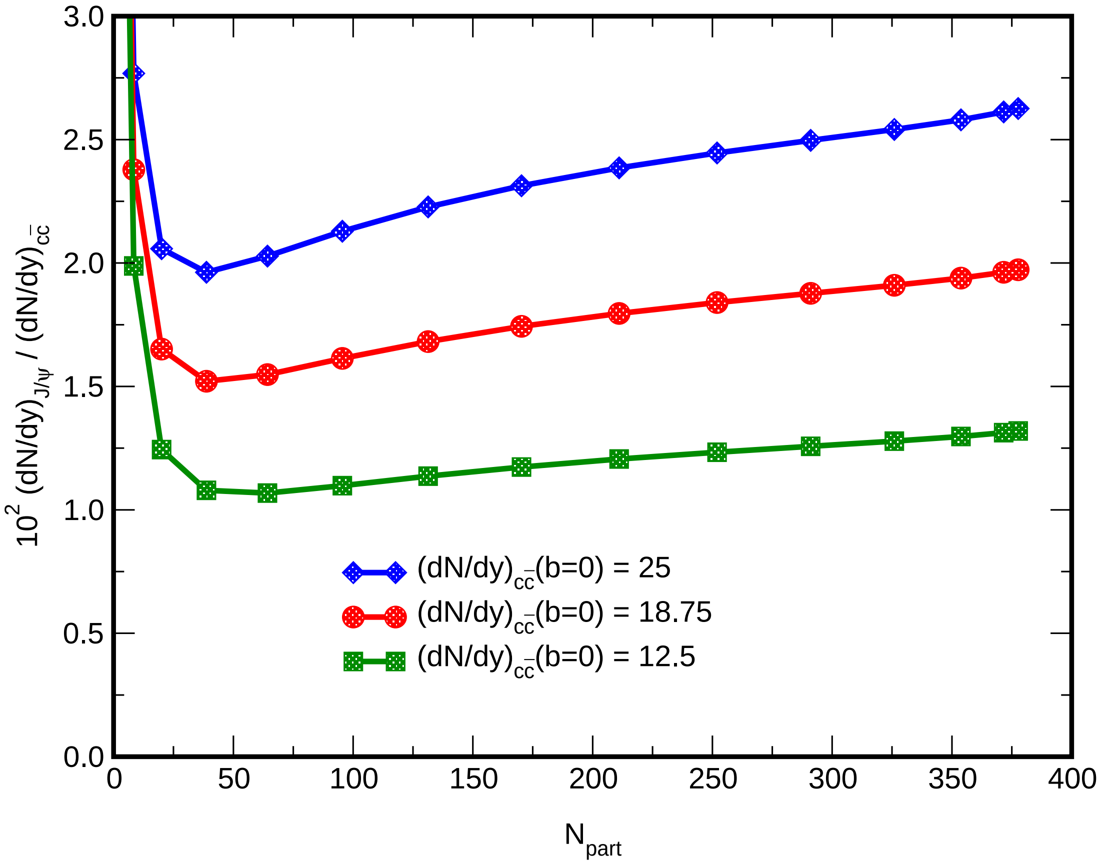
- LHC : J/ψ yield per $c\bar{c}$ pair



$\triangleright$ 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 :

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

  - $V(\tau)$: τ-dependent volume (expansion plays against recombination)
  - ρ_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 $\epsilon(\tau) = \exp(-\int_{\tau_i}^{\tau} d\tau\, \rho_g \lambda_D)$

Kinetic formation

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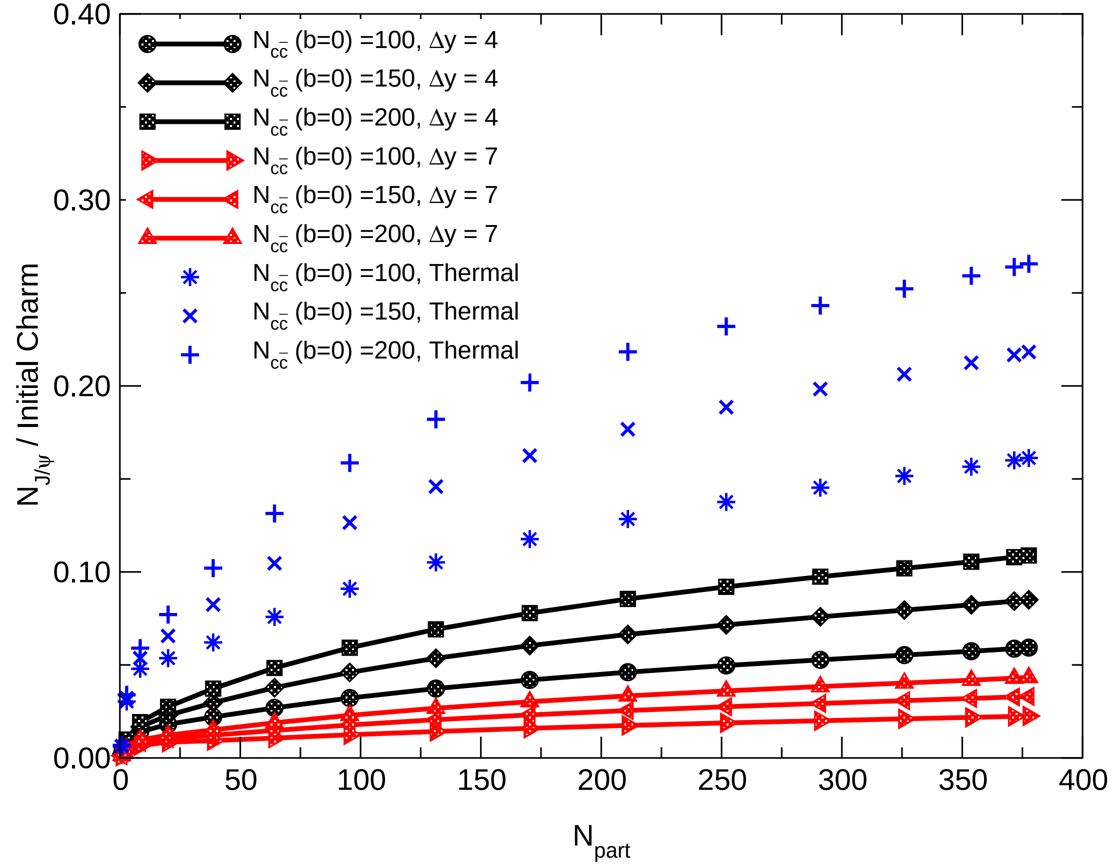
- LHC : J/ψ yield per $c\bar{c}$ pair



  - 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

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Bound states in a medium

- Hadronization in vaccum
- in-medium suppression
- lattice results

Bound states in a dense medium

Quarkonium production in vacuum

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- More difficult than the inclusive fragmentation $c \to D + X$
- 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)

Charmonium suppression in the QGP

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- Hadronization in vaccum
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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/ψ] / [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

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- 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

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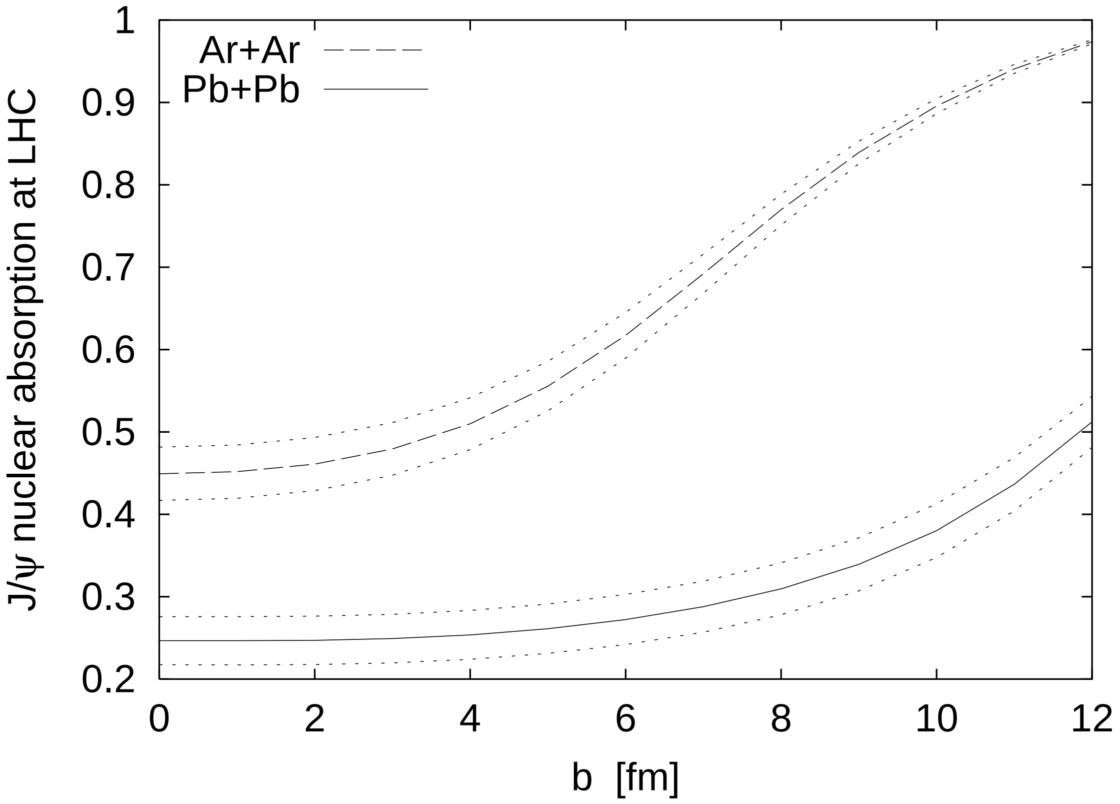
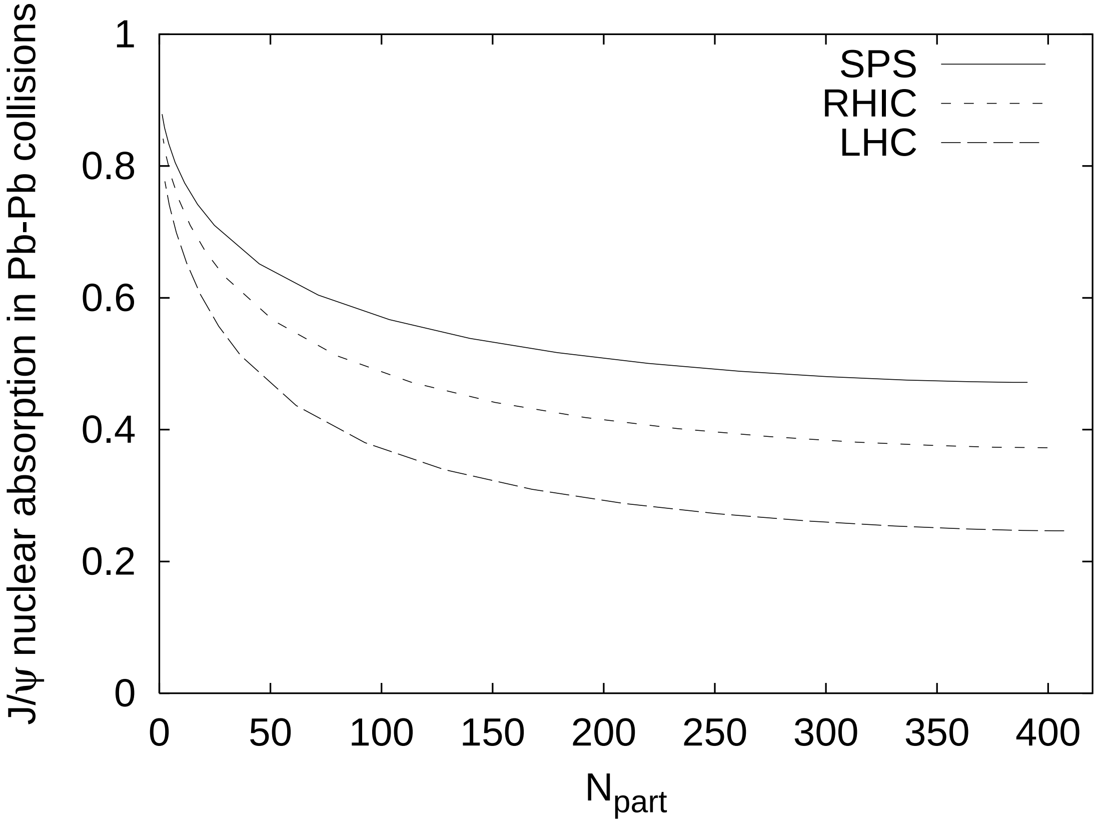
- Impact parameter dependence of the survival probability :



Normal nuclear suppression

- N_{part} dependence of the survival probability :



Lattice results

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- 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

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

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

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

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

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

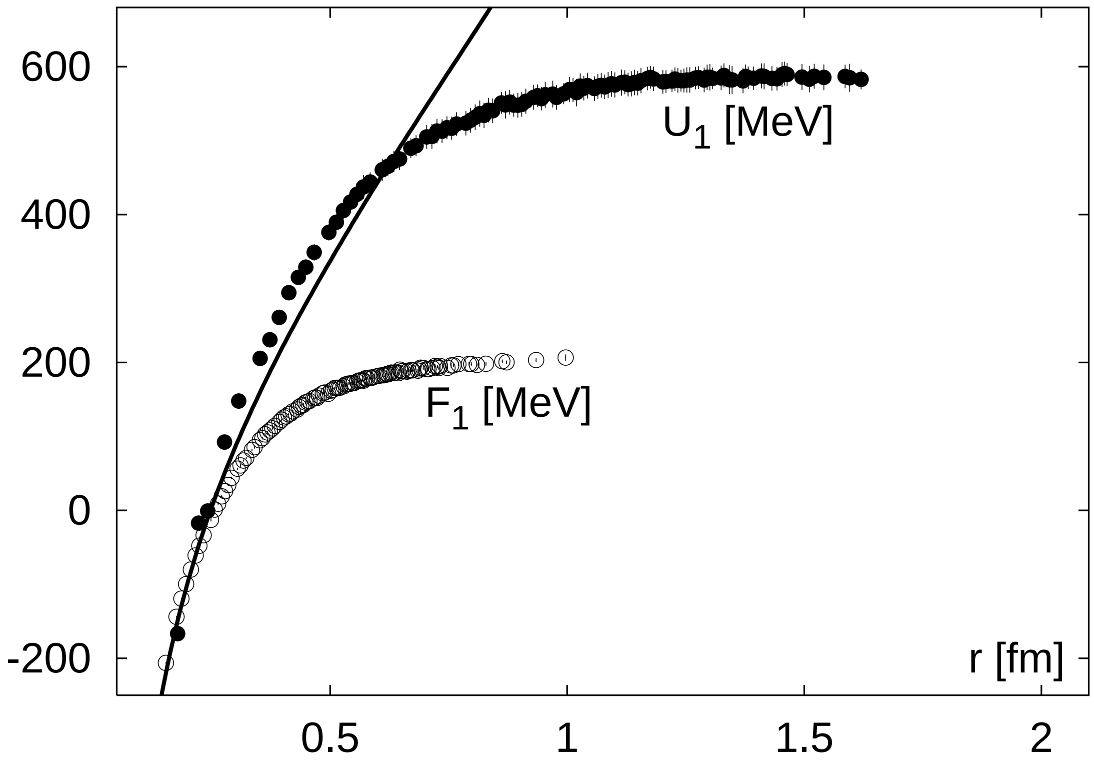
$$e^{-F_8(r,T)/T} = \frac{1}{8}\left\langle \mathrm{tr}L(\vec{\boldsymbol{r}})\,\mathrm{tr}L^\dagger(\vec{0})\right\rangle - \frac{1}{24}\left\langle \mathrm{tr}L(\vec{\boldsymbol{r}})L^\dagger(\vec{0})\right\rangle$$

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

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

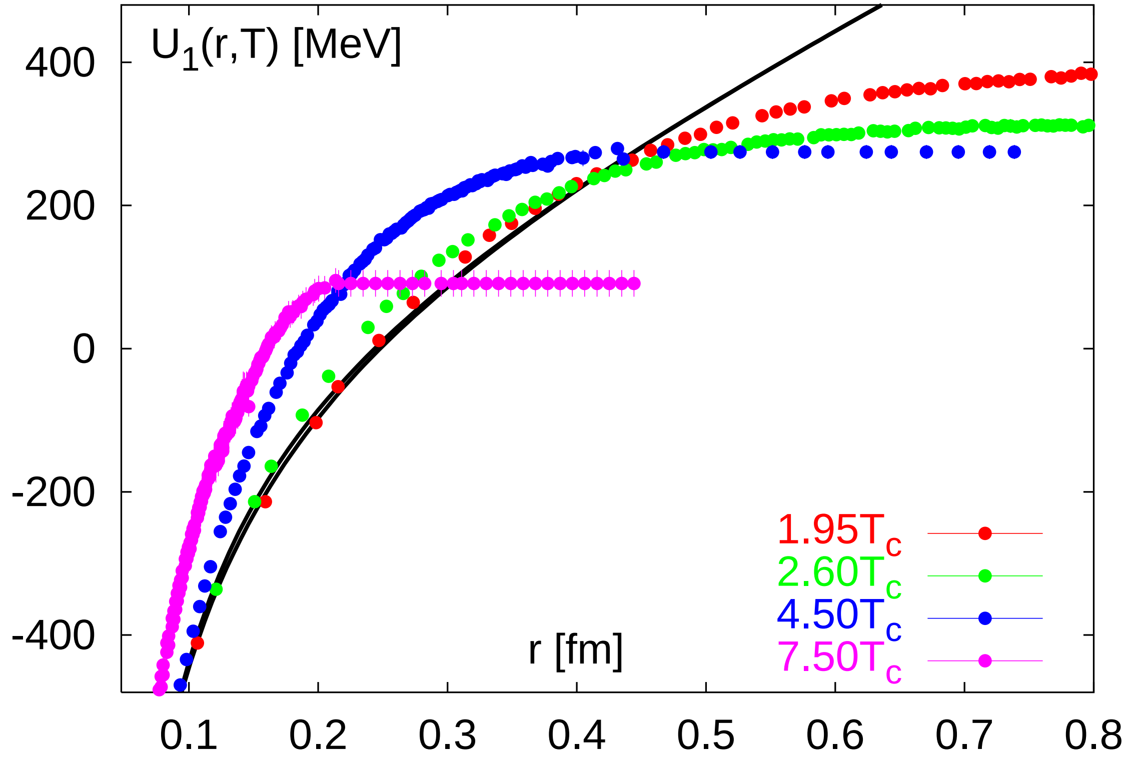
Heavy quark potential

- Results for $T/T_c = 1.5$:



Heavy quark potential

- T-dependence of the potential above T_c :



Heavy quark potential

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

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

  - 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

$\triangleright$ the quarkonium states do not get immediately dissolved above the critical temperature

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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

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- 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

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

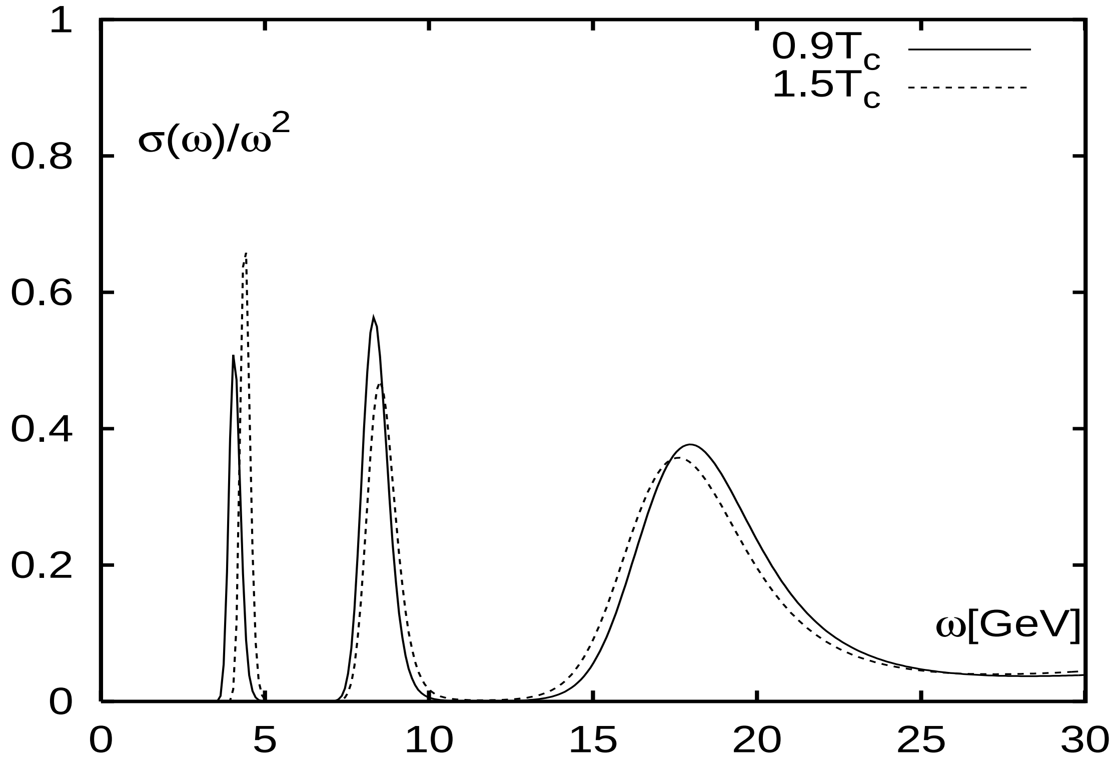
  - MEM :

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

▷ 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

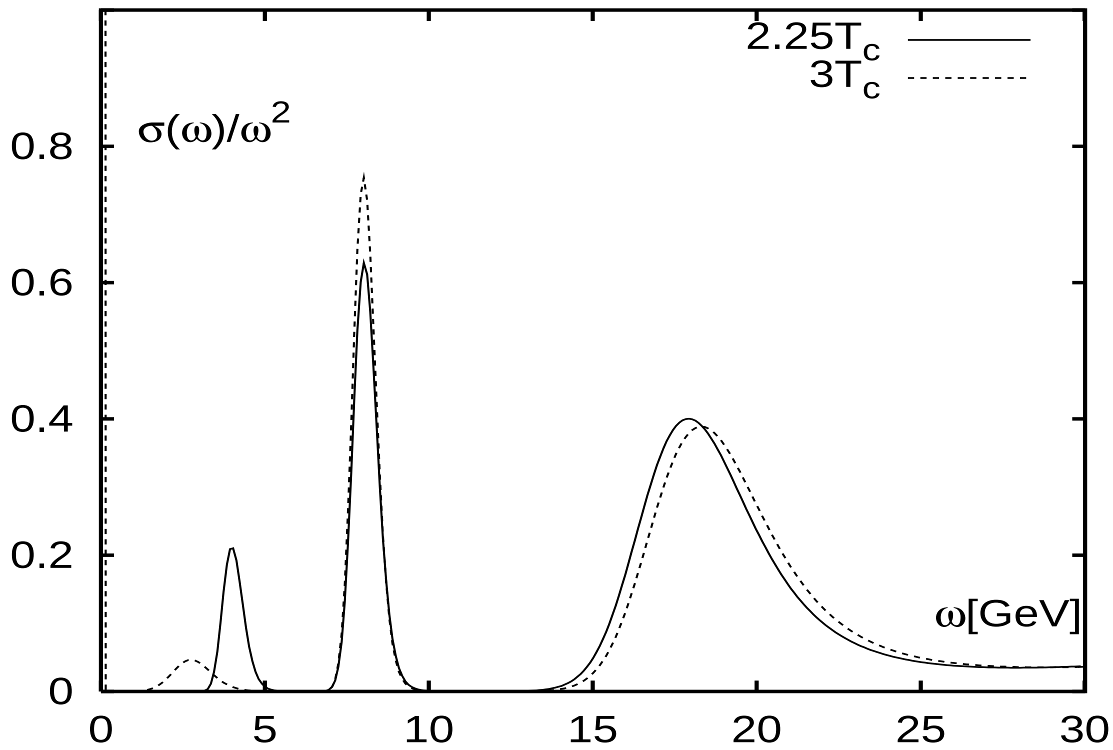
- J/ψ spectral function below T_c :



- 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