

XVII Conference on Theoretical Nuclear Physics (TNPI 2019)

Quarkonium Production and TMDs at the LHC

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in collaboration with

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University and INFN Cagliari

"Quarkonium at LHC energies"

Project funded by Fondazione Sardegna – University of Cagliari

Summary

- The LHCSpin proposal - (polarized) fixed target experiment at LHCb [SMOG,SMOG2]
- 3D structure of hadrons, parton orbital angular momentum, proton spin
- 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 (SSA) and azimuthal asymmetries [Gluon Sivers Function]
- Complementarity with SIDIS, pp at RHIC, e^+e^- collisions, Electron Ion Collider

Reference material

- For the 3D structure of the nucleon and the TMD approach see talk by M. Boglione

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/>]
[AFTER@LHC, LHCSpin@LHCb, ALICE,...]
- For a recent, more extensive perspective on inclusive production of quarkonia see
J.P. Lansberg, *New Observables in Inclusive Production of Quarkonia*
arXiv 1903.09185 [hep-ph]
- For a recent overview on the Gluon Sivers Function (GSF) see
D. Boer, C. Lorcé, C. Pisano, J. Zhou
The gluon Sivers distribution: status and future prospects
Adv. High Energy Phys. 2015, 371396 - arXiv 1504.04332 [hep-ph]

Quarkonium and TMDs at pp colliders

- Quarkonium production as a tool for studying gluon TMDs (RHIC, LHC, EIC)
- Unpol. and linearly polarized gluon TMDs (first LHCSpin stage, SMOG2)
- Gluon Sivers function (needs transv. polarized target, 2nd LHCSpin stage)

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

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

- Associated back-to-back quarkonium production

$$pp^\uparrow \rightarrow J/\psi + J/\psi + X; \quad pp^\uparrow \rightarrow J/\psi + \psi' + X; \quad pp^\uparrow \rightarrow \Upsilon + \Upsilon + X$$

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

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

Open points:

Factorization, universality, process dependence, evolution with scale, TMD + NRQCD,...

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$$A_N \propto \frac{m_q \alpha_S(p_T)}{p_T} \rightarrow 0 \text{ per } p_T \gg \Lambda_{QCD} \text{ in "collinear" pQCD}$$

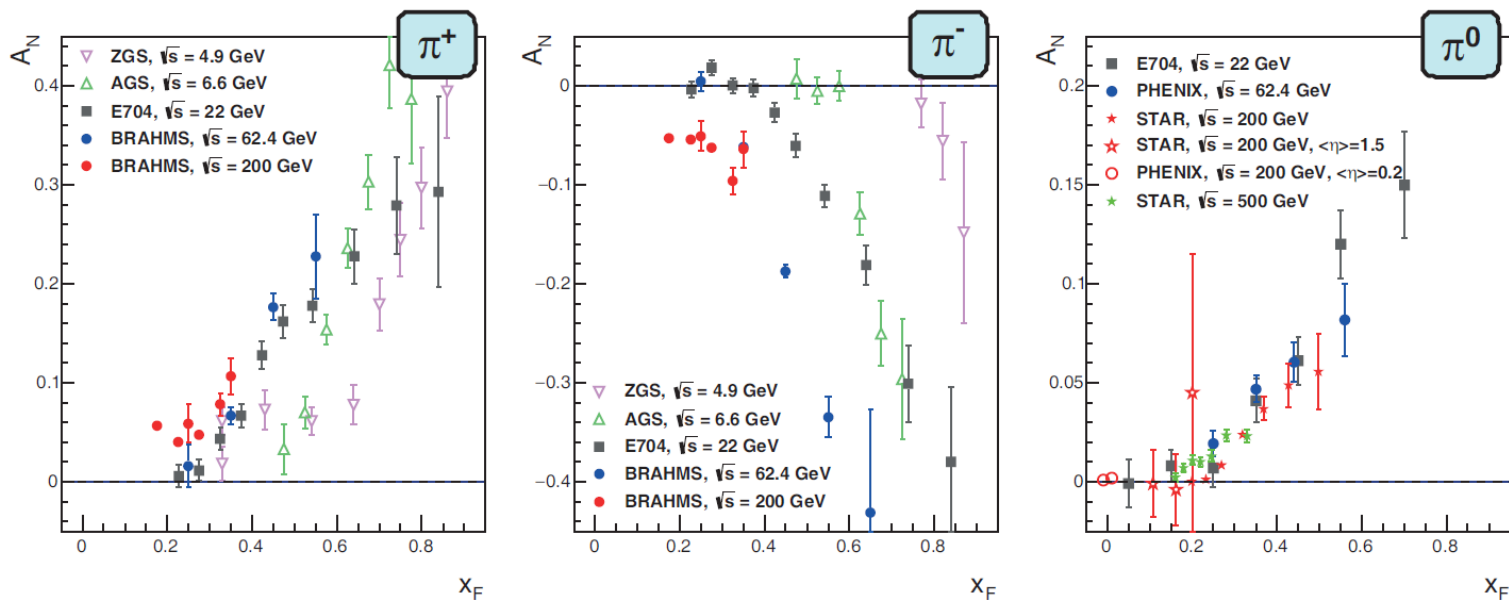
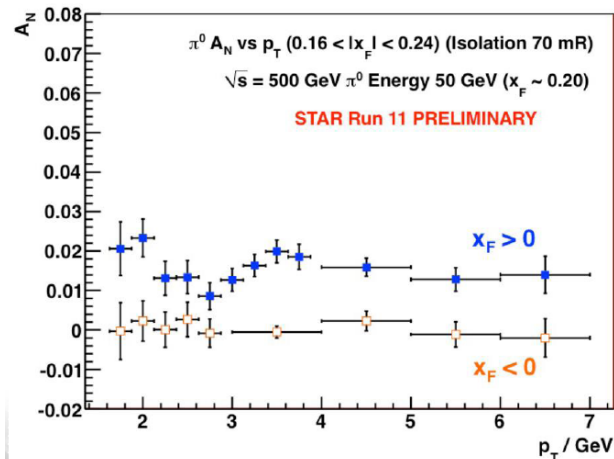
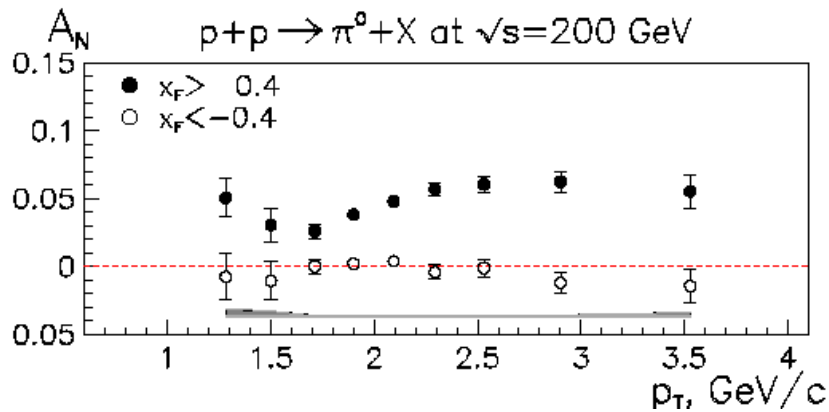


Fig. 1. Transverse single-spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as a function of Feynman- x , x_F .



Leading-Twist TMDs

8 TMDs with different polarization direction of nucleons and quarks

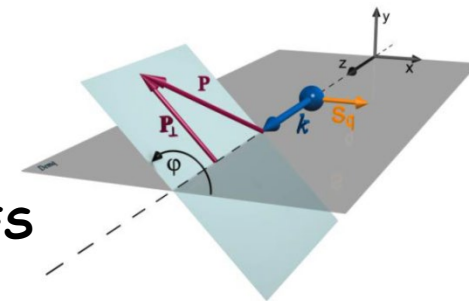
		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x, k_T^2)$		$h_1^\perp(x, k_T^2)$ <i>Boer-Mulders</i>
	L		$g_1(x, k_T^2)$	$h_{1L}^\perp(x, k_T^2)$
	T	$f_1^\perp(x, k_T^2)$ <i>Sivers</i>	$g_{1T}(x, k_T^2)$	$h_1(x, k_T^2)$ <i>Transversity</i> $h_{1T}^\perp(x, k_T^2)$

Leading twist TMD FFs

Unpolarized and spin zero hadrons: unpolarized and Collins TMD FFs

Spin 1/2 hadrons: same as PDFs reversing quark/hadron role

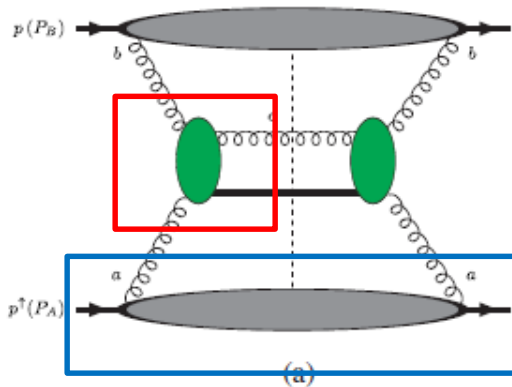
Polarizing FF: analogous of Sivers function, relevant for Lambda pol.



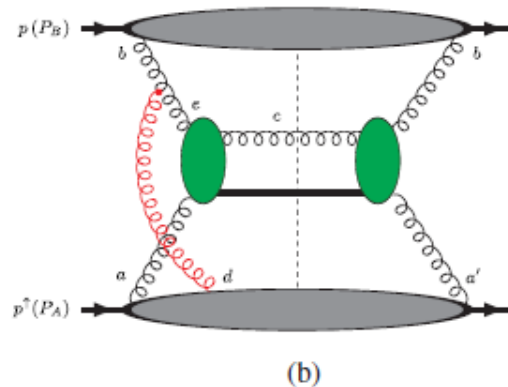
Collins FF

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

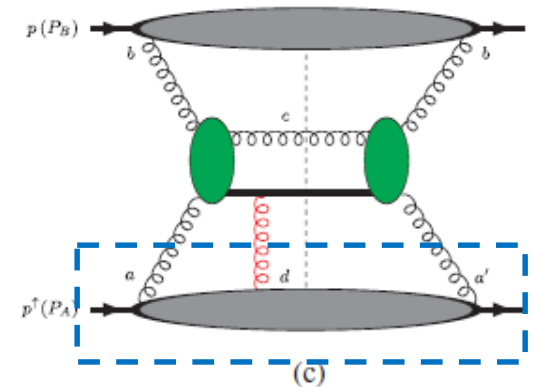
- TMD Generalized Parton Model - spin and transv. momentum effects, helicity formalism
- Color gauge invariant (CGI) extension – LO ISIs and FSIs included
[see also the alternative collinear twist-3 approach – factorization proven]
- NRQCD, color singlet model (step 1) - asymmetries independent of LDMEs
- 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(s) (basically almost unknown)
- Role of intrinsic transverse motion in J/ψ polarization (to be done)



TMD GPM



Color Gauge Invariant GPM



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

$$p(p_A) + p(p_B) \rightarrow Q(p_Q) + X$$

$$g(p_a) + g(p_b) \rightarrow Q\bar{Q}[^3S_1^{(1)}](p_Q) + g(p_g)$$

$$d\sigma \equiv E_Q \frac{d\sigma}{d^3p_Q} = \frac{\alpha_s^3}{s} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} d^2k_{\perp a} d^2k_{\perp b} f_{g/p}(x_a, k_{\perp a}) f_{g/p}(x_b, k_{\perp b}) H_{gg \rightarrow J/\psi g}^U(\hat{s}, \hat{t}, \hat{u}) \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$

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

$$d\Delta\sigma^{\text{GPM}} \equiv \frac{E_Q d\sigma^\uparrow}{d^3p_Q} - \frac{E_Q d\sigma^\downarrow}{d^3p_Q} = \frac{2\alpha_s^3}{s} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} d^2k_{\perp a} d^2k_{\perp b} \times \underbrace{\left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g}(x_a, k_{\perp a}) \cos\phi_a}_{\text{Gluon Sivers Function}} f_{g/p}(x_b, k_{\perp b}) H_{gg \rightarrow J/\psi g}^U(\hat{s}, \hat{t}, \hat{u}) \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$

$$d\Delta\sigma^{\text{CGI}} \equiv \frac{E_Q d\sigma^\uparrow}{d^3p_Q} - \frac{E_Q d\sigma^\downarrow}{d^3p_Q} = \frac{2\alpha_s^3}{s} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} d^2k_{\perp a} d^2k_{\perp b} \times \underbrace{\left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g(f)}(x_a, k_{\perp a}) \cos\phi_a}_{\text{f-type Gluon Sivers Function}} f_{g/p}(x_b, k_{\perp b}) \underbrace{\left(-\frac{1}{2} H_{gg \rightarrow J/\psi g}^U(\hat{s}, \hat{t}, \hat{u})\right)}_{\text{Modified "hard scattering" contribution}} \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$

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

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

$$H_{gg \rightarrow J/\psi g}^U = \frac{5}{9} |R_0(0)|^2 M \frac{\hat{s}^2(\hat{s} - M^2)^2 + \hat{t}^2(\hat{t} - M^2)^2 + \hat{u}^2(\hat{u} - M^2)^2}{(\hat{s} - M^2)^2(\hat{t} - M^2)^2(\hat{u} - M^2)^2}$$

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

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

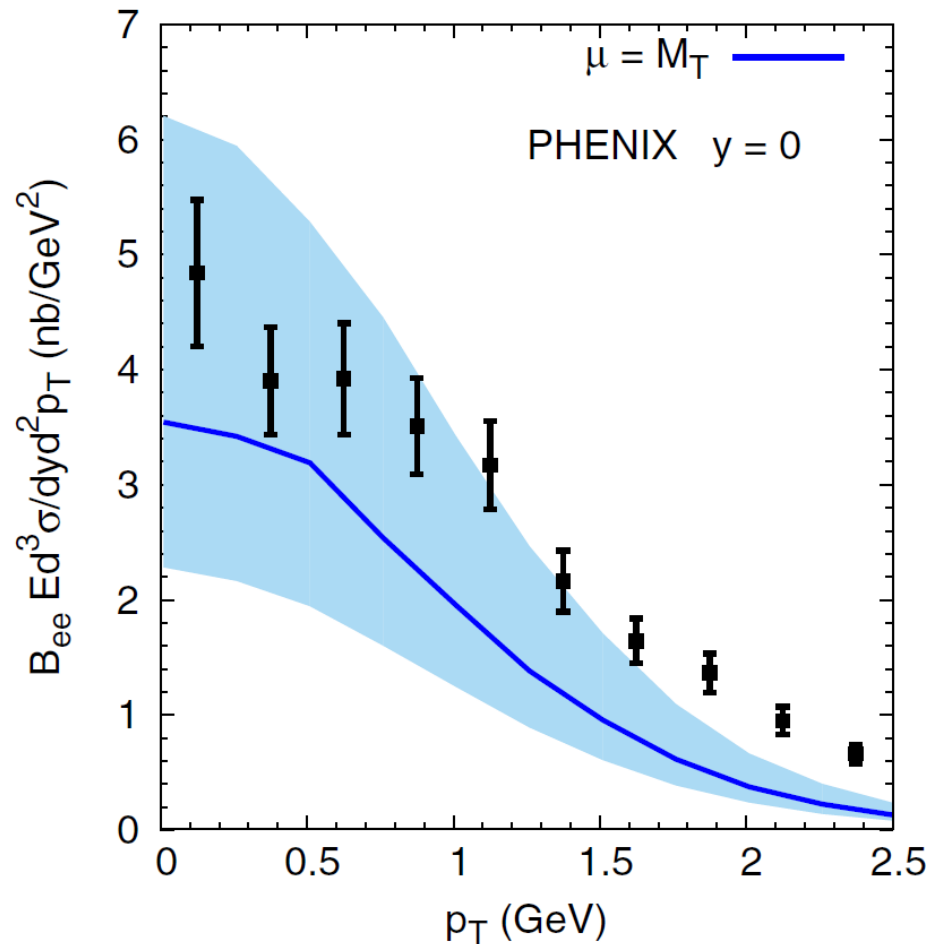
$$M = 3.097 \text{GeV}, \quad |R_0(0)|^2 = 1.01 \text{GeV}^3, \quad \text{Br}(J/\psi \rightarrow e^+e^-) = 0.0597$$

$$\Delta^N f_{g/p \uparrow}(x, k_{\perp}) = 2 \frac{\sqrt{2e}}{\pi} \mathcal{N}_g(x) f_{g/p}(x) \sqrt{\frac{1-\rho}{\rho}} k_{\perp} \frac{e^{-k_{\perp}^2 / \rho \langle k_{\perp}^2 \rangle}}{\langle k_{\perp}^2 \rangle^{3/2}}$$

$$\mathcal{N}_g(x) = N_g x^{\alpha} (1-x)^{\beta} \frac{(\alpha + \beta)^{(\alpha + \beta)}}{\alpha^{\alpha} \beta^{\beta}}$$

$$|N_g| \leq 1, \quad 0 < \rho < 1$$

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



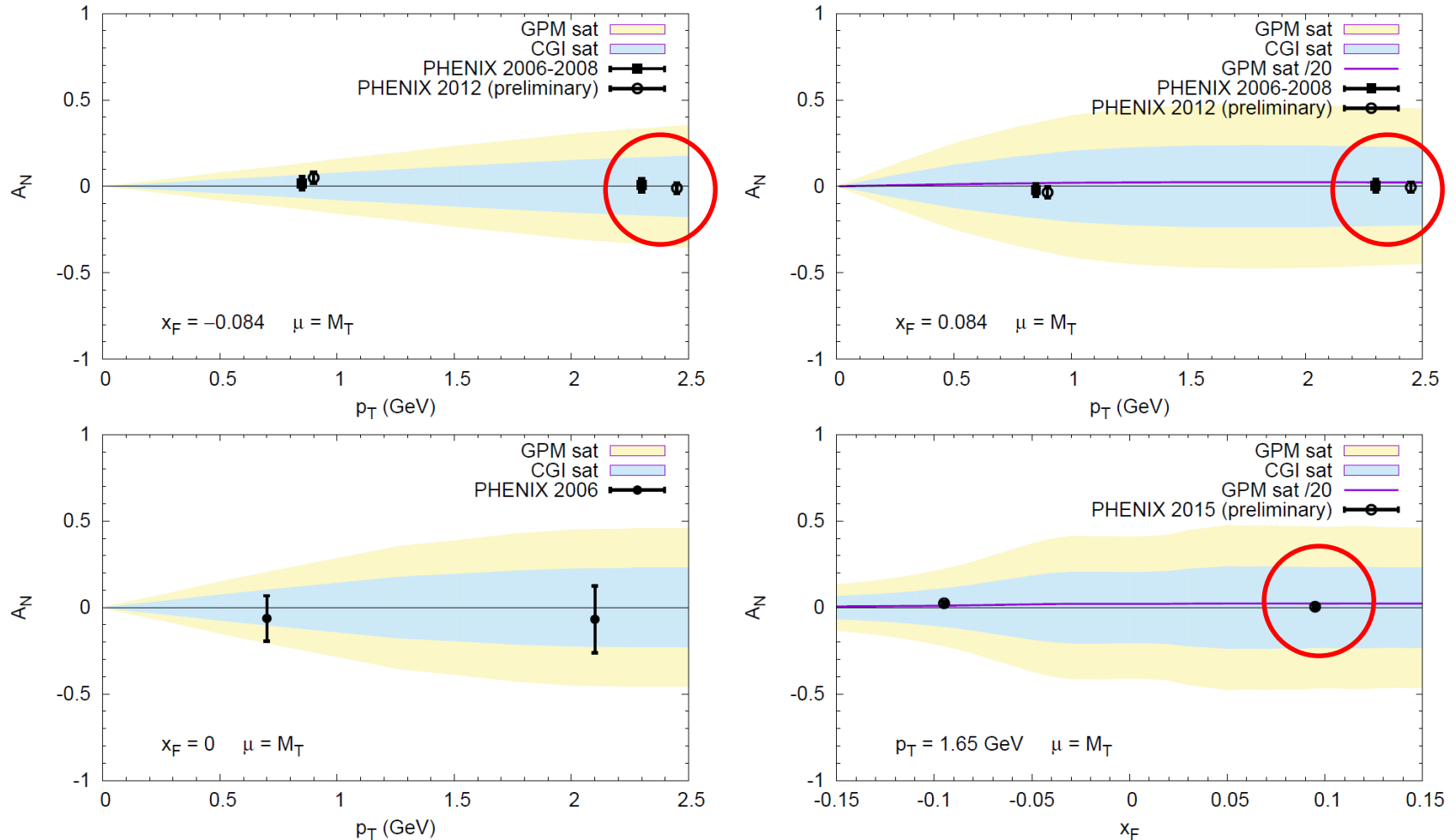
Data include feed-down contributions

Expected fraction of direct J/ψ production: 0.58

PHENIX PRD82 012001 (2010)

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

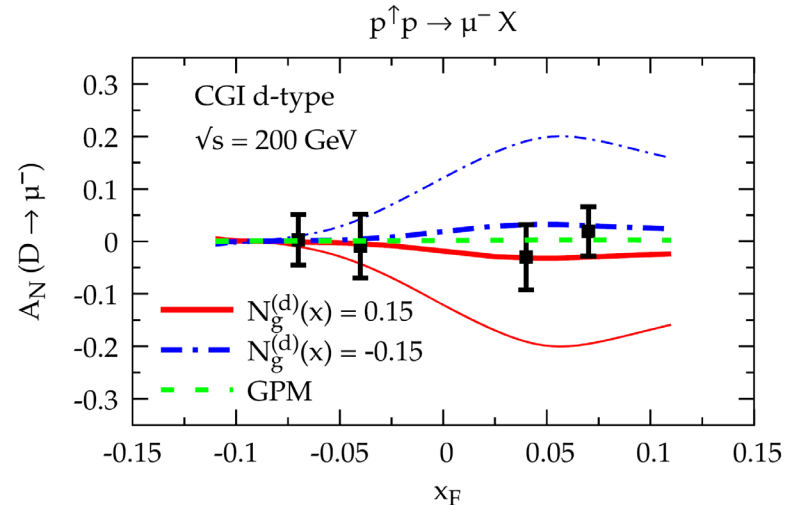
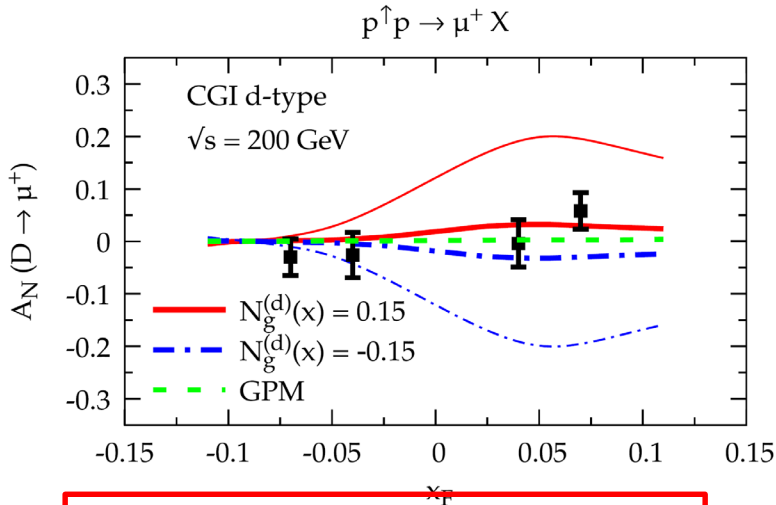
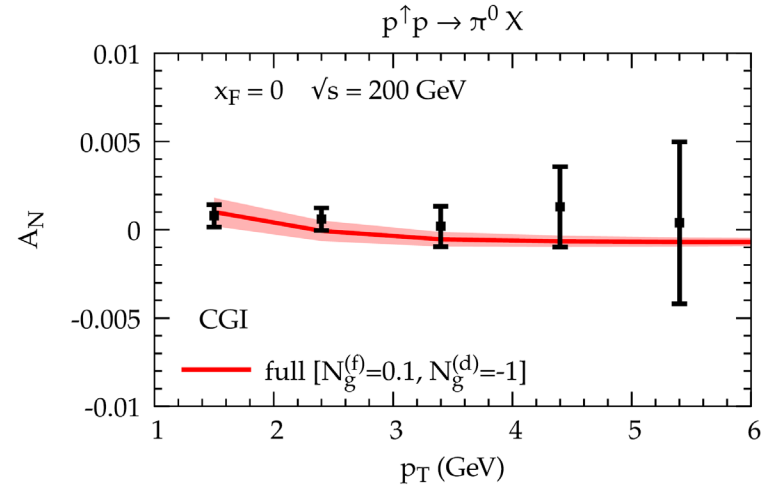
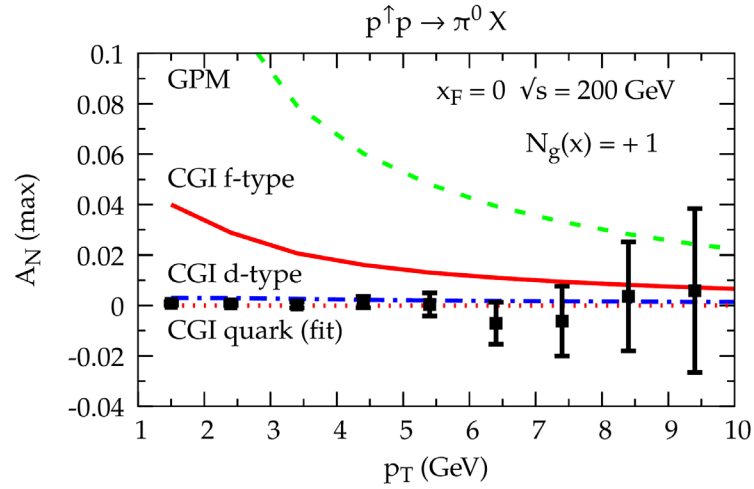
$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Comparison with PHENIX data



U. D'Alesio, FM, C. Pisano, S. Rajesh, DIS2019, arXiv 1909.00763 [hep-ph]

**Notice: These results on the J/ψ Siverts SSA update and superseded those of
U. D'Alesio, FM, C. Pisano, P. Taels, PRD 96, 036011 (2017)**

$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Constraining the GSF using pion and D meson SSA data

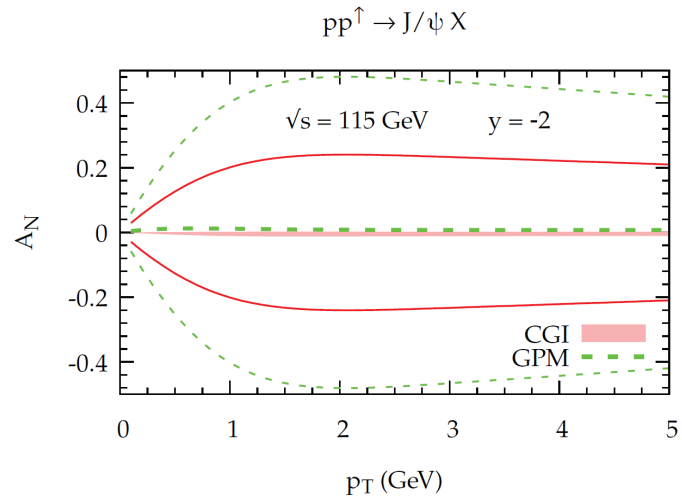
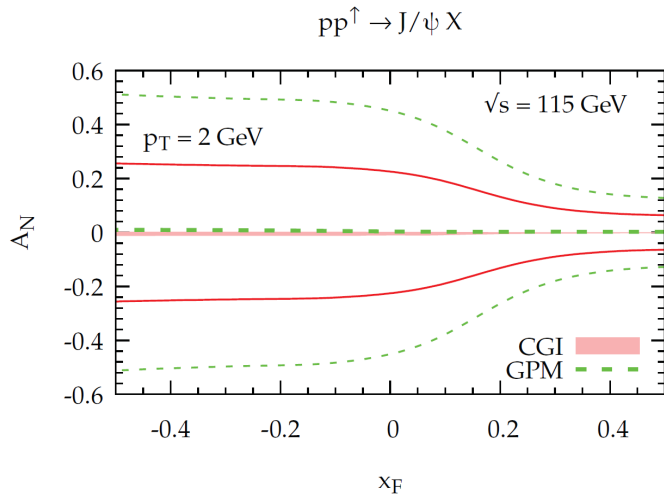
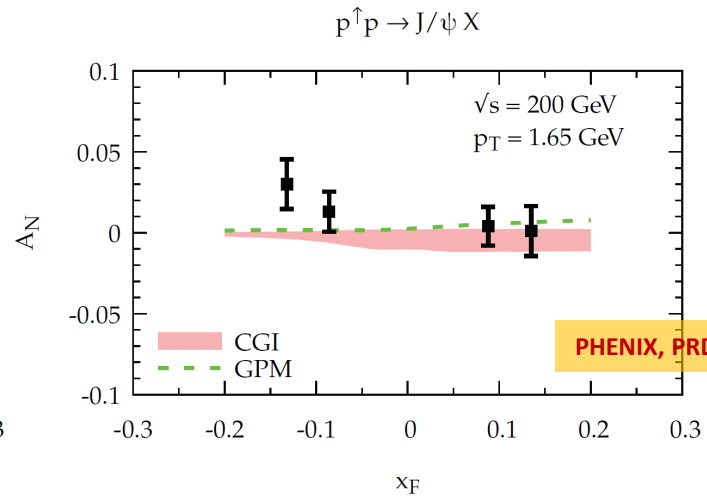
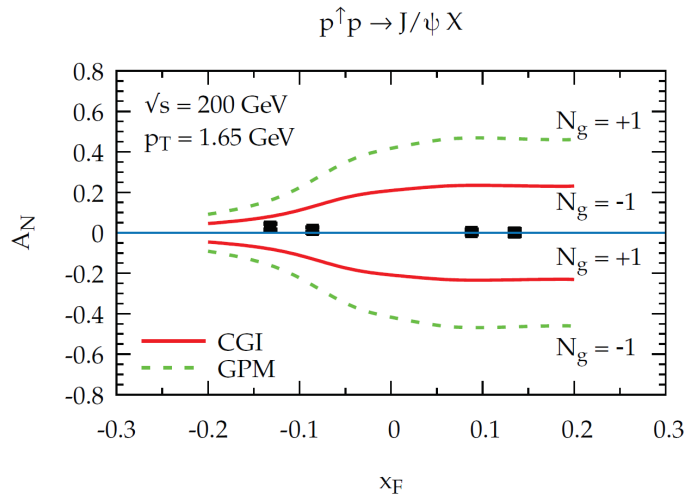


$$\mathcal{N}_g^{(d)} = -0.15 \rightarrow \mathcal{N}_g^{(f)} = +0.05$$

$$\mathcal{N}_g^{(d)} = +0.15 \rightarrow \mathcal{N}_g^{(f)} = -0.01$$

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

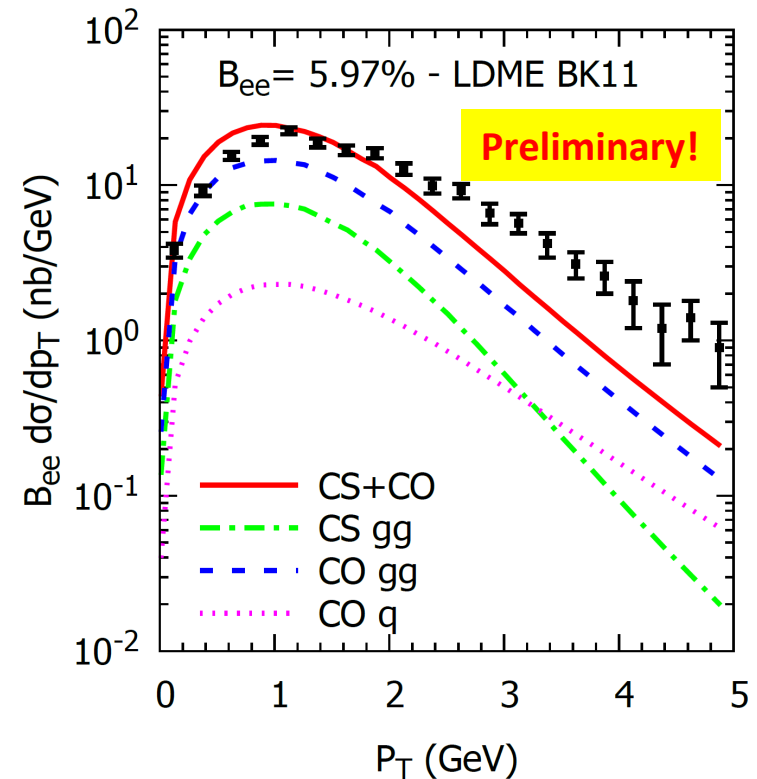
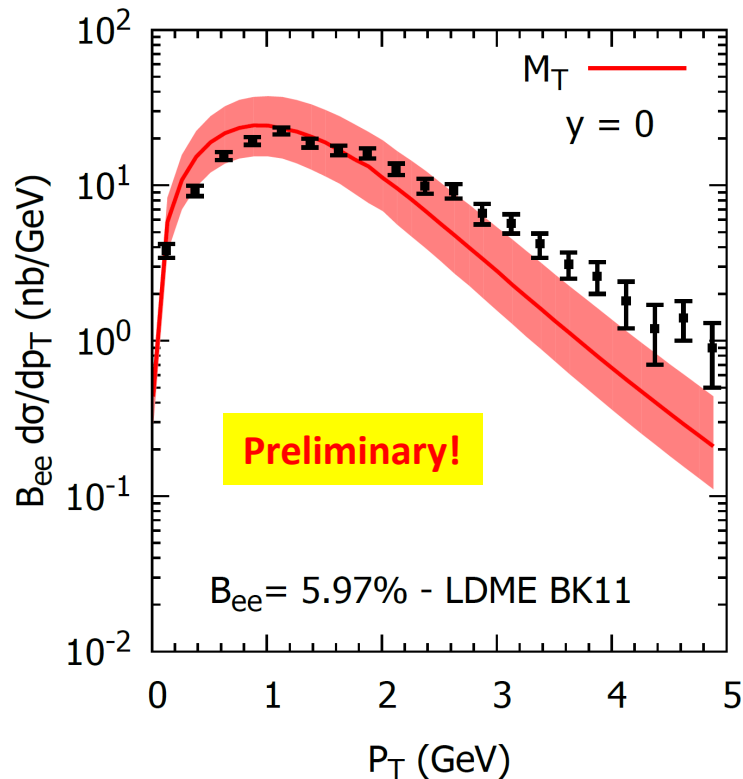
$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Constraining the GSF using pion and D meson SSA data



U. D'Alesio, FM, C. Pisano, S. Rajesh, DIS2019, arXiv 1909.00763 [hep-ph]
 Notice: These results on the J/ψ Sivvers SSA update and superseded those of
U. D'Alesio, C. Flore, FM, C. Pisano, P. Taelis, PRD 99, 036013 (2019)

Present status of quarkonium production project

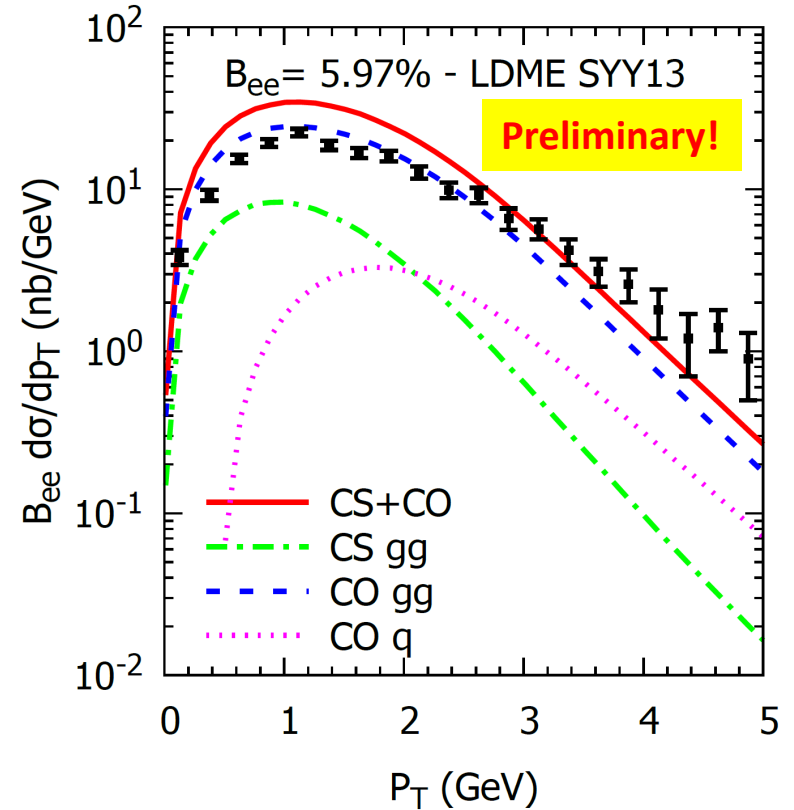
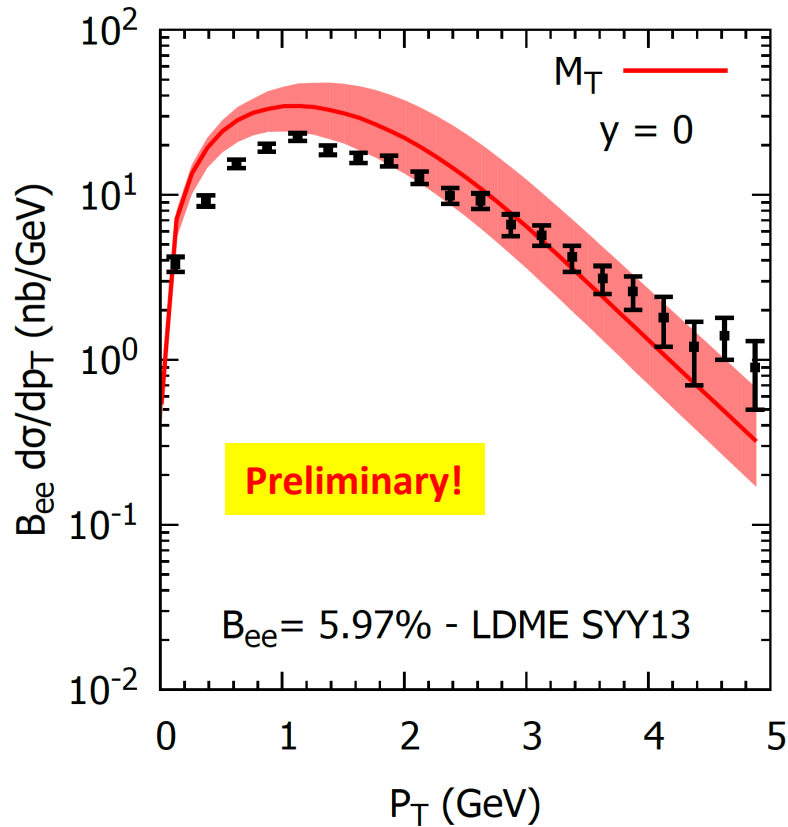
- Inclusive quarkonium production in (un)polarized pp collisions in the low p_T region [$0 \leq p_T \leq 5$ GeV] [direct production, feed-down contributions to be included]
- LO TMD GPM and NRQCD with CS and CO contributions (calculation completed)



U. D'Alesio, FM, C. Pisano, S. Rajesh, In preparation

BK11: Butenschoen, Kniehl
PRD84, 051501 (2011)

Present status of quarkonium production project



U. D'Alesio, FM, C. Pisano, S. Rajesh, In preparation

SYY13: Sun, Yuan, Yuan
PRD88, 054008 (2013)

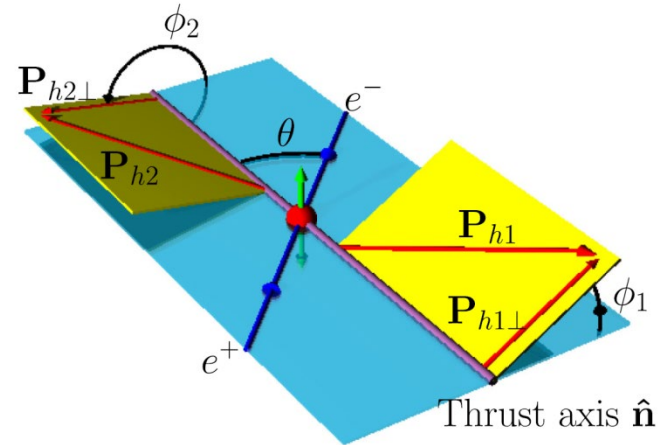
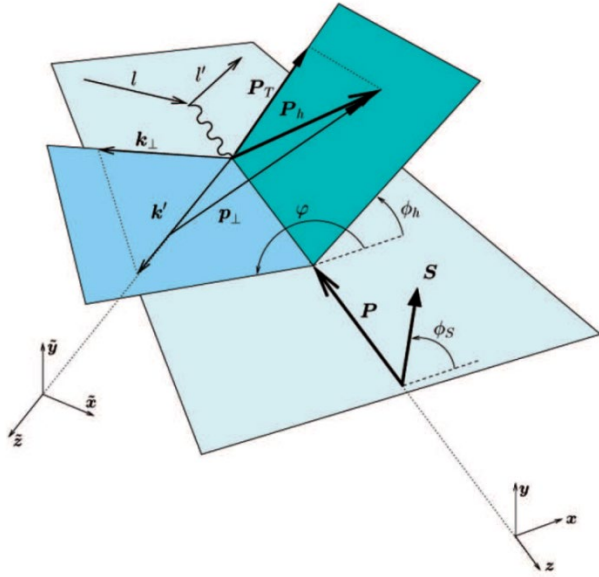
Quarkonium production project: open points and perspectives

- 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
- Full Color Gauge Invariant GPM + NRQCD calculation is under way

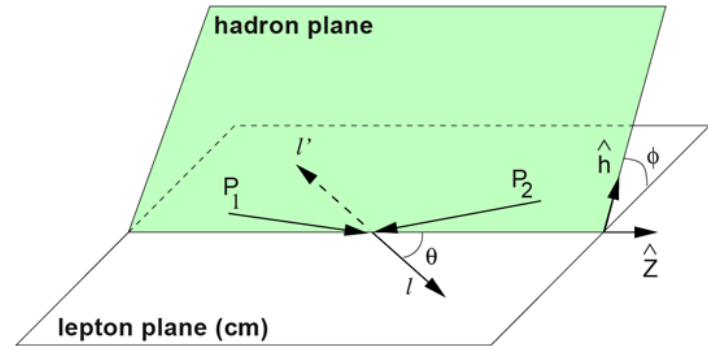
**Thanks for
your attention!**

Backup Slides

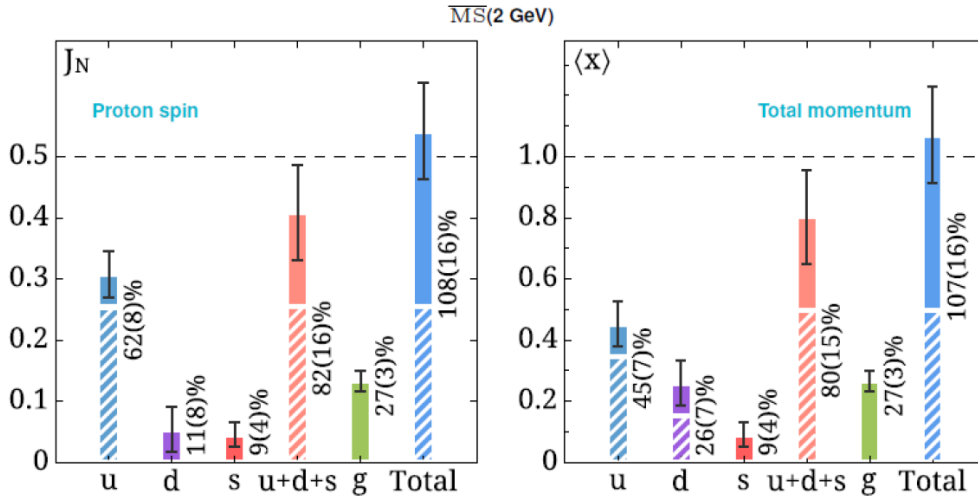
Azimuthal spin asymmetries in SIDIS, Drell-Yan and $e^+e^- \rightarrow h_1 h_2 + X$



$$\begin{aligned} \frac{dN}{d\Omega} &\equiv \frac{d\sigma}{d^4q d\Omega} \bigg/ \frac{d\sigma}{d^4q} \\ &= \frac{3}{4\pi} \frac{1}{\lambda + 3} \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi \right. \\ &\quad \left. + \frac{\nu}{2} \sin^2\theta \cos 2\phi \right). \end{aligned}$$



Proton spin and quark OAM on the lattice

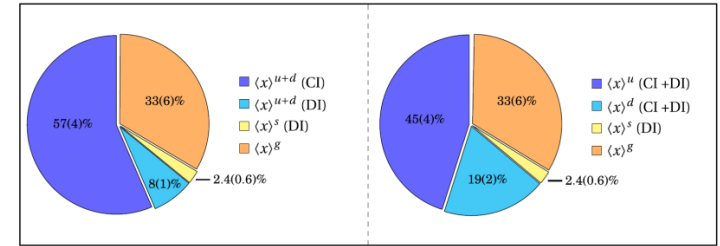


Striped segments: valence quark contributions (connected)

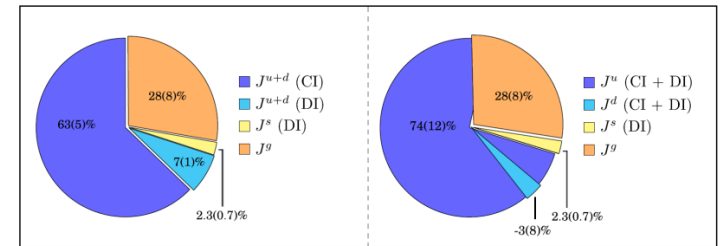
Solid segments: sea quark & gluon contributions (disconnected)

	$\frac{1}{2} \Delta \Sigma$	J	L	$\langle x \rangle$
u	0.415(13)(2)	0.308(30)(24)	-0.107(32)(24)	0.453(57)(48)
d	-0.193(8)(3)	0.054(29)(24)	0.247(30)(24)	0.259(57)(47)
s	-0.021(5)(1)	0.046(21)(0)	0.067(21)(1)	0.092(41)(0)
g	...	0.133(11)(14)	...	0.267(22)(27)
Tot.	0.201(17)(5)	0.541(62)(49)	0.207(64)(45)	1.07(12)(10)

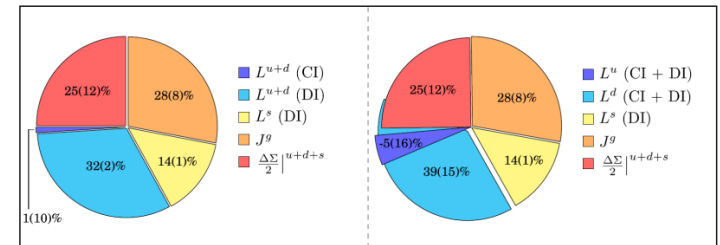
C. Alexandrou et al. PRL 119, 142002 (2017)



(a)



(b)



χ QCD Collaboration
PRD 91, 014505 (2015)

Experimental activity on TMDs and Spin Physics

