Unpolarised quark TMDs: extraction, problems and prospects

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3DSPIN MAPPING THE PROTON IN 3D

European Research Council

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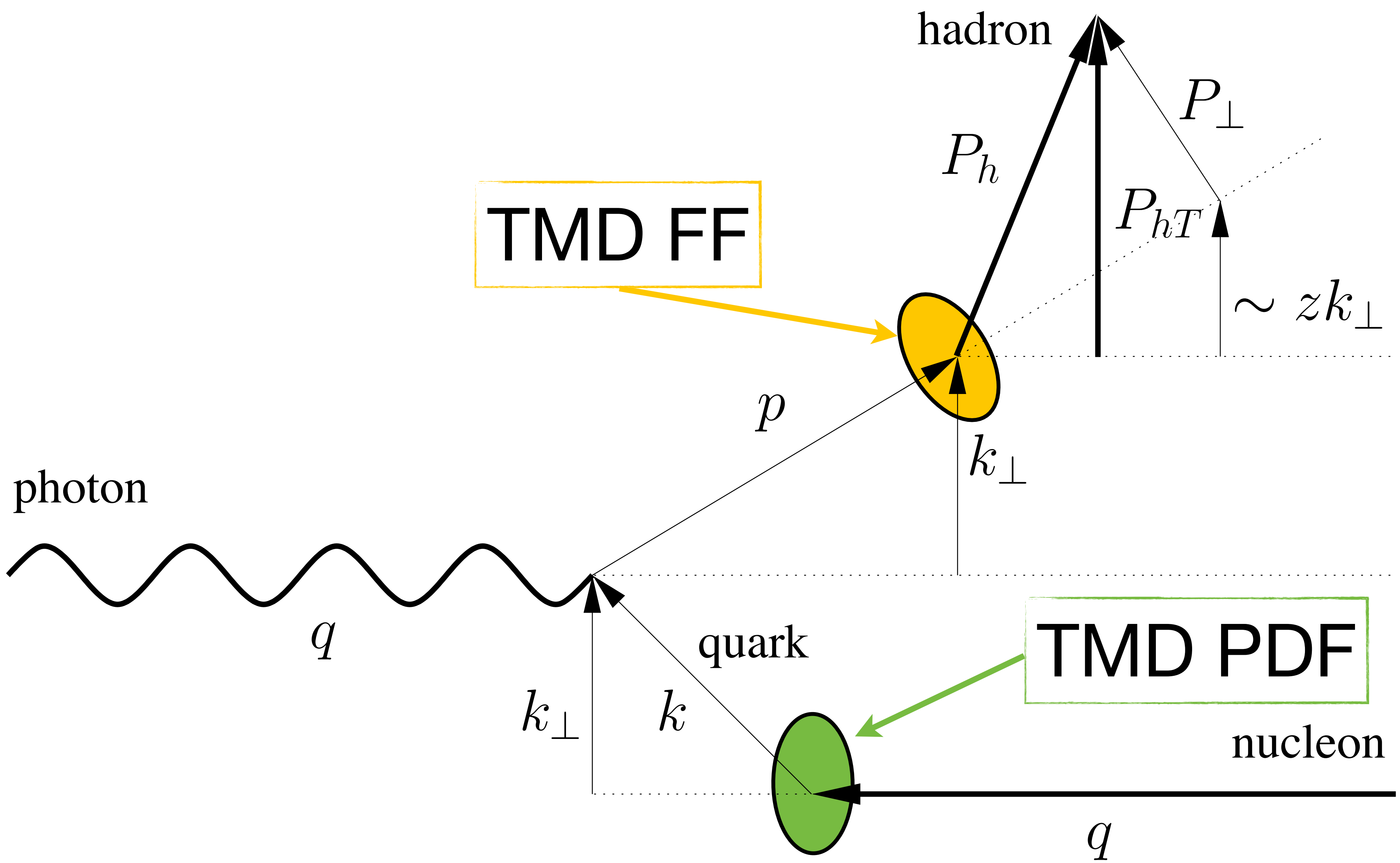
Part 1
Unpolarised quark TMD:
past, present and future of an almost-global fit

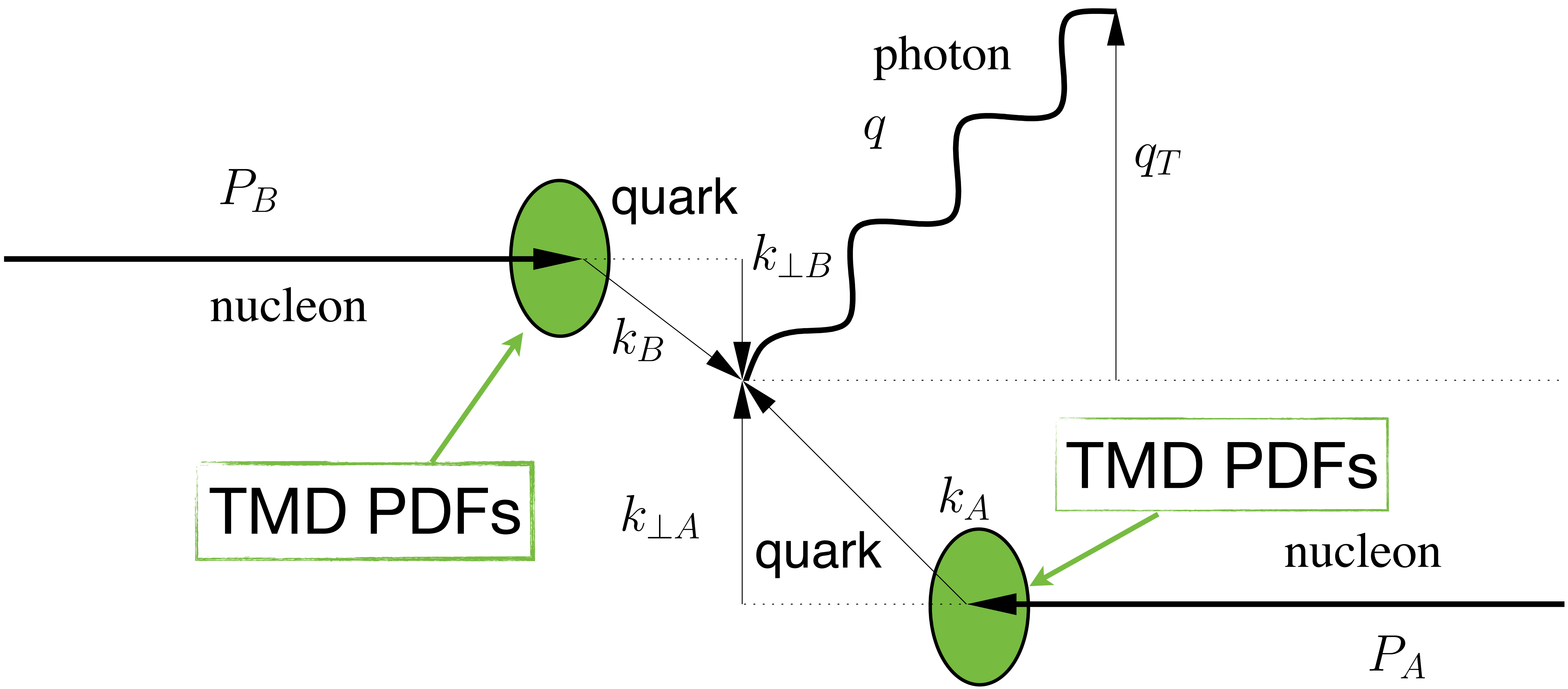
Semi-inclusive Deep Inelastic Scattering

$$l(\ell) + N(\mathcal{P}) \to l(\ell') + h(\mathcal{P}_h) + X$$



Drell-Yan processes and Z production

$$A + B \to \gamma^* \to l^+ l^- \qquad A + B \to Z \to l^+ l^-$$



A selection of results

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

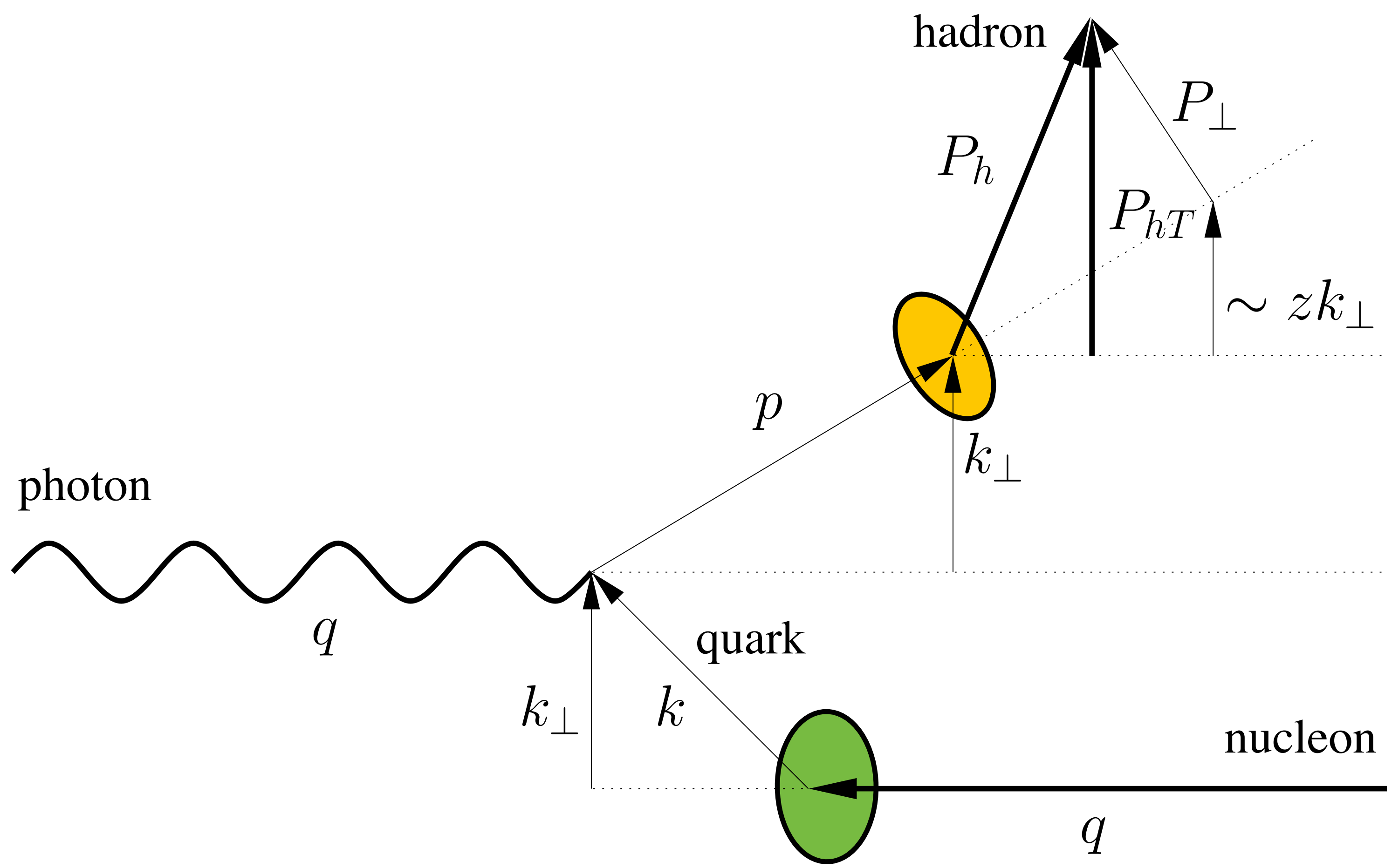
Pavia (realistically) 2019: NLO-NLL + LHC data!

SIDIS: fitting the hadron multiplicities

$$m_N^h(x, z, |\boldsymbol{P}_{hT}|, Q^2) = \frac{d\sigma_N^h/(dx\,dz\,d|\boldsymbol{P}_{hT}|\,dQ^2)}{d\sigma_{\mathrm{DIS}}/(dx\,dQ^2)} = \frac{2\pi\,|\boldsymbol{P}_{hT}|F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) + \cancel{2\pi\varepsilon|\boldsymbol{P}_{hT}|F_{UU,L}(x, z, \boldsymbol{P}_{hT}^2, Q^2)}}{F_T(x, Q^2) + \cancel{\varepsilon F_L(x, Q^2)}}$$

higher in α_s

$M^2 \ll Q^2$, $P_{hT}^2 \ll Q^2$



At present accuracy

(LO-NLL)

$\mathcal{H}_{UU,T} \simeq \mathcal{O}\left(\alpha_s^0\right)$

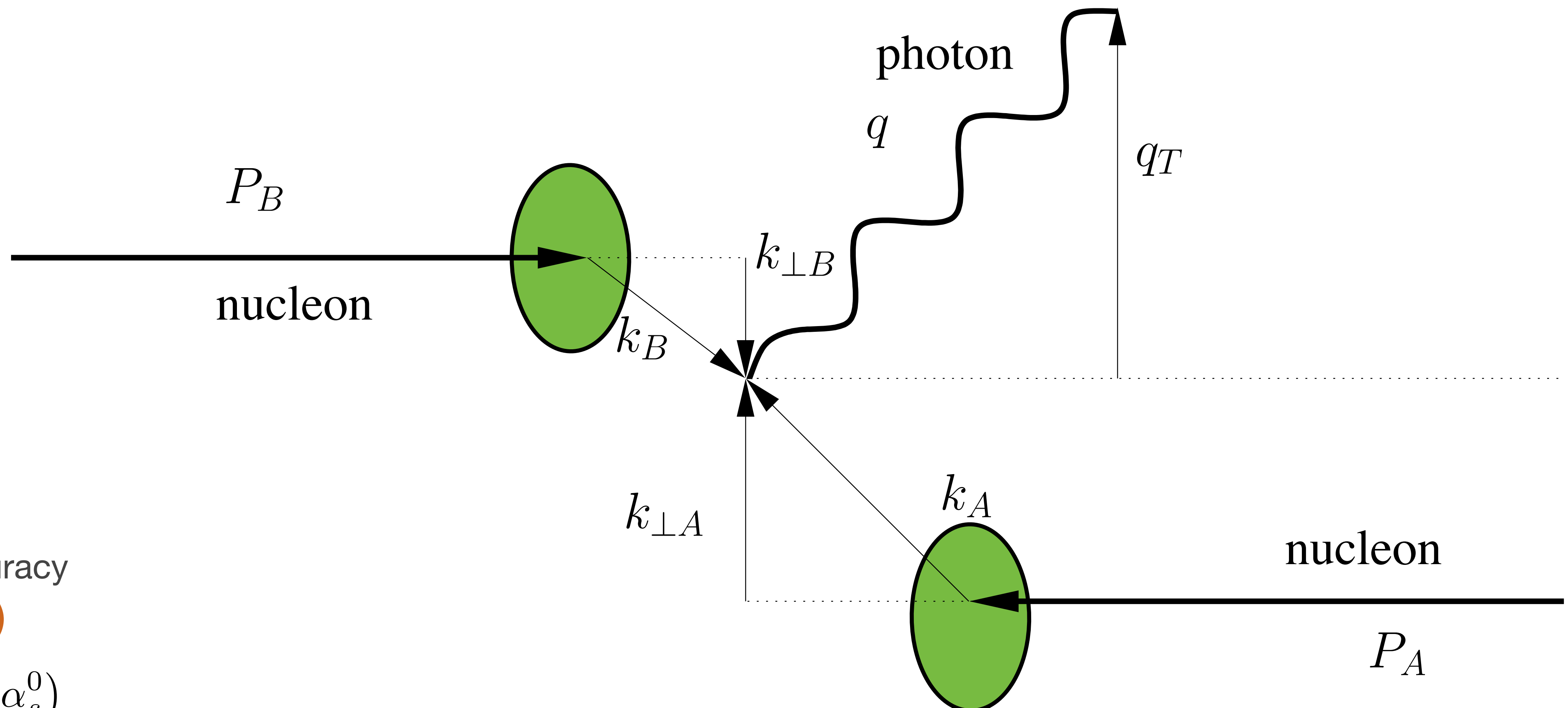
$Y_{UU,T}\left(Q^2, P_h^2 T\right) \simeq 0$

$$\boxed{F_{UU,T}\left(x, z, P_{hT}^2, Q^2\right)} = \sum_a \overset{1}{\cancel{\mathcal{H}^a_{UU,T}(Q^2;\mu^2)}} \int d^2k_T\, d^2P_T\, f_1^a\left(x, k_T^2; \mu^2\right) D_1^{h/a}\left(z, P_T^2; \mu^2\right)$$

$$\cdot\delta^2(zk_T - P_{hT} + P_T) + \cancel{Y_{UU,T}(Q^2, P_{hT}^2)} + \mathcal{O}\left(M^2/Q^2\right)$$

DY: fitting the q_T distributions

$$\frac{d\sigma}{dQ^2\, dq_T^2\, d\eta} = \sigma_0^{\gamma,Z} \left(F_{UU}^1 + \cancel{\frac{1}{2} F_{UU}^2} \right) \quad q_T^2 \ll Q^2$$



At present accuracy
(LO-NLL)

$\mathcal{H}_{UU,T} \simeq \mathcal{O}\left(\alpha_s^0\right)$

$Y_{UU,T}\left(Q^2, P_h^2 T\right) \simeq 0$

$$\boxed{F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2)} = \sum_a \overset{1}{\cancel{\mathcal{H}_{UU}^{1a}(Q^2)}} \times \int d^2\boldsymbol{k}_{\perp A} d^2\boldsymbol{k}_{\perp B} \boxed{f_1^a(x_A, \boldsymbol{k}_{\perp A}^2; Q^2)} \boxed{f_1^{\bar{a}}(x_B, \boldsymbol{k}_{\perp B}^2; Q^2)} \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$
$$+ \cancel{Y_{UU}^1(Q^2, \boldsymbol{q}_T^2)} + \mathcal{O}(M^2/Q^2)\,.$$

Evolution of TMDs

analogous formula for FF

Fourier transform: $\xi_T(b_T)$ space

$$f_1^a\left(x, k_\perp; \mu^2\right) = \frac{1}{2\pi}\int d^2\xi_T e^{-i\xi_T\cdot k_\perp}\tilde{f}_1^a\left(x, \xi_T; \mu^2\right)$$

$$\tilde{f}_1^a\left(x, \xi_T; \mu^2\right) =$$

$$= \sum_i \left(\tilde{C}_{a/i}\otimes f_1^i\right)\left(x, \bar{\xi}_*; \mu_b\right) e^{\tilde{S}(\bar{\xi}_*;\mu_b,\mu)} e^{g_K(\xi_T)\ln(\mu/\mu_0)} \hat{f}_{NP}^a\left(x, \xi_T\right)$$

collinear PDF
(extracted from data)

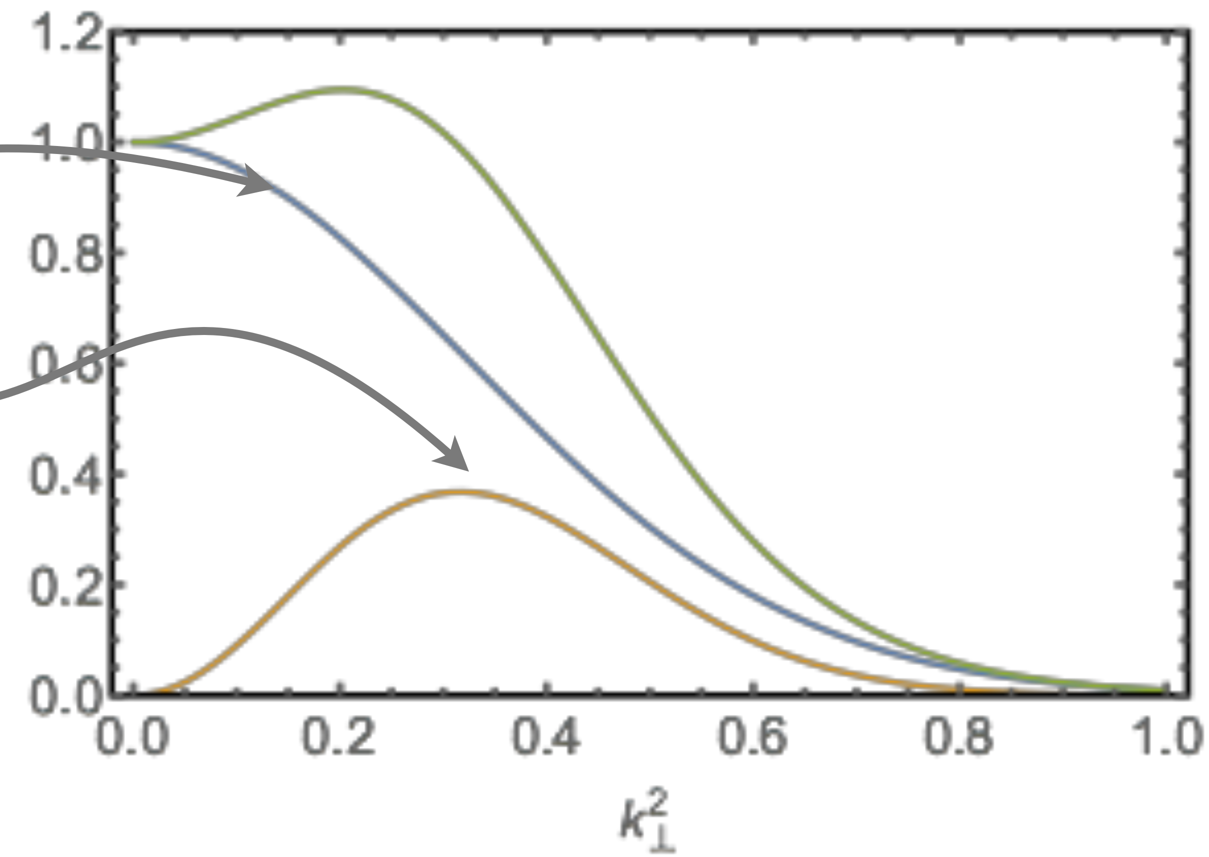
NP part of evolution
(extracted from data)

NP part of TMD
(extracted from data)

perturbative QCD

Model: non perturbative elements

$$f^a_{1NP}(x,k_\perp^2) = \frac{1}{\pi}\frac{(1+\lambda k_\perp^2)}{g_{1a}+\lambda g_{1a}^2}\, e^{-\frac{k_\perp^2}{g_{1a}}}$$



$$N_1 \equiv g_1(\hat{x}) \qquad \hat{x} = 0.1$$

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

weighted sum of two Gaussian distributions:

same widths for TMD PDFs

different widths for TMD FFs

$$D^{a\to h}_{1NP}(z,P_\perp^2) = \frac{1}{\pi}\frac{1}{g_{3a\to h}+(\lambda_F/z^2)g^2_{4a\to h}}\left(e^{-\frac{P_\perp^2}{g_{3a\to h}}} + \lambda_F \frac{P_\perp^2}{z^2}\, e^{-\frac{P_\perp^2}{g_{4a\to h}}}\right)$$

$$\hat{z} = 0.5$$

$$g_{3,4}(z) = N_{3,4}\frac{(z^\beta+\delta)(1-z)^\gamma}{(\hat{z}^\beta+\delta)(1-\hat{z})^\gamma}$$

Inspired by **model calculations**:

Matevosyan et al.
Phys. Rev. D85, 014021 (2012), 1111.1740
Bacchetta et al.
Phys. Lett. B659, 234 (2008), 0707.3372
Bacchetta at al.
Phys. Rev. D65, 094021 (2002),
hep-ph/0201091

Model: non-perturbative evolution

$$g_K(b_T; g_2) = -g_2 \frac{b_T^2}{2}$$

Large bt correction to evolution (other functional forms to be explored)

There are **11 free parameters** in a flavor independent scenario

Model: b$_T$-integration

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

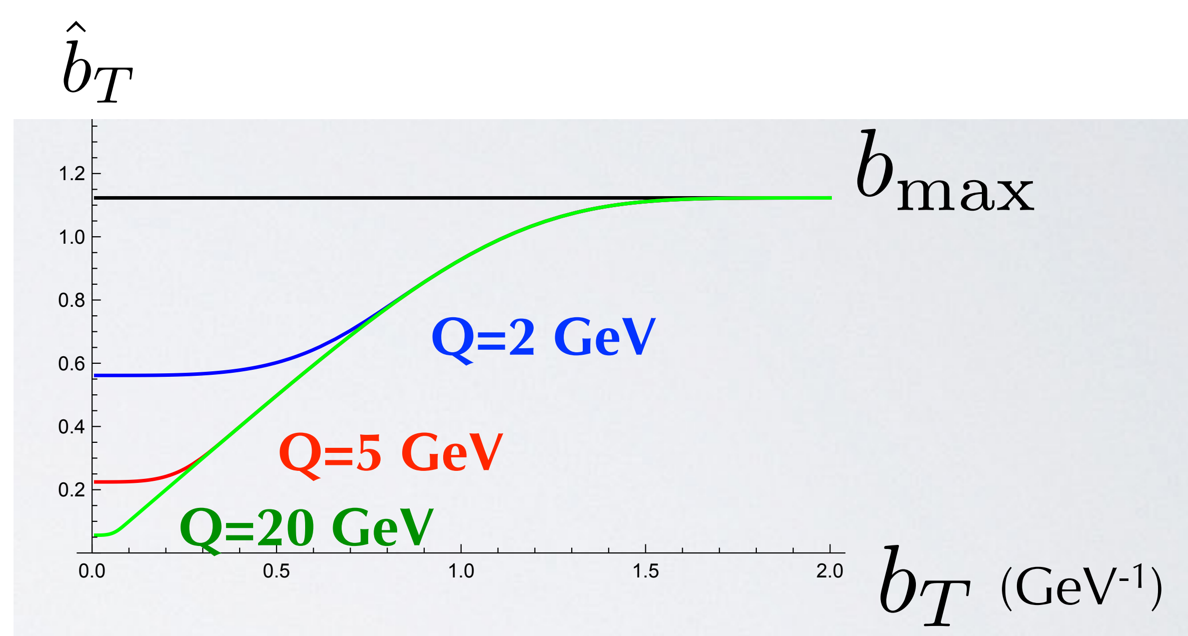
$b_{\max}$, $b_T \to +\infty$ avoid Landau pole

$b_{\min}$, $b_T \to 0$ recover collinear fact.

$b_{min}=2e^{-gammaE}$, $b_{max}=2e^{-gammaE}/Q$

Regularization needed to **recover the cross section integrated over qT** in collinear factorization.

Crucial from the **theory** point of view and for the **phenomenology of SIDIS (low Q)**



Experimental data

SIDIS μN

6252
data points

SIDIS eN

1514
data points

March 2018: 2124 new data points —> fit in progress!

Total: 8059 data points

E288

E605

Drell-Yan

203
data points

Z Production

90
data points

Work in progress!

7 TeV
8 TeV

$$q\bar{q} \to Z_0/\gamma^* + X$$

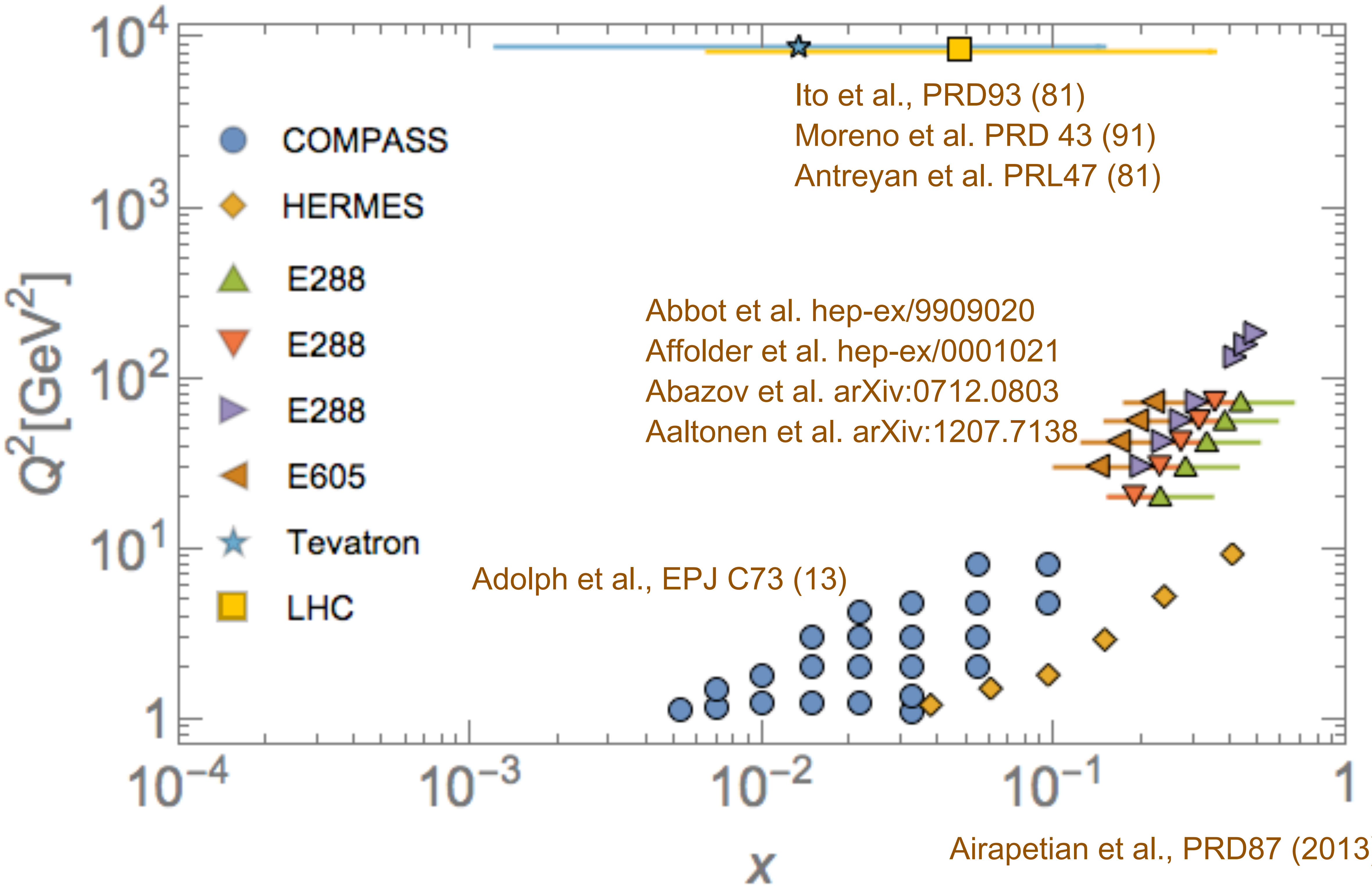
7 TeV
8 TeV

$$pp \to Z_0/\gamma^* \to (\mu^+ + \mu^-/e^+ + e^-)$$

7 TeV
8 TeV
13 TeV

$$pp \to Z_0 \to \mu^+ + \mu^-$$

Distribution of data



Data selection: SIDIS

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Reference	[61]			
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \mathrm{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV			
Points	190	190	189	187
Max. Q^2	9.2 GeV^2			
x range	$0.06 < x < 0.4$			

TMD factorization
($P_{hT}^2/z^2 << Q^2$)

avoid target fragmentation
(low z)
and exclusive contributions
(high z)

Problem with normalization
in the previous release

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Reference						
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \mathrm{Min}[0.2\ Q, 0.6\ Qz] + 0.5$ GeV					
Points	188	188	186	187	3024	3021
Max. Q^2	9.2 GeV^2				10 GeV^2	
x range	$0.06 < x < 0.4$				$0.006 < x < 0.12$	
					Observable: $\dfrac{m_N^h(x, z, \boldsymbol{P}_{hT}^2, Q^2)}{m_N^h(x, z, \mathrm{Min}[\boldsymbol{P}_{hT}^2], Q^2)}$	

Data selection: Drell-Yan & Z

	E288 200	E288 300	E288 400	E605
Cuts	$q_T < 0.2\ Q + 0.5$ GeV			
Points	45	45	78	35
$\sqrt{s}$	19.4 GeV	23.8 GeV	27.4 GeV	38.8 GeV
Q range	4-9 GeV	4-9 GeV	5-9, 11-14 GeV	7-9, 10.5-18 GeV
Kin. var.	y=0.4	y=0.21	y=0.03	$-0.1 < x_F < 0.2$

Drell-Yan data

Z production data

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Cuts	$q_T < 0.2\ Q + 0.5$ GeV $= 18.7$ GeV			
Points	31	14	37	8
$\sqrt{s}$	1.8 TeV	1.8 TeV	1.96 TeV	1.96 TeV

An almost-global fit

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059

PROs

almost a **global fit** of quark unpolarized TMDs

includes **TMD evolution**

replica (bootstrap) fitting methodology

kinematic dependence for intrinsic k_T

beyond Gaussian assumption for intrinsic k_T

CONs

no “pure” info on TMD FFs (would need $e^+ e^-$ data)

accuracy of TMD evolution: not the state of the art*

only “low” q_T (no fixed order and Y-term)*

no flavor dependence**

*** working on it!**

**** thinking about working on it!**

Agreement data-theory

Flavor independent configuration
11 parameters

Points	Parameters	χ^2	χ^2/d.o.f.
8059	11	12629 ± 363	1.55 ± 0.05

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Points	190	190	189	187
χ^2/points	4.83	2.47	0.91	0.82

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Points	190	190	189	189	3125	3127
χ^2/points	3.46	2.00	1.31	2.54	1.11	1.61

	E288 [200]	E288 [300]	E288 [400]	E605
Points	45	45	78	35
χ^2/points	0.99	0.84	0.32	1.12

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Points	31	14	37	8
χ^2/points	1.36	1.11	2.00	1.73

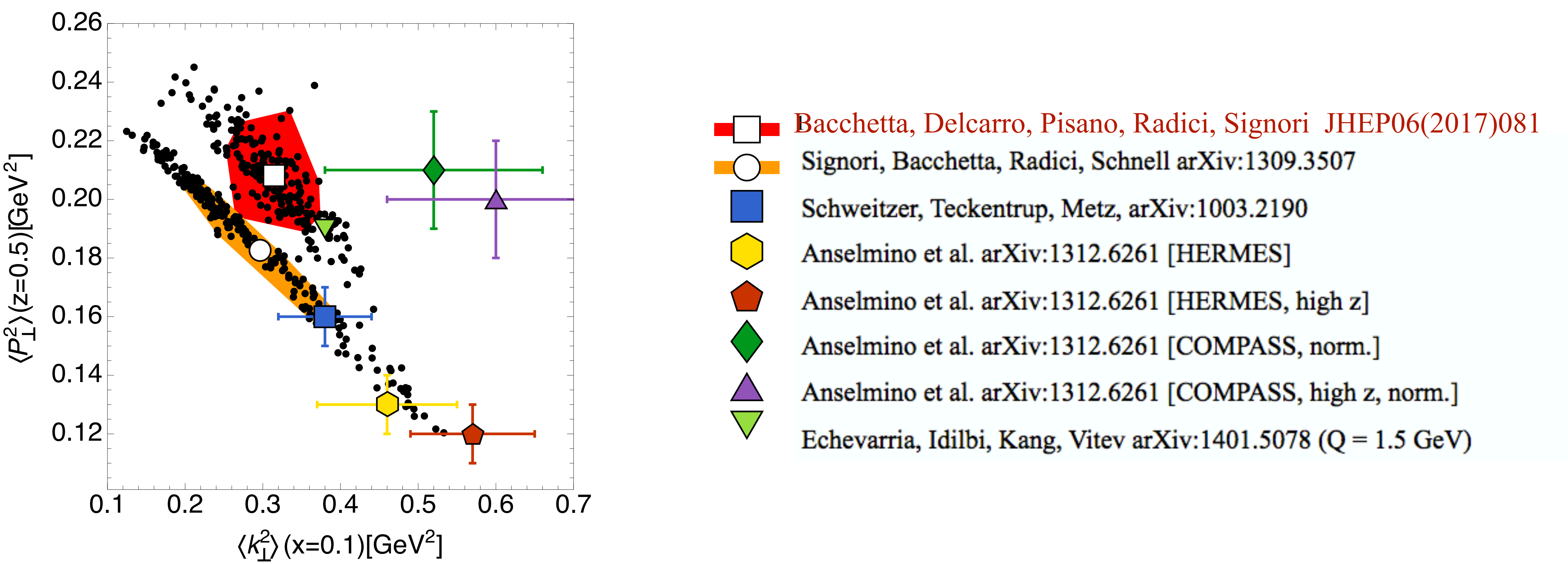
Hermes P/D into π+:
problems at low z

Hermes kaons better than pions:
larger uncertainties from FFs

Compass : better agreement due to
#points and normalization

Stay tuned for LHC data and NLO-NLL

Average transverse momenta



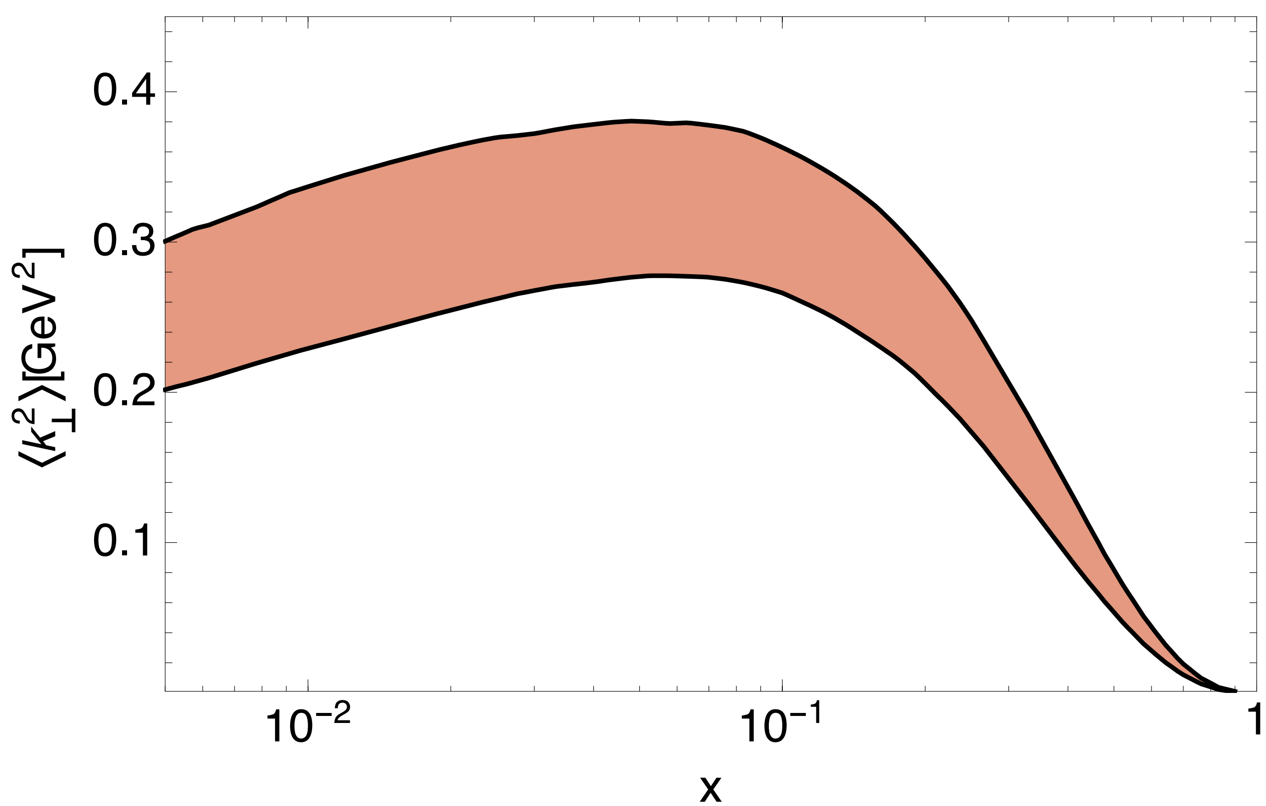
Red/orange regions: **68% CL** from replica method

Inclusion of DY/Z diminishes the correlation

Inclusion of Compass increases the $\langle P_\perp^2 \rangle$ and reduces its spread

e+e- would further reduce the correlation

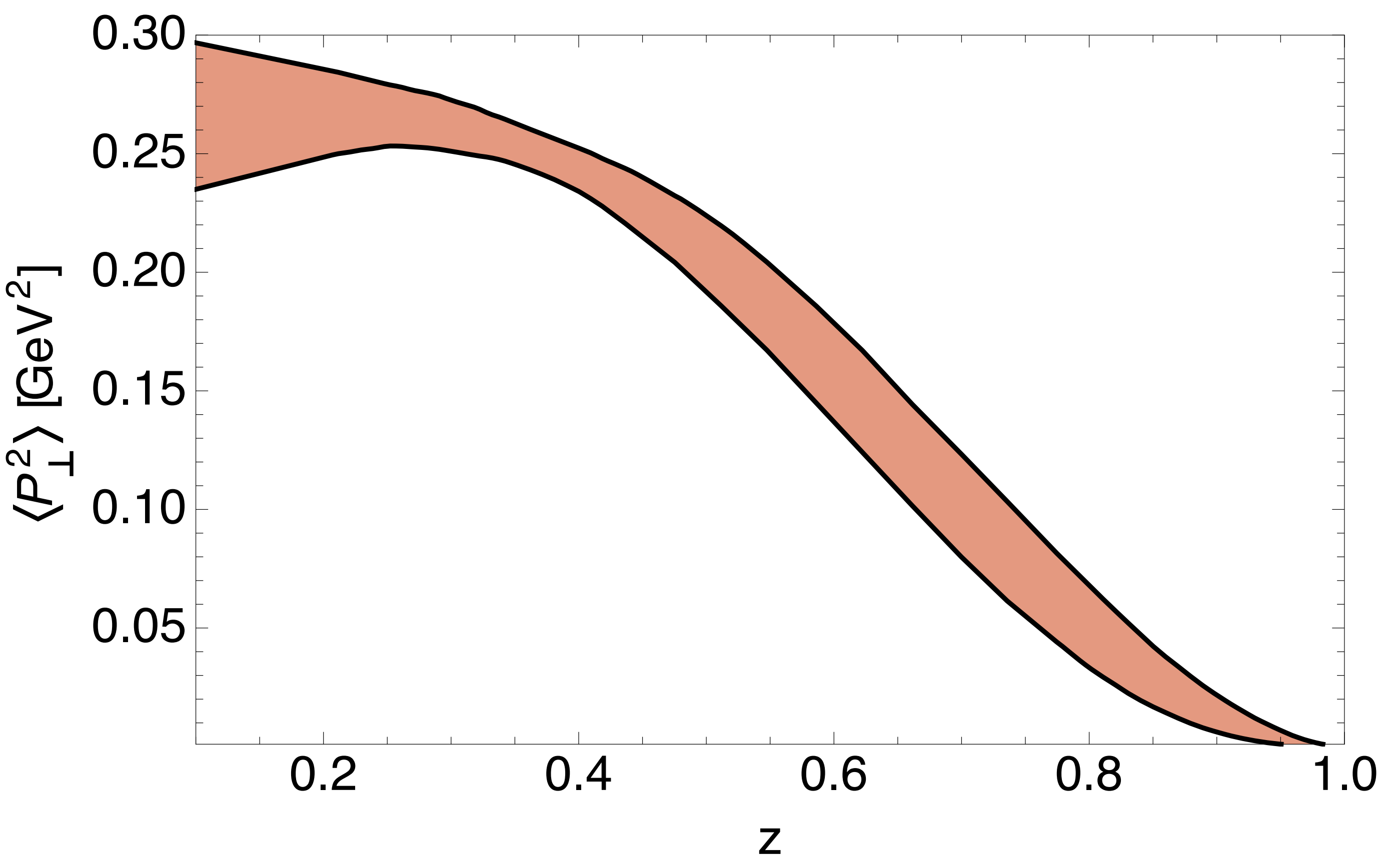
Average transverse momentum



x-dependence width
(Q^2=1GeV^2)

TMD PDF

$$\langle k_\perp^2 \rangle(x) = \frac{\int d^2k_\perp \; k_\perp^2 \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}{\int d^2k_\perp \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}$$



TMD FF

$$\langle P_\perp^2 \rangle(z) = \frac{\int d^2P_\perp \; P_\perp^2 \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}{\int d^2P_\perp \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}$$

Stability of the results

Best χ^2/dof = **1.55**

If we

- **normalize** HERMES data as we did for COMPASS: χ^2/dof = **1.27**

- **change collinear PDFs**: w.r.t to NLO GJR 2008 default choice:
NLO MSTW 2008 (χ^2/dof = **1.84**), NLO CJ12 (χ^2/dof = **1.85**)

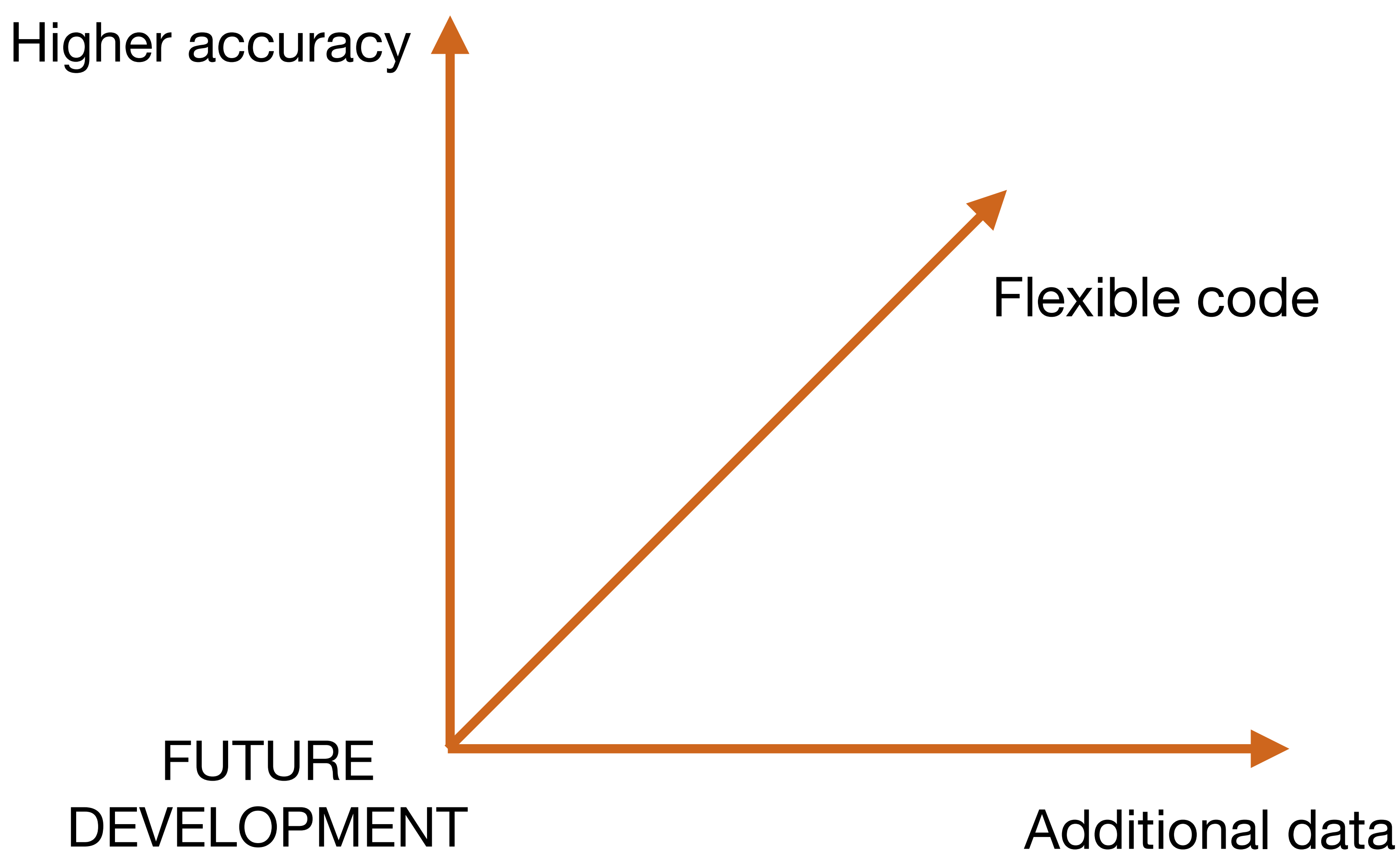
- **choose more stringent cuts** (deeper into TMD factorization region):
$Q^2 > 1.5$ GeV^2; $0.25 < z < 0.6$; $P_{hT} < 0.2Qz \Rightarrow \chi^2$/dof = **1.02** (477 bins)

Conclusions and open issues

First global extraction of TMDs from SIDIS, DY and Z boson

Test of the universality and evolution formalism of partonic TMDs

Definition of a parametrization of TMDs from 8000 data points



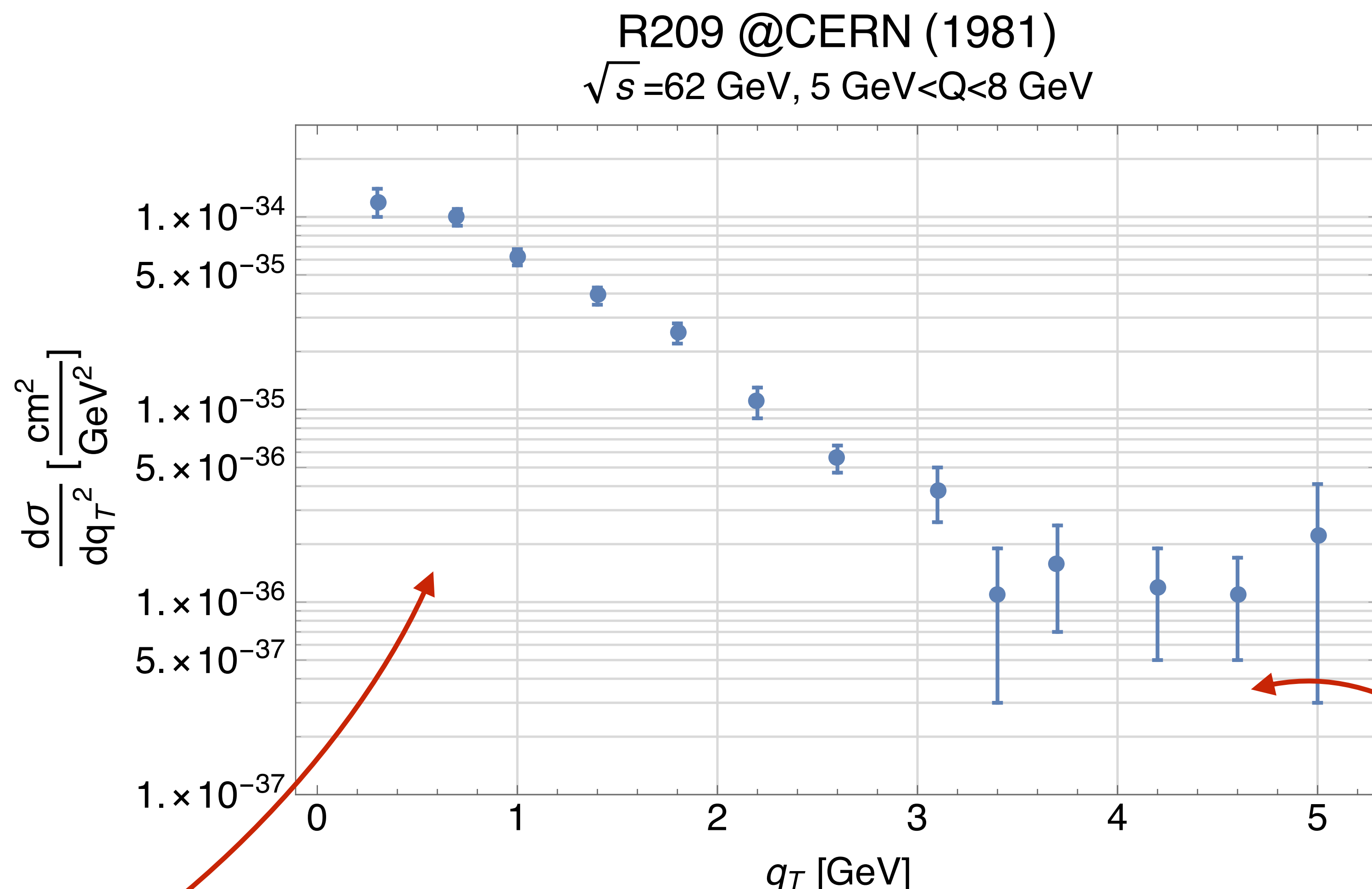
Part 2
Stumbling into unexpected problems:
Drell-Yan at low Q^2 and high q_T

Low-energy Drell-Yan data

Experiment	Reaction	Year	TMD fits	PDF fits
R209	p-p	1981	✔	✘
E288	p-Cu(Pt)	1981	✔	✘
E605	p-Cu	1991	✔	✔
E866	p-p(d)	2003	✘	✔
E615	pi-W	1989	✘	✔

$$20\,GeV \lesssim \sqrt{s} \lesssim 60\,GeV$$

Transverse momentum of Drell-Yan pairs



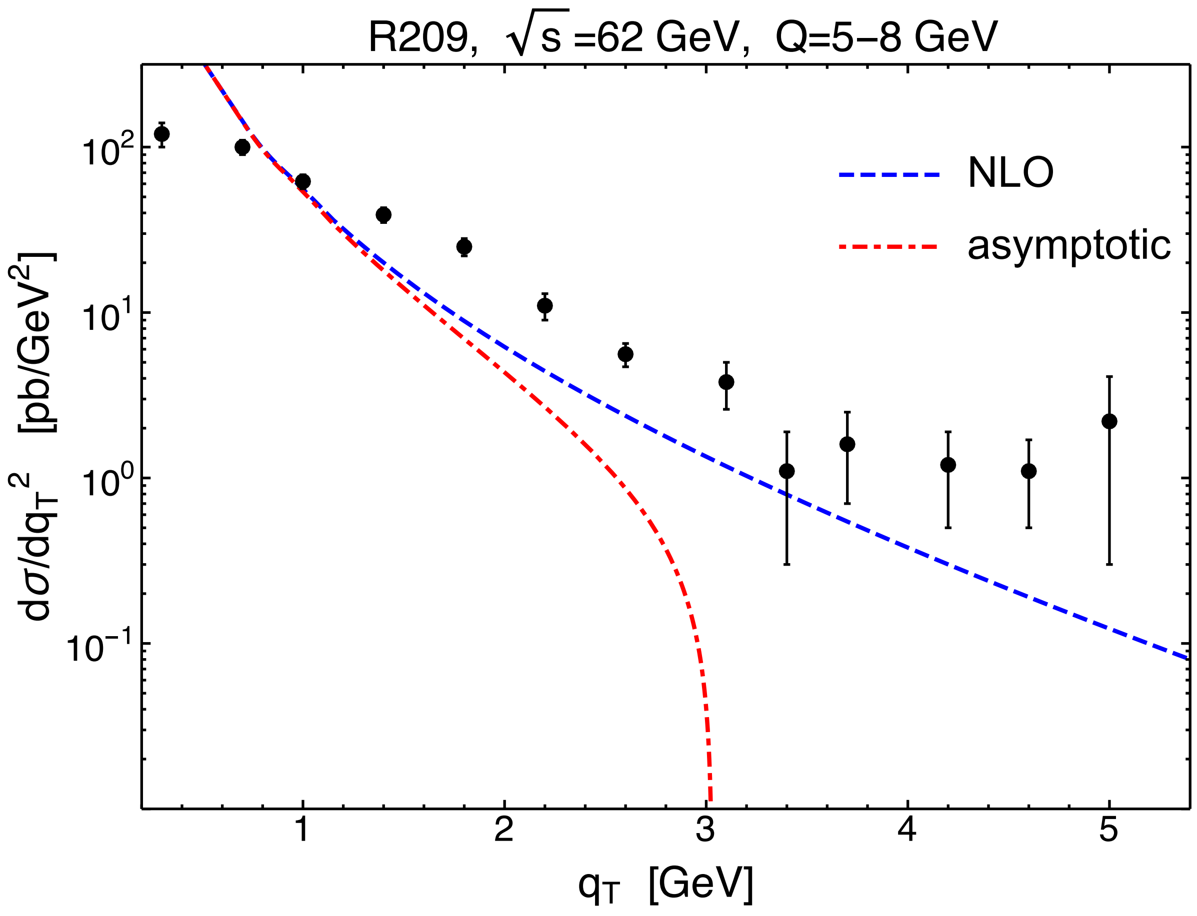
Transverse momentum resummation (q_T-logs) $\alpha_s^n \ln^m \frac{q_T^2}{Q^2}$
+ non-perturbative

Fixed order collinear factorization

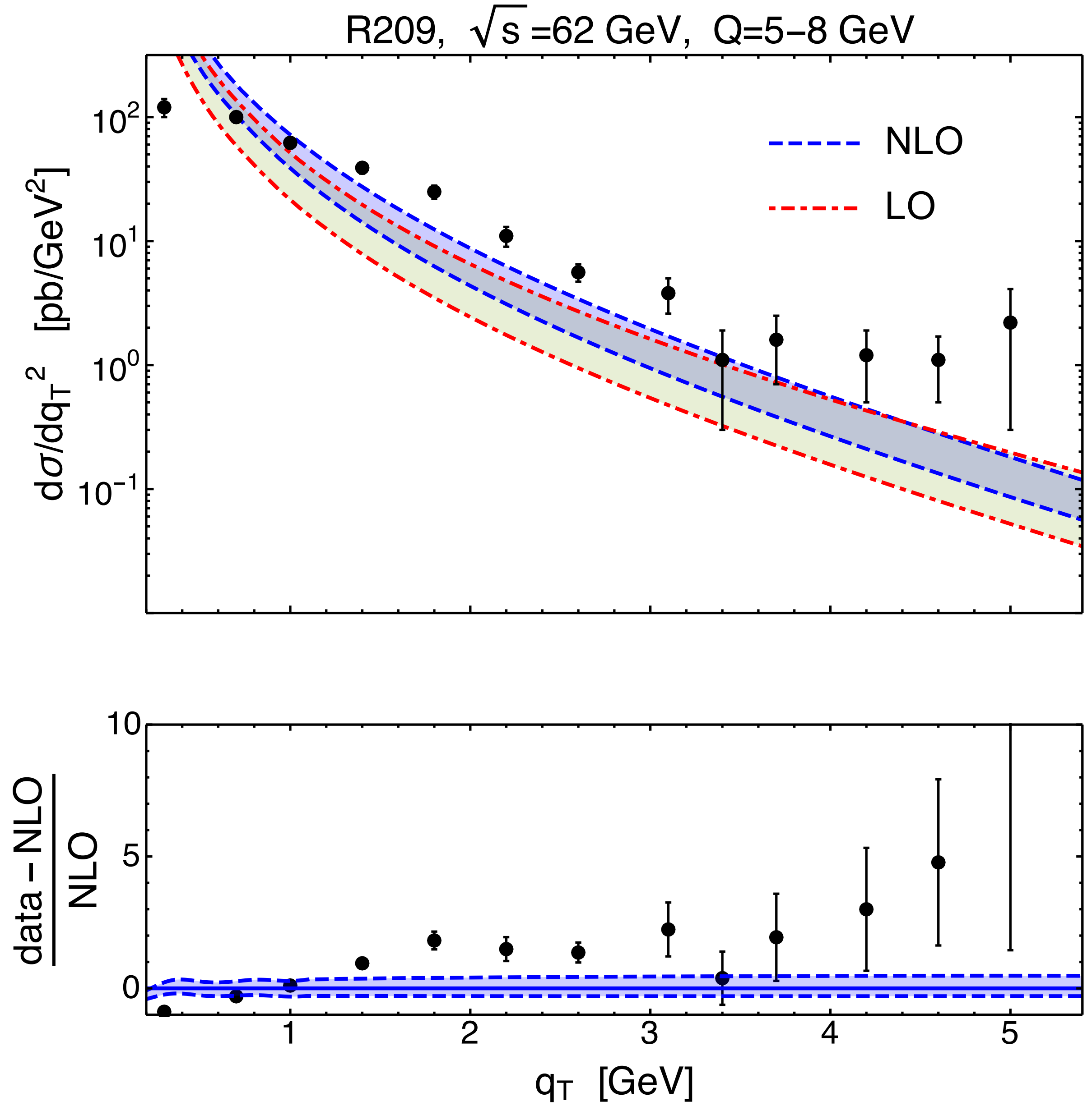
Asymptotic term

$$\frac{d\sigma}{dq_T^2}(matched) = \underbrace{\frac{d\sigma}{dq_T^2}(resum)_{NLL}}_{W} - \underbrace{\frac{d\sigma}{dq_T^2}(expanded)\Big|_{\mathcal{O}(\alpha_s)} + \frac{d\sigma}{dq_T^2}\,(LO)}_{Y}$$

R209@CERN



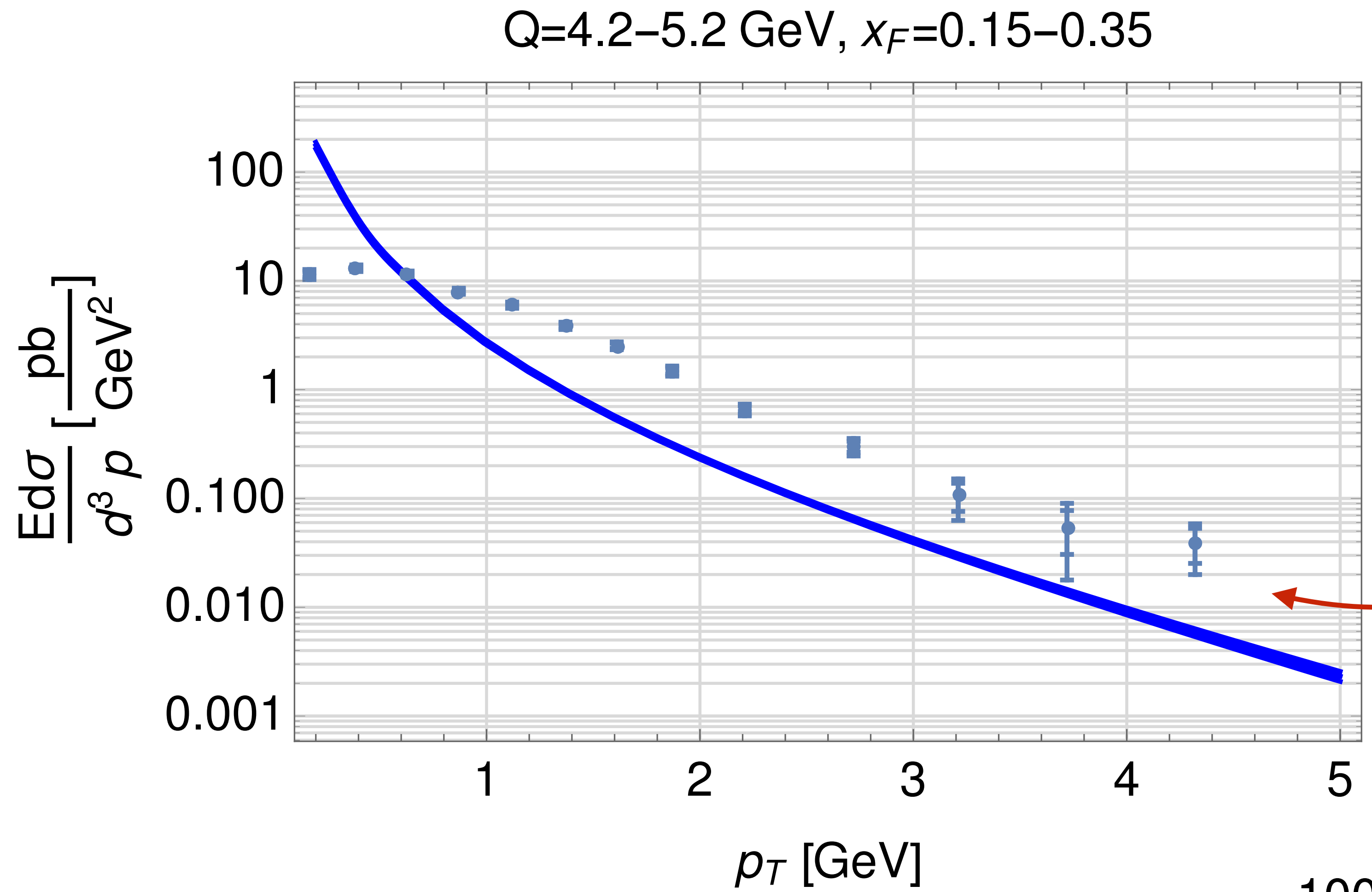
scale uncertainty



E866/NuSea

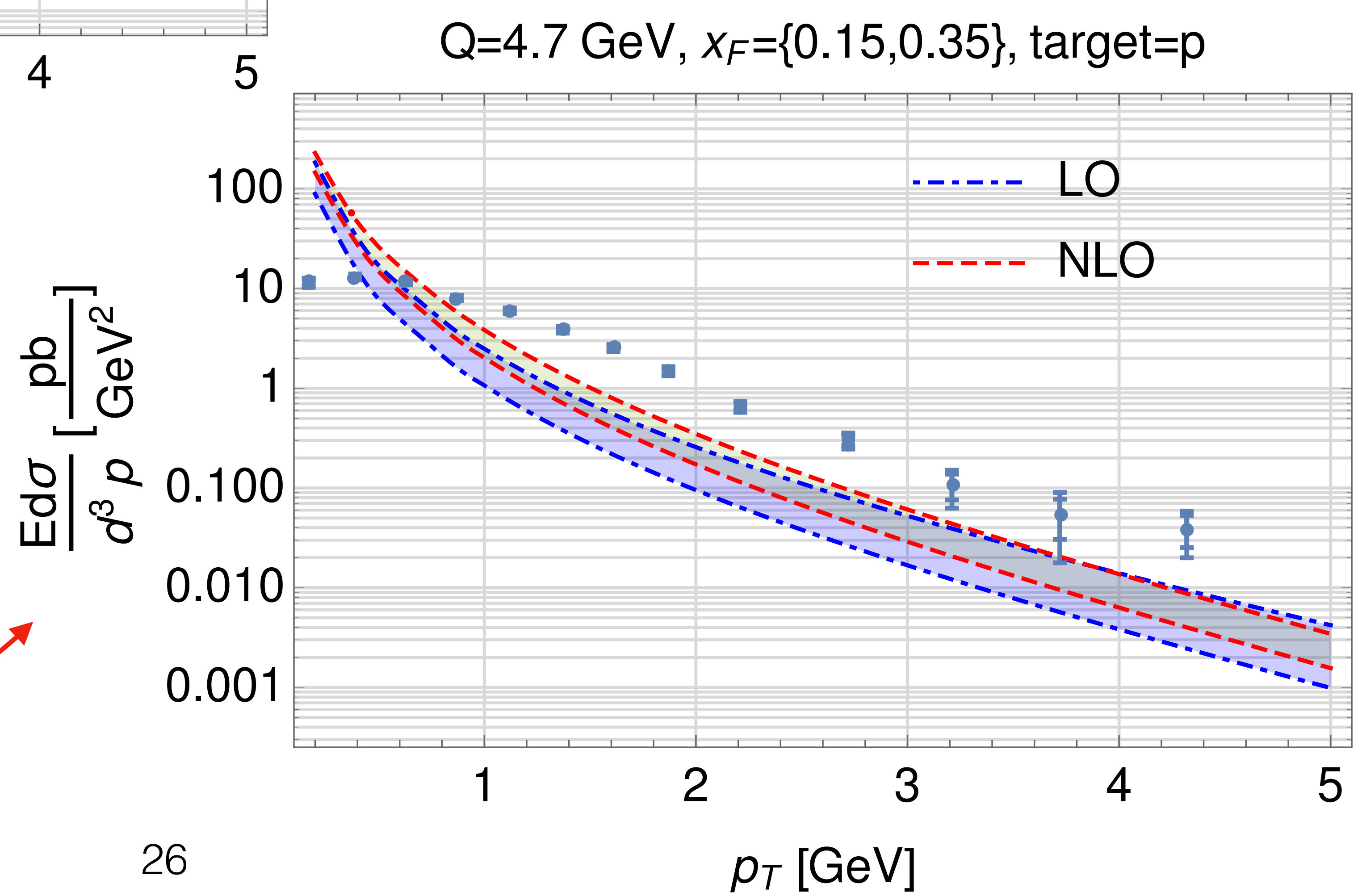
$$p\,p \to \mu^+\mu^- X$$

$$\sqrt{s} = 38.8\,GeV$$



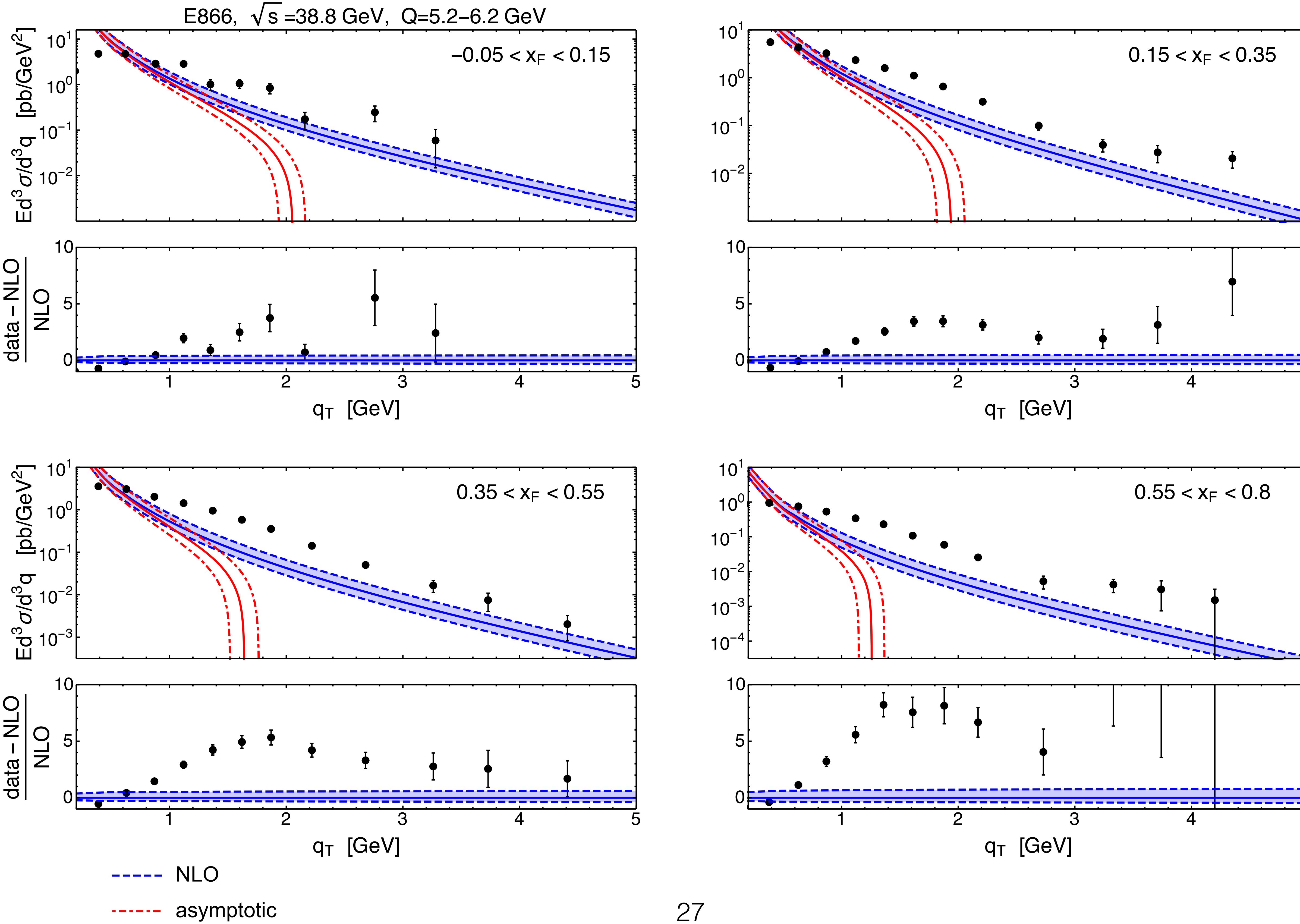
NLO $\mathcal{O}(\alpha_s^2)$
+PDF uncertainty

scale uncertainty

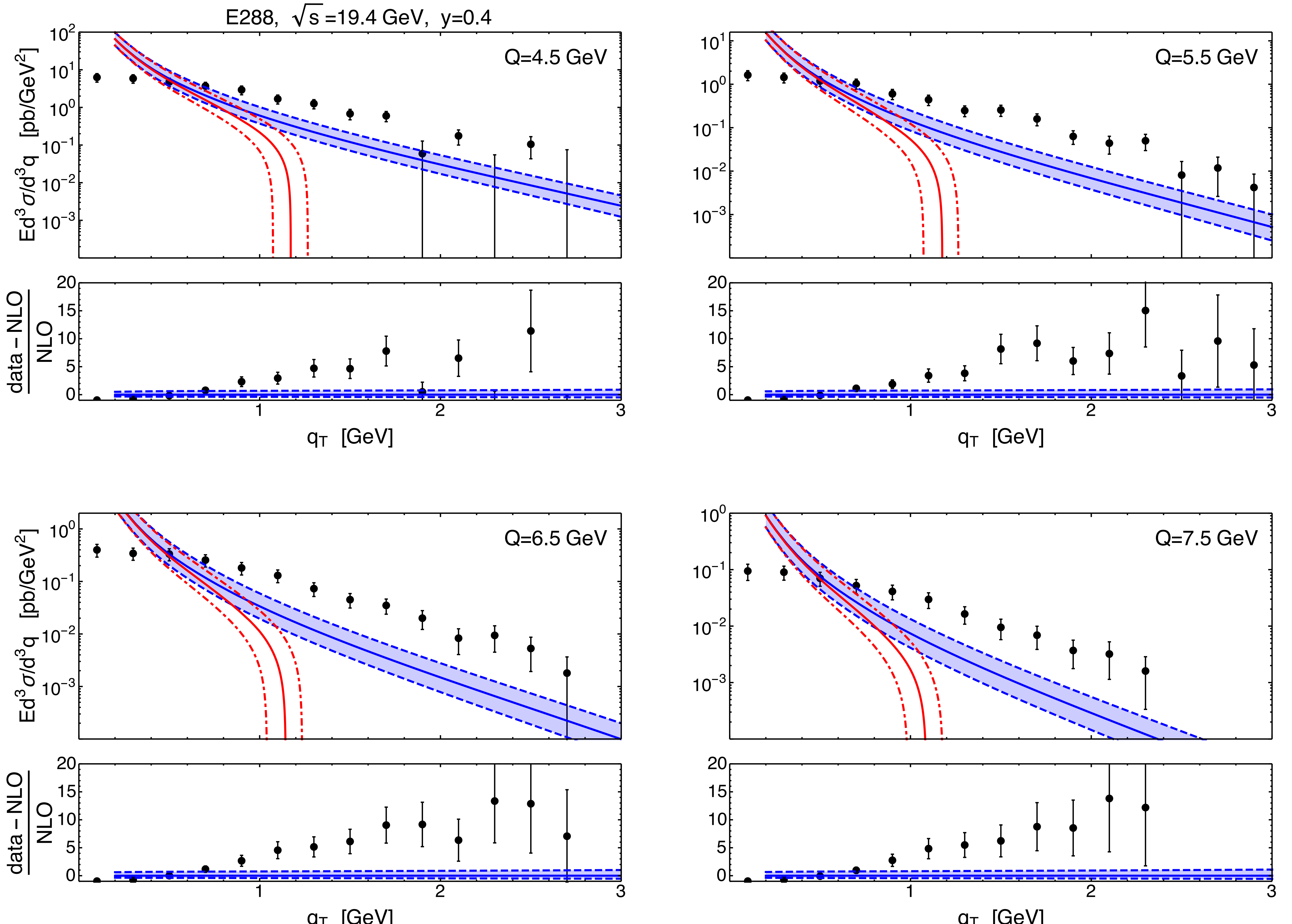


E866/NuSea

$$p\,p \to \mu^+\mu^- X$$
$$\sqrt{s} = 38.8\,GeV$$

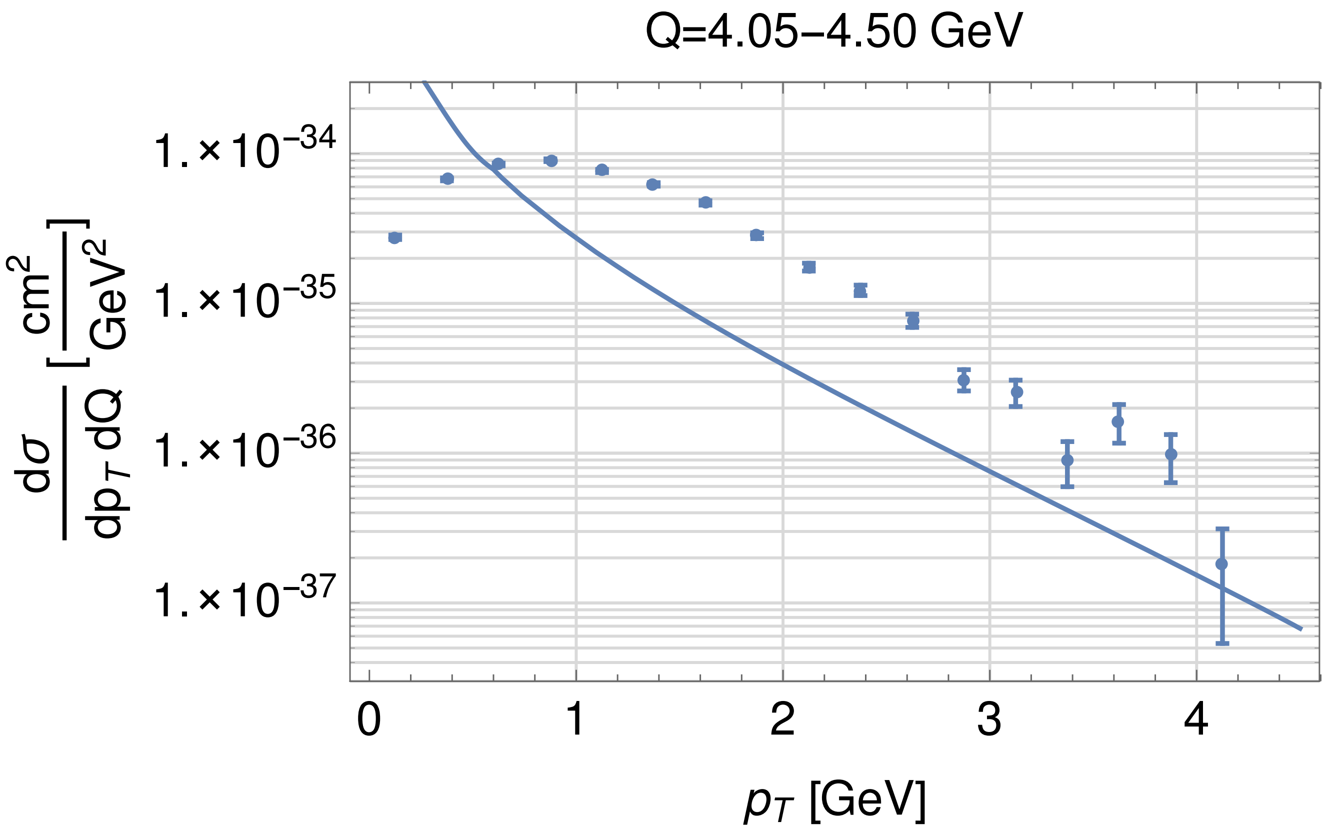


E288 $\quad p\,Cu(Pt) \to \mu^+\mu^- X$

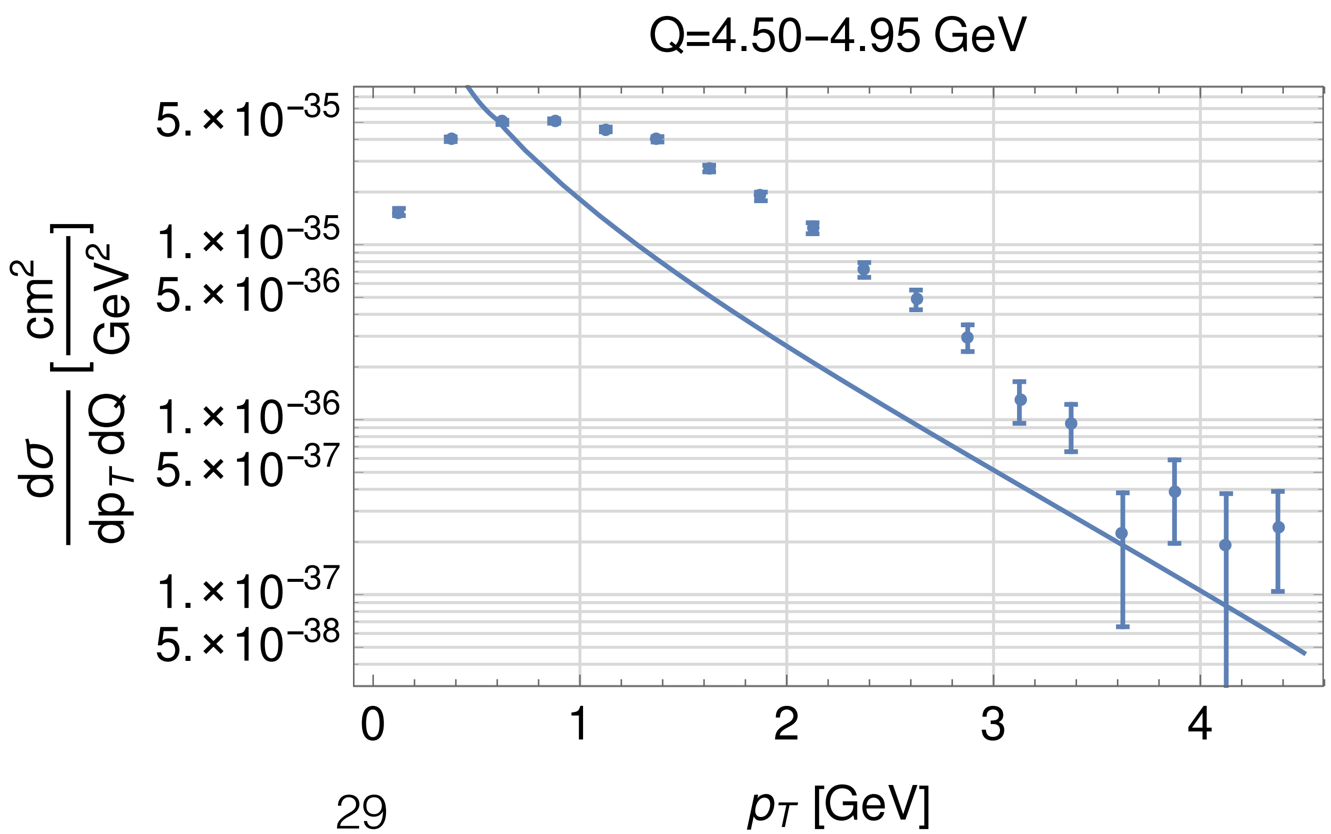


E615

$$\pi W \to \mu^+ \mu^- X$$
$$\sqrt{s} = 21.8\ GeV$$



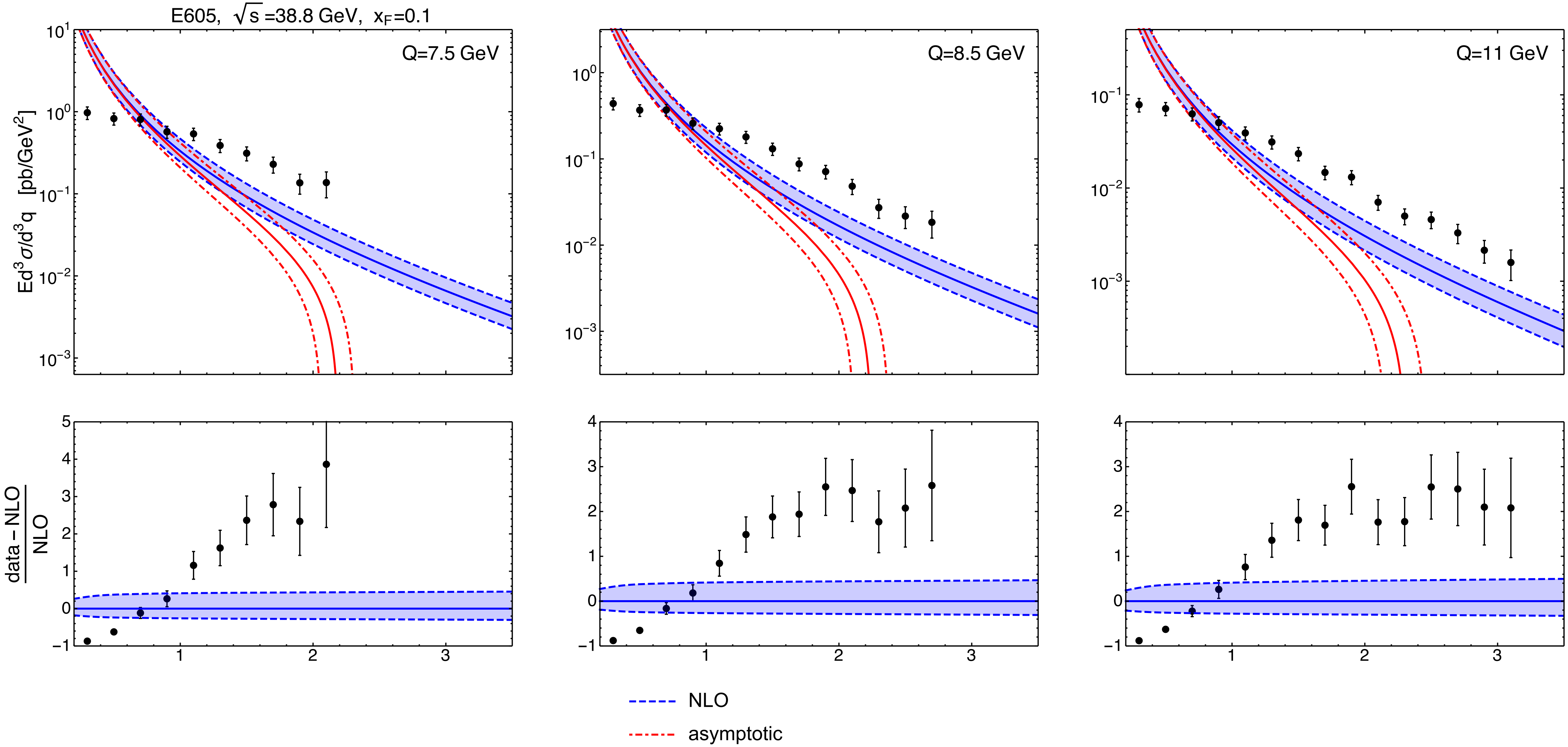
NLO $\mathcal{O}(\alpha_s^2)$



E605

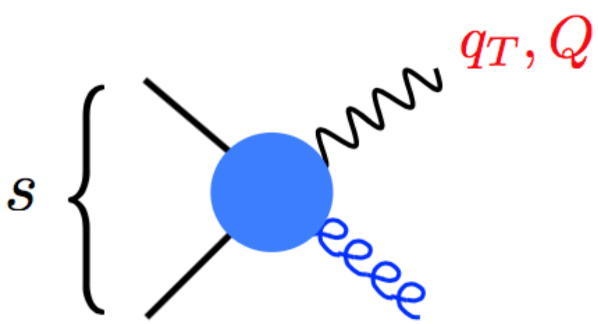
$p\ Cu(Pt) \rightarrow \mu^+\mu^- X$

$\sqrt{s} = 38.8\ GeV$



threshold resummation

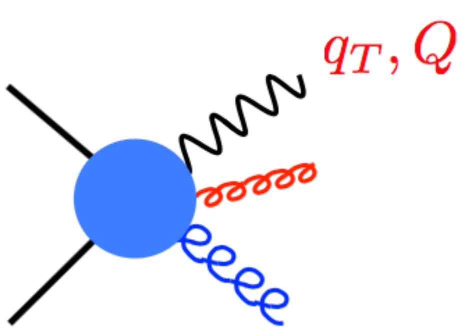
- LO :



$$\sqrt{s} \geq q_T + \sqrt{Q^2 + q_T^2}$$

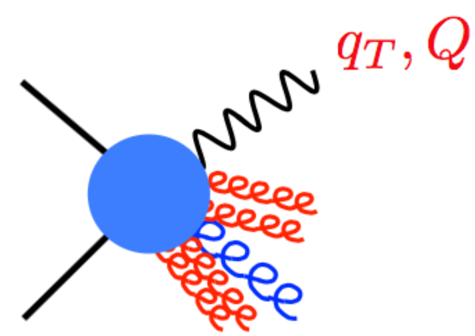
$$y_T \equiv \frac{q_T + \sqrt{q_T^2 + Q^2}}{\sqrt{s}} \leq 1$$

- NLO :



$$\frac{d\hat{\sigma}^{\mathrm{NLO}}}{dq_T} \propto \alpha_s \left[\mathcal{A} \log^2(1 - y_T^2) + \mathcal{B} \log(1 - y_T^2) + \mathcal{C} \right]$$

- N^{k}LO :

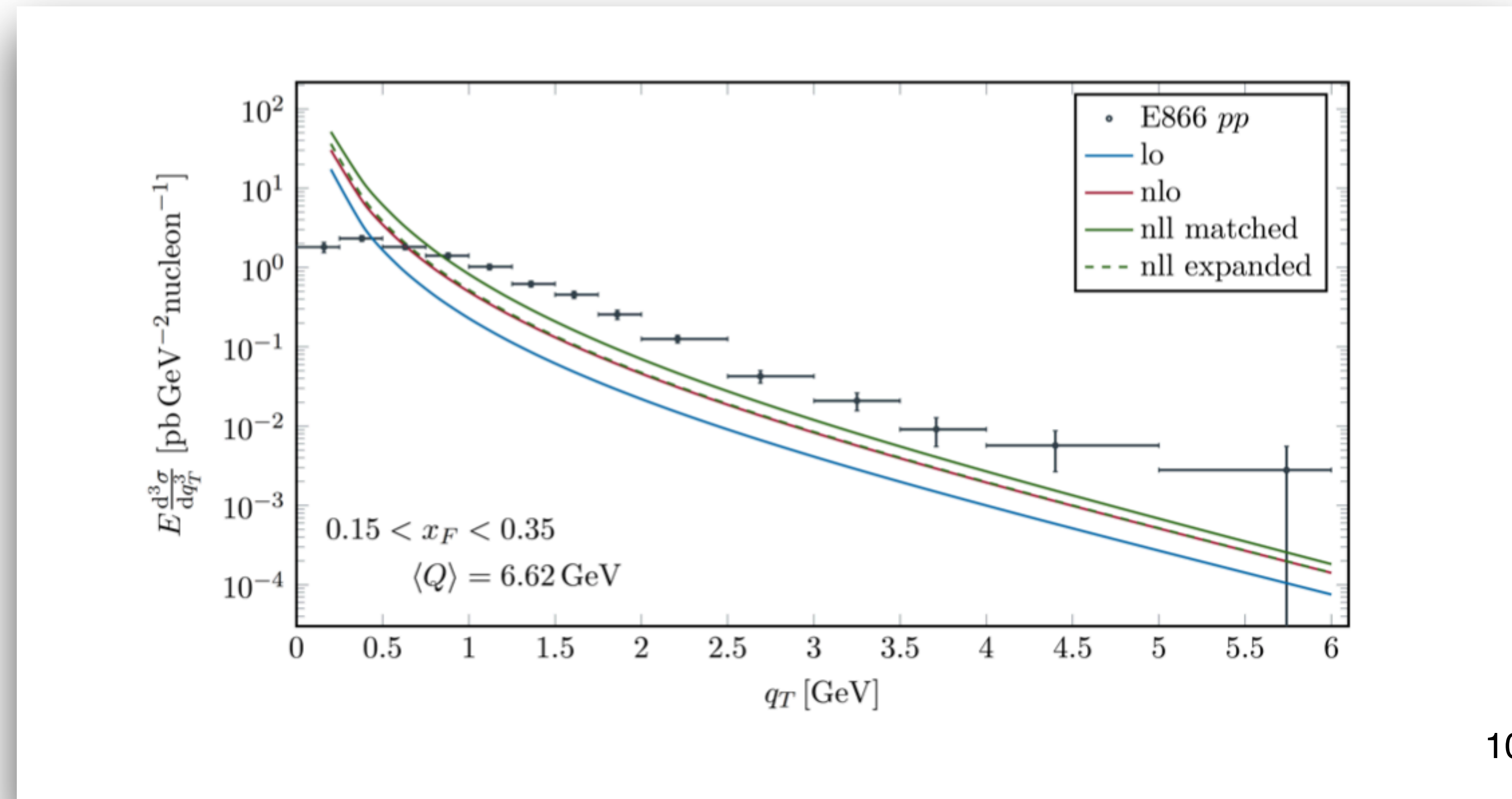


$$\frac{d\hat{\sigma}^{\mathrm{N}^k\mathrm{LO}}}{dq_T} \propto \alpha_s^k \log^{2k}(1 - y_T^2) + \ldots$$

- threshold logarithms

W. Vogelsang @Transversity 2017

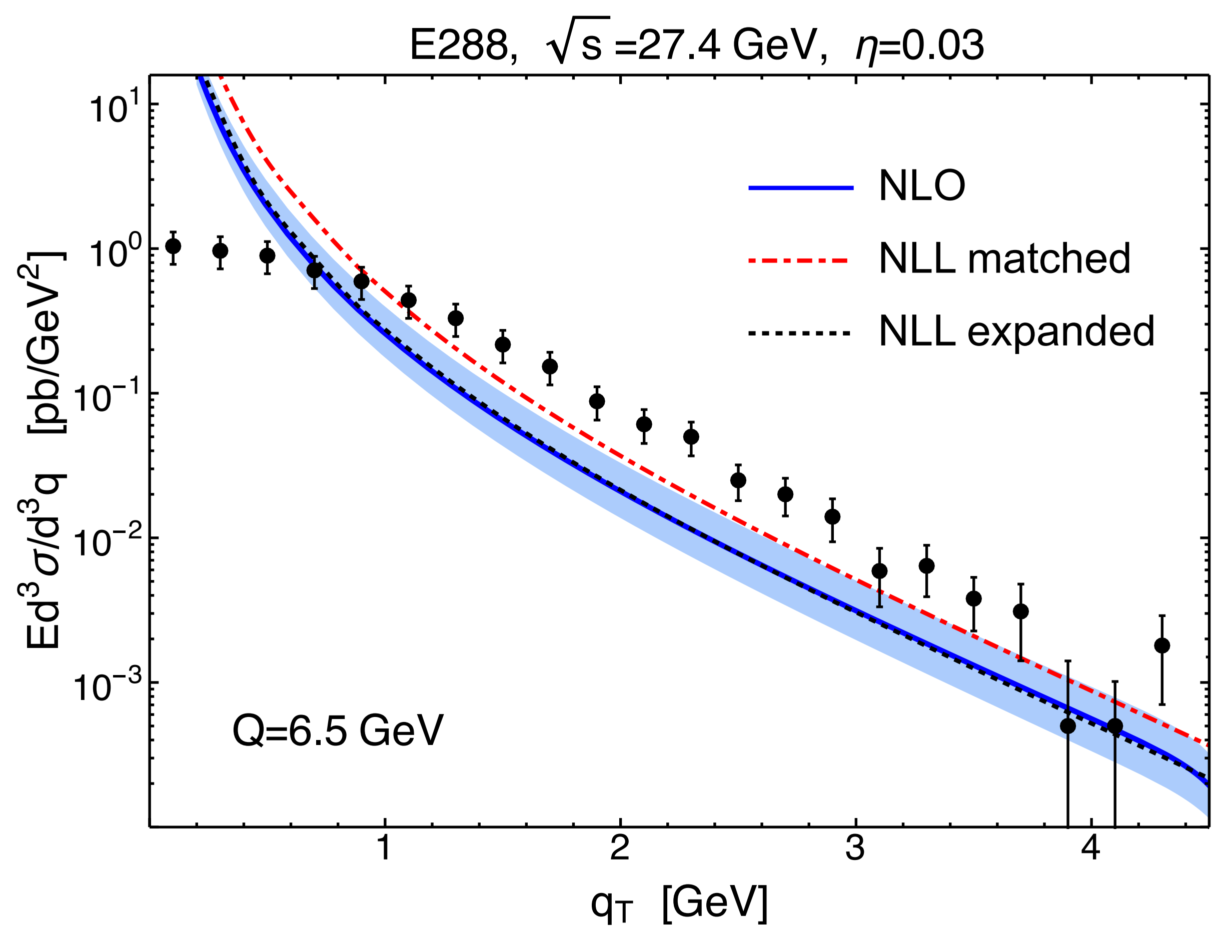
threshold resummation



E866/NuSea

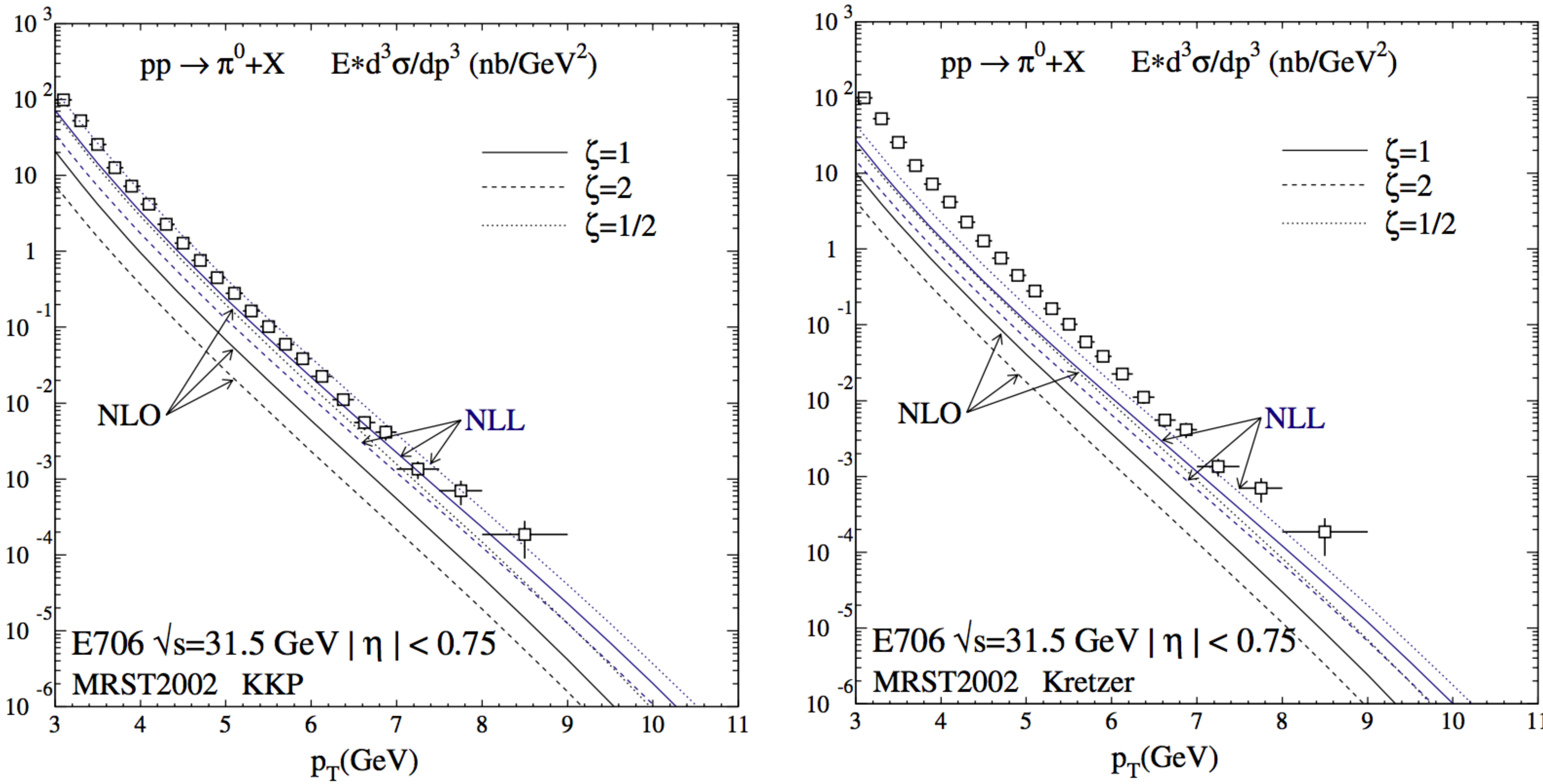
W. Vogelsang @Transversity 2017

E288



known similar cases

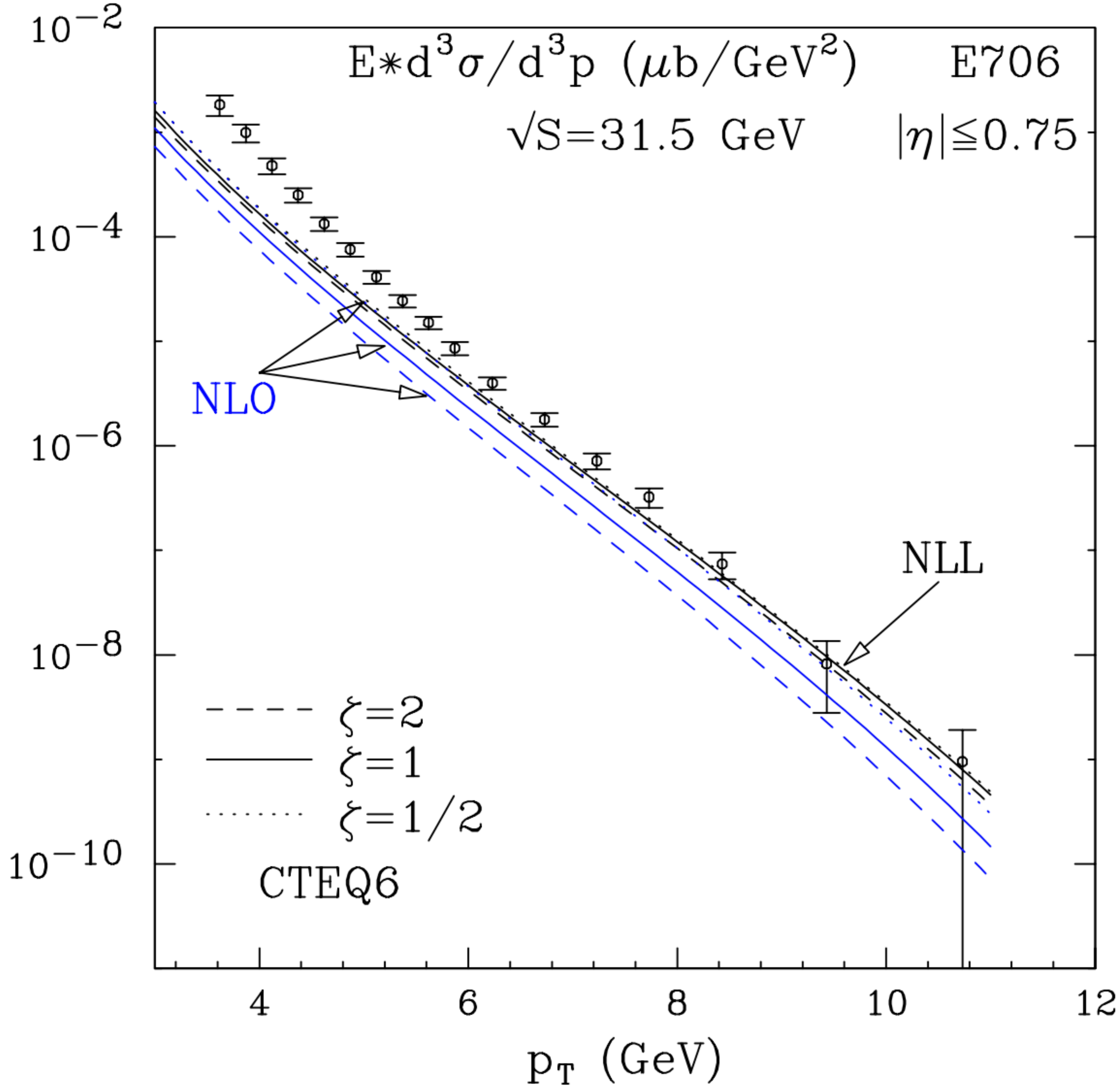
pion production



de Florian Vogelsang PRD 71 114004 (2005)

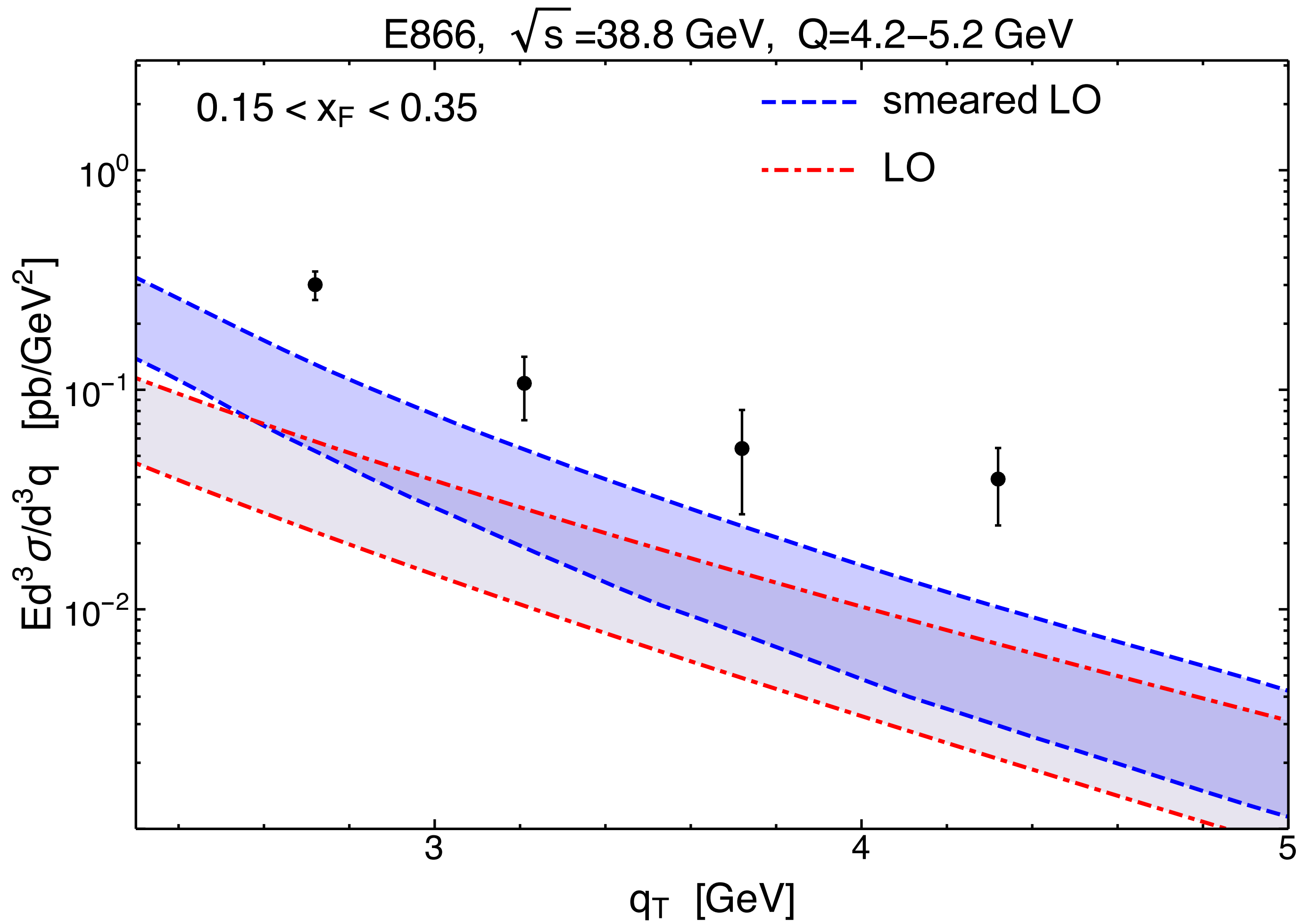
known similar cases

prompt photon



de Florian Vogelsang PRD 72 014014 (2005)

intrinsic k_T smearing



$$f_q\left(x, \mathbf{k}_T\right) = f\left(x\right) \frac{1}{\pi < k_T^2 >} e^{-\frac{k_T^2}{<k_T^2>}}$$

$$\left\langle k_T^2 \right\rangle = 0.81\, GeV^2$$

taken from TMD fit
flavour-blind and kinematical-independent
(gluons as well!)

Conclusions (?)

- fixed-order pQCD largely underestimates low-energy Drell-Yan data at high q_T
- neither threshold resummation nor intrinsic-k_T models seem to help
- more high q_T data needed
- important to see effects of E866 data in TMD fits
- any help/hint/comment/suggestion is welcome!

Part 3
Impact on precision measurements at the LHC: the W mass case

The extraction of physical quantities

Observables

- accessible via counting experiments: cross sections and asymmetries

Pseudo-Observables

- functions of cross sections and symmetries
- require a model to be properly defined
  - M_Z at LEP as pole of the Breit-Wigner resonance factor
  - M_W at hadron colliders as fitting parameter of a *template fit* procedure

Template fit

1. generate several histograms with the highest available theoretical accuracy and degree of realism in the detector simulation, and let the fit parameter (e.g. M_W) vary in a range
2. the histogram that best describes data selects the preferred (*i.e. measured*) M_W

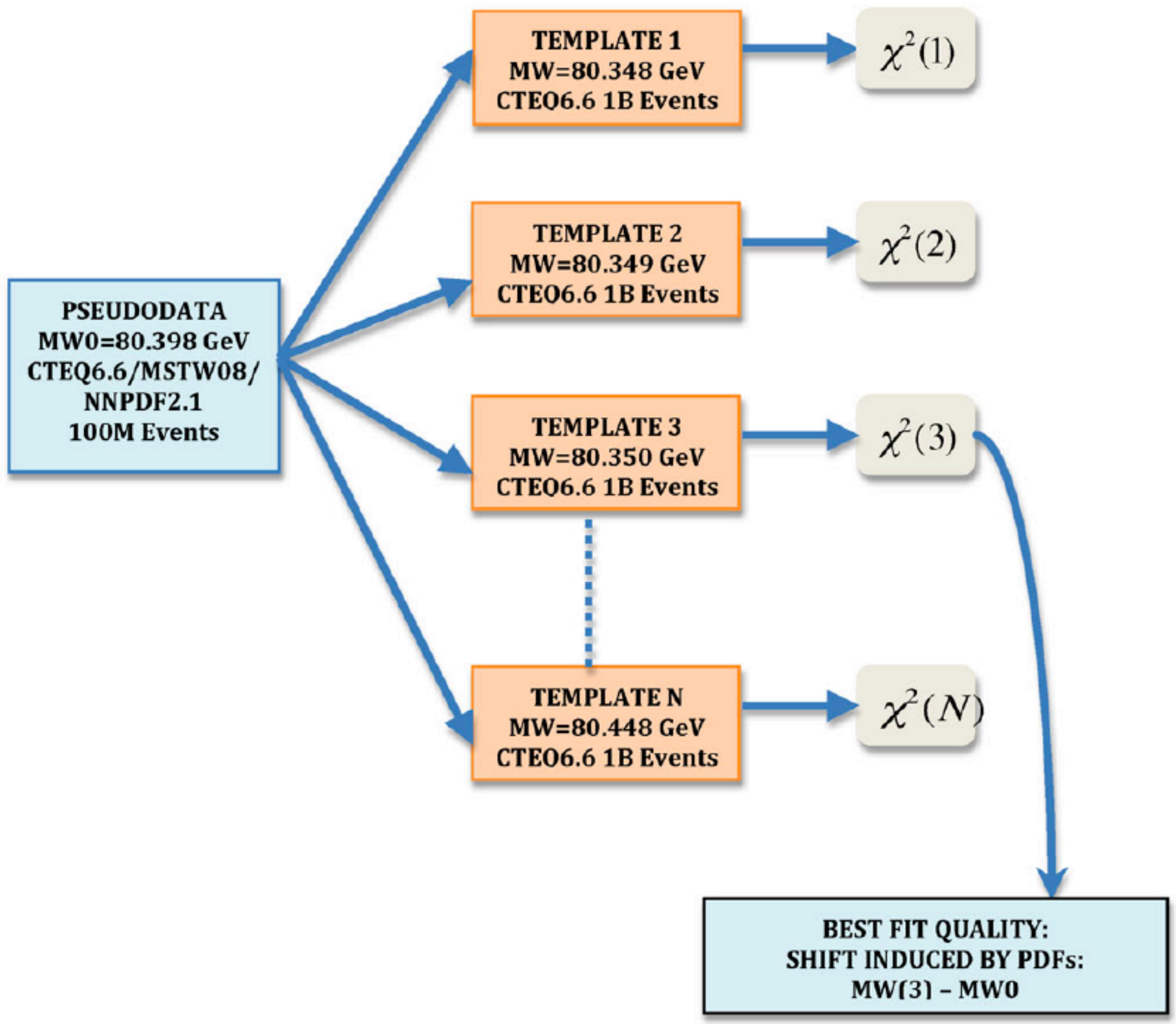
➡ the result of the fit depends on the hypotheses used to compute the templates (PDFs, scales, non-perturbative, different prescriptions, …)

➡ these hypotheses should be treated as theoretical systematic errors

General template-fit strategy (example: PDF uncertainty)

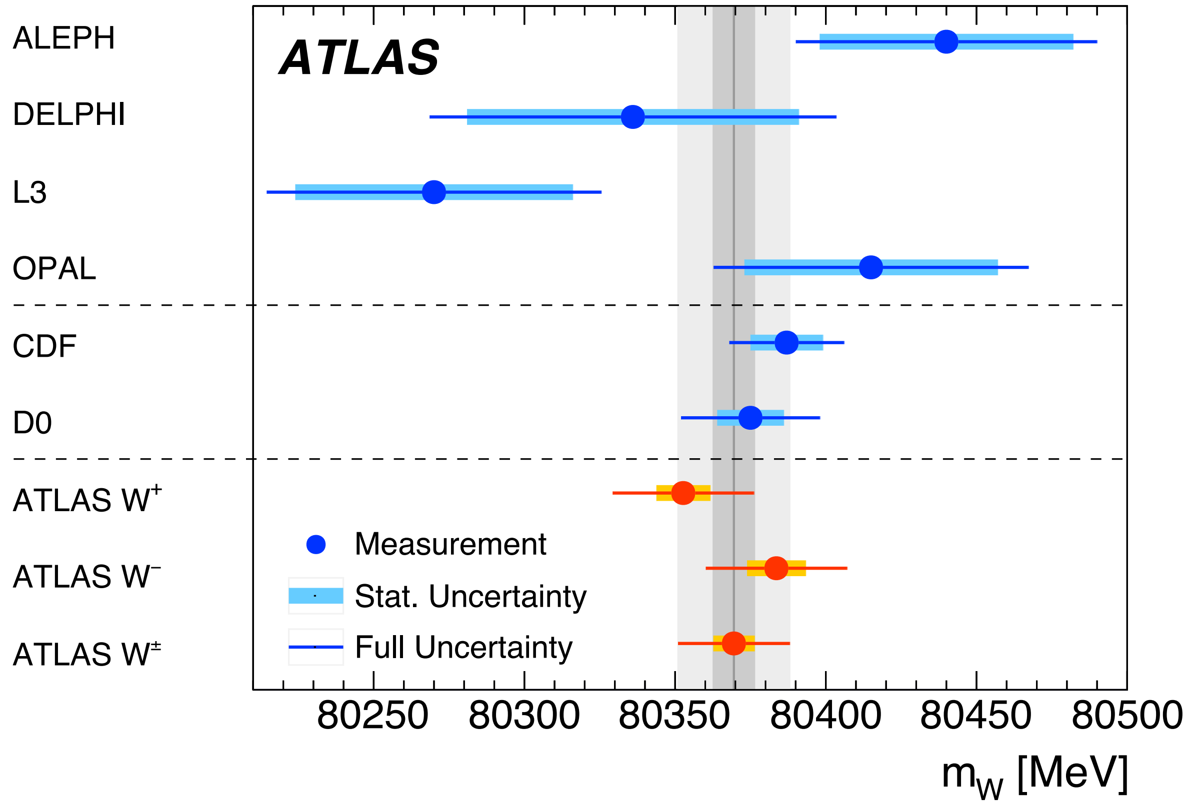
Bozzi, Rojo, Vicini PRD 83, 113008 (2011)

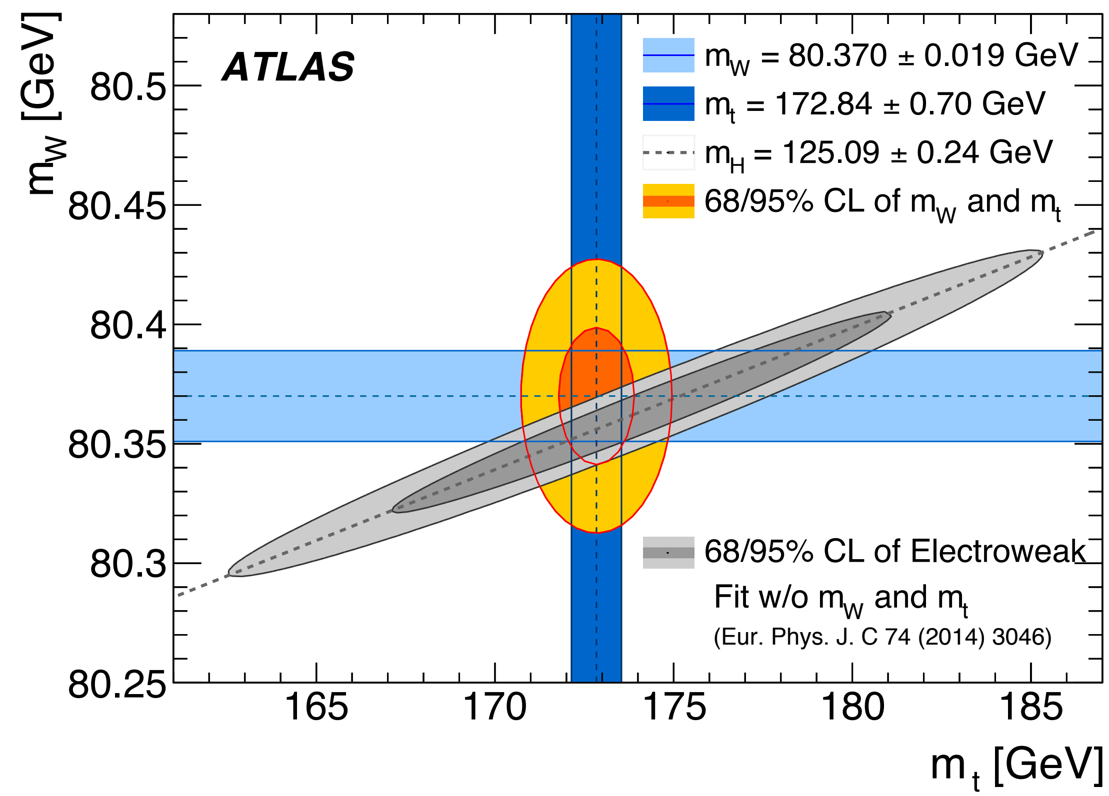
- **pseudodata** with different PDF sets: low-statistics (100M) and fixed M_{W0}
- **templates** with a reference PDF set (CTEQ6.6): high-statistics (1B) and different M_W
- same code used to generate both pseudodata and templates → only effect probed is the PDF one



The W mass

ATLAS, EPJC 78, 110 (2018)





Experimental measurements

$$M_W = 80.379 \pm 12 \text{ MeV}$$

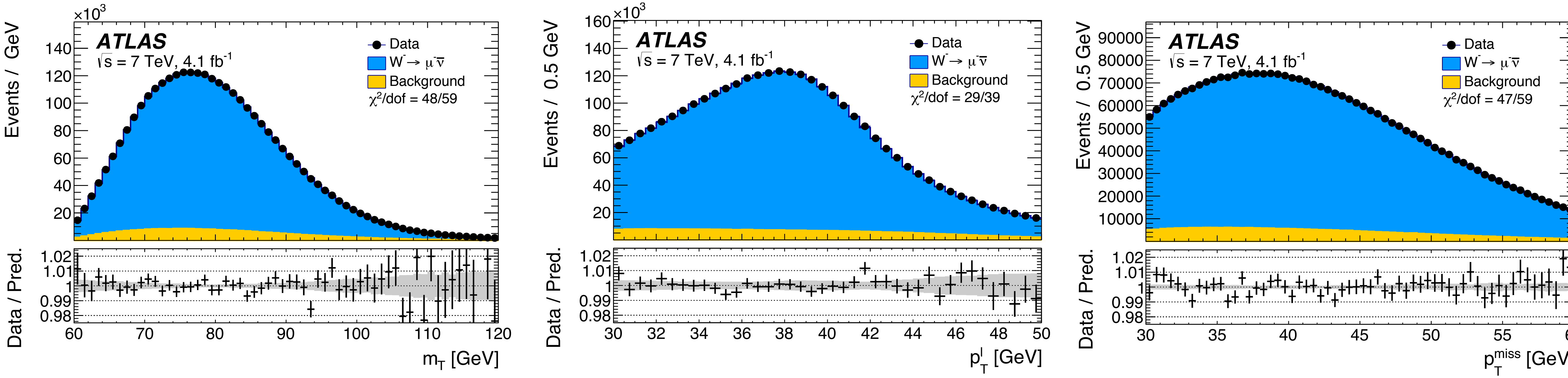
(7 stat, 11 exp, 14 th)

Global EW fit

$$M_W = 80.356 \pm 8 \text{ MeV}$$

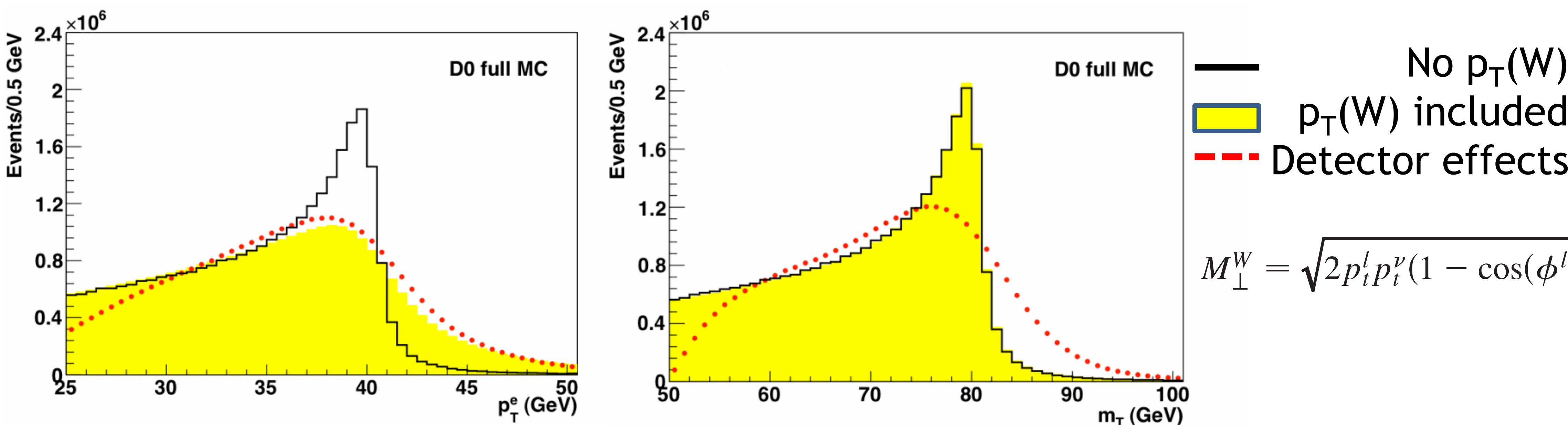
The determination of the W-boson mass from the global fit of the electroweak parameters has an uncertainty of 8 MeV, which sets a natural target for the precision of the experimental measurement of the mass of the W boson. The modelling uncertainties, which currently dominate the overall uncertainty on the m_W measurement presented in this note, need to be reduced in order to fully exploit the larger data samples available at centre-of-mass energies of 8 and 13 TeV. A better knowledge of the PDFs, as achievable with the inclusion in PDF fits of recent precise measurements of W- and Z-boson rapidity cross sections with the ATLAS detector [41], and improved QCD and electroweak predictions for Drell-Yan production, are therefore crucial for future measurements of the W-boson mass at the LHC.

Observables and techniques



M_W extracted from the study of the shape of m_T, p_{Tl}, p_{Tmiss}

jacobian peak enhances sensitivity to M_W



$$M_{\perp}^{W} = \sqrt{2 p_t^l p_t^\nu (1 - \cos(\phi^l - \phi^\nu))},$$

Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

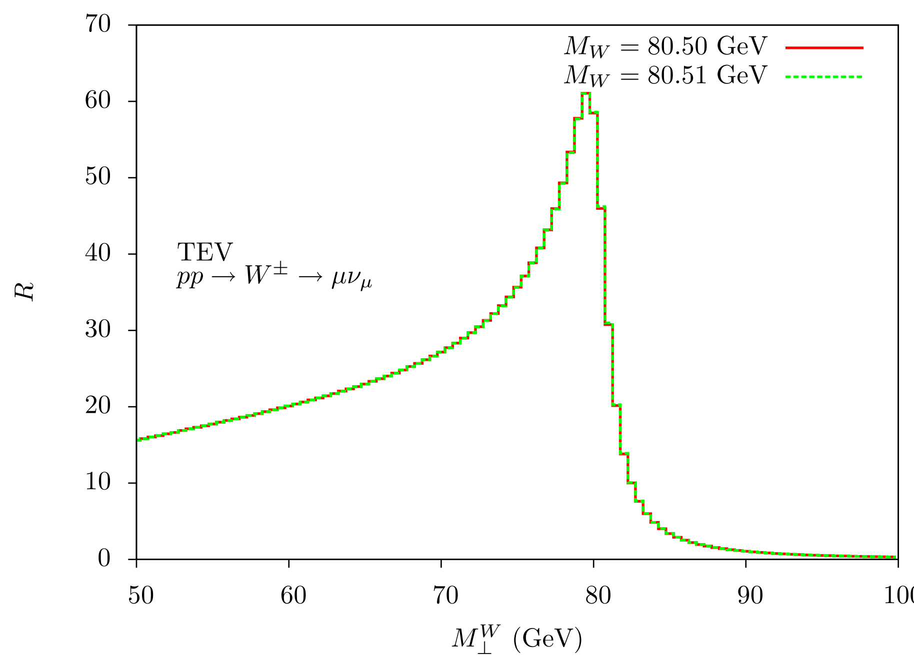
Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

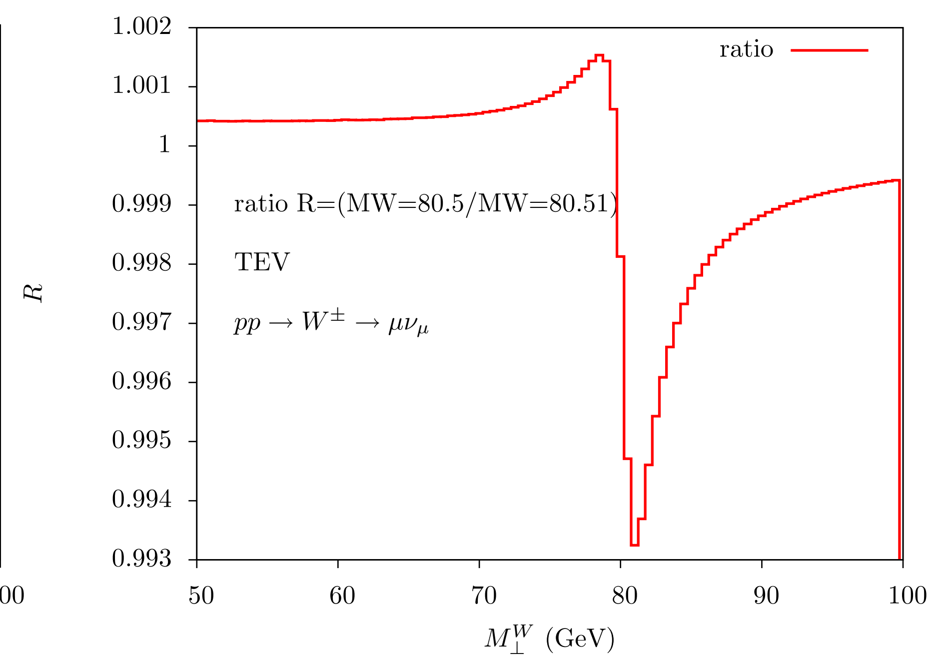
p_{TW} modelling depends on flavour and all-order treatment of QCD corrections

Observables and techniques

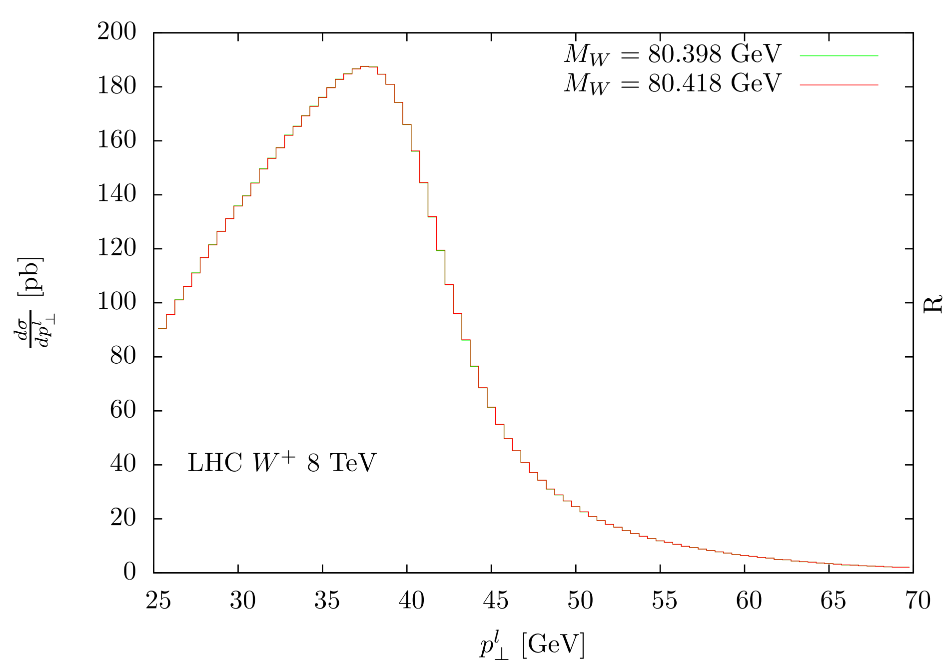
Challenging shape measurement: a distortion at the few per mille level of the distributions yields a shift of O(10 MeV) of the M_W value

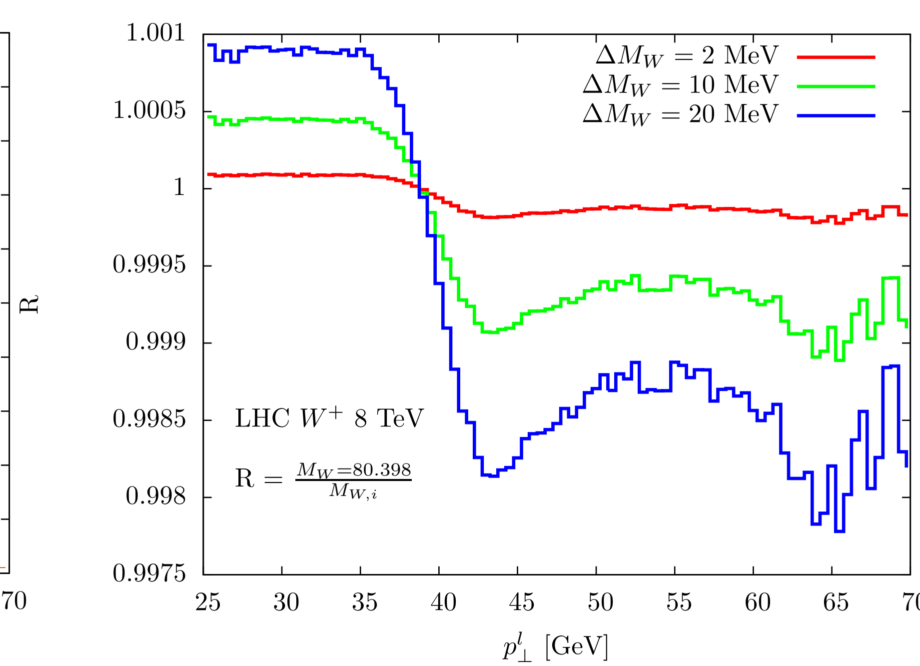
m_T





p_{Tl}





Uncertainties on M_W due to p_{TW}

CDF

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

p_T^ℓ fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

D0

Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

ATLAS

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

p_{TW} and the modelling of intrinsic k_T

- $p_{TI} \Leftarrow p_{TW} \Leftarrow$ QCD initial state radiation + intrinsic k_T (usually, a Gaussian in k_T)
- Intrinsic k_T effects measured on *Z* data and used to predict *W* distributions, *assuming universality*

but

different flavour structure

different phase space available

—> *different Gaussian factors for different flavours*

$$f_1^{aNP}(x, k_\perp^2; Q^2) = \frac{f_1^a(x, Q^2)}{\pi \langle k_\perp^2 \rangle_a} e^{-k_\perp^2/\langle k_\perp^2 \rangle_a}$$

$$\langle k^2_{\perp,u_v} \rangle \neq \langle k^2_{\perp,d_v} \rangle \neq \langle k^2_{\perp,u_s} \rangle \neq \langle k^2_{\perp,d_s} \rangle \neq \langle k^2_{\perp,sea} \rangle$$

Flavor and ~~kinematic~~ dependent widths

Choice of NP parameters

$$\frac{d\sigma}{dq_T} \sim \mathrm{FT}\ \exp\{-g_{NP} b_T^2\} \longrightarrow$$

Fit to Z/γ^* Tevatron data: $g_{NP} \sim 0.8\ \mathrm{GeV}^2$

[Guzzi, Nadolsky, Wang (2014)]

For each TMD: $0.4\ \mathrm{GeV}^2 \sim g^a_{NP} \longrightarrow g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) + g_a \longrightarrow$ *variation range for g_a*

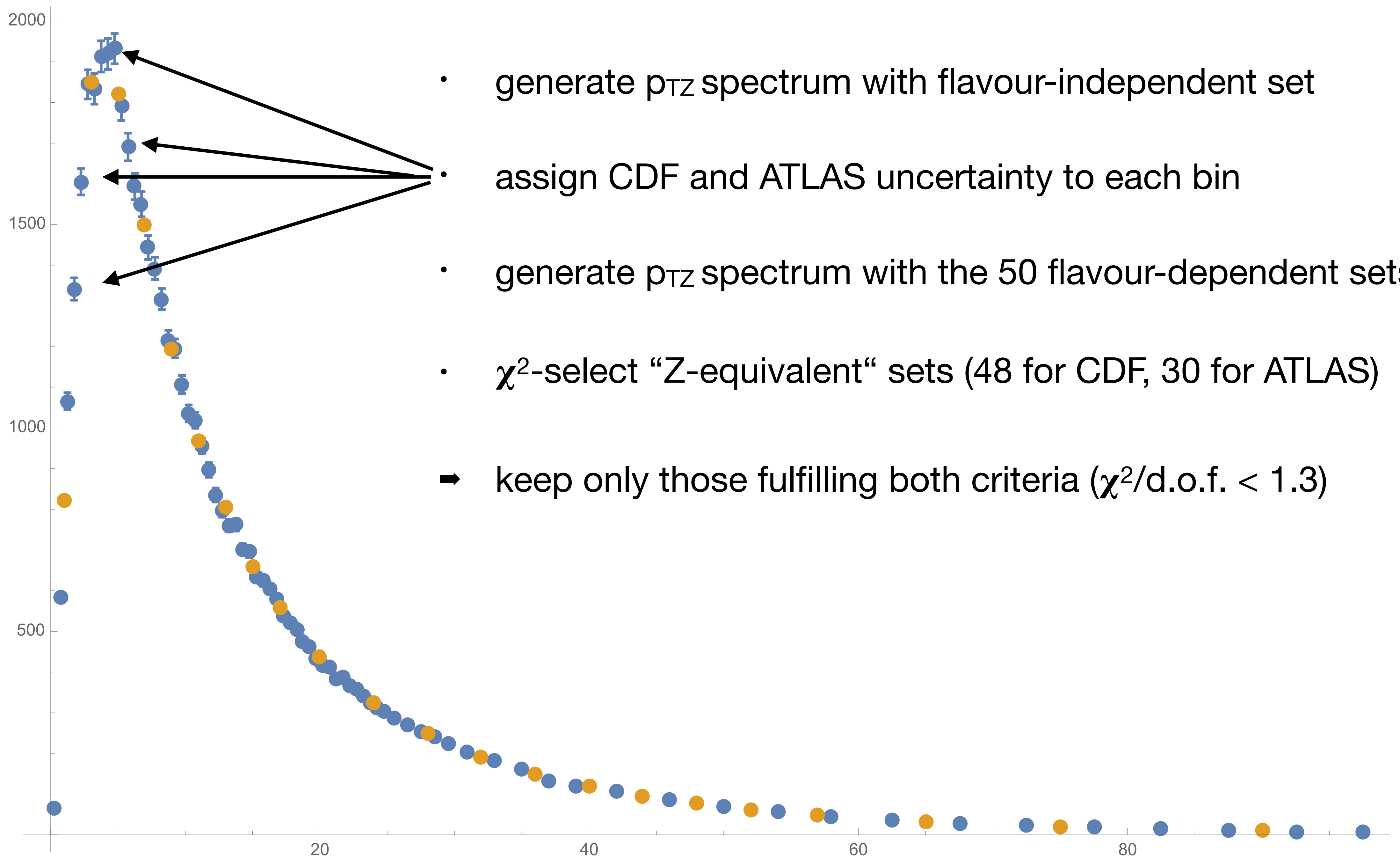
Fit to SIDIS/DY/Z data: $g_{evo} \ln\left(\frac{Q^2}{Q_0^2}\right) \in [0.17, 0.39]\ \mathrm{GeV}^2$

[Bacchetta, Delcarro, Pisano, Radici, Signori (2017)]

We consider :

- **50 flavour-dependent sets** $\{g^{u_v}_{NP}, g^{d_v}_{NP}, g^{u_s}_{NP}, g^{d_s}_{NP}, g^{s}_{NP}\}$ with $g^a_{NP} \in [0.2, 0.6]\ \mathrm{GeV}^2$
- **1 flavour-independent set** with $g^a_{NP} = 0.4\ \mathrm{GeV}^2$

“Z-equivalent” sets



- generate p_{TZ} spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin
- generate p_{TZ} spectrum with the 50 flavour-dependent sets
- χ^2-select “Z-equivalent“ sets (48 for CDF, 30 for ATLAS)

➡ keep only those fulfilling both criteria (χ^2/d.o.f. < 1.3)

NLL+LO QCD curves obtained through a modified version of the **DYqT** code [Bozzi, Catani, deFlorian, Ferrera, Grazzini (2009,2011)] (Tevatron 1.96 TeV & LHC 7 TeV)

Impact on the determination of M_W

- Take the "Z-equivalent" *flavour-dependent* parameter sets and compute *low-statistics* (135M) m_T and p_{Tl} distributions

➡ these are our **pseudodata**

- Take the *flavour-independent* parameter set and compute *high-statistics* (750M) m_T and p_{Tl} distributions for 30 different values of M_W

➡ these are our **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: zero or few MeV shifts, generally favouring lower values for W^- (preferred by EW fit)

- lepton pt: quite important shifts (W^+ set 3: **9 MeV**, envelope: **up to 15 MeV**)

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

NLL+LO QCD analysis obtained through a modified version of the **DYRes** code [Catani, deFlorian, Ferrera, Grazzini (2015)] (LHC 7 TeV, ATLAS acceptance cuts)

Statistical uncertainty: 2.5 MeV

Bacchetta, Bozzi, Radici, Ritzmann, Signori (arXiv:1807.02101)

Outlook

- First flavour-dependent study of the impact of intrinsic transverse momentum on the determination of the W mass
- Flavour effects are both important and detectable: no “flavour-blind” analysis allowed
- Future: possible flavour effects on W mass at LHCb, on CC/NC ratios (i.e., ptW/ptZ), …