Top quark physics at the LHC

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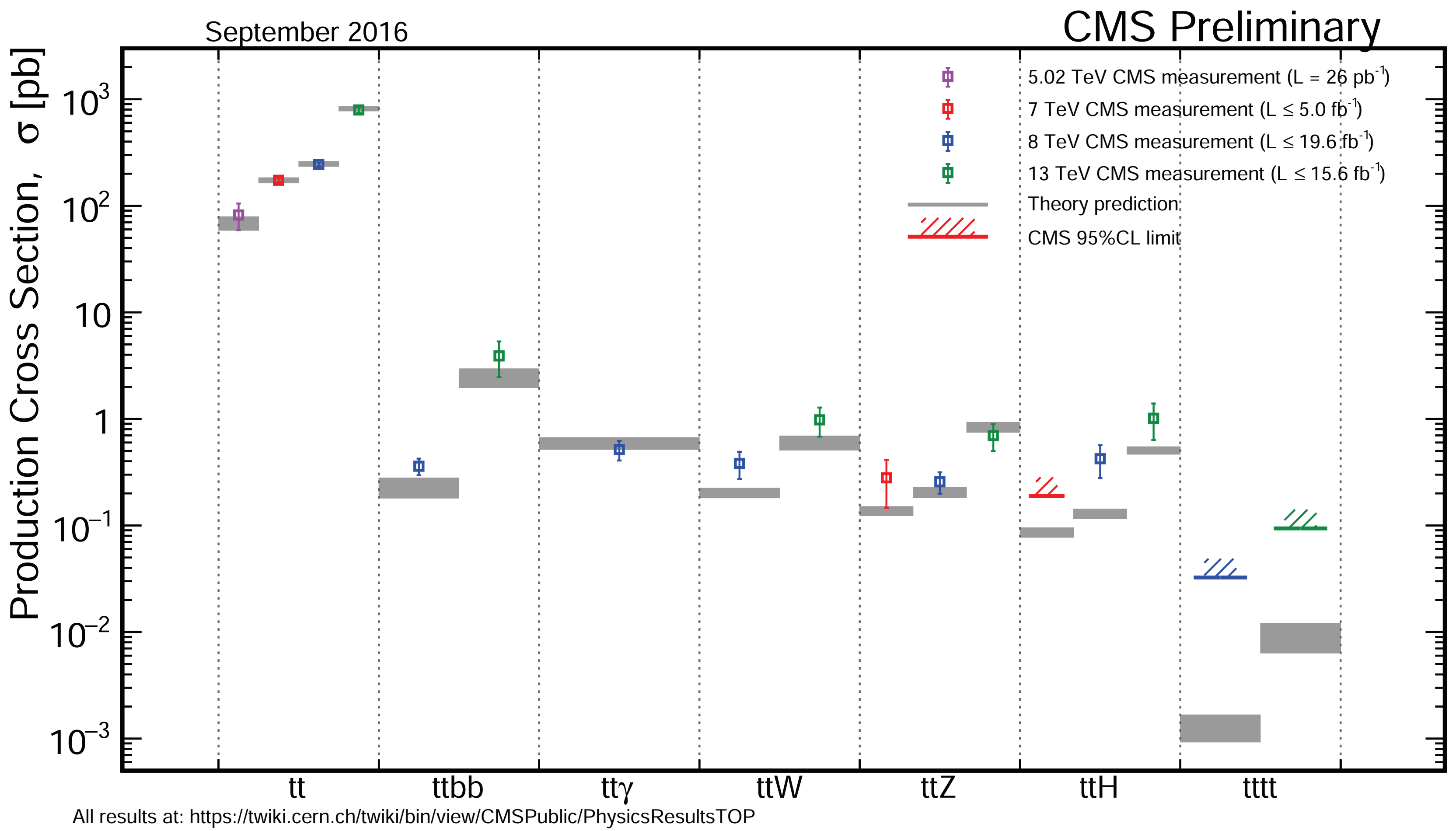
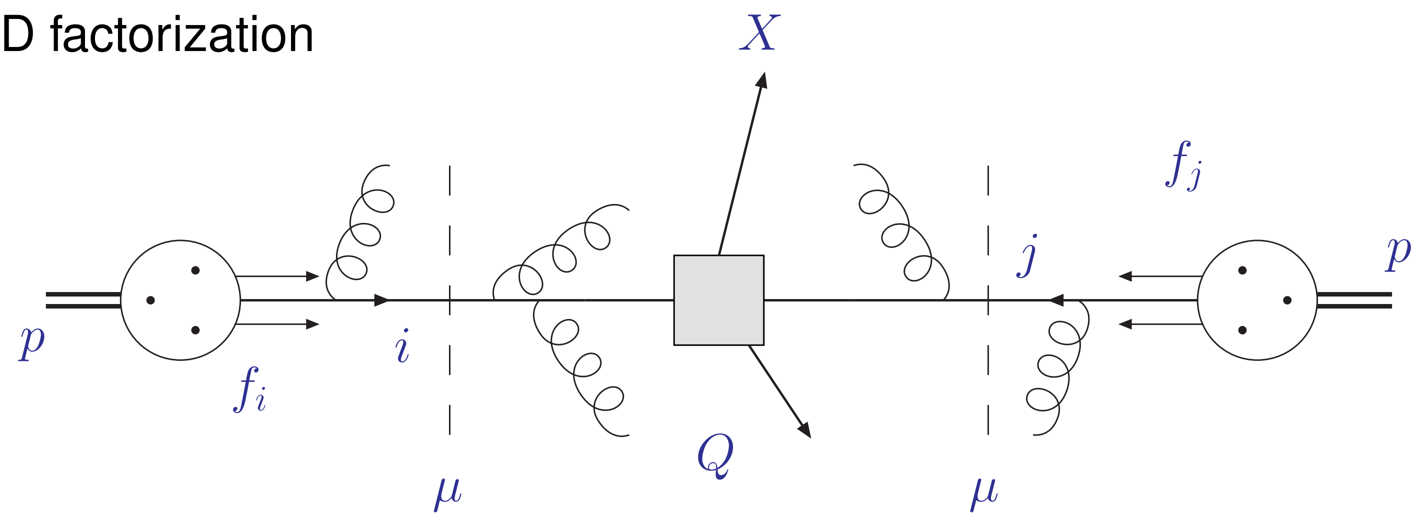
Experimental status as of 2016



- Top quark physics at the LHC in run II with $\sqrt{s} = 13$ TeV is becoming precision science
  - very big statistics for events with t-quarks
  - measurements limited by systematics

QCD factorization

- QCD factorization



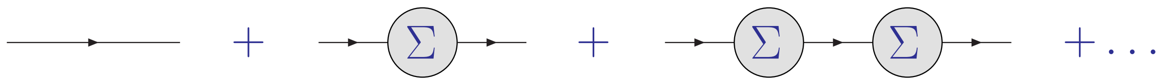
$$\sigma_{pp\to X} \quad = \quad \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \underbrace{\hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)}$$

$$= \hat{\sigma}^{(0)}_{ij\to X} + \alpha_s\, \hat{\sigma}^{(1)}_{ij\to X} + \alpha_s^2\, \hat{\sigma}^{(2)}_{ij\to X} + \ldots$$

- 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, ...

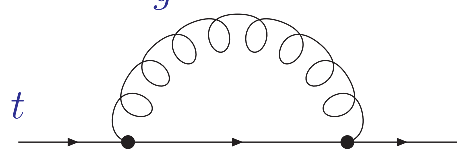
Quark mass renormalization

- Heavy-quark self-energy $\Sigma(p, m_q)$



$$= \frac{\mathrm{i}}{\not{p} - m_q - \Sigma(p, m_q)}$$

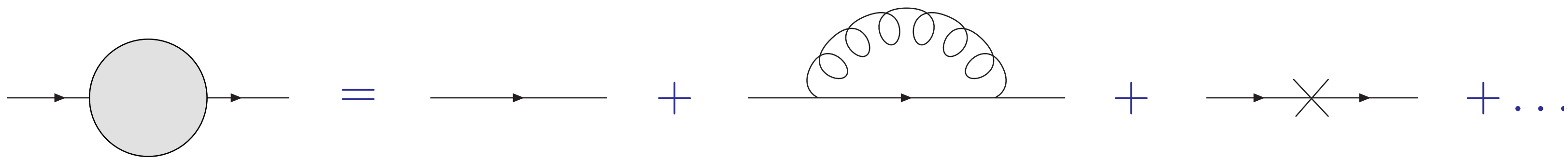
QCD



- QCD corrections to self-energy $\Sigma(p, m_q)$
  - dimensional regularization $D = 4 - 2\epsilon$
  - one-loop: UV divergence $1/\epsilon$ (Laurent expansion)

$$\Sigma^{(1),\mathrm{bare}}(p, m_q) = \frac{\alpha_s}{4\pi}\left(\frac{\mu^2}{m_q^2}\right)^{\epsilon}\left\{(\not{p} - m_q)\left(-C_F\frac{1}{\epsilon} + \text{fin.}\right) + m_q\left(3C_F\frac{1}{\epsilon} + \text{fin.}\right)\right\}$$

- Relate bare and renormalized mass parameter $m_q^{\mathrm{bare}} = m_q^{\mathrm{ren}} + \delta m_q$



$\Sigma^{\mathrm{ren}}(p, m_q)$

$(Z_\psi - 1)\not{p} - (Z_m - 1)m_q$

Mass renormalization scheme

Pole mass

- Based on (unphysical) concept of top-quark being a free parton
  - $m_q^{\rm ren}$ coincides with pole of propagator at each order

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

- Definition of pole mass ambiguous up to corrections $\mathcal{O}(\Lambda_{QCD})$
  - heavy-quark self-energy $\Sigma(p, m_q)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{QCD})$
- Bounds:
  - lattice QCD $\Delta m_q \geq 0.7 \cdot \Lambda_{QCD} \simeq 200$ MeV Bauer, Bali, Pineda '11
  - perturbative QCD: $\Delta m_q \simeq 70$ MeV Beneke, Marquard, Nason, Steinhauser '16

$\overline{\rm MS}$ *scheme*

- $\overline{\rm MS}$ mass definition: for example one-loop minimal subtraction

$$\delta m_q^{(1)} = m_q \frac{\alpha_s}{4\pi} 3C_F \left(\frac{1}{\epsilon} - \gamma_E + \ln 4\pi\right)$$

- $\overline{\rm MS}$ scheme induces scale dependence: $m(\mu)$

Theory status as of 2016

Multi-particle final states

- Top-quark production in association with jets, bosons, ...
- NLO QCD corrections
  - one loop computations for $2 \to 5$ processes with massive particles
- Off-shell effects from top-quark decays included
- Matching to parton shower
  - POWHEG-BOX Alioli, Nason, Oleari, Re [arXiv:1002.2581]
    with contributions of [many people]
  - aMC@NLO Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [arXiv:1405.0301]

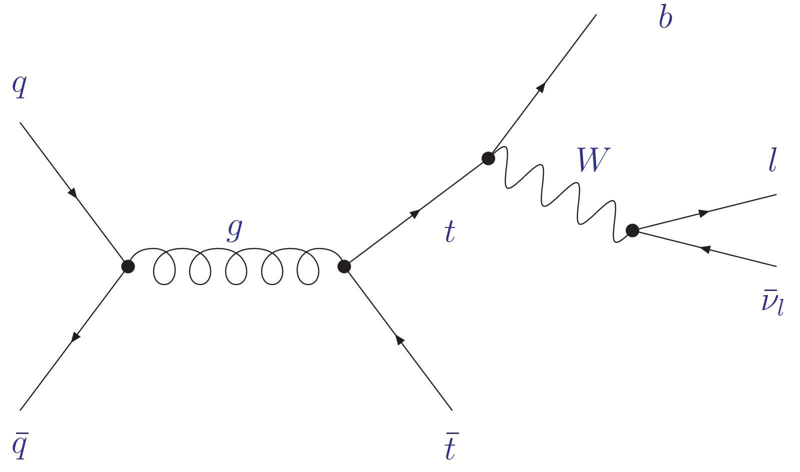
Production of top-quarks (singly or in pairs)

- NNLO QCD corrections
  - two loop computations for $2 \to 2$ processes with massive particles
- Top-quark treated as stable particle
- Theoretical uncertainties match precision of experimental data

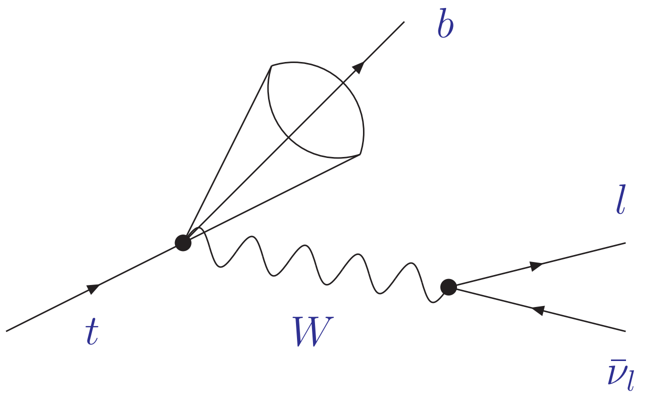
Top-quark decays

Top-quark decay

- Born process ($q\bar{q}$-channel) with leptonic decay $t \to b l \bar{\nu}_l$

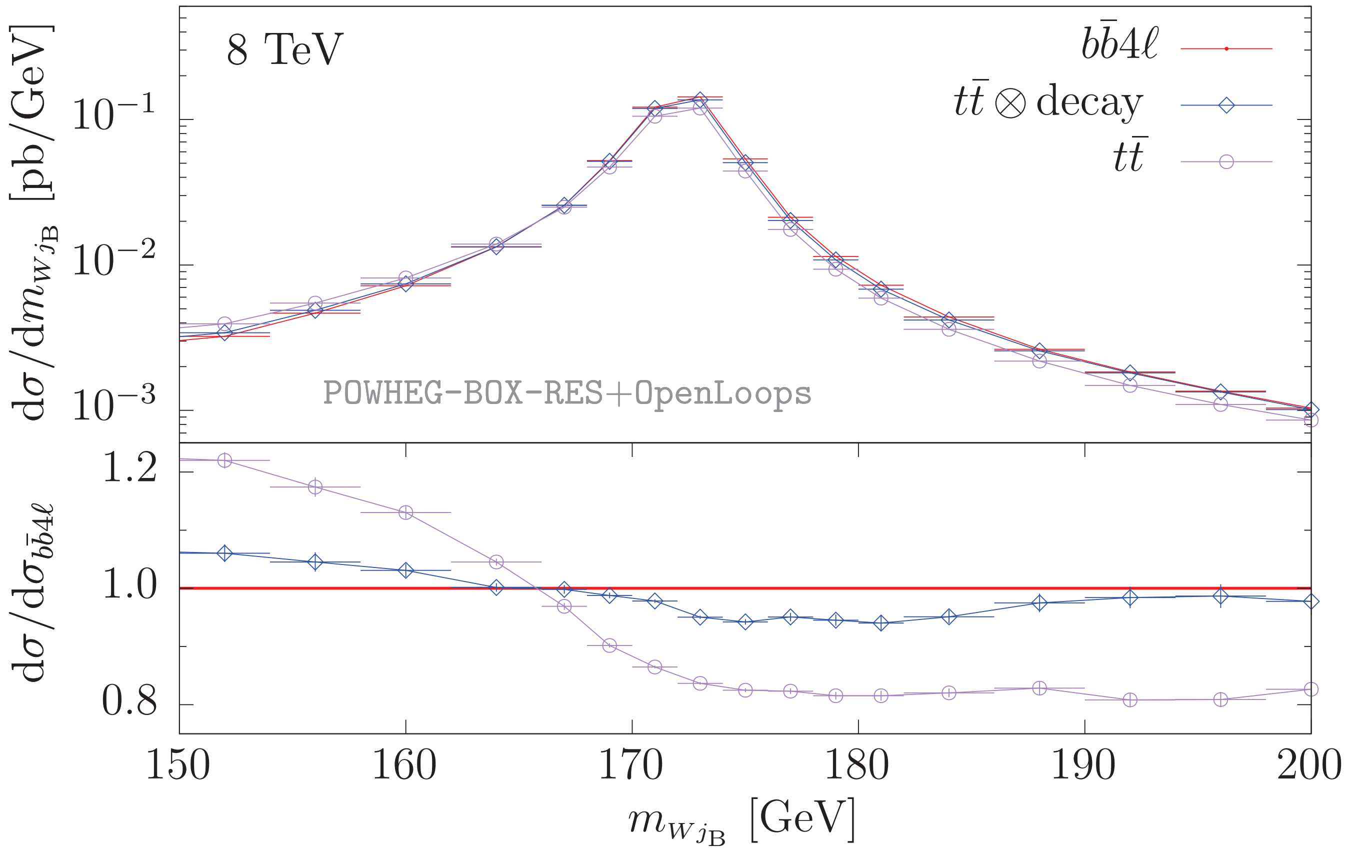


- Top-quark mass based on reconstructed physics objects
  - jets, identified charged leptons, missing transverse energy
  - $m_t^2 = (p_{W-\mathrm{boson}} + p_{b-\mathrm{jet}})^2$



Off-shell top-quarks

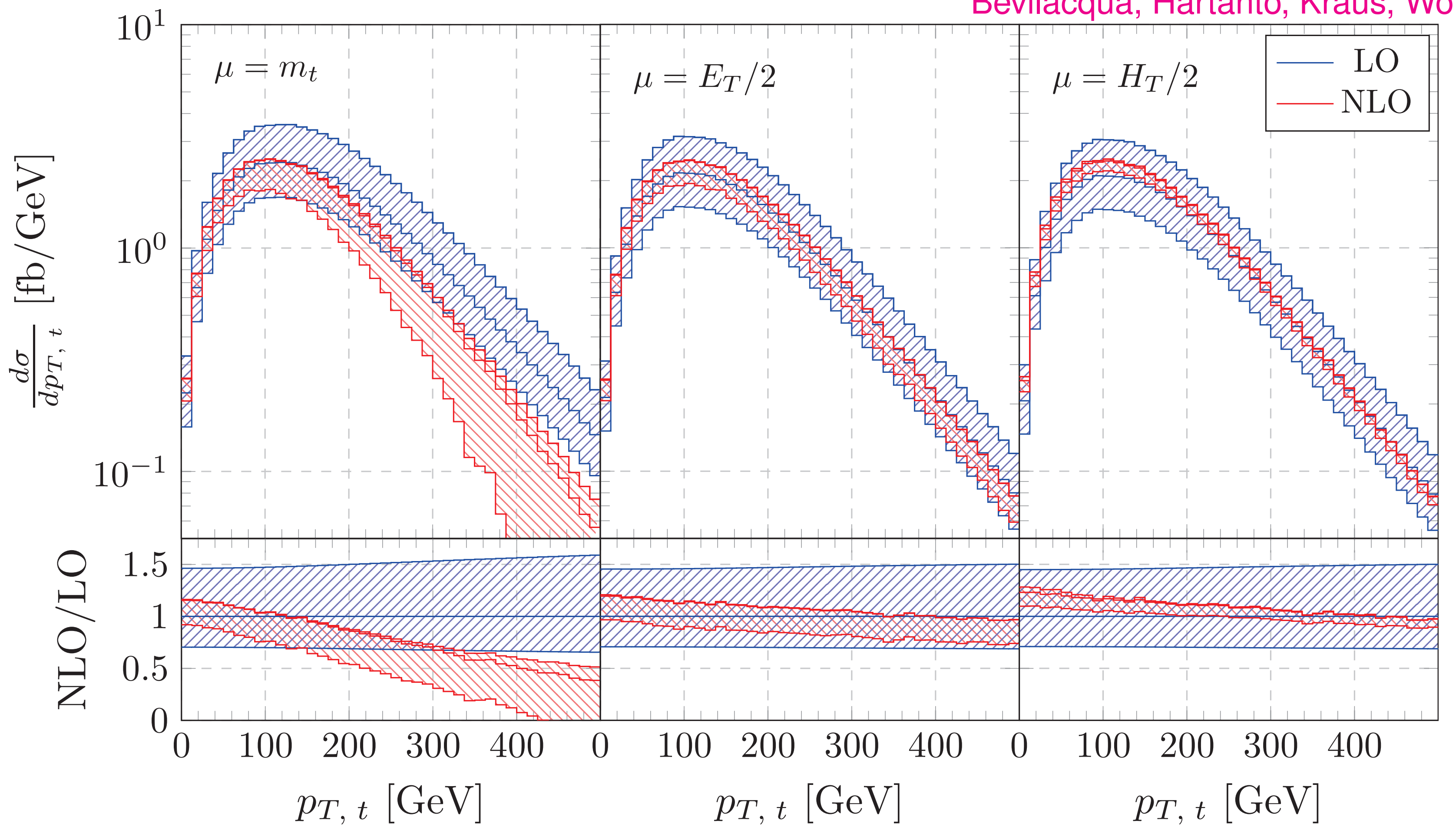
Jezo, Lindert, Nason, Oleari Pozzorini '16



- NLO+PS generator for $t\bar{t}$ and Wt production and decay
  - non-resonant and interference effects included
  - Wj_B mass distribution near the top peak for three generators

Off-shell top-quarks and jets

Bevilacqua, Hartanto, Kraus, Worek '16



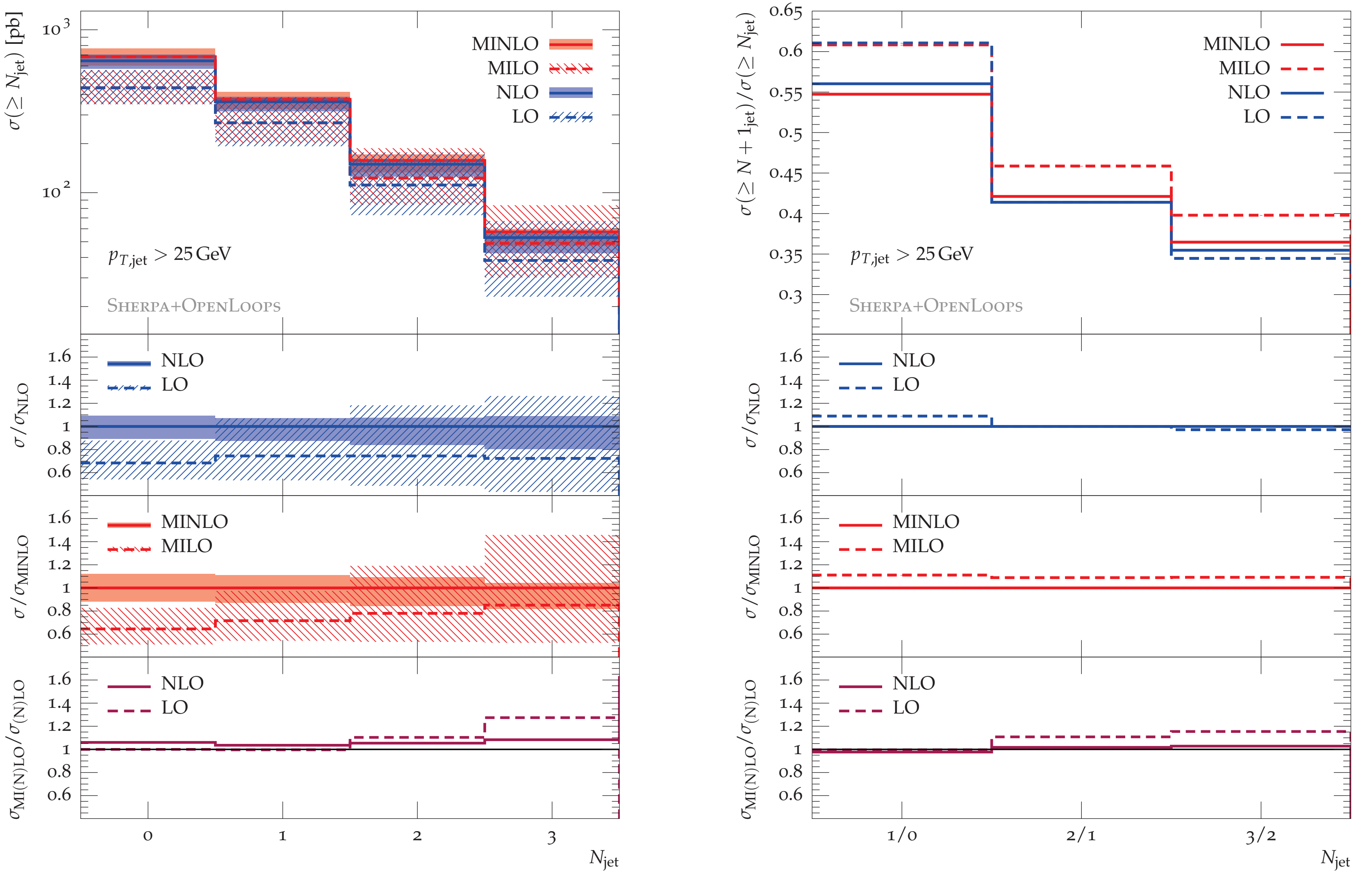
- NLO QCD corrections for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} j + X$ LHC with $\sqrt{s} = 13$ TeV
  - scale choices:

$$E_T = m_{T,\,t} + m_{T,\,\bar{t}} = \sqrt{m_t^2 + p_{T,\,t}^2} + \sqrt{m_t^2 + p_{T,\,\bar{t}}^2}$$

$$H_T = p_{T,\,e^+} + p_{T,\,\mu^-} + p_{T,\,j_{b_1}} + p_{T,\,j_{b_2}} + \not{p}_T + p_{T,\,j_1}$$

Top-quarks and multiple jets

Höche, Maierhöfer, Moretti, Pozzorini, Siegert '16



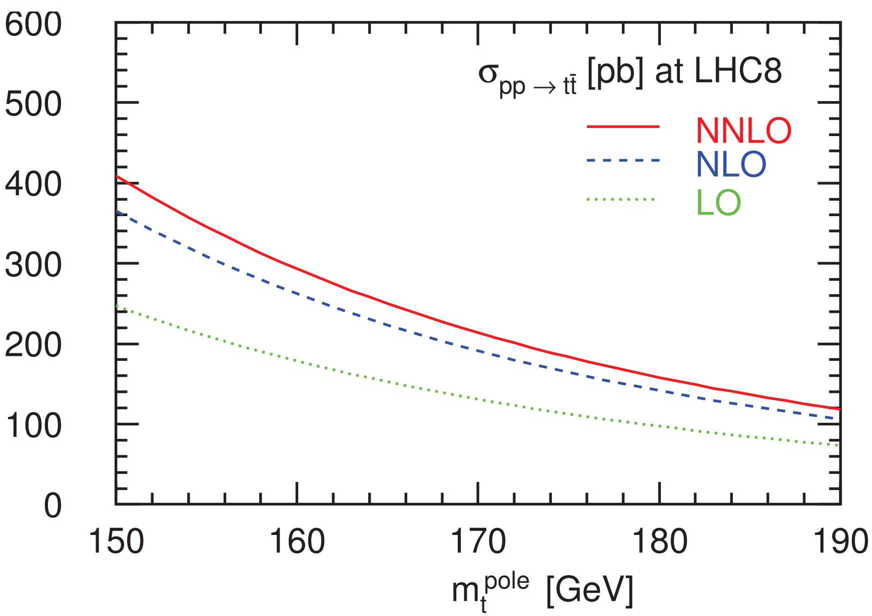
- Inclusive $t\bar{t}+$ multijet cross sections with minimum of $N = 0, 1, 2, 3$ jets
- Ratios of $t\bar{t} + N$ jet over $t\bar{t} + (N-1)$ jet

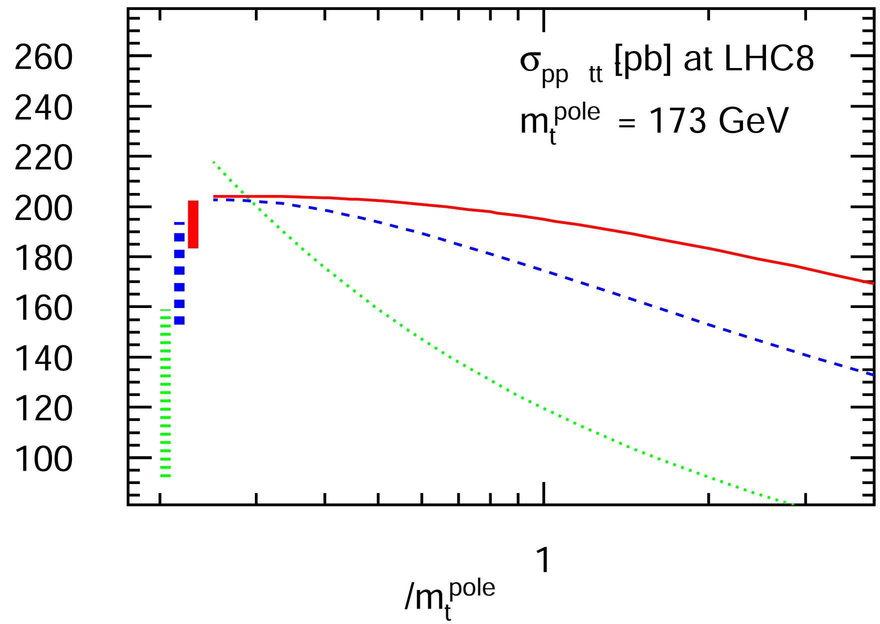
Top-quark pair production

Top-quark pair production

Total cross section at NNLO in QCD

Czakon, Fiedler, Mitov ‘13



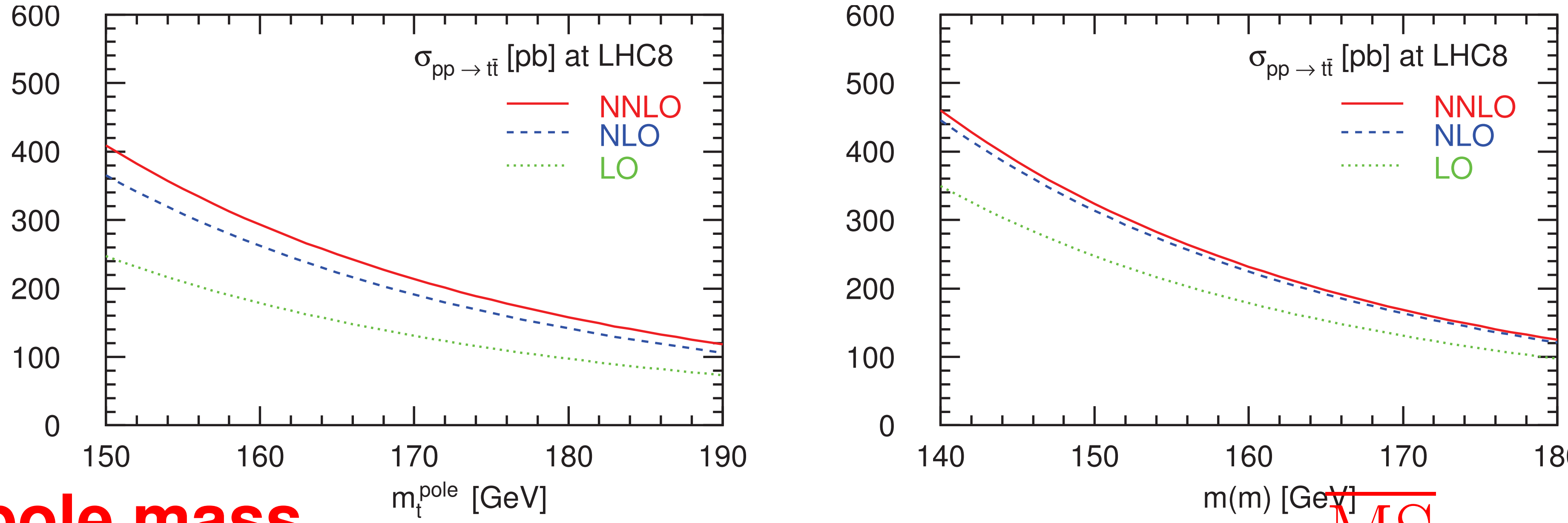


- NNLO perturbative corrections (e.g. at LHC8)
  - K-factor (NLO $\to$ NNLO) of $\mathcal{O}(10\%)$
  - scale stability at NNLO of $\mathcal{O}(\pm 5\%)$

Total cross section with running mass

Comparison pole mass vs. $\overline{\mathrm{MS}}$ mass (I)

Dowling, S.M. '13



pole mass

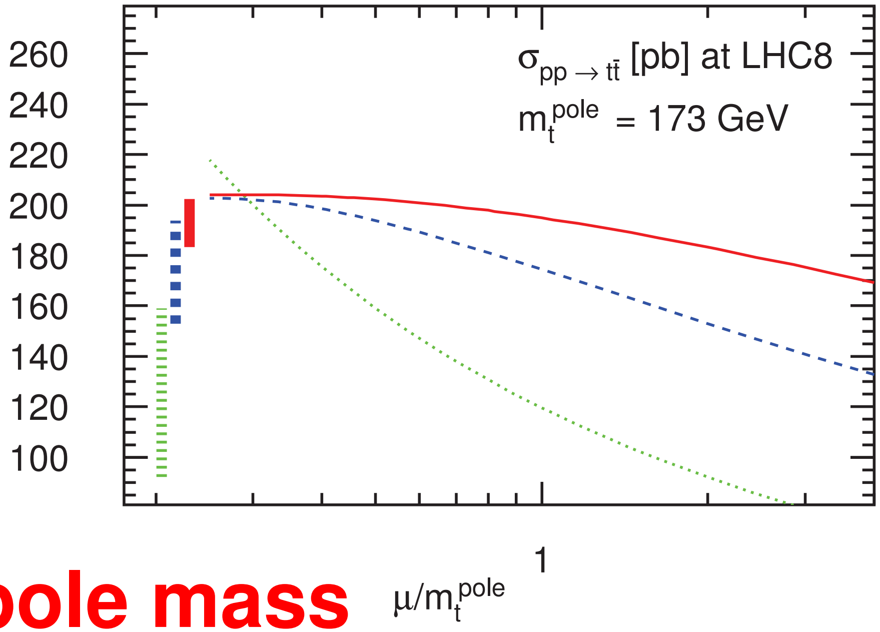
$\overline{\mathrm{MS}}$ mass

- NNLO cross section with running mass significantly improved
  - good apparent convergence of perturbative expansion
  - small theoretical uncertainity from scale variation

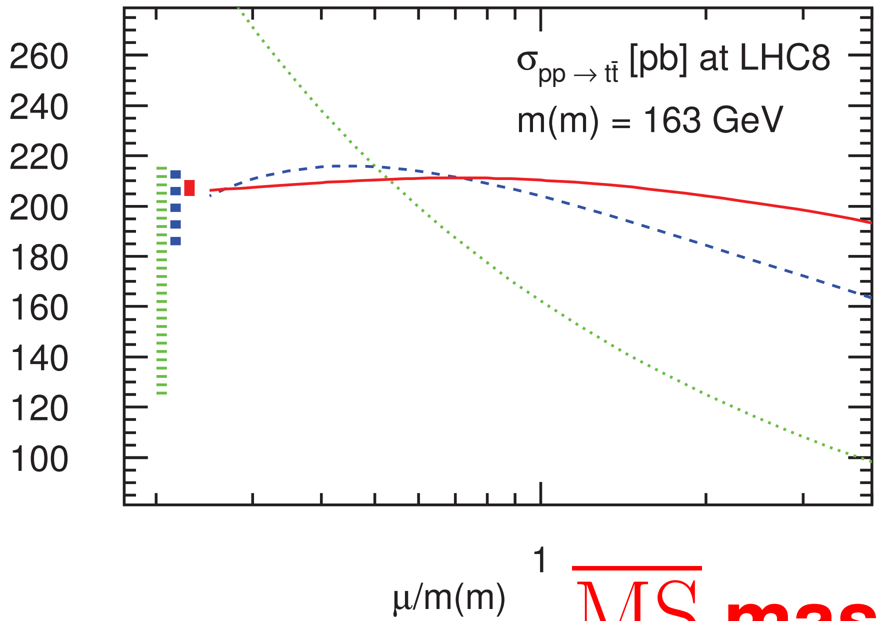
Total cross section with running mass

Comparison pole mass vs. $\overline{\mathrm{MS}}$ mass (II)

Dowling, S.M. '13



pole mass

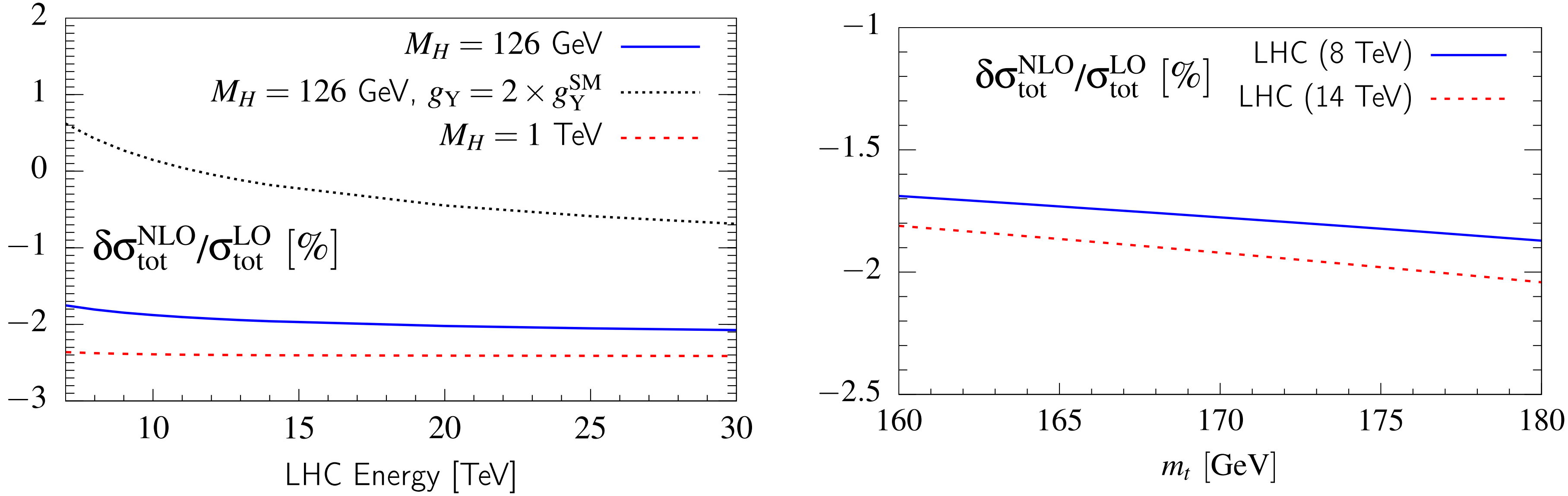


$\overline{\mathrm{MS}}$ **mass**

- NNLO cross section with running mass significantly improved
  - good apparent convergence of perturbative expansion
  - small theoretical uncertainity from scale variation

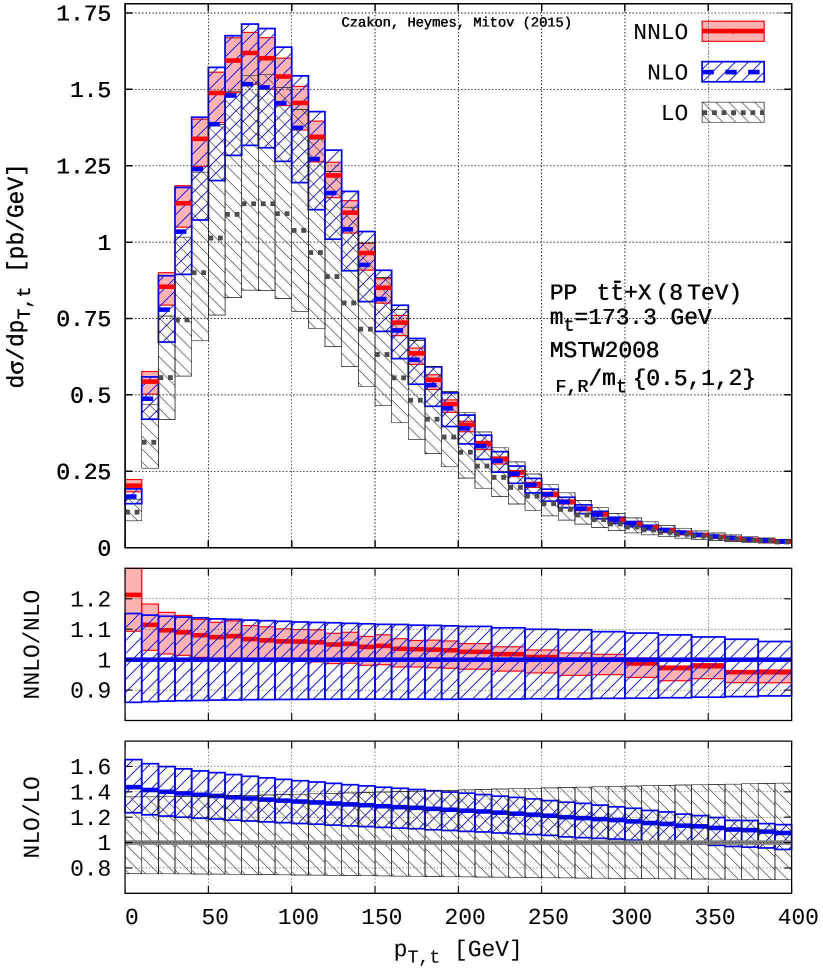
Electroweak corrections

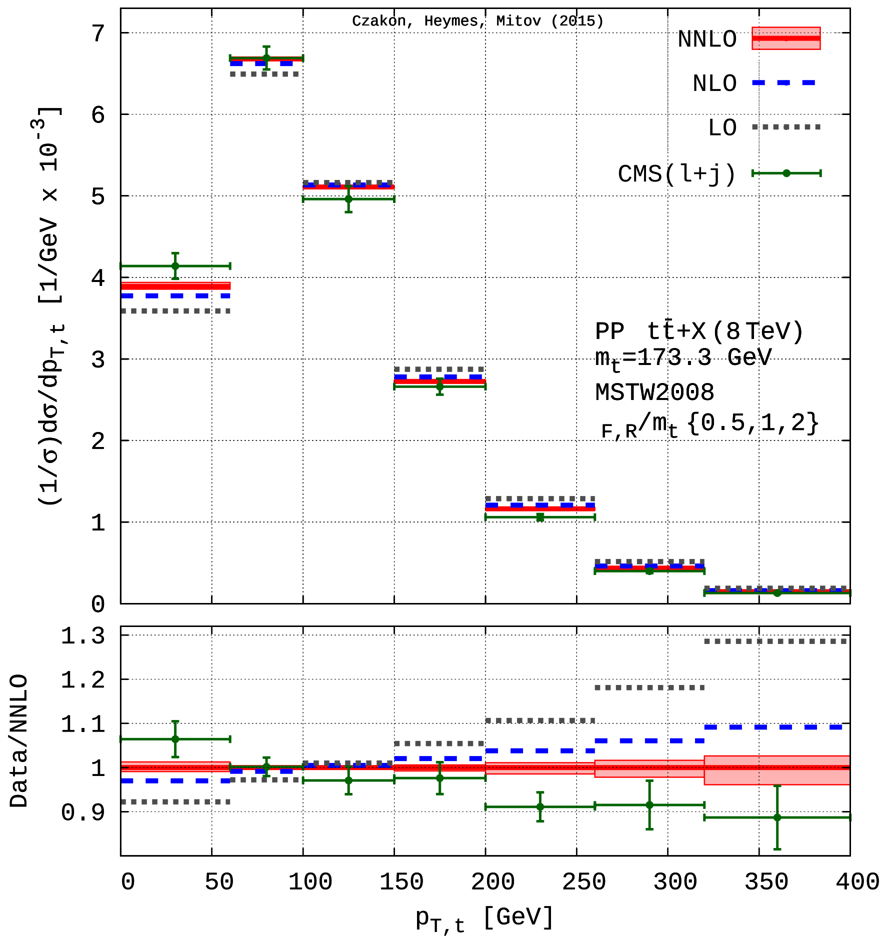
- Electroweak corrections (ratio of $\sigma_{\rm EW}/\sigma_{\rm LO}$)
  Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth '94; Bernreuther, Fücker '05;
  Kühn, Scharf, Uwer '06



- Left: $\sigma_{\rm EW}/\sigma_{\rm LO}$ as function of total cms energy (effect depends on Higgs mass and Higgs-Yukawa coupling)
- Right: $\sigma_{\rm EW}/\sigma_{\rm LO}$ as function of top-quark mass:
  $\mathcal{O}(2\%)$ with respect to $\sigma_{\rm LO}$ negative contribution to total cross section
- NLO EW corrections now included in update of Hathor (v2.1)
  Kühn, Scharf, Uwer '13

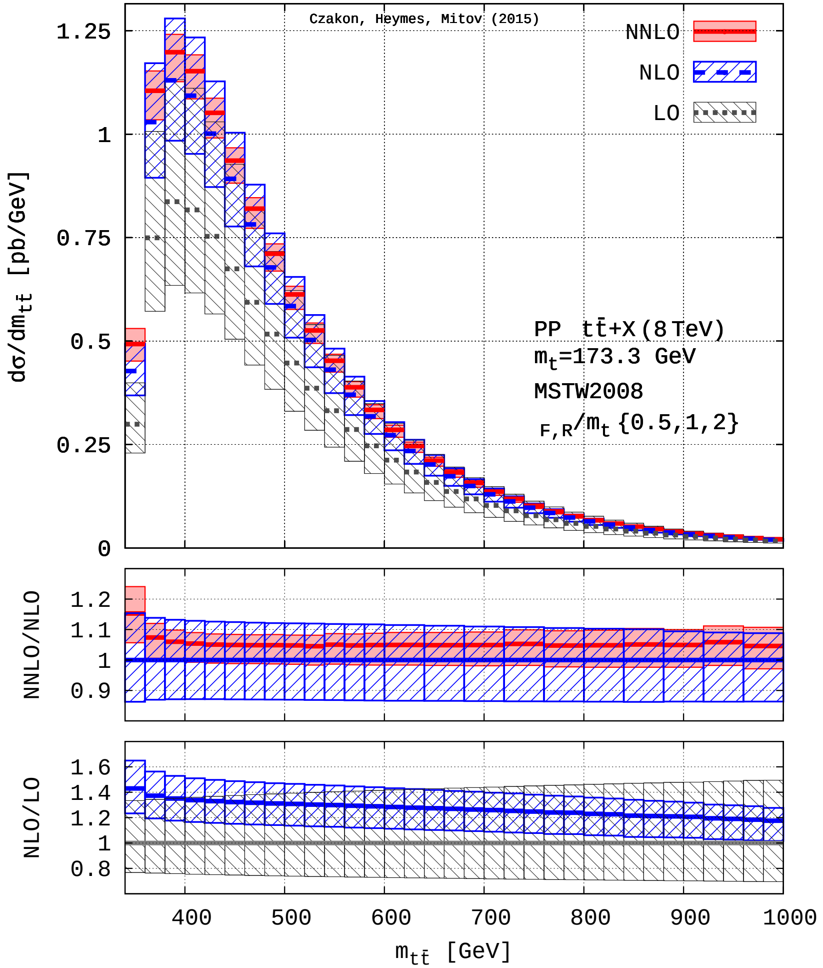
Differential distributions (I)

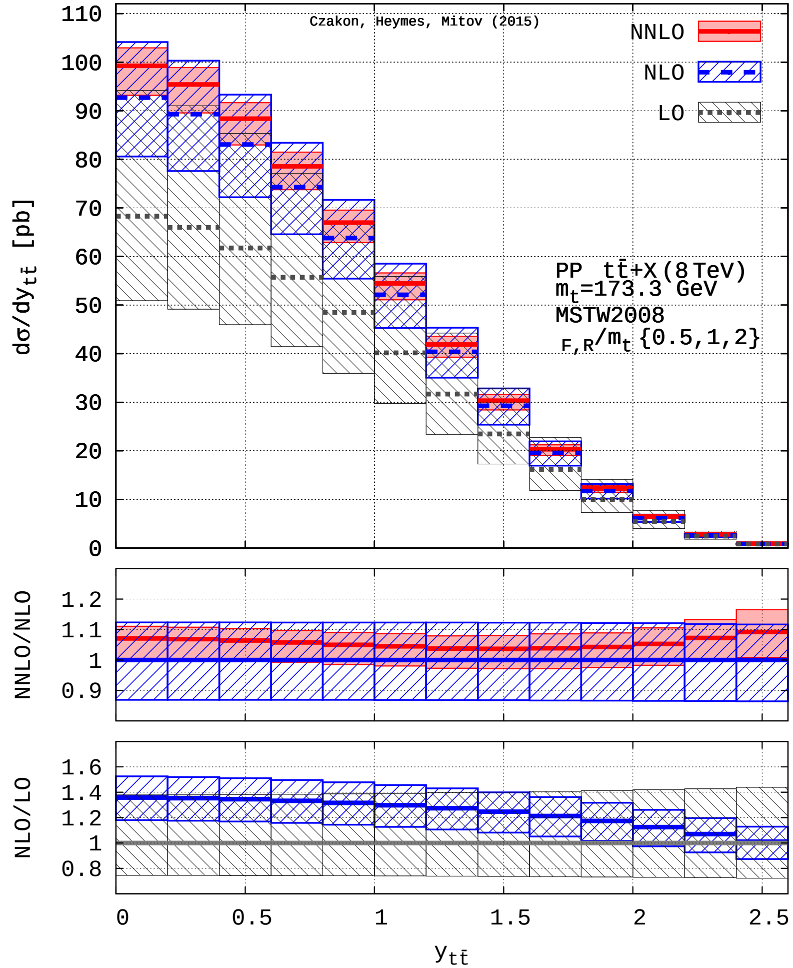




- Differential distributions at NNLO for pole mass Czakon, Heymes, Mitov ‘15
  - sizable corrections for $p_{T,\,t}$–distribution
  - convergence of perturbative expansion within scale uncertainties (improved with dynamical scales)

Differential distributions (II)



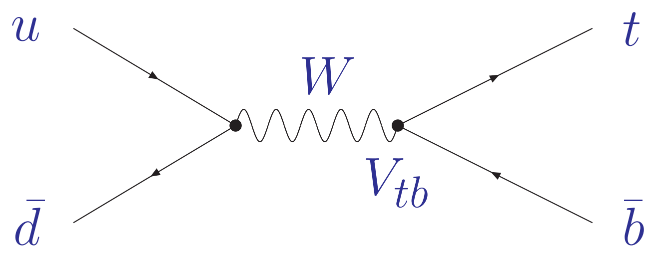


- Differential distributions at NNLO for pole mass Czakon, Heymes, Mitov '15
  - $y_{t\bar{t}}$- and $M_{t\bar{t}}$-distribution

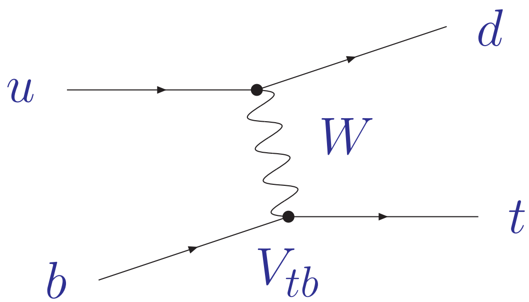
Single top-quark production

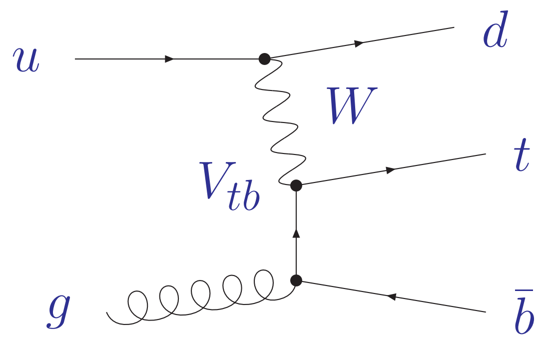
Single top-quark production

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

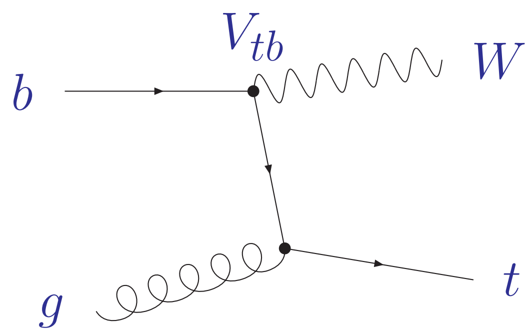


- t-channel production
  - sensitivity to light flavor PDFs
  - bg-channel at NLO enhanced by gluon luminosity



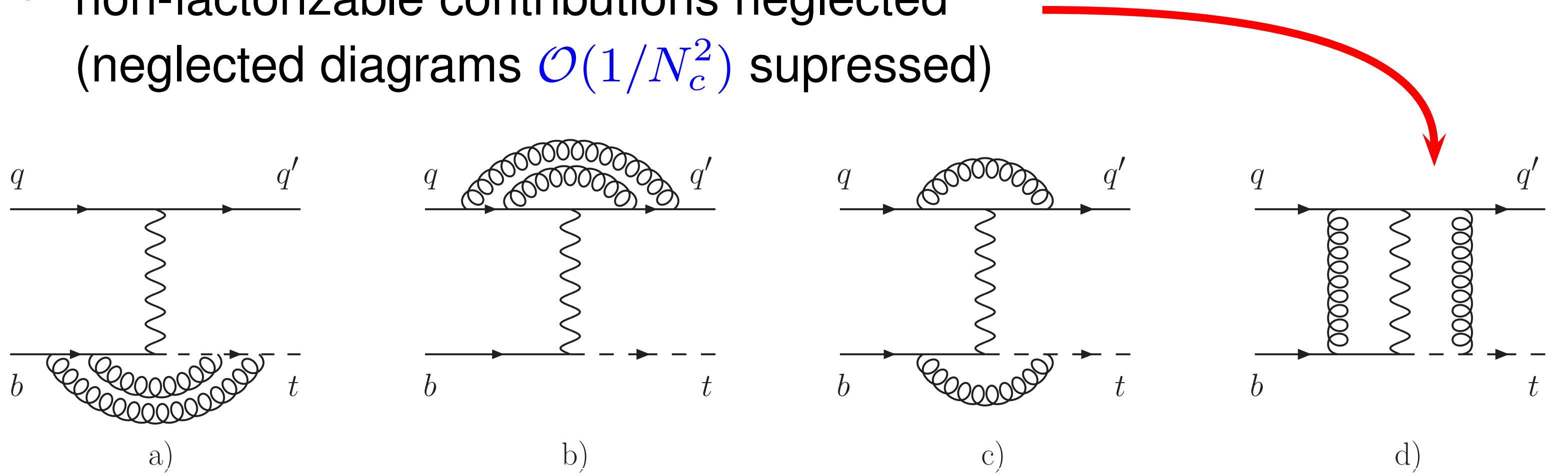


- Wt-production
  - contributes at LHC (small at Tevatron)



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

$p_\perp$	σ_{LO}, pb	σ_{NLO}, pb	δ_{NLO}	σ_{NNLO}, pb	δ_{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

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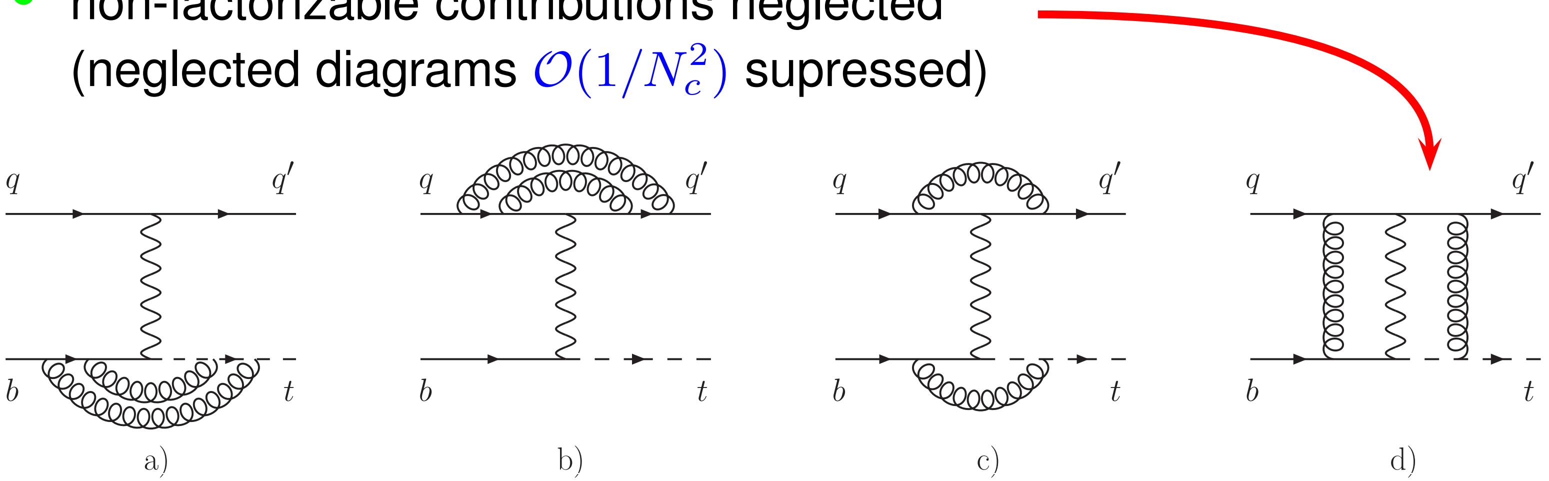
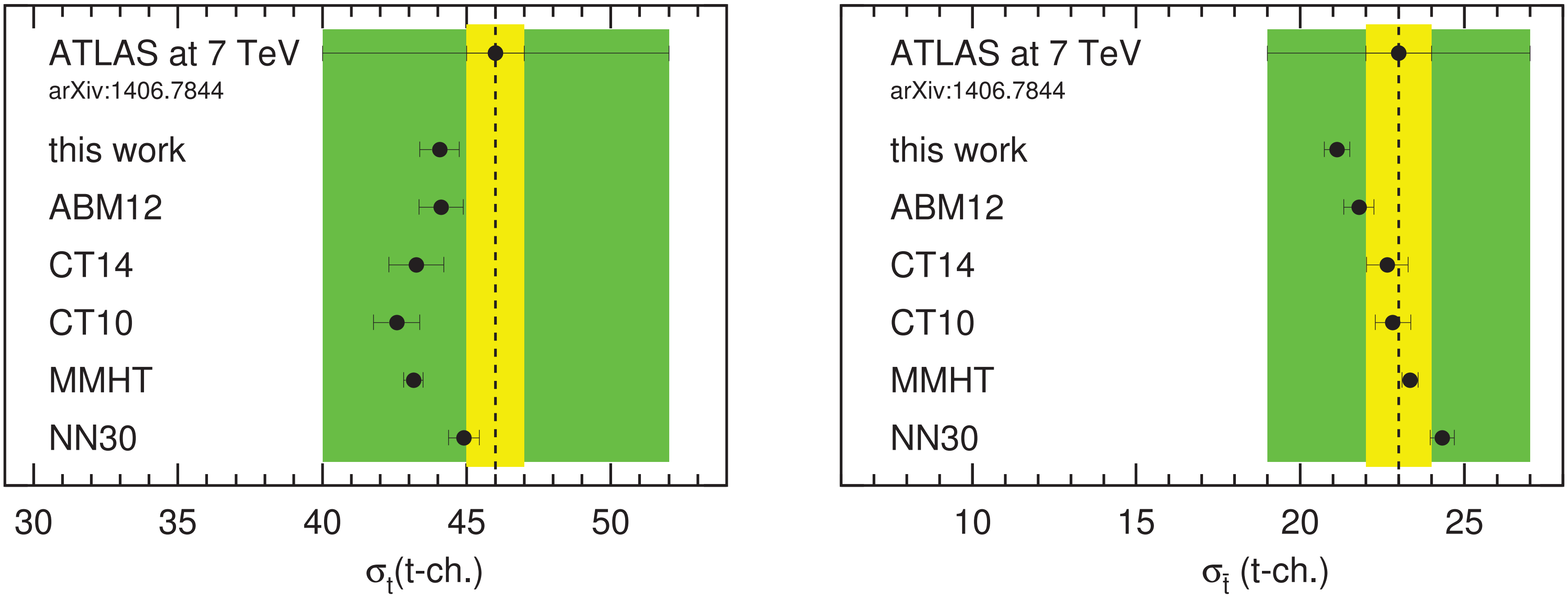


- QCD corrections to t-channel single anti-top quark production at LHC8

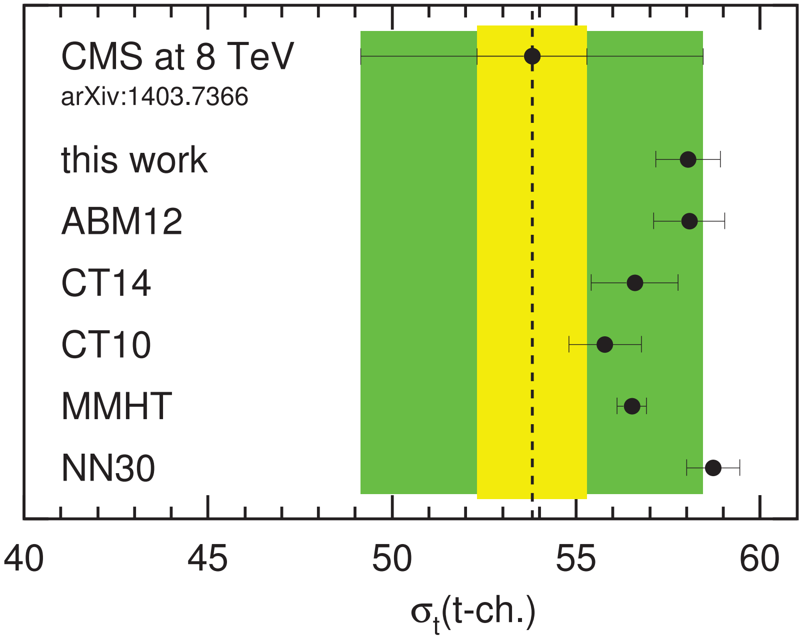
$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$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

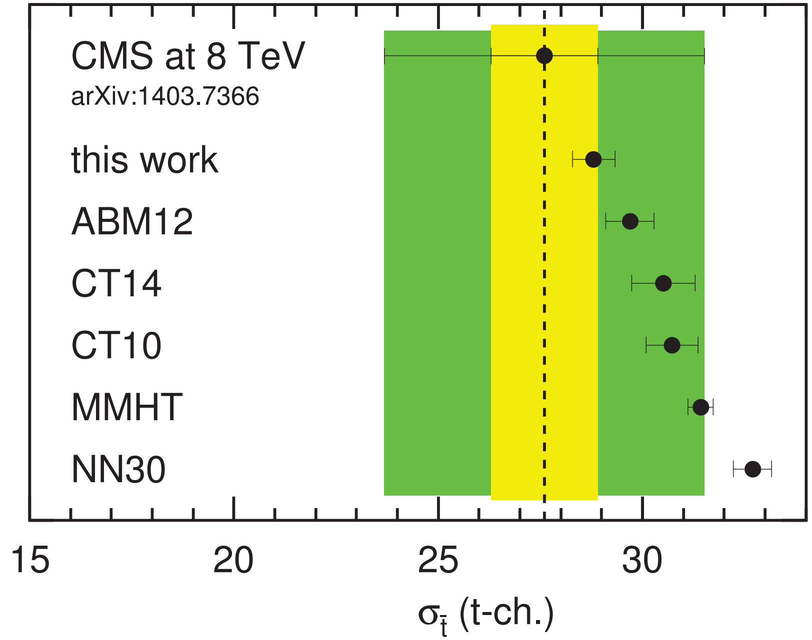
Single-top inclusive cross sections (I)



- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties Alekhin, Blümlein, S.M., Plačakytė '15
  - 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

Single-top inclusive cross sections (II)





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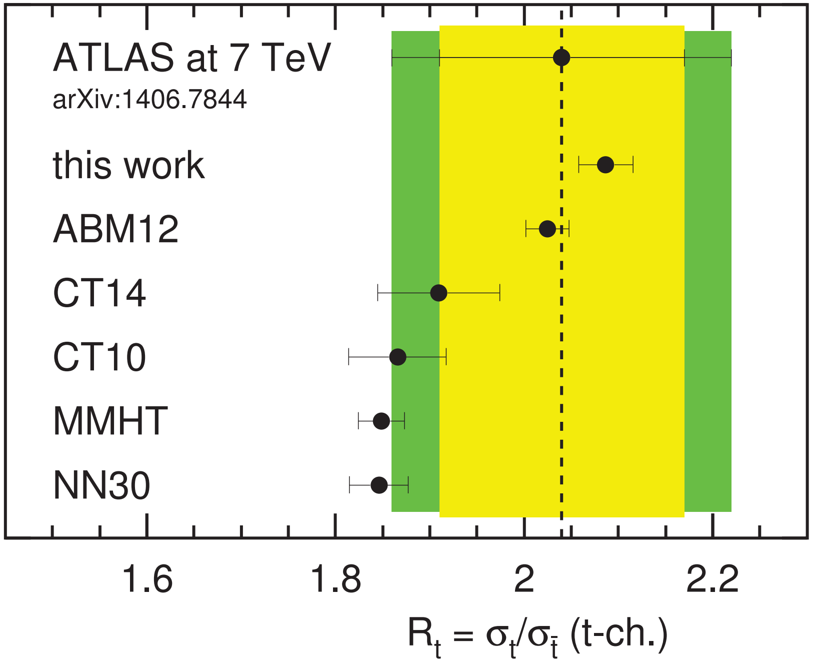
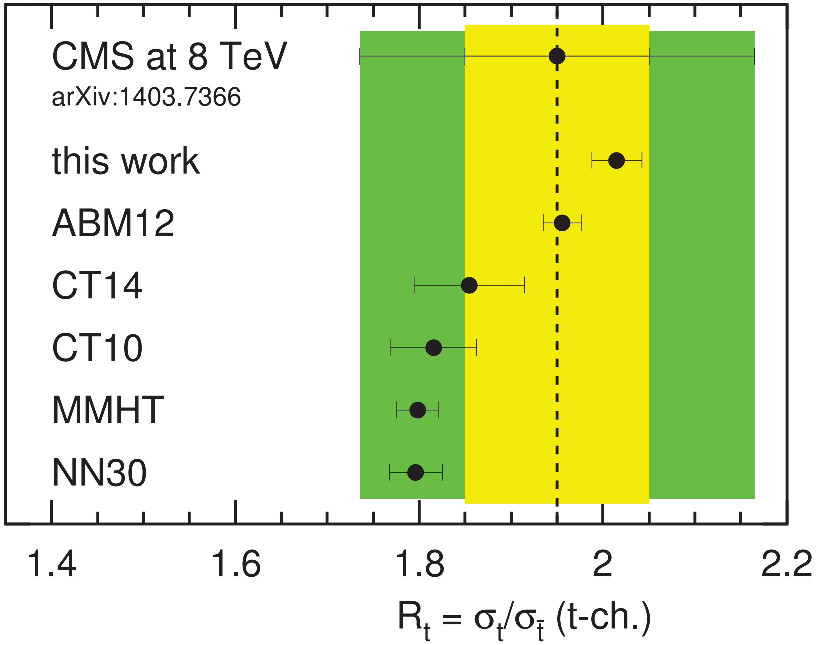
- Data at $\sqrt{s} = 8$ TeV from CMS
  - inner (yellow) band for statistical uncertainty and outer (green) band for combined statistics and systematics uncertainty

Single-top cross section ratio





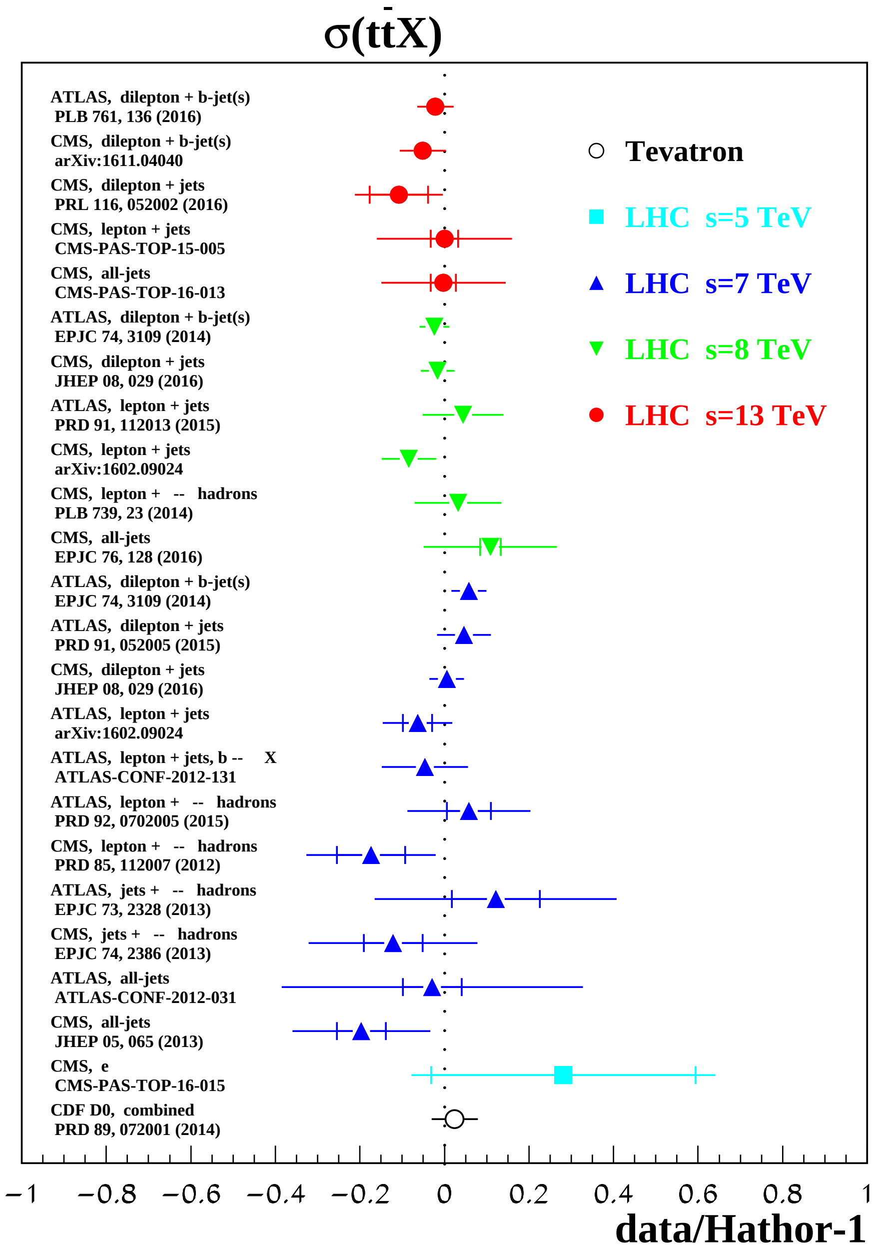
- Cross section ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ is very sensitive probe Alekhin, Blümlein, S.M., Plačakytė '15
  - data from ATLAS and CMS dominated by inner (yellow) band for statistical uncertainty, systematics largey cancel
- Theory predictions sensitive to ratio d/u of PDFs
  - 1σ PDF uncertainties in R_t small

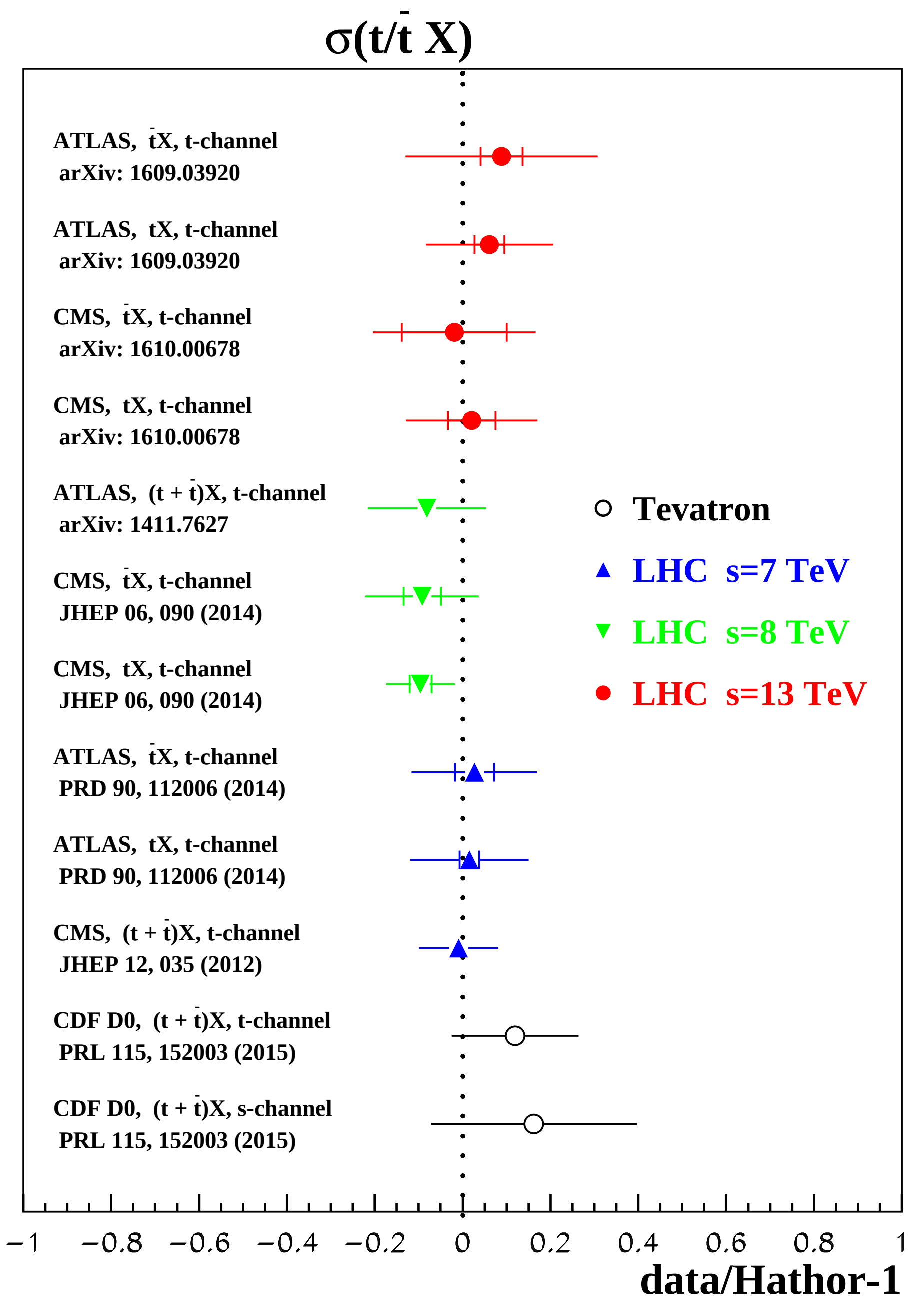
Upshot

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

Top-quark data

Top-quark total cross section data



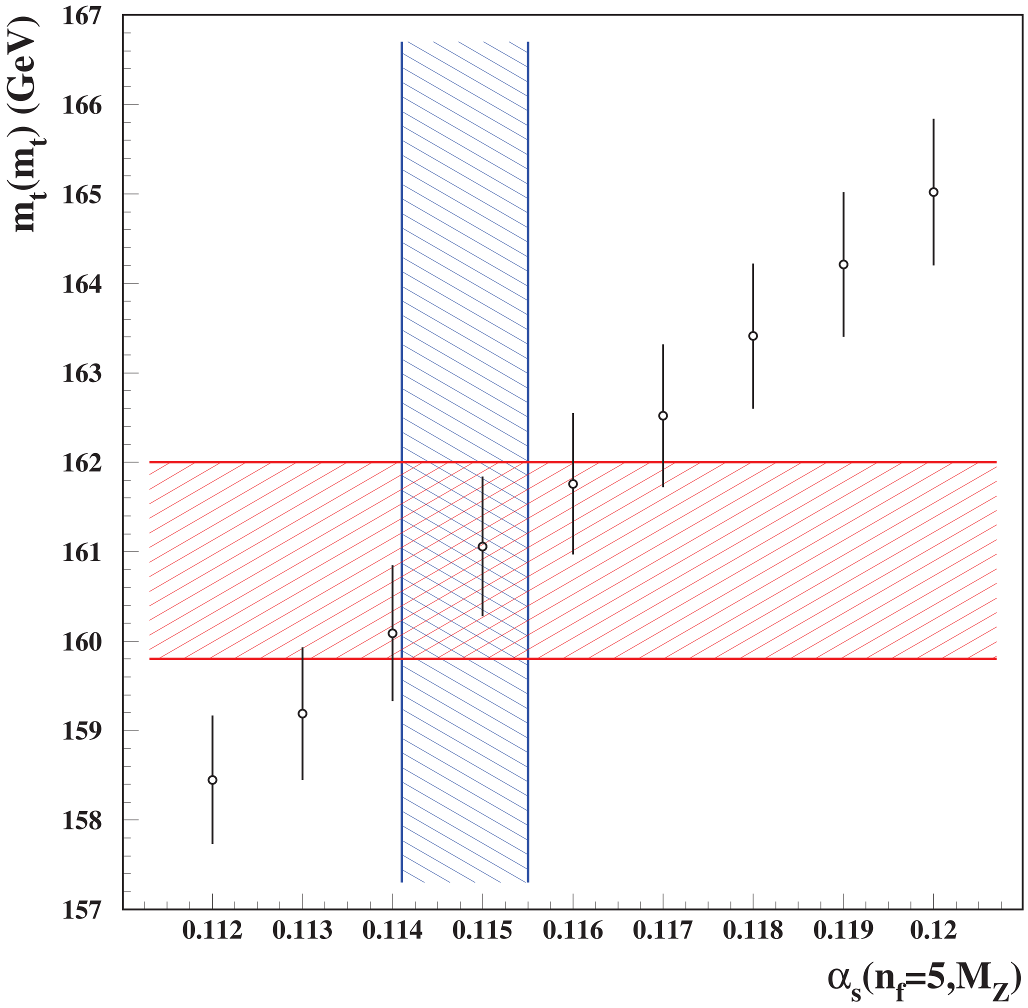


Correlations

Top-quark mass

Alekhin, Blümlein, S.M., Plačakytė ‘16

- Fit with correlations
  - gluon $g(x)$ and $\alpha_s(M_Z)$ already well constrained by global fit
  - strongly correlated with m_t
- Top-quark mass
  $m_t(m_t) = 160.9 \pm 1.1$GeV
- Strong coupling constant
  $\alpha_s(M_Z) = 0.1145 \pm 0.0009$



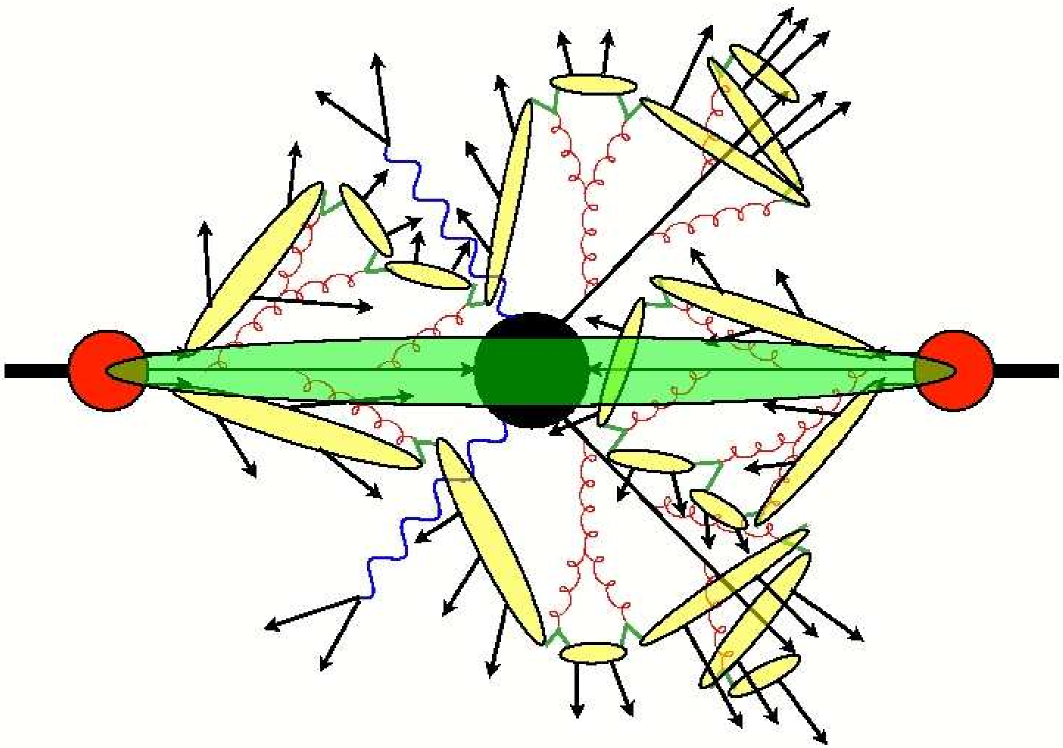
Gluon PDF

- Determinations of large-x gluon PDFs with differential distributions
  Czakon, Hartland, Mitov, Nocera, Rojo ‘16
  - fixing m_t and $\alpha_s(M_Z)$ lacks correlations

Monte Carlo mass

Monte Carlo mass

- Hard interaction and parton emission in QCD followed by hadronization
- Top-quark decays on shell (e.g. leptonic decay $t \to bW \to bl\bar{\nu}_l$)



[picture by B.Webber]

- Intuition: Monte Carlo mass identified with pole mass due to kinematics

$$m_q^2 = E_q^2 - p^2$$

- Caveat: heavy quarks in QCD interact with potential due to gluon field

Calibration of Monte-Carlo Mass (I)

Idea Kieseler, Lipka, S.M. '15

- Simultaneous fit of $m^{\rm MC}$ and observable $\sigma(m_t)$ sensitive to m_t, e.g., total cross section, differential distributions, ...
- Observable σ does not rely on any prior assumptions about relation between m_t and $m^{\rm MC}$
- Extraction of m_t from $\sigma(m_t)$ calibration of $m^{\rm MC}$, e.g. pole mass
$$\Delta_m = m_t^{\rm pole} - m^{\rm MC}$$

Implementation

- Confront N^d reconstructed events to N^p simulated ones
    - model parameters $\vec{\lambda}$

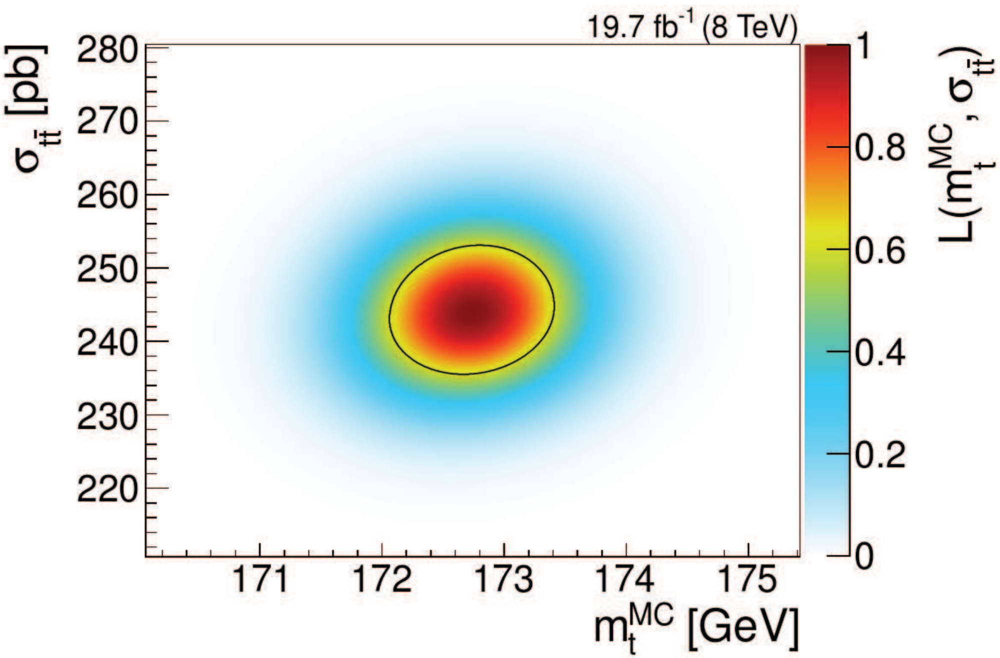
$$N^p = \mathcal{L} \cdot \underbrace{\epsilon(m^{\rm MC}, \vec{\lambda})}_{\text{efficiency}} \cdot \underbrace{\sigma}_{\text{observable}} \cdot \underbrace{n^p(m^{\rm MC}, \vec{\lambda})}_{\text{predicted shape contribution}} + \underbrace{N^{bg}(\vec{\lambda})}_{\text{background}}$$

-
    - shape of distribution constrains $m^{\rm MC}$, normalization determines σ

Top-Quark Monte-Carlo Mass (II)

Likelihood fit [J. Kieseler, DESY-THESIS-2015-054]

- Correlations between $m^{\rm MC}$ and σ present in $\epsilon(m^{\rm MC}, \vec{\lambda})$
  - minimize in $m^{\rm MC}$ dependence in efficiency
- Reduce contribution of $m^{\rm MC}$ to total uncertainty of σ
  - constrain $m^{\rm MC}$ in predicted events $n^p(m^{\rm MC}, \vec{\lambda})$



- Calibration of $m^{\rm MC}$ with uncertainty of approximately $1-2$ GeV on $\Delta_m = m_t^{\rm pole} - m^{\rm MC}$ possible

Summary

Theory predictions for rates and shapes

- Precision predictions of inclusive and differential observables for LHC measurements
- QCD corrections
  - NLO for $2 \to 5$ proceses; NNLO for $2 \to 2$ reactions
- Electroweak corrections at NLO available for most important reactions
- Quality of perturbative expansion depends on scheme for top-quark mass

Top-quark mass

- Top quark mass is parameter of Standard Model Lagrangian
- Measurements of m_t require careful definition of observable
- Correlations in data analysis are important, e.g. with α_s and PDFs
- Relation of Monte Carlo mass $m^{\rm MC}$ to pole mass with additional theory uncertainty Δm_t

Future tasks

- Joint effort theory and experiment