TMD effects in unpolarised processes – experiment overview

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

CHARLES UNIVERSITY
Faculty of mathematics and physics

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Introduction: TMDs

Parton polarisation	Parent hadron polarization: Unpolarised	Longitudinal	Transverse
U	$f_1(x, k_\mathrm{T}^2)$ (unpolarised)		$f_{1\mathrm{T}}^{\perp}(x, k_\mathrm{T}^2)$ (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)

8 leading twist TMD PDFs, 2 are relevant for unpolarised hadrons.

Introduction: TMDs

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Parton polarisation	Unpolarised hadron
U	$f_1(x, k_T^2)$ (unpolarised)
L/C	
T/L	k_T — $h_1^\perp(x, k_T^2)$ (Boer–Mulders)

Parton distribution functions

Parton polarisation	Unpolarised hadron
U	$D_1(z, P_\perp^2)$ (unpolarised)
L/C	
T/L	k_T — $H_1^\perp(z, P_\perp^2)$ (Collins)

Fragmentation functions

- Parton polarisation:
  L/C: longitudinal (quarks) or circular (gluons).
  T/L: transverse (quarks) or linear (gluons).
- Boer–Mulders function
  Quarks: chiral-odd,
  Gluons: chiral-even.

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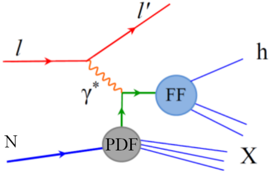
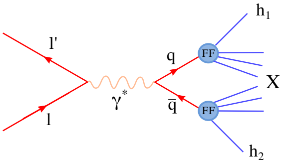
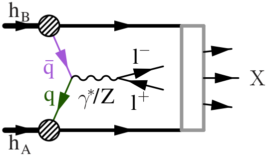


Hadron production in DIS (SIDIS)



Hadron production in e^+e^- annihilation.



Drell–Yan process or Z boson production.

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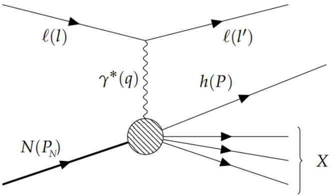
$$\mathrm{l}(l) + \mathrm{N}(P_\mathrm{N}) \to \mathrm{l}'(l') + \mathrm{h}(P) + \mathrm{X}$$

The cross section is [A. Bacchetta *et al.*, JHEP 02 (2007) 093]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_\mathrm{h}\mathrm{d}P_\mathrm{T}^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{2xM^2}{Q^2}\right)\Big(F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\sqrt{2\varepsilon(1-\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\Big)$$
$$= \sigma_0\left(1 + \varepsilon_1 A_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\varepsilon_3 A_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\right)$$

- x, y, Q^2: usual DIS variables,
- λ: beam polarisation (≈ 0.8 at COMPASS),
- ε: ratio of longitudinal and transverse photon flux,
- z: fraction of γ^* energy carried by h.
- P_T: transverse momentum of h in the γN frame, ϕ_h is its azimuthal angle.
- $F_{\mathrm{XU}}^{f(\phi_\mathrm{h})}(x, z, P_\mathrm{T}^2, Q^2)$ are structure functions.
- $A_{\mathrm{XU}}^{f(\phi_\mathrm{h})}(x, z, P_\mathrm{T}^2, Q^2)$ are commonly called azimuthal asymmetries.



Semi-inclusive DIS.

$$\mathrm{l}(l) + \mathrm{N}(P_\mathrm{N}) \to \mathrm{l}'(l') + \mathrm{h}(P) + \mathrm{X}$$

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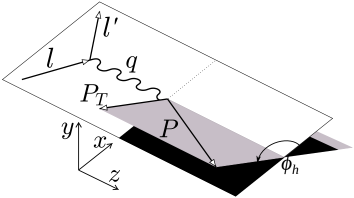

γ–nucleon frame.

Hadron production in DIS: Cross section

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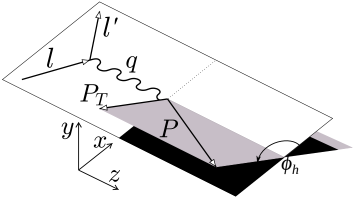

γ–nucleon frame.

Hadron production in DIS: Cross section

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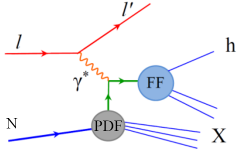
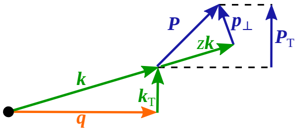
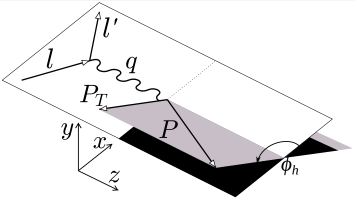
TMD factorisation ($P_\mathrm{T} \ll Q$): $\sigma \propto$ TMD PDF $\otimes$ hard part $\otimes$ TMD FF.





$\boldsymbol{P}_\mathbf{T} \approx z\boldsymbol{k}_\mathbf{T} + \boldsymbol{P}_\perp$



γ–nucleon system.

$$\mathcal{C}[wfD] = x\sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_\mathbf{T}\,\mathrm{d}^2\boldsymbol{P}_\perp\,\delta^{(2)}(z\boldsymbol{k}_\mathbf{T} + \boldsymbol{P}_\perp - \boldsymbol{P}_\mathbf{T})w(k_\mathrm{T}, P_\perp)\,f^q(x, k_\mathrm{T}, Q^2)\,D^{q\to\mathrm{h}}(z, P_\perp, Q^2)$$

Up to order $\frac{1}{Q}$ and in Wandzura–Wilczek-type approximation:

TMD PDFs:

- f_1 : unpolarised
- $h_1^\perp$: Boer–Mulders

TMD FFs:

- D_1 : unpolarised
- $H_1^\perp$: Collins

$F_{\mathrm{UU,T}} = \mathcal{C}[f_1 D_1]$ $\qquad F_{\mathrm{UU,L}} = 0$ $\qquad F_{\mathrm{LU}}^{\sin\phi_\mathrm{h}} = 0 + \ldots$ $\leftarrow$ pure qgq

$$F_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathbf{T})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp) - (\boldsymbol{k}_\mathbf{T}\cdot\boldsymbol{P}_\perp)}{zMM_h} h_1^\perp H_1^\perp\right]$$ $\leftarrow$ +Cahn as $1/Q^2$

$$F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}} = -\frac{2M}{Q}\mathcal{C}\left[\underbrace{\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathbf{T})}{M} f_1 D_1}_{\text{Cahn effect}} + \underbrace{\frac{k_\mathrm{T}^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)}{zM^2M_\mathrm{h}} h_1^\perp H_1^\perp}_{\text{Boer–Mulders effect}} + \ldots\right] \qquad \hat{\boldsymbol{h}} = \frac{\boldsymbol{P}_\mathbf{T}}{|\boldsymbol{P}_\mathbf{T}|}$$

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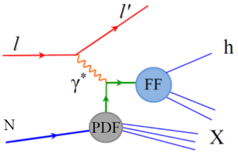
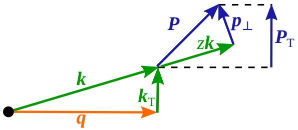
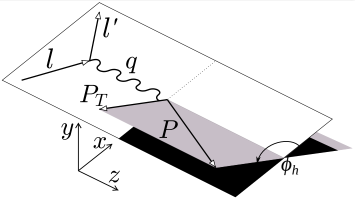
TMD factorisation ($P_{\mathrm{T}} \ll Q$): $\sigma \propto$ TMD PDF $\otimes$ hard part $\otimes$ TMD FF.





$$\boldsymbol{P}_{\mathbf{T}} \approx z\boldsymbol{k}_{\mathbf{T}} + \boldsymbol{P}_{\perp}$$



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$$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - (\boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{P}_{\perp})}{zMM_h} h_1^{\perp} H_1^{\perp}\right] \quad \leftarrow +\text{Cahn as } 1/Q^2$$

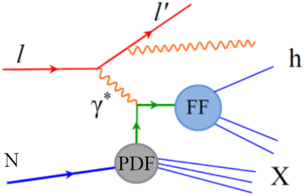
$$F_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}} = -\frac{2M}{Q}\mathcal{C}\left[\underbrace{\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})}{M} f_1 D_1}_{\text{Cahn effect}} + \underbrace{\frac{k_{\mathrm{T}}^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp})}{zM^2M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}}_{\text{Boer–Mulders effect}} + \ldots\right] \qquad \hat{\boldsymbol{h}} = \frac{\boldsymbol{P}_{\mathbf{T}}}{|\boldsymbol{P}_{\mathbf{T}}|}$$

Hadron production in DIS: Radiative corrections

TMD interpretation defined at tree level
→ QED radiative effects need to be accounted for:

- renormalisation of the vertices,
- radiation of photons along the ℓ, ℓ' and γ^*,

→ changes in x, Q^2, tail from elastic scattering,
→ orientation of γ–nucleon system distorted.



Inclusive corrections – mostly used in the past.

- [A.A. Akhundov *et al.*, Fortschr. Phys. 44 (1996) 373]
  - Semi-analytical approach, parametrised in TERAD program.
- MC generators RADGEN, POLRAD (for longitudinally polarised $e^{\pm}$)
  [I. Akushevich, Böttcher, Ryekbosh, hep-ph/9906408 (1998)]

Taking into account hadron phase space, z-,P_{T}- and ϕ_{h}-dependences is needed for TMDs.

- HAPRAD [I. Akushevich, N. Shumeiko, A. Soroko, Eur.Phys.J.C10 (1999) 681–687]:
  - 5D $(x, y, z, P_{\mathrm{T}}^2, \phi_{\mathrm{h}})$ corrections for inclusive h leptoproduction,
  - [I. Akushevich, A. Ilyichev, M. Osipenko, Phys. Lett. B672 (2009) 35-44.]: tail from excl. ep → eπnγ
- DJANGOH (DJANGO6)
  - radiative effects from HERACLES.
  - hadronic final state using LEPTO (JETSET).
  - [K. Charchula, G.A. Schuler, H. Spiesberger, Comput.Phys.Commun. 81 (1994) 381-402]
  - Updated (mentioned in [E.C. Aschenauer *et al.*, Phys.Rev.D88 (2013) 114025])

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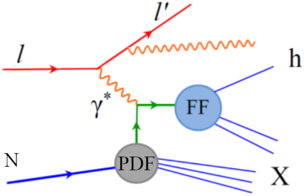

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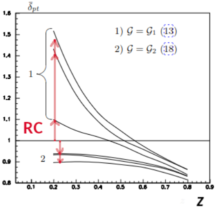


Fig. 3. *Radiative correction to $<p_t^2>$ defined in eq. (23) for HERMES kinematics, $\sqrt{S}$ =7.19 GeV, y=0.4. Curves from top to bottom corresponds to x=0.15, 0.05 and 0.45.*

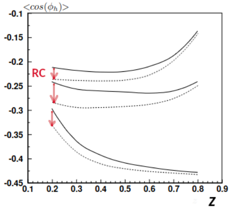
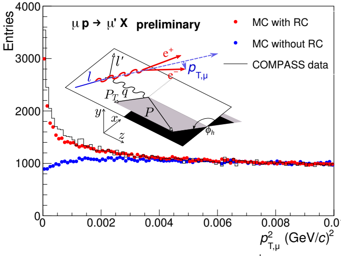


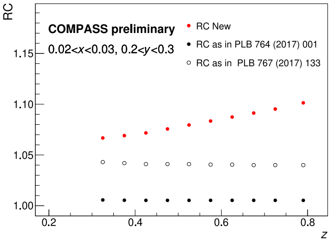
Fig. 4. *Azimuthal asymmetry $<\cos\phi_h>$ vs z for y =0.2 within HERMES kinematics; $\sqrt{S}$=7.19 GeV. Dashed (solid) lines correspond to born(observed) asymmetries. Curves from top to bottom correspond to x=0.7, 0.45 and 0.05.*

[I. Akushevich, N. Shumeiko, A. Soroko, Eur.Phys.J.C10 (1999) 681–687]

- Sizeable corrections in both approaches.
- MC–data checks are very important.
- Model-dependence → iterative approach (e.g. the P_T-slope, possibly ϕ_h-modulations).
- Useful to publish the corrections used.



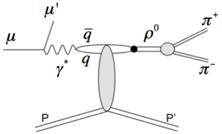
DJANGOH reproduces $e^\pm$ from radiative γ in COMPASS data.

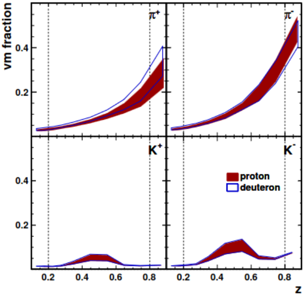


DJANGOH RC for h multiplicity

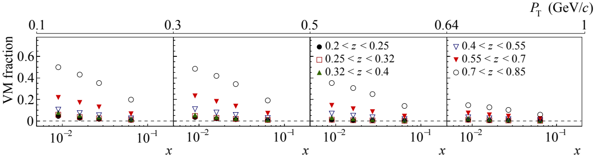
[M. Stolarski (COMPASS), MENU2023]

- Exclusive vector mesons (EVM) inherit polarization from γ^*
  $\rightarrow$ large amplitudes of azimuthal modulations for decay products.
- Significant contributors: $\rho \rightarrow \pi^+\pi^-$ and $\phi \rightarrow K^+K^-$





[HERMES, Phys.Rev.D87 (2013) 074029]



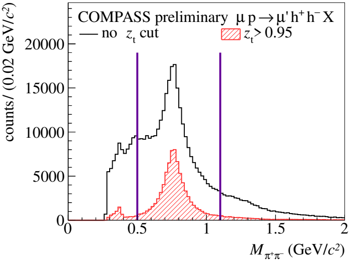
[COMPASS, Nucl.Phys.B 956 (2020) 115039]

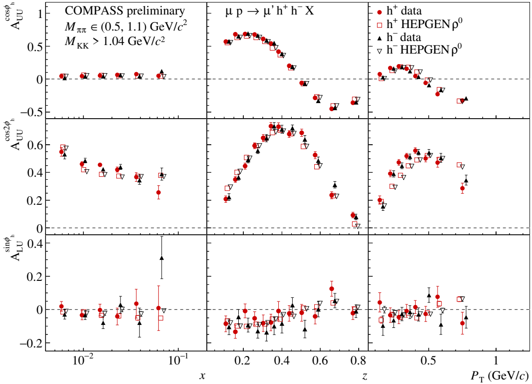
- Strong x-, z- and P_{T}-dependence.
- Up to 50% of observed hadrons at low x, low P_{T} and high z are from EVMs!
- Important for multiplicities, cross sections.

Azimuthal dependence studied:

[COMPASS, Nucl.Phys.B 956 (2020) 115039] [V. Benešová (COMPASS), DIS2024]

- Events with only $\mu' h^+ h^-$ reconstructed in the spectrometer.
- $z_t = z_1 + z_2 > 0.95$ and ρ^0 mass selected.





→ large modulations seen for the h^+ and h^-, here reasonably reproduced by HEPGEN MC [A. Sandacz, P. Sznajder, arXiv:1207.0333].

Hadron production in DIS: P_{T}-dependent distributions

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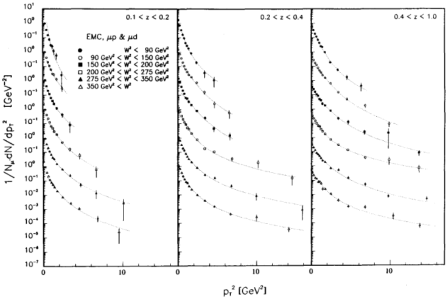
First measurements:

[SLAC, Phys.Rev.Lett. 31 (1973) 786].

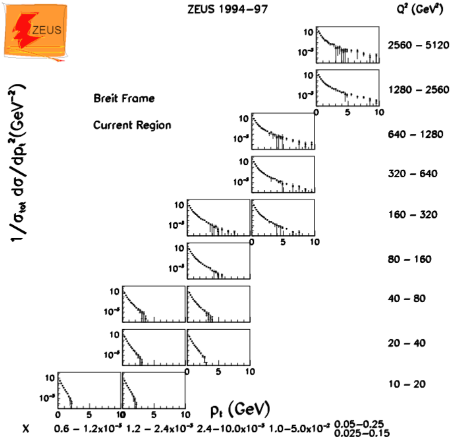
[Cornell, Phys.Rev.Lett.37 (1976) 651].

EMC



Hadron multiplicity differential in P_{T}^2 in bins of z : W^2 [EMC, Z.Phys.C52 (1991) 361-388]

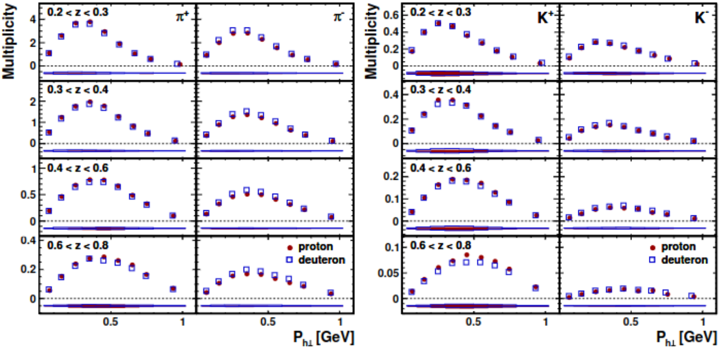
- μ p/d → μ′ h X, $\sqrt{s} = 14$–24 GeV.
- Inclusive RC.
- no EVM corr.



Hadron multiplicity differential in P_{T}^2 in bins of x : Q^2 [ZEUS, Eur.Phys.J.C11 (1999) 251]

- e p → e' h X, $\sqrt{s} = 14$–300 GeV.
- RC from DJANGOH
- no EVM corr. (likely small large Q^2).

HERMES



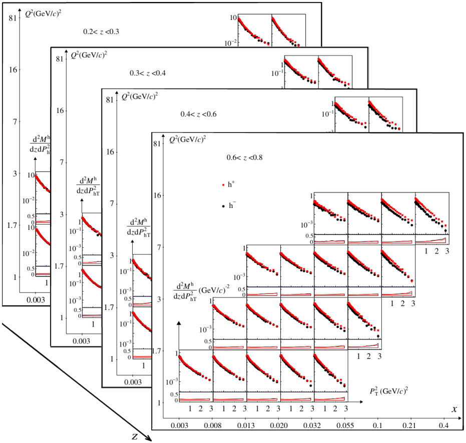
$\pi^{\pm}$ and $\mathrm{K}^{\pm}$ multiplicity in $z : P_{\mathrm{T}}$

[HERMES, Phys.Rev.D87 (2013) 074029]

- e p/d $\to$ e' π/K$^{\pm}$ X, $\sqrt{s} = 18$ GeV.
- 3D binning in $Q^2 : z : P_{\mathrm{T}}^2$ and $x : z : P_{\mathrm{T}}^2$.
- Inclusive RC from RADGEN.
- EVM correction: PYTHIA (tuned to EVM prod. at HERMES).

Hadron production in DIS: P_T-dependent distributions

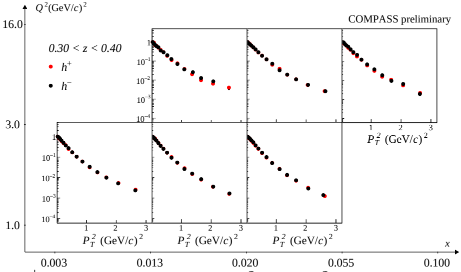
Charles University



$h^{\pm}$ multiplicity in $x : Q^2 : z : P^2_\mathrm{T}$
[COMPASS, Phys.Rev.D97 (2018) 032006]

- μ ^{6}LiD $\to$ μ' $h^{\pm}$ X, $\sqrt{s} = 18$ GeV.
- Inclusive RC from RADGEN.
- EVM correction: HEPGEN (no SDMEs).

COMPASS

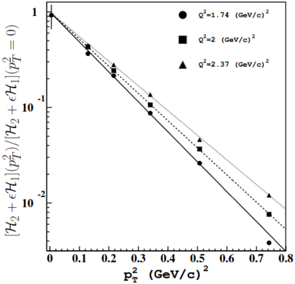


$h^{\pm}$ distributions in $x : Q^2 : z : P^2_\mathrm{T}$ (2nd z bin)
[A. Moretti (COMPASS), Proc. of ICNFP 2020]

- μ p $\to$ μ' $h^{\pm}$ X, $\sqrt{s} = 18$ GeV.
- Normalised to the lowest-P_T point.
- Kinematic domain to be expanded.
- No RC, coming soon (DJANGOH)
- Visible EVM decays excluded.
- Remaining EVMs subtracted (HEPGEN with SDMEs).
- More in Andrea Bressan's talk.

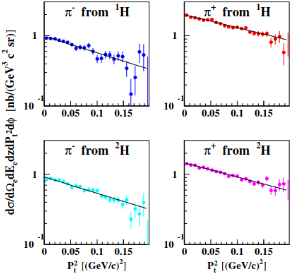
Hadron production in DIS: P_{T}-dependent distributions

JLab6 ($\sqrt{s} = 3.5$ GeV): CLAS Hall C JLab E06-010



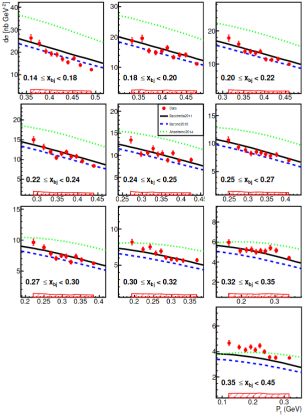
[CLAS, Phys.Rev.D 80 (2009) 032004]

- e p → e' π^+ X.
- Binning in $Q^2 : x : z : P_{\mathrm{T}}$.
- RC from HAPRAD.
- No EVM correction.



[Hall C, Phys.Rev.C85 (2012) 015202]

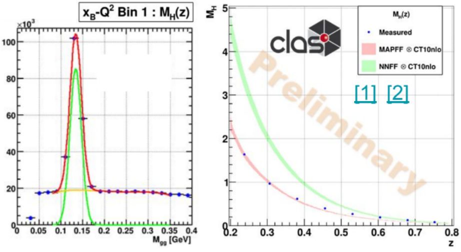
- e p/d → e' $\pi^\pm$ X.
- Binning in P_{T}^2.
- Semi-incl. RC (SIMC, HAPRAD).
- EVM correction: SIMC+PYTHIA (tuned).



[Phys.Rev.C 95 (2017) 035209]

- e ^{3}He → e' $\pi^\pm$ X.
- Binning in $x : P_{\mathrm{T}}^2$.
- RC from HAPRAD.
- No EVM correction.

CLAS12 – ongoing work



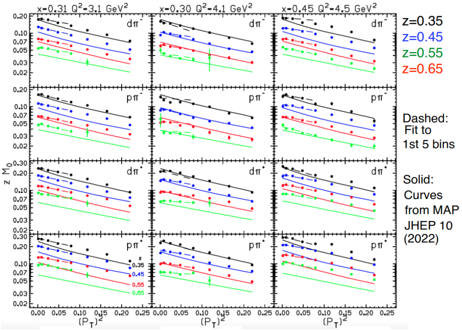
[M. Diehl (CLAS), Transversity 2024]

- e p $\to$ e' π^0 X.
- No EVM contributiomn to π^0.

More to come...

- e p/d $\to$ e' $\pi^\pm$ X.
- High-statistics, fully differential.
- RC from HAPRAD.
- EVM contribution being studied.
- Separation of $F_{UU,T}$, $F_{UU,L}$.

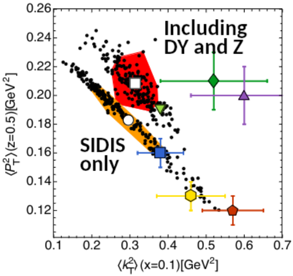
Hall C 11 GeV – ongoing work



[E.R. Kinney, DIS2024]

- e p/d $\to$ e' $\pi^\pm$/$K^\pm$ X.
- Multi-D binning.
- RC?
- Missing mass cut to avoid exclusive proc.
- Soon also π^0 production.

Fitting the unpolarised TMD PDFs



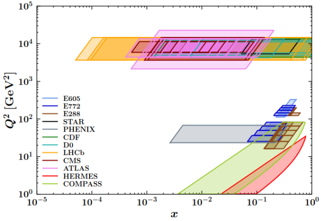
$\langle k_T^2 \rangle$ and $\langle P_\perp^2 \rangle$ from global fits

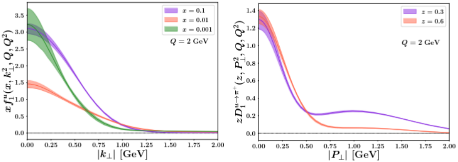
$\rightarrow$ strong anti-correlation with SIDIS-only.

[A. Bacchetta *et al.*, JHEP 06 (2017) 081]

- Precision era: N^3LL, global analysis
  - fixed-target Drell–Yan,
  - collider Drell–Yan and Z production,
  - e^+e^- (?)
- Similar approach (SIDIS and DY):

  [I. Scimemi, A. Vladimirov, JHEP 06 (2020) 137]
- More on Thursday morning...

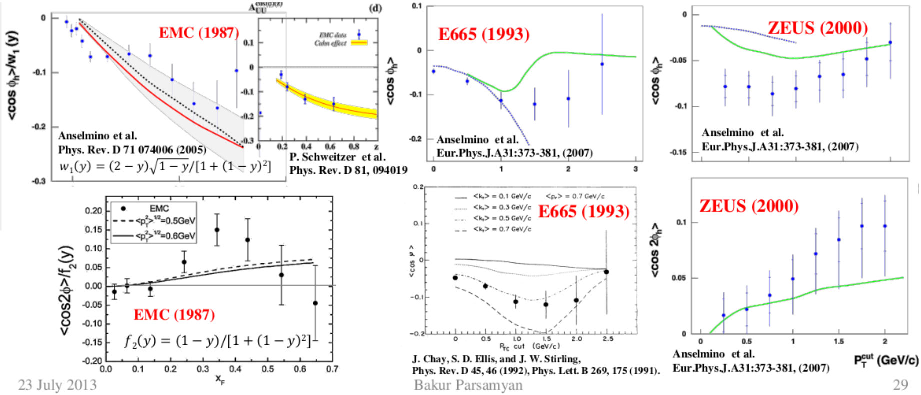




[MAP, JHEP 10 (2022) 127]

Flavour separation

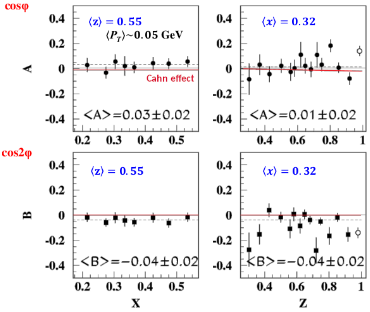
- Relies mostly on HERMES data.
- [A. Signori et.al, JHEP 11 (2013) 194]
  - $\langle P^2_{T,\mathrm{unfav.}} \rangle = 1.2 \langle P^2_{T,\mathrm{fav.}} \rangle \approx \langle P^2_{T,u\to K} \rangle$
- Soon: $\pi^{\pm,0}$, $K^\pm$ from JLab, COMPASS



First measurements (compilation [B. Parsamyan, IWHSS2013])

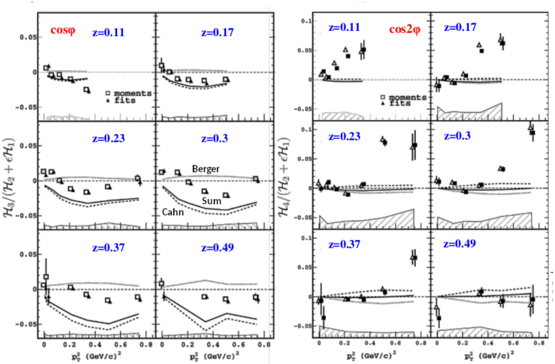
- [EMC, Phys.Lett.B130 (1983) 118–122]
- [EMC, Z.Phys.C34 277 (1987)]
- [E665, Phys.Rev.D48, 5057 (1993)]
- [ZEUS, Phys.Lett.B481 (2000) 199]
  - e p → e' h X, $\sqrt{s} = 300$ GeV,
  - RC from DJANGOH.
  - no EVM corr. (likely small large Q^2).

Hadron production in DIS: Asymmetries $A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}$, $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$



[Hall C, Phys.Lett.B665 (2008) 20]

- e p/d → e' $\pi^{\pm}$ X.
- Binning in P_{T}^2.
- Semi-incl. RC.
- EVM correction.
- Similar: [Hall C, Phys.Rev.C85 (2012) 015202]

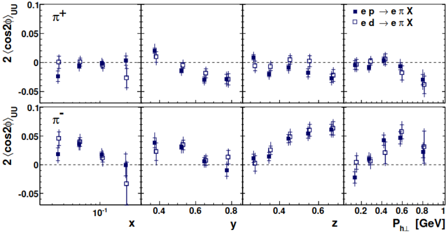


Data: [CLAS, Phys.Rev.D 80 (2009) 032004]
Predictions: [R.N. Cahn, Phys.Rev.D40 (1989) 3107.], [M. Anselmino *et al.*, Phys.Rev.D71 (2005) 074006], [A. Brandenburg *et al.*, Phys.Lett.B347 (1995) 413].

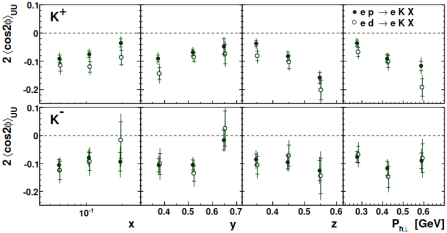
- e p → e' π^{+} X.
- Binning in $Q^2 : x : z : P_{\mathrm{T}}$.
- RC from HAPRAD.
- No EVM correction.

Hadron production in DIS: Asymmetries $A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}$, $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$

Charles University



$\varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$ for $\pi^{\pm}$.



$\varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$ for $\mathrm{K}^{\pm}$.

[HERMES, Phys.Rev.D87 (2013) 012010]

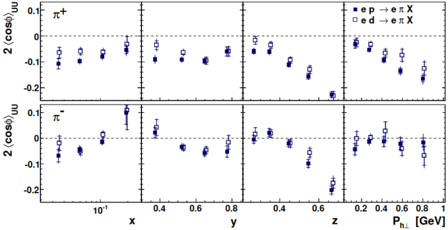
- e p/d → e' $\pi^{\pm}$/$\mathrm{K}^{\pm}$/$\mathrm{h}^{\pm}$ X. ($\sqrt{s} = 7.5$ GeV)
- Binning in $x : y : z : P_{\mathrm{T}}$.
- Inclusive (?) RC from RADGEN.
- No EVM correction.

- Similar on p and d → $h_1^{\perp,\mathrm{u}} \approx h_1^{\perp,\mathrm{d}}$.
- Known: $H_{1,\mathrm{fav.}}^{\perp} \approx -H_{1,\mathrm{unfav.}}{}^{\perp}$
- π behaviour ≈ expected [V. Barone, A. Prokudin, B.Q. Ma, Phys.Rev.D78 (2008) 045022]
- K very different from π.
- Interesting flavour dependence...

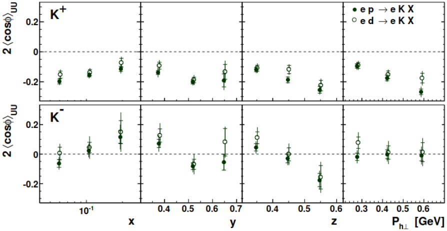
$$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - (\boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{P}_{\perp})}{zMM_h} h_1^{\perp} H_1^{\perp}\right] + \frac{M^2}{Q^2}\mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot k_{\mathrm{T}})^2 - k_{\mathrm{T}}^2}{M^2} f_1 D_1 + \ldots\right]$$

Hadron production in DIS: Asymmetries $A_{UU}^{\cos\phi_h}$, $A_{UU}^{\cos 2\phi_h}$

Charles University



$\varepsilon_1 A_{UU}^{\cos\phi_h}$ for $\pi^\pm$.



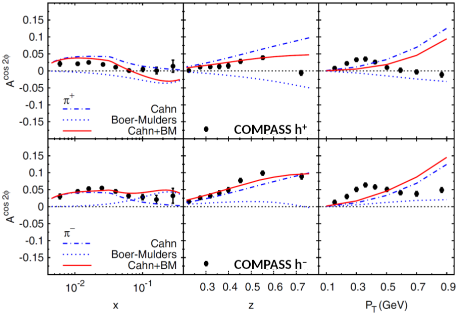
$\varepsilon_1 A_{UU}^{\cos\phi_h}$ for $K^\pm$.

[HERMES, Phys.Rev.D87 (2013) 012010]

- e p/d → e' $\pi^\pm/K^\pm/h^\pm$ X. ($\sqrt{s} = 7.5$ GeV)
- Binning in $x : y : z : P_T$.
- Inclusive (?) RC from RADGEN.
- No EVM correction.

- Small difference between p and d targets.
- Difference between π^+, π^- → Boer–Mulders effect, different $\langle k_T^2 \rangle$?
- K similar to π (while being different for $\cos 2\phi_h$).

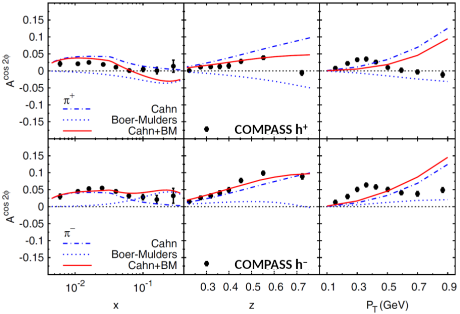
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q}\mathcal{C}\left[\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)}{M} f_1 D_1 + \frac{k_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)}{zM^2M_h} h_1^\perp H_1^\perp + \ldots\right]$$



COMPASS $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$ for $\mathrm{h}^{\pm}$ on ^{6}LiD (d) target [COMPASS, Nucl.Phys.B886 (2014) 1046–1077], fitted [V. Barone *et al.*, Phys.Rev.D91 (2015) 074019].

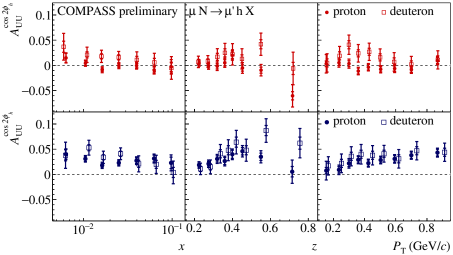
- $\mu\ ^6\mathrm{LiD} \to \mu'\ \mathrm{h}^{\pm}\ \mathrm{X}$. ($\sqrt{s} = 18$ GeV)
- Binning in $x : z : P_{\mathrm{T}}$.
- No RC.
- No EVM correction.

$$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - (\boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{P}_{\perp})}{zMM_h} h_1^{\perp} H_1^{\perp}\right] + \frac{M^2}{Q^2}\mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot k_{\mathrm{T}})^2 - k_{\mathrm{T}}^2}{M^2} f_1 D_1 + \ldots\right]$$



COMPASS $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$ for $\mathrm{h}^{\pm}$ on ^{6}LiD (d) target [COMPASS, Nucl.Phys.B886 (2014) 1046–1077], fitted [V. Barone *et al.*, Phys.Rev.D91 (2015) 074019].

- $\mu\ ^{6}\mathrm{LiD} \to \mu'\ \mathrm{h}^{\pm}\ \mathrm{X}$. ($\sqrt{s} = 18$ GeV)
- Binning in $x : z : P_{\mathrm{T}}$.
- No RC.
- No EVM correction.

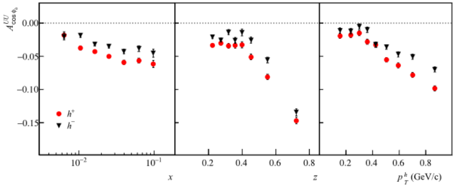


COMPASS $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$ for $\mathrm{h}^{\pm}$ on d and p targets with EVM contribution subtracted (no RC).

Updates:

- EVM contribution subtracted $(x : z : P_{\mathrm{T}})$ [COMPASS, Nucl.Phys.B956 (2020) 115039]
- Data on p target being analysed
  - Visible EVM decays excluded.
  - Remaining EVMs subtracted (HEPGEN with SDMEs).
  - RC from DJANGOH.
  - More in Andrea Bressan's talk.

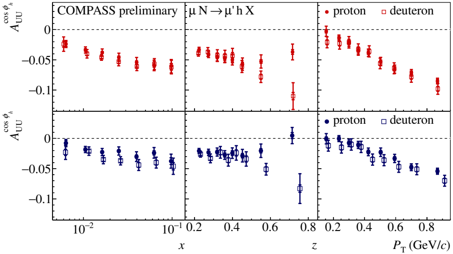
$$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - (\boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{P}_{\perp})}{zMM_h} h_1^{\perp} H_1^{\perp}\right] + \frac{M^2}{Q^2}\mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot k_{\mathrm{T}})^2 - k_{\mathrm{T}}^2}{M^2} f_1 D_1 + \ldots\right]$$



COMPASS $A_{UU}^{\cos\phi_h}$ for $h^\pm$ on ^{6}LiD (d) target
[COMPASS, Nucl.Phys.B886 (2014) 1046–1077]
(no EVM correction, no RC).

- μ ^{6}LiD → μ′ $h^\pm$ X. ($\sqrt{s} = 18$ GeV)
- Binning in $x : z : P_T$.
- No RC.
- No EVM correction.

$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q}\mathcal{C}\left[\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})}{M} f_1 D_1 + \frac{k_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)}{zM^2M_h} h_1^\perp H_1^\perp + \ldots\right]$$

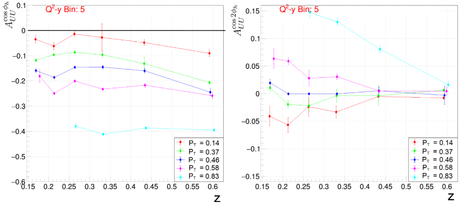


COMPASS $A_{UU}^{\cos\phi_h}$ for $h^\pm$ on d and p targets with EVM contribution subtracted (no RC).

Updates:

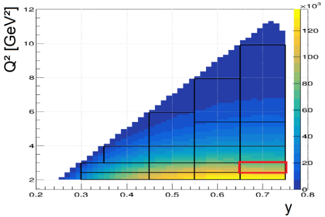
- EVM contribution subtracted $(x : z : P_T)$
  [COMPASS, Nucl.Phys.B956 (2020) 115039]
- Data on p target being analysed
  - Visible EVM decays excluded.
  - Remaining EVMs subtracted (HEPGEN with SDMEs).
  - RC from DJANGOH.
  - More in Andrea Bressan's talk.

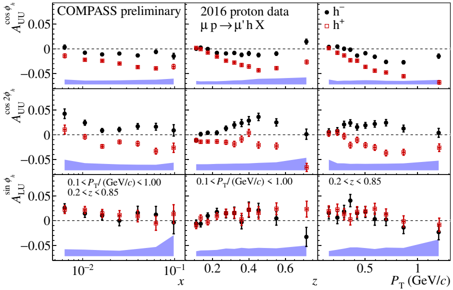
More interesting results on the horizon...



Stefan Diehl's talk.

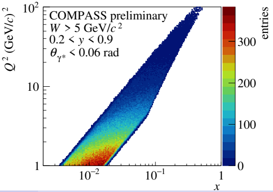
- Ongoing CLAS12 analysis.
- e p/d $\rightarrow$ e' π^+ X.
- 4D binning $Q^2 : y : z : P_\mathrm{T}$.





See Andrea Bressan's talk...

- μ p $\rightarrow$ μ' $h^{\pm}$ X. ($\sqrt{s} = 18$ GeV)
- New RC from DJANGOH applied.



$A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$ is a pure twist-3 object (qgq-correlations):

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right)$$

→TMDs and FFs

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

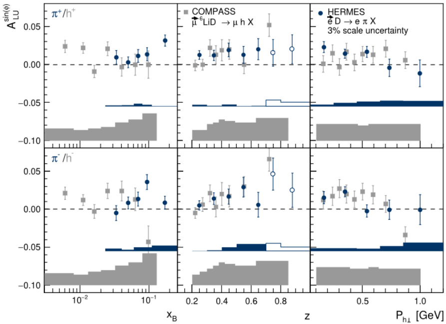
twist-3 t-odd dist. funcion

Boer-Mulders

twist-3 FF

(borrowed from Stefan Diehl's slides)

- HERMES ($Q \approx 1.6$ GeV)
  - [HERMES, Phys.Lett.B 797 (2019) 134886]
  - e p/d → e' $\pi^{\pm}$/$K^{\pm}$/$p^{\pm}$ X.
- COMPASS ($Q \approx 1.7$ GeV)
  - [COMPASS, Nucl.Phys.B886 (2014) 1046–1077]
  - μ ^{6}LiD → μ′ $h^{\pm}$ X.
- CLAS ($Q \approx 1.4$ GeV)
  - [CLAS, Phys. Rev. D89 (2014) 072011]
  - e p → e' $\pi^{\pm,0}$ X.
- RC are negligible for $\sin\phi_{\mathrm{h}}$.
- EVM correction not applied.
- Limited statistics (1D/2D binning).



[HERMES, Phys.Lett.B 797 (2019) 134886]

Hadron production in DIS: Beam-spin asymmetry $A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$

Charles University

$A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$ is a pure twist-3 object (qgq-correlations):

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right)$$

→TMDs and FFs

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

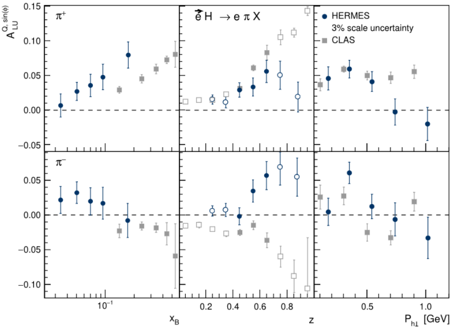
twist-3 t-odd dist. funcion

Boer-Mulders

twist-3 FF

(borrowed from Stefan Diehl's slides)

- HERMES ($Q \approx 1.6$ GeV)
  - [HERMES, Phys.Lett.B 797 (2019) 134886]
  - e p/d → e' $\pi^{\pm}$/$K^{\pm}$/$p^{\pm}$ X.
- COMPASS ($Q \approx 1.7$ GeV)
  - [COMPASS, Nucl.Phys.B886 (2014) 1046–1077]
  - μ ^{6}LiD → μ′ $h^{\pm}$ X.
- CLAS ($Q \approx 1.4$ GeV)
  - [CLAS, Phys. Rev. D89 (2014) 072011]
  - e p → e' $\pi^{\pm,0}$ X.
- RC are negligible for $\sin\phi_{\mathrm{h}}$.
- EVM correction not applied.
- Limited statistics (1D/2D binning).



[HERMES, Phys.Lett.B 797 (2019) 134886]

Hadron production in DIS: Beam-spin asymmetry $A_{LU}^{\sin\phi_h}$

Charles University

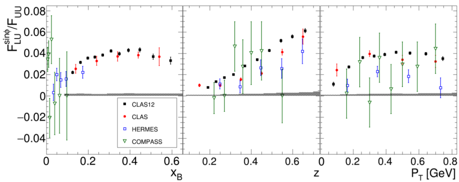
$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

➔TMDs and FFs

twist-3 pdf, Collins FF, unpolarized dist. function, twist-3 FF, twist-3 t-odd dist. funcion, Boer-Mulders, twist-3 FF

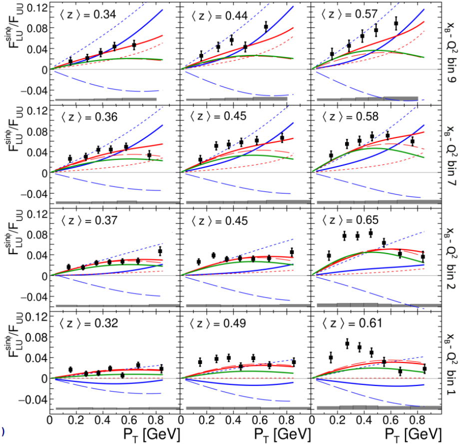
(borrowed from Stefan Diehl's slides)

NEW from CLAS12:



π^+ (CLAS, HERMES) and h^+ (COMPASS).

- e p → e' π^+ X
  [CLAS, Phys.Rev.Lett. 128 (2022) 062005]
- e p → e' $\pi^{\pm,0}/K^+$ X
  (preliminary, Stefan Diehl's talk)
- 4D binning ($Q^2 : x : z : P_T$).
- EVM contribution being studied.



Hadron production in DIS: Beam-spin asymmetry $A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$

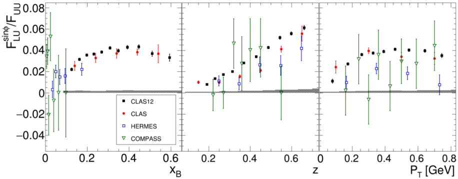
$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp} \frac{\tilde{E}}{z}\right)\right)$$

→TMDs and FFs

twist-3 pdf | Collins FF | unpolarized dist. function | twist-3 FF | twist-3 t-odd dist. funcion | Boer-Mulders | twist-3 FF

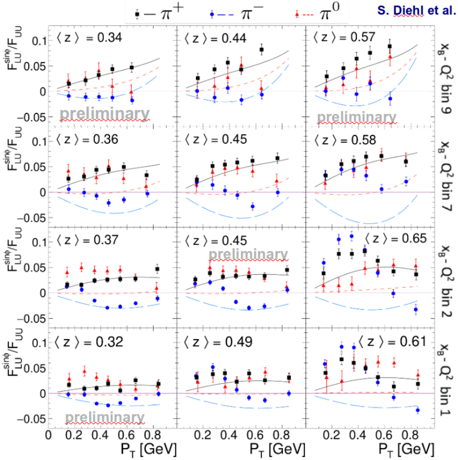
(borrowed from Stefan Diehl's slides)

NEW from CLAS12:

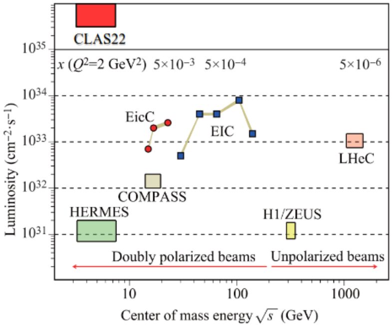


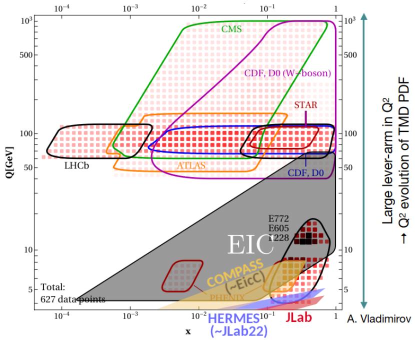
π^+ (CLAS, HERMES) and h^+ (COMPASS).

- e p → e' π^+ X
  [CLAS, Phys.Rev.Lett. 128 (2022) 062005]
- e p → e' $\pi^{\pm,0}/K^+$ X
  (preliminary, Stefan Diehl's talk)
- 4D binning ($Q^2 : x : z : P_{\mathrm{T}}$).
- EVM contribution being studied.



Hadron production in DIS: Future





- SoLID @ JLab12 (Haylin Gao's talk)
  - Large luminosity → multi-D.
  - High x region.
- JLab22
  - HERMES-like kinematic region.
  - Really large luminosity.
- EicC (Yuxiang Zhao's talk)
  - COMPASS-like kinematic region.

- EIC (Elke Aschenauer's talk)
  - [Snowmass 2021, 2203.13199 [hep-ph]]
  - Large lever arm in Q^2
    → evolution,
    → wider region of $P_{\mathrm{T}} \ll Q$
    → closer to high-energy DY, Z data.
  - Gluon TMDs.
    - E.g. l N → l' jet jet X,
      jets back-to-back
    - Quarkonium + γ, quarkonium + jet
      [A. Mukherjee, IWHSS2023]
    - Daniel Boer's talk.

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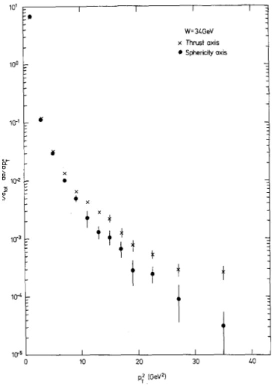

TASSO, 1984

- [TASSO, Z.Phys.C22 (1984) 307–340]
- [TASSO, Z.Phys. C47 (1990) 187–198]
- [PLUTO, Z.Phys. C22 (1984) 103]
- [MARK-II, Phys.Rev.D37 (1988) 1]

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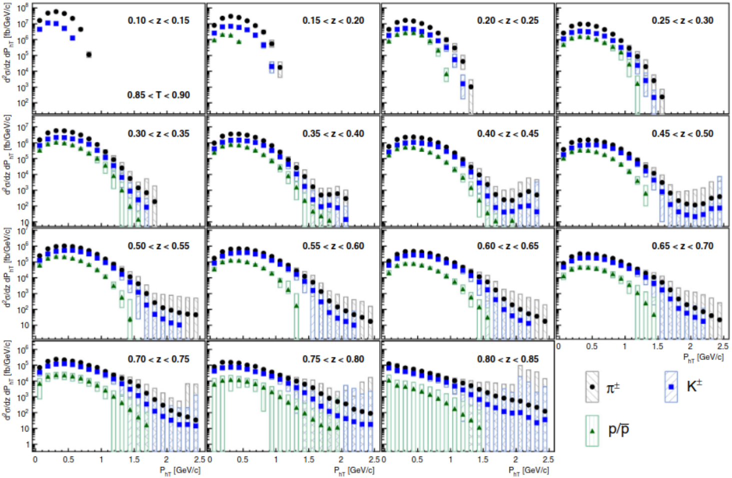
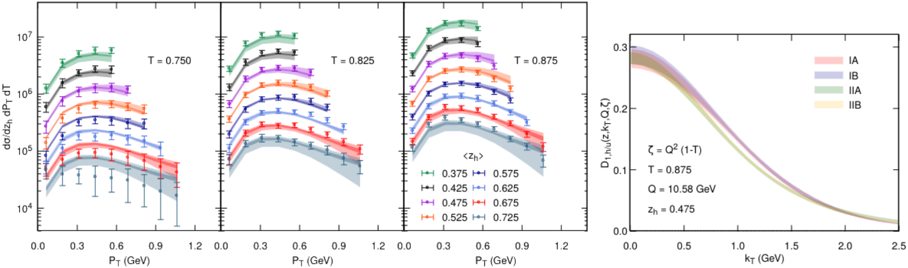


[Belle, Phys.Rev.D99 (2019) 11, 112006]

- $P_\perp$ defined with respect to the thrust axis.
- Factorisation formalism developed, possibility to enter global fits?

  [Z.B. Kang, D.Y. Shao, F. Zhao, JHEP12 (2020) 127] [M. Boglione, A. Simonelli, JHEP 02 (2021) 076]

Hadron production in e^+e^-: Single hadrons



[M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, Phys.Rev.D106 (2022) 074024]

Hadron production in e^+e^-: Collins asymmetry

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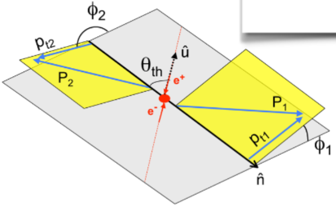
See D. Boer, NPB 806, 23 (2009)

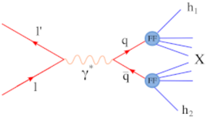
$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar{q}}\frac{3\alpha^2}{Q^2}\frac{e_q^2}{4}z_1^2z_2^2\Big[(1+cos^2\theta)D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2)+ + sin^2(\theta)cos(\phi_1+\phi_2)H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$

All quantities in e+e- center of mass

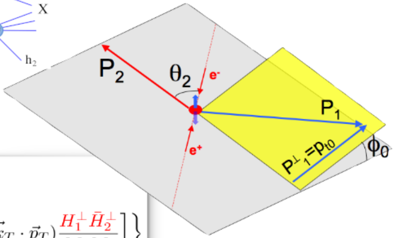
RF12



θ: angle between the e⁺e⁻ axis and the thrust axis;
$\varphi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane



RF0



θ_2: angle between the e⁺e⁻ axis and P_{h2};
φ_0: angle between the plane spanned by P_{h2} and the e⁺e⁻ axis, and the direction of P_{h1} perpendicular to P_{h2}.

All quantities in e+e- center of mass

$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2}z_1^2z_2^2\Big\{A(y)\mathcal{F}[D_1\bar{D}_2]+ + B(y)cos(2\phi_0)\mathcal{F}\Big[(2\hat{h}\cdot\vec{k}_T\hat{h}\cdot\vec{p}_T-\vec{k}_T\cdot\vec{p}_T)\frac{H_1^\perp\bar{H}_2^\perp}{M_1M_2}\Big]\Big\}$$

[I. Garzia, IWHSS2023.]

Hadron production in e^+e^-: Collins asymmetry

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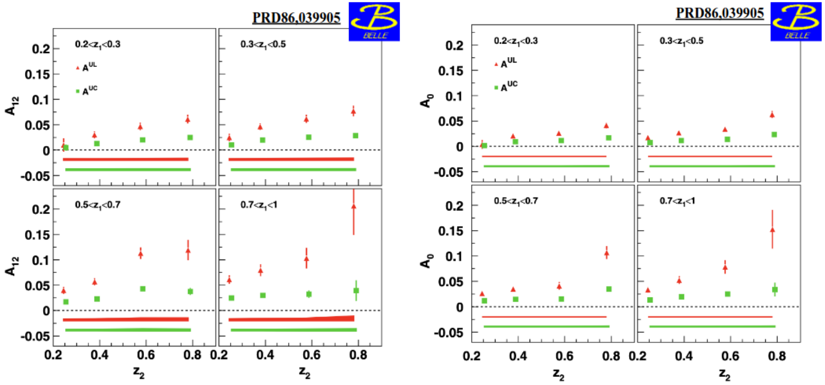

- $\mathcal{L} \sim 547\ \text{fb}^{-1}$ at ~10.58 GeV

- 1st measurement: [Belle, Phys.Rev.Lett.96 (2006) 232002] [Belle, Phys.Rev.D 78 (2008) 032011]
- Belle $\pi^{\pm}\pi^{\pm,0}$, $\pi^{\pm}\eta$ [Phys.Rev.D 100 (2019) 9, 092008]
- BaBar $\pi\pi$ [Phys.Rev.D 90 (2014) 5, 052003]
- BaBar KK, Kπ [Phys.Rev.D 92 (2015) 11, 111101]
  $\rightarrow D_1^{u\rightarrow K}$ [M. Anselmino *et al.*, Phys.Rev.D93 (2016) 3, 034025]
- BESIII $\pi\pi$ [Phys.Rev.Lett. 116 (2016) 4, 042001]

Drell–Yan process and Z production: Cross section

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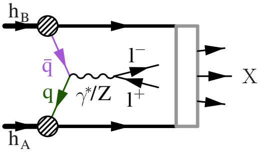
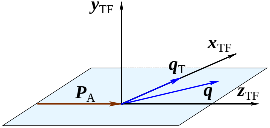
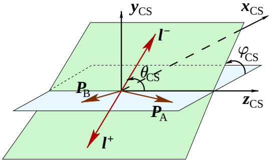




Target frame.



Collins–Soper frame

Cross-section with unpolarised target:

$$\frac{d\sigma}{dQ^2 dq_T^2 d\eta} = \frac{4\pi^2 \alpha_{em}^2}{3Q^2 s}\left(F_{UU}^1 + F_{UU}^{\cos 2\varphi_{CS}}\right).$$

$$\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 \begin{array}{l} + \lambda \cos^2\theta_{CS} \\ + \mu \sin 2\theta \cos\varphi_{CS} \\ + \frac{\nu}{2}\sin^2\theta \cos 2\varphi_{CS} \end{array}\right).$$

- $\lambda = \frac{F_{UU}^1 - 2F_{UU}^{\cos 2\phi_{CS}}}{F_{UU}^1 + 2F_{UU}^{\cos 2\varphi_{CS}}}$,
- $\mu = \frac{F_{UU}^{\cos\varphi_{CS}}}{F_{UU}^1 + 2F_{UU}^{\cos 2\varphi_{CS}}}$,
- $\nu = \frac{2F_{UU}^{\cos 2\varphi_{CS}}}{F_{UU}^1 + 2F_{UU}^{\cos 2\varphi_{CS}}}$.
- At leading twist:
  $F_{UU}^{\cos\varphi_{CS}} = 0$,
  $F_{UU}^1 \propto f_{1,A} \otimes f_{1,B}$,
  $F_{UU}^{\cos\varphi_{CS}} \propto h_{1,A}^{\perp} \otimes h_{1,B}^{\perp}$.
- h h $\to$ Z X: cross section also $\propto F_{UU}^1 + F_{UU}^{\cos 2\varphi_{CS}}$

Drell–Yan process and Z production: q-distributions

Numerous pp experiments, e.g.:

A.S. Ito et al., *Measurement of the continuum of dimuons produced in high-energy proton-nucleus collisions*, Phys. Rev. **D 23** (1981) 604 [INSPIRE].

G. Moreno et al., *Dimuon production in proton-copper collisions at $\sqrt{s} = 38.8$ GeV*, Phys. Rev. **D 43** (1991) 2815 [INSPIRE].

E772 collaboration, *Cross-sections for the production of high mass muon pairs from 800 GeV proton bombardment of H-2*, Phys. Rev. **D 50** (1994) 3038 [Erratum ibid. **D 60** (1999) 119903] [INSPIRE].

PHENIX collaboration, *Measurements of $\mu\mu$ pairs from open heavy flavor and Drell-Yan in $p+p$ collisions at $\sqrt{s} = 200$ GeV*, Phys. Rev. **D 99** (2019) 072003 [arXiv:1805.02448] [INSPIRE].

CDF collaboration, *The transverse momentum and total cross section of e^+e^- pairs in the Z boson region from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. Lett. **84** (2000) 845 [hep-ex/0001021] [INSPIRE].

CDF collaboration, *Transverse momentum cross section of e^+e^- pairs in the Z-boson region from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. **D 86** (2012) 052010 [arXiv:1207.7138] [INSPIRE].

D0 collaboration, *Measurement of the inclusive differential cross section for Z bosons as a function of transverse momentum in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. **D 61** (2000) 032004 [hep-ex/9907009] [INSPIRE].

D0 collaboration, *Measurement of the shape of the boson transverse momentum distribution in $p\bar{p} \to Z/\gamma^* \to e^+e^- + X$ events produced at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. Lett. **100** (2008) 102002 [arXiv:0712.0803] [INSPIRE].

D0 collaboration, *Measurement of the normalized $Z/\gamma^* \to \mu^+\mu^-$ transverse momentum distribution in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Lett. **B 693** (2010) 522 [arXiv:1006.0618] [INSPIRE].

LHCb collaboration, *Measurement of the forward Z boson production cross-section in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **08** (2015) 039 [arXiv:1505.07024] [INSPIRE].

LHCb collaboration, *Measurement of forward W and Z boson production in pp collisions at $\sqrt{s} = 8$ TeV*, JHEP **01** (2016) 155 [arXiv:1511.08039] [INSPIRE].

LHCb collaboration, *Measurement of the forward Z boson production cross-section in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **09** (2016) 136 [arXiv:1607.06495] [INSPIRE].

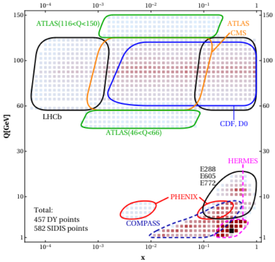
ATLAS collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP **09** (2014) 145 [arXiv:1406.3660] [INSPIRE].

ATLAS collaboration, *Measurement of the transverse momentum and ϕ^*_η distributions of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. **C 76** (2016) 291 [arXiv:1512.02192] [INSPIRE].

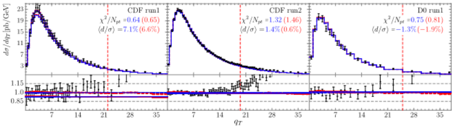
CMS collaboration, *Measurement of the rapidity and transverse momentum distributions of Z bosons in pp collisions at $\sqrt{s} = 7$ TeV*, Phys. Rev. **D 85** (2012) 032002 [arXiv:1110.4973] [INSPIRE].

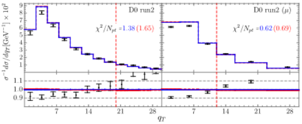
CMS collaboration, *Measurement of the transverse momentum spectra of weak vector bosons produced in proton-proton collisions at $\sqrt{s} = 8$ TeV*, JHEP **02** (2017) 096 [arXiv:1606.05864] [INSPIRE].

Used in global TMD fits, e.g.



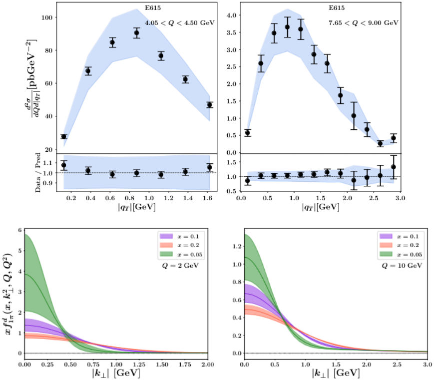
[I. Scimemi, A. Vladimirov, JHEP 06 (2020) 137]



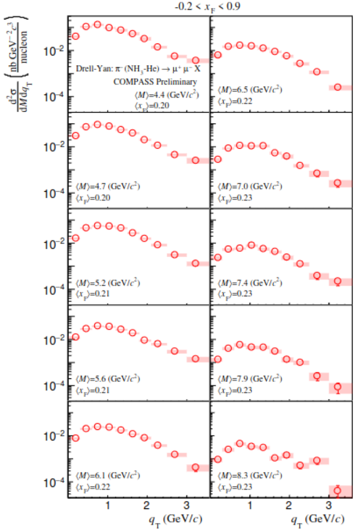


Example: fit of CDF and D0 data.

π–p Drell–Yan → TMD distribution of the pion



[MAP, Phys.Rev.D 107 (2023) 1, 014014]

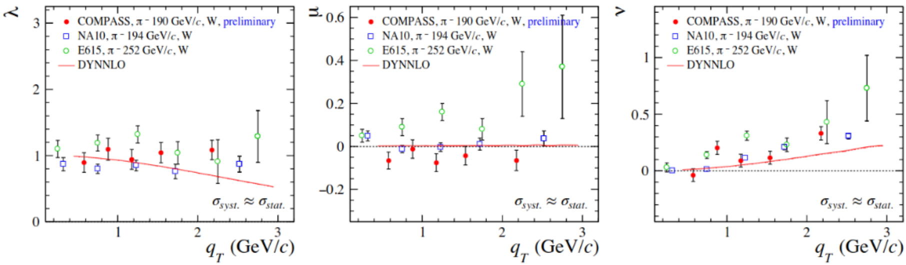


[V. Andrieux (COMPASS), DIS2024]

- E615, NA10.
- NEW: COMPASS π^-N
- Future: AMBER $\pi^\pm$C → access to the sea.
  (both in Catarina's talk)

Drell–Yan process and Z production: Azimuthal dependence

Charles University



Azimuthal modulations from π–N DY ((NA10, E615 and preliminary COMPASS).
→ Catarina's talk.

- Perturbative and possible non-perturbative origin of the modulations.
- There seems to be room for Boer–Mulders...

$$\nu \propto h_{1,\mathrm{A}}^{\perp} \otimes h_{1,\mathrm{B}}^{\perp}.$$

- pp, pd Drell–Yan:
  - E866 NuSea, Phys. Rev. Lett. 99 (2007) 082301
  - E866 NuSea, Phys. Rev. Lett. 102 (2009) 182001
  - New: [SeaQuest, SPIN2023].
  - Small asymmetry (role of the sea).

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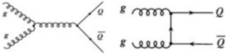
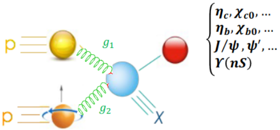
In high-energy hadron collisions, heavy quarks are dominantly produced through gg fusion:

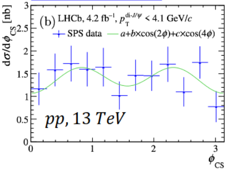


The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**

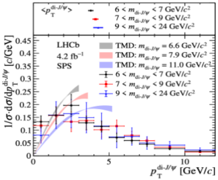
- **Inclusive quarkonia production in (un)polarized pp interaction** ($pp^{(\uparrow)} \to [Q\bar{Q}]X$) turns out to be an ideal observable to access gTMDs (assuming TMD factorization)
- TMD factorization requires $q_T(Q) \ll M_Q$. Can look at **associate quarkonia production**, where only the relative q_T needs to be small, e.g.: $pp^{(\uparrow)} \to J/\psi + J/\psi + X$



JHEP 03 (2024) 088



$$d\sigma_{J/\psi+J/\psi} = a + b \times \cos(2\phi_{CS}) + c \times \cos(4\phi_{CS})$$
$$a = F_1 \mathcal{C}[f_1^g f_1^g] + F_2 \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}],$$
$$b = F_3 \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \mathcal{C}[w_3' h_1^{\perp g} f_1^g],$$
$$c = F_4 \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}],$$
$$\langle \cos 2\phi_{CS} \rangle = -0.029 \pm 0.050 \text{ (stat)} \pm 0.009 \text{ (syst)},$$
$$\langle \cos 4\phi_{CS} \rangle = -0.087 \pm 0.052 \text{ (stat)} \pm 0.013 \text{ (syst)}.$$



...but very challenging at fixed-target kinematics!

[LHCb, JHEP 03 (2024)]

- More collider results,
- AMBER,
- SpinQuest
- LHCSpin (Charlotte's talk)

Conclusion