When charm and beauty adjoin the top

First measurement of the cross section of top quark pair production with additional charm jets using the dilepton final state in pp collisions at $\sqrt{s}$=13 TeV

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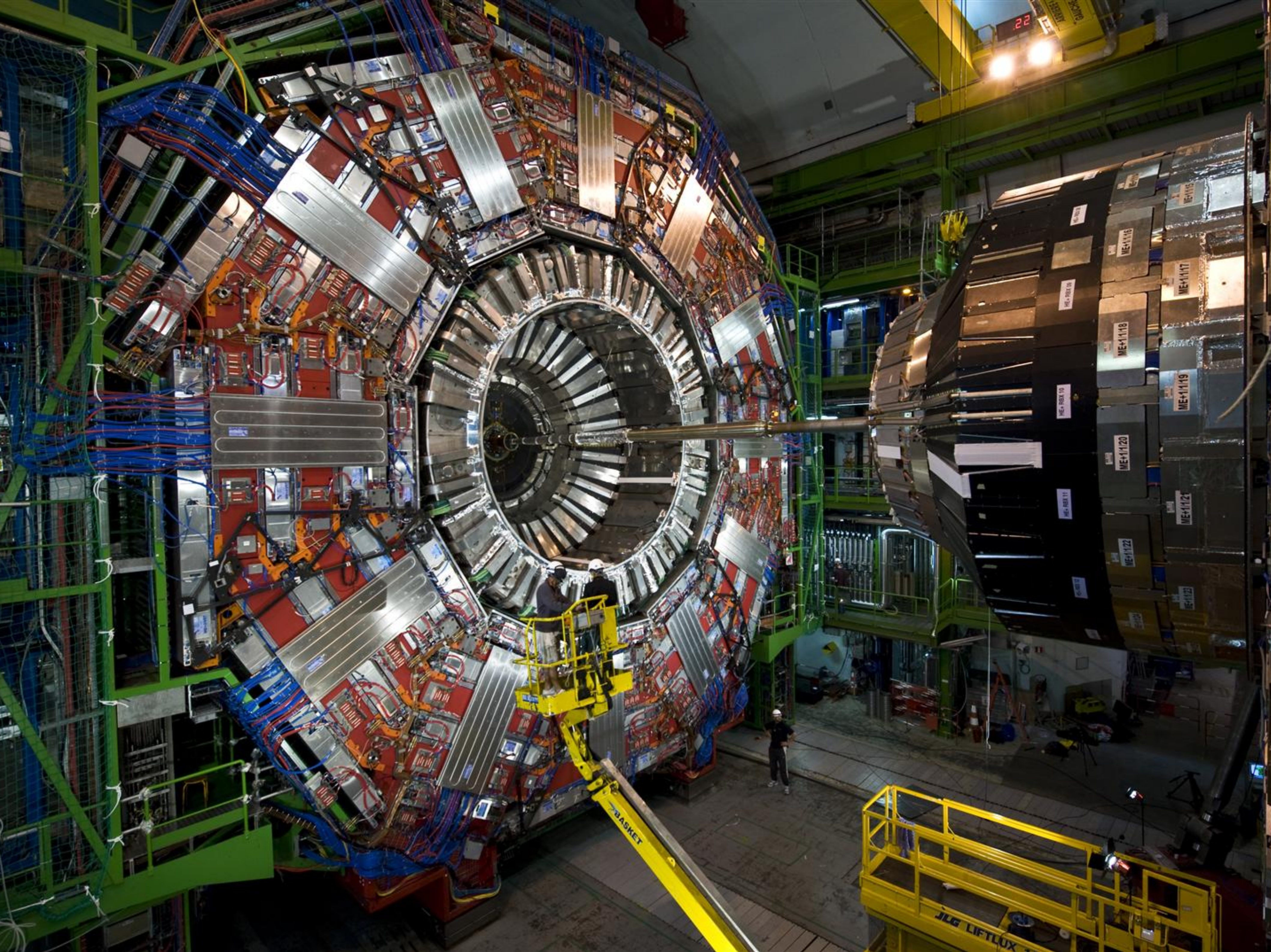
On behalf of the CMS Collaboration

PAS-TOP-20-003

Be.h Winter Solstice meeting, 16-12-2020


CMS
LHC
27 km
100 m under ground
CERN
Divonne-les-Bains
D1005
Gex
Cessy
Schweiz
France
Chens-sur-Léman
VAUD
GENÈVE
Versoix
Veigy-F
Corsier
Ferney-Voltaire
Collonge-Bellerive
enis-Pouilly
Pregny-Chambésy
Le Grand-Saconnex
Meyrin
E62
Satigny
Google
Genève


22
ME+1/1/18
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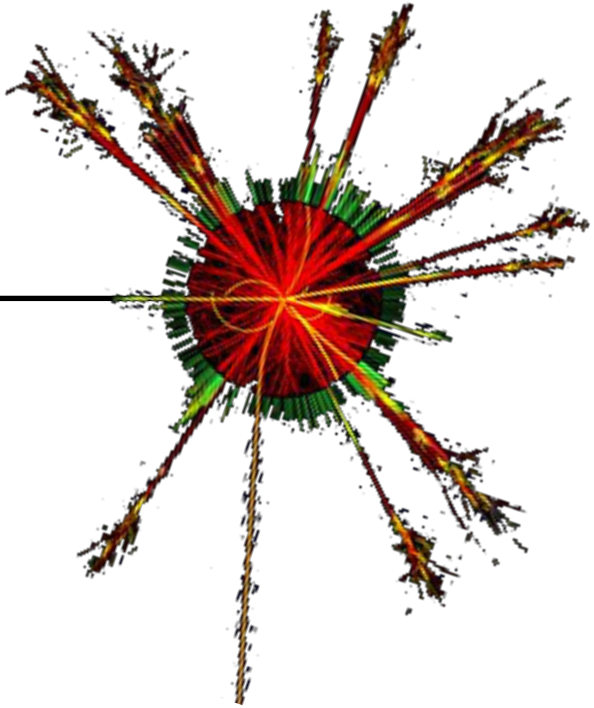
BASKET
JLG LIFTLUX

$t\bar{t}$ + HF: Theory



Theoretical modelling of $t\bar{t}$+HF

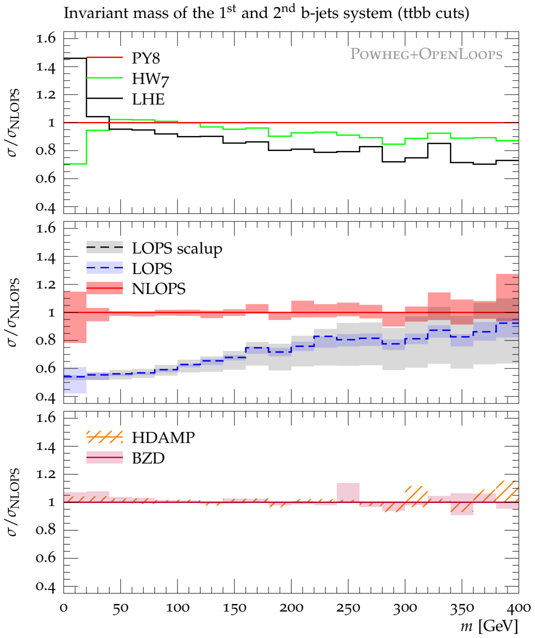
Simulating these processes remains an active field of study

Theory predictions / Simulation of the $t\bar{t}$+HF final state is highly non-trivial. It deals with very different scales ranging from the top quark mass down to momenta of the relatively soft additional jets.

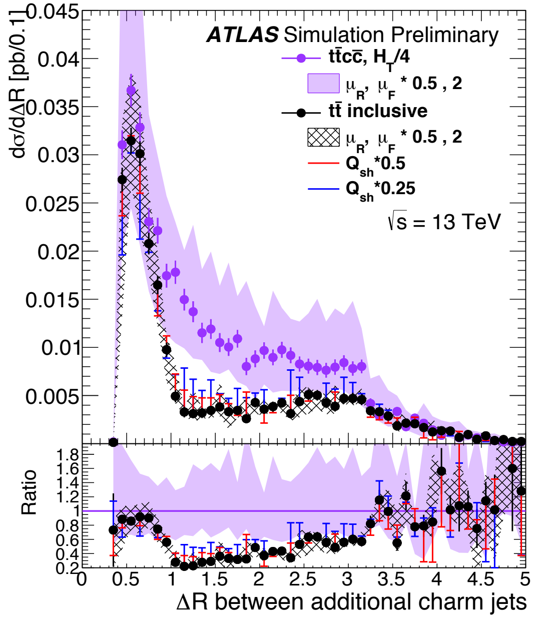
- Matrix Element vs Parton Shower.
- $t\bar{t}b\bar{b}$@LO vs NLO vs $t\bar{t}b\bar{b}j$@NLO (large k-factor, depending on scale choice) [Buccioni F. et al, JHEP 12 (2019), 015].
- Factorization/Renormalization/Shower/matching scales.
- Inclusive $t\bar{t}$+jets versus dedicated $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ simulation.

Still a very active field of study!
[Sigert F, Jan 2020, Zürich Phenomenology Workshop]
[Pozzorini et al., October 2020, ttH-HXSWG meeting]
[Pozzorini et al., December 2020, CMS TOP Workshop]

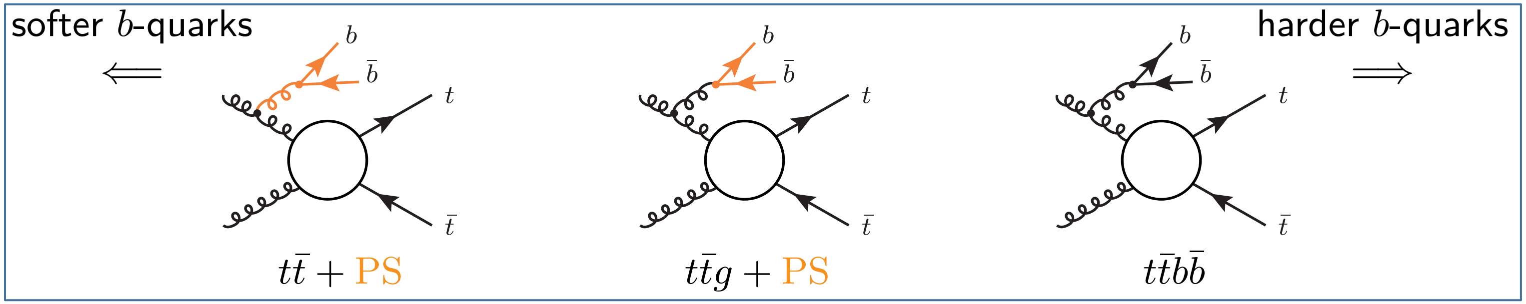
T. Ježo et al., *Eur. Phys. J.* **C78** (2018), no. 6 502, [arXiv:1802.00426]


Invariant mass of the 1st and 2nd b-jets system (ttbb cuts)

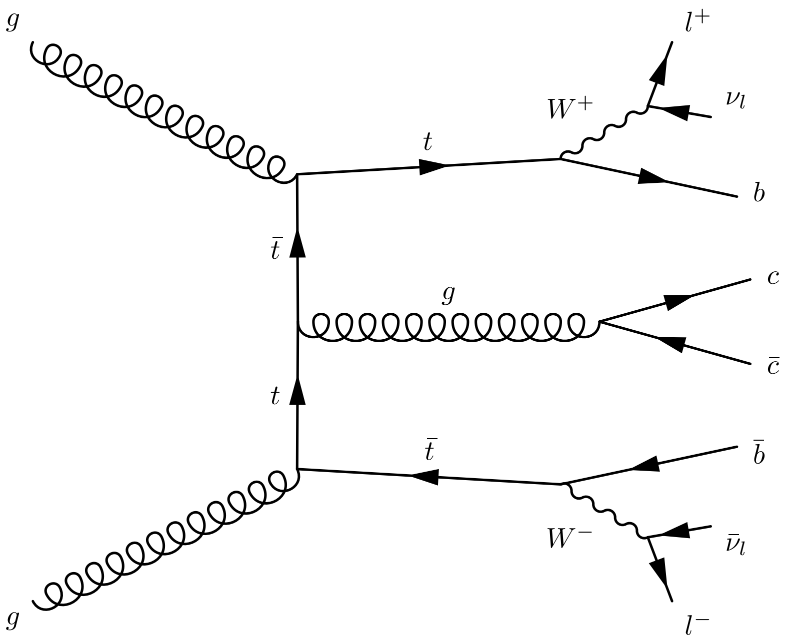
ATL-PHYS-PUB-2016-011

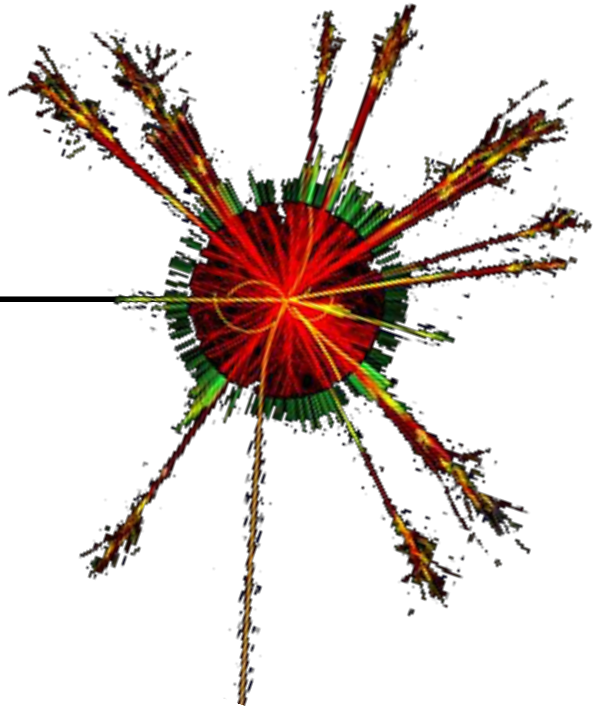


S. Pozzorini, Theory progress on $t\bar{t}H(b\bar{b})$ background, TOP2018 @ Bad Neuenahr, Germany



$t\bar{t}$ + charm jets!

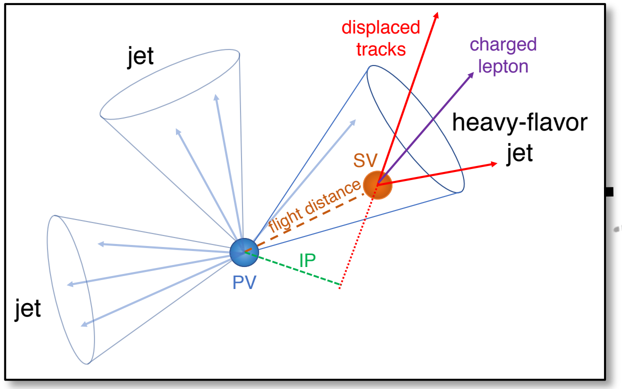




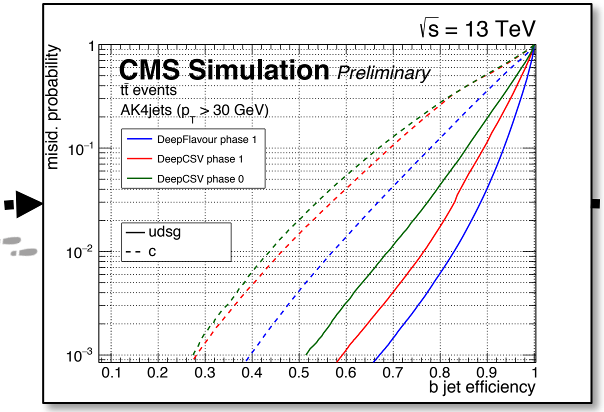
Measurement of $t\bar{t}+c\bar{c}$ production

A roadmap towards a successful measurement

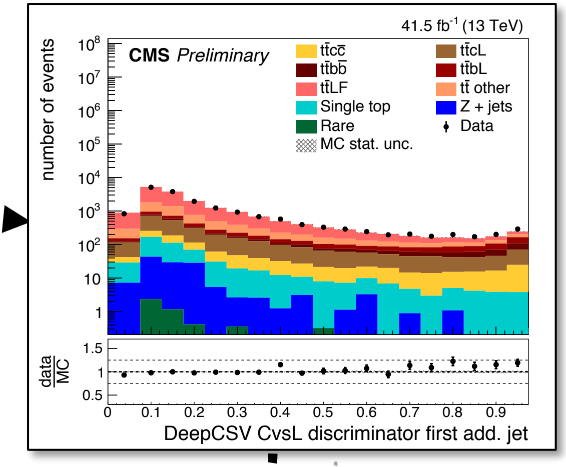
① c, b and t quarks require jets and heavy flavor tagging (new **c-tagger**)



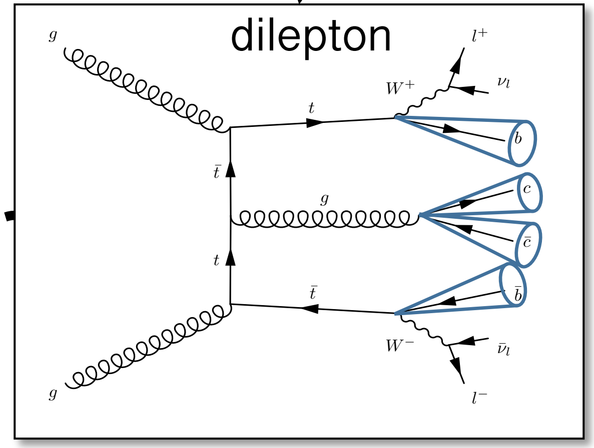
② Improved ML techniques for HF tagging (**DeepCSV**/DeepJet)



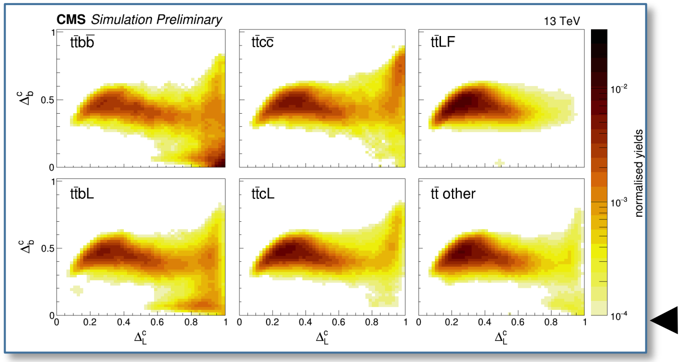
③ Calibration performance (charm tagger shape)



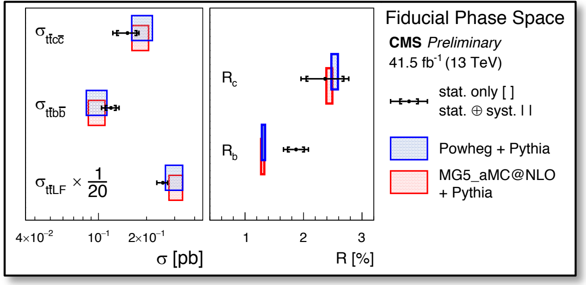
④ Selection and reconstruction of the $t\bar{t}$+HF topology (jet-parton match)



⑤ Differentiating $t\bar{t}$+HF categories (ML classifier)



⑥ Resulting cross section measurement



First measurement of the inclusive $\mathrm{t\bar{t}c\bar{c}}$ cross section

Simultaneously measure $\sigma(\mathrm{t\bar{t}c\bar{c}})$, $\sigma(\mathrm{t\bar{t}b\bar{b}})$, $\sigma(\mathrm{t\bar{t}LF})$

and $R_{c/b} = \sigma(\mathrm{t\bar{t}+c\bar{c}/b\bar{b}}) / \sigma(\mathrm{t\bar{t}+jj})$

Measurement performed in the dilepton channel

Data collected by CMS in 2017, corresponding to 41.5 fb^{-1} of integrated luminosity

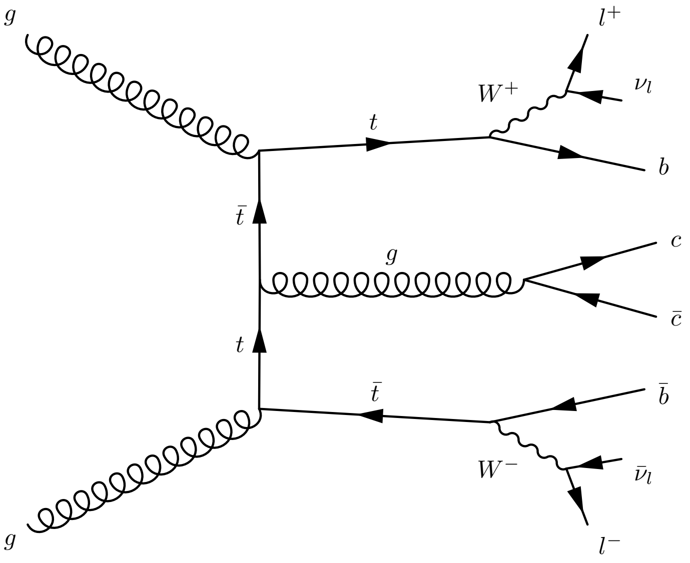
Key ingredients:

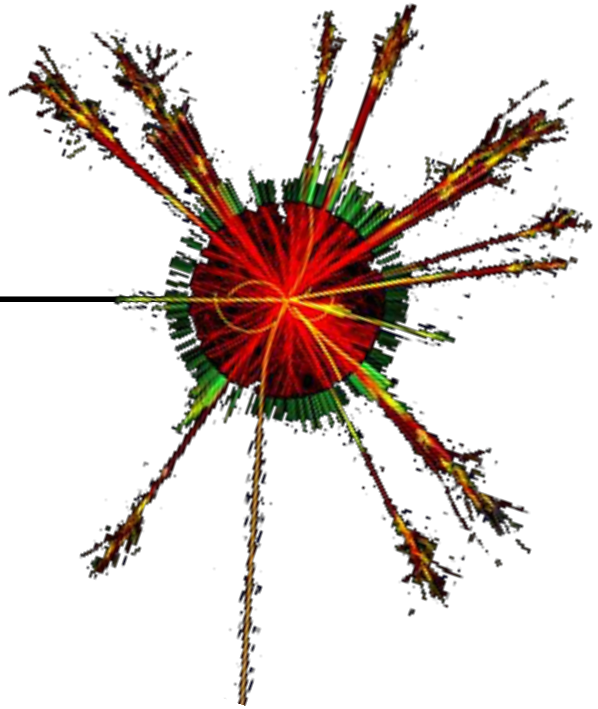
Use neural network for matching jets to partons.

Rely on charm-jet identification to separate the different signals!

Calibrate the c-tagger discriminants (full shape)

Signal definition + event selection





Signal definition

Fiducial and full phase space

Definition of heavy-flavor jets

Heavy-flavor definition in simulation based on ghost hadron clustering *Phys.Lett.B* 659 (2008) 119-126

Fiducial phase space

- $pp \to t\bar{t}jj \to \ell^+\bar{\nu}_\ell b\ell^-\nu_\ell\bar{b}jj$ (dilepton)
- Two generated leptons with $p_T > 25$ GeV and $|\eta|<2.4$ (electron/muon/tau)
- Two particle-level b jets from top quark decay with $p_T > 20$ GeV and $|\eta|<2.4$
- At least two additional particle-level jets (not from top quark decay) with $p_T > 20$ GeV and $|\eta|<2.4$ and $\Delta R(l,jet)>0.4$

Full phase space

- $pp \to t\bar{t}jj \to W^+bW^-\bar{b}jj$
- dilepton / single lepton / all-hadronic
- At least two additional particle–level jets (not from top quark decay) with pT > 20 GeV and $|\eta|<2.4$ and $\Delta R(l,jet)>0.4$

Categorization based on flavor of additional jets

- $t\bar{t}b\bar{b}$: ≥ 2 add. b jets with at least one b hadron
- $t\bar{t}bL$: 1 add. b jet with at least one b hadron (merged or missing jet)
- $t\bar{t}c\bar{c}$: ≥ 2 add. c jets with at least one c hadron (if not $t\bar{t}b\bar{b}$/ $t\bar{t}bL$)
- $t\bar{t}cL$: 1 add. c jet with at least one c hadron (if not $t\bar{t}b\bar{b}$/L, merge/missing jet)
- $t\bar{t}LF$: no add. b or c jets, but 2 add. light jets pass acceptance requirements.
- $t\bar{t}$ other: failing visible/full phase space requirements

Event selections

Dileptonic top quark pair events + 2 additional jets

Global

- ==2 isolated leptons (e/μ)
- >= 4 jets
- >= 2 b-tagged jets

Electrons

- $p_T > 25$ GeV
- $|\eta| < 2.4$
- $|\eta| \notin [1.4442 - 1.566]$ ("transition region")
- Rel. Iso < 0.15

Muons

- $p_T > 25$ GeV
- $|\eta| < 2.4$
- Rel. Iso < 0.15

Dilepton invariant mass

- $m_{ll} > 12$ GeV
- $\mu\mu/ee$: $m_{ll} \notin [m_Z - 15$ GeV , $m_Z + 15$ GeV $]$

MET

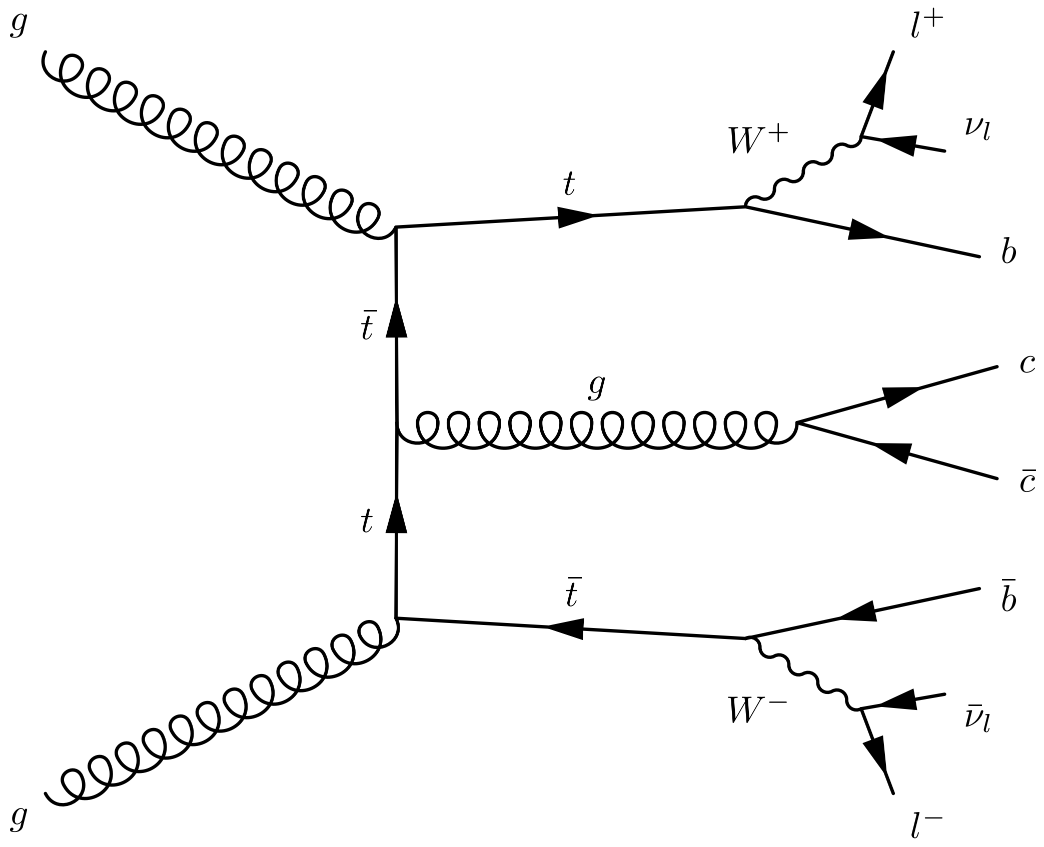
- $\mu\mu/ee$: MET>30 GeV

Jets

- $p_T > 30$ GeV
- $|\eta| < 2.5$
- ΔR(lepton,jet)>0.5
- DeepCSV value > 0

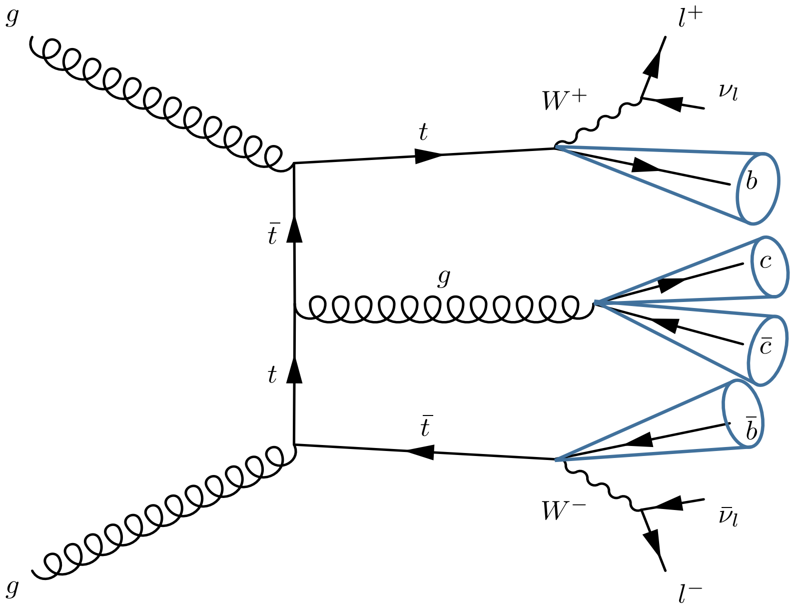
b-jets/c-jets

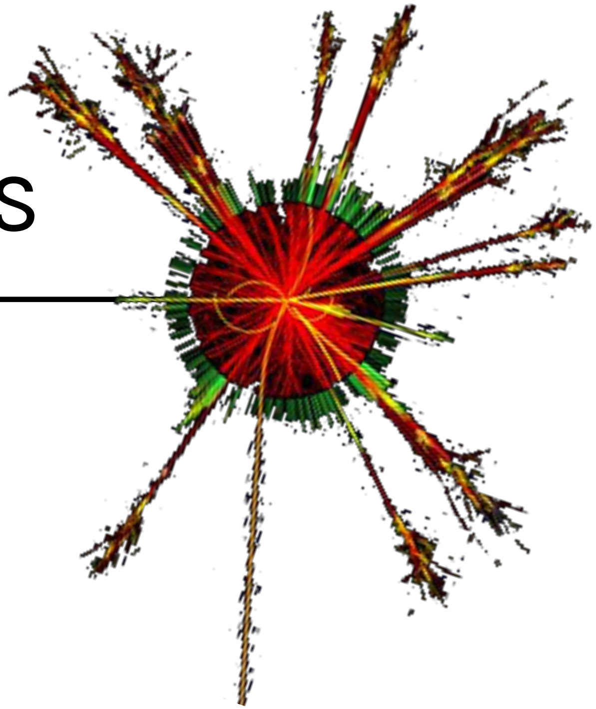
- 2 top-matched jets: Medium DeepCSV b-tagged



Results in >95% $t\bar{t}$ + $\geq$2 jets!

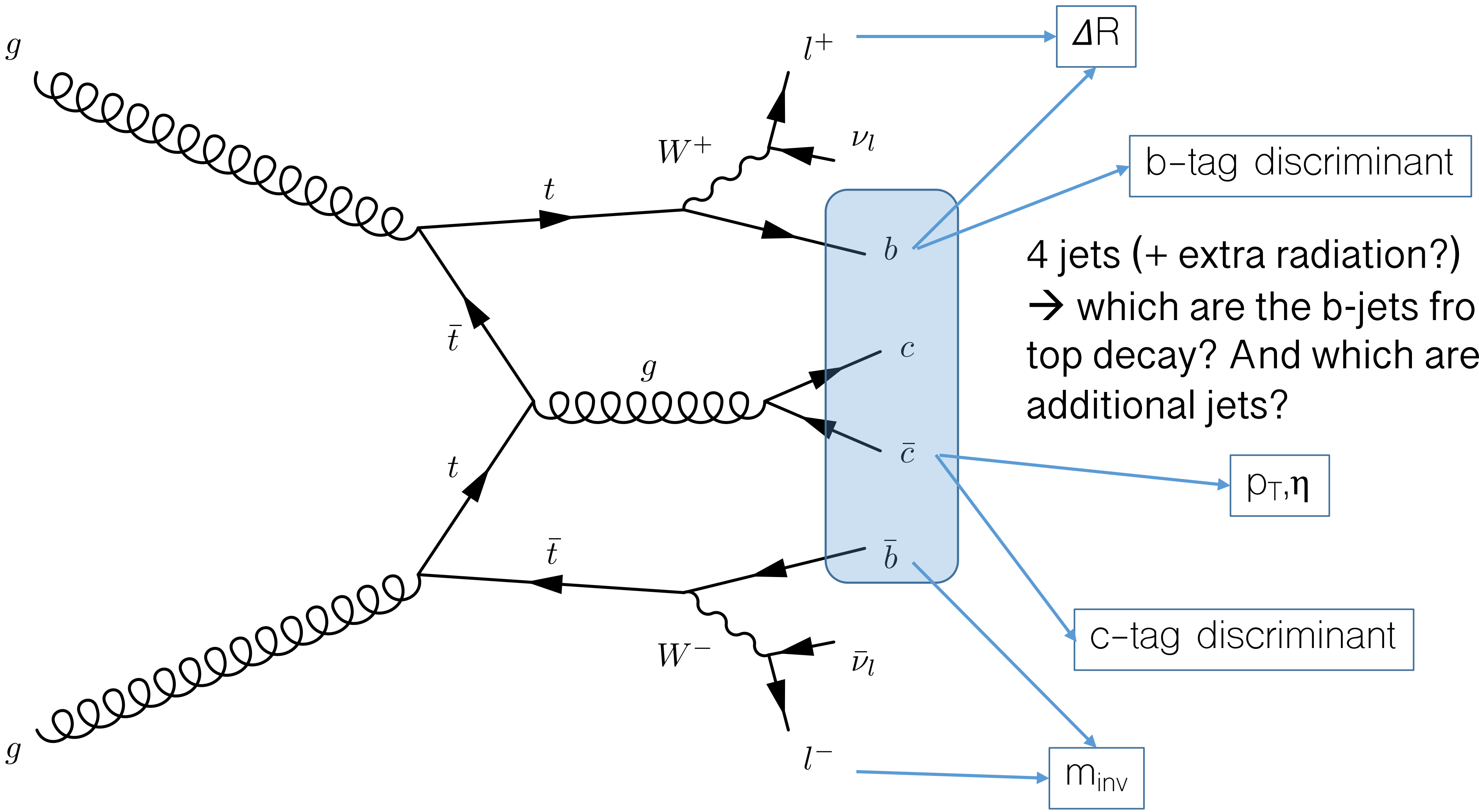
Matching jets to partons





Jet-parton matching

Event kinematics + jet flavour as input to a neural network (NN)



4 jets (+ extra radiation?)
→ which are the b-jets from the top decay? And which are the additional jets?

→ Combine in a NN and pick the best jet-parton assignment

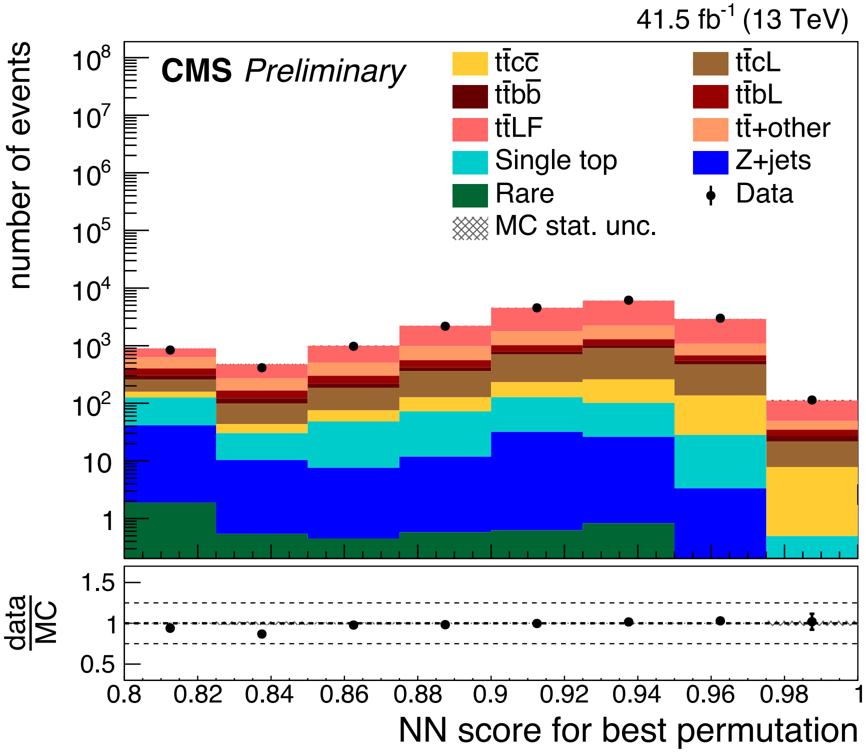
Jet-parton matching

Performance and neural network output

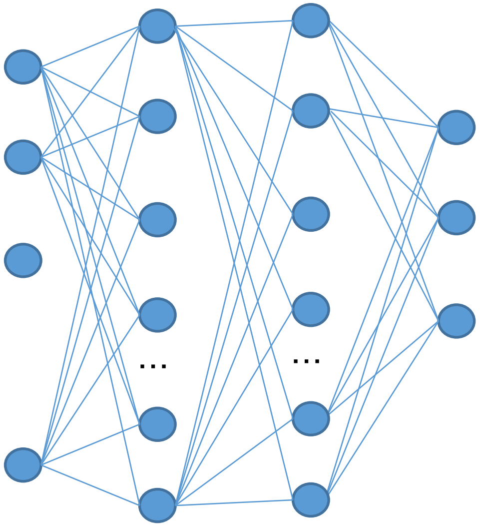
Only ~ 76% of events have two b jets matched to two gen-level b quarks from top quark within $\Delta R<0.3$. Only these are used in the training of the NN.

The network correctly identifies the two additional c (b) jets in **50% (30%)** of the cases for $t\bar{t}c\bar{c}$ ($t\bar{t}b\bar{b}$) events.

Good agreement between the data (black markers) and the simulation (filled histograms).



Two hidden layers that comprise 50 neurons each, with ReLu activation functions and a 10% dropout



3 x ΔR

3 x m_{inv}

8 x p_T,η

...

12 x b/c-tag

Correct = P_C

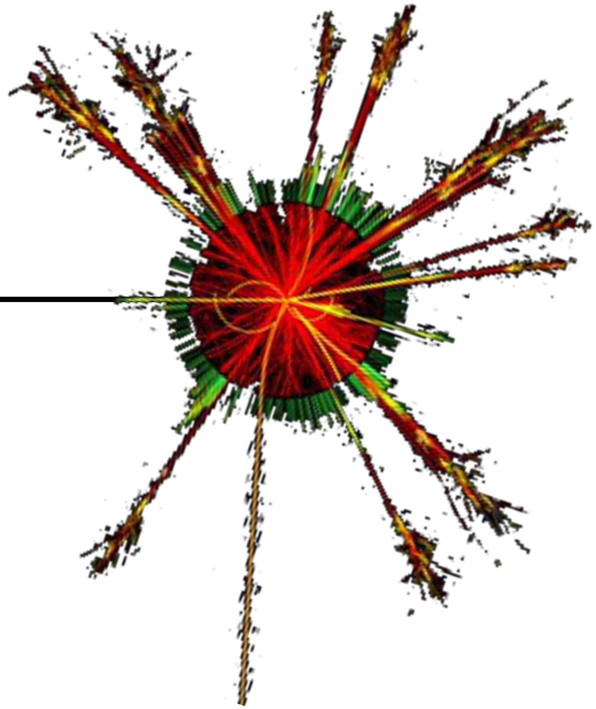
Flipped = P_F

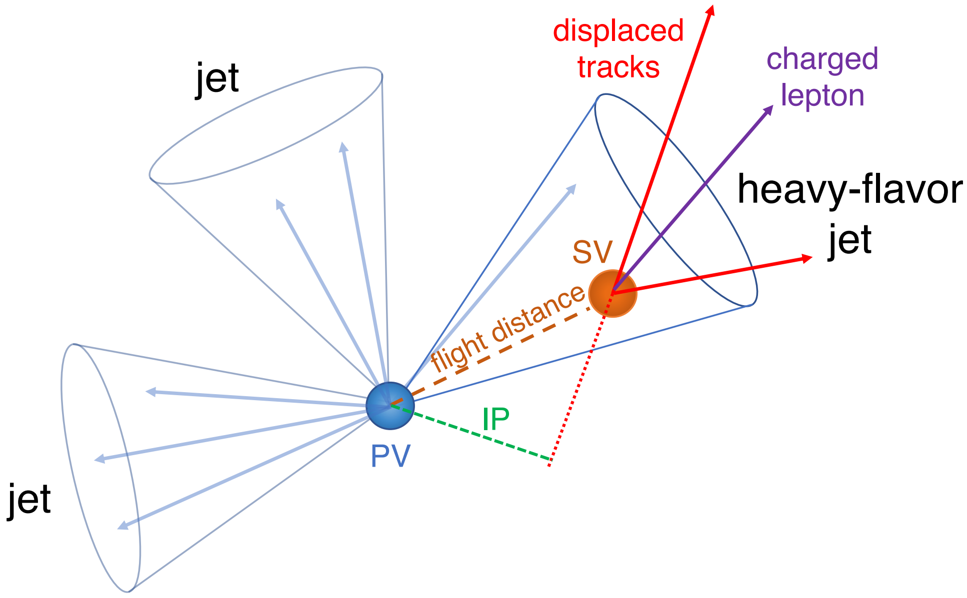
Wrong = P_W

NN score for best permutation

$$= \max\left(\frac{P_C}{P_C+P_W}\ ,\ \frac{P_F}{P_F+P_W}\right)$$

Charm tagging





c-tagger calibration

Charm jet identification using the DeepCSV algorithm

The DeepCSV heavy-flavour tagging algorithm is a multi-class algorithm that predicts probabilities (P) for jets to originate from a b, c or light-flavour (udsg) quark (or gluon).

This discrimination is based on properties such as track displacement, secondary vertex mass/flight distance, …

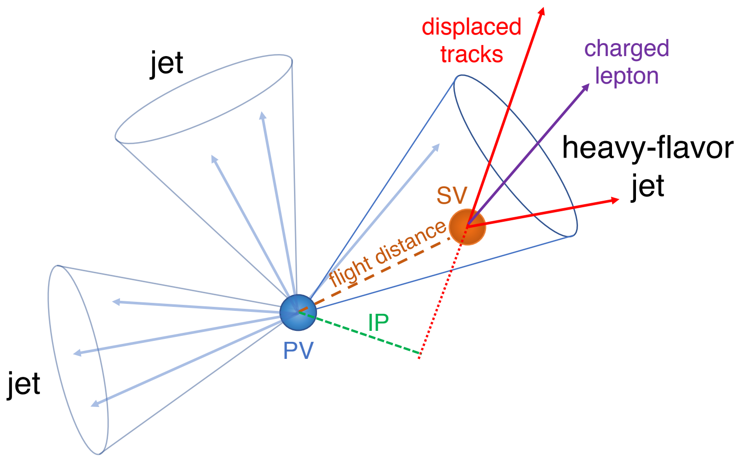
Properties from c jets are distributed midway between those of b or light-flavour jets → two c-tagging discriminants!

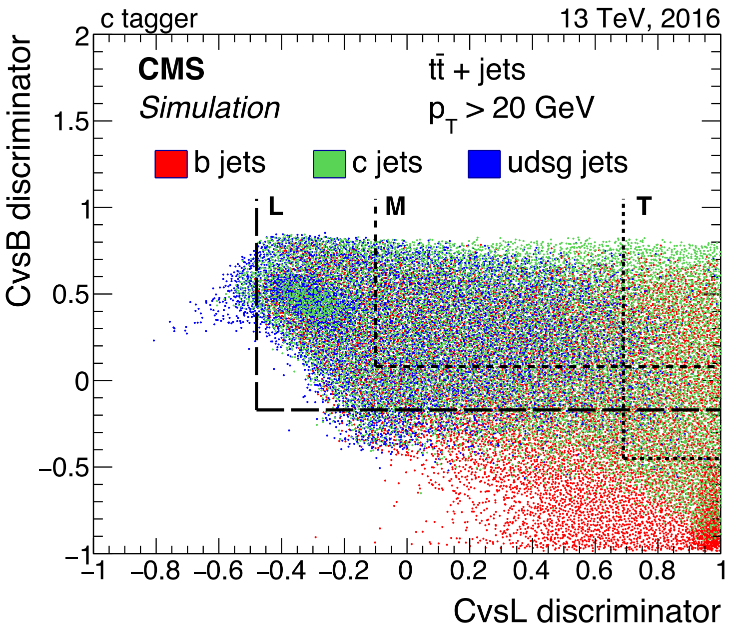
$$\mathrm{P(CvsL)} = \frac{\mathrm{P(c)}}{\mathrm{P(c)} + \mathrm{P(udsg)}}, \qquad \mathrm{P(CvsB)} = \frac{\mathrm{P(c)}}{\mathrm{P(c)} + \mathrm{P(b)} + \mathrm{P(bb)}}.$$

To use these discriminants in a neural network, the 2-dim shape in simulations needs to be calibrated to the data!

Novel shape calibration of the two-dimensional CvsL and CvsB DeepCSV c-tagger discriminators

JINST 13 (2018) P05011

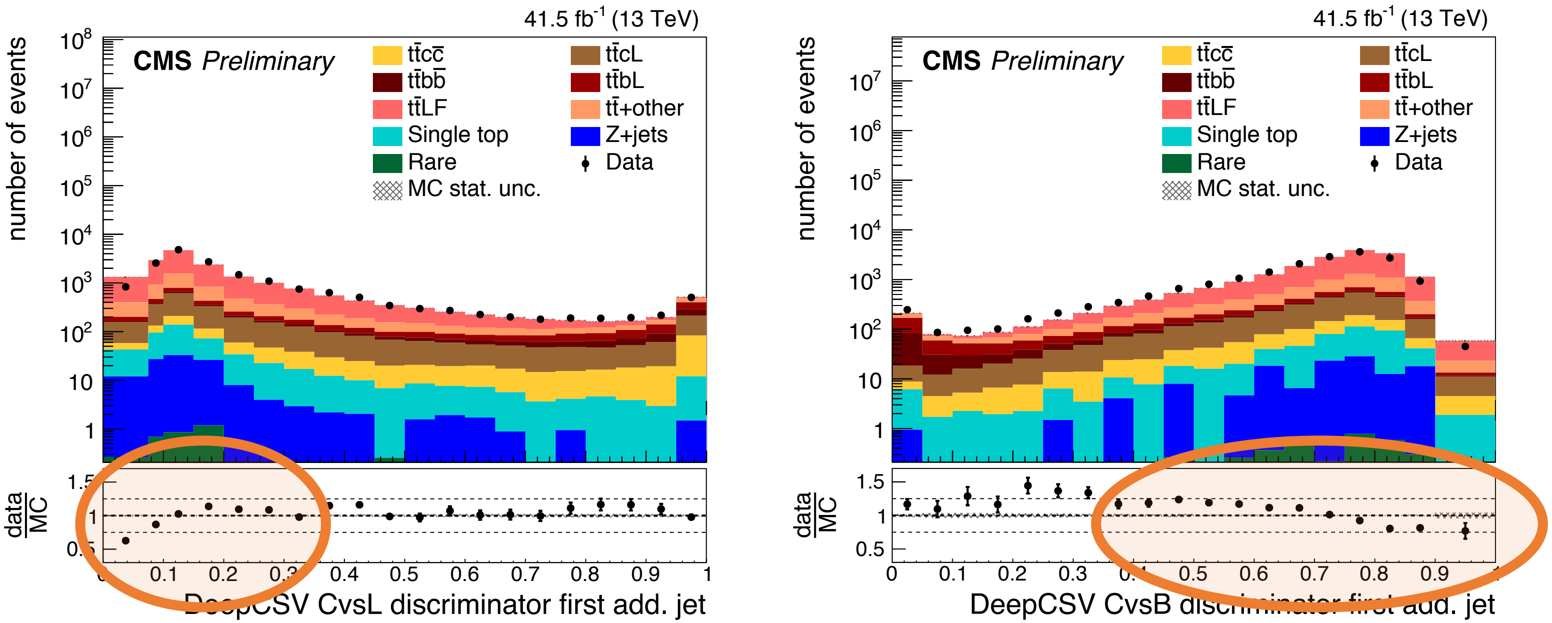




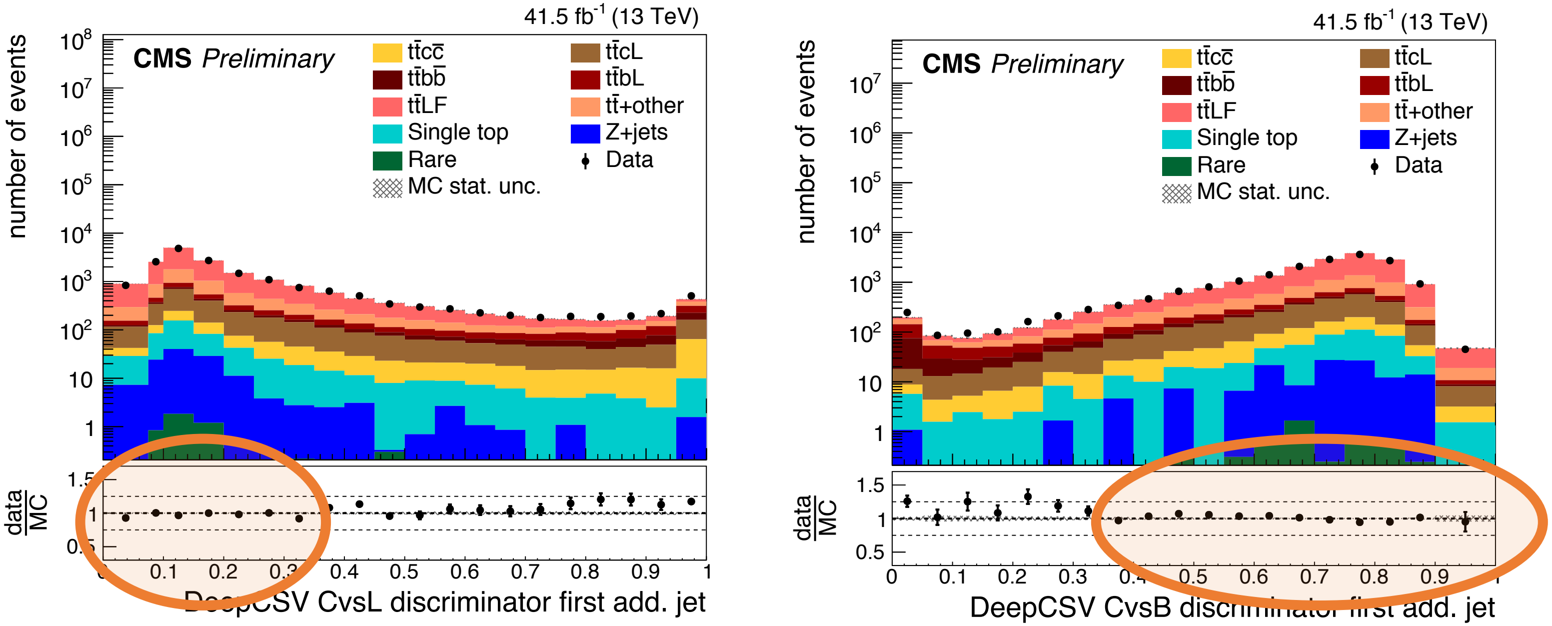
c-tagger calibration

Effect of the calibration on the additional jet CvsL/CvsB

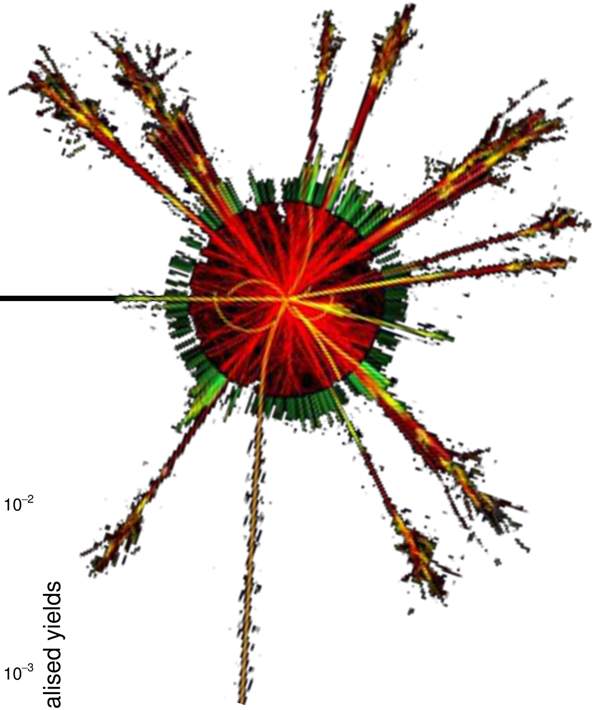
Before

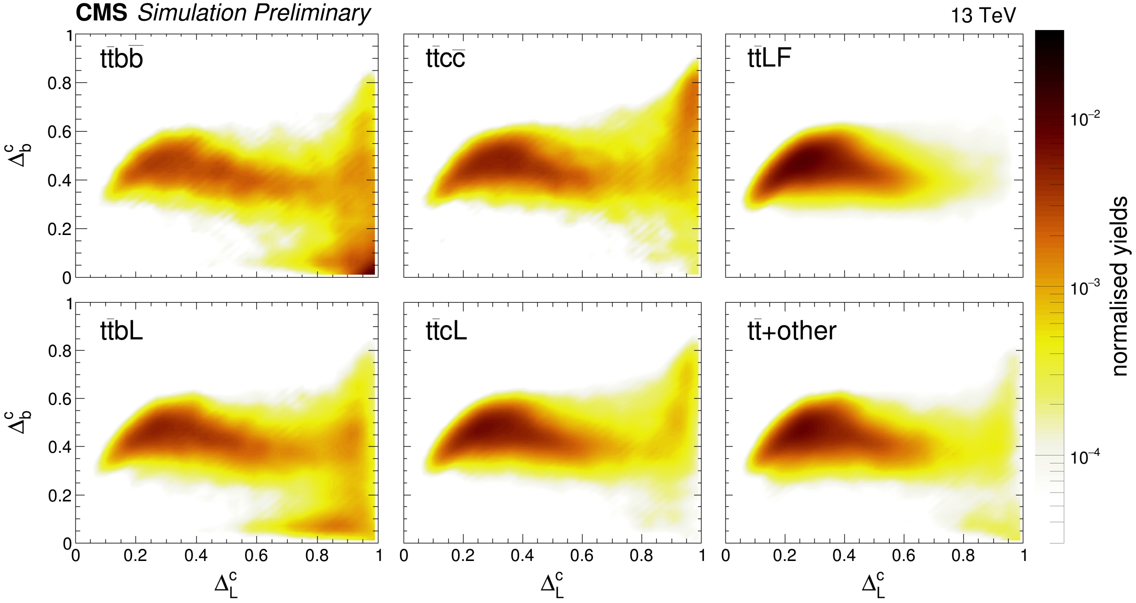


After



Template fit to a neural network classifier

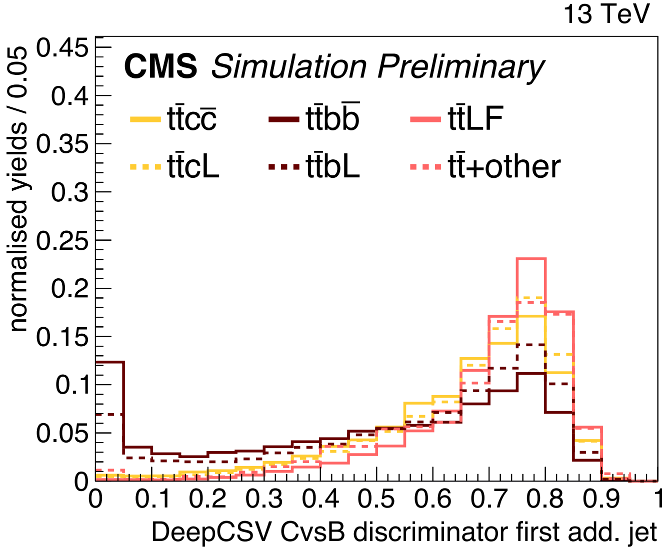




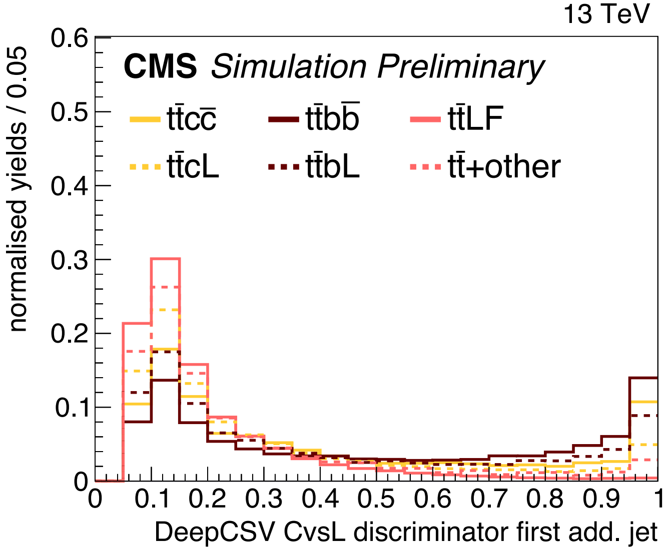
Template fit using NN discriminator

Sensitive observables to distinguish between $t\bar{t}c\bar{c}$, $t\bar{t}b\bar{b}$, $t\bar{t}$LF

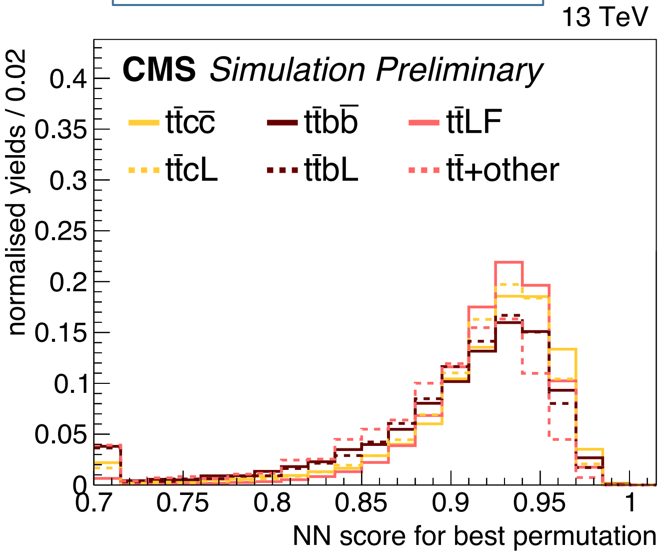
CvsB add. Jet 1



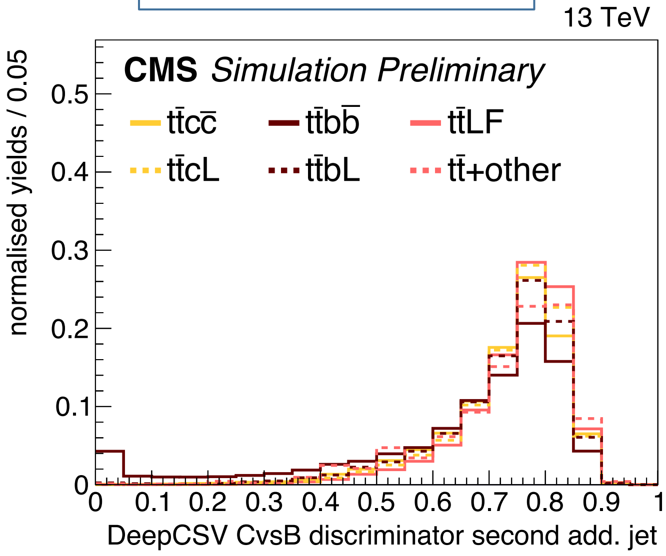
CvsL add. Jet 1



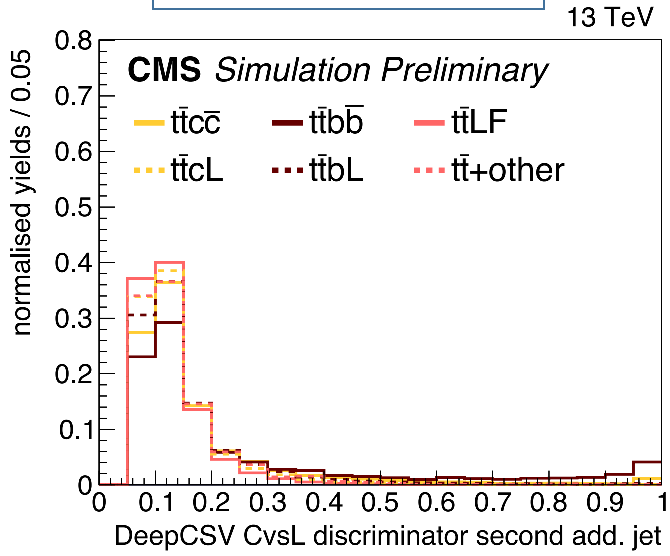
parton match NN



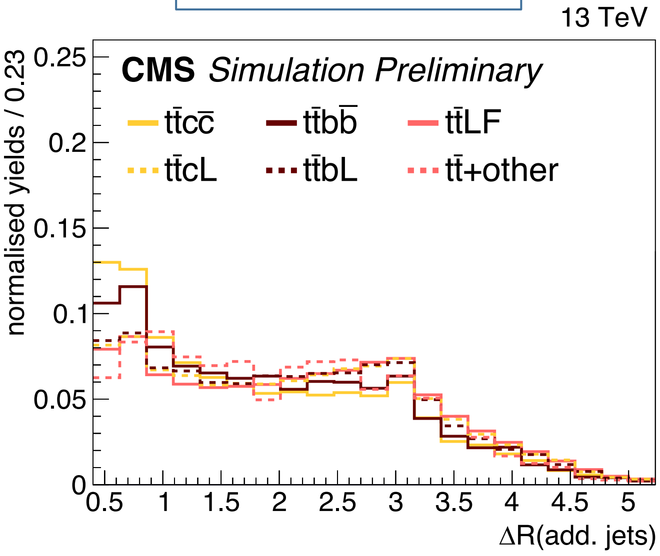
CvsB add. Jet 2



CvsL add. Jet 2



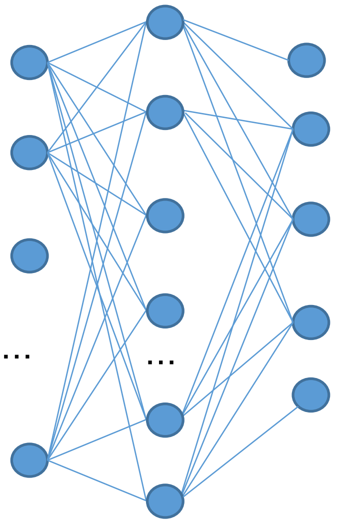
ΔR(add. Jets)



Template fit using NN discriminator

Defining the neural network

one hidden layer that comprises 30 neurons with
ReLu activation functions and a 10% dropout



- CvsL add. jet 1
- CvsL add. jet 2
- CvsB add. jet 1
- CvsB add. jet 2
- Parton match NN
- ΔR(add. Jets)

- $\mathrm{P}(t\bar{t}c\bar{c})$
- $\mathrm{P}(t\bar{t}c\mathrm{L})$
- $\mathrm{P}(t\bar{t}b\bar{b})$
- $\mathrm{P}(t\bar{t}b\mathrm{L})$
- $\mathrm{P}(t\bar{t}\mathrm{LF})$

$$\Delta_b^c = \frac{\mathrm{P}(t\bar{t}c\bar{c})}{\mathrm{P}(t\bar{t}c\bar{c}) + \mathrm{P}(t\bar{t}b\bar{b})}$$

$$\Delta_L^c = \frac{\mathrm{P}(t\bar{t}c\bar{c})}{\mathrm{P}(t\bar{t}c\bar{c}) + \mathrm{P}(t\bar{t}\mathrm{LF})}$$

Δ_b^c and Δ_L^c can be interpreted as topology-specific c-tagger discriminants

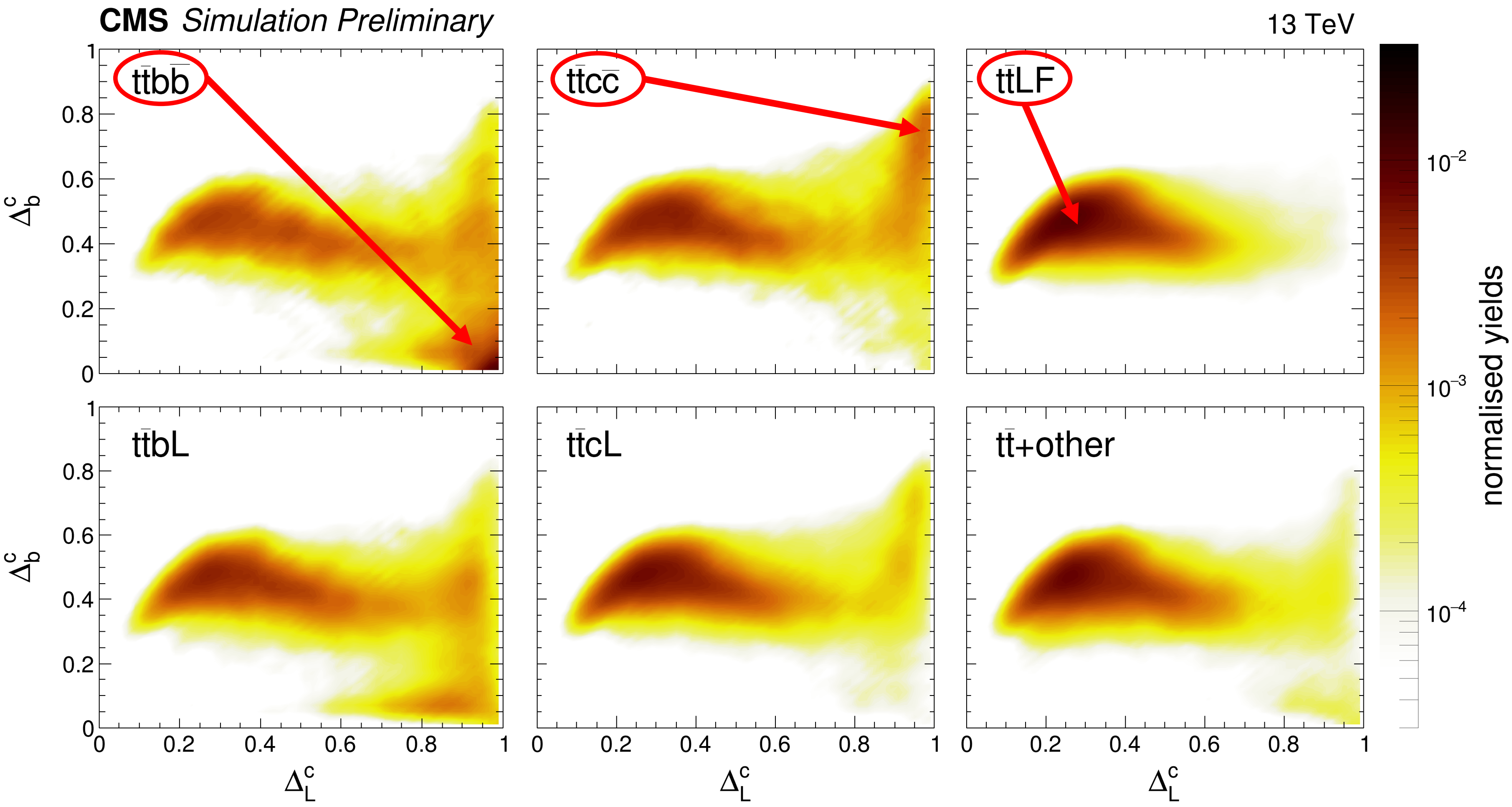
Information on the flavour of the two additional jets

Additional information on the event kinematics to most optimally distinguish different signal categories

Template fit using NN discriminator

Two-dimensional simulated templates used in the fit

The fit is performed on two-dimensional distributions



Clear separation between the $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$ and $t\bar{t}$LF contributions

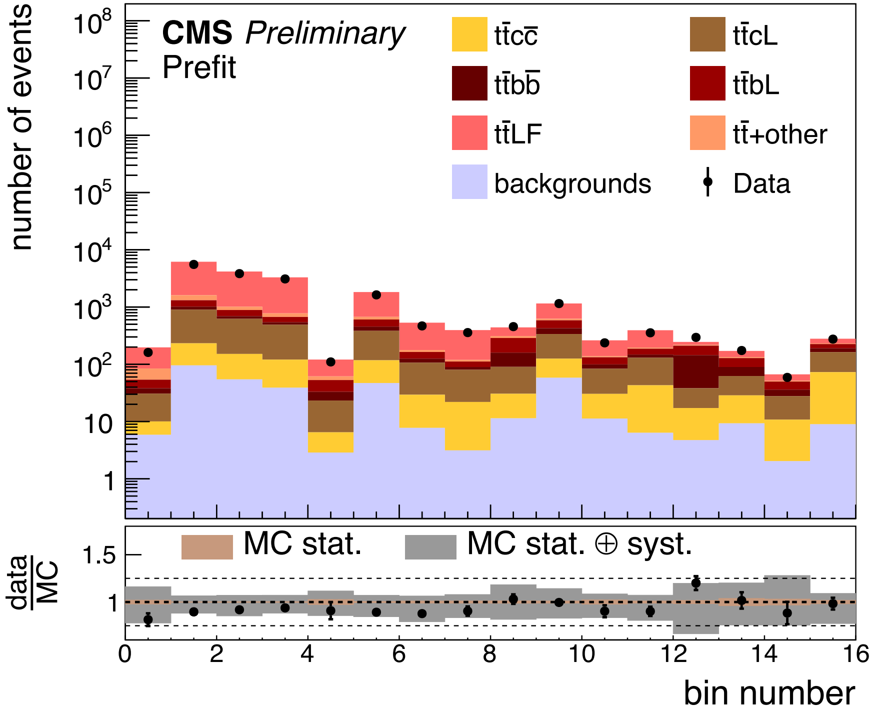
Results

Comparison between the prefit and the postfit distributions

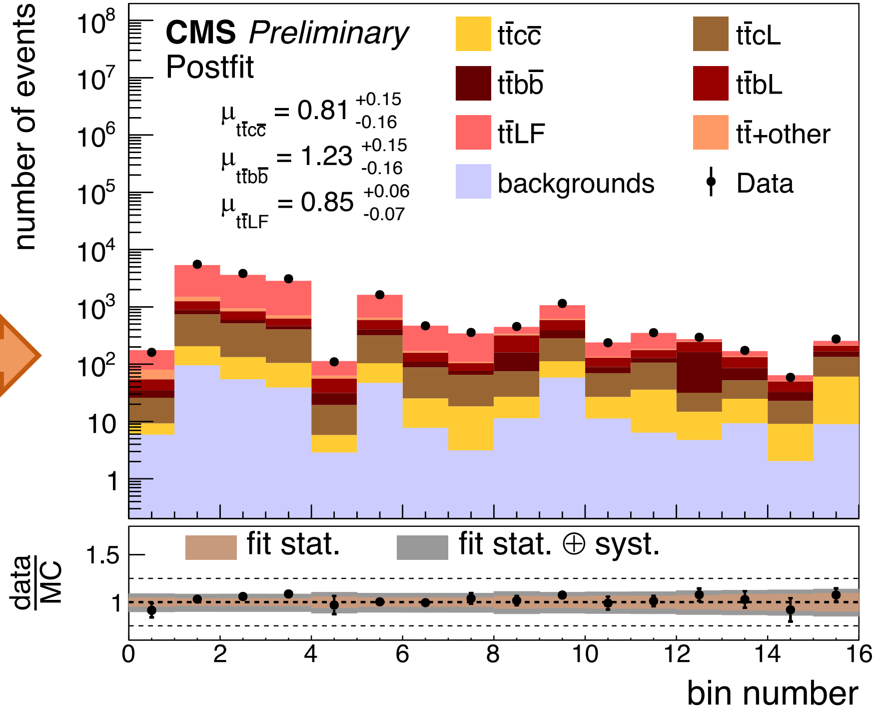
Two-dimensional distributions are unrolled onto a one-dimensional histogram
4x4 binning results in 16 bins with varying flavor composition:

$$\Delta^{c}_{L} \otimes \Delta^{c}_{b} : [0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0]$$

Prefit



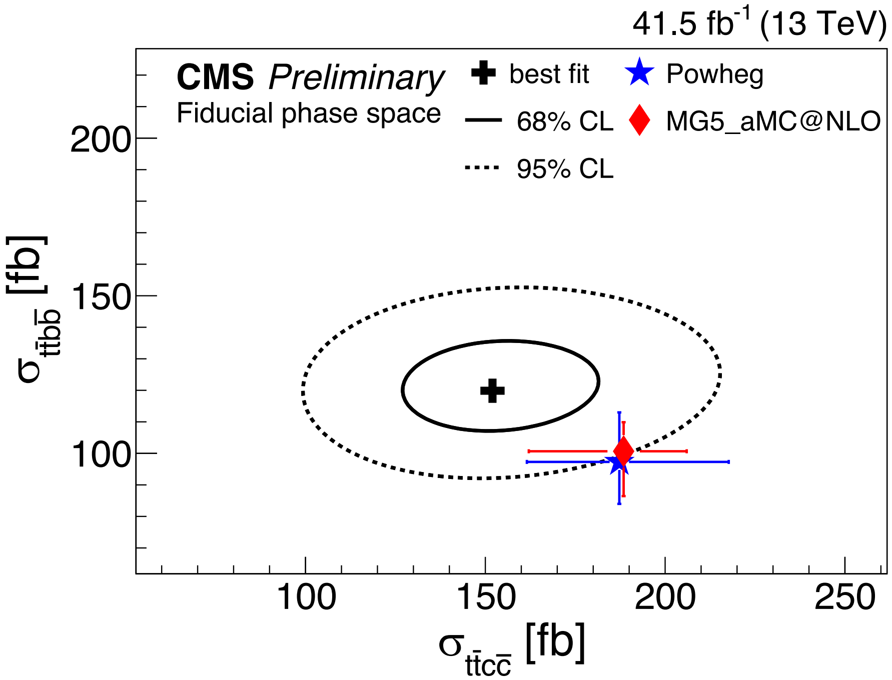
Postfit

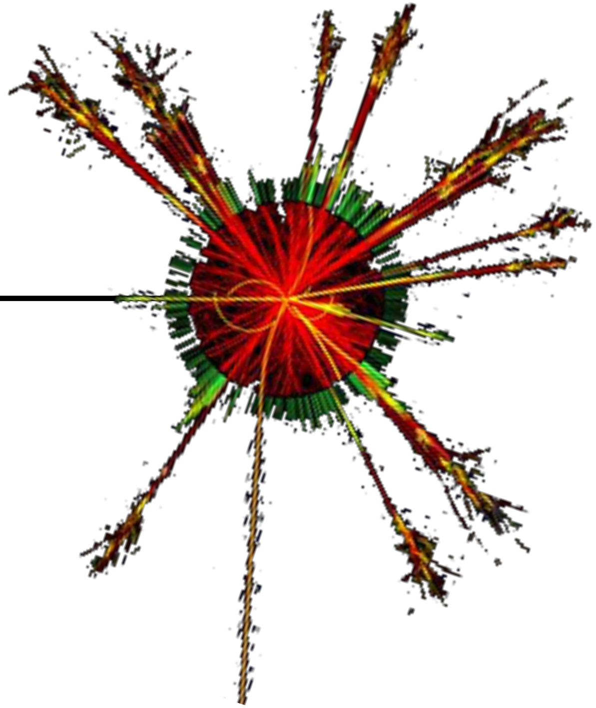


μ represents the scaling factor of the simulated templates
(cross section above or below theory prediction)

related to the cross section: $\sigma = \frac{\mu \times N^{MC}}{\mathcal{L}^{int} \times \epsilon}$

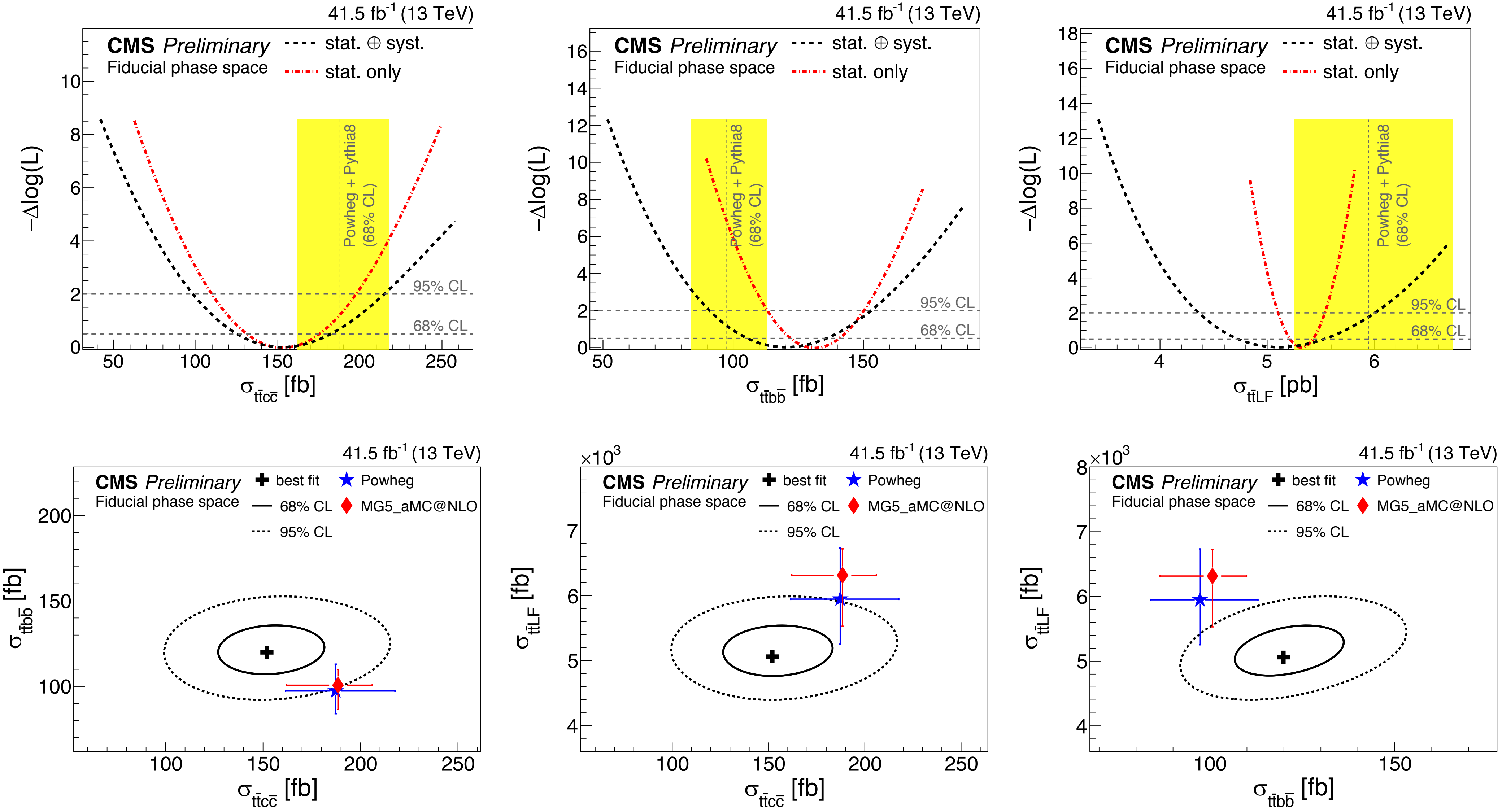
Results


41.5 fb^{-1} (13 TeV)
CMS *Preliminary*
Fiducial phase space
best fit
68% CL
95% CL
Powheg
MG5_aMC@NLO
$\sigma_{t\bar{t}b\bar{b}}$ [fb]
200
150
100
$\sigma_{t\bar{t}c\bar{c}}$ [fb]
100
150
200
250



Results

Inclusive cross sections in the fiducial phase space



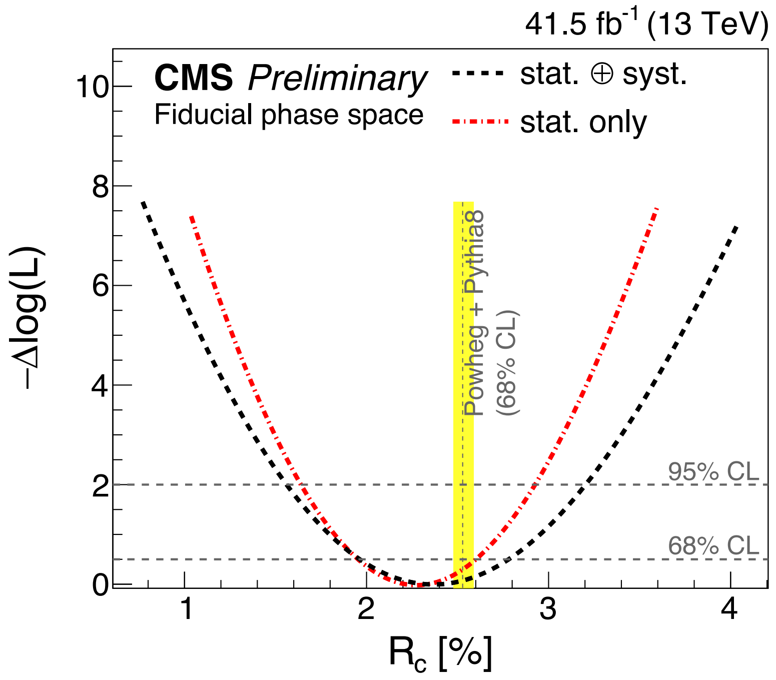
Some tension observed, but overall agreement within 1-2 standard deviations

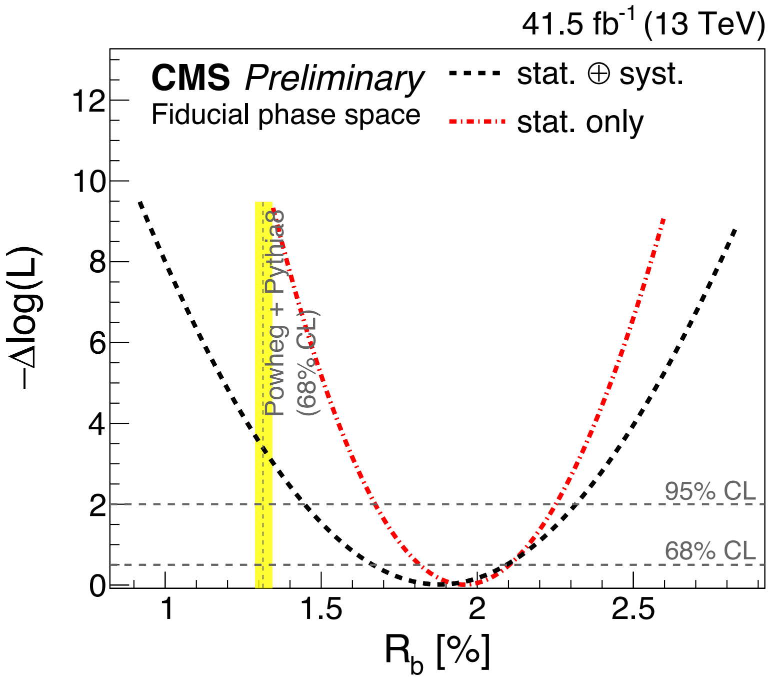
Dominant uncertainties from flavour-tagging, JES, and modelling

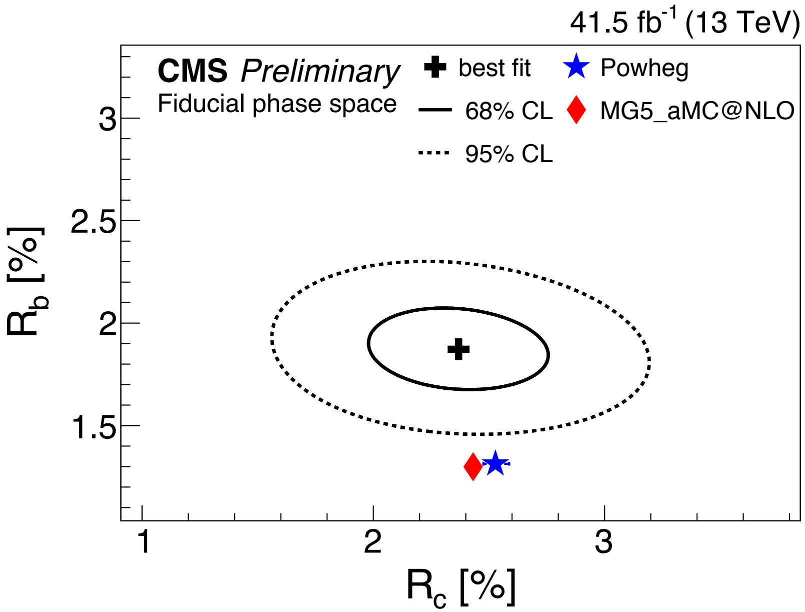
$$R_{c/b} = \sigma(t\bar{t}+c\bar{c}/b\bar{b}) \Big/ \sigma(t\bar{t}+jj)$$

Results

Ratios R_c and R_b in the fiducial phase space

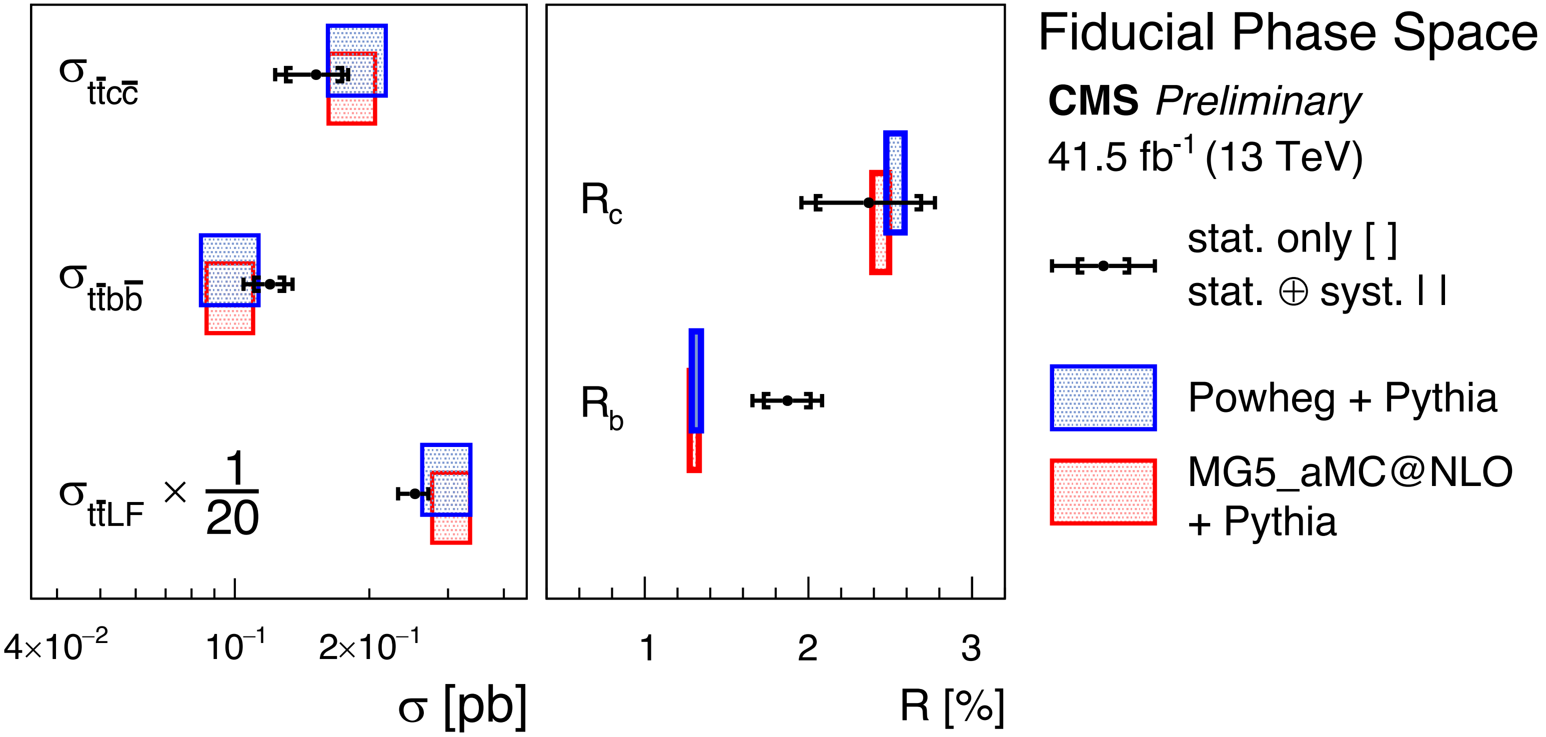






Results

Summary in the fiducial phase space (visual)



First measurement of the $t\bar{t}$ + $c\bar{c}$ cross section!

Fiducial PS: $\sigma(t\bar{t} + c\bar{c})$ = 152 ± 22 (stat.) ± 19 (syst.) fb (~ 19% uncertainty)

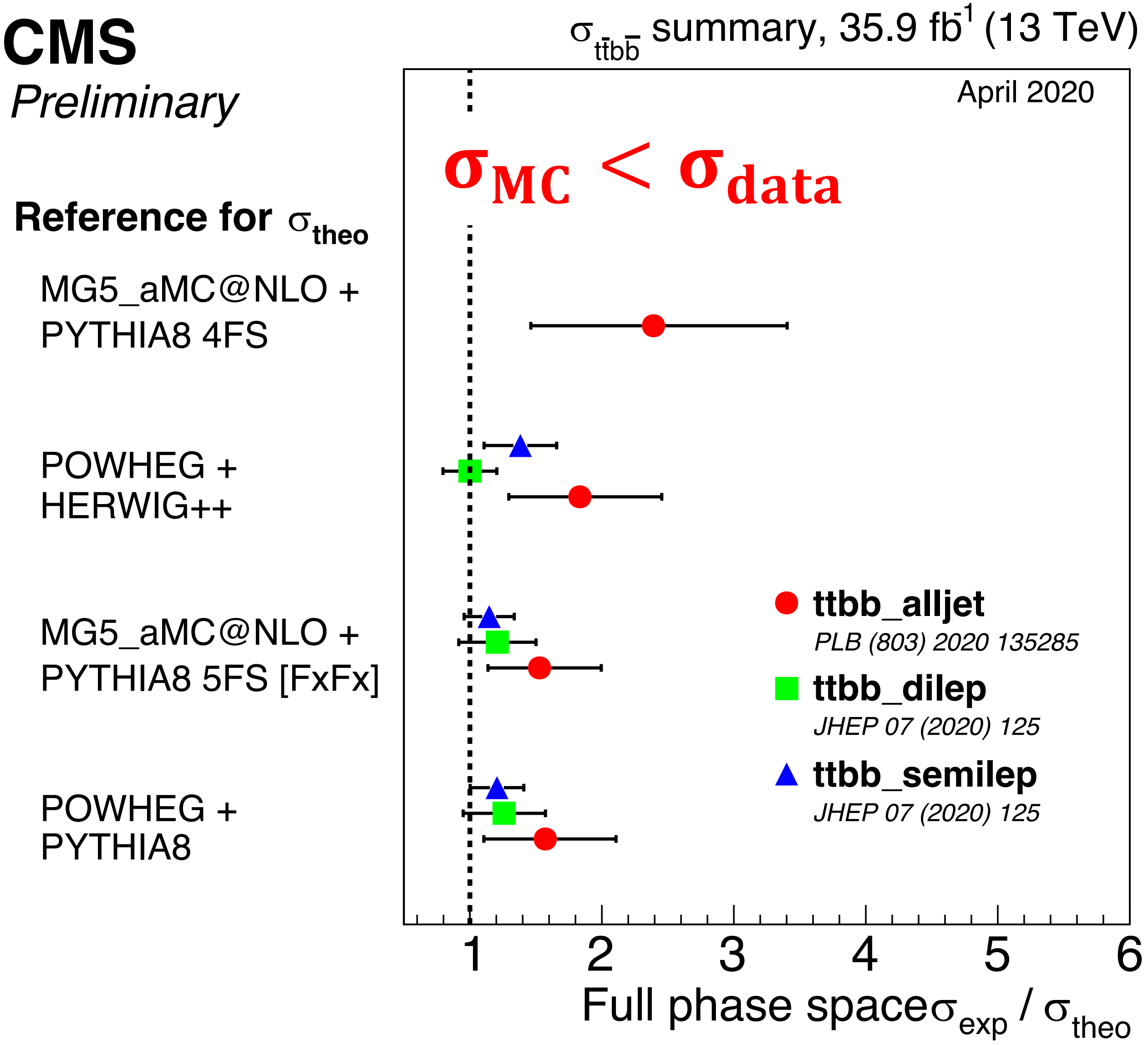
Rc = 2.37 ± 0.32 (stat.) ± 0.25 (syst.) % (~ 17% uncertainty)

Full PS: $\sigma(t\bar{t} + c\bar{c})$ = 7.43 ± 1.07 (stat.) ± 0.95 (syst.) pb

Rc = 2.64 ± 0.36 (stat.) ± 0.29 (syst.) %

Comparison of the CMS $t\bar{t}b\bar{b}$ measurements

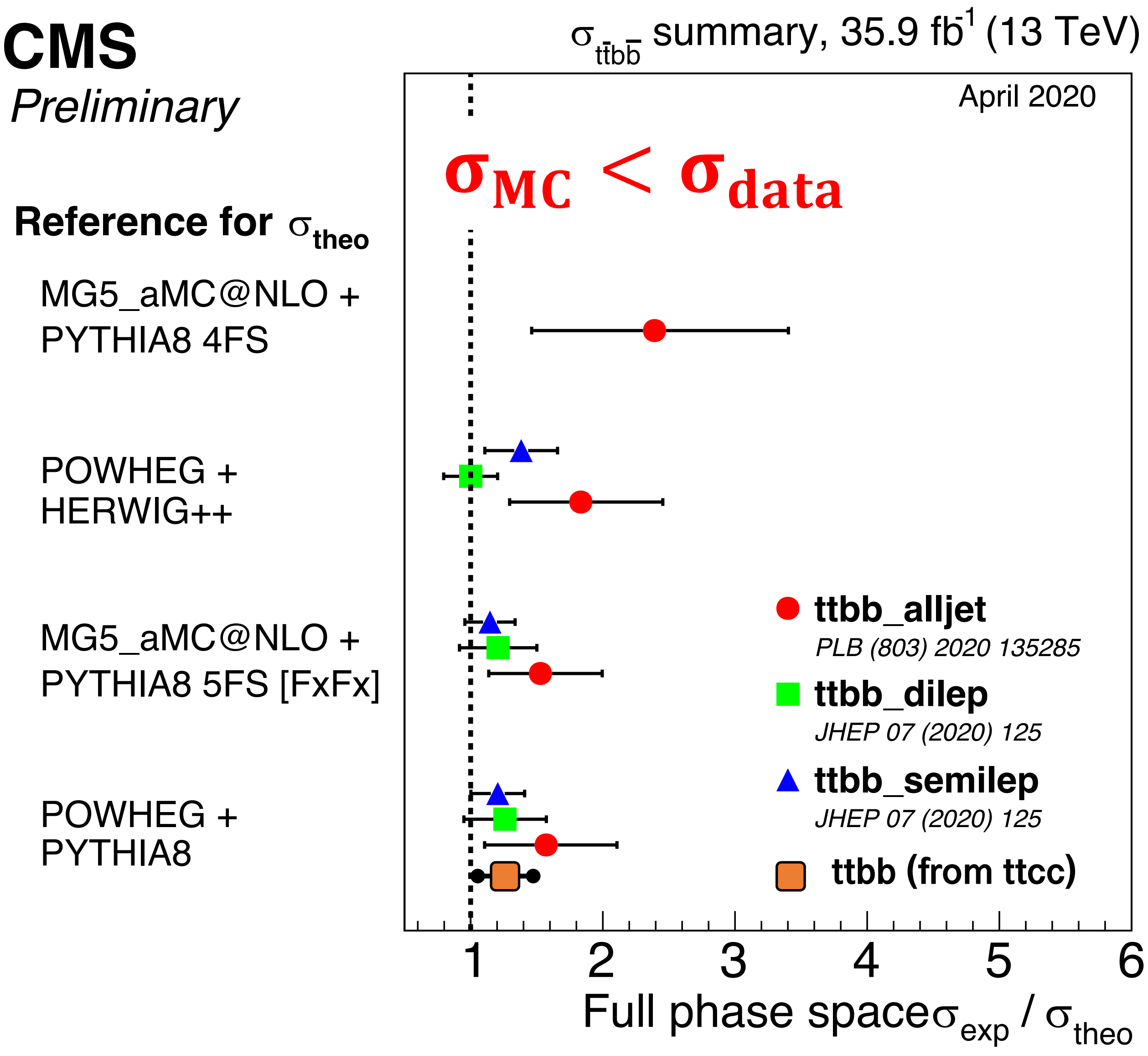
Consistently, the $t\bar{t}b\bar{b}$ cross section is under-estimated in simulations



$\sigma_{MC} < \sigma_{data}$

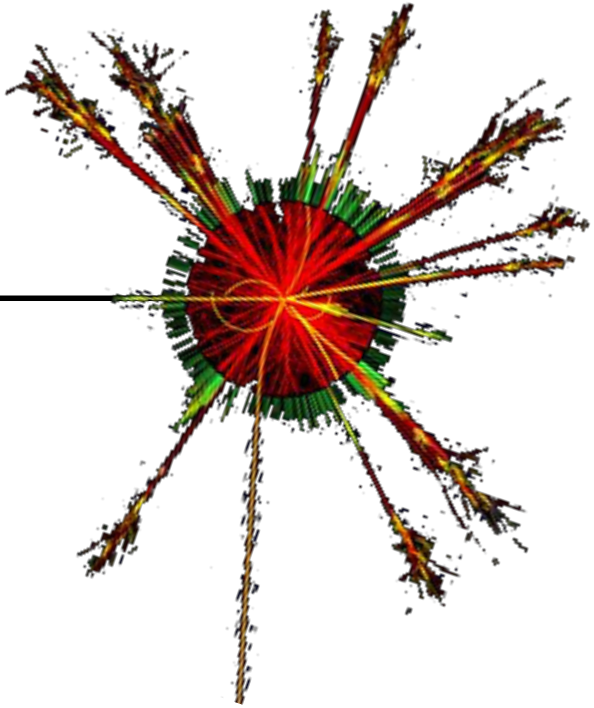
Comparison of the CMS $t\bar{t}b\bar{b}$ measurements

Consistently, the $t\bar{t}b\bar{b}$ cross section is under-estimated in simulations



$\sigma_{MC} < \sigma_{data}$

Conclusion



Conclusion

First measurement of the $t\bar{t} + c\bar{c}$ cross section!

Fiducial PS: $\sigma(t\bar{t} + c\bar{c}) = 152 \pm 22\,(\text{stat.}) \pm 19\,(\text{syst.})$ fb (~ 19% uncertainty)
$\text{Rc} = 2.37 \pm 0.32\,(\text{stat.}) \pm 0.25\,(\text{syst.})\,\%$ (~ 17% uncertainty)

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$\text{Rc} = 2.64 \pm 0.36\,(\text{stat.}) \pm 0.29\,(\text{syst.})\,\%$

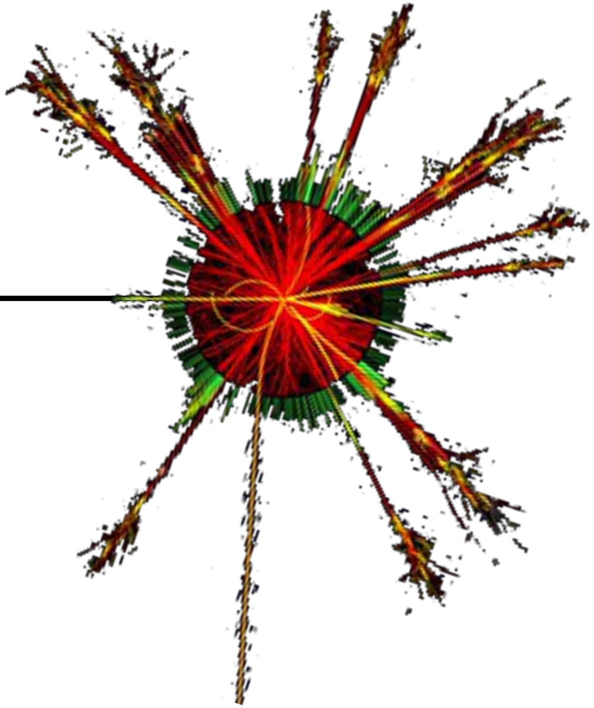
Simultaneous extraction $\sigma_{t\bar{t}c\bar{c}}, \sigma_{t\bar{t}b\bar{b}}, \sigma_{t\bar{t}LF}, R_b = {}^{\sigma_{t\bar{t}b\bar{b}}}/_{\sigma_{t\bar{t}jj}}$ and $R_c = {}^{\sigma_{t\bar{t}c\bar{c}}}/_{\sigma_{t\bar{t}jj}}$
→ Fully coherent treatment of different jet flavours in $t\bar{t}$ + 2 jets!

Results are consistent with Powheg predictions within ~ 1 - 2 σ.

Higher observed $\sigma_{t\bar{t}b\bar{b}}$ (or R_b) is consistent with previous $t\bar{t}b\bar{b}$ analyses.

For the first time, we also see that the $t\bar{t}c\bar{c}$ process is slightly overestimated in simulations (but within uncertainties)

Backup



Motivation for measuring $t\bar{t}$+HF
Theoretical modelling

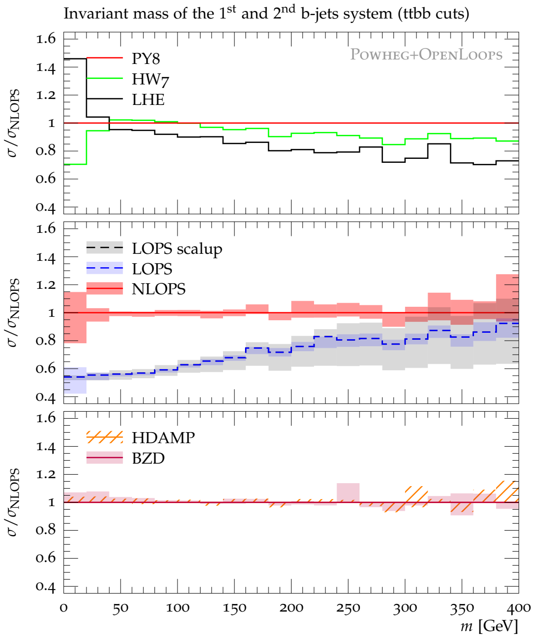
Theory predictions / Simulation of the $t\bar{t}$+HF final state is highly non-trivial. It deals with very different scales from the top quark mass down to momenta of the relatively soft additional jets

1. Matrix Element vs Parton Shower
2. LO vs NLO (large k-factor, depending on scale choice)
3. Factorization/Renormalization/Shower scales
4. Inclusive $t\bar{t}$+jets versus separate $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ sim.

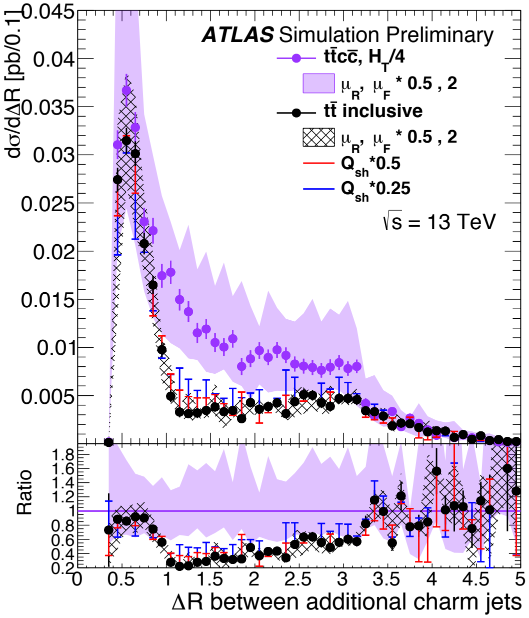
Motivated CMS and ATLAS to measure $t\bar{t}+b\bar{b}$ [arXiv:1411.5621, 1705.10141, 2003.06467, 1909.05306, 1304.6386, 1508.06868, 1811.12113]

$t\bar{t}c\bar{c}$ has not been measured experimentally!

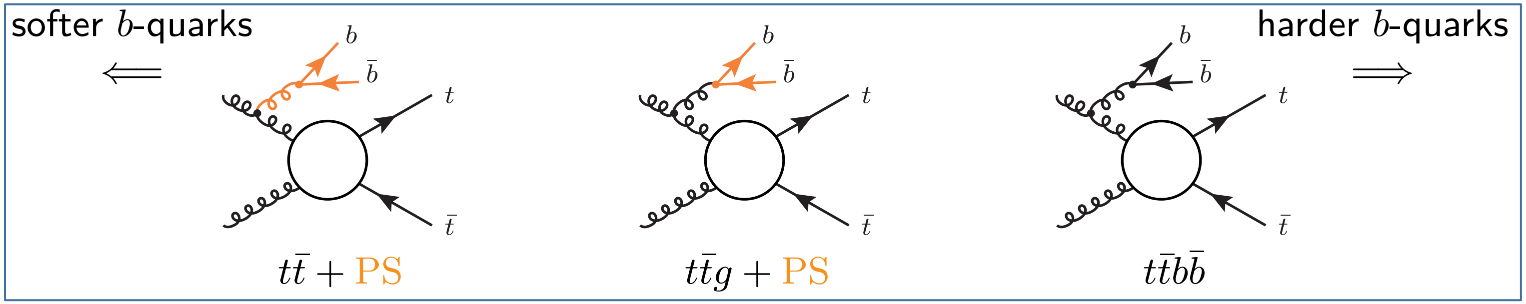
T. Ježo et al., *Eur. Phys. J.* **C78** (2018), no. 6 502, [arXiv:1802.00426]



ATL-PHYS-PUB-2016-011



S. Pozzorini, Theory progress on $t\bar{t}H(b\bar{b})$ background, TOP2018 @ Bad Neuenahr, Germany

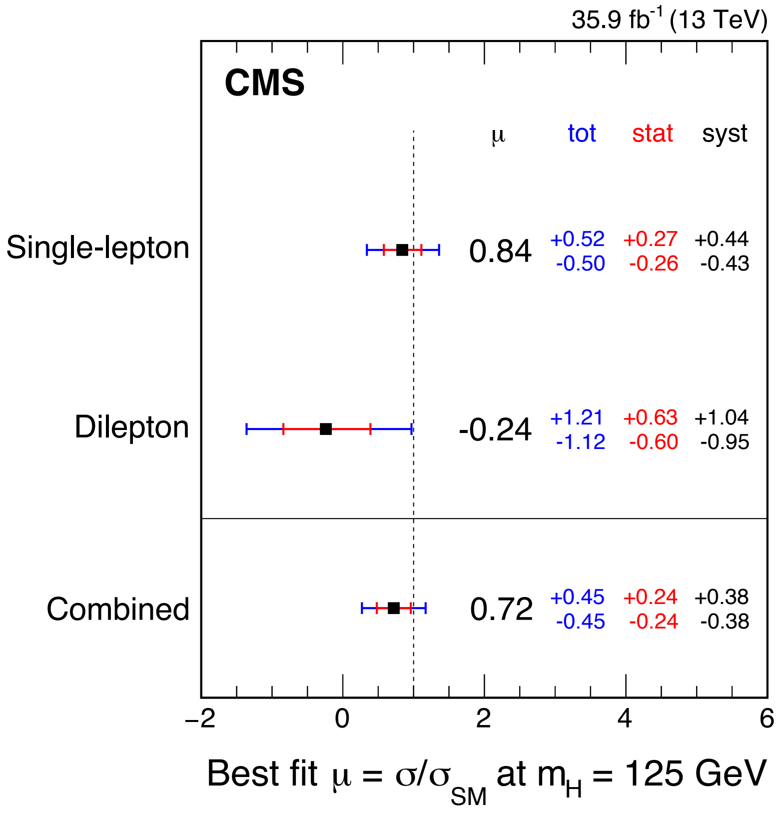


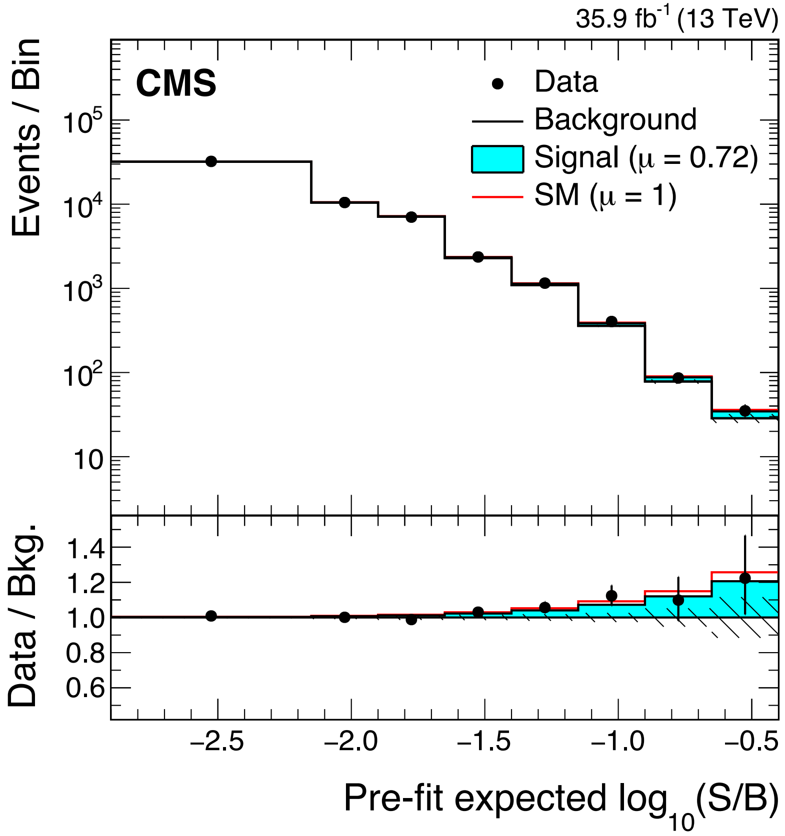
Motivation for measuring $t\bar{t}$+HF

Interplay between Higgs boson and top/bottom quarks

measurement of $t\bar{t}H(H \rightarrow b\bar{b})$ arXiv:1804.03682

observed (expected) significance of 1.6 (2.2)



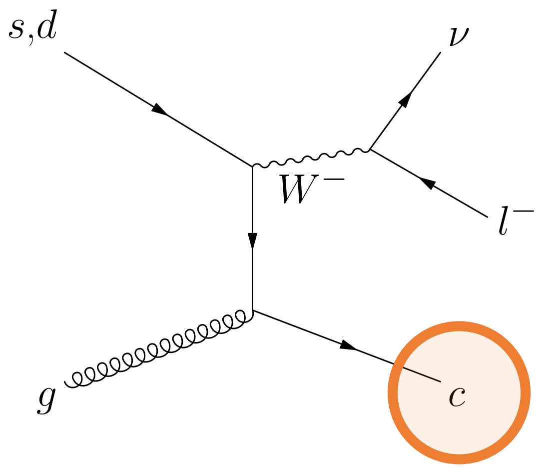


$t\bar{t}H$ ($H \rightarrow b\bar{b}$) suffers from an irreducible background of (gluon-induced) $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ (through mistags) events!

c-tagger calibration

Three control regions for flavor enrichment

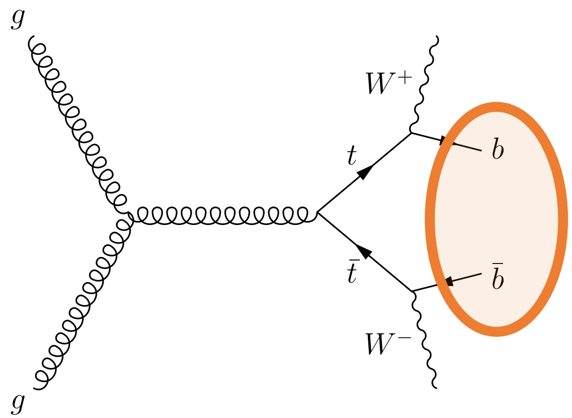
W+charm



c-enriched (93% pure)

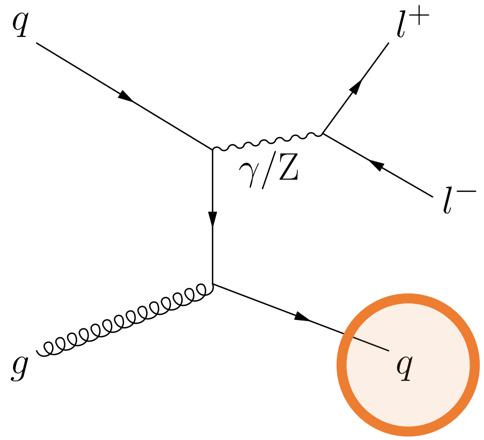
(after OS-SS subtraction)

semi-leptonic $t\bar{t}$



b-enriched (81% pure)

DY + jets



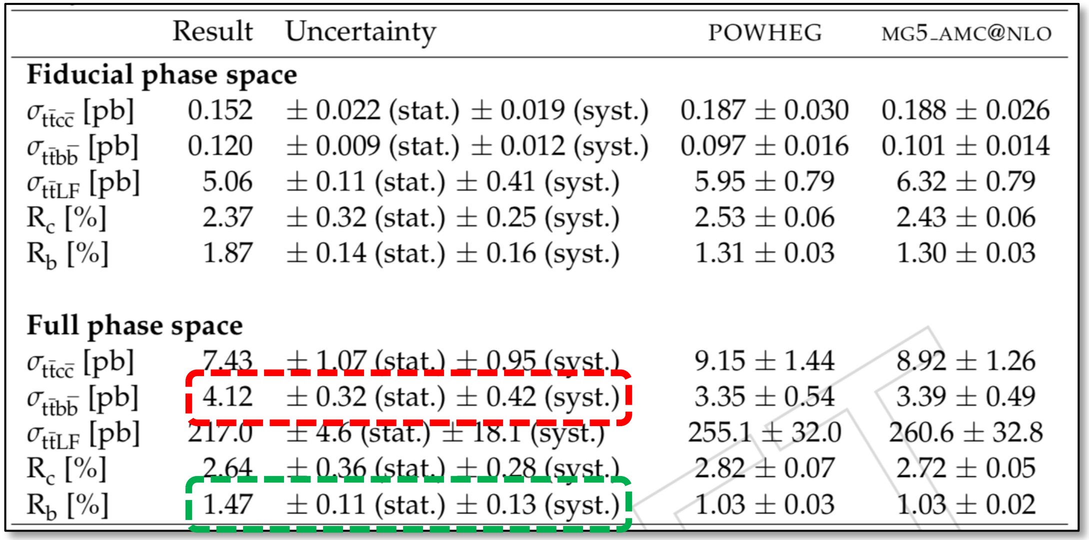
light-enriched (86% pure)

Very good purity in different control regions!

Iterative fitting procedure per (2-dim.) bin, by iterating multiple times over the three control regions → 2-dim SF maps
i.e. SF(CvsL, CvsB, flavour)

Results

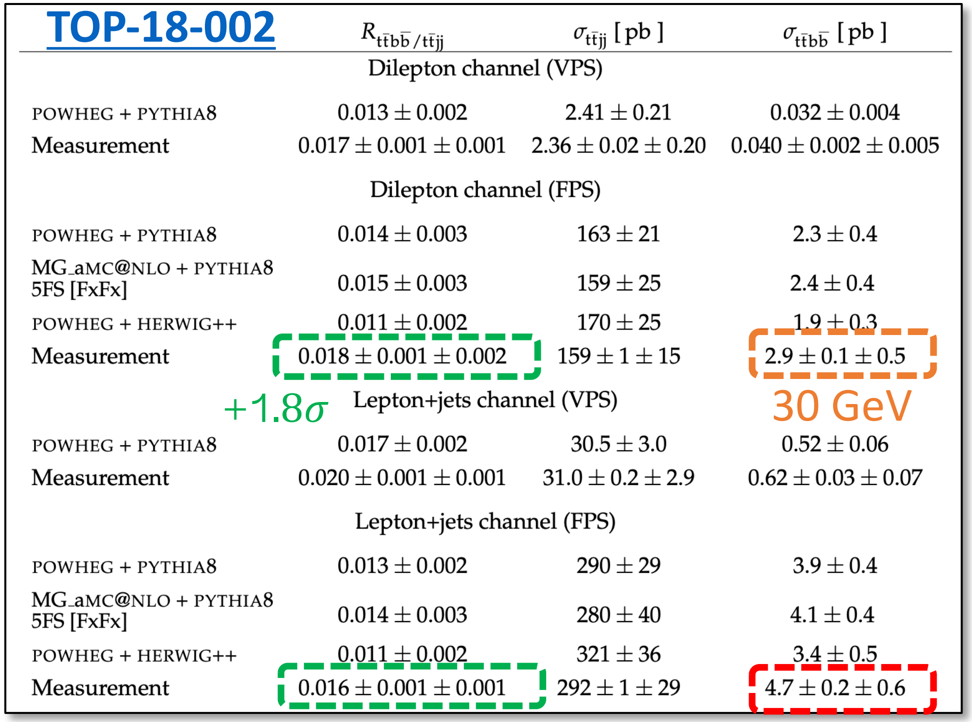
Comparison to other ttbb analyses



	Result	Uncertainty	POWHEG	MG5_AMC@NLO
Fiducial phase space				
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	0.152	± 0.022 (stat.) ± 0.019 (syst.)	0.187 ± 0.030	0.188 ± 0.026
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	0.120	± 0.009 (stat.) ± 0.012 (syst.)	0.097 ± 0.016	0.101 ± 0.014
$\sigma_{t\bar{t}LF}$ [pb]	5.06	± 0.11 (stat.) ± 0.41 (syst.)	5.95 ± 0.79	6.32 ± 0.79
R_c [%]	2.37	± 0.32 (stat.) ± 0.25 (syst.)	2.53 ± 0.06	2.43 ± 0.06
R_b [%]	1.87	± 0.14 (stat.) ± 0.16 (syst.)	1.31 ± 0.03	1.30 ± 0.03
Full phase space				
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	7.43	± 1.07 (stat.) ± 0.95 (syst.)	9.15 ± 1.44	8.92 ± 1.26
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	4.12	± 0.32 (stat.) ± 0.42 (syst.)	3.35 ± 0.54	3.39 ± 0.49
$\sigma_{t\bar{t}LF}$ [pb]	217.0	± 4.6 (stat.) ± 18.1 (syst.)	255.1 ± 32.0	260.6 ± 32.8
R_c [%]	2.64	± 0.36 (stat.) ± 0.28 (syst.)	2.82 ± 0.07	2.72 ± 0.05
R_b [%]	1.47	± 0.11 (stat.) ± 0.13 (syst.)	1.03 ± 0.03	1.03 ± 0.02

PAS-TOP-20-003

$+2.5\sigma$



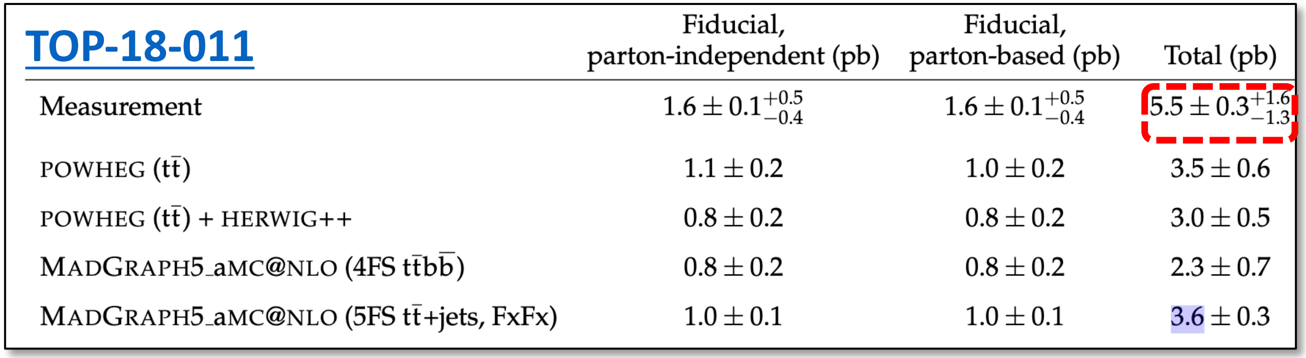
TOP-18-002

	$R_{t\bar{t}b\bar{b}/t\bar{t}jj}$	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}$ [pb]
Dilepton channel (VPS)			
POWHEG + PYTHIA8	0.013 ± 0.002	2.41 ± 0.21	0.032 ± 0.004
Measurement	0.017 ± 0.001 ± 0.001	2.36 ± 0.02 ± 0.20	0.040 ± 0.002 ± 0.005
Dilepton channel (FPS)			
POWHEG + PYTHIA8	0.014 ± 0.003	163 ± 21	2.3 ± 0.4
MG_aMC@NLO + PYTHIA8 5FS [FxFx]	0.015 ± 0.003	159 ± 25	2.4 ± 0.4
POWHEG + HERWIG++	0.011 ± 0.002	170 ± 25	1.9 ± 0.3
Measurement	0.018 ± 0.001 ± 0.002	159 ± 1 ± 15	2.9 ± 0.1 ± 0.5
Lepton+jets channel (VPS)			
POWHEG + PYTHIA8	0.017 ± 0.002	30.5 ± 3.0	0.52 ± 0.06
Measurement	0.020 ± 0.001 ± 0.001	31.0 ± 0.2 ± 2.9	0.62 ± 0.03 ± 0.07
Lepton+jets channel (FPS)			
POWHEG + PYTHIA8	0.013 ± 0.002	290 ± 29	3.9 ± 0.4
MG_aMC@NLO + PYTHIA8 5FS [FxFx]	0.014 ± 0.003	280 ± 40	4.1 ± 0.4
POWHEG + HERWIG++	0.011 ± 0.002	321 ± 36	3.4 ± 0.5
Measurement	0.016 ± 0.001 ± 0.001	292 ± 1 ± 29	4.7 ± 0.2 ± 0.6

$+1.8\sigma$

30 GeV

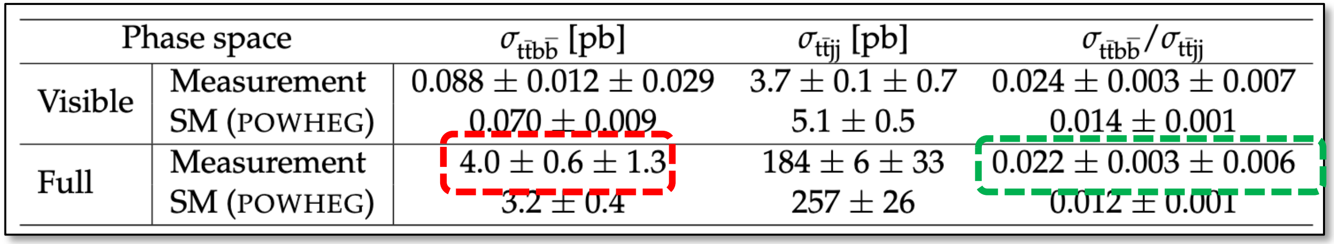
$+2.1\sigma$



TOP-18-011

	Fiducial, parton-independent (pb)	Fiducial, parton-based (pb)	Total (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS $t\bar{t}$+jets, FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

TOP-16-010



Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	0.088 ± 0.012 ± 0.029	3.7 ± 0.1 ± 0.7	0.024 ± 0.003 ± 0.007
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	4.0 ± 0.6 ± 1.3	184 ± 6 ± 33	0.022 ± 0.003 ± 0.006
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

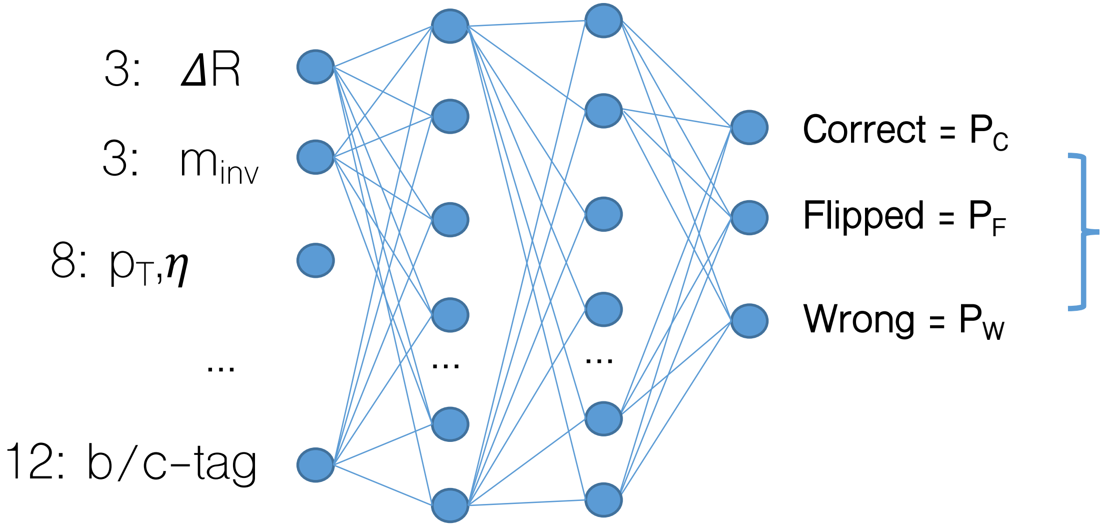
$+1.5\sigma$

Jet-parton matching

Performance and neural network output

- Neural network trained with Keras (TensorFlow backend)
- 26 inputs (Standard Normalization, μ=0, σ= 1) → see backup
- 2 hidden layers with 50 neurons each and ReLu activation
- 10% Dropout in each hidden layer (regularization)
- 3 outputs with SoftMax activation
  - Correctly matched
  - Flipped matching
  - Wrong matching
- Loss function = categorical cross-entropy
- Optimizer = Stochastic Gradient Decent
  *learning rate (init) = 0.001, decay = init / (5*n_epoch), nesterov momentum = 0.8*
- n_epoch = 100, batch_size = 128
- Weights added after 30 epochs (ttbb/ttcc = 20, ttbL = 10, ttcL = 5, ttLL = 1)

jet p_T	jet η	b–tag	CvsL c–tag	CvsB c–tag	m_{inv}	ΔR
$p_T(b_t)$	$\eta(b_t)$	$\mathrm{BvsAll}(b_t)$	$\mathrm{CvsL}(b_t)$	$\mathrm{CvsB}(b_t)$	$m_{inv}(b_t, \ell^+)$	$\Delta\mathrm{R}(b_t, \ell^+)$
$p_T(b_{\bar{t}})$	$\eta(b_{\bar{t}})$	$\mathrm{BvsAll}(b_{\bar{t}})$	$\mathrm{CvsL}(b_{\bar{t}})$	$\mathrm{CvsB}(b_{\bar{t}})$	$m_{inv}(b_{\bar{t}}, \ell^-)$	$\Delta\mathrm{R}(b_{\bar{t}}, \ell^-)$
$p_T(j_1)$	$\eta(j_1)$	$\mathrm{BvsAll}(j_1)$	$\mathrm{CvsL}(j_1)$	$\mathrm{CvsB}(j_1)$	$m_{inv}(j_1, j_2)$	$\Delta\mathrm{R}(j_1, j_2)$
$p_T(j_2)$	$\eta(j_2)$	$\mathrm{BvsAll}(j_2)$	$\mathrm{CvsL}(j_2)$	$\mathrm{CvsB}(j_2)$		



3: ΔR

3: m_{inv}

8: p_T,η

...

12: b/c-tag

Correct = P_C

Flipped = P_F

Wrong = P_W

NN matching output =

$$= \max\left(\frac{P_C}{P_C+P_W}\ ,\ \frac{P_F}{P_F+P_W}\right)$$

Template fit using NN discriminator

Fits to extract inclusive cross sections and their ratios

Full phase space

Fiducial phase space

Reconstructed phase space

Higgs Combine framework

Absolute cross sections

$\sigma_{t\bar{t}c\bar{c}}, \sigma_{t\bar{t}b\bar{b}}, \sigma_{t\bar{t}LF}$

Ratios

$R_b = {}^{\sigma_{t\bar{t}b\bar{b}}}/_{\sigma_{t\bar{t}jj}}$ and $R_c = {}^{\sigma_{t\bar{t}c\bar{c}}}/_{\sigma_{t\bar{t}jj}}$

Fit provides results in the fiducial phase space by taking into account an efficiency ϵ.

$t\bar{t}cL$ ($t\bar{t}bL$/ $t\bar{t}$ other) scaled with the same factor as $t\bar{t}c\bar{c}$ ($t\bar{t}b\bar{b}$ / $t\bar{t}LF$), i.e. ratio fixed to MC prediction (with uncertainties)

Event category	$t\bar{t}b\bar{b}$	$t\bar{t}bL$	$t\bar{t}c\bar{c}$	$t\bar{t}cL$	$t\bar{t}LF$
Efficiency ϵ (%)	12.5	8.9	7.1	5.9	4.7
Acceptance $\mathcal{A}$ (%)	2.9	2.5	2.0	2.0	2.3

Results in the fiducial phase space are extrapolated to the full phase space by means of an acceptance A.

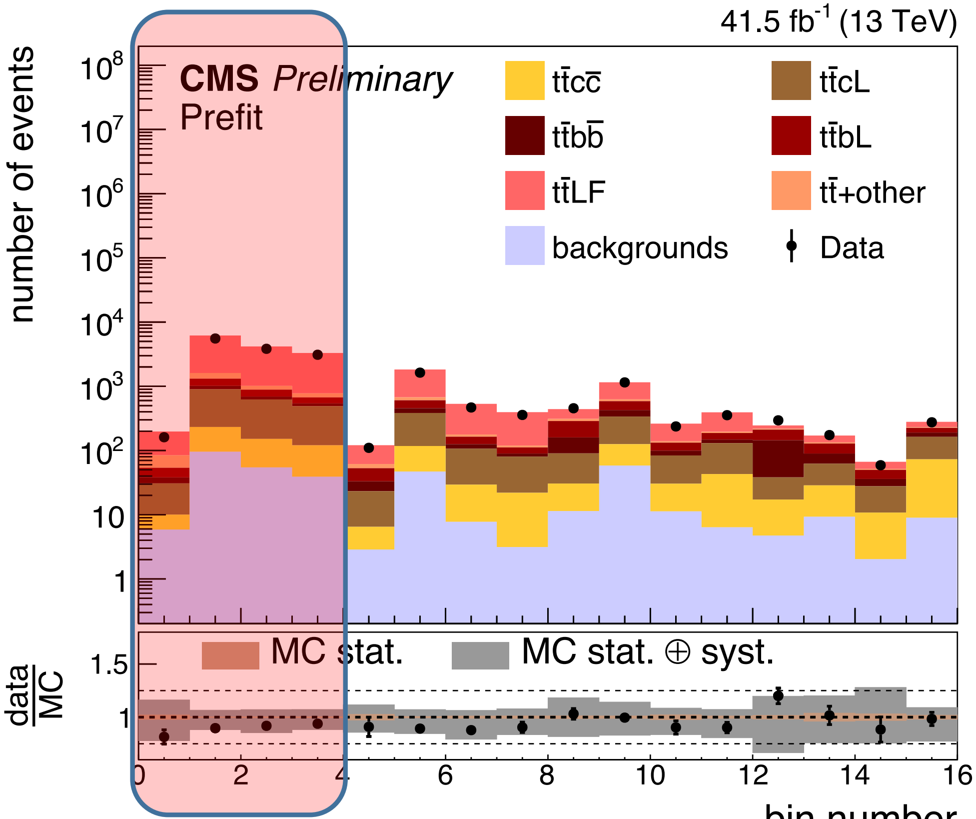
Template fit using NN discriminator

Unrolling the 2-dim. templates into 1-dim. histograms

Unrolling 2D histogram into 1D

4x4 binning results in 16 bins with varying flavor composition

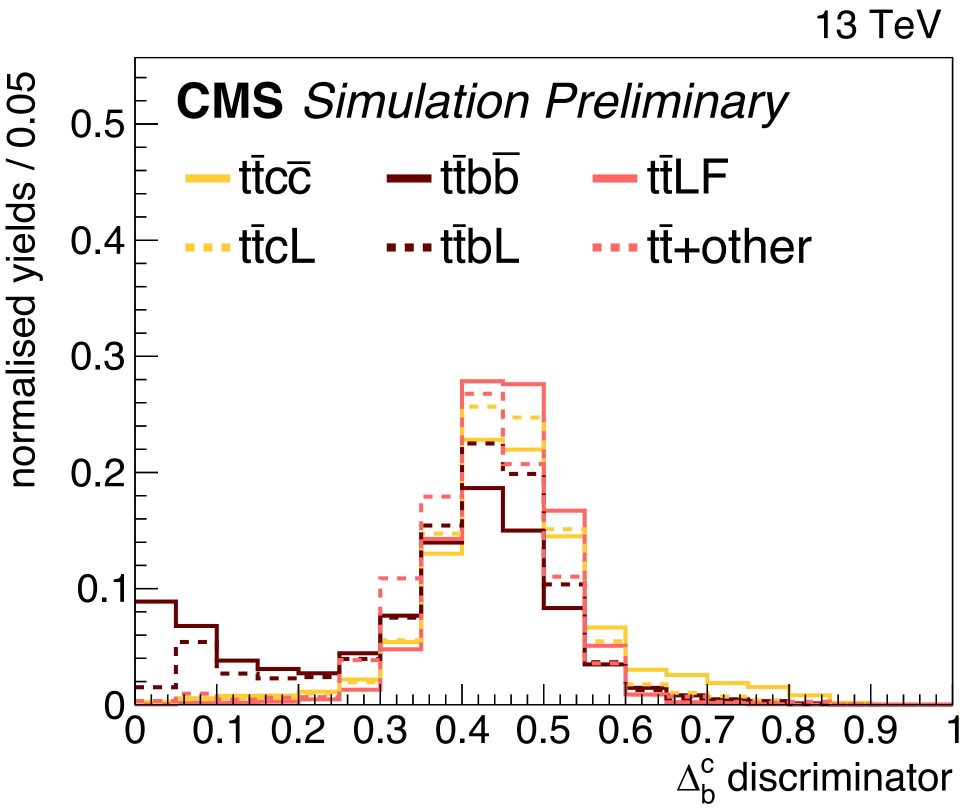
$$\Delta^{\mathrm{c}}_{\mathrm{L}} \otimes \Delta^{\mathrm{c}}_{\mathrm{b}} : [0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0]$$



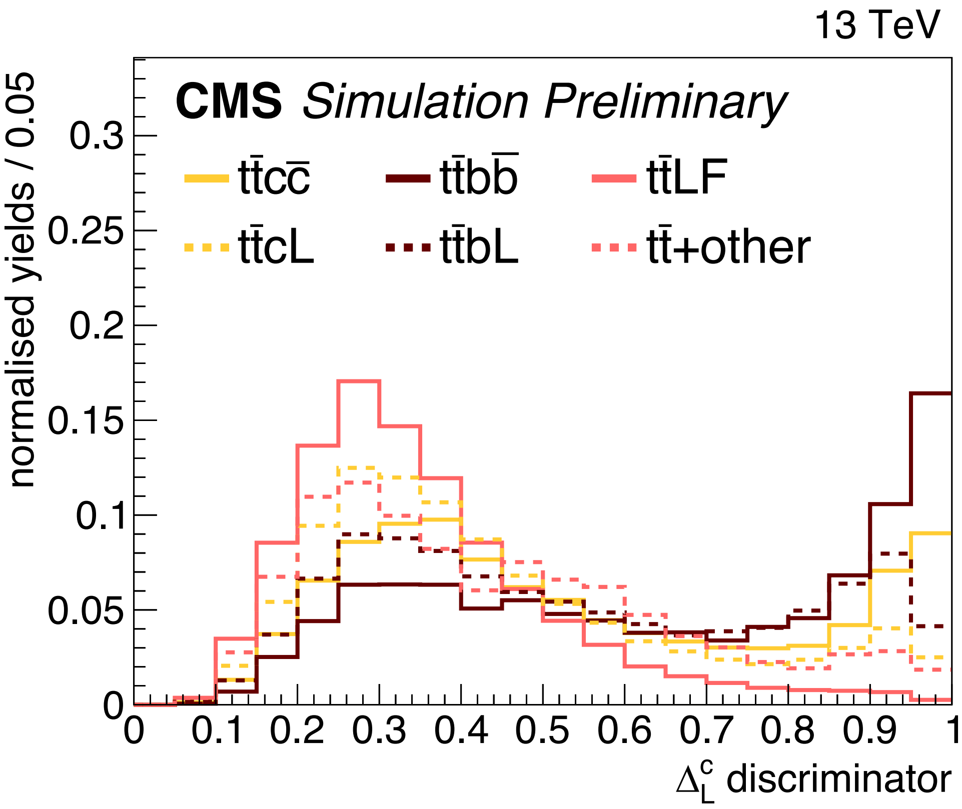
Bins 1 – 4 : $\Delta^c_L \in [0, 0.45]$, and increasing bins in Δ^c_b

Template fit using NN discriminator

Templates from simulated top quark pair events



Constructed to separate $t\bar{t}c\bar{c}$ from $t\bar{t}b\bar{b}$ events

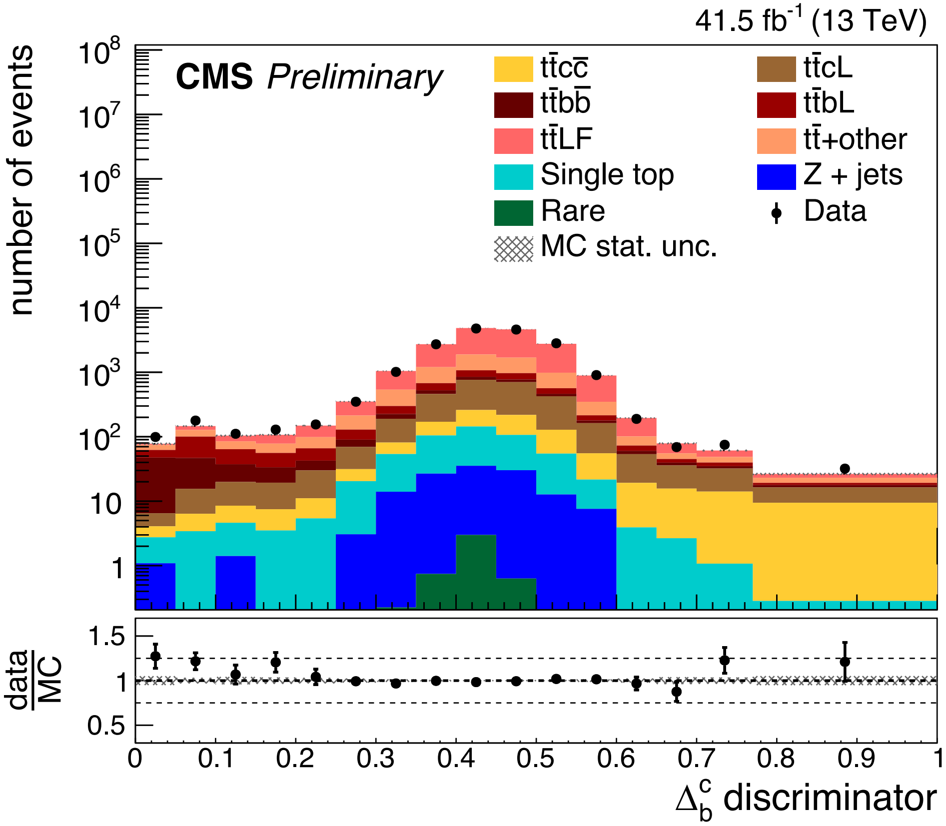


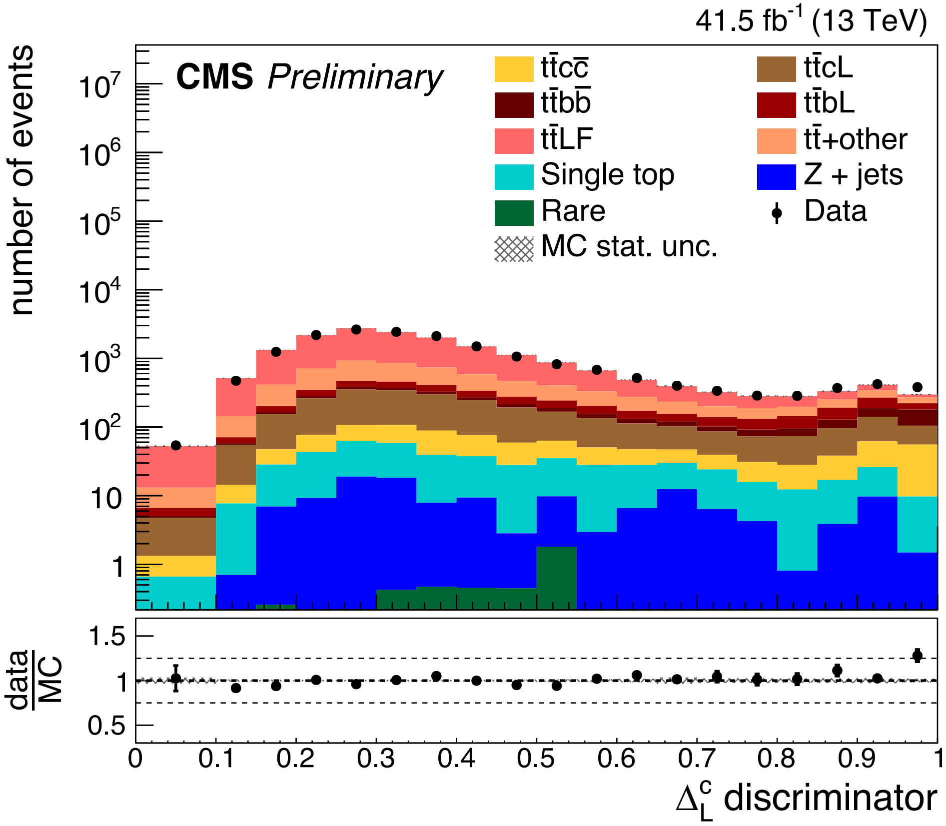
Constructed to separate $t\bar{t}c\bar{c}$ from $t\bar{t}LF$ events

Fitting these templates to the data allows to extract the cross sections for each of the signal processes

Template fit using NN discriminator

Comparison between data and simulation (prefit)





Template fit using NN discriminator

Impact of the systematic uncertainties on parameters of interest

numbers in %	fiducial phase space				
	$\Delta\sigma_{t\bar{t}c\bar{c}}$	$\Delta\sigma_{t\bar{t}b\bar{b}}$	$\Delta\sigma_{t\bar{t}LF}$	ΔR_c	ΔR_b
Jet energy scale	7.3	3.3	5.7	3.2	3.4
Jet energy resolution	1.4	0.3	1.2	2.1	1.2
c-tagging calibration	6.7	6.9	2.2	6.9	7.4
Lepton id and isolation	1.3	1.2	1.2	0.2	0.1
Trigger	2.0	2.0	2.0	< 0.1	< 0.1
Pileup	1.2	0.8	0.7	1.6	0.4
Total integrated luminosity	2.4	2.3	2.3	< 0.1	< 0.1
μ_R and μ_F scales in ME	4.3	2.4	0.8	4.1	2.7
Parton shower scale	0.4	1.0	0.1	0.4	0.9
PDF α_s	0.5	< 0.1	0.1	0.4	0.1
Matching ME-PS (hdamp)	6.5	4.9	3.1	2.9	1.4
Underlying event	1.2	1.3	0.7	0.3	0.4
$t\bar{t}bL(cL)/t\bar{t}b\bar{b}(c\bar{c})$ and $t\bar{t}$+other/$t\bar{t}$LF	2.4	1.7	1.2	2.0	1.5
Efficiency (theoretical)	2.0	2.0	2.0	< 0.1	< 0.1
Simulated sample size	4.3	2.7	1.1	4.2	2.7
Background normalisation	0.7	0.1	0.5	0.2	0.5

Dominant experimental uncertainties from c-tagging calibration and JES

Dominant theoretical uncertainties from QCD scales in the ME and ME-PS matching

Template fit using NN discriminator

Systematic uncertainties

Normalization only:

- Luminosity (2.3%)
- background normalization (25%)
- Efficiency (theoretical) (2%)
- Fixed ratios from MC
  - (ttbL/ttbb, ttcL/ttcc, tt other/ttLF)
- Bin-by-bin statistical uncertainty (MC)

These experimental uncertainties **affect the overall efficiency** from the fiducial to the reconstructed phase space, but do not change the shapes of the simulated templates.

Shape + normalization:

- JES, JER
- lepton ID/iso/reco/trigger
- Pileup
- c-tagging calibration

On top of affecting the selection efficiency, these experimental uncertainties **also change the shapes of the templates.**

Shape only:

- μ_R, μ_F in ME generator
- ISR+FSR: α_s in PS
- Parton distribution function
- Matching between ME/PS
- Underlying event Tune
- B-Fragmentation (not considered for now)

For these theoretical uncertainties, **only the change in shape of the templates** and their impact on the **acceptance** is considered in the extraction of the results. Their impact on the yield is quoted as an uncertainty on the theory prediction to which the measurement is compared.

Template fit using NN discriminator

Fits to extract inclusive cross sections and their ratios

- Two fits, one to extract the inclusive cross sections, one to extract their ratios
- Systematic uncertainties as nuisance parameters in the fit
- Fit is performed simultaneously in the ee/ μμ and eμ channels
- tt̄cL (tt̄bL/ tt̄ other) scaled with the same factor as tt̄cc̄ (tt̄bb̄ / tt̄LF), i.e. ratio fixed to MC prediction (with uncertainties)
- Background contribution (<5%) is fixed at MC prediction (with 25% uncertainty)

Absolute cross sections

- Measure $\sigma_{\mathrm{t\bar{t}c\bar{c}}}, \sigma_{\mathrm{t\bar{t}b\bar{b}}}, \sigma_{\mathrm{t\bar{t}LF}}$

$$
\begin{aligned}
f\left(\sigma^{\mathrm{vis}}_{t\bar{t}c\bar{c}}, \sigma^{\mathrm{vis}}_{t\bar{t}b\bar{b}}, \sigma^{\mathrm{vis}}_{t\bar{t}\mathrm{LF}}\right) = \mathcal{L}^{int} \cdot \Bigg\{ & \sigma^{\mathrm{vis}}_{t\bar{t}c\bar{c}} \cdot \epsilon_{t\bar{t}c\bar{c}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{t\bar{t}c\bar{c}} + \frac{N^{\mathrm{MC}}_{t\bar{t}c\mathrm{L}}}{N^{\mathrm{MC}}_{t\bar{t}c\bar{c}}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}cL} \right) \\
& + \sigma^{\mathrm{vis}}_{t\bar{t}b\bar{b}} \cdot \epsilon_{t\bar{t}b\bar{b}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{t\bar{t}b\bar{b}} + \frac{N^{\mathrm{MC}}_{t\bar{t}b\mathrm{L}}}{N^{\mathrm{MC}}_{t\bar{t}b\bar{b}}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}bL} \right) \\
& + \sigma^{\mathrm{vis}}_{t\bar{t}\mathrm{LF}} \cdot \epsilon_{t\bar{t}\mathrm{LF}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{t\bar{t}\mathrm{LF}} + \frac{N^{\mathrm{MC}}_{t\bar{t}+\mathrm{Other}}}{N^{\mathrm{MC}}_{t\bar{t}LF}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}+\mathrm{Other}} \right) \\
& + \sigma_{\mathrm{DY}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{DY}} + \sigma_{\mathrm{ST}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{ST}} + \sigma_{\mathrm{Rare}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{Rare}} \Bigg\}
\end{aligned}
$$

Ratios

- Measure $\mathrm{R_b} = {}^{\sigma_{\mathrm{t\bar{t}b\bar{b}}}}/_{\sigma_{\mathrm{t\bar{t}jj}}}$ and $\mathrm{R_c} = {}^{\sigma_{\mathrm{t\bar{t}c\bar{c}}}}/_{\sigma_{\mathrm{t\bar{t}jj}}}$

$$
\begin{aligned}
f\left(\sigma^{\mathrm{vis}}_{\mathrm{t\bar{t}}jj}, \mathrm{R_c}, \mathrm{R_b}\right) = \mathcal{L}^{int} \cdot \sigma^{\mathrm{vis}}_{\mathrm{t\bar{t}}jj} \cdot \Bigg\{ & \mathrm{R_c} \cdot \epsilon_{\mathrm{t\bar{t}c\bar{c}}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{\mathrm{t\bar{t}c\bar{c}}} + \frac{N^{\mathrm{MC}}_{\mathrm{t\bar{t}cL}}}{N^{\mathrm{MC}}_{t\bar{t}c\bar{c}}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}cL} \right) \\
& + \mathrm{R_b} \cdot \epsilon_{\mathrm{t\bar{t}b\bar{b}}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{\mathrm{t\bar{t}b\bar{b}}} + \frac{N^{\mathrm{MC}}_{\mathrm{t\bar{t}bL}}}{N^{\mathrm{MC}}_{t\bar{t}b\bar{b}}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}bL} \right) \\
& + (1 - \mathrm{R_c} - \mathrm{R_{cL}} - \mathrm{R_b} - \mathrm{R_{bL}}) \cdot \epsilon_{\mathrm{t\bar{t}LF}} \cdot \left(\mathrm{H}^{\mathrm{norm}}_{\mathrm{t\bar{t}LF}} + \frac{N^{\mathrm{MC}}_{t\bar{t}+\mathrm{Other}}}{N^{\mathrm{MC}}_{t\bar{t}LF}} \cdot \mathrm{H}^{\mathrm{norm}}_{t\bar{t}+\mathrm{Other}} \right) \Bigg\} \\
& + \mathcal{L}^{int} \cdot \{ \sigma_{\mathrm{DY}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{DY}} + \sigma_{\mathrm{ST}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{ST}} + \sigma_{\mathrm{Rare}} \cdot \mathrm{H}^{\mathrm{norm}}_{\mathrm{Rare}} \}
\end{aligned}
$$

$$
\text{with} \quad \begin{cases} \mathrm{R_{cL}} = \mathrm{R_c} \cdot \left(\dfrac{N^{\mathrm{MC}}_{\mathrm{t\bar{t}cL}}\, \epsilon_{\mathrm{t\bar{t}cL}}}{N^{\mathrm{MC}}_{t\bar{t}c\bar{c}}\, \epsilon_{\mathrm{t\bar{t}c\bar{c}}}} \right) \\ \mathrm{R_{bL}} = \mathrm{R_b} \cdot \left(\dfrac{N^{\mathrm{MC}}_{\mathrm{t\bar{t}bL}}\, \epsilon_{\mathrm{t\bar{t}bL}}}{N^{\mathrm{MC}}_{t\bar{t}b\bar{b}}\, \epsilon_{\mathrm{t\bar{t}b\bar{b}}}} \right) \end{cases}
$$

Results in the fiducial phase space are extrapolated to the full phase space by means of acceptance A.

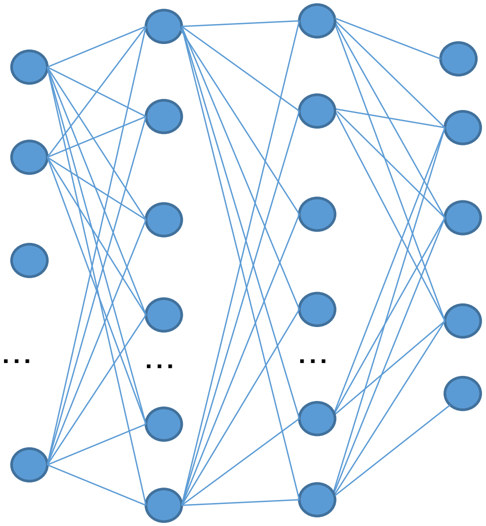
Event category	tt̄bb̄	tt̄bL	tt̄cc̄	tt̄cL	tt̄LF
Efficiency ϵ (%)	12.5	8.9	7.1	5.9	4.7
Acceptance $\mathcal{A}$ (%)	2.9	2.5	2.0	2.0	2.3

Template fit using NN discriminator

Defining the neural network

- Neural network trained with Keras (TensorFlow backend)
- 6 inputs (Standard Normalization, μ=0, σ= 1)
- 1 hidden layer with 30 neurons and ReLu activation
- 10% Dropout in hidden layer (regularization)
- 5 outputs with SoftMax activation
- Loss function = categorical cross-entropy
- Optimizer = Stochastic Gradient Decent

  *learning rate (init) = 0.001, decay = init / (5*n_epoch), nesterov momentum = 0.8*
- n_epoch = 100, batch_size = 128



CvsL add. Jets

CvsB add. Jets

Parton match NN

ΔR(add. Jets)

P(ttcc)

P(ttcL)

P(ttbb)

P(ttbL)

P(ttLF)

$$\Delta_b^c = \frac{\mathrm{P}(t\bar{t}c\bar{c})}{\mathrm{P}(t\bar{t}c\bar{c}) + \mathrm{P}(t\bar{t}b\bar{b})}$$

$$\Delta_L^c = \frac{\mathrm{P}(t\bar{t}c\bar{c})}{\mathrm{P}(t\bar{t}c\bar{c}) + \mathrm{P}(t\bar{t}\mathrm{LF})}$$

Results

Numerical values + extrapolation to the full phase space

	Result	Uncertainty	POWHEG	MG5_AMC@NLO	
Fiducial phase space					
$\sigma_{\mathrm{t\bar{t}c\bar{c}}}$ [pb]	0.152	± 0.022 (stat.) ± 0.019 (syst.)	0.187 ± 0.030	0.188 ± 0.026	~19 %
$\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ [pb]	0.120	± 0.009 (stat.) ± 0.012 (syst.)	0.097 ± 0.016	0.101 ± 0.014	
$\sigma_{\mathrm{t\bar{t}LF}}$ [pb]	5.06	± 0.11 (stat.) ± 0.41 (syst.)	5.95 ± 0.79	6.32 ± 0.79	
$\mathrm{R_c}$ [%]	2.37	± 0.32 (stat.) ± 0.25 (syst.)	2.53 ± 0.06	2.43 ± 0.06	~17 %
$\mathrm{R_b}$ [%]	1.87	± 0.14 (stat.) ± 0.16 (syst.)	1.31 ± 0.03	1.30 ± 0.03	
Full phase space					
$\sigma_{\mathrm{t\bar{t}c\bar{c}}}$ [pb]	7.43	± 1.07 (stat.) ± 0.95 (syst.)	9.15 ± 1.44	8.92 ± 1.26	
$\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ [pb]	4.12	± 0.32 (stat.) ± 0.42 (syst.)	3.35 ± 0.54	3.39 ± 0.49	
$\sigma_{\mathrm{t\bar{t}LF}}$ [pb]	217.0	± 4.6 (stat.) ± 18.1 (syst.)	255.1 ± 32.0	260.6 ± 32.8	
$\mathrm{R_c}$ [%]	2.64	± 0.36 (stat.) ± 0.28 (syst.)	2.82 ± 0.07	2.72 ± 0.05	
$\mathrm{R_b}$ [%]	1.47	± 0.11 (stat.) ± 0.13 (syst.)	1.03 ± 0.03	1.03 ± 0.02	