Precision event generation for top-quark production

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Outline & introduction

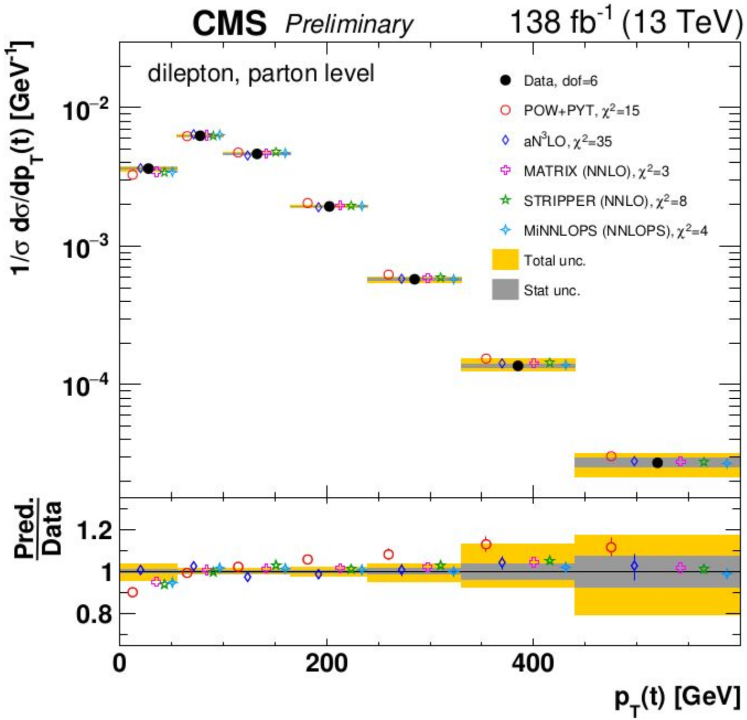
- review of some recent results
- focus mostly on $t\bar{t}$, few comments on $t\bar{t}$+X

- Fully-differential partonic results: NNLO QCD (prod. and decay), NLO EW corrections known (+ analytic resummation)

- MC event generators (from data to parton-level / background for BSM / measure parameters):
  - stable tops: NLO+PS established, NNLO+PS available, approximated decays
  - full final state (leptons+jets) with QCD corrections: NLO+PS methods available (+ ongoing developments)
  - full assessment of TH uncertainties missing (→ NLL showers will play crucial role)

$t\bar{t}$ measurements: status

[CMS-PAS-TOP-20-006]

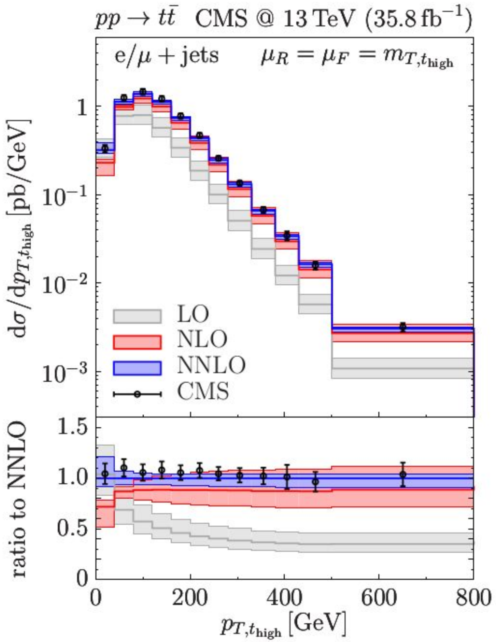


- TH in this plot: NLO+PS, NNLO, NNLO+PS (and aN3LO)

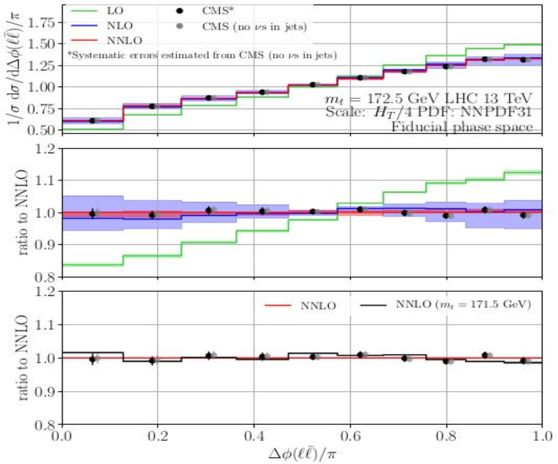
- scale choice: $\mu=H_T/4=(m_T(t)+m_T(\bar{t}))/4$
studied in [1606.0350]

- NNLO corrections → fix long-standing issue with $p_T(t)$

$t\bar{t}$ (differential) parton-level computations

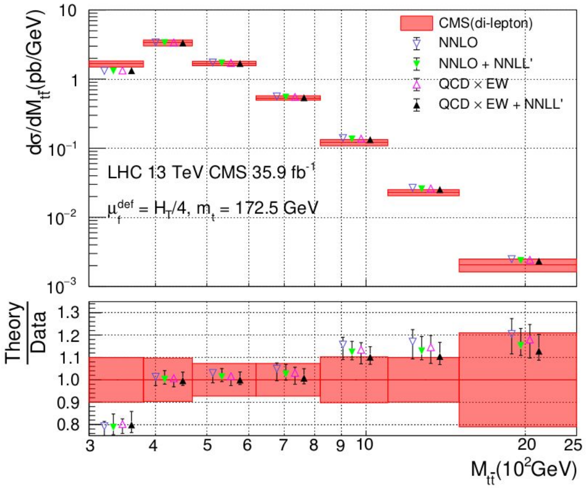


[Catani,Devoto,et al.'19]



[Czakon,Mitov,Poncelet '20]

$$d\sigma = d\sigma_{t\bar{t}} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}$$



[Czakon et al. 1901.08281]

- NNLO known for prod & decay
- decay: NWA, spin correlations
- NNLO x NNLO x NNLO

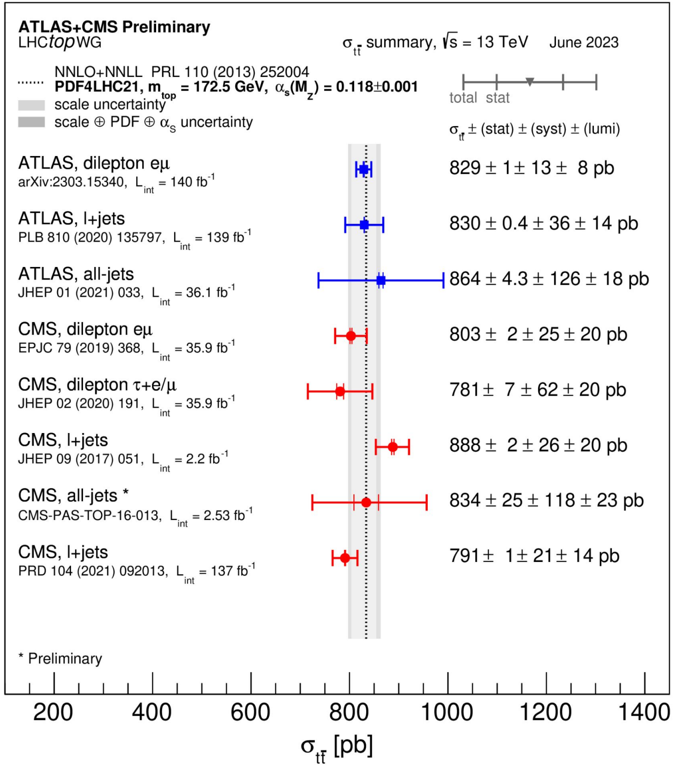
- EW/QCD combination

$$\Sigma_{\rm QCD\times EW} \equiv \Sigma_{\rm QCD+EW} + (K^{\rm NLO}_{\rm QCD} - 1) \times \Sigma_{\rm NLO\ EW}$$

Parton-level results: summary

- QCD corrections: clear picture, good perturbative convergence
- different scale choices possible: H_T-like seems to do a good job for distributions
  - insights on hardness vs. kinematics in $t\bar{t}$:
  [Caola,Dreyer et al. 2101.06068]
- Full NLO EW available [Denner,Pellen '16], possible to validate different approximations.
- Combination of EW and QCD corrections: done for stable top quarks (possible to supplement it with resummation(s))
- Residual uncertainty (size, PDF vs μ) depends on observables

Foundations on which MC developments are based



[ATL-PHYS-PUB-2023-014]

MC event generators: status

- Several NLO+PS generators available: **POWHEG BOX**, **MG5_aMC@NLO**, **Sherpa**, **Herwig** (through `Matchbox`).

- Approximations made to include decays and off-shell effects (e.g. `ttb_NLO_dec`: prod@NLO x decay@NLO)

- Exact MC simulation for decay, offshell effects and interferences:
  `bb4l` NLO+PS generator [Ježo,Lindert et al. '16]
  - NEW: NLOPS matching for off-shell tt+Wt production with semileptonic decays [Ježo,Lindert,Pozzorini '23]

- Multijet merging up to 2 jets @ NLO+PS [MEPS@NLO, FxFx, '12-'13]

- tt̄ NNLO+PS results available [Mazzitelli,Monni,Nason,ER,Wiesemann,Zanderighi '20-'21]

- NNLO+PS available for b-bar, ongoing work on tt̄+H [Mazzitelli,Wiesemann,Ratti,Zanderighi '23/Mazzitelli,Wiesemann WIP]

NNLO+PS: goals and accuracy

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- Sudakov resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- preserve the PS accuracy (leading log - LL)
  - possibly, no merging scale required.

- methods: reweighted MiNLO′ (“NNLOPS”) [Hamilton,et al. ’12,’13,...], UNNLOPS [Höche,Li,Prestel ’14,...] / [Plätzer ’12] Geneva [Alioli,Bauer,et al. ’13,’15,’16,...], MiNNLO$_{\mathrm{PS}}$ [Monni,Nason,ER,Wiesemann,Zanderighi ’19,...]

[Notation: From this point, $X = \sum_k \left(\frac{\alpha_S}{2\pi}\right)^k [X]^{(k)}$]

top pair-production @ NNLO+PS: MiNNLO (I)

- from p_T resummation, differential cross section for $F+X$ production can be written as:

$$\frac{d\sigma}{dp_T d\Phi_F} = \frac{d}{dp_T}\left\{\mathcal{L}(\Phi_F, p_T)\exp(-\tilde{S}(p_T))\right\} + R_{\text{finite}}(p_T)$$

$$\mathcal{L}(\Phi_F, p_T) \ni \{H^{(1)}, H^{(2)}, C^{(1)}, C^{(2)}, (G^{(1)} \cdot G^{(1)})\} \qquad R_{\text{finite}}(p_T) = \frac{d\sigma_{FJ}}{d\Phi_F dp_T} - \frac{d\sigma^{\text{sing}}}{d\Phi_F dp_T}$$

- recast it, to match the POWHEG $\bar{B}^{(FJ)}(\Phi_{FJ})$

$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)]\left\{D(p_T) + \frac{R_{\text{finite}}(p_T)}{\exp[-\tilde{S}(p_T)]}\right\}$$

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T} \qquad \tilde{S}(p_T) = \int_{p_T}^{Q}\frac{dq^2}{q^2}\left[A_f(\alpha_S(q))\log\frac{Q^2}{q^2} + B_f(\alpha_S(q))\right]$$

- expand the above integrand in power of $\alpha_S(p_T)$, keep the terms that are needed to get NLO$^{(F)}$ & NNLO$^{(F)}$ accuracy, when integrating over p_T

top pair-production @ NNLO+PS: MiNNLO (II)

$$\frac{\mathrm{d}\bar{B}(\Phi_{\rm FJ})}{\mathrm{d}\Phi_{\rm FJ}} = \exp[-\tilde{S}(p_{\rm T})]\left\{\frac{\alpha_S(p_{\rm T})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\rm FJ}}{\mathrm{d}\Phi_{\rm FJ}}\right]^{(1)}\left(1+\frac{\alpha_S(p_{\rm T})}{2\pi}[\tilde{S}(p_{\rm T})]^{(1)}\right) + \left(\frac{\alpha_S(p_{\rm T})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\rm FJ}}{\mathrm{d}\Phi_{\rm FJ}}\right]^{(2)} + [D(p_{\rm T})]^{(\geq 3)} F_\ell^{\rm corr}(\Phi_{\rm FJ})\right\}$$

- $$[D(p_{\rm T})]^{(\geq 3)} = \underbrace{-\frac{\mathrm{d}\tilde{S}(p_{\rm T})}{\mathrm{d}p_{\rm T}}\mathcal{L}(p_{\rm T}) + \frac{\mathrm{d}\mathcal{L}(p_{\rm T})}{\mathrm{d}p_{\rm T}}}_{D} - \frac{\alpha_S(p_{\rm T})}{2\pi}[D(p_{\rm T})]^{(1)} - \left(\frac{\alpha_S(p_{\rm T})}{2\pi}\right)^2 [D(p_{\rm T})]^{(2)}$$
- $F_\ell^{\rm corr}(\Phi_{\rm FJ})$: projection $\rightarrow$ recover $[D(p_{\rm T})]^{(\geq 3)}$ when integrating over $\Phi_{\rm FJ}$ at fixed $(\Phi_{\rm F}, p_{\rm T})$

. The second radiation is generated by the usual POWHEG mechanism.

$$\mathrm{d}\sigma = \bar{B}(\Phi_{\rm FJ})\,\mathrm{d}\Phi_{\rm FJ}\left\{\Delta_{\rm pwg}(\Lambda_{\rm pwg}) + \mathrm{d}\Phi_{\rm rad}\Delta_{\rm pwg}(p_{\rm T,rad})\frac{R(\Phi_{\rm FJ},\Phi_{\rm rad})}{B(\Phi_{\rm FJ})}\right\}$$

. if emissions are strongly ordered, same emission probabilities as in k_t-ordered shower
$\rightarrow$ LL shower accuracy preserved

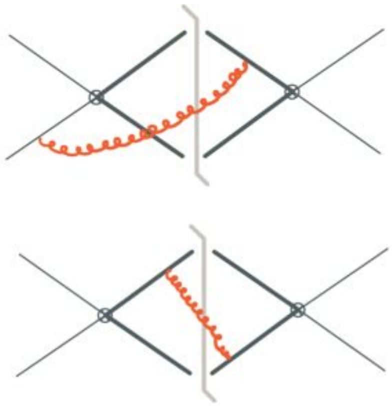
top pair-production @ NNLO+PS: MiNNLO for $t\bar{t}$

- Starting point: resummation formula for $t\bar{t}$ transverse momentum. [Catani,Grazzini,Torre '14]
  Very schematically:

$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int \frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

$${\rm Tr}(\mathbf{H}\boldsymbol{\Delta}) = \langle M|\boldsymbol{\Delta}|M\rangle, \quad \boldsymbol{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}_t^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}_t^{(2)}\right]\right\}$$



- With some approximations (respecting our goal), terms due to soft interference can be rearranged so that the "resummation" can be eventually recasted as:

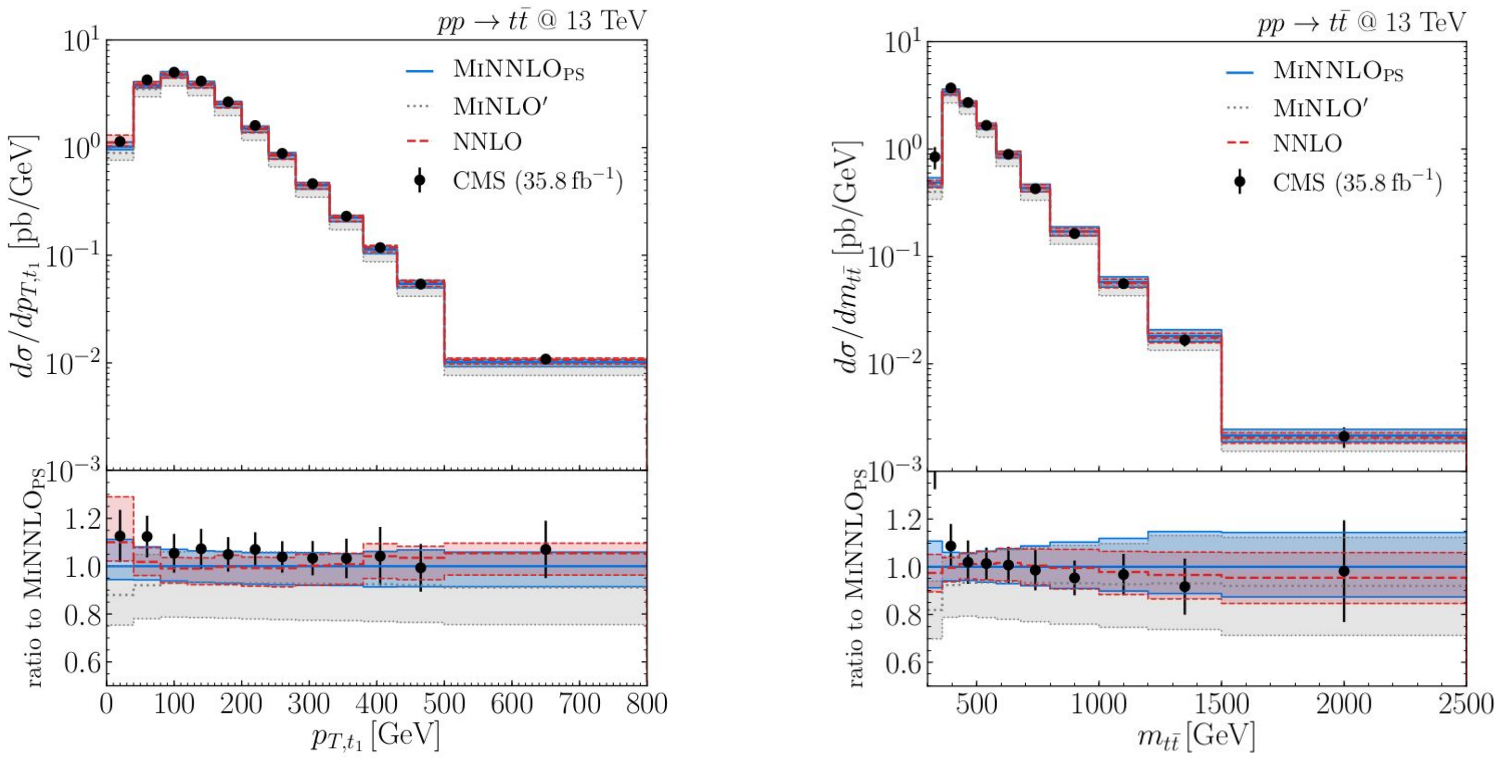
$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{\sum_{i\in\text{colours}} e^{-\overline{S}_i}\,\underbrace{c_i\,\overline{H}\,\overline{(C\otimes f)}\,\overline{(C\otimes f)}}_{\equiv\,\overline{\mathscr{L}}_i}\right\} + \mathcal{O}(\alpha_S^5)$$

inputs from [Catani, Devoto, Grazzini, Kallweit, Mazzitelli + Sargsyan '19]

paper: [Catani, Devoto, Grazzini, Mazzitelli '23]

- Each term has the "same structure" as in the color-singlet case!

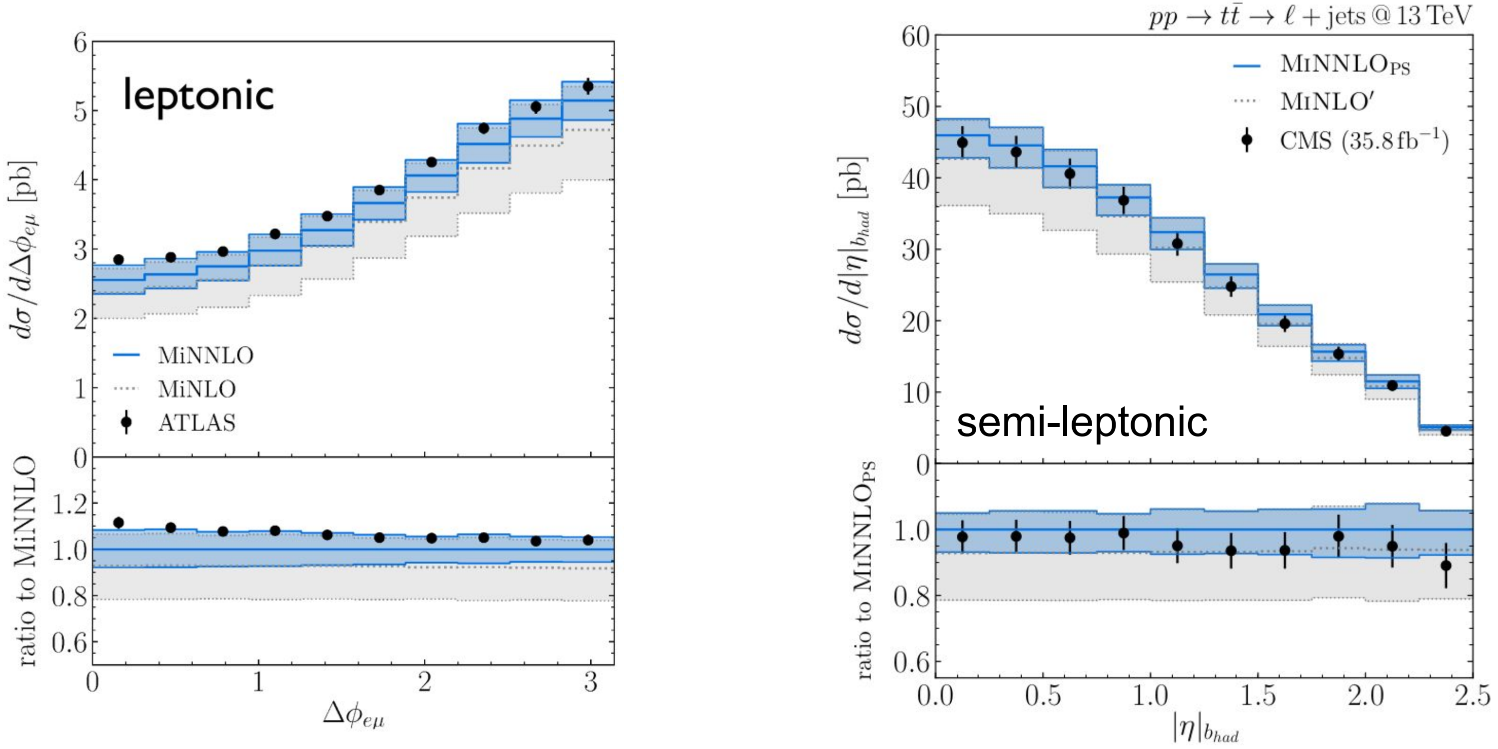
top pair-production @ NNLO+PS: results I



[Mazzitelli,Monni,Nason,ER,Wiesemann,Zanderighi ‘20-’21]

- nice agreement with NNLO (and with data - both ATLAS and CMS). $\mu_{core} = H_T/4$
- m(tt̄), 1st bin: finite-width effects + non-relativistic effects + QED

top pair-production @ NNLO+PS: results II

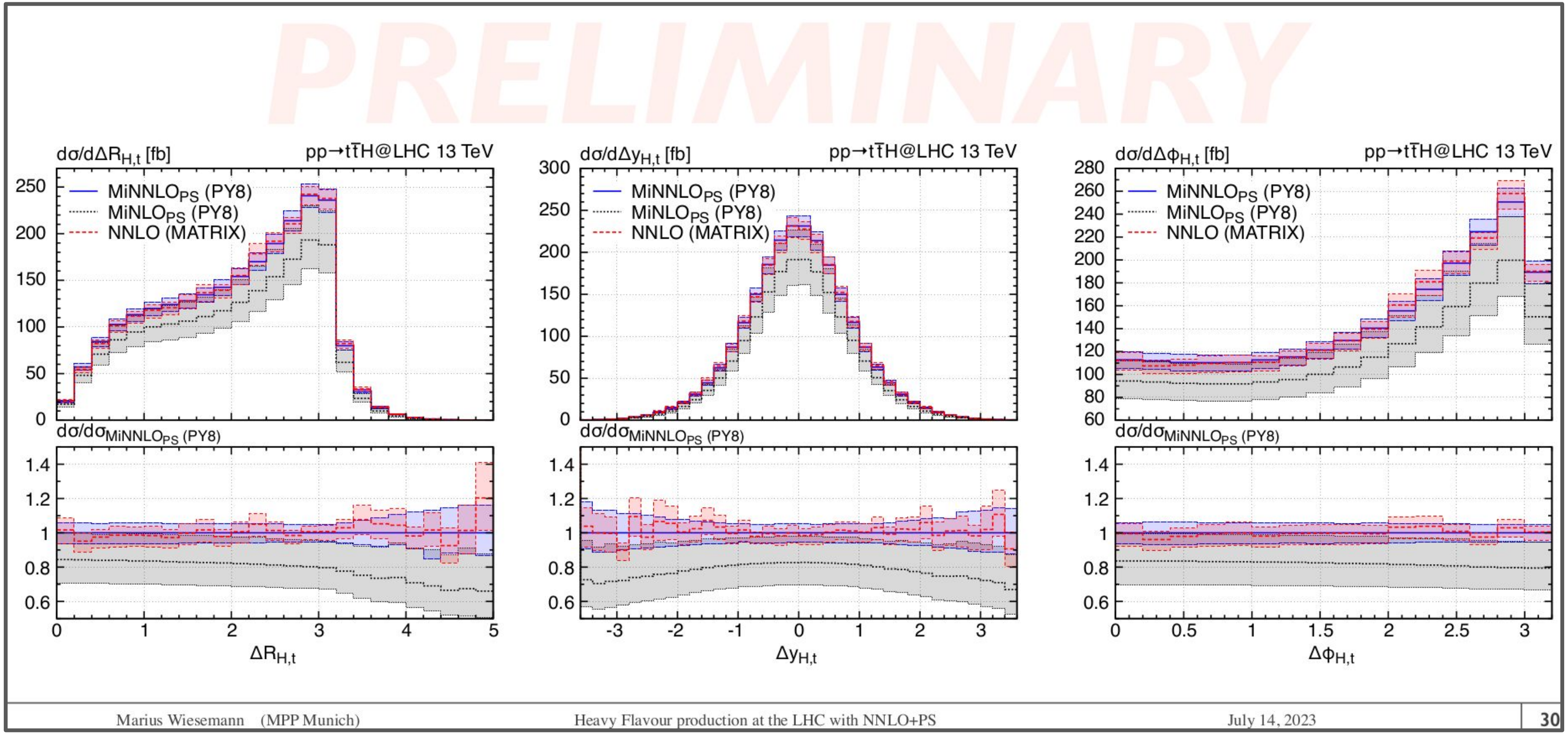


[Mazzitelli,Monni,Nason,ER,Wiesemann,Zanderighi '20-'21]

- implemented top-quark decays @ tree level + approximated off-shell effects
- NB: if analysis probes off-shell/non-resonant regions →`bb4l` **NLO+PS** should be method of choice

ttH production @ NNLO+PS

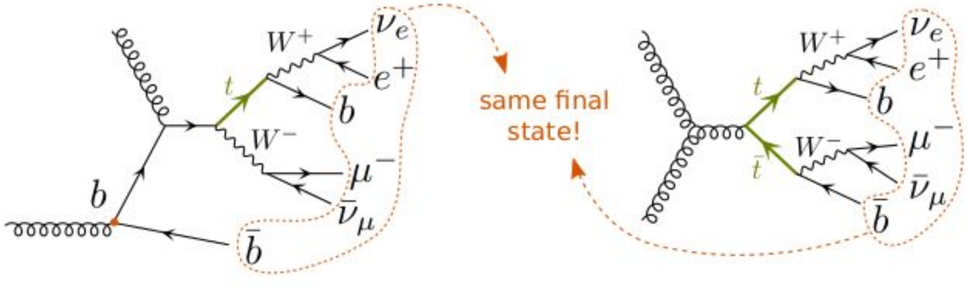
[Mazzitelli,Wiesemann WIP]



[slide from Wiesemann's talk at SM@LHC]

- soft function computation extended (arbitrary kinematics): [Devoto,Mazzitelli WIP]
- 2-loops using "soft Higgs" approximation [Catani et al. 2210.07846→talk by S. Devoto]

$t\bar{t}$ / Wt: EXP/TH status



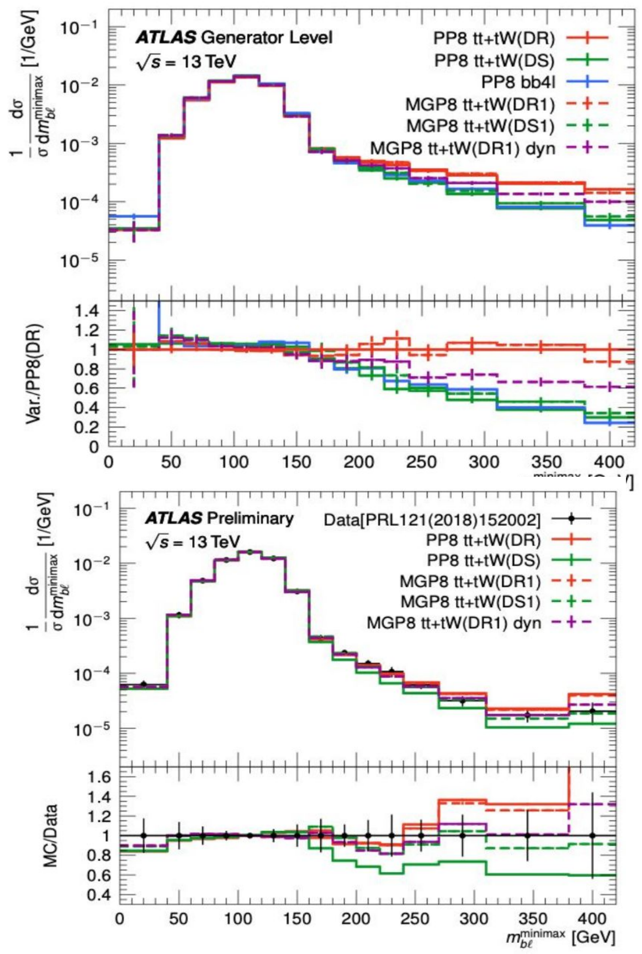
[diagrams from slides by T. Ježo]

- Interference tt/Wt: long-standing issue
- Approximations made (DR/DS) to treat processes separately, with unstable resonances in final state
- DR/DS differences might become an issue in BSM search regions

- **bb4l NLOPS** generator in POWHEG-BOX-RES: interferences/off-shell effects, top decay at NLO

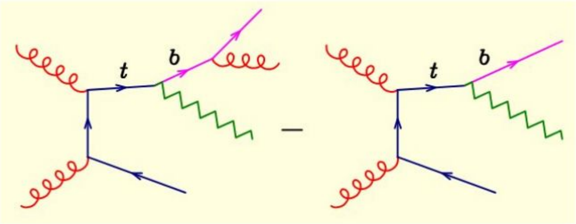
- resonant-aware methods also in MG5_aMC@NLO

[ATL-PHYS-PUB-2021-042]



$m_{b\ell}^{\text{minimax}} = \min\{\max(m_{b_1,\ell_1}, m_{b_2,\ell_2}), \max(m_{b_2,\ell_1}, m_{b_1,\ell_2})\}$

Off-shell $t\bar{t}$ + tW: status



$$d\sigma = d\Phi_{\rm rad}\bar{B}(\Phi_B)\frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}\times \exp\left[-\int \frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}d\Phi_{\rm rad}\right]$$

$\Phi_B \to (\Phi_B, \Phi_{\rm rad})$ mapping does not preserve virtuality
⇒ *R/B* can become large also far from collinear singularity

→

- NW limit spoiled
- BW shape distorted

"Resonant-aware" NLO+PS methods [Ježo,Nason '15 / Frederix et al. '16]

- project full MEs onto "resonance histories": $B = \sum_{f_b} B_{f_b}$, where $B_{f_b} \equiv \frac{P^{f_b}(\Phi_B)}{\sum_{f'_b} P^{f'_b}(\Phi_B)} B(\Phi_B)$

$P^{f_b}(\Phi_B)$ (products of) Breit-Wigner functions ⇔ resonance history f_b

- each term (Born- and real-like) is attributed to an unique resonance history
    - virtuality-preserving mappings
    - POWHEG radiation can be assigned a resonance → (up to) 1 emission per resonance

Off-shell $t\bar{t}$ + tW: status → recent progress

- `bb4l` **NLO+PS** [1607.04538]: generator available for leptonic decays
  (used also for TH studies, e.g. [Ferrario Ravasio,Ježo et al. '18])

- NEW: [Ježo,Lindert,Pozzorini 2307.15653]: improvements + semi-leptonic decays

1. width effects
2. improved resonance histories

Off-shell $t\bar{t}$ + tW: recent progress

[Ježo,Lindert,Pozzorini 2307.15653]

1. width effects:

NWA: $$\mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma \frac{\mathrm{d}\Gamma}{\Gamma}$$

naive: $$\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 \frac{\mathrm{d}\Gamma_0}{\Gamma_{\mathrm{NLO}}} + \mathrm{d}\sigma_1 \frac{\mathrm{d}\Gamma_0}{\Gamma_{\mathrm{NLO}}} + \mathrm{d}\sigma_0 \frac{\mathrm{d}\Gamma_1}{\Gamma_{\mathrm{NLO}}}$$

$$\int_{\mathrm{dec}} \mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1 - \mathrm{d}\sigma_1 \frac{\Gamma_1}{\Gamma_{\mathrm{NLO}}}$$

consistent [0907.3090]: $$\int_{\mathrm{dec}} \mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 \left[\left(1 - \frac{\Gamma_1}{\Gamma_0}\right)\int_{\mathrm{dec}} \frac{\mathrm{d}\Gamma_0}{\Gamma_0} + \int_{\mathrm{dec}} \frac{\mathrm{d}\Gamma_1}{\Gamma_0}\right] + \mathrm{d}\sigma_1 \int_{\mathrm{dec}} \frac{\mathrm{d}\Gamma_0}{\Gamma_0} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1$$

multi resonances: $$\mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right) \mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} - \left(\sum_{r\in\mathcal{R}} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) \mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{prod}\times\mathrm{dec}}$$

offshell → NLO+PS: $$\mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{off-shell}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right) \left[\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{off-shell}} - \left(\sum_{r\in\mathcal{R}} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) \mathrm{d}\sigma^{(0)}_{\mathrm{off-shell}}\right]$$

$$\delta\kappa^{t\bar{t}+X}_{\mathrm{spurious}} \simeq -2\,\frac{\mathrm{d}\sigma_1}{\mathrm{d}\sigma_0}\,\frac{\Gamma_{t,1}}{\Gamma_{t,0}}$$

17%

- last equation: used in new **`bb4l-dl/sl`** generators

Off-shell $t\bar{t}$ + tW: recent progress

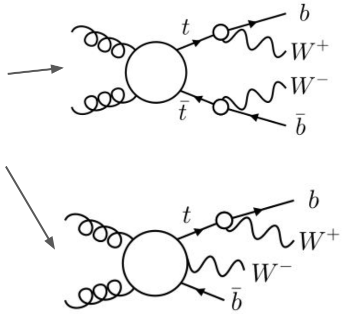
[Ježo,Lindert,Pozzorini 2307.15653]

2. improved resonance histories:

- original **bb4l**: {tt, Z}

- **bb4l-dl/sl**: {tt, tW$^+$, tW$^-$}
  → expect better treatment of "decay" emissions

resonance history	production subprocess
$t\bar{t}$	$pp \to t\bar{t}$
tW^-	$pp \to t\,W^-\bar{b}$
$\bar{t}W^+$	$pp \to \bar{t}\,W^+b$
Z	$pp \to Z/H + b\bar{b}$



- ME-based projectors:

$$\rho^{(\text{hist})}_{t\bar{t}}(\Phi_{\text{B}})\big|_{\text{ME}} = |\mathcal{A}_{t\bar{t}}|^2\,,$$

$$\rho^{(\text{hist})}_{\bar{t}W^+}(\Phi_{\text{B}})\big|_{\text{ME}} = |\mathcal{A}_{\bar{t}W^+}|^2$$

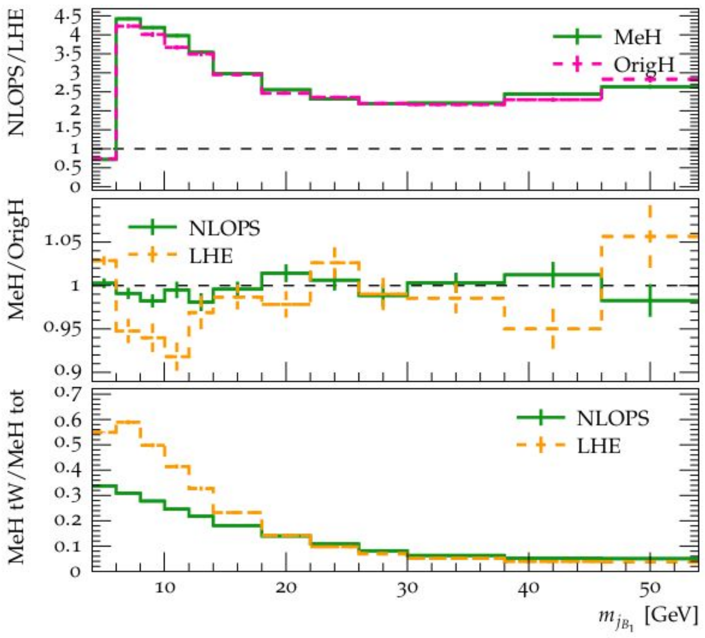
$$\rho^{(\text{hist})}_{tW^-}(\Phi_{\text{B}})\big|_{\text{ME}} = |\mathcal{A}_{tW^-}|^2$$

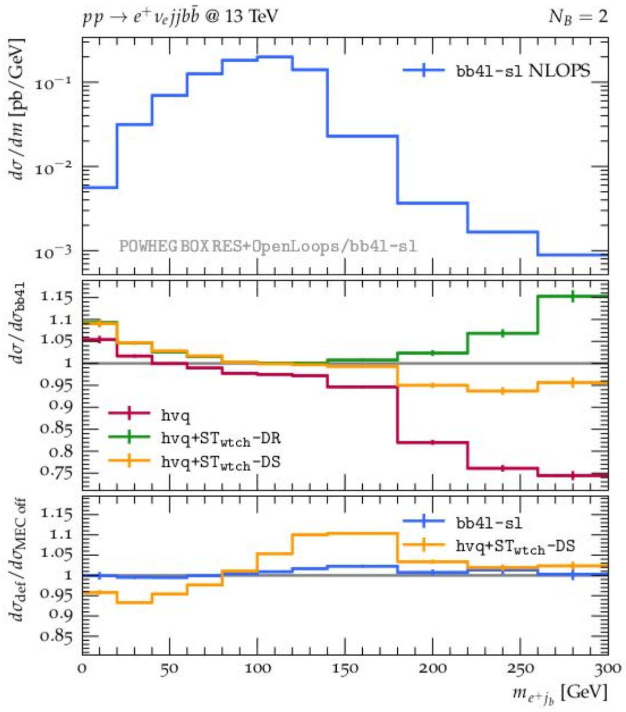
- several variations, new mappings, thorough validation

$$\sigma_{t\bar{t}} = \lim_{\xi_t \to 0}\left(\xi_t^2\, \sigma_{\text{bb4l}}\Big|_{\Gamma_t \to \xi_t \Gamma_t}\right)$$

Off-shell tt̄ + tW: results

[Ježo,Lindert,Pozzorini 2307.15653]





- LHS: resonance histories ambiguities (in off-shell regions*) → negligible after PS

- RHS: even when interference effects large, `hvq+wtch-DS` ≈ **`bb4l`**

- naive width → $\left.\frac{\sigma_{\mathtt{bb4l-sl}}}{\sigma_{\mathtt{hvq+ST}}}\right|_{\text{no } 1/\Gamma_t \text{ expansion}} = 1.074$

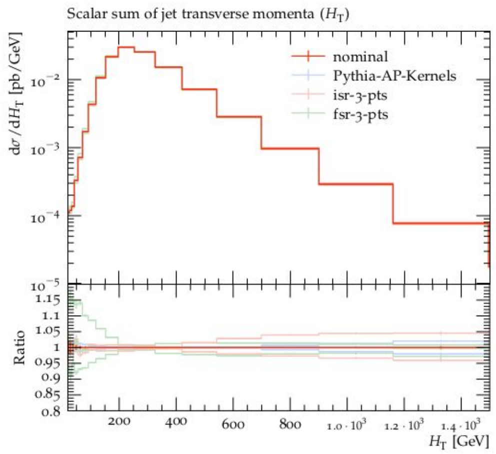
* $Q_{\text{off-shell}} = \max\left\{|Q_t - m_t|, |Q_{\bar{t}} - m_t|\right\} > 60\,\text{GeV}$

TH uncertainties in MC generators

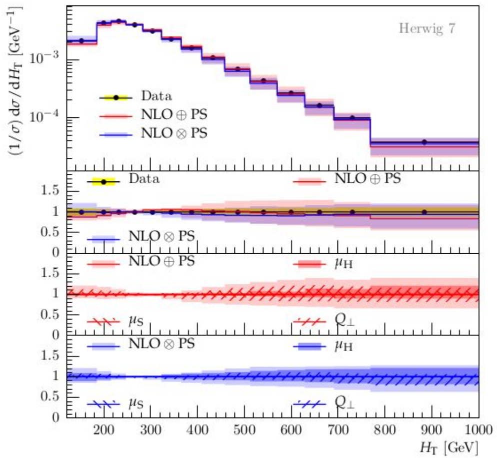
Possible TH uncertainties:

- scale variation (hard matrix elements)
- matching uncertainties (e.g. `hdamp` in POWHEG, hard veto scale in MC@NLO,...)
- change matching scheme / shower [e.g. Matchbox study, 1810.06493]
- other "shower-related" pQCD uncertainties can be probed
- recoil scheme
- ….
- non-perturbative parameters & tuning

- possible to include such variations (→certainly not the ultimate solution)
- within the current paradigms for matching & merging, rethinking needed for some of the above items, once matching to NLL parton showers will be achieved (`Panscales`, `Alaric`, FHP, ….)



[LH19 (2003.01700)]



[1810.06493]

Conclusions

- MC event generators play a role in ~ all EXP analysis
  - data to parton-level, background for BSM, measure parameters
- processes with top quarks: NNLO+PS available (with MiNNLOPS method), approximate decays
- full off-shell final state (leptons+jets): NLO+PS "resonance-aware" methods available

- full assessment of TH uncertainties missing (→ NLL showers will play crucial role)
- $t\bar{t}$+X: once NNLO known (exactly or approximately) → NNLO+PS possible

- Other approaches: `Geneva` for $t\bar{t}$….[2111.03632 (0-jettiness resummation)]

Thank you for your attention!

Backup slides

top pair-production @ NNLO+PS: MiNNLO for $t\bar{t}$

$$\frac{d\sigma}{d\vec{q}_\perp d\Phi_F} \sim \sum_f |M^{(0)}_{f\bar{f}\to t\bar{t}}|^2 \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{q}_\perp} e^{-R_f(b)} \mathrm{Tr}\left(\mathbf{H}_f \mathbf{\Delta}_{\mathrm{soft}}\right) \sum_{i,j} (C_{fi} \otimes h^{[i]})(C_{\bar{f}j} \otimes h^{[j]})$$

$$\mathrm{Tr}\left(\mathbf{H}_f \mathbf{\Delta}_{\mathrm{soft}}\right) = \frac{\langle M_{f\bar{f}} | \mathbf{\Delta} | M_{f\bar{f}} \rangle}{|M^{(0)}_{f\bar{f}}|^2}, \qquad \mathbf{\Delta} = \mathbf{V}^\dagger \mathbf{D} \mathbf{V}$$

- LL+NNLO accuracy: azimuthally averaged distribution becomes

$$\mathbf{V} = \mathcal{P} \exp\left\{ - \int_{\frac{b_0^2}{b^2}}^{M^2_{t\bar{t}}} \frac{dq^2}{q^2} \mathbf{\Gamma}_t(\Phi_{t\bar{t}}, \alpha_s(q)) \right\}$$

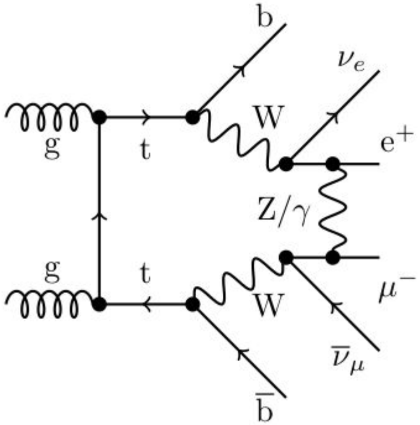
$$\left[\frac{d\sigma}{d\vec{q}_\perp d\Phi_F}\right]_\phi \sim \frac{d}{dq_\perp} \left[\sum_f e^{-S_f(q_\perp)} \langle M^{(0)}_{f\bar{f}} | (\mathbf{V}_{\mathrm{NLL}})^\dagger \mathbf{V}_{\mathrm{NLL}} | M^{(0)}_{f\bar{f}} \rangle [\mathrm{Tr}\left(\mathbf{H}_f \mathbf{D}_{\mathrm{soft}}\right) \sum_{i,j} (C_{fi} \otimes h^{[i]})(C_{\bar{f}j} \otimes h^{[j]})]_\phi \right]$$

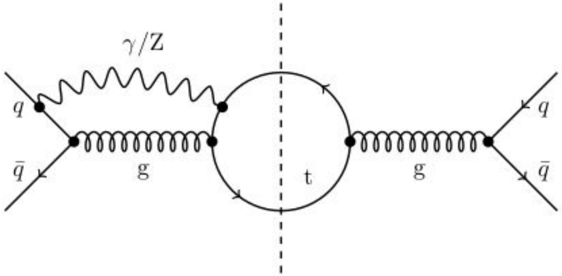
$$B(\alpha_s) = \frac{\alpha_s}{2\pi} B^{(1)} + \frac{\alpha_s^2}{(2\pi)^2} B^{(2)}$$

$$\sim \frac{\langle M^{(0)}_{f\bar{f}} | \mathbf{D}^{(1)} | M^{(0)}_{f\bar{f}} \rangle}{|M^{(0)}_{f\bar{f}}|^2} \left((C^{(1)}_{fi} \otimes f_i)(f_{\bar{f}}) \right)$$

- diagonalization of $\mathbf{V}_{\mathrm{NLL}}$ → recast as sum of “colour-singlet-like” terms

EW corrections: from total cross sections….



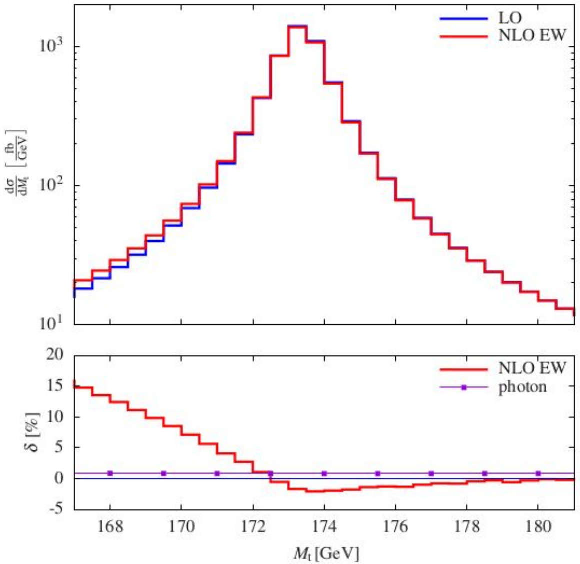


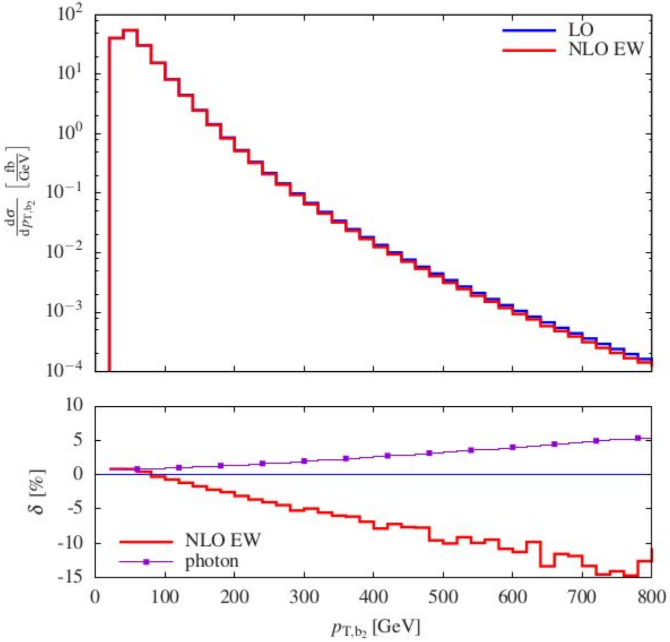
Ch.	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO\ EW}$ [fb]	δ [%]
gg	2824.2(2)	2834.2(3)	0.35
$q\bar{q}$	375.29(1)	377.18(6)	0.50
$gq(/\bar{q})$		0.259(4)	
γg		27.930(1)	
pp	3199.5(2)	3211.7(3)	0.38

- fully exclusive results (2 lep channel)
- NLO EW = $O(\alpha_s^2\ \alpha^5)$
- total x-section: EW corrections < 1%
- no uncertainty on EW corrections
  (but irrelevant for total x-section)

[Denner,Pellen ‘16]

….to differential distributions

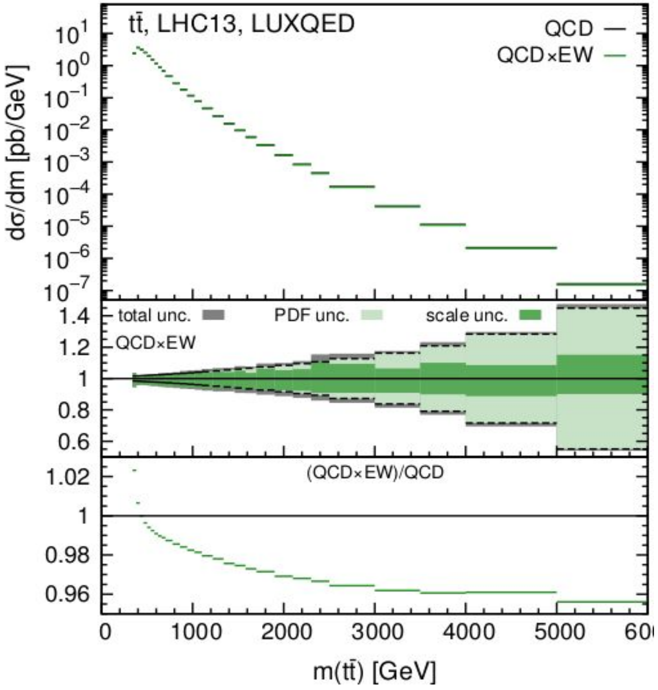




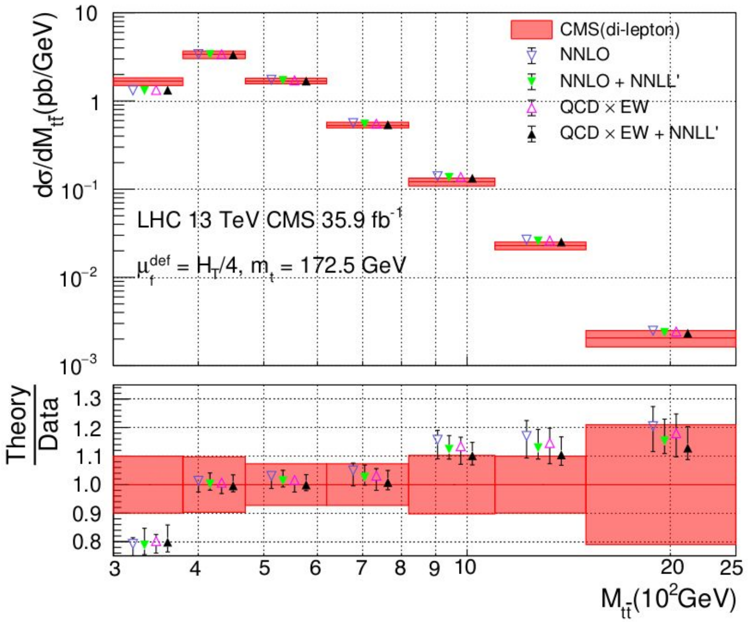
- corrections ~ 10-15 % (radiative tails (left) / Sudakov logs (right))
- here: no approximations. Possible to study “DP approximations” for tops or Ws.
- scales fixed at top mass (enter in α_s & PDFs)
- TH uncertainties: needed? Uncharted territory: change of scheme (?),...

EW and QCD combined results

[1705.04105]



[1901.08281]

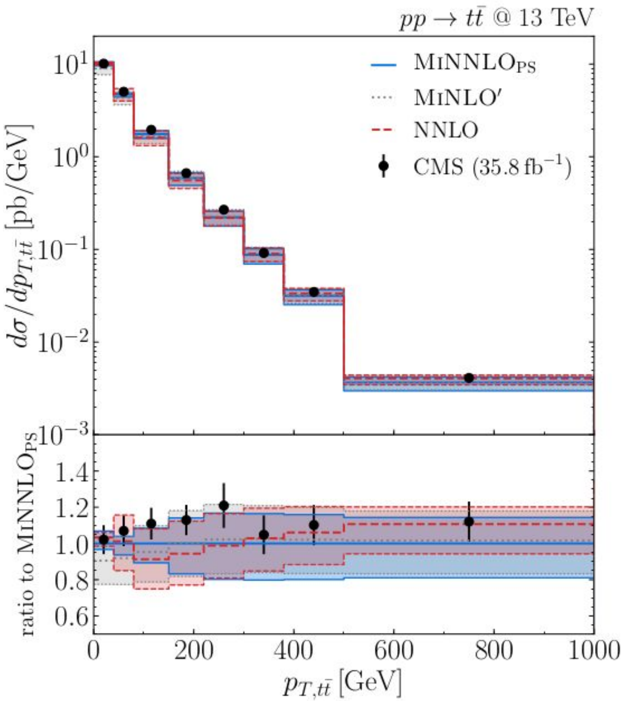


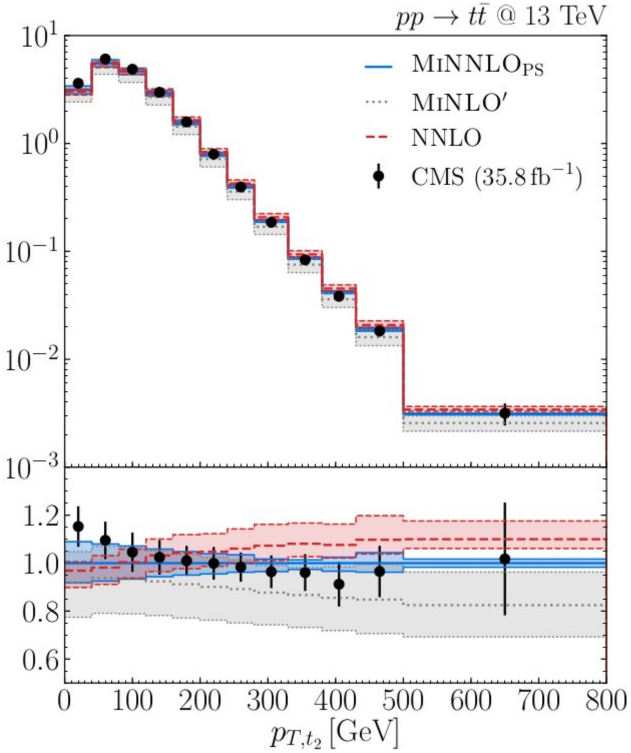
$$\Sigma_{\mathrm{QCD}\times\mathrm{EW}} \equiv \Sigma_{\mathrm{QCD+EW}} + (K^{\mathrm{NLO}}_{\mathrm{QCD}} - 1) \times \Sigma_{\mathrm{NLO\ EW}}$$

preferred combination: multiplicative ⇒

- stabilize scale uncertainty of $\Sigma_{\mathrm{NLO\ EW}} = O(\alpha_s^2\,\alpha)$
- $\Sigma_{\mathrm{mixed}} = O(\alpha_s^3\,\alpha) \approx \Sigma_{\mathrm{NLO\ QCD}}\,\Sigma_{\mathrm{NLO\ EW}} / \Sigma_{\mathrm{LO\ QCD}}$
- correct in regime “soft gluon” + “Sudakov log”

top pair-production @ NNLO+PS: results III





- nice agreement with NNLO (and with data - both ATLAS and CMS). $\mu_{core} = H_T/4$

Resonant-aware NLO+PS: details I

1. complete matrix elements for $W^+W^-b\bar{b}$: need to project each partonic subprocess onto all possible "resonance histories":
   - each contribution should be dominated by a single resonance history:

$$B = \sum_{f_b} B_{f_b}, \quad \text{where} \quad B_{f_b} \equiv \frac{P^{f_b}(\Phi_B)}{\sum_{f'_b} P^{f'_b}(\Phi_B)} B(\Phi_B)$$

$P^{f_b}(\Phi_B)$ (products of) Breit-Wigner functions $\Leftrightarrow$ resonance history f_b

   - for real contributions, split also according to compatible FKS regions

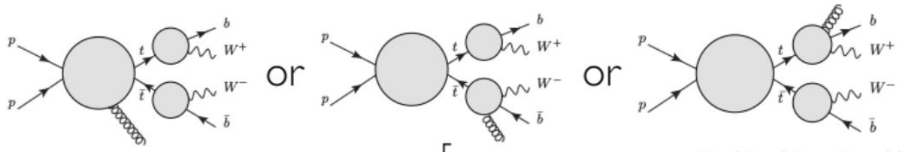
     $\Rightarrow$ a term R_{α_r} is dominant if the collinear partons of region α_r have the smallest k_T, and the corresponding resonance history is the closest to its mass shell.

2. each term (Born-like and real) is attributed to an unique resonance history
   - virtuality-preserving mappings between Φ_B and $(\Phi_B, \Phi_{\mathrm{rad}})$ can be used
   - POWHEG radiation(s) can now be assigned to a resonance
   - (& other technical but crucial subtleties...)

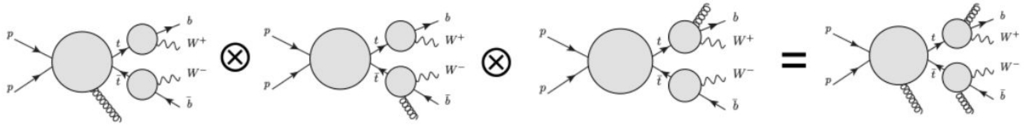
Resonant-aware NLO+PS: details II

"multiplicative POWHEG": keep multiple emissions before showering [☜]

- by default POWHEG is additive: keeps only the hardest emission
- keep hard radiation and the emissions from all decaying resonances, then merge them into a single radiation phase space with several radiated partons, up to one for each resonance



$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\rm cut}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\rm rad}))}{B(\Phi_B)}\, d\Phi_{\rm rad} \right]$$



$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \prod_{\alpha=\alpha_b,\alpha_{\bar b},\alpha_{\rm ISR}} \left[\Delta_\alpha(q_{\rm cut}) + \Delta_\alpha(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi^\alpha_{\rm rad}))}{B(\Phi_B)}\, d\Phi^\alpha_{\rm rad} \right]$$

- in the above case, the interface to parton shower becomes more complicated.

TH uncertainties in MC generators: looking ahead

- plots from: [Hamilton et al. 2301.09645]
- thrust in e^+e^-: NLO+PS multiplicative matching + NLL shower

- dots: modified splitting function in hard region
- dashes: μ_R scale variation (also in hard matrix elements)

- here matching fulfils NNDL accuracy (i.e. the same accuracy of a NLL resummation matched with NLO)

$$\Sigma(O < e^L) = h_1(\alpha_s L^2) + \sqrt{\alpha_s}\, h_2(\alpha_s L^2) + \alpha_s h_3(\alpha_s L^2) + \ldots$$