Quarkonium Production and TMDs at LHC

Francesco Murgia – INFN Sezione di Cagliari

in collaboration with
Umberto D'Alesio, Carlo Flore, Cristian Pisano, Sangem Rajesh, Pieter Taels
University and INFN Cagliari

"Quarkonium at LHC energies"
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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 (SSA) and azimuthal asymmetries [Gluon Sivers Function]**
- **Complementarity with SIDIS, pp at RHIC, e^+e^- collisions, Electron Ion Collider**

Reference material

- For the LHCSpin experimental setup see next talk by P. Di Nezza
- For linearly polarized gluon TMDs see previous talk by C. Pisano
- See also the Summary and Outlook talk by J.P. Lansberg

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 more extensive perspective on inclusive production of quarkonia see
  J.P. Lansberg, *New Observables in Inclusive Production of Quarkonia*
  arXiv 1903.09185 [hep-ph]

See also talk by Elena Ferreiro on "Quarkonium Theory" on Wednesday

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:

- $pp^{\uparrow} \rightarrow (h_1 h_2) + X$ **- di-hadron fragmentation functions, collinear factorization**
- $pp^{\uparrow} \rightarrow (h + jet) + X$ **– 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, with small transv. momentum imbalance:

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

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**
- **Unpol. and linearly polarized gluon TMDs (first stage, SMOG2)** [Talk by Cristian Pisano]
- **Gluon Sivers function (needs transv. polarized target, 2nd 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

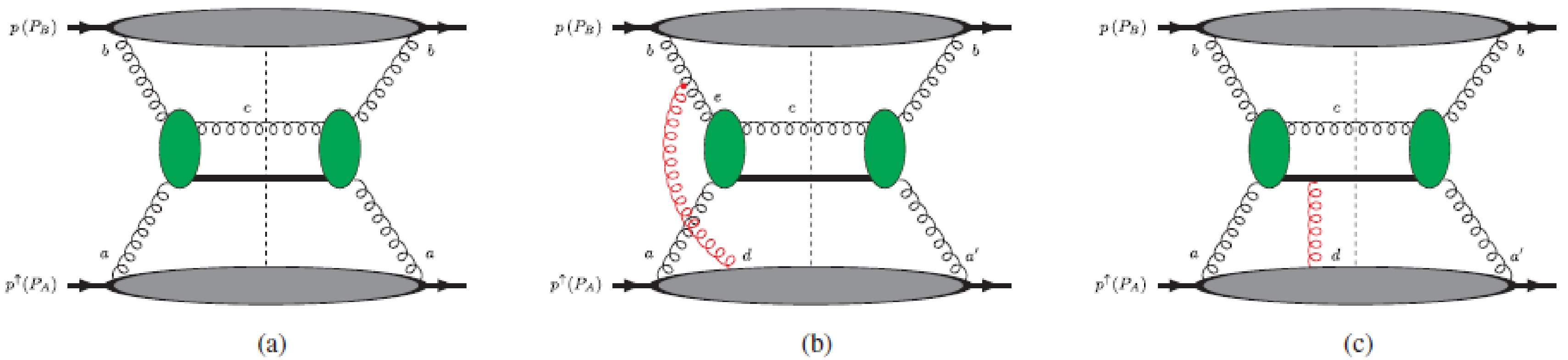
$$pp^{\uparrow} \to J/\psi, \Upsilon + X; \quad pp^{\uparrow} \to D + X; \quad pp^{\uparrow} \to \pi + X; \quad pp^{\uparrow} \to \gamma + X$$

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

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

- TMD Generalized Parton Model - spin and transv. momentum effects, helicity formalism
- Color gauge invariant (CGI) extension – LO ISIs and FSIs included
- 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

See also talk by C. Pisano

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

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

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

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

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

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

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

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

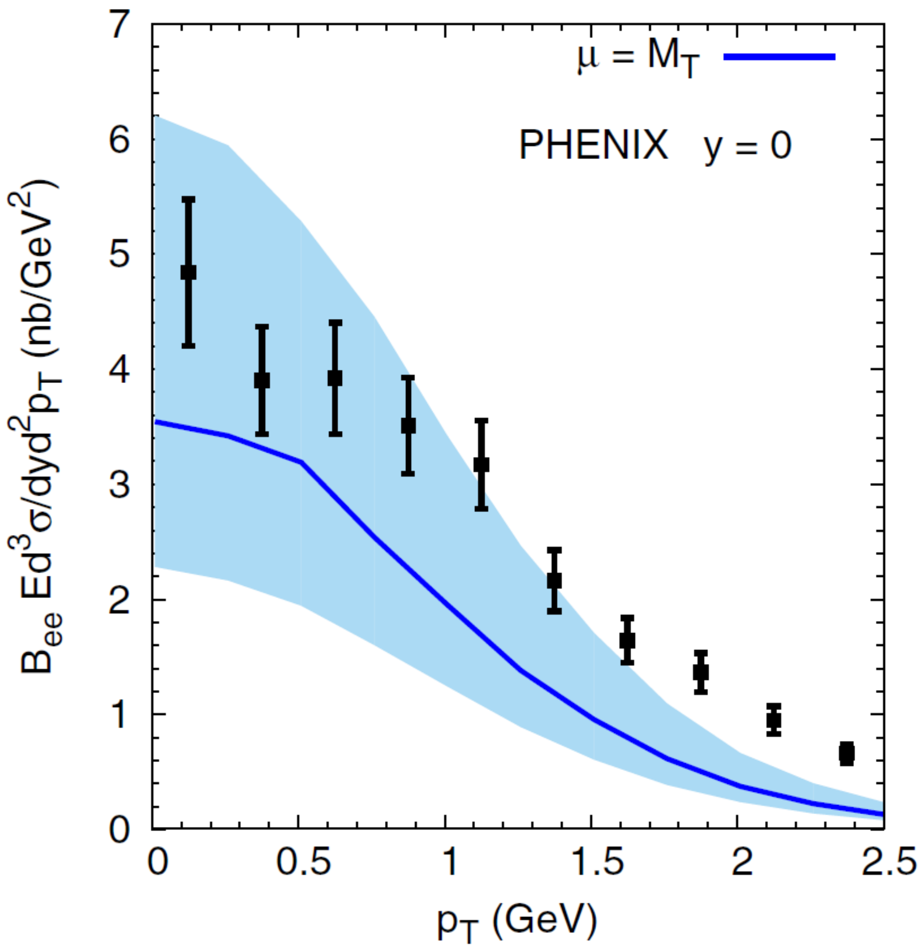
$$H^U_{gg\to J/\psi g} = \frac{5}{9}\,|R_0(0)|^2\,M\,\frac{\hat{s}^2(\hat{s}-M^2)^2 + \hat{t}^2(\hat{t}-M^2)^2 + \hat{u}^2(\hat{u}-M^2)^2}{(\hat{s}-M^2)^2(\hat{t}-M^2)^2(\hat{u}-M^2)^2}$$

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

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

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

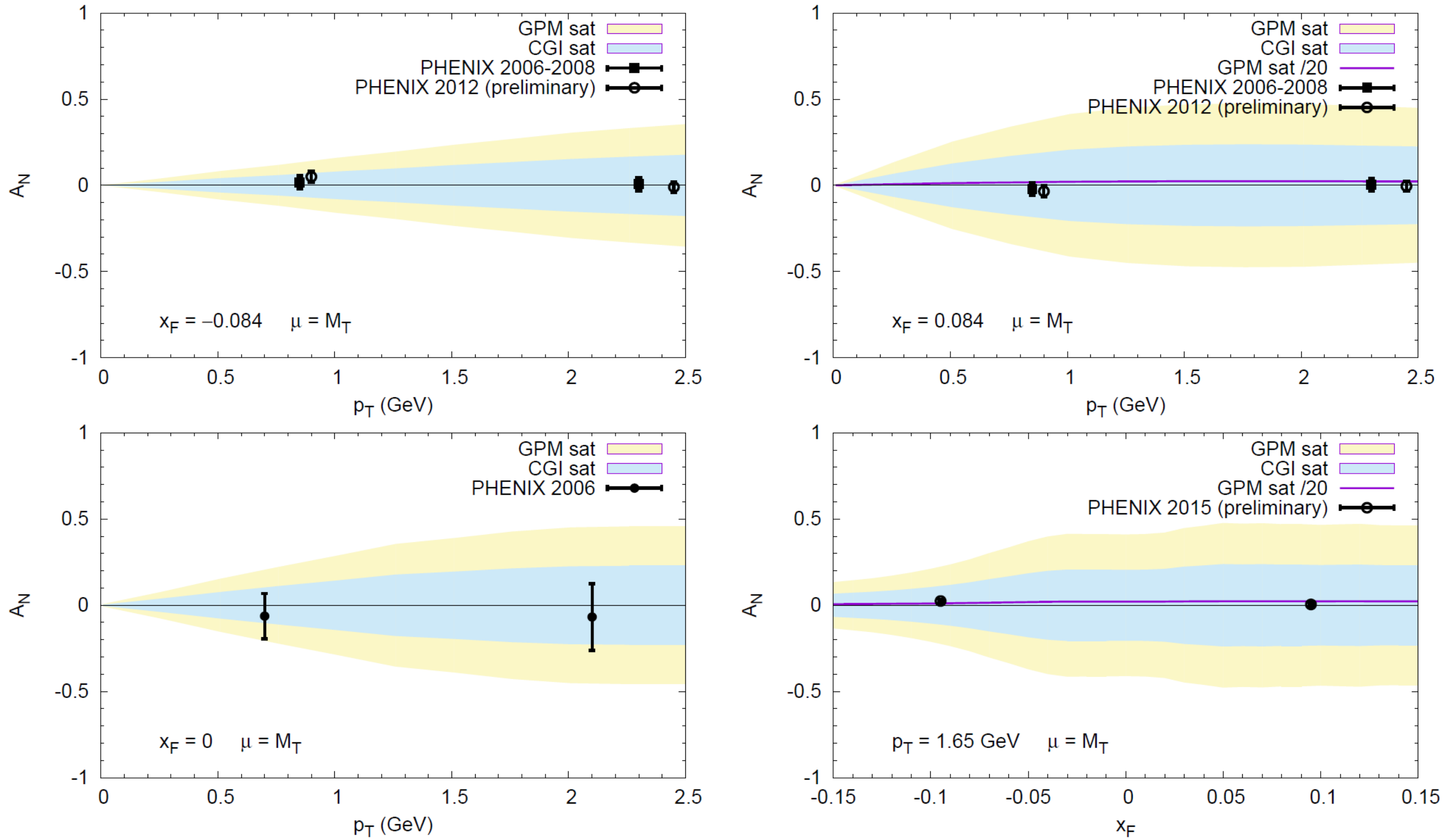
$pp^{(\uparrow)} \to J/\psi + X$ (step 1)



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)

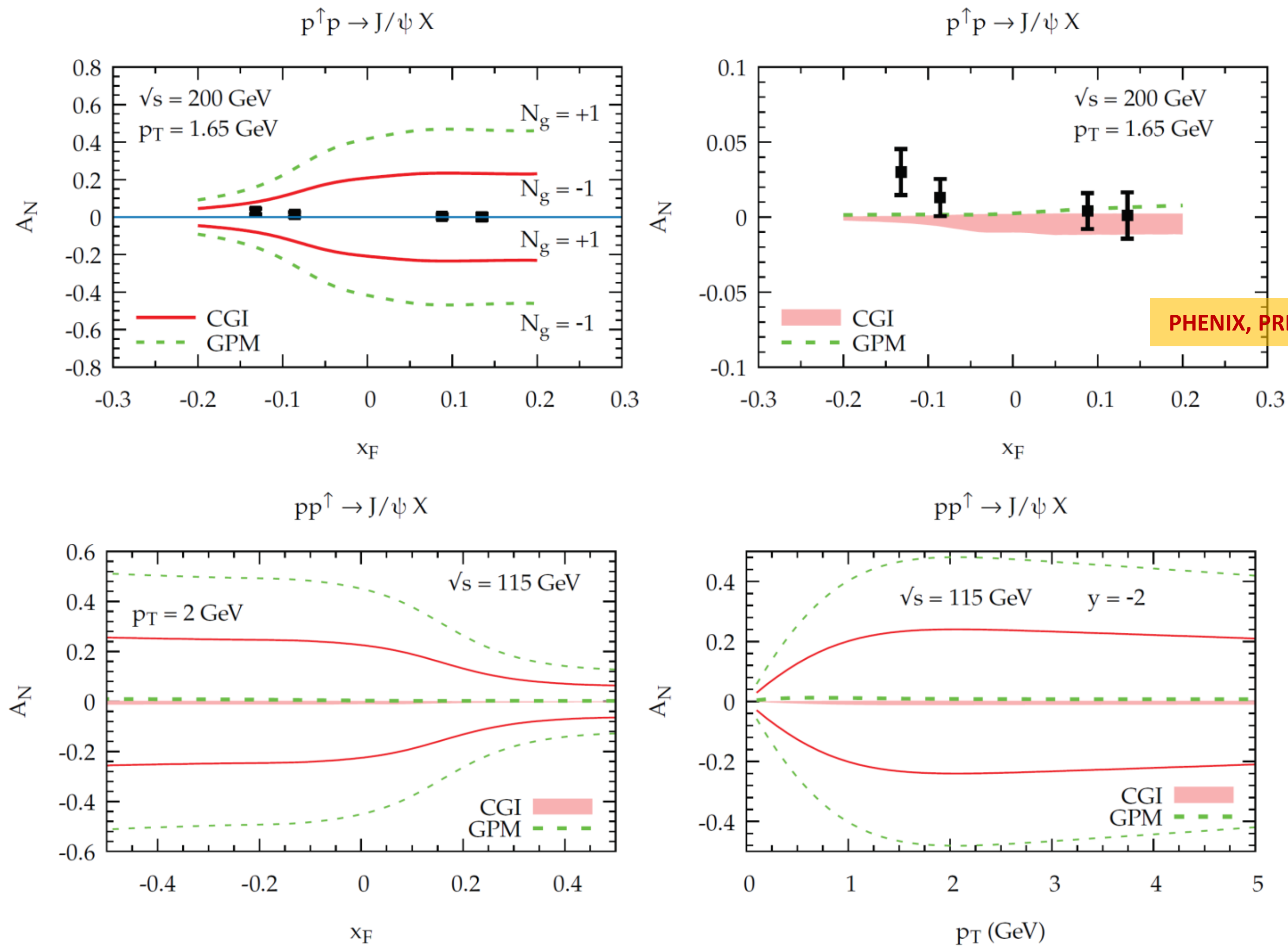
$pp^{(\uparrow)} \rightarrow J/\psi + X$ - Comparison with PHENIX data



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

Notice: These results on the J/ψ Sivers SSA update and supersed 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

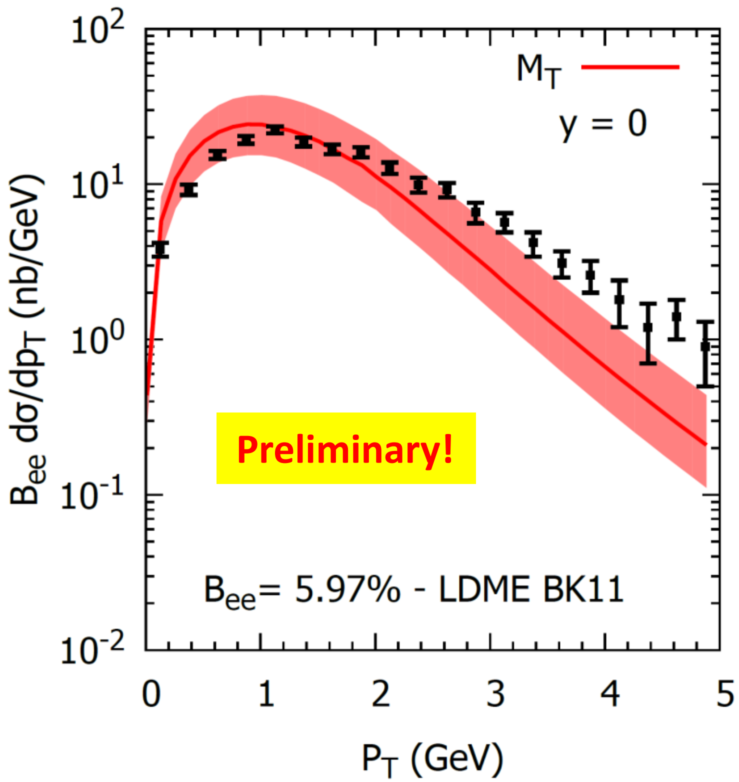


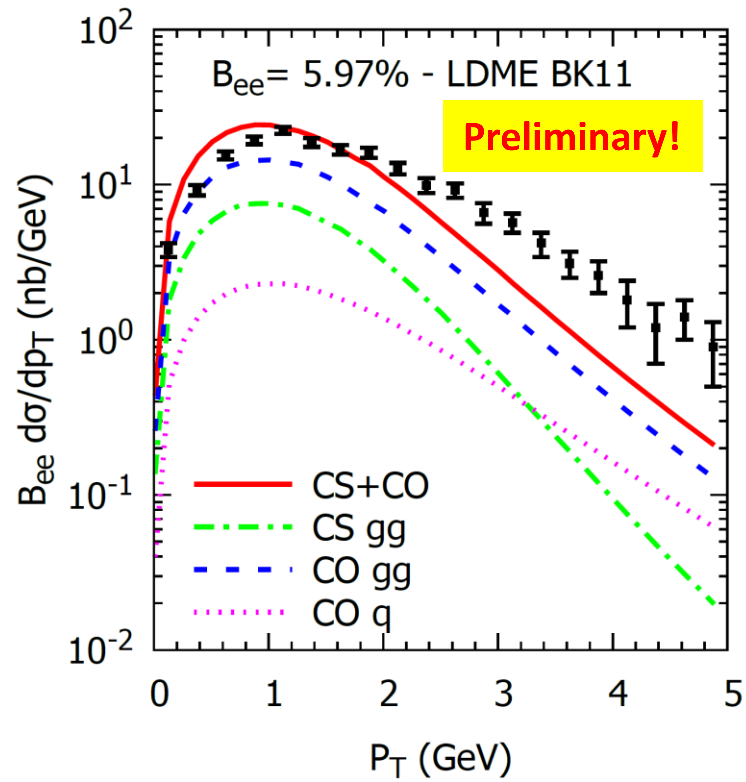
PHENIX, PRD 98, 012006 (2018)

U. D'Alesio, FM, C. Pisano, S. Rajesh, DIS2019, arXiv 1909.00763 [hep-ph]
Notice: These results on the J/ψ Sivers SSA update and supersed those of U. D'Alesio, C. Flore, FM, C. Pisano, P. Taels, 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)

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

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

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

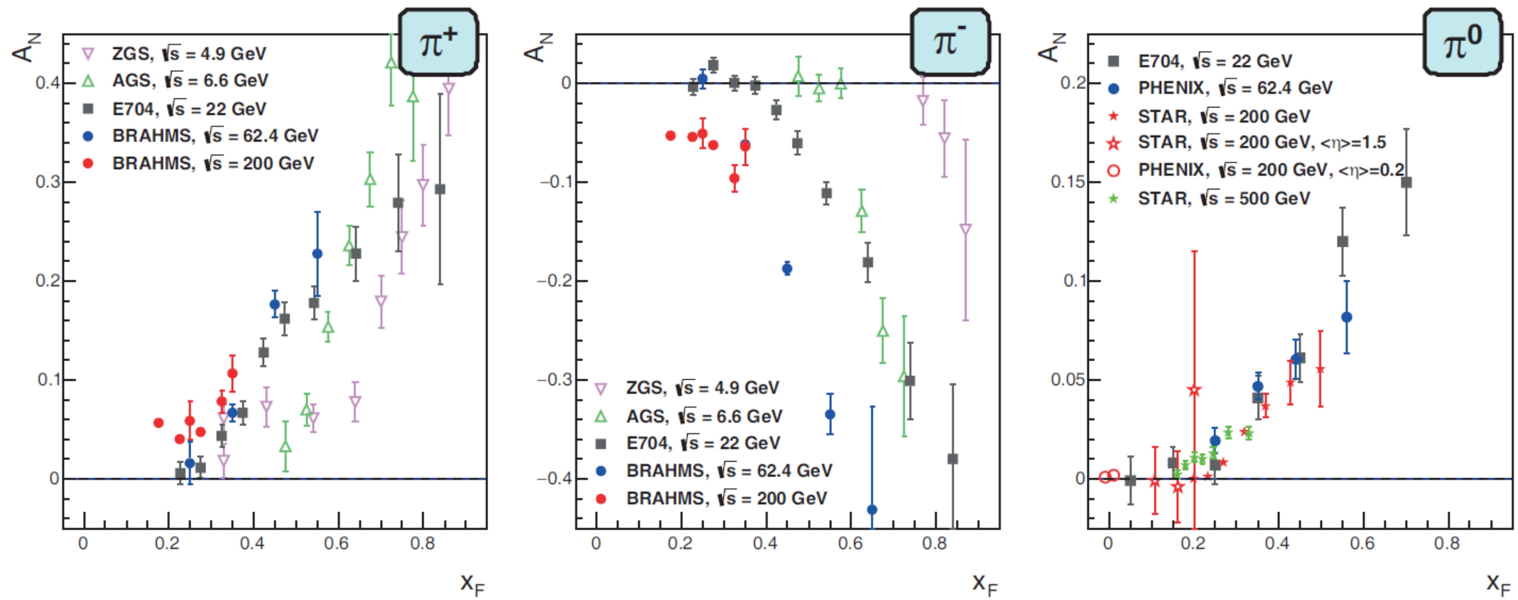
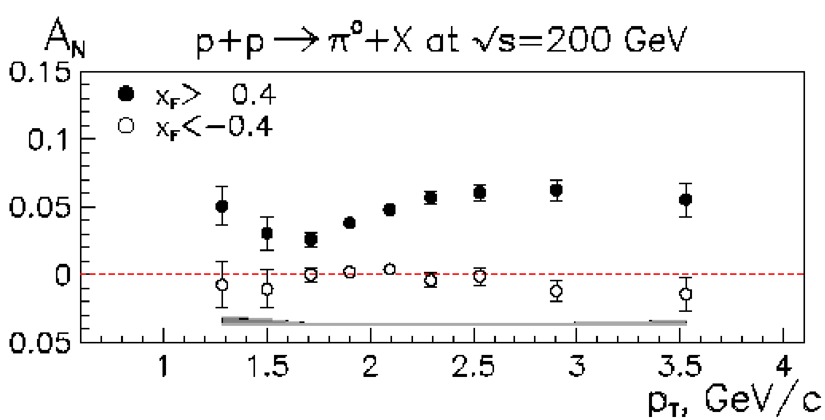
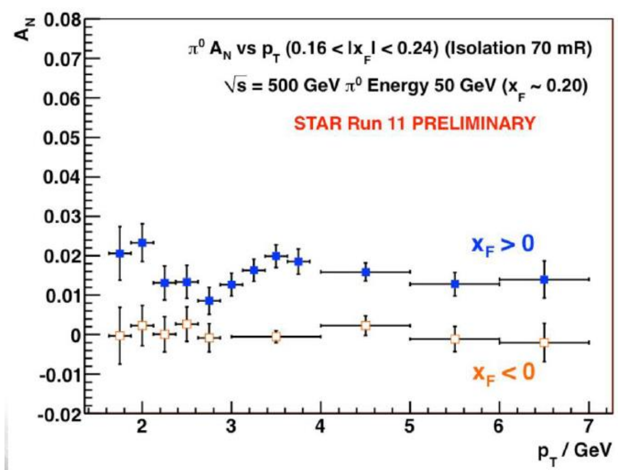


Fig. 1. Transverse single-spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as a function of Feynman-x, x_F.





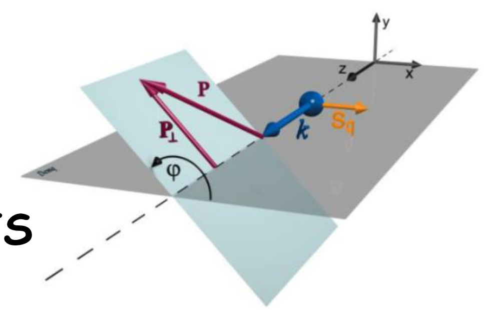
Leading-Twist TMDs

8 TMDs with different polarization direction of nucleons and quarks

Nucleon Polarization \ Quark Polarization	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ – Boer-Mulders
L		$g_1(x,k_T^2)$ – Helicity	$h_{1L}^\perp(x,k_T^2)$ – Long-Transversity
T	$f_1^\perp(x,k_T^2)$ – Sivers	$g_{1T}(x,k_T^2)$ – Trans-Helicity	$h_1(x,k_T^2)$ – Transversity $h_{1T}^\perp(x,k_T^2)$ – Pretzelosity

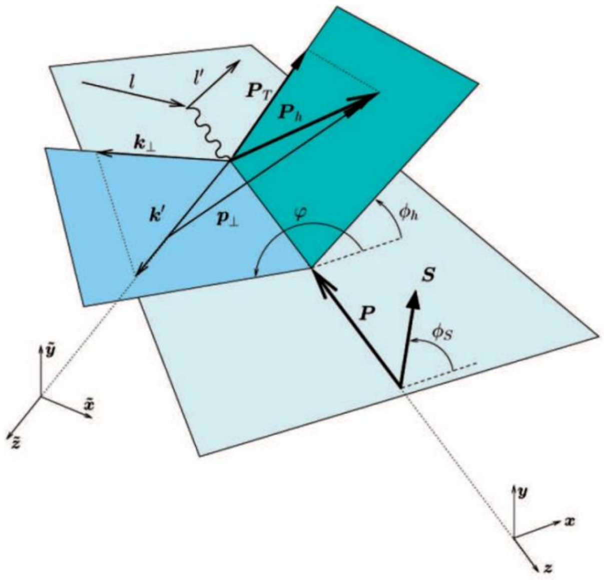
Leading twist TMD FFs

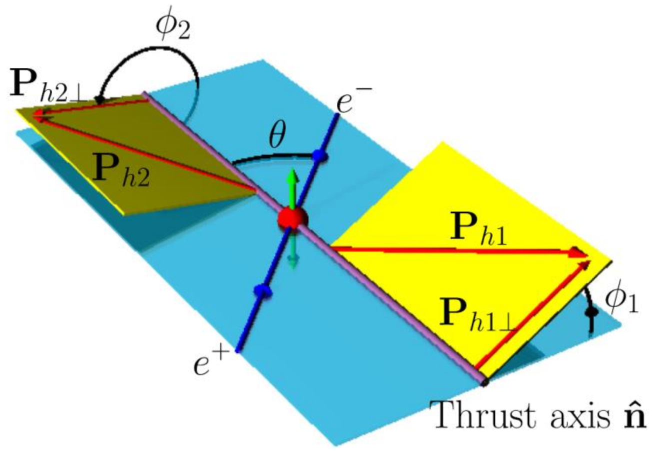
Unpolarized and spin zero hadrons: unpolarized and Collins TMD FFS
Spin 1/2 hadrons: same as PDFs reversing quark/hadron role
Polarizing FF: analogous of Sivers function, relevant for Lambda pol.



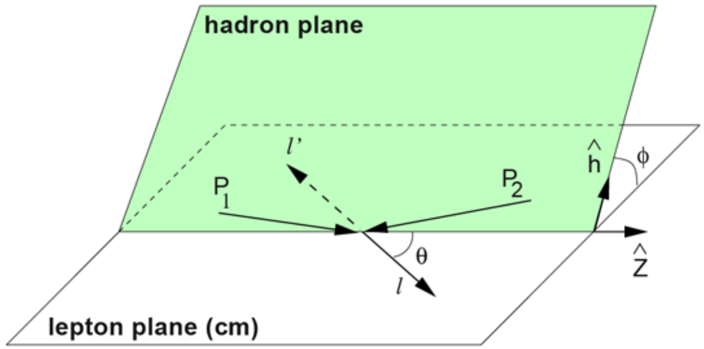
Collins FF

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

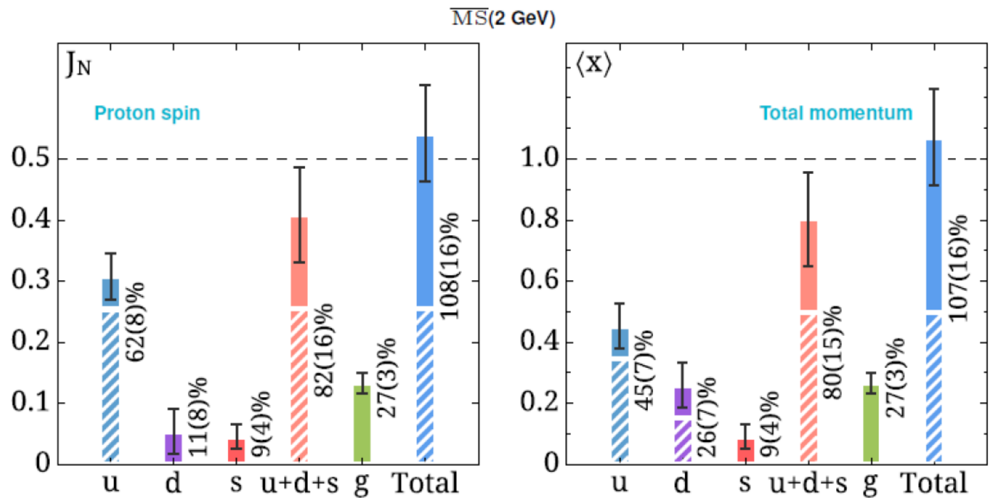




$$\frac{dN}{d\Omega} \equiv \frac{d\sigma}{d^4q\,d\Omega}\Big/\frac{d\sigma}{d^4q}$$
$$= \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right).$$

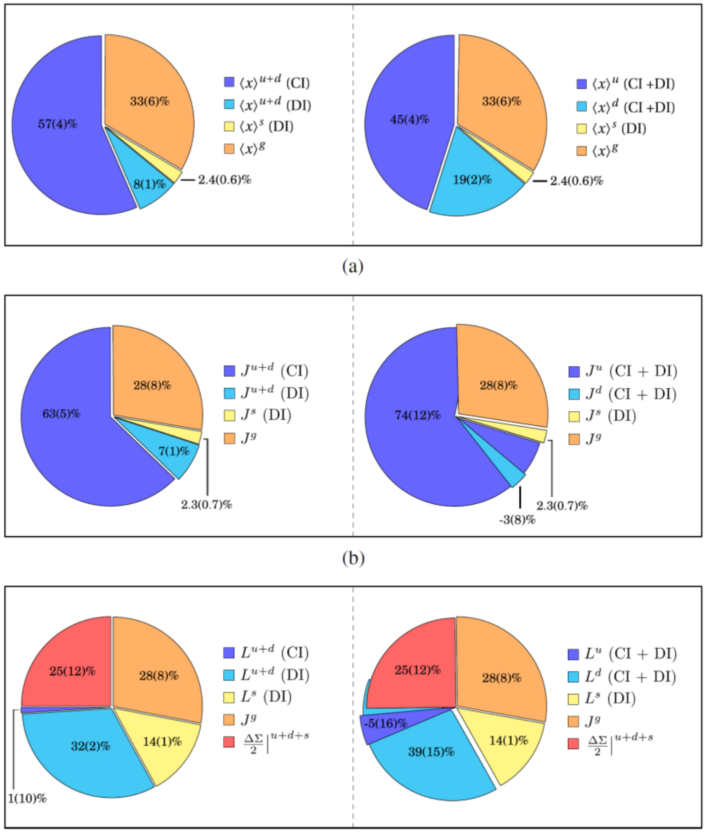


Proton spin and quark OAM on the lattice



Striped segments: valence quark contributions (connected)

Solid segments: sea quark & gluon contributions (disconnected)

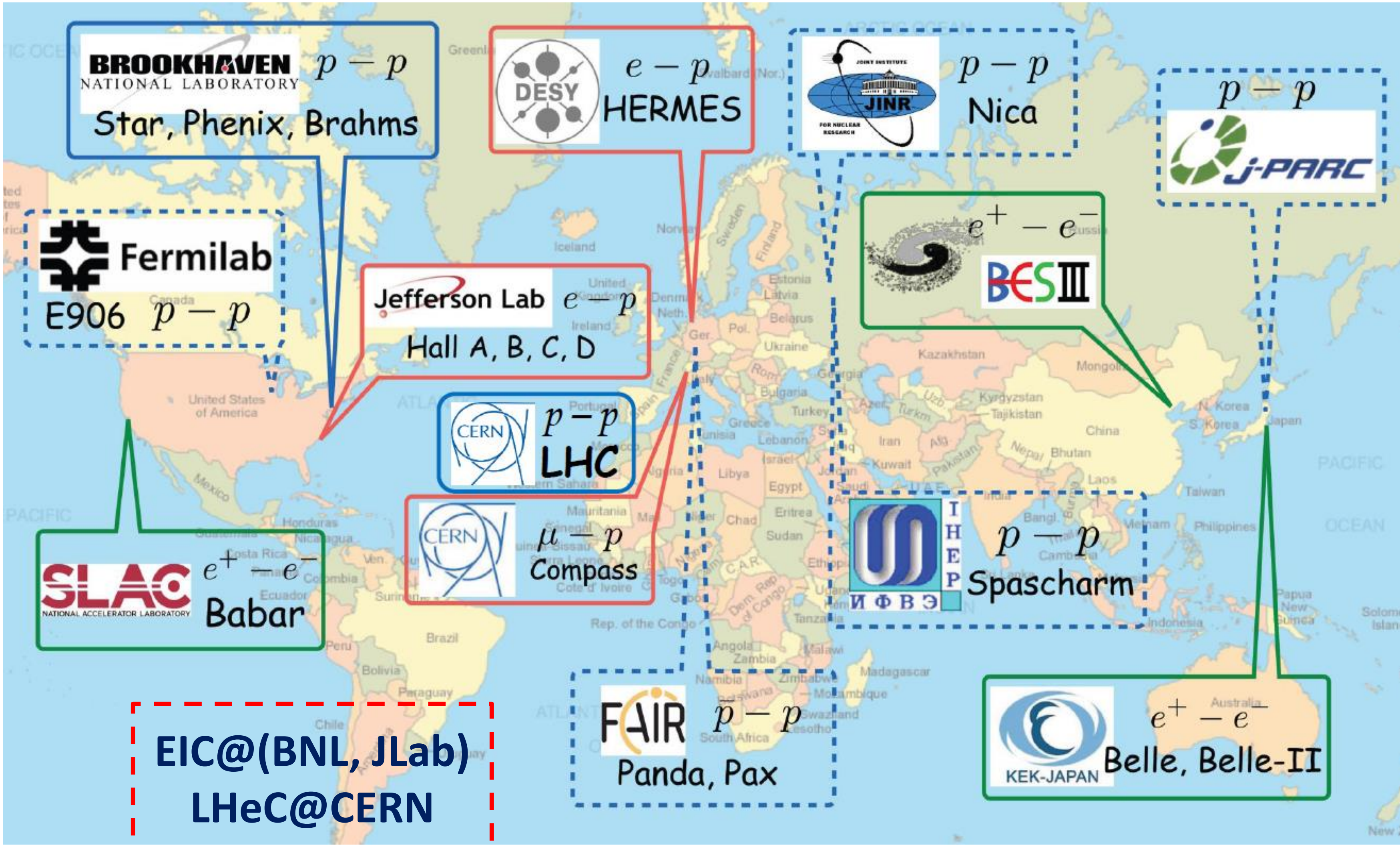


	$\frac{1}{2}\Delta\Sigma$	J	L	$\langle x\rangle$
u	0.415(13)(2)	0.308(30)(24)	−0.107(32)(24)	0.453(57)(48)
d	−0.193(8)(3)	0.054(29)(24)	0.247(30)(24)	0.259(57)(47)
s	−0.021(5)(1)	0.046(21)(0)	0.067(21)(1)	0.092(41)(0)
g	⋯	0.133(11)(14)	⋯	0.267(22)(27)
Tot.	0.201(17)(5)	0.541(62)(49)	0.207(64)(45)	1.07(12)(10)

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

χQCD Collaboration PRD 91, 014505 (2015)

Experimental activity on TMDs and Spin Physics



EIC@(BNL, JLab)
LHeC@CERN
EIC@HIAF