NLO+PS predictions for top-pair and Wt production and decay

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work in collaboration with:

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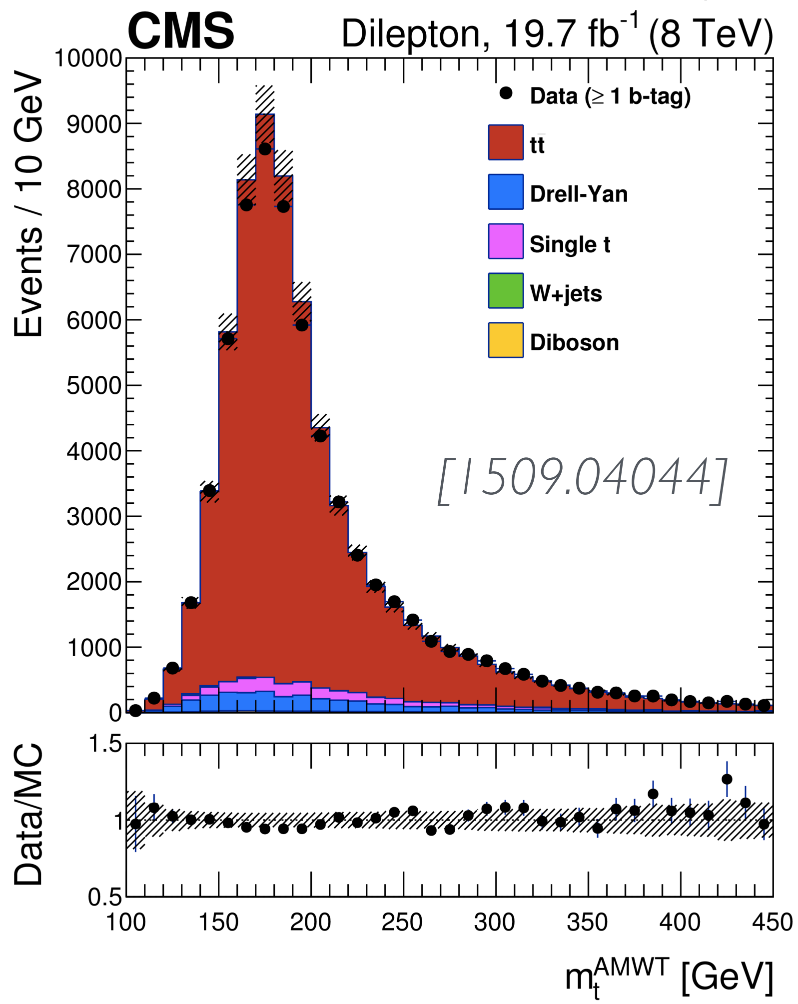
based on [Ježo, Nason; '15] & [Ježo, JML, Nason, Oleari, Pozzorini; '16]

DESY Theory Workshop

DESY, Hamburg, 29th September 2016

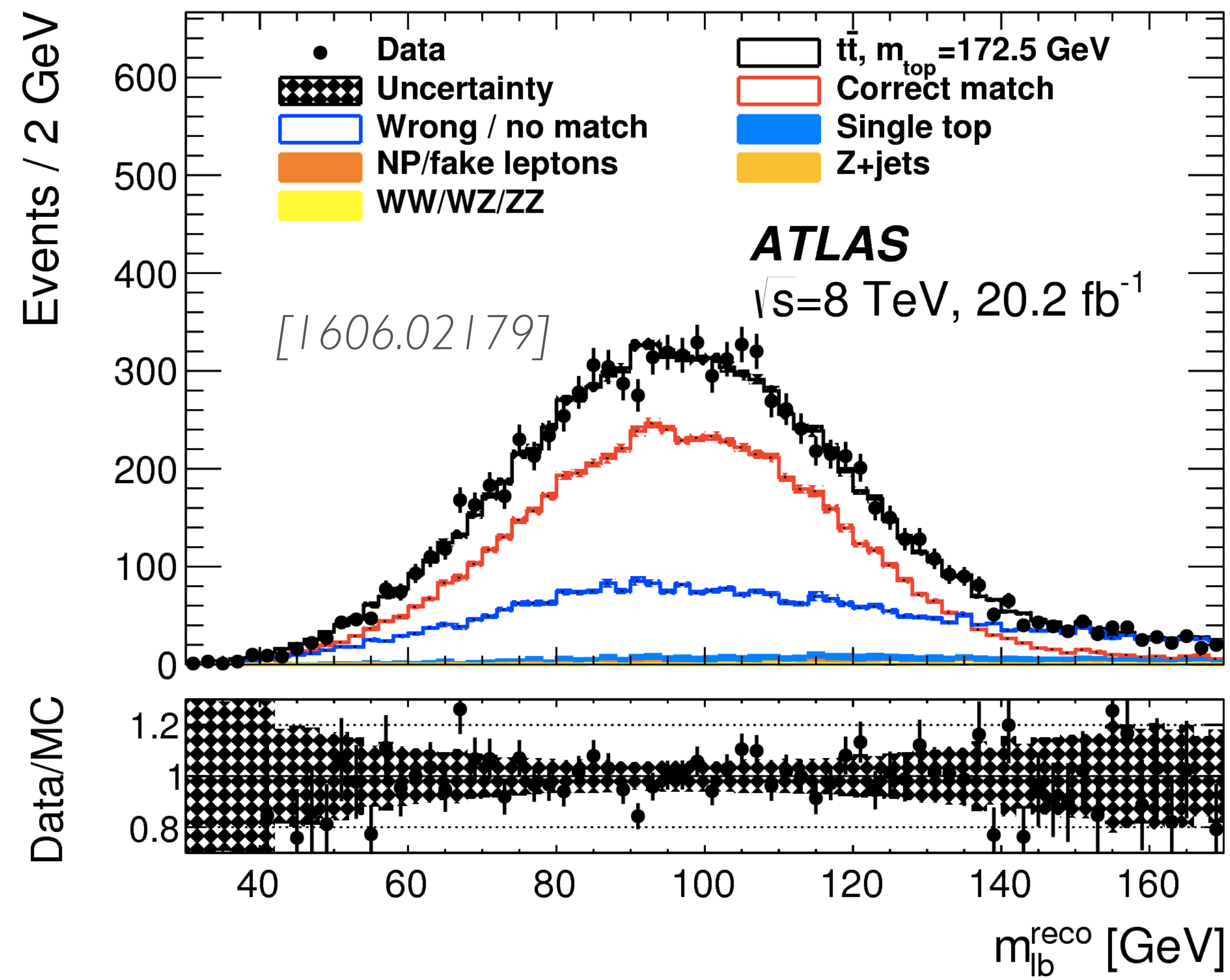
precision top-quark mass measurements rely on Monte Carlo modelling

via reconstruction using analytical distributions derived from simulated samples



mtop = 172.82 ± 0.19 (stat) ± 1.22 (syst) GeV

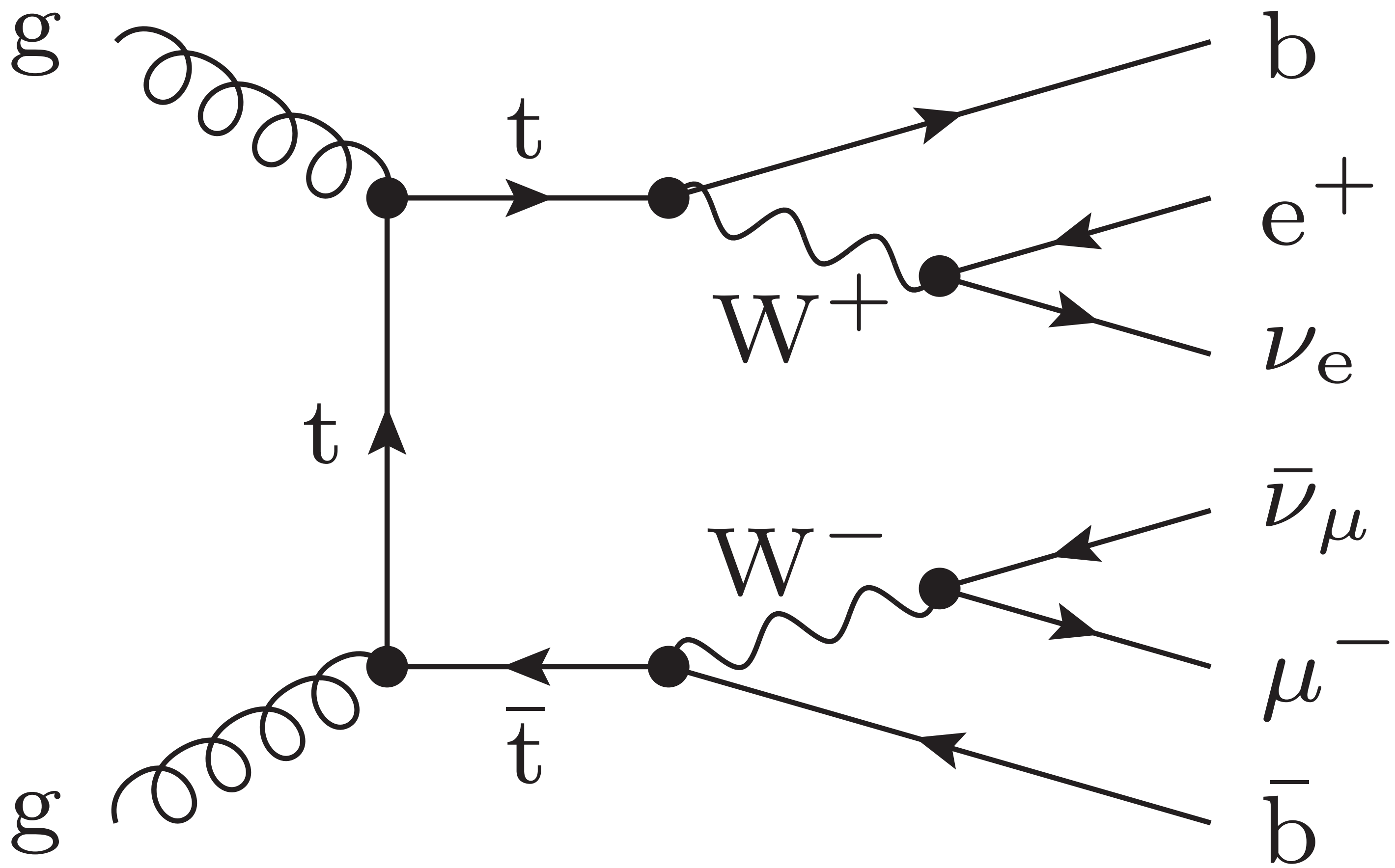
via template fit of lepton-b-jet invariant mass



mtop = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV

- these kinematic measurements strongly rely on MC modelling!

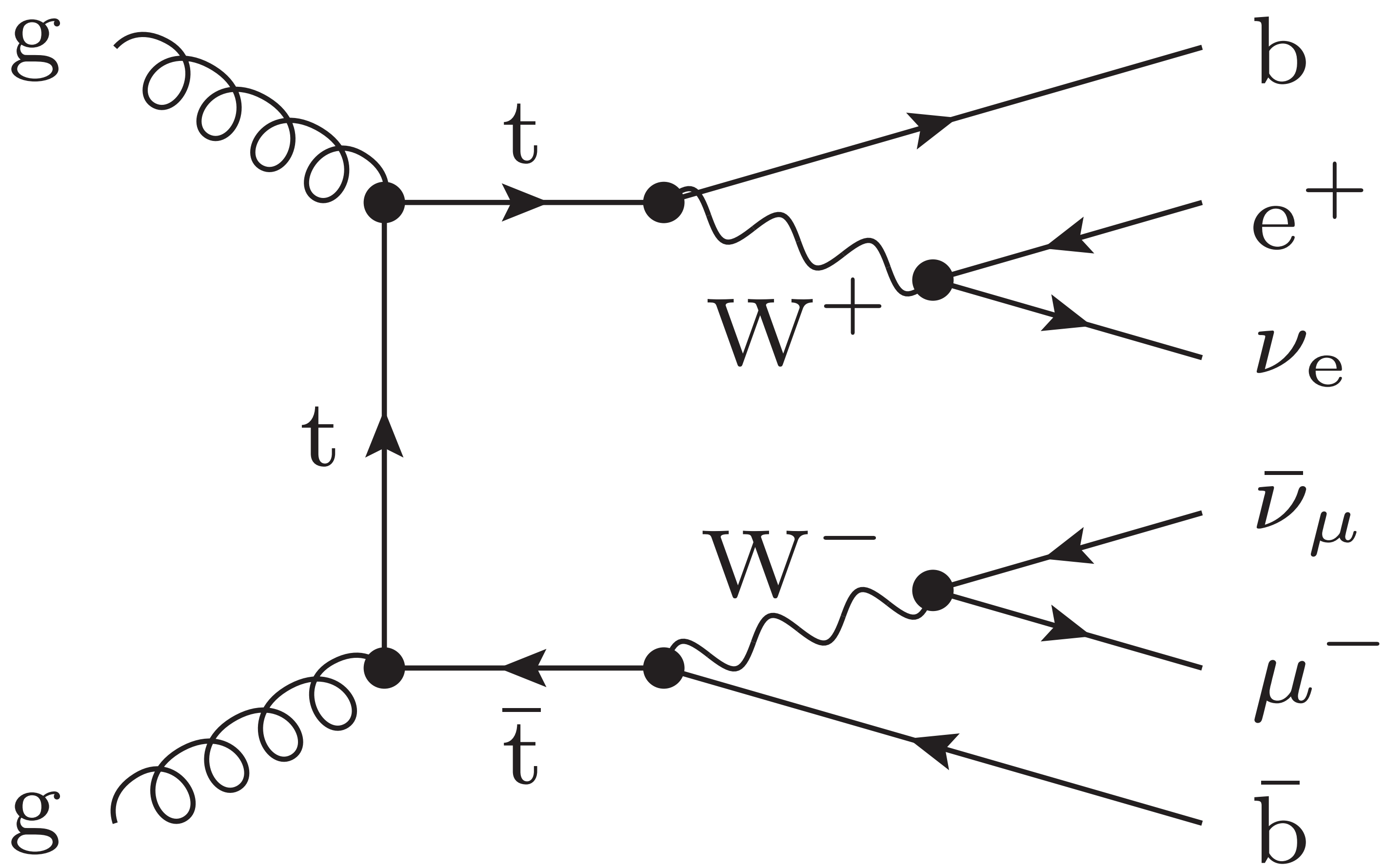
top-pair production and decay



@ NLO

NLO QCD 5FS: *[Bevilacqua, Czakon, van. Hameren, Papadopoulos, Worek; '11]*
[Denner, Dittmaier, Kallweit, Pozzorini; '11+'12] [Heinrich, Maier, Nisius, Schlenk, Winter; '14]
4FS: *[Frederix '14] [Cascioli, Kallweit, Maierhöfer, Pozzorini; '14]*
NLO EW 5FS: *[Denner, Pellen '16]*

top-pair production and decay



@ NLO+PS

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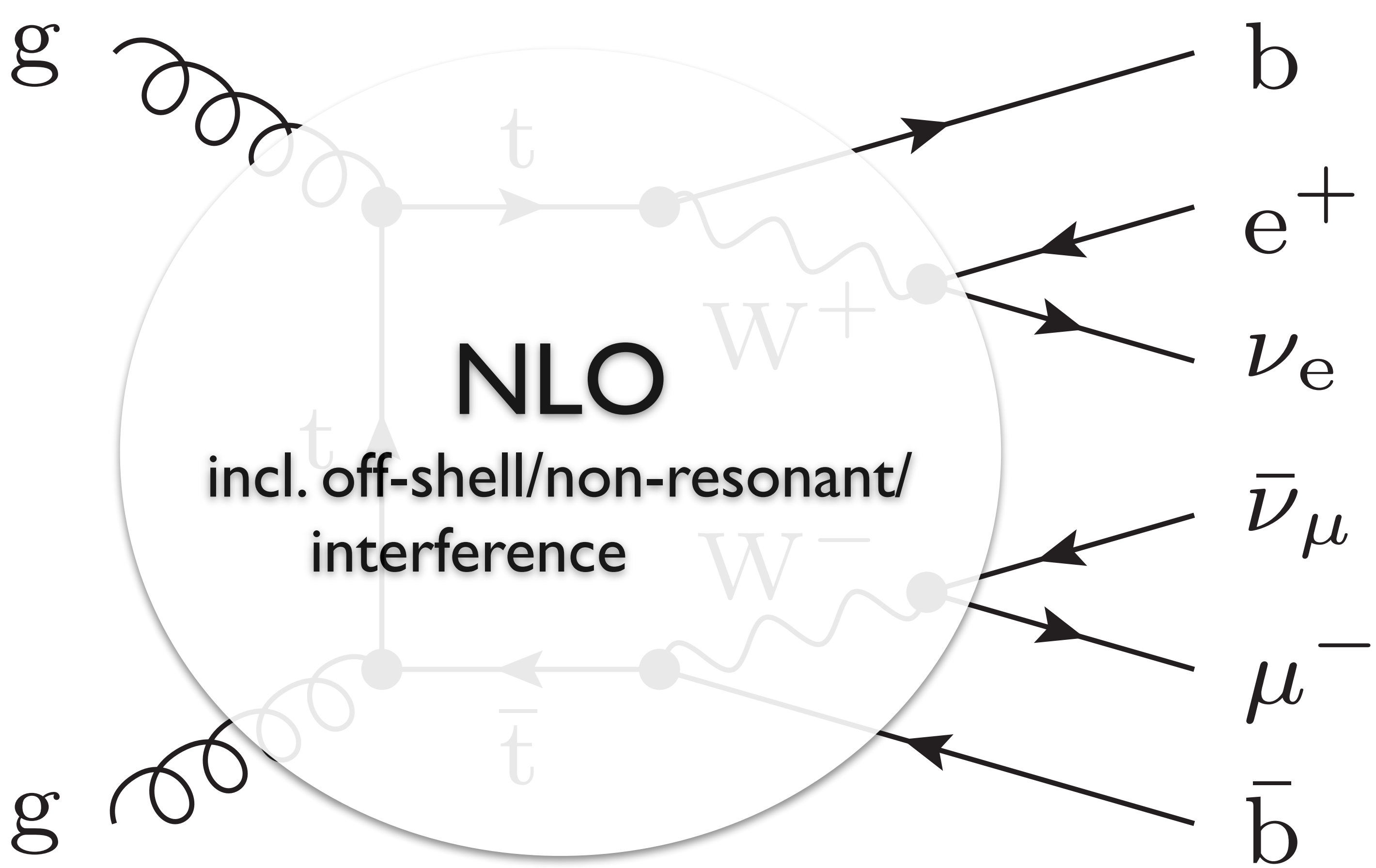
NLO QCD+PS 5FS: *[Garzelli, Kardos, Trocsanyi; '14]*

top-pair production and decay



@ NLO+PS

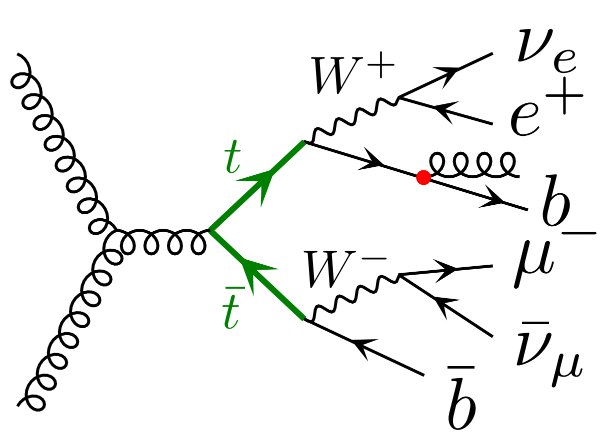
- In a traditional off-shell NLO+PS calculation:
  subtraction, matching and PS do not see/preserve intermediate resonances
  - ➡ **NLO**: efficiency problem
  - ➡ **NLO+PS**: distortion of important kinematic shapes!

Problem in POWHEG language

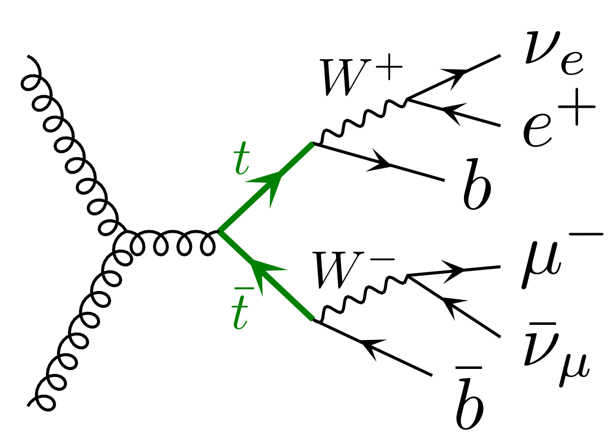
- **Efficiency problem at NLO**:
  - FKS subtraction (and similar CS) does not preserve virtuality of intermediate resonances
  - i.e. Real (R) and Subtraction-term (S~B) with different virtualities of intermediate resonances

$$(\Phi_{\mathrm{B}}, \Phi_{\mathrm{rad}}) \xleftrightarrow{\text{FKS}} \Phi_{\mathrm{R}}$$

$$\Phi_{\mathrm{R}} = \text{real phase-space}$$
$$\Phi_{\mathrm{B}} = \text{(underlying) Born phase-space}$$
$$\Phi_{\mathrm{rad}} = \text{radiation phase-space}$$



R ⟹ B



  - IR cancellation spoiled

$\Longrightarrow$ **severe efficiency problem for narrow resonances!**

Problem in POWHEG language

- **Fundamental problems at NLO+PS**:
  - **NLO+PS** matching according to POWHEG formula:

$$d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left\{ \Delta(q_{\text{cut}}) + \Delta(k_T) \frac{R(\Phi_R(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)}\, d\Phi_{\text{rad}} \right\}$$

$$\bar{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int R(\Phi_R(\Phi_B\,, \Phi_{\text{rad}}))\, d\Phi_{\text{rad}}$$

$$\Delta(q) = \exp\left[- \int_{k_T > q} \frac{R(\Phi_R(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)}\, d\Phi_{\text{rad}} \right]$$

➡ FKS mappings $(\Phi_B, \Phi_{\text{rad}}) \overset{\text{FKS}}{\longleftrightarrow} \Phi_R$ do not preserve intermediate resonances

➡ **R/B** might become large by coincidence (e.g. R on-peak, B off-peak), but should be small (of the order of α_S) or approach Altarelli-Parisi splitting functions.

➡ Radiation (incl. Sudakov form-factor) generated from uncontrollable **R/B** ratios

  - also subsequent radiation by the **PS** itself reshuffles internal momenta and does in general not preserve the virtuality of intermediate resonances.

$\Longrightarrow$ **expect uncontrollable distortion of important kinematic shapes!**

Resonance aware POWHEG

Rigorous solution to all these issues within POWHEG according to *[Ježo, Nason; '15]*

Idea: ***preserve invariant mass of intermediate resonances at all stages!***

✓ **NLO**:

- Split phase-space integration into regions dominated by a single **resonance history**
- within a given resonance history **modify FKS mappings**, such that they *always* preserve intermediate resonances

$$(\Phi_\mathrm{B}, \Phi_\mathrm{rad}) \overset{\mathrm{RES\ FKS}}{\longleftrightarrow} \Phi_\mathrm{R}$$

⟹ R and S~B *by construction* with same virtuality of intermediate resonances

⟹ **IR cancellation restored**

✓ **NLO+PS**:

- R and B related via resonance-aware FKS mappings

⟹ **R/B** ratio with fixed virtuality of intermediate resonances

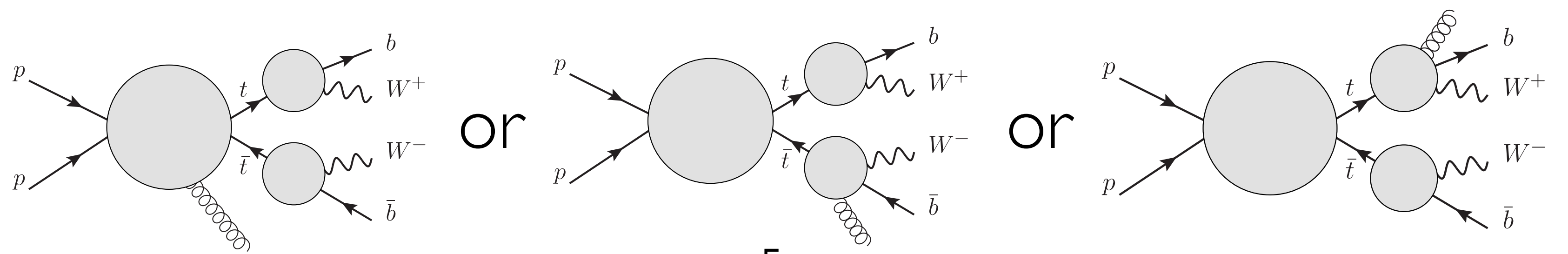
⟹ **Sudakov form-factor preserves intermediate resonances**

✓ **PS**:

- pass information about resonance histories to the shower (via extension of LHE)
- tell **PS to respect intermediate resonances** (available in Pythia8)

Multiple-radiation scheme

- In traditional approach only hardest radiation is generated by POWHEG:

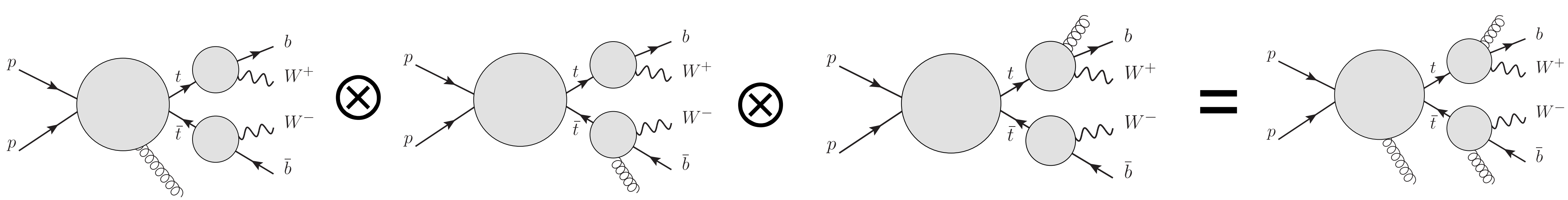


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \left[\Delta(q_{\rm cut}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{\rm B}, \Phi_{\rm rad}))}{B(\Phi_{\rm B})}\, d\Phi_{\rm rad} \right]$$

BUT: for top-pair (or single-top) production and decay, emission from production is almost always the hardest.

➡ emission off decays are mostly generated by the shower.

- **Multiple-radiation scheme**: . *introduced in [Campbell, Ellis, Nason, Re; '15]*
  - keep hardest emission from all resonance histories.
  - merge emissions into a single radiation event with several radiated partons

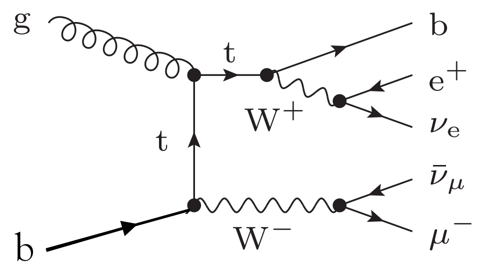


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \prod_{\alpha=\alpha_b, \alpha_{\bar{b}}, \alpha_{\rm ISR}} \left[\Delta_{\alpha}(q_{\rm cut}) + \Delta_{\alpha}(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{\rm B}, \Phi_{\rm rad}^{\alpha}))}{B(\Phi_{\rm B})}\, d\Phi_{\rm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

Interplay between top-pair and Wt single-top production

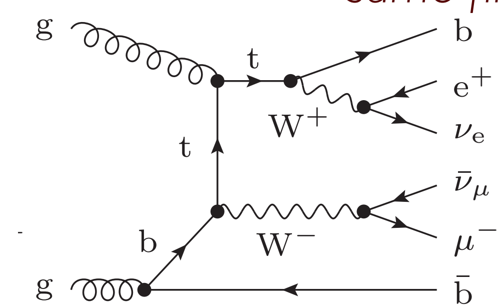
5FS

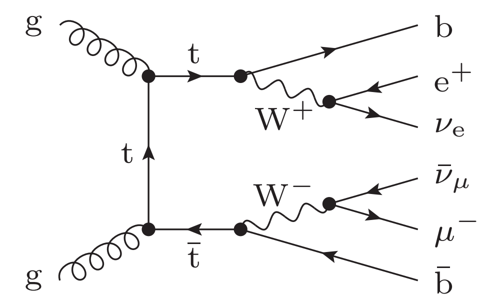
LO



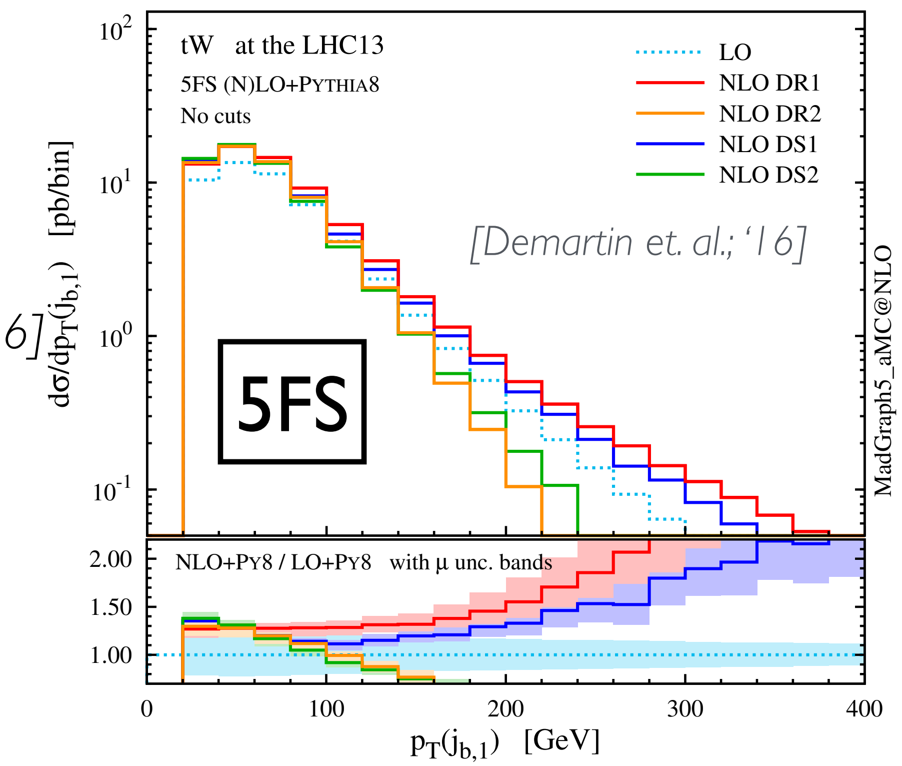
NLO

same finale state!



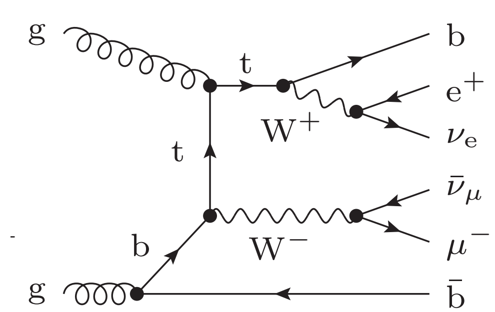


- NLO corrections to Wt swamped by LO $t\bar{t}$+decay
- requires ad-hoc subtraction prescription: DRI, DRII, DSI, DSII
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

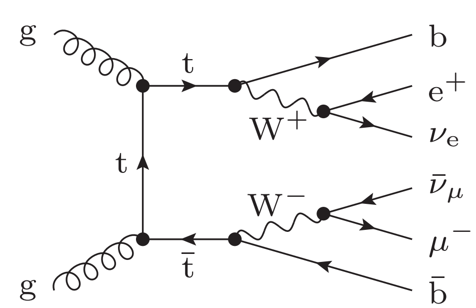


4FS

LO



Wt



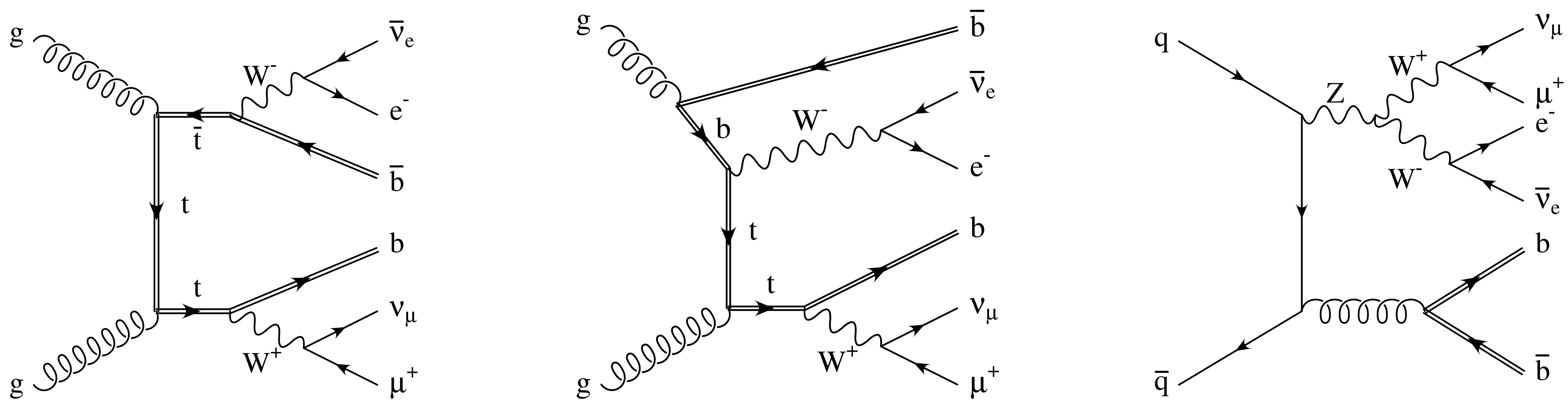
$t\bar{t}$

same finale state!

- **unified treatment of top-pair and Wt including interference**
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

The new $b\bar{b}4l$ generator

- We consider the full process $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ with massive b's (**4FS scheme**)
- Implemented in the **POWHEG-BOX-RES** framework
- All matrix elements from **OpenLoops** *[Cascioli, JML, Maierhöfer, Pozzorini]*

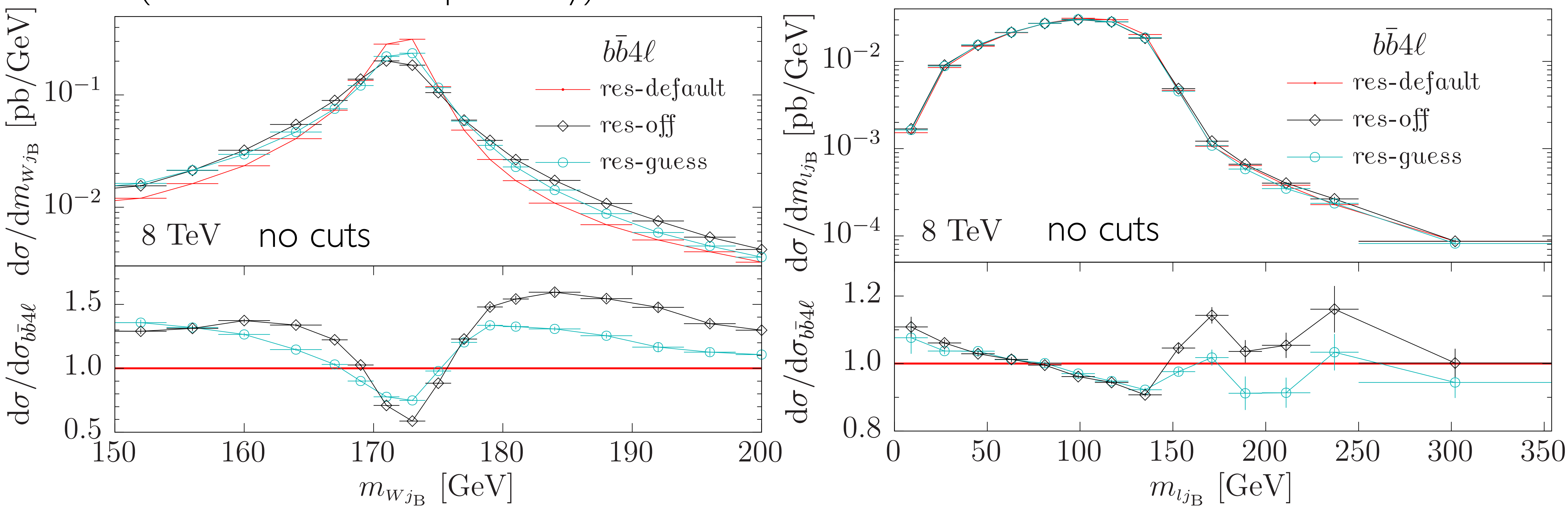


Physics features:

- exact **non-resonant** / **off-shell** / **interference** / **spin-correlation** effects at NLO
- unified treatment of **top-pair and Wt** production with interference at NLO
- access to phase-space regions with **unresolved b-quarks** and/or jet vetoes
- **consistent NLO+PS treatment of top resonances,** including quantum corrections to top propagators and off-shell top-decay chains

Results: top-resonance

- default: resonance aware matching & multiple-radiation scheme
- off: resonance unaware matching
- guess: resonance unaware matching but kinematic guess off resonance structure before PS (based on kinematic proximity)



⟹ resonance unaware matching yields distortions of important kinematic shapes

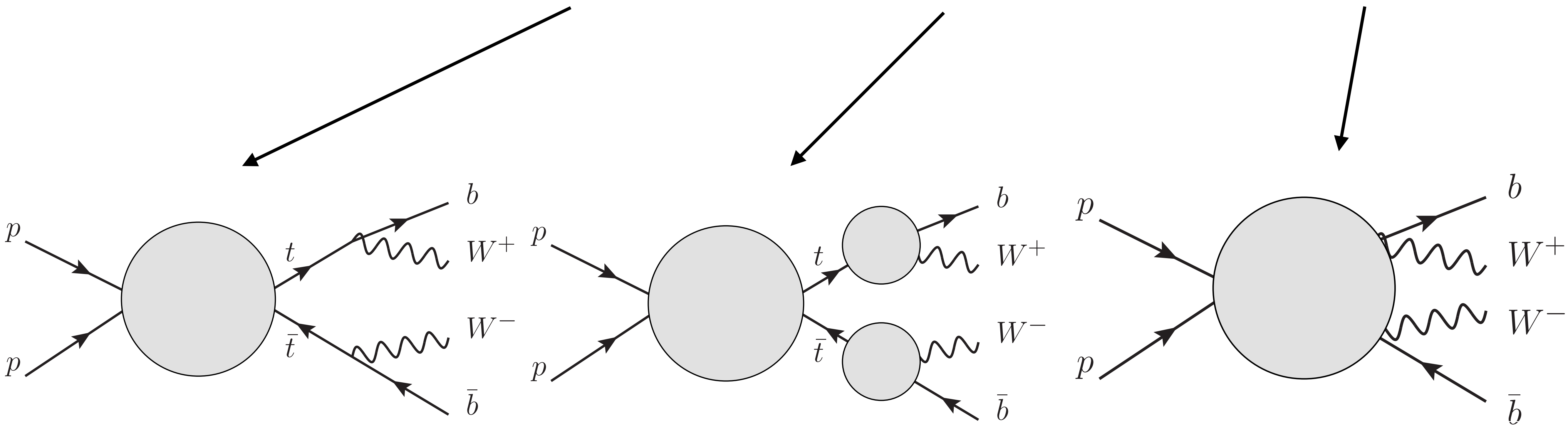
⟹ control of these shapes crucial for **precise top-mass measurements!**

⟹ resonance assignment based on kinematic proximity with standard matching not sufficient

Top-pair production in POWHEG

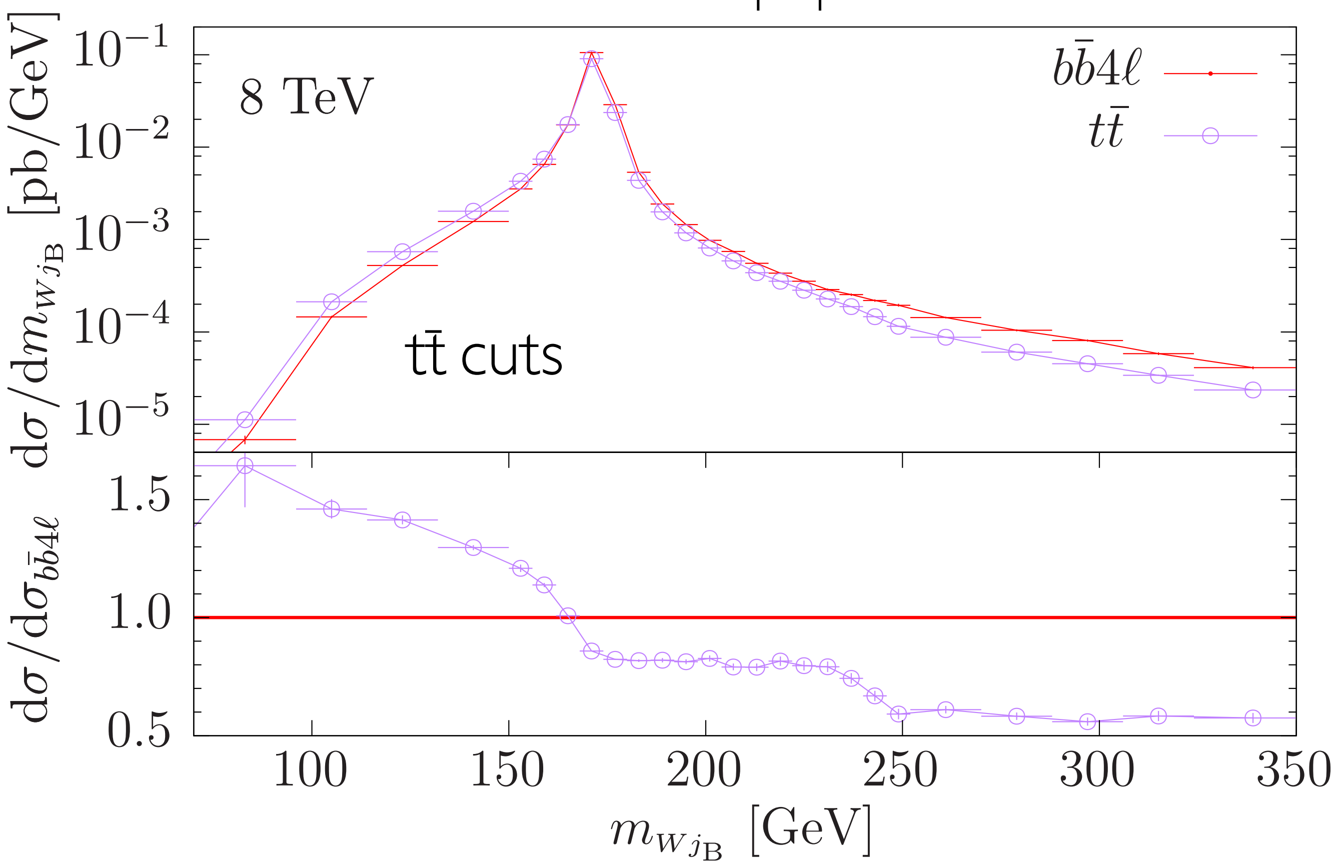
label	$t\bar{t}$ NLOPS	$t\bar{t}$+decay NLOPS	$b\bar{b}4\ell$ NLOPS-RES
NLO matrix elements	$\mathrm{t\bar{t}}$	$\mathrm{t}(\to \mathrm{e}^+\nu_\mathrm{e}\mathrm{b})\bar{\mathrm{t}}(\to \mu^-\bar{\nu}_\mu\bar{\mathrm{b}})$	$\mathrm{b\bar{b}e^+}\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$
decay accuracy	LO+PS	NLO+PS	NLO+PS
NLO radiation	single	multiple	multiple
spin correlations	approx.	exact	exact
off-shell $t\bar{t}$ effects	BW smearing	LO $\mathrm{b\bar{b}}4\ell$ reweighting	exact
Wt & non-resonant effects	no	LO $\mathrm{b\bar{b}}4\ell$ reweighting	exact

. [Frixione, Nason, Ridolfi; '07] *[Campbell, Ellis, Nason, Re; '15]* *[Ježo, JML, Nason, Oleari, Pozzorini; '16]*

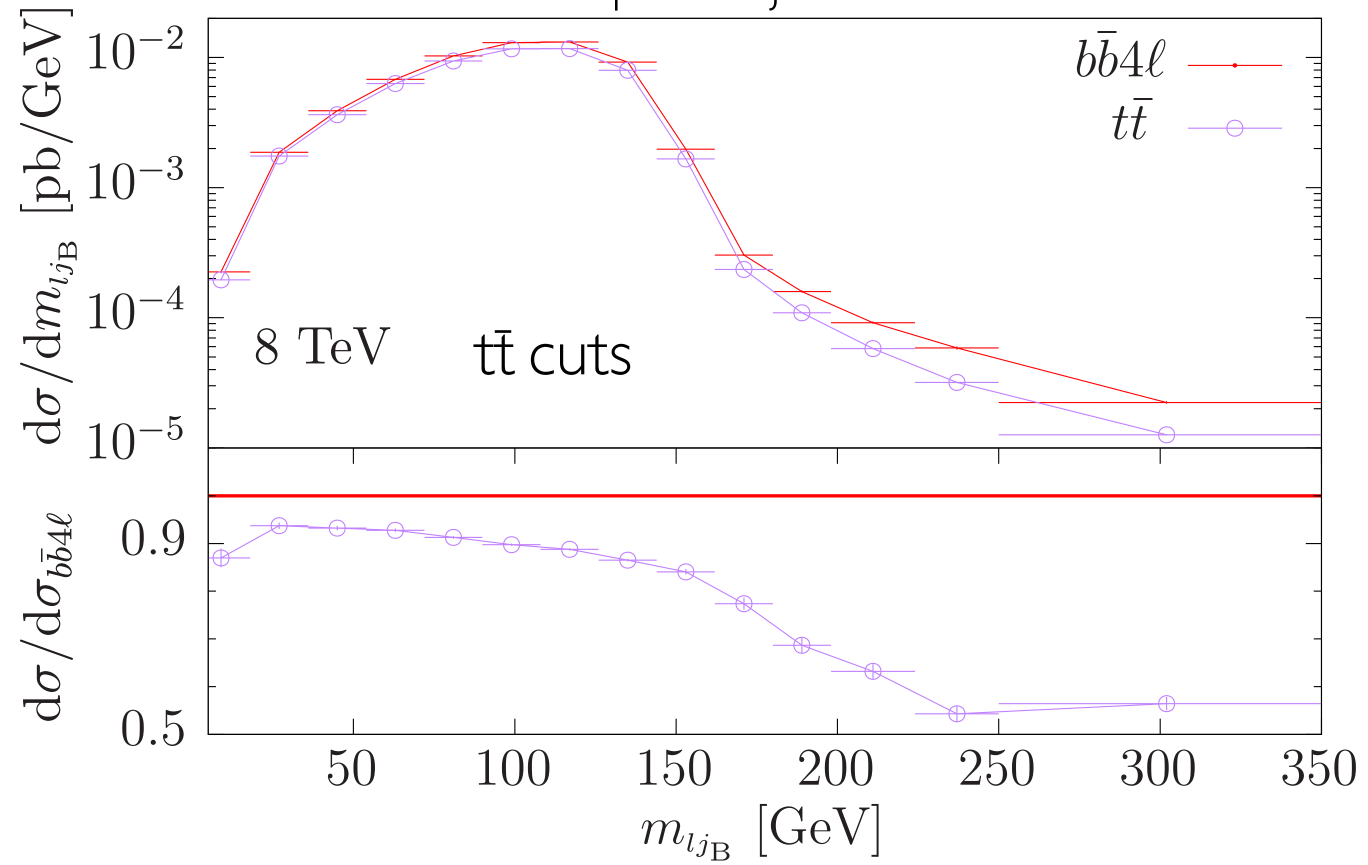


Results: on-shell tt̄ vs. bb4l

reconstructed top-quark mass

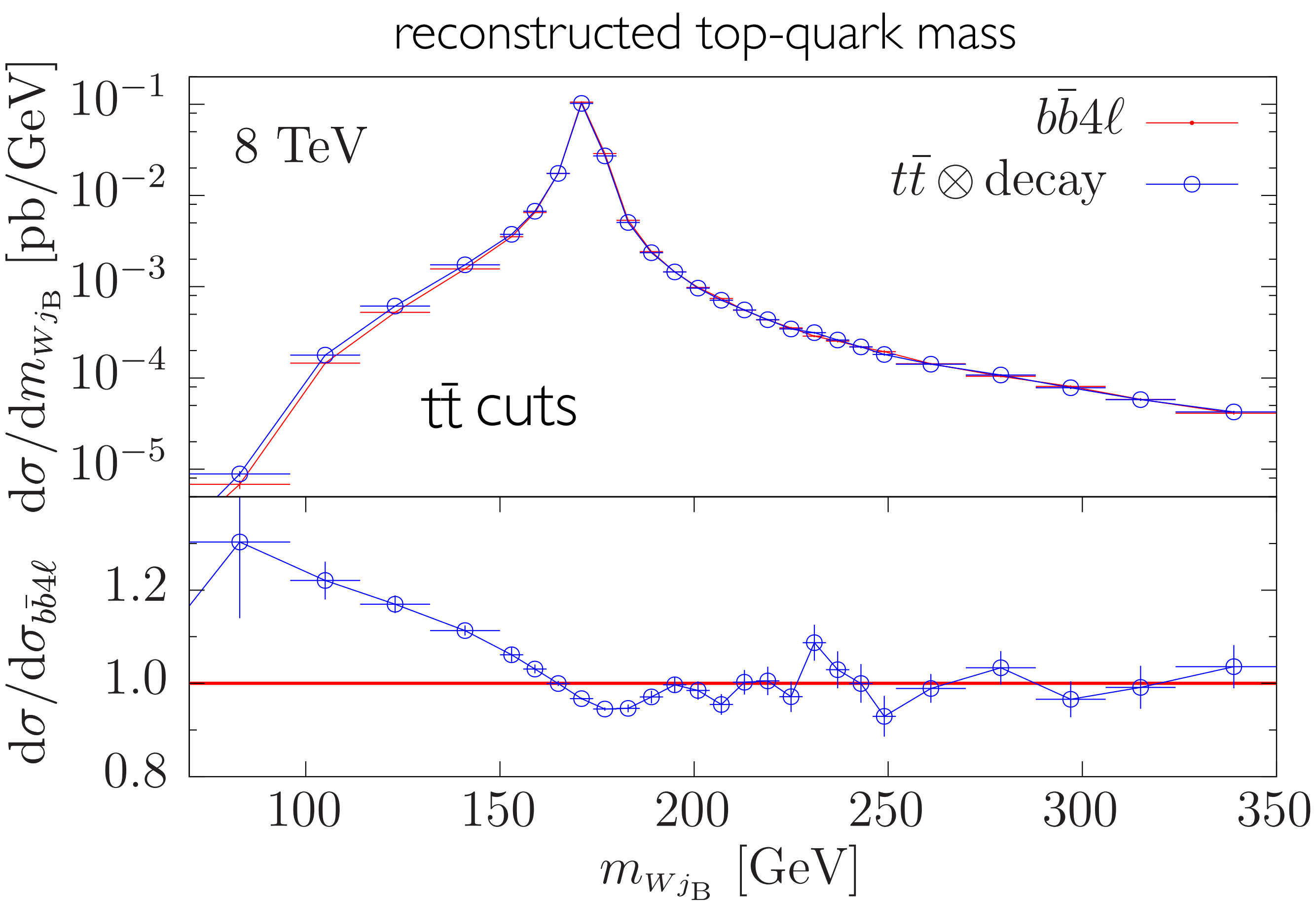


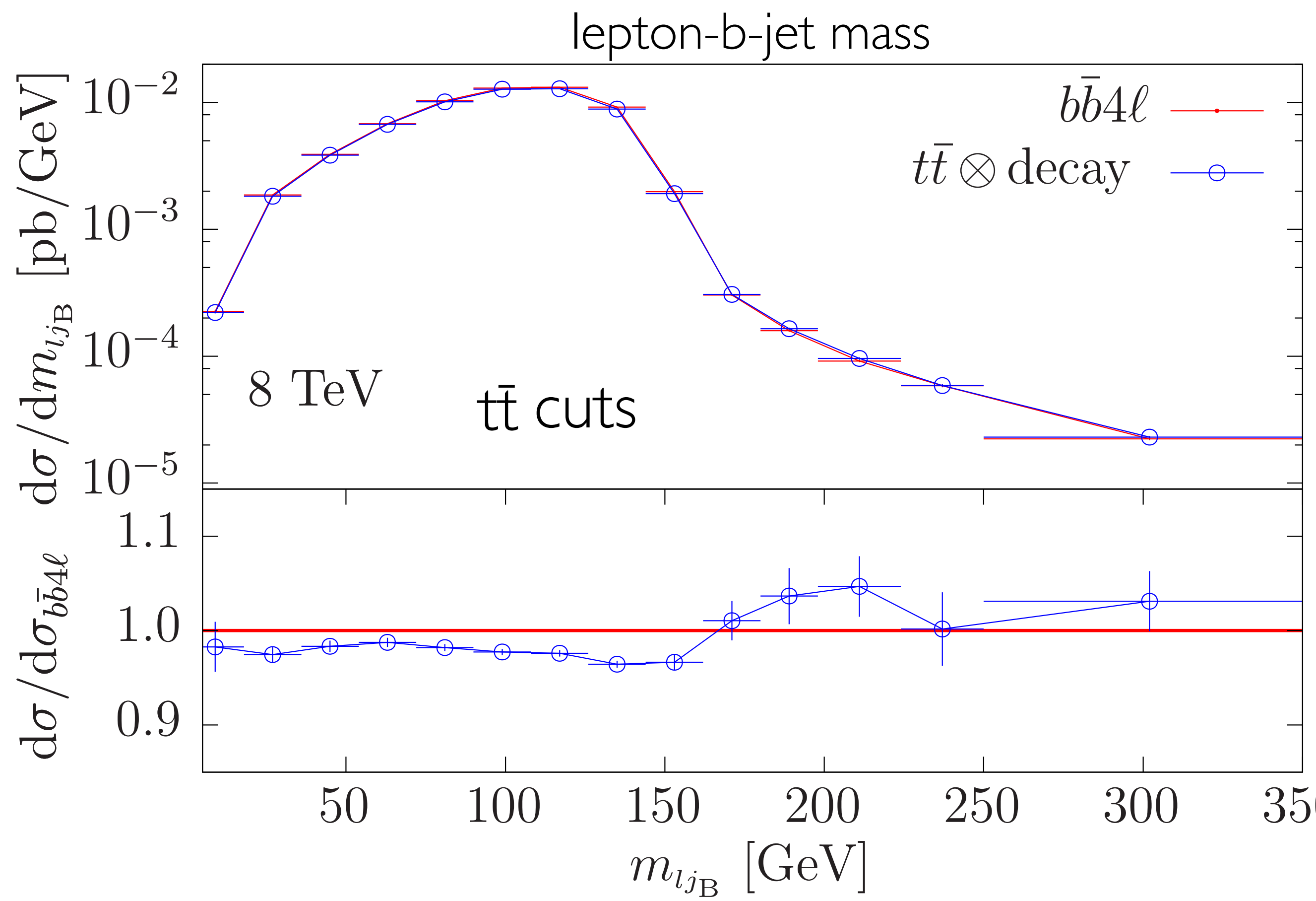
lepton-b-jet mass



- significant shape distortions around resonance with respect to on-shell calculation
- very relevant for top mass determination
- average m_{Wj_B} roughly 500 MeV smaller in on-shell tt̄ (in ±30 GeV around mtop)
- ~20-30% effects around the b-jet-lepton invariant mass edge

Results: tt̄⊗decay vs. bb4l



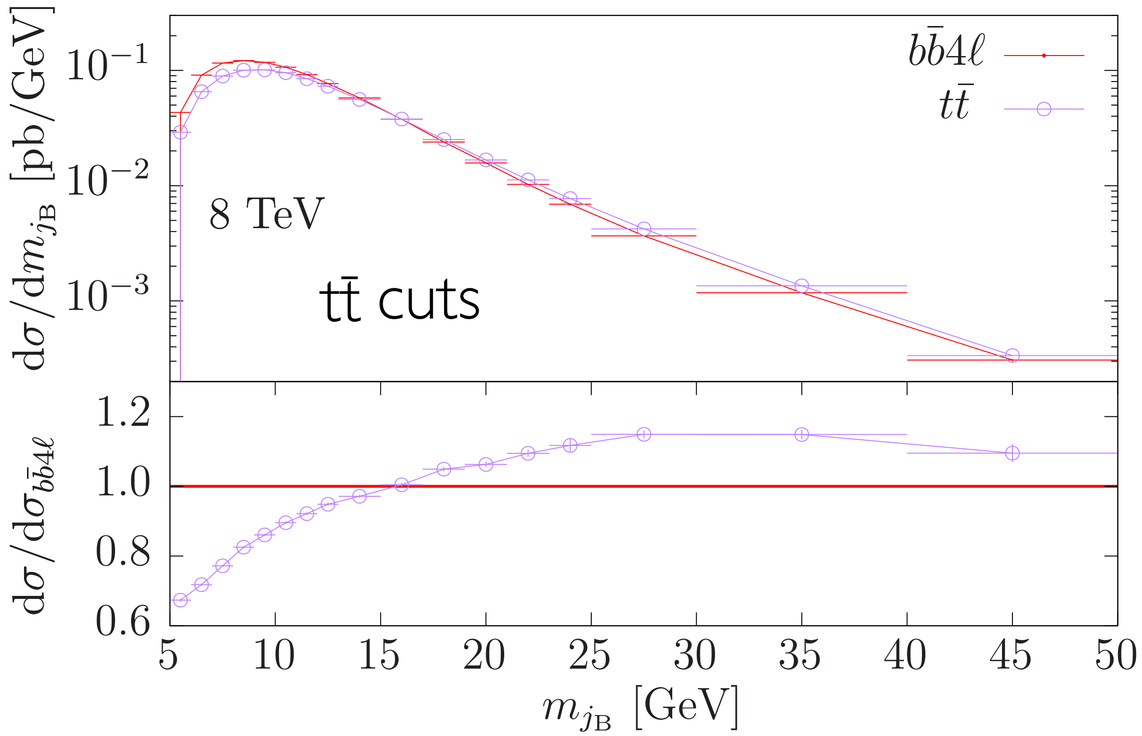


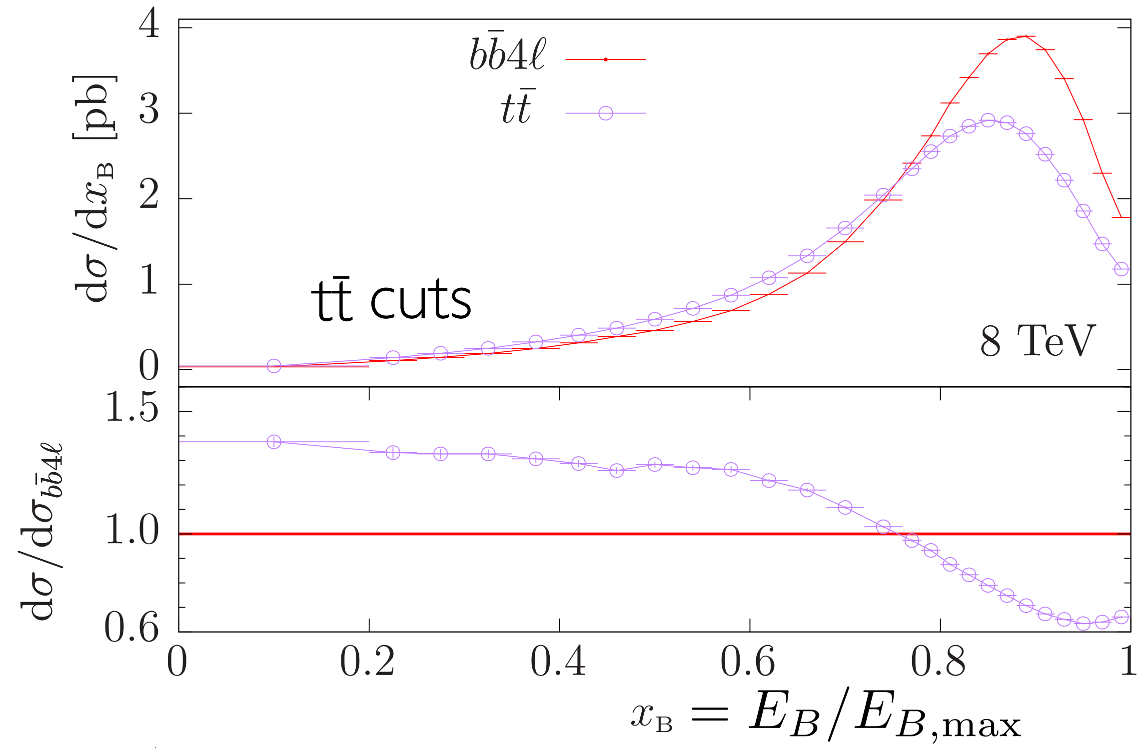
- very good agreement mostly <5% level between the two predictions
- the two calculations support each other (natural factorization of radiation between production and decay in tt⊗decay)
- average m_{Wj_B} roughly 100 MeV smaller in tt⊗decay (in ±30 GeV around mtop)

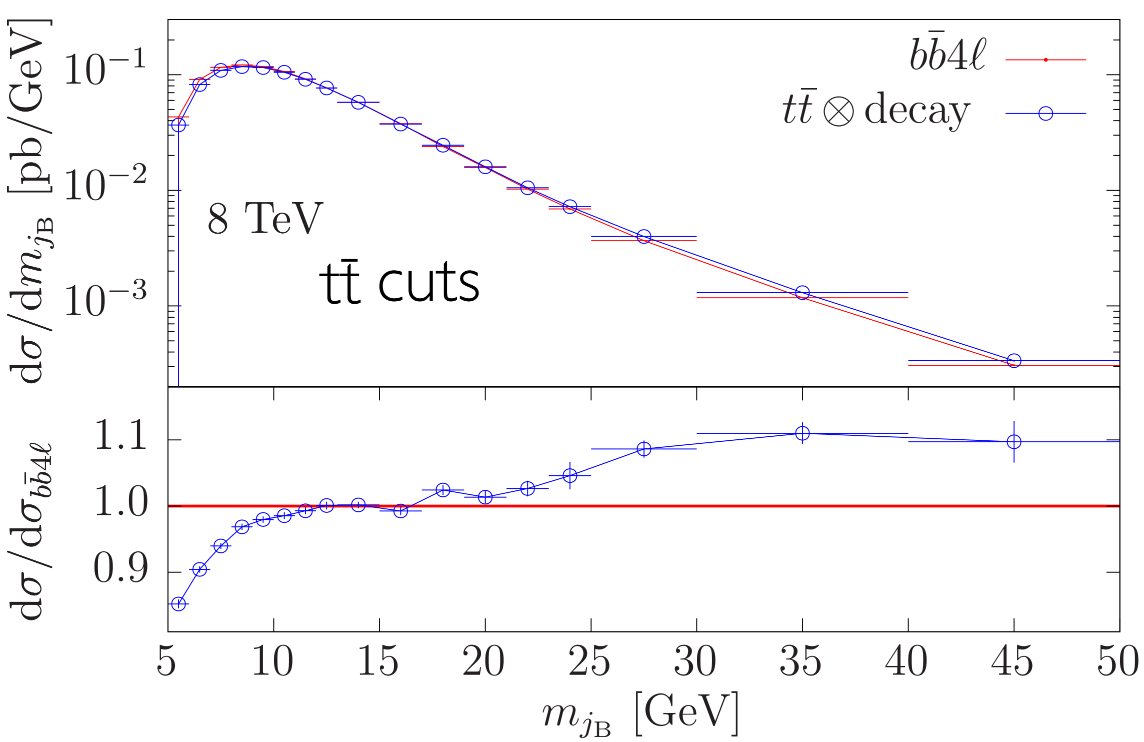
b-jet radiation properties

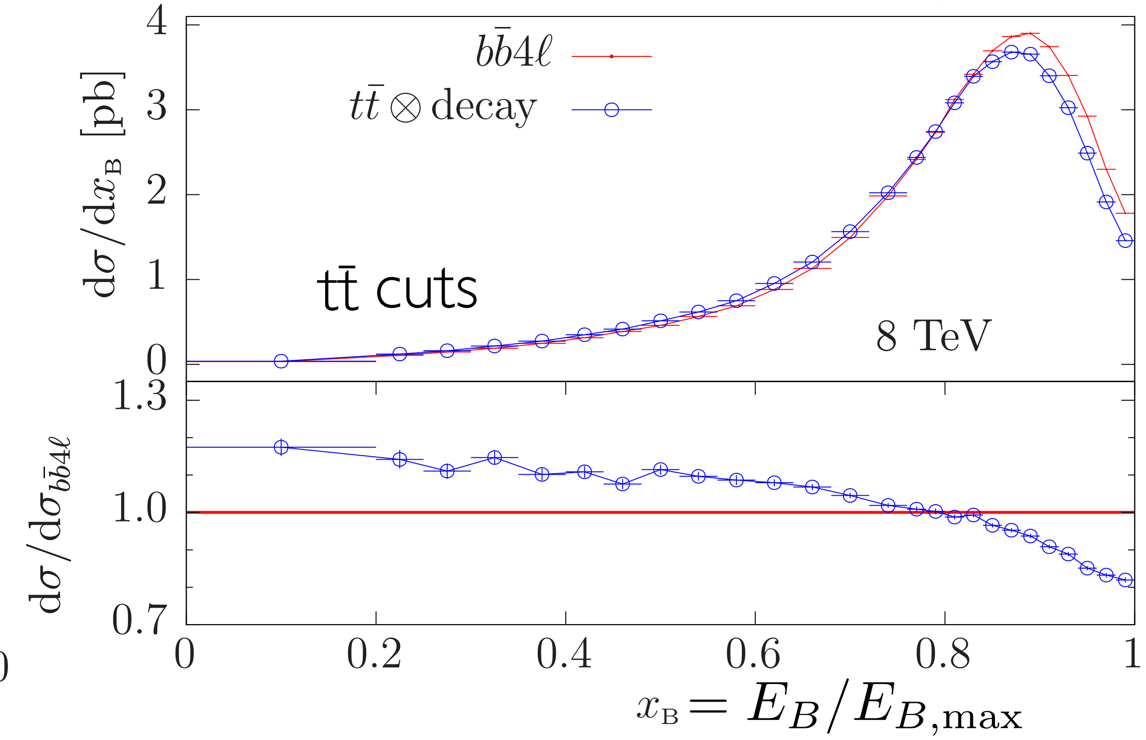
b-jet invariant mass

B-hadron fragmentation function



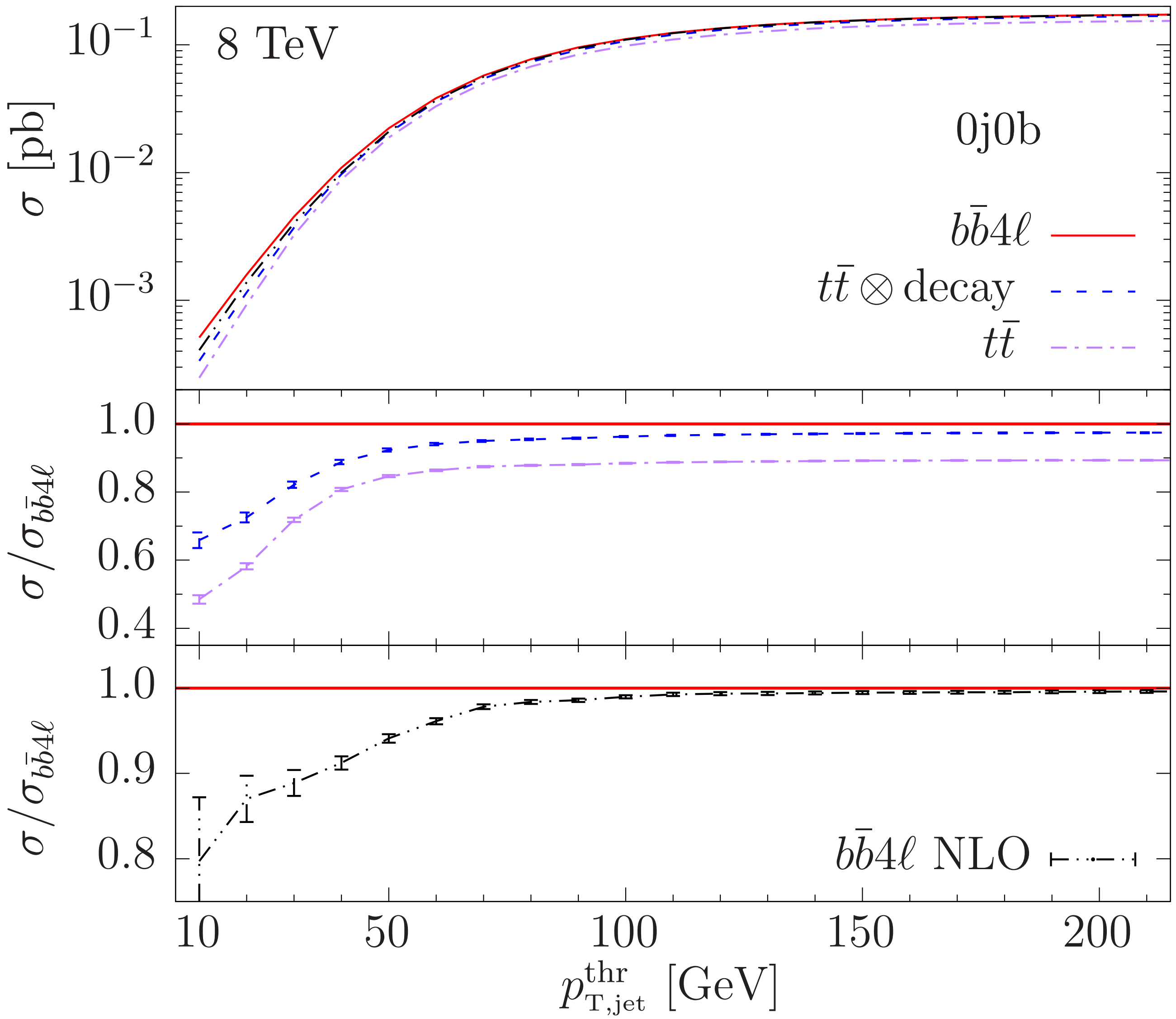


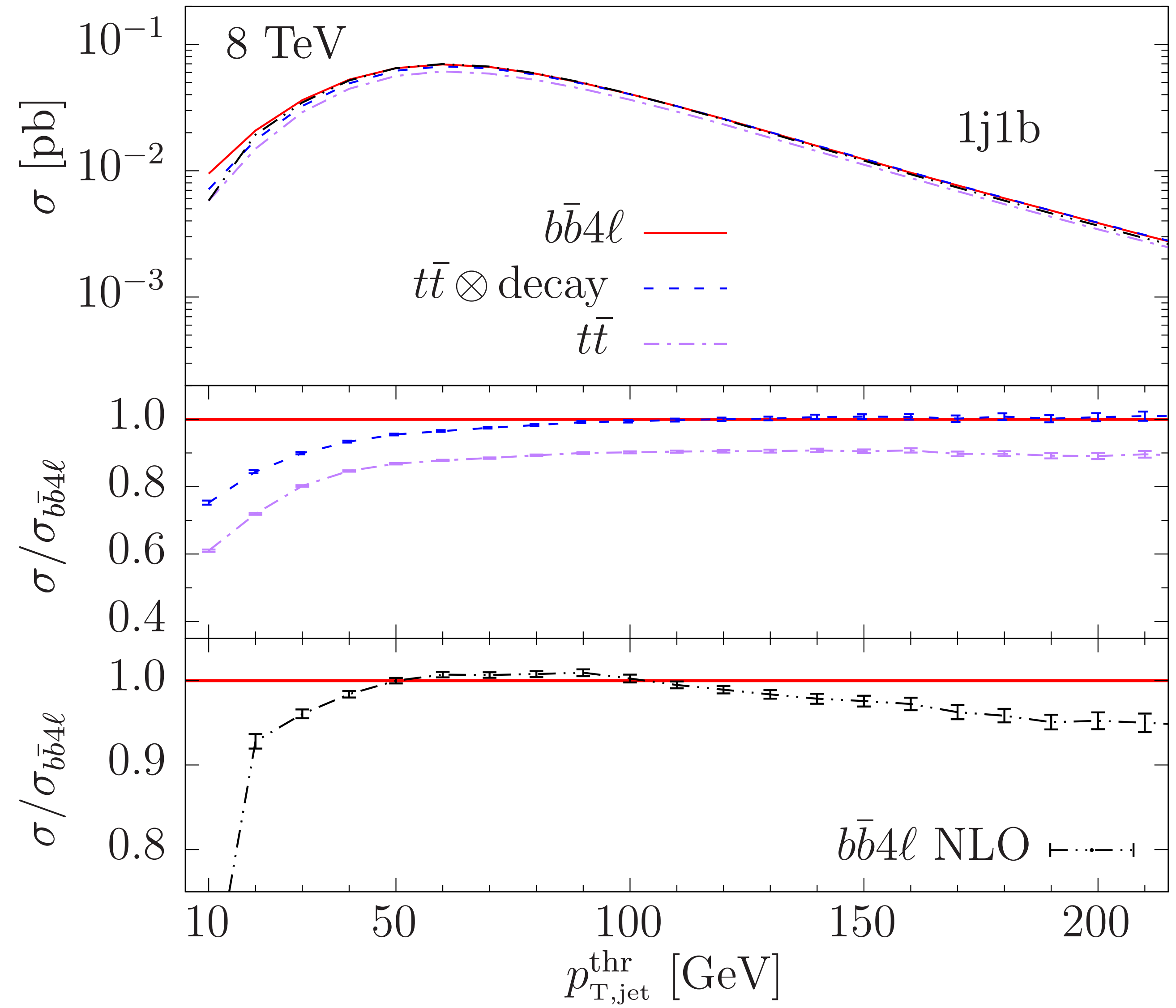


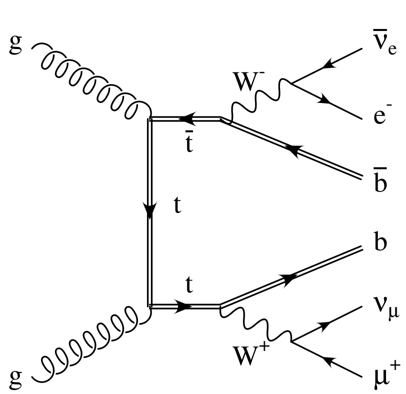


- narrower b-jets and harder B-fragmentation in bb̄4l
- due to reduced radiation from b's in bb̄4l

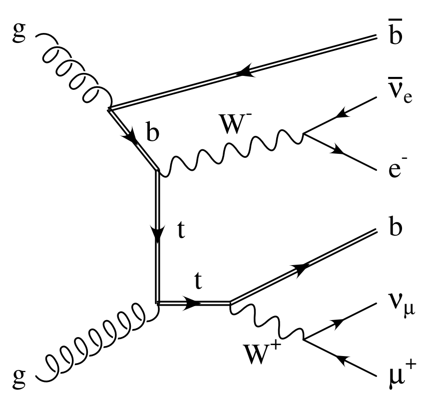
jet vetoes and single-top enriched observables







VS.



- for small jet thresholds Wt single-top reaches 40-50%
- $t\bar{t}\otimes$decay includes Wt only at LO and treats tops on-shell at NLO $\Longrightarrow$ overestimates radiation in Wt region
- 10-20% jet veto resummation effects
- important for any $t\bar{t}$ background with jet vetoes (e.g. $H \rightarrow W^+W^-$)

Conclusions

Technology:

- Resonance-aware matching is pivotal for processes with intermediate resonances
  - ➡ (quite) Rigorous solution within POWHEG by *[Ježo, Nason; '15]*
- New POWHEG framework: **POWHEG-BOX-RES** (http://powhegbox.mib.infn.it/)
  - resonance-aware subtraction and matching for any process
  - automated generation of resonance histories and phase-space
  - process independent **POWHEG-BOX+OpenLoops** interface

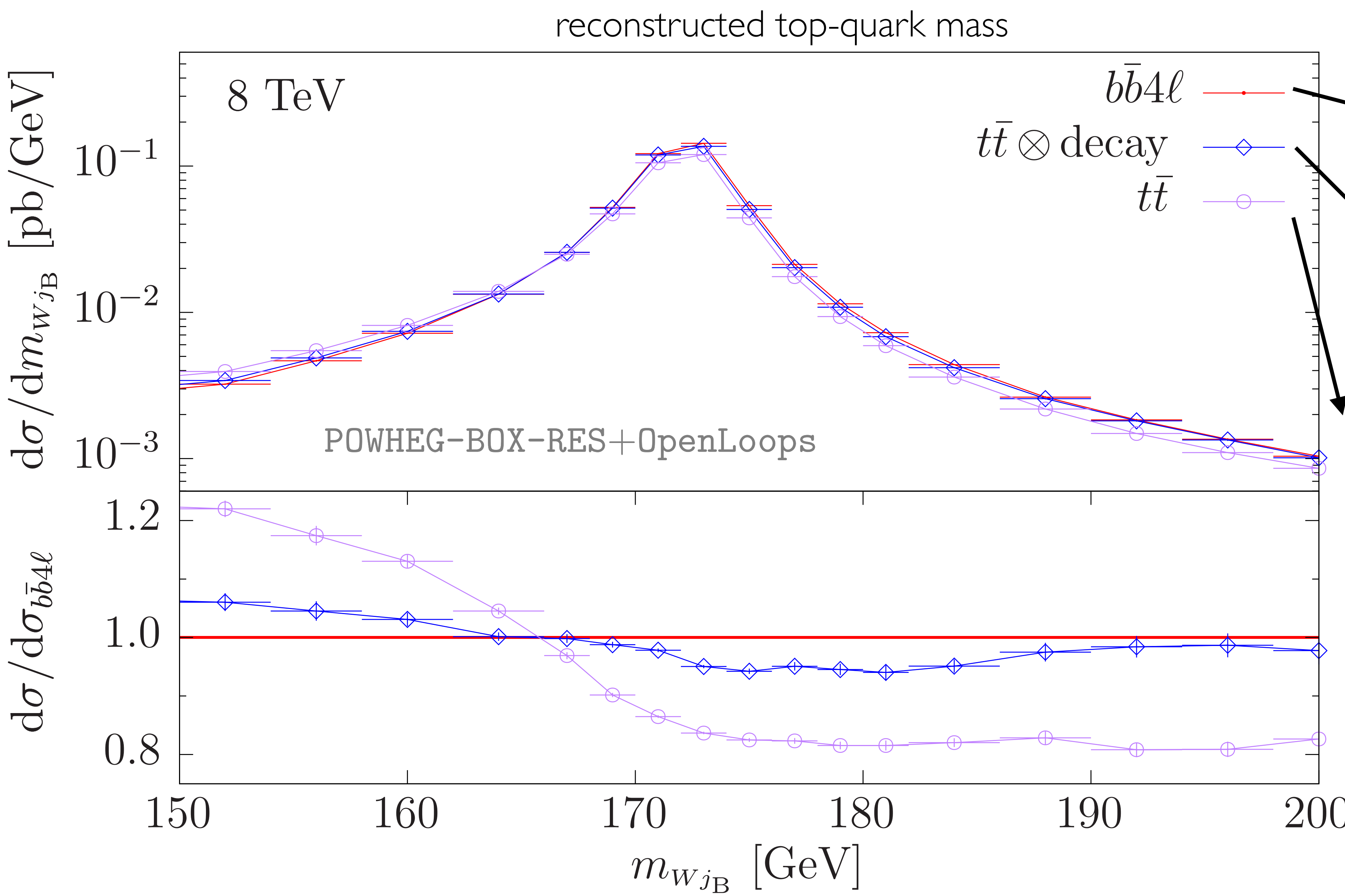
Phenomenology:

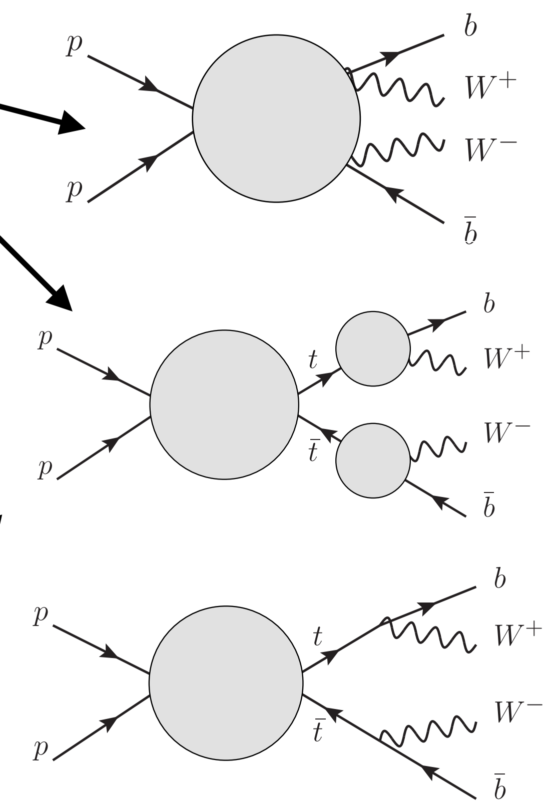
- resonance-aware matching crucial for kinematic precision top-mass measurements
- unified treatment of $t\bar{t}$ & $W\bar{t}$ important for precision single-top physics
- ….and for modelling of $t\bar{t}$ backgrounds subject to jet vetoes.

Outlook:

- Detailed investigation of effects on top mass measurements
- Hadronic top decays

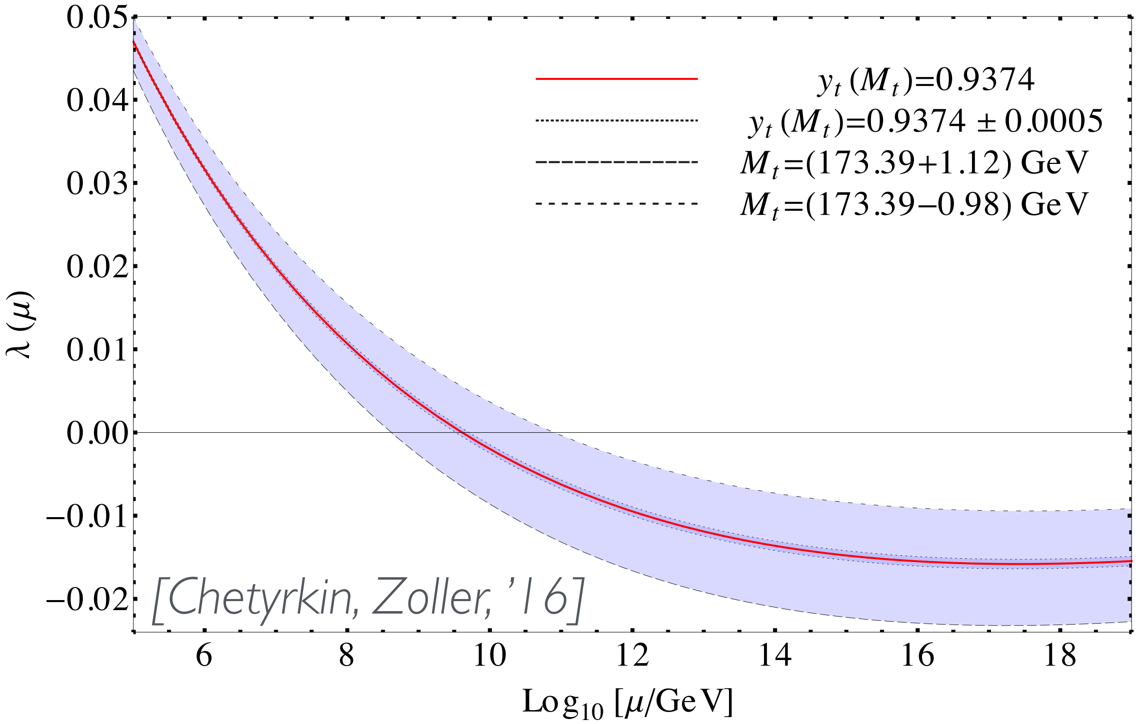
Summary of the results

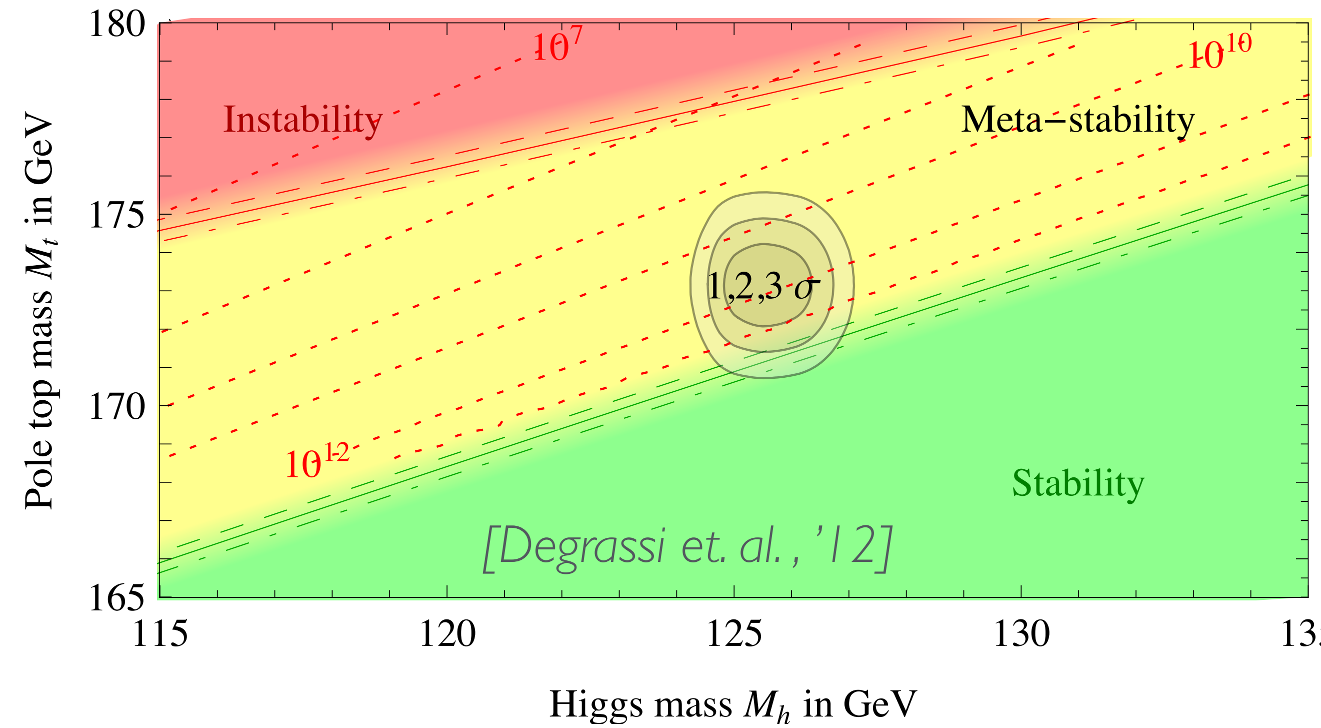


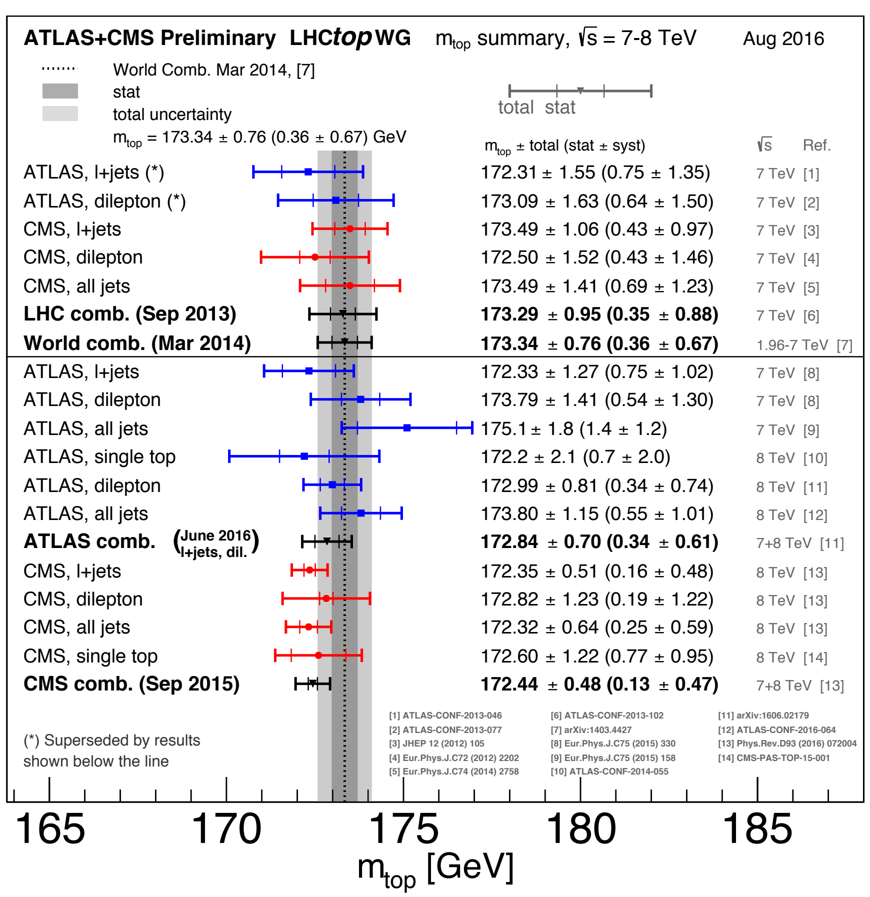


Backup slides

top-quark mass: crucial SM input parameter





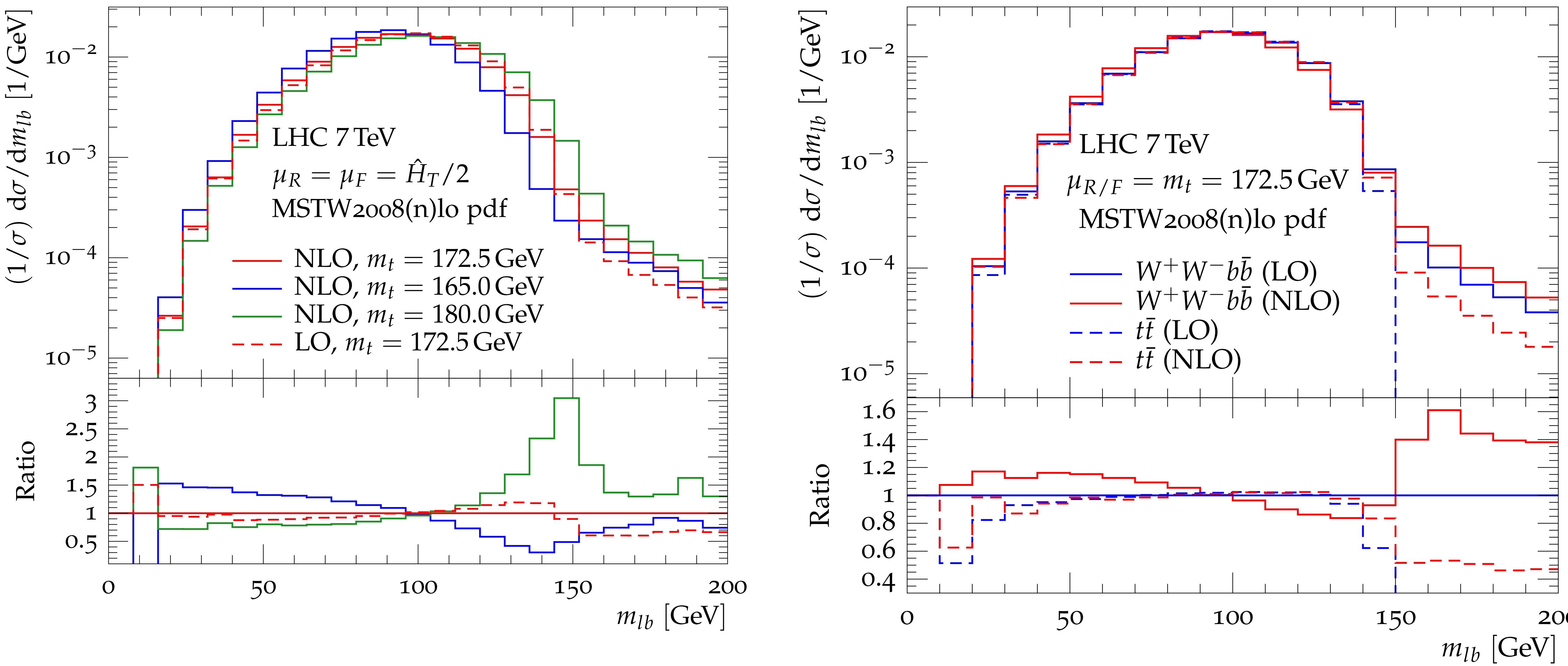


- top-mass measurements at the LHC via combination of different strategies:
  - total x-section, tt̄+jet, kinematic reconstruction, kinematic edges,….
- many techniques rely on kinematic information of top decay products

➡ need realistic MC modelling

kinematic top-quark mass measurements: theory

[Heinrich, Maier, Nisius, Schlenk, Winter; '14]



- m_{lb} is straightforward to measure and shows strong dependence on top mass
- off-shell and NLO effects crucial for precise modelling of shape at the edge

Setup

$$m_Z = 91.188 \text{ GeV}, \qquad \Gamma_Z = 2.441 \text{ GeV},$$
$$m_W = 80.419 \text{ GeV}, \qquad \Gamma_W = 2.048 \text{ GeV},$$
$$m_H = 125 \text{ GeV}, \qquad \Gamma_H = 4.03 \times 10^{-3} \text{ GeV},$$
$$m_t = 172.5 \text{ GeV}, \qquad \Gamma_t = 1.329 \text{ GeV},$$
$$m_b = 4.75 \text{ GeV}.$$

$$G_\mu = 1.16585 \times 10^{-5} \text{ GeV}^{-2}$$

Complex-mass-scheme: $\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \quad \text{for} \quad i = W, Z, t, H$

$$\sin\theta_W^2 = 1 - \cos\theta_W^2 = 1 - \frac{\mu_W^2}{\mu_Z^2}$$

For $t\bar{t}$ resonance histories: $\mu_\mathrm{R} = \mu_\mathrm{F} = \left[\left(m_t^2 + p_{T,t}^2\right)\left(m_{\bar{t}}^2 + p_{T,\bar{t}}^2\right)\right]^{\frac{1}{4}}$

For Z resonance histories: $\mu_\mathrm{R} = \mu_\mathrm{F} = \frac{\sqrt{p_Z^2}}{2}$

PDFs: MSTW2008NLO

$t\bar{t}$ cuts: at least one b- and one $\bar{b}$-jet with $p_T^j > 30 \text{ GeV}, \quad |\eta^j| < 2.5$

$$p_T^l > 20 \text{ GeV}, \qquad |\eta^l| < 2.5, \qquad p_T^\mathrm{miss} > 20 \text{ GeV}$$

Resonance histories

This approach is rigorous up to the point that assignment of resonance histories requires a prescription.

Idea: ***define resonance histories according to well defined NWA limit (valid to all orders)!***

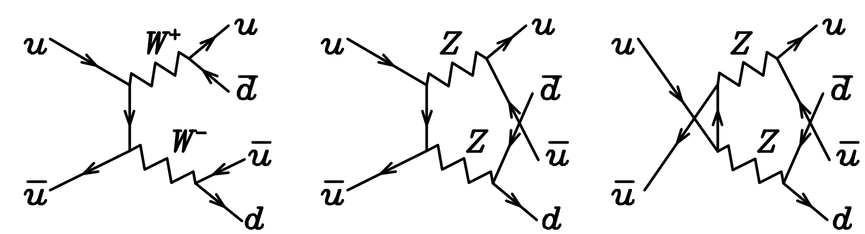
Project onto these resonance histories f_b and f_r based on kinematic proximity:

$$B_{F_b} = \sum_{f_b \in T(F_b)} B_{f_b}, \qquad B_{f_b} = \Pi_{f_b} B_{F_b}$$

$$\Pi_{f_b} = \frac{P^{f_b}}{\sum_{f_b' \in T(F_b(f_b))} P^{f_b'}}, \qquad P^{f_b} = \prod_{i \in \mathrm{Nd}(f_b)} \frac{M_i^4}{(s_i - M_i^2)^2 + \Gamma_i^2 M_i^2}$$

(similar for R: separation into resonance structures and *compatible* FKS singular regions)

Example: $u\bar{u} \to u\bar{d}\bar{u}d$ @ $\mathcal{O}(\alpha^4)$



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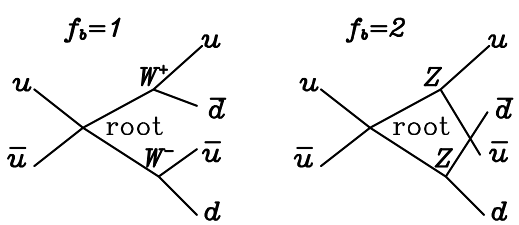
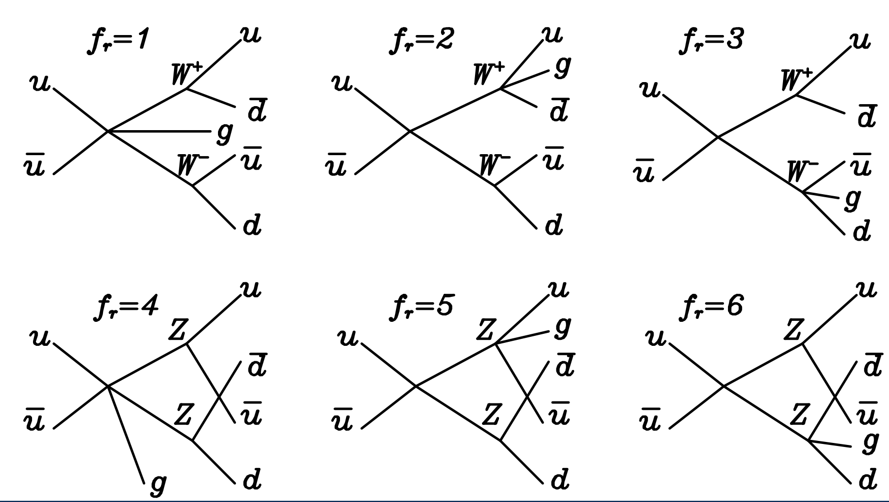


R



Efficiency study

		resonance aware	resonance unaware
NLO cross section	rel. accuracy (*)	0,11%	0,79%
efficiency of generation of radiation	vetos per event	750	15000
speed of event generation	events per hour	1500	200

⟹ factor of ~7 improvement in convergence/efficiency/speed!

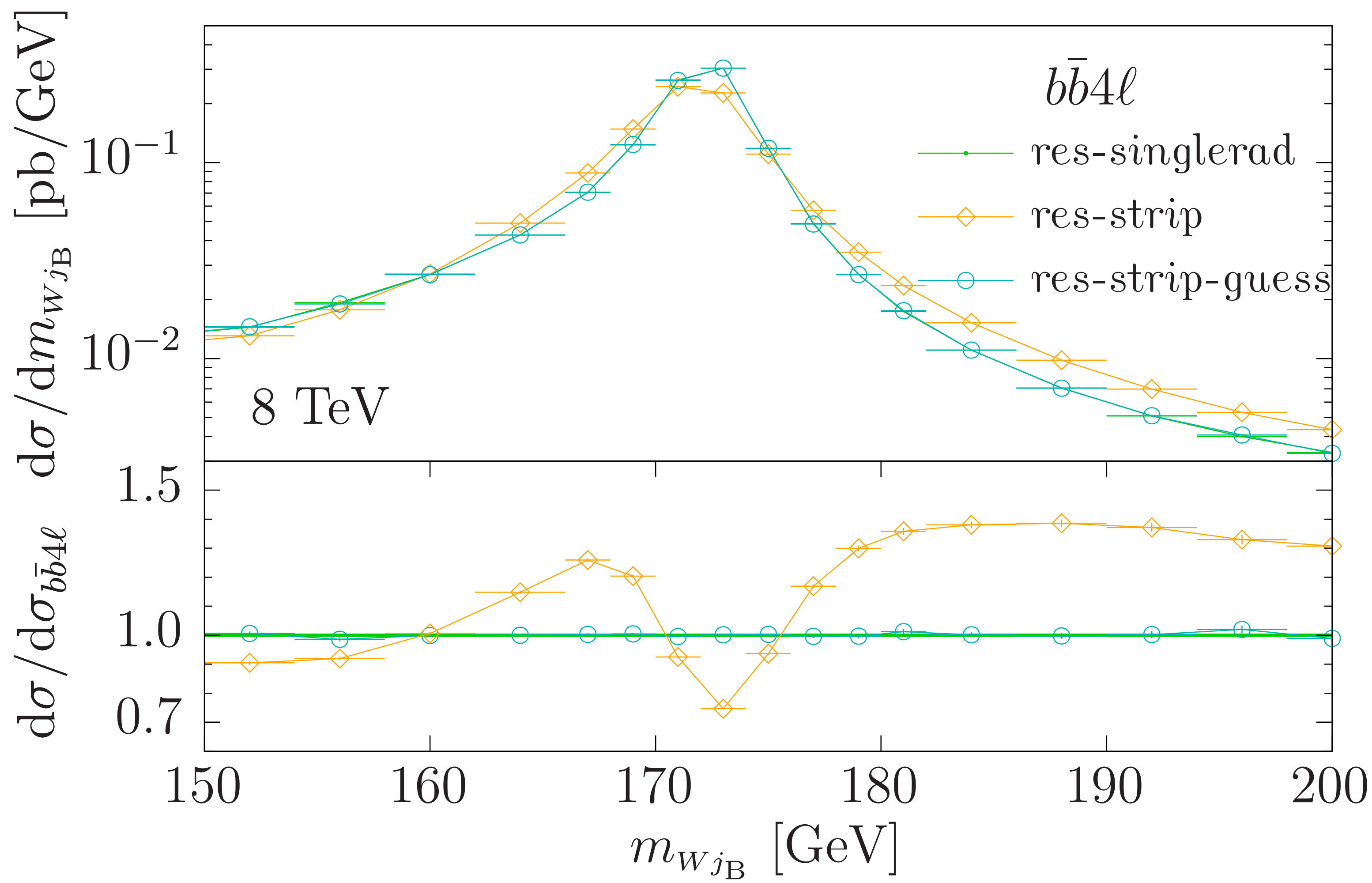
(*) NLO POWHEG setup

- stage 1: ncalls=80k, itmx=2
- stage 2: ncalls=100k, itmx=4
- nrun = 64

(typical setup for small cluster/blade)

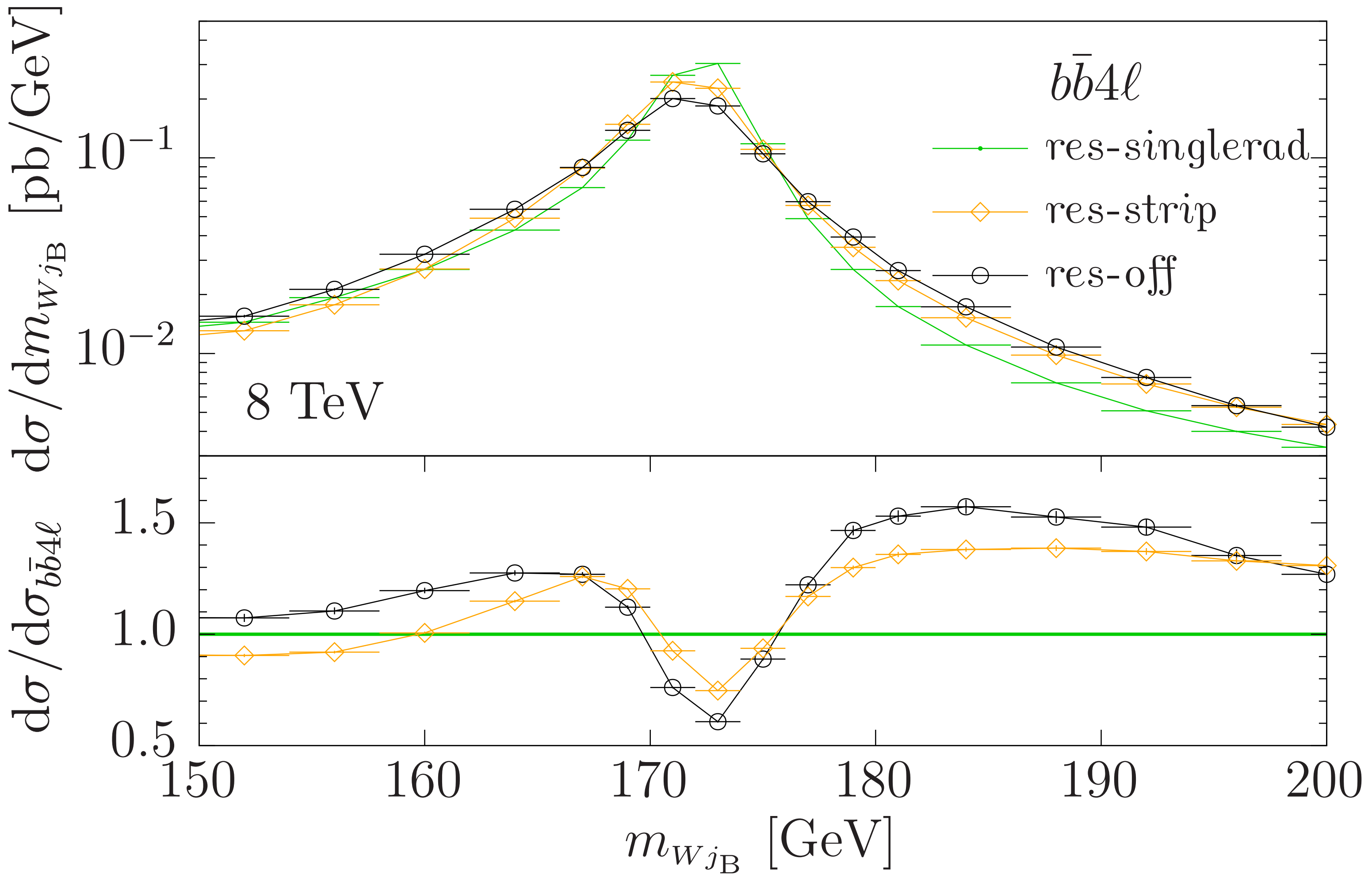
Kinematic guess

- res-singlerad: resonance aware matching & single-radiation scheme
- res-strip: resonance aware matching, but resonance information not passed to PS
- res-strip-guess: resonance aware matching, resonance information first stripped and then guessed (based on kinematic proximity) before passing to PS



Impact of PS momentum reshuffling

- res-singlerad: resonance aware matching & single-radiation scheme
- res-strip: resonance aware matching, but resonance information not passed to PS
- res-off: resonance unaware matching

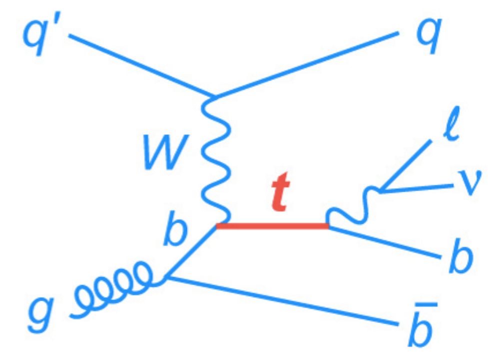


⟹ res-strip in-between res-singlerad and res-off

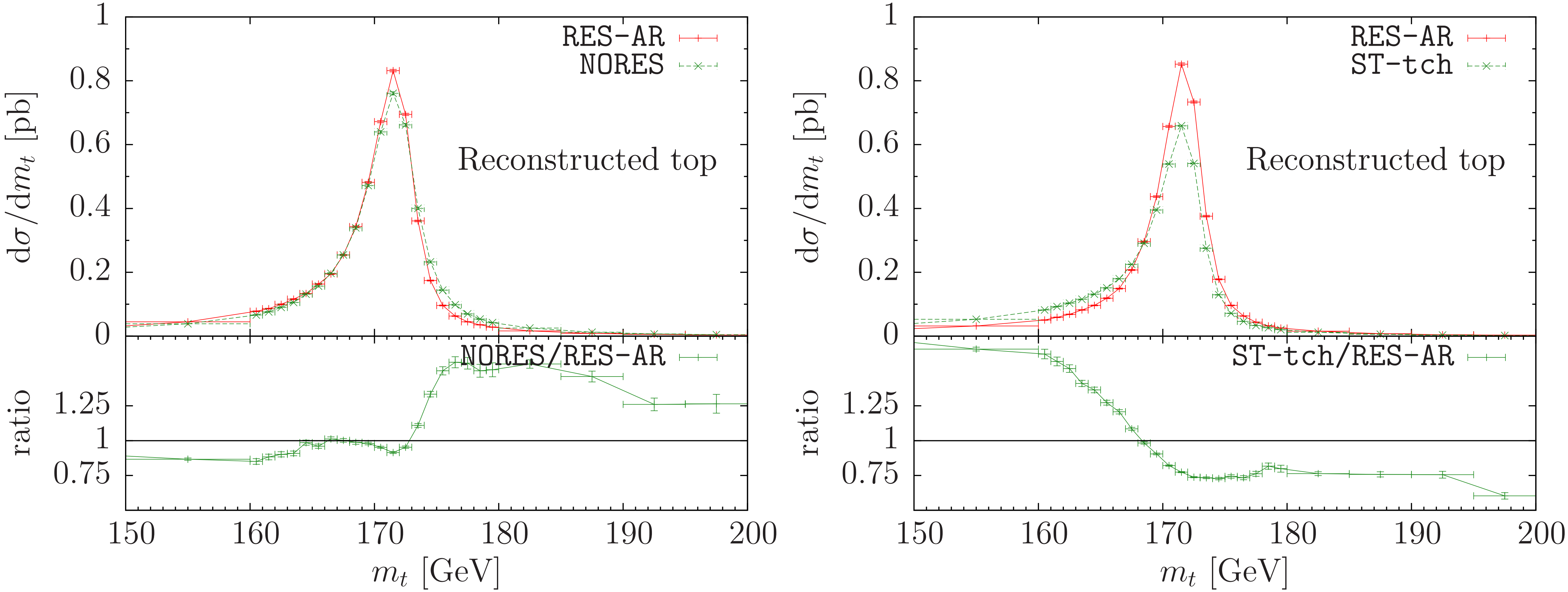
⟹ both effects important:

I) first emission governed by resonance preserving R/B
II) PS reshuffling preserves the resonance masses

Single-top t-channel NLO+PS

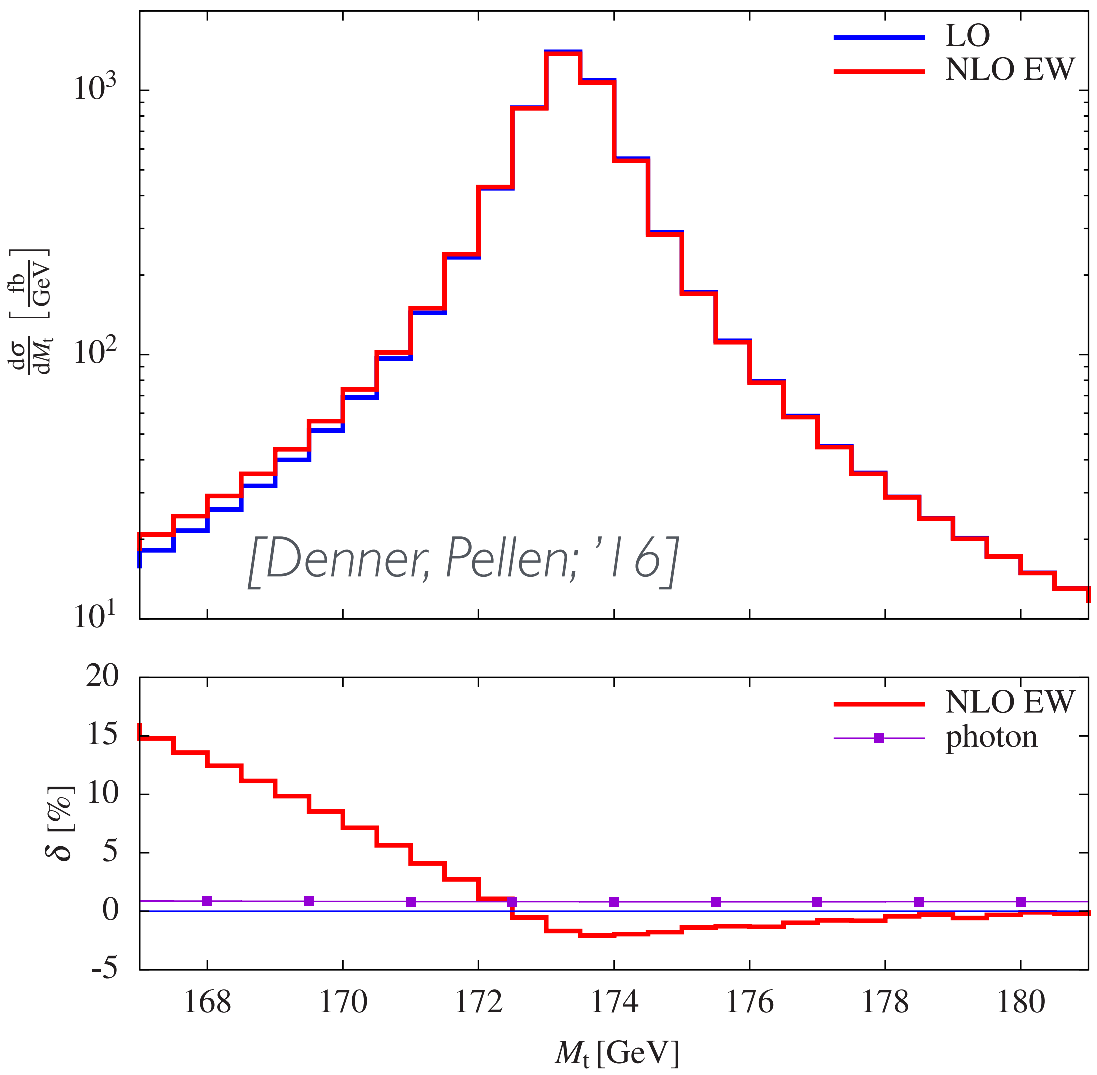


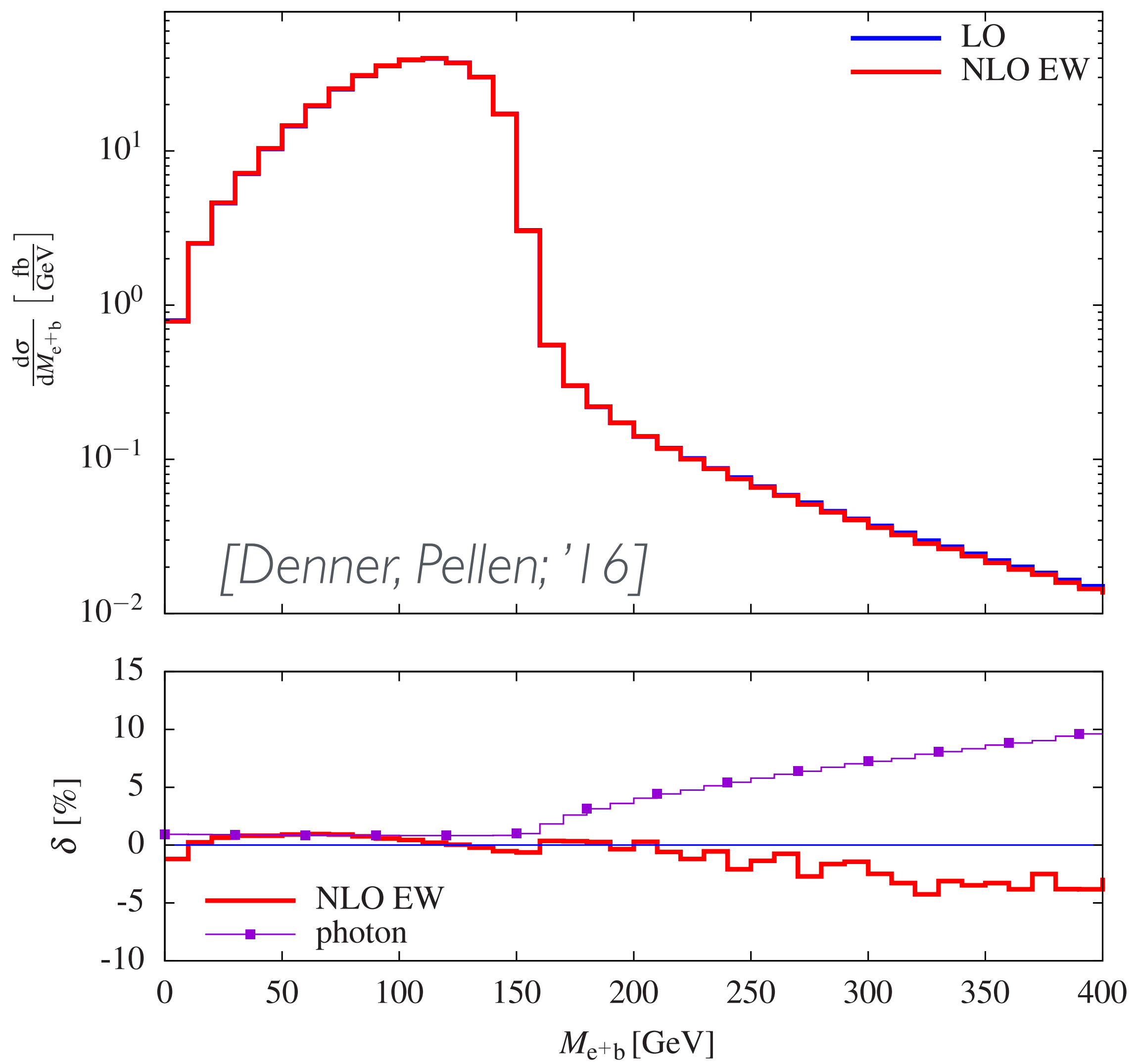
[Ježo, Nason; '15]



- significant shape distortions in resonance unaware calculation and with respect to on-shell top calculation *[Alioli, Nason, Oleari, Re; '09]*

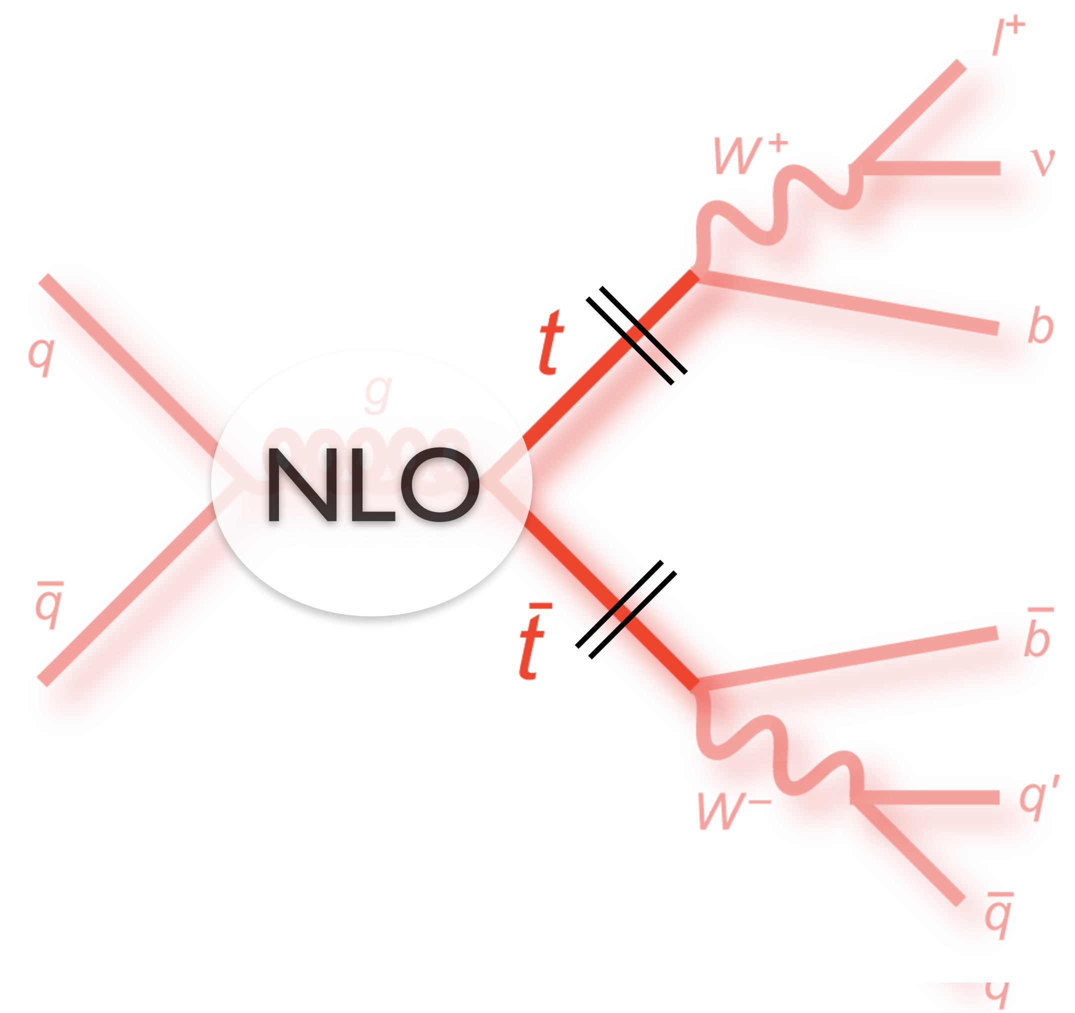
NLO EW





- NLO EW ~5% around top peak, up to 15% below the peak
- sizeable photon-induced contributions in m_{lb} (using NNPDF2.3QED)

Top-pair production and decay



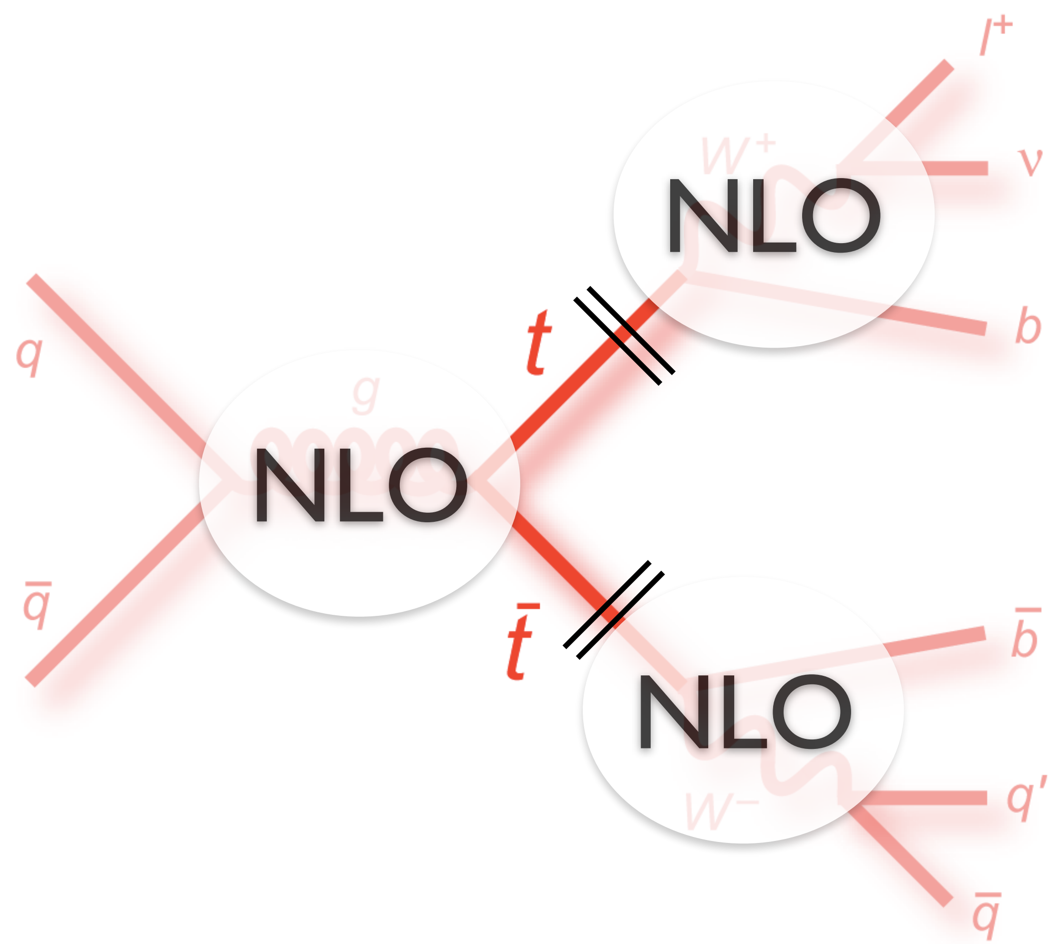
NLO QCD *[Bernreuther, Brandenburg, Si; '04, Melnikov, Schulze;'09, Campbell, Ellis; '15] [Bevilacqua, Czakon, van. Hameren, Papadopoulos, Worek; '11, Denner, Dittmaier, Kallweit, Pozzorini; '11+'12, Heinrich, Maier, Nisius, Schlenk, Winter; '14, Frederix '14, Cascioli, Kallweit, Maierhfer, Pozzorini; '14]*

NNLO *[Czakon, Fiedler, Mitov; '13, Czakon, Heymes, Mitov; '16]*

NLO EW *[Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth; '94, Bernreuther, Fuecker, Si; '06+'08, Kühn, Scharf, Uwer; '07,+'15, Hollik, Pagani; '07, Pagani, Tsinikos, Zaro,; '16] [Bernreuther, Si;'10] [Denner, Pellen '16]*

NLO QCD+PS *[Frixione, Nason, Webber, '03, Frixione, Nason, Ridolfi; '07] [Campbell, Ellis, Nason, Re, '15] [Garzelli, Kardos, Trocsanyi; '14]*

Top-pair production and decay



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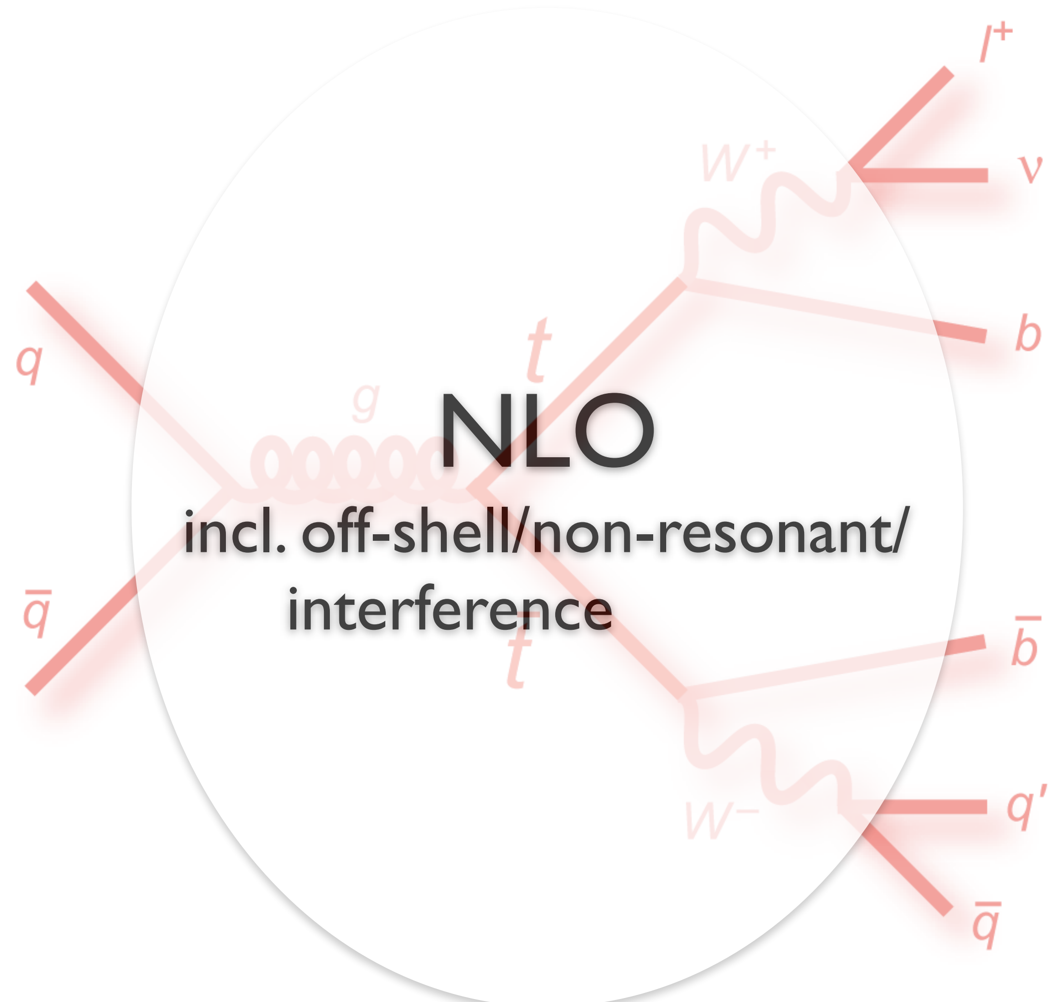

NLO QCD *[Bernreuther, Brandenburg, Si; '04, Melnikov, Schulze;'09, Campbell, Ellis; '15]* ***[Bevilacqua, Czakon, van. Hameren, Papadopoulos, Worek; '11, Denner, Dittmaier, Kallweit, Pozzorini; '11+'12, Heinrich, Maier, Nisius, Schlenk, Winter; '14, Frederix '14, Cascioli, Kallweit, Maierhfer, Pozzorini; '14]***

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NLO QCD+PS *[Frixione, Nason, Webber, '03, Frixione, Nason, Ridolfi; '07]* *[Campbell, Ellis, Nason, Re, '15]* ***[Garzelli, Kardos, Trocsanyi; '14]***