Quarkonium Production and TMDs at LHC

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in collaboration with
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"Quarkonium at LHC energies" project
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Summary

- Physics case for the LHCSpin project - (polarized) fixed target experiment at LHCb
- 3D structure of hadrons
- Spin and parton intrinsic motion correlations in inclusive processes [TMD approach]
- Transverse momentum dependent PDFs and FFs (TMDs)
- Quarkonium production via gluon-gluon fusion mechanism and gluon TMDs
- TMD and NRQCD approaches
- Transverse single spin and azimuthal asymmetries
- Complementarity with SIDIS, pp at RHIC, e^+e^- collisions, Electron Ion Collider

Reference material

- For a more extensive perspective on polarized fixed target physics at LHC see previous talk by J.P. Lansberg in this session
- For the LHCSpin experimental setup see previous talk by L. Pappalardo in this session
- For a complementary analysis in lepton-proton scattering see next talk by P. Taels
- For a more detailed study of the gluon Sivers function in quarkonium, D meson and pion production in polarized pp collisions see talk by C. Pisano on Wednesday, WG6

More detailed information in:

- The LHCSpin project
  C. Aidala et al. arXiv 1901.08002 [hep-ex] prepared for the ESPPU
- Community support to a fixed-target programme for the LHC
  J.D. Bjorken et al., prepared for the ESPPU [https://indico.cern.ch/event/777124/]
- For an overview on spin and TMD physics see also yesterday's plenary talk by A. Bacchetta

The LHCSpin physics case - 1

- **Quark TMD distributions, in particular at medium-large light-cone momentum fraction**
- **Mainly Sivers function, transversity and tensor charge; Boer-Mulders function, Collins FF,...**
- **Polarized hydrogen and deuterium targets at $\sqrt{s}$ = 115 GeV**

Two-particle production in the same hemisphere:

- $pp^{\uparrow} \to (h_1 h_2) + X$ - **di-hadron fragmentation functions, collinear factorization**
- $pp^{\uparrow} \to (h + jet) + X$ − **azimuthal moments as in SIDIS, TMDs in fragmentation, Collins FF**
- **Polarized Drell-Yan process, change of sign of the Sivers function as compared to SIDIS**

Two-particle production in the opposite hemisphere:

$$pp^{\uparrow} \to h_1 + h_2 + X, \qquad pp^{\uparrow} \to h + jet + X, \qquad pp^{\uparrow} \to h + \gamma + X$$

TMD factorization could be violated; still useful and relevant to possibly assess the (unknown) relative size of factorization breaking terms in different kinematical regimes

The LHCSpin physics case - 2

- Quarkonium production as a tool for studying gluon TMDs
- Unpolarized and linearly polarized gluon TMDs (first stage)
- Gluon Sivers function (needs polarized target, next stage)

- Quarkonium and isolated photons in opposite hemispheres (relative $p_T \ll M_Q$)

$$pp^{\uparrow} \to J/\psi + \gamma + X; \quad pp^{\uparrow} \to \psi' + \gamma + X; \quad pp^{\uparrow} \to \Upsilon + \gamma + X; \quad etc.$$

- Associated back-to-back quarkonium production

$$pp^{\uparrow} \to J/\psi + J/\psi + X; \quad pp^{\uparrow} \to J/\psi + \psi' + X; \quad pp^{\uparrow} \to \Upsilon + \Upsilon + X$$

- Single inclusive Quarkonium, D meson, pion and photon production
  Unpolarized and transversely polarized cases

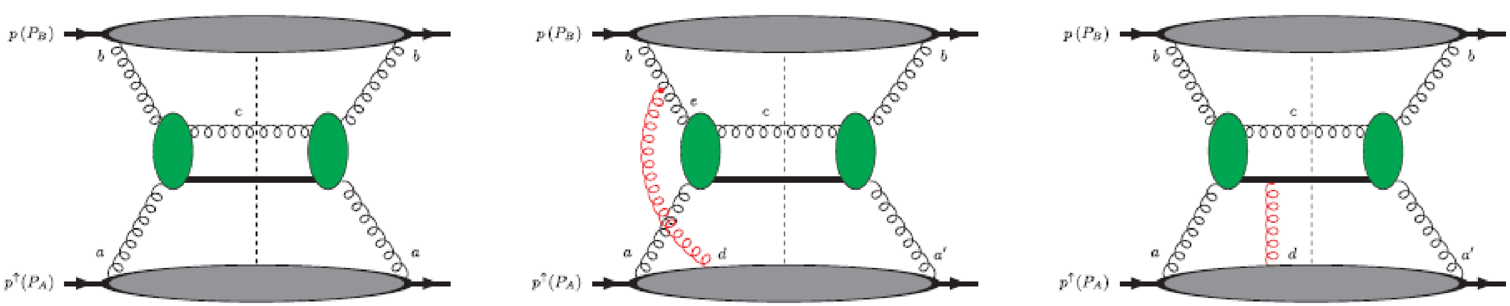
$$pp^{\uparrow} \to J/\psi, \Upsilon + X; \quad pp^{\uparrow} \to D + X; \quad pp^{\uparrow} \to \pi + X; \quad pp^{\uparrow} \to \gamma + X$$

Open points: Factorization, universality, process dependence, evolution with scale

$pp^{(\uparrow)} \rightarrow J/\psi + X$ (stage 1)

- **TMD Generalized Parton Model - spin and transv. momentum effects, helicity formalism**
- **Color gauge invariant (CGI) extension – LO ISIs and FSIs included**
- **NRQCD, color singlet model (stage 1) - asymmetries independent of LDMEs**

- **Unpolarized cross sections, low p_T spectrum (reasonable result is sufficient at this stage)**
- **Main interest: Transverse SSAs and azimuthal asymmetries (many theoretical uncertainties cancel out , at least partially, in the ratios of cross sections)**
- **Gluon Sivers function (almost unknown)**
- **Role of intrinsic transverse momentum in J/ψ polarization (in the future)**



(a) (b) (c)

$pp^{(\uparrow)} \to J/\psi + X$ - some technical details

$$p(p_A) + p(p_B) \to \mathcal{Q}(p_\mathcal{Q}) + X$$

See talk by C. Pisano on Wednesday, WG6

$$g(p_a) + g(p_b) \to Q\overline{Q}[{}^3S_1^{(1)}](p_\mathcal{Q}) + g(p_g)$$

$$\mathrm{d}\sigma \equiv E_\mathcal{Q}\,\frac{\mathrm{d}\sigma}{\mathrm{d}^3\boldsymbol{p}_\mathcal{Q}} = \frac{\alpha_s^3}{s}\int \frac{\mathrm{d}x_a}{x_a}\,\frac{\mathrm{d}x_b}{x_b}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\mathrm{d}^2\boldsymbol{k}_{\perp b}\,f_{g/p}(x_a,k_{\perp a})\,f_{g/p}(x_b,k_{\perp b})\,H^U_{gg\to J/\psi g}(\hat{s},\hat{t},\hat{u})\,\delta(\hat{s}+\hat{t}+\hat{u}-M^2)$$

$$A_N \equiv \frac{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow}{\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow} \equiv \frac{\mathrm{d}\Delta\sigma}{2\mathrm{d}\sigma}$$

$$\begin{aligned}\mathrm{d}\Delta\sigma^{\mathrm{GPM}} \equiv{}& \frac{E_\mathcal{Q}\,\mathrm{d}\sigma^\uparrow}{\mathrm{d}^3\boldsymbol{p}_\mathcal{Q}} - \frac{E_\mathcal{Q}\,\mathrm{d}\sigma^\downarrow}{\mathrm{d}^3\boldsymbol{p}_\mathcal{Q}} = \frac{2\alpha_s^3}{s}\int \frac{\mathrm{d}x_a}{x_a}\,\frac{\mathrm{d}x_b}{x_b}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\mathrm{d}^2\boldsymbol{k}_{\perp b}\\ &\times \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g}(x_a,k_{\perp a})\cos\phi_a\,f_{g/p}(x_b,k_{\perp b})\,H^U_{gg\to J/\psi g}(\hat{s},\hat{t},\hat{u})\,\delta(\hat{s}+\hat{t}+\hat{u}-M^2)\end{aligned}$$

$$\begin{aligned}\mathrm{d}\Delta\sigma^{\mathrm{CGI}} \equiv{}& \frac{E_\mathcal{Q}\,\mathrm{d}\sigma^\uparrow}{\mathrm{d}^3\boldsymbol{p}_\mathcal{Q}} - \frac{E_\mathcal{Q}\,\mathrm{d}\sigma^\downarrow}{\mathrm{d}^3\boldsymbol{p}_\mathcal{Q}} = \frac{2\alpha_s^3}{s}\int \frac{\mathrm{d}x_a}{x_a}\,\frac{\mathrm{d}x_b}{x_b}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\mathrm{d}^2\boldsymbol{k}_{\perp b}\\ &\times \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g\,(f)}(x_a,k_{\perp a})\cos\phi_a\,f_{g/p}(x_b,k_{\perp b}) \left(-\frac{1}{2}\,H^U_{gg\to J/\psi g}(\hat{s},\hat{t},\hat{u})\right)\delta(\hat{s}+\hat{t}+\hat{u}-M^2)\end{aligned}$$

$pp^{(\uparrow)} \rightarrow J/\psi + X$ - some technical details

$$\frac{k_\perp}{M_p}\,|f_{1T}^{\perp a}(x_a, k_{\perp a})| \leq f_{a/p}(x_a, k_{\perp a})$$

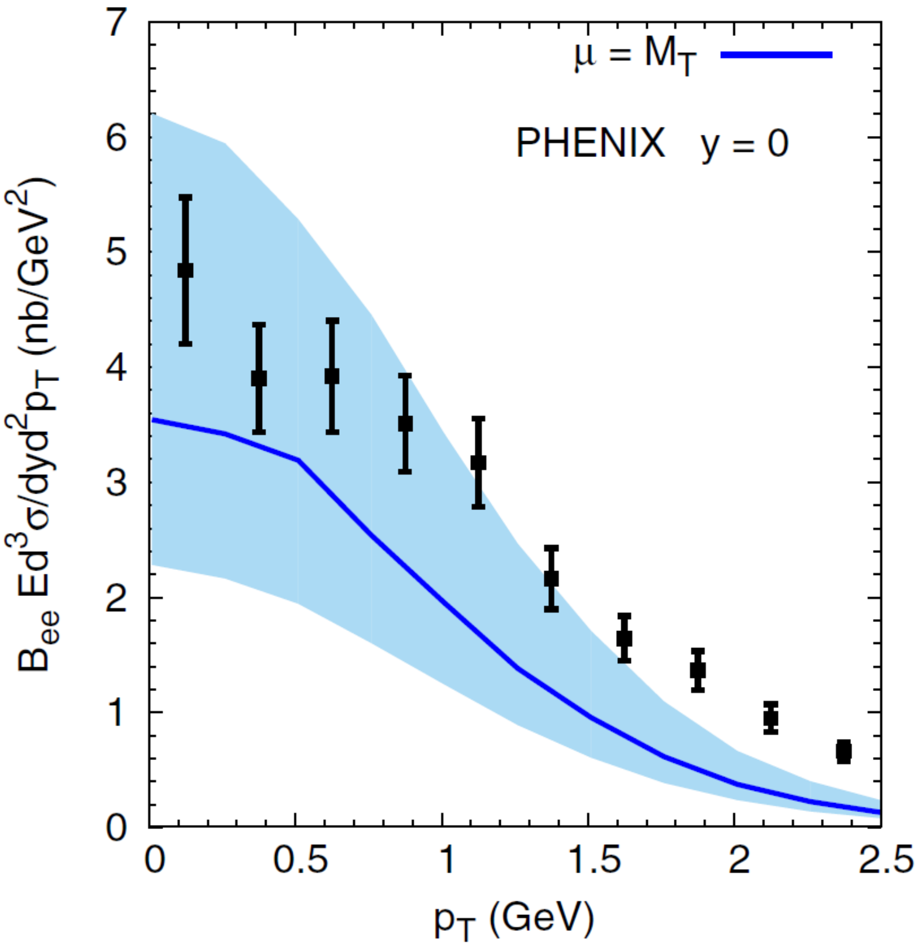
$$H^U_{gg\to J/\psi g} = \frac{5}{9}\,|R_0(0)|^2\, M\,\frac{\hat{s}^2(\hat{s}-M^2)^2+\hat{t}^2(\hat{t}-M^2)^2+\hat{u}^2(\hat{u}-M^2)^2}{(\hat{s}-M^2)^2(\hat{t}-M^2)^2(\hat{u}-M^2)^2}$$

$$f_{g/p}(x, k_\perp) = f_{g/p}(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

$$\langle k_\perp^2\rangle = 1\mathrm{GeV}^2, \qquad M_T/2 \leq \mu \leq 2M_T\,, \qquad M_T = \sqrt{p_T^2 + M^2}$$

$$M = 3.097\mathrm{GeV}, \qquad |R_0(0)|^2 = 1.01\mathrm{GeV}^3, \qquad \mathrm{Br}(J/\psi \to e^+e^-) = 0.0597$$

$pp^{(\uparrow)} \rightarrow J/\psi + X$ (stage 1)

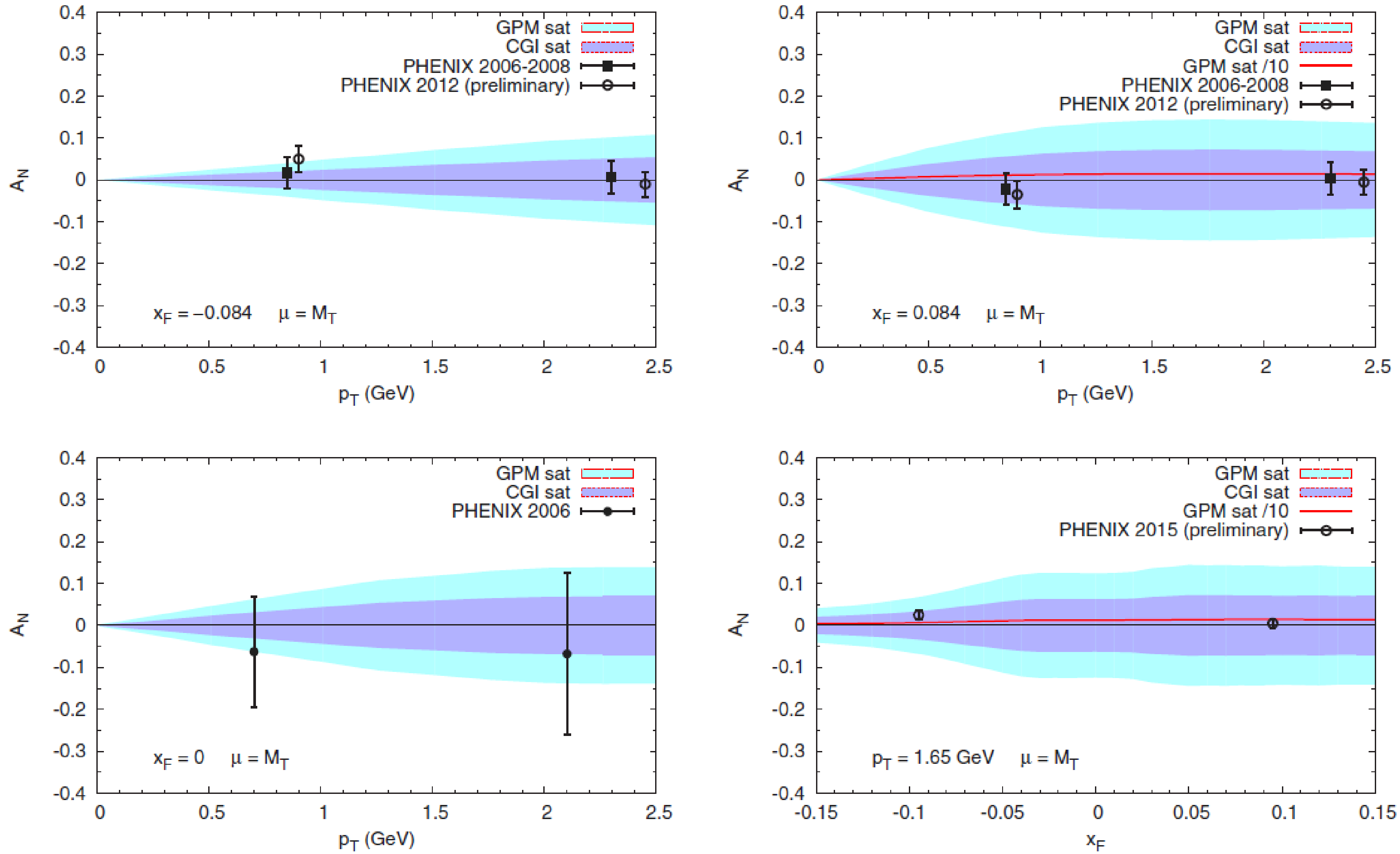


Data include feed-down contributions

Expected fraction of direct J/ψ production: 0.58

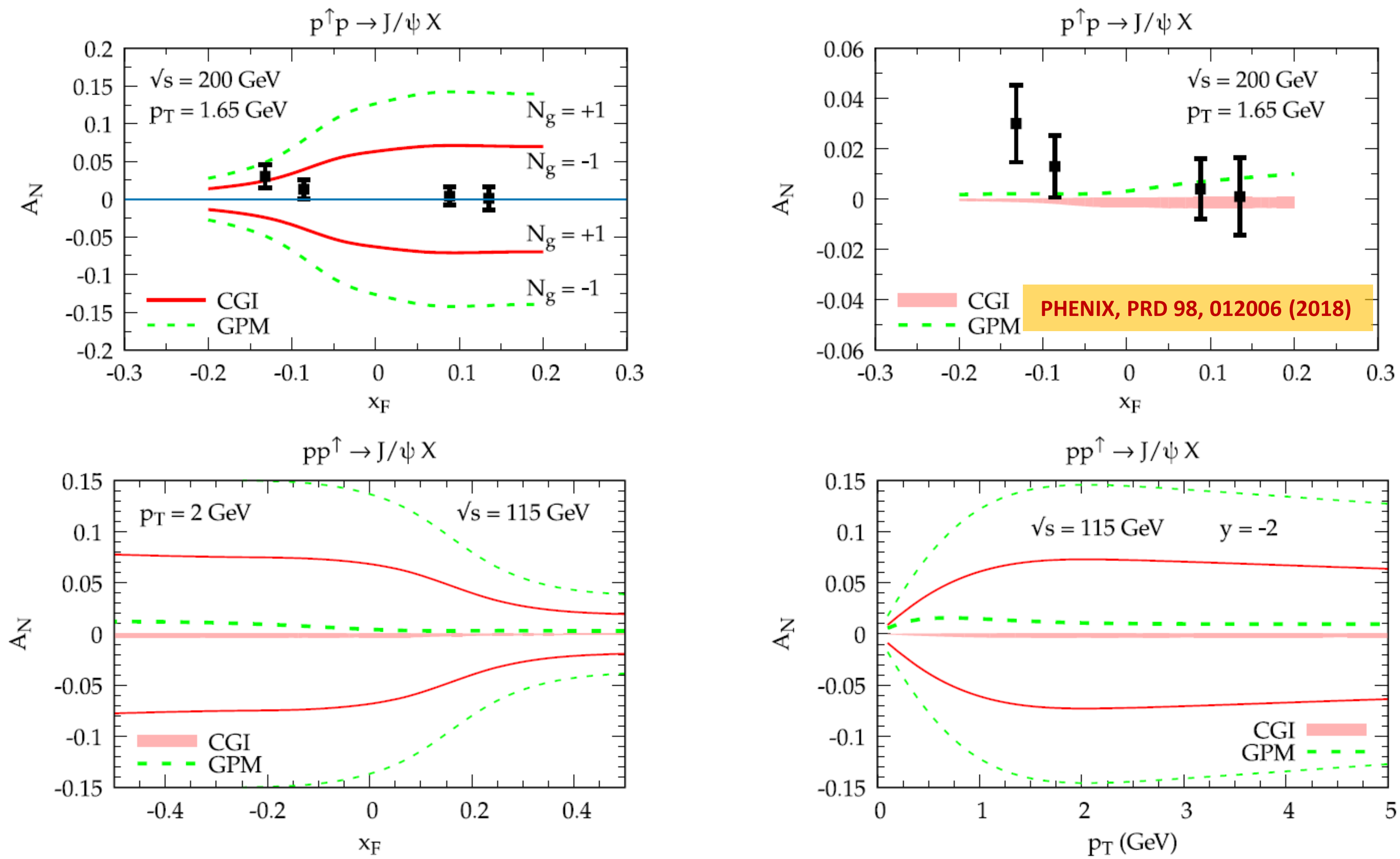
U. D'Alesio, FM, C. Pisano, P. Taels, PRD 96, 036011 (2017)

$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Comparison with PHENIX data



U. D'Alesio, FM, C. Pisano, P. Taels, PRD 96, 036011 (2017)

$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Constraining the gluon Sivers function



U. D'Alesio, C. Flore, FM, C. Pisano, P. Taels, PRD 99, 036013 (2019)

See talk by C. Pisano, WG6

Present status of quarkonium production project

- Inclusive quarkonium production in (un)polarized pp collisions in the low p_T region [$0 \leq p_T \leq 4$ GeV] [direct production, feed-down contributions to be included]
- LO TMD GPM and NRQCD with CS and CO contributions (calculation completed)
- Phenomenology just started: Facing with many problems/uncertainties to be fixed
  - NRQCD Long Distance Matrix Elements: Several sets available optimized for different observables and kinematical configurations
  - At very low p_T CO contribution diverges: NLO calculation and resummation of $\log^2(M_Q/p_T)$ in CSS formalism [see e.g. Qiu-Watanabe 1710.06928]
  - Non perturbative (intrinsic) transverse momentum contribution effectively accounts for these effects and regulate CO divergences
  - Dependence on possible soft regulators in the hard contributions
  - Factorization scale dependence
- Many of these issues are less relevant for single spin and azimuthal asymmetries whic remain our main goal
- Color Gauge Invariant GPM calculation is under way

Thanks for your attention!