Particle Production in pA Collisions in the CGC Framework

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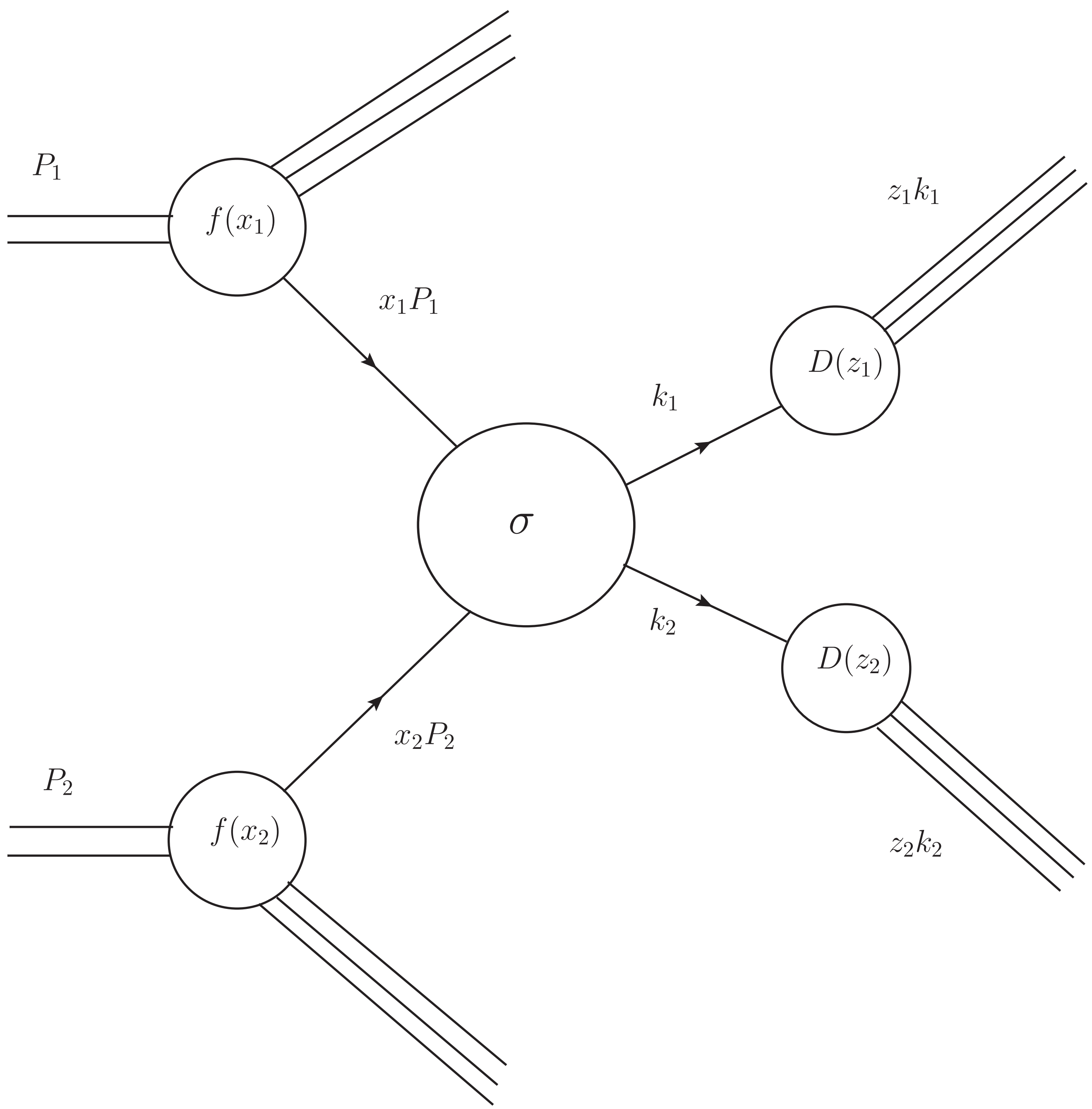
Particle production in hadronic collisions



- Collinear factorization separates perturbative from non-perturbative regimes

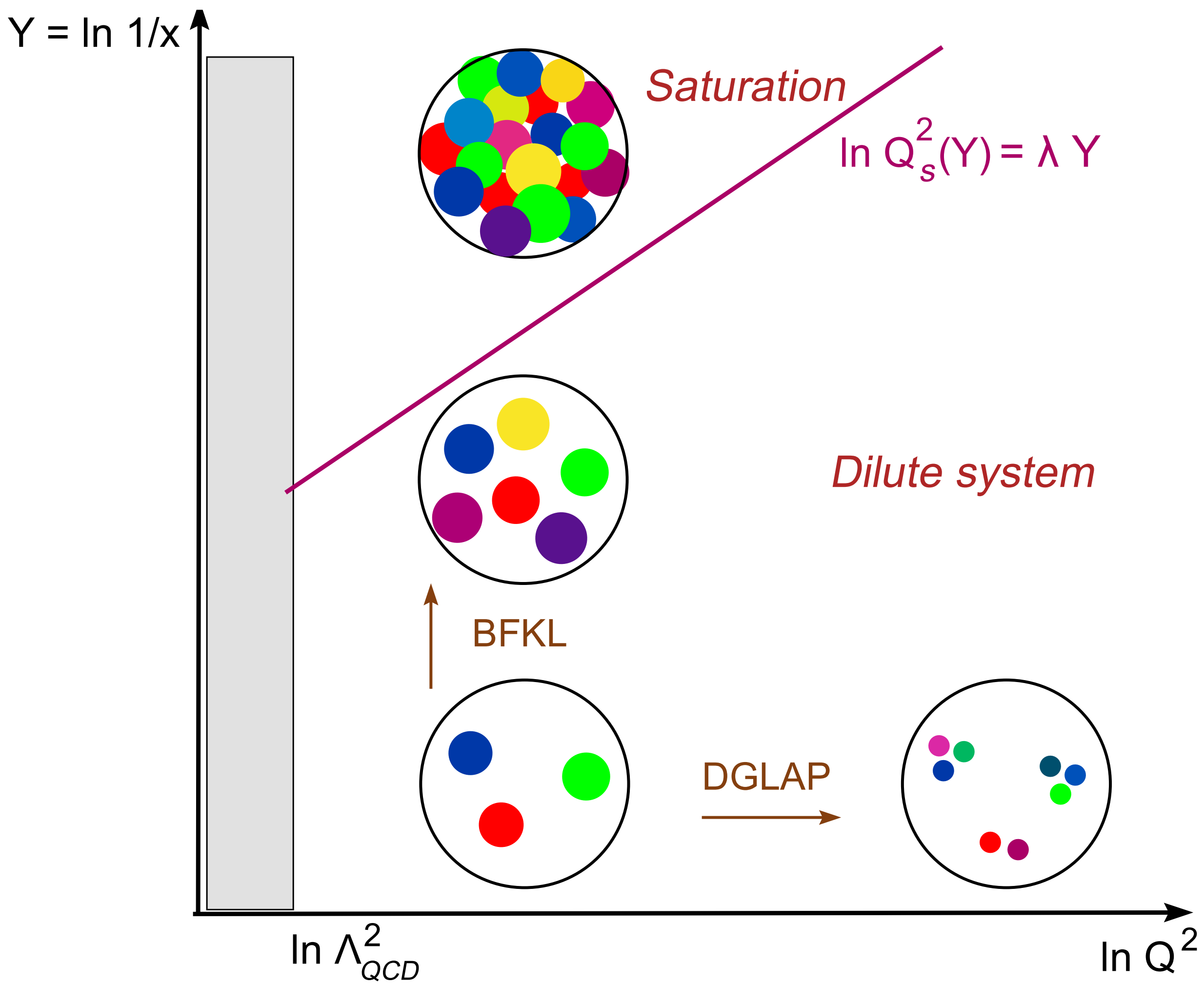
- Assumptions:
  - All energy scales are of the same order
  - Inclusive processes
  - Single large momentum transfer

Factorization for heavy ion collisions

- Believed to hold in a modified way for hard probes

- No longer valid for bulk of particle production
    - High densities at small-x
    - Multiple soft scatterings dominate over single hard ones

Small-x regime



- Soft gluon emission is enhanced at large rapidities
- BFKL dynamics predicts a large growth in gluon densities at small-x
- Nonlinear dynamics generates a semi-hard momentum scale (saturation momentum)

Basics of CGC

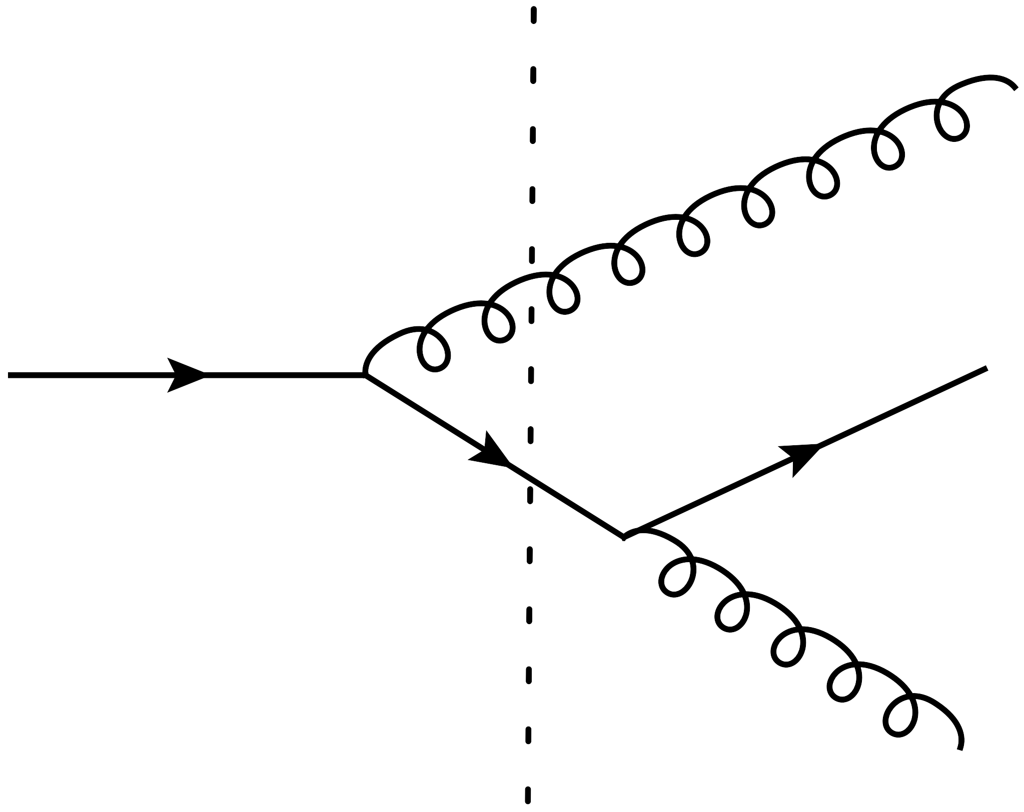
- Low-x degrees of freedom considered as classical field due to large occupation numbers
- Field configuration has to be averaged using a (non-perturbative) weighting functional
- Energy dependence computed perturbatively (JIMWLK)

Probing High Density Regime

- Dilute projectile probing a dense target (DIS, pA collisions)
- Use the eikonal approximation to account for the multiple scatterings of a fast moving parton in a background field (in a covariant gauge)
- Calculate observables in a fixed background field, then average over field configurations with an appropriate weighting functional
- Medium effects are visible through the field correlators

Particle Production

- High energy parton splits
- Whole system interacts coherently with high energy target
- Interaction looks instantaneous due to Lorentz contraction
- Final particles can have any rapidity



Multiple scatterings - Wilson lines

- In the high-energy limit, fast moving partons are eikonal with a fixed transverse coordinate

- In a covariant gauge, the effect of multiple interactions can be resummed into a Wilson line

$$U(x) = \mathcal{P} \exp \left\{ ig \int dz^+ \, \alpha_a(z^+, x) T^a \right\}$$

- This are the appropriate degrees of freedom

- Nuclear effects encoded in the correlators of several Wilson lines

Known Results

- DIS total cross section
- One-particle observables
  - SIDIS
  - Single-hadron production in pA colisions
  - Vector meson photoproduction
- Two-particle observables
  - Di-hadron production in DIS
  - Di-hadron production in pA colisions
    - Quark channel
    - Gluon channel

PDF’s, nPDF’s

Dipole: trace of two Wilson lines

TMD’s

Quadrupole: Trace of four Wilson lines

Inclusive Observables

- Integrating over transverse momentum puts the particle at the same transverse coordinate in the amplitude and conjugate amplitude

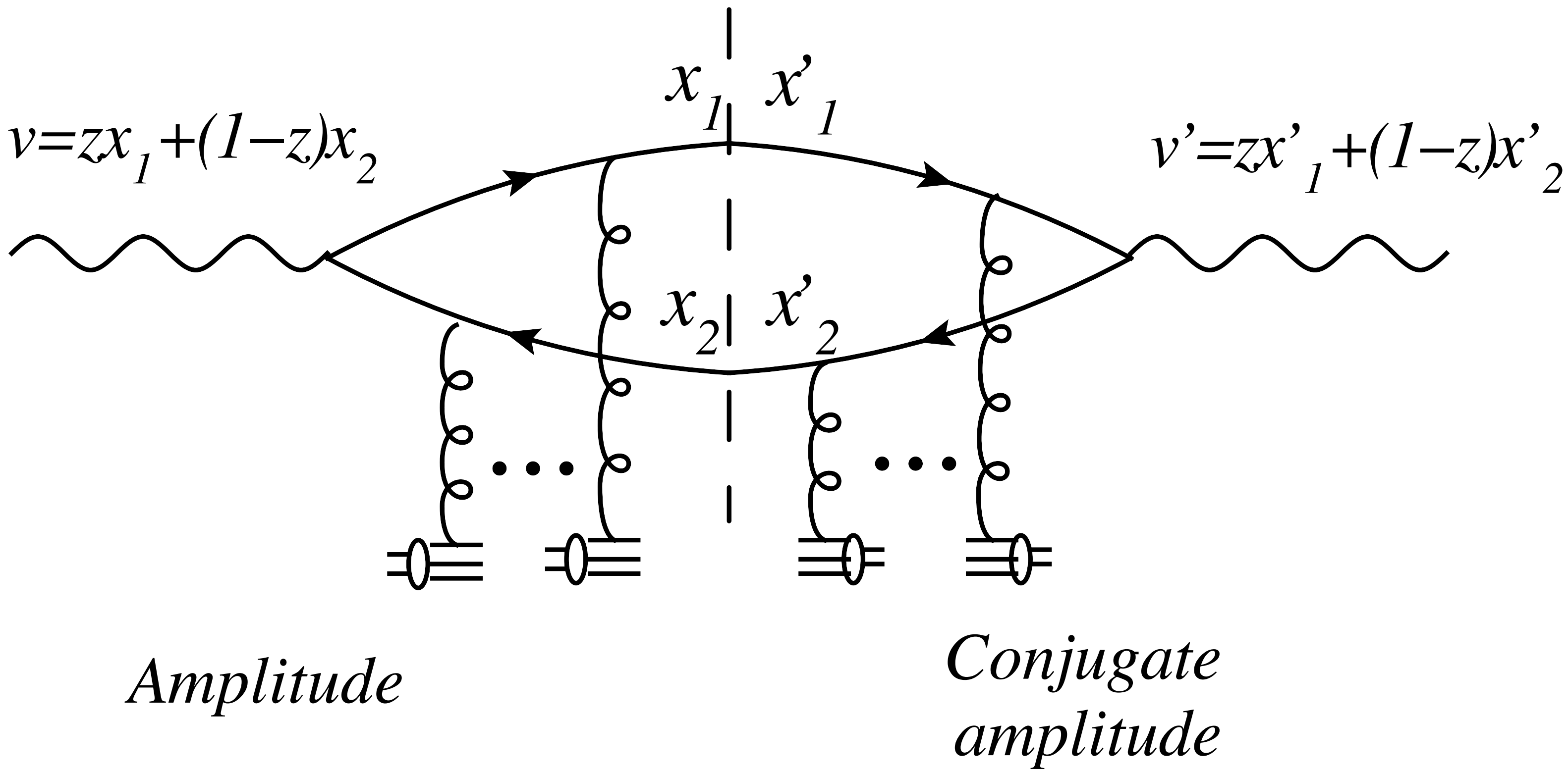
- Real-virtual cancelations take place

- Total cross sections and single-particle observables can be described with only dipole amplitudes

Two-Particle Observables

- Having two independent momenta in the final state leads to four independent transverse coordinates
- Cross sections involve traces of four Wilson lines at different coordinates

Two-particle production in DIS



$$\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{d^3k_1 d^3k_2} = N_c \alpha_{em} e_q^2 \delta(p^+ - k_1^+ - k_2^+) \int \frac{d^2x_1}{(2\pi)^2}\frac{d^2x_1'}{(2\pi)^2}\frac{d^2x_2}{(2\pi)^2}\frac{d^2x_2'}{(2\pi)^2}$$

$$\times\, e^{-ik_{1\perp}\cdot(x_1-x_1')} e^{-ik_{2\perp}\cdot(x_2-x_2')} \sum \psi_T^*(x_1-x_2)\psi_T(x_1'-x_2')$$

$$\times \left[1 + Q_{x_g}(x_1,x_2;x_2',x_1') - S^{(2)}_{x_g}(x_1,x_2) - S^{(2)}_{x_g}(x_1',x_2')\right]$$

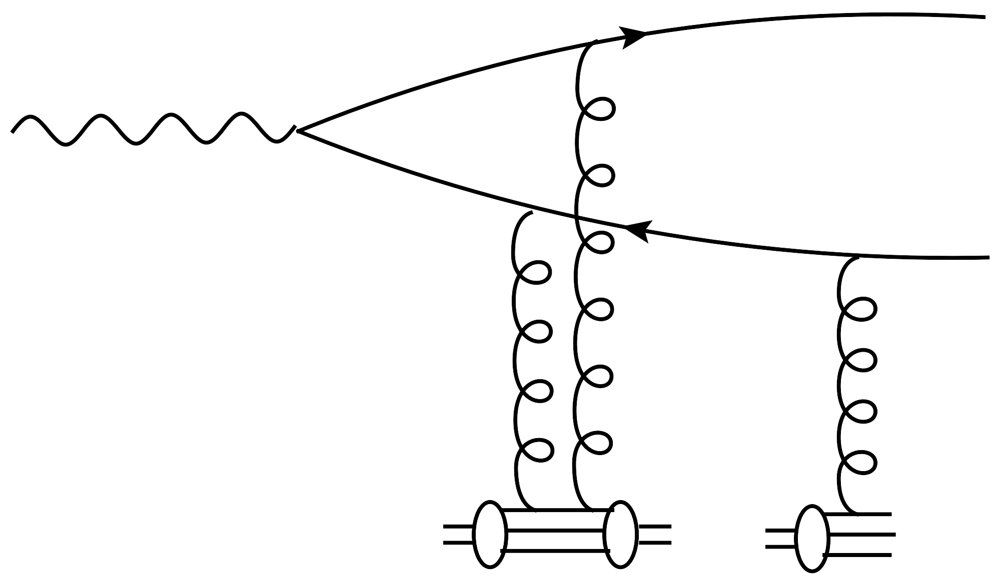
$$Q_{x_g}(x_1,x_2;x_2',x_1') = \frac{1}{N_c}\left\langle \mathrm{Tr} U(x_1)U^\dagger(x_1')U(x_2')U^\dagger(x_2)\right\rangle_{x_g} \qquad S^{(2)}_{x_g}(x_1,x_2) = \frac{1}{N_c}\left\langle \mathrm{Tr} U(x_1)U^\dagger(x_2)\right\rangle_{x_g}$$

Correlation limit

- Factorization requires a separation of scales

- Take momentum imbalance much smaller than individual transverse momenta

- In coordinate space this amounts to take a very small separation for the quark-antiquark pair



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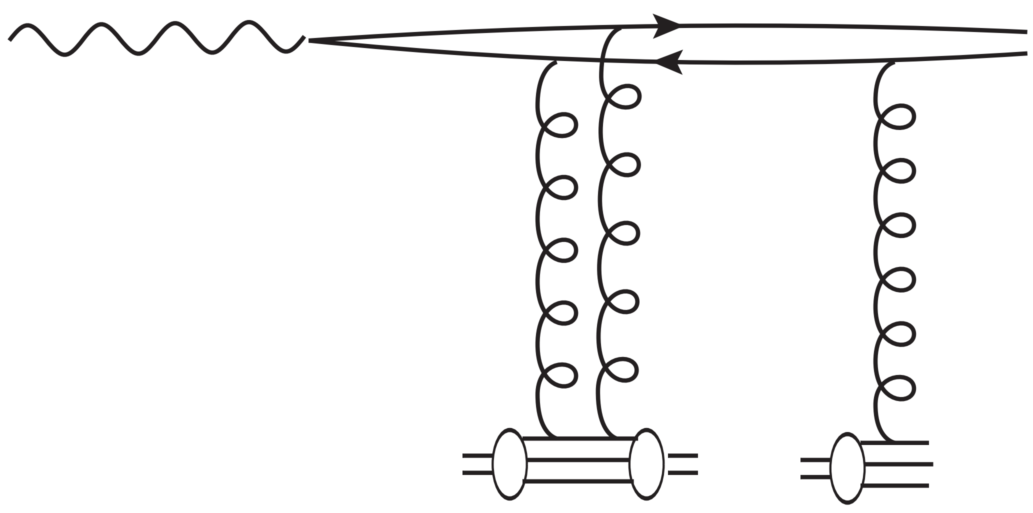

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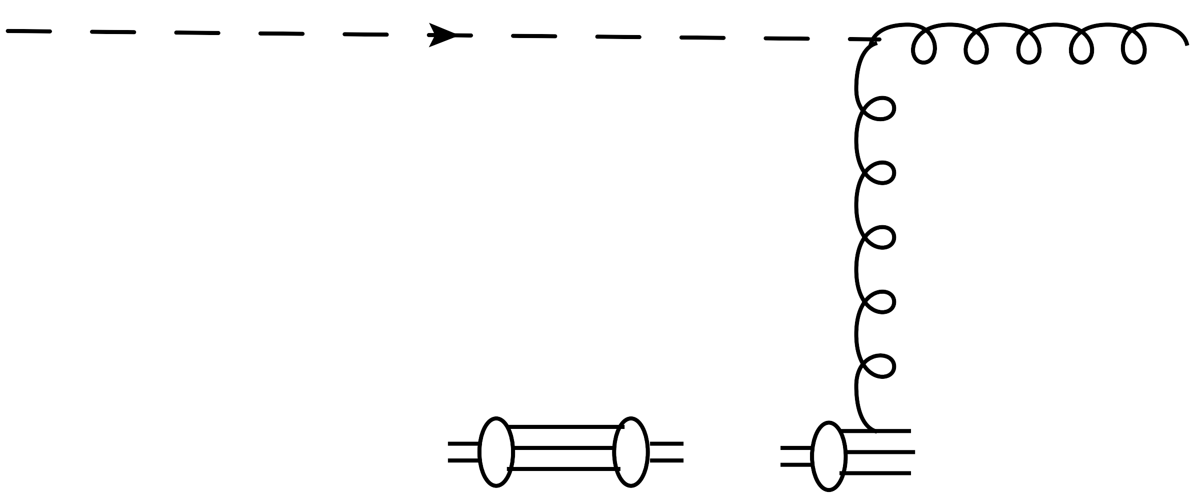

Looks like colorless current liberating a gluon

Factorized form

$$\frac{d\sigma^{\gamma_T^* A\to q\bar{q}X}}{dy_1 dy_2 d^2P_\perp d^2q_\perp} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z(1-z)\left(z^2+(1-z)^2\right)\left[\frac{\delta_{ij}}{(\tilde{P}_\perp^2+\epsilon_f^2)^2}-\frac{4\epsilon_f^2\tilde{P}_{\perp i}\tilde{P}_{\perp j}}{(\tilde{P}_\perp^2+\epsilon_f^2)^4}\right]$$
$$\times(16\pi^3)\int\frac{d^3v d^3v'}{(2\pi)^6}e^{-iq_\perp\cdot(v-v')}2\left\langle\mathrm{Tr}\left[F^{i-}(v)\mathcal{U}^{[+]\dagger}F^{j-}(v')\mathcal{U}^{[+]}\right]\right\rangle_{x_g}$$

Factorized form

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$$\times(16\pi^3)\int \frac{d^3v d^3v'}{(2\pi)^6} e^{-iq_\perp\cdot(v-v')} 2\left\langle \mathrm{Tr}\left[F^{i-}(v)\mathcal{U}^{[+]\dagger}F^{j-}(v')\mathcal{U}^{[+]}\right]\right\rangle_{x_g}$$

$$\frac{1}{2}\delta^{ij}xG^{(1)}(x,q_\perp) + \frac{1}{2}\left(\frac{2q_\perp^i q_\perp^j}{q_\perp^2} - \delta^{ij}\right) xh_\perp^{(1)}(x,q_\perp)$$

Factorized form

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WW Unpolarized distribution

Factorized form

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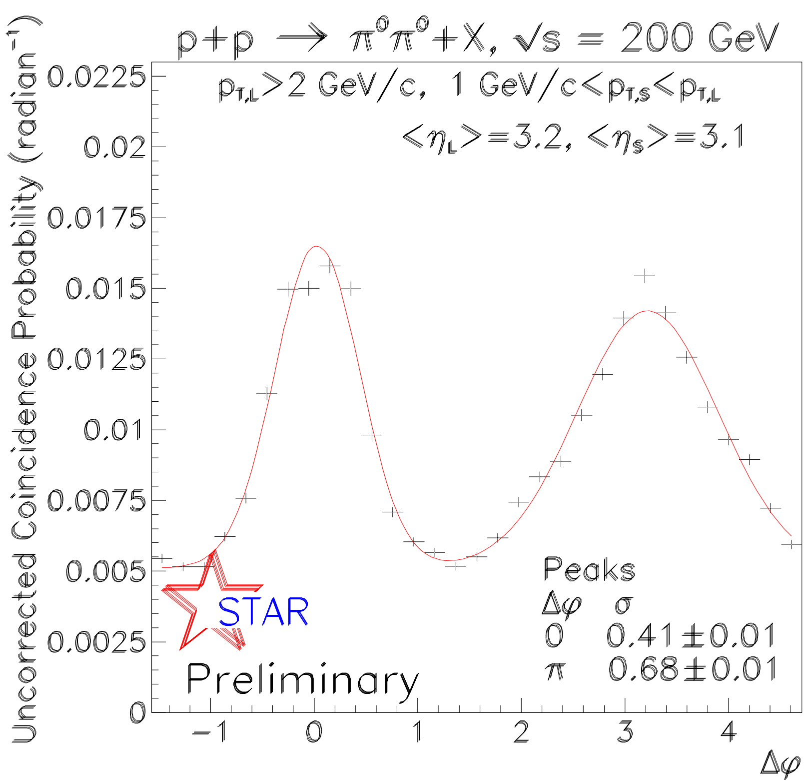
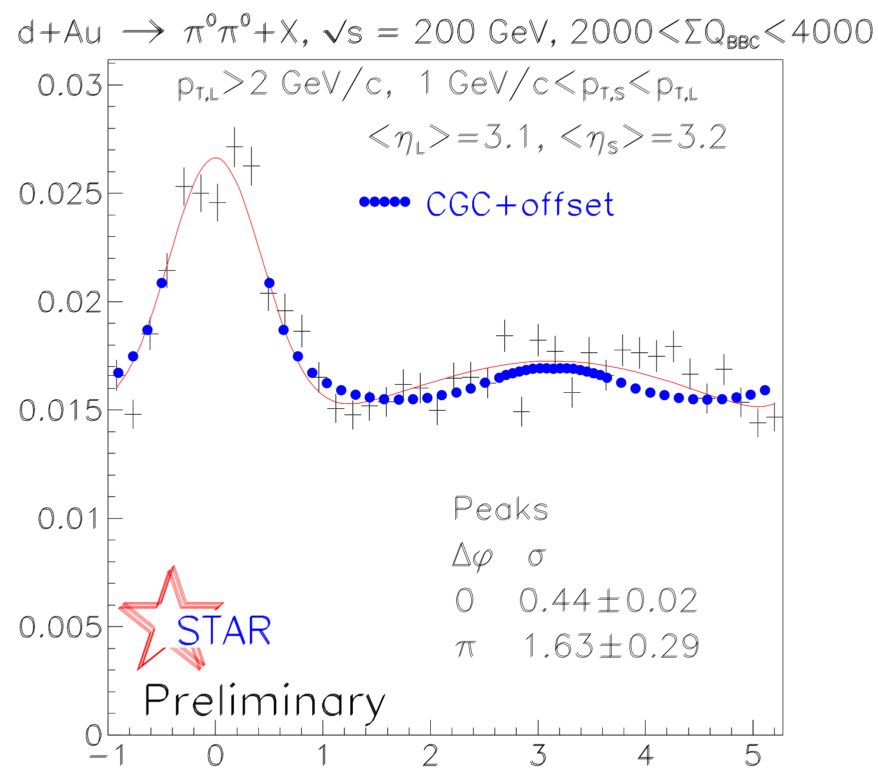
WW Unpolarized distribution

WW Linearly polarized distribution

Di-hadron production in pA collisions

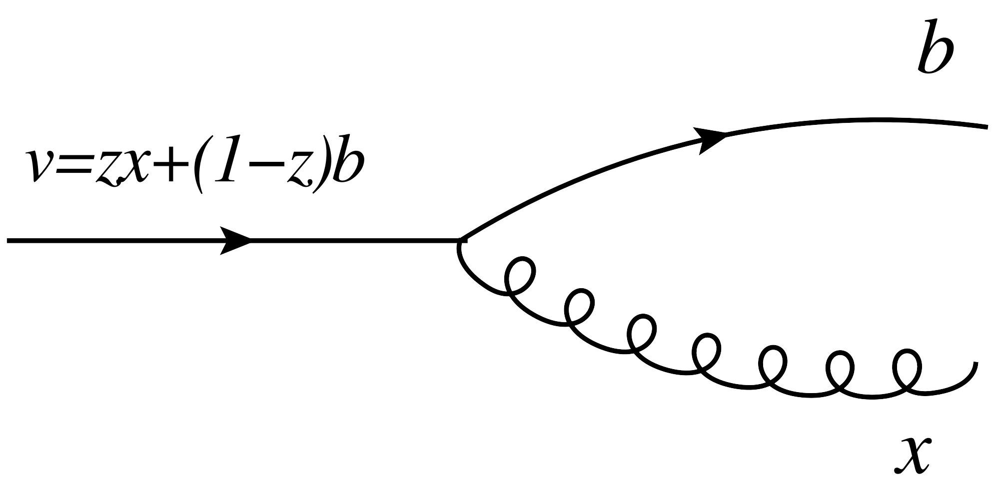


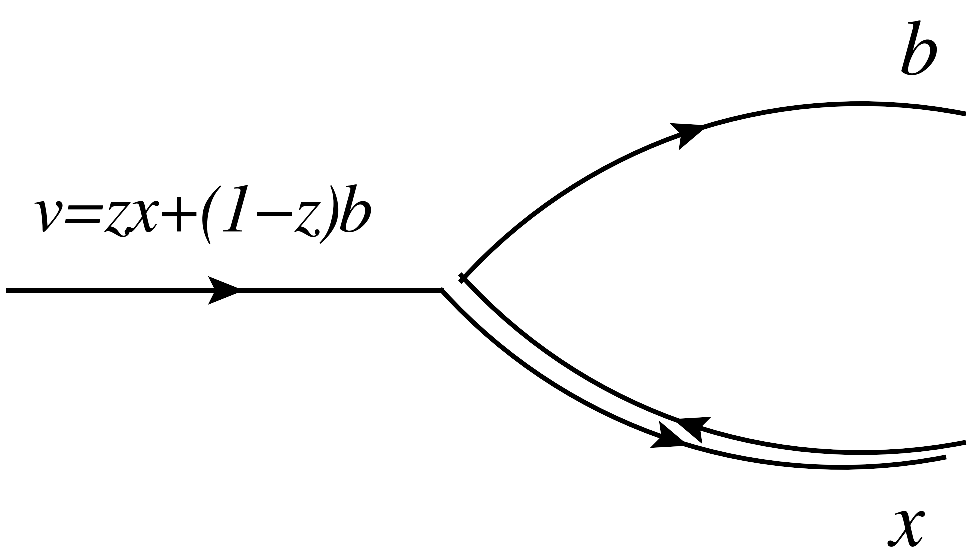


Suppression of away peak due to momentum broadening

Di-hadron production in pA collisions

- There are both initial and final state interactions





Large-Nc Limit

- Replace gluon lines with quark-antiquark pairs

- Averages of products of traces of fundamental Wilson lines factorize (mean field approximation - well justified for large nuclei)

- Each trace gives a factor of Nc

Universality of n-particle production

- Adding more particles to the final state requires computing more complicated correlators of Wilson lines
- But, in the large-Nc limit, they all reduce to products of dipoles and quadrupoles
- Direct consequence of color conservation

Summary

- For some processes factorized expressions (kt-dependent) can be found
- In large-Nc limit, only dipole and quadrupole amplitudes are necessary for an arbitrary number of particles
- Still valid at higher orders (additional gluons can be virtual fluctuations)
- These results are preserved when small-x evolutino is taken into account