Top theory

What role for precision in top-quark physics?

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Plan

Theory status

- Top-quark pair-production
- Single top-quark production
- Electroweak effects
- Asymmetries

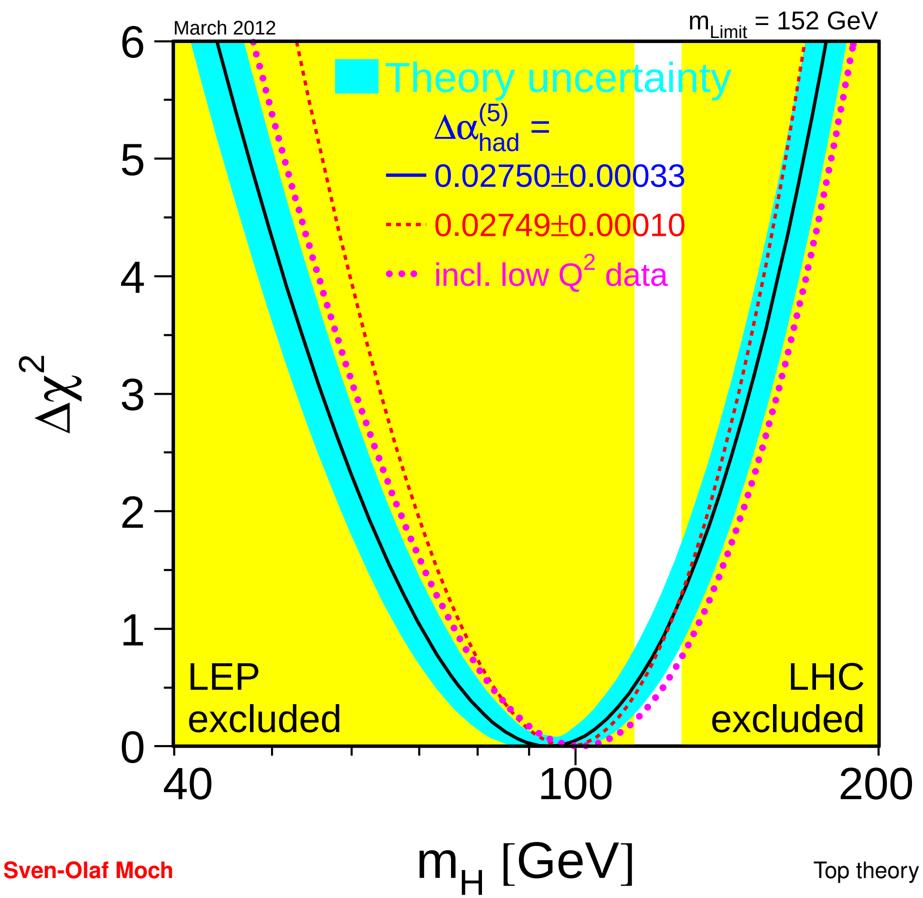
Big question

- Top-quark mass

Why precision?

Long history of indirect searches for new physics

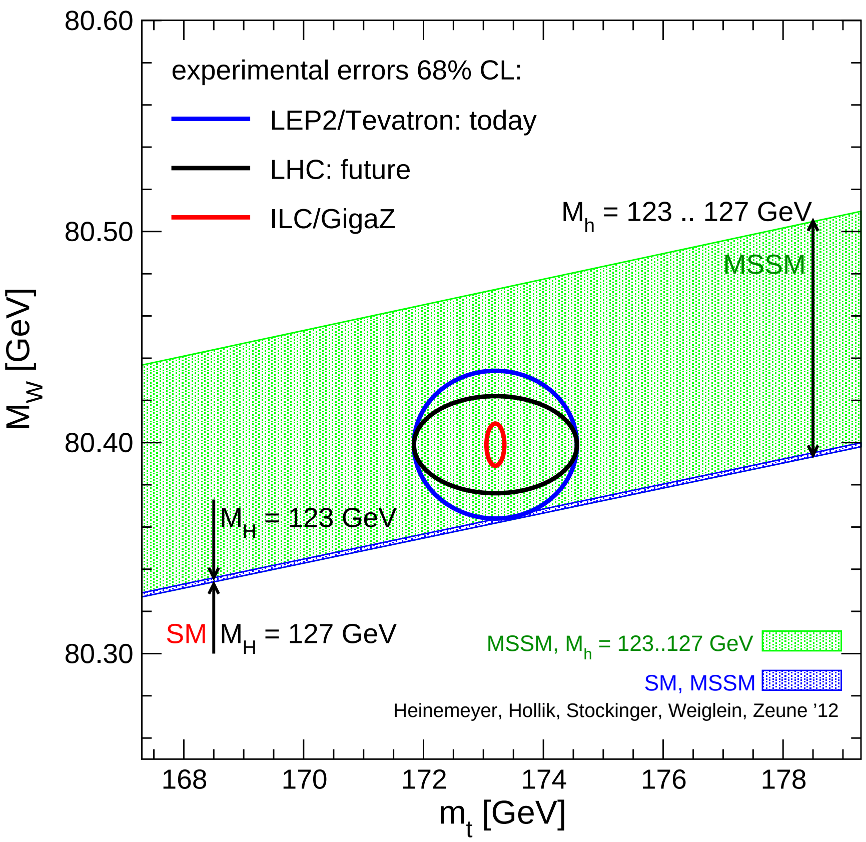
- In absence of direct evidence for new physics look for deviations in precision measurements
- Constraints for parameter space through precision tests
  - e.g., LEP electroweak precision data predicts low Higgs mass M_H



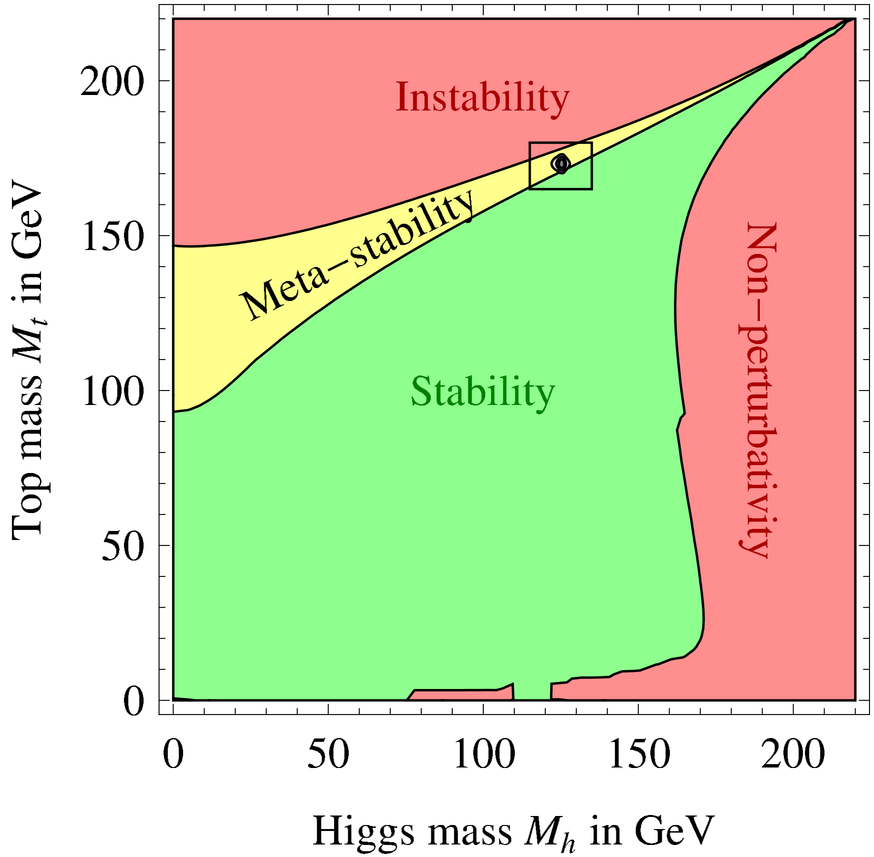
After the Higgs boson discovery

Electroweak precision fits

- Extension to MSSM Heinemeyer, Hollik, Stöckinger, Weiglein, Zeune '12
- Relations for radiative corrections known through two loops
  - need for precise input parameters: M_W and top-quark mass m_t



Electroweak vacuum stability



Bezrukov, Kalmykov, Kniehl, Shaposhnikov '12;
Degrassi, Di Vita, Elias-Miro, Espinosa,
Giudice et al. '12;
Alekhin, Djouadi, S.M. '12; Masina '12;
Buttazzo, Degrassi, Giardino, Giudice, Sala,
Salvio, Strumia '13;
[many people]

- Phase diagram if Standard Model extrapolated up to Planck scale M_P
  - relation between Higgs mass m_H and top quark mass m_t
  - condition of absolute electroweak vacuum stability dependent on m_t
- Precision on m_t decisive for "fate of universe"

Top-quark pair-production

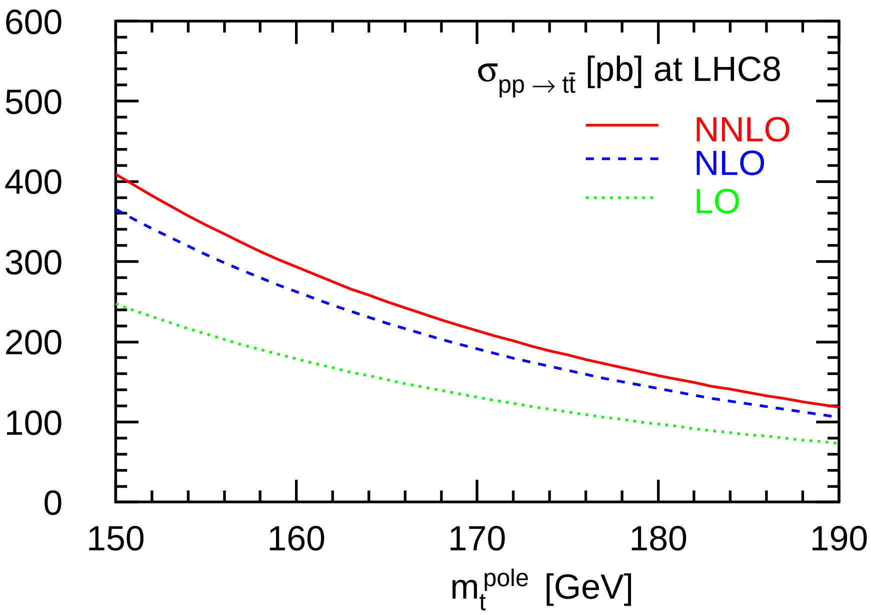
Rates and shapes

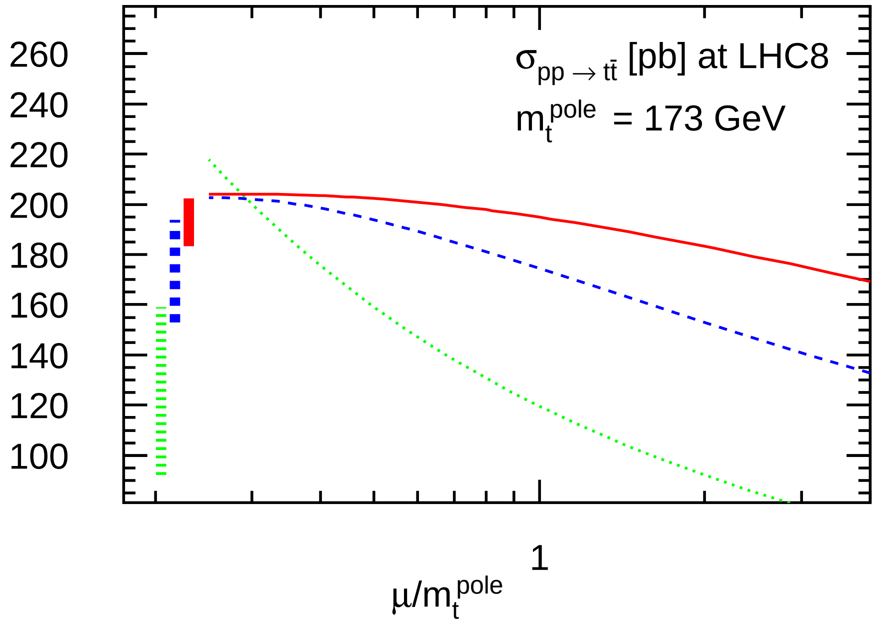
- Requirements for precision of theory predictions
  - driven by accuracy of experimental data
  - QCD corrections at least to NLO in QCD
- NNLO QCD corrections mandatory if data accuracy of $\mathcal{O}(10\%)$ or better
  - inclusive cross section for top-quark pairs at LHC8
  - expected for differential distributions in run II
- Electroweak corrections become important as well, since order $\alpha_s^2 \sim \alpha_{\rm EW}$

Total cross section

Exact result 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 of $\mathcal{O}(\pm 5\%)$
- Beyond NNLO
  - theory improvements with soft gluon resummation [many people]
  - K-factor (NNLO $\to$ resummed) small; scale stability further improved

Top-quark mass from total cross section

- Intrinsic limitation of sensitivity in total cross section

$$\left| \frac{\Delta \sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \right| \simeq 5 \times \left| \frac{\Delta m_t}{m_t} \right|$$

- QCD factorization for cross section

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

  - joint dependence on non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, masses m_X

Correlations are essential

- Cross section at LHC has correlation of m_t, $\alpha_S(M_Z)$ and gluon PDF $\sigma_{t\bar{t}} \sim \alpha_s^2 m_t^2 g(x) \otimes g(x)$
  - effective parton $\langle x \rangle \sim 2m_t/\sqrt{s} \sim 2.5 \dots 5 \cdot 10^{-2}$
  - fit with fixed values of m_t and $\alpha_S(M_Z)$ carries significant bias
    Czakon, Mangano, Mitov, Rojo ‘13
  - fit with PDF re-weighting and fixed values of m_t insufficient
    Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan ‘12

Going differential

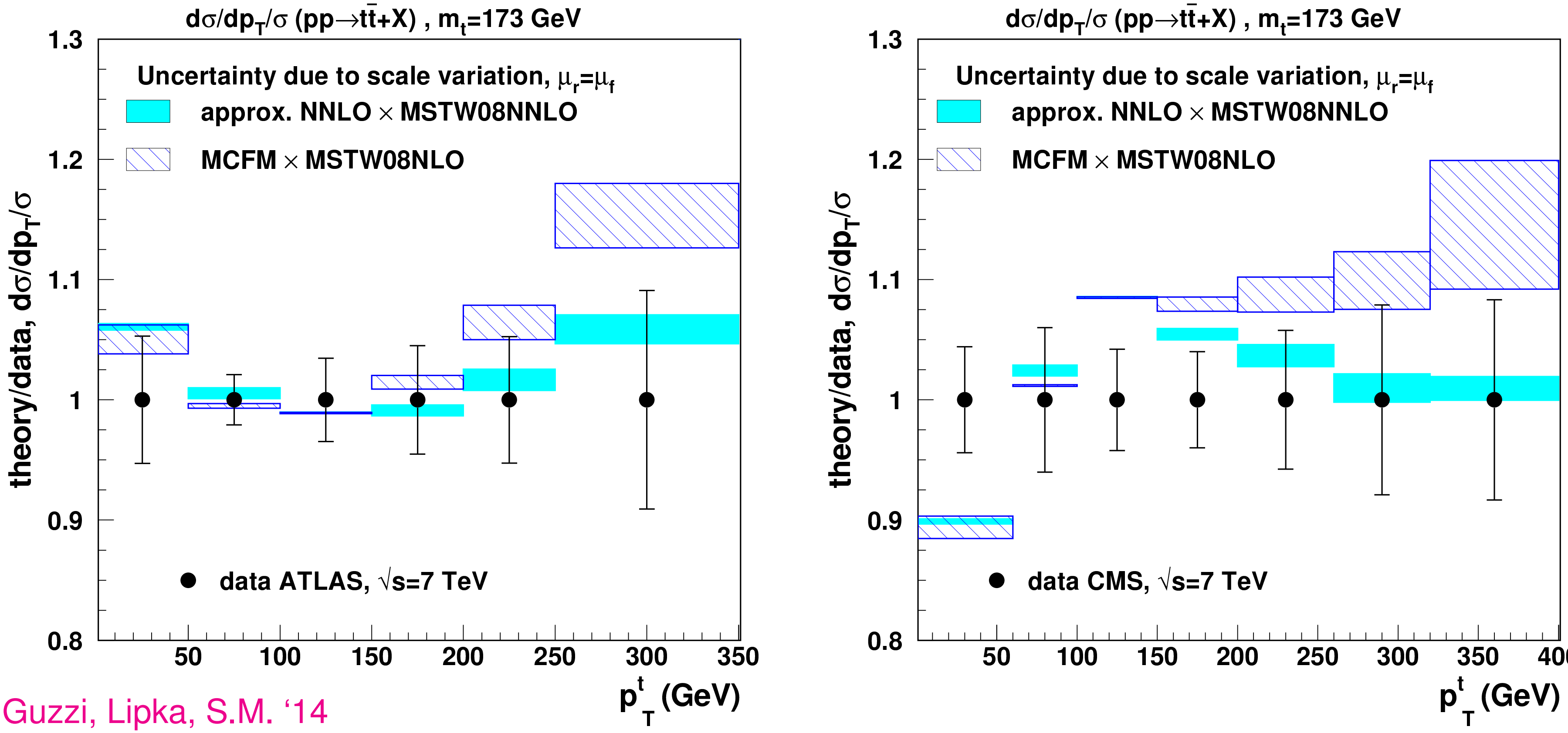
Shapes

- NNLO QCD corrections mandatory if data accuracy of $\mathcal{O}(10\%)$ or better
- Case for:
  - inclusive cross section for top-quark pairs at LHC8
  - expected for differential distributions in run II

Strategy

- In absence of complete NNLO QCD predictions can resort to approximations
- Exploit Sudakov resummation of soft gluon emission
  - physical cross sections convolution with parton luminosity dominated by threshold logarithms
- Approximate NNLO results in (semi-inclusive) kinematics
  Kidonakis, Sterman '96; . . . ; Ahrens, Ferroglia, Neubert, Pecjak, Yang '11; Kidonakis '12; Ferroglia, Pecjak, Yang '13
- Upshot: single variable differential distributions in p_T^t, y^t, $m_{t\bar{t}}$ available

Distributions at (approximately) NNLO



Guzzi, Lipka, S.M. '14

- Approximate NNLO results show trend in right direction for comparison with data
- Great opportunity for high statistics measurements in run II
  - fast and reliable numerical codes are essential (interface to fastNLO or Applgrid)

Tools 4 you: available codes

Total cross section

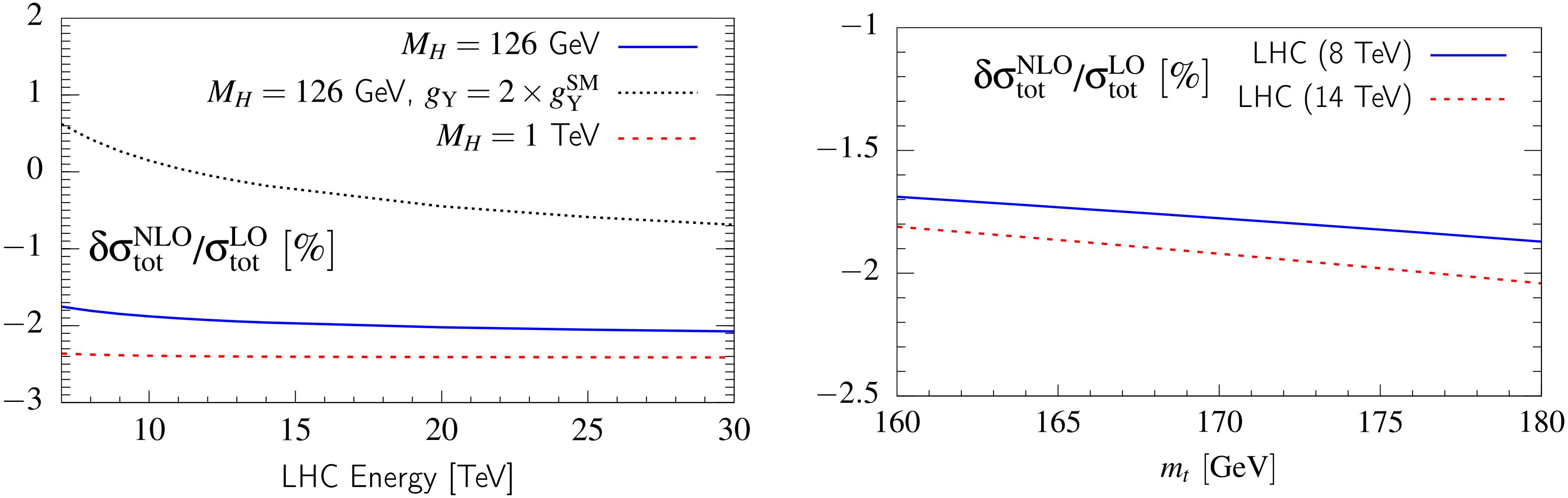
- NNLO QCD corrections and soft gluon resummation
  - Hathor Aliev, Lacker, Langenfeld, S.M., Uwer, Wiedermann [arXiv:1007.1327]
  - Top++ Czakon, Mitov [arXiv:1112.5675]
  - TOPIXS Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan [arXiv:1206.2454]

Differential distributions

- NLO QCD corrections (in association with jets, leptons, . . .)
- Fixed order with on-shell top-quarks or decays
  - MCFM Campbell, Ellis [arXiv:1204.1513]
- Matched to parton shower
  - MC@NLO Frixione, Webber [hep-ph/0305252]
  - 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]

Electroweak corrections

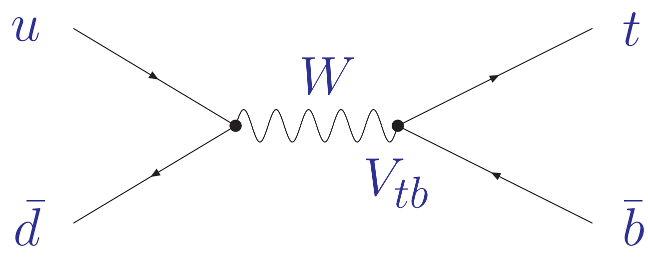
- Electroweak corrections (ratio of $\sigma_{\mathrm{EW}}/\sigma_{\mathrm{LO}}$)
  Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth '94; Bernreuther, Fücker '05; Kühn, Scharf, Uwer '06



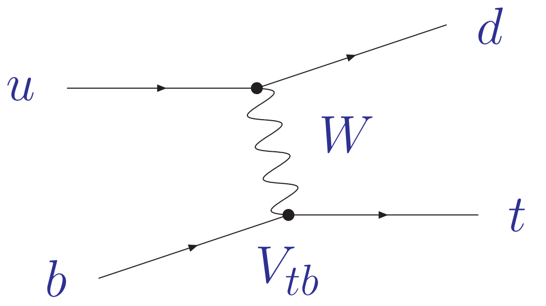
- Left: $\sigma_{\mathrm{EW}}/\sigma_{\mathrm{LO}}$ as function of total cms energy (effect depends on Higgs mass and Higgs-Yukawa coupling)
- Right: $\sigma_{\mathrm{EW}}/\sigma_{\mathrm{LO}}$ as function of top-quark mass:
  $\mathcal{O}(2\%)$ with respect to σ_{LO} negative contribution to total cross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

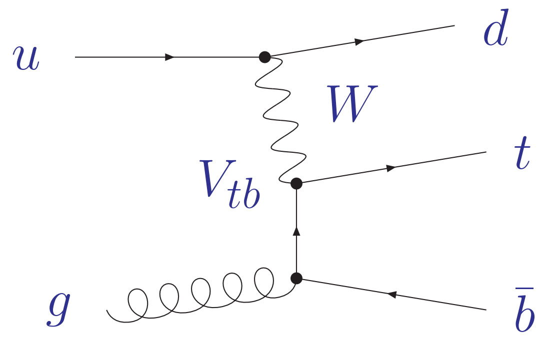
Single top-quark production

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

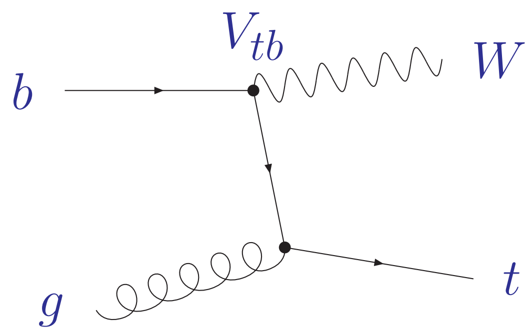


- t-channel production
  - bg-channel at NLO enhanced by gluon luminosity





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



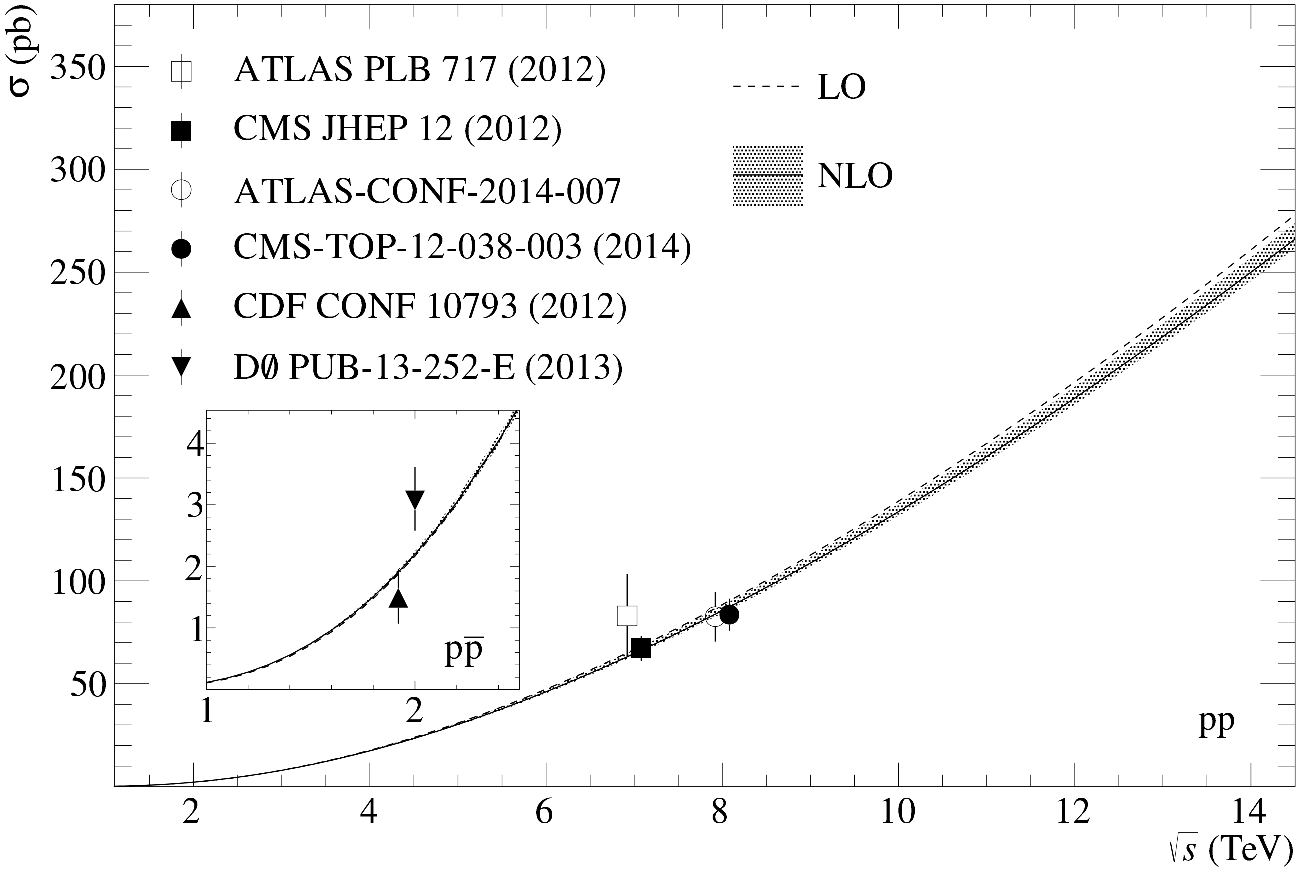
Theory status

- QCD corrections known
  - complete NLO Harris, Laenen, Phaf, Sullivan, Weinzierl '02; Sullivan '04; Campbell, Frederix, Maltoni, Tramontano '09; [+ many people]
  - implementations merged with parton shower
    - in MC@NLO Frixione, Laenen, Motylinski, Webber, White '09
    - in POWHEG Aioli, Nason, Oleari, Re '09
  - approximate NNLO corrections Kidonakis '11, '13

Treatment of heavy quarks

- Scheme with $n_l = 4$ light flavors + heavy quark of mass m_b at low scales
  - no mass singularities for $m_b, m_t \gg \Lambda_{QCD}$, no (evolving) PDFs
- Scheme with $n_l = 5$ light flavors
  - b PDF for $Q \ggg m_b$ generated perturbatively

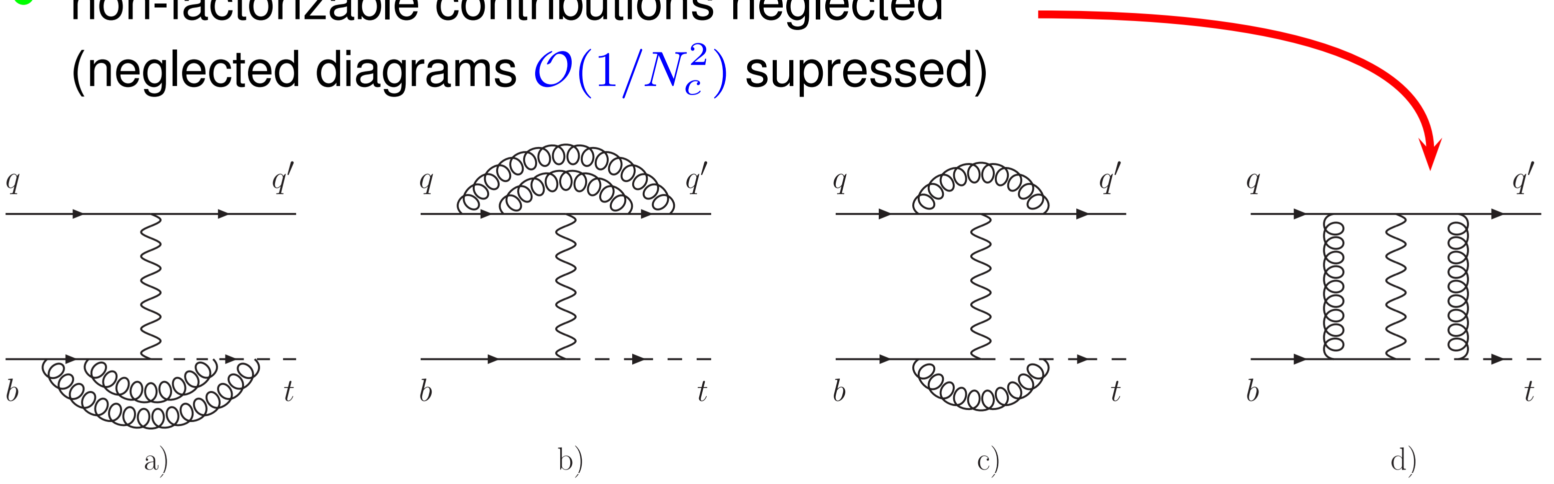
Single top-quark t-channel production



- **New:** Approximate NNLO QCD corrections in Hathor v2.0
  Kant, Kind, Kintscher, Lohse, Martini, Mölbitz, Rieck, Uwer [to appear]

QCD corrections at NNLO

- **New:** 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	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

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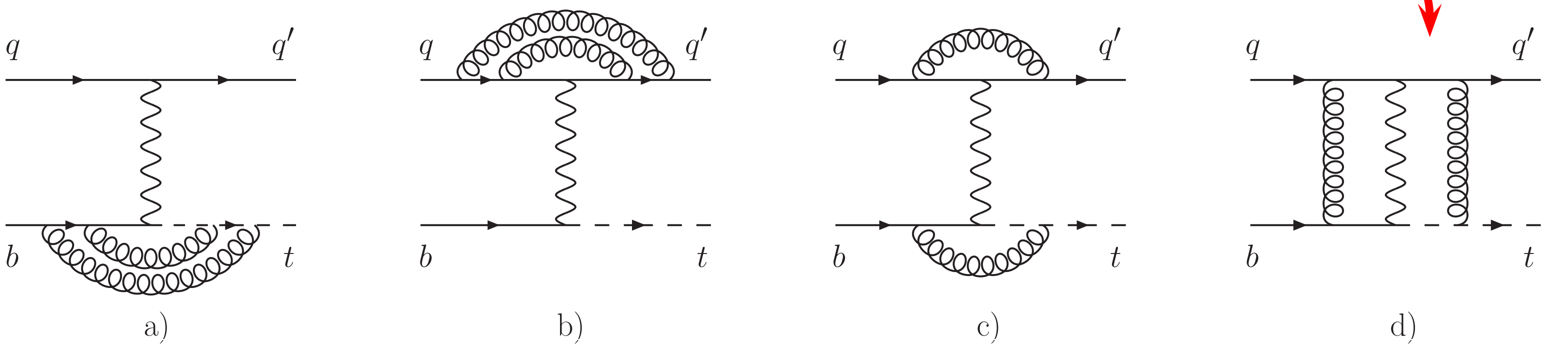
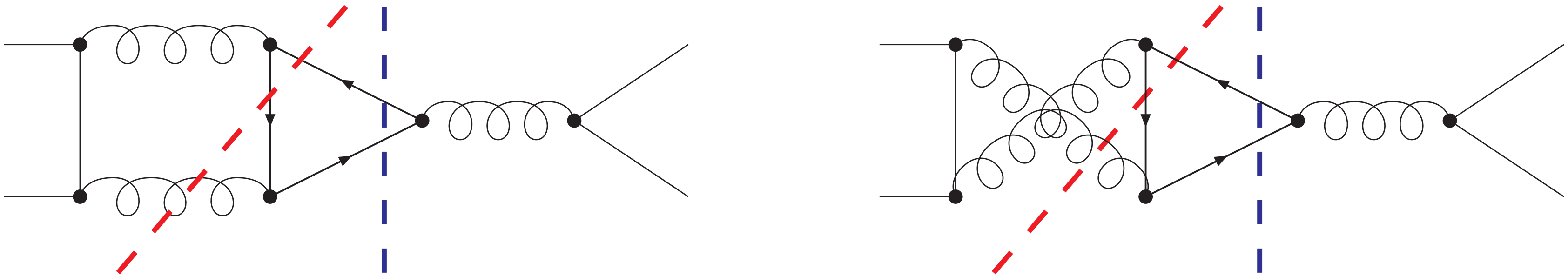


- QCD corrections to t-channel single anti-top quark production at LHC8

$p_\perp$	$\sigma_{\rm LO}$, 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	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

Charge asymmetry

- Top-quark charge asymmetry arises from interference between real emission and virtual contributions
  - interference term does not contribute to total cross section (Furry's theorem)
- Asymmetric contribution for un-integrated $t\bar{t}$ phase space
  - virtual corrections
  - real corrections

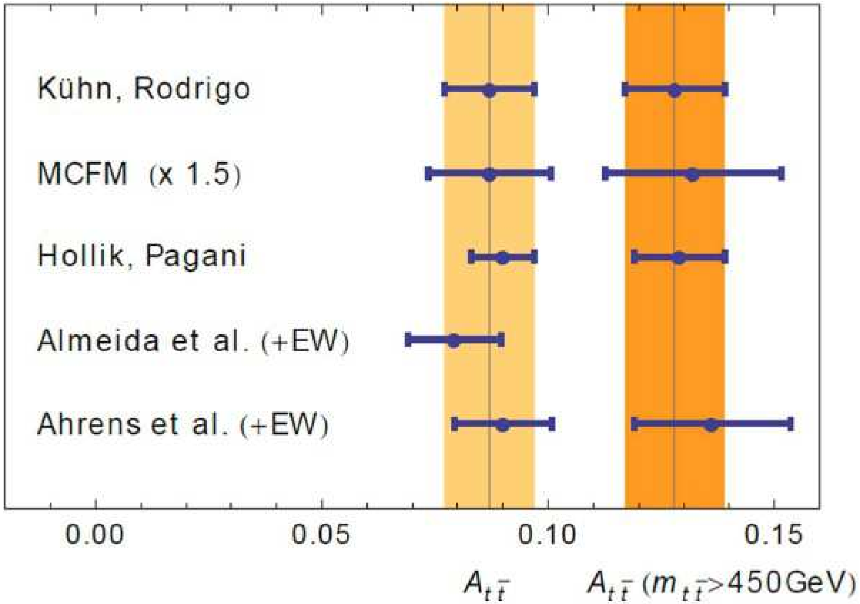


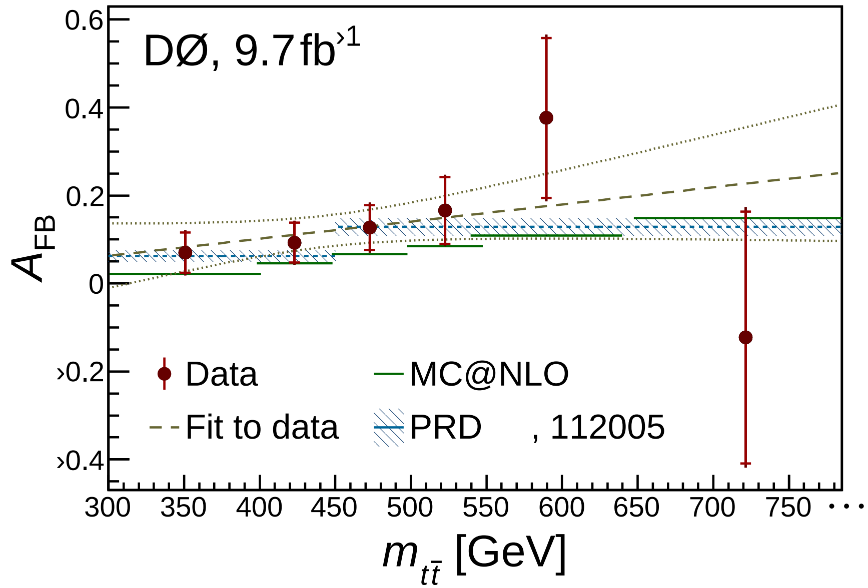
- Asymmetry is genuine quantum effect
  - theory predictions effectively leading order only
  - interpretation requires good understanding of the quantum level

Forward-backward asymmetry at Tevatron

- Top-quark forward-backward asymmetry A_{FB} definitions at Tevatron with $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$

$$A_{\rm FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} > 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} > 0)}$$





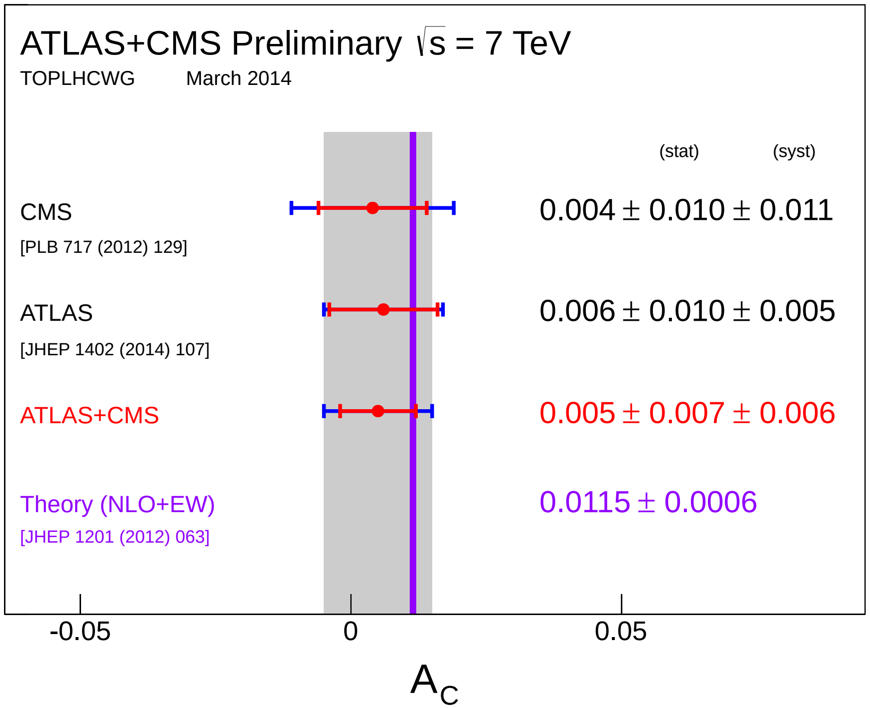
- Consistent picture from theory predictions include QCD+EW corrections Kühn, Rodrigo '11; Hollik, Pagani '11 or soft gluon resummation Almeida, Sterman, Vogelsang '08; Ahrens, Ferroglia, Neubert, Pecjak, Yang '11
- Two-loop QCD corrections neded for assessment of theory uncertainty

Charge asymmetry at LHC

- Top-quark charge asymmetry A_C at LHC with $\Delta|y| = |y_t| - |y_{\bar{t}}|$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| > 0)}{N(\Delta|y| > 0) + N(\Delta|y| > 0)}$$

  - no forward backward charge asymmetry, because initial state at LHC is P symmetric



- Consistency with theory predictions, but again two-loop QCD corrections needed

Top quark mass

What is the value of the top quark mass ?

$$m_t = ?$$

Quark masses in Standard Model

- Higgs boson gives mass to matter fields via Higgs-Yukawa coupling
  - large top quark mass m_t

QCD

- Classical part of QCD Lagrangian

$$\mathcal{L} \quad = \quad -\frac{1}{4} F^a_{\mu\nu} F_b^{\mu\nu} + \sum_{\text{flavors}} \bar{q}_i \left(\mathrm{i} \not{D} - m_q \right)_{ij} q_j$$

  - field strength tensor $F^a_{\mu\nu}$ and matter fields $q_i, \bar{q}_j$
  - covariant derivative $D_{\mu,ij} = \partial_\mu \delta_{ij} + \mathrm{i} g_s \left(t_a \right)_{ij} A^a_\mu$

- Formal parameters of the theory (no observables)
  - strong coupling $\alpha_s = g_s^2/(4\pi)$
  - quark masses m_q

Challenge

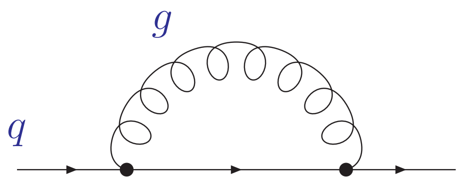
- Suitable observables for measurements of α_s, m_q, . . .
  - comparison of theory predictions and experimental data

Quark mass renormalization

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 $\mathcal{O}(\Lambda_{QCD})$
- Ambiguity Δm_q in definition of pole mass up to corrections $\mathcal{O}(\Lambda_{QCD})$
Bigi, Shifman, Uraltsev, Vainshtein '94; Beneke, Braun '94; Smith, Willenbrock '97
  - lattice QCD bound: $\Delta m_q \geq 0.7 \cdot \Lambda_{QCD} \simeq 200$ MeV Bauer, Bali, Pineda '11

Short distance mass

- Short distance masses ($\overline{MS}$, 1S Hoang, Ligeti, Manohar '98; Hoang, Teubner '99, PS Beneke '98, . . .) probe at scale of hard interaction:
$m_{\rm pole} = m_{\rm short\ distance} + \delta m$
- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
- Conversion between $m_{\rm pole}$ and $\overline{MS}$ mass $m(\mu_R)$ in perturbation theory
Gray, Broadhurst, Gräfe, Schilcher '90; Chetyrkin, Steinhauser '99; Melnikov, v. Ritbergen '99

Top quark mass

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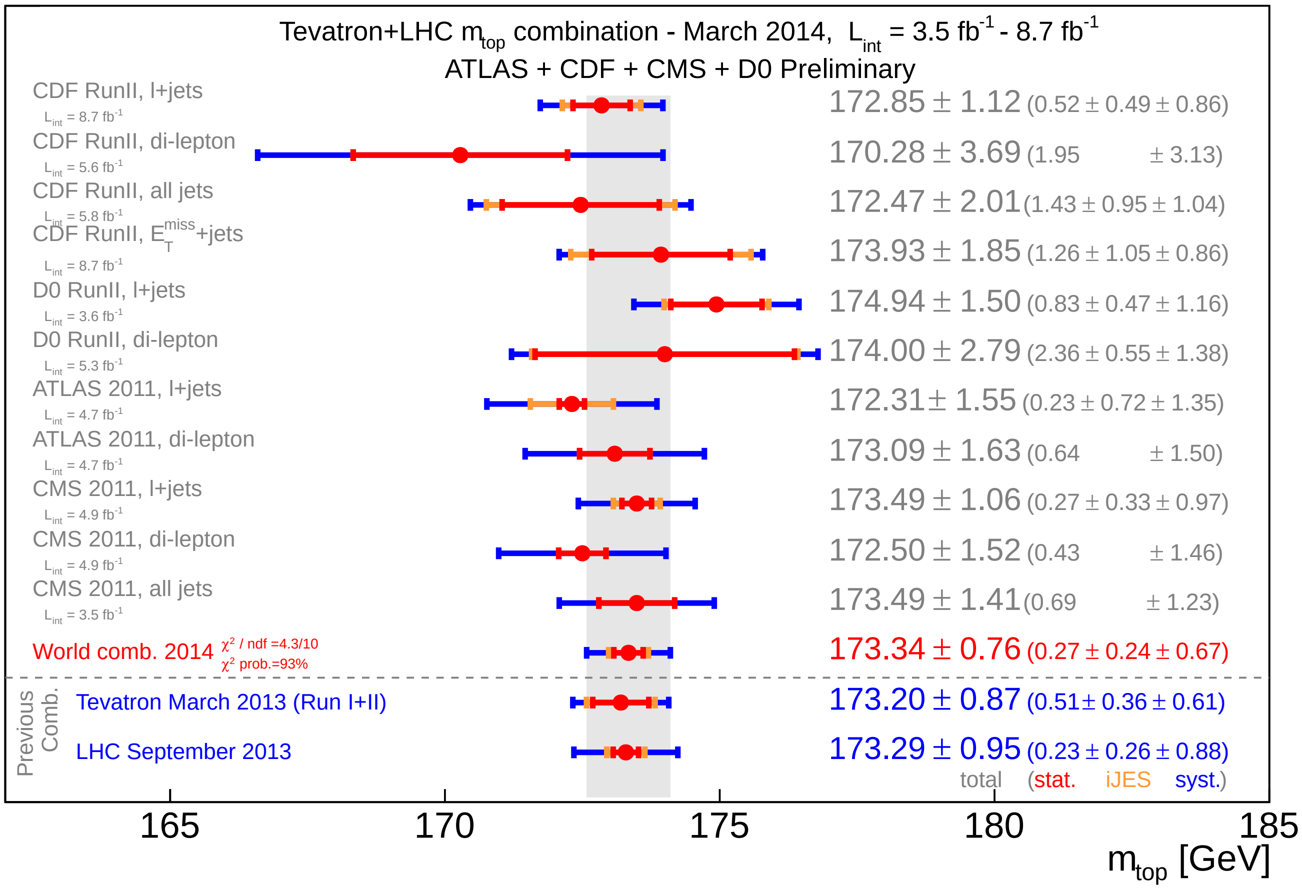
Some Answers



World combination

Experiment: ATLAS, CDF, CMS & D0 coll. 1403.4427

$$m_t = 173.34 \pm 0.76\,\text{GeV}$$

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In all measurements considered in the present combination, the analyses are calibrated to the Monte Carlo (MC) top-quark mass definition.

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Theory:

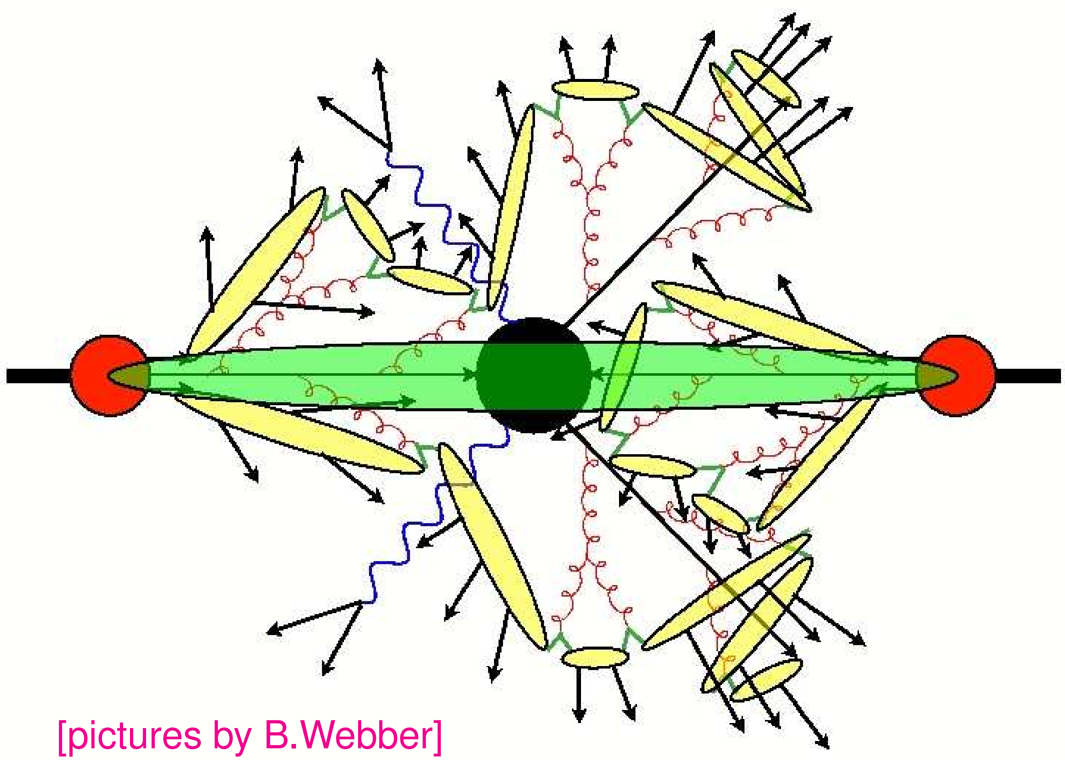
That is, we can state as the final result for the likely relation between the top quark mass measured using a given Monte Carlo event generator ("MC") and the pole mass as

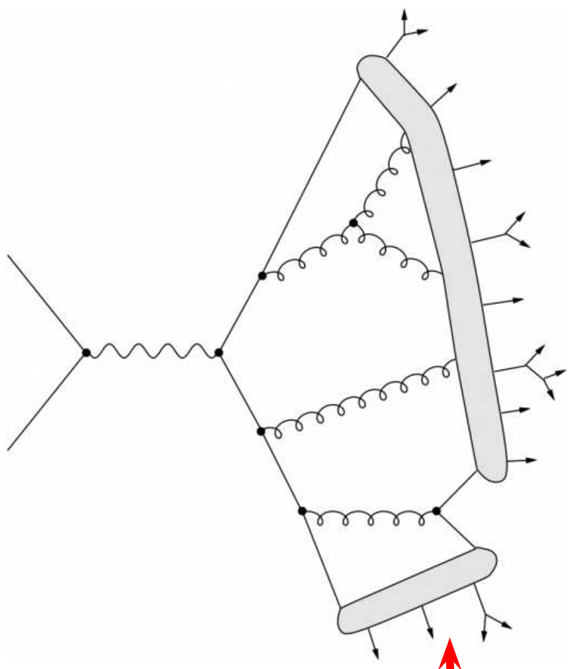
$$m_{\text{pole}} = m_{\text{MC}} + Q_0 \left[\alpha_s(Q_0) c_1 + \ldots\right]$$

where $Q_0 \sim 1$ GeV and c_1 is unknown, but presumed to be of order 1 and, according to the argument above, presumed to be positive.

A. Buckley et al. arXiv:1101.2599

Monte Carlo mass



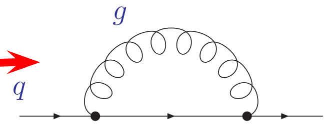


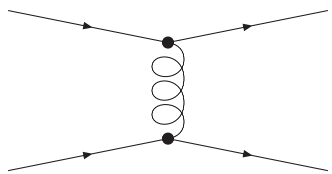
[pictures by B.Webber]

- Intuition tells, that Monte Carlo mass is pole mass due to kinematics $E_q^2 - p^2 = m_q^2$
- Quantum mechanics considers particles in potential
  - heavy quarks interact with potential due to gluon field
- String hadronization model based on potential energy of heavy-quark pair (colored sources)

Static energy of heavy-quark

- Consider static energy $E_{\rm stat}$ of heavy-quark pair
  - well-defined problem in perturbation theory at large scales R
  - use lattice at small scales
- QCD corrections to static energy receives from
  - heavy-quark self-energy $\Sigma(p, m_q)$
  - heavy-quark potential $V(R)$





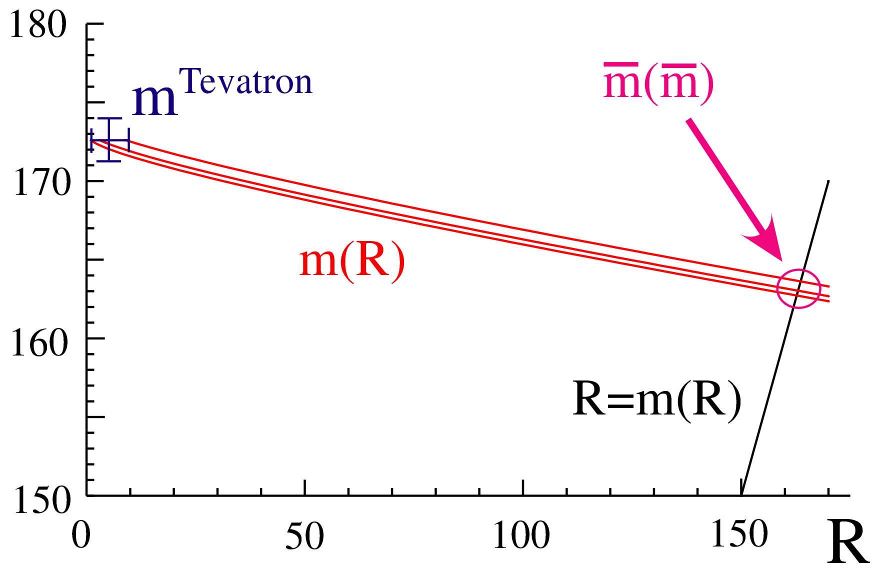
- Renormalon ambiguities in QCD corrections can cancel between $\Sigma(p, m_q)$ and $V(R)$

$$
\begin{aligned}
E_{\rm stat} &= 2m_q + 2\Sigma(m_q, m_q) + V(R) \\
&= 2m_{\rm pole} + V(R) \\
&= 2m^{\rm MSR}(R) + \Big(2\Sigma^{\rm fin}(R, R) + V(R)\Big)
\end{aligned}
$$

- Extraction of a short-distance mass $m^{\rm MSR}(R)$ from the quarkonium spectrum is free of an ambiguity of order $\mathcal{O}(\Lambda_{QCD})$
  Hoang, Smith, Stelzer, Willenbrock '98

Conversion of Monte Carlo mass to pole mass

- Running of $m^{\mathrm{MSR}}(R)$ mass
  Hoang, Stewart '08



Strategy

- Identify Monte Carlo mass with short distance mass at low scale $\mathcal{O}(1)$ GeV
  $m^{\mathrm{MC}} \to m^{\mathrm{MSR}}(R)$ with $R \simeq 1 \ldots 9\mathrm{GeV}$
- Choice 1: run $m^{\mathrm{MSR}}(R)$ from low scale to $R = m_t$: $m^{\mathrm{MSR}}(R) \to m(m)$ and convert from $m(m)$ to pole mass [arXiv:1405.4781]

$m^{\mathrm{MSR}}(1)$	$m^{\mathrm{MSR}}(3)$	$m^{\mathrm{MSR}}(9)$	$\overline{m}(\overline{m})$	$m^{\mathrm{pl}}_{1\mathrm{lp}}$	$m^{\mathrm{pl}}_{2\mathrm{lp}}$	$m^{\mathrm{pl}}_{3\mathrm{lp}}$
173.72	173.40	172.78	163.76	171.33	172.95	173.45

- Choice 2: convert from $m^{\mathrm{MSR}}(R)$ at low scale directly to pole mass

$m^{\mathrm{MSR}}(1)$	$m^{\mathrm{MSR}}(3)$	$m^{\mathrm{MSR}}(9)$	$m^{\mathrm{pl}}_{1\mathrm{lp}}$	$m^{\mathrm{pl}}_{2\mathrm{lp}}$	$m^{\mathrm{pl}}_{3\mathrm{lp}}$
173.72	173.40	172.78	173.72	173.87	173.98

Conversion of Monte Carlo mass to pole mass

Summary

$$m_{\rm pole} \;=\; 173.34 \,\pm\, 0.76\,\text{GeV (exp)} \;+\; \Delta m\text{(th)}$$

with

$$\Delta m\text{(th)} \;=\; \pm 0.7\,\text{GeV}\,(m^{\rm MC} \to m^{\rm MSR}(3\text{GeV})) \;+\; 0.5\,\text{GeV}\,(m(m) \to m_{\rm pole})$$

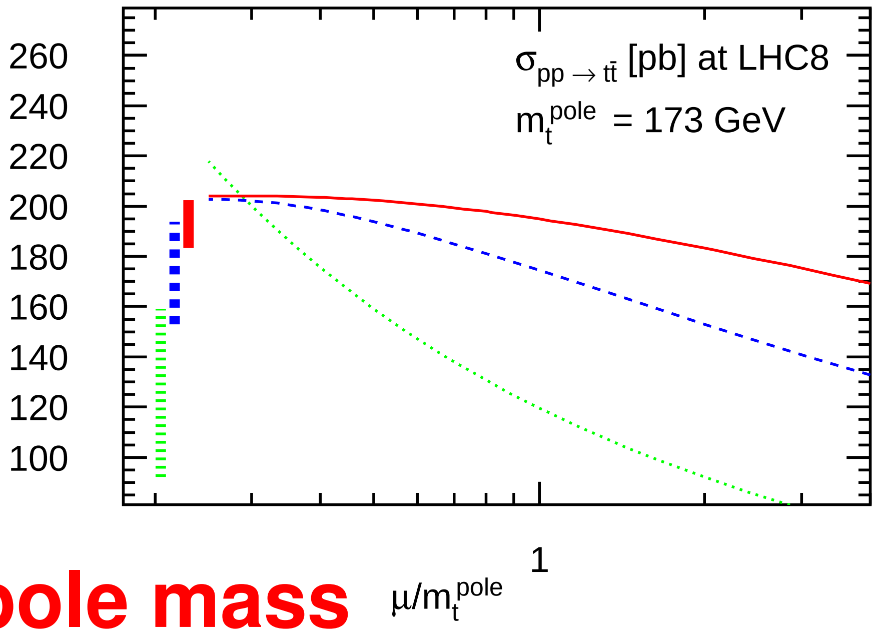
Alternative mass measurements

- Rates and shapes of distributions offer possibility for top mass determination with well-defined renormalization scheme
- Requirements:
  - theory predictions at least to NLO in QCD
  - sufficient sensitivity to m_t (kinematics)
- Observables (examples):
  - inclusive cross section
  - shapes of distributions; e.g., m_{lb} distribution or jet rates

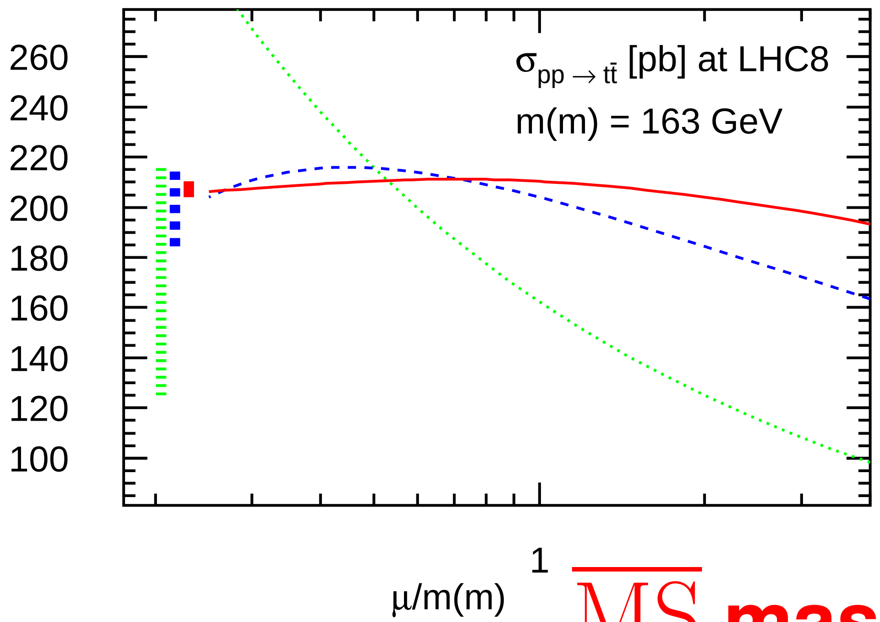
Total cross section with running mass

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

Dowling, S.M. '13



pole mass

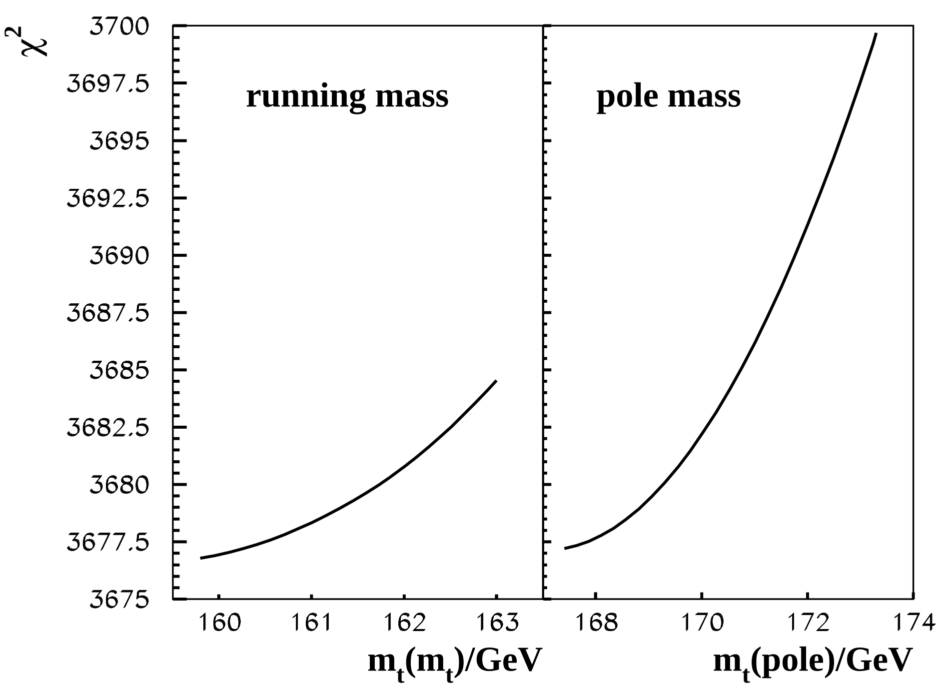


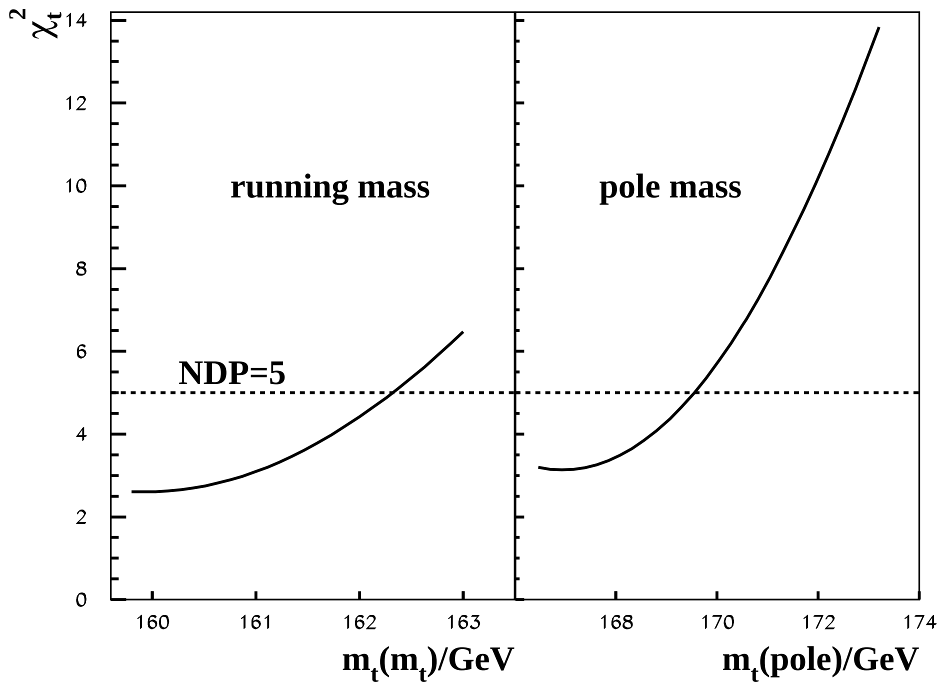
$\overline{\mathrm{MS}}$ mass

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

Top cross section data in ABM12 fit

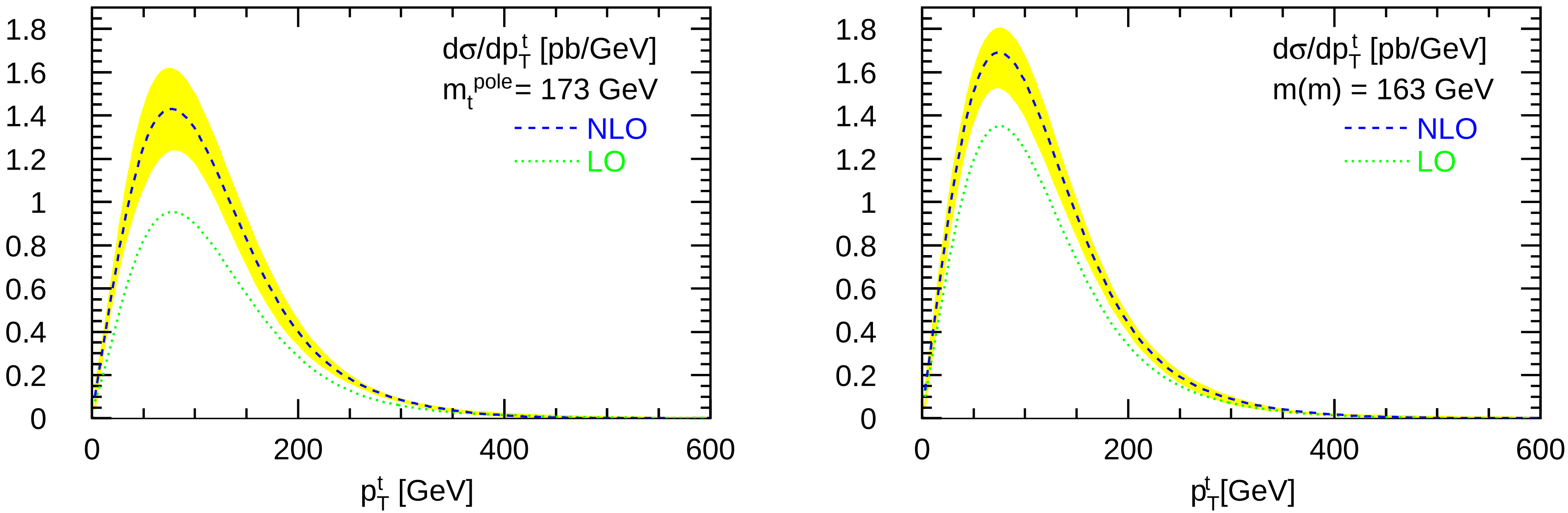
- Fit with correlations
  - $g(x)$ and $\alpha_s(M_Z)$ already well constrained by global fit (no changes)
  - for fit with $\chi^2/NDP = 5/5$ obtain value of $m_t(m_t) = 162.3 \pm 2.3$ GeV (equivalent to pole mass $m_t = 171.2 \pm 2.4$ GeV) Alekhin, Blümlein, S.M. '13
  - χ^2-profile steeper for pole mass (bigger impact of top-quark data and greater sensitivity to theoretical uncertainty at NNLO)





Differential cross sections

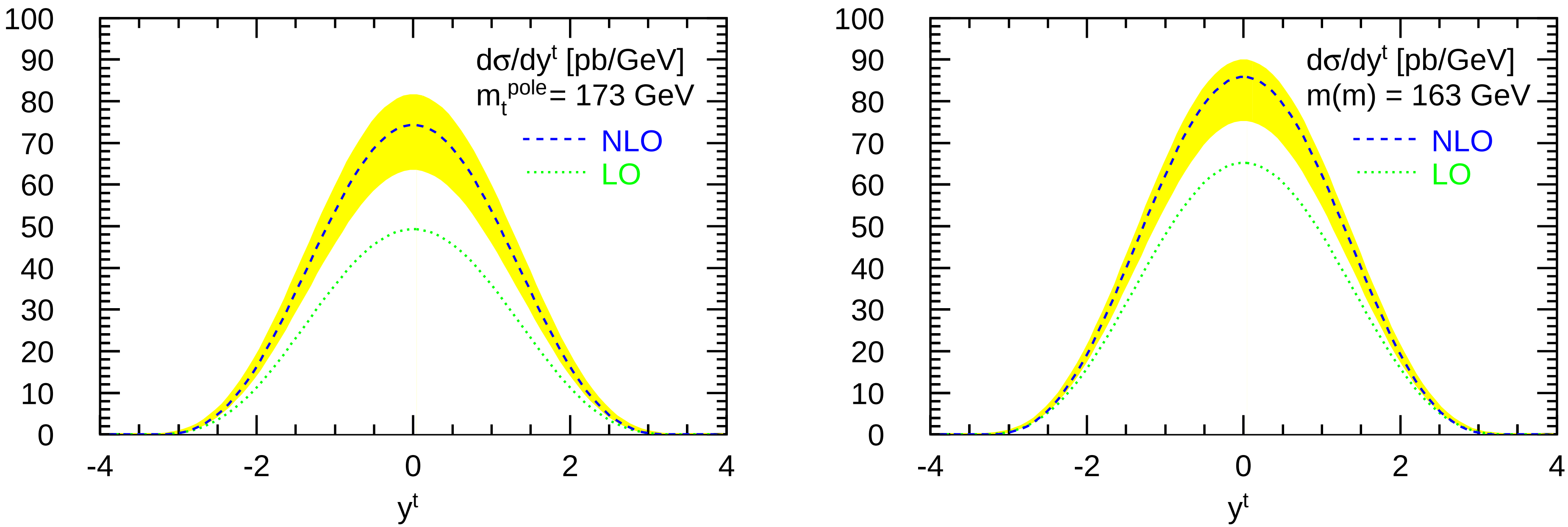
NLO in QCD



- Running mass for differential distributions show same features, e.g. p_T^t-distribution Dowling, S.M. ‘13

Differential cross sections

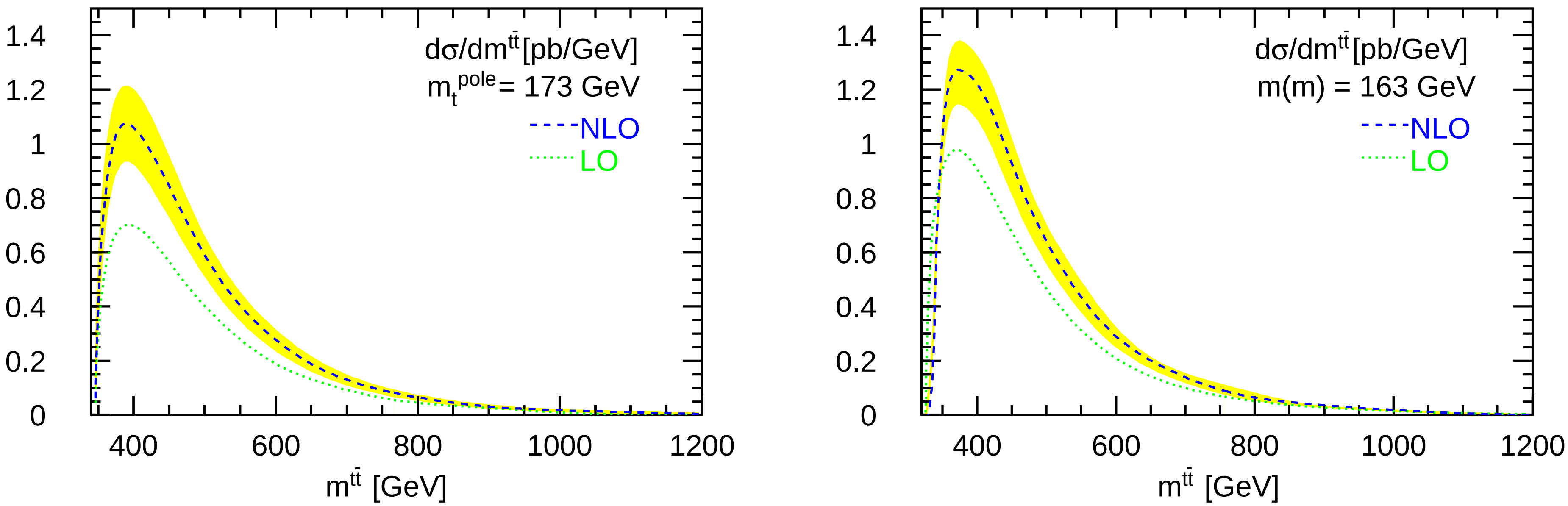
NLO in QCD



- Running mass for differential distributions show same features, e.g. y^t-distribution Dowling, S.M. '13

Differential cross sections

NLO in QCD



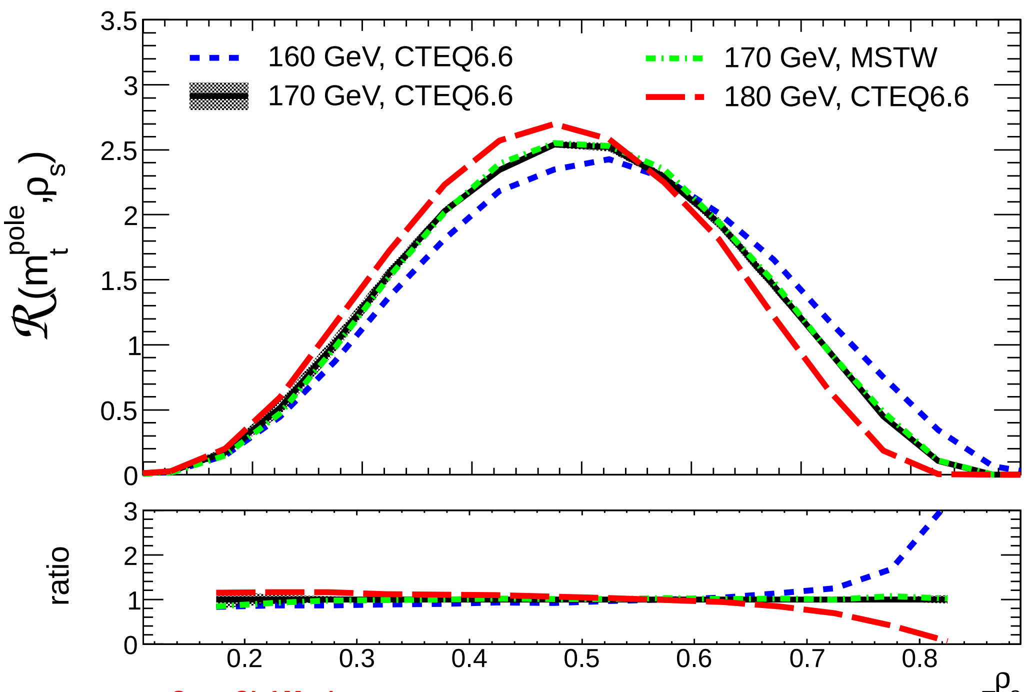
- Running mass for differential distributions show same features, e.g. $m_{t\bar{t}}$-distribution Dowling, S.M. '13

Top-quark pairs with one jet

- Mass measurement from shape of distribution for invariant mass of $t\bar{t} + 1\mathrm{jet}$ system — Alioli, Fernandez, Fuster, Irles, S.M., Uwer, Vos '13
  - variable $\rho_s = \frac{2 \cdot m_0}{\sqrt{s_{t\bar{t}+1\mathrm{jet}}}}$ with fixed scale $m_0 = 170\,\mathrm{GeV}$
- Normalized-differential $t\bar{t} + \mathrm{jet}$ cross section

$$\mathcal{R}(m_t, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1\mathrm{jet}}}{d\rho_s}(m_t, \rho_s)$$

  - significant mass dependence for $0.4 \leq \rho_s \leq 0.5$ and $0.7 \leq \rho_s$

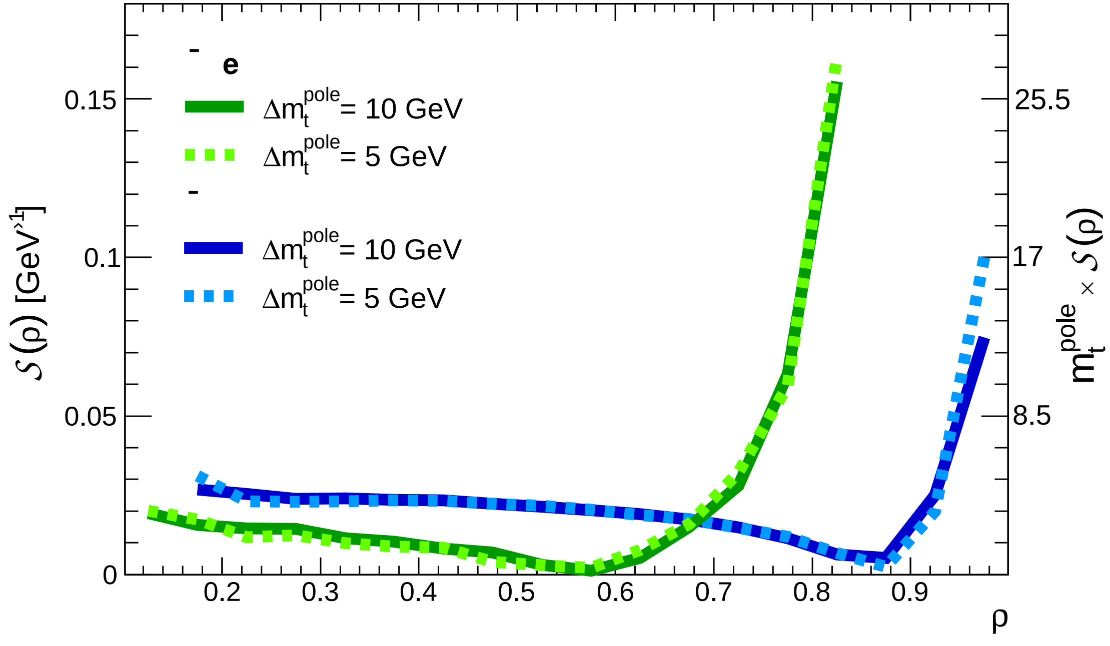


Mass sensitivity

- Differential cross section $\mathcal{R}(m_t, \rho_s)$
  - good pertubative stability, small theory uncertainties, small dependence on experimental uncertainties, ...
- Sensitivity to top-quark mass very good

$$\left|\frac{\Delta\mathcal{R}}{\mathcal{R}}\right| \simeq (m_t\mathcal{S}) \times \left|\frac{\Delta m_t}{m_t}\right|$$

  - increased sensitivity for system $t\bar{t} + \mathrm{jet}$ compared to $t\bar{t}$



Summary

Theory predictions for rates and shapes

- Precision predictions of inclusive and differential observables for LHC measurements
- QCD corrections at NNLO + electroweak corrections at NLO
- Quality of perturbative expansion depends on scheme for top-quark mass
- Short-distance masses $\overline{MS}$ $m(m)$ or $m^{\rm MSR}(R)$ show better convergence and scale stability

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