Top Precision for the Associated Top-Pair Production at the LHC

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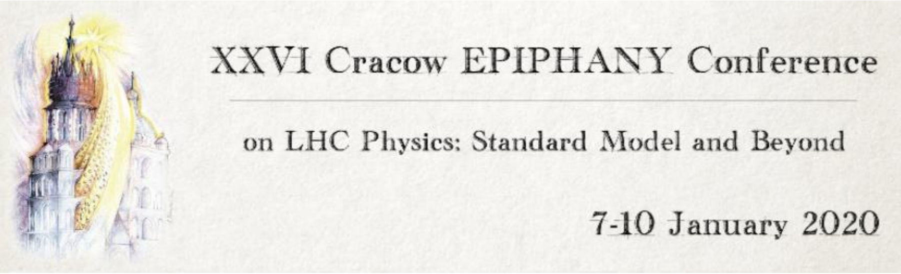
DFG Deutsche Forschungsgemeinschaft



TOP AT 25 !

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

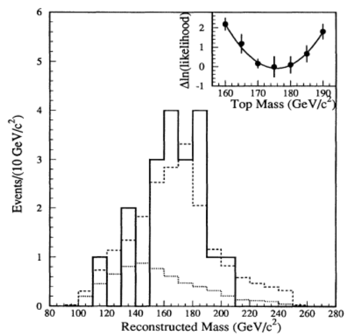
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]

(Received 24 February 1995)

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni



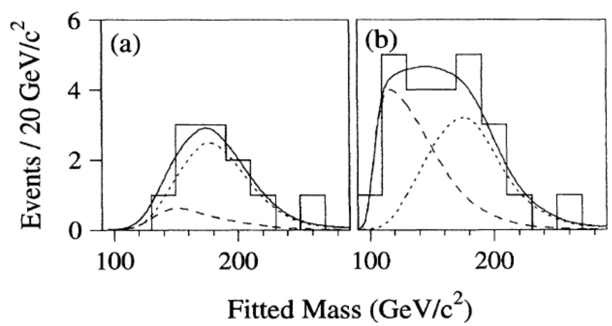
VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B. S. Acharya,[40] I. Adam,[10] D. L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20]
J. Alitti,[36] G. Álvarez,[16] G. A. Alves,[8] E. Amidi,[27] N. Amos,[22] E. W. Anderson,[17] S. H. Aronson,[3] R. Astur,[38] R. E.

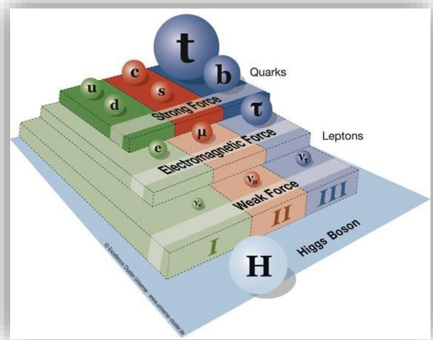
(Received 24 February 1995)

The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.



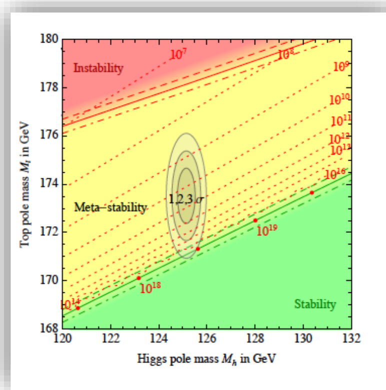
Since then more than **4300** publications in the INSPIRE database
and **275 million** top quarks produced @ the LHC in the Run 2 (139 fb^{-1}) alone !!

Top is…



- ... heavy. The heaviest particle in the SM.
- ... short-lived, hence „bare“. It decays before it can hadronize.

- ... Higgs-friendly. Large Yukawa coupling $y_t \sim 1$ of central relevance in Higgs physics.
- ... working behind the scenes. Top loops provide important contributions to many observables (e.g. M_H).



[Buttazzo et al.’13]

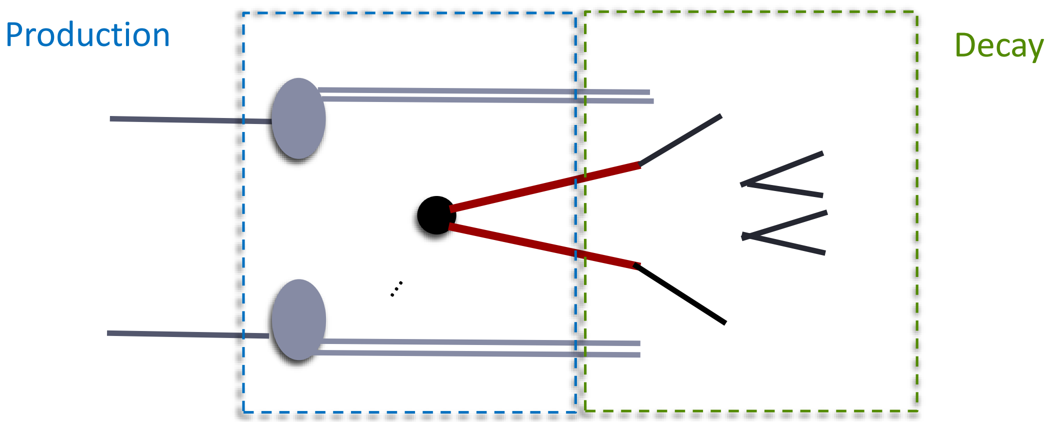
- ... consequential. It‘s mass, together with M_H determines the stability of the Universe,.
- ... probing the unknown. It offers a unique way to test the SM and search for BSM.

Top Precision

Top precision predictions

Fixed order perturbation theory

- QCD (N(N)LO)
  - ☞ *see R. Poncelet's talk on Friday*
- Combined QCD-EW



Top Precision

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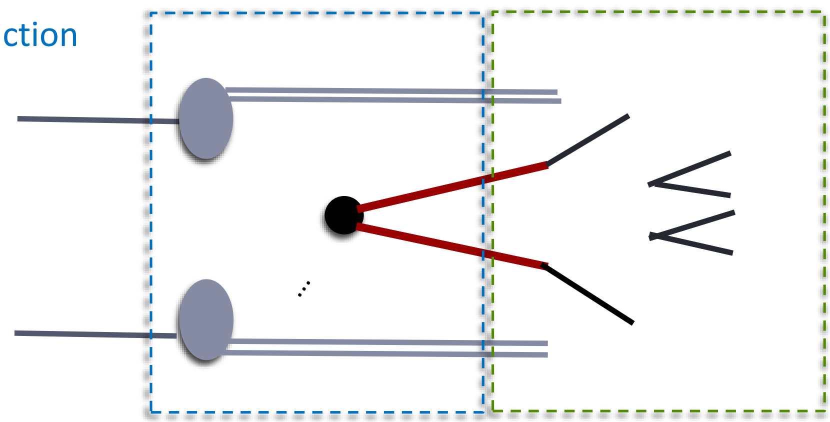
All-order soft/collinear QCD radiation (& Coulomb effects)

- Resummation (NLL, NNLL,..)
- Parton showers matched with fixed order predictions (LOPS, NLOPS,..)

Production



Decay

Top Precision

Top precision predictions

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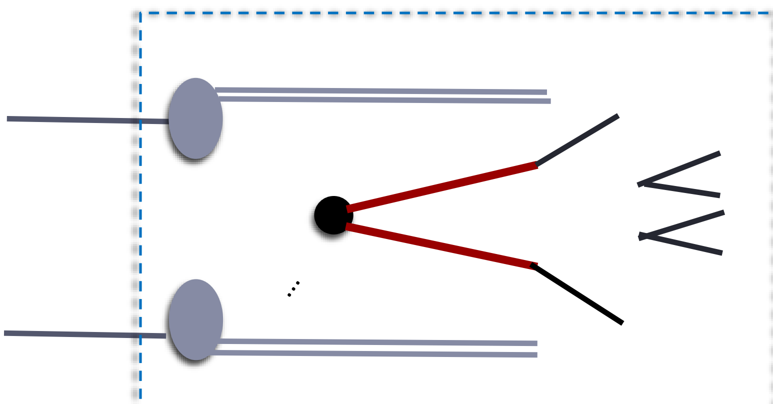
  - ☞ *see R. Poncelet's talk on Friday*
- Combined QCD-EW

All-order soft/collinear QCD radiation (& Coulomb effects)

- Resummation (NLL, NNLL,..)
- Parton showers matched with fixed order predictions (LOPS, NLOPS,..)

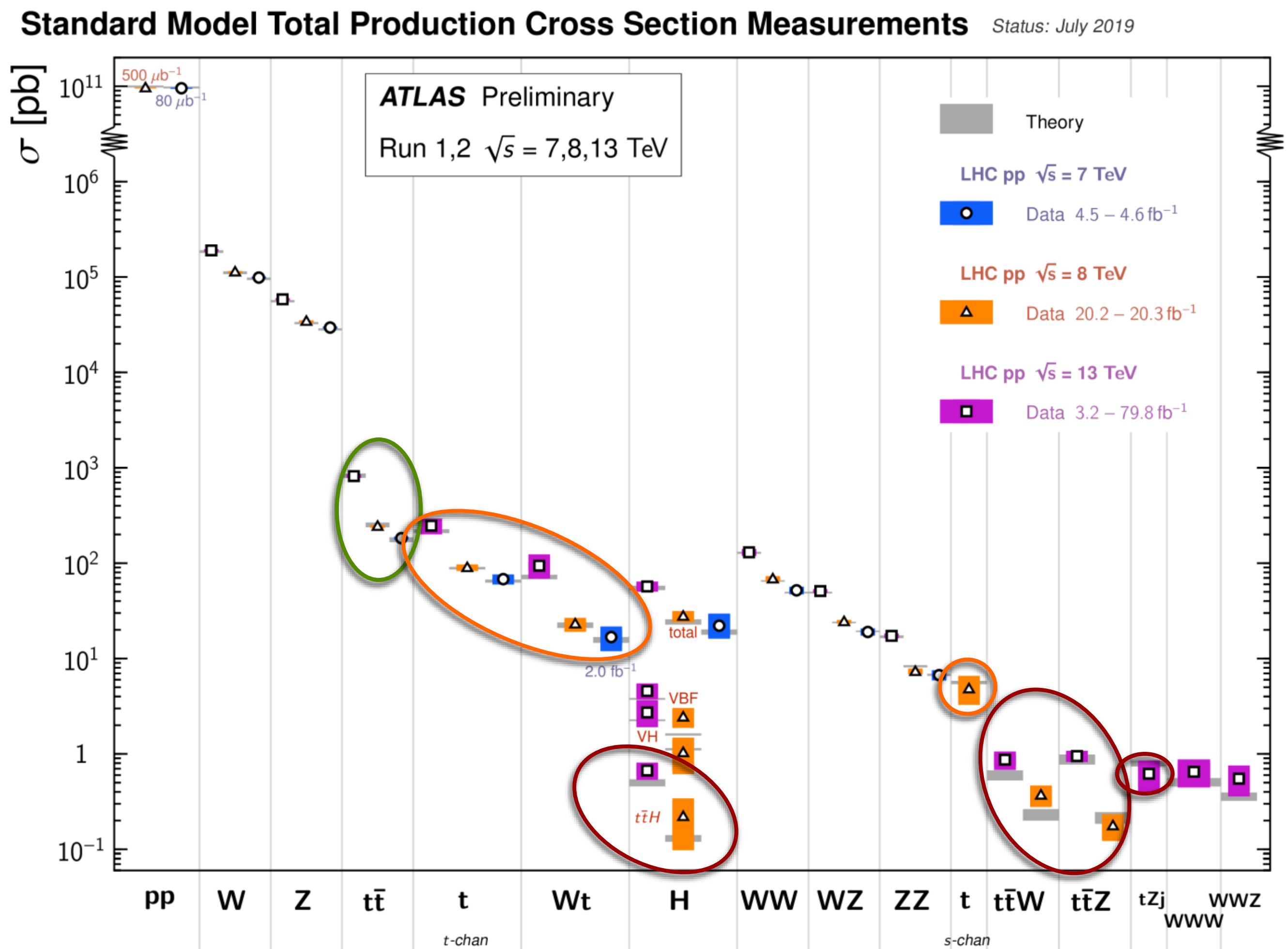
Beyond Narrow Width Approximation (NWA): calculations for final states including off-shell effects and non-resonant contributions

☞ *see G. Bevilacqua's talk on Friday*



Tops en Vogue

- Top-pairs
- Single top
- Associated production: ttH, ttZ, ttW



TOP PRECISION

Top precision predictions

Fixed order perturbation theory

- QCD (N(N)LO)
- **Combined QCD-EW NLO**

All-order soft/collinear QCD radiation

- **Resummation** (NLL, **NNLL**,..)
- Parton showers matched with fixed order predictions (LOPS, NLOPS,..)

Beyond Narrow Width Approximation (NWA): calculations for final states including off-shell effects and non-resonant contributions

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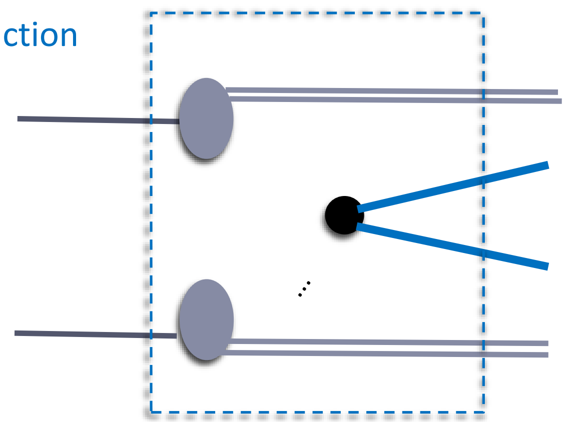
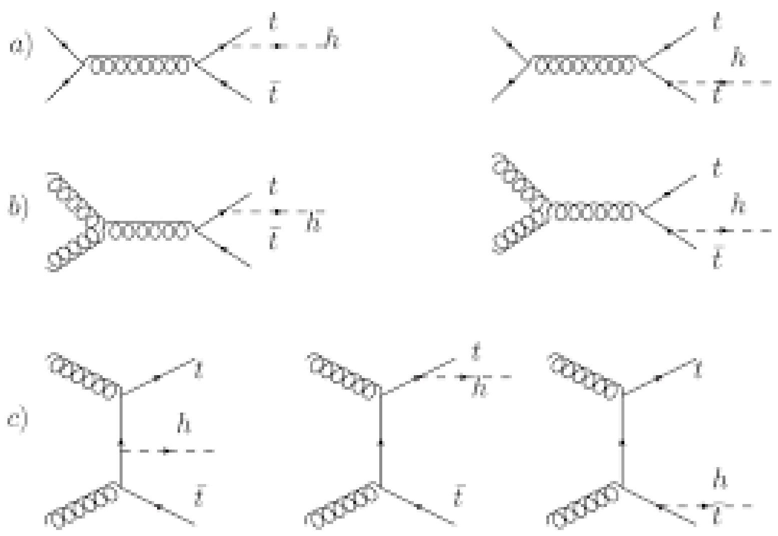


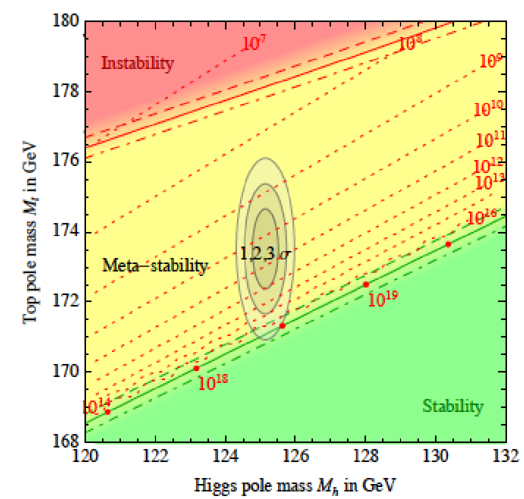
TTBAR+H

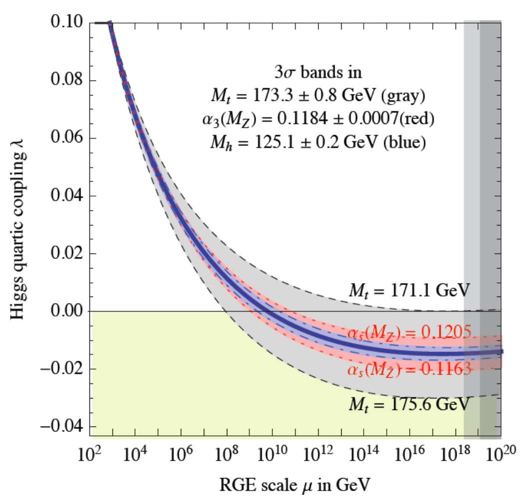
- Direct probe of the strength of the top-Yukawa coupling without making any assumptions regarding its nature



TTBAR+H

- Direct probe of the strength of the top-Yukawa coupling without making any assumptions regarding its nature
- Far-reaching consequences -> stability of our Universe





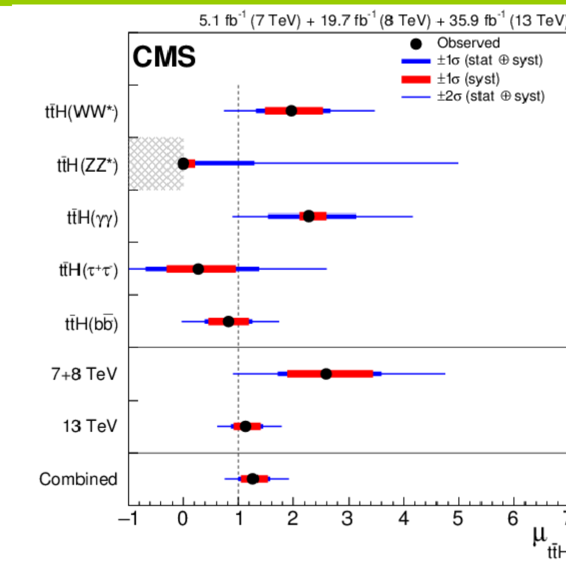
$$V = -\frac{m_H^2}{2}|H|^2 + \lambda|H^4|$$

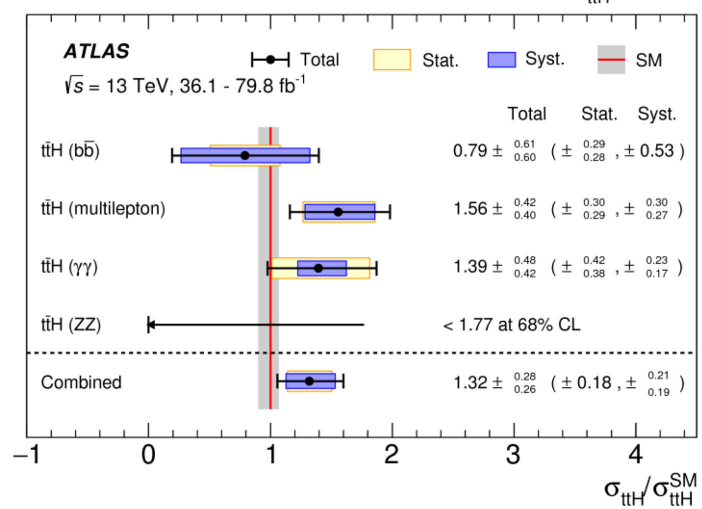
$$4\pi^2 \frac{d\lambda}{d\ln\mu^2} \simeq 3y_t^4 + 6\lambda y_t^2 + 12\lambda^2 + \ldots$$

[Buttazzo et al.'13]

TTBAR+H

- Direct probe of the strength of the top-Yukawa coupling without making any assumptions regarding its nature
- Far-reaching consequences -> stability of our Universe
- Fundamental Yukawa interactions probed only very recently (2018)
- Small cross section σ≈ 500 fb @13 TeV
  - need advanced experimental techniques
  - precise theory for signal and background

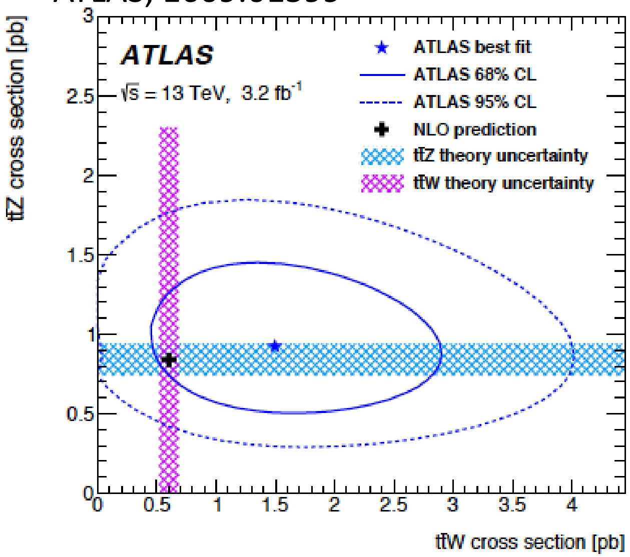




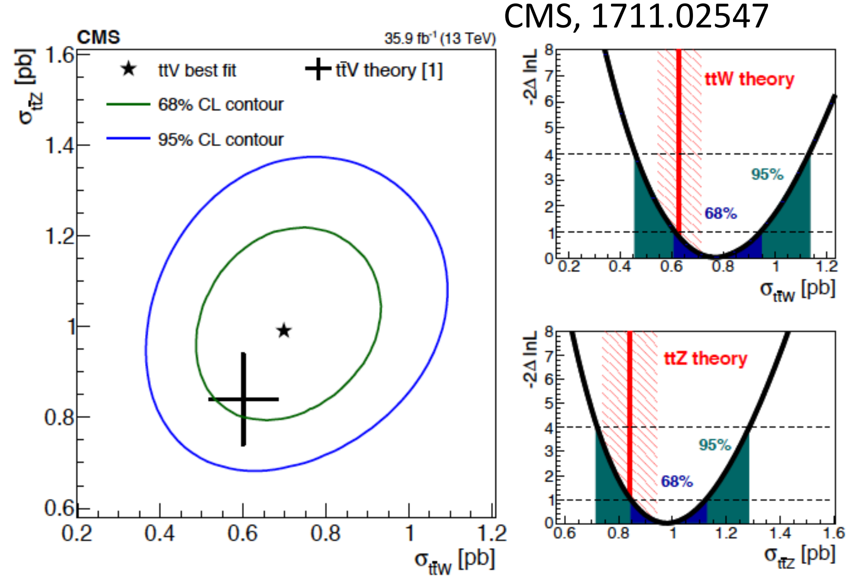
TTBAR+W,Z

- Probes of top-quark couplings
- Sensitive to BSM contributions
- Dominant backgrounds to searches and SM precision measurements (*ttH* included)

ATLAS, 1609.01599



CMS, 1711.02547



- Signal strength (CMS, 1907.11270) $\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.95 \pm 0.05\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\,\mathrm{pb}$
- Measurement of the transverse momentum distribution of the Z boson (CMS, 1907.11270)

Theory Status: TTbarH at Fixed Order

- NLO QCD available since (almost) 20 years *[Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas '01-'02][Reina, Dawson'01][Reina, Dawson, Wackeroth'02][Dawson,Orr,Reina,Wackeroth'03] [Dawson, Jackson, Orr, Reina, Wackeroth'03]*
- NLO QCD matched with parton showers
  - POWHEG-Box *[Garzelli, Kardos,Papadopoulos,Trocsanyi'11] [Hartanto, Jäger,Reina, Wackeroth'15]*
  - aMC@NLO *[Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli'11]*
  - SHERPA+RECOLA *[Biedermann et al.'17]*
- QCD and EW@NLO *[Frixione, Hirschi, Pagani,Shao,Zaro'14-'15][Zhang, Ma, Zhang, Chen, Guo'14][Biedermann, Bräuer, Denner, Pellen, Schumann, Thompson'17]*
- NLO QCD *[Denner, Feger'15]* and EW *[Denner,Lang, Pellen, Uccirati'16]* with tops off-shell
  - Top decays into b quarks and leptons: $pp \to ttH \to W^+W^-bbH \to e^+\nu_e\, \mu^-\nu_\mu\, bb\, H$
  - All resonant, non-resonant, interference and off-shell effects included

Theory Status: ttbar+W,Z at Fixed Order

- NLO QCD *[Lazopoulos, Melnikov, Petriello'07] [Lazopoulos, McElmurry, Melnikov, Petriello'08] [Kardos, Trocsanyi, Papadopoulos'12]* with decays at NLO *[Campbell, Ellis'12][Roentsch, Schulze'14-'15]*
- NLO interfaced to parton showers in aMC@NLO *[Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattalaer, Shao Stelzer, Torrieli, Zaro,'14] [Maltoni, Mangano, Tsinikos, Zaro,'14] [Maltoni, Pagani, Tsinikos'15]* and POWHEG-Box *[Garzelli, Kardos,Papadopoulos,Trocsanyi'12]*
- EW corrections *[Frixione, Hirschi, Pagani,Shao,Zaro'14-15][Frederix, Pagani, Zaro'18]*

THEORY STATUS: TTBAR+W,Z AT FIXED ORDER

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From LHC HXSWG Report 4:

Process	$\sqrt{s}$	$\sigma^{\rm NLO}_{\rm QCD}$	$\sigma^{\rm NLO}_{\rm QCD+EW}$	$K_{\rm QCD}$	$\delta_{\rm EW}[\%]$	Scale[%]	PDF[%]	$\alpha_S[\%]$
$t\bar{t}Z$	13	841.3(1.6)	839.3(1.6)	1.39	-0.2	$+9.6\%$ -11.3%	$+2.8\%$ -2.8%	$+2.8\%$ -2.8%

THEORY STATUS: TTBAR+W,Z AT FIXED ORDER

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From CMS, 1907.11270 (13 TeV, 77.5 fb^{-1}):

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.95 \pm 0.05\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\,\mathrm{pb}$$

± 5.3%(stat) ± 6.3%(syst)

!

Beyond NLO QCD: Threshold Resummation

- *ttH:* NLL+NLO resummation in the absolute threshold limit, $\hat{s} \to M^2 = (m_t + m_{\bar{t}} + m_B)^2$ obtained using direct QCD approach *[AK, Motyka, Stebel, Theeuwes'15]*
- *ttH:* NLL+NLO soft gluon and Coulomb resummation in the absolute threshold limit in SCET *[Ju and Yang'19]*
- *ttH:* "Approximated" NNLO based on the SCET approach to resummation in the invariant mass limit, $\hat{s} \to Q^2 = (p_t + p_{\bar{t}} + p_B)^2$ *[Broggio, Ferroglia, Pecjak, Signer, Yang'15]*
- *ttH:* NLL+NLO in the invariant mass limit for production with pseudoscalar Yukawa couplings *[Broggio, Ferroglia, Fiolhais, Onofre'17]*
- *ttW:* NNLL+NLO resummation in the invariant mass limit, SCET *[Li, Li, Li'14]*
- *ttH, ttW, ttZ:* NNLL+NLO resummation in the invariant mass limit, hybrid SCET/direct QCD method *[Broggio, Ferroglia, Ossola, Pecjak'16] [Broggio, Ferroglia, Pecjak, Yang'16][Broggio, Ferroglia, Ossola, Pecjak, Samoshima'17] [Broggio et al. 19]*
- *ttH, ttW, ttZ:* NNLL+NLO QCD (+EW) resummation in the invariant mass limit, direct QCD method *[AK, Motyka, Stebel, Theeuwes'16], [AK, Motyka, Stebel, Theeuwes'17], [AK, Motyka, Schwartländer, Stebel, Theeuwes'18-'19]*

Resummation for TTbar+B (B=H,Z,W)

- Threshold limit in the invariant mass kinematics: $\hat{s} \to Q^2 = (p_t + p_{\bar{t}} + p_B)^2$
- Large logarithmic contributions of the form $\alpha_s^n \left(\frac{\log^m(1-\hat{\rho})}{1-\hat{\rho}}\right)_+$; $\hat{\rho} = Q^2/\hat{s}$; $m \leq 2n-1$
- Direct QCD $\longrightarrow$ *N* space:

$$\frac{d\tilde{\hat{\sigma}}_{ij\to klB}}{dQ^2}(N, Q^2, \{m^2\}, \mu_F^2, \mu_R^2) = \int_0^1 d\hat{\rho}\, \hat{\rho}^{N-1} \frac{d\hat{\sigma}_{ij\to klB}}{dQ^2}(\hat{\rho}, Q^2, \{m^2\}, \mu_F^2, \mu_R^2)$$

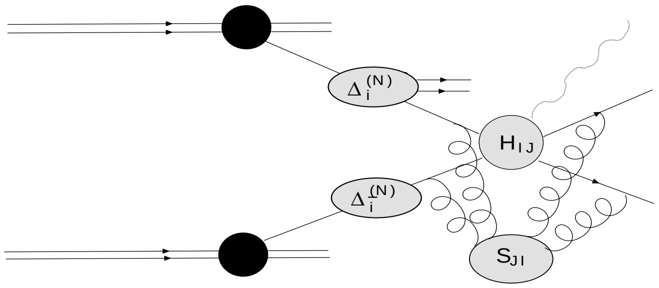
- In Mellin space, logarithms of $1-\hat{\rho}$ become logarithms of Mellin moments *N*
- Resummation

$$\hat{\sigma}^{(N)} \sim \mathcal{C}(\alpha_s) \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

LL: $\alpha_s^n \log^{n+1}(N)$ NLL: $\alpha_s^n \log^n(N)$ NNLL: $\alpha_s^n \log^{n-1}(N)$

Resummation for ttbar+B (B=H,Z,W)

- Resummation ↔ all-order factorization of soft and collinear emissions
- Exponentiation ↔ solutions of RGEs



$$\frac{d\tilde{\hat{\sigma}}^{(\mathrm{res})}_{ij\to klB}}{dQ^2}(N, Q^2, \{m^2\}, \mu_F^2, \mu_R^2) =$$

$$= \mathrm{Tr}\left[\mathbf{H}_{ij\to klB}(Q^2, \{m^2\}, \mu_F^2, \mu_R^2)\mathbf{S}_{ij\to klB}(N+1, Q^2, \{m^2\}, \mu_R^2)\right]\Delta^i(N+1, Q^2, \mu_F^2, \mu_R^2)\Delta^j(N+1, Q^2, \mu_F^2, \mu_R^2)$$

Hard off-shell — Soft wide-angle: Process-dependent

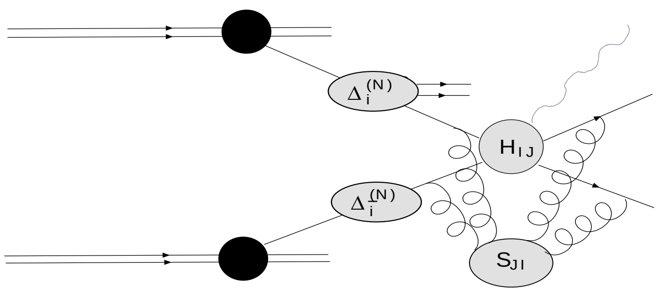
Collinear: Universal, known ✓

[Kodaira, Trentadue'82-'83][Catani, d'Emilio, Trentadue'88][Sterman'87][Moch, Vermaseren, Vogt'04]

Processes with four or more legs carrying colour: hard and soft functions are matrices in colour space

RESUMMATION FOR TTBAR+B (B=H,Z,W)

- Resummation ↔ all-order factorization of soft and collinear emissions
- Exponentiation ↔ solutions of RGEs



$$\frac{d\tilde{\hat{\sigma}}^{(\mathrm{res})}_{ij\to klB}}{dQ^2}(N,Q^2,\{m^2\},\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2) =$$

$$= \mathrm{Tr}\left[\mathbf{H}_{ij\to klB}(Q^2,\{m^2\},\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)\mathbf{S}_{ij\to klB}(N+1,Q^2,\{m^2\},\mu_{\mathrm{R}}^2)\right]\Delta^i(N+1,Q^2,\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)\Delta^j(N+1,Q^2,\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)$$

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[Kodaira, Trentadue'82-'83][Catani, d'Emilio, Trentadue'88][Sterman'87][Moch, Vermaseren, Vogt'04]

→ $\mathbf{H}^{(1)}$ extracted from aMC@NLO *[Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli'11]* (*ttH, ttW, ttZ*) and PowHel (HELAC-NLO *[Bevilacqua et al.'11]* +POWHEG-Box) package *[Garzelli, Kardos, Papadopoulos, Trocksanyi'11]* (*ttH*)

RESUMMATION-IMPROVED NNLL+NLO TOTAL CROSS SECTION

- NNLL resummed expression has to be matched with the full NLO (QCD+EW) result

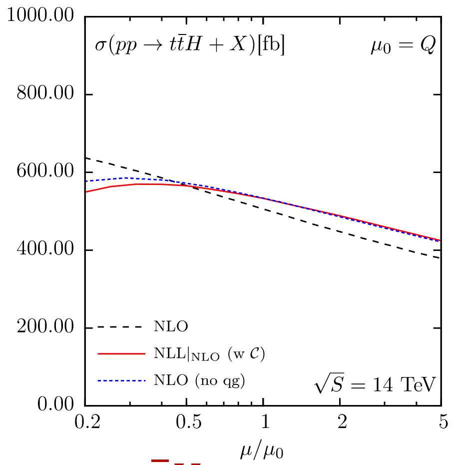
$$\sigma^{(\mathrm{match})}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2) = \sum_{i,j=q,\bar{q},g} \int_{C_{\mathrm{MP}}-i\infty}^{C_{\mathrm{MP}}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N}\, f^{(N+1)}_{i/h_1}(\mu^2)\, f^{(N+1)}_{j/h_2}(\mu^2)$$
$$\times \left[\hat{\sigma}^{(\mathrm{res},N)}_{ij \to kl}(\{m^2\}, \mu^2) - \hat{\sigma}^{(\mathrm{res},N)}_{ij \to kl}(\{m^2\}, \mu^2)\,\Big|_{NLO\ QCD} \right]$$
$$+ \sigma^{NLO\ QCD\ +\ EW}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2)\,,$$

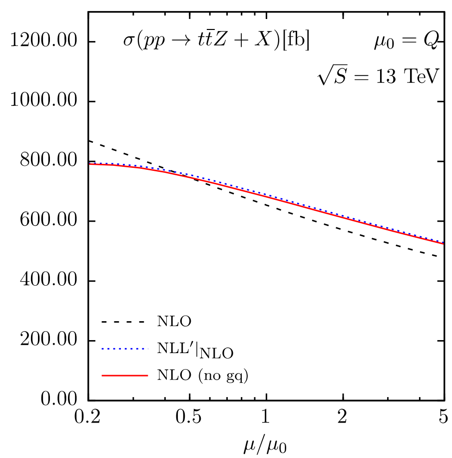
- Inverse Mellin transform evaluated using a contour in the complex *N* space according to 'Minimal Prescription' *[Catani, Mangano, Nason Trentadue'96]*

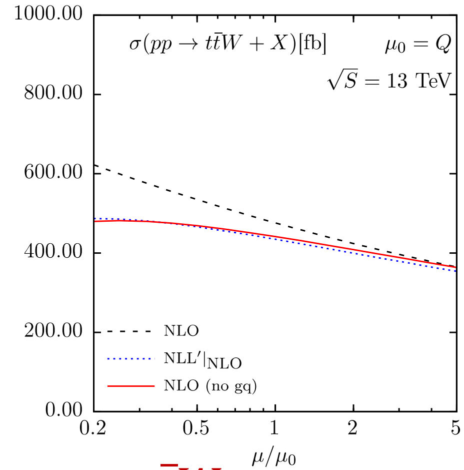
- NLO QCD+EW result obtained from `MadGraph5_aMC@NLO` *[Frederix, Frixione, Hirschi,Pagani,Zaro'18]* using `LUXqed17_plus_PDF4LHC15_nnlo_100` pdfs, contains all mixed $\alpha^n\ \alpha_s^m$ terms

NLO vs. $NLL_{|NLO}$

[AK, Motyka, Stebel, Theeuwes'17][AK, Motyka, Schwartläder, Stebel, Theeuwes'18]



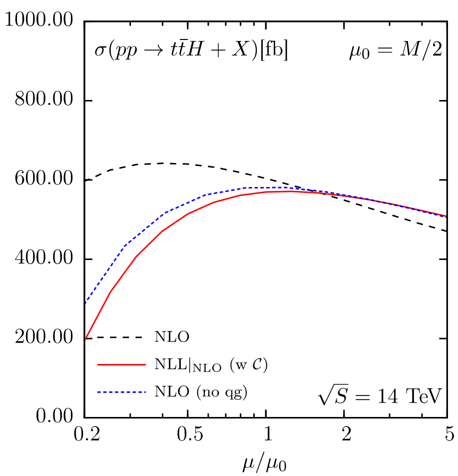


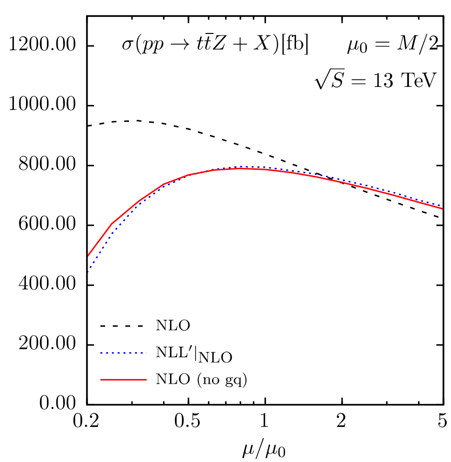


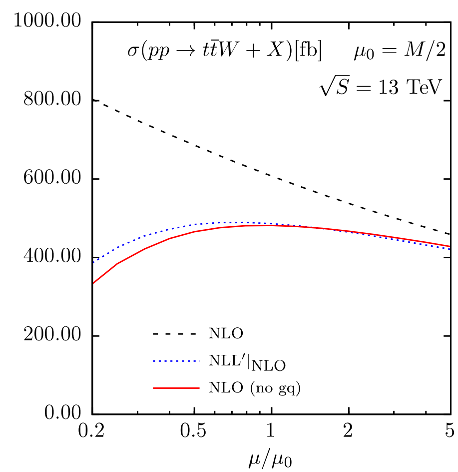
$\mu_0 = Q$

$t\bar{t}H$ $t\bar{t}Z$ $t\bar{t}W$

$\mu_F = \mu_R = \mu$







$\mu_0 = \frac{M}{2} = m_t + \frac{M_B}{2}$

Total Cross Section for TTbarH

[AK, Motyka, Stebel, Theeuwes'17 and to appear]

μ_0	NLO[fb]	NLO+NLL[fb]	NLO+NLLwC[fb]	NLO+NNLL[fb]	K_{NNLL}
Q	$425^{+12.1\%}_{-11.6\%}$	$445^{+10.0\%}_{-9.2\%}$	$489^{+8.4\%}_{-8.5\%}$	$505^{+7.5\%}_{-7.0\%}$	1.19
H_T	$434^{+11.6\%}_{-11.4\%}$	$451^{+9.5\%}_{-8.9\%}$	$491^{+7.9\%}_{-8.2\%}$	$502^{+7.3\%}_{-6.7\%}$	1.16
$Q/2$	$476^{+9.9\%}_{-10.8\%}$	$484^{+8.7\%}_{-8.2\%}$	$503^{+6.2\%}_{-7.3\%}$	$505^{+5.7\%}_{-6.4\%}$	1.06
$H_T/2$	$484^{+8.9\%}_{-10.4\%}$	$490^{+8.4\%}_{-8\%}$	$503^{+5.5\%}_{-6.8\%}$	$502^{+5.4\%}_{-6.1\%}$	1.04
$M/2$	$506^{+6\%}_{-9.3\%}$	$510^{+8.2\%}_{-7.8\%}$	$512^{+5.9\%}_{-6.2\%}$	$510^{+5.6\%}_{-6.1\%}$	1.01

$K_{\mathrm{NNLL}} = \sigma_{\mathrm{NLO+NNLL}} / \sigma_{\mathrm{NLO}}$

error from scale variation
using the 7-point method

$$\mathbf{H}_R \tilde{\mathbf{S}}_R = \mathbf{H}_R^{(0)} \tilde{\mathbf{S}}_R^{(0)} + \frac{\alpha_{\mathrm{s}}}{\pi} \left[\mathbf{H}_R^{(1)} \tilde{\mathbf{S}}_R^{(0)} + \mathbf{H}_R^{(0)} \tilde{\mathbf{S}}_R^{(1)} \right]$$

Total Cross Section for TTbarH

[AK, Motyka, Stebel, Theeuwes'17 and to appear]

μ_0	NLO[fb]	NLO+NLL[fb]	NLO+NLLwC[fb]	NLO+NNLL[fb]	K_{NNLL}
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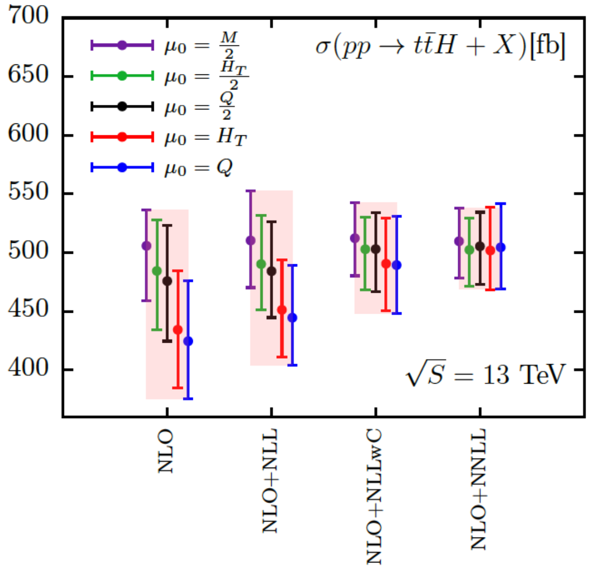
$K_{\mathrm{NNLL}} = \sigma_{\mathrm{NLO+NNLL}} / \sigma_{\mathrm{NLO}}$



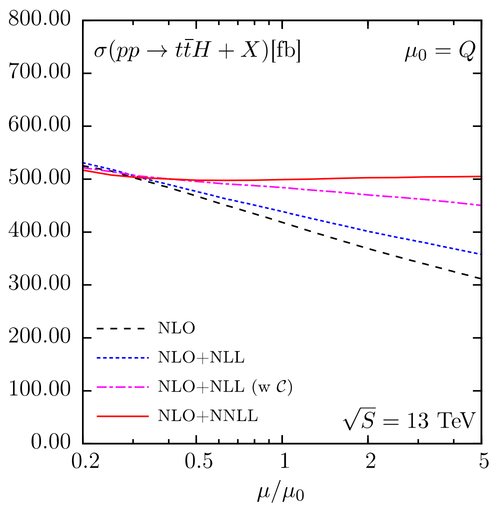
- Compared to NLO, remarkable stability of NLO+NNLL
- Stability improves with increasing accuracy of resummation
- Reduction of the theory scale error
- "Best" (envelope) NNLL+NLO prediction in agreement with NLO QCD+EW at $\mu_0 = M/2$

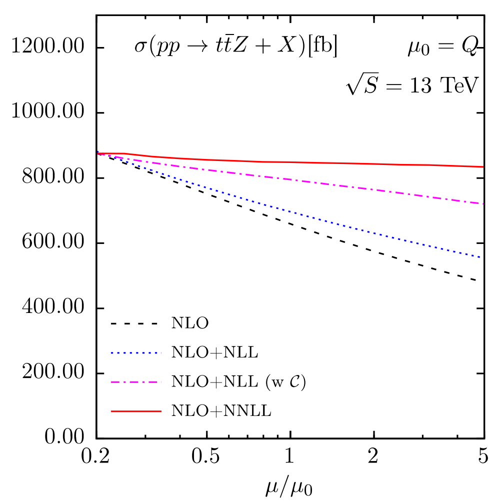
$$\sigma_{t\bar{t}H}^{\mathrm{NLO+NNLL}} = 504^{+7.6\%+2.4\%}_{-7.1\%-2.4\%} \text{ fb}$$

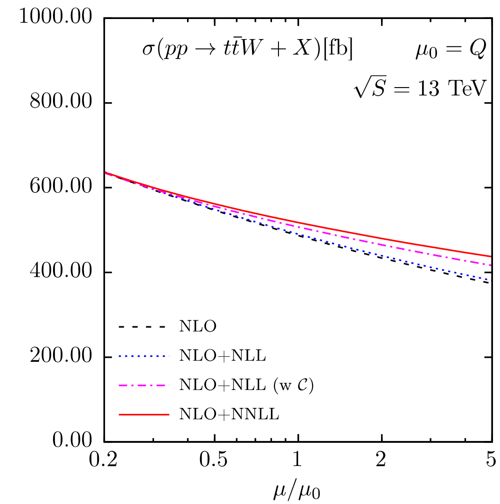
(± scale) (± pdf)

SCALE DEPENDENCE OF THE TOTAL CROSS SECTION

$\mu_F = \mu_R = \mu$







- For $\mu_0 = Q$, decrease in scale dependence with increasing accuracy. NLO+NNLL scale dependence in the $\mu_0/2$ - $2\mu_0$ range of order 1%.
- For $\mu_0 = M/2$, mostly similar behaviour

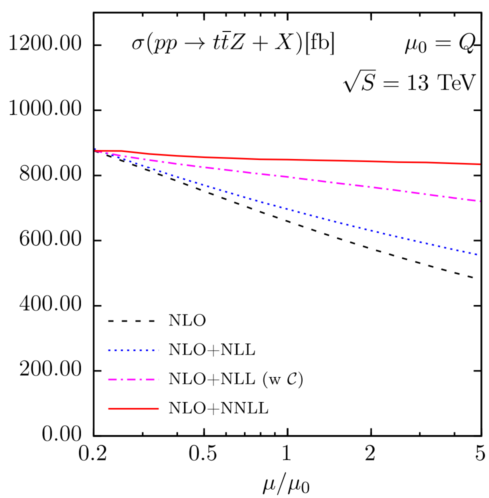
[AK, Motyka, Stebel, Theeuwes'17]

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18]

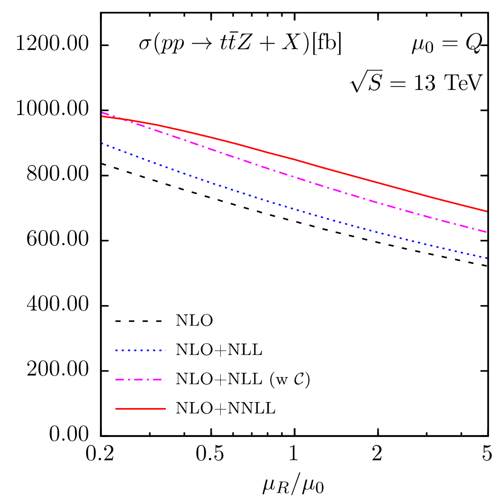
SCALE DEPENDENCE OF THE TOTAL CROSS SECTION

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18]

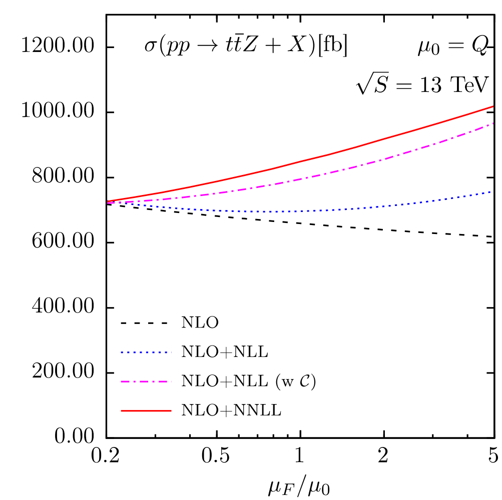
$\mu_F = \mu_R = \mu$ varied



μ_F fixed, μ_R varied



μ_R fixed, μ_F varied



- Apparent cancellations between μ_F and μ_R scale dependence → 7-point used for estimation of scale variation error: conservative scale error estimate

Total Cross section for TTbar+W,Z

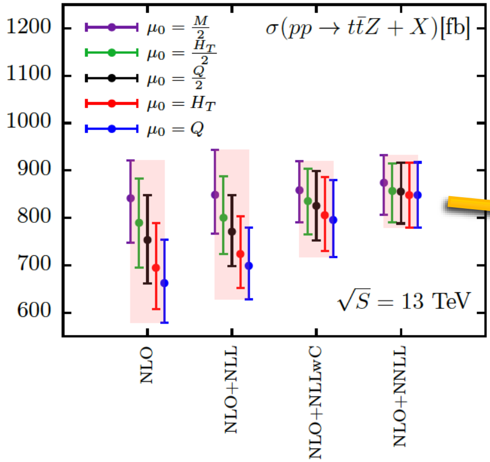
[AK, Motyka, Schwartländer, Stebel, Theeuwes'18 and to appear]

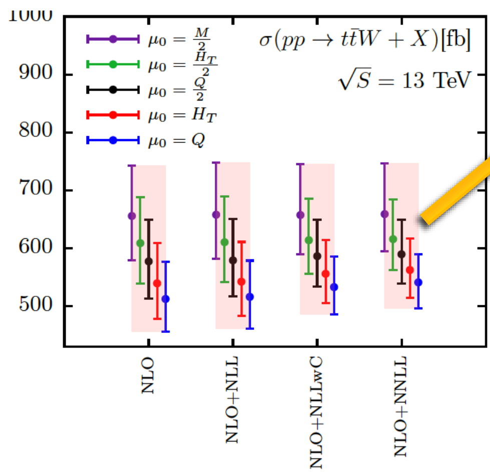
process	μ_0	NLO[fb]	NLO+NLL[fb]	NLO+NLLwC[fb]	NLO+NNLL[fb]	K_{NNLL}
$t\bar{t}Z$	Q	$661^{+13.8\%}_{-12.5\%}$	$698^{+11.5\%}_{-10.1\%}$	$795^{+10.6\%}_{-9.7\%}$	$847^{+8.1\%}_{-8.2\%}$	1.28
	H_T	$694^{+13.6\%}_{-12.6\%}$	$723^{+11.0\%}_{-9.8\%}$	$805^{+10.0\%}_{-9.5\%}$	$848^{+7.9\%}_{-8.0\%}$	1.22
	$Q/2$	$752^{+12.5\%}_{-12.1\%}$	$770^{+10.6\%}_{-9.4\%}$	$824^{+8.8\%}_{-8.8\%}$	$854^{+7.1\%}_{-7.8\%}$	1.14
	$H_T/2$	$788^{+11.7\%}_{-11.9\%}$	$798^{+10.7\%}_{-9.5\%}$	$834^{+8.1\%}_{-8.4\%}$	$855^{+6.6\%}_{-7.7\%}$	1.09
	$M/2$	$841^{+9.4\%}_{-11.1\%}$	$848^{+11.2\%}_{-9.7\%}$	$858^{+7.1\%}_{-7.9\%}$	$874^{+6.7\%}_{-7.8\%}$	1.04
$t\bar{t}W$	Q	$512^{+12.5\%}_{-11.1\%}$	$516^{+12.1\%}_{-10.6\%}$	$533^{+9.9\%}_{-8.9\%}$	$541^{+8.9\%}_{-8.4\%}$	1.06
	H_T	$539^{+13.0\%}_{-11.3\%}$	$542^{+12.6\%}_{-10.9\%}$	$556^{+10.5\%}_{-9.0\%}$	$562^{+9.6\%}_{-8.5\%}$	1.04
	$Q/2$	$577^{+12.5\%}_{-11.1\%}$	$579^{+12.3\%}_{-10.8\%}$	$586^{+10.7\%}_{-9.0\%}$	$590^{+10.0\%}_{-8.5\%}$	1.02
	$H_T/2$	$609^{+13.0\%}_{-11.5\%}$	$610^{+13\%}_{-11.2\%}$	$614^{+11.8\%}_{-9.5\%}$	$616^{+11.2\%}_{-8.8\%}$	1.01
	$M/2$	$656^{+13.2\%}_{-11.7\%}$	$658^{+13.6\%}_{-11.6\%}$	$657^{+13.4\%}_{-10.3\%}$	$659^{+13.3\%}_{-9.8\%}$	1.00

- Significant reduction in the scale dependence of the *ttZ* total cross section
- Depending on the central scale, correction up to ~30% for the *ttZ* cross section
- Smaller impact on the ttW predictions: only $q\bar{q}$ initial channel at LO

TTBAR+W,Z AT NLO+NNLL

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18 and to appear]





Envelope over results for different central scales

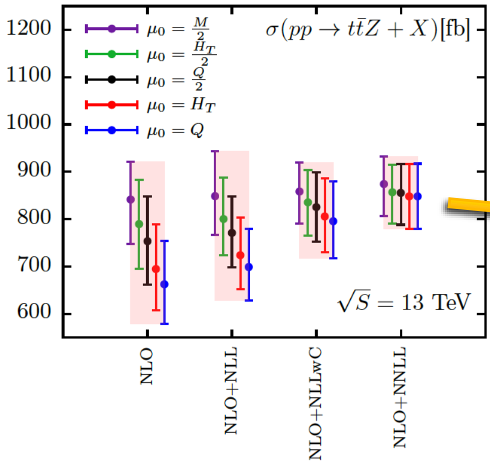
NLO(QCD+EW) +NNLL (± scale) (± pdf)

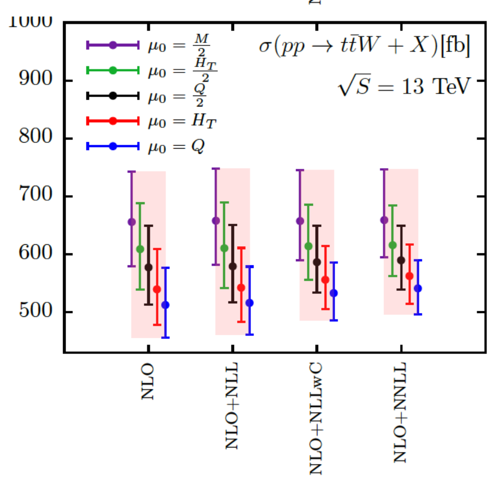
$$\sigma_{t\bar{t}Z}^{\mathrm{NLO+NNLL}} = 859^{+8.6\%+2.3\%}_{-9.5\%-2.3\%}\ \mathrm{fb}\,,$$

$$\sigma_{t\bar{t}W}^{\mathrm{NLO+NNLL}} = 592^{+26.1\%+2.1\%}_{-16.2\%-2.1\%}\ \mathrm{fb}$$

TTBAR+W,Z AT NLO+NNLL

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18 and to appear]





Envelope over results for different central scales

NLO(QCD+EW) +NNLL (± scale) (± pdf)

$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 859^{+8.6\%+2.3\%}_{-9.5\%-2.3\%} = 0.859^{+0.073+0.028}_{-0.085-0.028} \text{ pb}$$

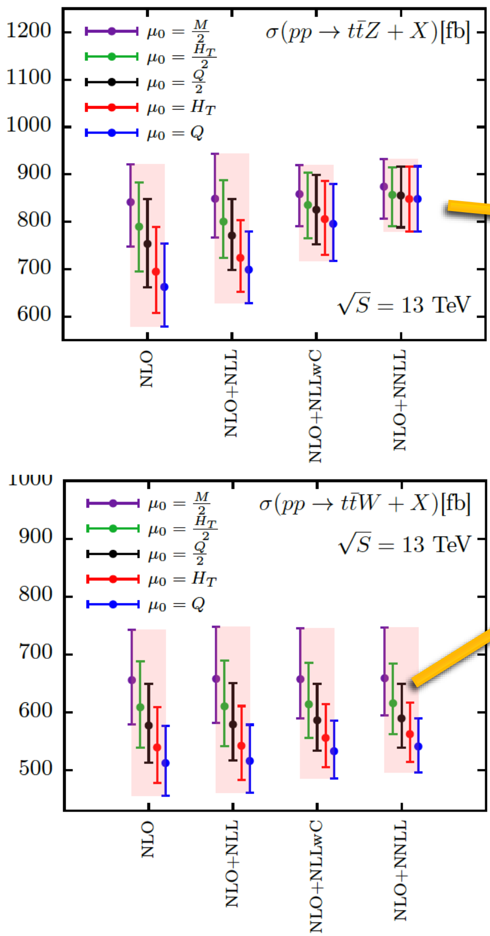
CMS, 1907.11270:

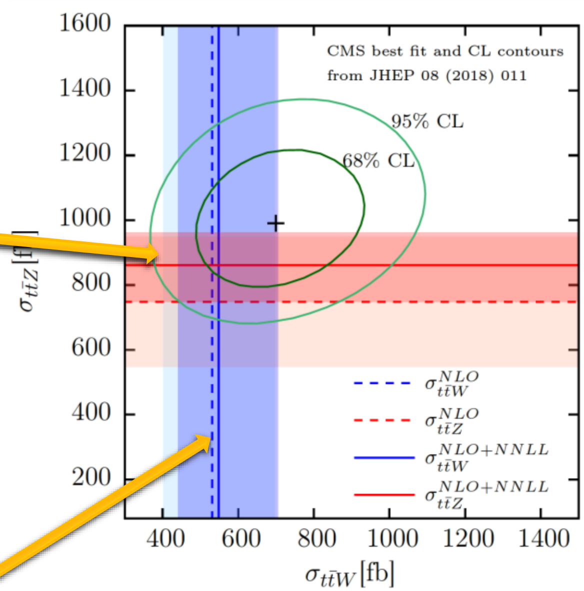
$$\sigma(\text{pp} \to \text{t}\bar{\text{t}}\text{Z}) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$$

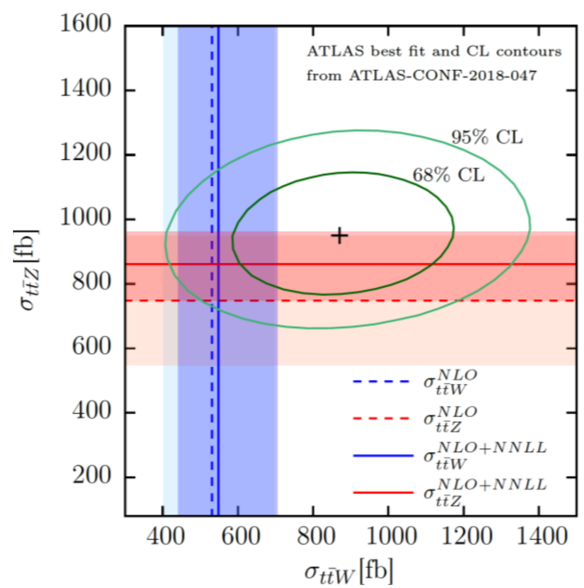
Accuracy of the NLO+NNLL result comparable with experimental precision!

TTBAR+W,Z AT NLO+NNLL

[AK, Motyka, Schwartländer, Stebel, Theeuwes'18 and to appear]



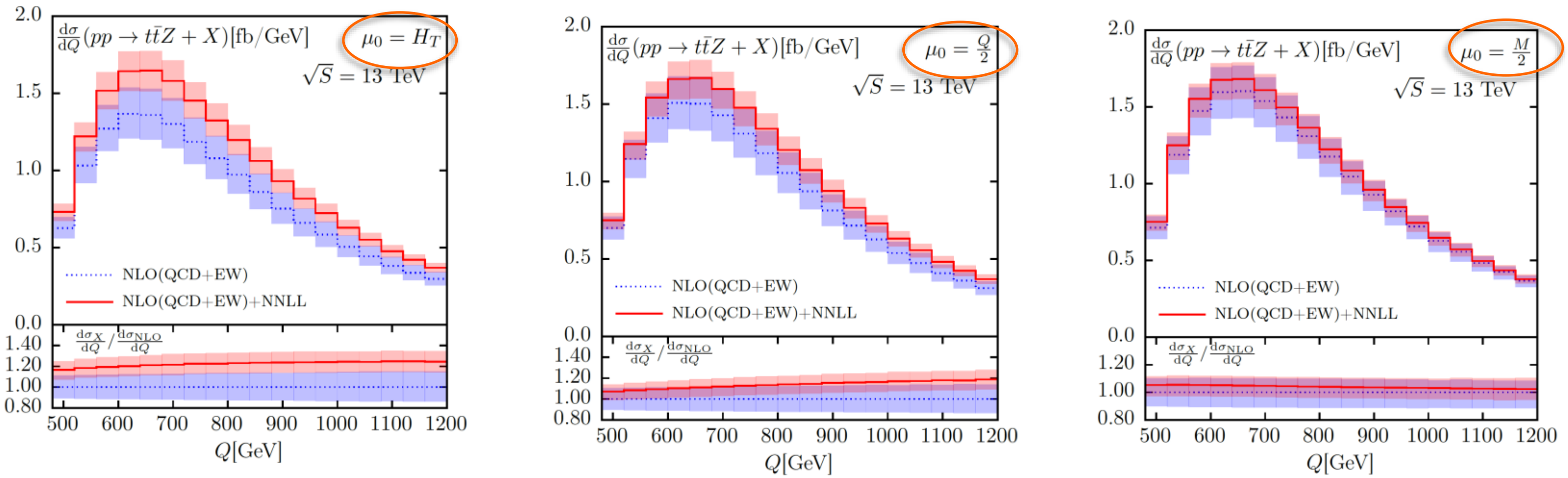




- Central values of the theoretical predictions brought closer to the measured cross section; theory errors reduced (by half for *ttZ*)

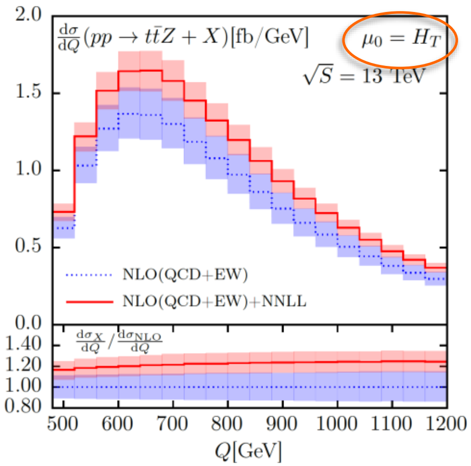
TTbarZ: Invariant Mass Distribution

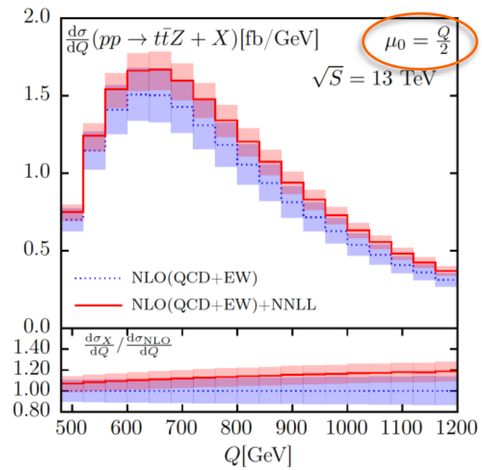
[AK, Motyka, Schwartländer, Stebel, Theeuwes'19 and to appear]

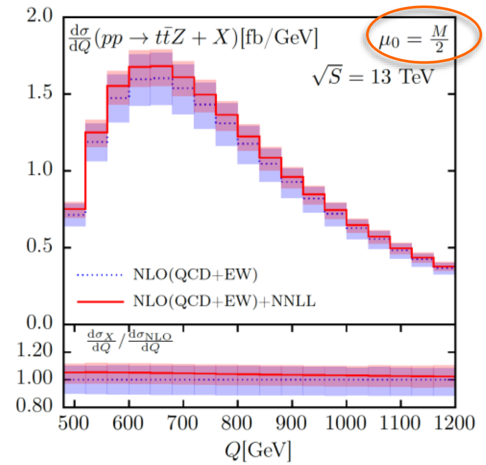


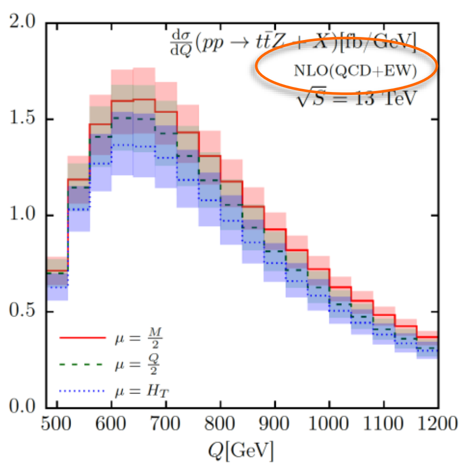
TTbarZ: Invariant Mass Distribution

[AK, Motyka, Schwartländer, Stebel, Theeuwes'19 and to appear]

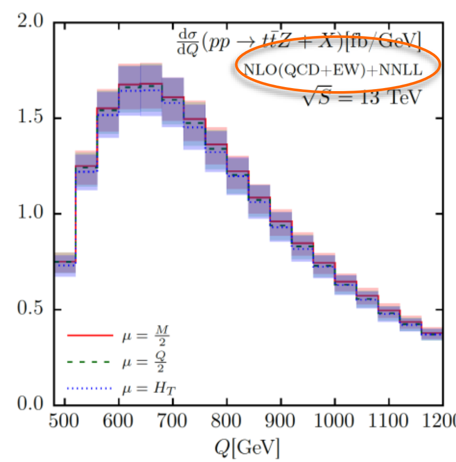






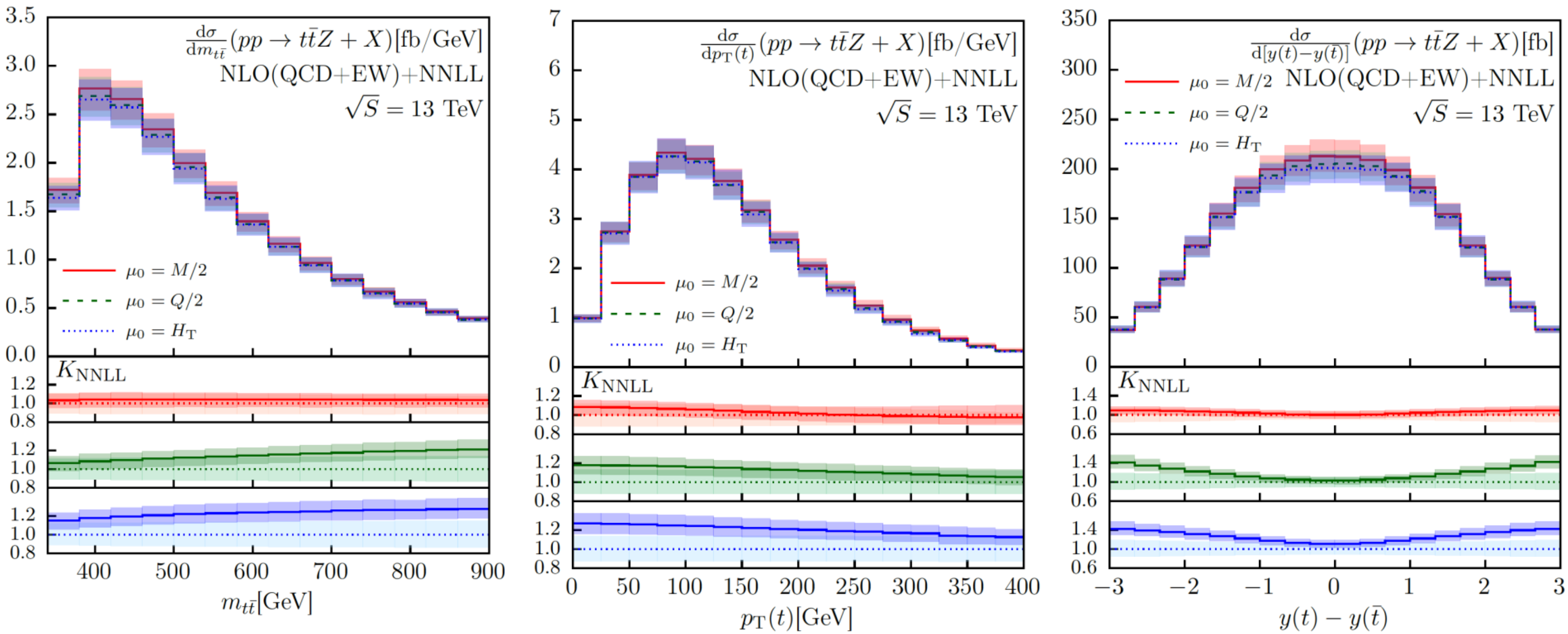


vs.



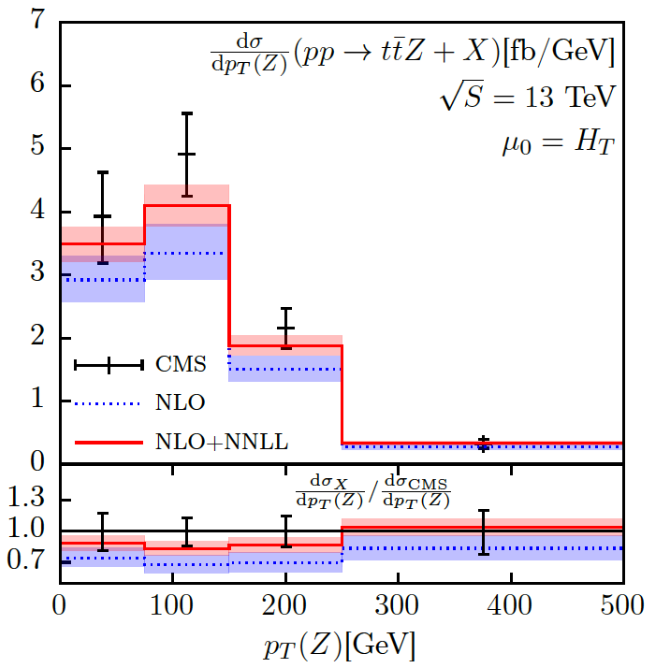
TTbarZ: Differential Distributions at NLO(QCD+EW)+NNLL

[AK, Motyka, Stebel, Schwartländer, Theeuwes, to appear]



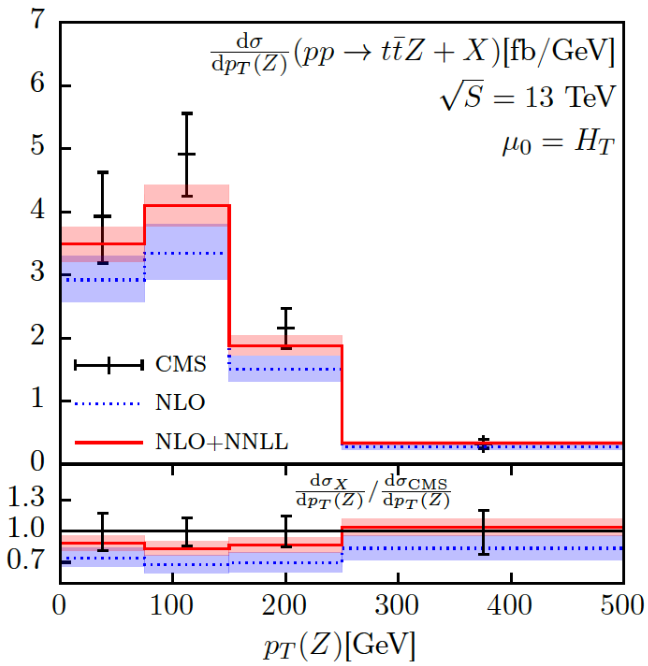
TTbarZ: Z's Transverse Momentum Distribution at NLO(QCD+EW)+NNLL

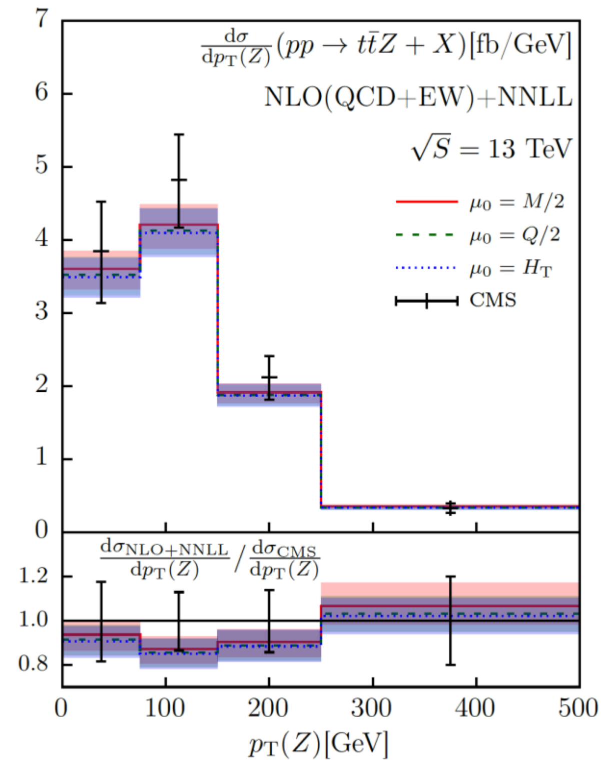
[AK, Motyka, Schwartländer, Stebel, Theeuwes'19 and to appear]



TTbarZ: Z's Transverse Momentum Distribution at NLO(QCD+EW)+NNLL

[AK, Motyka, Schwartländer, Stebel, Theeuwes'19 and to appear]





SUMMARY

- Associated top quark pair-production @ the LHC is one of the most promising windows onto new physics → precise theoretical prediction are essential → a lot of recent progress!
- Most precise predictions for the production processes $pp \to t\bar{t}H,\ pp \to t\bar{t}W^{\pm},\ pp \to t\bar{t}Z$ involve resummation and reach NNLL+NLO (QCD+EW) accuracy -- first application of threshold resummation to a class of 2 → 3 processes
  - Remarkable stability of the NNLL+NLO differential and total cross sections w.r.t. scale variation
  - Stability improves with growing accuracy of the calculations
  - Reduction of the theory error due to scale variation → for ttZ the NLO+NNLL theory error comparable with experimental uncertainty of the latest CMS measurement