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Top and Electroweak, Theory

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LHC: FIRST RESULTS AND OUTLOOK

Disclaimer: This is not a review. It is meant to be a random walk through (mostly) top and (a bit of) EW physics.

LHC: first results (not really) and outlook (very much so)

top pair production
- total cross section, invariant mass distribution
- general purpose (fixed-order) MC, including decay
- issues regarding top quark mass
- spin correlations

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

electroweak
- Drell-Yan
- W charge asymmetry

standard blah blah about top:

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

$e_Q; T_3;$ 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 ...

one-page summary

- width known at α_s^2 and one-loop electroweak $\Rightarrow$ theoretical uncertainty $\sim 1\%$ [Czarnecki, Melnikov; Chetyrkin et.al; Denner, Sack; Eilam et.al.]
- $m_{t,\mathrm{pole}}/\overline{m_t}(\overline{m_t})$ known at α_s^3 [Chetyrkin, Steinhauser]
- top quark pair production known at $\sim$ one-loop $\Rightarrow$ see later
  electroweak corrections known [Bernreuther et.al.]
  inclusive cross section two-loop nearly known and resummation of logs under control
  $\Rightarrow$ see later
  included in MC@NLO and POWHEG [Frixione, Nason, Webber . . . . . .]
- single top production known at $\sim$ one-loop $\Rightarrow$ see later
  all channels included in MC@NLO and POWHEG [Frixione, Laenen, Motylinski, Nason, Re, Webber, White . . . . . .]
- $pp \to t\bar{t}H$ known at $\sim$ one-loop $\Rightarrow$ see later
- $pp \to t\bar{t}j$ known at $\sim$ one-loop [Dittmaier, Uwer, Weinzierl]
- $pp \to t\bar{t}jj$ and $pp \to t\bar{t}b\bar{b}$ known at $\sim$ one-loop [Bredenstein et.al; Bevilacqua 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 . . .]

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

- 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 . . . . . . (sorry)]

  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

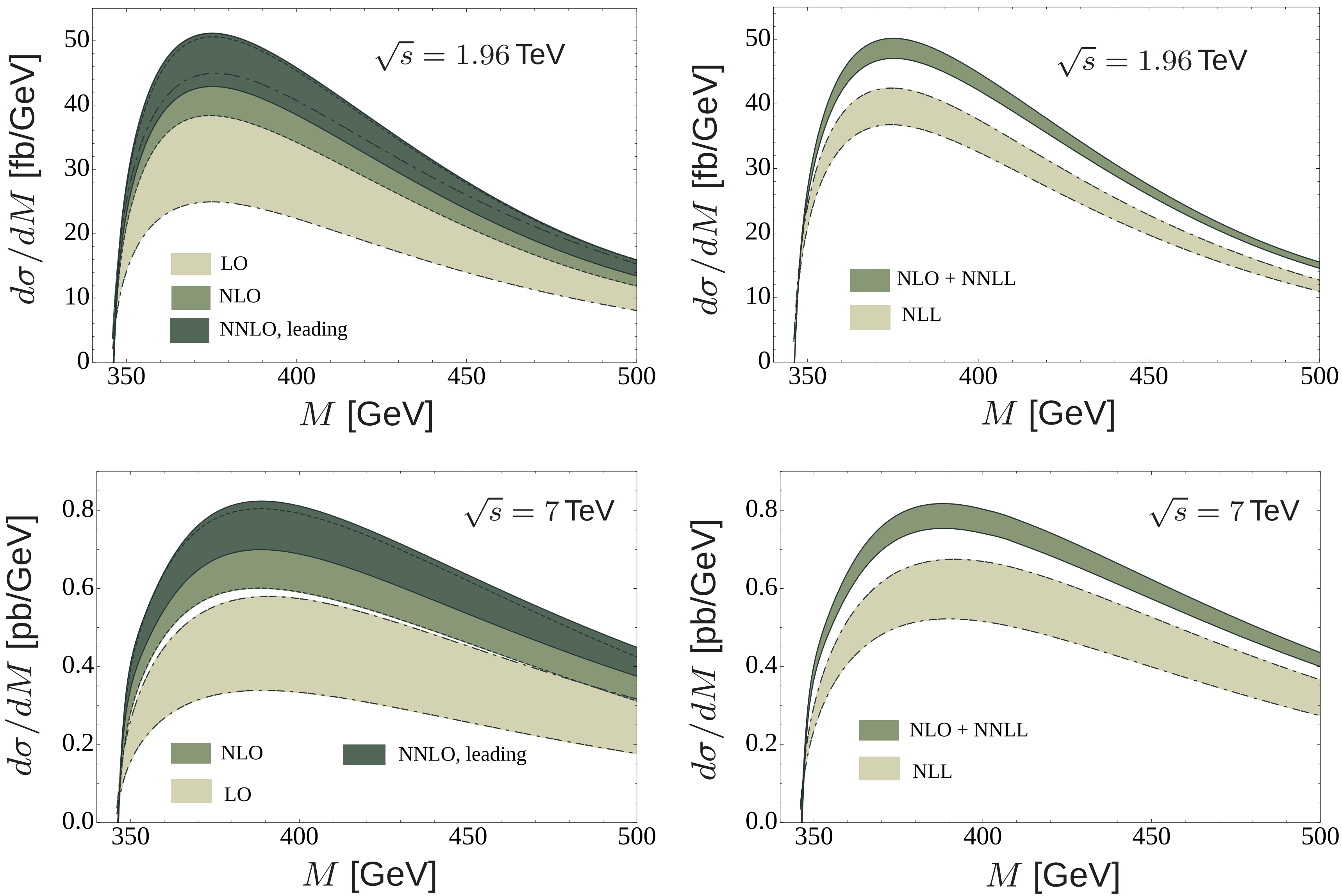
  total cross section: $\log(1 - 4m^2/s)$

  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]



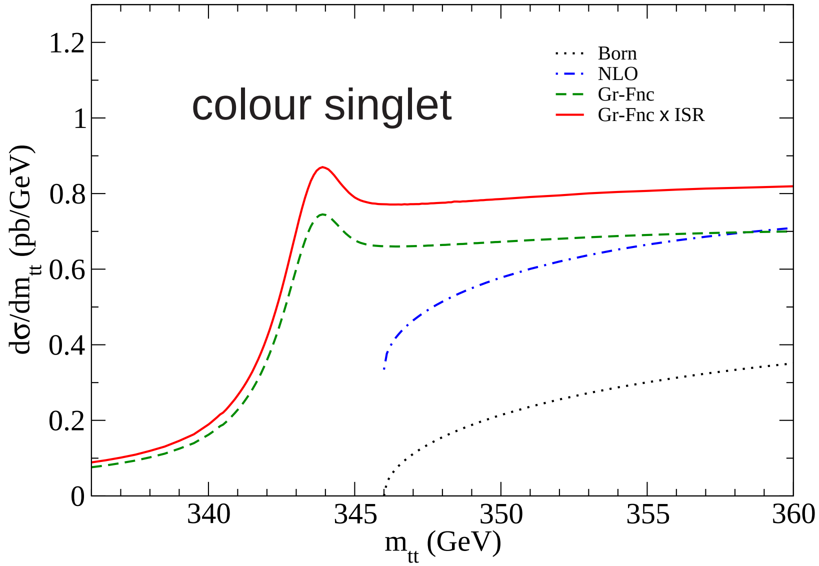
bound-state effects

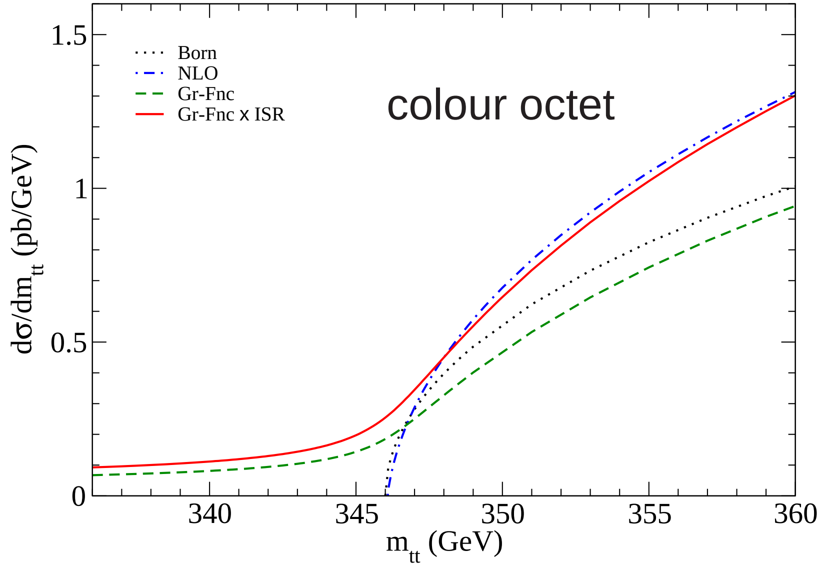
- near threshold Coulomb potential is dominating effect:

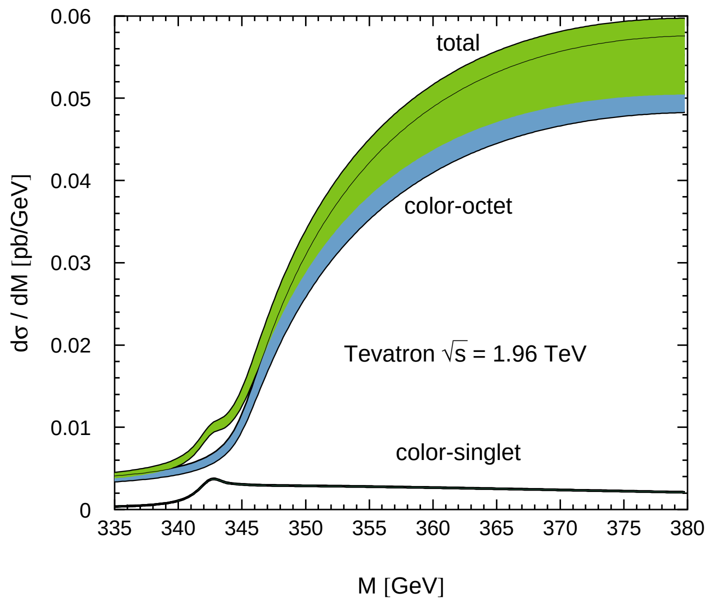
  colour singlet: $V(r) \simeq -\alpha_s \frac{C_F}{r}$ attractive

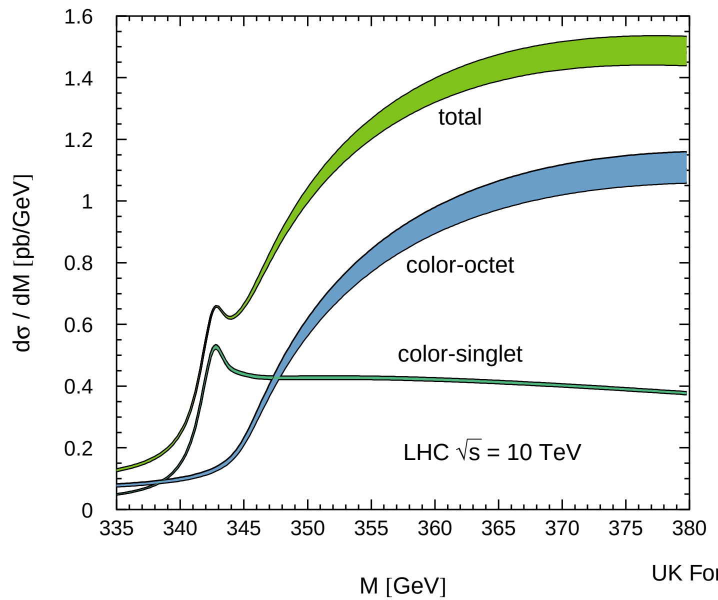
  colour octet: $V(r) \simeq -\alpha_s \frac{C_F - C_A/2}{r}$ repulsive
- for $\Gamma_t \to 0$ collections of bound states (as for bottom), for $\Gamma_t \simeq 1.4\ \mathrm{GeV}$ a single “bump” in invariant mass remains.
- resummation of $(\alpha/\beta)^n$ (from Coulomb potential $\longrightarrow$ “bound-state” 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.

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







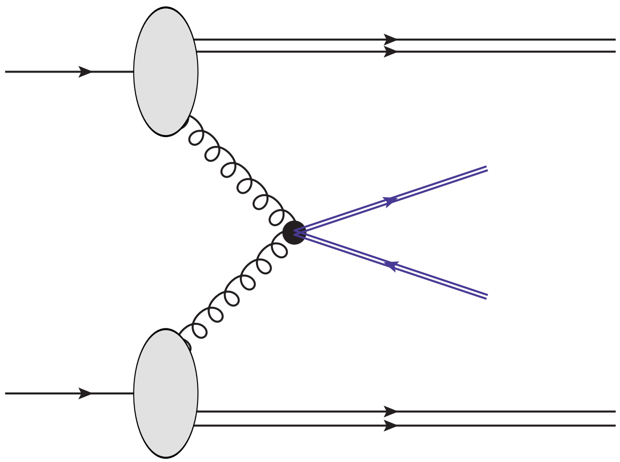


Fully exclusive quantities

- 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

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



- top as final state

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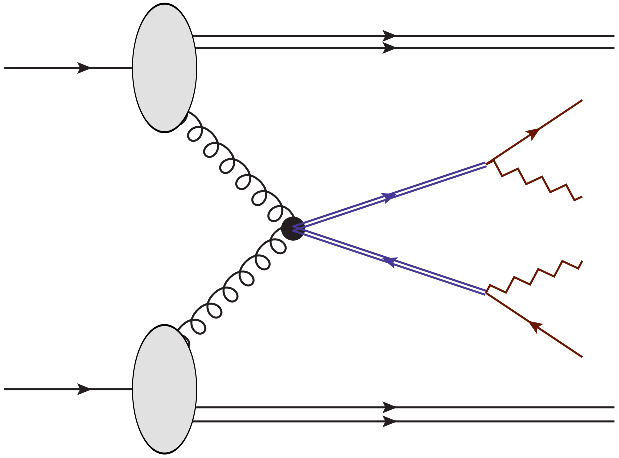

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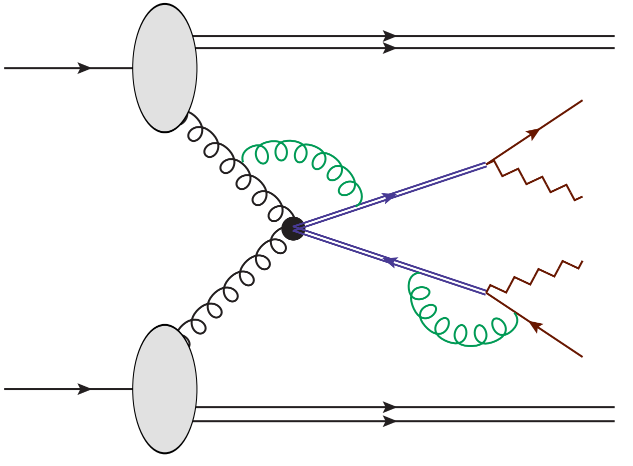

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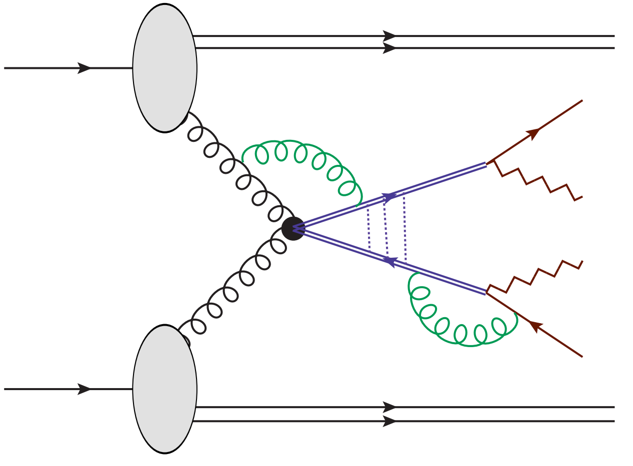

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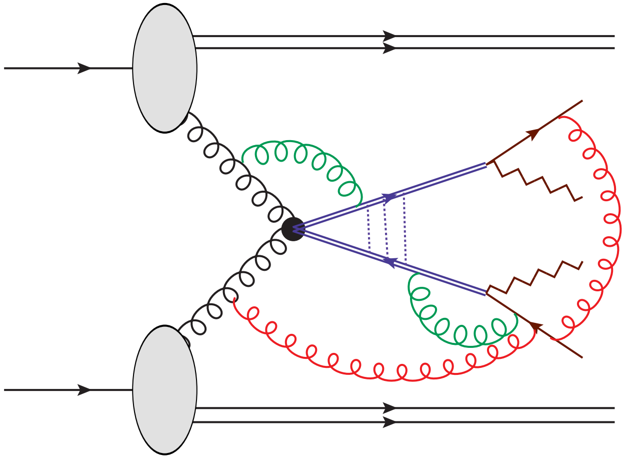

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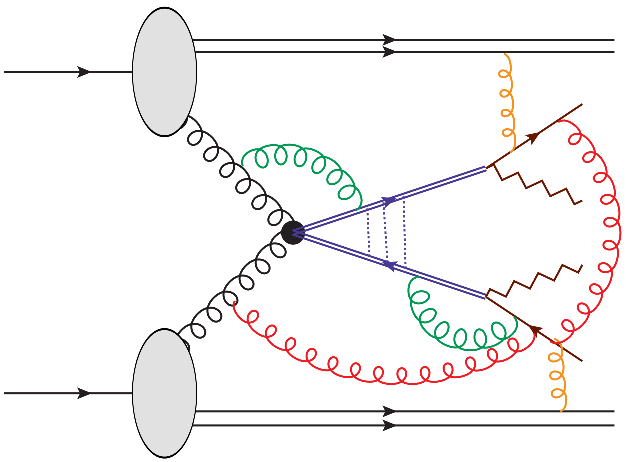

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- (non-perturbative) colour connection to proton remnants: rough estimate $\Delta m_t \sim 0.5\ \mathrm{GeV}$ [Skands, Wicke]

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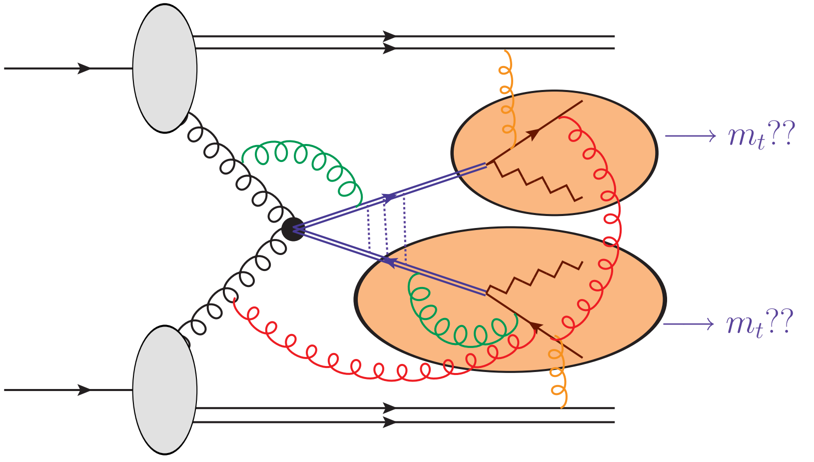

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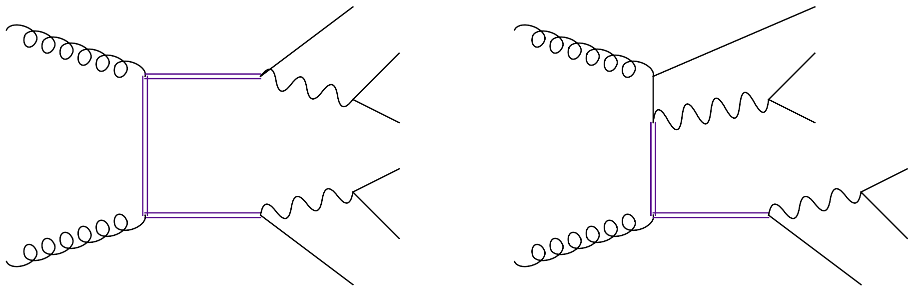
beyond $pp \to t\bar{t} \to W^+W^-b\bar{b}$ have to consider the decay for experimental cuts

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



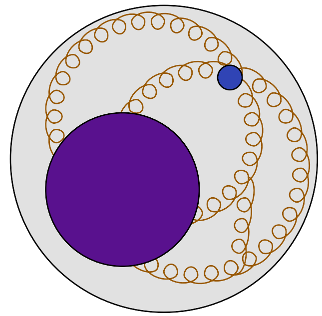
in general: $p^2 = m_t^2$ $\Rightarrow$ singularity $\Rightarrow$ include width $\Rightarrow$ gauge invariance issues
importance of these effects crucially depends on final state cuts

- 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.

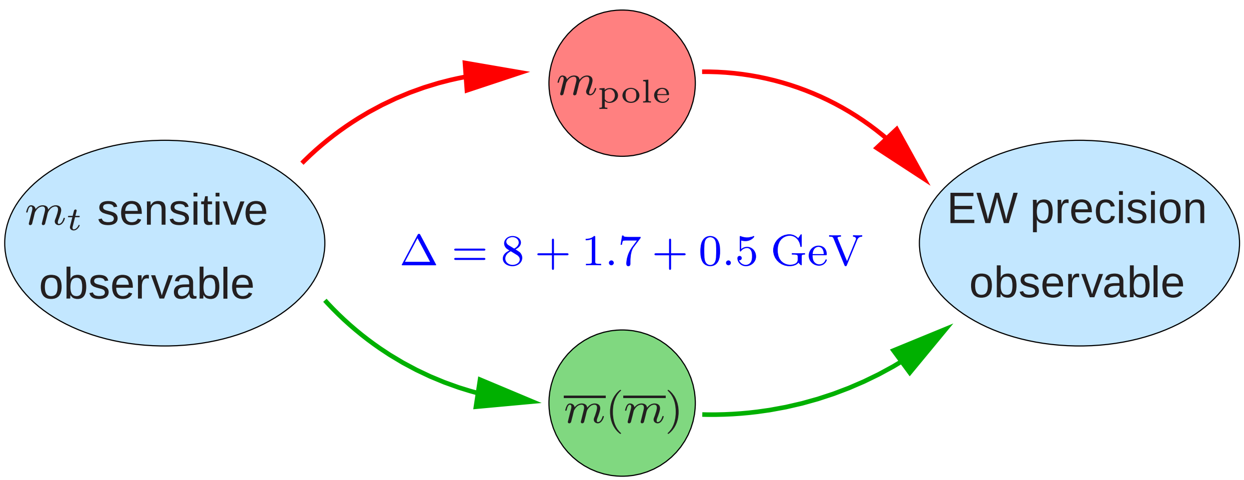
The mass is simply a parameter of the theory (renormalization scheme dependent!)
The pole mass has an intrinsic uncertainty of order Λ_{QCD} in perturbation theory (infrared sensitivity, renormalon ambiguity)

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 linear collider could be solved in principle [Hoang, Stewart]

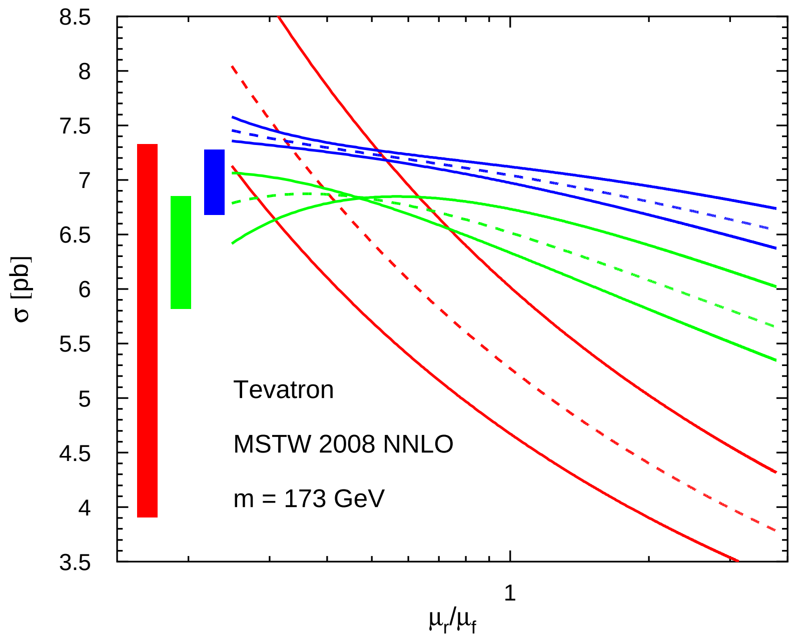


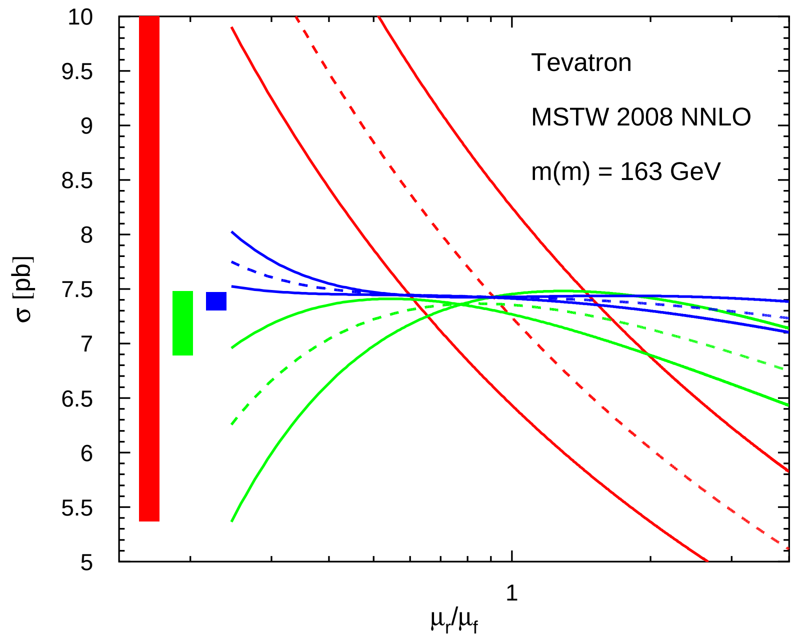
renormalization scheme

- 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 $p_t^2 \simeq m_t^2 \longrightarrow$ 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 $m_{\mathrm{exp}} \stackrel{??}{=} m_{\mathrm{pole}}$

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

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





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

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

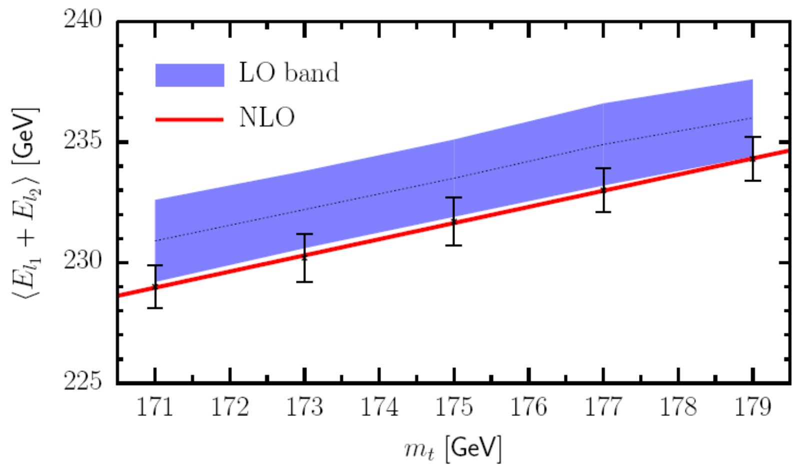
find observable with large m_t sensitivity and compute beyond LO

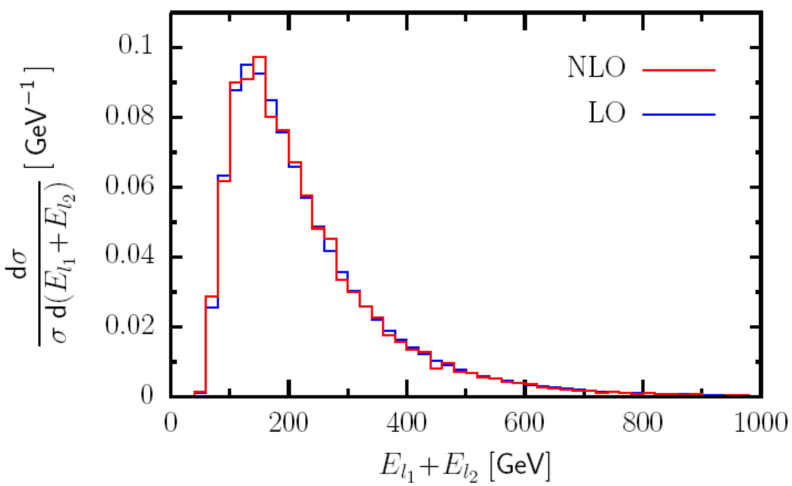
e.g. $E_\ell + E_{\ell'}$ in lab frame

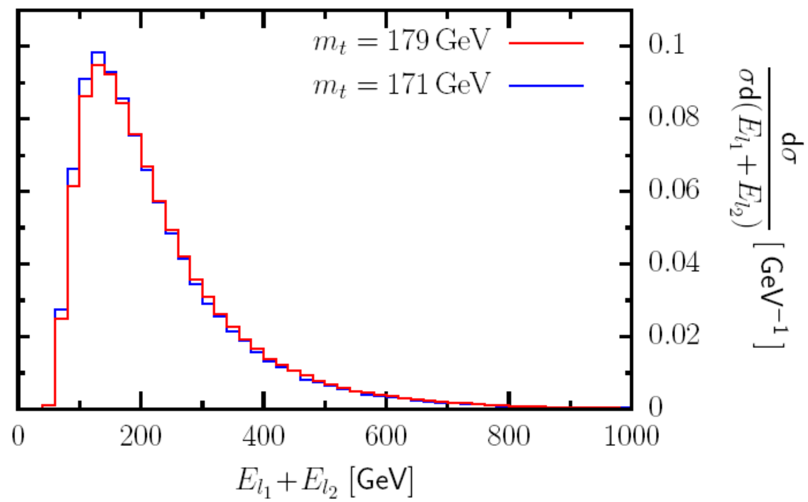
compare $\delta_{\rm th} m$ (PDF, higher order) with m_t sensitivity

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) $\to$ 1 GeV (NLO)

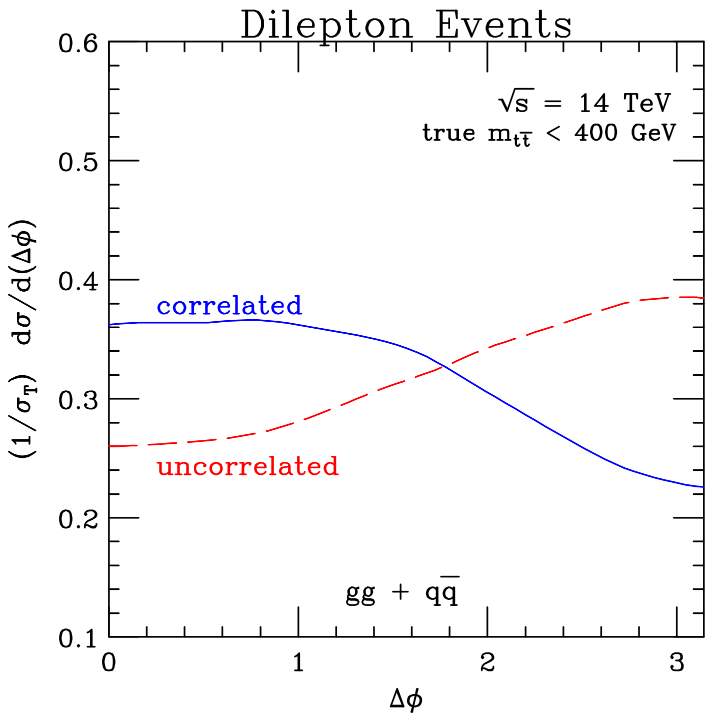


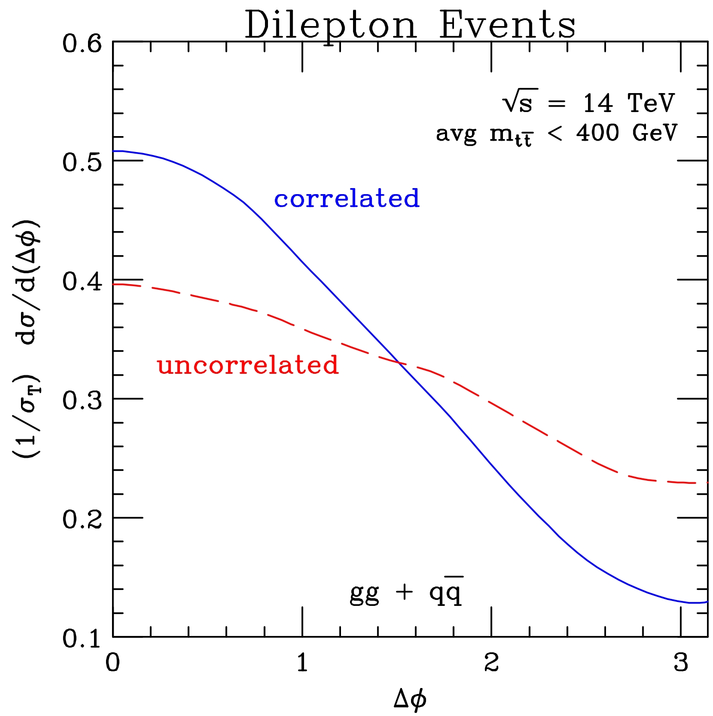




- decay of top not (much) affected by hadronisation $\longrightarrow$ information of spin in decay products
- desperate hope for non-SM top decay
- obviously, this needs decay of top implemented, with NLO corrections in production and decay [Bernreuther et.al.]
- at LHC, mostly $gg \to t\bar{t}$, this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

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

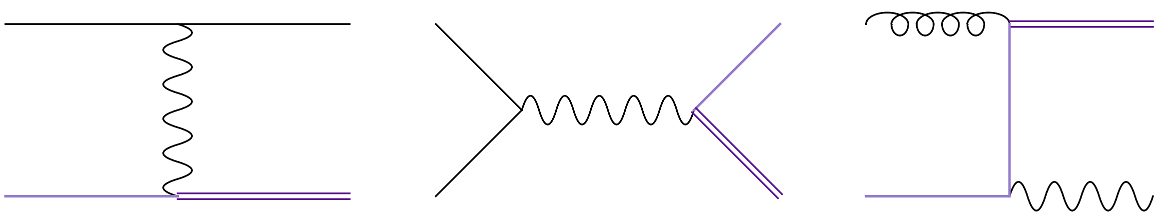




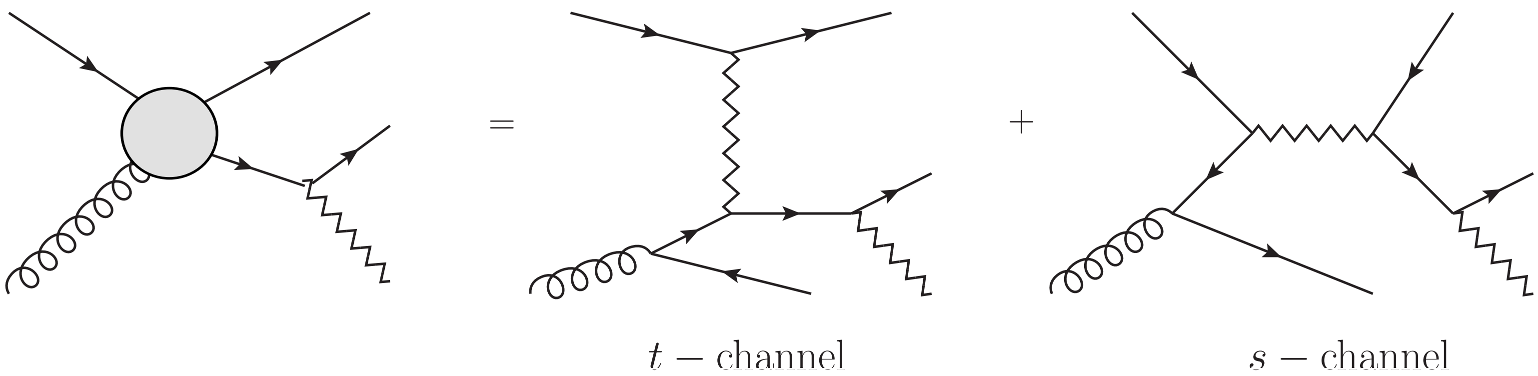
cannot get true $M_{t\bar{t}} < 400$ GeV due to ambiguity from ν in leptonic decay $\longrightarrow$
cut on average of reconstructed $M_{t\bar{t}} < 400$ GeV (right)
or: use semi-leptonic decay ($\longrightarrow$ ambiguity on which jet is d jet)

Theory status

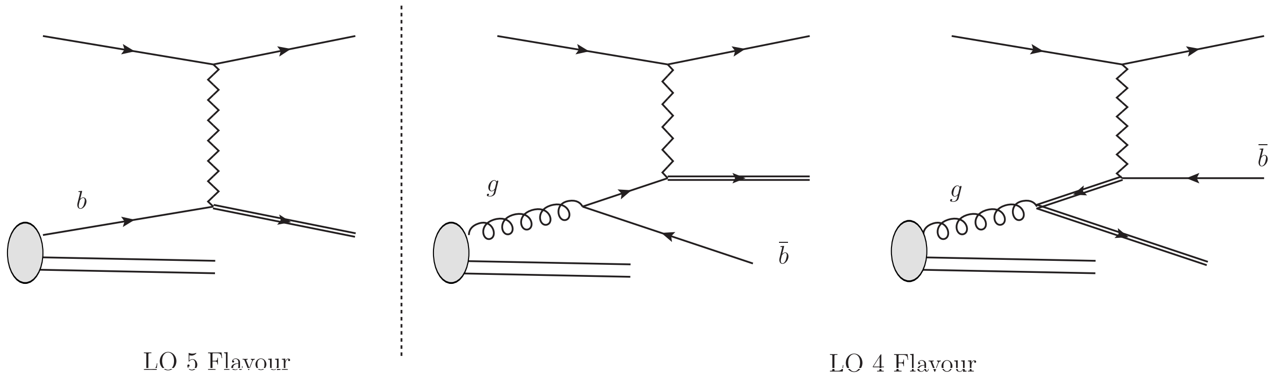
- NLO QCD corrections, production and hadronic decay for t–, s–channel and Wt known [. . ., Harris et.al; Campbell, Ellis, Tramontano (MCMF)], all included in MC@NLO and POWHEG, EW corrections known [Beccaria et.al; Macorini et.al]



- s and t channel mix (beyond LO) $\longrightarrow$ more aproproate to talk about (tJ), (tb) and (tW) cross sections ($\longrightarrow$ see later)



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



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.

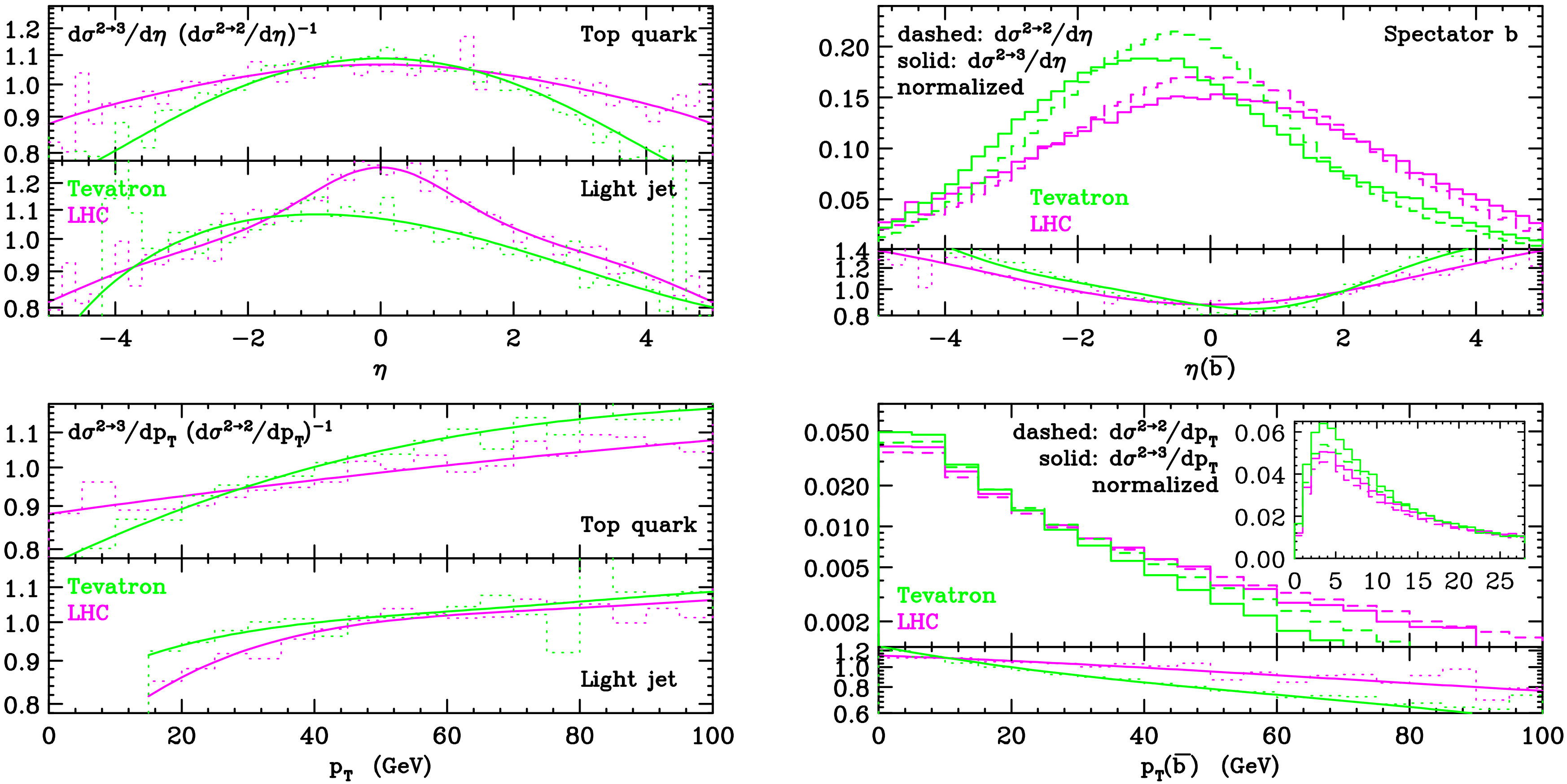
	LHC t	LHC $\bar{t}$
5F	$(153)156^{+4+3}_{-4-4}$	$(89)93^{+3+2}_{-2-2}$
4F	$(143)146^{+4+3}_{-7-3}$	$(81)86^{+4+2}_{-3-2}$

just about consistent, effects of logs?

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

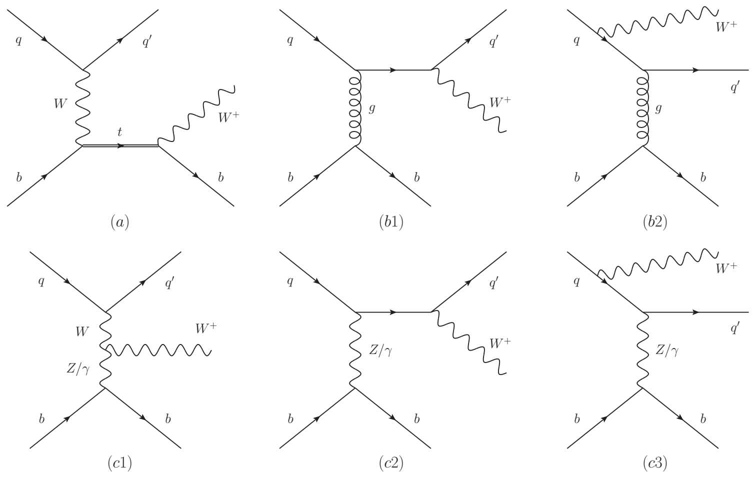
$m_b = 4.7\ \mathrm{GeV}$, mass effects are not important for “normal” quantities

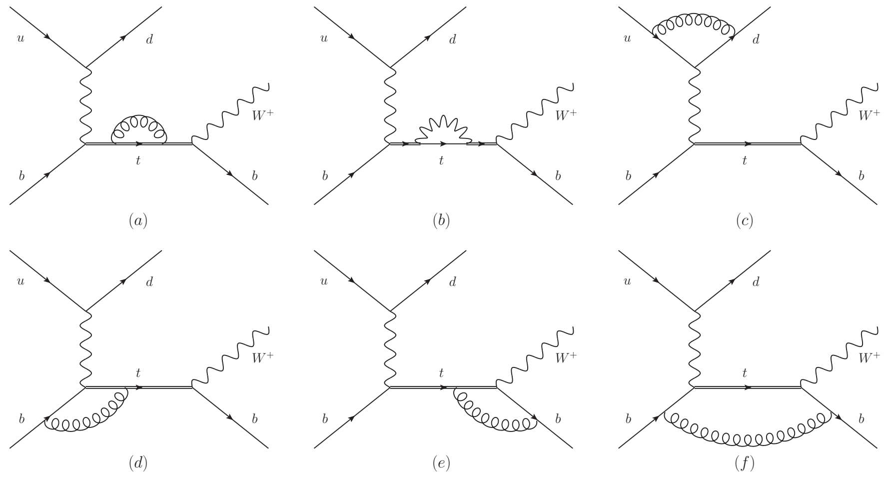
4-flavour (solid) vs. 5-flavour (dashed) scheme [Campbell et.al. 0903.0005]



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

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





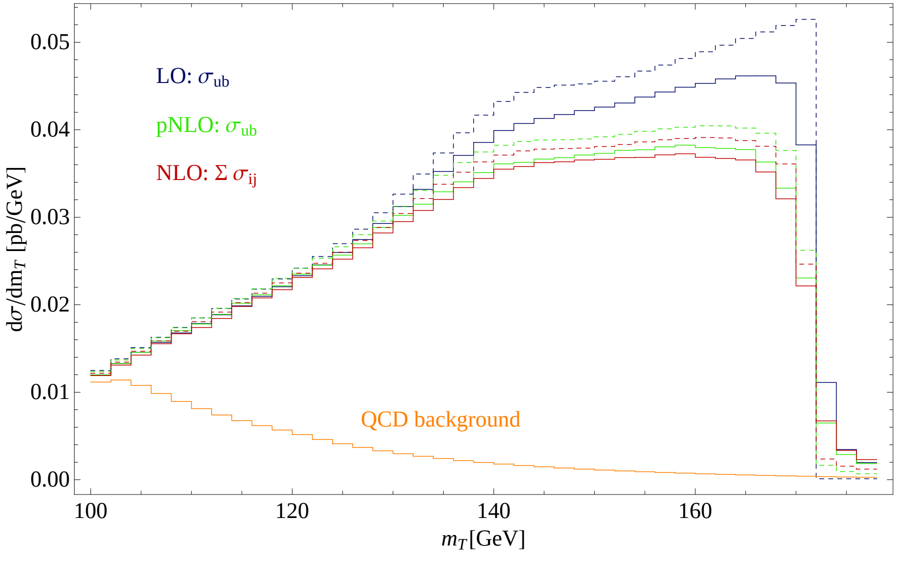
QCD background is signal (exactly same final state), but suppressed, no resonant propagator !!
LHC cross section $7\ \mathrm{TeV}$ with and without (reasonable) cuts: $\sim p_T, \not{E}_T > 20\ \mathrm{GeV}$

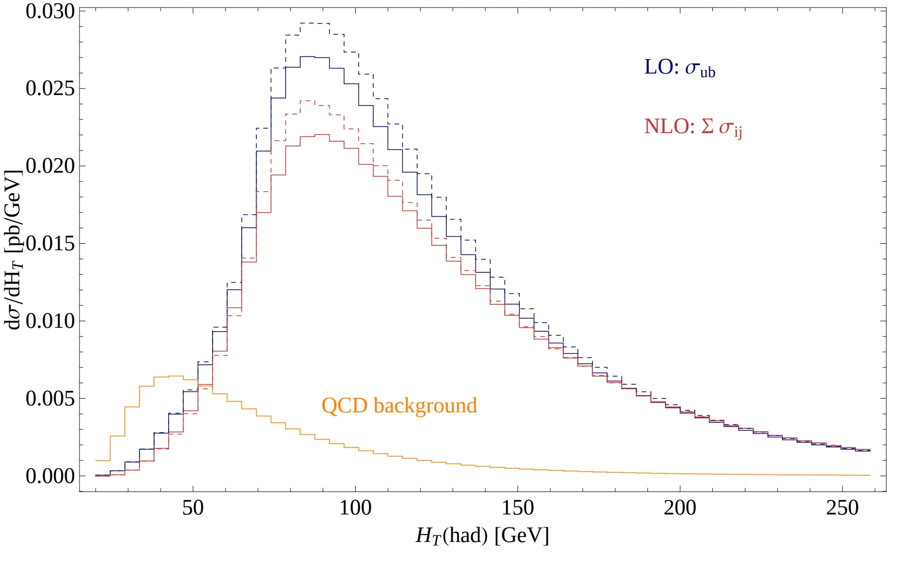
	on-shell t	off-shell t	%
no cuts	84.9	86.3	+ 1.7%
cuts	2.31	2.23	- 3.6%

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 transverse mass and $H_\mathrm{T}(\mathrm{had}) = |p_T(J_b)| + |p_T(J_l)|$ with cuts:

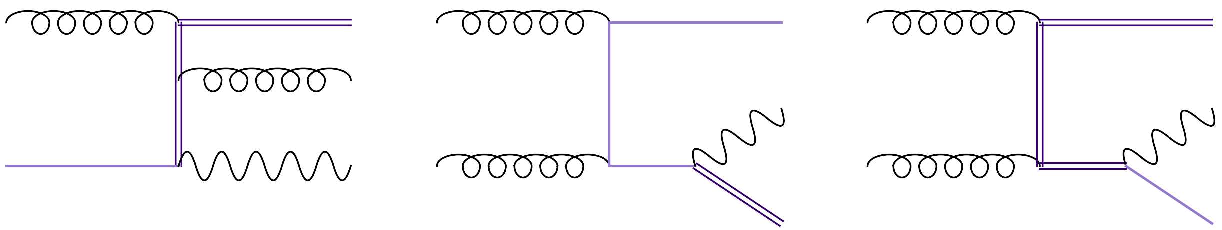




- non-factorizable corrections are a sizeable part of full NLO corrections
- for precision physics (m_t) they might have an impact

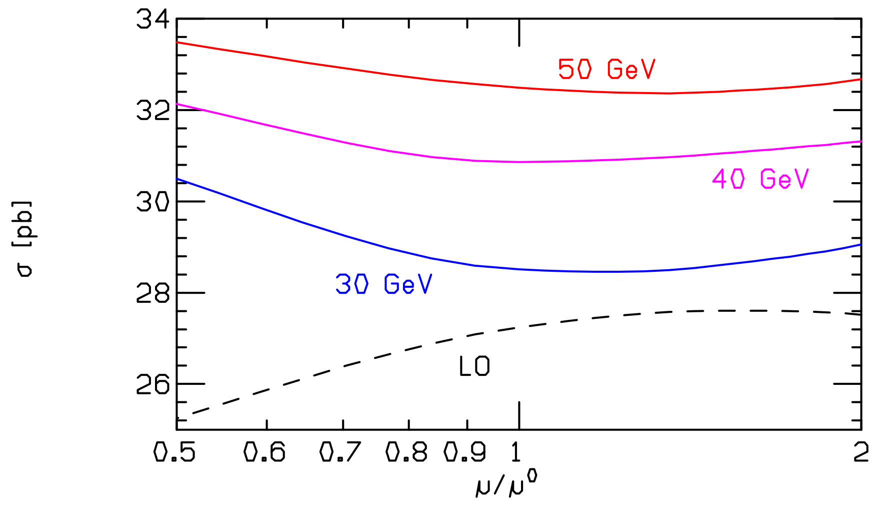
Separation of Wt and $t\bar{t}$

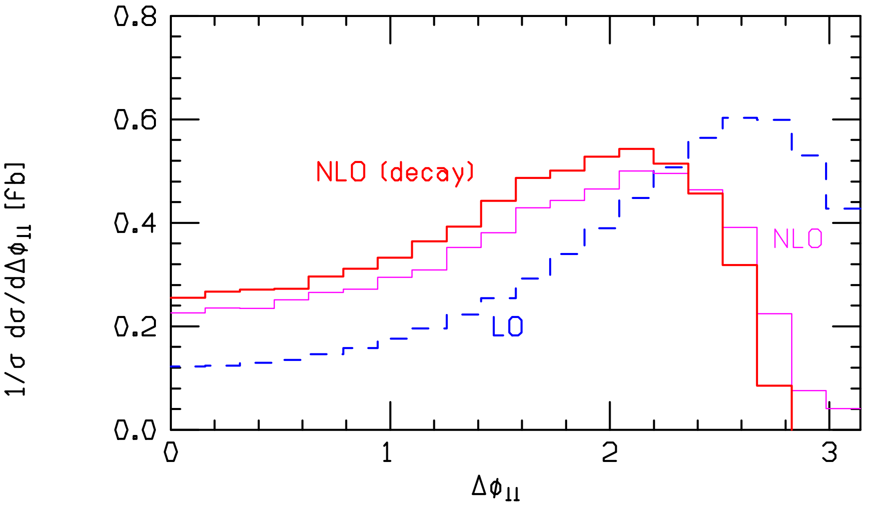
- note at NLO tW mixes with $t\bar{t}$ through inclusion of real radiation diagrams



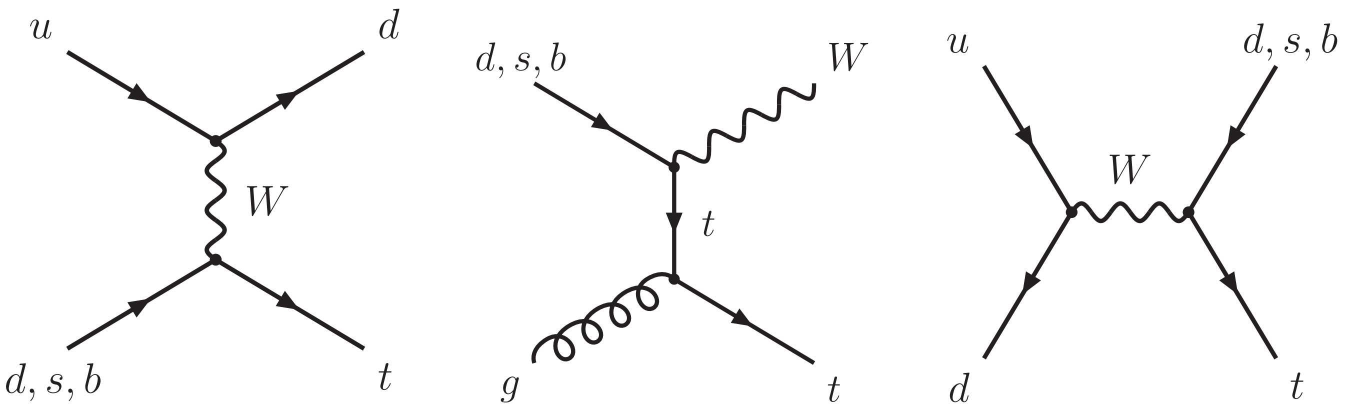
- the last diagram is the same as $t\bar{t}$ production with (one) subsequent t decay
- disentangle:
  - subtract contribution from resonant diagram [Tait]
  - make cut on invariant mass M_{Wb} to prevent top from becoming resonant [Belayev, Boos,Dudko]
  - the use p_t of b quarks as discriminating variable is preferable [Campbell, Tramontano]
- similar effect: “wrong” t-channel part of $u\,g \to d\,b\,W\,\bar{b}$ can be much larger than s-channel part.

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



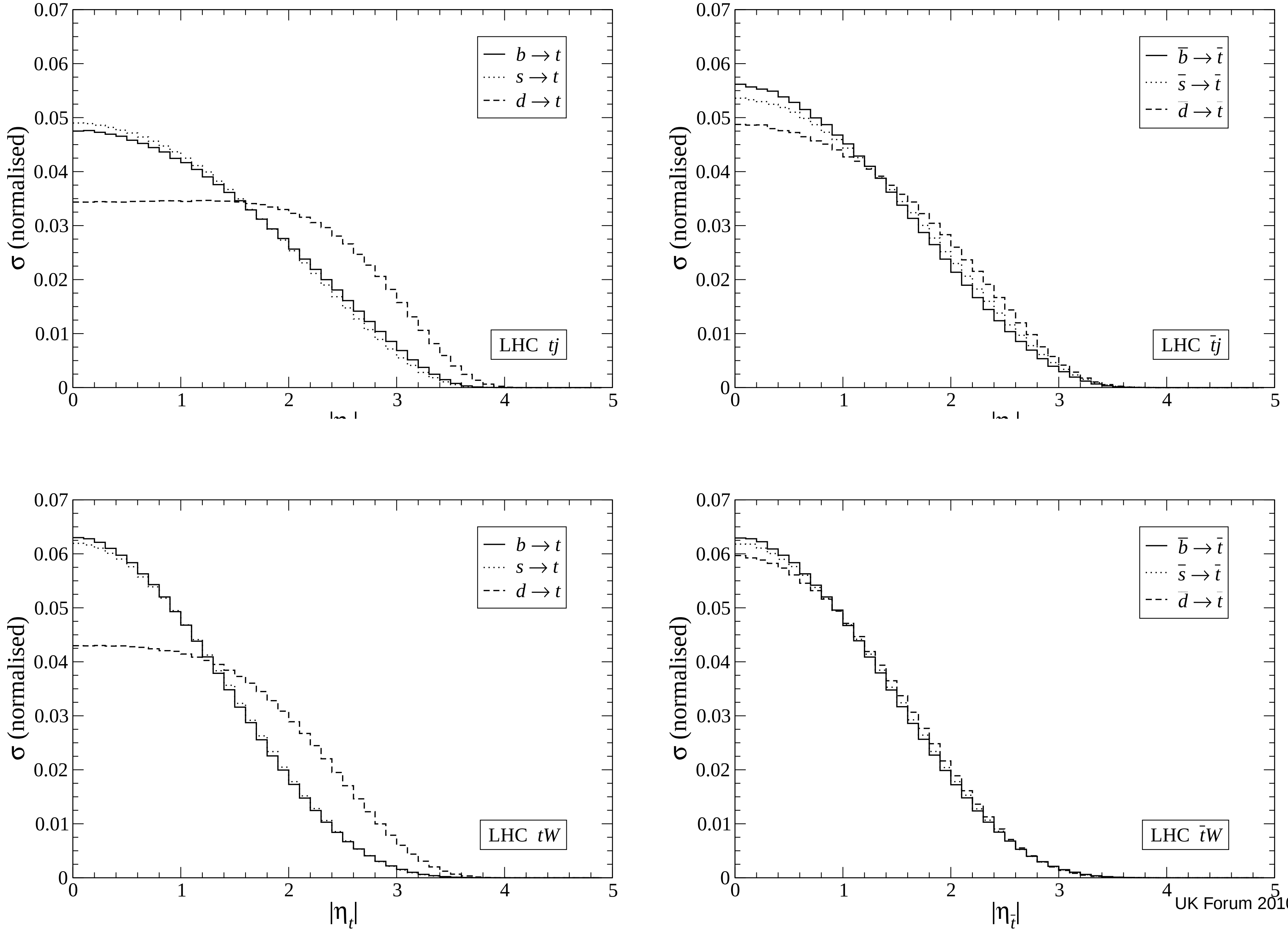


Disentangle $V_{tb},\ V_{ts},\ V_{td}$: LHC $\sqrt{s} = 14\ \mathrm{TeV}$ with $10\mathrm{fb}^{-1}$; [Aguilar-Saavedra, Onofre]



- consider (tJ), (tW) and (tb)
- make use of top rapidity distribution (different for d quark contribution $\longrightarrow$ 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]



huge progress in computation of NLO corrections to multiparton processes, e.g:

- NLO QCD to $W\,W\,J$ [Dittmaier, Kallweit, Uwer] and $Z\,Z\,J$ [Karg et.al. (Golem)]
- NLO $t\,\bar{t}\,b\,\bar{b}$ [Bredenstein et.al., Bevilacqua et.al.]
- NLO $Wb\bar{b}$ and $Zb\bar{b}$ including bottom mass effects [Cordero, Reina, Wackeroth]
- NLO $W\gamma\gamma$ [Baur, Wackeroth, Webber]
- VBFNLO package, $VVJJ$, $HJJ(J)$, VVV ...

NLO: more reliable, reduced scale dependence, idea of theoretical uncertainty .

Often inclusion of non-SM (anomalous) couplings.

anomalous couplings: need form factors !! couplings meaningless, do not compare !!

More “QCD” like computations $V + nJ$ with $n \leq 3(4)$ done using “on-shell” techniques.

More “EW” like calculations (several mass scales) done “conventionally”, i.e. with Feynman diagrams.

Currently the two techniques meet at $t\,\bar{t}\,b\,\bar{b}$ with “on-shell” techniques invading Feynman-diagram territory.

$pp \longrightarrow \{W\ Z\} X$

- W mass and width, luminosity monitor
- theory goal: 1% !?! $\longrightarrow$ huge theoretical effort [Alpgen, FEWZ, Horace, MC@NLO, MCFM, Resbos, Wgrad . . . . . .]
- NNLO QCD [Anastasiou, Dixon, Melnikov, Petriello]
- EW-Sudakov logarithms (large at high energies)

$$A = A_B \left[1 + \sum_{n \geq 1} \alpha^n \sum_{k=0}^{2n} C_{n,k} \log^n (Q^2/M_W^2) \right]$$

known at NNLO $n = 2$ for $4 \geq k \geq 1$. [Melles et.al, Manohar et.al]
large cancellations! $\longrightarrow$ effect of cuts ?

- merged with parton showers, multiple photon radiation, photon induced processes
- full $\mathcal{O}(\alpha)$ EW corrections
- work on combining $\mathcal{O}(\alpha)$ EW and $\mathcal{O}(\alpha_s)$ QCD corrections ($\longrightarrow$ next slide)

compare two ways to combine QCD and EW, differences of $\mathcal{O}(\alpha\,\alpha_s)$ [Vicini et.al. Radcor 09]

$$d\sigma_{\mathrm{QCD\&EW}} = d\sigma_{\mathrm{QCD}} + \left(d\sigma_{\mathrm{EW}} - d\sigma^{(0)}\right)|_{PS}$$

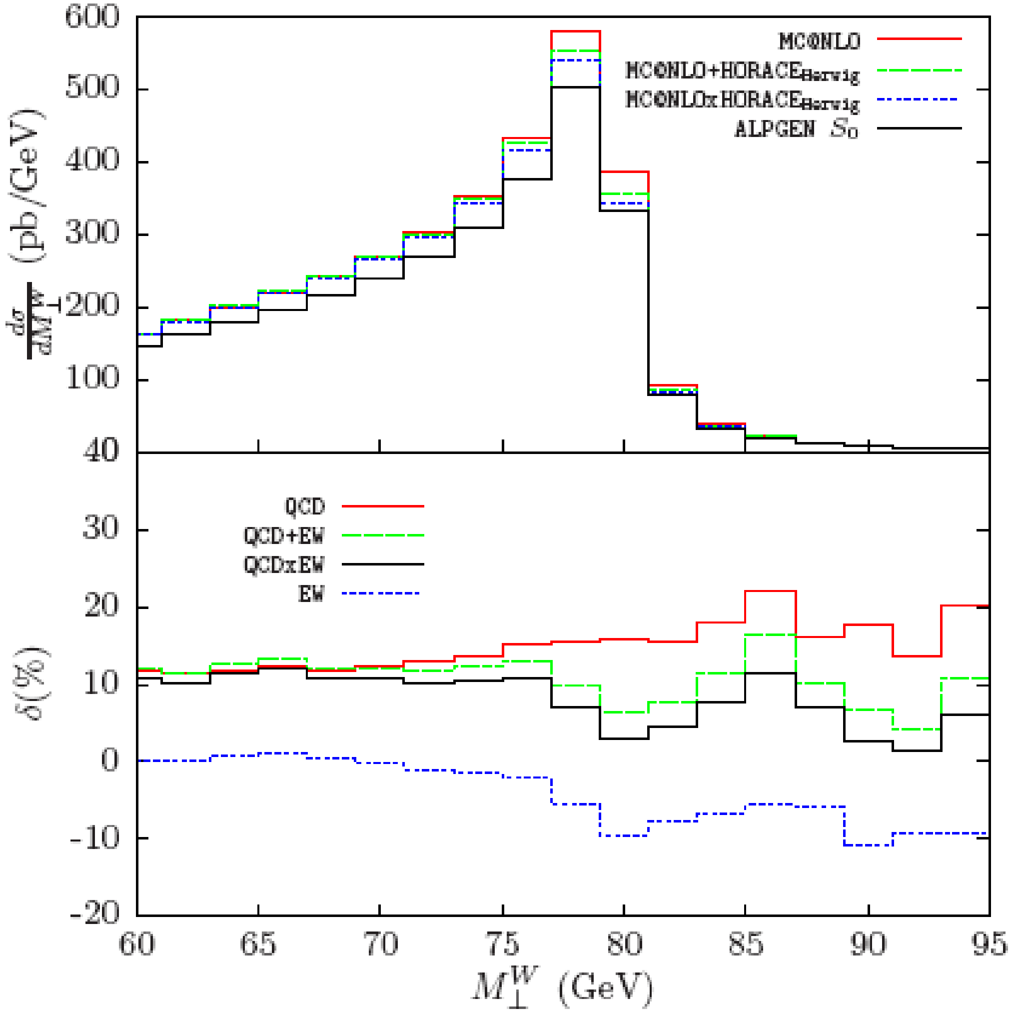
$\sim$ EW $\times(\log)$

$$d\sigma_{\mathrm{QCD}\times\mathrm{EW}} = (1+\delta_{\mathrm{QCD}})\,(d\sigma_{\mathrm{EW}})\,|_{PS}$$

$\sim$ EW $\times(\log + \mathrm{cst})$

differences $\sim 2-3\%$

need full $\mathcal{O}(\alpha\,\alpha_s)$ corrections



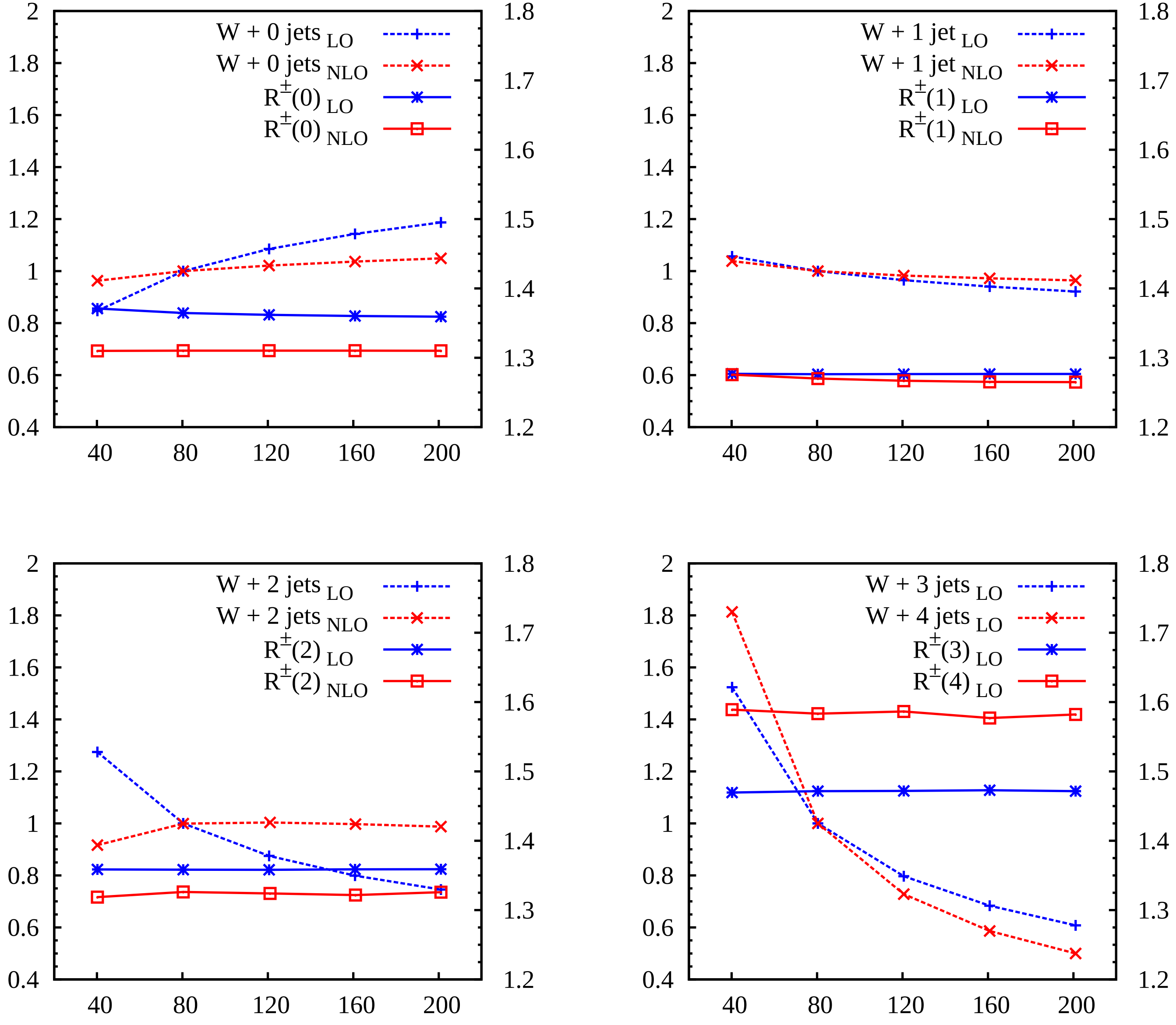
W charge asymmetry $\sigma(W^+)/\sigma(W^-)$

- usually taken to constrain PDF $u(x)/d(x)$
- taking $u(x)/d(x)$ as input, can use charge asymmetry to look for $W^+ - W^-$ symmetric contributions (Higgs, $t\bar{t}$, BSM) [Kom, Stirling]
- theoretical uncertainties cancel to a large extent ($\rightarrow$ next slide)
  $W + nJ$ scale dependence increases for increasing n, but ratio remains stable.
- now $W + nJ$ known at NLO for $n \leq 3$ [Ellis et.al; Blackhat] and (nearly/soon) $n = 4$ [Blackhat, Sherpa]
- numbers at NLO [Blackhat, Sherpa]

	0	1	2	3	4
W^+/W^- LO	1.656	1.507	1.596	1.694	1.82
W^+/W^- NLO	1.58	1.50	1.57	1.66	...

- can also play games with $\sigma(W + nJ)/\sigma(W + (n-1)J)$

$W + J$ ratios [Kom, Stirling, 1004.3404] awaits NLO input for $n = 3, 4$



conclusions

- at the LHC we won't see a single top quark
- if a very high (theoretical) precision is required, decay of top has to be considered
- many "small" effects require further work
- a general purpose MC for $t\bar{t}$ icluding all known effects (resummation, decay, electroweak corrections, finite width effects . . .) would be most welcome
- "exclusive" NNLO is next milestone
- need many different ways to measure top mass

- huge effort in high-precision Drell-Yan, full $\mathcal{O}(\alpha\,\alpha_s)$ (and more) needed for 1% precision.
- massive progress in computation of one-loop corrections, on-shell methods slowly start to push out conventional Feynman diagram techniques