The Higgs-boson, the top-quark and electroweak vacuum stability

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Fate of the universe

Higgs boson mass Atlas & CMS coll. ‘13

$$m_H = 125.6 \pm 0.3\,\text{GeV}$$

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Bound on from vacuum stability

$$m_H \geq 129.2\,\text{GeV}$$

Fate of the universe

Higgs boson too light ? Are we doomed ?

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WORLD

Scientists studying so-called subatomic 'God particle' say there will be an universe-ending 'catastrophe'

The end of the universe won't come for tens of billions of years, but when it does happen it will destroy everything, according to researchers studying the Higgs boson particle. "If you use all the physics that we know now and you do what you think is a straightforward calculation, it's bad news," theoretical physicist Joseph Lykken said Monday.

Comments (24)

REUTERS

TUESDAY, FEBRUARY 19, 2013, 11:44 AM

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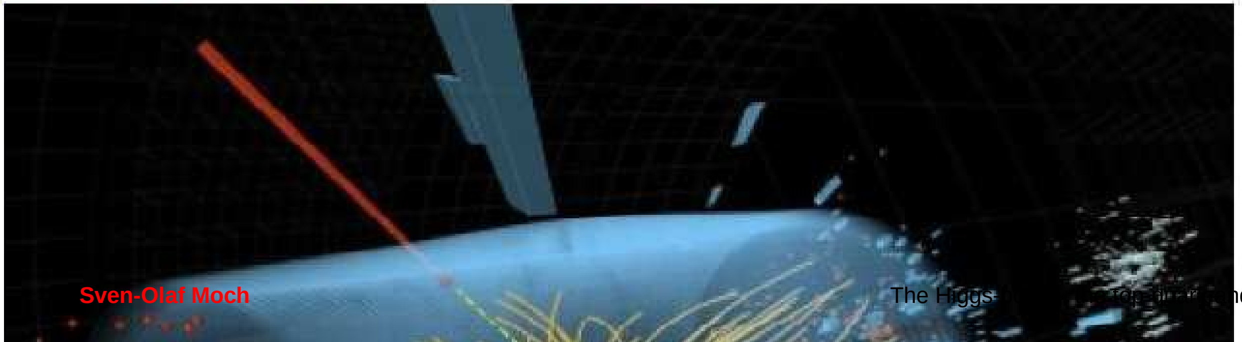

Fate of the universe

Well, . . . [check the fine print]

$$m_H \geq 129.2\text{GeV} + 1.8 \times \left(\frac{m_t - 173.2\text{GeV}}{0.9\text{GeV}} \right) + \ldots$$

Top quark mass

Experimental result CDF & D0 coll. 1305.3929

$$m_t = 173.20 \pm 0.87\,\mathrm{GeV}$$

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Which top quark mass has this value ?

$$? = 173.20 \pm 0.87\,\mathrm{GeV}$$

Introduction

Classical mechanics

- Mass is defined as product of density and volume of matter
  - classical concept

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  A body twice as dense in double the space is quadruple in quantity. This quantity I designate by the name of body or of mass.
  Newton

PHILOSOPHIÆ NATURALIS

PRINCIPIA MATHEMATICA.

DEFINITIONES.

DEFINITIO I.

Quantitas materiæ est mensura ejusdem orta ex illius densitate et magnitudine conjunctim.

AER densitate duplicata, in spatio etiam duplicato, fit quadruplus; in triplicato sextuplus. Idem intellige de nive & pulveribus per compressionem vel liquefactionem condensatis. Et par est ratio corporum omnium, quæ per causas quascunque diversimode condensantur. Medii interea, si quod fuerit, interstitia partium libere pervadentis, hic nullam rationem habeo. Hanc autem quantitatem sub nomine corporis vel massæ in sequentibus passim intelligo. Innotescit ea per corporis cujusque pondus: Nam ponderi proportionalem esse reperi per experimenta pendulorum accuratissime instituta, uti posthac docebitur.

DEFINITIO II.

Quantitas motus est mensura ejusdem orta ex velocitate et quantitate materiæ conjunctim.

Motus totius est summa motuum in partibus singulis; ideoque in corpore duplo majore, æquali cum velocitate, duplus est, & dupla cum velocitate quadruplus.

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Atomic theory

- Mass is conserved Lavoisier
- Mass of body is sum of mass of its constituents
  $M(X) = N_A m_a(X)$ Avogadro

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Special relativity

- Equivalence principle
  $E = mc^2$ Einstein

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A

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 $D_{\mu,ij} = \partial_\mu \delta_{ij} + \mathrm{i} g_s \left(t_a \right)_{ij} A^a_\mu$

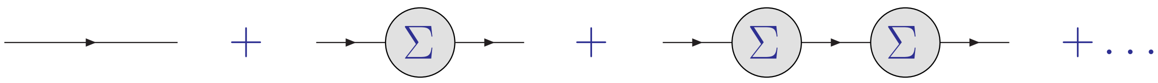
- Formal parameters of the theory (no observables)
  - strong coupling $\alpha_s = g_s^2/(4\pi)$
  - quark masses m_q

Challenge

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

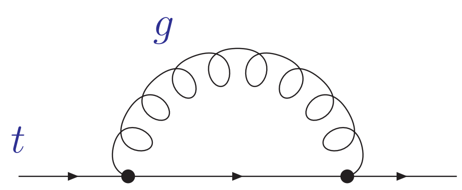
Quark mass renormalization

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



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

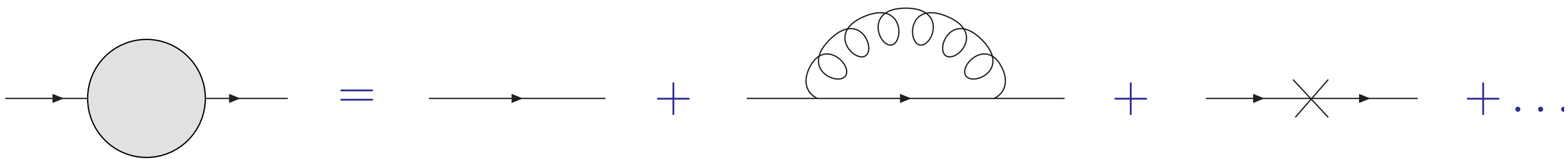
QCD



- 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 $m_q^{\mathrm{bare}} = m_q^{\mathrm{ren}} + \delta m_q$



$\Sigma^{\mathrm{ren}}(p, m_q)$ $\qquad$ $(Z_\psi - 1)\not{p} - (Z_m - 1)m_q$

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 $\mathcal{O}(\Lambda_{QCD})$

$\overline{MS}$ *scheme*

- $\overline{MS}$ mass definition
  - one-loop minimal subtraction

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

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

Scheme transformations

- Conversion between different renormalization schemes possible in perturbation theory
- Relation for pole mass and $\overline{MS}$ mass
  - known to three loops in QCD Gray, Broadhurst, Gräfe, Schilcher ‘90; Chetyrkin, Steinhauser ‘99; Melnikov, v. Ritbergen ‘99
  - example: one-loop QCD

$$m^{\rm pole} = m(\mu) \left\{ 1 + \frac{\alpha_s(\mu)}{4\pi} \left(\frac{4}{3} + \ln\left(\frac{\mu^2}{m(\mu)^2} \right) \right) + \dots \right\}$$

Running quark mass

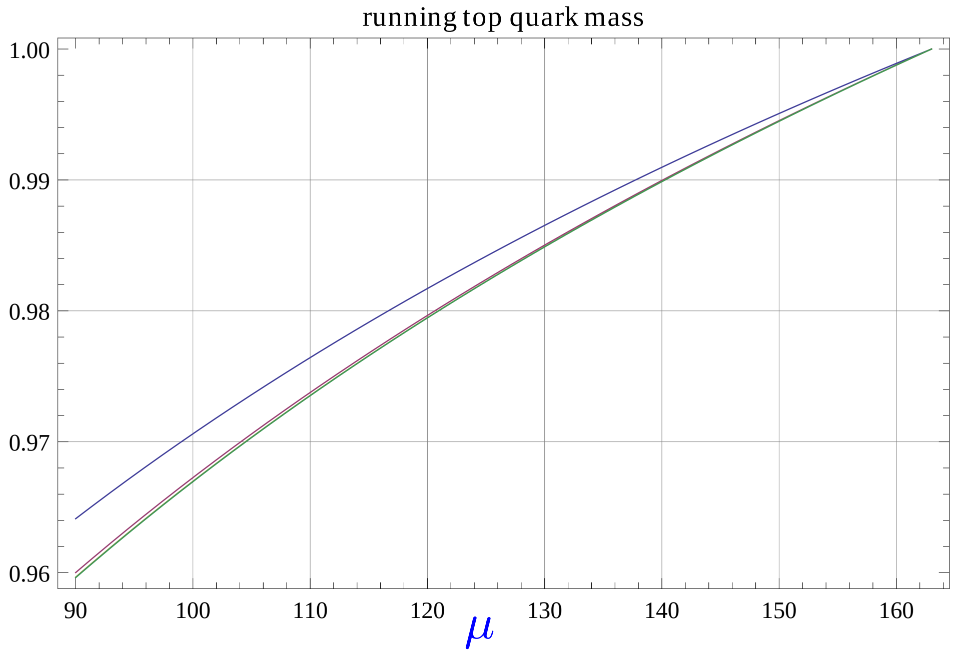
Scale dependence

- Renormalization group equation for scale dependence
  - mass anomalous dimension γ known to four loops

    Chetyrkin '97; Larin, van Ritbergen, Vermaseren '97

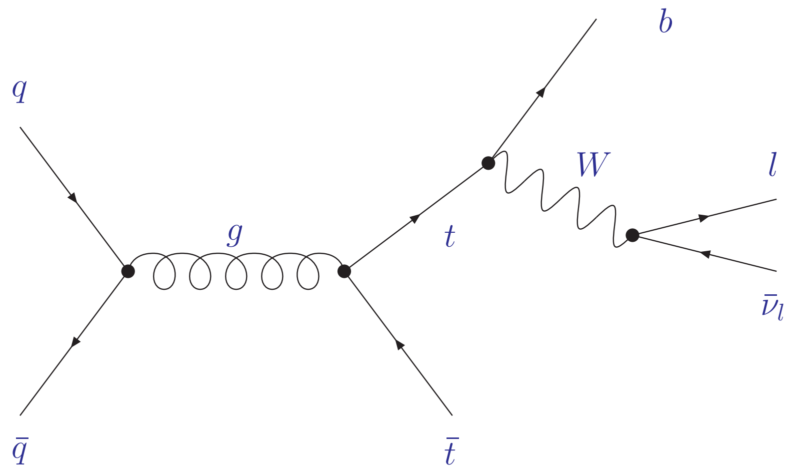
$$\left(\mu^2 \frac{\partial}{\partial \mu^2} + \beta(\alpha_s) \frac{\partial}{\partial \alpha_s}\right) m(\mu) = \gamma(\alpha_s) m(\mu)$$

- Plot mass ratio $m_t(163\text{GeV})/m_t(\mu)$



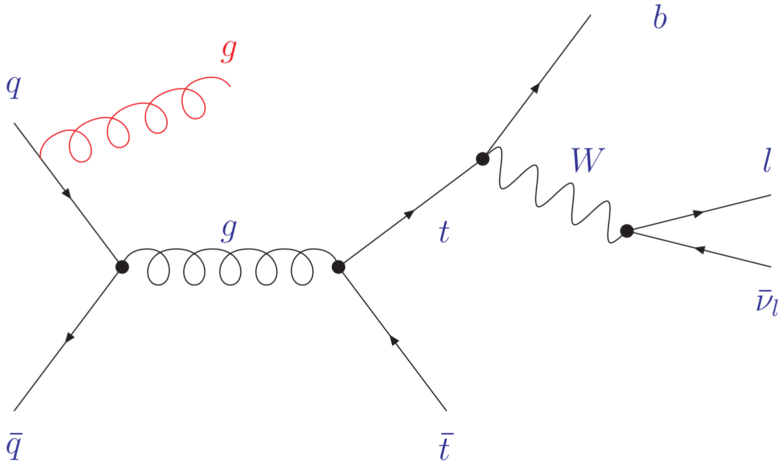
Hard scattering process

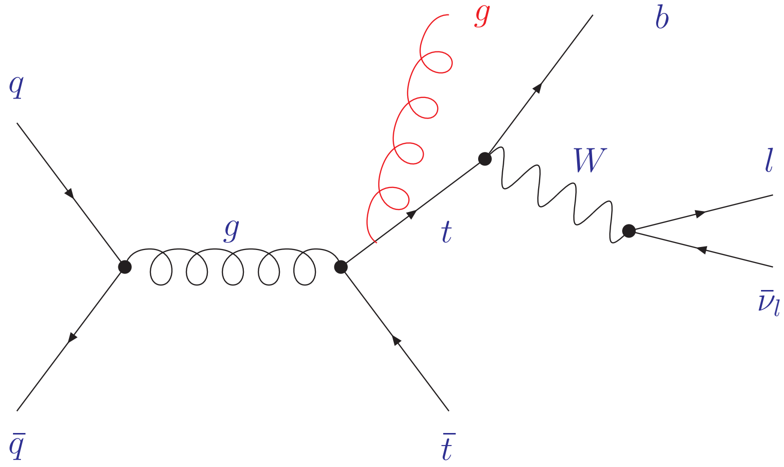
- Born process ($q\bar{q}$-channel) with leptonic decay $t \to b l \bar{\nu}_l$



Radiative corrections

- Real corrections (examples): gluon emission
  - phase space integration $\rightarrow$ infrared divergences (soft/collinear singularities)



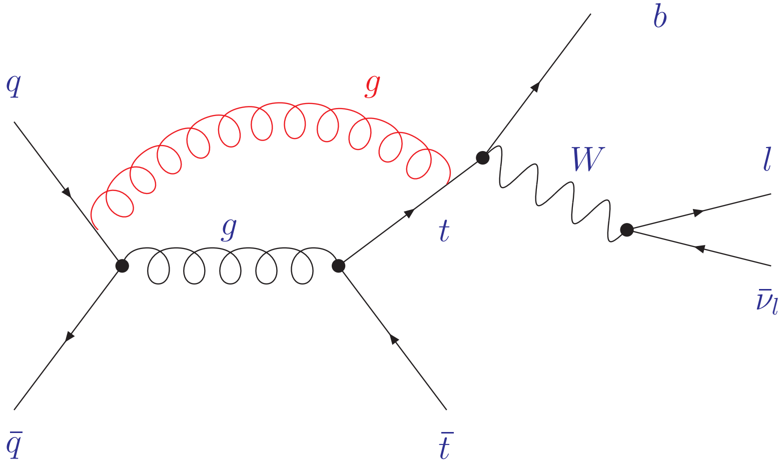


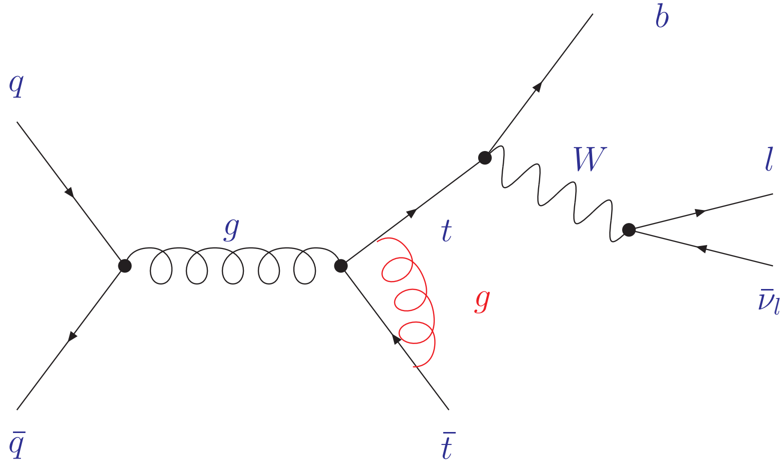
- Parton shower MC
  - emission probability modeled by Sudakov exponential with cut-off Q_0
  - leading logarithmic accuracy

$$\Delta\left(Q^2, Q_0^2\right) \;=\; \exp\left(-C_F\,\frac{\alpha_s}{2\pi}\,\ln\left(\frac{Q^2}{Q_0^2}\right)\right)$$

Radiative corrections

- Virtual corrections (examples): gluon exchange
  - box diagram (left) and vertex corrections (right)
  - infrared divergences cancel against real emission contributions





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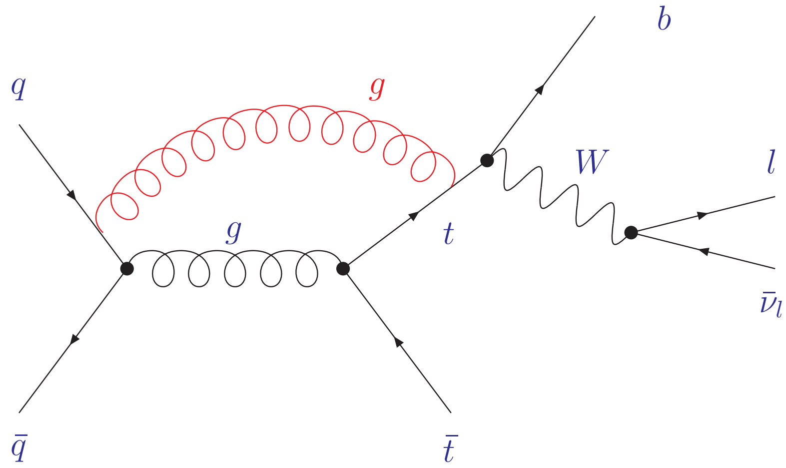
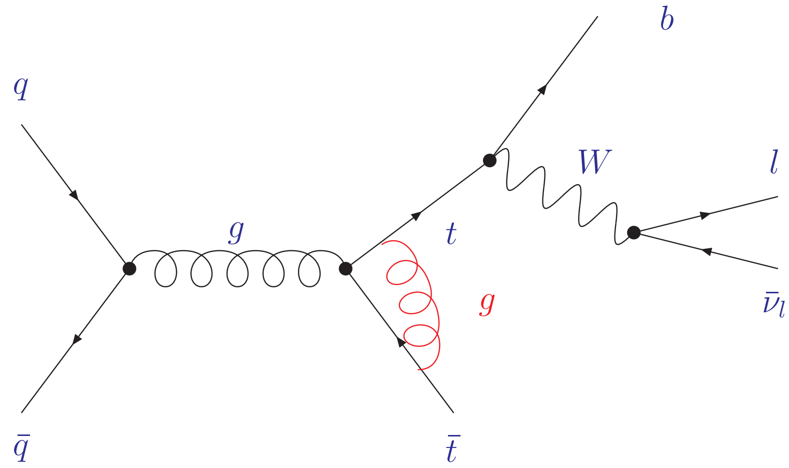
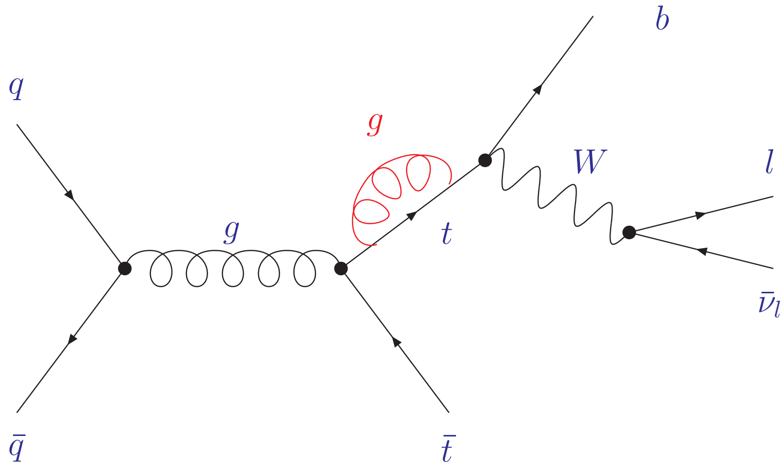


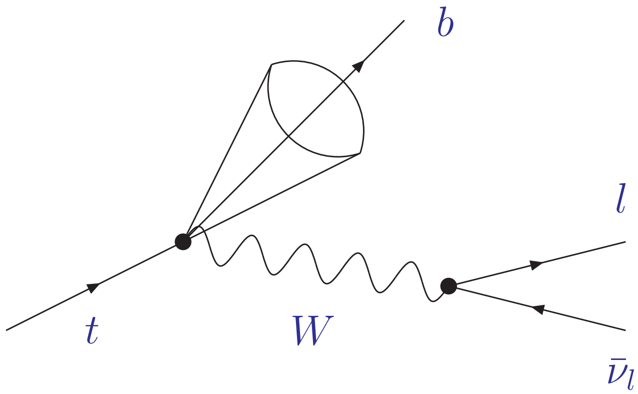


- Mass renormalization from self-energy corrections to top quark



Current methods

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



Template method

- Distributions of kinematically reconstructed top mass values compared to templates for nominal top mass values
  - distributions rely on parton shower predictions
  - no NLO corrections applied

Matrix element method

- Event-by-event likelihood for kinematic configurations arising from events of a given top mass.
  - tree level matrix elements only
  - combinatorics of assignment of jets to top quarks

Tevatron combination

- Error budget in Tevatron determination
  CDF & D0 coll. 1207.1069
  - lepton+jets channel with matrix element method
- *Modeling signal* encompasses all perturbative uncertainties
  - radiative corrections (initial/final)
  - higher order QCD corrections
  - . . .
- Uncertainties too optimistic
  $\Delta m_t \simeq 150 \ldots 250$ MeV
- Contradicts lattice bound
  $\Delta m_t \geq 200$ MeV
  (if interpreted as pole mass)

TABLE VIII: Individual components of uncertainty on CDF and D0 m_t measurements in the lepton+jets channel for Run II data [26, 27].

Systematic Source	Uncertainty [GeV] CDF (5.6 fb^{-1}) $m_t = 173.00$ GeV	D0 (3.6 fb^{-1}) $m_t = 174.94$ GeV
DETECTOR RESPONSE		
Jet energy scale		
Light-jet response (1)	0.41	n/a
Light-jet response (2)	0.01	0.63
Out-of-cone correction	0.27	n/a
Model for b jets	0.23	0.07
Semileptonic b decay	0.16	0.04
b-jet hadronization	0.16	0.06
Response to $b/q/g$ jets	0.13	0.26
In-situ light-jet calibration	0.58	0.46
Jet modeling	0.00	0.36
Jet energy resolution	0.00	0.24
Jet identification	0.00	0.26
Lepton modeling	0.14	0.18
MODELING SIGNAL		
Signal modeling	0.56	0.77
Parton distribution functions	0.14	0.24
Quark annihilation fraction	0.03	n/a
Initial and final-state radiation	0.15	0.26
Higher-order QCD corrections	n/a	0.25
Jet hadronization and underlying event	0.25	0.58
Color reconnection	0.37	0.28
Multiple interactions model	0.10	0.05
MODELING BACKGROUND		
Background from theory	0.27	0.19
Higher-order correction for heavy flavor	0.03	0.07
Factorization scale for W+jets	0.07	0.16
Normalization to predicted cross sections	0.25	0.07
Distribution for background	0.07	0.03
Background based on data	0.06	0.23
Normalization to data	0.00	0.06
Trigger modeling	0.00	0.06
b-tagging modeling	0.00	0.10
Signal fraction for calibration	n/a	0.10
Impact of multijet background on the calibration	n/a	0.14
METHOD OF MASS EXTRACTION		
Calibration method	0.10	0.16
STATISTICAL UNCERTAINTY	0.65	0.83
UNCERTAINTY ON JET ENERGY SCALE	0.80	0.83
OTHER SYSTEMATIC UNCERTAINTIES	0.67	0.94
TOTAL UNCERTAINTY	1.23	1.50

Alternative methods

- Top mass from leptonic decay: m_{lb} distribution
- Top mass from jet rates
- Top mass from total cross section

Top mass from leptonic decay

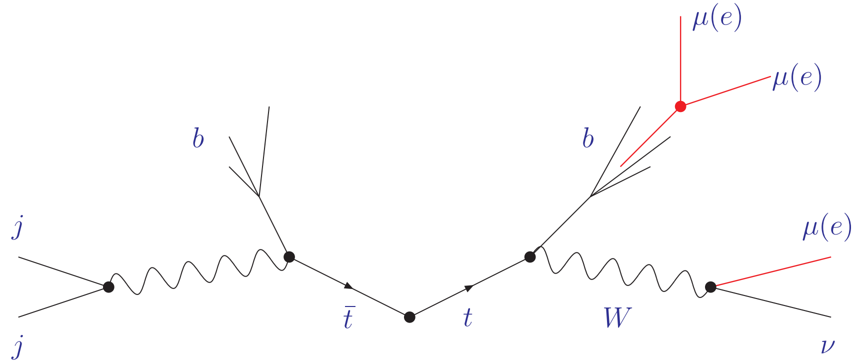
- Top mass from exclusive hadronic states

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

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

    Kharchilava '00

    Chierici, Dierlamm '06

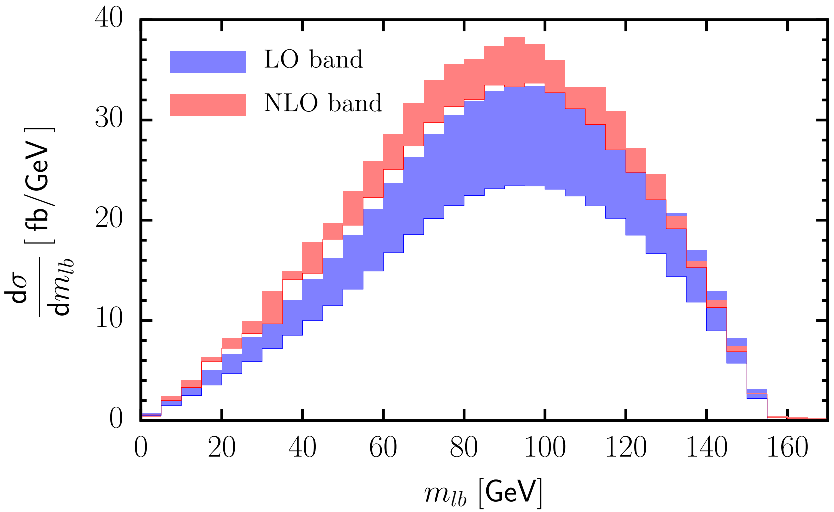


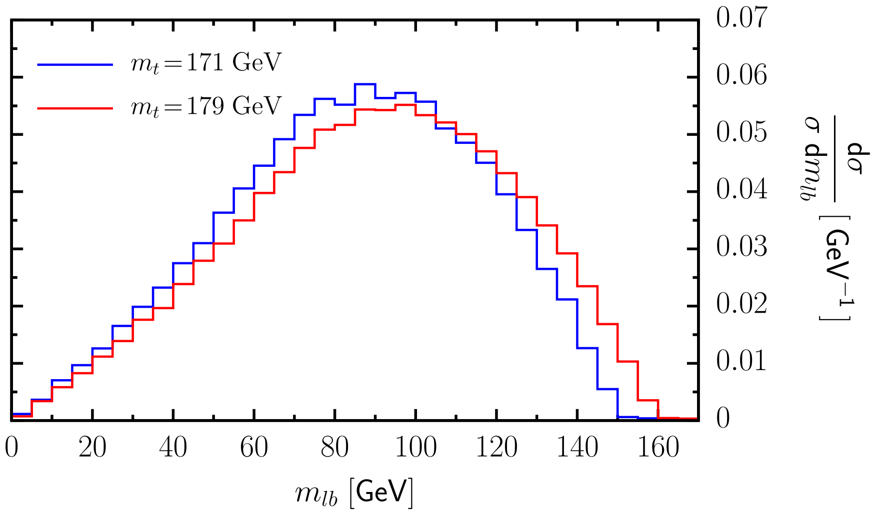
Top mass from leptonic decay

- Top mass from exclusive hadronic states

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

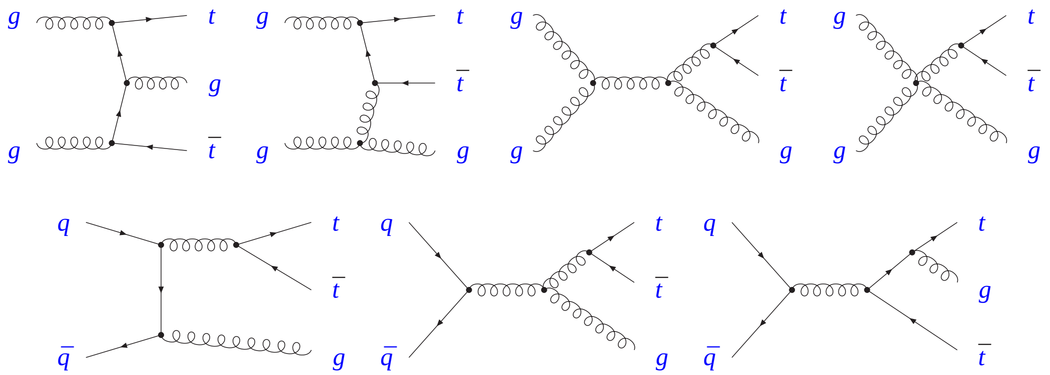
- Study of m_{lb} distribution at NLO in QCD Biswas, Melnikov, Schulze '10
  - NLO QCD corrections to production **and** decay very important for value of m_t (effects of order $\Delta m_t = \mathcal{O}(\text{few})$ GeV
- Invariant mass distribution of lepton and b-jet (LHC14)
  - scale dependence at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

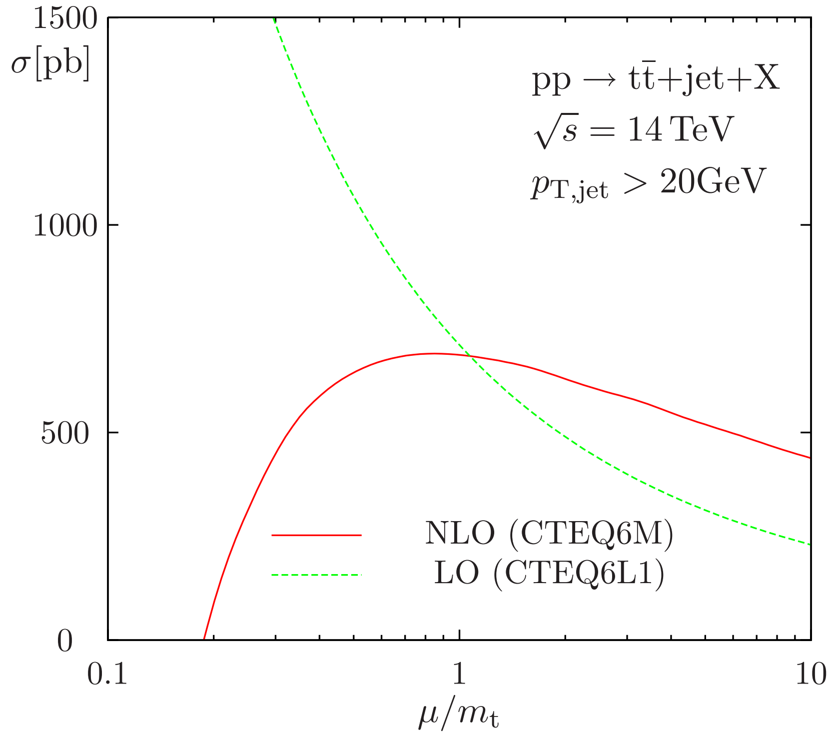




Top-quark pairs with one jet

- LHC: large rates for production of $t\bar{t}$-pairs with additional jets
- NLO QCD corrections for $t\bar{t} + 1\text{jet}$ 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





- Additional jet raises kinematical threshold
  - invariant mass $\sqrt{s_{t\bar{t}+1\text{jet}}}$

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

- Mass measurement with new observable

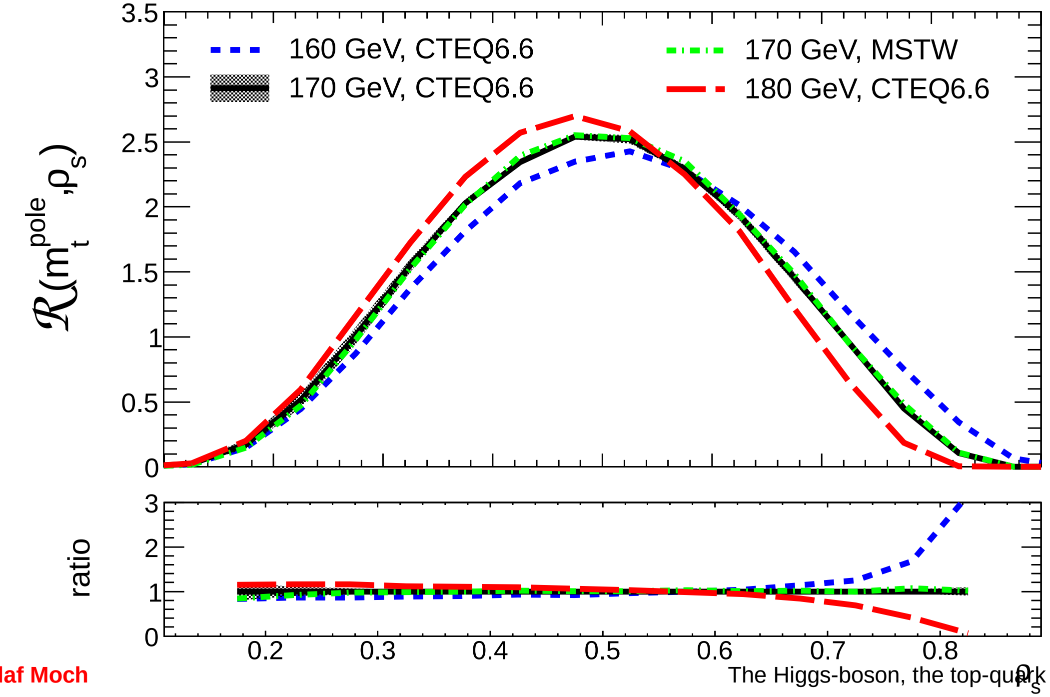
  Alioli, Fernandez, Fuster, Irles, S.M., Uwer, Vos '13

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

- Normalized-differential $t\bar{t}+\text{jet}$ cross section

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

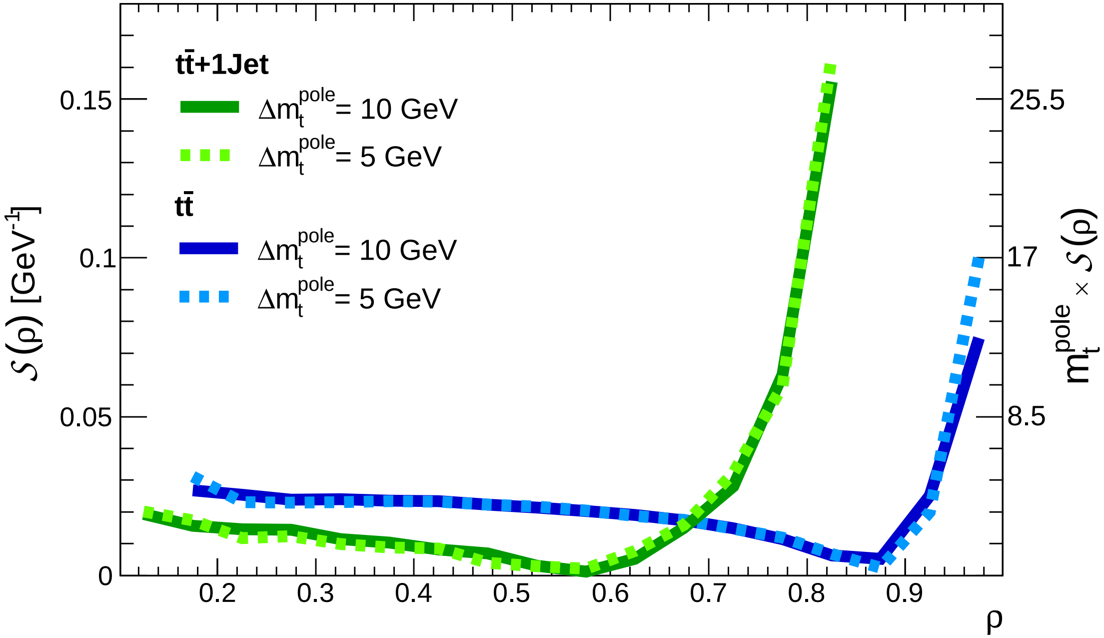
  - significant mass dependence for $0.4 \leq \rho_s \leq 0.5$ and $0.7 \leq \rho_s$



- 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 $t\bar{t}$

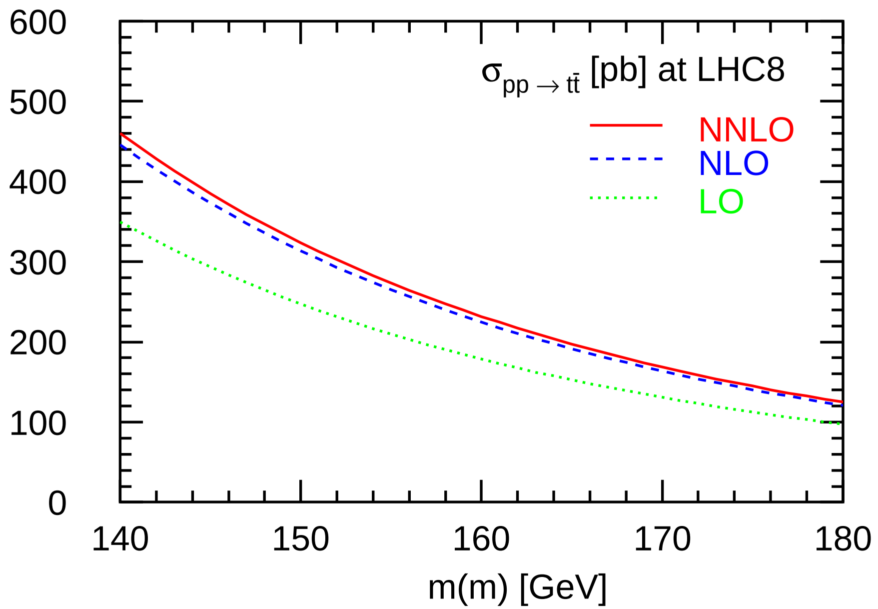


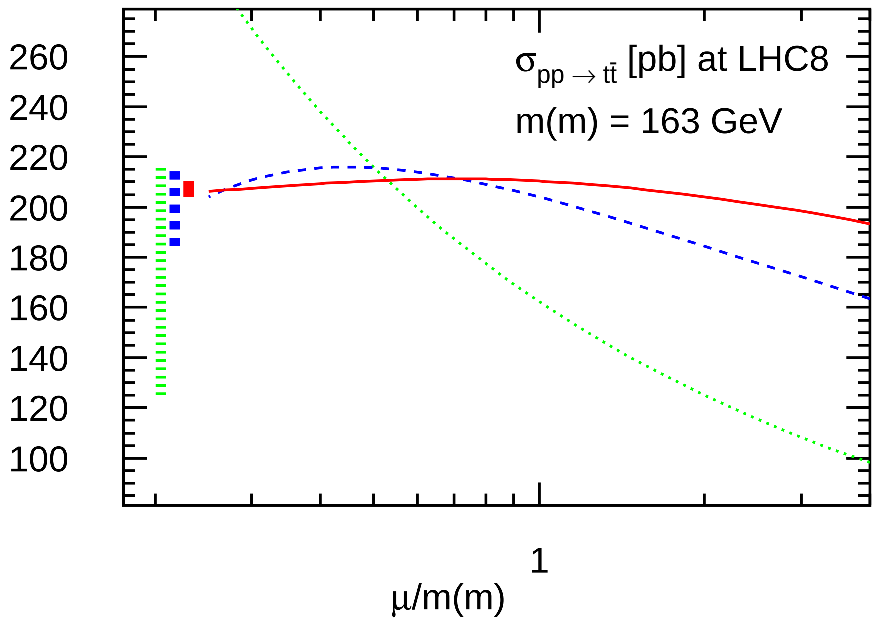
Upshot

- Precision determination of well-defined top-quark mass m_t possible
  - alternative to inclusive cross sections

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: $m_t = m(\mu_R)\left(1 + a_s(\mu_R) d^{(1)} + a_s(\mu_R)^2 d^{(2)}\right)$
- Good apparent convergence of perturbative expansion
- Small theoretical uncertainity form scale variation





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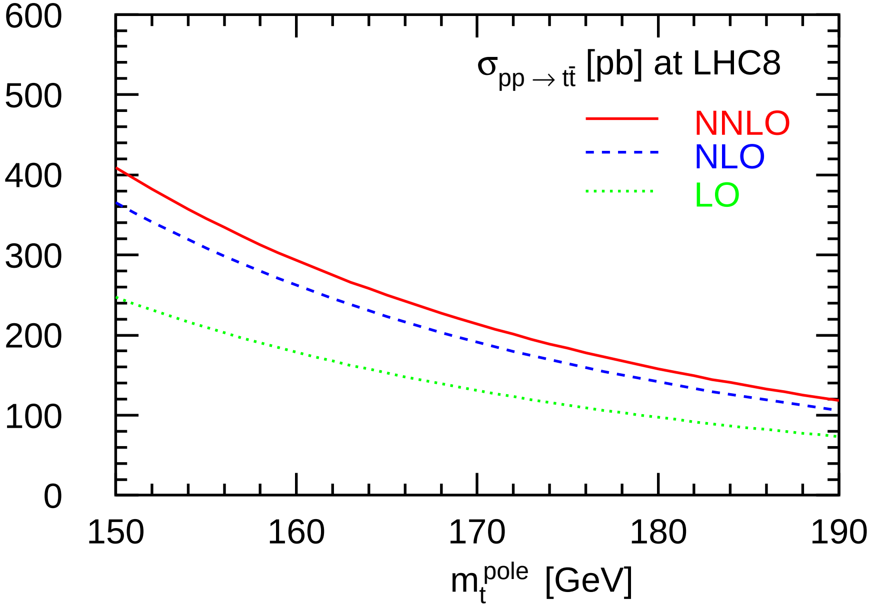
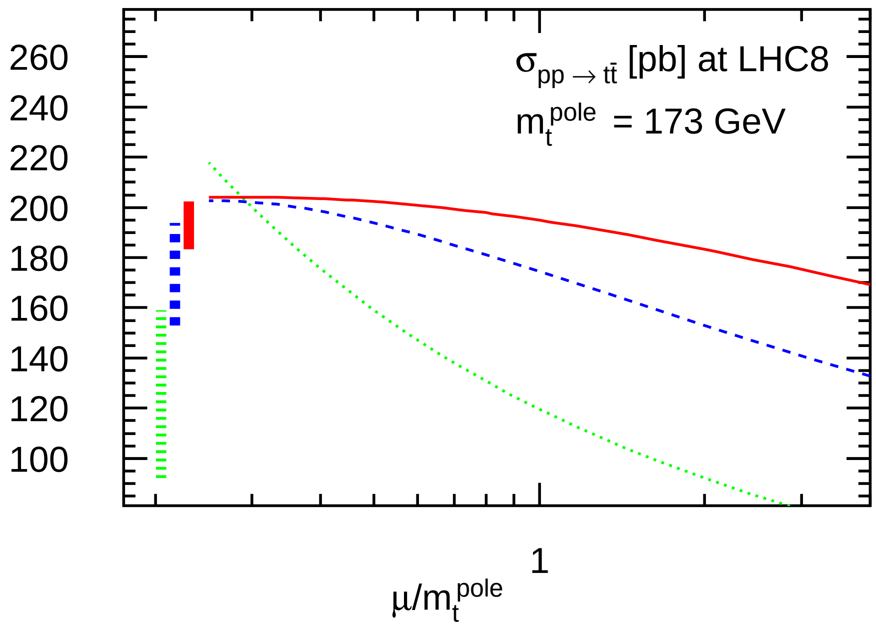
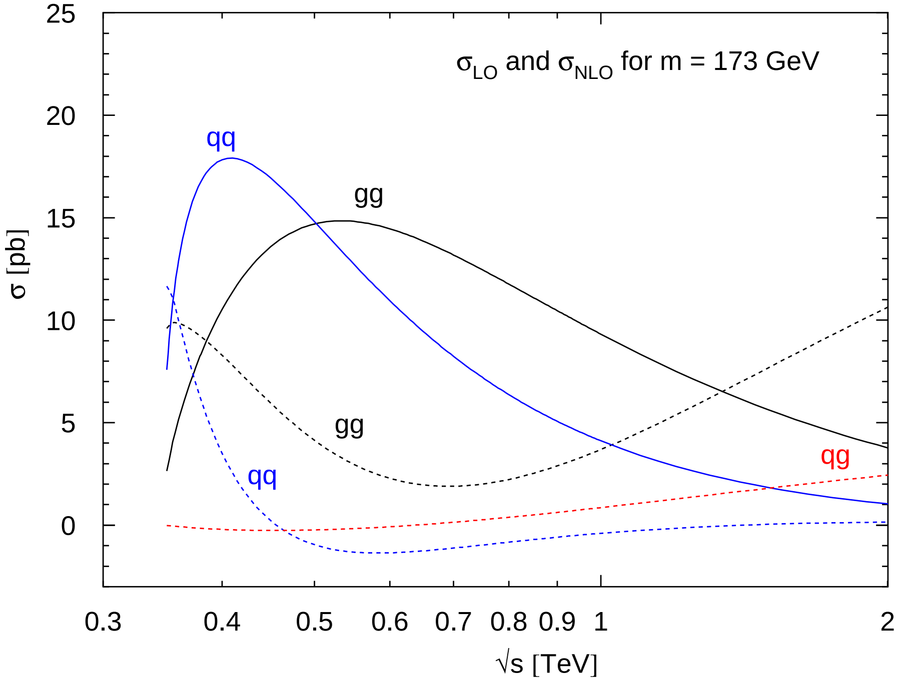
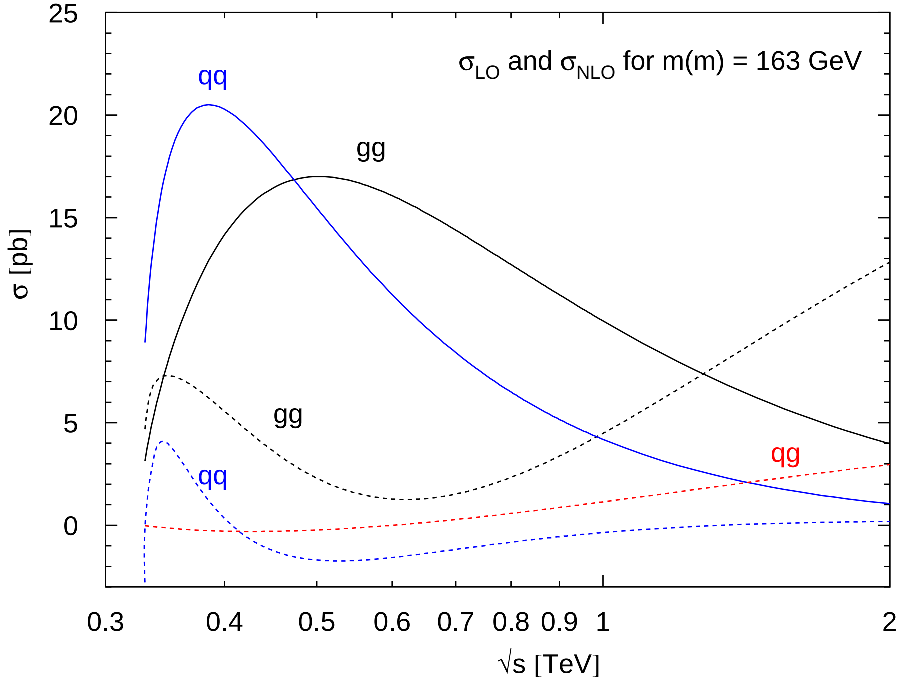
- Pole mass scheme for comparison



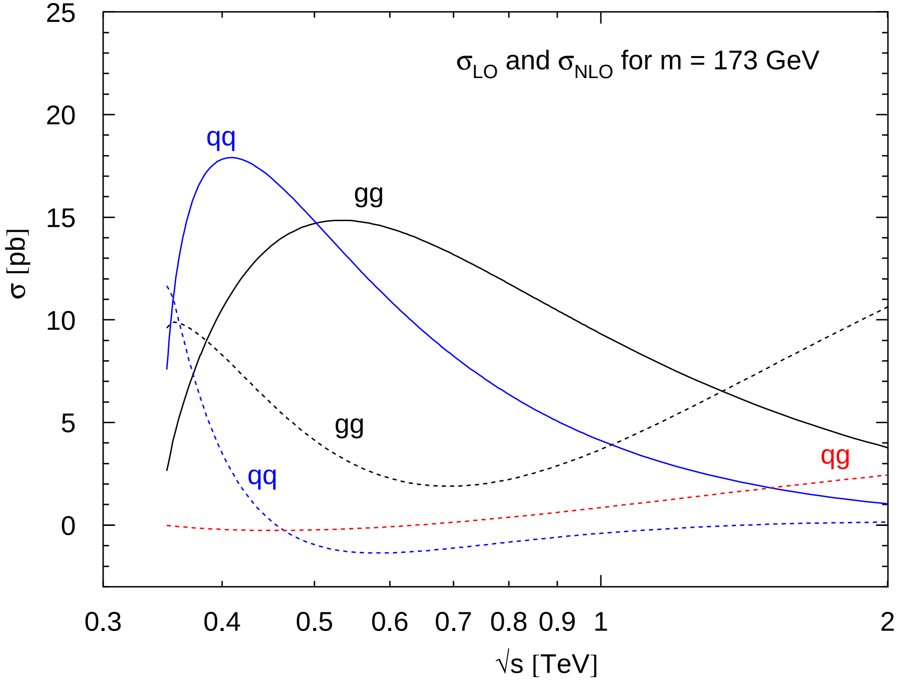


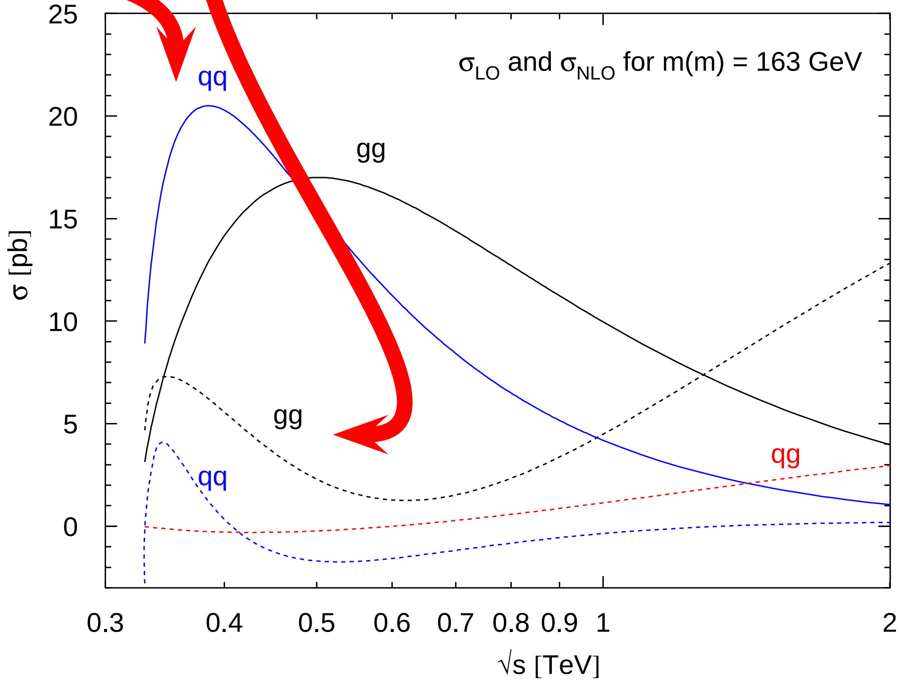
- Perturbative stability of predictions with $\overline{MS}$ mass definition
- Parton cross section for channels $q\bar{q}$, gg and qg
  - on-shell scheme for $m_t = 173$ GeV (left)
  - $\overline{MS}$ scheme for $m(m) = 163$ GeV (right)





- 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)
- $\overline{MS}$ scheme
  - more emphasis on LO contribution
  - less significance to threshold region at NLO



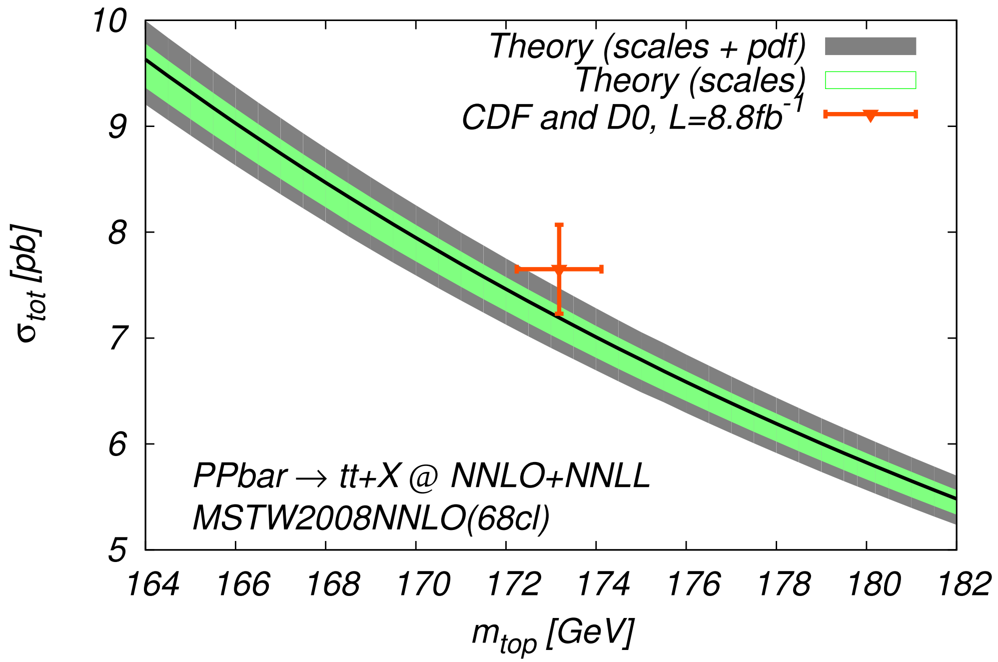


Top mass from total cross section

Exact result at NNLO in QCD

Czakon, Fiedler, Mitov ‘13

- Illustration of mass dependence for Tevatron (pole mass)



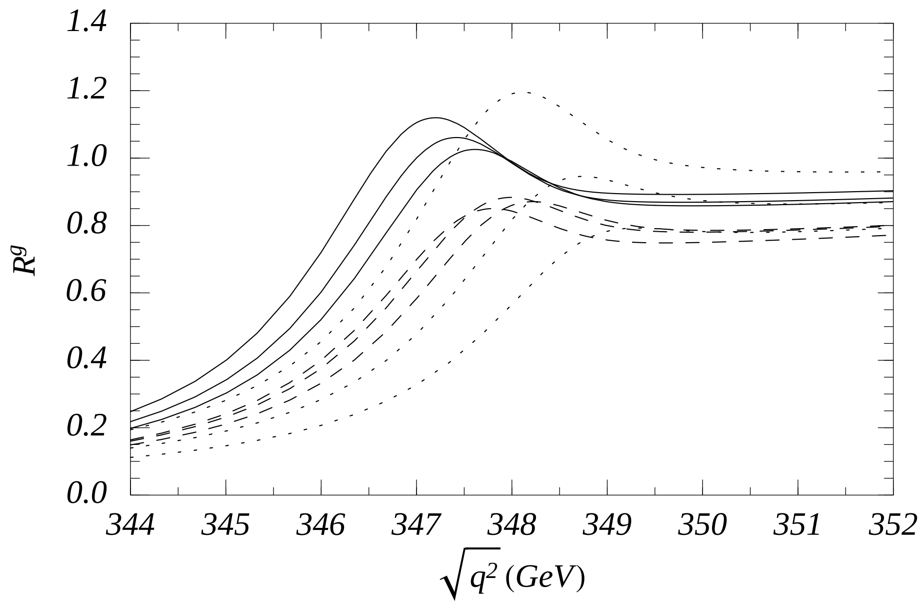
- NNLO perturbative corrections (e.g. at LHC8)
  - K-factor (NLO $\to$ NNLO) of $\mathcal{O}(10\%)$
  - scale stability at NNLO of $\mathcal{O}(\pm 5\%)$

Top quark pole mass

Illustration for top quark pole 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)

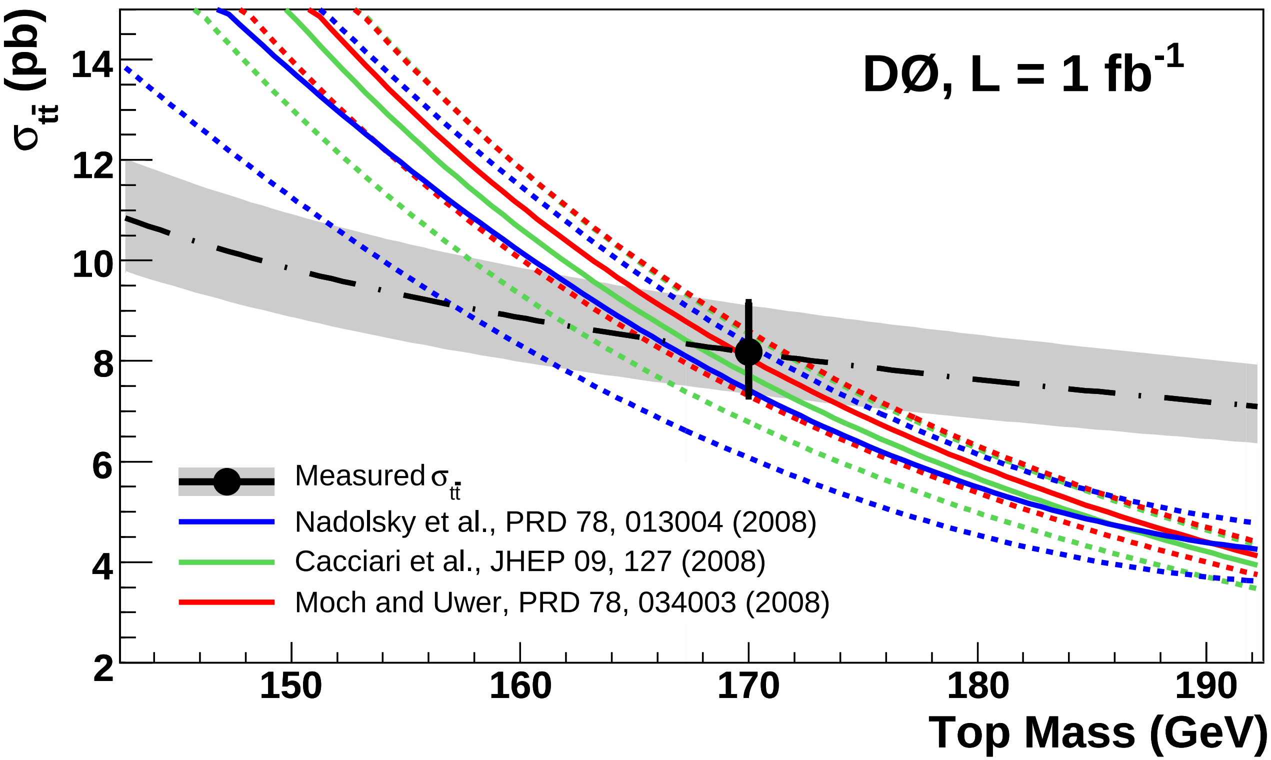


Top quark pole mass

Illustration for top quark pole 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 $m_t = 169.1^{+5.9}_{-5.2}$; ...



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 running mass $m_t(m_t)$ for individual PDFs
  - parton luminosity at Tevatron driven by $q\bar{q}$
  - $\overline{MS}$-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

The fine print

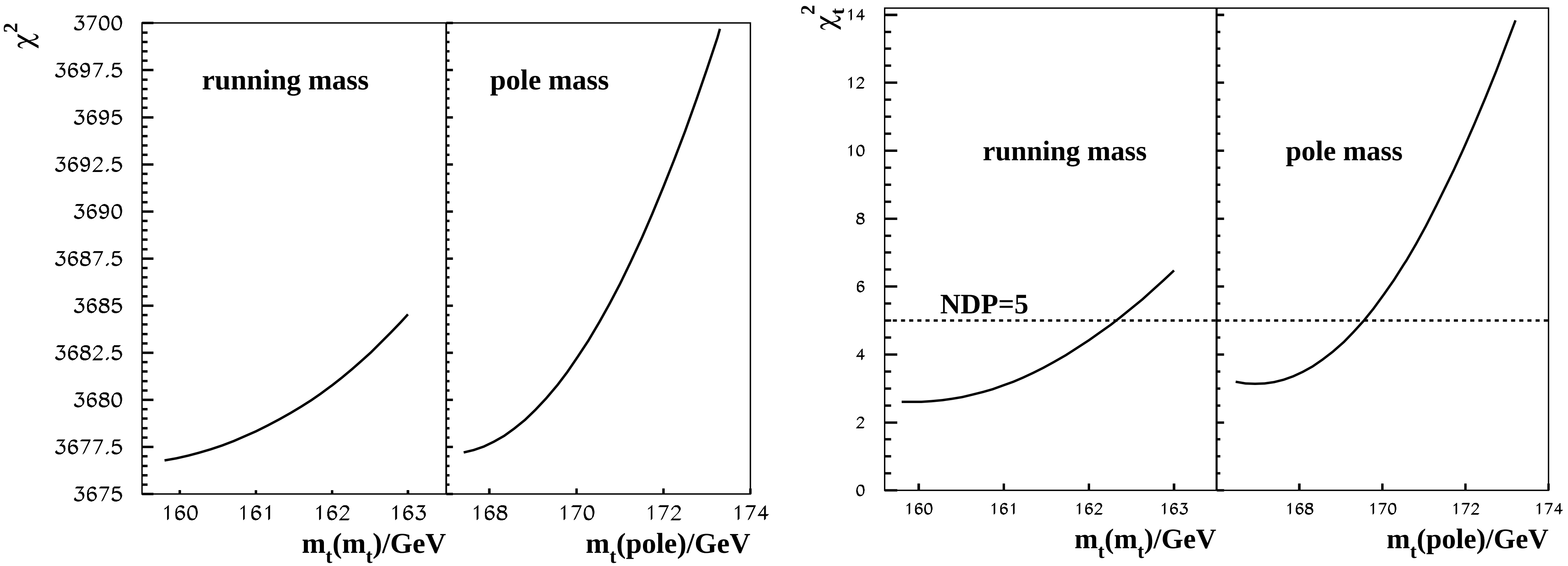
- Intrinsic limitation of sensitivity in total cross section

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

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

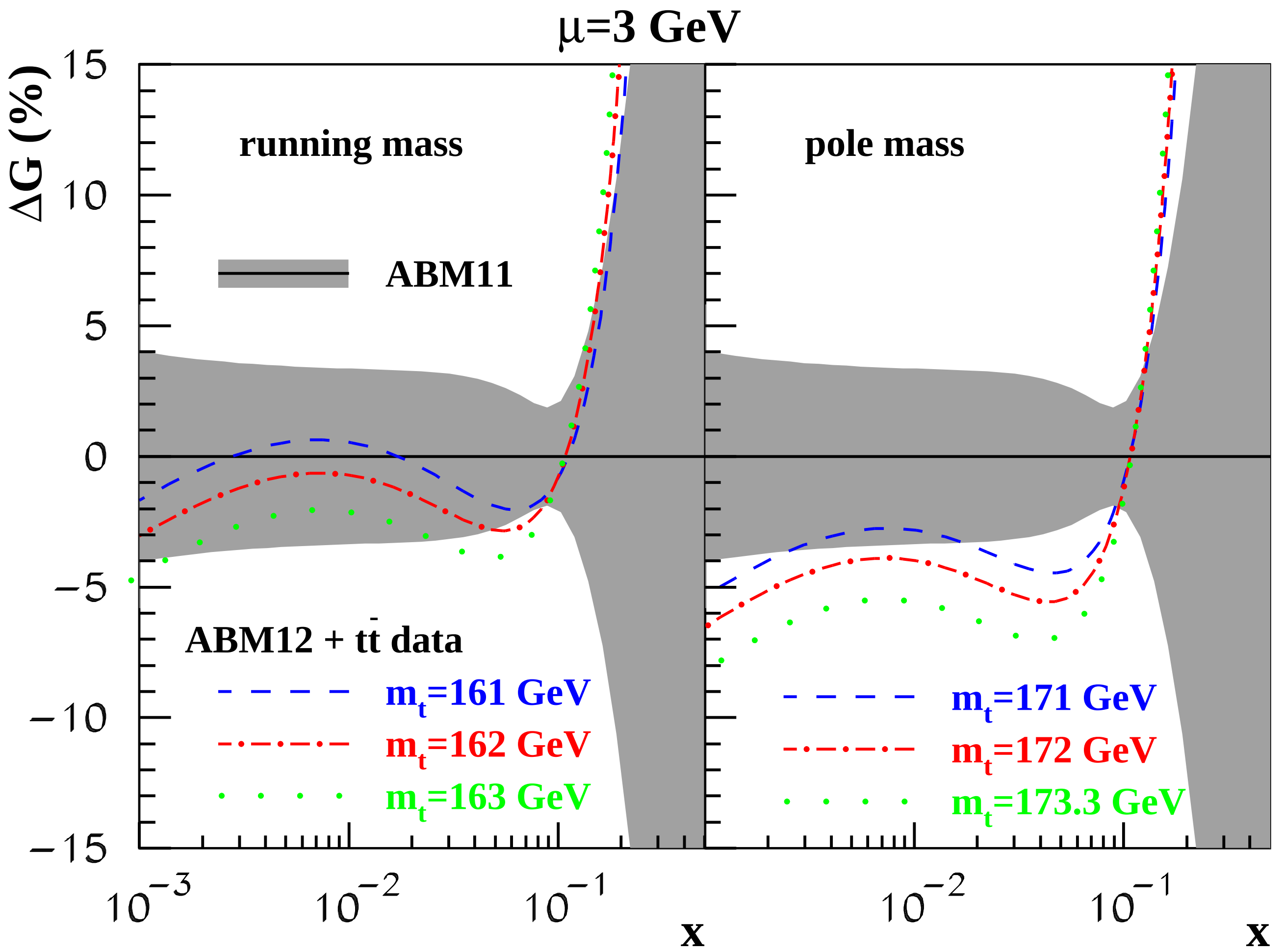
The fine print

- 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 $m_t(m_t) = 162$ GeV Alekhin, Blümlein, S.M. '13
  - χ^2-profile steeper for pole mass (bigger impact of top-quark data)



The fine print

- Fit with correlations
  - $g(x)$ and $\alpha_s(M_Z)$ already well constrained by global fit (no changes)
  - correlation of gluon PDF with value of m_t
    (illustration of bias in recent analysis Czakon, Mangano, Mitov, Rojo '13)



Higgs potential

Renormalization group equation

- Quantum corrections to Higgs potential $V(\Phi) = \lambda \left|\Phi^\dagger \Phi - \frac{v}{2}\right|^2$
- Radiative corrections to Higgs self-coupling λ
  - electro-weak couplings g and g' of $SU(2)$ and $U(1)$
  - top-Yukawa coupling y_t

$$16\pi^2 \frac{d\lambda}{dQ} \;=\; 24\lambda^2 - \left(3g'^2 + 9g^2 - 12y_t^2\right)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 + \dots$$

Higgs potential

Triviality

- Large mass implies large λ
  - renormalization group equation dominated by first term

$$16\pi^2 \frac{d\lambda}{dQ} \simeq 24\lambda^2 \qquad \longrightarrow \qquad \lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

- $\lambda(Q)$ increases with Q
- Landau pole implies cut-off Λ
  - scale of new physics smaller than Λ to restore stability
  - upper bound on m_H for fixed Λ

$$\Lambda \leq v \exp\left(\frac{4\pi^2 v^2}{3m_H^2}\right)$$

- Triviality for $\Lambda \to \infty$
  - vanishing self-coupling $\lambda \to 0$ (no interaction)

Higgs potential

Vacuum stability

- Small mass
  - renormalization group equation dominated by y_t

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

- $\lambda(Q)$ decreases with Q
- Higgs potential unbounded from below for $\lambda < 0$
- $\lambda = 0$ for $\lambda_0 \simeq \frac{3}{8\pi^2} y_0^4 \ln(Q/Q_0)$
- Vacuum stability

$$\Lambda \leq v \exp\left(\frac{4\pi^2 m_H^2}{3y_t^4 v^2}\right)$$

  - scale of new physics smaller than Λ to ensure vacuum stability
  - lower bound on m_H for fixed Λ

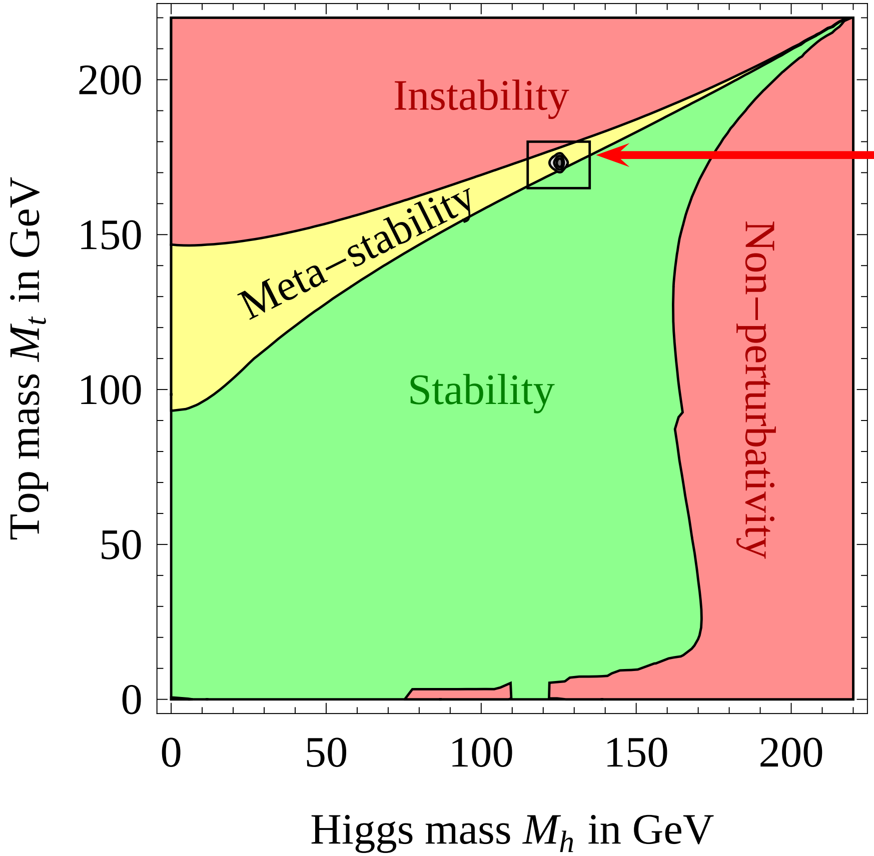
Implications on electroweak vacuum

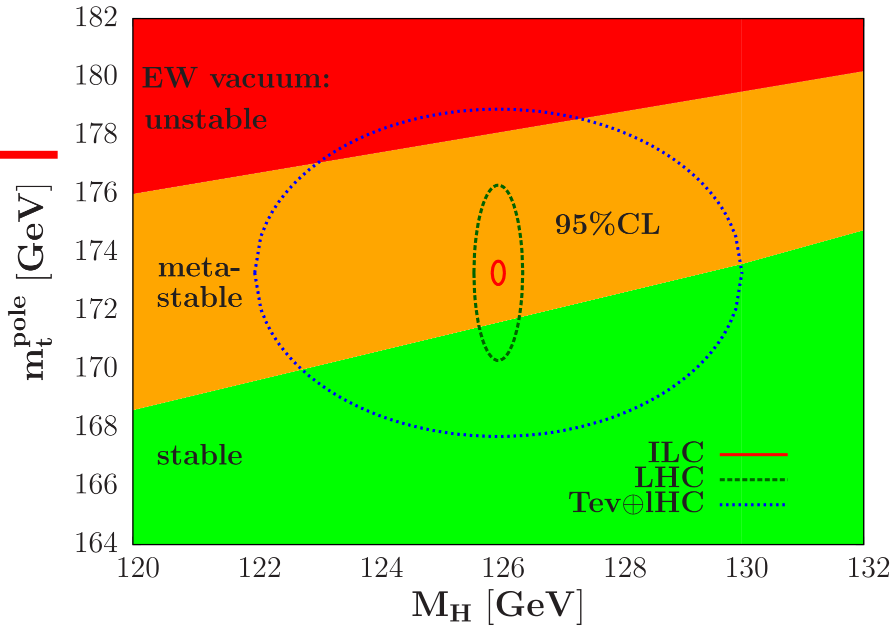
- Relation between Higgs mass m_H and top quark mass m_t
  - condition of absolute stability of electroweak vacuum $\lambda(\mu) \geq 0$
  - extrapolation of Standard Model up to Planck scale M_P
  - $\lambda(M_P) \geq 0$ implies lower bound on Higgs mass m_H

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

  - recent NNLO analyses Bezrukov, Kalmykov, Kniehl, Shaposhnikov '12; Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12
  - uncertainity in results due to α_s and m_t (pole mass scheme)
- Top quark mass from Tevatron in well-defined scheme
  - $m_t^{\overline{\text{MS}}}(m_t) = 163.3 \pm 2.7 \text{ GeV}$ implies in pole mass scheme $m_t^{\text{pole}} = 173.3 \pm 2.8 \text{ GeV}$
  - good consistency of mass value between different PDF sets

Fate of the universe

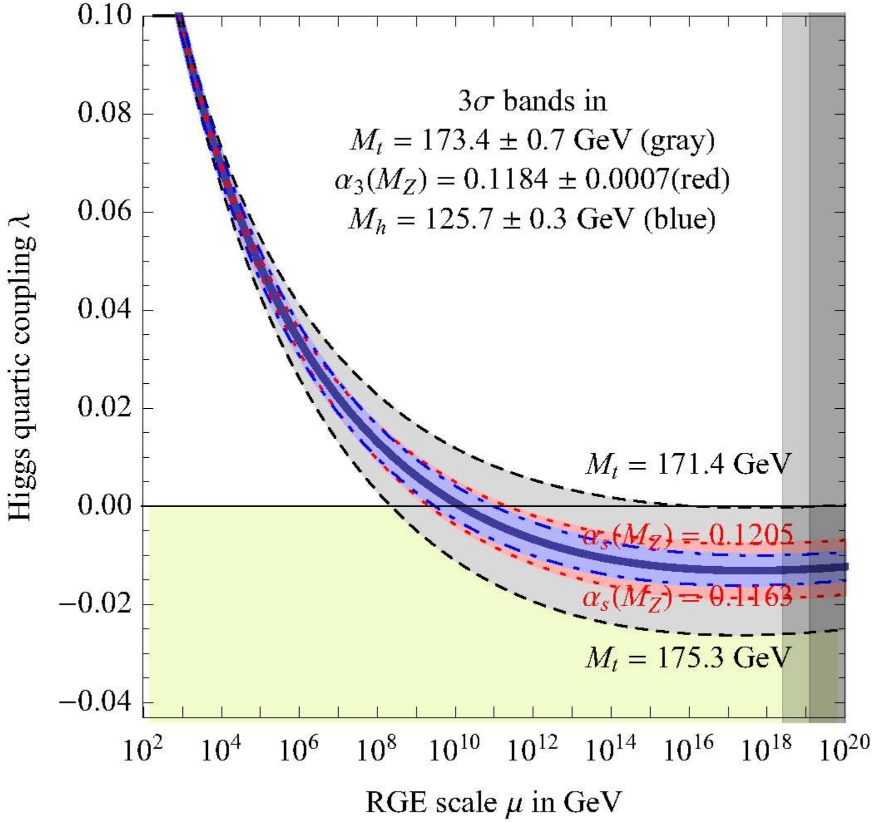




Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12; Alekhin, Djouadi, S.M. '12; Masina '12

- Uncertainty in Higgs bound due to m_t from in $\overline{MS}$ scheme
  - bound relaxes $m_H \geq 129.4 \pm 5.6$ GeV
  - "fate of universe" still undecided

Higgs self-coupling



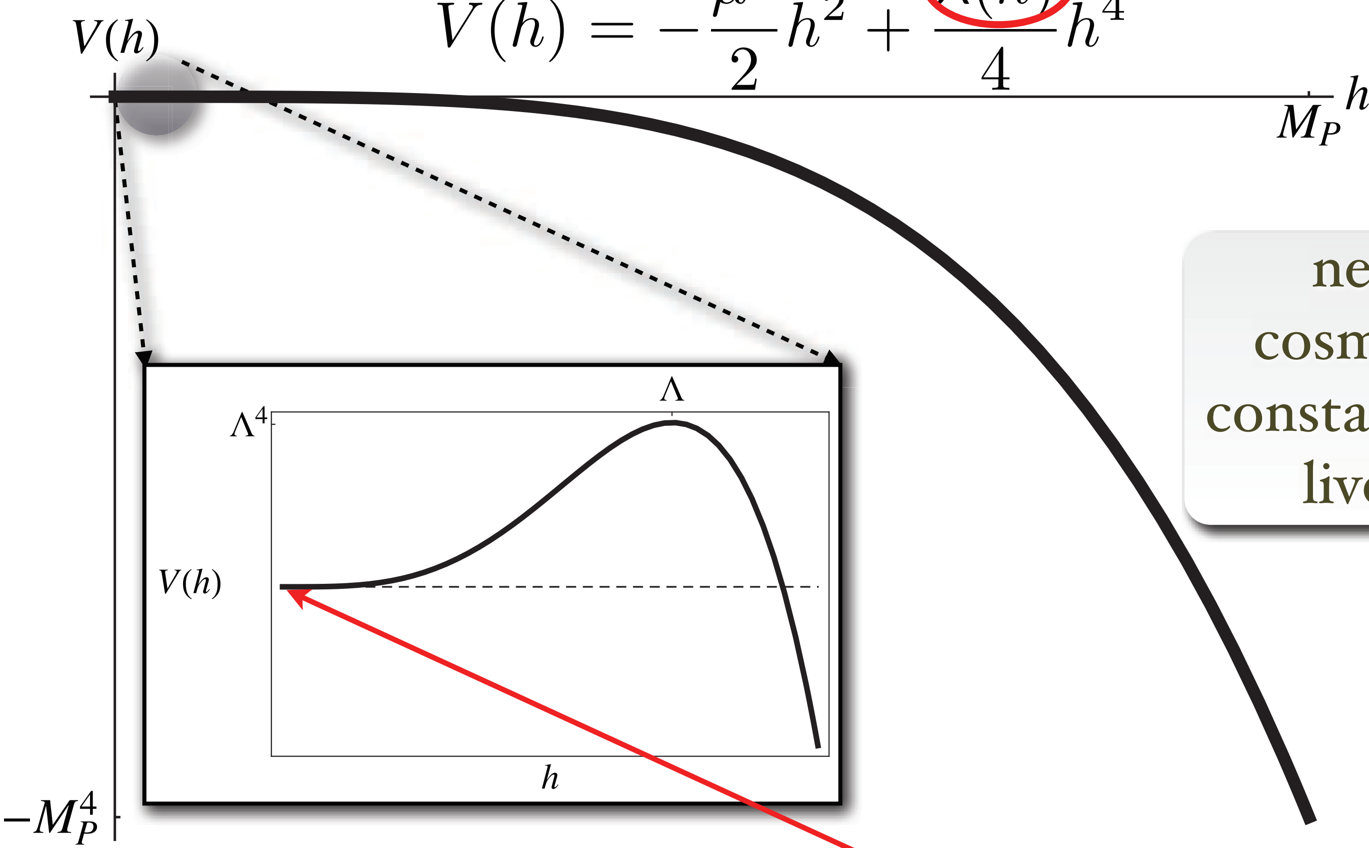
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13

- Renormalization group evolution of λ with uncertainties in m_H, m_t and α_s
  - top-quark mass least precise parameter
- Vacuum stability bound at M_P in terms of m_t

$$m_t \;\leq\; (171.36 \pm 0.15 \pm 0.25_{\alpha_3} \pm 0.17_{m_h})\,\text{GeV} \;=\; (171.36 \pm 0.46)\,\text{GeV}$$

the Higgs scalar potential ... if the coupling runs negative!

$$V(h) = -\frac{\mu^2}{2}h^2 + \frac{\lambda(h)}{4}h^4$$



negative cosmological constant: cannot live here!

$\Lambda \sim 10^{10}\,\text{GeV} \sim 10^{-8} M_P$

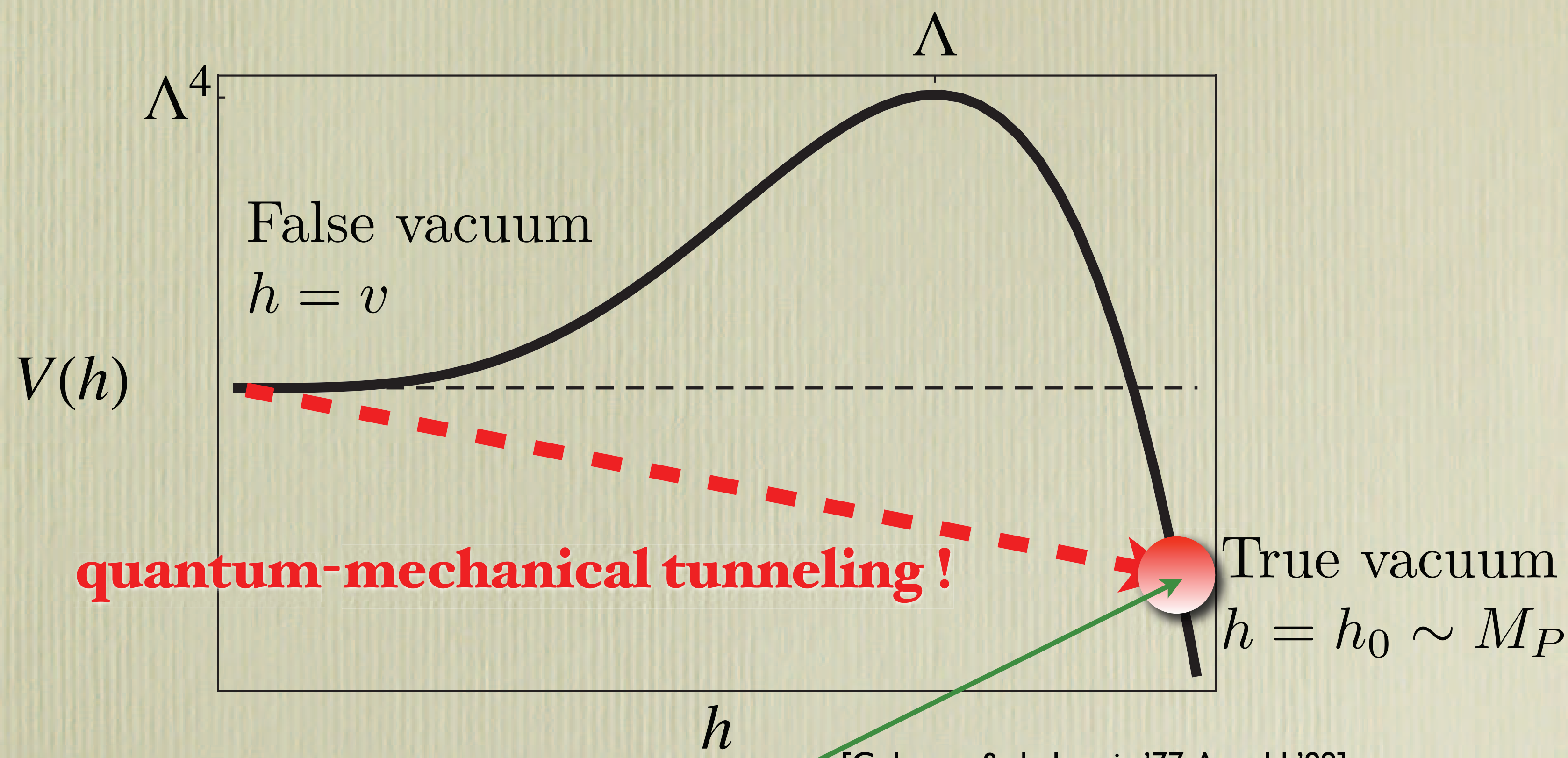
$\Lambda^4 \sim (10^{10}\,\text{GeV})^4 \sim 10^{-32} M_P^4$

SM Higgs vacuum

$v \sim 10^2\,\text{GeV} \sim 10^{-16} M_P$

A. Westphal (DESY seminar 06/13)

vacuum instability ...



[Coleman & de Luccia '77; Arnold '89]
[Isidori, Rychkov, Strumia & Tetradis '07]
[Arkani-Hamed, Dubovsky, Senatore & Villadoro '08]

a bubble of true vacuum forms !

decay rate:

$$\Gamma \sim e^{-S_E} \ll \frac{1}{\text{age of Universe}}$$

A. Westphal (DESY seminar 06/13)

Summary

Top quark mass

- On-shell scheme (pole mass) at NNLO in QCD

$$m_t = 173.20 \pm 0.87 \pm \mathcal{O}(\text{few})\,\text{GeV}$$

- Running mass ($\overline{\text{MS}}$ scheme) at NNLO in QCD

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

Summary

Top quark mass

- Top quark mass is parameter of Standard Model Lagrangian
- Measurements of m_t require careful definition of observable
- Radiative corrections at higher orders mandatory for scheme definition

Current measurements

- Kinematic reconstruction
  - very precise value, but only leading order/leading logarithm
  - lacking renormalization scheme definition
- $\overline{\mathrm{MS}}$ mass from total cross section
  - NNLO QCD determination available
  - uncertainty $\mathcal{O}(3)$ GeV from Tevatron analyses
  - LHC analyses affected by uncertainty in parton distributions, $\alpha_S(M_Z)$

Future challenge

- Study of new observables which meet all requirements
- Joint effort theory and experiment