Extraction of unpolarized TMDs from Drell-Yan and SIDIS data

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Outlook

This talk is mainly based on [Scimemi,AV,1912.06532] = SV19 fit

Main features of SV19

- Joined description of DY and SIDIS
- NNLO matching and NNLO/N^{3}LO TMD evolution (NNLL' or N^{3}LL)
- ζ-prescription and independent defenitions of non-perturbative elements

artemide

https://github.com/VladimirovAlexey/artemide-public

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TMD factorization formula (in ζ-prescription)

Rapidity anomalous dimension

$\mathcal{D} \sim \langle 0 | \frac{\text{Tr}}{N_c} F_{+b} [\text{staple link}] | 0 \rangle$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

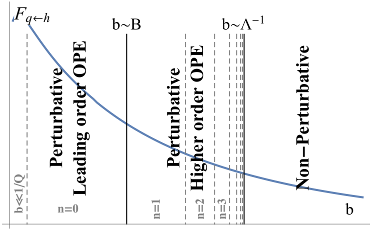
$F \sim \langle P | \bar{q} [\text{staple link}] q | 0 \rangle$

$$\frac{d\sigma}{dx dz dQ^2 d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\left(\frac{Q}{\mu}\right) \int d^2 b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)} \left(\frac{Q^2}{\zeta_\mu[\mathcal{D}]}\right)^{-2\mathcal{D}(b,\mu)} F_{f\leftarrow h}(x,b) D_{f'\leftarrow h}(z,b)$$

- Each data-point is a product (convolution) of **three independent non-perturbative** functions
- Functions do not "cross-talk" and could be modeled independently
- Each function is responsible for a separate kinematic variable
  - Rapidity AD: $\mathcal{D}$ $\rightarrow$ Q and b
  - TMD PDF: F $\rightarrow$ x and b
  - TMD FF: D $\rightarrow$ z and b

Each TMD distribution is **independent** non-perturbative function

$$F(x,b)=\int \frac{dz}{2\pi} e^{-ixzp^+} \langle p|\bar q(zn+b)[zn+b,-\infty n+b]\gamma^+[-\infty n,0]q(0)|p\rangle$$



$F(x,b)$ has too much parametric freedom

Matching to PDFs at small-b

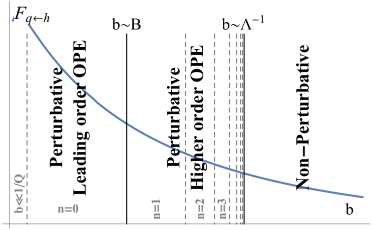
$$F(x,b)=C_1\otimes f_1(x)+\mathbf{b}^2(C_2\otimes f_1(x)+C_3\otimes T(x))+....$$

- C_1 is known at N^{3}LO [Ebert,Mistlberger,Vita,2006.05329]
- All b^2-powers with twist-2/3 [Moos,AV,2008.01744]

Small-b reduces parametric freedom

Each TMD distribution is **independent** non-perturbative function

$$F(x,b) = \int \frac{dz}{2\pi} e^{-ixzp^+} \langle p|\bar{q}(zn+b)[zn+b,-\infty n+b]\gamma^+[-\infty n,0]q(0)|p\rangle$$



The model for TMDs

$$F(x,b) = C_1 \otimes f_1(x) f_{NP}(x,b)$$

- **SV19 (& Pavia19) uses C_1 at NNLO**
- f_{NP} is subject of fitting
  - 5 parameters for TMDPDF
  - 4 parameters for TMDFF
  - No flavor dependence

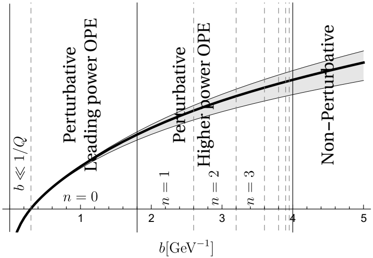
$$f_{NP}(x,b) = \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right)$$

$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z+\eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right)$$

Each TMD distribution is **independent** non-perturbative function

$$\mathcal{D}(b,\mu) = \lambda \frac{ig}{2} \frac{\int_0^1 d\beta \langle 0|F_{b+}(-\lambda n + b\beta)W_{C'}|0\rangle}{\langle 0|W_{C'}|0\rangle}$$

[AV,Phys.Rev.Lett. 125 (2020)]



Small-b OPE for CS-kernel

$$\mathcal{D}(b,\mu) = \mathcal{D}_0(b,\mu) + \mathbf{b}^2\mathcal{D}_1 + ...$$

- $\mathcal{D}_0$ is known at N^{3}LO [AV,1610.05791]

Model for CS-kernel

$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{resum}}(b,\mu) + c_0 b b^*.$$

- **SV19 (& Pavia19) uses $\mathcal{D}_0$ at N^{3}LO**
- Linear asymptotic at $b \to \infty$

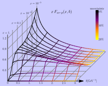
Low-energy
E228, E605,...
PHENIX

→ **Drell-Yan fit**
$\chi^2/N_{pt} = 1.2$ ←

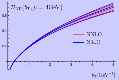
High-energy
ATLAS, LHCb,...
CDF, D0

Unpolarized DY

uTMDPDF (5 params)



RAD (1 param)

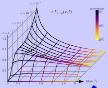


[V.Bertone,I.Scimemi,AV;1902.08474]

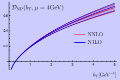
Unpolarized DY

Low-energy E228, E605,... PHENIX → Drell-Yan fit $\chi^2/N_{pt} = 1.2$ ← High-energy ATLAS, LHCb,... CDF, D0

uTMDPDF (5 params)



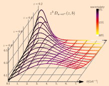
RAD (1 param)



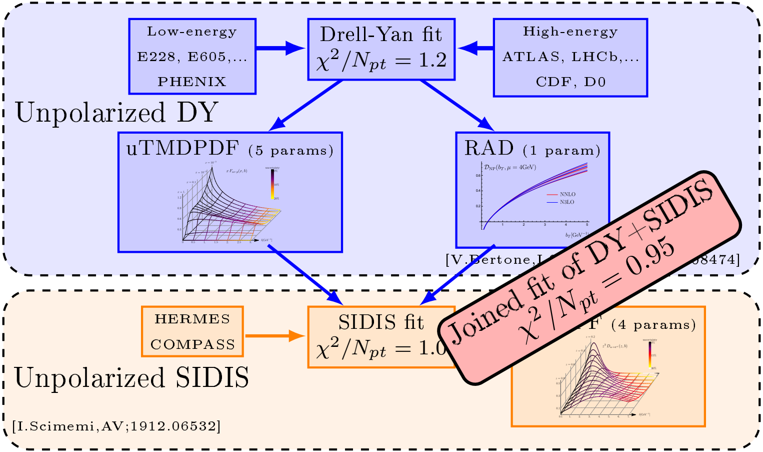
[V.Bertone,I.Scimemi,AV;1902.08474]

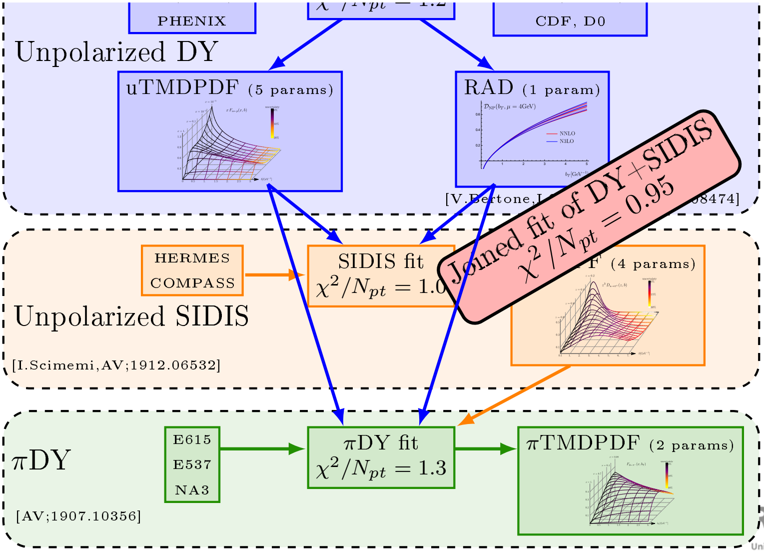
Unpolarized SIDIS

HERMES COMPASS → SIDIS fit $\chi^2/N_{pt} = 1.0$ → TMDFF (4 params)

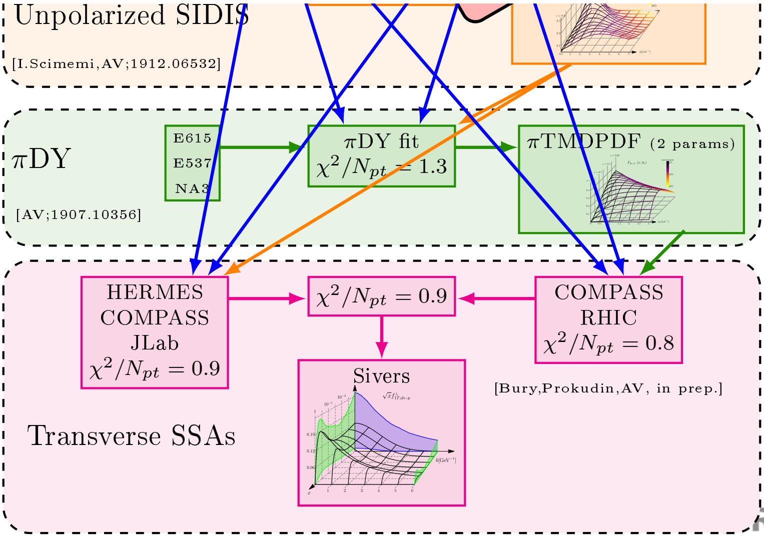


[I.Scimemi,AV;1912.06532]


Low-energy
E228, E605,...
PHENIX
Drell-Yan fit
$\chi^2/N_{pt} = 1.2$
High-energy
ATLAS, LHCb,...
CDF, D0
Unpolarized DY
uTMDPDF (5 params)
RAD (1 param)
NNLO
N3LO
HERMES
COMPASS
SIDIS fit
$\chi^2/N_{pt} = 1.0$
(4 params)
Unpolarized SIDIS
[I.Scimemi,AV;1912.06532]
Joined fit of DY+SIDIS
$\chi^2/N_{pt} = 0.95$


PHENIX
CDF, D0
Unpolarized DY
uTMDPDF (5 params)
RAD (1 param)
NNLO
N3LO
[V.Bertone,I.
08474]
Joined fit of DY+SIDIS
$\chi^2/N_{pt} = 0.95$
HERMES
COMPASS
SIDIS fit
$\chi^2/N_{pt} = 1.0$
(4 params)
Unpolarized SIDIS
[I.Scimemi,AV;1912.06532]
πDY
E615
E537
NA3
πDY fit
$\chi^2/N_{pt} = 1.3$
πTMDPDF (2 params)
[AV;1907.10356]

Universality & the chain of extractions



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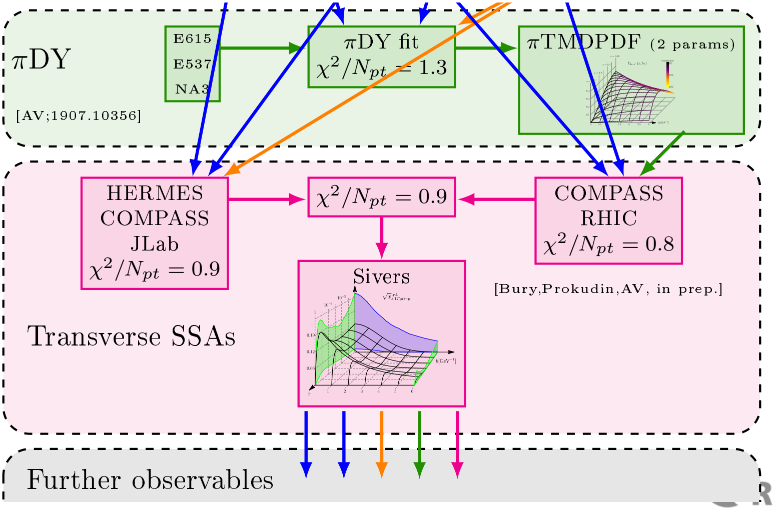
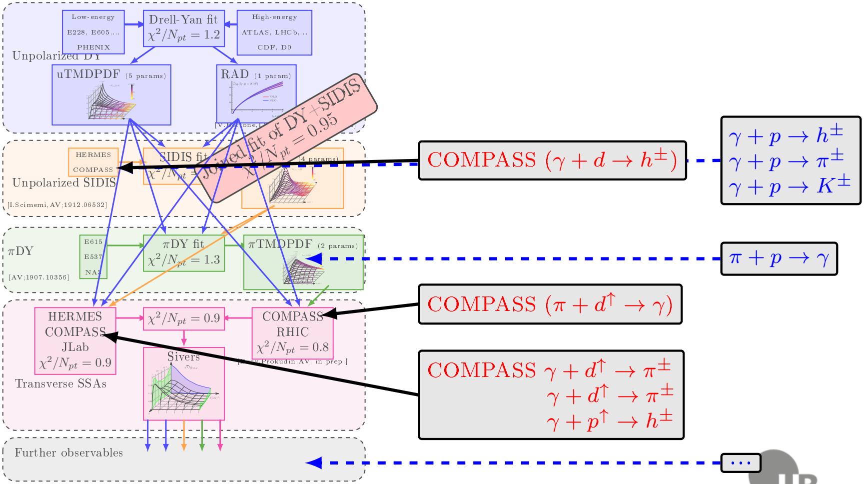
Universality & the chain of extractions



Role of the COMPASS data



There are plenty of details/questions

- Where is the limit of TMD factorization?
  - How to cut the data?
- Power corrections:
  - Induced (ATLAS, LHCb) (linear in q_T ?)
  - Kinematic
  - In the definition of collinear frame
  - Target mass and produced mass
- Universality and correlations
- ... many others ...
- What do we learn from it?

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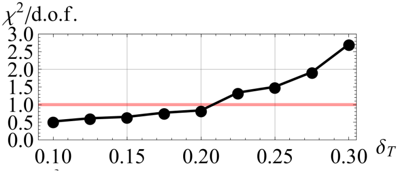
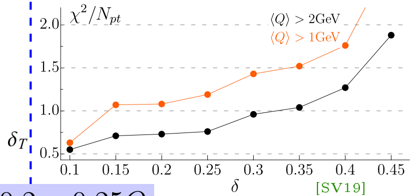
Test by inclusion of the data with $q_T < \delta \cdot Q$

unpolarized DY



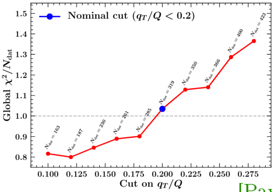
[I.Scimemi,AV,1706.01473]

unpolarized SIDIS



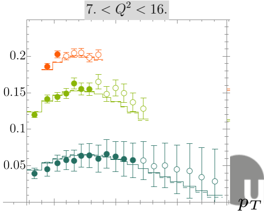
[SV19]

$q_T < 0.2 - 0.25Q$

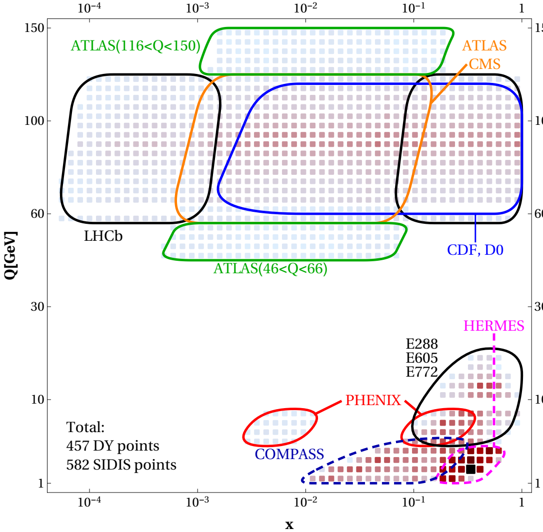


[Pavia19]

COMPASS



Data survived after the cut

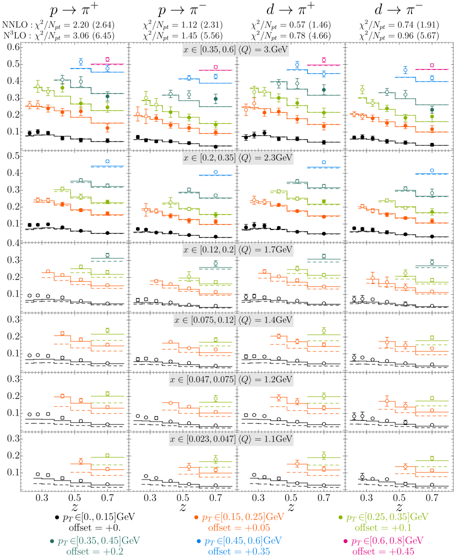


High energy DY:	194 points
Low energy DY:	263 points
(Low energy) SIDIS:	582 points
TOTAL:	1038 points

NNLO: $\chi^2_{global}/N_{pt} = 0.95$

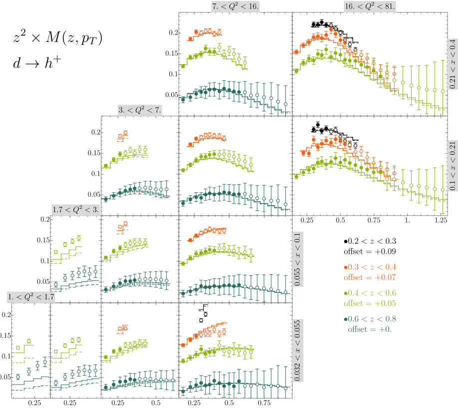
N^{3}LO: $\chi^2_{global}/N_{pt} = 1.05$

`artemide` v.2.02



Example of SIDIS data

No contradiction between HERMES and COMPASS



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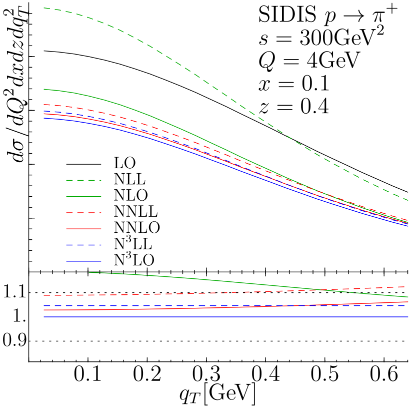
Possible sources of agreement/disagreement

Perturbative corrections

- At low-Q perturbative corrections:
  - NLL $\longrightarrow$ NNLL $\sim 40\%$
  - NNLL $\longrightarrow$ N^{3}LL $\sim 7\%$
  - NLL [Pavia17] $\longrightarrow$ N^{3}LL [SV19] $\sim 45\%$



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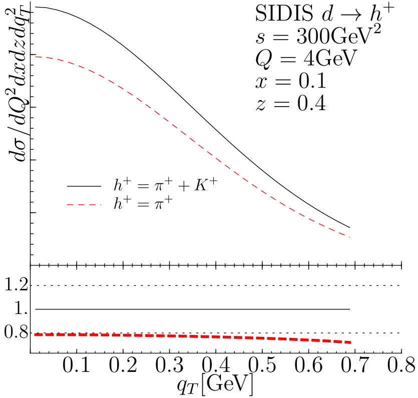
Possible sources of agreement/disagreement

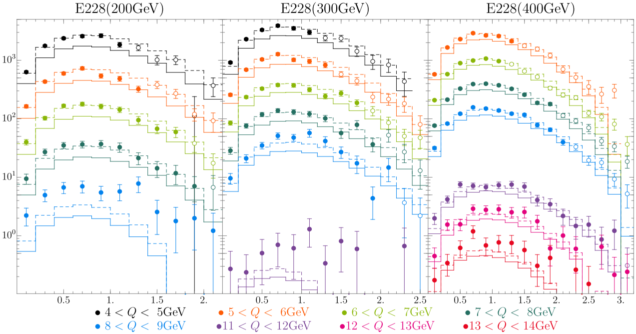
Final state interpretation

- COMPASS measured $\gamma + d \to h^{\pm}$
  - [Pavia17] and we identify $h \equiv \pi$.
  - [SV19] $h^{\pm} \simeq \pi^{\pm} + K^{\pm}$
- Kaon channel gives ∼20% contribution
- Proton channel gives ∼2-3% contribution (neglected in SV19)



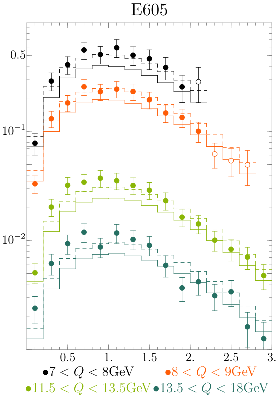
Example of low-energy DY

Some problem with normalization

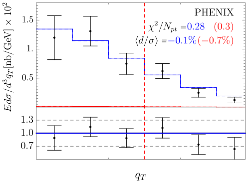


+30% +25% +15%

Norm.error of data 25%

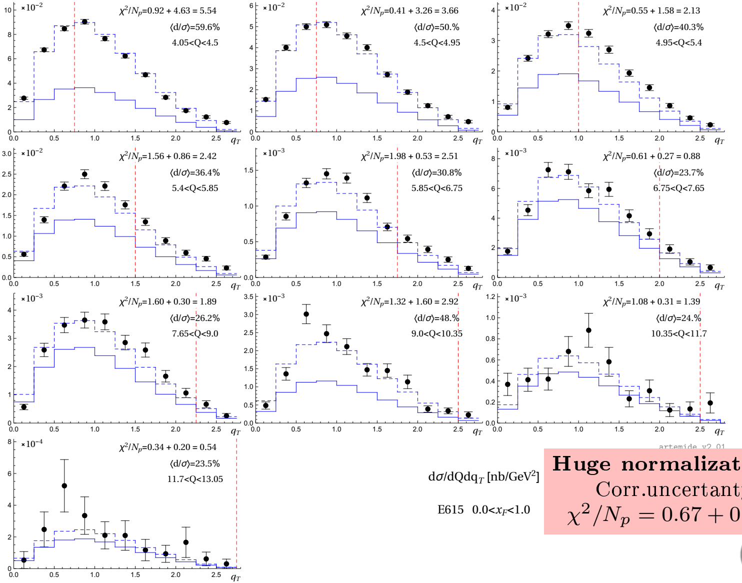


+15%



I bet that this discrepancy is due to large-x.

Situation is worse in the case of πDY



Huge normalization deficit

Corr.uncertanty=16%

$\chi^2/N_p = 0.67 + 0.77 = 1.44$

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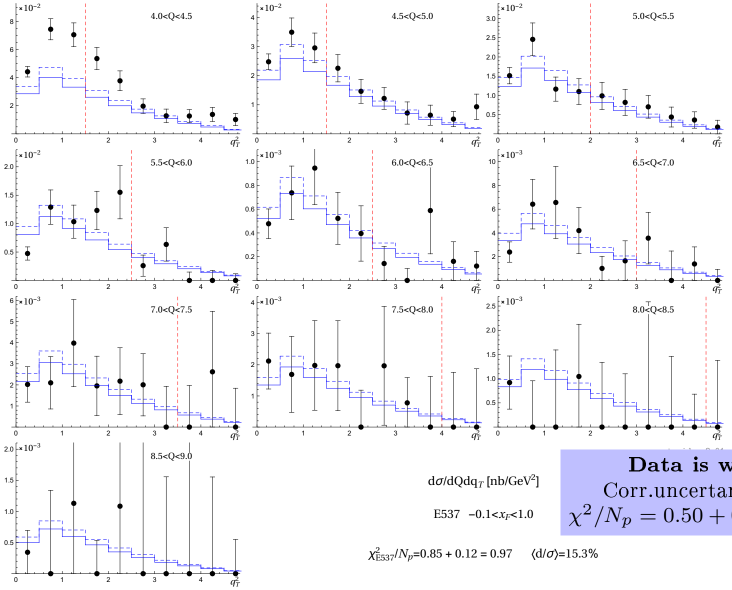

Data is worse

Corr.uncertanty=8%

$\chi^2/N_p = 0.50 + 0.11 = 0.61$

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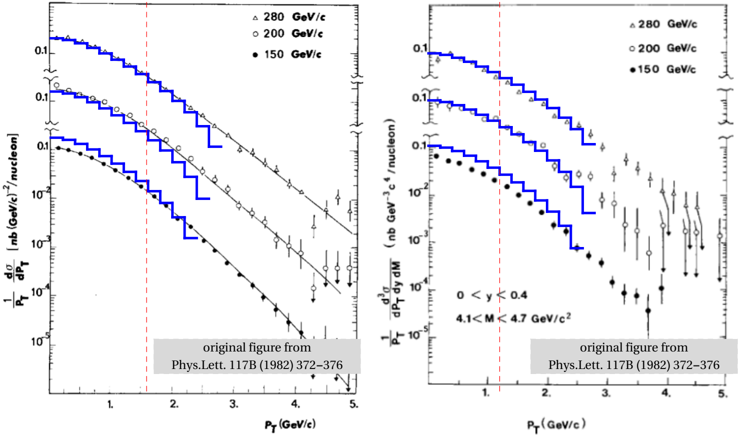
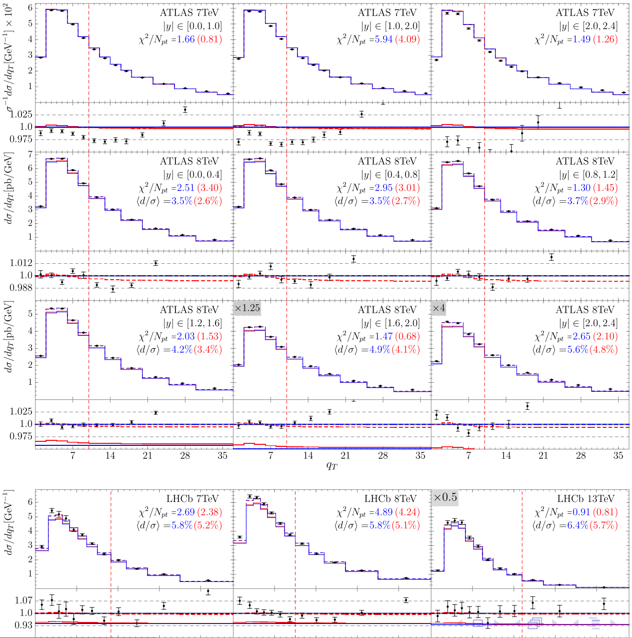


πDY-data from NA3 abd E537 does not show such anomalous behavior

Waiting for unpolarized πDY by COMPASS

LHC data within TMD factorization



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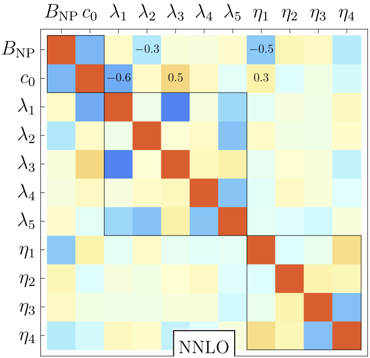
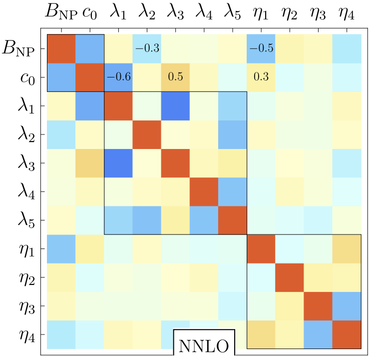


Evolution : 2 parameters
TMDPDF : 5 parameters + PDF
TMDFF : 4 parameters + NNFF

Different NP functions are almost decorrelated



Evolution : 2 parameters
TMDPDF : 5 parameters + PDF
TMDFF : 4 parameters + NNFF

Different NP functions are almost decorrelated

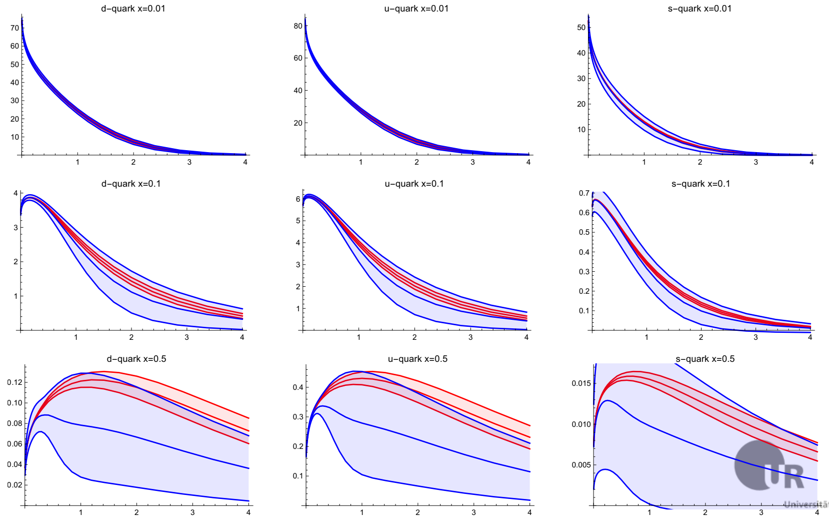
Fit quality essentially depends on the collinear input.

Vary NNPDF within the 1σ band

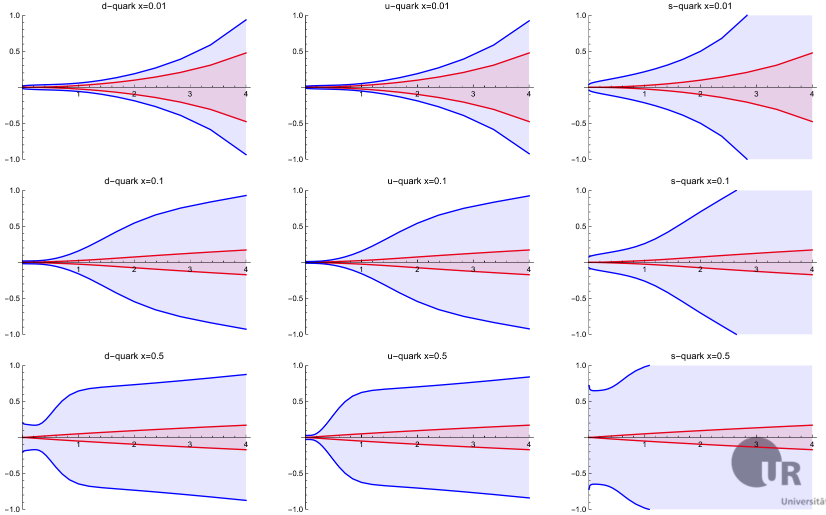
$$\chi^2/N_{pt} \in [0.8, 6.]$$

We cannot estimate accurately the PDF uncertainty.

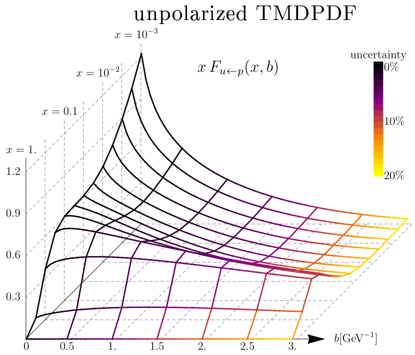
$$F(x,b) = C(x,b,\mu_{OPE}) \otimes \underbrace{f_1(x,\mu_{OPE})}_{\pm\delta f(\text{reweighted})} \underbrace{f_{NP}(x,b)}_{\pm\delta f_{NP}}$$

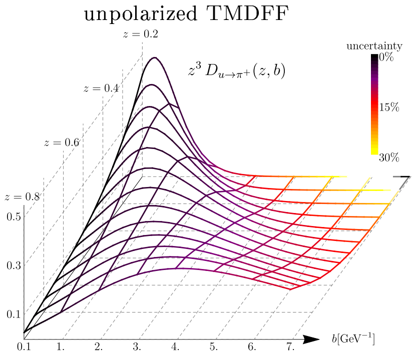


$$F(x,b) = C(x,b,\mu_{OPE}) \otimes \underbrace{f_1(x,\mu_{OPE})}_{\pm\delta f(\text{reweighted})} \underbrace{f_{NP}(x,b)}_{\pm\delta f_{NP}}$$



unpolarized TMD-distributions

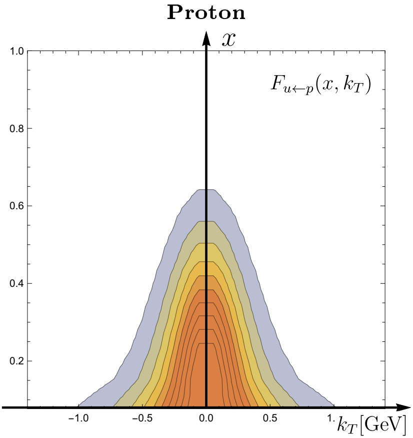


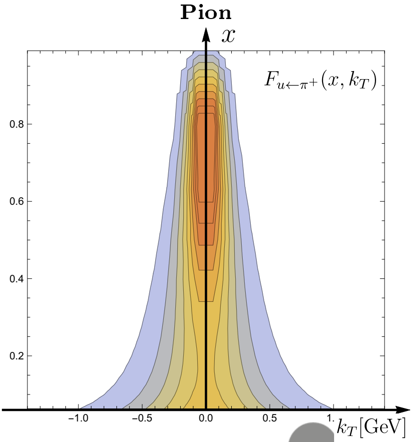


... systematic error 10-20%

... evolution does not have this systematics

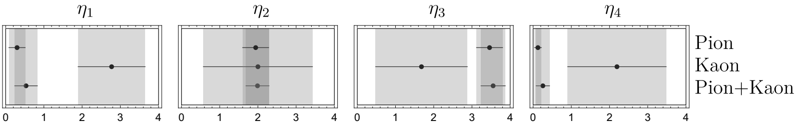
All distributions are different!

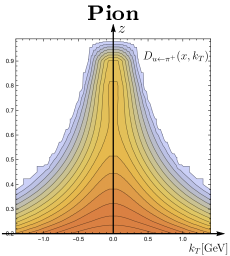


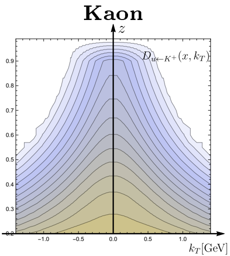


In SV19 no flavor/particle dependence

What if I try to add it?



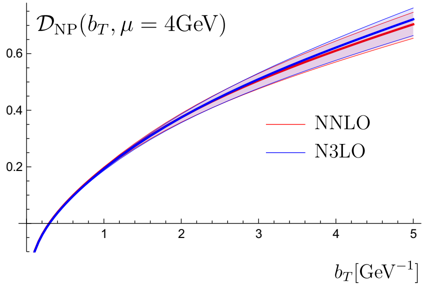




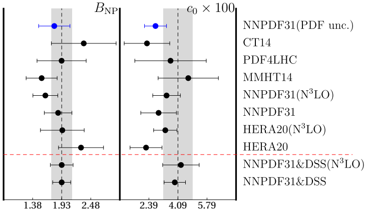
I see definite difference between π/K TMDFFs, however, uncertainties are large and current data could be fit with single TMDFF

COMPASS SIDIS with identified particles is very welcome!

Universal TMD evolution kernel

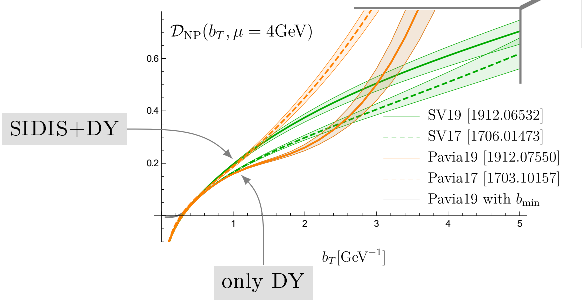


$$\mathcal{D}_{\rm NP}(b,\mu) = \mathcal{D}_{\rm perp}(b^*,\mu) + c_0 b b^*, \qquad b^* = b/\sqrt{1+b^2/B_{NP}^2}$$



- Linear asymptotic at $b \to \infty$
- RAD is independent on PDF set

Universal TMD evolution kernel
Comparison



- SV19 $\sim b$
- SV17 $\sim b^2$
- Pavia19 $\sim b^4$
- Pavia17 $\sim b^2$

CS-kernel is the window to a QCD vacuum!

CS-kernel measures the properties of QCD vacuum [AV,2003.02288]

$$\mathcal{D}(b,\mu) = \lambda \frac{ig}{2} \frac{\int_0^1 d\beta \langle 0|F_{b+}(-\lambda n + b\beta) W_{C'}|0\rangle}{\langle 0|W_{C'}|0\rangle}$$

Power correction

$$\mathcal{D}(b,\mu) = \mathcal{D}_0 + \mathbf{b}^2 \mathcal{D}_2 + ..., \qquad \mathcal{D}_2 \simeq \frac{\pi^2}{72} \frac{G_2}{\Lambda^2_{\text{QCD}}} \simeq (1.-5.) \times 10^{-2} \text{GeV}^{-1}$$

	Pavia17	SV19	SV17	Pavia19	BLNY(03/14)
$\mathcal{D}_2 \times 10^2$	2.8 ± 0.5	2.9 ± 0.6	$0.7^{+1.2}_{-0.7}$	0.9 ± 0.2	$20 - 35$

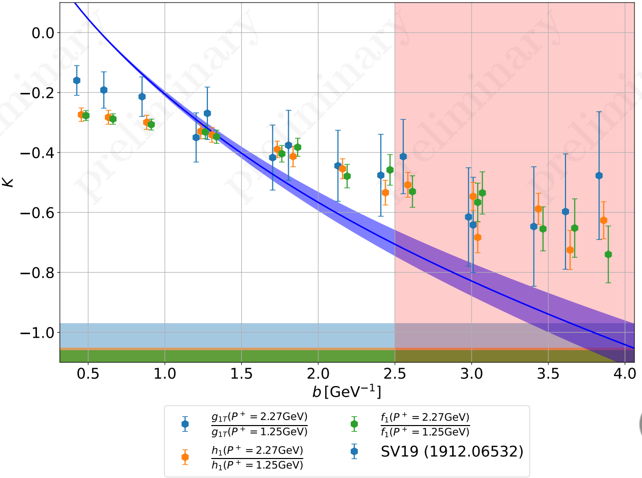
Amazing function...

- String tension
- Confining potential
- ...

First measurement of CS-kernel on lattice

based on [AV,Schafer,2002.07527] see also [Ebert,Stewart,Zhao,1811.00026]

Regensburg lattice group



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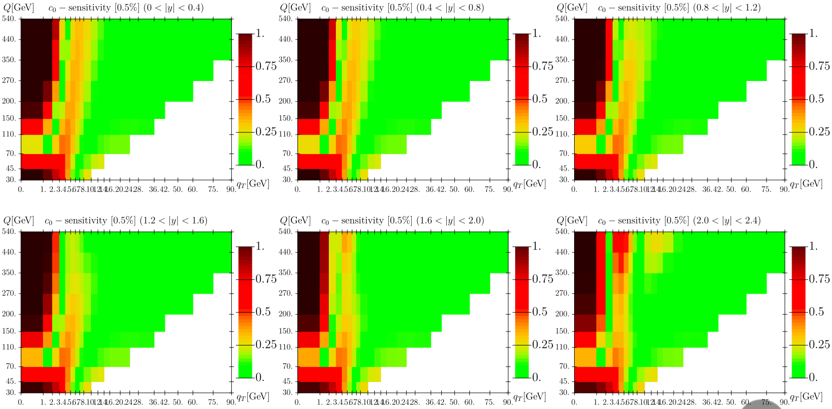
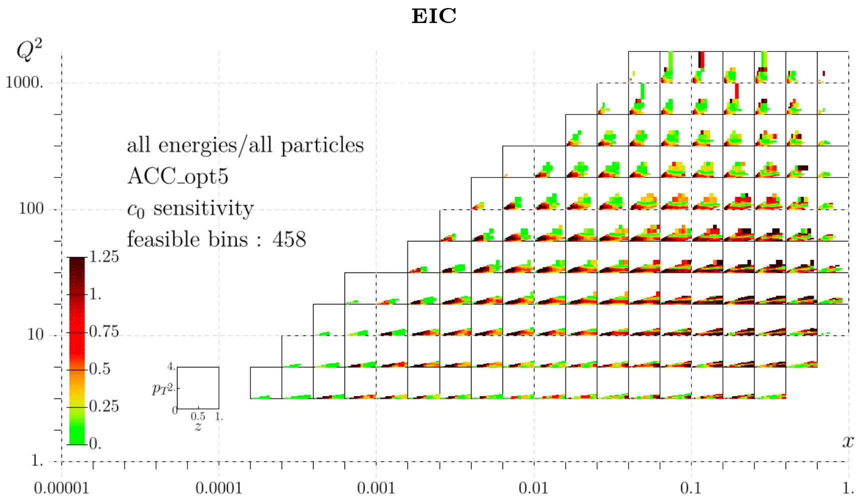
Where to measure CS-kernel?

LHC



Where to measure CS-kernel?



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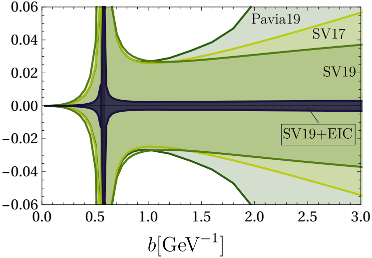
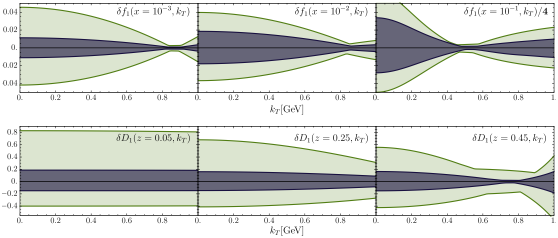
Expected impact of EIC





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Conclusion

Unpolarized TMD distributions are known

But this is only the first step

Problems to solve in the nearest future

- Uncertainties
- Flavor dependence
- Issue(s) with normalization of certain data

What to expect

- Inclusion of new observables (COMPASS your turn!)
- New tools (TMDlib)
- Lattice
- Non-perturbative modeling
- ...

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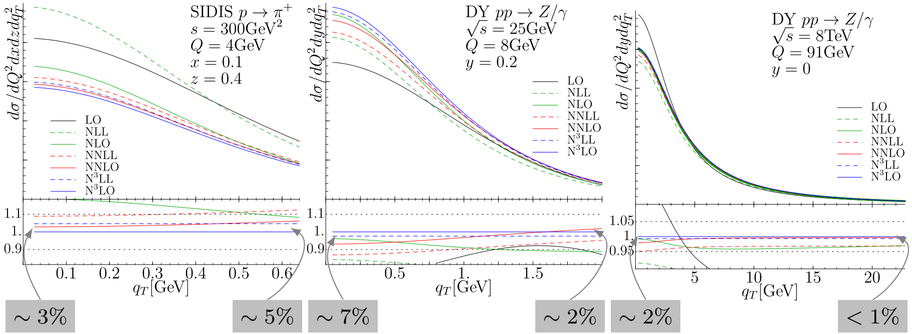
Backup slides

In ζ-prescription: $\mu \sim Q$

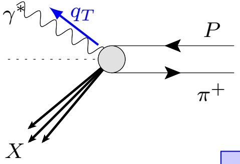
Matching scales μ_{OPE} are intrinsic for each function



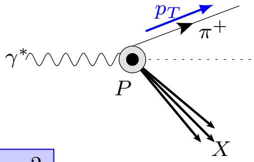
Difference between NNLO and N^{3}LO is not that important

Proof of factorization is done in the Breit frame

Breit frame



Lab frame



$$q_T^2 = \frac{p_T^2}{z^2}\frac{1+\gamma^2}{1-\varsigma^2}$$

$$\gamma = \frac{2Mx}{Q}$$

$$\varsigma = \gamma\frac{m}{zQ}$$

$$x_1 = -x\frac{2}{\gamma^2}\left(1-\sqrt{1+\gamma^2\left(1-\frac{\mathbf{q}_T^2}{Q^2}\right)}\right), \qquad z_1 = z\frac{x_1}{x}\frac{1+\sqrt{1-\varsigma^2}}{2\left(1-\frac{\mathbf{q}_T^2}{Q^2}\right)}$$

In practice: $q_T < 0.25Q$

- Most part of data is not TMD factorisable.
- Low z's are not accessible
- H1, ZEUS data have no TMD points, too low z.

Test of importance of power correction

These are not all power corrections,
but only those that we know how to account

include (m/Q)	yes	**no**	yes	yes	**no**	**no**
include (M/Q)	yes	yes	**no**	yes	**no**	**no**
include (q_T/Q) in kinematics	yes	yes	yes	**no**	**no**	**no**
include (q_T/Q) in x_S, z_S	yes	yes	yes	yes	yes	**no**
χ^2/N_{pt}	1.00	1.00	1.09	1.06	1.16	1.31

Most important corrections are $\frac{M}{Q}$ and $\frac{q_T}{Q}$ from the rotation Breit→Lab