Extraction of TMD distributions: status and plans

Alexey Vladimirov

Introduction

Project P4.a

Semi-inclusive reactions in TMD factorization theorems

(i) Global analysis of unpolarized SIDIS data

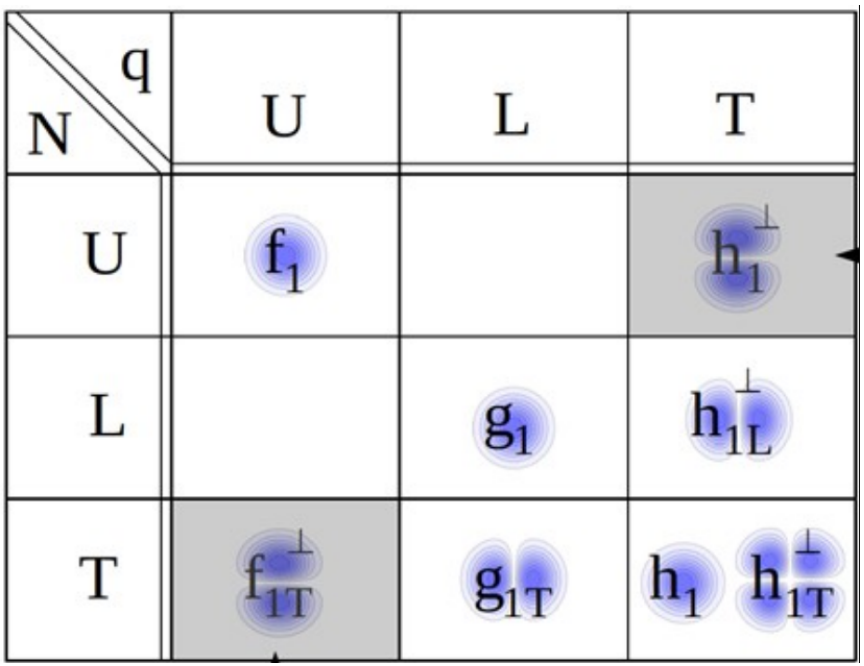
(ii) NLO analysis of single-spin asymmetry

Plan of the talk

- structure of TMD factorization
- general strategy of extraction of TMDs
- DY and unpolarized TMDPDF
- non-perturbative TMD evolution
- joined fit SIDIS+DY
- future plans

There many TMD distributions, but (honestly) we know very little about them.

Transverse momentum distributions of leading order



+ 8 gluon TMDs
+ 2 (or 8) TMD fragmentation function
+ non-perturbative evolution kernel

There are plenty of TMD fit, but all of them outdated

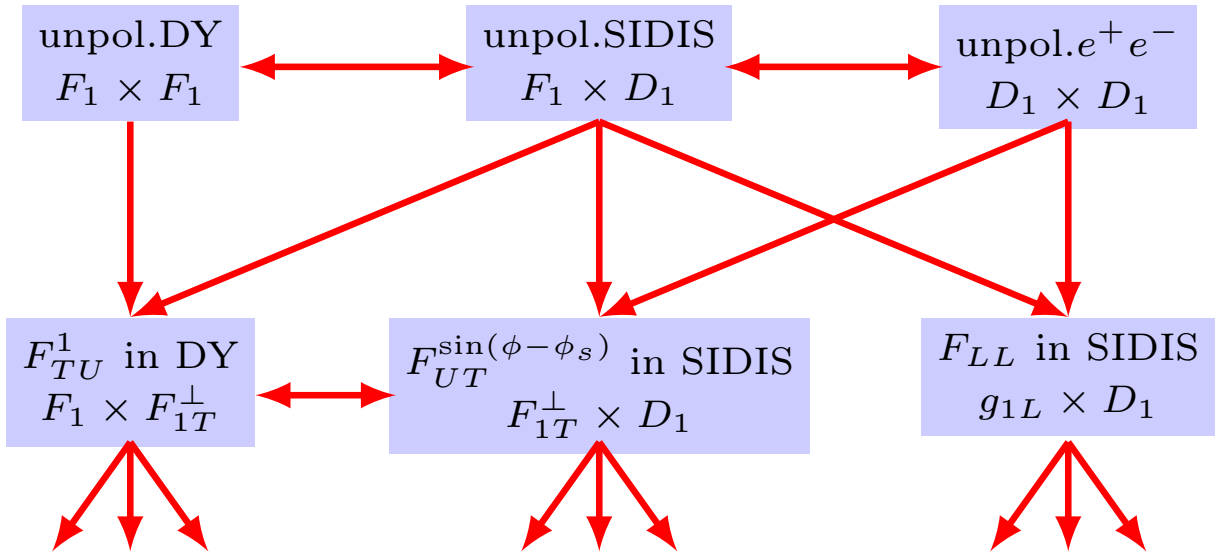
- (not always) inconsistent TMD evolution
- (often) no perturbative matching
- fits are disconnected

All TMDs are correlated

Each TMD factorized cross-section has three NP functions

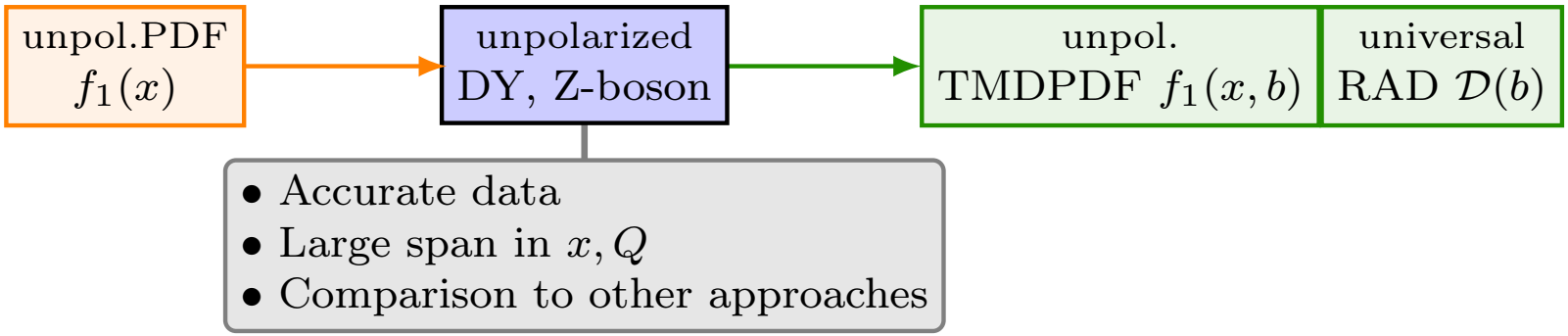
$$\frac{d\sigma}{dp_T^2 dQ} \simeq \sigma_0(Q) \int d^2\mathbf{b} e^{i\mathbf{b}\mathbf{p}_T} \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(Q,b)} F_1(x_1,\mathbf{b}) F_2(x_2,\mathbf{b})$$

- Two TMD distributions F_1 & F_2
- non-perturbative evolution $\mathcal{D}$



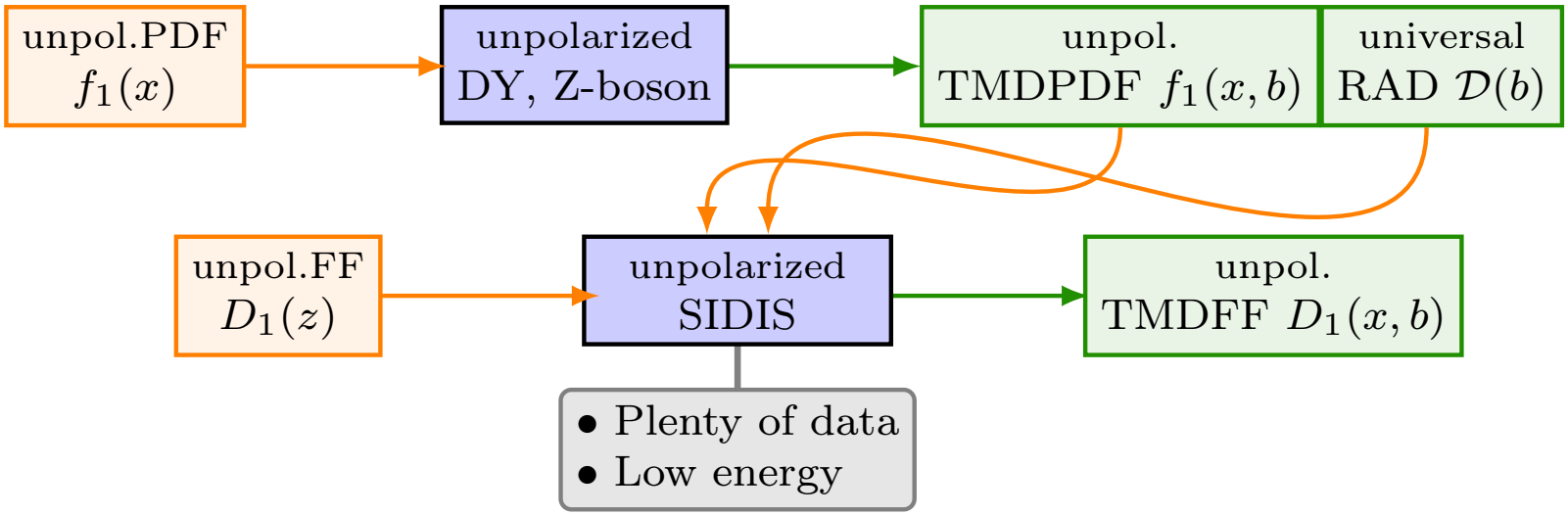
The main goals of project 4.a: **preparation of TMD factorization tools for EIC**

- unpolarized TMDFF (F_1)
- TMDs for SSA ($F_{1T}^{\perp}$, $D_1^{\perp}$)
- ...
- consistent framework for predictions and analysis



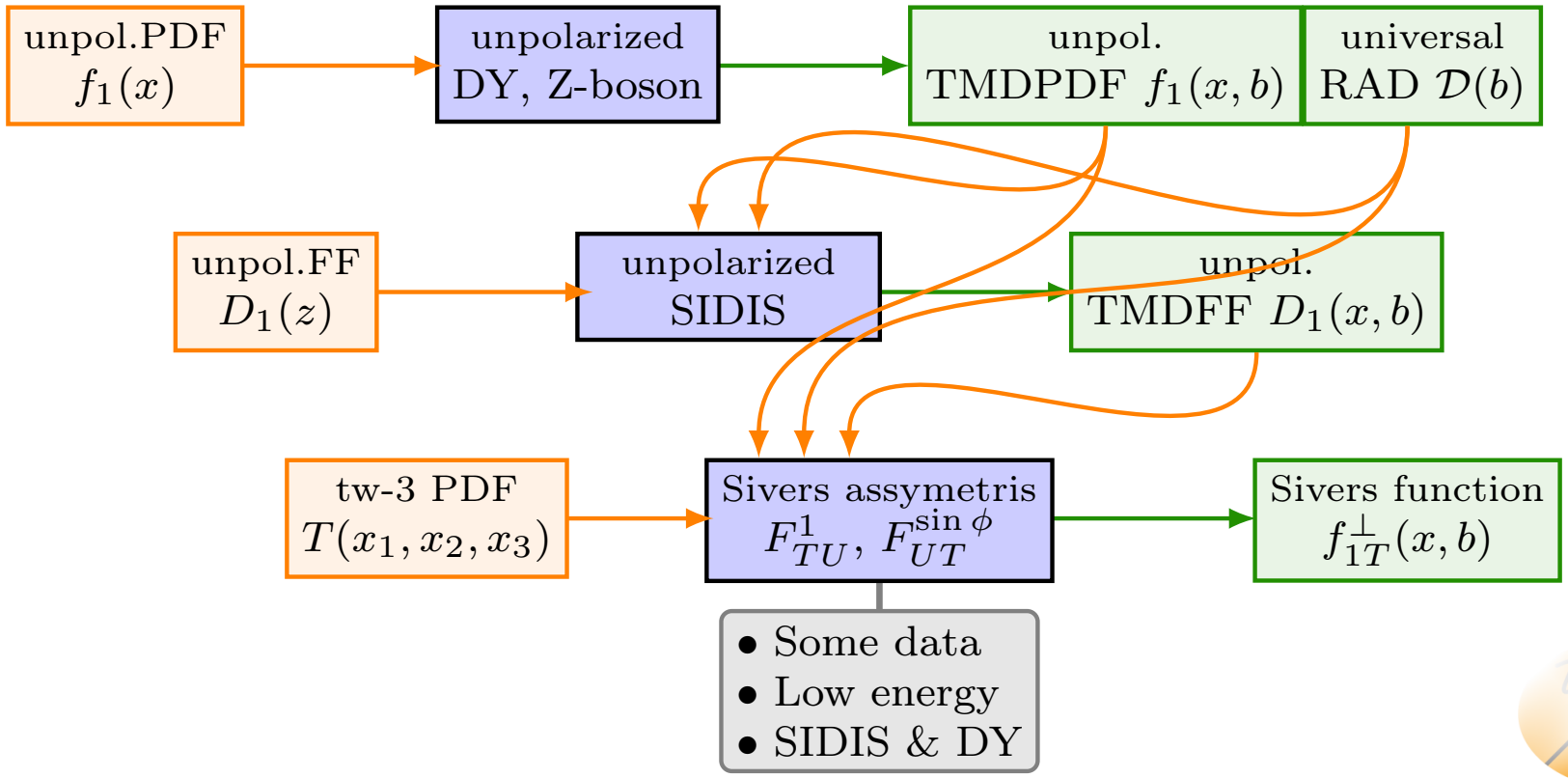
The main goals of project 4.a: **preparation of TMD factorization tools for EIC**

- unpolarized TMDFF (F_1)
- TMDs for SSA ($F_{1T}^{\perp}$, $D_1^{\perp}$)
- ...
- consistent framework for predictions and analysis



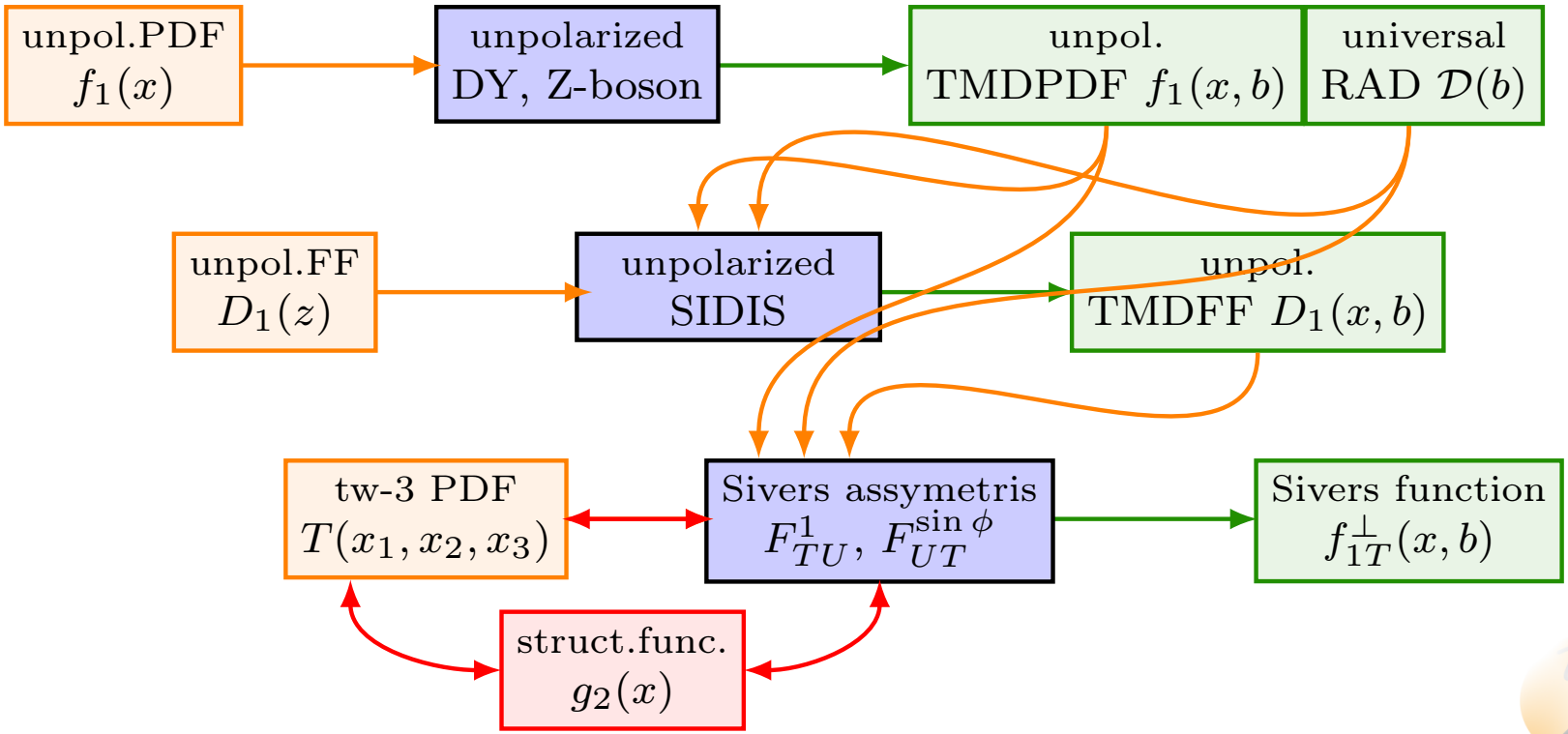
The main goals of project 4.a: **preparation of TMD factorization tools for EIC**

- unpolarized TMDFF (F_1)
- TMDs for SSA ($F_{1T}^{\perp}$, $D_1^{\perp}$)
- ...
- consistent framework for predictions and analysis



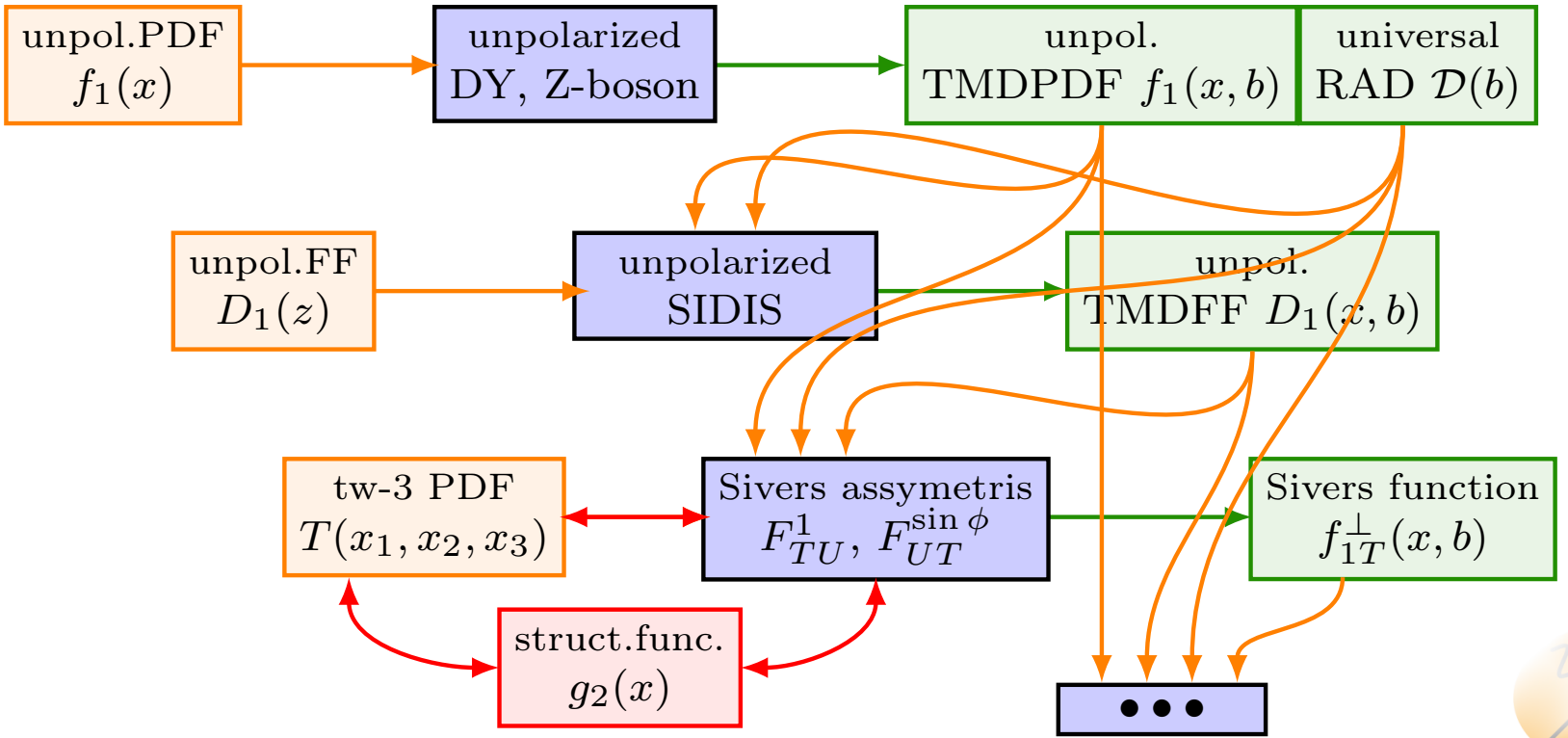
The main goals of project 4.a: **preparation of TMD factorization tools for EIC**

- unpolarized TMDFF (F_1)
- TMDs for SSA ($F_{1T}^{\perp}$, $D_1^{\perp}$)
- ...
- consistent framework for predictions and analysis



The main goals of project 4.a: **preparation of TMD factorization tools for EIC**

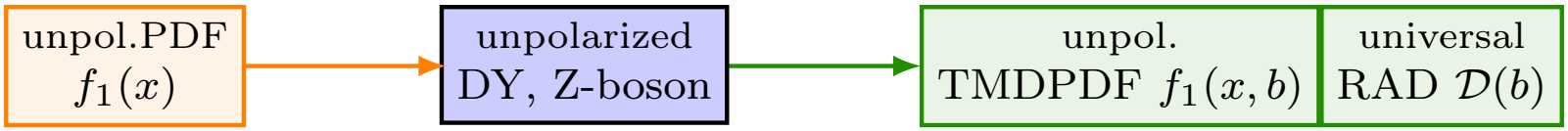
- unpolarized TMDFF (F_1)
- TMDs for SSA ($F_{1T}^{\perp}$, $D_1^{\perp}$)
- ...
- consistent framework for predictions and analysis

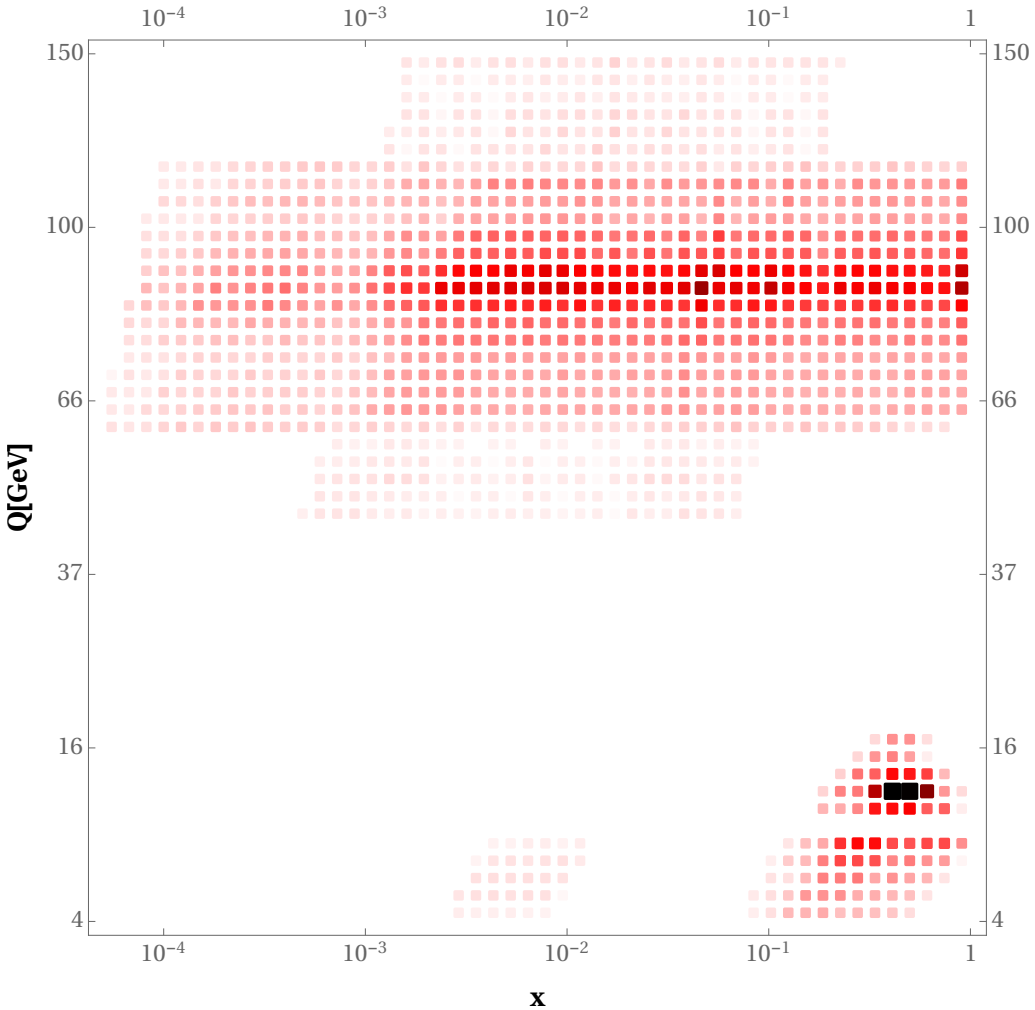


Theory input

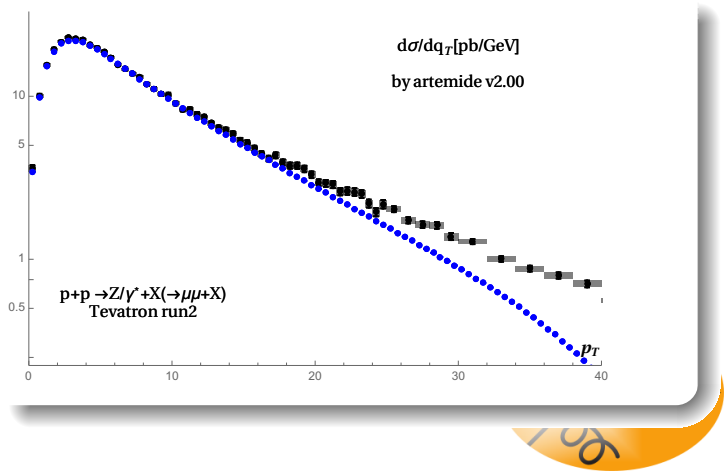
		LO	NLO	NNLO	N^3LO
	Hard coef.function				
	TMD evolution at $b \to 0$				
twist-2	unpol.TMDPDF at $b \to 0$				
	unpol.TMDFF at $b \to 0$				
	transversity TMDPDF at $b \to 0$				
	lin.gluon TMDPDF at $b \to 0$				
	helicity TMDPDF at $b \to 0$				
twist-3	Sivers TMDPDF at $b \to 0$				
	Rest				
:	**Collins function**, pretzelocity				

Stage 1 (DONE!)
[V.Bertone, I.Scimemi, AV, 1902.08474]



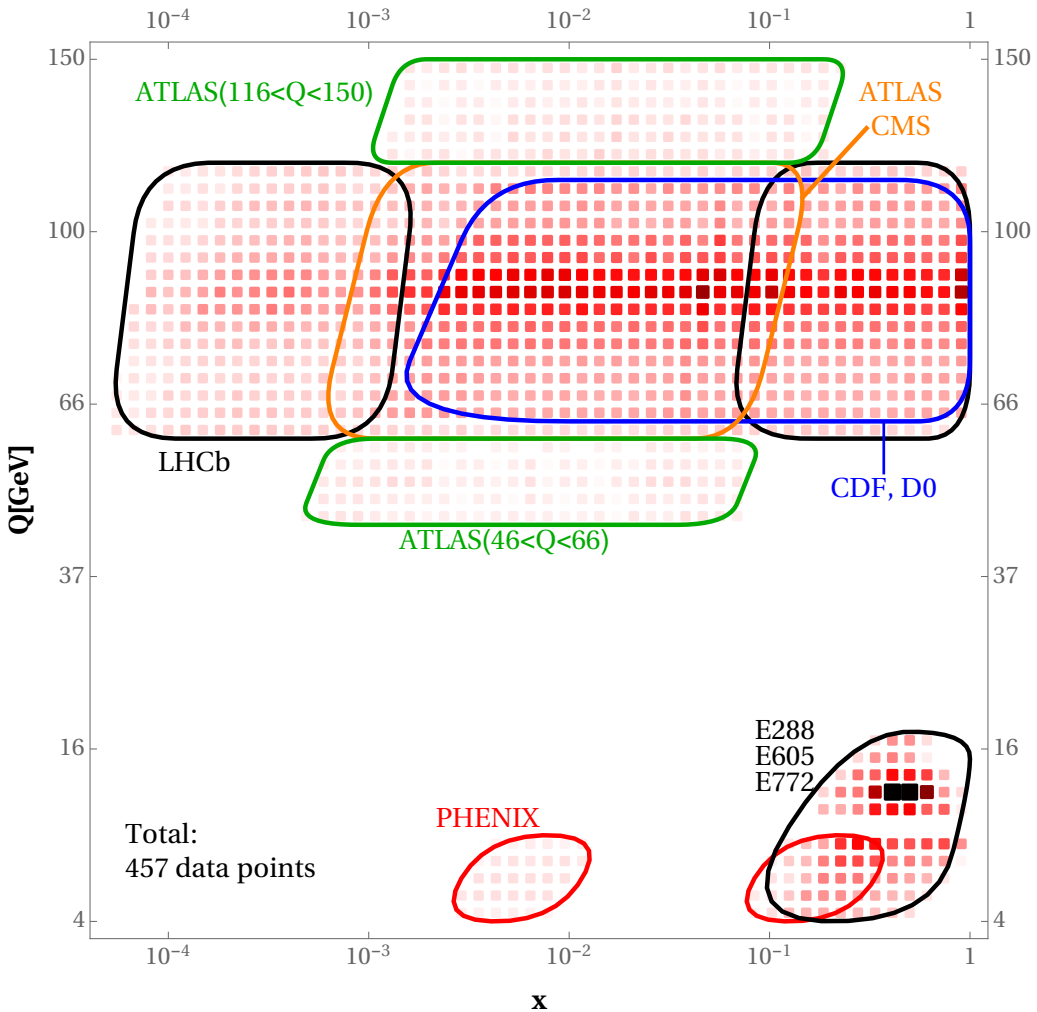


$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y} \sqrt{1 + \frac{q_T^2}{Q^2}}$$



Stage 1 (DONE!)
[V.Bertone, I.Scimemi, AV, 1902.08474]

unpol.PDF $f_1(x)$ → unpolarized DY, Z-boson → unpol. TMDPDF $f_1(x,b)$ | universal RAD $\mathcal{D}(b)$



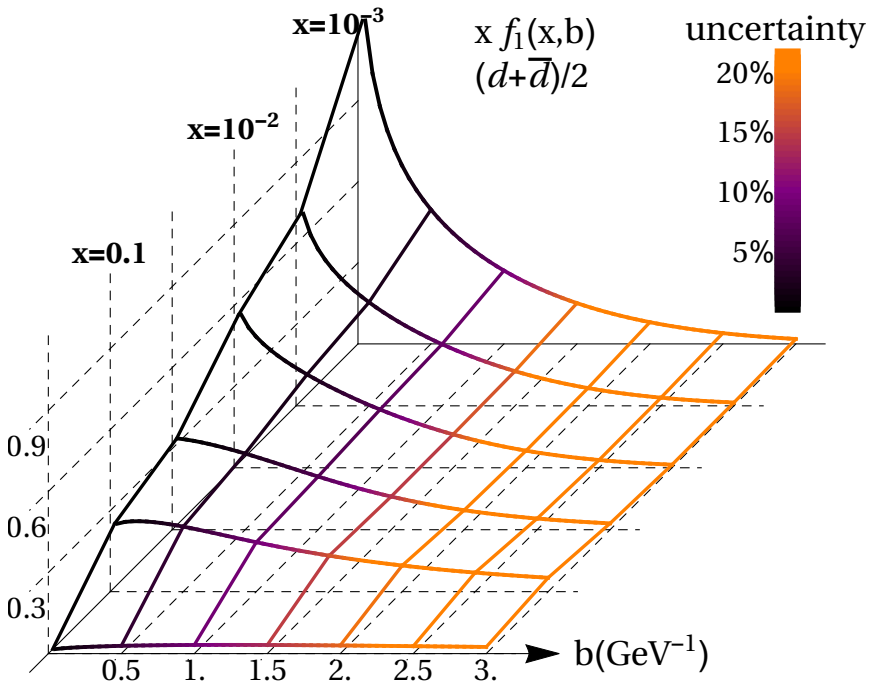
$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y} \sqrt{1 + \frac{q_T^2}{Q^2}}$$

High-energy: CDF, D0, ATLAS, CMS, LHCb
194 points

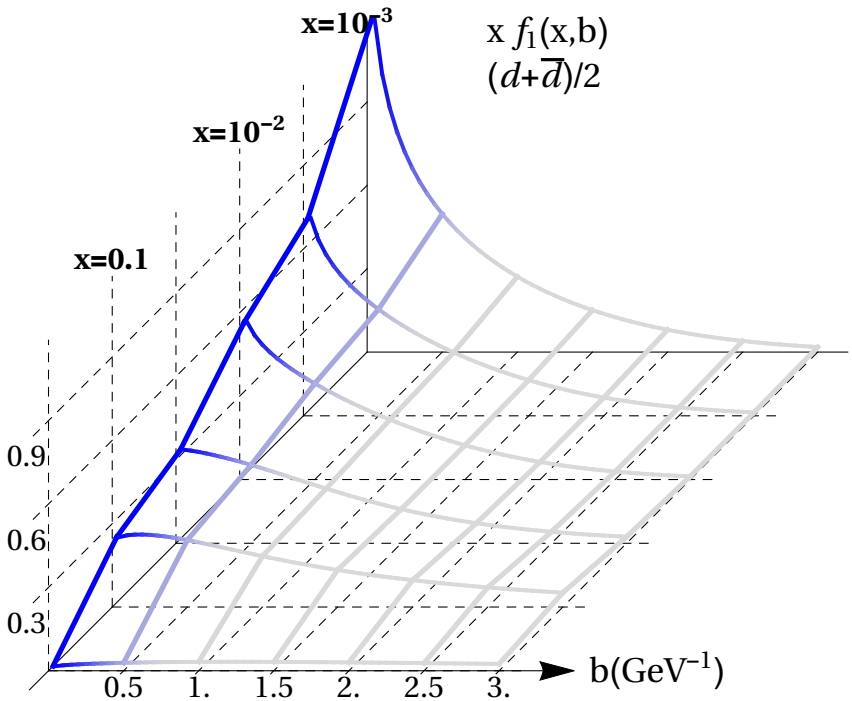
Low-energy: E288, E605, E772, PHENIX
263 points

Total: 457 points
$4 < Q < 150\text{GeV}$
$x > 10^{-4}$

Unpolarized TMDPDF

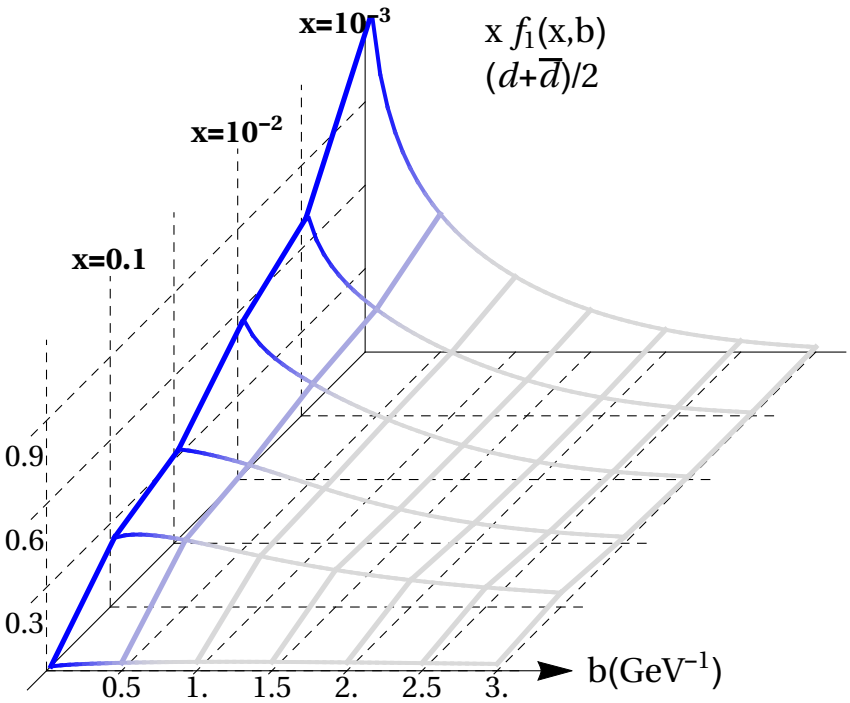


Unpolarized TMDPDF



$$f_1(x,b) = \begin{cases} f_1(x) & b = 0 \\ C \otimes f_1(x) & b \to 0 \\ C \otimes f_1(x) f_{NP}(x,b) & b > 0 \end{cases}$$

Unpolarized TMDPDF

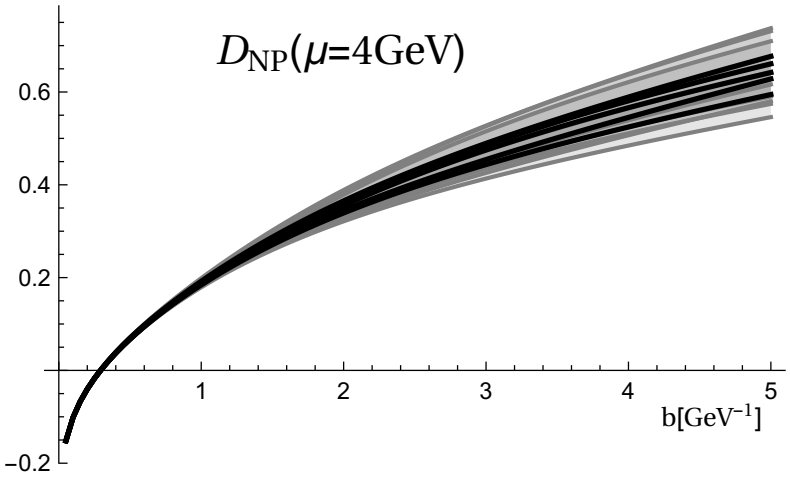


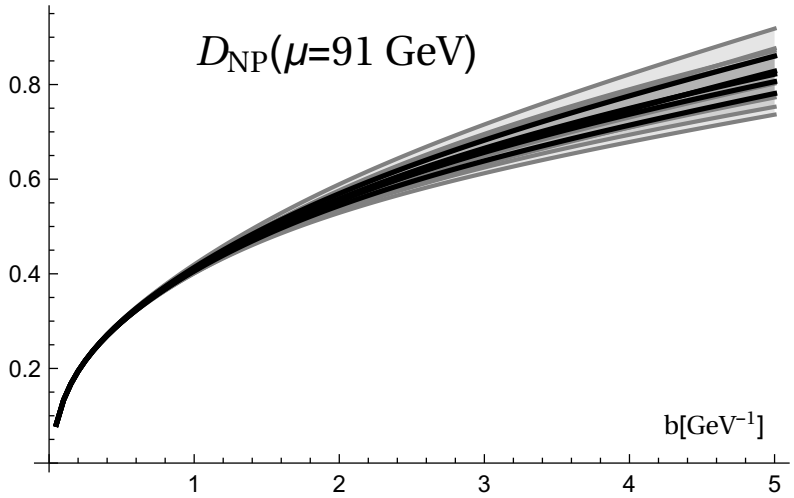
$$f_1(x,b) = \begin{cases} f_1(x) & b = 0 \\ C \otimes f_1(x) & b \to 0 \\ C \otimes f_1(x) f_{NP}(x,b) & b > 0 \end{cases}$$

- `HERAPDF20` $\chi^2/N = 0.95$
- `HERAPDF20` $\chi^2/N = 0.95(\mathrm{N^3LL})$
- `NNPDF3.1` $\chi^2/N = 1.04(\mathrm{N^3LL})$
- `NNPDF3.1` $\chi^2/N = 1.17$
- `MMHT14` $\chi^2/N = 1.35$
- `PDF4LHC_5` $\chi^2/N = 1.56$
- `CT14` $\chi^2/N = 1.63$

TMD factorization be used to restrict PDF uncertainties

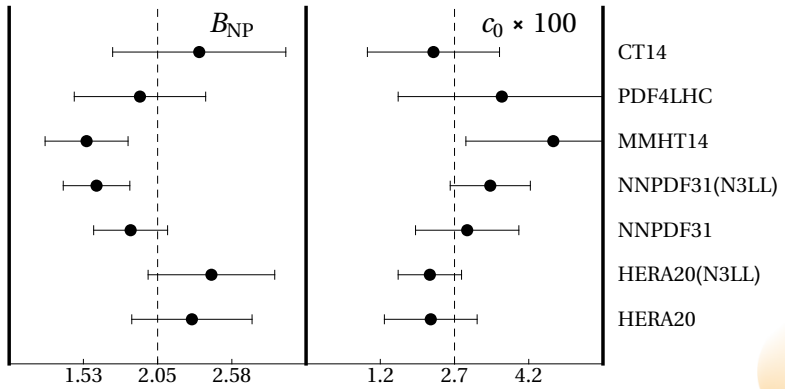
Non-perturbative evolution kernel



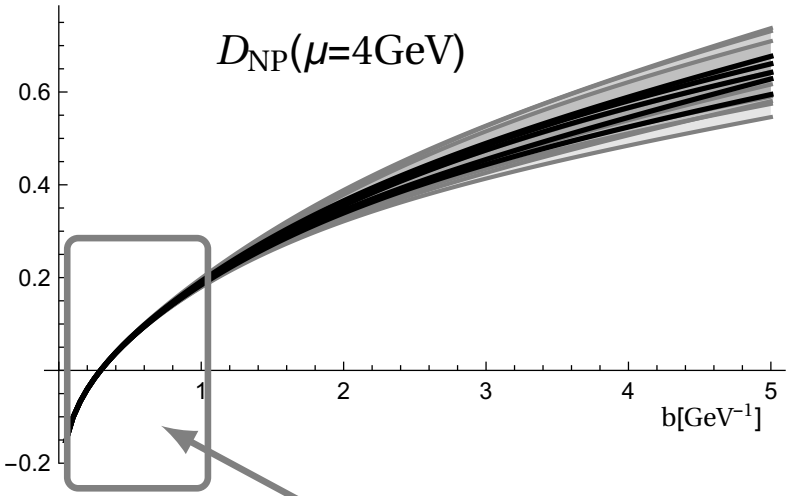


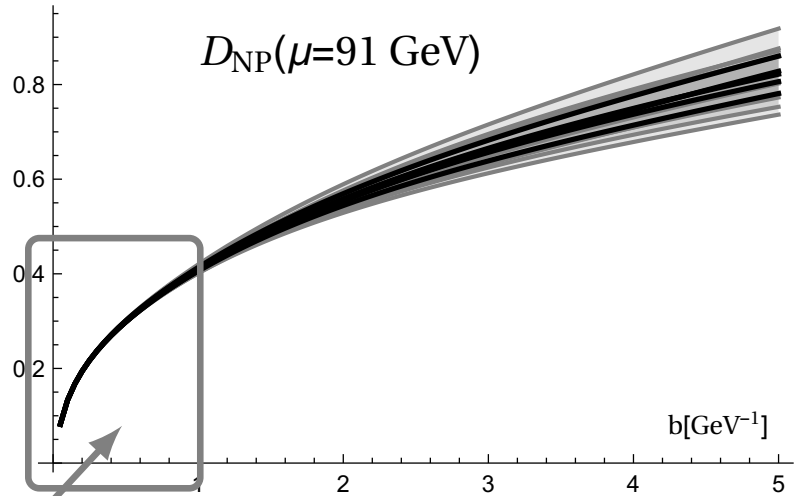
$$\mathcal{D}(\mathbf{b}) = \mathcal{D}_{\rm pert}(b^*(\mathbf{b})) + c_0 \mathbf{b} b^*(\mathbf{b}), \qquad b^*(\mathbf{b}) = \mathbf{b}/\sqrt{1+\mathbf{b}^2/B_{\rm NP}^2}$$

$B_{\rm NP} \simeq 2{\rm GeV}$
$c_0 \simeq 0.03{\rm GeV}^2$



Non-perturbative evolution kernel

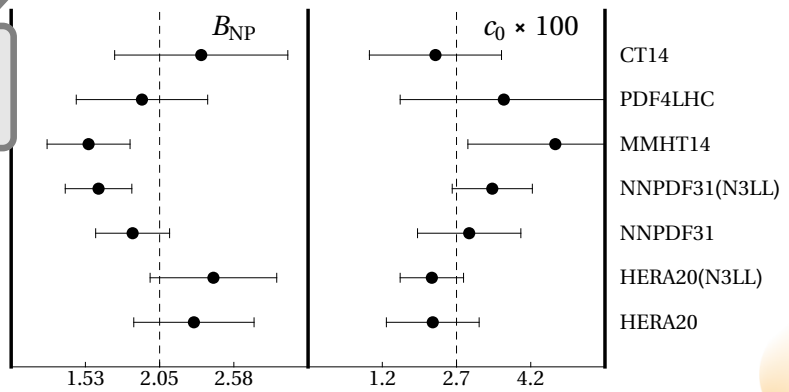




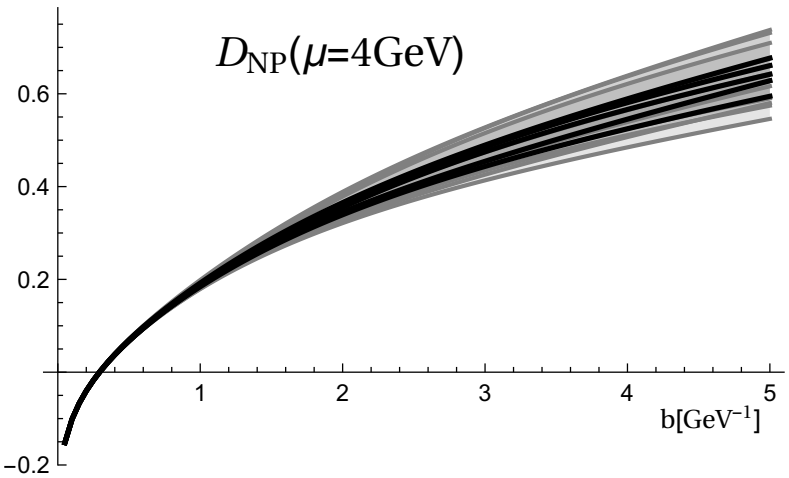
$$\mathcal{D}(\mathbf{b}) = \mathcal{D}_{\rm pert}(b^*(\mathbf{b})) + c_0 \mathbf{b} b^*(\mathbf{b}), \qquad b^*(\mathbf{b}) = \mathbf{b}/\sqrt{1+\mathbf{b}^2/B_{\rm NP}^2}$$

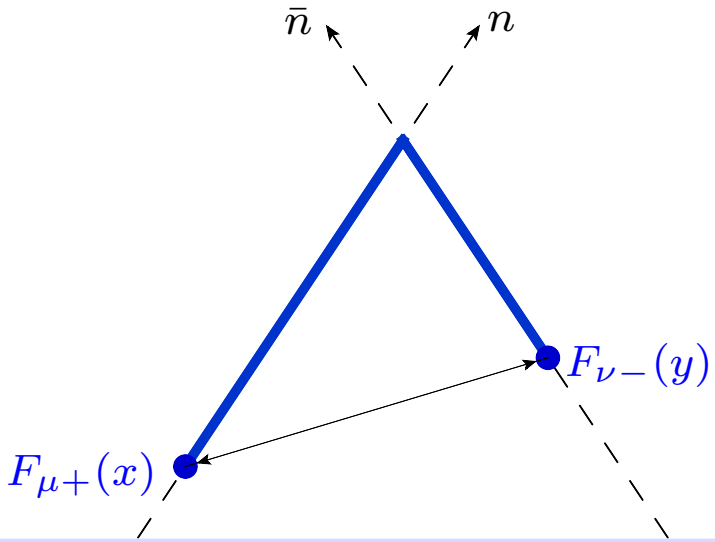
LHC sensitive region

$B_{\rm NP} \simeq 2$
$c_0 \simeq 0.03$GeV^{-2}



Non-perturbative evolution kernel
measures properties of QCD vacuum
(but requires model for interpretation)



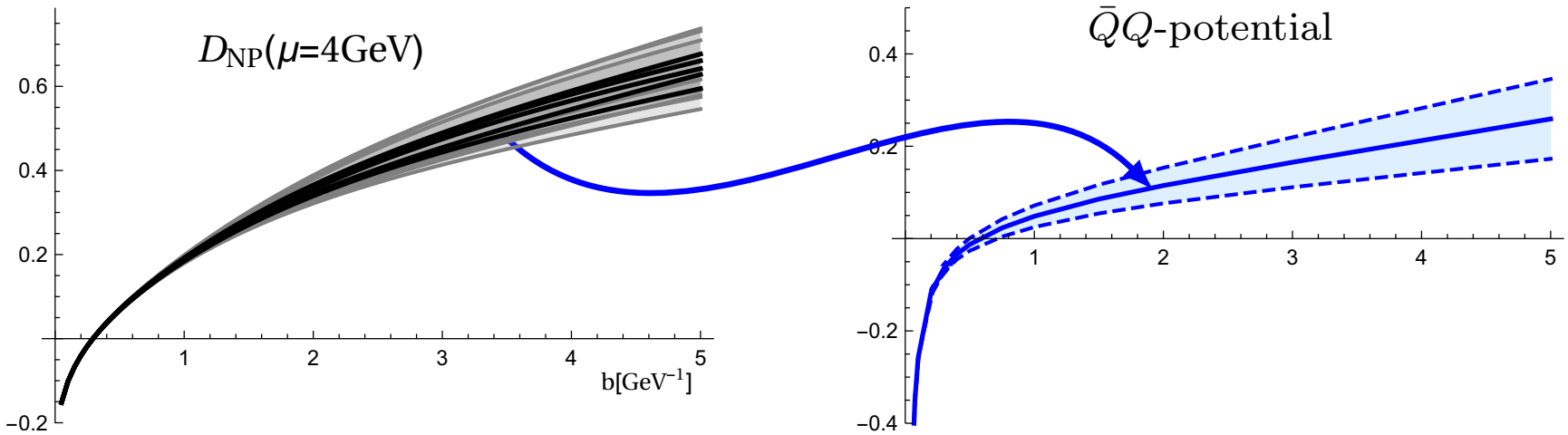


Non-perturbative definition of RAD

$$\mathcal{D} \sim \frac{\langle 0|F_{+b}S|0\rangle}{\langle 0|S|0\rangle}.$$

- Small-b OPE: gluon-correlators with **minimal length connections**
- Non-Abelian Stokes theorem
- A path for model calculations (and interpretation)

Non-perturbative evolution kernel
measures properties of QCD vacuum
(but requires model for interpretation)



Stochastic Vacuum model

- The simplest model of QCD vacuum (Wilson-lines **unimportant**)
- Allows for definition of "confining potential" (linear)

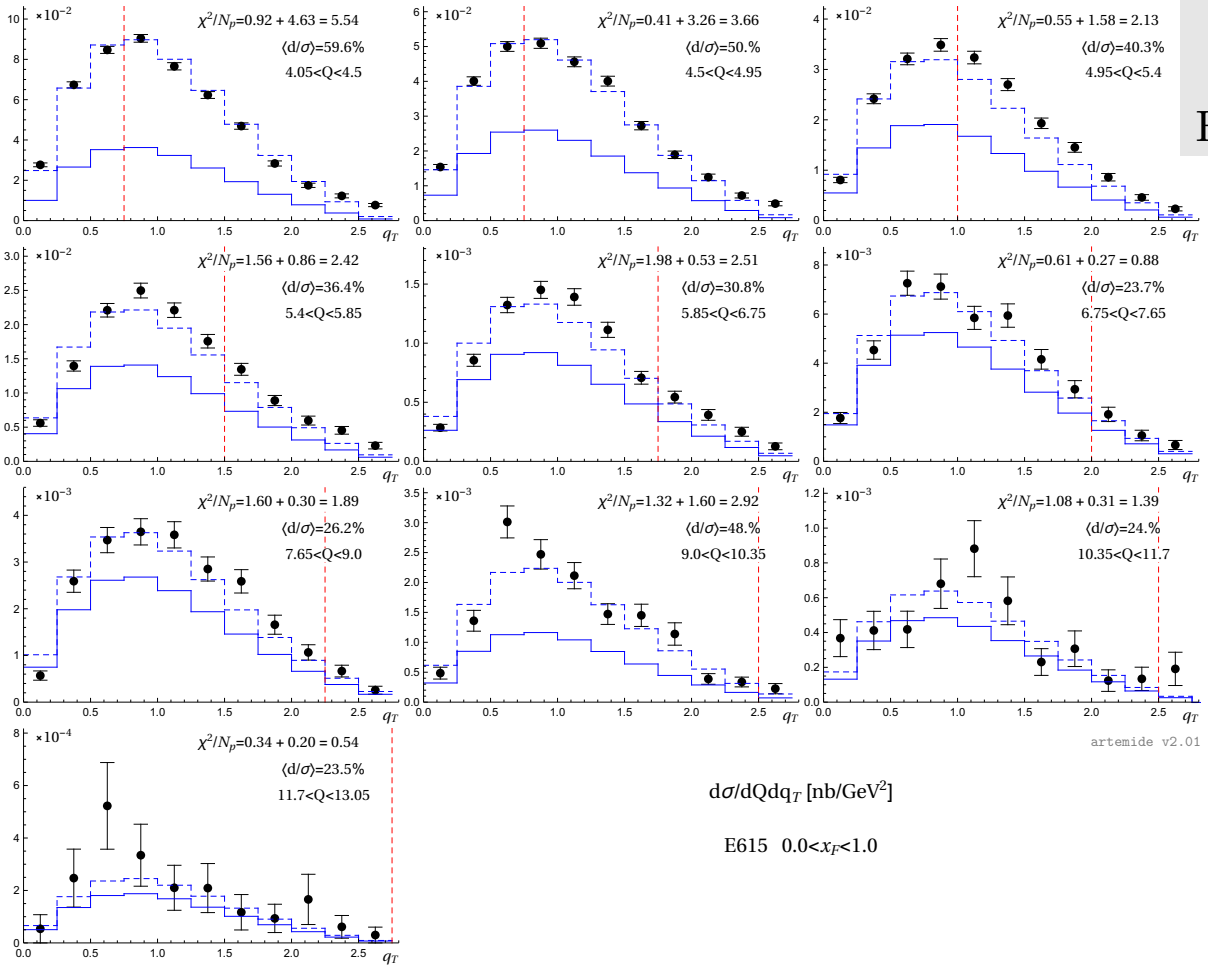
$$V(\mathbf{r}) \quad = \quad \mathbf{r}\frac{\pi}{4}\mathcal{D}''(0) + \frac{\mathcal{D}'(0)}{2} + \frac{\mathbf{r}^2}{2}\int_{\mathbf{r}}^{\infty} d\mathbf{x}\frac{\mathcal{D}'(\mathbf{x})}{\mathbf{x}^2\sqrt{\mathbf{x}^2-\mathbf{r}^2}}.$$

- "String tension" $\sigma = \frac{\pi}{4}\mathcal{D}''(0) = \frac{\pi}{2}c_0 \simeq 0.05 \pm 0.02\text{GeV}^2$ vs. 0.19GeV^2

Extracted
non-perturbative rapidity anomalous dimension
is universal for all TMDs (except gluon)
can be used to extract/analyze/predict other reactions.

lets check...

Pion-induced Drell-Yan [AV,1907.10356]

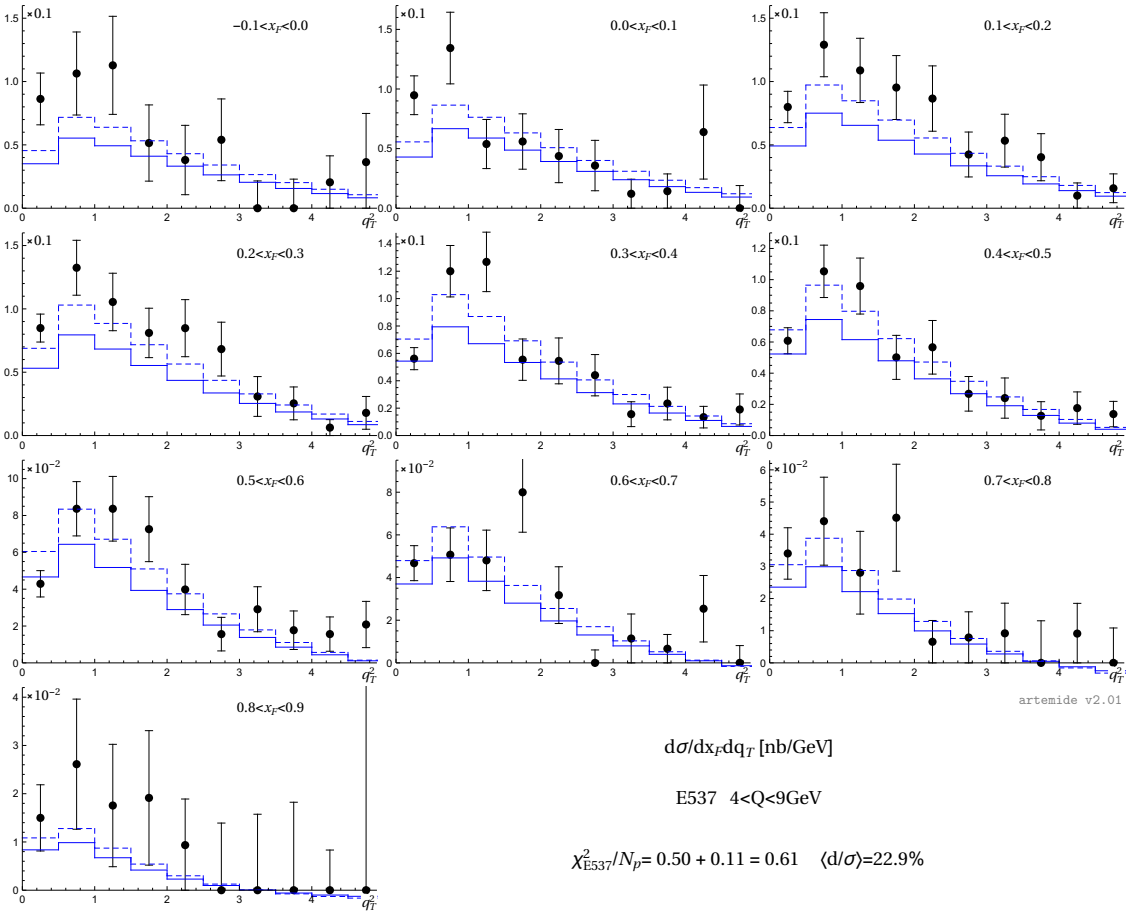


E615
$\chi^2/(N_p = 80) = 1.44$
E615 normalization issue?

dependance on PDF

- `HERAPDF20` 1.44
- `NNPDF3.1` 1.70
- `MMHT14` 1.45

Pion-induced Drell-Yan [AV,1907.10356]

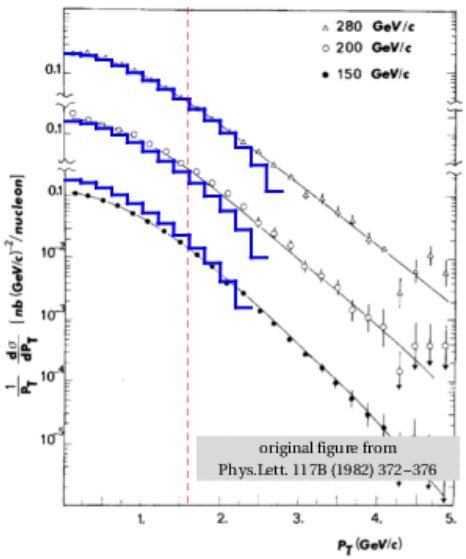


$d\sigma/dx_F dq_T$ [nb/GeV]

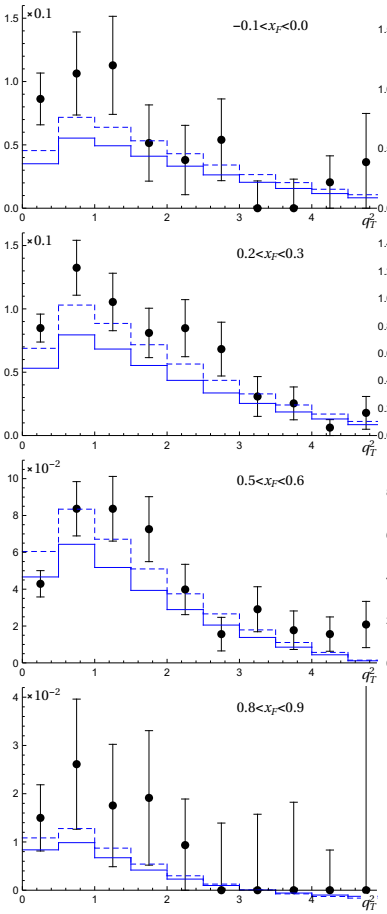
E537 4<Q<9GeV

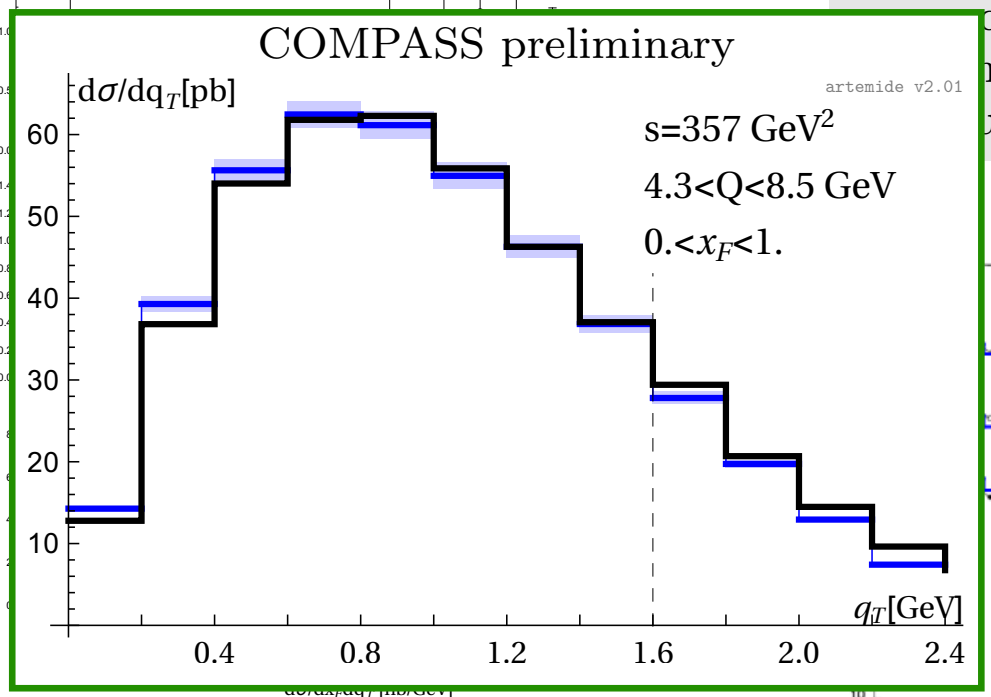
χ^2_{E537}/N_p= 0.50 + 0.11 = 0.61 $\langle d/\sigma \rangle$=22.9%

E537, NA3
does not show
normalization problem
(but quality of data is low)

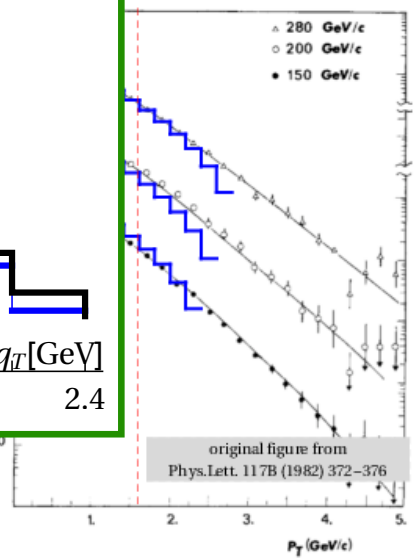


Pion-induced Drell-Yan [AV,1907.10356]

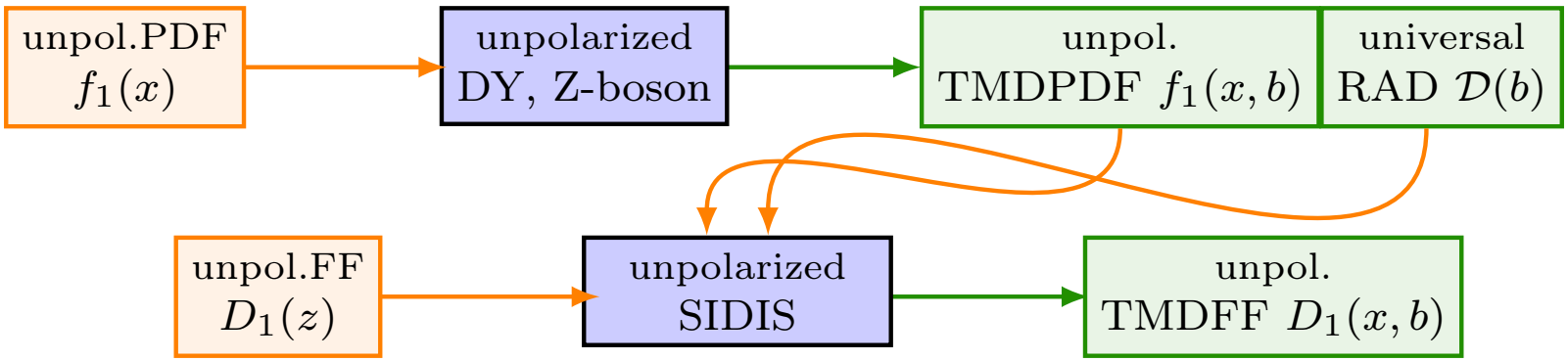


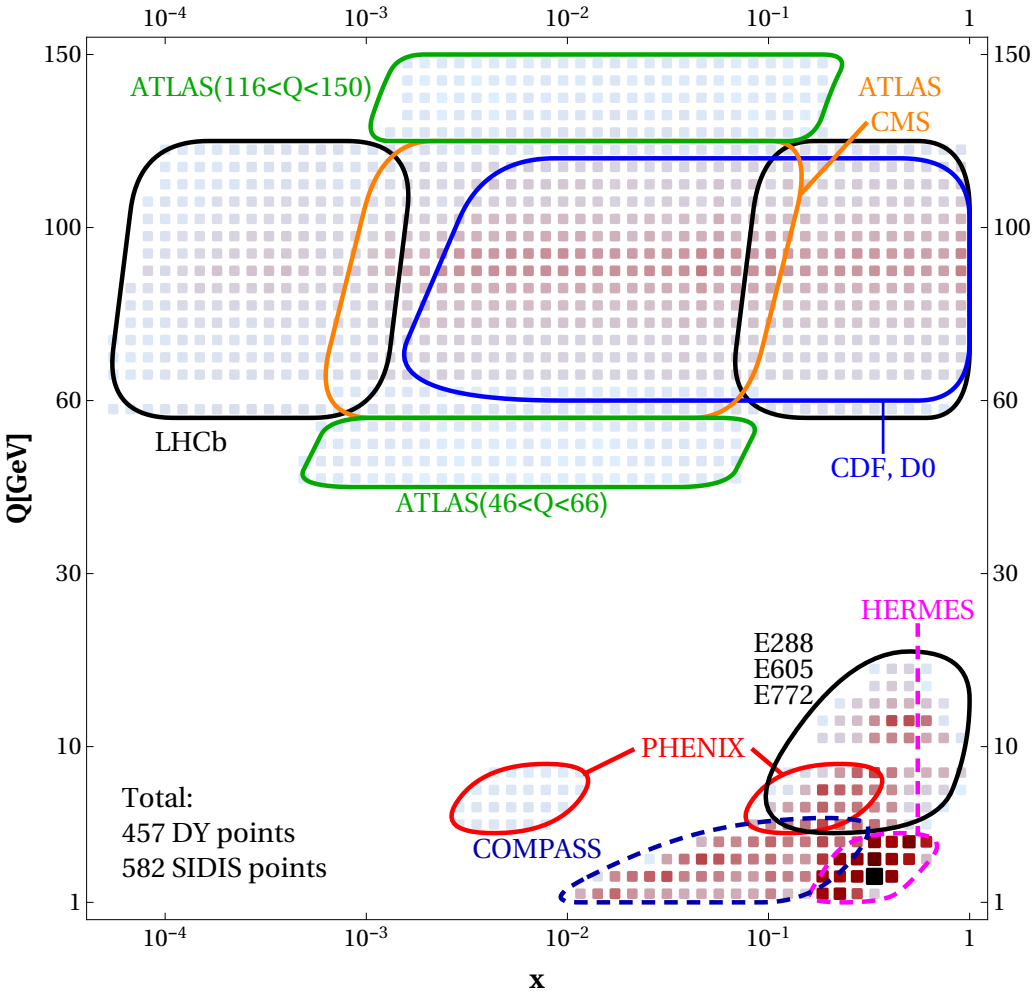


E537, NA3
does not show
nalization problem
uality of data is low)



Stage 2
[I.Scimemi, AV, 2019 (in preparation)]





Same cut as in DY:

$q_T \simeq \frac{p_\perp}{z} < 0.25Q$

Additionally:

$\langle Q \rangle > 2\text{GeV}$

HERMES: 192
COMPASS: 390

Total: 582 points

SIDIS multiplicities are **easily** described by TMD factorization

PDF	FF	χ^2/N_{pt}
NNPDF3.1	DSS14	1.00
NNPDF3.1	JAM19	1.07
HERA20	DSS14	0.77
HERA20	JAM19	0.93
NNPDF3.1	NNFF1.1	6.9

Compare to A.Bacchetta, et al [1703.10157] $\chi^2/N = 1.55$ (NLO/LO/b^*)

SIDIS multiplicities are **easily** described by TMD factorization

PDF	FF	χ^2/N_{pt}
NNPDF3.1	DSS14	1.00
NNPDF3.1	JAM19	1.07
HERA20	DSS14	0.77
HERA20	JAM19	0.93
NNPDF3.1	NNFF1.1	6.9

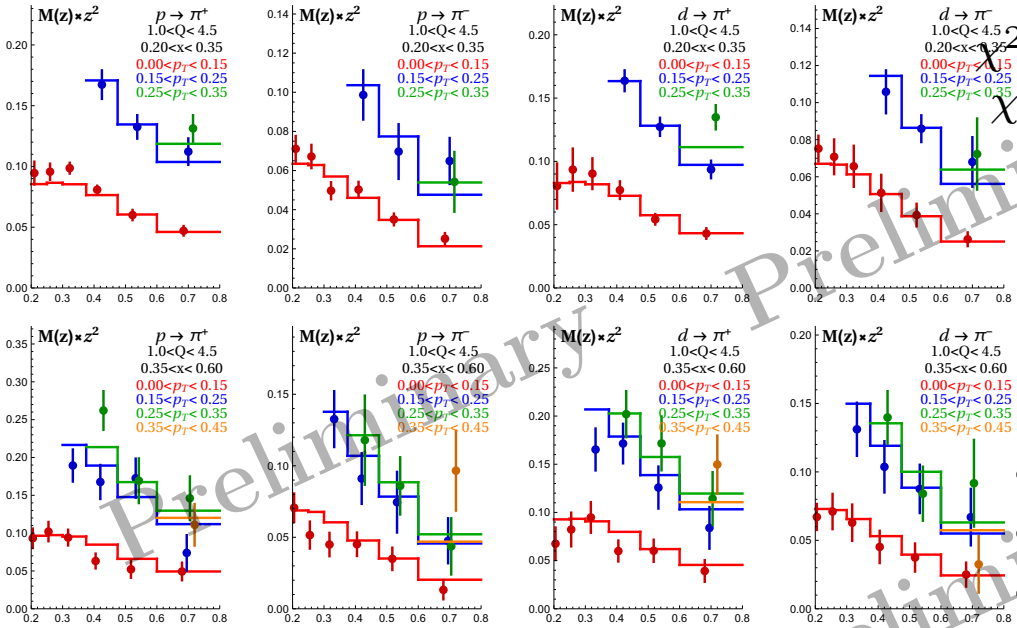
Compare to A.Bacchetta, et al [1703.10157] $\chi^2/N = 1.55$ (NLO/LO/b^*)

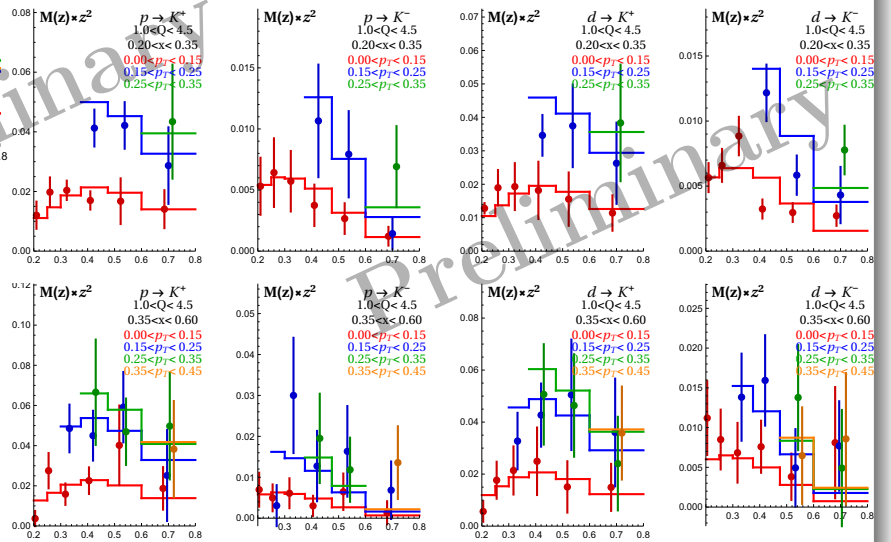
Small-χ^2 resulted by COMPASS measurement:

- Large uncorrelated systematic

$\Rightarrow$ Smooth lines with (uncorrelated) large-uncertainty.

HERMES





HERMES

$\chi^2/(N_p = 192) = 1.05$ (NNPDF+DSS)

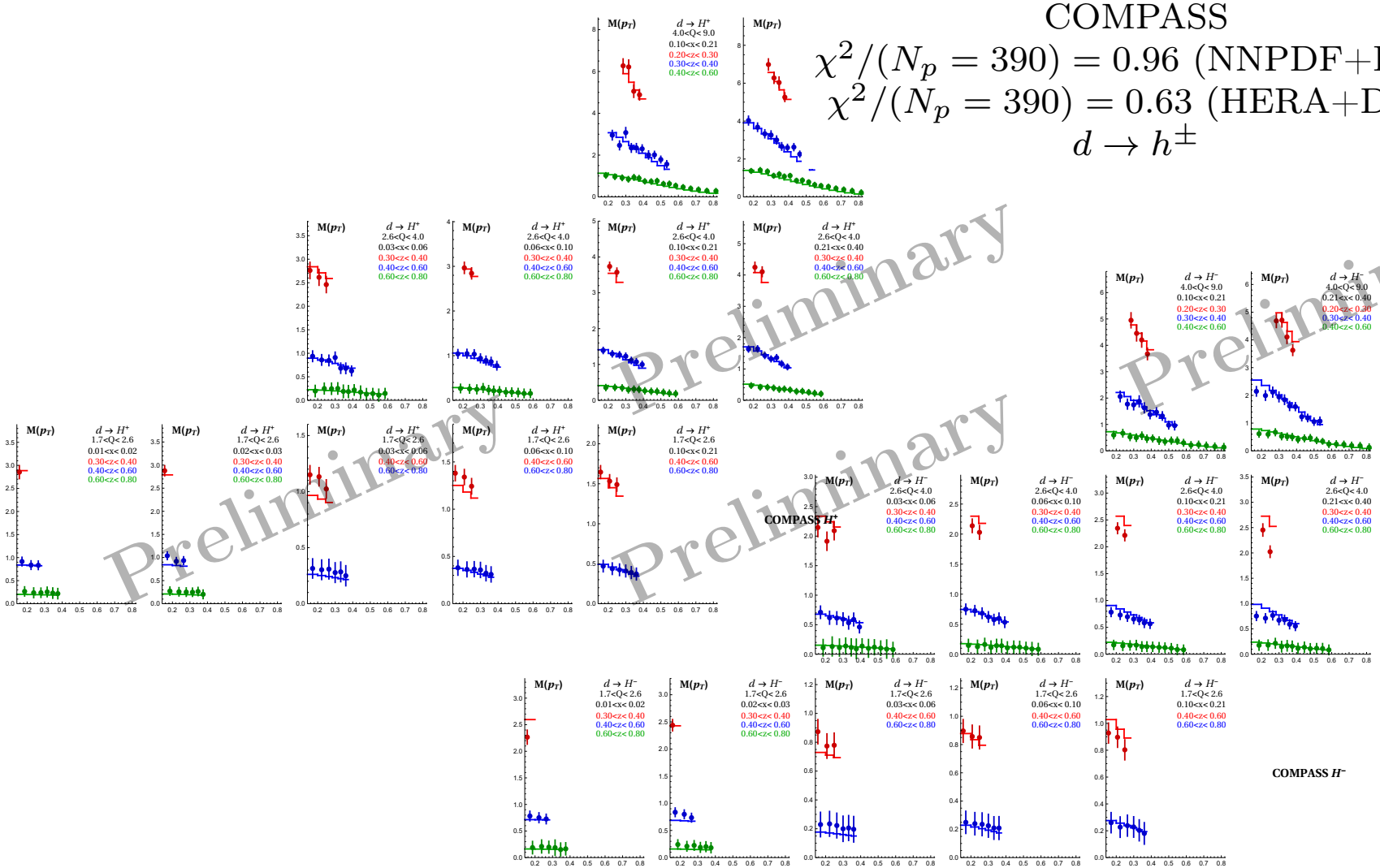
$\chi^2/(N_p = 192) = 1.02$ (HERA+DSS)

$p \to \pi^{\pm}$

$d \to \pi^{\pm}$

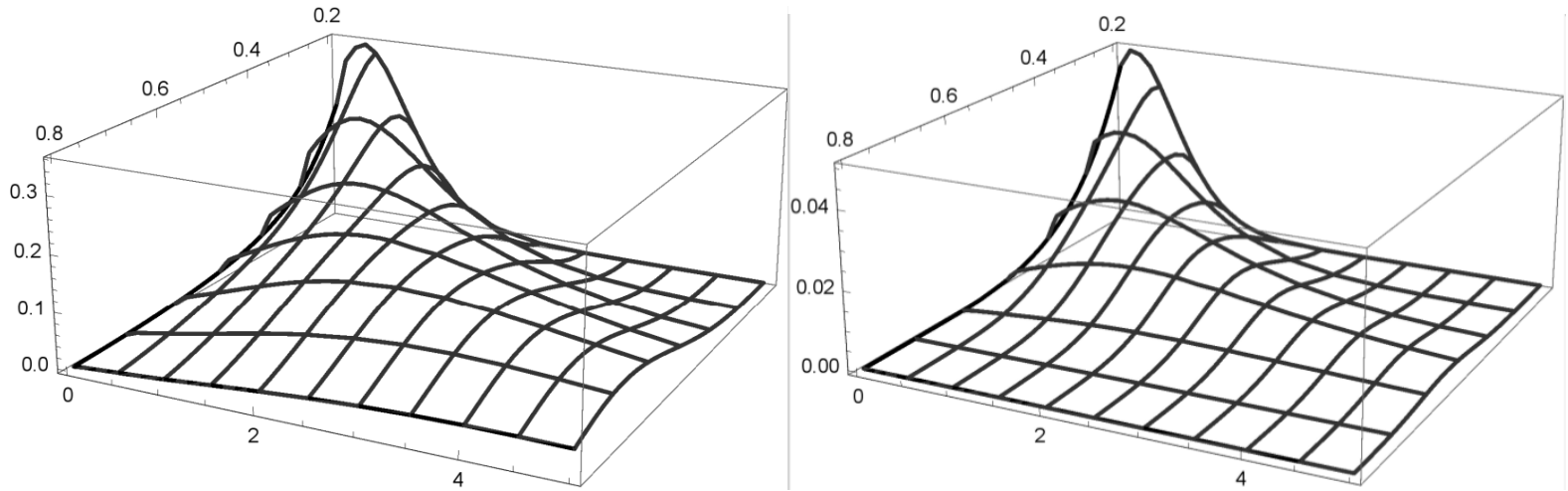
$p \to K^{\pm}$

$d \to K^{\pm}$


COMPASS
$\chi^2/(N_p = 390) = 0.96$ (NNPDF+DSS)
$\chi^2/(N_p = 390) = 0.63$ (HERA+DSS)
$d \to h^{\pm}$
Preliminary
Preliminary
Preliminary
Preliminary
COMPASS H^+
COMPASS H^-

Global fit: DY+SIDIS
fine-tuning of parameters
$\chi^2 : 1.00 \to 0.94$

Work still in progress (error-propagation)



Conclusion

What is done

- **non-perturbative TMD evolution** (NNLO/N^{3}LO)
- unpolarized TMDPDF (proton/pion)
- unpolarized TMDFF (pion/kaon)

Meanwhile...

Unpolarized low-q_T spectrum is under control

- restriction on collinear distributions (join fits?)
- pseudo-data/predictions for on-going/future experiments (`artemide`)

Future

- Sivers function (NLO)
  - Theory calculation ✓
  - Implementation of $T(x_1, x_2, x_3)$ evolution (in progress)
  - Joined fit of g_2 and SSA