Parton distributions, nonperturbative functions, quark-mass effects in W mass measurements

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Based on the work with
C. Brock, A. Belyaev, S. Berge, S. Doyle, M. Guzzi, N. Kidonakis, A. Konychev, J. Gao, T. J. Hobbs, T.-J. Hou, G. Ladinsky, F. Olness, B. T. Wang, B. W. Wang, C.-P. Yuan

CTEQ-TEA group / ResBos developers

1. Parton distributions in TMD factorization for W, Z boson production

- …introduce a systematic uncertainty of order $\delta M_W \gtrsim 10$ MeV
- Two kinds:
  a. $f_a(x,\mu)$ -- collinear PDFs [e.g., CT14 NNLO]
  b. $\mathcal{P}_a(x,\vec{k}_T)$ and $\overline{\mathcal{P}}_a(x,\vec{b})$ -- transverse-momentum-dependent (TMD) or transverse-position-dependent PDFs
- $\overline{\mathcal{P}}_a(x,\vec{b})$ is related to $f_a(x,\mu)$ at $b^2 \ll 1/\Lambda^2$, where $\Lambda \sim 1$ GeV

$$\overline{\mathcal{P}}_a(x,\vec{b}) = \int_x^1 \frac{d\xi}{\xi} C_{a/a'}\left(\frac{x}{\xi}, \frac{b\mu_b}{2e^{-\gamma_E}}; \alpha_s(\mu_b)\right) f_{a'}\left(x, \mu_b \sim \frac{1}{b}\right) + O(\Lambda^2 b^2)$$

The power-suppressed terms of order $\Lambda^{2p} b^{2p}$ must be constrained by data just as the collinear PDFs $f_a(x,\mu)$

⇒ global analyses of q_T distributions (in the future, PDFs+q_T distributions)

⇒ **constraining $f_a(x,\mu)$ and $\overline{\mathcal{P}}_a(x,\vec{b})$ at NNLO is a large coupled problem!**

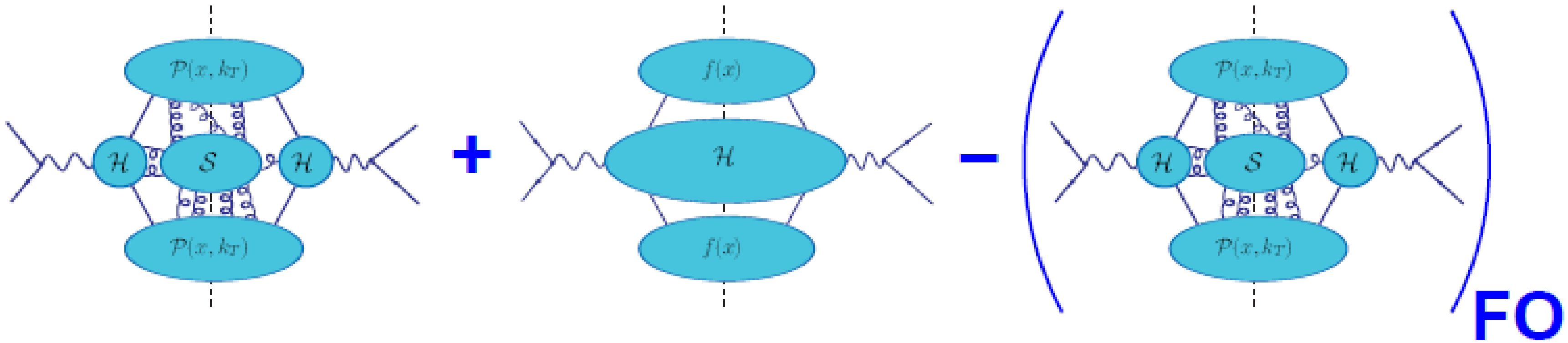
QCD factorization as a function of q_T

(according to Collins, Soper, and Sterman approach in ResBos)

Small-q_T term — $\Lambda_{QCD}^2 \ll q_T^2 \ll Q^2$

Large-q_T term — $\Lambda_{QCD}^2 \ll q_T^2 \sim Q^2$

Overlap term



- k_T-dependent PDFs $\mathcal{P}_a(x, \vec{k}_T)$ ✦ ★
- Sudakov function $\mathcal{S}(x, \vec{k}_T)$ ✦ ✡
  - ▷ actually, their impact parameter (b) space transforms

$\mu_Q \sim Q,\ \mu_b \sim 1/b$

- Collinear PDFs $f_a(x, \mu)$ ✦
- hard matrix elements $\mathcal{H}$ of order N

$\mu \sim Q \sim q_T$

- Truncated perturbative expansion

$$\sum_{k=0}^{N} \alpha_s^k \sum_{m=0}^{2k-1} c_{km} \ln^m \left(\frac{q_T^2}{Q^2} \right)$$

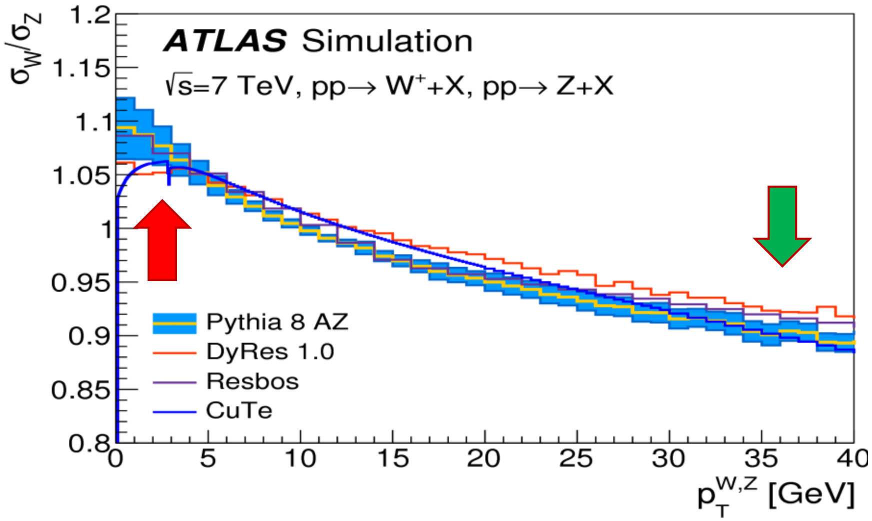
[also depends on $f_a(x, \mu)$ ✦]

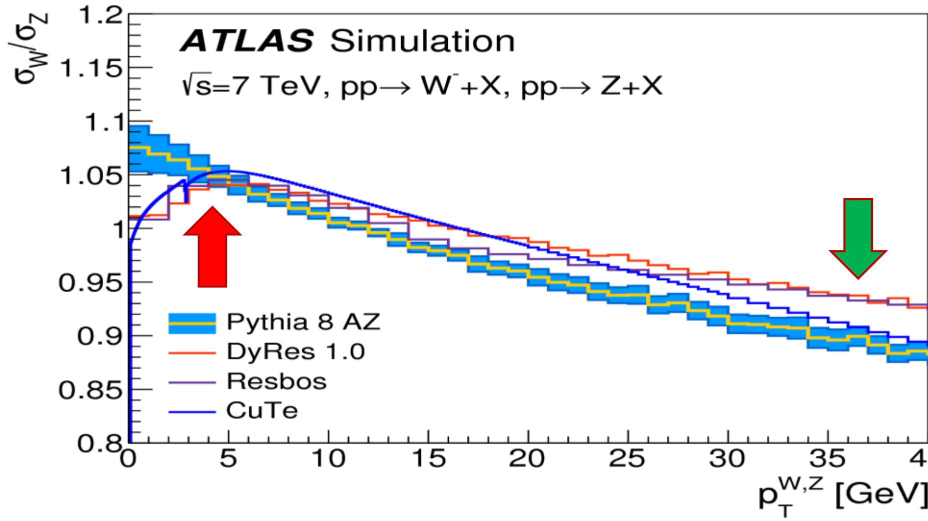
✦ long-distance

★ depends on $f_a(x, \mu)$

✡ flavor-independent

Example: $\sigma(W^+/Z^0)$ & $\sigma(W^-/Z^0)$ vs. $p_T^{W,Z}$





Various flavor combinations of $f_a(x,\mu)$ and $\overline{\mathcal{P}}_a(x,\vec{b})$ enter in a range of QCD scales from 1 GeV to $\gtrsim M_{W,Z}$; do not cancel in some xsec ratios!

Parton luminosities as percentages of the total cross section:

W^+: $u\bar{d}$ (~70%), $c\bar{s}$ (20%), gq, …
W^-: $d\bar{u}$ (60%), $s\bar{c}$ (25%), gq, ...

Z^0: $u\bar{u}$ (30%), $d\bar{d}$ (30%), $s\bar{s}$(15%), $c\bar{c}$(8%), $b\bar{b}$ (5%)….

q_{sea} and $\bar{q}_{sea}$ dominate the PDF uncertainties; impossible to **guess** which ones
Quark mass effects in c, b channels; included at NLO in ResBos 1

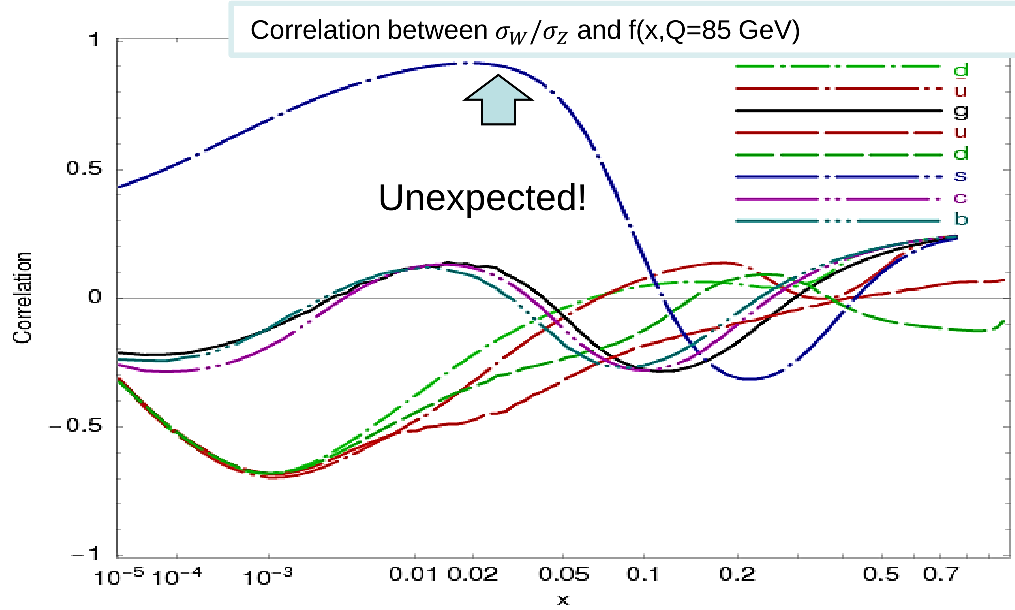
Statistical methods to identify the PDF dependence

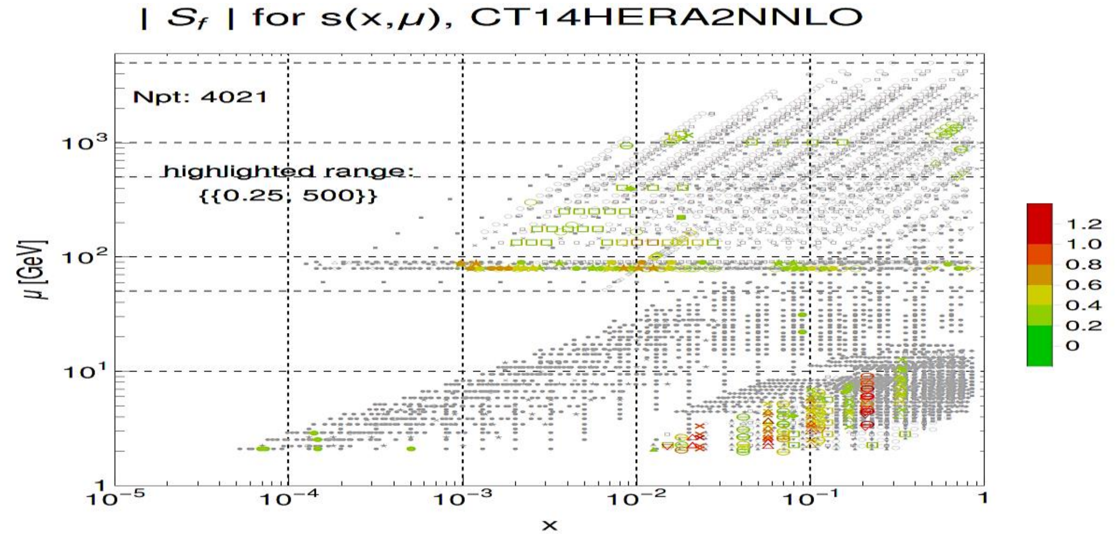
1. PDF-driven correlations [CTEQ6.6, arXiv:0802.0007]
$\cos\varphi > 0.7$ shows that the ratio σ_W/σ_Z at the LHC must be sensitive to the strange PDF $s(x,Q)$

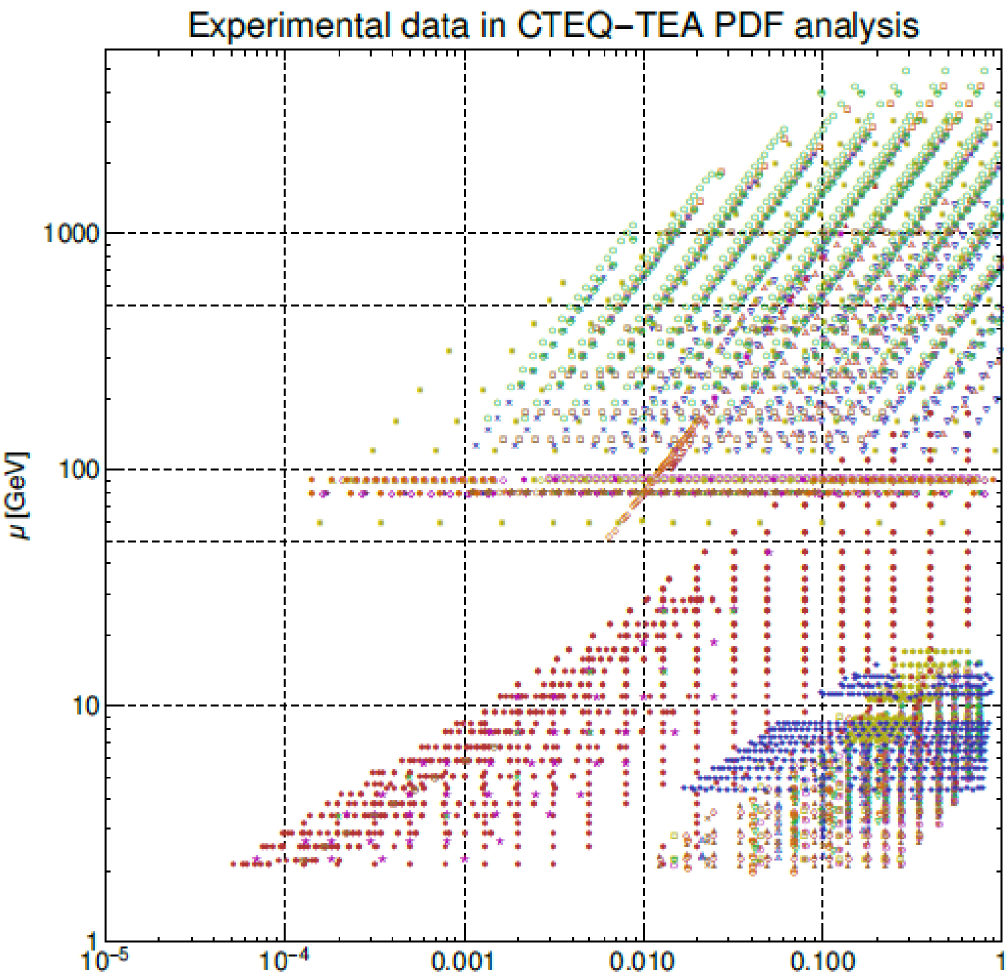
Useful, but incomplete information!

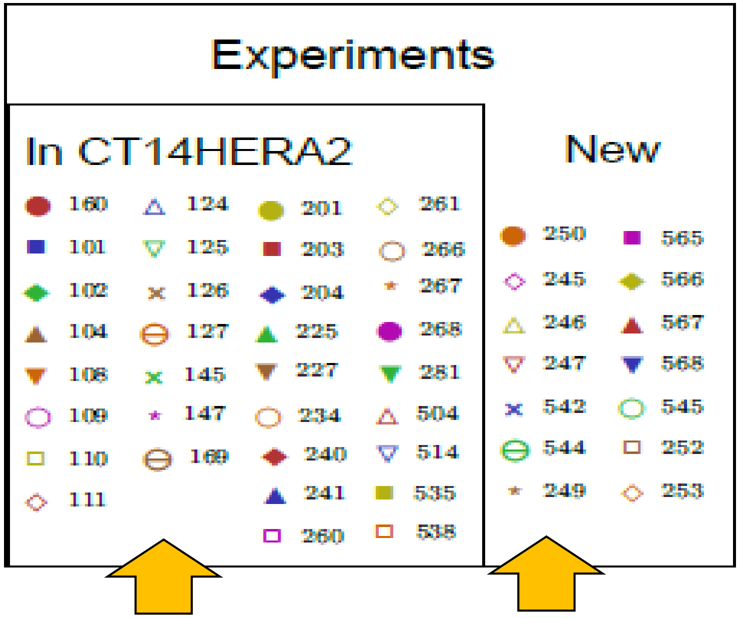
2. Program PDFSense,
B.W. Wang, T.J. Hobbs, et al., : arXiv:1803.02777

Quickly identifies **sensitivity $\boldsymbol{S_f}$** of experimental data to any PDF-dependent quantity:
$\boldsymbol{\sigma(W)/\sigma(Z), \sigma_{ResBos}/\sigma_{DYRES}}$, etc.









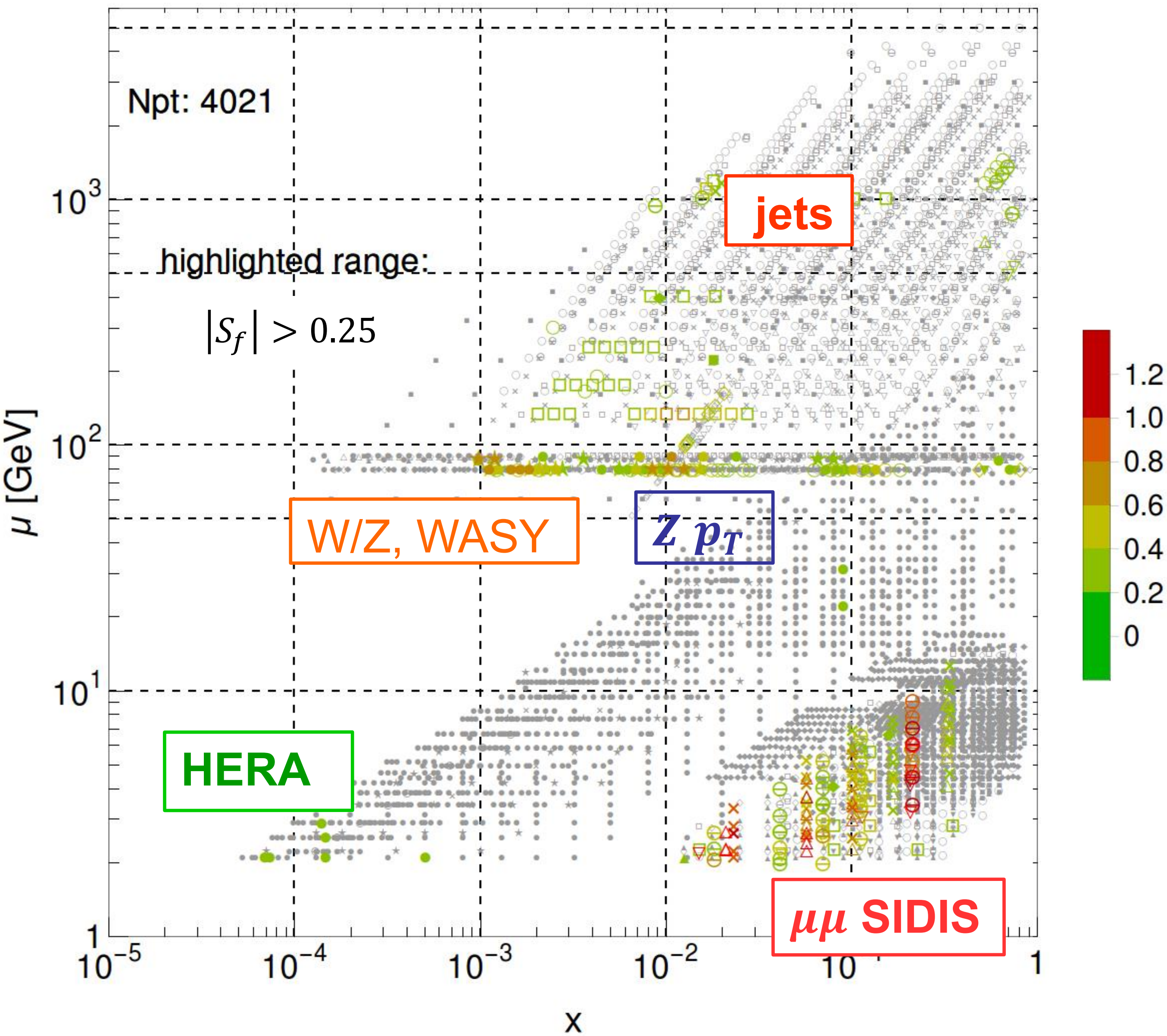
Experiments in the CT14 HERA2 NNLO fit (N_{pt} = 3258)

New experiments considered for the fit (ATLAS, CMS, LHCb; N_{pt} = 734)

ID#	Experimental dataset		N_{pt}
245	LHCb 7 TeV Z/W muon forward-η Xsec (1.0 fb^{-1})	[71]	33
246	LHCb 8 TeV Z electron forward-η $d\sigma/dy_Z$ (2.0 fb^{-1})	[72]	17
247	ATLAS 7 TeV $d\sigma/dp_T^Z$ (4.7 fb^{-1})	[73]	8
249	CMS 8 TeV W muon, Xsec, $A_\mu(\eta^\mu)$ (18.8 fb^{-1})	[74]	33
250	LHCb 8 TeV W/Z muon, Xsec, $A_\mu(\eta^\mu)$ (2.0 fb^{-1})	[75]	42
252	ATLAS 8 TeV Z ($d^2\sigma/d|y|_{ll}dm_{ll}$) (20.3 fb^{-1})	[76]	48
253	ATLAS 8 TeV ($d^2\sigma/dp_T^Z dm_{ll}$) (20.3 fb^{-1})	[77]	45

260	DØ Run-2 Z $d\sigma/dy_Z$ (0.4 fb^{-1})	[63]	28
261	CDF Run-2 Z $d\sigma/dy_Z$ (2.1 fb^{-1})	[64]	29
266	CMS 7 TeV $A_\mu(\eta)$ (4.7 fb^{-1})	[65]	11
267	CMS 7 TeV $A_e(\eta)$ (0.840 fb^{-1})	[66]	11
268	ATLAS 7 TeV W/Z Xsec, $A_\mu(\eta)$ (35 pb^{-1})	[67]	41

$|S_f|$ for s(x,μ), CT14HERA2NNLO

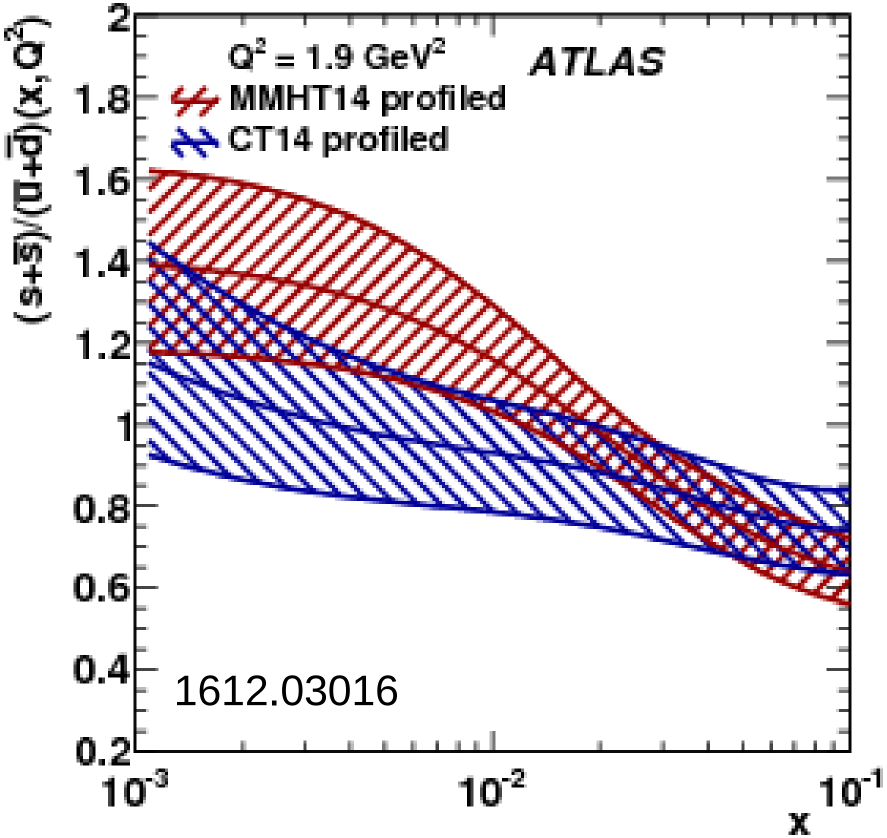


- Points with a large S_f have a stronger sensitivity to $s(x_i, \mu_i)$
- Constraints on $s(x, \mu)$ are weaker than on the other flavors

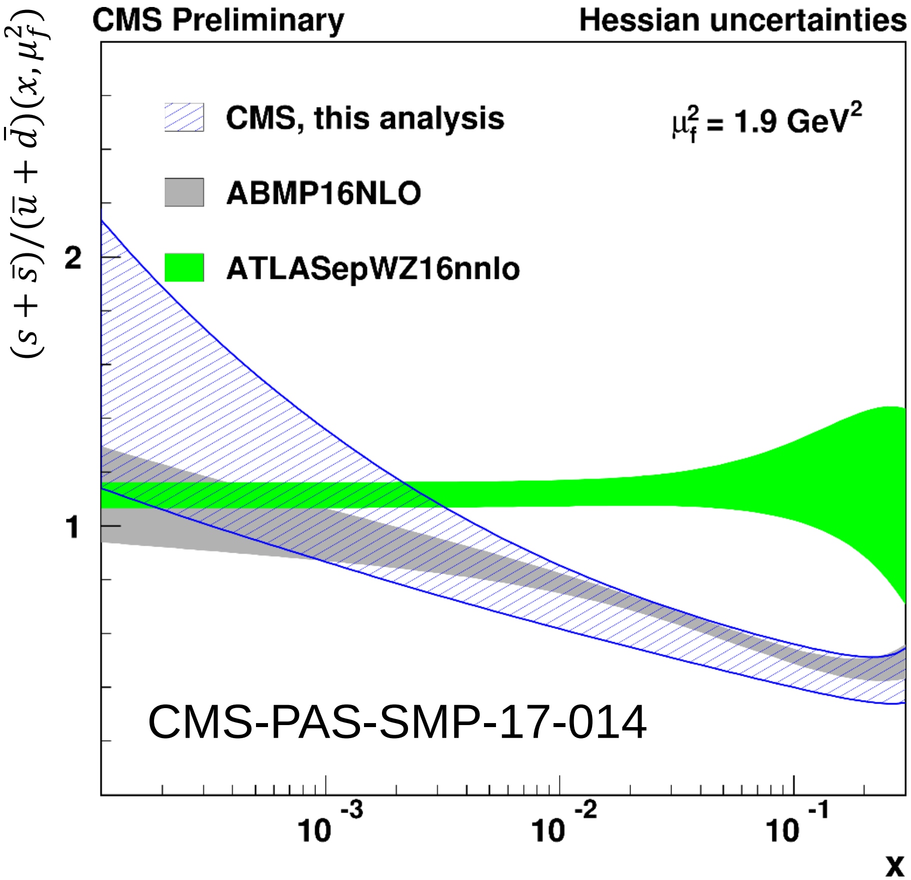
NuTeV, CCFR dimuon SIDIS, HERA DIS most sensitive

- Combined $|S_f|$ of CMS7+8 jet data comparable to $|S_f|$ of one of NuTeV, CCFR data sets
- W ASYmmetry, σ_W, σ_Z are weakly sensitive

But, wait, LHC experiments do not agree on strangeness

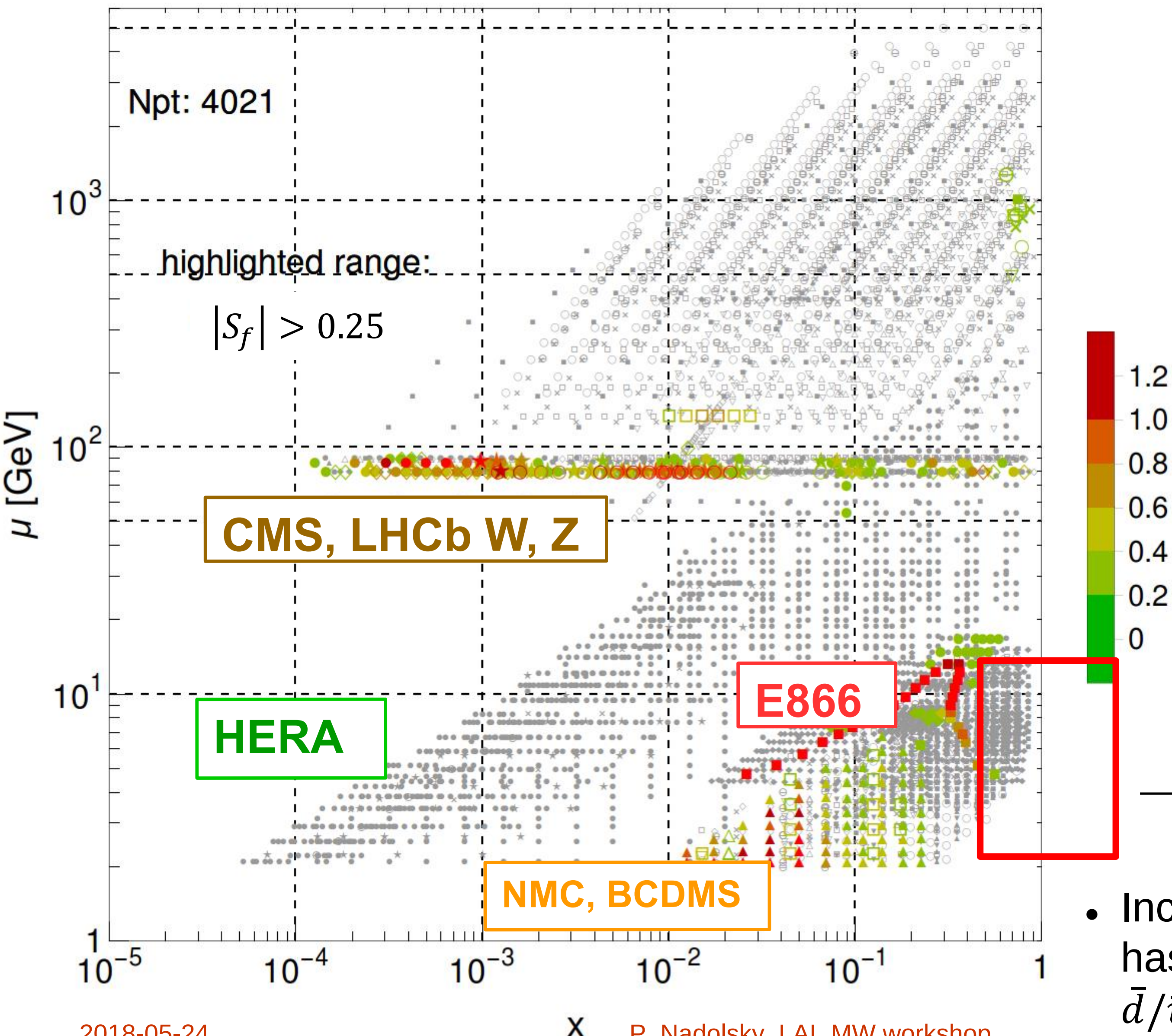


CT14 and MMHT14 NNLO PDFs profiled using ATLAS 7 TeV (4.6 fb^{-1}) $W^{\pm}$, Z xsecs prefer $s(x, 1.9\ GeV) \sim 1$ @ $x = 0.023$



CMS W,Z, CMS W+c (13 TeV) prefer smaller $s(x,\mu)$ than ATLAS for $x \gtrsim 10^{-3}$

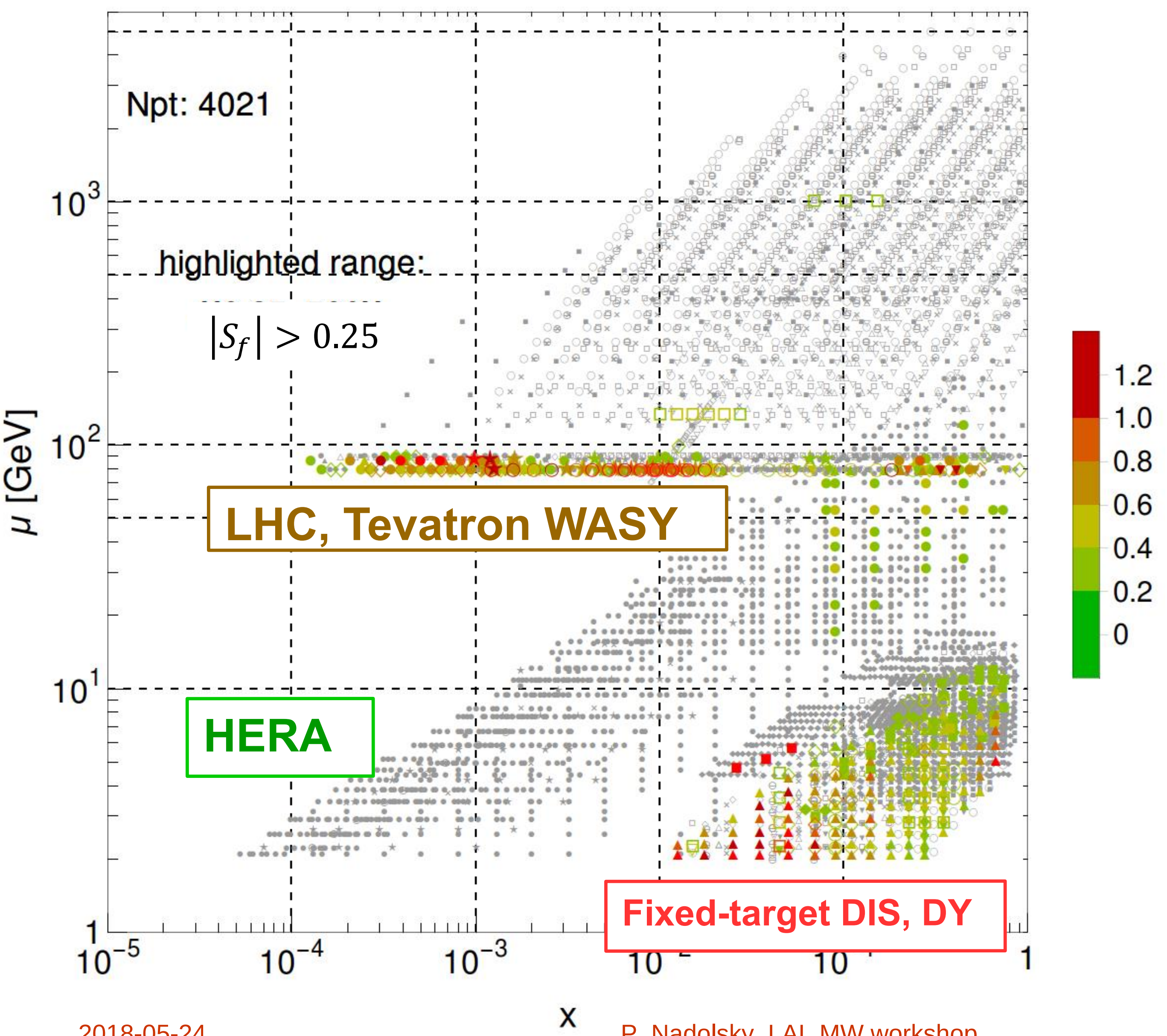
$|S_f|$ for $\bar{d}/\bar{u}(x,\mu)$, CT14HERA2NNLO



HERA DIS:
large N_{pt} ⇒
large total $|S_f|$

- the large E866 pd/pp sensitivity *degrades* at larger x
  - this is a prime motivation for higher x DY measurements at **E906** (SeaQuest)
- Inclusive jet production has potential to constrain $\bar{d}/\bar{u}$ in the near future

$|S_f|$ fo $d/u(x,\mu)$, CT14HERA2NNLO



HERA, fixed-target DIS still most sensitive!

Individually, LHC W, Z experiments provide the essential reach to d/u and $\bar{d}/\bar{u}$ at $x \sim 10^{-2}$

In the fit, they do not tangibly reduce the PDF error because they don't quite agree

Questions to address

1. Which experiments constrain the PDFs in the M_W, $\sin\theta_w$ measurements?

2. What needs to be done to reduce the PDF uncertainty on M_W? To phase out the fixed-target DIS/DY experiments?

[These questions can be studied as a part of the M_W analysis using the PDFSense tool, without relying on PDF reweighting or profiling]

3. **Benchmarking exercise for NNLO QCD + NLO EW W, Z rapidity distributions and asymmetries**

Similar in spirit to the PDF4LHC benchmarking exercise that reduced $\delta_{PDF}\sigma(H_0)$ from 7% to 3% [arXiv:1510.03865]

All NNLO/resummation/PDF fitting codes must agree on benchmark **inclusive** W, Z cross sections. [Often, they don't.] Check for numerical issues. PDF fits are often done with fast NNLO QCD interfaces for "bare Born" lepton production.

Fitted W, Z experiments must agree with one another, or we cannot reduce the CT14 PDF uncertainty. [They don't.]

2. Nonperturbative parameters in the TMD factorization

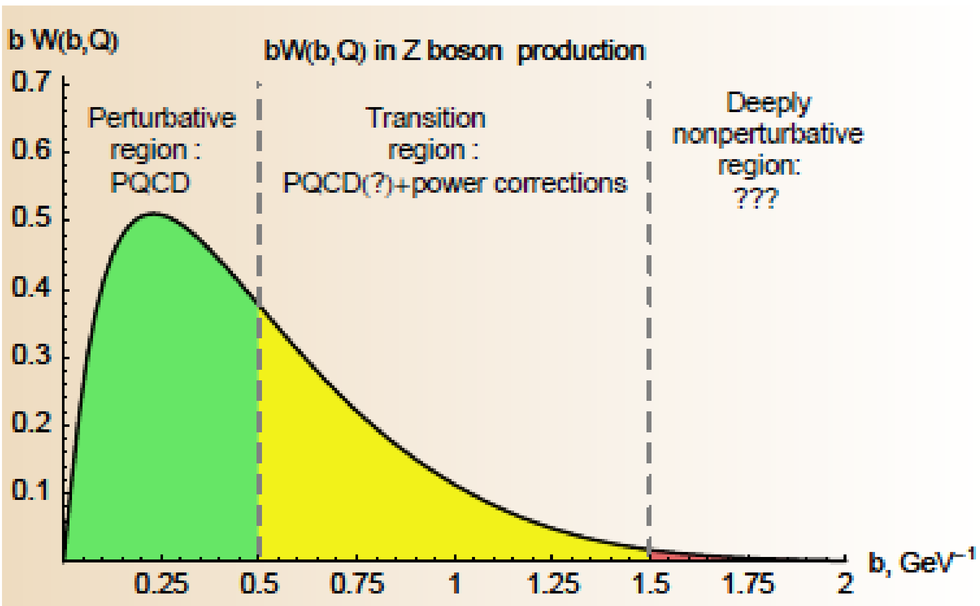
Arise at $b > 0.5\ \mathrm{GeV}^{-1}$ from…

…the soft (Sudakov) function $S(b, Q)$

flavor-independent, x-independent; linear in $\ln(Q/Q_{ref})$; dominate at $Q = M_{W,Z}$; shift M_W by ×100 MeV

…TMD PDFs $\overline{\mathcal{P}}_a(x, \vec{b})$

depend on the flavor & x, not on Q; marginal, poorly known; shift M_W by × 1 MeV



Universal in e^+e^-, SIDIS, DY & compatible with $\overline{MS}$ PDFs in the CSS framework *[Collins, Metz, 2004];*

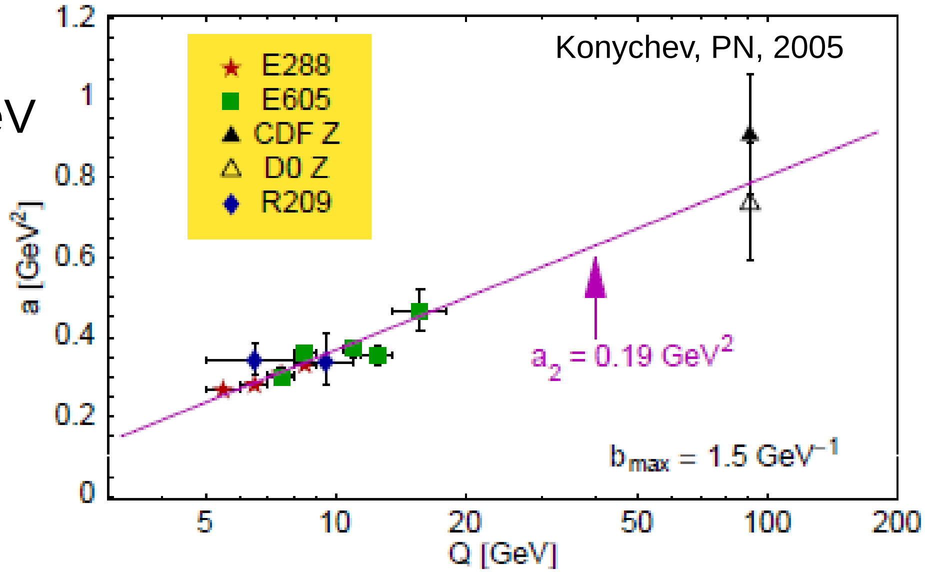
not automatically universal in all resummation/event generator frameworks

A Gaussian nonperturbative function, example

$$F_{NP}(b,Q) = b^2\, a(Q, x_A, x_B)$$

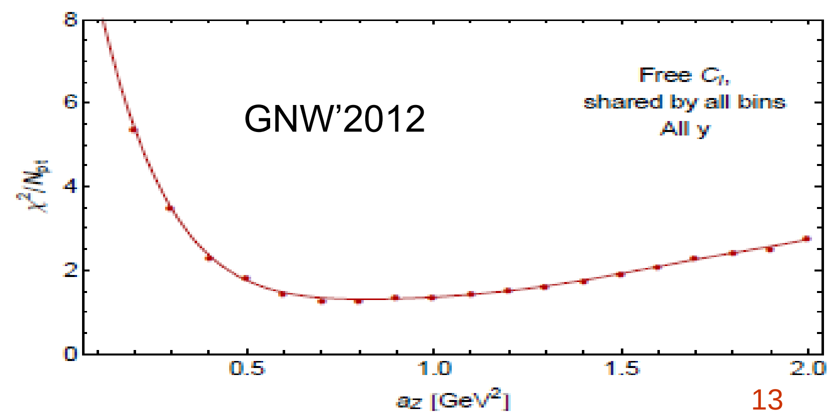
Adequate in DY processes for Q >5 GeV

Guzzi, PN, Wang [arXiv: 1309.1393]:
$Q_{ref} = M_Z$, $b_{max} = 1.5\ GeV^{-1}$;
NNLL+$O(\alpha_s^2)$ (ResBos 1)
Fitted to Tevatron Run-2 $\frac{d\sigma(Z)}{dy d\varphi^*_\eta}$ using
fixed or free scales $C_{1,2,3}$



$$a(Q,\sqrt{s}) = a_Z(1.96\ \mathrm{TeV}) + a_2 \ln\left(\frac{Q}{M_Z}\right) + a_3 \ln\left(\frac{Q^2}{M_Z^2}\frac{s}{(1.96\ \mathrm{TeV})^2}\right).$$

$a_Z = 0.79^{+0.2}_{-0.03}$, $a_2 = 0.17 \pm 0.03$,
$a_3 = -0.03 \pm 0.02$ (in GeV^2)



For $Q \approx M_{W,Z}$: $a(Q,\sqrt{s}) \approx a_Z$ -- a 1-parameter fit with the scales $C_{1,2,3}$ as nuisance parameters

Some alternative nonperturbative functions

- BLNY form with small-x broadening in ResBos

  [Berge, PN, Olness, Yuan, hep-ph/0410375]

$$F_{NP}(b, Q, x_A, x_B)$$
$$= b^2 \left[0.21 + 0.68\, ln\left(\frac{Q}{3.2\ GeV}\right) - 0.126 \ln \frac{x_A x_B}{0.1^2} + g_3 \left(\frac{1}{x_A} + \frac{1}{x_B}\right)\right]$$

- Joint form for DY+SIDIS

  [Sun, Isaacson, Yuan, Yuan, 1406.0373]

$$F_{NP}(b, Q, x_A, x_B) = b^2 \left[0.212 + 0.84\, ln\left(\frac{Q}{1.55\ GeV}\right) + g_3 \left(\left(\frac{0.01}{x_A}\right)^{0.2} + \left(\frac{0.01}{x_B}\right)^{0.2}\right)\right]$$

Current Drell-Yan data are compatible with $g_3 = 0$

- The Gaussian approximation fails at $Q < 5$ GeV. A more complete parametrization is discussed, e.g., in J. Collins, T. Rogers, 1412.3820
- A variety of other forms were proposed, hard to discriminate by data

3. TMD PDFs with quark mass dependence

(PN, Kidonakis, Olness, Yuan, : hep-ph/0210082; Berge, PN, Olness, hep-ph/0509023; Recent work in SCET at NNLL-NNLO by Pietrulewisz et al., 1703.09702)

In ResBos 1, finite-mass effects are included in $\overline{\mathcal{P}}_a(x,\vec{b})$ for $a=c,b$ at NLO in the S-ACOT-χ mass scheme – the scheme used to determined CT14 PDFs

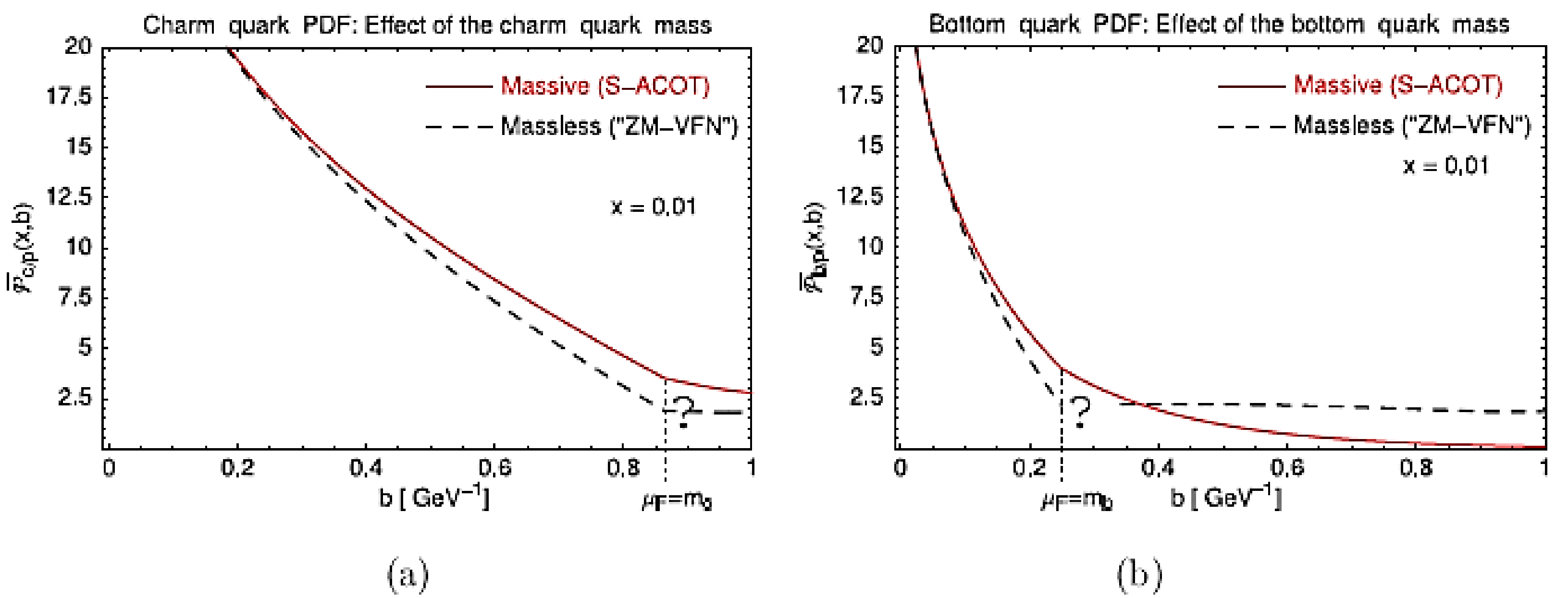
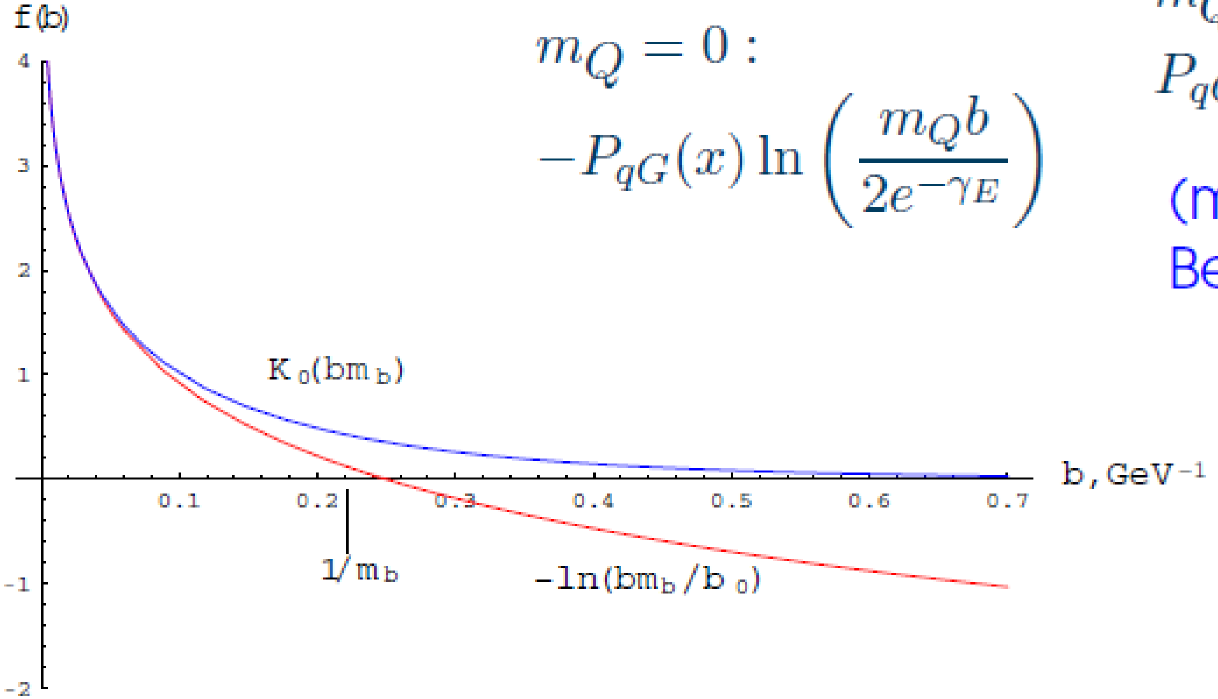


Figure 1: The b-dependent parton densities $\overline{\mathcal{P}}_{Q/A}(x,b,m_Q)$ vs. the impact parameter b for (a) charm quarks and (b) bottom quarks. The solid and dashed curves correspond to the S-ACOT and massless ("ZM-VFN") factorization schemes, respectively.

m_Q suppresses contributions from $1/b \lesssim m_Q$



$m_Q = 0:$

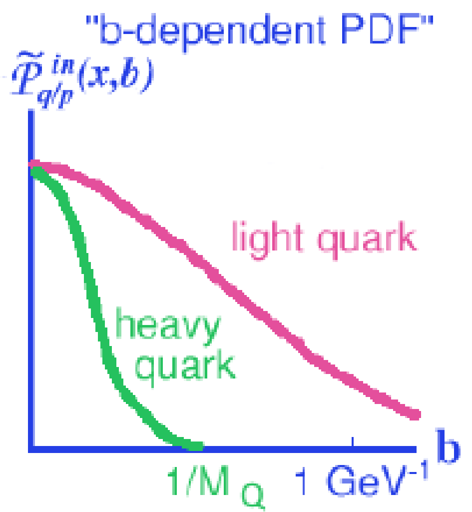
$$-P_{qG}(x)\ln\left(\frac{m_Q b}{2e^{-\gamma_E}}\right)$$

$m_Q \neq 0:$

$$P_{qG}(x) K_0(m_Q b)$$

(modified Bessel function)

For $m_Q^2 \gg \Lambda_{QCD}^2$, the resummed cross section can be calculated without the nonperturbative input from $b \sim \Lambda_{QCD}$!



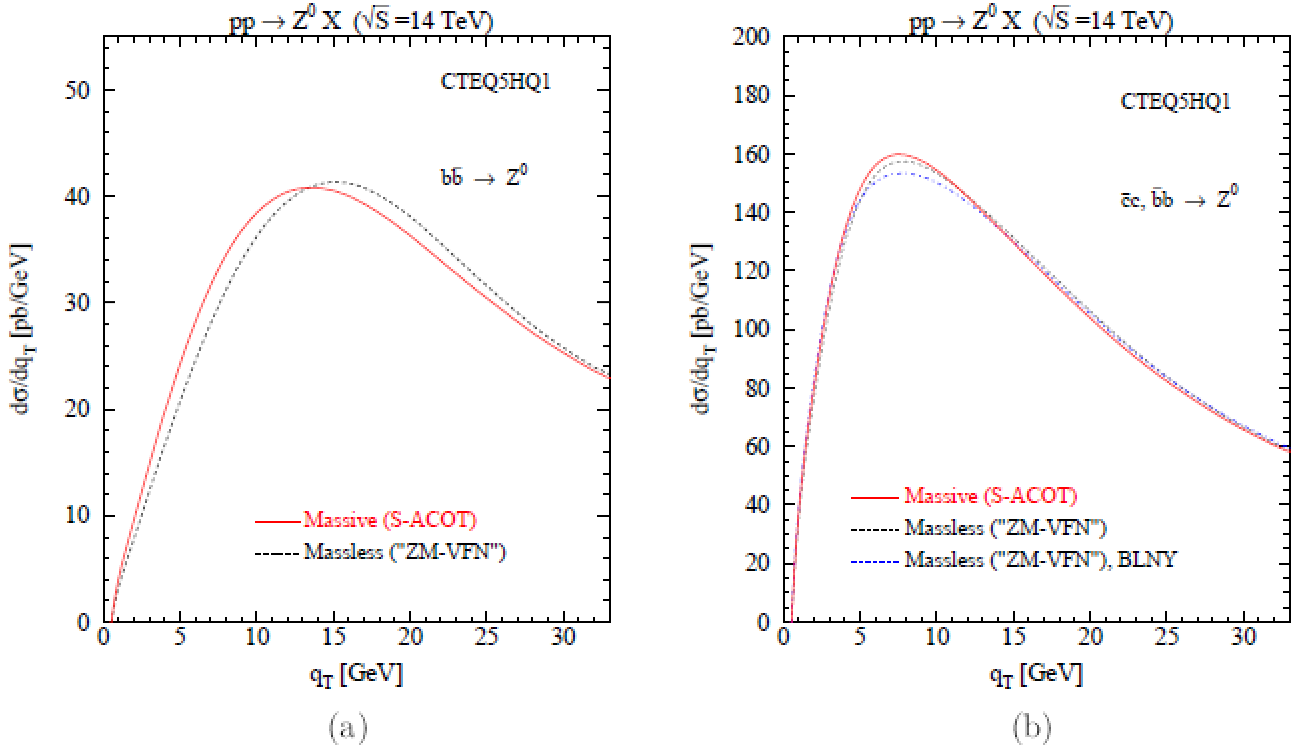


Figure 3: $d\sigma/dq_T$ for $c\bar{c}$, $b\bar{b} \to Z^0$ boson production at the LHC: (a) $b\bar{b}$ channel only, (b) combined $c\bar{c}$ and $b\bar{b}$ channels. The solid (red) curve shows the distribution in the massive (S-ACOT) scheme. The dashed (black) curve shows the distribution in the massless ("ZM-VFN") scheme, computed using the parametrization (11) of the nonperturbative function $\mathcal{F}_{NP}(b, Q)$. The dot-dashed (blue) line was calculated in the "ZM-VFN" scheme using an alternative parameterization [48] of the nonperturbative function $\mathcal{F}_{NP}(b, Q)$.

Total $\Delta M_W \sim$ 10 MeV [~0 MeV] for $d\sigma/dp_T^e$ [$d\sigma/dM_T^{e\nu}$] at 14 TeV due to $m_{c,b} \neq 0$

Extra details

Experiments in the CT14 HERA2 fit

ID#	Experimental dataset		N_d
101	BCDMS F_2^p	[47]	337
102	BCDMS F_2^d	[48]	250
104	NMC F_2^d/F_2^p	[49]	123
108	CDHSW F_2^p	[50]	85
109	CDHSW F_3^p	[50]	96
110	CCFR F_2^p	[51]	69
111	CCFR xF_3^p	[52]	86
124	NuTeV $\nu\mu\mu$ SIDIS	[40]	38
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[40]	33
126	CCFR $\nu\mu\mu$ SIDIS	[41]	40
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[41]	38
145	H1 σ_r^b (57.4 pb^{-1})	[53][54]	10
147	Combined HERA charm production (1.504 fb^{-1})	[39]	47
160	HERA1+2 Combined NC and CC DIS (1 fb^{-1})	[6]	1120
169	H1 F_L (121.6 pb^{-1})	[55]	9

ID#	Experimental dataset		N_d
201	E605 DY	[56]	119
203	E866 DY, $\sigma_{pd}/(2\sigma_{pp})$	[57]	15
204	E866 DY, $Q^3 d^2\sigma_{pp}/(dQ dx_F)$	[58]	184
225	CDF Run-1 $A_e(\eta^e)$ (110 pb^{-1})	[59]	11
227	CDF Run-2 $A_e(\eta^e)$ (170 pb^{-1})	[60]	11
234	DØ Run-2 $A_\mu(\eta^\mu)$ (0.3 fb^{-1})	[61]	9
240	LHCb 7 TeV W/Z muon forward-η Xsec (35 pb^{-1})	[62]	14
241	LHCb 7 TeV W $A_\mu(\eta^\mu)$ (35 pb^{-1})	[62]	5
260	DØ Run-2 Z $d\sigma/dy_Z$ (0.4 fb^{-1})	[63]	28
266	CMS 7 TeV $A_\mu(\eta)$ (4.7 fb^{-1})	[64]	11
267	CMS 7 TeV $A_e(\eta)$ (0.840 fb^{-1})	[65]	11
268	ATLAS 7 TeV W/Z Xsec, $A_\mu(\eta)$ (35 pb^{-1})	[66]	41
281	DØ Run-2 $A_e(\eta)$ (9.7 fb^{-1})	[67]	13
504	CDF Run-2 incl. jet $(d^2\sigma/dp_T^j dy_j)$ (1.13 fb^{-1})	[36]	72
514	DØ Run-2 incl. jet $(d^2\sigma/dp_T^j dy_j)$ (0.7 fb^{-1})	[37]	110
535	ATLAS 7 TeV incl. jet $(d^2\sigma/dp_T^j dy_j)$ (35 pb^{-1})	[68]	90
538	CMS 7 TeV incl. jet $(d^2\sigma/dp_T^j dy_j)$ (5 fb^{-1})	[69]	133

Candidate experiments in the CTEQ-TEA fit

ID#	Experimental dataset		N_d
245	LHCb 7 TeV Z/W muon forward-η Xsec (1.0 fb^{-1})	[70]	33
246	LHCb 8 TeV Z electron forward-η $d\sigma/dy_Z$ (2.0 fb^{-1})	[71]	17
247	ATLAS 7 TeV $d\sigma/dp_T^Z$ (4.7 fb^{-1})	[72]	8
249	CMS 8 TeV W muon, Xsec, $A_\mu(\eta^\mu)$ (18.8 fb^{-1})	[73]	33
250	LHCb 8 TeV W/Z muon, Xsec, $A_\mu(\eta^\mu)$ (2.0 fb^{-1})	[74]	42
252	ATLAS 8 TeV Z $(d^2\sigma/d\|y\|_{ll} dm_{ll})$ (20.3 fb^{-1})	[75]	48
253	ATLAS 8 TeV $(d^2\sigma/dp_T^Z dm_{ll})$ (20.3 fb^{-1})	[76]	45
542	CMS 7 TeV incl. jet, R=0.7, $(d^2\sigma/dp_T^j dy_j)$ (5 fb^{-1})	[34]	158
544	ATLAS 7 TeV incl. jet, R=0.6, $(d^2\sigma/dp_T^j dy_j)$ (4.5 fb^{-1})	[33]	140
545	CMS 8 TeV incl. jet, R=0.7, $(d^2\sigma/dp_T^j dy_j)$ (19.7 fb^{-1})	[35]	185
565	ATLAS 8 TeV $t\bar{t}$ $d\sigma/dp_T^t$ (20.3 fb^{-1})	[38]	8
566	ATLAS 8 TeV $t\bar{t}$ $d\sigma/dy_{<t/\bar{t}>}$ (20.3 fb^{-1})	[38]	5
567	ATLAS 8 TeV $t\bar{t}$ $d\sigma/dm_{t\bar{t}}$ (20.3 fb^{-1})	[38]	7
568	ATLAS 8 TeV $t\bar{t}$ $d\sigma/dy_{t\bar{t}}$ (20.3 fb^{-1})	[38]	5

N_d is the number of data points

Q_T distribution for $AB \to VX$

$$\frac{d\sigma_{AB\to VX}}{dQ^2 dy dq_T^2} = \sum_{a,b=g,\overset{(-)}{u},\overset{(-)}{d},\dots} \int \frac{d^2b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}}\widetilde{W}_{ab}(b,Q,x_A,x_B) + Y(q_T,Q,x_A,x_B)$$

$$\widetilde{W}_{ab}(b,Q,x_A,x_B) = |\mathcal{H}_{ab}|^2\, e^{-\mathcal{S}(b,Q)}\overline{\mathcal{P}}_a(x_A,b)\overline{\mathcal{P}}_b(x_B,b)$$

$\mathcal{S}$ is the soft (Sudakov) function:

$$\mathcal{S}(b,Q) = \int_{b_0^2/b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\mathcal{A}(\alpha_s(\bar{\mu}))\ln\frac{\bar{\mu}^2}{Q^2} + \mathcal{B}(\alpha_s(\bar{\mu}))\right], \quad b_0 = 2e^{-\gamma_E} \approx 1.12$$

$\overline{\mathcal{P}}_a(x,b)$ are b-dependent PDF's; if $b^2 \ll Q^{-2}$,

$$\overline{\mathcal{P}}_a(x,b) = \sum_c \left[\mathcal{C}_{a/c}\otimes f_c\right](x,b,\mu_F = \frac{b_0}{b})$$

Y is the difference of the finite-order and overlap (asymptotic) terms