QCD studies and Higgs searches at the LHC
part three

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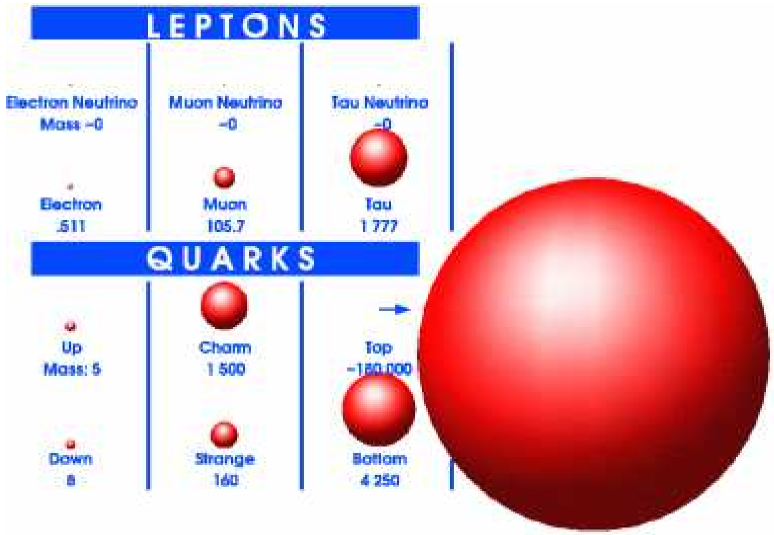
Plan

- Some new results on the heaviest elementary particle



Abundant production of top-quarks

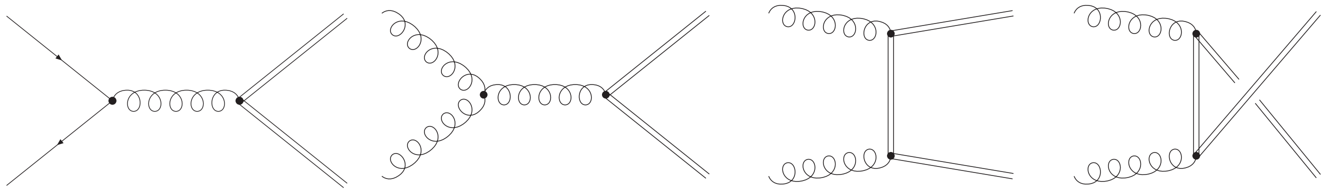
- Orders for top-quarks from www.particlezoo.com

Top-quark decays

Top quark production

- Leading order Feynman diagrams

$$\begin{aligned} q + \bar{q} &\longrightarrow Q + \bar{Q} \\ g + g &\longrightarrow Q + \bar{Q} \end{aligned}$$

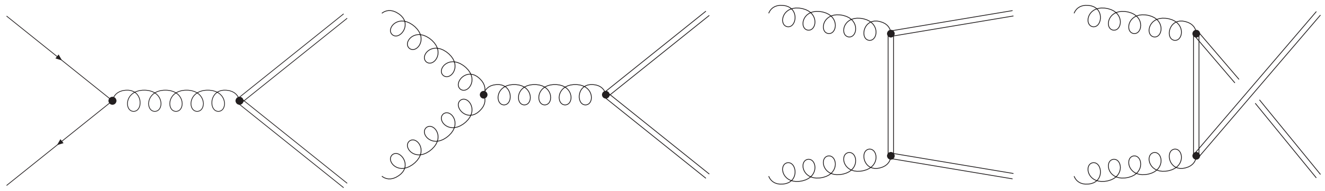


- NLO in QCD Nason, Dawson, Ellis ‘88; Beenakker, Smith, van Neerven ‘89; Mangano, Nason, Ridolfi ‘92; Bernreuther, Brandenburg, Si, Uwer ‘04; Mitov, Czakon ‘08; . . .
  - accurate to $\mathcal{O}(15\%)$ at LHC

Top quark production

- Leading order Feynman diagrams

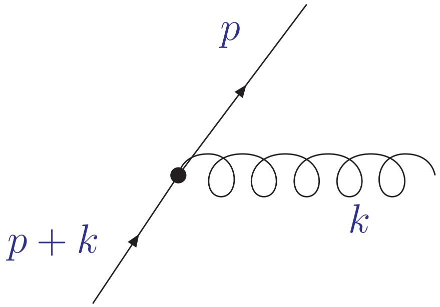
$$\mathrm{q} + \bar{\mathrm{q}} \longrightarrow \mathrm{Q} + \bar{\mathrm{Q}}$$
$$\mathrm{g} + \mathrm{g} \longrightarrow \mathrm{Q} + \bar{\mathrm{Q}}$$



- NLO in QCD Nason, Dawson, Ellis ‘88; Beenakker, Smith, van Neerven ‘89; Mangano, Nason, Ridolfi ‘92; Bernreuther, Brandenburg, Si, Uwer ‘04; Mitov, Czakon ‘08; ...
  - accurate to $\mathcal{O}(15\%)$ at LHC
- First steps towards higher orders in QCD: explore limits
- Study of massive QCD amplitudes in high-energy limit $s \gg m^2$
  - exploit high-energy factorization in BFKL formalism
- Partonic threshold $s \simeq 4m^2$
  - Sudakov logarithms $\ln\beta$ (velocity of heavy quark $\beta = \sqrt{1 - 4m^2/s}$)

Sudakov logarithms

- Recall perturbative QCD:
  - calculation of observables as series in $\alpha_s \ll 1$
  - but: large logarithmic corrections, $\ln(\dots) \gg 1$
    double logarithms (Sudakov)
- Soft/Collinear regions of phase space
  - double logarithms from singular regions in Feynman diagrams
  - propagator vanishes for: $E_g = 0$, soft $\theta_{qg} = 0$ collinear



$$\frac{1}{(p+k)^2} = \frac{1}{2p\cdot k} = \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

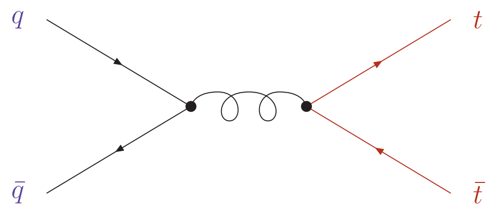
$$\alpha_s \int d^4k \frac{1}{(p+k)^2} \longrightarrow \alpha_s \int dE_g\, d\sin\theta_{qg}\, \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

$$\longrightarrow \alpha_s \ln^2(\dots)$$

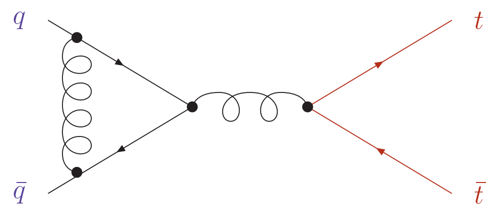
- Improved perturbation theory: resum logarithms to all orders
  - long history of resummation Kidonakis, Sterman '97; Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01; . . .

Sudakov logarithms in cross sections

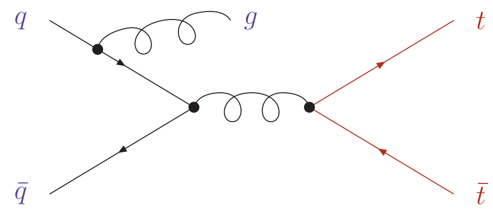
- Intuitive aspects of higher order corrections
  - lowest order, elastic



  - first order correction
    $virtual < 0$ (elastic)



  - first order correction
    $Brems > 0$ (inelastic)

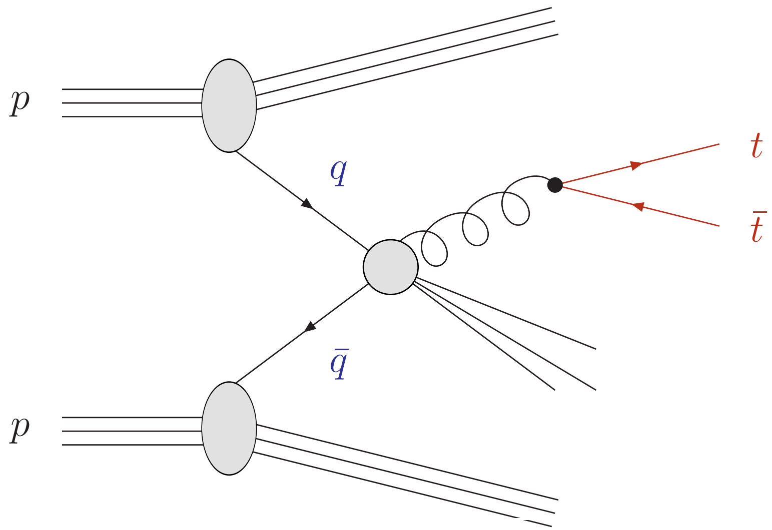


- at threshold for $\mathrm{t\bar{t}}$-creation
  - strong Sudakov-supression inelastic tendency

$$\sigma \sim \exp\left[-\alpha_s \ln^2(1 - 4m_t^2/s)\right]$$

  - universal factor for parton splittings (leading log accuracy)
    modelling of MC parton showers

- Hadronic reaction $p\bar{p}$:
  - recall master equation $$\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$$
  - initial partons: also Sudakov-supressed



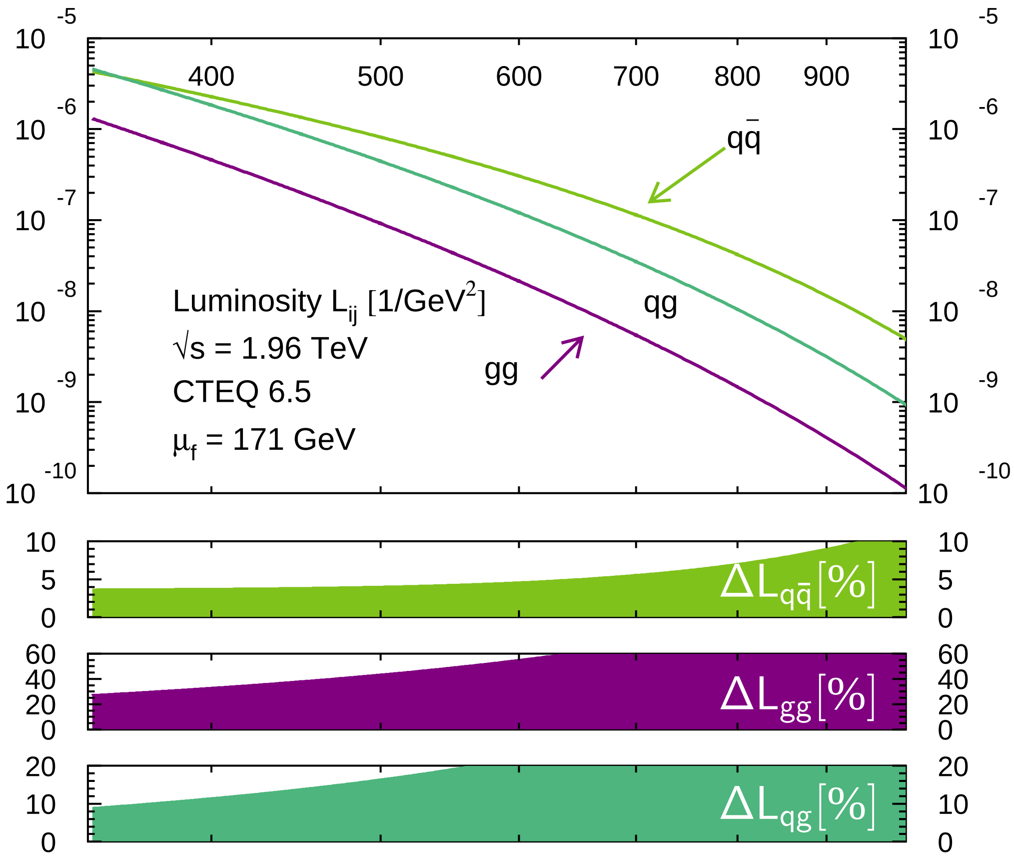
- Parton cross section $\hat{\sigma}_{ij\to t\bar{t}}$
  - Sudakov-enhancement after mass factorization

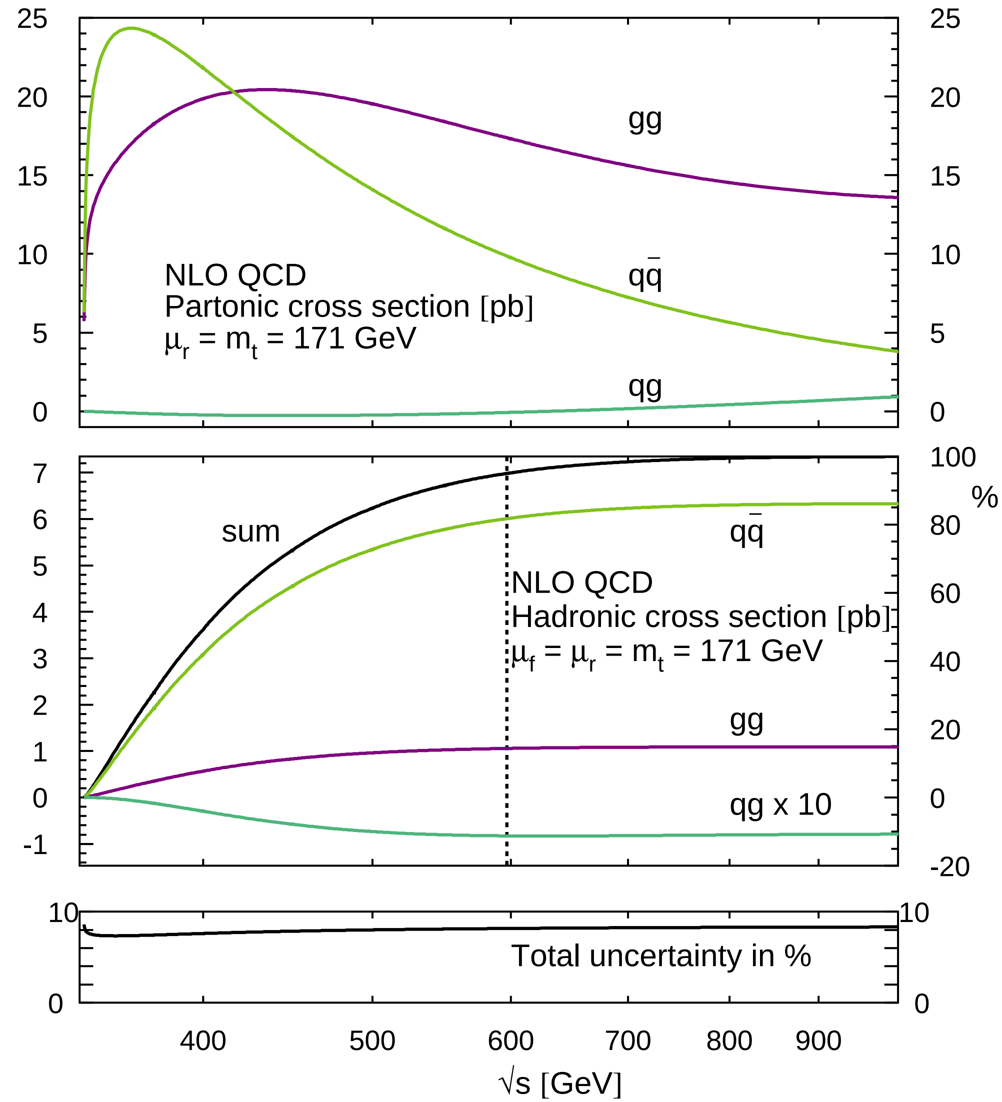
$$\hat{\sigma}_{ij\to t\bar{t}} = \frac{\sigma_{pp\to t\bar{t}}}{f_i \otimes f_j} = \frac{e^{-\alpha_s \ln^2(\dots)}}{\left(e^{-\alpha_s \ln^2(\dots)}\right)^2} = e^{+\alpha_s \ln^2(\dots)}$$

  - large double logarithms

Total cross section at Tevatron

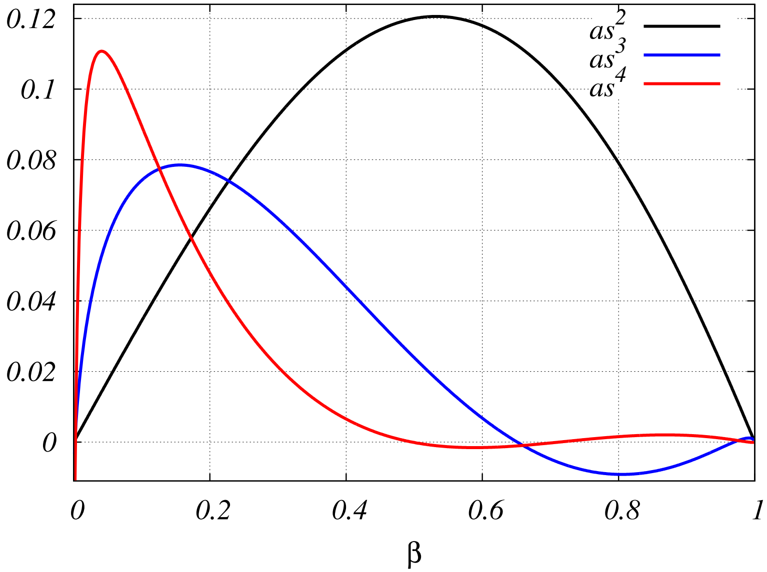
$$\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$$





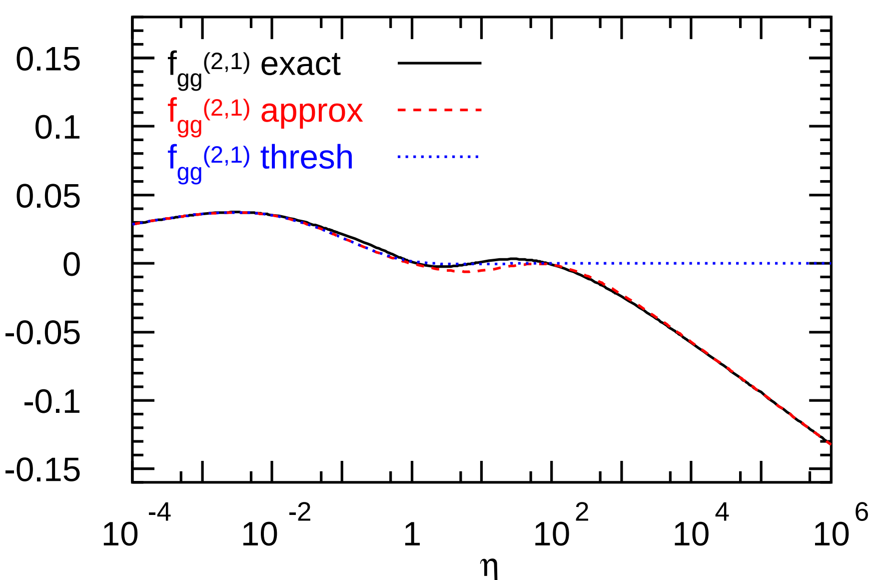
Top-pair hadro-production

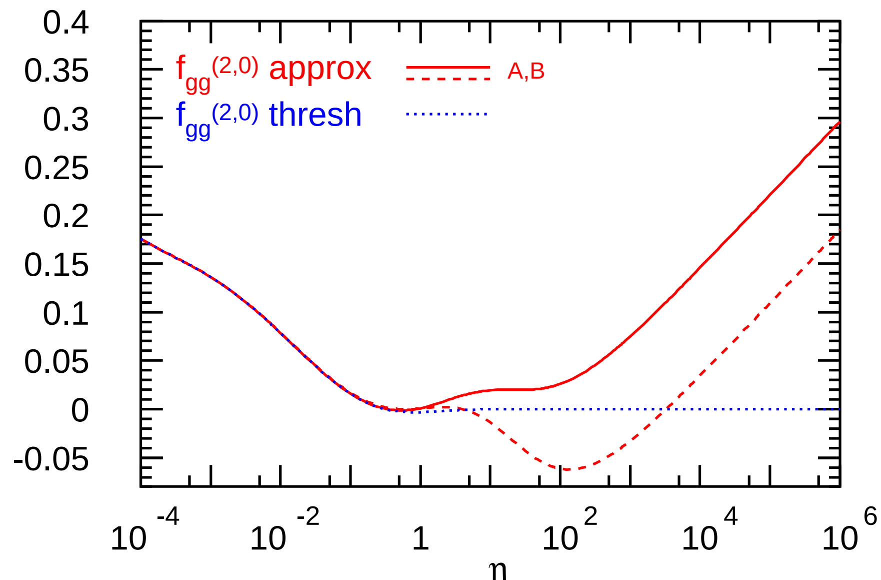
- NNLO cross section for heavy-quark hadro-production
- Exact results for channel $q\bar{q} \to t\bar{t}$ Czakon, Mitov '12



Top-pair hadro-production

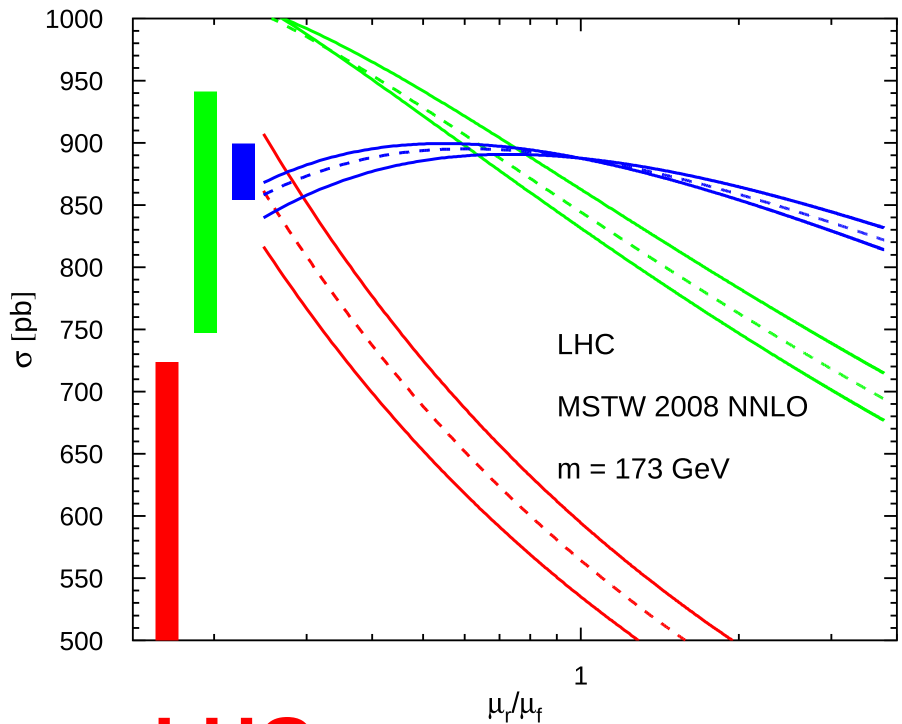
- NNLO cross section for heavy-quark hadro-production
- Approximate results for channel $\mathrm{qg}/\mathrm{gg} \to \mathrm{t\bar{t}}$
  - threshold at $s \simeq 4m_t^2$ with logarithms $\ln(\beta)$ in velocity of heavy quark $\beta = \sqrt{1 - 4m_t^2/s}$ at $\mathrm{n^{th}}$-order
    S.M, Uwer '08;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

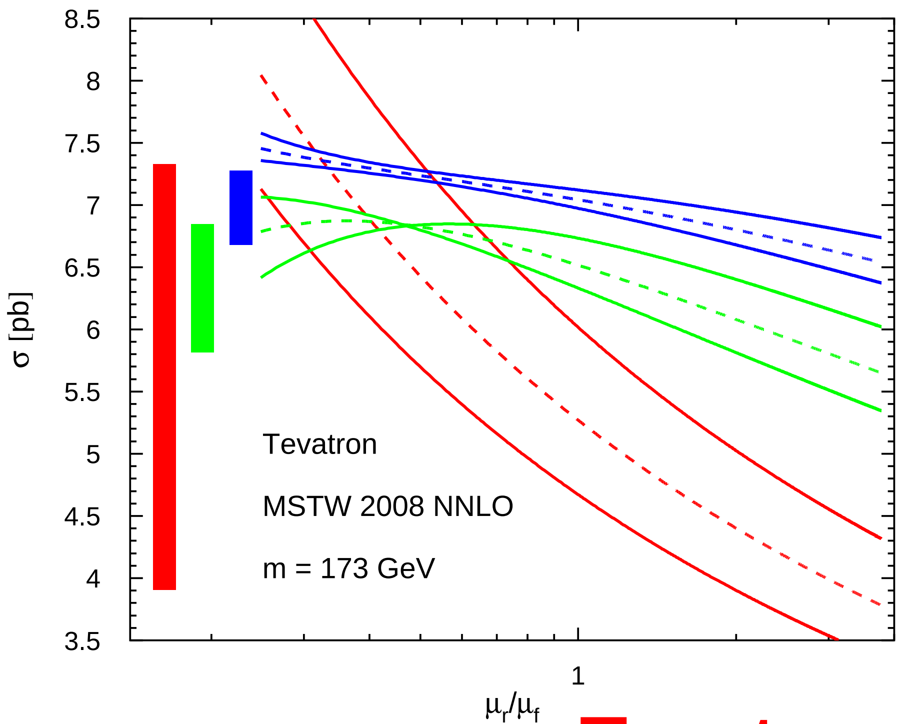




Scale dependence

- Theoretical uncertainty from variation of scales μ_R, μ_F
  - plot with PDF set MSTW 2008 (but largely independent on PDFs)
  - mass $m_t = 173$ GeV
  - stable predictions in range $\mu_R, \mu_F \in [m_t/2, 2m_t]$
    - $-3\% \leq \Delta\sigma \leq +1\%$ at LHC
    - $-5\% \leq \Delta\sigma \leq +3\%$ at Tevatron

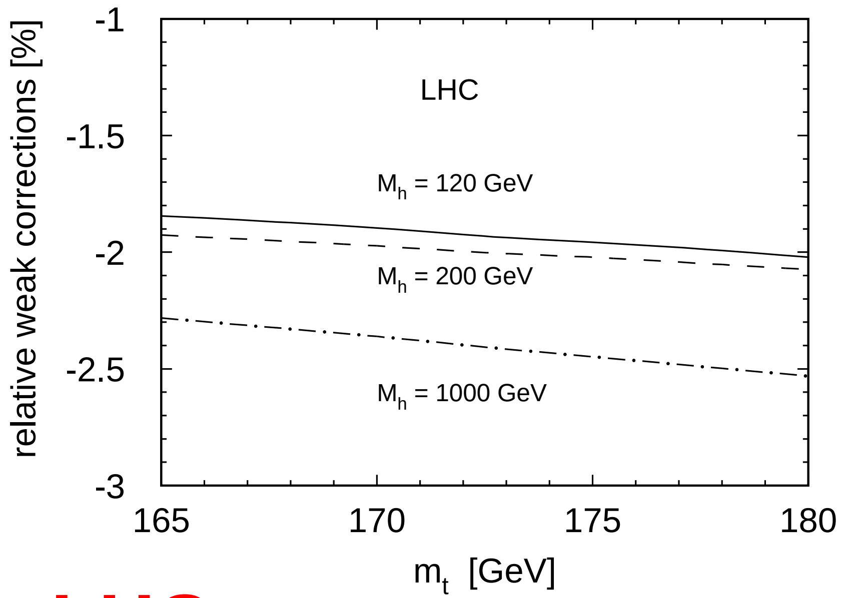




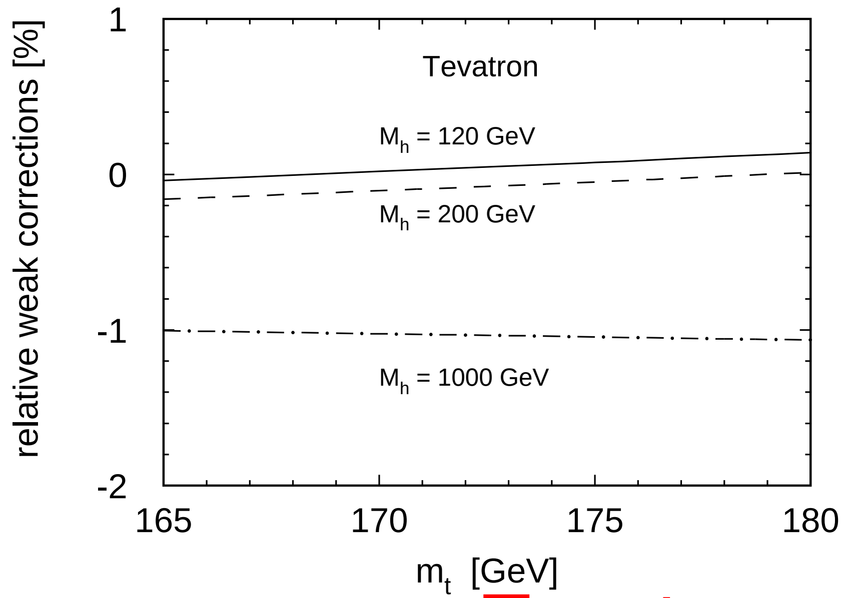
LHC **Tevatron**

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 $m_H = 120$GeV, $m_H = 200$GeV, $m_H = 1000$GeV)



LHC



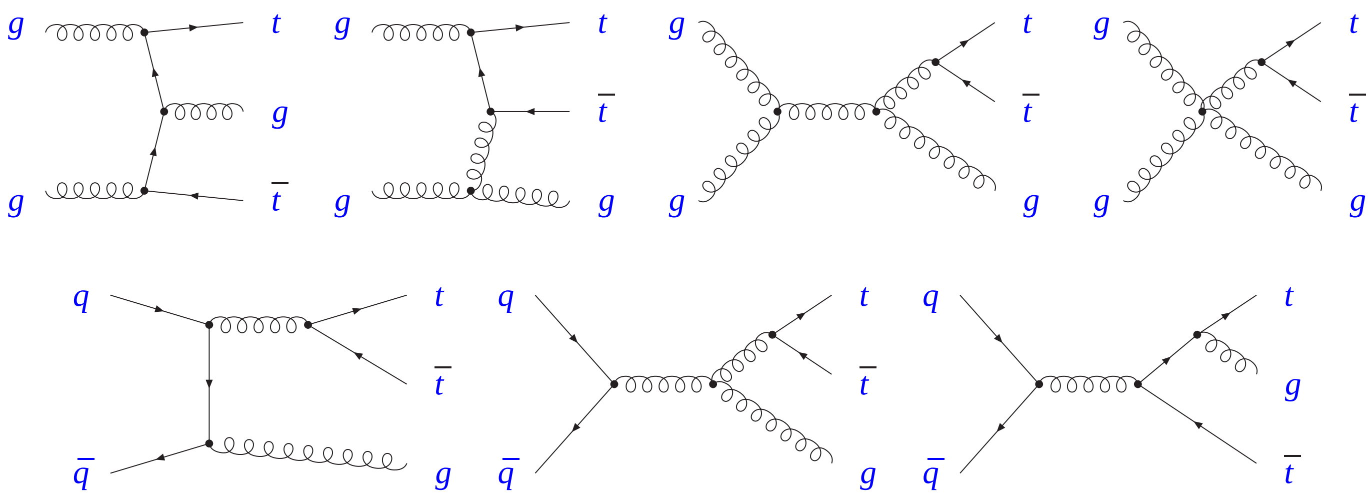
Tevatron

- 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

Top-quark pairs with one jet

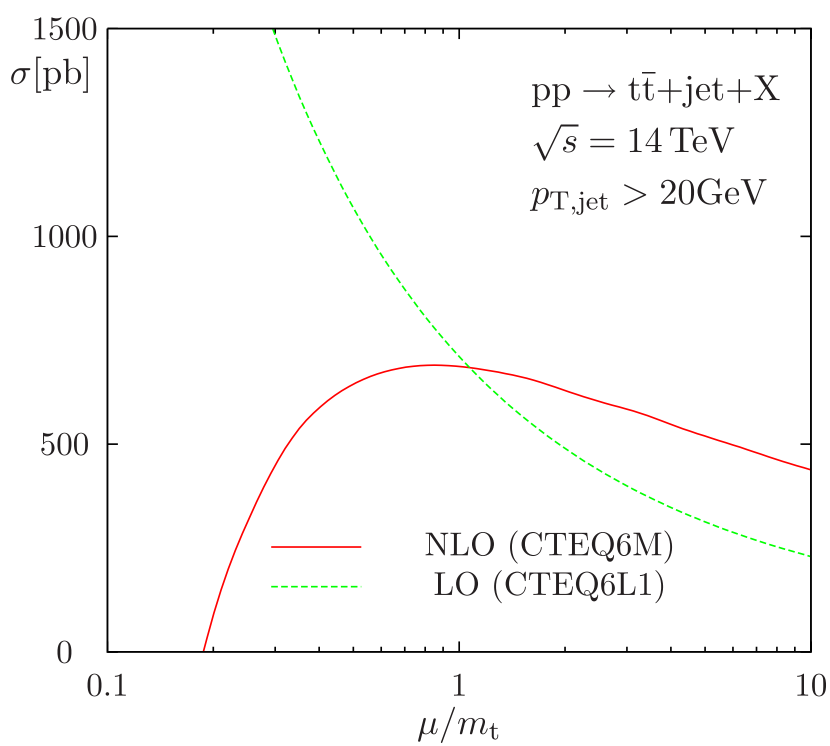
Production of $t\bar{t}$+jet at fixed order

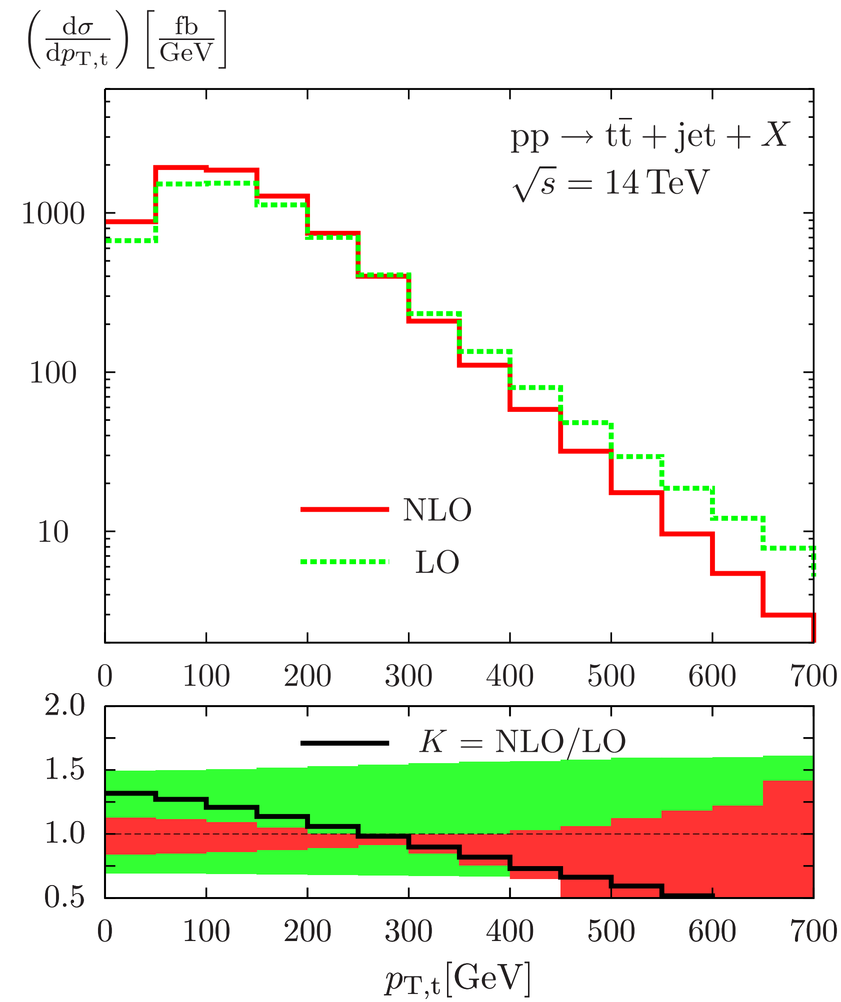
- LHC: large rates for production of $t\bar{t}$-pairs with additional jets
- Scale dependence at LO large



- Feynman diagrams (sample) for $t\bar{t}+$ jet production at LO

Production of $t\bar{t}+$ jet at NLO





- NLO QCD corrections Dittmaier, Uwer, Weinzierl '07-'08
  - scale dependence greatly reduced at NLO
  - corrections for total rate at scale $\mu_r = \mu_f = m_t$ are almost zero
  - transverse-momentum distributions of top-quark $p_{T,t}$ along with K-factor and scale variation $m_t/2 \le \mu \le 2m_t$

Monte Carlo and parton showers at NLO

- Merging of fixed order NLO with parton shower Monte Carlo
  Frixione, Webber '02, Nason '04
  - combining accuracy of exact hard matrix elements for large angle scattering at NLO with soft/collinear emission of parton shower
- POWHEG BOX as standard interface to parton shower programs PYTHIA or HERWIG Alioli, Nason, Oleari, Re '10
- Production of $t\bar{t}+$ jet and parton showers
  Kardos, Papadopoulos, Trocsanyi '11, Alioli, S.M., Uwer '11

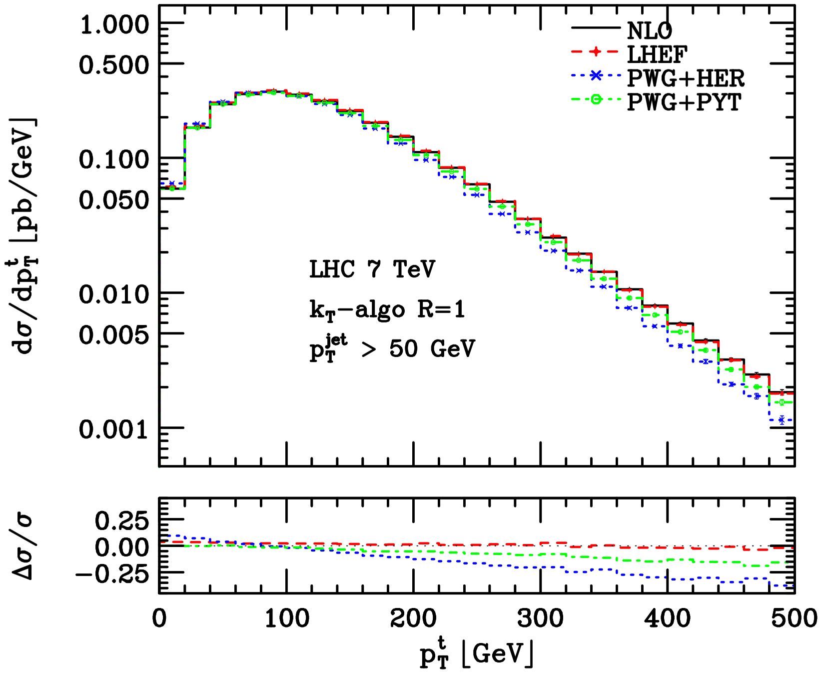
Implementation

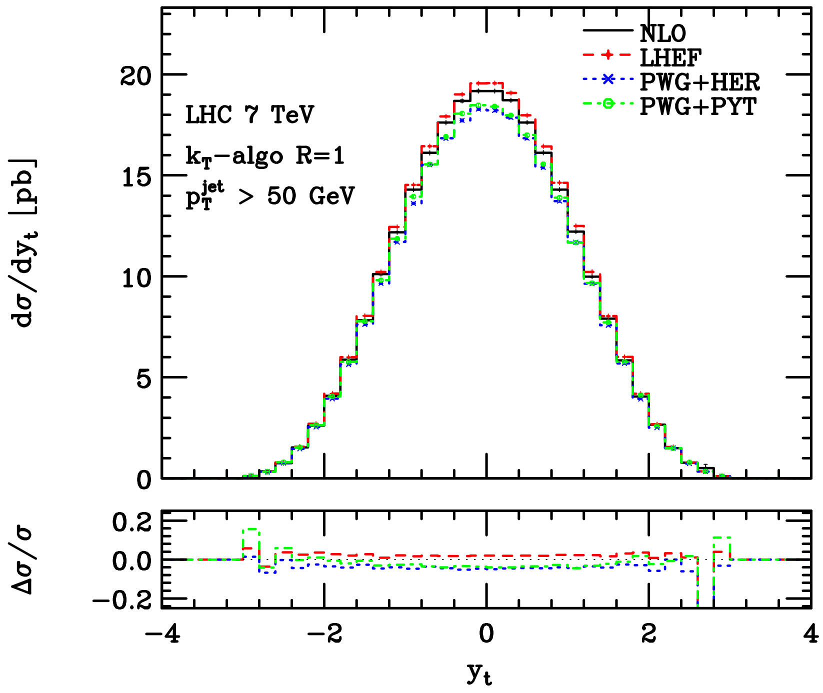
- Event generation with cut on $p_t^{\text{gen}} \simeq 1$ GeV
- Alternative option for soft and collinear divergences at Born level: generation of weighted events with Born suppression factor
  $\bar{B}_{\text{supp}} = \bar{B} \times F(p_t)$ Alioli, Nason, Oleari, Re '10

$$F(p_t) = \left(\frac{p_t^2}{p_t^2 + (p_t^{\text{supp}})^2} \right)^n$$

Production $t\bar{t}+$ jet and parton shower (I)

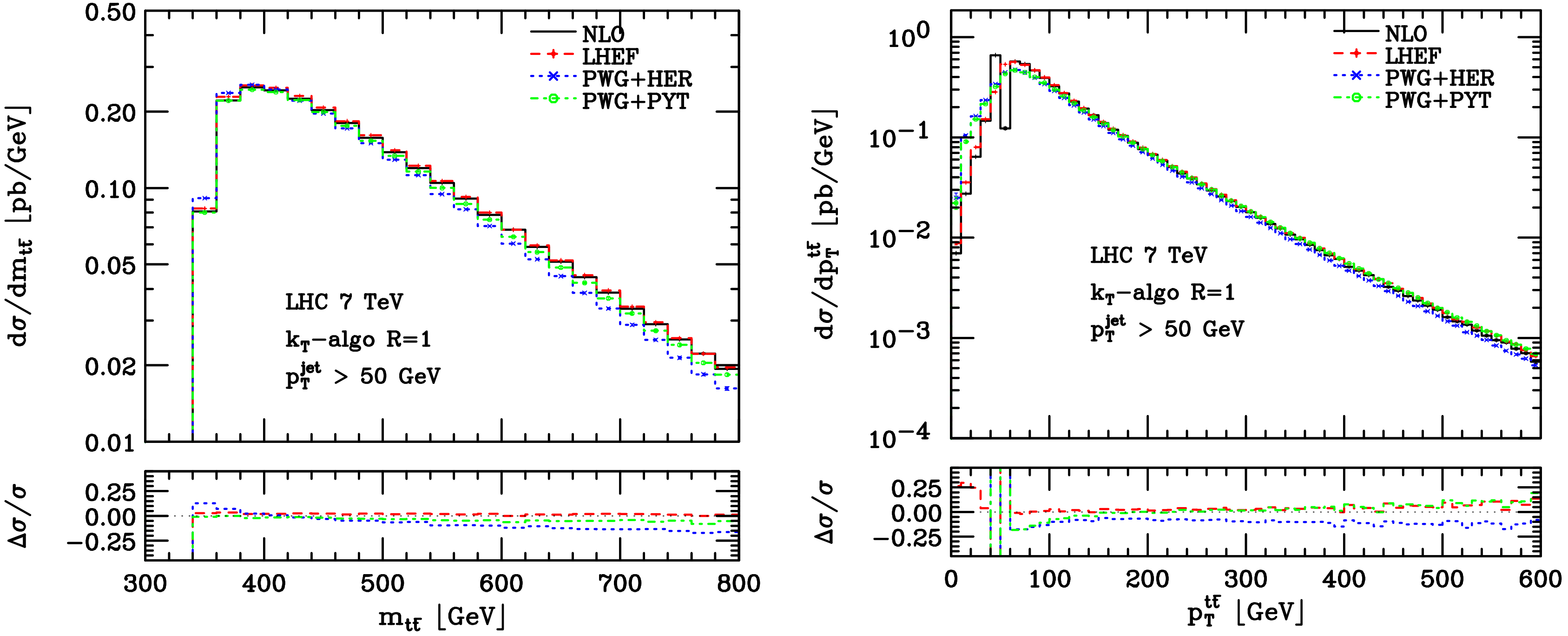
- Differential distributions in top-quark's transverse momentum p_T^t and rapidity y_t at LHC7
  - comparision of NLO, LHEF for POWHEG hardest emission without showering, and POWHEG with shower/hadronization with HERWIG or PYTHIA





Production $t\bar{t}+$ jet and parton shower (II)

- Differential distributions as function of $t\bar{t}$-pair invariant mass $m_{t\bar{t}}$ and transverse momentum $p_T^{t\bar{t}}$ at LHC7



Heavy-quark masses

QCD Lagrangian

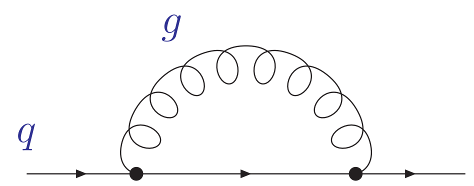
$$\mathcal{L} \quad = \quad -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{\text{flavors}} \bar{q} \,(\mathrm{i} \not{D} - m_q)\, q$$

- Covariant derivative $D_\mu = \partial_\mu + \mathrm{i} g_s A_\mu$
- Formal parameters of the theory (no observables)
  - strong coupling $\alpha_s = g_s^2/(4\pi)$
  - quark masses m_q
- Quantum corrections (loop integrals) require UV renormalization; (scheme dependence):
  - $\alpha_s \rightarrow$ asymptotic freedom, running coupling ($\overline{MS}$ scheme)
  - $m_q \rightarrow$ pole mass or running mass ($\overline{MS}$ scheme)

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 $\mathcal{O}(\Lambda_{QCD})$
- Definition of pole mass ambiguous up to corrections $\mathcal{O}(\Lambda_{QCD})$

Running quark masses

- $\overline{MS}$ mass definition $m(\mu_R)$ realizes running mass (scale dependence)
  - renormalization group equation (mass anomalous dimension γ)

$$\left(\mu_R^2 \frac{\partial}{\partial \mu_R^2} + \beta(\alpha_s) \frac{\partial}{\partial \alpha_s}\right) m(\mu_R) \;=\; \gamma(\alpha_s) m(\mu_R)$$

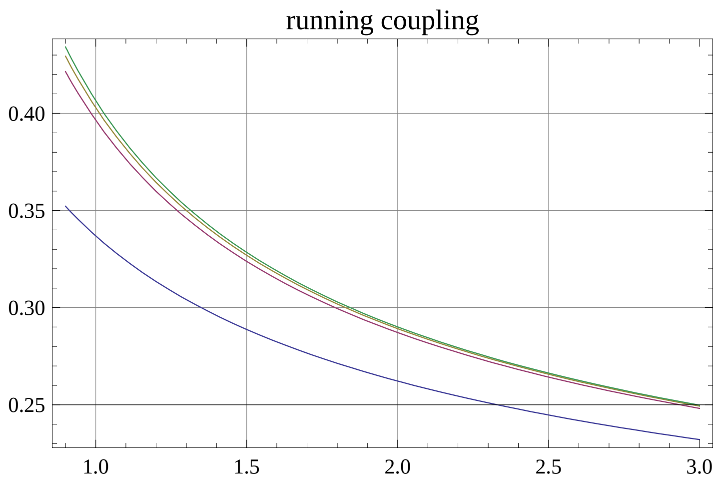
  - short distance mass probes at scale of hard scattering
    $m_{\text{pole}} = m_{\text{short distance}} + \delta m$
  - conversion between pole mass and $\overline{MS}$ mass definition in perturbation theory: $m = m(\mu_R)\left(1 + a_s(\mu_R) d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$

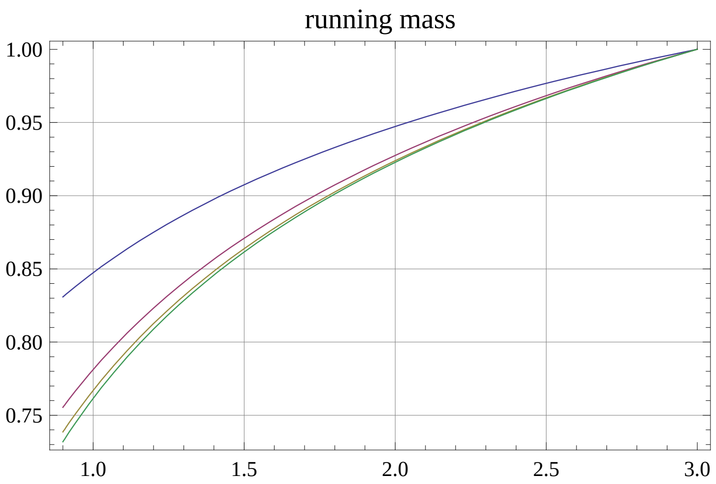
Scale dependence

- Renormalization group equation for scale dependence
  - strong coupling α_s and mass m

$$\mu^2 \frac{d}{d\mu^2} \alpha_s(\mu) = \beta(\alpha_s) \qquad \mu^2 \frac{d}{d\mu^2} m(\mu) = \gamma(\alpha_s) m(\mu)$$

- Perturbative expansion known to four loops
  - β-function van Ritbergen, Vermaseren, Larin '97 and mass anomalous dimension γ Chetyrkin '97; Larin, van Ritbergen, Vermaseren '97
  - very good convergence of perturbative series even at low scales
- Plot at low scales $\mu = 1.0 \ldots 3.0$ GeV
  α_s (left) and mass ratio $m(3\text{GeV})/m(\mu)$ (right)





- Use of charm-quark mass $m_c(m_c)$ is well justified

Illustration for top-quark mass

ILC

- Pole mass measurements are strongly order-dependent
  - e.g. threshold scan of cross section in e^+e^- collision
    Beneke, Signer, Smirnov '99; Hoang, Teubner '99; Melnikov, Yelkhovsky '98; Penin, Pivovarov '99; Yakovlev '99
  - LO (dotted), NLO (dashed), NNLO (solid)

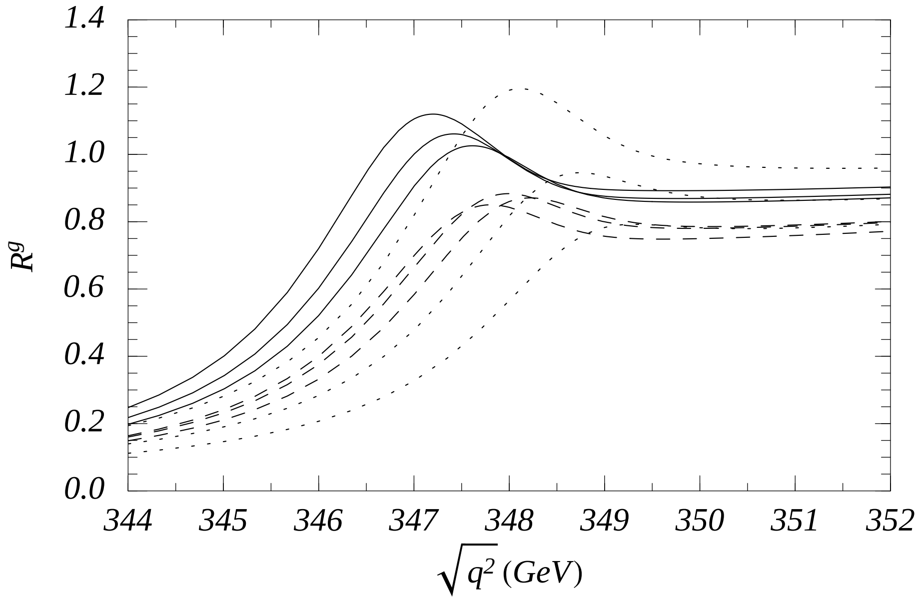
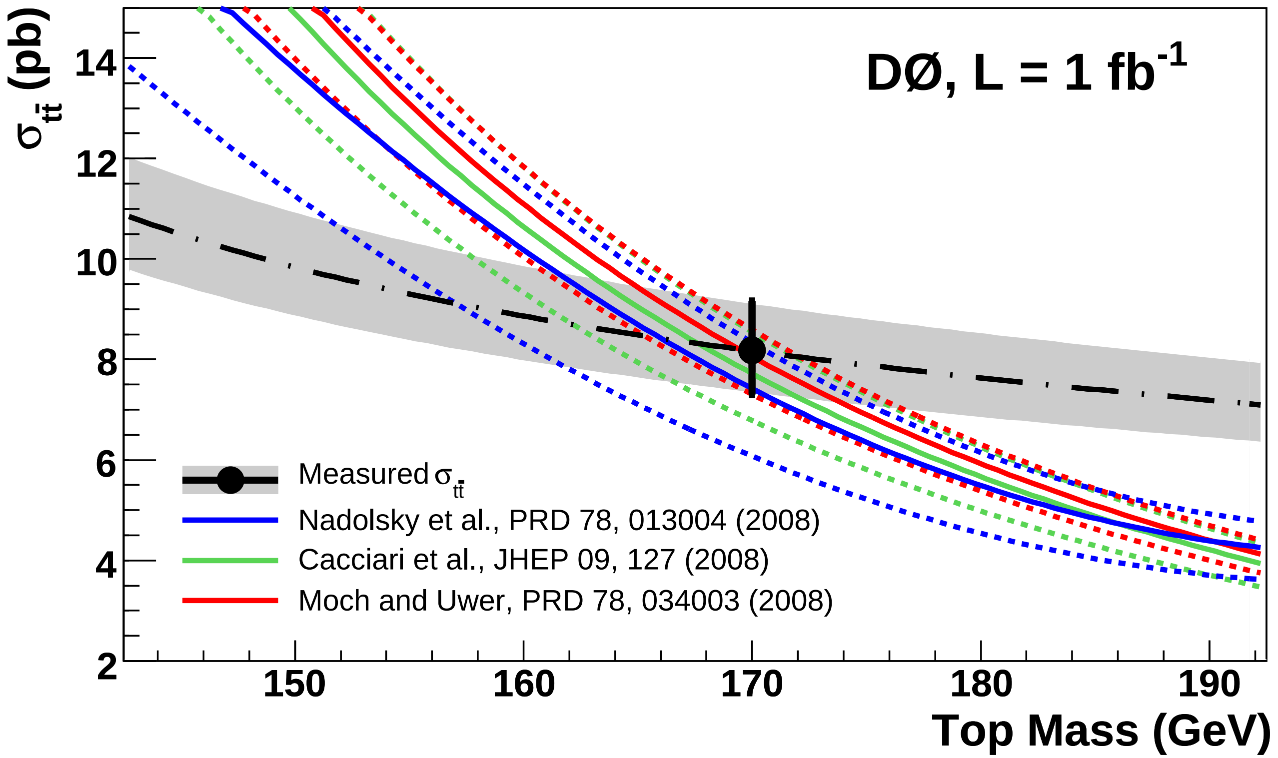


Illustration for top-quark mass

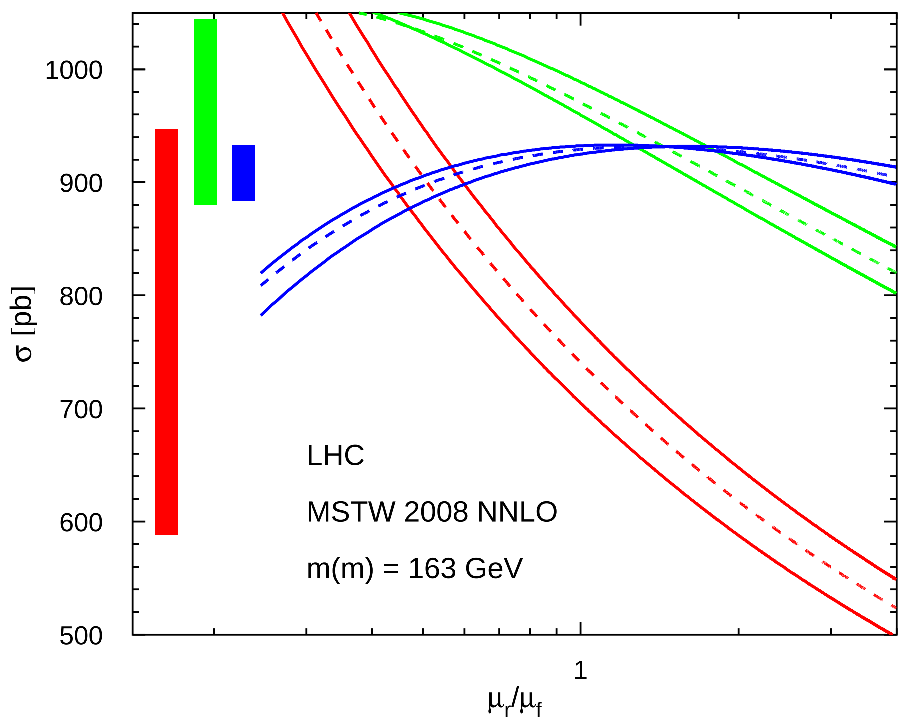
Tevatron

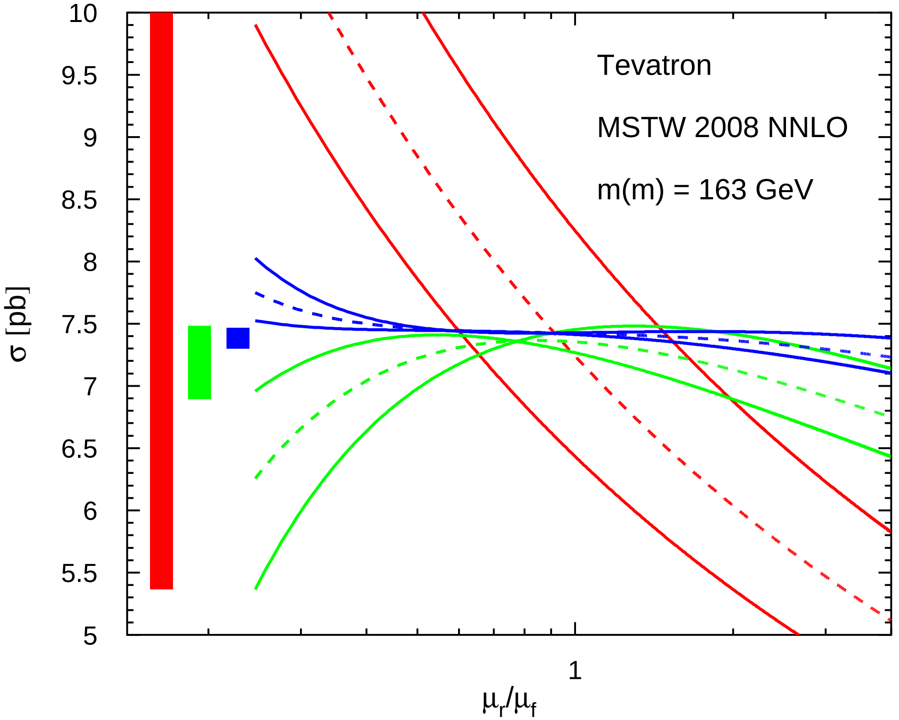
- Total cross section and different channels of Tevatron analyses (theory uncertainty band from scale variation)
- Determination of m_t from total cross section (slope $d\sigma/dm_t$)
  - e.g. DZero '09: NLO $m_t = 165.5^{+6.1}_{-5.9}$; NNLO $m_t = 169.1^{+5.9}_{-5.2}$; ...



The running top-quark 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





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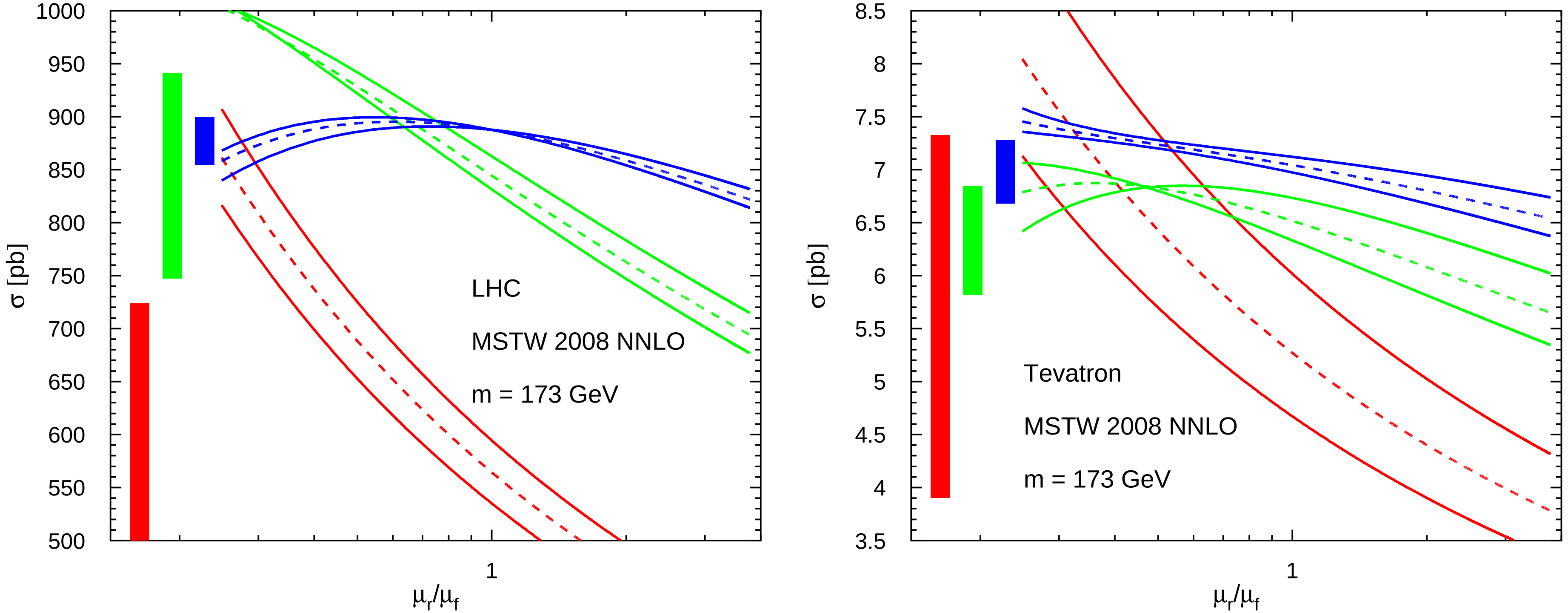
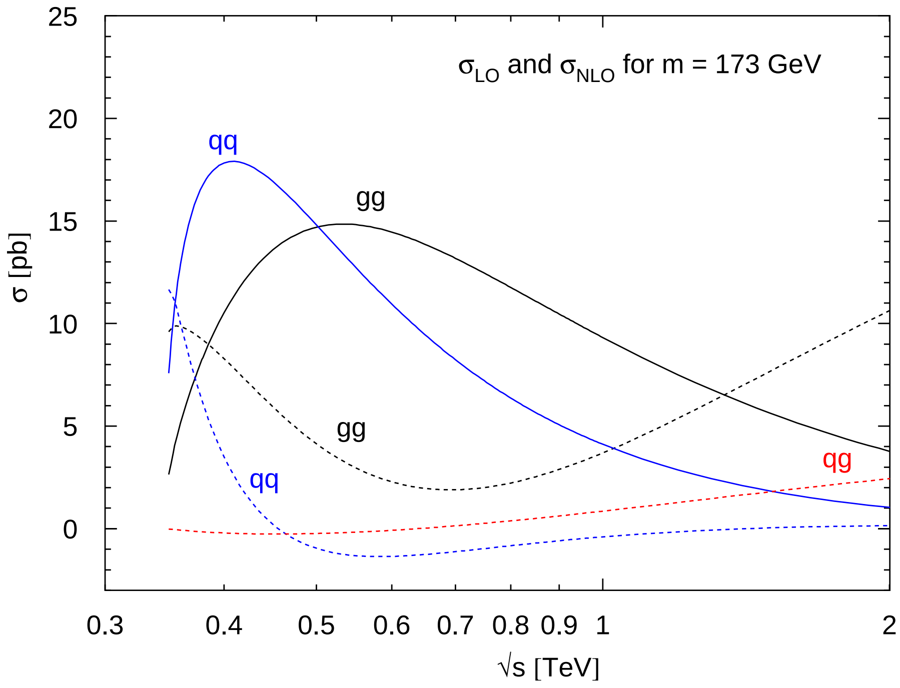
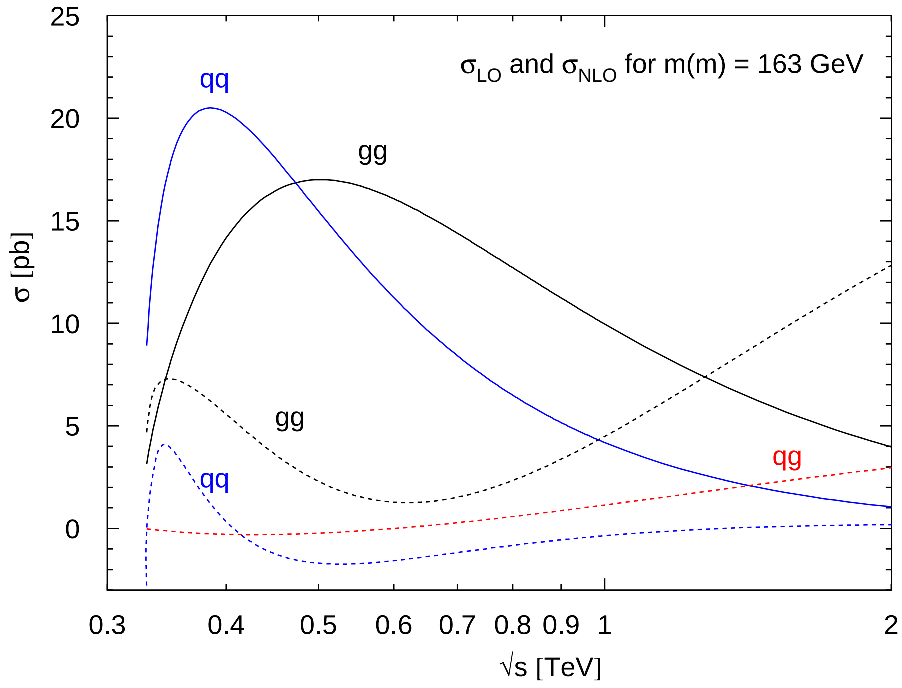
- Pole mass scheme for comparison



- Perturbative stability of predictions with $\overline{MS}$ mass definition
- Parton cross section for channels $q\bar{q}$, gg and qg
  - on-shell scheme for $m_t = 173$ GeV (left)
  - $\overline{MS}$ scheme for $m(m) = 163$ GeV (right)





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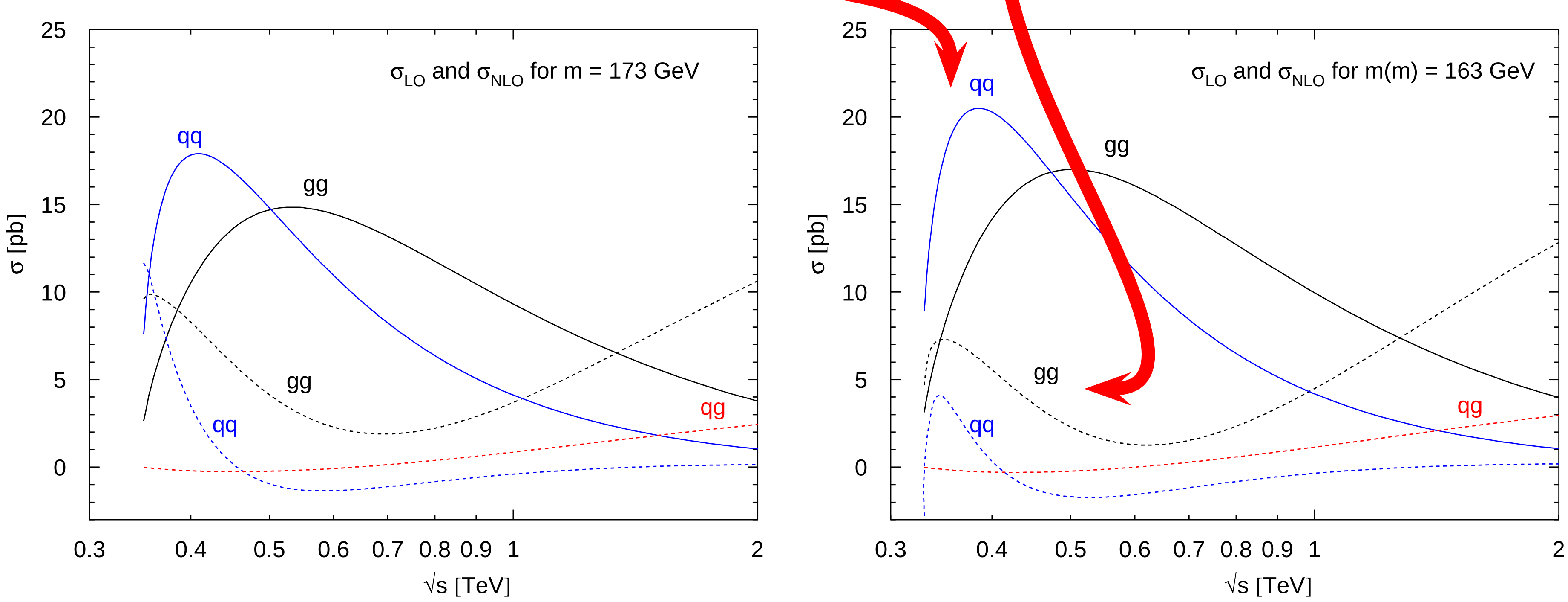
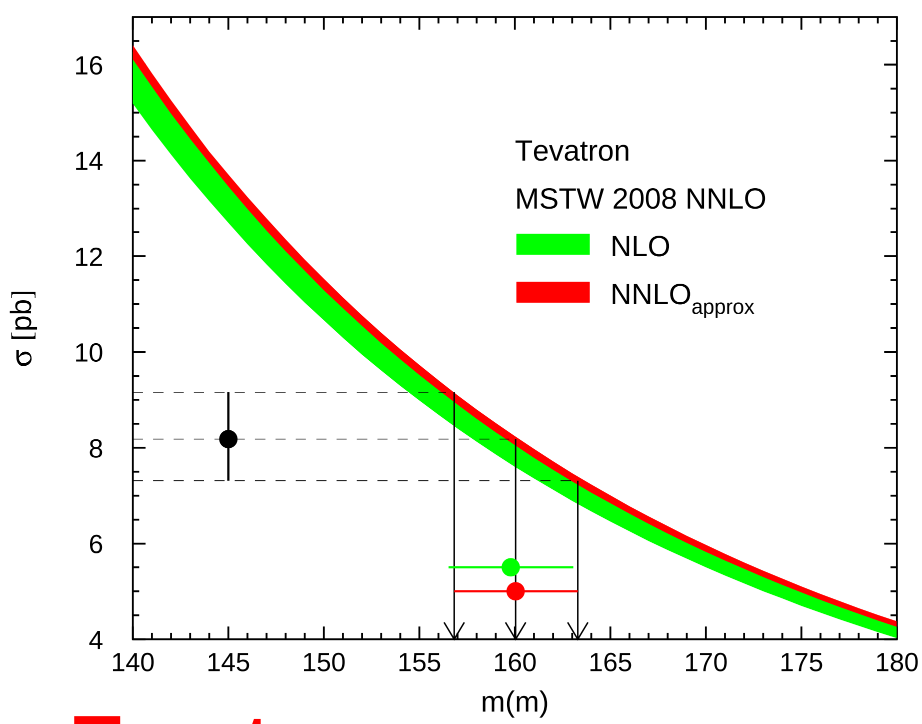
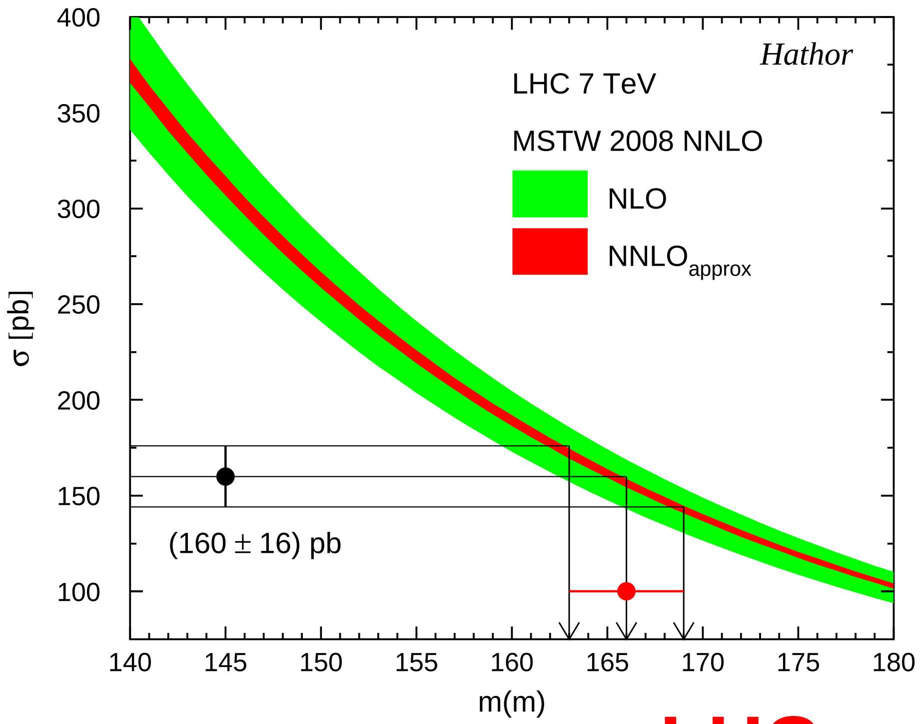
  - on-shell scheme for $m_t = 173$ GeV (left)
  - $\overline{MS}$ scheme for $m(m) = 163$ GeV (right)
- $\overline{MS}$ scheme
  - more emphasis on LO contribution
  - less significance to threshold region at NLO



Top quark's $\overline{MS}$ mass dependence

- Total top-quark cross section as function of $\overline{m}$
  Langenfeld, S.M., Uwer '09
  - theoretical uncertainity (band) due to variation of $\mu_R \in [\overline{m}/2, 2\overline{m}]$ for fixed set $\mu_F \in \overline{m}/2, \overline{m}, 2\overline{m}$





Tevatron **LHC**

Top quark mass determination

- 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 $q\bar{q}$)

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

Top quark cross section at 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
- 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 $^{+2.1}_{-2.0}\,^{+0.7}_{-1.4}$	165.3 $^{+2.3}_{-2.2}\,^{+0.6}_{-1.2}$	166.0 $^{+2.3}_{-2.2}\,^{+0.7}_{-1.5}$	166.7 $^{+2.3}_{-2.2}\,^{+0.8}_{-1.3}$
$m_t^{\rm pole}$	168.6 $^{+2.3}_{-2.2}\,^{+0.7}_{-1.5}$	175.1 $^{+2.4}_{-2.3}\,^{+0.6}_{-1.3}$	176.4 $^{+2.4}_{-2.3}\,^{+0.8}_{-1.6}$	177.4 $^{+2.4}_{-2.3}\,^{+0.8}_{-1.4}$
$(m_t^{\rm pole})$	(166.1 $^{+2.2}_{-2.1}\,^{+1.7}_{-2.3}$)	(172.6 $^{+2.4}_{-2.3}\,^{+1.6}_{-2.1}$)	(173.5 $^{+2.4}_{-2.3}\,^{+1.8}_{-2.5}$)	(174.5 $^{+2.4}_{-2.3}\,^{+2.0}_{-2.3}$)

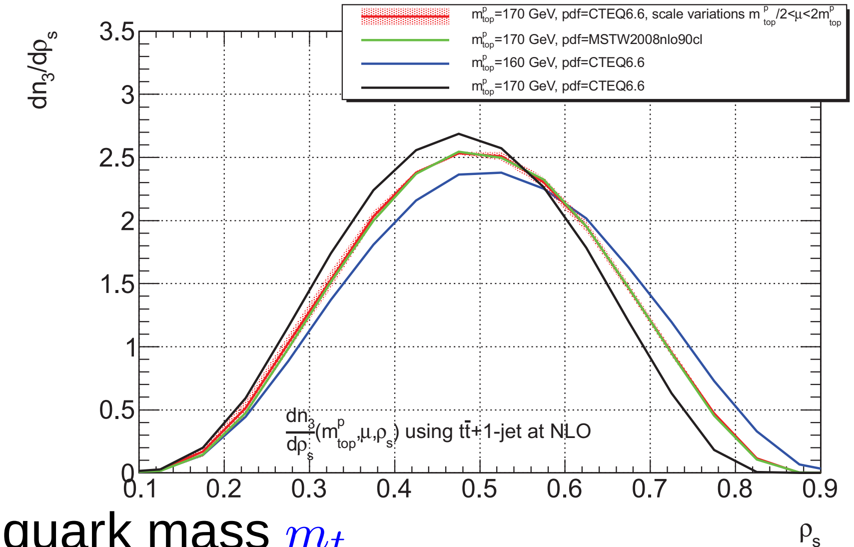
New Observable

Mass measurement with $t\bar{t} + jet$-samples

- Mass determination with new observable
  Alioli, Fuster, Irles, S.M., Uwer, Vos '12
  - define normalized-differential $t\bar{t} + jet$ cross section

$$\frac{dn_3}{d\rho_s}(m_{top}, \mu, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1jet}} \frac{d\sigma_{t\bar{t}+1jet}}{d\rho_s}(m_{top}, \mu, \rho_s)$$

  - variable $\rho_s = \frac{2 \cdot m_0}{\sqrt{s_{t\bar{t}+1jet}}}$
    with $m_0 = 170\,\mathrm{GeV}$
    and invariant mass
    of multi-jet system $\sqrt{s_{t\bar{t}+1jet}}$



Upshot

- Independent determination of top-quark mass m_t
  - alternative to kinematic reconstruction and extraction from total cross section

Implications on electroweak vacuum

- Relation between Higgs mass m_H and top-quark mass m_t
  - condition of absolute stability of electroweak vacuum $\lambda(\mu) \geq 0$
  - extrapolation of Standard Model up to Planck scale M_P
  - $\lambda(M_P) \geq 0$ implies lower bound on Higgs mass m_H

$$m_H \geq 129.2 + 1.8 \times \left(\frac{m_t^{\mathrm{pole}} - 173.2\ \mathrm{GeV}}{0.9\ \mathrm{GeV}} \right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0\ \ \mathrm{GeV}$$

  - recent NNLO analyses Bezrukov, Kalmykov, Kniehl, Shaposhnikov ‘12; Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et a. ‘12
  - uncertainity in results due to α_s and m_t (pole mass scheme)

$\mathcal{T}$riviality $\mathcal{B}$ound

- **Quantum corrections to the Higgs potential:** $V(\Phi) = \lambda[\Phi^\dagger\Phi - \frac{v^2}{2}]^2$
- **Corrections to coupling λ**

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 + \text{higher order}$$

- **Large mass** $\rightsquigarrow$ λ dominated renormalisation group equation (RGE):

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 \qquad \Longrightarrow \qquad \lambda(Q) = \frac{M_H^2}{2v^2 - \frac{3}{2\pi^2} M_H^2 \ln(Q/v)}$$

λ increases with Q

- **Landau pole**

$$\Lambda \leq v e^{4\pi^2 v^2/3M_H^2}$$

New Physics must appear before this point to restore stability

$\Longrightarrow$ For Λ fixed upper bound on M_H

- **Triviality** No quantum theory for $\Lambda \to \infty$: trivial theory $\lambda = 0$.

$\mathcal{V}$acuum $\mathcal{S}$tability

- **Corrections to coupling λ**

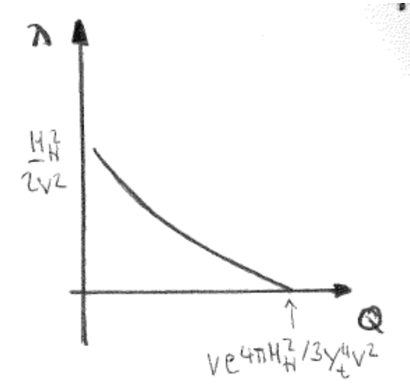
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 + \text{higher order}$$

- **Small mass** $\rightsquigarrow$ y_t dominated RGE:

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4 \qquad \Longrightarrow \qquad \lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

λ decreases with Q; $\lambda < 0 \rightsquigarrow$ potential unbounded from below

$\lambda = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2}\, y_0^4 \ln \frac{Q}{Q_0}$



- **Vacuum stability**

$$\Lambda \leq v e^{4\pi^2 M_H^2 / 3 y_t^4 v^2}$$

New Physics must appear before this point to ensure vacuum stability

$\Longrightarrow$ For Λ fixed lower bound on M_H

M.M.Mühlleitner, 24-26 July 2012, Dubna

M. Mühlleitner (CALC 2012)

Implications on electroweak vacuum

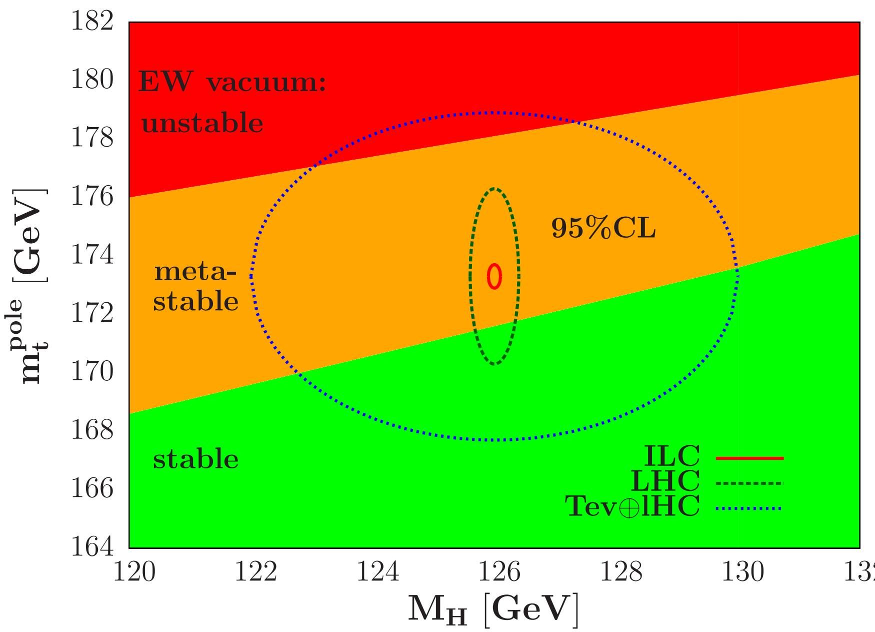
- Relation between Higgs mass m_H and top-quark mass m_t

$$m_H \geq 129.2 + 1.8 \times \left(\frac{m_t^{\text{pole}} - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0 \text{ GeV}$$

- Uncertainty in Higgs bound due to m_t determined in $\overline{MS}$ scheme

$$m_t^{\overline{\text{MS}}}(m_t) = 163.3 \pm 2.7 \text{ GeV}$$

- Implications:
  - m_t in pole mass scheme:
    $m_t^{\text{pole}} = 173.3 \pm 2.8 \text{ GeV}$
  - bound on
    $m_H \geq 129.4 \pm 5.6 \text{ GeV}$



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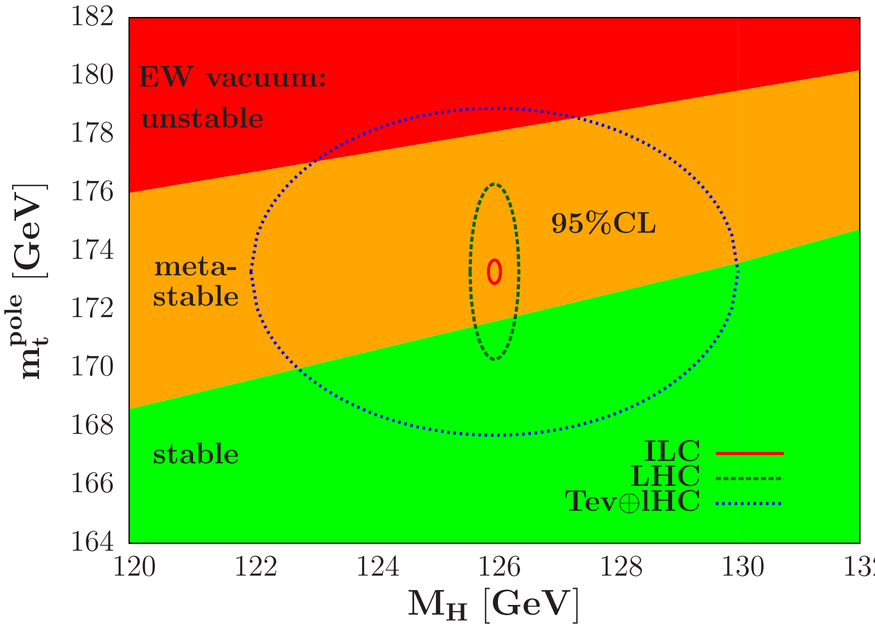
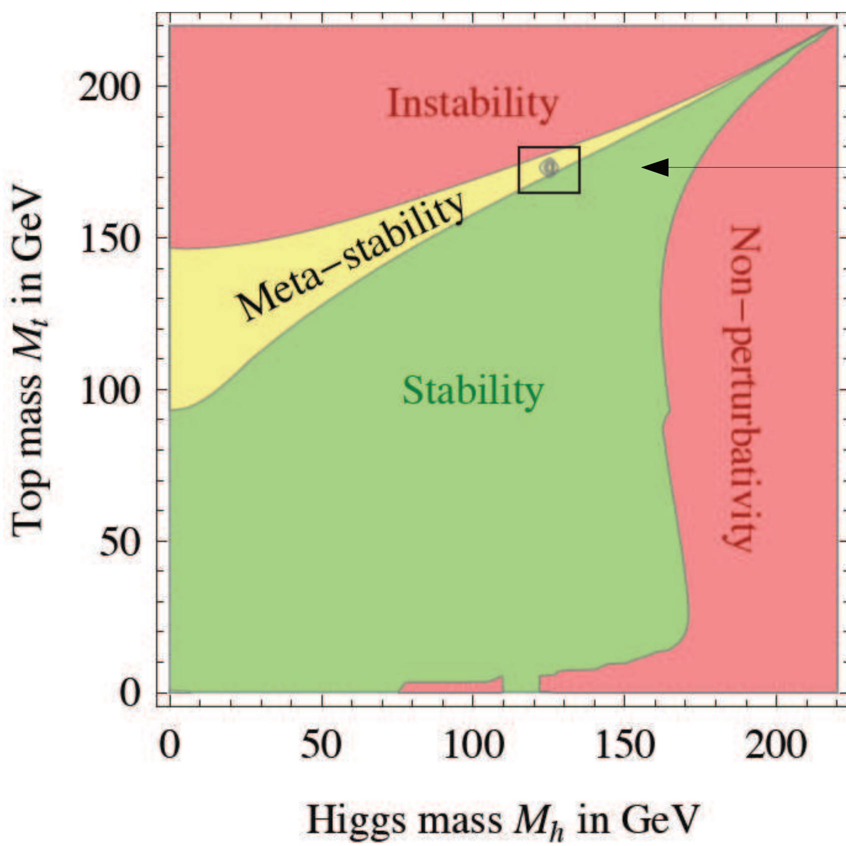
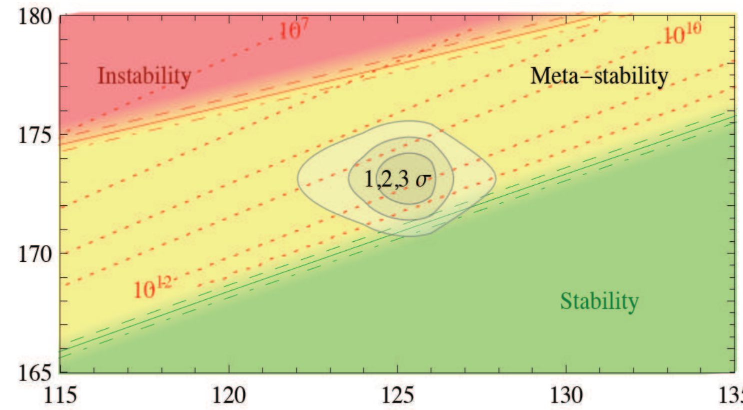


▶ *Speculations on Planck-scale dynamics*





Looking at the plane from a more distant perspective, it appears more clearly that "we live" in a quite "peculiar" region...

And moving m_t down by ~ 2 GeV, we reach the even more peculiar configuration where $\lambda(M_{pl})=0$

Froggatt, Nielsen, Takanishi, '01
Arkani-Hamed *et al.*, '08
Shaposhnikov, Wetterich, '10
...

G. Isidori (Higgs Hunting 2012)

Summary (part III)

- Top quark theory
  - improved understanding of theory and application of new concepts
  - resummation important for Tevatron and LHC phenomenology
- Cross sections
  - NNLO predictions for $t\bar{t}$
  - NLO corrections to $t\bar{t}+$ jet
  - electroweak corrections
- $\overline{MS}$ mass definition
  - greatly reduced scale dependence
  - much improved convergence of perturbation theory