The top quark and Higgs boson masses and the stability of the electroweak vacuum

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Theory Colloquium, Hamburg, Oct 24, 2012

Plan

- Top-quark mass
- Higgs boson mass
- Electroweak vacuum

Introduction

Classical mechanics

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

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  Newton

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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.

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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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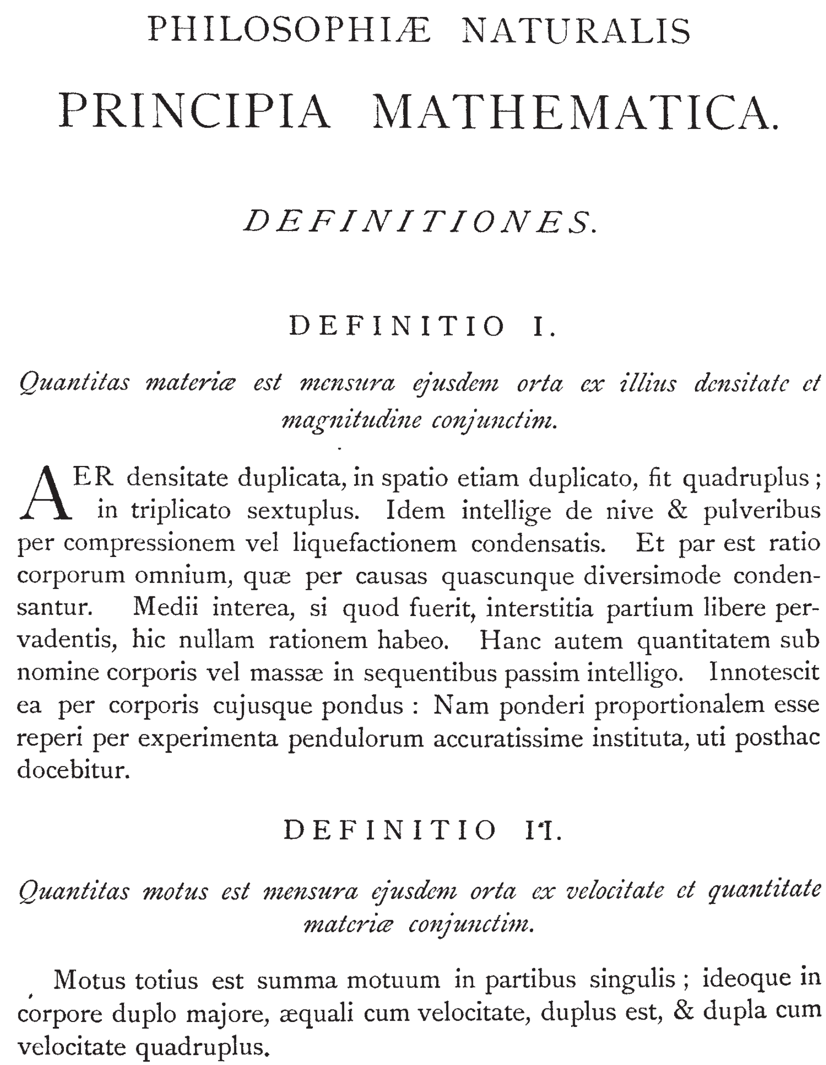

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- Mass of body is sum of mass of its constituents
  $M(X) = N_A m_a(X)$ Avogadro

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Special relativity

- Equivalence principle
  $E = mc^2$ Einstein

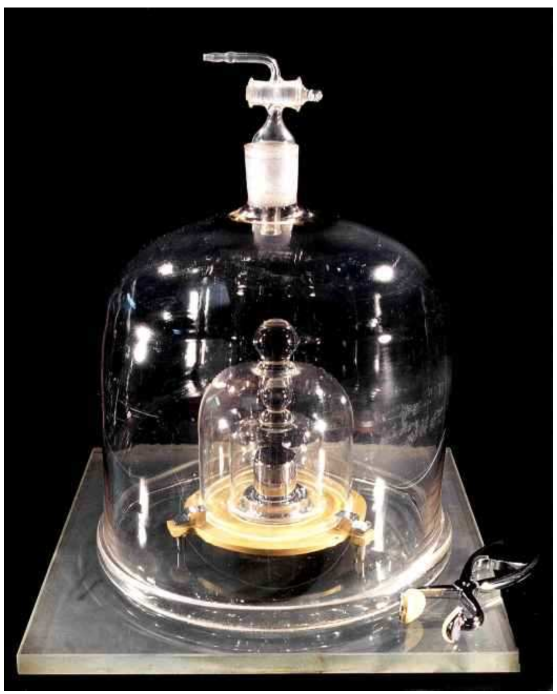
Kilogram

Definition

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

- International prototype kilogram (IPK):
  made in 1889, 39 mm high, alloy of platinum and iridium

Orginal des Bureau International des Poids et Mesures



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

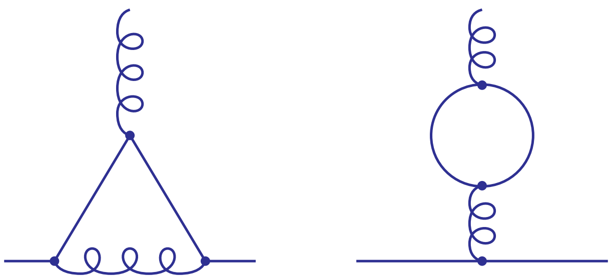
Challenge

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

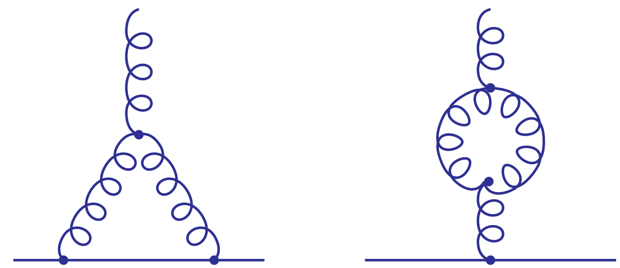
Renormalization

Quantum field theory

- Parameters of Lagrangian have no unique physical interpretation
  - radiative corrections require definition of renormalization scheme
- Running coupling constant α_s



– screening (like in QED)



– anti-screening (color charge of g)

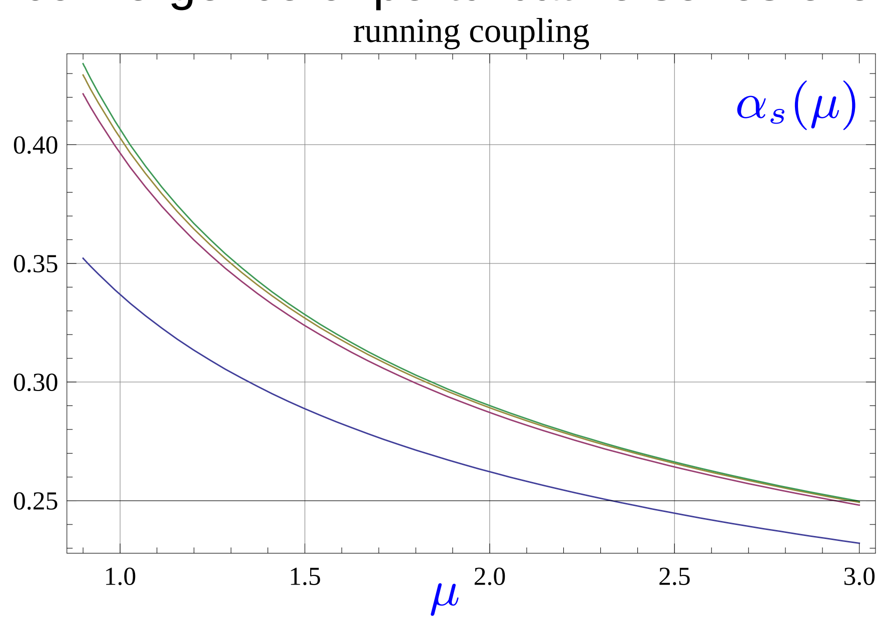
Renormalization

Quantum field theory

- Parameters of Lagrangian have no unique physical interpretation
  - radiative corrections require definition of renormalization scheme
- Running coupling constant α_s
  - renormalization group equation for scale dependence

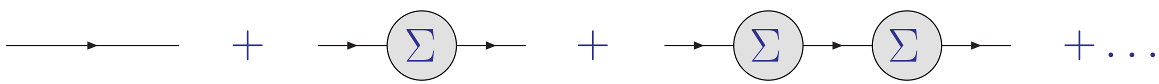
$$\mu^2 \frac{d}{d\mu^2} \alpha_s(\mu) \, = \, \beta(\alpha_s)$$

  - perturbative expansion to four loops van Ritbergen, Vermaseren, Larin '97
  - very good convergence of perturbative series even at low scales



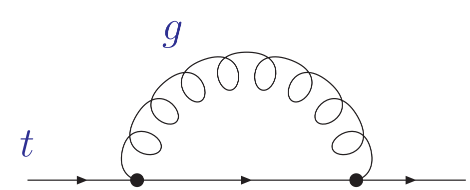
Quark mass renormalization

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



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

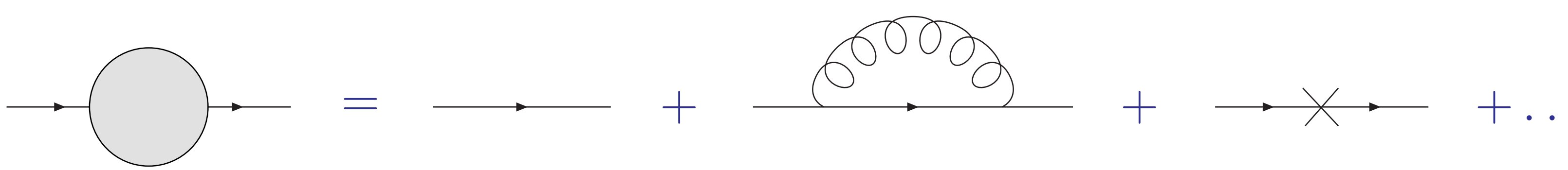
QCD



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



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

Quark mass renormalization

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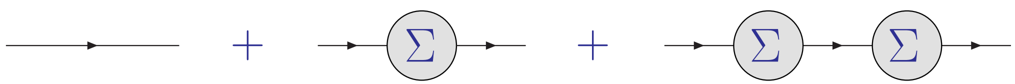
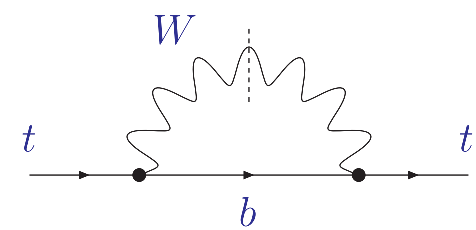


$$+ \ldots = \frac{\mathrm{i}}{\not{p} - m_q - \Sigma(p, m_q)}$$

EW sector



- EW corrections to top quark self-energy
  - on-shell intermediate (virtual) W-boson
  - m_t complex parameter with imaginary part $\Gamma_t = 2.0 \pm 0.7$ GeV
  - $\Gamma_t > 1$ GeV: top quark decays before it hadronizes

Mass renormalization scheme

Pole mass

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

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

- 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 $\mathcal{O}(\Lambda_{QCD})$
  - bound from lattice QCD: $\Delta m_q \geq 0.7 \cdot \Lambda_{QCD} \simeq 200$ MeV
    Bauer, Bali, Pineda '11

$\overline{MS}$ *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: $m(\mu)$

Running quark mass

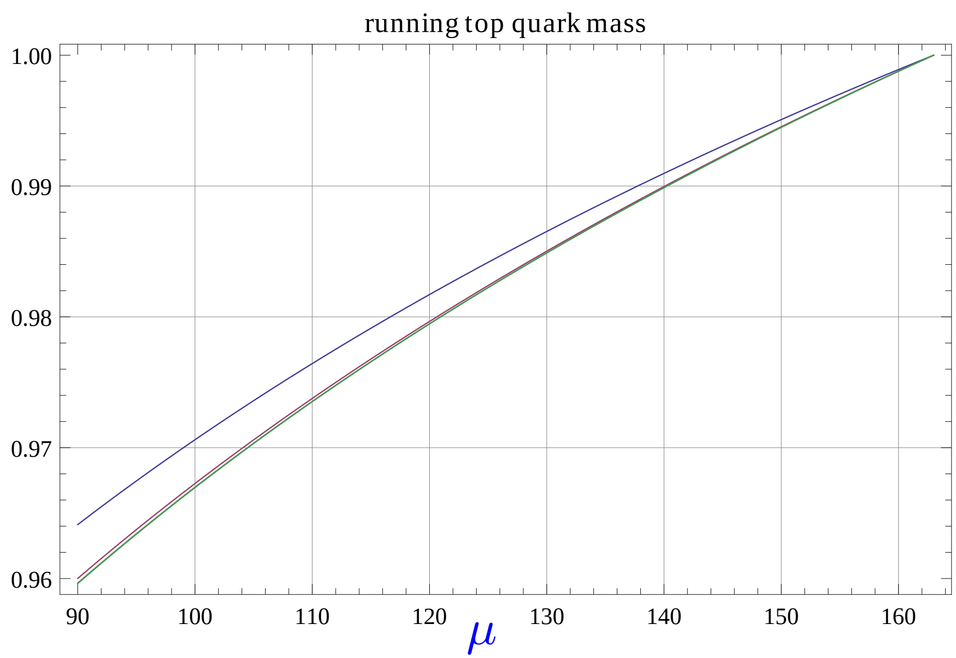
Scale dependence

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



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
  - EW sector known to $\mathcal{O}(\alpha_{\rm EW}\alpha_{\rm s})$ Jegerlehner, Kalmykov '04; Eiras, Steinhauser '06
  - example: one-loop QCD

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

Top quark mass

Experimental result CDF & D0 coll. 1207.1069

$$m_t = 173.18 \pm 0.94\,\text{GeV}$$

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Which is the value of the top quark mass ?

$$m_t = \; ?$$

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Which is the value of the top quark mass ?

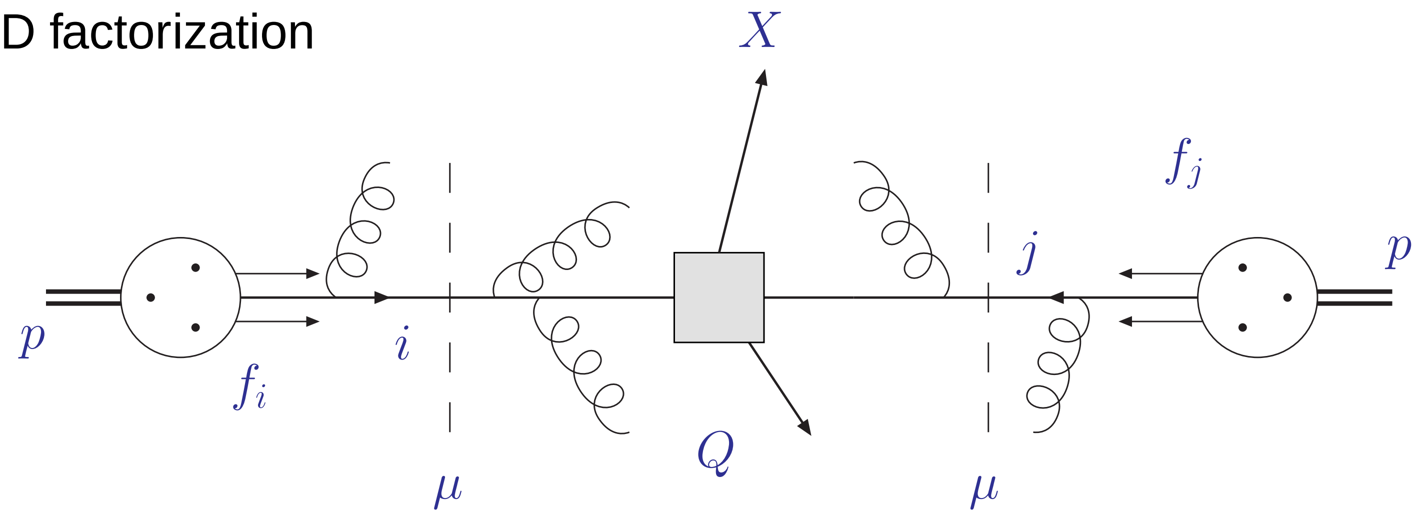
$$m_t = ?$$

Which top quark mass has this value ?

$$? = 173.18 \pm 0.94\,\mathrm{GeV}$$

QCD factorization

- QCD factorization

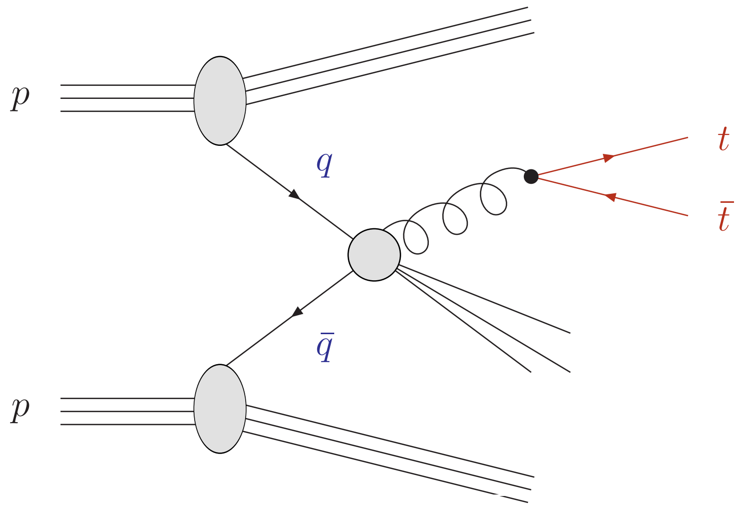


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - known to NLO, NNLO, ... ($\mathcal{O}(\text{few}\%)$ theory uncertainty)
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, ...

Top-quark pair production

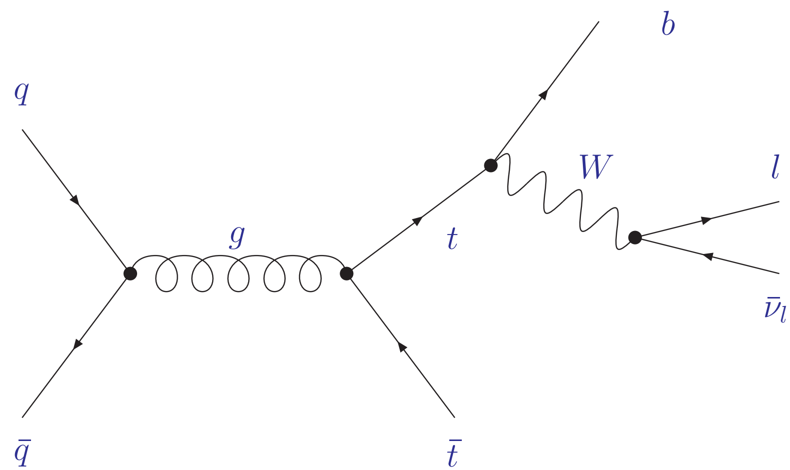
- Hadronic reaction $pp/p\bar{p}$:
  - recall master equation $\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$



- 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 $\beta = \sqrt{1 - 4m^2/s}$)

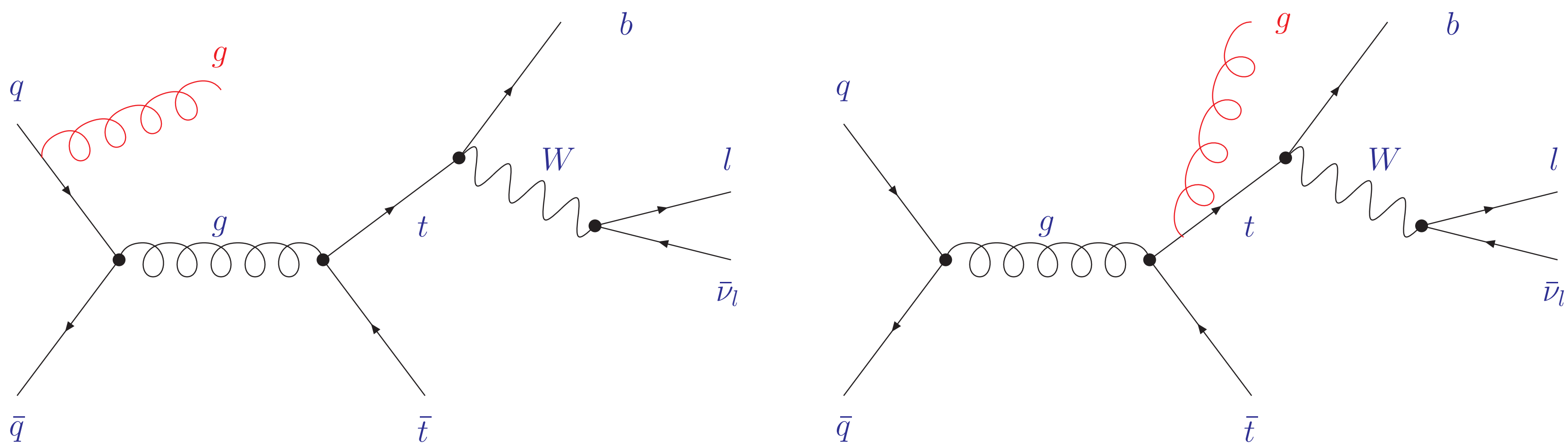
Hard scattering process

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



Radiative corrections

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

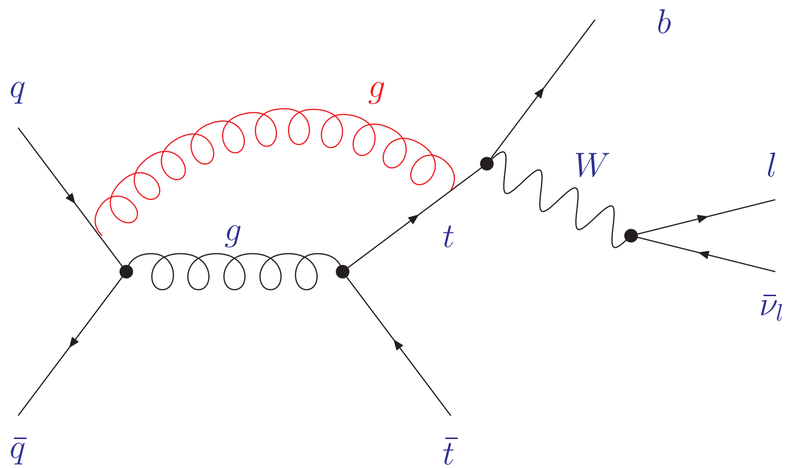


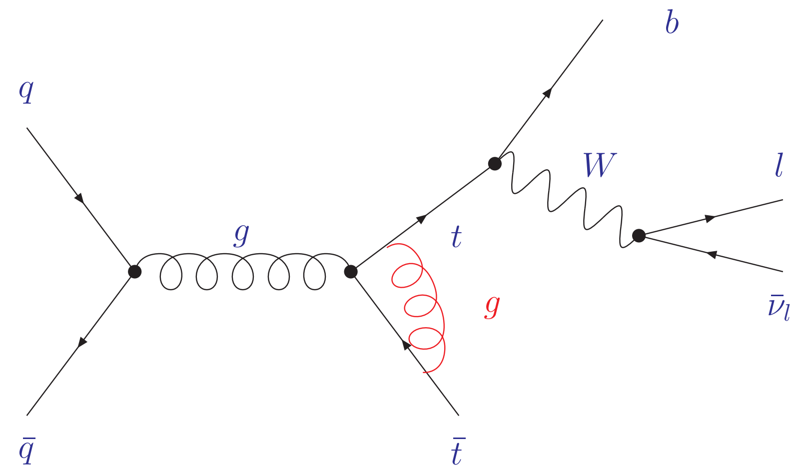
- Parton shower MC
  - emission probability modeled by Sudakov exponential with cut-off Q_0
  - leading logarithmic accuracy

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

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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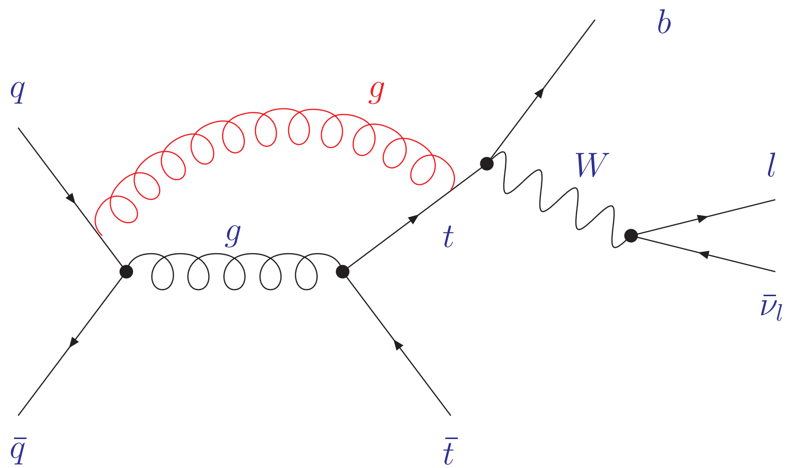
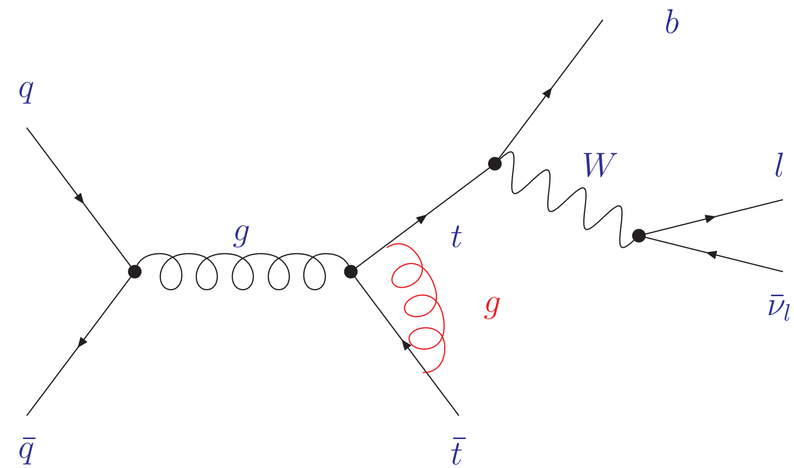
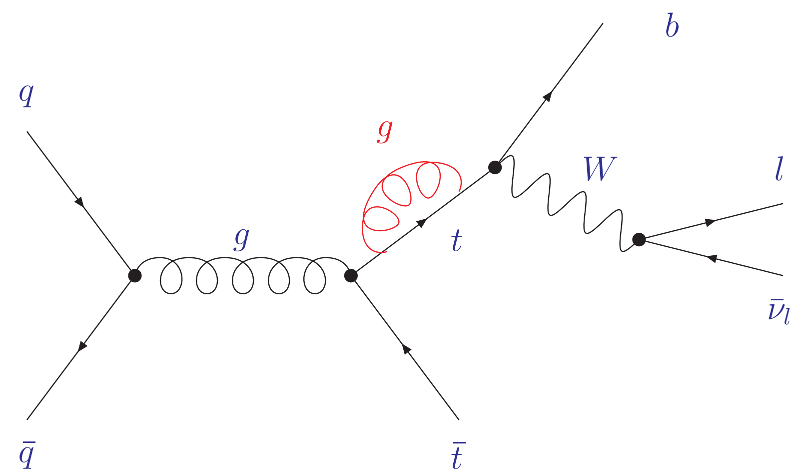


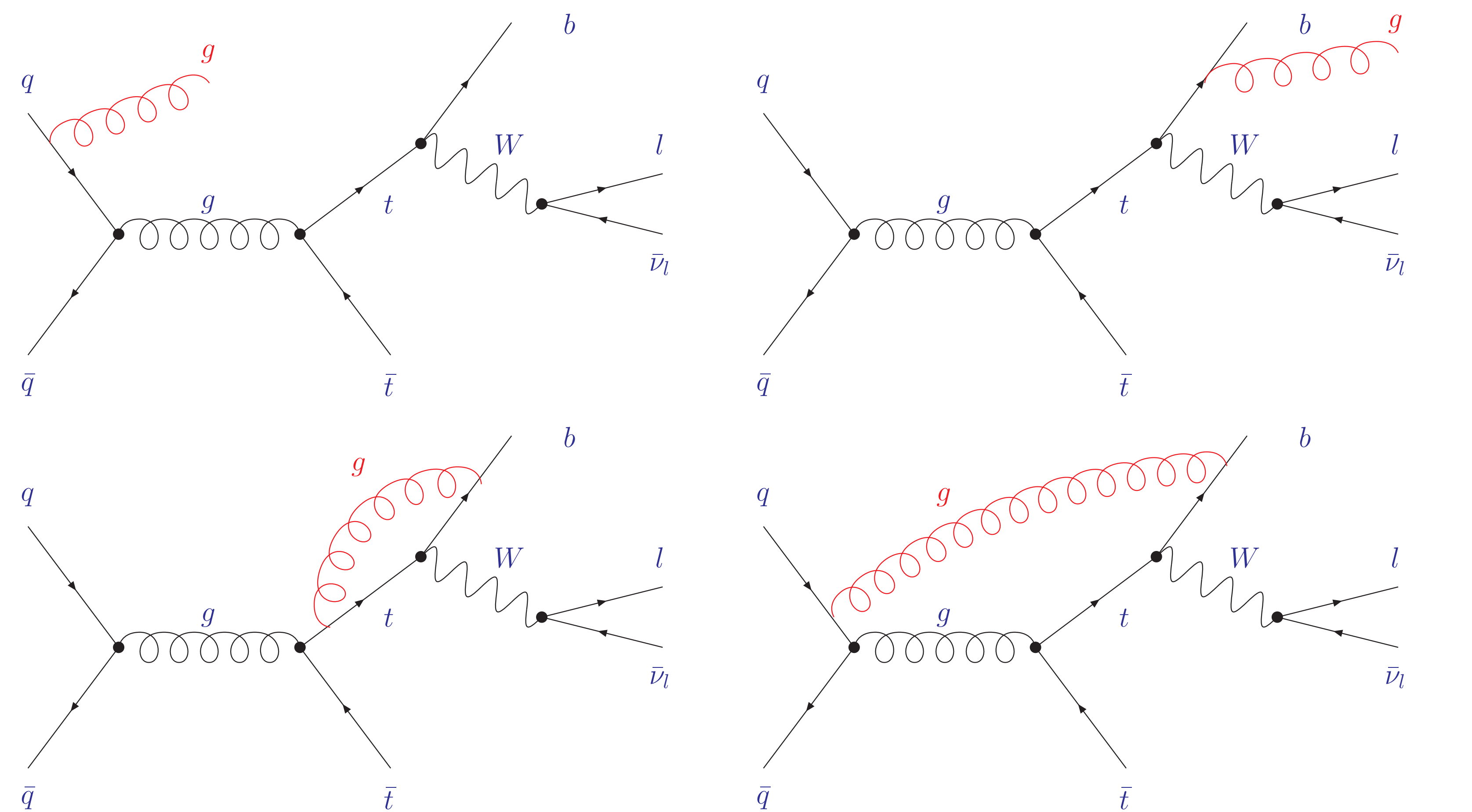


- Mass renormalization from self-energy corrections to top quark



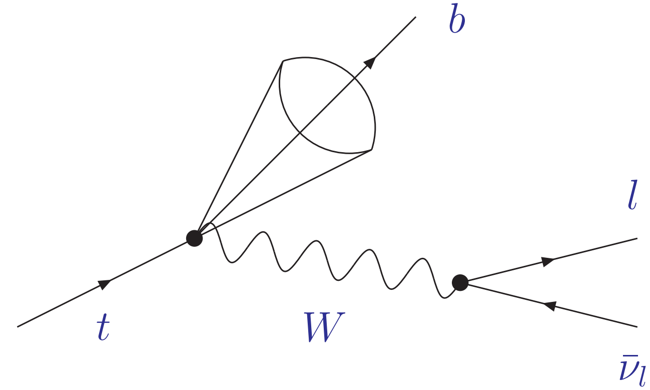
Heavy-to-light corrections

- Interference between top quark and its decay products (b quark)
  - real emission and virtual diagrams
  - complete NLO corrections for top production and decay
    Melnikov, Schulze '09; Bernreuther, Si '10 (contained in MCFM Campbell, Ellis '12)



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
- Future improvements:
  - use of NLO QCD predictions matched to parton shower (MC@NLO, Powheg, . . .)
  - systematic study of distributions sensitive to m_t
  - template overlap method for infrared safe jet observables

    Almeida, Lee, Perez, Sterman, Sung ‘10

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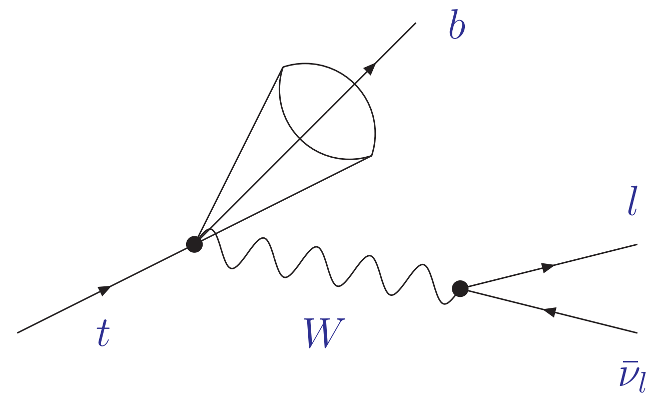
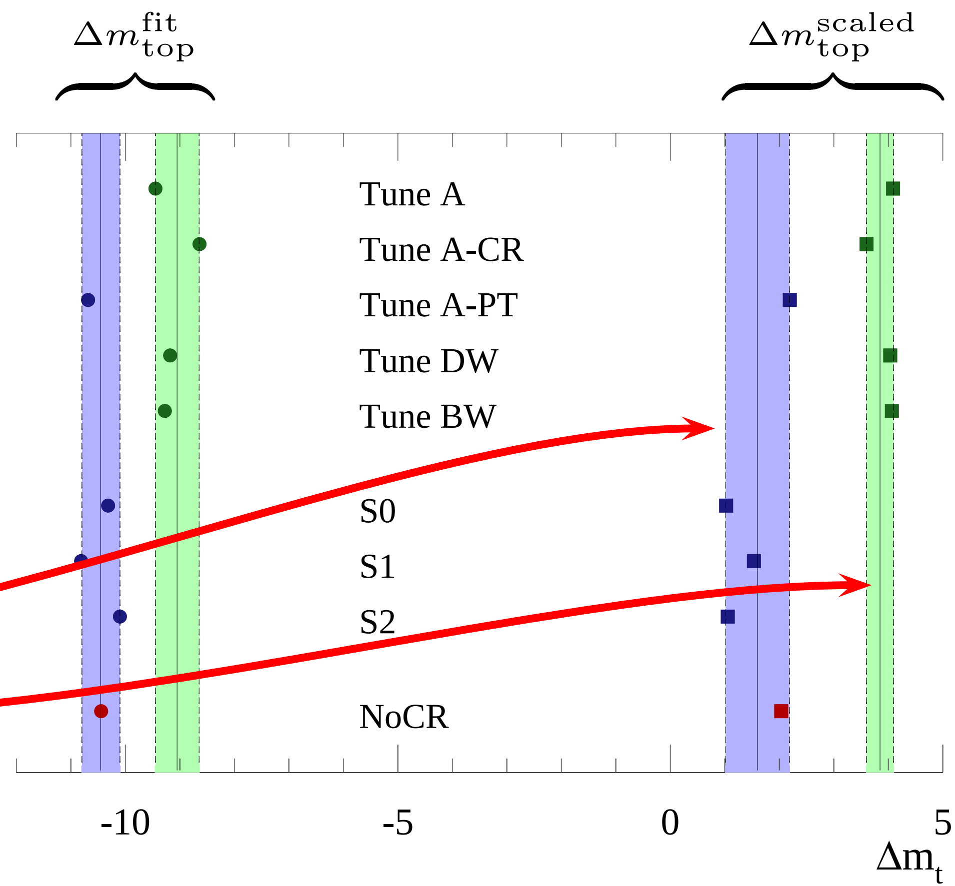


Matrix element method

- 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
- Future improvements:
  - advance matrix element method include QCD radiation Alwall, Freitas, Mattelaer '10
  - computation of NLO weighted events Campbell, Giele, Williams '12

Non-perturbative corrections

- Simulation of top mass measurement Skands, Wicke '07
  - test of different Monte Carlo tunes for non-perturbative physics / colour reconnection
  - calibration offsets before/after scaling with jet energy scale corrections
- Parton shower models:
  - p_T-ordered (blue);
  - virtuality ordered (green)
- Uncertainty in parton shower models (non-perturbative) is $\mathcal{O}(\pm 500)$ MeV



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
  $\Delta m_t \simeq 150 \dots 250$ 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 total cross section

Top mass from leptonic decay

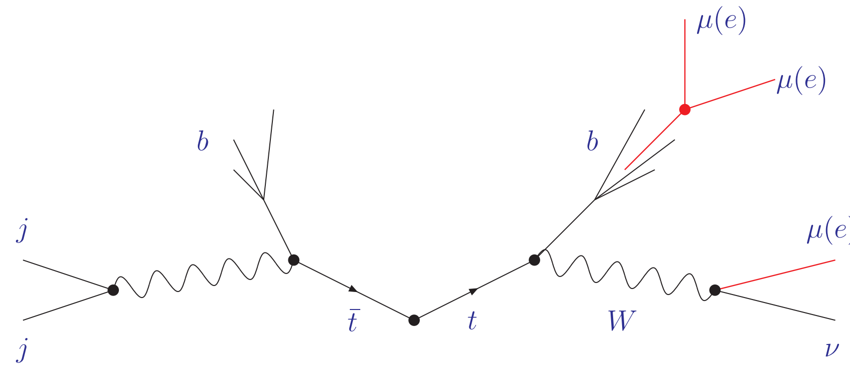
- Top mass from exclusive hadronic states

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

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

    Kharchilava '00

    Chierici, Dierlamm '06

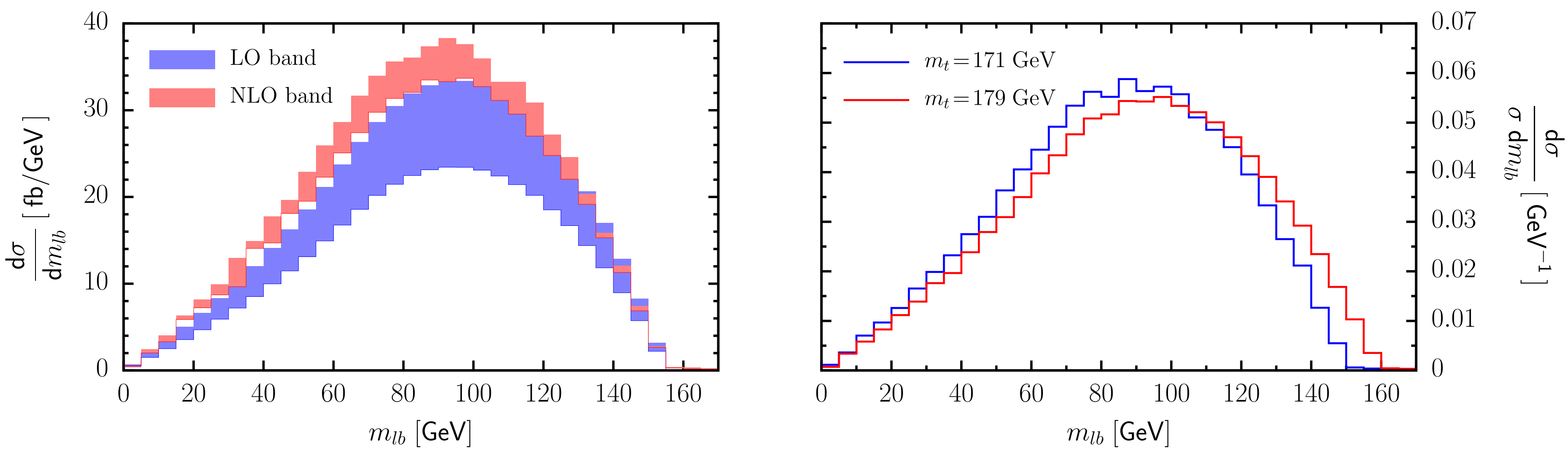


Top mass from leptonic decay

- Top mass from exclusive hadronic states

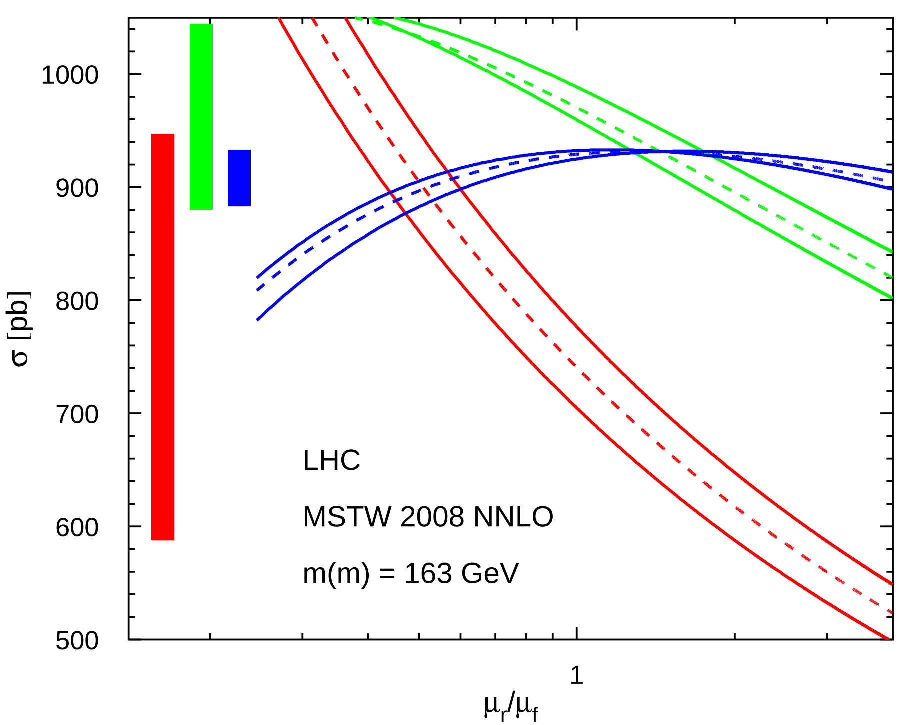
$$pp \to (t \to W^+ + b \to W^+ + J/\psi) + (\bar{t} \to W^- + \bar{b})$$

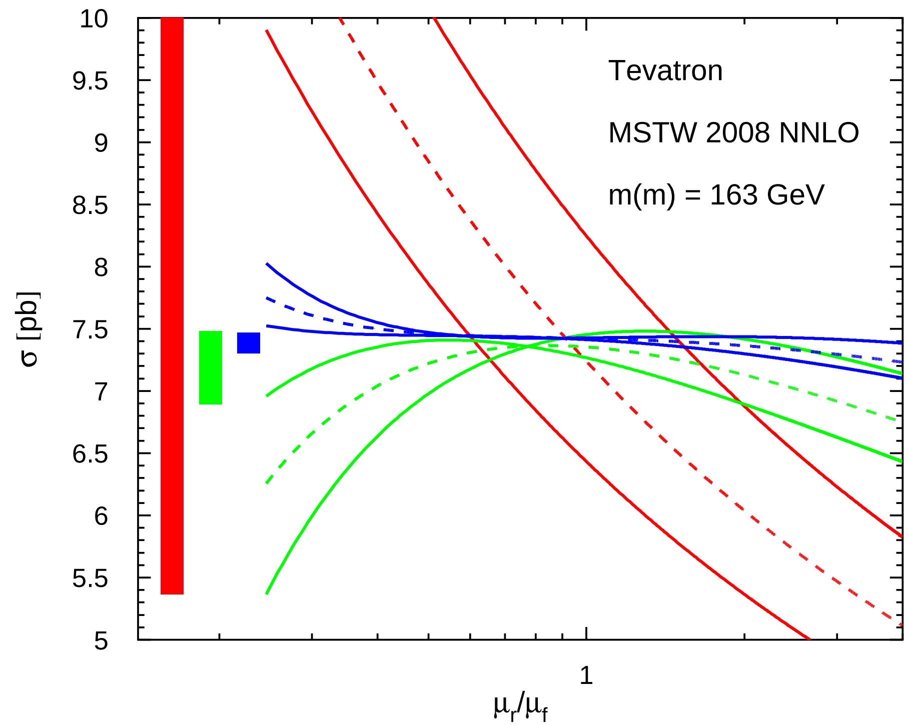
- Study of m_{lb} distribution at NLO in QCD Biswas, Melnikov, Schulze '10
  - NLO QCD corrections to production **and** decay very important for value of m_t (effects of order $\Delta m_t = \mathcal{O}(\text{few})$ GeV
- Invariant mass distribution of lepton and b-jet (LHC14)
  - scale dependence at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



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





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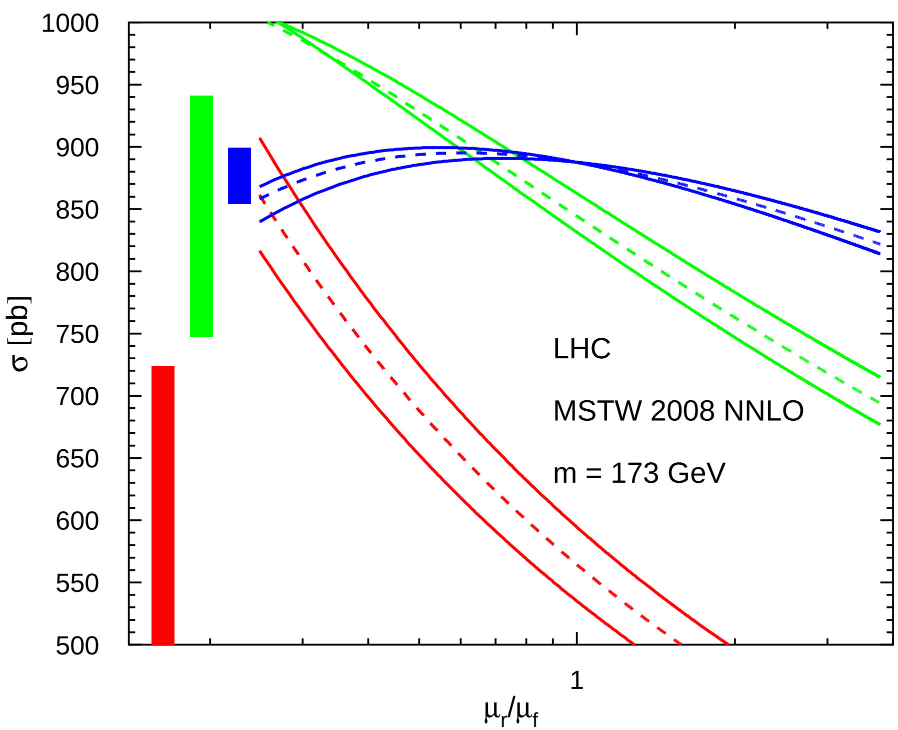
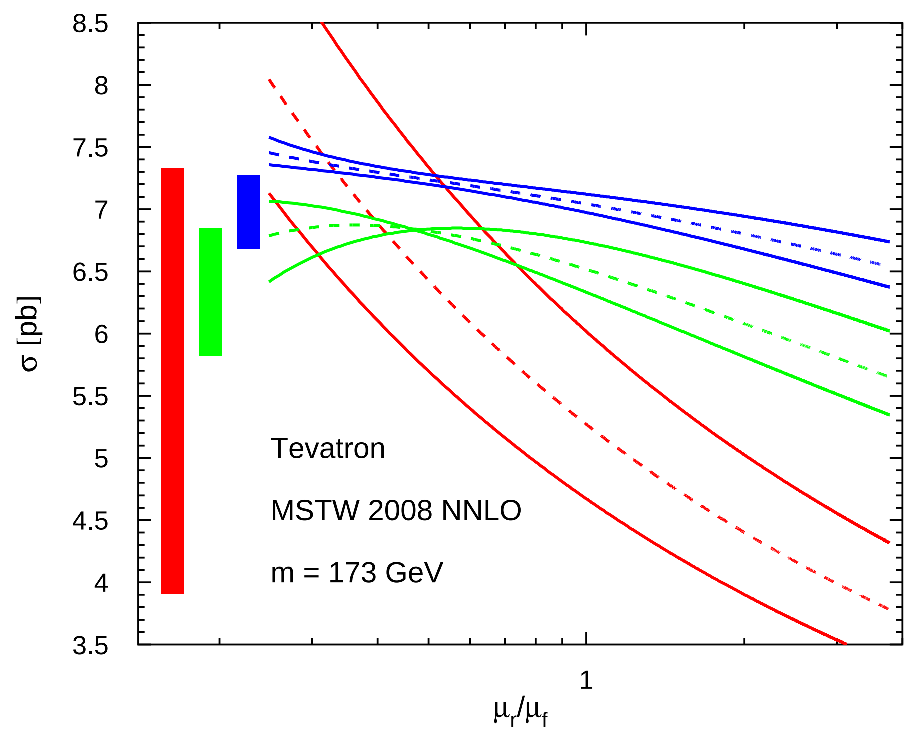
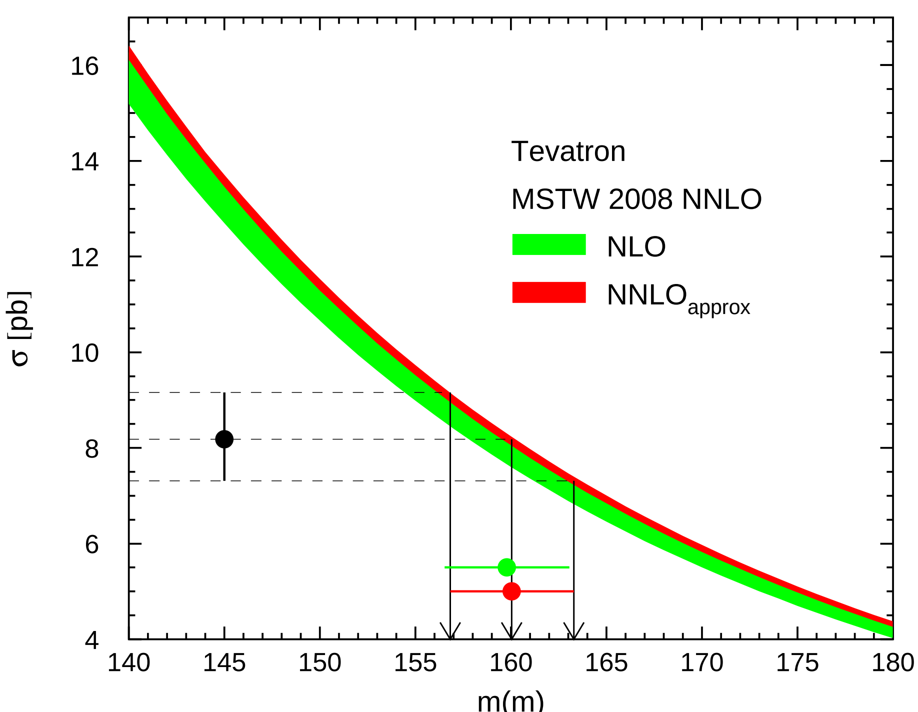
- Pole mass scheme for comparison

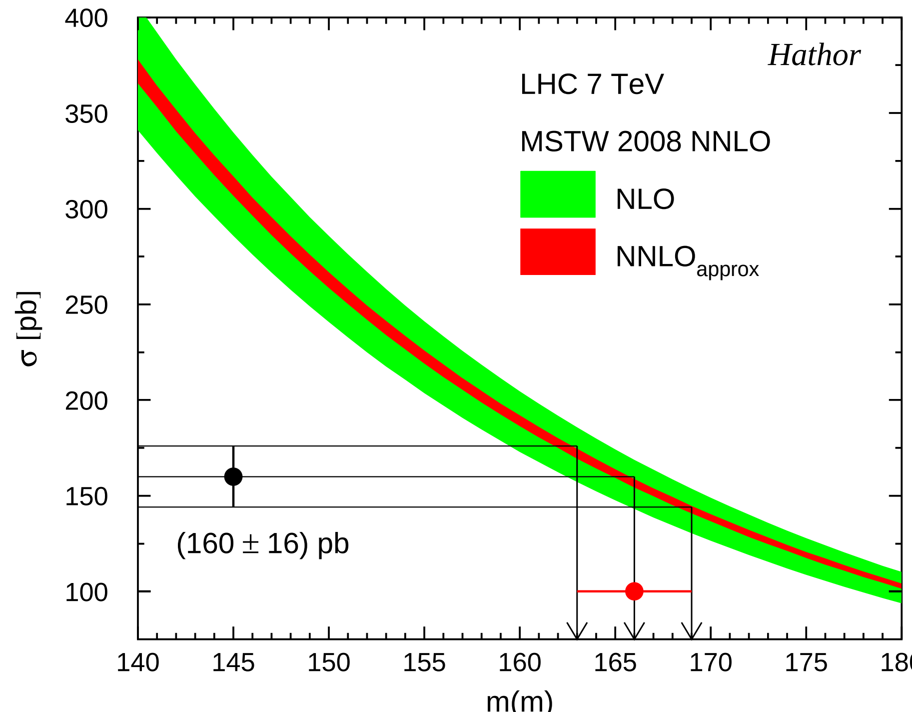




Top mass from total cross section

- 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 $q\bar{q}$
  - $\overline{\mathrm{MS}}$-scheme for $m_t^{\overline{\mathrm{MS}}}(m_t)$, then scheme transformation to pole mass m_t^{pole} at NNLO

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\mathrm{MS}}}(m_t)$	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^{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^{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 $^{+2.3}_{-2.3}\,^{+1.4}_{-1.2}$)

- Good consistency within errors for $m_t^{\mathrm{pole}} = 171.7 \dots 174.9$ 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 $\sigma_{\mathrm{t\bar{t}}} = 177^{+11}_{-10}$ pb
  Atlas coll. ATLAS-CONF-2012-024
- CMS at $\sqrt{s} = 7$ TeV $\sigma_{\mathrm{t\bar{t}}} = 165.8^{+13.3}_{-13.3}$ pb
  CMS coll. CMS-PAS-TOP-11-024

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\mathrm{MS}}}(m_t)$	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^{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^{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 $^{+2.4}_{-2.3}\,^{+2.0}_{-2.3}$)

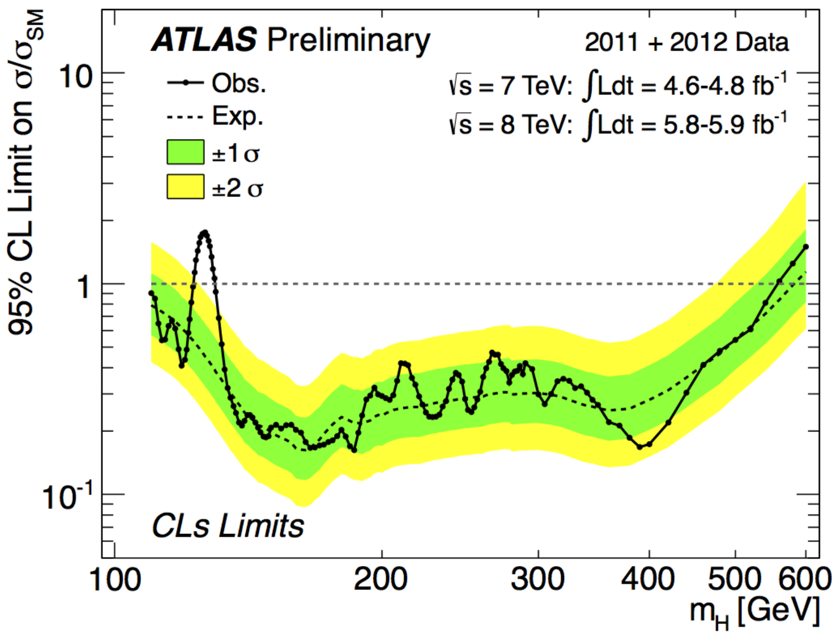
- Large spread $m_t^{\mathrm{pole}} = 168.6 \ldots 177.4$ at NNLO (marginally consistent)
  - larger gluon and α_s imply larger m_t^{pole}

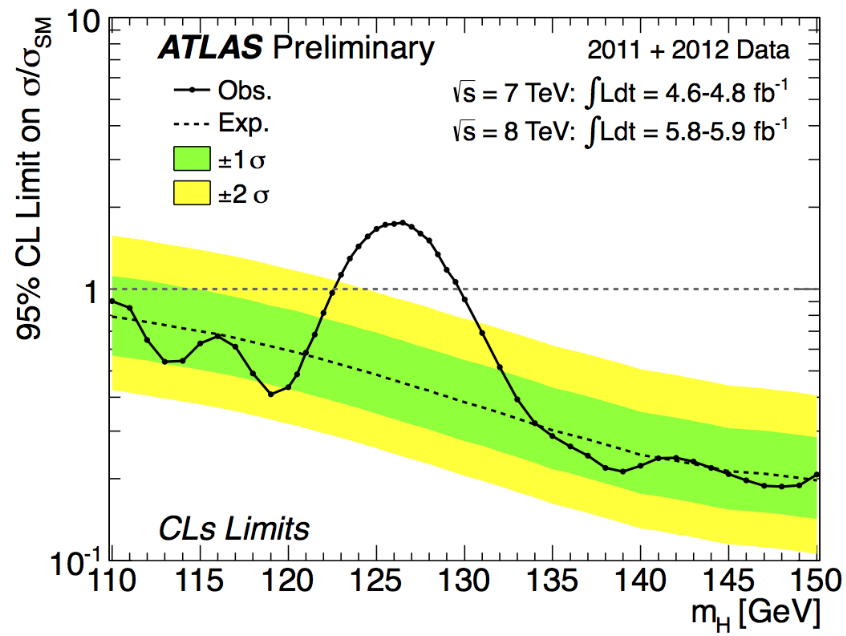
Higgs boson mass

Experimental result Atlas arXiv:1207.7214; CMS coll. arXiv:1207.7235

$$m_H \simeq 126\text{GeV}$$

Higgs discovery at LHC



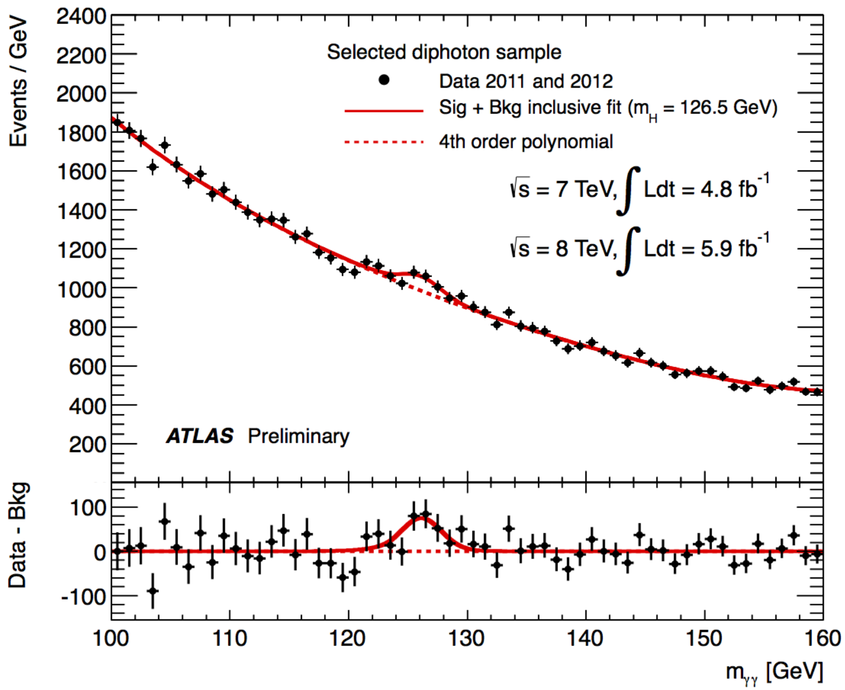


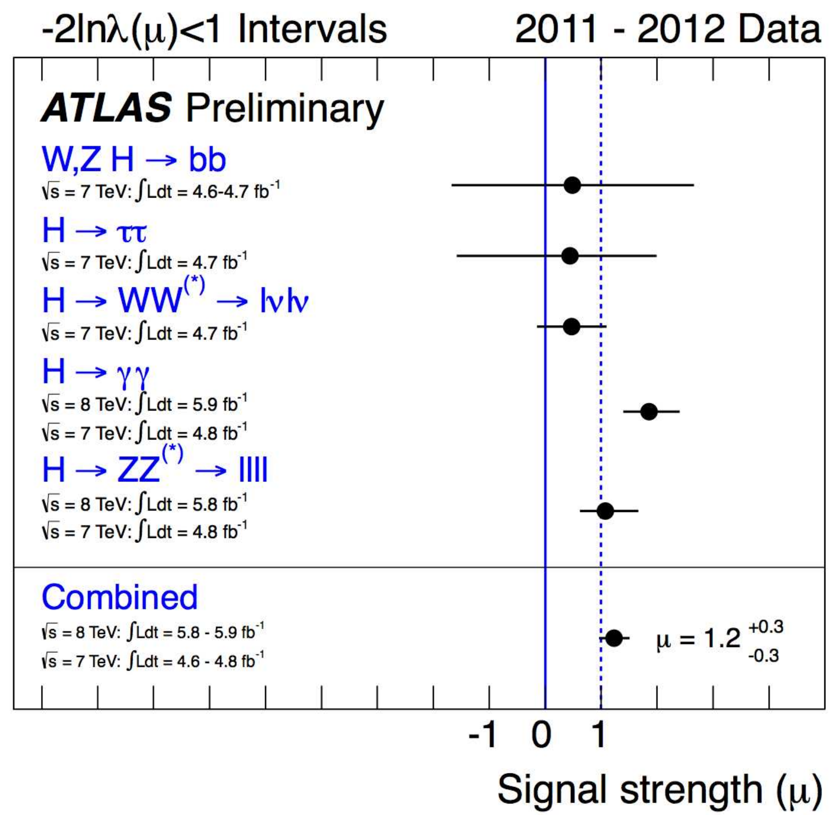
Atlas coll. July 2012

- Higgs mass in the range $m_H \simeq 126$ GeV
  - Higgs search driven predominantly by $gg \to H$
  - signal significance and range of excluded Higgs masses sensitive to gluon PDFs (Tevatron assumptions in the past too optimistic)

LHC measurements

Atlas coll. July 2012



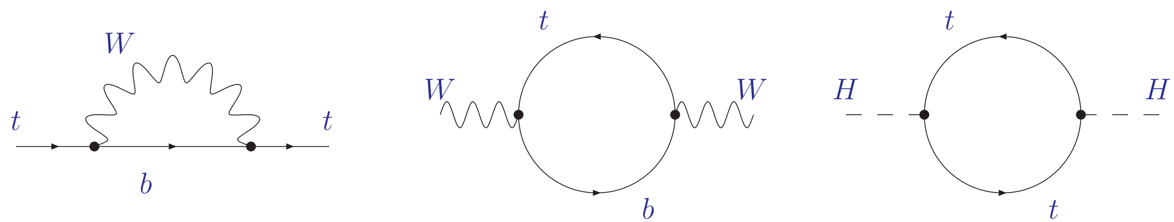


- Measured $H \to \gamma\gamma$ decay mode (left)
- Signal strength of all analyzed decay modes normalized to SM expectation (right)
- Agreement with SM for $H \to ZZ$; excess of $H \to \gamma\gamma$ (new physics ?)

Higgs boson and the electroweak sector

Electroweak sector

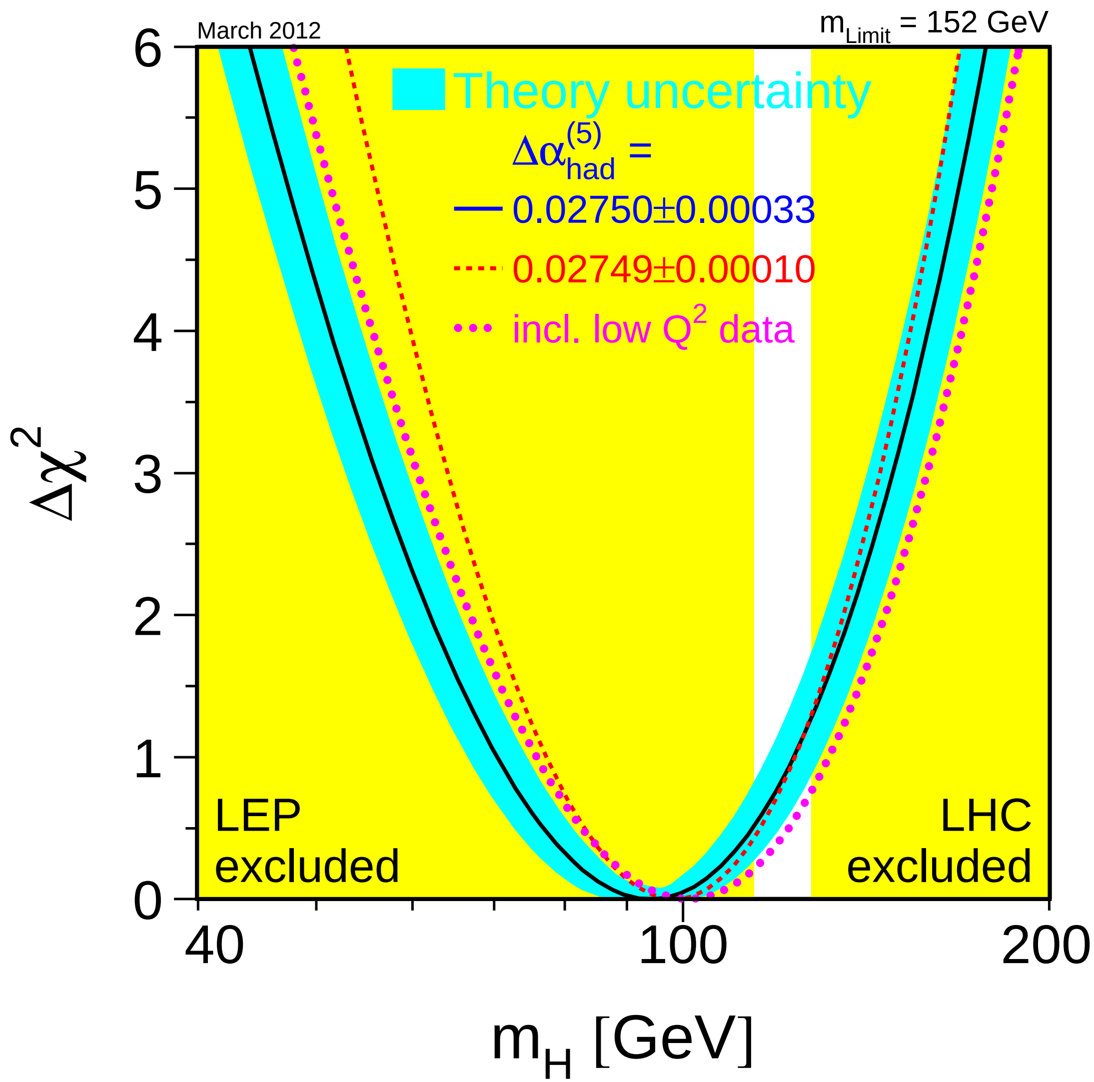
- Radiative corrections (one and two loops) provide relation between SM parameters (masses, couplings)



- Use m_t in precision analysis of electroweak observables (together with M_W) for constraints on m_H

Indirect Higgs searches

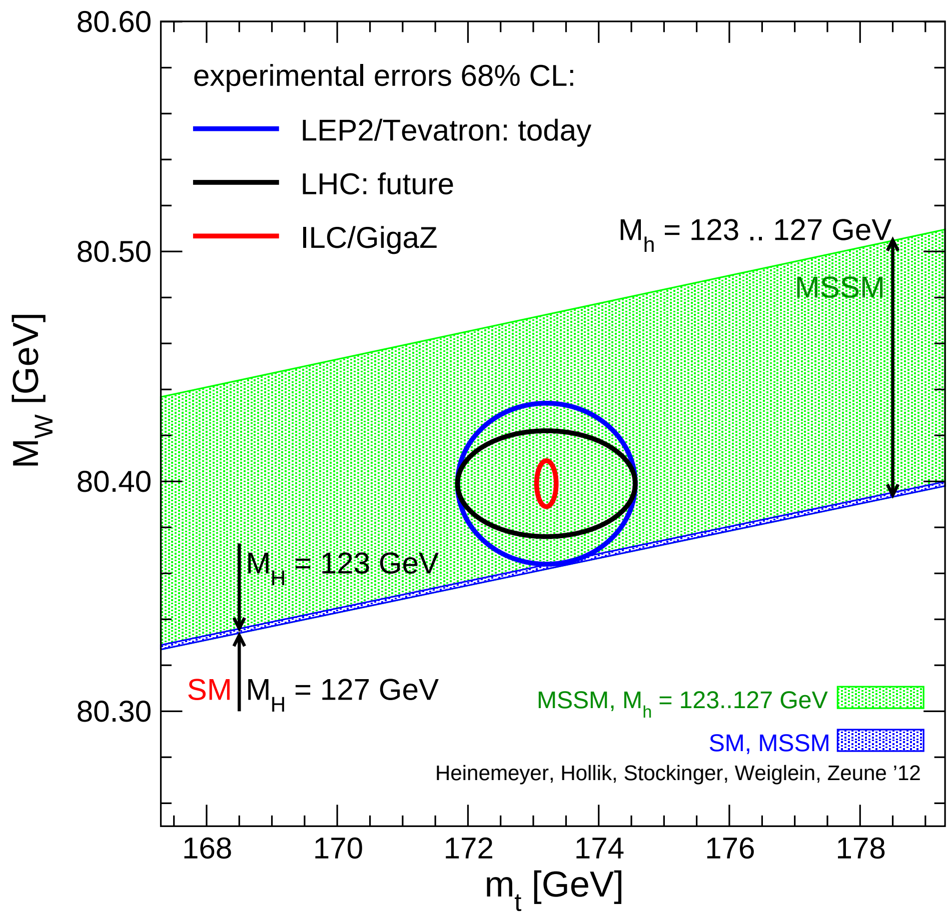
- Electroweak precision data constrains M_H



- Precision tests of SM indicate lighter SM Higgs mass

Constraints on M_W and m_t

- Extension of electroweak precision fits to MSSM
  Heinemeyer, Hollik, Stöckinger, Weiglein, Zeune ‘12
- Relations for radiative corrections known through two loops



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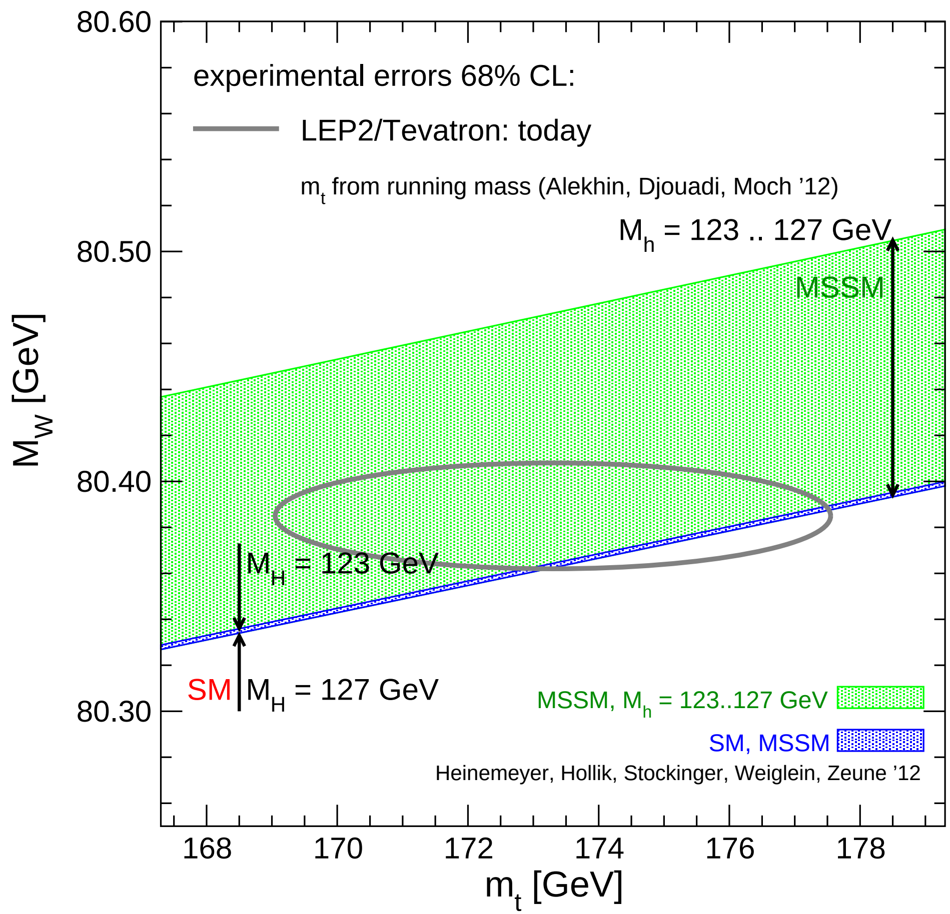


- Pole mass determination in well-defined scheme $m_t = 173.3 \pm 2.8 \mathrm{GeV}$ gives no preference to MSSM

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

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

- $\lambda(Q)$ 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

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

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

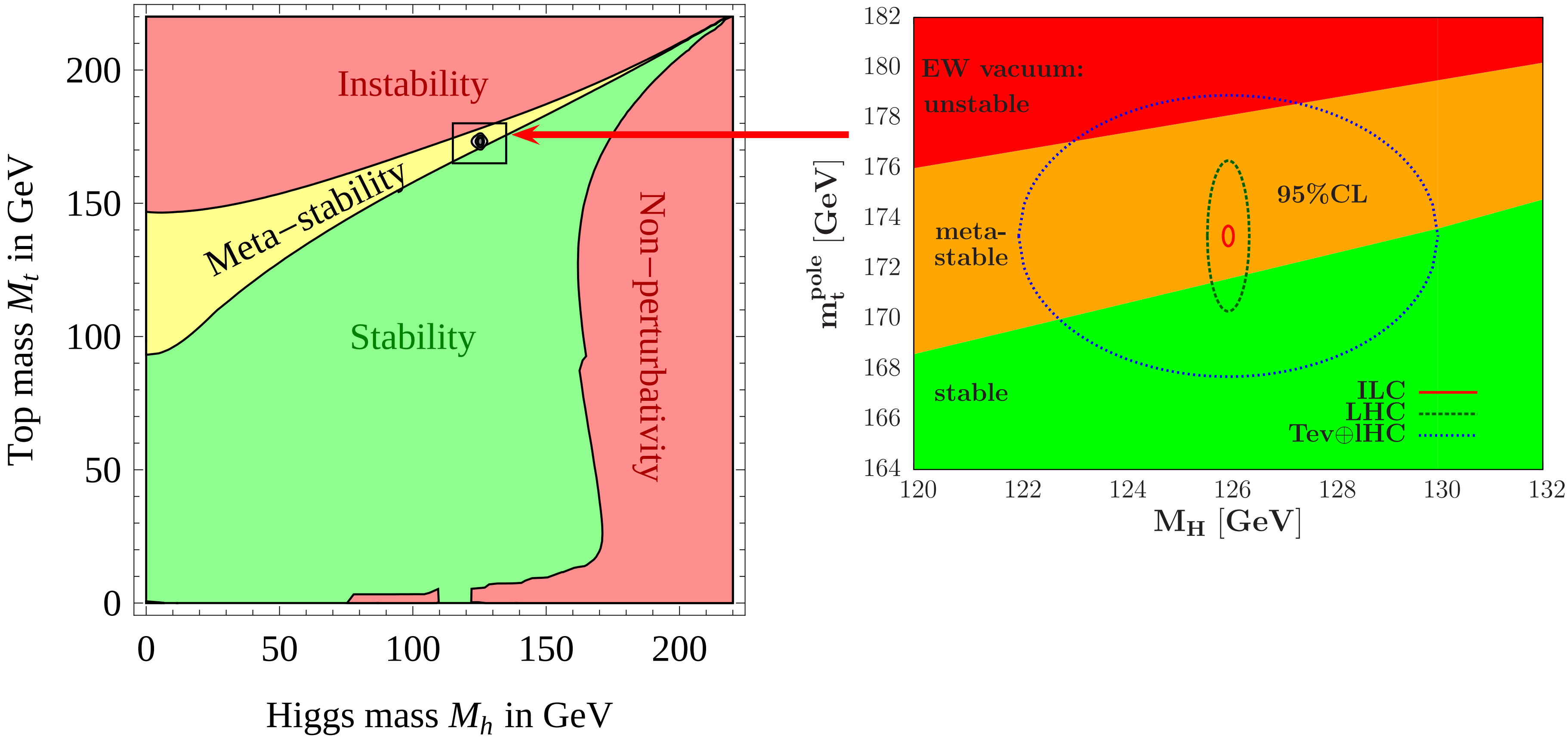
Implications on electroweak vacuum

- 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

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

  - 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
  - $m_t^{\overline{\rm MS}}(m_t) = 163.3 \pm 2.7 \text{ GeV}$ implies in pole mass scheme $m_t^{\rm pole} = 173.3 \pm 2.8 \text{ GeV}$
  - 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

Summary

Top quark mass

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

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

Higgs mass

- First result from LHC

$$m_H \simeq 126 \mathrm{GeV}$$

Fate of the universe

- Still undecided . . .

Summary

Physics at the Terascale

- Discovery of (SM like scalar) Higgs boson opens new avenue for studies of Standard Model physic and beyond
- Precision determinations of non-perturbative parameters is essential
  - masses m_t, M_W, m_H, . . .
  - coupling constants $\alpha_s(M_Z)$
  - parton content of proton (PDFs)
- Precision measurements require careful definition of observable
  - top-quark mass m_t in well defined scheme
- Radiative corrections at higher orders in QCD and EW are mandatory
  - continuous challenge for theory
  - search for new observables which meet experimental requirements
- Joint effort theory and experiment