CMS overview

"When charm and beauty adjoin the top"

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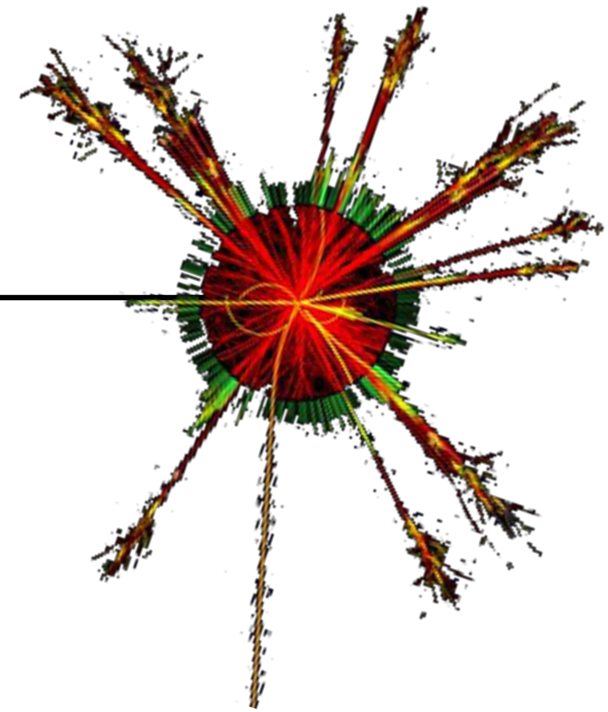
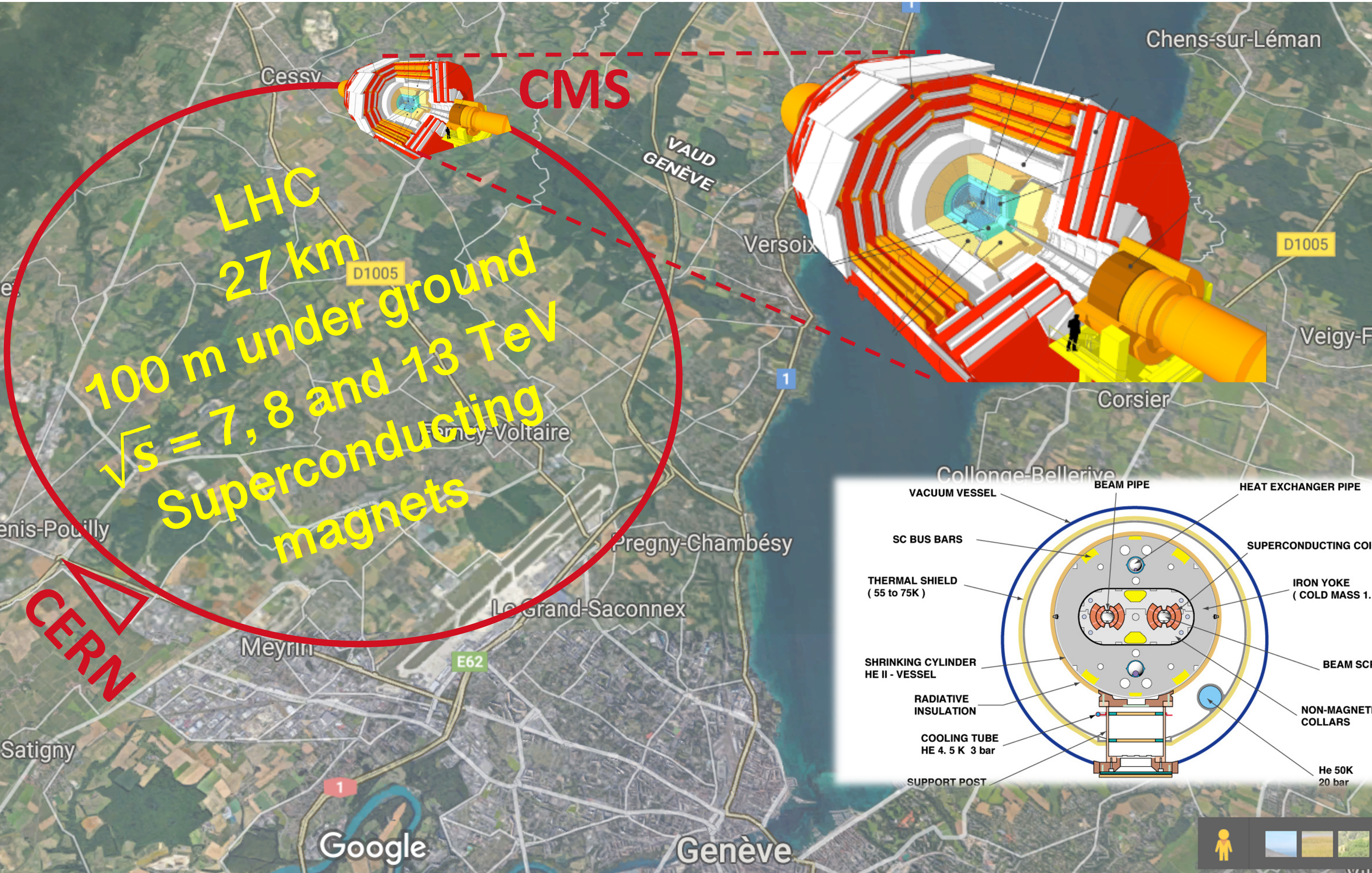
IIHE Annual Meeting (Virtual) 18-12-2020

The LHC and CMS



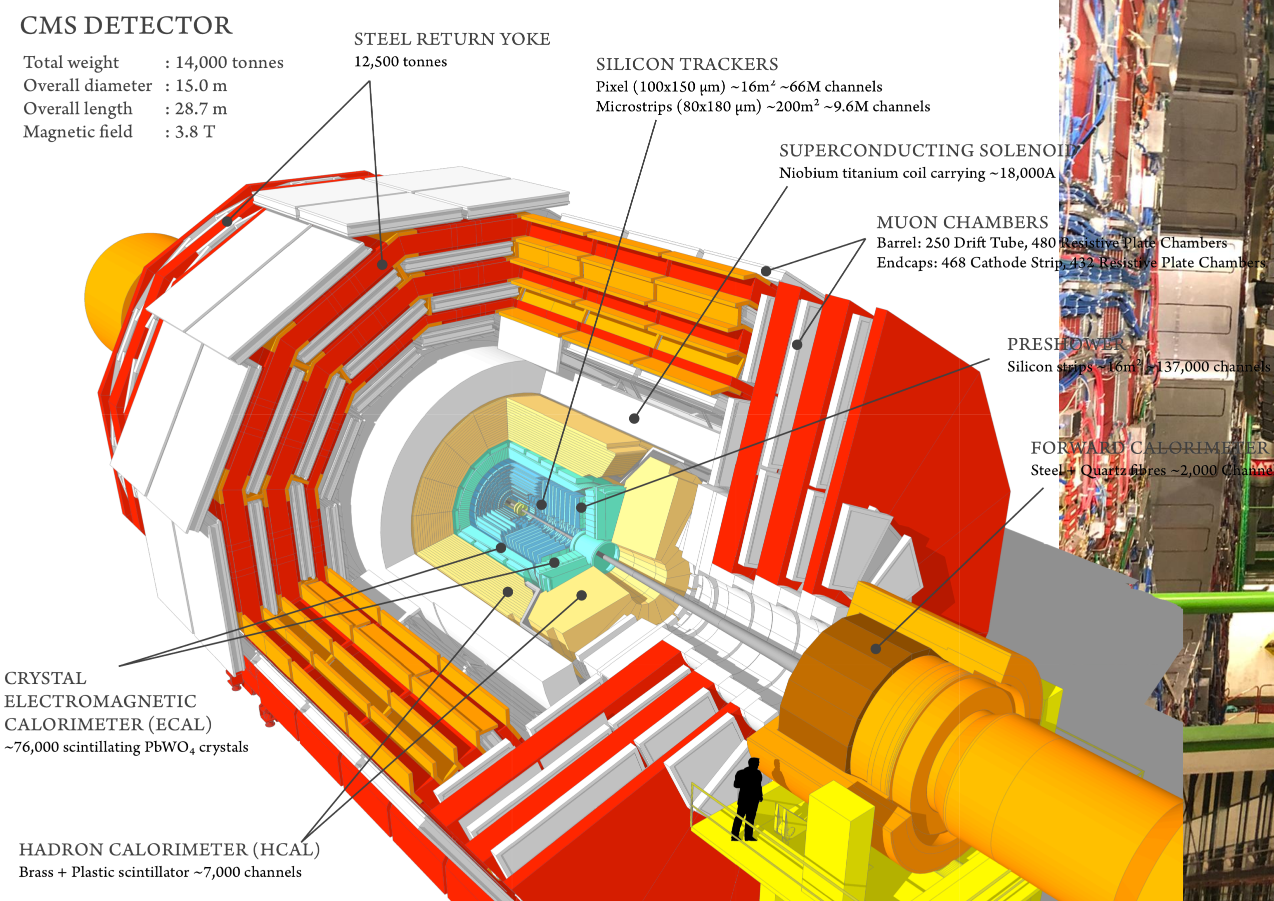
The Large hadron collider at CERN

High energy proton collisions + high luminosity



The Compact Muon Solenoid (CMS)

Particle detector with layered cylindrical structure

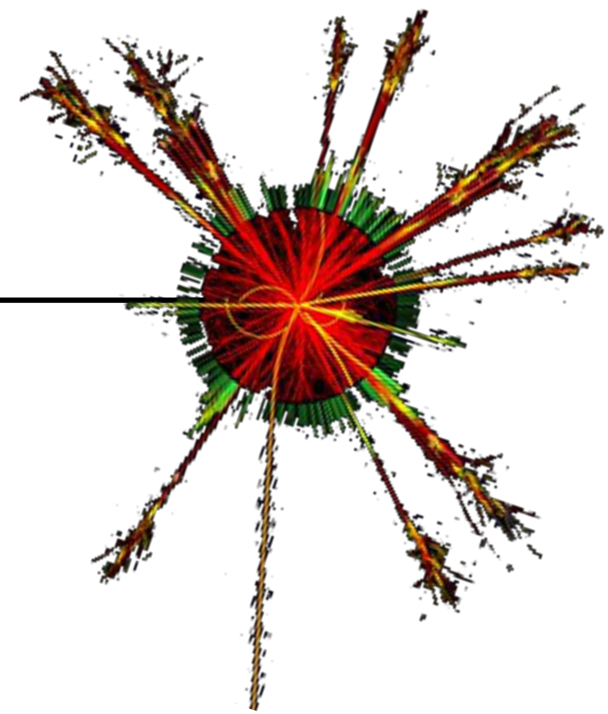


LHC data-taking

Schedule of the LHC over the past and future years

Run-2 **Run-3** **Phase-2**

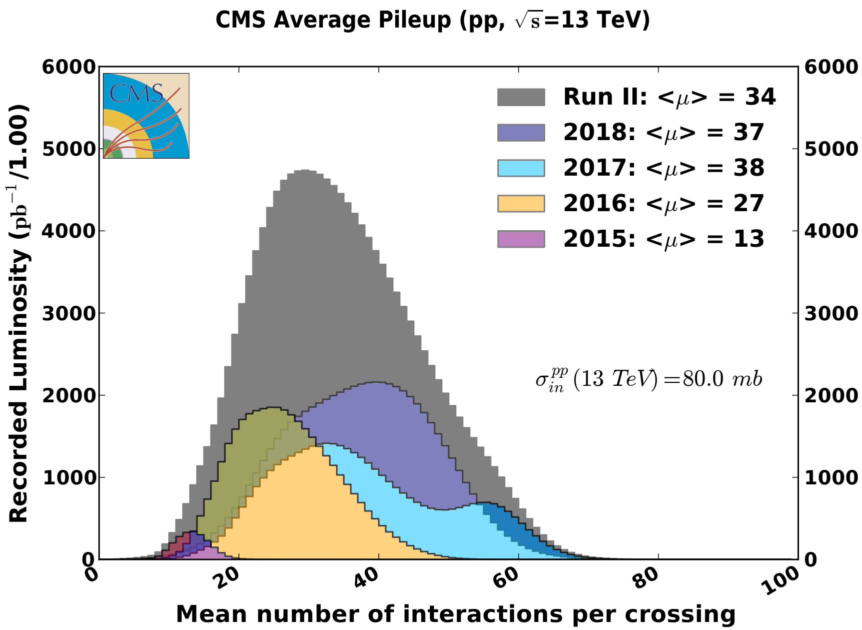
Run-2 has finished!

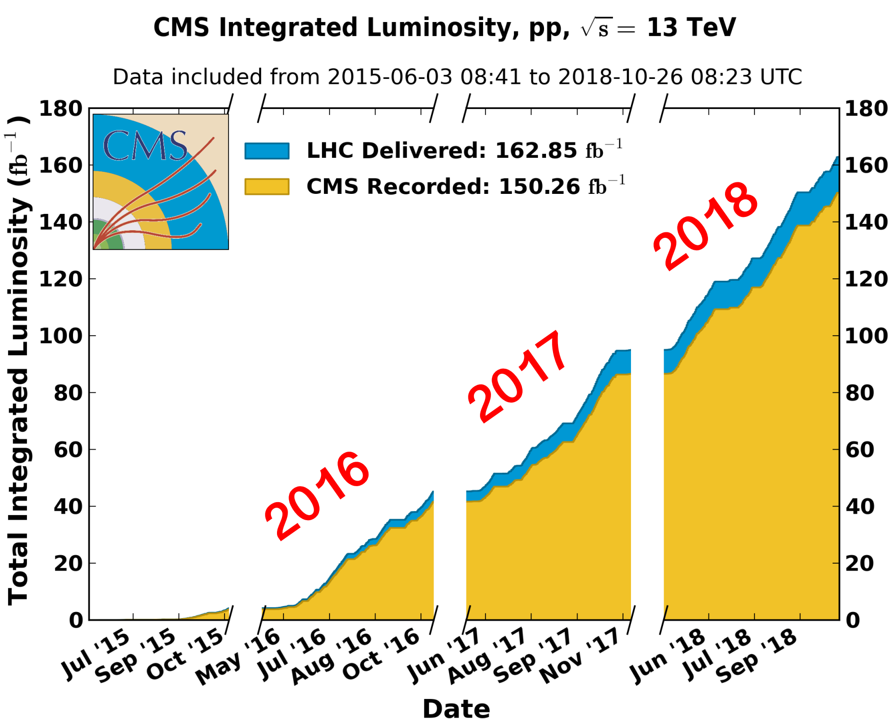


Run-2 achievements

CMS accumulated 137 fb^{-1} of data for physics analyses!

137 fb^{-1} =
~ O(100 million) top-quark pairs
~ O(10 million) Higgs bosons

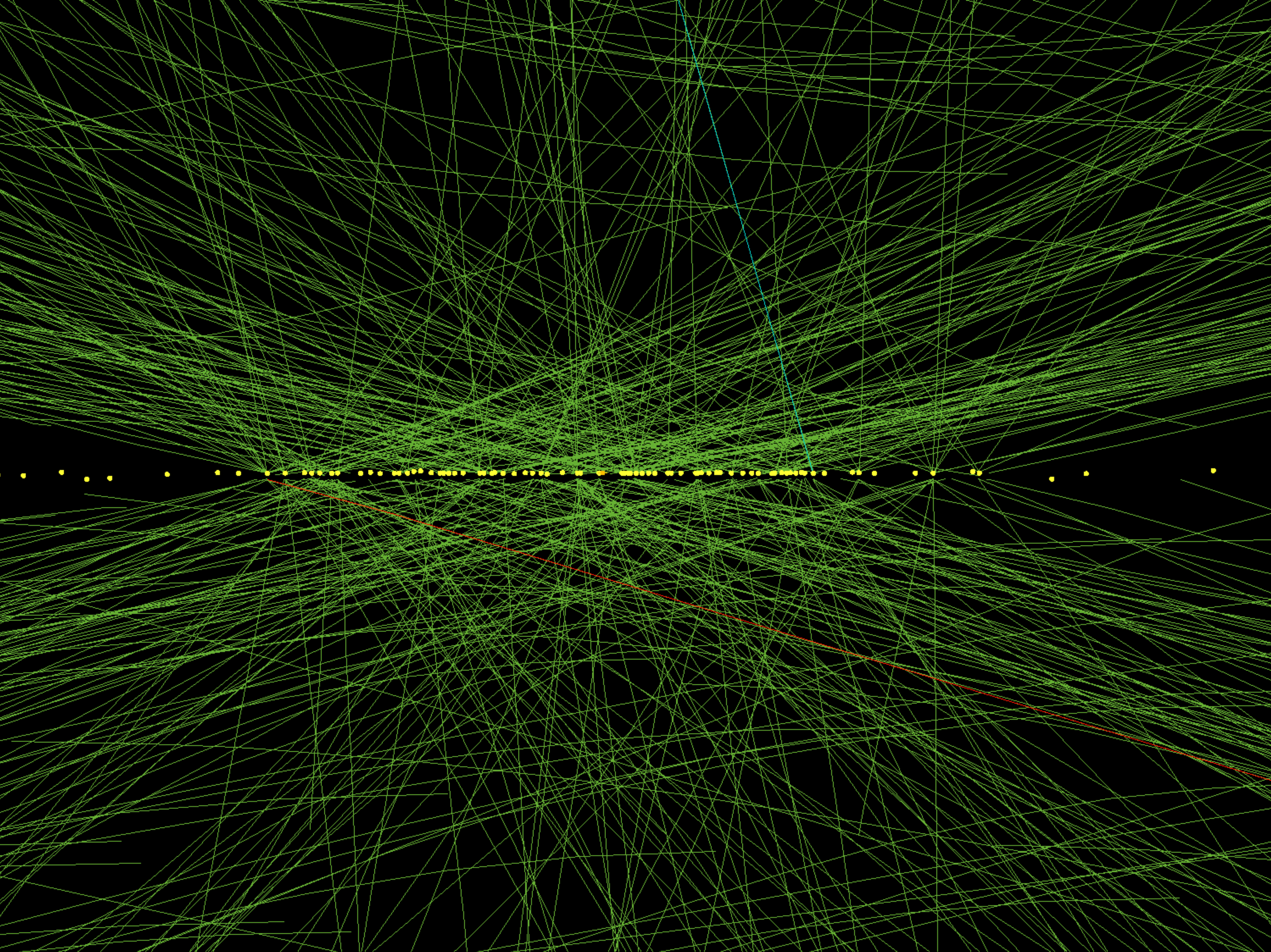




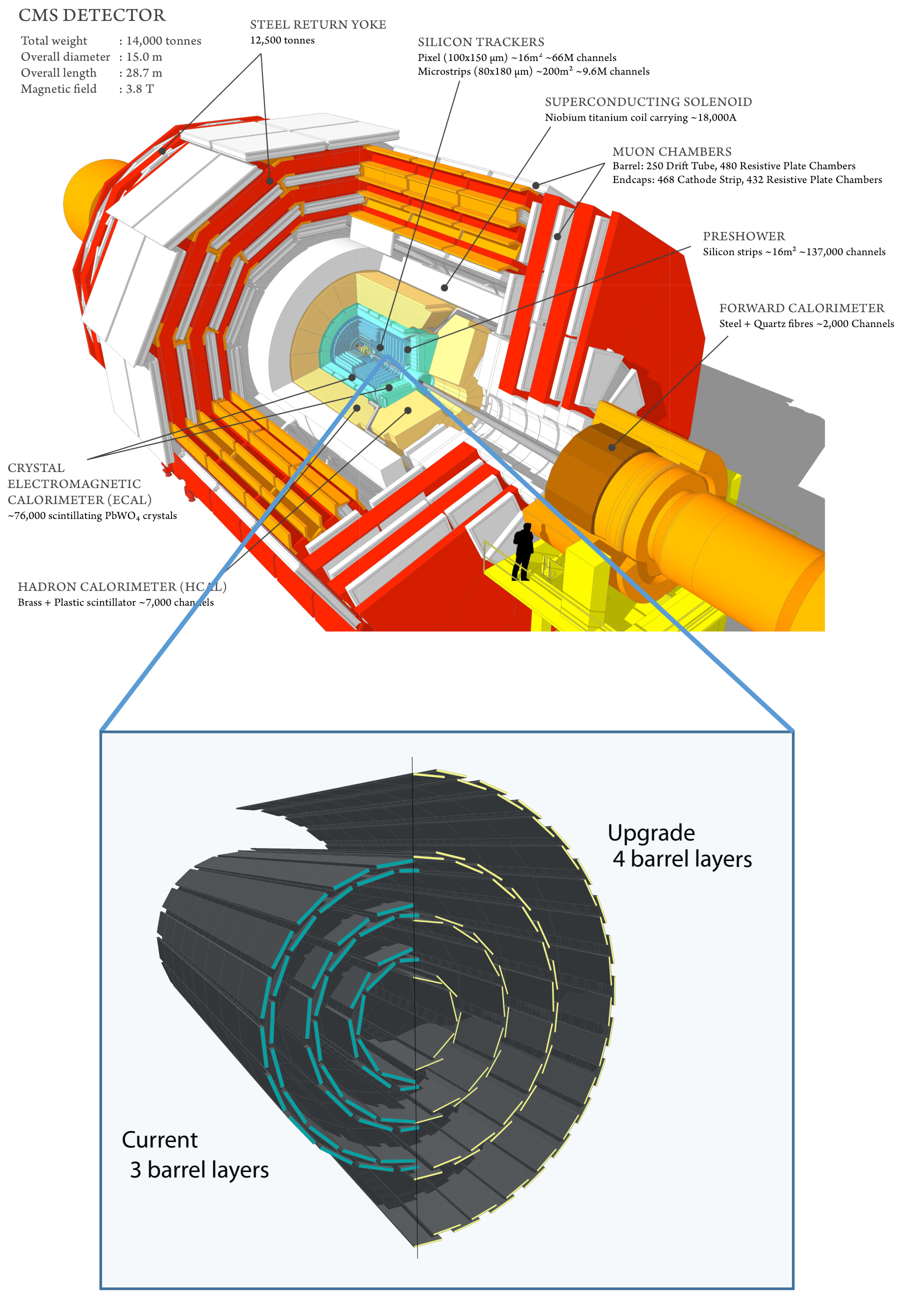
Pileup grows over the years!
Average growing close to 40 interactions per bunch crossing in Run-2.

We can handle this, and more in the future!

Phase-2 (2030?) ~ 200 average pileup!
Requires innovation both in software and hardware.



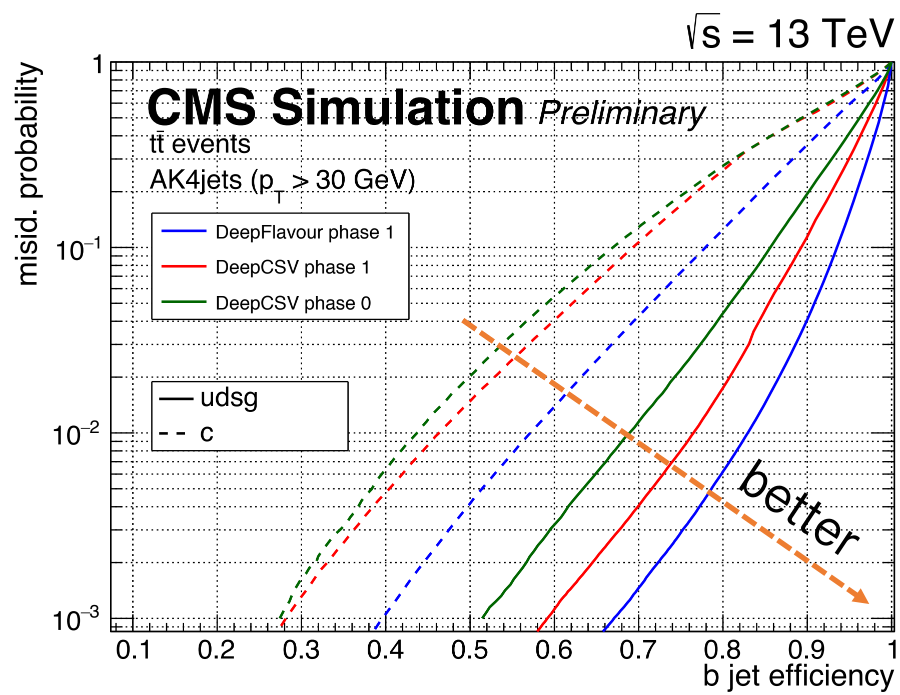
New pixel tracker clearly benefits the Collaboration!



After years of preparation:
2016-2017: upgrade to ‘Phase-1’ Pixel tracker (repair for radiation damage)

New 4-layer pixel tracker geometry
Additional layer closer to the beampipe

Clear improved performance, for example for b tagging ($H\to b\bar{b}$, $t \to bW$)! But also from software developments (@IIHE)!

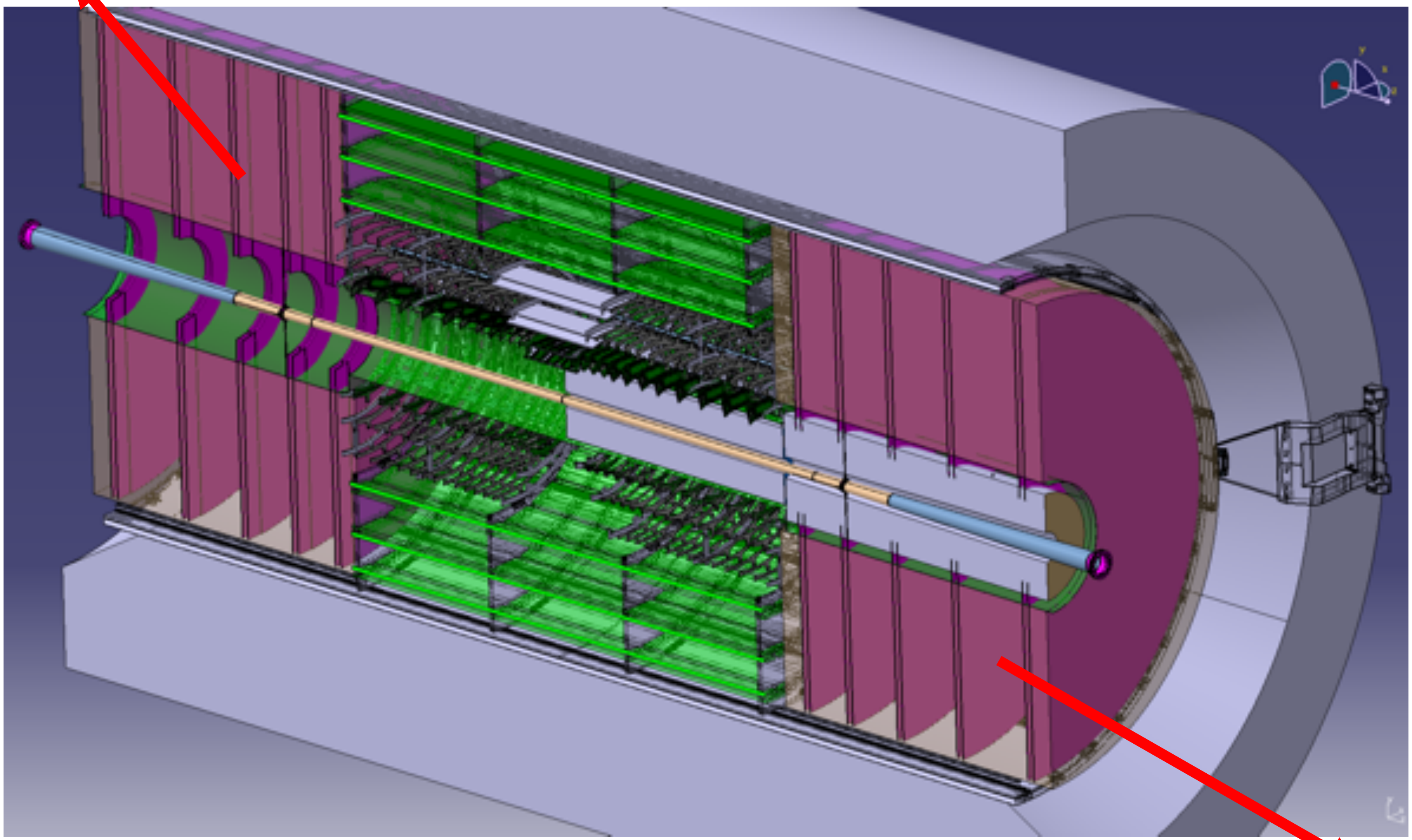


Phase-2 tracker assembly @ IIHE

Belgium was assigned to construct one endcap of the Phase-2 tracker!

Phase-2 tracker upgrade, intended for the High-luminosity upgrade of the LHC

Belgium



DESY

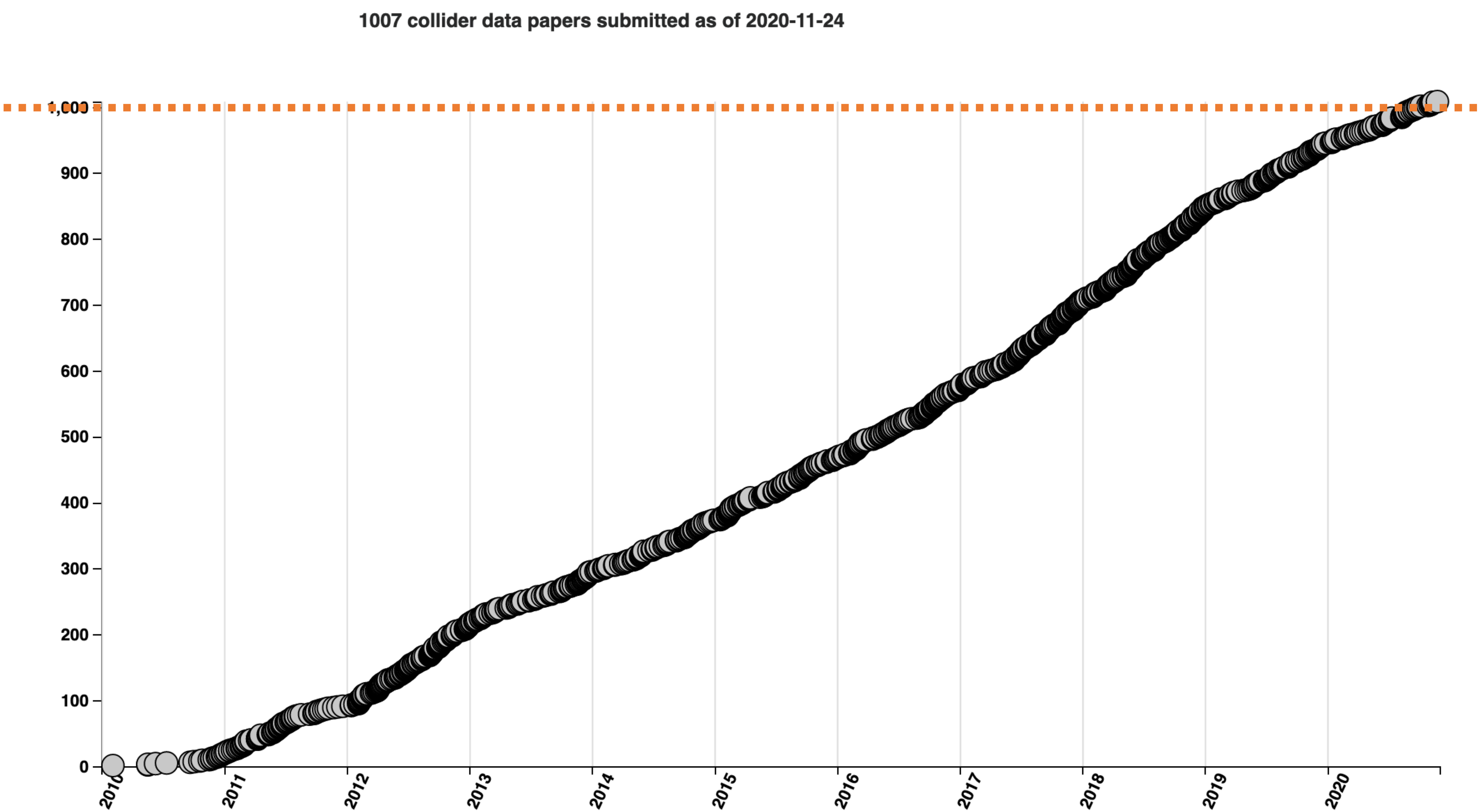
Phase-2 tracker assembly @ IIHE

Successful “remote prototyping of CMS modules” in times of COVID-19!

May-June 2020

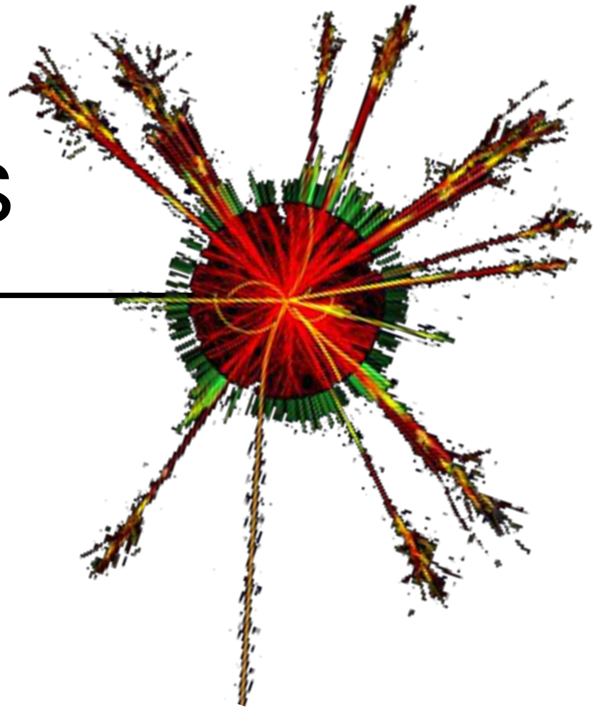
assembly control room as a shared screen, displaying the previously-prepared assembly workflow, the gluing robot control interface, front and side views of the robot with Ali handling the gluing jigs, and the view from Ali's cell phone camera.

CMS has published > 1000 papers!



Run-2 physics highlights

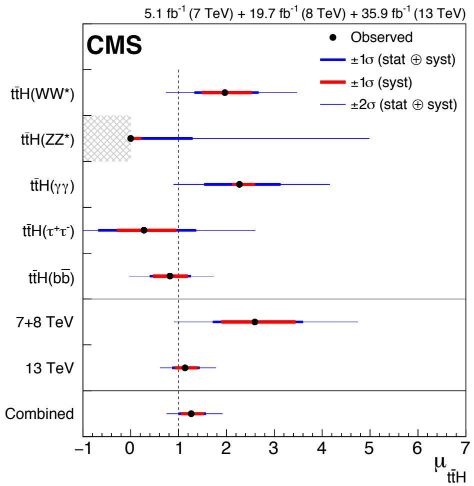
Non exhaustive list!
Focusing on the Higgs-top interplay



Run-2 achievements

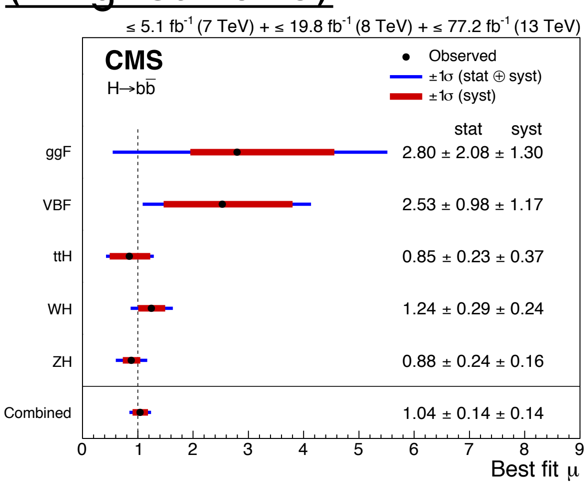
Probing Higgs couplings to 3rd generation!

Observation of $t\bar{t}H$ production!
(April 2018)

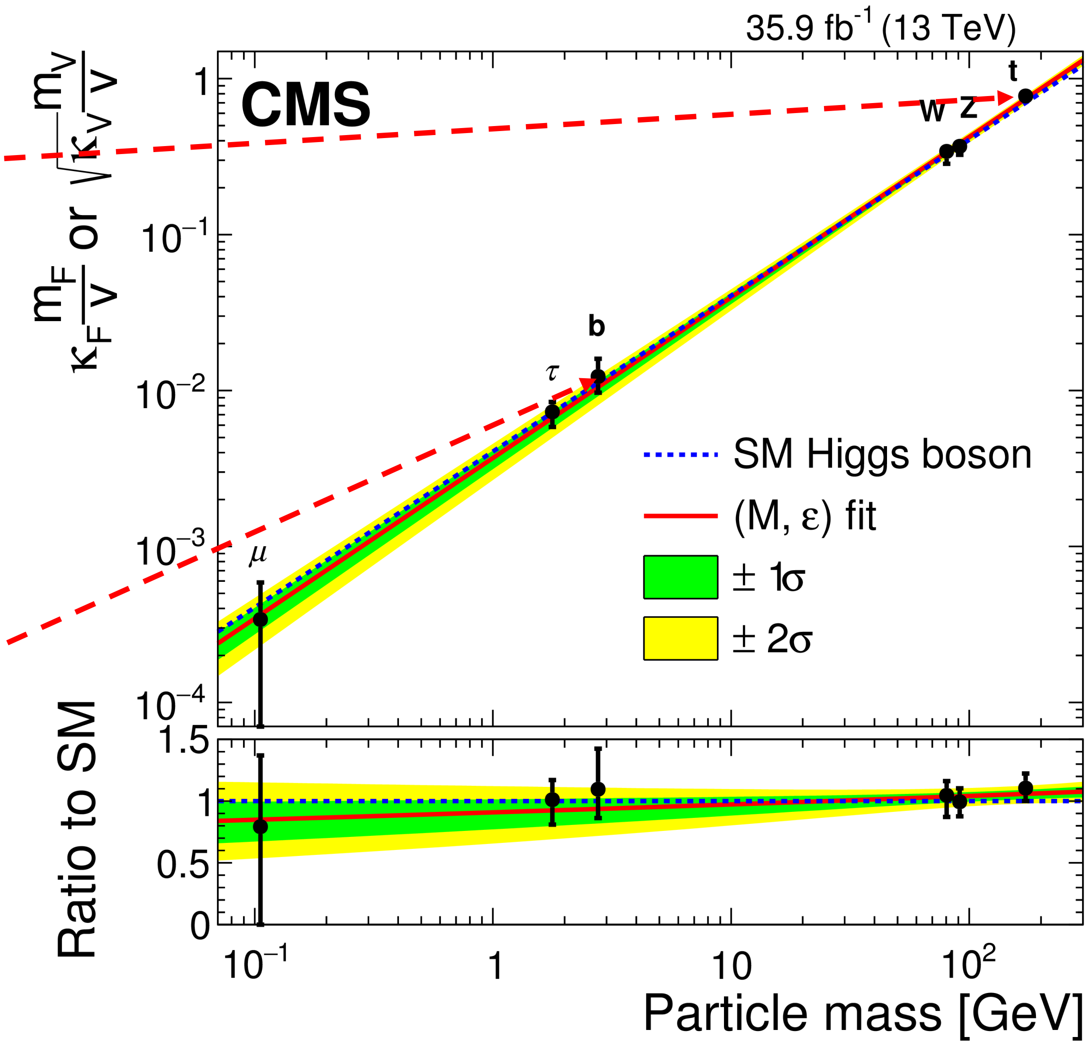


arXiv:1804.02610

Observation of $H \rightarrow b\bar{b}$ decay!
(August 2018)



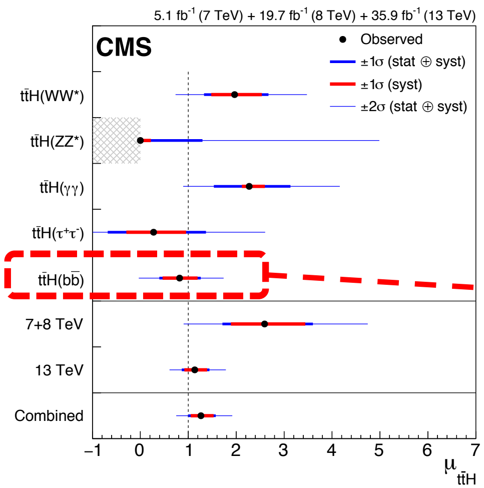
arXiv:1808.08242



Run-2 achievements

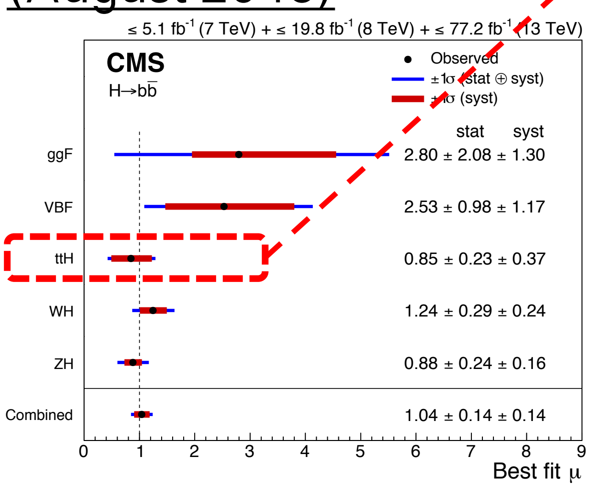
Probing Higgs couplings to 3rd generation!

Observation of tt̄H production! (April 2018)



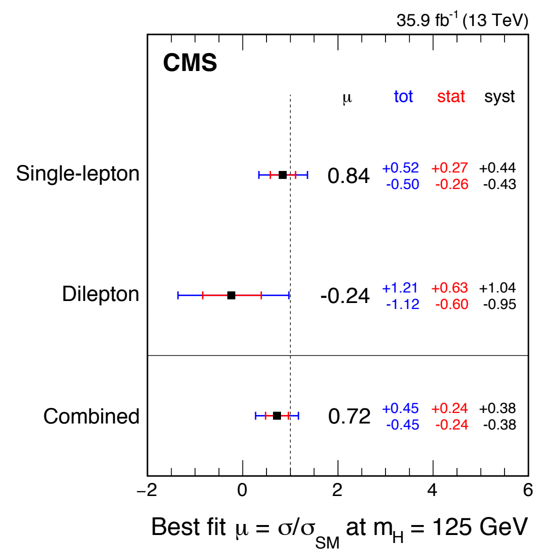
arXiv:1804.02610

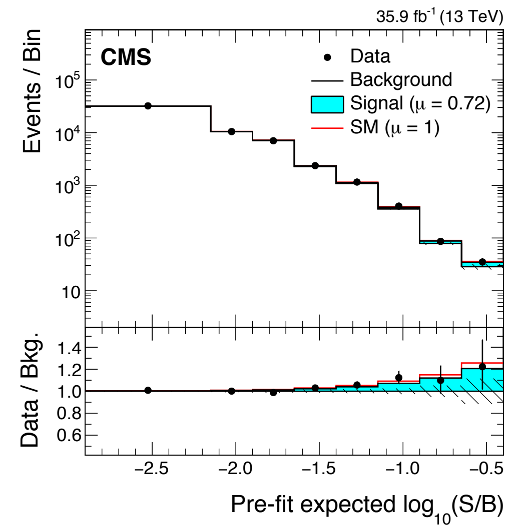
Observation of $H \to b\bar{b}$ decay! (August 2018)



arXiv:1808.08242

Both discoveries rely on a measurement of $t\bar{t}H(H \to b\bar{b})$ arXiv:1804.03682





observed (expected) significance of 1.6 (2.2)

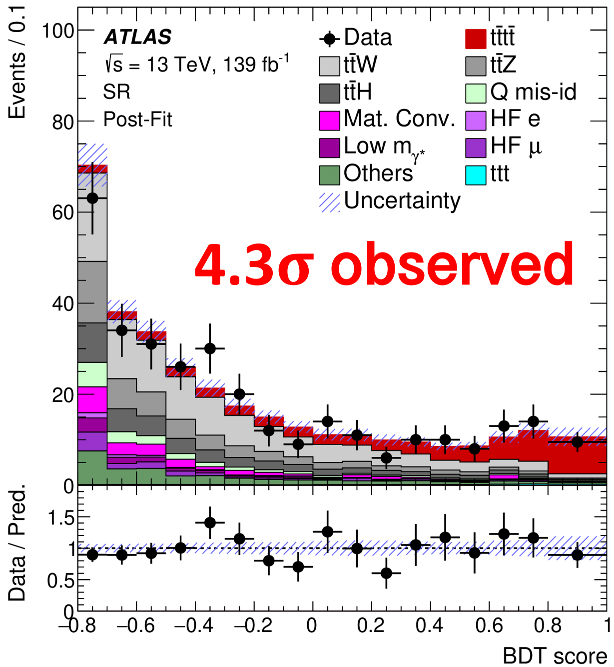
$t\bar{t}H\ (H \to b\bar{b})$ suffers from an irreducible (non-resonant) background of (gluon-induced) $t\bar{t}$+$b\bar{b}$ and $t\bar{t}$+$c\bar{c}$ (through mistags)

Topic of the 2nd part!

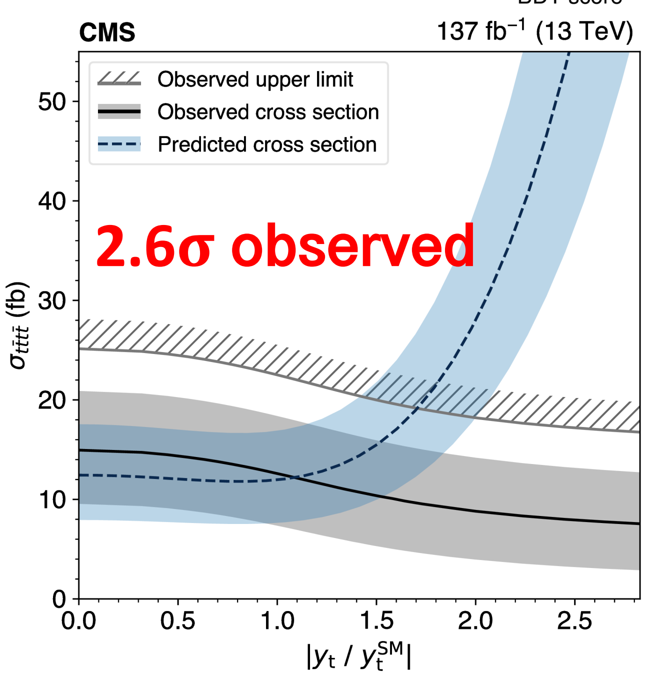
Run-2 achievements

Evidence for four top quark production + EFT interpretations

ATLAS, Eur.Phys.J.C 80 (2020) 11, 1085



CMS, Eur. Phys. J. C 80 (2020) 75

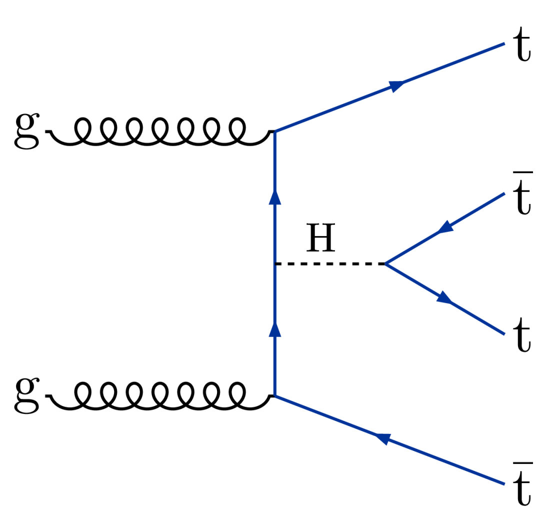


The extensive content of the Run-2 Legacy dataset triggers **global EFT interpretations**.

ex. ML for EFT in $t\bar{t}b\bar{b}$ → Arxiv:1807.02130 (@IIHE collab between pheno and CMS group)

Global EFT interpretation already exists in CMS for tt+Z/W/H/tZq/tHq (PAS-TOP-19-001)

Could be also very promising to have a global EFT interpretation in tt+HF/tttt/ttH
→ **modified tH, tg or four-quark vertices**



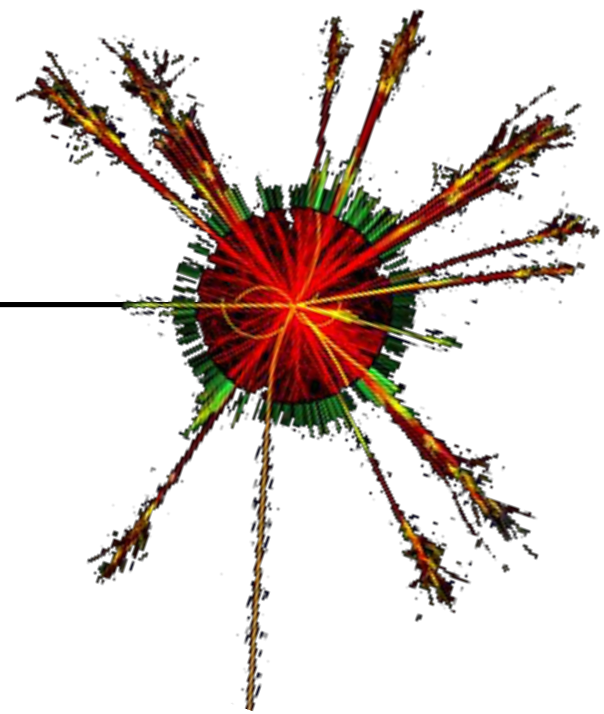
Is this $t\bar{t}H$?

Or $t\bar{t}t\bar{t}$?

Or $t\bar{t}b\bar{b}$ (replace t by b)?

Or all together?

Run-2 was for the
3rd generation

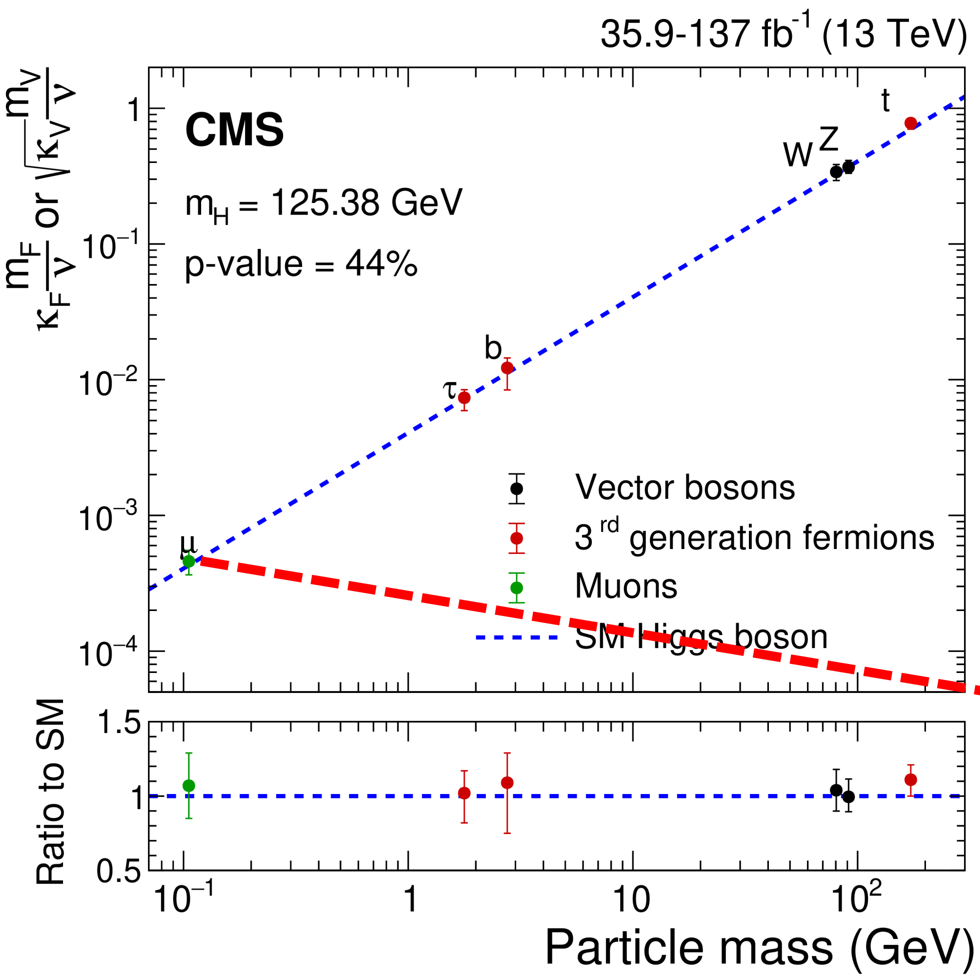


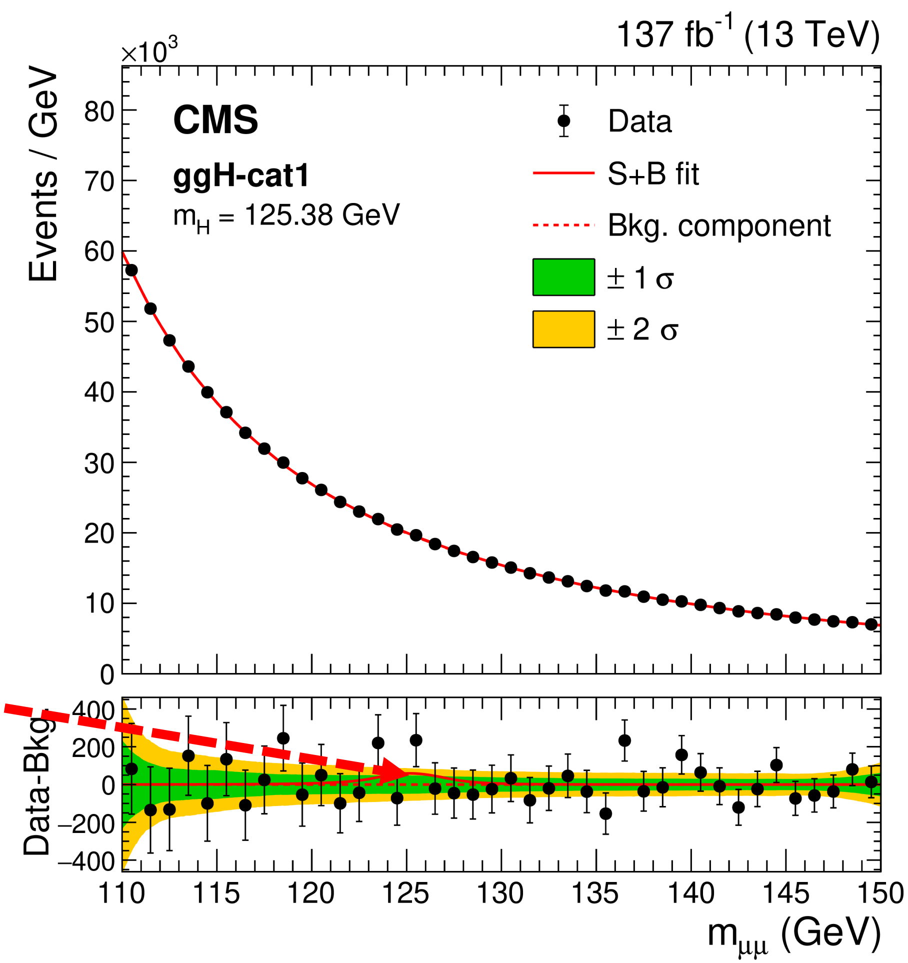
Run-3 will be for
the 2nd generation

Probing interactions between Higgs and 2nd generation: Muons

PAS-HIG-19-006

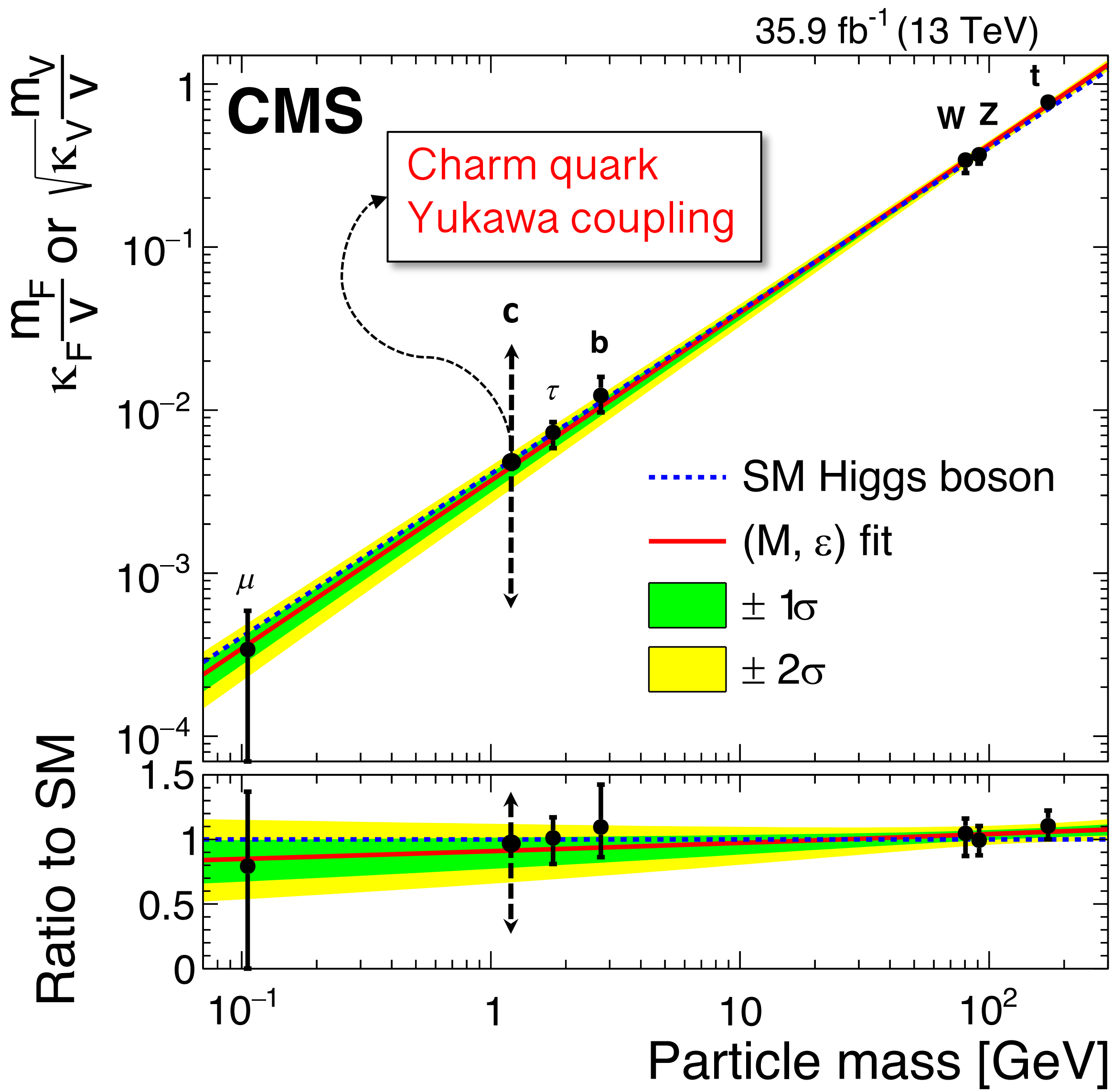
Evidence for H-μ coupling (significance of 3σ)
→ Observation in Run-3?





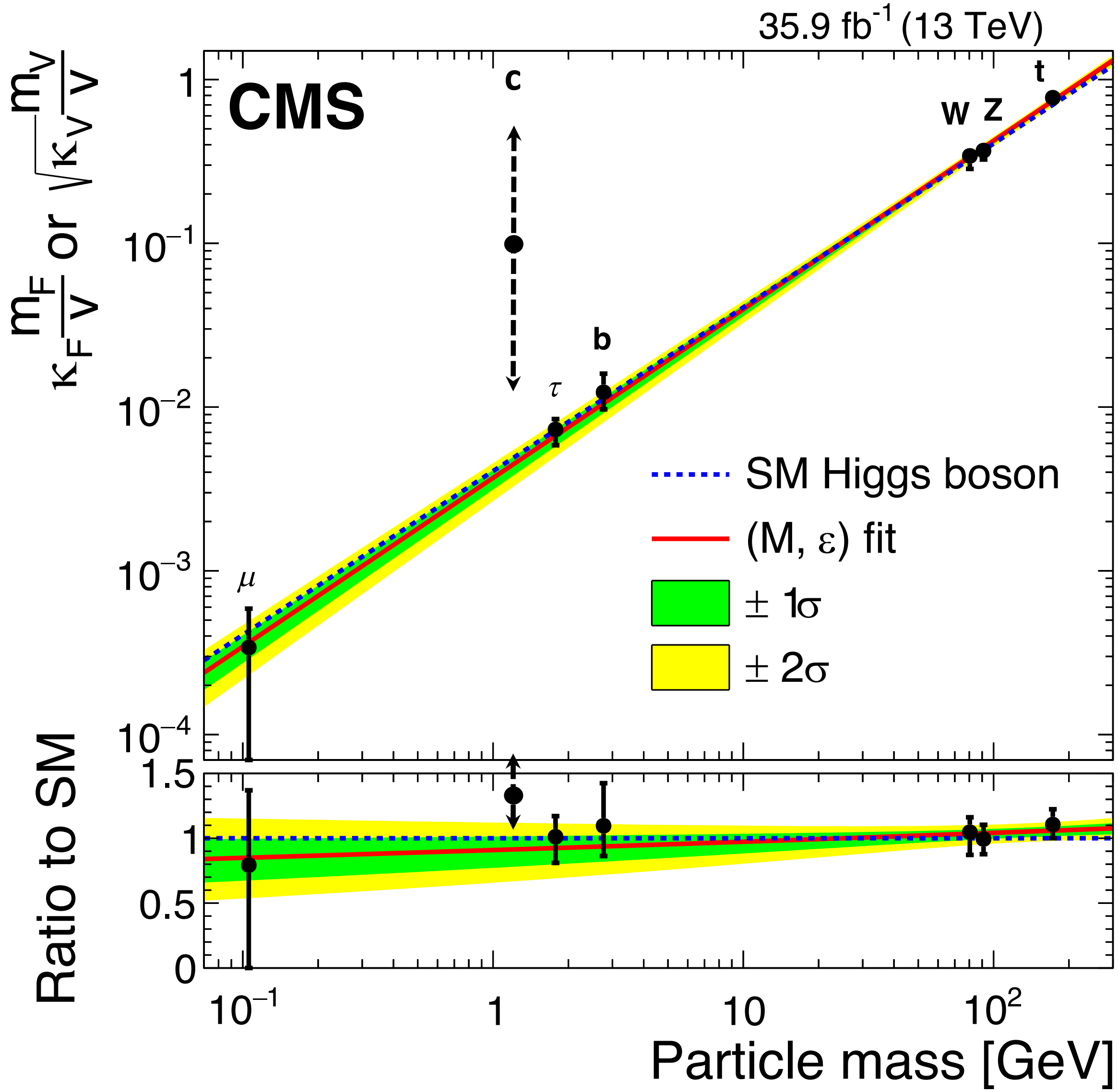
Probing **interactions between Higgs and 2nd generation quarks**

Standard Model ?



Probing **interactions between Higgs and 2nd generation quarks**

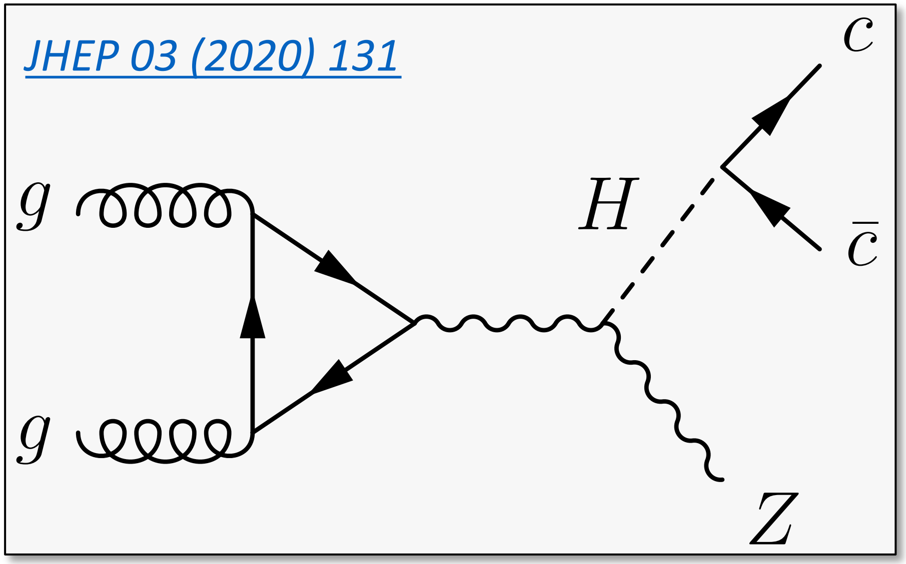
Beyond Standard Model ?



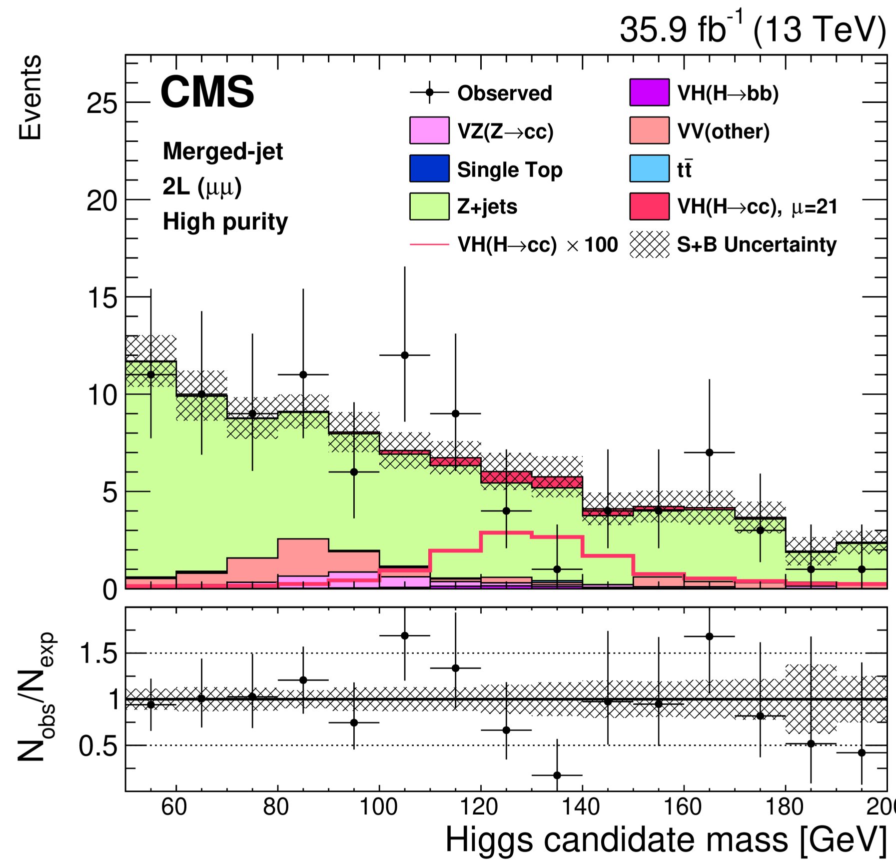
Run-3 objectives

How? Through decay of $H \rightarrow c\bar{c}$ (Run-2 result)

JHEP 03 (2020) 131



$$\mu = \frac{\sigma(pp \rightarrow ZH) \times BR(H \rightarrow c\bar{c})}{\sigma_{SM}(pp \rightarrow ZH) \times BR_{SM}(H \rightarrow c\bar{c})} < 70 \quad \text{(95\% CL)}$$

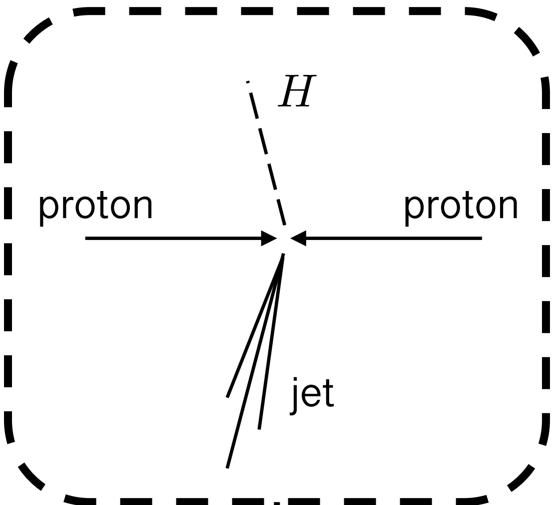


This analysis relies a lot on charm-tagging!

→ relies on techniques developed at IIHE

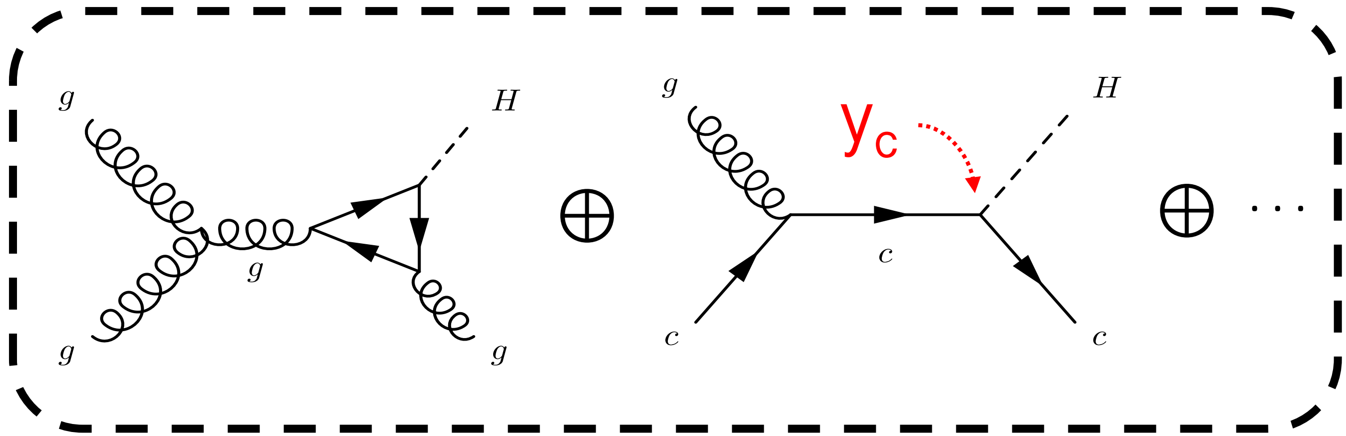
How? Through H+jet production

In the detector



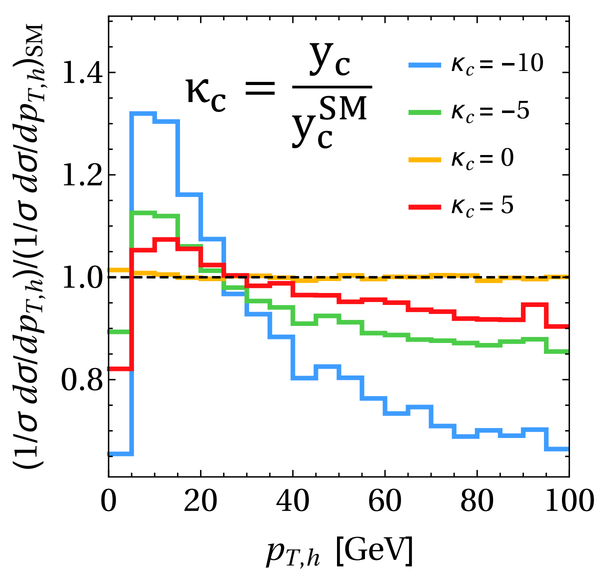
In the theory

$=$



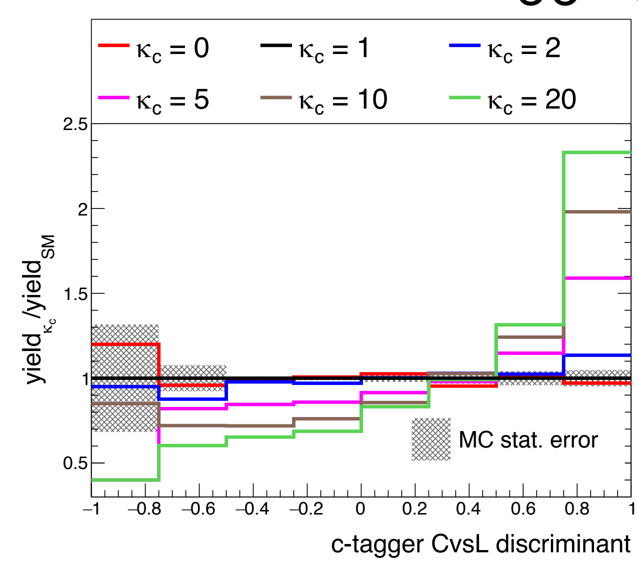
Sensitive properties:

Higgs kinematics



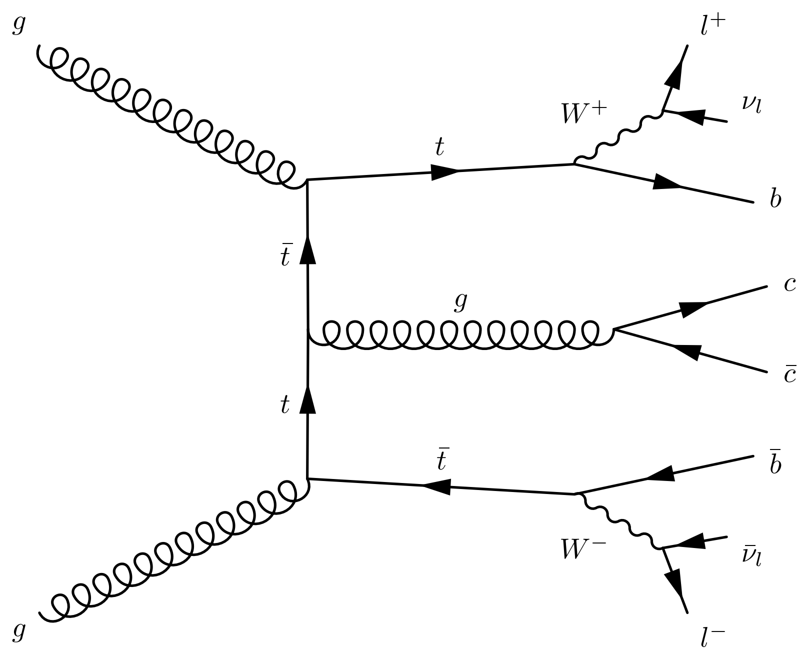
Phys.Rev.Lett. 118 (2017) no.12, 121801

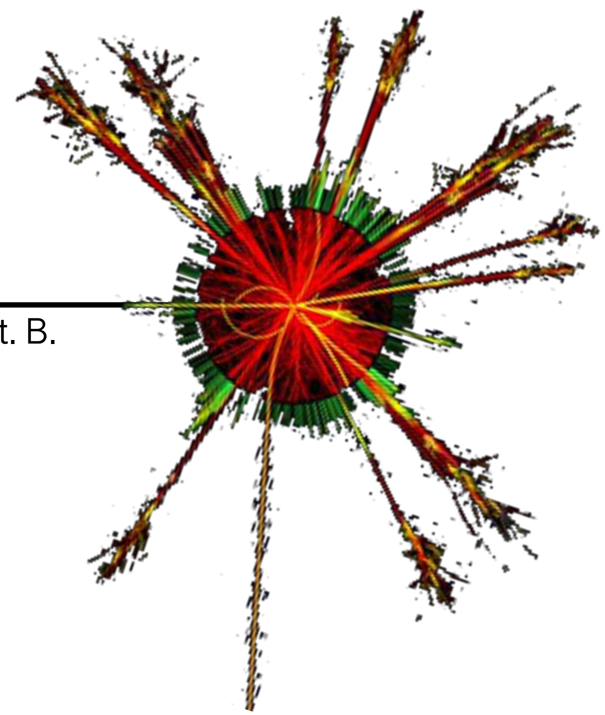
Jet flavour → c-tagging



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

arXiv: 2012.09225 / CMS-TOP-20-003 / Submitted to Phys. Lett. B.

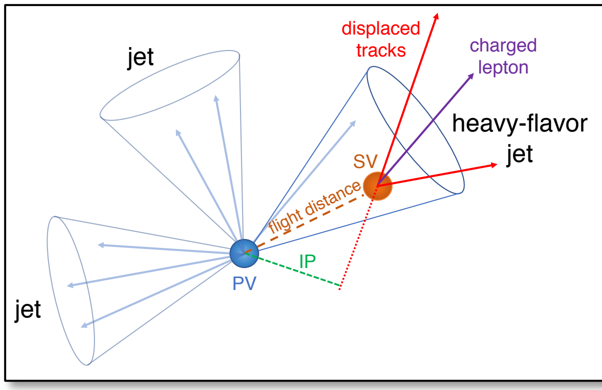




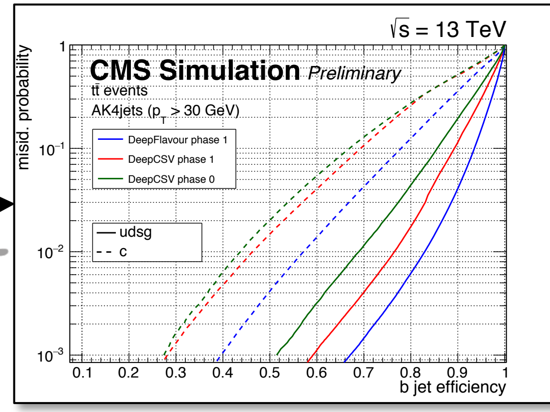
Measurement of $t\bar{t}+c\bar{c}$ production

A roadmap towards a successful measurement

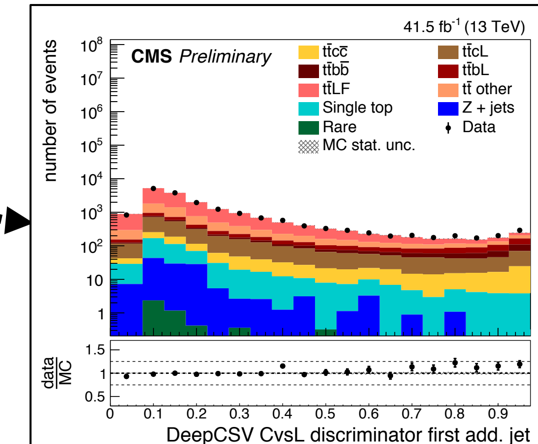
① c, b and t quarks require jets and heavy flavor tagging (new **c-tagger**)



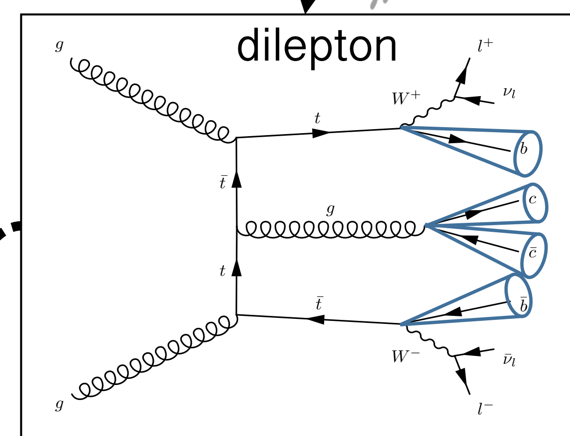
② Improved ML techniques for HF tagging (**DeepCSV**/DeepJet)



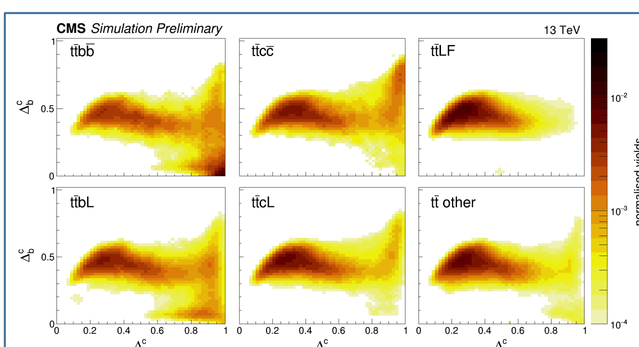
③ Calibration performance (charm tagger shape)



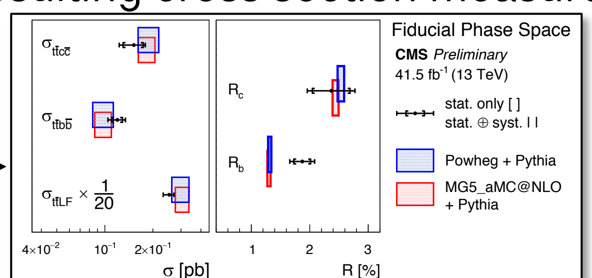
④ Selection and reconstruction of the $t\bar{t}$+HF topology (jet-parton match)



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

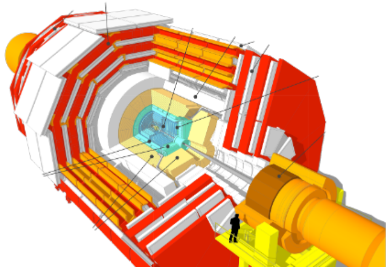


⑥ Resulting cross section measurement



Fiducial phase space

"what the detector can see"



- $pp \rightarrow t\bar{t}jj \rightarrow \ell^{+}\bar{\nu}_{\ell}b\ell^{-}\nu_{\ell}\bar{b}jj$ (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

"what a theorist can see"

- $pp \rightarrow t\bar{t}jj \rightarrow W^{+}bW^{-}\bar{b}jj$
- 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

- $t\bar{t}b\bar{b}$: $\geq$ 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)
- $t\bar{t}c\bar{c}$: $\geq$ 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)
- $t\bar{t}LL$: 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: **low backgrounds**

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

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

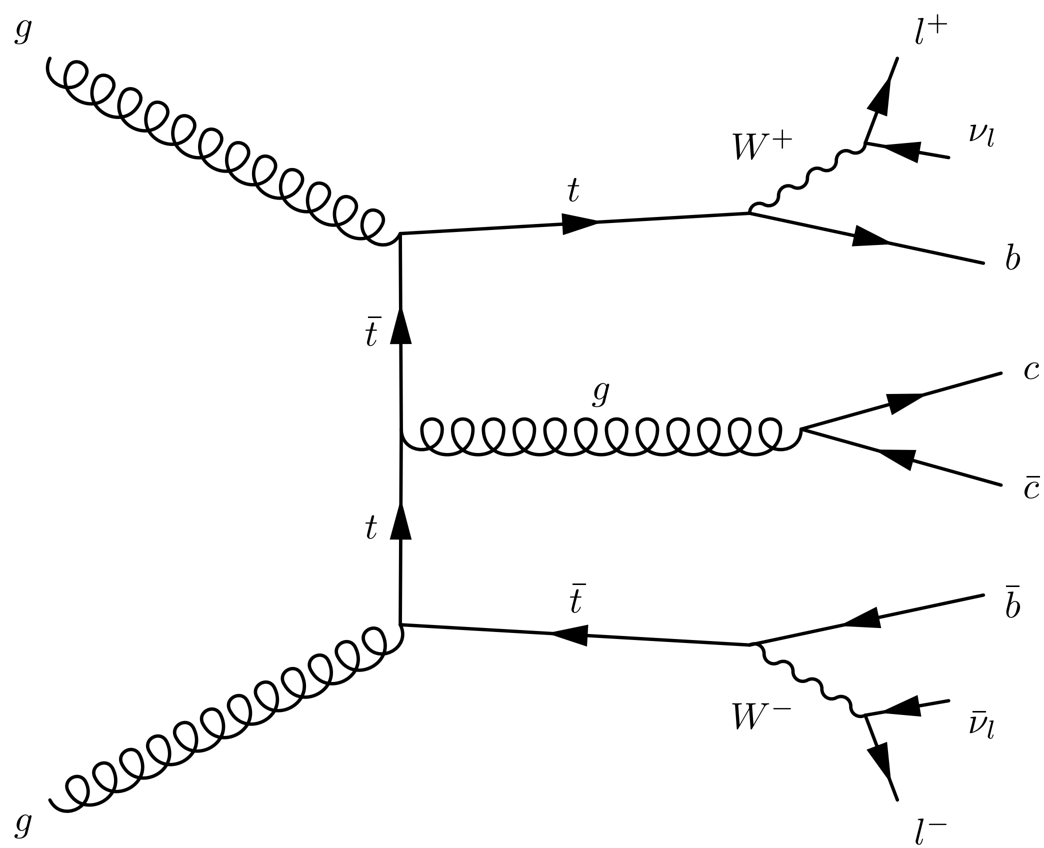
b-jets/c-jets
- 2 top-matched jets: Medium DeepCSV b-tagged

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]

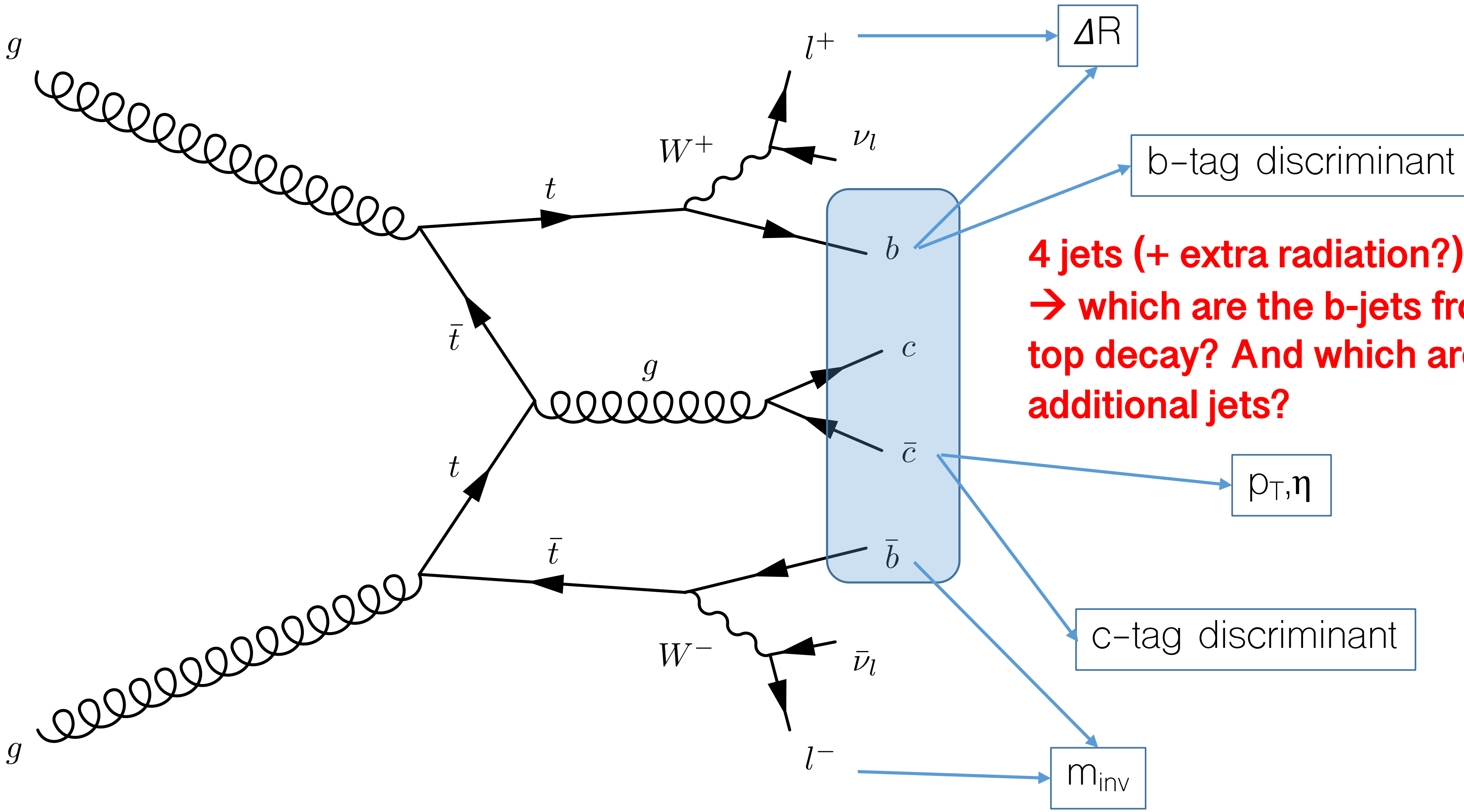
MET
- $\mu\mu/ee$: MET>30 GeV



Results in >95% $t\bar{t}$+2 jet events

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

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, …

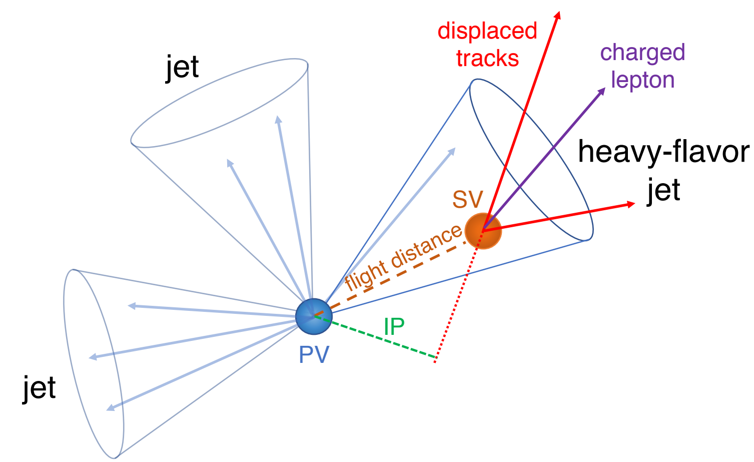
Properties from c jets are distributed midway between those of b or light-flavour jets → two c-tagging discriminants!

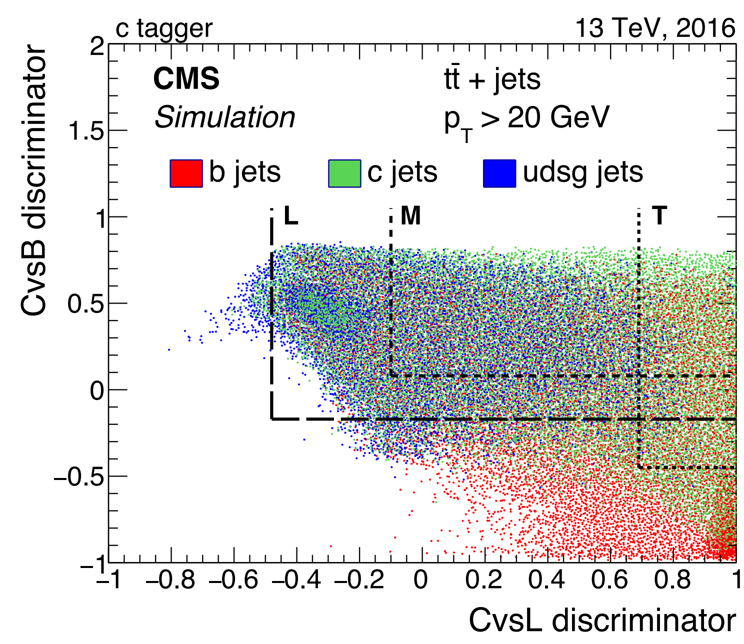
$$\mathrm{P(CvsL)} = \frac{\mathrm{P(c)}}{\mathrm{P(c) + P(udsg)}}, \qquad \mathrm{P(CvsB)} = \frac{\mathrm{P(c)}}{\mathrm{P(c) + P(b) + P(bb)}}.$$

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

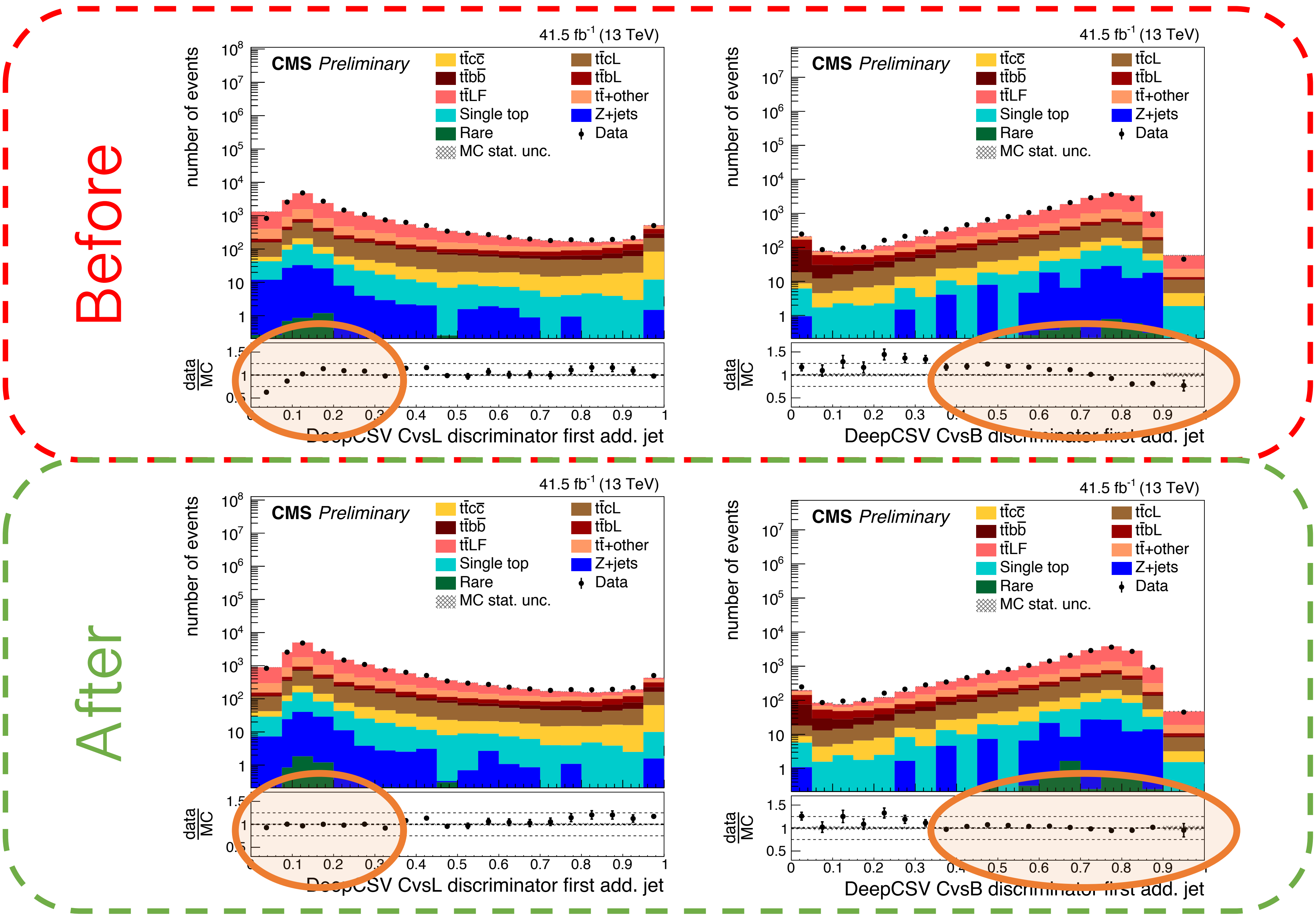
JINST 13 (2018) P05011





c-tagger calibration

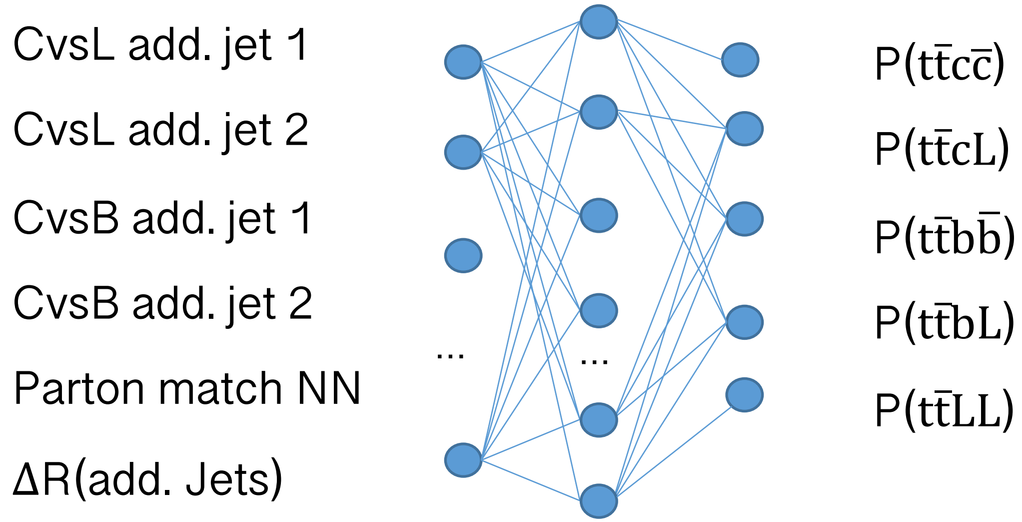
Effect of the calibration on the additional jet CvsL/CvsB



Template fit using NN discriminator

Use machine learning to discriminate signals

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



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

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

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

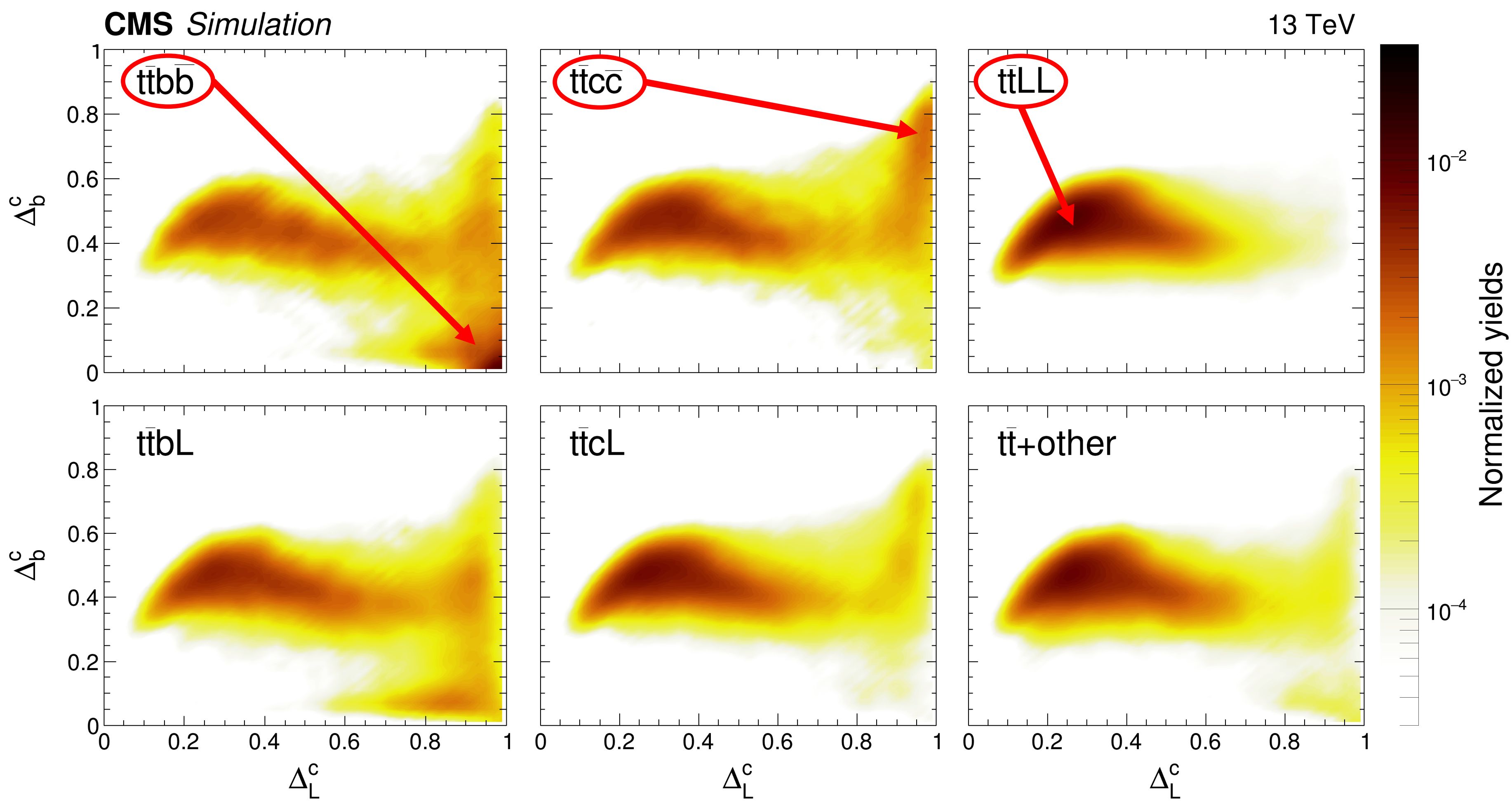
Information on the flavour of the two additional jets

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

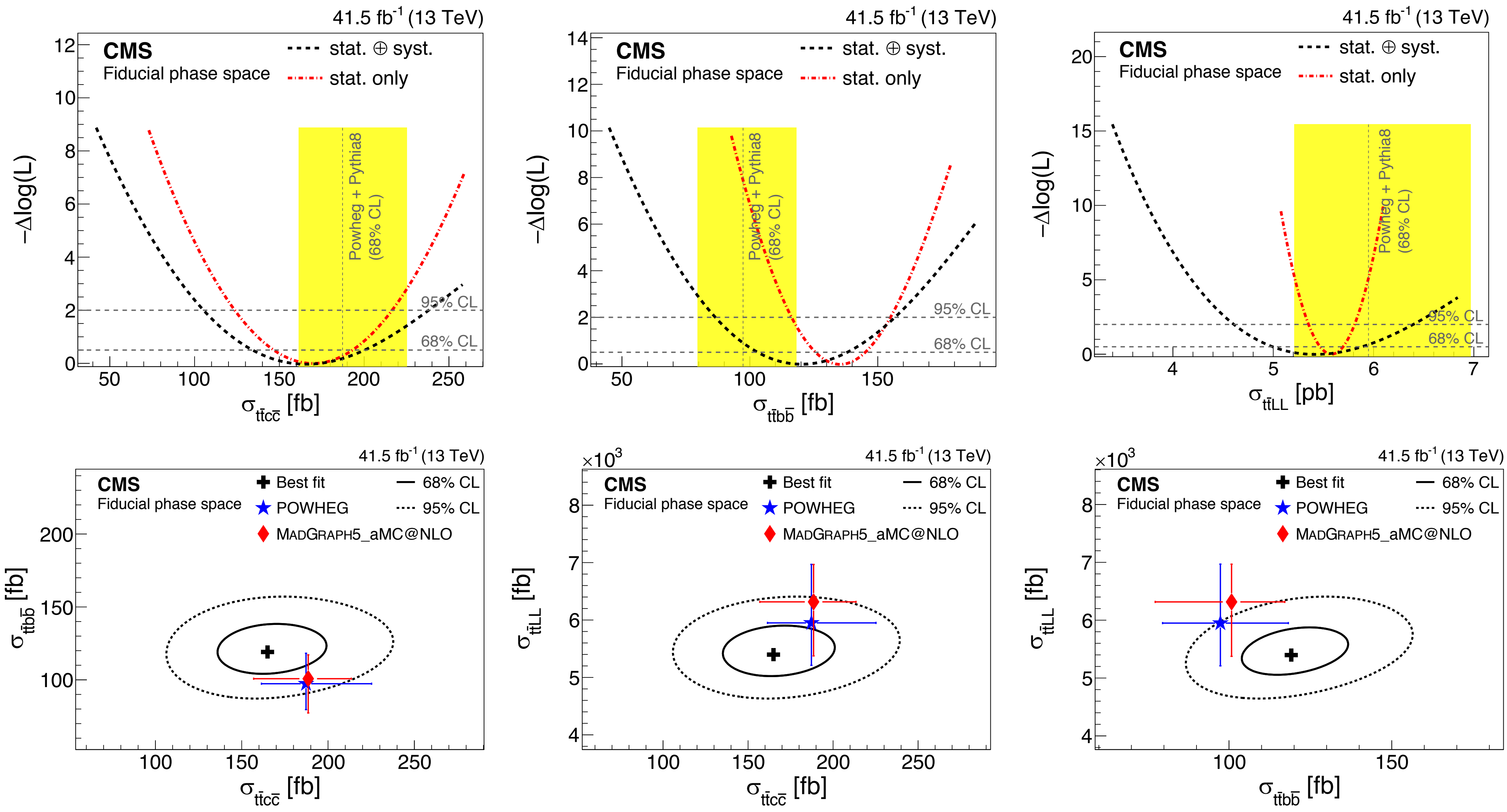
The fit is performed on two-dimensional distributions



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

Results

Inclusive cross sections in the fiducial phase space

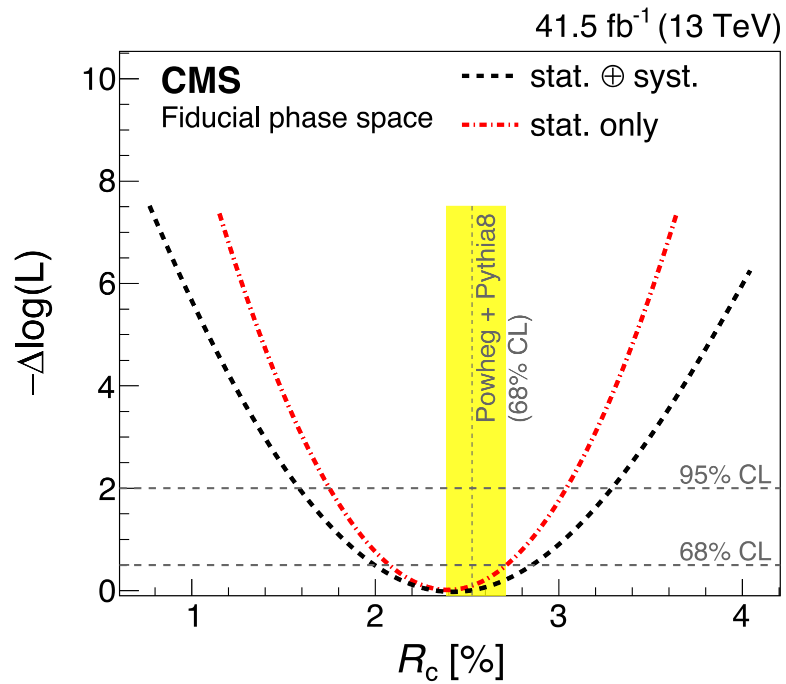


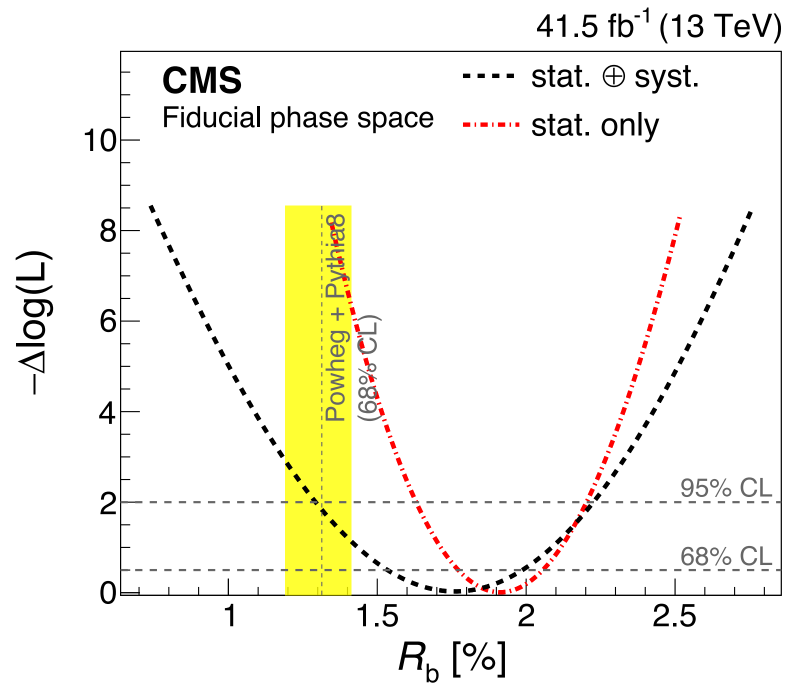
Some tension observed, but overall agreement within 1-2 standard deviations

Dominant uncertainties from flavour-tagging, JES, and modelling

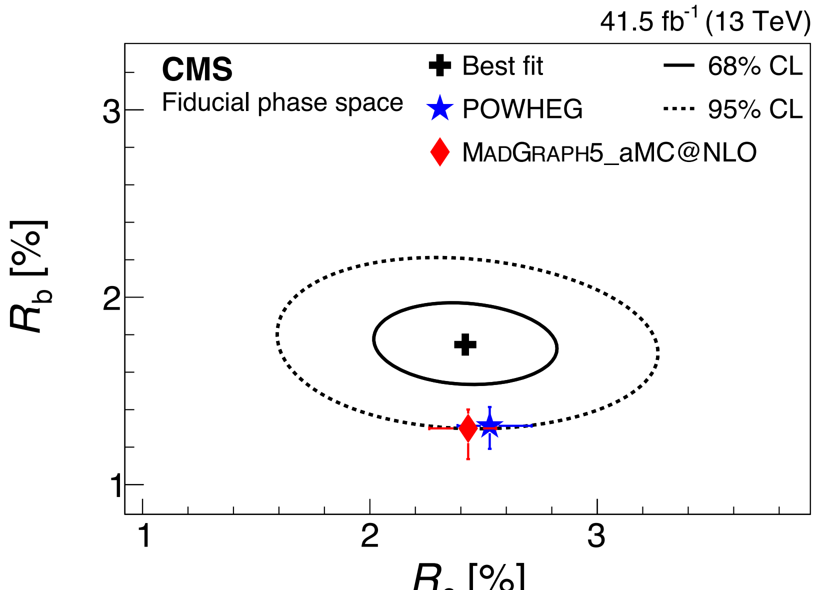
Results

Ratios R_c and R_b in the fiducial phase space



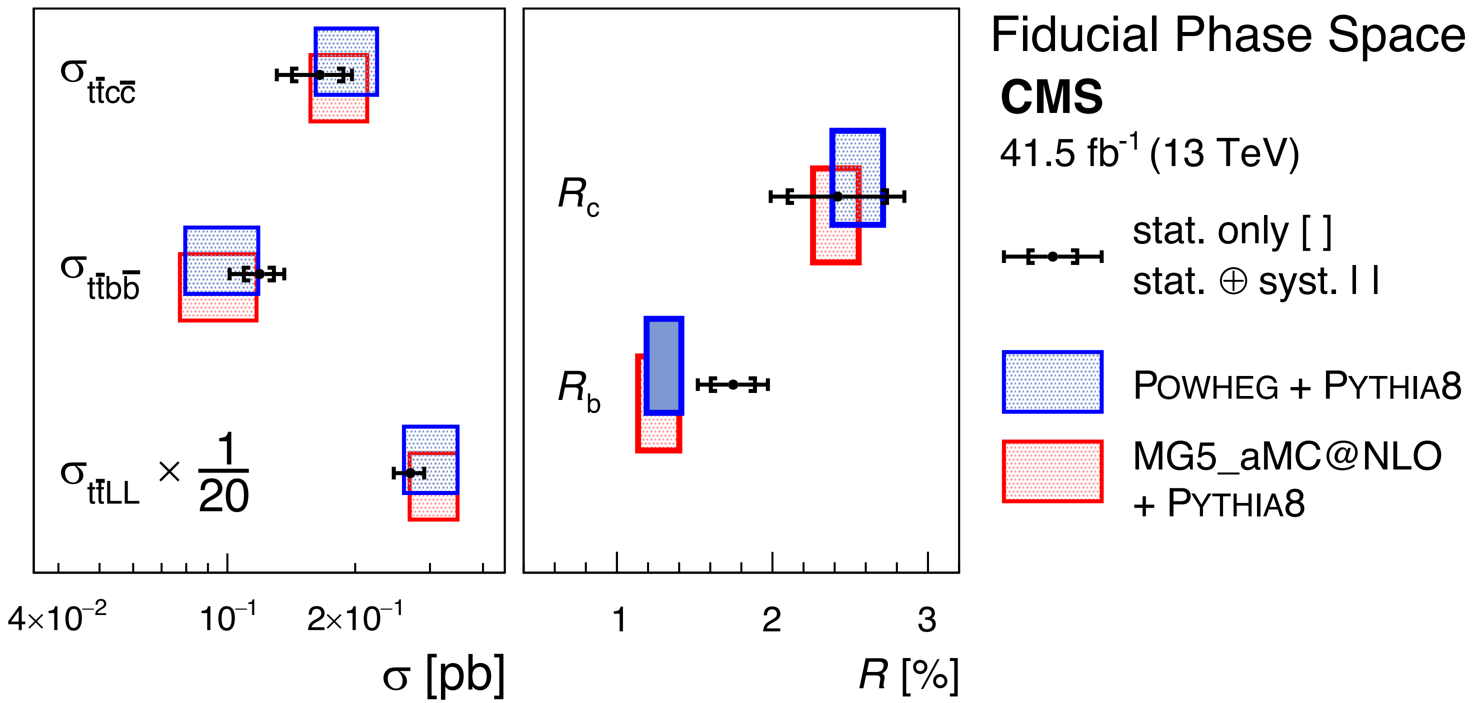


$$R_{c/b} = \sigma(t\bar{t} + c\bar{c}/b\bar{b}) \Big/ \sigma(t\bar{t} + jj)$$



The CMS dilepton $t\bar{t}c\bar{c}$ measurement

Summary of the results



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

Fiducial PS:

$\sigma(t\bar{t}c\bar{c}) = 165 \pm 23$ (stat.) ± 25 (syst.) fb (~ 20% uncertainty)

$R_c = 2.42 \pm 0.32$ (stat.) ± 0.29 (syst.) % (~ 18% uncertainty)

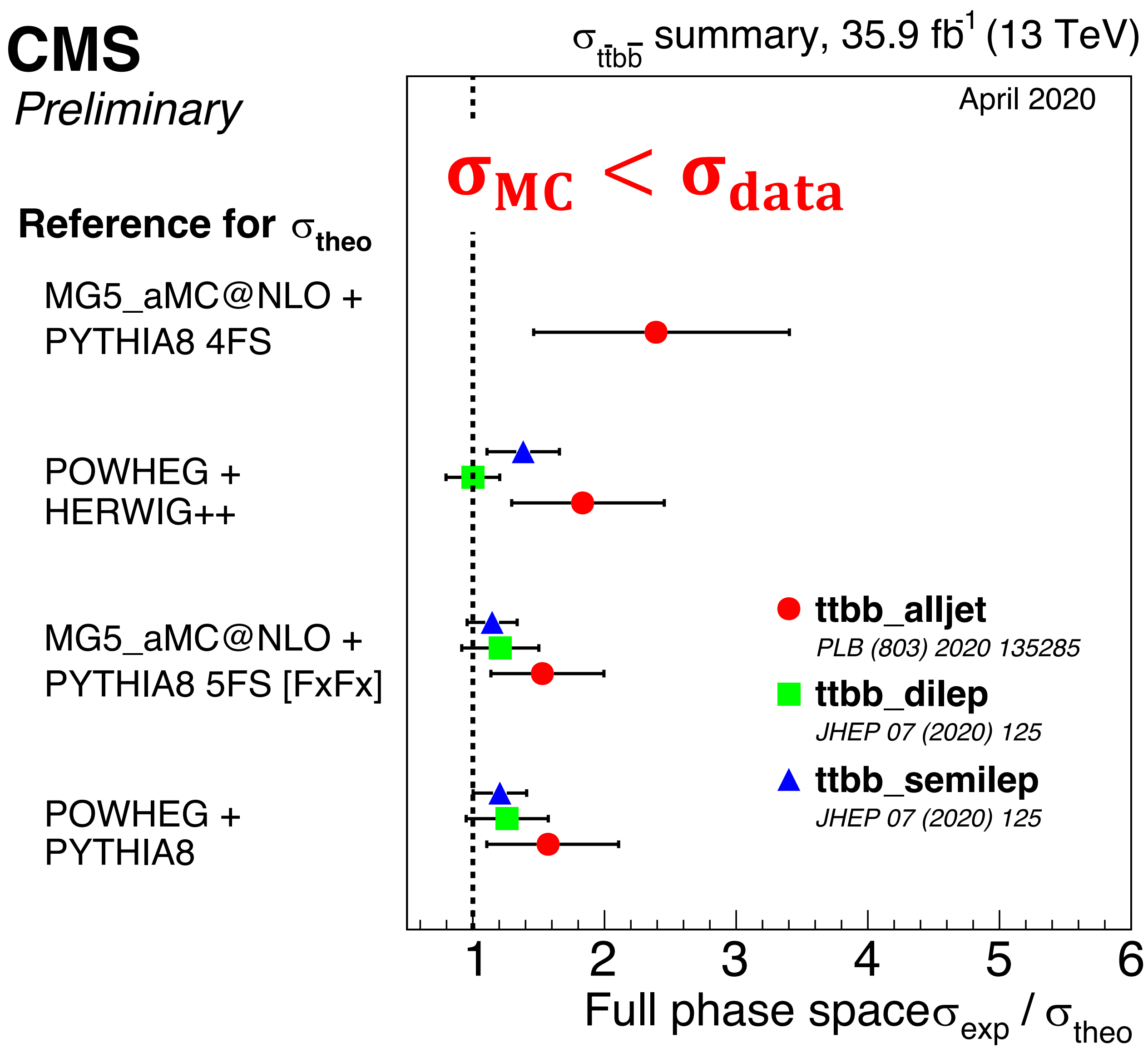
Full PS:

$\sigma(t\bar{t}c\bar{c}) = 8.0 \pm 1.1$ (stat.) ± 1.3 (syst.) pb

$R_c = 2.69 \pm 0.36$ (stat.) ± 0.32 (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



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

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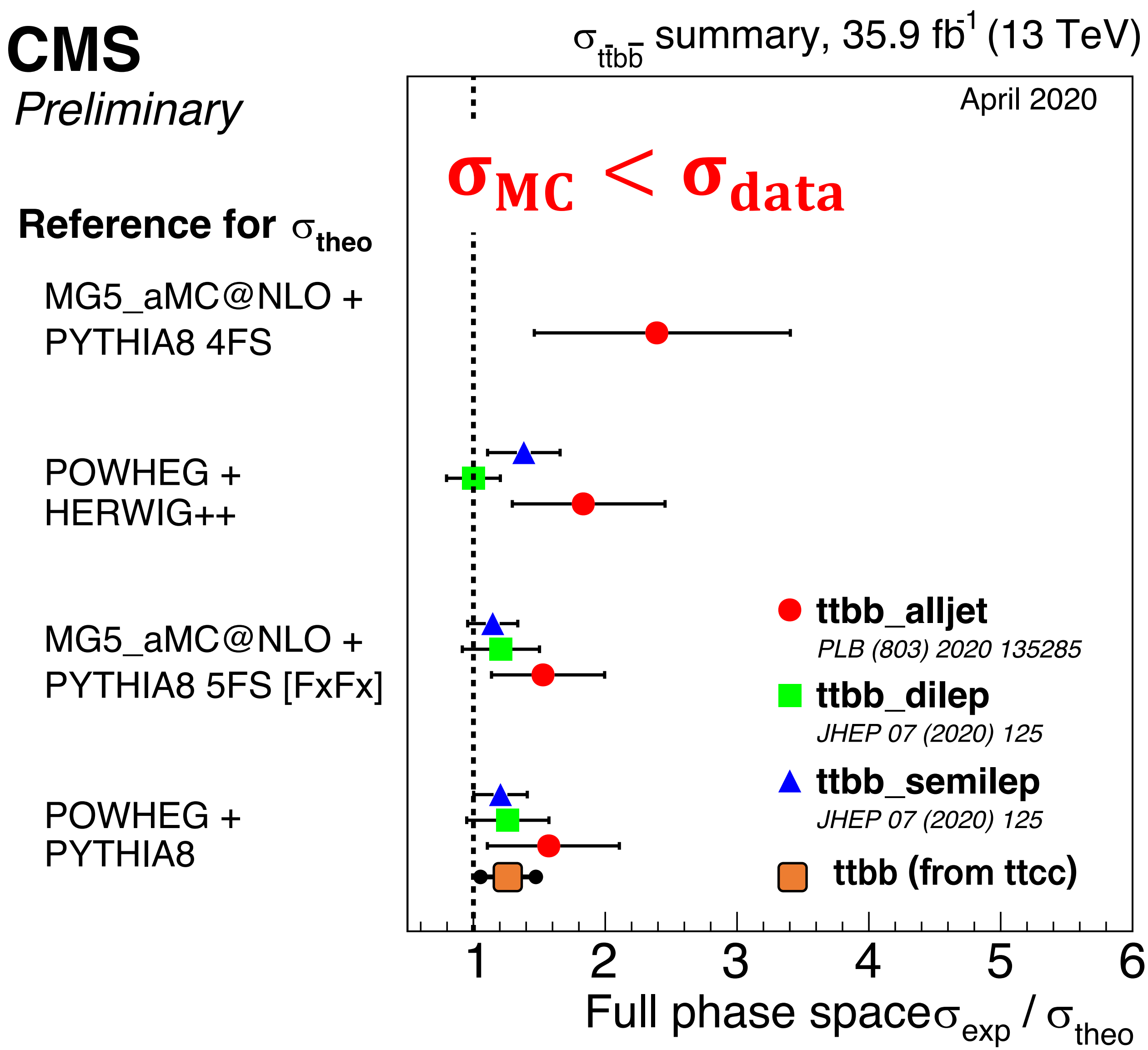
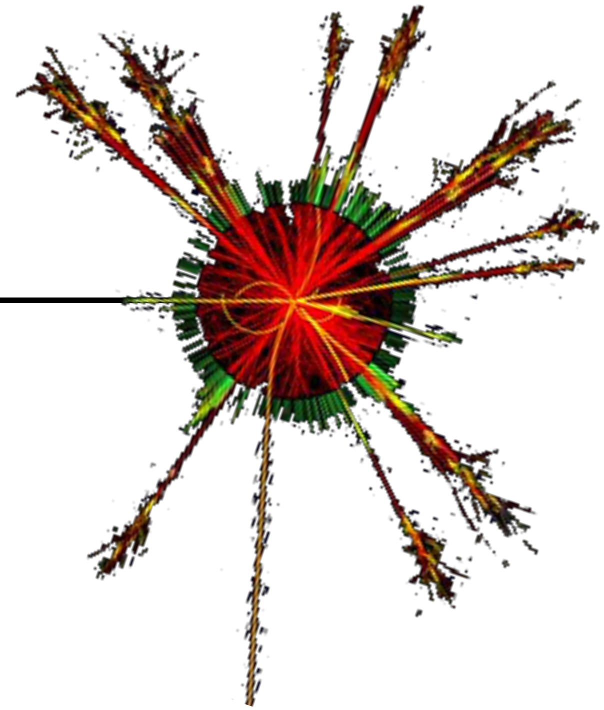


Conclusions



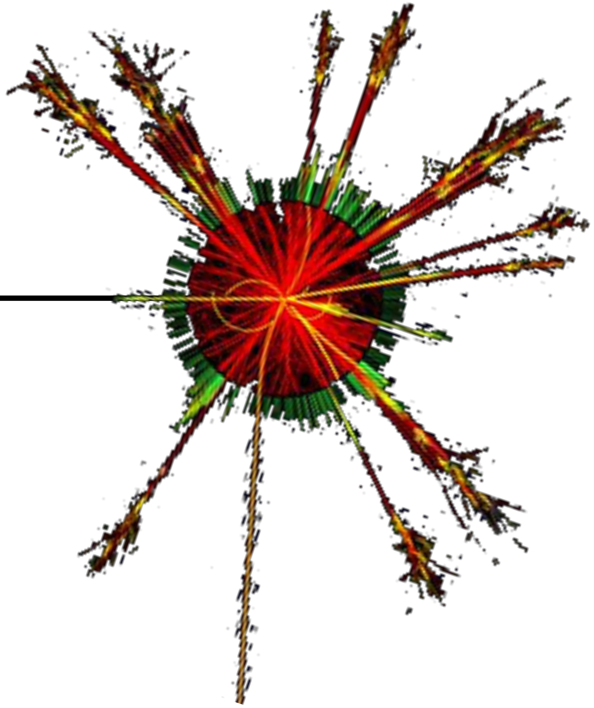
Summary and conclusions

Run-2 was for the
3rd generation

With state-of-the art HF-taggers
we can explore the charm quark!

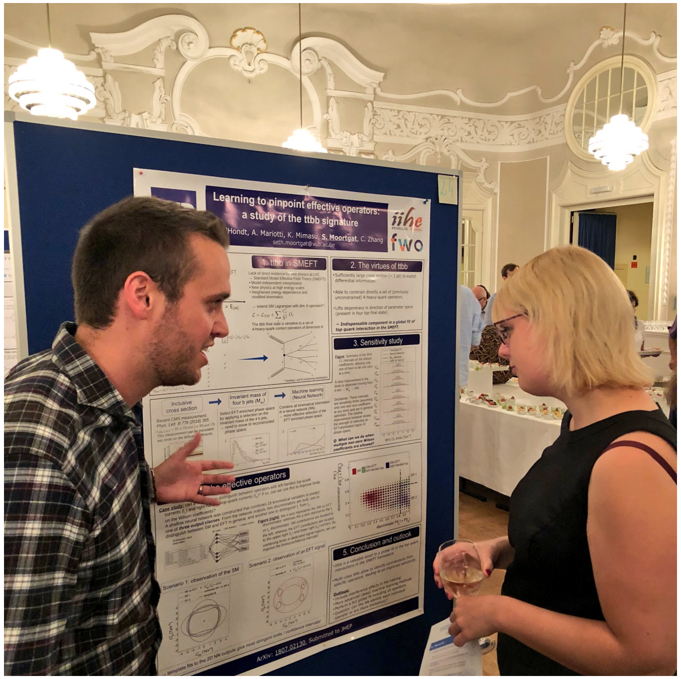
Run-3 will be for
the 2nd generation

Backup



The CMS dilepton $t\bar{t}c\bar{c}$ measurement

Inspiration/Motivation



Throwback: TOP2018 - Bad Neuenahr

Poster session:

$t\bar{t}b\bar{b}$ in the SMEFT using ML

Plenaries:

Theory progress on $t\bar{t}H(b\bar{b})$ backgrounds (S. Pozzorini)

$t\bar{t}b\bar{b}$ @ CMS and ATLAS (A. Khanov)

Take-home messages (with personal bias):

1. Theoretical modelling of $t\bar{t}$+heavy-flavour (HF) jets is very challenging!
2. You can not simply consider $t\bar{t}b\bar{b}$ without considering at the same time $t\bar{t}c\bar{c}$ and $t\bar{t}$ + light-flavour jets ($t\bar{t}$LF).
3. Not only b-tagging, but c-tagging is crucial!

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

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

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

Measurement performed in the dilepton channel

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

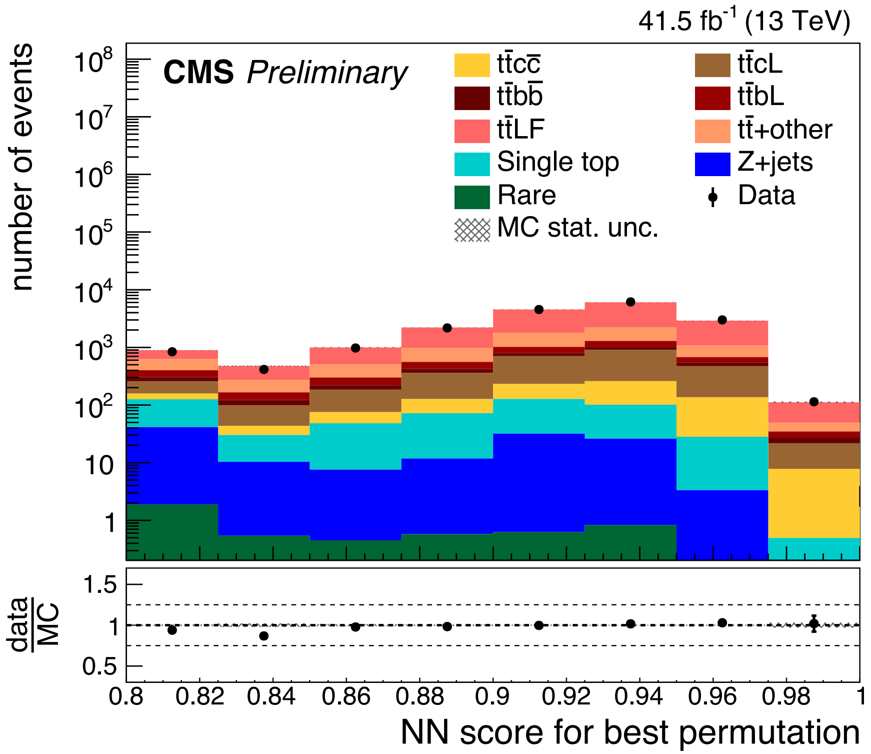
Key ingredients:

- 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)

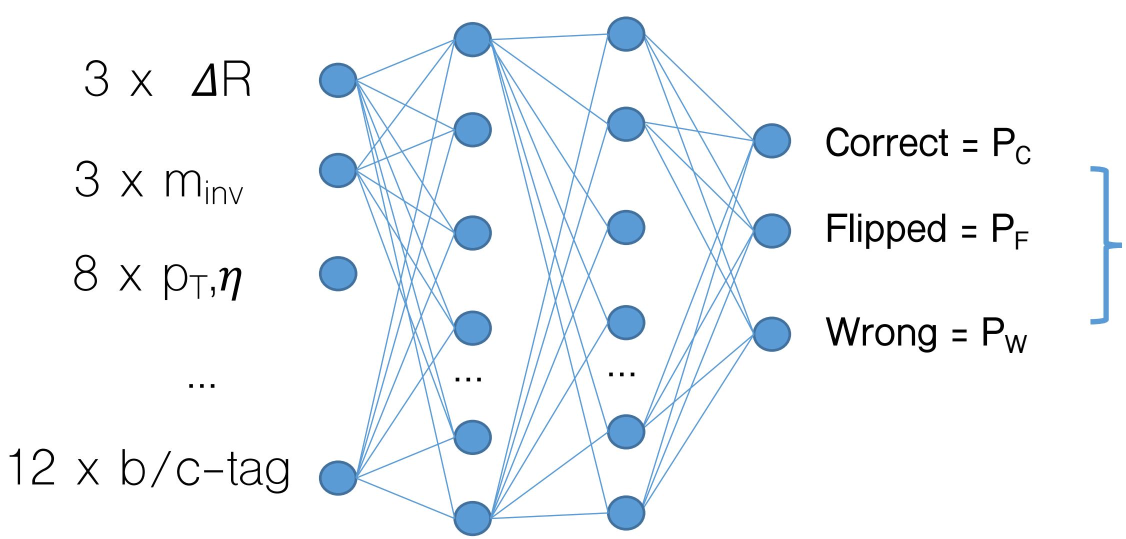
Only ~ 76% of events have two b jets matched to two gen-level b quarks from top quark within $\Delta R<0.3$. Only these are used in the training of the NN.

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

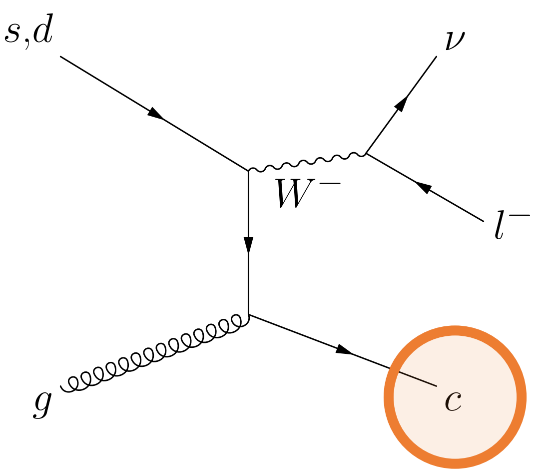


NN score for best permutation

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

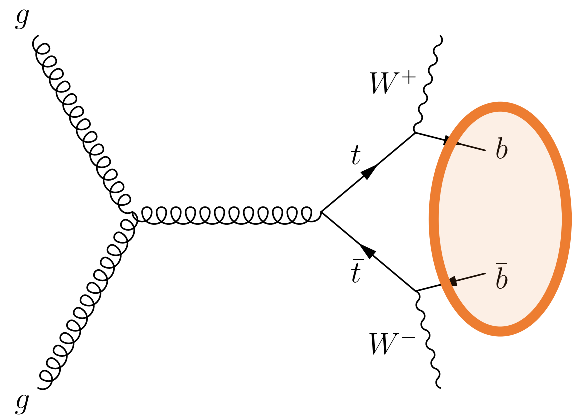
Three control regions for flavor enrichment

W+charm



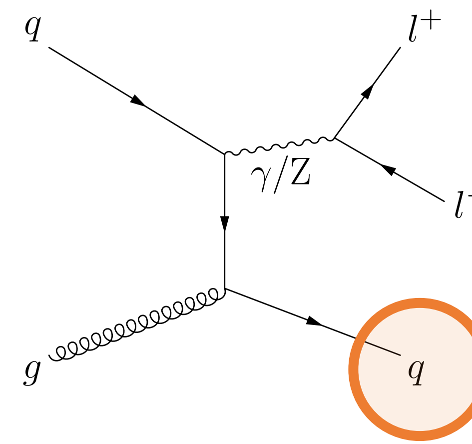
c-enriched (93% pure)
(after OS-SS subtraction)

semi-leptonic $t\bar{t}$



b-enriched (81% pure)

DY + jets



light-enriched (86% pure)

Very good purity in different control regions!

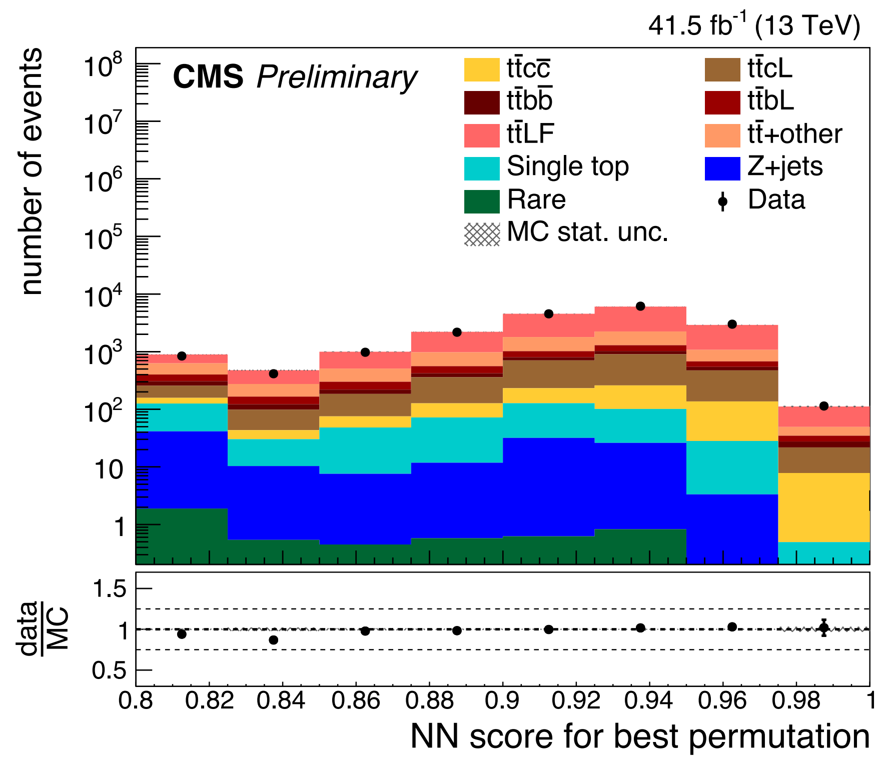
Iterative fitting procedure per (2-dim.) bin, by iterating multiple times over the three control regions → 2-dim SF maps
i.e. SF(CvsL, CvsB, flavour)

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.



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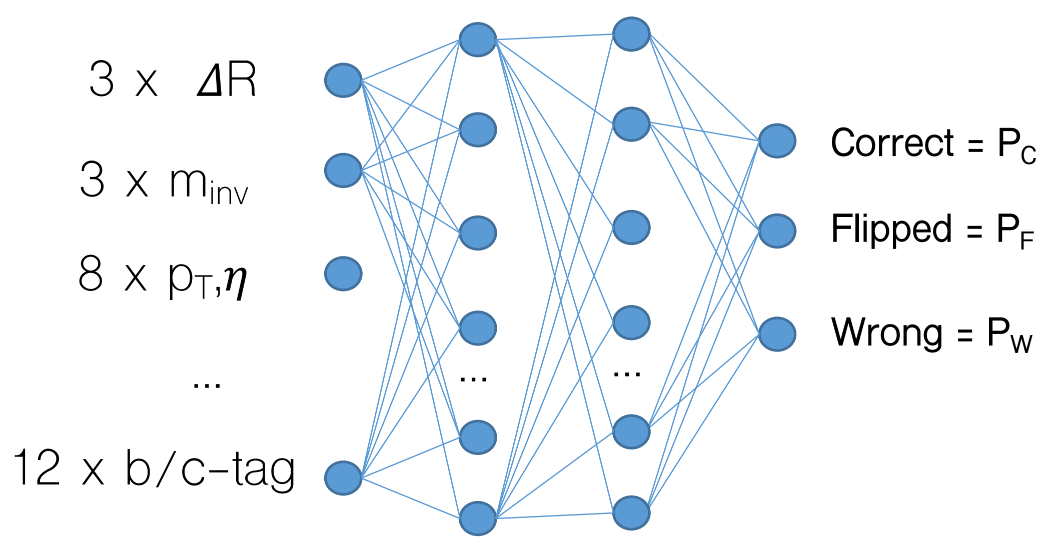

NN score for best permutation

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Charm jet identification using the DeepCSV algorithm

[JINST 13 (2018) P05011]

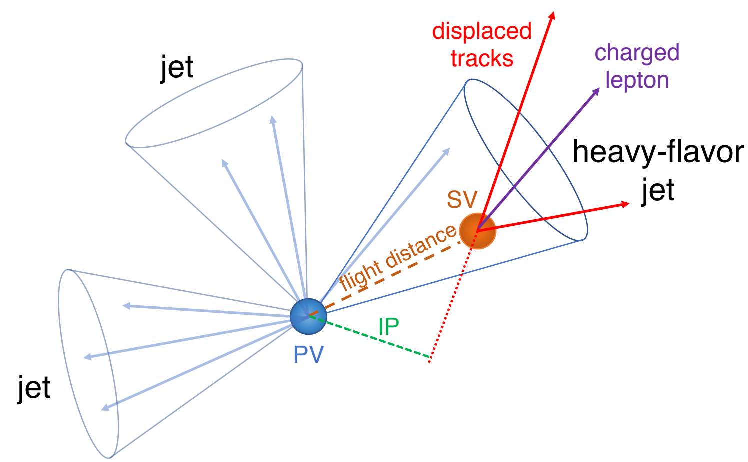
The DeepCSV heavy-flavour tagging algorithm is a multi-class algorithm that predicts probabilities (P) for jets to originate from a b, c or light-flavour (udsg) quark (or gluon).

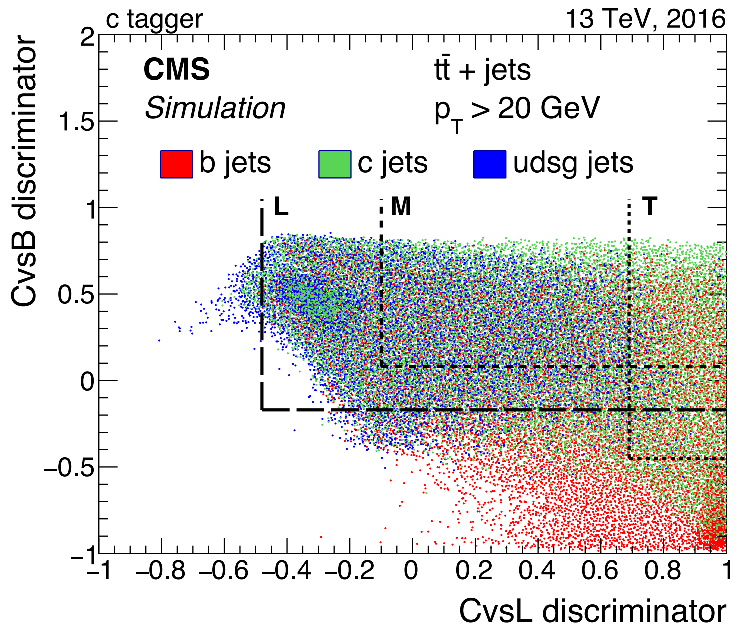
This discrimination is based on properties such as track displacement, secondary vertex mass/flight distance, …

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

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

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

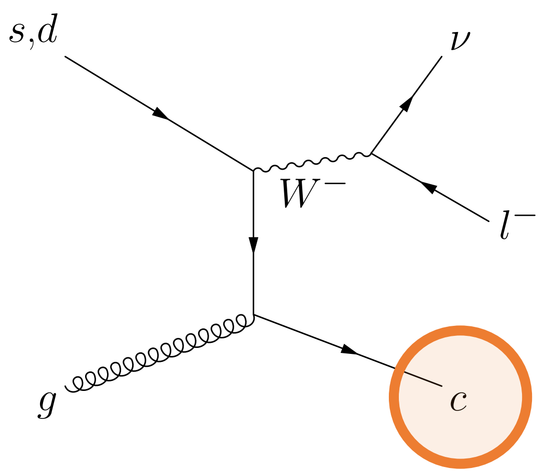




Novel shape calibration of the two-dimensional CvsL and CvsB DeepCSV c-tagger discriminators

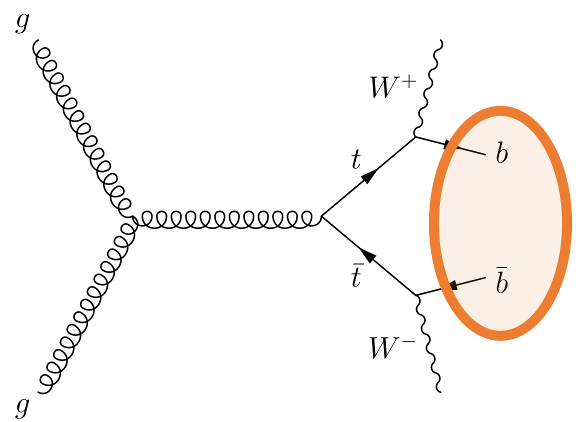
Three control regions for flavor enrichment

W+charm



c-enriched (93% pure)
(after OS-SS subtraction)

semi-leptonic $t\bar{t}$



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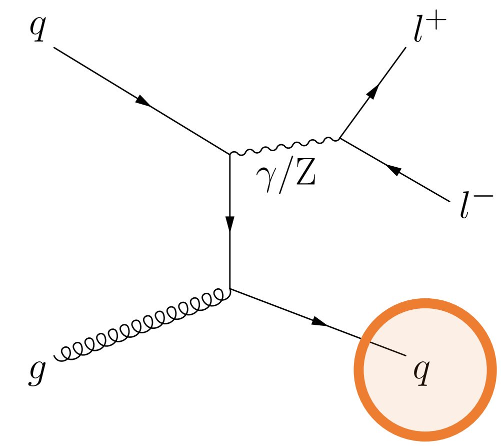

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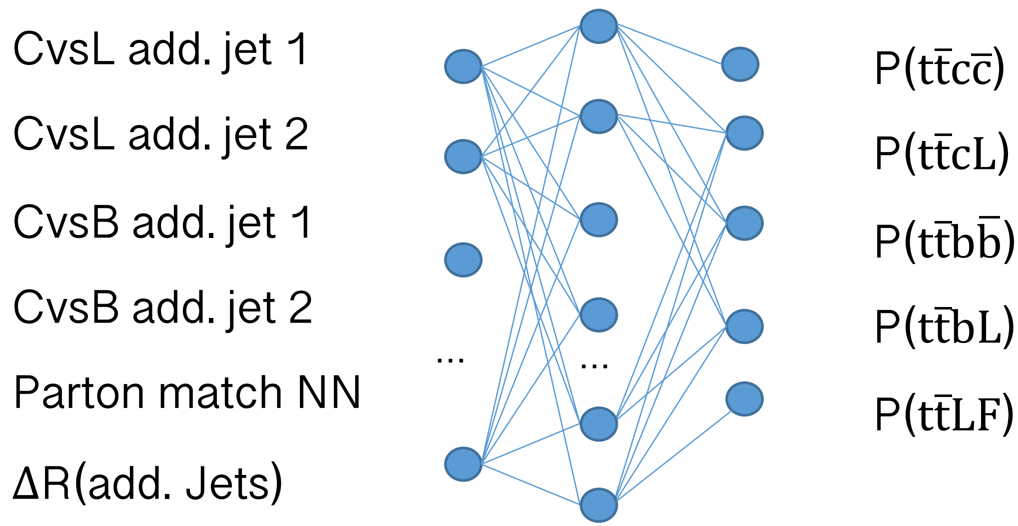
Iterative fitting procedure per (2-dim.) bin, by iterating multiple times over the three control regions → 2-dim SF maps
i.e. SF(CvsL, CvsB, flavour)

Template fit using NN discriminator

Defining the neural network

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



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

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

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

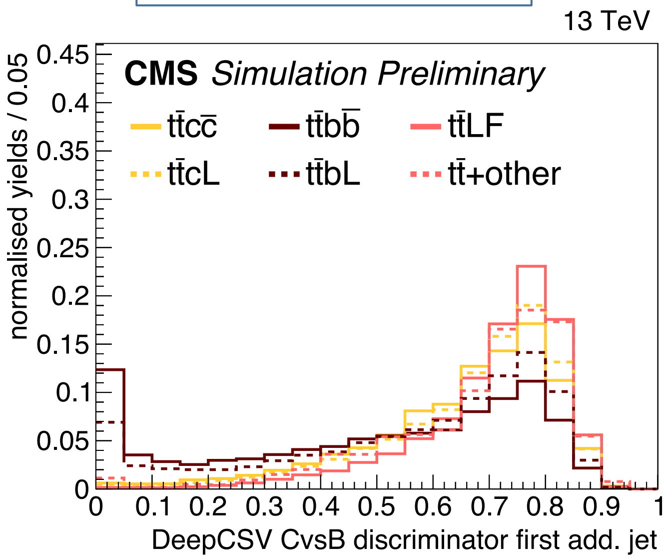
Information on the flavour of the two additional jets

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

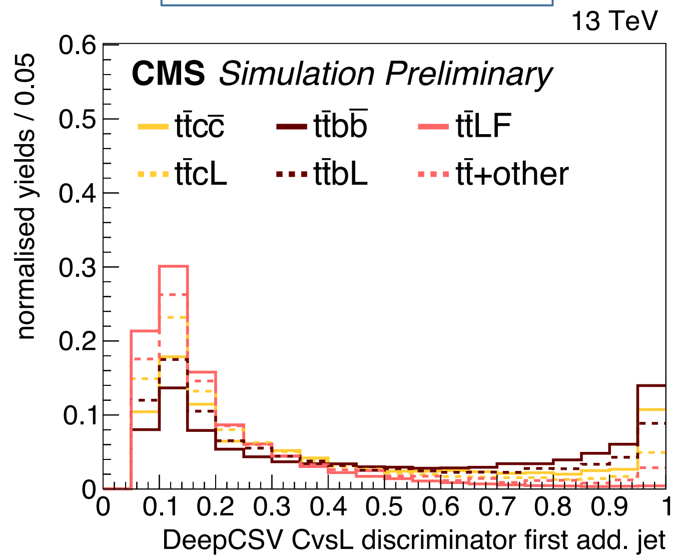
Template fit using NN discriminator

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

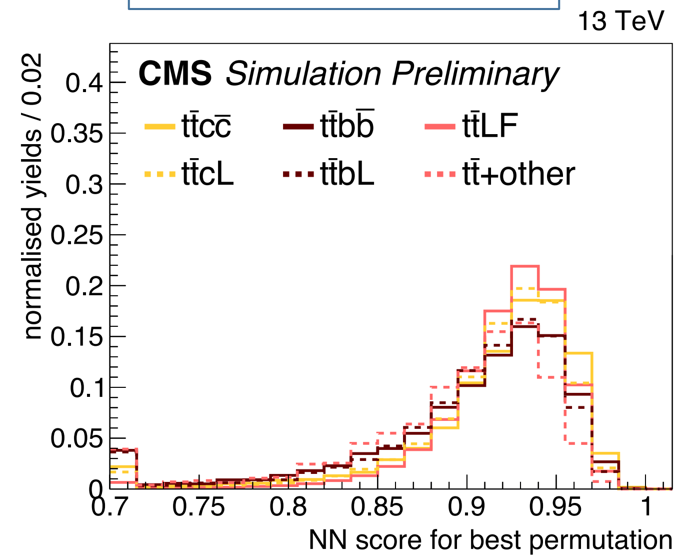
CvsB add. Jet 1



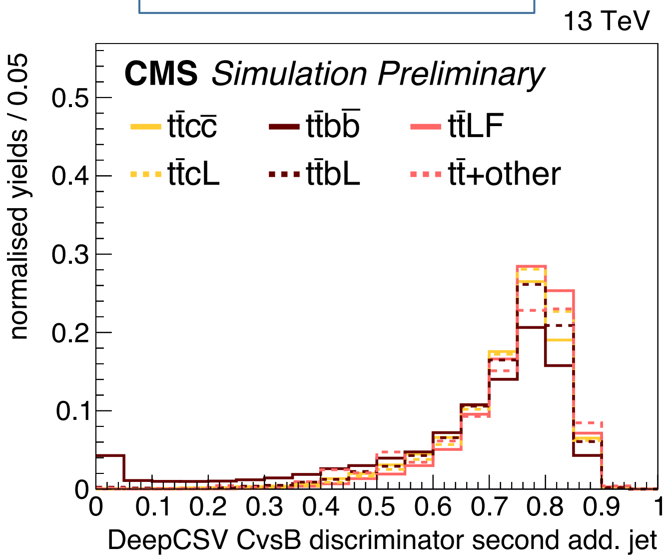
CvsL add. Jet 1



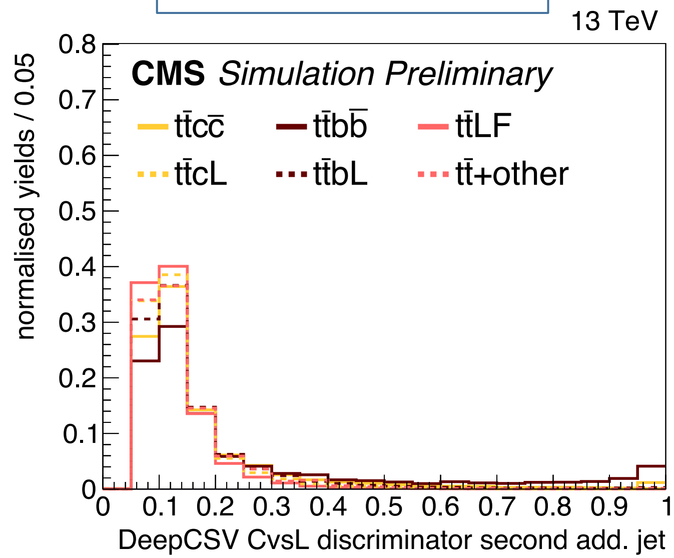
parton match NN



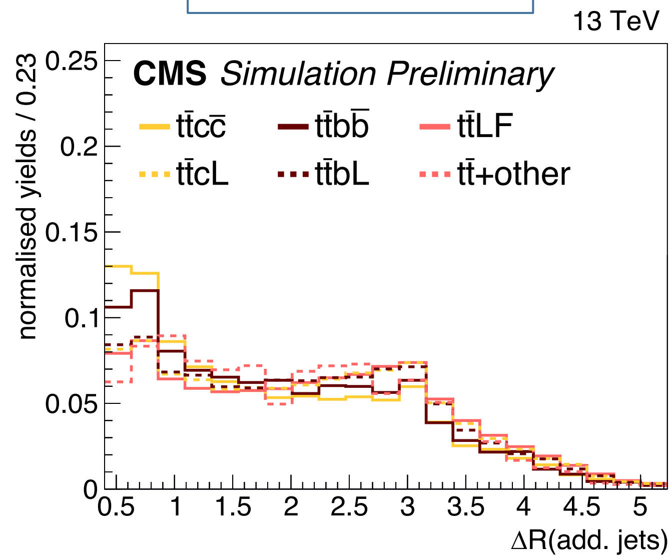
CvsB add. Jet 2



CvsL add. Jet 2

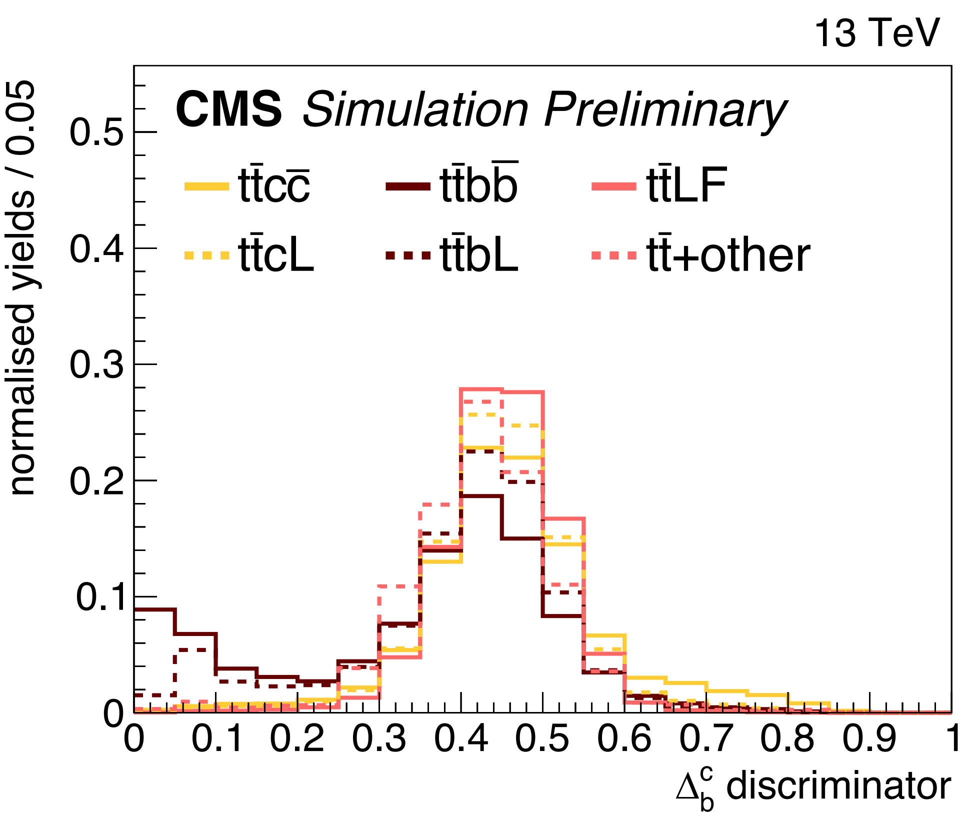


ΔR(add. Jets)

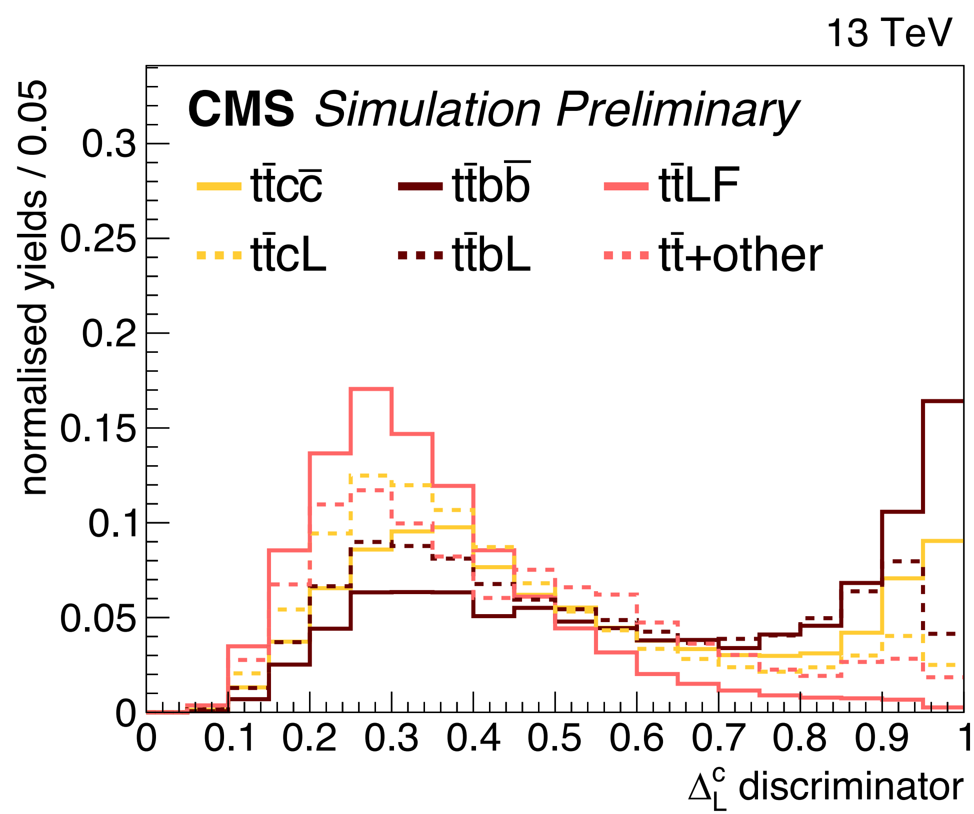


Template fit using NN discriminator

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

Fits to extract inclusive cross sections and their ratios

Full phase space

Fiducial phase space

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)

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 $R_c = \sigma_{t\bar{t}c\bar{c}}/\sigma_{t\bar{t}jj}$

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

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

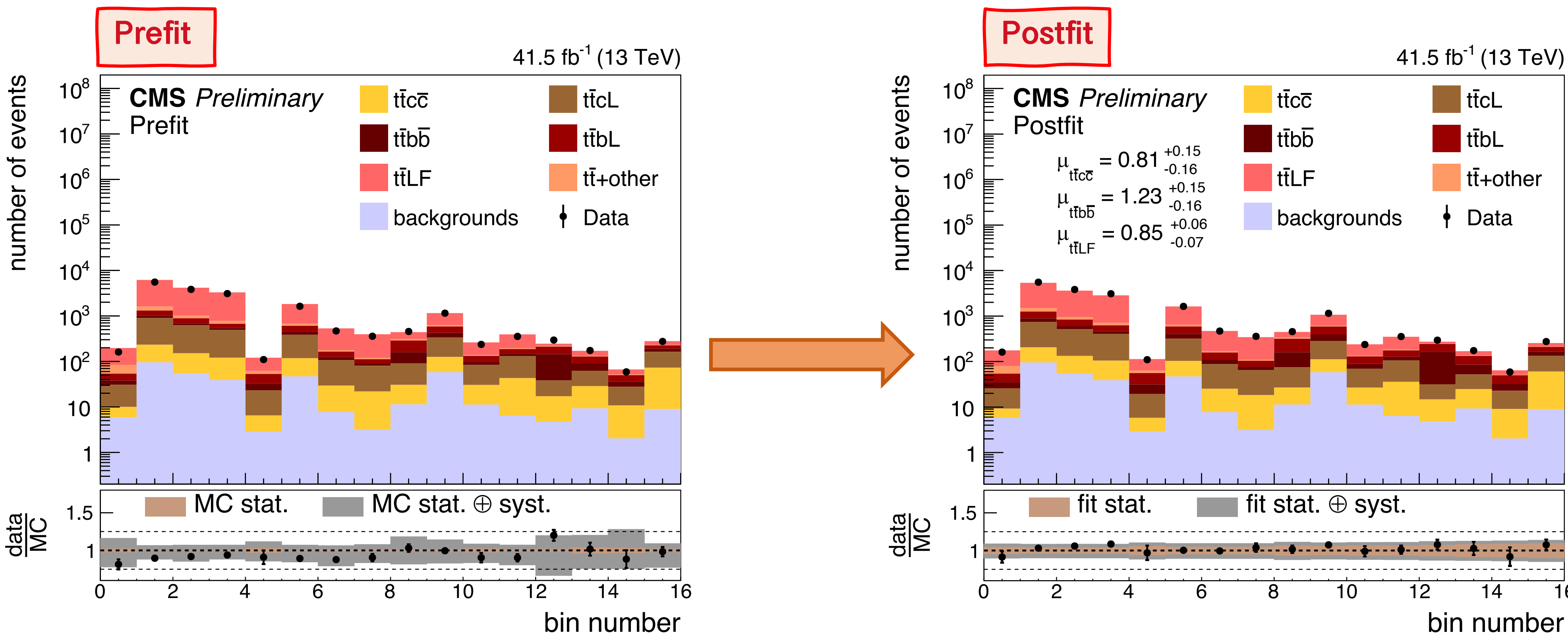
Dominant theoretical uncertainties from QCD scales in the ME and ME-PS matching

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:

$$\Delta_L^c \otimes \Delta_b^c : [0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0]$$



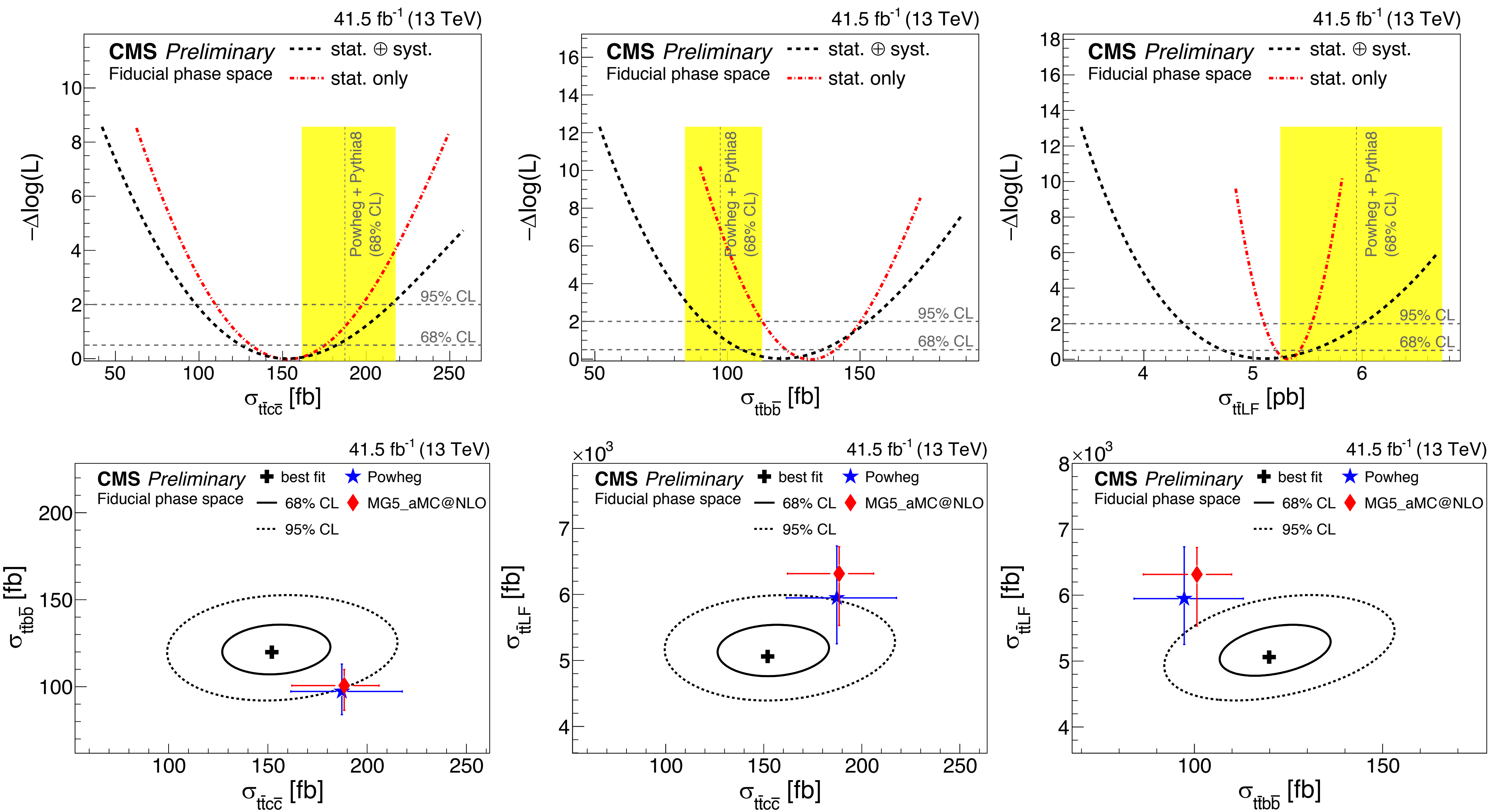
μ represents the scaling factor of the simulated templates

(cross section above or below theory prediction)

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

Results

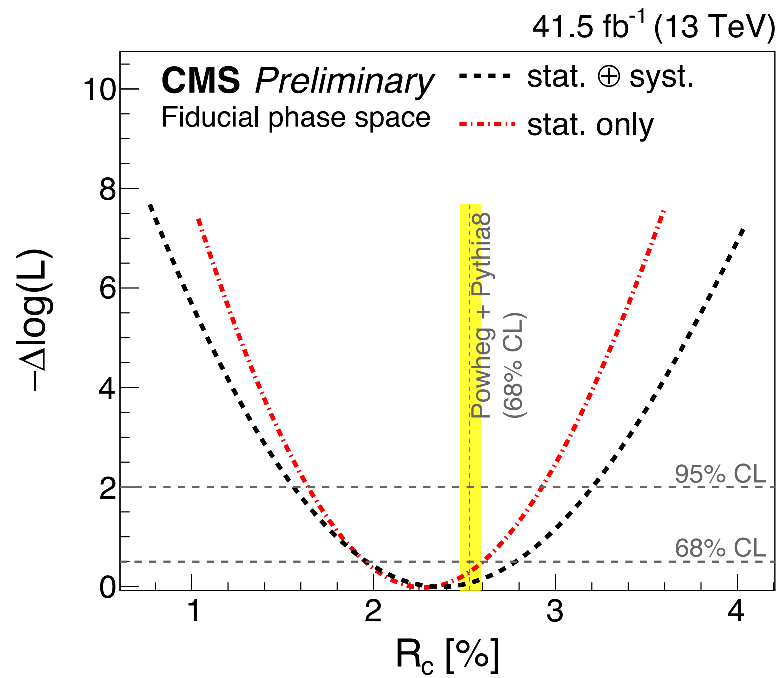
Inclusive cross sections in the fiducial phase space

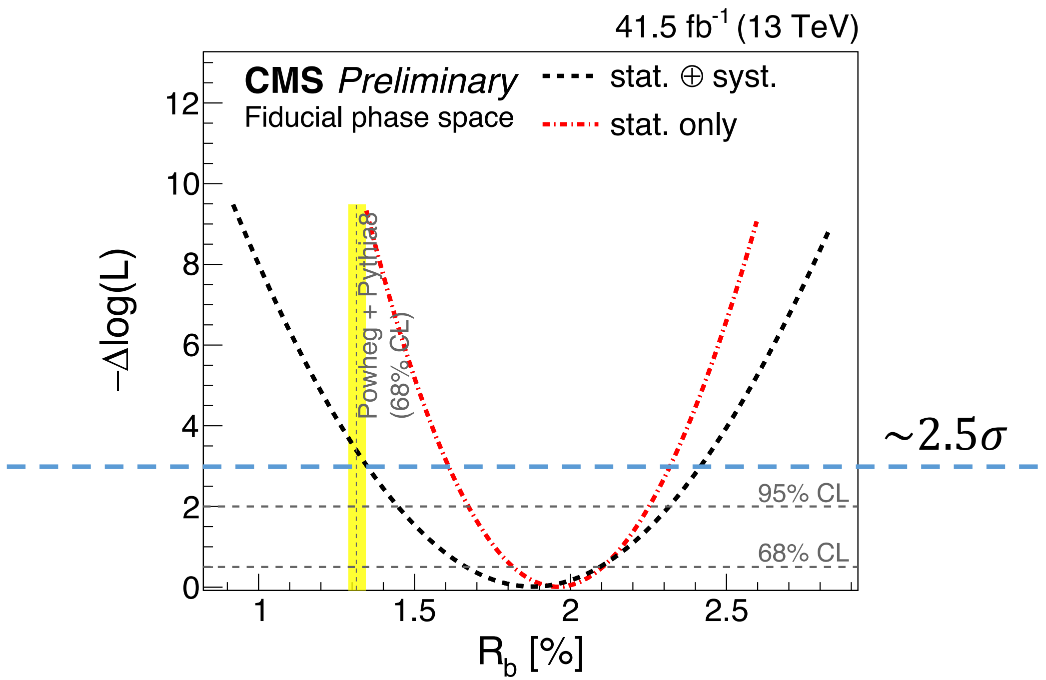


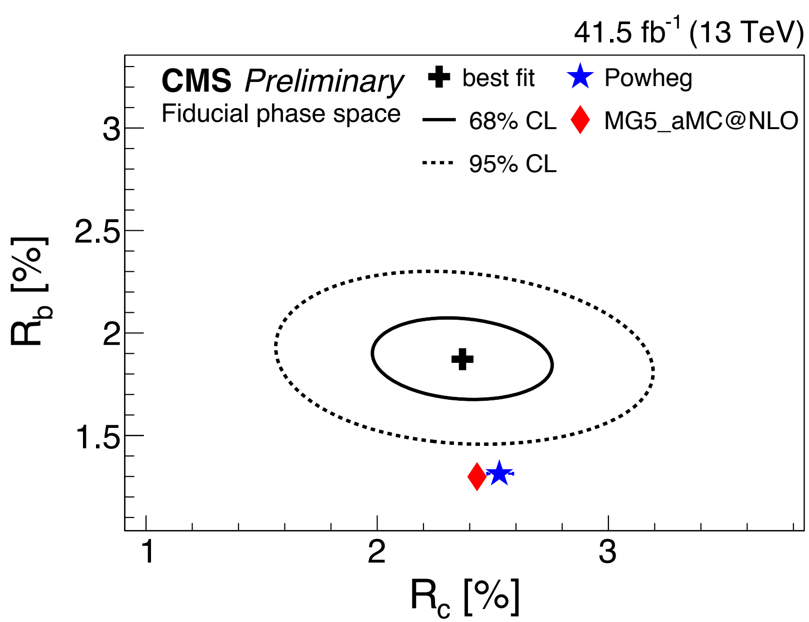
Some tension observed, but overall agreement within 1-2 standard deviations

→measured $t\bar{t}b\bar{b}$ ($t\bar{t}c\bar{c}$ and $t\bar{t}$LF) cross section higher (lower) than predicted.

Ratios R_c and R_b in the fiducial phase space







R_c is in very good agreement with theory prediction.

Largest tension observed for R_b

$-\Delta \log L \sim 3 \rightarrow \sim 2.5\sigma$

Results

Numerical values + extrapolation to the full phase space

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

Results

Comparison to other ttbb analyses

PAS-TOP-20-003

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

$+2.5\sigma$

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	$0.017 \pm 0.001 \pm 0.001$	$2.36 \pm 0.02 \pm 0.20$	$0.040 \pm 0.002 \pm 0.005$
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	$0.018 \pm 0.001 \pm 0.002$	$159 \pm 1 \pm 15$	$2.9 \pm 0.1 \pm 0.5$
Lepton+jets channel (VPS)			
POWHEG + PYTHIA8	0.017 ± 0.002	30.5 ± 3.0	0.52 ± 0.06
Measurement	$0.020 \pm 0.001 \pm 0.001$	$31.0 \pm 0.2 \pm 2.9$	$0.62 \pm 0.03 \pm 0.07$
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	$0.016 \pm 0.001 \pm 0.001$	$292 \pm 1 \pm 29$	$4.7 \pm 0.2 \pm 0.6$

$+1.8\sigma$

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	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

$+1.5\sigma$