IoP Half-Day meeting on Top Quark Physics

Top in the Standard Model

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introduction	• overview • theory status and glossary
top mass	• theoretical issues • “non-standard” measurements
forward-backward asymmetry	• Tevatron results vs SM predictions • prospects for LHC
spin correlations	• from top-pair production • from single-top production
wrap up	

why top ?

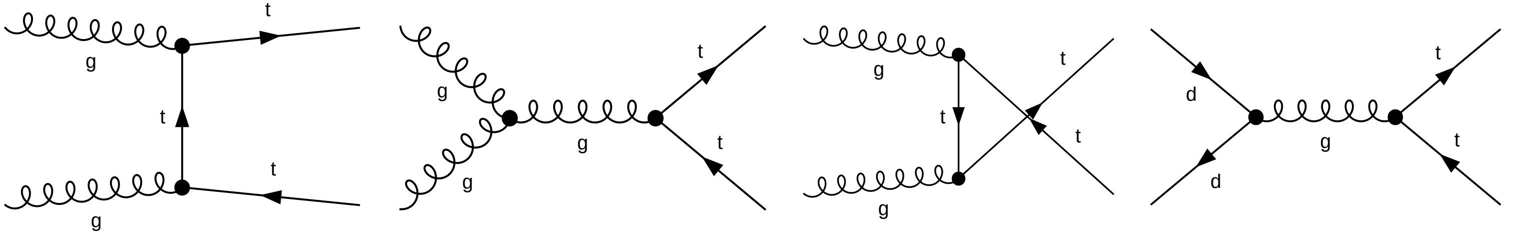
- top is a window to physics beyond the Standard Model
- in most, if not all, extensions of the SM, top plays a special role (Technicolor, topcolor SUSY, little Higgs)
- Yukawa coupling $y_t \sim \sqrt{2}\, m_t/v \simeq 1$, as it should
- width $\Gamma_t \sim 1.4$ GeV $\gg \Lambda_{\rm QCD} \quad \Longrightarrow$: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

top mass: important input for other observables

other measurements: make precise and detailed SM investigations and hope for a deviation

The focus in this talk is to understand the SM top

top pair production



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

	Tevatron	7 TeV LHC	14 TeV LHC
$t\,\bar{t}$	7	150	900
$q\,\bar{q}$	$\sim$ 90%	$\sim$ 20%	$\sim$ 10%
$g\,g$	$\sim$ 10%	$\sim$ 80%	$\sim$ 80%

SM top quark pair production: theory status

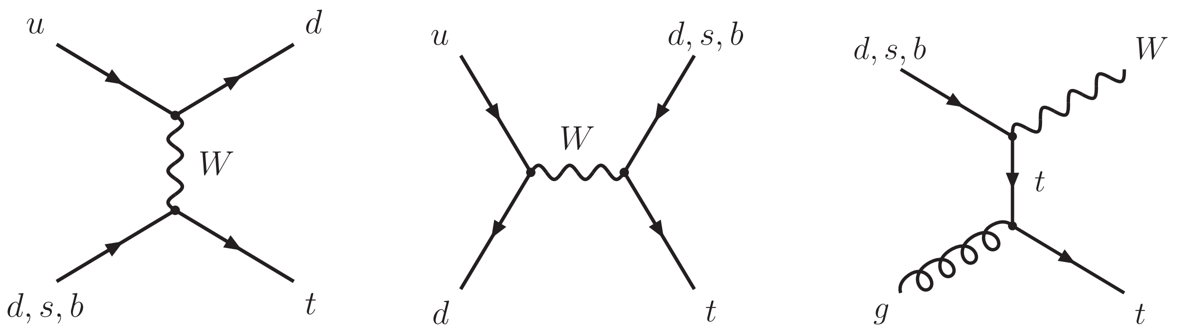
- fully exclusive known at $\sim$ one-loop

  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

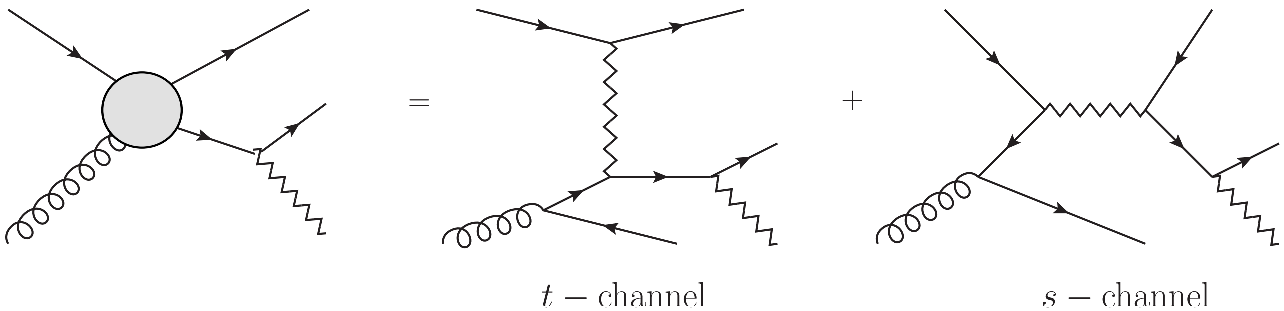
  two-loop nearly known [Czakon et.al, Moch et.al, . . .]
  bound-state effects computed [Hagiwara et.al., Kiyo et.al.]
  non-factorizable corrections computed [Beenakker et.al.]
  resummation of logs under control [Ahrens et.al, Beneke et.al . . .]

single top production



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

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



SM single top: theory status

- NLO QCD corrections, production and hadronic decay for t–, s–channel and Wt known [. . ., Harris et.al; Campbell, Ellis, Tramontano (MCMF)]
- 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.]
- 4-flavour vs. 5-flavour scheme studied [Campbell et.al.]
- resummation of inclusive cross section [Kidonakis, Wang et.al.]
- Note: s and t channel mix (beyond LO)
  $\rightarrow$ more aproproate to talk about (tJ), (tb) and (tW) cross sections

$t\bar{t}$ total cross section

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

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

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

$$\hat{\sigma}^{(1)}_{ij} = \underbrace{\frac{\#}{\beta}}_{\text{Coulomb}} + \underbrace{\# \log^2 \beta + \# \log \beta}_{\text{soft gluon}} + c^{(1)}_{ij} \Big] \Big)$$

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

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

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

$t\bar{t}$ total cross section, resummation of logs

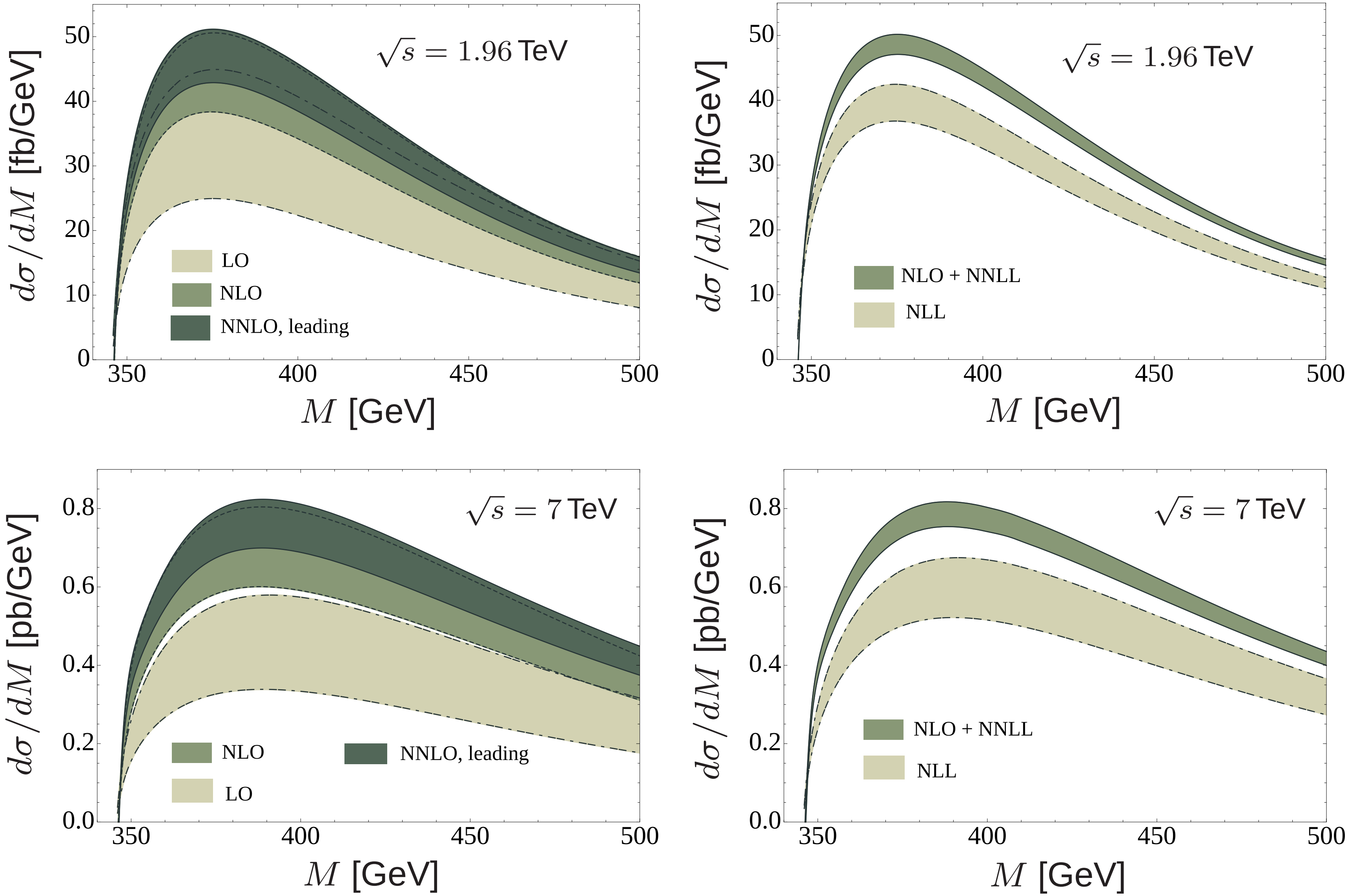
- resummation of soft logs (in threshold region $\sqrt{1 - 4m_t^2/s} \equiv \beta \to 0$)

  initially to NLL [Bonciani, Czakon, Catani, Mangano, Mitov, Nason . . . . . .]

  now NNLL [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: $1 - z \equiv 1 - M^2/\hat{s} \to 0 \Rightarrow \alpha_s^n \frac{\ln^m(1-z)}{(1-z)}$ with $m < 2n - 1$
  - single-particle inclusive: $s_4 \equiv p_X^2 - m_t^2 \to 0 \Rightarrow \alpha_s^n \ln^m(1 - s_4/m_t)/s_4$ with $m < 2n - 1$
- recover total cross section by integration $\Rightarrow$ formally subleading terms are numerically important
- resummation for “fully exclusive” quantities ??

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



$t\bar{t}$ bound-state effects

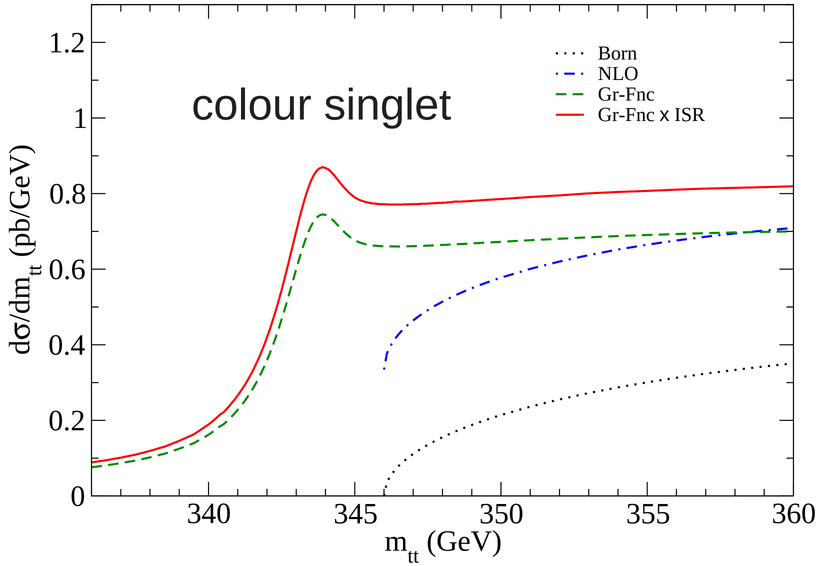
- near threshold Coulomb potential is dominating effect:

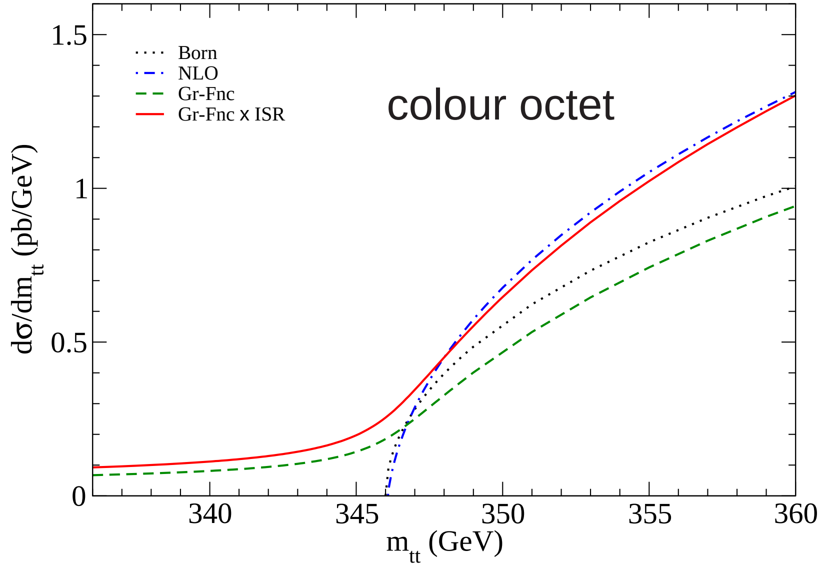
  colour singlet: $V(r) \simeq -\alpha_s \frac{C_F}{r}$ attractive

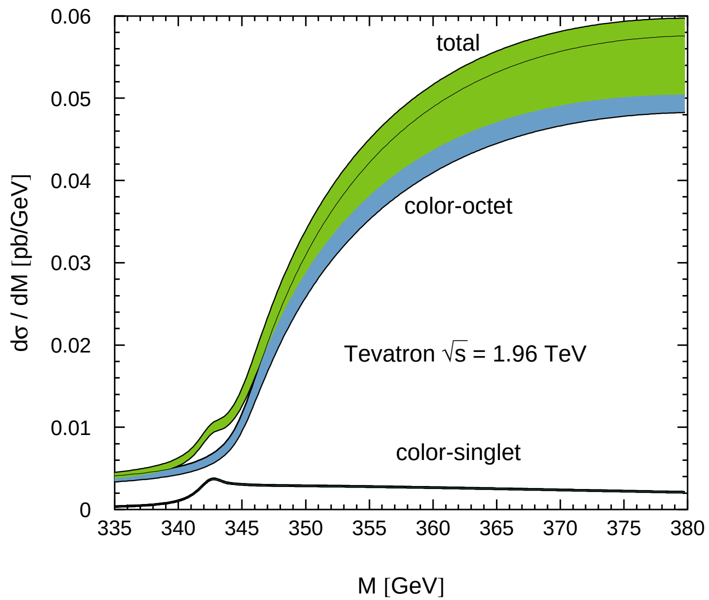
  colour octet: $V(r) \simeq -\alpha_s \frac{C_F - C_A/2}{r}$ repulsive

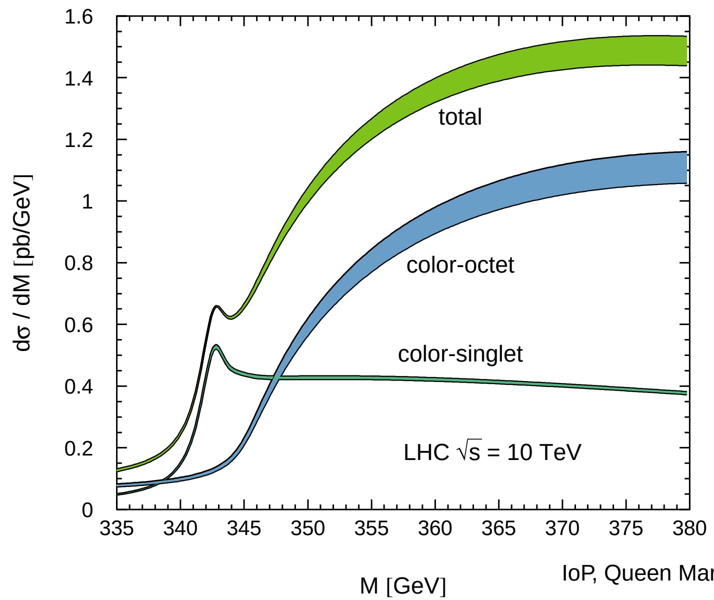
- for $\Gamma_t \to 0$ collections of bound states (as for bottom), for $\Gamma_t \simeq 1.4\ \mathrm{GeV}$ a single "bump" in invariant mass remains. [Fadin, Khoze]
- resummation of $(\alpha/\beta)^n$ (from Coulomb potential $\longrightarrow$ "bound-state" effects) [Hagiwara et.al., Kiyo et.al.] results 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 effect on total cross section should be taken into account.

bound-state effects [Hagiwara et.al. 0804.1014; Kiyo et.al. 0812.0919]

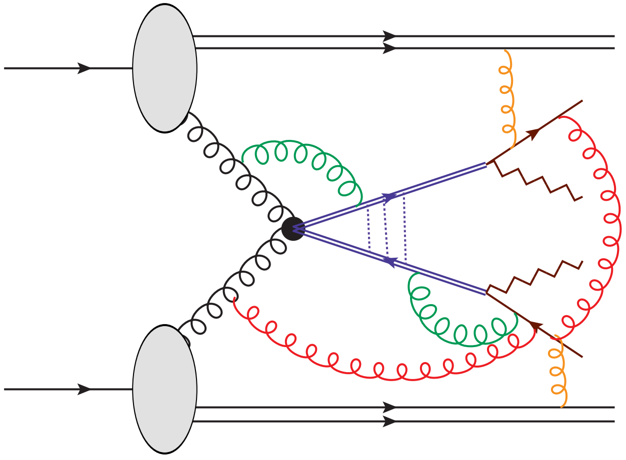






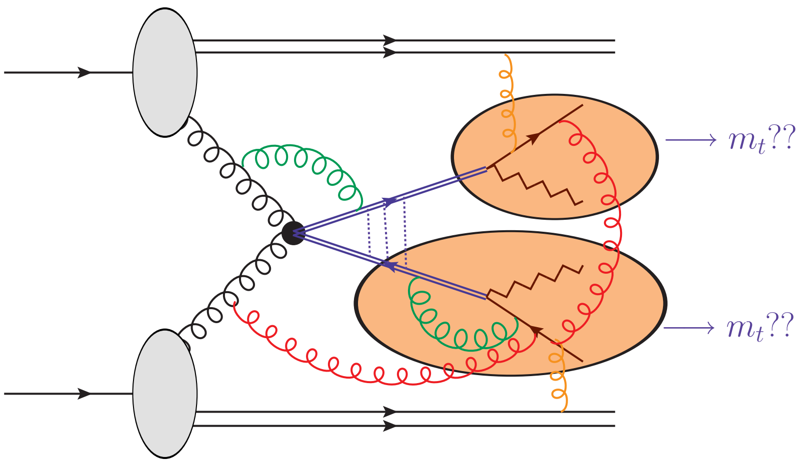


fully “exclusive” top pair production



- NLO corrections to production and decay [Bernreuther et.al, Melnikov et.al.]
- off-shell and off-resonance effects studied at tree level [Kauer, Zeppenfeld]
- non-factorizable corrections computed, [Denner et.al, Bevilacqua et.al.]
- (non-perturbative) colour connection to proton remnants: rough estimate $\Delta m_t \sim 0.5$ GeV [Skands, Wicke]

fully “exclusive” top pair production



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- most of these effects are not taken into account in m_t determination ! This is potentially problematic for $\delta m_t \lesssim \Gamma_t$

There are two (unrelated) problems with current m_t determinations through kinematic of decay products:

Problem 1

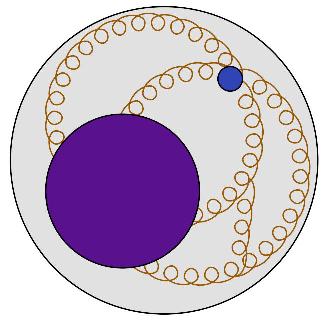
- current m_t measurements are basically tree-level determinations
- at tree level, formally all ren. schemes are equivalent, but $m_{\overline{\rm MS}} - m_{\rm pole} \sim 10$ GeV ??
- m_t extracted using decay products is "something like" the pole mass (small higher-order corrections)
- "something like" means propagator has to be resonant for $p_t^2 \simeq m_t^2 \to$ ambiguity of $\mathcal{O}(\Gamma_t)$
- alternative ways to measure m_t desperately needed, even if (apparently) not competitive
- care has to be taken when interpreting $m_{\rm exp} \overset{??}{=} m_{\rm pole}$
  however $m_{\rm exp} \overset{!!}{=} m_{\rm pole} + \mathcal{O}(\Gamma_t)$ is fine.

Problem 2: conceptual problem with pole mass

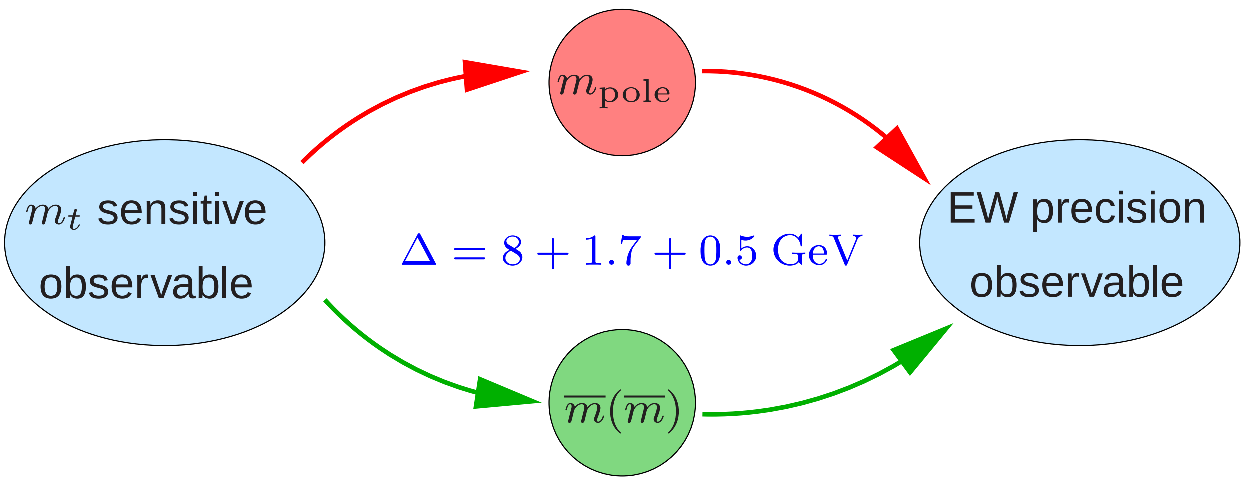
The pole mass has an intrinsic uncertainty of order Λ_{QCD} in perturbation theory (infrared sensitivity, renormalon ambiguity)

consider (fictitious) meson:

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

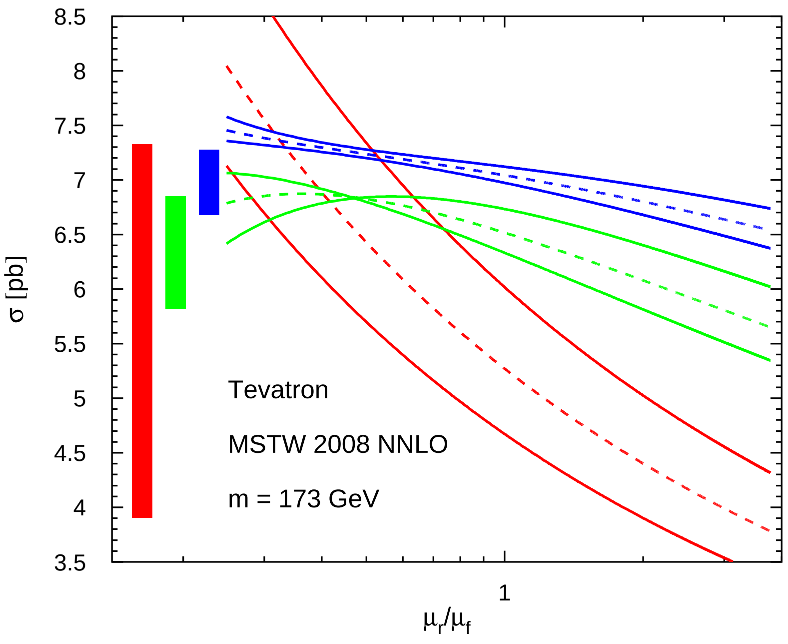


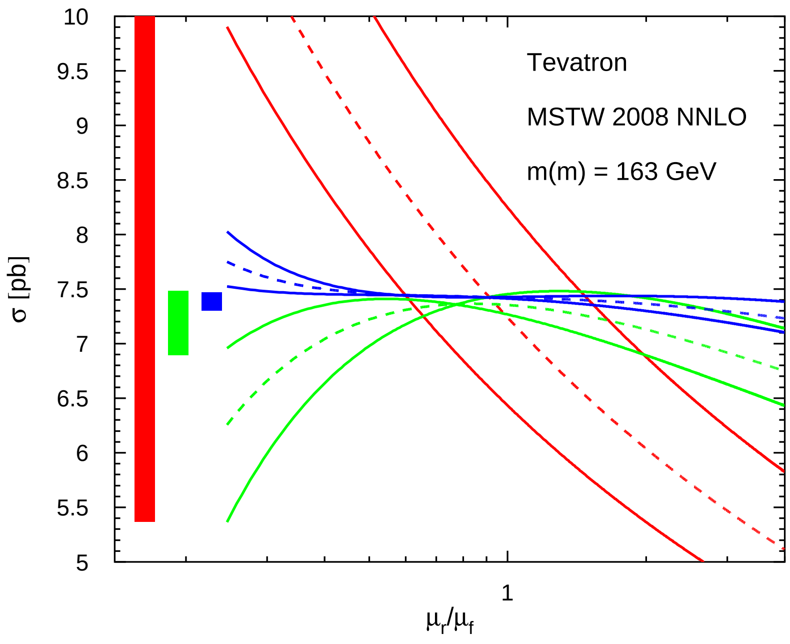
There is a principal limitation of the usefulness of the pole mass
$\delta m_t > \Lambda_{\text{QCD}} \Longrightarrow$ probably not relevant for LHC, only for linear collider m_t determinations
could be solved in principle [Hoang, Stewart]



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... ??

determination of m_{pole} through cross section [Biswas, Melnikov, Schulze, 1006.0910]

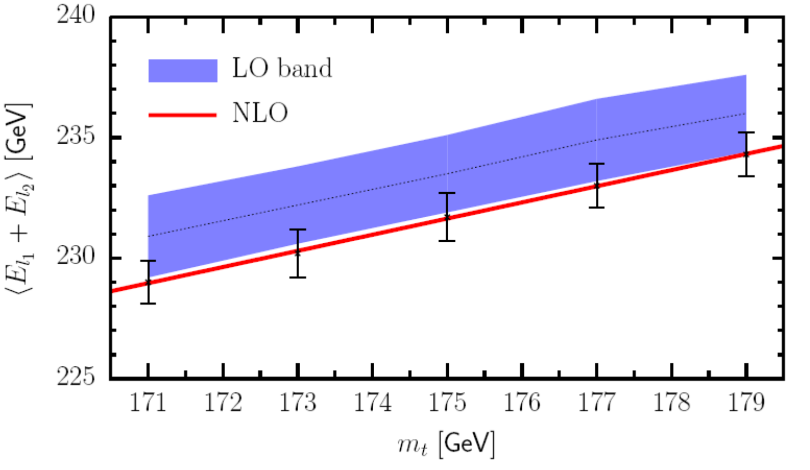
find observable with large m_t sensitivity and compute beyond LO

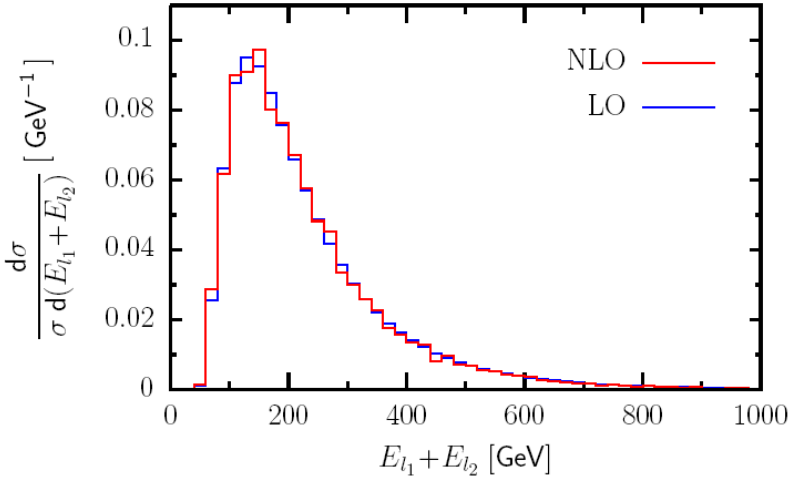
e.g. $E_\ell + E_{\ell'}$ in lab frame

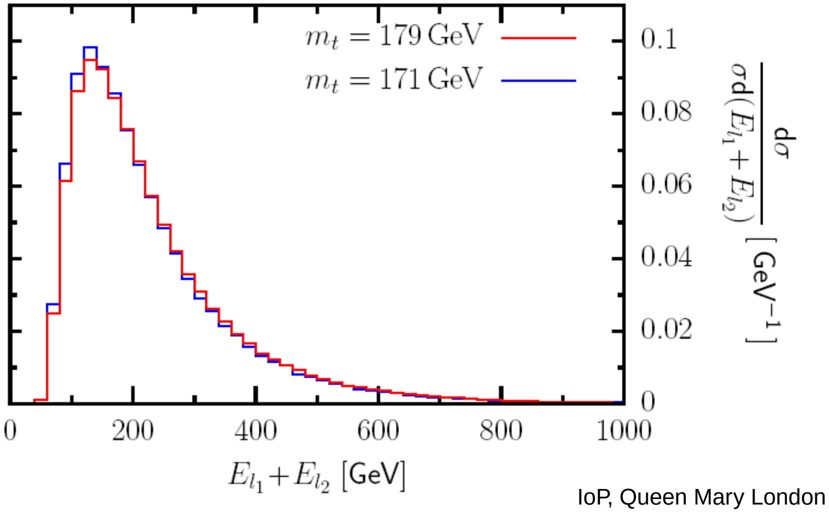
compare $\delta_{\text{th}} m$ (PDF, higher order) with m_t sensitivity

example here: evaluate $\langle E_\ell + E_{\ell'} \rangle$ for {MRST, CTEQ} $\times \mu \in \{0.5, 0.75, 1, 1.25\} m_t$

claimed $\delta_{\text{th}} m$: 1.7 (LO) $\longrightarrow$ 1 GeV (NLO)





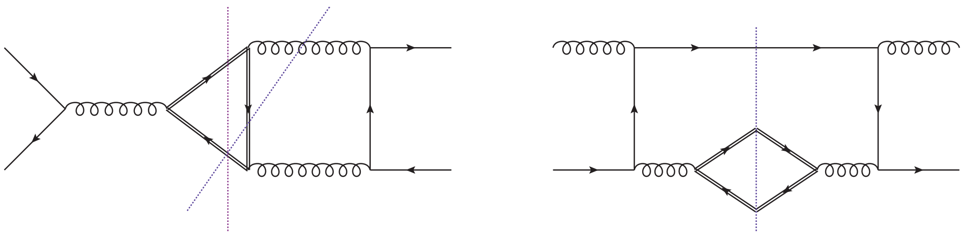


Forward-backward asymmetry at Tevatron

definition: $A_{\rm FB}^{t\bar{t}} = \dfrac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$ with $\Delta y \equiv y_t - y_{\bar{t}}$

SM prediction: [Kuhn, Rodrigo; Almeida et.al, Ahrens et.al]

- zero for QCD @ LO, non-zero but very small for EW @ LO
- QCD @ NLO (from $q\bar{q}$ only) $A_{\rm FB}^{p\bar{p}} \sim 5\%$ and $A_{\rm FB}^{t\bar{t}} \sim 8\%$ for Tevatron



$$A_{\rm FB} = \frac{\alpha_s^3 + \mathcal{O}(\alpha_s^4)}{\alpha_s^2 + \mathcal{O}(\alpha_s^3)} = \sigma^{\rm virt} + \sigma^{\rm real} = +\infty - \infty \simeq 5\%$$ (soft singularities)

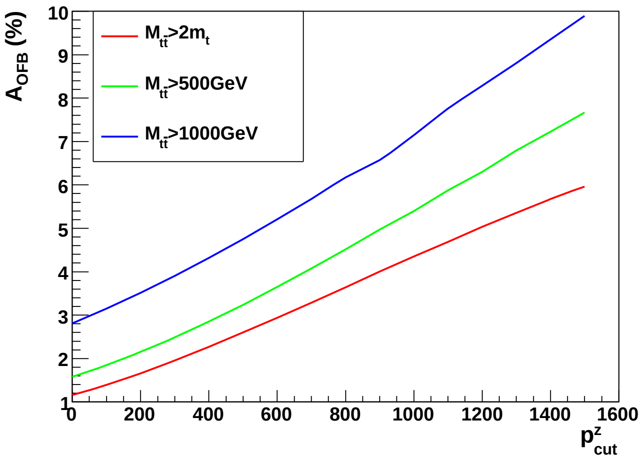
- new CDF measurement of $A_{\rm FB}^{t\bar{t}}$

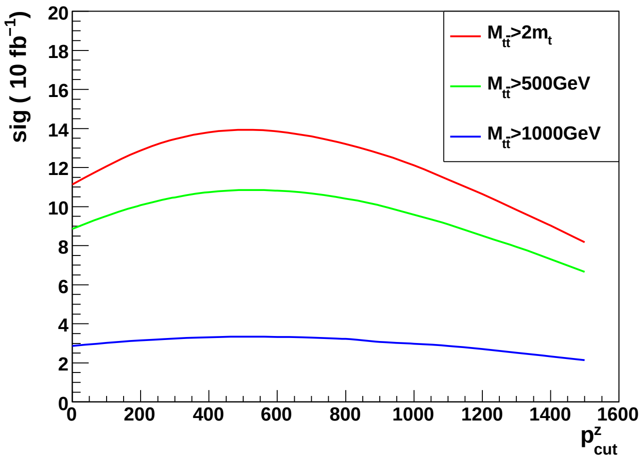
	$M_{t\bar{t}} < 450$ GeV	$M_{t\bar{t}} > 450$ GeV
CDF	-0.116 ± 0.154	0.475 ± 0.114
MCFM	0.040 ± 0.006	0.088 ± 0.013

- QCD @ NNLO: not known exactly, but from threshold resummation small corrections expected $\Rightarrow$ a SM value of $A_{\rm FB}^{t\bar{t}} > 0.2$ seems highly unlikely.

Prospects for LHC

- “eliminate” large denominator, i.e. gg initial state, use $f_q(x) > f_g(x), f_{\bar{q}}(x)$ for x large.
- several possibilities [Antunano et.al, Wang et.al . . .]
  - central charge asym: $A = \dfrac{\sigma_t(|y_t| < y_{\mathrm{cut}}) - \sigma_{\bar{t}}(|y_t| < y_{\mathrm{cut}})}{\sigma_t(|y_t| < y_{\mathrm{cut}}) + \sigma_{\bar{t}}(|y_t| < y_{\mathrm{cut}})} \sim 1\%$
  - LHCb: $A = \left.\dfrac{\sigma_t - \sigma_{\bar{t}}}{\sigma_t + \sigma_{\bar{t}}}\right|_{\eta\in 2-5}$
  - one-side asym: $A = \left.\dfrac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}\right|_{P_{t\bar{t}} > P_{\mathrm{cut}}, M_{t\bar{t}} > M_{\mathrm{cut}}}$





(example for 7 TeV LHC [Wang, Xiao, Zhu: arXiv:1008.2685])

- use (large) A_{FB} in $t\,\bar{t}\,j$ as cross-check for new-physics scenarios
  $t\,\bar{t}\,j$ known at NLO [Dittmaier et.al.]

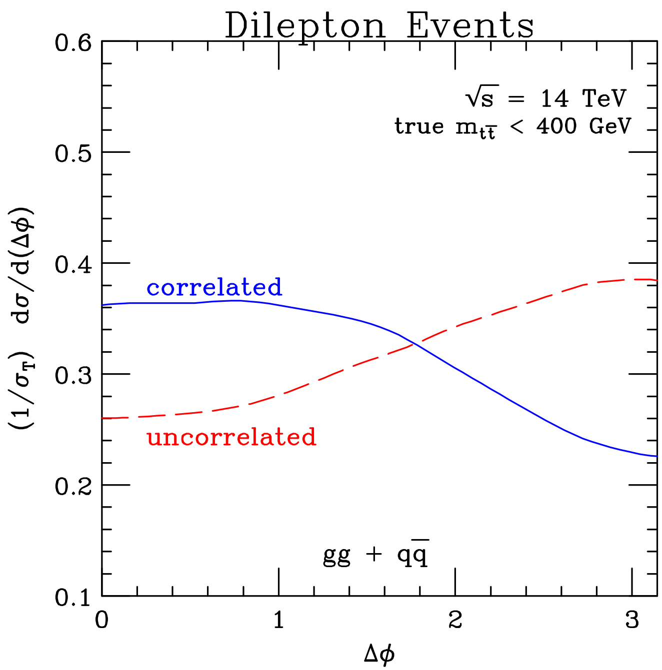
- decay of top not (much) affected by hadronisation $\longrightarrow$ information of spin in decay products $\longrightarrow$ desperate hope for non-SM top decay
- needs decay of top implemented, preferably with NLO corrections
- can be done for top-pair production and single-top production
- direct measurement of F_L, F_0, F_R (W helicity in its rest frame) is difficult
- better (?) way: find observable (angle) that is sensitive to spin correlations
- compare true correlated top decay to uncorrelated top decay (spherically in rest frame) or to SM+BSM with anomalous top couplings
  - anomalous $W\,t\,b$ vertex [Aguilar-Saavedra et.al.]

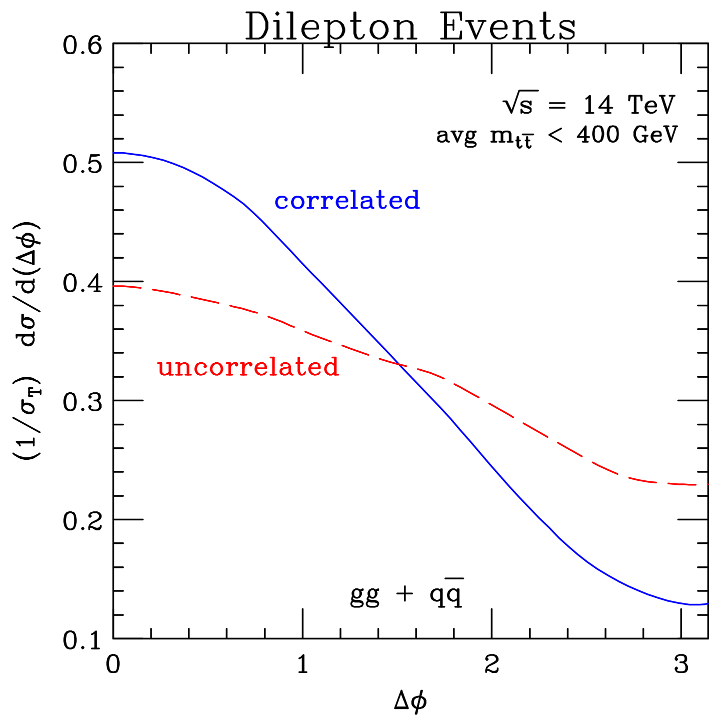
$$-\frac{g}{\sqrt{2}}\,\bar{b}\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\,\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

  - effective dimension 6 (and higher) operators [Willenbrock et.al.], affect production and decay e.g: $O_{\phi q} = i(\phi^{+}\tau D_{\mu}\phi)(\bar{q}\gamma^{\mu}\tau q)$ or $O_{tW} = (\bar{q}\,\sigma^{\mu\nu}\tau\,t\,\tilde{\phi})W_{\mu\nu}$
  - similar to anomalous triple-gauge couplings, with similar problems (form factors), but might be useful to check possible link between different effects.

top pair production [Mahlon, Parke; Melnikov, Schulze]

- at LHC, mostly $gg \to t\bar{t}$, this has more complicated helicity structure than $q\bar{q} \to t\bar{t}$.
- for low (high) $M_{t\bar{t}}$ like (opposite) helicity gluons dominate [Mahlon, Parke]
- make cut $M_{t\bar{t}} < 400$ GeV ($\sim$ 10% of cross section survives) and investigate $\Delta\phi_{\ell\,\ell'}$, angle between leptons $\Rightarrow$ correlations $\pm 40\%$ [Mahlon, Parke, arXiv:1001.3422]





- cannot get true $M_{t\bar{t}} < 400$ GeV due to ambiguity from ν in leptonic decay $\to$ cut on average of reconstructed $M_{t\bar{t}} < 400$ GeV (right)
  or: use semi-leptonic decay ($\to$ ambiguity on which jet is d jet)

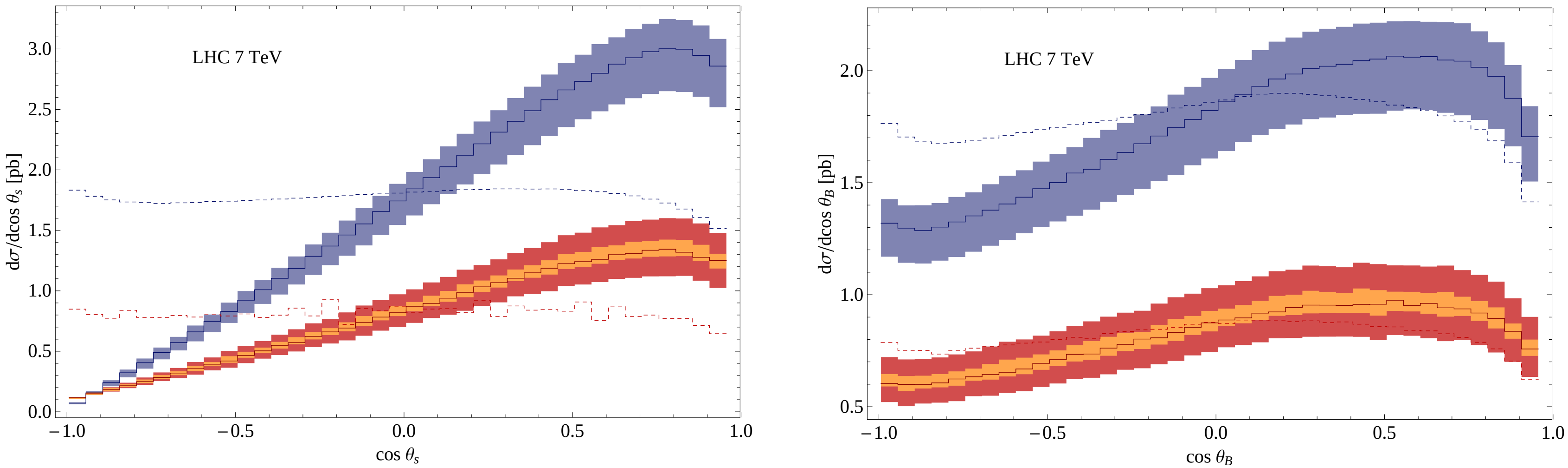
single top production [Cao et.al; Motylinski; Falgari et.al.]

compare $\cos\theta$ distributions with and without (dashed) spin correlations

$$\cos\theta_S = \frac{\vec{p}_s^{\,*}\cdot\vec{p}_\ell^{\,*}}{|\vec{p}_s^{\,*}|\,|\vec{p}_\ell^{\,*}|} \qquad \text{and} \qquad \cos\theta_B = \frac{\vec{p}_p^{\,*}\cdot\vec{p}_\ell^{\,*}}{|\vec{p}_p^{\,*}|\,|\vec{p}_\ell^{\,*}|}$$

$\vec{p}_s^{\,*}$: momentum of spectator jet in top-quark rest frame

$\vec{p}_b^{\,*}$: momentum of proton (beam) jet in top-quark rest frame



[Falgari et.al: arXiv 1102.5267]

- cross sections
  - don't be fooled by "NNLO", "NNLL" etc labels! A one-loop (two-loop) calculation does not describe every quantity at NLO (NNLO)!
  - actually measured cross sections (rather than only interpolated total cross sections) would be very useful
- top mass
  - for a precise determination of the top mass, $m_{\rm pole} \neq m_{\rm MC}$
  - need many different ways to measure top mass to get better (i.e. some) control on non-perturbative effects, even if some measurements are "not competitive"
- SM varia
  - y_t: direct test of Higgs mechanism $\rightarrow$ extremely important (note $pp \rightarrow t\bar{t}H$ known at NLO [Beenakker et.al])
  - Γ_t: well known (computed) in SM, sensitive to BSM $\rightarrow$ important
  - CKM: direct measurement of V_{tb}, indirect constraints on other matrix elements (?)
  - Q, T_3: very unlikely to differ from SM $\rightarrow$ less important