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on behalf of the CMS Collaboration

MEASUREMENTS OF TOP QUARK PROPERTIES AT CMS RUN-2

THE TOP QUARK

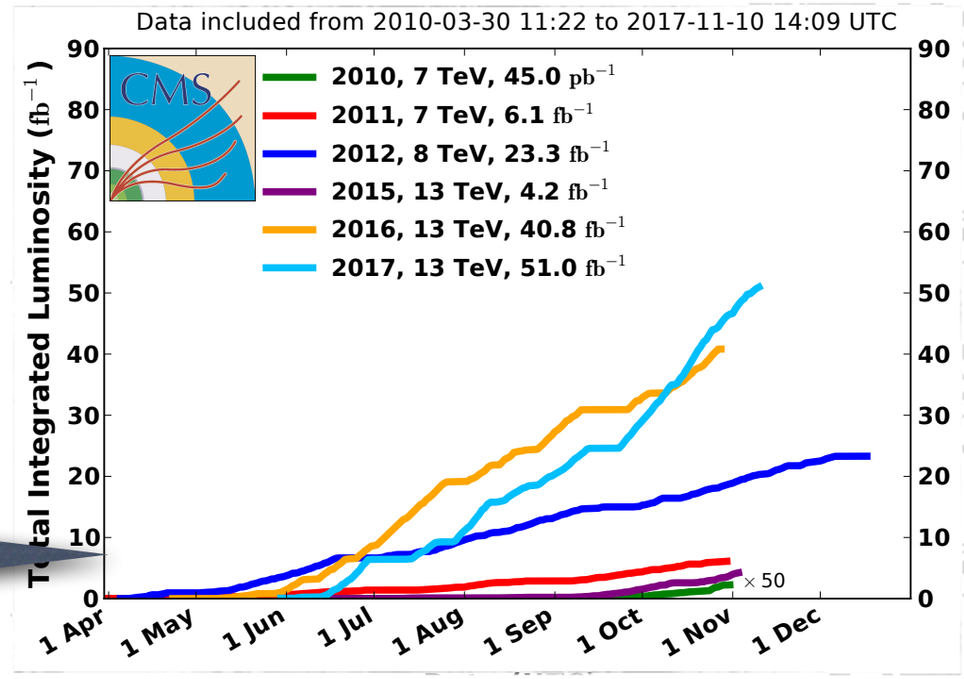
- **Top quark is heavy**
  - The **HEAVIEST** known point-like particle; ~36 times heavier than the bottom quark. *Any particular reason?*
  - Mass from Yukawa coupling in SM, **strongly coupled with the Higgs boson**. Play a significant role in the Higgs physics.
- **Top quark is short lived**
  - Lifetime is calculated to be very short, $\tau \sim 5 \times 10^{-25}$ sec.
  - It **decays before hadronization** — the only "free" quark — no bound states exist (ie. no mesons nor baryons with top).

Decay to the final products without any dilution:
allow experimentalists to access to the quark properties directly!

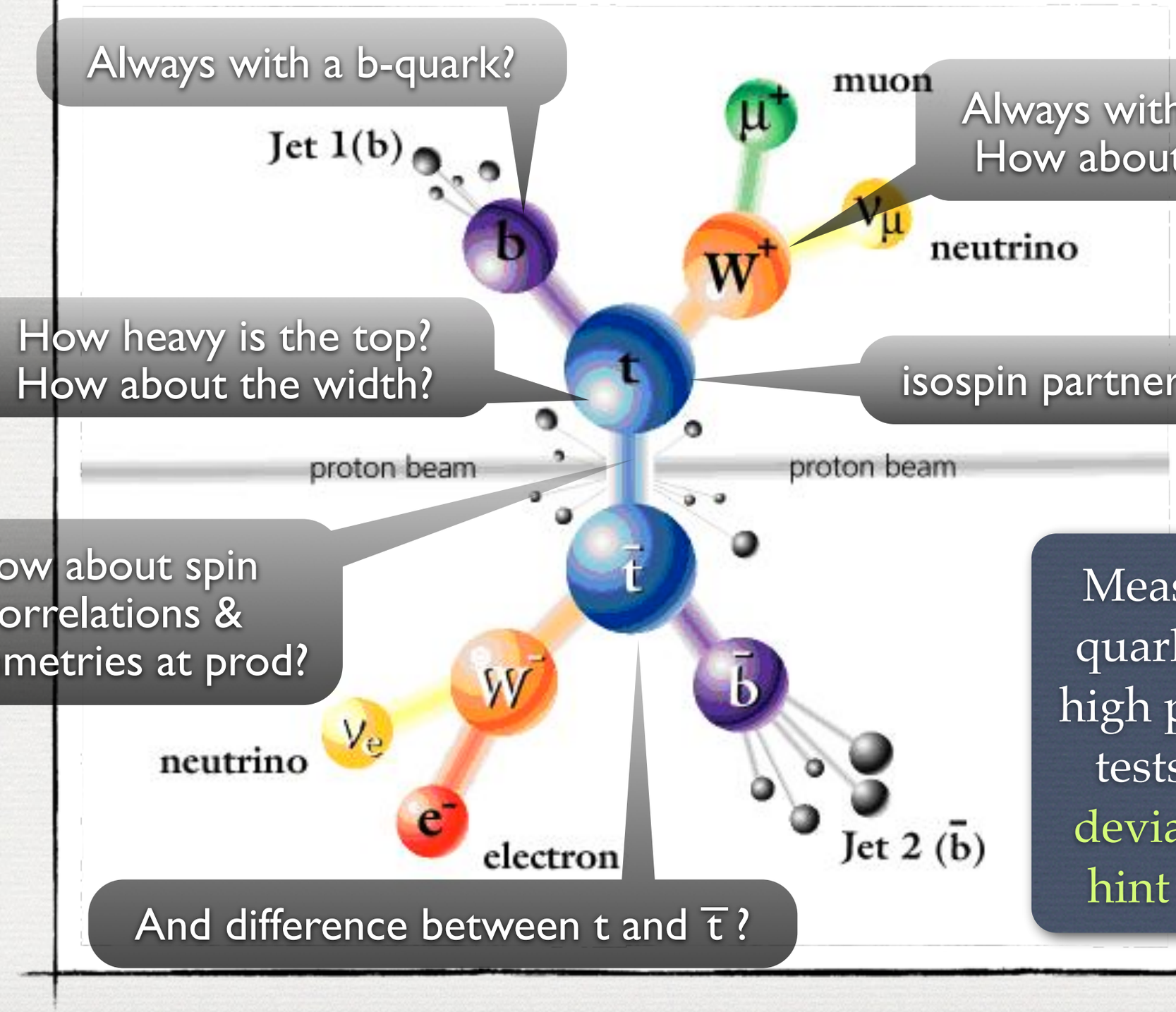
TOP QUARKS AT LHC

- LHC is an ideal place to look top quark properties: large top production cross section at the high center of mass energy — **A TOP QUARK FACTORY**.
- The LHC has delivered a sizable amount of proton collisions to the experiments already.
- Up to the end of 2017 we already have:
  - 5 fb^{-1} @ 7 TeV, 20 fb^{-1} @ 8 TeV
  - In particular **90 fb^{-1} @ 13 TeV**
  - Still one more year before the end of Run-2!

10× to the statistics in Run-1 – **>60 M** top quark pairs have been produced in Run-2



TOP PROPERTIES



Always with a b-quark?

Always with a W-boson?
How about its helicity?

How heavy is the top?
How about the width?

isospin partner of b-quark?

How about spin correlations & asymmetries at prod?

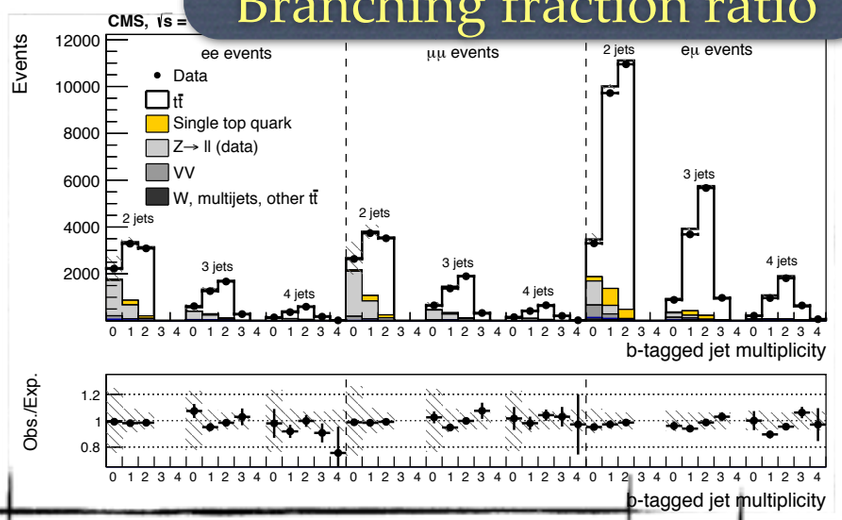
And difference between t and $\bar{t}$?

Measurements of top quark properties with high precision are good tests of the SM. Any deviations would be a hint of New Physics!

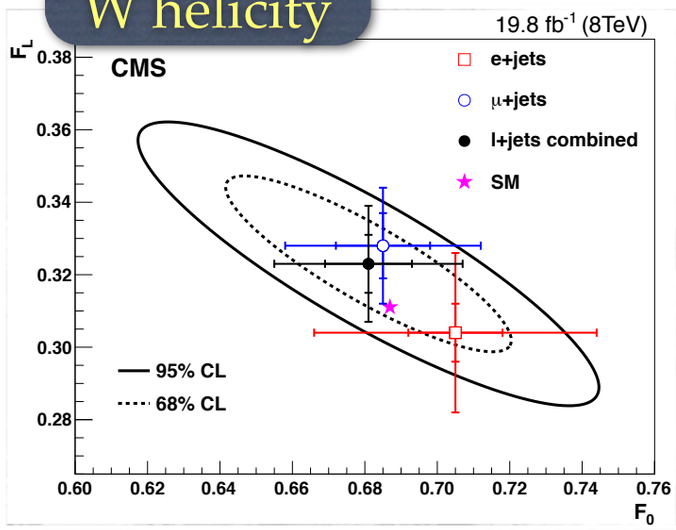
LHC RUN-1 LEGACY

- Many top property measurements have been performed with Run-1 data already. More data at Run-2 would significantly improve the statistics power!

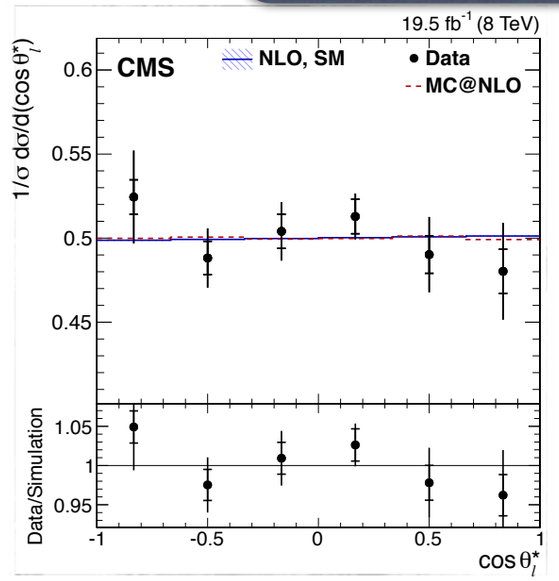
Branching fraction ratio

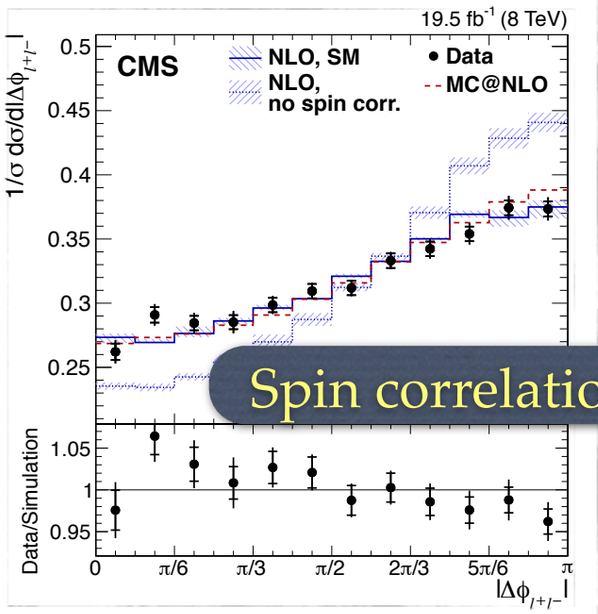


W helicity



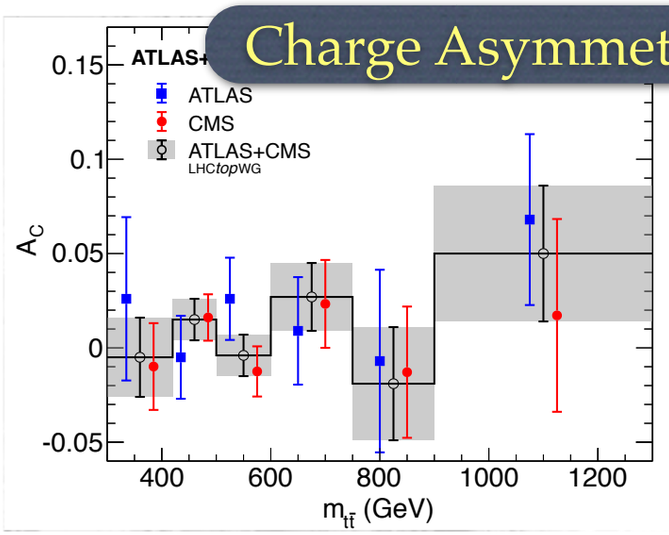
Polarization

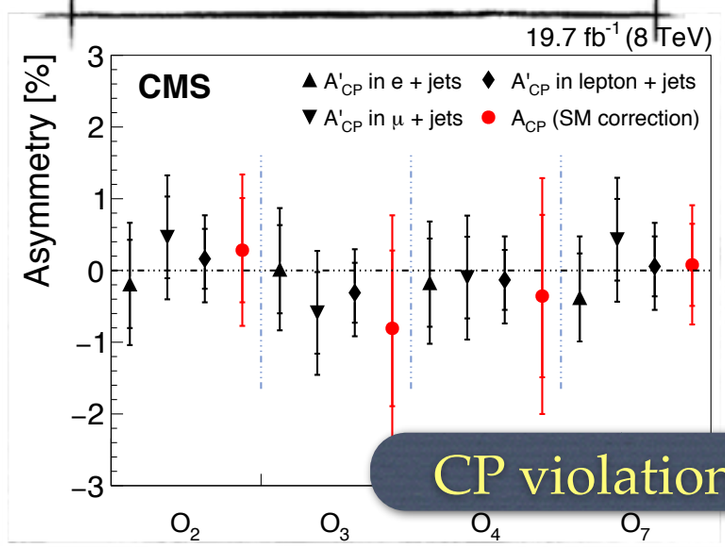




Spin correlation

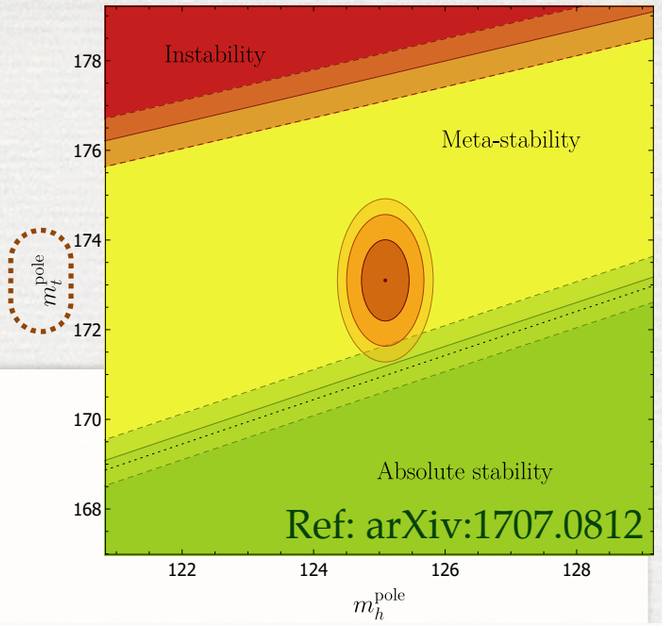
Charge Asymmetry



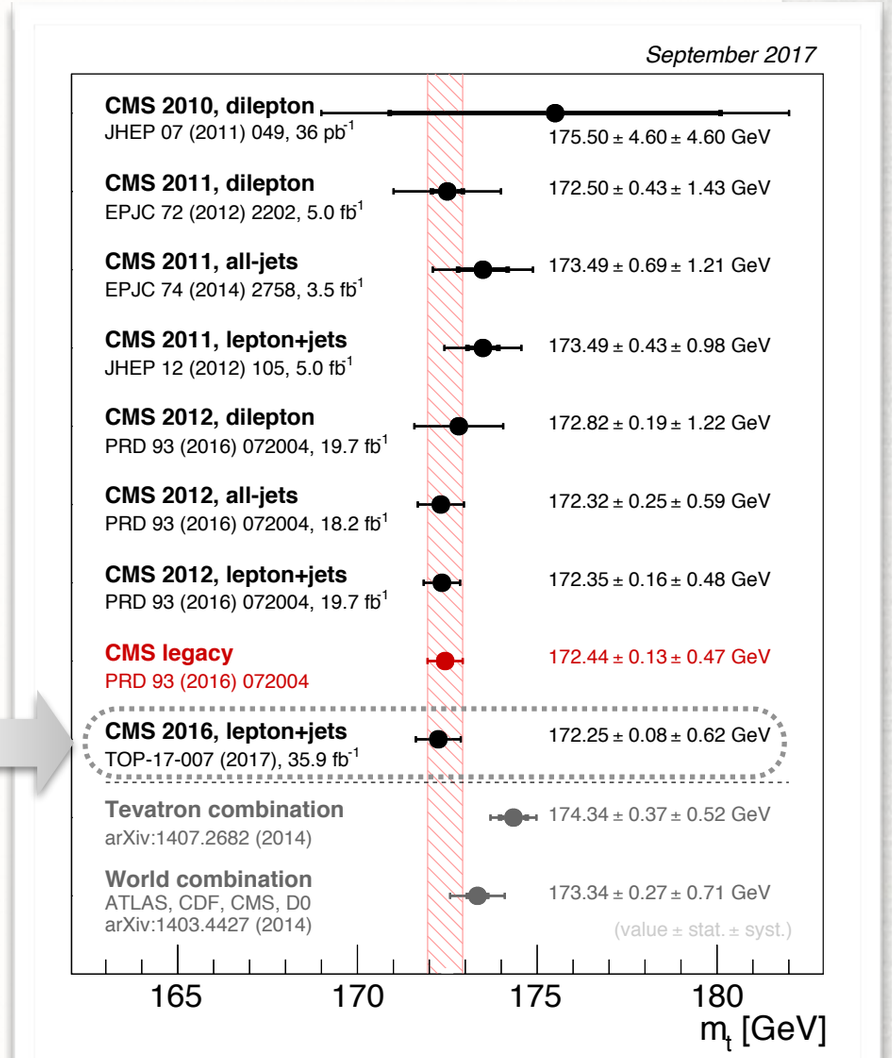


CP violation

MEASURING TOP QUARK MASS



- The top quark mass is an essential parameter of the SM. It plays an important role on the stability of the electroweak vacuum of the universe.
- Excellent measurements with LHC Run-1 data, *systematics dominant analysis*.
- Understanding of the theoretical interpretation of the measurements is also a key issue.
- This work: direct measurement of top mass with 13 TeV data based on the classical **Ideogram method** with kinematic fit of the decay products, and go **differential**!



TOP RECONSTRUCTION & MASS FITS

- The top mass is determined simultaneously with the jet energy scale factor (JSF) in a joint likelihood fit.
- Observables: m_t^{fit} in the kinematic fit and the reconstructed W boson mass m_W^{reco}, as an in-situ estimator for JSF.
- Updated treatment of model uncertainties.

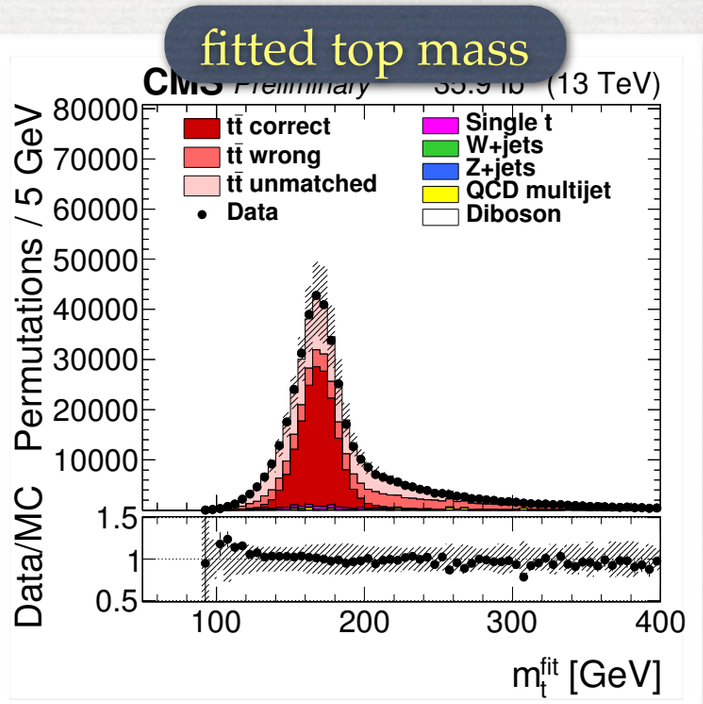
From a "hybrid" analysis with prior on JSF from jet energy correction measurements:

Mt = 172.25 ± 0.08 (stat+JSF) ± 0.62 (syst) GeV

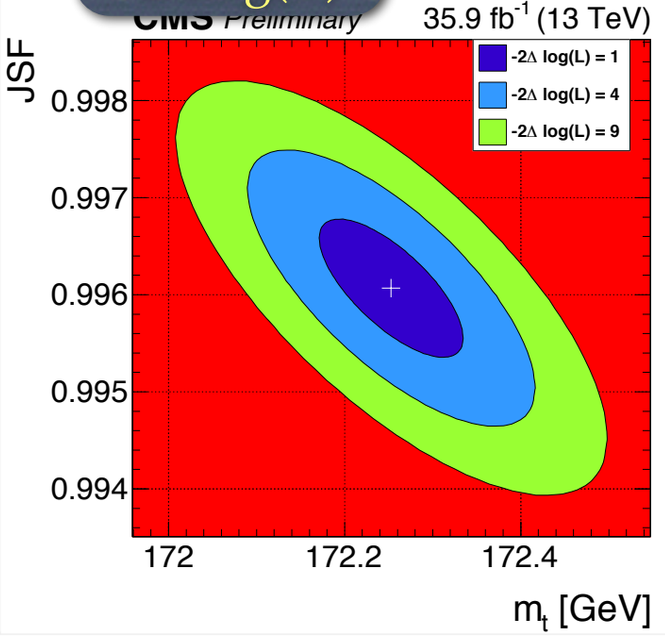
JSF = 0.996 ± 0.001 ± 0.008

Ref. CMS-TOP-17-007

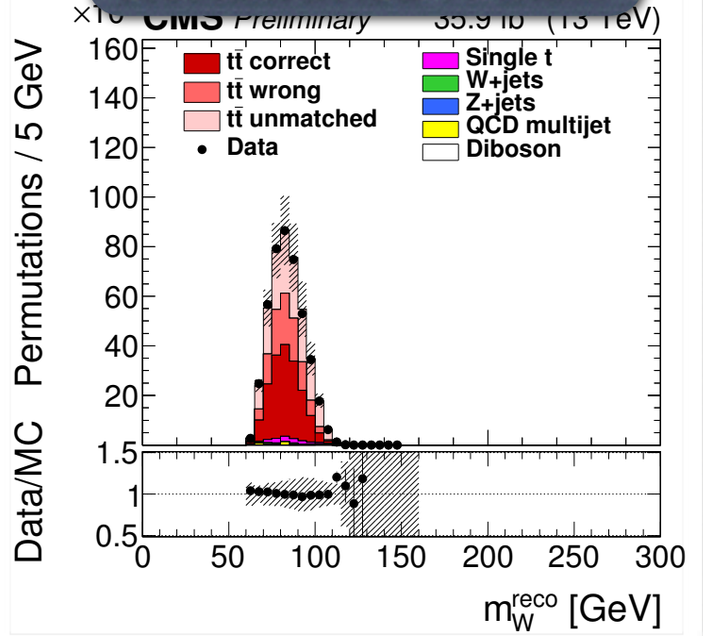
fitted top mass



−2Δlog(ℒ)



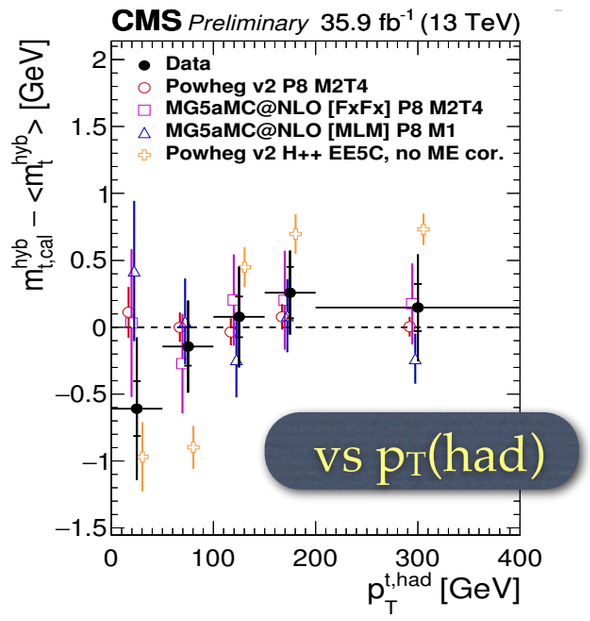
reconstructed W mass



…AND GO DIFFERENTIAL

- Comparison of different models is the main source of systematics!
- Differential measurements as functions of the kinematic properties of the $t\bar{t}$ system are a good validation of models and probing potential effects from color reconnection, ISR/FSR, and the kinematics of the jets coming from the top decays.
- **No indications of a kinematical bias in the measurements.**

Ref. CMS-TOP-17-007



BOUNDING TOP QUARK WIDTH

- Another fundamental property of the top quark! But less accurately determined comparing to the mass value itself.
- SM NLO prediction is **1.35 GeV**.
- Ways to determine the top quark width:
  - **Indirect method** – *by combining branching fraction measurement and single top t-channel cross section*:

$$\mathrm{D0} : \Gamma_t = 2.00^{+0.47}_{-0.43}\ \mathrm{GeV} \qquad \mathrm{CMS} : \Gamma_t = 1.36 \pm 0.02^{+0.14}_{-0.11}\ \mathrm{GeV}$$

  - **Direct method** – *by reconstructing top mass line shape and comparing to MC simulated predictions*:

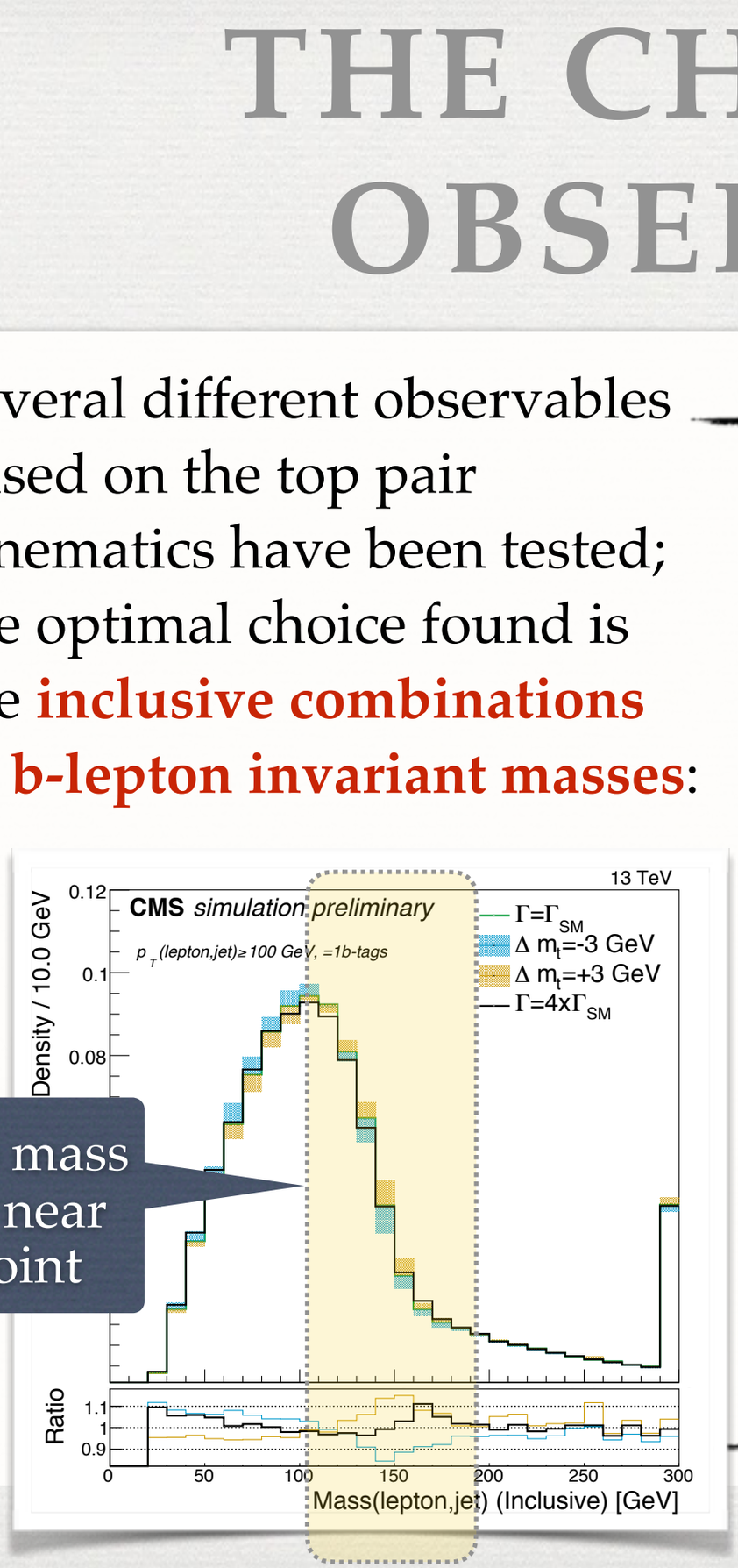
$$\mathrm{CDF} : \Gamma_t < 6.38\ \mathrm{GeV}$$

- This work: a direct measurement of the top quark width from observables which partially reconstruct the top quark kinematics, from **high purity dilepton + 2 jets (at least 1 b-tagged) events**.

THE CHOICE OF OBSERVABLE

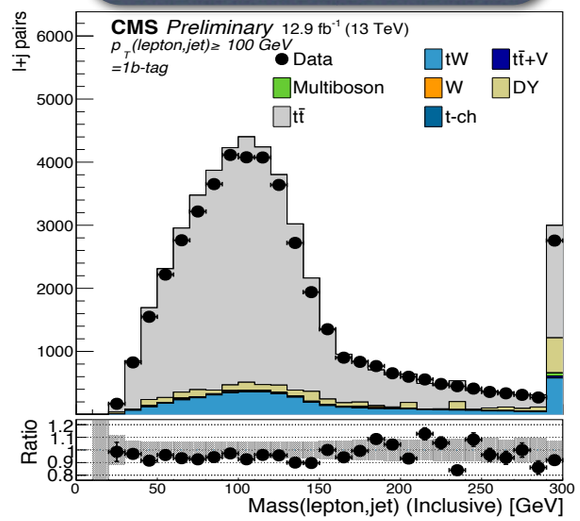
Ref. CMS-TOP-16-019

- Several different observables based on the top pair kinematics have been tested; the optimal choice found is the **inclusive combinations of b-lepton invariant masses**:

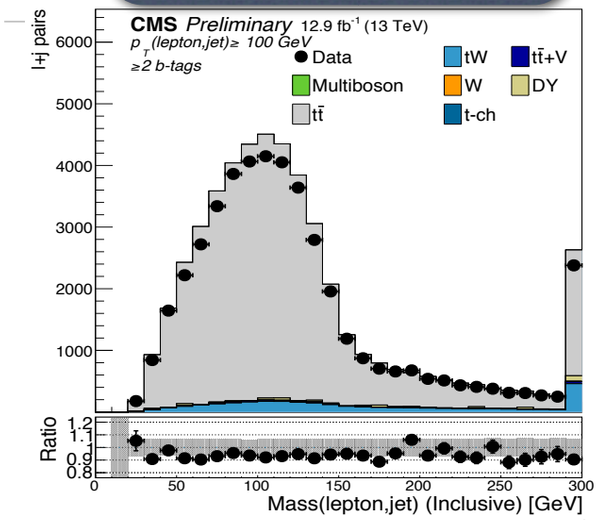


sensitive to mass variations near the endpoint

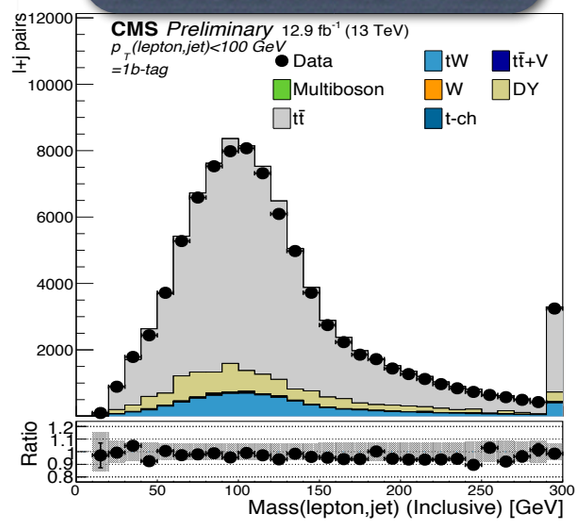
boosted + 1b



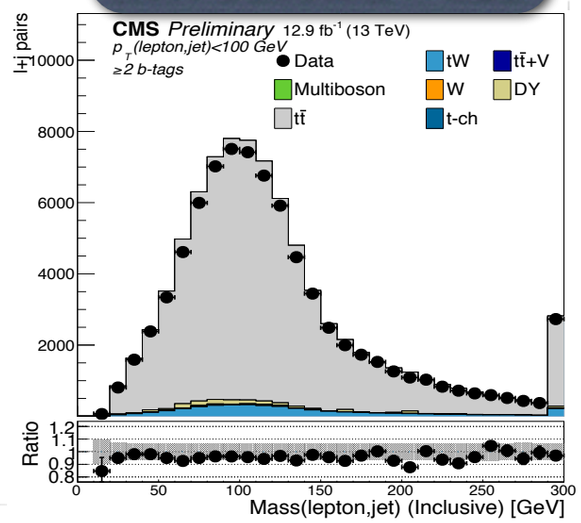
boosted + ≥2b



non-boosted + 1b



non-boosted + ≥2b



Up to 4 combinations of M(lb) per event

RESULTING BOUNDARIES

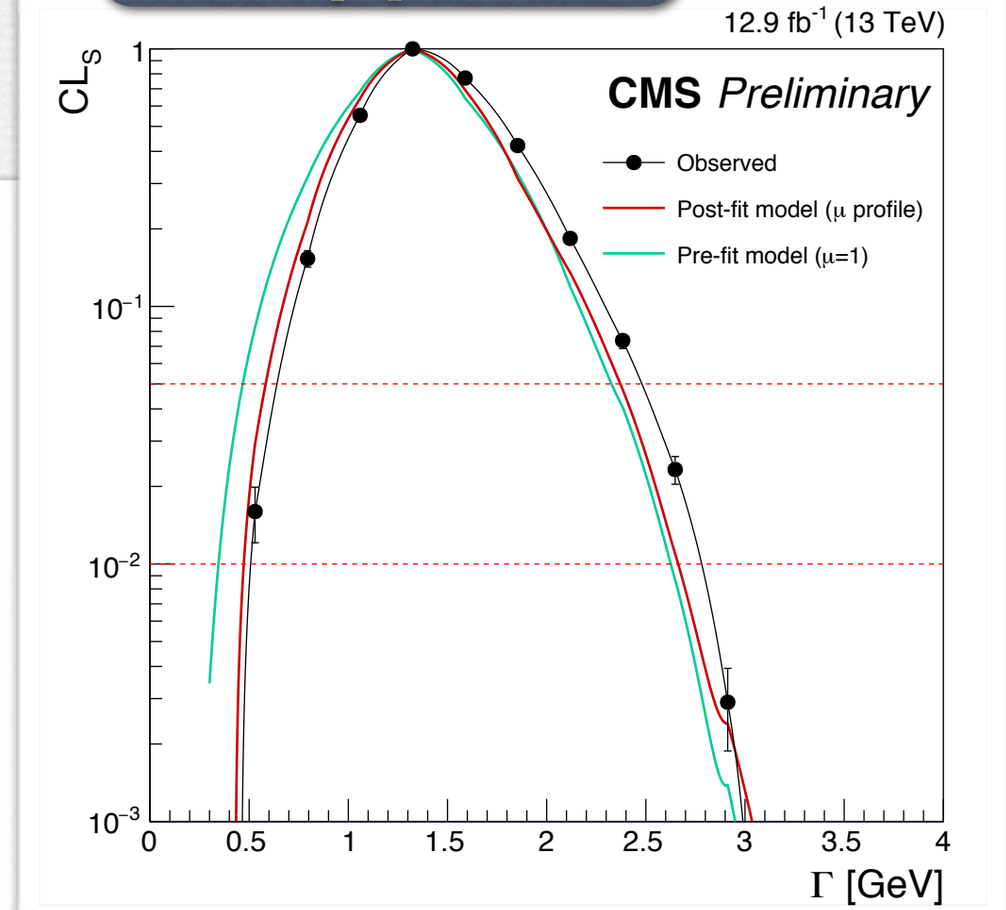
- Boundaries on top quark width are extracted using a **binary hypothesis test**:
  - Test statistic defined by likelihood ratios between the **alternative** and the **SM hypotheses**.
  - Hypothesis separation is measured via the CL_s criterion.
- Observed bounds at the 95% confidence level are

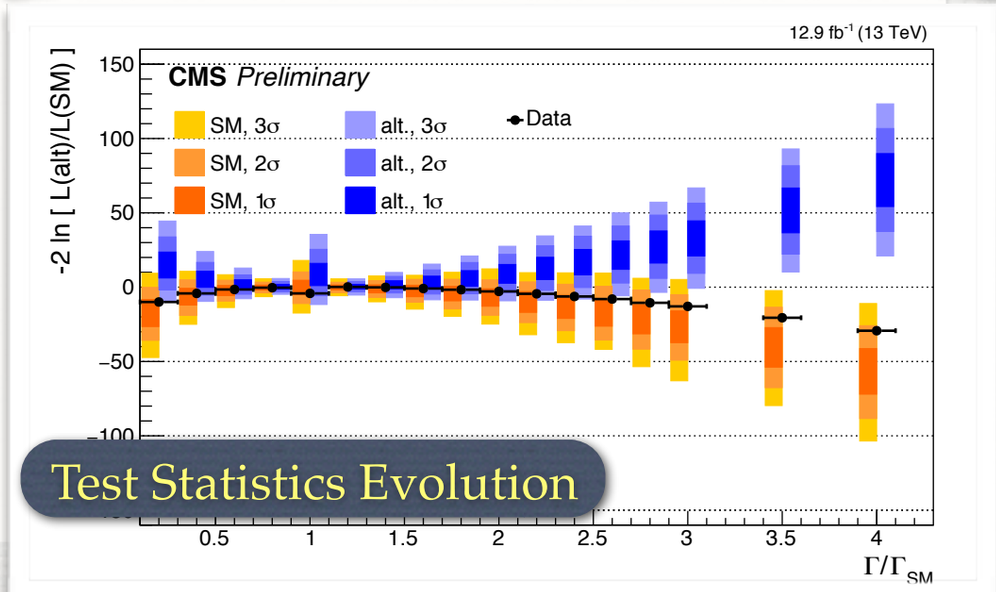
$0.6 \leq \Gamma_t \leq 2.5$ GeV
@ the 95% CL

most precise direct bound to date!

Ref. CMS-TOP-16-019

CL_s vs top quark width

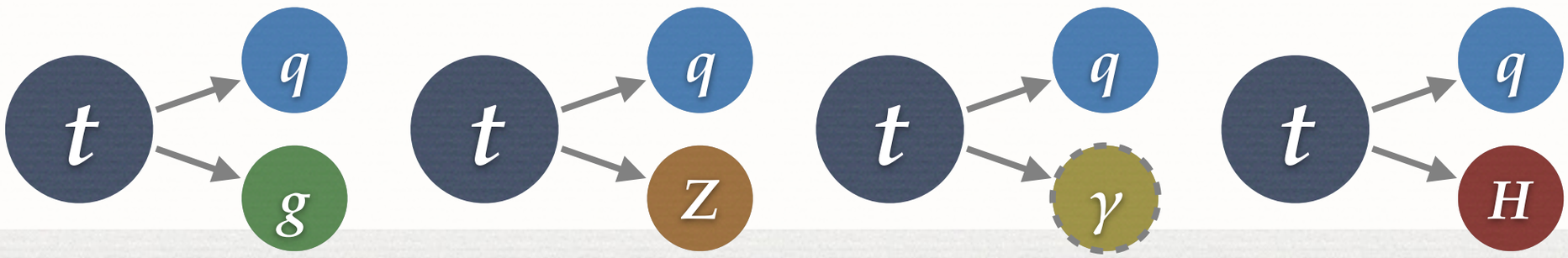




Test Statistics Evolution

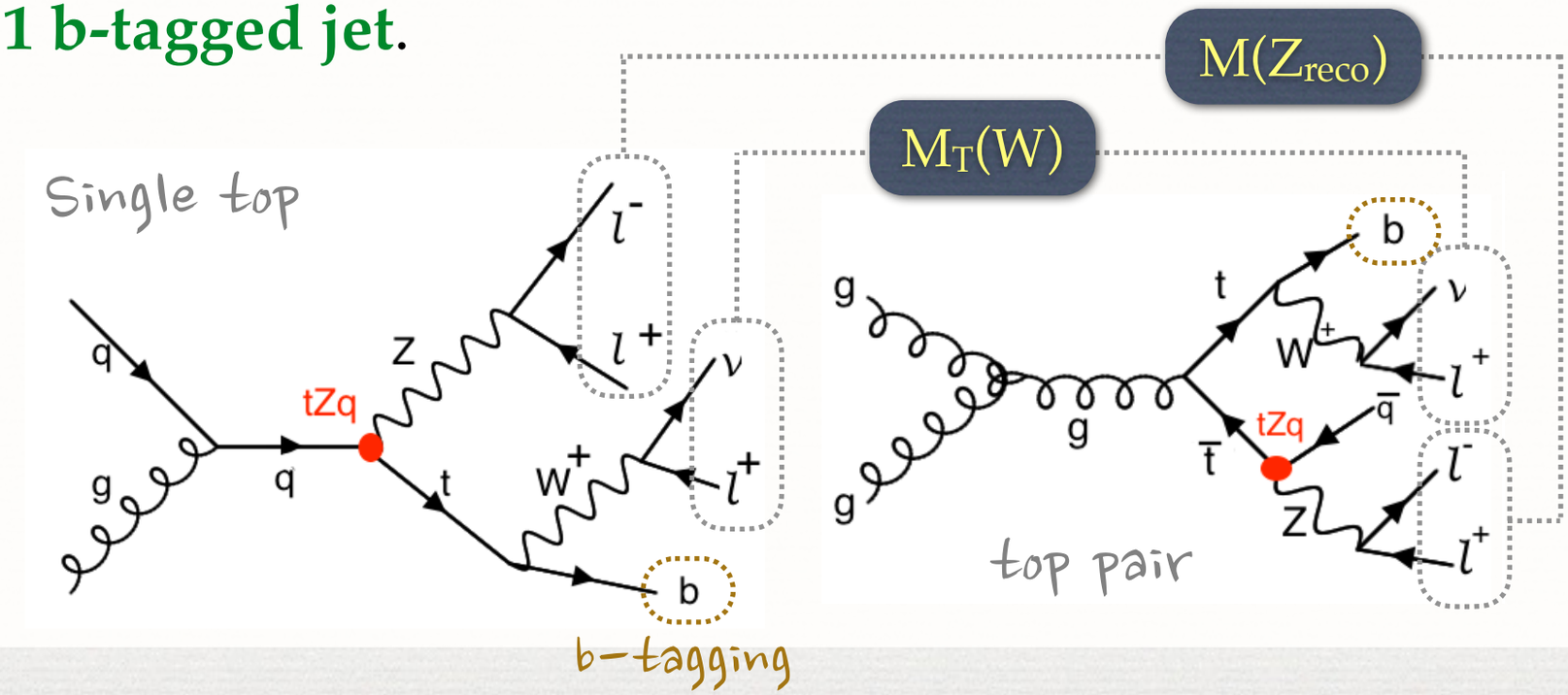
TOP FCNC

- **Flavour-changing neutral current (FCNC)** transitions are forbidden at tree level by the GIM mechanism. They are still possible in the SM in the higher orders via loop induced processes, but are highly suppressed in the top decays.
- Some extensions of the SM could **ENLARGE** the FCNC decay rates by including new physics particles (e.g. SUSY, Technic color, etc.).
- Top FCNC decays may contain distinctive event signatures, e.g. a Z or an isolated photon. The detection of these events is not difficult for the experiments.
- The **FCNH** decay (=FCNC with Higgs) newly joined the game, and bring in a more richer signatures and physics.



TOP FCNC WITH 3 LEPTONS

- The search focusses on the evidence of a **FCNC tZq vertex**, where the quark q can be either up or charm.
- The tZq vertex leads to a single top quark production though q → tZ, or a top quark pair production with one of the top quarks decaying with t → qZ subprocess. When the W and Z boson decay leptonically, it generates a clean **3 lepton final state**.
- Also take at least 1, up to 3 jets. Signal region contains **1 b-tagged jet**.



Lepton flavours
Z($e^{\pm}e^{\mp}$) $e^{\pm}$
Z($e^{\pm}e^{\mp}$) $\mu^{\pm}$
Z($\mu^{\pm}\mu^{\mp}$) $e^{\pm}$
Z($\mu^{\pm}\mu^{\mp}$) $\mu^{\pm}$

Ref. CMS-TOP-17-017

ANALYSIS STRATEGY

- Main background sources:
  - *With 3 prompt leptons*: **WZ**, **ttZ**, **SM tZq**
  - *With 2 prompt leptons + 1 non-prompt lepton*: **DY+jets**, **$t\bar{t}$**, **WW**.
- The rate to find a non-prompt lepton is estimated by data containing lepton candidates with inverted isolation requirement.
- Event categorizing with **2 signal regions** + **3 control regions**:

	single t SR	$t\bar{t}$ SR	single t CR	$t\bar{t}$ CR	WZ CR
N(jets)	1	≥2, ≤3	1	≥2, ≤3	≥1, ≤3
N(b-jets)	1	≥1	1	≥1	0
Z mass window	Yes	Yes	No	No	Yes

estimated by flipping b-tagging

estimated by Z-mass sideband

Ref. CMS-TOP-17-017

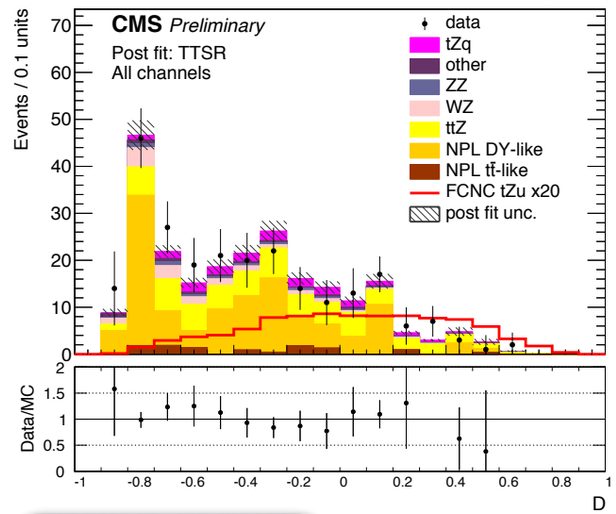
A simultaneous global fit is performed to resolve the background contamination in the signal regions.

ANALYSIS STRATEGY (II)

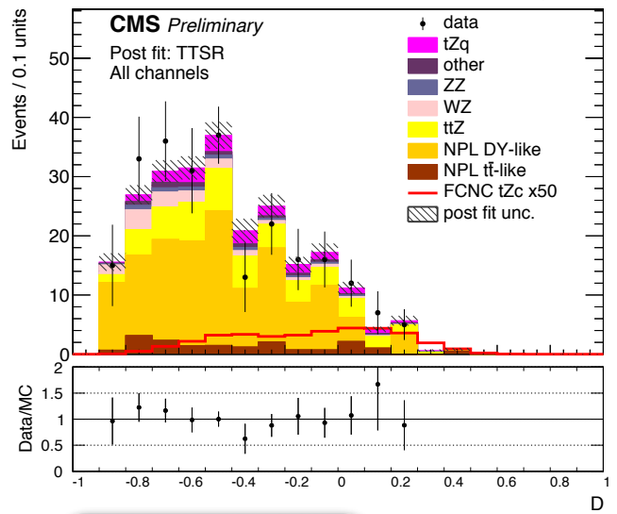
Ref. CMS-TOP-17-017

- Extended background suppression with BDT, including several **kinematical variables** and **b-tagging information**, against backgrounds excluding non-prompt leptons.
- Separate BDTs trained for different lepton flavours, single top or top pair categories, and for up/charm coupling.

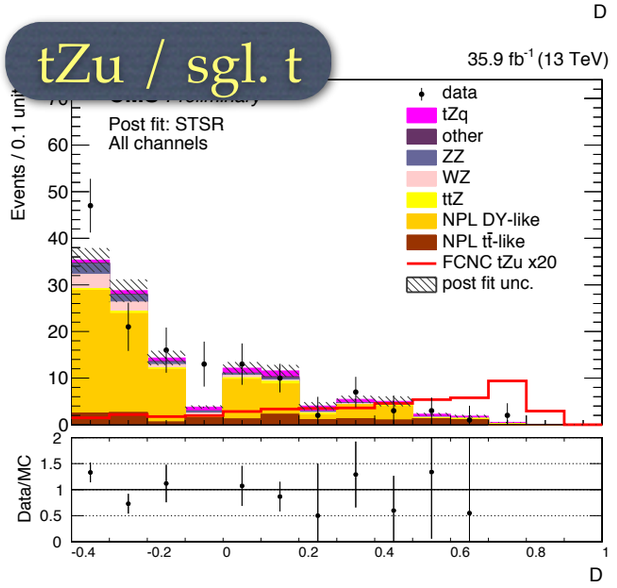
tZu / tt̄



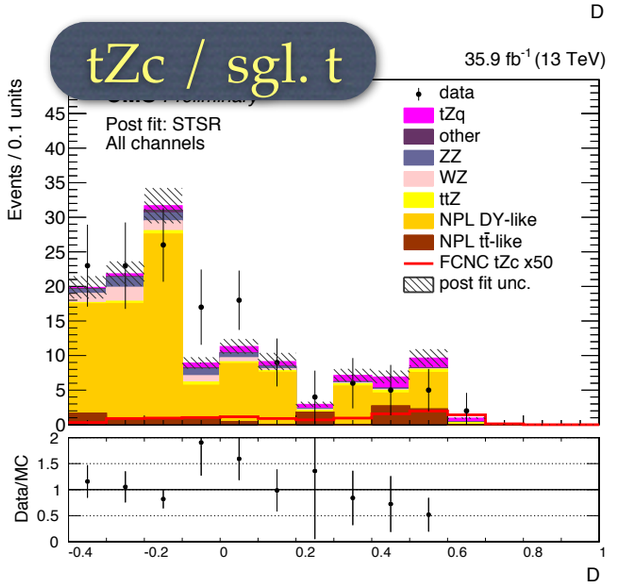
tZc / tt̄



tZu / sgl. t



tZc / sgl. t



Post fit BDT distributions

RESULTS INTERPRETATION

- The FCNC process is characterized using EFT approach:

$$\mathcal{L}_{\mathrm{FCNC}}^{tZq} = \sum_{q=u,c} \left[\frac{\sqrt{2}}{4} \frac{g}{\cos\theta_W} \frac{\kappa_{tZq}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f_{Zq}^{L} P_L + f_{Zq}^{R} P_R \right) qZ_{\mu\nu} \right] + h.c.$$

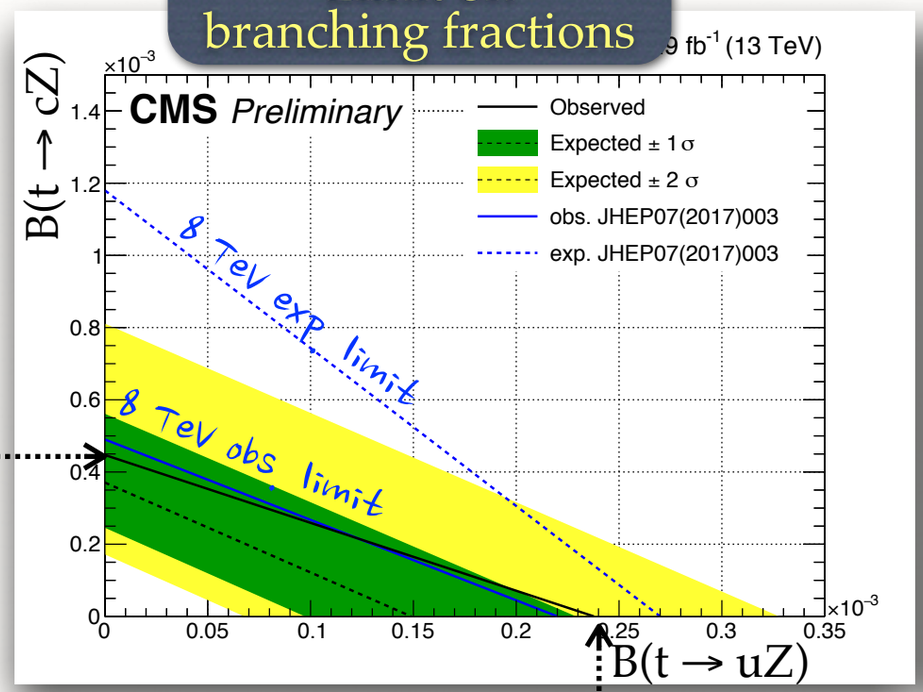
where κ_{tZq}/Λ represents the couplings at scale Λ.

If only one coupling is considered:

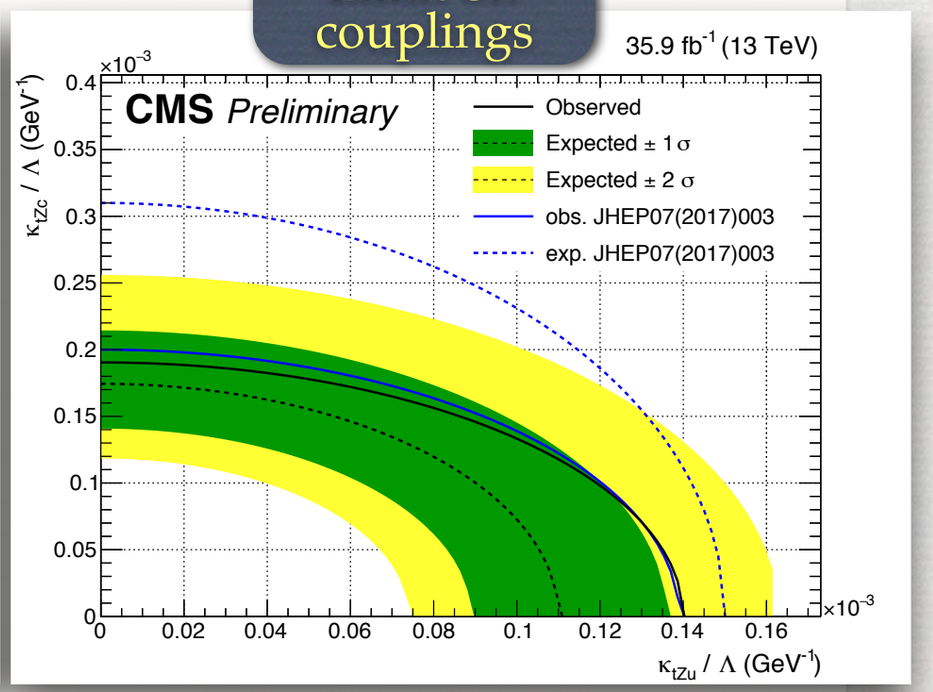
Channel	Observed limit
B(t→cZ)	**<0.045%**
B(t→uZ)	**<0.024%**

Ref. CMS-TOP-17-017

Limit on branching fractions



Limit on couplings



8 TeV ⇒ 13 TeV: Significant improvement on the expected limit; compatible observed limit.

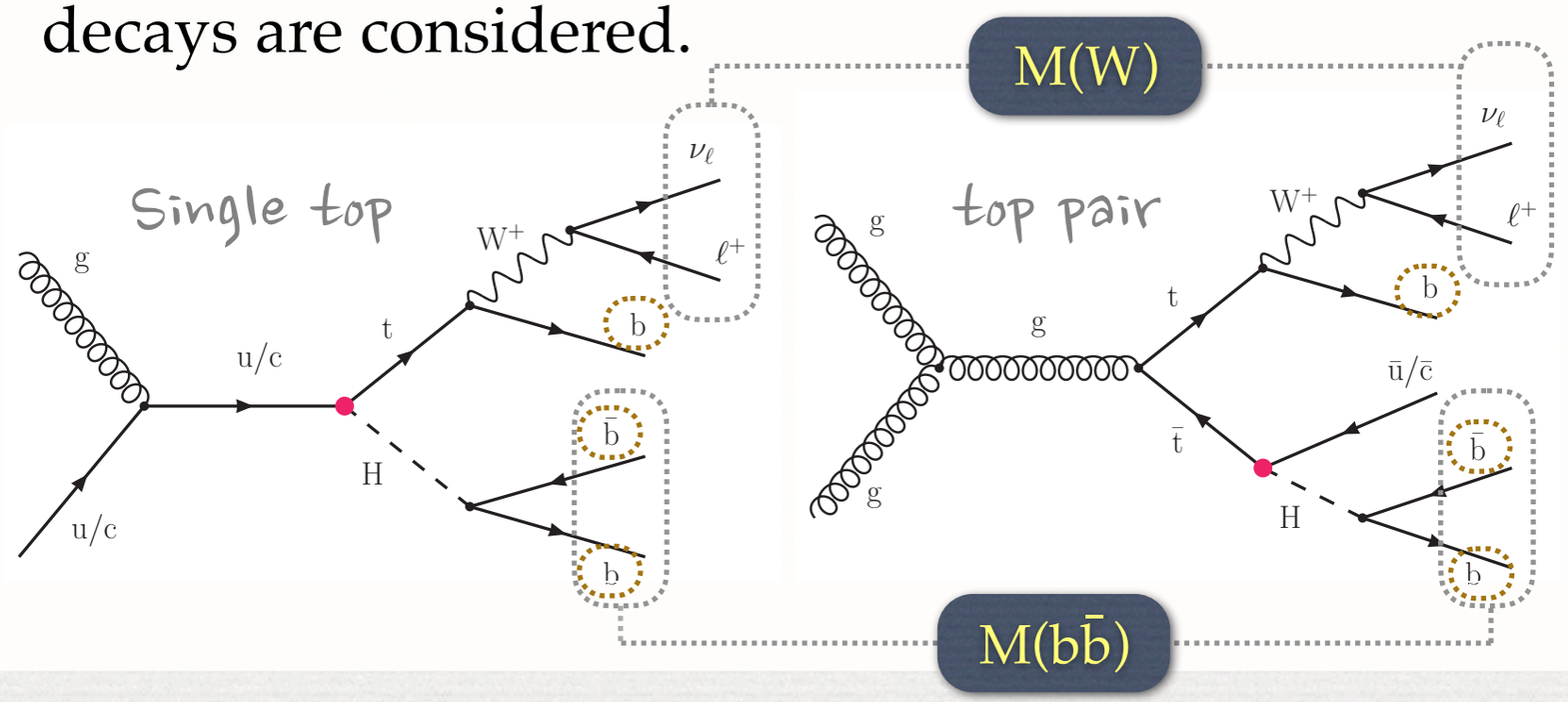
TOP FCNH WITH H→bb

- The FCNC processes that correspond to t-H interactions "FCNH" are described by the following effective Lagrangian:

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} \left(f_{Hq}^{L} P_L + f_{Hq}^{R} P_R \right) q H + h.c.$$

  where κ_{Hqt} is the effective coupling.

- The t-H FCNH interaction is studied in two channels: **single top quark + H** and **FCNH decays of top pair** events, while $H \to b\bar{b}$ decays are considered.



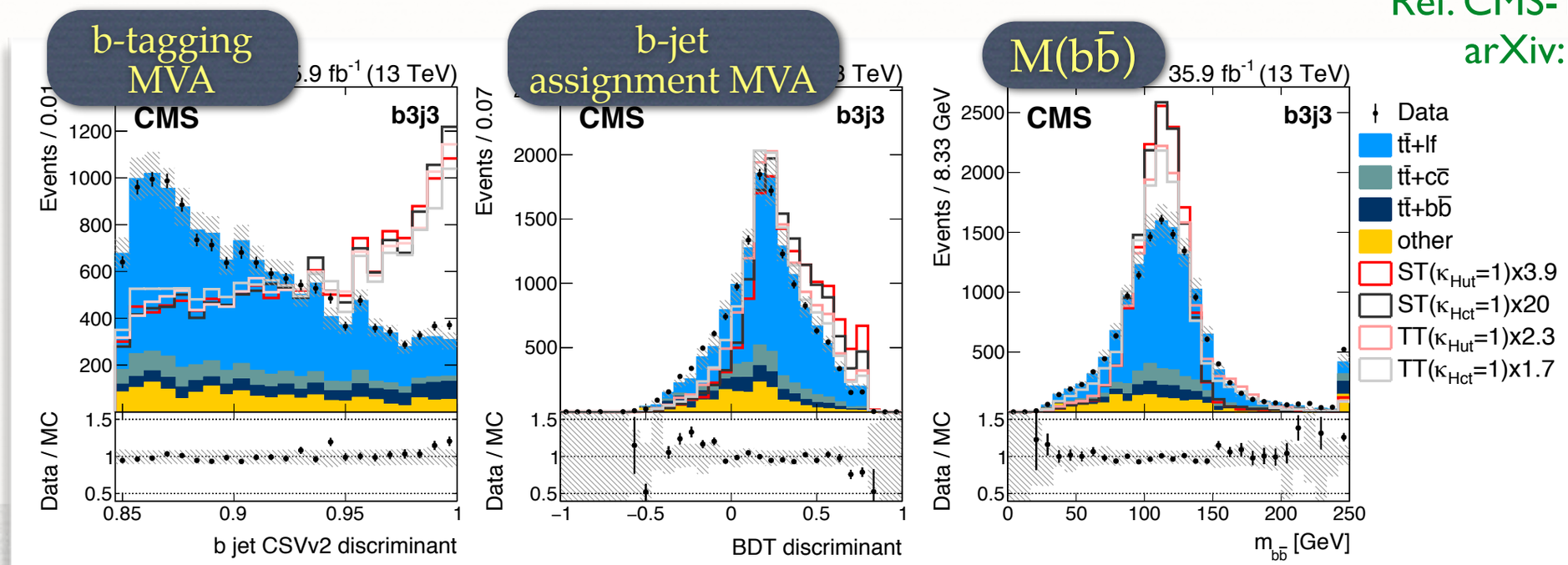
Signal single top:
1L+3b
Signal top pair:
1L+3b+u/c-jet
Background $t\bar{t}$:
1L+2b+2j

Ref. CMS-TOP-17-003
arXiv:1712.02399

EVENT RECONSTRUCTION

- The event is reconstructed with full kinematical information under several event hypotheses: **semileptonic $t\bar{t}$**, **signal single top + Higgs**, **signal $t\bar{t}$ with Higgs**.
- For each jet permutation, **likelihood minimization** is performed over momentum/energy resolution functions for reconstructed leptons and jets.
- b-jet assignment is further improved by requiring an additional MVA trained on correct/wrong permutations.

Ref. CMS-TOP-17-003
arXiv:1712.02399



EVENT CATEGORIZING

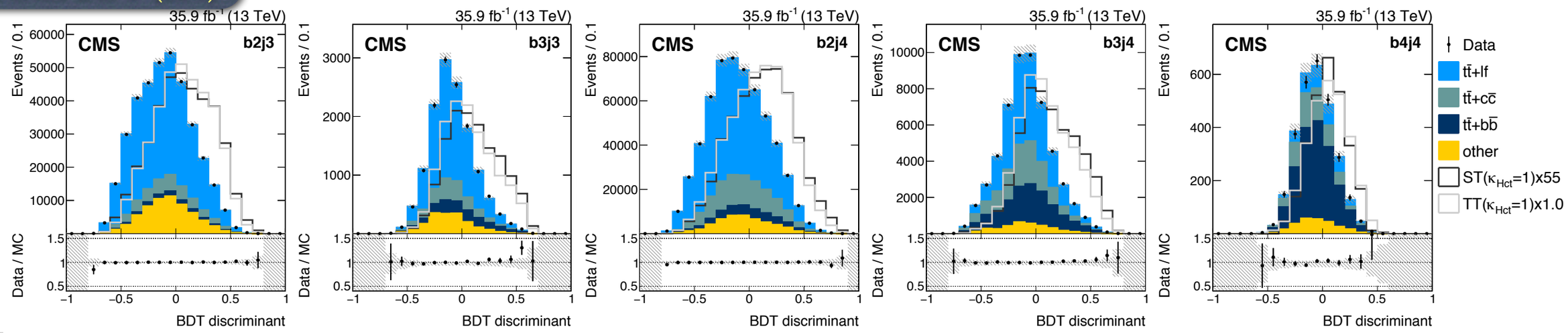
- 3 or 4 jets are required, ≥2 jets are b-tagged. Events are categorized by **"how many jets in total"** and **"how many jets are b-tagged"**.
- Signal/background discrimination by BDT trained separately for t→uH and t→cH, and for each category.

Ref. CMS-TOP-17-003
arXiv:1712.02399

Category	b2j3	b3j3	b2j4	b3j4	b4j4
Data	365890	13481	575500	53352	2764
Total bkg (uH)	$(365\pm23)\times10^3$	$(132\pm13)\times10^2$	$(574\pm25)\times10^3$	$(528\pm34)\times10^2$	-
Total bkg (cH)	$(365\pm17)\times10^3$	$(131\pm10)\times10^2$	$(574\pm18)\times10^3$	$(528\pm23)\times10^2$	2682 ± 185

Data consists with SM bkg.

Final BDT (cH)



RESULTING UPPER LIMITS

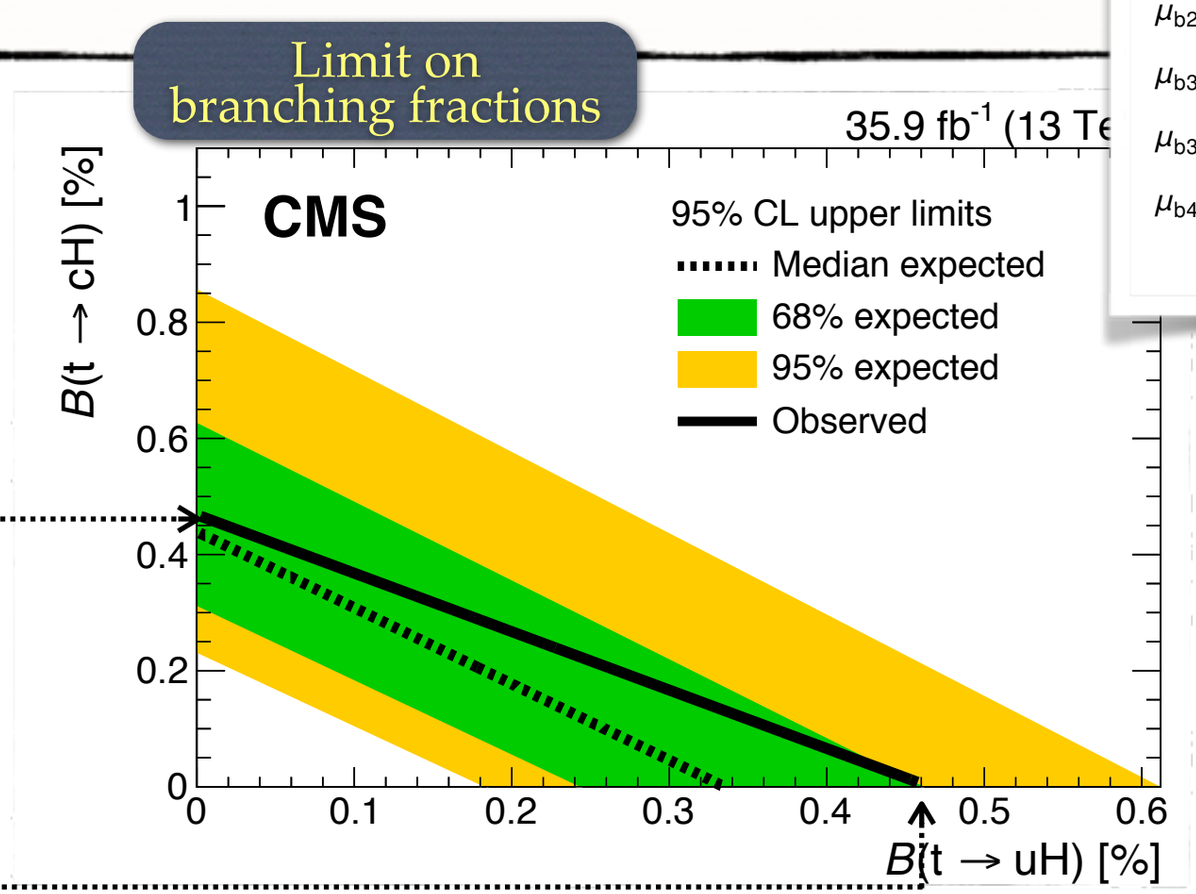
- First search for FCNH in both single top + Higgs and top pair decaying into Higgs together.
- Based on the standard CL_s method, the limits are obtained. Best CMS t→uH limit!

Assuming only one decay channel:

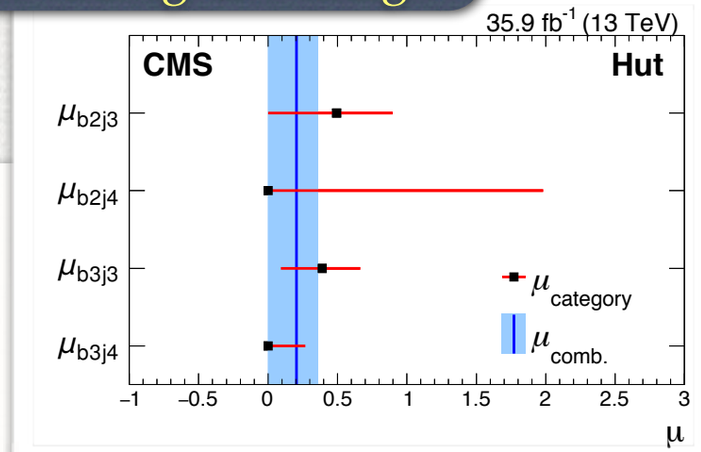
Channel	Observed limit
B(t→cH)	<0.47%
B(t→uH	<0.47%

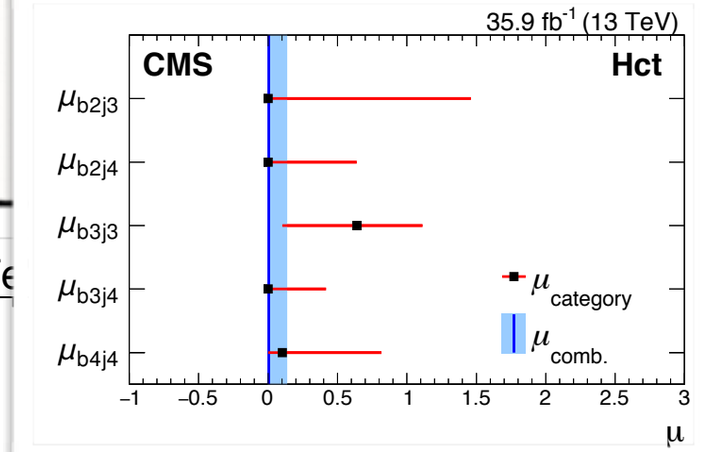
Ref. CMS-TOP-17-003
arXiv:1712.02399

Limit on branching fractions



best fit signal strength

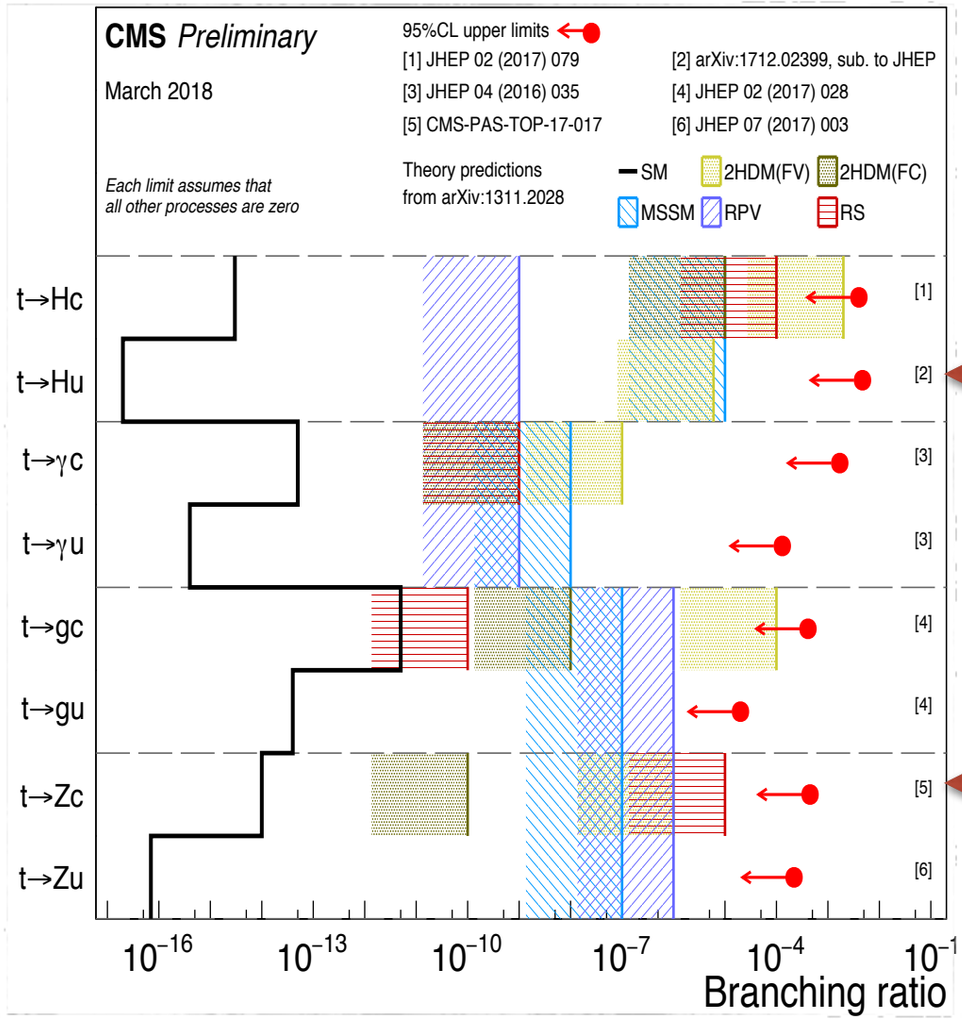




Significant improvement from the 8 TeV analysis!

SUMMARY

- Top quark mass measurements now go differential!
- A direct bound on the top quark decay width is obtained with Run-2 data. Consistent with SM.
- Several possible top FCNC vertices have been probed! No signal has been seen by the experiments.
- Most of the limits on FCNC branching fractions are at **$O(10^{-3})$~$O(10^{-4})$**, already getting close to the predictions of some most favorable NP scenarios!



Stay tuned! Many analyses to be updated with a much larger data set at 13 TeV!

BACKUP SLIDES