ABM11 PDFs confronting LHC data

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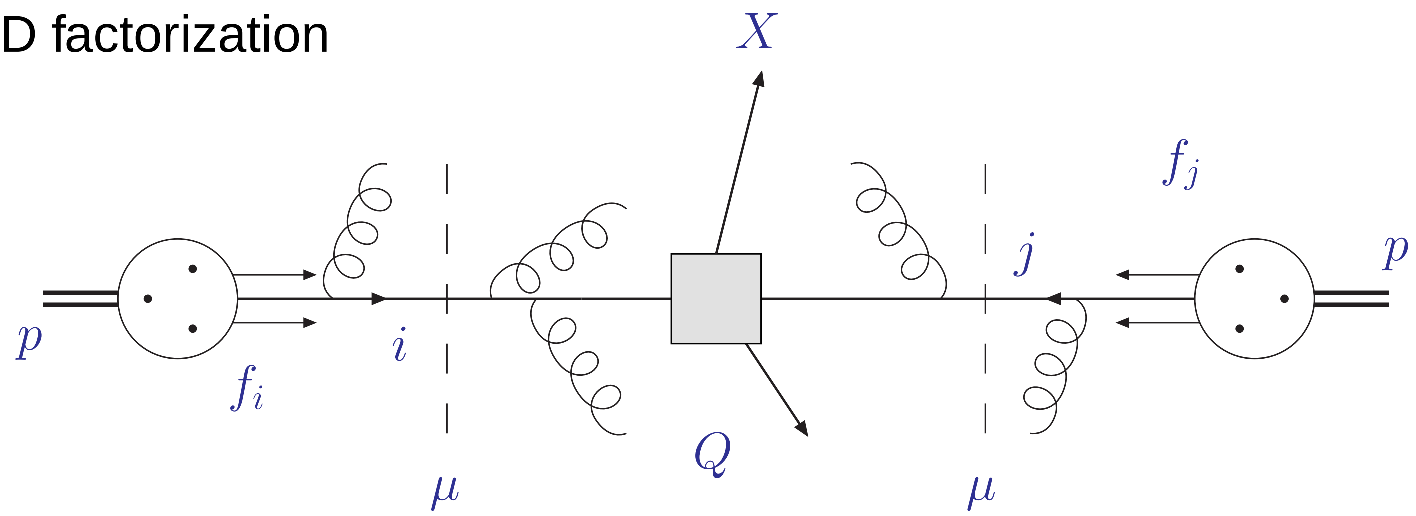
Plan

- Talk based on results on . . .
  - . . . precise parton distribution functions from global fits
    ABKM09 S. Alekhin, J. Blümlein, S. Klein and S. M.
    arXiv:0908.2766
    ABM10 S. Alekhin, J. Blümlein and S. M. arXiv:1007.3657
    new → ABM11 S. Alekhin, J. Blümlein and S. M. arXiv:1202.2281
  - . . . NNLO benchmarks cross sections at the Terascale
    S. Alekhin, J. Blümlein, P. Jimenez-Delgado, S. M. and E. Reya
    arXiv:1011.6259
  - . . . Higgs production rates and constraints from fixed-target DIS data
    S. Alekhin, J. Blümlein and S. M. arXiv:1011.5261
  - . . . the running charm-quark mass
    S. Alekhin and S. M. arXiv:1011.5790

Introduction

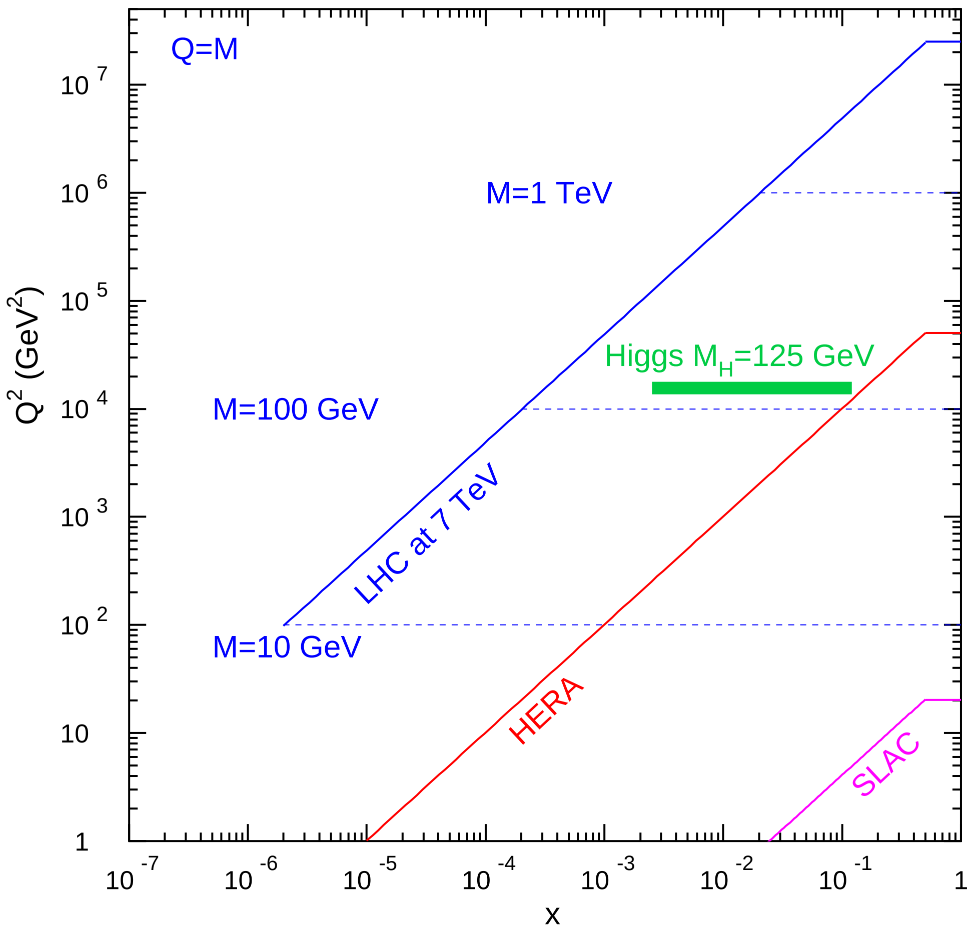
- QCD factorization



$$\sigma_{pp \to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \to X} \left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2 \right)$$

- Hard parton cross section $\hat{\sigma}_{ij \to X}$ calculable in perturbation theory
  - known to NLO, NNLO, ... ($\mathcal{O}(\text{few}\%)$ theory uncertainty)
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, ...

Parton luminosity at LHC



- LHC run at $\sqrt{s}$ = 7/8 TeV
  - parton kinematics well covered by HERA and fixed target experiments
- Parton kinematics at effective $\langle x \rangle = M/\sqrt{S}$
  - 100 GeV physics: small-x, sea partons
  - TeV scales: large-x

ABM11 parton distributions

ABM11 in a nut shell Alekhin, Blümlein, S.M. '12

- Determination of PDFs and strong coupling constant α_s to NNLO QCD
- Consistent scheme for treatment of heavy quarks
  - fixed-flavor number scheme for $n_f = 3, 4, 5$
- Full account of error correlations

Data considered in the fit

- Analysis of world data for deep-inelastic scattering and fixed-target data for Drell-Yan process
  - inclusive DIS data HERA, BCDMS, NMC, SLAC
  - Drell-Yan data (fixed target) E-605, E-866
  - neutrino-nucleon DIS data (di-muon production) CCFR/NuTeV

ABM ansatz

- PDFs parameterized at scale $Q_0 = 3\mathrm{GeV}$ in scheme with $n_f = 3$
  - ansatz for valence-/sea-quarks, gluon with polynomial $P(x)$
  - strange quark is taken in charge-symmetric form
  - 24 parameters in polynomials $P(x)$
  - 4 additional fit parameters: $\alpha_s^{(n_f=3)}(\mu = 3$ GeV), m_c, m_b and deuteron correction

$$
\begin{aligned}
xq_v(x,Q_0^2) &= \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} x^{a_q}(1-x)^{b_q} x^{P_{qv}(x)} \\
xu_s(x,Q_0^2) = x\bar{u}_s(x,Q_0^2) &= A_{us} x^{a_{us}}(1-x)^{b_{us}} x^{a_{us} P_{us}(x)} \\
x\Delta(x,Q_0^2) = xd_s(x,Q_0^2) - xu_s(x,Q_0^2) &= A_\Delta x^{a_\Delta}(1-x)^{b_\Delta} x^{P_\Delta(x)} \\
xs(x,Q_0^2) = x\bar{s}(x,Q_0^2) &= A_s x^{a_s}(1-x)^{b_s}\,, \\
xg(x,Q_0^2) &= A_g x^{a_g}(1-x)^{b_g} x^{a_g P_g(x)}
\end{aligned}
$$

- Ansatz provides sufficient flexibility; no additional terms required to improve the quality of fit

Quark masses in PDF fits

- Choice of value for heavy-quark masses part of uncertainty
- PDF fits assume pole mass scheme for heavy-quarks
  - numerical values systematically lower than those from PDG (2-loop conversion to pole mass)

[GeV]	PDG	ABKM	GJR	HERAPDF	MSTW	CT10	NNPDF21
m_c	1.66 $^{+0.09}_{-0.15}$	1.5 $^{+0.25}_{-0.25}$	1.3	1.4 $^{+0.25}_{-0.05}$	1.3	1.3	1.41
m_b	4.79 $^{+0.19}_{-0.08}$	4.5 $^{+0.5}_{-0.5}$	4.2	4.75 $^{+0.25}_{-0.45}$	4.75	4.75	4.75

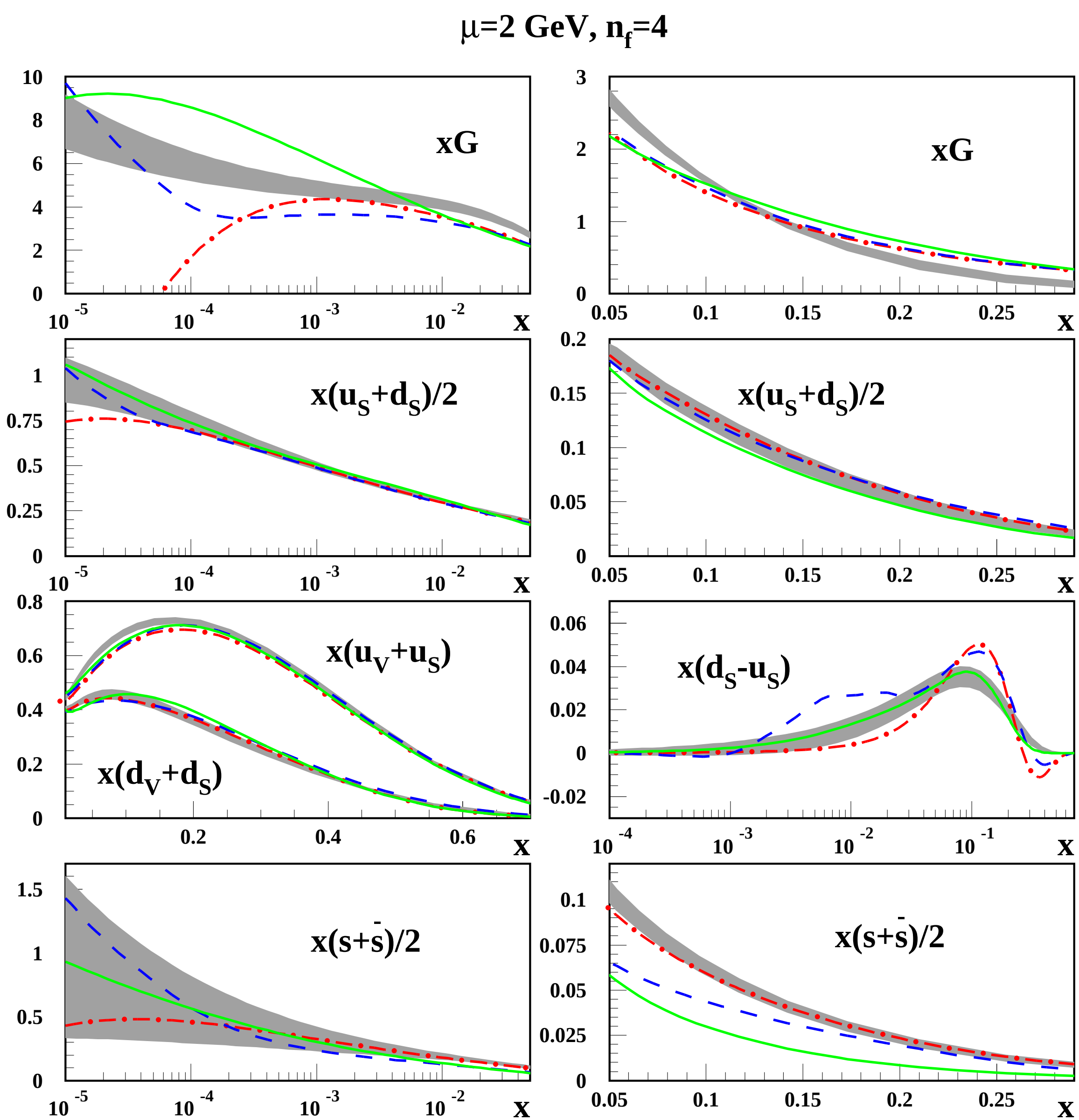
PDG

- PDG quotes running masses:
  charm: $m_c(m_c) = 1.27^{+0.07}_{-0.11}$ GeV, bottom: $m_b(m_b) = 4.20^{+0.17}_{-0.07}$ GeV

ABM11

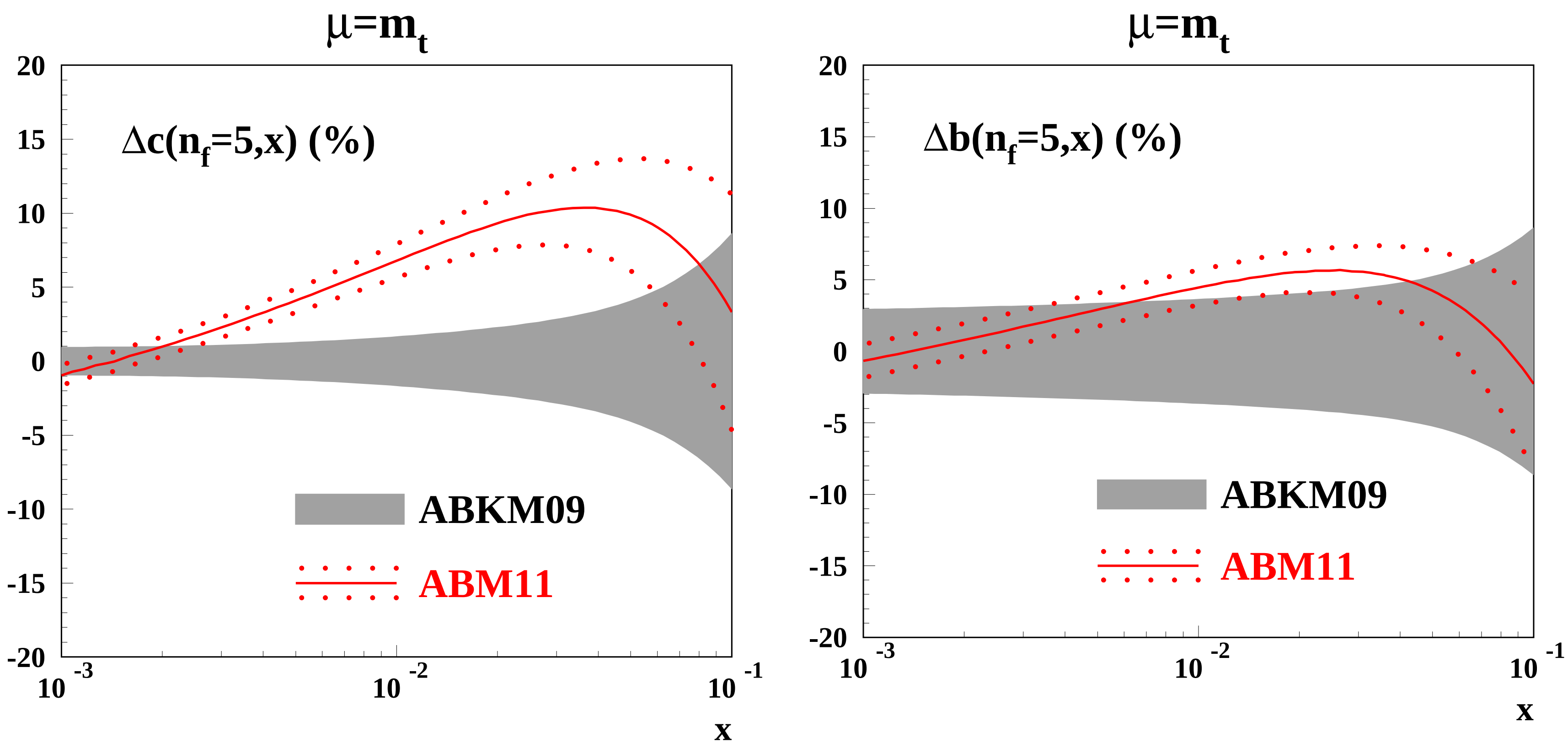
- ABM11 uses running masses:
  charm: $m_c(m_c) = 1.27^{+0.08}_{-0.08}$ GeV, bottom: $m_b(m_b) = 4.19^{+0.13}_{-0.13}$ GeV

Parton distributions for the LHC



- 1σ band for ABM11 PDFs (NNLO, 4-flavors) at $\mu = 2$ GeV
  Alekhin, Blümlein, S.M.'12
- comparison with:
  JR09 (solid lines),
  MSTW (dashed dots) and
  NN21 (dashes)
- Some interesting observations to be made . . .

Charm and bottom-quark PDFs



- Heavy-quark PDFs generated from $n_f = 3$ PDFs
  - $\pm 1\sigma$ band of relative uncertainties (in percent)
- Changes due to running-mass definition (comparison to ABKM09)
  - modification of the massive OMEs
- Reduced uncertainty in b-PDF $\longrightarrow$ impact on single-top production

Quality of fit

	Experiment	NDP	χ^2(NNLO)	χ^2(NLO)
DIS inclusive	H1&ZEUS	486	537	531
	H1	130	137	132
	BCDMS	605	705	695
	NMC	490	665	661
	SLAC-E-49a	118	63	63
	SLAC-E-49b	299	357	357
	SLAC-E-87	218	210	219
	SLAC-E-89a	148	219	215
	SLAC-E-89b	162	133	132
	SLAC-E-139	17	11	11
	SLAC-E-140	26	28	29
Drell-Yan	FNAL-E-605	119	167	167
	FNAL-E-866	39	52	55
DIS di-muon	NuTeV	89	46	49
	CCFR	89	61	62
Total		3036	3391	3378

Covariance matrix

- Correlations of PDF fit parameters (I)

	a_u	b_u	$\gamma_{1,u}$	$\gamma_{2,u}$	a_d	b_d	A_Δ	b_Δ	A_{us}	a_{us}	b_{us}	a_g	b_g	$\gamma_{1,g}$
a_u	1.0000	0.9692	0.9787	-0.7929	0.7194	0.5279	-0.1460	-0.1007	0.7481	0.6835	-0.4236	-0.2963	0.3391	0.3761
b_u		1.0000	0.9396	-0.7244	0.6792	0.4939	-0.1146	-0.1099	0.7404	0.6840	-0.4146	-0.3138	0.3464	0.3738
$\gamma_{1,u}$			1.0000	-0.8940	0.6506	0.4646	-0.1865	-0.0539	0.6728	0.6093	-0.4799	-0.2755	0.3441	0.3717
$\gamma_{2,u}$				1.0000	-0.4102	-0.2267	0.2357	-0.0182	-0.4075	-0.3495	0.4543	0.1713	-0.3156	-0.3149
a_d					1.0000	0.8827	-0.2155	-0.1964	0.6875	0.6435	-0.3030	-0.3354	0.2635	0.3500
b_d						1.0000	-0.2462	-0.0979	0.5359	0.5099	-0.2957	-0.3443	0.3157	0.3763
A_Δ							1.0000	-0.2068	-0.0689	-0.0698	0.2381	-0.0168	0.0384	0.0453
b_Δ								1.0000	0.1015	0.1279	-0.4146	-0.0852	-0.1185	-0.0892
A_{us}									1.0000	0.9884	-0.4678	-0.4679	0.1961	0.2504
a_{us}										1.0000	-0.4520	-0.5195	0.1982	0.2596
b_{us}											1.0000	0.1436	0.0444	-0.0180
a_g												1.0000	-0.6289	-0.7662
b_g													1.0000	0.9392
$\gamma_{1,g}$														1.0000

Covariance matrix

- Correlations of PDF fit parameters (II)

	$\alpha_s(\mu_0)$	$\gamma_{1,\Delta}$	$\gamma_{1,us}$	$\gamma_{1,d}$	$\gamma_{2,d}$	A_s	b_s	a_s	$\gamma_{3,u}$	$m_c(m_c)$	$\gamma_{3,us}$	$m_b(m_b)$	a_Δ
a_u	-0.0435	0.0000	-0.8480	0.6008	0.1535	-0.0034	-0.0437	-0.0355	0.8111	0.0796	-0.4797	0.0044	-0.1718
b_u	-0.1251	0.0316	-0.8375	0.5537	0.1806	0.0008	-0.0345	-0.0276	0.7001	0.0625	-0.4889	-0.0005	-0.1452
$\gamma_{1,u}$	-0.0849	-0.0637	-0.8133	0.5422	0.1667	-0.0324	-0.0671	-0.0638	0.8948	0.0726	-0.4033	0.0075	-0.2028
$\gamma_{2,u}$	0.0920	0.1659	0.5760	-0.3308	-0.2276	0.0799	0.0966	0.1098	-0.9749	-0.0631	0.1728	-0.0142	0.2353
a_d	-0.0321	-0.0137	-0.7618	0.9630	-0.1842	0.0007	-0.0414	-0.0167	0.4878	0.0227	-0.4735	-0.0078	-0.2088
b_d	-0.1666	-0.1167	-0.6060	0.9351	-0.5969	-0.0064	-0.0249	-0.0203	0.3007	-0.0045	-0.3782	-0.0132	-0.2121
A_Δ	0.0206	0.8718	0.1649	-0.2544	0.1916	-0.0232	-0.0212	-0.0294	-0.2398	0.0202	0.0667	0.0034	0.9721
b_Δ	0.0086	-0.6291	-0.1067	-0.1834	-0.1103	0.0594	0.0577	0.0711	0.0052	-0.0063	-0.1768	-0.0083	-0.0662
A_{us}	0.0043	-0.0481	-0.8662	0.5862	0.0768	-0.0341	-0.0659	-0.0493	0.4485	0.1559	-0.8164	-0.0008	-0.0417
a_{us}	-0.0459	-0.0650	-0.8255	0.5493	0.0606	-0.0119	-0.0441	-0.0255	0.3870	0.0940	-0.8628	-0.0055	-0.0375
b_{us}	-0.0382	0.3783	0.7032	-0.3288	0.1278	-0.0734	-0.0445	-0.0807	-0.4262	-0.0100	0.3911	0.0040	0.1782
a_g	0.3785	0.0061	0.3050	-0.3280	0.1338	0.0936	0.0718	0.1165	-0.1744	-0.0137	0.4886	0.0323	-0.0360
b_g	-0.6085	0.1017	-0.0873	0.2827	-0.2104	-0.0543	-0.0114	-0.1223	0.2973	0.1560	-0.1337	0.0141	0.0066
$\gamma_{1,g}$	-0.4642	0.1021	-0.1778	0.3605	-0.1962	-0.0708	-0.0396	-0.1230	0.3132	0.0425	-0.1977	0.0071	0.0201

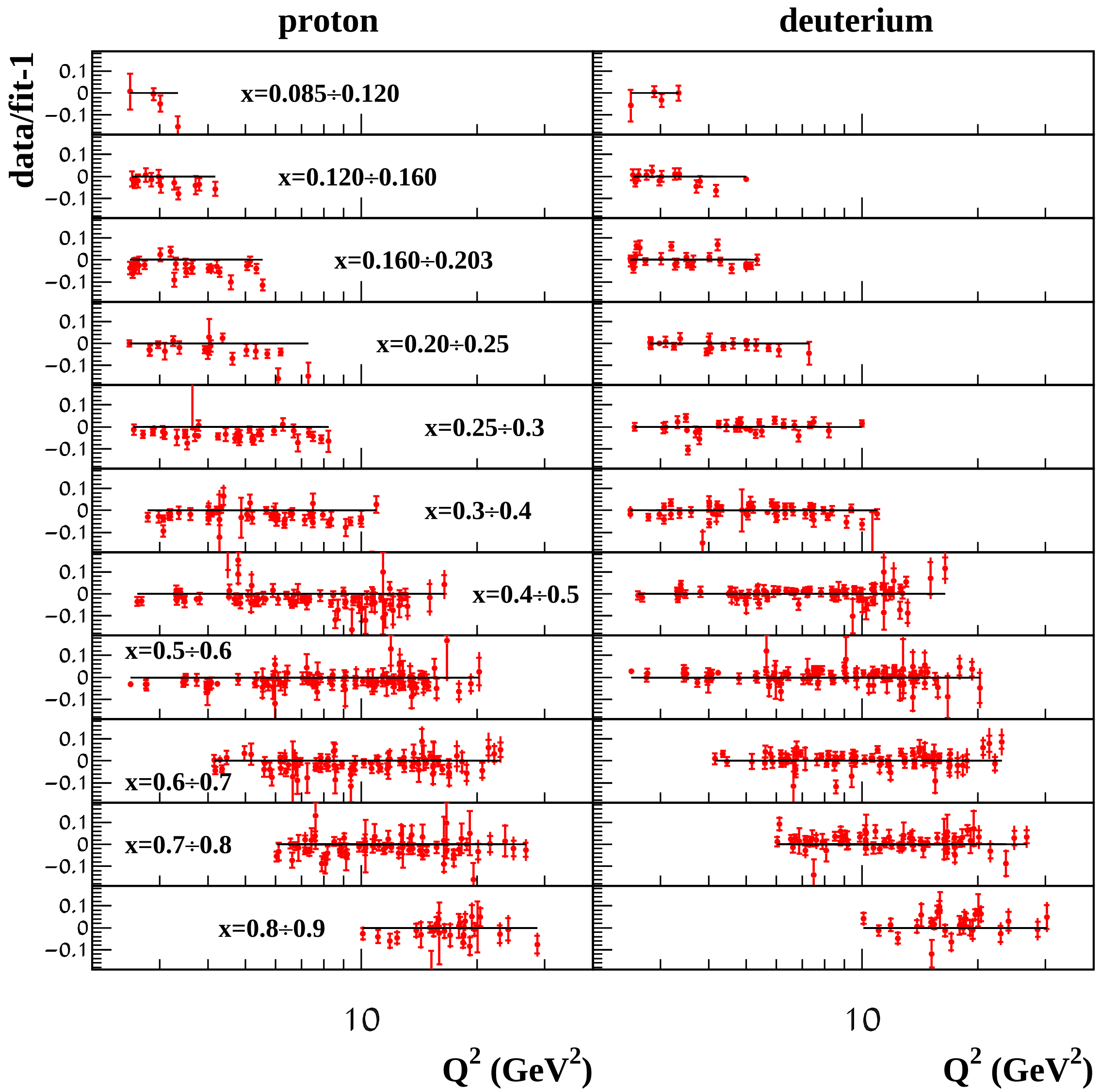
Covariance matrix

- Correlations of PDF fit parameters (III)

	$\alpha_s(\mu_0)$	$\gamma_{1,\Delta}$	$\gamma_{1,us}$	$\gamma_{1,d}$	$\gamma_{2,d}$	A_s	b_s	a_s	$\gamma_{3,u}$	$m_c(m_c)$	$\gamma_{3,us}$	$m_b(m_b)$	a_Δ
$\alpha_s(\mu_0)$	1.0000	0.0176	-0.0394	-0.0798	0.2357	-0.0018	-0.0982	-0.0075	-0.0291	0.1904	0.0676	0.0562	0.0136
$\gamma_{1,\Delta}$		1.0000	0.1183	-0.0802	0.2640	-0.0427	-0.0489	-0.0550	-0.1595	0.0193	0.0985	0.0069	0.7657
$\gamma_{1,us}$			1.0000	-0.6753	-0.0493	-0.0525	0.0158	-0.0445	-0.6039	-0.0656	0.6590	0.0017	0.1487
$\gamma_{1,d}$				1.0000	-0.4041	-0.0213	-0.0513	-0.0366	0.4145	0.0148	-0.3931	-0.0086	-0.2284
$\gamma_{2,d}$					1.0000	0.0308	-0.0016	0.0326	0.1801	0.0276	-0.0510	0.0111	0.1212
A_s						1.0000	0.8570	0.9749	-0.0664	-0.0206	-0.4355	0.0017	-0.0139
b_s							1.0000	0.8730	-0.0894	-0.0706	-0.3708	0.0005	-0.0127
a_s								1.0000	-0.0967	-0.1234	-0.4403	-0.0050	-0.0172
$\gamma_{3,u}$									1.0000	0.0674	-0.2082	0.0153	-0.2378
$m_c(m_c)$										1.0000	-0.0010	0.0505	0.0141
$\gamma_{3,us}$											1.0000	0.0083	0.0276
$m_b(m_b)$												1.0000	0.0006
a_Δ													1.0000

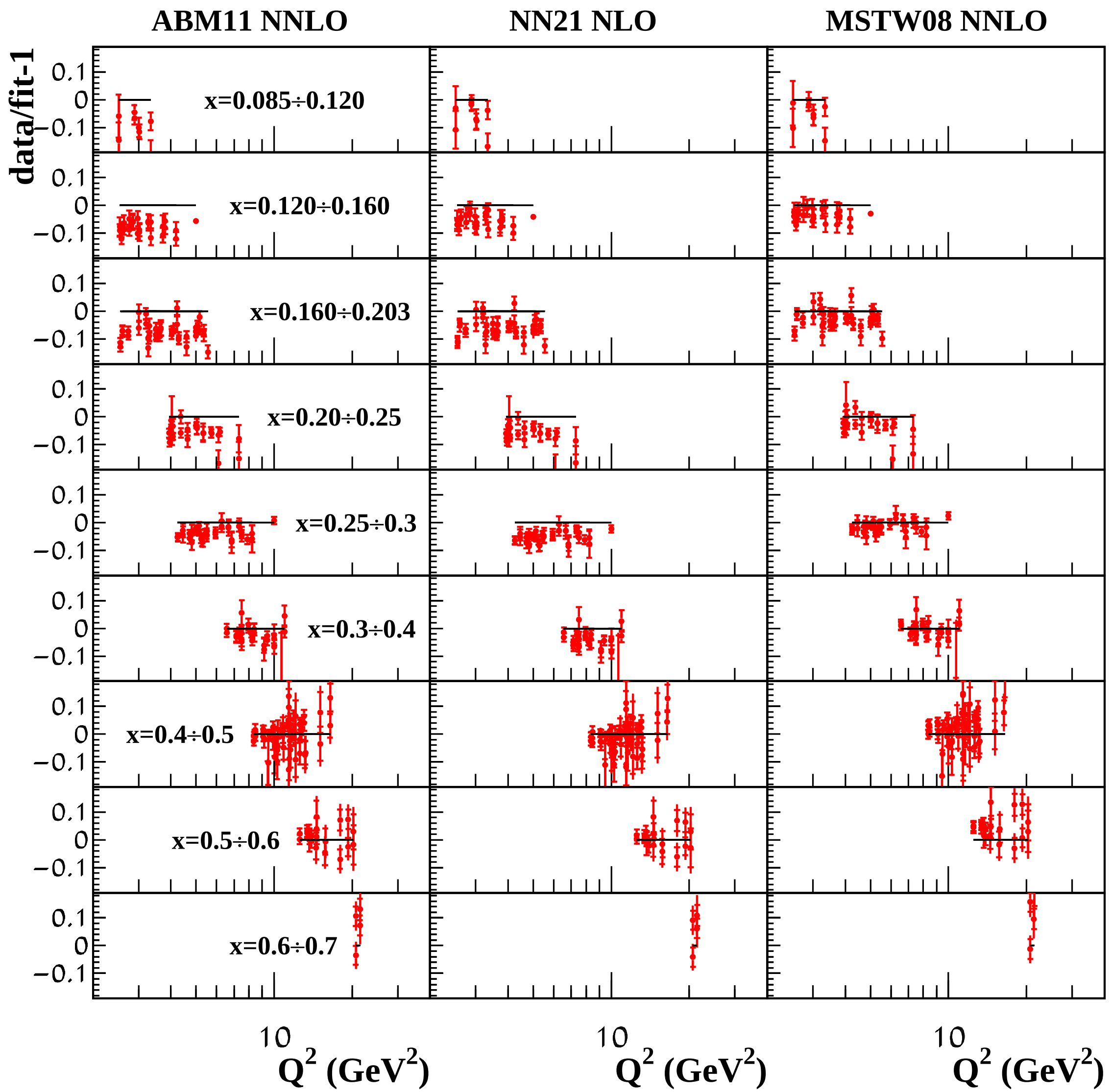
Pulls

- Comparision to SLAC inclusive DIS cross section data (proton and deuterium target)

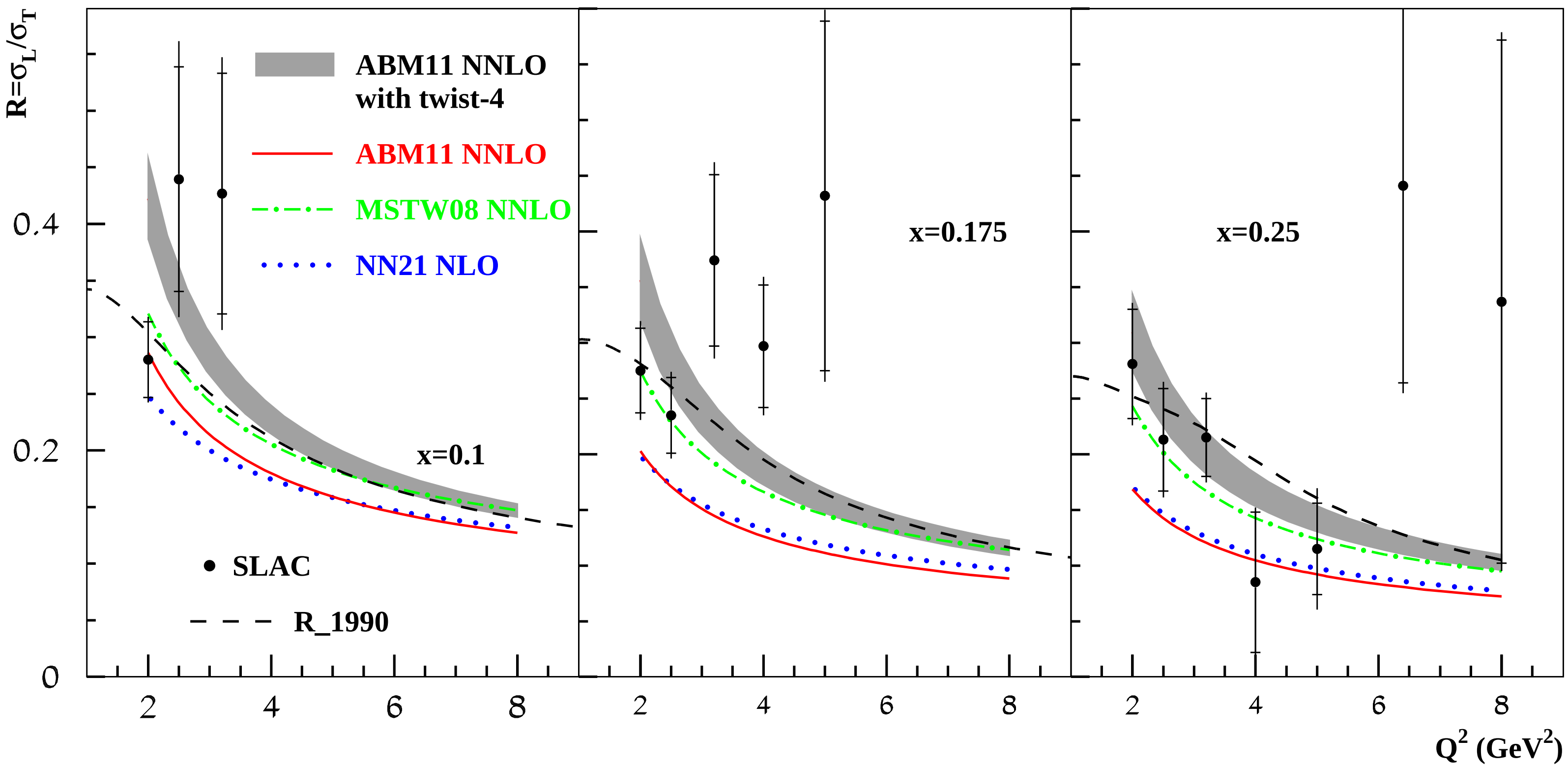


Testing higher twist

- Fit of SLAC data without higher twist contributions
  (data cut at $W^2 > 12.5\ \mathrm{GeV}^2$, $Q^2 > 2.5\ \mathrm{GeV}^2$)



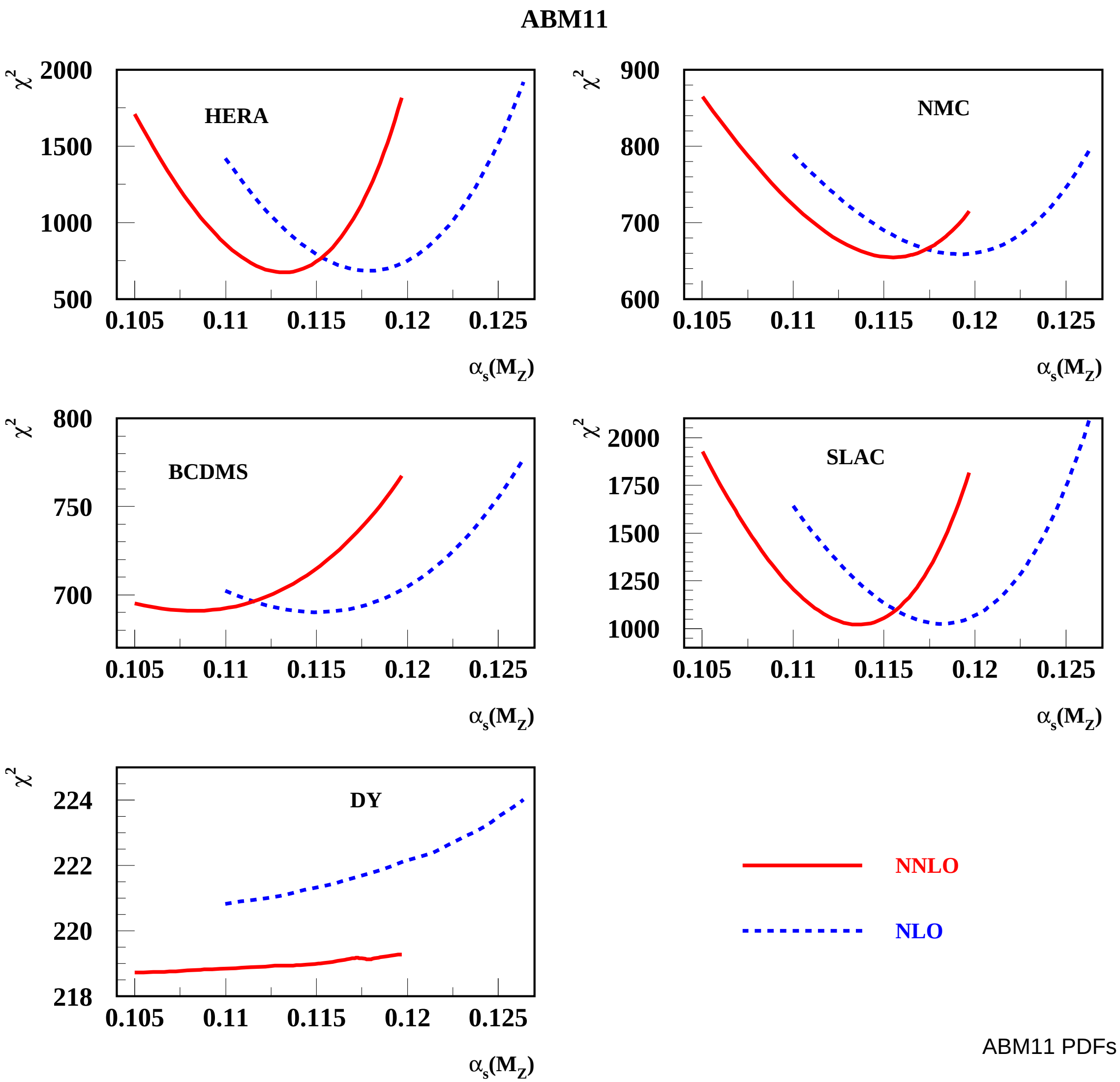
Value of $R = \sigma_L/\sigma_T$ from SLAC



- $R = \sigma_L/\sigma_T$ as function of Q^2 for different values of x
  - 1σ band of for ABM11 NNLO predictions
  - comparison to MSTW, NN21 PDFs and ABM11 variant without twist-4 terms
  - empirical parameterization R_{1990} superimposed
- Similar discussion for NMC data Alekhin, Blümlein, S.M. `arXiv:1101.5261`

Strong coupling constant

α_s from DIS and PDFs



Strong coupling constant

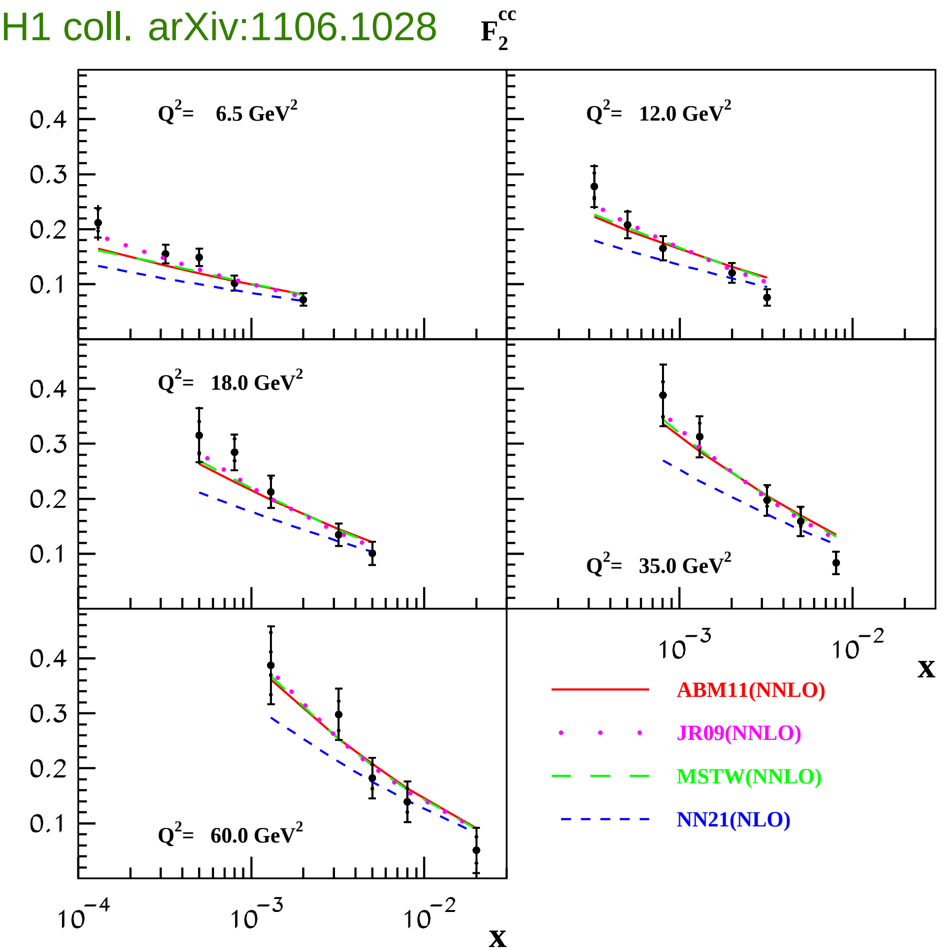
α_s from DIS and PDFs

- Comparison of α_s values
  - effects for differences between ABM and MSTW understood

	α_s at NNLO	target mass corr.	higher twist	error correl.
ABM11	0.1134 ± 0.0011	**yes**	**yes**	**yes**
NNPDF21	0.1166 ± 0.0008	**yes**	**no**	**yes**
MSTW	0.1171 ± 0.0014	**no**	**no**	**no**

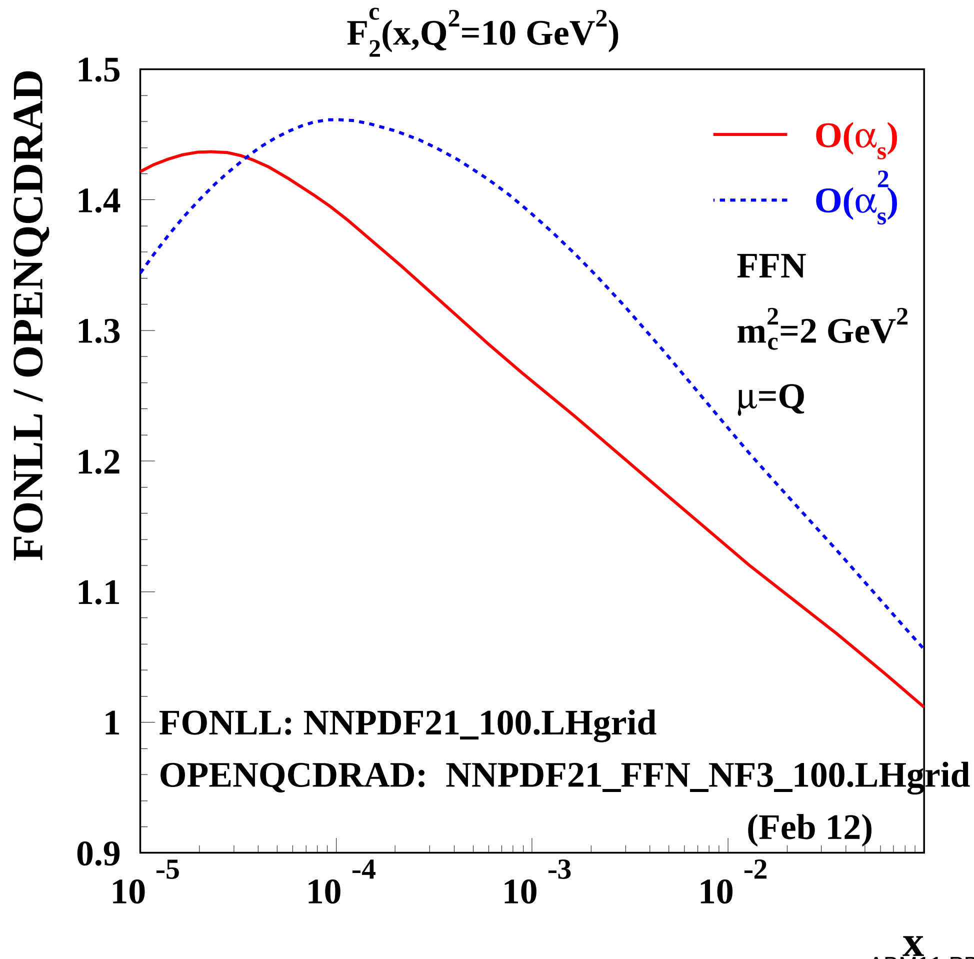
Heavy quark DIS

- Comparison with predictions of PDF sets at NLO and NNLO
  - all PDF sets in FFNS with $n_f = 3$ and $\overline{\mathrm{MS}}$-mass $m_c = 1.27$ GeV
  - data for F_2^{cc} H1 coll. arXiv:1106.1028



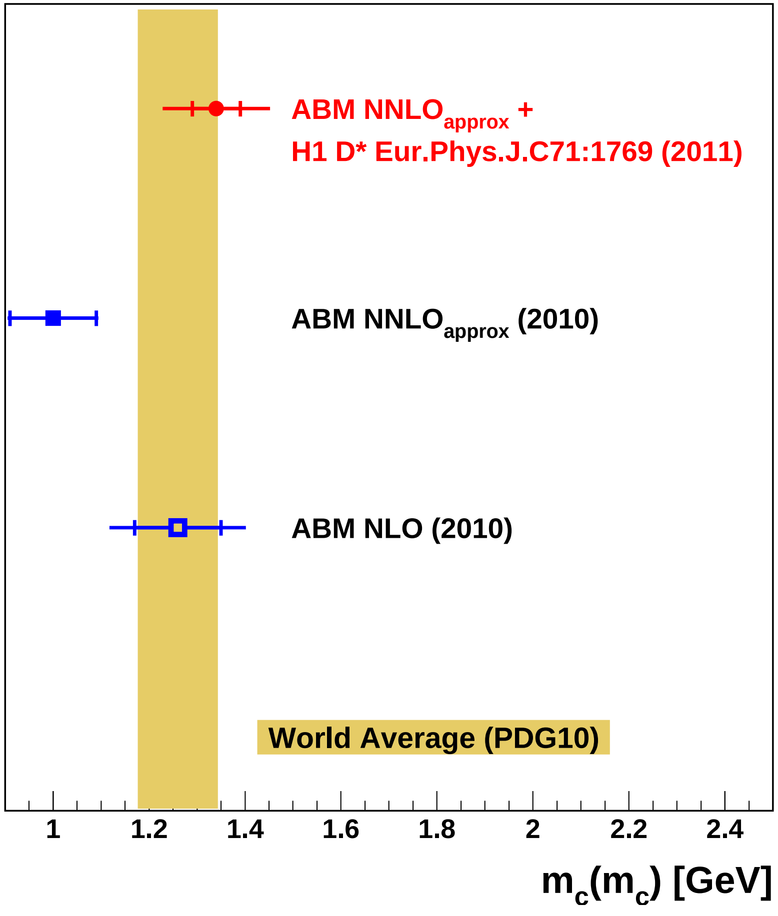
Heavy quarks

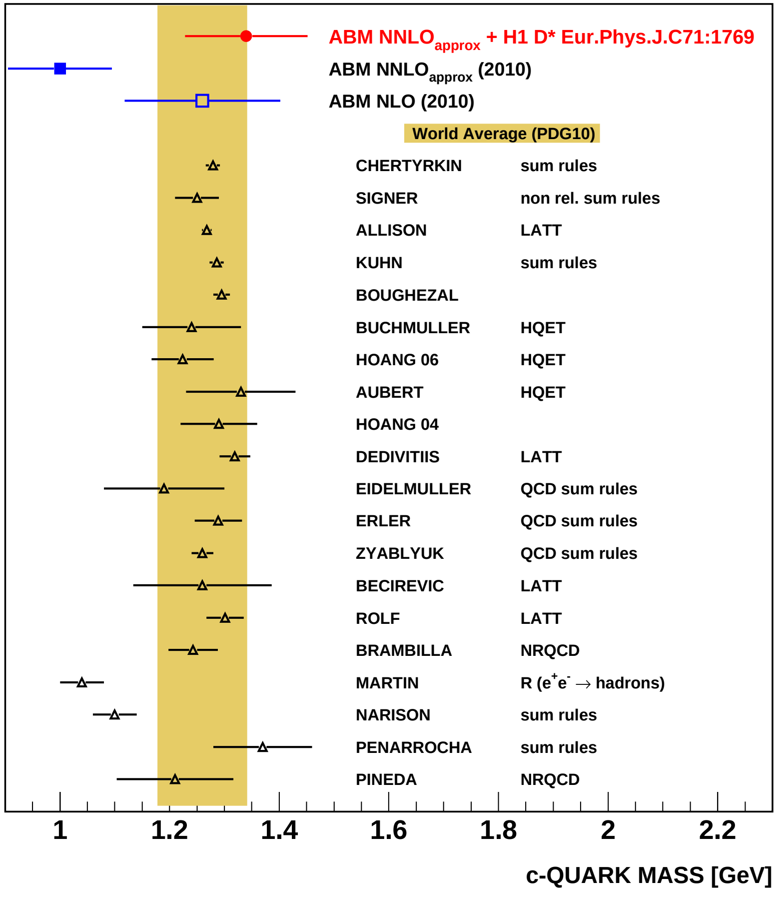
- NNPDF21 undershoots data for F_2^{cc}
  - comparision to FONLL code reveals significant differences both in LO and NLO QCD predictions for F_2^{cc}
  - benchmarks computed with OPENQCDRAD Alekhin '11



Charm mass from HERA

- Determination of $\overline{\mathrm{MS}}$-mass $m_c(m_c)$ in DIS
  - significant impact of data on F_2^c from HERA II
  - ongoing work (Alekhin, Daum, Lipka, S.M.)





Top quark production

- Determine top quark mass from Tevatron cross section data
  - $\sigma_{\mathrm{t\bar{t}}} = 7.56^{+\,0.63}_{-\,0.56}$ pb D0 coll. arXiv:1105.5384
  - $\sigma_{\mathrm{t\bar{t}}} = 7.46^{+\,0.66}_{-\,0.80}$ pb CDF coll. arXiv:1010.1202
- Fit of m_t for individual PDFs
  (parton luminosity at Tevatron driven by $q\bar{q}$)

	ABM11	JR09	MSTW	NNPDF21
$\overline{\mathrm{MS}}$ $m_t(m_t)$	161.8	163.2	162.8	164.1
pole m_t	169.9	171.3	171.1	172.6

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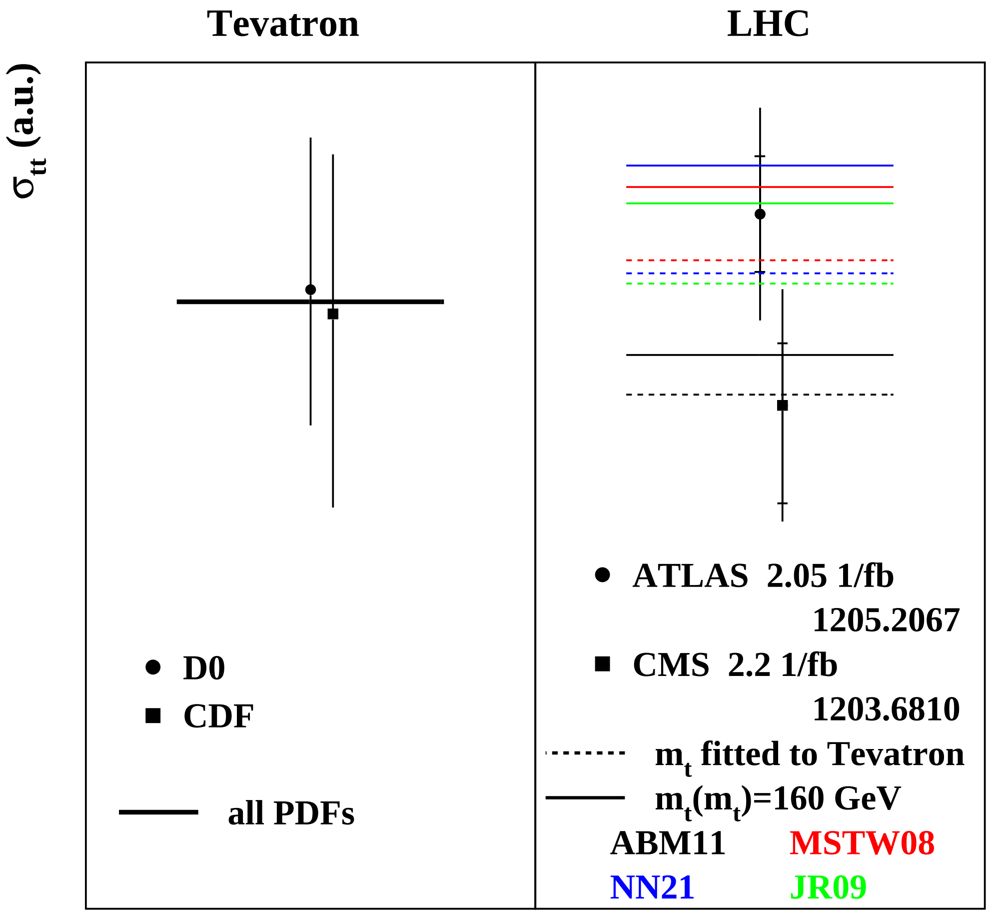
- Fit of m_t for individual PDFs
  (parton luminosity at Tevatron driven by $q\bar{q}$)
- Check predictions at LHC with $\sqrt{s} = 7$ TeV
  - cross section computation with HATHOR Aliev, Lacker, Langenfeld, S.M., Uwer, Wiedermann '10

	ABM11	JR09	MSTW	NNPDF21
$\sigma_{\mathrm{t\bar{t}}}$ (fit m_t)	145.5	170.4	175.6	172.7
$\sigma_{\mathrm{t\bar{t}}}$ ($\overline{\mathrm{MS}}$ $m_t(m_t) = 160$ GeV)	154.4	188.4	192.0	196.9

Top quark cross section at LHC



- Atlas at $2.05\ 1/\mathrm{fb}\ \sigma_{t\bar{t}} = 186 \pm 13(\mathrm{stat}) \pm 20(\mathrm{syst}) \pm 7(\mathrm{lumi})$
  Atlas coll. arXiv:1205.2067
- CMS at $2.2\ 1/\mathrm{fb}\ \sigma_{t\bar{t}} = 143 \pm 14(\mathrm{stat}) \pm 22(\mathrm{syst}) \pm 3(\mathrm{lumi})$
  CMS coll. arXiv:1203.6810

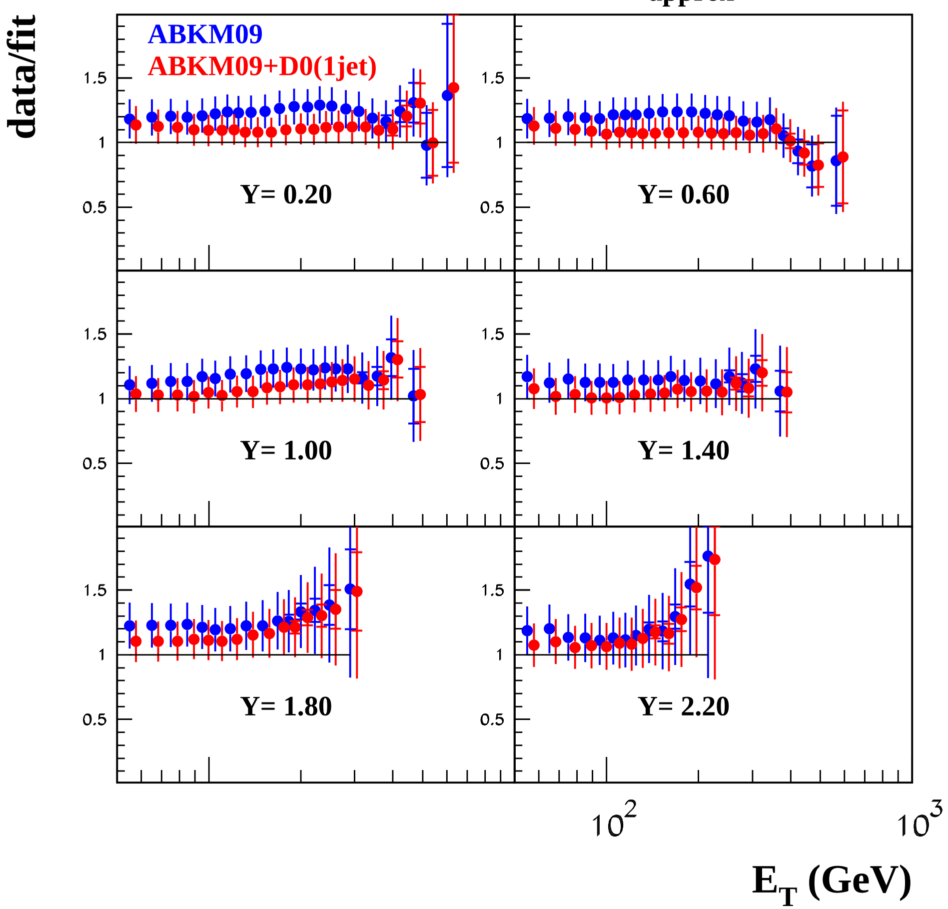
Jet production

General remarks

- QCD corrections important
  - only NLO known exactly
  - soft logarithms for 1-jet inclusive distributions define $\text{NNLO}_{\text{approx}}$
    Kidonakis, Owens ‘01
  - ongoing effort towards NNLO Gehrmann, Glover, . . . (many others)
- PDF fits with 3-flavors for DIS, 5-flavors for jets
  (matching from 3 to 5-flavors)
- QCD evolution over large range
- Possible impact of jet definition and algorithm

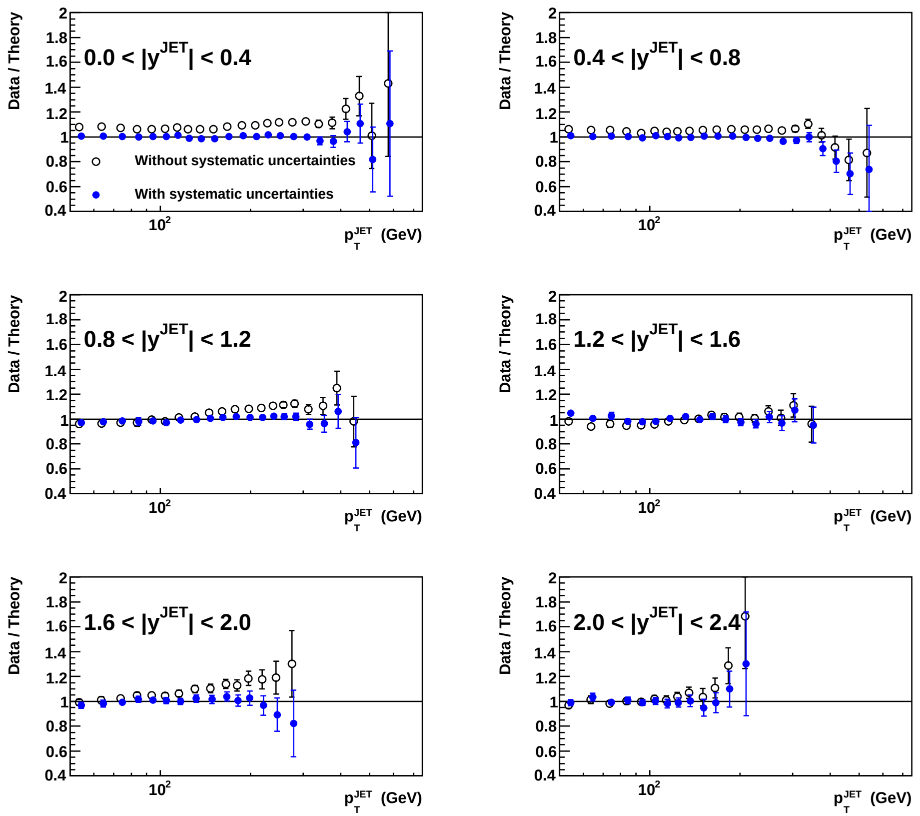
Tevatron jet data (D0) – 1-jet inclusive

D0(1jet) - NNLO(evol) + $\text{NNLO}_{\text{approx}}$(coeff)



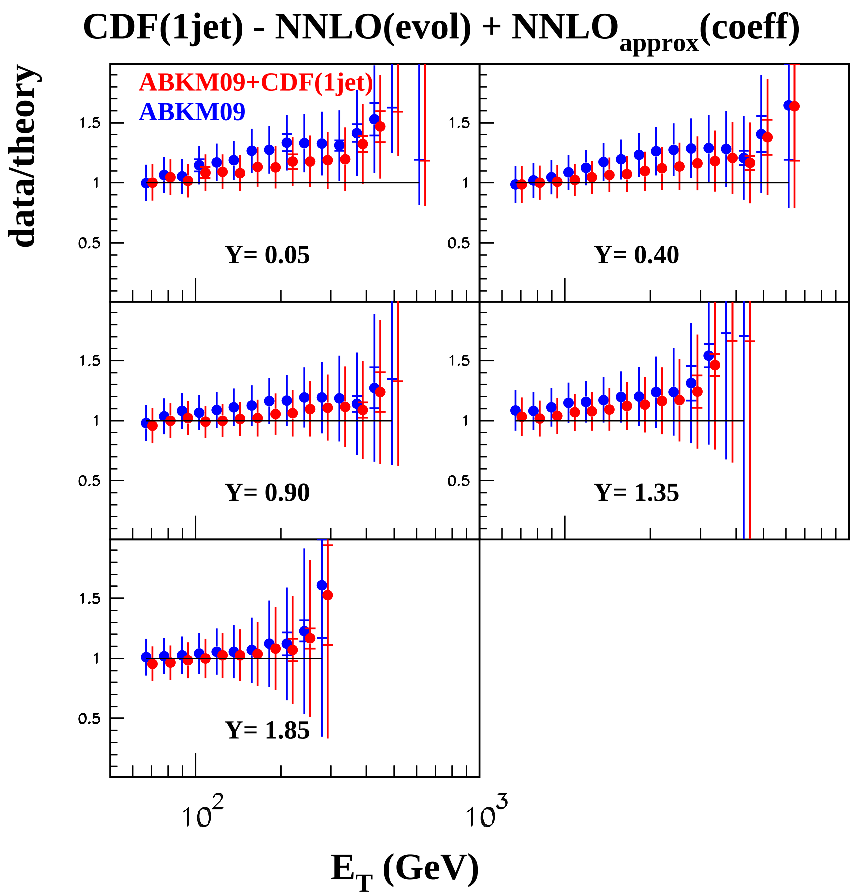
D∅ Run II inclusive jet data (cone, R = 0.7)

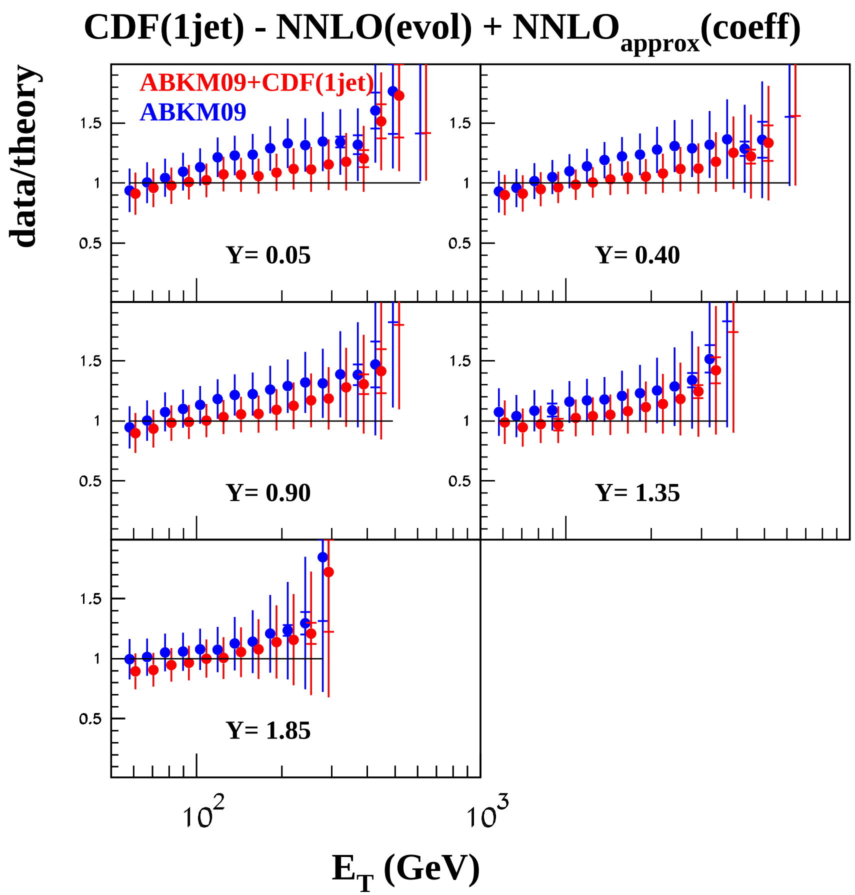
MSTW 2008 NLO PDF fit ($\mu_R = \mu_F = p_T^{JET}$), χ^2 = 114 for 110 pts.



- PDF fits to Tevatron jet data (with $\text{NNLO}_{\text{approx}}$ corr. Kidonakis, Owens '01) Alekhin, Blümlein, S.M. '11 (left); MSTW `arXiv:0901.0002` (right)
- 3-flavor PDFs for DIS, 5-flavor PDFs for jets, scale $\mu_r = \mu_f = E_T$

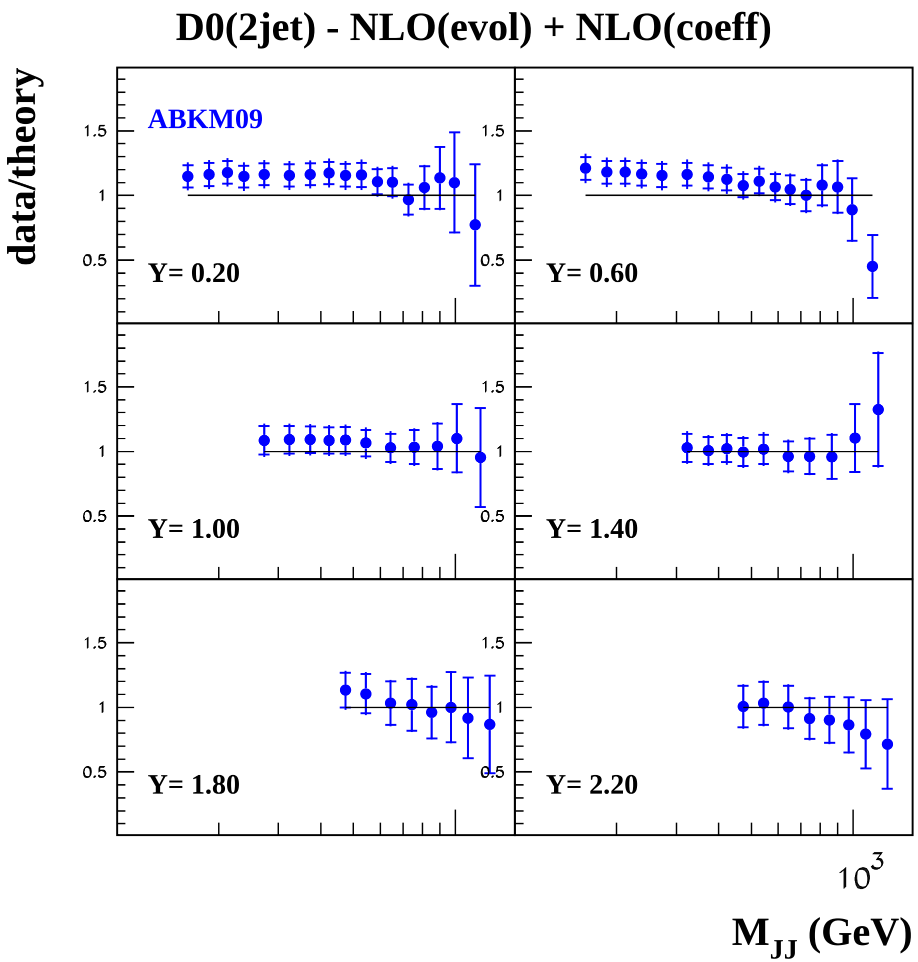
Tevatron jet data (CDF) – 1-jet inclusive

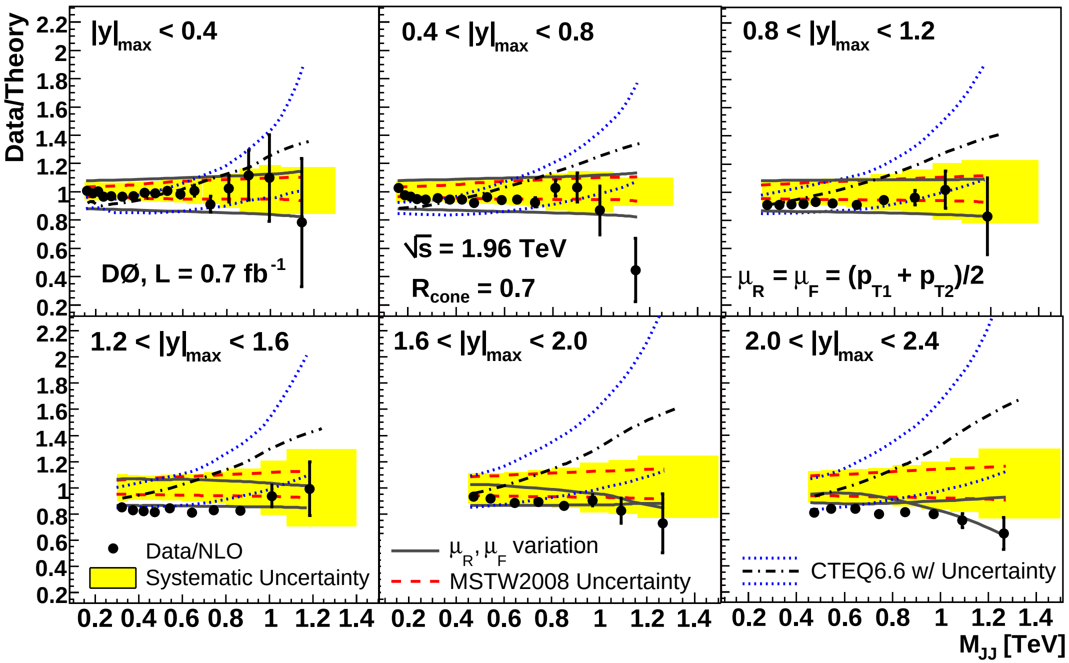




- Cone algorithm (left); k_T algorithm (right); scale $\mu_r = \mu_f = p_T$
- Disagreement in slope at large E_T can hardly be improved
  - large E_T is dominated by quark-quark scattering; PDFs well constrained

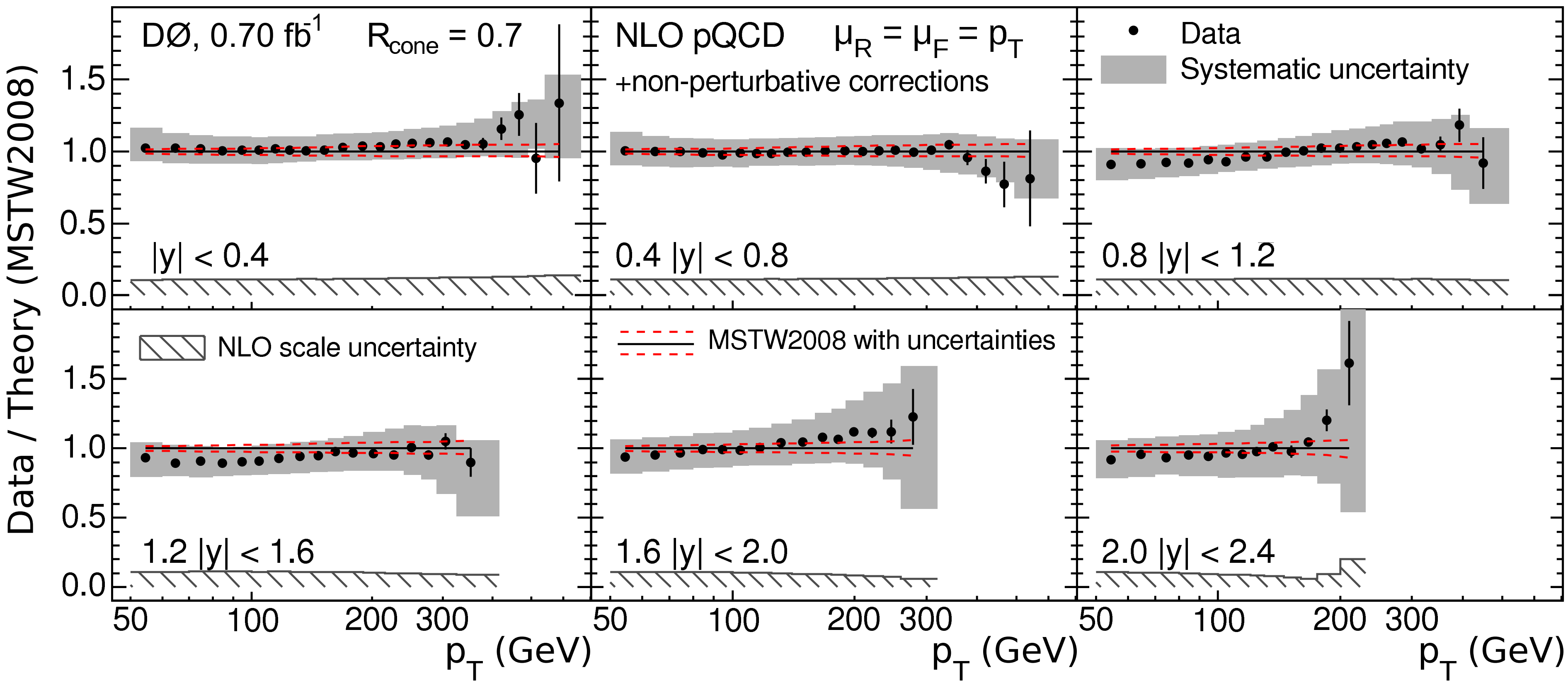
Tevatron jet data (D0) – di-jet invariant mass





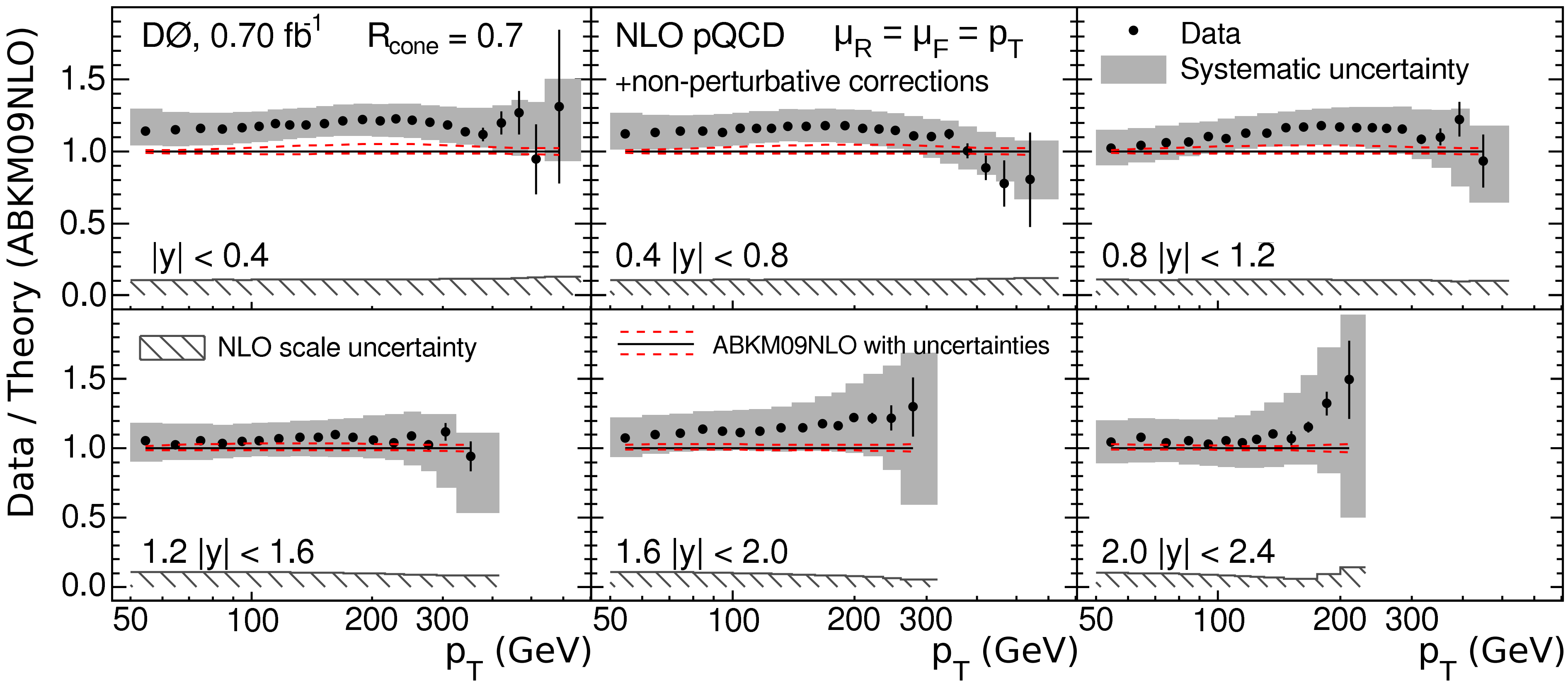
- Predictions for Tevatron di-jet data (no NNLO corrections known)
  Alekhin, Blümlein, S.M. '11 (left); D0 coll. `arXiv:1002.4594` (right)
- Uncertainty due to missing NNLO corrections; scale $\mu_r = \mu_f = M_{JJ}$

New analysis (D0) – 1-jet inclusive



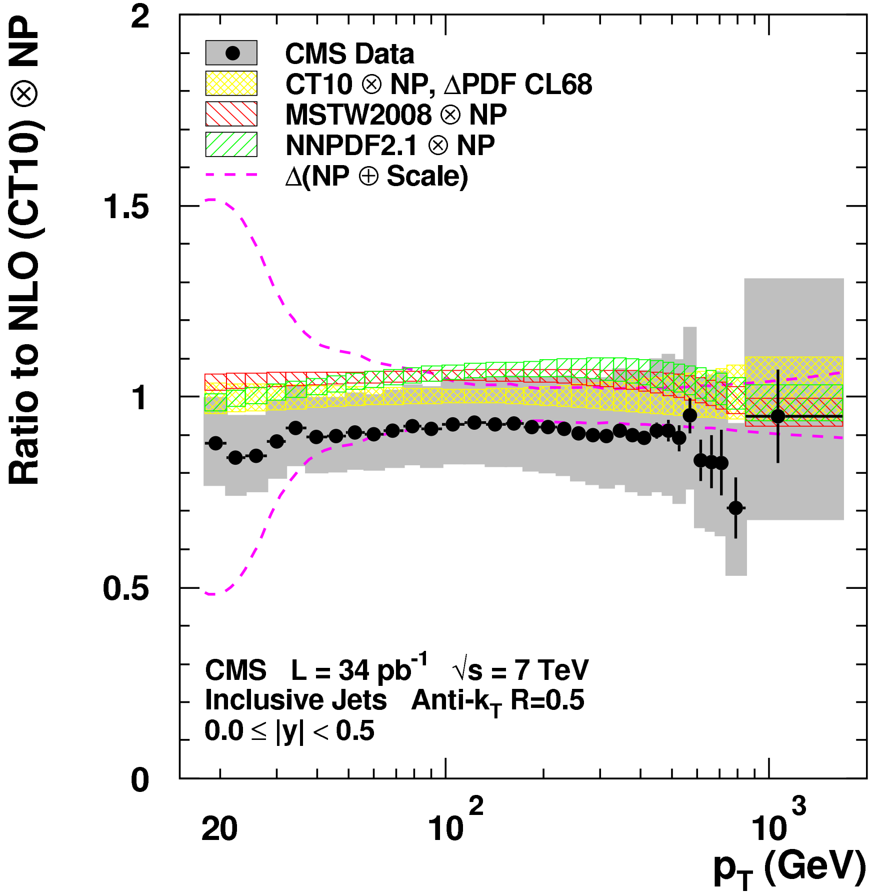
- New analysis of 1-jet inclusive data D0 coll. arXiv:1110.3771
  - MSTW PDF set with PDF (red) and theory (shaded) uncertainty

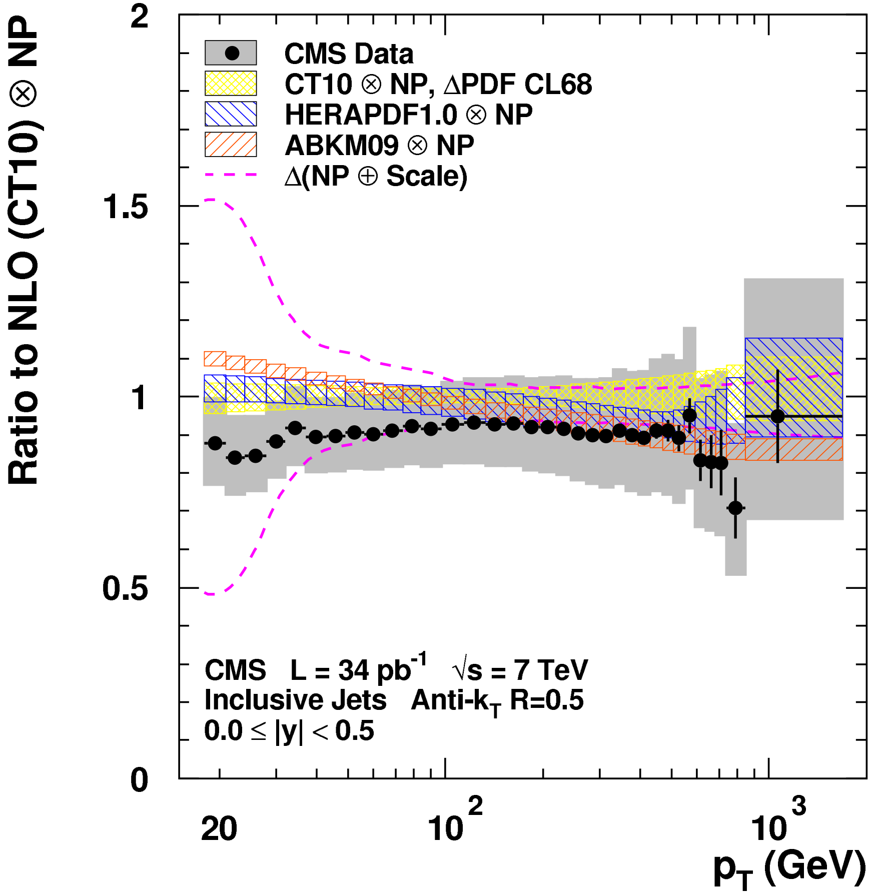
New analysis (D0) – 1-jet inclusive



- New analysis of 1-jet inclusive data D0 coll. arXiv:1110.3771
  - ABKM PDF set with PDF (red) and theory (shaded) uncertainty

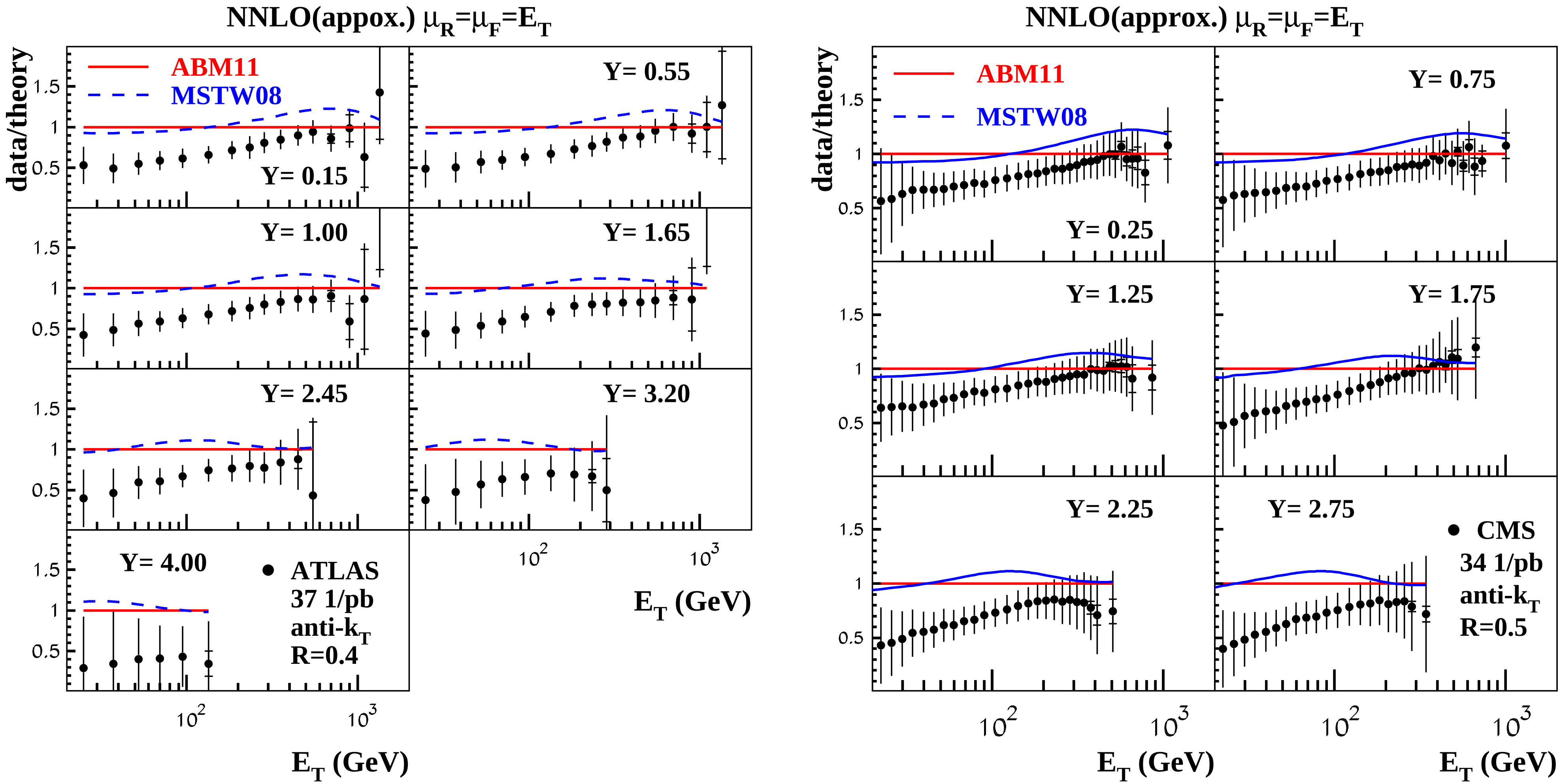
LHC jet data (CMS) – 1-jet inclusive





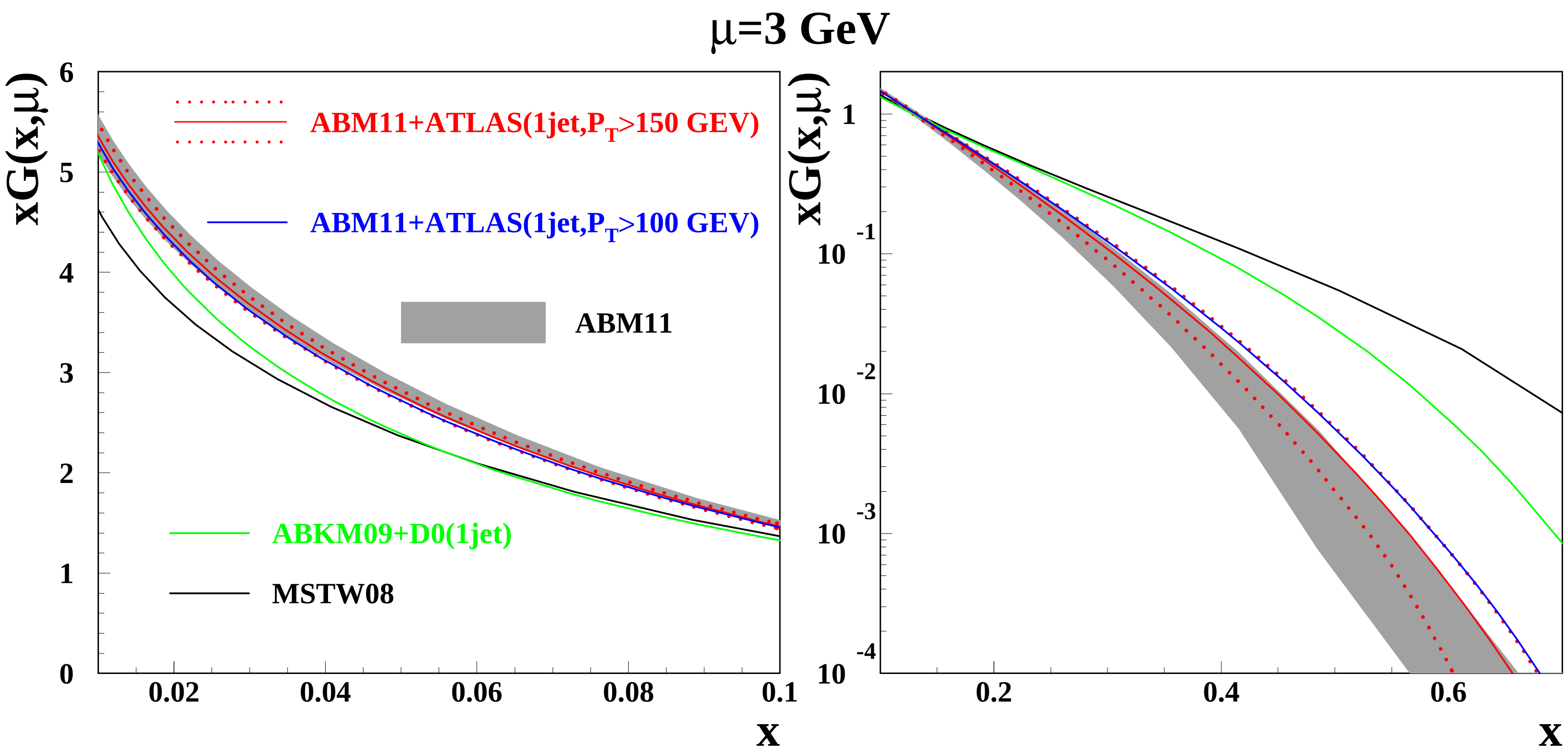
- Analysis of 1-jet inclusive data CMS coll. `CMS NOTE 2011/004`
  - Comparisions of various PDF sets courtesy K. Rabbertz

LHC jet data



- Comparision to LHC data: ATLAS coll. (left) and CMS coll. (right) in good agreement
- LHC jet data prefers small gluon PDF at large x

Atlas jet data in ABM11 fit



- $\chi^2/\text{NDP} = 55/55$ for ATLAS inclusive jet data with $p_T > 100/150$ GeV
- ATLAS jet data suggest softer gluons than Tevatron jets
- Comparison of α_s values
  - ABM11: $\alpha_s(M_Z) = 0.1134(11)$; Atlas jets: $\alpha_s(M_Z) = 0.1141(8)$
  - NLO analysis: $\alpha_s(M_Z) = 0.1151 \pm 0.0047(\text{exp}) \pm 0.0023(\text{PDFs})$
    Malaescu, Starovoitov '12

Impact on Higgs production rates (Atlas jets)

- Rates for Higgs production at LHC for m_H = 125 GeV
- Cross sections prediction fully consistent with ABM11

LHC at $\sqrt{s} = 7$ TeV	ABM11	Atlas jets $p_T \geq 100$ GeV	Atlas jets $p_T \geq 150$ GeV
$\sigma(H)$ [pb]	$\mathbf{13.23\ {}^{+1.35}_{-1.31}\ {}^{+0.30}_{-0.30}}$	$13.32\ {}^{+1.37}_{-1.33}\ {}^{+0.22}_{-0.22}$	$13.23\ {}^{+1.35}_{-1.31}\ {}^{+0.22}_{-0.22}$

LHC at $\sqrt{s} = 8$ TeV	ABM11	Atlas jets $p_T \geq 100$ GeV	Atlas jets $p_T \geq 150$ GeV
$\sigma(H)$ [pb]	$\mathbf{16.99\ {}^{+1.69}_{-1.63}\ {}^{+0.37}_{-0.37}}$	$17.10\ {}^{+1.71}_{-1.65}\ {}^{+0.27}_{-0.27}$	$16.98\ {}^{+1.69}_{-1.63}\ {}^{+0.27}_{-0.27}$

- MSTW for comparison
  - $\sigma(H) = 14.39\ {}^{+1.54}_{-1.47}\ {}^{+0.17}_{-0.22}$ for LHC7
  - $\sigma(H) = 18.36\ {}^{+1.92}_{-1.82}\ {}^{+0.21}_{-0.28}$ for LHC8

Summary

Parton distributions, $\alpha_S(M_Z)$ and all that

- New ABM11 fit with improvements driven by theory
  - very good description of hadron collider data
- Strong coupling constant
  - ABM11 $\alpha_s(M_Z) = 0.1134(11)$ (ABKM09 $\alpha_s(M_Z) = 0.1135(14)$)
  - differences with respect to other groups understood
- Continuous benchmarking mandatory
  - source of interesting observations

Confronting LHC data

- PDFs with LHC jet data change gluon PDF and $\alpha_s(M_Z)$ within quoted uncertainty
  - Atlas jets prefer softer gluon than Tevatron
- Cross sections for Higgs prduction in gluon fusion almost unchanged compared to ABM11
- Top-quark production cross section with m_t from Tevatron data

Extra slides

Heavy quarks (cont'd)

- Comparision to FONLL code reveals significant differences both in LO and NLO QCD predictions for F_2^{cc}
  - benchmarks computed with OPENQCDRAD Alekhin '11
  - same $n_f = 3$ PDF set used