Theory status for hadronic top-quark pair production

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— RWTH Aachen —

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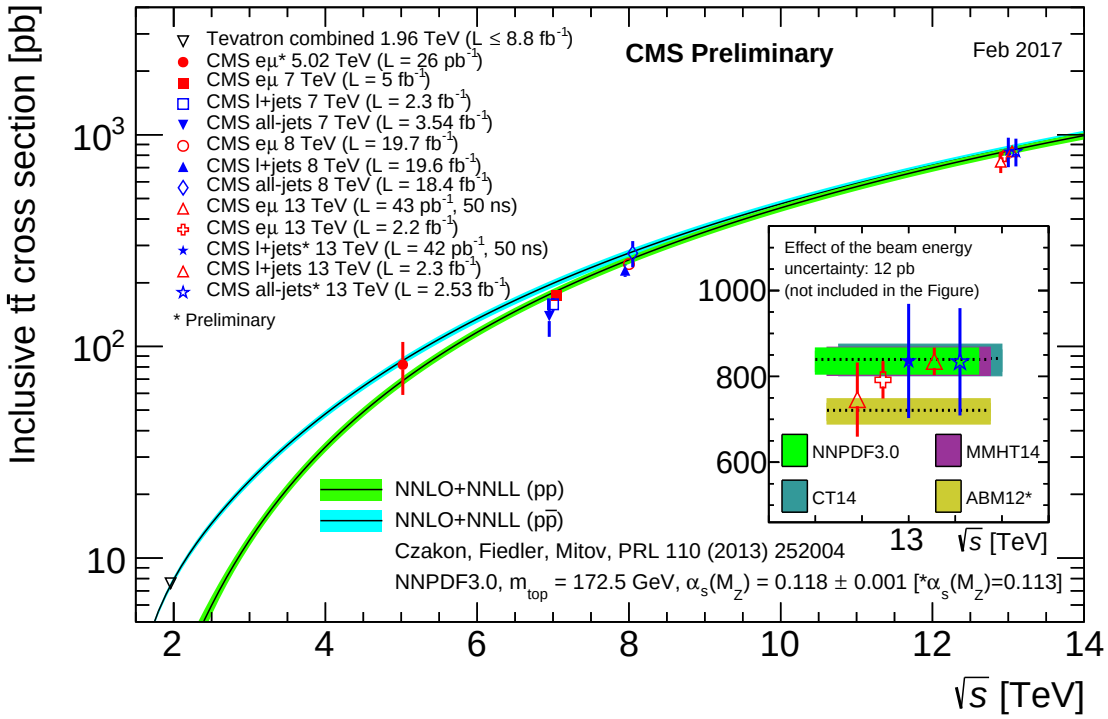
Highlights of $t\bar{t}$ physics at LHC

- total $\sigma_{t\bar{t}}$ measured with $\sim 3-4\%$ precision
  - Sensitive to m_t, α_s, gluon PDF
  - challenge to precision of NNLO calculation

    $\Rightarrow$ dominant higher-order corrections?



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- total $\sigma_{t\bar{t}}$ measured with $\sim 3-4\%$ precision
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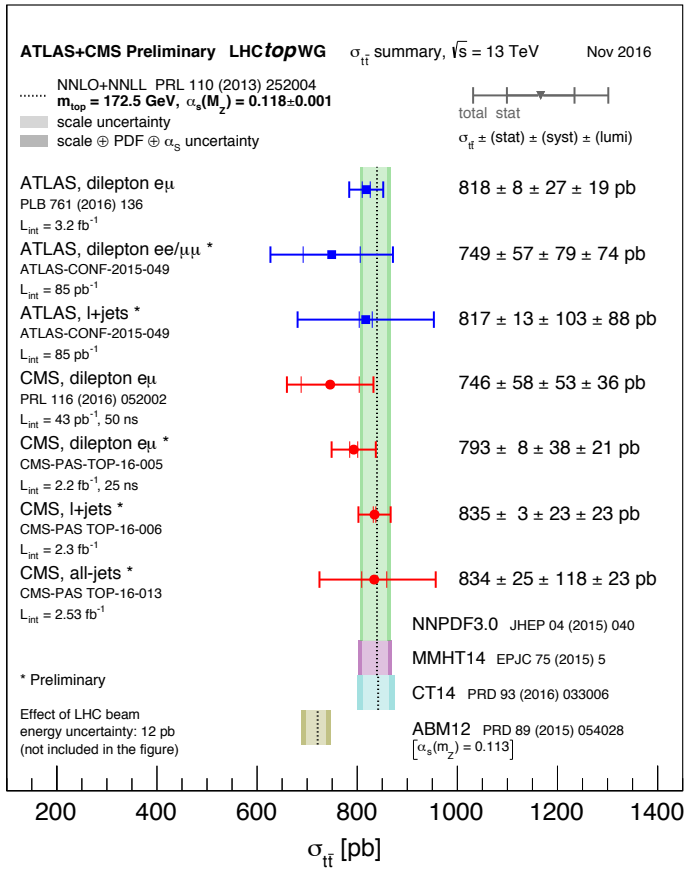
  - challenge to precision of NNLO calculation
    $\Rightarrow$ dominant higher-order corrections?
- Differential cross sections
  - sensitivity to Z', g_{KK} with $M \sim 5\,\mathrm{TeV}$ (Talk by Strobbe)
  - increasing relevance of EW corrections
- m_t-measurement with precision $< 1\mathrm{GeV}$
  - theoretical interpretation?
  - uncertainty of theory modelling of $t\bar{t}$ production and decay?
- Topics not discussed: $t\bar{t} + H/\gamma/Z/j$,
  effects of anomalous couplings/dim-6 EFFT operators

Fixed-order prediction in QCD (Bärnreuther/Czakon/Fiedler/Mitov 12–13)

$$\sigma_{t\bar{t}}^{\mathrm{NNLO}}(13\mathrm{TeV}) = \begin{cases} 802.85^{+28.12\,+42.03}_{-44.97\,-29.15}\mathrm{pb} & \mathrm{MMHT2014} \\ 805.14^{+28.28\,+46.01}_{-45.29\,-45.35}\mathrm{pb} & \mathrm{CT14} \\ 794.00^{+28.18\,+17.13}_{-45.13\,-17.35}\mathrm{pb} & \mathrm{NNPDF3.1} \\ 785.02\,\underbrace{^{+26.50}_{-42.68}}\,\underbrace{^{+19.37}_{-19.37}}\mathrm{pb} & \mathrm{ABMP16} \end{cases}$$

scale PDF+α_s

$m_t = 173.3\,\mathrm{GeV}$, $\alpha_s(M_Z) = 0.118 \pm 0.002$;
ABPM16: $m_t = 170.4\,\mathrm{GeV}$, $\alpha_s(M_Z) = 0.1147 \pm 0.0008$



- $\sigma_{t\bar{t}}$ included in PDF fits
- Scale uncertainty $\sim 5\% \gtrsim$ PDF+α_s uncertainty
- Experimental uncertainty reaches $\sim 3-4\%$

Resummation of threshold-enhanced corrections, $\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}} \to 0$

$$\hat{\sigma}_{pp'} \propto \sigma^{(0)} \exp\Big[\underbrace{\ln\beta\, g_0(\alpha_s \ln\beta)}_{\text{(LL)}} + \underbrace{g_1(\alpha_s \ln\beta)}_{\text{(NLL)}} + \underbrace{\alpha_s g_2(\alpha_s \ln\beta)}_{\text{(NNLL)}} + \underbrace{\alpha_s^2 g_3(\alpha_s \ln\beta)}_{\text{(N}^3\text{LL)}} + \ldots\Big]$$
$$\times \sum_{k=0} \left(\frac{\alpha_s}{\beta}\right)^k \times \Big\{ \underbrace{1}_{\text{(LL,NLL)}} ; \underbrace{\alpha_s, \beta}_{\text{(NNLL)}} ; \underbrace{\alpha_s^2, \alpha_s\beta, \beta^2}_{\text{(NNLL', N}^3\text{LL)}} ; \ldots \Big\} :$$

- Mellin-space NNLL resummation of threshold logarithms

  (Czakon/Mitov/Sterman 09/Cacciari et al. 11, ⇒ TOP++)

- SCET/NRQCD resummation of threshold logarithms and Coulomb corrections α_s/β (Beneke/Falgari/(Klein)/CS 09/11; ⇒ TOPIXS)

Expansion of resummed cross-section to $\text{N}^3\text{LO}_{\text{approx}}$

- NNLL in one-particle inclusive kinematics (Kidonakis 14)
- Including subleading collinear; $\beta \to 1$ terms (Muselli et al. 15)
- Partial N^3LL including Coulomb terms (Piclum/CS 18)

Total cross section

Reduction of scale uncertainty from threshold resummation

$$\sigma_{t\bar{t}}^{\mathrm{NNLO}}(13\mathrm{TeV}) = 802.83^{+28.12(3.5\%)}_{-44.97(5.6\%)}\mathrm{pb} \Rightarrow \begin{cases} \mathrm{NNLL(top++)}: & 821.37^{+20.28(2.5\%)}_{-29.60(3.6\%)}\mathrm{pb} \\ \mathrm{NNLL(topixs)}: & 807.13^{+24.72(3.2\%)}_{-39.03(5.0\%)}\mathrm{pb} \end{cases}$$

(NNLL' terms in top++; resummation uncertainty $\approx \pm 2\%$ in topixs)

Expansion to N^{3}LO: complementary estimate of higher orders

- Partial N^{3}LL: $+1.6\%$ relative to NNLO (Piclum/CS 18)

$$\sigma_{t\bar{t}}^{\mathrm{N^3LO_{app}}}(13\mathrm{TeV}) = 815.70^{+19.88(2.4\%)}_{-27.12(3.3\%)}(\mathrm{scale})^{+9.49(1.2\%)}_{-6.27(0.8\%)}(\mathrm{approx})\mathrm{pb},$$

includes estimate of systematic uncertainty of approx:

$$\Delta\sigma_{t\bar{t}}^{\mathrm{N^3LO_{app}}}(\mathrm{approx.}) = \underbrace{^{+7.87}_{-6.24}}_{C^{(3)}} \quad \underbrace{^{+5.3}_{-0.0}}_{\text{kin.ambiguity}} \pm \underbrace{0.11}_{3-\text{loop soft-an.dim}} \pm \underbrace{0.60}_{\text{Coulomb}} \ \mathrm{pb},$$

- N^{3}LO Coulomb corrections only fully known for colour singlet (Beneke et al. 15)
- three-loop massive soft anomalous dimension not known for colour octet

Total cross section

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- NNLL in one-particle inclusive kinematics: (Kidonakis 14)
  $+2.7\%$ relative to NNLO; $\Delta\sigma_{t\bar{t}}^{\mathrm{N^3LO_{app}}} = ^{+2.9\%}_{-2.0\%}(\mathrm{scale})$

- Including subleading collinear; $\beta \to 1$ terms (Muselli et al. 15)
  $+4.2\%$ relative to NNLO (soft only: $+2.3\%$);

$$\Delta\sigma_{t\bar{t}}^{\mathrm{N^3LO_{app}}} = \pm 2.7\%(\mathrm{scale}) \pm 1.9\%(\mathrm{approx})$$

Applications of total cross section measurements:

- Pole mass

$$m_t = 173.8^{+1.7}_{-1.8}\text{GeV}$$

from σ_{tt} measurement

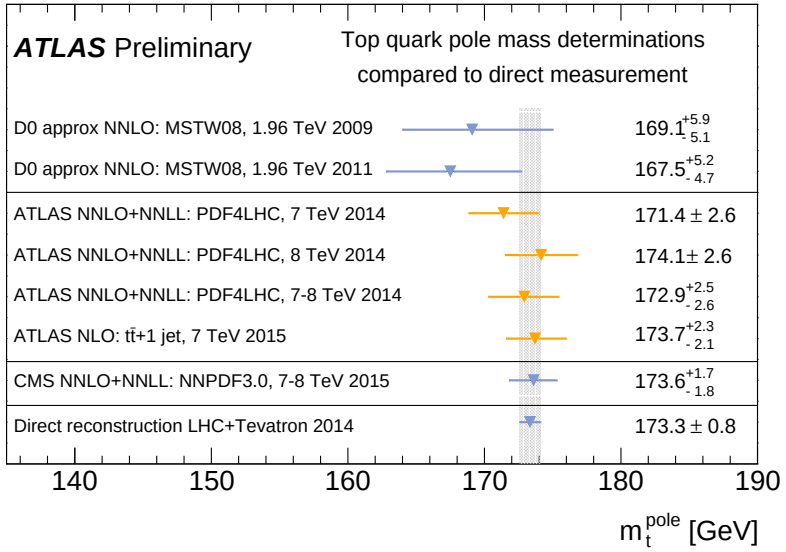
(CMS 16)

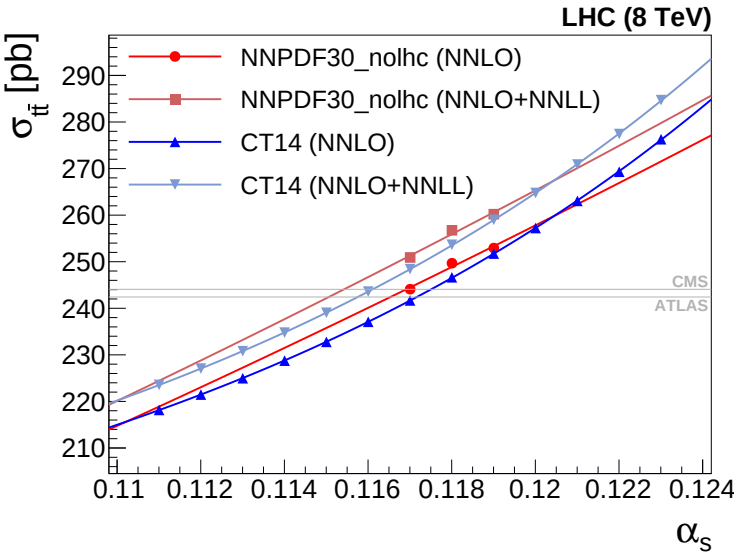
- Strong coupling:

$$\alpha_s(M_Z) = 0.1177^{+0.0034}_{-0.0036}$$

(Klijnsma/Bethke/Dissertori/Salam 17)

  - use only PDFs that do not fit σ_{tt}
  - m_t uncertainty included in error





Differential NNLO QCD calculation (Czakon/(Fiedler)/Heymes/Mitov 16)

- NLO fast tables (Czakon/Heymes/Mitov 17)
- use in PDF fits (Czakon/Hartland/Mitov/Nocera/Rojo 16)

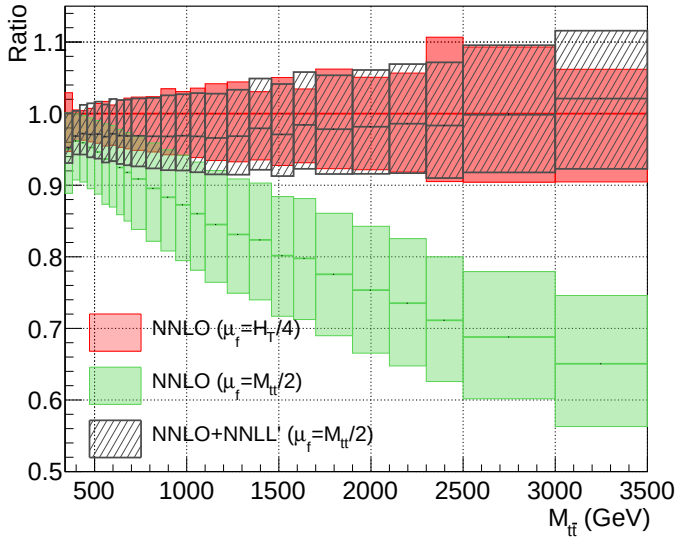
Soft-gluon resummation for p_T, $M_{t\bar{t}}$ distributions

(Kidonakis; Ahrens et al.; low p_T: Zhu et al; Catani et al; boosted tops: Ferroglia et al.)

Matching of NNLO QCD with NNLL soft-gluon resummation in pair-invariant mass kinematics $\left(1 - \frac{M_{t\bar{t}}}{\hat{s}}\right) \to 0$. (Czakon et al.18)

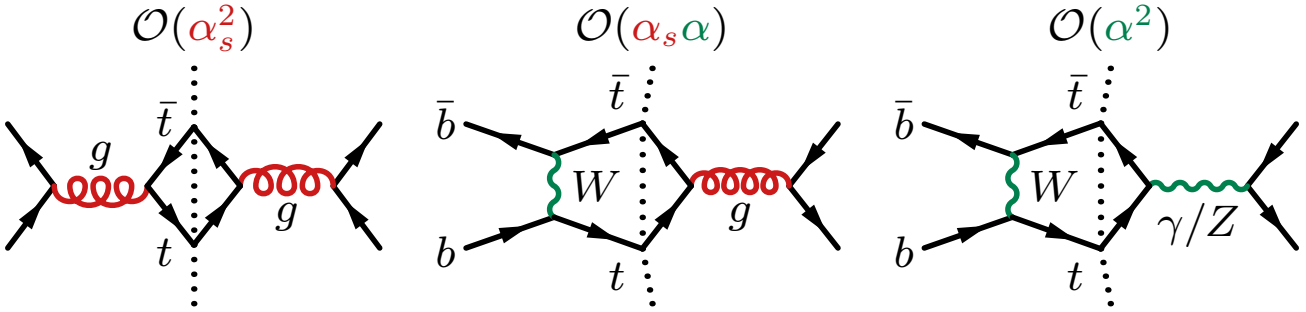
- further "boosted-soft" resummation of $\ln(m_t^2/\hat{s})$ terms
- scale choices
  - $\mu_f = H_T/4 = \frac{1}{4}(\sqrt{m_t^2+p_{T,t}^2} + \sqrt{m_t^2+p_{T,\bar{t}}^2})$ for $M_{t\bar{t}}$ spectrum
  - $\mu_f = m_T/2$ for p_t spectrum

  minimize higher-order corrections

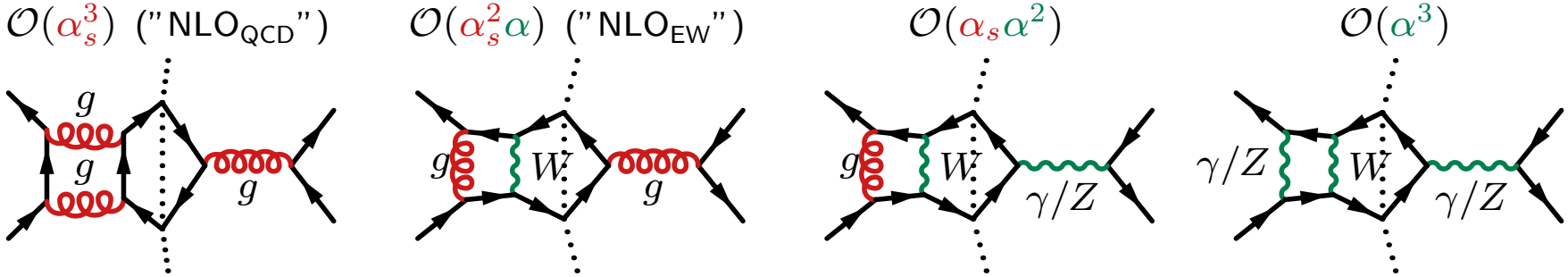


EW corrections

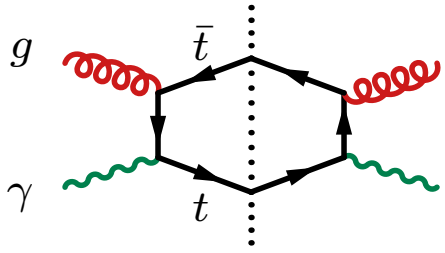
Interference of QCD and EW Born contributions:



"EW" and "QCD" orders entangled by loop corrections:



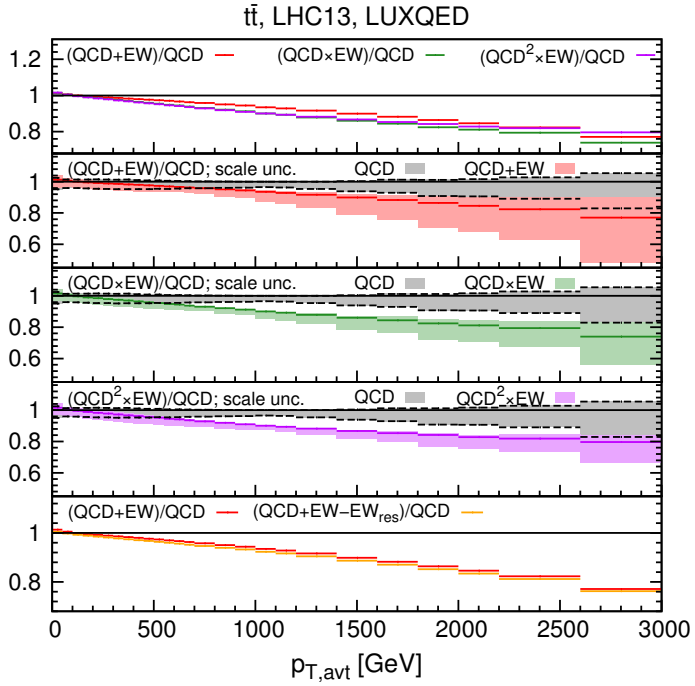
Photon induced $\mathcal{O}(\alpha_s\alpha)$ contributions: ($\Rightarrow$ LUXQED PDF (Manohar et al. 16))

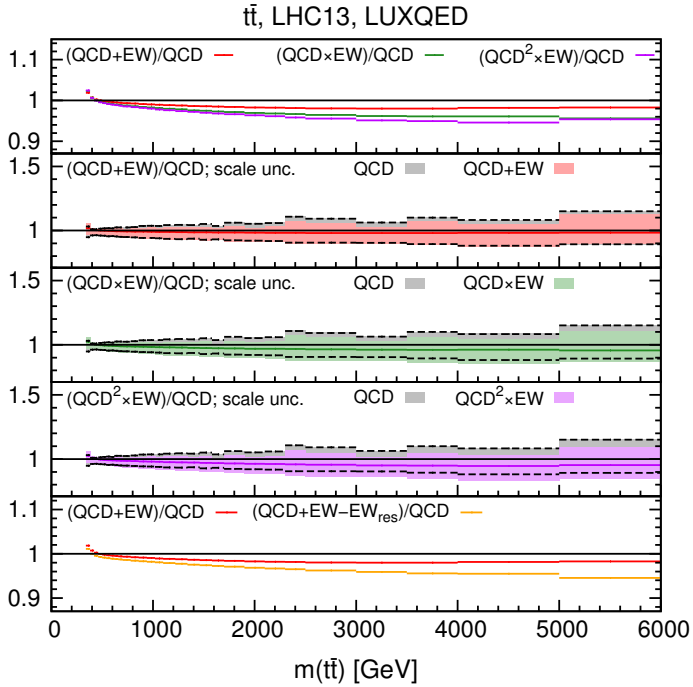


Additive/Multiplicative combination of NLO-EW and NNLO-QCD

(Czakon et al. 17)

- $\mathrm{EW} = \mathrm{LO}_{\mathcal{O}(\alpha_s\alpha)} + \mathrm{NLO}_{\mathcal{O}(\alpha_s^2\alpha)} + \underbrace{\mathrm{LO}_{(\alpha^2)} + \mathrm{NLO}_{\mathcal{O}(\alpha_s\alpha^2)+\mathcal{O}(\alpha^3)}}_{\mathrm{EW_{res}}}$
- γg initial state included in $\mathrm{LO}_{\mathcal{O}(\alpha_s\alpha)}$
- $\mathrm{EW}\times\mathrm{QCD} = \mathrm{EW} + \mathrm{QCD} + (K_{\mathrm{QCD}}^{\mathrm{NLO}} - 1)\mathrm{NLO}_{\mathcal{O}(\alpha_s^2\alpha)}$
  expected to describe NNLO $\mathrm{EW_{Sudakov}} \times \mathrm{QCD_{soft}}$ corrections at $\mathcal{O}(\alpha_s^3\alpha)$.





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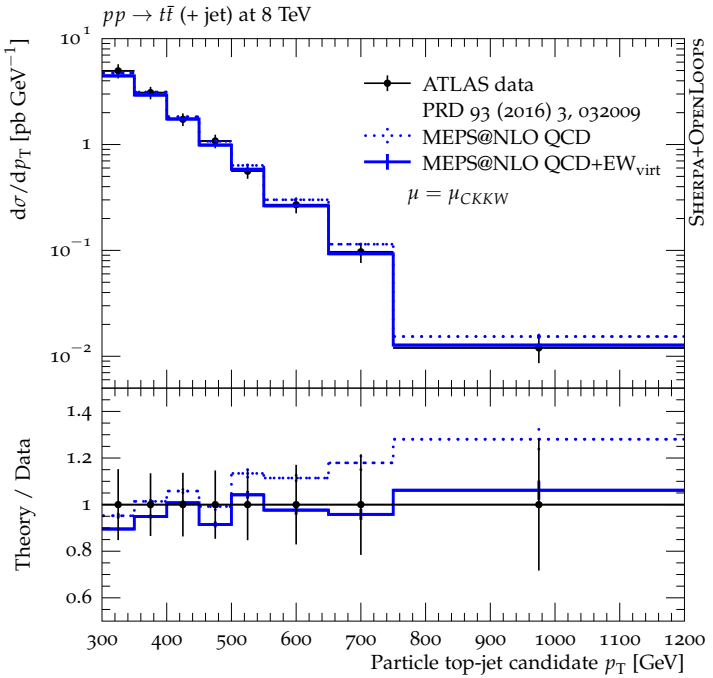
Parton-shower merging of $t\bar{t}$ and $t\bar{t}j$ with NLO QCD+EW

(Gütschow, Lindert, Schönherr 18)

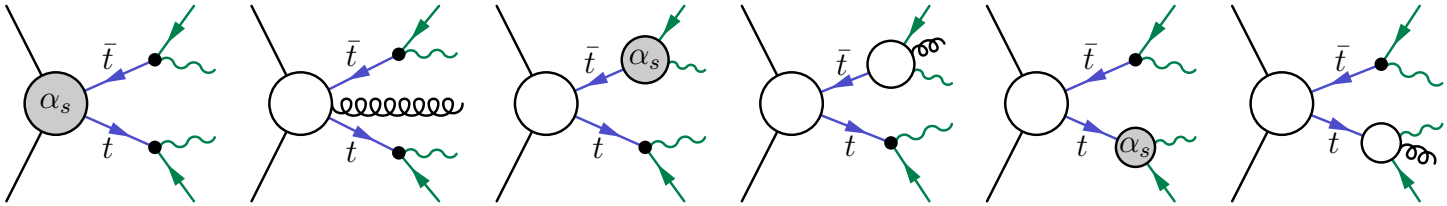
- Includes exact virtual EW corrections, real γ in YFS
- merged with $t\bar{t} + 2, 3, 4j$ at LO



Top production and decay in narrow-width approximation:

$$\frac{1}{(p^2-m_t^2)^2+(m_t\Gamma_t)^2} \Rightarrow \frac{2\pi}{2\Gamma_t m_t}\delta(p^2-m_t^2) \Rightarrow \sigma_{pp'\to b\bar{b}\,4f} \Rightarrow \sigma_{pp'\to t\bar{t}} \times \frac{\Gamma_{t\to b f_1 f_2}}{\Gamma_t}\frac{\Gamma_{\bar{t}\to \bar{b} f_3 f_4}}{\Gamma_t}$$

- NLO QCD including spin correlations (Bernreuther et.al. 04, Melnikov/Schulze 09, Campbell/Ellis 12); NLO QCD+EW (Bernreuther/Si 10)
- $\text{NNLO}_{\text{approx}}$ QCD (Gao/Papanastasiou 17)



Predictions for $t\bar{t}$ production and decay

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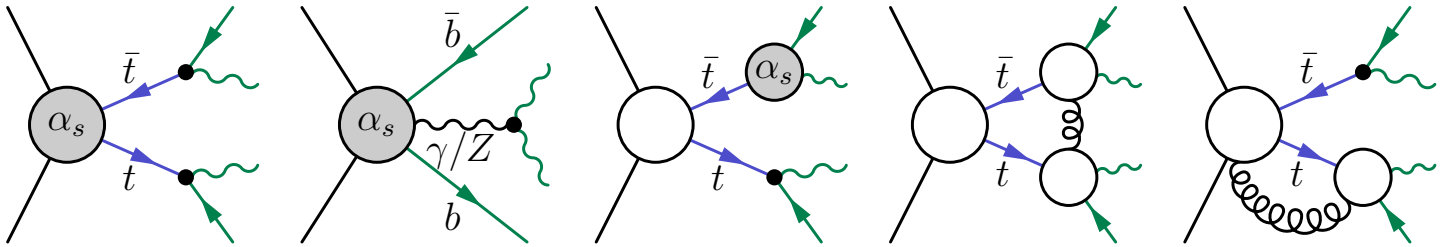
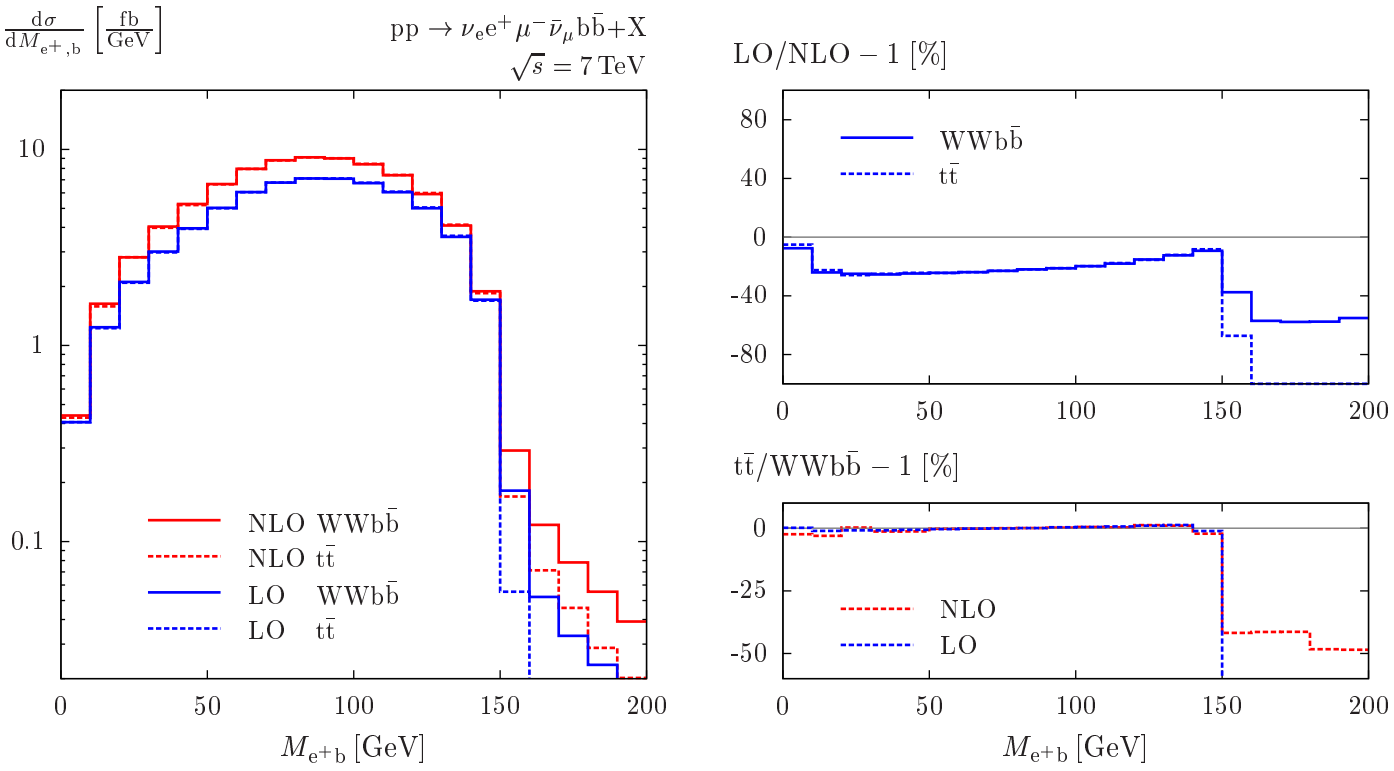
- $\text{NNLO}_{\text{approx}}$ QCD (Gao/Papanastasiou 17)

Off-shell calculations including finite-width effects, non-resonant diagrams, non-factorizable corrections

- NLO QCD for $pp \to b\bar{b}\ell\ell\nu\nu$ (Bevilaqua et al. 10, Denner et al. 10; Heinrich et al. 13), m_b-effects (Cascioli et al. 13), NLO EW (Denner/Pellen 16), NLO QCD for $pp \to b\bar{b}\mu^-\bar{\nu}_\mu jj$ (Denner/Pellen 17)



- Comparison of NWA and off-shell NLO QCD calculations
  - Accuracy of NWA $\sim \frac{\Gamma_t}{m_t} \lesssim 1\%$ for σ_{tot} and generic kinematics
  - Finite-width effects; NLO decay corrections $\gg 10\%$ near kinematic edges



(Denner et al. in Les Houches 2011)

Predictions for $t\bar{t}$ production and decay

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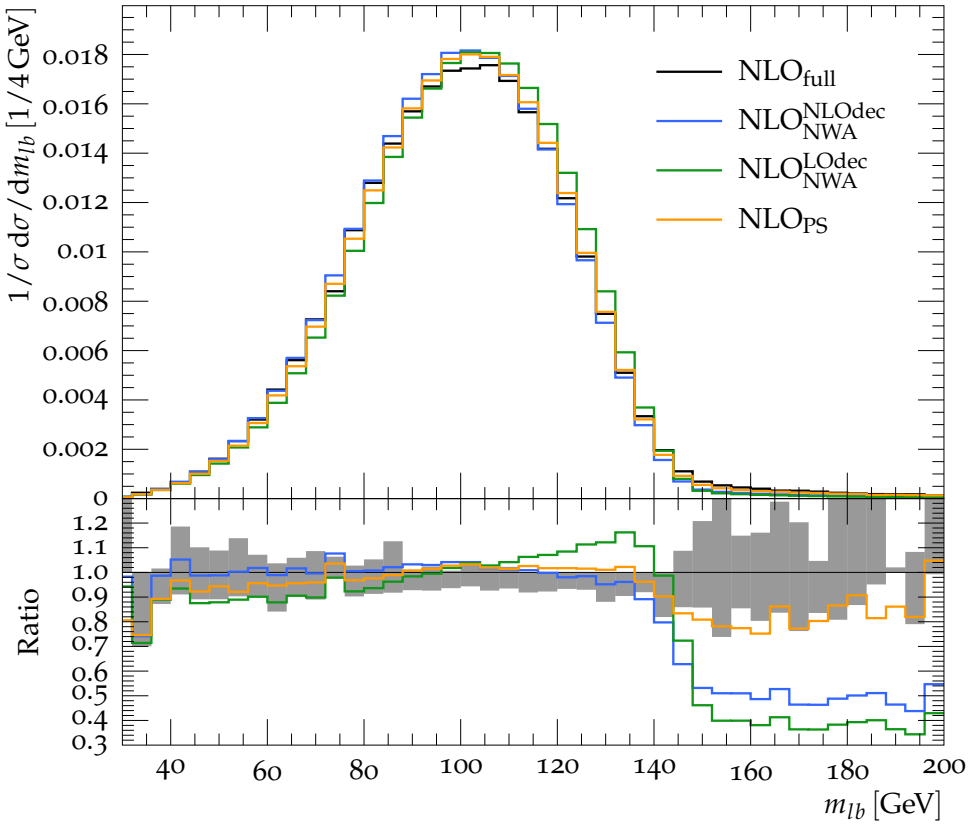

(Heinrich et al. 17)

Predictions for $t\bar{t}$ production and decay

- PS matching of $t\bar{t}$ production and decay
  - hvq: NLO on-shell production; PS with decay correction (Frixione/Nason/Ridolfi 07)
  - $t\bar{t}dec$: NLO in production/decay with NWA (Campbell/Ellis/Nason/Re 14)
  - $b\bar{b}4\ell$: full NLO with off-shell effects (Jezo/Lindert/Nason/Oleari/Pozzorini 16)
- effects on mass determination estimated from $m_{b\ell}$ peak position (Ferrario/Jezo/Nason/Oleari 18)

	PS only		full	
	No smearing	smearing	No smearing	smearing
$b\bar{b}4\ell$	172.522 GeV	171.403 GeV	172.793 GeV	172.717 GeV
$t\bar{t}dec - b\bar{b}4\ell$	-18 ± 2 MeV	$+191 \pm 2$ MeV	$+21 \pm 6$ MeV	$+140 \pm 2$ MeV
$hvq - b\bar{b}4\ell$	-24 ± 2 MeV	-89 ± 2 MeV	$+10 \pm 6$ MeV	-147 ± 2 MeV

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	No smearing		15 GeV smearing	
	He7.1	Py8.2 − He7.1	He7.1	Py8.2 − He7.1
$b\bar{b}4\ell$	172.727 GeV	$+66 \pm 7$ MeV	171.626 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 GeV	$+39 \pm 5$ MeV	171.678 GeV	$+1179 \pm 2$ MeV
hvq	173.038 GeV	-235 ± 5 MeV	172.319 GeV	$+251 \pm 2$ MeV

- Larger effects found from template fits using partonic results (Heinrich et al. 17)
- interpretation of kinematic measurements in terms of pole mass or MC mass controversial (Hoang/Stewart 08; Nason 2018)

Summary

Total cross section

- state of the art: NNLO QCD with $\pm 5\%$ scale uncertainty
- NNLL/N^{3}LO$_{\text{approx}}$: reduced scale uncertainty;
  $1-2\%$ systematic uncertainty

Differential cross sections

- NNLO QCD+NNLL for boosted tops
  - dynamical scale choices reduce higher-order corrections
- Combination of QCD with NLO EW
  - additive/multiplicative combinations, PS merging
  - improves agreement with data for large p_t

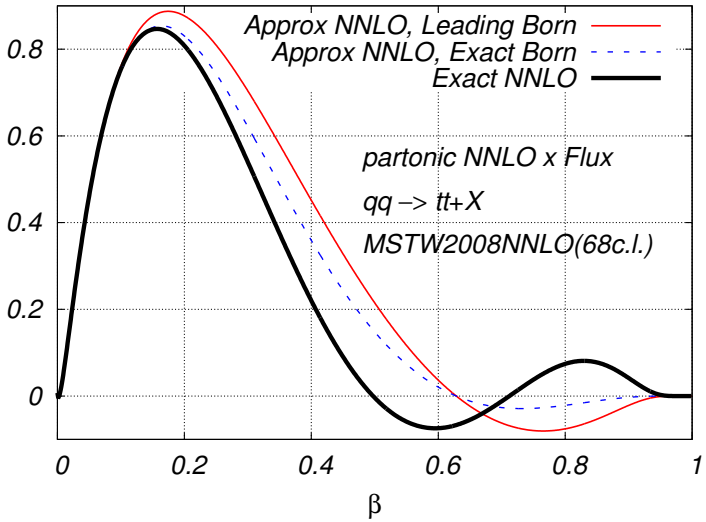
NLO QCD description with off-shell effects

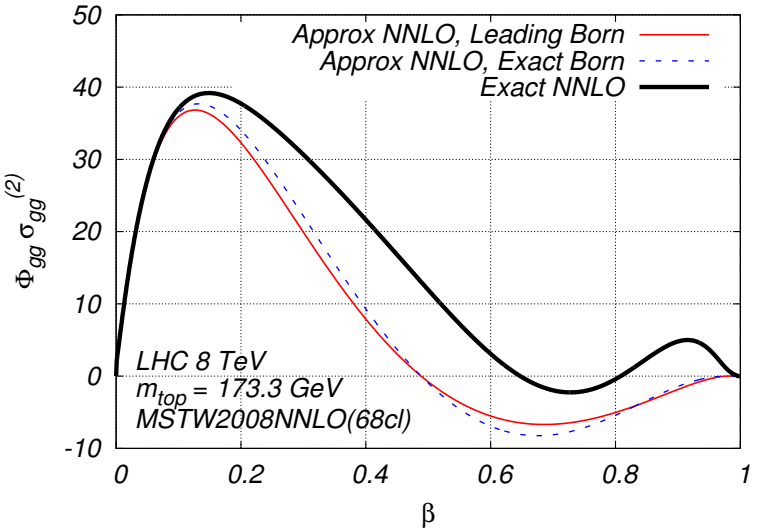
- significant off-shell effects near kinematic edges
- studies to estimate effect on m_t measurement

Backup slides

- Top-pair production dominated by $\beta \sim 0.6$

  $\Rightarrow$ justification of threshold approximation?





$\frac{d\sigma}{d\beta} = \frac{8\beta m_t^2}{s(1-\beta^2)^2} L(\beta,\mu_f)\hat{\sigma}$, (Bärnreuther/Czakon/Mitov 12; Czakon/Fiedler/Mitov 13)

$\Rightarrow$ threshold corrections give estimate of higher-order corrections

$\Rightarrow$ careful estimate of uncertainties necessary

- resummation not mandatory for $t\bar{t}$ production at LHC

$\Rightarrow$ compare resummed results to fixed-order expansions

NNLL vs NNLO

Reduction of scale uncertainty from threshold resummation

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`top++`: Mellin space resummation (Sterman 87; Catani/Trentadue 89)

- Includes 2-loop constant term H_2 in threshold expansion

$$\sigma_{t\bar{t}}^{\mathrm{NLLL}}|_{H_2=0} = 812.20 \text{ pb}$$

`topixs`: combined soft/Coulomb resummation

- RGE for momentum-space resummation (Becher/Neubert 06)
- dependence on scales μ_f, $\mu_h \sim 2M$: $\Delta_{\mathrm{scale}}\sigma_{t\bar{t}}^{\mathrm{NNLL}} = {}^{+15.64}_{-37.71}$ pb
- resummation uncertainty: choice of $\mu_s \sim M\beta^2$, kinematic ambiguities, higher-order terms: $\Delta_{\mathrm{res}}\sigma_{t\bar{t}}^{\mathrm{NNLL}} = {}^{+20.26}_{-14.37}$ pb
- Includes bound-state effects $\sigma_{t\bar{t}}^{\mathrm{NNLL}}|_{\mathrm{BS}} = 2.8$ pb

Input to resummation formula at N^{3}LL

- Constant in NNLO thresh. expansion (Bärnreuther/Czakon/Fiedler 13)
- 2-loop soft function for singlet/octet

  (Belitzky 98;Becher/Neubert/Xu 07; Czakon/Fiedler 13)
- Coulomb function:
  - NNLO Green function sums terms $\alpha_s^n/\beta^n \times (\alpha_s^2, \alpha_s v, v^2)$

    (Beneke/Signer/Smirnov; Hoang/Teubner 99,. . .)
  - spin-dependent $\alpha_s^3 \ln^{2,1} \beta$ terms from N^{3}LO Green function, only known fully for $e^- e^+ \to t\bar{t}$ (Beneke et al. 16)
- RGE functions
  - 4-loop γ_{cusp} (Moch/Ruijl/Ueda/Vermaseren/Vogt 17; not needed for N^{3}LO$_{\text{app}}$)
  - 3-loop collinear anom. dim. (Moch/Vermaseren/Vogt 04/05)
  - missing: 3-loop massive soft anomalous dimension (massless: Almelid/Duhr/Gardi 15)