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Top Quark Physics

Theory Summary

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outline

$e_Q; T_3;$ spin; $SU(N_c)$	test indirect constraints not main motivation	$t \to Wb; \quad pp \to t\bar{t}\gamma$
m_t (what mass?)	input for (EW) precision THE measurement	$t\bar{t}$ production other possibilities?
Yukawa coupling y_t	direct test of Higgs mech. important	$pp \to t\bar{t}H$
CKM element V_{tb}	(only) direct measurement nice	single top production
width Γ_t	SM theory accurate at 1% (would be) really nice	only at ILC ??
anom. coupl; BSM	we are desperate for it no comment	spin correlations, rare decays, single top ...

outline

- within the Standard Model, there are only two free parameters, m_t and V_{tb}
- top is a window to physics beyond the Standard Model
- in most, if not all, extensions of the SM, top plays a special role (Technicolor, topcolor SUSY, little Higgs)
- Yukawa coupling $y_t \sim \sqrt{2}\, m_t/v \simeq 1$, as it should
- width $\Gamma_t \sim 1.4$ GeV $\gg \Lambda_{\rm QCD} \quad \Longrightarrow$: top behaves like a “free quark” [Bigi, Dokshitzer, Khoze, Kühn, Zerwas]
- spin information of top is transformed to decay products $\Longrightarrow$ spin correlations
- the top is the white sheep in a herd of black sheep

theory status

one-page summary

- width known at α_s^2 and one-loop electroweak $\Rightarrow$ theoretical uncertainty $\sim 1\%$ [Czarnecki, Melnikov; Chetyrkin et.al; Denner, Sack; Eilam et.al.]
- $m_{t,\text{pole}}/\overline{m_t}(\overline{m_t})$ known at α_s^3 [Chetyrkin, Steinhauser]
- top quark pair production known at $\sim$ one-loop $\Rightarrow$ see later
  included in MC@NLO [Frixione, Webber]
- single top production known at $\sim$ one-loop $\Rightarrow$ see later
  s- and t-channel included in MC@NLO [Frixione, Laenen, Motylinski, Webber]
- $pp \to t\bar{t}H$ known at $\sim$ one-loop $\Rightarrow$ see later
- $pp \to t\bar{t}j$ known at $\sim$ one-loop [Dittmaier, Uwer, Weinzierl]

Theory status (top not decaying)

- NLO QCD corrections to top pair production [Dawson et.al.; Beenakker et.al. . . .]
- resummation (in threshold region $\beta \to 0$) [not for arbitrary distributions] [Bonciani, Catani, Mangano, Nason . . . . . .]

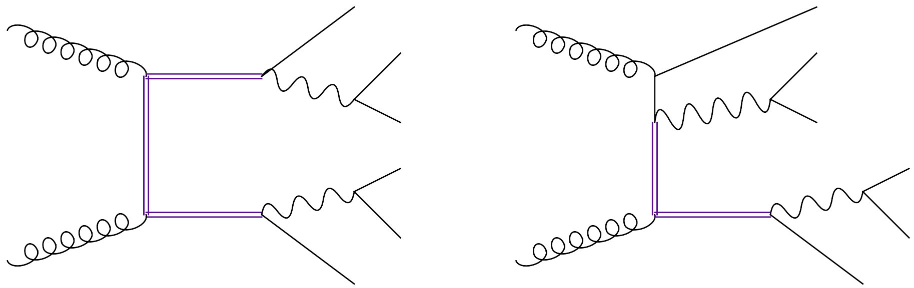
$$\hat{\sigma}^{(1)}_{t\bar{t}} = \hat{\sigma}^{(0)}_{t\bar{t}} \left(1 + \alpha_s \Big[\underbrace{\sim \frac{1}{\beta}}_{\text{not res.}} + \underbrace{\sim \log^2 \beta + \sim \log \beta}_{\text{resummed}} + c \Big] \right)$$

resummation of logarithms considerably improves the scale dependence of the cross section

- one-loop electroweak corrections known [Beenakker et.al., Kao, Wackeroth, Bernreuther et.al; Kühn, Scharf, Uwer]
small for total cross section, can be important for differential distributions

Theory status (top decaying) have to consider the decay for experimental cuts

- off-shell and off-resonance effects studied at tree level [Kauer, Zeppenfeld]



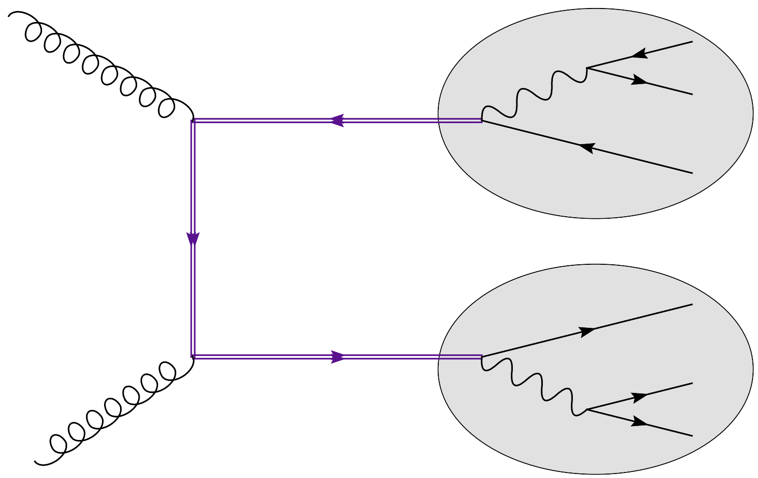
in general: $p^2 = m_t^2 \Rightarrow$ singularity $\Rightarrow$ include width $\Rightarrow$ gauge invariance issues
importance of these effects crucially depends on final state cuts

- spin correlations known at NLO [Bernreuther, Brandenburg, Si, Uwer]
- no general purpose MC avaliable including all these effects
- non-factorizable corrections neglected $\sim \alpha_s \Gamma_t / m_t$

theoretical uncertainty for cross section (mainly scale and PDF's) $> 10\%$
$\Longrightarrow$ uncertainty $\delta m_t > 4\ \mathrm{GeV}$ for top mass measurements from cross section
$\Longrightarrow$ top mass measurements only via invariant mass of decay products??

m_t measurements from invariant mass of top decay products (which mass ??)

measurement of pole mass, potentially a problem if $\delta m_t < 1\ \mathrm{GeV}$ (see next slide)



$pp \to t\bar{t}X$

m_t measurements from invariant mass of top decay products (which mass ??)

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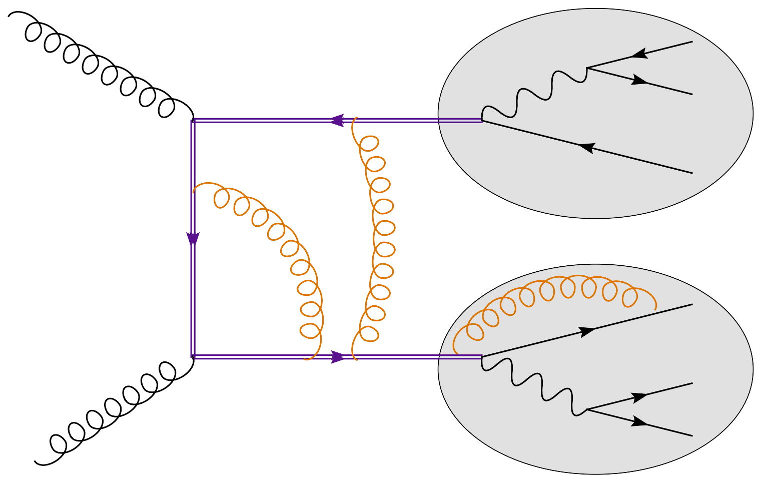
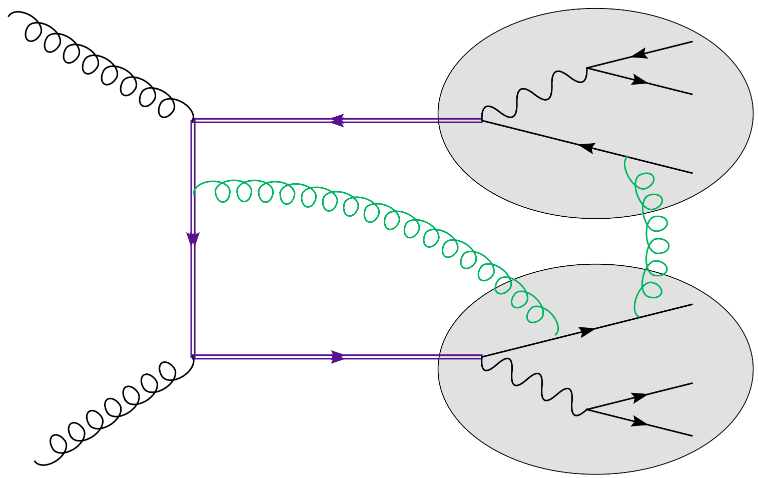
corrections to production and decay of on-shell top are included



m_t measurements from invariant mass of top decay products (which mass ??)

measurement of pole mass, potentially a problem if $\delta m_t < 1$ GeV (see next slide)
corrections to production and decay of on-shell top are included
but non-factorizable corrections not included

- usual argument: they are suppressed by $\alpha_s \Gamma_t / m_t$, since top propagators not on-shell any longer
- not true for soft gluons $E \sim \Gamma_t$ $\Rightarrow$ impact on m_t measurement ?? cp. FSR !!

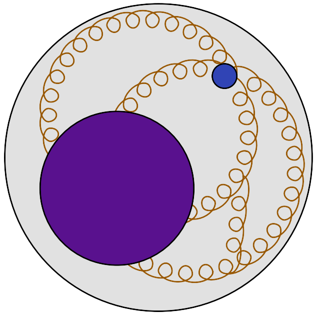


top mass

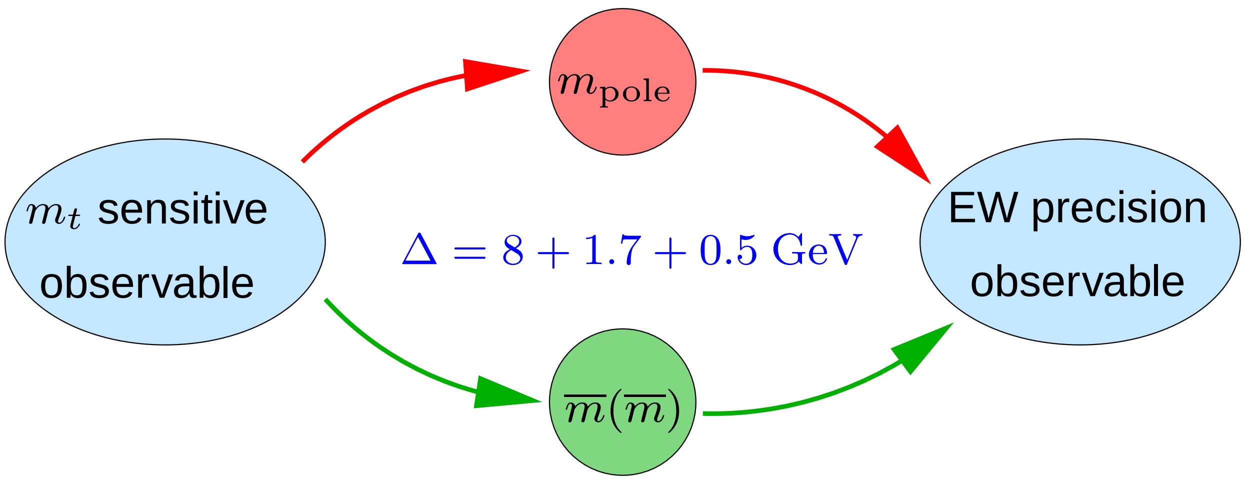
The mass is simply a parameter of the theory (renormalization scheme dependent!)
The pole mass has an intrinsic uncertainty of order $\Lambda_{\rm QCD}$ in perturbation theory (infrared sensitivity, renormalon ambiguity)

consider (fictitious) meson:

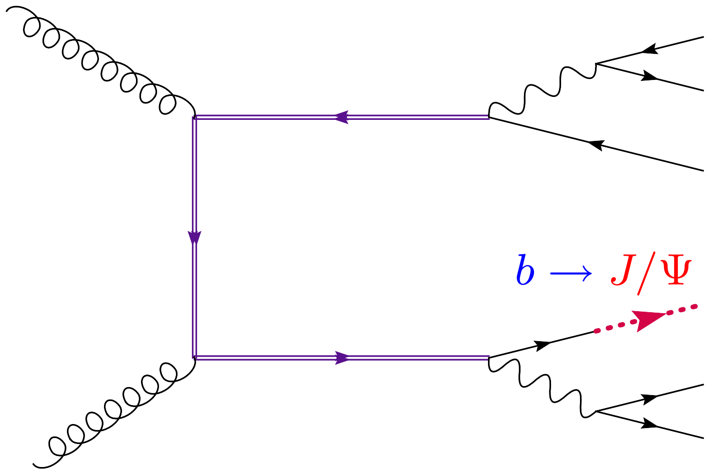
$$\underbrace{M}_{\text{well def. pole mass}} = \underbrace{m_Q}_{\text{pert. ambiguity}} + m_q + \underbrace{V(q^2)}_{\text{pert. ambiguity}}$$



There is a principal limitation of the usefulness of the pole mass
probably not relevant for LHC unless . . . (see next slide)



top mass from $t \to \ell\nu J/\Psi X$



- small branching ratio, but clean signal
- determine m_t from $M_{J/\Psi\,\ell}$
- initial claims $\delta m_t \lesssim 1\ \mathrm{GeV}$ [Kharchilava]
- updated analysis $\delta m_t \sim 1.5\ \mathrm{GeV}$, theory dominated [Chierici, Dierlamm]

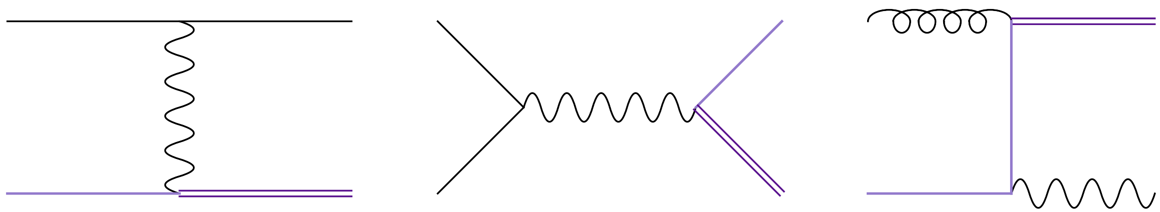
- theory error due to higher orders $\sim 0.7\ \mathrm{GeV}$ from scale variation in PYTHIA (??)
- theory error due to fragmentation function $\sim 0.5\ \mathrm{GeV}$ from variation of Peterson fragmentation function parameter (??)
- using directly moments :

$$\int dM_{b\ell}\, M_{b\ell}^n \frac{d\sigma}{dM_{b\ell}}$$

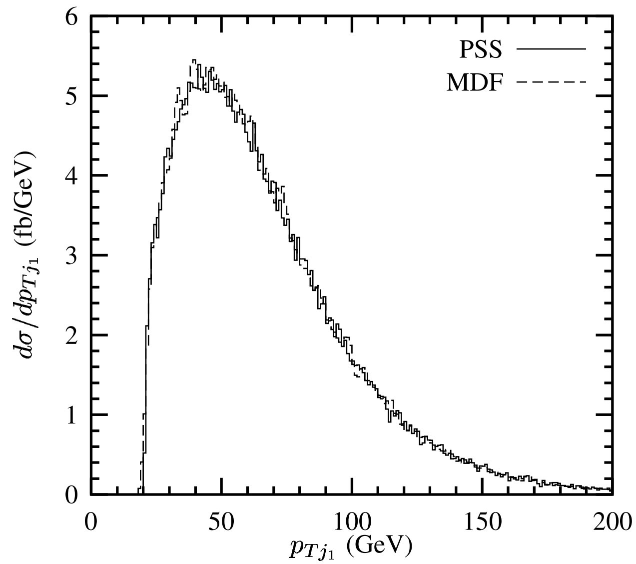
claim $\delta m_t \sim 0.5\ \mathrm{GeV}$ (???) [Nekrasov]

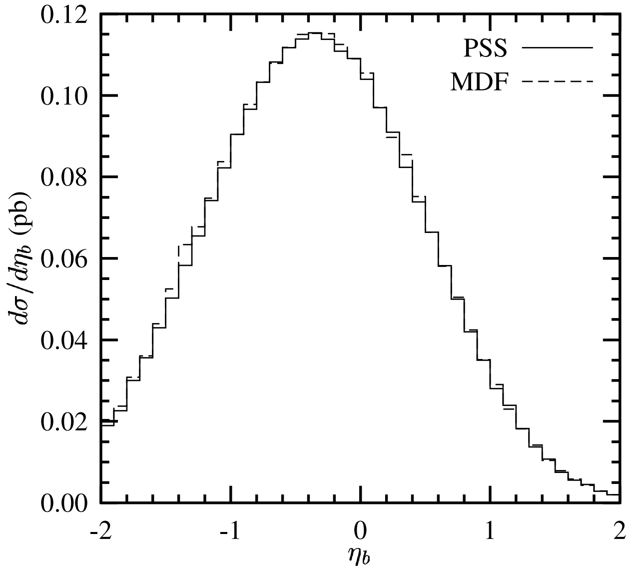
Theory status

- NLO QCD corrections, production and hadronic decay for t–, s–channel and Wt known [. . ., Harris et.al (plots below); Campbell, Ellis, Tramontano (MCMF)]



- non-factorizable corrections neglected (usually no problem)

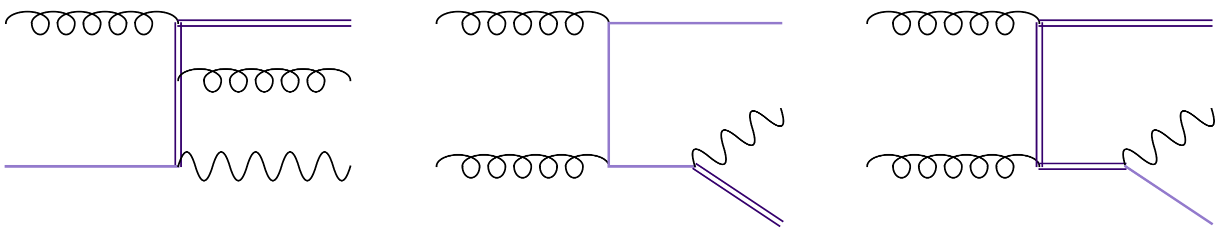




single top

Separation of Wt and $t\bar{t}$

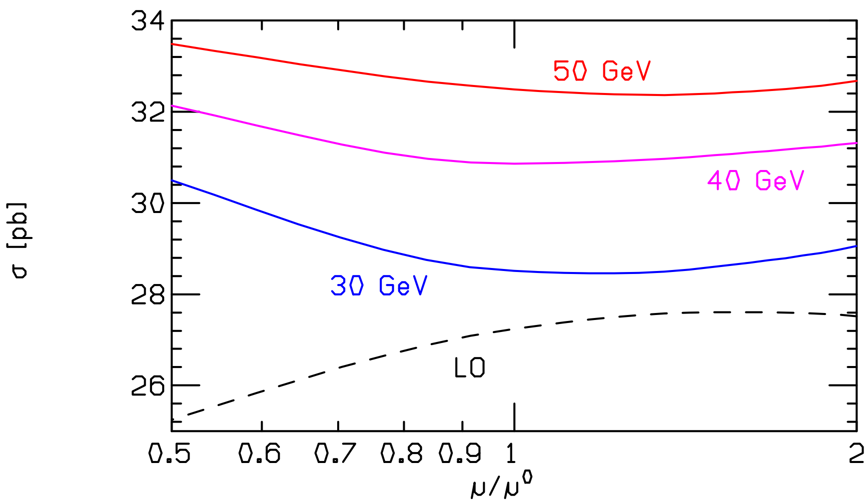
- note at NLO tW mixes with $t\bar{t}$ through inclusion of real radiation diagrams

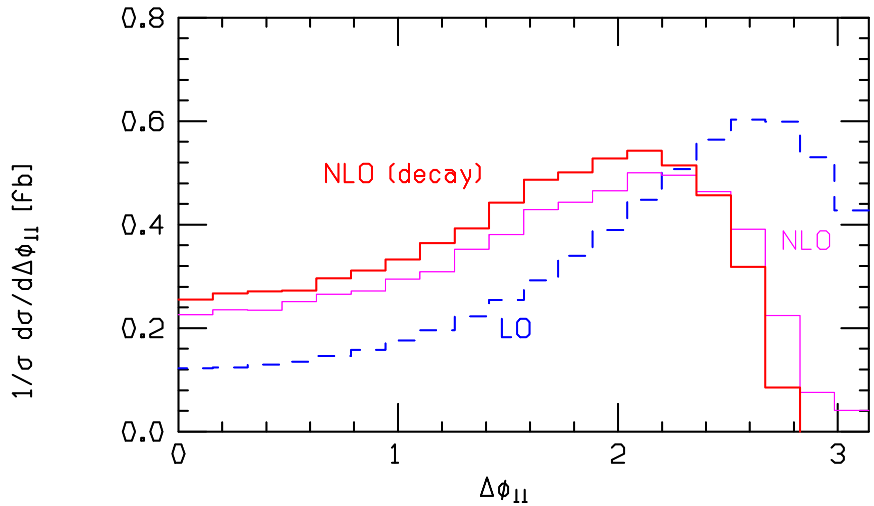


- the last diagram is the same as $t\bar{t}$ production with (one) subsequent t decay
- disentangle:
  - subtract contribution from resonant diagram [Tait]
  - make cut on invariant mass M_{Wb} to prevent top from becoming resonant [Belayev, Boos,Dudko]
  - the use p_t of b quarks as discriminating variable is preferable [Campbell, Tramontano]

single top

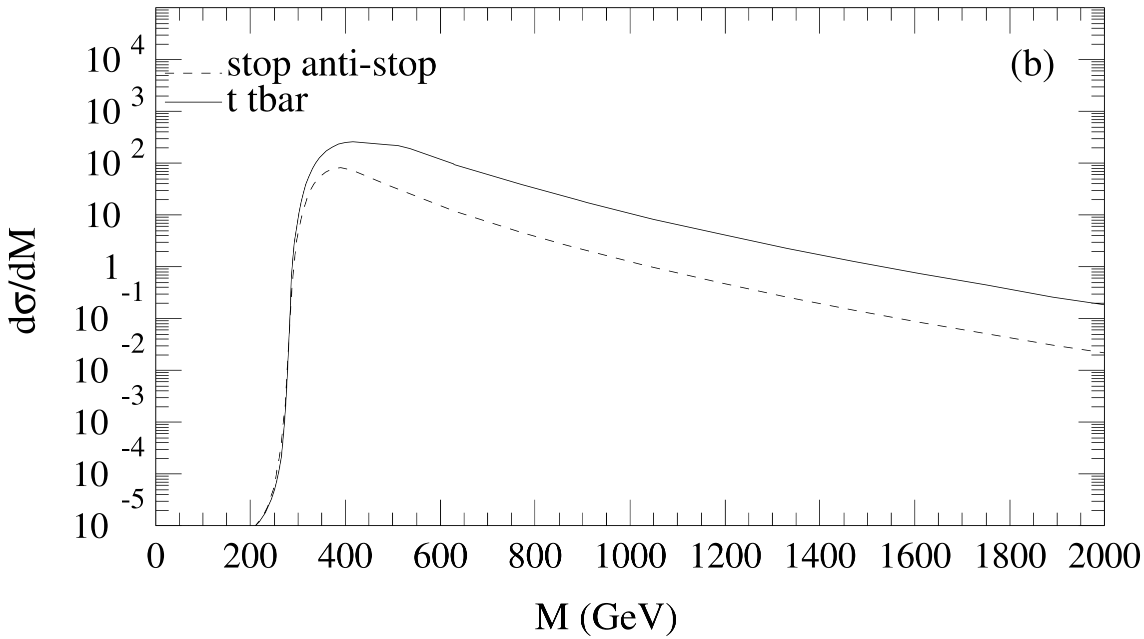
- initial state b quarks from "collinear" splitting of gluons
- resum these contributions, up to a certain factorization scale μ_F via PDF
- must choose μ_F small enough such that collinear splitting is a reasonable approximation $\mu_F \sim (m_W + m_t)/4 \sim 65\ \mathrm{GeV}$
- veto b jets with $p_t > \mu_F$ [Campbell, Tramontano]





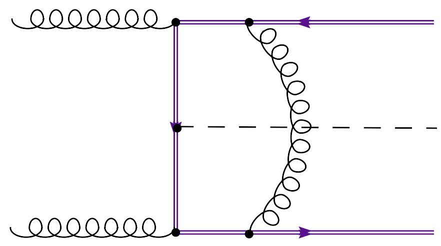
other m_t measurements?

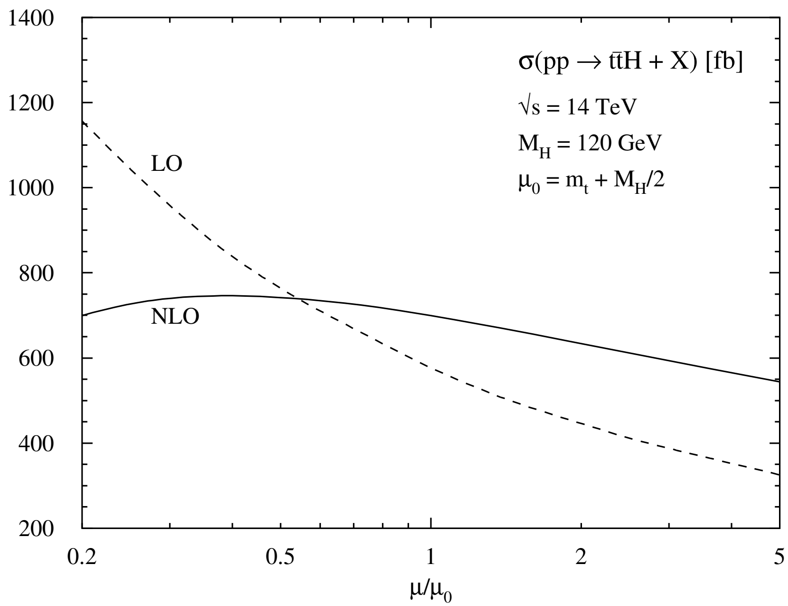
- m_t from single top production ??
  in particular associated production $pp \to tW$ would be affected by "different" non-factorizble corrections (no cross talk between two decaying top quarks)
- ratios of cross sections ??
  a smart ratio might decrease the dependence on the PDF's
  in principle preferable from theoretical point of view
- a "linear collider" measurement ??

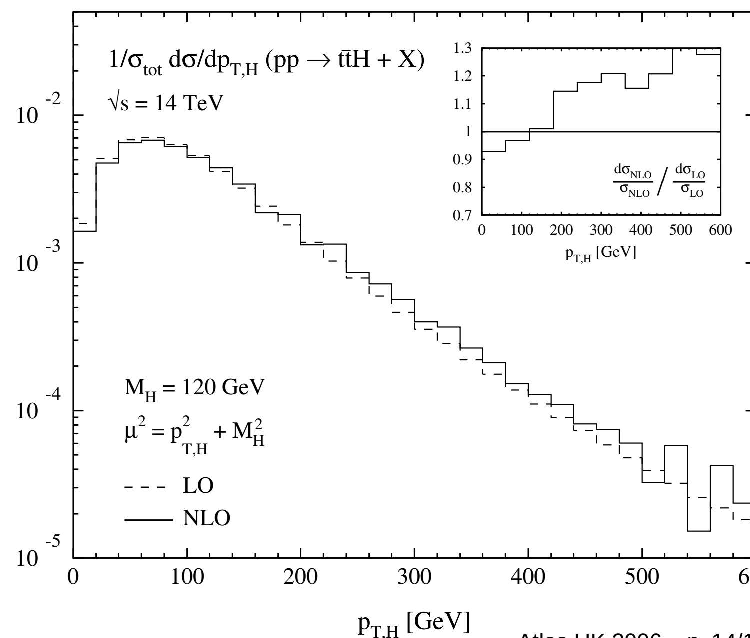


Theory status

- NLO QCD corrections available, involves computation of pentagon diagrams [Beenakker et. al. (plots below); Reina et.al.]
- reduced scale dependence
  - $\sim 20\%$ for total cross section
  - $\lesssim 30\%$ for Higgs differential distributions
  - $\lesssim 10\%$ for top differential distributions







anomalous couplings

Generalized couplings to e.g. $V \in \{\gamma, Z\}$ and W:

$$\begin{aligned} M_\mu^{(V)} &= e\gamma_\mu \left[Q_v^{(V)} F_{1v}^{(V)} + Q_a^{(V)} F_{1a}^{(V)} \gamma_5\right] \\ &+ \frac{ie}{2m_t}\sigma_{\mu\nu}k^\nu \left[Q_v^{(V)} F_{2v}^{(V)} + Q_a^{(V)} F_{2a}^{(V)} \gamma_5\right] \\ M_\mu^{(W)} &= \frac{g}{\sqrt{2}}\gamma_\mu \left[P_l F_{1l}^{(W)} + P_r F_{1r}^{(W)}\right] \\ &+ \frac{ig}{2\sqrt{2}m_t}\sigma_{\mu\nu}k^\nu \left[P_l F_{2l}^{(W)} + P_r F_{2r}^{(W)}\right] \end{aligned}$$

SM values: $F_{1v}^{(\gamma)} = F_{1v}^{(Z)} = F_{1a}^{(Z)} = F_{1l}^{(W)} = 1$

e.g. measurable value of EDM $F_{2a}^{(V)} \Rightarrow$ new physics

conclusions

- overall theory is in rather good shape
- most important one-loop corrections to most important processes are known
- one-loop corrections to 6 parton processes (e.g. $pp \to t\bar{t}jj$) still are very difficult/tedious to compute (don't expect too many in the near future)
- some formally higher order terms included via resummation (don't expect full two-loop anytime soon)
- many "small" effects require further work
- a general purpose MC for $t\bar{t}$ icluding all known effects (resummation, decay, electroweak corrections, finite width effects . . .) would be most welcome