Single-top production at the LHC as a standard candle process

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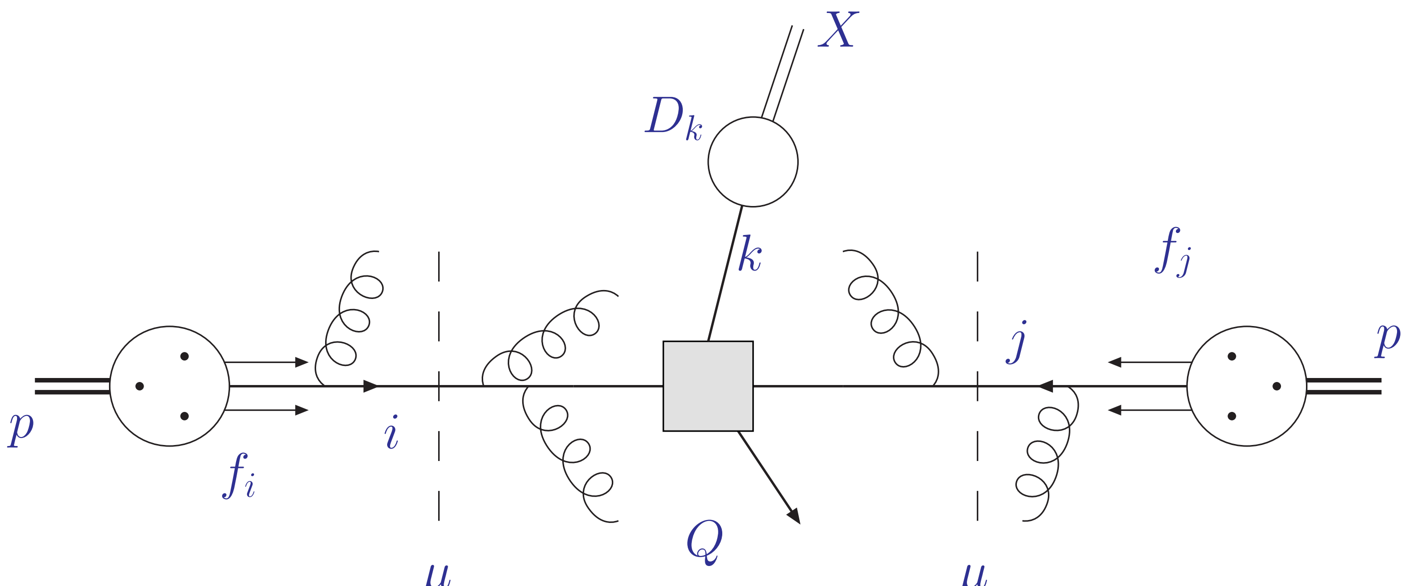
LHC discussion: *New results from Top Physics* Hamburg, Nov 02, 2015

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

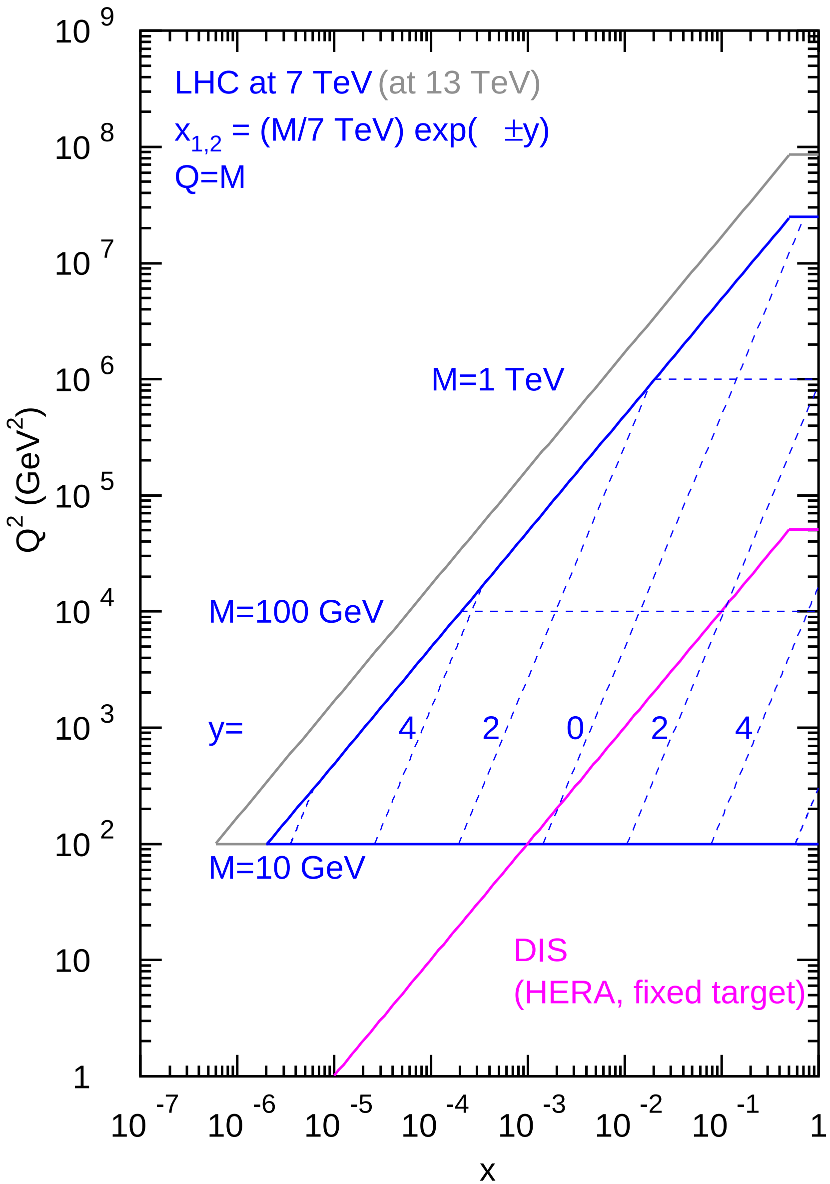


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- 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



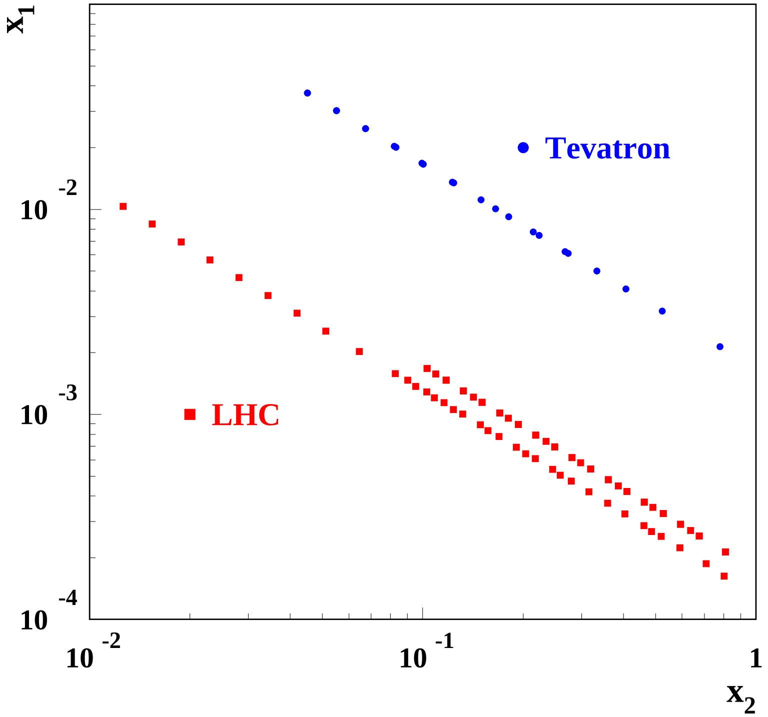
- LHC run at $\sqrt{s}$ = 7/8 TeV
  - parton kinematics well covered by HERA and fixed target experiments
- Parton kinematics with $x_{1,2} = M/\sqrt{S}\mathrm{e}^{\pm y}$
  - forward rapidities sensitive to small-x
- Cross section depends on convolution of parton distributions
  - small-x part of f_i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

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

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

$W^{\pm}$- 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 $x \simeq 10^{-4}$
  - leading order kinematics

$\sigma(W^+) \simeq u(x_2)\bar{d}(x_1)$

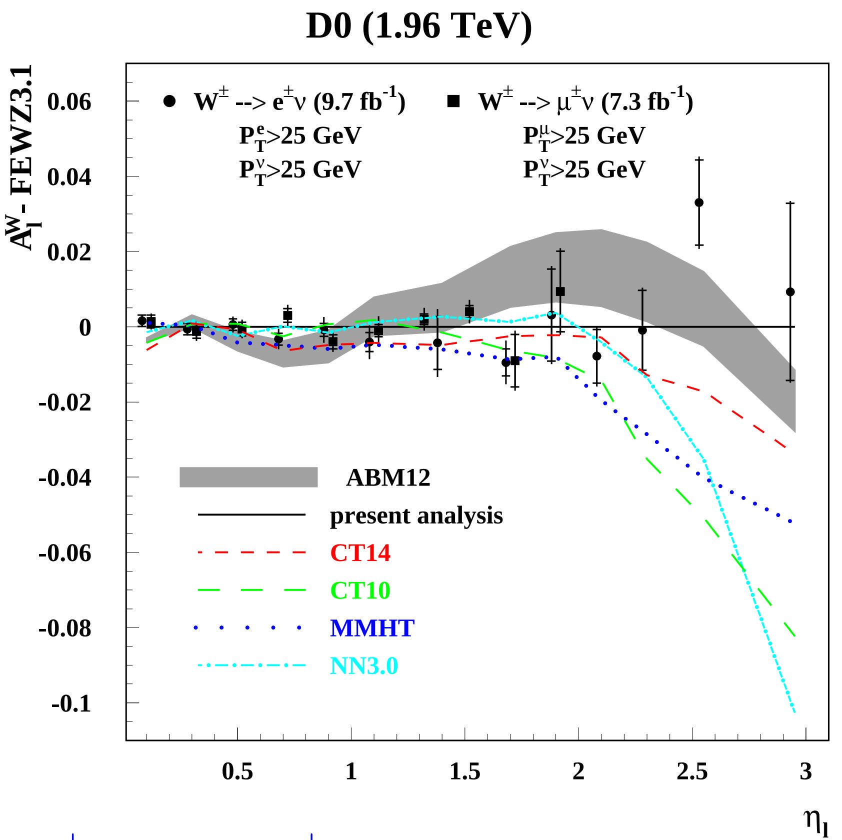
$\sigma(W^-) \simeq d(x_2)\bar{u}(x_1)$

$\sigma(Z) \simeq Q_u^2 u(x_2)\bar{u}(x_1) + Q_d^2 d(x_2)\bar{d}(x_1)$

cf. $\sigma(\text{DIS}) \simeq q_u^2 u(x) + q_d^2 d(x)$

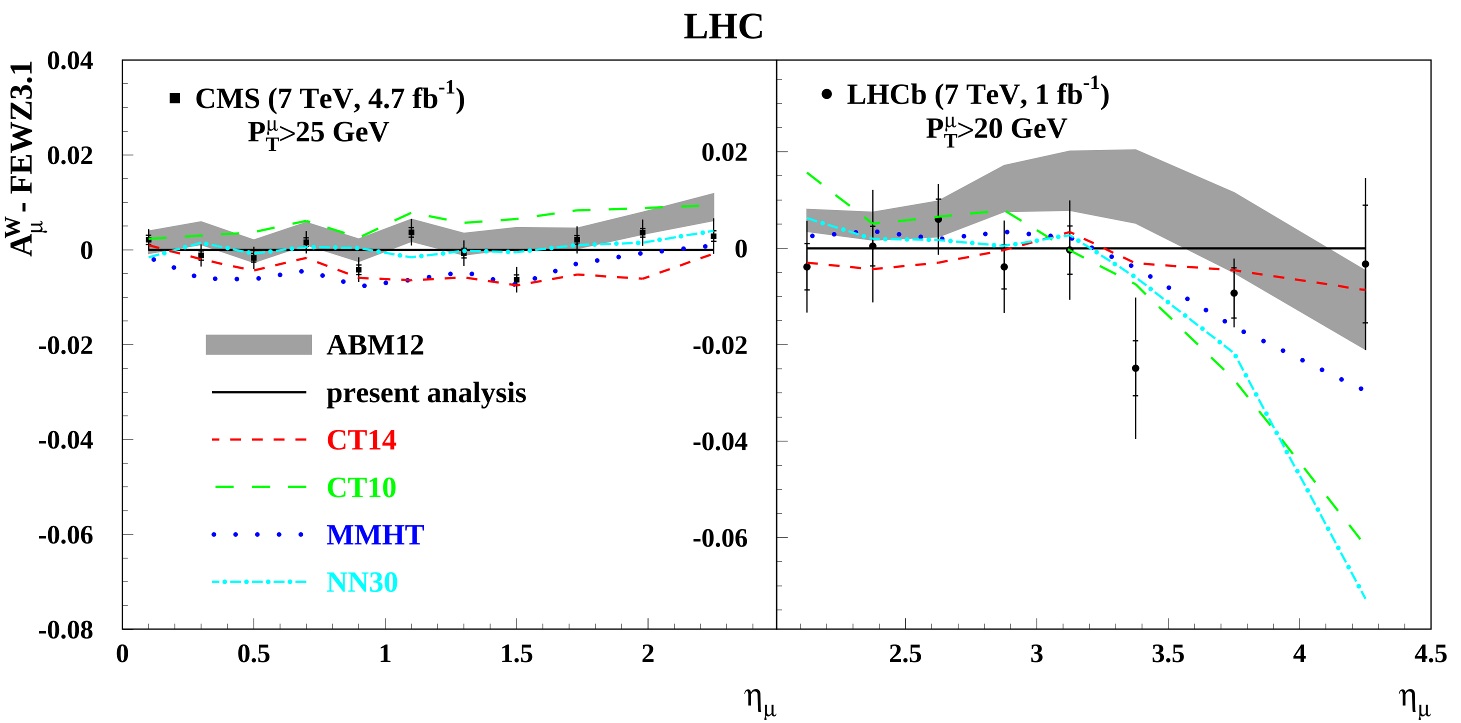
Experiment	ATLAS	CMS	D0		LHCb	
$\sqrt{s}$ (TeV)	7	7	1.96		7	8
Final states	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$
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

Tevatron charged lepton asymmetry



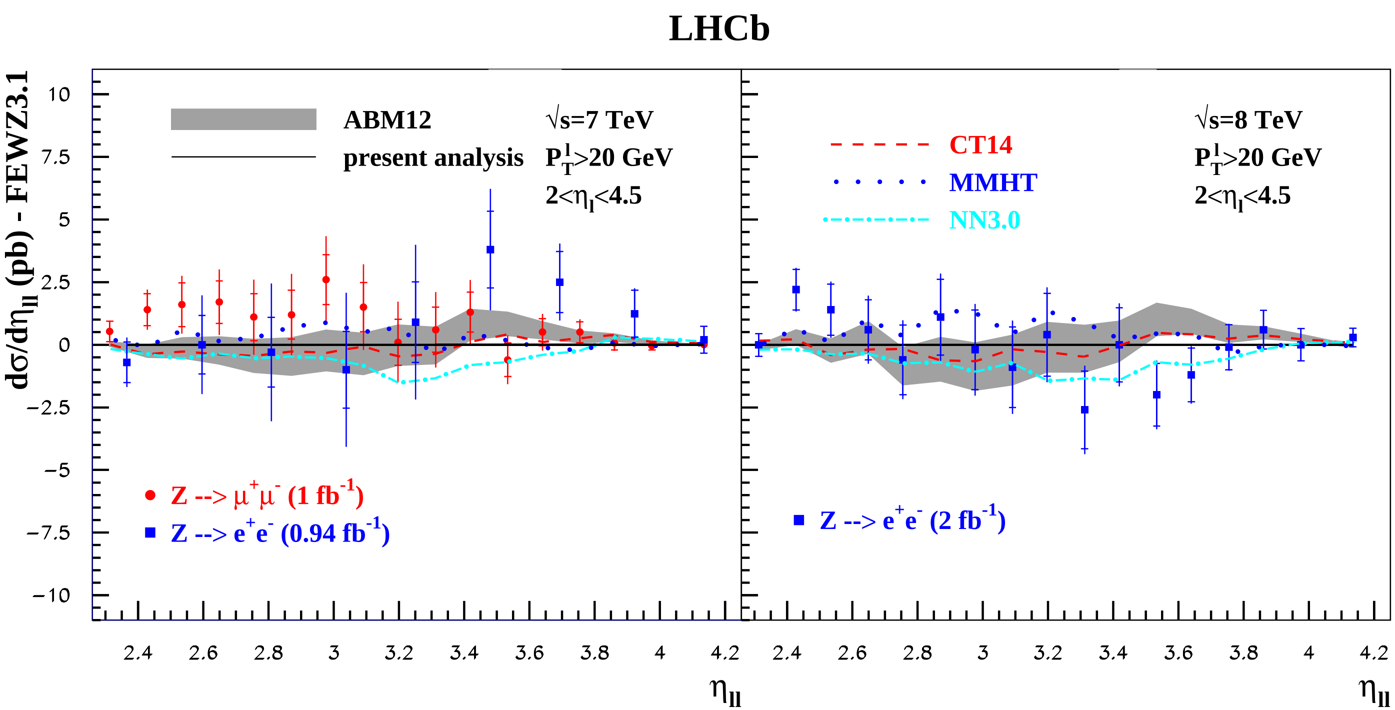
- D0 data for $p\bar{p} \to W^\pm + X \to l^\pm\nu$ (electrons and muons) at $\sqrt{s} = 1.96$ TeV
- Charged lepton asymmetry as function of pseudo-lepton rapidity η_l
- NNLO QCD predictions with FEWZ (version 3.1)
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT10, CT14, MMHT, and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



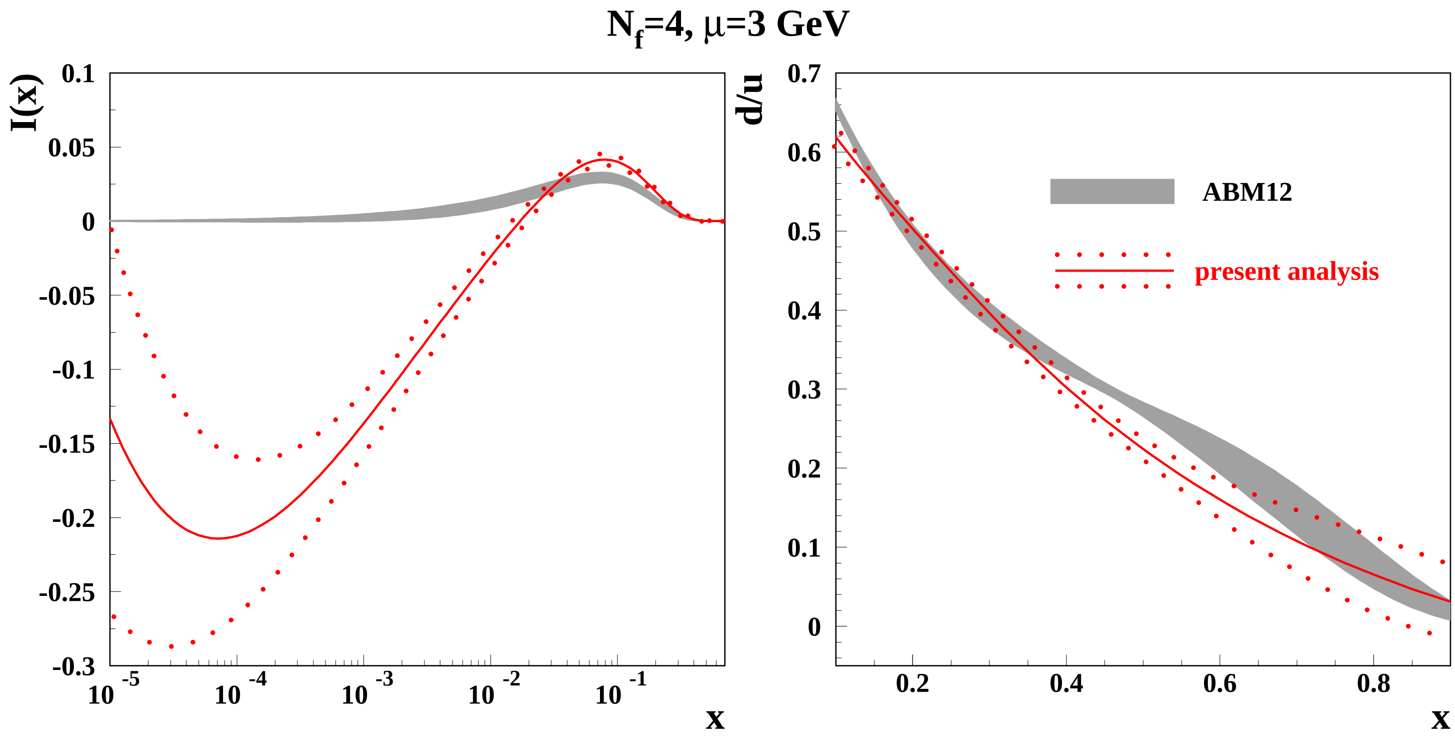
- LHCb data for $pp \to Z + X \to l\bar{l}$ (muon and electron) at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT14, MMHT, and NN3.0

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	42	–[c]	–	34.7	–	–
	HERAFitter	–	–	13	19	–	–
	MMHT14	39	–	21	–	–	–
	NN3.0	35.4	18.9	–	–	–	–

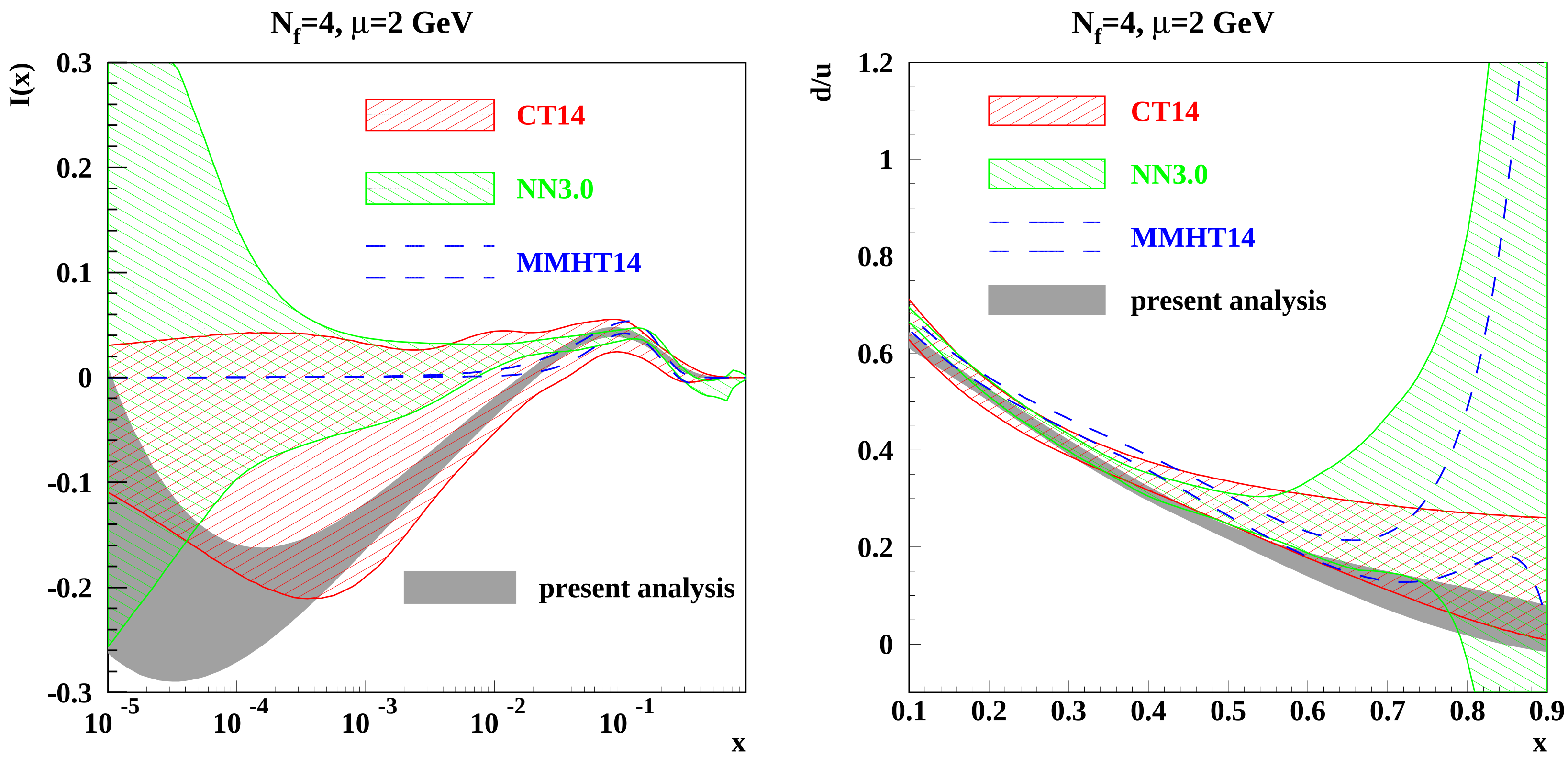
[a] Variants with all collider DY and $W^{\pm}$-boson data excluded except the one given.
[b] Value obtained assuming systematic uncertainties to be uncorrelated.
[c] Statistically less significant data with the cut of $P_T^{\mu} > 35$ GeV are used.

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 $x \simeq 10^{-4}$

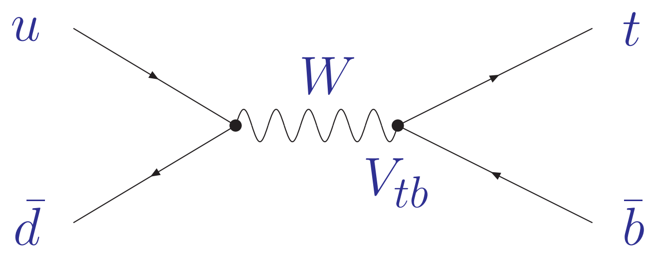
Comparision with other PDFs



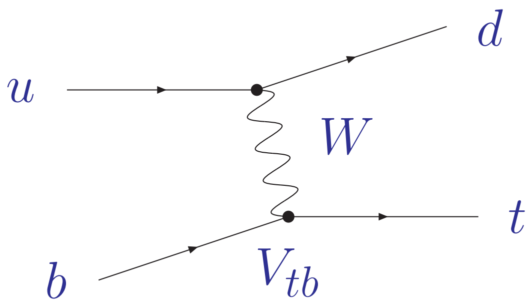
- Iso-spin asymmetry of sea $I(x)$ at small x and ratio d/u at large x with 1σ uncertainty band
- Comparison with CT14, MMHT14, NN3.0
  - CT14 finds non-vanishing $I(x)$ from fit to Tevatron charged lepton asymmetry (D0 data), but with large uncertainties

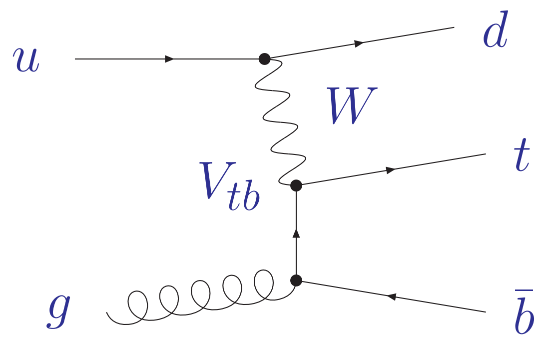
Single top-quark production

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

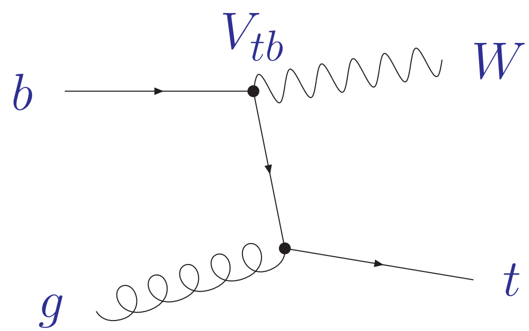


- t-channel production
  - sensitivity to light flavor PDFs
  - bg-channel at NLO enhanced by gluon luminosity



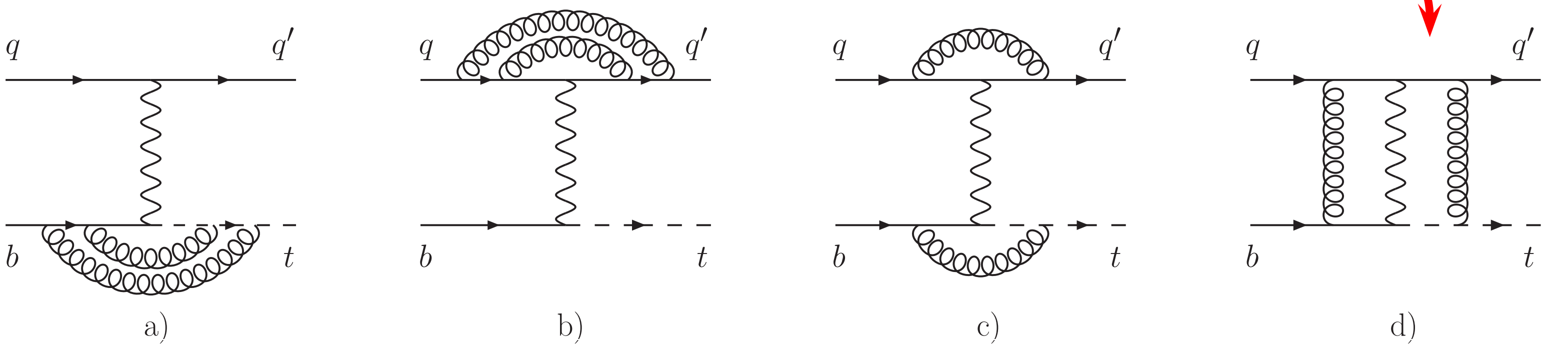


- Wt-production
  - contributes at LHC (small at Tevatron)



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
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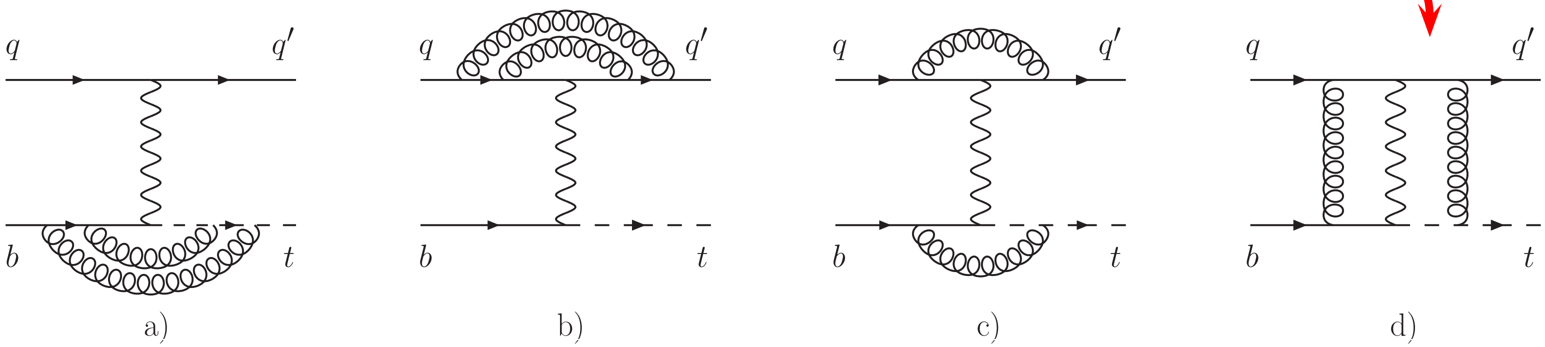
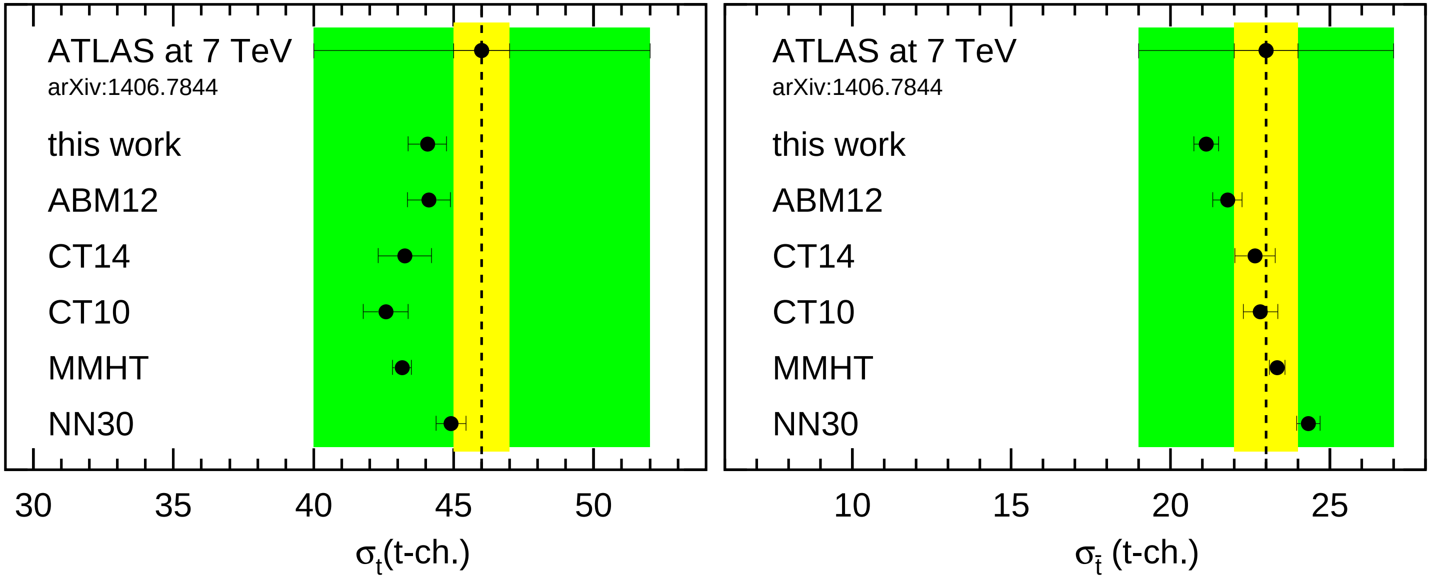


- QCD corrections to t-channel single anti-top quark production at LHC8

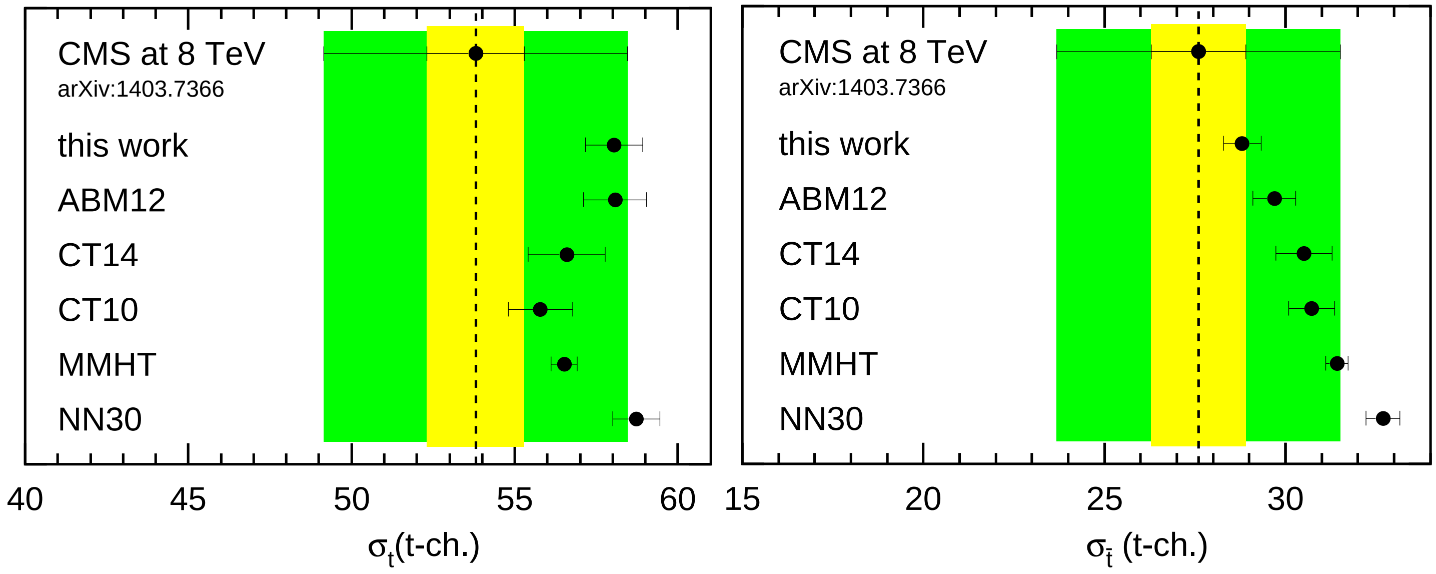
$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$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



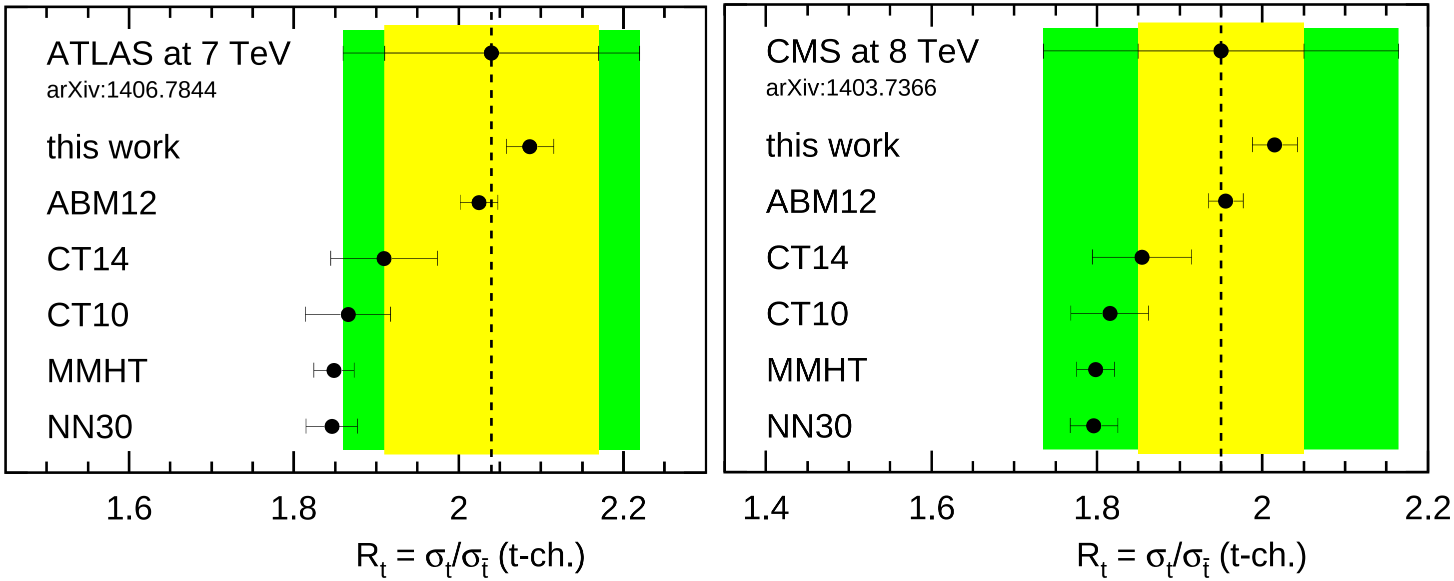
- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties
  - computation of hard cross section to NLO in QCD with Hathor for $\overline{\mathrm{MS}}$ mass $m_t(m_t) = 163$ GeV at scale $\mu_R = \mu_F = m_t(m_t)$
- Data at $\sqrt{s} = 7$ TeV from ATLAS
  - 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 $\overline{\mathrm{MS}}$ 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
  - iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
  - top-quark mass m_t
- Experimental precision of $\lesssim 1\%$ puts pressure on accuracy of theoretical predictions
  - 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