Birmingham 8. Dec. 2010

Top Quark Physics at the LHC

from a theoretical point of view

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The focus in this talk is to understand the SM top, not on the many new-physics models involving the top

introduction
- top as a window to new physics

top pair production
- theory status
- inclusive vs. exclusive quantities
- issues regarding top quark mass
- spin correlations

single top
- theory status
- non-factorizable corrections
- spin correlations
- determination of CKM matrix elements

conclusions

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

Focus on precise and detailed SM investigations and hope for a deviation

current “deviations” (e.g. forward-backward asymmetry) are not convincing

$e_Q; T_3;$ 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 ...

general

- 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.]
- $m_{t,\mathrm{pole}}/\overline{m_t}(\overline{m_t})$ known at α_s^3 [Chetyrkin, Steinhauser]

top quark pair production

- fully exclusive known at $\sim$ one-loop
  electroweak corrections known [Bernreuther et.al.]
  spin correlations included [Bernreuther et.al., Melnikov et.al.]
  included in MC@NLO and POWHEG [Frixione, Nason, Webber . . . . . .]
  two-loop corrections on their way . . .
  non-factorizable 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]

- 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 of soft 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 . . . . . .]

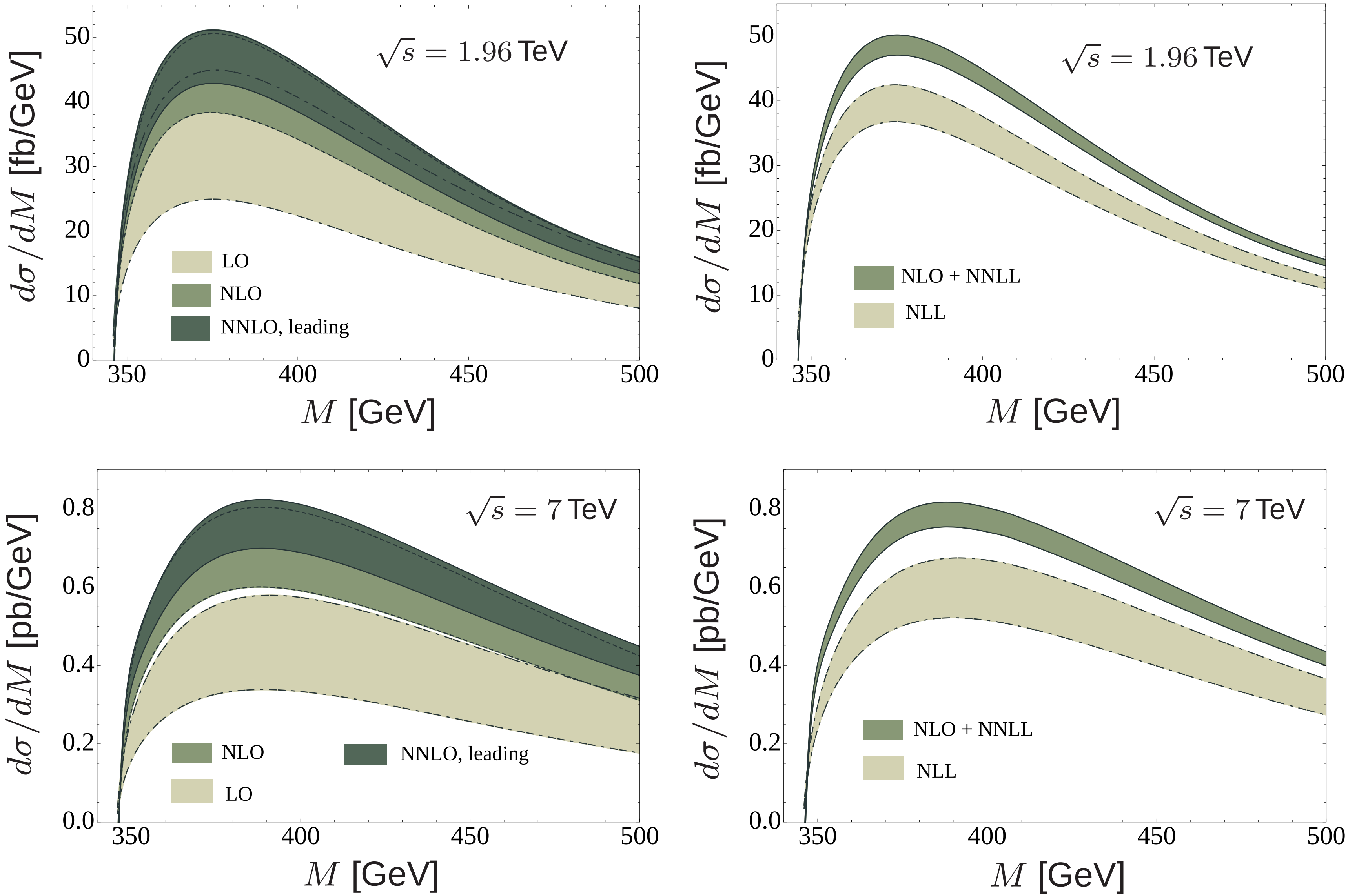
  now NNLL [Czakon et.al., Beneke et.al., Ahrens et.al., ...]
- resummation of $\log \beta$ does not yield large numerical contributions, but considerably improves the scale dependence of the cross section
- resumation more important for Tevatron than LHC
- note: different kind of logs for different quantities

  total cross section: $\log(1-4m^2/s)$

  p_T distribution: $\log(1-4(m^2+p_t^2)/s)$

  invariant mass distribution: $\log(1-M_{t\bar{t}}/\hat{s})$
- resummation for “fully exclusive” quantities ??

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



bound-state effects

- near threshold Coulomb potential is dominating effect:

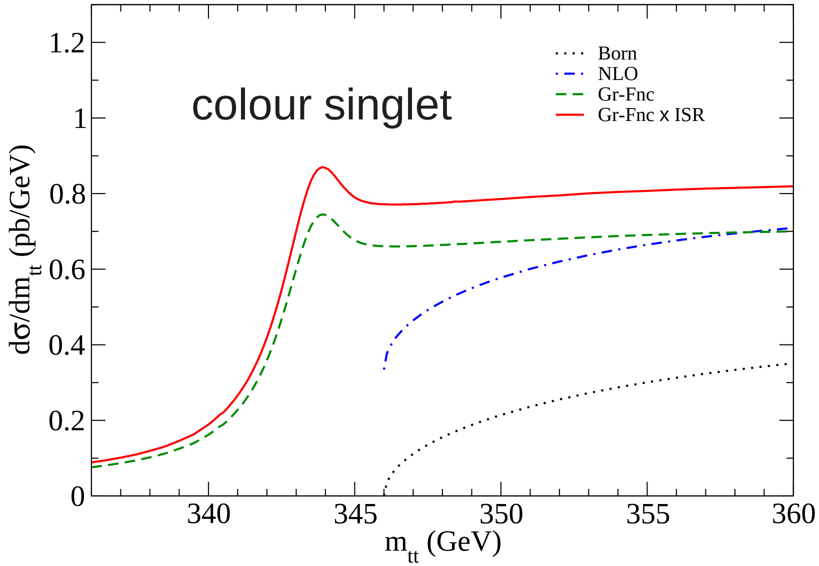
  colour singlet: $V(r) \simeq -\alpha_s \frac{C_F}{r}$ attractive

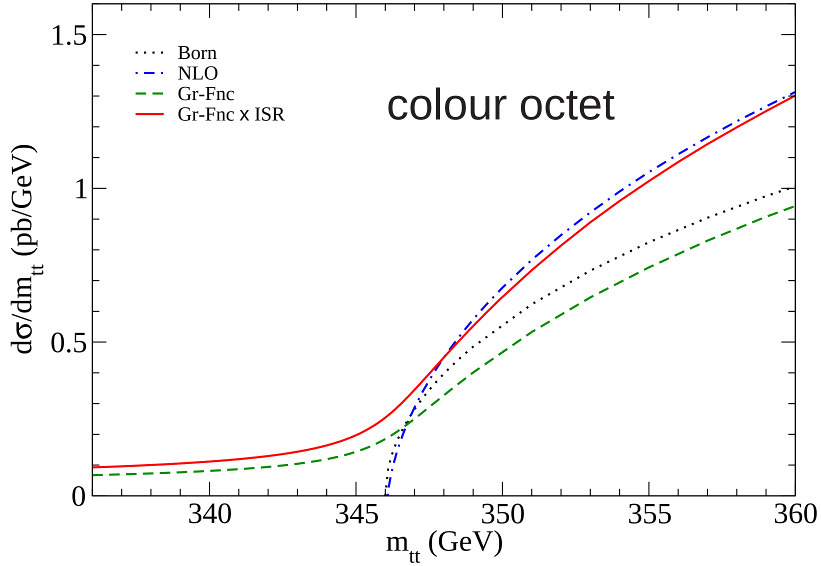
  colour octet: $V(r) \simeq -\alpha_s \frac{C_F - C_A/2}{r}$ repulsive

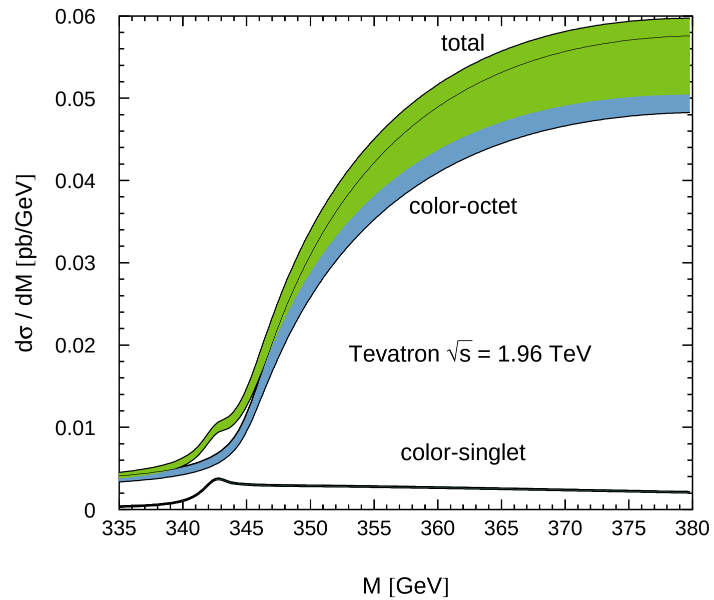
- for $\Gamma_t \to 0$ collections of bound states (as for bottom), for $\Gamma_t \simeq 1.4\ \mathrm{GeV}$ a single “bump” in invariant mass remains.
- resummation of $(\alpha/\beta)^n$ (from Coulomb potential $\longrightarrow$ “bound-state” effects) [Hagiwara et.al., Kiyo et.al.] results in modification 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.

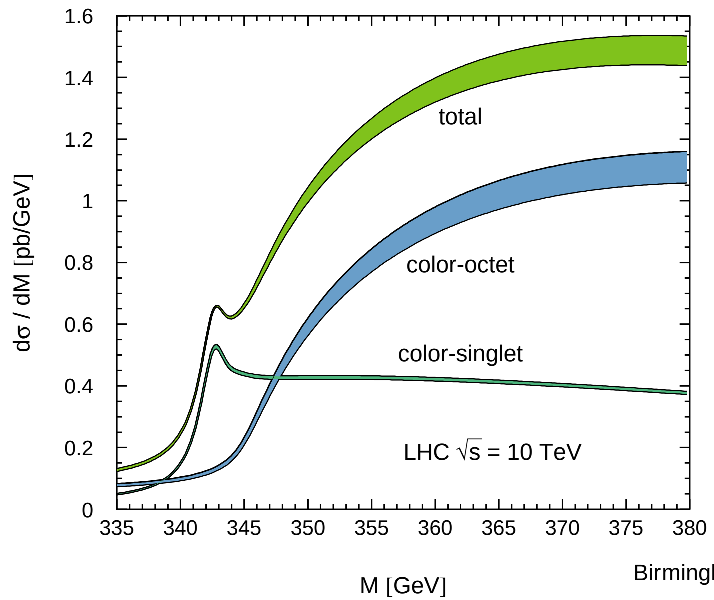
$M_{t\bar{t}}$ *invariant mass*

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







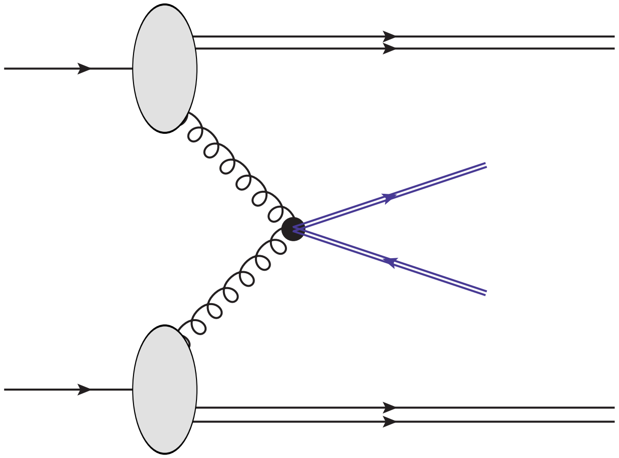


more realistic quantities

- impressive progress for inclusive quantities, well under control
- what does this have to do with measured quantities ??
- final state is not t, but $\ell\,\nu\,J_b$ or $J_1\,(J_2,)\,J_b$
- include top decay, allow for cuts
  - NLO QCD corrections in production and decay taken into account [Bernreuther et.al., Melnikov et.al.]
  - electroweak corrections included, generally quite small [Bernreuther et.al.]
  - non-factorizable corrections not included (only in inclusive case [Beenakker et.al.])
- cancellations for non-factorizable corrections [Fadin et.al; Melnikov et.al] disturbed if cuts applied
- small effects might be important for a mass determination with $\delta m_t \lesssim \Gamma_t$

m_t measurements from top decay products measurement of pole mass, potentially a problem if

$\delta m_t \lesssim \Gamma_t \sim 1.5\ \mathrm{GeV}$



- top as final state

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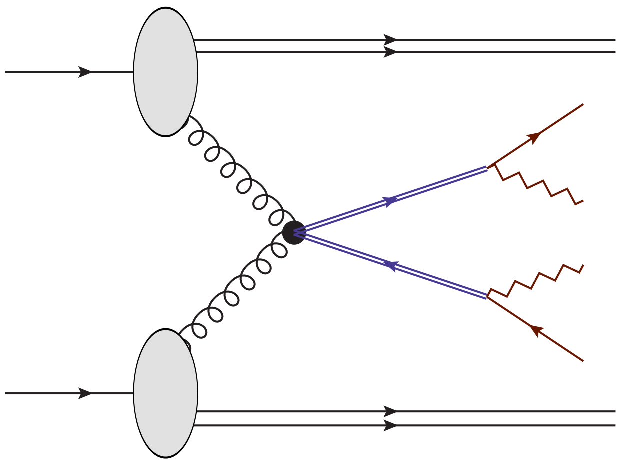

- top decay taken into account

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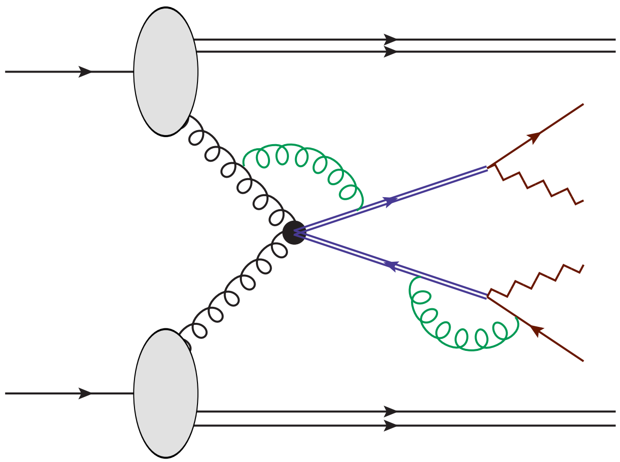

- top decay taken into account
- NLO corrections to production and decay [Bernreuther et.al, Melnikov et.al.]

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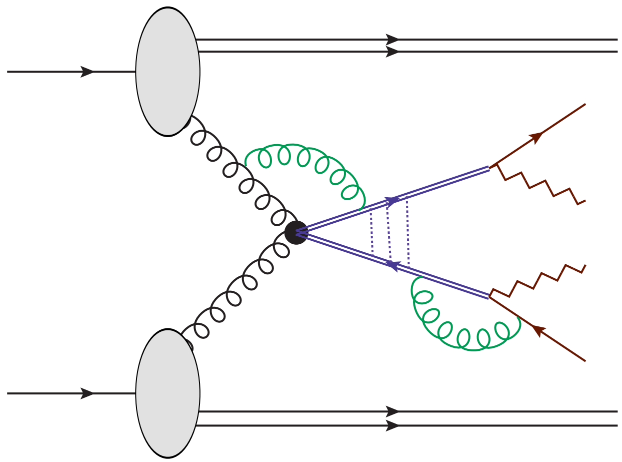

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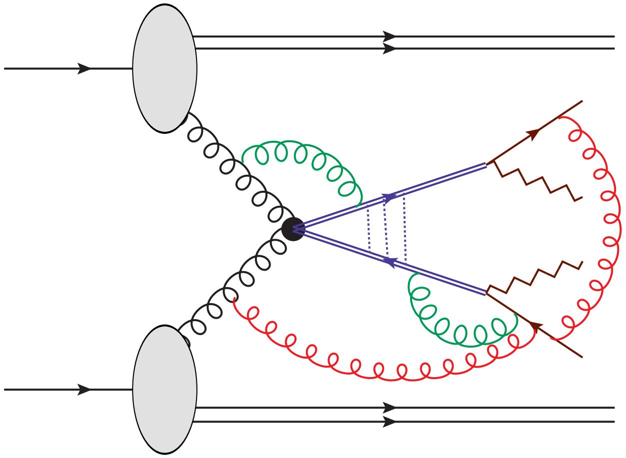

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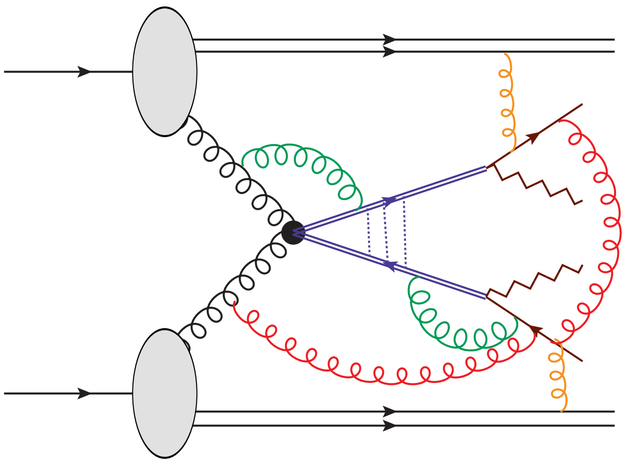

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- (non-perturbative) colour connection to proton remnants: rough estimate $\Delta m_t \sim 0.5\ \mathrm{GeV}$ [Skands, Wicke]

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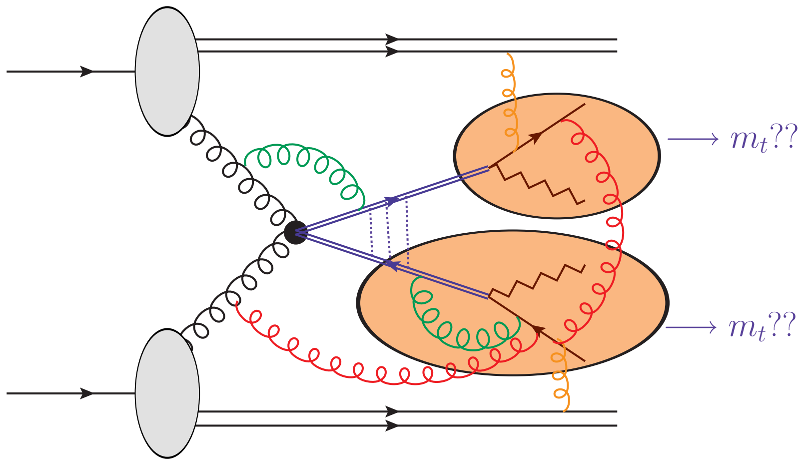

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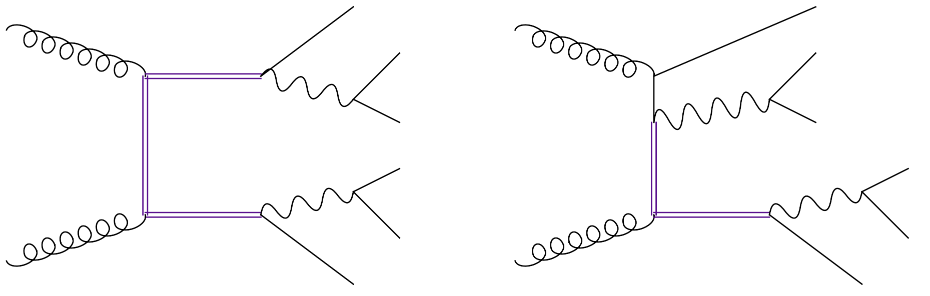
beyond $pp \to t\bar{t} \to W^+W^-b\bar{b}$ have to consider the decay for experimental cuts

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



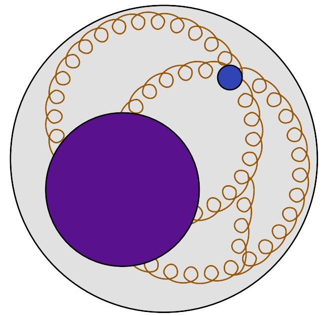
in general: $p^2 = m_t^2 \Rightarrow$ singularity $\Rightarrow$ include width $\Rightarrow$ gauge invariance issues
importance of these effects crucially depends on final state cuts

- non-factorizable corrections studied for (inclusive) invariant mass distribution $\longrightarrow$ small effect $\Delta m_t \sim 100\ \mathrm{MeV}$ [Beenakker, Berends, Chapovsky]
- cancellation theorems for NF corrections in inclusive case [Fadin et.al, Melnokov et.al]
- NF corrections become more important when cuts are applied ($\longrightarrow$ single top case)
- no general purpose MC avaliable including all these effects,
  invariant mass of top decay products is treated at tree level.

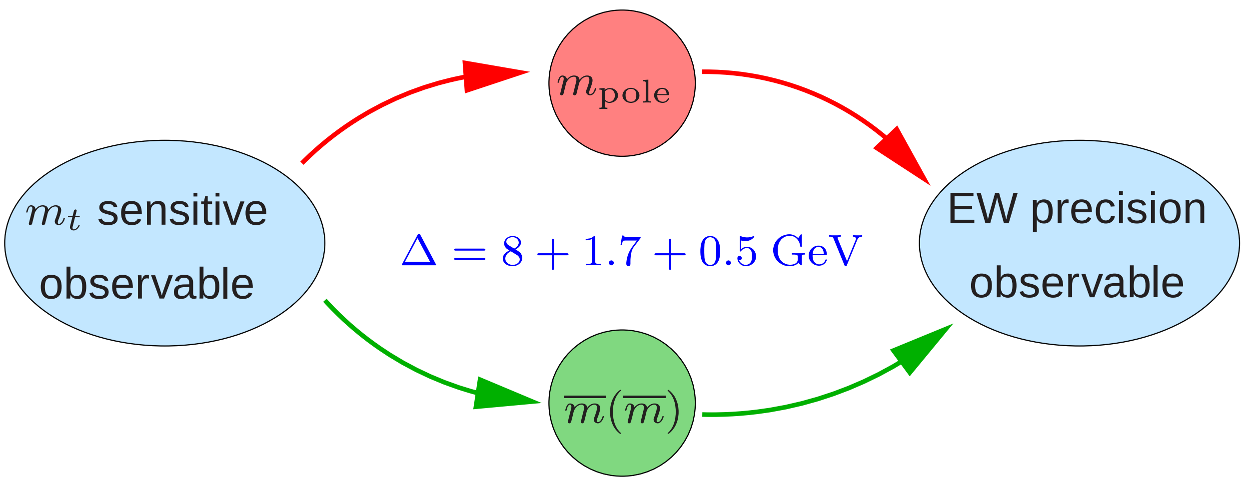
The mass is simply a parameter of the theory (renormalization scheme dependent!)
The pole mass has an intrinsic uncertainty of order $\Lambda_{\rm QCD}$ in perturbation theory (infrared sensitivity, renormalon ambiguity)

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
$\delta m_t > \Lambda_{\rm QCD} \Longrightarrow$ probably not relevant for LHC, only linear collider
could be solved in principle [Hoang, Stewart]

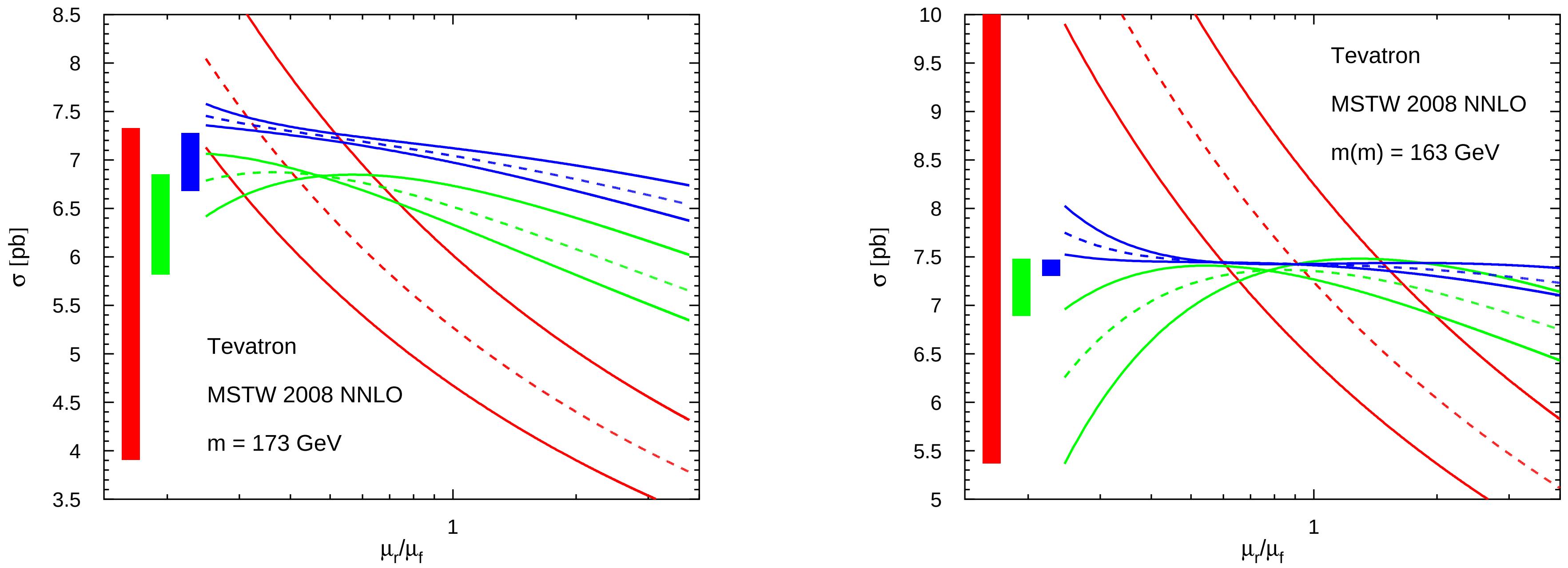


renormalization scheme

- at tree level, in principle any renormalization scheme is equivalent, but $m_{\overline{\mathrm{MS}}} - m_{\mathrm{pole}} \sim 10\ \mathrm{GeV}$??
- 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 $p_t^2 \simeq m_t^2 \rightarrow$ ambiguity of $\mathcal{O}(\Gamma_t)$
- this is a purely perturbative problem !!
- there are also many further (smaller) problems, some non-perturbative (renormalon ambiguity of pole mass, colour reconnection)
- alternative ways to measure m_t desperately needed, even if (apparently) not competitive
- care has to be taken when interpreting $m_{\mathrm{exp}} \overset{??}{=} m_{\mathrm{pole}}$

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 $m_{\rm pole}$ through cross section [Biswas, Melnikov, Schulze, 1006.0910]

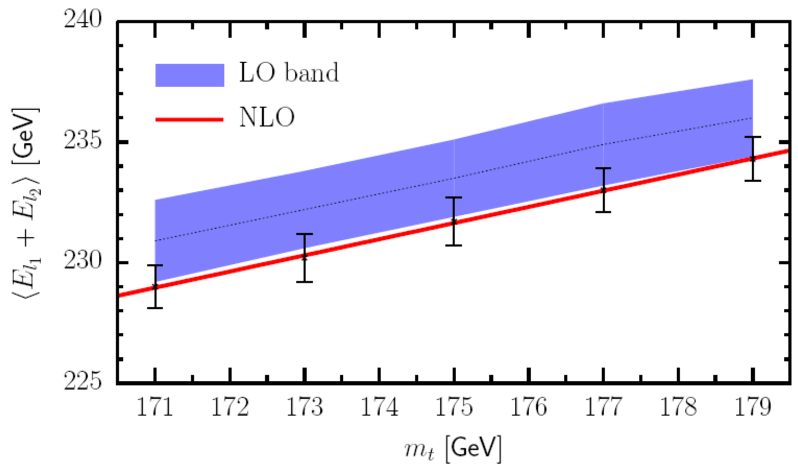
find observable with large m_t sensitivity and compute beyond LO

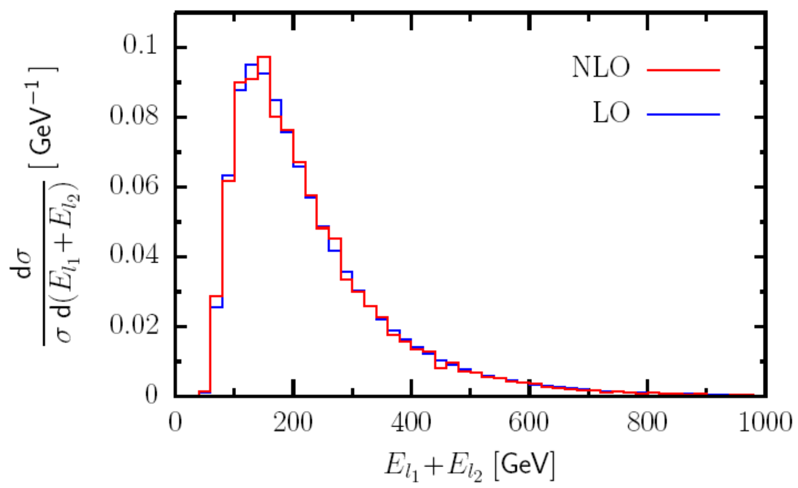
e.g. $E_\ell + E_{\ell'}$ in lab frame

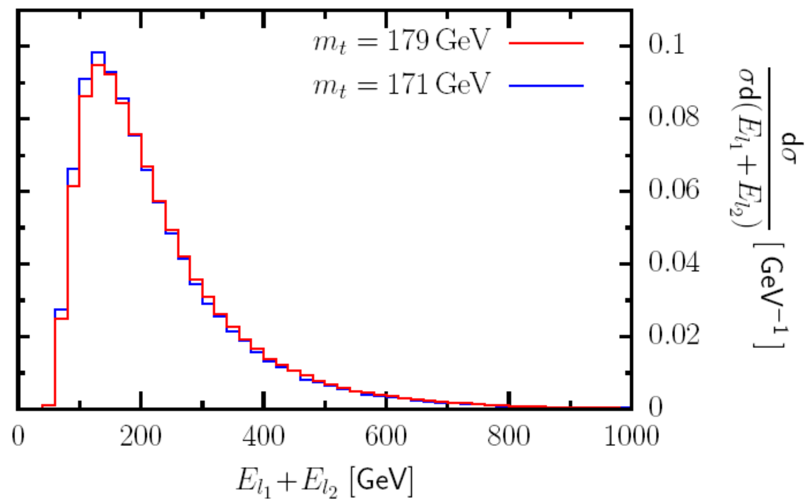
compare $\delta_{\rm th} m$ (PDF, higher order) with m_t sensitivity

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 $\delta_{\rm th} m$: 1.7 (LO) $\rightarrow$ 1 GeV (NLO)

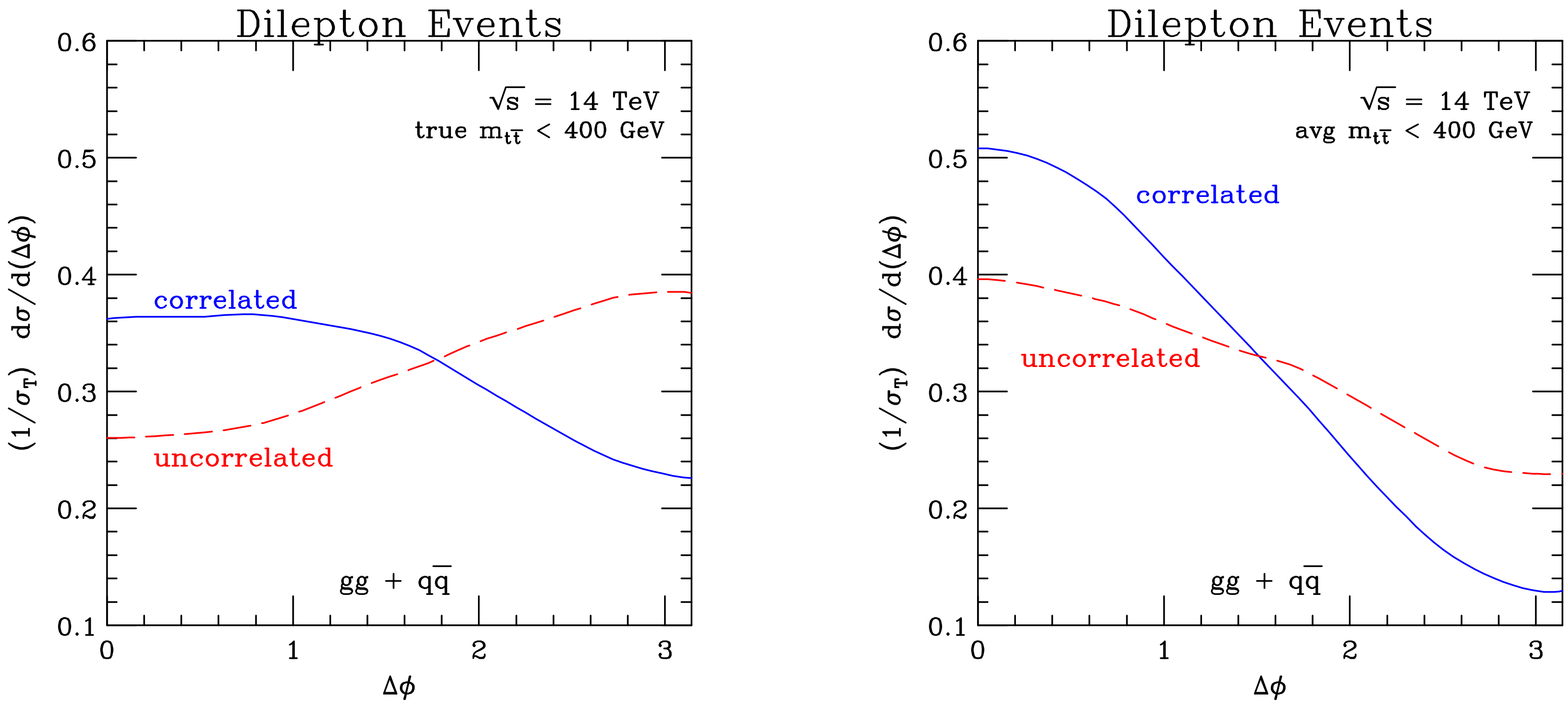






- decay of top not (much) affected by hadronisation $\longrightarrow$ information of spin in decay products
- desperate hope for non-SM top decay
- obviously, this needs decay of top implemented, with NLO corrections in production and decay [Bernreuther et.al.]
- at LHC, mostly $gg \to t\bar{t}$, this 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
- compare true correlated top decay to uncorrelated top decay (spherically in rest frame) $\longrightarrow$ next slide
- only punishment for 14 TeV $\to$ 7 TeV is smaller cross section

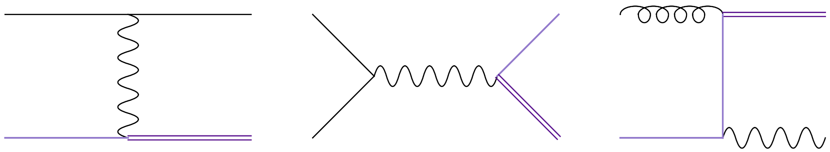
correlations $\pm 40\%$ [Mahlon, Parke, arXiv:1001.3422]



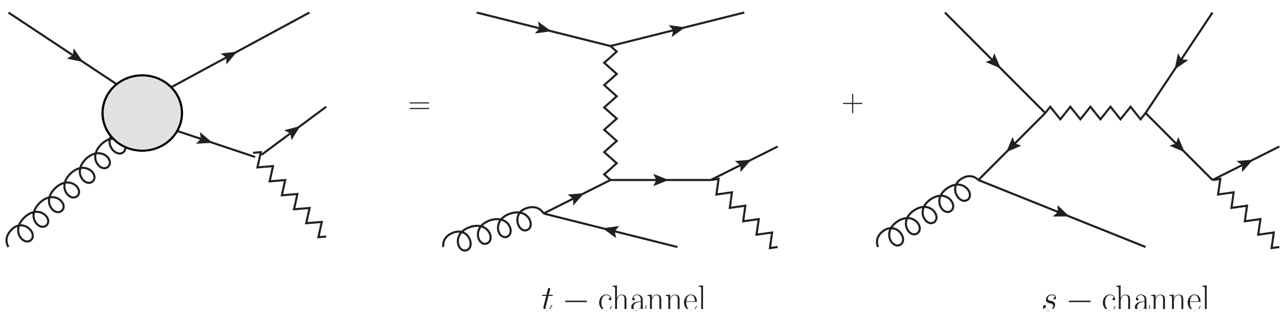
cannot get true $M_{t\bar{t}} < 400$ GeV due to ambiguity from ν in leptonic decay $\rightarrow$
cut on average of reconstructed $M_{t\bar{t}} < 400$ GeV (right)
or: use semi-leptonic decay ($\rightarrow$ ambiguity on which jet is d jet)

Theory status

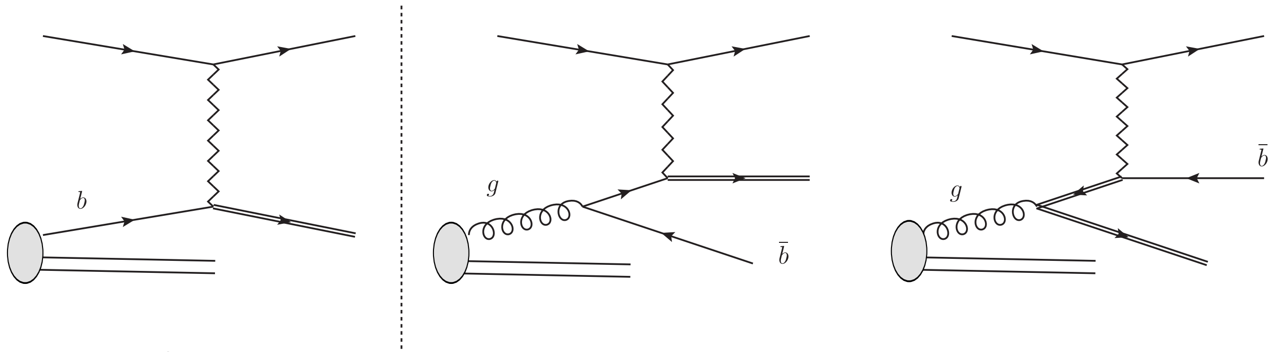
- NLO QCD corrections, production and hadronic decay for t–, s–channel and Wt known [. . ., Harris et.al; Campbell, Ellis, Tramontano (MCMF)]



- all channels included in MC@NLO and POWHEG [Frixione, Laenen, Motylinski, Nason, Re, Webber, White . . . . . .]
- EW corrections known [Beccaria et.al; Macorini et.al]
- non-factorizable corrections known [Falgari et.al.]
- Note: s and t channel mix (beyond LO)
  $\longrightarrow$ more aproproate to talk about (tJ), (tb) and (tW) cross sections



4-flavour vs. 5-flavour scheme [Campbell et.al.]



LO 5 Flavour | LO 4 Flavour

5F scheme calculation is simpler and resums potentially large logs (due to collinear split $g \to b\bar{b}$.) via PDF. Thus this is better than 4F scheme, unless we are interested in b spectator quark. For NLO description of b spectator quark, need 4F (NLO) calculation.

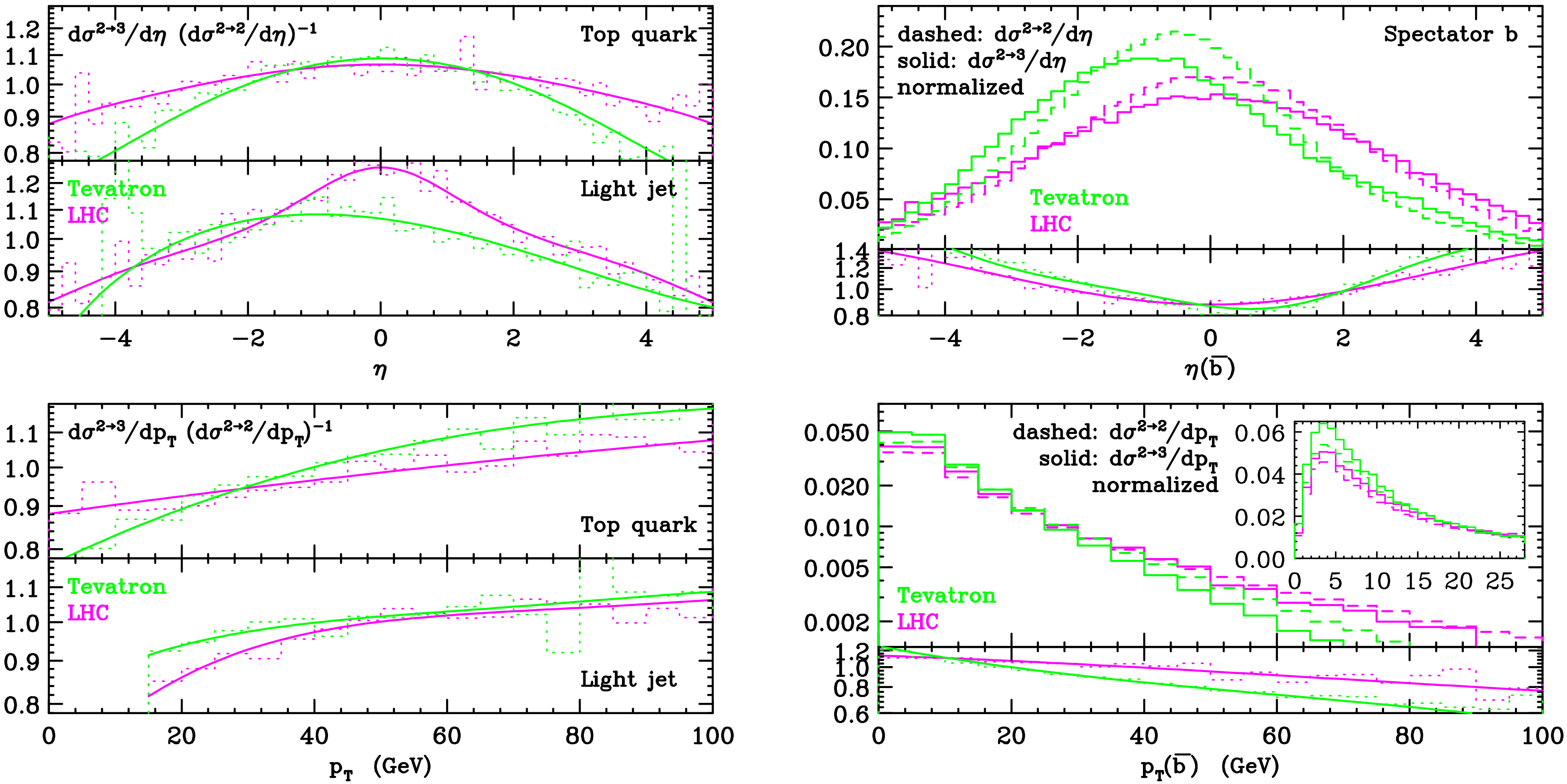
	LHC t	LHC $\bar{t}$
5F	$(153)156^{+4+3}_{-4-4}$	$(89)93^{+3+2}_{-2-2}$
4F	$(143)146^{+4+3}_{-7-3}$	$(81)86^{+4+2}_{-3-2}$

just about consistent, effects of logs?

(LO) NLO total cross section (in pb) for LHC, 14 TeV, scale and pdf error

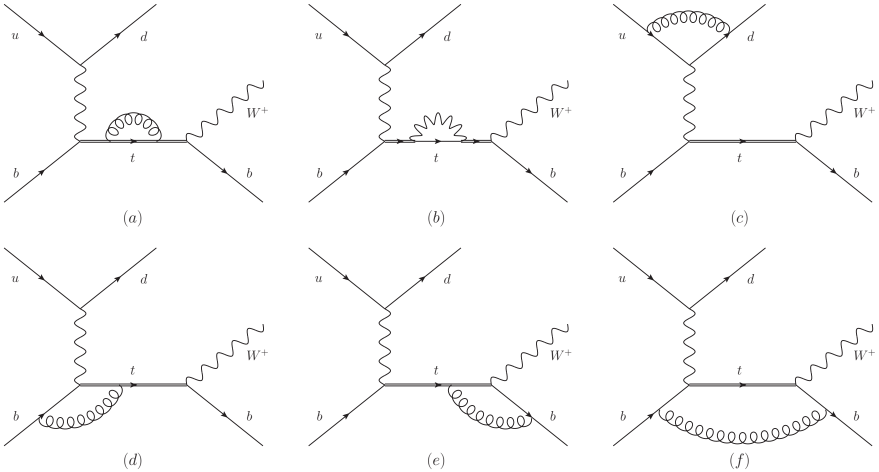
$m_b = 4.7$ GeV, mass effects are not important for “normal” quantities

4-flavour (solid) vs. 5-flavour (dashed) scheme [Campbell et.al. 0903.0005]



generally reasonable agreement, $\sim 10 - 20$ % difference, but b spectator quantities??

effect of non-factorizable corrections enhanced by cuts [Falgari, Mellor, AS]



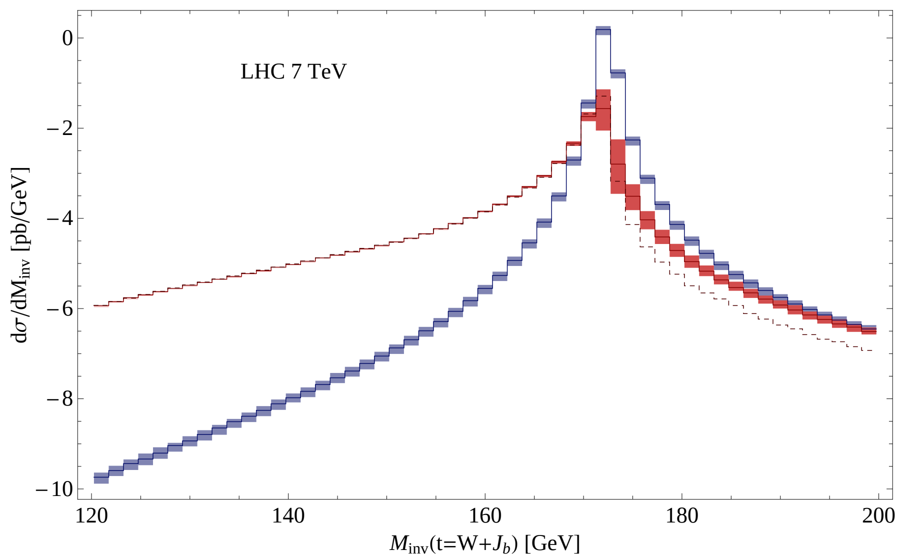
LHC cross section $7\ \mathrm{TeV}$ with and without (reasonable) cuts: $\sim p_T, \not{E}_T > 20\ \mathrm{GeV}$

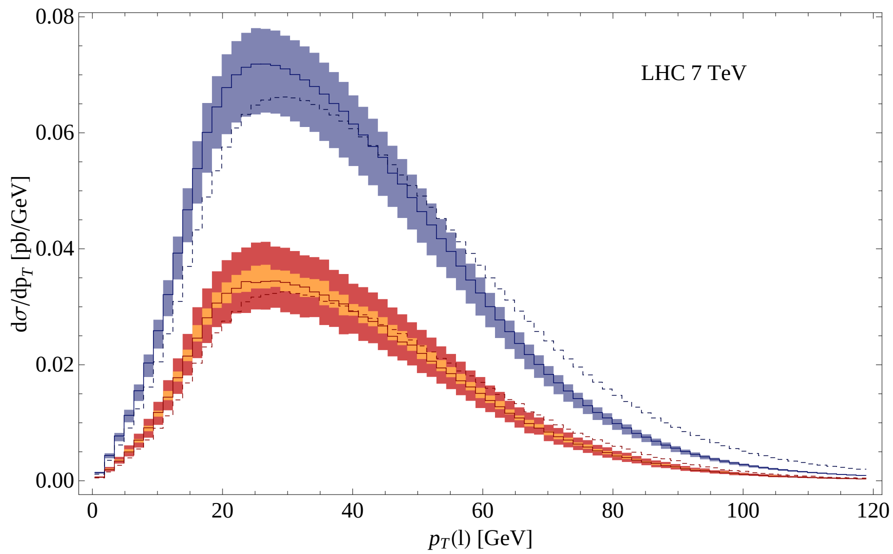
	on-shell t	off-shell t	%
no cuts	84.9	86.3	+ 1.7%
cuts	2.31	2.23	- 3.6%

full NLO corrections $\sim$ 15%
non-factorizable part is not (always) negligible

effect of non-factorizable corrections [Falgari, Mellor, AS]

compare distributions with (solid) and without (dashed) non-factorizable corrections for e.g. invariant mass and $p_T(\ell)$; t-channel at LHC, with cuts:

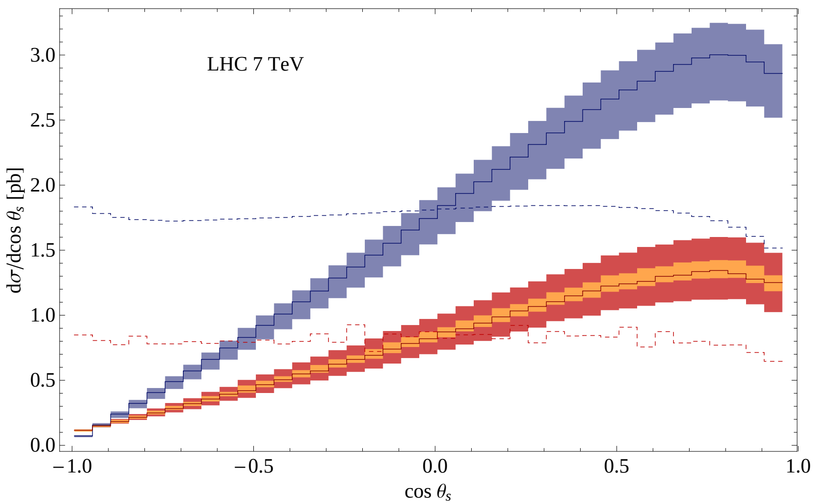


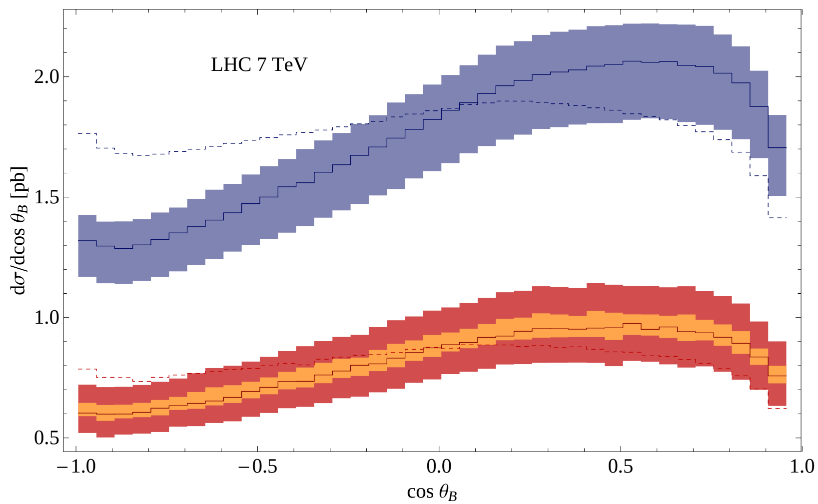


- note: large corrections (due to cuts)
- NLO outside LO-scale band $m_t/4 \leq \mu \leq m_t$

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

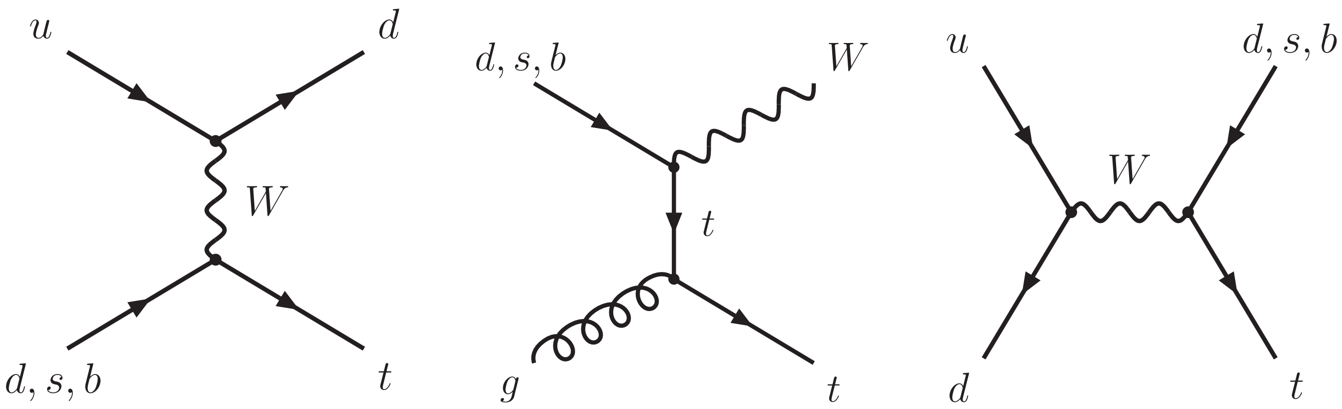
$$\cos\theta_S = \frac{\vec{p}_s^{\,*}\cdot\vec{p}_\ell^{\,*}}{|\vec{p}_s^{\,*}|\,|\vec{p}_\ell^{\,*}|} \qquad \text{and} \qquad \cos\theta_B = \frac{\vec{p}_p^{\,*}\cdot\vec{p}_\ell^{\,*}}{|\vec{p}_p^{\,*}|\,|\vec{p}_\ell^{\,*}|}$$





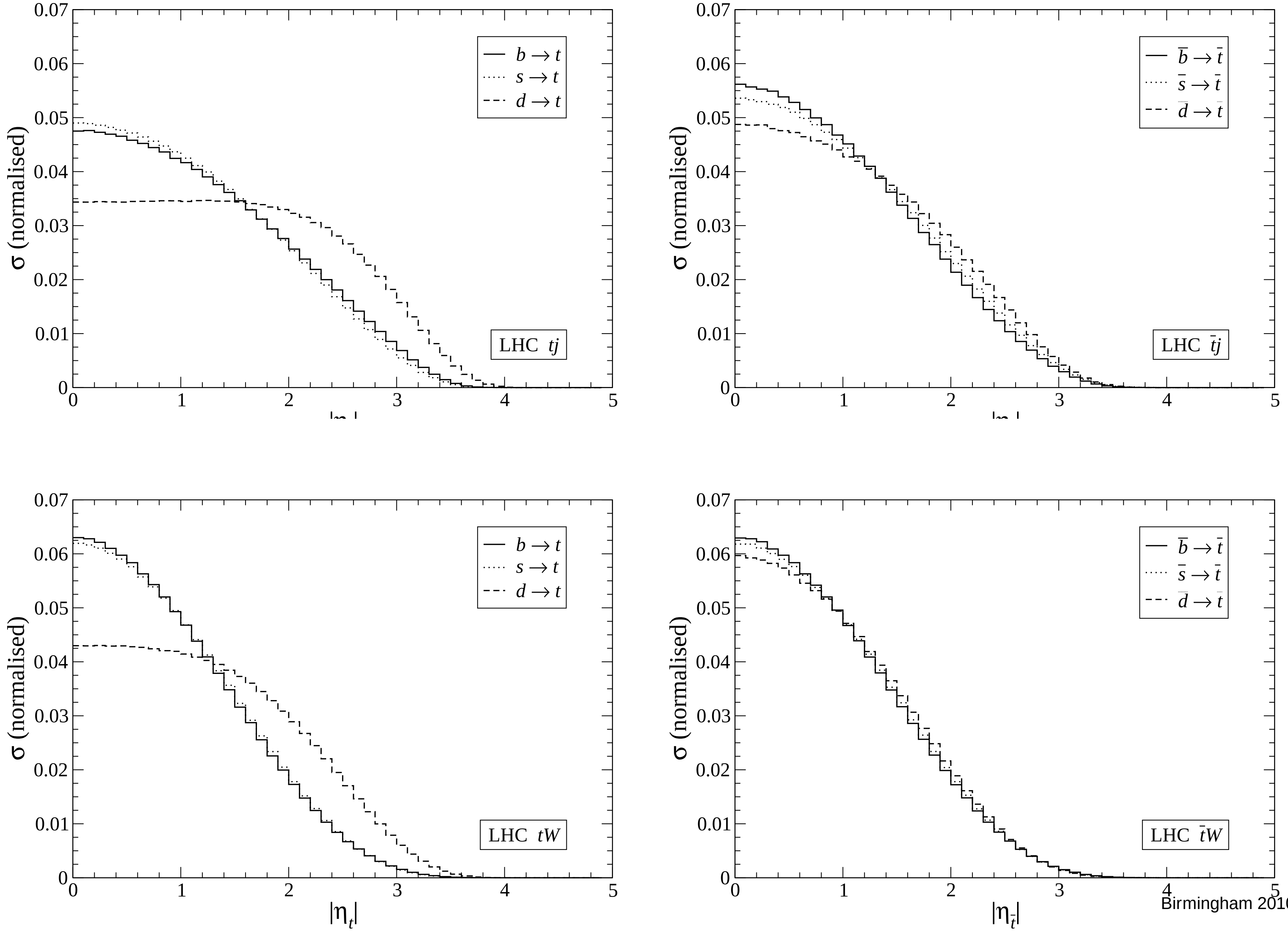
$\vec{p}_s^{\,*}$: momentum of spectator jet in top-quark rest frame
$\vec{p}_b^{\,*}$: momentum of proton (beam) jet in top-quark rest frame

Disentangle $V_{tb},\ V_{ts},\ V_{td}$: LHC $\sqrt{s} = 14$ TeV with 10fb^{-1}; [Aguilar-Saavedra, Onofre]



- consider (tJ), (tW) and (tb)
- make use of top rapidity distribution (different for d quark contribution → next slide)
- impacts not only on V_{tb} but indirectly also on V_{td}
- claimed limits (14 TeV, 10 fb^{-1}): $|V_{td}| \leq 0.12,\ |V_{ts}| \leq 0.27,\ 0.94 \leq |V_{tb}| \leq 1.05$
- effect of jet definition, higher-order corrections, inclusion of decay ??

rapidity of top: LHC $\sqrt{s} = 14$ TeV with 10fb^{-1}; [Aguilar-Saavedra, Onofre 1002.4718]

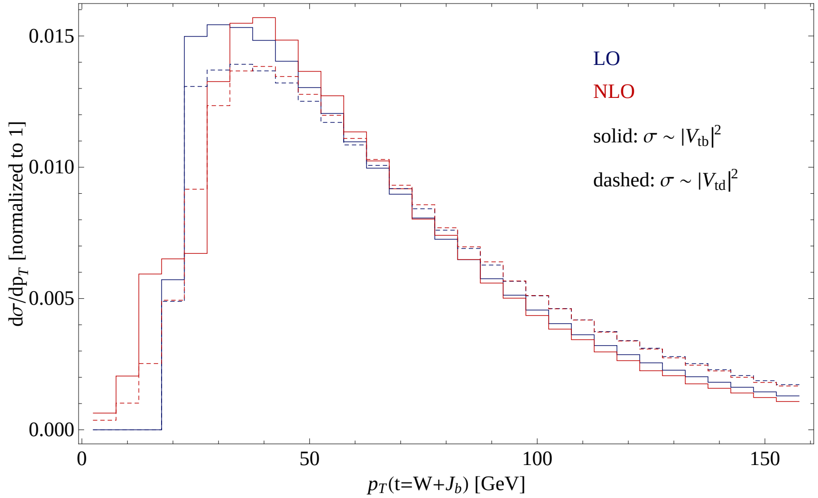


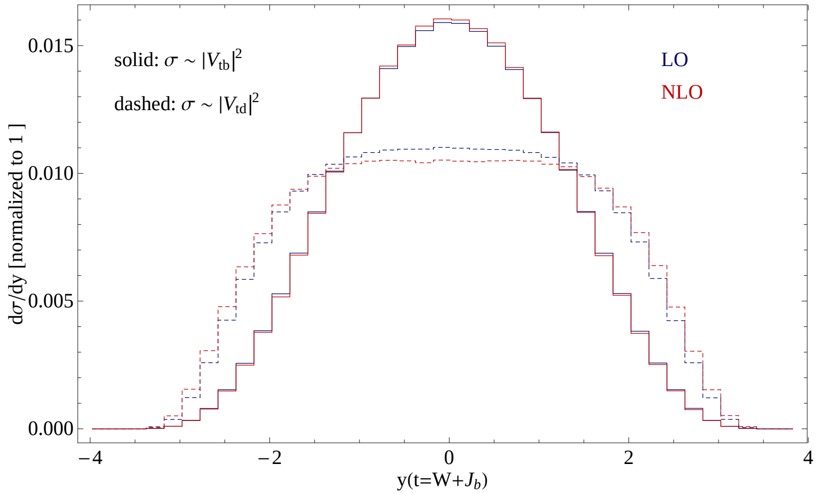
t-channel, LHC 7 TeV NLO result [Falgari, Giannuzzi, Mellor, AS]

$p_T(J_b) > 20\ \mathrm{GeV}; \quad p_T(J_h) > 20\ \mathrm{GeV};$

if there is a $\bar{b}$-jet, $p_T(J_{\bar{b}}) < 15\ \mathrm{GeV};$

$\not{E}_T + p_T(\ell) \geq 60\ \mathrm{GeV}$





general picture not-affected by higher-order corrections

d-quark contribution top-quarks have different signature → useful ??

- at the LHC we won't see a single top quark
- don't be fooled by "NNLO" etc labels! A one-loop (two-loop) calculation does not describe every quantity at NLO (NNLO)!
- if a very high (theoretical) precision is required, decay of top has to be considered
- many "small" effects require further work
- for a precise determination of the top mass, $m_{\rm pole} \neq m_{\rm MC}$
- a general purpose MC for $t\bar{t}$ icluding all known effects (resummation, decay, electroweak corrections, finite width effects . . .) would be most welcome
- "exclusive" NNLO will be next milestone
- need many different ways to measure top mass to get better (i.e. some) control on non-perturbative effects