Parton distributions from LHC data and implications for single top-quark production

Sven-Olaf Moch

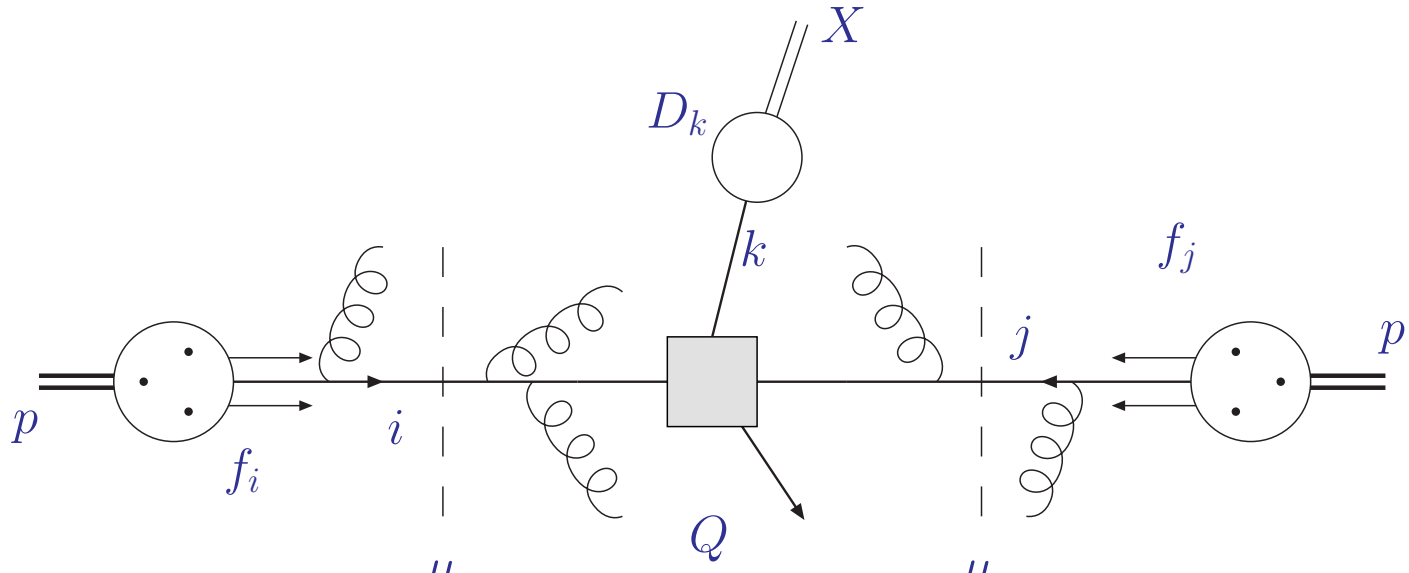
Universität Hamburg

Matter To The Deepest: Recent Developments In Physics of Fundamental Interactions Ustron, Sep 14, 2015

Work done in collaboration with:

- *Iso-spin asymmetry of quark distributions and implications for single top-quark production at the LHC*
  S. Alekhin, J. Blümlein, S. M. and R. Plačakytė arXiv:1508.07923

QCD factorization

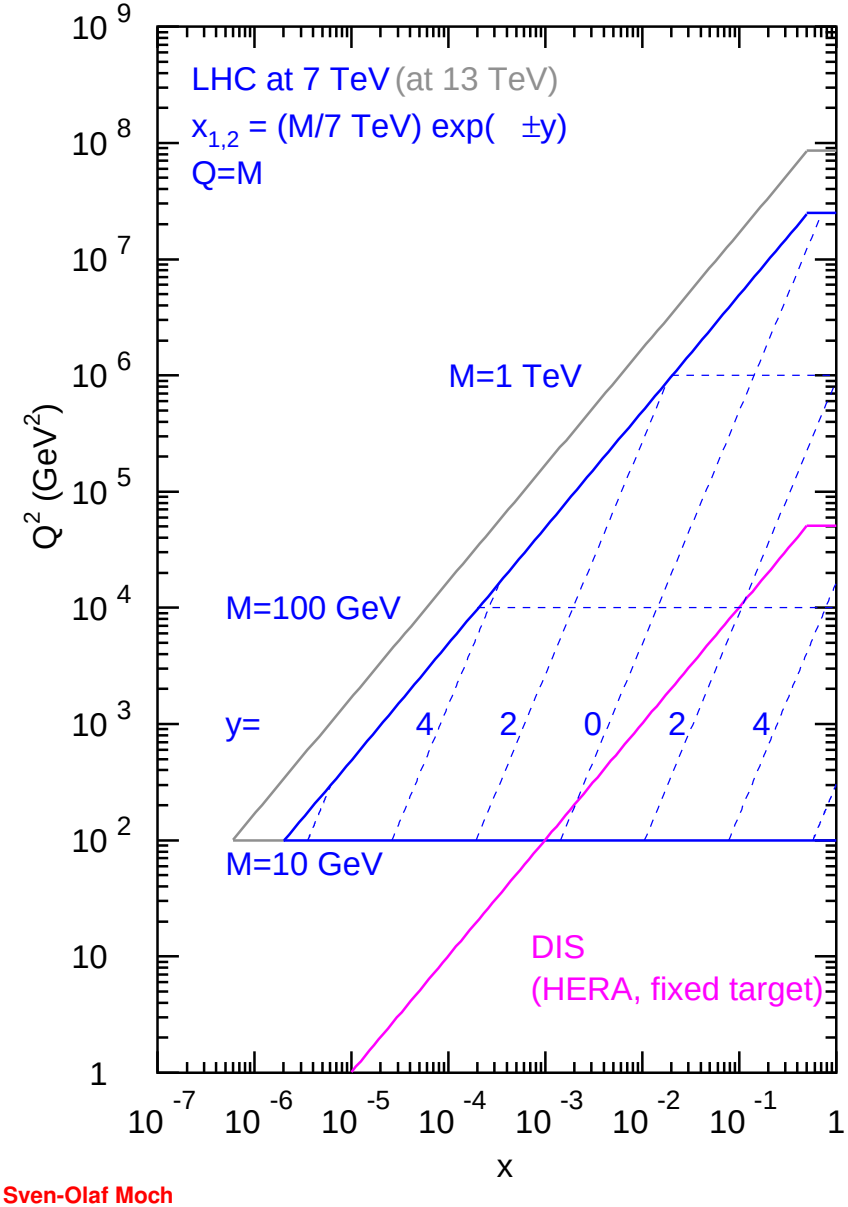


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Factorization at scale μ
  - separation of sensitivity to dynamics from long and short distances
- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- 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 kinematics at LHC

- Information on proton structure depends on kinematic coverage



- LHC run at $\sqrt{s}$ = 7/8 TeV
  - parton kinematics well covered by HERA and fixed target experiments
- Parton kinematics with $x_{1,2} = M/\sqrt{S}\mathrm{e}^{\pm y}$
  - forward rapidities sensitive to small-x
- Cross section depends on convolution of parton distributions
  - small-x part of f_i and large-x PDFs f_j

$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \left[\dots\right]$$

Parton distribution fits

Global PDF fits

- PDF sets currently available
  - ABM12 Alekhin, Blümlein, S.M. ‘13
  - CT14 Dulat et al. ‘15
  - MMHT Martin, Motylinski, Harland-Lang, Thorne ‘15
    (previously: MSTW Martin, Stirling, Thorne, Watt ‘09)
  - NNPDF (NN3.0) 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

ABM PDFs

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 $(NDP = 2699)$
  - semi-inclusive DIS charm production data HERA $(NDP = 52)$
  - Drell-Yan data (fixed target) E-605, E-866 $(NDP = 158)$
  - neutrino-nucleon DIS (di-muon data) CCFR/NuTeV $(NDP = 178)$
  - LHC data for $W^{\pm}$- and Z-boson production ATLAS, CMS, LHCb $(NDP = 60)$

Theory considerations

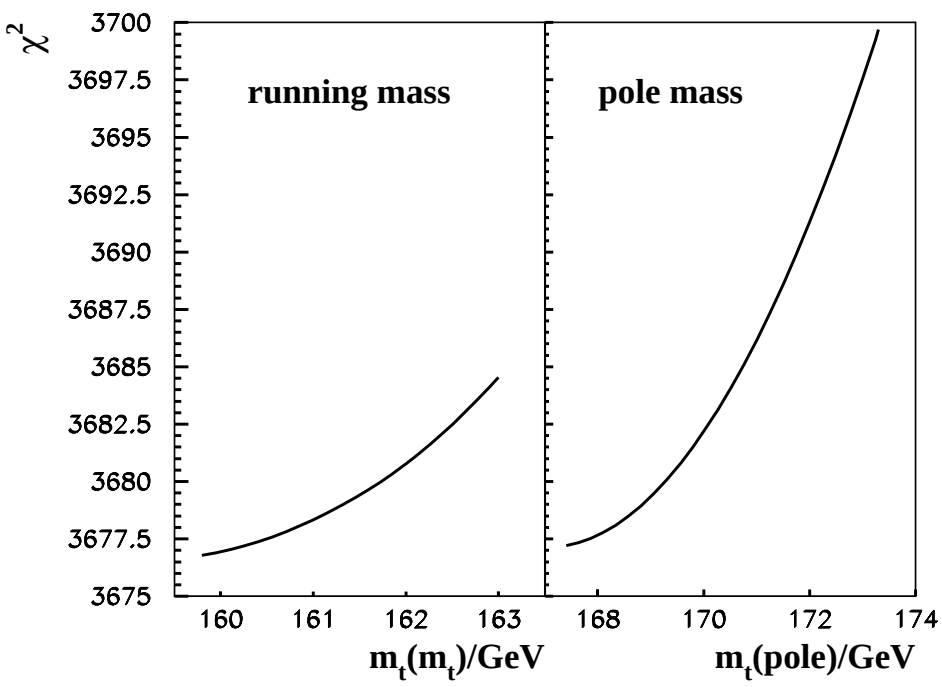
- Consistent theory description for consistent data sets
  - low scale DIS data with account of higher twist
- Determination of PDFs and strong coupling constant α_s to NNLO QCD
- Consistent scheme for treatment of heavy quarks
  - fixed-flavor number scheme for $n_f = 3, 4, 5$
  - $\overline{\rm MS}$-scheme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

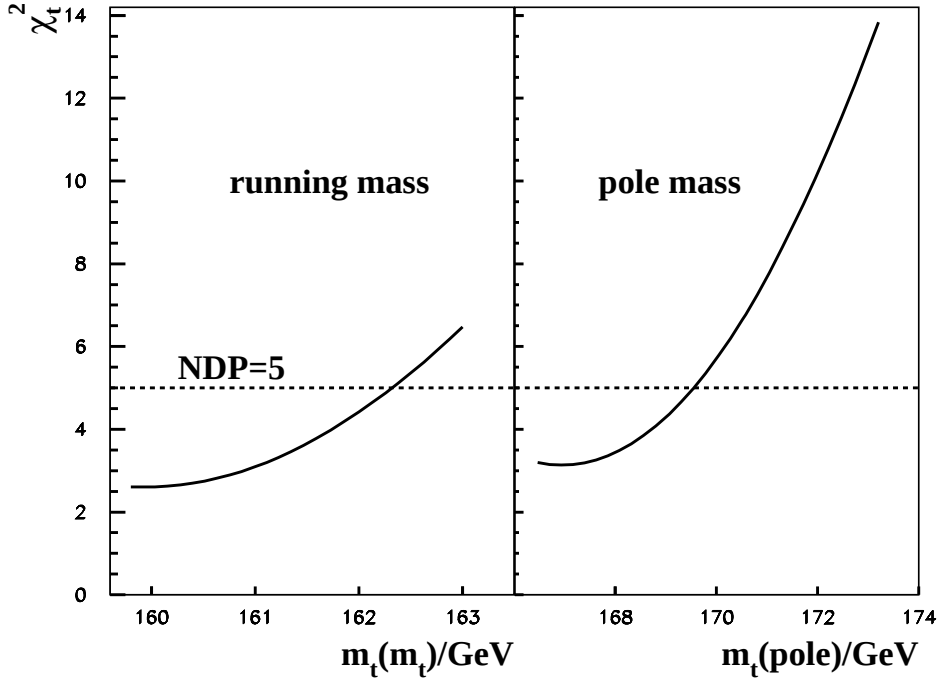
Benchmark measurements at LHC

- Complete NNLO QCD corrections available for
  - $W^{\pm}$- and Z-boson production
    Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02
  - hadro-production of top-quark pairs Czakon, Fiedler, Mitov '13
  - single top-quark production (t-channel) Brucherseifer, Caola, Melnikov '14

Top-quark pair production

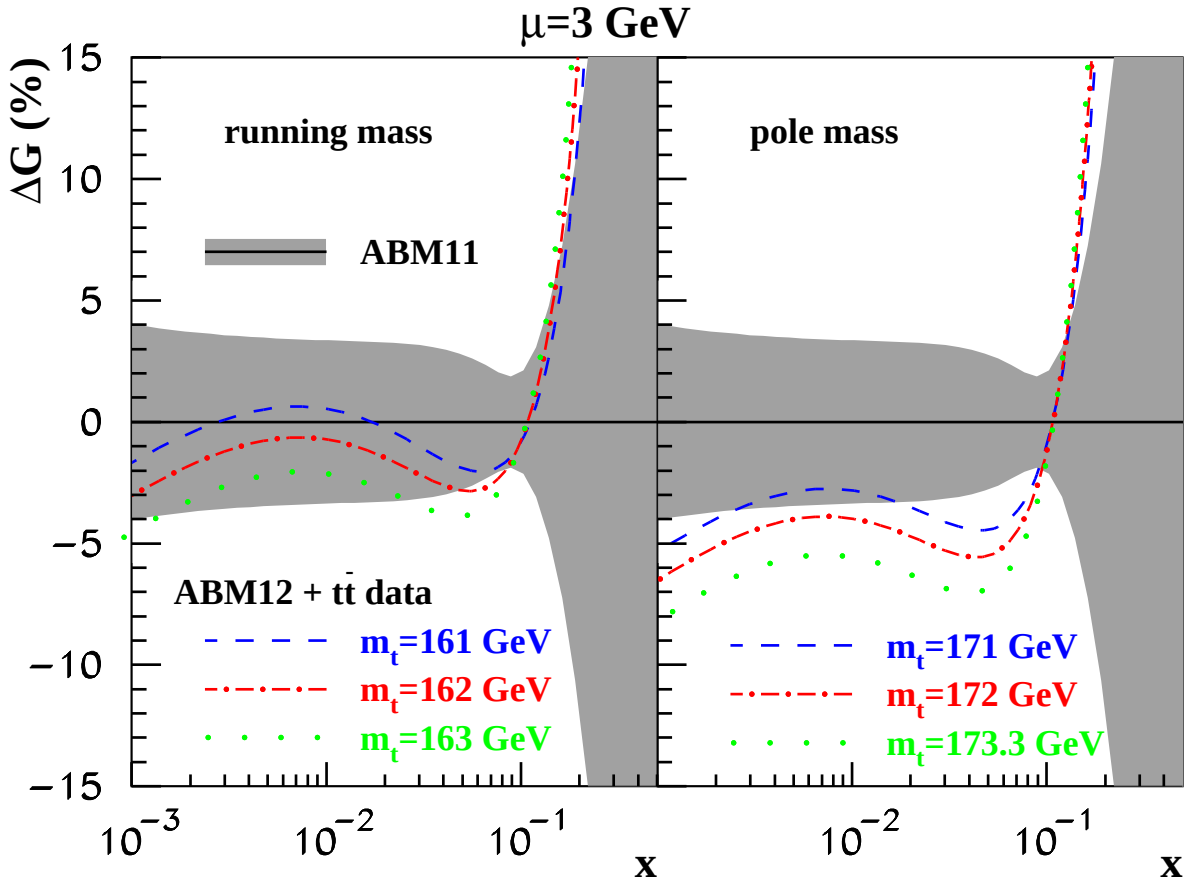
- Cross section at LHC has correlation of m_t, $\alpha_S(M_Z)$ and gluon PDF
  $\sigma_{t\bar{t}} \sim \alpha_s^2 \, m_t^2 \, g(x) \otimes g(x)$
  - $g(x)$ and $\alpha_s(M_Z)$ already well constrained by global fit (no changes)
  - fit of top-quark mass $m_t(m_t) = 162.3 \pm 2.3$ GeV (equivalent to pole mass $m_t = 171.2 \pm 2.4$ GeV) with $\chi^2/NDP = 5/5$
  - χ^2-profile steeper for pole mass (bigger impact of top-quark data and greater sensitivity to theoretical uncertainty at NNLO)





Constraints from top-quark data

- Correlation of of gluon PDF with value of m_t is essential
  - fit with PDF re-weighting and fixed values of m_t insufficient
    Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan '12
  - fit with fixed values of m_t and $\alpha_S(M_Z)$ carries significant bias and shifts in gluon PDF Czakon, Mangano, Mitov, Rojo '13



$W^{\pm}$- and Z-boson production

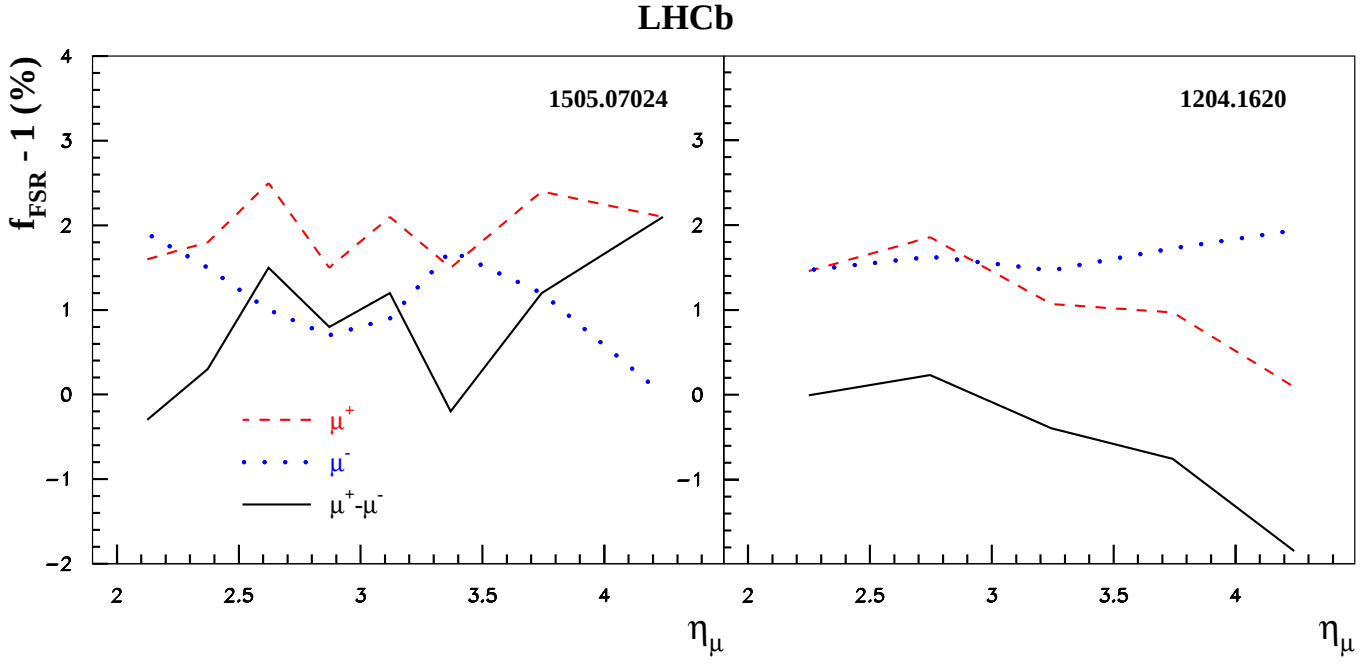
- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - statistically significant $NDP = 112$
  - differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$

Experiment	ATLAS	CMS	D0		LHCb	
$\sqrt{s}$ (TeV)	7	7	1.96		7	8
Final states	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$
Reference	1109.5141	1312.6283	1309.2591	1412.2862	1505.07024	1503.00963
Cut on the lepton P_T	$P_T^l > 20$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 20$ GeV
Luminosity (1/fb)	0.035	4.7	7.3	9.7	1.	2.
NDP	30	11	10	13	31	17

Theory issues (I)

Final-state-radiation effects

- QED corrections in $W^{\pm}$- and Z-boson decays applied to data of LHCb
  - left: FSR effects from mean of simulations with Herwig++ and Pythia8 with anomalous irregularity at $\eta_\mu = 3.375$
  - right: earlier analysis of LHCb with smooth FSR corrections from PHOTOS Monte Carlo Golonka, Was '05

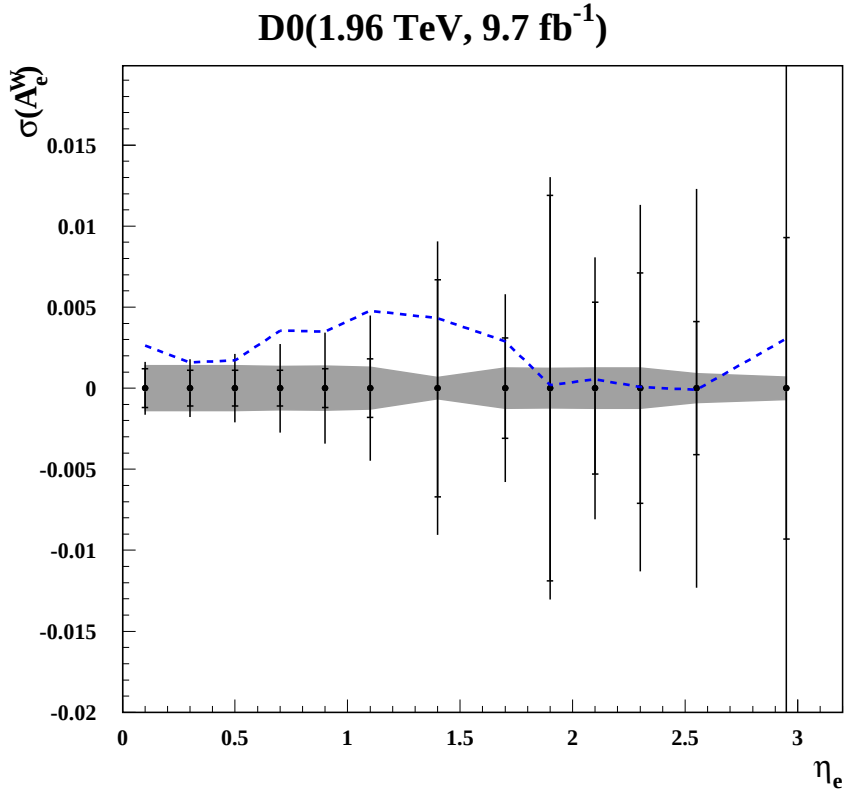


- Dropping problematic data points at $\eta_\mu = 3.375$ reduces χ^2 value by some 10 units

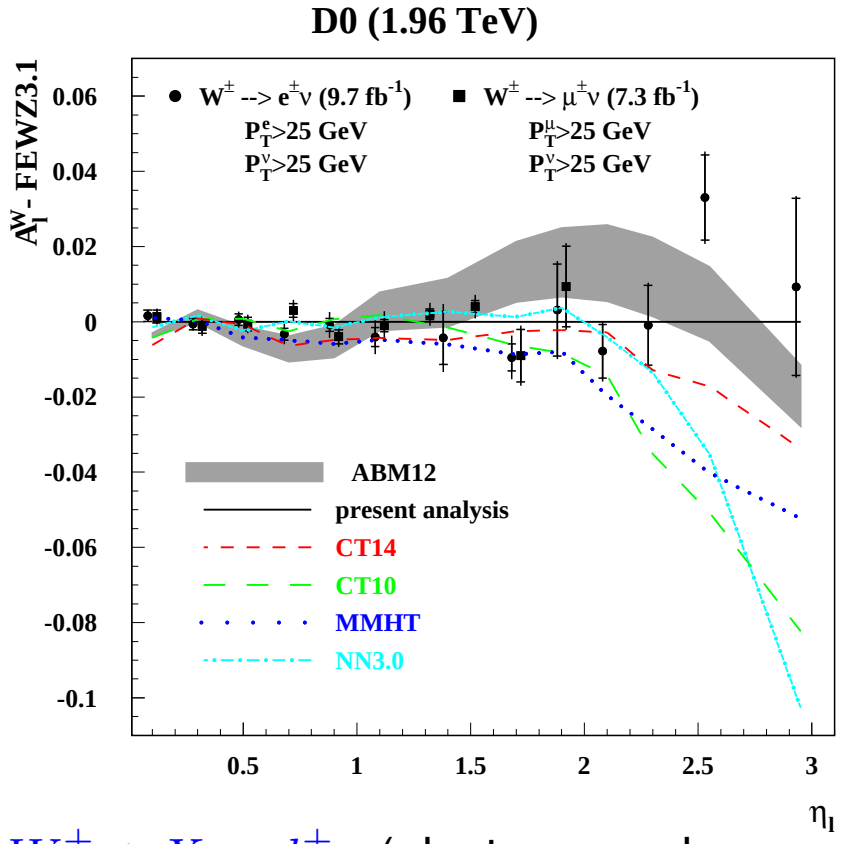
Theory issues (II)

NNLO QCD corrections

- Precision of experimental uncertainties challenges accuracy of numerical integration in QCD NNLO predictions
  - data on electron asymmetry with high precision at central rapidities D0
  - numerical accuracy of NNLO grids (shaded area) obtained with FEWZ
  - NNLO corrections in coefficient functions not uniform in η_e (dashed curve)

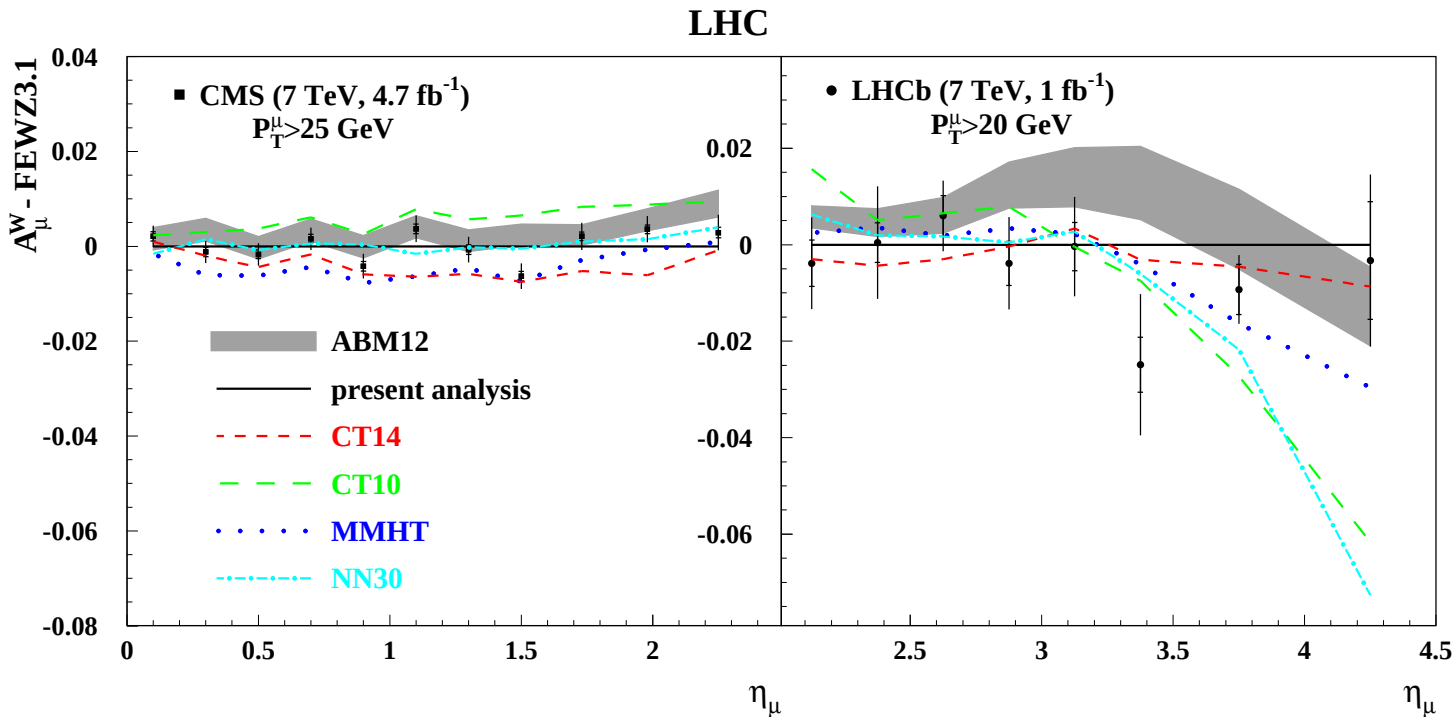


Tevatron charged lepton asymmetry



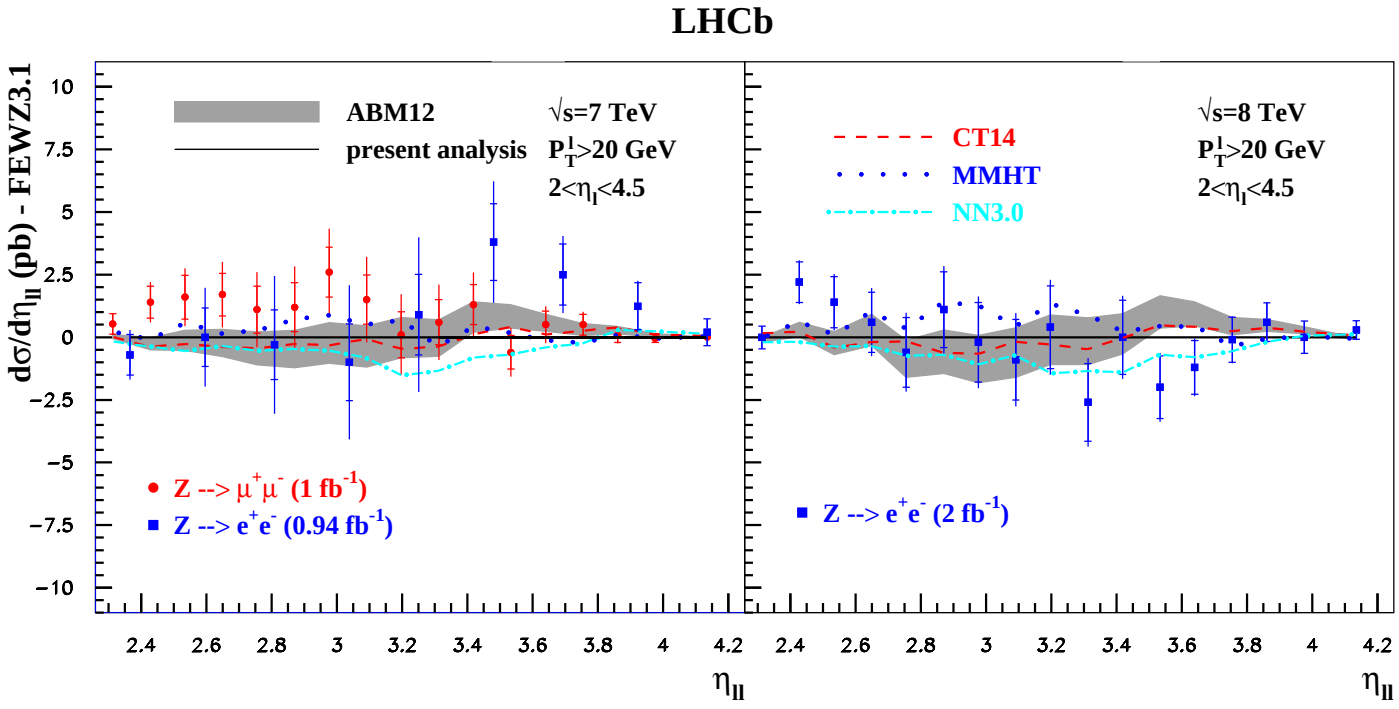
- D0 data for $p\bar{p} \to W^\pm + X \to l^\pm\nu$ (electrons and muons) at $\sqrt{s} = 1.96$ TeV
- Charged lepton asymmetry as function of pseudo-lepton rapidity η_l
- NNLO QCD predictions with FEWZ (version 3.1)
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT10, CT14, MMHT, and NN3.0

Muon charge asymmetry from LHC



- CMS and LHCb data for $pp \to W^{\pm} + X \to \mu^{\pm}\nu$ at $\sqrt{s} = 7$ TeV
- Problematic data points at $\eta_\mu = 3.375$ in LHCb data are omitted in fit

Z-boson production from LHC



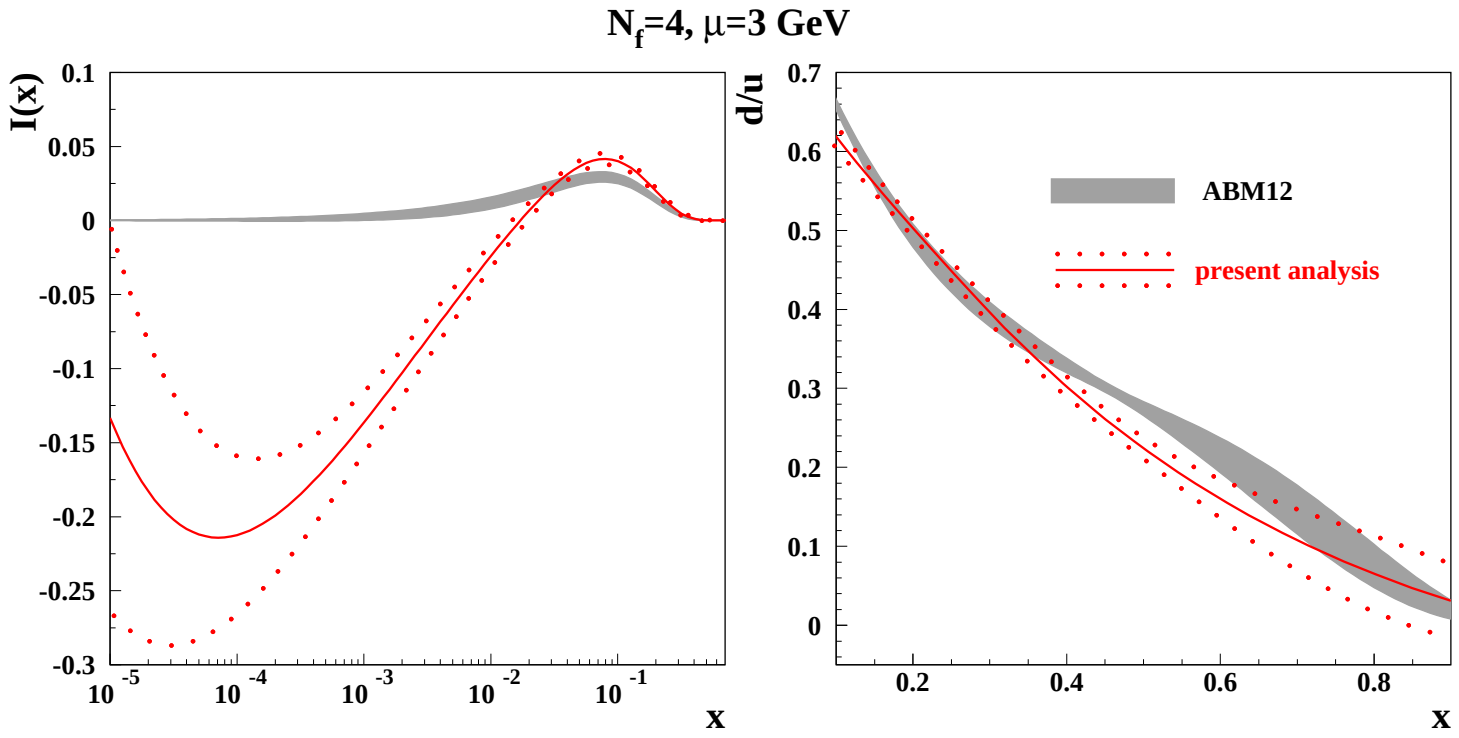
- LHCb data for $pp \to Z + X \to l\bar{l}$ (muon and electron) at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT14, MMHT, and NN3.0

Fit quality

Experiment		ATLAS	CMS	D0		LHCb	
$\sqrt{s}$ (TeV)		7	7	1.96		7	8
Final states		$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$
Reference		1109.5141	1312.6283	1309.2591	1412.2862	1505.07024	1503.00963
NDP		30	11	10	13	31	17
χ^2	this work	29.8	22.5	16.9	18.0	44.1	18.2
	this work[a]	32.3	19.5(13.5[b])	13.5	9.5	34.7	19.1
	ABM12	34.5	–	–	–	–	–
	CT14	–[c]	–[d]	–	34.7	–	–
	HERAFitter	–	–	13	19	–	–
	MMHT14	39	–	21	–	–	–
	NN3.0	35.4	18.9	–	–	–	–

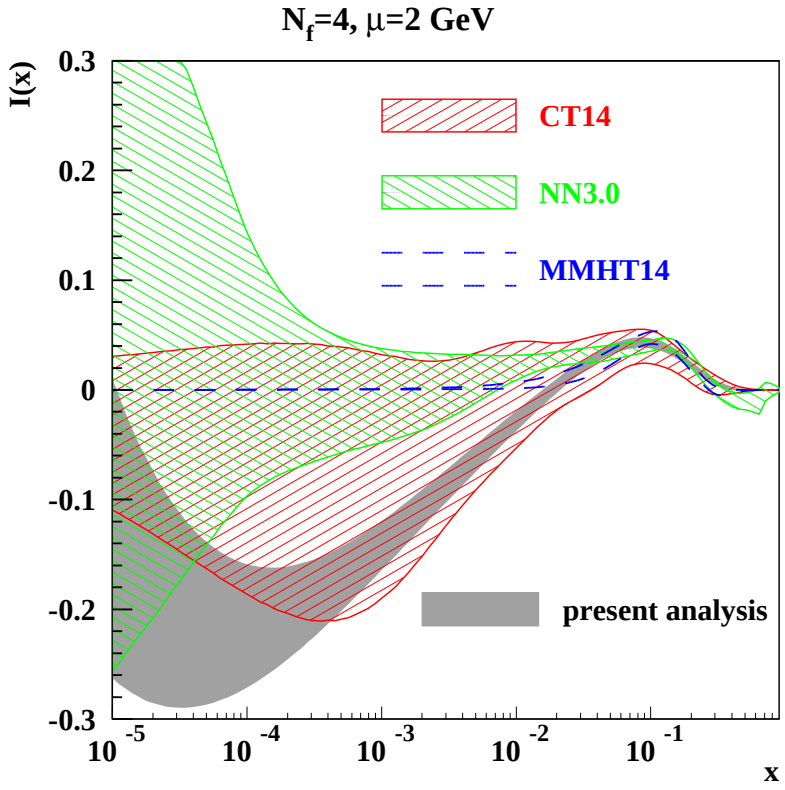
[a] Variants with all collider DY and $W^\pm$-boson data excluded except the one given.
[b] Value obtained assuming systematic uncertainties to be uncorrelated.
[c] ATLAS data on $W^\pm$- and Z-boson production cross sections are used in combination the lepton charge asymmetry data. The value of $\chi^2/NDP = 51/41 = 1.25$ is obtained for this sample.
[d] Statistically less significant data with the cut of $P_T^\mu > 35$ GeV are used.

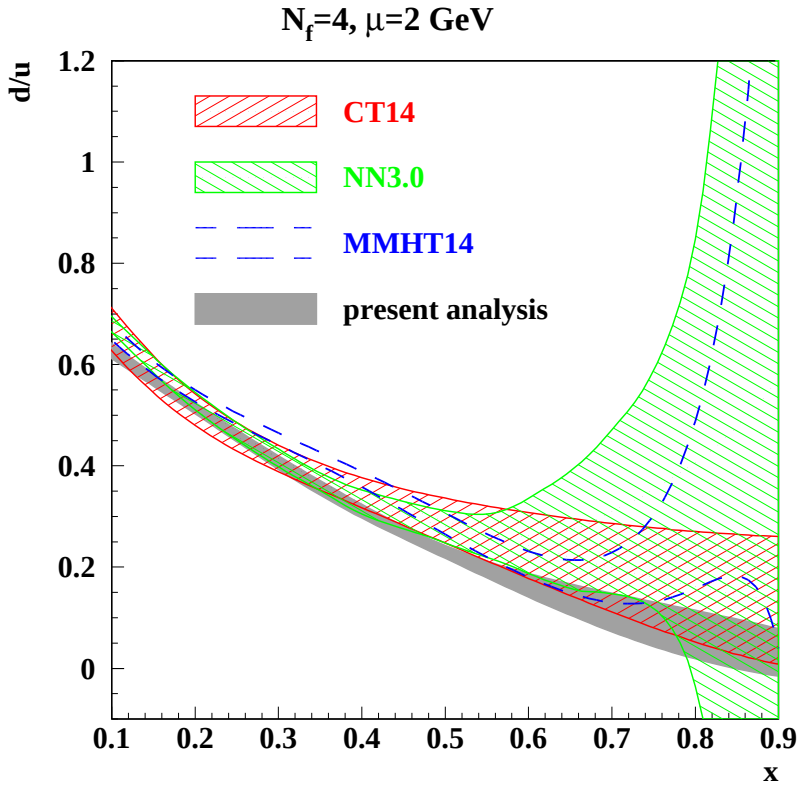
Light flavor PDFs



- Light flavor decomposition not well constrained in DIS data
  - ratio d/u at large x from fixed target Drell-Yan data E-605, E-866 at the price of modelling nuclear corrections
- Iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
  - Regge theory arguments for small x predict $I(x) \simeq 0$
  - $I(x)$ at small x constrained by new Tevatron and LHC data
- Upshot: non-vanishing $I(x)$ at small $x \simeq 10^{-4}$

Comparision with other PDFs

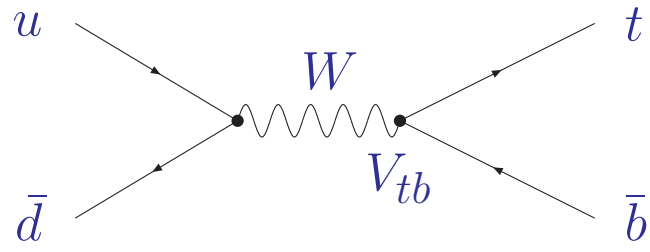




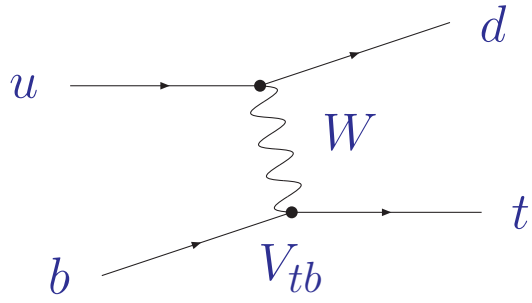
- Iso-spin asymmetry of sea $I(x)$ at small x and ratio d/u at large x with 1σ uncertainty band
- Comparison with CT14, MMHT14, NN3.0
  - CT14 finds non-vanishing $I(x)$ from fit to Tevatron charged lepton asymmetry (D0 data), but with large uncertainties

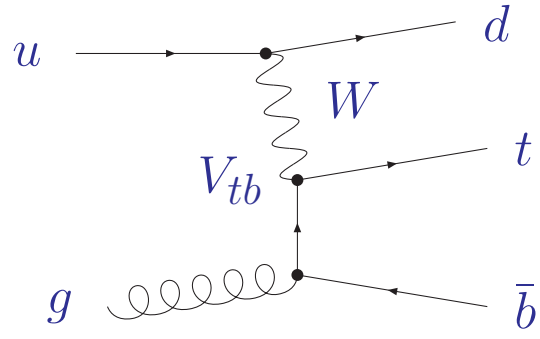
Single top-quark production

- Study of charged-current weak interaction of top quark
- s-channel production

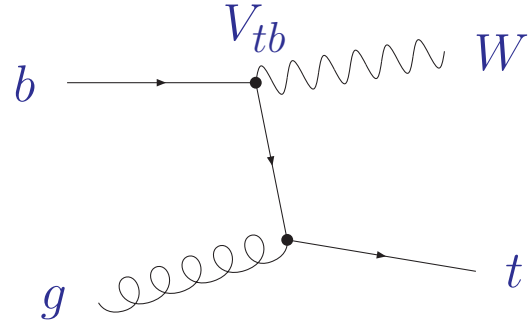


- t-channel production
  - sensitivity to light flavor PDFs
  - bg-channel at NLO enhanced by gluon luminosity



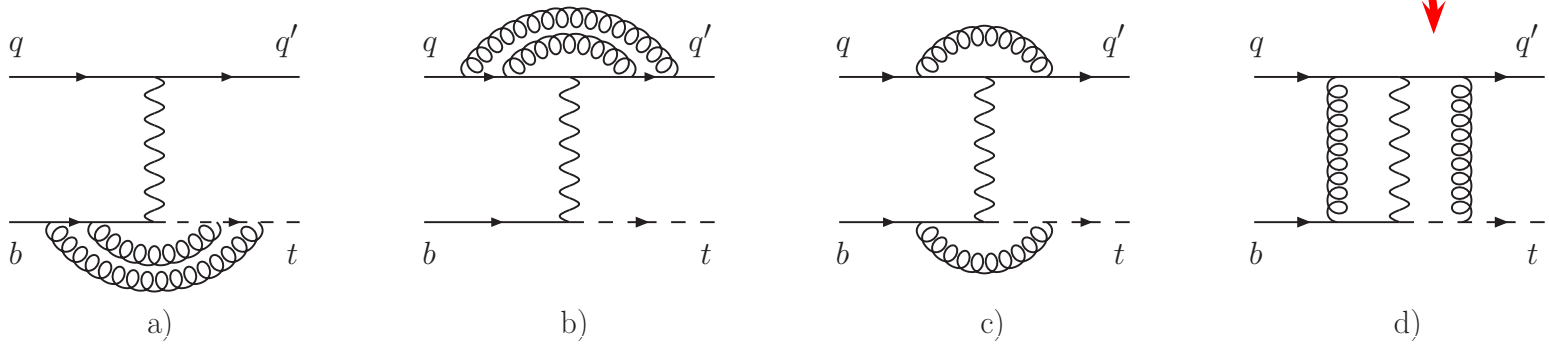


- Wt-production
  - contributes at LHC (small at Tevatron)



QCD corrections at NNLO

- Computation of NNLO QCD corrections Brucherseifer, Caola, Melnikov '14
  - fully differential, with cuts on p_T
- QCD corrections treated in structure function approach
  - non-factorizable contributions neglected
    (neglected diagrams $\mathcal{O}(1/N_c^2)$ supressed)

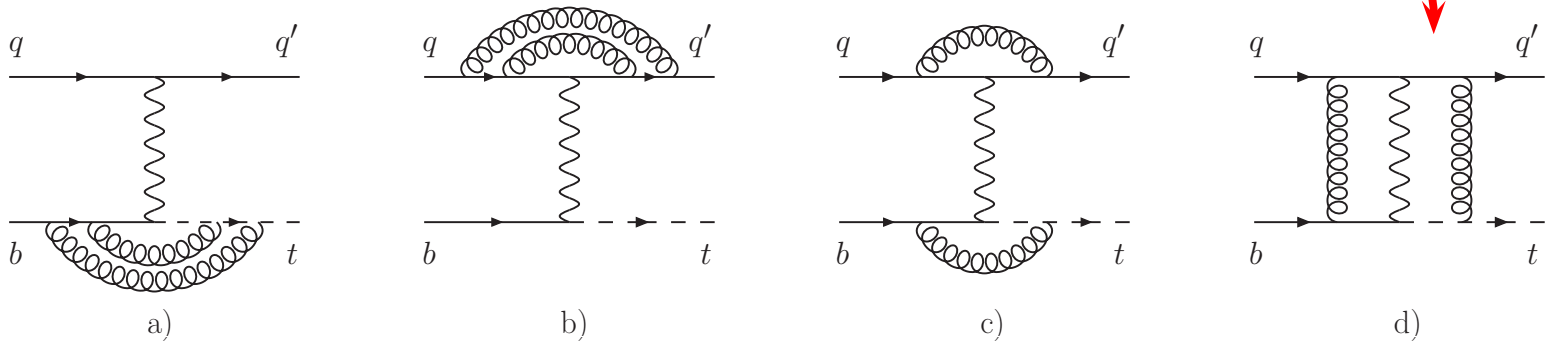


- QCD corrections to t-channel single top quark production at LHC8

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

QCD corrections at NNLO

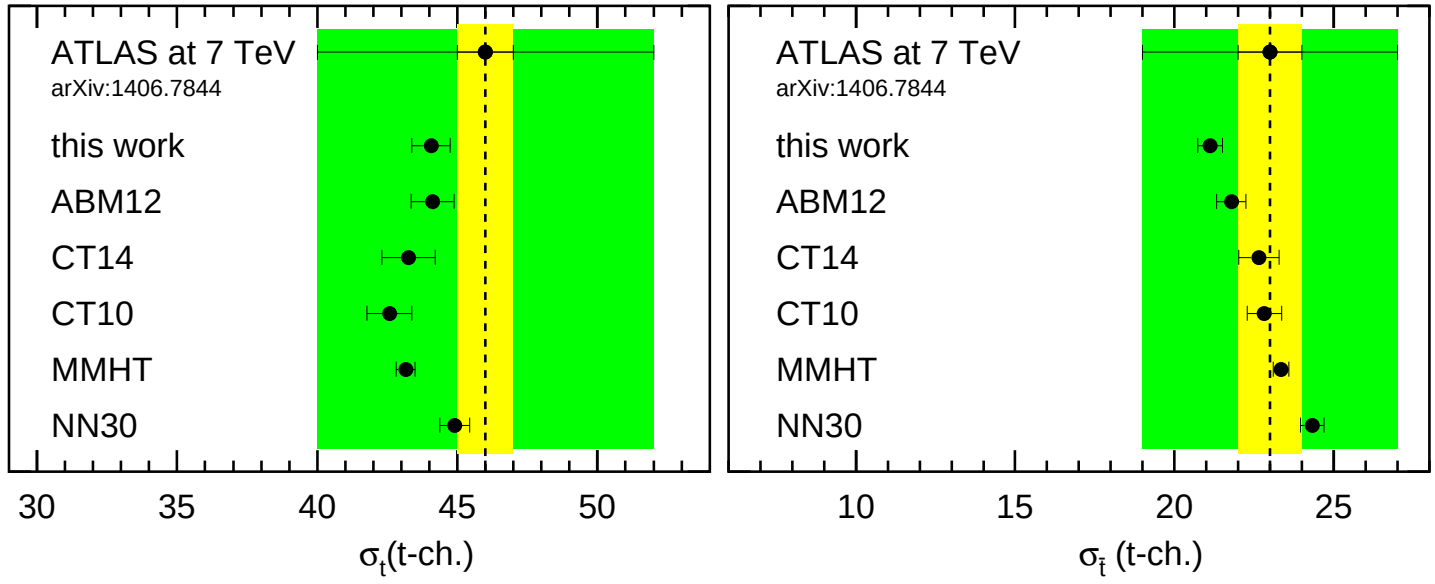
- Computation of NNLO QCD corrections Brucherseifer, Caola, Melnikov '14
  - fully differential, with cuts on p_T
- QCD corrections treated in structure function approach
  - non-factorizable contributions neglected
    (neglected diagrams $\mathcal{O}(1/N_c^2)$ supressed)



- QCD corrections to t-channel single anti-top quark production at LHC8

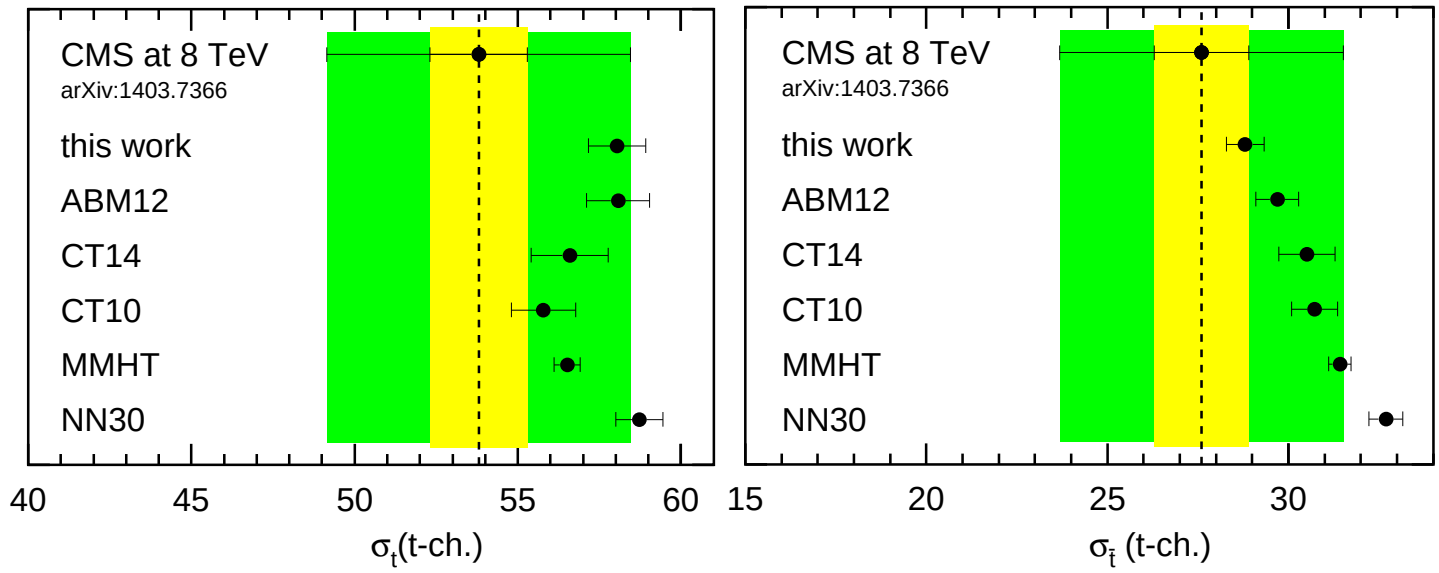
$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$	$19.1^{+0.3}_{+0.1}$	$+11.7\%$	$19.3^{-0.2}_{+0.1}$	$+1.0\%$
60 GeV	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

Inclusive cross sections (I)



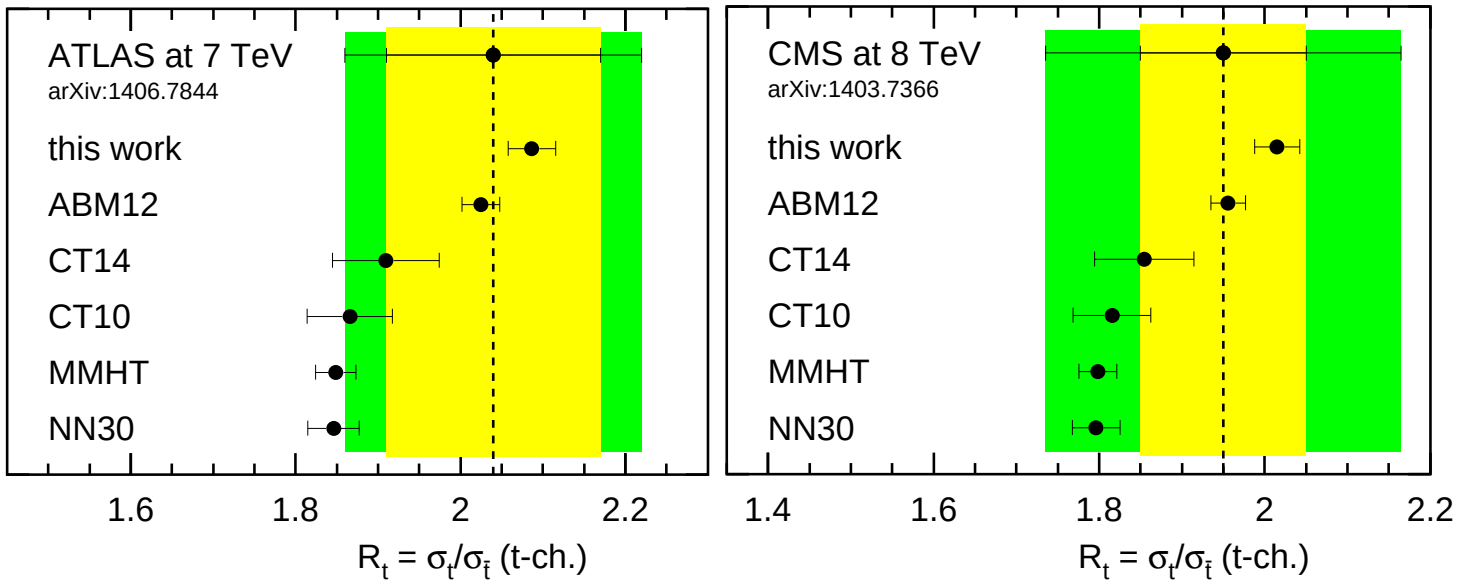
- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties
  - computation of hard cross section to NLO in QCD with Hathor for $\overline{\rm MS}$ mass $m_t(m_t) = 163$ GeV at scale $\mu_R = \mu_F = m_t(m_t)$
- Data at $\sqrt{s} = 7$ TeV from ATLAS
  - inner (yellow) band for statistical uncertainty and outer (green) band for combined statistics and systematics uncertainty

Inclusive cross sections (II)



- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties
  - computation of hard cross section to NLO in QCD with Hathor for $\overline{\rm MS}$ mass $m_t(m_t) = 163$ GeV at scale $\mu_R = \mu_F = m_t(m_t)$
- Data at $\sqrt{s} = 8$ TeV from CMS
  - inner (yellow) band for statistical uncertainty and outer (green) band for combined statistics and systematics uncertainty

Cross section ratio



- Cross section ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ is very sensitive probe
  - data from ATLAS and CMS dominated by inner (yellow) band for statistical uncertainty, systematics largey cancel
- Theory predictions sensitive to ratio d/u of PDFs
  - 1σ PDF uncertainties in R_t small

Upshot

- Production of single top-quarks at LHC can serve as standard candle for the light quark flavor content of proton

Summary

Parton distributions, α_s and all that

- PDFs and $\alpha_s(M_Z)$ well constrained by existing data
- Complementary information from benchmark measurements at LHC
  - $W^{\pm}$- and Z-bosons, top-quark pairs, single top-quark
  - top-quark mass m_t
  - iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
- Experimental precision of $\lesssim 1\%$ puts pressure on accuracy of theoretical predictions
  - FSR QED corrections for forward $W^{\pm}$- and Z-bosons
  - NNLO QCD differential distributions

Single Top at the LHC

- Radiative corrections at higher orders in QCD well under control
- High statistics measurements at Run II of LHC can provide constraints on light quark PDFs