

NLO+PS $t\bar{t}b\bar{b}$ in Powheg+OpenLoops

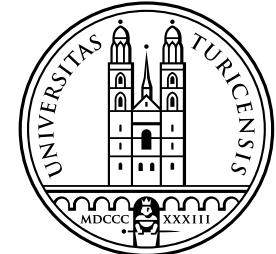
Tomáš Ježo

University of Zürich

In collaboration with:

J. Lindert, N. Moretti and S. Pozzorini

Common meeting on $t\bar{t} + b$ -jet backgrounds
to $t\bar{t}H(b\bar{b})$, November 6th 2017



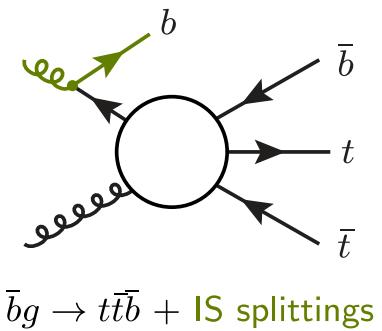
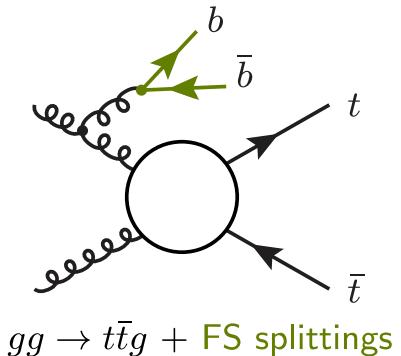
**Universität
Zürich^{UZH}**

Outline and goal

- We perform NLO+PS matching of $pp \rightarrow t\bar{t}b\bar{b}$ with the POWHEG method
 - ▶ Using 4 flavour number scheme
 - ▶ includes b -quark mass effects
 - ▶ makes the full $t\bar{t}b$ -jet phase space available
 - ▶ Employing the brand new POWHEG BOX RES [T.J., Nason 2015]
 - ▶ allows the choice of the most suitable FKS mapping
- Here I present a progress update
 - ▶ Comparison against Sherpa+OpenLoops [Cascioli et al. 2013]
 - ▶ Stability with respect to the choice of SMC
 - ▶ Shower sensitivity: $t\bar{t}$ vs $t\bar{t}b\bar{b}$
 - ▶ Dependence on `hdamp`

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

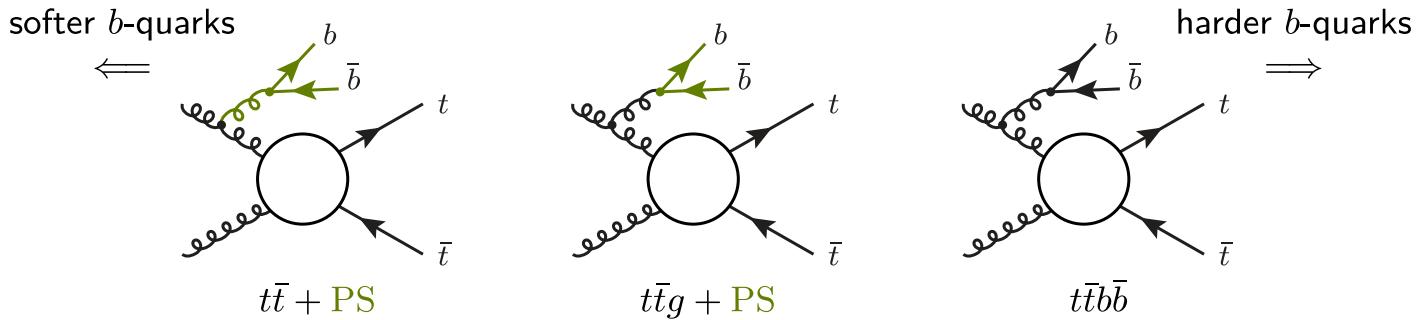
- Option 1: NLO+PS $t\bar{t}$ 5F
 - ▶ $t\bar{t}j$ tree MEs + $g \rightarrow b\bar{b}$ shower splittings



- ▶ 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 uncertainty estimates

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

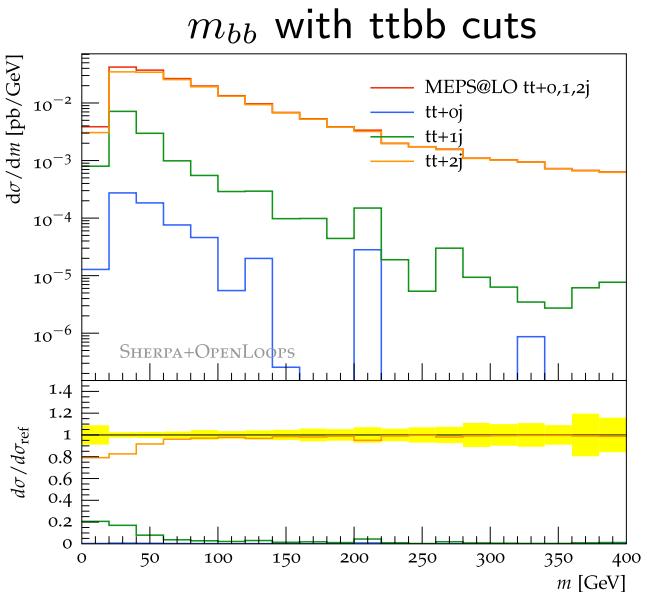
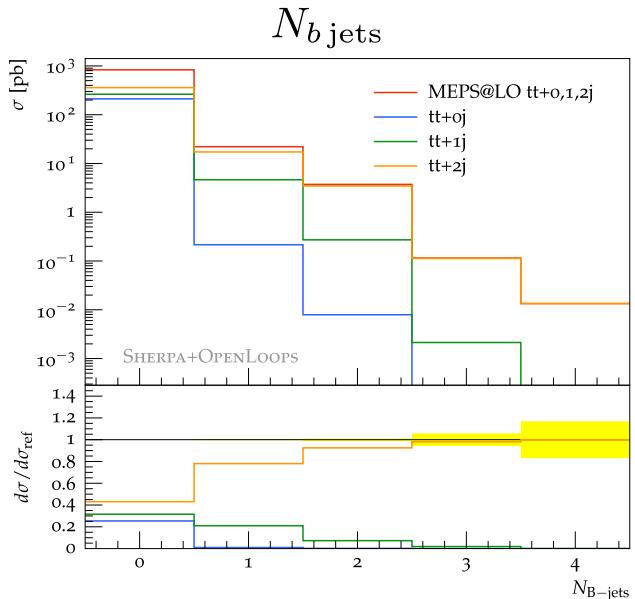
- Option 1: NLO+PS $t\bar{t}$ 5F ... insufficient precision
- Option 2: (N)LO merging $t\bar{t} + 0, 1, 2$ jets 5F
 - ▶ $t\bar{t} + 0, 1, 2$ jet MEs and $g \rightarrow b\bar{b}$ splittings



- ▶ 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?

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

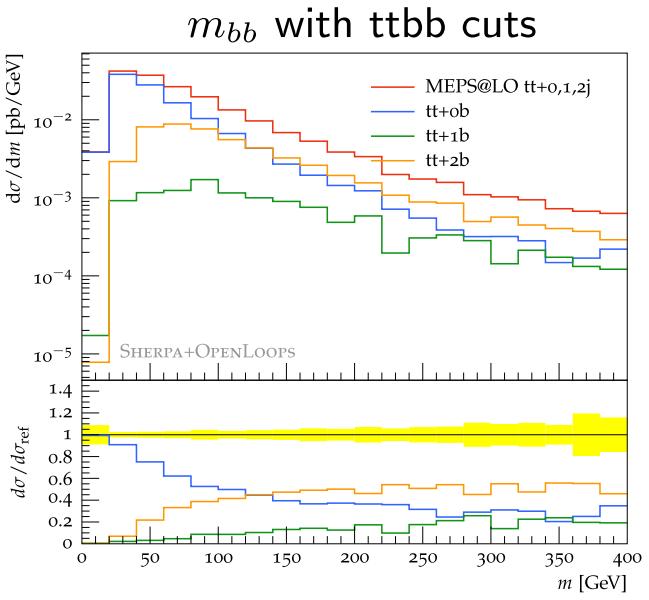
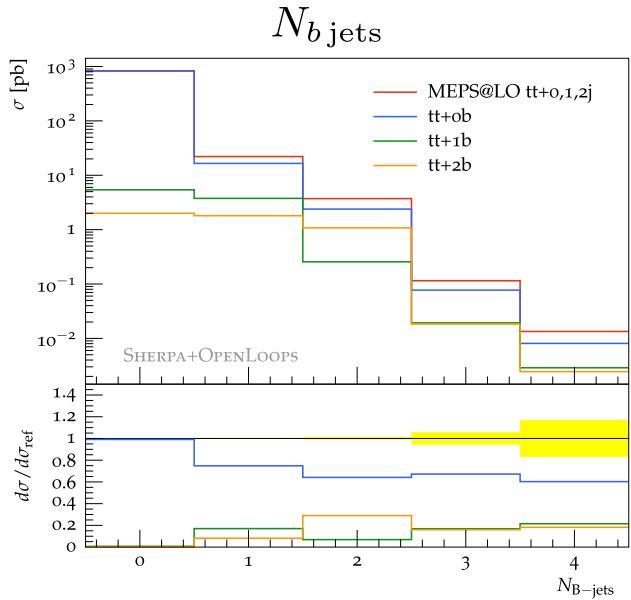
- $t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\text{cut}} = 20$ GeV



- 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

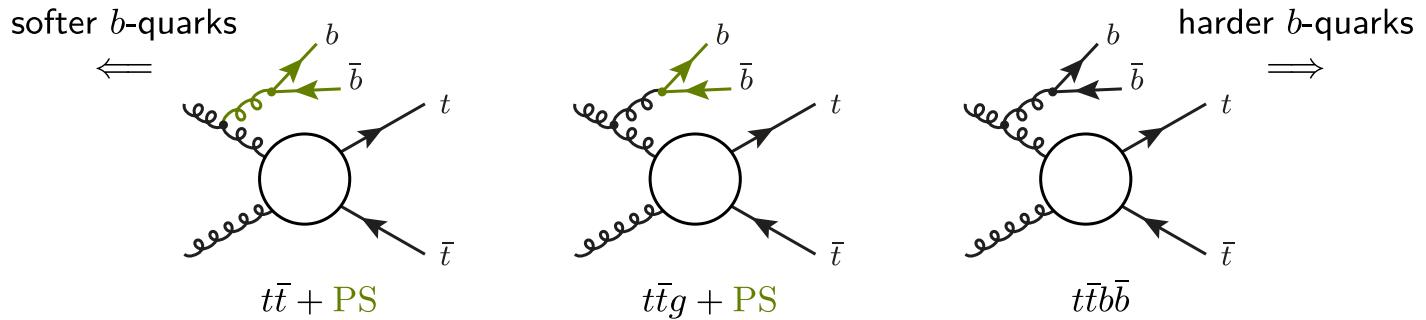
- $t\bar{t} + 0, 1, 2$ jet LO merging with $Q_{\text{cut}} = 20$ GeV



- 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 $g \rightarrow b\bar{b}$ splittings



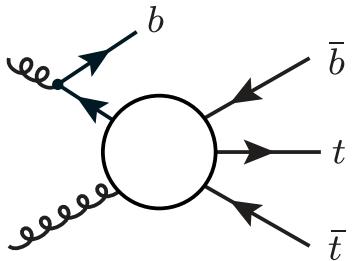
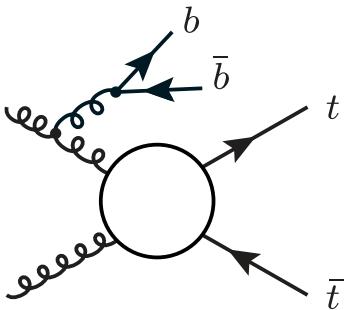
- ▶ Precision and CPU cost strongly dependent on the merging cut Q_{cut}
- ▶ Does this describe $t\bar{t} + b$ -jets mostly through $t\bar{t}b\bar{b}$ MEs though?

No!

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

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

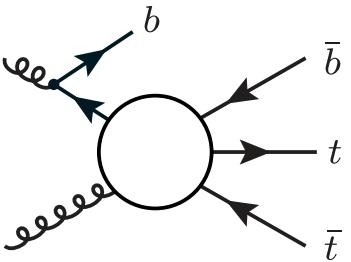
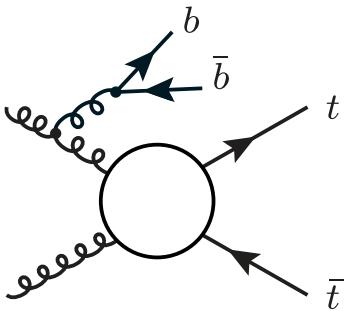
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- Option 3: $t\bar{t}b\bar{b}$ at NLO+PS



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

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

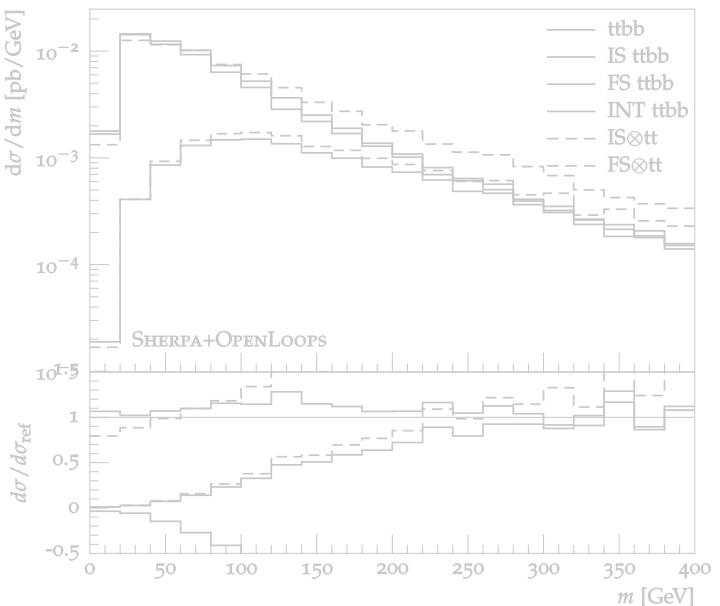
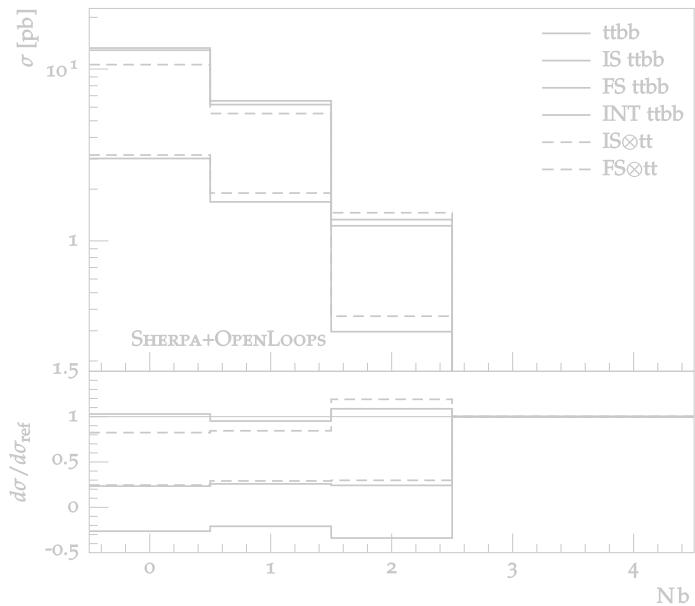
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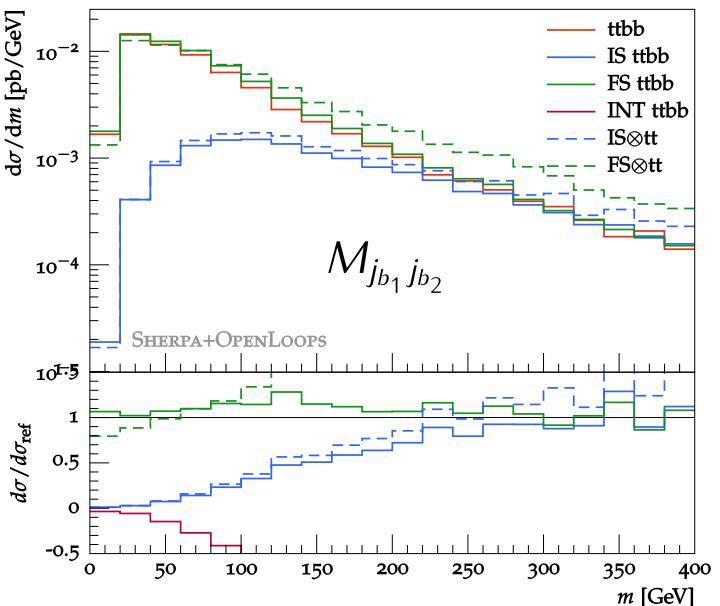
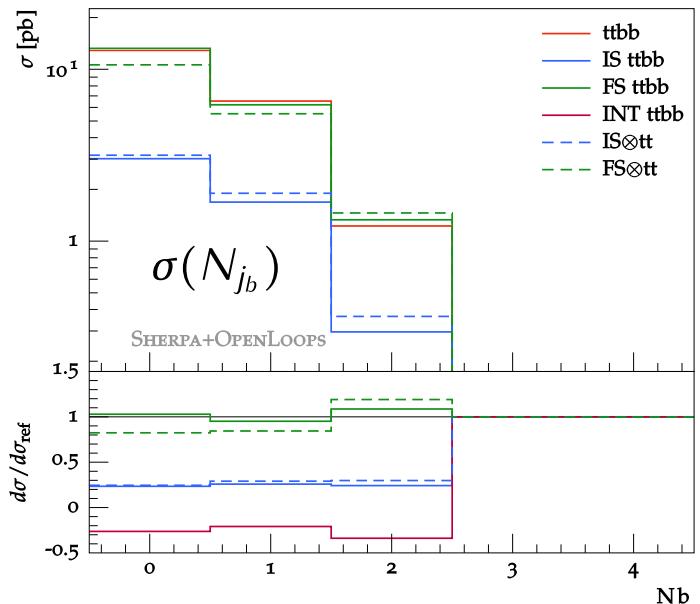
QCD production of $t\bar{t}b\bar{b}$

- Key features of 4F $pp \rightarrow t\bar{t}b\bar{b}$:
 - ▶ 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 $g \rightarrow bb$ splittings



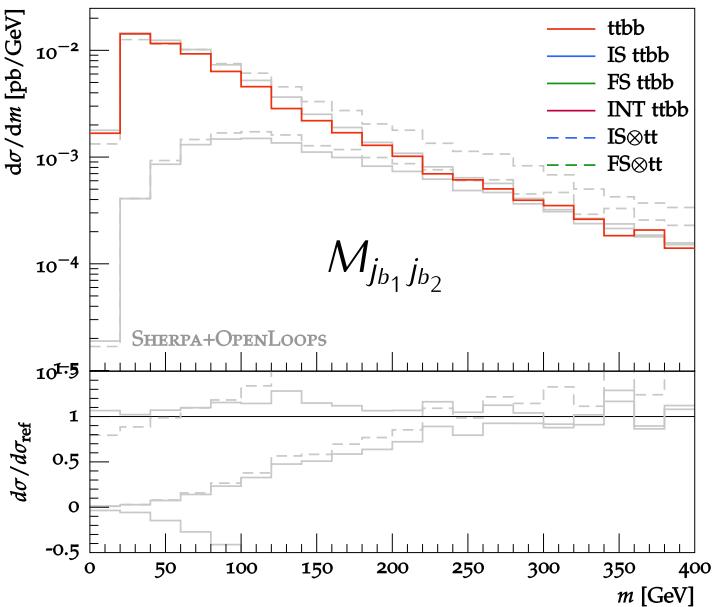
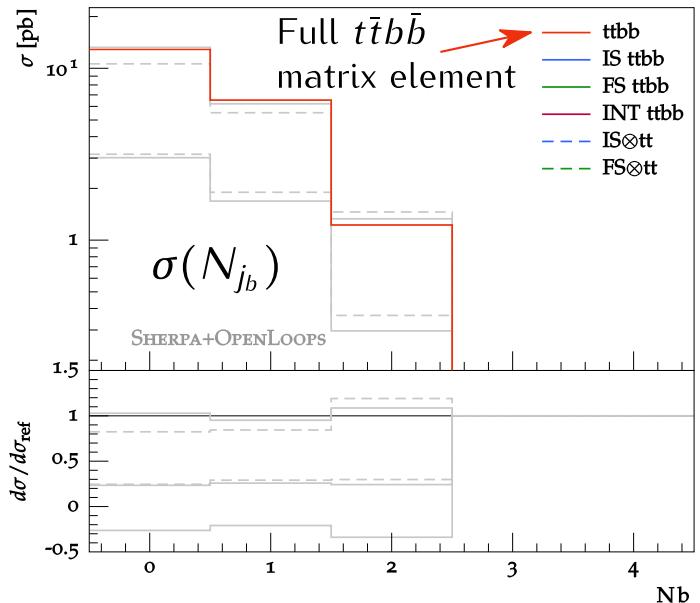
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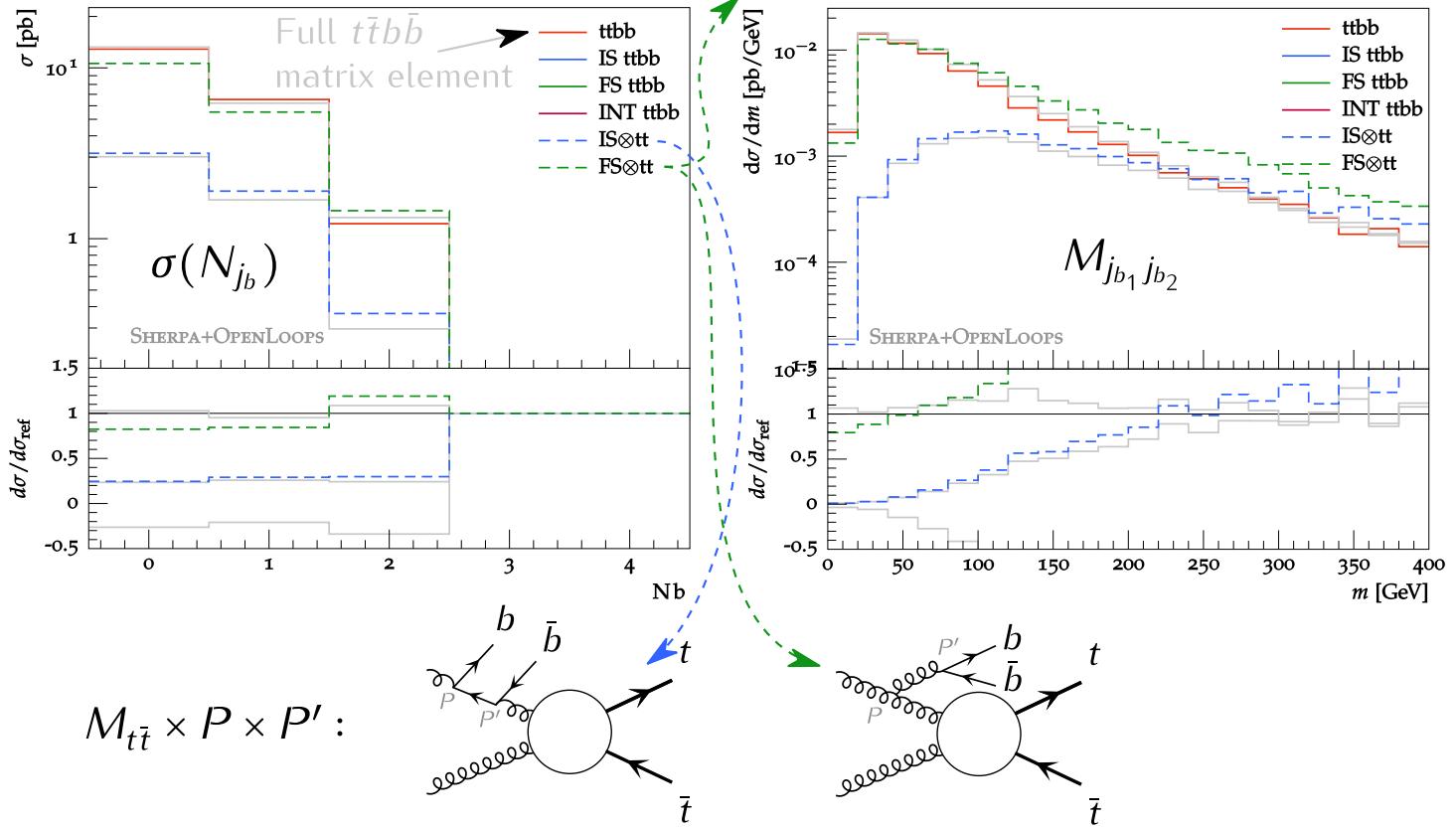
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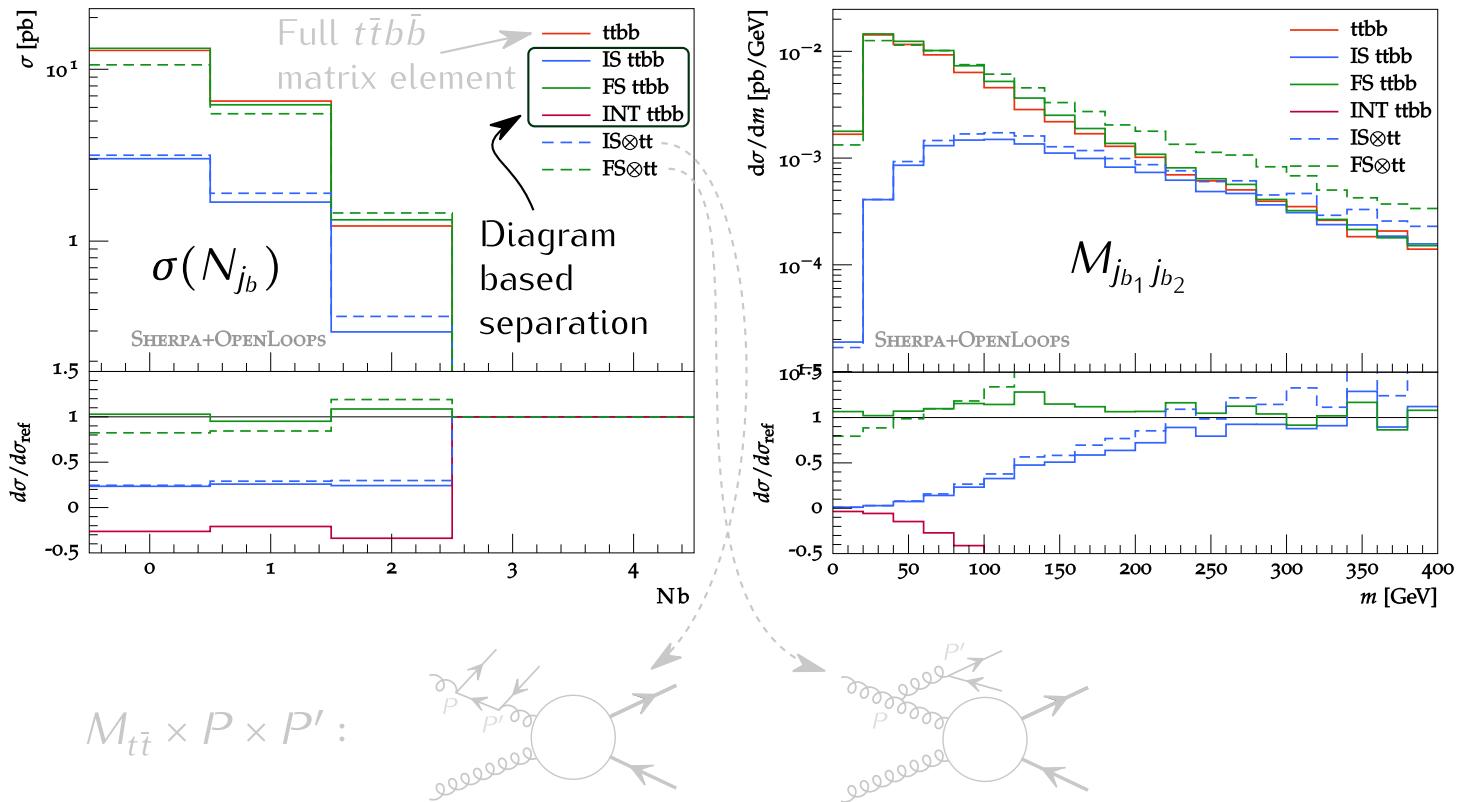
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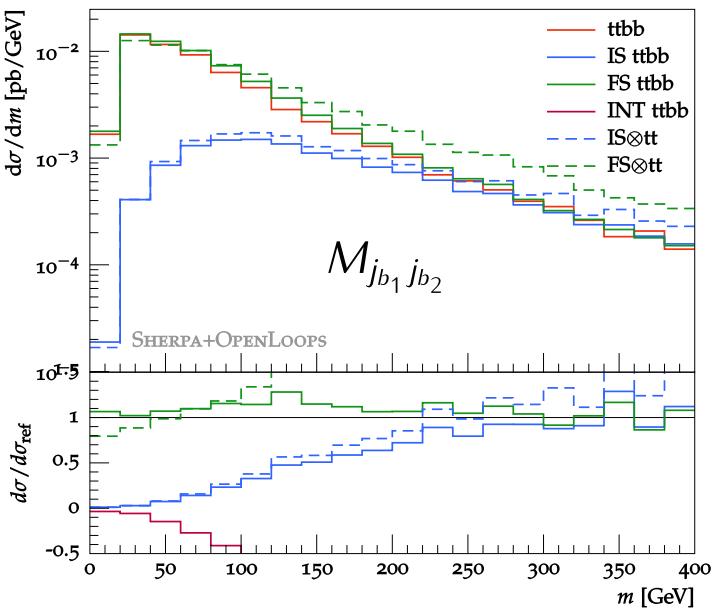
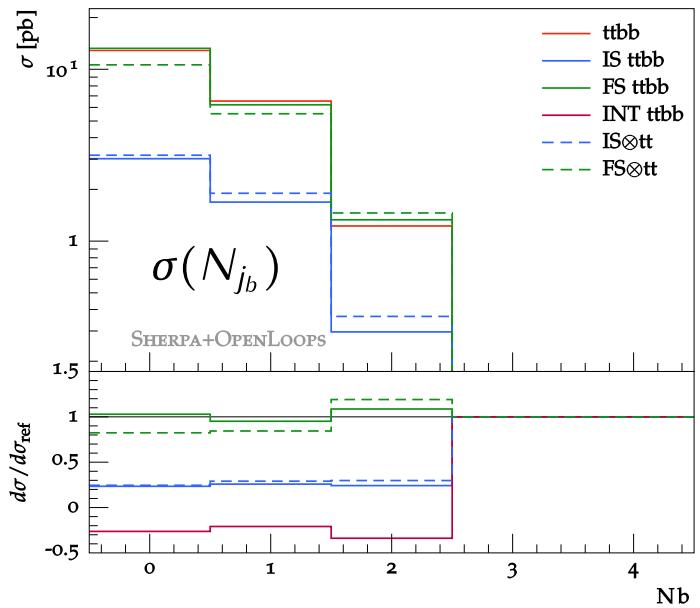
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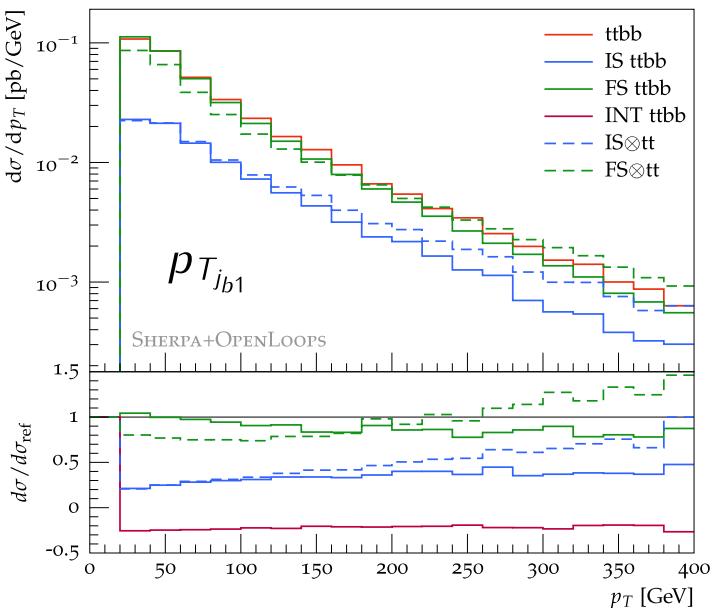
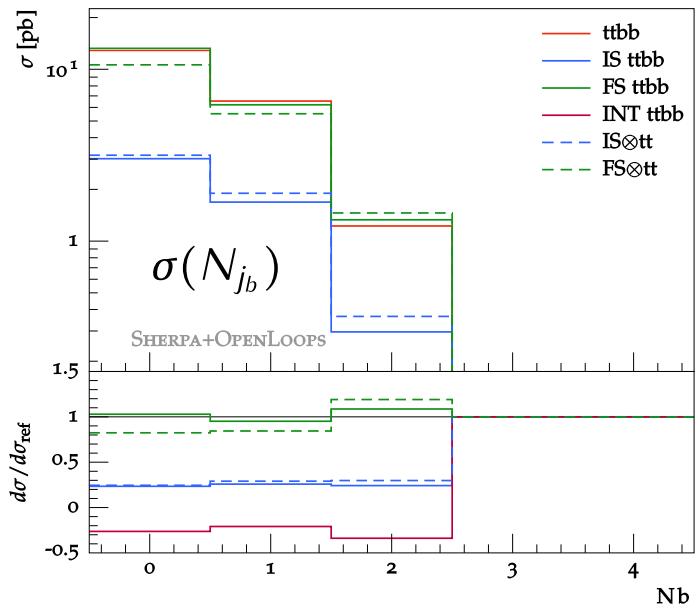


- FS $g \rightarrow b\bar{b}$ dominant, also away from collinear regime
- IS $g \rightarrow b\bar{b}$ subdominant (no need for 5F resummation)

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

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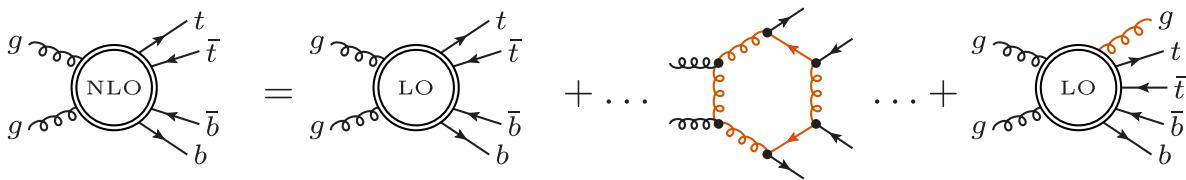


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QCD production of $t\bar{t}b\bar{b}$ @NLO

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

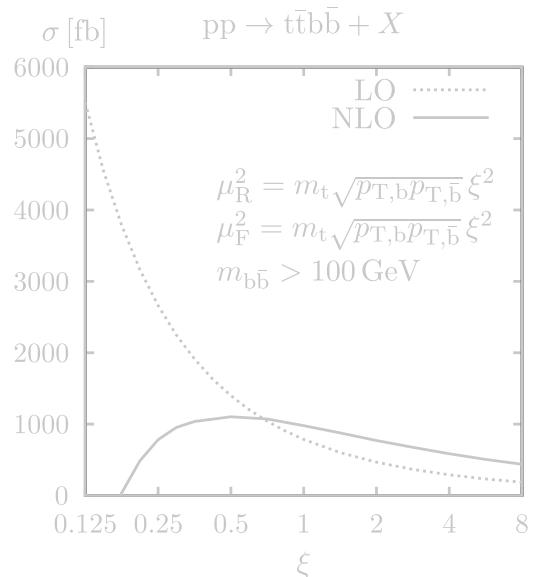


- ▶ 5FNS ($m_b = 0$): [Bredenstein et al. '09-'10; Bevilacqua et al. '10]
- ▶ 4FNS ($m_b > 0$): [Cascioli et al. '13]

- $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R)$ \Rightarrow scale uncertainty:

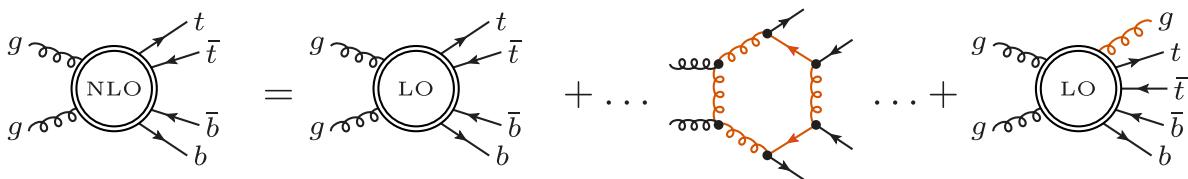
- ▶ $\sim 80\%$ @ LO
- ▶ $20 - 30\%$ @ NLO

- NLO+PS predictions mandatory for realistic analysis



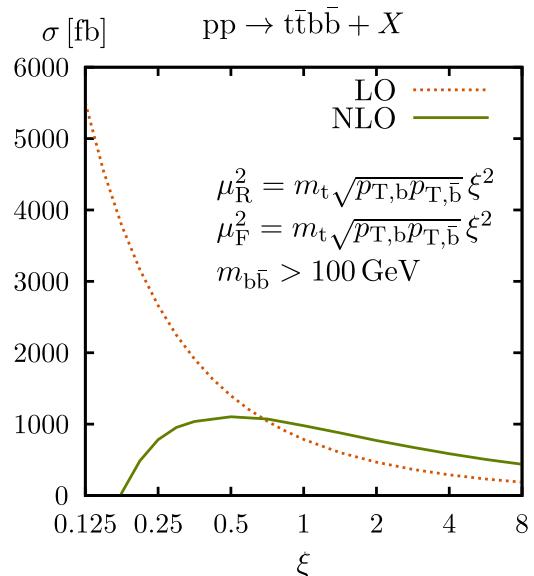
QCD production of $t\bar{t}b\bar{b}$ @NLO

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



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



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



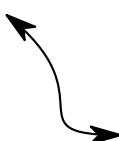
- Available $t\bar{t}b\bar{b}$ calculations @NLO+PS:
 - ▶ Powhel [Garzelli et al. '13/'14]
 - ▷ POWHEG matching
 - ▷ 5F scheme, $m_b = 0$
 - ▷ requires a generation cut
 - ▶ Sherpa+OpenLoops [Cascioli et al. '13]
 - ▷ S-MC@NLO matching
 - ▷ 4F scheme, $m_b > 0$
 - ▶ PowHel [Bevilacqua et al. '17]
 - ▷ POWHEG matching
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 - ▶ POWHEG-BOX+OpenLoops [T.J. et al. upcoming]
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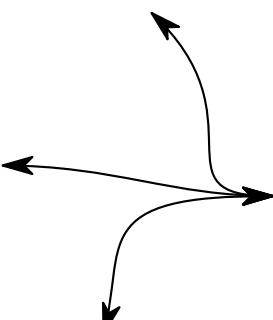
- ▶ POWHEG matching
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MEs cannot describe quasi-collinear $g \rightarrow b\bar{b}$ splittings

- ▶ Sherpa+OpenLoops [Cascioli et al. '13]

- ▶ S-MC@NLO matching
 - ▶ 4F scheme, $m_b > 0$



MEs cover full b -quark phase space

- ▶ PowHel [Bevilacqua et al. '17]

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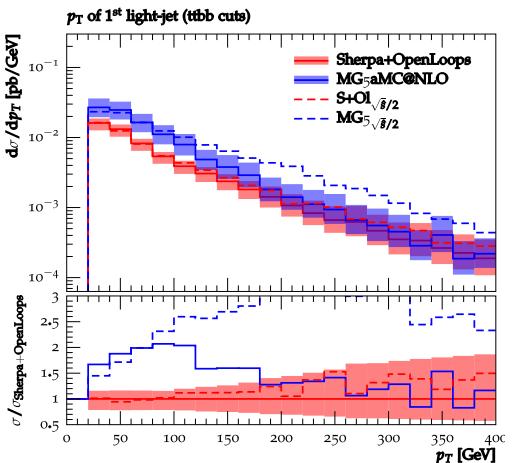
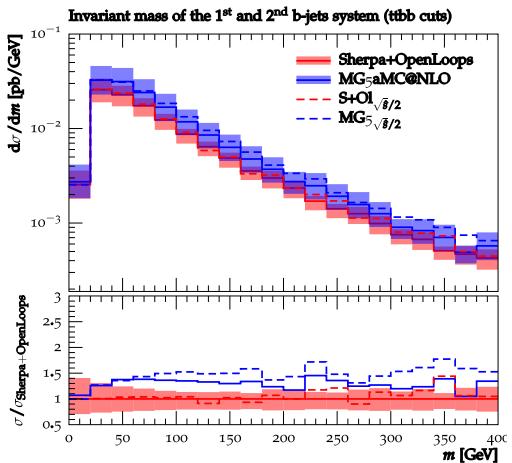
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This talk

Motivations

Dependence on resummation scale μ_Q



Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

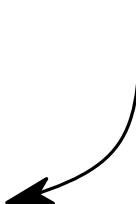
- MG5_aMC supports only* $\mu_Q = f(\xi)\sqrt{\hat{s}} \Rightarrow$ smearing function restricted to $0.1 < f(\xi) < 0.25$ to mimic recommended $\mu_Q = H_T/2$ implemented in Sherpa

μ_Q variations enhance the discrepancy

- $\mu_Q = \sqrt{\hat{s}}/2$ in Sherpa to mimic MG5_aMC default choice $0.1 < f(\xi) < 1$
- strong μ_Q -sensitivity of MG5_aMC \Rightarrow much more pronounced deviations

* Ongoing studies with new MG5 version supporting $H_T/2$. See talks by Zaro & Neu.

Pozzorini
July '17



Setup

- LHC 13 TeV
- 4F scheme
- NNPDF30_nlo_as_0118_nf_4
- α_S from 4F PDFs
- $m_t = 172.5 \text{ GeV}$, $m_b = 4.75 \text{ GeV}$
- $\mu_r = \mu_f = \sqrt{0.5 \sqrt{E_T^b E_T^{\bar{b}}} \sqrt{E_T^t E_T^{\bar{t}}}}$
- Top decay off, MPI off, Hadronization off, QED shower off
- Sherpa
 - ▶ $\mu_Q = H_T/2$
 - ▶ Default shower settings
- POWHEG BOX RES
 - ▶ $hdamp = 1.5m_t$
 - ▶ Pythia 8.2 with PowhegHooks, A14 tune

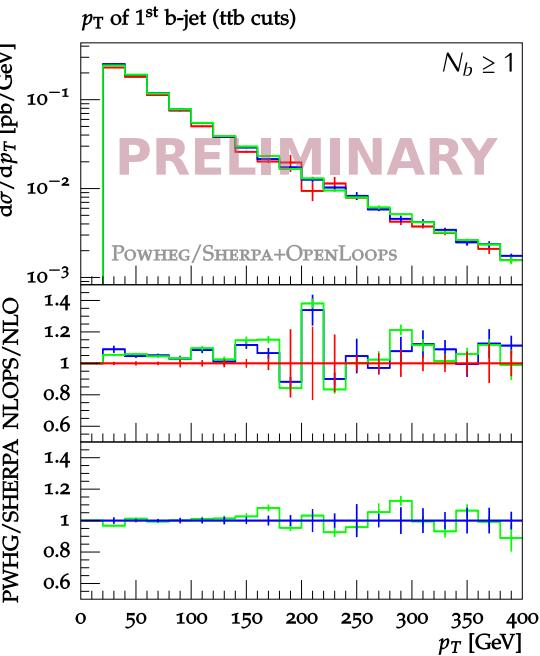
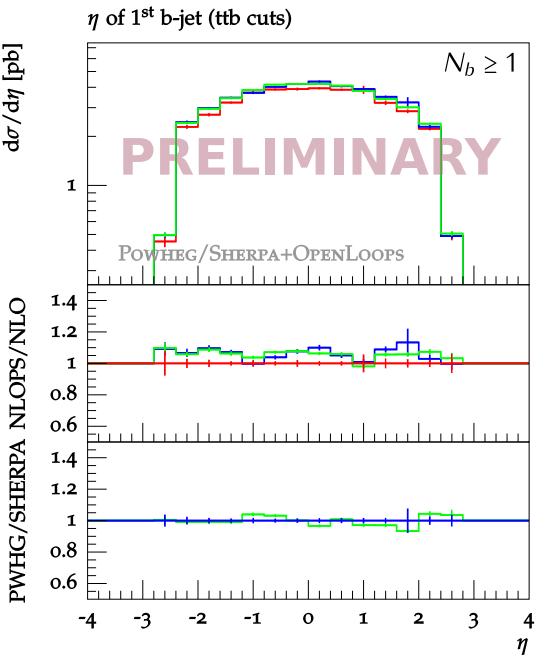
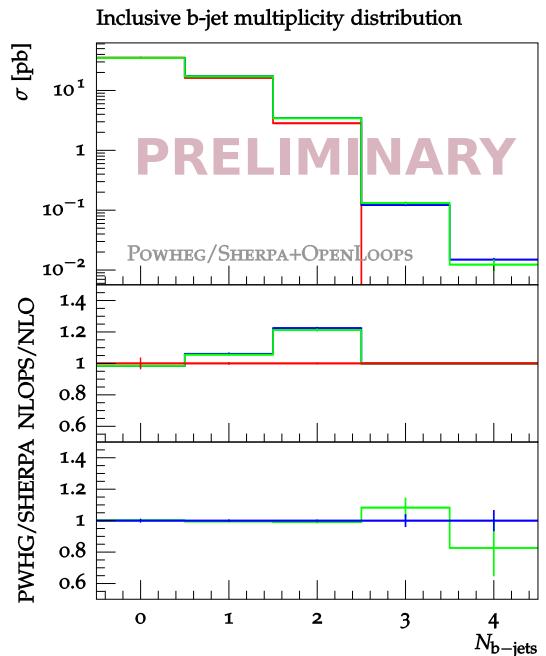
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improves perturbative convergence

POWHEG BOX RES vs SHERPA

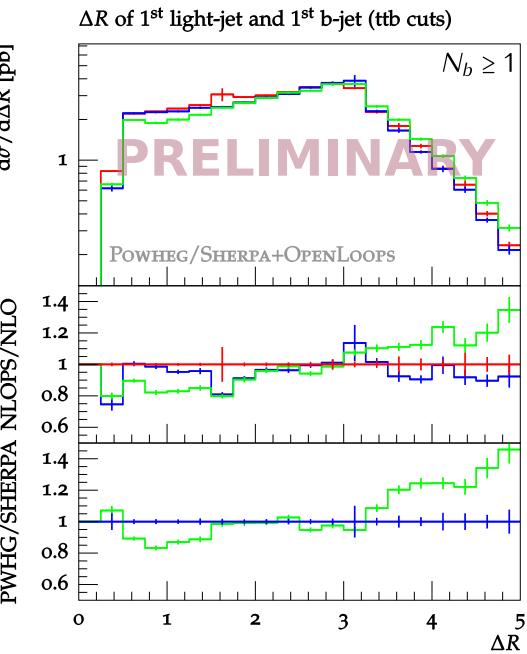
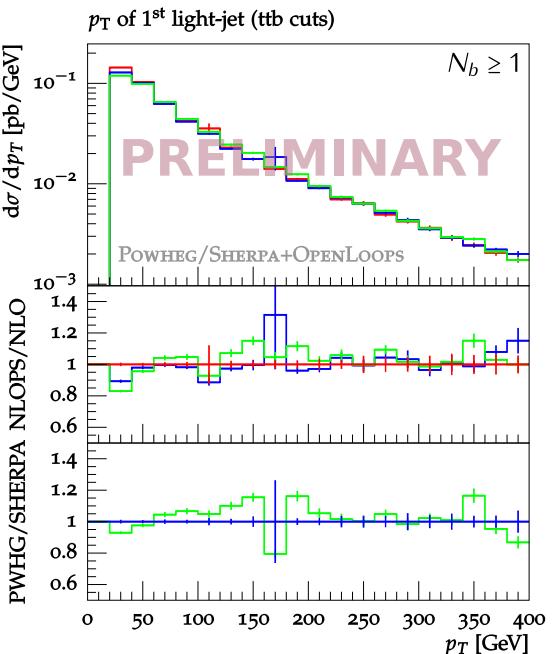
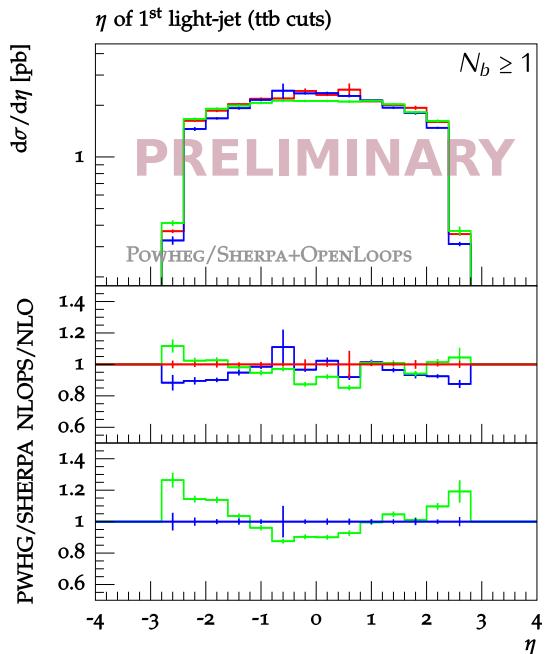
+ PWHG NLO + PWHG NLOPS + SHERPA NLOPS



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

POWHEG BOX RES vs SHERPA

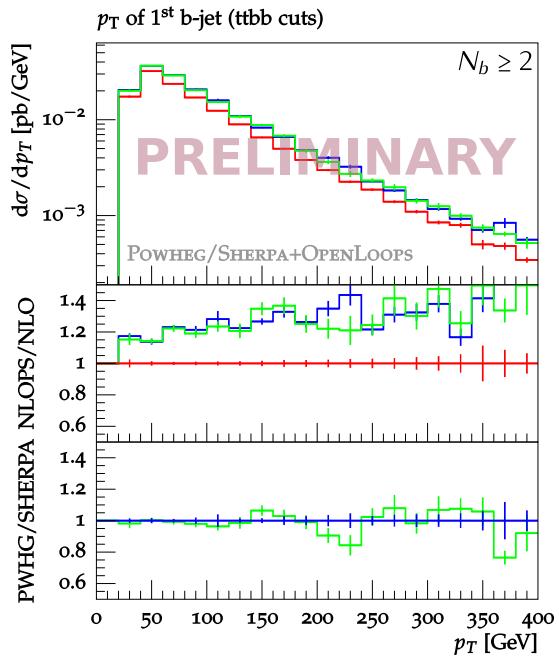
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- Good agreement for LOPS accurate ttbj observables
 - ▶ Agreement to ~20%; expected scale uncertainty ~50%

POWHEG BOX RES vs SHERPA

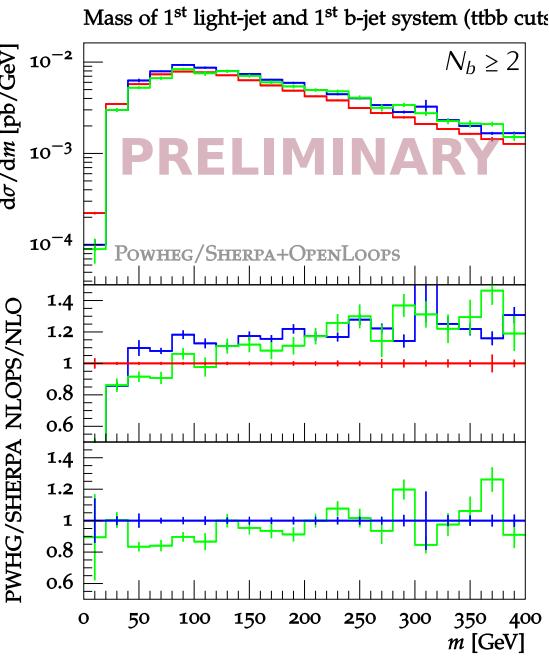
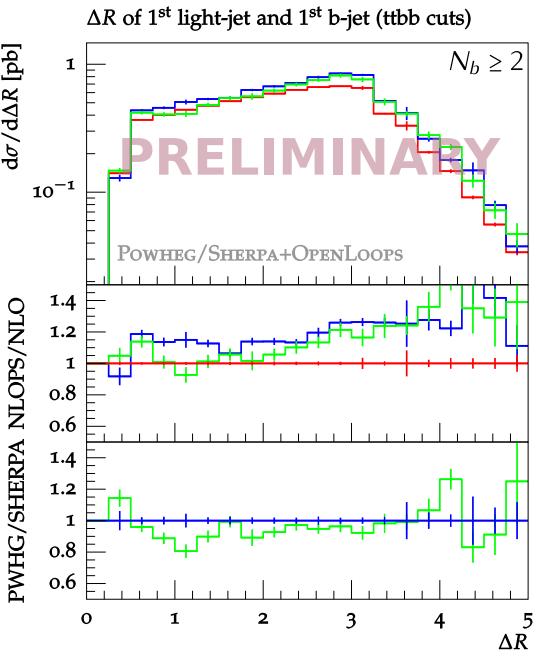
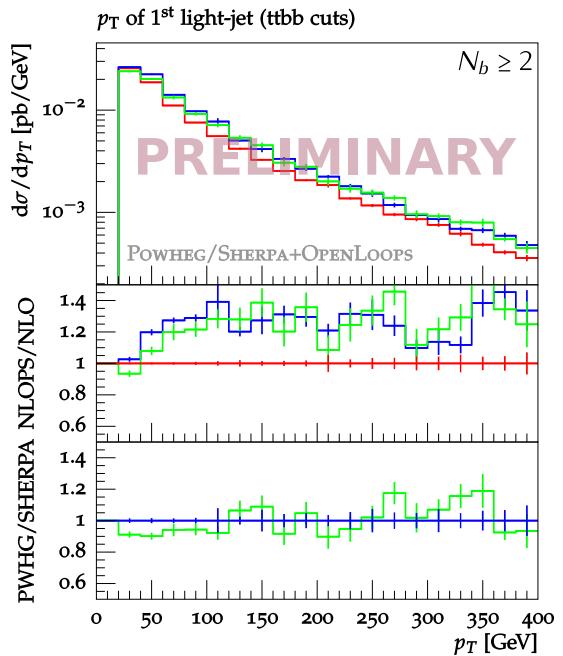
+ PWHG NLO + PWHG NLOPS + SHERPA NLOPS



- Remarkable agreement for NLO accurate ttbb observables
 - ▶ Agreement well under 5%; expected scale uncertainty $\sim 20\%$
- POWHEG BOX RES confirms the “double splitting” enhancement

POWHEG BOX RES vs SHERPA

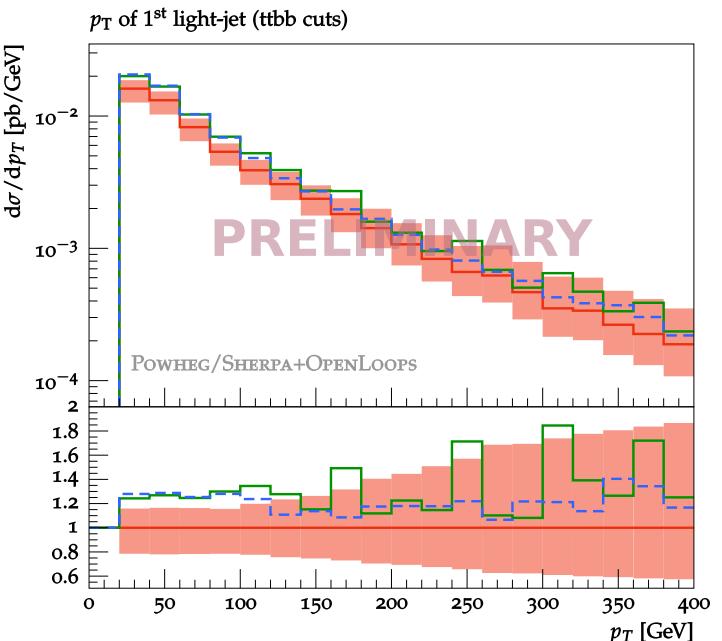
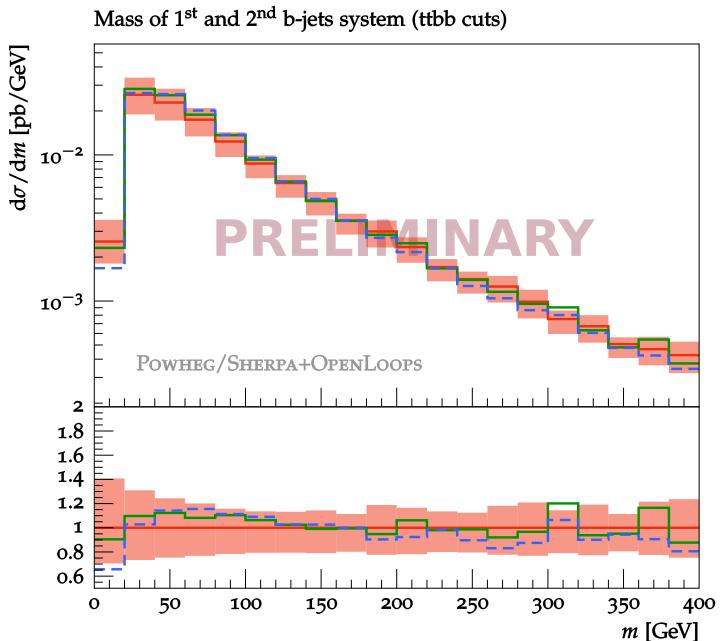
—+— PWHG NLO —+— PWHG NLOPS —+— SHERPA NLOPS



- Good agreement for LOPS accurate ttbbj observables
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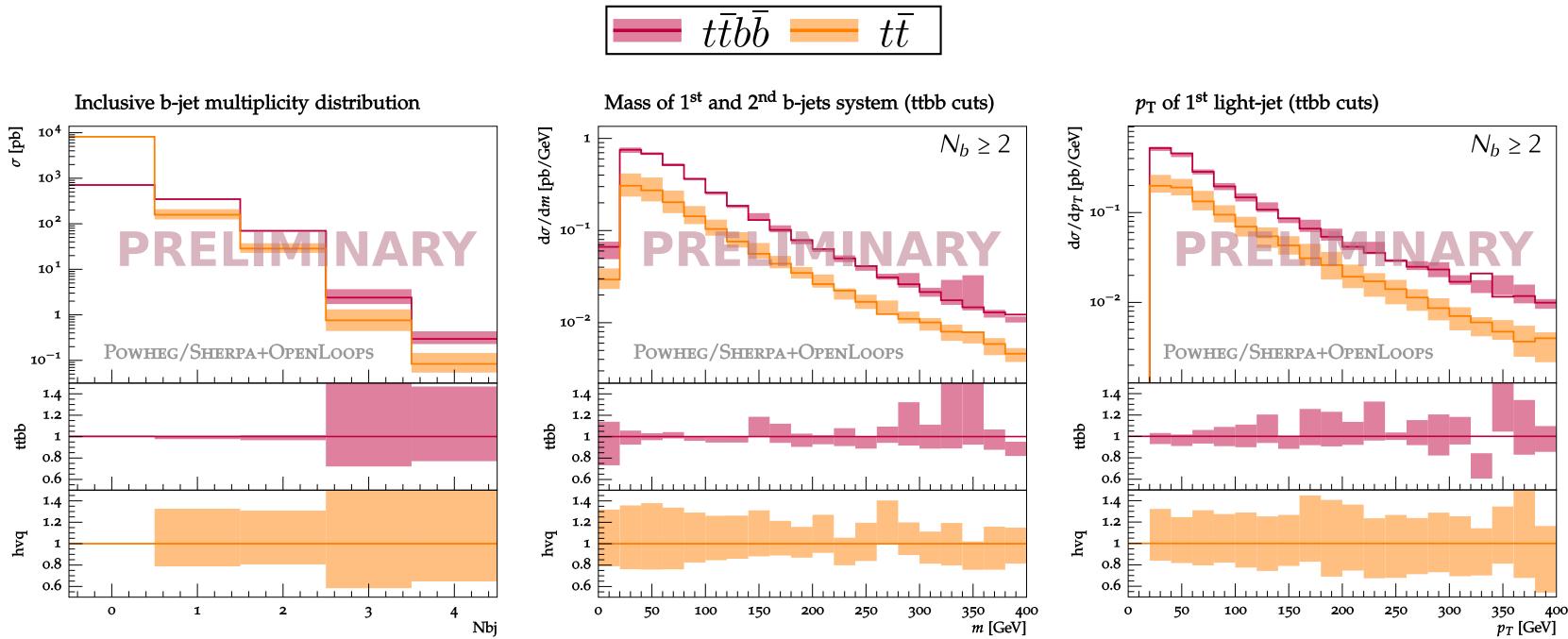
SMC dependence





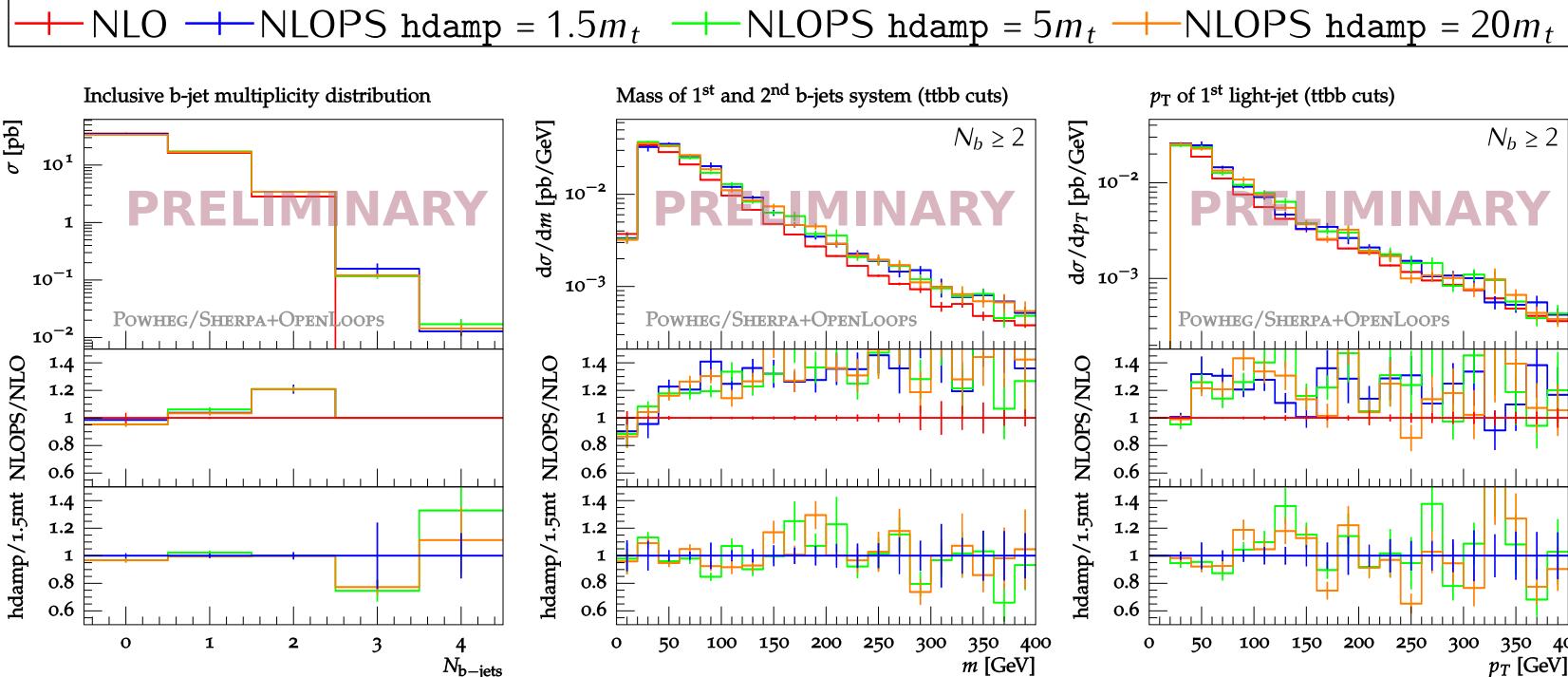
- Remarkable stability with respect to the choice of shower (Pythia 8.210 vs. Herwig 7.1.0)

Shower sensitivity: $t\bar{t}$ vs. $t\bar{t}b\bar{b}$



- $t\bar{t}$ + Pythia vs. $t\bar{t}b\bar{b}$ + Pythia
 - ▶ Decent shape agreement
- Vary `weightGluonToQuark` $\in \{2, 4, 6, 8\}$ and `renormMultFac` $\in \{0.1, 10\}$
 - ▶ $t\bar{t}b\bar{b}$ significantly less sensitive

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

Calculation costs

- Calculation cost for 1M events, assuming 100 cores:
 - ▶ Integration (st1-st3): 2.6hrs
 - ▷ virtual contribution switched off
 - ▷ modified subtraction
 - ▶ Event generation (st4): 1.8hrs
 - ▷ including rwgt with the virtual correction
 - ▷ employing partial unweighting
 - ▶ Shower with Pythia: <10min

Summary

- Use POWHEG BOX RES framework to match 4F $t\bar{t}b\bar{b}$ at NLO QCD with PS
 - ▶ Matrix elements obtained from OpenLoops using the new OpenLoops+POWHEG BOX RES interface
 - ▶ The default `hdamp` behaviour extended in order to account for final state b -jets
- Comparison against Sherpa+OpenLoops
 - ▶ We observe a remarkable agreement
 - ▶ POWHEG BOX RES+OpenLoops confirms the “double splitting” enhancement
- SMC dependence, shower and `hdamp` sensitivity
 - ▶ Predictions obtained by showering Pythia and Herwig agree well
 - ▶ $t\bar{t}b\bar{b}$ significantly less sensitive to shower setting variations than $t\bar{t}$
 - ▶ We observe very good stability with respect to `hdamp` variations

hdamp



- POWHEG radiation formula:

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

► 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:

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

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

hdamp



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$\xrightarrow{\text{finite}}$ singular

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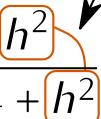
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maybe be thought of as an analogue to μ_Q in MC@NLO

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hdamp



hdamp



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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 `hdampIS` and `hdampFS` independent
 - ▷ Further investigation underway
 - ▷ New POWHEG BOX RES features could be exploited for better understanding of the `hdamp` dependence