Summary of points for the discussion of theoretical issues in the determination and interpretation of the top mass

TOP LHC WG Open mtg
CERN, May 21-23 2013

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Factor the discussion as follows

- What is m_{MC} ?
  - in view of its use elsewhere (e.g. EW fits)
  - in view of a possible impact on the measurement itself
  - relation between $m_{MC\text{-}1}$ and $m_{MC\text{-}2}$
- Use of different renormalization schemes (e.g. MSbar vs pole) for NLO results : what is the relation between the mass used in a theoretical calculation (MC or PL) and corresponding observables
- Interplay of perturbative and hadronization effects/systematics: status and future progress

m_{MC} : why there is an issue at all

Consider a simplified example

Hoang

Take $\mu \to e\nu\nu$.

$m_\mu = m_{pole}$ and $m_\mu{}^2 = [p(e)+p(\nu)+p(\nu)]^2$

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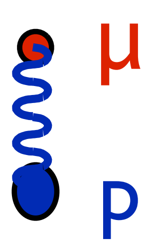

$$E = m_p + m_\mu + (K + V)_\mu = m_p + m_\mu - m_\mu\, \alpha^2/2 = m_p + m_{\mu,MSR}$$

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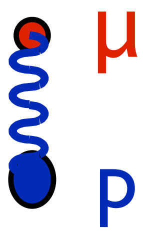

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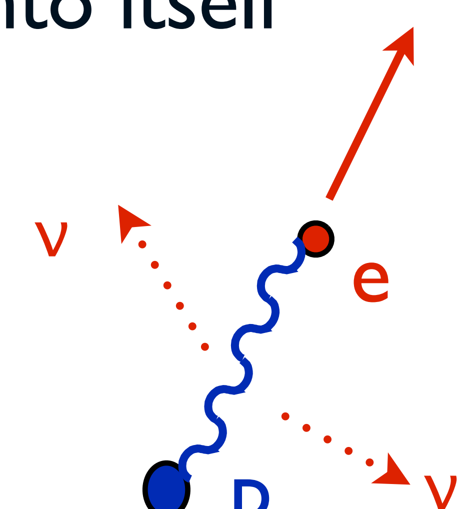
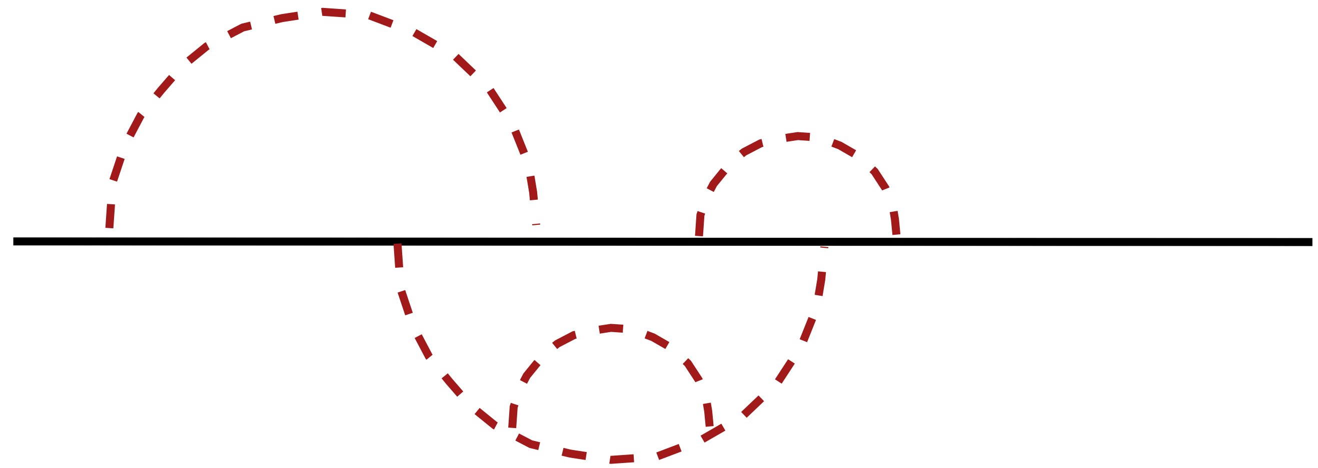
It is a "useful" mass, since, once the muon decays,

$[p(e)+p(\nu)+p(\nu)]^2 = m_{\mu,MSR}{}^2$, which $\neq m_\mu{}^2$ by $O(\alpha^2)$

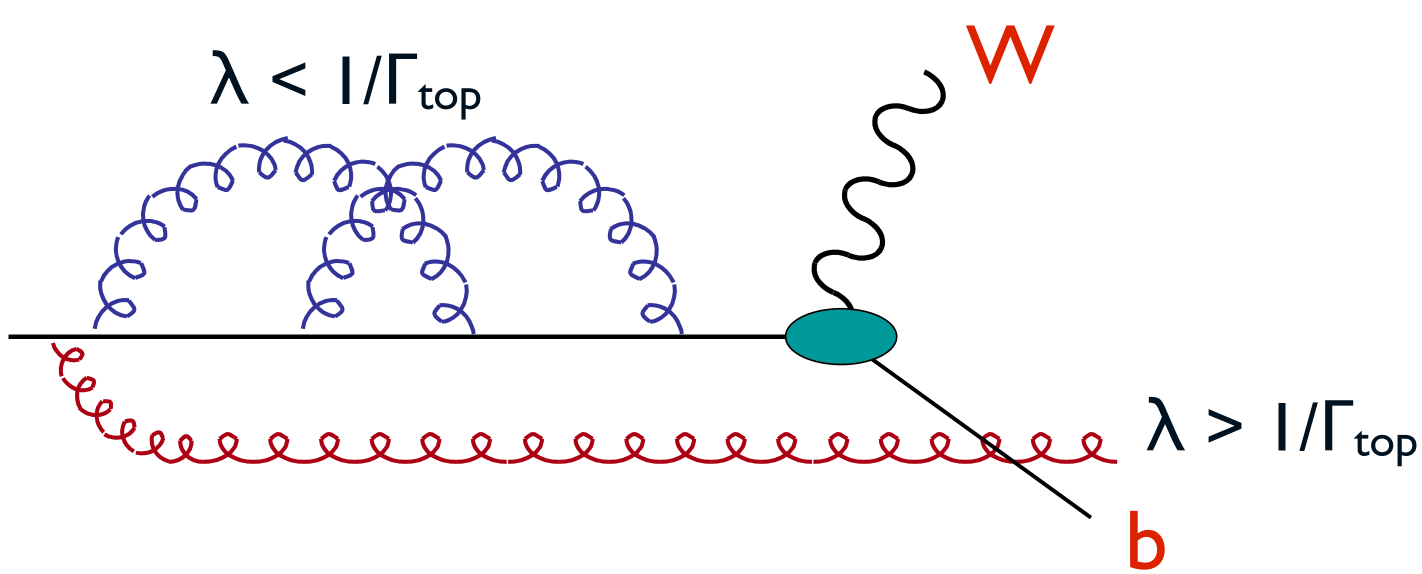


The reason is that the electron, to escape, must overcome the Coulomb potential, and its energy will be shifted by $V = -m_\mu\alpha^2$

In the case of a quark, the potential is the due to the interaction with its own gluon field



The pole mass is defined by resumming the effects of all these diagrams, absorbing all divergences. However, we know that we find problems if we integrate the loop momenta below the scale Λ_{QCD}, where perturbation theory breaks down. If we do it, to define m_{pole}, the perturbative series can only be resummed up to a (“renormalon”) ambiguity. If we stop before, at some scale, we dump into a m_{MSR} mass the self-energy potential due to modes with wavelength above that scale.
This is further justified for the top, which anyway only lives $1/\Gamma_{top}$, so gluons with wavelength > $1/\Gamma_{top}$ are cutoff:

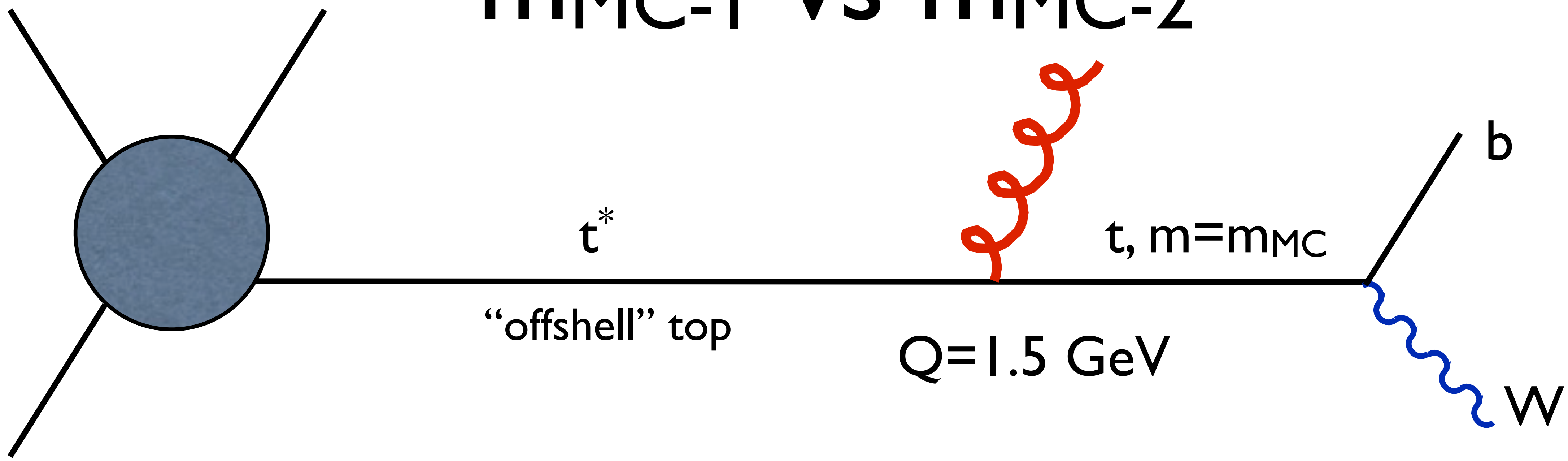


In this case,

$$\delta m \sim \ \alpha_S \ \Gamma_{top}$$

what is the coefficient ?

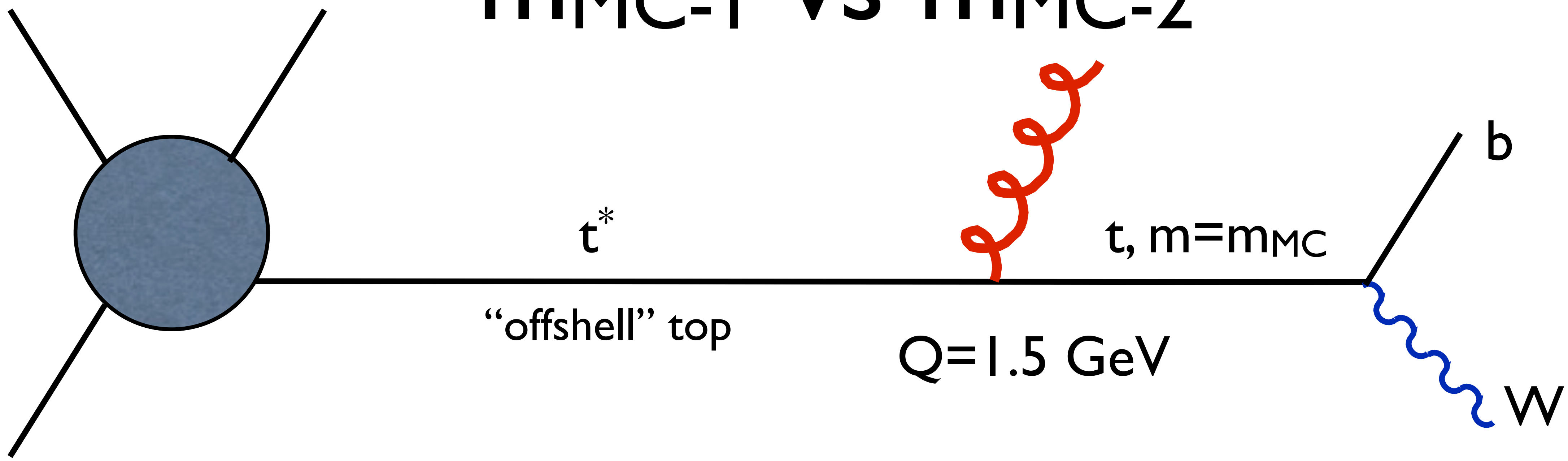
m_{MC-1} vs m_{MC-2}



This emission at scale Q=1.5 GeV may or may not be present in the MC, depending on the IR cutoff scale of the shower (e.g. 1 GeV vs 2 GeV). One may consider this is as using m_{MSR} defined at different scales, or as using different top-mass definitions.

The question is whether the emission of the extra gluons in the region ($cutoff_{MC-1}$ – $cutoff_{MC-2}$) affects the observables used to measure m_{MC} and change the measured value

$m_{MC\text{-}1}$ vs $m_{MC\text{-}2}$



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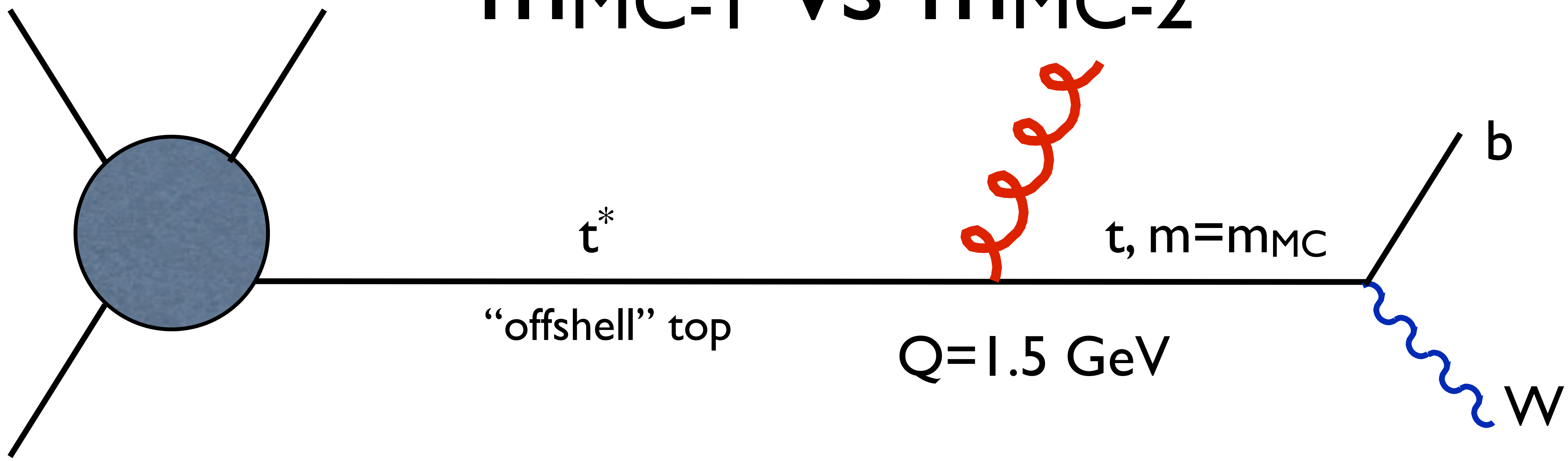

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Studies like those shown by CMS (Da Silva, mtop vs different production configurations) are crucial to understand the sensitivity to these effects, the consistency of the modeling in different MC, with data and with themselves

remarks

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Could a MC scheme in which the top is "forced" to hadronize before it decays (m_{MC} replaced by m_T) become a useful benchmark ? (Corcella)

Pole vs MSbar masses

$$m_{pole} = \overline{m} \times \left[1 + g_1 \frac{\bar{\alpha}}{\pi} + g_2 \left(\frac{\bar{\alpha}}{\pi}\right)^2 + g_3 \left(\frac{\bar{\alpha}}{\pi}\right)^3\right]$$ where

$$\overline{m} = m_{MS}(m_{MS})$$

$$\bar{\alpha} = \alpha(\overline{m})$$

$$g_1 = \frac{4}{3}$$

$$g_2 = 13.4434 - 1.0414 \sum_k \left(1 - \frac{4}{3} \frac{\overline{m}_k}{\overline{m}}\right)$$

$$g_3 = 0.6527\, n_l^2 - 26.655\, n_l + 190.595$$

Melnikov, van Ritbergen, Phys.Lett. B482 (2000) 99

In the range m_{top} = 171 – 175 GeV, α_S is ~constant, and, using the 3-loop expression above,

$$m_{pole} = \overline{m} \times [1 + 0.047 + 0.010 + 0.003] = 1.060 \times \overline{m}$$

showing an excellent convergence. In comparison, the expansion for the bottom quark mass behaves very poorly:

$$m^b_{pole} = \overline{m}^b \times [1 + 0.09 + 0.05 + 0.04]$$

Assuming that after the 3rd order the perturbative expansion of m_{pole} vs m_{MS} start diverging, the smallest term of the series, which gives the size of the uncertainty in the resummation of the asymptotic series, is of O(0.003 * m), namely O(500 MeV), consistent with Λ_{QCD}

This same O(α_S^3) term gives also: $\overline{m}^{(3-loop)} - \overline{m}^{(2-loop)} = 0.49\,\mathrm{GeV}$

Meson vs hvy-Q masses

Heavy meson $\Longrightarrow$ (point-like color source) + (light antiquark cloud):
properties of "light-quark" cloud are independent of mQ for mQ$\rightarrow\infty$

$$m_M = m_Q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_Q}$$

$$m_{M^*} = m_Q + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_Q}$$

$$\langle M|\,\bar{h}_Q\,(iD)^2 h_Q\,|M\rangle = -\lambda_1\,\mathrm{tr}\{\,\overline{\mathcal{M}}\,\mathcal{M}\,\} = 2M\,\lambda_1\,,$$
$$\langle M|\,\bar{h}_Q\,s_{\alpha\beta}G^{\alpha\beta}h_Q\,|M\rangle = -\lambda_2(\mu)\,\mathrm{tr}\{\,i\sigma_{\alpha\beta}\,\overline{\mathcal{M}}\,s^{\alpha\beta}\mathcal{M}\,\} = 2d_M M\,\lambda_2(\mu)\,,$$

$d_{M^*} = -1,\ d_M = 3$

See e.g. Falk and Neubert, arXiv:hep-ph/9209268v1

where $\bar{\Lambda},\ \lambda_1,\ \lambda_2$ are independent of m_Q

From the spectroscopy of the B-meson system:

$m(B^*) - m(B) = 2\,\lambda_2/m_b \Rightarrow \lambda_2 \sim 0.15\ \mathrm{GeV}^2$

QCD sum rules: $\lambda_1 \sim 1\ \mathrm{GeV}^2$

QCD sum rules: $\Lambda = 0.5 \pm 0.07$ GeV

thus corrections of $O(\lambda_{1,2}/m_{top})$ are of O(few MeV) and totally negligible

Separation between mQ and Λ is however ambiguous:
renormalon ambiguity on the pole mass:

$$\delta m_{pole} = \frac{C_F}{2N_f|\beta_0|} e^{-C/2}\, m(\mu = m) \exp\left(\frac{1}{2N_f\beta_0\alpha(m)}\right)$$
$$= \frac{C_F}{2N_f|\beta_0|} e^{-C/2}\, \Lambda_{QCD} \left(\ln\frac{m^2}{\Lambda^2_{QCD}}\right)^{\beta_1/(2\beta_0^2)},$$

where $\beta_1 = -1/(4\pi N_f)^2 \times (102 - 38N_f/3)$ is the second coefficient of the β-function

δm_{pole}=270 MeV for mtop.

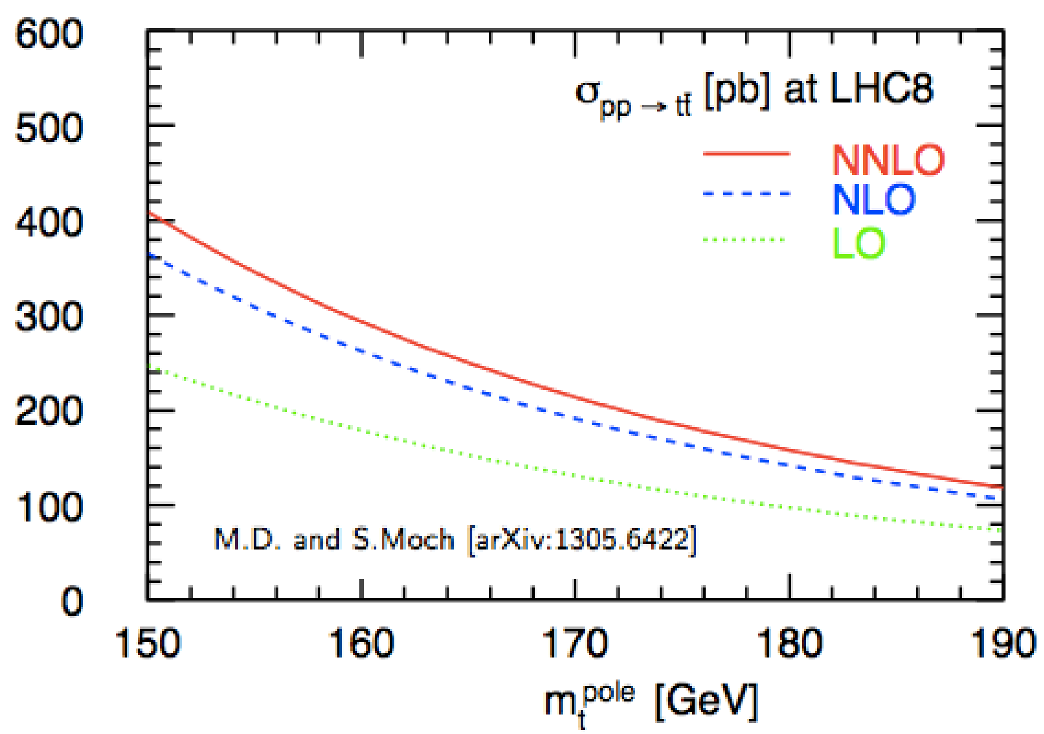
This is smaller than the difference between MSbar masses obtained using the 3-loop or 2-loop MSbar vs pole mass conversion.

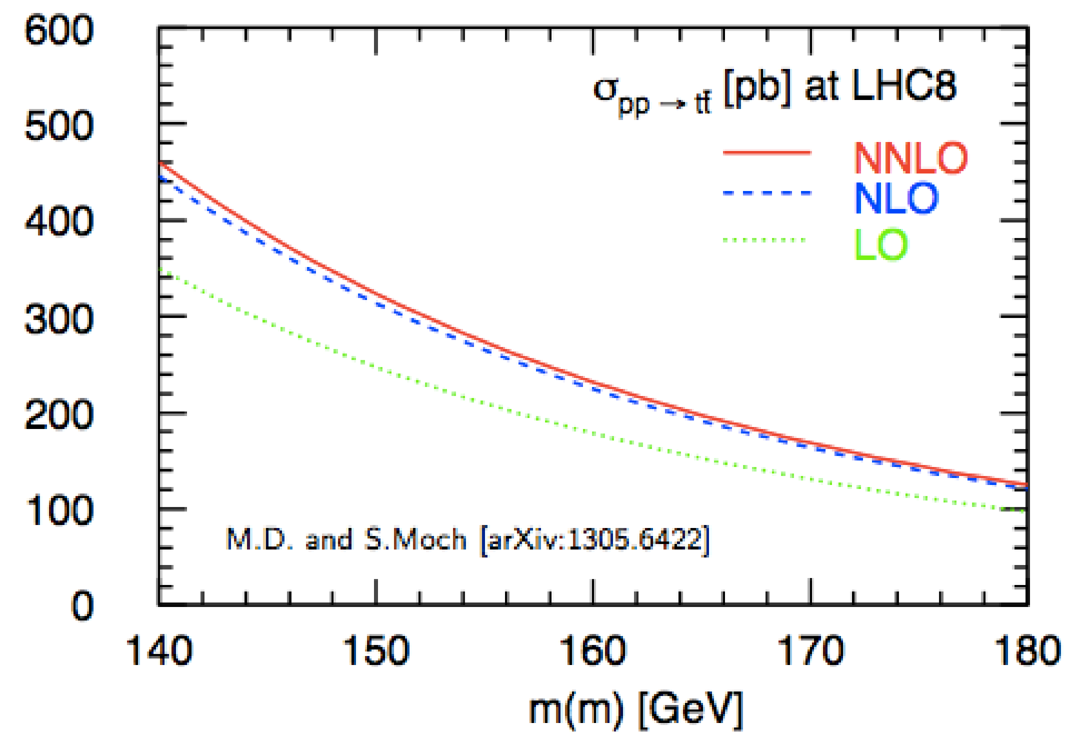
It would be very interesting to have a 4-loop calculation of MSbar vs m_{pole}, to check the rate of convergence of the series, and improve the estimate of the m_{pole} ambiguity for the top

Beneke and Braun, Nucl. Phys. B426, 301 (1994)
Bigi et al, 1994

MSbar vs Mpole N^n LO results and observables

Dowling





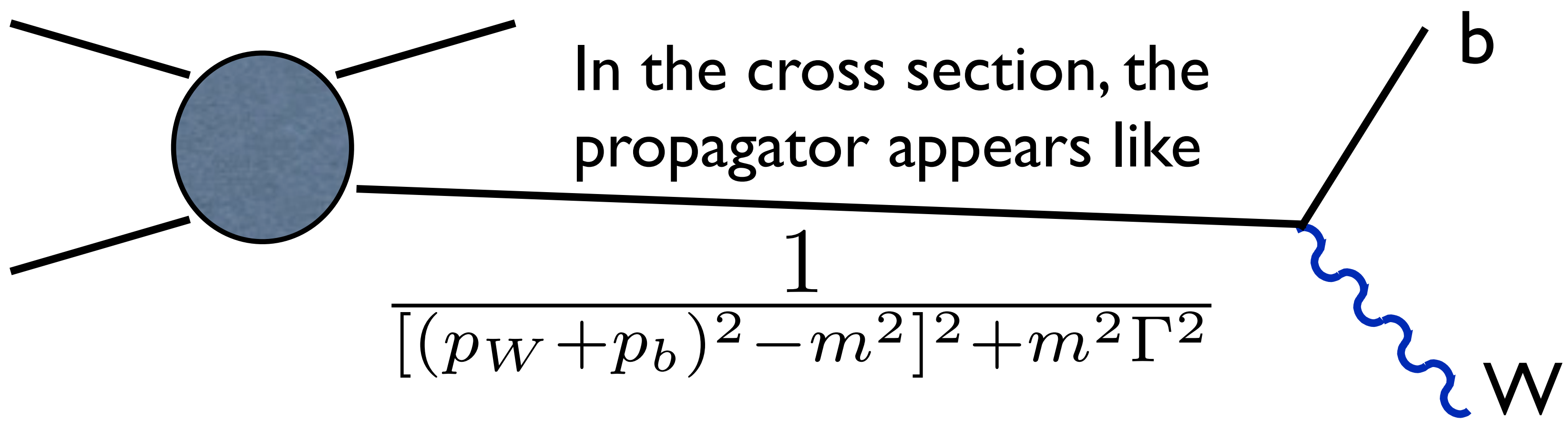
⇒ improvement in the convergence of PT in MSbar

σ(tt) is defined as the rate to produce event with tops, regardless of the top production and decay properties (never mind issues like non-resonant contamination to WWbb final states, etc)

In this case, application and use of a MSbar NLO calculation is well defined.

MSbar vs Mpole N^n LO results and observables

The use of MSbar to describe observables related to the top decay products, requires more care. The kinematics of the decay products is **not** driven by m(MSbar).



In the cross section, the propagator appears like

$$\frac{1}{[(p_W+p_b)^2-m^2]^2+m^2\Gamma^2}$$

What defines the kinematics of the final state, is the relation $(p_W+p_b)^2 \sim m^2$

In the pole-mass ren scheme, $m=m_{pole}$
In the MSbar scheme, m=m(MSbar) [1+ $O(\alpha_S)$], where the correction is such as to return the pole mass, in such a way that the kinematics is still driven by m_{pole}

A calculation in m_{pole} (or m_{MSR}) scheme allows to factorize production and decay using the relative mass. In the MSbar scheme, one should not factorize prod and decay using the MSbar mass.

So one should be careful in defining what is meant, e.g., by p_T(top) in the result of $d\sigma/dp_T$(top) calculated in the MSbar scheme

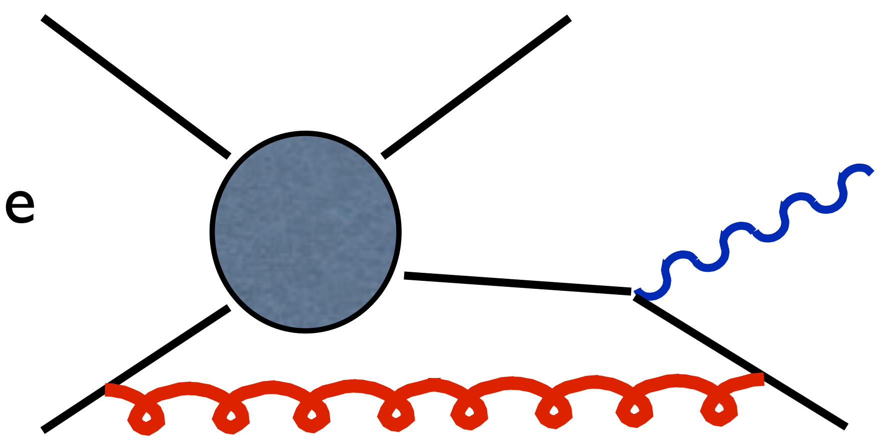
Recent progress at NLO, interplay of PT and hadronization, systematics, ...

Winter

Calculation of NLO effects for full off-shell and non resonant production of WbWb final states allow to probe sensitivity to

- top width
- "environmental" influence on the decay products

E.g. diagrams like this expose the interaction of b and initial state, absorbing part of what happens during the formation of color singlet clusters before hadronization



It is likely that inclusion of these effects will reduce the impact of hadronization effects, and to a reduction of their systematics. Much the study of implications of these new calculations, in a realistic mtop analysis, remains to be studied in detail

New ideas, techniques, observables

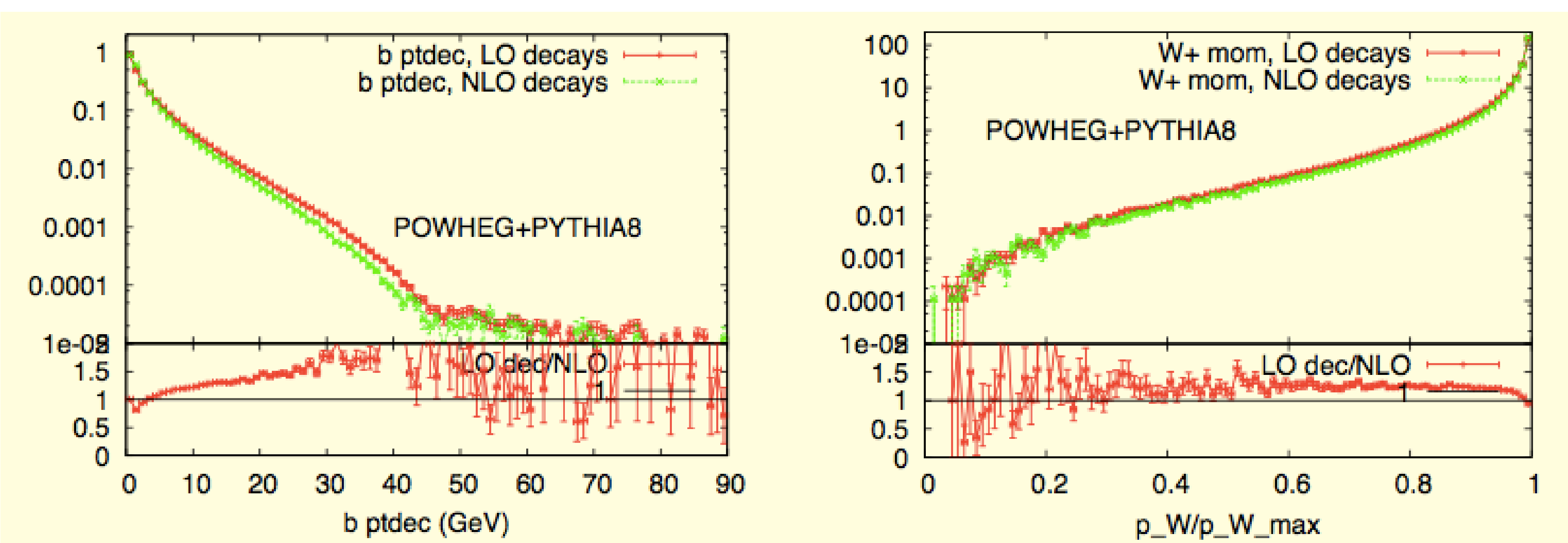
Artoisenet, Kawabata, Mitov, Franceschini

Trying to achieve the optimal balance between exptl/NP systematics (jet energy scales, hadronization, fragmentation, etc) and perturbative/theoretical systematics (ISR modeling, formal definition of m, scale dependence, etc)

No clear winner as yet

Any observable involving objects from the evolution of the b (b-jet, B hadron, B hadron decay product, etc) hit the wall of the b fragmentation function.
This must be addressed with dedicated measurements of the frag function, and of b-jet properties, in top decays. Issues like interaction of the b-jet partons with the rest of the event cannot emerge from the study of b fragmentation in Z decays

Also purely leptonic observables can be affected by what happens to the b jet (since in the CMF $E_W = [m_{top}^2 + m_W^2 - m^2_{\text{b-jet}}] / 2m_{top}$). E.g p_W in the top rest frame:



Nason