J/ψ polarization in nuclear collisions from CGC perspective

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Plan:
Jpsi polarization in pp
Glasma and HQ in AA

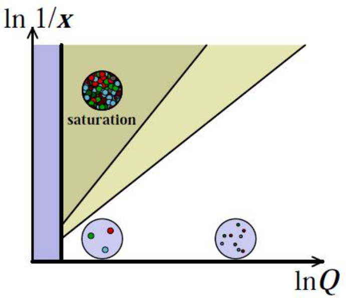
My background so far

- Heavy quark, dijets production in CGC formalism
- Glasma instability and its time-evolution
- Photon production in hadronization stage
- Critical fluctuation and its time evolution near QCD critical point
- Lefschetz thimble approach to the sign problem at finite density
- ...

Not well aware of recent progress in polarization study of HIC,
And like to learn much about it thru this WS!

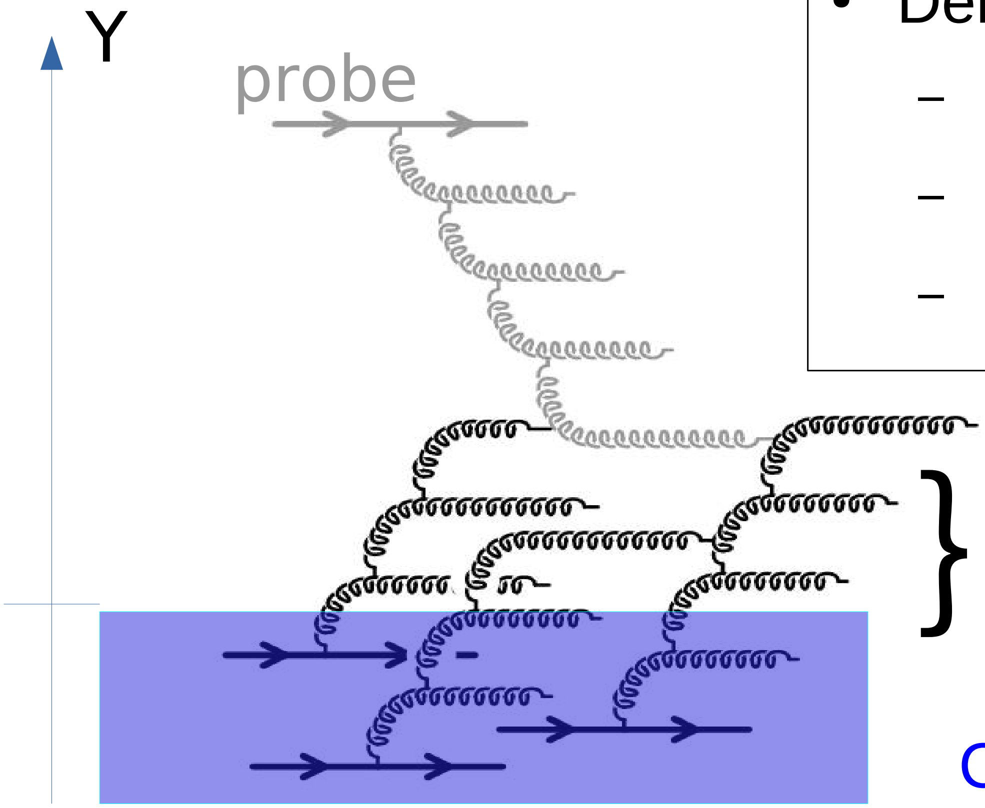
Color Glass Condensate = EFT for small-x

- Dense small-x gluons
  - Non-linear x-evolution
  - Sat scale Qs ~ intr. kT
  - Multiple scatterings



Slow
Small x

Fast
Large x



} fluctutions

$Q_s(x) >> \Lambda_{QCD}$

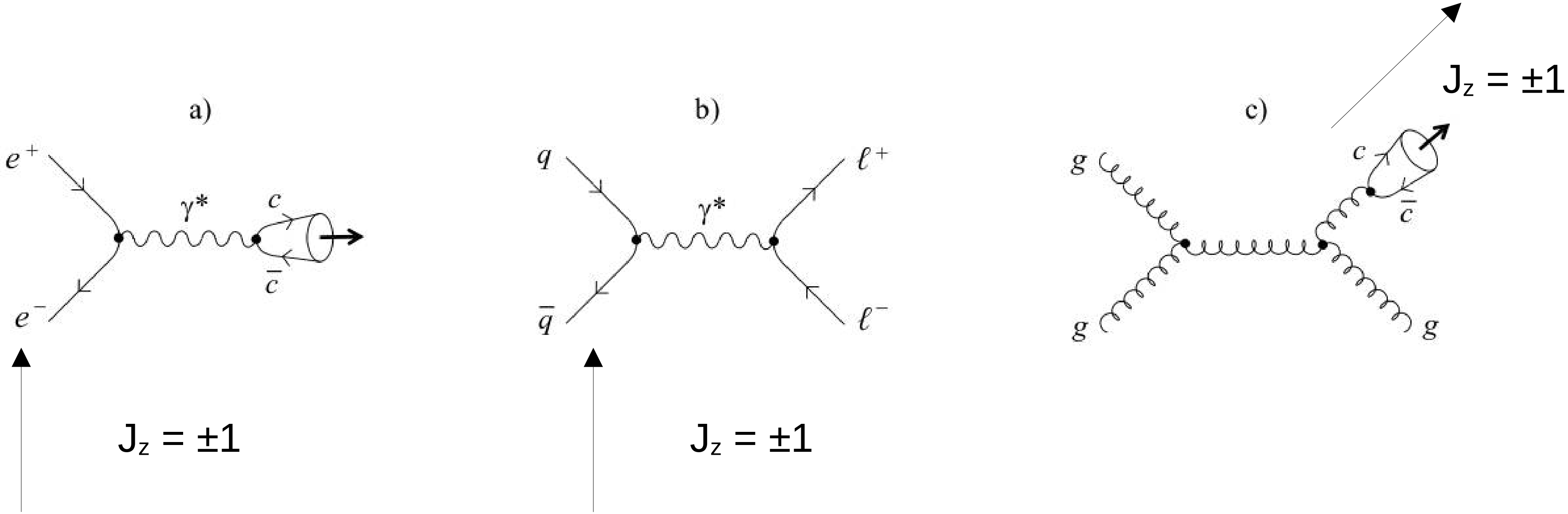
Color charge

This talk

a brief recap and comments
on J/ψ polarization from CGC perspective

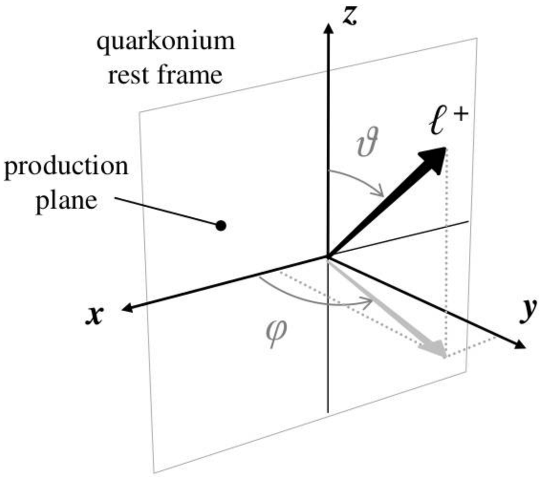
J/ψ production in pp

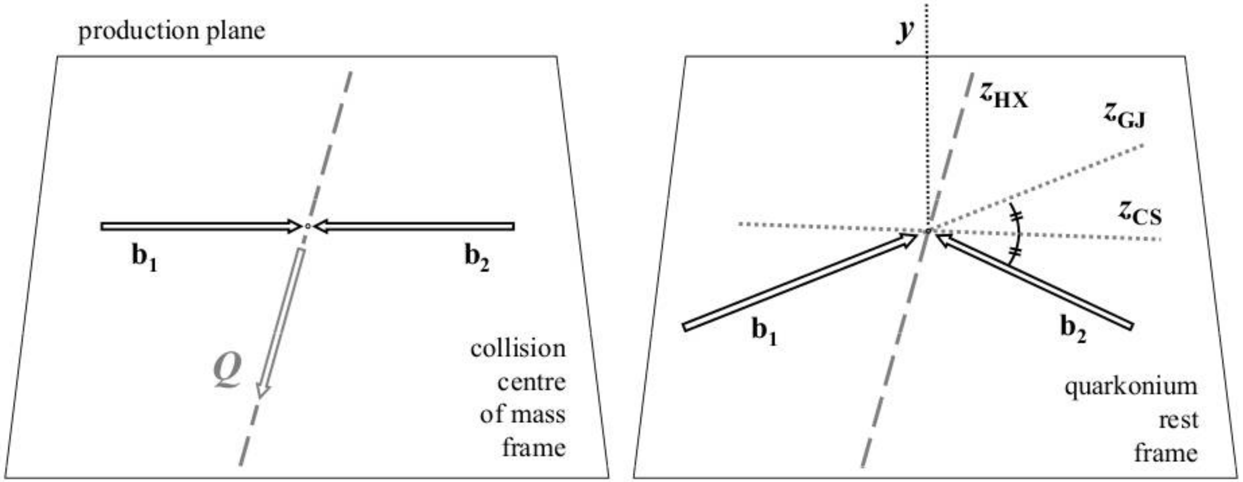
- Famous prediction of transverse polarization of high-pT J/ψ (octet contrib) by NRQCD at LO in (α_s, $v=q/M$)



Review by Faccioli et al.

Coordinate choice for polarization





Review by Faccioli et al.

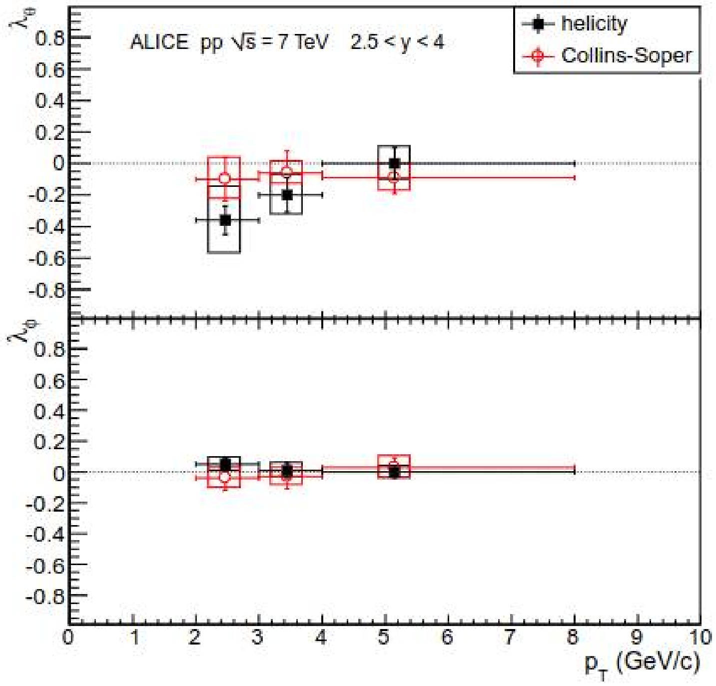
- Helicity frame refers to Jpsi mom directio
- CS frame refers to parton mon (in 2bdy kinema)

Mostly no polarization observed in pp

$$W(\theta, \phi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi,$$

- Example
  - Jpsi pp √s = 7 TeV

Alice, PRL108 (2012) 082001



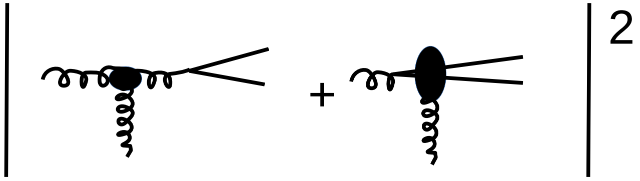
- NRQCD:
  - NLO found to be important
- At low pT and at forward rapidity, small-x DOF plays a role : CGC

Jpsi polarization in dilute-dense collisions in CGC+NRQCD

$$d\sigma_{ij} = \sum_{\kappa} d\hat{\sigma}_{ij}^{\kappa} \langle \mathcal{O}_{\kappa} \rangle$$

Ma-Stebel-Venugopalan
Stebel-Watanabe

Short Distance parts



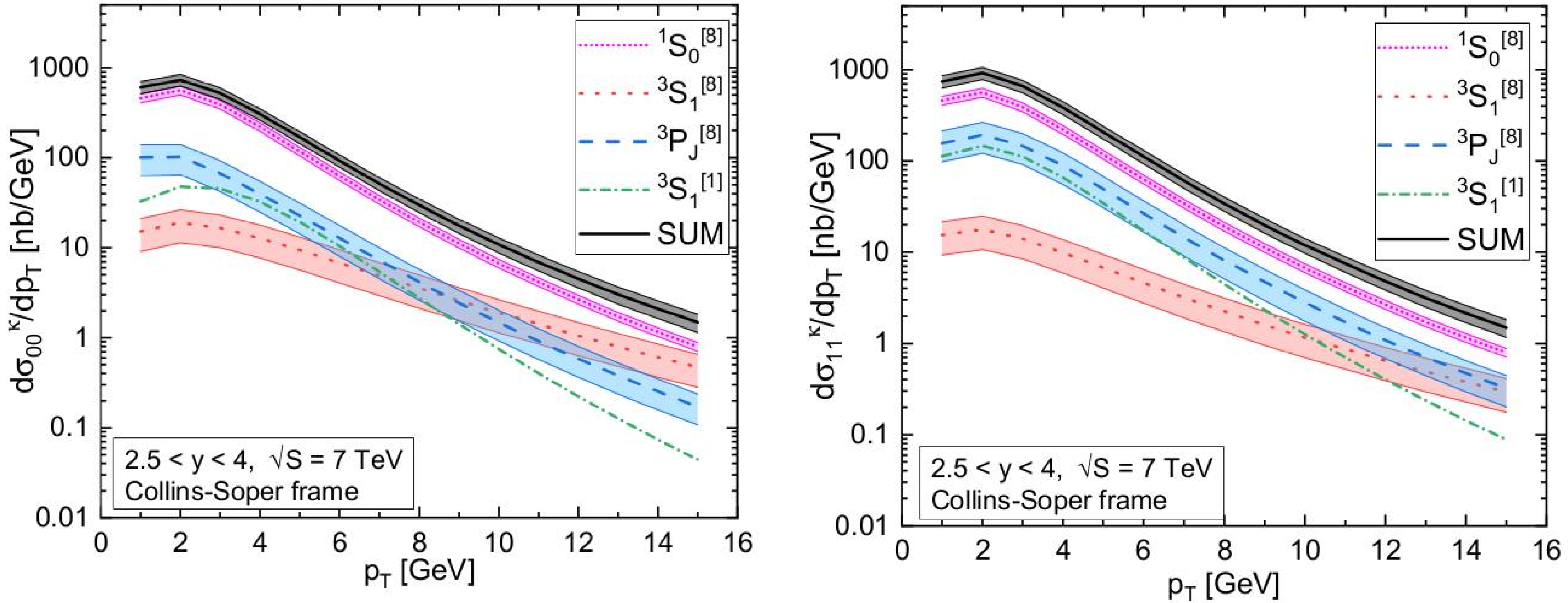
projected on ${}^3S_1^{[1]},\ {}^1S_0^{[8]},\ {}^3S_1^{[8]},\ {}^3P_J^{[8]}$

LDMEs are taken from NLO NRQCD fit

$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]}) \rangle \quad \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle \quad \langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]}) \rangle \quad \langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle,$$

Jpsi polarization in dilute-dense collisions in CGC+NRQCD

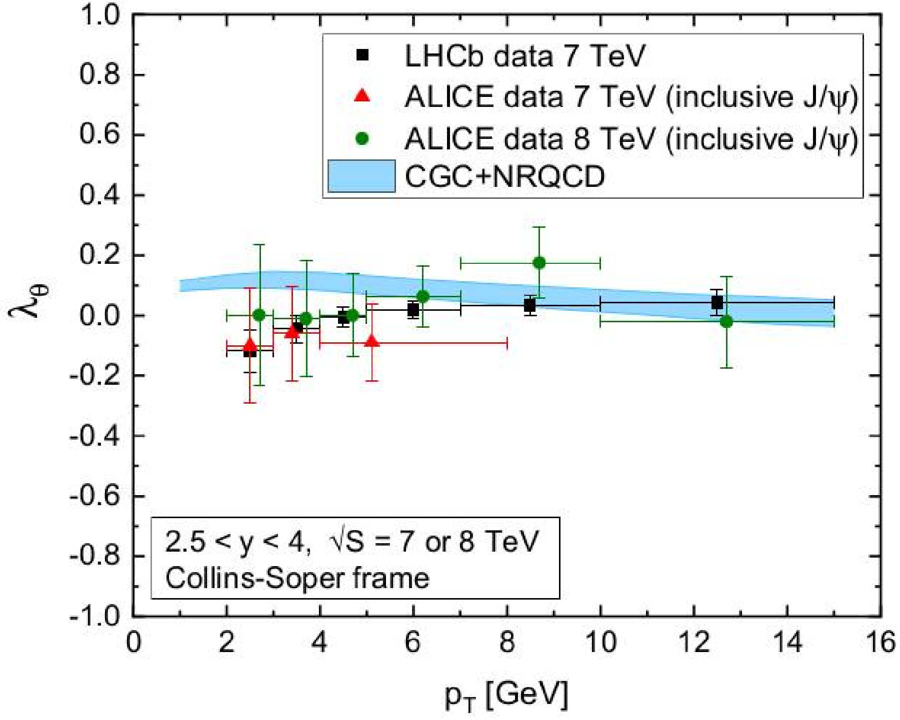
Ma-Stebel-Venugopalan
Stebel-Watanabe

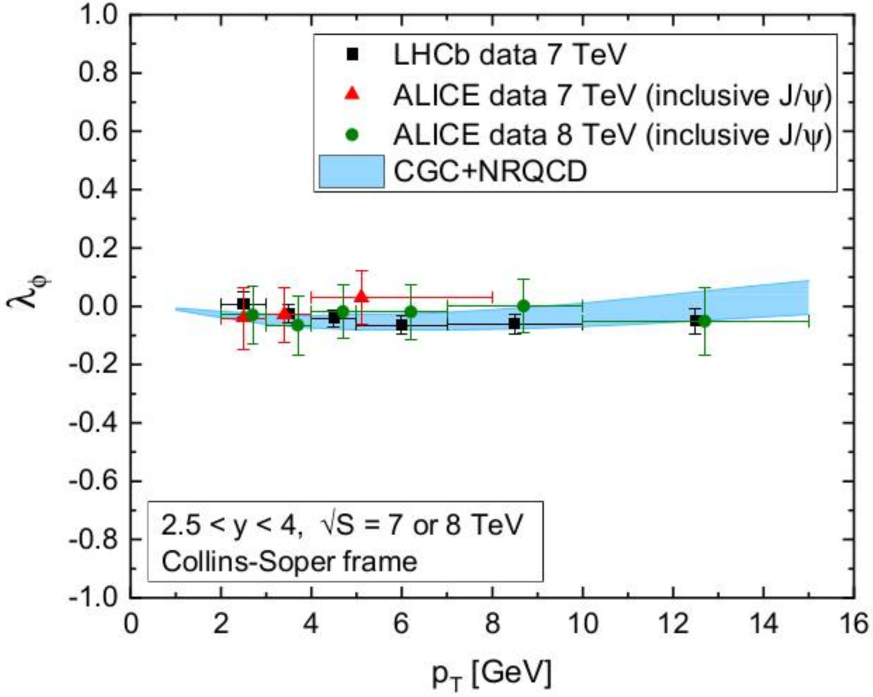


Jpsi polarization in dilute-dense collisions in CGC+NRQCD

Ma-Stebel-Venugopalan
Stebel-Watanabe

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}$$

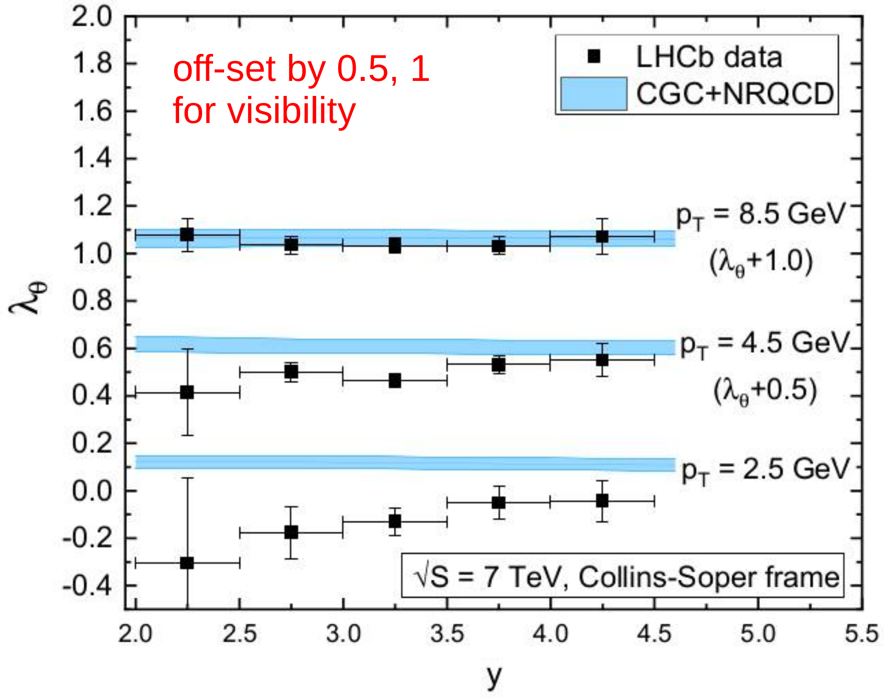




Small summary of J/ψ in pp

Ma-Stebel-Venugopalan
Stebel-Watanabe

- Mostly unpolarized and reasonably described by CGC+NRQCD
- Weak rapidity dependence



J/ψ pols observed in PbPb colls

ALICE, PLB 815 (2021) 136146, arXiv:2005.11128

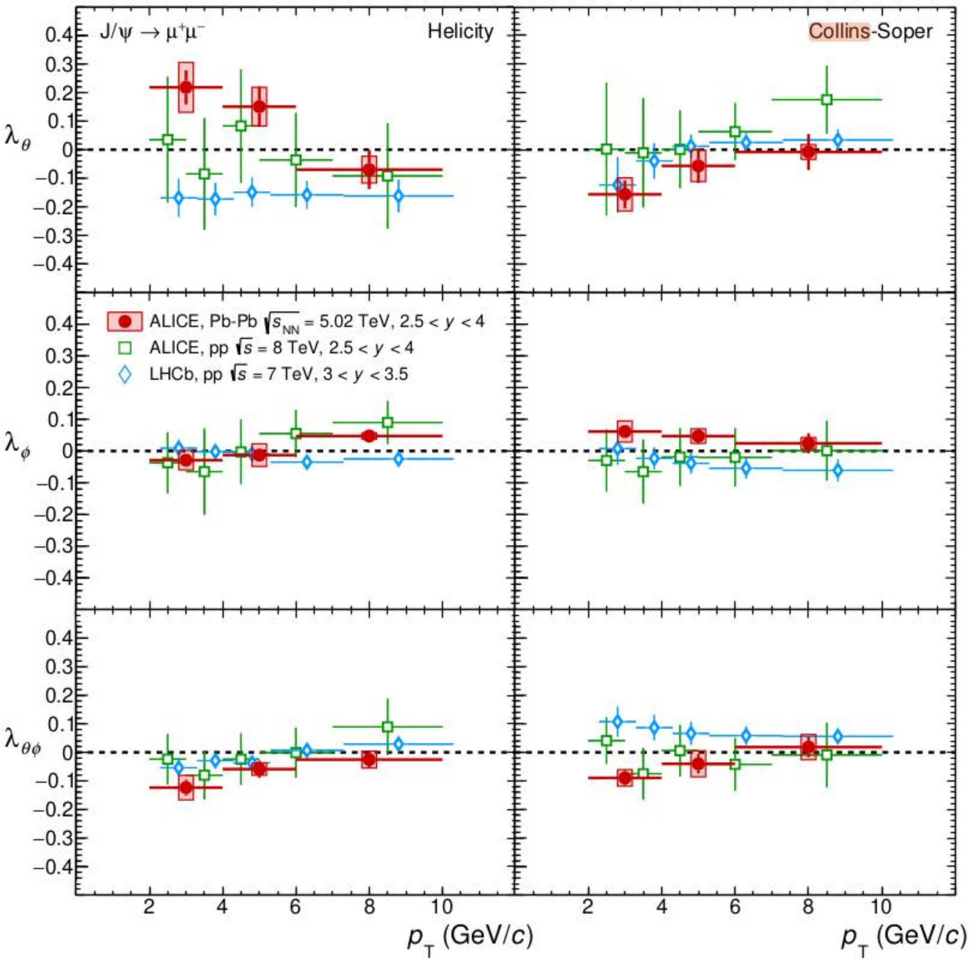


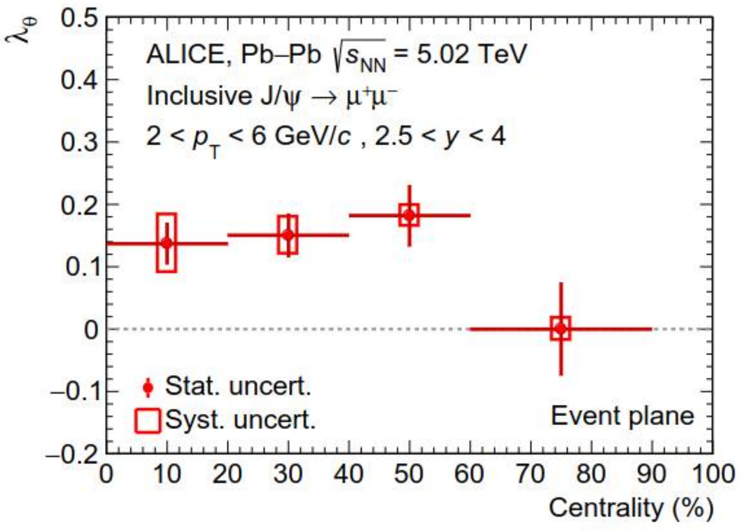
Figure 3: Inclusive J/ψ polarization parameters as a function of transverse momentum for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with results obtained in pp collisions by ALICE at $\sqrt{s} = 8$ TeV [23] and by LHCb for prompt J/ψ at $\sqrt{s} = 7$ TeV [24] (the LHCb markers were shifted horizontally by +0.3 GeV/c for better visibility) in the rapidity interval $3 < y < 3.5$. The error bars represent the total uncertainties for the pp results, while for Pb–Pb statistical and systematic uncertainties are plotted separately as a vertical bar and a shaded box, respectively. In the left part of the plot the polarization parameters in the helicity reference frame are reported, in the right those for the Collins-Soper frame.

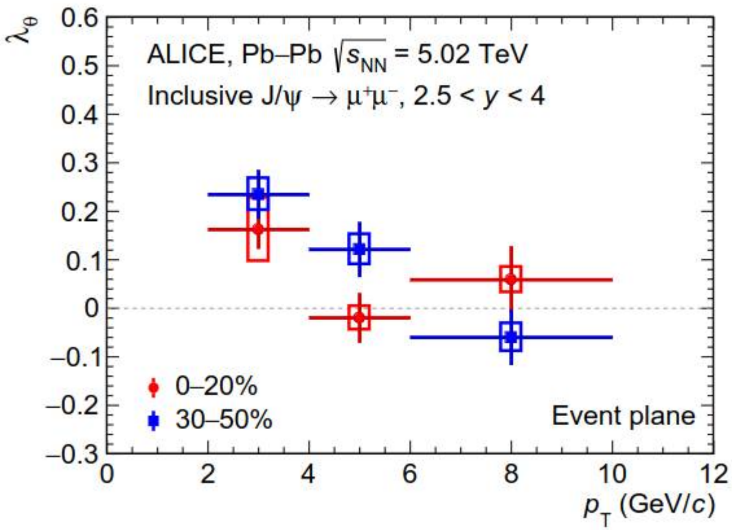
J/ψ pols w.r.t event plane

ALICE PRL131 (2023) 042303,
arXiv:2204.10171

- Heavy-Ion collision is characterized by *Event Plane*
- Transverse pol w.r.t. Event Plane is observed

- Centrality dependence ⇒ response of J/ψ to B field and/or vorticity of QGP?
- Early stage dynamics important?

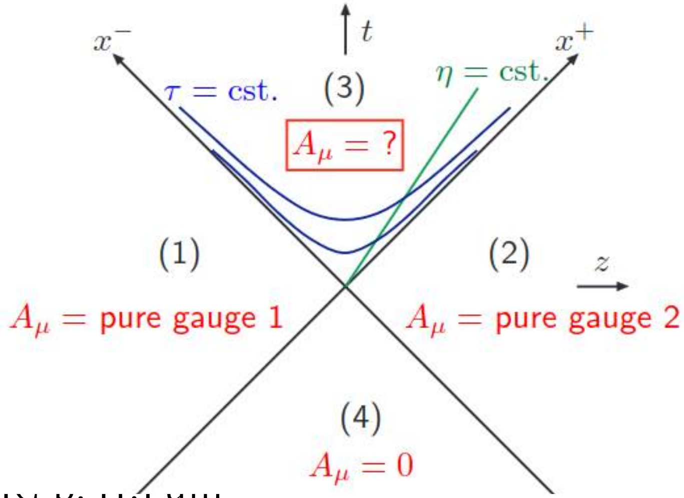




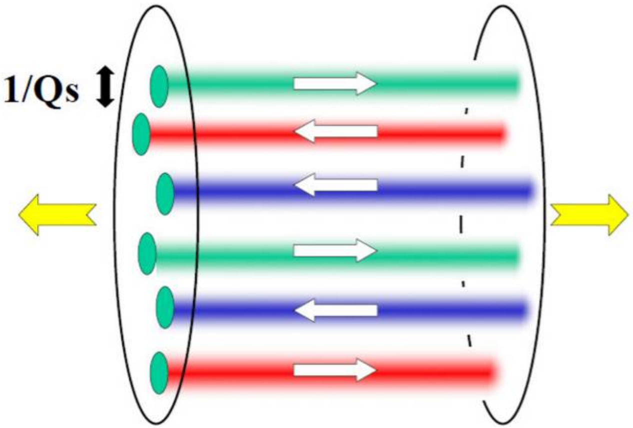
Early stage important? - Glasma

Lappi-McLerran

- Non-zero commutators give longitudinal color fields at initial time
- $c\bar{c}$ and $b\bar{b}$ produced in initial hard scatterings, τ~.06, .02 fm/c (light quarks as well as gluons are produced during the glasma decay and after, although non-trivial)

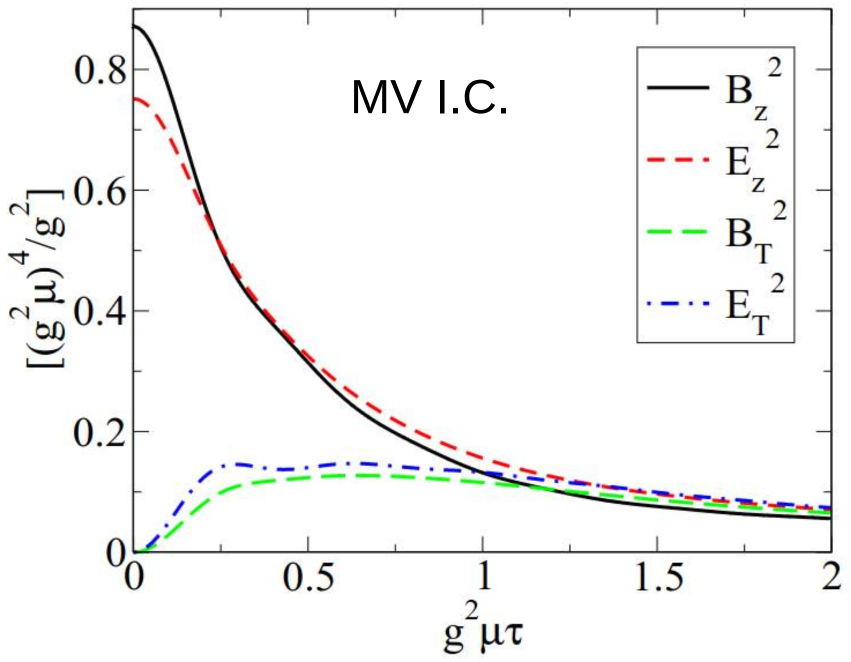


$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

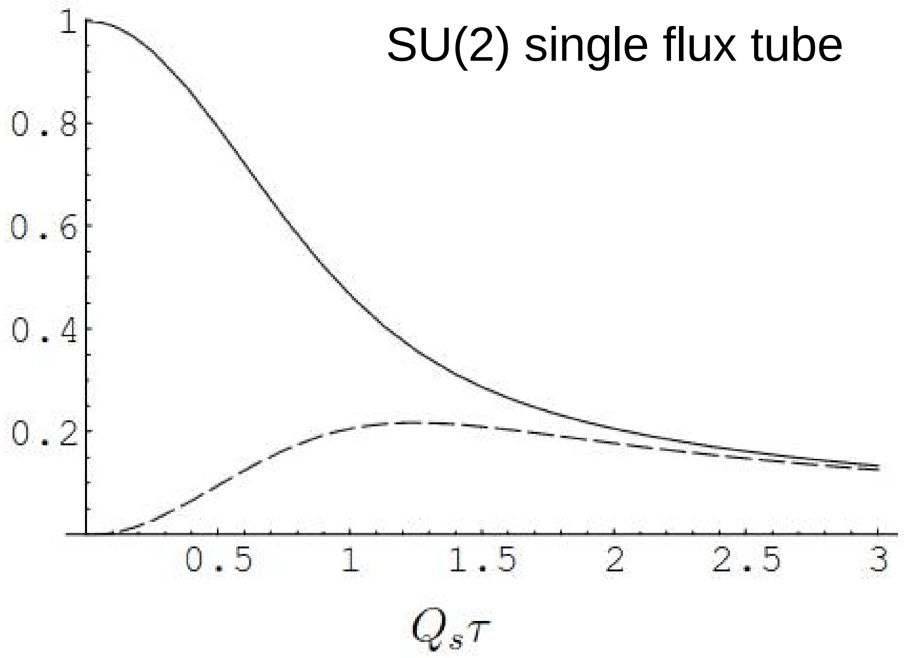


Early stage important? - Glasma

- Transverse fields are generated in time evolution



Lappi-McLerran



Fujii-Itakura

Early stage important? - Glasma

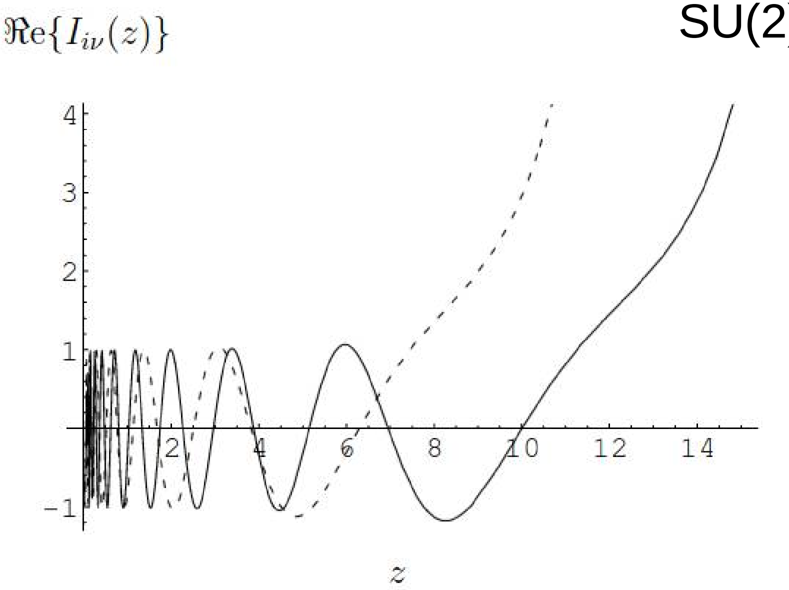
- Fluctuation around the flux-tube is unstable

$$\partial_\tau^2 f + \frac{1}{\tau}\partial_\tau f + \left(-gB + \frac{\nu^2}{\tau^2}\right) f = 0\,.$$

Nielsen-Olesen type instability

- Off-diagonal color components
- *Negative spring constant* for small long.mom. ν

SU(2)



- Many more studies on glasma evolution so far

Fujii-Itakura

Glasma

- Color charges in nuclei act coherently in longitudinal direction
- Fluctuating *randomly* with scale *Qs* in transverse directions
- Supposedly decays rapidly to a QGP within $\tau < 0.6$ fm (?)
  - Unstable I.C. (Weibel/NielseOlesen)
  - Evolve to a turbulence (?)

	w.r.t. event plane	Range in trans.plane	It's bigger at *b*=	lifetime
B field	Perp	long	Mid-central	~ QGP
glasma	Irrelevant	1/Qs	Most central	Very short

Glasma effect on vector meson polarization

- Any observables are integrals of evolution history
  - Early stage effects should be included
- Kumar-Yang-Mueller, see Kumar’s talk yesterday

Glasma effect on jets and HQ

- Exploratory study: solving Wong's equations on top of boost-inv Glasma

Simulating jets and heavy quarks in the Glasma using the colored particle-in-cell method

Dana Avramescu,[1,2,*] Virgil Băran,[3,†] Vincenzo Greco,[4,5,‡]
Andreas Ipp,[6,§] David Müller,[6,¶] and Marco Ruggieri[4,**]

Phys. Rev. D 107 (2023), 114021

- Classical colored particles without spin

$$\frac{\mathrm{d}x^i}{\mathrm{d}t} = \frac{p^i}{E},$$
$$\frac{\mathrm{d}p^i}{\mathrm{d}t} = gQ^a F^{i\mu,a}\frac{p_\mu}{E},$$
$$\frac{\mathrm{d}Q^a}{\mathrm{d}t} = -gf^{abc}A^b_\mu Q^c \frac{p^\mu}{E},$$

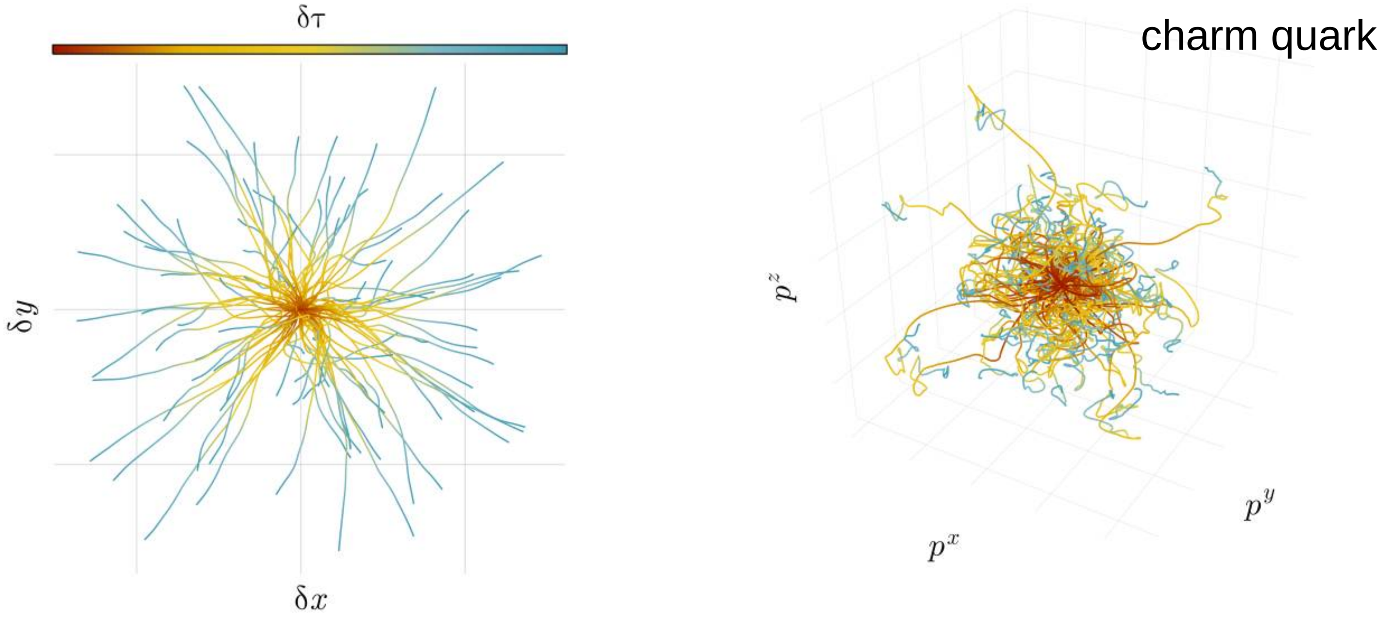
Momentum broadening (w/o deflection):

$$\langle \delta p^2_\mu(\tau)\rangle_R = g^2 \int_{\tau_{\mathrm{form}}}^{\tau} \mathrm{d}\tau' \int_{\tau_{\mathrm{form}}}^{\tau} \mathrm{d}\tau'' \left\langle \mathrm{Tr}\left[\widetilde{\mathcal{F}}_\mu(\tau')\widetilde{\mathcal{F}}_\mu(\tau'')\right]\right\rangle_R .$$

$$\widetilde{\mathcal{F}}_\mu(\tau) \equiv \mathcal{U}^\dagger(\tau,\tau_0)\,\mathcal{F}_\mu(\tau)\,\mathcal{U}(\tau,\tau_0)$$

Glasma effect on jets and HQ

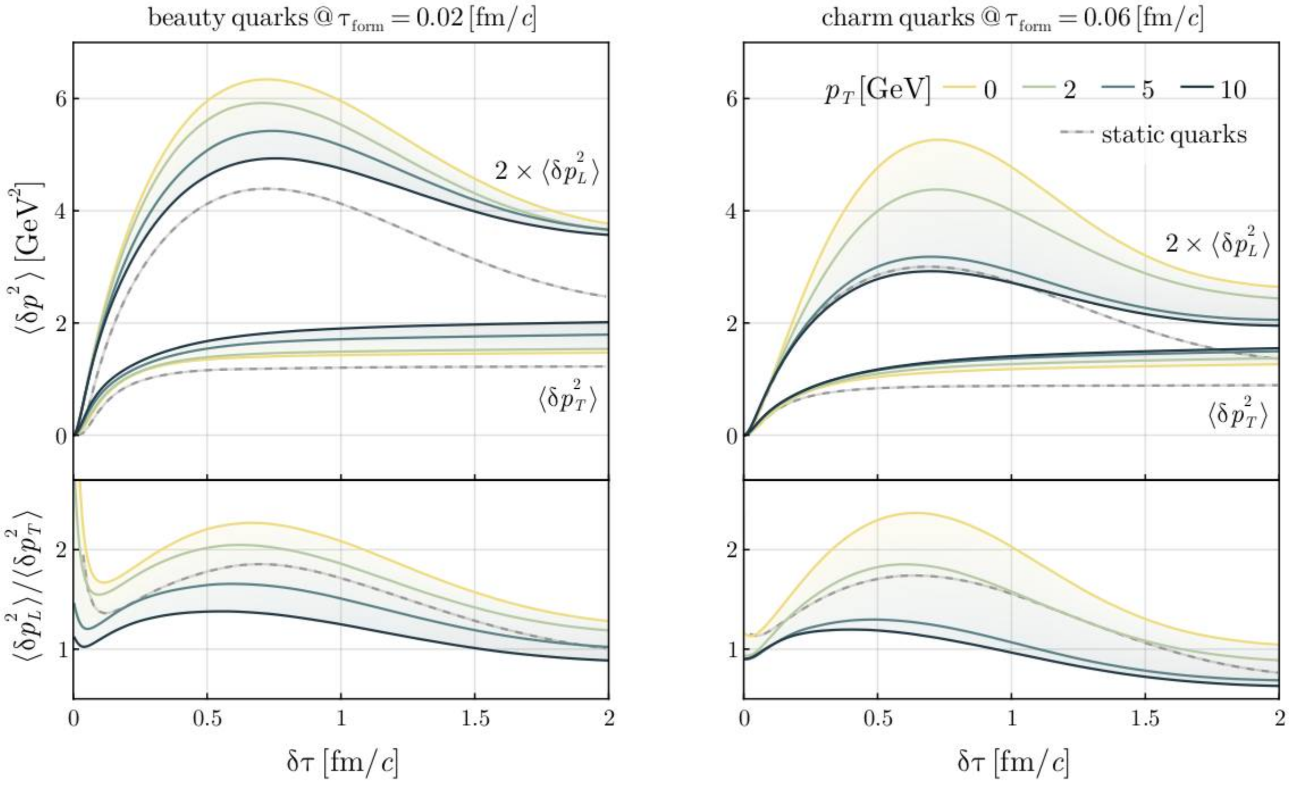
- Exploratory study: solving Wong's equations on top of boost-inv Glasma



(a) Trajectories in the transverse plane (b) Trajectories in momentum space

Glasma effect on jets and HQ

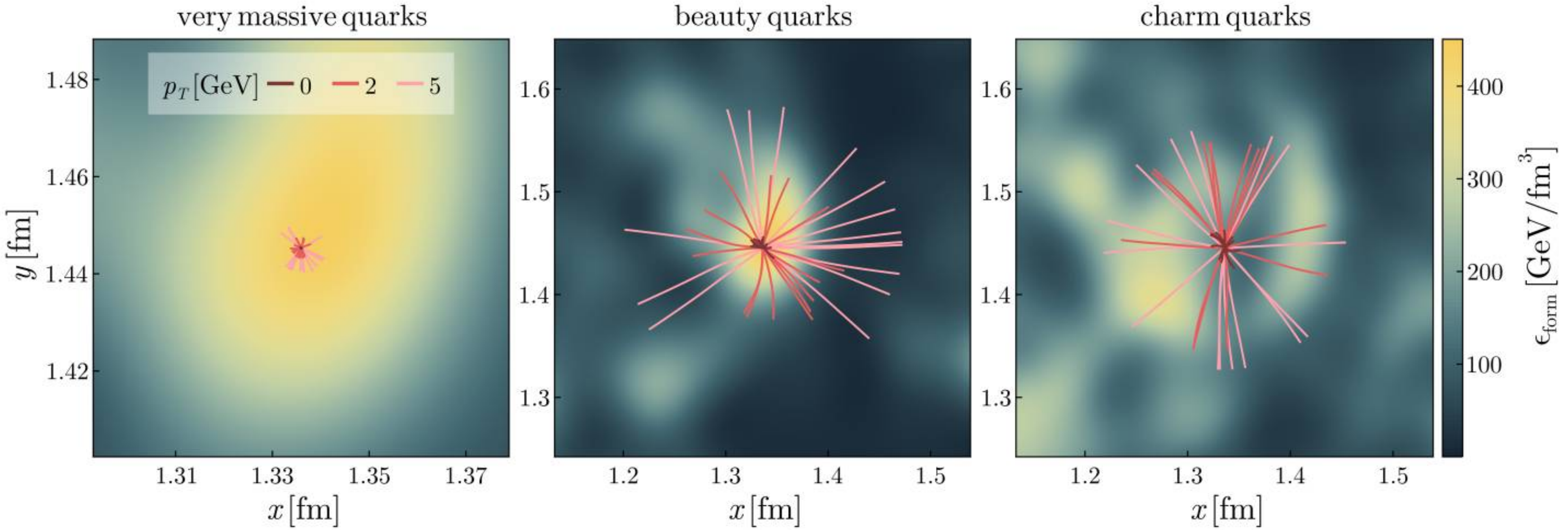
- Exploratory study: solving Wong's equations on top of boost-inv Glasma



Glasma effect on jets and HQ

- Exploratory study: solving Wong's equations on top of boost-inv Glasma

$\delta\tau = 0.2\ \mathrm{fm/c}$



Formation time, 0.02, 0.06 fm/c. Initial pT chosen randomly for 0, 2, 5 GeV/c

Speculation: glasma effect on J/ψ

- *Direct production*: color coherence between the two HQ with spin should be taken into account
- *Recombination*: Two independent HQ’s traverse the glasma and recombine to form the J/ψ wavefunction

Is it possible to simulate the evolution of two HQ’s with spin on top of Glasma?

Summary

- Elementray production of J/ψ is likely to be unpolarized, and described by CGC+NRQCD
- Polarization of J/ψ in nuclear collisions may reflect info of EM field effect on HQ's
- Glasma may randomize the HQ's mom&spin, but the size of its effect is unknown
- Simulating HQ evolution with spin d.o.f on top of the glasma seems intriguing topic (even in a simplified setup)

NRQCD factorization

- Failed to explain the polarization of the prompt Jpsi in pp collisions at Tevatron

Braaten-Kniehl-Lee (2000)

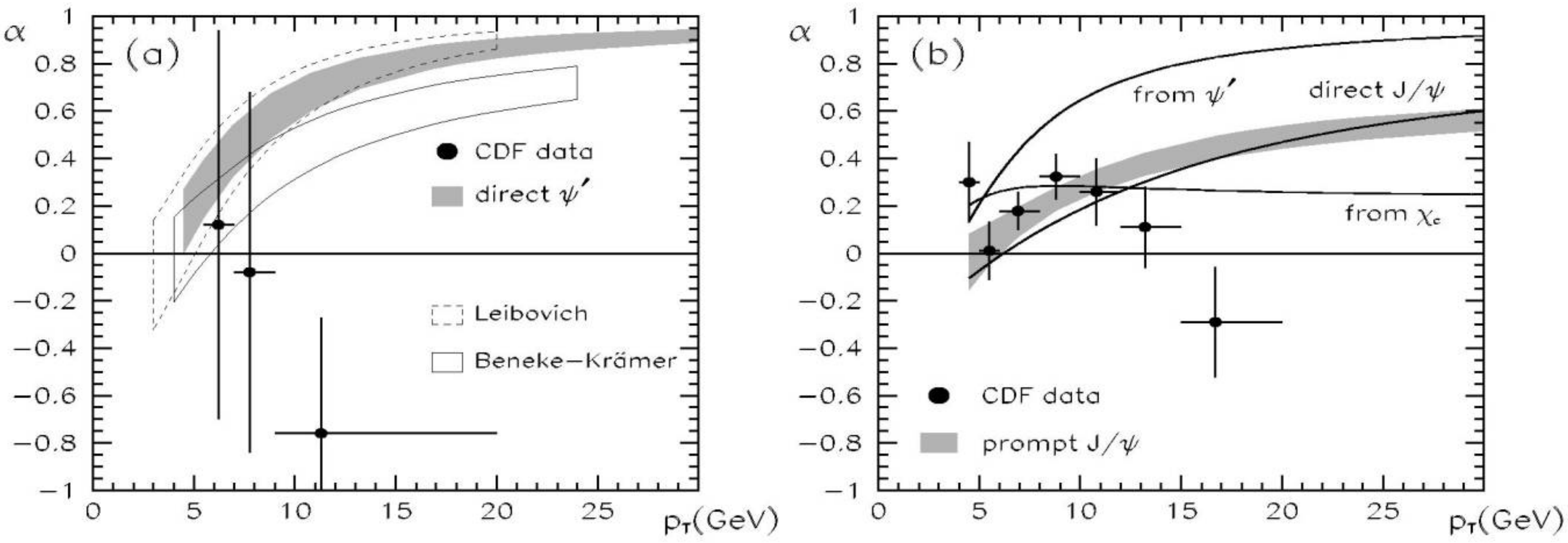


FIG. 1. Polarization variable α vs p_T for (a) direct ψ' and (b) prompt J/ψ compared to CDF data.