Parton distribution functions
– *status and perspectives* –

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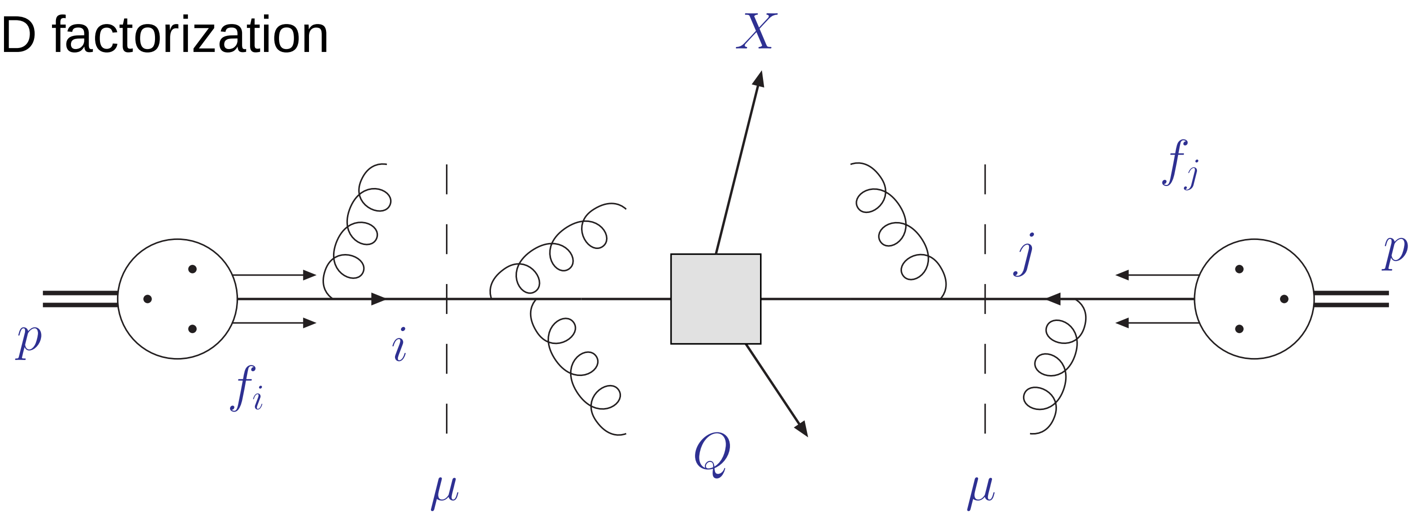
– *5th Annual Workshop of the Helmholtz Alliance "Physics at the Terascale"*, Bonn, Dec 08, 2011 –

Plan

- Talk based on results on . . .
  - . . . precise parton distribution functions from global fits
    S. Alekhin, J. Blümlein, S. Klein and S. M. arXiv:0908.2766
    S. Alekhin, J. Blümlein and S. M. arXiv:1007.3657
  - . . . 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

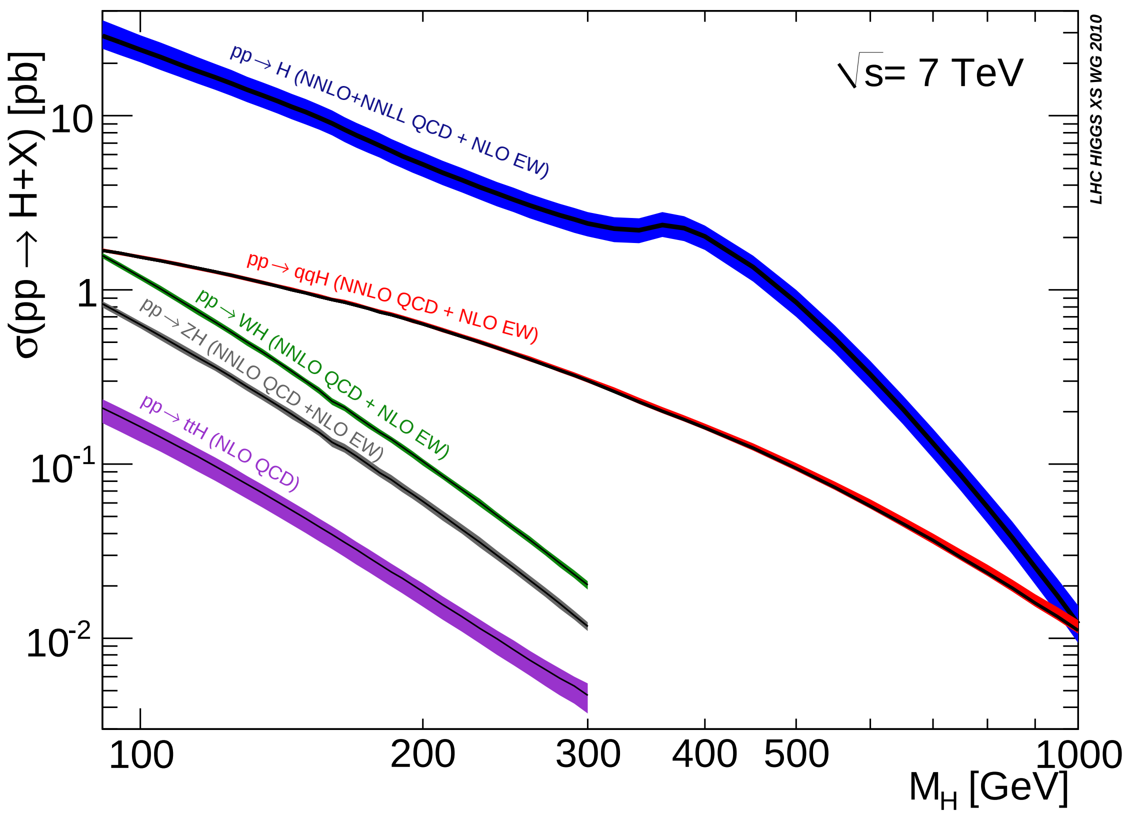


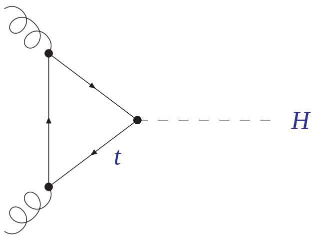
$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- 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, . . .

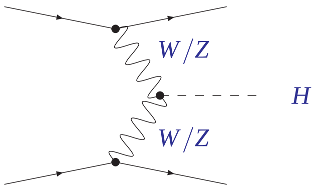
Cross section for Higgs production

- Dominant channels for Higgs boson production LHC Higgs XS WG ‘10

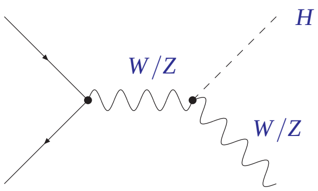




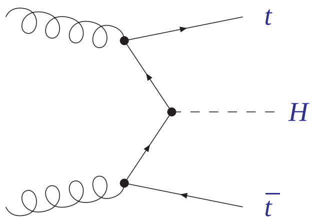
gg-fusion



weak boson fusion

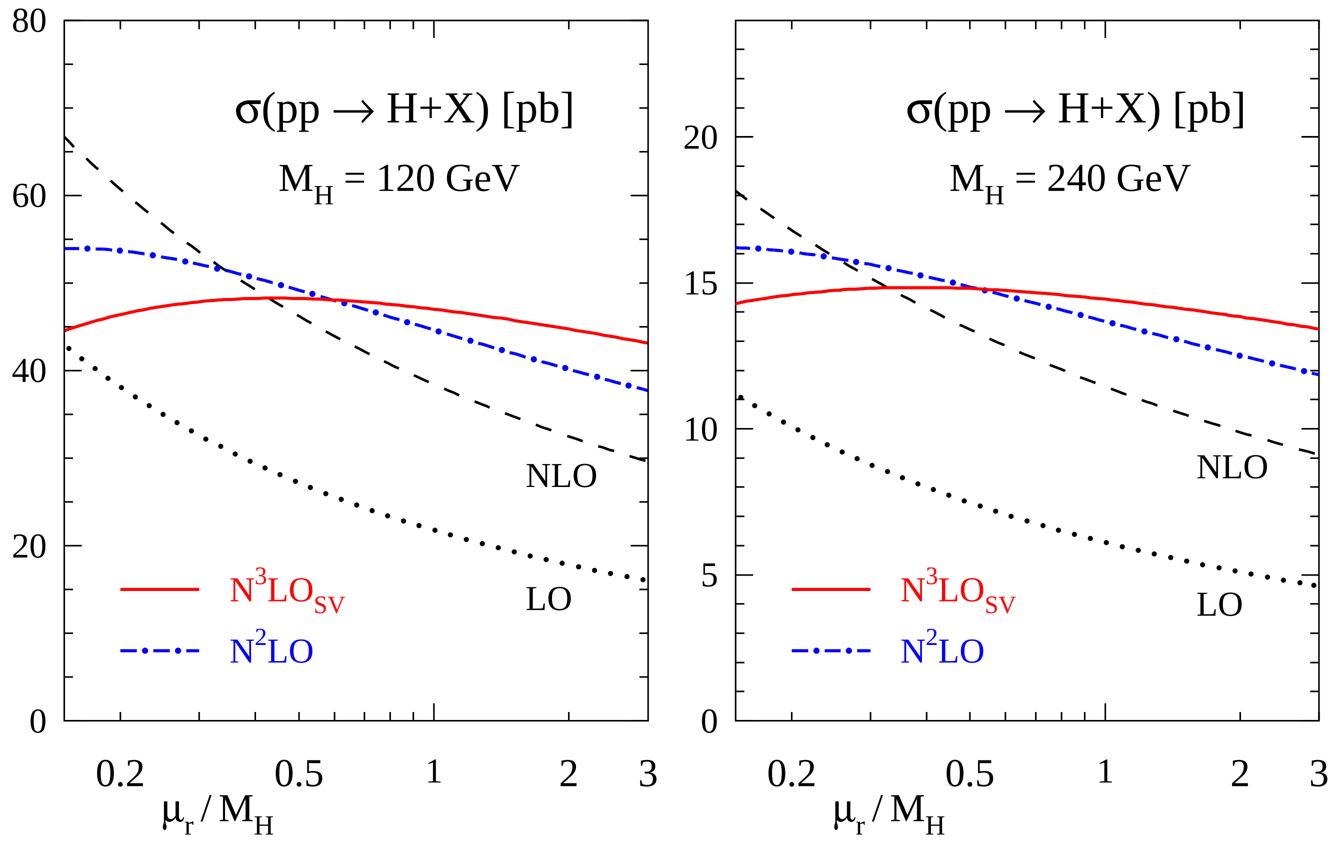


Higgs strahlung



$t\bar{t}H$-channel

Perturbation theory at work



- Apparent convergence of perturbative expansion
  - NNLO corrections still large
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - improvement through complete soft N^3LO corrections S.M., Vogt '05 or NNLL resummtion Catani, de Florian, Grazzini, Nason '03, Ahrens et al. '10
- Perturbative stability under renormalizaion scale variation

Non-perturbative parameters

Input for collider phenomenology

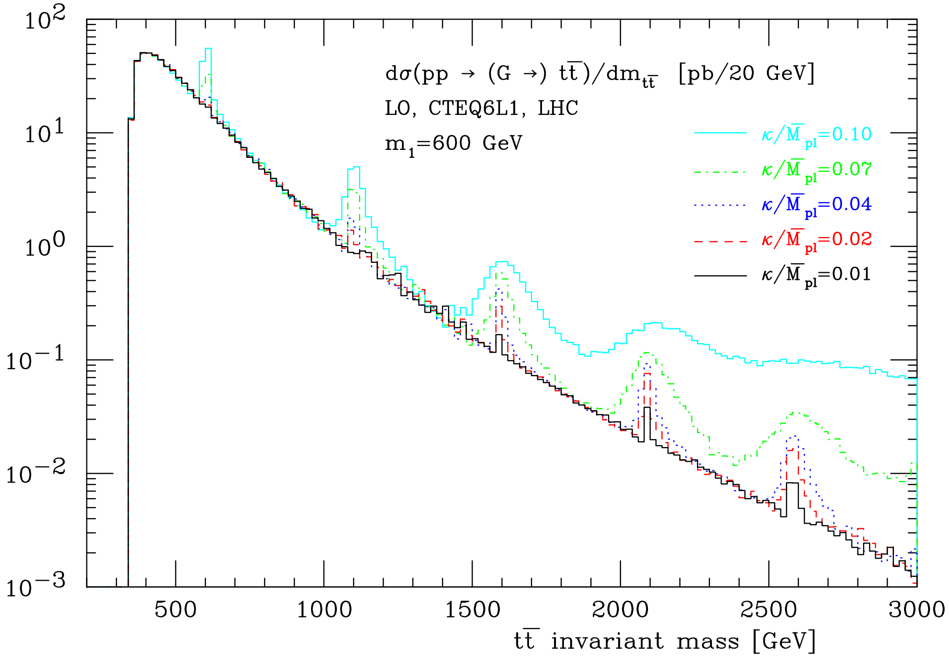
- Non-perturbative parameters are universal
- Determination from comparision to experimental data
  - masses of heavy quarks m_c, m_b, m_t
  - parton distribution functions $f_i(x, \mu^2)$
  - strong coupling constant $\alpha_s(M_Z)$

Interplay with perturbation theory

- Accuracy of determination driven by precision of theory predictions
- Non-perturbative parameters sensitive to
  - radiative corrections at higher orders
  - renormalization and factorization scales μ_R, μ_F
  - chosen scheme (e.g. ($\overline{MS}$ scheme)
  - . . .

New physics discoveries

- Suppose we observe . . .
  - . . . e.g. Kaluza-Klein resonances
    (s-channel graviton in $t\bar{t}$ invariant mass spectrum at LHC)
    Frederix, Maltoni '07



- Which non-perturbative parameters ?

New physics discoveries

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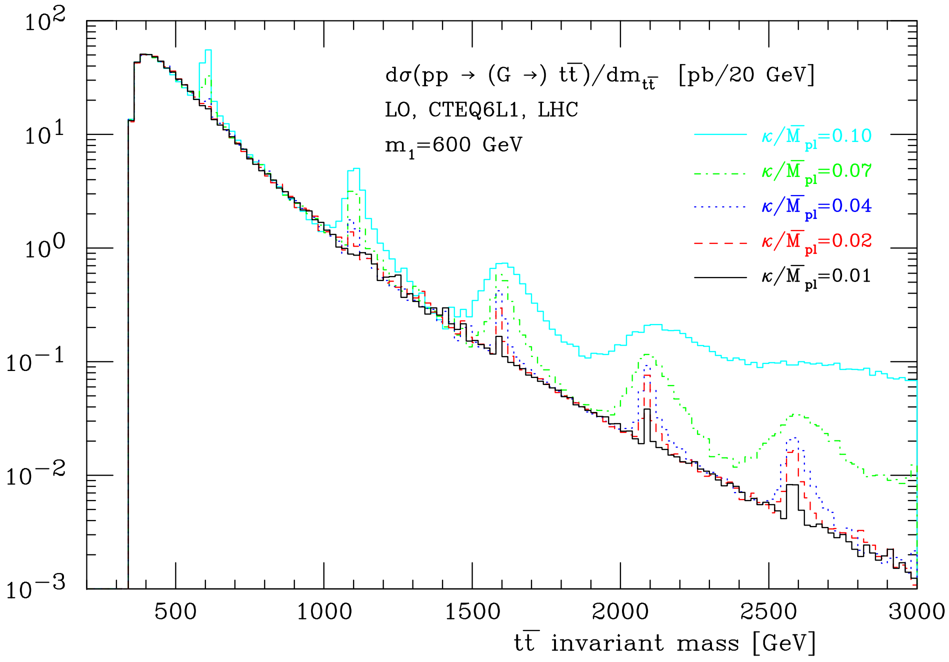
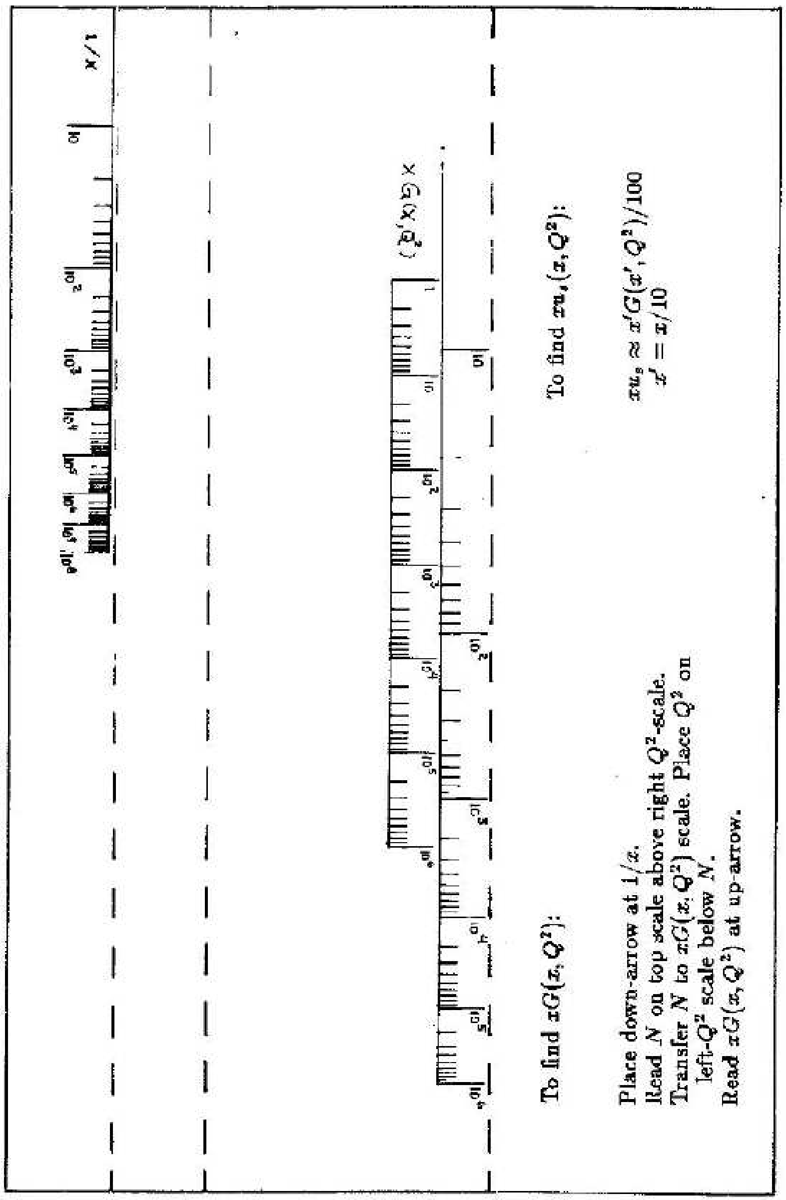


- Which non-perturbative parameters ?
  - $\alpha_s(M_Z) = 0.13$, $m_c = 1.5$ GeV, $m_b = 4.5$ GeV, . . .
  - any PDF set

J. Ralston (Phys.Lett. B172 (1986) 430)

Pocket partonometer



for t- or heavier particle distributions one must model thresholds numerically such as done in ref. [4] [‡4]. However, departures from a symmetrically distributed sea, which complicate the boundary conditions, can be reproduced by the ratios $u_s \approx d_s \approx s_s \approx 2c_s \approx 2b_s$.

The analytic gluon solution (3), boundary conditions included, is calculated by the partonometer (fig. 2). The scales automate the logarithms of certain functions of $1/x$ and Q^2 left to the reader. In systematic testing the accuracy of the gizmo is at the 10–20% level depending on the operator's ability to read logarithmic scales. It is much better than interpolating between graphs such as fig. 1a. The speed is even faster than adding a new card [‡4] to an existing program that runs.

Gluon distributions are read off directly; see the example below. Quark sea distributions can be evaluated using the identity

$$xu_s(x,Q^2) = (2/b)\partial xG(x,Q^2)/\partial y, \qquad (7)$$

and evaluating the derivative numerically. But wait! To minimize reading errors, one finds that the derivative above and the normalization change are roughly represented by

$$xu_s(x,Q^2) \approx x'G(x',Q^2)/100, \quad x' = x/10. \qquad (8)$$

This estimate is actually quite close to the re-scaled $xu_s(x,Q^2)$ of ref. [5] and is not too bad a match to

[‡4] Private communication with well known phenomenologist.

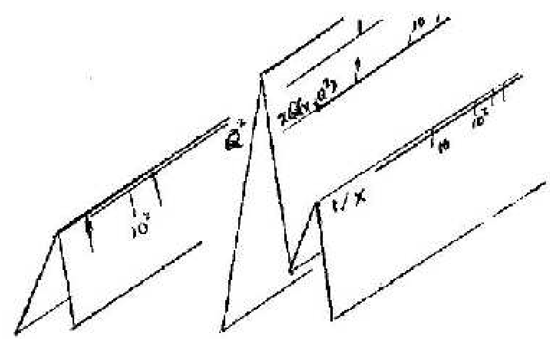
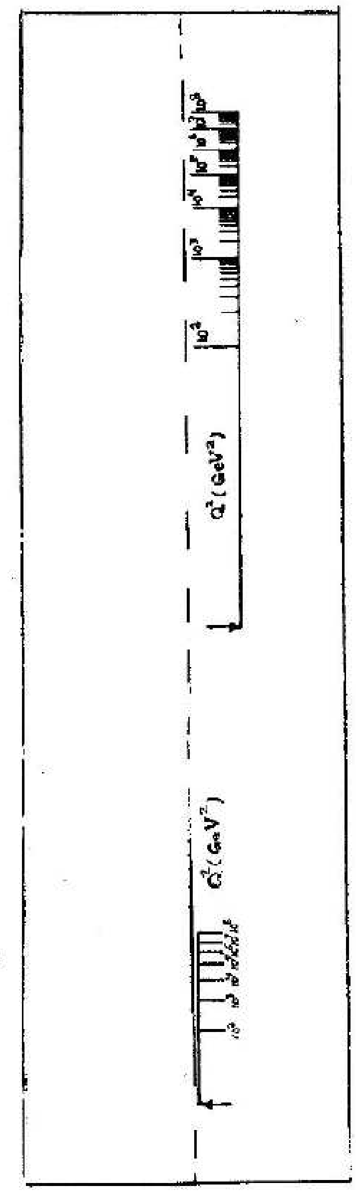


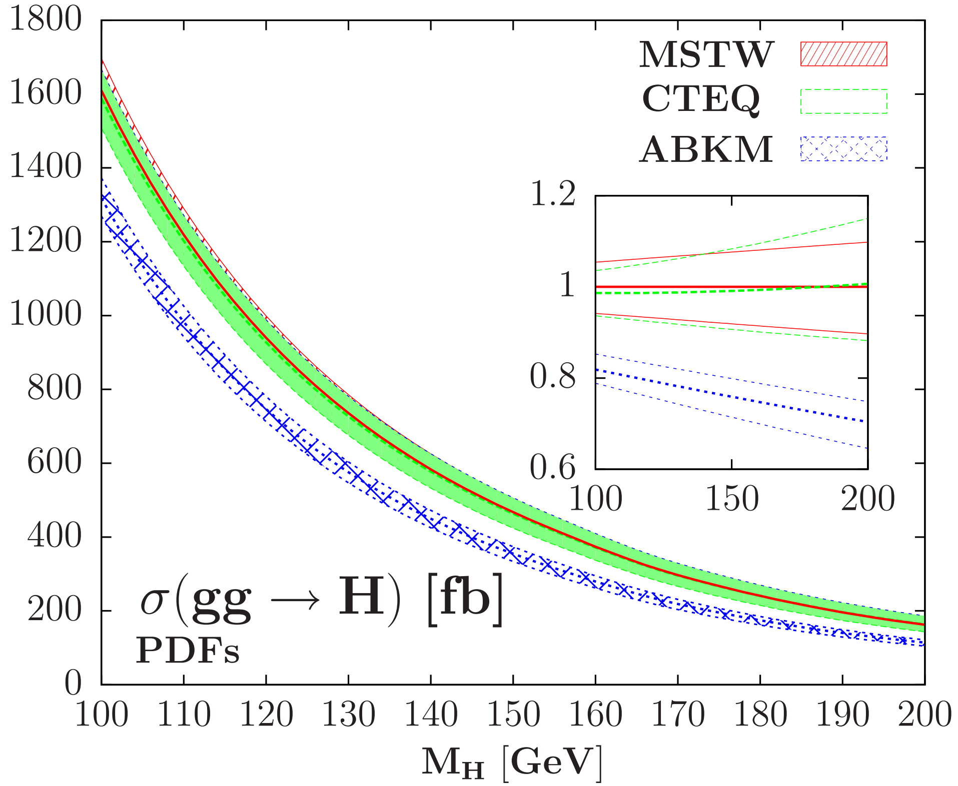
Fig. 2. The partonometer. To assemble: cut on solid lines, fold on dotted lines.



PDF fitters

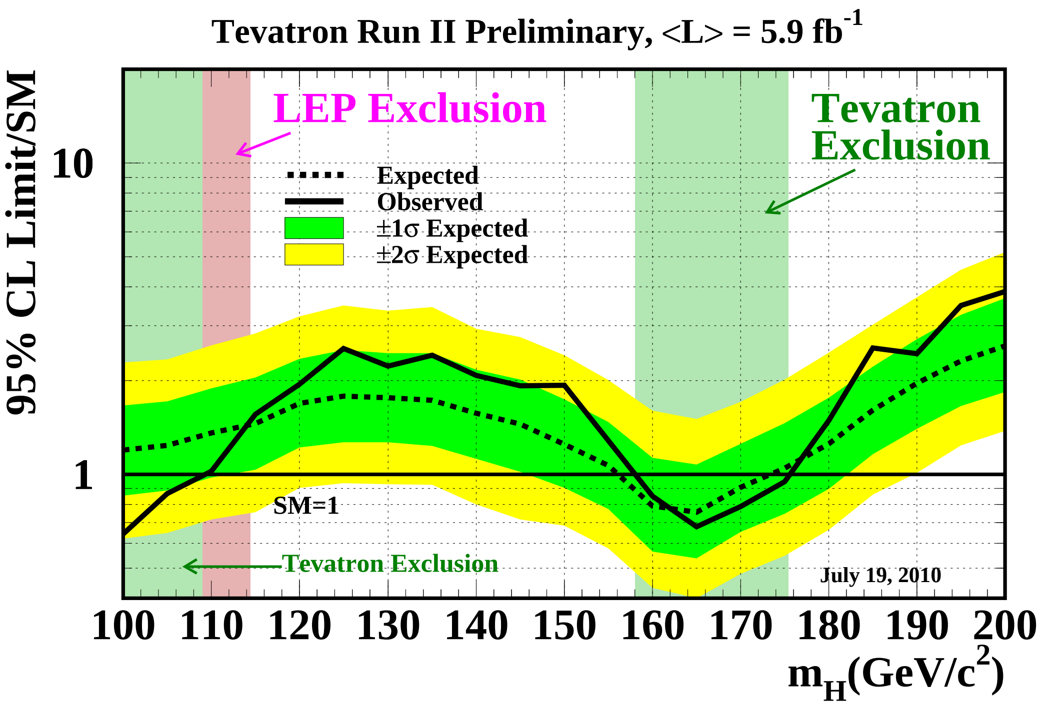
- Currently active groups
  - ABKM/ABM Alekhin, Blümlein, S.M.
  - CTEQ/CT Tung & friends
  - HERAPDF H1 and Zeus coll.
  - JR Jimenez-Delgado, Reya
  - MSTW Martin, Stirling, Thorne, Watt
  - NNPDF Ball et al.
- Strong activities in Germany resp. Terascale Alliance
  ABM, JR, HERAPDF
- Differences in theory treatment (QCD at NLO, NNLO, etc.), data sets included in fit (HERA only, etc.) and modelling of data (higher twist, nuclear corrections, etc.)

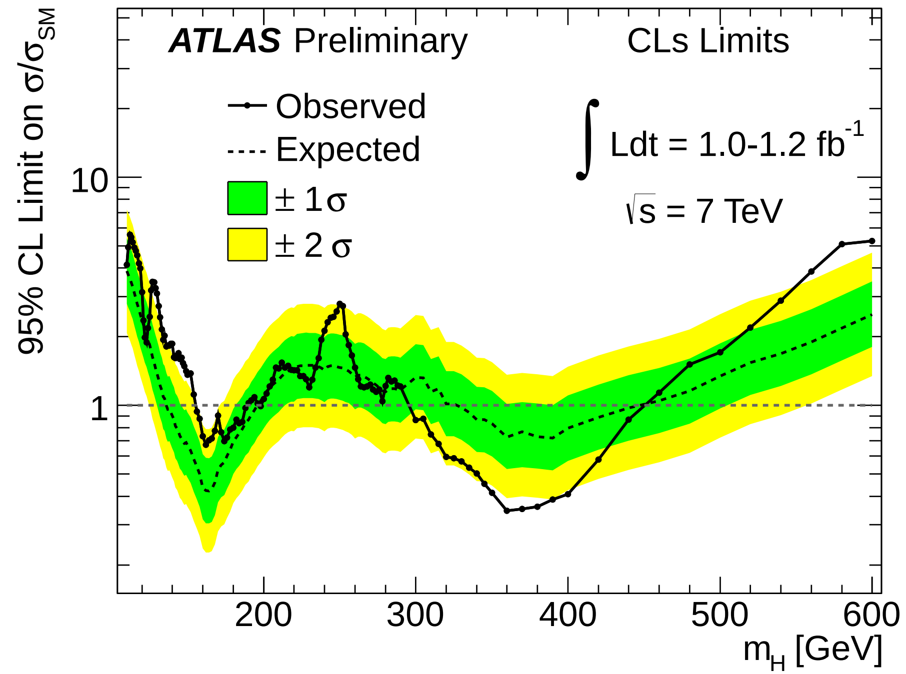
Cross section for Higgs production



- NNLO cross section $\sigma(gg \to H + X)$ at Tevatron with PDF uncertainties bands at $90\% CL$
  - largest differences in predictions from PDFs and value of α_s
    Baglio, Djouadi '10; Baglio, Djouadi, Ferrag, Godbole '11
  - e.g. at $M_H = 165$ GeV:
    MSTW $+35\%$ higher than ABKM; $+4.0\sigma$ standard deviation

Higgs searches at Tevatron and LHC





Tevatron New Phenomena & Higgs Working Group `http://tevnphwg.fnal.gov/` (left)
ATLAS coll. `ATLAS-CONF-2011-112` (right)

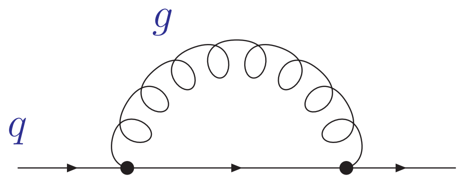
- Higgs search driven predominantly by $gg \to H$
  - large perturbative corrections at higher orders enhance signal
  - current range of excluded Higgs masses at Tevatron doubtful and at LHC rather optimistic

Heavy-quark masses

Pole mass

- Based on (unphysical) concept of top-quark being a free parton

$$\not p - m_q - \Sigma(p, m_q)\Big|_{p^2=m_q^2}$$



  - heavy-quark self-energy $\Sigma(p, m_q)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{QCD})$
- Definition of pole mass ambiguous up to corrections $\mathcal{O}(\Lambda_{QCD})$

Running quark masses

- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
  - short distance mass probes at scale of hard scattering
    $m_{\rm pole} = m_{\rm short\ distance} + \delta m$
  - conversion between pole mass and $\overline{MS}$ mass definition in perturbation theory: $m = m(\mu_R)\left(1 + a_s(\mu_R)d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$

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	NNPDF2.1
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

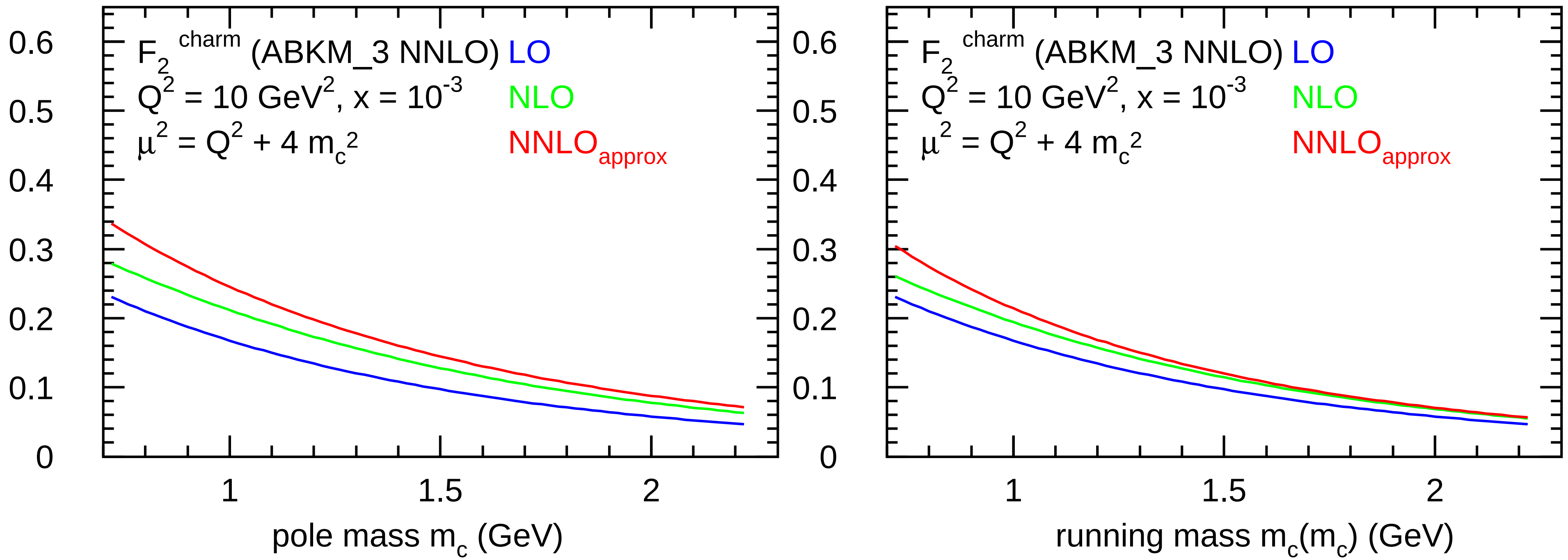
Impact on LHC cross sections

- $W^{\pm}$ and Z cross sections at LHC
- Uncertainties due to choice of pole mass value sizable
  - $\Delta\sigma_{W^{\pm}/Z} \simeq 4\%$ for $m_c = \pm 0.35$ GeV   MSTW arXiv:1007.2624

Variable $\alpha_S(M_Z^2)$		Tevatron ($\sqrt{s} = 1.96$ TeV)			LHC ($\sqrt{s} = 7$ TeV)			LHC ($\sqrt{s} = 14$ TeV)		
m_c (GeV)	m_b (GeV)	$\delta\sigma^W$	$\delta\sigma^Z$	$\delta\sigma^H$	$\delta\sigma^W$	$\delta\sigma^Z$	$\delta\sigma^H$	$\delta\sigma^W$	$\delta\sigma^Z$	$\delta\sigma^H$
1.05		-2.6	-2.8	+0.4	-4.1	-4.6	-2.4	-5.1	-5.5	-3.8
1.10		-2.2	-2.4	+0.2	-3.5	-3.9	-2.1	-4.3	-4.7	-3.3
1.15		-1.8	-1.9	+0.1	-2.9	-3.3	-1.8	-3.6	-3.9	-2.8
1.20		-1.4	-1.5	+0.1	-2.3	-2.6	-1.5	-2.8	-3.1	-2.3
1.25		-1.0	-1.1	0.0	-1.7	-1.9	-1.2	-2.1	-2.3	-1.7
1.30		-0.7	-0.7	0.0	-1.1	-1.3	-0.8	-1.4	-1.5	-1.2
1.35		-0.3	-0.4	0.0	-0.6	-0.6	-0.4	-0.7	-0.8	-0.6
1.40	**4.75**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.45		+0.3	+0.3	0.0	+0.6	+0.6	+0.4	+0.7	+0.8	+0.6
1.50		+0.6	+0.6	0.0	+1.1	+1.3	+0.8	+1.3	+1.5	+1.2
1.55		+0.8	+0.9	+0.1	+1.6	+1.9	+1.2	+2.0	+2.3	+1.8
1.60		+1.1	+1.2	+0.2	+2.1	+2.5	+1.8	+2.6	+3.0	+2.5
1.65		+1.3	+1.5	+0.1	+2.6	+3.0	+2.0	+3.2	+3.7	+2.9
1.70		+1.5	+1.8	+0.2	+3.1	+3.6	+2.5	+3.8	+4.4	+3.6
1.75		+1.8	+2.0	+0.3	+3.5	+4.2	+2.9	+4.3	+5.1	+4.1

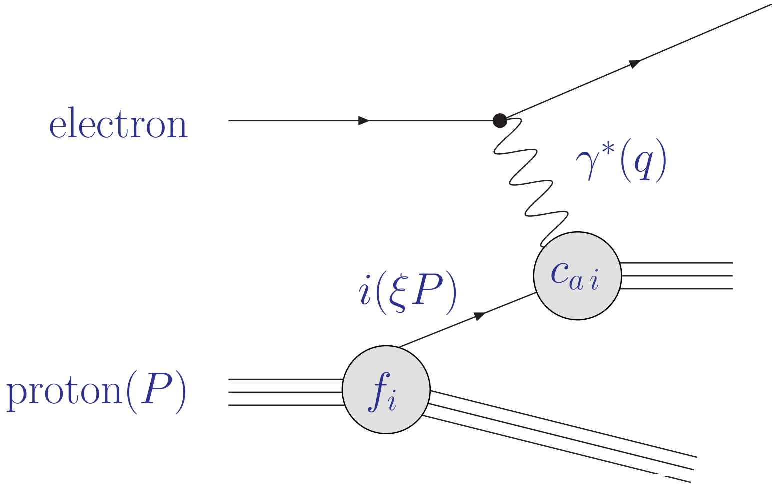
Running quark masses in DIS

- Charm structure function



- Running quark masses in DIS
  - improved convergence
  - reduced scale dependence
- Comparison with pole mass scheme

Fixed-target DIS data



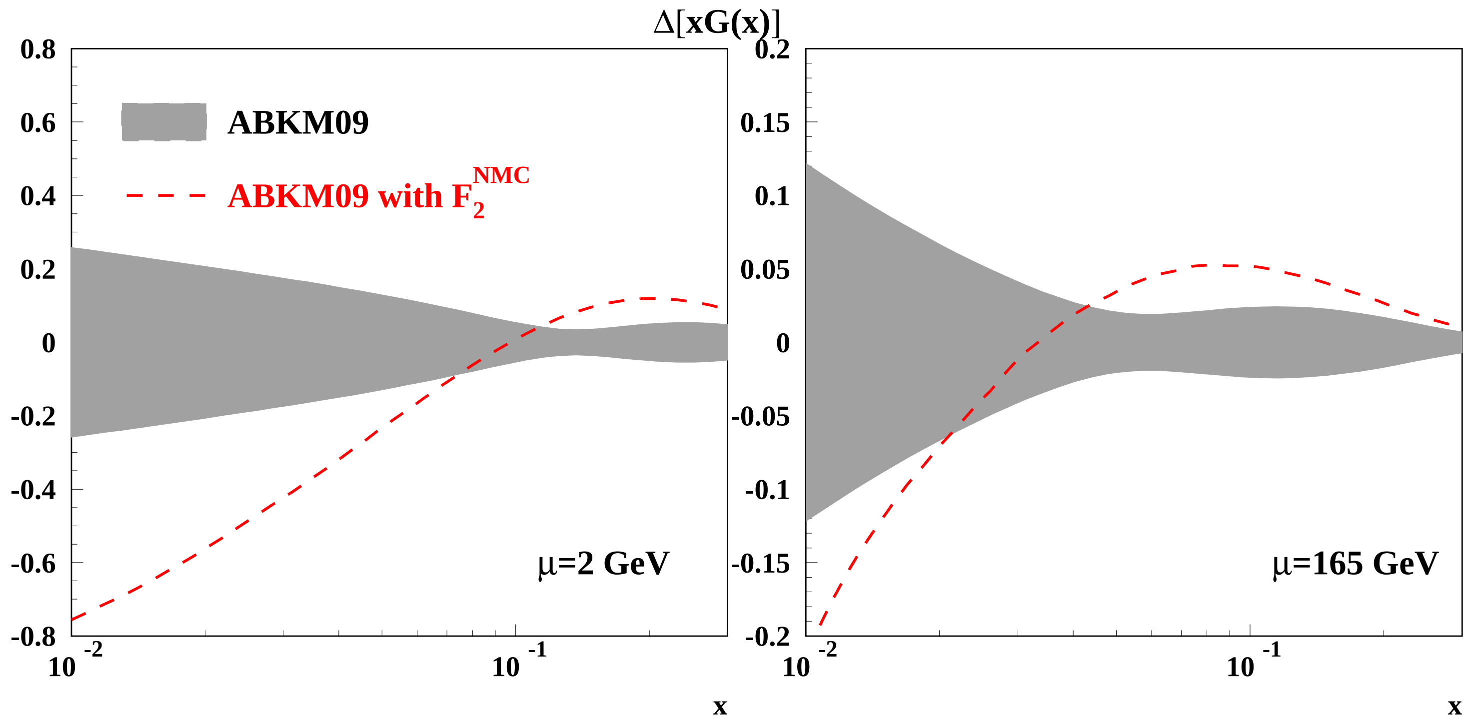
- **Kinematic variables**
  - Photon momentum transfer $Q^2 = -q^2$
  - Bjorken variable $x = Q^2/(2P\cdot q)$
  - Inelasticity $y = q\cdot P/k\cdot P$ with lepton momentum k

- Cross section depends on DIS structure functions F_2 and F_L (or alternatively $R = \sigma_T/\sigma_L$)
  - structure functions include QCD corrections at higher orders

$$\frac{d^2\,\sigma(x,Q^2)}{dx dQ^2} =$$

$$\frac{4\pi\alpha^2}{xQ^4}\left\{1 - y - xy\frac{M^2}{s} + \left(1 - \frac{2m_l^2}{Q^2}\right)\left(1 + 4x^2\frac{M^2}{Q^2}\right)\frac{y^2}{2(1+R(x,Q^2))}\right\} F_2(x,Q^2)$$

Fixed-target data in global PDF fits



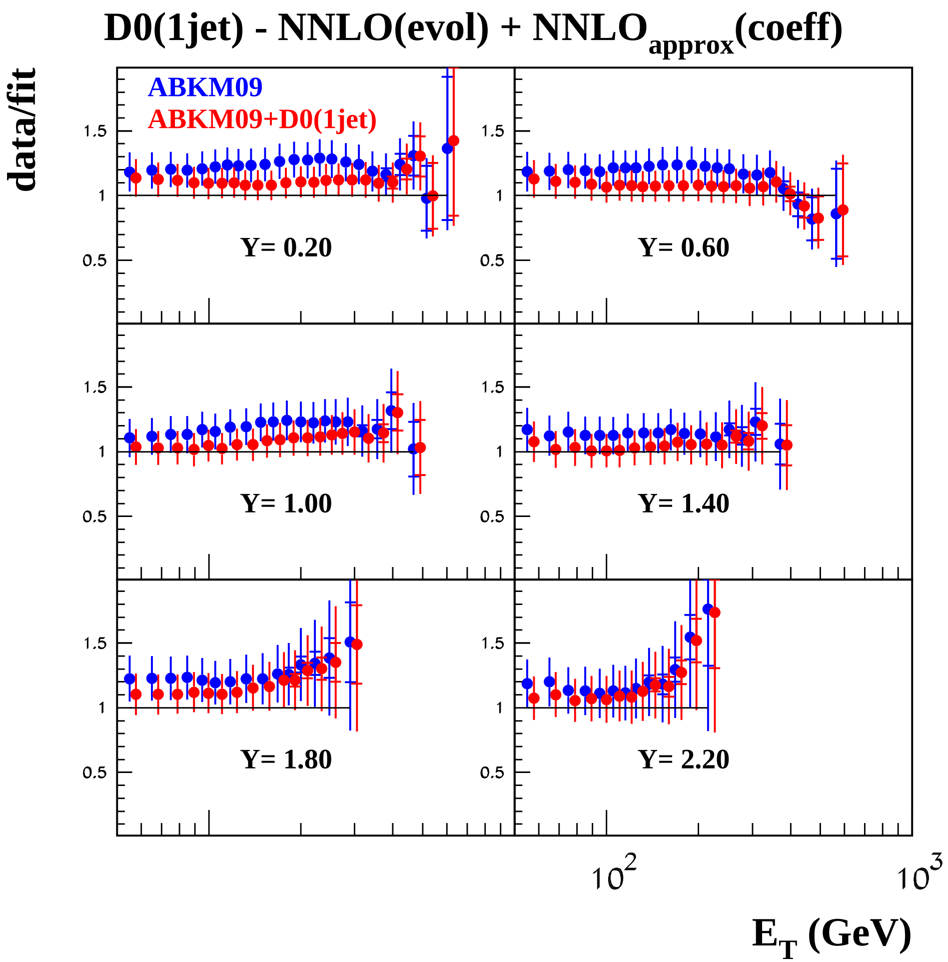
- Two variants for including fixed-target DIS data in PDF fits
  - variant 1 (consistent):
    use the differential cross section $d^2\sigma/dxdQ^2$
  - variant 2 (inconsistent):
    use published values for structure function F_2
- Inconsistent variant leads to larger gluon PDF at $x \simeq 0.1$

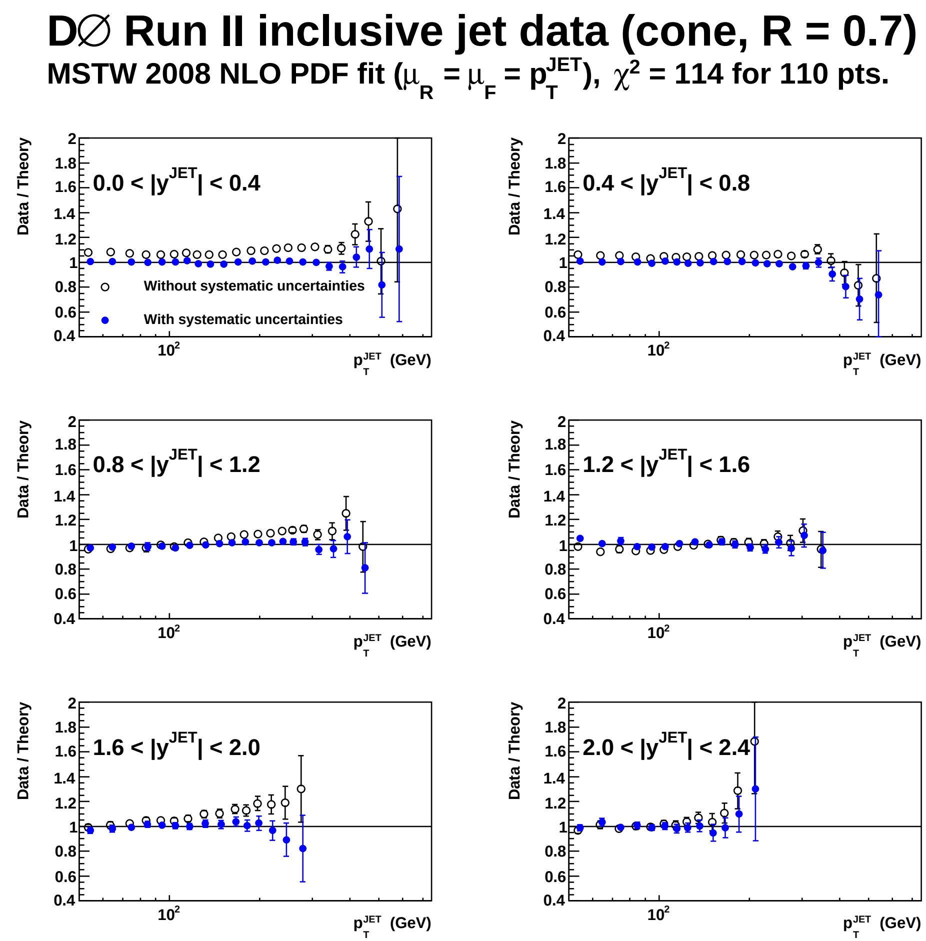
Jet data from Tevatron and LHC

General remarks

- QCD corrections only known to NLO
  (1-jet inclusive distributions with $\text{NNLO}_{\text{approx}}$ corr. Kidonakis, Owens '01)
- 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

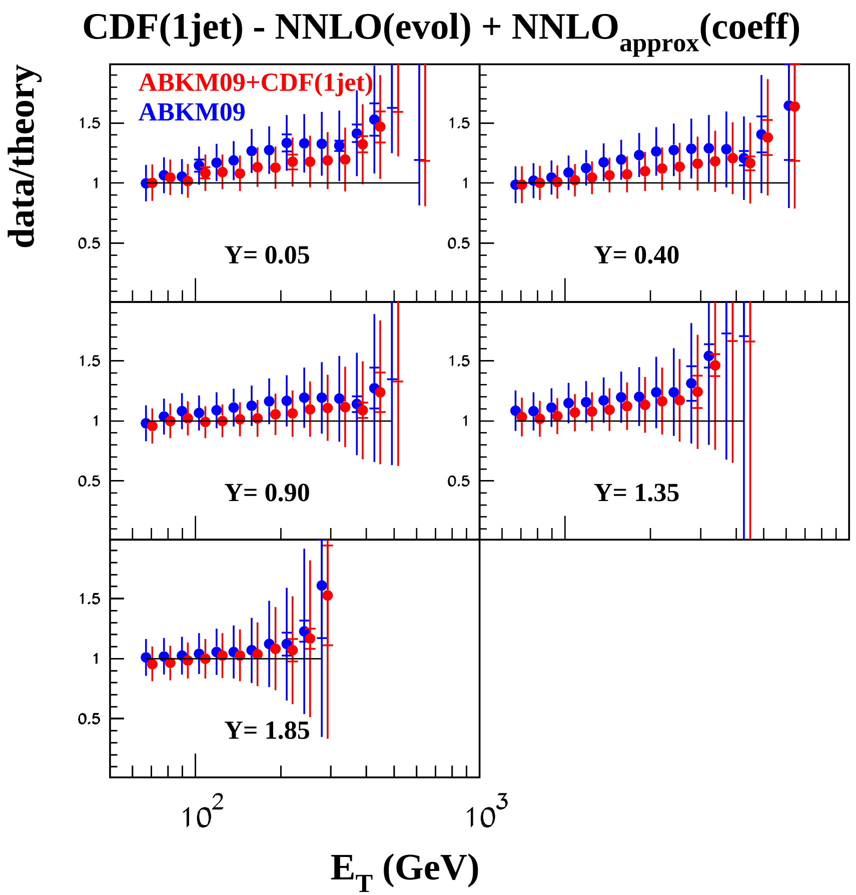
Tevatron jet data (D0) – 1-jet inclusive

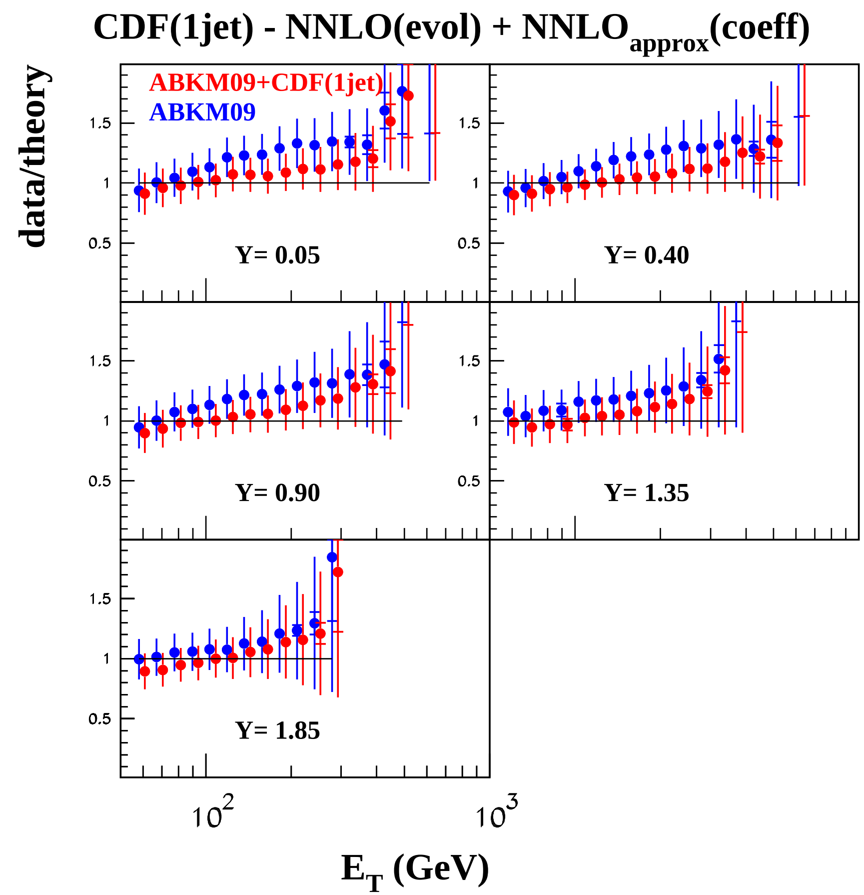




- PDF fits to Tevatron jet data (with NNLO$_{\rm approx}$ corr. Kidonakis, Owens ‘01) Alekhin, Blümlein, S.M. ‘11 (left); MSTW `arXiv:0901.0002` (right)
- 3-flavor PDFs for DIS, 5-flavor PDFs for jets, scale $\mu_r = \mu_f = E_T$

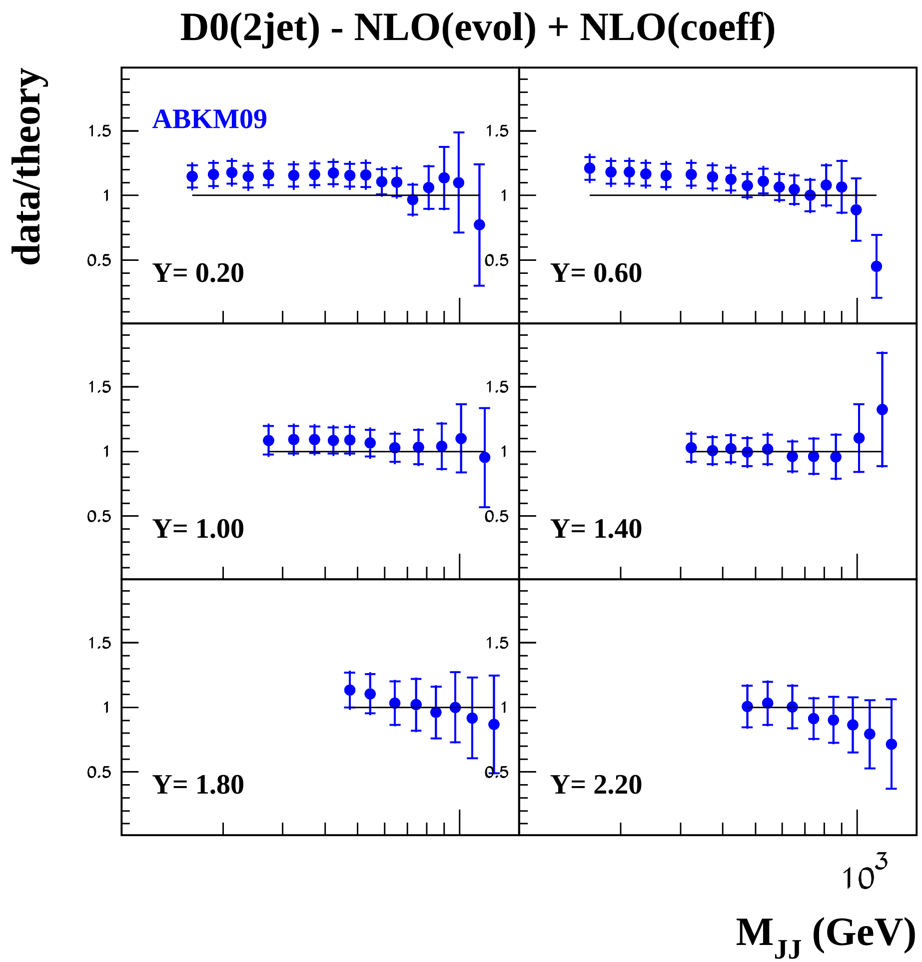
Tevatron jet data (CDF) – 1-jet inclusive

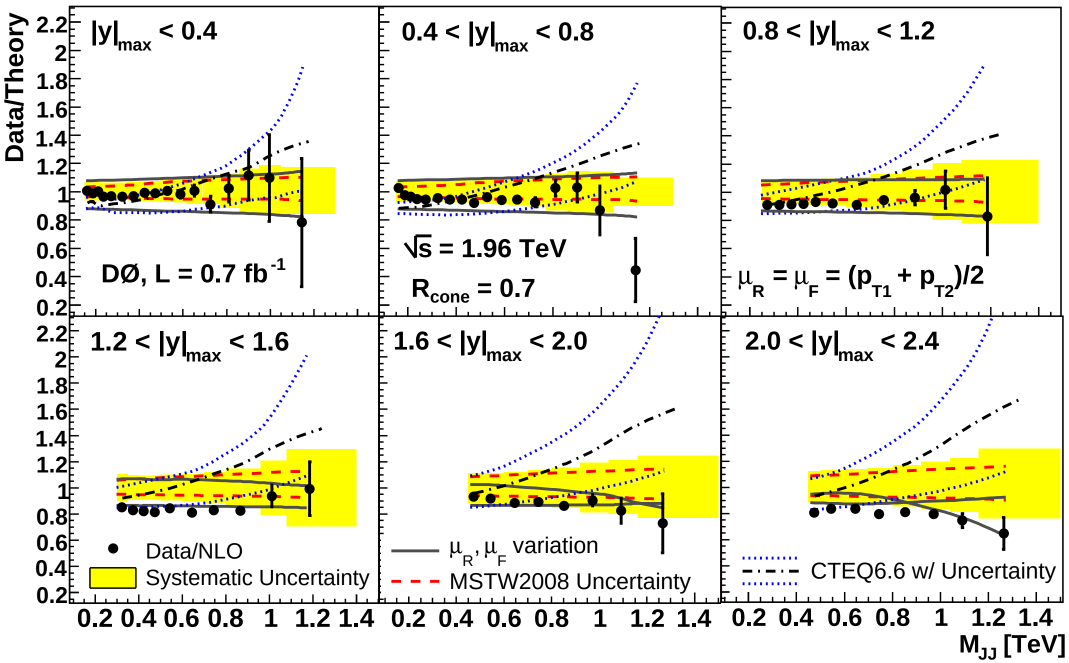




- Cone algorithm (left); k_T algorithm (right); scale $\mu_r = \mu_f = p_T$
- Disagreement in slope at large E_T can hardly be improved
  - large E_T is dominated by quark-quark scattering; PDFs well constrained

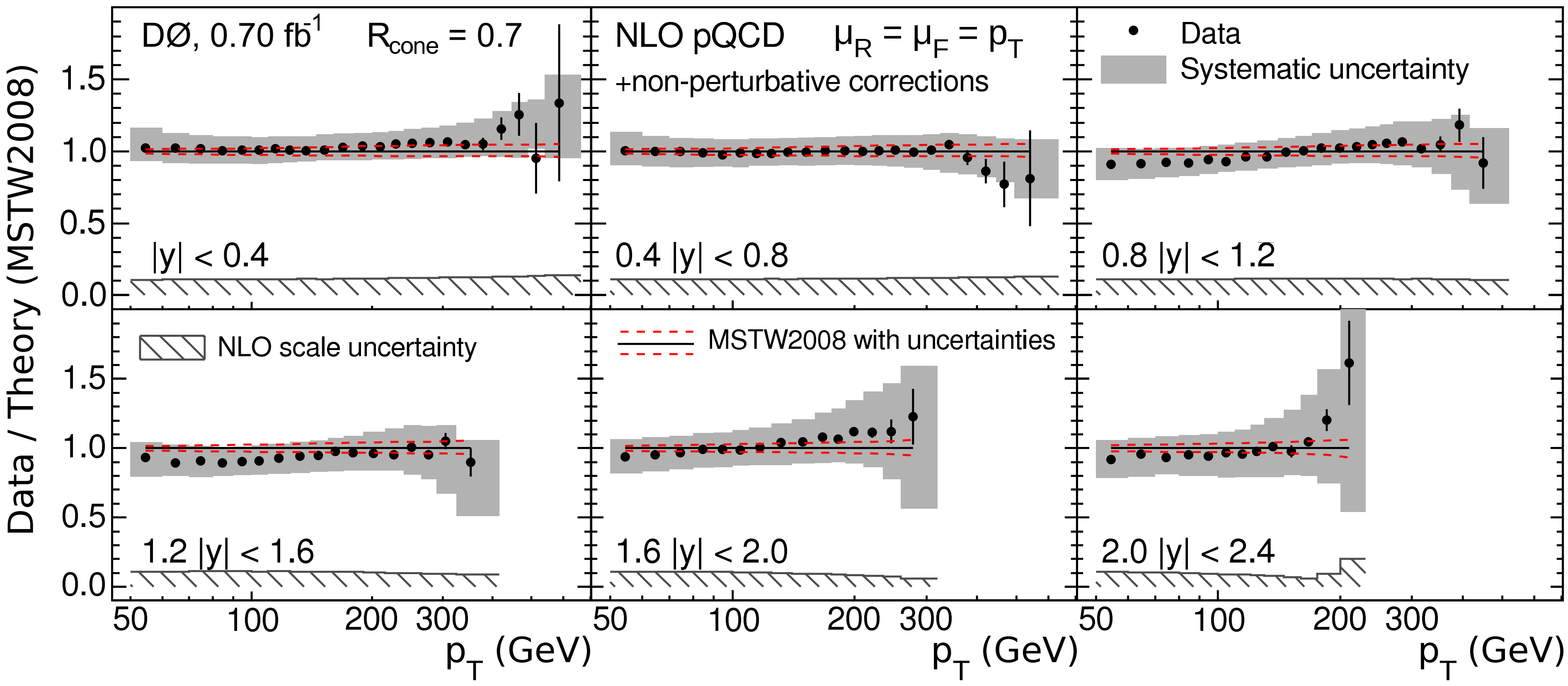
Tevatron jet data (D0) – di-jet invariant mass





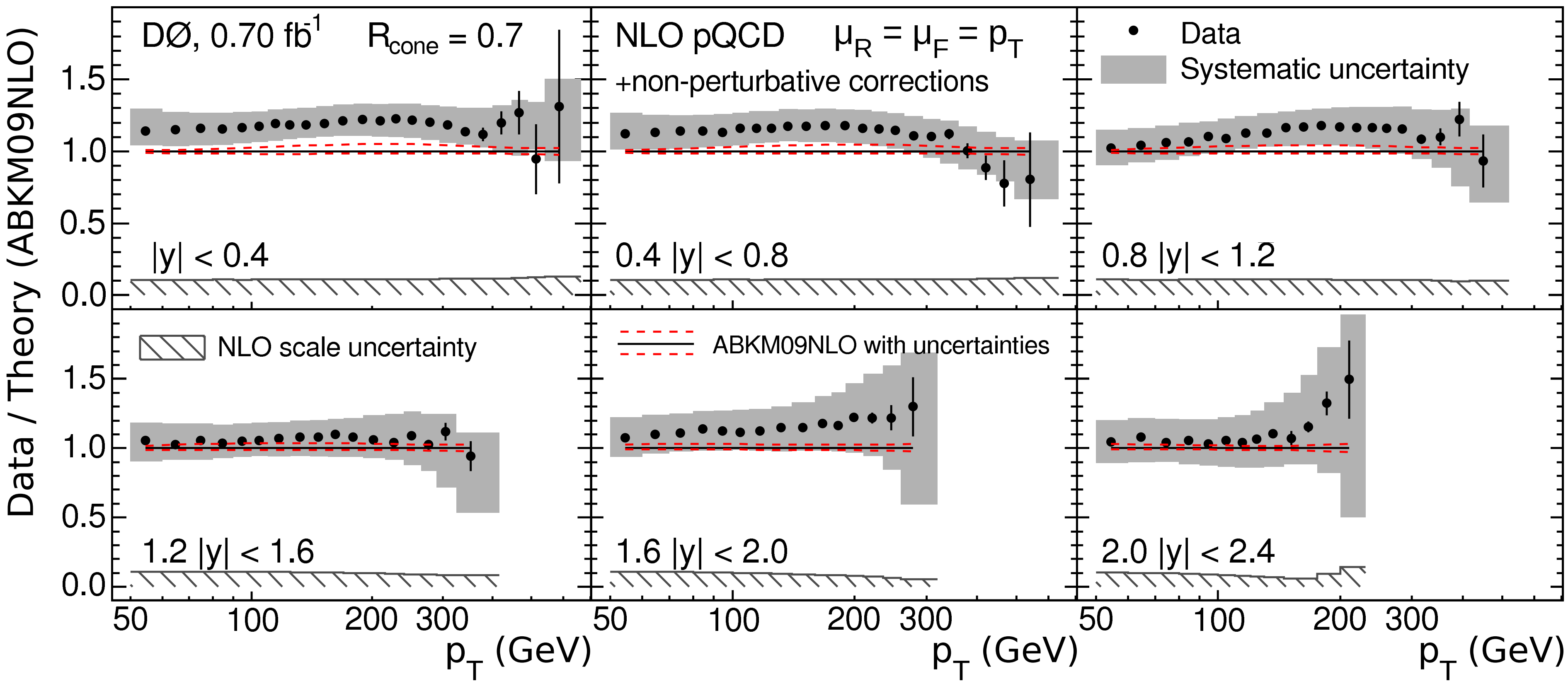
- Predictions for Tevatron di-jet data (no NNLO corrections known)
  Alekhin, Blümlein, S.M. '11 (left); D0 coll. `arXiv:1002.4594` (right)
- Uncertainty due to missing NNLO corrections; scale $\mu_r = \mu_f = M_{JJ}$

New analysis (D0) – 1-jet inclusive



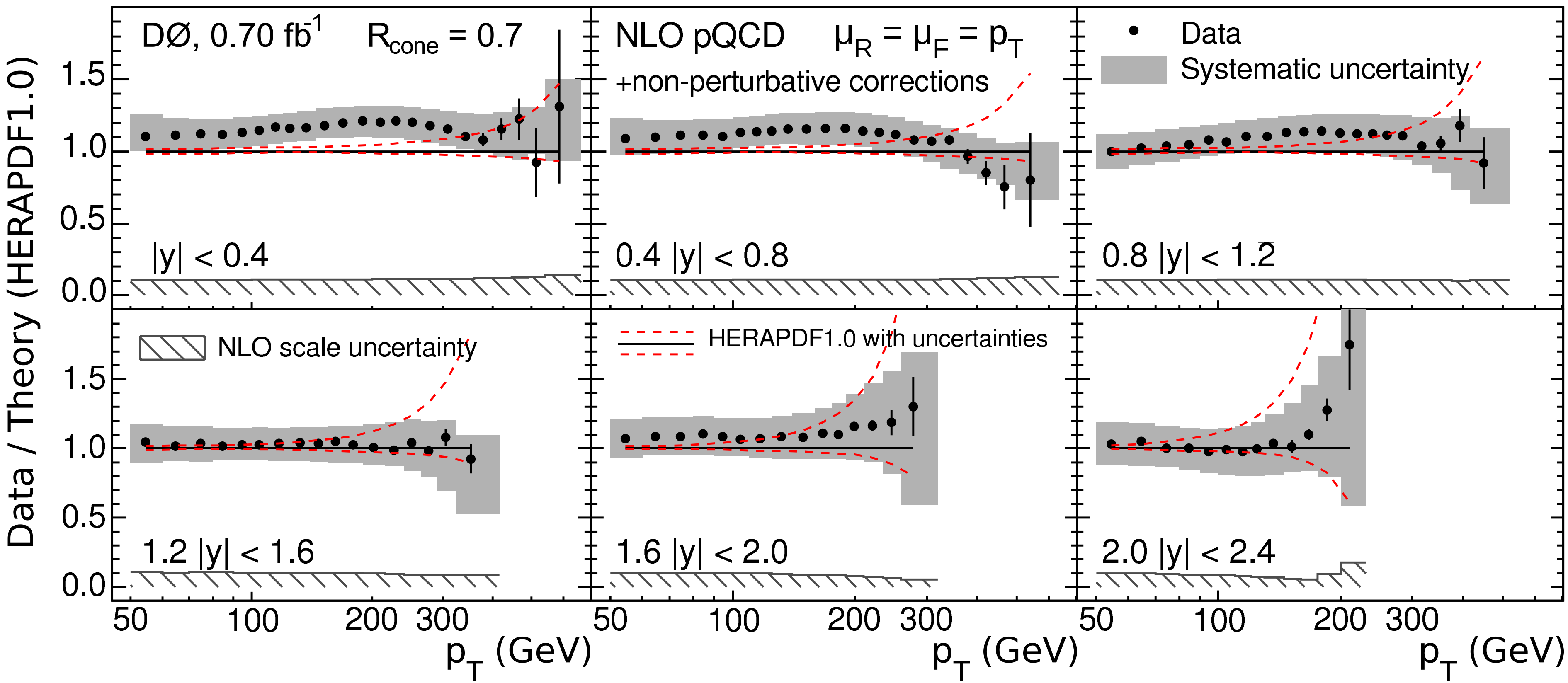
- New analysis of 1-jet inclusive data D0 coll. arXiv:1110.3771
  - MSTW PDF set with PDF (red) and theory (shaded) uncertainty

New analysis (D0) – 1-jet inclusive



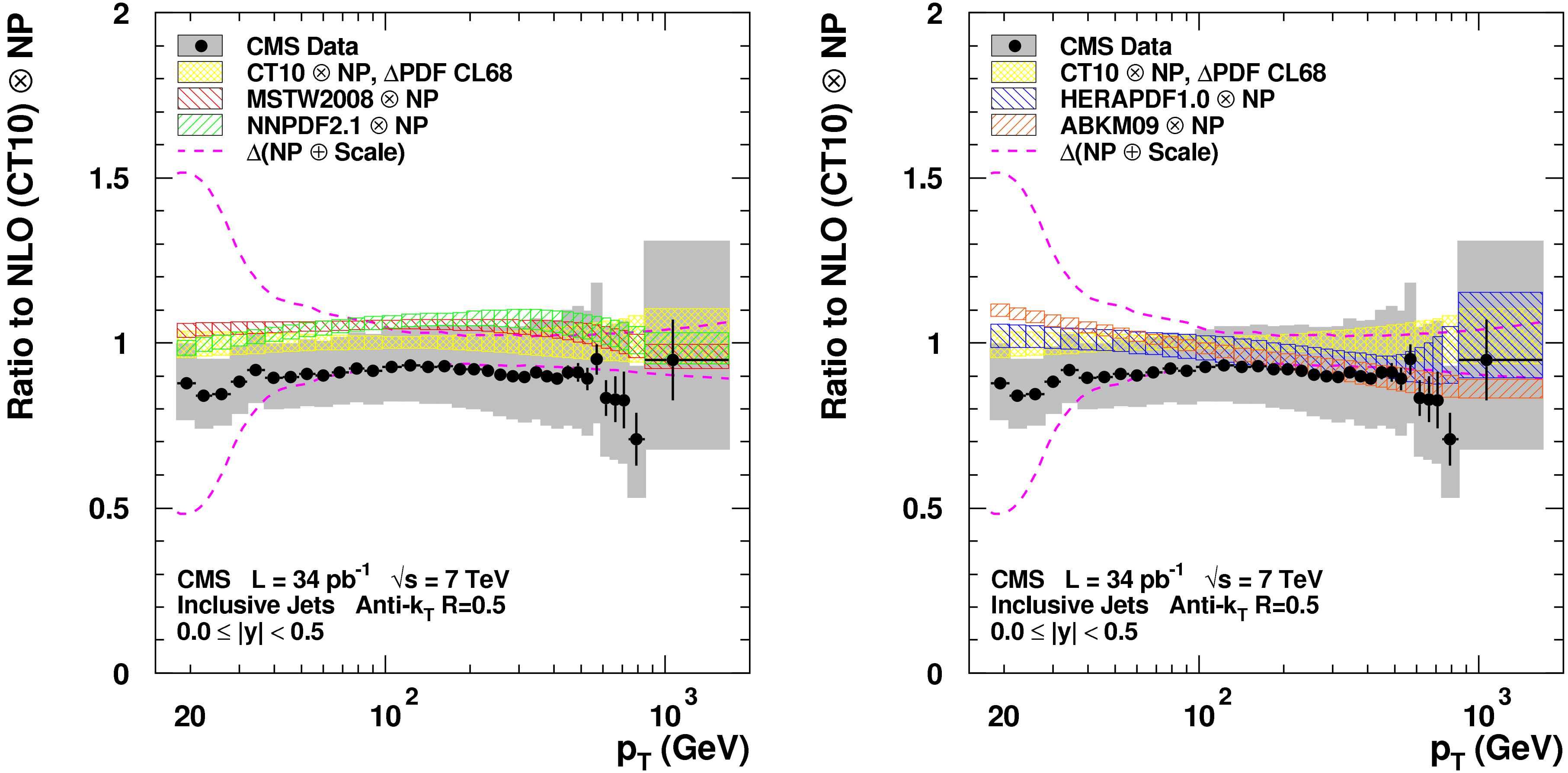
- New analysis of 1-jet inclusive data D0 coll. arXiv:1110.3771
  - ABKM PDF set with PDF (red) and theory (shaded) uncertainty

New analysis (D0) – 1-jet inclusive



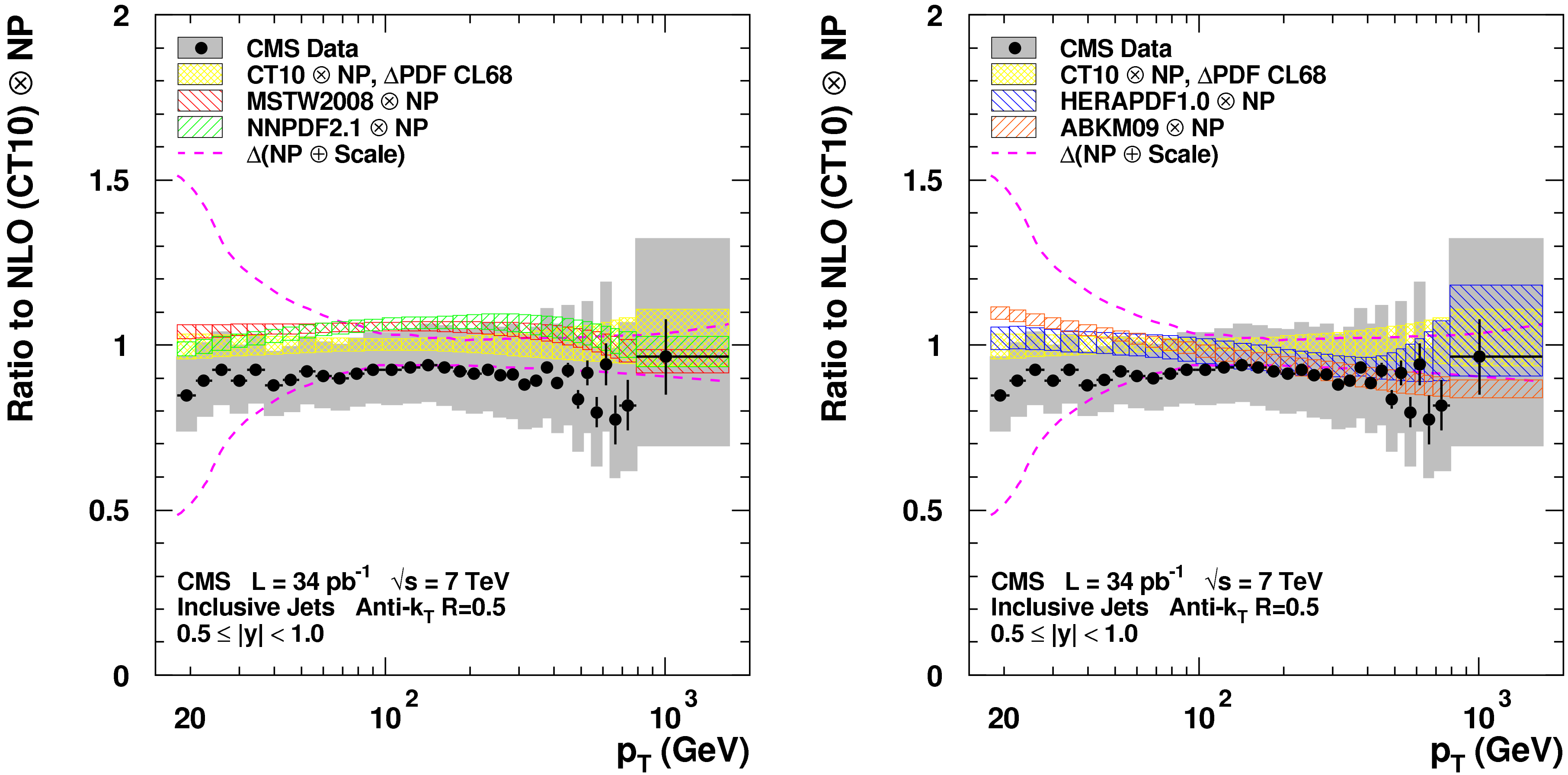
- New analysis of 1-jet inclusive data D0 coll. arXiv:1110.3771
  - HERAPDF PDF set with PDF (red) and theory (shaded) uncertainty

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 (CMS) – 1-jet inclusive



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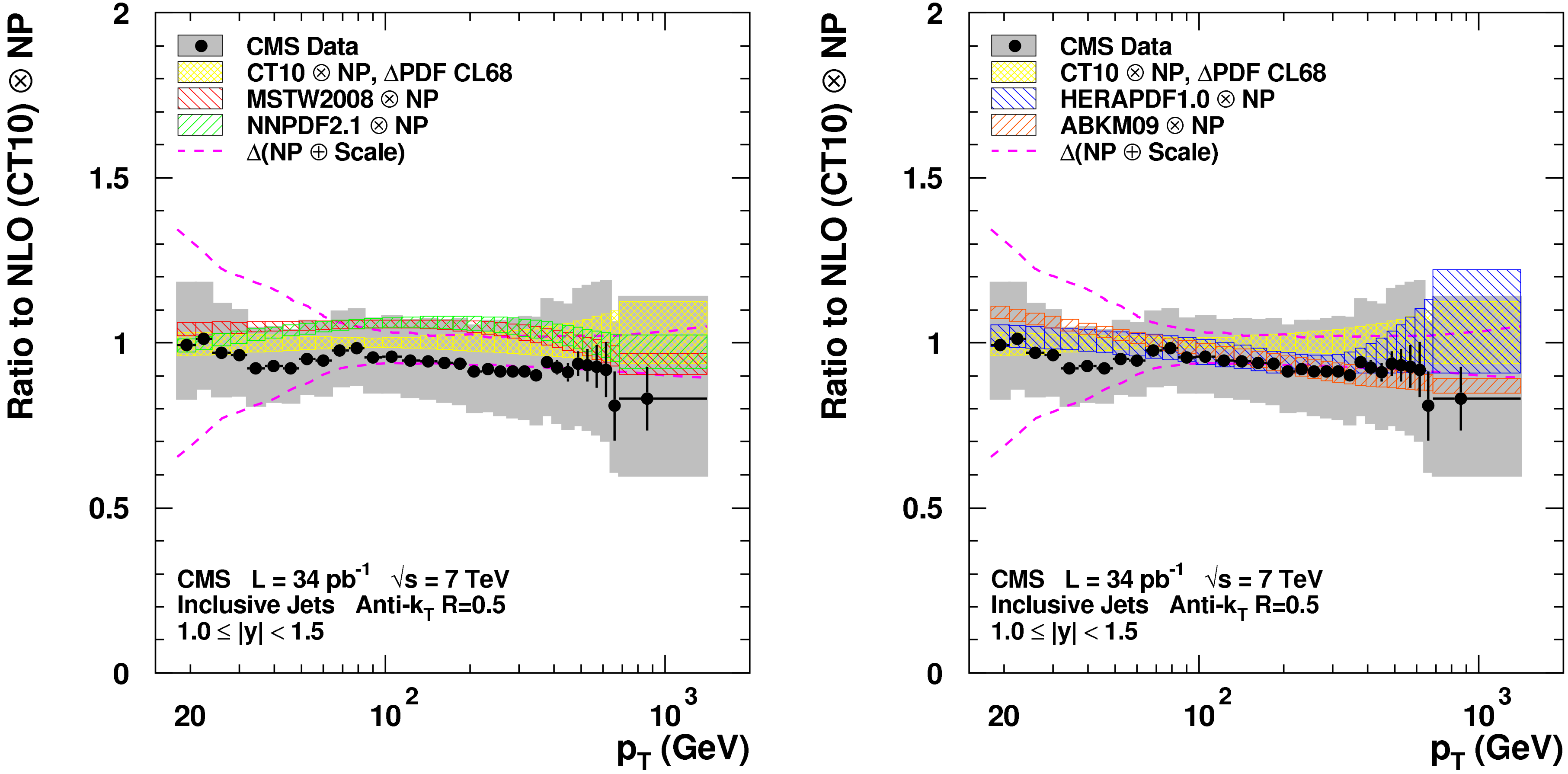

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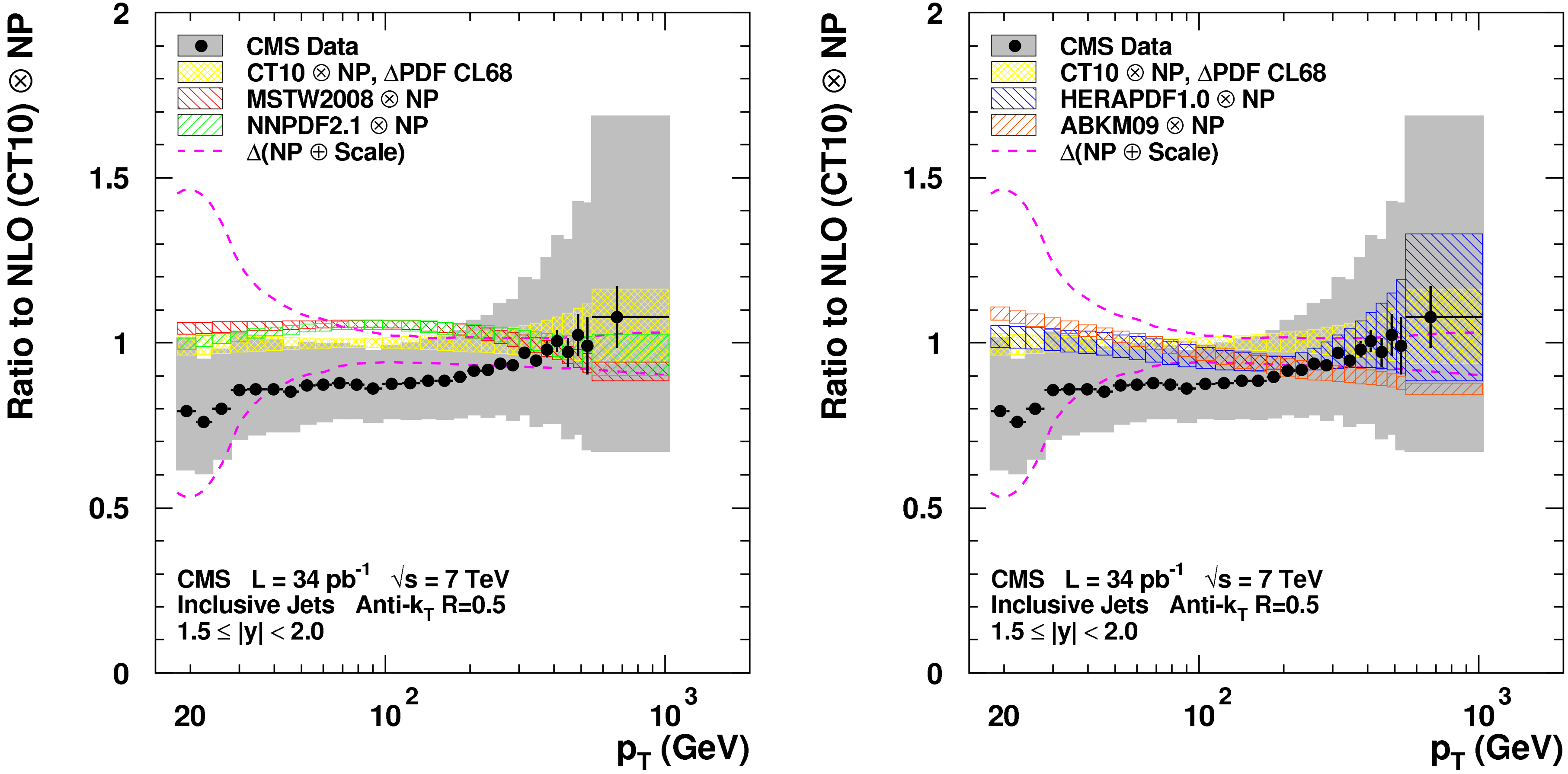
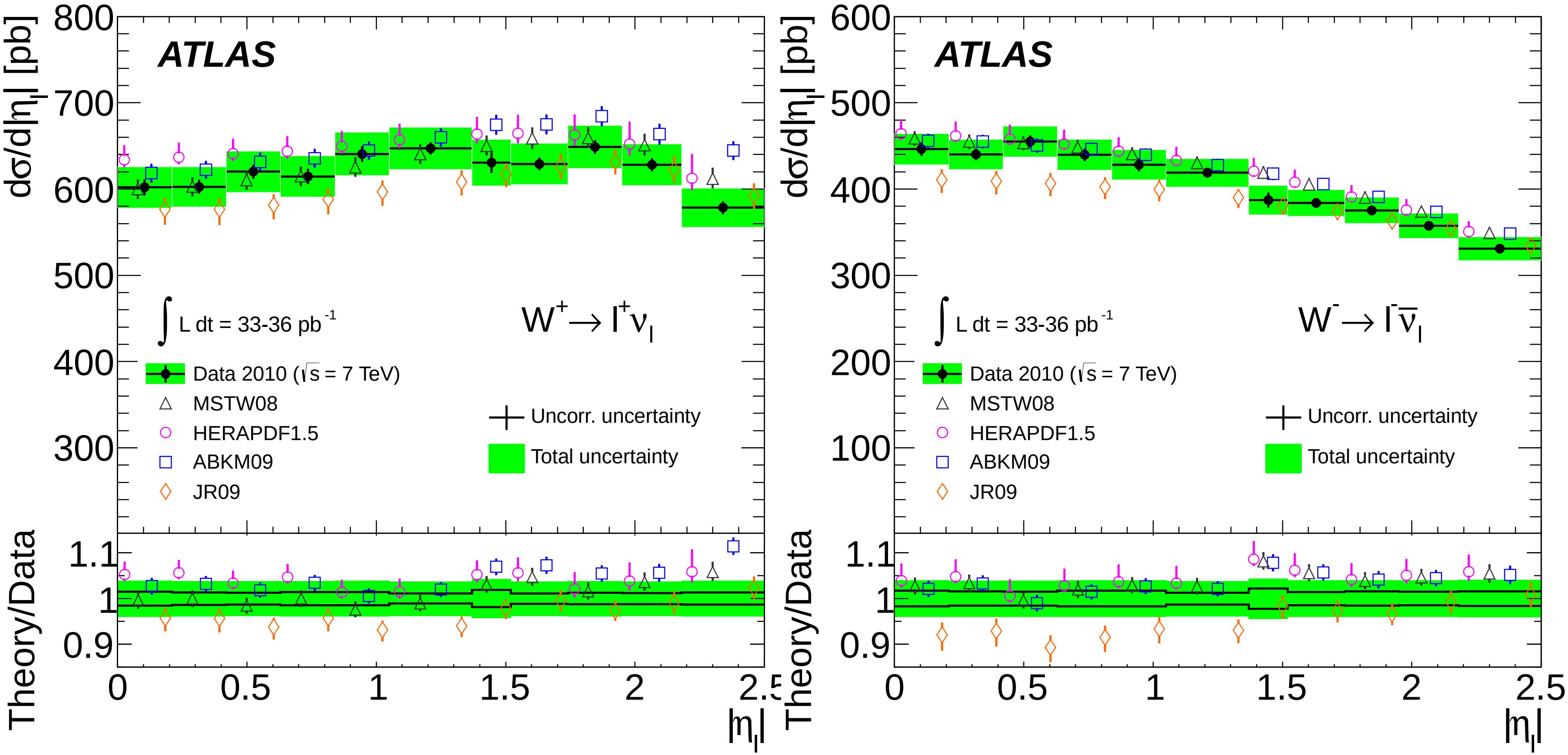


- Analysis of 1-jet inclusive data CMS coll. `CMS NOTE 2011/004`
  - Comparisions of various PDF sets courtesy K. Rabbertz

LHC data (ATLAS) for $W^{\pm}$-boson production



- LHC data for charged lepton rapidity distribution in $W^{\pm}$-boson productions and comparison of NNLO PDF sets
  - kinematic requirements: $p_T > 20$ GeV, $p_{T,\nu} > 25$ GeV and $m_T > 40$ GeV

Strong coupling constant

Essential facts

- $\alpha_s(M_Z)$ from e^+e^- data high
- $\alpha_s(M_Z)$ from DIS data low
- World average 1992
  $\alpha_s(M_Z) = 0.117 \pm 0.004$

Bethke, Catani CERN TH-6484/92

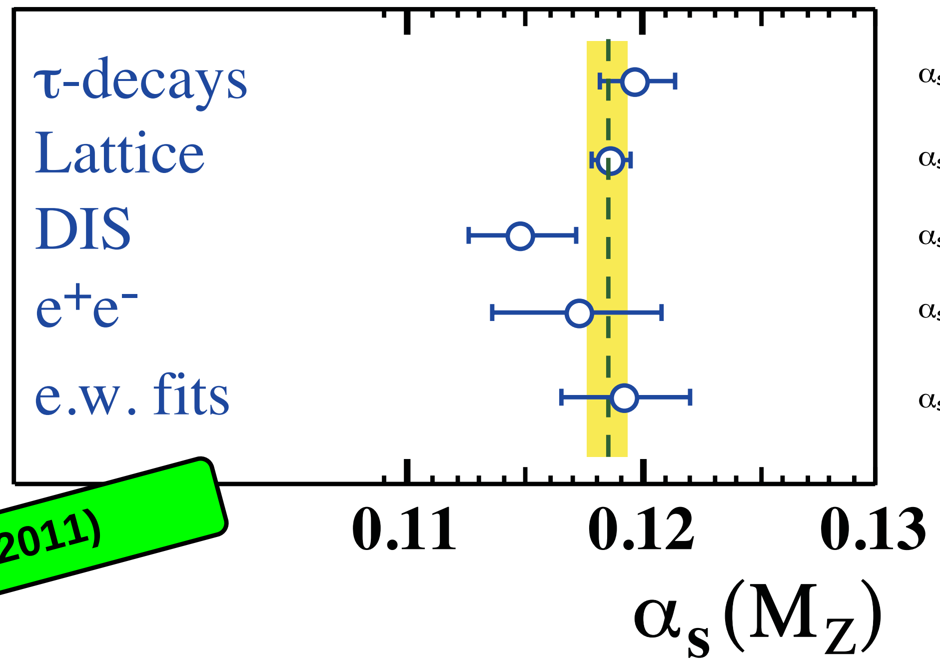
	Process	Ref.	Q [GeV]	$\alpha_s(Q)$	$\alpha_s(M_{Z^0})$	$\Delta\alpha_s(M_{Z^0})$ exp.	$\Delta\alpha_s(M_{Z^0})$ theor.	order of perturb.
1	R_τ [LEP]	[7-10]	1.78	$0.318 {}^{+0.048}_{-0.039}$	$0.117 {}^{+0.006}_{-0.005}$	${}^{+0.003}_{-0.004}$	${}^{+0.005}_{-0.004}$	NNLO
2	R_τ [world]	[2]	1.78	0.32 ± 0.04	$0.118 {}^{+0.004}_{-0.006}$	–	–	NNLO
3	DIS [ν]	[3]	5.0	$0.193 {}^{+0.019}_{-0.018}$	$0.111 {}^{+0.006}_{-0.007}$	${}^{+0.004}_{-0.006}$	0.004	NLO
4	DIS [μ]	[12]	7.1	0.180 ± 0.014	0.113 ± 0.005	0.003	0.004	NLO
5	$J/\Psi, \Upsilon$ decay	[4]	10.0	$0.167 {}^{+0.015}_{-0.011}$	$0.113 {}^{+0.007}_{-0.005}$	–	–	NLO
6	e^+e^- [σ_{had}]	[14]	34.0	0.163 ± 0.022	0.135 ± 0.015	–	–	NNLO
7	e^+e^- [shapes]	[15]	35.0	0.14 ± 0.02	0.119 ± 0.014	–	–	NLO
8	$p\bar{p} \to b\bar{b}X$	[11]	20.0	$0.136 {}^{+0.025}_{-0.024}$	$0.108 {}^{+0.015}_{-0.014}$	0.006	${}^{+0.014}_{-0.013}$	NLO
9	$p\bar{p} \to W$ *jets*	[13]	80.6	0.123 ± 0.027	0.121 ± 0.026	0.018	0.020	NLO
10	$\Gamma(Z^0 \to$ had.)	[5]	91.2	0.133 ± 0.012	0.133 ± 0.012	0.012	${}^{+0.003}_{-0.001}$	NNLO
11	Z^0 ev. shapes							
	ALEPH	[7]	91.2	$0.119 {}^{+0.008}_{-0.010}$		–	–	NLO
	DELPHI	[8]	91.2	0.113 ± 0.007		0.002	0.007	NLO
	L3	[9]	91.2	0.118 ± 0.010		–	–	NLO
	OPAL	[10]	91.2	$0.122 {}^{+0.006}_{-0.005}$		0.001	${}^{+0.006}_{-0.005}$	NLO
	SLD	[6]	91.2	$0.120 {}^{+0.015}_{-0.013}$		0.009	${}^{+0.012}_{-0.009}$	NLO
	Average	[6-10]	91.2		0.119 ± 0.006	0.001	0.006	NLO
12	Z^0 ev. shapes							
	ALEPH	[7]	91.2	0.125 ± 0.005		0.002	0.004	resum.
	DELPHI	[8]	91.2	0.122 ± 0.006		0.002	0.006	resum.
	L3	[9]	91.2	0.126 ± 0.009		0.003	0.008	resum.
	OPAL	[10]	91.2	$0.122 {}^{+0.003}_{-0.006}$		0.001	${}^{+0.003}_{-0.006}$	resum.
	Average	[7-10]	91.2		0.123 ± 0.005	0.001	0.005	resum.

Table 1: Summary of measurements of α_s. For details see text.

2

α_s 2011

World Summary of α_s 2011:



$\alpha_s(M_Z) = 0.1197 \pm 0.0016$

$\alpha_s(M_Z) = 0.1186 \pm 0.0008$

$\alpha_s(M_Z) = 0.1148 \pm 0.0024$

$\alpha_s(M_Z) = 0.1172 \pm 0.0037$

$\alpha_s(M_Z) = 0.1193 \pm 0.0028$

S. Bethke (Ringberg 2011)

–> $\alpha_s(M_Z) = 0.1185 \pm 0.0008$

(–> RPP 2012)

$\Lambda_{\overline{MS}}^{(5)} = (214 \pm 10)$ MeV

$\Lambda_{\overline{MS}}^{(4)} = (298 \pm 12)$ MeV

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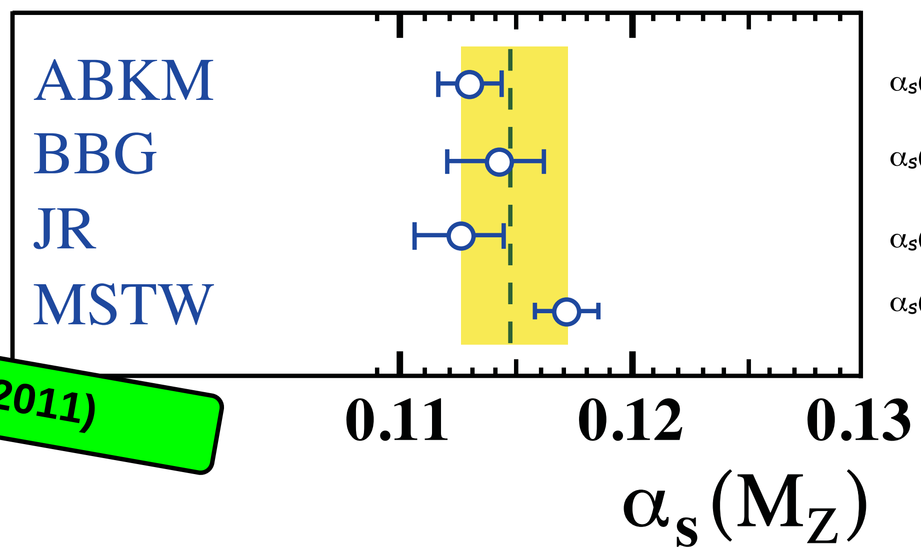
α_s 2011

α_s from DIS structure functions

- determination of parton densities from DIS; QCD in NNLO (up to N3LO);
- MSTW: include hadron collider jet data (in order to constrain gluon at large x)



$\alpha_s(M_Z) = 0.1129 \pm 0.0014$

$\alpha_s(M_Z) = 0.1142 \pm 0.0023$

$\alpha_s(M_Z) = 0.1124 \pm 0.0020$

$\alpha_s(M_Z) = 0.1172 \pm 0.0014$

S. Bethke (Ringberg 2011)

–> $\alpha_s(M_Z) = 0.1148 \pm 0.0024$

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Theory issues

Benchmark processes

- Theory improvements needed
  - QCD corrections to NNLO
- Deep-inelastic scattering
  - Heavy-quark structure functions for neutral and charged current
  - $ep \to 2 + 1$ jets inclusive production
- Hadron colliders
  - production of $pp \to 1$ jet $+ X$ inclusive, $pp \to 2$ jets, ...
  - $pp \to W/Z + 1$ jet production
  - top-quark production ($t\bar{t}$ and single-t)
  - ...

Summary

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

- Currently source of largest differences for Higgs cross section predictions
- Recent improvements are mainly theory driven
- Continuous benchmarking mandatory

Experimental perspectives

- Need for high precision data ($\mathcal{O}(\text{few}\%)$ uncertainty) for benchmark processes
  - structure functions from HERA (final run II analysis)
  - (differential) $W^\pm/Z$ production at LHC
  - jet data from LHC (Tevatron)

Theoretical perspectives

- Need for improved predictions at NNLO QCD for Standard Model processes