DPG Physics School on Heavy Particles at the LHC

Theory of
Top Quark Physics

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overview	• why top physics • tops @ Tevatron, LHC and ILC • what do we want to know
$t\,\bar{t}$	• top production at (N)NLO • resummation • including the decay of top • off-shell effects
top mass	• renormalon issue with pole mass • issue with m_t from invariant mass • 'alternative' m_t determinations • m_t @ ILC
single top	• recap (resummation, decay, off-shell effects) • definition of process • 4-flavour scheme vs 5-flavour scheme

outline

forward-backward asymmetry A_{FB}

- theory vs. experiment
- Tevatron vs. LHC
- BSM effects

testing the SM

- spin correlations
- anomalous couplings vs. effective theory
- Higgs and top

conclusions

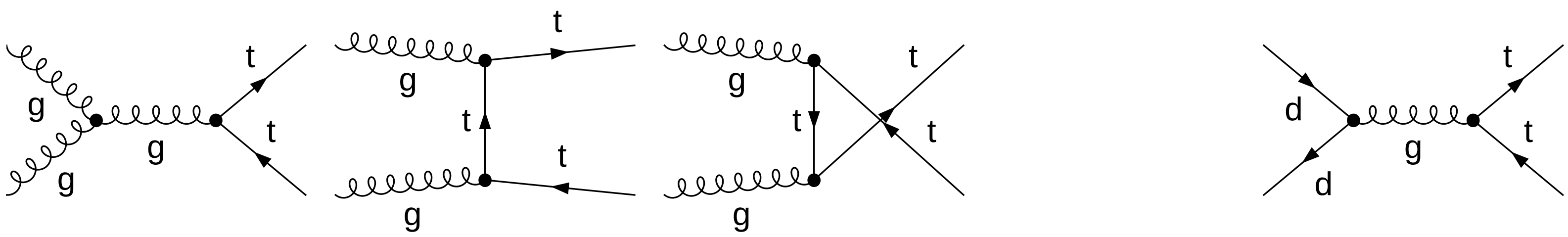
Part I

Overview

why top physics?

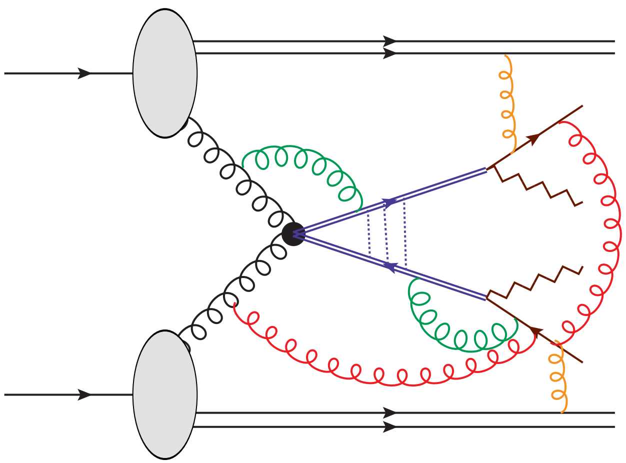
- top is a “free” quark
  - typical hadronization time governed by $\Lambda_{\rm QCD}^{-1} \sim (250\ {\rm MeV})^{-1}$
  - top lifetime $(\Gamma_t)^{-1} \sim (1.4\ {\rm GeV})^{-1}$
  - top quark does not (quite) form bound states and decays before hadronization does its dirty business
- top is relevant in many BSM scenarios
  - top has proper Yukawa coupling $y_t = \sqrt{2} m_t/v \sim 1$
  - top plays important role in EW symmetry breaking
- a lucky coincidence !!
  - top observables can be computed (hadronization not a show stopper)
  - top observables can be measured (“easy” to produce)
  - top observables are relevant (window for BSM)
- the top is the only quark that behaves properly!

  $\Longrightarrow$ It’s the white sheep in a herd of black sheep
- also input for other branches of particle physics



approximate (!)
expected / measured
SM cross sections in pb

	Tevatron	7 TeV LHC	14 TeV LHC
$t\,\bar{t}$	7	160	900
$q\,\bar{q}$	$\sim$ 90%	$\sim$ 20%	$\sim$ 10%
$g\,g$	$\sim$ 10%	$\sim$ 80%	$\sim$ 90%



- cross sections are large
- tops are seen only through their decay products $t \to W b \to \{\ell\nu, q'\bar{q}\}\, b$
- information from top quark carried over to decay products
- the full process is still far from simple

SM $t\,\bar{t}$ theory status

- fully exclusive known at $\sim$ one-loop

  electroweak corrections known [Bernreuther et.al., Kuhn et.al.]
  spin correlations included [Bernreuther et.al., Melnikov et.al.]
  non-factorizable corrections computed [Denner et.al., Bevilacqua et.al.]
  included in MC@NLO and POWHEG [Frixione, Nason, Webber . . . . . .]
  two-loop corrections on their way . . .

- inclusive cross section(s) known at $\sim$ two-loop

  two-loop nearly known [Czakon et.al, Moch et.al, . . .]
  bound-state effects computed [Hagiwara et.al., Kiyo et.al.]
  non-factorizable corrections computed [Beenakker et.al.]
  resummation of logs under control [Ahrens et.al, Beneke et.al . . .]

- further processes known at one-loop:

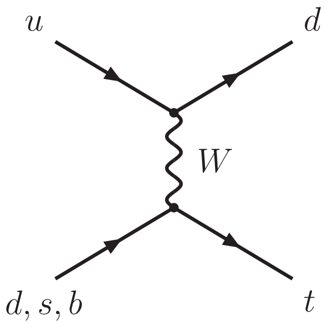
  $t\bar{t}H$ [Beenakker et.al] and $t\bar{t}j$ [Dittmaier et.al.] ; $\Rightarrow$ MC@NLO and POWHEG

  $t\bar{t}bb$ [Bredenstein et.al; Bevilacqua et.al.] and $t\bar{t}jj$ [Bevilacqua et.al.]

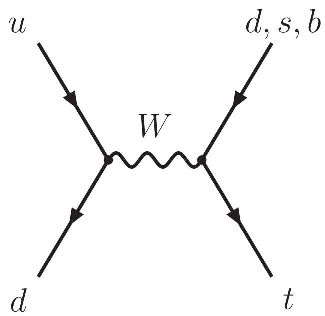
  “background” processes $V + \mathrm{jets}$

single top production

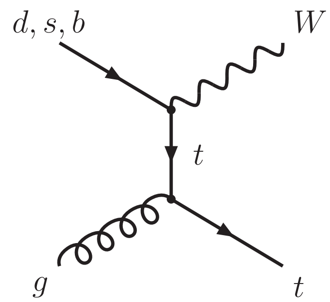
t-channel



s-channel

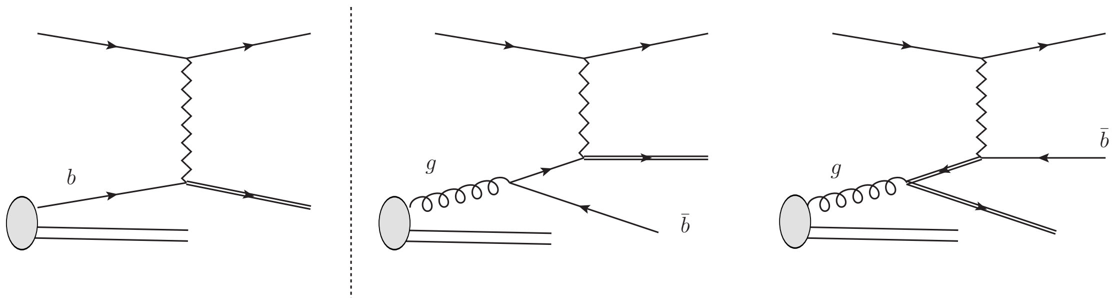


associated production



approximate (!)
expected / measured
SM cross sections in pb

	Tevatron	7 TeV LHC	14 TeV LHC
$t\ (\bar{t})$ "t"-ch	1.2	40 (20)	150 (100)
$t\ (\bar{t})$ "s"-ch	0.55	2.5 (1.4)	7 (4)
$t\,W^-$	0.15	8	45



LO 5 Flavour   LO 4 Flavour

cross sections not much smaller than for $t\bar{t}$

where does b come from?

precise definition of process not obvious beyond LO

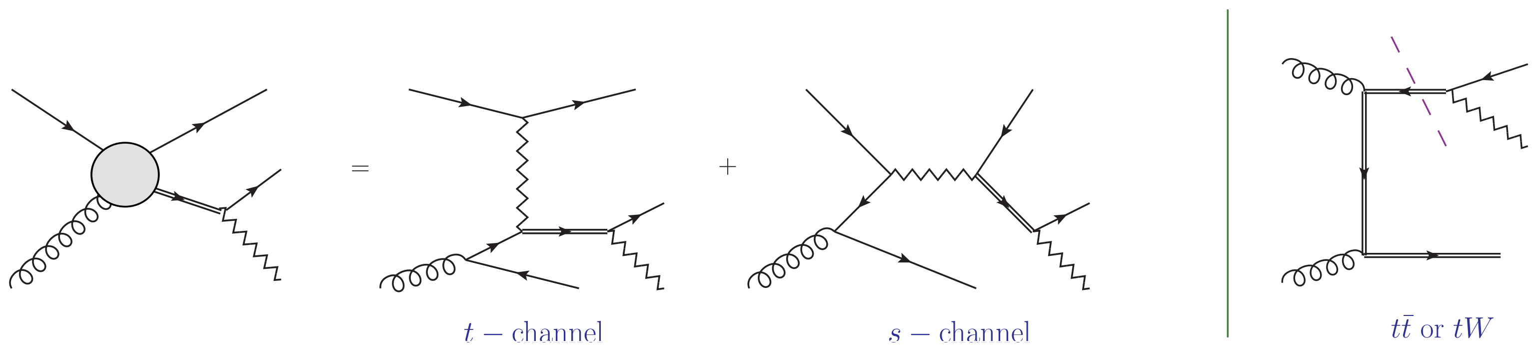
SM single top theory status

- NLO QCD corrections, production and hadronic decay for t–, s–channel and Wt known [Harris et.al; Campbell et.al; Cao et.al . . .]
- all channels included in MC@NLO and POWHEG [Frixione, Laenen, Motylinski, Alioli, Nason, Re, Webber, White . . . . . .]
- EW corrections known [Beccaria et.al; Macorini et.al]
- non-factorizable corrections known [Falgari et.al.]
- resummation of inclusive cross section [Kidonakis, Wang et.al.]
- Note: issues with definition of cross section:

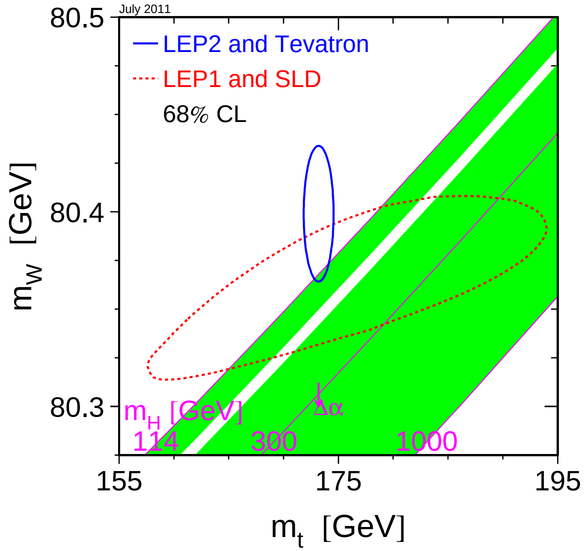
s and t channel mix (beyond LO)

$\rightarrow$ more appropriate to talk about (tJ), (tb) and (tW) cross sections

disentangling Wt vs $t\bar{t}$ non-trivial [Frixione et.al.]



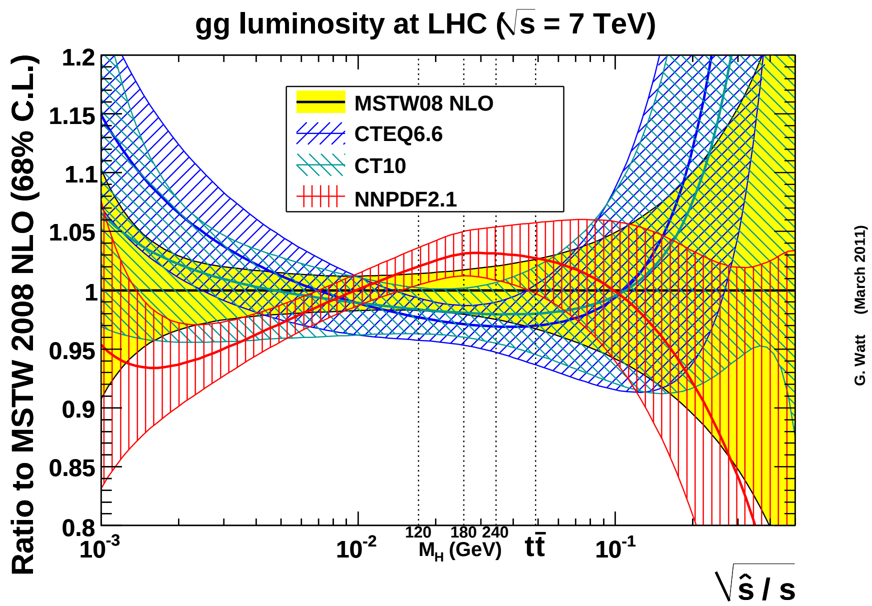
ew precision



LEP EWWG

m_t, but also V_{tb}

pdf



plot from G.Watt (HepForge)

σ_{tt}, but also single top $\sigma_t/\sigma_{\bar{t}}$

other measurements: y_t, Γ_t, A_{FB} . . . mainly as test of SM (or establishing BSM)

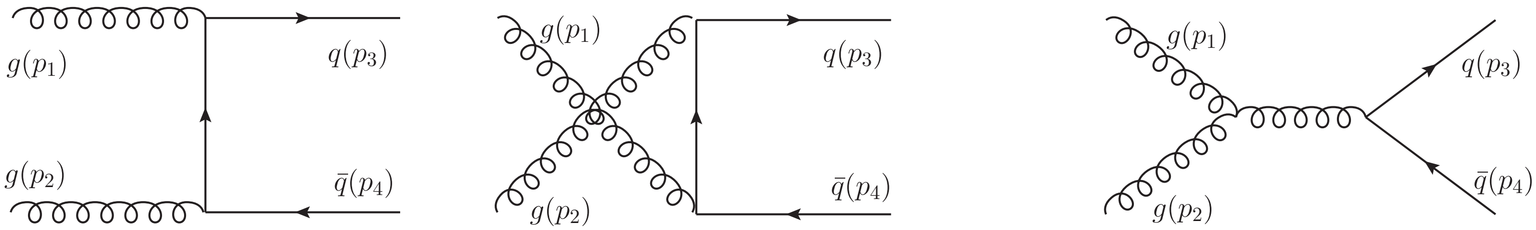
outline

e_Q; T_3; spin; $SU(N_c)$	test indirect constraints not main motivation	$t \to Wb$; $pp \to t\bar{t}\gamma$
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	$pp \to t\bar{t}H$, ILC ??
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, A_{FB}, rare decays, single top

Part II

Top Pair Production

Compute matrix element squared $\mathcal{M}^{(0)} \equiv \mathcal{A}^{(0)}\mathcal{A}^{(0)\,*}$



$\sim (T^{a_1}T^{a_2})_{i_3\,i_4}$ $\sim (T^{a_2}T^{a_1})_{i_3\,i_4}$ $\sim (T^{a_1}T^{a_2})_{i_3\,i_4} - (T^{a_2}T^{a_1})_{i_3\,i_4}$

colour:

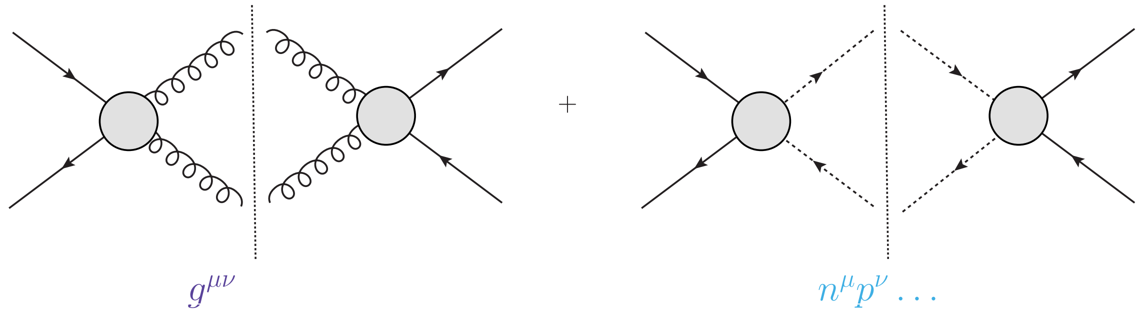
$$\mathcal{A}^{(0)} = (T^{a_1}T^{a_2})_{i_3\,i_4} A_{12}(s,t,u) + (T^{a_2}T^{a_1})_{i_3\,i_4} A_{21}(s,t,u)$$

$$\mathcal{M}^{(0)} = \underbrace{\frac{(N_c^2-1)^2}{4\,N_c}}_{\text{leading colour}} \left(|A_{12}|^2 + |A_{21}|^2\right) - \underbrace{\frac{(N_c^2-1)}{4\,N_c}}_{\text{subleading colour}} \left(A_{12}\,A_{21}^* + A_{12}^*\,A_{21}\right)$$

Structure of (sub)amplitude: $A_{\#\#} = \bar{u}_\alpha(p_3) v_\beta(p_4) \varepsilon^\mu(p_1) \varepsilon^\nu(p_2)\,(a_{\mu\nu})_{\alpha\beta}$

tree level

squaring the amplitude



conventional:

$$\sum_{\text{pols}} \varepsilon^\mu(p_i)\varepsilon^{\nu *}(p_i) \to -g^{\mu\nu} + \underbrace{\frac{n_i^\mu p_i^\nu + p_i^\mu n_i^\nu}{(n_i p_i)} - \frac{n_i^2 p_i^\mu p_i^\nu}{(n_i p_i)^2}}_{n_i^\mu \text{ arbitrary}}; \quad \sum_{\text{pols}} u_\alpha(p)\bar{u}_\beta(p) = (\not{p} + m)_{\alpha\beta};$$

QED: can drop n^μ parts, since $p^\mu_{3/4}\, a_{\mu\nu} = 0$

QCD: $p^\mu_{3/4}\, a_{\mu\nu} \neq 0$, but result independent of $n^\mu_{3/4}$.
alternatively, drop n^μ parts but include ghost diagrams in squaring the amplitude.

In D dimensions we get (including mass terms) e.g.

$$|a_{12}|^2 = -\frac{2\,\alpha_s^2}{s^2 t^2}\left((D-2)t(s+t)\left((D-2)s^2 + 4st + 4t^2\right) + 16m^4 s^2 + 16m^2 st(s+t)\right)$$

helicity method:

fix helicities of external particles and express amplitude in terms of spinor inner products:

$\langle ij\rangle = \langle p_i - |p_j+\rangle \equiv \bar{u}(p_i,-)u(p_j,+)\,;\quad [ij] = \langle p_i + |p_j-\rangle \equiv \bar{u}(p_i,+)u(p_j,-)$) ;

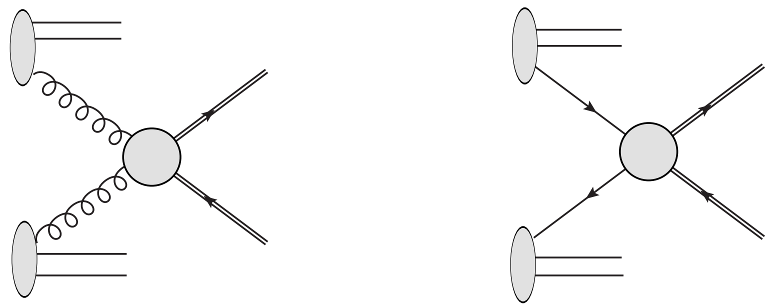
for massive quarks: $p = p^\flat + \dfrac{m_t^2}{2p^\flat\cdot\eta}\,\eta_p$ then $u_\pm(p,m) = \dfrac{\not{p}+m}{\langle p^\flat \mp |\eta_p\pm\rangle}|\eta_p\pm\rangle$

for gauge bosons use $\varepsilon^\mu(p,\pm) = \pm\dfrac{\langle p\pm|\gamma^\mu|n\pm\rangle}{\sqrt{2}\langle n\mp|p\pm\rangle}$

- lightlike reference momentum n^μ drops out for gauge invariant quantities
- very compact results, e.g: $a_{12}(g_1^-, g_2^-, t_3^+, \bar{t}_4^+) = ig^2\dfrac{m_t^3\langle\eta_3\eta_4\rangle[12]}{\langle 12\rangle\langle 1|3|1]\langle 3^\flat\eta_3\rangle[4^\flat\eta_4]}$
- simplifications (due to gauge cancellations) at amplitude level
- sum over all (non-vanishing) helicity configurations

$$|a_{12}|^2 = \sum_{h_i}|a_{12}(g_1^{h_1}, g_2^{h_2}, q_3^{h_3}, \bar{q}_4^{h_4})|^2$$

- have to treat external particles in 4 dimensions hadronic cross section



$$d\sigma_{H_1(P_1)H_2(P_2)\to t\bar{t}} = \int_0^1 dx_1\, f_{g/H_1}(x_1,\mu_F) \int_0^1 dx_2\, f_{g/H_2}(x_2,\mu_F)\, d\hat{\sigma}_{g(x_1P_1)g(x_2P_2)\to t\bar{t}}(\alpha_s(\mu_R)\ldots) + \ldots$$

μ_F: factorization scale; μ_R: renormalization scale

$f_{g/H_1}(x_1,\mu_F)$: parton distribution functions

$d\hat{\sigma}$: hard partonic cross section, at tree level $d\hat{\sigma}^{(0)} = d\sigma^{(0)}$

there are additional partonic processes for $H_1H_2 \to t\bar{t}$ beyond LO ($qg \to t\bar{t}q$)

$$\begin{aligned} d\sigma_{H_1H_2\to t\bar{t}} &= \int_0^1 dx_1\, f_{g/H_1}(x_1) \int_0^1 dx_2\, f_{g/H_2}(x_2)\, d\hat{\sigma}_{gg\to t\bar{t}} \\ &+ \sum_{q\in\{u,d,c,s,(b)\}} \int_0^1 dx_1\, f_{q/H_1}(x_1) \int_0^1 dx_2\, f_{\bar{q}/H_2}(x_2)\, d\hat{\sigma}_{q\bar{q}\to t\bar{t}} + \{q \leftrightarrow \bar{q}\} \end{aligned}$$

one loop

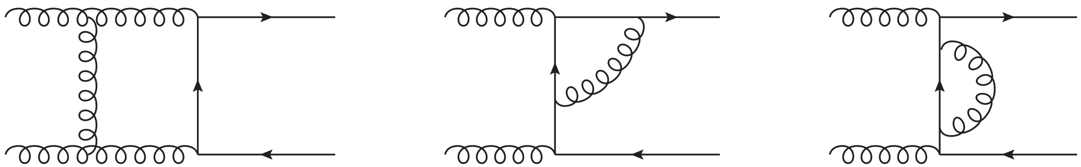
Tree-level: $d\hat{\sigma}^{(0)} = d\sigma^{(0)}$

1-loop: $d\hat{\sigma}^{(1)} = \underbrace{d\sigma^{(0)}}_{\mathcal{O}(\alpha_s^2)} + \underbrace{d\sigma^{\mathrm{virt}} + d\sigma^{\mathrm{real}} + d\sigma^{\mathrm{coll}}}_{\mathcal{O}(\alpha_s^3)}$

- All $\mathcal{O}(\alpha_s^3)$ are (in general) divergent and only the sum is finite (for properly defined, i.e. infrared-safe observables).
- Regularize divergences by working in $D = 4 - 2\epsilon$ dimensions: $\int d^4k \to \mu_R^{2\epsilon} \int d^D k$; singularities $\to$ poles $1/\epsilon$ (dimensional regularization).
- Other possibilities in principle, but not in practice.
- Strictly speaking, only internal momenta have to be D dimensional. There is some freedom how to treat external particles (recall helicity method needs these to be 4 dimensional)
- different schemes (variant of dimensional regularization) possible but observable is independent of this choice

one loop

virtual corrections



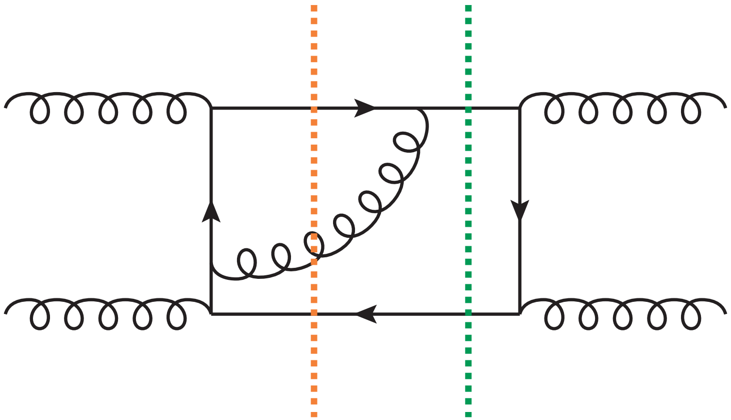
amplitude:

$$\mathcal{A}^{(1)} = (T^{a_1}T^{a_2})_{i_3\, i_4} \left(\frac{N_c}{2} A_{12}^{L}(s,t,u) + \frac{1}{2N_c} A_{12}^{S}(s,t,u) + \frac{N_F}{2} A_{12}^{F}(s,t,u) \right)$$
$$+ \quad \{12 \leftrightarrow 21\}$$
$$+ \quad \delta_{i_3 i_4} \frac{1}{2} \mathrm{Tr}\,(T^{a_1}T^{a_2}) \left(A_{\mathrm{tr}}(s,t,u) + \frac{N_F}{N_c} A_{\mathrm{tr}}^{F}(s,t,u) \right)$$

$$A_{12}^{L} = \frac{1}{\epsilon^2} \left[c_s \left(\frac{-s}{\mu^2} \right)^{-\epsilon} + c_t \left(\frac{-t}{\mu^2} \right)^{-\epsilon} + \ldots \right] + \frac{1}{\epsilon}\, \text{mess}(\log) + \text{finite mess}(\log^2, \mathrm{Li}_2)$$

- UV singularities ($1/\epsilon$ per loop) $\Longrightarrow$ renormalization
- soft and final-sate collinear sing. ($1/\epsilon$ per loop) $\Longrightarrow$ combine with real corrections
- soft-collinear singularities ($1/\epsilon^2$ per loop) $\Longrightarrow$ combine with real corrections
- initial-sate collinear sing. ($1/\epsilon$ per loop) $\Longrightarrow$ combine with collinear counterterm $d\sigma^{\mathrm{coll}}$

virtual corrections



“squaring” the amplitude:

$$\mathcal{A}_{t\bar{t}} = \underbrace{\mathcal{A}^{(0)}_{t\bar{t}}}_{\sim\alpha_s} + \underbrace{\mathcal{A}^{(1)}_{t\bar{t}}}_{\sim\alpha_s^2} + \ldots \Longrightarrow \mathcal{M}^{(0)} = |\mathcal{A}^{(0)}_{t\bar{t}}|^2 \sim \alpha_s^2 \text{ and } \mathcal{M}^{(1)} = 2\,\mathrm{Re}\left(\mathcal{A}^{(1)}_{t\bar{t}}\mathcal{A}^{(0)\,*}_{t\bar{t}}\right) \sim \alpha_s^3$$

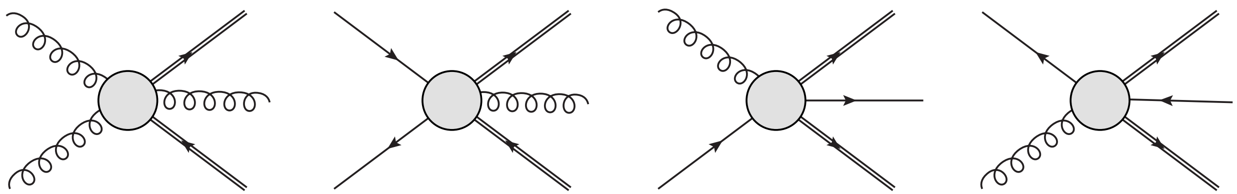
the “same” diagram with a different cut is part of the real corrections

$$\mathcal{M}^{(0)}(gg \to t\bar{t}g) = |\mathcal{A}^{(0)}_{t\bar{t}g}|^2 \sim \alpha_s^3$$

Real corrections

$$d\sigma^{\rm real} = \sum_{\bar a_i} \int d\Phi_3(p_1,p_2;p_3,p_4,p_5)\langle \mathcal{M}^{(0)}(a_1,a_2;\bar a_3,\bar a_4,\bar a_5)\rangle$$

processes: $\mathcal{M}^{(0)}(g,g;t,\bar t,g)$, but also new partonic channels $\mathcal{M}^{(0)}(q,g;t,\bar t,q)$ etc. calculation of $\mathcal{M}^{(0)}$ as for tree-level.



$\mathcal{M}^{(0)}$ has no $1/\epsilon$ poles, but has (non-integrable) singularities in some regions of phase space.

$$\underbrace{\int d\Phi_{n-1}\left(\mathcal{M}^{(0)} - \sum_{\rm sing} \mathcal{M}^{\rm appr}\right)}_{\text{finite}} + \underbrace{\int d\Phi_{n-1} \sum_{\rm sing} \mathcal{M}^{\rm appr}}_{\text{use dim reg}}$$

Real corrections naive example (e.g. gluon g soft, $x \sim$ energy)

$$\mathcal{A}(g,g,t,\bar{t},g) \overset{g\to 0}{\sim} \frac{1}{\langle pg\rangle}\mathcal{A}(g,g,t,\bar{t}) + \mathcal{A}^{\rm rem} \sim \frac{1}{\sqrt{x}}\mathcal{A}(g,g,t,\bar{t}) + \mathcal{A}^{\rm rem}$$

$$\mathcal{M}(g,g,t,\bar{t},g) \sim \frac{1}{x}\mathcal{M}(g,g,t,\bar{t}) + \frac{1}{\sqrt{x}}\mathcal{M}^{\rm rem}$$

$$\int d\Phi_3^D\,\mathcal{M}(g,g,t,\bar{t},g) = \underbrace{\int d\Phi_3^4\left(\mathcal{M}(g,g,t,\bar{t},g) - \frac{1}{x}\mathcal{M}(g,g,t,\bar{t})\right)}_{\text{term 1}} + \underbrace{\int d\Phi_3^D\,\frac{1}{x}\mathcal{M}(g,g,t,\bar{t})}_{\text{term 2}}$$

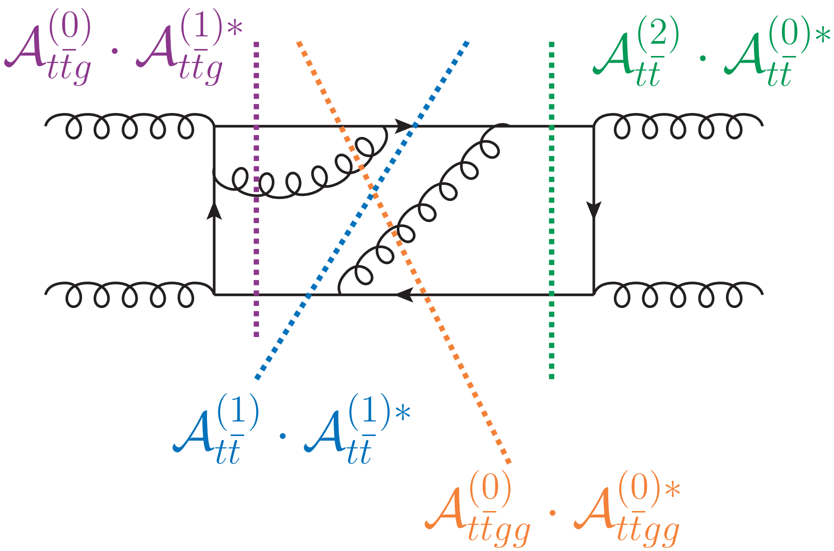
term 1: evaluate numerically in 4 dimensions, square root singularities !

term 2: $\int x^{-\epsilon}\,\frac{1}{x}\int d\Phi_2^4\,\mathcal{M}(g,g,t,\bar{t}) = -\frac{1}{\epsilon}\int d\Phi_2^4\,\mathcal{M}(g,g,t,\bar{t})$

there are several well established (and automatised) general procedures

$\Longrightarrow$ FKS, Dipole subtraction . . .

nnlo contributions



- at NNLO there are double real, virtual, real-virtual and one-loop squared contributions
- separate parts have singularities $1/\epsilon^n$ with $n \leq 4$
- singularities cancel in the sum of all contributions
- no general procedure yet for double-real integration, but many partial results
- $q\bar{q} \to t\bar{t}$ total cross section known (numerically) at NNLO [Czakon et al.]

$t\bar{t}$ total cross section

- total cross section (LHC dominated by $\hat{\sigma}_{gg}$, beyond LO we also need $\hat{\sigma}_{qg}$)

$$\hat{\sigma}_{ij} = \hat{\sigma}_{ij}^{(0)} \left[1 + \frac{\alpha_s}{4\pi} \hat{\sigma}_{ij}^{(1)} + \frac{\alpha_s^2}{(4\pi)^2} \hat{\sigma}_{ij}^{(2)} + \ldots \right]$$

- NLO QCD (and EW) corrections known [Dawson et.al.; Beenakker et.al.; Kao, Wackeroth, Bernreuther et.al; Kühn, Scharf, Uwer . . .]

$$\hat{\sigma}_{ij}^{(1)} = \underbrace{\frac{a_{ij}^{(1,-1)}}{\beta}}_{\text{Coulomb}} + \underbrace{b_{ij}^{(1,2)} \log^2 \beta + b_{ij}^{(1,1)} \log \beta}_{\text{soft gluon}} + c_{ij}^{(1)}$$

- NNLO QCD corrections not (yet) fully known [Czakon et.al, Moch et.al, Beneke et.al, Ahrens et.al, Körner et.al. . . . (Hathor)]

$$\hat{\sigma}_{ij}^{(2)} = \underbrace{\frac{\#}{\beta^2} + \frac{\# \log^2 \beta + \# \log \beta + \#}{\beta}}_{\text{Coulomb}} + \underbrace{\# \log^4 \beta + \# \log^3 \beta + \ldots}_{\text{soft gluon}} + c_{ij}^{(2)}$$

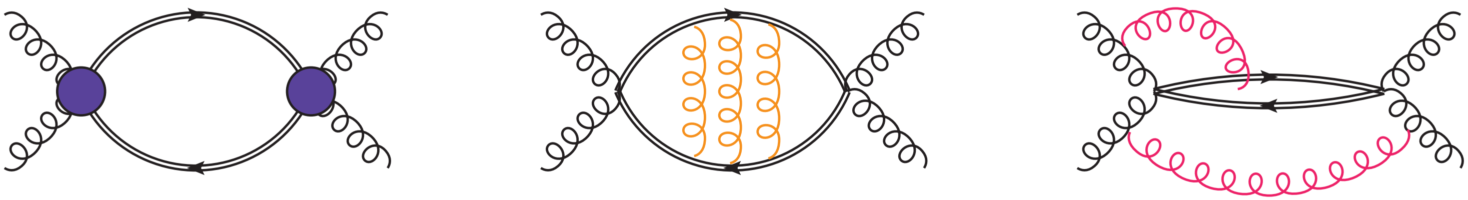
- problematic terms from threshold and soft gluon region $\sqrt{1 - 4m_t^2/s} \equiv \beta \to 0$

resummation

enhancements from special kinematic regions $\Longrightarrow$ order by order in α_s not sufficient

- in threshold region $\sqrt{1-4m_t^2/s} \equiv \beta \to 0$
  - "bound state" effects $(\alpha_s/\beta)^n$, can be resummed [Fadin, Khoze; Hagiwara et.al, Kiyo et.al, Beneke et.al]
  - resummation of soft logs $\alpha_s^n \log^{2n} \beta$, initially to NLL now NNLL and partly NNNLL [Bonciani, Catani, Mangano, Mitov, Nason, Czakon et.al., Beneke et.al., Ahrens et.al., Kidonakis, ...]
- note: cross section not necessarily dominated by small β, can use different resummation parameter (done at NNLL)
  - standard: $\beta \to 0 \Rightarrow \alpha_s^n \ln^m \beta$ with $m < 2n$
  - invariant mass: $1-z \equiv 1 - M^2/\hat{s} \to 0 \quad \Rightarrow \quad \alpha_s^n \frac{\ln^m(1-z)}{(1-z)}$ with $m < 2n-1$
  - SPI: $s_4 \equiv p_X^2 - m_t^2 \to 0 \quad \Rightarrow \quad \alpha_s^n \frac{\ln^m(s_4/m_t)}{s_4}$ with $m < 2n-1$
- recover total cross section by integration
  $\Rightarrow$ treatment of formally subleading terms are numerically relevant
- approximate "NNLO" cross section [Aliev et.al. (Hathor), Ahrens et.al, Beneke et.al, Kidonakis . . .]

structure of higher-order corrections: hard, Coulomb and soft



study either in Mellin space $\sigma_{t\bar{t}}(N) \equiv \int_0^1 d\rho\, \rho^{N-1} \sigma_{t\bar{t}}(\rho)$ with $\rho \equiv \frac{s}{4m_t^2}$

or directly in momentum space via SCET

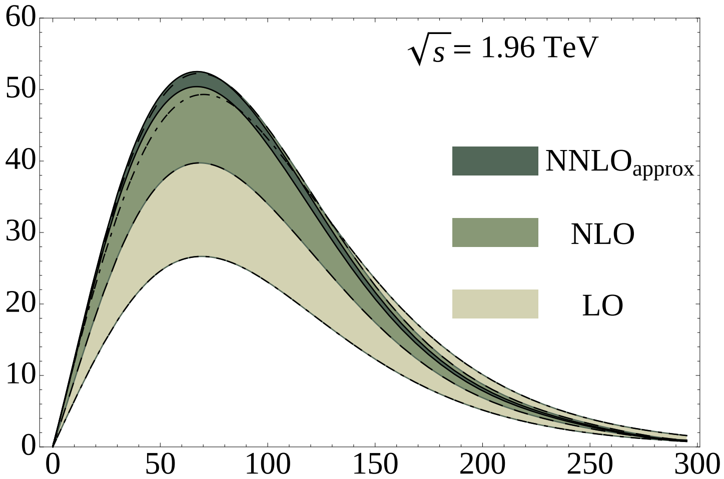
cross section factorizes (into product in Mellin space and convolution in SCET)

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{(h)} \otimes \underbrace{\sigma_{t\bar{t}}^{(Coul)}}_{(\alpha_s/\beta)^n} \otimes \underbrace{\sigma_{t\bar{t}}^{(s)}}_{\log\beta}$$

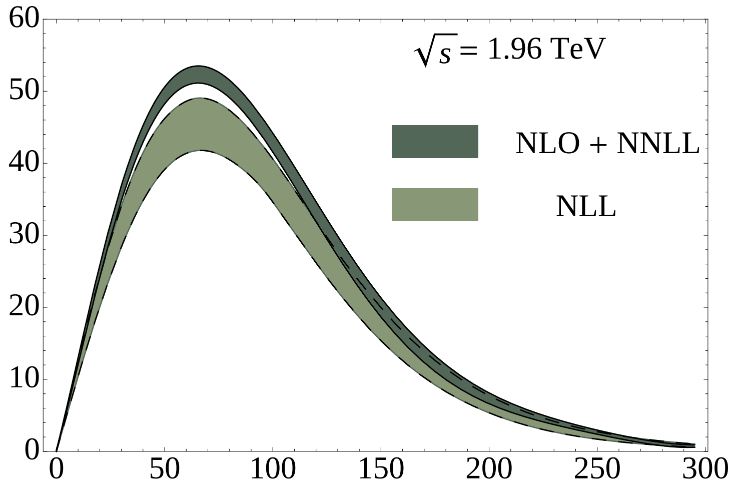
$\sigma_{t\bar{t}}^{(Coul)}$ only in threshold expansion, but $\sigma_{t\bar{t}}$ at LHC/Tev not dominated by small β.

inverse Mellin transform needs prescription to avoid Landau pole, or re-expansion of resummed expression to certain order in perturbation theory comparison fixed-order vs. resummed cross section for p_t [Ahrens et al. 1103.0550]

fixed order

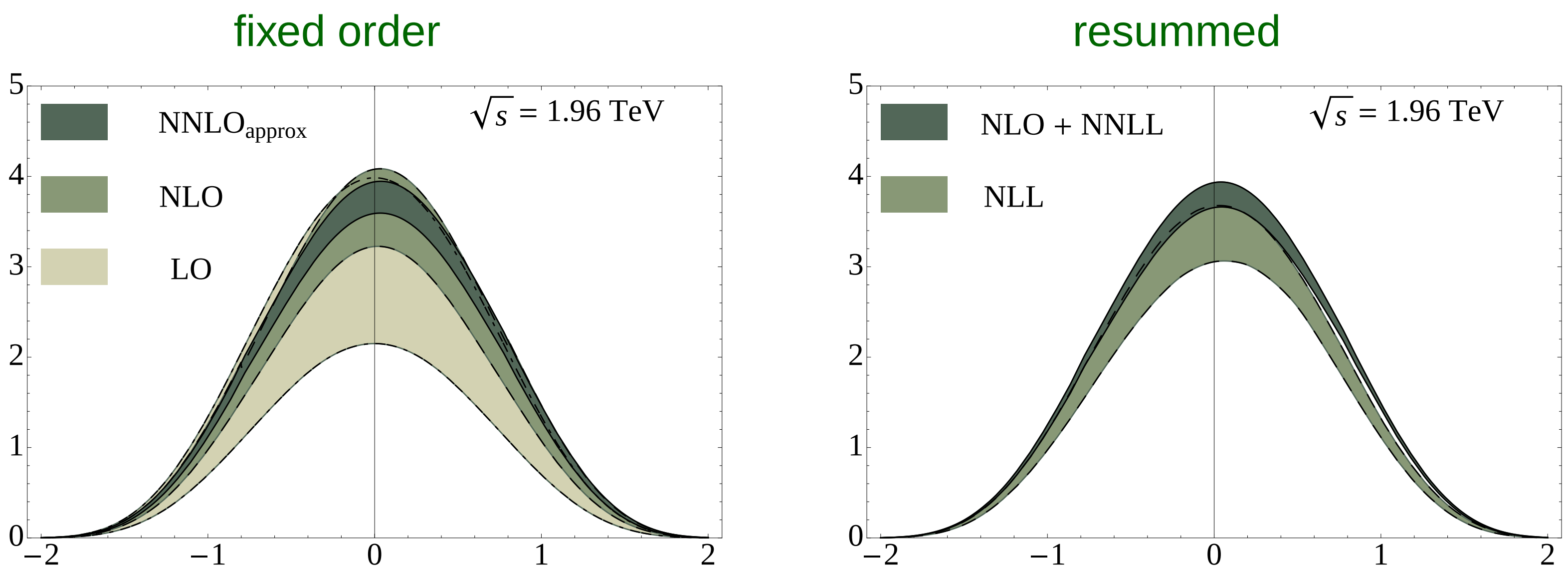


resummed



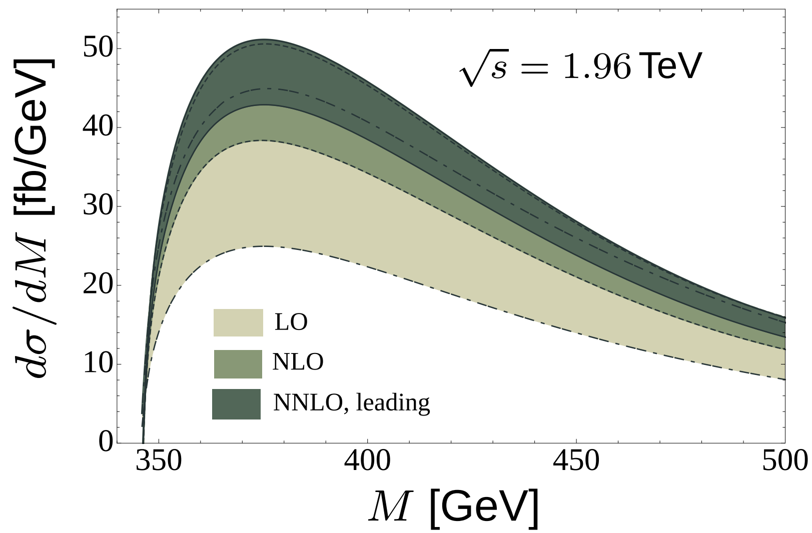
- no large numerical shift in distributions
- scale dependence substantially reduced $\Longrightarrow$ more reliable predictions
- error estimate via scale dependence more questionable than ever
  - scale dependence enters via logs, but higher-order terms also have constants
  - scale dependence is an estimate of importance of missing logs
  - higher-order logs can be predicted and resummed, but constants are still missing

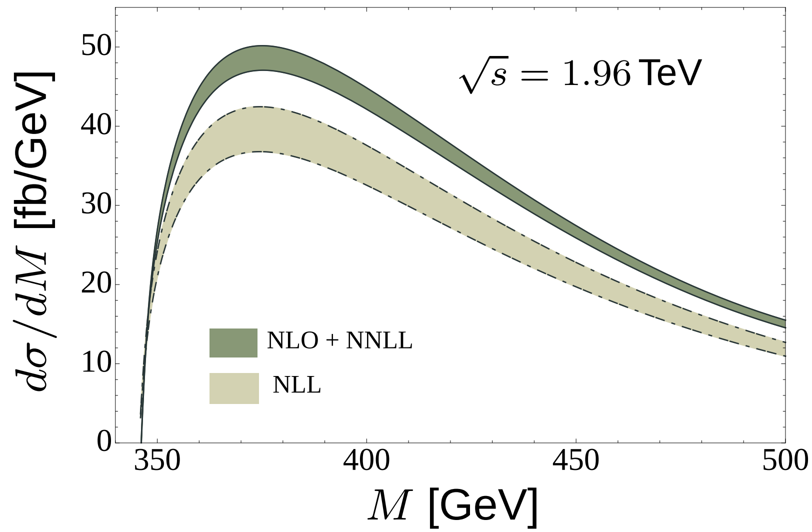
comparison fixed-order vs. resummed cross section for y_t [Ahrens et al. 1103.0550]

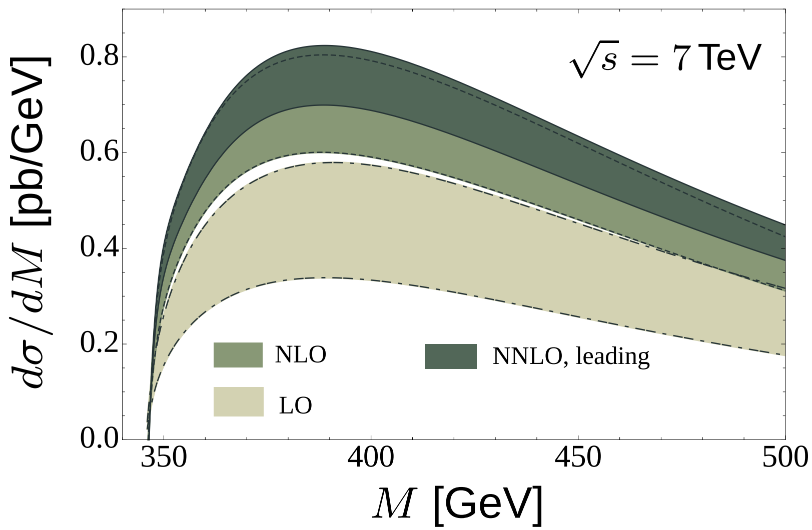


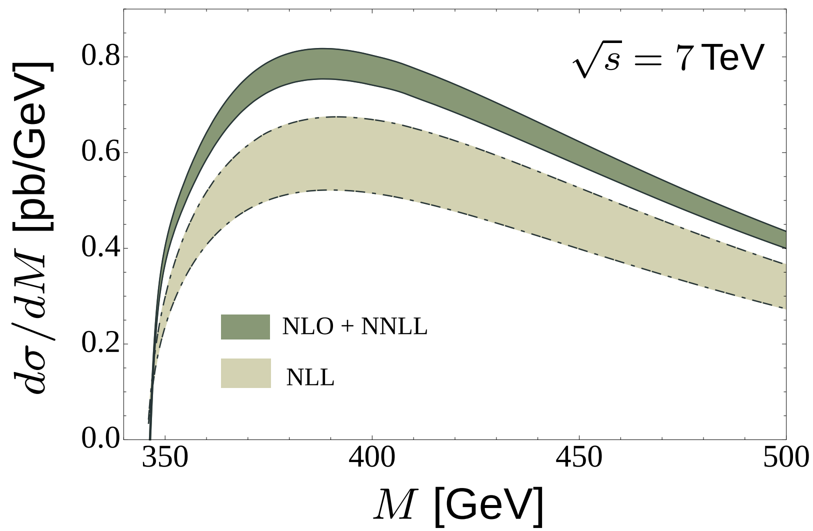
- similar picture as for p_t distribution
- neither resummation nor approximate (!!) NNLO have a large effect
- NLO prediction seems to be fairly reliable but full NNLO still missing!!
- impact on A_{FB} $\Longrightarrow$ later

Resummation of logs: for invariant mass [Ahrens et.al. arXiv:1003.5827]









bound-state effects

- near threshold Coulomb potential is dominating effect:

  colour singlet: $V(r) \simeq -\alpha_s \dfrac{C_F}{r}$ attractive

  colour octet: $V(r) \simeq -\alpha_s \dfrac{C_F - C_A/2}{r}$ repulsive

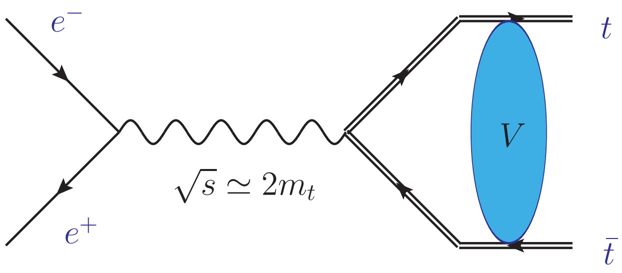
- for $\Gamma_t \to 0$ collections of bound states (as for bottom), for $\Gamma_t \simeq 1.4\ \mathrm{GeV}$ a single “bump” in invariant mass remains.
- resummation of $(\alpha/\beta)^n$ (from Coulomb potential $\to$ “bound-state” effects) [Hagiwara et.al., Kiyo et.al.] results in modification of invariant mass spectrum
- effect small for colour octet, i.e. Tevatron ($q\bar{q}$ is pure octet at LO), but “large” (for a theorist) at the LHC
- “bump” is impossible to be seen, but there is an effect on total cross section (threshold expansion $\sigma_{t\bar{t}}^{(Coul)}$)

Top threshold scan at linear collider

top pair produced near threshold

$E \equiv \sqrt{s} - 2m \ll m$

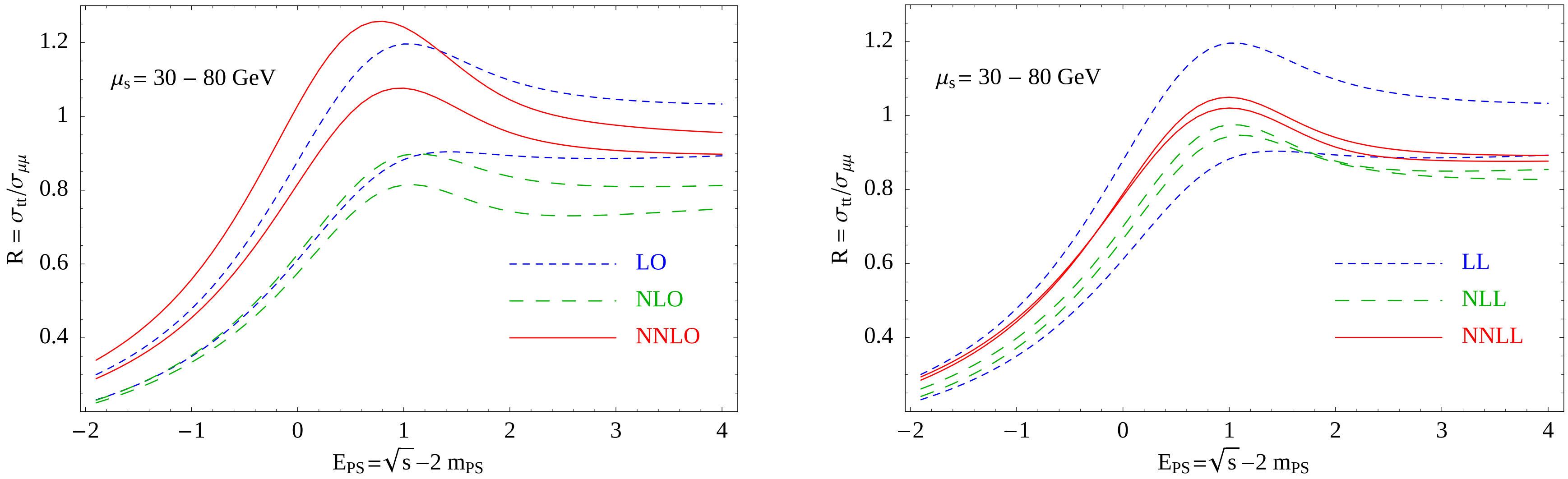
non-relativistic $\longrightarrow$ NRQCD



- lifetime for top $\tau \simeq 1/\Gamma_t \simeq 5 \times 10^{-25}$ s
- typical hadronization time $\tau_{\rm had} \simeq 1/\Lambda_{\rm QCD} \simeq 2 \times 10^{-24}$ s
- $\tau < \tau_{\rm had} \Rightarrow$ top decays before it forms hadrons
- Schrödinger eq: $\left(\frac{\Delta}{m^2} - \frac{\alpha_s C_F}{r} + \delta V - (E + i\Gamma_t)\right) G(\vec{r}, \vec{r}\,', E) = \delta(\vec{r} - \vec{r}\,')$
- poles (bound states) become a bump (would-be bound state)
- position of bump $\Rightarrow$ determination of mass
- height and width of bump $\Rightarrow$ determination of Γ_t
- typical scale: $\mu \simeq 2\, m\, v \simeq 2 \left(m \sqrt{E^2 + \Gamma_t^2}\right)^{1/2} \gtrsim 30$ GeV $\Rightarrow$ perturbation theory

Top threshold scan at linear collider [Pineda, AS]

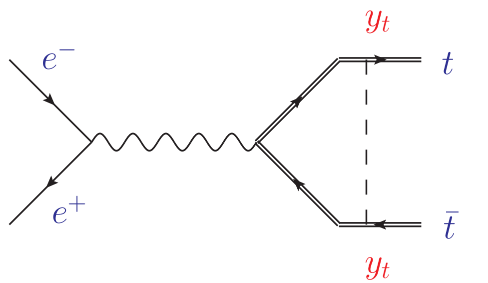
no resummation of $\log v$ — with resummation of $\log v$



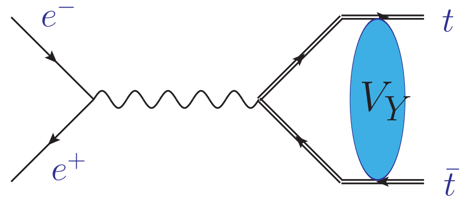
- normalization of cross section much more stable after resummation
- smaller scale dependence, smaller size of corrections
- potential to measure (well defined) top mass to an accuracy of $\delta m_t \simeq 50\ \mathrm{MeV}$
- potential for a precise measurement of Γ_t and maybe even the Yukawa coupling

$t\bar{t}$ threshold at linear collider

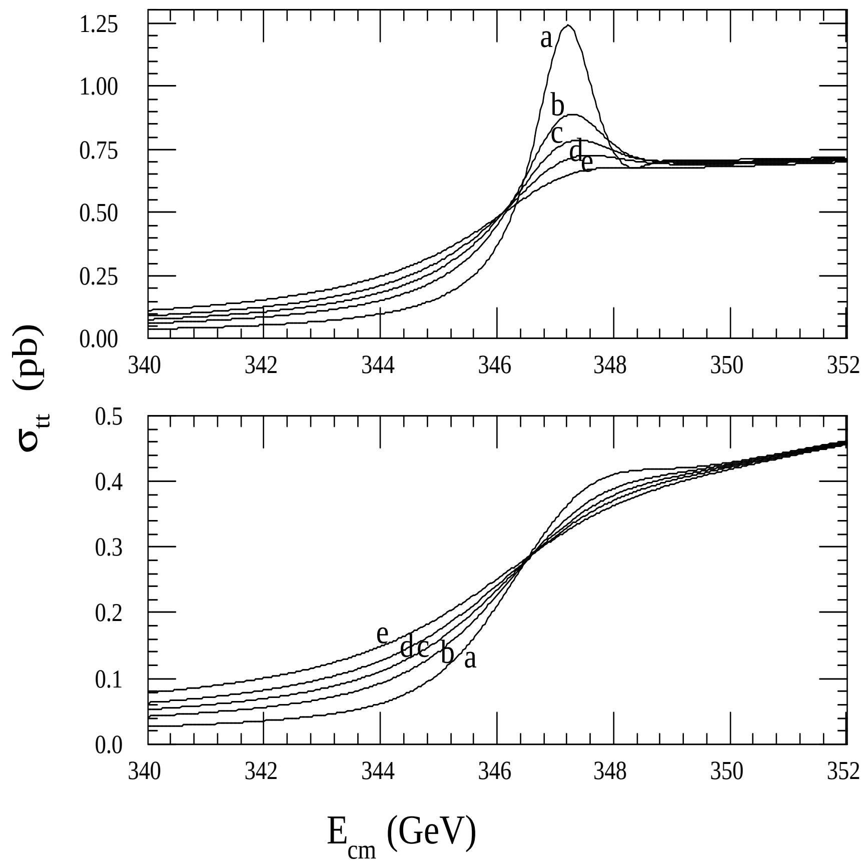
measurement of Higgs-Yukawa potential $\to y_t$?? treating Higgs as "new physics"



$\Leftrightarrow$



$$V_Y = -\frac{y_t^2}{4\pi}\,\frac{e^{-m_h\, r}}{r}$$



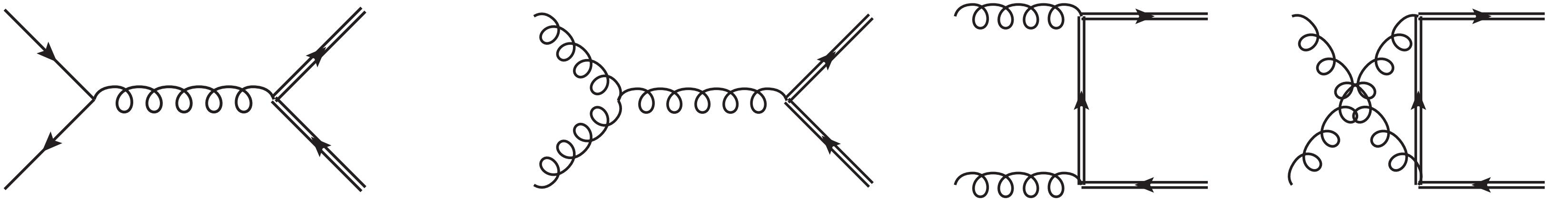
measurement of Γ_t [Frey et.al.]

- Γ_t affects shape of threshold scan
- different curves correspond to $\Gamma_t/\Gamma_t^{\rm SM} =$ (a) 0.5, (b) 0.8, (c) 1.0, (d) 1.2, and (e) 1.5
- before (top) and after (bottom) bremsstrahlung corrections

$t\bar{t}$ threshold at LHC/Tev

threshold “scan” at Tevatron/LHC [Hagiwara et al. 0804.1014]

Tevatron | LHC

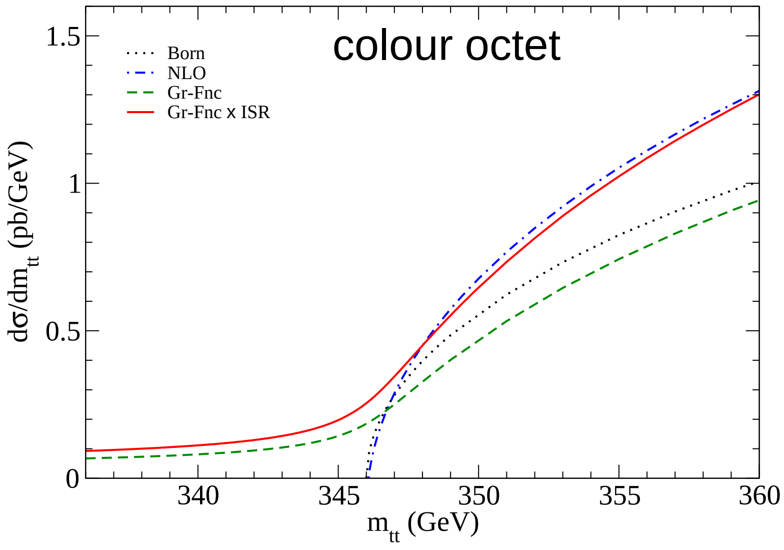


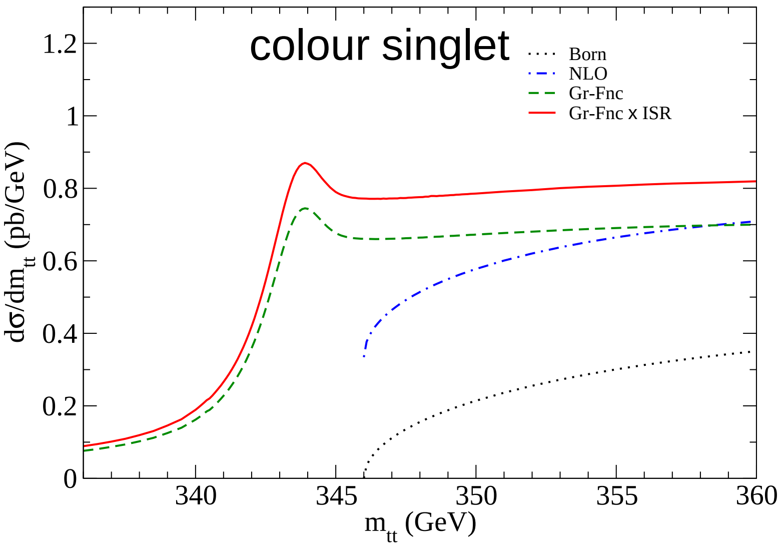
$$V_{\rm o} = -\frac{\alpha\,(C_F - C_A/2)}{r}$$

repulsive

$$V_{\rm s} = -\frac{\alpha\,C_F}{r}$$

attractive

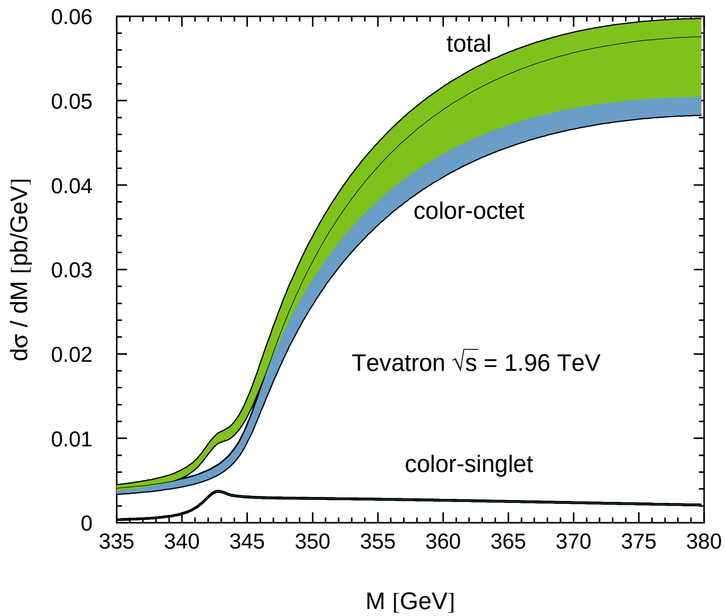




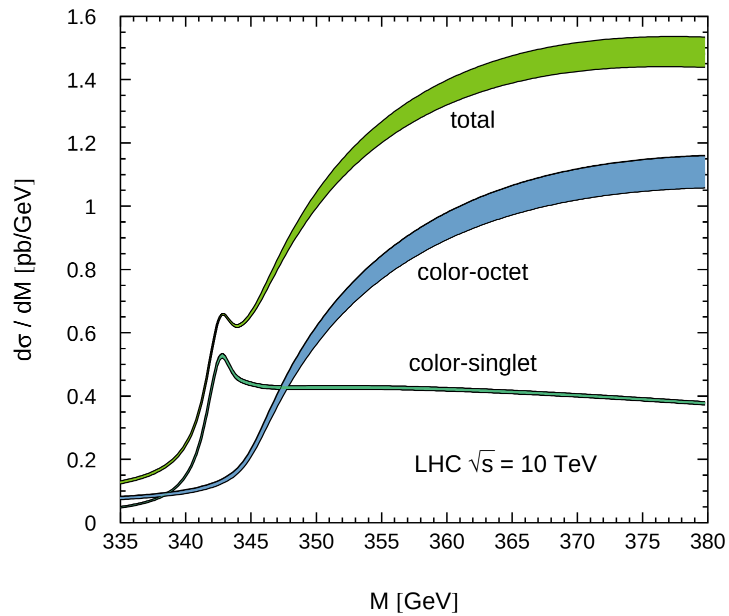
Top "threshold scan" at LHC [Kiyo et al. 0812.091]

including all channels and parton-distribution functions:

Tevatron

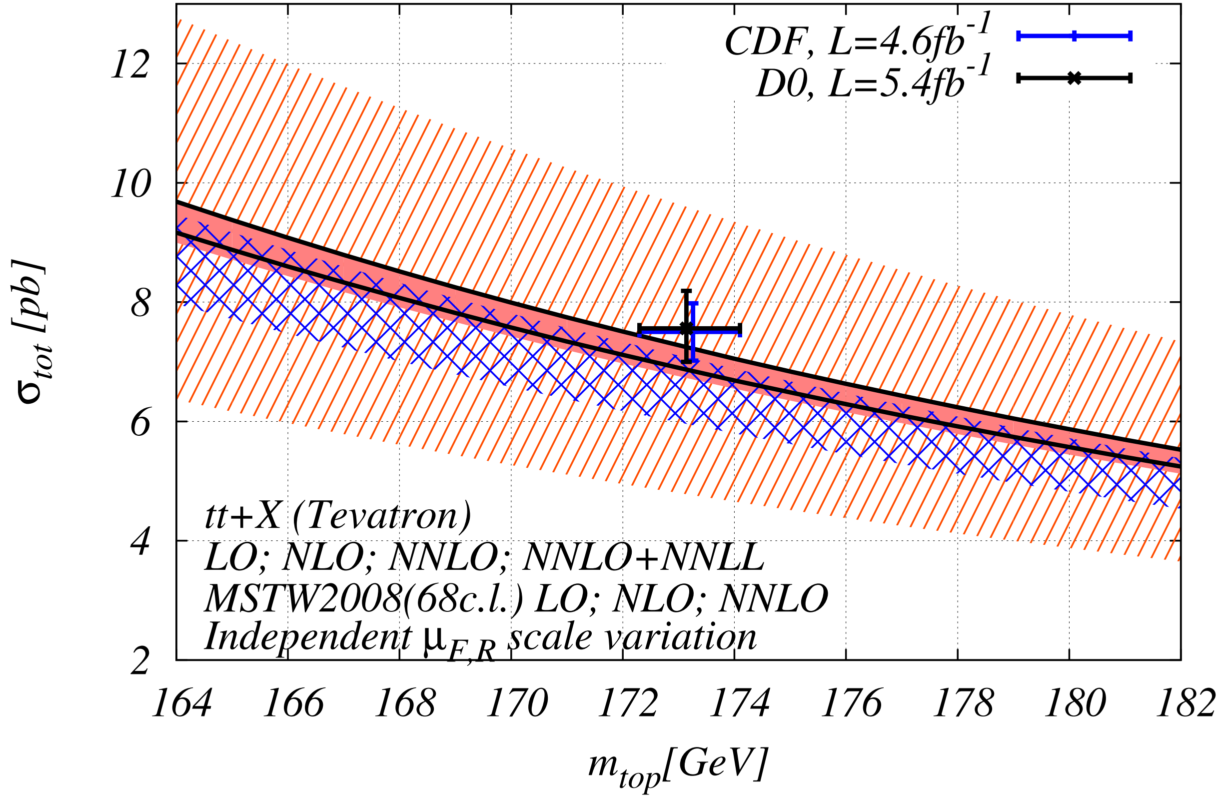


LHC



this bump cannot be seen directly but has some (small) impact on the total cross section total cross section, $\sigma^{(2)}_{q\bar{q}}$ computed numerically [Bärnreuther, Czakon, Mitov]

$$\hat{\sigma}_{ij} = \alpha_s^2 \left[\sigma_{ij}^{(0)} + \alpha_s \left(\sigma_{ij}^{(1,0)} + \sigma_{ij}^{(1,1)} \log(\mu^2/m^2)\right)\right.$$
$$\left. + \alpha_s^2 \left(\sigma_{ij}^{(2,0)} + \sigma_{ij}^{(2,1)} \log(\mu^2/m^2) + \sigma_{ij}^{(2,2)} \log^2(\mu^2/m^2)\right)\right]$$

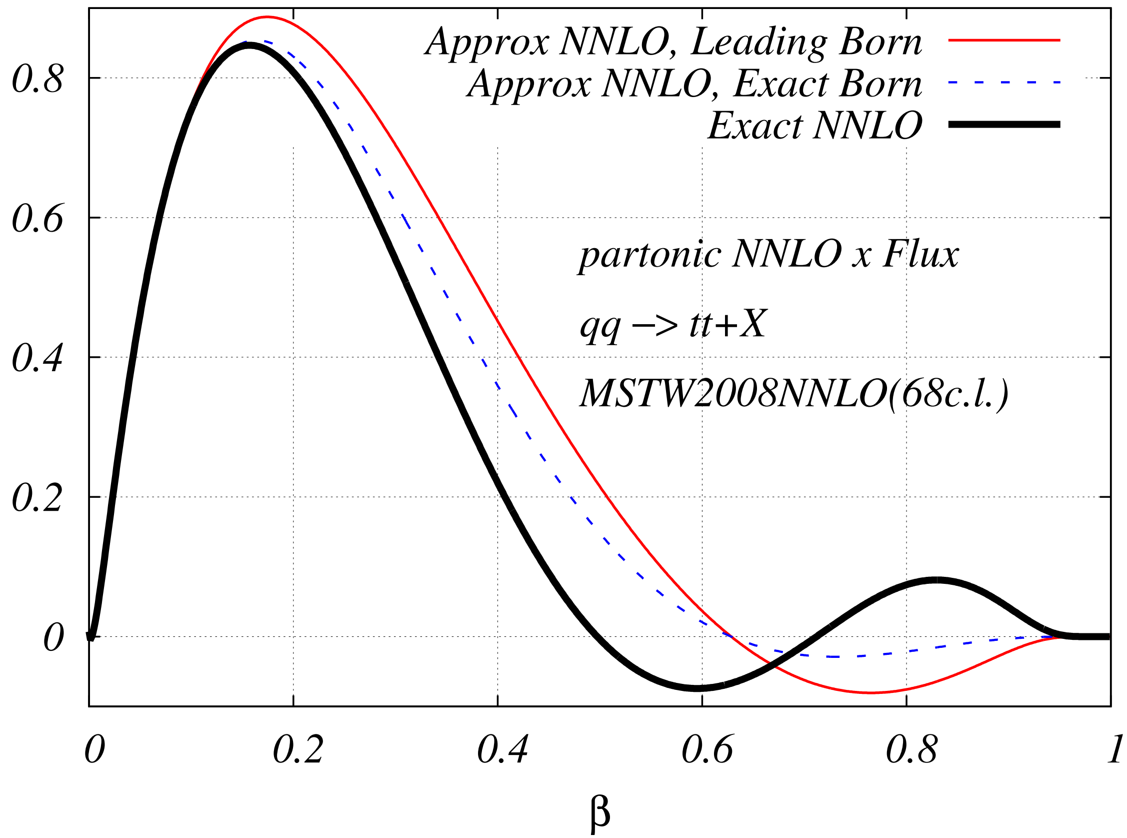


$q\bar{q} \to t\bar{t}$ at NNLO

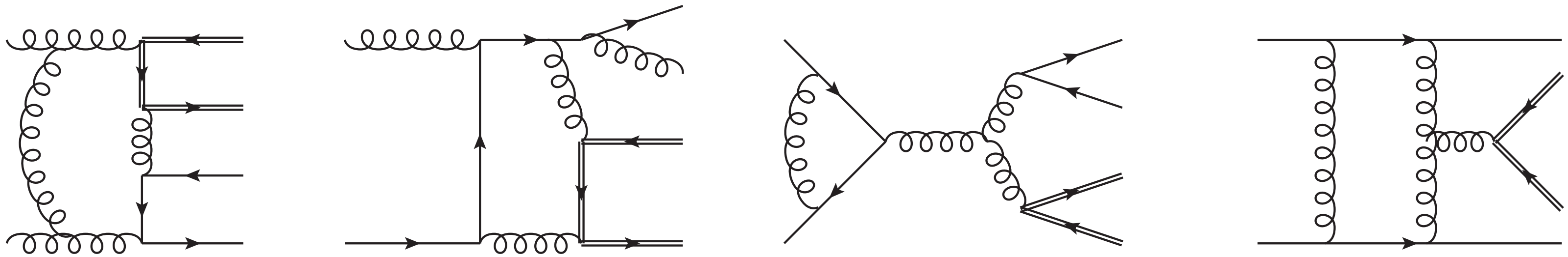
total cross section [Bärnreuther, Czakon, Mitov]

$\sigma_{ij}^{(2,i)}$ expanded in β corresponds to threshold expansion [Beneke et.al.]

$$\sigma_{q\bar{q}}^{(2,0)} = \sigma_{q\bar{q}}^{(0)} \left[\frac{k^{(2,0)}}{\beta^2} + \sum_{n=0}^{2} \frac{k^{(1,n)}}{\beta} \log^n \beta + \sum_{n=0}^{4} k^{(0,n)} \log^n \beta \right]$$



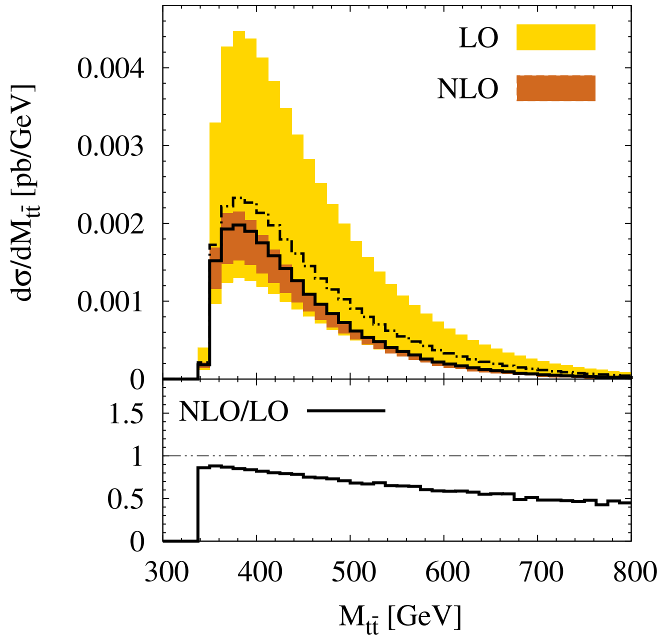
many partonic processes, up to 6-point interals: (tree level $\sim \alpha_s^4(\mu)$!!)



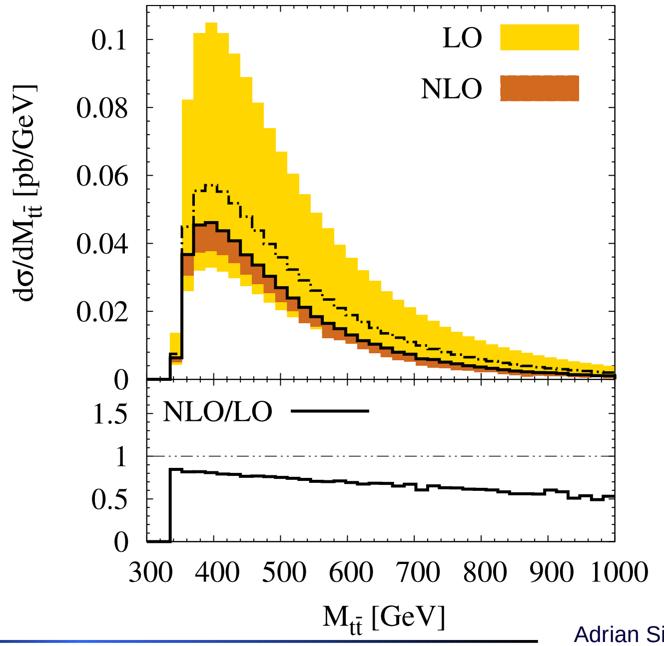
$gg \to t\bar{t}q\bar{q}$ $gq \to t\bar{t}gq$ $q\bar{q} \to t\bar{t}q\bar{q}$ $qq' \to t\bar{t}qq'$

e.g: invariant mass of top pair [Bevilacqua et al. 1108.2851]

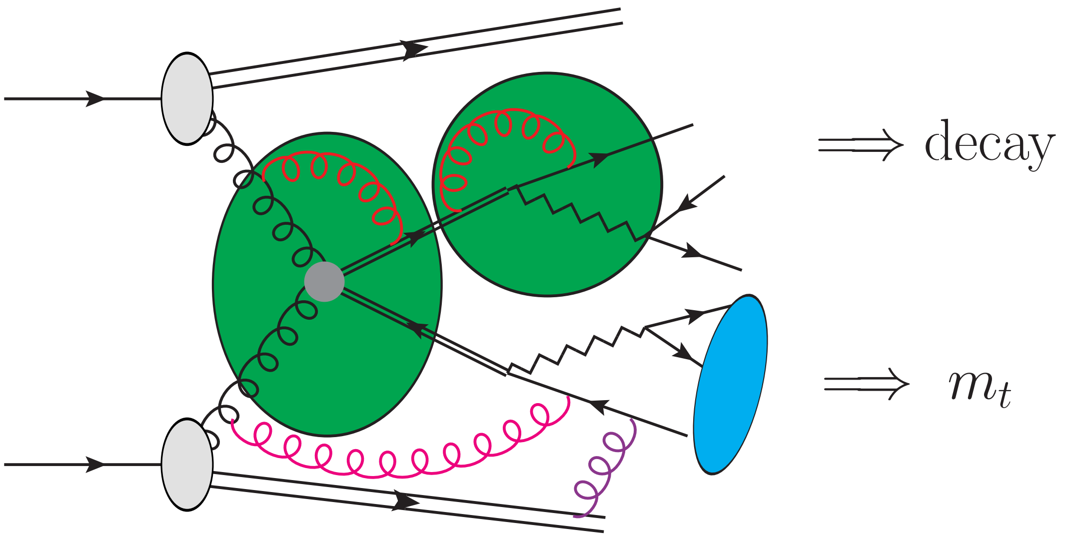
Tevatron



LHC

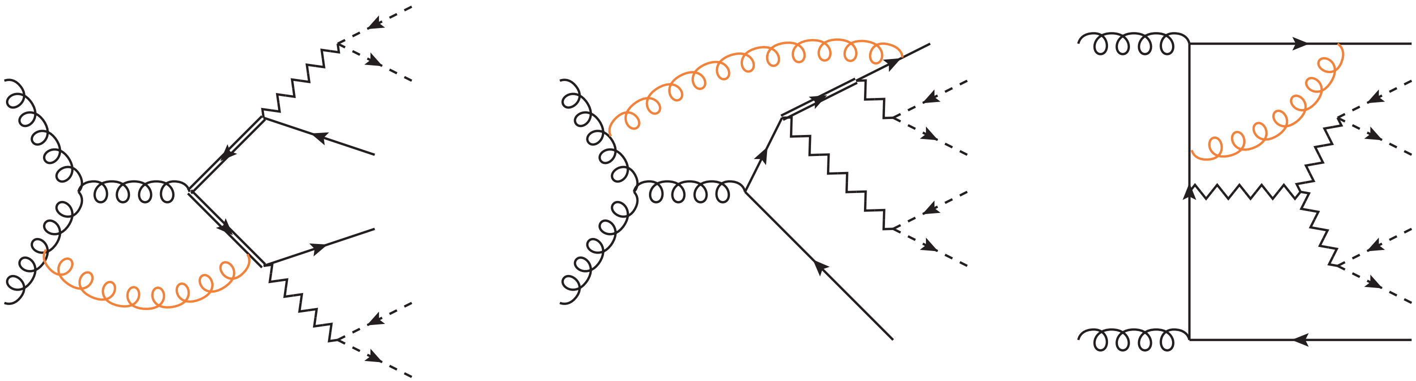


more detailed questions



- cuts on decay products (missing E_T, rapidity and p_t of leptons etc.)
- testing decay of top (spin correlations)
- non-factorizable corrections (off-shell effects)
- colour connection between decay products and proton remnants

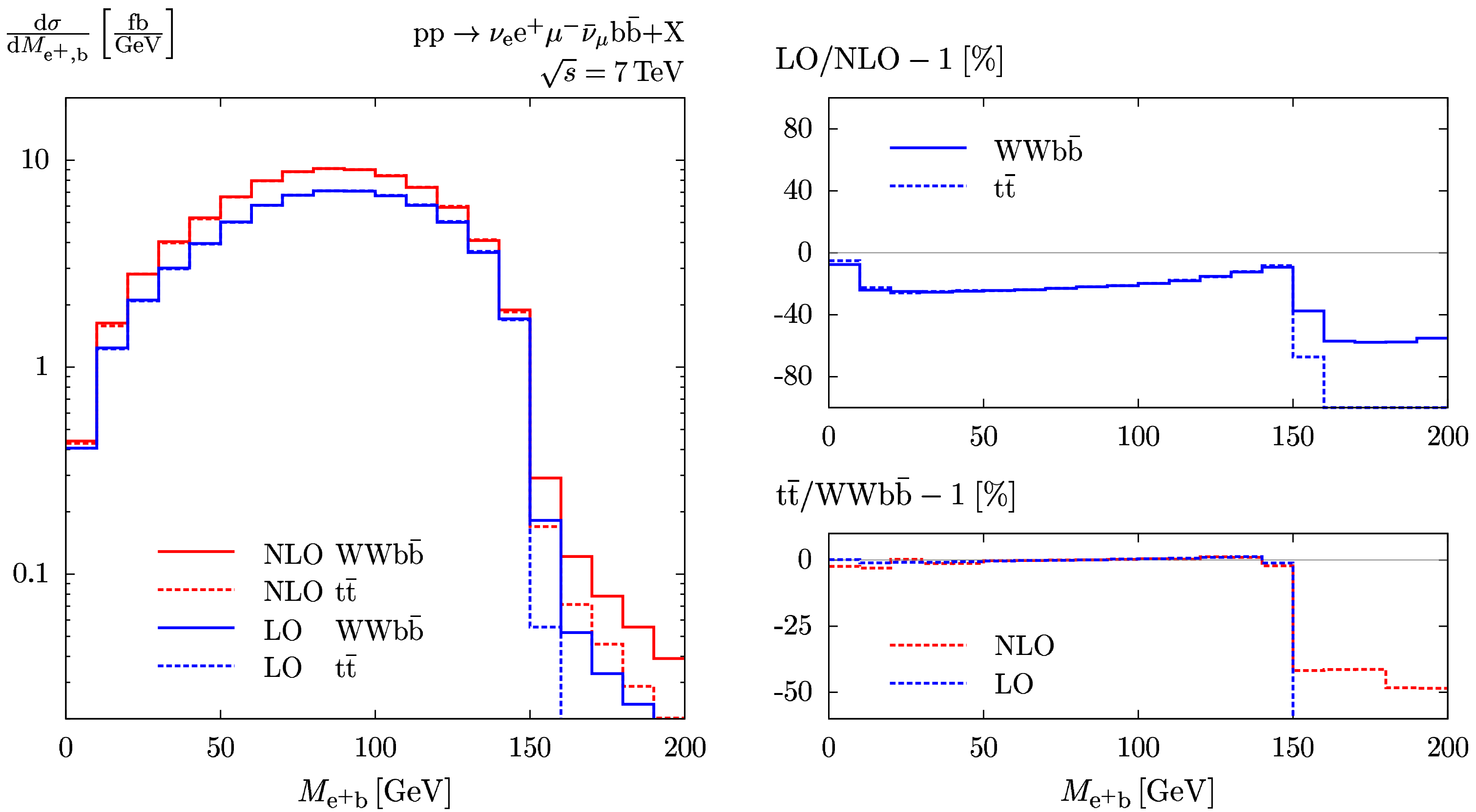
include decay of top and W, $gg \to W^+ b\, W^- \bar{b}$



double resonant   single resonant   non-resonant

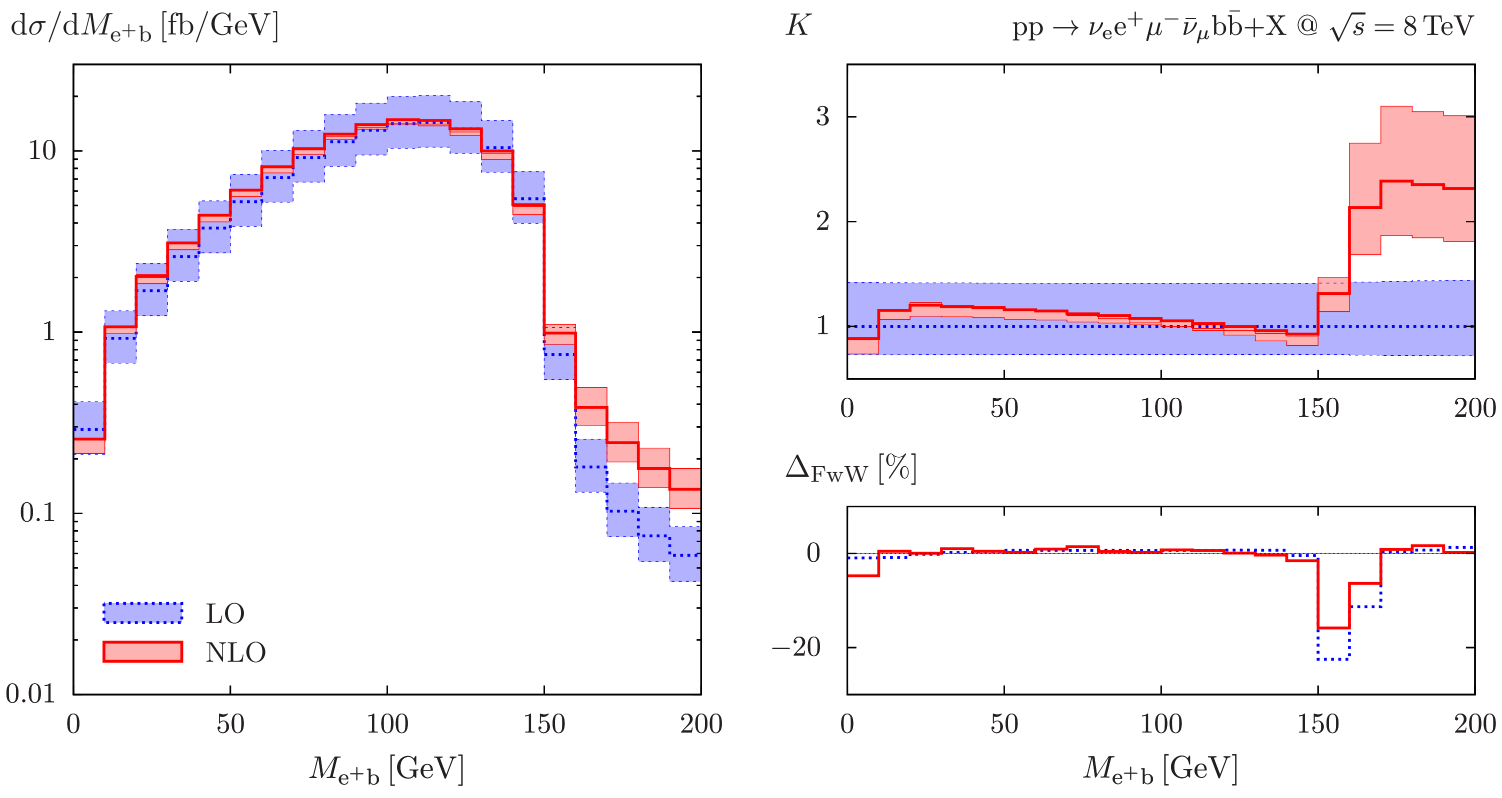
- calculation available by two groups [Bevilacqua et al; Denner et. al]
- complex mass scheme for treatment of intermediate unstable particles
  $m_t^2 \to \mu_t^2 \equiv m_t^2 - i m_t \Gamma_t$
- requires integrals with complex masses
- treatment of W (with leptonic decay): also resonant or non-resonant

top quark M_{eb} distribution distribution for 8 TeV LHC [Denner et al. 1203.6803]



- off-shell effects (from top) small in general
- can be enhanced at kinematic boudaries (at LO: $M_{eb}^2 < m_t^2 - M_W^2$)

M_{eb} distribution for 8 TeV LHC [Denner et al. 1207.5018]



- off-shell effects (from W) small except in specal (but possibly important) kinematic regions (m_t measurement)

Part III

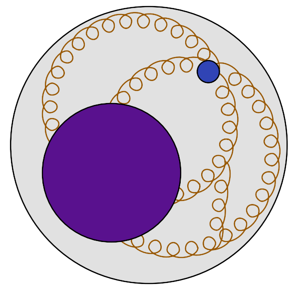
Top Mass

Problem 1: conceptual problem with pole mass; $\mathcal{O}(\Lambda_{\rm QCD})$

The pole mass has an intrinsic uncertainty of order $\Lambda_{\rm QCD}$ in perturbation theory (infrared sensitivity, renormalon ambiguity)

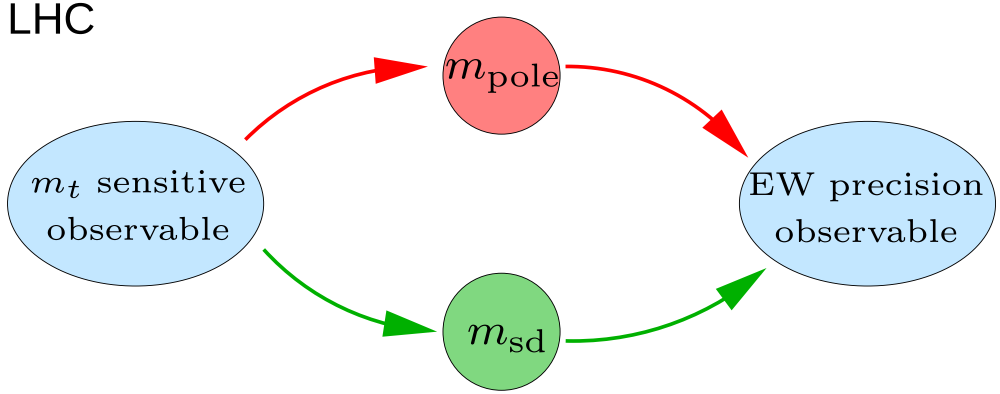
consider (fictitious) meson:

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



There is a principal limitation of the usefulness of the pole mass: $\delta m_t > \Lambda_{\rm QCD}$

- can be solved in principle by using other (short-distance) mass definitions
- highly relevant for m_t determinations at linear collider [Beneke et.al, Hoang et.al]
- probably (??) not relevant for LHC



scheme dependence

Problem 2: scheme dependence

- m_t has no meaning, unless you precisely specify what you mean by it
- quark mass definition is not unique, it is simply a theoretical parameter
- different definitions (schemes) are possible and widely used e.g. $m_{\rm pole}, \overline{m}, m_{\rm PS}, m_{\rm 1S}, \overline{m}_{\rm DR} \ldots$
- for each (acceptable) scheme s_1 the mass m_{s_1} can be related to the bare mass m_0 by divergent relations to any order in perturbation theory

$$m_{s_1}^{(i)} = m_0 \, (1 + \alpha_s \, d_{s_1}^{(1)} + \alpha_s^2 \, d_{s_1}^{(2)} + \ldots + \alpha_s^i \, d_{s_1}^{(i)})$$

- the masses in two (acceptable) schemes s_1 and s_2 are related by finite relations

$$m_{s_1}^{(i)} = m_{s_2}^{(i)} \, (1 + \alpha_s \, f_{s_1,s_2}^{(1)} + \alpha_s^2 \, f_{s_1,s_2}^{(2)} + \ldots + \alpha_s^i \, f_{s_1,s_2}^{(i)})$$

- at tree level, all mass definitions are equal, but the higher-order coefficients can be numerically large, e.g. relating $m_{\rm pole}^{(3)}$ to $\overline{m}^{(3)}$:

$$172.5 \text{ GeV} \simeq (162.0 + 8.0 + 1.9 + 0.6) \text{ GeV}$$

observable O, mass scheme s_1

$$\underbrace{\underbrace{\underbrace{O_{\rm exp} = O^{(0)}_{s_1}(m_{s_1}\ldots)}_{\text{determination of } m^{(0)}_{s_1}} + \alpha_s\, O^{(1)}_{s_1}(m_{s_1}\ldots)}_{\text{determination of } m^{(1)}_{s_1}=m^{(0)}_{s_1}(1+c^{(1)}_{s1}\alpha_s)} + \alpha_s^2\, O^{(2)}_{s_1}(m_{s_1}\ldots)}_{\text{determination of } m^{(2)}_{s_1}=m^{(0)}_{s_1}(1+c^{(1)}_{s1}\alpha_s+c^{(2)}_{s1}\alpha_s^2)} + \ldots$$

- working at order α_s^n, the determinations of m_{s_2} by
  - using mass scheme s_2 directly in determination above
  - using mass scheme s_1 as above and then converting m_{s_1} to m_{s_2}

  are different at order α_s^{n+1}
- to get a reliable top-mass determination we either have to work to very high order in perturbation theory or use a scheme were the corrections are not large.

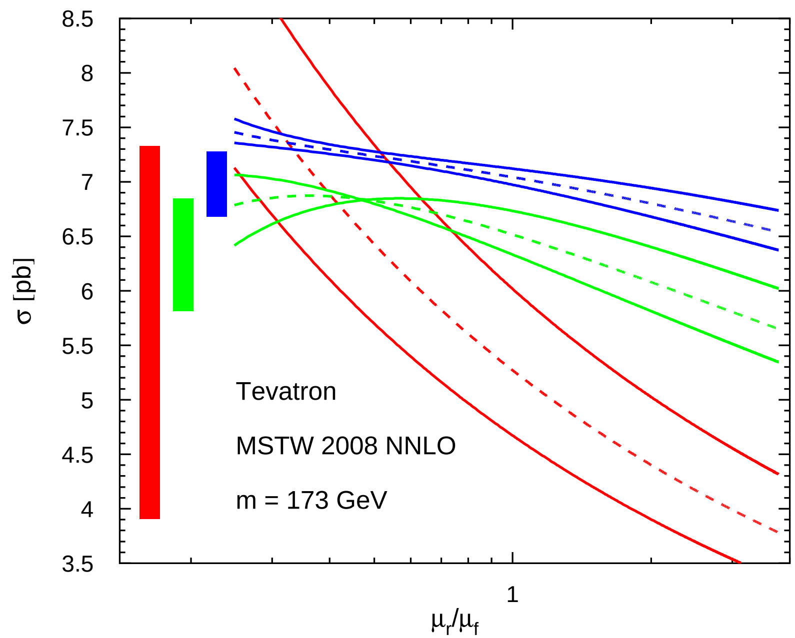
Problem 2: how to relate m_{exp} to pole mass; $\mathcal{O}(\Gamma_t)$

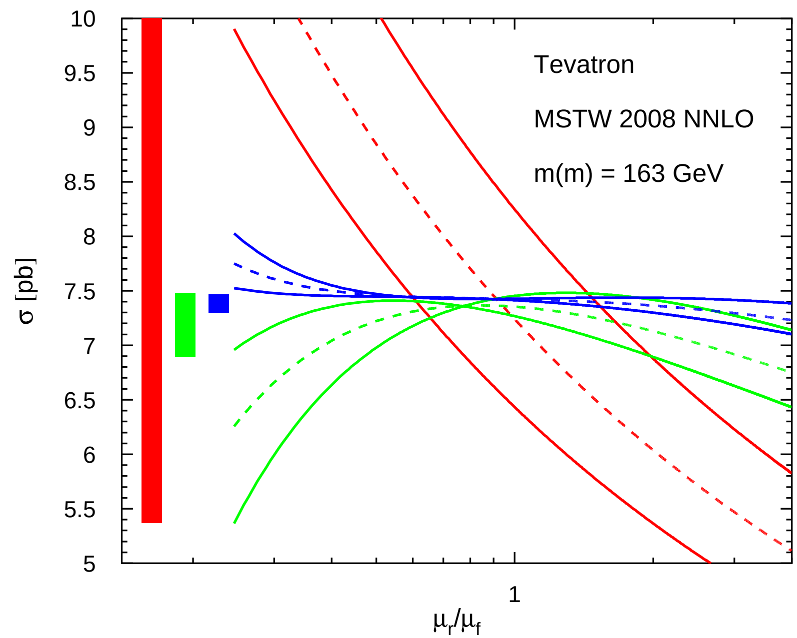
- m_X determination by requiring $O^{\text{th}}(m_X) \stackrel{!}{=} O^{\text{exp}}$, in principle for any scheme X and any (mass sensitive and well measurable) observable O
- in practice limitation through lack of higher-order terms in O^{th}
- m_t measurements through kinematics of decay products are basically tree-level determinations
- pick a scheme where higher-order corrections are small, i.e. pole scheme $\Longrightarrow$ m_t extracted using decay products is "something like" the pole mass
- the issue is not (and never was) whether this mass m_{exp} is the pole mass or $\overline{\text{MS}}$ mass, but what the precise relation between m_{exp} and m_{pole} is
- care has to be taken when interpreting $m_{\text{exp}} \stackrel{??}{=} m_{\text{pole}}$
  however $m_{\text{exp}} \stackrel{!!}{=} m_{\text{pole}} + \mathcal{O}(\Gamma_t)$ is fine. (Note: non-factorizable corrections have been computed and seem to be small [Denner et.al., Bevilacqua et.al.])
- alternative ways to measure m_t, using different O, where higher-order corrections are known, e.g. total cross section [Langenfeld et.al] or other choices [Melnikov et.al.]
- the ultimate m_t determination with $\delta m_t \sim 100\ \text{MeV}$ from threshold scan at ILC.

$t\bar{t}$ top mass

determination of $\overline{m}(\overline{m})$ through cross section [Langenfeld, Moch, Uwer]

compare $\sigma_{\rm tot}$ expressed in terms of pole and $\overline{\rm MS}$ mass (for $\mu_F \in \{0.5, 1, 2\} \times m_t$)





- $\overline{\rm MS}$ scheme more reliable (bands overlap, smaller uncertainty)
- direct extraction of $\overline{\rm MS}$ mass $\overline{m}(\overline{m})$ with $\delta m \simeq 3$ GeV
- PDF uncertainties etc... ??

Compare direct vs. indirect determination of pole mass [Alekhin, Djouadi, Moch]

Tevatron

CDF&D0	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\rm MS}}(m_t)$	$162.0\,^{+2.3}_{-2.3}\,^{+0.7}_{-0.6}$	$163.5\,^{+2.2}_{-2.2}\,^{+0.6}_{-0.2}$	$163.2\,^{+2.2}_{-2.2}\,^{+0.7}_{-0.8}$	$164.4\,^{+2.2}_{-2.2}\,^{+0.8}_{-0.2}$
$m_t^{\rm pole}$	$171.7\,^{+2.4}_{-2.4}\,^{+0.7}_{-0.6}$	$173.3\,^{+2.3}_{-2.3}\,^{+0.7}_{-0.2}$	$173.4\,^{+2.3}_{-2.3}\,^{+0.8}_{-0.8}$	$174.9\,^{+2.3}_{-2.3}\,^{+0.8}_{-0.3}$
$(m_t^{\rm pole})$	$169.9\,^{+2.4}_{-2.4}\,^{+1.2}_{-1.6}$	$171.4\,^{+2.3}_{-2.3}\,^{+1.2}_{-1.1}$	$171.3\,^{+2.3}_{-2.3}\,^{+1.4}_{-1.8}$	$172.7\,^{+2.3}_{-2.3}\,^{+1.4}_{-1.2}$

LHC

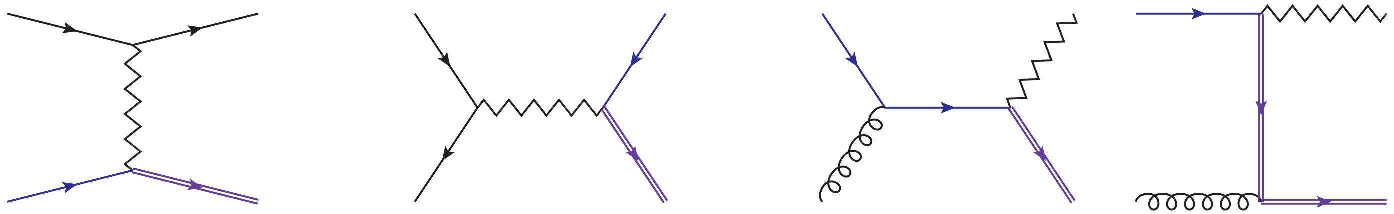
ATLAS&CMS	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\rm MS}}(m_t)$	$159.0\,^{+2.1}_{-2.0}\,^{+0.7}_{-1.4}$	$165.3\,^{+2.3}_{-2.2}\,^{+0.6}_{-1.2}$	$166.0\,^{+2.3}_{-2.2}\,^{+0.7}_{-1.5}$	$166.7\,^{+2.3}_{-2.2}\,^{+0.8}_{-1.3}$
$m_t^{\rm pole}$	$168.6\,^{+2.3}_{-2.2}\,^{+0.7}_{-1.5}$	$175.1\,^{+2.4}_{-2.3}\,^{+0.6}_{-1.3}$	$176.4\,^{+2.4}_{-2.3}\,^{+0.8}_{-1.6}$	$177.4\,^{+2.4}_{-2.3}\,^{+0.8}_{-1.4}$
$(m_t^{\rm pole})$	$166.1\,^{+2.2}_{-2.1}\,^{+1.7}_{-2.3}$	$172.6\,^{+2.4}_{-2.3}\,^{+1.6}_{-2.1}$	$173.5\,^{+2.4}_{-2.3}\,^{+1.8}_{-2.5}$	$174.5\,^{+2.4}_{-2.3}\,^{+2.0}_{-2.3}$

- with errors $\delta m_t \sim 2 - 3\ \text{GeV}$ renormalon problems are not main issue.
- if $\delta m_t \lesssim 1\ \text{GeV}$ must not use pole mass

Part IV

Single Top

basic processes



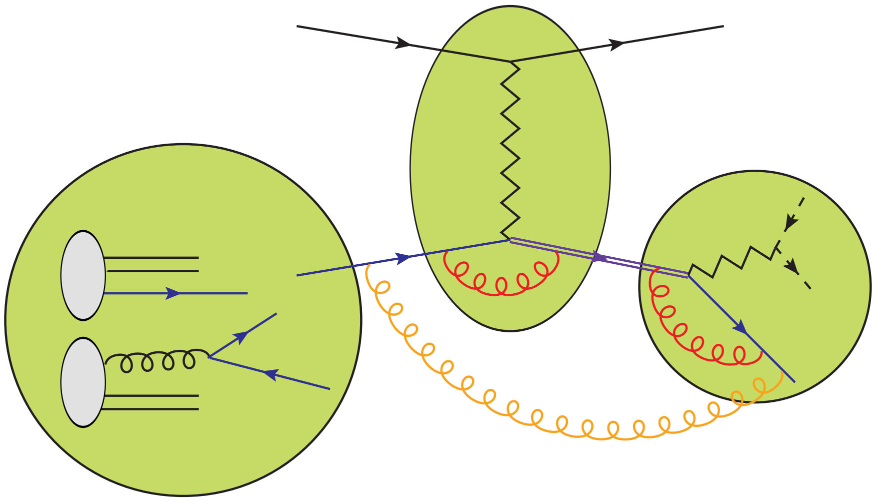
$t-\text{channel}$ $s-\text{channel}$ $W\,t \quad (\text{or } H^-\,t) \quad \text{production}$

classification of physical processes is not that straightforward

approximate (!) expected / measured SM cross sections in pb

	Tevatron	7 TeV LHC	14 TeV LHC
$t\ (\bar{t})$ "t"-ch	1.2	40 (20)	150 (100)
$t\ (\bar{t})$ "s"-ch	0.55	2.5 (1.4)	7 (4)
$t\,W^-$	0.15	8	45

more detailed questions



- NLO corrections in production
- resummation of soft logs → “N”NLO corrections
- top decay, at LO/NLO, spin correlations
- off-shell effects / non-factorizable corrections
- initial b quark and m_b effects : 5 flavour scheme vs. 4-flavour scheme
- matching to parton showers

theory status

- fully differential NLO QCD corrections for t–, s–channel and Wt known [Harris et.al; Sullivan; Zhu . . .]
- resummation at NNLL of inclusive cross section [Kidonakis; Wang et.al.]
  $\longrightarrow$ "poor man's" NNLO corrections
- top decay added, with NLO corrections in production and decay [Campbell et.al; Cao et.al]
  $\longrightarrow$ issues with definition of channel
  $\longrightarrow$ spin correlations
- EW corrections known in SM and MSSM [Beccaria et.al; Macorini et.al]
  effect small, a few %
- non-factorizable corrections known [Falgari et.al]
  $\longrightarrow$ effects small, except at kinematic boundaries
- 4-flavour vs. 5-flavour scheme [Campbell et.al]
  $\longrightarrow$ generally good agreement at NLO
- all channels (including $t\,H^-$) included in MC@NLO and POWHEG [Frixione,Frederix, Laenen, Motylinski, Alioli, Nason, Re, Webber, White . . . . . .]
- BSM effects (e.g. anomalous trilinear couplings) included in WHIZARD
  $\longrightarrow$ interference with background diagrams on its way [Bach, Kilian, Ohl. . .]

resummed cross section

s-channel: Kidonakis [1001.5034]

- resummation in moment space
- $s_4 \equiv (p_a + p_b - p_1)^2 - m_t^2 = s + t + u - m_t^2$ for $s_4 \to 0 \Rightarrow$

$$\alpha_s^n \, L^{2n-1} \equiv \alpha_s^n \, [\log^{2n-1}(s_4/m_t^2)/s_4]_+$$

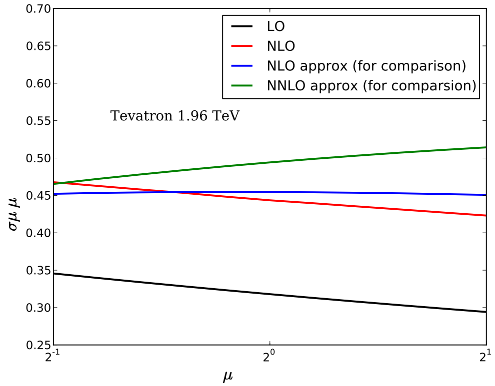
- NLL $\rightarrow$ NNLO: $\alpha_s^2 \, L^3$ and $\alpha_s^2 \, L^2$ NLLO$_{\rm approx}$/NLO $\sim$10% increase
  NNLL $\rightarrow$ NNLO: also $\alpha_s^2 \, L^1$ and $\alpha_s^2 \, L^0$ NLLO$_{\rm approx}$/NLO further 3-4% increase
- soft limit good approximation for Tevatron and LHC
- damping factors (to limit soft gluon contributions away from threshold) improve soft approximation
- "best" predictions, MSTW2008 NNLO pdf:

Kidonakis $m_t = 173$ GeV	Zhu et.al. $m_t = 173.2$ GeV
$\sigma_{\rm TeV} = 0.523^{+0.001+0.030}_{-0.005-0.028}$ pb	$\sigma_{\rm TeV} = 0.467^{+0.01}_{-0.01}$ pb
$\sigma_{\rm LHC\ 7} = 3.17^{+0.06+0.13}_{-0.06-0.10}$ pb	$\sigma_{\rm LHC\ 7} = 2.81^{+0.16}_{-0.10}$ pb

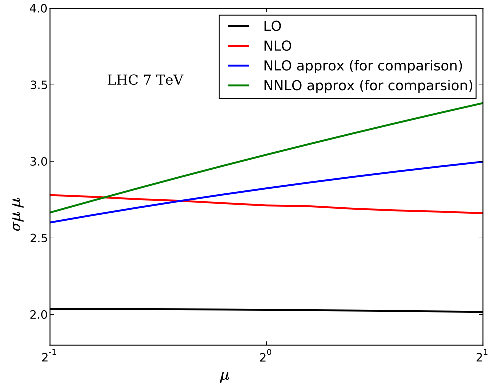
resummed cross section

s-channel: Zhu, Li, Wang, Zhang [1006.0681]

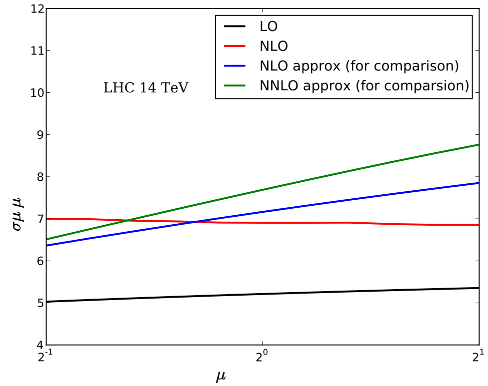
- resummation via SCET
- different definition of resummation variable $s_4 \equiv (p_a + p_b - p_t)^2$ also includes hard-collinear logarithms
- soft/coll limit good approximation for Tevatron, not very good for LHC



Tevatron



LHC @ 7 TeV



LHC @ 14 TeV

t-channel: Kidonakis [1103.2792] vs Wang, Li, Zhu, Zhang [1010.4509]

- similar technical (moments vs SCET) and physical (resummation kinematics and virtual contribution) differences as for s-channel
- soft gluon approximation not considered reliable
- results for $m_t = 173$ GeV and MSTW2008 NNLO pdf

Kidonakis	Wang et.al.
$\sigma_{\rm TeV} = 1.04^{+0.00}_{-0.02} \pm 0.06\ {\rm pb}$	$\sigma_{\rm TeV} = 0.982\ {\rm pb}$
$\sigma_{\rm LHC\ 7} = 41.7^{+1.6}_{-0.2} \pm 0.8\ {\rm pb}$	$\sigma_{\rm LHC\ 7} = 40.9^{+0.1}_{-0.1}\ {\rm pb}$
$\sigma_{\rm LHC\ 14} = 151^{+4}_{-1} \pm 3\ {\rm pb}$	$\sigma_{\rm LHC\ 7} = 152.4^{+0.4}_{-1.0}\ {\rm pb}$

- better numerical agreement than for s-channel
- resummation effects decrease scale dependence

resummed cross section

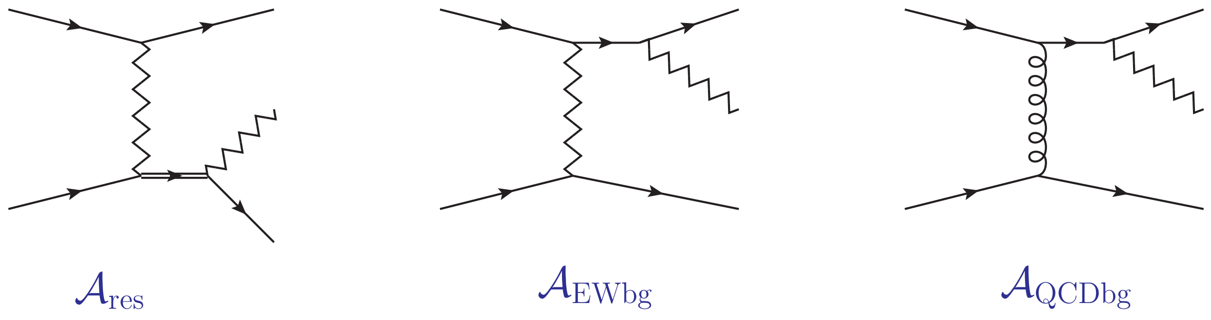
$W\,t$ and $H^-\,t$: Kidonakis [1005.4451]

- resummed cross section re-expanded:

$$\sigma^{(2)} = \sigma^{(0)}\alpha_s^2 \left(\underbrace{c_3 L^3 + c_2 L^2}_{\rm NLL} + \underbrace{c_1 L^1 + c_0 L^0}_{\rm NNLL} \right)$$

- soft gluons claimed to be dominant
- damping factors applied
- NLO $\longrightarrow$ 'N'NLO: 8% increase at 7 TeV LHC
- $m_t = 173$ GeV, MSTW2008 NNLO pdf: $\sigma(t\,W^-) = 7.8 \pm 0.2^{+0.5}_{-0.6}$ pb
- scale variation error < pdf error
- similar analysis for $H^-\,t$: corrections NLO $\longrightarrow$ 'N'NLO: 15-20%, depending on m_H

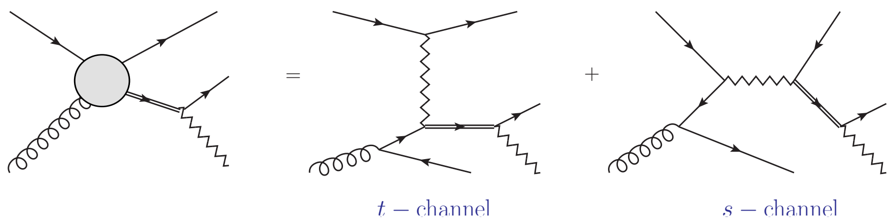
- new issue: definition of process, e.g t-channel



- it is an "irrelevant coincidence" at LO that

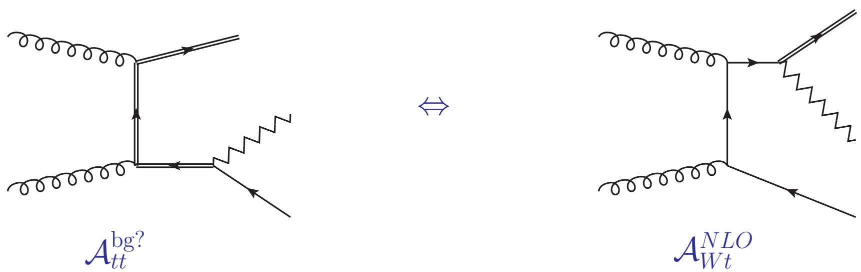
$$|\mathcal{A}_{\rm res} + \mathcal{A}_{\rm EWbg} + \mathcal{A}_{\rm QCDbg}|^2 = |\mathcal{A}_{\rm res} + \mathcal{A}_{\rm EWbg}|^2 + |\mathcal{A}_{\rm QCDbg}|^2$$

- shouldn't we define a proper observable (to which $\mathcal{A}_{\rm QCDbg}$ contributes) with proper final states (e.g. b-jets), rather than try to subtract $|\mathcal{A}_{\rm QCDbg}|^2$?
- similar comment regarding distinction between s-channel and t-channel



- mixing but no interference at NLO (another "irrelevant coincidence"), beyond NLO there is interference

- this issue is particularly acute for $W\,t$ and has been studied extensively [Kersevan et.al; Tait; Belyaev et.al; Campbell et.al; Frixione et.al]



- possible remedies
  - invariant mass (anti-) cut $|M_{W\,b} - m_t|^2 \gg \Gamma_t$
  - $p_T^b < p_T^{\mathrm{veto}}$ (hard b tend to come from t decay)
  - Diagram removal $\mathcal{A}_{(W\,t)} + \mathcal{A}_{(tt)} \to \mathcal{A}_{(W\,t)}$
  - Diagram subtraction

$$|\mathcal{A}_{(W\,t)} + \mathcal{A}_{(tt)}|^2 \to |\mathcal{A}_{(W\,t)}|^2 + 2\mathrm{Re}(\mathcal{A}_{(W\,t)}\mathcal{A}^*_{(tt)}) + |\mathcal{A}_{(tt)}|^2 - \widetilde{|\mathcal{A}_{(tt)}|}^2$$

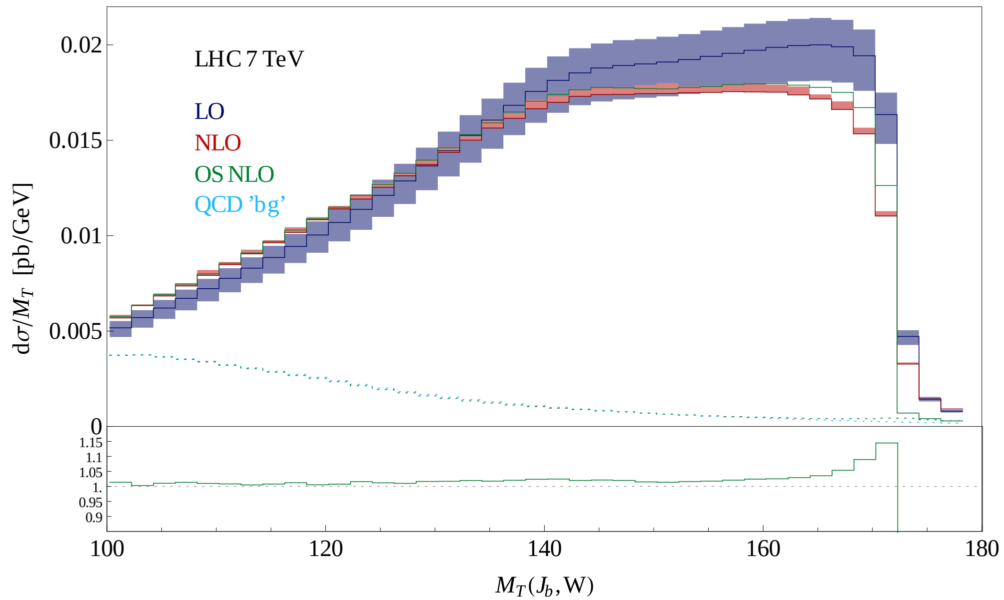
- using b-jet rather than b-parton allows to define (at least theoretically) clean observables

off-shell effects

non-factorizable corrections have been extensively studied [Fadin et.al; Melnikov et.al; Beenakker et.al; Denner et.al.; Jadach et.al; . . .] but usually neglected at hadron colliders:

- they seem to be more difficult to compute (not really)
- they are generally small [Beenakker et.al; Pittau]
  - resonant → non-resonant propagator unless $E \lesssim \Gamma$ is small (soft)
  - cancellations for “inclusive” observables [Fadin, Khoze, Martin]
- include off-shell effects: consistently combine non-factorizable with propagator corrections:

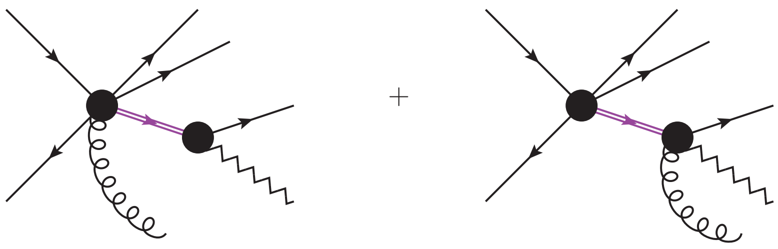
  [Falgari et.al] e.g. transverse mass: $M_T = \sum_{J_b,\ell,\nu} |p_T|^2 - (\sum_{J_b,\ell,\nu} \vec{p}_T)^2$



off-shell effects

effective-theory inspired calculation (hard/soft through method of region)

real amplitude:



$$\mathcal{A}^g_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^0_{\rm dec} \quad + \quad \mathcal{A}^0_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^g_{\rm dec}$$

corrections to production (soft and coll singularities):

$\int d\Phi_{n+1} \left| \mathcal{A}^g_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^0_{\rm dec} \right|^2$ plus (hard) virtual corrections for t-production is IR finite

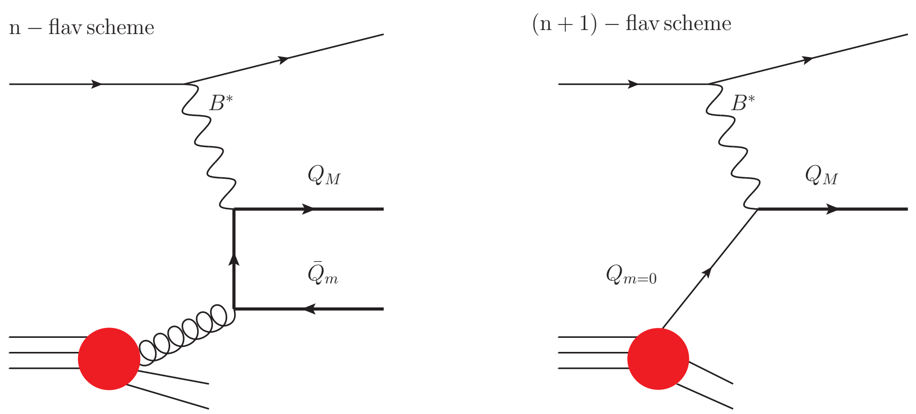
corrections to decay (soft and coll singularities):

$\int d\Phi_{n+1} \left| \mathcal{A}^0_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^g_{\rm dec} \right|^2$ combined with (hard) virtual correction for decay is IR finite

non-factorizable corrections (soft singularities only):

$\int d\Phi_{n+1}\, 2\,{\rm Re} \left(\mathcal{A}^0_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^{\rm g}_{\rm dec} \right) \left(\mathcal{A}^{\rm g}_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^0_{\rm dec} \right)^*$ plus soft virtual is IR finite

4-flavour scheme vs. 5-flavour scheme

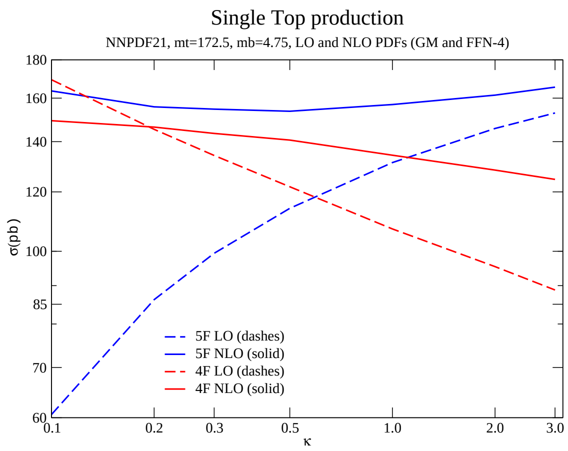


$b \notin p$: 4 flavour scheme	$b \in p$: 5 flavour scheme
$\exists \bar{b}$ @ LO	$\nexists \bar{b}$ @ LO
only 1 $\log \mu_f^2/m_b^2$ @ NLO	$\log \mu_f^2/m_b^2$ resummed
m_b effects can be included	$m_b = 0$ for initial state

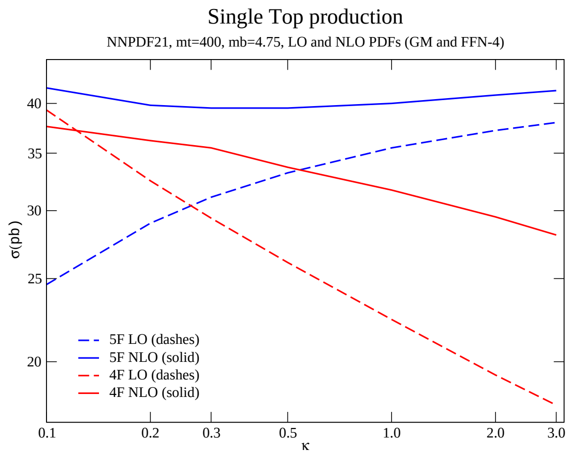
- Comparison 4F vs 5F for single top at NLO [Campbell et.al]:
- Generally good agreement already at NLO
- A detailed single-top analysis POWHEG vs aMC@NLO in 4F (and 4F vs 5F including parton showers) is under way [Frederix, Re, Torrielli]

4-flavour scheme vs. 5-flavour scheme

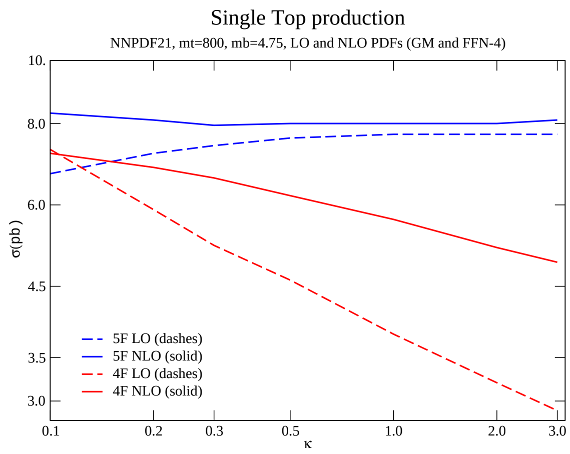
- general analysis 4F vs 5F [Maltoni, Ridolfi, Ubiali (1203.6393)]
- resummation of $\log \mu_f^2/m_x^2$ numerically not very important (except for x large)
- scale in $\log$ suppressed through phase space



$m_t = 172.5$ GeV



$m_t = 400$ GeV



$m_t = 800$ GeV

tools

tools (no claim for completeness!)

- resummed total cross sections available
  - for s- and t-channel by two groups
  - for $W\,t$, $H\,t$ by one group
- several fixed-order NLO calculations (including decay and spin correlations) available
- off-shell effects at NLO available
- all channels (s-, t-, $W\,t$, $H\,t$) implemented in POWHEG and MC@NLO
- t-channel in 4 flavour scheme (very soon) available in POWHEG and (a)MC@NLO
- all channels (s-, t-, $W\,t$, $H\,t$) available in WHIZARD
  - up to 6 final state partons at LO
  - including “background” diagrams
  - BSM models implemented
  - including interface to shower

Part V

Forward-Backward Asymmetry

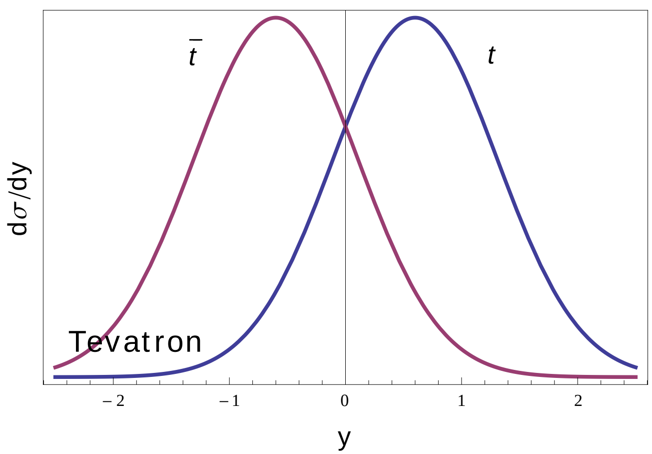
possible deviation from SM in forward-backward asymmetry $A_{\rm FB}$?

Note: this is a subtle quantity! A classic case of a detailed test of SM and our ability to compute and measure!

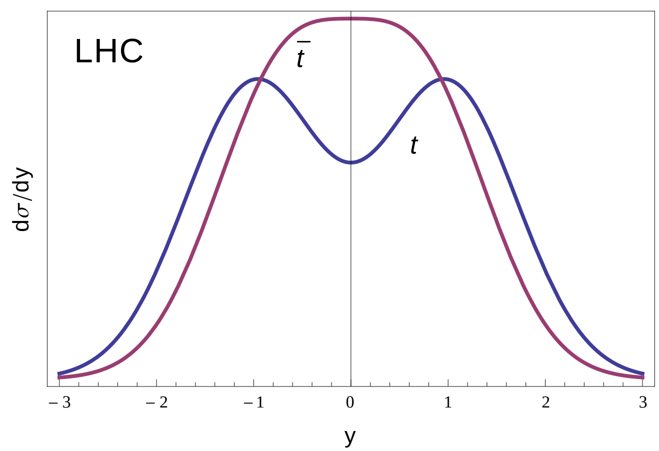
definition:

$$A_{\rm FB}^{\rm Tev} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)} \quad \text{or} \quad A_{\rm FB}^{\rm LHC} = \frac{\sigma(\Delta |y| > 0) - \sigma(\Delta |y| < 0)}{\sigma(\Delta |y| > 0) + \sigma(\Delta |y| < 0)}$$

$$\Delta y \equiv y_t - y_{\bar{t}} \qquad \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



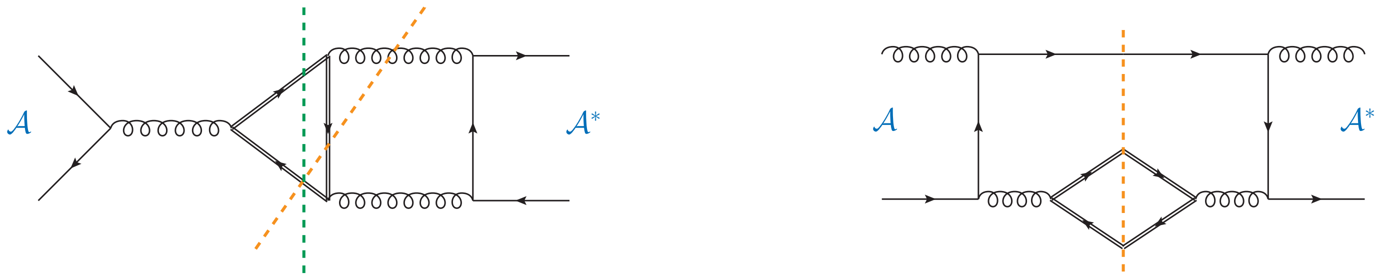
t ($\bar{t}$) follows p ($\bar{p}$)



$\bar{t}$ more central

$$A_{\mathrm{FB}}^{\mathrm{Tev}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)} \quad \text{or} \quad A_{\mathrm{FB}}^{\mathrm{LHC}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$$

- zero for QCD @ LO, non-zero but small for EW @ LO
- QCD @ NLO (from $q\bar{q} \sim d_{abc}^2$ and qg initial states only) [Kuhn, Rodrigo]



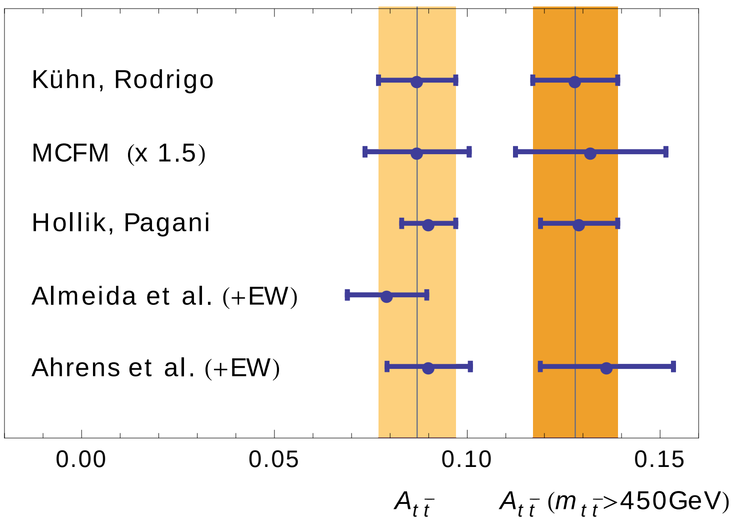
$$A_{\mathrm{FB}} = \frac{\alpha_s^3 + \mathcal{O}(\alpha_s^4)}{\alpha_s^2 + \mathcal{O}(\alpha_s^3)} = \sigma^{\mathrm{virt}} + \sigma^{\mathrm{real}} = +\infty - \infty \simeq \mathrm{few}\% \quad \text{(soft singularities)}$$

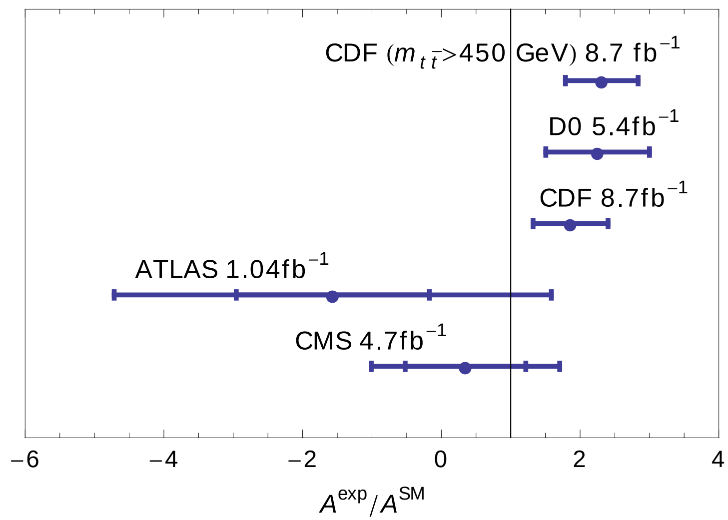
- EW @ NLO: increase $A_{\mathrm{FB}}^{t\bar{t}}$, but not too much ($\sim 20\%$) [Hollik, Pagani]
- QCD @ NNLO: not known exactly, but from resummation small corrections expected, a SM value of $A_{\mathrm{FB}}^{t\bar{t}} \gtrsim 0.2$ seems highly unlikely. [Almeida et.al, Ahrens et.al]
- Need BSM (tree-level) contributions to get $A_{\mathrm{FB}}^{t\bar{t}} \gtrsim 0.2$

A_{FB} theory vs. experiment

- effect enhanced for large $m_{t\bar{t}}$
- at LHC, effect smaller (small fraction of $q\bar{q}$ events)
- "eliminate" large denominator, i.e. gg initial state, use $f_q(x) > f_g(x), f_{\bar{q}}(x)$ for x large.
- enhance A_{FB} at LHC with cuts, e.g one-side asymmetry:

$$A = \left.\frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}\right|_{P_{t\bar{t}} > P_{\mathrm{cut}}, M_{t\bar{t}} > M_{\mathrm{cut}}}$$





[plots from Rodrigo]

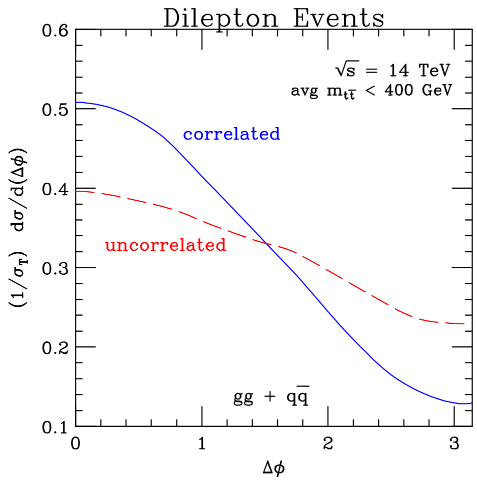
- there is a tension between experiment at the Tevatron and the theoretical SM value
- results at the LHC are in complete agreement with theory
- this could be BSM, but a more boring explanation is as likely
- complete NNLO QCD result not yet available (only total cross section known so far)
- too have a large effect, new physics should enter at tree level and have sizeable couplings (e.g. axigluon)
- it is easy to explain A_{FB} with BSM, but very difficult to do so without getting into conflict with other data
- use A_{FB} in $t\,\bar{t}\,j$ and $t\,\bar{t}\,j\,j$ as cross-check for new-physics scenarios

Part VI

Top and BSM

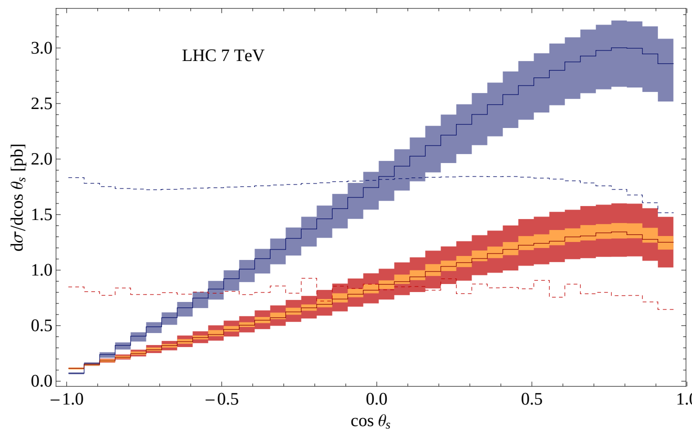
- $\Gamma_t > \Lambda_{\rm QCD} \Longrightarrow$ top quark decays before QCD blurs spin information [Mahlon, Parke; Bernreuther et.al; Motylinski; Cao et.al; Melnikov, Schulze, . . .]
- detailed test of $t \to Wb \to \ell\nu b$ possible
- details depend on process (top pair production / single top), collider (Tevatron / LHC) and kinematic regime (invariant mass)
- find observable that strongly depends on spin correlation, e.g:

$t\bar{t}$: $\Delta\phi_{\ell\,\ell'}$ with $M_{t\bar{t}} < 400$ GeV



[Mahlon, Parke, arXiv:1001.3422]

single top: $\cos(\vec{p}^{\,*}_{\rm spec}, \vec{p}^{\,*}_{\ell})$



[Falgari et.al: arXiv:1102.5267]

- test against SM and BSM predictions

parametrizing ignorance [Aguilar-Saavedra et.al, Willenbrock et.al. . . .]

- general approach, finite number of possibilities, respect generic constraints
- general vertices (e.g. $W\,t\,b$) with anomalous couplings

$$-\frac{g}{\sqrt{2}}\,\bar{b}\gamma^\mu\,(V_L P_L + V_R P_R)\,t\,W_\mu^- - \frac{g}{\sqrt{2}}\,\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_\mu^- + \text{h.c.}$$

- effective dimension 6 (and higher) operators e.g:

$$O_{\phi q} = i(\phi^+\tau D_\mu\phi)(\bar{q}\gamma^\mu\tau q) \quad \text{or} \quad O_{tW} = (\bar{q}\,\sigma^{\mu\nu}\tau\,t\,\tilde{\phi})W_{\mu\nu}$$

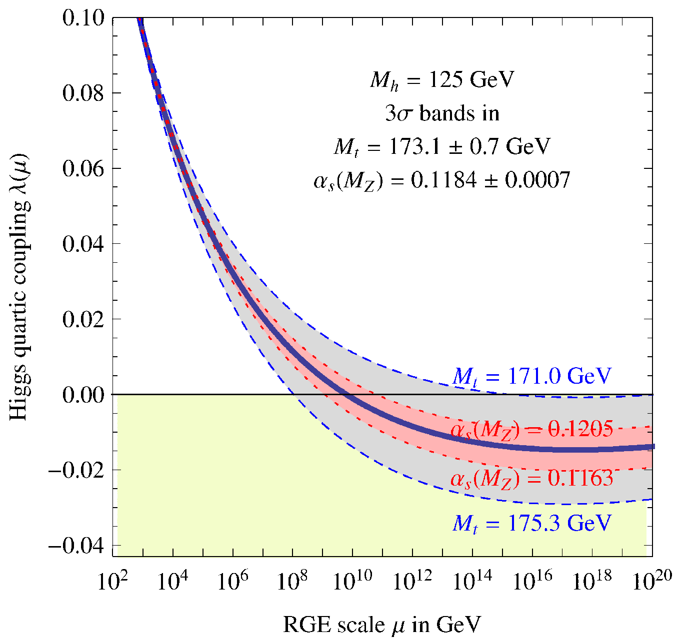
  complete analysis possible, devise sensitive observables
- similar to anomalous triple-gauge couplings

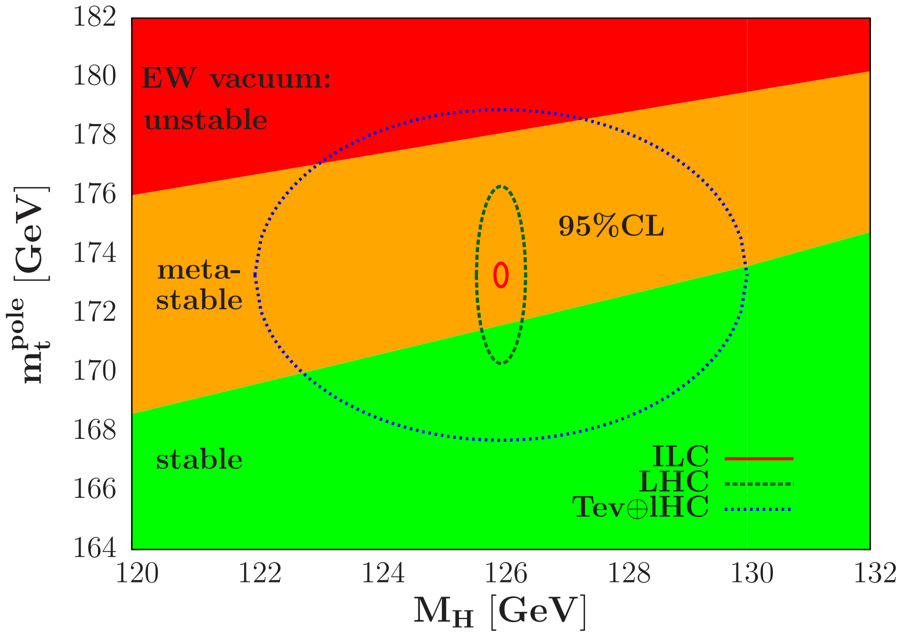
explicit models (i.e. a very long list of possible explicit models) [. . . (sorry)]

- more information
- can extend to high-energy region
- can compute anomalous couplings for a given explicit model

[Degrassi et.al; Alekhin, Djouadi, Moch]

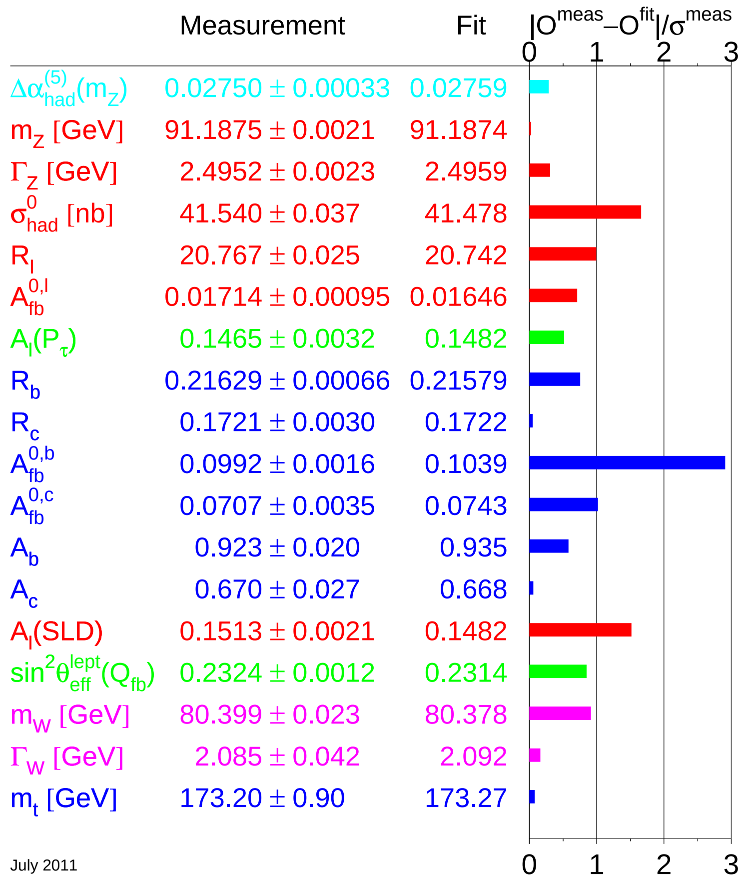
- Running of Higgs quartic coupling $\lambda(\mu)$ crucially depends on m_t (and α_s)
- could SM be consistent up to very high energies? need $\lambda(\mu) > 0$
- remarkable coincidence (??) between m_H and m_t values





conclusions

- overall theory of top is in pretty good shape, with further progress on its way
- so far, most experimental results agree reasonably well with SM predictions, apart from . . .
- possible problem in A_{FB} (this somehow sounds familiar)
- $2 - 3\sigma$ deviations are usually not due to new physics



[LEP EWWG]