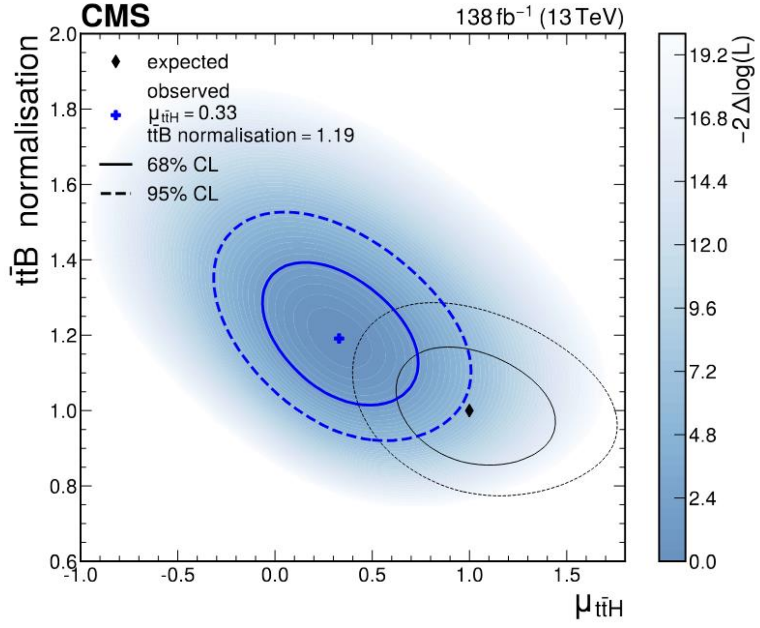
tt+HF modelling

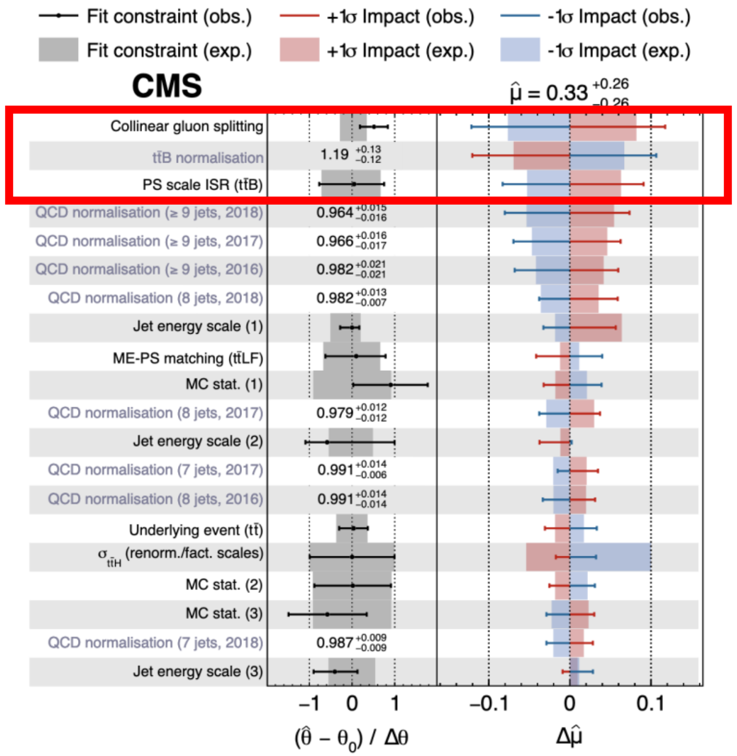
- “traditional” 4FS and 5FS calculations
- simulations used by ATLAS and CMS
- new predictions in variable flavour number scheme

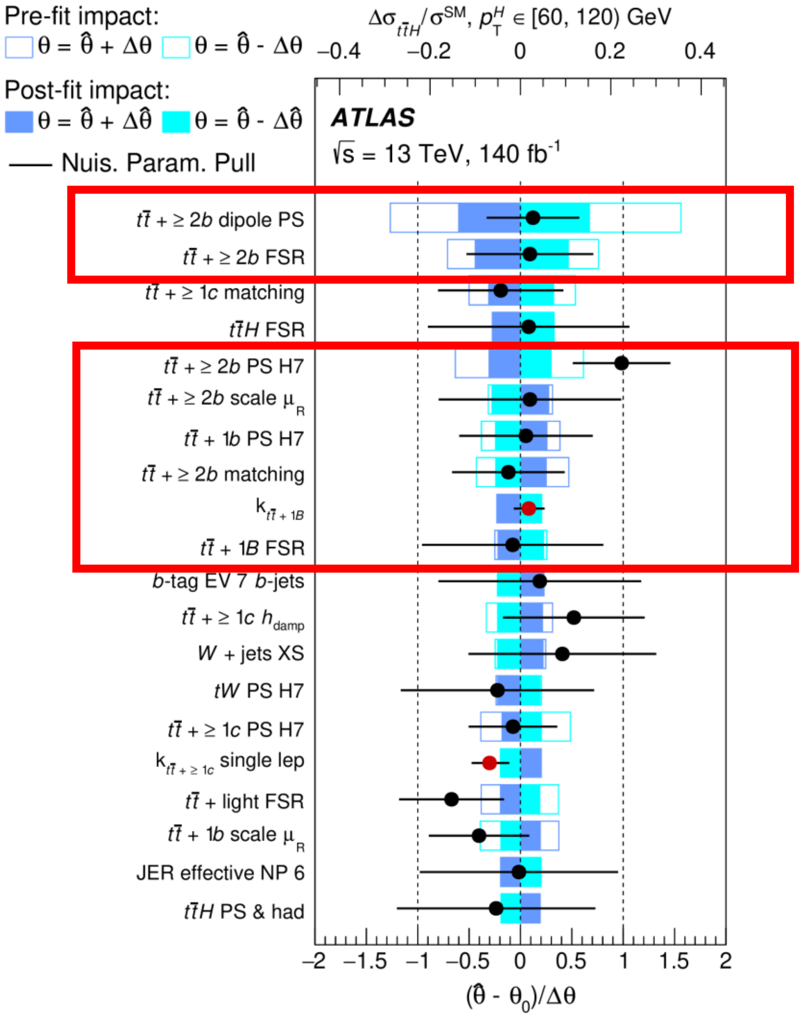
Judith Katzy (DESY)

Motivation



48% anti-correlation between ttbb normalization and mu ttH observed

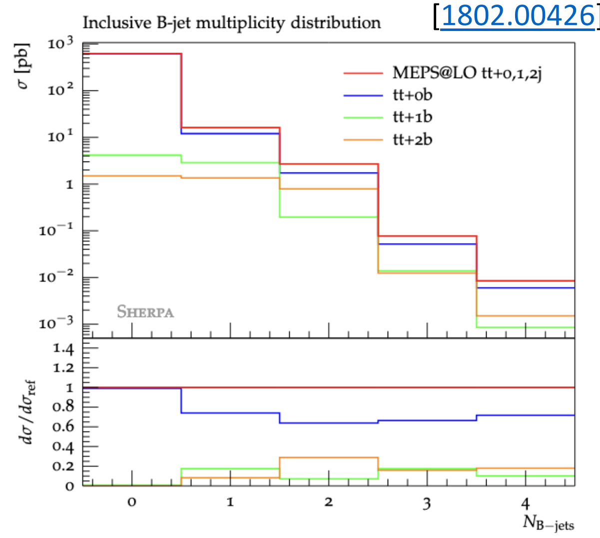




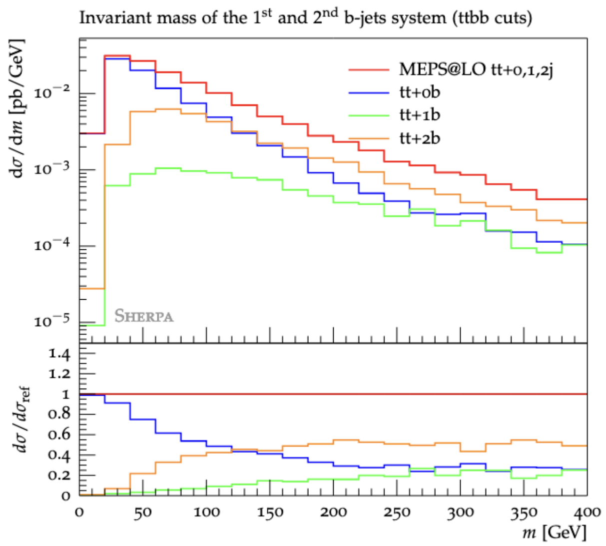
Also relevant for diHiggs and 4top production

Traditional predictions of ttbb@LHC
- five flavour scheme (5FS)

[1802.00426]



- "inclusive" tt@NLO ME + PS with HF from PS g->bb splittings
  - evolution of α_S and the running of the PDF with five active parton flavors
- Multi-leg merged tt+jets sample with HF from higher-order MEs with massless b-quarks (hard b) or parton shower g->bb splittings (soft/collinear b)
  - effects of a reduced phase space and inhibited QCD radiation in the collinear region might not be modeled correctly



Surprising feature:

- Jet production described by hard MEs but b-jets mostly from final state soft/collinear g->bb splitting in the PS which transforms gluon jets into b-jets [1802.00426]

Traditional predictions of ttbb@LHC - four flavour scheme (4FS)

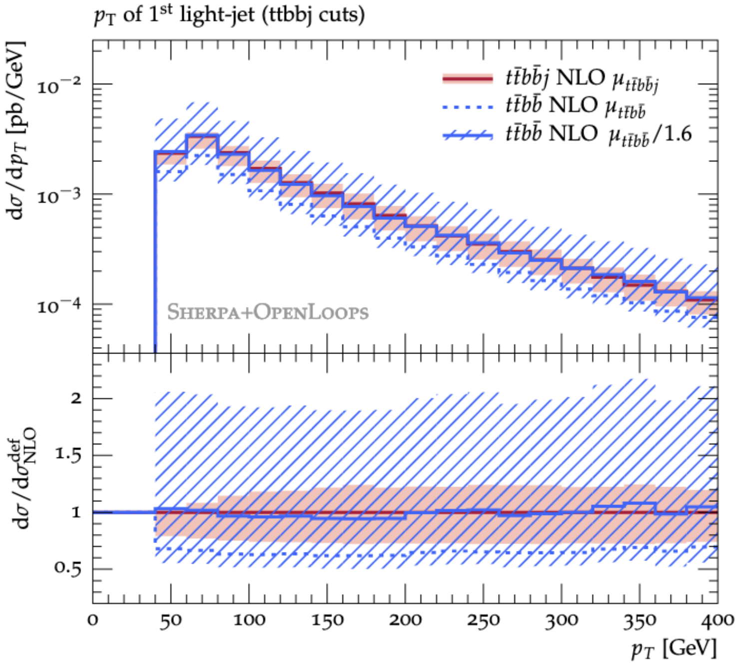
- ttbb@NLO ME + PS with massive b-quarks

- No additional b-jet through initial-state gluon splitting due to the vanishing b-quark PDF
- only include Sudakov suppression to first order in the strong coupling
- cannot account for resumed higher-order effects
  - Needed if large scale hierarchies in the process are present

1907.13624

Scale for ttbb@NLO 4FS

- Determined scale by Fixed-order study of ttbbj at NLO
- Recommended choice for ttbb obtained by tuned comparison: $\mu_R = (E_{T,t}E_{T,\bar{t}}E_{T,b}E_{T,\bar{b}})^{1/4}/1.6$



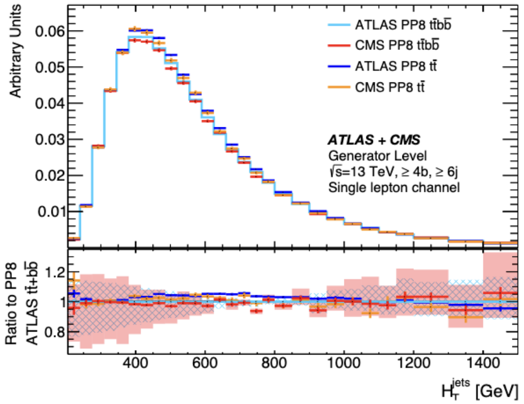
[2301.11670](2301.11670)

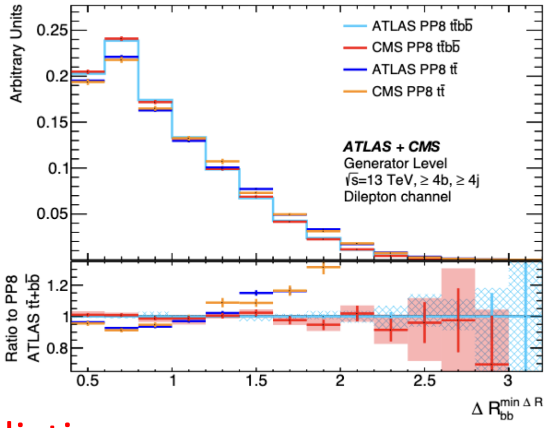
ATLAS and CMS ttbb simulations

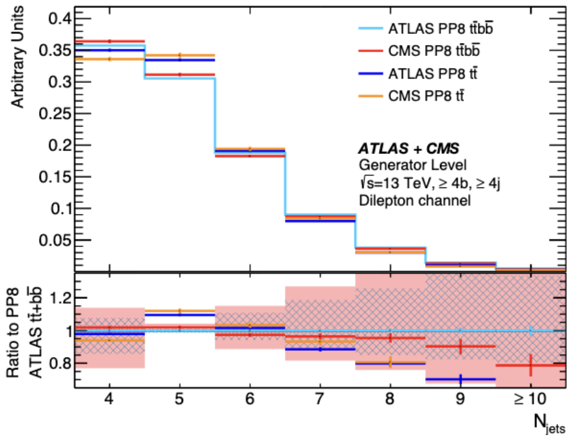
Comparison of settings in MC production of nominal samples used for full Run2 analyses

	ME Generator	μ_R	μ_F
4FS	ATLAS $t\bar{t}b\bar{b}$-POWHEG $t\bar{t}b\bar{b}$	$\frac{1}{2}\sqrt[4]{m_{T,t}\cdot m_{T,\bar{t}}\cdot m_{T,b}\cdot m_{T,\bar{b}}}$	$\frac{1}{2}(m_{T,t}+m_{T,\bar{t}}+m_{T,b}+m_{T,\bar{b}}+m_{T,g})$
	CMS $t\bar{t}b\bar{b}$-POWHEG $t\bar{t}b\bar{b}$	$\frac{1}{2}\sqrt[4]{m_{T,t}\cdot m_{T,\bar{t}}\cdot m_{T,b}\cdot m_{T,\bar{b}}}$	$\frac{1}{4}(m_{T,t}+m_{T,\bar{t}}+m_{T,b}+m_{T,\bar{b}}+m_{T,g})$
	SHERPA 2.2.10	$\frac{1}{2}\sqrt[4]{m_{T,t}\cdot m_{T,\bar{t}}\cdot m_{T,b}\cdot m_{T,\bar{b}}}$	$\frac{1}{2}(m_{T,t}+m_{T,\bar{t}}+m_{T,b}+m_{T,\bar{b}}+m_{T,g})$
5FS	ATLAS POWHEG $t\bar{t}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$
	CMS POWHEG $t\bar{t}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$
	ATLAS aMC $t\bar{t}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$	$\sqrt{0.5\cdot(m^2_{T,t}+m^2_{T,\bar{t}})}$

Pythia8 Parton Shower
ATLAS: A14 tune
CMS: CP5 tune



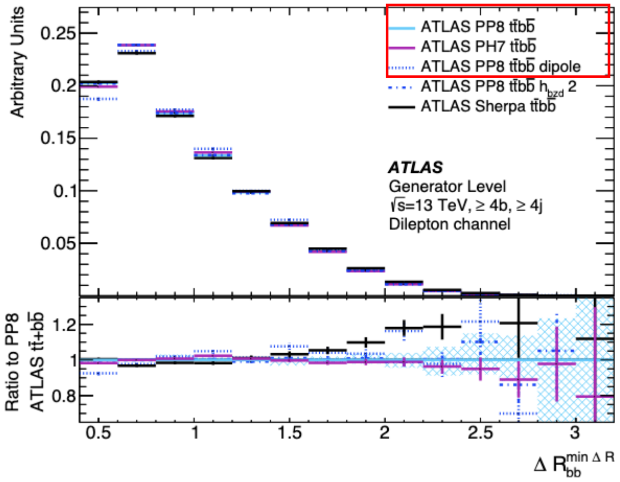




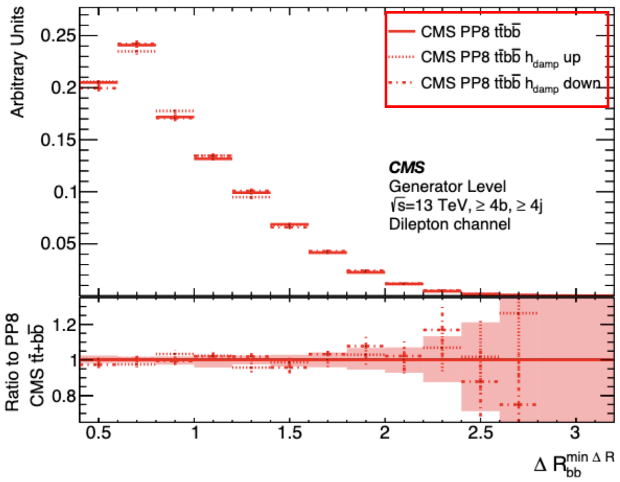
Differences between tt and ttbb predictions
almost no differences between ATLAS and CMS predictions in normalized distributions

[2301.11670](https://arxiv.org/abs/2301.11670)

ATLAS and CMS ttbb modeling variations



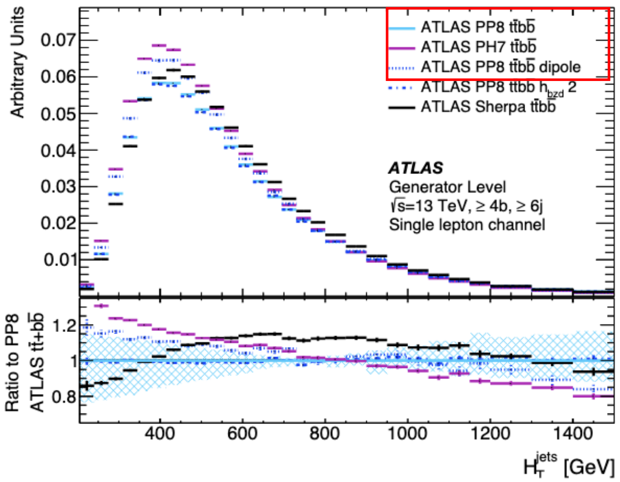
systematics for ttHbb + p_T^{hard} variation for matching

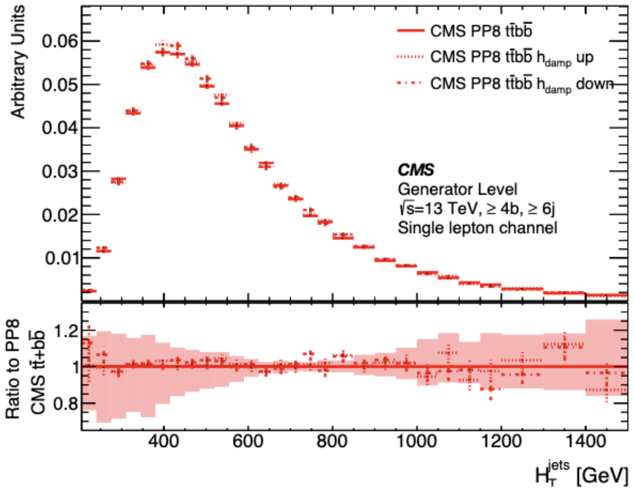


Matching systematics for ttHbb

+

100% uncertainty on collinear gluon splitting (tt+jet containing 2 b-hadrons)





Next round of tt+jets simulations

Goals:

For ttbb: allows to account for both the effect of finite parton masses at small scales, and the QCD evolution at large scales

Inclusive prediction for tt+jets and ttbb

- as light and charm jets are irreducible backgrounds to ttbb due to limited identification capabilities of detectors

Sherpa fusing idea

- Matching 4FS and 5FS calculations in a variable number flavour scheme
  - Here: Use FONLL algorithm:

  Resummation of the logarithms of pT /mb, with next-to-leading logarithmic accuracy (NLL), and the matching with the fixed-order, exact NLO calculation for massive quarks

- Done extensively for inclusive observables:
  - [Cacciari,Frixione,Mangano,Nason,Ridolfi] hep-ph/0312132,
  - [Forte,Napoletano,Ubiali] arXiv:1508.01529, arXiv:1607.00389, . . .

- Expand to differential distributions of Z+jets and Zbb
  - [Krause,Siegert,Hoeche] arXiv:1904.09382

- Now do it for tt+jets and ttbb
  - [Ferencz,JK,Siegert,Hoeche] arXiv:2402.15497

Fusing algorithm – step by step

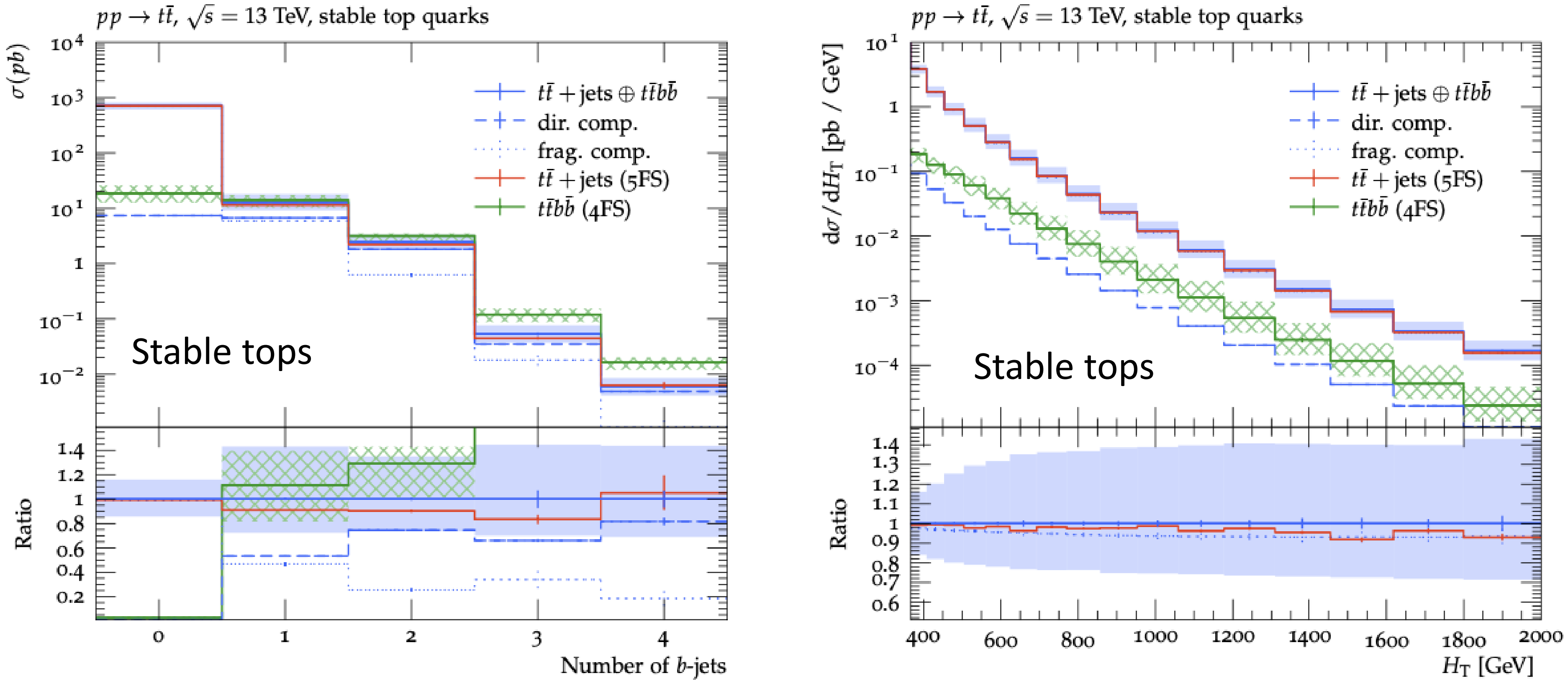
1. Start with a multi-jet merged simulation of tt+jets and a calculation of ttbb

2. Process the ttbb events as if they were part of tt+jets, i.e. apply the clustering procedure, the α_s reweighting and the Sudakov reweighting. Use custom scale definitions for renormalization and factorization scales according to the the core reaction. Adjust the renormalization of α_S. This part of the fused result is called the direct component

3. Remove all final-state configurations from tt+jets that have a parton-shower history which can also be generated at ME level in the reweighted ttbb computation. The remainder of tt+jets may still contribute configurations with final-state bottom quarks.This part of the fused result is called the fragmentation component.

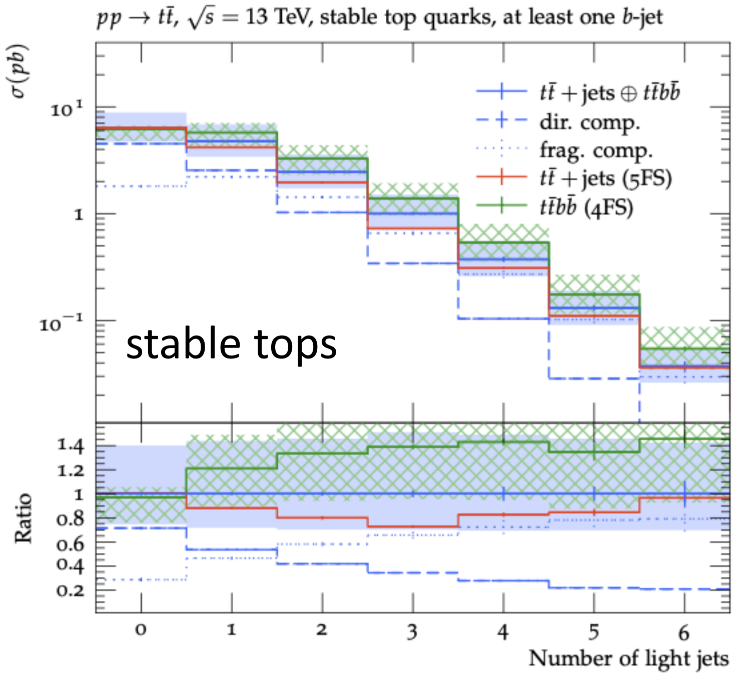
4. Add the modified event samples to obtain the overall prediction

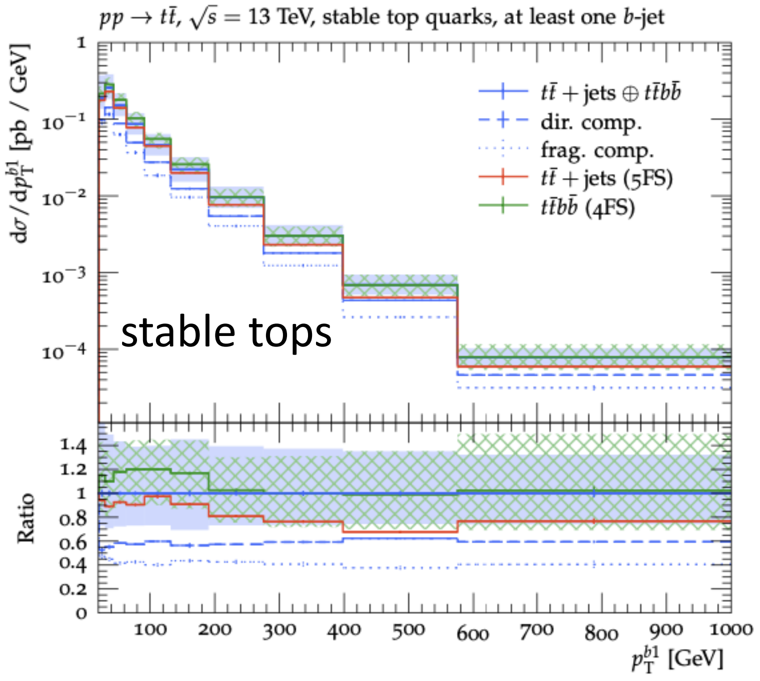
Fusing tt+jets and ttbb - predictions in inclusive phase space



Good agreement between fusing and tt+jets 5FS

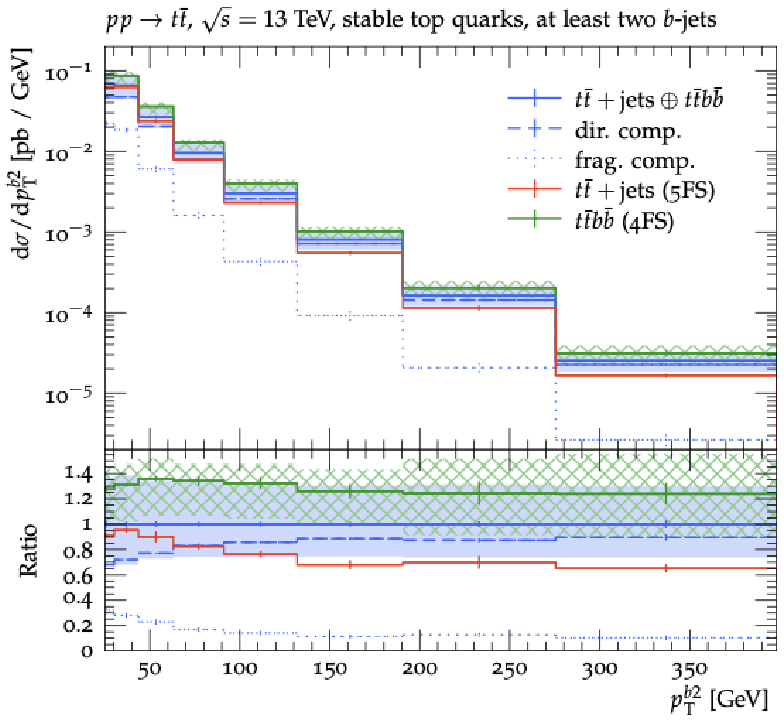
Fusing tt+jets and ttbb - 1b region

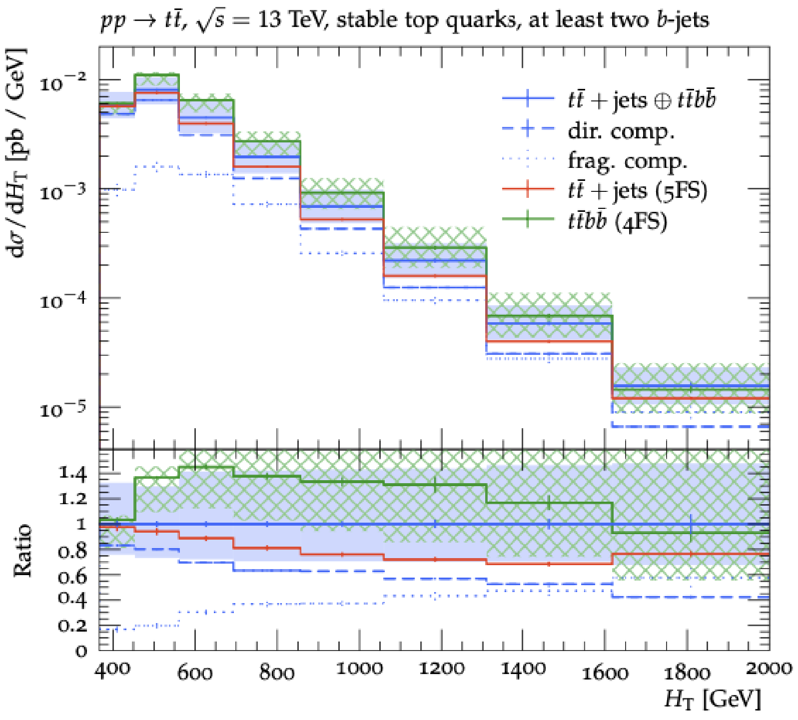




Good agreement between fusing and tt+jets 5FS
Reduced multi-jet rates compared to 4FS

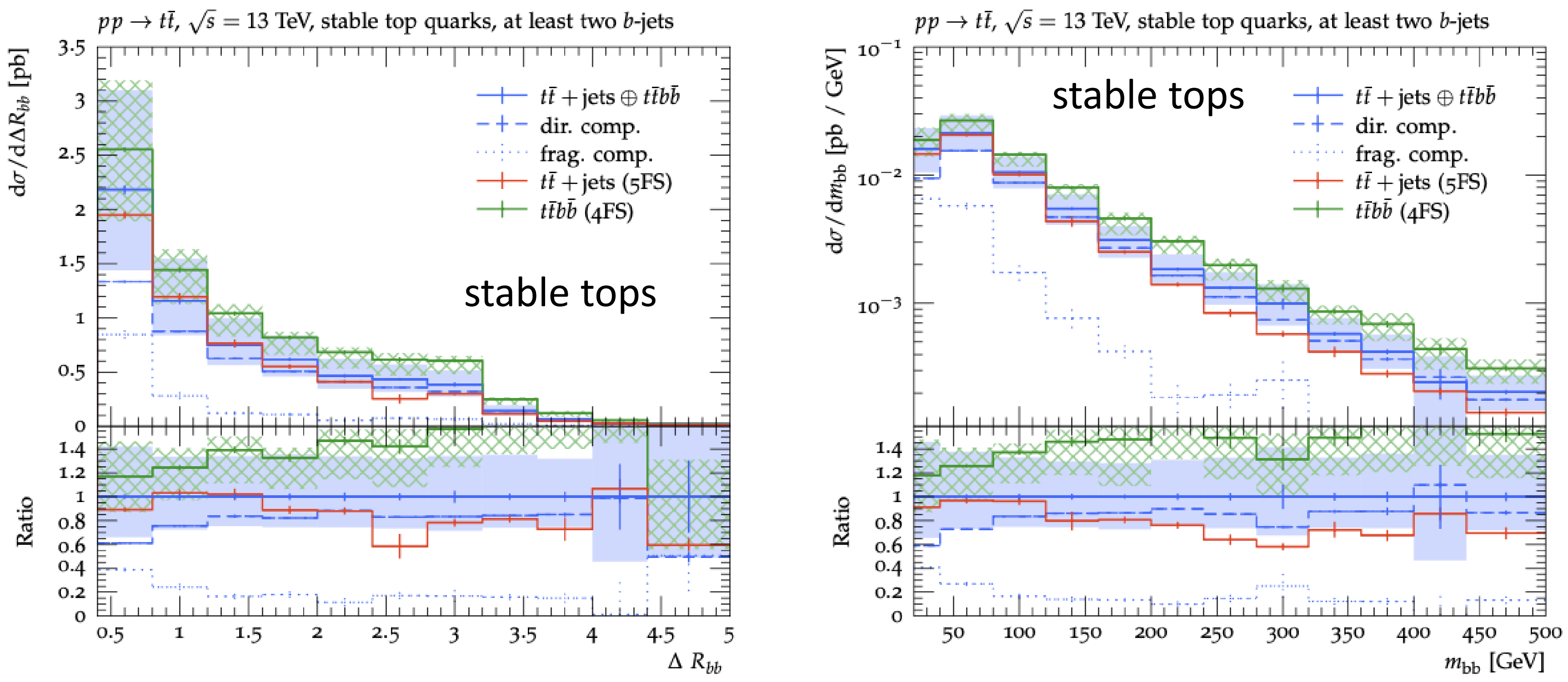
Fusing tt+jets and ttbb - 2b region





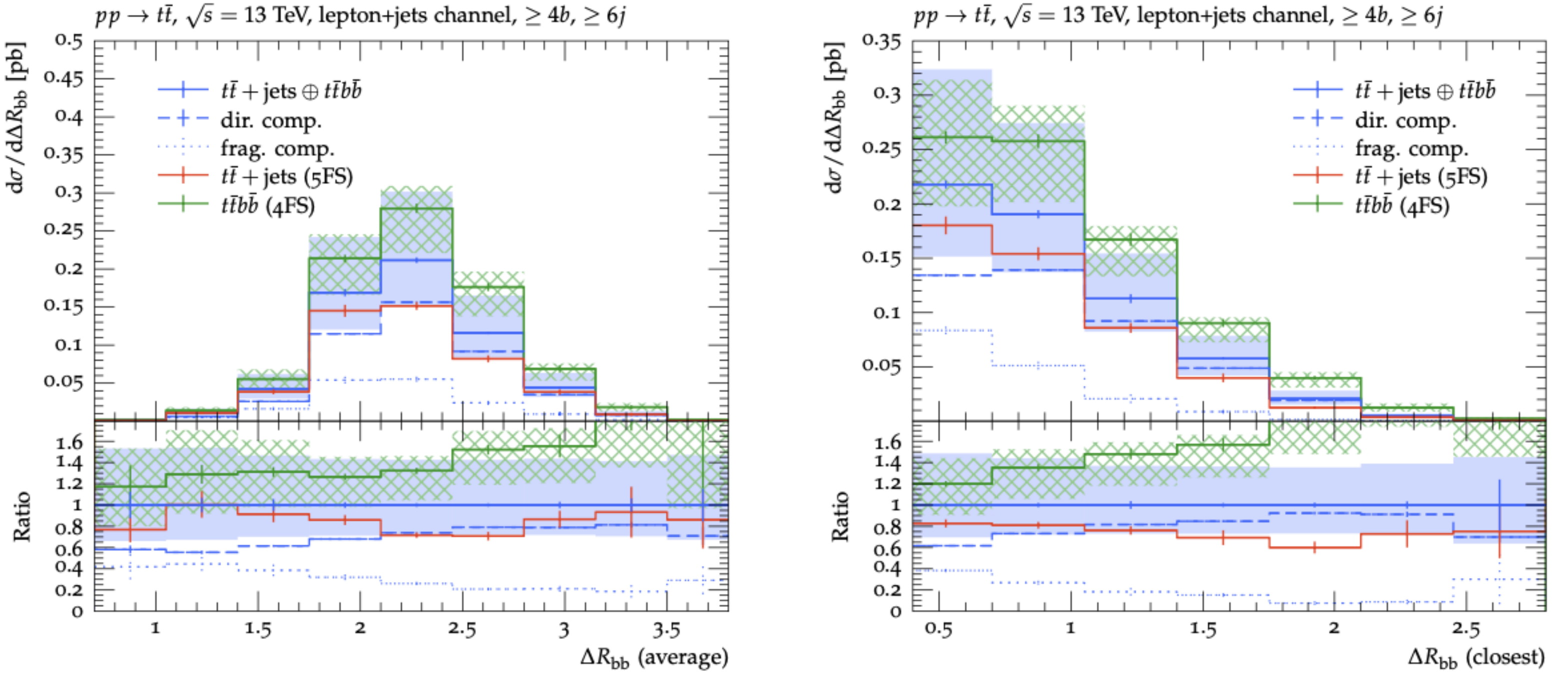
Fusing "interpolates" between 4FS and 5FS

Fusing tt+jets and ttbb - 2b region



Fusing "interpolates" between 4FS and 5FS

Fusing tt+jets and ttbb – 2b region decayed tops

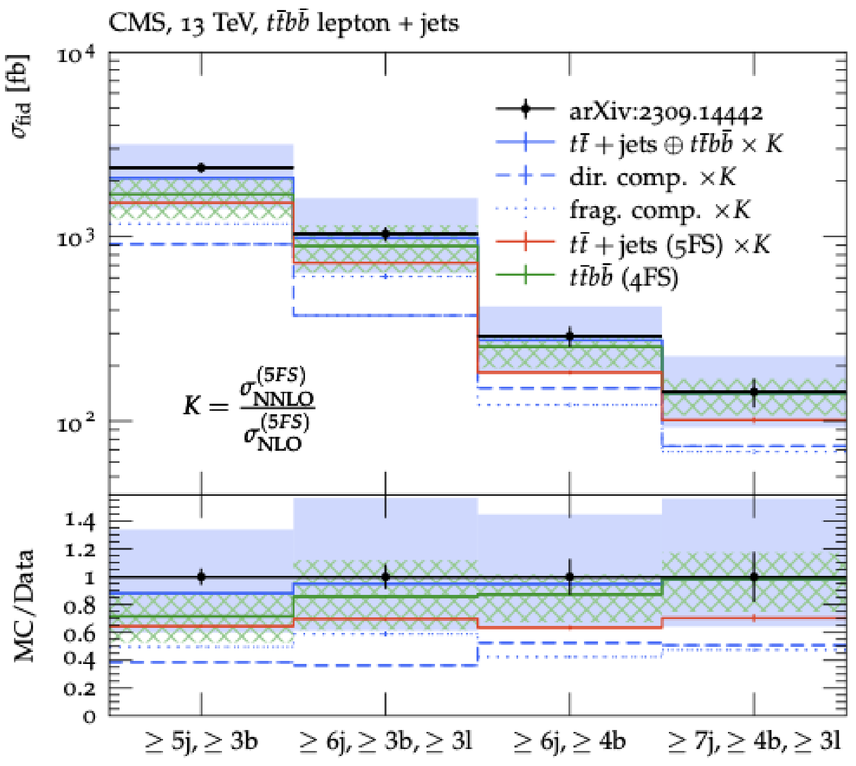


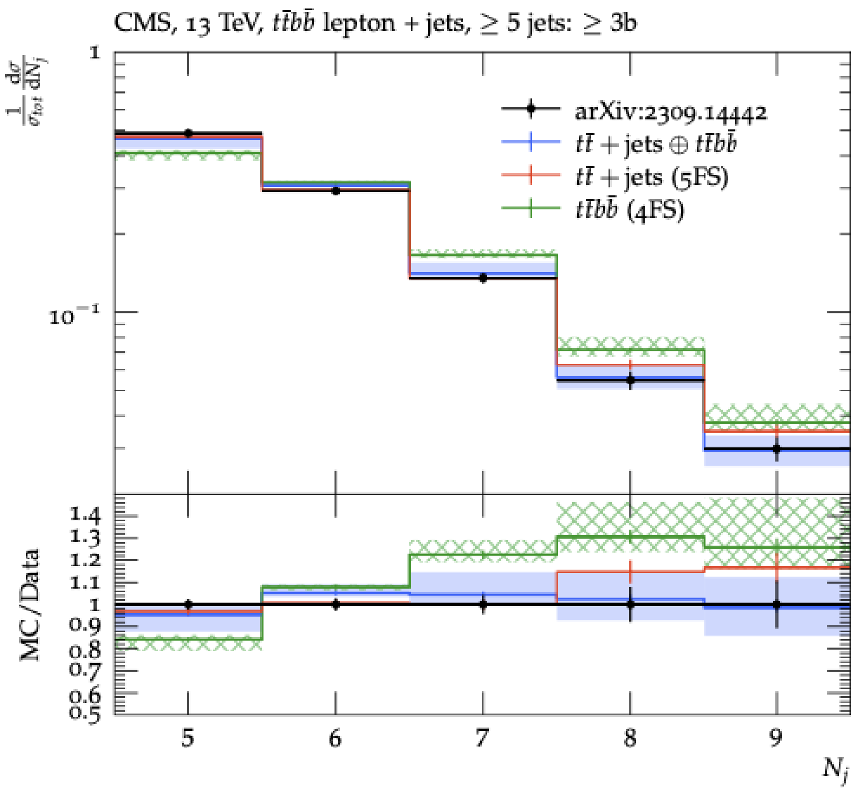
Large direct component, but still closer to 5FS than 4FS

CMS data:2309.14442

2402.15497

Comparison to CMS ttbb measurement





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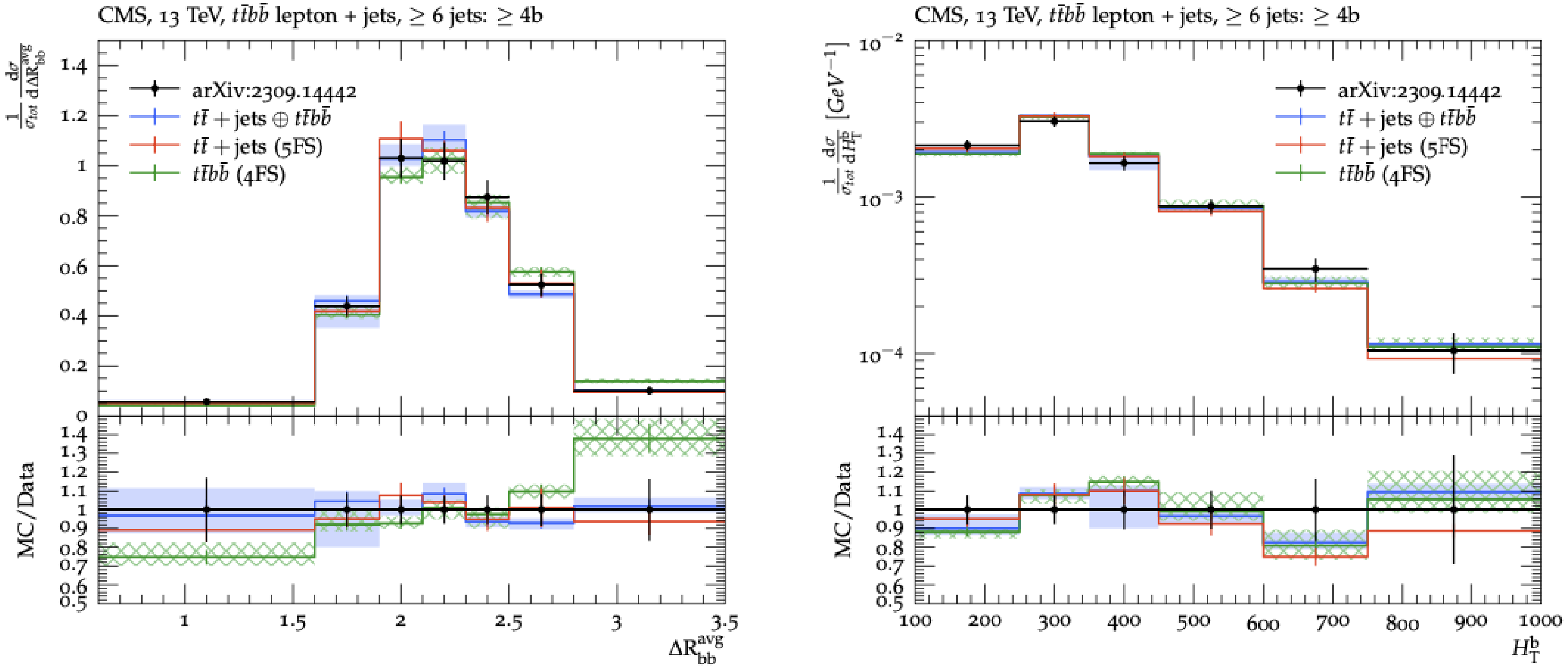
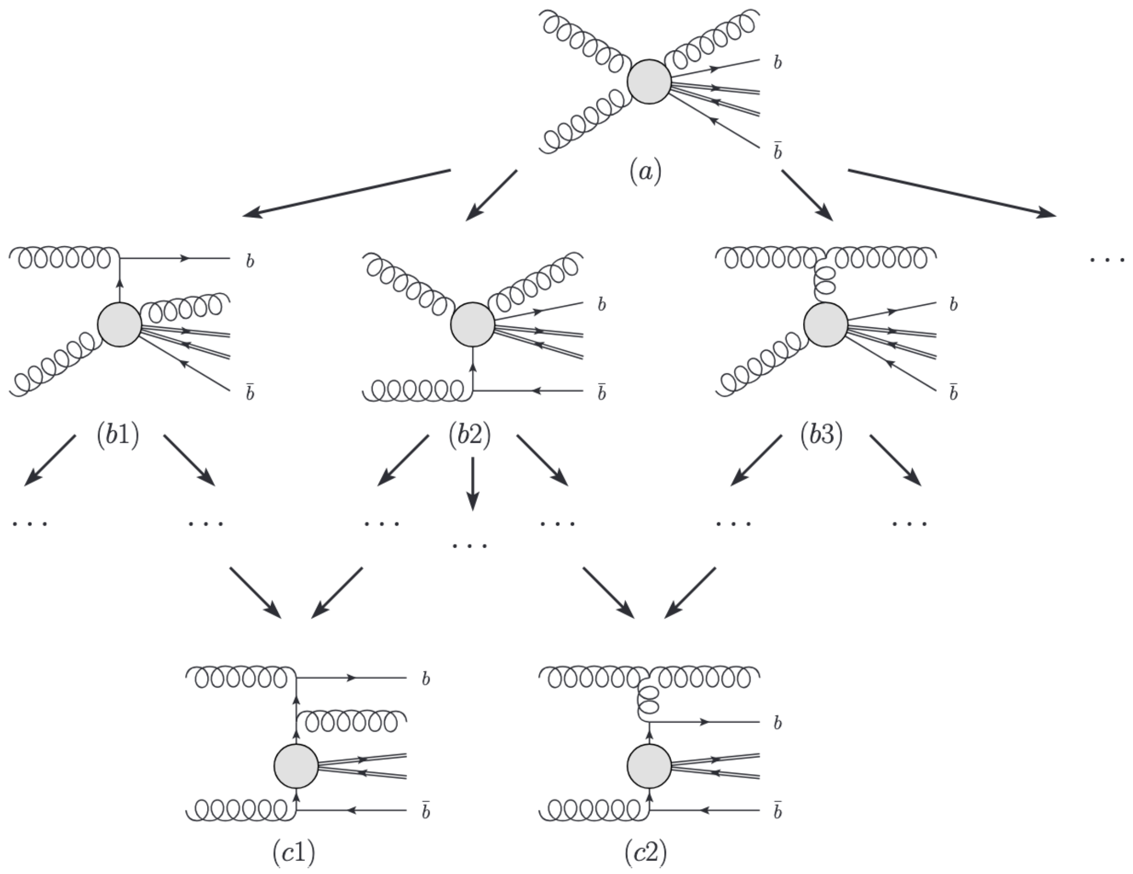


Summary

- ttbb a particularly striking example for challenges in HF simulation
- Showed current variations used in ATLAS and CMS
- New algorithm “Sherpa fusing” provides 4FS & 5FS predictions for the full tt+jets phase space combined in an automated fashion based on multijet merging and shows promising first results in comparison to LHC data

back - up

Example: parton shower histories for gg->ttbbg



tt+jets at LO
"fragmentation component"

ttbb at LO
"direct component"

ATLAS and CMS ttbb modeling variations - Variation of PowHeg internal damping parameters -

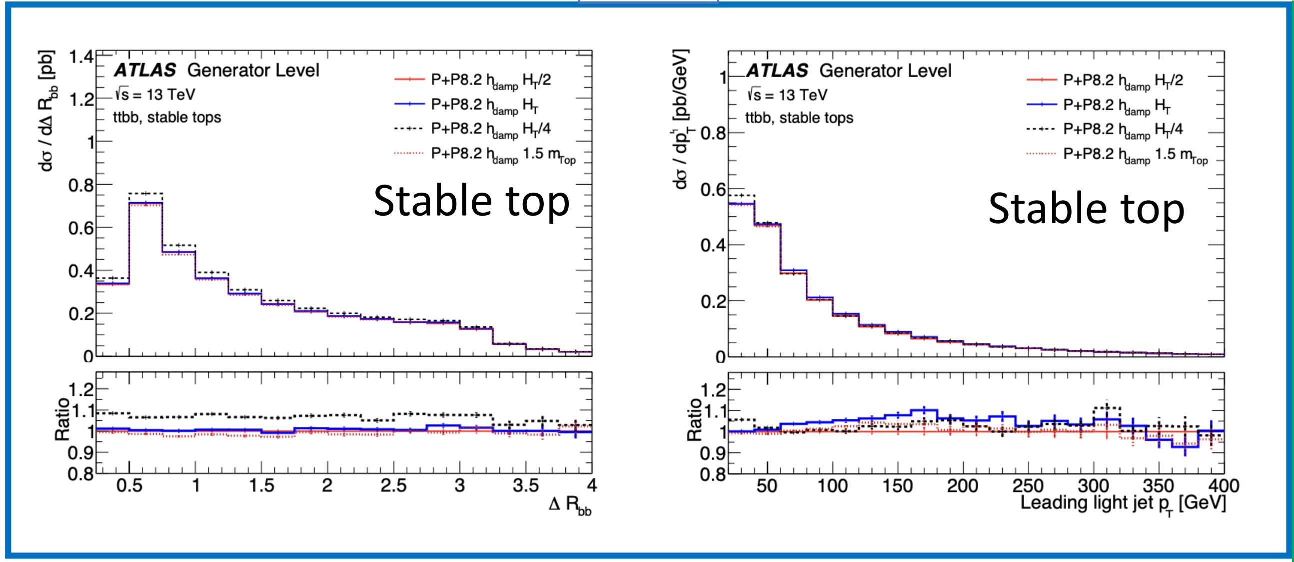
Split real emission phase space into finite region with fixed order calculation of resolved final state and singular region where divergences are resummed

$$R_s = F \cdot R$$
$$R_f = [1 - F]R,$$

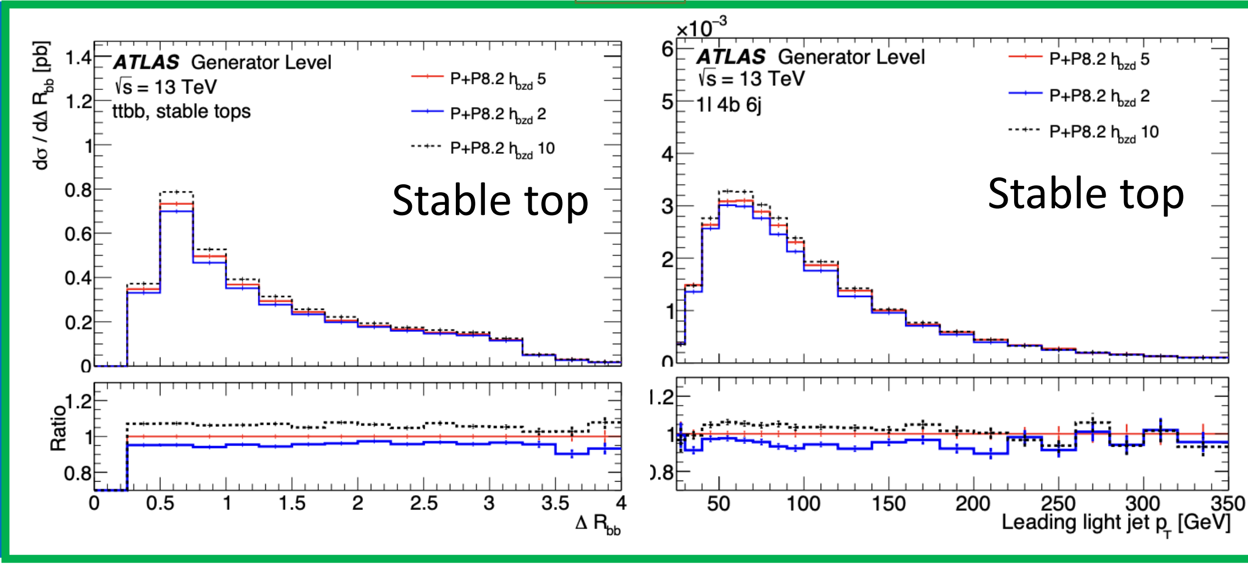
$$F = F_{damp} \cdot F_{bzd}$$

h_{damp} and h_{bzd} address different divergences

h_{damp}



h_{bzd}



Mostly normalization differences, very small effects differentially

ATLAS to CMS ttbb naming dictionary

Jet (R=0.4) containing	ATLAS	CMS
1 b-hadron	b-jet	-
2 b-hadrons	B-jet	-

Process	ATLAS	CMS
tt + >= 1 b-jet	tt+>= 1b	**ttB**
tt + 2 resolved b-jets	**tt+2b**	-
tt+ 1 jet containing 2 b-hadrons	**ttB**	**tt+2b**
tt + 1 resolved b-jet	tt + 1b	-