Precise parton distributions

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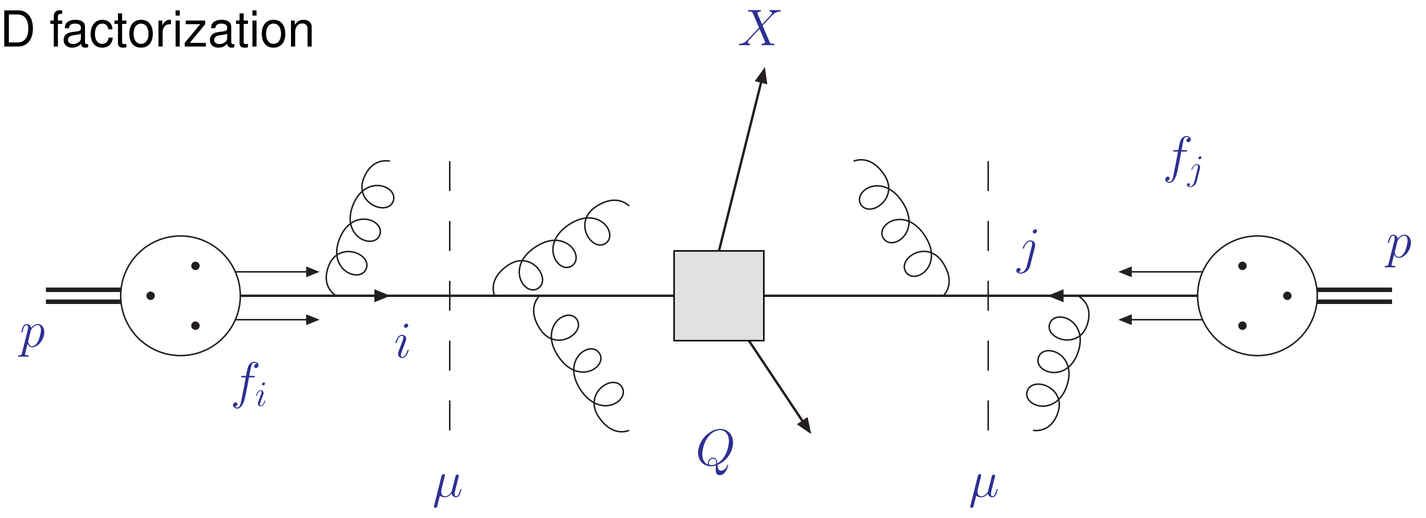
Workshop *Future Physics with HERA Data for Current and Planned Experiments*, Hamburg, Nov 12, 2014

QCD factorization

- QCD factorization

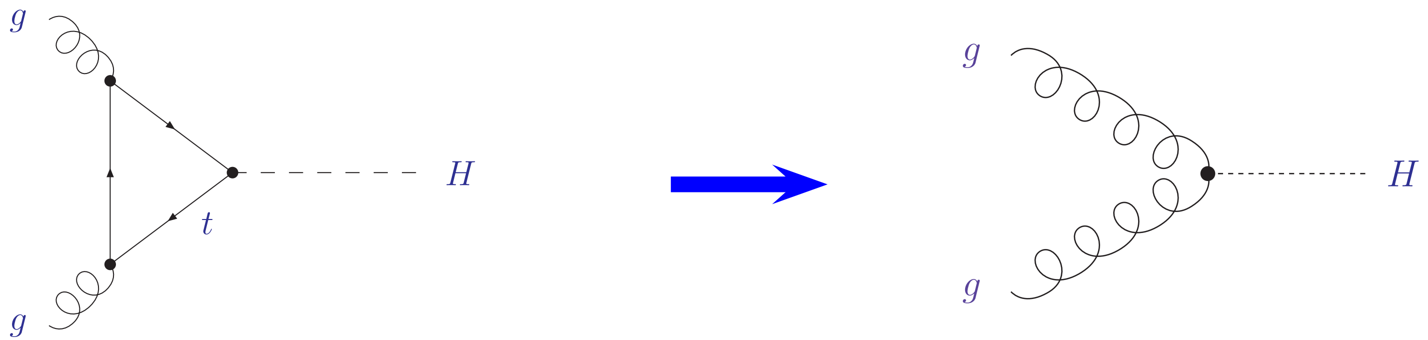


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- 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, ...

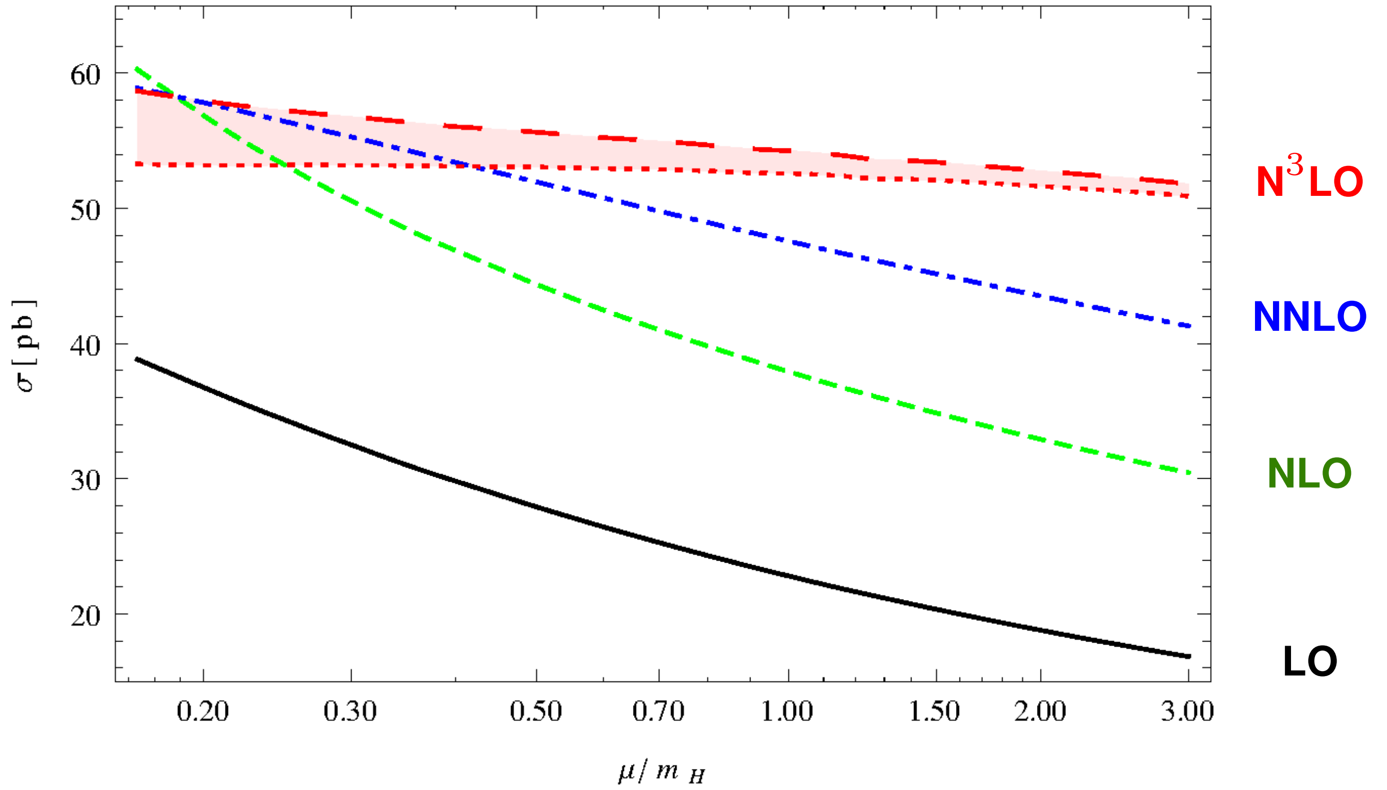
Higgs production in gg-fusion

Effective theory



- Hard scattering cross section $\hat{\sigma}_{ij\to H+X}$ dominated by gluon-gluon fusion
  - typically treated in effective theory in limit $m_t \to \infty$; Lagrangian $\mathcal{L} = -\frac{1}{4}\,\frac{H}{v}\,C_H\,G^{\mu\nu\,a}\,G^a_{\mu\nu}$
- QCD corrections significant
  - NNLO corrections still large
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - improvement with soft N^{3}LO corrections S.M., Vogt '05; Laenen, Magnea '05: in x-space '+'-distributions $\alpha_s^k \ln^{2k-1}(1-x)/(1-x)$
  - NNLL resummation Catani, de Florian, Grazzini, Nason '03; Ahrens et al. '10; [...]; Ahmed, Mahakhud, Rana, Ravindran '14
  - soft-virtual corrections completed recently: $\delta(1-x)$-term at N^{3}LO
    Anastasiou et al.'14

Perturbation theory at work



- Apparent convergence of perturbative expansion
  - improvement with soft-virtual N^{3}LO corrections (all powers of $\ln^k N$) supplemented by $\ln^k N/N$ corrections from physical kernels
    de Florian, Mazzitelli, S.M., Vogt '14
- Perturbative stability under renormalization scale variation
  - point of minimal sensitivity around $\mu = m_H/2$
  - overall theoretical uncertainty $\Delta\sigma(H)$ less than 5%

Dependence on parton distributions

- NNLO cross section $\sigma(gg \to H + X)$ at LHC with uncertainties:

$$\sigma(H) + \Delta\sigma(\text{scale}) + \Delta\sigma(\text{PDF} + \alpha_\text{s})$$

	LHC7	LHC8	LHC14
ABM11	$13.23\ ^{+1.35}_{-1.31}\ ^{+0.30}_{-0.30}$	$16.99\ ^{+1.69}_{-1.63}\ ^{+0.37}_{-0.37}$	$44.68\ ^{+4.02}_{-3.78}\ ^{+0.85}_{-0.85}$
ABM12	$13.28\ ^{+1.35}_{-1.32}\ ^{+0.31}_{-0.31}$	$17.05\ ^{+1.68}_{-1.64}\ ^{+0.39}_{-0.39}$	$44.81\ ^{+4.01}_{-3.80}\ ^{+0.94}_{-0.94}$
HiggsXSWG	$15.13\ ^{+1.07}_{-1.18}\ ^{+1.15}_{-1.07}$	$19.27\ ^{+1.39}_{-1.50}\ ^{+1.45}_{-1.33}$	$49.85\ ^{+6.08}_{-4.19}\ ^{+3.69}_{-3.09}$

- Comparison for PDF sets at NNLO
    - ABM11, ABM12 Alekhin, Blümlein, S.M. '13 and HiggsXSWG (used by ATLAS and CMS, relying on MSTW08 Martin, Stirling, Thorne, Watt '09 and with soft gluon resummation)
- Largest differences in predictions from PDFs and value of α_s
    - ABM central values significantly lower by some $11 - 14\%$
- PDF and α_s differences significantly larger than residual theory uncertainty due to incomplete N^{3}LO QCD corrections

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)
  - ...

Parton distribution fits

Global PDF fits

- PDF sets currently available
  - ABM12 Alekhin, Blümlein, S.M. ‘13
  - CT10 Gao et al. ‘13
  - HERAPDF (v1.5) H1 & ZEUS Coll. ‘11
  - JR09 Jimenez-Delgado, Reya ‘09
  - MSTW Martin, Stirling, Thorne, Watt ‘09
  - NNPDF (v3.0) Ball et al. ‘14

Iterative cycle of PDF fits

i) check of compatibility of new data set with available world data

ii) study of potential constraints due to addition of new data set to fit

iii) perform high precision measurement of the non-perturbative parameters
  - parton distributions
  - strong coupling $\alpha_s(M_Z)$
  - heavy quark masses

LHC measurements

General remarks

- QCD corrections important
  - require theory predictions to NNLO accuracy
- PDF fits with 3-flavors for DIS, 5-flavors for LHC data (matching from 3 to 5-flavors)
  - QCD evolution over large range

Benchmark processes

- Complete NNLO QCD corrections available for
  - $W^{\pm}$- and Z-boson production
    Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02
  - top-quark hadro-production Czakon, Fiedler, Mitov '13
- Jet data from Tevatron and LHC
  - QCD corrections only NLO known
  - possible impact of jet definition and algorithm
  - ongoing effort towards NNLO (corrections expected to be as big as $\mathcal{O}(15-20\%)$) Gehrmann-De Ridder, Gehrmann, Glover, Pires '13

Analysis choices

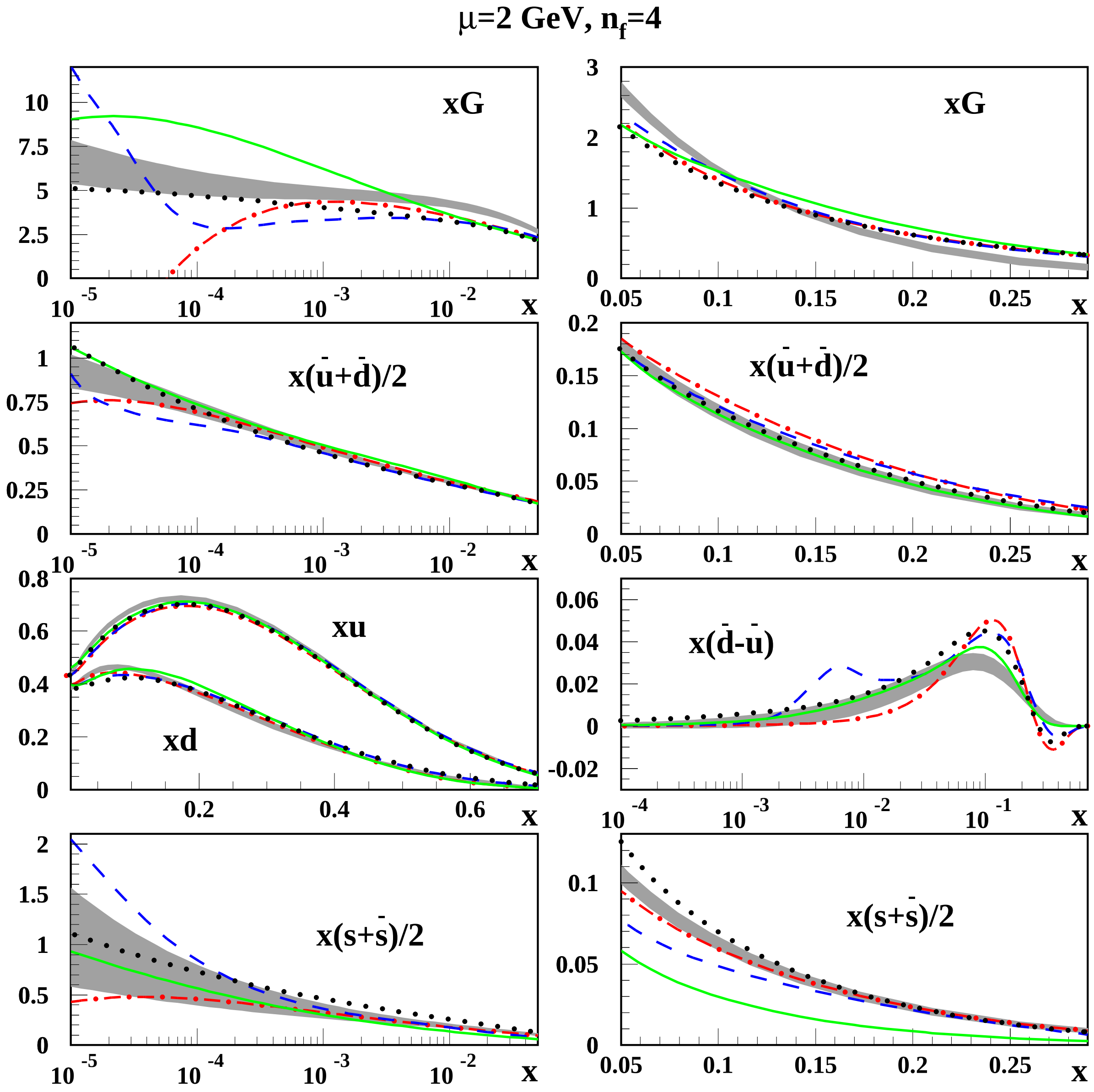
Data considered in the fit (ABM PDFs as example)

- Analysis of world data for deep-inelastic scattering and fixed-target data for Drell-Yan process
  - inclusive DIS data HERA, BCDMS, NMC, SLAC
  - semi-inclusive DIS charm production data (HERA)
  - Drell-Yan data (fixed target) E-605, E-866
  - neutrino-nucleon DIS data (di-muon production) CCFR/NuTeV
  - LHC data for $W^\pm$- and Z-boson production

Theory considerations

- Consistent theory description for consistent data sets
  - low scale DIS data with account of higher twist
- Determination of PDFs and strong coupling constant α_s to NNLO QCD
- Consistent scheme for treatment of heavy quarks
  - fixed-flavor number scheme for $n_f = 3, 4, 5$
  - $\overline{\mathrm{MS}}$-scheme for quark masses and α_s
- Full account of error correlations

Parton distributions tuned to LHC data



- 1σ band for ABM12 PDFs (NNLO, 4-flavors) at $\mu = 2$ GeV
  Alekhin, Blümlein, S.M.'13
- comparison with:
  JR09 (solid lines),
  MSTW (dashed dots),
  NN23 (dashes) and
  CT10 (dots)
- Observed differences due to differences in theory considerations and analysis procedures

Examples

- Strong coupling constant
- Quark masses
- Quark flavor separation

Strong coupling constant

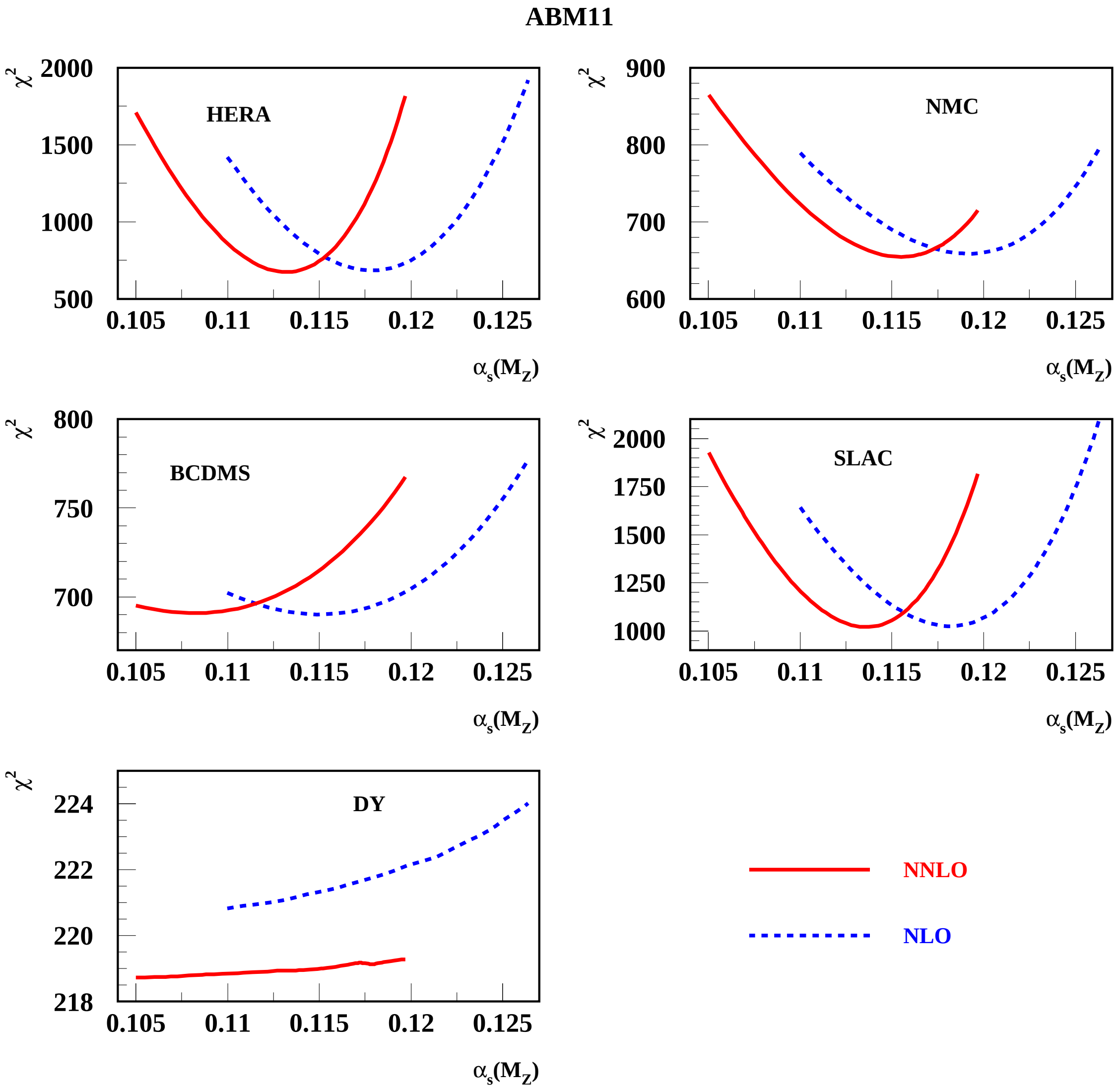
- Values of $\alpha_s(M_Z)$ at NNLO from PDF fits
  (compilation from proceedings of MITP workshop arXiv:1405.4781)

Alekhin [2001]	0.1143 ± 0.013	DIS	Alekhin '01
BBG [2004]	$0.1134\ {}^{+\ 0.0019}_{-\ 0.0021}$	valence analysis, NNLO	Blümlein, Böttcher, Guffanti '06
GRS	0.112	valence analysis, NNLO	Glück, Reya, Schuck '06
ABKM	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$	Alekhin, Blümlein, Klein, S.M. '09
JR14	0.1136 ± 0.0004	dynamical approach	Jimenez-Delgado, Reya '14
JR14	0.1162 ± 0.0006	including NLO jets	Jimenez-Delgado, Reya '14
MSTW	0.1171 ± 0.0014		Martin, Stirling, Thorne, Watt '09
Thorne	0.1136	[DIS+DY, HT*] (2014)	Thorne '14
ABM11$_J$	$0.1134 - 0.1149$ ± 0.0012	Tevatron jets (NLO) incl.	Alekhin, Blümlein, S.M. '11
ABM13	0.1133 ± 0.0011		Alekhin, Blümlein, S.M. '13
ABM13	0.1132 ± 0.0011	(without jets)	Alekhin, Blümlein, S.M. '13
CTEQ	$0.1159...0.1162$		Gao et al. '13
CTEQ	0.1140	(without jets)	Gao et al. '13
NN21	0.1174 ± 0.0007		NNPDF '11

- Values of $\alpha_s(M_Z)$ at NNLO from related measurements and lattice

e^+e^- thrust	$0.1131 \begin{array}{l} +\ 0.0028 \\ -\ 0.0022 \end{array}$	Gehrmann et al.	arXiv:1210.6945
e^+e^- thrust	0.1140 ± 0.0015	Abbate et al.	arXiv:1204.5746
CMS	0.1151 ± 0.0033	$t\bar{t}$	arXiv:1307.1907
NLO Jets ATLAS	$0.111 \begin{array}{l} +\ 0.0017 \\ -\ 0.0007 \end{array}$		arXiv:1312.5694
NLO Jets CMS	0.1148 ± 0.0055		arXiv:1312.5694
3-jet rate	0.1175 ± 0.0025	Dissertori et al. 2009	arXiv:0910.4283
Z-decay	0.1189 ± 0.0026	BCK 2008/12 (N^{3}LO)	arXiv:1201.5804
τ decay	0.1212 ± 0.0019	BCK 2008	arXiv:0801.1821
τ decay	0.1204 ± 0.0016	Pich 2011	arXiv:1110.0016
τ-decay rate	0.325 ± 0.018 (at m_τ)	FOTP:	Jamin '13
τ-decay rate	0.374 ± 0.025 (at m_τ)	CIPT:	Jamin '13
lattice	0.1205 ± 0.0010	PACS-CS 2009 (2+1 fl.)	arXiv:0906.3906
lattice	0.1184 ± 0.0006	HPQCD 2010	arXiv:1004.4285
lattice	0.1200 ± 0.0014	ETM 2012 (2+1+1 fl.)	arXiv:1201.5770
lattice	0.1156 ± 0.0022	2012 (2+1 fl.)	arXiv:1205.6155
lattice	$0.1130 \pm 0.0010(stat)$	RBC-UKQCD (prel., 2014)	UKQCD '14
world average	0.1184 ± 0.0007	(2012)	arXiv:1210.0325

α_s *from DIS and PDFs*



- Profile of χ^2 for different data sets in ABM11 PDF fit Alekhin, Blümlein, S.M. ‘12

Origin of differences in α_s values

- Inspection reveals differences in α_s values due to different physics models and analysis procedures Alekhin, Blümlein, S.M. '11
  - target mass corrections in DIS cross sections (powers of nucleon mass M_N^2/Q^2)
  - higher twist in DIS cross sections
    $F_2^{\rm ht} = F_2 + ht^{(4)}(x)/Q^2 + ht^{(6)}(x)/Q^4 + \dots$
  - error correlations among DIS data sets
- Check with variants of ABM analysis
  - no higher twist etc. reproduce larger α_s values

	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

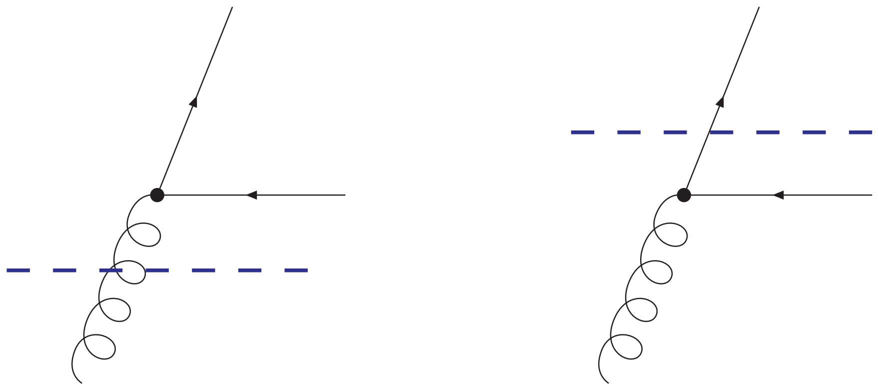
Treatment of heavy-quarks

Light quarks

- Neglect "light quark" masses $m_u, m_d \ll \Lambda_{QCD}$ and $m_s < \Lambda_{QCD}$ in hard scattering process
  - scale-dependent u, d, s, g PDFs from mass singularities

Heavy quarks

- No mass singularities for $m_c, m_b, m_t \gg \Lambda_{QCD}$, no (evolving) PDFs
  - c and b PDFs for $Q \ggg m_c, m_b$ generated perturbatively
  - matching of two distinct theories
    $\longrightarrow n_f$ light flavors + heavy quark of mass m at low scales
    $\longrightarrow n_f + 1$ light flavors at high scales



Effective theory for heavy-quarks

Example: Charm structure function

- F_2^c at HERA (assume no "intrinsic charm")
  - $Q \not\gg m_c$: Fixed flavor-number scheme FFNS
    u, d, s, g partons and massive charm coeff. fcts.
  - $Q \ggg m_c$: Zero-mass variable flavor-number scheme ZM-VFNS
    terms $m_c/Q \to 0$, $n_f = 4$ PDFs (matching), $m_c = 0$ coeff. fcts.
  - $Q \gg m_c$: General-mass variable flavor-number scheme GM-VFNS
    terms $m_c/Q \neq 0$, but quasi-collinear logs $\ln(Q/m_c)$ large
    $n_f = 4$ PDFs, "interpolating" coeff. fcts. (matching prescriptions)

FFNS

- Perturbative QCD predictions for F_2^c and F_L^c (neutral current)
  - complete NLO predictions Laenen, Riemersma, Smith, van Neerven '92
  - approximate expressions to NNLO
    Laenen, S.M. '98; Alekhin, S.M. '08; Lo Presti, Kawamura, S.M., Vogt '10
  - asymptotic NNLO terms at large $Q^2 \gg m^2$ Bierenbaum, Blümlein, Klein '09; Behring, Bierenbaum, Blümlein, De Freitas, Klein, Wissbrock '14

VFNS

- Variable flavor number schemes $\longrightarrow$ matching of two distinct theories
  Aivazis, Collins, Olness, Tung '94; Thorne, Roberts '98;
  Buza, Matiounine, Smith, van Neerven '98
  $\longrightarrow$ n_f light flavors + heavy quark of mass m at low scales
  $\longrightarrow$ $n_f + 1$ light flavors at high scales
- Important aspects of variable flavor number schemes
  - mass factorization to be carried out before resummation
    $\longrightarrow$ mass factorization involves both heavy and light component of structure function
  - matching conditions required through NNLO
    Chuvakin, Smith, van Neerven '00
- Details of implementation matter in global fits

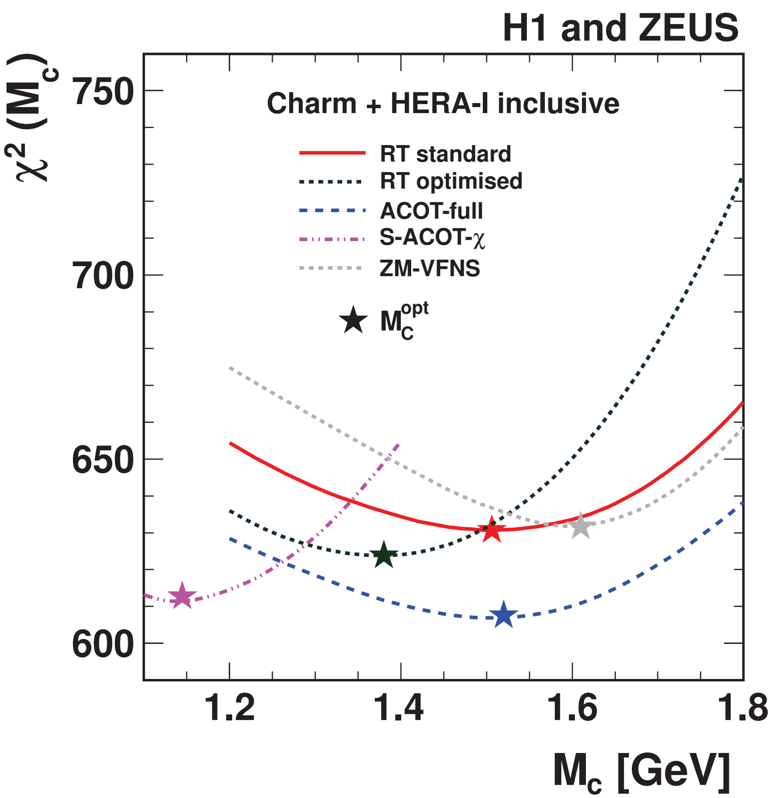
Heavy quark mass

- Data on F_2^c at HERA has correlation of m_c, $\alpha_S(M_Z)$, gluon PDF

  $\sigma_{c\bar{c}} \sim \alpha_s \, m_c^2 \, g(x)$

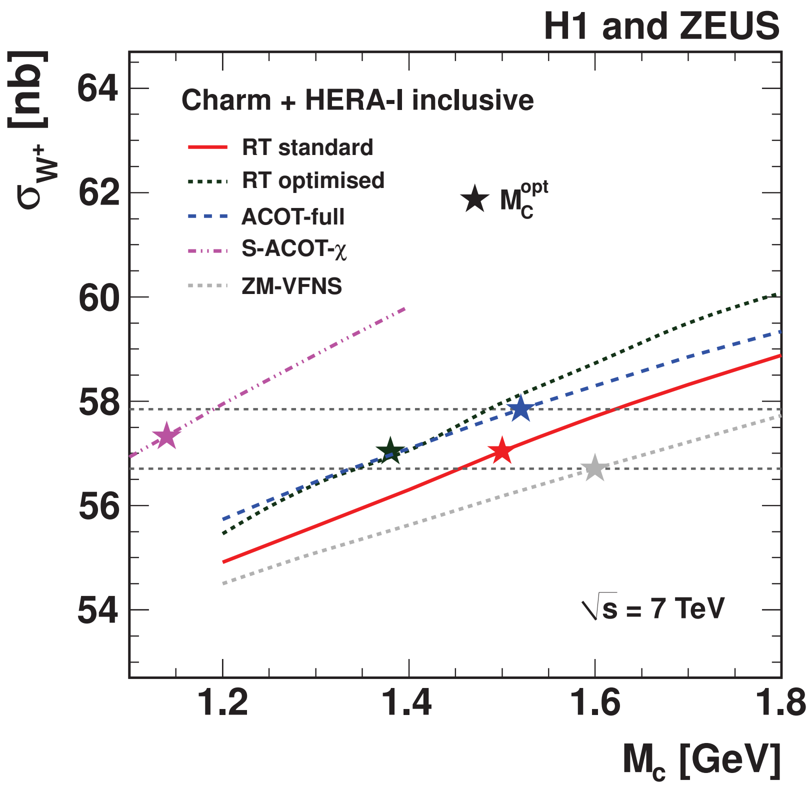
- Comparison of measured data with predictions in various VFNS schemes
  - data shows very good sensitivity to value of m_c
  - fit of value of m_c strongly dependent on particular choice of VFNS

    H1 coll. arxiv:1211.1182



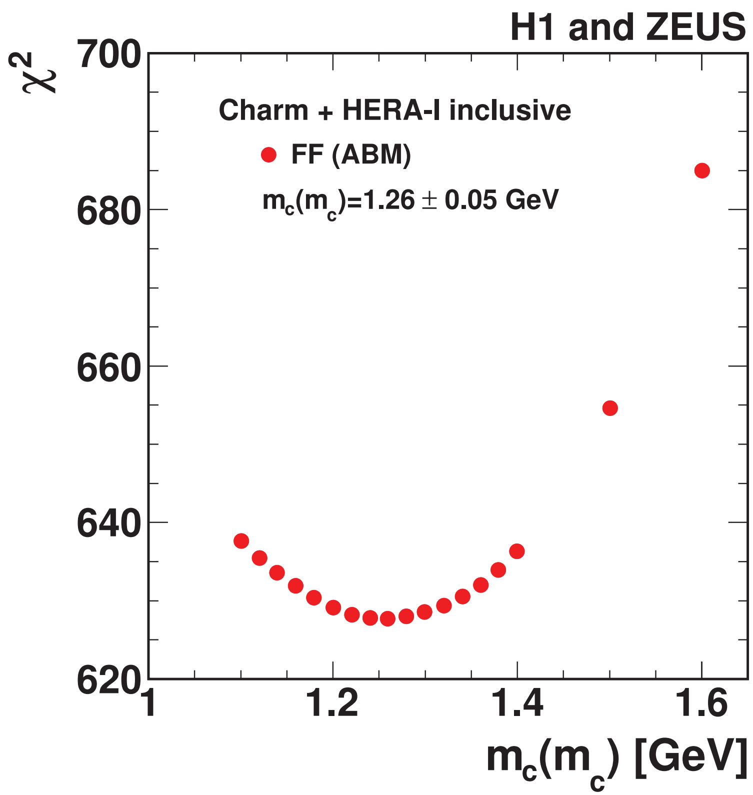
Heavy quark mass

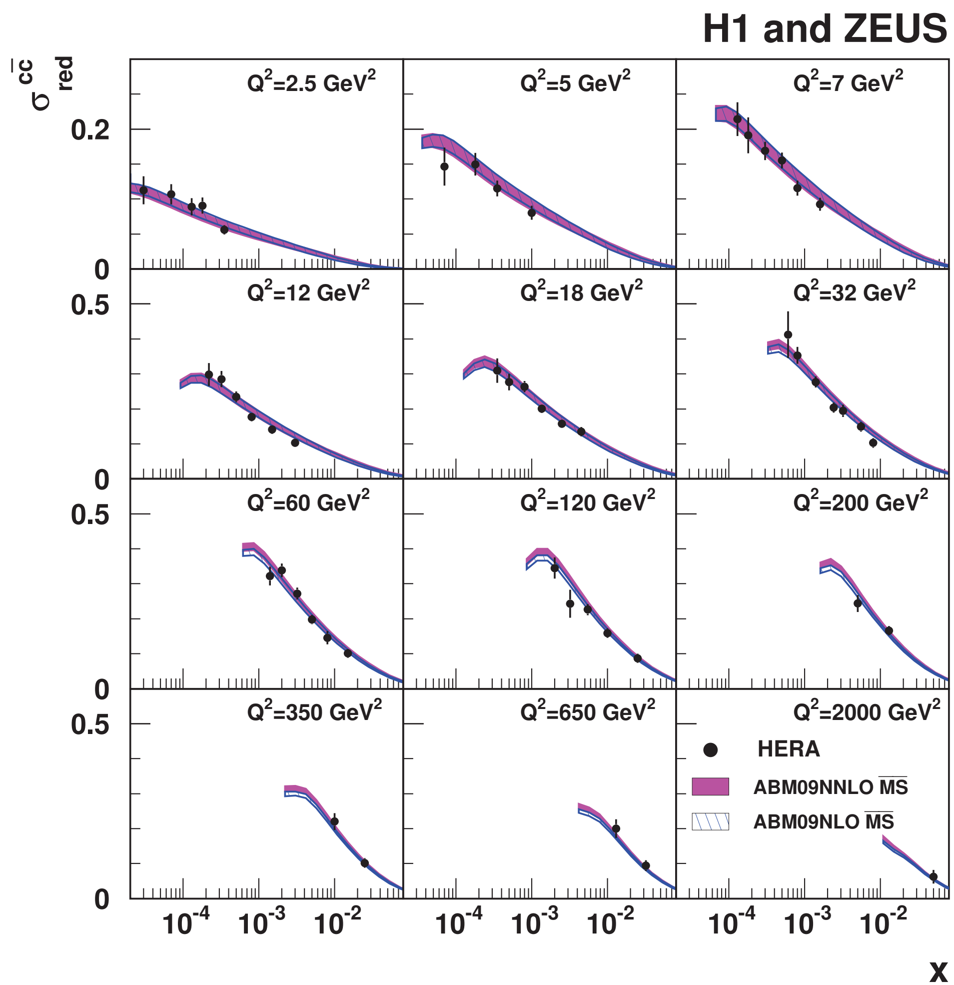
- Significant impact on cross section predictions at LHC
  - e.g., W^+-production



Running charm quark mass in $\overline{MS}$-scheme

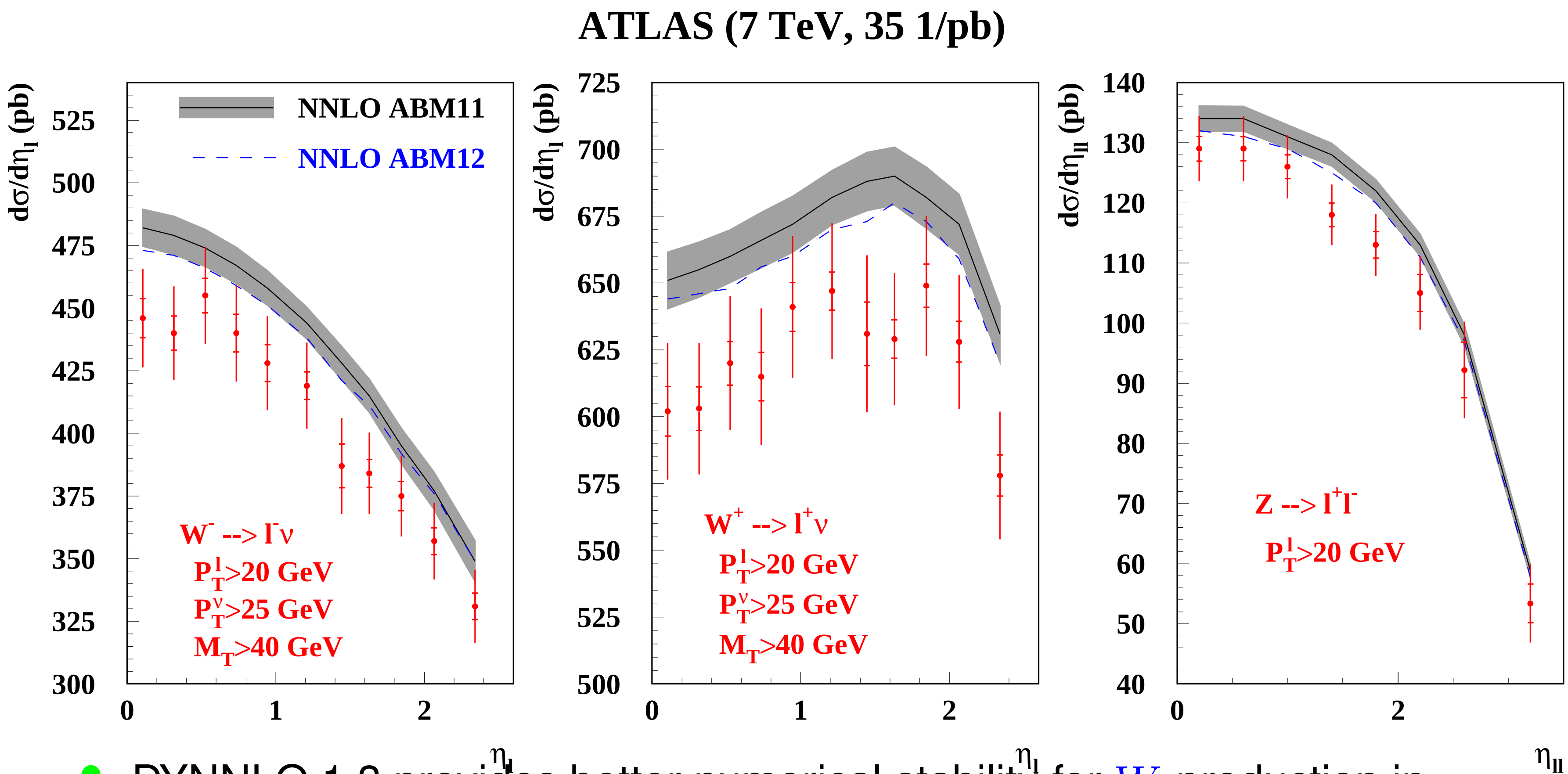
- Determination of $\overline{\mathrm{MS}}$-mass $m_c(m_c)$ in DIS H1 coll. arxiv:1211.1182
- Very good description of data; cf. PDG values:
  charm: $m_c(m_c) = 1.27^{+0.07}_{-0.11}$ GeV, bottom: $m_b(m_b) = 4.20^{+0.17}_{-0.07}$ GeV





Quark flavour constraints from LHC data

Fit to LHC Drell-Yan data Alekhin, Bümlein, S.M. '13



- DYNNLO 1.3 provides better numerical stability for W-production in central region ($\sim$ 200h) Catani, Cieri, Ferrera, de Florian, Grazzini '09
- FEWZ 3.1 more convenient/stable for estimation of PDF uncertainties ($\sim$ 2d x 24 processors) Li, Petriello '12
- Central values computed with DYNNLO and the PDF errors with FEWZ

ABM PDFs with LHC data

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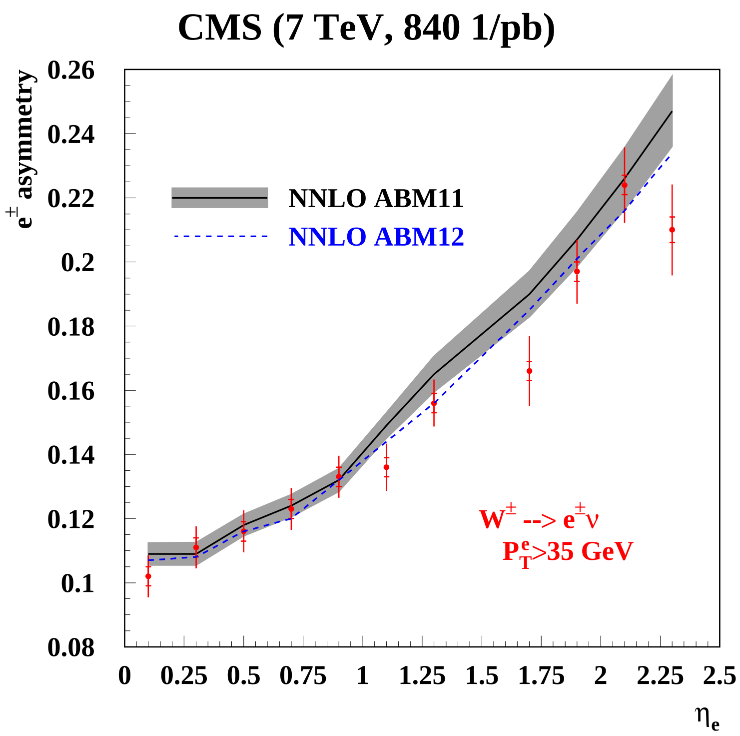

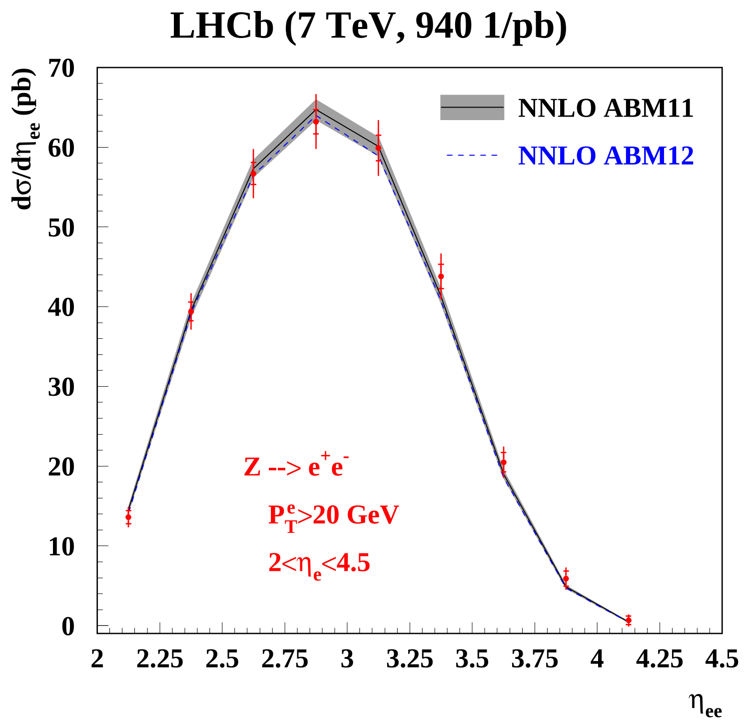

- Good overall agreement with data of CMS '10 and LHCb '12, '13

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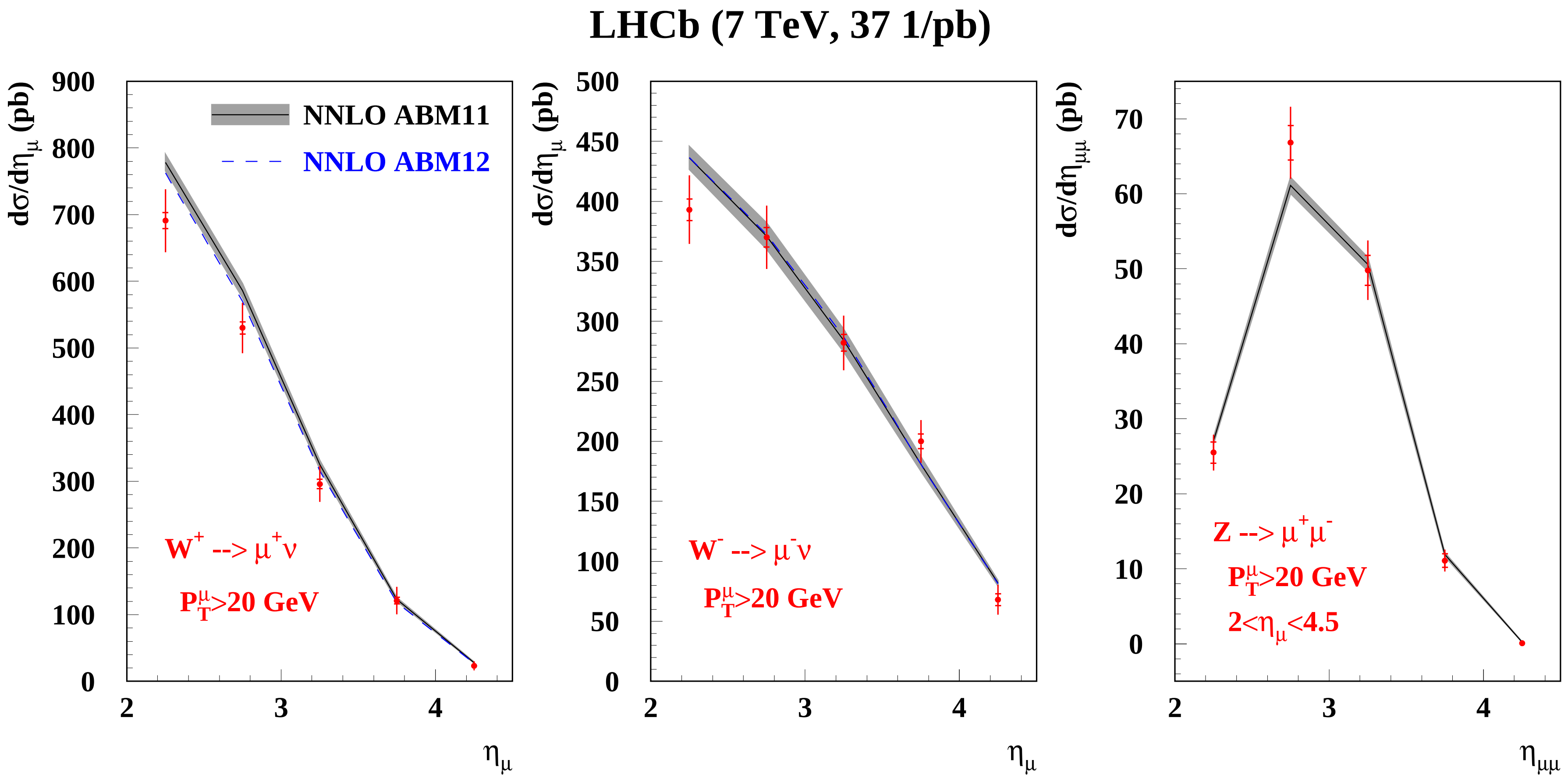


- Good overall agreement with data of CMS ‘10 and LHCb ‘12, ‘13

Benchmarking of ABM PDFs

Experiment	ATLAS '11	CMS '12	LHCb '12	LHCb '12
Final states	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$Z \to e^+e^-$
Luminosity (1/pb)	35	840	37	940
NDP	30	11	10	9
χ^2 (ABM11)	35.7(7.7)	10.6(4.7)	13.1(4.5)	11.3(4.2)
χ^2 (ABM12)	35.6	9.3	14.4	13.4

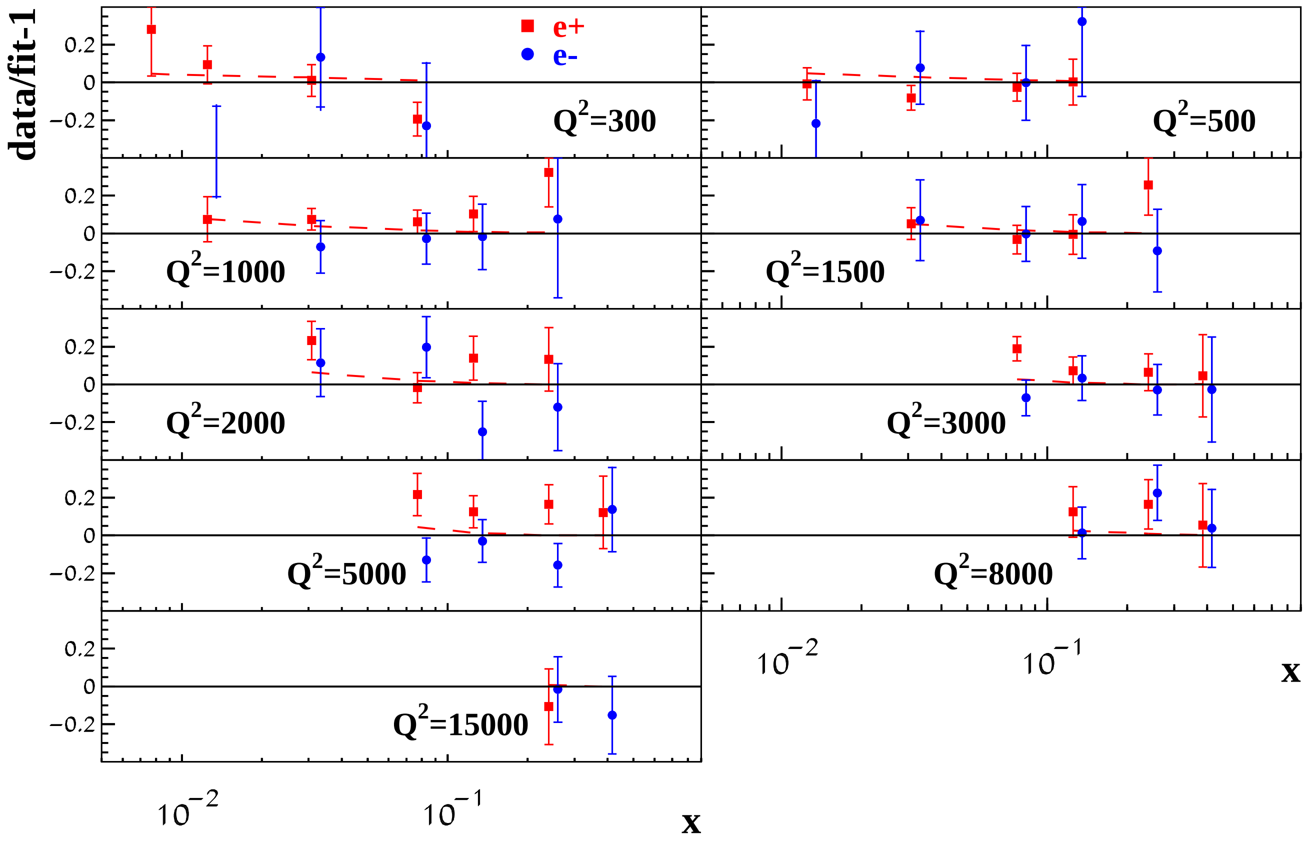
- value of χ^2 for Drell-Yan data at the LHC with NNLO ABM11 PDFs (+ 1σ standard deviation of χ^2 equal to $\sqrt{2NDP}$)
- Caution: If benchmarking, make sure to get it right
  - Wrong χ^2 values for PDF comparison to ABM11 (NLO theory with MCFM and K-factors, no PDF errors, shifted α_s) reported in arXiv:1211.5142 (Ball, Carrazza, Del Debbio, Forte, Gao, Hartland, Huston, Nadolsky, Rojo, Stump, Thorne, Yuan)

Strange sea determination

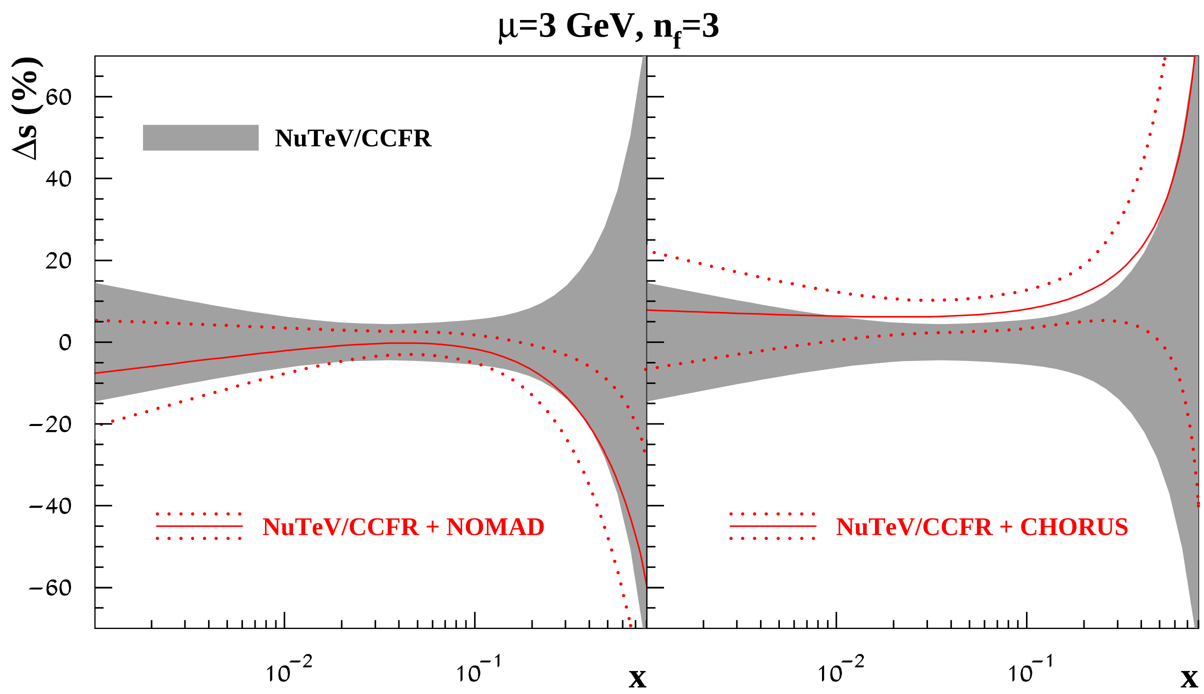
Charged current DIS

Alekhin, Bümlein, Caminada, Lipka, Lohwasser, S.M. Petti, Placakyte '14

- CC DIS inclusive data (HERA), CC DIS di-muon production data (NOMAD) and CC DIS charmed-hadron production data (CHORUS)
- Theory description with exact NLO QCD corrections and asymptotic NNLO terms at large $Q^2 \gg m^2$ Buza van Neerven '97



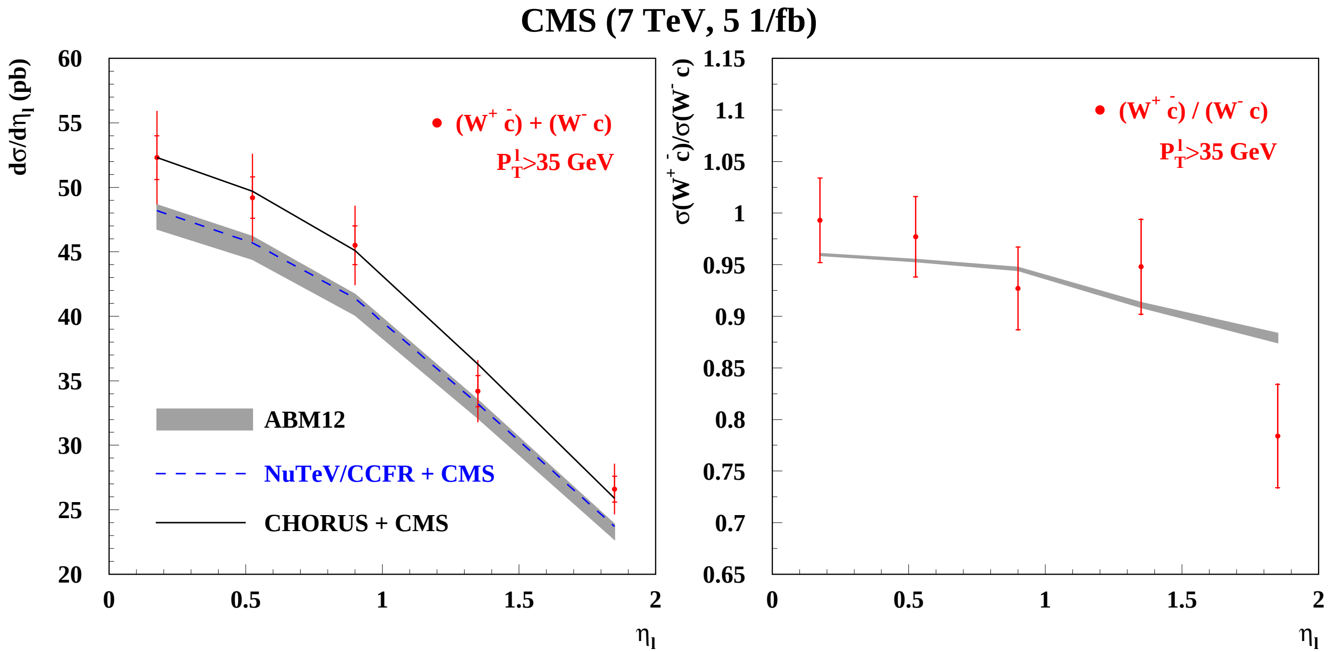
Strange sea from new fixed target data



- Nomad data on ratio of di-muon sample to incl. CC DIS with statistics of 15000 events (much more than CCFR and NuTeV samples)
  - systematics, nuclear corrections, etc. cancel in ratio
  - pull down strange quarks at $x > 0.1$; sizable reduction of uncertainty
  - $m_c(m_c) = 1.23 \pm 0.03(\text{exp.})\text{GeV}$
- Chorus data pull strangeness up
  - statistical significance the effect is poor

W+charm production at LHC

- Cross check with LHC data for W+charm production

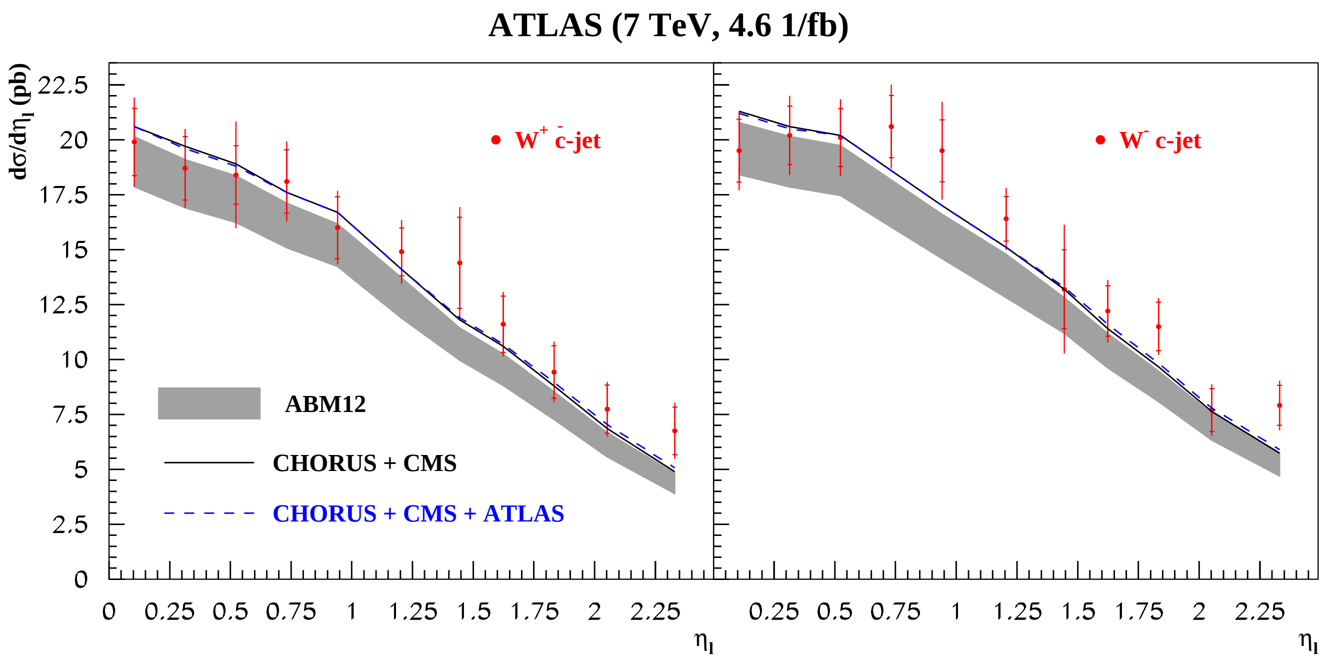


CMS

- CMS data above NuTeV/CCFR by 1σ
- Charge asymmetry in a good agreement with charge-symmetric strange sea

W +charm production at LHC

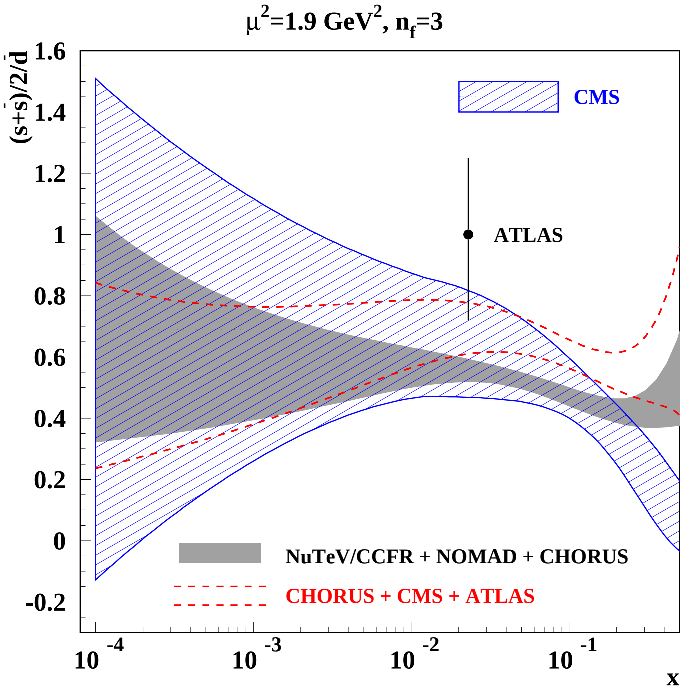
- Cross check with LHC data for W+charm production

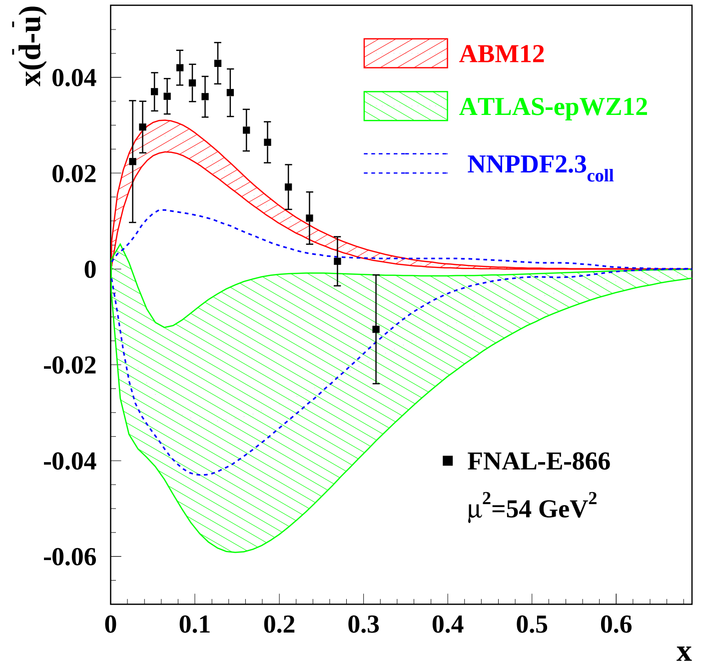


ATLAS

- ATLAS data in good agreement with NuTeV/CCFR
- Highest bin in η_l deviates

Comparision with earlier determinations





- ABM update (NuTeV/CCFR+NOMAD+CHORUS) in good agreement with CMS results
- ATLAS strange-sea in enhanced, but correlated with $\bar{d}$-quark sea suppression (disagreement with the FNAL-E-866 data)
- Upper margin of ABM analysis (CHORUS+CMS+ATLAS) is lower than ATLAS

Summary

Parton distributions at the LHC

- Precision determinations of non-perturbative parameters is essential
  - parton content of proton (PDFs)
  - coupling constants $\alpha_s(M_Z)$
  - masses m_c, m_b, m_t, M_W, m_H, ...

Precision PDFs

- Precision measurements require careful definition of observable
  - experimental precision makes NNLO in QCD mandatory
  - global analyses sensitive to theory description of cross section and to analysis procedures $\longrightarrow$ main source of discrepancy
- Confronting LHC data requires continuous benchmarking