Top quark cross section and applications

Sven-Olaf Moch

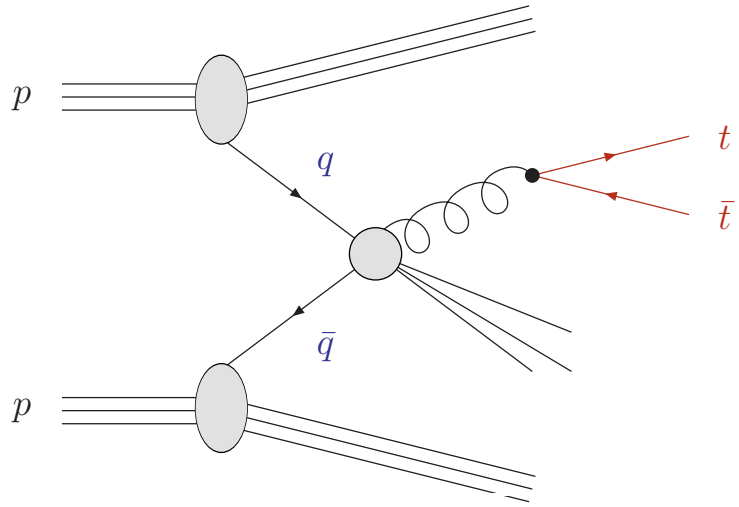
Universität Hamburg & DESY, Zeuthen

LHC physics discussions: Top, Hamburg, Oct 30, 2012

https://indico.desy.de/conferenceDisplay.py?confId=6492

Top-quark pair production

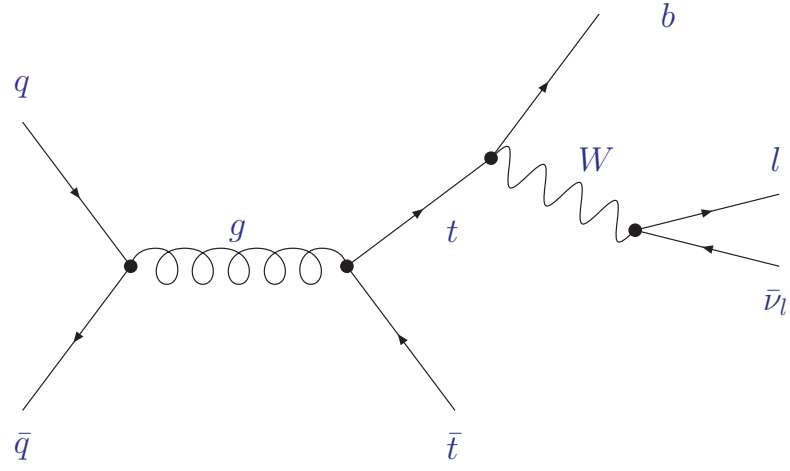
- Hadronic reaction $pp/p\bar{p}$:
  - QCD factorization: $\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$



- Parton cross section $\hat{\sigma}_{ij\to t\bar{t}}$ known to NLO in QCD Nason, Dawson, Ellis '88; Beenakker, Smith, van Neerven '89; Mangano,Nason, Ridolfi '92; Bernreuther, Brandenburg, Si, Uwer '04; Mitov, Czakon '08; ...
  - NLO accurate to $\mathcal{O}(15\%)$ at LHC (NNLO around the corner)
- Relevant kinematics:
  - high-energy limit $s \gg m^2$ with BFKL logarithms $\ln s/m^2$
  - partonic threshold $s \simeq 4m^2$ with Sudakov logarithms $\ln \beta$ (velocity of heavy quark $\beta = \sqrt{1-4m^2/s}$)

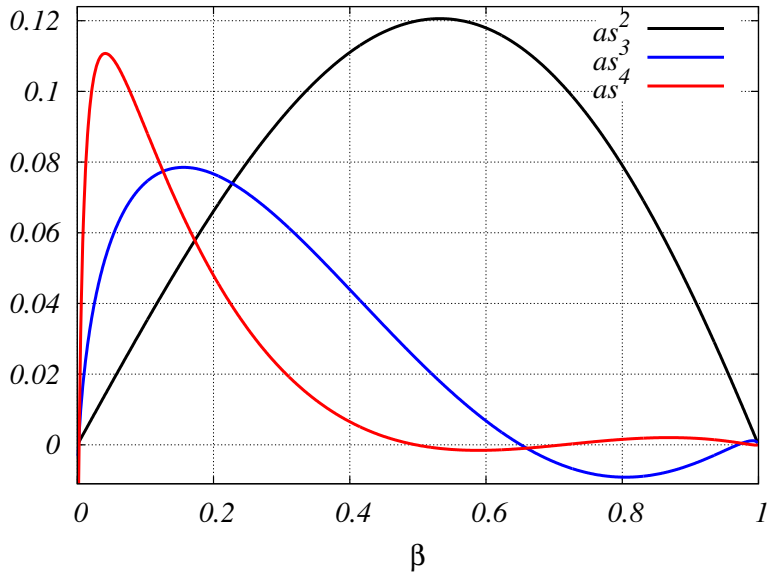
Hard scattering process

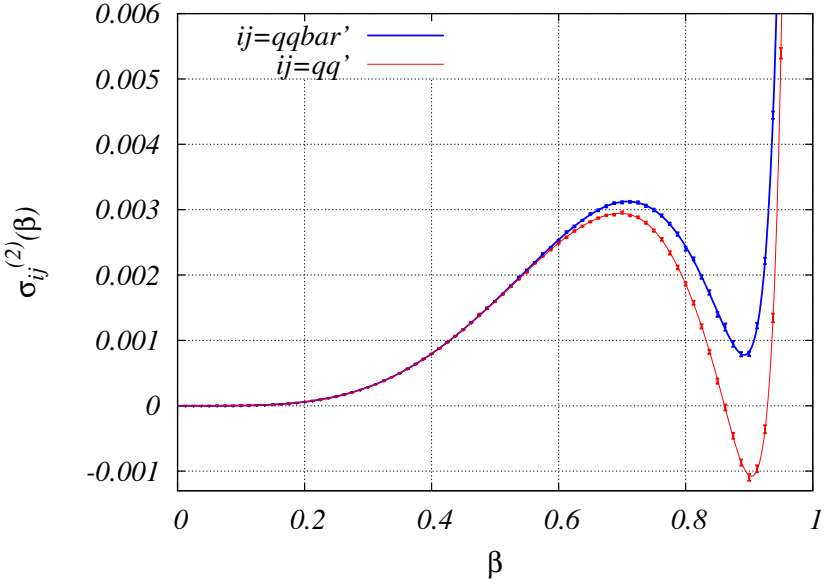
- Born process ($q\bar{q}$-channel) with leptonic decay $t \to bl\bar{\nu}_l$



Top-pair hadro-production

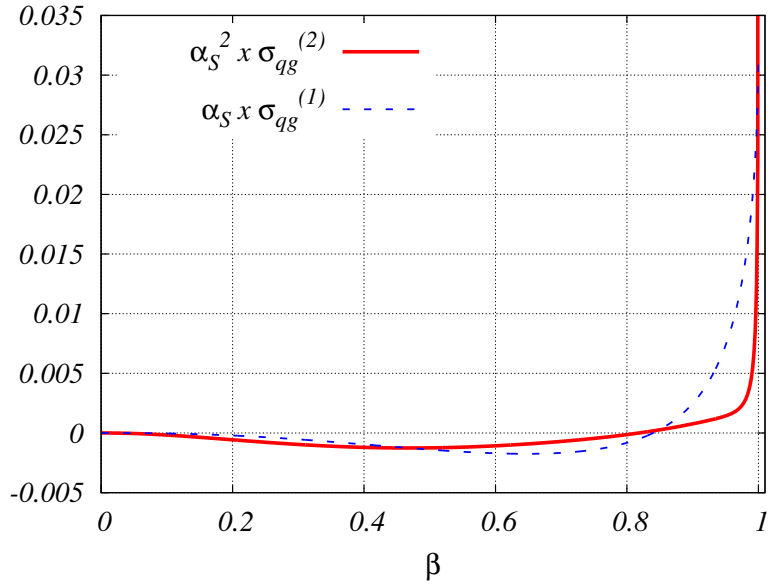
- NNLO cross section for heavy-quark hadro-production
- Exact results for channel $q\bar{q} \to t\bar{t}$ Czakon, Mitov '12
  - gluon exchange in s-channel (left) and t-channel (right)





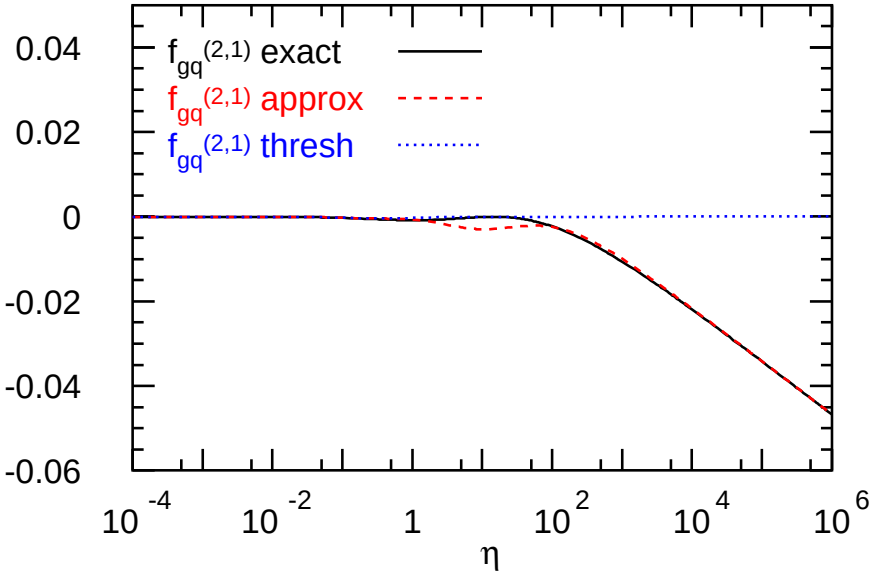
Top-pair hadro-production

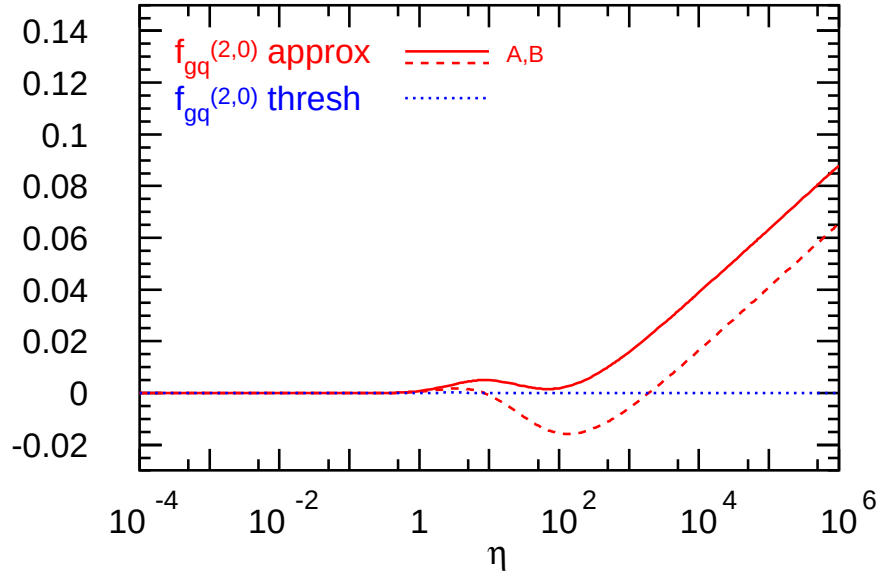
- NNLO cross section for heavy-quark hadro-production
- Exact results for channel $qg \to t\bar{t}$ Czakon, Mitov '12



Top-pair hadro-production

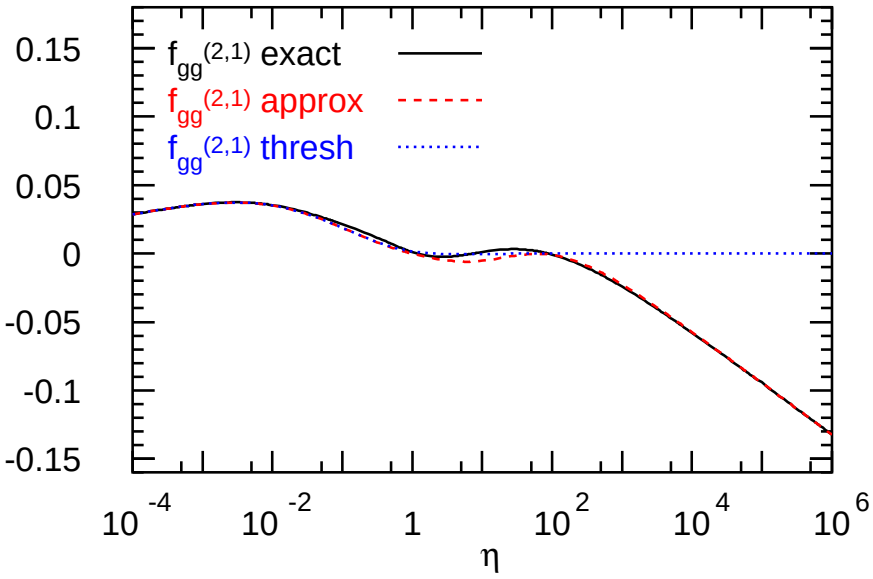
- Approximate results for channel $\mathrm{qg}/\mathrm{gg} \to \mathrm{t\bar{t}}$
  - threshold at $s \simeq 4m_t^2$ with logarithms $\ln(\beta)$ in velocity of heavy quark $\beta = \sqrt{1 - 4m_t^2/s}$ at $\mathrm{n^{th}}$-order
    S.M, Uwer '08; Beneke, Czakon, Falgari, Mitov, Schwinn '09
  - high-energy limit for $\rho = 4m_t^2/s \to 1$ proportional to $\ln(\rho)$ at two loops Catani, Ciafaloni, Hautmann '91; Ball, Ellis '01
  - approximate results for channel $qg \to t\bar{t}$ S.M, Uwer, Vogt '12

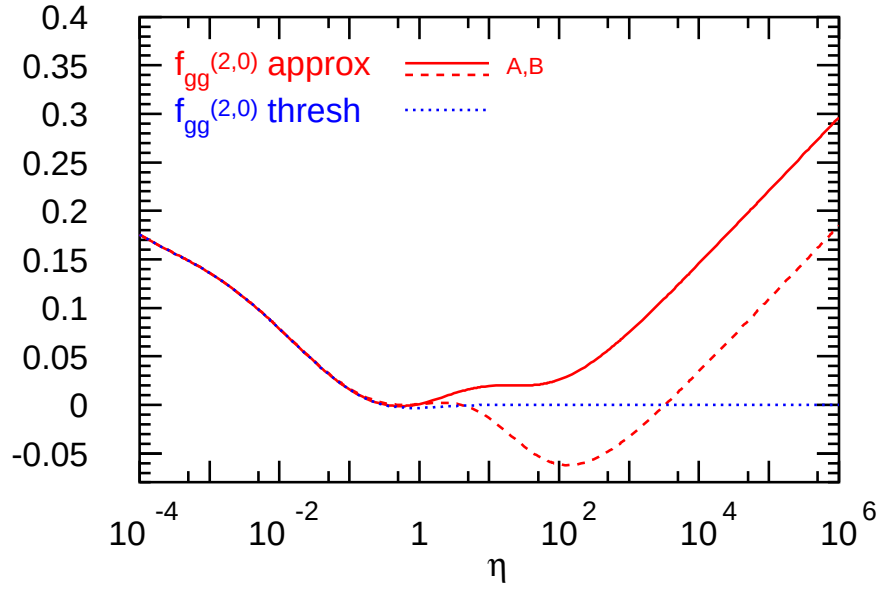




Top-pair hadro-production

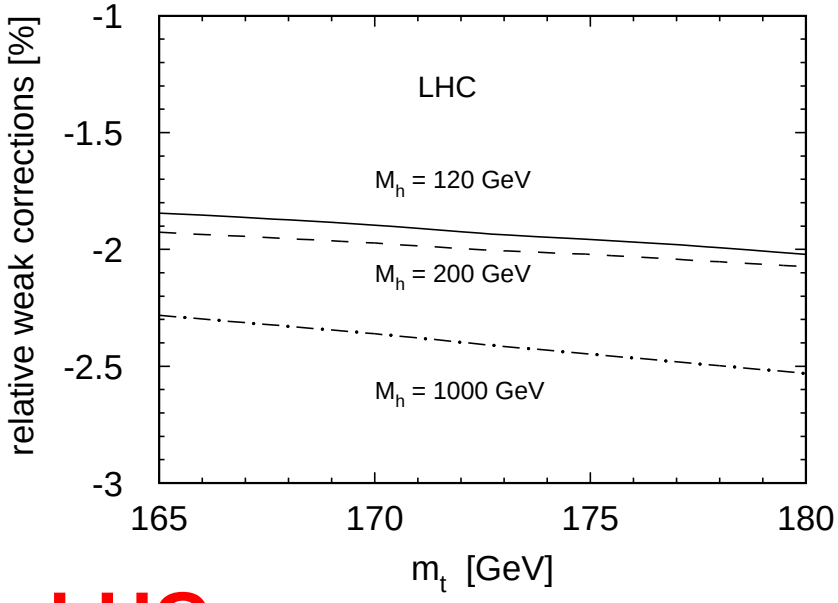
- Approximate results for channel $\mathrm{qg}/\mathrm{gg} \to \mathrm{t\bar{t}}$
  - threshold at $s \simeq 4m_t^2$ with logarithms $\ln(\beta)$ in velocity of heavy quark $\beta = \sqrt{1 - 4m_t^2/s}$ at $\mathrm{n^{th}}$-order
    S.M, Uwer '08; Beneke, Czakon, Falgari, Mitov, Schwinn '09
  - high-energy limit for $\rho = 4m_t^2/s \to 1$ proportional to $\ln(\rho)$ at two loops Catani, Ciafaloni, Hautmann '91; Ball, Ellis '01
  - approximate results for channel $gg \to t\bar{t}$ S.M, Uwer, Vogt '12



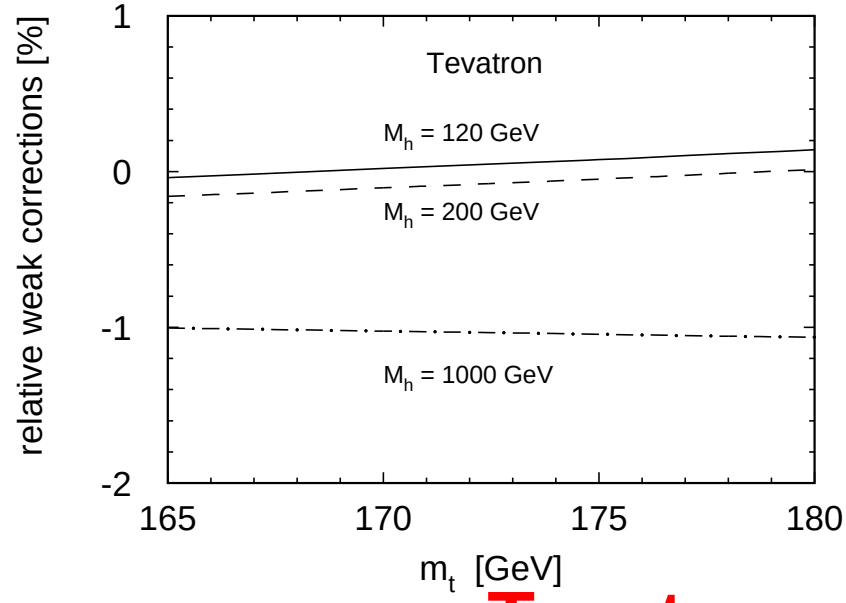


Electroweak corrections

- Electroweak corrections (ratio of $\sigma_{\rm EW}/\sigma_{\rm LO}$)
  Bernreuther, Fücker '05; Kühn, Uwer,Scharf '06
- Effect depends on Higgs mass
  (choices $m_H = 120\text{GeV}, m_H = 200\text{GeV}, m_H = 1000\text{GeV}$)



LHC

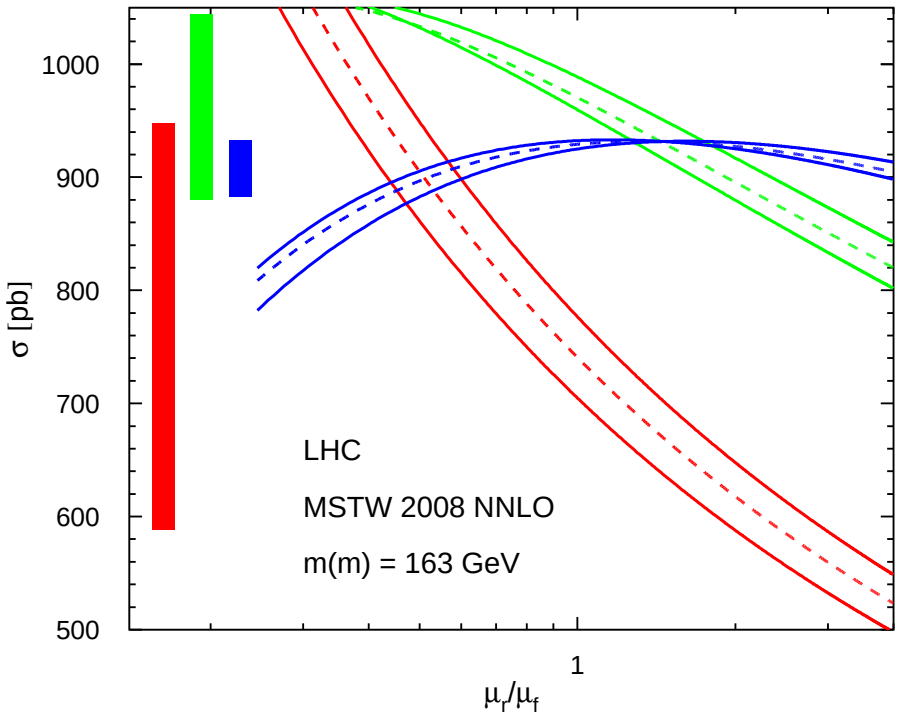


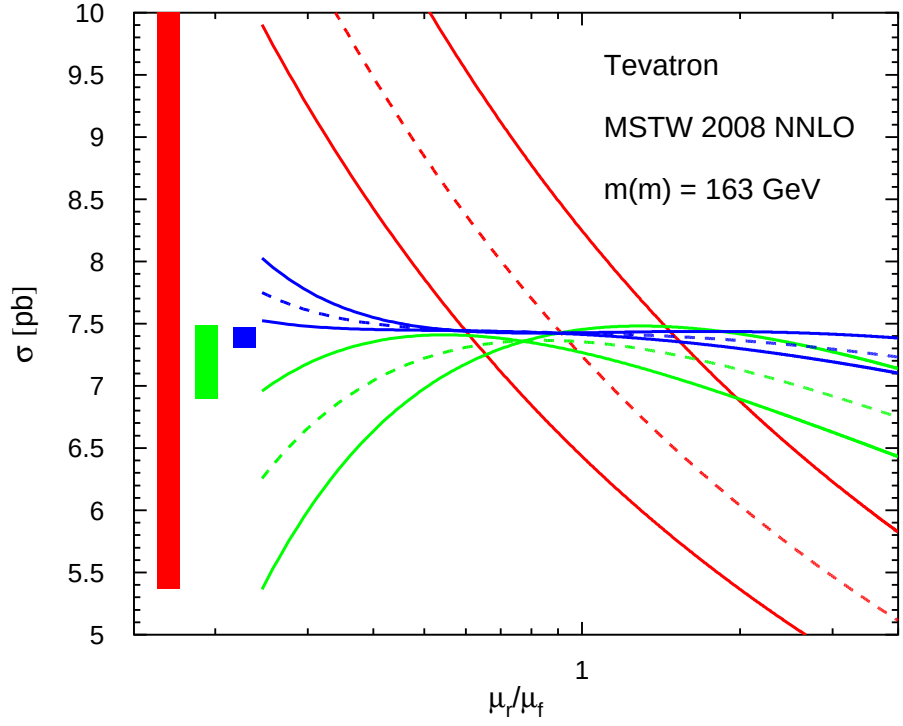
Tevatron

- Tevatron: vanishing contribution for light Higgs
- LHC: $\mathcal{O}(2\%)$ with respect to $\sigma_{\rm LO}$
  negative contribution to total cross section $\Delta\sigma_{\rm EW} \simeq \mathcal{O}(10-15)$ pb

Total cross section with $\overline{MS}$ mass

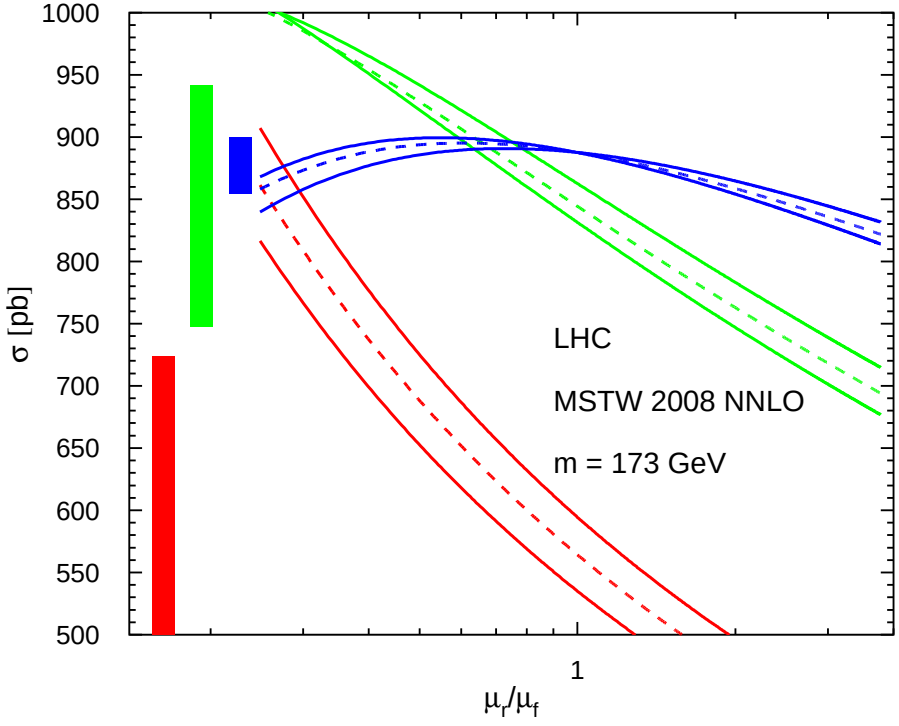
- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
  - short distance mass probes at scale of hard scattering
  - conversion between pole mass and $\overline{MS}$ mass definition in perturbation theory: $m_t = m(\mu_R)\left(1 + a_s(\mu_R)d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$
- Scale dependence greatly reduced

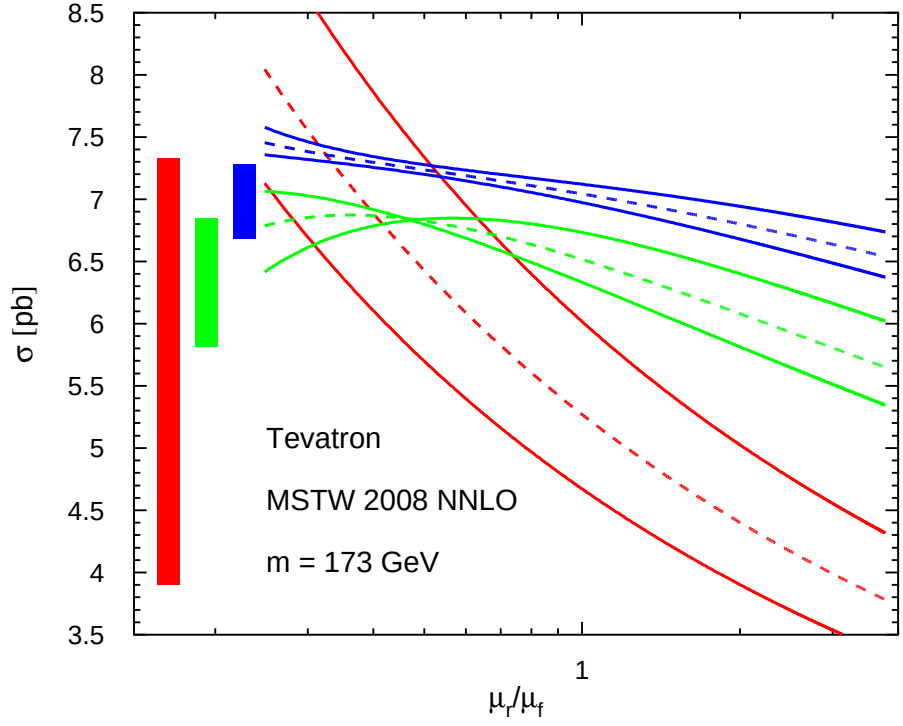




Total cross section with $\overline{MS}$ mass

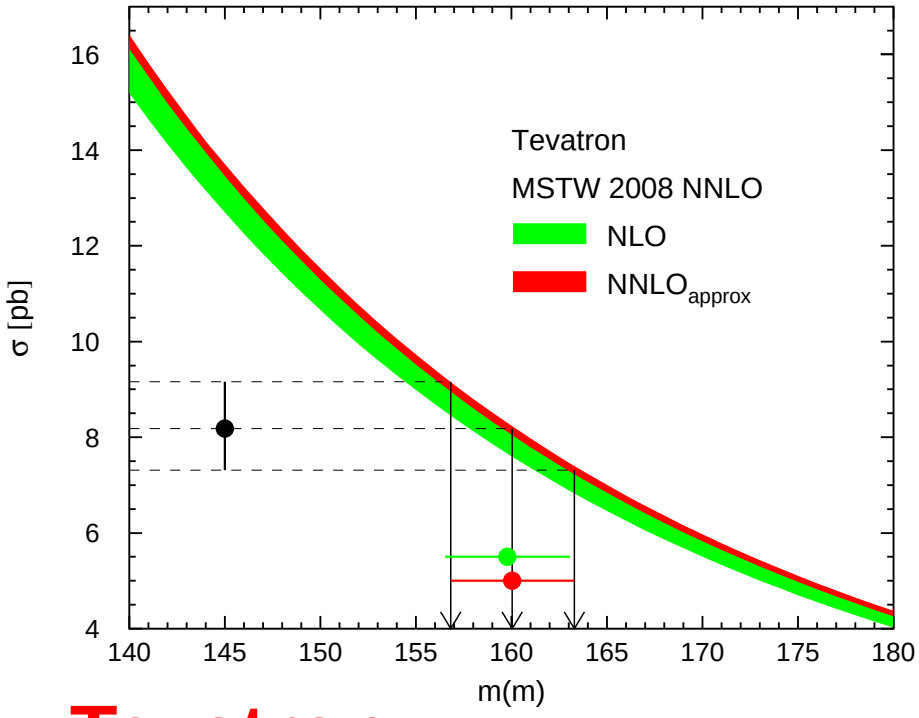
- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
  - short distance mass probes at scale of hard scattering
  - conversion between pole mass and $\overline{MS}$ mass definition in perturbation theory: $m_t = m(\mu_R)\left(1 + a_s(\mu_R)d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$
- Pole mass scheme for comparison



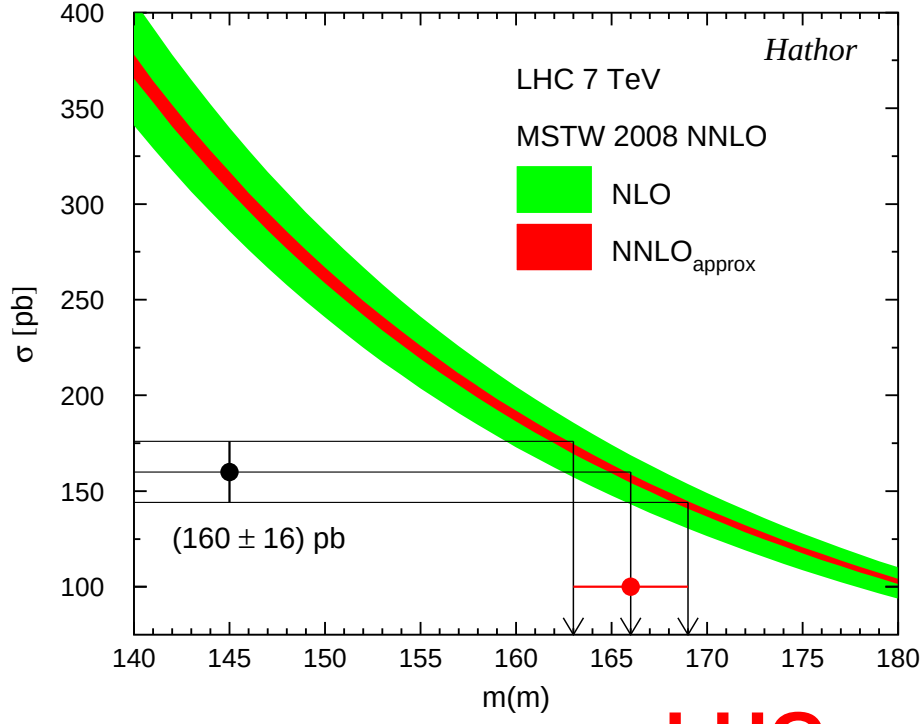


Top mass from total cross section

- Total top quark cross section as function of $\overline{MS}$ mass
  Langenfeld, S.M., Uwer '09
  - good apparent convergence of perturbative expansion
  - small theoretical uncertainity form scale variation



Tevatron



LHC

Tevatron

- Determine top quark mass from Tevatron cross section data
  - $\sigma_{t\bar{t}} = 7.56^{+\,0.63}_{-\,0.56}$ pb D0 coll. arXiv:1105.5384
  - $\sigma_{t\bar{t}} = 7.50\,^{+0.48}_{-0.48}$ pb CDF coll. CDF-note-9913
- Fit of m_t for individual PDFs
  - parton luminosity at Tevatron driven by $q\bar{q}$
  - $\overline{\rm MS}$-scheme for $m_t^{\overline{\rm MS}}(m_t)$, then scheme transformation to pole mass $m_t^{\rm pole}$ at NNLO

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\rm MS}}(m_t)$	$162.0\,^{+2.3\,+0.7}_{-2.3\,-0.6}$	$163.5\,^{+2.2\,+0.6}_{-2.2\,-0.2}$	$163.2\,^{+2.2\,+0.7}_{-2.2\,-0.8}$	$164.4\,^{+2.2\,+0.8}_{-2.2\,-0.2}$
$m_t^{\rm pole}$	$171.7\,^{+2.4\,+0.7}_{-2.4\,-0.6}$	$173.3\,^{+2.3\,+0.7}_{-2.3\,-0.2}$	$173.4\,^{+2.3\,+0.8}_{-2.3\,-0.8}$	$174.9\,^{+2.3\,+0.8}_{-2.3\,-0.3}$
$(m_t^{\rm pole})$	$(169.9\,^{+2.4\,+1.2}_{-2.4\,-1.6})$	$(171.4\,^{+2.3\,+1.2}_{-2.3\,-1.1})$	$(171.3\,^{+2.3\,+1.4}_{-2.3\,-1.8})$	$(172.7\,^{+2.3\,+1.4}_{-2.3\,-1.2})$

- Good consistency within errors for $m_t^{\rm pole} = 171.7 \ldots 174.9$ at NNLO

LHC

- Check predictions at LHC with $\sqrt{s} = 7$ TeV
  - cross section computation with HATHOR (version 1.3)
    Aliev, Lacker, Langenfeld, S.M., Uwer, Wiedermann '10; S.M., Uwer, Vogt '12

- Atlas at $\sqrt{s} = 7$ TeV $\sigma_{t\bar{t}} = 177^{+11}_{-10}$ pb
  Atlas coll. ATLAS-CONF-2012-024
- CMS at $\sqrt{s} = 7$ TeV $\sigma_{t\bar{t}} = 165.8^{+13.3}_{-13.3}$ pb
  CMS coll. CMS-PAS-TOP-11-024

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\rm MS}}(m_t)$	$159.0\,^{+2.1\,+0.7}_{-2.0\,-1.4}$	$165.3\,^{+2.3\,+0.6}_{-2.2\,-1.2}$	$166.0\,^{+2.3\,+0.7}_{-2.2\,-1.5}$	$166.7\,^{+2.3\,+0.8}_{-2.2\,-1.3}$
$m_t^{\rm pole}$	$168.6\,^{+2.3\,+0.7}_{-2.2\,-1.5}$	$175.1\,^{+2.4\,+0.6}_{-2.3\,-1.3}$	$176.4\,^{+2.4\,+0.8}_{-2.3\,-1.6}$	$177.4\,^{+2.4\,+0.8}_{-2.3\,-1.4}$
$(m_t^{\rm pole})$	$(166.1\,^{+2.2\,+1.7}_{-2.1\,-2.3})$	$(172.6\,^{+2.4\,+1.6}_{-2.3\,-2.1})$	$(173.5\,^{+2.4\,+1.8}_{-2.3\,-2.5})$	$(174.5\,^{+2.4\,+2.0}_{-2.3\,-2.3})$

- Large spread $m_t^{\rm pole} = 168.6 \ldots 177.4$ at NNLO (marginally consistent)
  - larger gluon and α_s imply larger $m_t^{\rm pole}$

Summary

Top quark cross section

- Radiative corrections at higher orders in QCD and EW are mandatory
  - continuous challenge for theory
- Cross section predictions
  - NNLO QCD corrections for total cross section almost complete
  - study of new observables to comply with experimental requirements under way
- Precision determinations of non-perturbative parameters is essential
  - careful definition of observable required
  - top-quark mass m_t in well defined scheme
- Joint effort theory and experiment

Extra slides

Top mass from leptonic decay

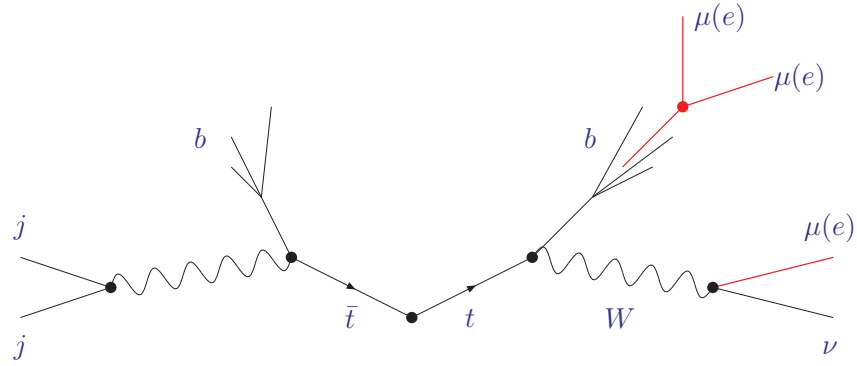
- Top mass from exclusive hadronic states

$$pp \to (t \to W^+ + b \to W^+ + J/\psi) + (\bar{t} \to W^- + \bar{b})$$

  - identification of μ-pair in J/ψ decay; leptonic or hadronic decay of W

    Kharchilava '00

    Chierici, Dierlamm '06



Top mass from leptonic decay

- Top mass from exclusive hadronic states

$$pp \to (t \to W^+ + b \to W^+ + J/\psi) + (\bar{t} \to W^- + \bar{b})$$

- Study of m_{lb} distribution at NLO in QCD Biswas, Melnikov, Schulze '10
  - NLO QCD corrections to production **and** decay very important for value of m_t (effects of order $\Delta m_t = \mathcal{O}(\text{few})$ GeV
- Invariant mass distribution of lepton and b-jet (LHC14)
  - scale dependence at LO and NLO (left)
  - normalized m_{lb} distributions, $m_t = 171$ GeV and 179 GeV (right)