Parallel Session 4: 3D nucleon and nucleus structure

Anna Martin, Barbara Pasquini

part 2: **TMDs**

study of the transverse spin and transverse momentum structure of the nucleon

see also Parallel Session 3

Parallel Session 4: 3D nucleon and nucleus structure

Anna Martin, Barbara Pasquini

part 2: **TMDs**

- Zhangbo Kang: Phenomenological Extractions of TMDs: progress and new opportunities
- Cristian Pisano: A first determination of unpolarised quark TMDs from a global analysis
- Franco Bradamante: Point-by-point extraction of parton distribution functions from SIDIS single transverse–spin asymmetries
- Umberto D'Alesio: A_N in $lp \rightarrow hX$ within a TMD approach and quasi-real photon contribution
- Markus Diefenthaler: Mapping the hadronization description in to the correlation functions of TMD factorization (*)
- Osvaldo Gonzalez Hernandez: Opportunities for the Extraction of TMD Fragmentation Functions (*)
- Alexey Vladimirov: Limits and uncertainties of TMD factorisation theorem (**)

- Daniel Guitarrez Reyes: Features of spin dependent TMDs (**)

(*) joint PS 2 and 4 (**) joint PS 3 and 4

no overview talk on experiment results

a lot of data shown in the different talks

no overview talk on experiment results

a lot of data shown in the different talks

overview talk

Zhangbo Kang

Phenomenological extractions of TMDs: progress and new opportunities

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overview talk

Zhangbo Kang

Phenomenological extractions of TMDs: progress and new opportunities

Besides unpolarized TMDs: Sivers and Collins

TMD factorization in a nut-shell

TMD global analysis

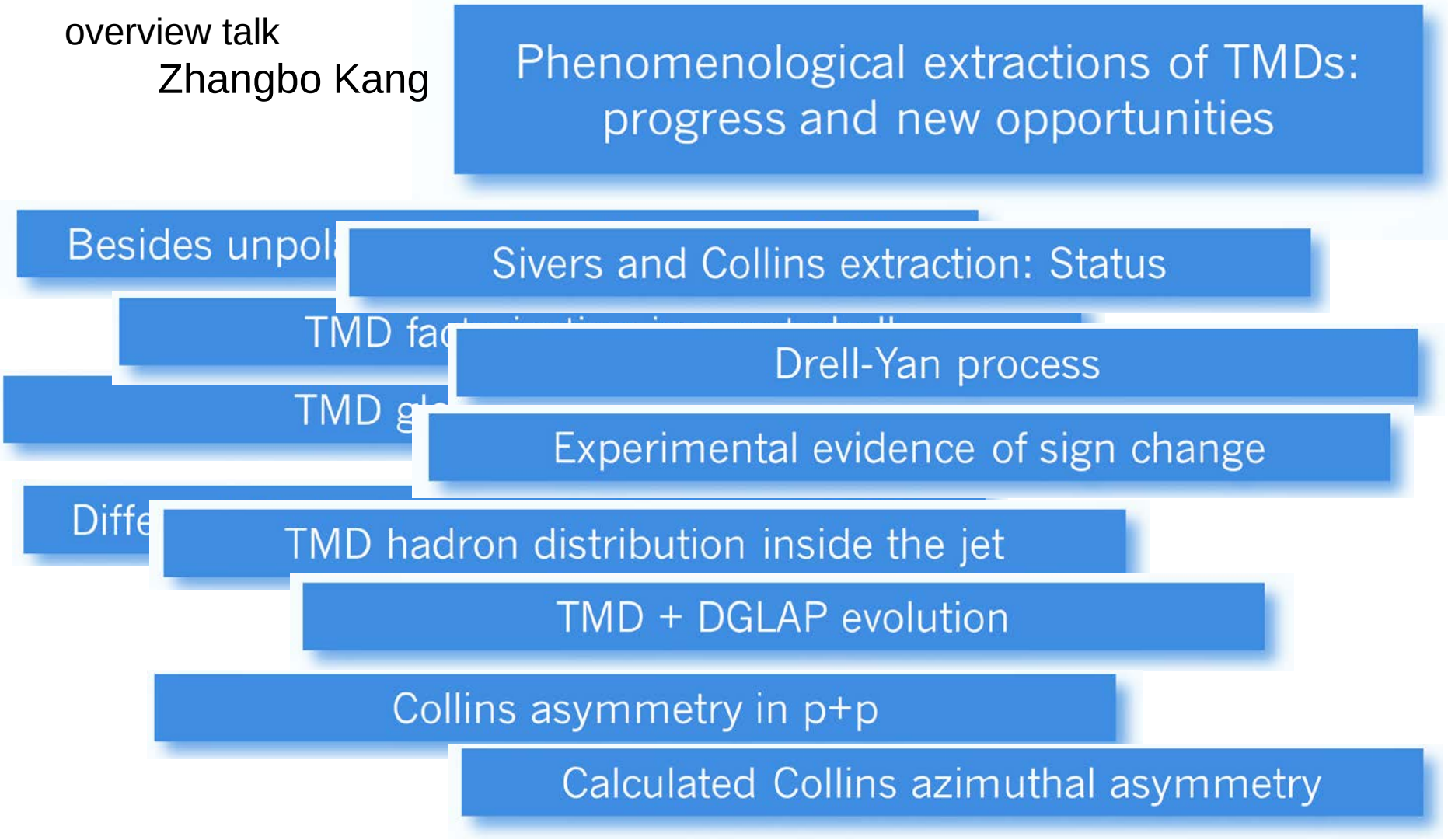
Different fits to date: unpolarized quark TMDs

no overview talk on experiment results

a lot of data shown in the different talks

overview talk

Zhangbo Kang



no overview talk on experiment results

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overview talk

Zhangbo Kang

Phenomenological extractions of TMDs: progress and new opportunities

Bes

Diff

TMD study

- Study on TMDs are extremely active in the past few years, lots of progress have been made
- With great excitement, we look forward to the future experimental results from COMPASS/RHIC, as well as Jefferson Lab, of course also LHC, most importantly, the EIC
- Better strategy for fitting, more observables/channels for TMDs

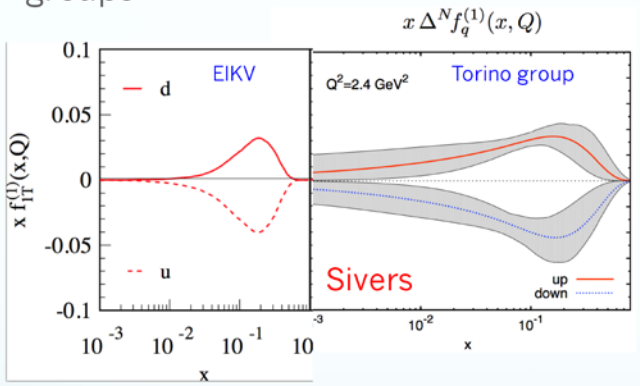
Calculated Collins azimuthal asymmetry

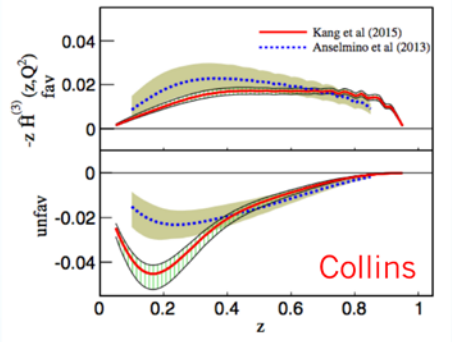
unpolarised TMDs

- Osvaldo Gonzalez Hernandez:
  Opportunities for the Extraction of TMD Fragmentation Functions
- Cristian Pisano:
  A first determination of unpolarised quark TMDs from a global analysis
- Alexey Vladimirov:
  Limits and uncertainties of TMD factorisation theorem

Sivers and Collins extraction: Status

- Within the region constrained by the experimental data, the spin-dependent TMDs seem to be rather consistent among different groups





- TMD evolution cancels between the ratios?? Need more data on the absolute cross section
- However, the extrapolations can be very different

Zhongbo Kang

unpolarised TMDs

Quark unpol. TMD: extractions

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 *hep-ph/0506225*	NLL/NLO	✘	✘	✔	✔	98
Pavia 2013 *arXiv:1309.3507*	No evo	✔	✘	✘	✘	1538
Torino 2014 *arXiv:1312.6261*	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 *arXiv:1407.3311*	NNLL/NLO	✘	✘	✔	✔	223
EIKV 2014 *arXiv:1401.5078*	NLL/LO	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016 *arXiv:1703.10157*	NLL/LO	✔	✔	✔	✔	8059
SV 2017 *arXiv:1706.01473*	NNLL/ NNLO	✘	✘	✔	✔	309

Alessandro Bacchetta

unpolarised TMDs

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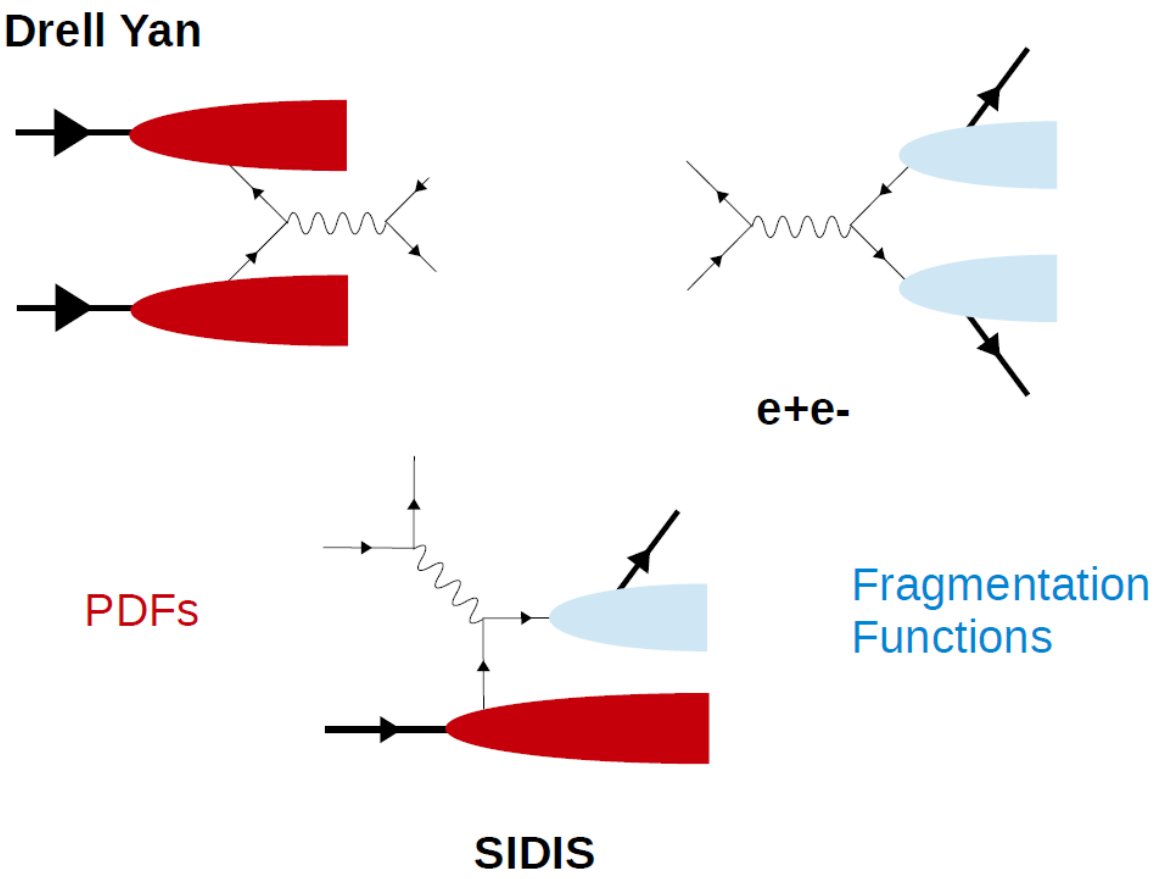
Alessandro Bacchetta

J. Osvaldo Gonzalez-Hernandez

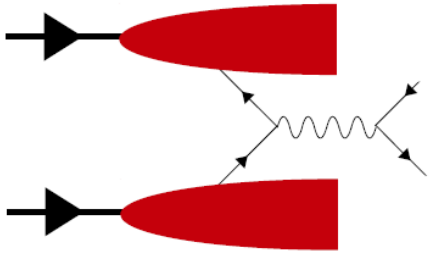
Opportunities for the Extraction Of TMD Fragmentation Functions

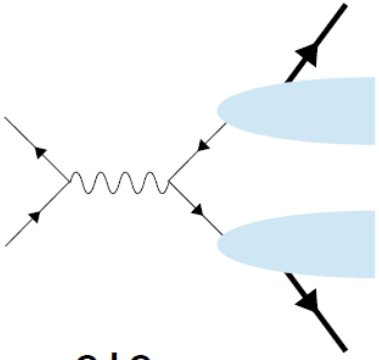


J. Osvaldo Gonzalez-Hernandez

Opportunities for the Extraction Of TMD Fragmentation Functions

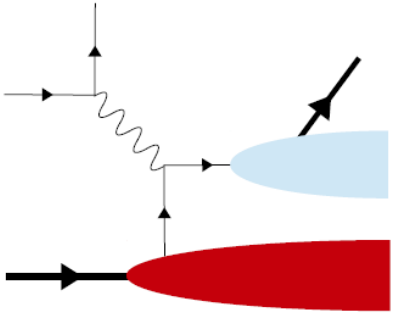
Drell Yan





e+e-

precise implementation of the R criterion on data is work in progress

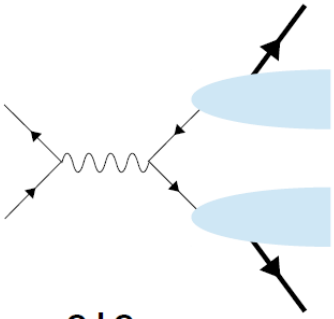


SIDIS

?

Available data is likely to receive contributions from non-TMD physics.

EIC projected energies



e+e-

J. Osvaldo Gonzalez-Hernandez

Power law to model transverse momentum dependence

$$D_{h/q}(z, p_\perp) = d_{h/q}(z)\, h_d(p_\perp)$$

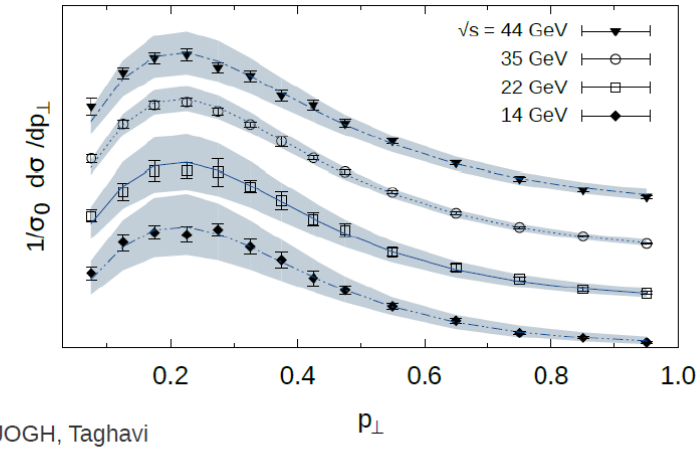
$$h(p_\perp) = 2(\alpha - 1)\mathrm{M}^{2\,(\alpha-1)} \frac{1}{\left(p_\perp^2 + \mathrm{M}^2\right)^\alpha}$$

No modern unpolarized measurements are available.

TASSO, MARK II available for
e+e- → X h

- **pT** distributions
- different energies
- integrated over **z**

FIT TO TASSO



Boglione, JOGH, Taghavi

Phys.Lett. B772 (2017) 78-86

The lack of information about **z** hinders a full TMD extraction of the FF.

Future upcoming data by BELLE on unpolarized one-hadron production may allow for a combined analysis with TASSO and MARK II data.

unpolarised TMDs

Quark unpol. TMD: extractions

	Framework	HERMES	COMPASS	DY	Z production	N of points
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Cristian Pisano

Alessandro Bacchetta

A first determination of the unpolarized quark TMDs from a global analysis

Cristian Pisano

- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different Q^2?
- How wide is the transverse momentum distribution? Is it wider at low x?

Bacchetta, Delcarro, CP, Radici, Signori, JHEP 1706 (2017)

Total number of data points: 8059

Total number of free parameters: 11

- 4 for TMD PDFs
- 6 for TMD FFs
- 1 for TMD evolution

plus normalisation

Total $\chi^2/\text{dof} = 1.55 \pm 0.05$

A first determination of the unpolarized quark TMDs from a global analysis

Cristian Pisano

- A ... universal?
- ... for a descri...
- ... momentum ...

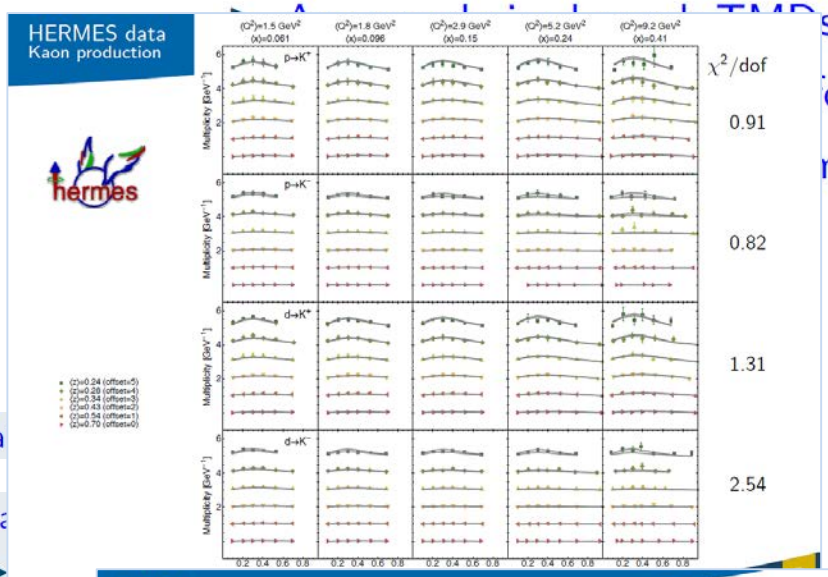
Bacchet...

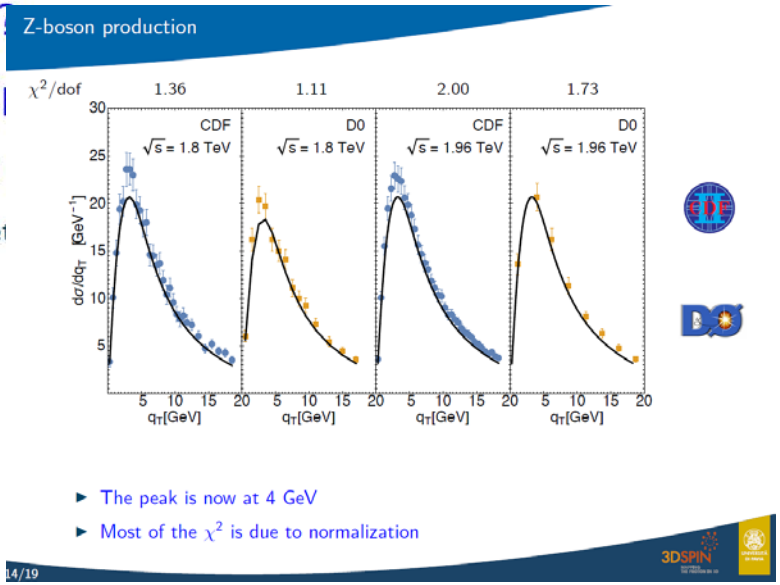
Tota...

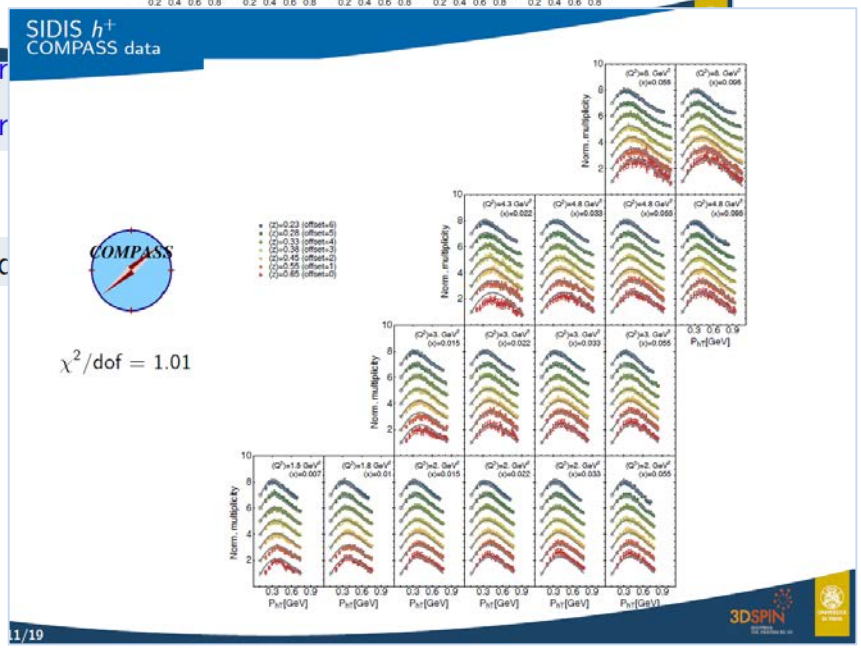
Tota...

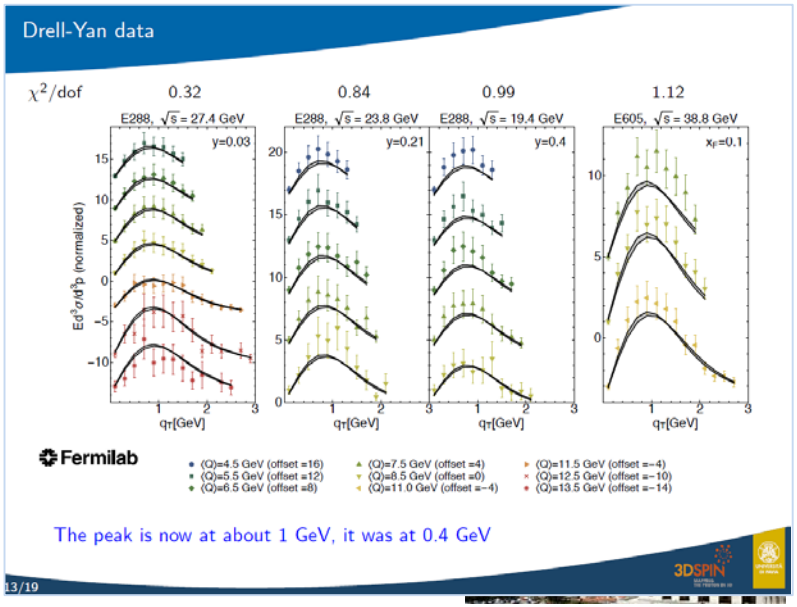
- ...
- ... for
- 1 for

Total χ^2/d...









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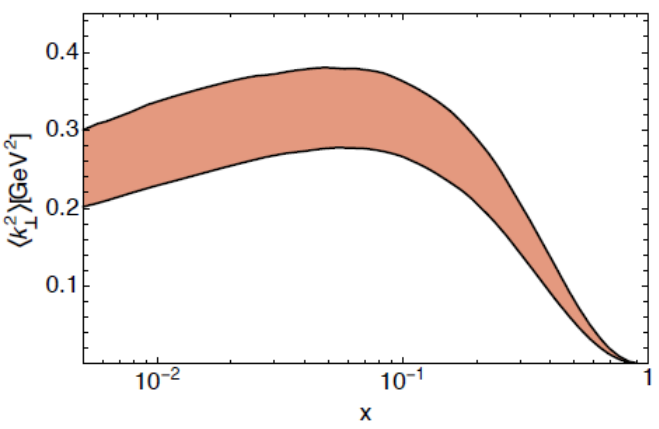
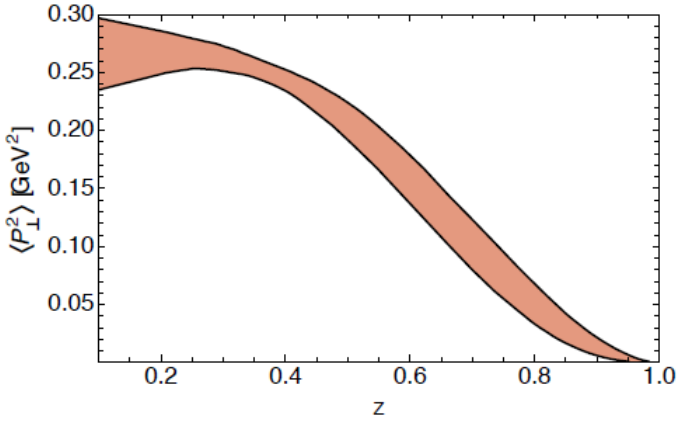
In TMD distribution functions



In TMD fragmentation functions



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Alexey Vladimirov

Alessandro Bacchetta

Limits and uncertainties of TMD factorization

Alexey A. Vladimirov

- The theory of TMD made huge progress in recent years
  - Evolution at N^3LO [Li & Zhu,1604.01404; AV,1610.05791]
  - Coefficient function at NNLO [many]
  - Matching coefficients at NNLO [many]
  - Structure of power suppressed terms on small-b OPE [Scimemi & AV,1609.06047]
- Not widely used in phenomenology!

We have made the global fit of Drell-Yan data, that include high and low energy measurements, and the extraction of unpolarized TMDPDF with the use of latest theory achievements.

Included data

	reaction	$\sqrt{s}$	Q	comment	points
E288	$p+Cu \to \gamma^* \to \mu\mu$	19.4 GeV	4-9 GeV	norm=0.8	35
E288	$p+Cu \to \gamma^* \to \mu\mu$	23.8 GeV	4-9 GeV	norm=0.8	45
E288	$p+Cu \to \gamma^* \to \mu\mu$	27.4 GeV	4-9 & 11-14 GeV	norm=0.8	66
CDF+D0	$p+\bar{p} \to Z \to ee$	1.8 TeV	66-116 GeV		44
CDF+D0	$p+\bar{p} \to Z \to ee$	1.96 TeV	66-116 GeV		43
ATLAS	$p+p \to Z \to \mu\mu$	7 & 8 TeV	66-116 GeV	tiny errors!	18
CMS	$p+p \to Z \to \mu\mu$	7 & 8 TeV	60-120 GeV		14
LHCb	$p+p \to Z \to \mu\mu$	7 & 8 & 13 TeV	60-120 GeV		30
ATLAS	$p+p \to Z/\gamma^* \to \mu\mu$	8 TeV	46-66 GeV		
ATLAS	$p+p \to Z/\gamma^* \to \mu\mu$	8 TeV	116-150 GeV		

$\chi^2/d.o.f$

	Model 1	Model 2	Model 3
NLL	9.21	9.07	8.90
NLO	2.62	2.64	1.90
NNLL	1.43	1.46	1.16
NNLO	1.84 (1.40)	1.79 (1.39)	1.94 (1.42)

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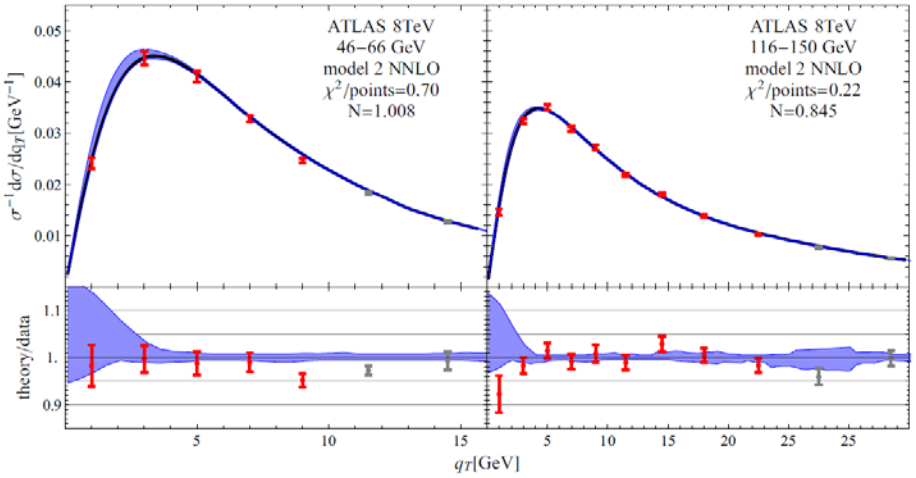

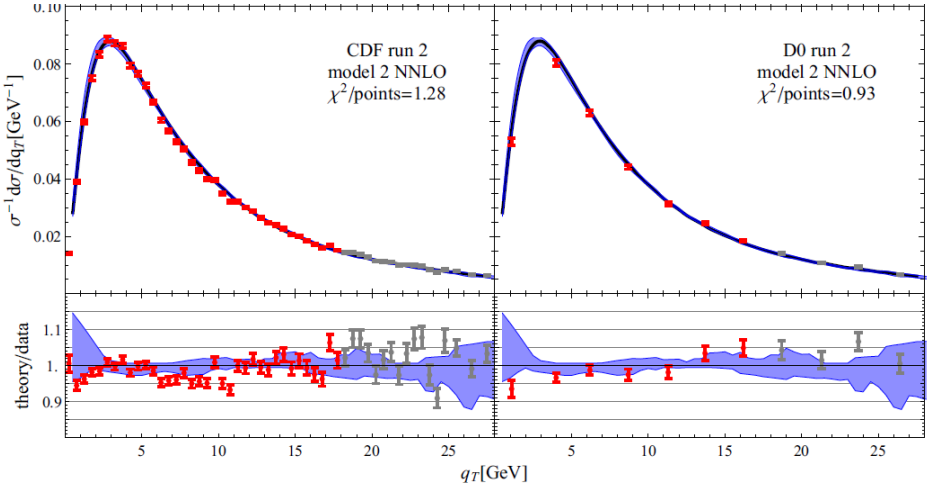

transversity and spin dependent TMDs

- Daniel Guitarrez Reyes: Features of spin dependent TMDs

Daniel Gutiérrez Reyes

Features of spin dependent TMDs

NLO and NNLO calculations

Matching coefficients

Transversity - Transversity small-b expression

$$h_1(x,\boldsymbol{b}) = \Big[\delta C_{q\leftarrow q}(\boldsymbol{b}) \otimes \delta f_q\Big](x) + \mathcal{O}(\boldsymbol{b}^2)$$

Agrees with A.Bachetta, A.Prokudin 1303.2129!

NLO matching coefficient

$$\delta C_{q\leftarrow q} = \delta(\bar{x}) + a_s C_F\Big(-2\mathbf{L}_\mu \delta p_{qq} + \delta(\bar{x})\left(-\mathbf{L}_\mu^2 + 2\mathbf{L}_\mu \mathbf{l}_\zeta - \zeta_2\right)\Big) + \mathcal{O}(a_s^2)$$

Calculations at NNLO are in progress!!

Pretzelosity - Transversity small-b expression

Non zero!

$$h_{1T}^{\perp}(x,\boldsymbol{b}) = \Big[\delta^{\perp} C_{q\leftarrow q}(\boldsymbol{b}) \otimes \delta f_q\Big](x) + \mathcal{O}(\boldsymbol{b}^2) = \Big[\big(0 + \mathcal{O}(a_s^2)\big) \otimes \delta f_q\Big](x) + \mathcal{O}(\boldsymbol{b}^2)$$

NLO matching coefficient

$$\delta^{\perp} C_{q\leftarrow q} = -4 a_s C_F \boldsymbol{B}^{\epsilon} \Gamma(-\epsilon) \bar{x} \epsilon^2$$

At NLO the coefficient is $\sim \epsilon$

This observation is supported by the measurement of $\sin(3\phi_h - \phi_S)$ asymmetries by HERMES and COMPASS!

C.Lefky, A.Prokudin 1411.0580

Daniel Gutiérrez Reyes

Features of spin dependent TMDs

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Agrees with A.Bacchetta, A.Prokudin 1303.2129!

- **Pretzelosity** has ϵ-suppressed matching coefficient ⇨ non zero at NNLO. Natural explanation of its smallness in phenomenological analyses
- Complete ϵ-dependent expressions ⇨ Open the path to the NNLO evaluation (work in progress!) and phenomenological studies (fits planned!, for unpolarized fits see A. Vladimirov talk)

NLO matching coefficient

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C.Lefky, A.Prokudin 1411.0580

transversity and spin dependent TMDs

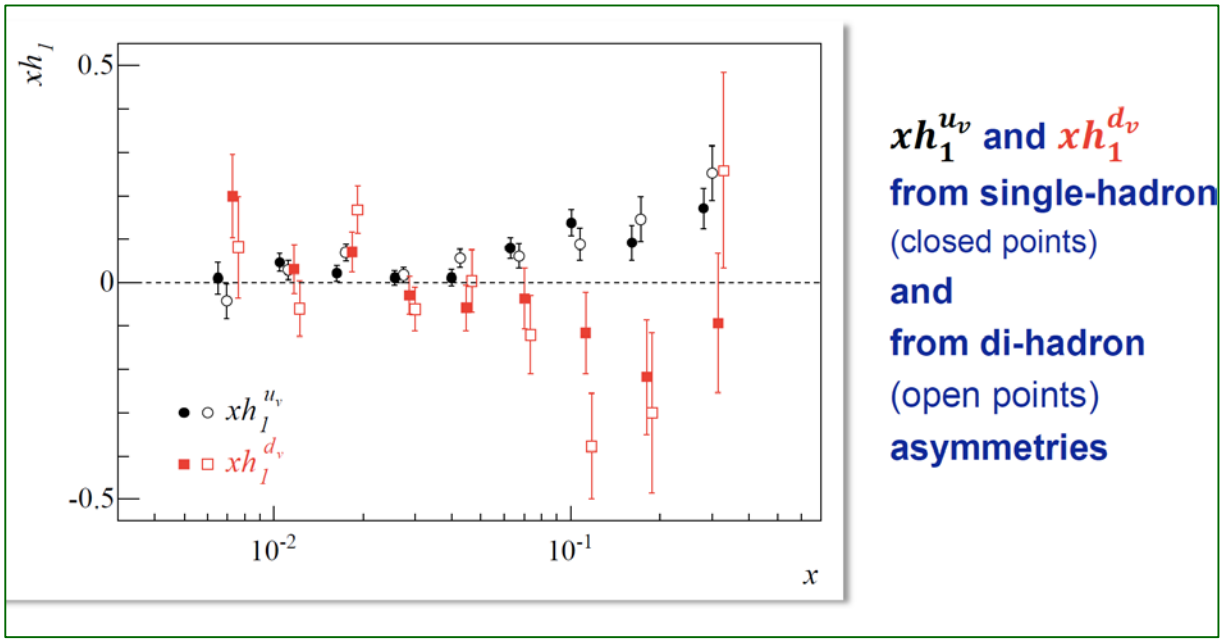
- Franco Bradamante: Point-by-point extraction of parton distribution functions from SIDIS single transverse–spin asymmetries
- Umberto D'Alesio: A_N in $lp \rightarrow hX$ within a TMD approach and quasi-real photon contribution

Franco Bradamante

Point-by-point extraction of parton distribution functions from SIDIS single transverse–spin asymmetries

from COMPASS p and d data
at the measured x, Q^2 values

$$g_T = \delta u - \delta d$$



$xh_1^{u_v}$ and $xh_1^{d_v}$
from single-hadron
(closed points)
and
from di-hadron
(open points)
asymmetries

no parametrisation of PDFs

only possible with p and d data at the same kinematics

Phys.Rev. D91 (2015) no.1, 014034
Phys.Rev. D95 (2017) no.9, 094024

Franco Bradamante

Point-by-point extraction of parton distribution functions from SIDIS single transverse–spin asymmetries

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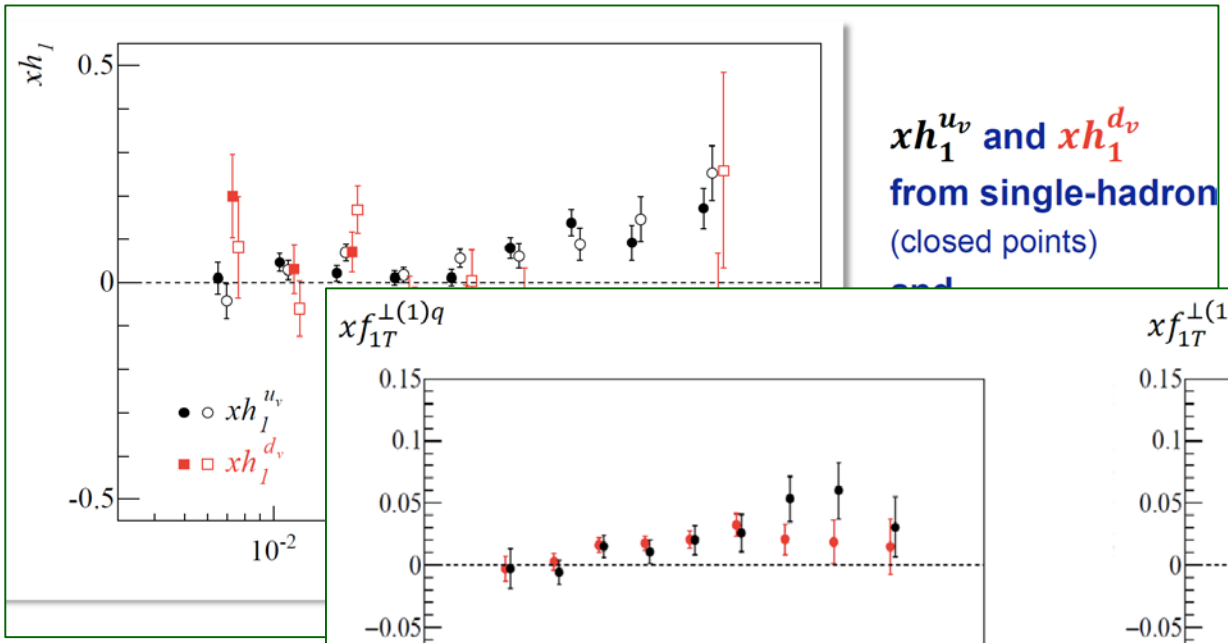

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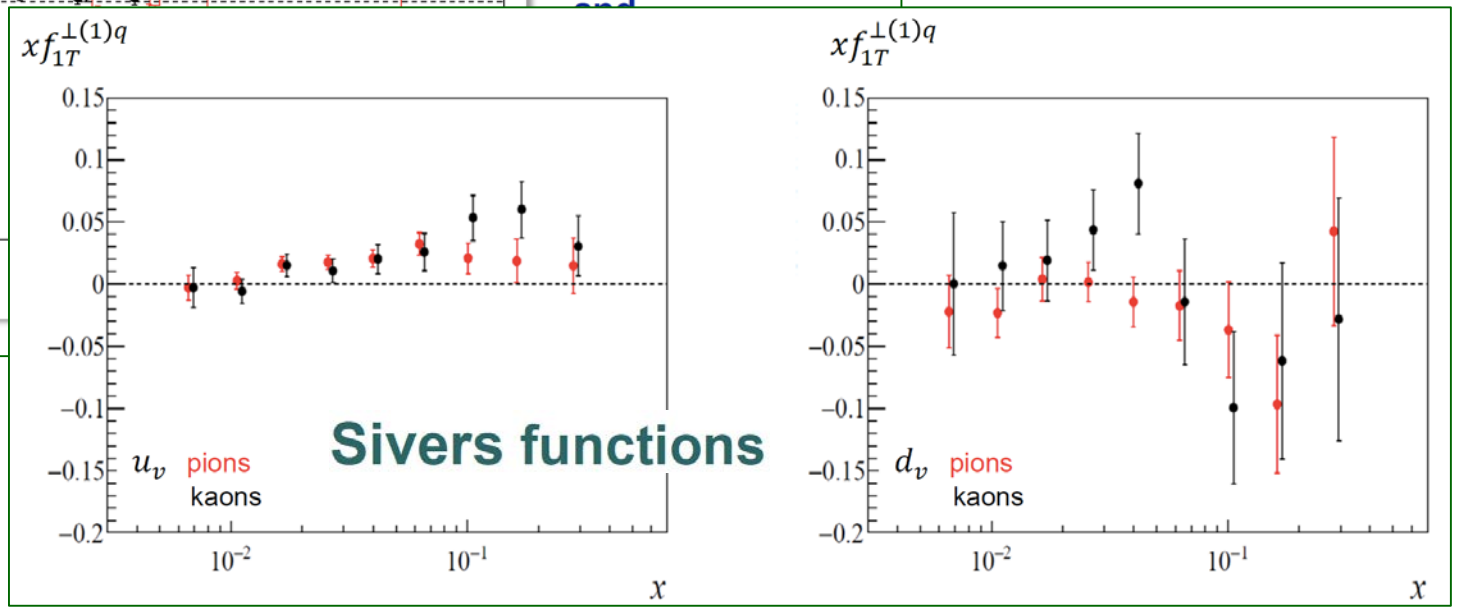
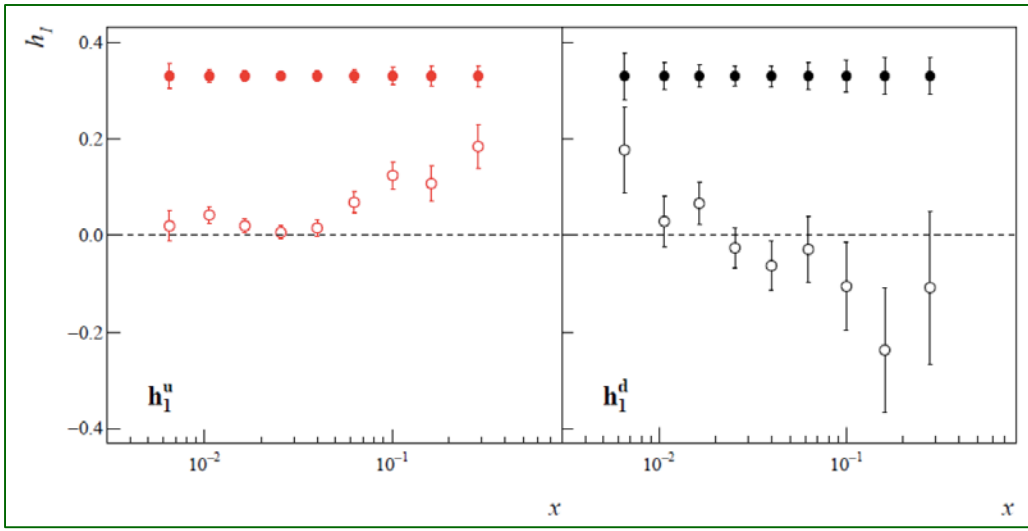


Franco Bradamante

Point-by-point extraction of parton distribution functions from SIDIS single transverse–spin asymmetries

from COMPASS p and d data
at the measured x, Q^2 values

relevance of balanced p d statistics

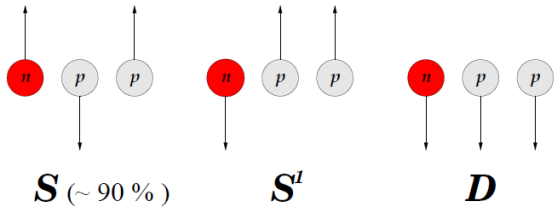


with one year of COMPASS SIDIS measurement with ^{6}LiD transversely polarized target

3D nuclear parton structure

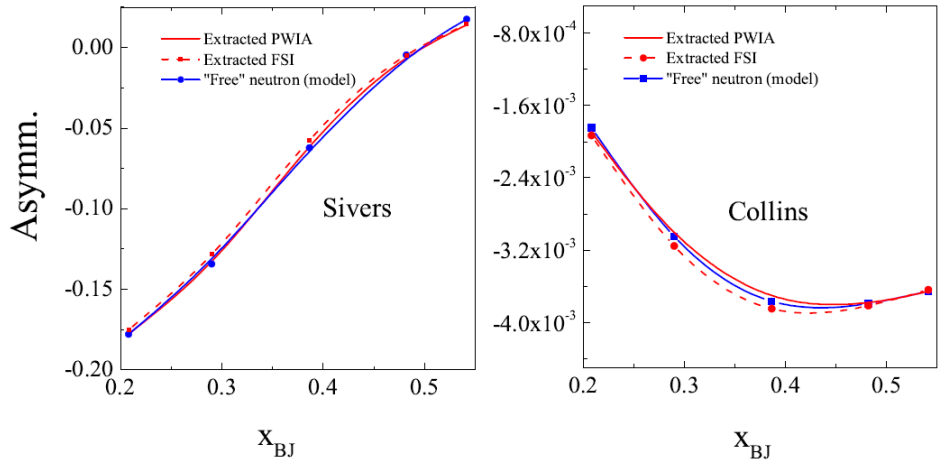
Sergio Scopetta

^{3}He is the ideal target to study the polarized neutron:



In $S-$wave
$^3\vec{H}e = \vec{n}$!

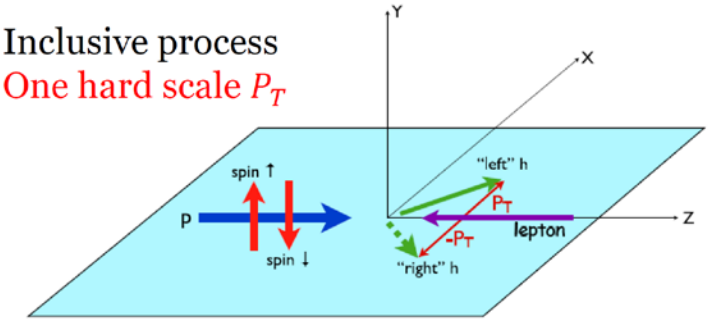
Good news from GEA studies of FSI!



Effects of GEA-FSI (shown at $E_i = 8.8$ GeV) in the dilution factors and in the effective polarizations compensate each other to a large extent: the usual extraction is safe!

A_N in $l\,p \to h\,X$
TMD approach and quasireal photon contribution

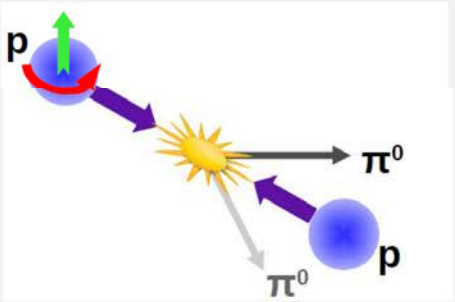
Umberto D'Alesio



❑ Transverse SSAs in inclusive processes:
large amount of data in pp collisions: sizeable from low to high energies (RHIC)

❑ Single scale processes, sub-leading SSAs

❑ Approaches:
Twist-three formalism (collinear factorization proven)
TMD scheme (phenomenological approach)



❑ In both cases phenomenology quite involved: many channels, many effects

❑ SSAs in inclusive particle production in lepton-proton collisions
Simpler (theor.): less channels, less color structure
- Close to SIDIS…a sort of bridge to pp collisions
A testing ground for
- approaches (twist-3 vs. TMD)
- a TMD unified picture (use of same TMDs as extracted from SIDIS)

First study: LO (Anselmino, Boglione, UD, Melis, Murgia, Prokudin 2014):

- inclusive and tagged event categories (large Q^2 component)

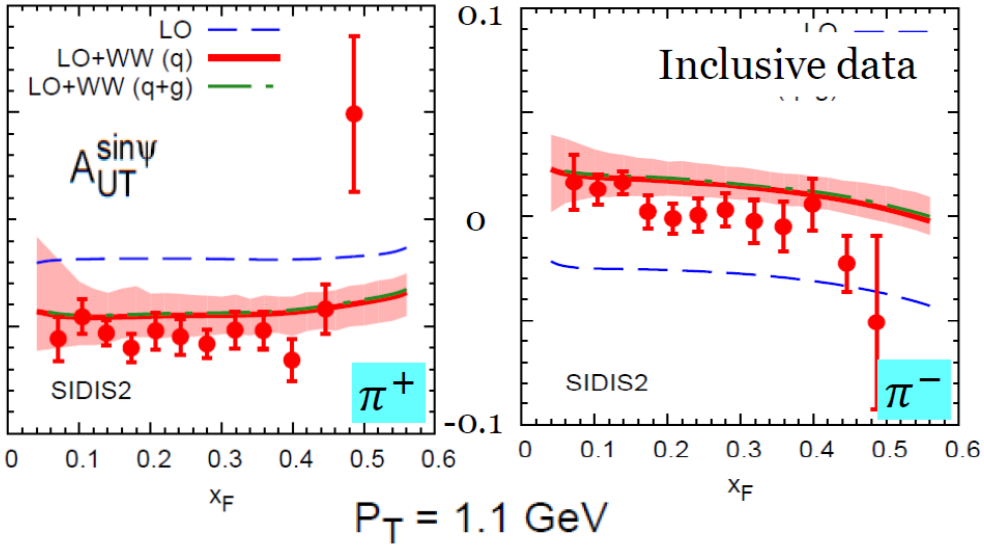
This study (UD, Flore, Murgia 2017):

- improvement in description of inclusive events (low Q^2component)
- anti-tagged events (new)

Only quark Sivers and (marginally) Collins effects sizeable

Predictions from SIDIS extractions

HERMES data (2014), $P_T > 1$ GeV



WW: big improvement vs. LO!

First study: LO (Anselmino, Boglione, UD, Melis, Murgia, Prokudin 2014):

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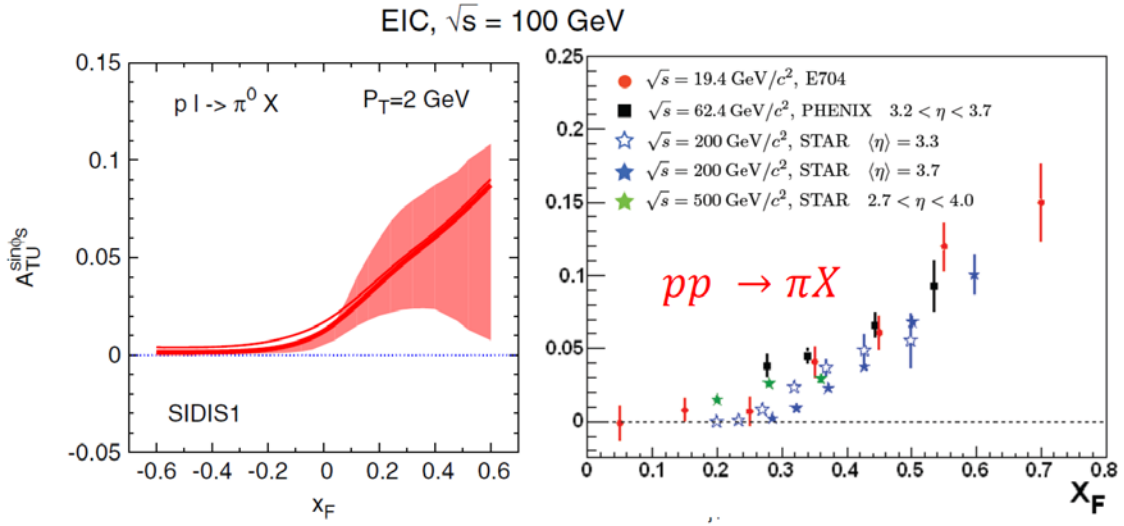
Transverse single spin asymmetries



- Studies of SSAs at EIC: expected similar behaviour in x_F and P_T as in $pp \to hX$

towards a unified TMD picture of SSAs

MC & TMDs Markus Diefenthaler: Mapping the hadronization description in to the correlation functions of TMD factorization

LDRD project at Jefferson Lab

NP – QCD factorization theorem

- interpret collision experiments using QCD factorization theorem
- development driven by **John Collins** (2009 J. J. Sakurai Prize)
- Novel way to study confinement: QCD factorization theorem for TMDs

HEP – Monte Carlo Event Generator

- describe collision processes by a combination of theory and phenomenological models
- **Pythia**, development led by LUND group (**Leif Lönnblad**), recognized by 2012 J. J. Sakurai Prize (for T. Sjöstrand)

Correlation functions of TMD factorization ⟷ Pythia MCEG

LDRD goal

Markus Diefenthaler:

Work plan

FY17

Publication: DIS in Pythia8

Publication: LUND validation

FY18

+ TMD observables

Publication: Hadronization in NP and HEP

- comparison Pythia8-TMD factorization
- language dictionary
- Pythia8 with spin-independent TMDs

FY19

Spin-dependent hadronization

Hadronization plugin