NLO+PS matching for $t\bar{t}b\bar{b}$ production with massive b-quarks

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In collaboration with:
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QCD@LHC, August 29 2017

Universität Zürich[UZH]

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- Summarize results of ttH search at the LHC
- Discuss various ways of simulating $t\bar{t}b\bar{b}$
- Present a LO study on the relative importance of IS and FS $g \to b\bar{b}$ splittings
- Review existing NLO+PS tools for $t\bar{t}b\bar{b}$ and compare them
- Present our results

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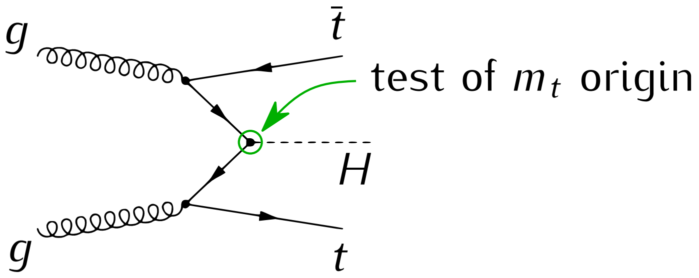
$t\bar{t}H$ @ LHC run 2

- Direct probe of top-quark Yukawa coupling



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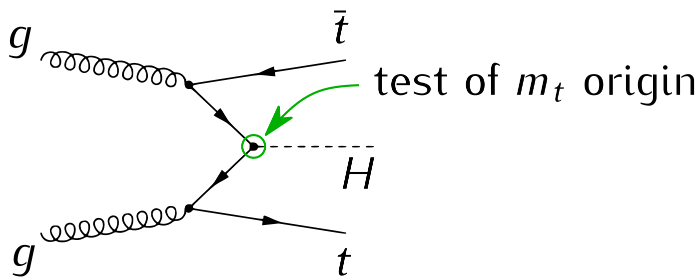

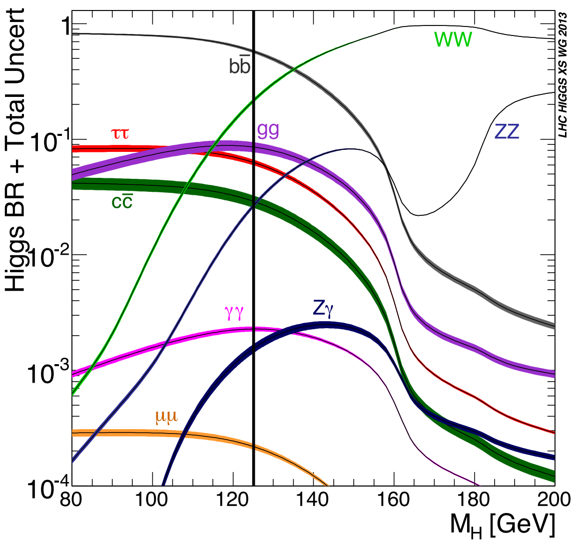

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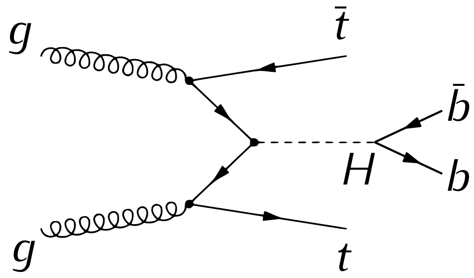

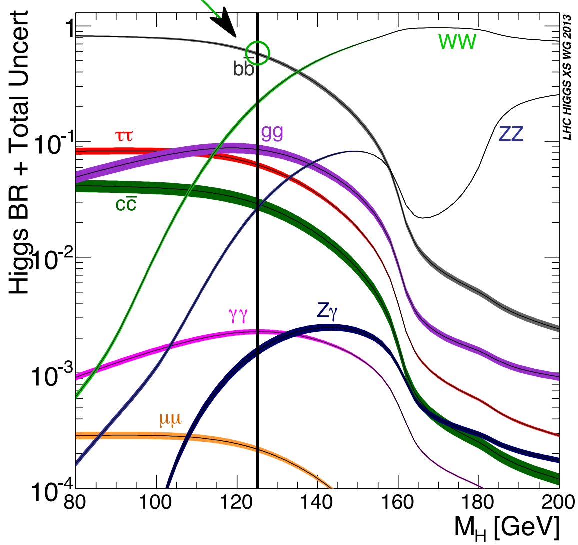

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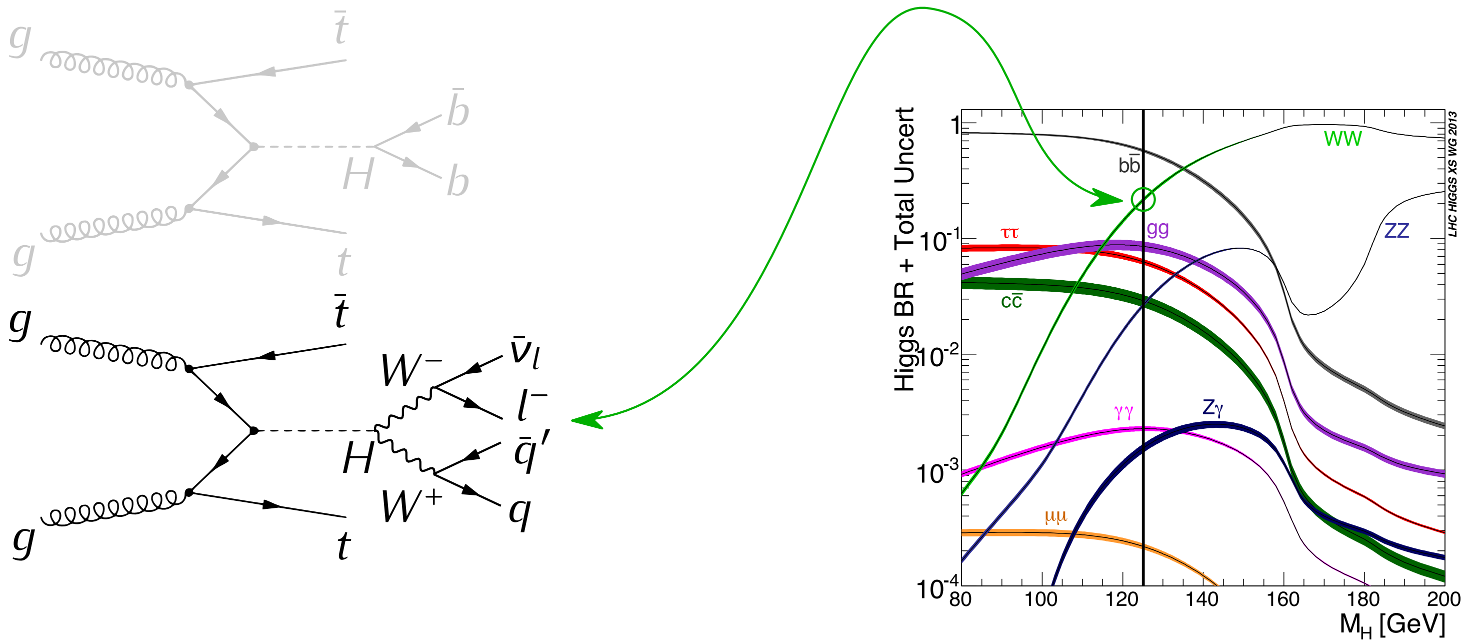

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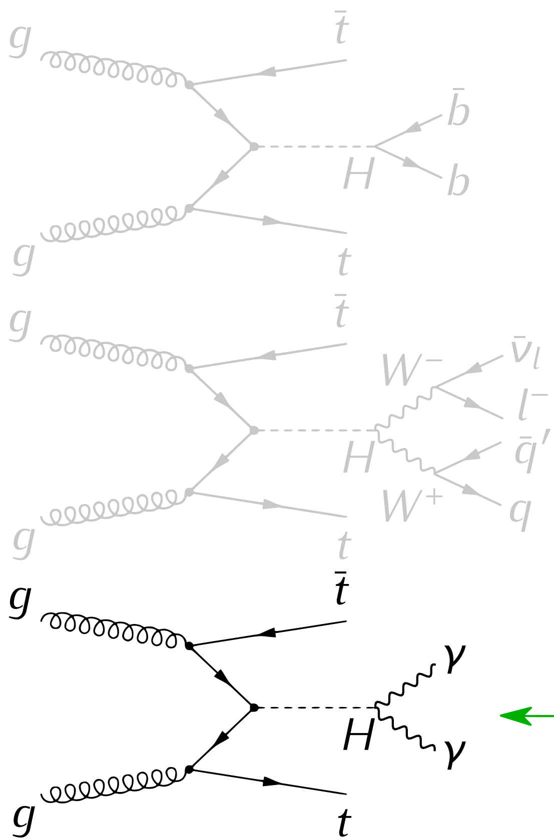

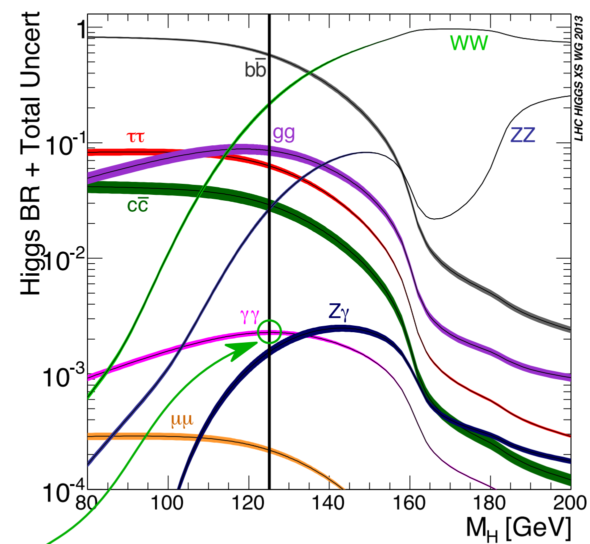

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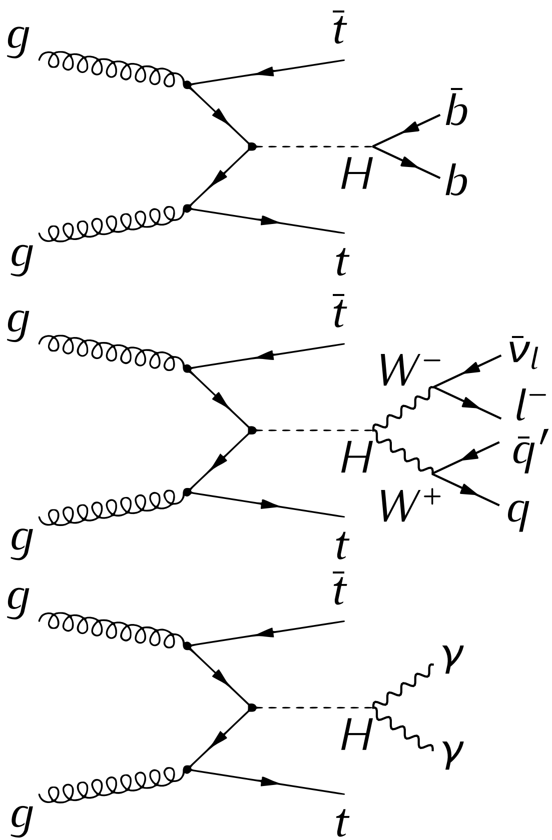

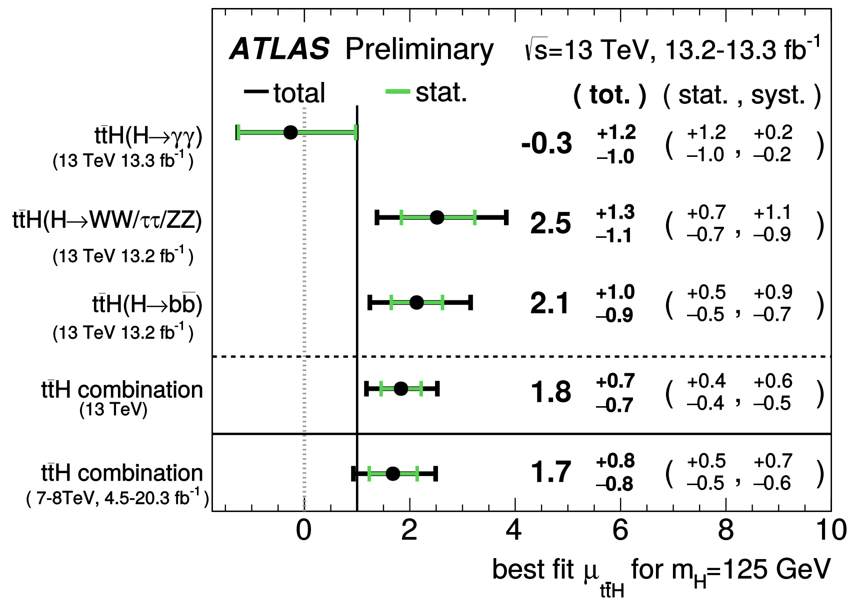

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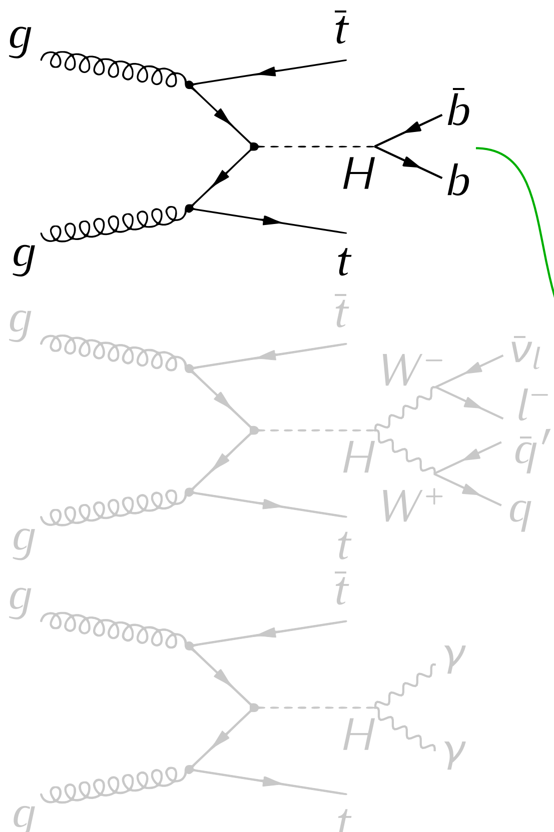

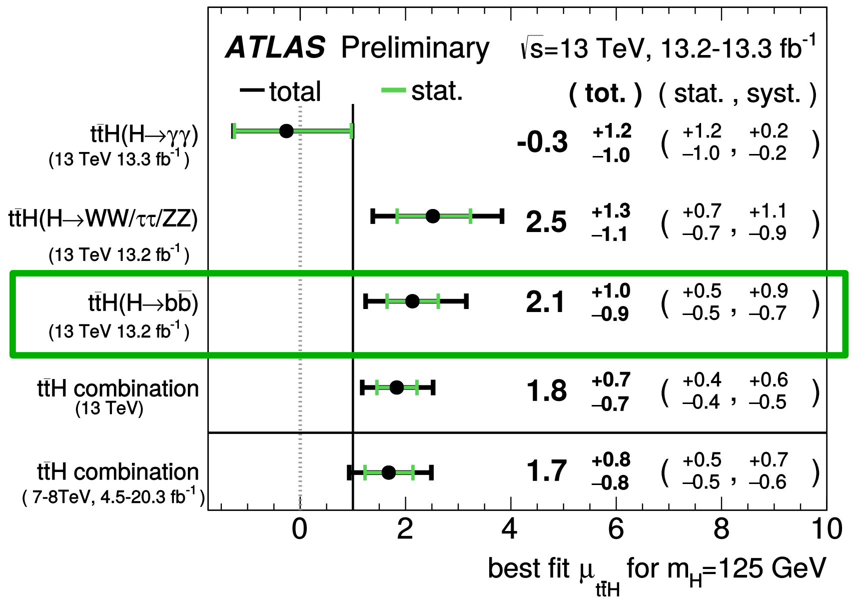

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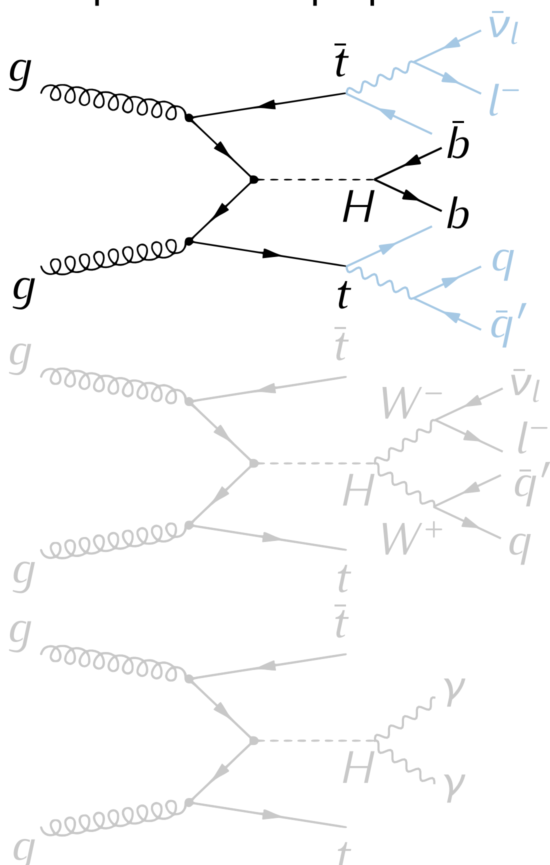

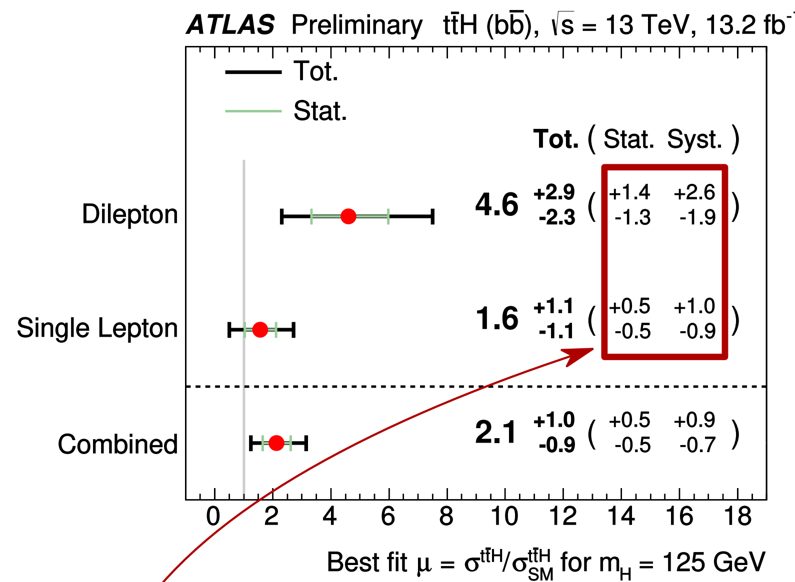

Dominated by systematics!

$t\bar{t}H$ @ LHC run 2

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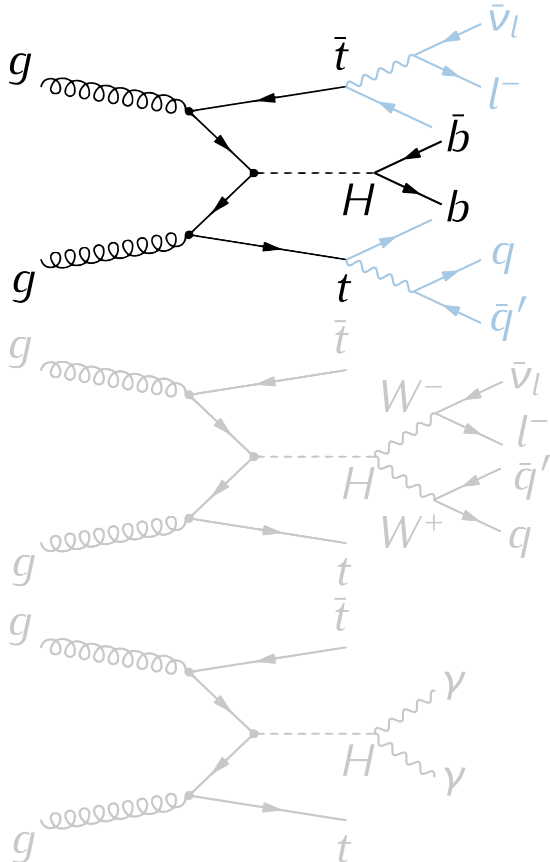
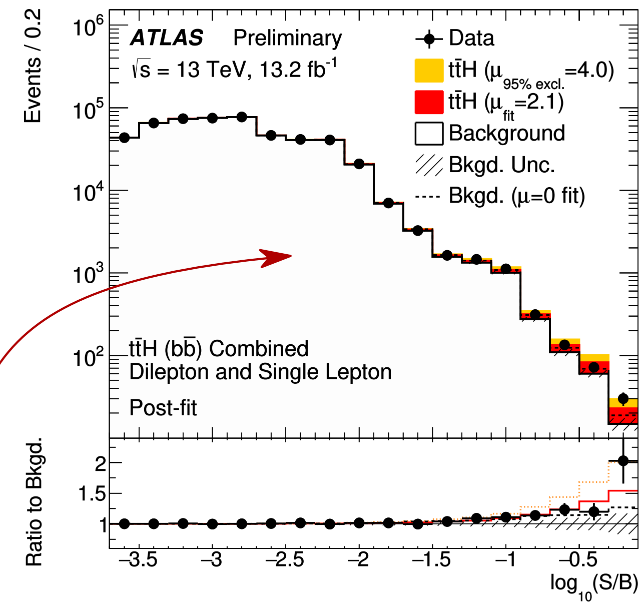
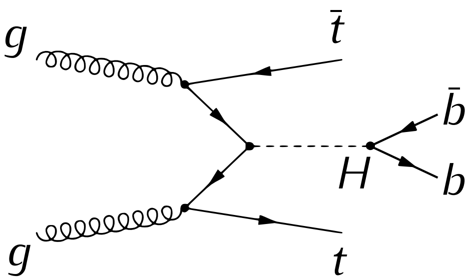


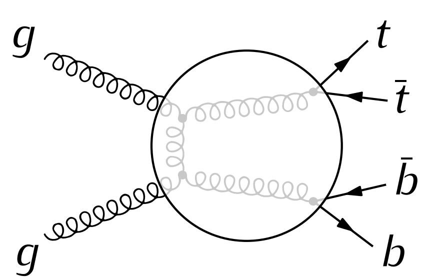


Background dominated!

$t\bar{t}H$ @ LHC run 2

- Large $t\bar{t}+b$-jets background and its theory uncertainities are bottleneck of $t\bar{t}H(b\bar{b})$ searches

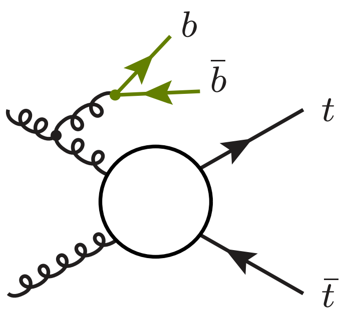




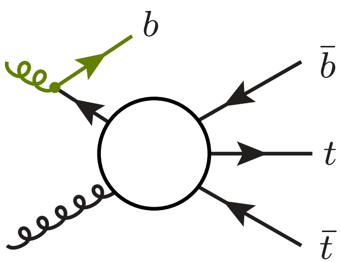
- Modern tools support automated $t\bar{t}b\bar{b}$ simulations, but it remains highly nontrivial multi-particle multi-scale process
- Realistic estimates of theory uncertainities necessitate understanding of dynamics governing $pp \to t\bar{t}b\bar{b}$ as well as technical aspects related to:
  - 5F/4F scheme choice
  - NLO+PS matching
  - PS effects

How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F
  - $t\bar{t}j$ tree MEs + $g \to b\bar{b}$ shower splittings



$gg \to t\bar{t}g$ + FS splittings



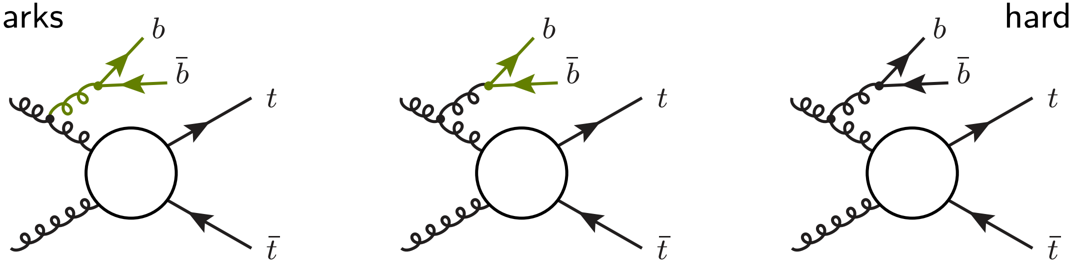
$\bar{b}g \to t\bar{t}\bar{b}$ + IS splittings

  - Not even LO precision (although PS allows for accurate tuning to data)
  - Description based on $t\bar{t}b\bar{b}$ MEs crucial for realistic theory uncertainity estimates

How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient precision
- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F
  - $t\bar{t} + 0, 1, 2$ jet MEs and $g \to b\bar{b}$ splittings

softer b-quarks ⟸



⟹ harder b-quarks

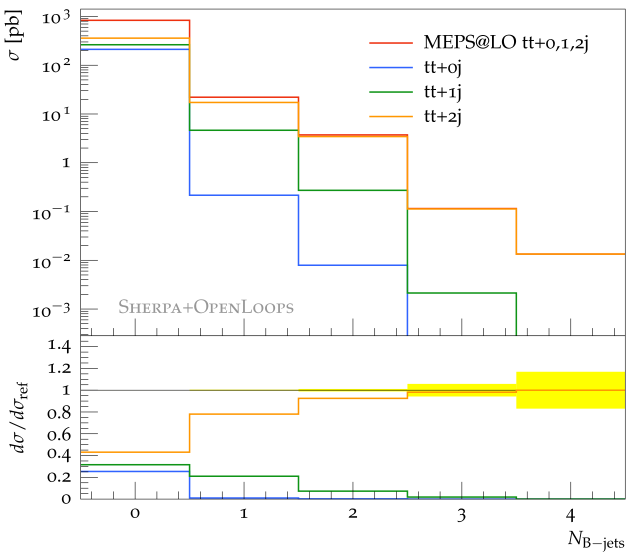
$t\bar{t} + \mathrm{PS}$ $\quad$ $t\bar{t}g + \mathrm{PS}$ $\quad$ $t\bar{t}b\bar{b}$

  - Precision and CPU cost strongly dependent on the merging cut Q_{cut}
  - Does this describe $t\bar{t} + b$-jets mostly through $t\bar{t}b\bar{b}$ MEs though?

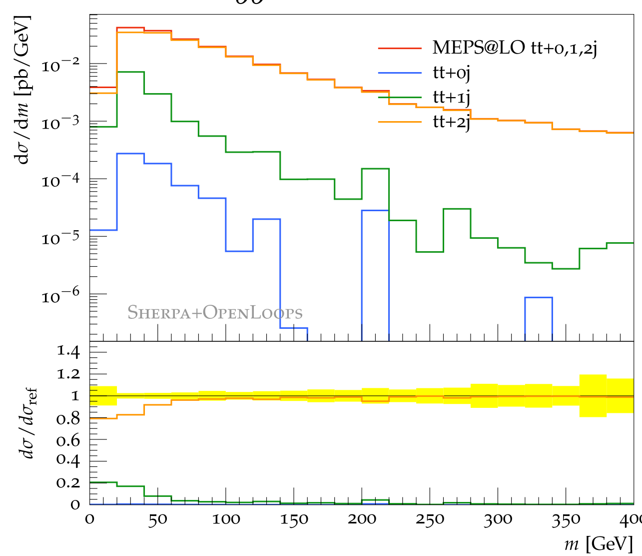
Amount of $t\bar{t}$+jets ME information

- $t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\rm cut} = 20$ GeV

$N_{b\,\rm jets}$



m_{bb} with ttbb cuts

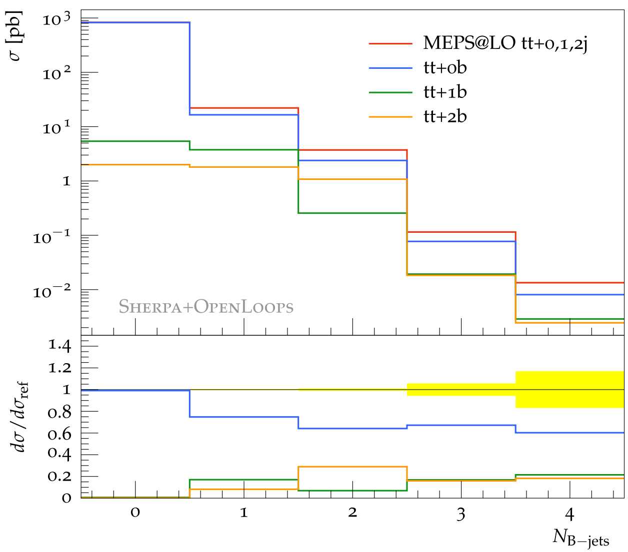


- Observables with ≥ 1 additional b-jets
  - dominated by $t\bar{t} + 2$jet MEs (suggesting ME precision)

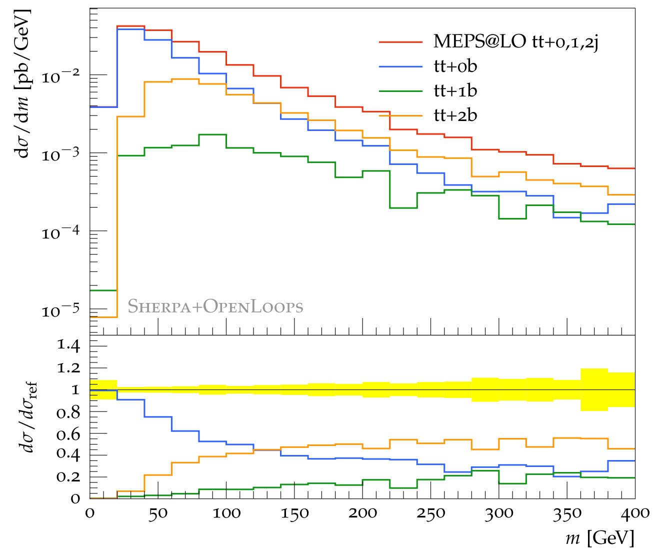
Amount of $t\bar{t}+b$-jets ME information

- $t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\text{cut}} = 20$ GeV

$N_{b\,\text{jets}}$



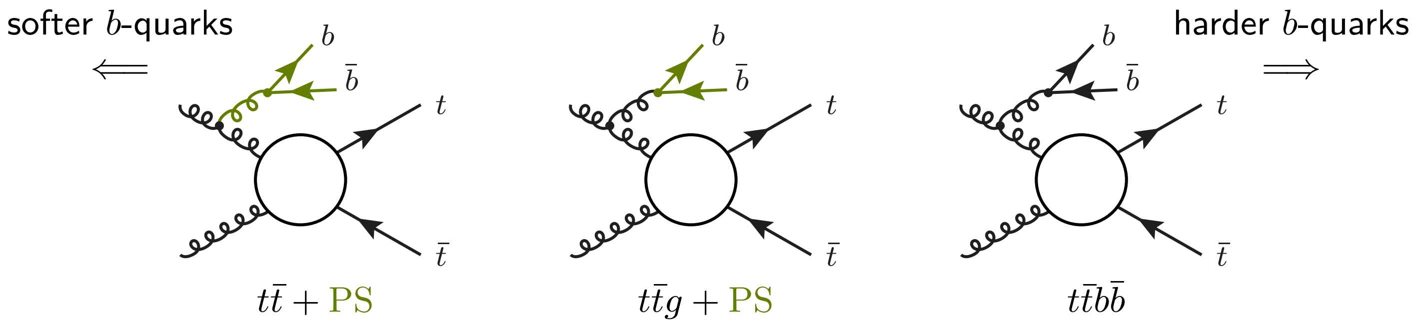
m_{bb} with ttbb cuts



- Observables with ≥ 1 additional b-jets
  - actually dominated by MEs with 2 light jets and no b-jets (up to $Q \sim$ 100 GeV)!

How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient precision
- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F
  - $t\bar{t} + 0, 1, 2$ jet MEs and $g \to b\bar{b}$ splittings



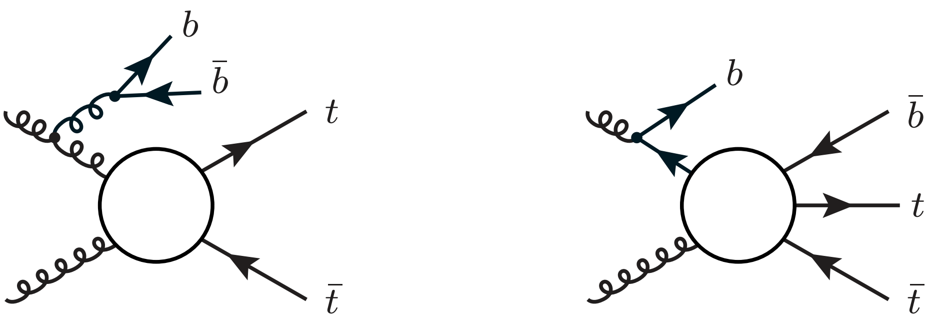
  - Precision and CPU cost strongly dependent on the merging cut Q_{cut}
  - Does this describe $t\bar{t} + b$-jets mostly through $t\bar{t}b\bar{b}$ MEs though?

No!

Direct description in terms of $t\bar{t}b\bar{b}$ MEs preferable.

How to simulate $t\bar{t} + b$-jets?

- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient precision
- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F ... observables with ≥ 1 additional b-jets dominated by MEs with 2 light jets
- Option 3: $t\bar{t}b\bar{b}$ at NLO+PS



  - NLO+PS precision for $t\bar{t} + 2b$-jet and $t\bar{t} + 1b$-jet observables

How to simulate $t\bar{t} + b$-jets?

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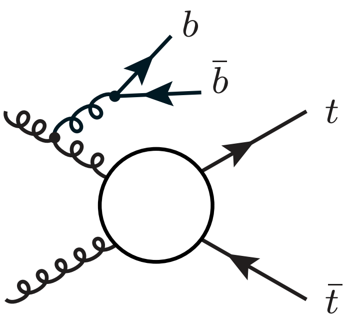
- Option 3: $t\bar{t}b\bar{b}$ at NLO+PS



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This talk

QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \to t\bar{t}b\bar{b}$:
  - 6 external coloured partons, $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R)$
  - 34 LO diagrams, multiple scales from 5 to 500 GeV
  - Dominated by topologies with FS $g \to bb$ splittings

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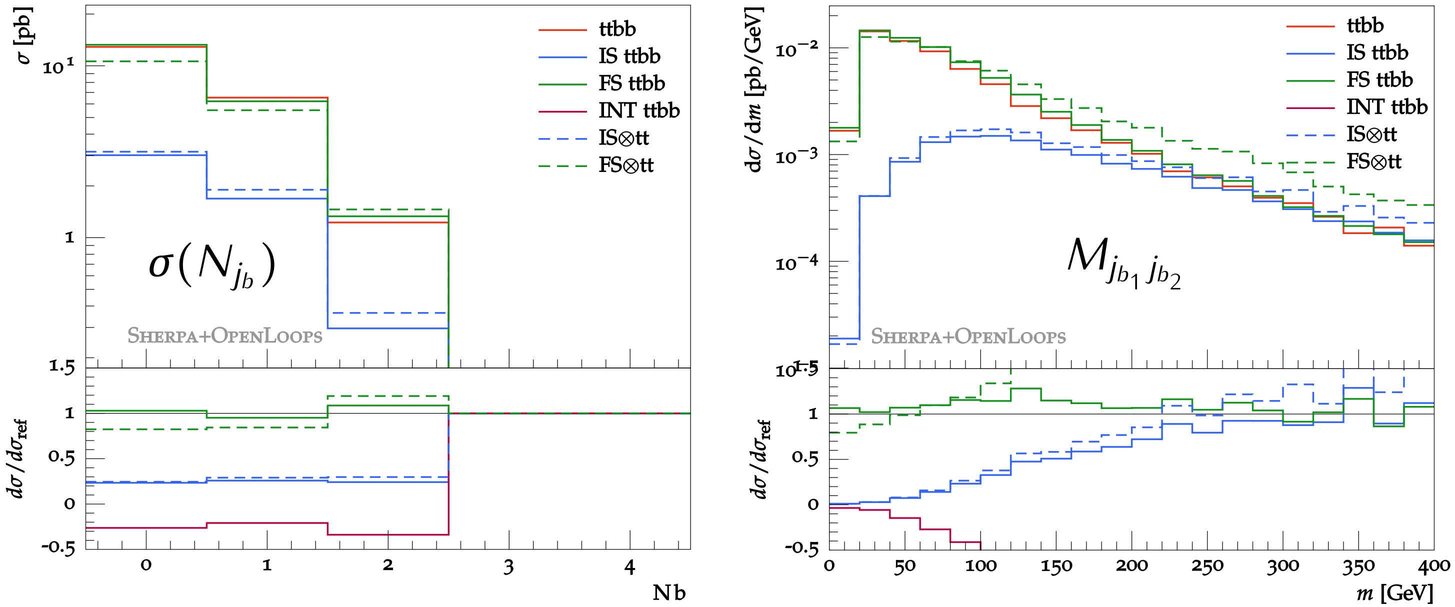

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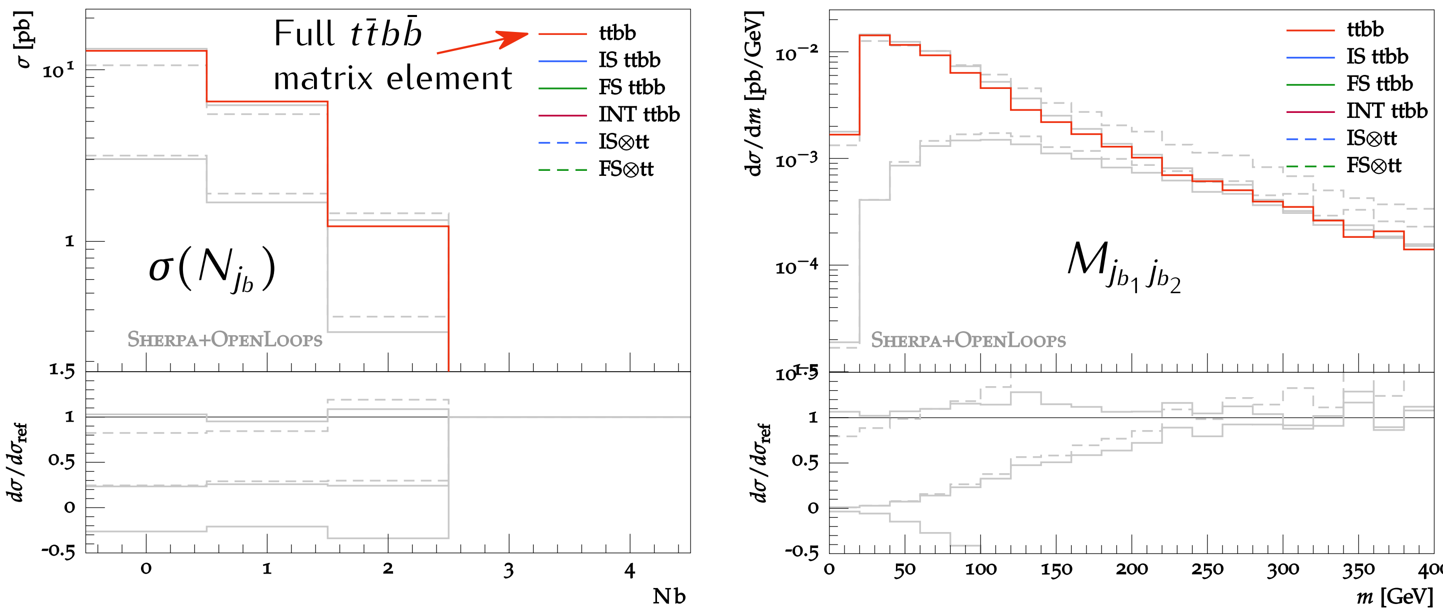

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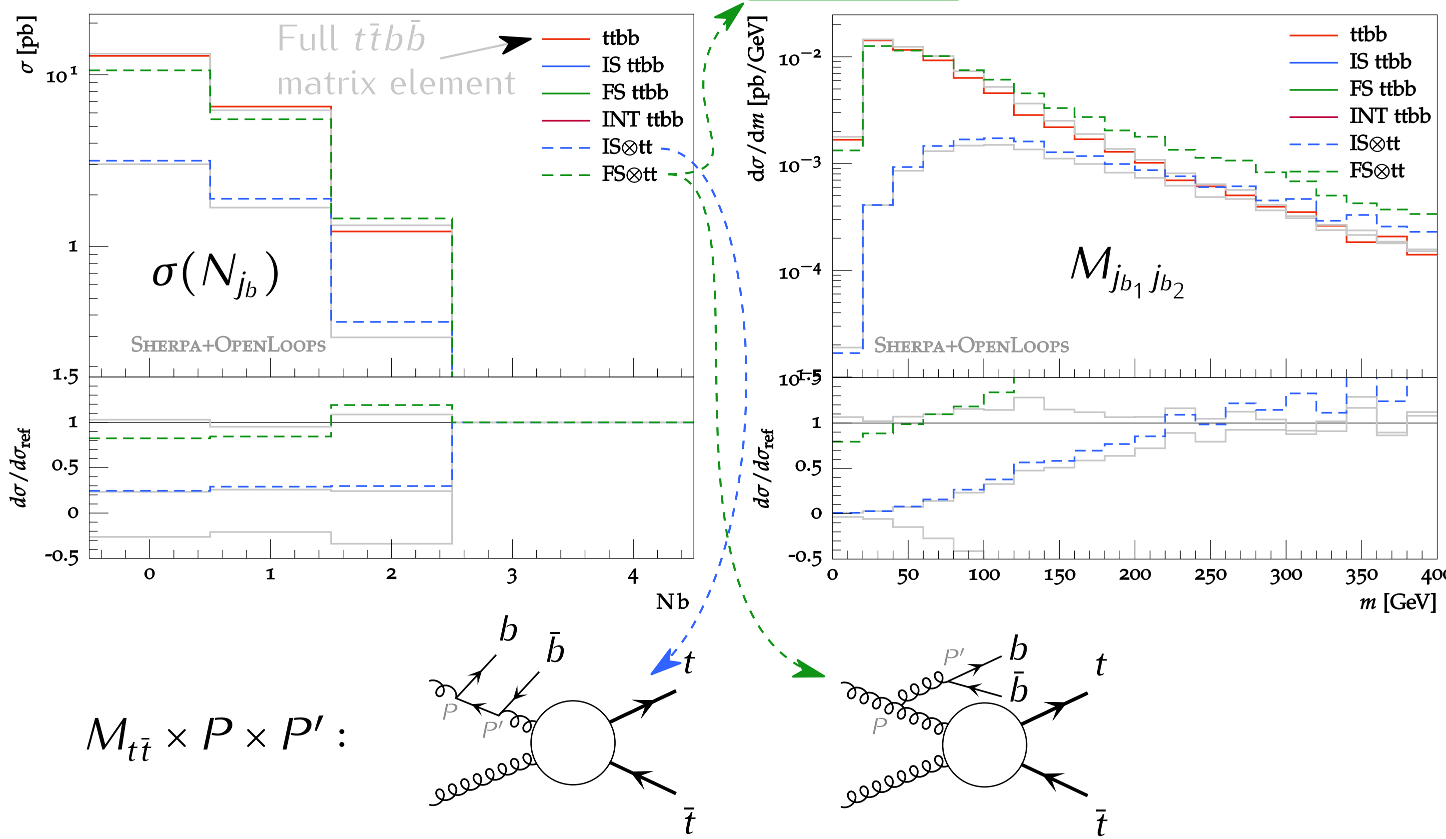

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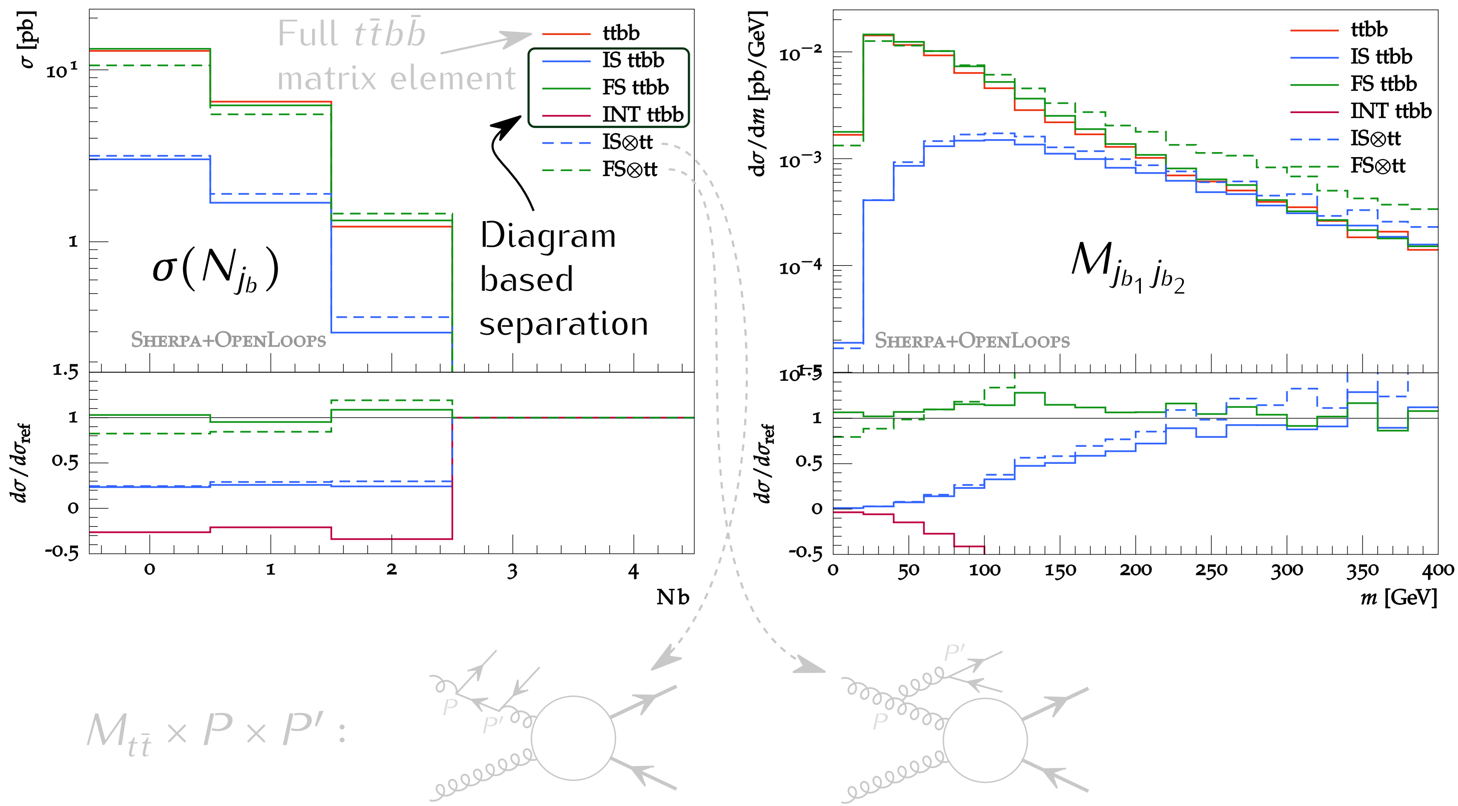

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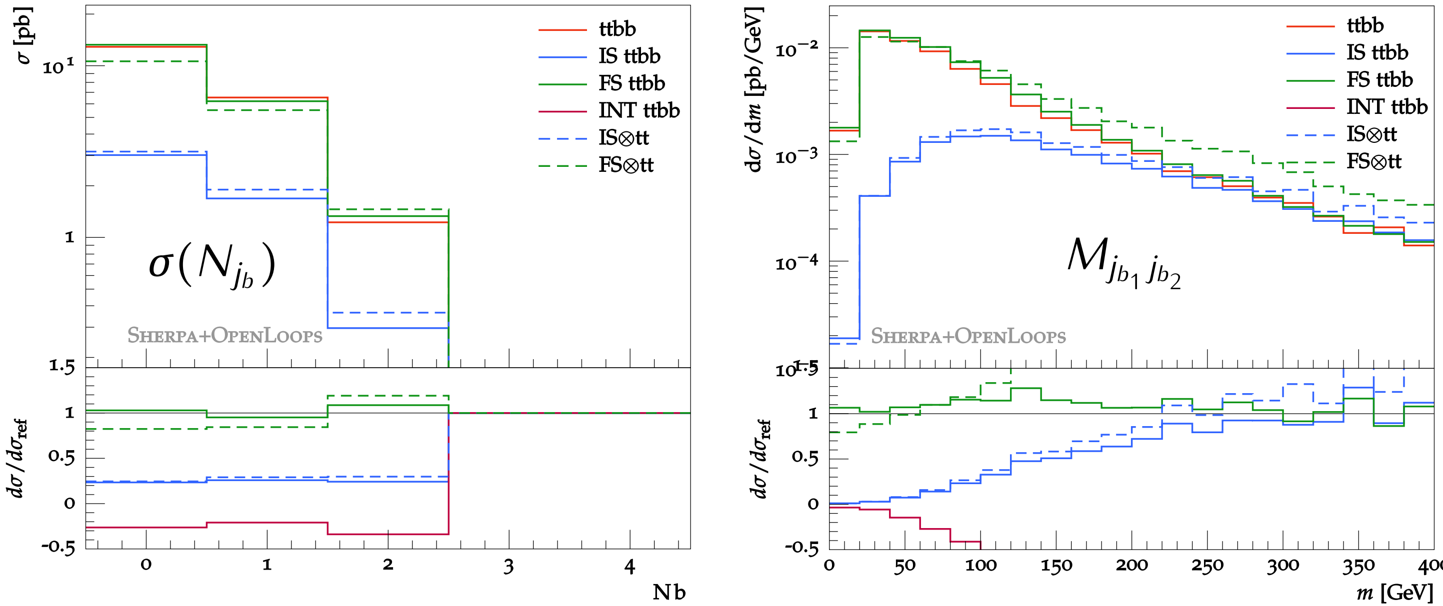


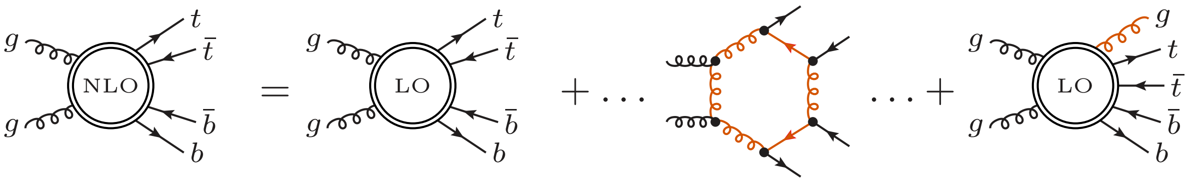
- FS $g \to b\bar{b}$ dominant, also away from collinear regime
- IS $g \to b\bar{b}$ subdominant (no need for 5F resummation)

supports choice of 4F scheme with $m_b > 0$ and no b-quark PDF

QCD production of $t\bar{t}b\bar{b}$ @NLO

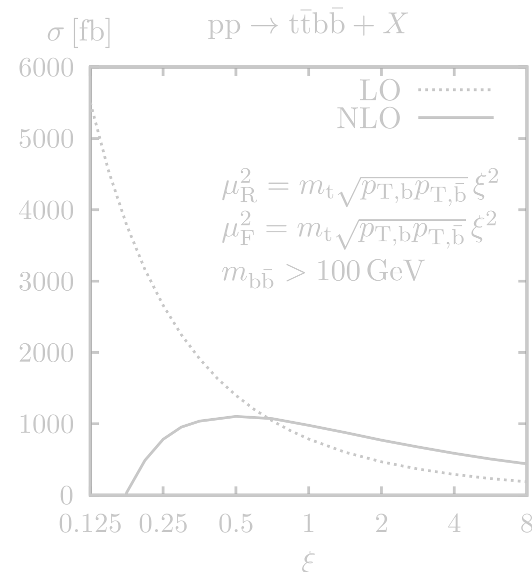
UZH

- $t\bar{t}b\bar{b}$ @ NLO QCD:



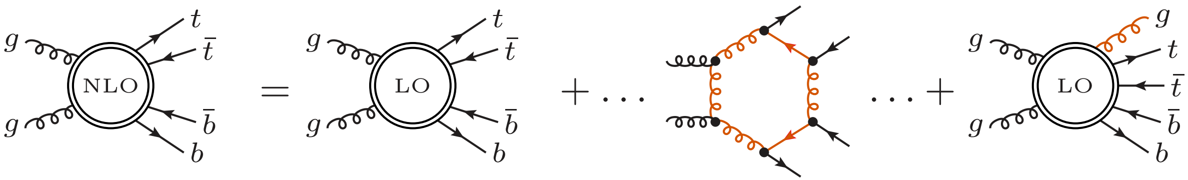
  - 5FNS ($m_b = 0$): [Bredenstein et al. '09–'10; Bevilacqua et al. '10]
  - 4FNS ($m_b > 0$): [Cascioli et al. '13]

- $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R) \Rightarrow$ scale uncertainity:
  - $\sim 80\%$ @ LO
  - $20 - 30\%$ @ NLO
- NLO+PS predictions mandatory for realistic analysis



QCD production of $t\bar{t}b\bar{b}$ @NLO

- $t\bar{t}b\bar{b}$ @ NLO QCD:



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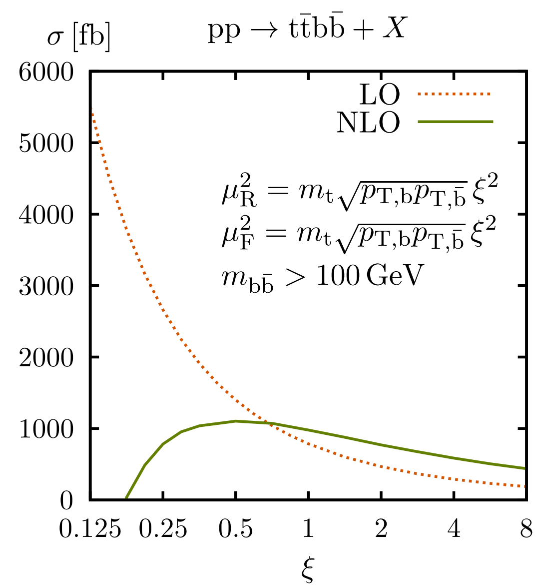

QCD production of $t\bar{t}b\bar{b}$ @NLO+PS

- Available $t\bar{t}b\bar{b}$ calculations @NLO+PS:

  - `Powhel` [Garzelli et al. '13/'14]
    - POWHEG matching
    - 5F scheme, $m_b = 0$
    - requires a generation cut

  - `Sherpa+OpenLoops` [Cascioli et al. '13]
    - S-MC@NLO matching
    - 4F scheme, $m_b > 0$

  - `POWHEG-BOX+OpenLoops` [upcoming]
    - POWHEG matching
    - 4F scheme, $m_b > 0$

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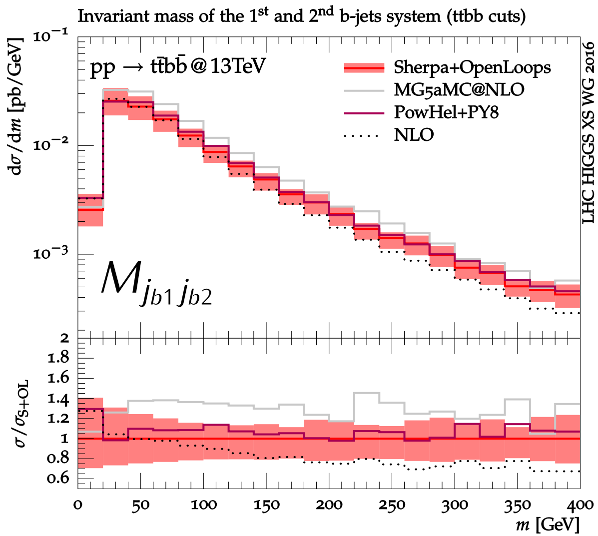
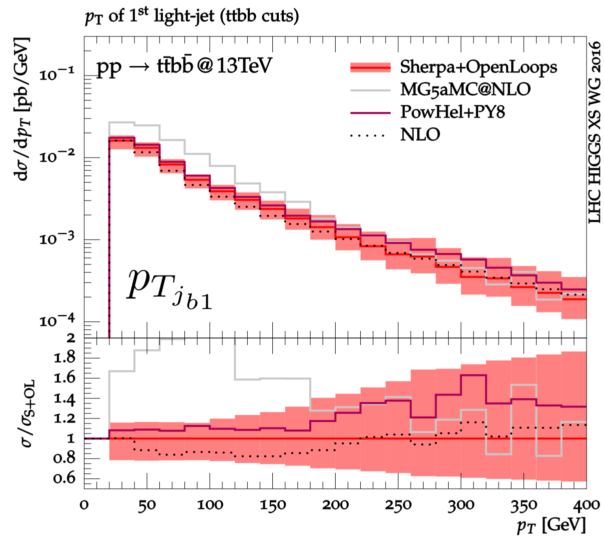
MEs cannot describe quasi-collinear $g \to b\bar{b}$ splittings

MEs cover full b-quark phase space

Why another $t\bar{t}b\bar{b}$ @NLO+PS?

- YR4 [arXiv:1610.07922]:





- `Sherpa+OpenLoops` vs. `PowHel+PY8`
  - Good agreement also in observables with large NLO+PS corrections
- `Sherpa+OpenLoops` vs. `MG5_aMC@NLO+PY8` [arXiv:1405.0301]
  - Sizable differences in NLO radiation pattern
  - Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$+jet in `MG5_aMC@NLO+PY8`

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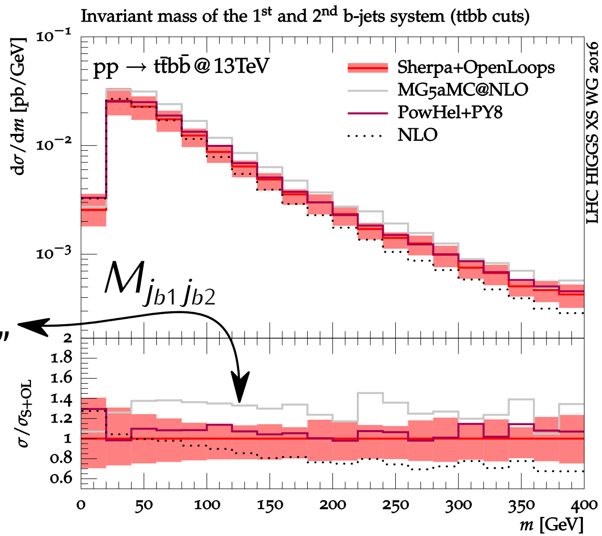
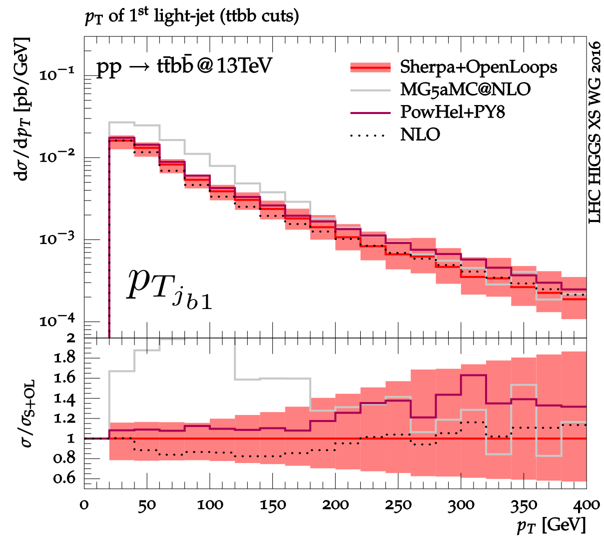


"double-splitting"



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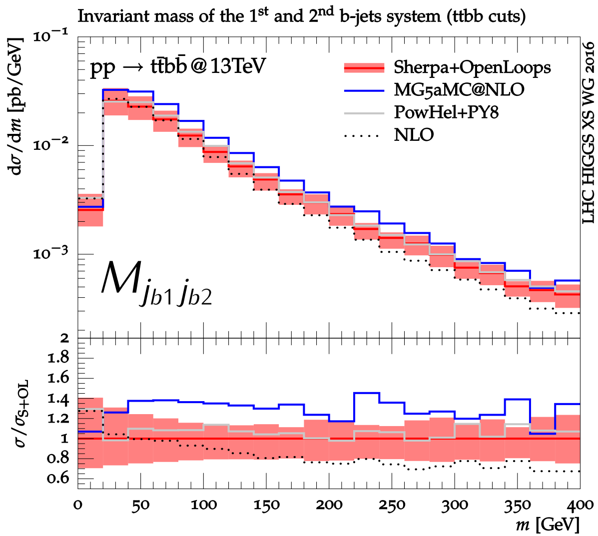
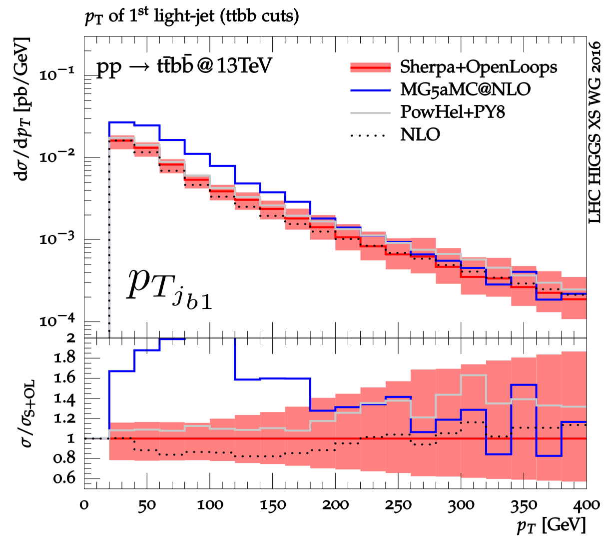
  - Sizable differences in NLO radiation pattern
  - Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$+jet in `MG5_aMC@NLO+PY8`

Why another $t\bar{t}b\bar{b}$ @NLO+PS?

- YR4 [arXiv:1610.07922]:





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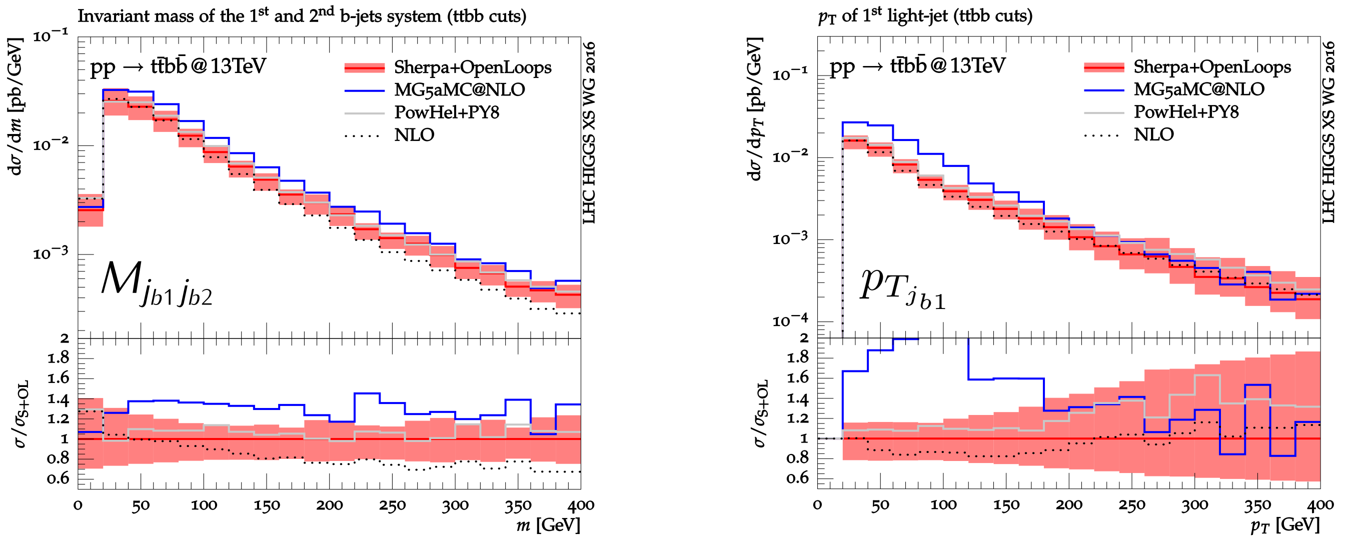

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  - Sizable differences in NLO radiation pattern
  - Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$+jet in MG5_aMC@NLO+PY8
  - New: MG5_aMC@NLO+HW++ in good agreement with Sherpa+OpenLoops

Why another $t\bar{t}b\bar{b}$ @NLO+PS?

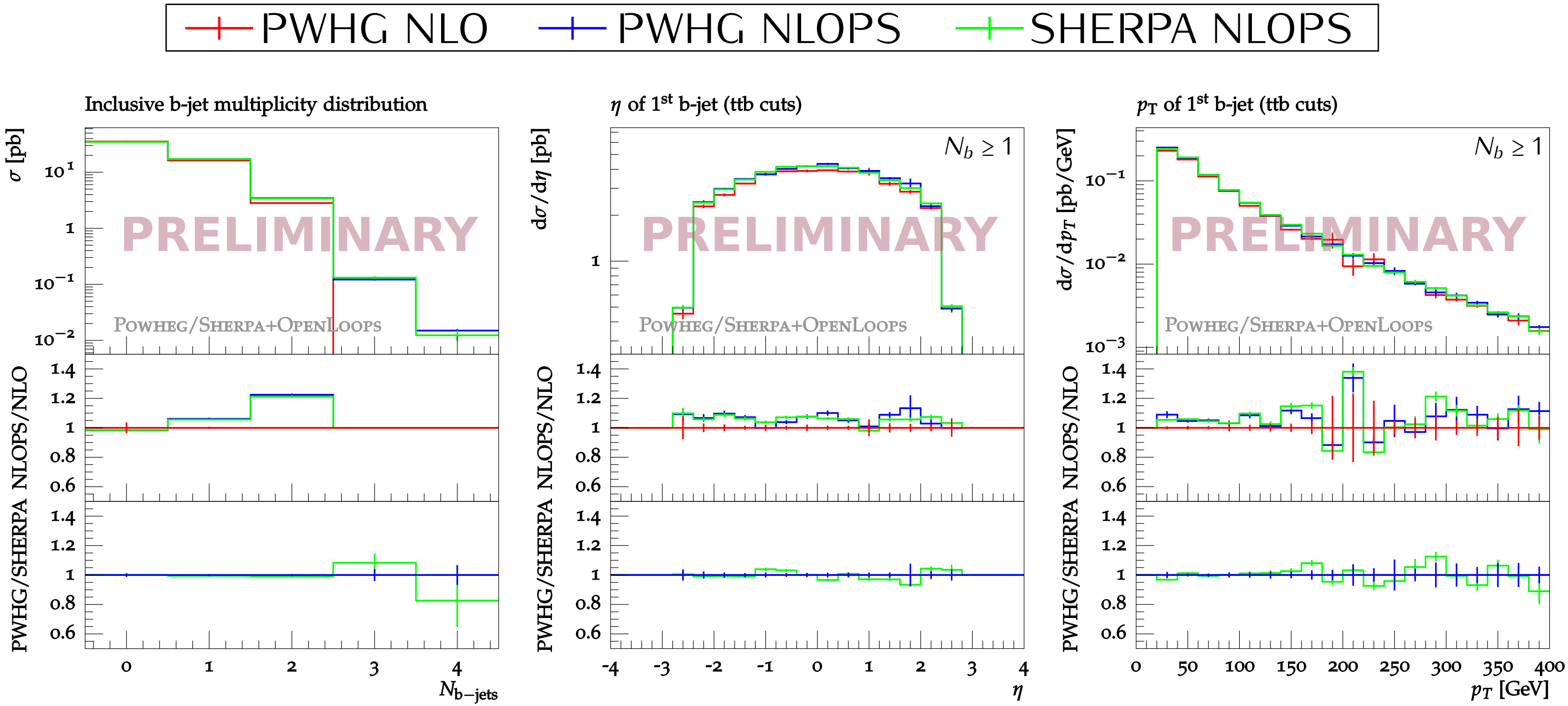
- Sherpa+OpenLoops vs. MG5_aMC@NLO+PY8
  - Sizable differences in NLO radiation pattern
  - Considerable resummation-scale sensitivity in MG5_aMC@NLO+PY8
  - Strong shower dependence in MG5_aMC@NLO (PY8 vs HW++)

$$\stackrel{?}{\Longrightarrow}$$

Surprisingly large matching/shower uncertainity? Issue in either Sherpa or MG5_aMC@NLO?

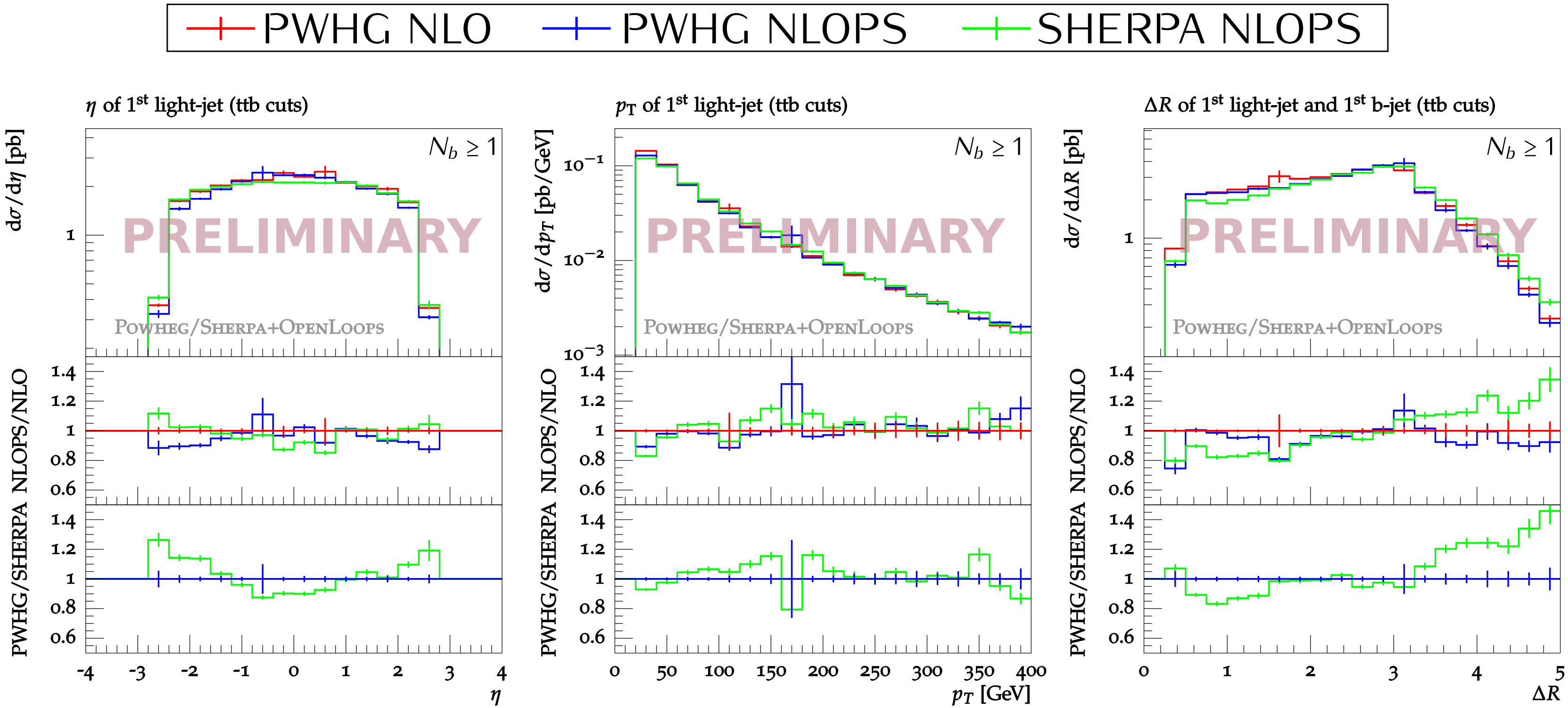
- How about we try a different matching method?
  - NLO+PS matching with POWHEG BOX (no resum.-scale dependence)
  - Matrix elements from OpenLoops
  - 4F scheme: $m_b > 0$ and no b PDF
  - Compare against Sherpa and study hdamp and shower dependence

POWHEG BOX vs SHERPA



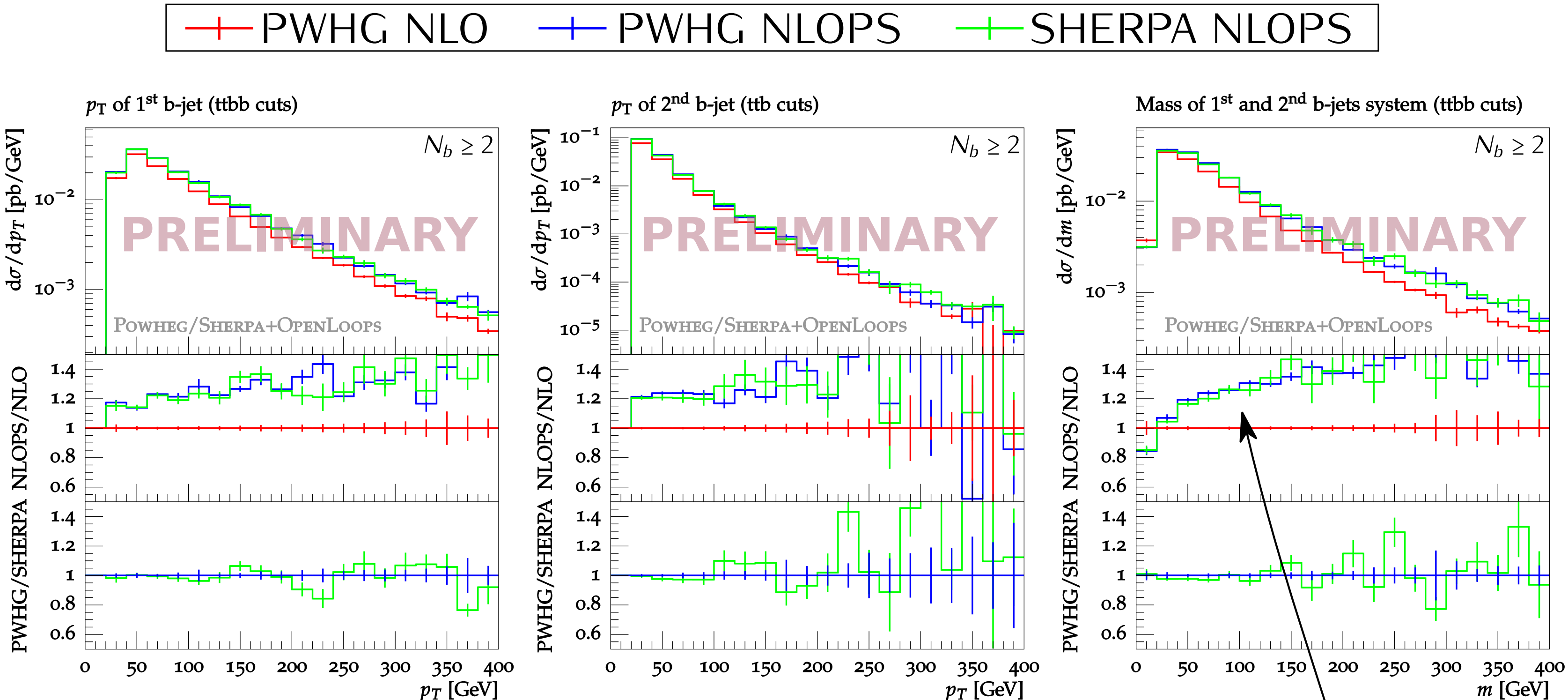
- Remarkable agreement for NLO accurate ttb observables
  - Agreement well under 5%; expected scale uncertainity ~20%
- Good agreement also in LOPS accurate bins 3 and 4 of $\sigma(N_{b-\text{jets}})$

POWHEG BOX vs SHERPA



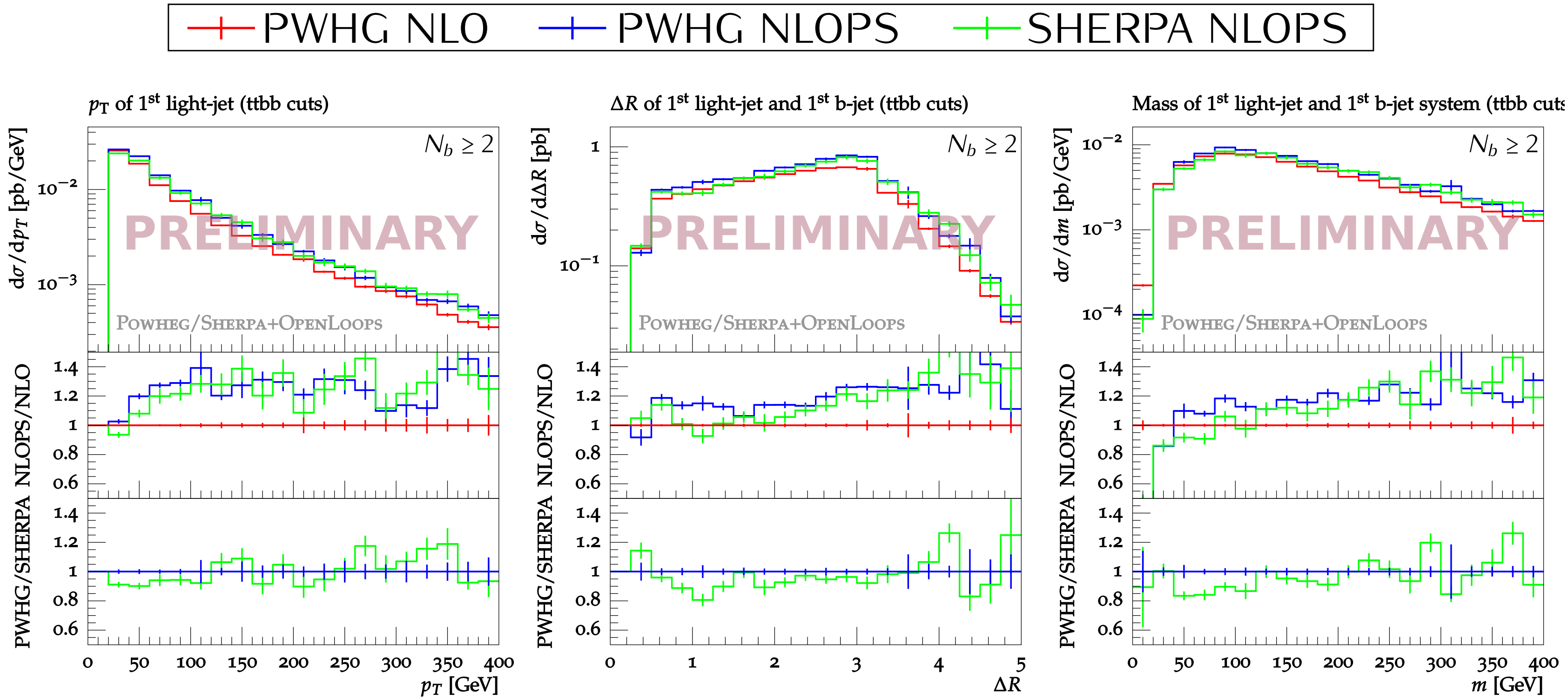
- Good agreement for LOPS accurate ttbj observables
  - Agreement to ~20%; expected scale uncertainity ~50%

POWHEG BOX vs SHERPA



- Remarkable agreement for NLO accurate ttbb observables
  - Agreement well under 5%; expected scale uncertainity ~20%
- POWHEG BOX RES confirms the “double splitting” enhancement

POWHEG BOX vs SHERPA



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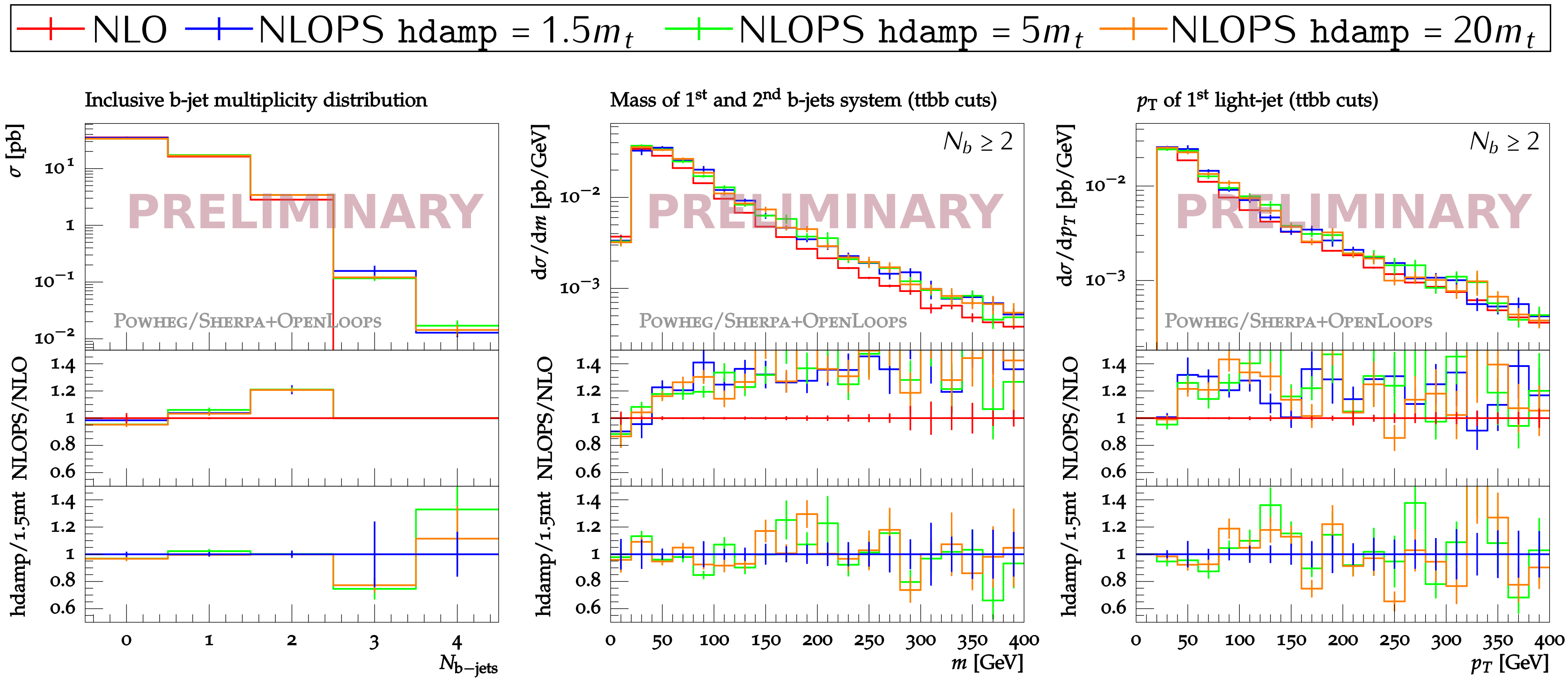
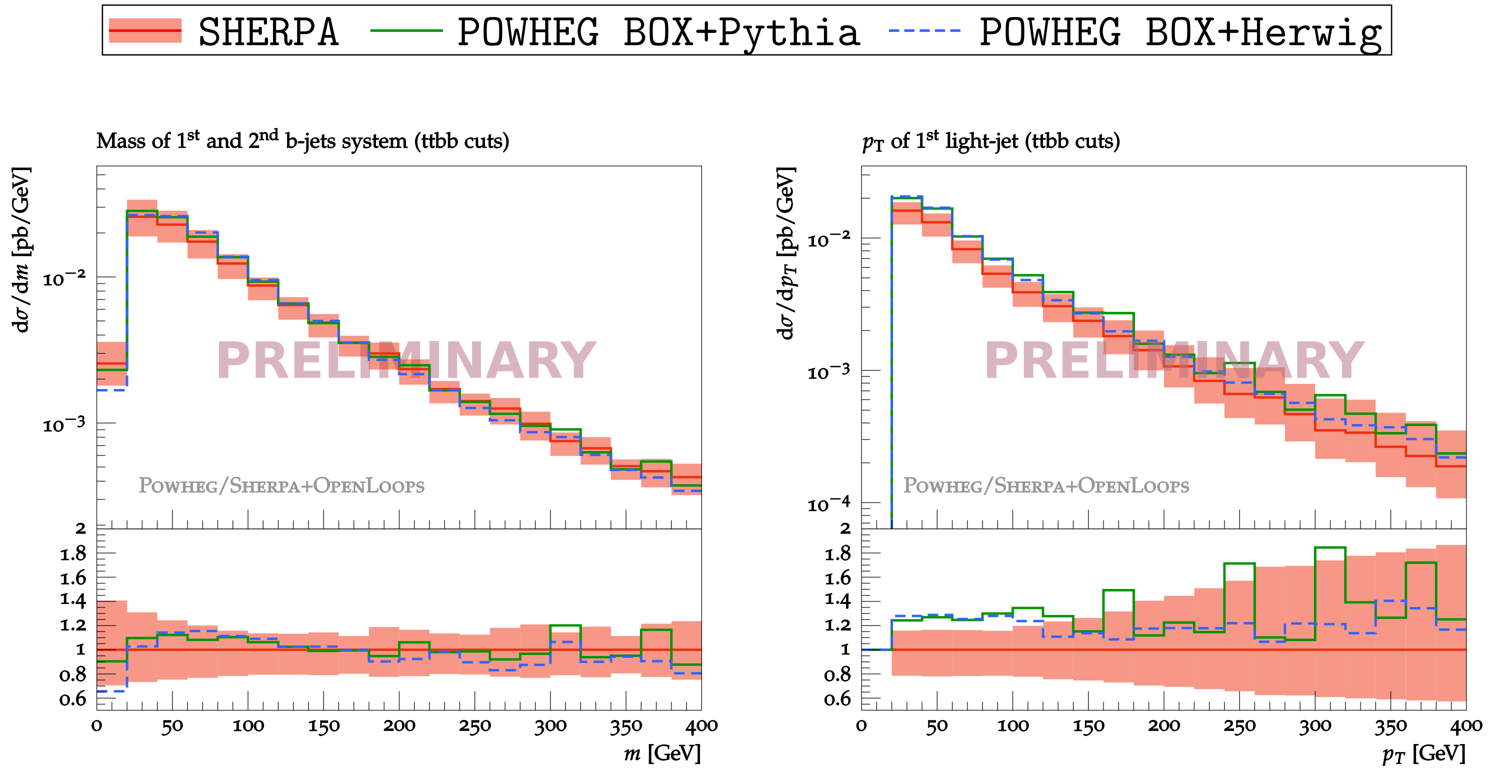
hdamp dependence



- Both NLO and LOPS accurate observables very stable with respect to hdamp†
  - Variations of at most 10% are observed

†hdamp applied also to final state massive emitters

Shower dependence



- Remarkable stability with respect to the choice of shower (`Pythia 8.210` vs. `Herwig 7.1.0`)

Conclusions

- $t\bar{t}b\bar{b}$ @NLO+PS preferable option for $t\bar{t}+b$-jet simulations
  - 4F scheme provides access to full $g \to b\bar{b}$ splitting phase space
  - 5F scheme resummation not too imporant because IS $g \to b\bar{b}$ subdominant

- Theory uncertainity of $t\bar{t}b\bar{b}$ bottleneck for $t\bar{t}H(b\bar{b})$ searches
  - HXSWG YR4 MC comparisons reveal significant matching/shower dependence
  - We now have three independent $t\bar{t}b\bar{b}$ 4F generators: `Sherpa`, `MG5_aMC@NLO`, `POWHEG BOX` (new!)
  - First results: `POWHEG BOX` shows good agreement with `Sherpa` and very mild `hdamp` and shower dependence

hdamp

- POWHEG radiation formula:

$$d\sigma = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\rm cut}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha^s(\Phi_\alpha(\Phi_B, \Phi_{\rm rad}))}{B(\Phi_B)}\, d\Phi_{\rm rad} \right] + (R_\alpha^r \text{contr.})$$

  - where $R_\alpha = R_\alpha^s + R_\alpha^r$
- Separation of the real contribution introduced to deal with "Born zeroes"
  - `if ( r0.gt.5*abs(rc+rs-rcs) ) then` ... R_α^r
  - `else` ... R_α^s
- More sophisticated separation introduced in the present form:

$$R_\alpha^s = R_\alpha F(k_T^2)\,, \qquad R_\alpha^r = R_\alpha \left[1 - F(k_T^2)\right]\,, \qquad F(k_T^2) = \frac{h^2}{k_T^2 + h^2}$$

- In top-pair production chosing `hdamp` $\sim m_t$ improves the description of the data
  - ATLAS tunes `hdamp` $= 1.5 m_t$, CMS sets to the same value

hdamp

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singular

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maybe be thought of as an analogue to μ_Q in MC@NLO

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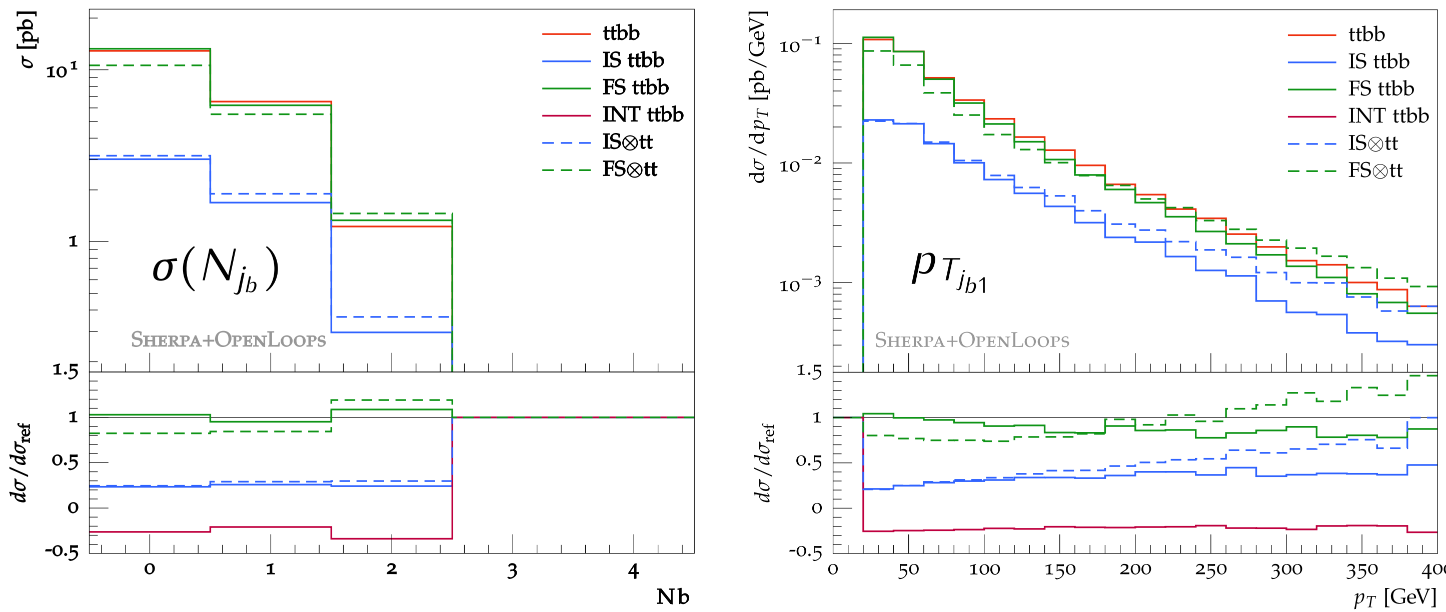
- In $t\bar{t}b\bar{b}$:
  - Default behaviour of `hdamp` needs modifying:
    - Default “`hdamp` applied only to IS” manifests convergence issues
    - We apply `hdamp` also to massive FS, with $\texttt{hdamp}_{\rm IS}$ and $\texttt{hdamp}_{\rm FS}$ independent
    - Further investigation underway
    - New `POWHEG BOX RES` features could be exploited for better understanding of the `hdamp` dependence

QCD production of $t\bar{t}b\bar{b}$

UZH

- Key features of 4F $pp \to t\bar{t}b\bar{b}$:
  - Dominated by topologies with FS $g \to bb$ splittings



- FS $g \to b\bar{b}$ dominant, also away from collinear regime
- IS $g \to b\bar{b}$ subdominant (no need for 5F resummation)

supports choice of 4F scheme with $m_b > 0$ and no b-quark PDF