TECHNISCHE UNIVERSITÄT DRESDEN
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Deutsche Forschungsgemeinschaft
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Monte-Carlo modelling and uncertainties in ttbb production

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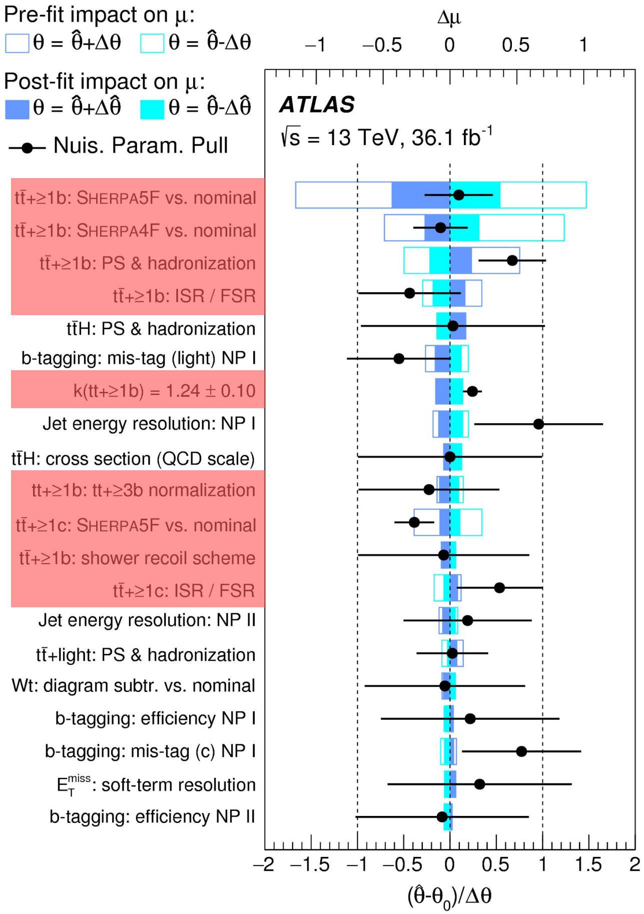
SM@LHC, Zürich, April 2019

Why do we care so much about ttbb?

- ATLAS and CMS ttH(bb) analyses rely on MC modelling for irreducible ttbb background
  - included as template in profile likelihood fit
- Largest sources of uncertainty on extracted signal strength related to tt+HF MC modelling!
- What can we improve?
  - **ATLAS & CMS:** relied on NLO+PS ttbar so far! More accurate theory with NLO ttbb used only to reweight HF fractions (ATLAS) or cross-checks (CMS)
  - **Theory:** Large perturbative ttbb uncertainties even enlarged by NLO+PS algorithms
  - **Both**: More rigorous combination of inclusive tt+jets and ttbb predictions.



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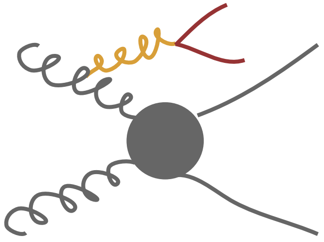
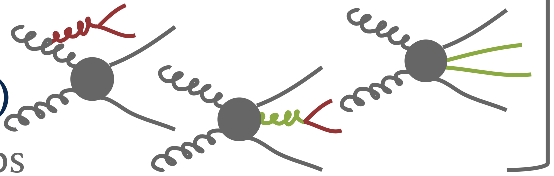
Event generation for tt + heavy flavour

Traditional approaches for tt+HF MC predictions:

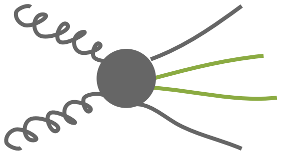
- "Inclusive" NLO+PS tt sample with HF production from **parton shower g→bb**
  - e.g. {Powheg,aMC@NLO}+{Pythia,Herwig}
- Multi-leg merged tt+jets sample with HF from **higher-order MEs** (hard b's) or **parton shower g→bb** (soft/collinear b's)
  - e.g. MG5_aMC+Pythia, Sherpa+OpenLoops





"5-flavour" schemes

- NLO+PS ttbb using **matrix elements** with **massive** b-quarks
  - e.g. Powheg+OpenLoops+Pythia8, Sherpa+OpenLoops

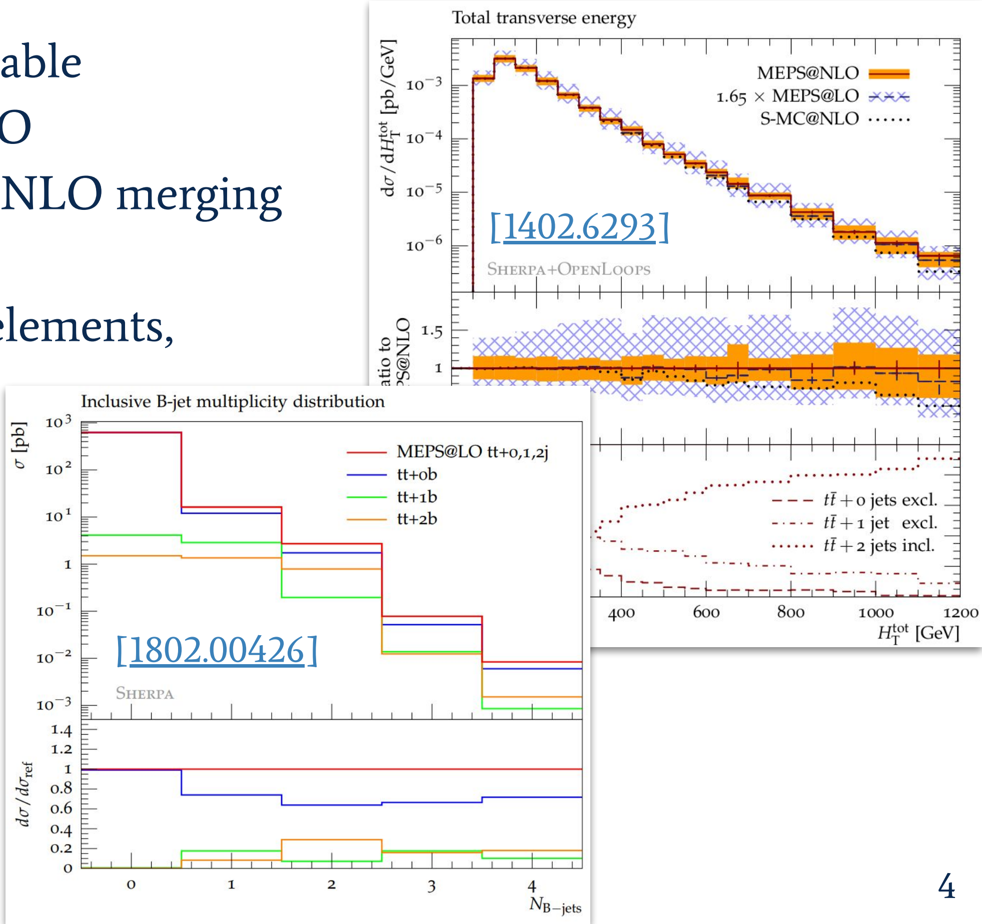


"4-flavour" schemes

Multileg MC

- Multi-leg merged prescriptions available up to tt+2jets@NLO and tt+4jets@LO
- Significant **uncertainty reduction** in NLO merging compared to LO merging
- Jet production described by matrix elements, but **b-jets** not always from b-MEs!
  - soft/collinear g→bb still from PS
  - can **transform** hard ME jets into b-jets
  - higher $N_{jet,max}$ and lower ME+PS parton separation cut will reduce effect

Problem or **feature**?



Anatomy of 4FS NLO+PS for ttbb

- 2→4 NLO QCD matrix elements with massive b-quarks

Final state g→bb **dominant**

- massive b’s → no (jet) cuts!
- collinear g→bb produced in ME

No initial state b in MEs

- 4FS PDFs
- IS g→bb in ME

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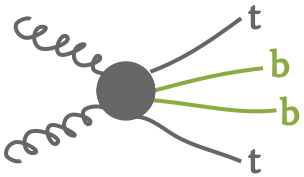

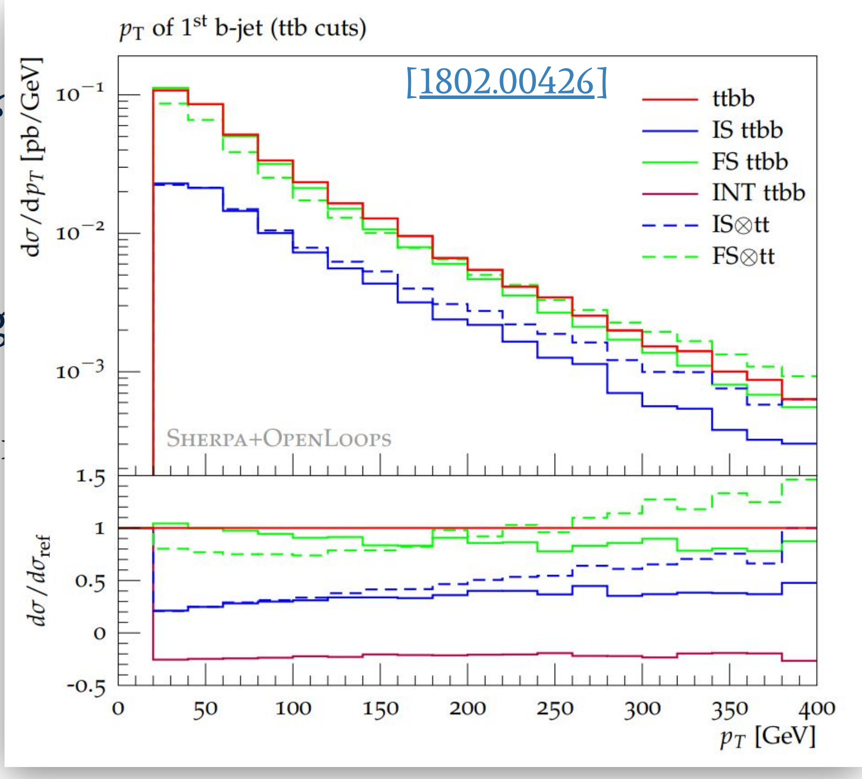

Final state g ... in MEs

- massive
- collinea ... ME

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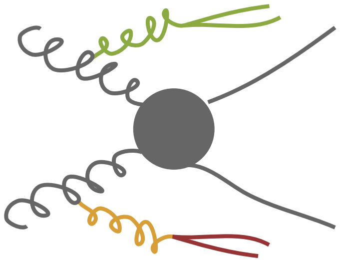
- Matched to parton shower for additional emissions
  - **"double-splitting"** contribution becomes relevant!



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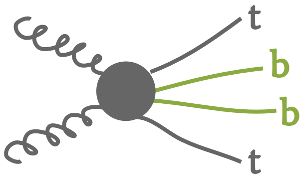
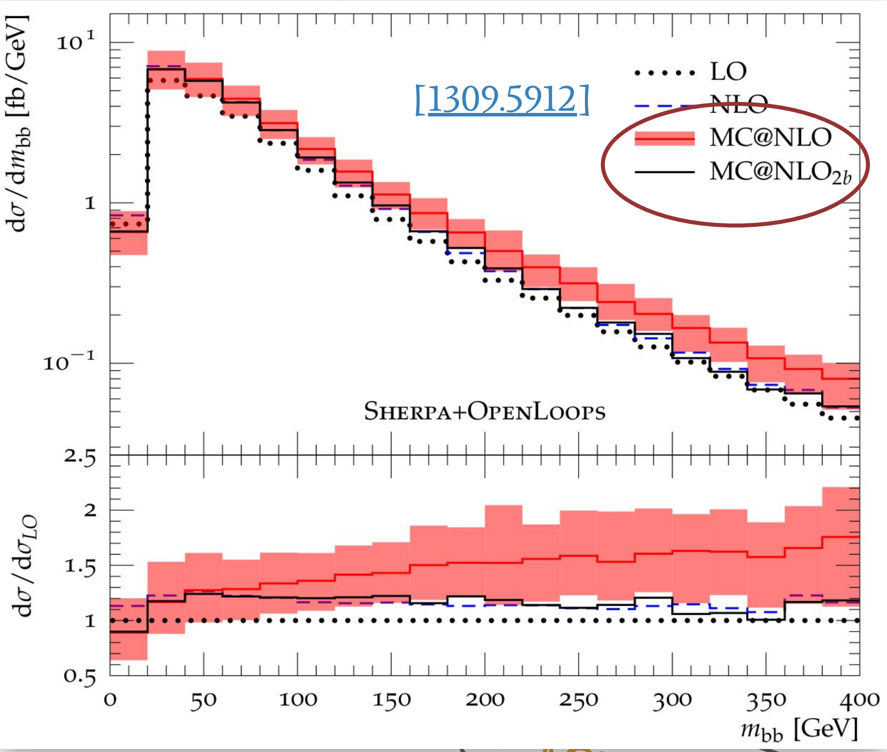




Final state g … in MEs

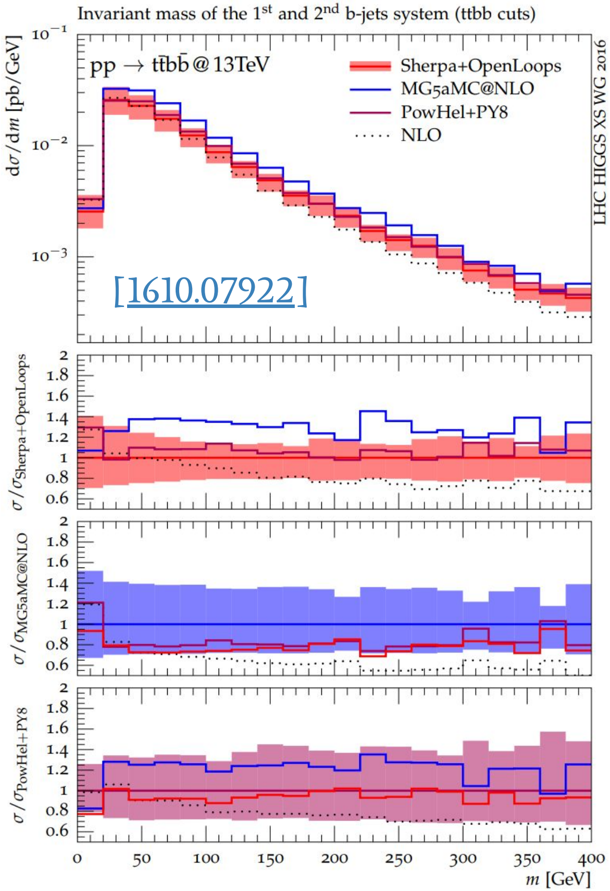
- massive …
- collinea … ME

- Matched to par…
additional emis…
  - "double-spli…
becomes re…

MC programs for 4FS ttbb at NLO+PS

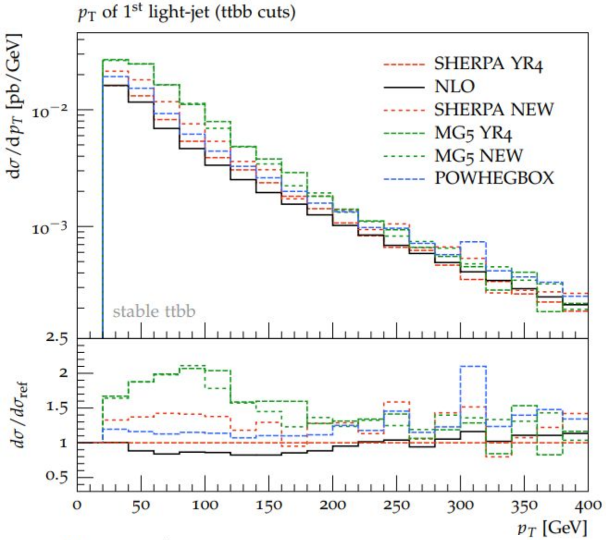
- Several tools on the market
  - Sherpa + OpenLoops [1309.5912]
  - PowHel + Pythia/Herwig [1709.06915]
  - PowhegBox + OpenLoops + Pythia/Herwig [1802.00426]
  - MG5_aMC + Pythia/Herwig
  - Herwig7 + OpenLoops
- History of out-of-the-box comparisons:
  - Large discrepancies
  - Partially due to large perturbative uncertainties
  - But also beyond!
    - Parton Shower?
    - NLO+PS matching algorithm?

Improve or accept as **uncertainties** (and kill ttHbb?)?



Diagnosis: Tuned comparisons

- Tuned comparison effort to compare matching and parton shower between various tools
  → Isolate algorithmic unc's in:
  - NLO+PS matching
  - Parton shower (e.g. recoil scheme effects)
- New input from PowhegBox implementation helps to pin down discrepancies
- Common [Rivet routine] for tt+1b and tt+2b final states in context of ttH subgroup in HXSWG



[from ttH-HXSWG]

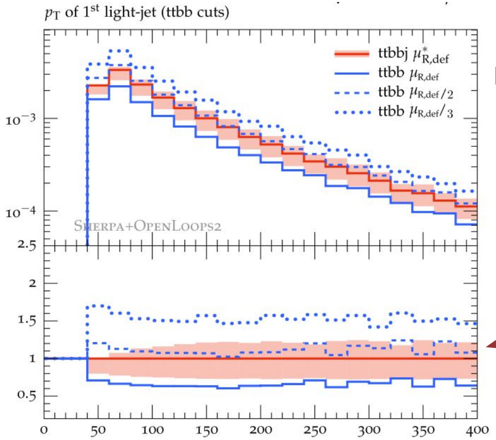
Tool	MC@NLO	Powheg	Pythia 8.2	Herwig 7.1.2	Sherpa2.2.4	MC contacts
SHERPA2.2+OPENLOOPS	x				x	F. Siegert, J. Krause
MG5_AMC@NLO	x		x	x		M. Zaro
MATCHBOX+OPENLOOPS	x			x		C. Reuschle, R. Posdkubka
POWHEG+HELAC		x	x	x		M.V. Garzelli, A. Kardos
POWHEGBOX+OPENLOOPS		x	x	x		T. Jezo, J. Lindert
	3	2	3	4	1	

Therapy: Tuned matching [Preliminary]

- Differences suspected as combination of 2 effects in MC@NLO matching:

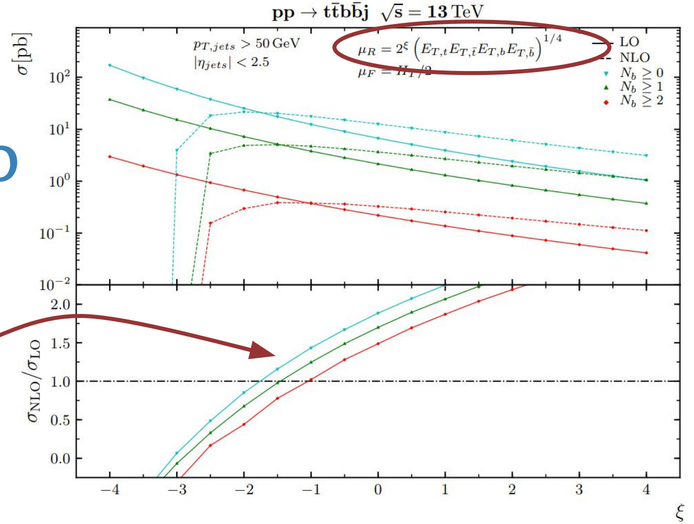
$$d\sigma^{(\text{NLO+PS})} = d\Phi_B \bar{\mathcal{B}} \Big[\underbrace{\Delta(t_0, \mu_Q^2)}_{\text{unresolved}} + \underbrace{\int_{t_0}^{\mu_Q^2} dt \frac{\mathcal{R}_{\text{PS}}}{\mathcal{B}} \Delta(t, \mu_Q^2)}_{\text{resolved, singular} \equiv \mathbb{S}} \Big] + d\Phi_R \underbrace{[\mathcal{R} - \mathcal{R}_{\text{PS}}]}_{\text{resolved, non-singular} \equiv \mathbb{H}}$$

  - large K-factor~1.9
  - spuriously large R_{PS} in MC@NLO matching with MadGraph5_aMC@NLO + Pythia/Herwig



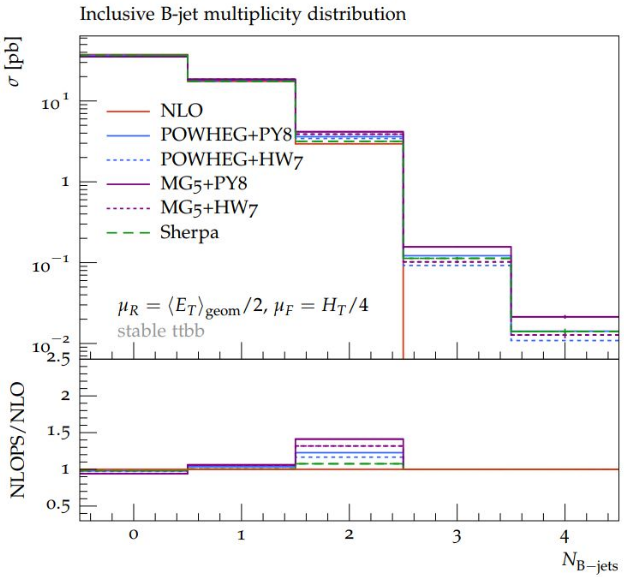
- Fixed-order studies of **ttbbj@NLO** with OpenLoops2+Sherpa [Buccioni, Pozzorini, Zoller 2019]
  - Reduced μ_R stabilises K-factor
  - No significant shape distortions

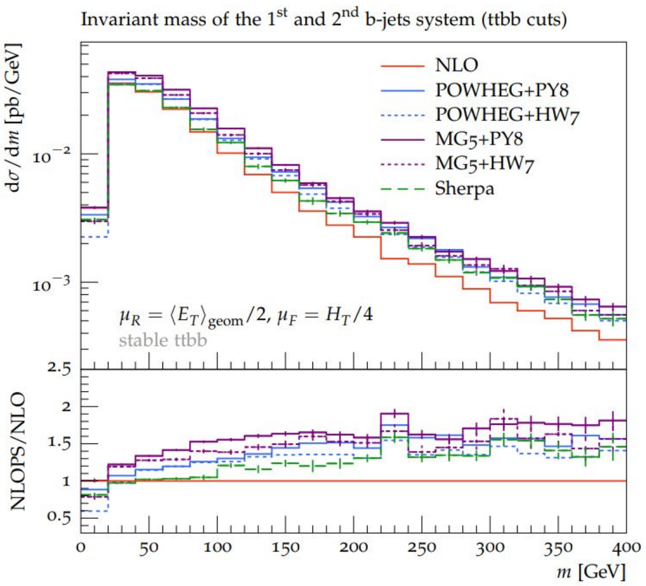
New benchmark for NLO+PS progs!

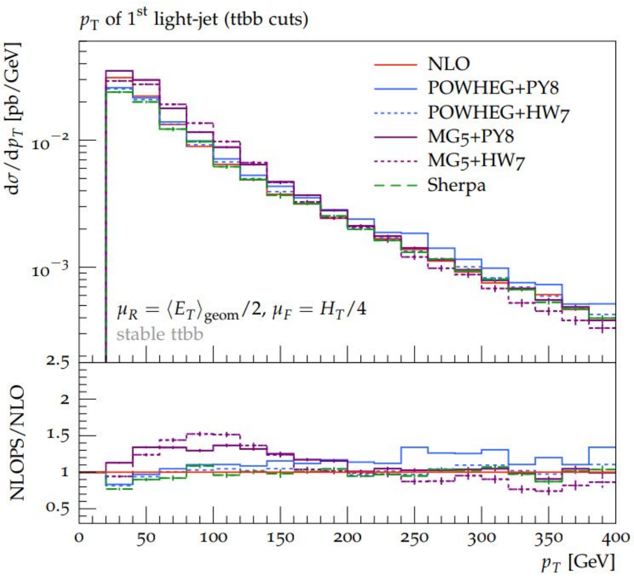


Therapy: Tuned matching [Preliminary]

- Application of reduced scale to tuned NLO+PS comparisons
  - improved agreement between NLO+PS tools for light-jet spectrum
  - still sizable O(40%) differences in N_{2b} region → further studies ongoing
  - eagerly waiting for actual benchmark tests with ttbbj@NLO!







Recap: Event generation for tt + heavy flavour

Traditional approaches for tt+HF MC predictions:

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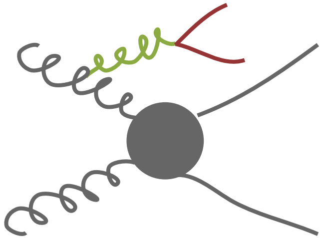

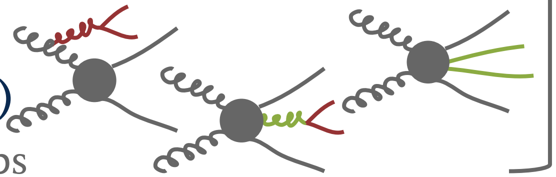

"5-flavour" schemes

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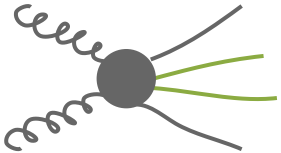
  - e.g. Powheg+OpenLoops+Pythia8, Sherpa+OpenLoops



"4-flavour" schemes

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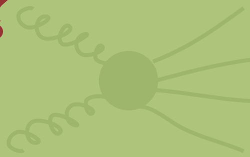


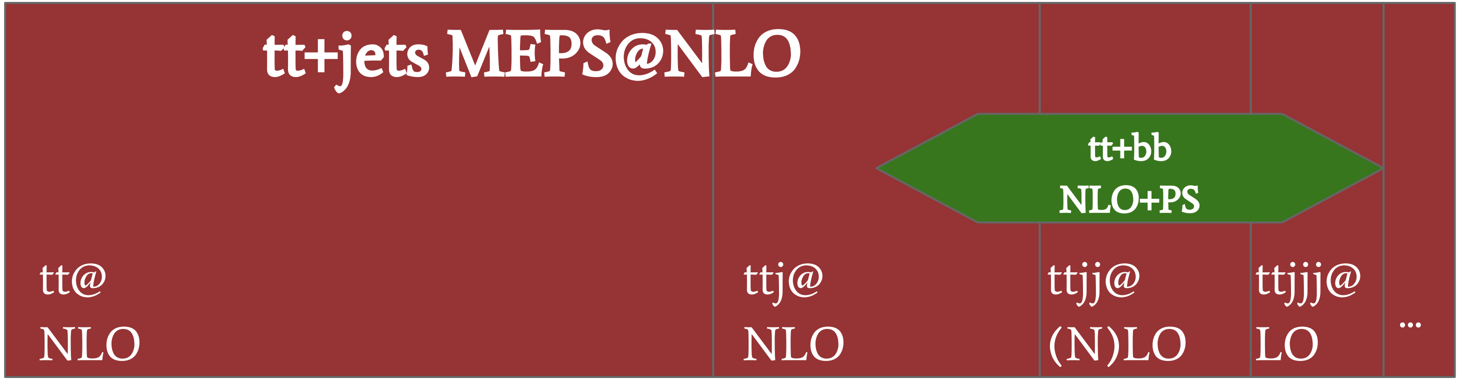
"4-flavour" schemes

Can we combine 4-flavour and 5-flavour multileg?

Fusing X+bb and X+jets in the Sherpa MC

aka "Multi-jet merging in a variable flavour number scheme"

[1904.09382]



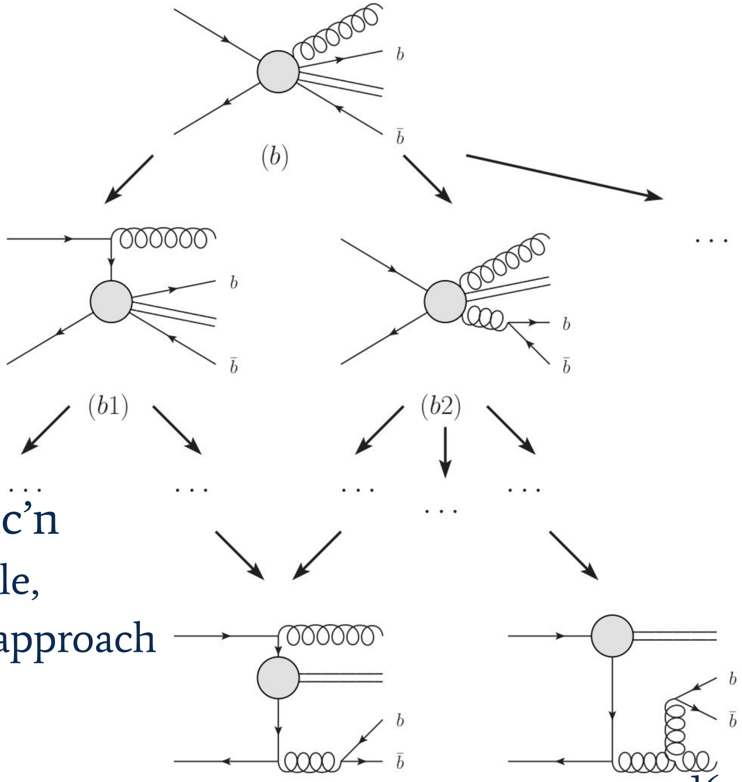
Three main ingredients:

1. Interpreting ttbb as merged contribution
2. Overlap removal
3. Matching 4F/5F in PDFs and α_s

Can be applied for LO and NLO merging!

Step 1: Embedding ttbb as merged contribution

- ttj(j(…)) matrix elements in **tt+jets MEPS@NLO** undergo special treatment:
  - clustering to get scale hierarchy of ME emissions ("shower history")
  - core scale based on 2→2 process
  - application of $\alpha_S(\mu_R^2) \to \alpha_S(p_T^2)$ reweighting for each emission
  - application of Sudakov factors $\Delta(t_1, t_2)$ along internal lines (event vetoes) for correct resummation properties



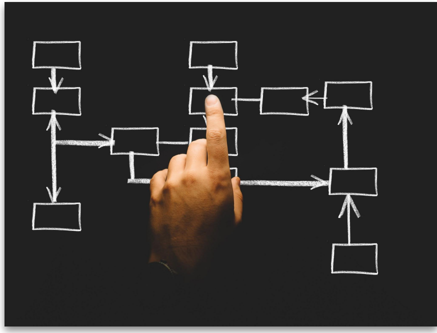
- Now: Same applied to **ttbb NLO+PS** massive calc'n
  - remains separate standalone ttbb NLO+PS sample, but generated consistent with multi-leg merged approach

Step 2: Heavy Flavour Overlap Removal

- HFOR used before in experiments in simplified form
  - dR(b,b)>0.4 → keep from ttbb ME
  - dR(b,b)<0.4 → keep from tt ME + bb from PS
- Here: from multi-leg merging prescription
  - Cluster **full event at PS level** using "reverse shower"
  - Look at **leading two emissions**
    - » Heavy Flavour → keep from **ttbb NLO+PS** simulation ("**direct component**")
    - » Light Flavour → keep from **tt+jets MEPS@NLO** ("**fragmentation component**")

⇒ Sub(sub)leading g→bb splittings not from ttbb ME, but from ttjjjj ME or from PS.

- (Extra: caution with b's from "FSR" in top decay products!)



Step 3: Matching 4F/5F in PDFs and α_S

- For consistent combination with tt+jets we produce the massive **ttbb NLO+PS** with a 5F PDF

  → m_b mismatch with massive NLO matrix elements

  - Looking at ideas from **FONLL** [Forte, Napoletano, Ubiali 2016] based on

    $$\sigma^{\text{FONLL}} = \sigma^{(5)} - \sigma^{(4),(0)} + \sigma^{(4)}$$

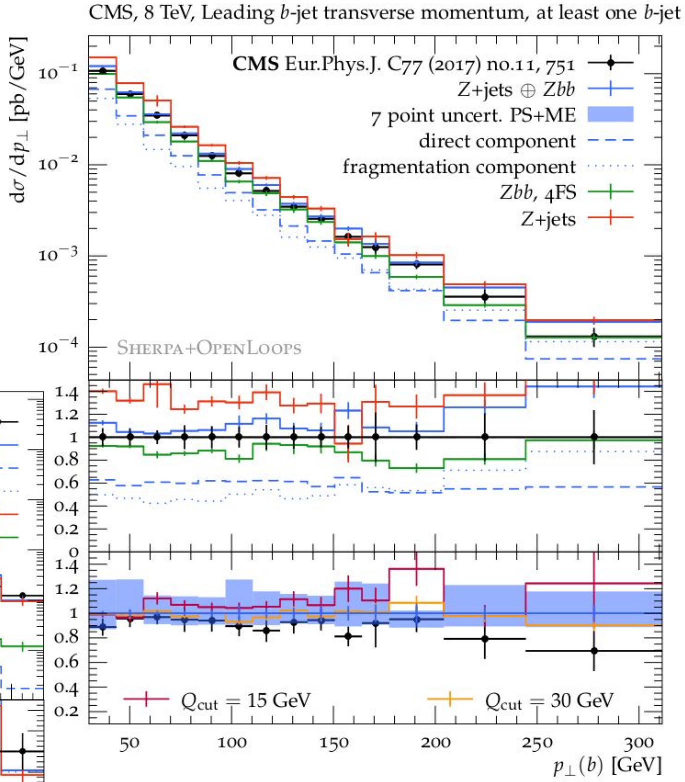
    we find that they are generated by prescription above!
  - NLO accuracy preserved from input matrix elements
  - LL/NLL accuracy according to shower used
    - » Overlap removal and embedding of ttbb as merged contribution with LL shower automatically generates leading log matching term
    - » Next-to-leading log would need explicit counterterms as event weights (complicated) or comes **automatically with NLL showers** in the future
- Additional event weights for mismatch between α_S evolution with $m_b = 0$ and virtuals with $m_b \neq 0$

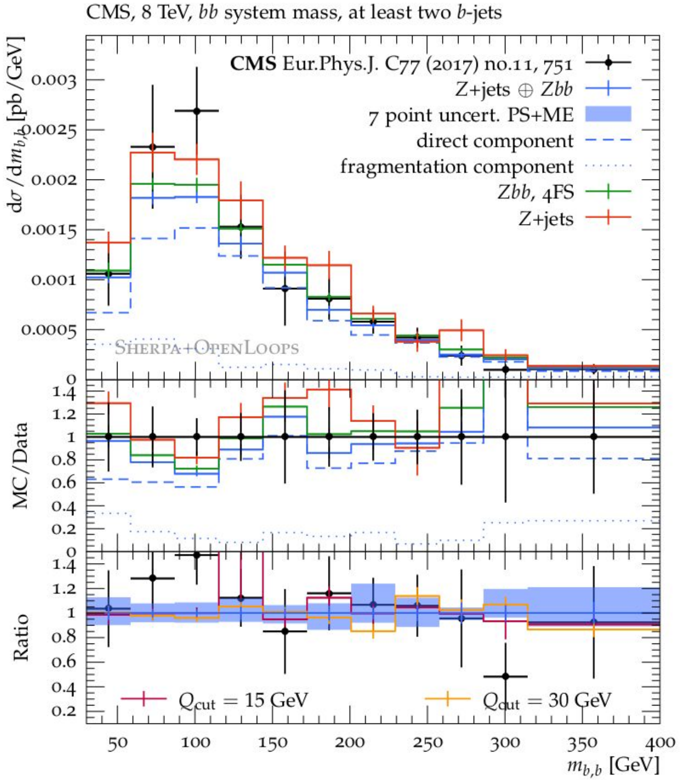
$$w^{\text{new}}_{q\bar{q}} = w_{q\bar{q}} \left(1 - \frac{4}{3} T_R \ln \frac{\mu_R^2}{Q^2} \frac{w^{\text{Born}}}{w^{\text{ME}}}\right)$$

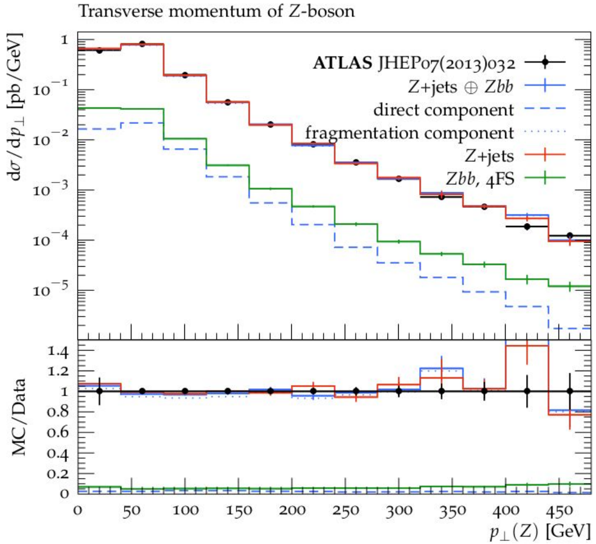
$$w^{\text{new}}_{gg} = w_{gg} \left(1 - \frac{4}{3} T_R \ln \frac{\mu_R^2}{m_b^2} \frac{w^{\text{Born}}}{w^{\text{ME}}}\right)$$

Validation for Z+HF production

- Implementation in Sherpa 2.2
- First application to Z+HF, compared to CMS 8 TeV data







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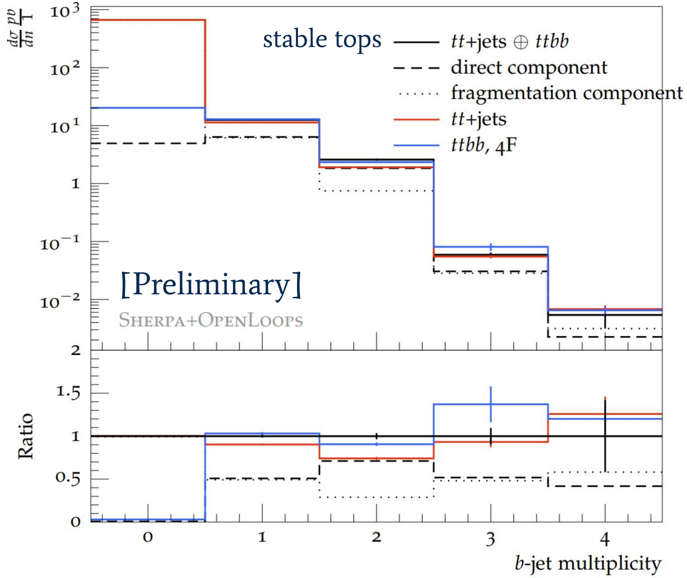
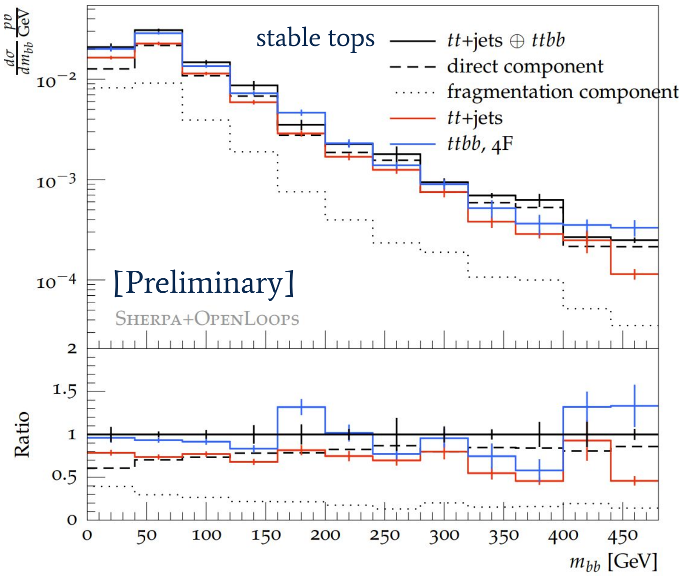
Sneak preview: Application to ttbb

- Application to fusion of MEPS@NLO tt + 0,1j@NLO + 2,3j@LO and massive ttbb@NLO
- 2-bjet production dominated by direct component, but 1-bjet observables with equal contributions from direct and fragmentation configurations!





[Katzy, Krause, Pollard, FS in prep]

~~Conclusions~~ Points for discussion

Interplay between experiment and theory crucial in ttH(bb), but:

- Experiments use theoretical predictions more and more indirectly.
- Profile likelihood fits re-shape impact of theory (MC) & its uncertainties in experimental analyses!
- Primarily needs guidance for transfer from control regions to signal regions!

1. How to transfer findings from V+HF to tt+HF?
   IS vs. FS g→bb dominance...
   Probably not in fit, but through tuning/validating Monte Carlos.

2. Can we constrain tt+HF using tt+jets data? In fit?
   Need agreed unc's prescription, neither too aggressive nor too conservative.