Standard Model Rangers: Top & Higgs

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Introduction

top

- The **heaviest elementary particle** ever discovered (1995)
- Almost exclusively decays to W boson and b quark
- **Short lifetime** makes it decay before hadronization (**$\tau \approx$** 4x10^{-25} s)
- Represents relatively clean experimental signature to study

Higgs

- The **most Godly particle** ever discovered (2012)
- The last predicted missing particle in SM now observed
- **Gives mass to all particles** via Higgs field
- Its properties and implications for SM are currently being studied in details

In SM top is expected to strongly couple to Higgs ($y_t \approx 1$)

Yukawa

Why top Yukawa coupling is so strong ?

Yukawa interaction with quarks:

Higgs field — Vacuum expectation

$$\mathcal{L} = \frac{1}{\sqrt{2}}\overline{Q}_{2/3}\lambda_{2/3}Q_{2/3}(H+v) + \frac{1}{\sqrt{2}}\overline{Q}_{-1/3}\lambda_{-1/3}Q_{-1/3}(H+v)$$

diagonalisation

$$\mathcal{L} = \overline{Q}_{2/3}(\frac{m_{2/3}}{v}H + m_{2/3})Q_{2/3} + \overline{Q}_{-1/3}(\frac{m_{-1/3}}{v}H + m_{-1/3})Q_{-1/3}$$

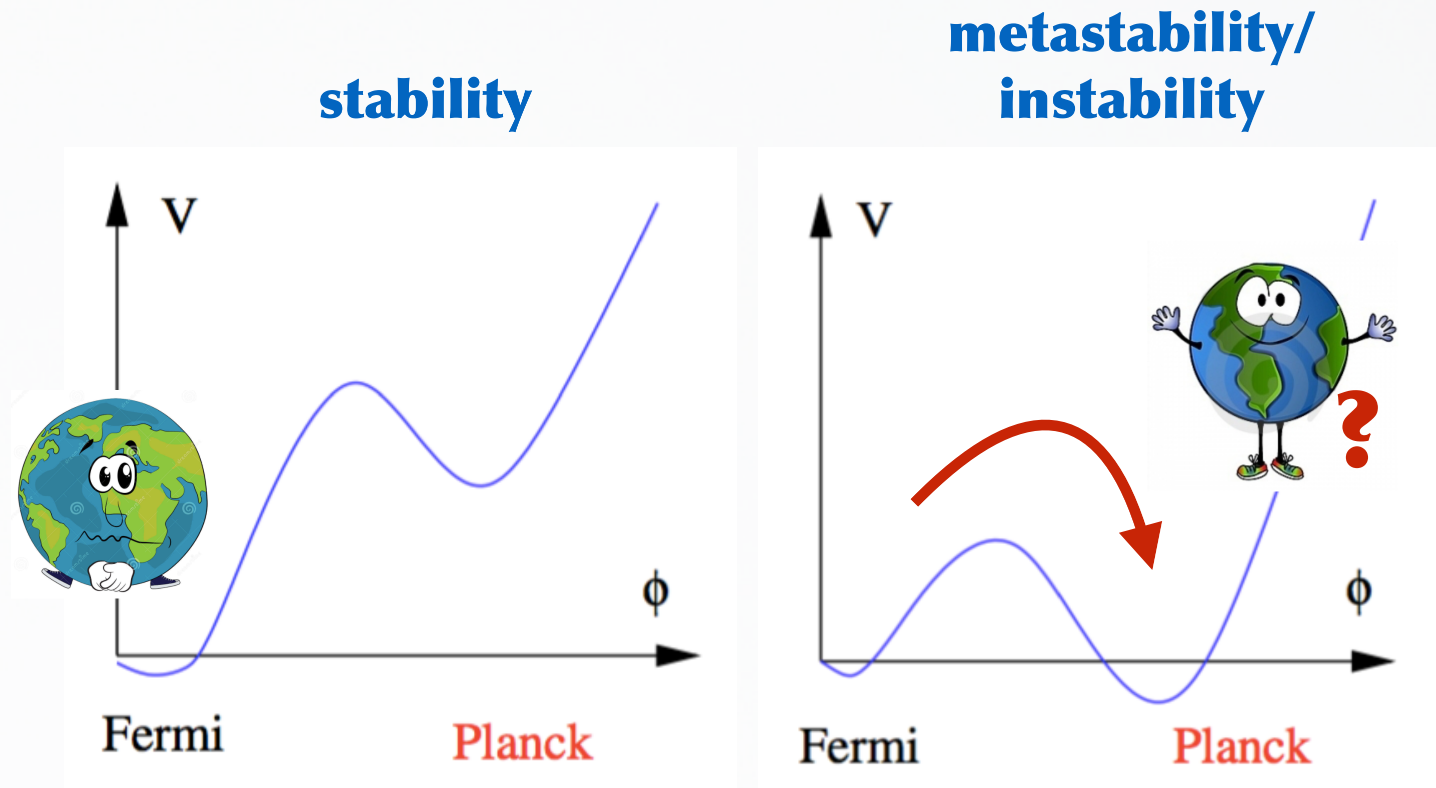
Yukawa coupling $= \sqrt{2}\frac{m_Q}{v}$

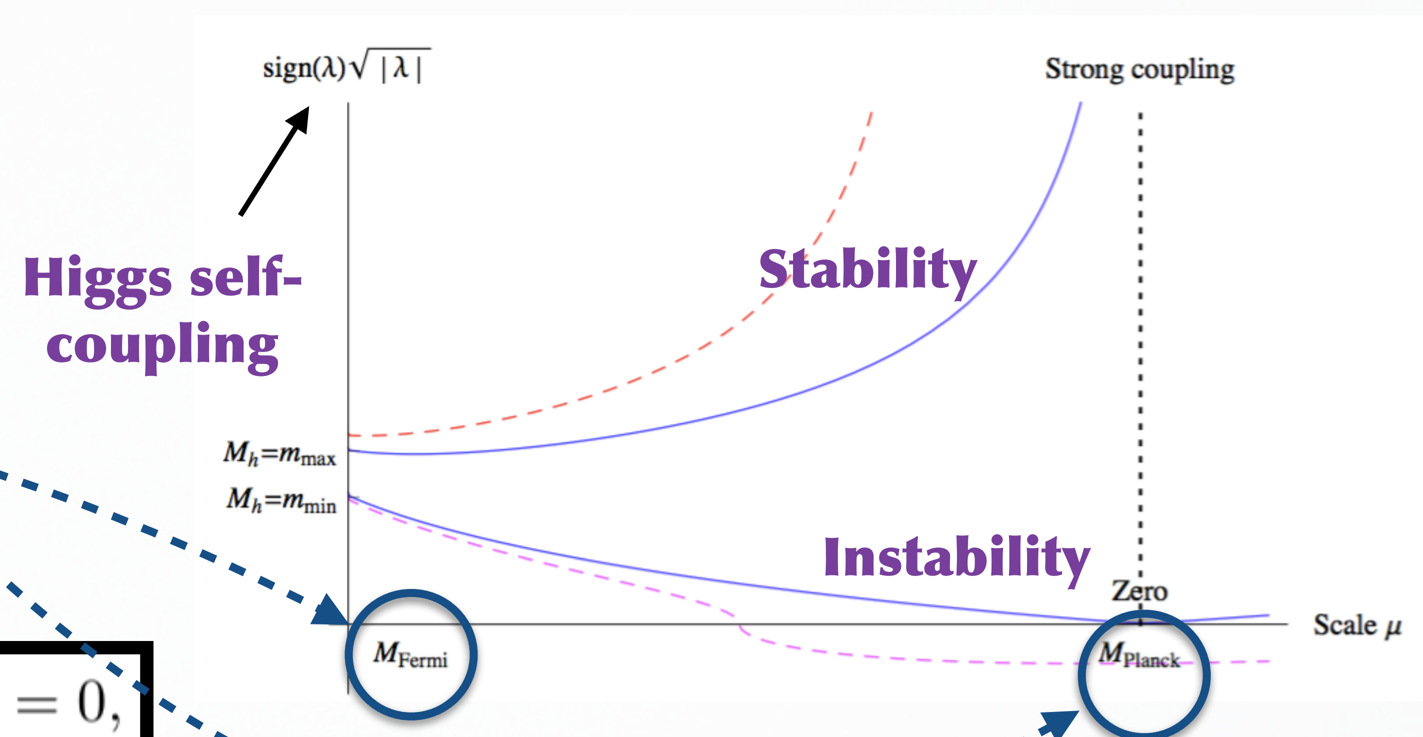
Top quark Yukawa coupling (y_t) = 1.4*(173 GeV)/(246 GeV) ≈ 0.98
precise calculations → 0.990 +/- 0.003

Is our world stable ?

- Our world is **stable** if there are no other potential minima $V < V_{Fermi}$
- Our world is **metastable** if there is another potential minimum with a tunneling time greater than the age of our universe ($P^{-1}_{tunnel} > \tau_{universe}$)
- Our world is **unstable** if $P^{-1}_{tunnel} < \tau_{universe}$
- **The answer is strongly connected to the top and Higgs properties !**
- $\mu^{thr} = O(v = 246 \text{ GeV})$
- $\mu^{cri} = O(M_{Planck} = 1.22 \times 10^{19} \text{ GeV})$

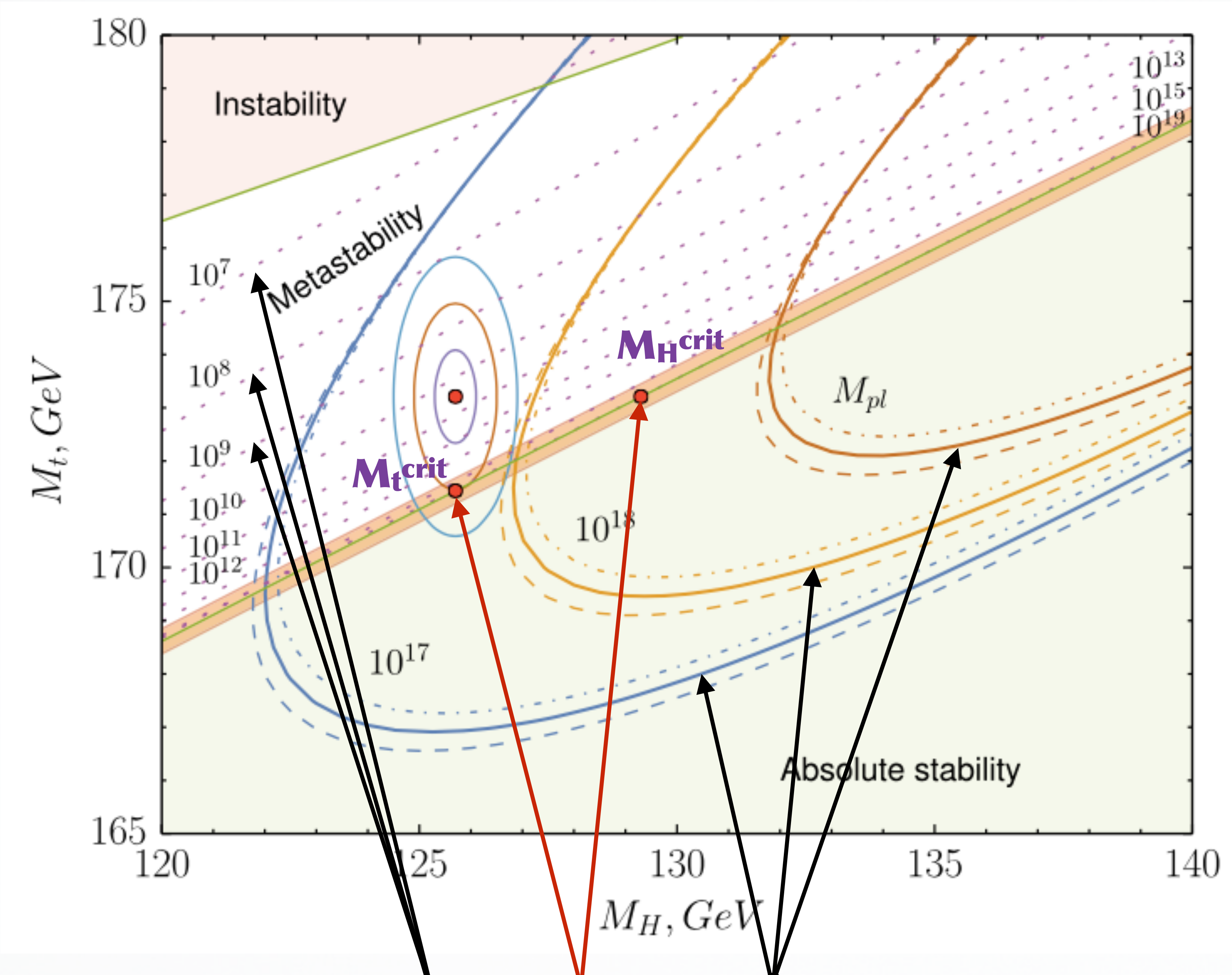
$$V(\phi_{SM}) = V(\phi_1), \quad V'(\phi_{SM}) = V'(\phi_1) = 0,$$





JHEP10 (2012) 140

When the world (almost) crashes down



$\lambda(\mu^0) = 0$ $\beta_\lambda(\mu^0) = 0$

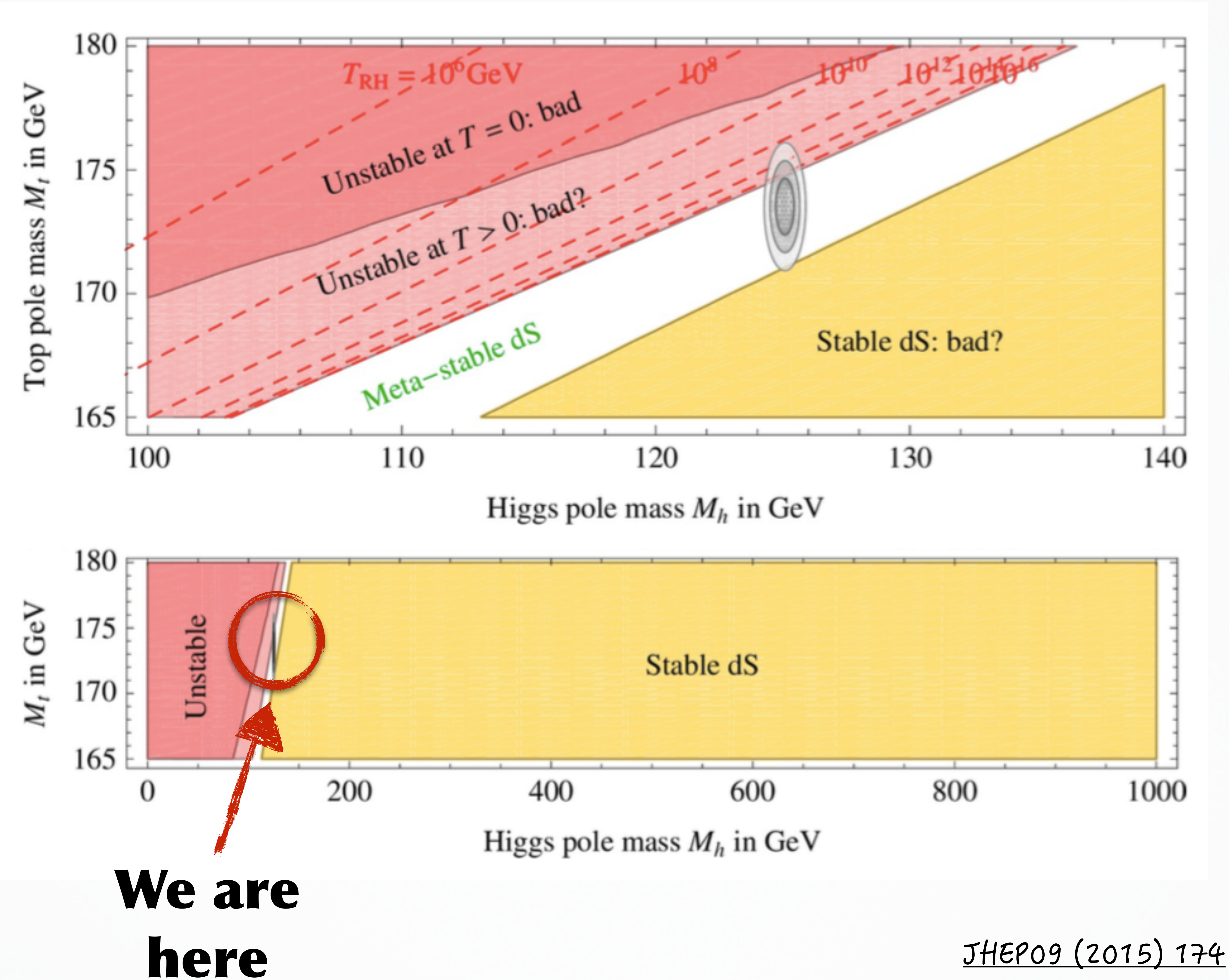
vacuum stability condition

$$\beta_\lambda = \mu \partial \lambda / \partial \mu$$

- Our world is **unstable** at **1.3σ**
- We seem to live in a **metastable** world → **transition time between two minima > lifetime of the universe**
- Main uncertainties on our fate come from $\mathbf{m_t}$, $\mathbf{m_H}$ and $\mathbf{y_t}$ **determination**

Phys. Rev. Lett. 115, 201802 (2015)

Lucky (?)

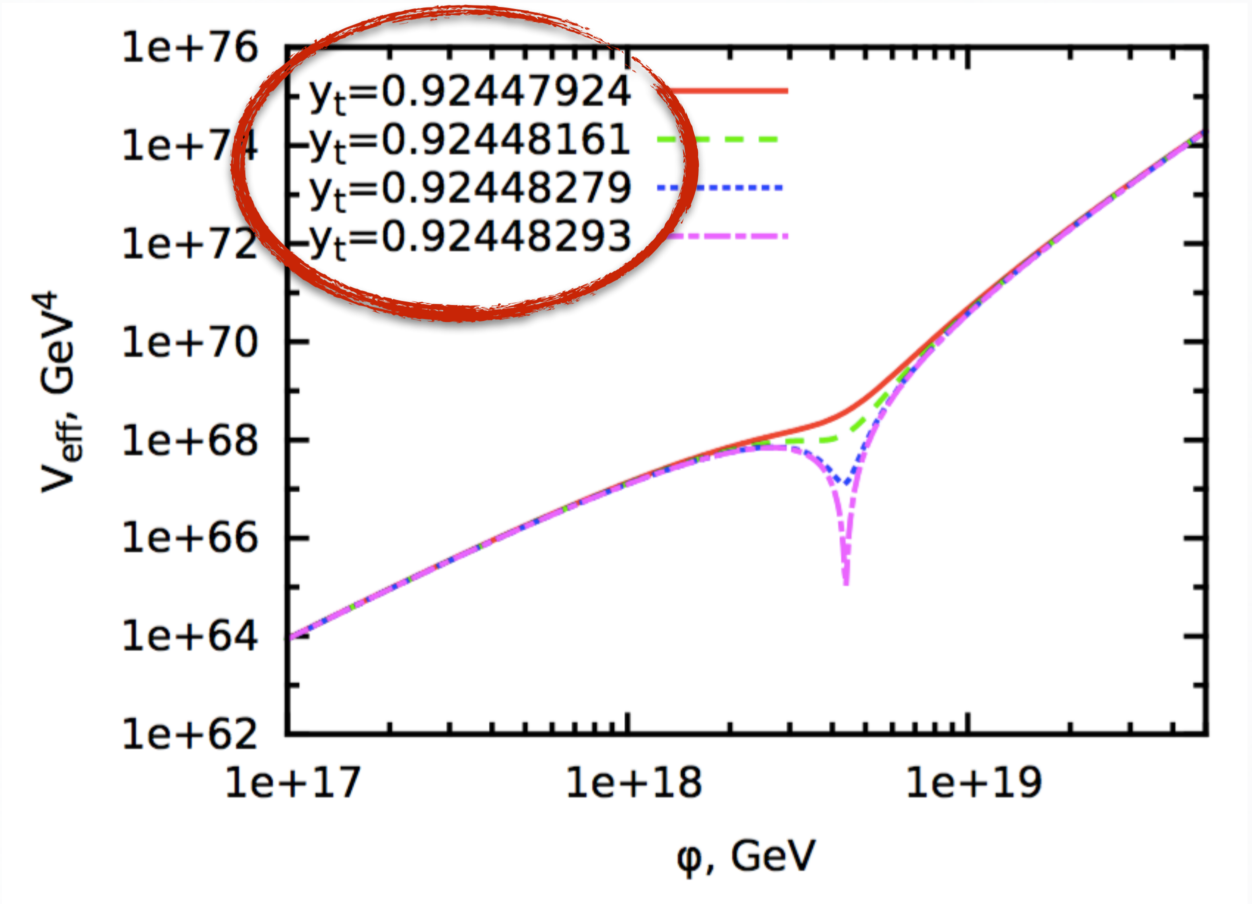


JHEP09 (2015) 174

The importance of being y_t

- **Critical y_t**: Higgs field has two degenerate minima
- **$y_t \in [y_t^{crit}, y_t^{crit} + 0.04]$**: the new minimum is deeper than ours, the age of the universe is smaller than the life-time of our vacuum (**metastability**)
- **$y_t > y_t^{crit} + 0.04$ ($m_t > 178$ GeV)**: the life-time of our vacuum is smaller than the age of the universe
- **$y_t < y_t^{crit}$ - 1.2×10^{-6}**: our vacuum is unique
- **$y_t \in [y_t^{crit} - 1.2\times10^{-6}, y_t^{crit}]$**: our vacuum is deeper than the other one

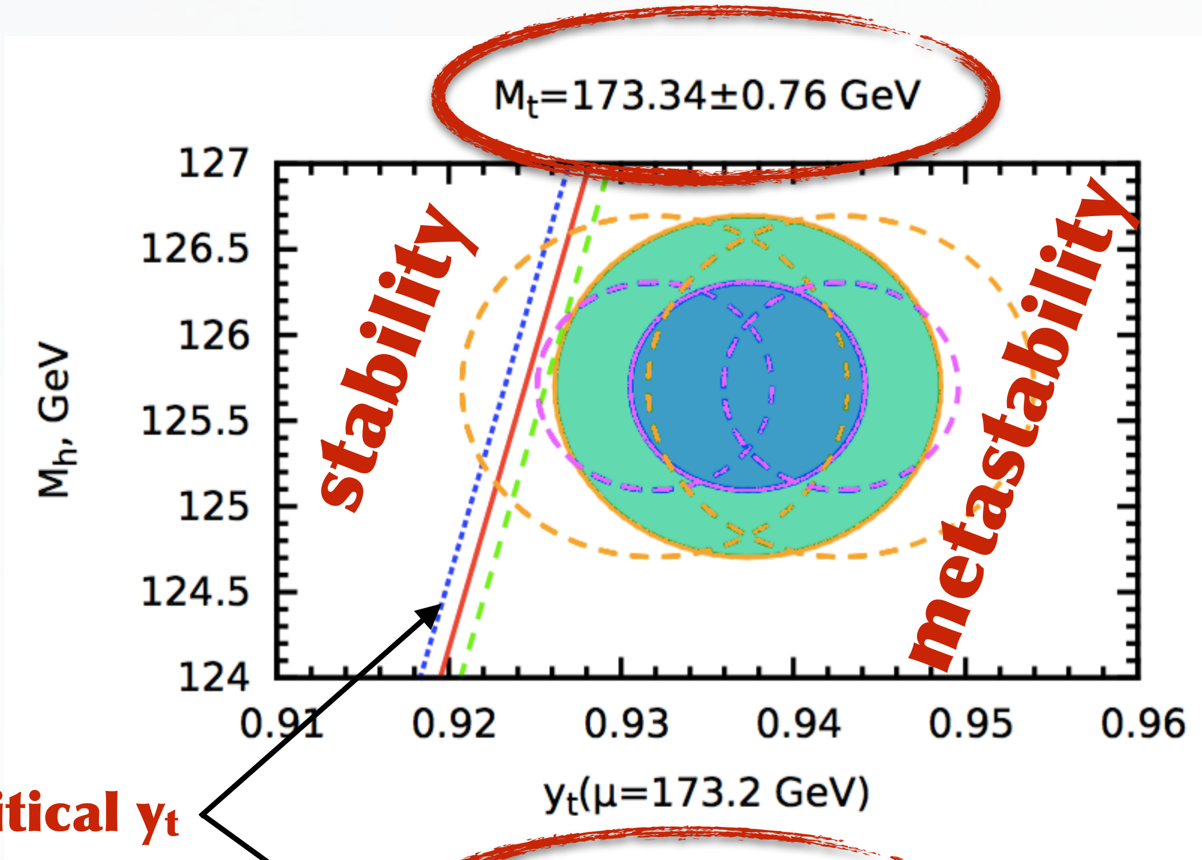
$$y_t^{\rm crit} = 0.9244 + 0.0012 \times \frac{M_h/{\rm GeV} - 125.7}{0.4} + 0.0012 \times \frac{\alpha_s(M_Z) - 0.1184}{0.0007}$$



J. Exp. Theor. Phys. 120 (2015) 3

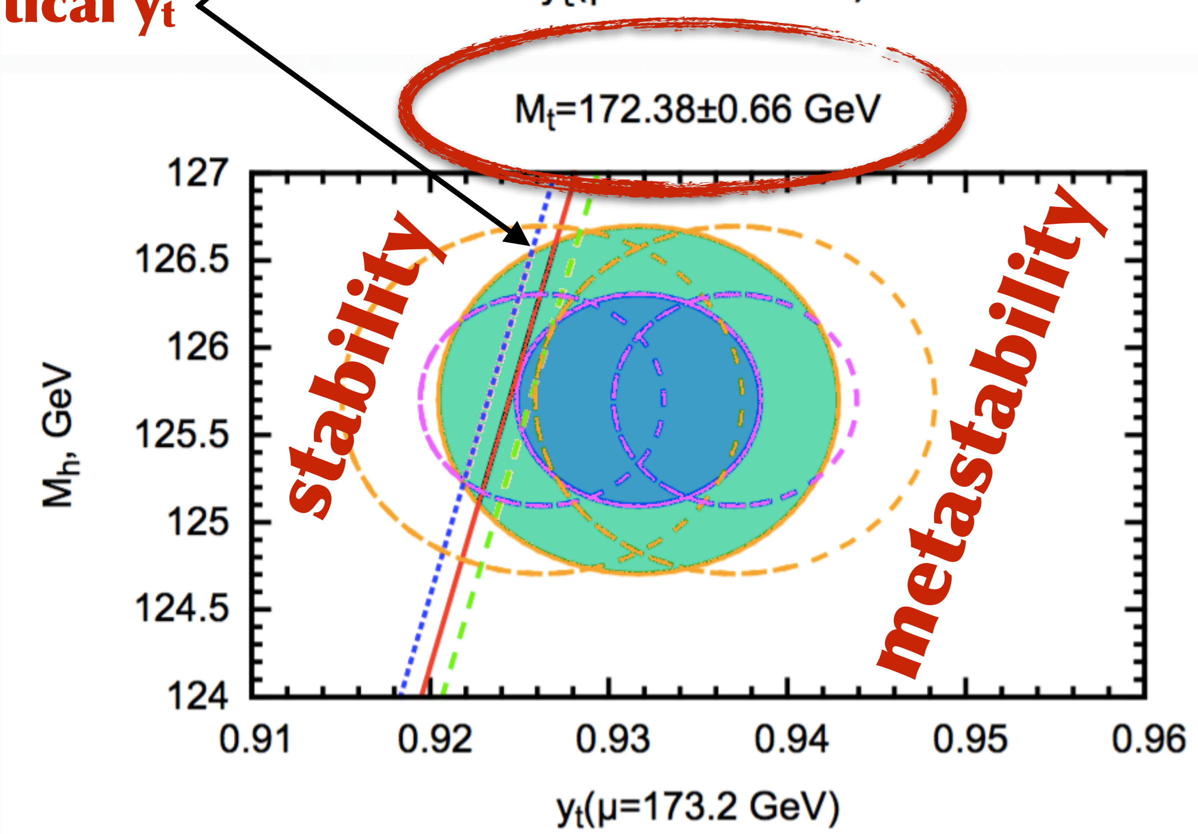
Mass, Yukawa and stability

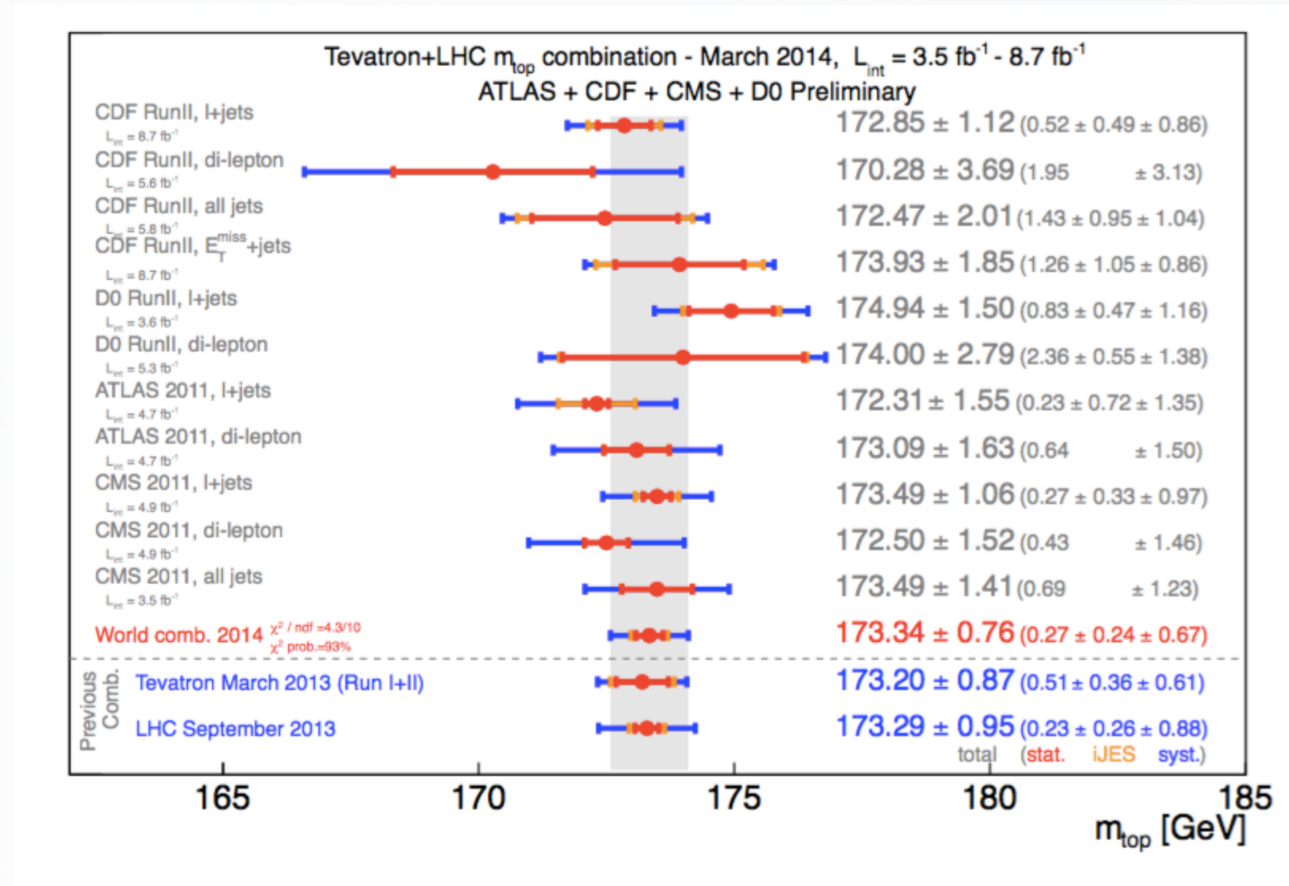
Latest results

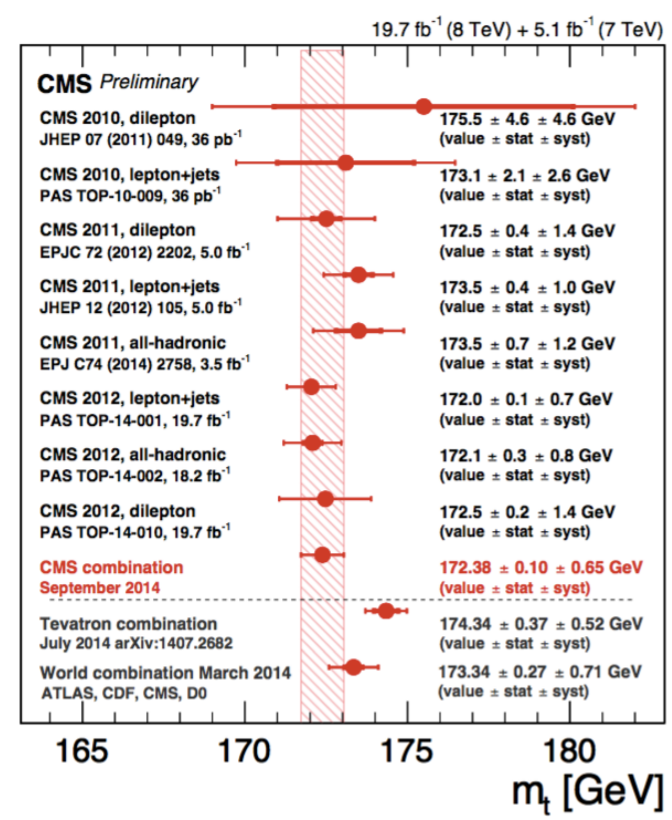


Critical y_t

Run I CMS results



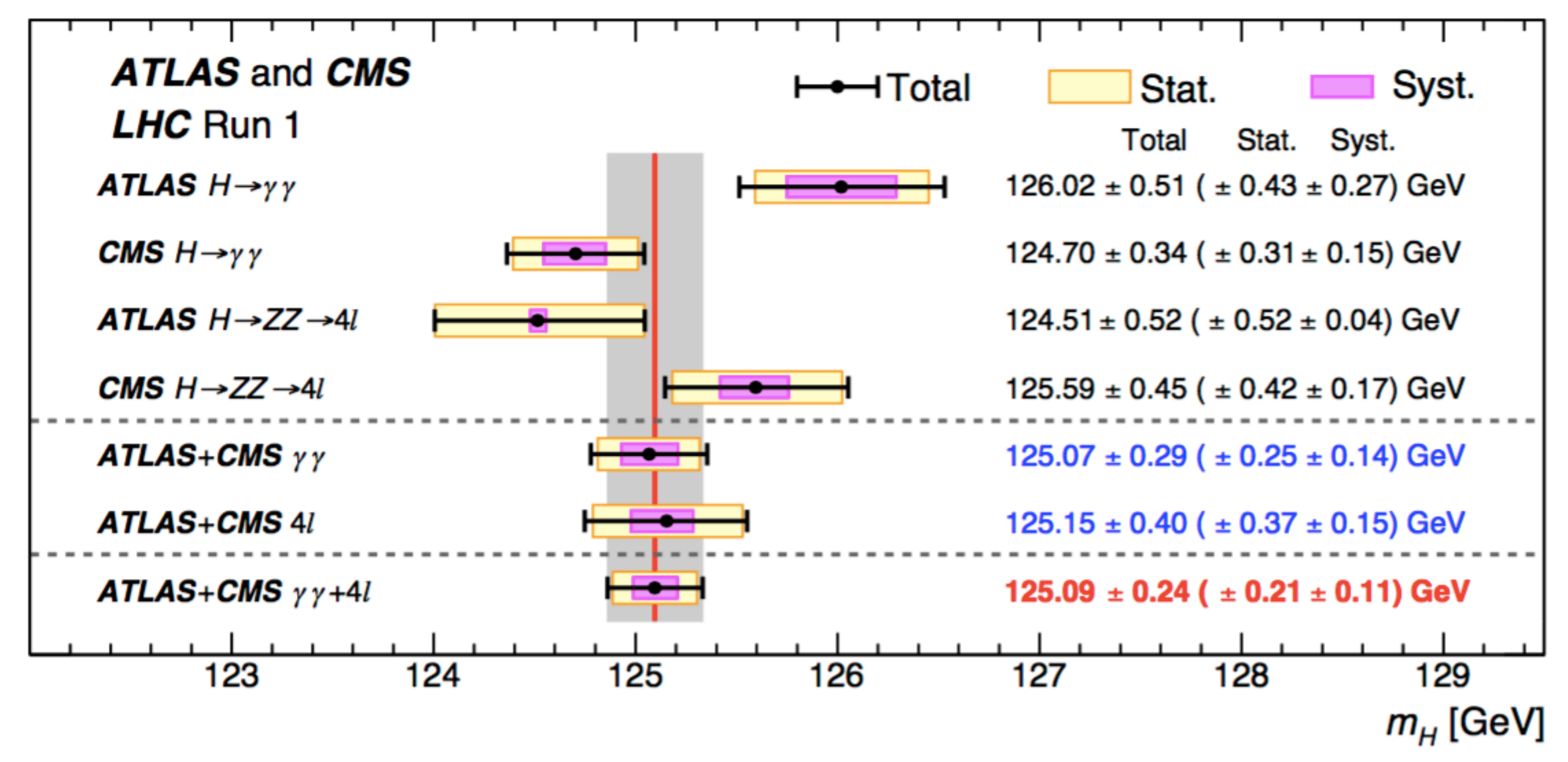




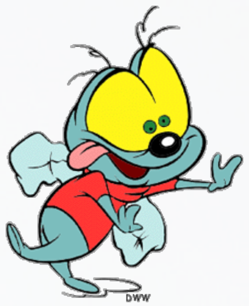
Precision mass measurements for top and Higgs, and y_t determination are crucial to understand where we live !

J. Exp. Theor. Phys. 120 (2015) 3

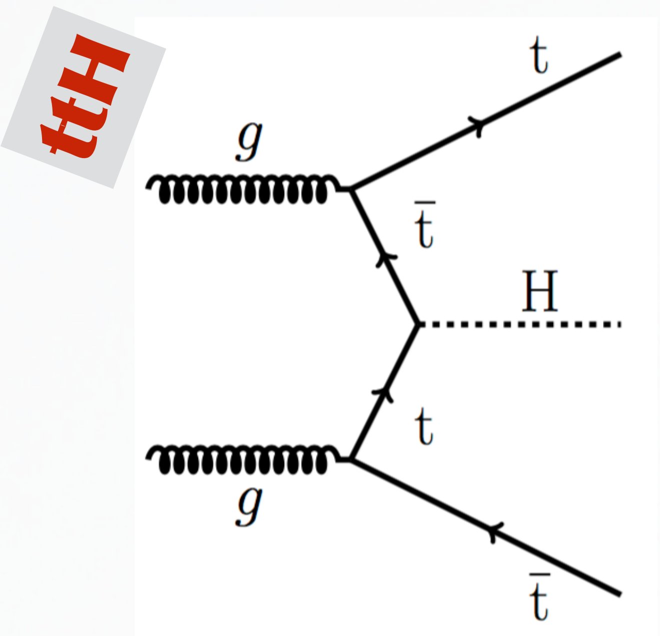
Higgs mass measurements

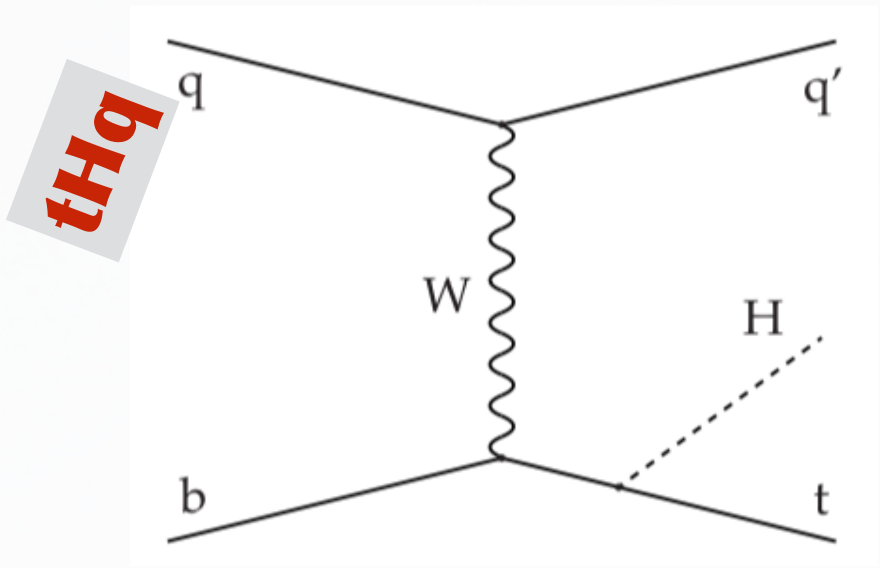


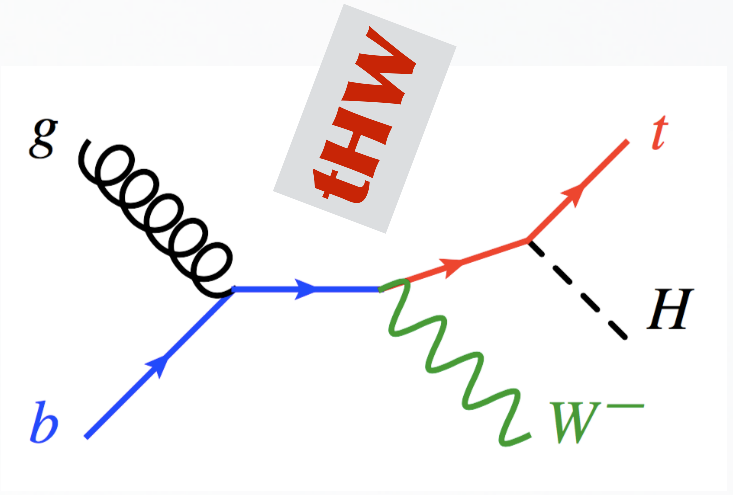
How to catch Yukawa ?



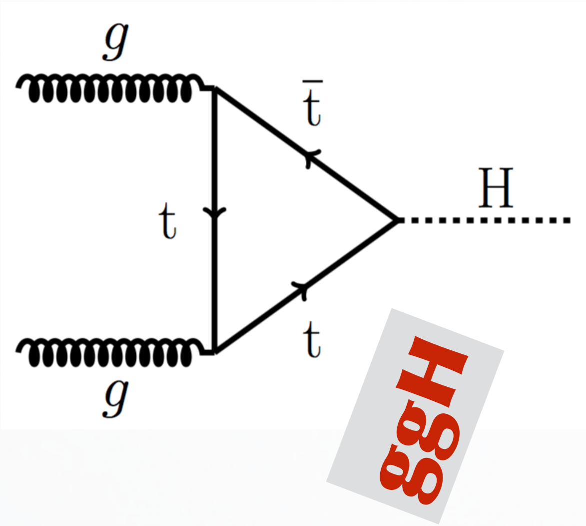
Directly

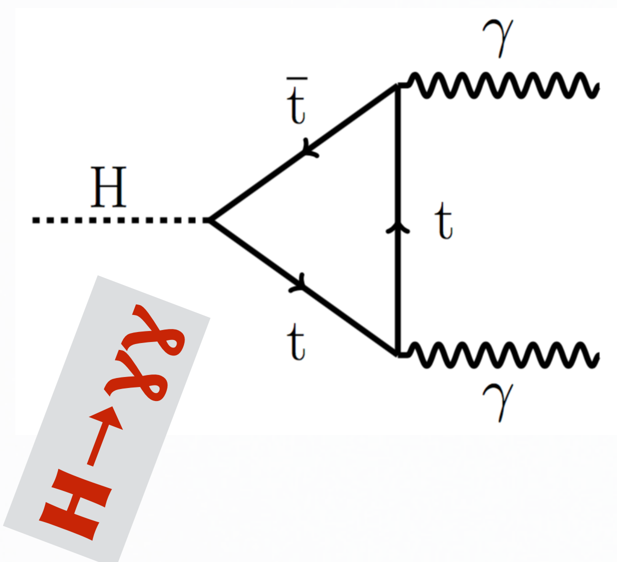


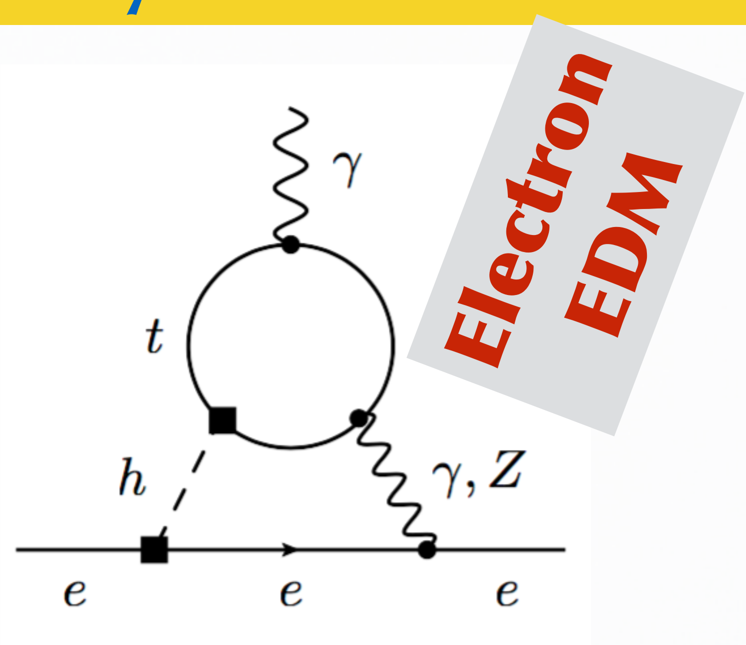




Indirectly

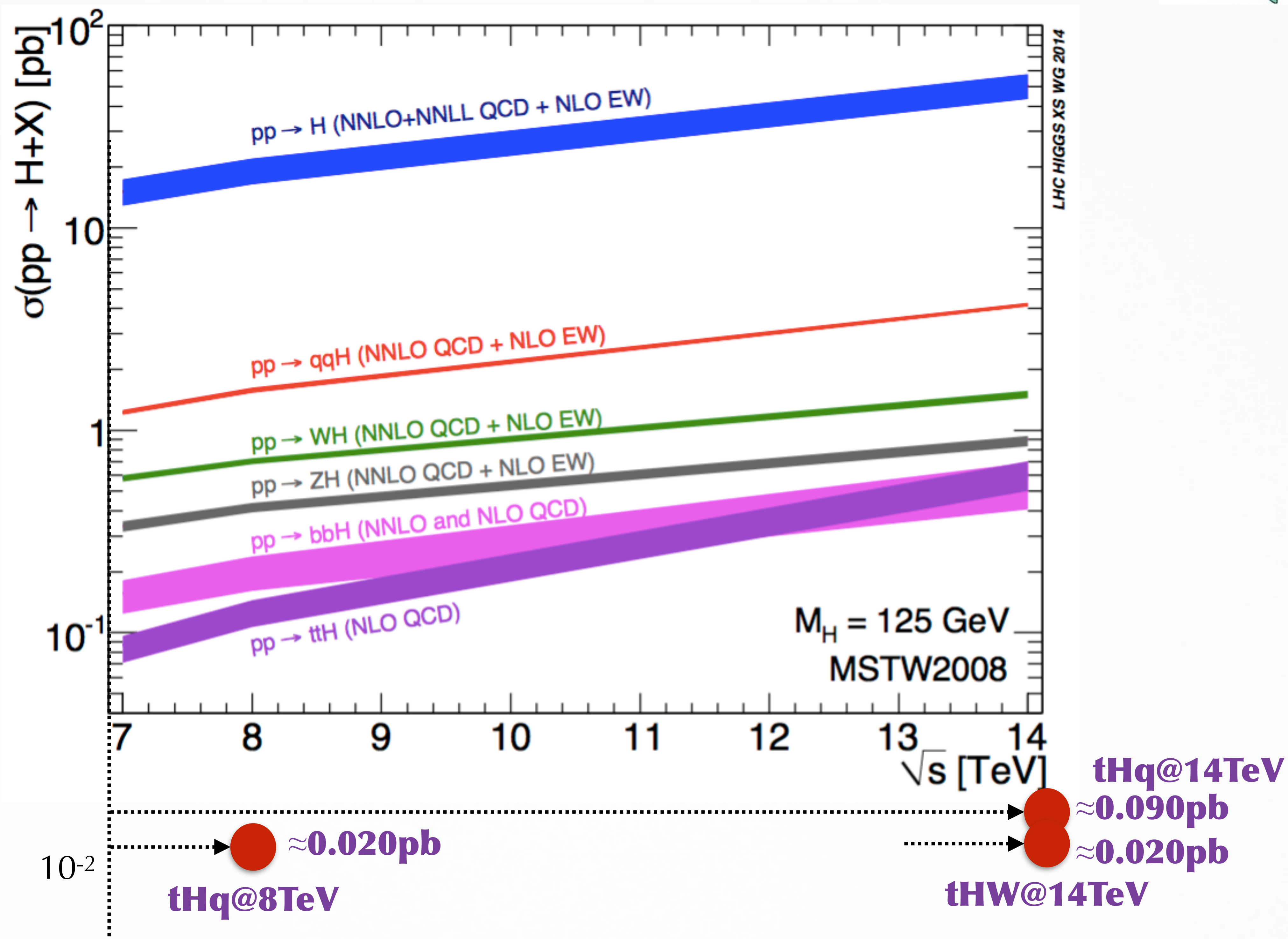






Caveat: new particles could contribute to the loops !

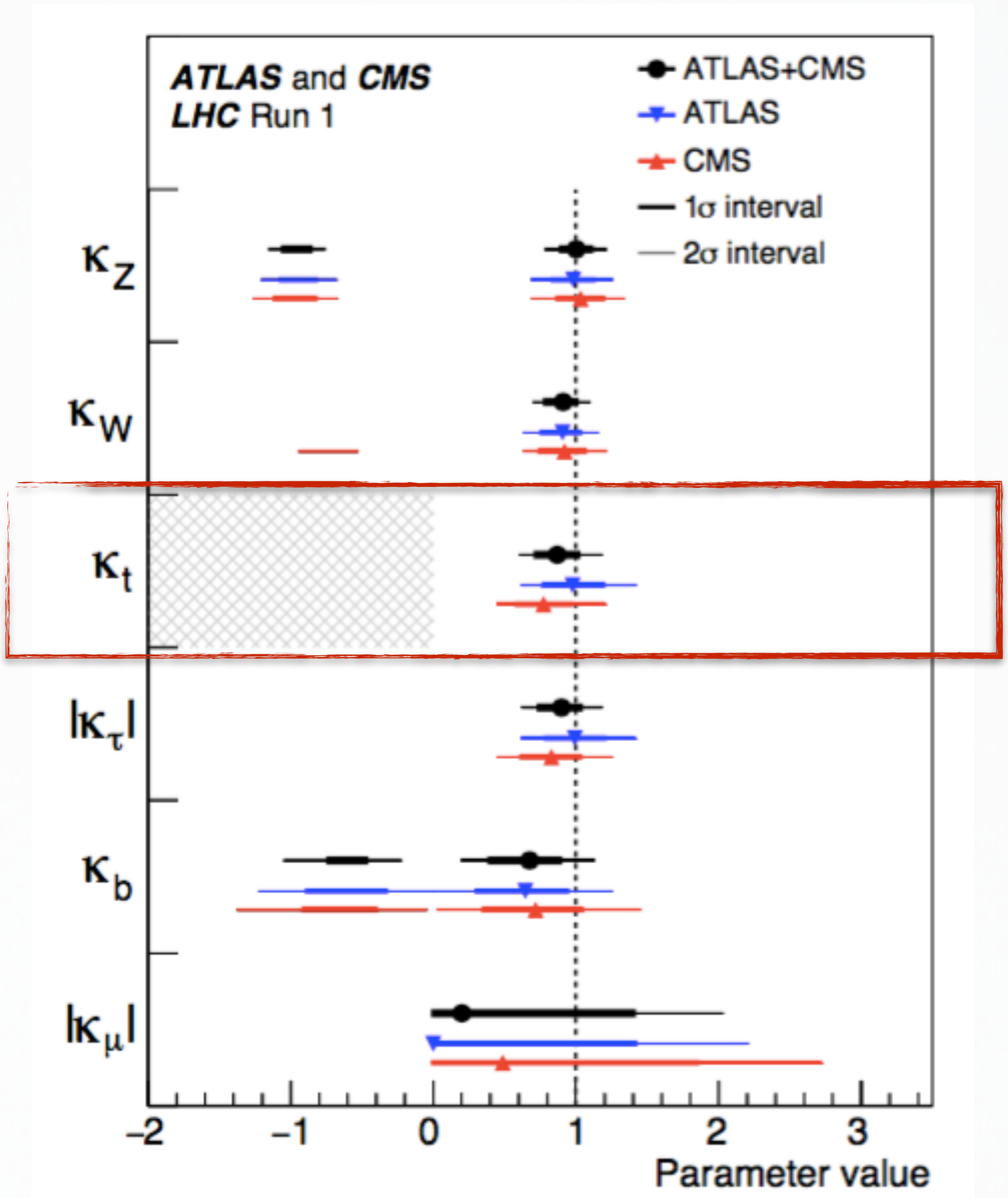
Catch me directly, if you can



How well do we know y_t ?

$$\kappa = \frac{y}{y_{SM}}$$

But mostly comes from indirect search analyses !



JHEP08 (2016) 045

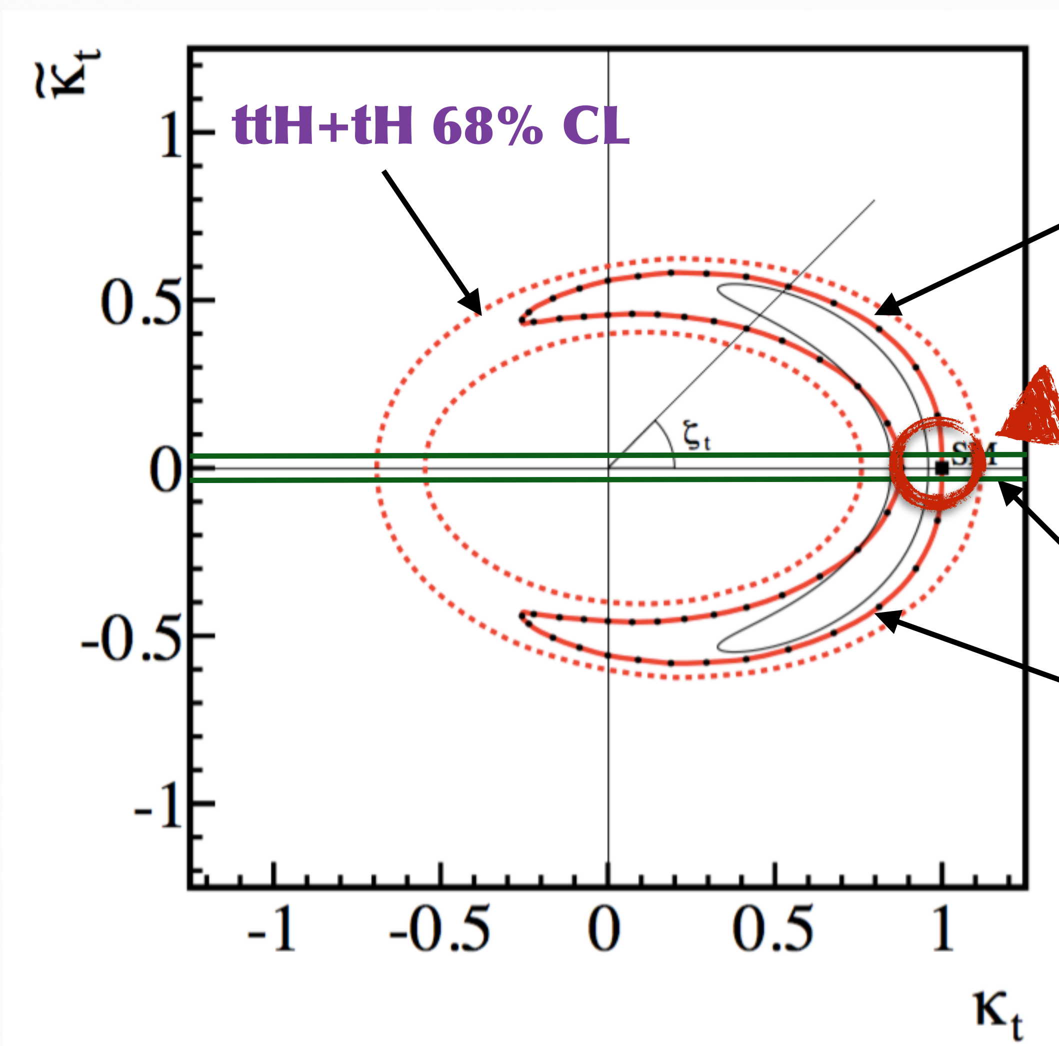
y_t and CP violation

Top-Higgs interaction

scalar **pseudoscalar**

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

CP violation phase: $\zeta_t = arctan(\tilde{\kappa}_t/\kappa_t)$



ttH+tH 95% CL

SM: $\kappa_t = 1$, $\tilde{\kappa}_t = 0$

Electron EDM (indirect):
$|\tilde{\kappa}_t| < 0.01$

All Higgs results

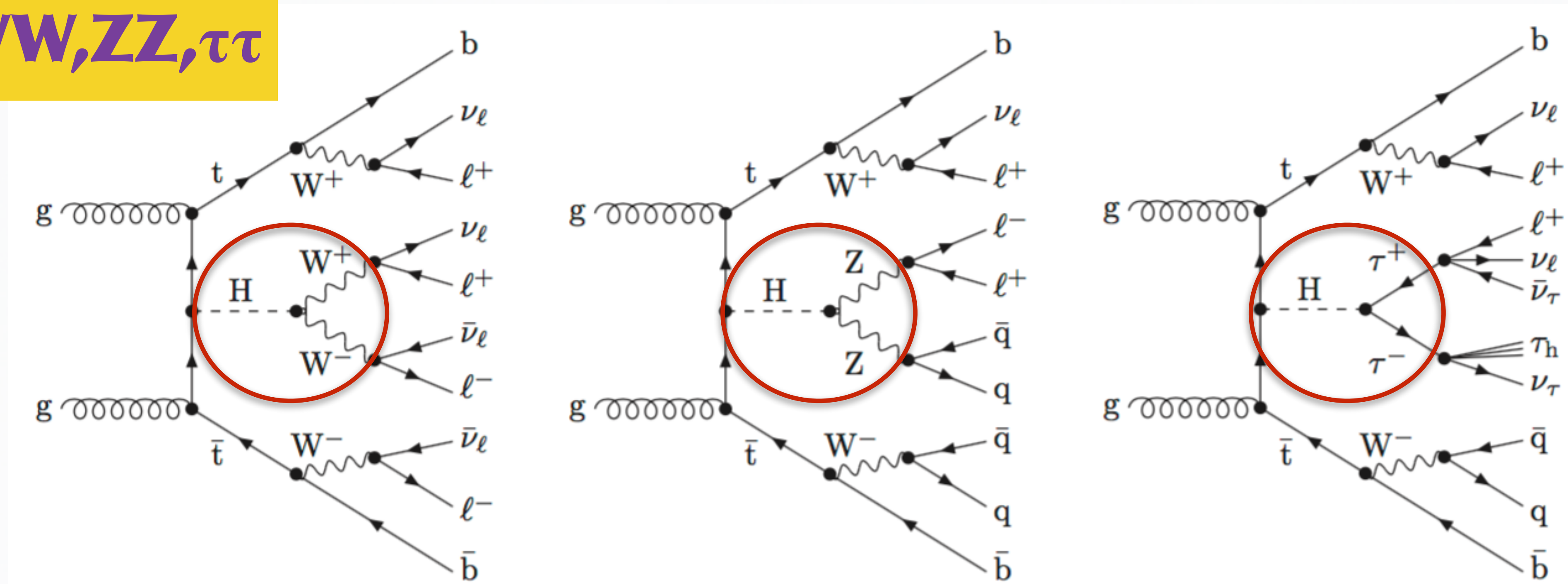
JHEP04 (2014) 004

JHEP 1311 (2013) 180

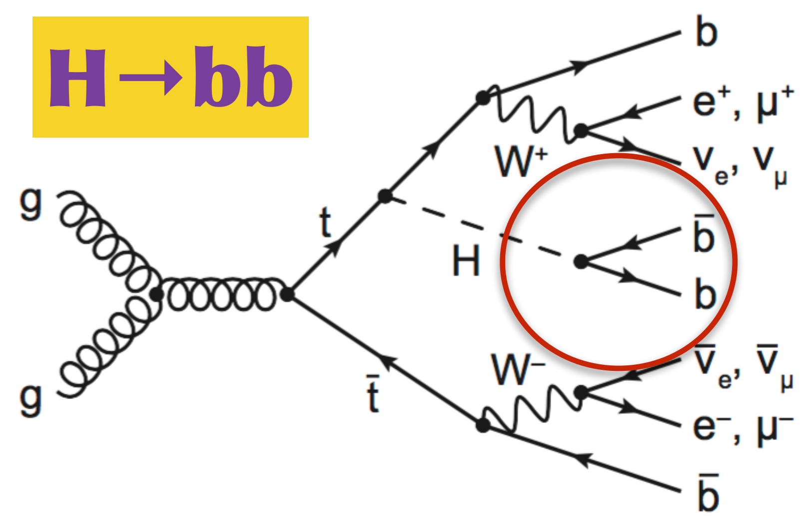
ttH

Golden process to directly probe y_t but a very complex final state !

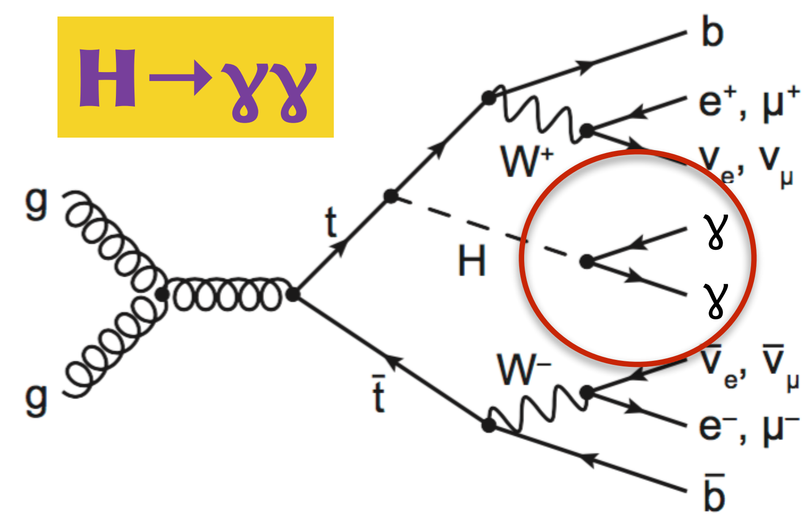
H→WW,ZZ,ττ



H→bb

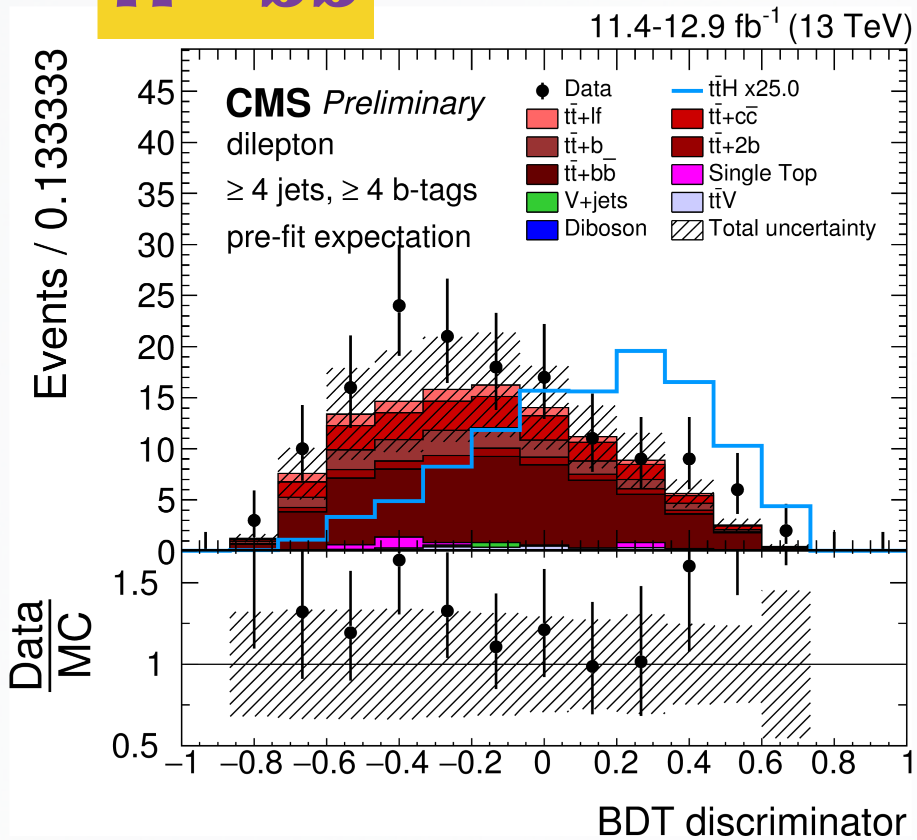


H→γγ



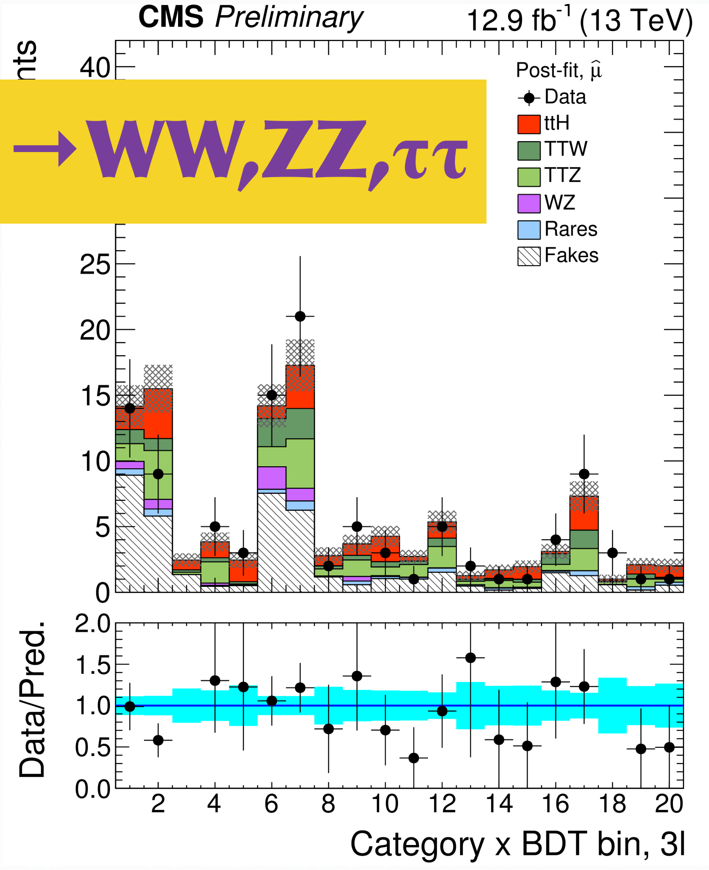
ttH search channels

H→bb



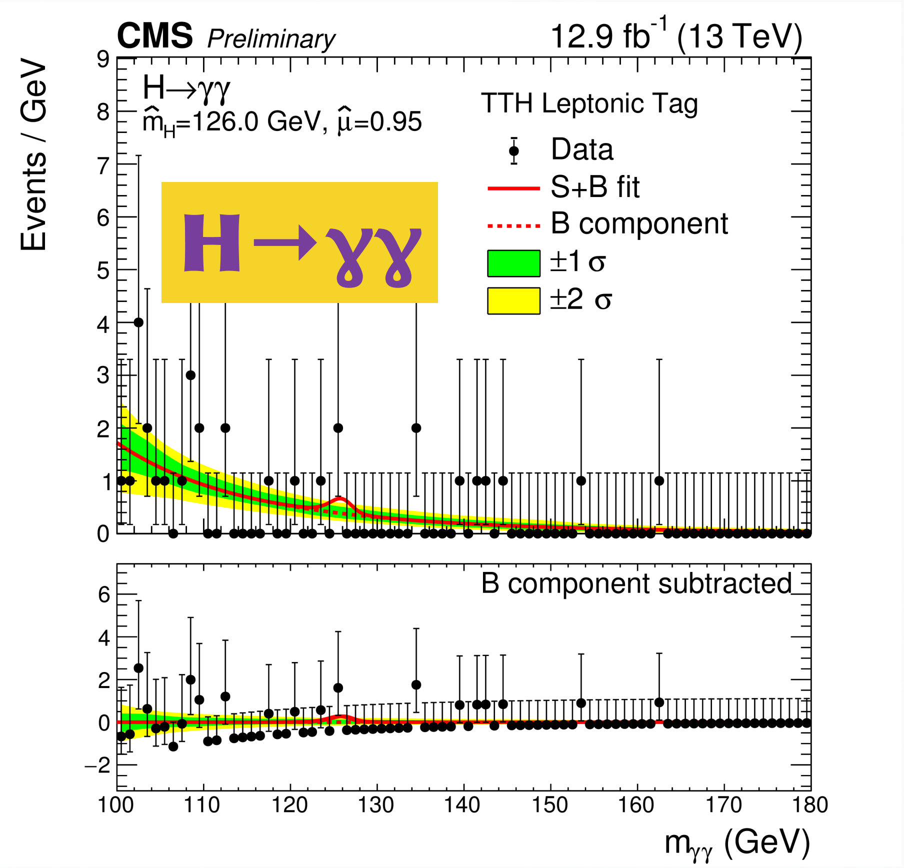
CMS-PAS-HIG-16-038

H→WW,ZZ,ττ



CMS-PAS-HIG-16-022

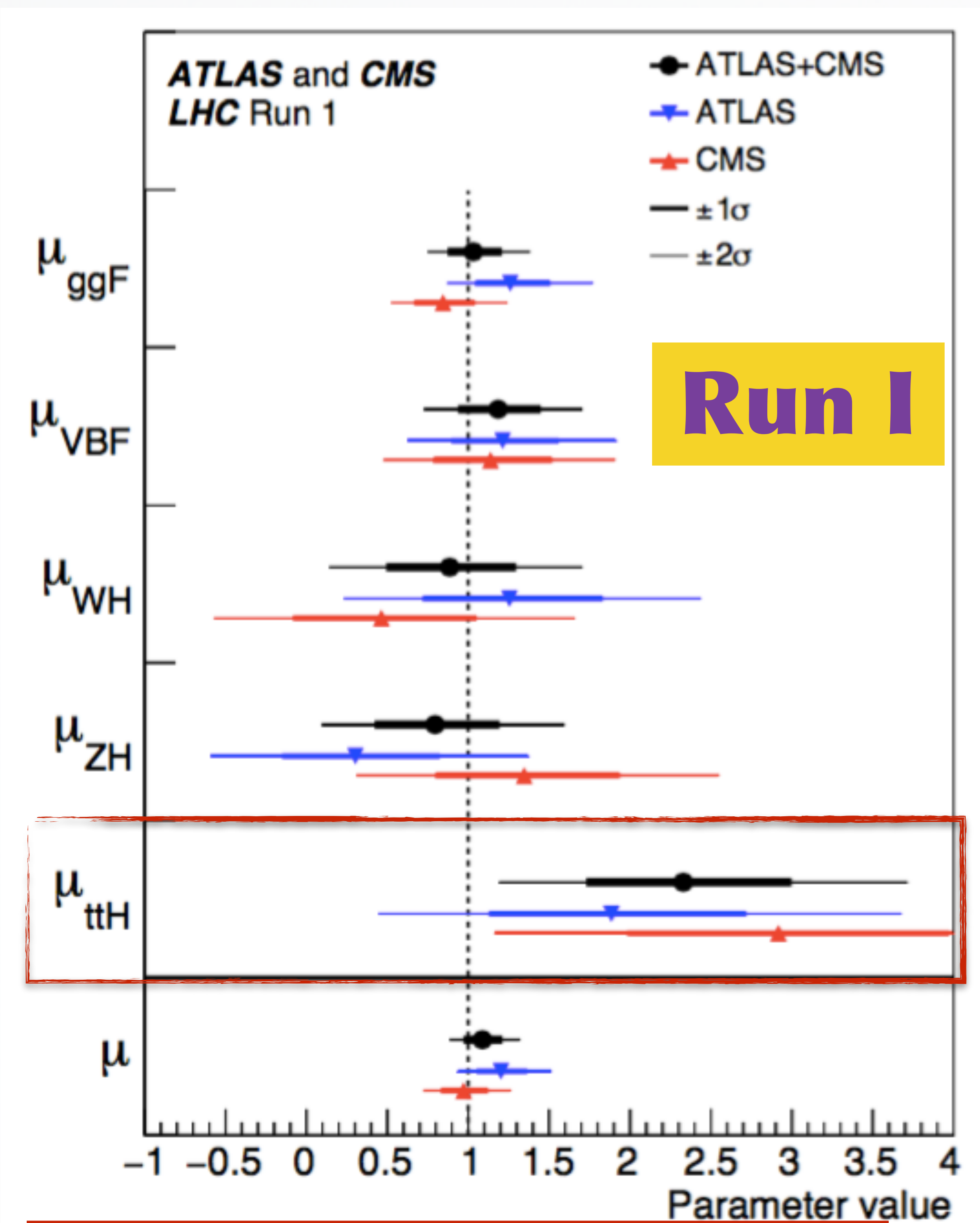
H→γγ



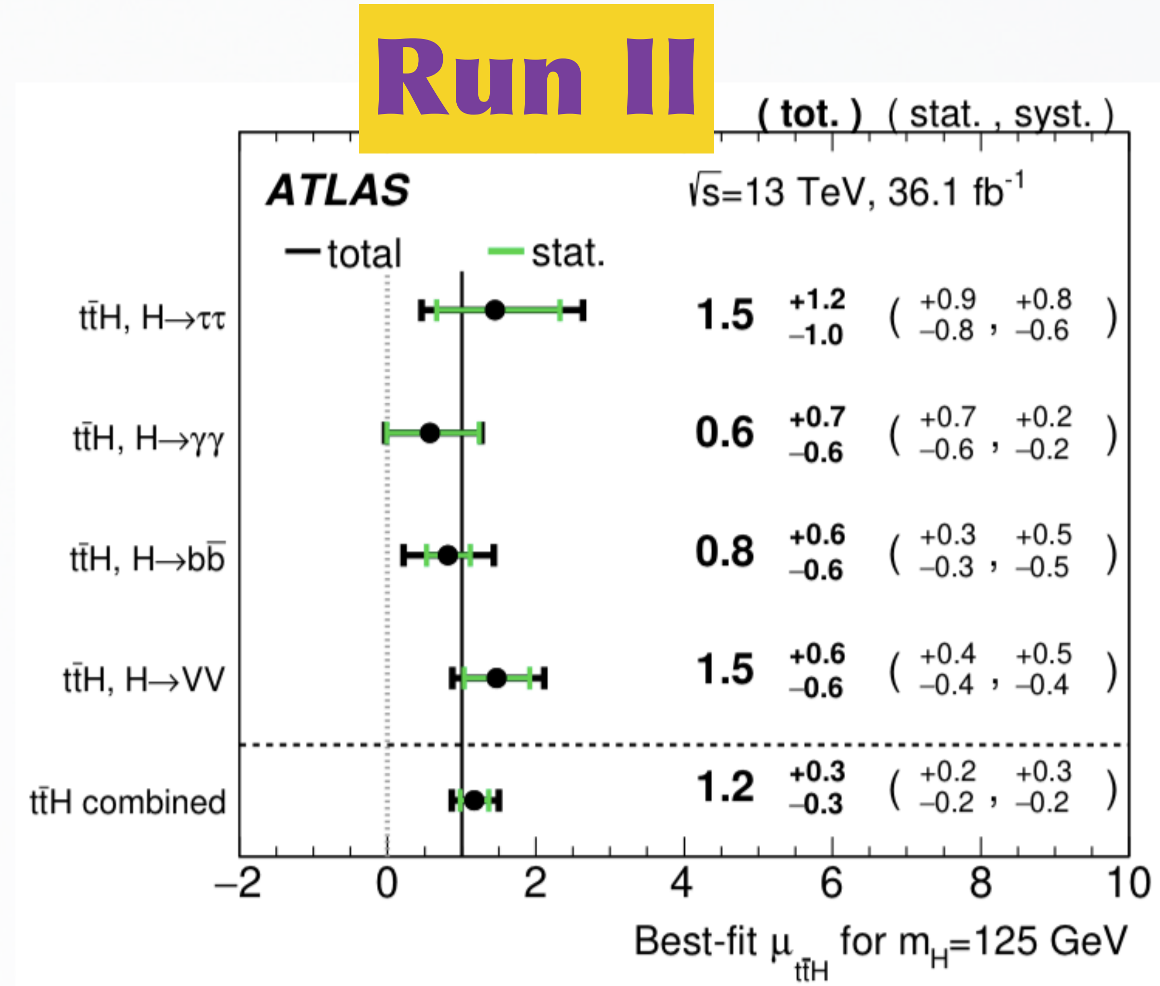
CMS-PAS-HIG-16-020

Summary of the latest ttH results

JHEP08 (2016) 045



Significance@8 TeV = 4.4 (2.0) σ



Significance@13 TeV = 4.2 (3.8) σ

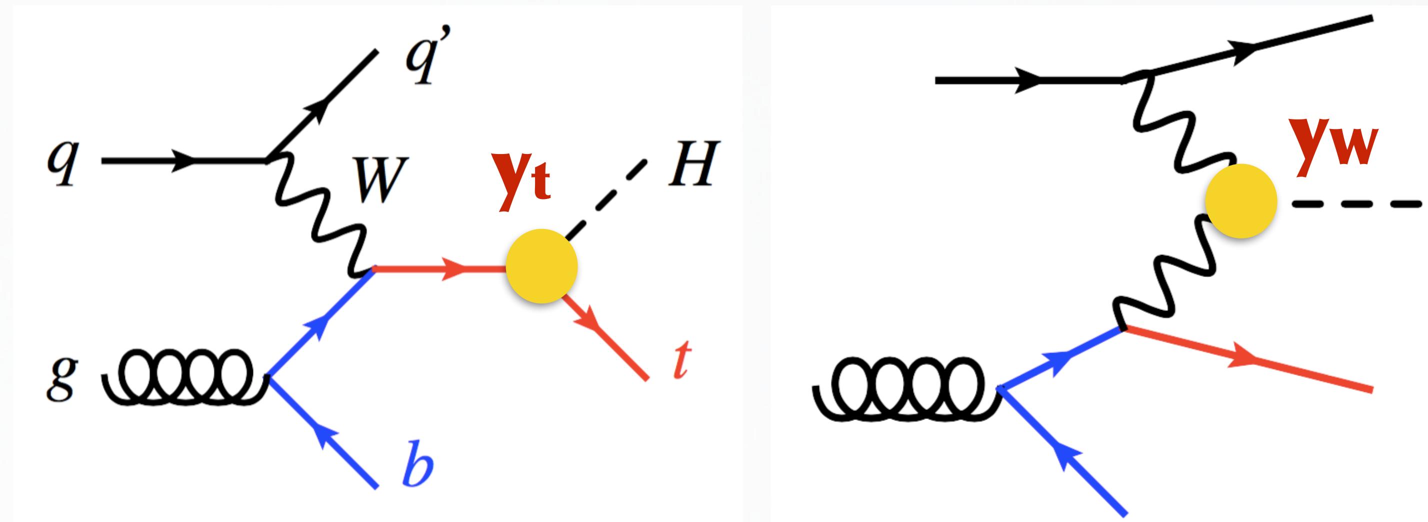
3.3 (2.5)σ @13TeV	**4.4 (2.0)σ @8TeV**	**4.2 (3.8)σ @13TeV**	**> 5σ ?**

2016 **2017** **2018**

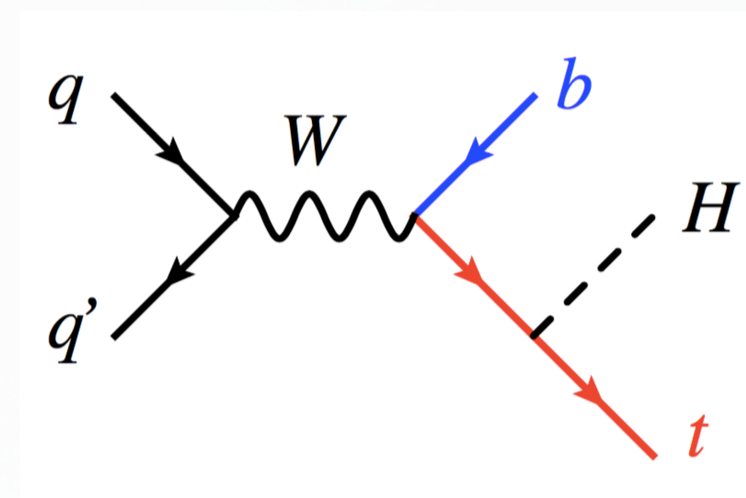
tHq

- Suppressed in SM by destructive interference: $\mathbf{y_t \cdot y_W < 0}$
- **tHq is sensitive to both magnitude and sign of $\mathbf{y_t}$**
- BSM can be looked for by probing **negative $\mathbf{y_t}$** still allowed from global fits
- 15x increase in tHq cross section assuming inverted coupling scenario, $y_t = -1$

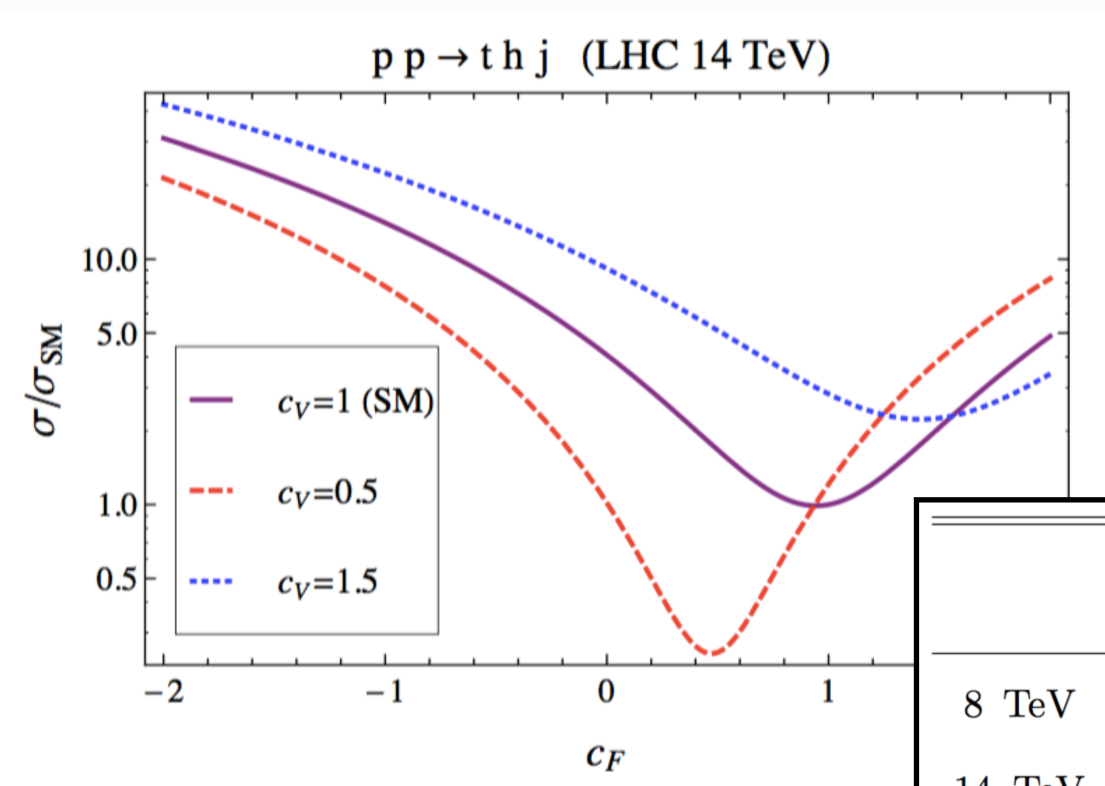
t channel



s channel



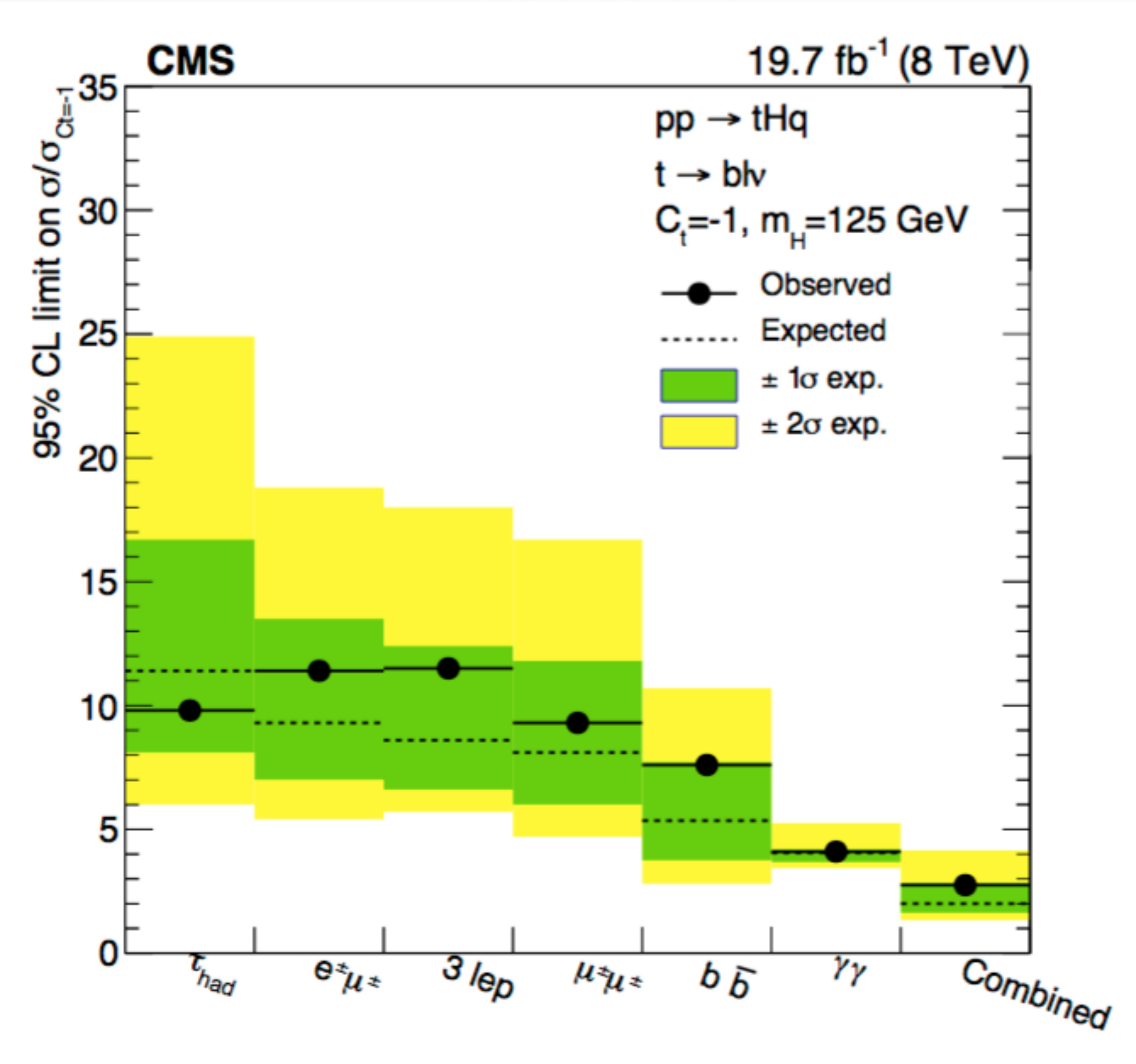
Eur. Phys. J. C (2015) 75: 267

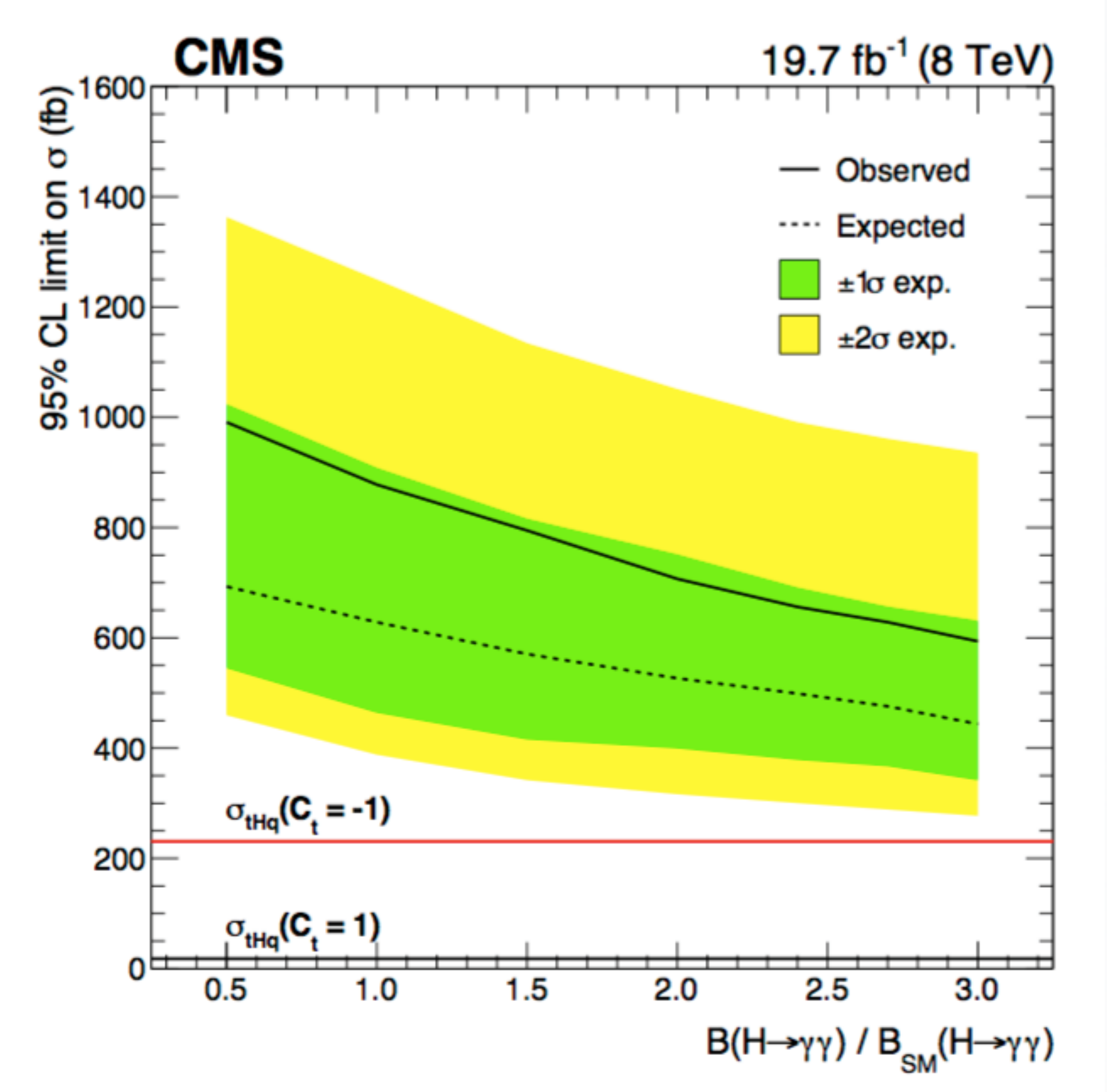


	$\sigma^{\rm NLO}(pp \to thj)$ [fb] $c_F = 1$	$\sigma^{\rm NLO}(pp \to thj)$ [fb] $c_F = -1$
8 TeV	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.}$
14 TeV	$88.2^{+1.7}_{-0.}$	982^{+28}_{-0}

J. High Energ. Phys. (2013) 2013: 22

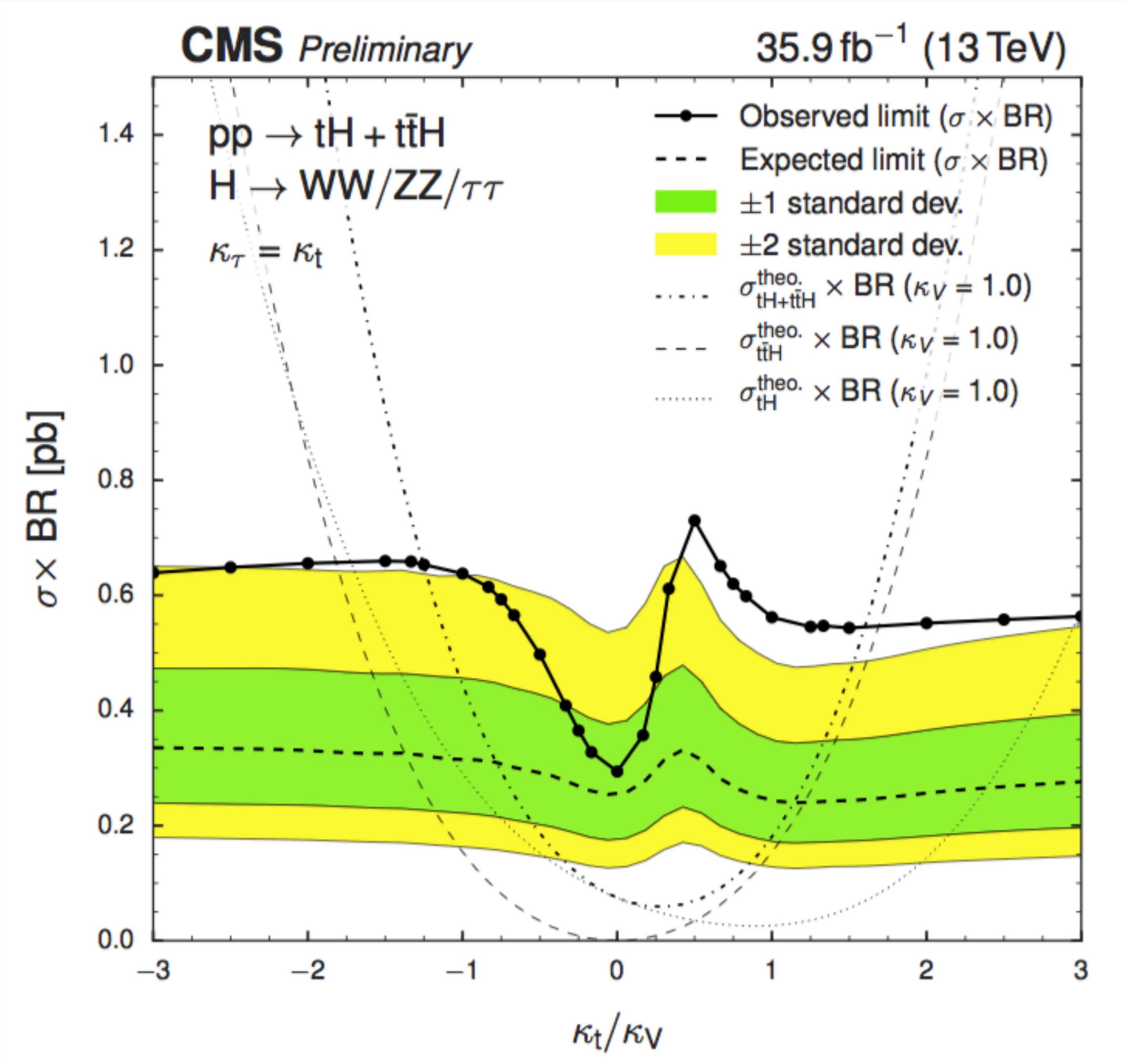
tHq results at 8 TeV





JHEP06 (2016) 177

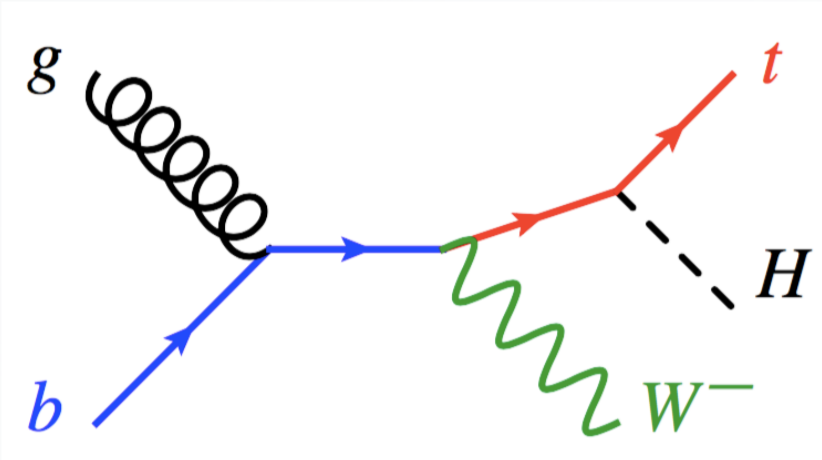
tHq results at 13 TeV

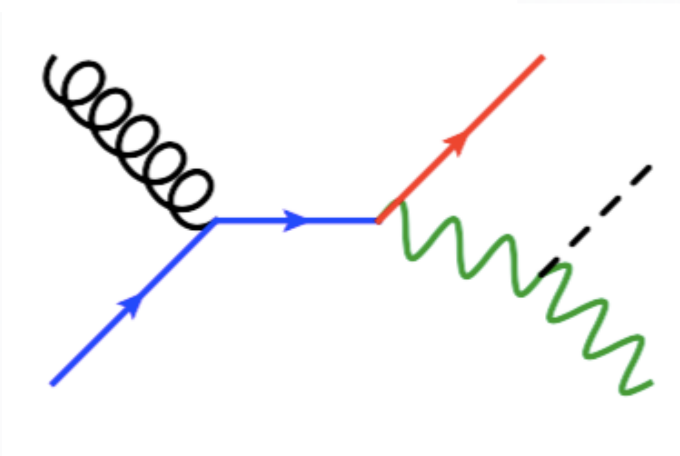


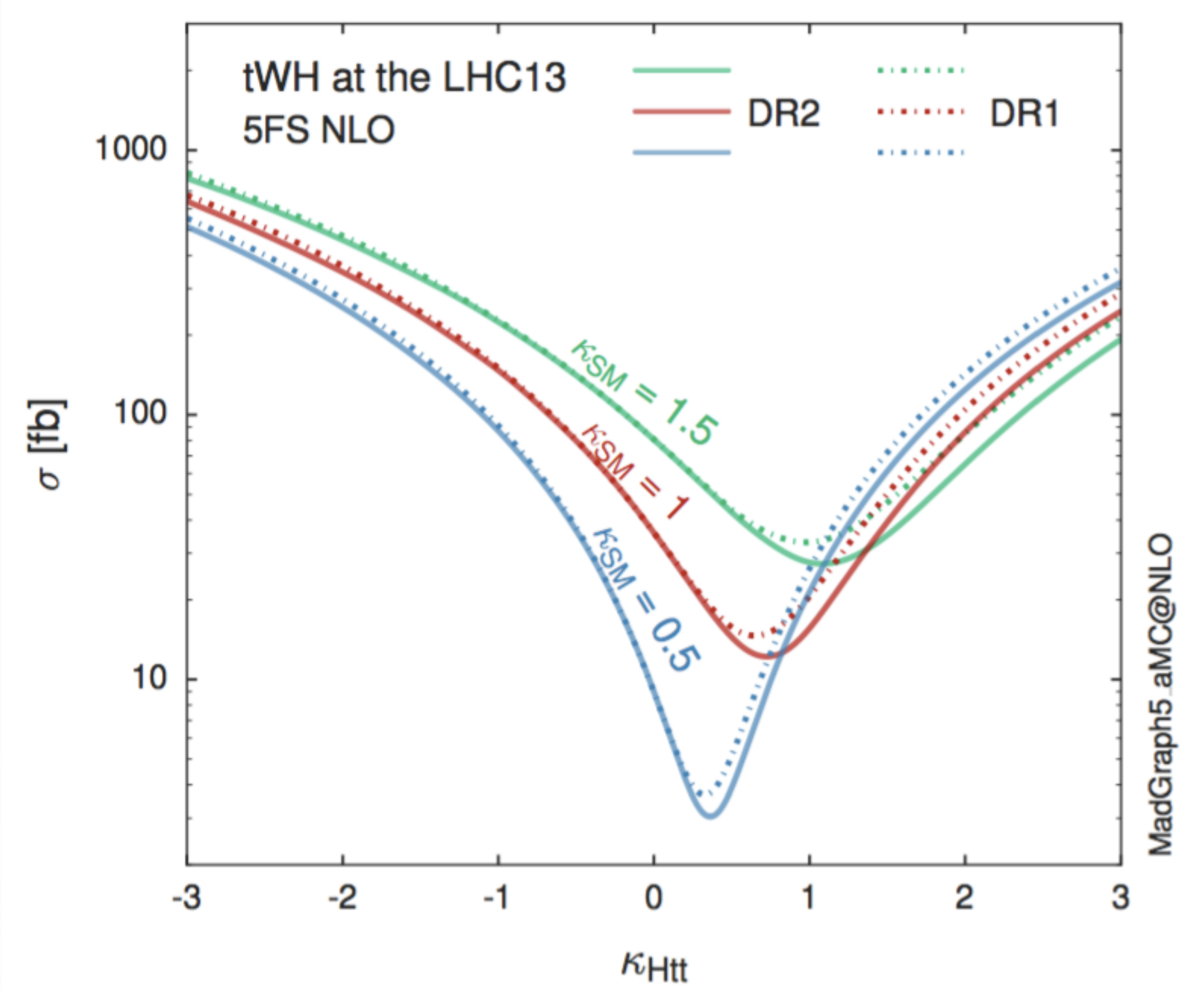
Observed (expected) 95% CL:
0.56 (0.24) pb =
3.1 x σ(ttH+tH)

HIG-17-005

tHW





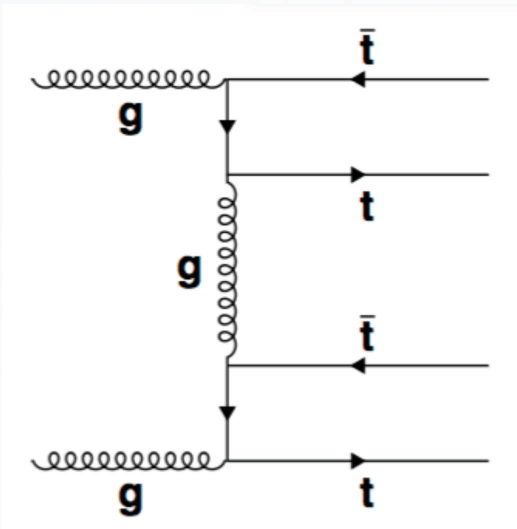


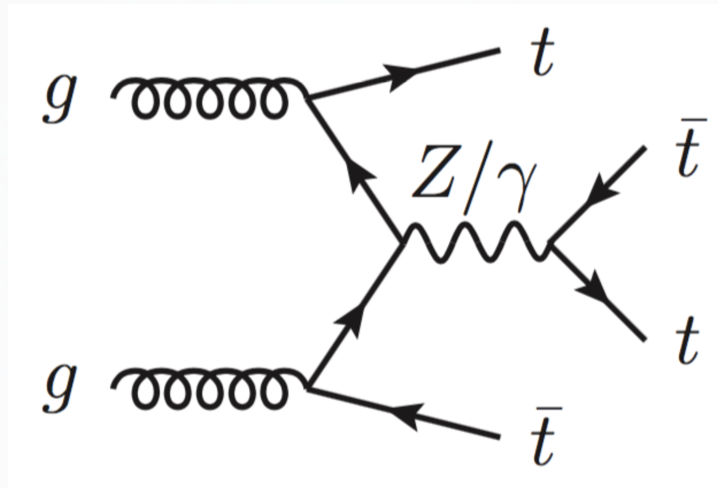
- As tHq, suppressed in SM by destructive interference: $\mathbf{y_t \cdot y_W < 0}$
- **Sensitive to both magnitude and sign of y_t**
- Significant increase in tHW cross section (up to 50x) in some phase space of (y_t,y_W)

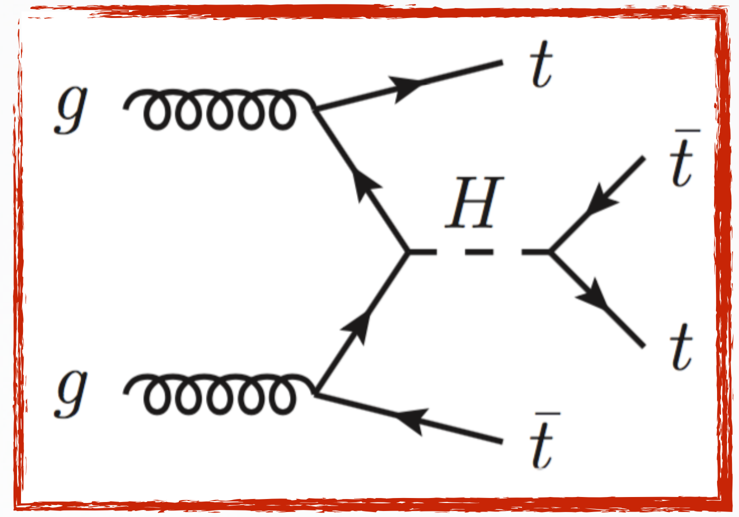
Eur. Phys. J. C (2017) 77: 34

No experimental results yet

Indirect probe of y_t in four tops



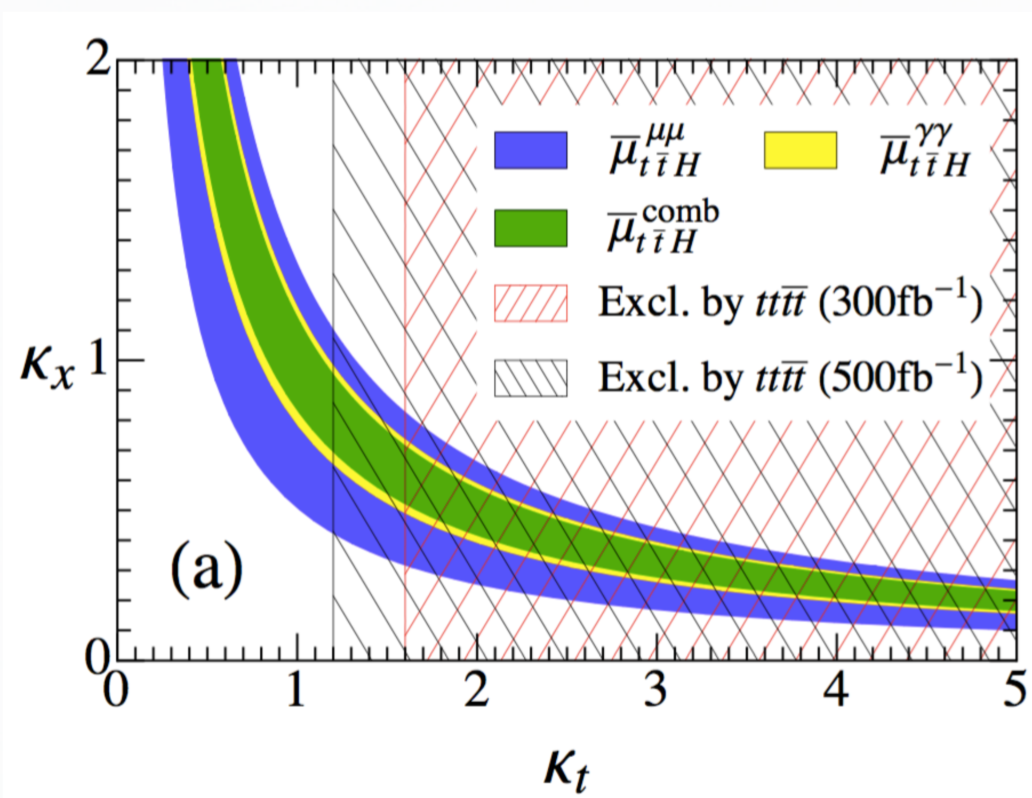




$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\text{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma_{\text{int}}^{\text{SM}} + \kappa_t^4 \sigma^{\text{SM}}(t\bar{t}t\bar{t})_H$$

arXiv:1602.01934

$$\kappa_x \equiv y_{Hxx}/y_{Hxx}^{\text{SM}}$$



	8 TeV	14 TeV
$\sigma^{\text{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\text{SM}}(t\bar{t}t\bar{t})_H$:	0.166 fb,	1.477 fb,
$\sigma^{\text{SM}}(t\bar{t}t\bar{t})_{\text{int}}$:	−0.229 fb,	−2.060 fb.

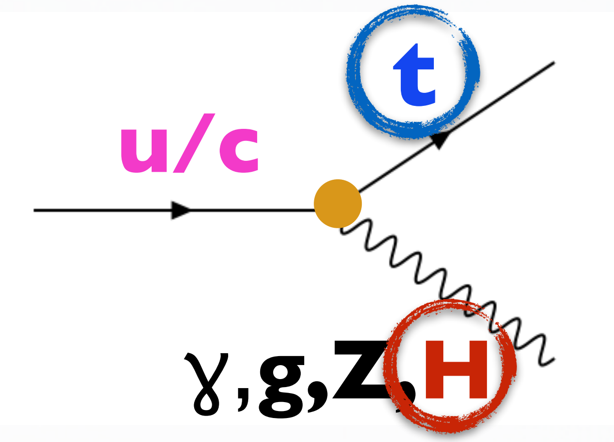
LHC data results @8TeV:

$\sigma(t\bar{t}t\bar{t}) \leq 23$ fb → $\kappa_t \leq 3.49$

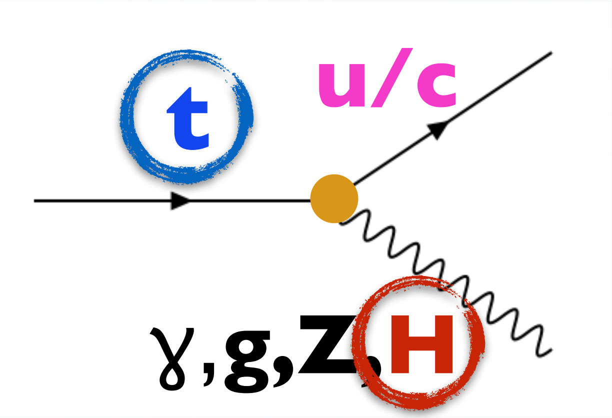
When flavours change but charge remains the same

- **Flavour-changing neutral currents (FCNC) forbidden at tree level in SM**
- Largely suppressed in higher orders by GIM mechanism
- But, could be significantly **enhanced in various BSM**
- Direct probe of **anomalous y_t**

FCNC in production



FCNC in decay

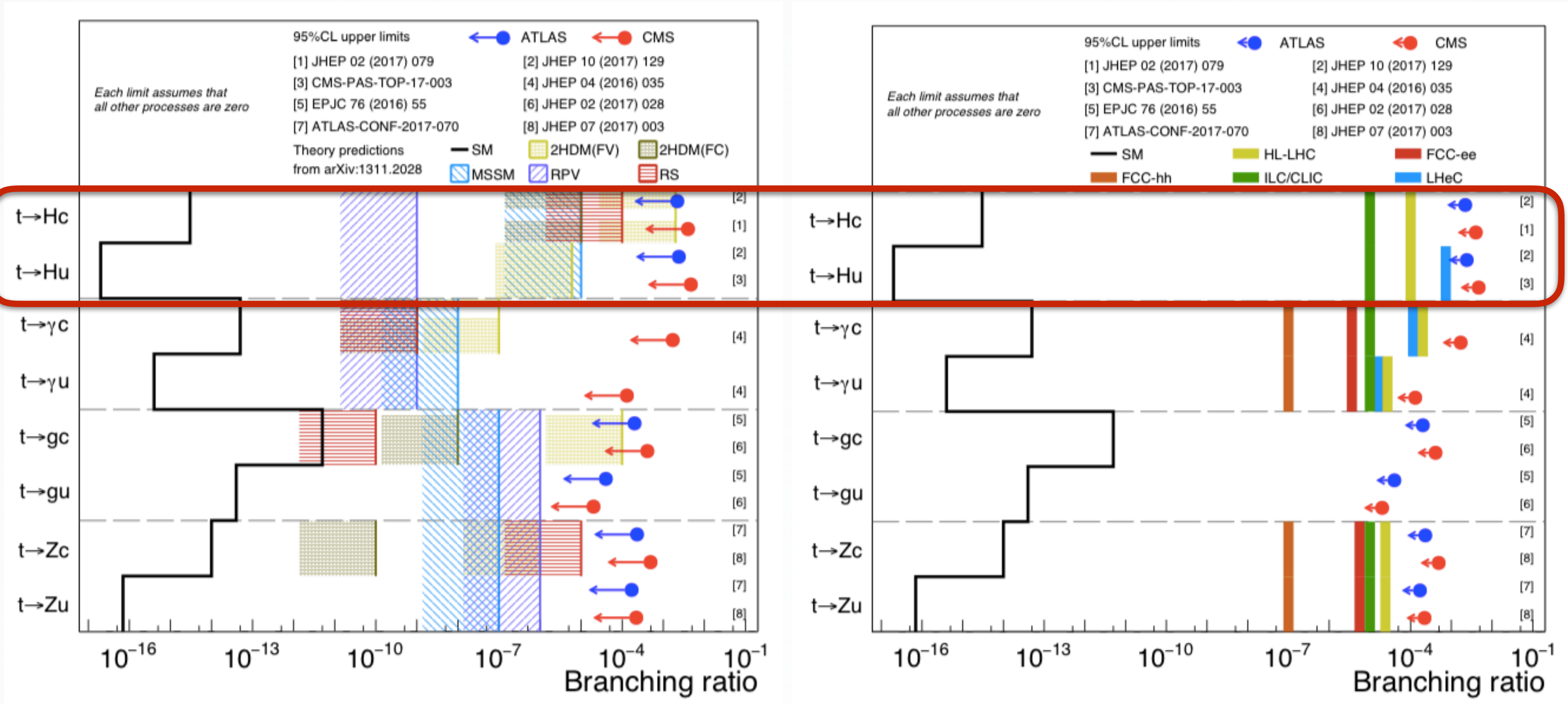


	SM	2HDM	MSSM	RS
$B(t\to cg)$	**10^{-12}**	10^{-8} - 10^{-4}	10^{-7} - 10^{-6}	10^{-10}
$B(t\to cZ)$	**10^{-14}**	10^{-10} - 10^{-6}	10^{-7} - 10^{-6}	10^{-5}
$B(t\to c\gamma)$	**10^{-14}**	10^{-9} - 10^{-7}	10^{-9} - 10^{-8}	10^{-9}
$B(t\to cH)$	**10^{-15}**	10^{-5} - 10^{-3}	10^{-9} - 10^{-5}	10^{-4}

arXiv:1311.2028

Top-Higgs FCNC results

BSM | **Future projections**

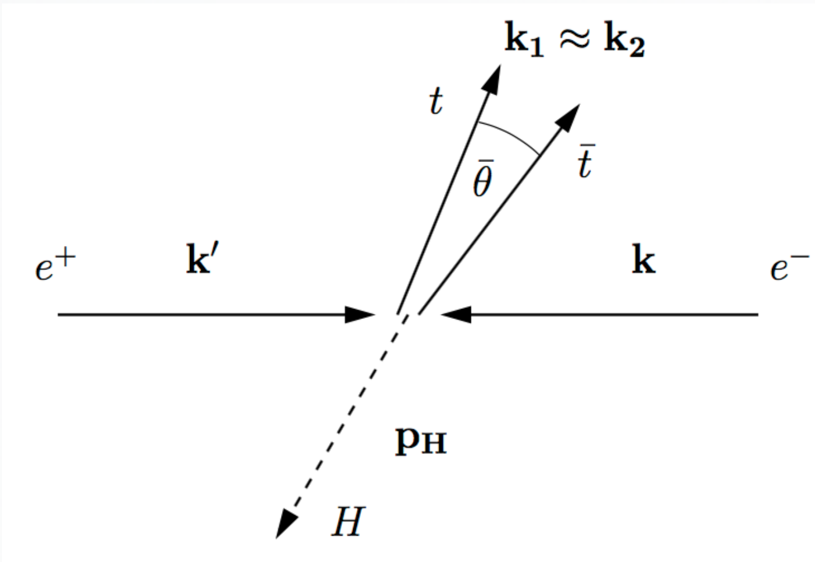


arXiv:1711.01852

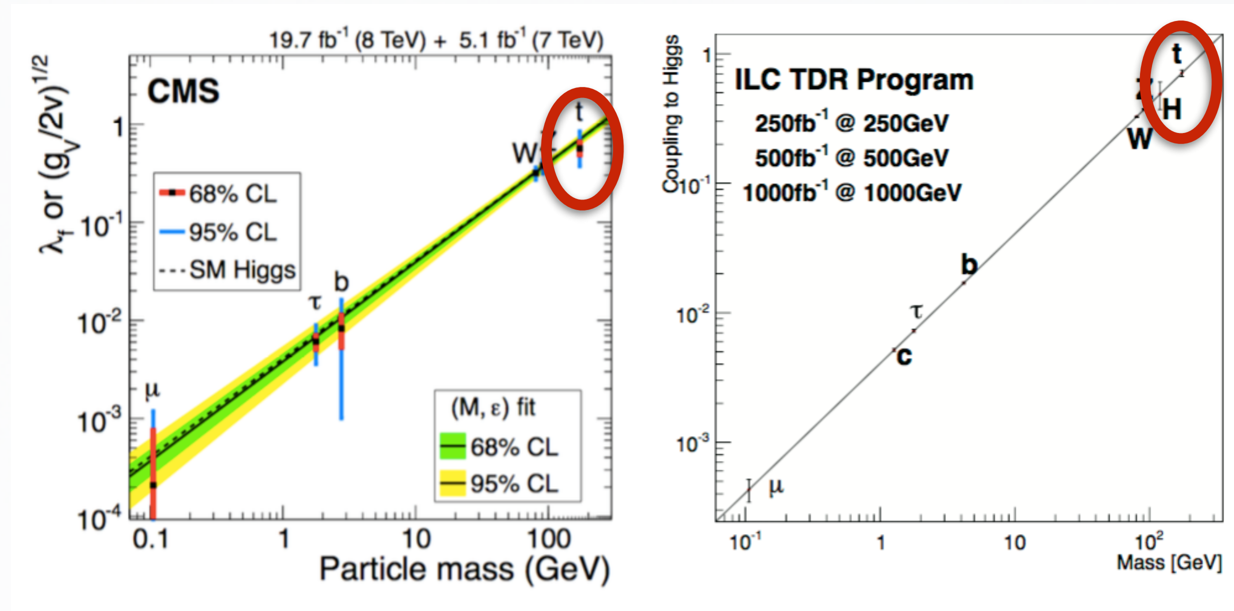
Study of y_t at future colliders

@ILC/CLIC

$e^+e^- \to Z/\gamma^* \to ttH$ arXiv:0604166



arXiv:1506.05992



@100TeV

arXiv:1507.08169		$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$m_t = 174.1$ GeV	0.3640	0.5307	0.6860
	$m_t = 172.5$ GeV	0.3707	0.5454	0.6800
100 TeV	$m_t = 174.1$ GeV	23.88	37.99	0.629
	$m_t = 172.5$ GeV	24.21	38.73	0.625

Collider	HL-LHC	ILC	LC 1-3 TeV	FCC-ee+hh
λ_t	4%	14%	$2-4\%$	$1-2\%$
λ_H	50%	83%	$10-15\%$	$5-10\%$

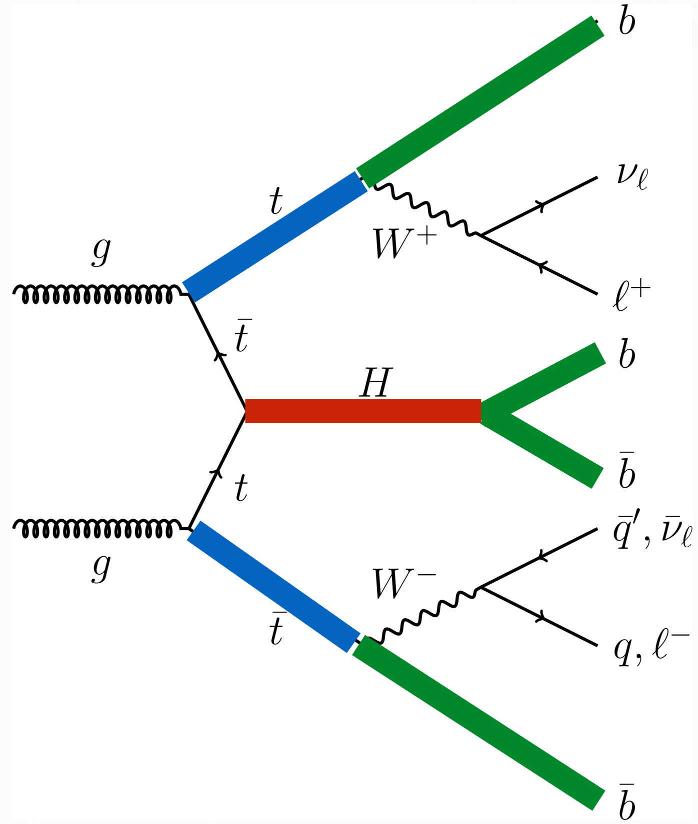
arXiv:1510.09056

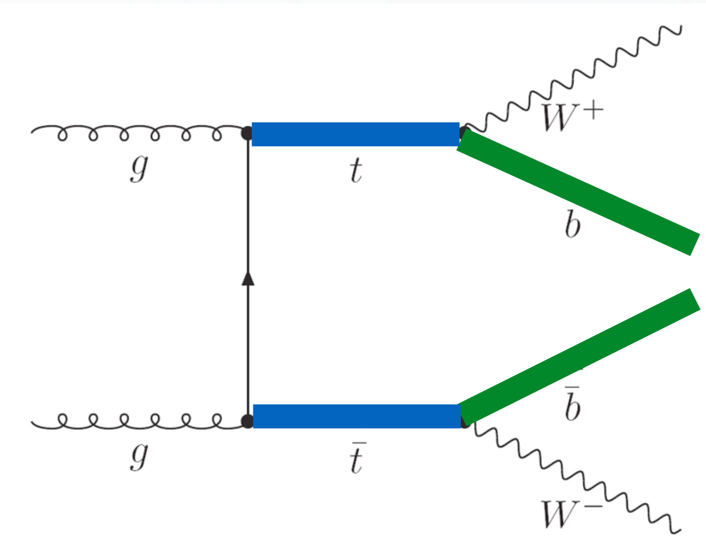
Expected precision in y_t determination

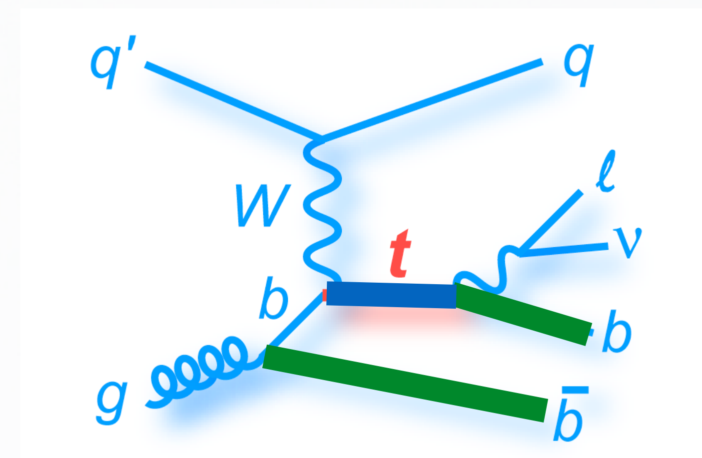
Top, Higgs and beauty

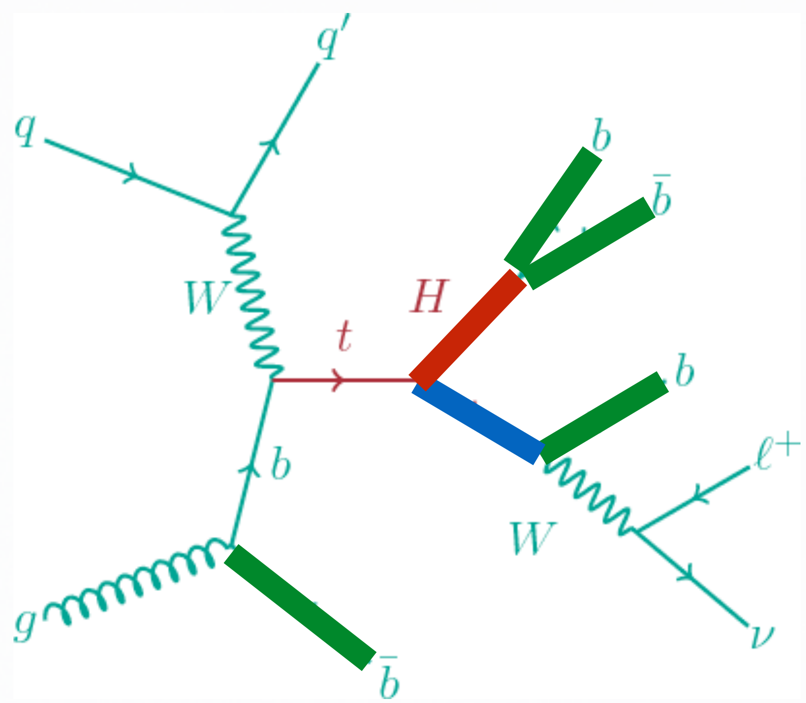
beauty **t** **H**

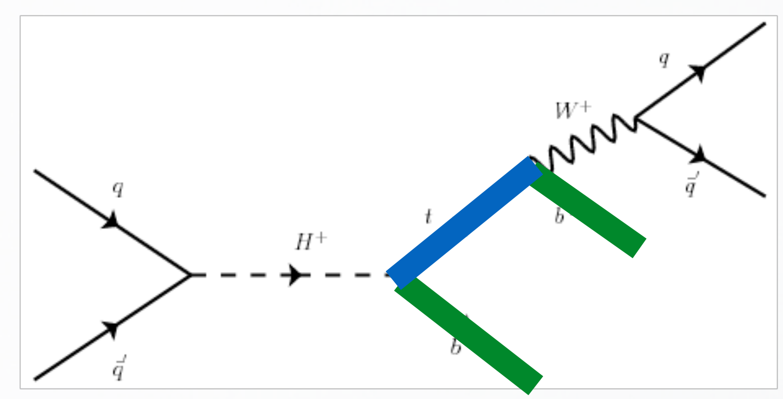
- b quarks are always present in top quark decays: $\boldsymbol{B}$(t→W**b**) ≈100%
- $\boldsymbol{B}$(H→**bb**) ≈59% is the dominant Higgs decay mode
- b jet identification (***b tagging***) is crucial for SM and BSM analyses with top and Higgs

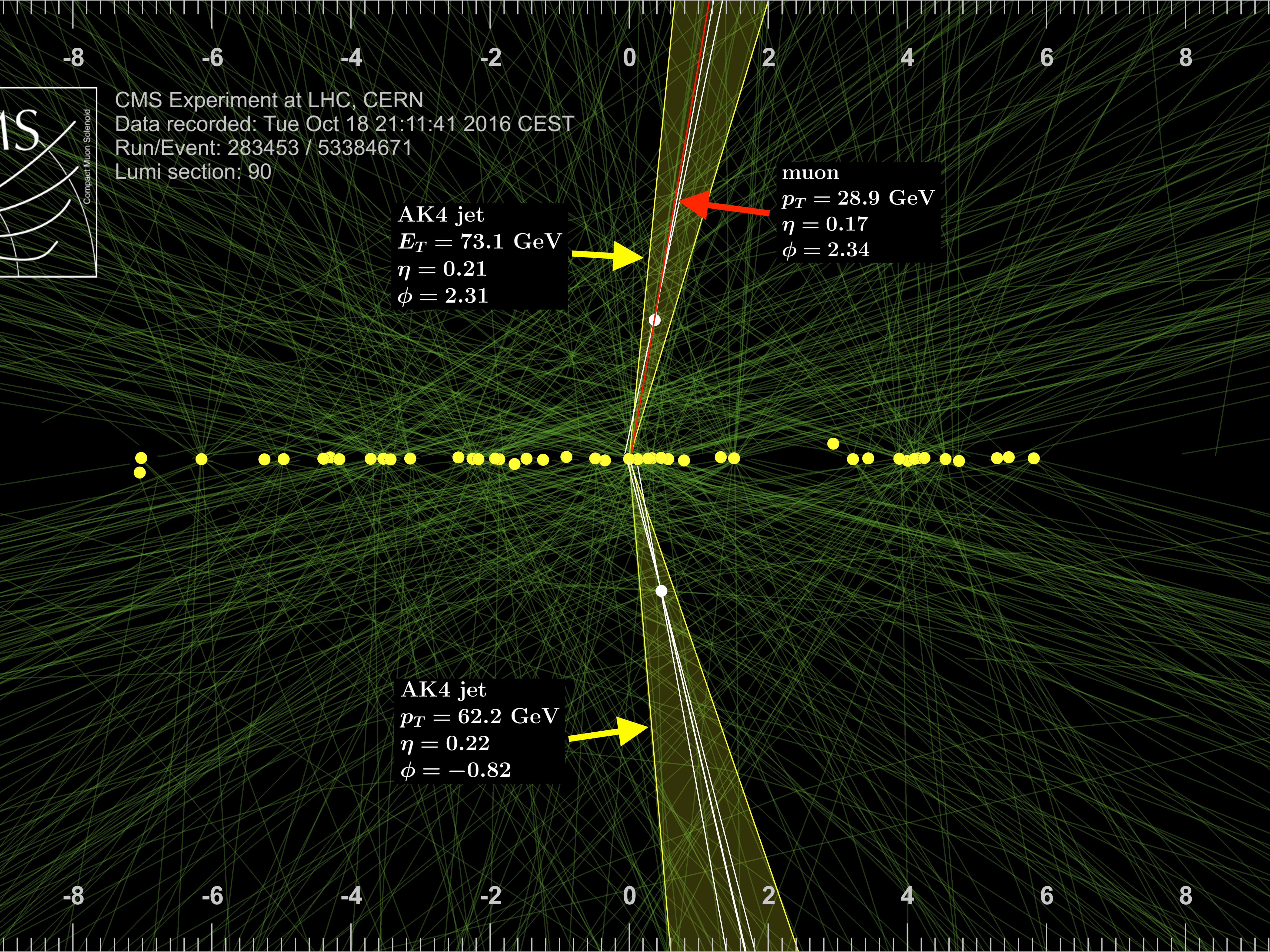










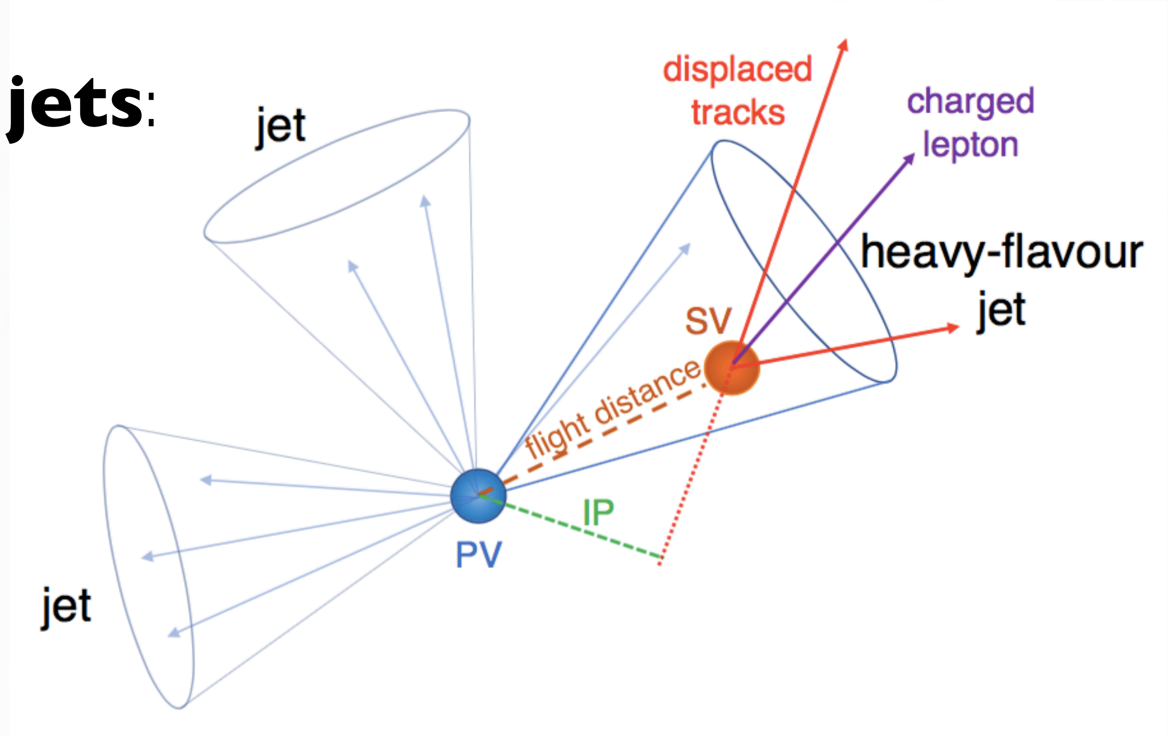


CMS Experiment at LHC, CERN
Data recorded: Tue Oct 18 21:11:41 2016 CEST
Run/Event: 283453 / 53384671
Lumi section: 90
Compact Muon Solenoid
AK4 jet
$E_T = 73.1$ GeV
$\eta = 0.21$
$\phi = 2.31$
muon
$p_T = 28.9$ GeV
$\eta = 0.17$
$\phi = 2.34$
AK4 jet
$p_T = 62.2$ GeV
$\eta = 0.22$
$\phi = -0.82$
-8 -6 -4 -2 0 2 4 6 8

How to tag the beauty

- **b** jets = hadronised **b** quarks

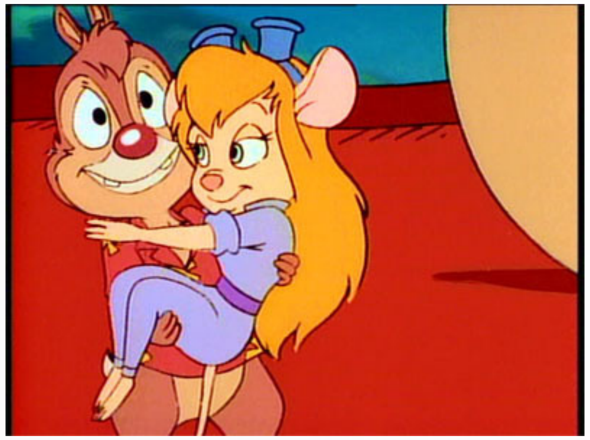
- Use **B hadron** properties to identify **b jets**:



  - Relatively large mass: 5-6 GeV
  - Long lifetime: $c\tau \approx 450\ \mu m$
    $E = 70$ GeV $\Rightarrow \beta\gamma c\tau \approx 5$ mm
  - Daughter particle multiplicity
    ≈ 5 charged tracks per decay
  - Possible presence of B semileptonic decays
    $b \to \mu\nu X$ (Br $\approx$ 11%), $b \to c \to \mu\nu X$ (Br $\approx$ 10%)
  - Tertiary vertex (B meson decay to a charmed hadron),
    $c\tau \approx 120\text{-}310\ \mu m$

b pickup methods

Algorithm	ATLAS	CMS
Impact parameter based	IP2D, IP3D, TrackCounting, JetProb	TCHP, TCHE, JP, JPB
Secondary vertex based	SV0, SV1, SV	SSVHP, SSVHE
Decay chain multi-vertex	JetFitter	
Soft lepton	SMT, p_TRel	Soft Lepton Taggers
Multivariate	JetFitterCombNN, MV1c, MV2	CSV, CSVv2, cMVAv2
Machine learning	**DL1**	**DeepCSV, DeepFlavour**

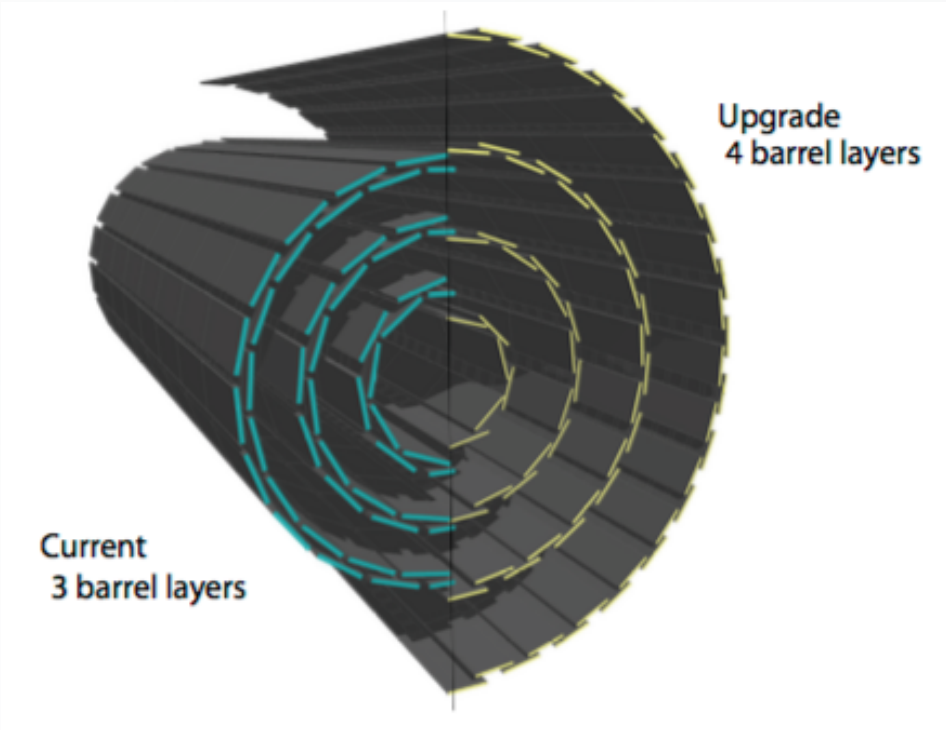


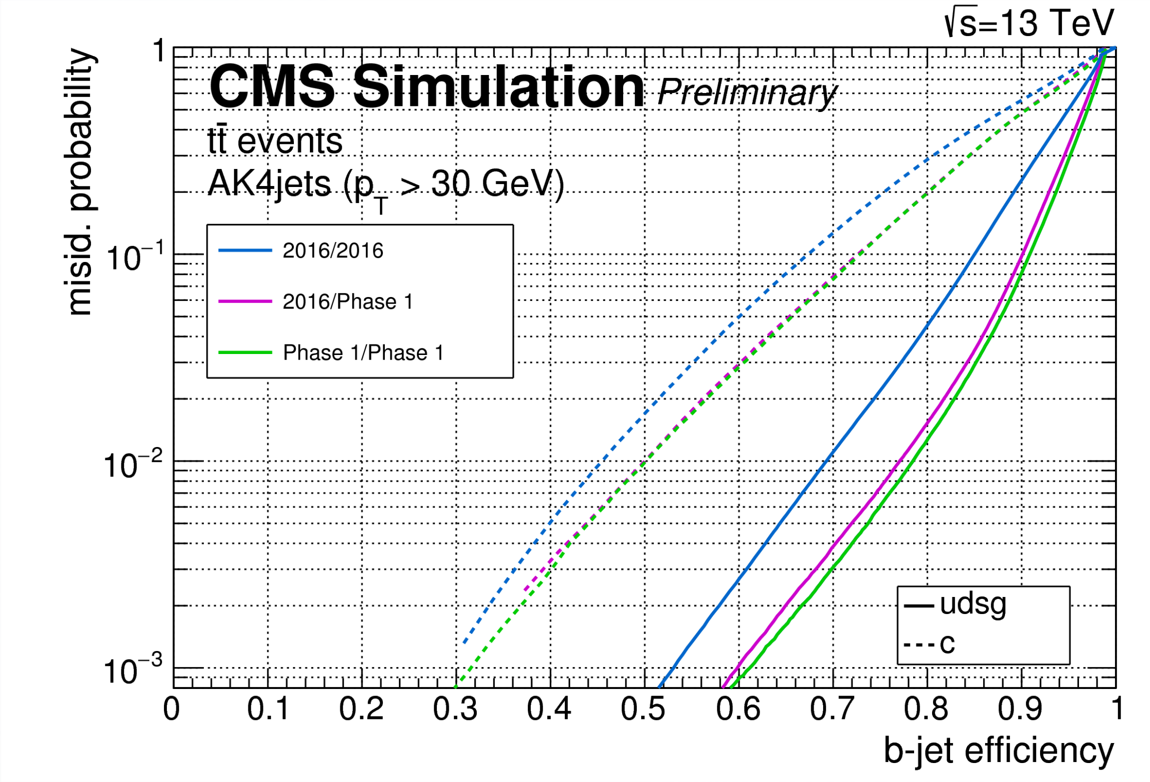
Operating points:

b tag: 60%, 70%, 77%, 85% (ATLAS)
mis tag: 0.1%, 1%, 10% (CMS)

CMS Phase I Pixel upgrade

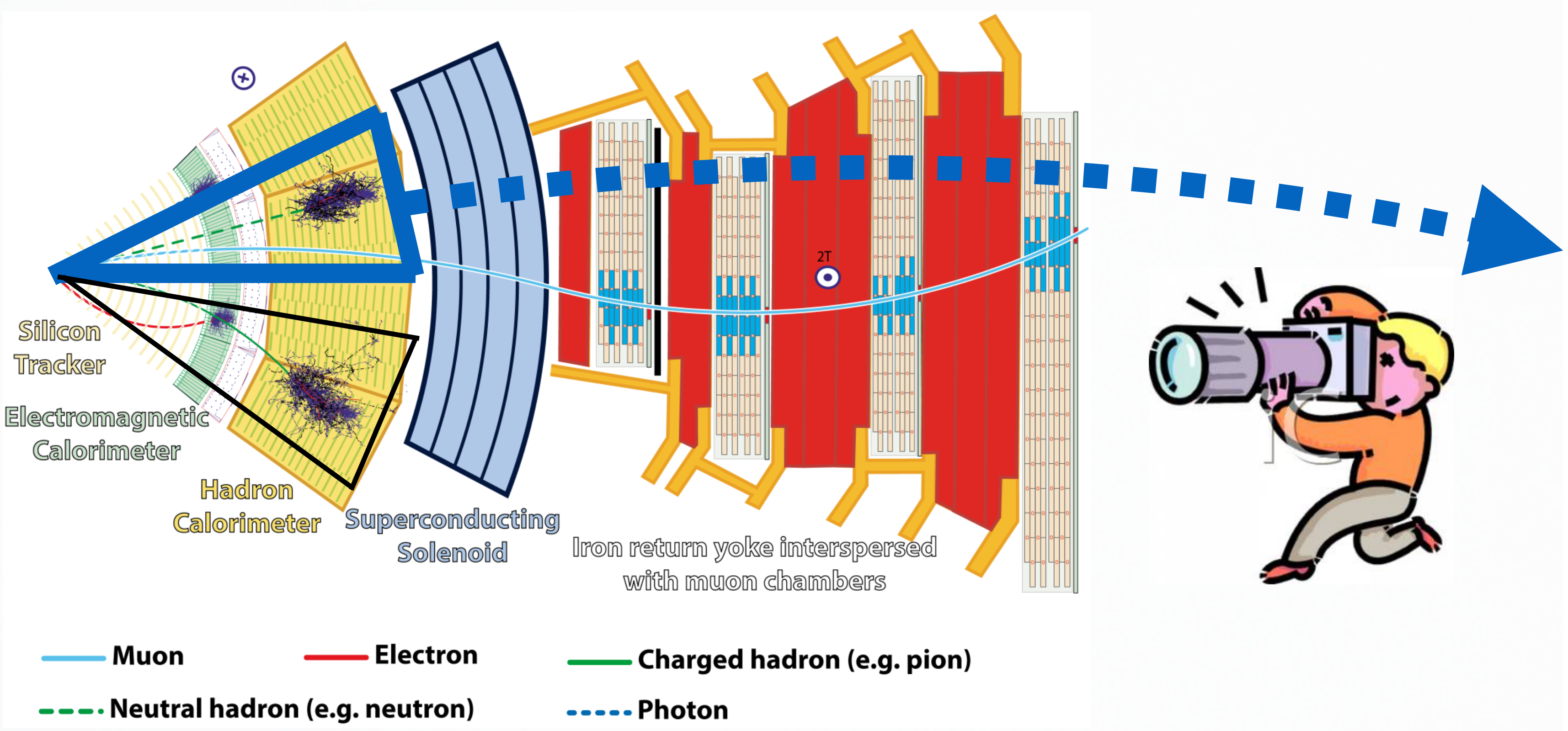
- The pixel detector completely replaced in 2016
- One additional pixel layer close to the new beam pipe installed in LS1 → **significant improvement in the flavour tagging**
- Reduced material budget, improved ROCs, higher $|\eta| < 2.5$ coverage
- Challenging commissioning of the new detector over 2017, but overall good b tagging performance

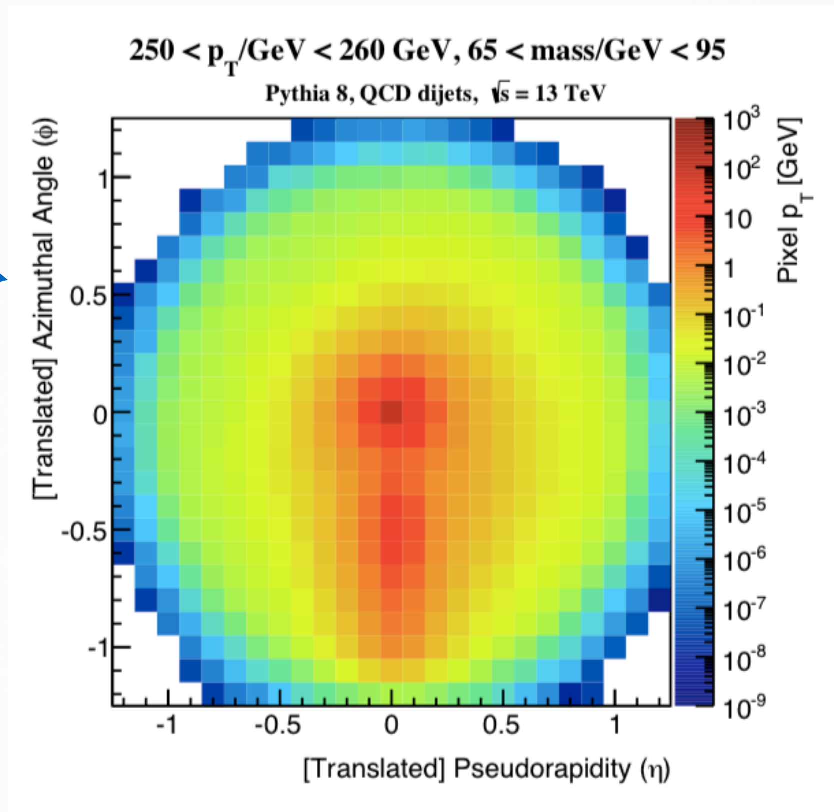




Rise of Machines

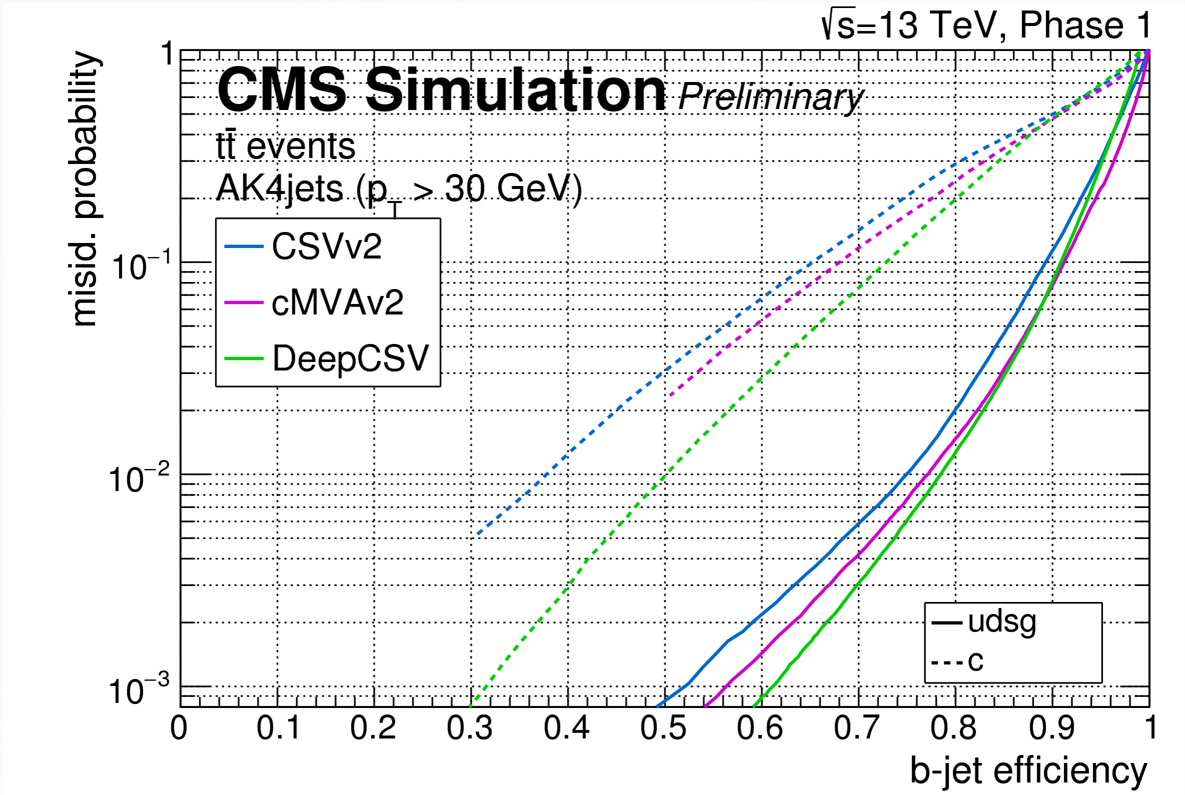
- **Machine learning** finds more and more applications in many fields of life and science
- The use of **convolutional** and **recurrent** neural networks to apply on **image-like data**
- Use a **large amount of raw information** in the most efficient way
- Possible to apply a **looser selection** on tracks and vertices
- Application to flavour tagging as **multi-classification** → tag all objects with one tagger

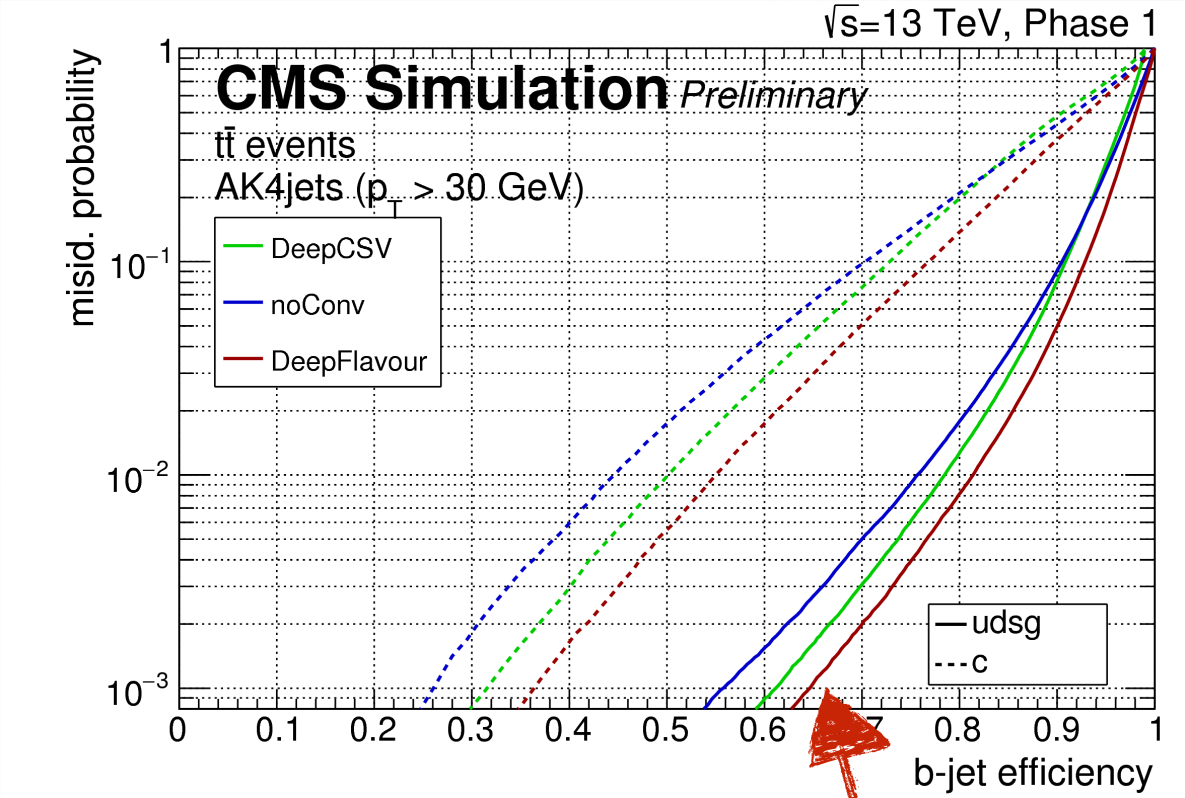


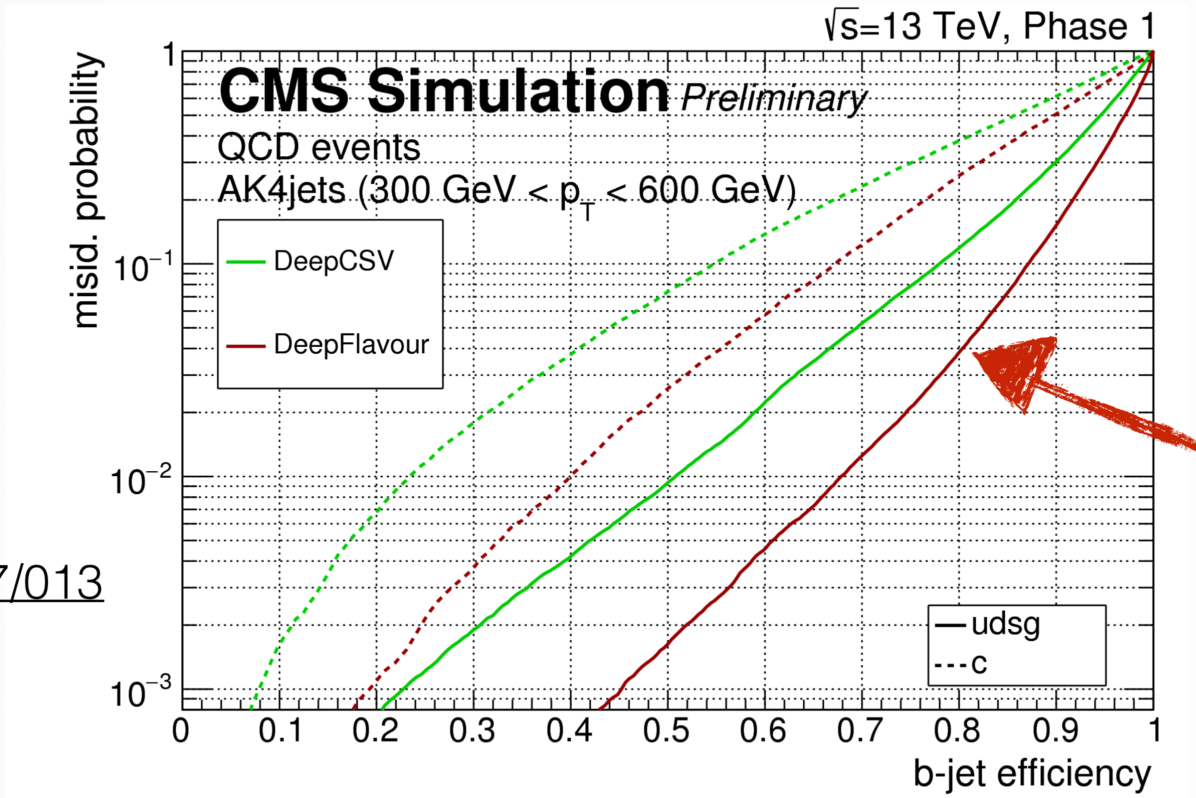


JHEP 07 (2016) 069

Performance results on MC





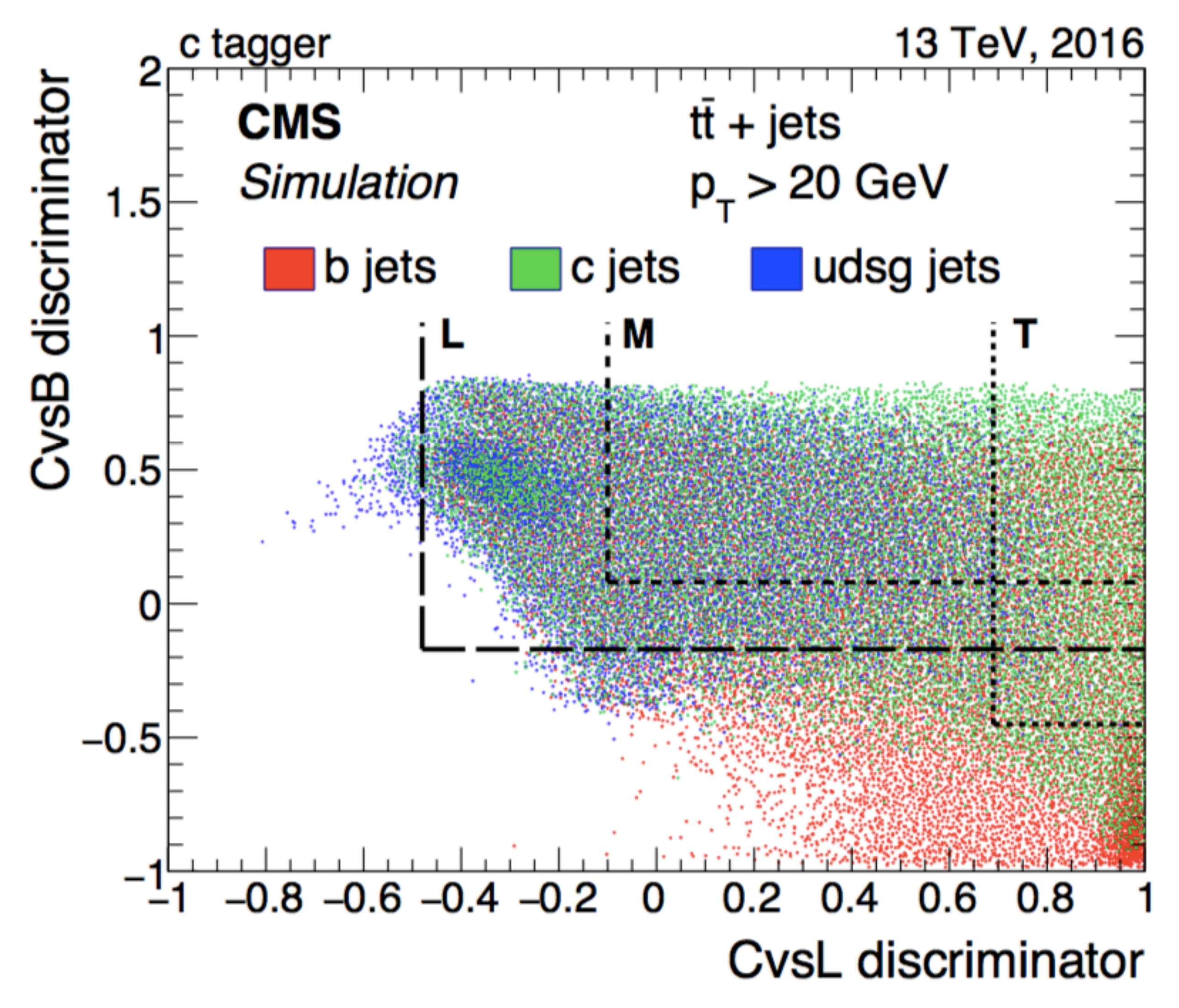


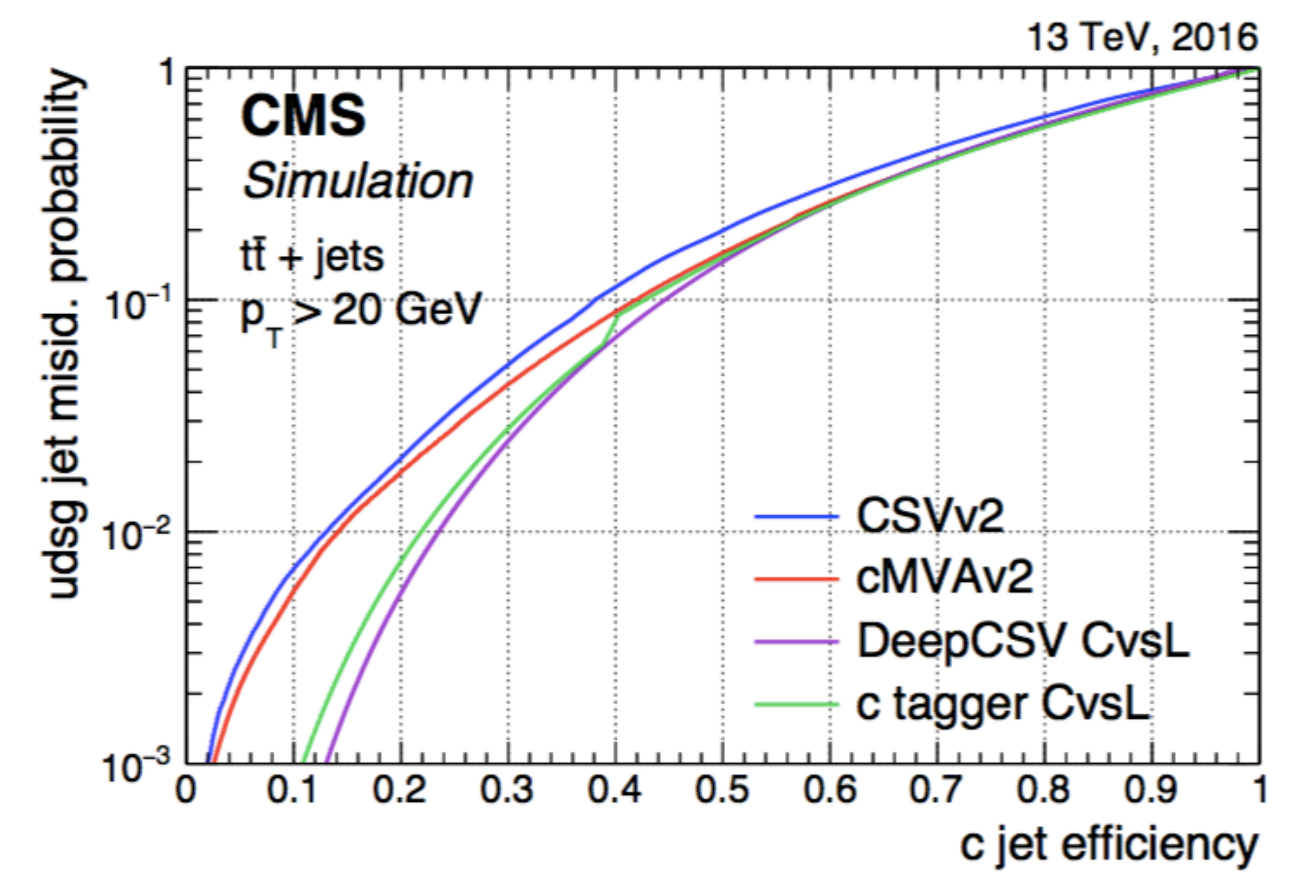
CMS DP-2017/013

- Significant improvement in b tagging performance with the use of DNN
- Huge gain for jets in boosted regime

Charm tagging

- Charm lies somewhere inbetween the beauty and the light **=>** **c tagging is more challenging** than b tagging
- Two dedicated trainings against b (**CvsB**) and light (**CvsL**) jets



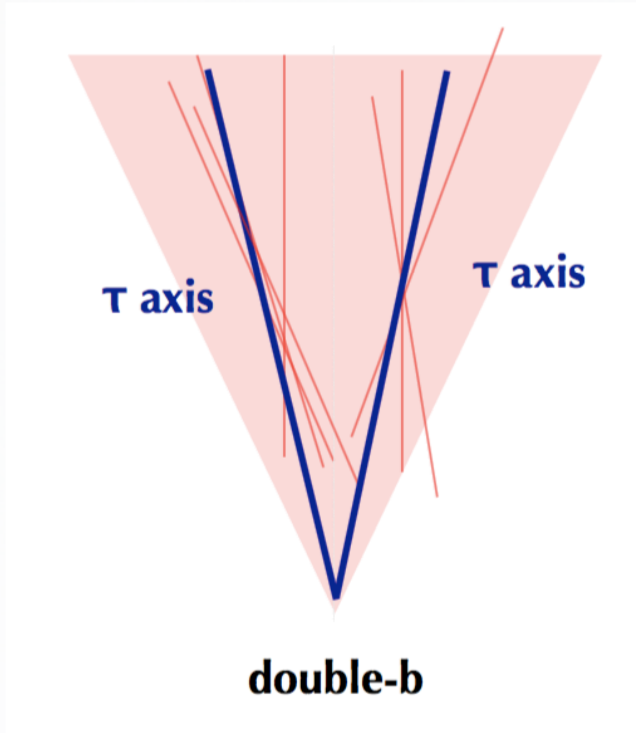


BTV-16-001 arXiv:1712.07158

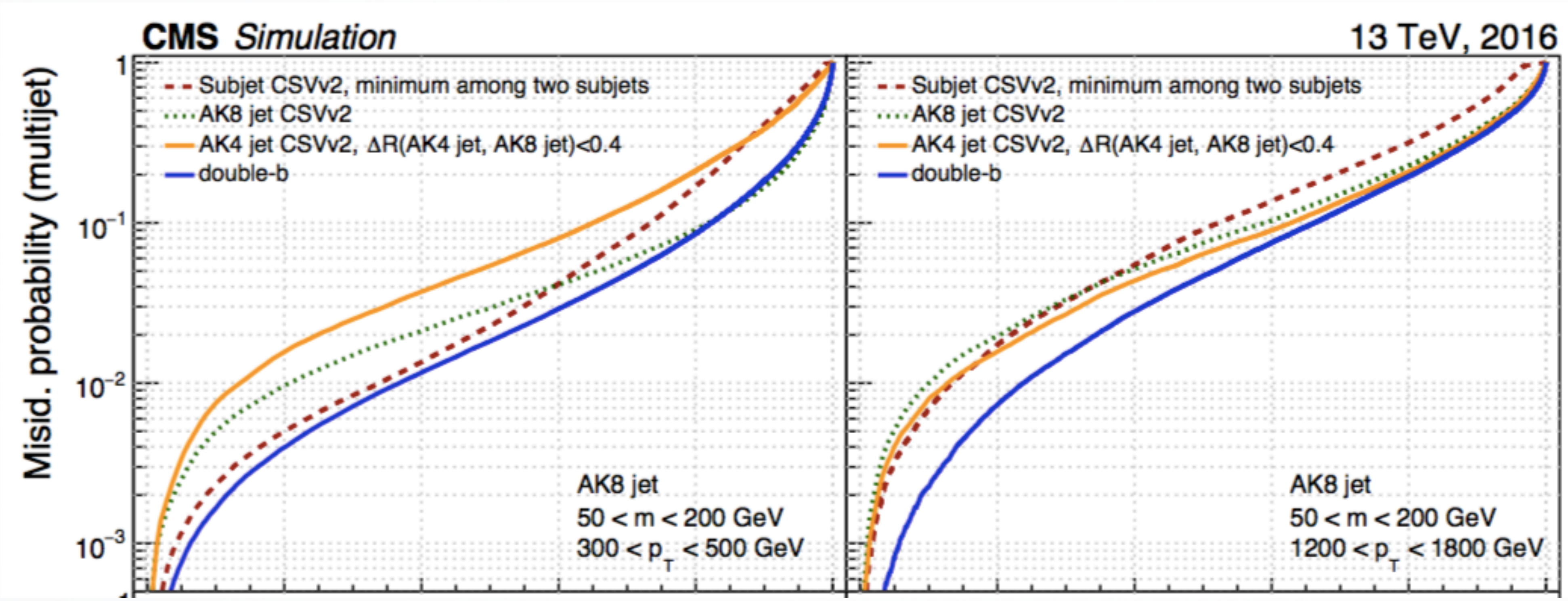
Higgs and double beauty

- More boosted objects with the increase of collision energy
- Decays of boosted particles clustered in large-R jets can also contain b quarks
- Use substructure techniques to reconstruct subjets

BTV-15-002 arXiv:1712.07158



$$\tau_N = \frac{1}{d_0} \sum_k p_T^k \min(\Delta R_{1,k}, ..., \Delta R_{N,k})$$

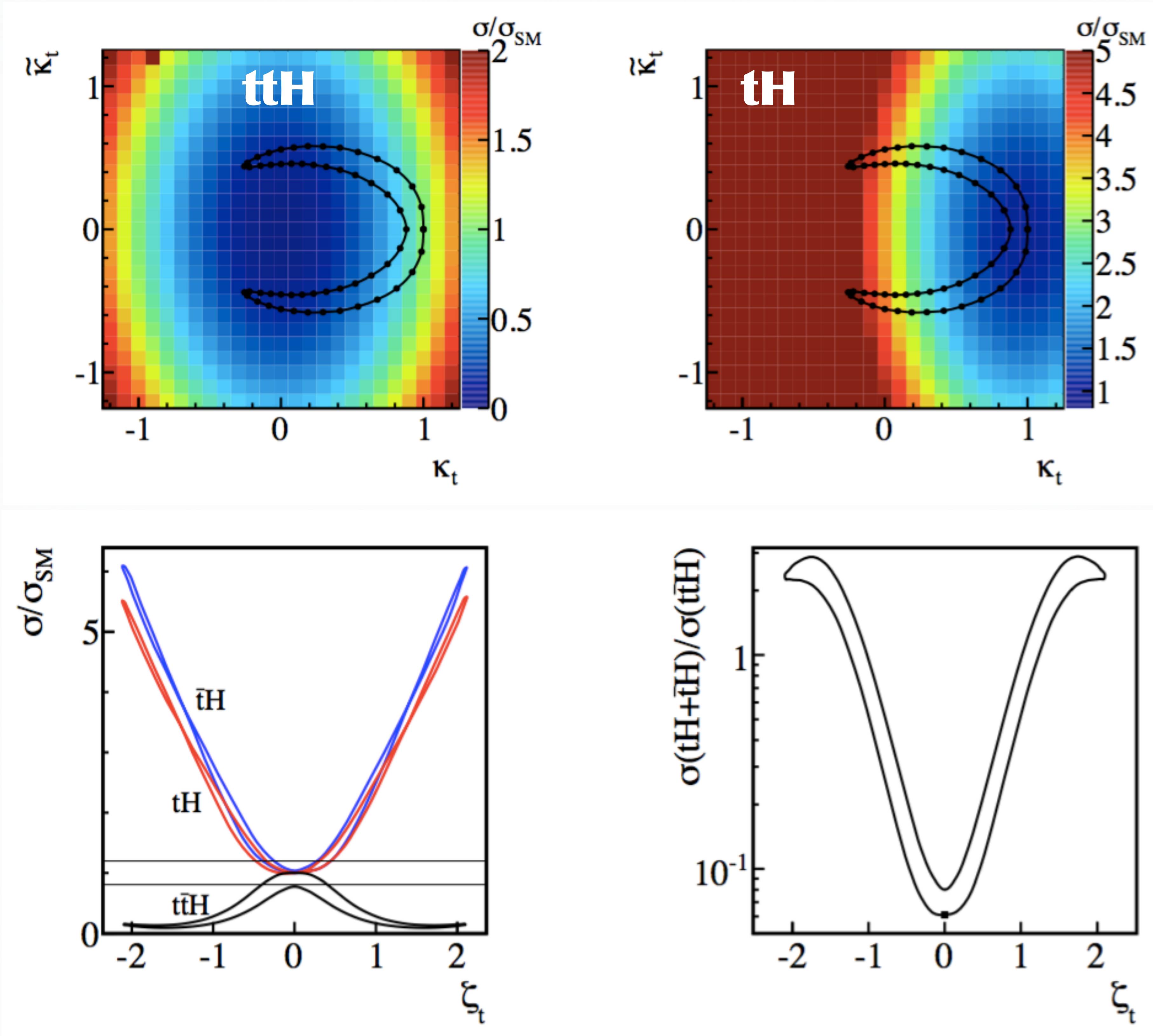


Conclusion

- We live in a beautiful metastable world
- Top quark Yukawa coupling might be a portal to other worlds of new physics
- Experimental studies of this vital fundamental parameter in SM have just begun
- A broad range of analyses in the top-Higgs sector is being performed by the LHC experiments with very good prospects for y_t determination at future colliders !
- Jet flavour tagging is crucial for the exploration of the top-Higgs sector

Backup

y_t and CP violation



Direct CP measurement of y_t

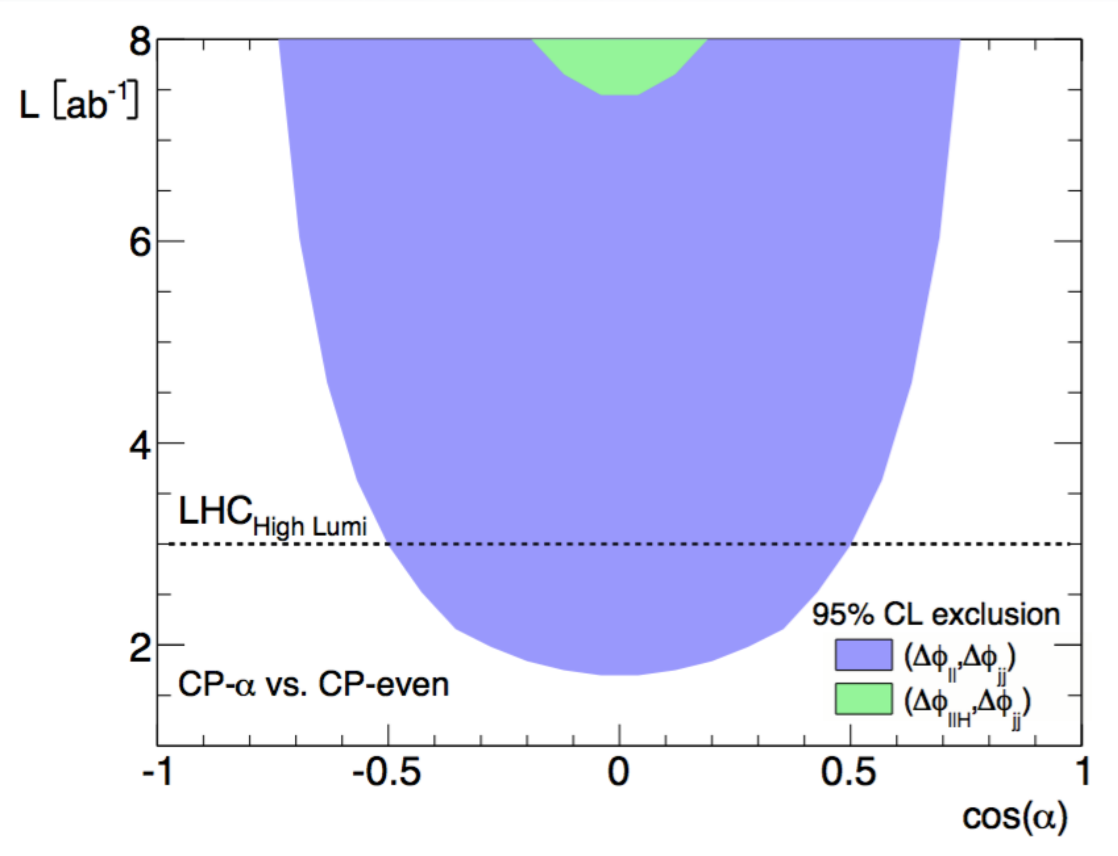
$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

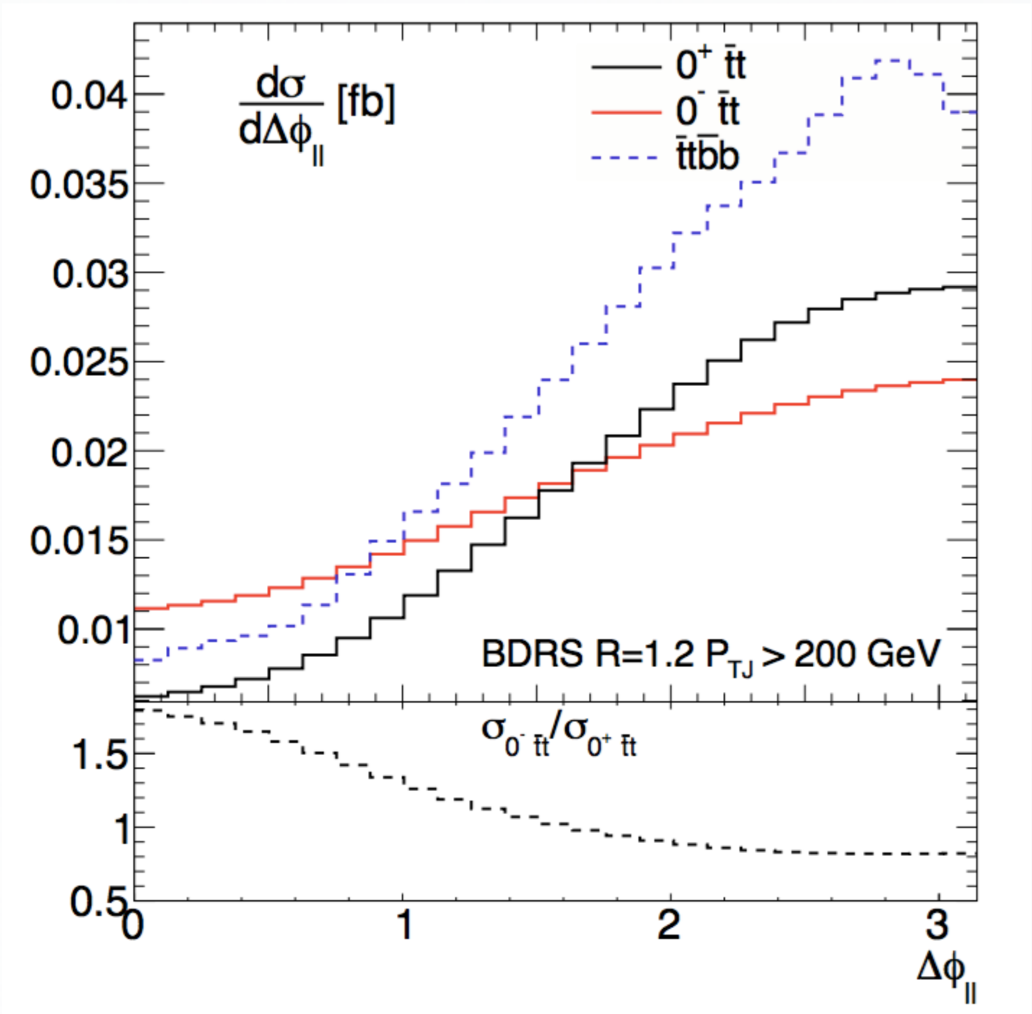
Real number (K) **CP-phase** (α)

CP-even SM Higgs 0^+ ($K=1, \alpha=0$)

CP-odd SM Higgs 0^- ($K=1, \alpha=\pi/2$)

- Probe CP of y_t in ttH dilepton events
- Sensitive to $\Delta\phi_{\ell\ell}$
- Even more pronounced in **boosted regime**

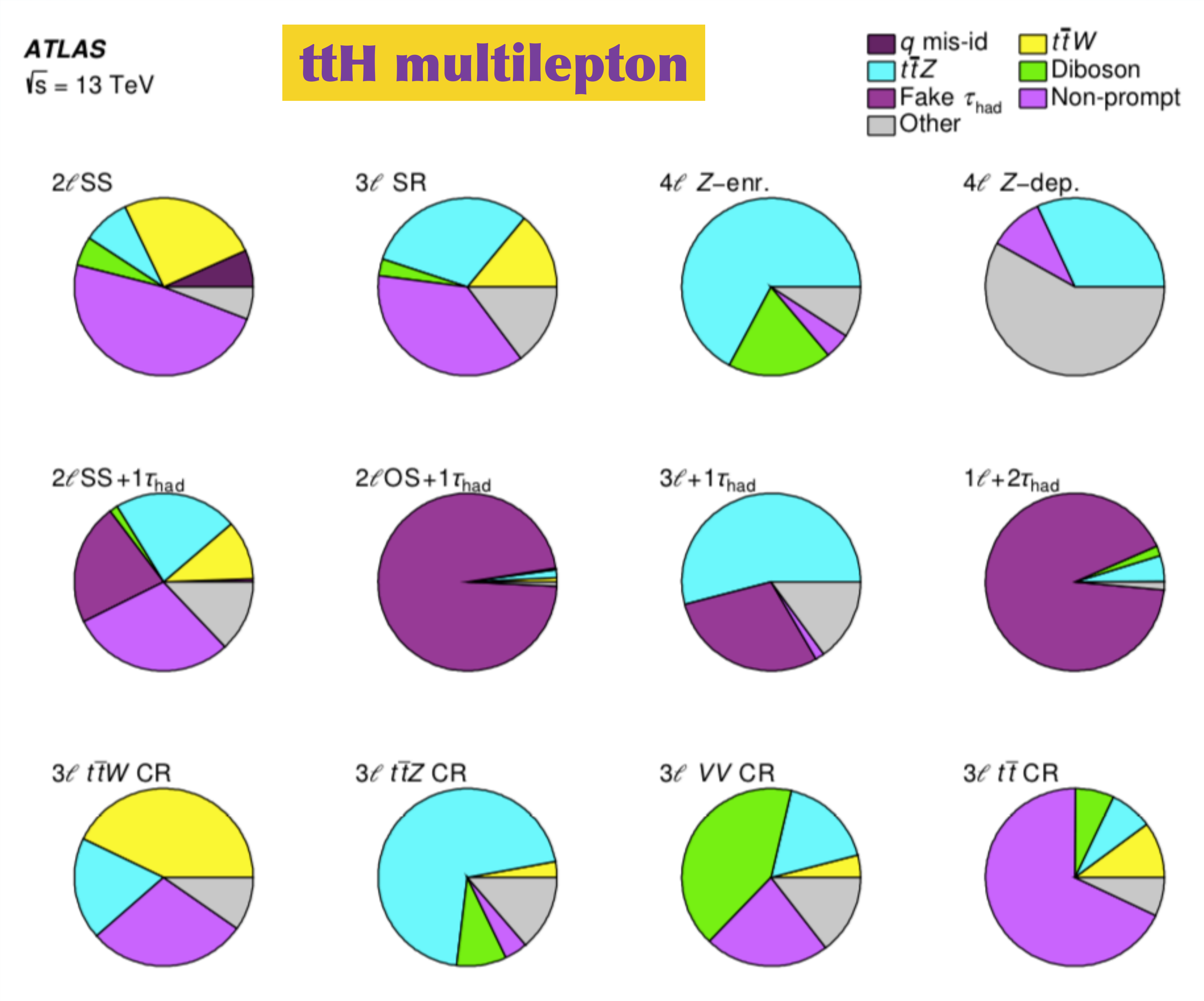




Phys. Rev. Lett. 116, 091801 (2016)

Categorisation

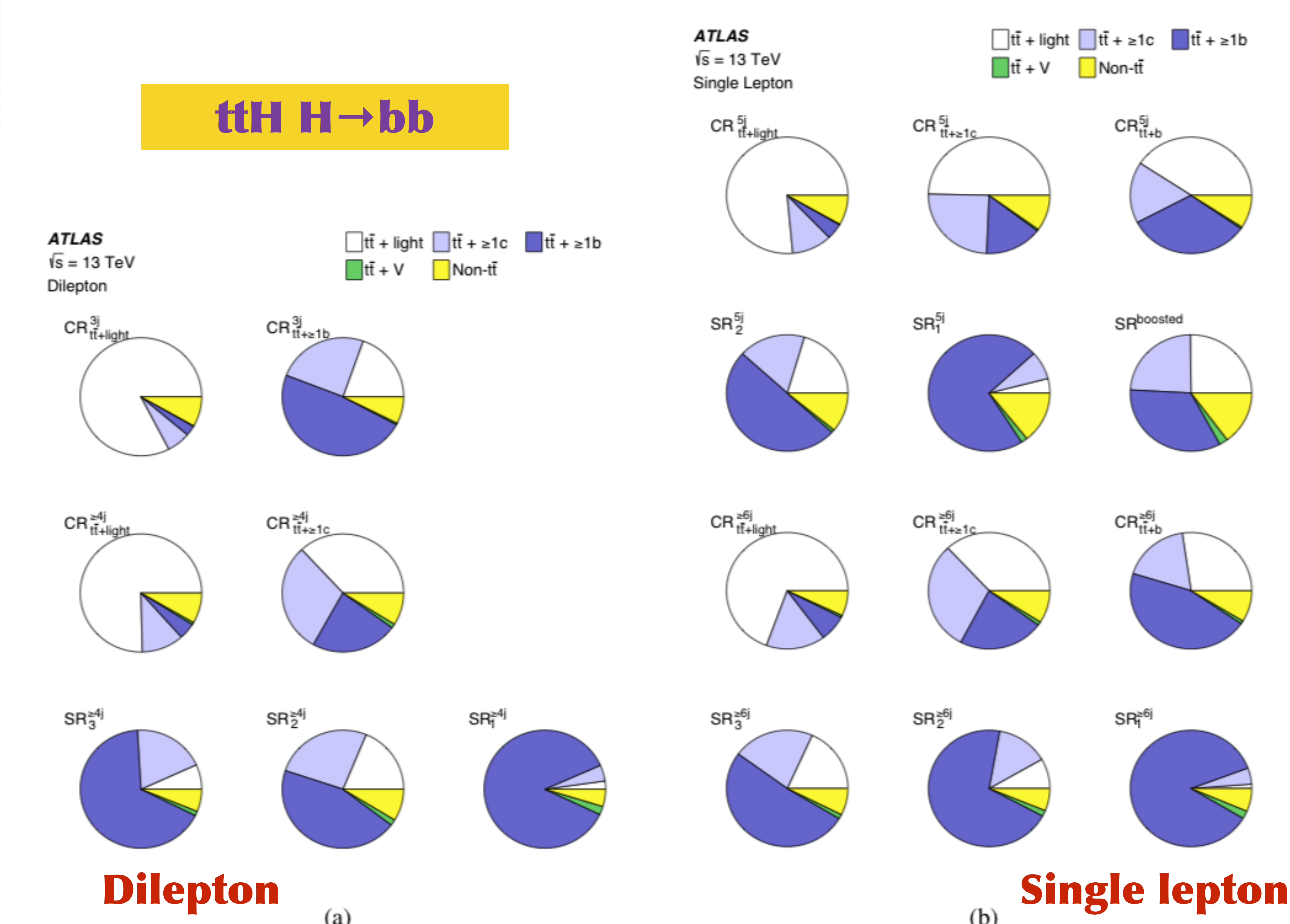
arXiv:1712.08891



Categorisation

arXiv:1712.08895

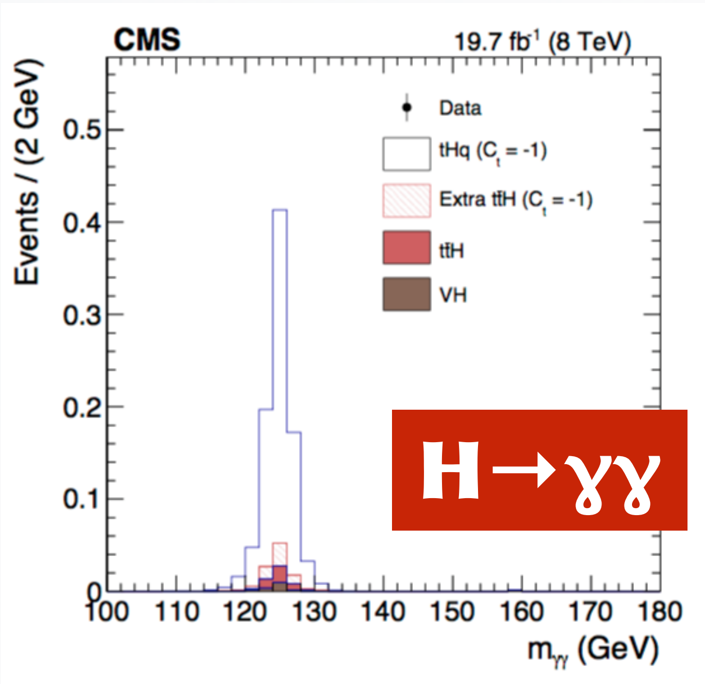
ttH H→bb

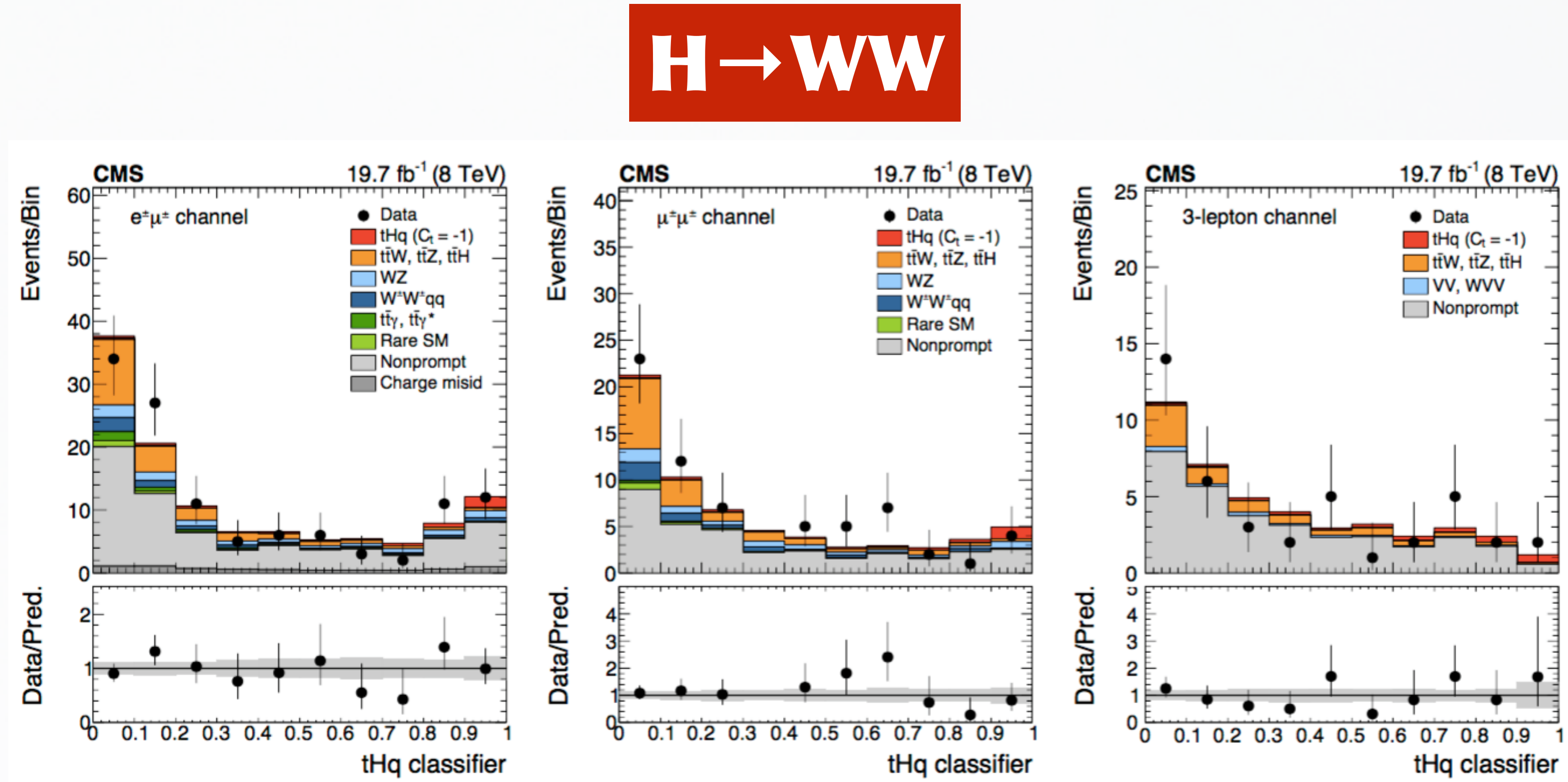


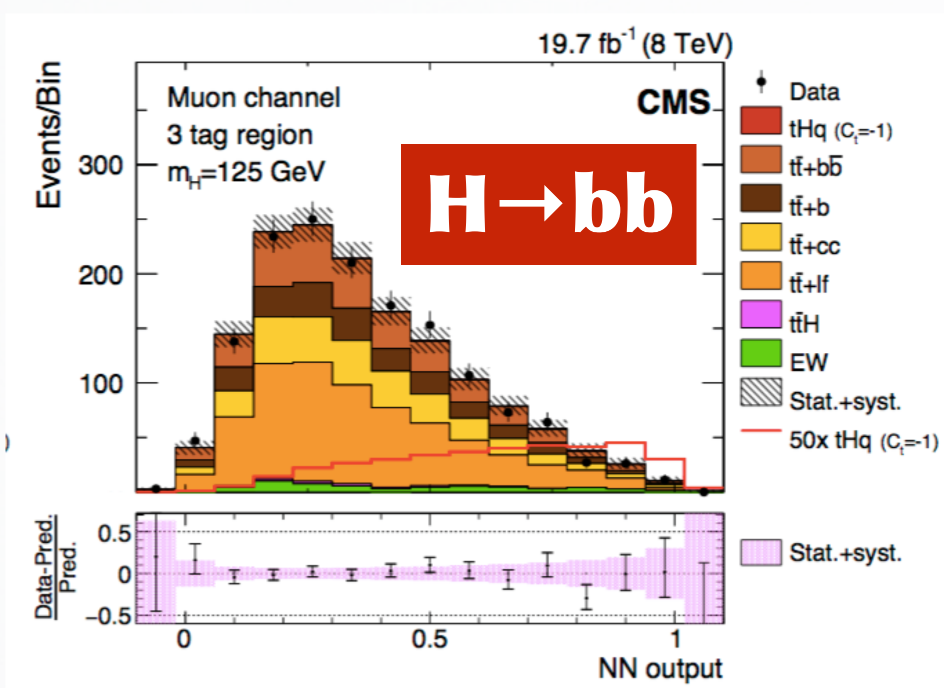
Dilepton

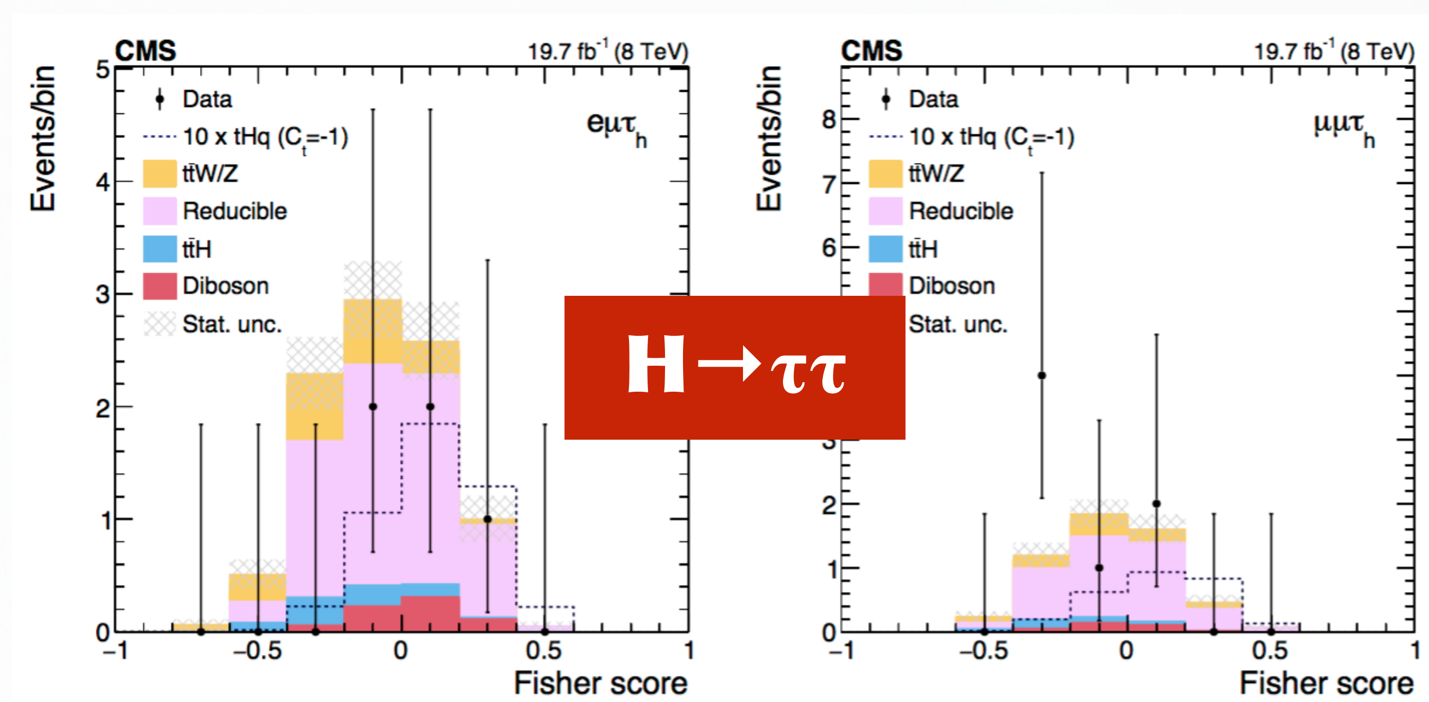
Single lepton

tHq results at 8 TeV









JHEP06 (2016) 177

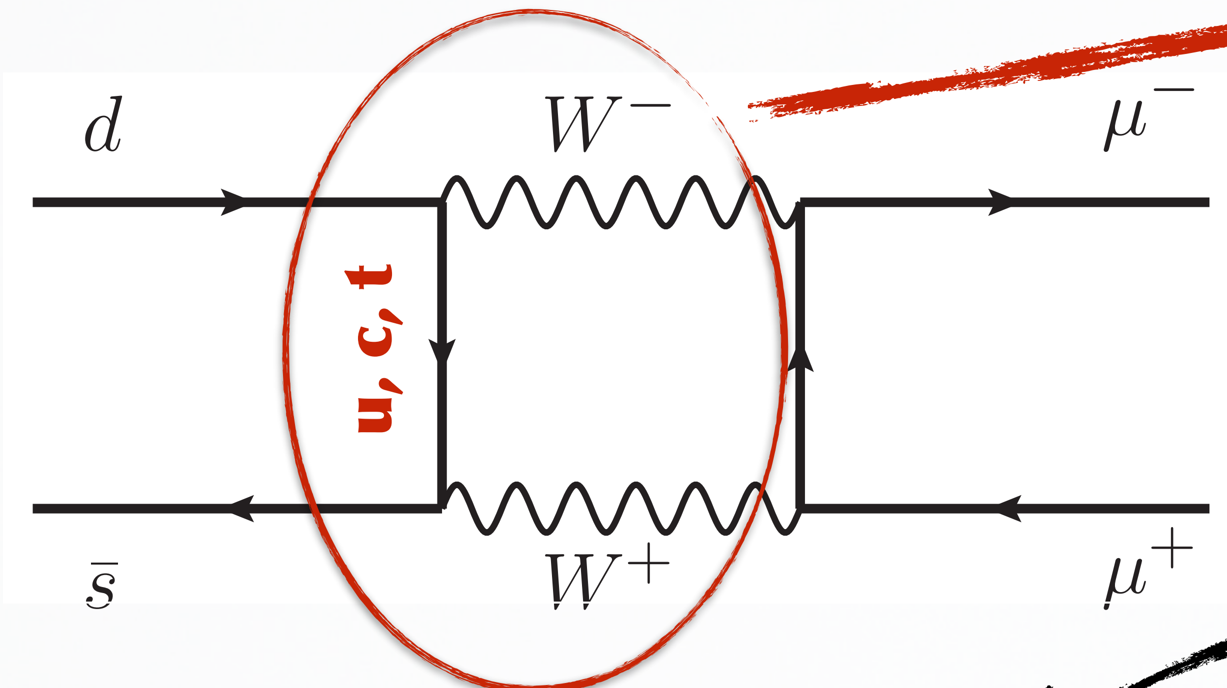
GIM mechanism

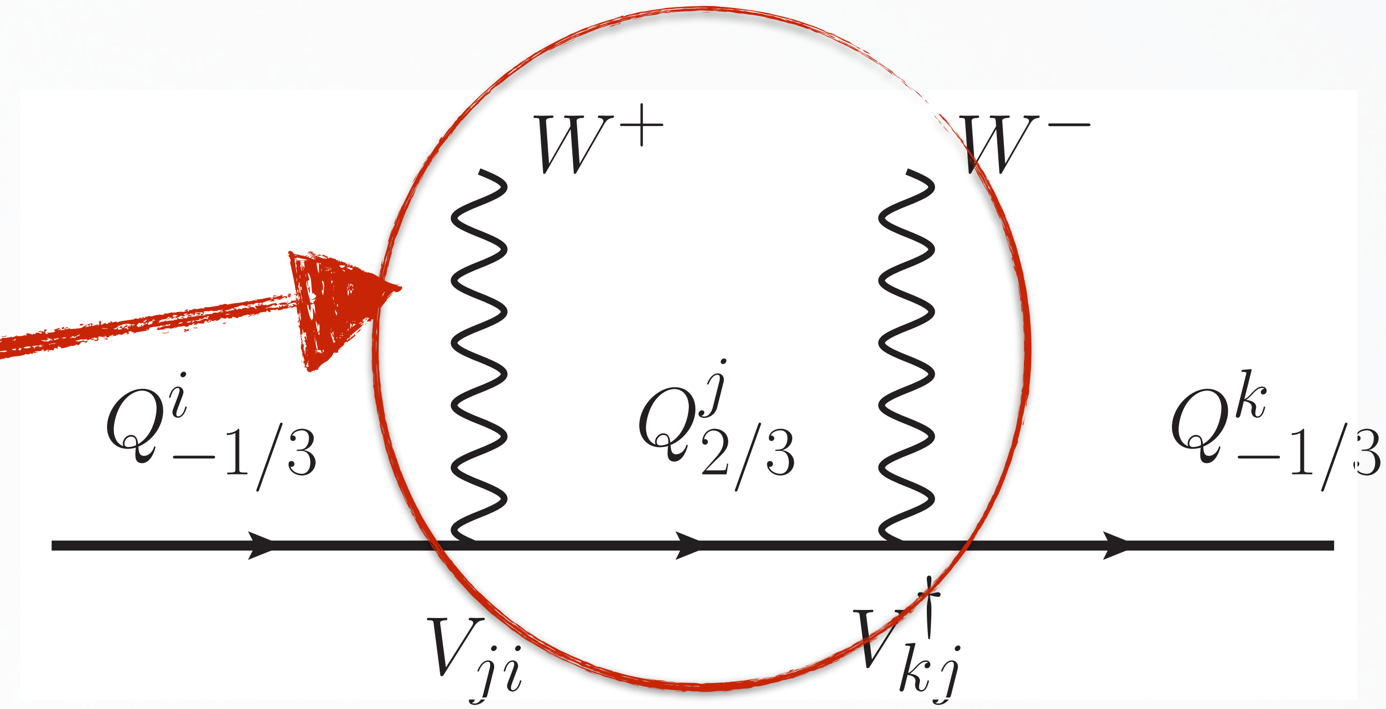
$$K^0 \to \mu^+ \mu^-$$

Back in 1968 people found strange this decay not to be observed

Br($K_L \to \mu^+\mu^-$) = $(6.84 \pm 0.11) \times 10^{-9}$ [BNL]

Flavour changing neutral current





$$\sum_j V^\dagger_{kj} V_{ji} \frac{q}{q^2 - m_j^2} = \delta_{ki}$$

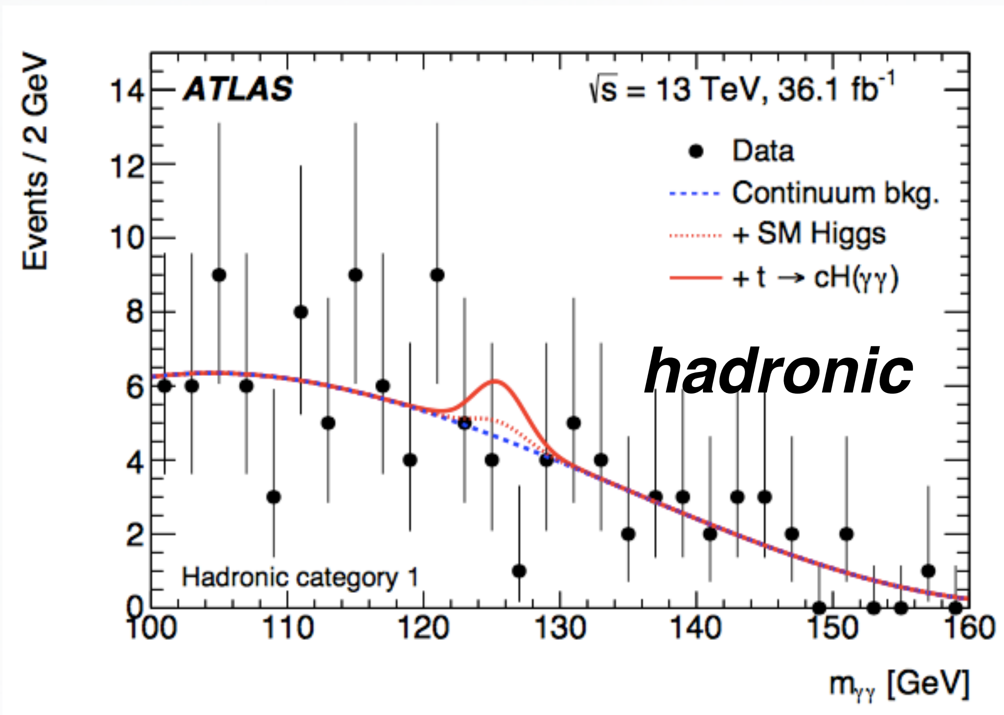
m^2

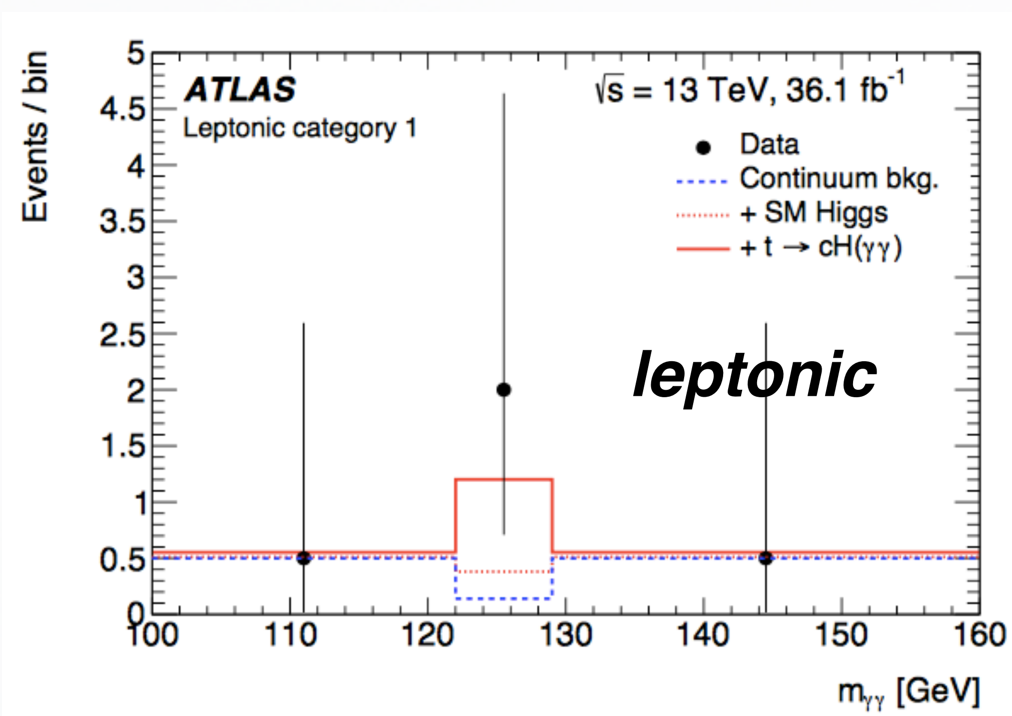
CKM matrix unitarity

Quark mass degeneracy → no FCNC = Glashow-Iliopoulos-Maiani (GIM) mechanism (1970)

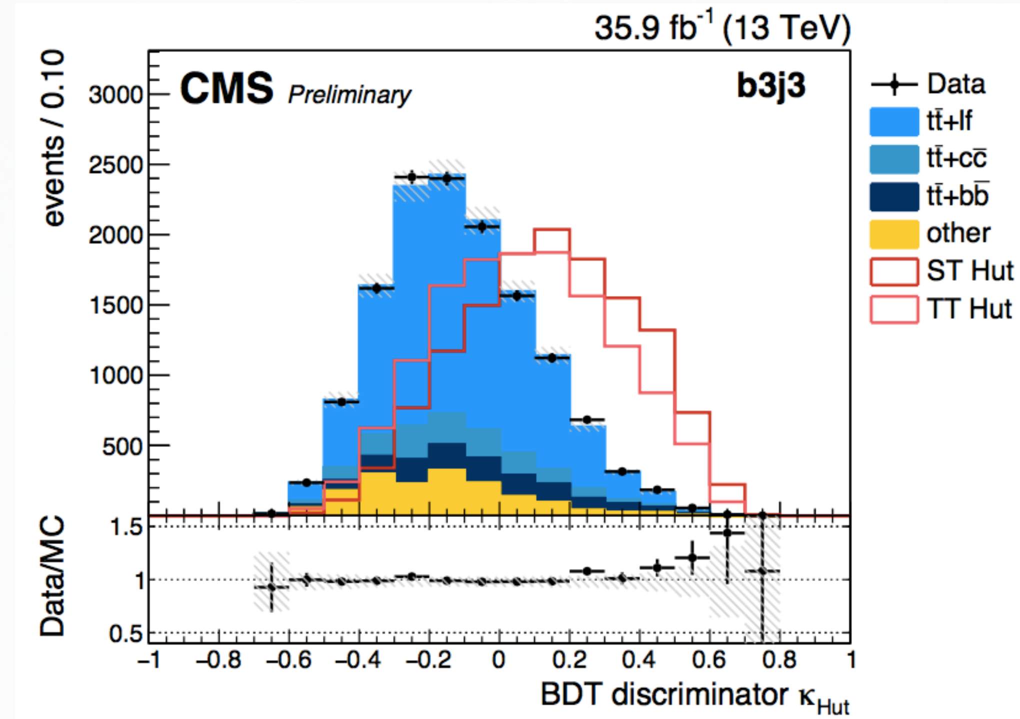
Top-Higgs FCNC results

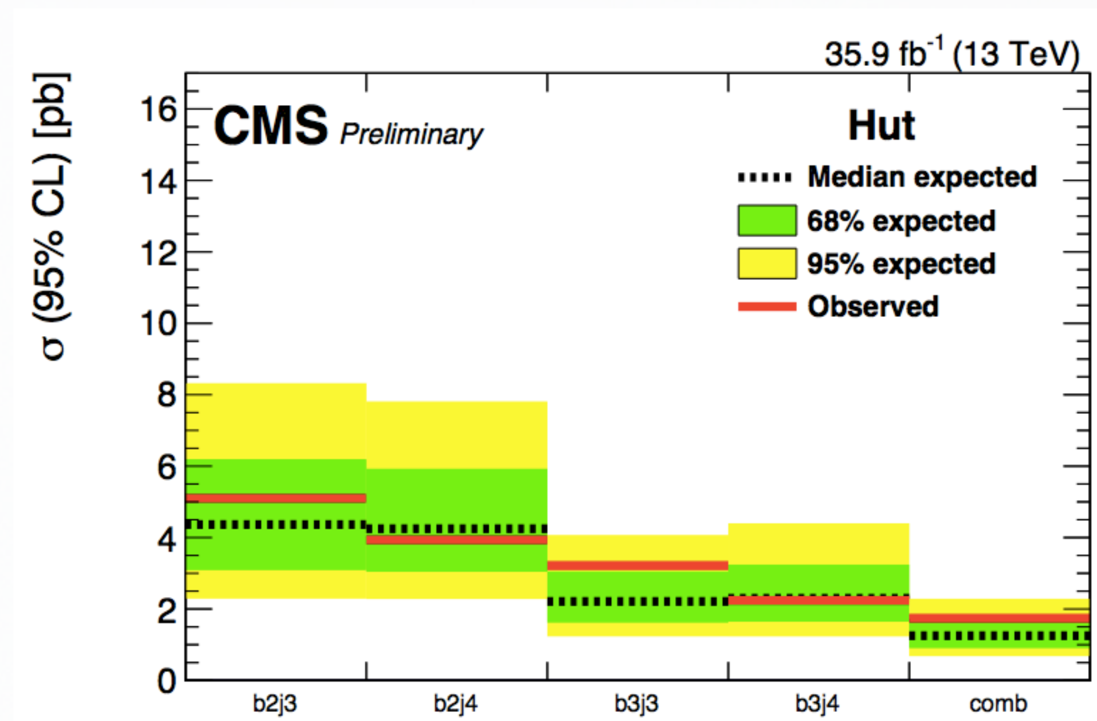
H→γγ JHEP 10 (2017) 129





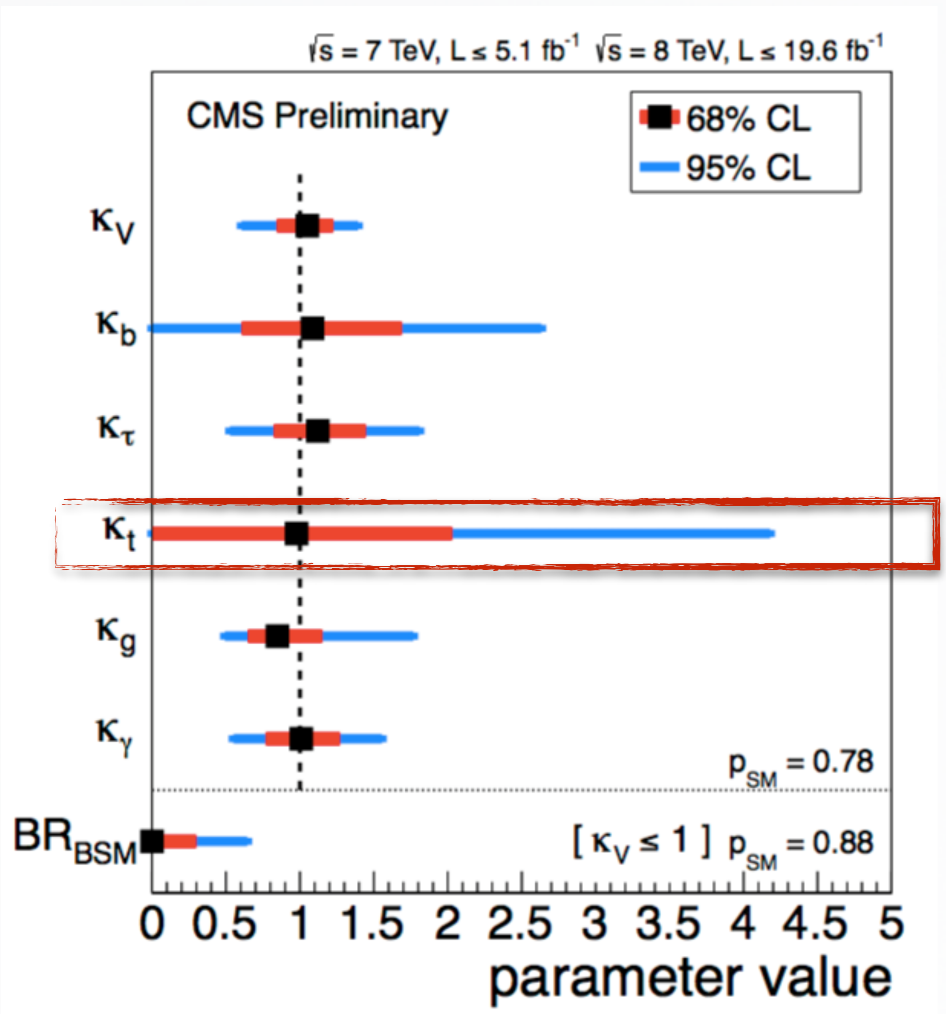
H→bb arXiv:1712.02399





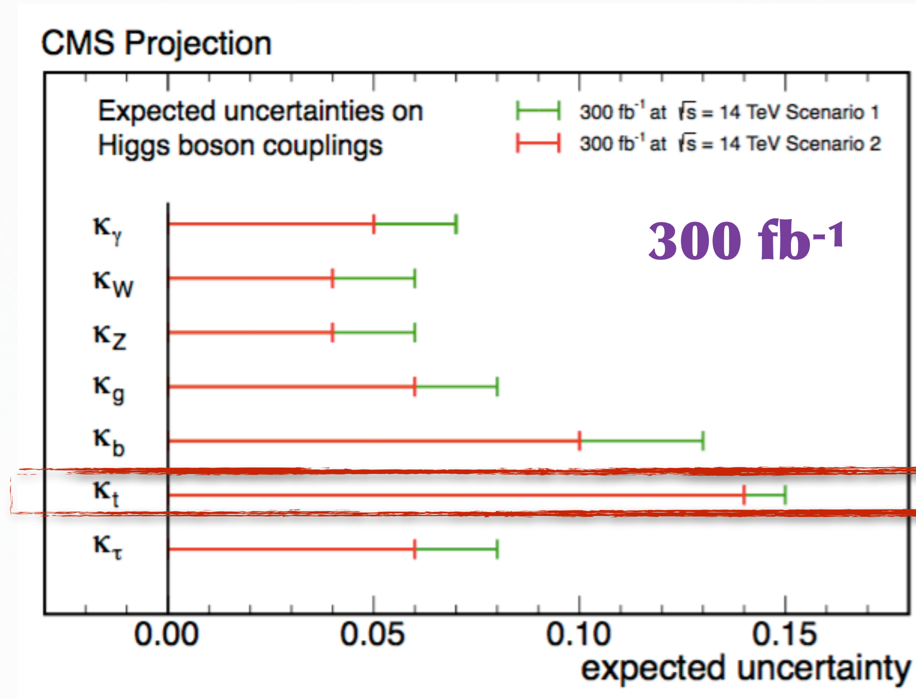
From LHC to HL-LHC

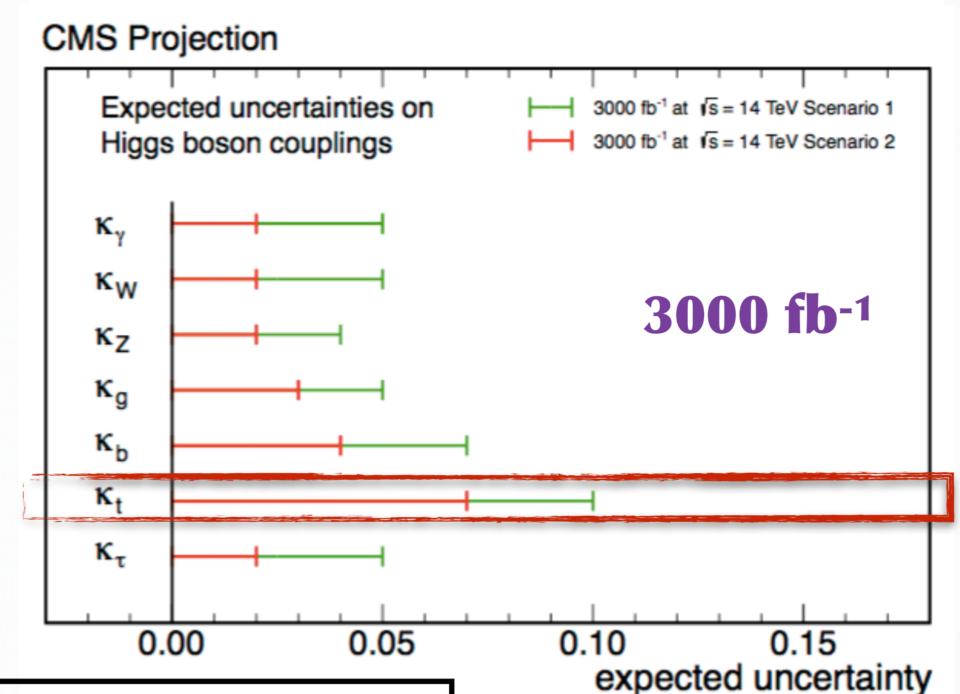
LHC Global data fit results



arXiv:1307.7135

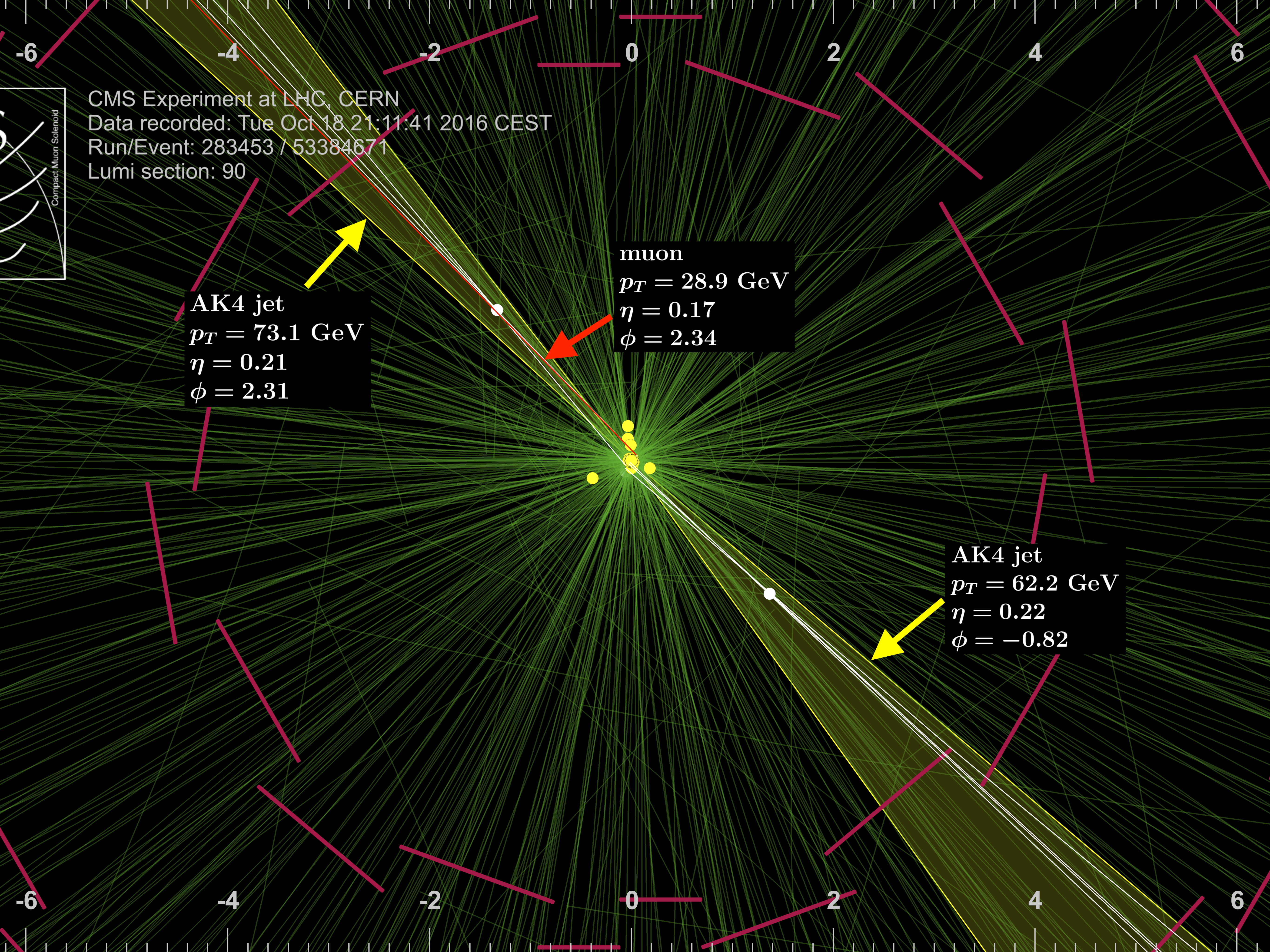
HL-LHC Projection





- ***Scenario 1***: systematics unchanged
- ***Scenario 2***: scale theoretical uncertainties by 1/2, others are scaled by IL

Could reach ≈5% precision in y_t !


CMS Experiment at LHC, CERN
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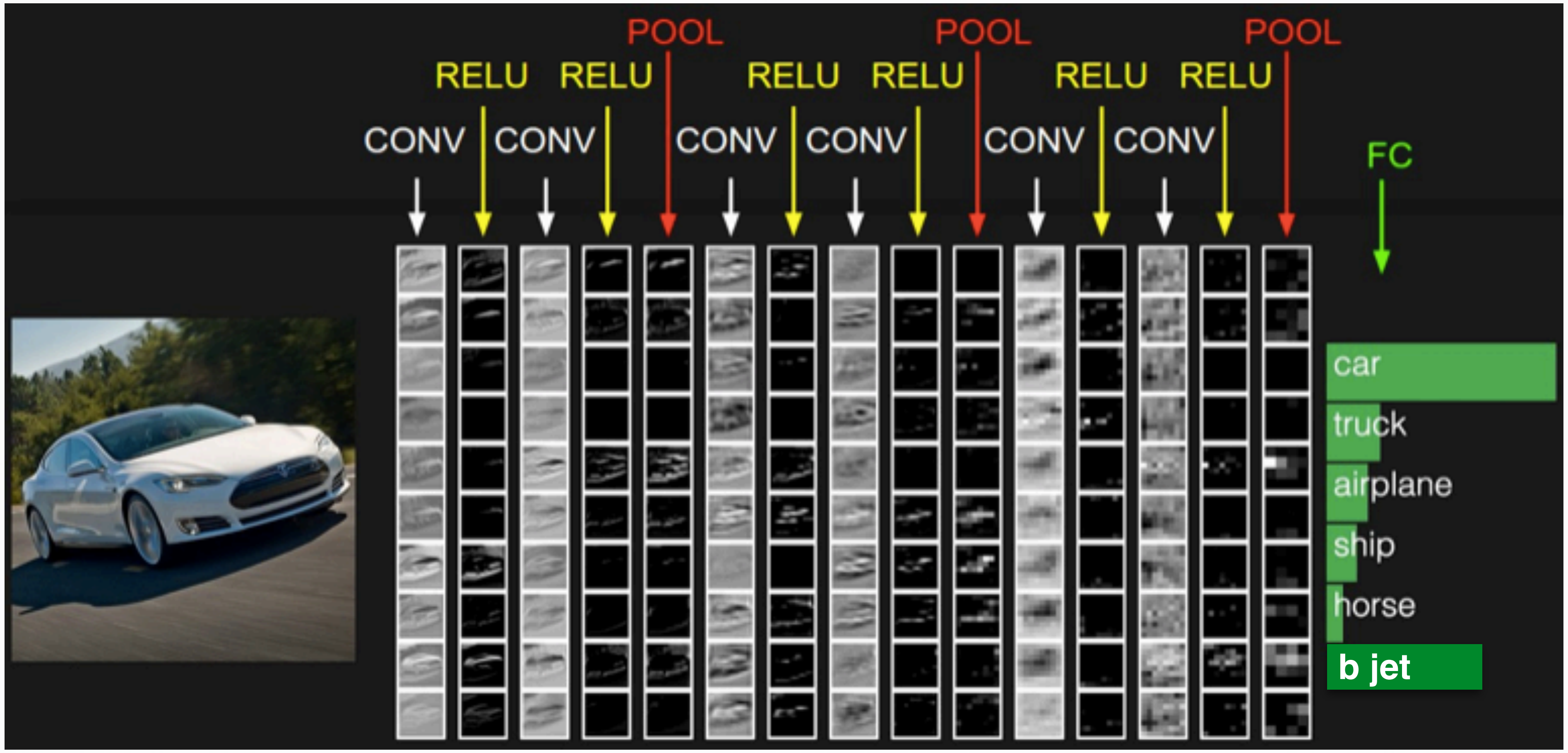
$\eta = 0.17$
$\phi = 2.34$
AK4 jet
$p_T = 62.2$ GeV
$\eta = 0.22$
$\phi = -0.82$
-6
-4
-2
0
2
4
6

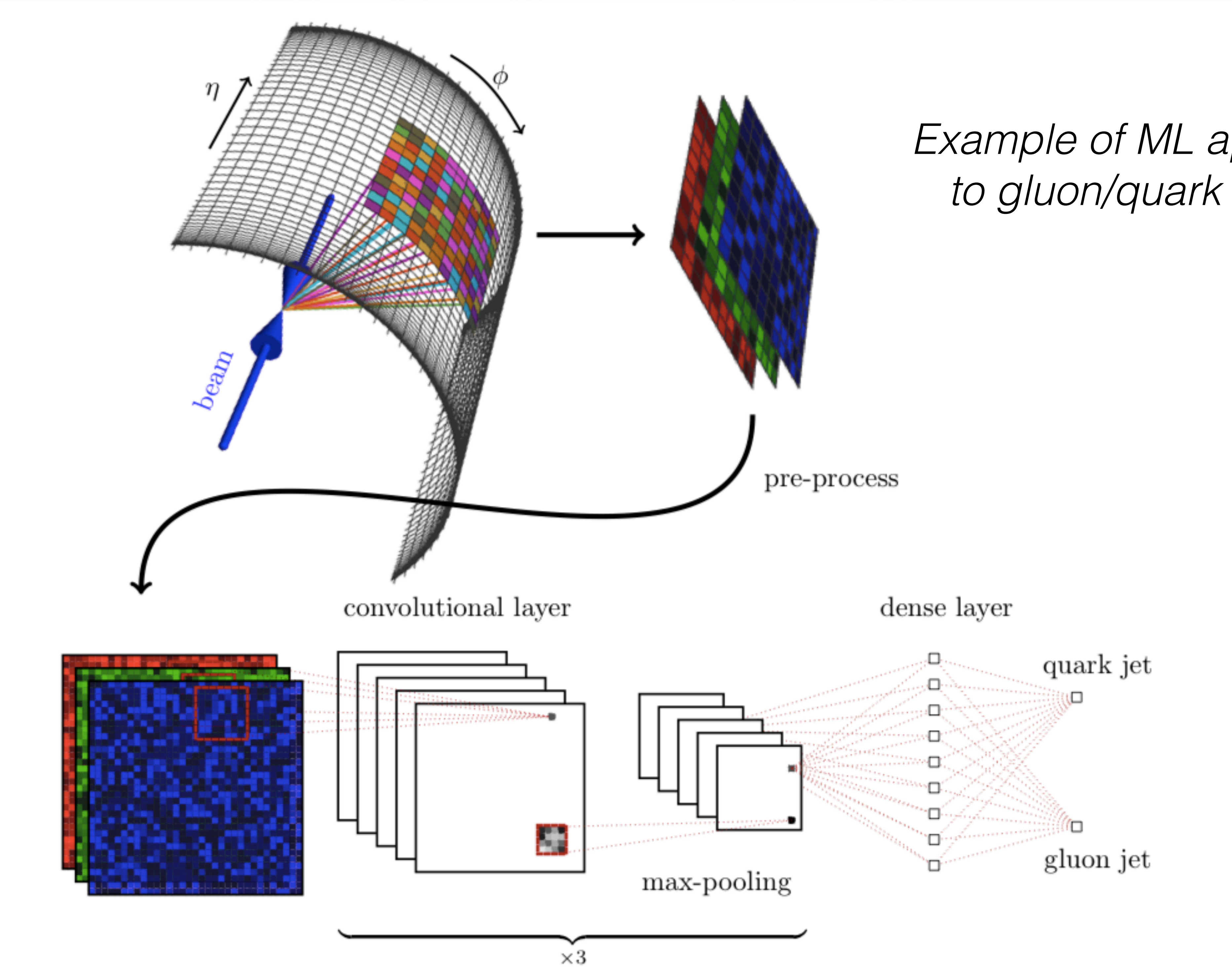
Image recognition



cs231n.github.io

- Strip the input image to a set of **pre-processed layers**
- **Convolutional** approach: treat input data as multidimensional images
- **Max-pooling**: reduce the number of network parameters via down-sampling
- Minimise the **loss function**: the difference between the network output and the true class
- More efficient recognition of low level features in early layers and high level features in later layers with **non-shallow** configurations
- ***Supervised*** or ***non-supervised*** learning

Jet imaging



Example of ML application to gluon/quark tagging

deep *= several hidden layers*

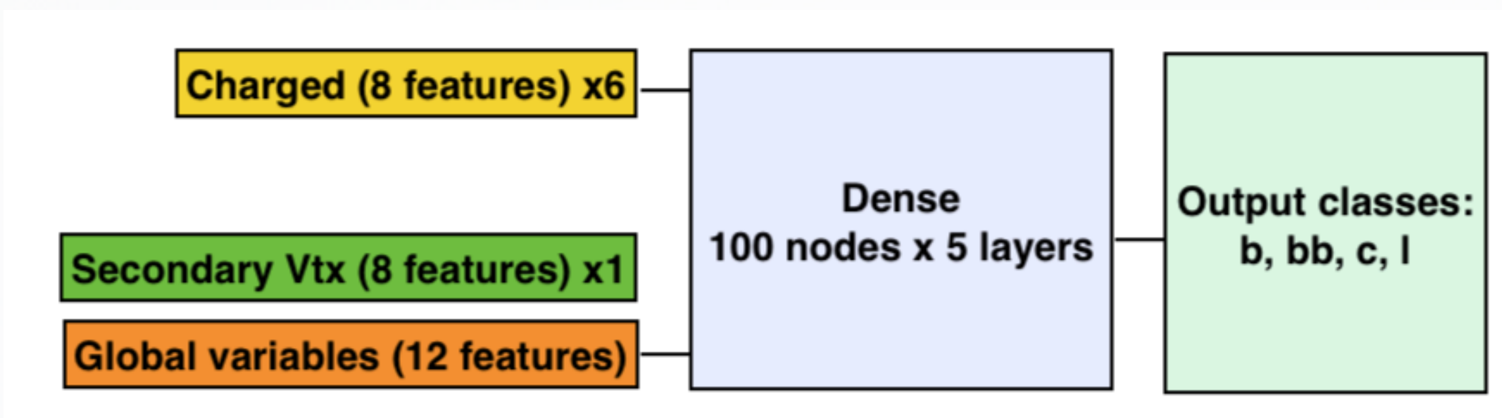
dense layer *= each of its units connects to all of the units in the previous layer*

JHEP 01 (2017) 110

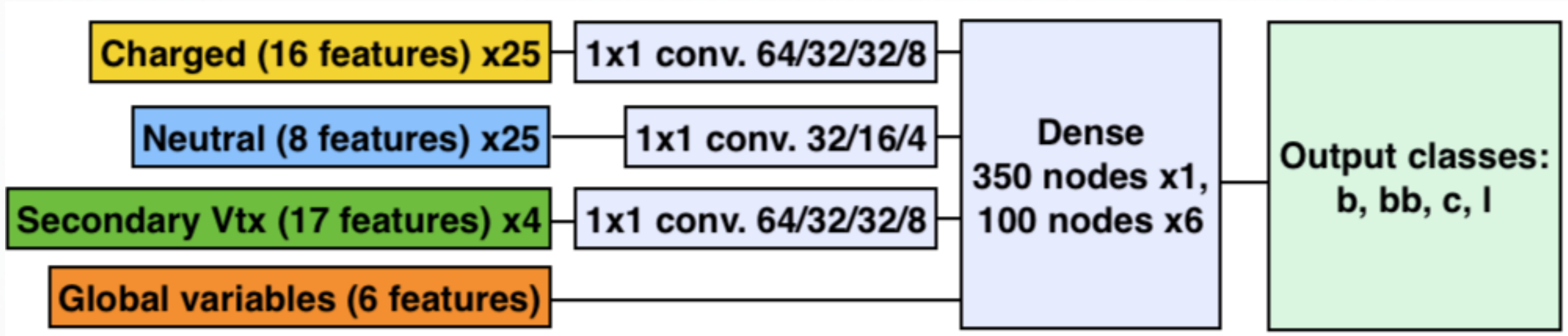
Inside of the Machine

- **DeepCSV** is currently the flagship tagger at CMS that is already commissioned in real data
  => DNN on CSVv2 inputs
- **DeepFlavour** is the upcoming tagger that uses deeper neural networks
  => more inputs, looser selection, more hidden layers
- Good prospects for the use of the full multi classification of reconstructed objects (flavour +q/g) with the deeper networks (**DeepJet**)
  => extension of DeepFlavour to jet multi classification

DeepCSV



DeepFlavour



ACAT2017

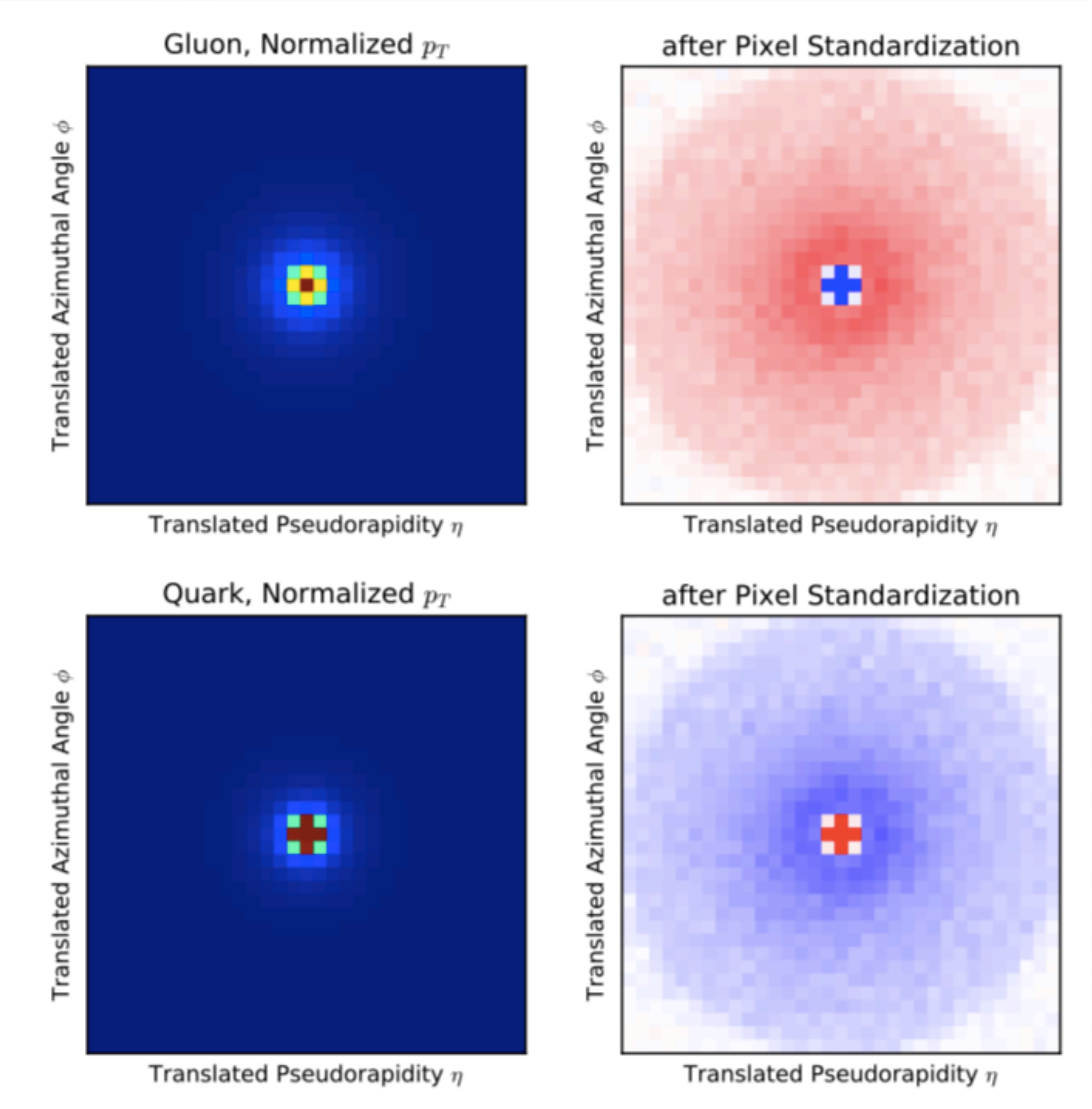
EPS2017

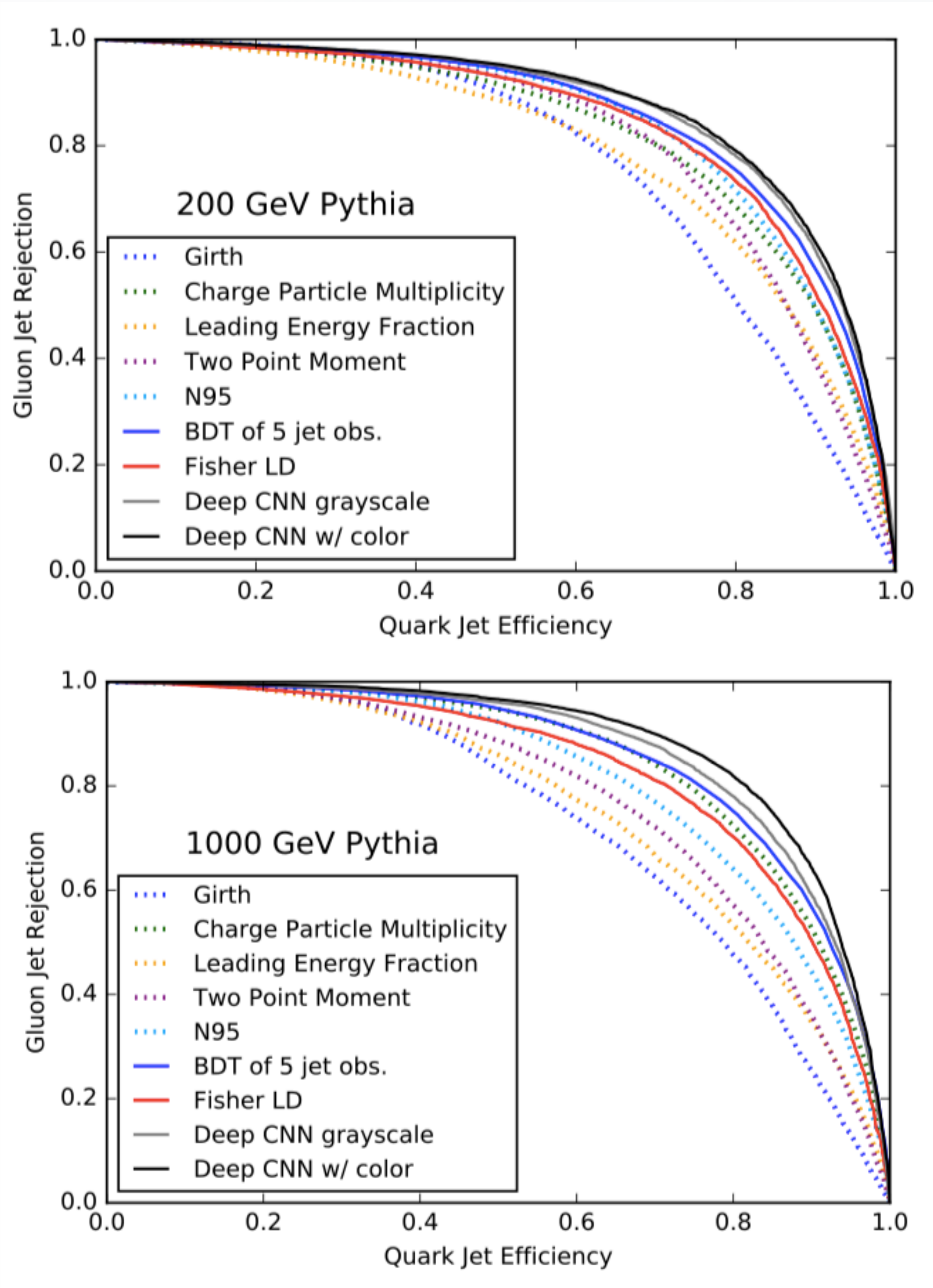
Jet imaging results

Standard pre-processing

Additional deep NN related pre-processing

Result discrimination





Is Machine Learning flawless ?

- Machine learning methods provide the best performance nowadays
- The performance is mostly limited by the size of the training dataset
- Powerful but delicate to configuration details

- Usual shortcomings:

  - ***Long training time***: a big amount of input information
    => mitigated by the use of GPUs

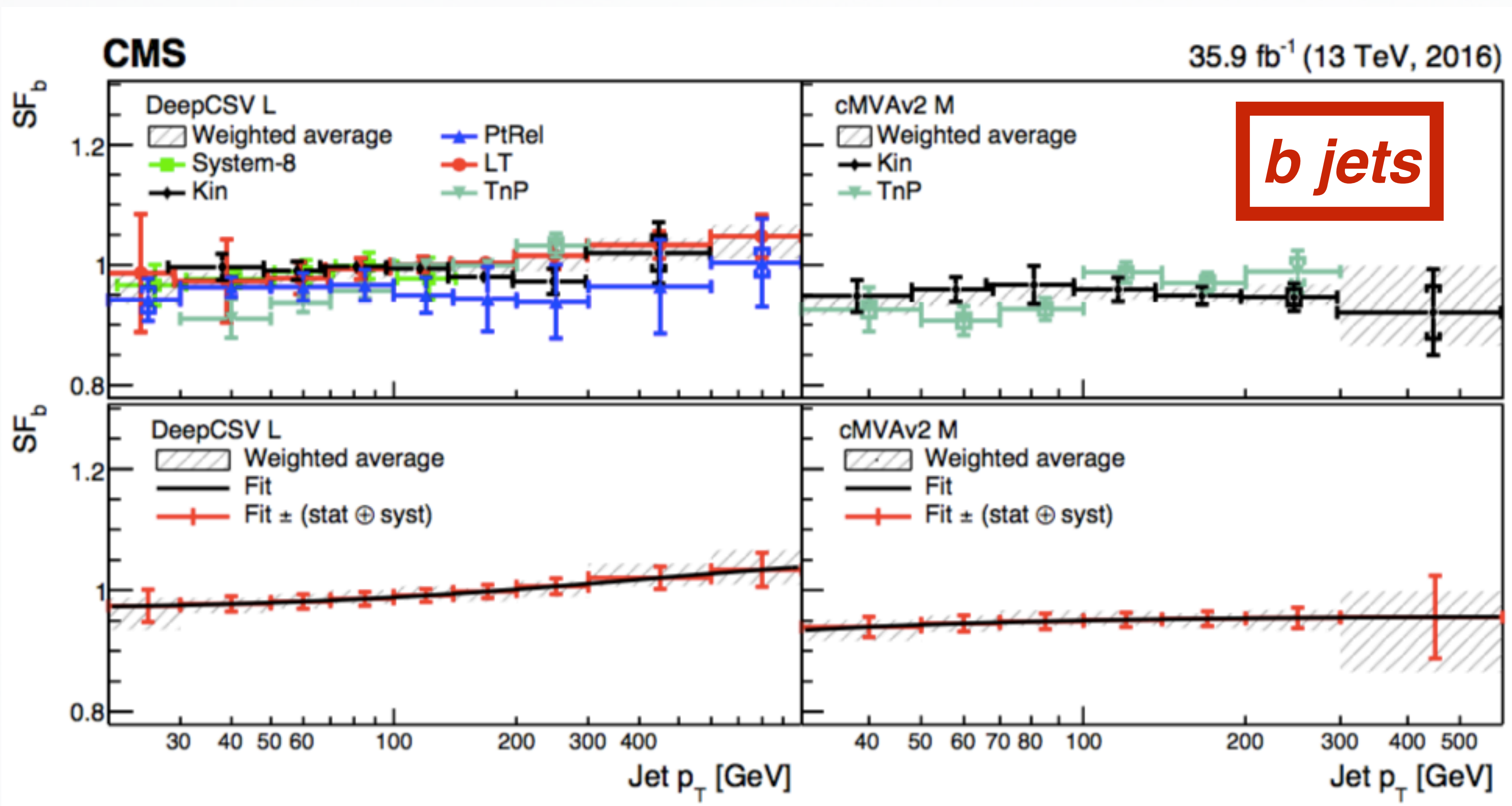
  - ***Unit saturation***: insensitivity of the network to the changes in the input unit values
    => mitigated by the use of the rectified linear units (ReLU) for activation functions

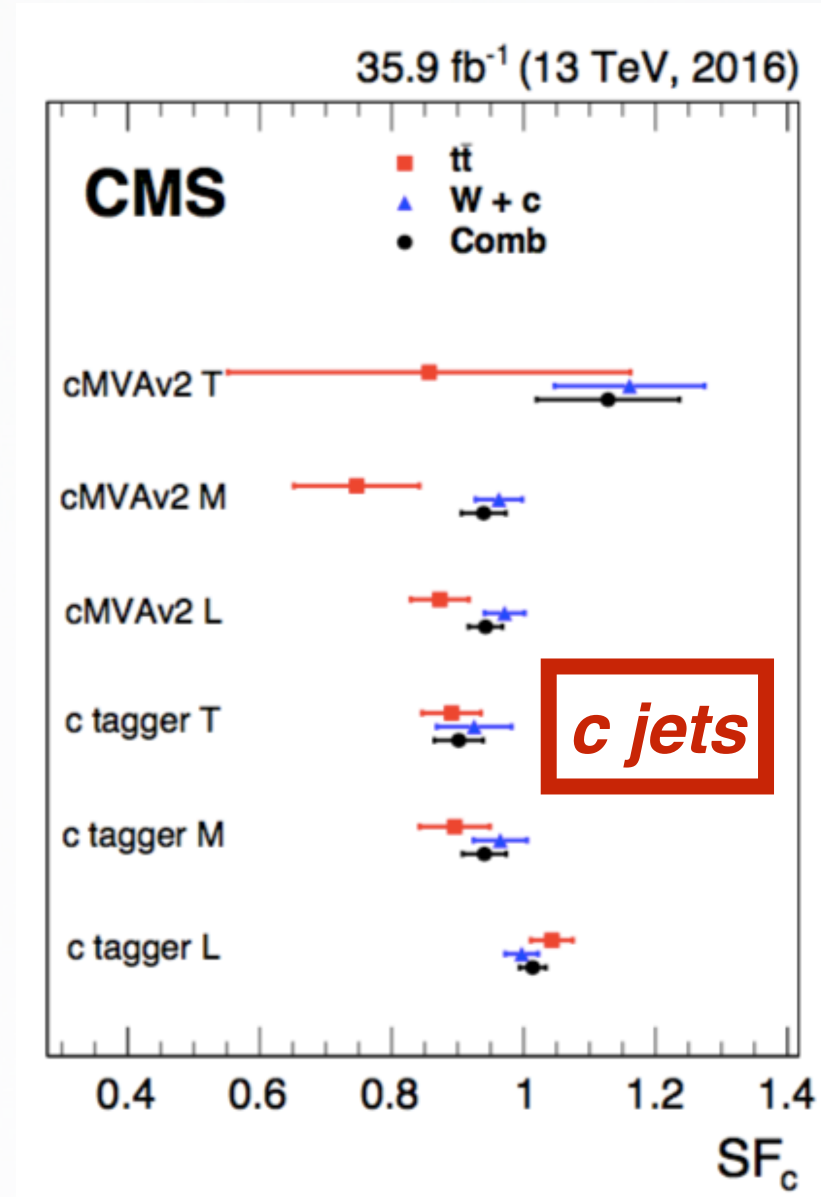
  - ***Overfitting***: overly-fine details in training sample lead to worse performance on test sample
    => avoid over-dependence on particular units with regularisation methods

JHEP 01 (2017) 110

Performance in 2016 data

- A large number of analyses to calibrate the performance of flavour tagging in data
- Calibration is done in **QCD** (b, l), **ttbar** (b, c) and **W+c** (c) events
- Similar performance in MC and data (SF ≈ 1)

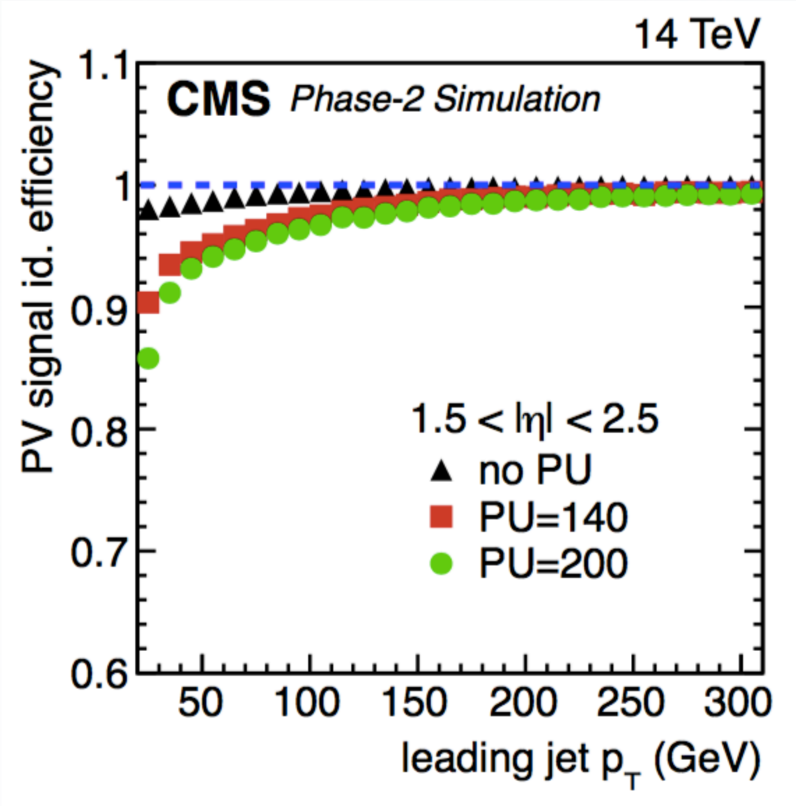


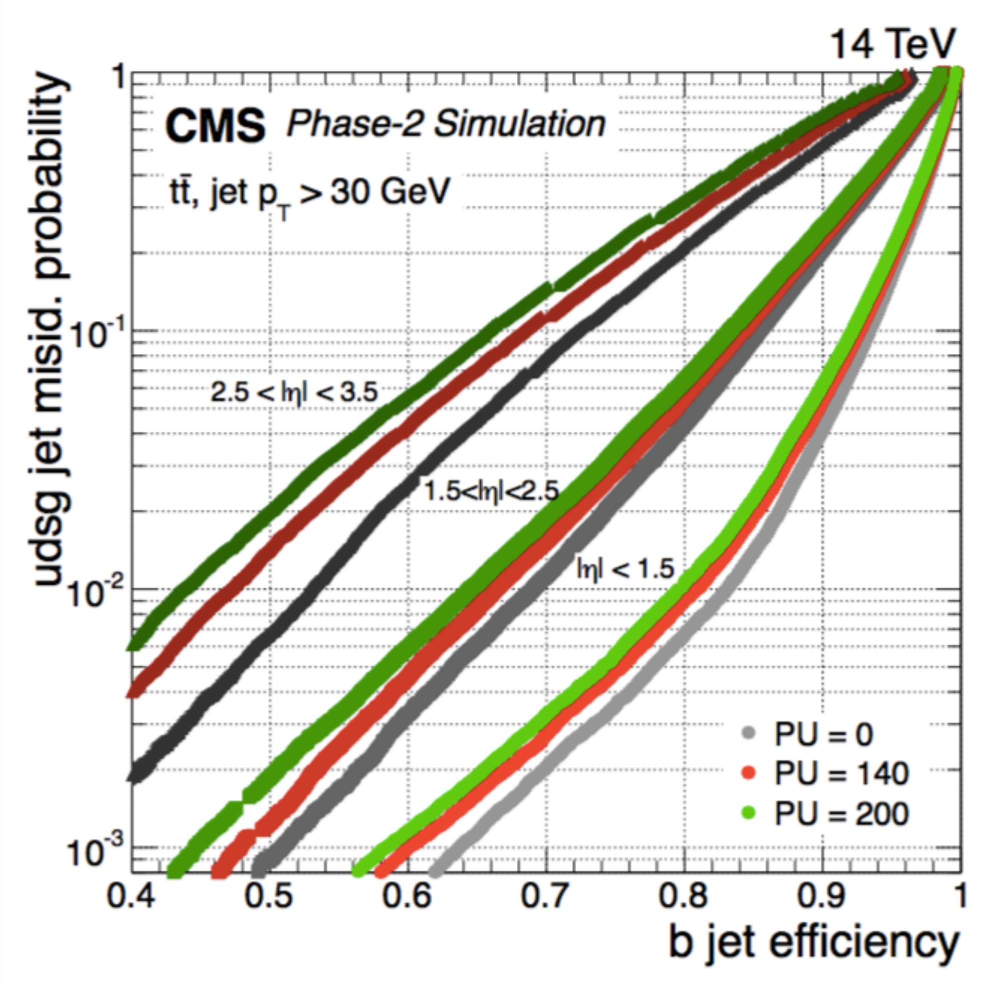


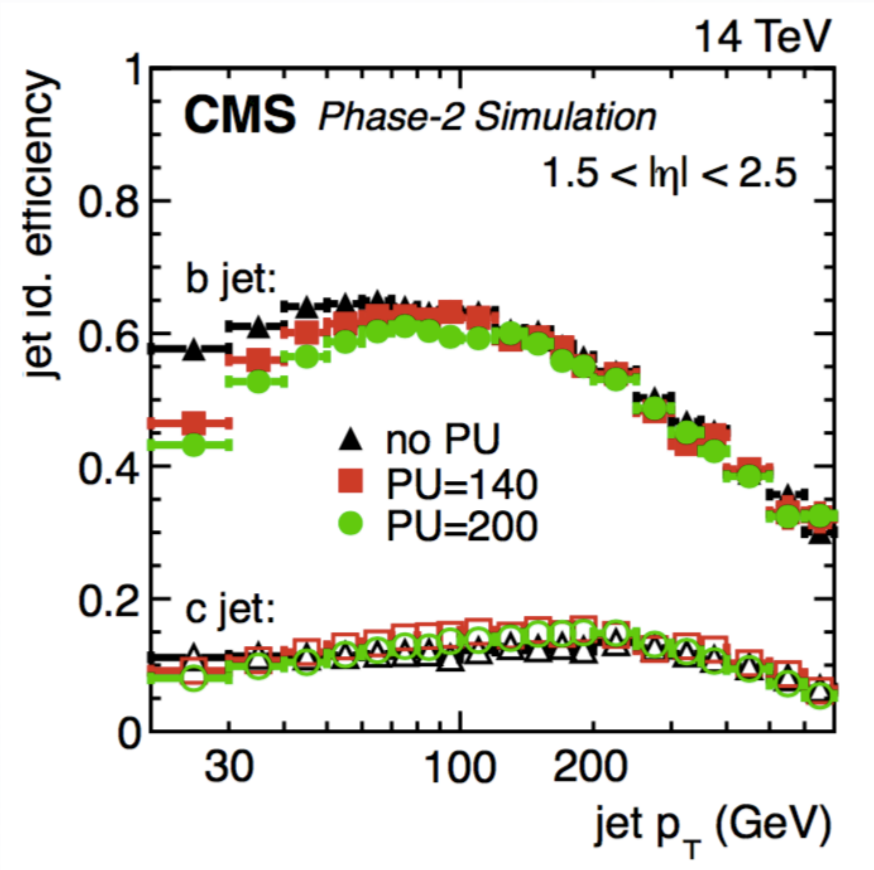
arXiv:1712.07158

Flavour tagging at HL-LHC

- Tracker to be completely replaced for Phase 2
- Finer granularity (4x), radiation hardness
- L1 track trigger
- Flavour tagging up to |η| < 3.5
- Preliminary studies with cMVAv2 (|η| < 1.5) and DeepCSV (|η| > 1.5)







CMS-TDR-17-001