Quarkonium and TMDs in lepton–nucleon interactions: past and future measurements

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Quarkonia as tools 2022
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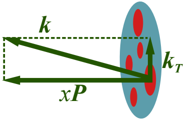
CHARLES UNIVERSITY
Faculty of mathematics
and physics

COMPASS

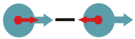
Outline

Introduction: TMDs

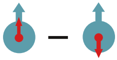


- Generalisation of PDFs,
  where parton intrinsic $\boldsymbol{k}_{\mathbf{T}}$ is not integrated over,
- "three-dimensional" objects $f(x, k_{\mathrm{T}}^2, Q^2)$.

Number density.



Helicity.



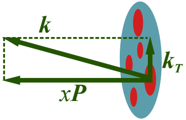
Transversity.

Parton polarisation		Parent hadron polarization: Unpolarised	Parent hadron polarization: Longitudinal	Parent hadron polarization: Transverse
	U	$f_1(x, k_{\mathrm{T}}^2)$ (number density)		$f_{1\mathrm{T}}^{\perp}(x, k_{\mathrm{T}}^2)$ (Sivers)
	L/C		$g_1(x, k_{\mathrm{T}}^2)$ (helicity)	$g_{1\mathrm{T}}(x, k_{\mathrm{T}}^2)$ (Kotzinian–Mulders)
	T/L	$h_1^{\perp}(x, k_{\mathrm{T}}^2)$ (Boer–Mulders)	$h_{1\mathrm{L}}^{\perp}(x, k_{\mathrm{T}}^2)$ (worm-gear)	$h_1(x, k_{\mathrm{T}}^2)$ (transversity) $h_{1\mathrm{T}}^{\perp}(x, k_{\mathrm{T}}^2)$ (pretzelosity)

Parton polarisation:
  L/C – longitudinal (quarks) or circular (gluons)
  T/L – transverse (quarks) or linear (gluons)

h_1^{g} integrated over $\boldsymbol{k}_{\mathbf{T}}$ vanishes, unlike h_1^{q}.

Introduction: TMDs



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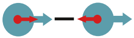

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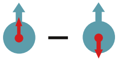


Transversity.

Sivers PDF.

Boer–Mulders PDF.

Pretzelosity PDF.

Introduction: TMDs process dependence

Quark TMD PDFs

- T-even TMDs universal,
- T-odd TMDs change sign for processes with ISI and FSI.
- The most prominent example being the Sivers function,

$$f_{1T}^{\perp}\big|_{\mathrm{Drell-Yan}} = -f_{1T}^{\perp}\big|_{\mathrm{SIDIS}}.$$

Gluon TMD PDFs

- Again, T-even TMDs are universal, T-odd change sign,
- In addition, 2 independent functions for each TMD:

$f^{[++]} = \pm f^{[--]}$: 'Weizsäcker–Williams type' (at small x),
[++] in $\ell p \to \ell Q\bar{Q}X$, $\ell p \to \ell J/\psi X$,...
[−−] in pp→ $J/\psi\gamma X$, pp→ $\eta_c X$,...
$f^{[+-]} = \pm f^{[-+]}$: 'Dipole type' (at small x),
[+−] in pp→ γ jet X

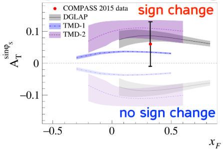
- In particular, for Sivers function:

$f_{1T}^{\perp g[++]} = -f_{1T}^{\perp g[--]}$ also called 'f-type',
$f_{1T}^{\perp g[+-]} = -f_{1T}^{\perp g[-+]}$ also called 'd-type'.

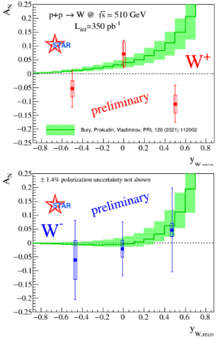
[D.Boer, Few-Body Syst. 58 (2017)]

[A.Bacchetta *et al.*, Eur.Phys.J. C80, 72 (2020)]

Sign-change in quark $f_{1T}^{\perp}$:



[COMPASS, Phys.Rev.Lett. 119(11), 112002 (2017)]



[O.Eyser for STAR, SPIN 2021]

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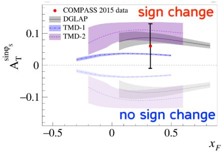

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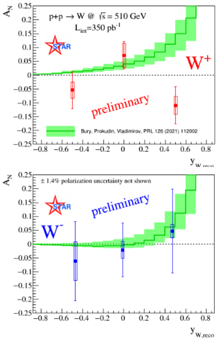

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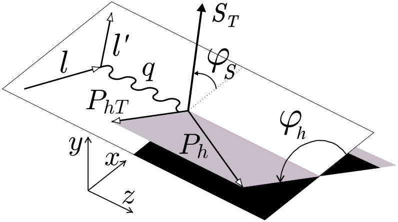
Introduction: Leptoproduction of quarkonium

$$\ell + N \to \ell' + \mathcal{Q} + X$$



Gamma–nucleon frame, usually used in TMD formalism.

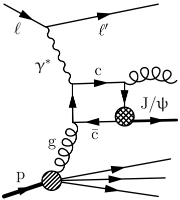
Variables used to describe semi-inclusive DIS:

- q 4-momentum of the virtual photon.
- P 4-momentum of the target nucleon.
- $\boldsymbol{S}$ target polarisation and its transverse component $\boldsymbol{S_\mathrm{T}} = S_\mathrm{T}(\cos\varphi_\mathrm{S}, \sin\varphi_\mathrm{S})$.
- $Q^2 = -q^2$.
- $x_\mathrm{B} = \frac{Q^2}{2P\cdot q}$ Bjorken x.
- P_h 4-momentum of the quarkonium.
- $\boldsymbol{P_\mathrm{hT}} = P_\mathrm{hT}(\cos\varphi_\mathrm{h}, \sin\varphi_\mathrm{h})$ Transverse momentum of the quarkonium, often just $\boldsymbol{P_\mathrm{T}}$.
- $z = \frac{P\cdot P_\mathrm{h}}{P\cdot q} = \frac{E_\mathrm{h}^\mathrm{lab}}{E_\ell^\mathrm{lab} - E_{\ell'}^\mathrm{lab}}$ fraction of available energy carried by the quarkonium in the laboratory system.

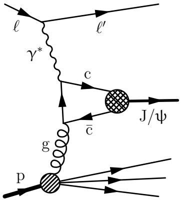
TMD measurements require high statistics – J/ψ is usually considered as the quarkonium.

Leptoproduction of J/ψ (or ϒ): Production models

A way to gluon TMDs via photon–gluon fusion sub-process.



Color singlet model (CSM).



Color evaporation (CEM) or color octet model (COM).

Factorisation into TMD, hard sub-process and quarkonium formation is always assumed.

$\mathcal{Q}$ formation
- CEM: $c\bar{c}$ states contribute according to statistical counting.
- NRQCD: transition probablities from various $c\bar{c}$ states (LDMEs).

Inclusive prod. ($z \lesssim 0.9$)
- Color singlet contributions relevant.
- Contribution of $q\gamma^{(*)} \to J/\psi q$ – suppressed as f_1^q is small at small x.
- Decay of b-hadrons may be dominant at small z or large P_T.
- Feed-downs. mostly from $\psi(2S)$.
- Resolved photon process relevant at low z and low Q^2.

Exclusive prod. ($z \approx 1$)
- COM (or CEM) contribution dominates over CSM.
- Diffractive production important!

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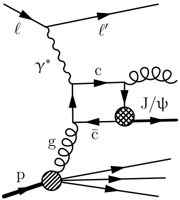

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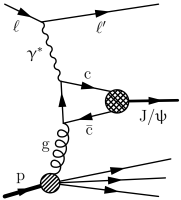

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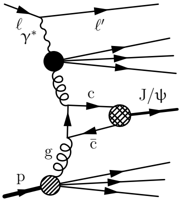

Resolved photon process + CEM/COM/CSM.

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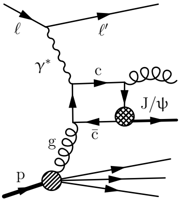

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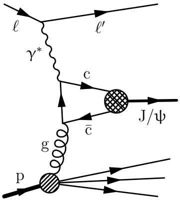

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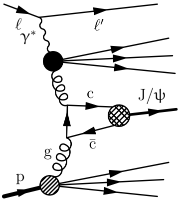

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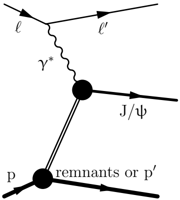

Diffractive production.

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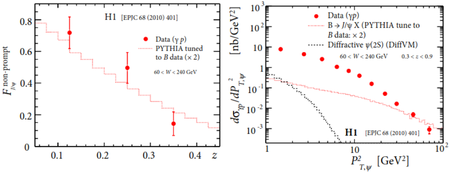
Leptoproduction of J/ψ (or ϒ): Backgrounds for the PGF process

Non-prompt production (b-hadron decay)



The non-prompt J/ψ in photoproduction is relevant at small z and large P_T.

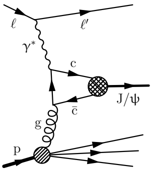
- Can be distinguished with a precise vertex detector (0.1 mm at LHC)

Feed-downs

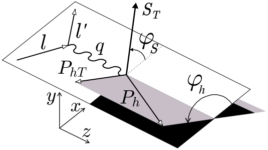
ψ(2S):
- 15–20% in inclusive production at HERA [H1, Eur.Phys.J. C68 (2010)]
- Measurable: $\psi(2S) \to J/\psi\pi^+\pi^-$ e.g. [ZEUS, Eur.Phys.J.C 27 (2003)]

χ_c:
- 1–7% in inclusive production at HERA [H1, Eur.Phys.J. C25 (2002)]
- Measurable: $\chi_c \to J/\psi\gamma$, but $E_\gamma = \mathcal{O}(400)$ MeV, may be difficult to detect.

Leptoproduction of J/ψ (or Υ): Azimuthal modulations at $z \approx 1$



J/ψ formed in PGF.



The γN frame.

- Assuming PGF process and NRQCD approach.
  [A.Mukherjee, S.Rajesh, Eur.Phys.J.C77 (2017)] (only Sivers, $\cos 2\varphi_{\mathrm{h}}$),
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- Sivers asymmetry in photoproduction using CEM:
  [R.Godbole *et al.*, Phys.Rev. D88 (2013)].
- In CSM mod. expected to vanish [F.Yuan, Phys.Rev. D78 (2008)]
- On unpolarised target:

  $\cos 2\varphi_{\mathrm{h}}$: access to Boer–Mulders TMD $h_1^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$.
- On transversely-polarised target:

  $\sin(\varphi_{\mathrm{S}} - \varphi_{\mathrm{h}})$: access to $f_{1\mathrm{T}}^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (Sivers TMD),
  $\sin(\varphi_{\mathrm{S}} + \varphi_{\mathrm{h}})$: access to $h_1^{\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (transversity TMD),
  $\sin(\varphi_{\mathrm{S}} - 3\varphi_{\mathrm{h}})$: access to $h_{1\mathrm{T}}^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (pretzelosity TMD).
- The modulation amplitudes A^w depend on the LDMEs and on $\mathcal{Q}$ polarisation.

Ratios independent of the LDMEs:

$$\frac{A^{\cos 2\varphi_{\mathrm{h}}}}{A^{\sin(\varphi_{\mathrm{S}}+\varphi_{\mathrm{h}})}} = \frac{k_{\mathrm{T}}^2}{M_{\mathrm{p}}^2} \frac{h_1^{\perp\mathrm{g}}}{h_1^{\mathrm{g}}}, \qquad \frac{A^{\sin(\varphi_{\mathrm{S}}-3\varphi_{\mathrm{h}})}}{A^{\cos 2\varphi_{\mathrm{h}}}} = -\frac{|k_{\mathrm{T}}|}{2M_{\mathrm{p}}} \frac{h_{1\mathrm{T}}^{\perp\mathrm{g}}}{h_1^{\perp\mathrm{g}}}, \qquad \frac{A^{\sin(\varphi_{\mathrm{S}}-3\varphi_{\mathrm{h}})}}{A^{\sin(\varphi_{\mathrm{S}}+\varphi_{\mathrm{h}})}} = -\frac{k_{\mathrm{T}}^2}{2M_{\mathrm{p}}^2} \frac{h_{1\mathrm{T}}^{\perp\mathrm{g}}}{h_1^{\mathrm{g}}},$$

Ratios of σ and of $A^{\cos 2\phi}$ in $\mathcal{Q}$ and open $\mathrm{Q\bar{Q}}$ production → LDMEs independent of TMDs.
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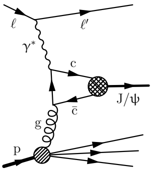

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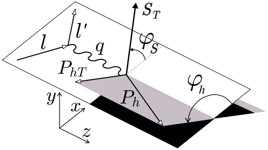

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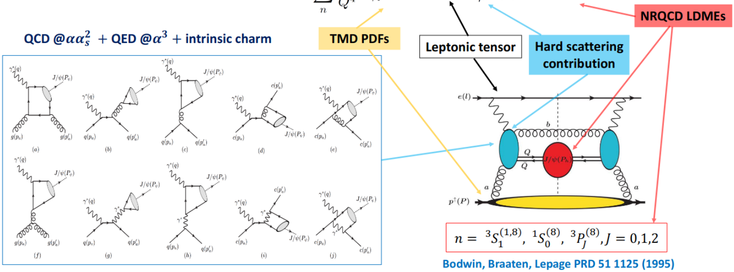
Leptoproduction of J/ψ (or Υ): Inclusive production

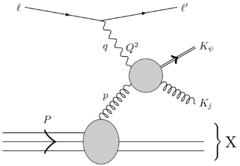
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}^2\boldsymbol{P}_T\,\mathrm{d}z} = \frac{1}{2S}\frac{2}{(4\pi)^4 z}\sum_a \int \frac{\mathrm{d}x_a}{x_a}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\delta\left(\hat{s}+\hat{t}+\hat{u}-M^2+Q^2\right) \times \sum_n \frac{1}{Q^4} f_{a/p}(x_a,k_{\perp a}) L^{\mu\nu} H^{a,U}_{\mu\nu}[n]\langle 0 \mid \mathcal{O}^{J/\psi}(n) \mid 0\rangle\,,$$



Taken from teh slides [F.Murgia, A.Mukherjee, C.Pisano, S.Rajesh, SPIN2021]

- [F.Murgia, A.Mukherjee, C.Pisano, S.Rajesh, SPIN2021] [S.Rajesh *et al.*, proceedings of DIS2021]
- TMD + generalized parton model (GPM) at NLO → Allows to access $z < 1$.
- NRQCD for J/ψ production from $c\bar{c}$.
- $0.3 < z < 0.9$ → avoid resolved photon, non-prompt J/ψ and the diffractive region.
- All partonic channels at $\alpha\alpha_s^2$, QED at α^3.
- Feed-down from ψ(2S) included.
- Sivers asymmetry $A^{\sin(\varphi_h-\varphi_S)}$: also here only CO and f-type $f_{1T}^{\perp g}$ contribute.

Leptoproduction of J/ψ (or Υ): Associated with a jet



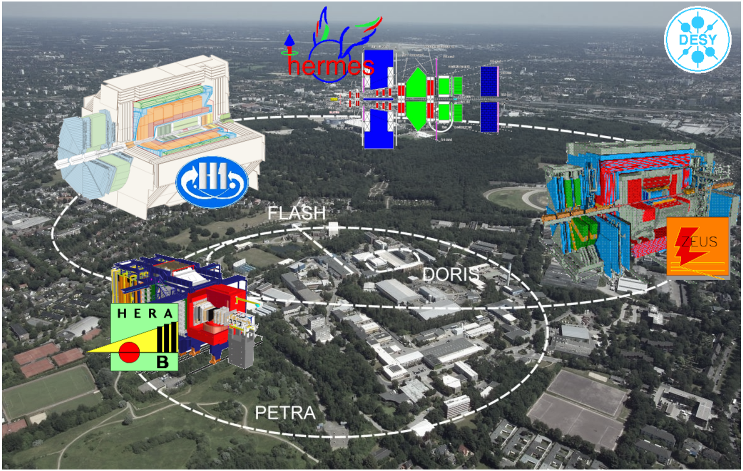
- [U.D'Alesio *et al.*, Phys.Rev.D 100 (2019)]
- $\mathrm{e} + \mathrm{p}^{(\uparrow)} \to \mathrm{e}' + \mathrm{J}/\psi(\Upsilon) + \mathrm{jet} + \mathrm{X}$
- $\left|\boldsymbol{P}_{\mathbf{T}}^{\mathrm{J}/\psi} + \boldsymbol{P}_{\mathbf{T}}^{\mathrm{jet}}\right|$ required to be small, but $P_{\mathrm{T}}^{\mathrm{J}/\psi}$ and $P_{\mathrm{T}}^{\mathrm{jet}}$ are not constrained.
  $\to$ scale (mass of the pair) can be varied.
- $z < 1$.
- The same azimuthal modulations, just the role of φ_{h} is played by ϕ_{T}, azimuthal angle of the pair.

  $\cos 2\phi_{\mathrm{T}}$: access to Boer–Mulders $h_1^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$.
  $\sin(\varphi_{\mathrm{S}} - \phi_{\mathrm{T}})$: access to $f_{1\mathrm{T}}^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (Sivers TMD),
  $\sin(\varphi_{\mathrm{S}} + \phi_{\mathrm{T}})$: access to $h_1^{\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (transversity),
  $\sin(\varphi_{\mathrm{S}} - 3\phi_{\mathrm{T}})$: access to $h_{1\mathrm{T}}^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$ (pretzelosity).
- In addition $\phi_\perp$, the azimuthal angle of the J/ψ:

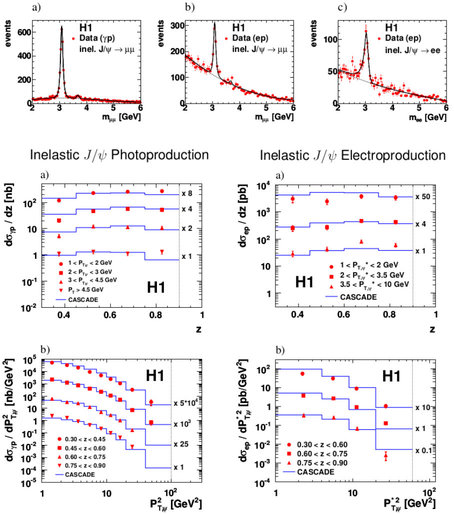
  $\cos 2(\phi_{\mathrm{T}} - \phi_\perp)$: access to Boer–Mulders $h_1^{\perp\mathrm{g}}(x, k_{\mathrm{T}}^2)$.

HERA: Introduction

- Collider of e^+ or e^- beam of 27.5 GeV/c and p beam of 920 GeV/c, $\sqrt{s} \approx 300$ GeV.
- Multi-purpose 4π detectors H1 and ZEUS, HERA-B (LHCb-like),
- HERMES: polarised fixed-target for SIDIS.



[H1, Eur.Phys.J. C68 (2010)] $e + p \to e' + J/\psi + X$

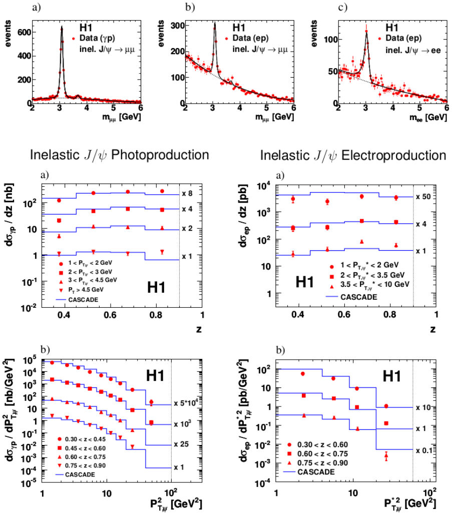


Multi-dimensional cross-section measurement. In addition, J/ψ polarisation was measured.

- Photoproduction: e' not detected $\to Q^2 < 2.5\ (\mathrm{GeV}/c)^2$ ≈ 2300 events, $165\ \mathrm{pb}^{-1}$.
- Electroproduction: $3.6\ (\mathrm{GeV}/c)^2 < Q^2 < 100\ (\mathrm{GeV}/c)^2$ ≈ 800 events, $315\ \mathrm{pb}^{-1}$.
- $P_T > 1\ \mathrm{GeV}/c$
- $0.3 < z < 0.9$
- Feed-down from $\psi(2S)$: 15–20% (MC and [ZEUS, Eur.Phys.J.C 27 (2003)]), χ_c negligible [H1, Eur.Phys.J. C25 (2002)].
- b-hadron decay: MC and a measurement based on impact-parameter distribution.
- φ_h not measured, P_T cut may complicate TMD interpretation.

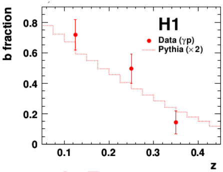
HERA: Inelastic J/ψ photo- and electroproduction

[H1, Eur.Phys.J. C68 (2010)] $e + p \to e' + J/\psi + X$



Multi-dimensional cross-section measurement. In addition, J/ψ polarisation was measured.

- Photoproduction: e' not detected $\to Q^2 < 2.5\ (\mathrm{GeV}/c)^2$ ≈ 2300 events, 165 pb^{-1}.
- Electroproduction: $3.6\ (\mathrm{GeV}/c)^2 < Q^2 < 100\ (\mathrm{GeV}/c)^2$ ≈ 800 events, 315 pb^{-1}.
- $P_\mathrm{T} > 1\ \mathrm{GeV}/c$
- $0.3 < z < 0.9$
- Feed-down from ψ(2S): 15–20% (MC and [ZEUS, Eur.Phys.J.C 27 (2003)]), χ_c negligible [H1, Eur.Phys.J. C25 (2002)].
- b-hadron decay: MC and a measurement based on impact-parameter distribution.



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HERA: Inelastic J/ψ photo- and electroproduction

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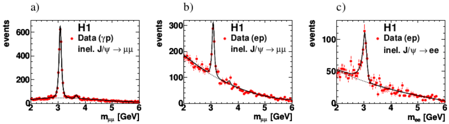

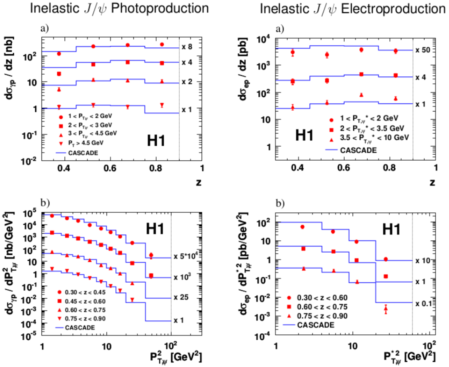

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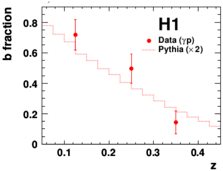
- b-hadron decay: MC and a measurement based on impact-parameter distribution.



- φ_h not measured, $\boldsymbol{P_T}$ cut may complicate TMD interpretation.

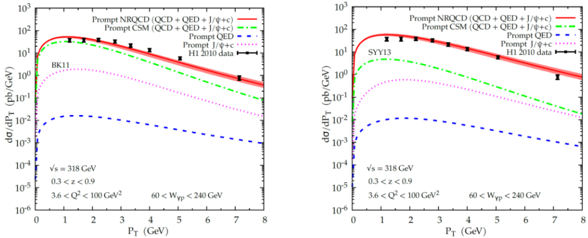
HERA: Inelastic J/ψ photo- and electroproduction

[H1, Eur.Phys.J. C68 (2010)] fitted by [F.Murgia, A.Mukherjee, C.Pisano, S.Rajesh, SPIN2021]

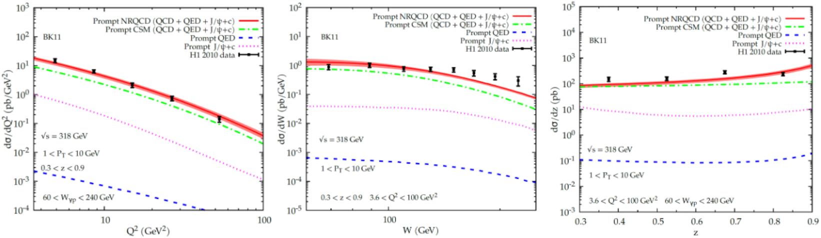
Gaussian Ansatz for f_1^g, $\langle k_{Tq}^2 \rangle = 0.25\ \mathrm{GeV}^2$ $\langle k_{Tg}^2 \rangle = 1.0\ \mathrm{GeV}^2$.

LDMEs: [Butenschoen, Kniehl, Phys.Rev.D 84 051501 (2011)] [Sun, Yuan, Yuan, Phys.Rev.D, 88 054008 (2013)]

LDMEs ψ(2S): [Sharma, Vitev, Phys.Rev.C 87 044905]

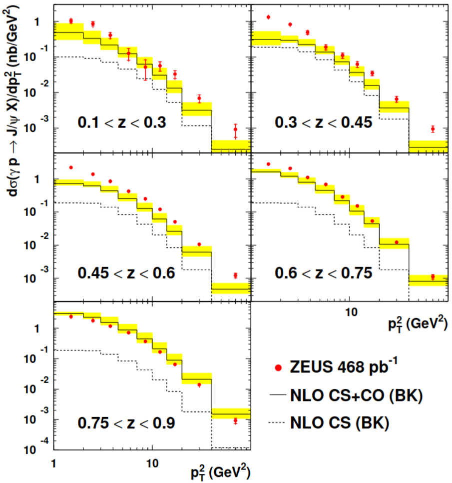


$\mu^2 = M^2 + P_T^2$ collinear PDFs CTEQ-L1 Data: H1 Collab. EPJC 68 401 (2010)



HERA: Inelastic J/ψ photo- and electroproduction

[ZEUS, JHEP 02 (2013) 071]



Multi-dimensional cross-section measurement. In addition, J/ψ polarisation was measured.

$e + p \to e' + J/\psi + X,$
$e + p \to e' + \psi(2S) + X$

- Photoproduction, $Q^2 < 1\ (\mathrm{GeV}/c)^2$
- ≈ 12000 J/ψ, 400 ψ(2S), 468 pb^{-1}.
- $P_T > 1$ GeV/c
- $0.1 < z < 0.9$
- φ_h not measured (in fact, at H1 and ZEUS in photoproduction e is in the beam pipe – φ_h cannot be measured).
- P_T cut may complicate TMD interpretation.

HERA: Exclusive J/ψ photoproduction

- Elastic – no p fragments, low $|t|$.
- Diffractive with p dissociation
  – p fragments seen, large $|t|$.
- Cannot be distinguished event by event (just cuts or statistical unfolding).
- Measurements in Q^2, $|t|$ and W.
- Angular dependence of the cross-section described with spin density matrix elements (SDMEs).

- Photoproduction:
  [ZEUS, JHEP 05 (2010) 085] (at high $|t|$)
  [H1, Eur.Phys.J.C 73 (2013) 6, 2466] (unfolding)
- Electroproduction:
  [H1, Eur.Phys.J.C 46 (2006) 585]
  Measured the angle φ_h (here Φ).

HERA: Exclusive J/ψ photoproduction

- Elastic – no p fragments, low $|t|$.
- Diffractive with p dissociation – p fragments seen, large $|t|$.
- Cannot be distinguished event by event (just cuts or statistical unfolding).
- Measurements in Q^2, $|t|$ and W.
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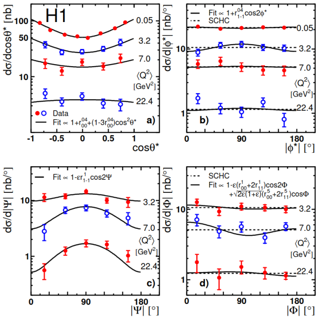

Anglular distributions in exclusive electroproduction.

- Photoproduction:
  [ZEUS, JHEP 05 (2010) 085] (at high $|t|$)
  [H1, Eur.Phys.J.C 73 (2013) 6, 2466] (unfolding)
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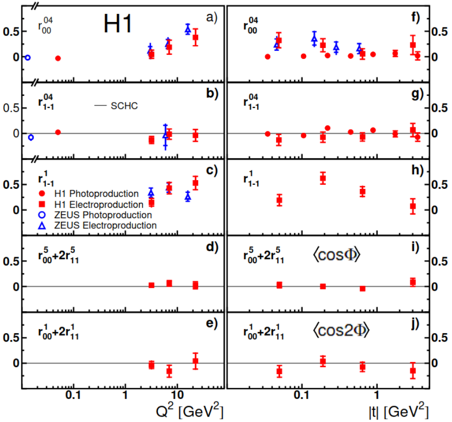
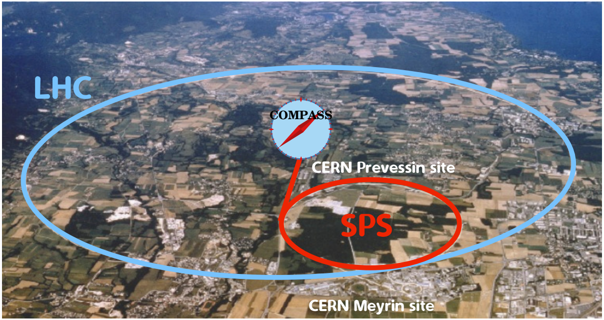
  [H1, Eur.Phys.J.C 46 (2006) 585]
  Measured the angle φ_h (here Φ).

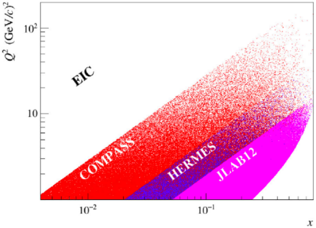


SDMEs in exclusive electroproduction.

COMPASS: Introduction

- Medium-sized collaboration.
- Experimental area: CERN Super Proton Synchrotron (SPS) North Area.
- Multi-purpose apparatus with rich physics program since 2002 aimed at hadron structure and spectroscopy.
- Wide range of measurements, including SIDIS with μ beam and polarised targets and $\pi^- p$ Drell–Yan, which is also relevant for J/ψ measurements.





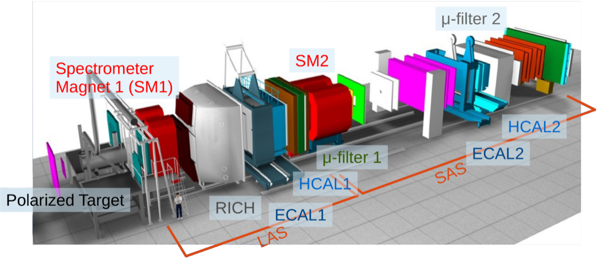
Kinematic coverage compared to other $\ell N^{\uparrow} \to \ell' hX$ experiments.

COMPASS: SIDIS experiments

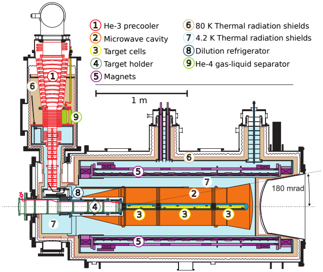
- Large polarised solid-state target with 2 or 3 oppositely-polarised cells.
- Two-stage spectrometer, about 350 detector planes, μ identification, RICH.
- Usually 160 GeV/c μ^+ beam (about 3.5×10^8 μ/spill of 10 s).

Data taking with muon beam

2002–2004 80% with $\vec{d}$, 20% with $d^\uparrow$ target (^{6}LiD).
2006 $\vec{d}$ target (^{6}LiD).
2007 50% with $\vec{p}$, 50% with $p^\uparrow$ taget (NH_3), larger-aperture PT magnet installed.
2010 $p^\uparrow$ target (NH_3).
2011 $\vec{p}$ target (NH_3, 200 GeV/c beam).
2017–2017 p target (liquid H, recoil p detection, $\mu^\pm$ beam, ECAL0).
2021–2022 $d^\uparrow$ target (^{6}LiD).



The SIDIS setup.

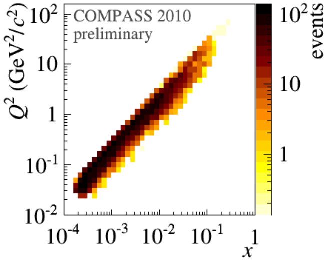


Polarised target.

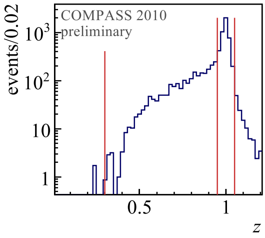
COMPASS: Sivers-like asymmetry in J/ψ leptoproduction

[J.M. for COMPASS, J.Phys.Conf.Ser. 678 (2016) 1]

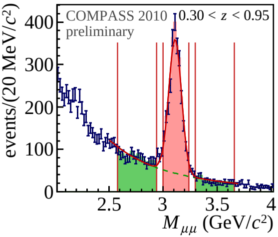
- $\mu^+ p^\uparrow \to \mu^+ J/\psi\, X \to \mu^+ \mu^+ \mu^- X$.
- Kinematic range: $Q \ll M_{J/\psi}$, $0 < P_T < 2$ GeV/c
- 2010 $p^\uparrow$ (NH_3) data.
- Two bins in z: inclusive, exclusive.
- Clear J/ψ signal (3.1 GeV/c^2, $\sigma \approx 55$ MeV/c^2).
- Limited statistics (≈ 2300 incl., 4500 excl.)
- The distributions are not acceptance-corrected (just background-subtracted using side-bands).



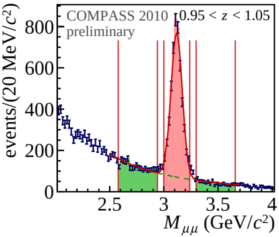
Distibution of events in x and Q^2.



Energy fraction transferred to J/ψ.

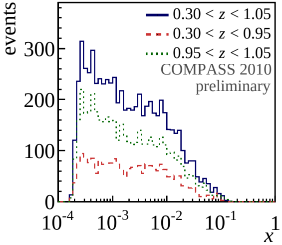


Invariant mass, inclusive bin.

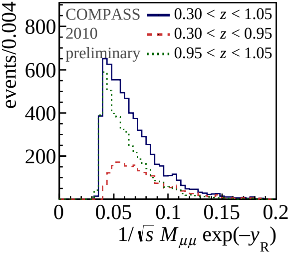


Invariant mass, exclusive bin.

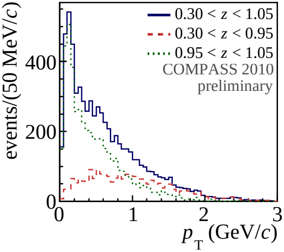
COMPASS: Results



The $x_{\mathrm{Bj.}}$ distribution.

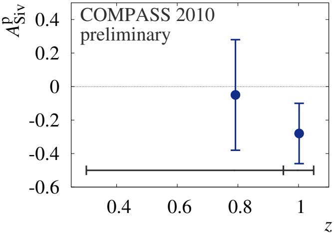


In the model, this corresponds to the gluon x_{g}. y_{R} is rapidity.



The P_{T} distribution.

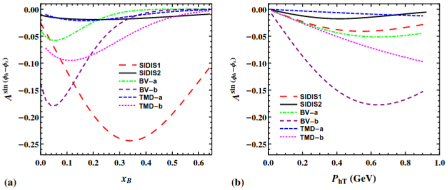
- $A^{\mathrm{p}}_{\mathrm{Siv}} = -0.28 \pm 0.18$ (preliminary, exclusive J/ψ).
- Prospects for improving statistics:
  - $\mathrm{e}^+\mathrm{e}^-$ channel: spectrometer not optimal for electrons, probably high background…
  - 2002–2004 ^{6}LiD data: rather small statistics,
  - 2007 NH_3 data could bring up to 50%,
  - Planned 2022 ^{6}LiD data: ≈ 2010 statistics.
- COMPASS is considering analysing other azimuthal modulations and writing a paper.
- Cross-section and SDMEs for exclusive J/ψ could be measured in 2016–2017 H_2 data.



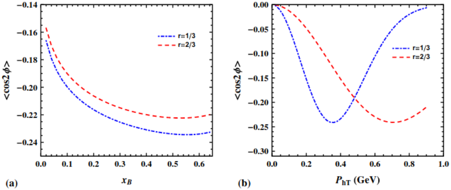
The measured Sivers-like asymmetry.

Exclusive bin

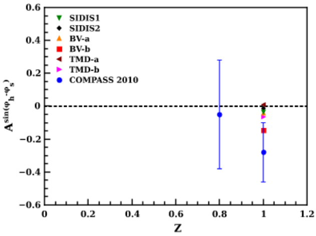
from [A.Mukherjee, S.Rajesh, Eur.Phys.J.C77 (2017)]:



Various evolution and parametrization choices.

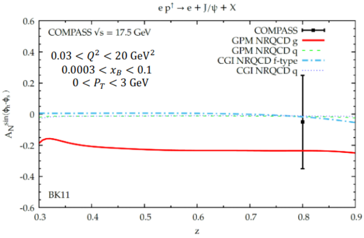


Projection for $\cos 2\varphi_h$ asymmetry.



- Diffractive contribution must be large.
- Naively, it dilutes the asymmetry.
- Bins in Q^2 or P_T can be tried.

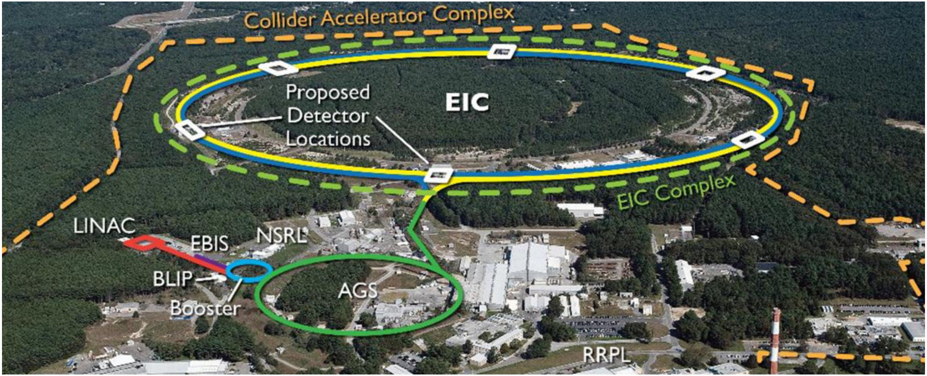
Inclusive bin



Maximized Sivers asymmetry from [F.Murgia, A.Mukherjee, C.Pisano, S.Rajesh, SPIN2021].

EIC: Introduction

- Based on existing RHIC facility.
- Hadron storage ring: 40–275 GeV/c, hadrons optionally polarised.
- Electron storage ring: 2.5–18 GeV/c
- 45 GeV $< \sqrt{s} <$ 140 GeV.
- High luminosity up to 10^{34} cm^{-2}s^{-1}.



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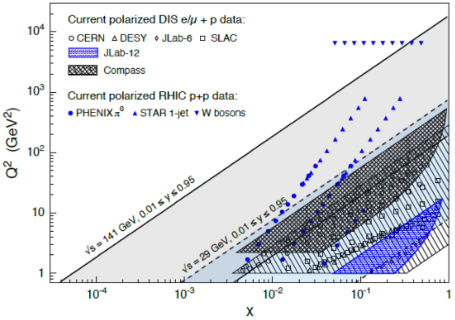
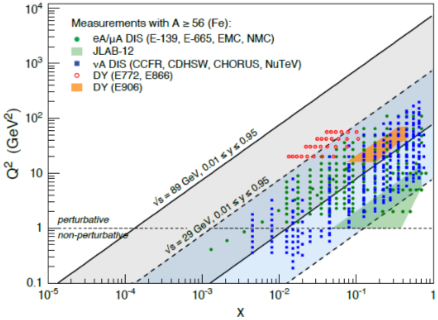
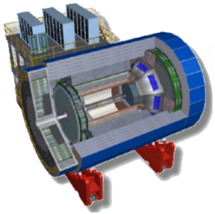
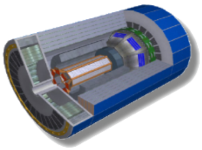




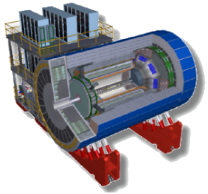
Three detector designs in preparation:



ATHENA



CORE



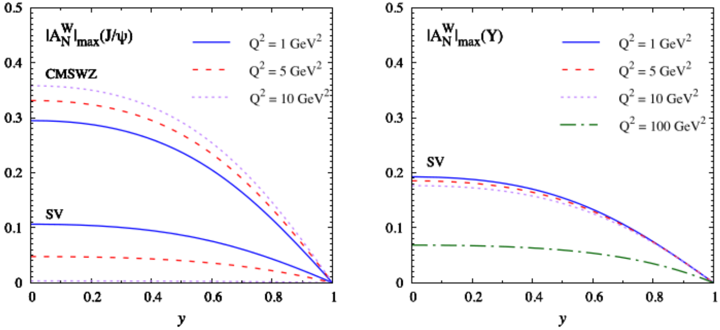
ECCE

- A Totally Hermetic Electron–Nucleus Apparatus.
- General purpose detector inspired by Yellow Report concept.
- New central magnet of up to 3 T.
- `https://www.athena-eic.org`

- COmpact detectoR for the Eic.
- Nearly hermetic, general-purpose compact detector.
- 2 T magnet (up to 4 T).
- `https://userweb.jlab.org/~hyde/EIC-CORE/`

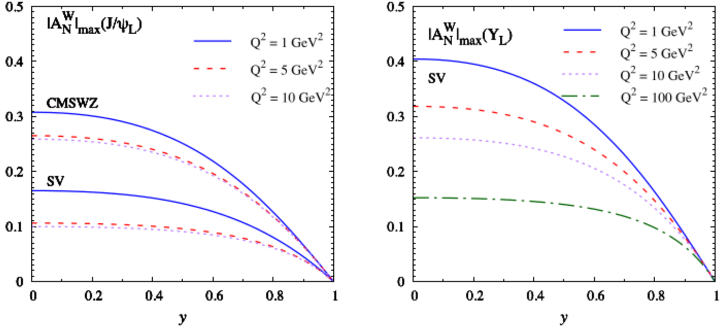
- EIC Comprehensive Chromodynamics Experiment.
- General purpose detector based on 1.5T BaBar magnet.
- `https://www.ecce-eic.org`

EIC: J/ψ leptoproduction at $z \approx 1$



Upper bounds on the $\langle \cos 2\varphi_h \rangle$ and on the asymmetries A^W with $W = \sin(\varphi_S + \varphi_h), \sin(\varphi_S - 3\varphi_h)$ for the production of J/ψ and Υ.

LDMEs: [K.-T.Chao, Y.-Q.Ma, H.-S.Shao, K.Wang, Y.-J.Zhang, Phys.Rev.Lett. 108, 242004 (2012)]
[R.Sharma, I.Vitev, Phys.Rev.C 87, 044905 (2013)]



Upper bounds on the $\langle \cos 2\varphi_h \rangle$ and on the asymmetries A^W with $W = \sin(\varphi_S + \varphi_h), \sin(\varphi_S - 3\varphi_h)$ for the production of J/ψ and Υ longitudinaly polarised in the $\gamma^* p$ center-of-mass system.

LDMEs: [K.-T.Chao, Y.-Q.Ma, H.-S.Shao, K.Wang, Y.-J.Zhang, Phys.Rev.Lett. 108, 242004 (2012)]
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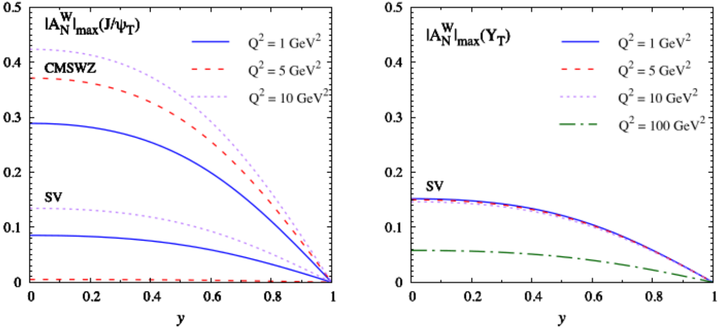
EIC: J/ψ leptoproduction at $z \approx 1$

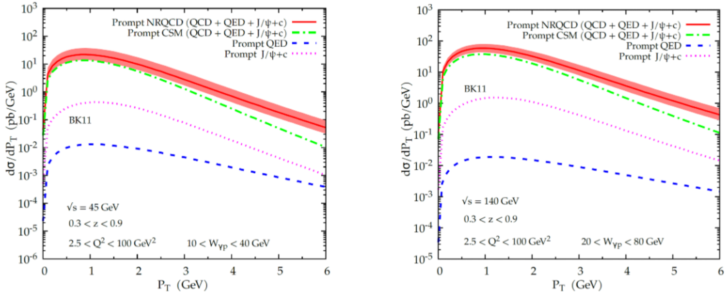


Upper bounds on the $\langle \cos 2\varphi_h \rangle$ and on the asymmetries A^W with $W = \sin(\varphi_S + \varphi_h), \sin(\varphi_S - 3\varphi_h)$ for the production of J/ψ and Υ transversely polarised in the γ^*p center-of-mass system.

LDMEs: [K.-T.Chao, Y.-Q.Ma, H.-S.Shao, K.Wang, Y.-J.Zhang, Phys.Rev.Lett. 108, 242004 (2012)]
[R.Sharma, I.Vitev, Phys.Rev.C 87, 044905 (2013)]

EIC: Inclusive J/ψ leptoproduction

[F.Murgia, A.Mukherjee, C.Pisano, S.Rajesh, SPIN2021]



Unpolarised cross-section for $\sqrt{s} = 45$ GeV (left), $\sqrt{s} = 140$ GeV (right).

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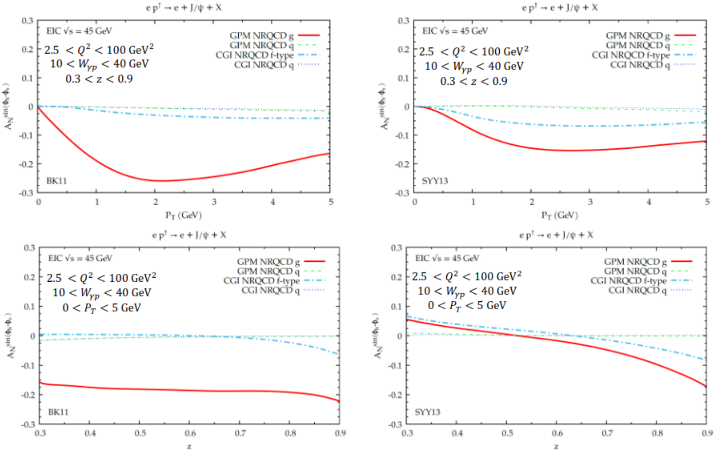

Maximized Sivers asymmetry for $\sqrt{s} = 45$ GeV.

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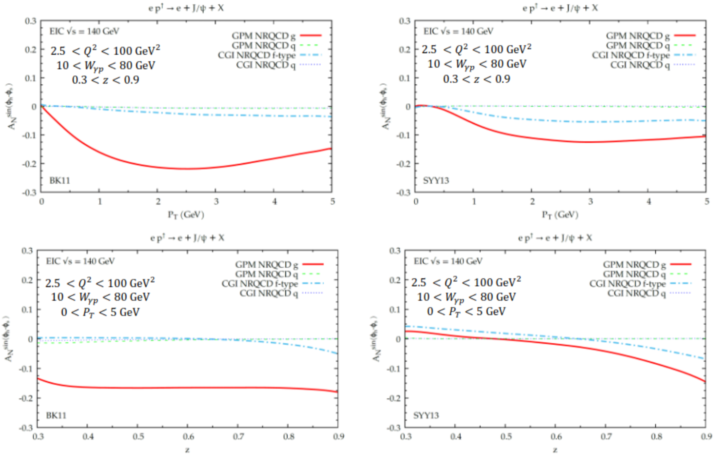
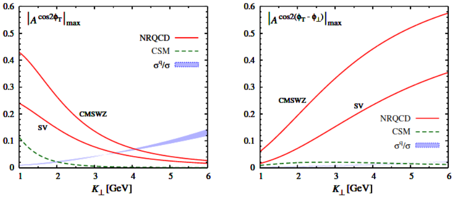


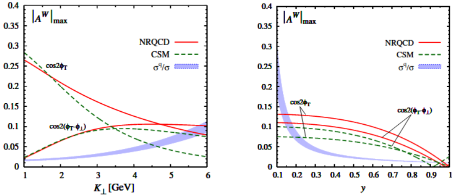
Maximized Sivers asymmetry for $\sqrt{s} = 140$ GeV.

EIC: Inclusive J/ψ (Υ) + jet leptoproduction

[U.D'Alesio *et al.*, Phys.Rev.D 100 (2019)]



Upper bounds on the amplitudes of the $\cos 2\phi_T$ modulation at $Q^2 = 10$ (GeV/c)^2, $z = 0.7$, $y = 0.3$ (left); and of the $\cos 2(\phi_T - \phi_\perp)$ modulation at $Q^2 = 10$ (GeV/c)^2, $z = 0.3$, $y = 0.7$ (right) for J/ψ production plotted as a function of the transverse momentum of the J/ψ.



Upper bounds on the same amplitudes for Υ

LDMEs: [K.-T.Chao, Y.-Q.Ma, H.-S.Shao, K.Wang, Y.-J.Zhang, Phys.Rev.Lett. 108, 242004 (2012)]
[R.Sharma, I.Vitev, Phys.Rev.C 87, 044905 (2013)]

Conclusion

- TMD measurements in quarkonium production have been discussed since about 10 years.
- Lately there has been a lot of progress on the theory side.
    - NRQCD incorporated, requirements for TMD factorisation spelled out,
    - the full angular structure explored,
    - asymmetry ratios independent of LDMEs,
    - inclusive production and J/ψ + jet.
- Numerous quarkonium measurements from HERA, but they lack the distribution of φ_{h}.
- COMPASS has done the first measurement of a transverse (single) spin asymmetry in quarkonium production.
- However, with limited statistics concentrated mostly in the exclusive region.
- The measurements are waiting for EIC...

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Thank you for your attention!