VNIVERSITAT DE VALÈNCIA

Top at threshold

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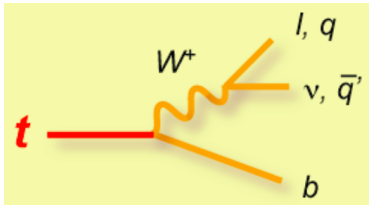
IX Jornadas de futuros colisionadores IFIC

18-19 December 2012

Why are we interested in the top quark?

- Heaviest known quark (plays an important role in EWSB in many models)
- Important for quantum effects affecting precision observables
- Very unstable, decays "before hadronization" $(\Gamma_t \approx 1.5\ \mathrm{GeV} \gg \Lambda_{\mathrm{QCD}})$

Combination of CDF and DØ results on the mass of the top quark using up to 5.8 fb^{-1} of data



The Tevatron Electroweak Working Group[1]
for the CDF and DØ Collaborations

$$M_{\mathrm{t}} = 173.2 \pm 0.9\ \mathrm{GeV}$$

0.5% precision !

Abstract

We summarize the top-quark mass measurements from the CDF and DØ experiments at Fermilab. We combine published Run I (1992–1996) measurements with the most precise published and preliminary Run II (2001-present) measurements using up to 5.8 fb^{-1} of data, adding new analyses (the $\not\!\!E_T$+Jets analysis) and updating old ones. Taking uncertainty correlations into account, and adding in quadrature the statistical and systematic uncertainties, the resulting preliminary Tevatron average mass of the top quark is $M_{\mathrm{t}} = 173.2 \pm 0.9\ \mathrm{GeV}/c^2$.

- How should we theorists judge this error?
- What is the theoretical error in this mass determination?
- What mass is it?

Concept of a Quark mass

Quantum Field Theory

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm classic} + \mathcal{L}_{\rm gauge-fix} + \mathcal{L}_{\rm ghost}$$

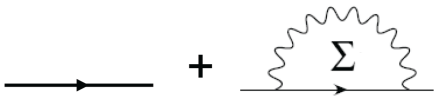
$$\mathcal{L}_{\rm classic} = -\frac{1}{4} F^A_{\alpha\beta} F_A^{\alpha\beta} + \sum_{\text{flavors } q} \bar{q}_\alpha (i\not{D} - m_q)_{\alpha\beta}\, q_b$$

Particles: Field-valued operators made from creation and annihilation operators

Classic action: m is the rest mass, no other mass concept exists at the classic level

- Beyond LO QCD predictions, the top-quark mass value depends on the **renormalization scheme**

Renormalization



$$= \not{p} - m^0 + \Sigma(p, m^0) \longrightarrow m^0 \frac{\alpha_s}{\pi} \left[-\frac{1}{\epsilon} + \text{finite stuff} \right]$$

Common mass renormalization schemes

Pole mass: mass = classic rest mass

$$m^0 = m^{\rm pole} + \Sigma(m^{\rm pole}, m^{\rm pole})$$

$\overline{\rm MS}$ mass:

$$m^0 = \overline{m}(\mu) - \frac{\alpha_s}{\pi} \frac{1}{\epsilon}$$

Unphysical due to confinement !

ambiguous by $\Delta m^{\rm pole} \sim \Lambda_{\rm QCD}$

$\mathcal{O}(m^{\rm pole}) \sim \sum \alpha_s^{n+1} (2\beta_0)^n\, n!$

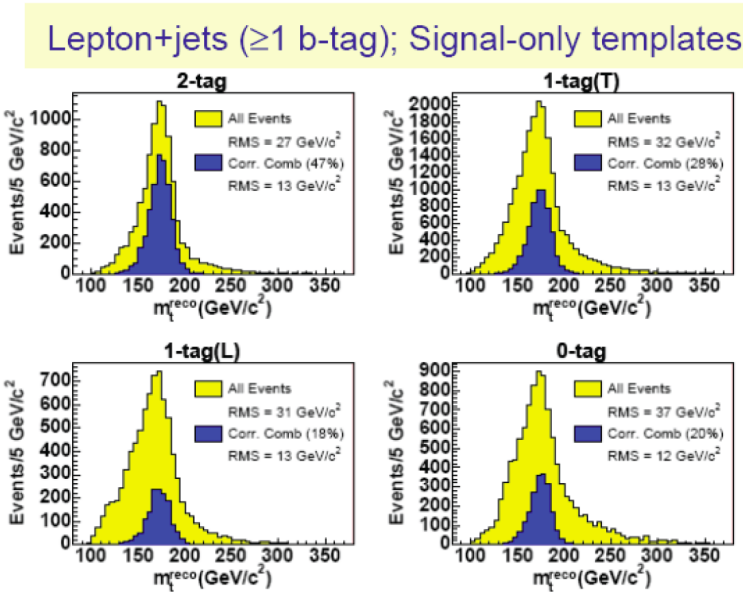
$O(\Lambda_{\rm QCD})$ renormalon problem

Direct measurements of the top mass @ Tevatron and LHC

Two main approaches to directly measure the top mass from the **reconstruction of the final states** in decays of top-antitop pairs

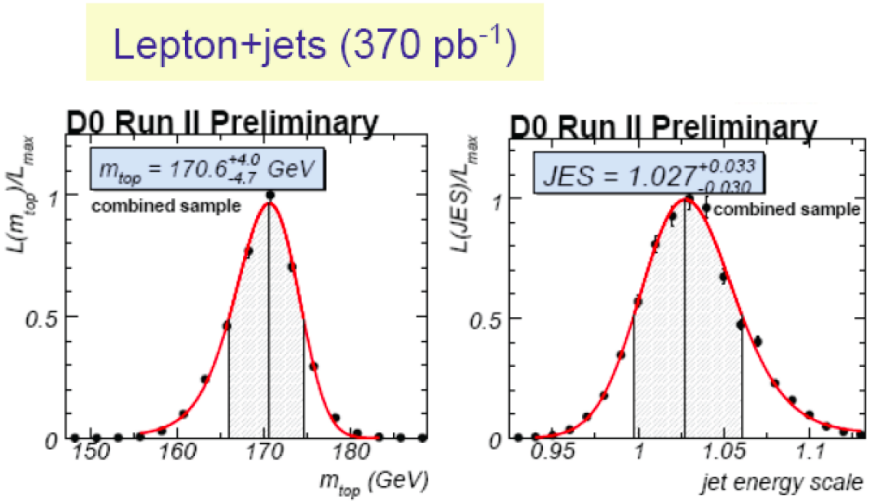
Template Method

Monte Carlo templates of reconstructed mass distributions are fit to data



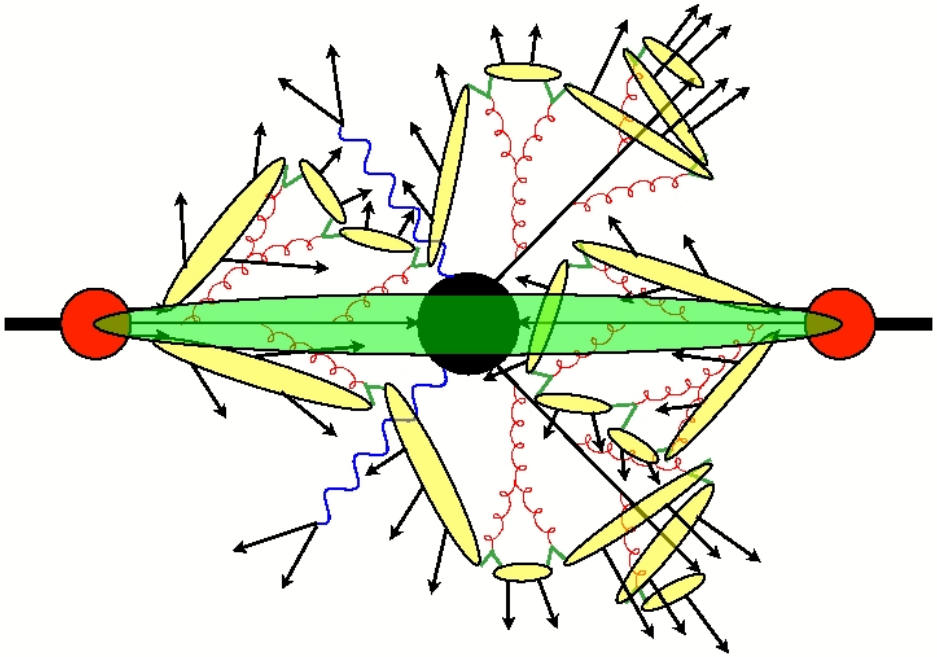
Matrix Element Method

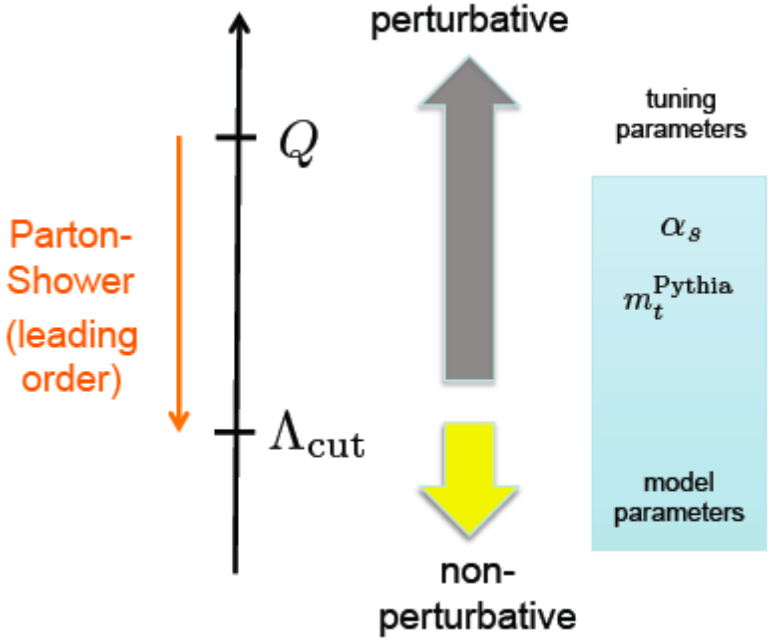
The top mass is extracted from the reconstructuction of the final states in the data using a calibration curve obtained from the Monte Carlo simulation



Parton shower Monte Carlo event generators

Computer program designed to simulate hadronic final states





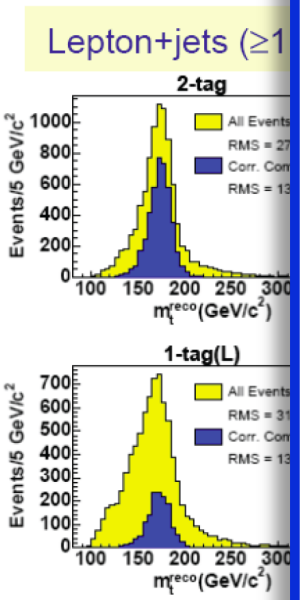
- **Parton shower: leading-log approximation**
- **Classic approximation**
- **No quantum interference between production and decay**
- **Infrared regularization scheme is not specified**

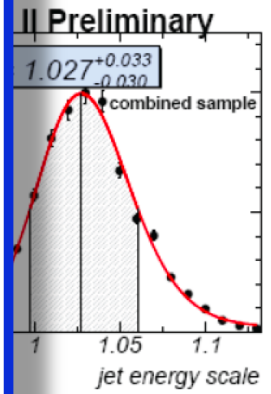
Direct measurements of the top mass @ Tevatron and LHC

Two main approaches to directly measure the top mass from the **reconstruction of the final sta**

Templa **ethod**

Monte Carlo te ed from the mass distributior l states in the urve obtained ion





What mass is measured? The top quark mass scheme used in the MC simulation $\rightarrow m_t^{\rm MC}$

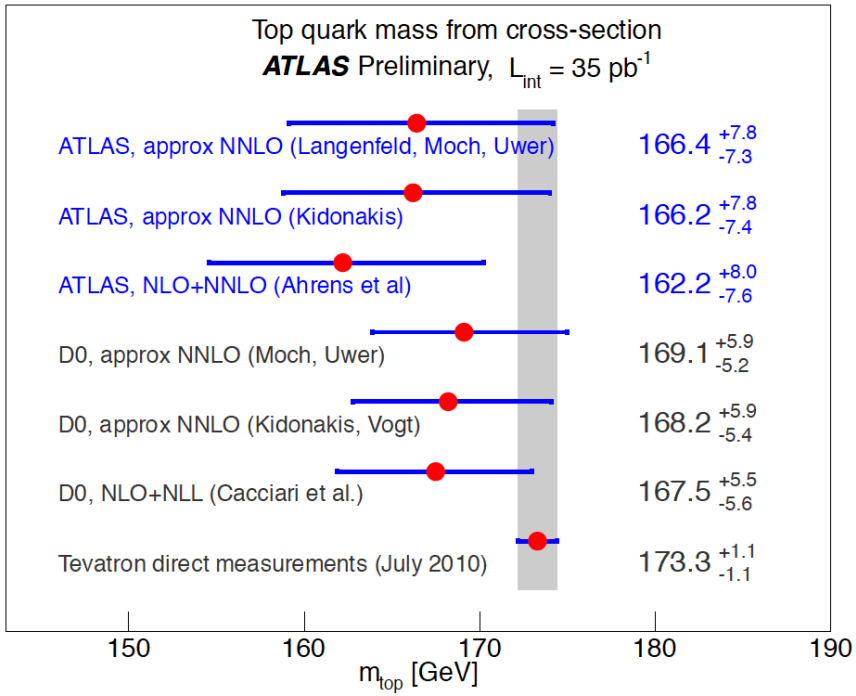
What is $m_t^{\rm MC}$? Not the pole mass!

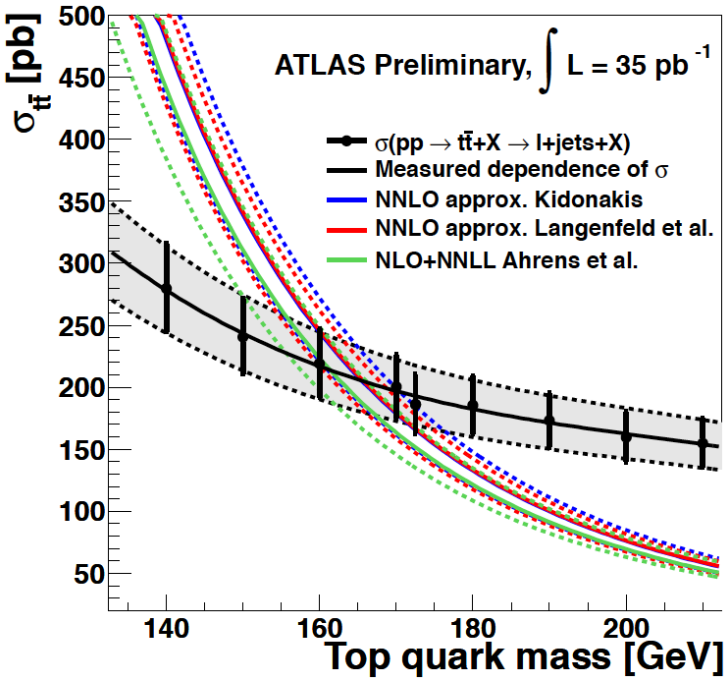
$m_t^{\rm MC} - m^{\rm pole} \sim \mathcal{O}(1{\rm GeV})$ *[Hoang, Stewart (2008)]*

It is not possible to establish a connection between $m_t^{\rm MC}$ and any other mass scheme without knowledge (at least) of parton showers at NLL accuracy

To make a statement on a top quark mass value extracted from data, **compare the measurement of a quantity depending on the top mass with a calculation using a consistent scheme**

Top mass extraction from the measured cross section





Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO [11]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO + NLL [12]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO + NNLL [13]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [14]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [15]	$166.7^{+5.2}_{-4.5}$	-2.8

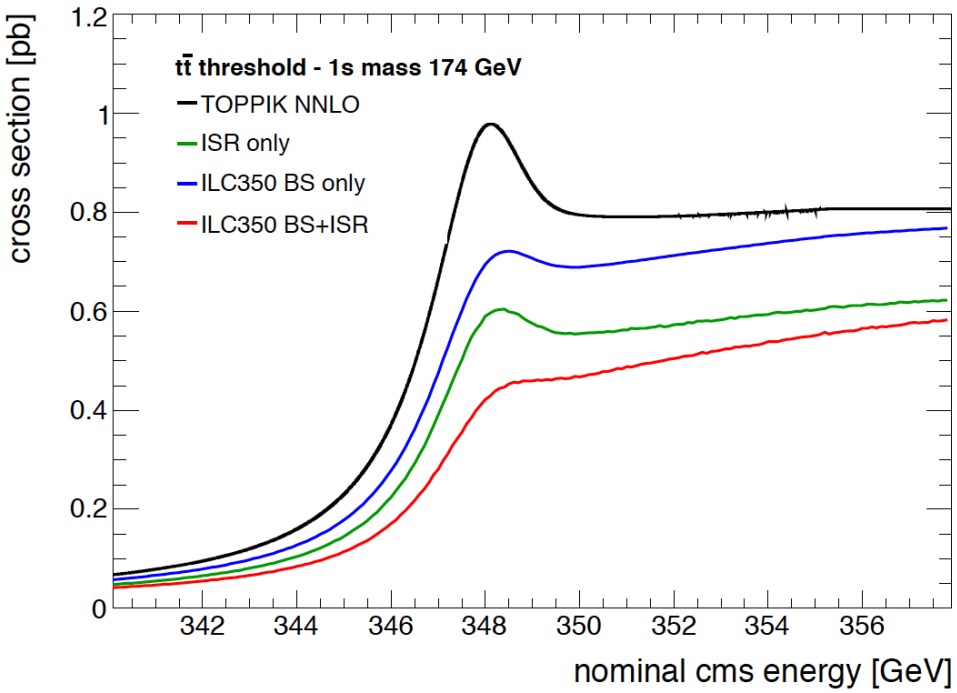
- Selection of t-tbar candidates in the cross section measurement introduces a dependence on m_t^{MC}
- Significant improvement of this measurement questionable due to syst. (theoretical) uncertainties
- **We need better precision !**

Top mass at the ILC

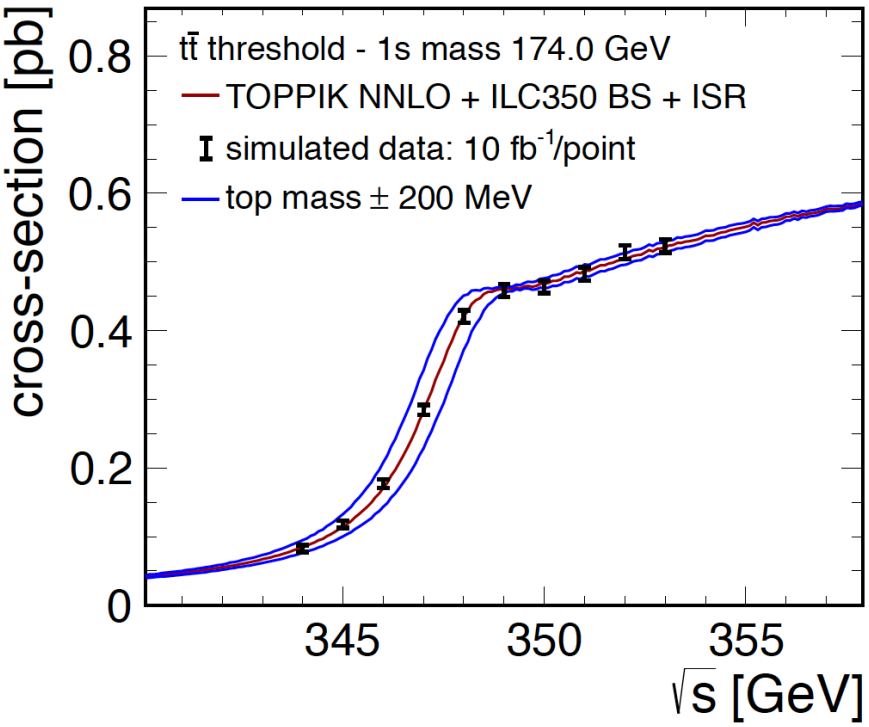
Threshold scan

$\sqrt{s} \simeq 2m_t$

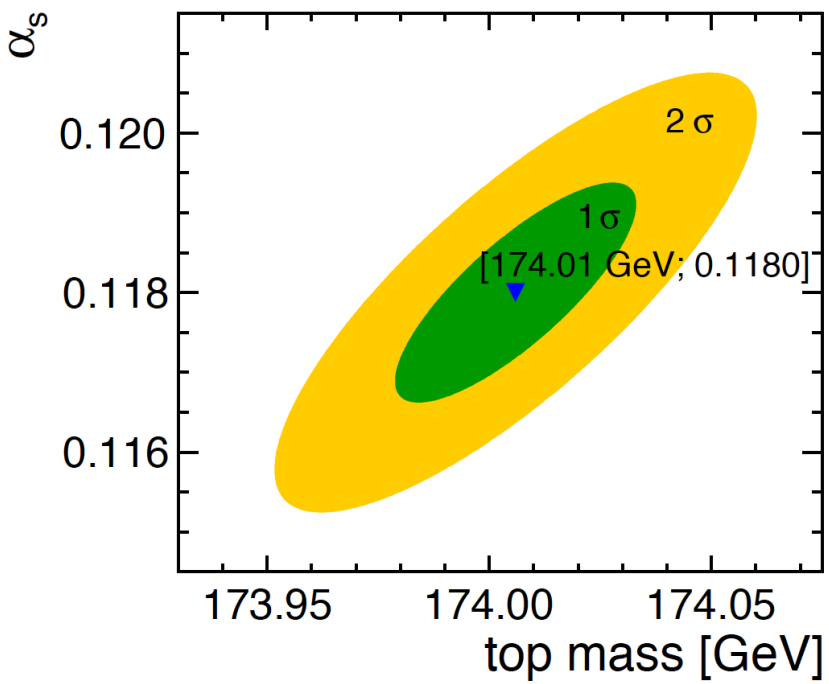
$\hookrightarrow$ Precise determination of the top mass m_t, the width Γ_t and the Yukawa coupling λ_t (one order of magnitude improvement with respect hadron colliders)



[Seidel, Simon, Tesar (2012)]



Prospects for the top mass measurement at the ILC



[Seidel, Simon, Tesar (2012)]

includes up to NNLO QCD corrections (no EW)

ILC 1D 1S top mass fit

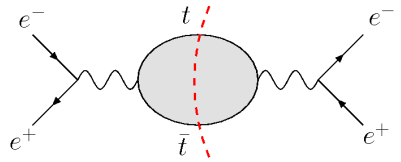
measurement	m_t stat. error	m_t th. syst. (1%/3%)	α_s syst.
six point scan 1D fit	18 MeV	15 MeV / 47 MeV	18 MeV
ten point scan 1D fit	18 MeV	13 MeV / 39 MeV	17 MeV

ILC 2D 1S top mass and α_s combined fit

measurement	m_t stat. error	m_t th. syst. (1%/3%)	α_s stat. error	α_s th. syst. (1%/3%)
six point 2D	31 MeV	2 MeV / 1 MeV	0.0011	0.0006 / 0.0018
ten point 2D	27 MeV	5 MeV / 9 MeV	0.0008	0.0007 / 0.0022

Status of QCD corrections

Top and antitop close to mass shell, use Non-Relat. EFT



Top quarks move slowly near threshold: $v = \sqrt{1 - \frac{4m_t^2}{s}} \sim \alpha_s \ll 1$

$\hookrightarrow$ sum $\left(\frac{\alpha_s}{v}\right)^n$ from "Coulomb gluons" to all orders

$$\frac{\alpha_s}{v} \sim 1$$

$$\begin{aligned} \text{LO} &\sim \left(\frac{\alpha_s}{v}\right)^n \\ \text{NLO} &\sim \{\alpha_s, v\} \times \left(\frac{\alpha_s}{v}\right)^n \\ \text{NNLO} &\sim \{\alpha_s^2, \alpha_s v, v^2\} \times \left(\frac{\alpha_s}{v}\right)^n \end{aligned}$$

✔ **fixed-order approach:** all **N^{3}LO** pieces known (compilation of all contributions to check convergence of perturbative series still pending) **Beneke, Kiyo, Schuller '05-08**

Further RG improvement by summing also $(\alpha_s \ln v)^m$: LL, NLL, ...

$$\frac{\alpha_s}{v} \sim 1 \qquad \alpha_s \ln v \sim 1$$

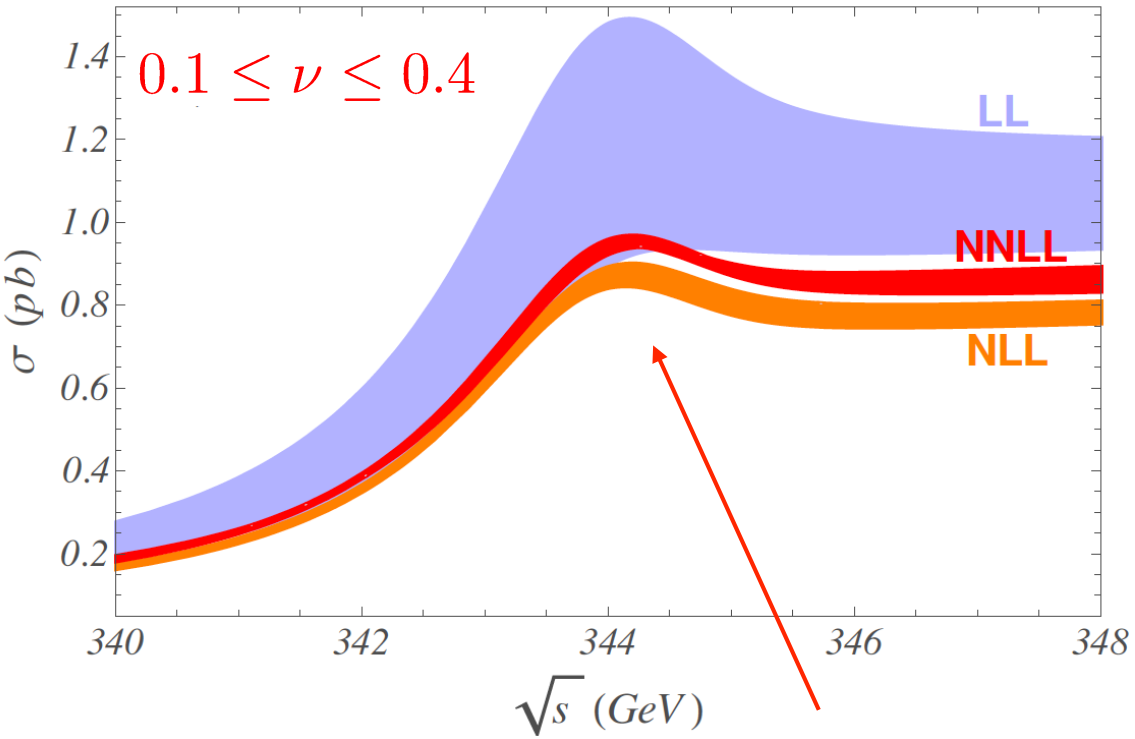
$$\begin{aligned} \text{LL} &\sim \left(\frac{\alpha_s}{v}\right)^n \sum_m (\alpha_s \ln v)^m \\ \text{NLL} &\sim \left(\frac{\alpha_s}{v}\right)^n \sum_m (\alpha_s \ln v)^m \times \{\alpha_s, v\} \end{aligned}$$

✔ **RG improved calculation: NNLL** almost complete (missing NNLL piece small)

Hoang, Manohar, Stewart, Teubner '00-01;
Hoang ´03; Pineda, Signer '06;
Hoang, Stahlhofen '06-11

Status of QCD corrections (cont.)

Hoang, Stahlhofen (2011)



$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim \pm(2-4)\%$

$M_{\rm peak} \simeq 2M_{\rm 1S} = 2m_t^{\rm pole} - 0.22\,\alpha_s^2 m_t^{\rm pole}$

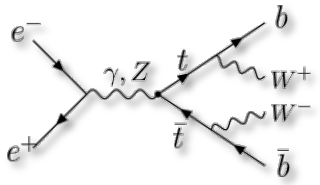
"threshold masses"

- missing QCD soft NNLL contributions small
- EW effects beyond LO and non-resonant effects not included

(at LO: $E = \sqrt{s} - 2m_t \to E + i\Gamma_t$)

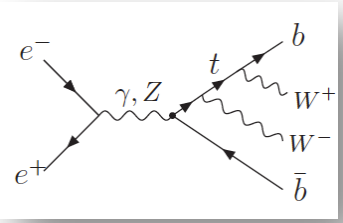
Effects from top-quark instability beyond LO

Note: once EW effects are turned on, the physical final state is $W^+W^-b\bar{b}$



resonant contributions: top and antitop close to mass-shell

- Non-resonant (hard) corrections to $e^+e^- \to W^+W^-b\bar{b}$ which account for the production of the Wb pairs by highly virtual tops or with only one or no top



Effective field theory (EFT) for pair production of unstable particles near threshold, based on separation of resonant and nonresonant fluctuations

Hoang, Reisser '05 ⟺ Beneke, Chapovsky, Khoze, Signer, Zanderighi '01-04; Actis, Beneke, Falgari, Schwinn, Signer, Zanderighi '07-08

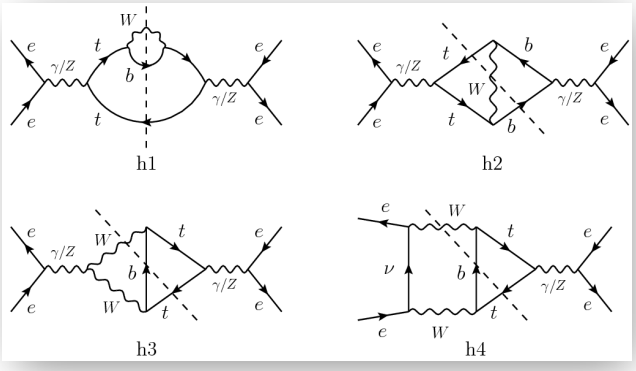
- power counting for finite width effects: $\dfrac{\Gamma_t}{m_t} \sim \alpha_{\rm EW} \sim \alpha_s^2 \sim v^2 \ll 1$

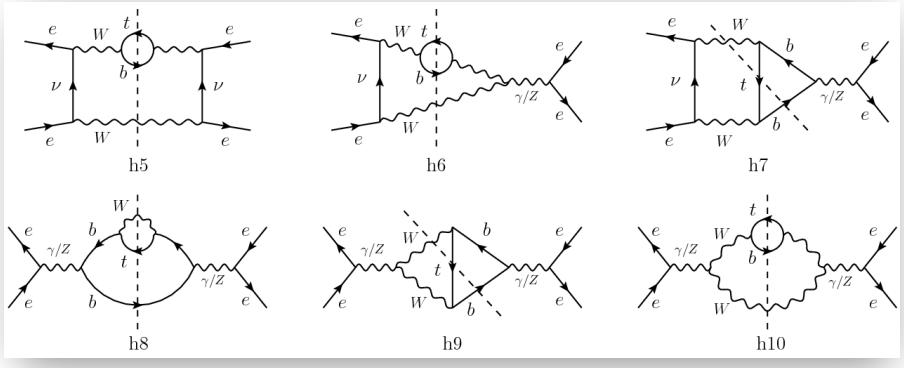
$\Rightarrow \quad \sigma(e^+e^- \to W^+W^-b\bar{b})$ in the $t\bar{t}$ resonance region and allow for invariant-mass cuts on reconstructed t, $\bar{t}$

Non-resonant corrections

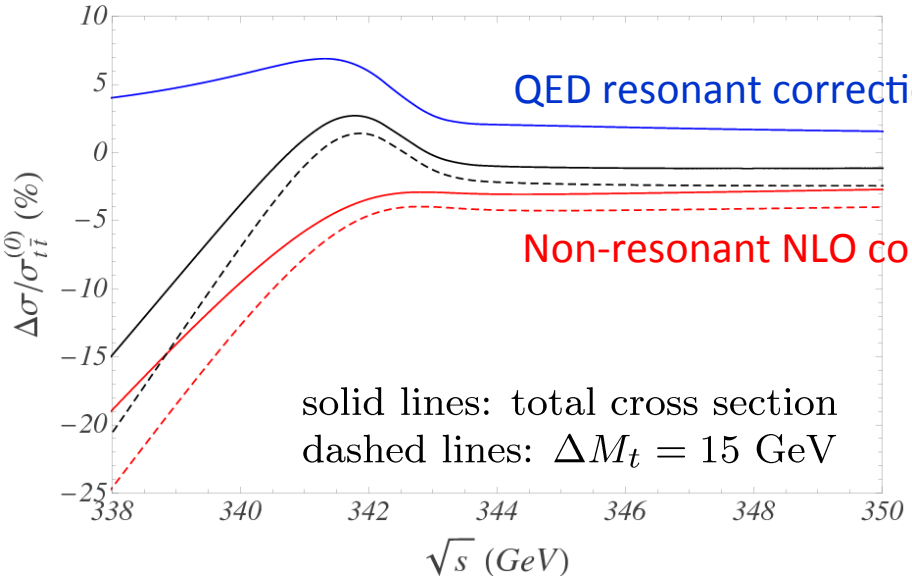
✔ **computed at NLO** for the total cross section and with top invariant-mass cuts

Beneke, Jantzen , RF (2010)





Relative sizes of EW NLO corrections w.r.t. LO



QED resonant correction ("Coulomb photons")

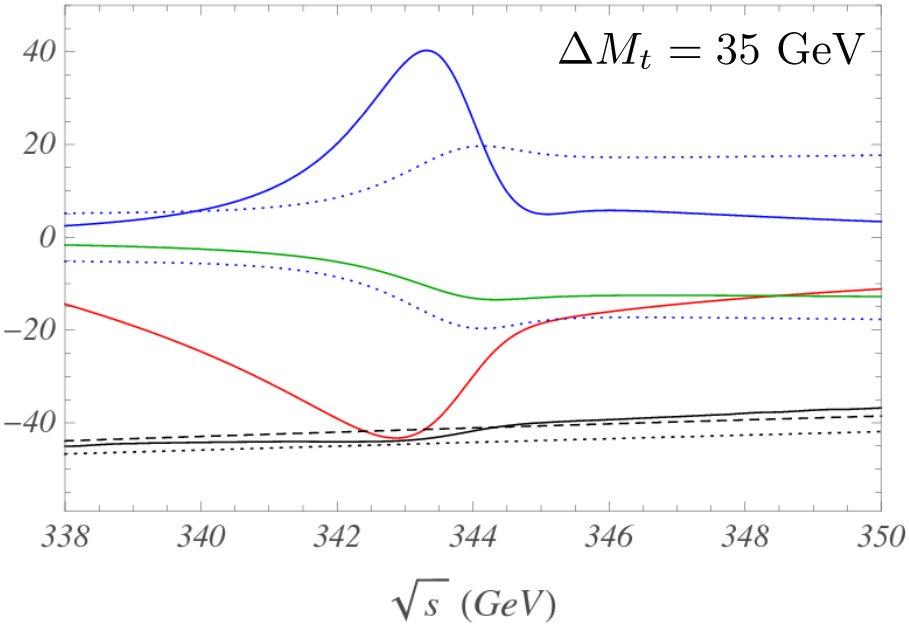
Combined EW NLO corrections

Non-resonant NLO correction → ~ -30 fb (-3% above and up to -20% below threshold) needed to meet the experimental precision at the ILC

Non-resonant corrections at NNLO

✔ Beyond NLO: **dominant NNLO and NNNLO terms** computed within the **phase space matching approach** with top invariant-mass cuts: $|\sqrt{p_{t,\bar{t}}^2} - m_t| \leq \Delta M_t$

Hoang, Reisser, RF (2010)



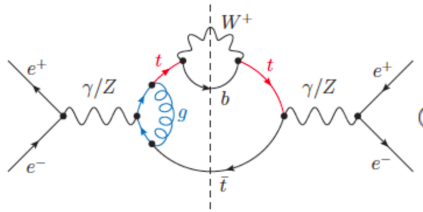
NNLL QED effects

NNLL hard one-loop EW effects

NNLL finite lifetime corrections

Non-resonant corrections (NLL, NNLL, N^{3}LL phase space matching contributions)

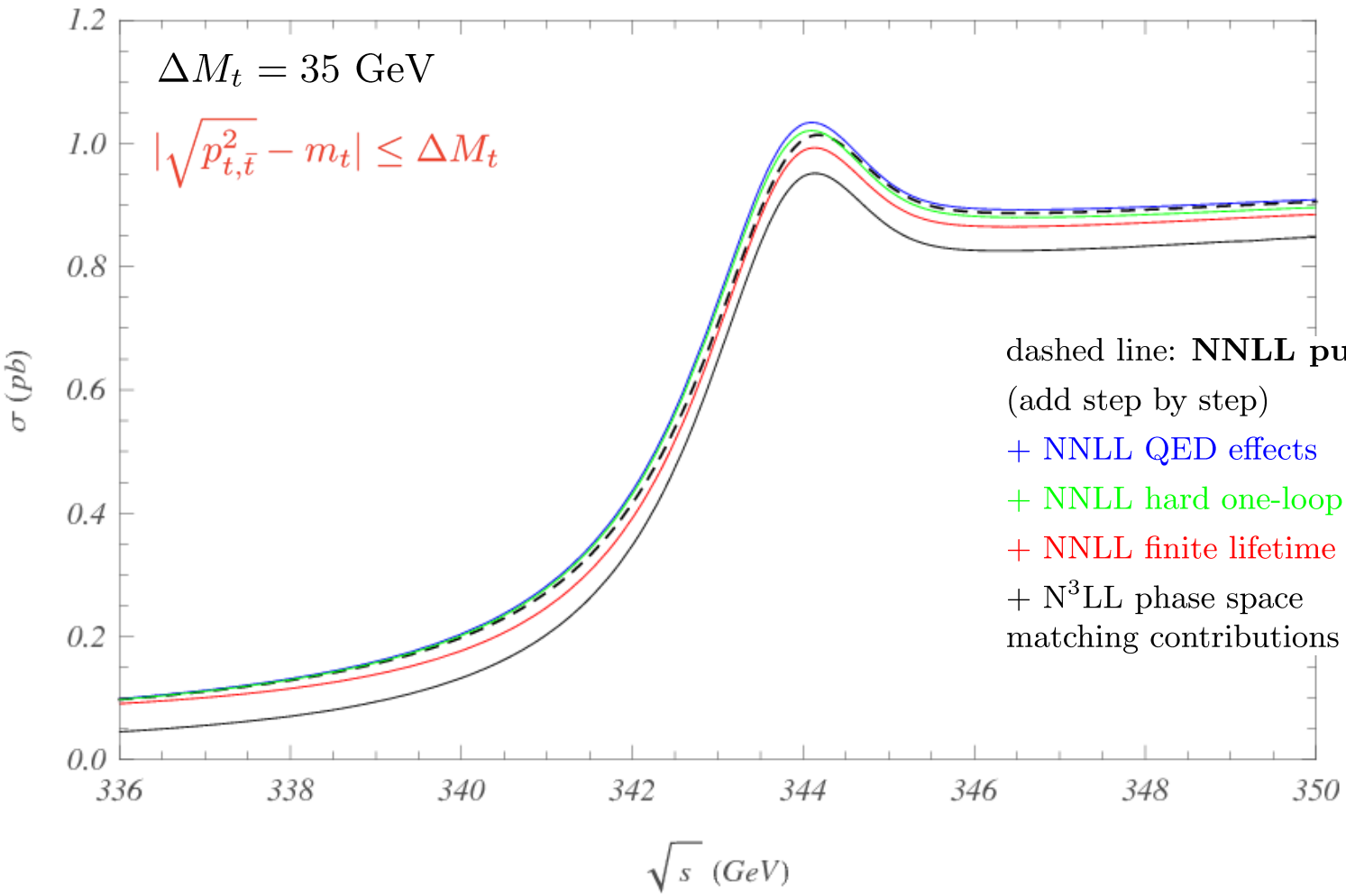
✘ full set of NNLO non-resonant corrections for the total cross section **currently unknown**

NNLO:  $\propto \alpha_s \frac{\Gamma_t}{\epsilon}$

✔ **Extraction of NNLO end-point divergences** almost complete **(Jantzen, RF)**

✘ **Finite parts:** overlapping of end-point and IR singularities calls for a modified subtraction method (work in progress...)

Top-pair production cross section



dashed line: **NNLL pure QCD prediction**

(add step by step)

+ NNLL QED effects

+ NNLL hard one-loop EW effects

+ NNLL finite lifetime corrections

+ N^3LL phase space matching contributions

Summary: theoretical status of ttbar production cross section

Resonant corrections (top and antitop close to mass shell)

- QCD contributions:
  - ✔ **fixed-order approach:** all **N^{3}LO** pieces known (compilation of all contributions shall appear soon...)
  - ✔ **RG improved calculation: NNLL** almost complete (missing NNLL piece small)
- Electroweak contributions known to **NNLL** accuracy

✘ Detailed error analysis of **theoretical uncertainties** in preparation...

3% theoretical uncertainty on the total cross section here seems realistic...

Non-resonant corrections (bW pairs from virtual tops or with only one or no top)

✔ **computed at NLO** for the total cross section and with top invariant-mass cuts

✔ Beyond: **dominant NNLO and NNNLO terms known only** when top invariant mass are included

✘ **In progress:** finite parts at NNLO, we expect the size to be small (few percent at most), but **can become very important below the peak region**

⟶ **include non-resonant corrections in future ILC top-quark mass measurement study**