Theory status of top production and decay

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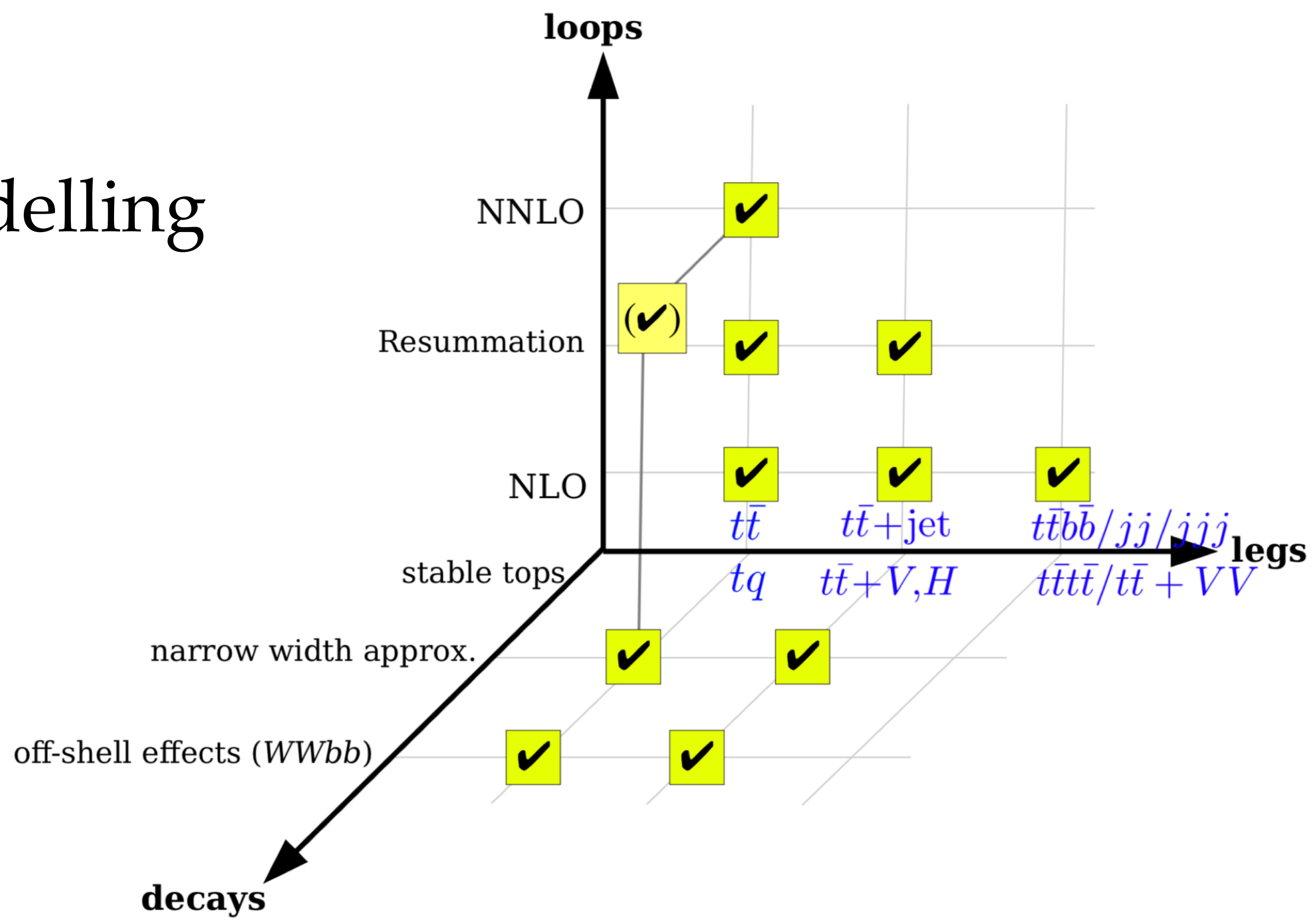
TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Standard Model at the LHC, April 25th 2019

Plan

1. Precision at high orders
2. Sophisticated decay modelling

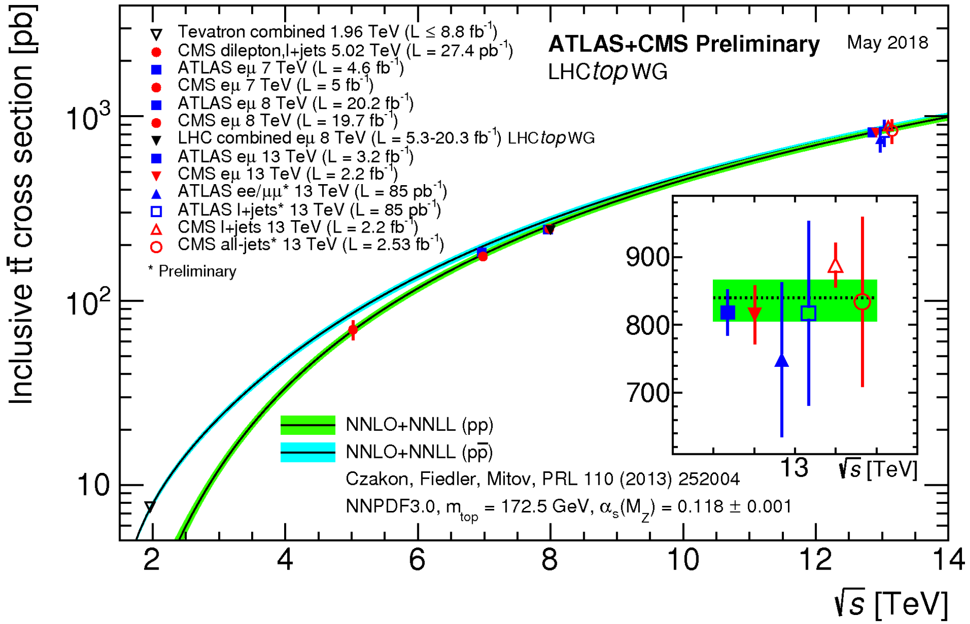
ONLY TOP QUARK PAIRS IN THIS TALK

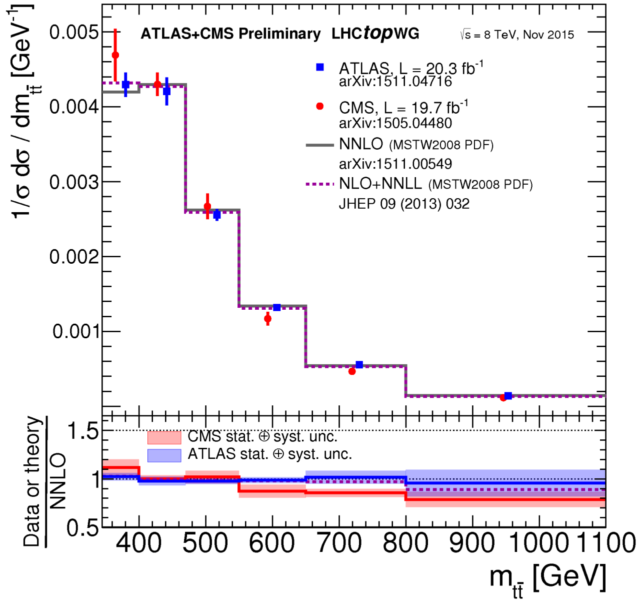


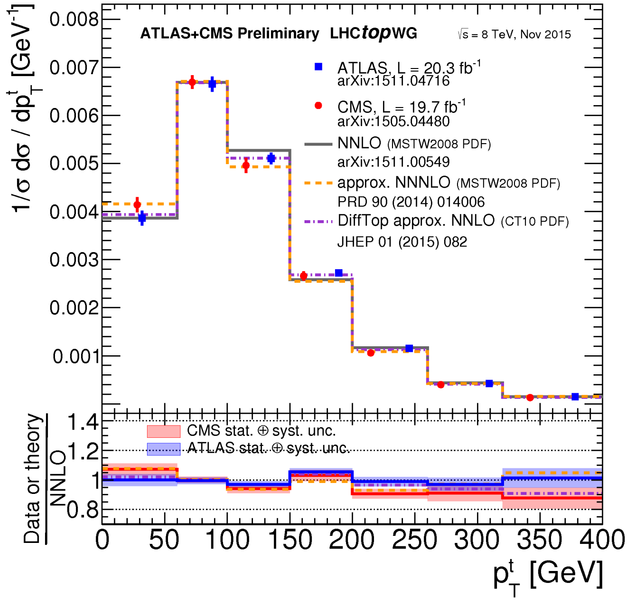
From M. Schulze, LHCP `18

Total and differential cross sections

- We are well in the hadron collider precision measurement territory !!!
- … for a few years now







LHC Run 1 (7 TeV, 8 TeV)

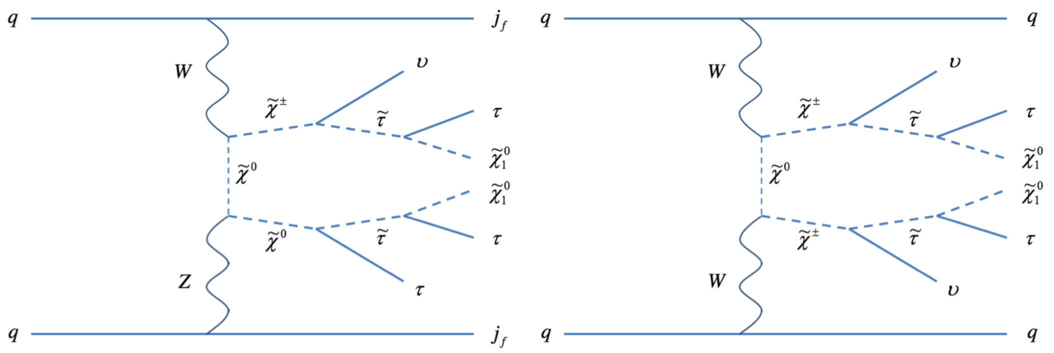
LHC Run 2 (13 TeV)

LHC	σ(tt) [pb]	L [fb^{-1}]	N_{event}
7 TeV	180	5	9×10^5
8 TeV	256	20	5×10^6
13 TeV	835	36	3×10^7

Search for Supersymmetry…

- An example of the importance of top-quark cross sections as background
- Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions

LHC @ 8 TeV

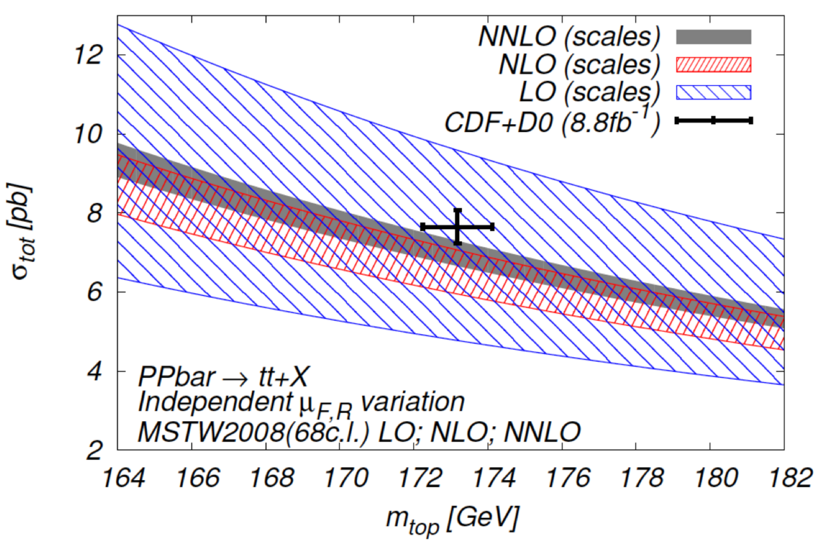


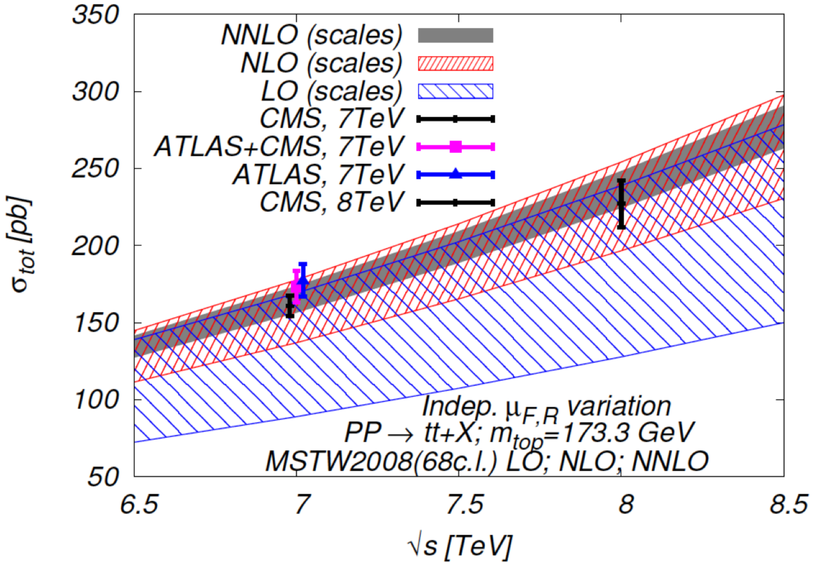
CERN-PH-EP/2015-213
2015/09/01

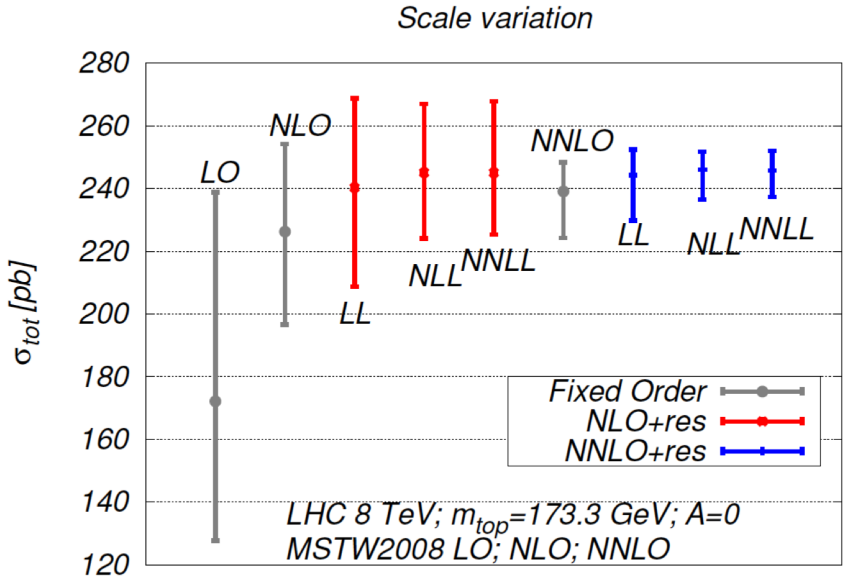
Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
Z+jets	4.3 ± 1.7	$3.7^{+2.1}_{-1.9}$	19.9 ± 2.9	12.3 ± 4.4
W+jets	<0.1	$4.2^{+3.3}_{-2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0^{+2.3}_{-2.4}$	11.7 ± 2.8	–
QCD	—	—	—	6.3 ± 1.8
Higgs boson	1.0 ± 0.1	1.1 ± 0.5	—	1.1 ± 0.1
VBF Z	—	—	—	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1^{+4.6}_{-4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

Precision at high orders

Perturbation theory convergence







Concurrent uncertainties:

Scales **~ 3%**

pdf (at 68%cl) **~ 2-3%**

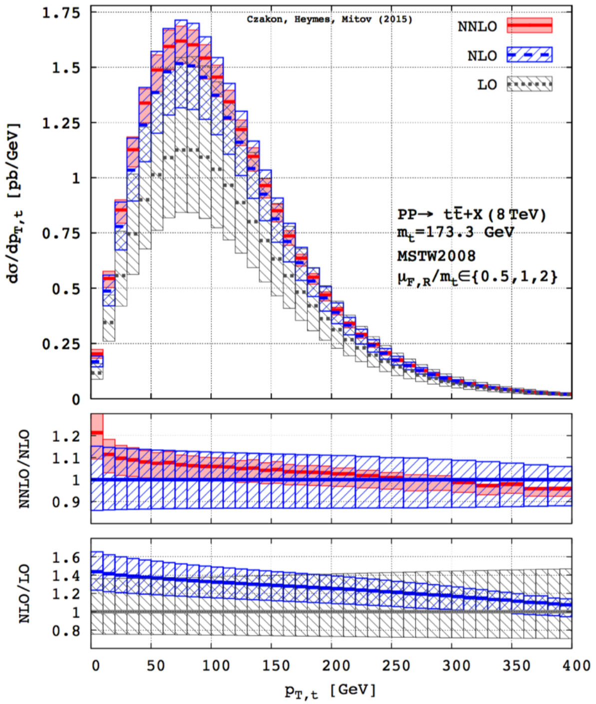
α_S (parametric) **~ 1.5%**

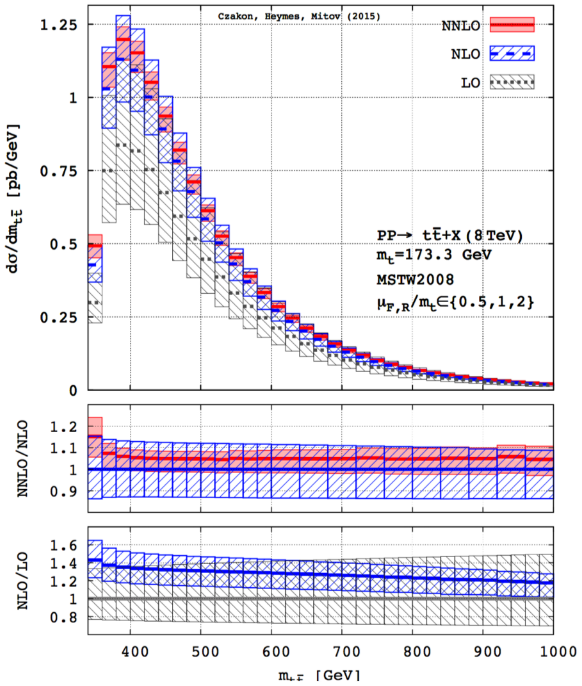
m_{top} (parametric) **~ 3%**

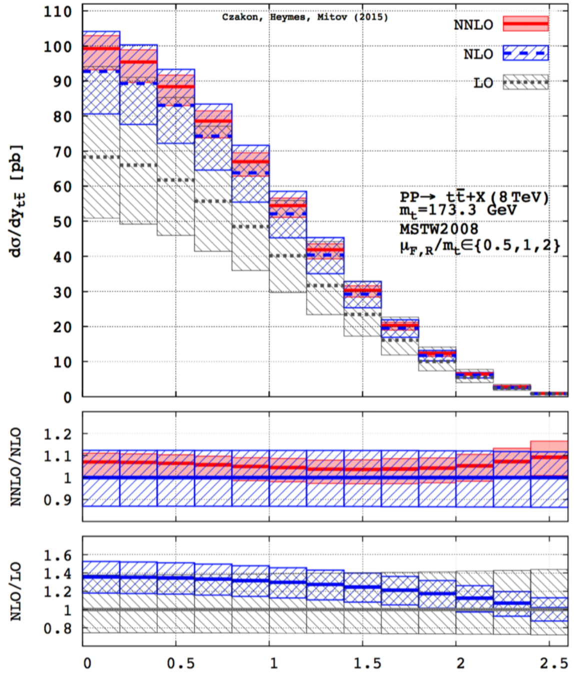
Soft gluon resummation makes a difference: **5% → 3%**

MC, Fiedler, Mitov `13

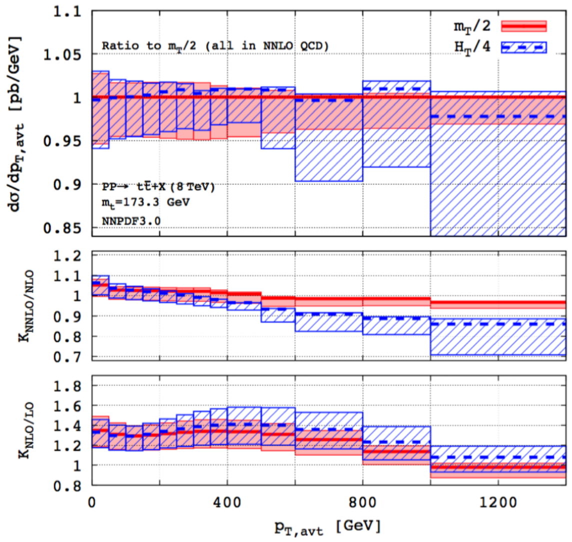
… for differential distributions

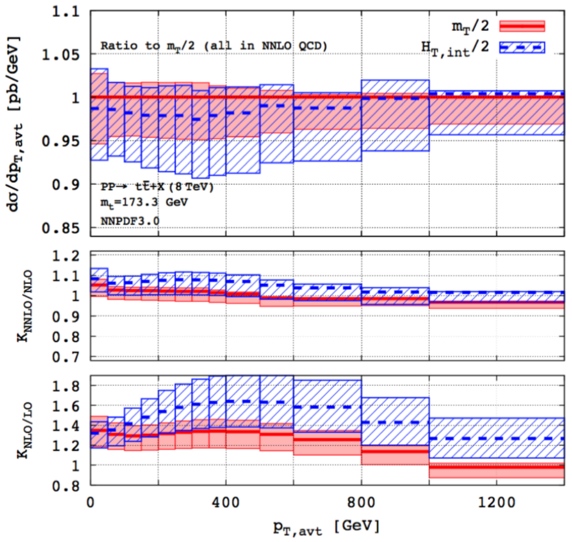






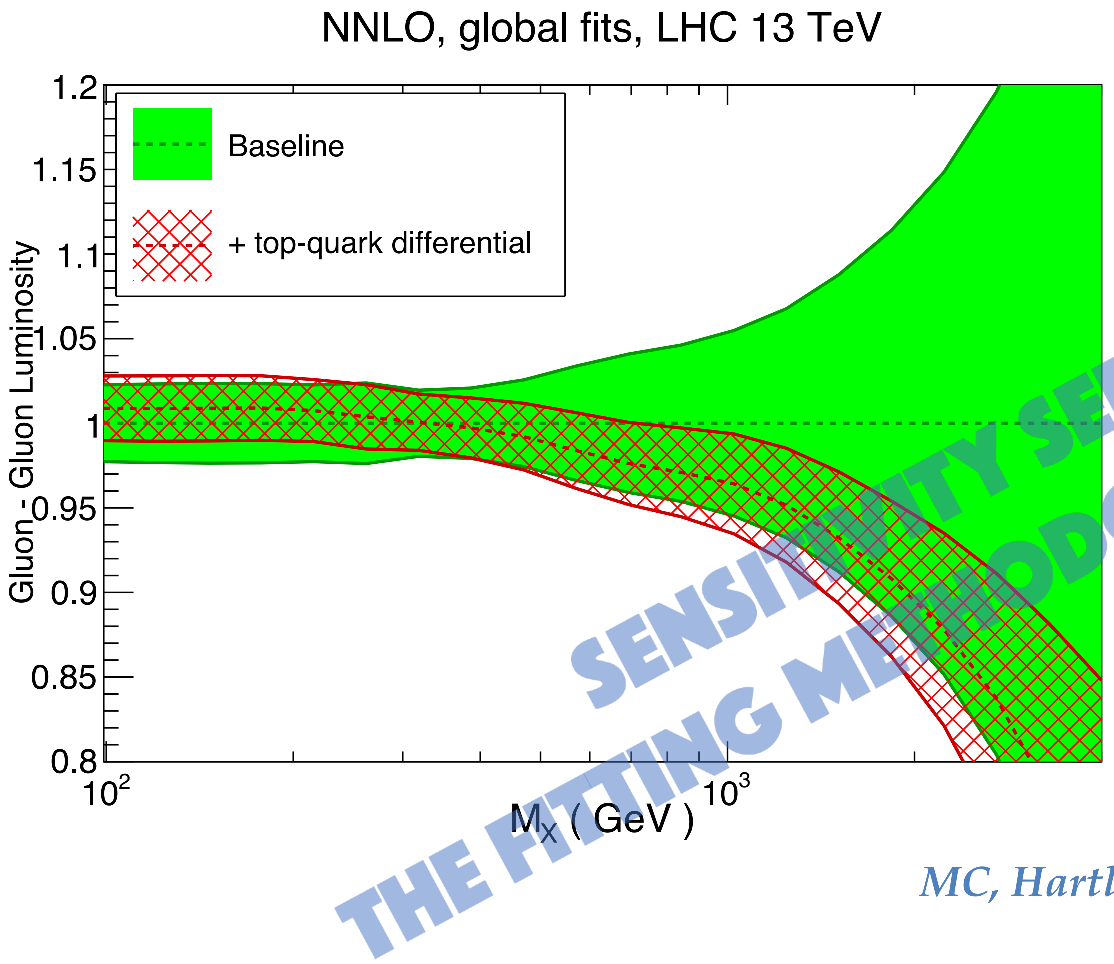
Convergence with
fixed and dynamical scales

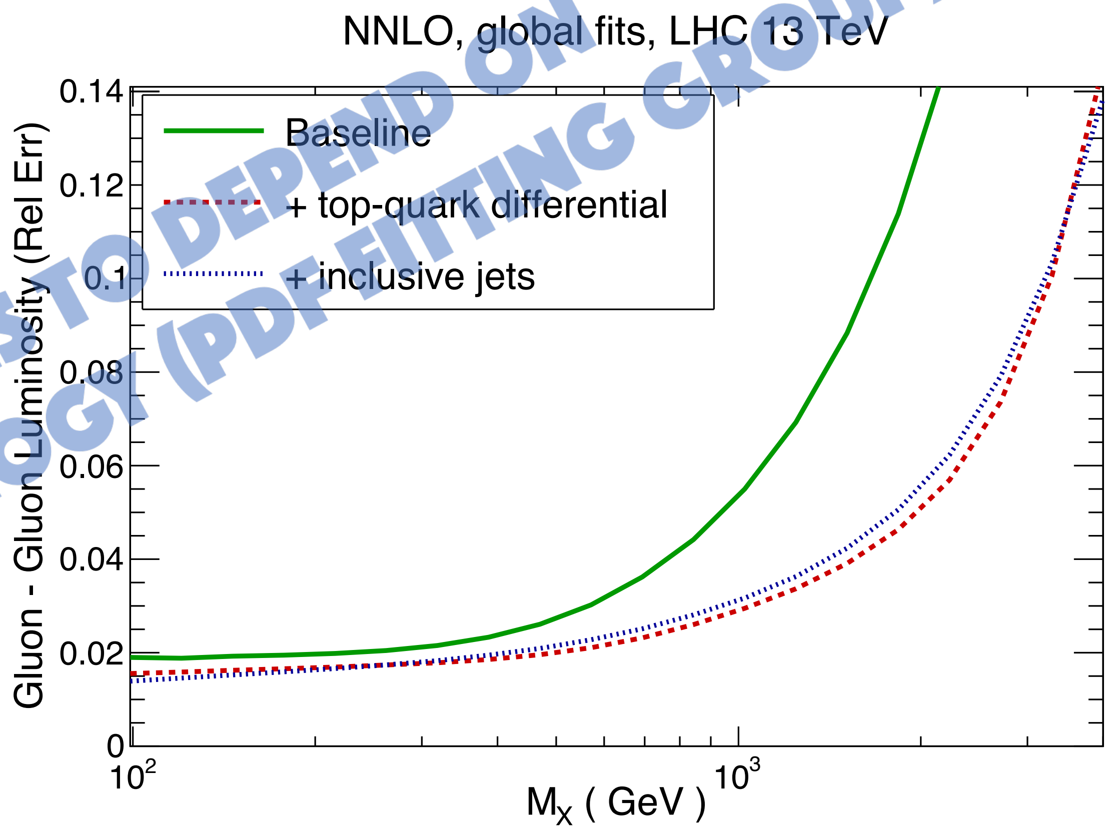




MC, Heymes, Mitov `15 `16

Application: PDF fits





MC, Hartland, Mitov, Nocera, Rojo `16

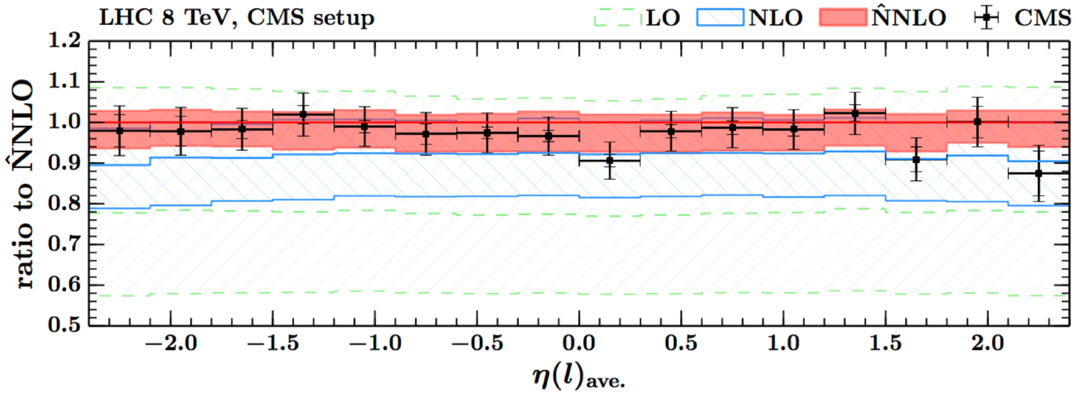
- the normalized y_t distribution from ATLAS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- the normalized $y_{t\bar{t}}$ distribution from CMS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- total inclusive cross-sections at $\sqrt{s} = 7$, 8 and 13 TeV (all available data).

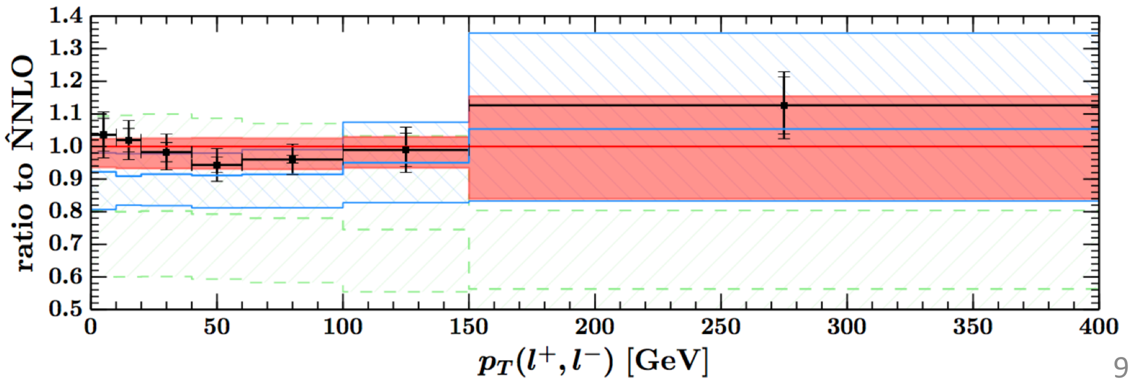
First step towards NWA @ NNLO

- Exact matrix elements for everything but the production mechanism at NNLO QCD

Gao, Papanastasiou `17

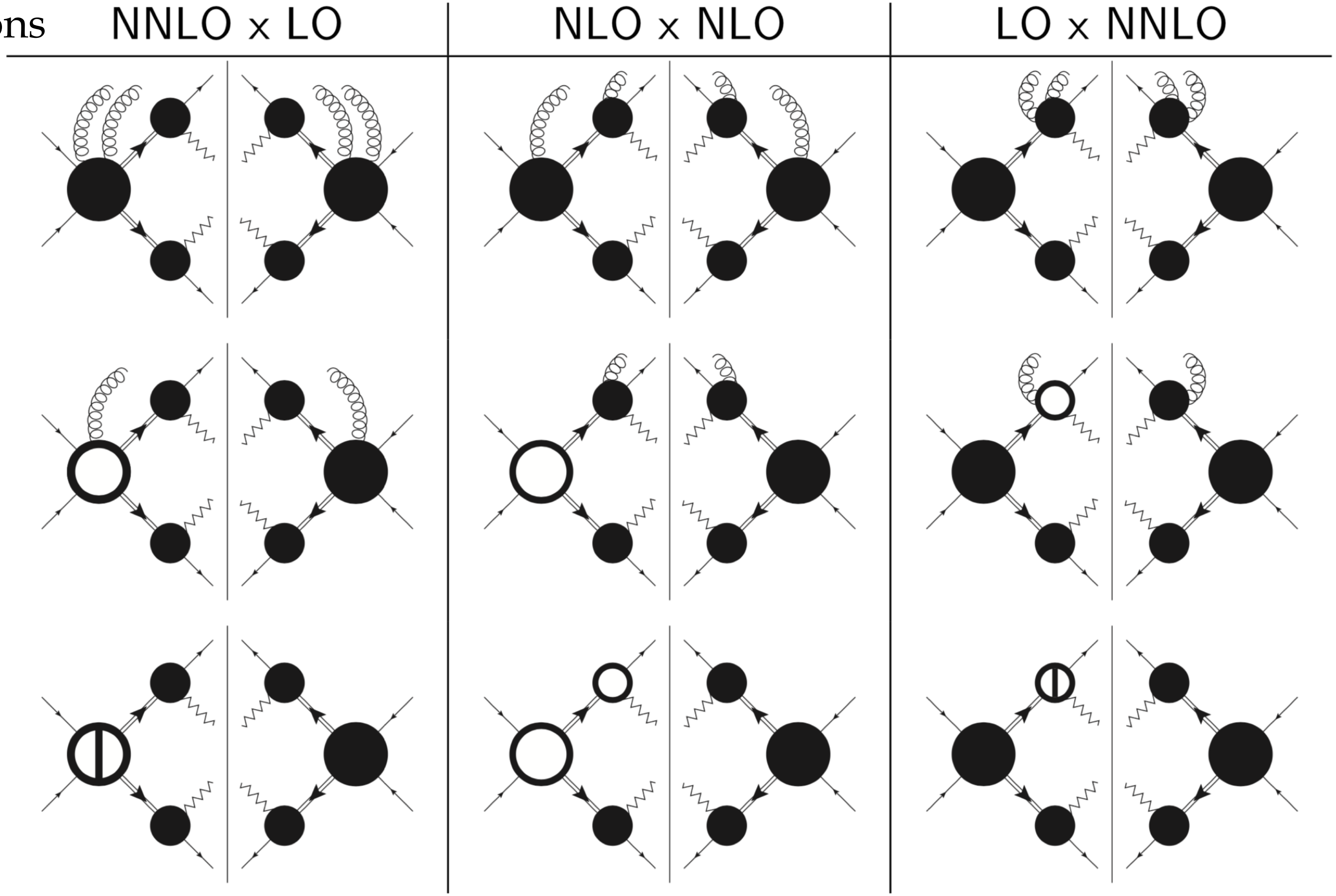
energy	fidual volume	LO [pb]	NLO [pb]	$\hat{\text{N}}$NLO [pb]	$\delta_{\text{dec.}}$	ATLAS [pb]
ATLAS setup, $e^{\pm}\mu^{\mp}$ channel [24]						
7 TeV	$p_T(l^{\pm}) > 25$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.5$	$1.592^{+39.2\%}_{-26.0\%}$	$2.007^{+11.9\%}_{-13.2\%}$	$2.210^{+2.2\%}_{-6.0\%}$	-0.3%	$2.305^{+3.8\%}_{-3.8\%}$
7 TeV	$p_T(l^{\pm}) > 30$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.4$	$1.265^{+39.3\%}_{-26.1\%}$	$1.585^{+11.8\%}_{-13.1\%}$	$1.736^{+2.2\%}_{-6.0\%}$	-0.8%	$1.817^{+3.8\%}_{-3.8\%}$
8 TeV	$p_T(l^{\pm}) > 25$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.5$	$2.249^{+37.9\%}_{-25.5\%}$	$2.855^{+11.9\%}_{-12.9\%}$	$3.130^{+2.3\%}_{-6.0\%}$	-0.3%	$3.036^{+4.1\%}_{-4.1\%}$
8 TeV	$p_T(l^{\pm}) > 30$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.4$	$1.788^{+38.0\%}_{-25.5\%}$	$2.256^{+11.7\%}_{-12.9\%}$	$2.461^{+2.3\%}_{-6.1\%}$	-0.7%	$2.380^{+4.1\%}_{-4.1\%}$
CMS setup, $e^{\pm}\mu^{\mp}, e^+e^-, \mu^+\mu^-$ channel [25], 2 b-jets required (anti-k_t algorithm [66], $R = 0.5$)						
energy	fiducial volume	LO [pb]	NLO [pb]	$\hat{\text{N}}$NLO [pb]	$\delta_{\text{dec.}}$	CMS [pb]
8 TeV	$p_T(l^{\pm}) > 20$ GeV, $\lvert\eta(l^{\pm})\rvert < 2.4$, $p_T(J_b) > 30$ GeV, $\lvert\eta(J_b)\rvert < 2.4$	$3.780^{+37.4\%}_{-25.3\%}$	$4.483^{+9.0\%}_{-11.5\%}$	$4.874^{+2.5\%}_{-6.8\%}$	-8.0%	$4.73^{+4.7\%}_{-4.7\%}$





Exact NWA results @ NNLO

- Contributions



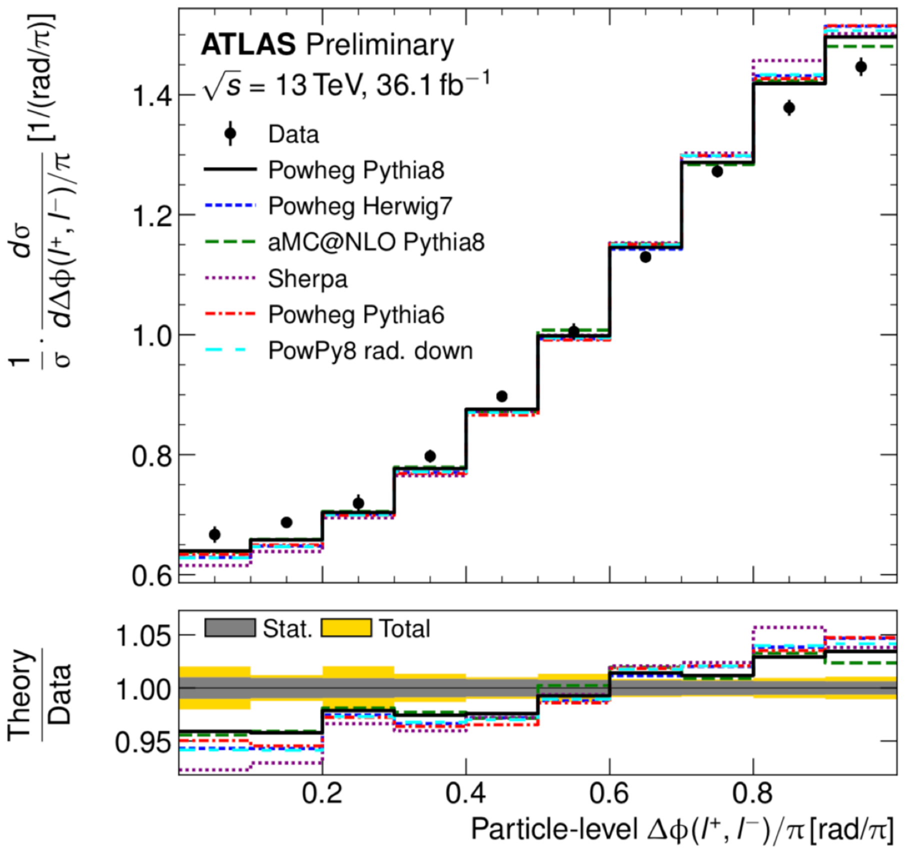
Behring, MC, Mitov, Papanastasiou, Poncelet `18

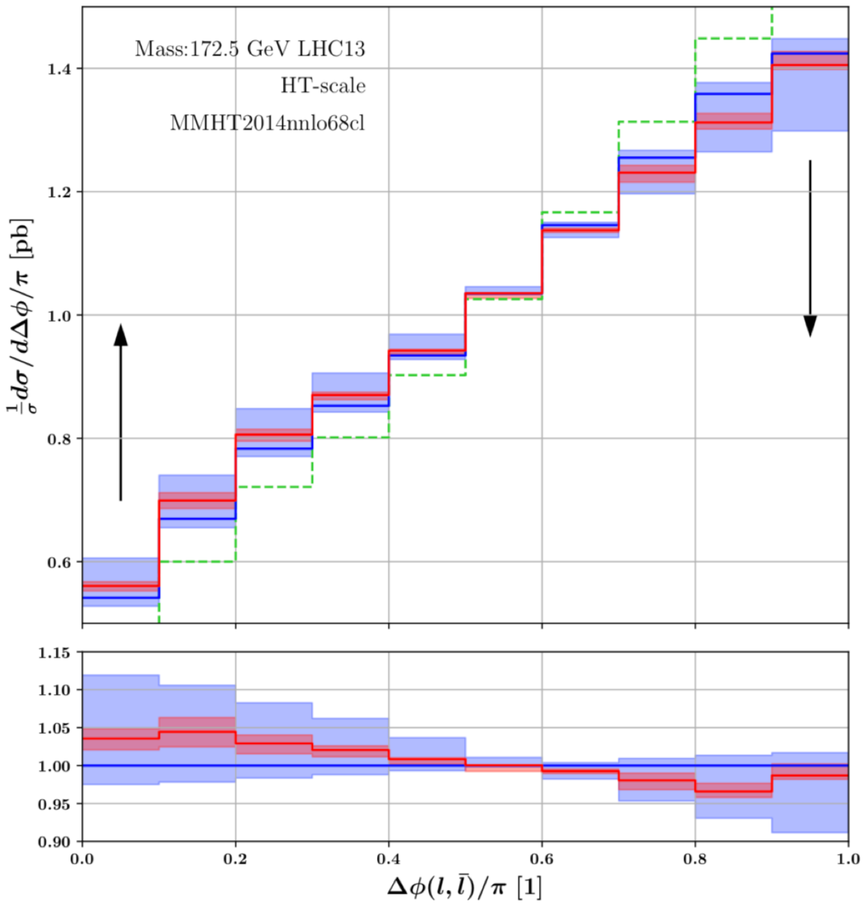
Exact NWA results @ NNLO

- Application in case of data/theory discrepancies

ATLAS-CONF-2018-027

NWA @ NNLO predictions

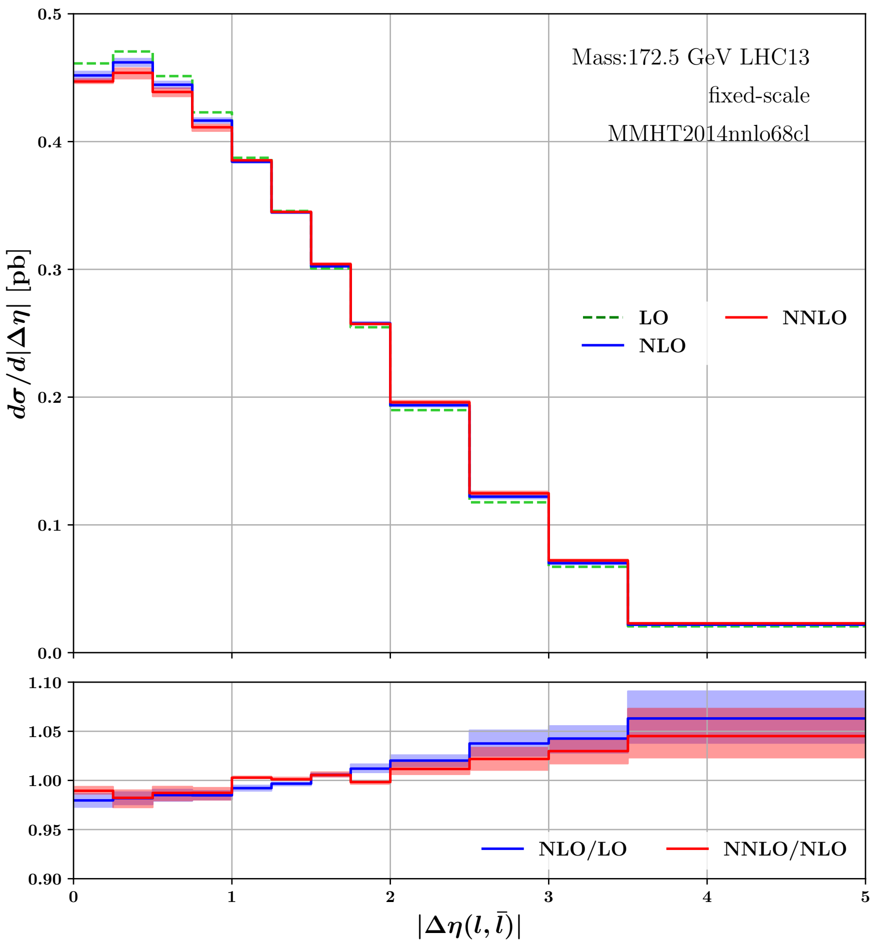




Behring, MC, Mitov, Papanastasiou, Poncelet `18

Exact NWA results @ NNLO

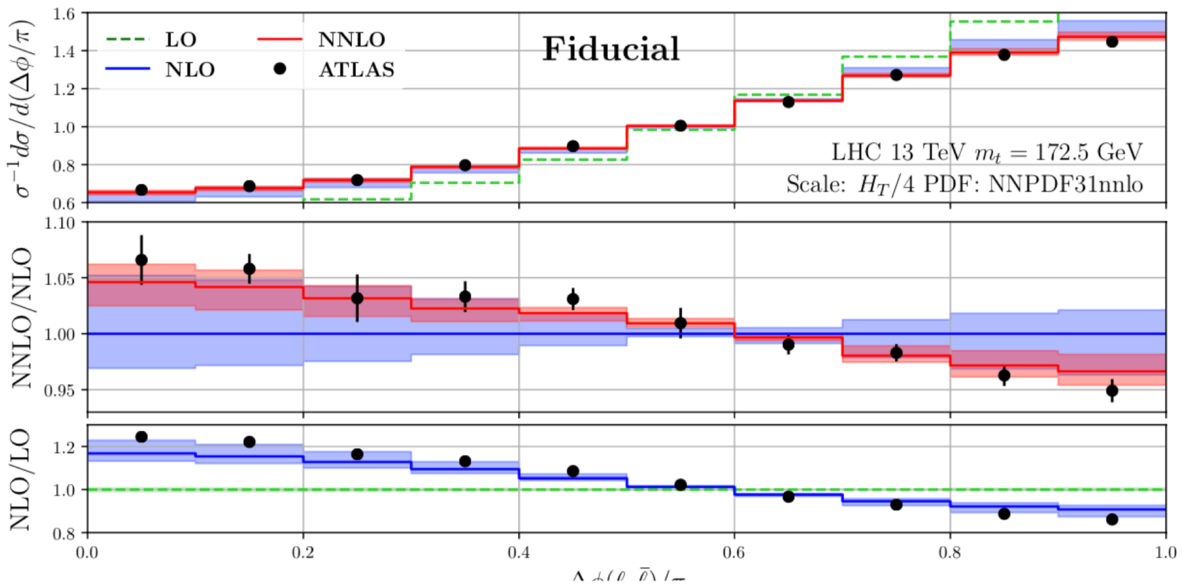
- Application in case of potentially noticeable effects in data

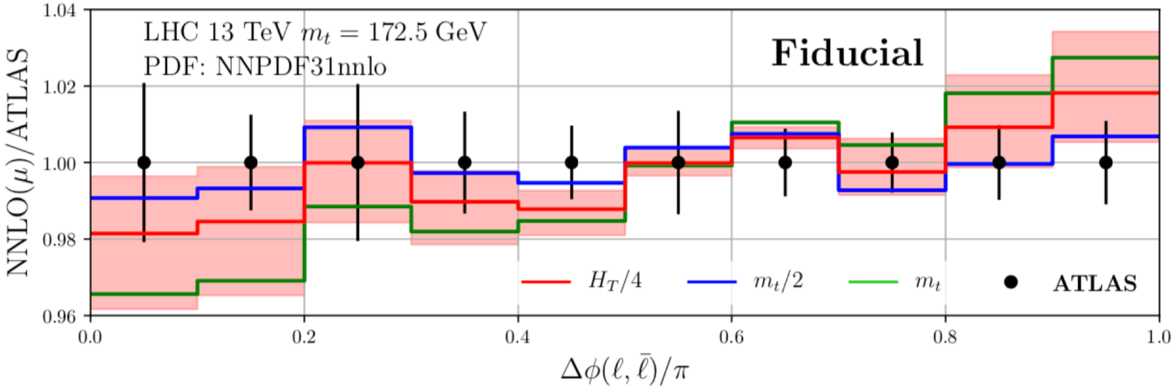


Behring, MC, Mitov, Papanastasiou, Poncelet `18

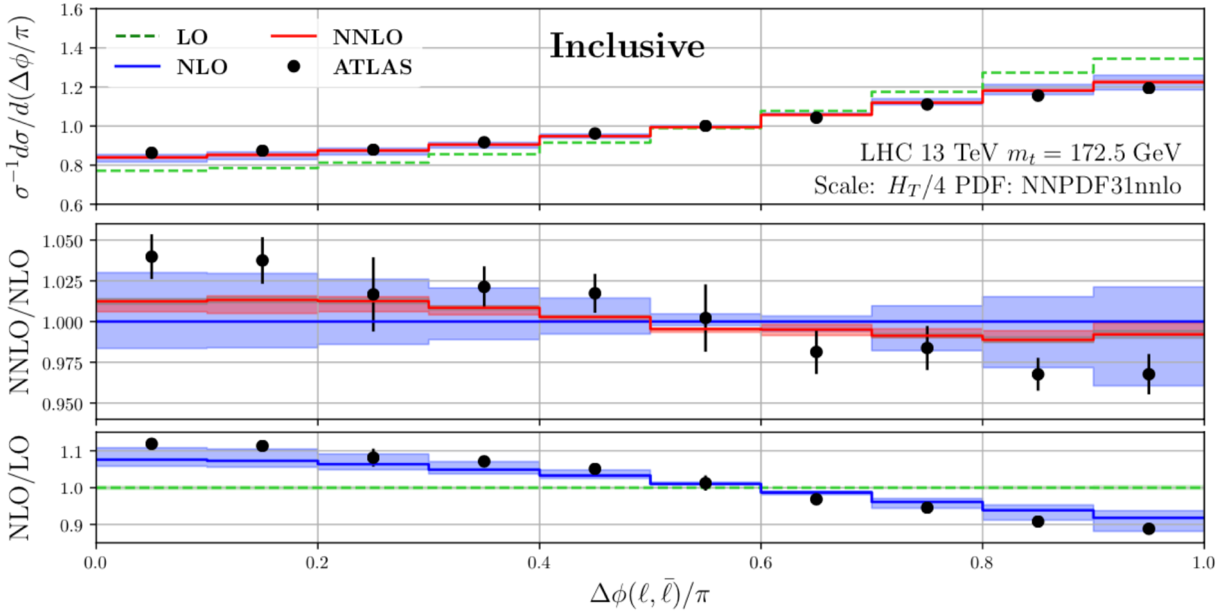
Exact NWA results @ NNLO

- Fine-tuned analysis reveals shortcomings in full phase space extrapolation





Negligible sensitivity to:
1. Top quark mass
2. Parton Distribution Functions
3. Electroweak effects
4. Radiation in the decay



Behring, MC, Mitov, Papanastasiou, Poncelet `19

Exact NWA results @ NNLO

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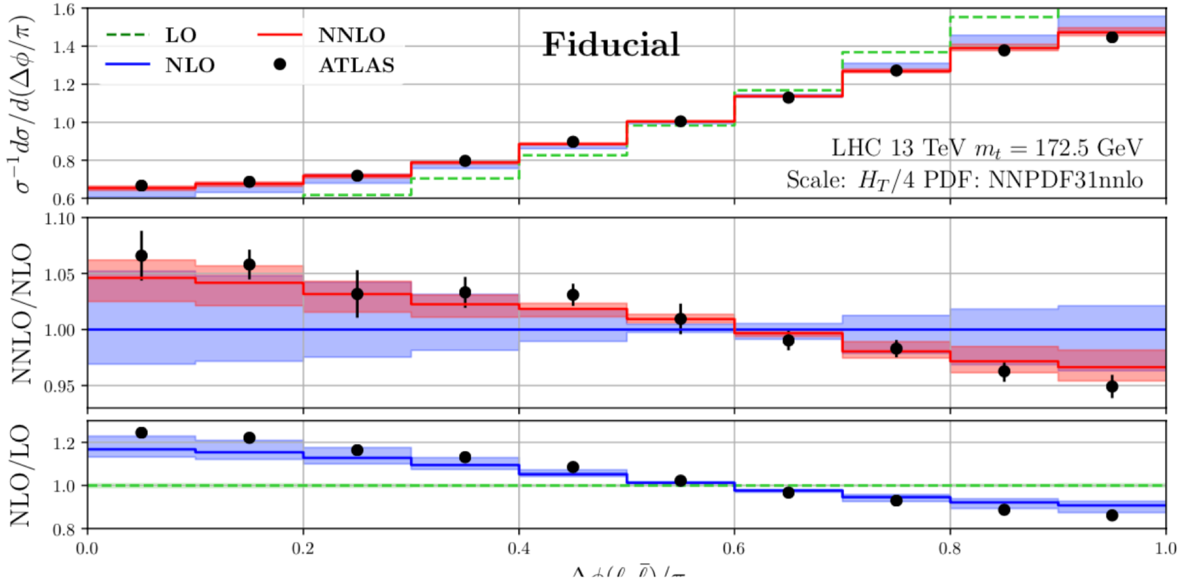

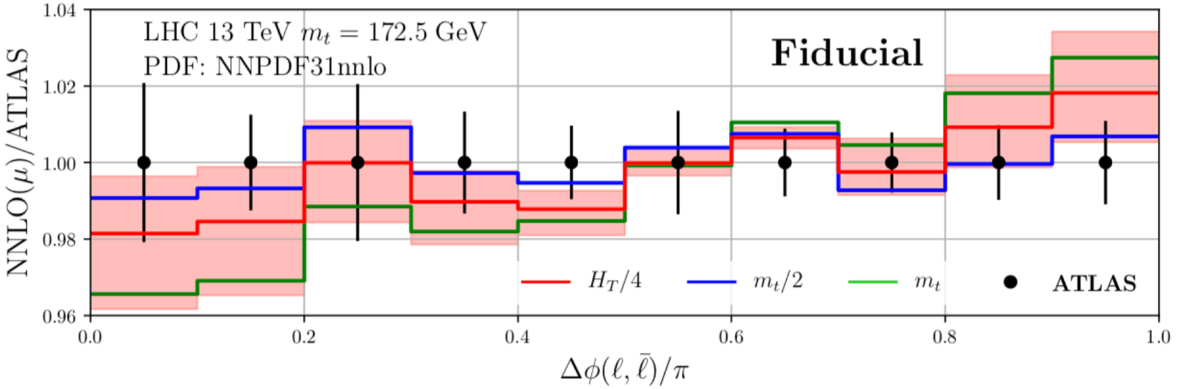

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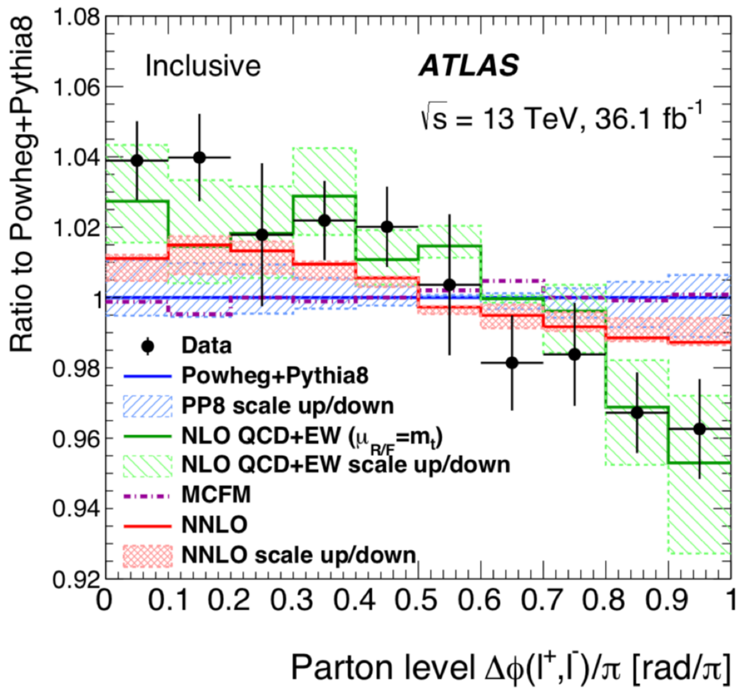
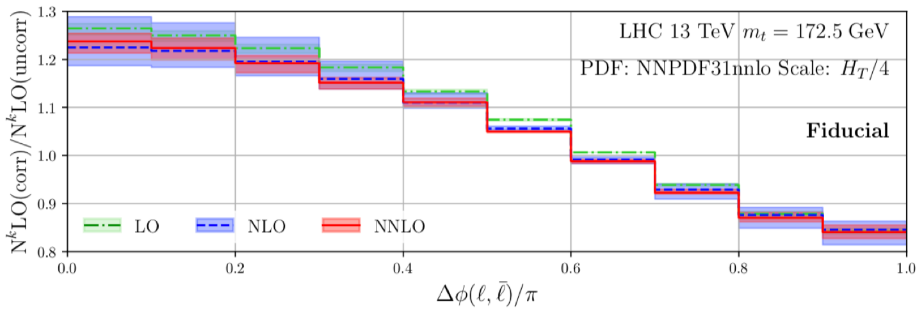
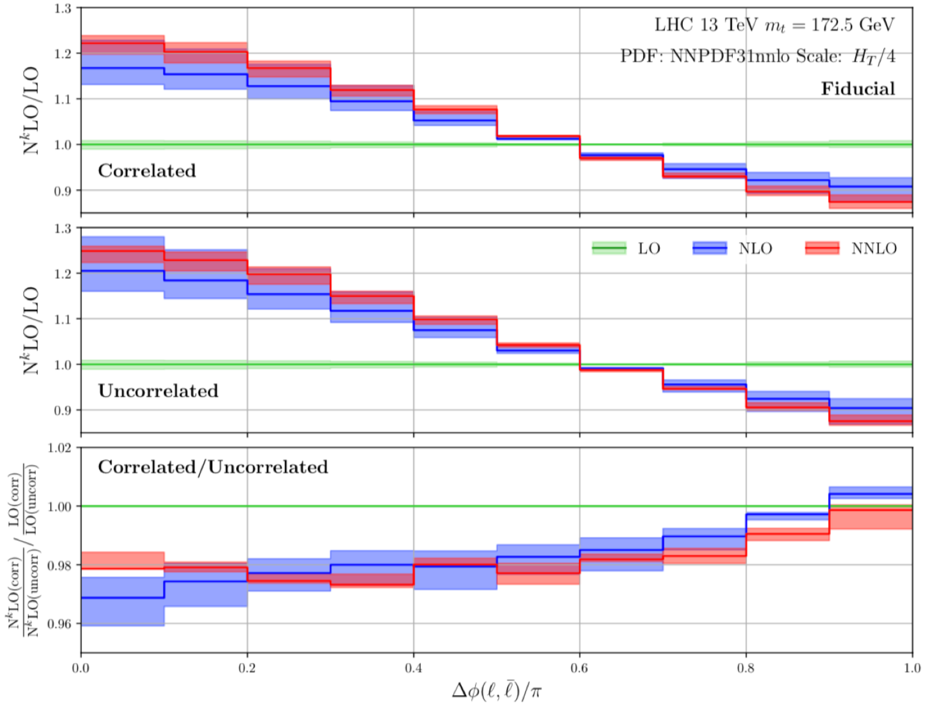


Behring, MC, Mitov, Papanastasiou, Poncelet `19

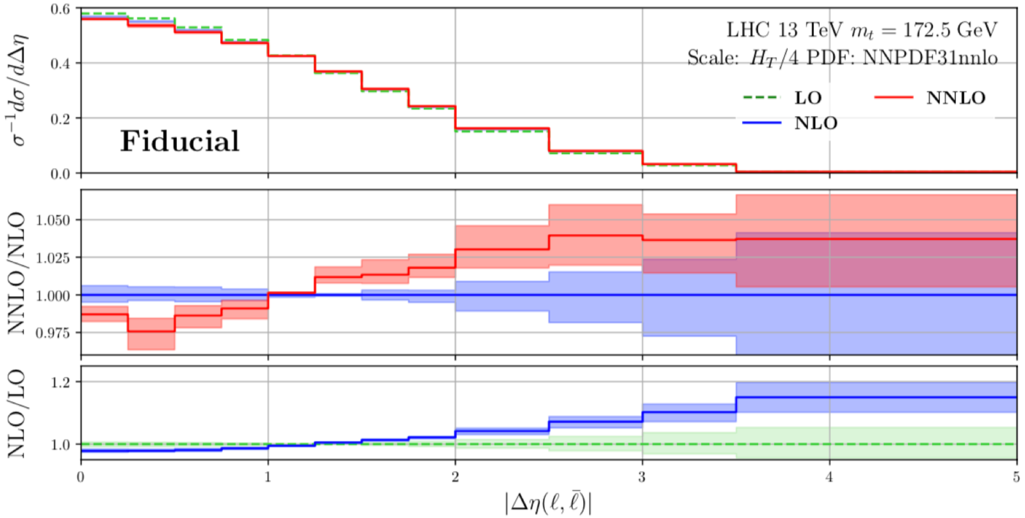
Exact NWA results @ NNLO

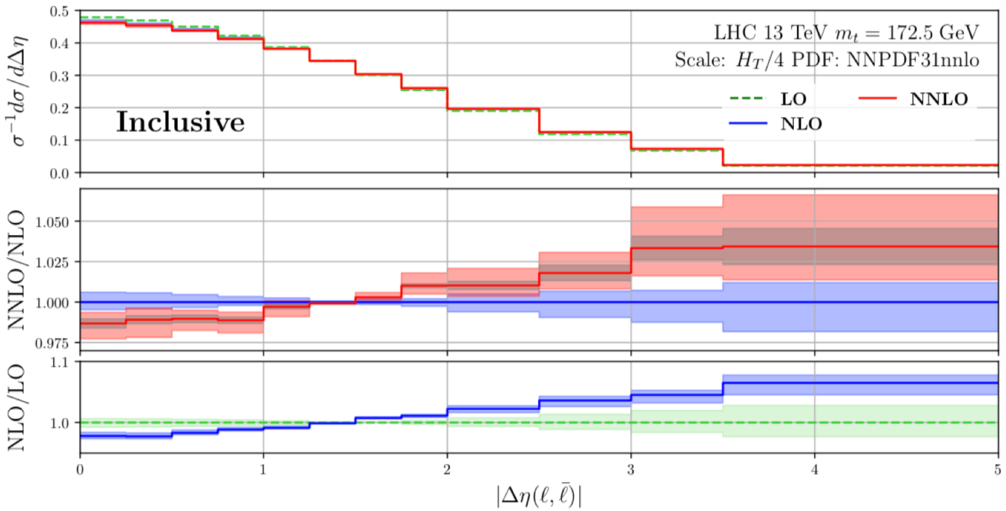
- Importance of spin correlations





- Impact on other observables

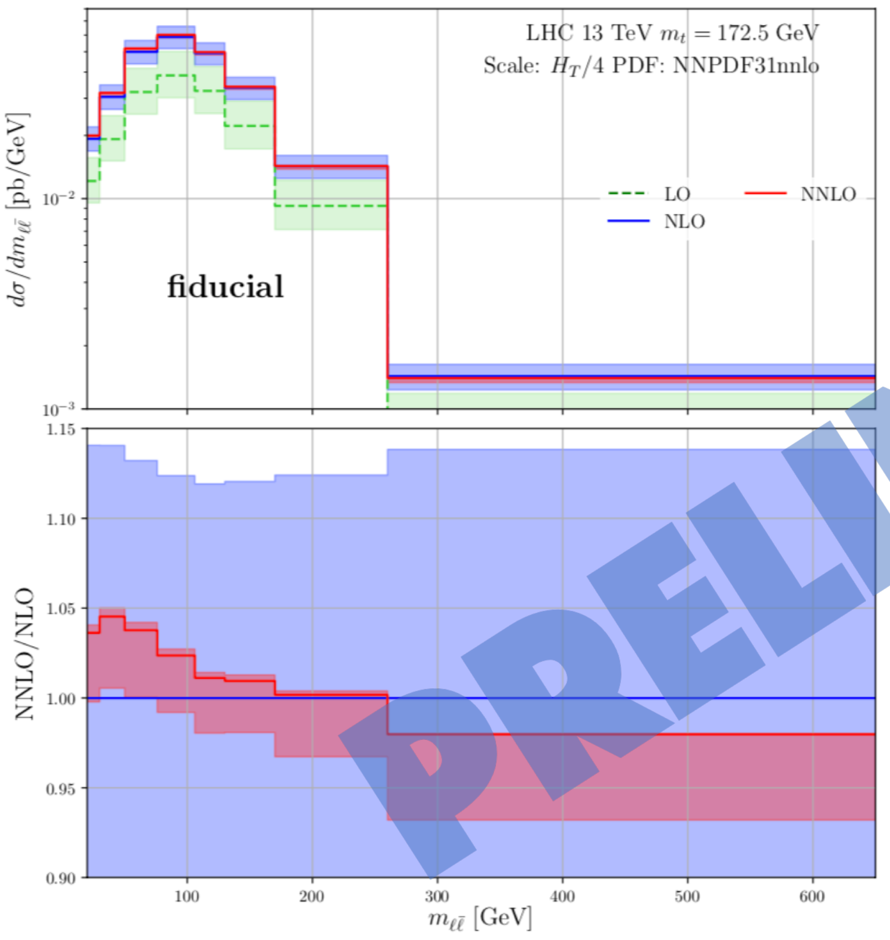


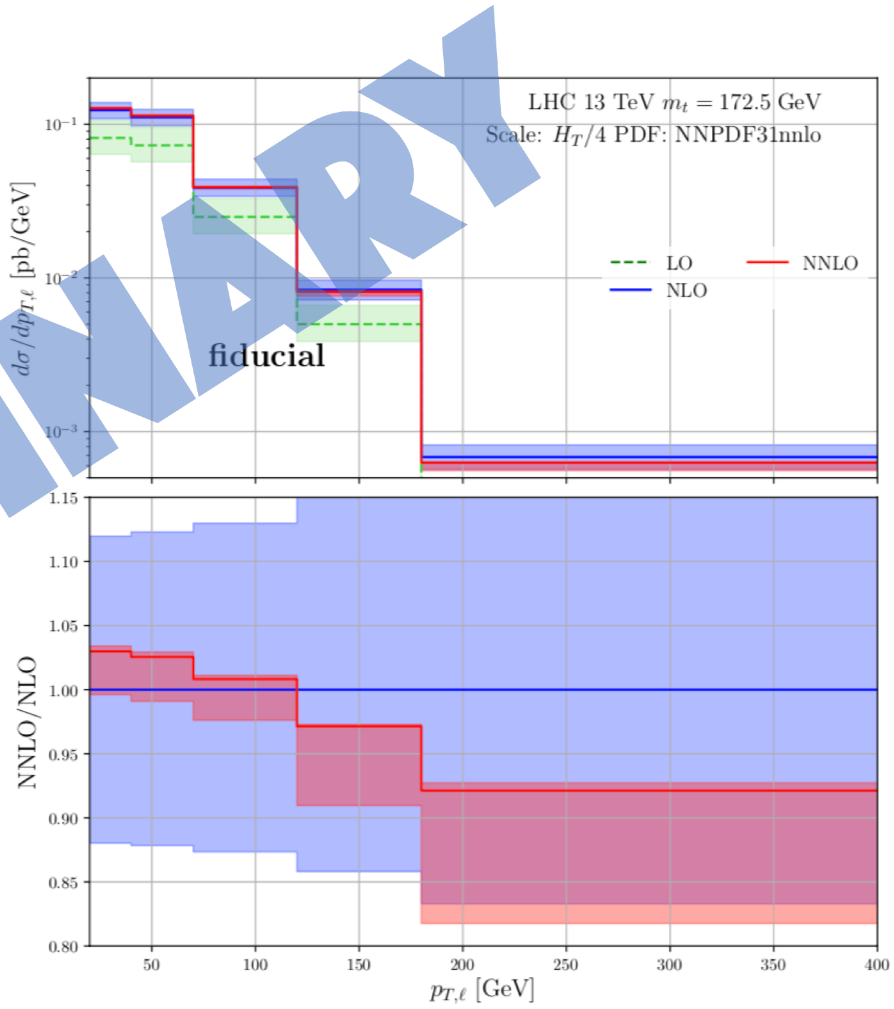


Behring, MC, Mitov, Papanastasiou, Poncelet `19

Exact NWA results @ NNLO

- Further work

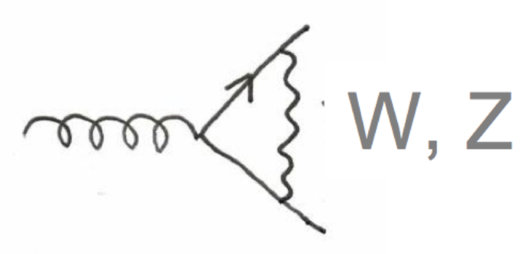




Electroweak effects for on-shell tops

- Long history
  - *Beennakker, Denner, Hollik, Mertig, Sack, Wackeroth `94*
  - *Bernreuther, Fücker, Si `05,`06*
  - *Moretti, Nolten, Ross `06*
  - *Kühn, Scharf, Uwer `05,`06,`14*
  - *Pagani, Tsinikos, Zaro `16*
  - *Denner, Pellen `16*

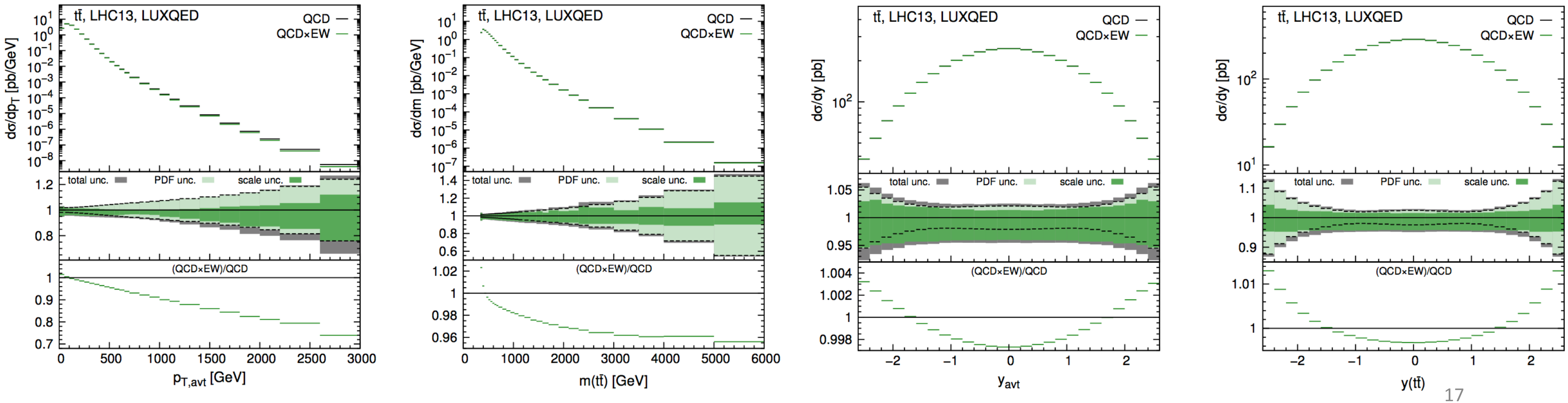
Large Sudakov logarithms



$$\log^2(p_{\mathrm{T}t}/M_{W,Z})$$

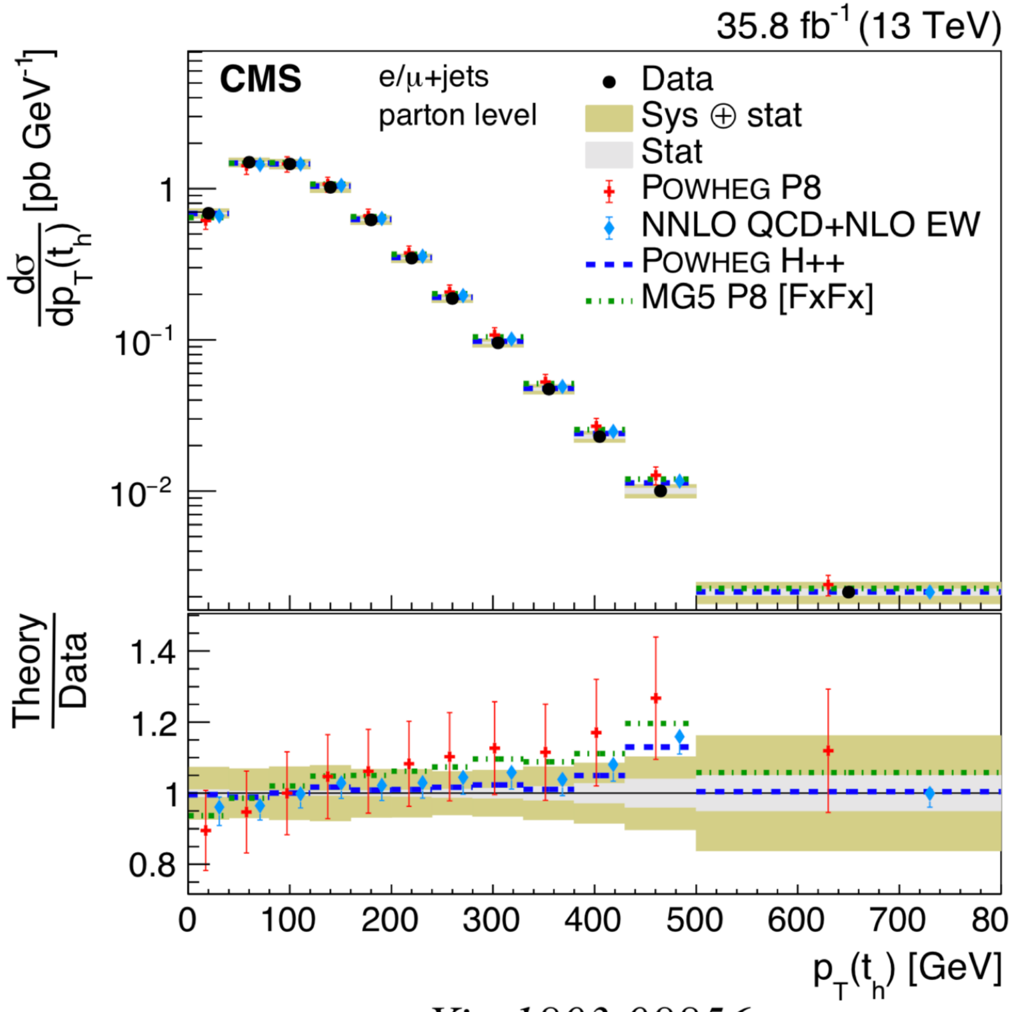
- Combination with NNLO QCD

MC, Heymes, Mitov, Pagani, Tsinikos, Zaro `17

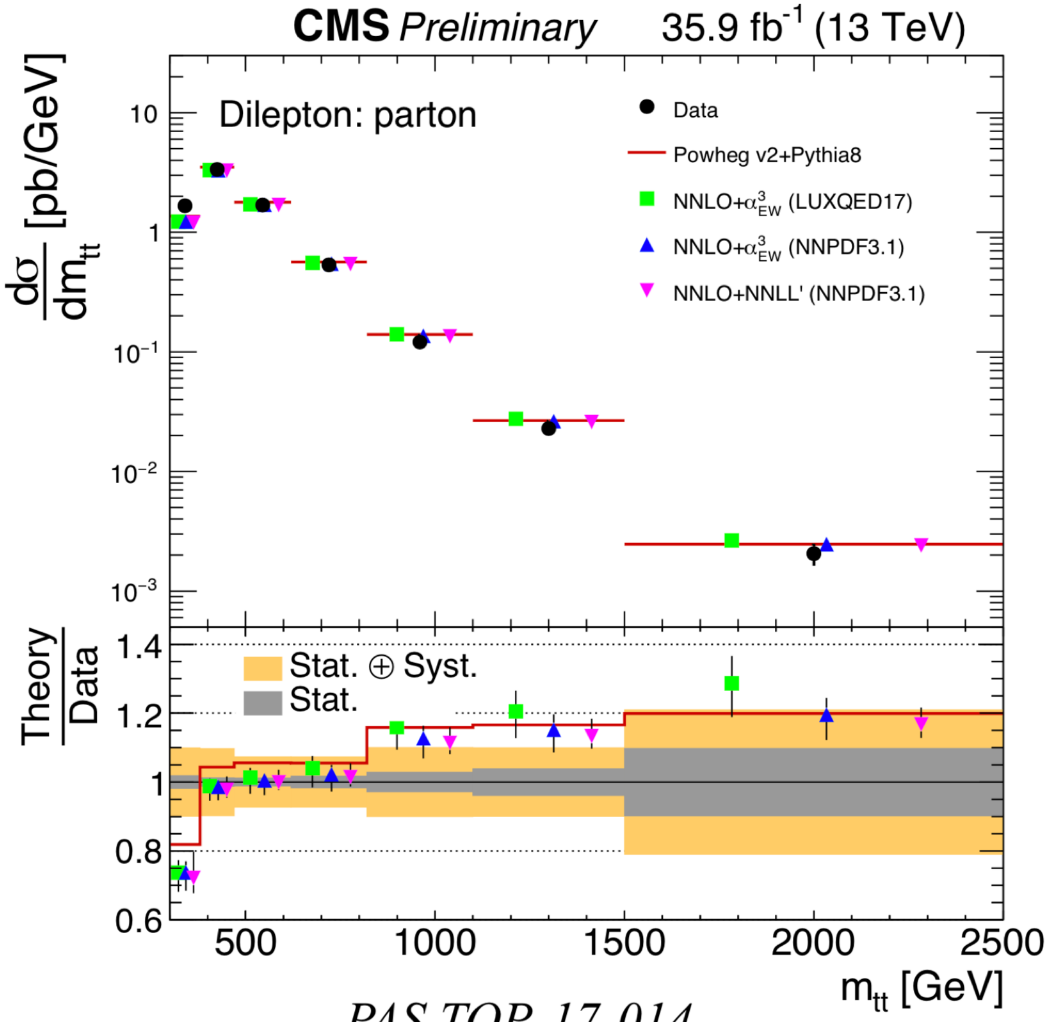


QCD x EW effects for on-shell tops

- Comparison with data after combination

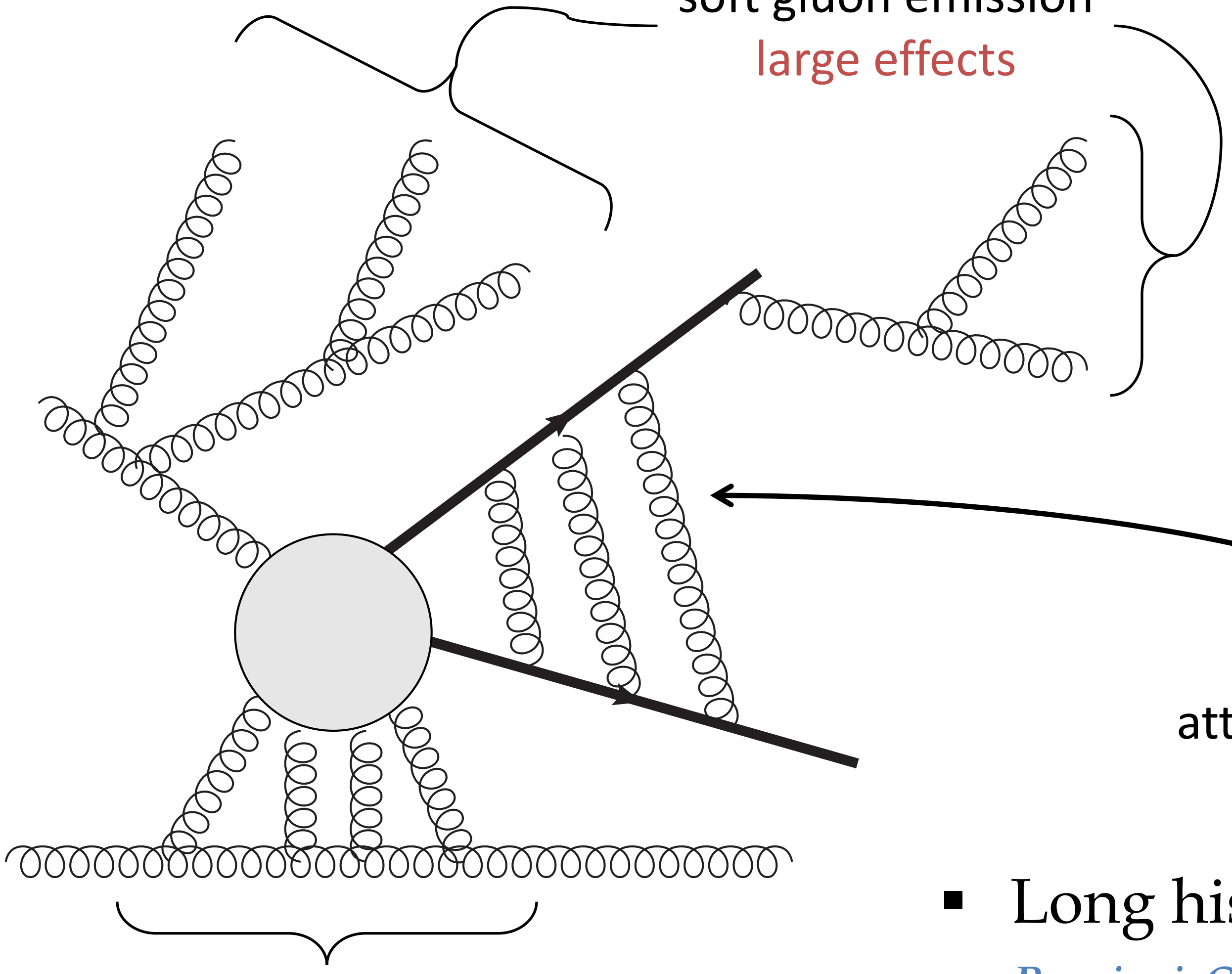


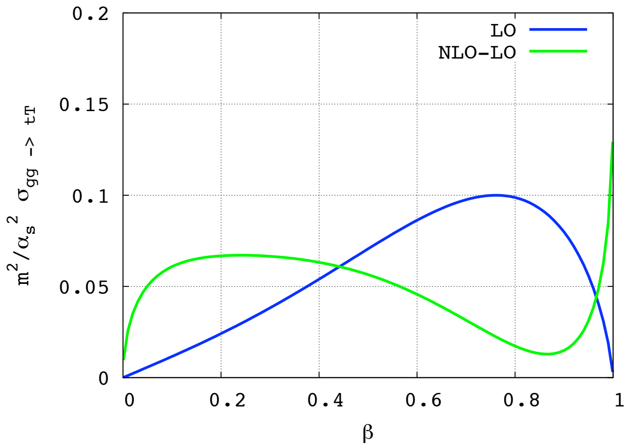
arXiv:1803.08856



PAS TOP-17-014

Dominant QCD effects and resummation





- Long history of soft gluon resummation

Bonciani, Catani, Mangano & Nason '98
Moch, Uwer '08, MC, Mitov, Sterman `09,
Beneke, Falgari, Schwinn `09,
Ahrens, Ferroglia, Neubert, Pecjak, Yang `10

Effects in the "Tails"

- Additionally to the potentially small gluon energies, m_t is small
- In this "boosted" regime there are two kinds of logs

$$\text{soft logs: } [\ln^n(1-z)/(1-z)]_+ \qquad (z \equiv M_{t\bar{t}}^2/\hat{s})$$

$$\text{small-mass (collinear) logs: } \ln m_t/M_{t\bar{t}}$$

- Widely separated scales

$$\text{Soft Limit:} \qquad \hat{s}, t_1, m_t^2 \gg \hat{s}(1-z)^2$$

$$\text{Boosted Soft Limit:} \qquad \hat{s}, t_1 \gg m_t^2 \gg \hat{s}(1-z)^2 \gg m_t^2(1-z)^2$$

- Factorization possible

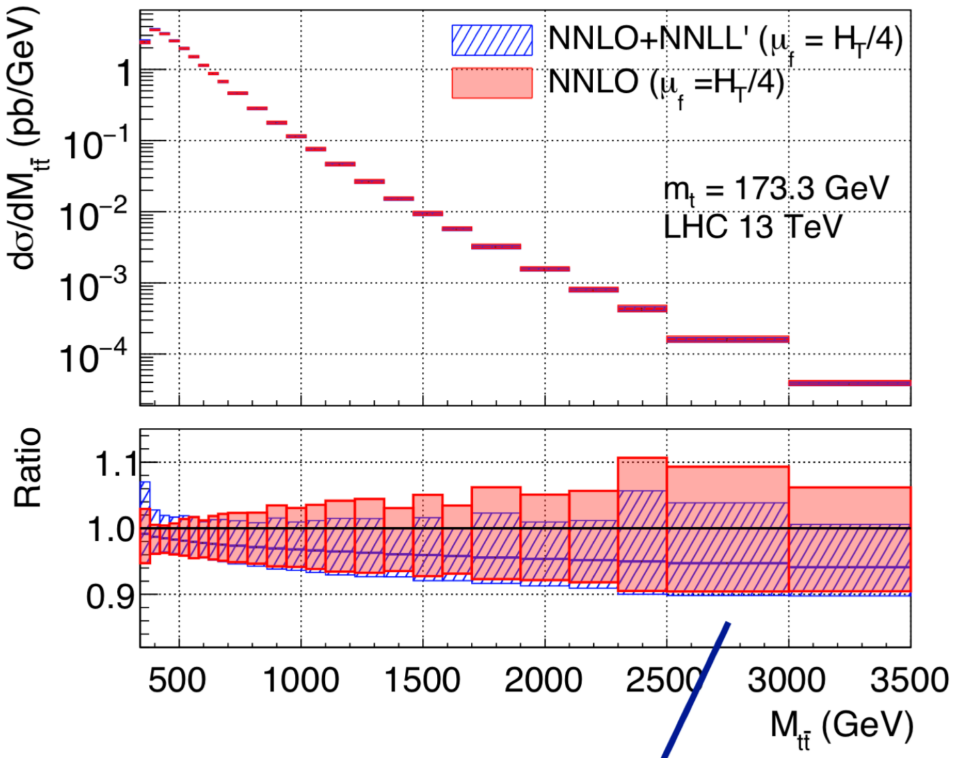
$$d\widetilde{\hat{\sigma}}_{ij}(\mu_f) = \mathrm{Tr}\Bigg[\widetilde{\mathbf{U}}_{ij}(\mu_f,\mu_h,\mu_s)\mathbf{H}_{ij}(M,\cos\theta,\mu_h)\widetilde{\mathbf{U}}_{ij}^\dagger(\mu_f,\mu_h,\mu_s)$$
$$\times\,\widetilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\bar{N}^2\mu_s^2},M,\cos\theta,\mu_s\right)\Bigg]\times\widetilde{U}_D^2(\mu_f,\mu_{dh},\mu_{ds})\,C_D^2(m_t,\mu_{dh})\,\tilde{s}_D^2\left(\ln\frac{m_t}{\bar{N}\mu_{ds}},\mu_{ds}\right)$$
$$+\,\mathcal{O}\left(\frac{1}{N}\right)+\mathcal{O}\left(\frac{m_t^2}{M^2}\right)$$

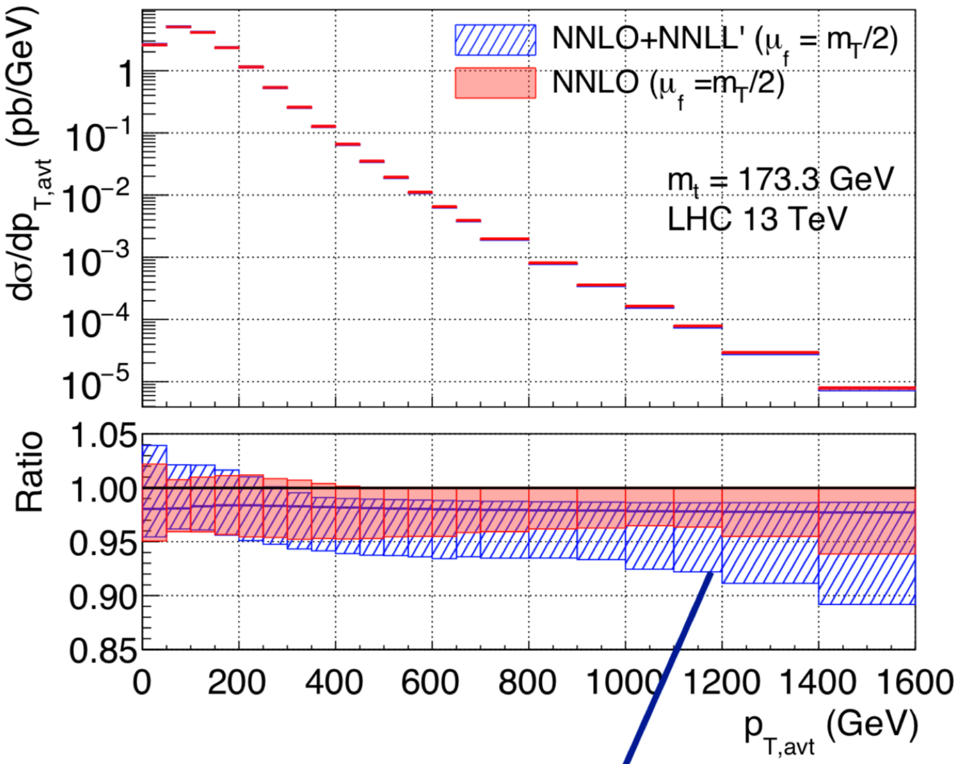
Ferroglia, Pecjak, Scott, Yang `13
Pecjak, Scott, Wang, Yang `16

- Notice that there are 5 (!) scales now

Matched NNLO+NNLL` results

MC, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang `18



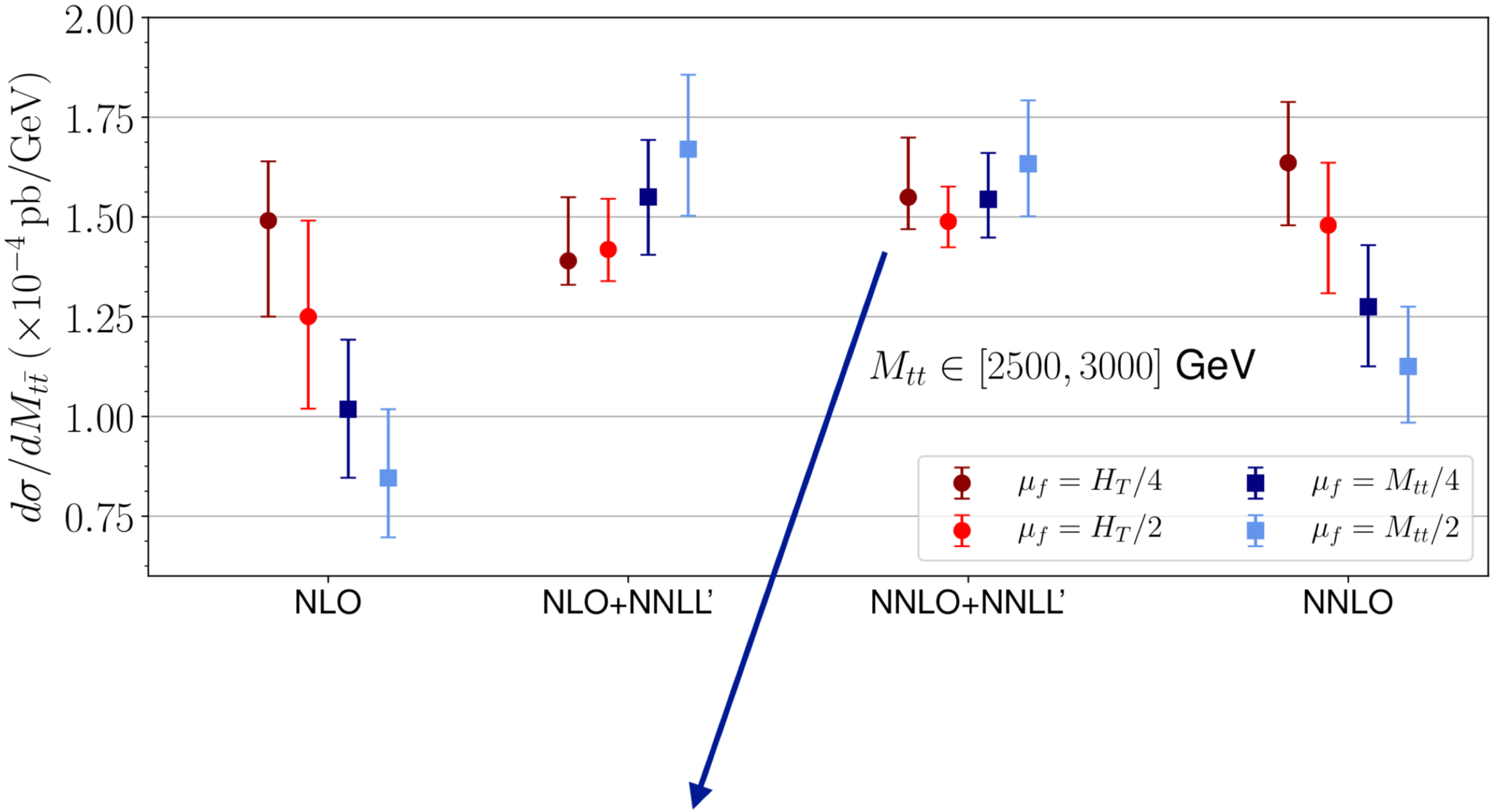


Resummation reduces scale variation

Resummation softens the spectrum

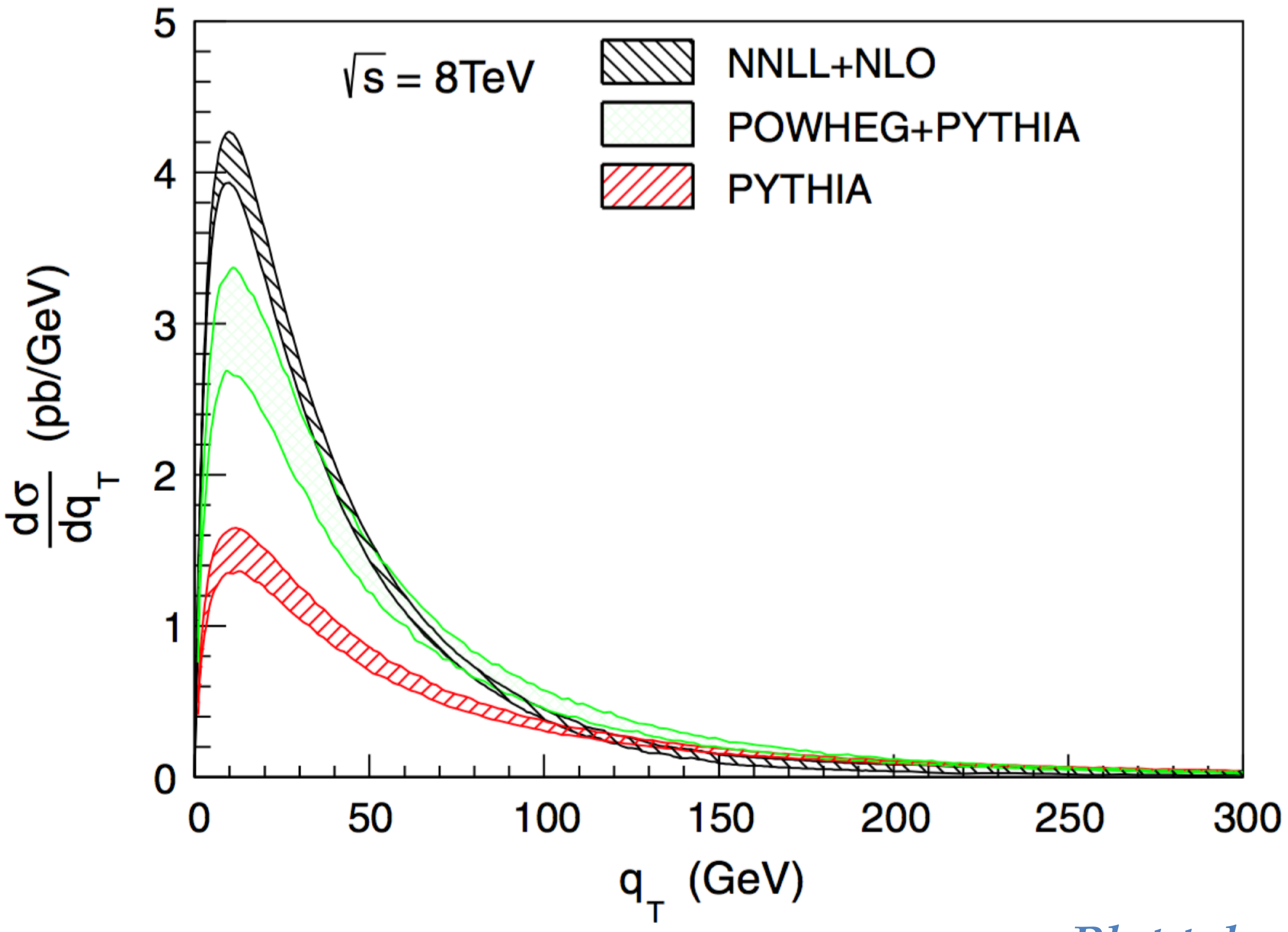
Matched NNLO+NNLL` results

MC, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang `18



Matched result insensitive to scale scheme choices

Another resummation: pT of the pair



Plot taken from Li et al.

Li, Li, Shao, Yang, Zhu `13
Catani, Grazzini, Torre `14

Sophisticated decay modelling

Decay Modeling @ NLO

- Off-shell effects through direct simulation of the final state $l^+\nu\, l^-\bar{\nu}\, b\bar{b}$

  Denner, Dittmaier, Kallweit, Pozzorini `11 `12

  Bevilacqua, MC, van Hameren, Papadopoulos, Worek `11

  Heinrich, Maier, Nisius, Schlenk, Winter `13

- Off-shell effects with massive b-quarks (simultaneous top-pair and single-top)

  Frederix `13

  Cascioli, Kallweit, Maierhöfer, Pozzorini `13

- Off-shell effects in the semi-leptonic channel

  Denner, Pellen '18

- Off-shell electroweak effects

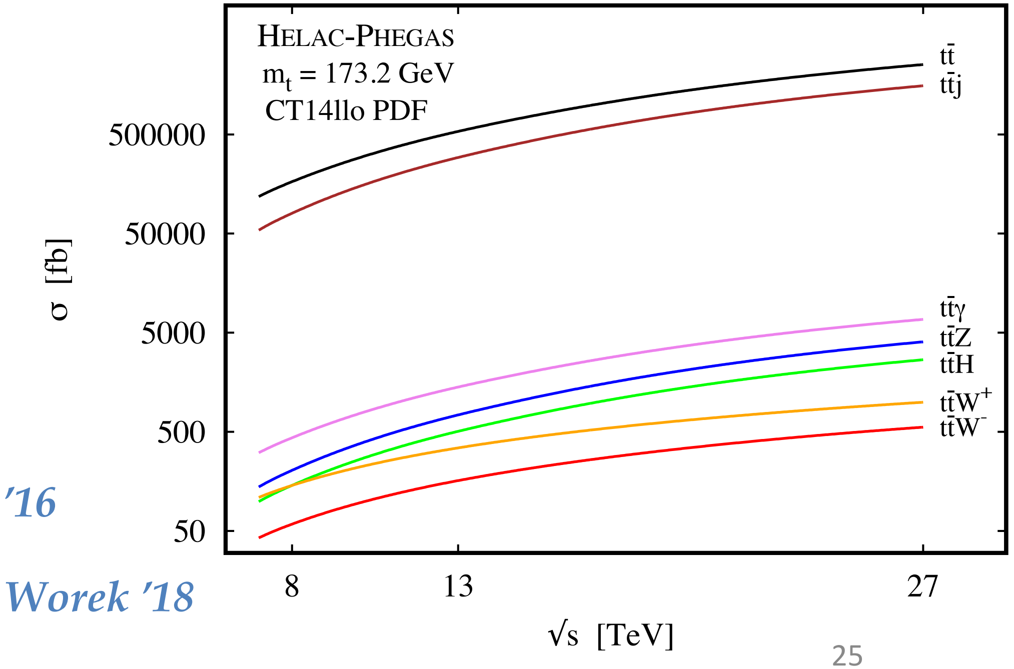
  Denner, Pellen '16

- More complicated processes

$l^+\nu\, l^-\bar{\nu}\, b\bar{b} + H$ — *Denner, Feger '15, Denner, Lang, Pellen, Uccirati '17*

$l^+\nu\, l^-\bar{\nu}\, b\bar{b} + jet$ — *Bevilacqua, Hartanto, Kraus, Worek '16*

$l^+\nu\, l^-\bar{\nu}\, b\bar{b} + \gamma$ — *Bevilacqua, Hartanto, Kraus, Weber, Worek '18*



Effects on Total Rates (Fiducial)

NWA → $\sigma_{t\bar{t}}$; Off-shell → $\sigma_{WWb\bar{b}}$

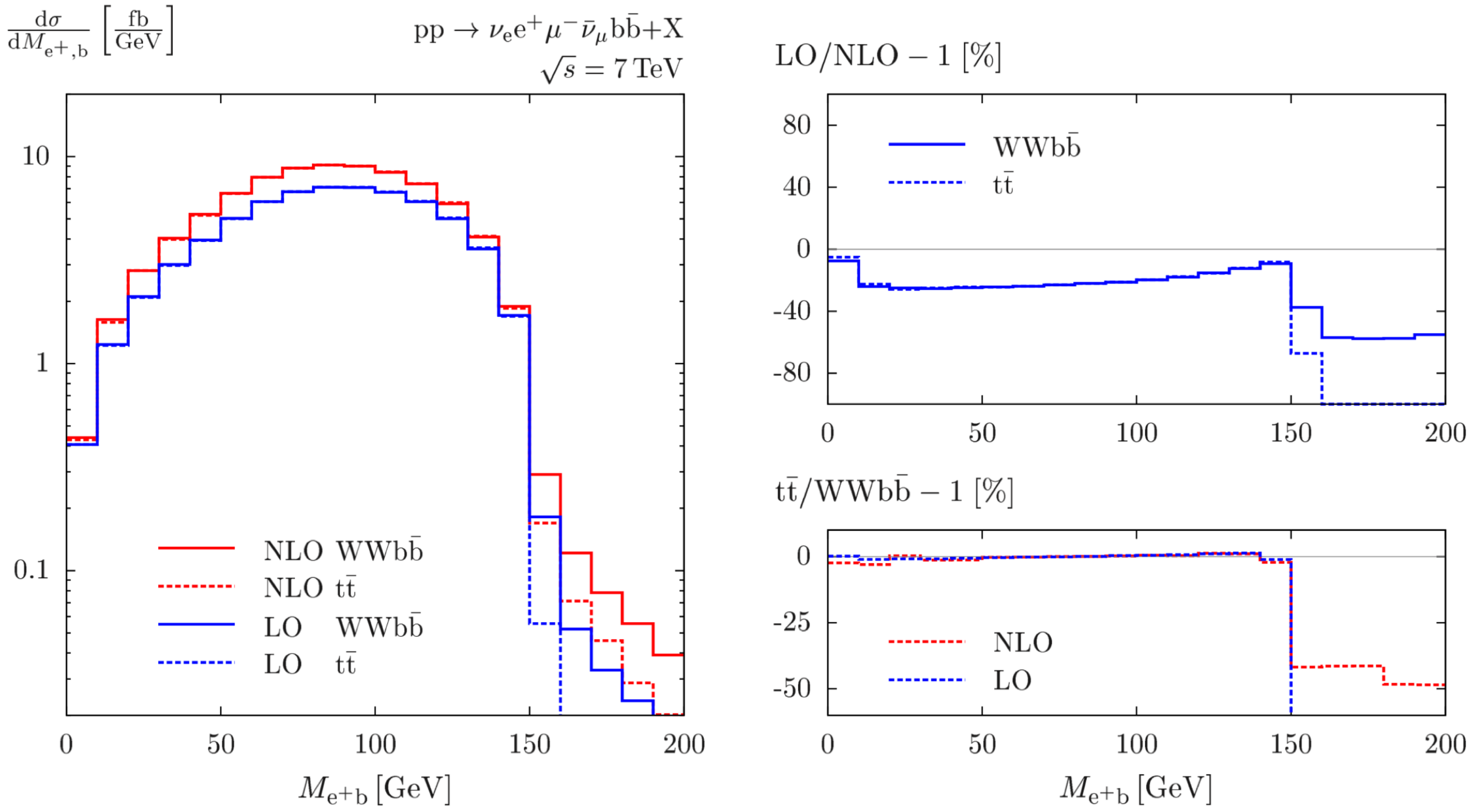
Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{WWb\bar{b}}$ [fb]	$\sigma_{t\bar{t}}/\sigma_{WWb\bar{b}} - 1$	Expected
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$	$+0.8\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$	$+0.9\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$	-0.4%
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$	-0.2%
LHC	14	LO	$3306.3(1)^{+1086.8}_{-763.6}$	$3334.6(2)^{+1098.5}_{-771.2}$	$-0.849(7)\%$	– – –
		NLO	$4253(3)^{+282}_{-404}$	$4286(7)^{+283}_{-407}$	$-0.77(19)\%$	– – –

Denner, Dittmaier, Kallweit, Pozzorini, Schulze `12

Tevatron (LHC) $R = 0.4\ (0.5)$ $p_{T,\mathrm{b-jet}} > 20\ (30)$ GeV, $|\eta_{\mathrm{b-jet}}| < 2.5$

$p_{T,\mathrm{miss}} > 25\ (20)$ GeV $p_{T,l} > 20$ GeV and $|\eta_l| < 2.5$

Finite Width Sensitive Observables



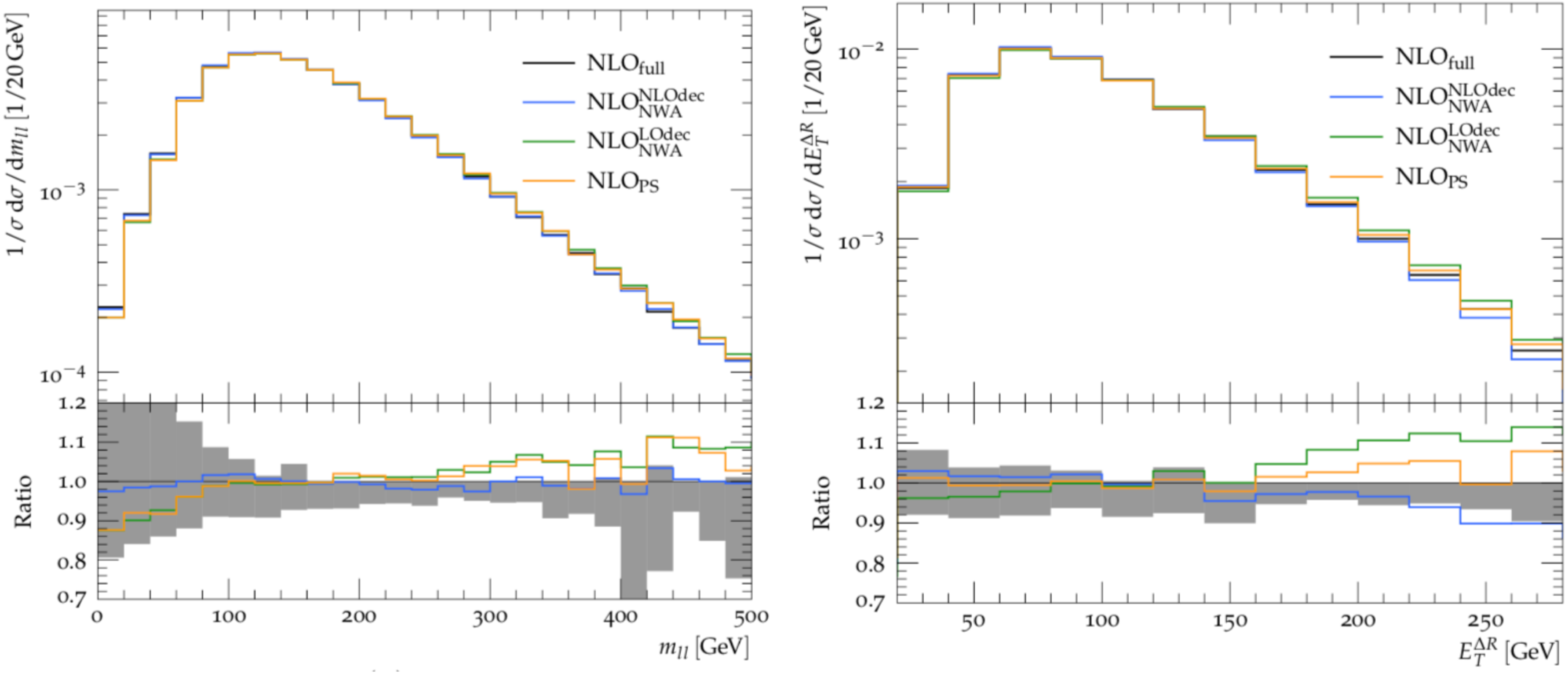
Denner, Dittmaier, Kallweit, Pozzorini, Schulze `12

- Large effects easily found by reaching past kinematic end-points

Finite Width Sensitive Observables

Off-shell, NWA, PS

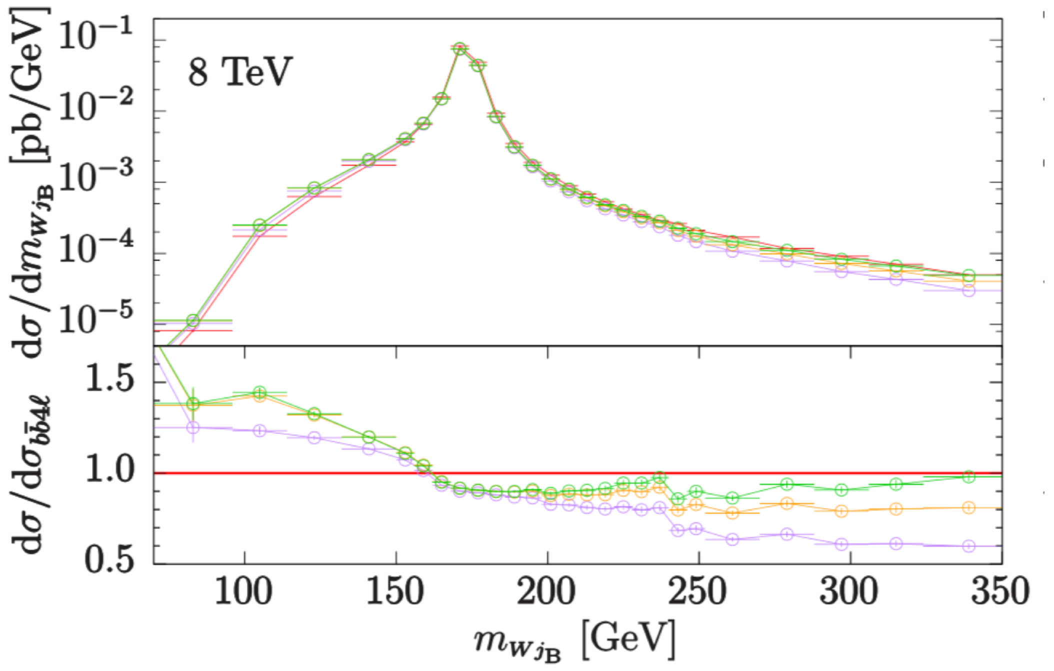
$pp \to t\bar{t} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}$ **@ 13 TeV LHC**

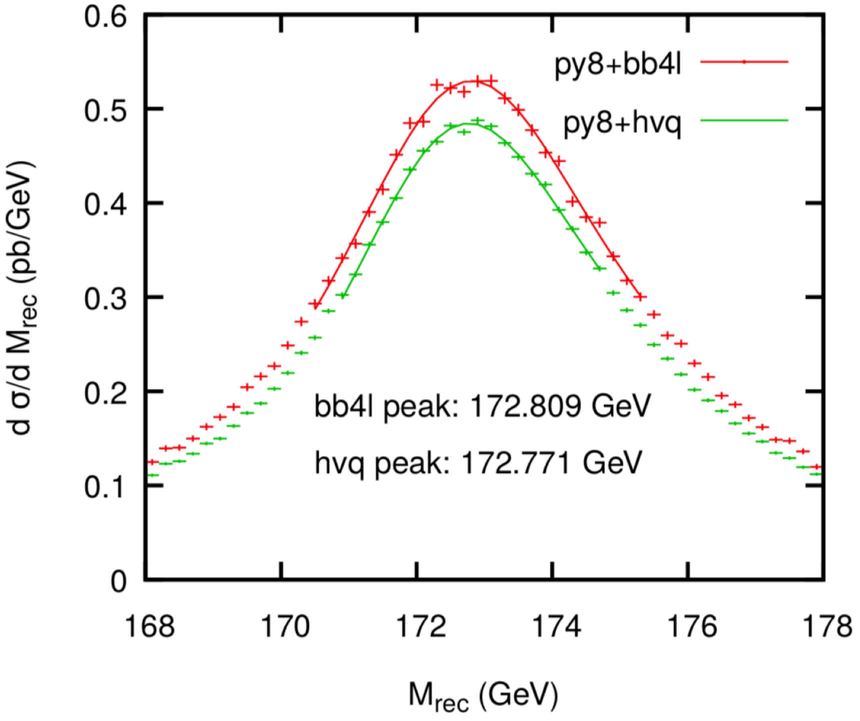


Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter '18

Off-shell matching to parton showers

- b_bbar_4l: $pp \to \ell^+ \nu_\ell\, l^- \bar{\nu}_l\, b\, \bar{b}$@NLO, allrad scheme
- hvq: $t\bar{t}$ @NLO, decay @LO, no Wt contribution
- hvq + ST_wtch_DS: tt & Wt @NLO, t decay @LO
- hvq + ST_wtch_DR: tt & Wt @NLO, t decay @LO





	M_{rec} (GeV)					
	Full			Shower only		
	$b\bar{b}4l$	hvq	Δ	$b\bar{b}4l$	hvq	Δ
$\sigma = 0$	172.809	172.771	0.038	172.544	172.493	0.051
$\sigma = 15$	172.698	172.548	0.150	171.396	171.303	0.093

Jezo, Lindert, Nason, Oleari and Pozzorini '16

Conclusions

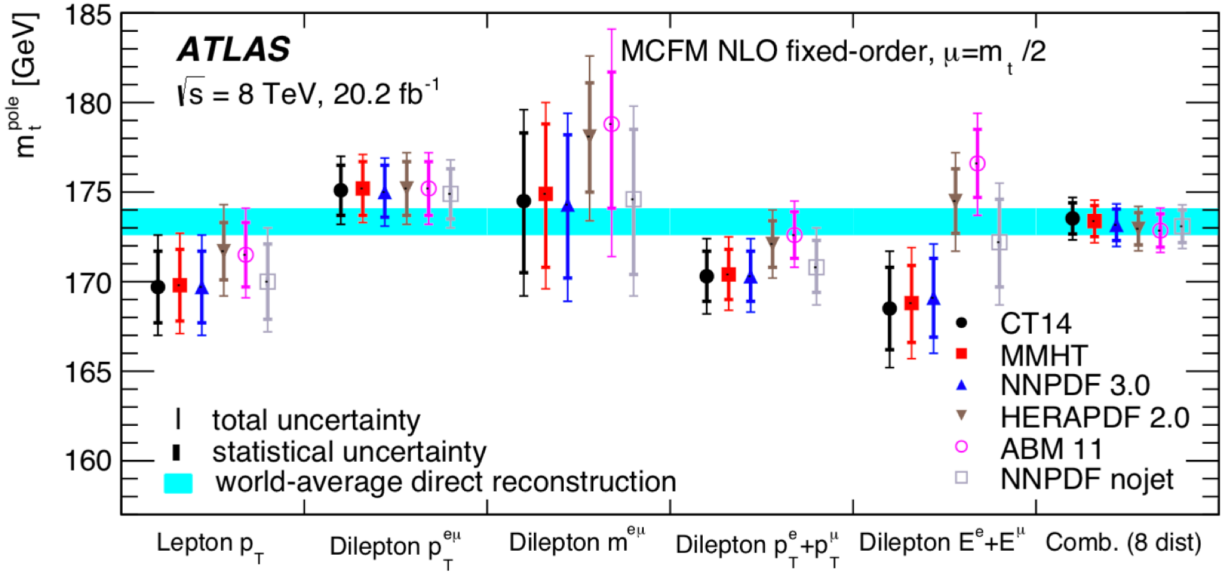
An example open problem

- Merging off-shell top quark effects @ NLO in QCD with NNLO QCD top quark predictions for ***pp → tt*** in ***di-lepton*** channel

- Determination of the top quark mass from leptonic observables → Fiducial $\boldsymbol{\sigma_{tt}}$

$$p_T^{\ell^+}\,,p_T^{\ell\ell}\,,M_{\ell\ell}\,,(E^{\ell^+}+E^{\ell^-})\,,(p_T^{\ell^+}+p_T^{\ell^-})\,,\eta^{\ell^+}\,,\eta^{\ell\ell}\,,\Delta\phi_{\ell\ell}$$

$$m_t = 172.2 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{syst.}) \pm 1.2\,(\text{th.})\ \text{GeV}$$



- Various tt NLO generators interfaced to PS used

- ***$d\sigma_{tt}/dX$*** modeled poorly by NLO+PS

- The most precise result obtained from fixed-order NLO predictions

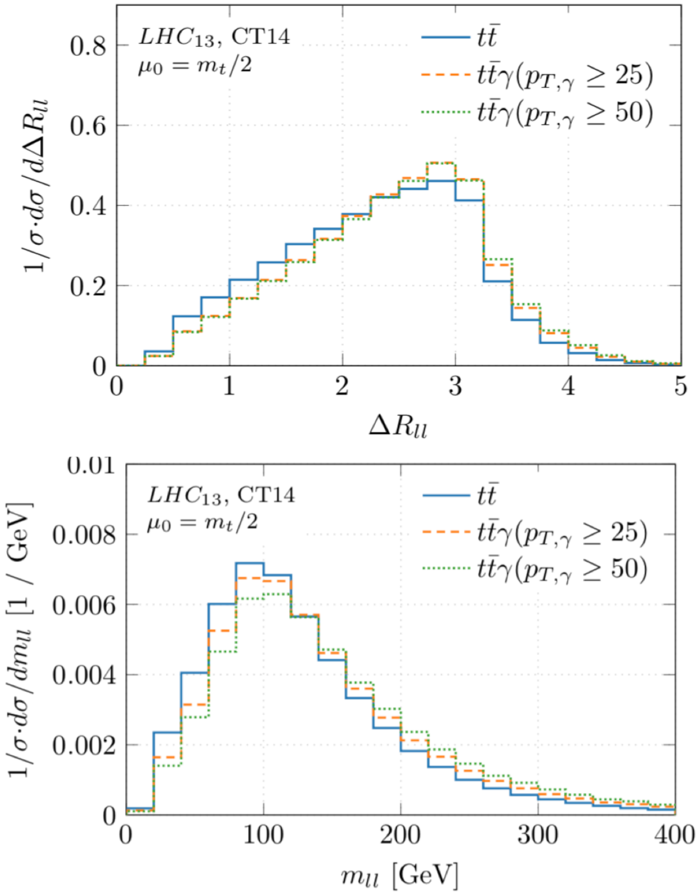
- ***Measurements limited by theory uncertainties stemming from modeling of top quark decays !***

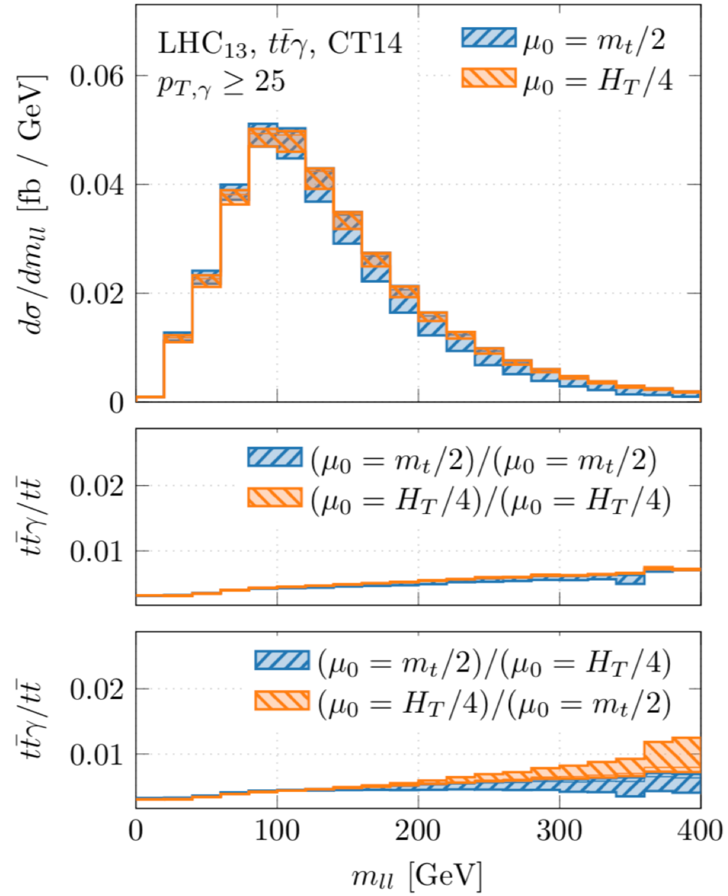
Precision improvement through ratios: ttγ/ tt

- ***1% – 3%*** precision for ***Integrated Cross Section Ratios***
- ***Differential Ratios*** with ***1% – 6%*** precision:
- Such high precision has only been reserved till now for NNLO !

Off-shell Tops

$M_{b\bar{b}}$, $M_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, p_{T,ℓ_1}



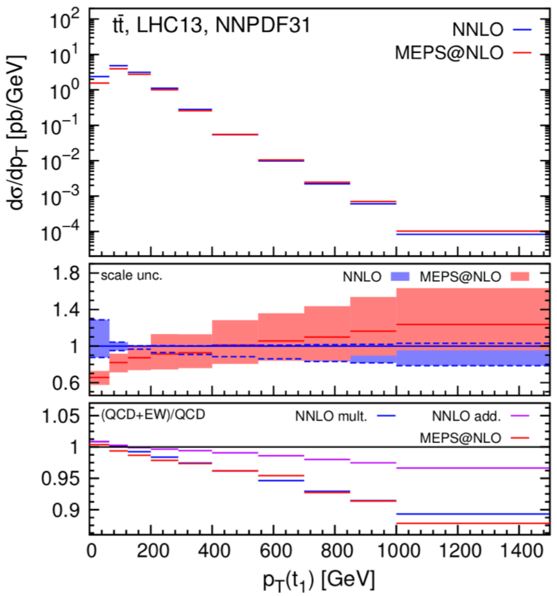


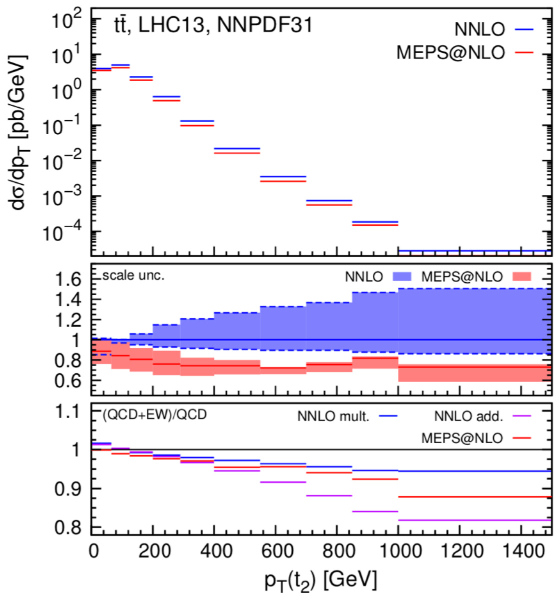
Bevilacqua, Hartanto, Kraus, Weber, Worek '19

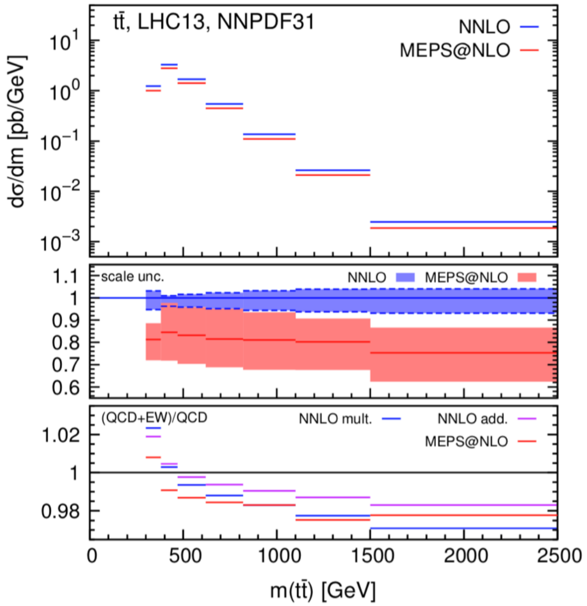
Merging vs Fixed Order

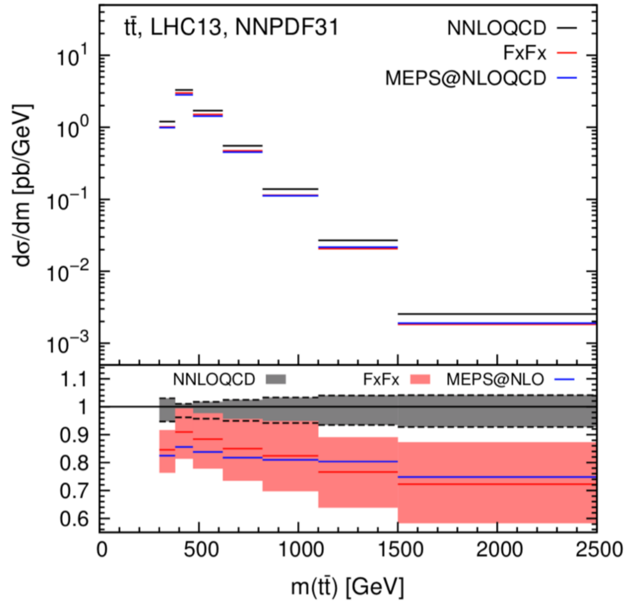
❖ *On-shell tops and EW corrections included*

Not described at Fixed Order









Large discrepancies to Merging

MC, Gütschow, Lindert, Mitov, Pagani, Papanastasiou, Schönherr, Tsinikos, Zaro '19

Top-quark physics

- Booming topic with lots of applications and interest outside the QCD community

- Fixed-order perturbation theory and resummation rather well understood

- Nevertheless, lots of work necessary for reliable predictions in the case of decay modelling

- How to include the knowledge in Monte Carlo event generators?