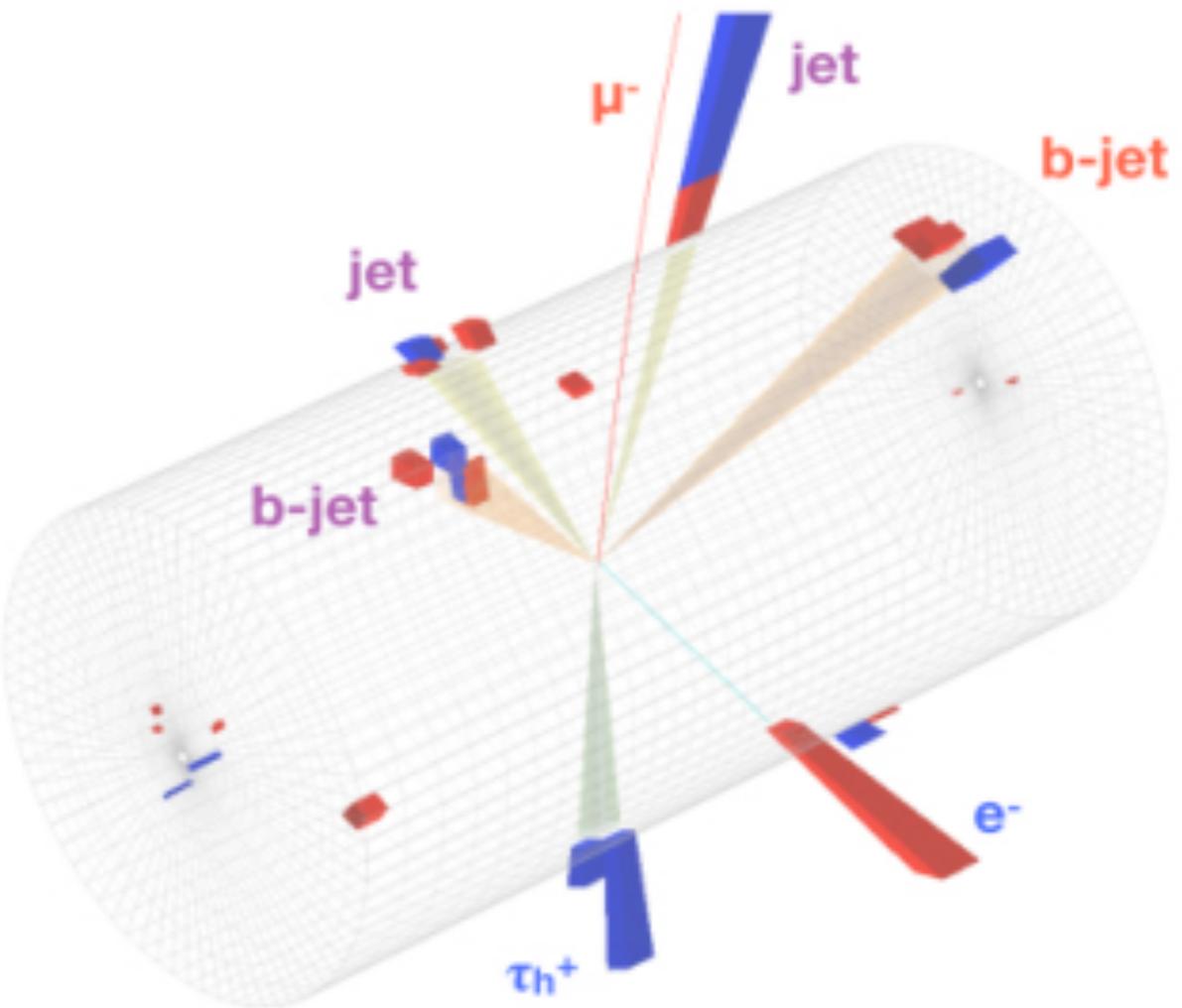


UR



# tth H $\rightarrow\tau\tau$ analysis in CMS

Cristina Martín Pérez

LLR - Ecole Polytechnique Paris

on behalf of the CMS Collaboration

Top LHC France

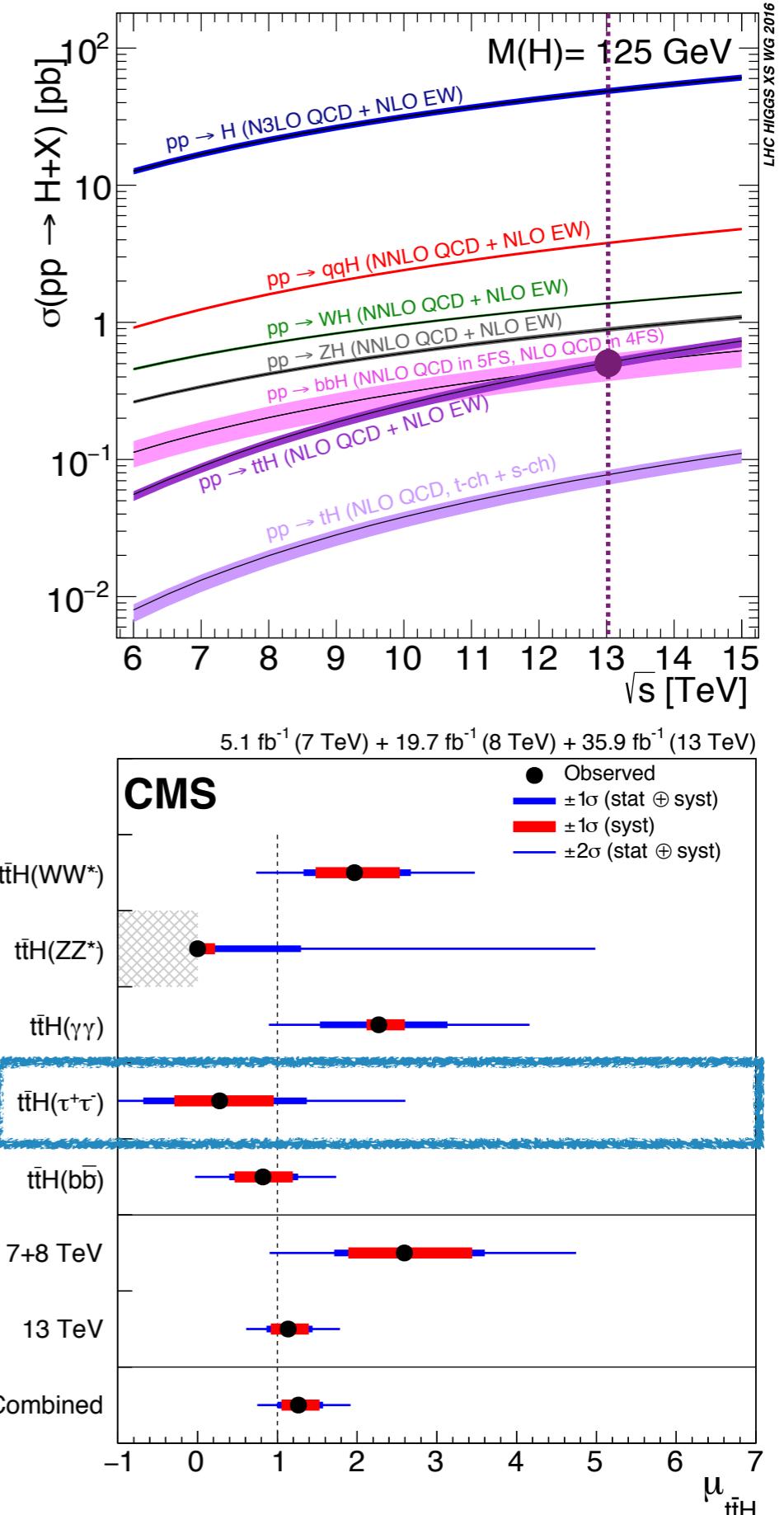
24 April 2019, LPSC Grenoble

# Motivation

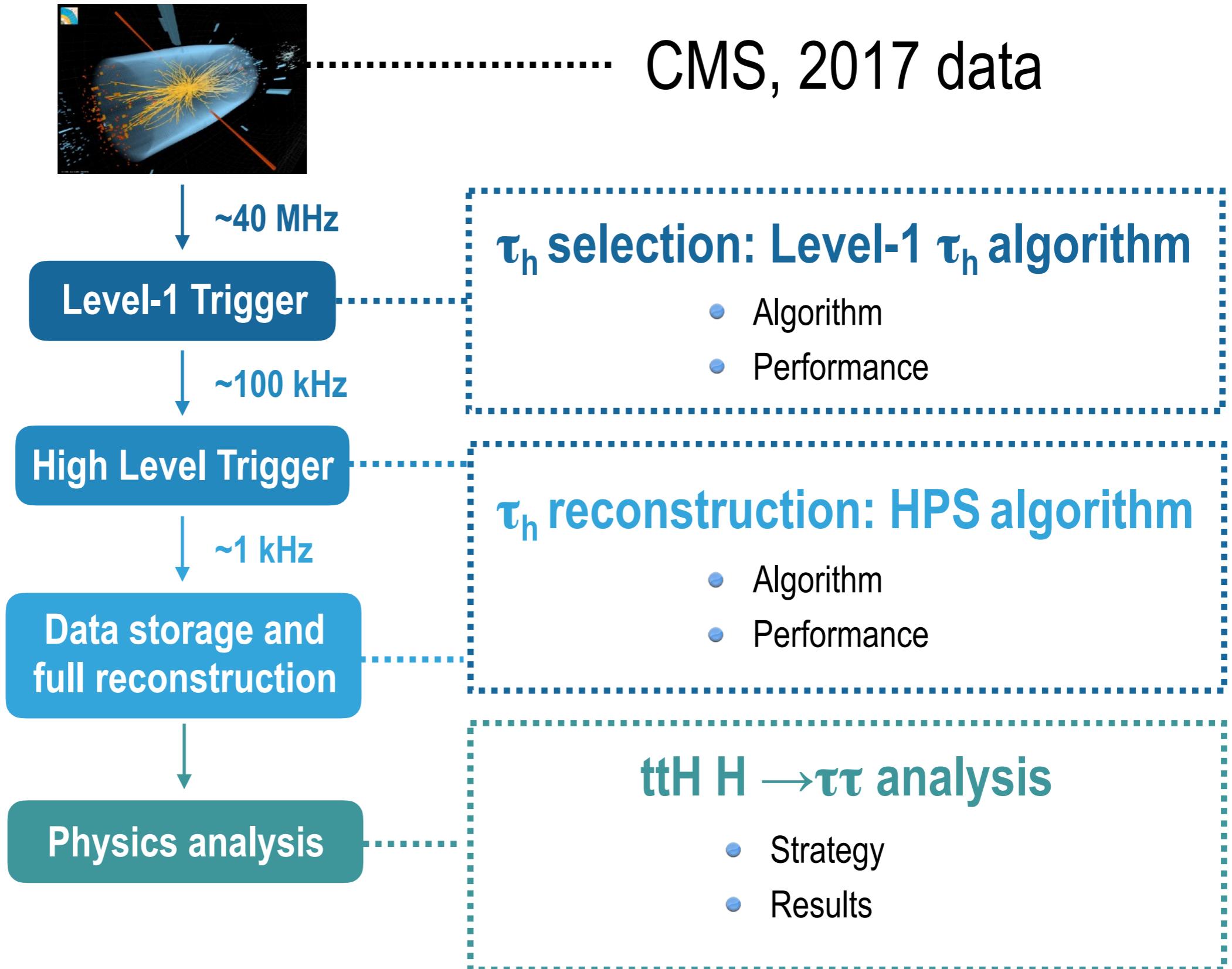
- The measurement of the **top Yukawa coupling** ( $y_t \propto m_t / v \approx 1$ ) of high phenomenological interest:
  - ▶ Extraordinarily large top quark mass  $\leftrightarrow$  special role in EWSB mechanism?
- Direct sensitivity from **ttH** process:
  - ▶ Observation by ATLAS / CMS<sup>(\*)</sup> April 18
  - ▶ Precision measurements
- $pp \rightarrow ttH$  process:
  - ▶ Very challenging: cross-section 510 fb @13 TeV
  - ▶ But accessible in a wide range of final states!
- This talk: **ttH** with  $H \rightarrow \tau\tau$ 
  - ▶ Low branching ratio (6%)
  - ▶ Complex final state
  - ▶ Significant fake background

Hadronic  $\tau$  selection and **identification** essential!

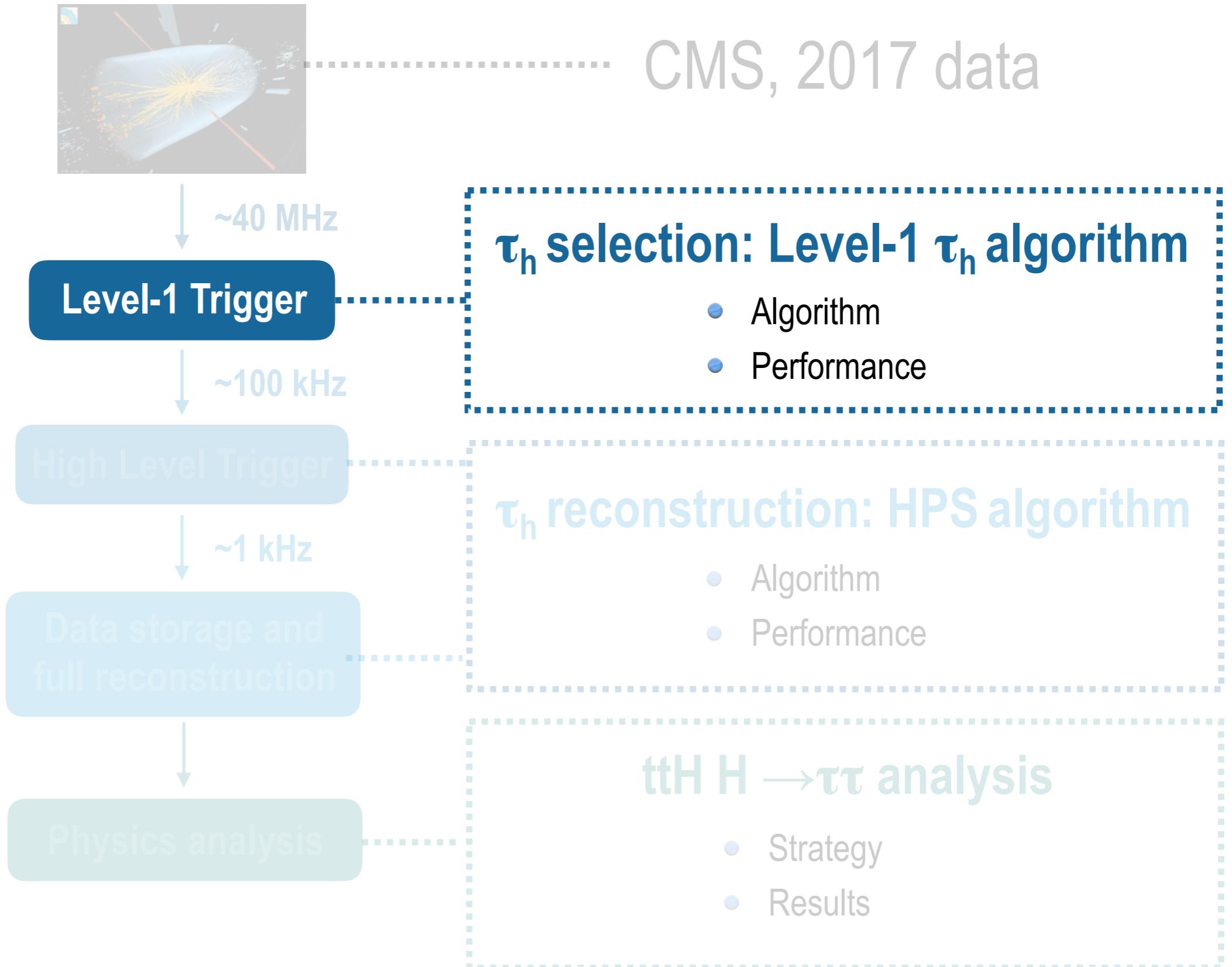
(<sup>\*</sup>) April 2018, Phys. Rev. Lett. 120, 231801 (2018)



# Outline

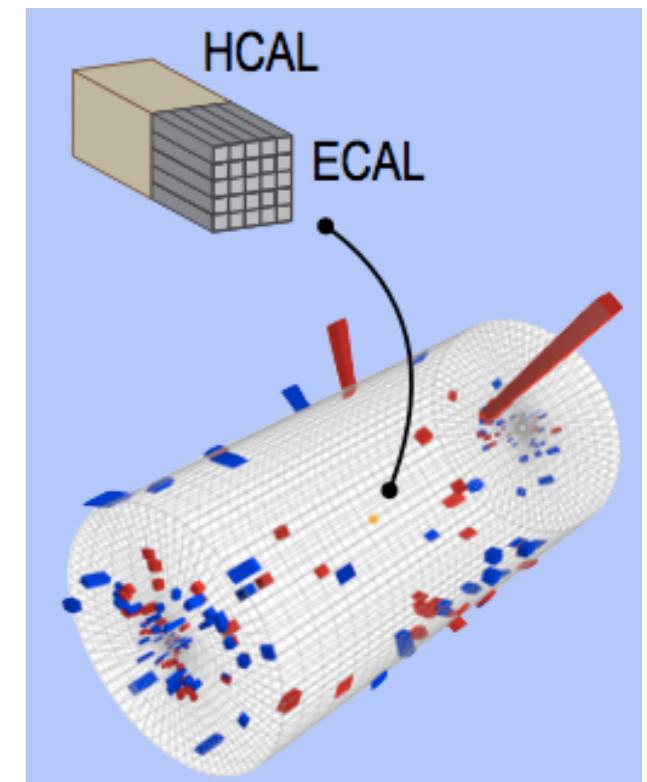
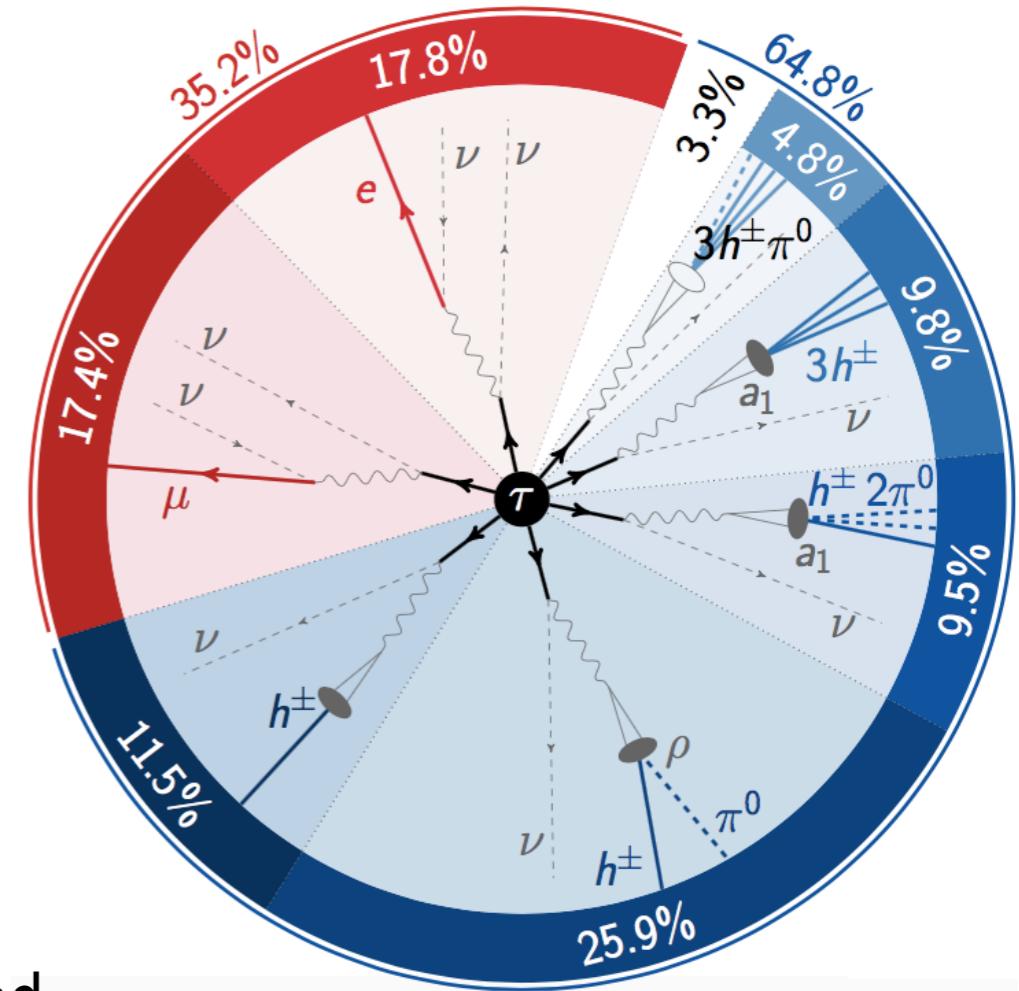


# Outline

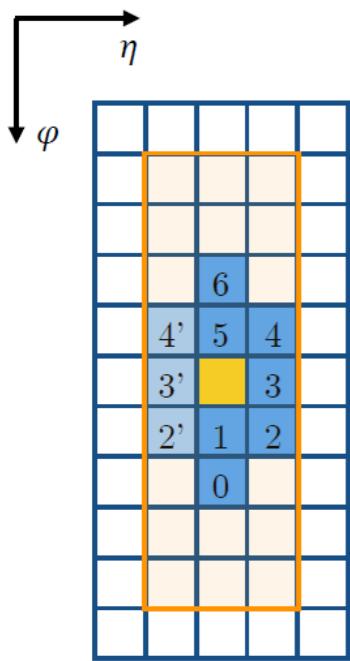


## Level-1 $\tau_h$ trigger

- $\tau$  leptonic decays (~35%):
  - ▶ clean signature
  - ▶ easily identified with corresponding e/ $\mu$
- $\tau$  hadronic decays (~65%):
  - ▶ challenging signature due to similarity with jets
  - ▶ identified with dedicated online/offline algorithms
- Level-1 hadronic  $\tau$  algorithm:
  - ▶ Dedicated Level-1 hadronic  $\tau$  algorithm implemented at hardware level for the first time at the start of Run 2
  - ▶ Benefited from Level-1 trigger upgrade: improved granularity, isolation and pileup resilience
  - ▶ Uses calorimeter inputs only (ECAL+HCAL trigger towers) and performs a decision in 3.8  $\mu$ s!
  - ▶ Its good performance made the fully-hadronic channel very sensitive in the  $H \rightarrow \tau\tau$  analysis, helping achieve the observation with 2016 data.



## Level-1 $\tau_h$ trigger: algorithm



1

Localized  $\tau_h$  energy deposits in calorimeters are identified through **dynamic clustering** of small groups of trigger towers.

3

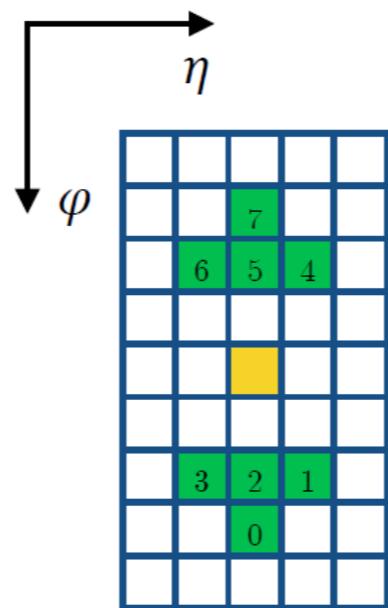
The energy is **calibrated** to correct for non-uniformities in the detector response or losses during clustering:

From simulation

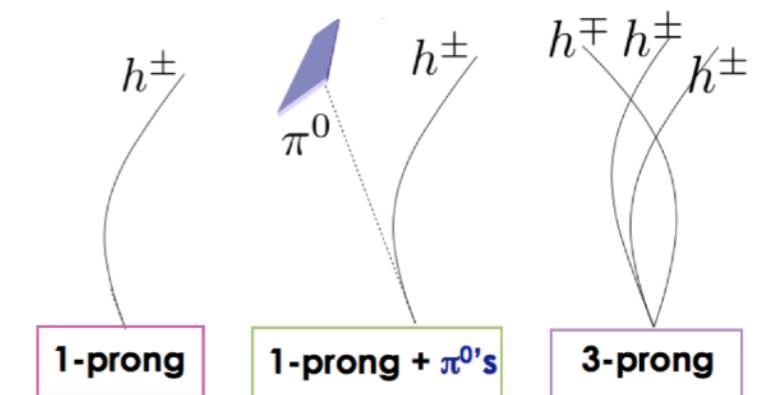
$$E_{T,\text{calib}}^{\tau} = c E_{T,\text{raw}}^{\tau}$$

$$c = c(E_{T,\text{raw}}^{\tau}, i\eta, i^{\text{Merged}}, i^{\text{EM}})$$

[CMS-DP-2015-009](#)



2

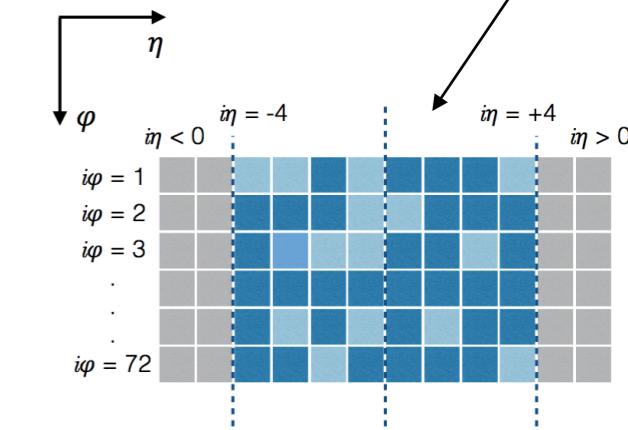
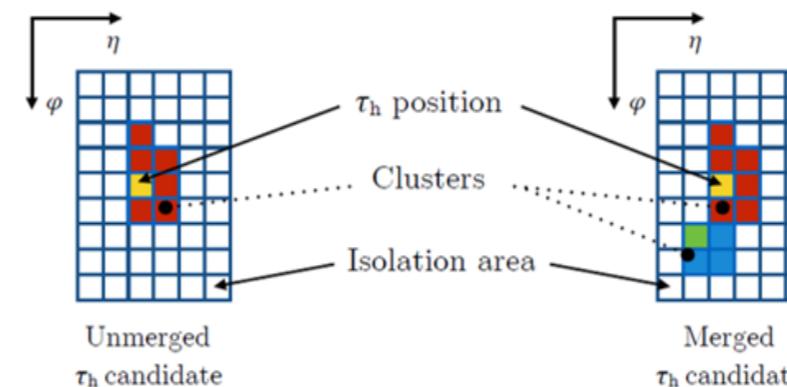


**Secondary clusters** from  $\tau$  decays, spread due to the magnetic field, are merged into a single candidate (~15%).

4

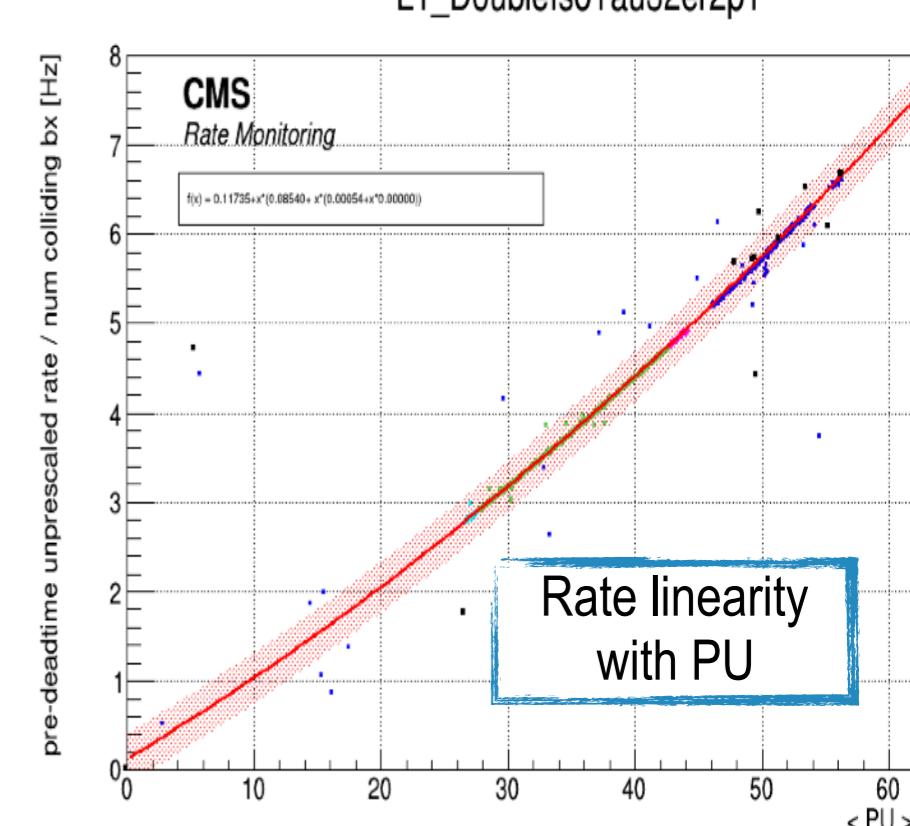
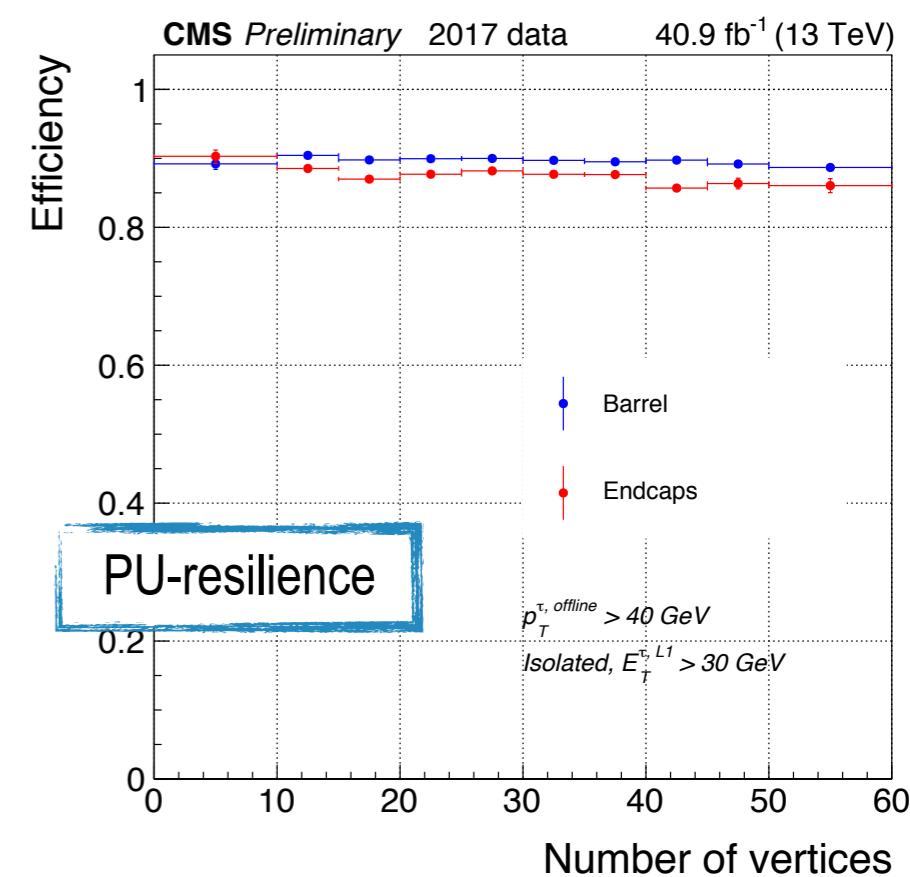
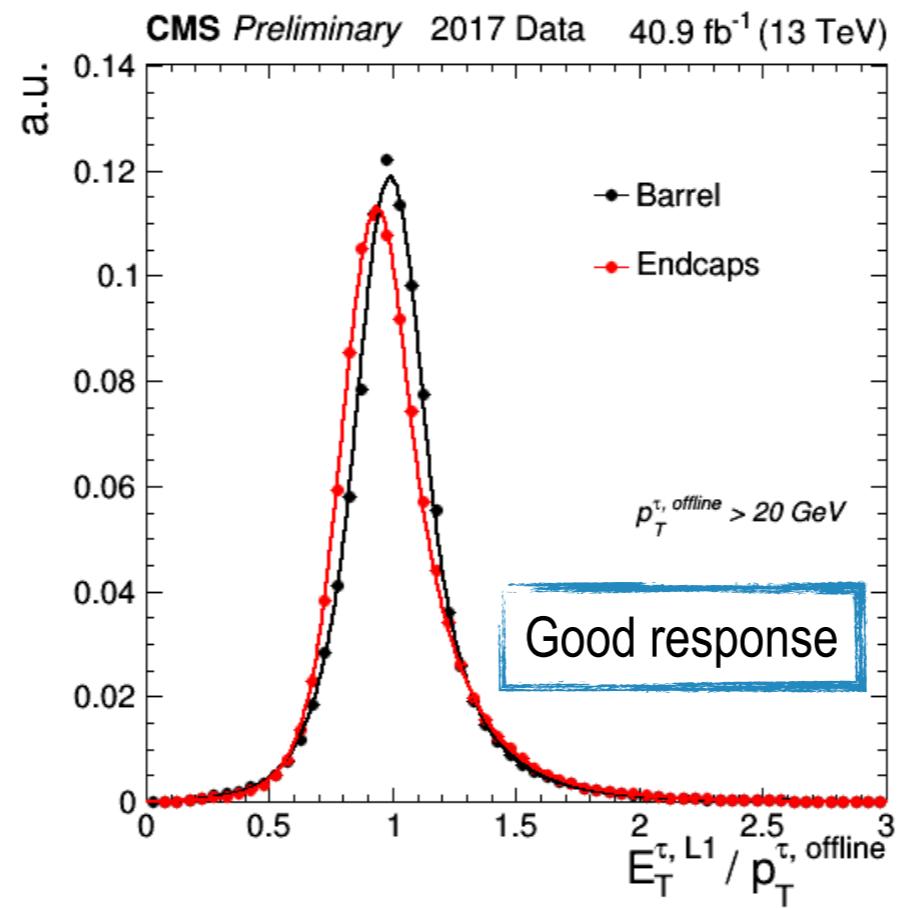
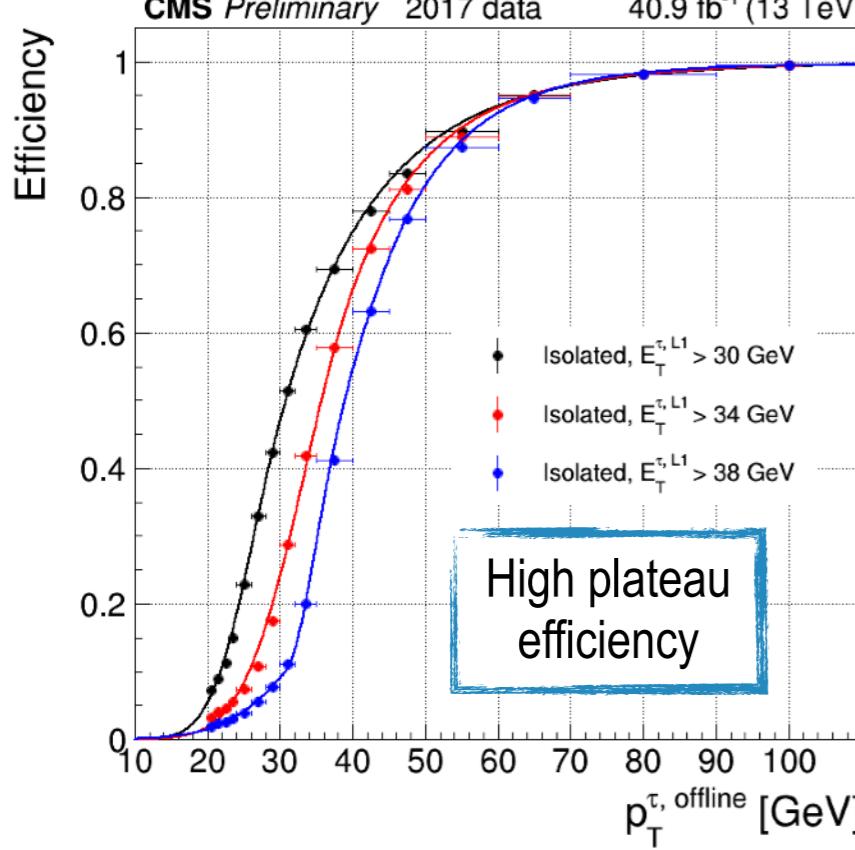
**Isolation** criterion is applied to reject quark and gluon background, dependent on the PU and relaxed with  $p_T$  to recover 100% efficiency:

$$E_{T,\text{iso}}^{\tau} = E_{T,\text{raw}}^{6 \times 9} - E_{T,\text{raw}}^{\tau} \quad \text{with} \quad E_{T,\text{iso}}^{\tau} < \xi(E_{T,\text{raw}}^{\tau}, i\eta, n_{TT})$$



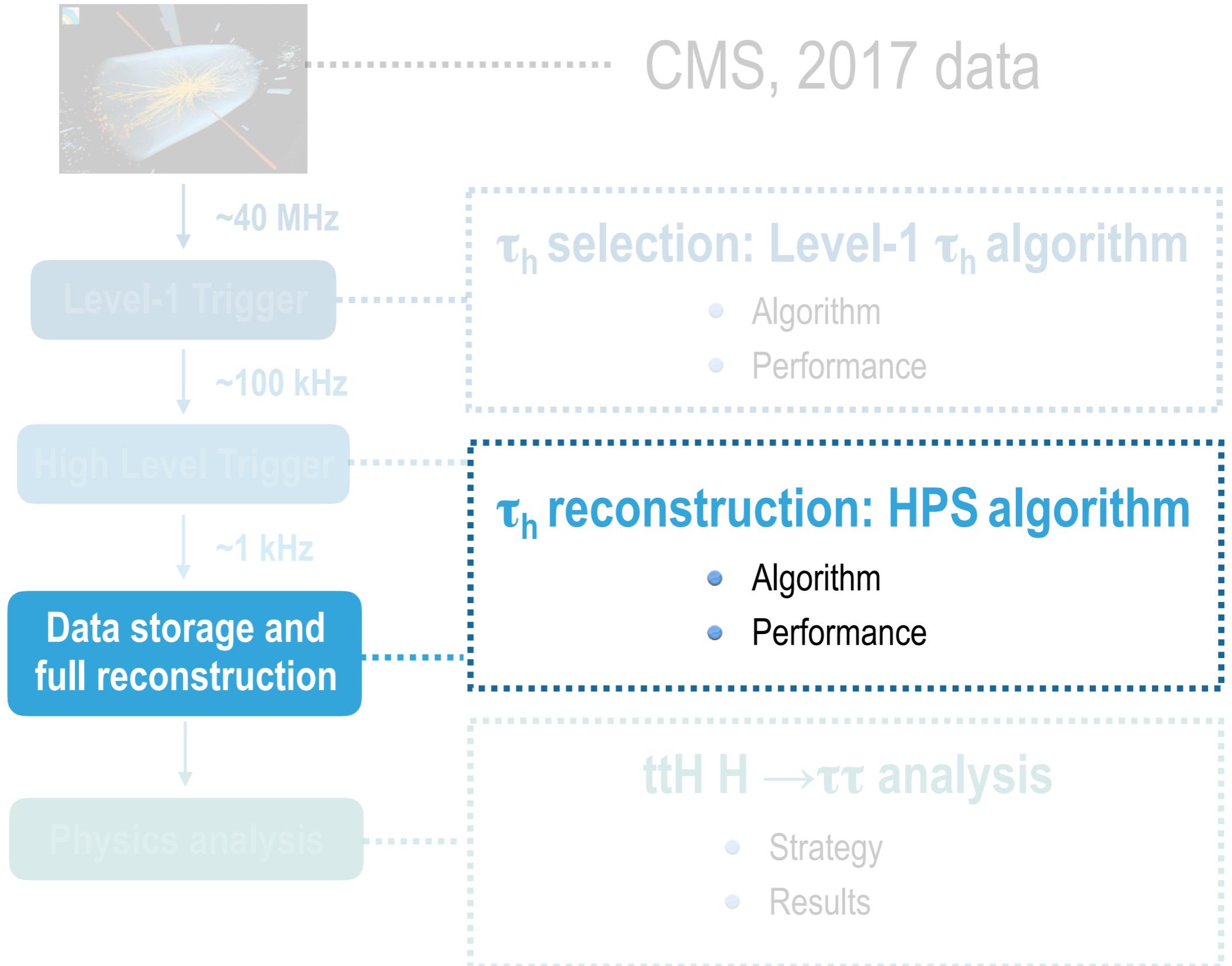
# Level-1 $\tau_h$ trigger: performance

[CMS-DP-2018-006](#)



Seed	Unprescaled in all columns	Physics
Single- $\tau_h$	L1_SingleTau120er2p1	Boosted Higgs
Double- $\tau_h$	L1_DoubleIsoTau32(30)er2p1	$H \rightarrow \tau_h \tau_h$
$e/\gamma + \tau_h$	LooseIsoEG22er2p1_IsoTau26er2p1_dR_Min0p3	$H \rightarrow \tau_h e$
$\mu + \tau_h$	L1_Mu22er2p1_IsoTau32er2p1	$H \rightarrow \tau_h \mu$
MET+ $\tau_h$	L1_IsoTau40er_ETM90	Charged Higgs

# Outline



# Offline $\tau_h$ reconstruction: Hadrons-Plus-Strips algorithm

**1** Seeded by the constituents of the jets (anti- $k_T$  R=0.4) reconstructed with the Particle Flow (PFlow) algorithm ( $e^\pm, \mu^\pm, \gamma, h^\pm, h^0$ )

**2** Identification of the different decay modes:

$$\tau^\pm \rightarrow [1, 3]h^\pm + [0 - 2]\pi^0 + \nu_\tau$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\gamma + \text{material} \rightarrow e^+e^-$$

- ▶  $\pi^0 \rightarrow \gamma\gamma$  signature dynamically clustered in rectangular  $\Delta\phi \times \Delta\eta$  ECAL strip
- ▶  $h^\pm (\pi^\pm, K^\pm)$  signature reconstructed with PFlow technique

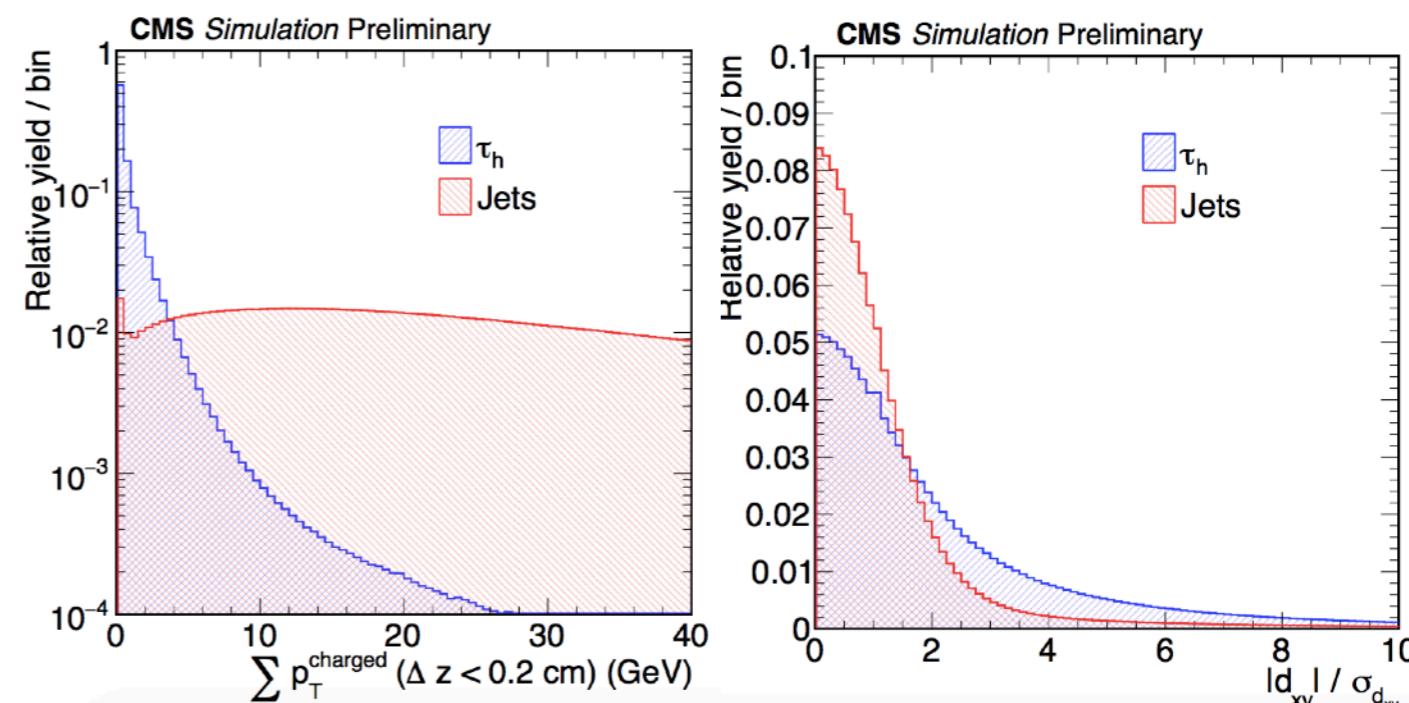
**3** Quality criteria applied:

- ▶  $\tau_h$  charge is  $\pm 1$
- ▶ invariant mass compatible with  $\rho(770) / a_1(1260)$
- ▶ cone size:

$$0.1 \geq R_{\text{sig}} = \frac{3 \text{ GeV}}{p_T} \geq 0.05$$

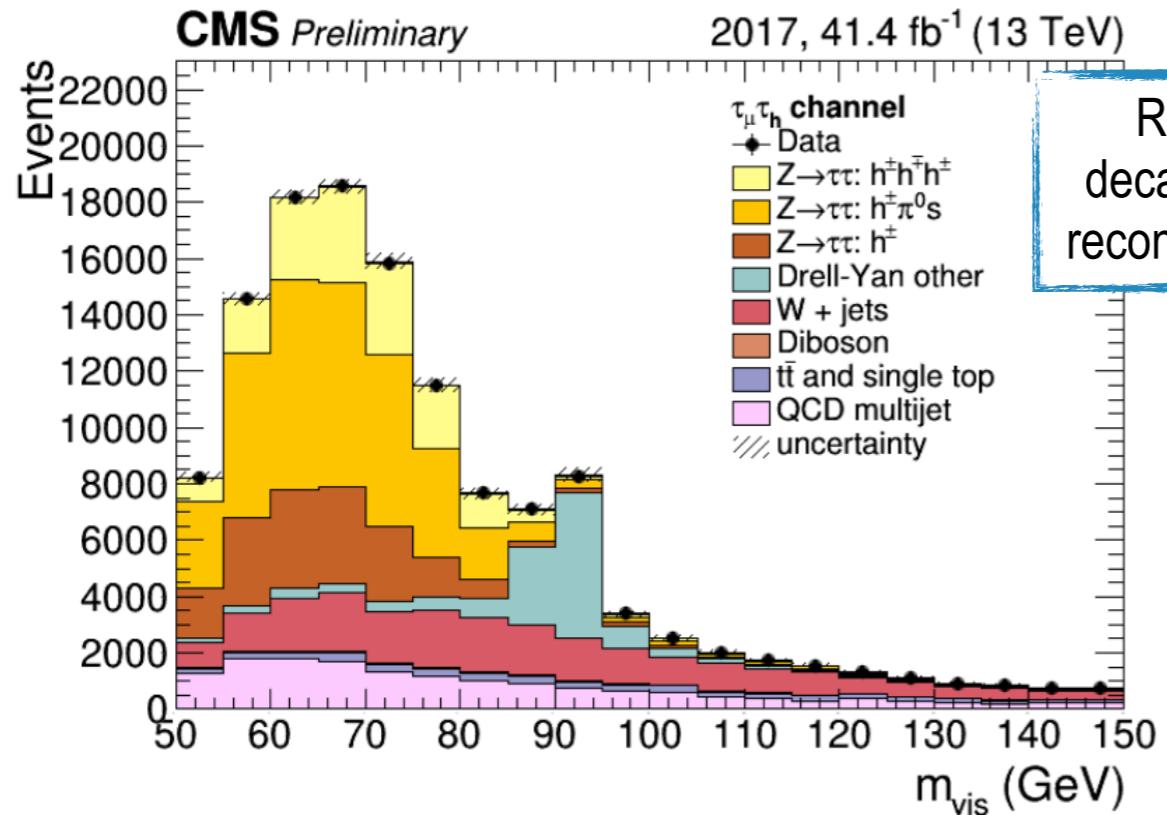
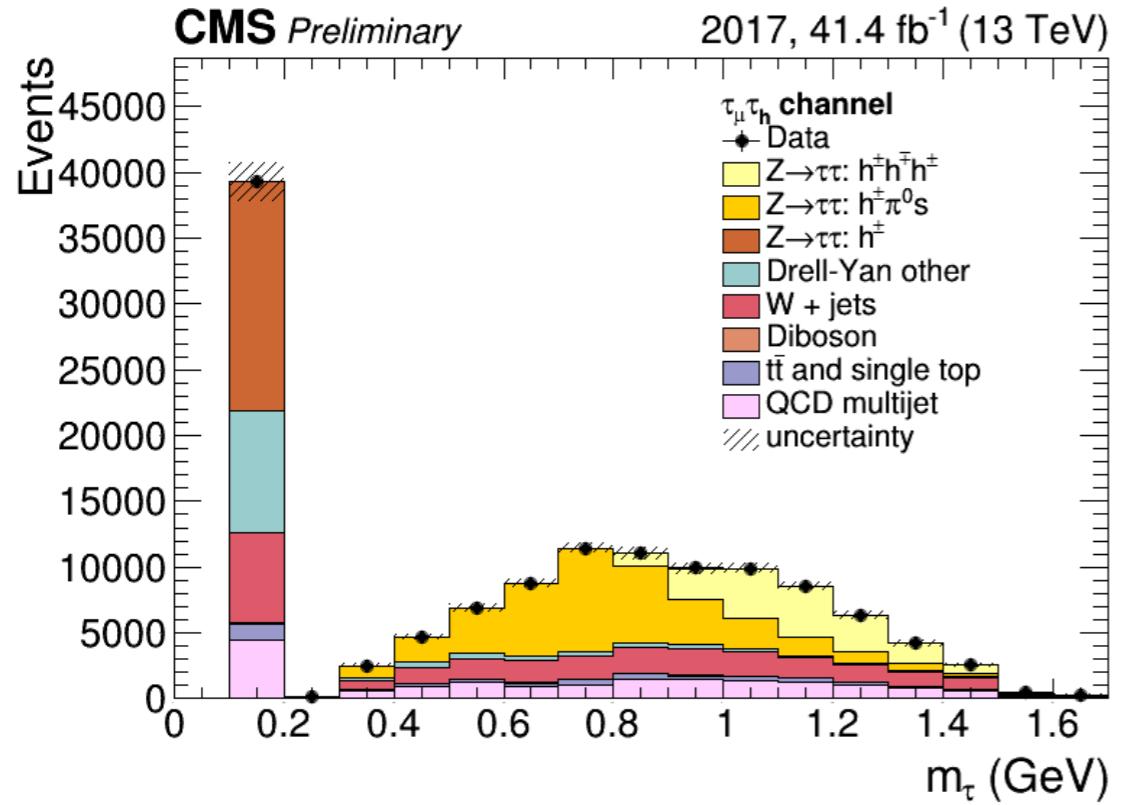
## MVA (BDT) discriminant vs. q/g jets:

- Charged/neutral isolation sums
- Lifetime (impact parameters, flight length)
- Reconstructed decay mode
- Particle multiplicity
- Differential strip information



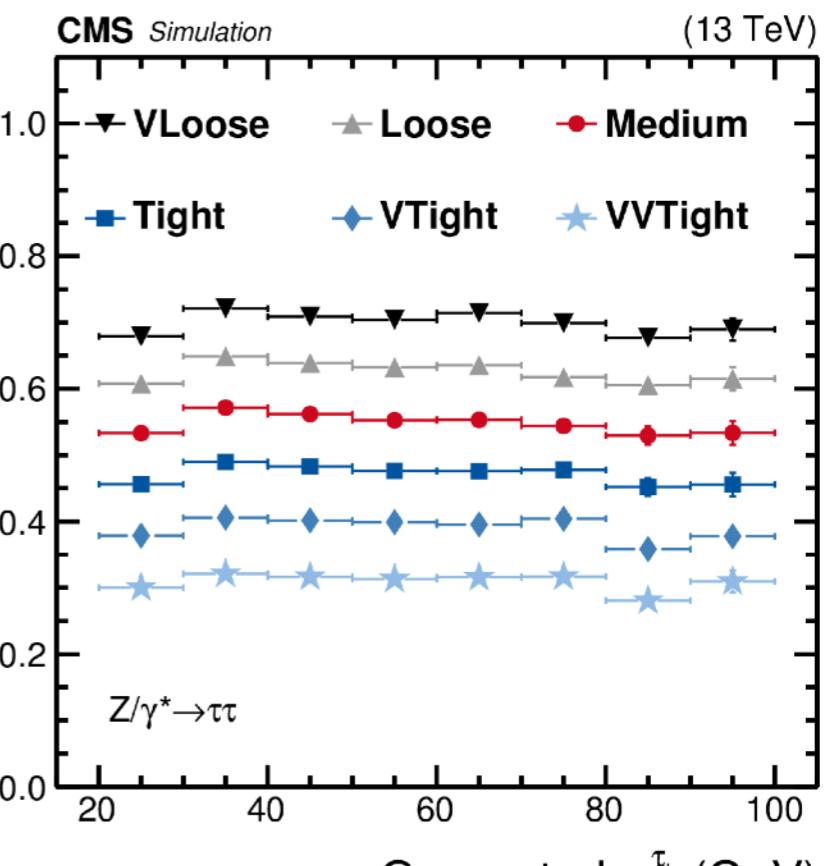
# Offline $\tau_h$ reconstruction: performance

[CMS-TAU-2016-003](#)

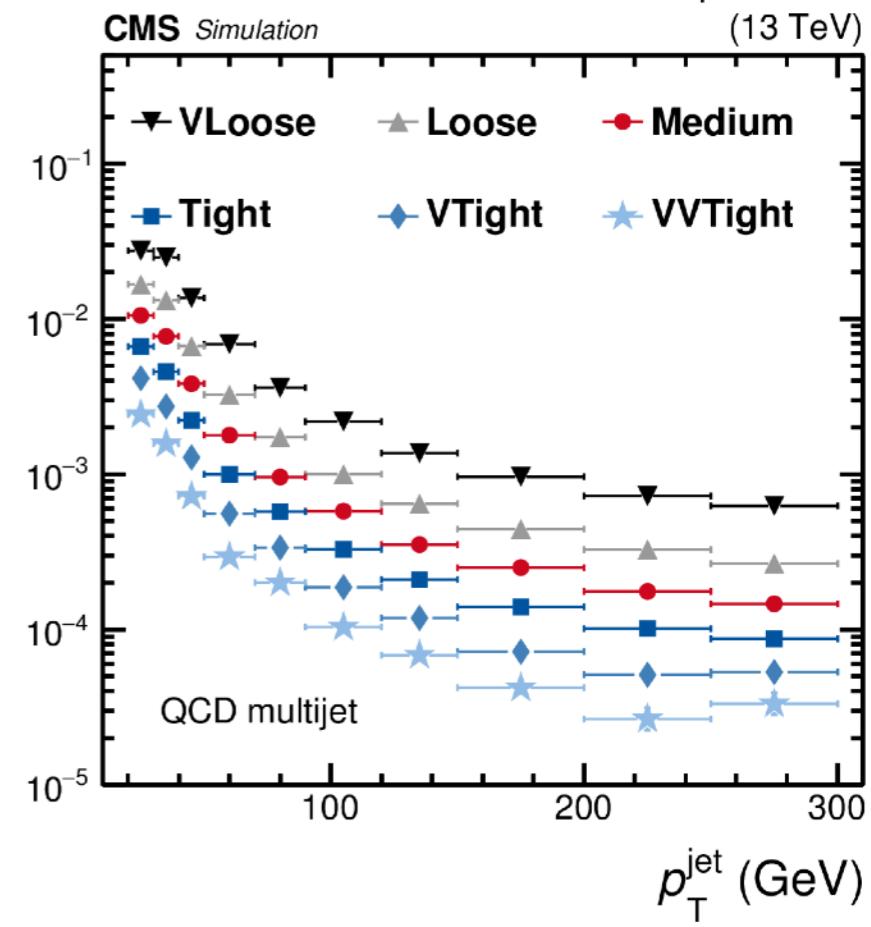


Robust decay mode reconstruction

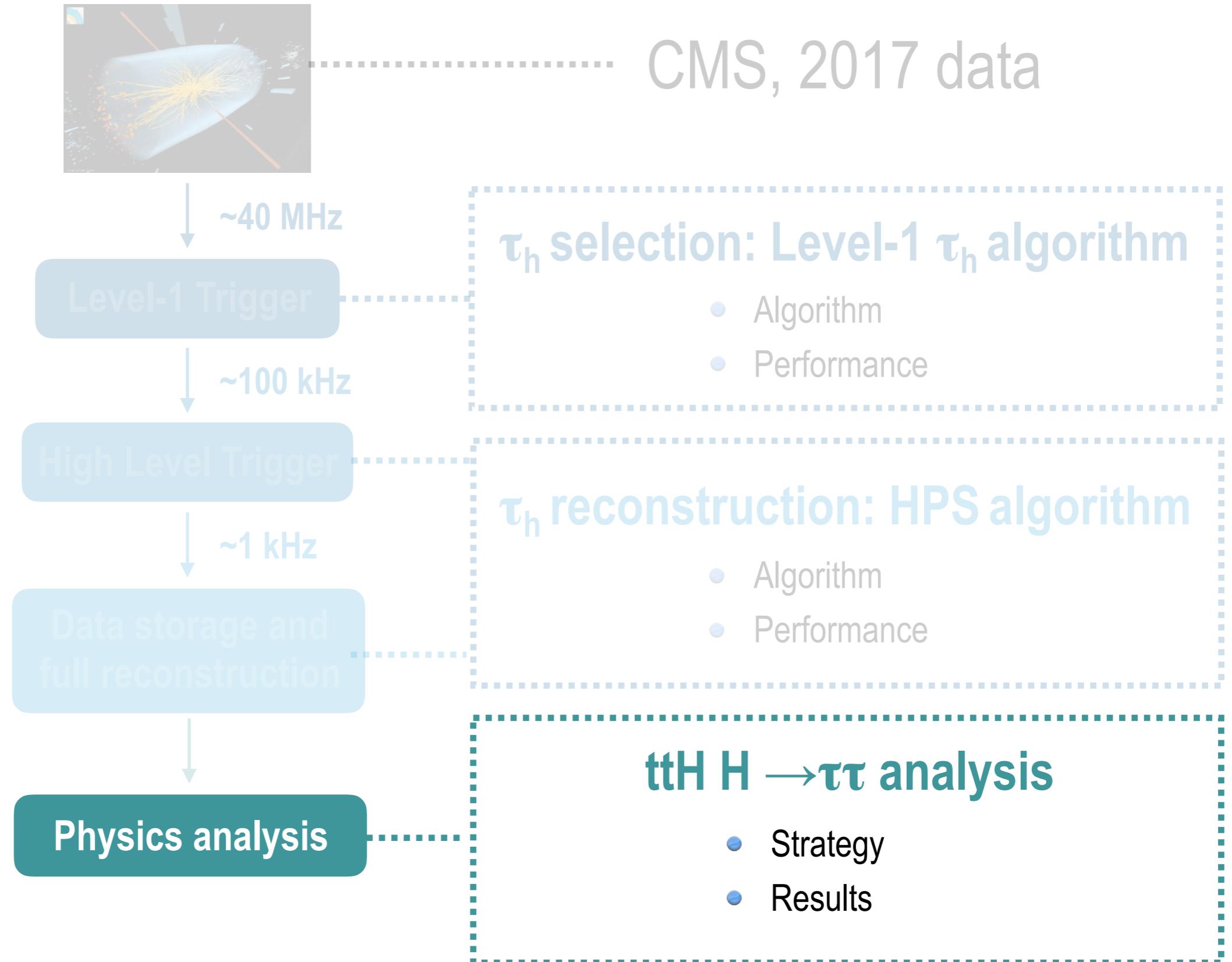
$\tau_h$  identification efficiency



Misidentification probability



# Outline



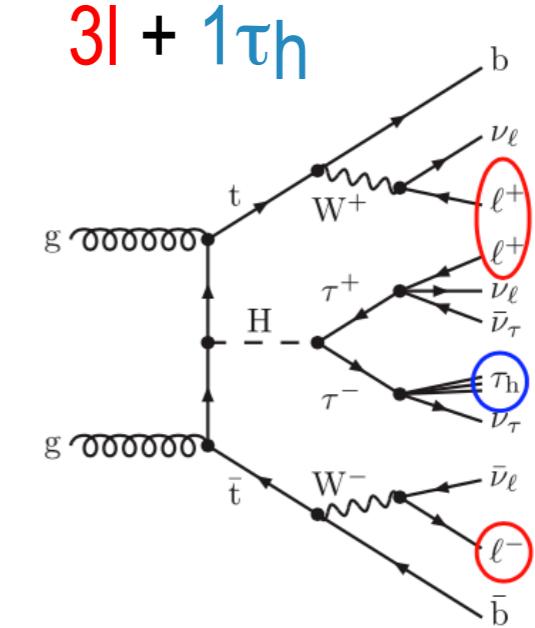
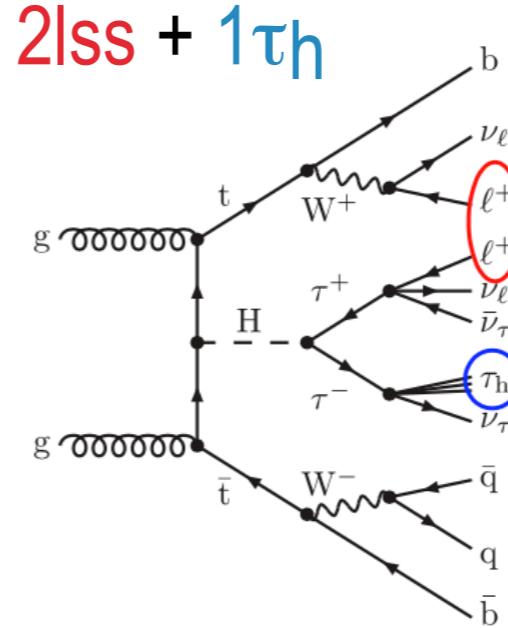
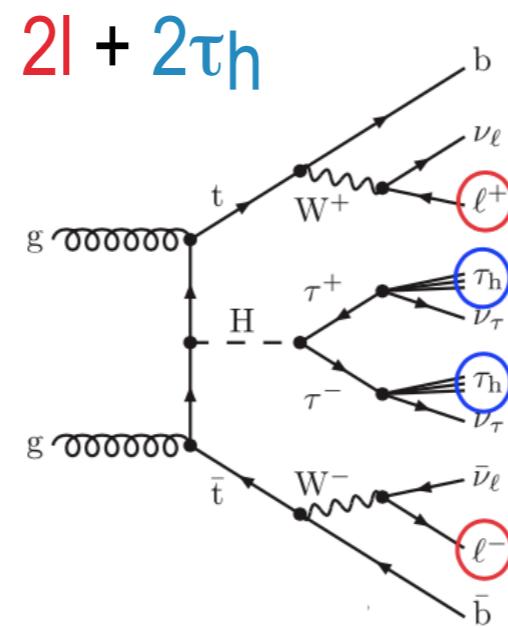
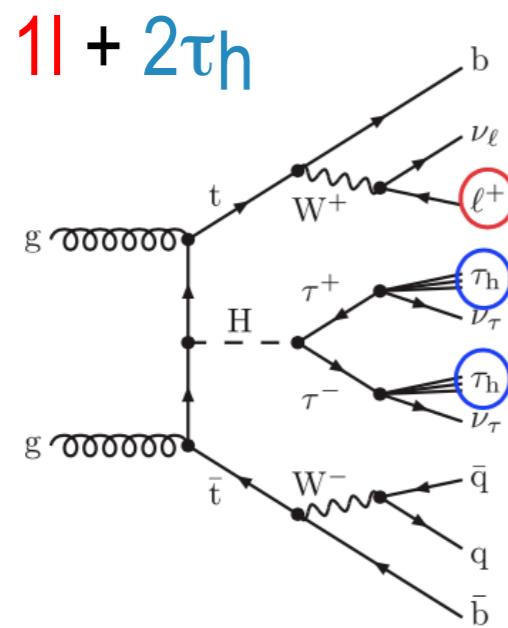
# Analysis strategy

[HIG-18-019](#)

- ttH  $H \rightarrow \tau\tau$  analysis looking for

$t \rightarrow b l \nu_l$	1 b-jet + 1 lepton + neutrinos
$t \rightarrow b q q$	1 b-jet + 2 light jets
$H \rightarrow \tau\tau$	1-2 $\tau_h$ (+ lepton + neutrinos)

- Targeting **4 exclusive categories** based on **lepton (e/ $\mu$ )** and  $\tau_h$  multiplicity:

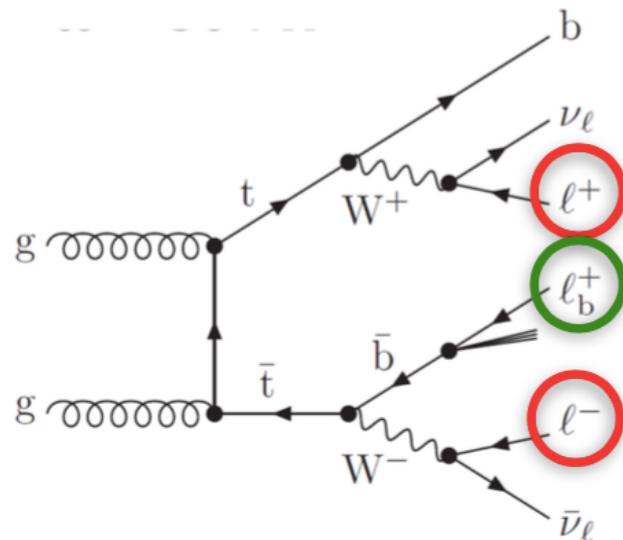


- **Complex event reconstruction:** large multiplicity of objects in the final state, high hadronic activity and presence of neutrinos.
- Extensive use of **MVA discriminants** for object identification (b-jets, leptons,  $\tau_h$ ) and signal extraction (MEM, BDT).

# Object reconstruction

[HIG-18-019](#)

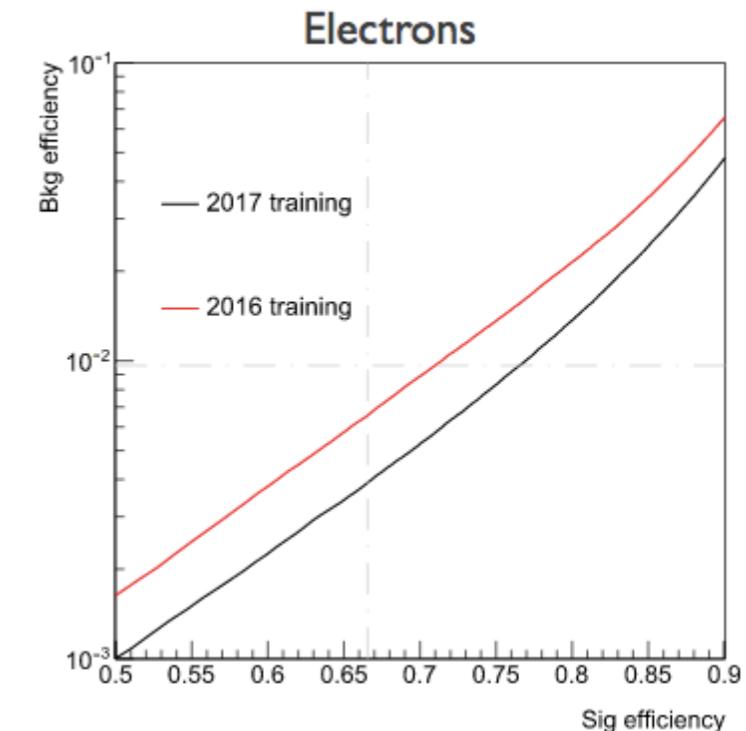
## Leptons (electrons, muons)



MVA: **prompt** leptons (from W, Z, T) vs. **non-prompt** leptons (b or light mesons), with inputs:

- ▶ Kinematics
- ▶ Vertex variables
- ▶ Properties nearest jet
- ▶ Identification criteria
- ▶ **Mini-isolation**

$$I_\ell = \sum_{\text{charged}} p_T + \max \left( 0, \sum_{\text{neutrals}} p_T - \rho \mathcal{A} \left[ \frac{R}{0.3} \right]^2 \right)$$



## Jets

MVA: **b-jets** vs. **light jets** (DeepCSV), with inputs:

- ▶ Lifetime
- ▶ Particle multiplicity
- ▶ Mass

## Neutrinos

Optimized linear discriminator (LD), combination of:

$$0.6 * \left( E_T^{\text{miss}} = - \sum_i \vec{p}_T(i) \right) + 0.4 * \left( H_T^{\text{miss}} = \left| \sum_{\text{leptons}} \vec{p}_{T\ell} + \sum_{\tau_h} \vec{p}_{T\tau} + \sum_{\text{jets}} \vec{p}_{Tj} \right| \right)$$

MET: Better resolution

MHT: PU resilience

# Backgrounds

Type	Process	Estimation
Irreducible	<b>ttV</b>	$ttZ^*], ttW(W)^*, tt\gamma$
	<b>Diboson</b>	$WW, WZ^*, ZZ$
	<b>Rares processes</b>	$t\bar{t}t, WWqq, tZq, VVV$
	<b>tH</b>	$tHq, tHW$
Reducible	<b>Fakes</b>	Non-prompt lepton or hadrons $\rightarrow$ prompt leptons
		Jets $\rightarrow T_h$ 's
	<b>Charge mismeasurement</b>	$OS \text{ leptons}$ $\rightarrow SS \text{ leptons}$

# Signal extraction: BDT

[HIG-18-019](#)

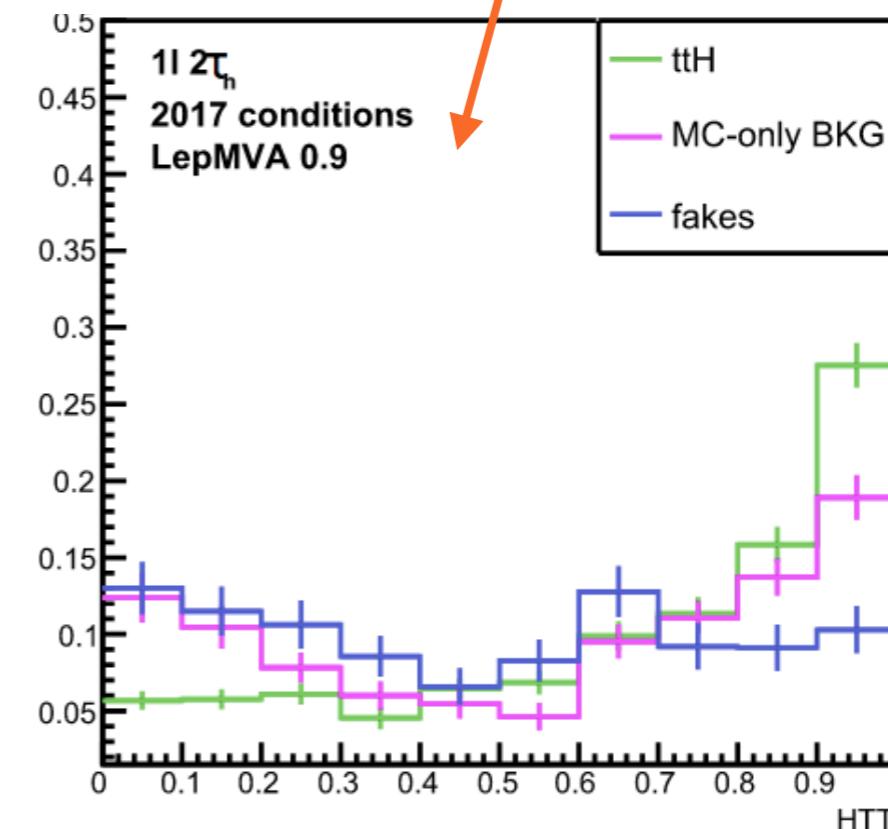
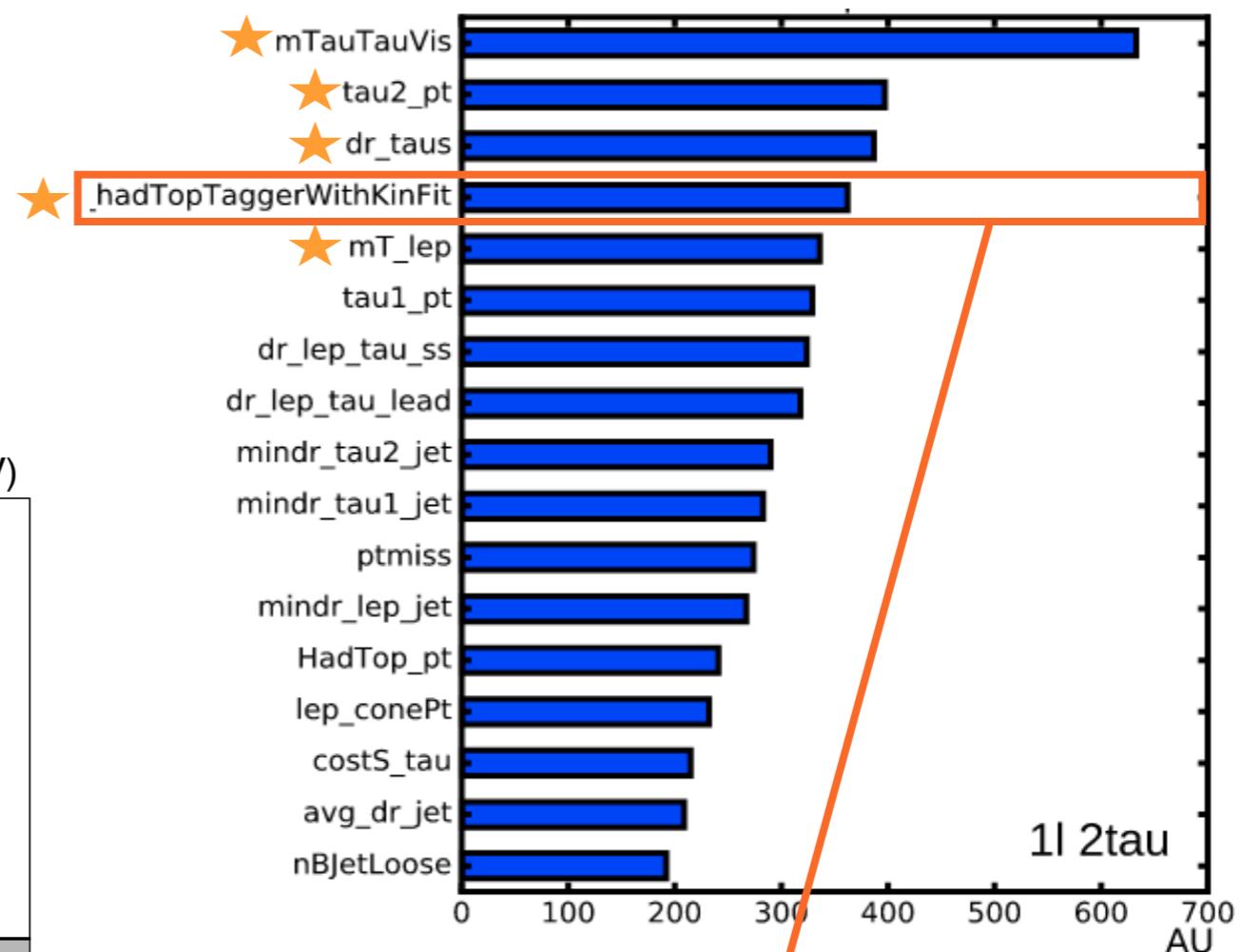
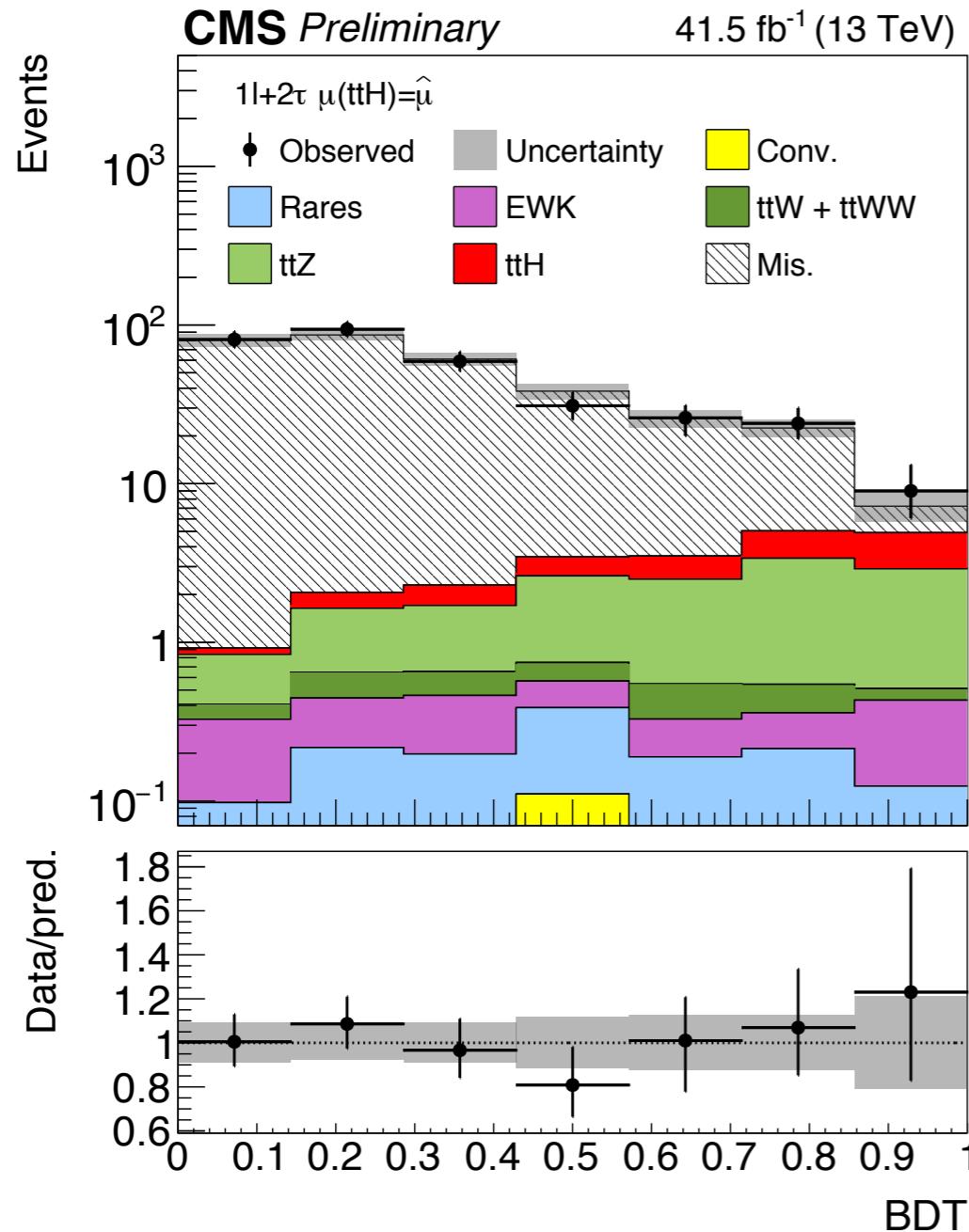
- BDTs used for signal extraction in all categories in the analysis of 2017 data (HIG-18-009).
- 1 BDT per category trained to discriminate ttH against the **sum of ttV and ttbar backgrounds**.
- Input variables:
  - ▶ Lepton/ $\tau_h$ /jet kinematics
  - ▶ Lepton/ $\tau_h$ /jet topological relations
  - ▶ Jet multiplicity and b-tagging score
  - ▶ Missing transverse energy
  - ▶ **Hadronic Top Tagger MVA** (**1l+2 $\tau_h$**  and **2lss+1 $\tau_h$** ): likelihood of a jet triplet to be compatible with hadronic top decay products.

Category	$1\ell + 2\tau_h$	$2\ell ss + 1\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$
Leading $\ell$ cone $p_T$	X		X	X
Trailing $\ell$ cone $p_T$		X		X
Minimum of $\Delta R$ (leading $\ell, j$ )	X	X	X	X
Minimum of $\Delta R$ (trailing $\ell, j$ )		X		
$\Delta R$ (leading $\ell$ , trailing $\ell$ )		X		X
Transverse Mass of leading $\ell$	X	X		
Transverse Mass of trailing $\ell$		X		
Maximum $ \eta $ of $\ell$ collection		X		X
Signal leading $\ell \times$ signal trailing $\ell$			X	
Average of $\Delta R(jj)$	X	X	X	
Number of jets ( $p_T > 25$ GeV)		X		X
Number of loose b-jets	X		X	
Mass of leading medium b-jet pair		X		
Mass of leading loose b-jet pair				X
$E_T^{\text{miss}}$	X	X		X
res-hTT	X	X		
Hadronic t $p_T$	X	X		
$D_{\text{had}}^{\max}$				
$D_{H_j}^{\max}$				
Leading $\tau_h p_T$	X	X	X	X
Trailing $\tau_h p_T$	X		X	
Mass of leading $\tau_h$ + trailing $\tau_h$	X		X	
$\Delta R$ (leading $\tau_h$ , trailing $\tau_h$ )	X		X	
$\cos(\theta)^*$ (leading $\tau_h$ , trailing $\tau_h$ )	X		X	
Minimum of $\Delta R$ (leading $\tau_h, j$ )	X	X		X
Minimum of $\Delta R$ (trailing $\tau_h, j$ )	X			
Minimum of $\Delta R(\tau_h, j)$			X	
Mass of leading $\ell$ + leading $\tau_h$				X
Mass of trailing $\ell$ + leading $\tau_h$		X		X
$\Delta R$ (leading $\ell$ , leading $\tau_h$ )	X	X		
$\Delta R$ (trailing $\ell$ , leading $\tau_h$ )		X		
$\Delta R(\ell, \tau_h)$ for same-sign pair of $(\ell, \tau_h)$	X			
Average of $\Delta R(\ell, \tau_h)$			X	

# Signal extraction: BDT

HIG-18-019

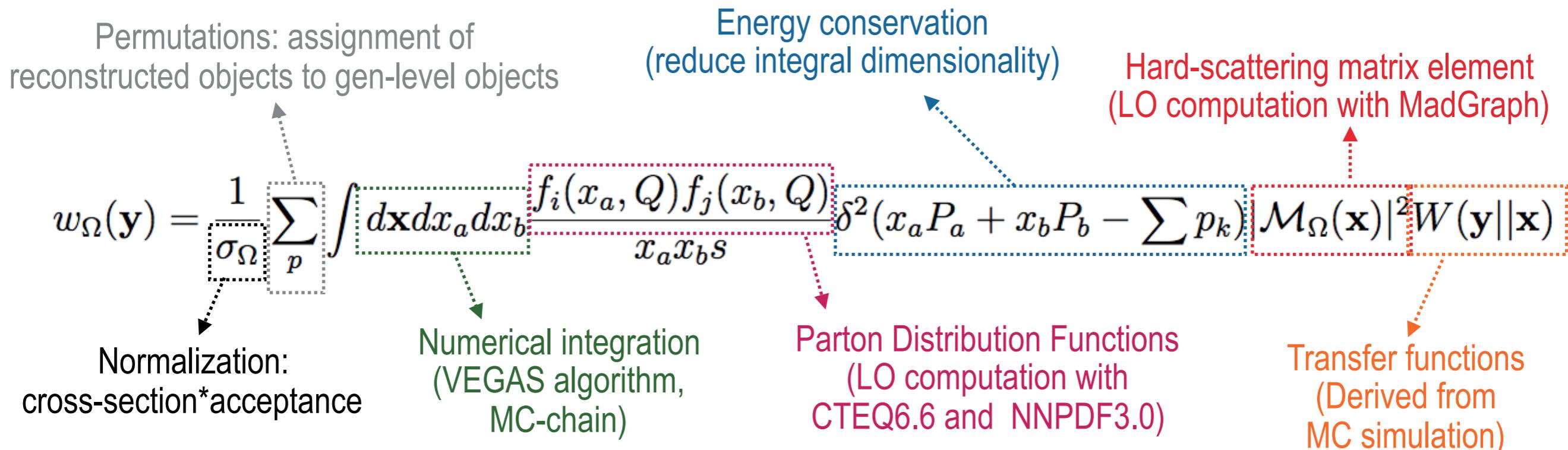
**1l + 2 $\tau$ h**



HIG-17-003

# Signal extraction: Matrix Element Method

- MEM was used for signal extraction in the  **$2lss + 1\tau_h$**  category in the analysis of 2016 data (HIG-17-003).
- Powerful classifier tool that exploits the **link** between the theory and the object reconstruction in the detector and can be applied to any process.
- MEM weights** give the probability of an event to be compatible with the signal hypothesis ttH or the background hypotheses (  **$ttZ Z \rightarrow \tau\tau$  /  $ttZ Z \rightarrow ll$  /  $ttbar$**  )



- MEM likelihood ratio:** coefficients  $\kappa(B)$  optimized for maximal S/B discrimination

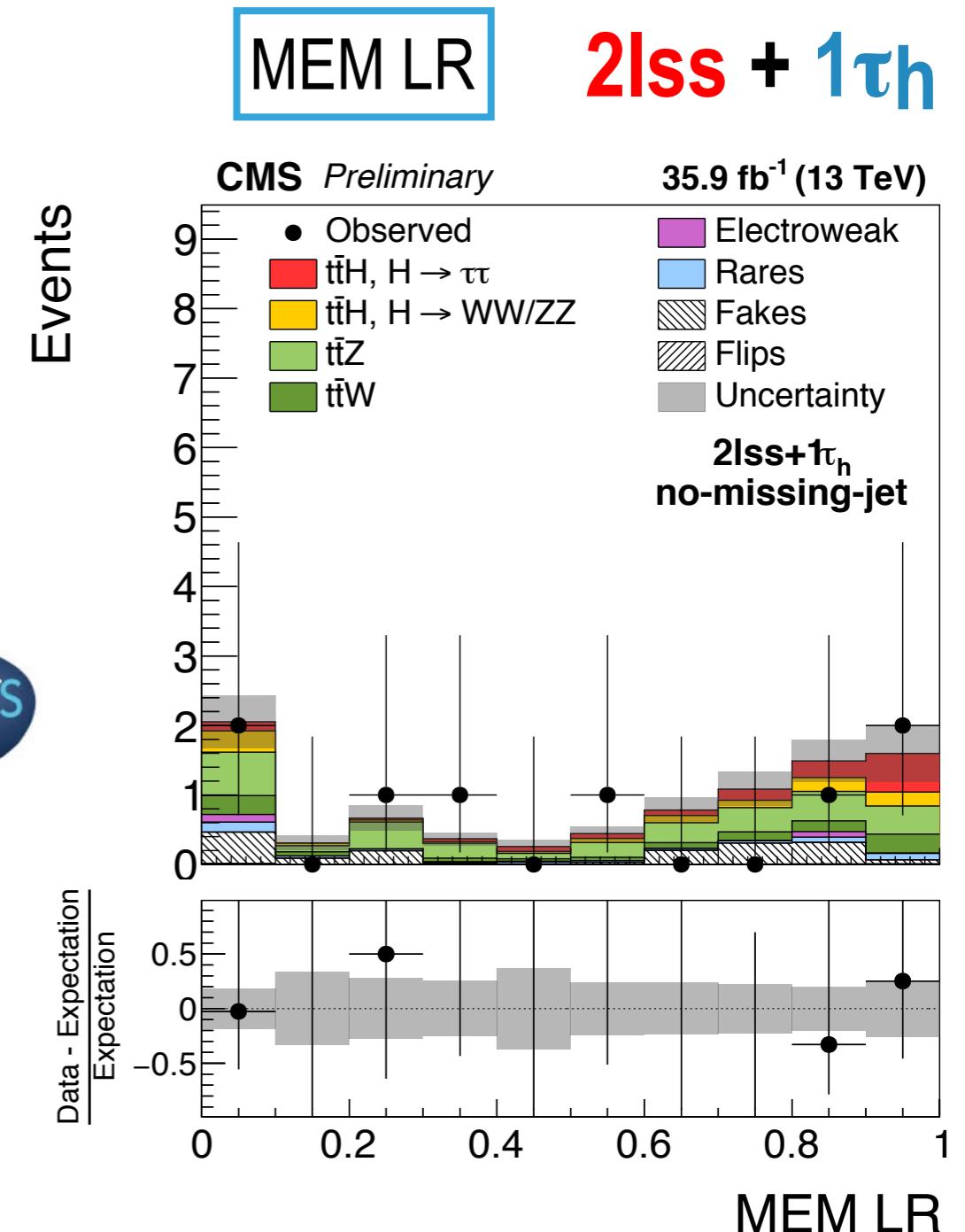
$$LR(\mathbf{y}) = \frac{w_{t\bar{t}H}(\mathbf{y})}{w_{t\bar{t}H}(\mathbf{y}) + \sum_B \kappa_B w_B(\mathbf{y})}$$

# Signal extraction: Matrix Element Method

- The high dimensional integrals in the MEM method makes it very CPU time consuming, requiring a powerful computing platform.
- In 2016, the MEM method was deployed on GPU's platform at CC-IN2P3 Computer Center (Lyon), bringing a computation time speed-up of **x200** with respect to CPU's.



- Subcategories:**
  - no-missing-jet*: all 4 jets reconstructed
  - missing-jet*: one light jet falls out of the detector acceptance or is merged with another one.



- The MEM will be used for signal extraction in the full Run 2 legacy analysis.

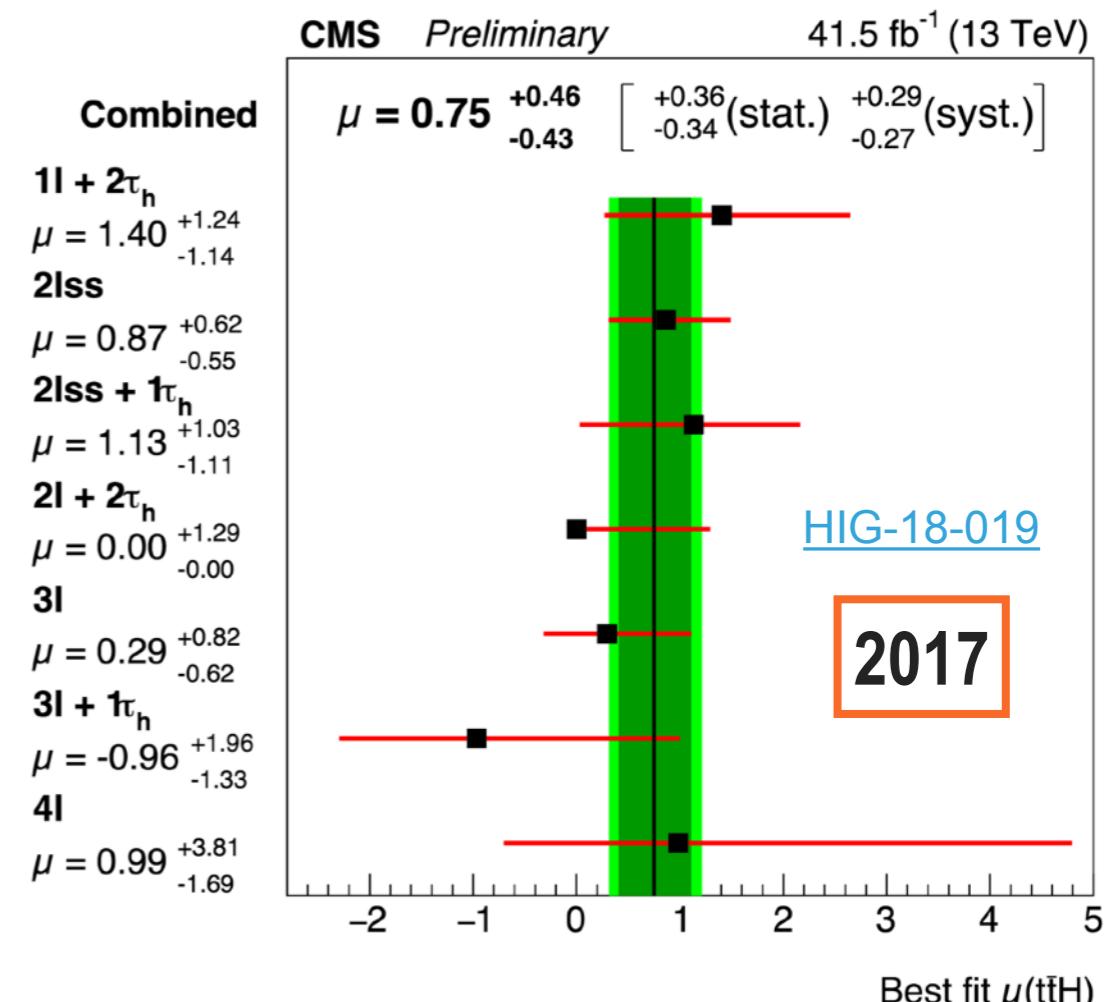
# Latest results

- **2017** data: ttH H  $\rightarrow$ WW, H  $\rightarrow$ ZZ and H $\rightarrow\tau\tau$  with final states with electrons, muons and hadronically decaying taus:

**2017**

signal strength $\pm 1\sigma$		
	Measured	Expected
$\mu_{t\bar{t}H}$	$0.75^{+0.46}_{-0.43}$	$1.00^{+0.39}_{-0.35}$
$\mu_{t\bar{t}W}$	$1.42^{+0.34}_{-0.33}$	$1.00^{+0.27}_{-0.23}$
$\mu_{t\bar{t}Z}$	$1.69^{+0.39}_{-0.33}$	$1.00^{+0.23}_{-0.20}$

$1.7\sigma$  ( $2.9\sigma$ )



- 2016+2017 combination:

[HIG-17-004](#)

$$\mu_{ttH} = 0.96^{+0.34}_{-0.31} \quad (1.00^{+0.30}_{-0.29})$$

[HIG-17-003](#)

[HIG-17-018](#)

$3.2\sigma$  ( $4.0\sigma$ )

- Main systematic uncertainties:

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)	$\Delta\mu/\mu$ [%] (Comb.)	Correlations
Theoretical sources	$\approx 8$	8	9	Correlated
e, $\mu$ selection efficiency	3–5	4	3	Correlated
$\tau_h$ selection efficiency	5	3	5	Correlated
$\tau_h$ energy calibration	1.2	1	2	Correlated
b tagging efficiency	2–15 [48]	10	5	Correlated
Jet energy calibration	2–15 [56]	3	3	Correlated
Fake background yield	$\approx 30$ –50	17	9	Un-correlated

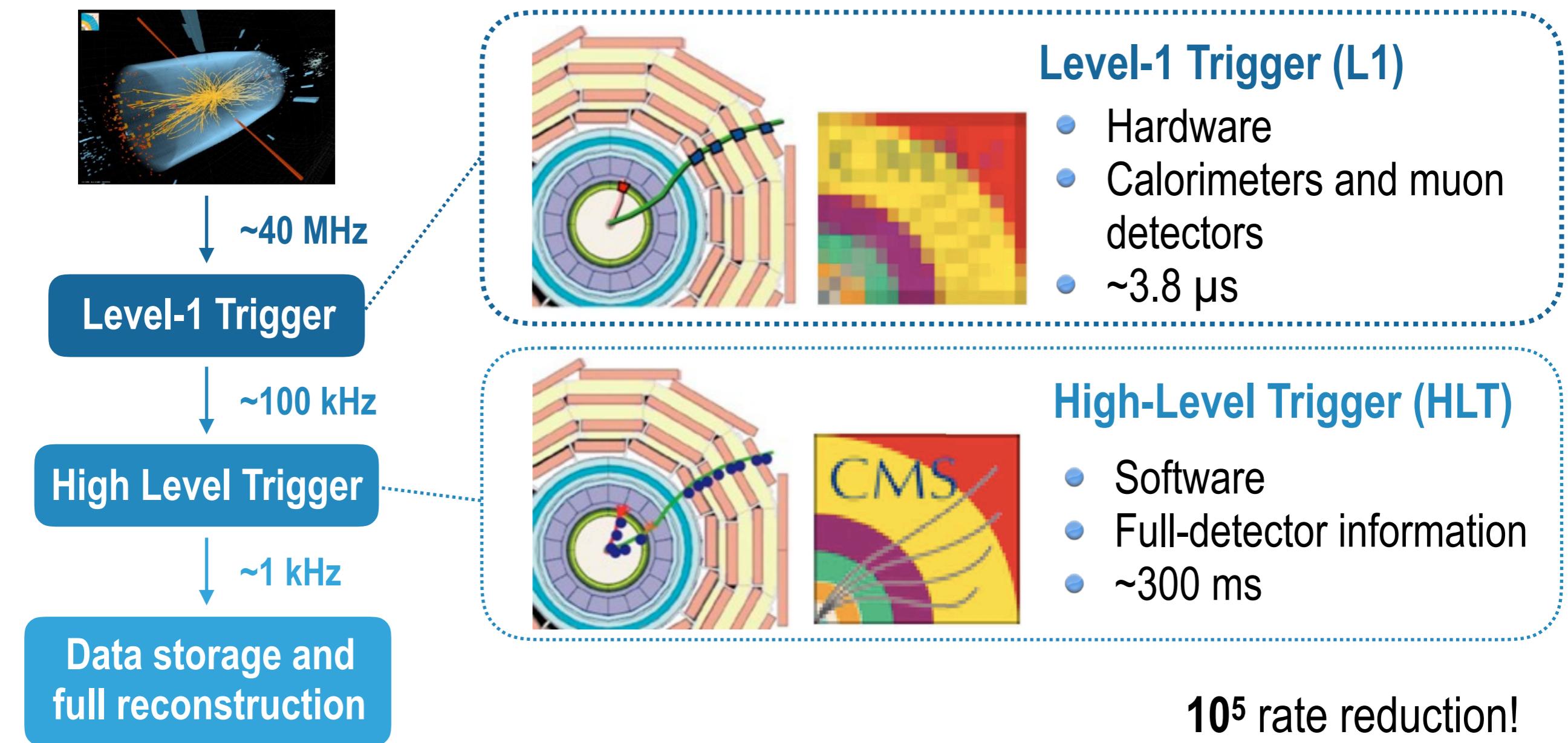
## Summary

- ttH  $H \rightarrow \tau\tau$  gives direct access to the Higgs coupling to top quarks and  $\tau$  leptons.
- It is a specially **challenging final state** due to the high hadronic activity, the presence of neutrinos and the high multiplicity of particles.
- The  **$\tau$  selection, reconstruction and identification** are done with robust algorithms both at trigger-level and offline, which exploit the different properties of the  $\tau$  decay modes and have shown very good performance in Run 2.
- The analysis is done in four **exclusive categories** based on the lepton and hadronic  $\tau$  multiplicity, with dedicated signal extraction methods (**BDT** and **MEM**) optimized for each category.
- Results with **2016 and 2017** data in combination with purely **leptonic** final states give an observed (expected) significance of  **$3.2\sigma$  ( $4\sigma$ )**.
- Optimization of the **ttH** analysis methods ongoing for the **full Run 2** analysis... stay tuned!

**Thank you for your attention**

# CMS trigger

- LHC bunch crossing rate: **~40 MHz** → data storage unsustainable.
- Trigger system: **fast** selection of interesting events based on kinematic cuts.
- Successive steps: rate reduction, increased granularity and complexity.



# Object selection

[HIG-18-019](#)

- Electrons

Observable	Loose	Fakeable	Tight
$p_T$	$> 7 \text{ GeV}$	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$
$ \eta $	$< 2.5$	$< 2.5$	$< 2.5$
$ d_{xy} $	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$
$ d_z $	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$
$d/\sigma_d$	$< 8$	$< 8$	$< 8$
$I_e$	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
EGamma POG MVA	$> \{-0.86 / -0.81 / -0.72\}^1$	$> \{-0.86 / -0.81 / -0.72\}^2$	$> \{-0.86 / -0.81 / -0.72\}^2$
$\sigma_{i\eta i\eta}$	—	$< \{0.011 / 0.011 / 0.030\}$	$< \{0.011 / 0.011 / 0.030\}$
H/E	—	$< 0.10$	$< 0.10$
$1/E - 1/p$	—	$> -0.04$	$> -0.04$
Conversion rejection	—	✓	✓
Missing hits	$\leq 1$	$= 0$	$= 0$
$p_T^e / p_T^j$	—	$> 0.6 \dagger (-)$	—
CSVv2 of nearby jet	—	$< 0.07 \dagger (< 0.4941)$	$< 0.4941$
Prompt-e MVA	—	—	$> 0.90$

- Muons

Observable	Loose	Fakeable	Tight
$p_T$	$> 5 \text{ GeV}$	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$
$ \eta $	$< 2.4$	$< 2.4$	$< 2.4$
$ d_{xy} $	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$
$ d_z $	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$
$d/\sigma_d$	$< 8$	$< 8$	$< 8$
$I_\mu$	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
Loose PF muon	✓	✓	✓
Medium PF muon	—	—	✓
Segment compatibility	—	$> 0.3 \dagger (-)$	—
$p_T^\mu / p_T^j$	—	$> 0.6 \dagger (-)$	—
CSVv2 of nearby jet	—	$< 0.07 \dagger (< 0.4941)$	$< 0.4941$
Prompt- $\mu$ MVA	—	—	$> 0.90$

# Event selection

[HIG-18-019](#)

	<b>1l + 2<math>\tau_h</math></b>	<b>2lss + 1<math>\tau_h</math></b>	<b>2l + 2<math>\tau_h</math></b>	<b>3l + 1<math>\tau_h</math></b>
<b>Triggers</b>	Single lepton, lepton+ $\tau$	Single/double lepton	Single/double/triple lepton	
<b>Lepton selection</b>	$p_T > 25$ (e) / 20 ( $\mu$ ) GeV, $ \eta  < 2.1$	$p_T > 25, 15$ (e) / 10 ( $\mu$ ) GeV, $ \eta  < 2.5$ (e), 2.4 ( $\mu$ )		$p_T > 20, 10, 10$ GeV, $ \eta  < 2.5$ (e), 2.4 ( $\mu$ )
<b>Hadronic <math>\tau</math> selection</b>	$p_T > 30, 20$ GeV, $ \eta  < 2.3$		$p_T > 20$ GeV, $ \eta  < 2.3$	
<b>Charge</b>	$\sum Q(\tau_h) = 0$	$\sum Q(l) = 0$ , quality		$\sum Q(\tau_h, l) = 0$
<b>Jet selection</b>	$\geq 3$ jets with $p_T > 25$ GeV, $ \eta  < 2.4$		$\geq 2$ jets with $p_T > 25$ GeV, $ \eta  < 2.4$	
<b>b-tagging</b>		$\geq 2$ loose b-tagged jets or $\geq 1$ tight b-tagged jets		
<b>MET LD</b>		$\geq 30$ GeV		$\geq 45$ (30) GeV if SFOS (no SFOS) leptons and $\leq 4$ jets
<b>Dilepton mass</b>		$m_{ll} > 12$ GeV		$ m_{ll} - m_Z  > 10$ (SFOS) GeV

# Fake background estimation

[HIG-18-019](#)

- Non-prompt lepton / hadron  $\rightarrow$  lepton
- Jet (q,g)  $\rightarrow \tau_h$

## Fake factor (FF) method:

- Same selection as SR but relaxing identification criteria (“tight” to “fakeable”): AR.
- Estimation of fake background in SR done applying weights to the events in the AR.
- Weights depend on the probability  $f_i$  of a misidentified lepton or  $\tau_h$  that passes the “fakeable” criteria to pass the “tight” criteria.

For events with 2 objects     $w_2 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 1 \\ -\frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 0 \end{cases}$

For events with 3 objects     $w_3 = \begin{cases} \frac{f_1}{1-f_1} & \text{if } N_p = 2 \\ -\frac{f_1 f_2}{(1-f_1)(1-f_2)} & \text{if } N_p = 1 \\ \frac{f_1 f_2 f_3}{(1-f_1)(1-f_2)(1-f_3)} & \text{if } N_p = 0 \end{cases}$

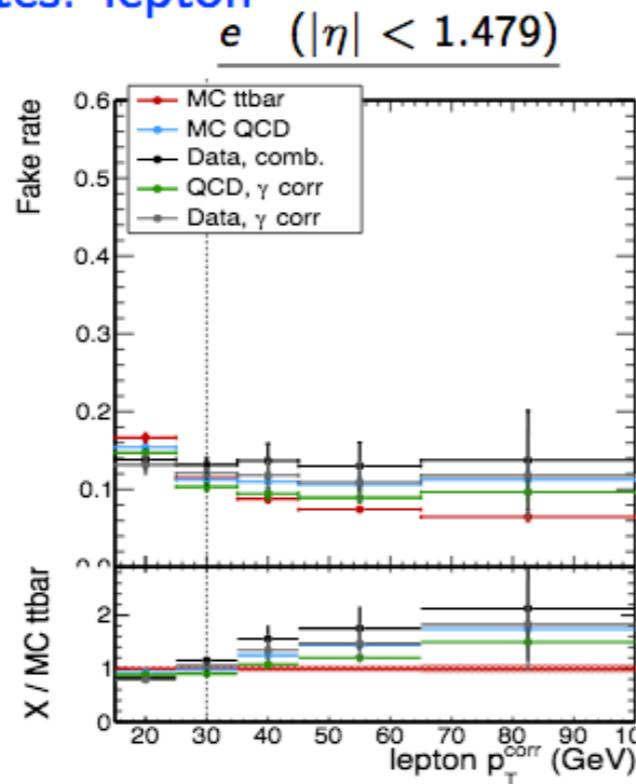
$N_p$  number of “fakeable” objects that pass the “tight” criteria

- Measured separately for e /  $\mu$  (multijets),  $\tau_h$  ( $t\bar{t}$ +jets) (DR)
- $2\ell SS + 1\tau_h$ ,  $3\ell + 1\tau_h$ : restricted to leptons.  $\tau_h$  contribution estimated from MC. (30% of the  $t\bar{t}H$  signal has fake  $\tau_h$ ).

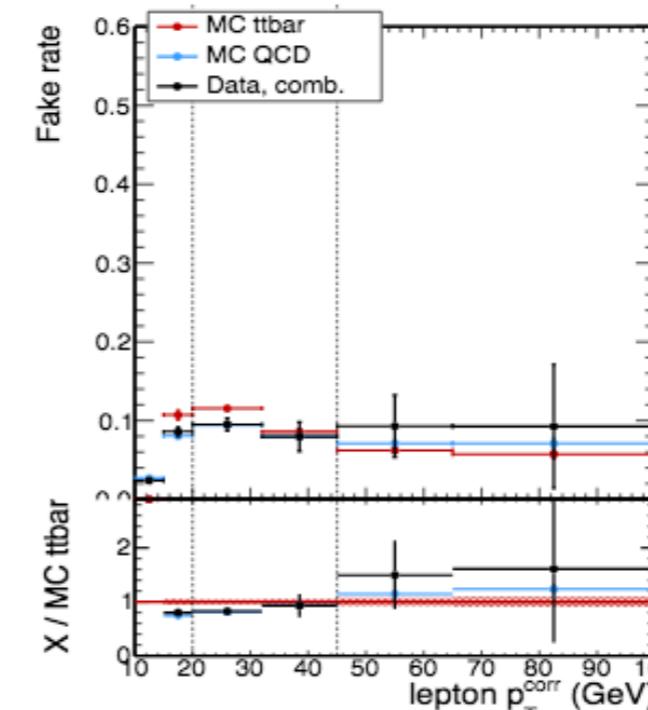
# Fake background estimation

[HIG-18-019](#)

## Fake rates: lepton

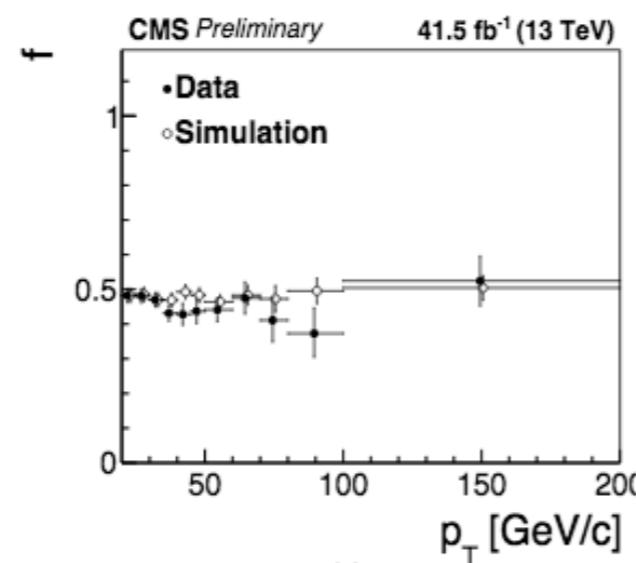


## $\mu \quad (|\eta| < 1.2)$

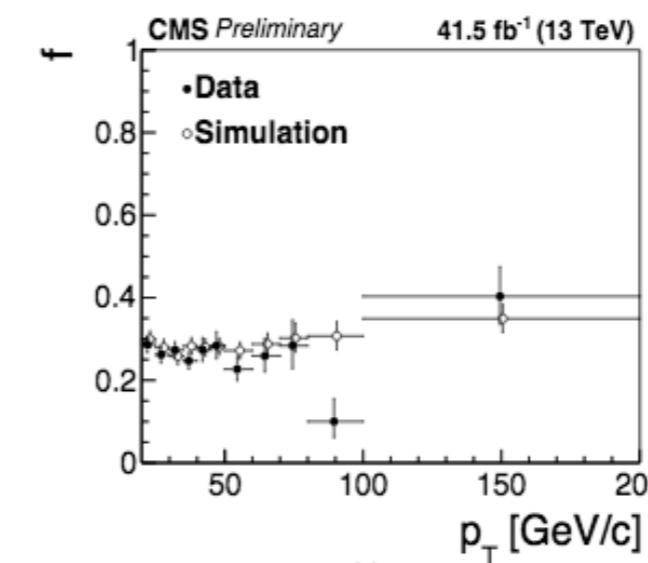


## Fake rates: $\tau_h$

Nominal  $\tau$  ID WP: Loose,  $|\eta| < 1.479$



Nominal  $\tau$  ID WP: Medium,  $|\eta| < 1.479$



# Charge flip background estimation

[HIG-18-019](#)

**$2\ell$ SS,  $2\ell$ SS+ $1\tau_h$**  categories

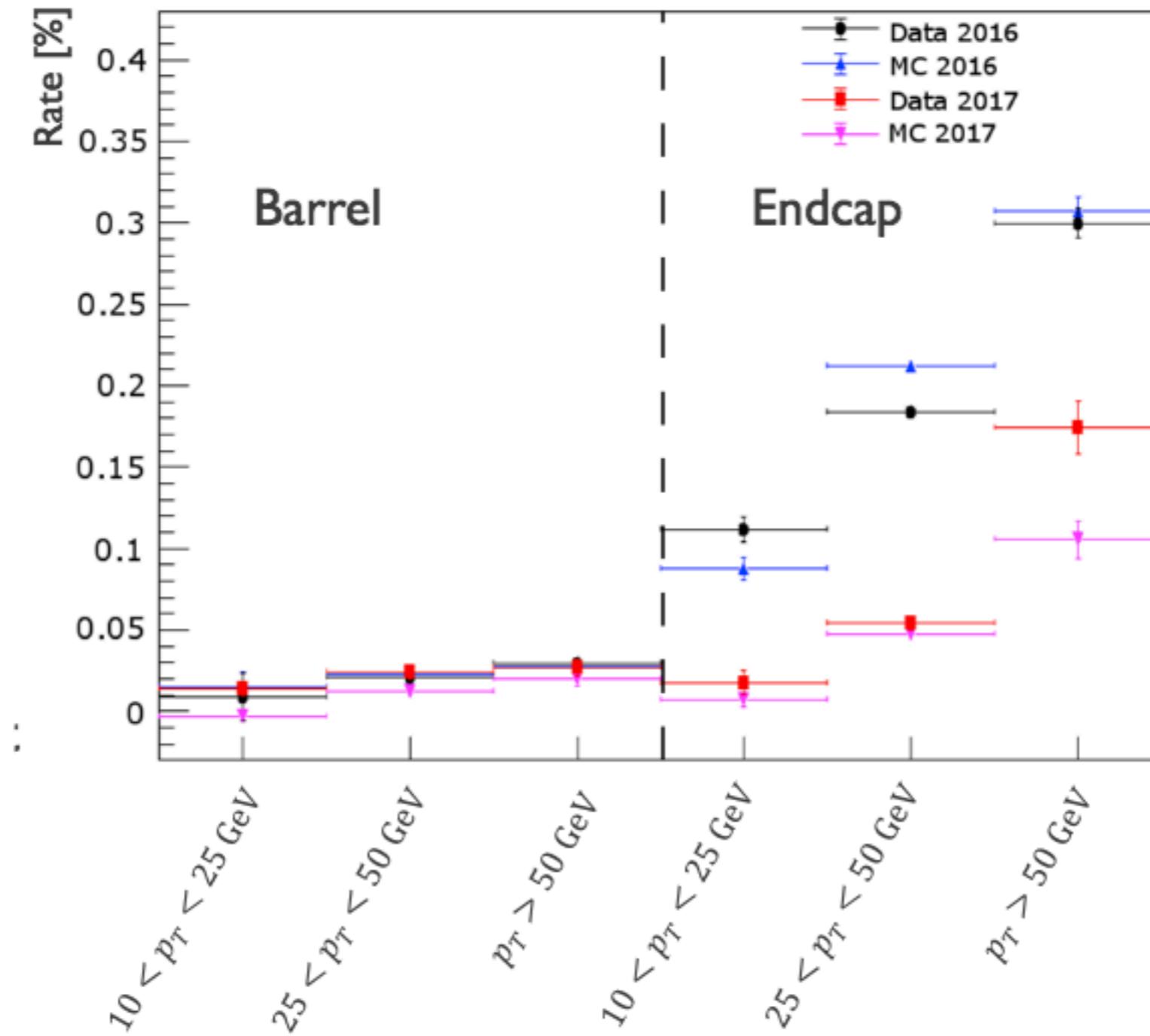
- 2IOS prompt leptons  $\rightarrow$   **$2\ell$ SS prompt leptons**

## Fake factor (FF) method:

- Same selection as SR but requiring 2 leptons opposite sign: AR.
- Estimation of fake background in SR done applying weights to the events in the AR.
- Weights depend on the probability  $f_i$  to mismeasure the charge of either one of the 2 leptons.
- **$2\ell$ SS**:  $\omega =$  sum of the probabilities to mismeasure the charge of either one of the two leptons
- **$2\ell$ SS+ $1\tau_h$** :  $\omega =$  the probability to mismeasure the sign of the lepton with the same sign as the  $\tau_h$  (charge requirements already applied)
- Measured separately for e ( $Z/\gamma^* \rightarrow ee$ ), mu ( $Z/\gamma^* \rightarrow \mu\mu$ ) (DR) as the ratio between SS and OS leptons.

# Charge flip background estimation

[HIG-18-019](#)



# Hadronic Top Tagger

[HIG-18-019](#)

- BDT-based discriminator aiming to reconstruct hadronic top decay
- Computes the likelihood of a jet triplet to be compatible with hadronic top decay products
- Full combinatorics of jet triplets in an event are tried
  - jet triplet: 1  $b$ -jet candidate + 2  $W$ -jet candidates  $W_1$  (higher in  $p_T$ ) and  $W_2$  (lower in  $p_T$ )
  - the one with the best score is used in the BDT for signal extraction
- 8 input variables
  - $b$ -tagging score of the  $b$ -jet candidate
  - masses of  $W_1 + W_2$  and  $b + W_1 + W_2$  and  $p_T$  of  $b + W_1 + W_2$
  - $p_T$  and quark-gluon discriminator of  $W$ -jet candidate with lower  $p_T$  (ie  $W_2$ )
  - value of the likelihood function  $L$  used in kinematic fit subject to mass constraints  $m_W = 80.4$  GeV and  $m_t = 173.1$  GeV:  
$$L = W(p_T^b | \hat{p}_T^b) W(p_T^{W1} | \hat{p}_T^{W1}) W(p_T^{W2} | \hat{p}_T^{W2})$$
where  $W$  refers to transfer function that relates true quantities (with hats) to reconstructed quantities (without hats)
  - ratio between the  $p_T$  of  $b$ -jet candidate before and after kinematic fit

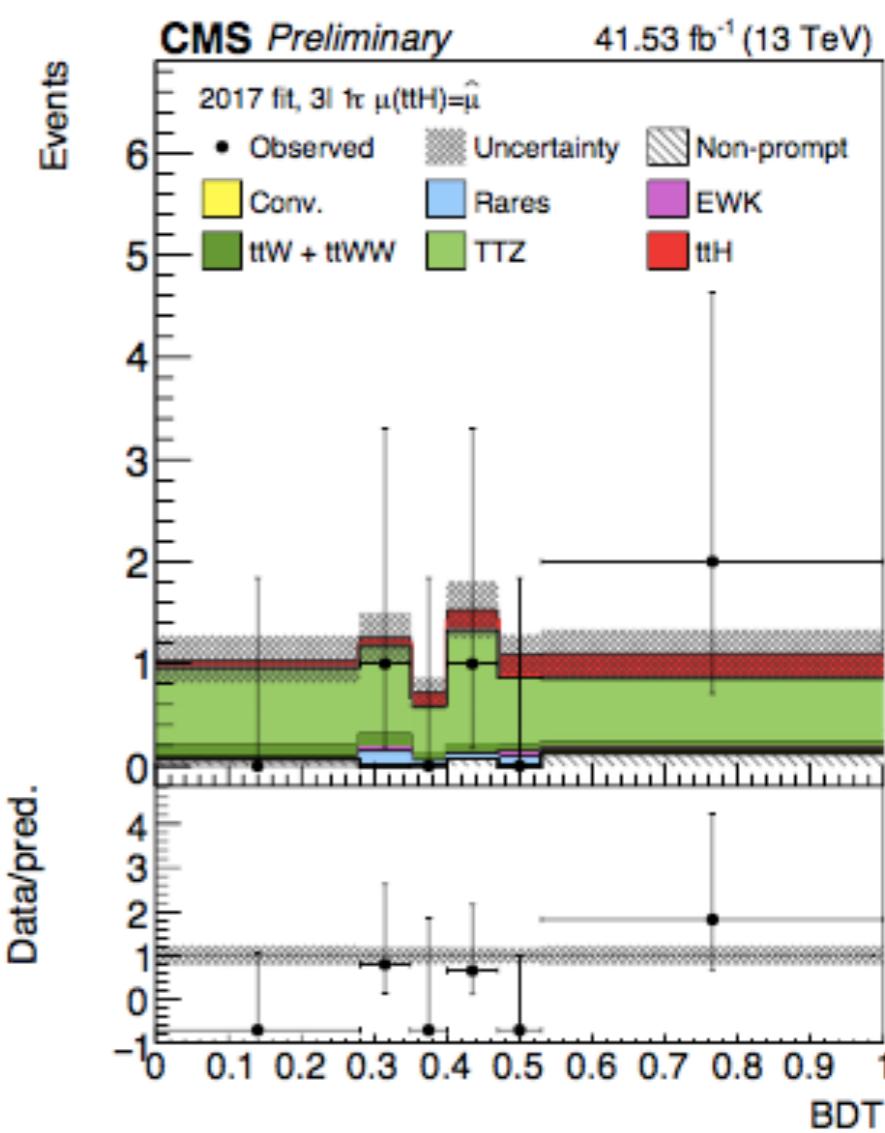
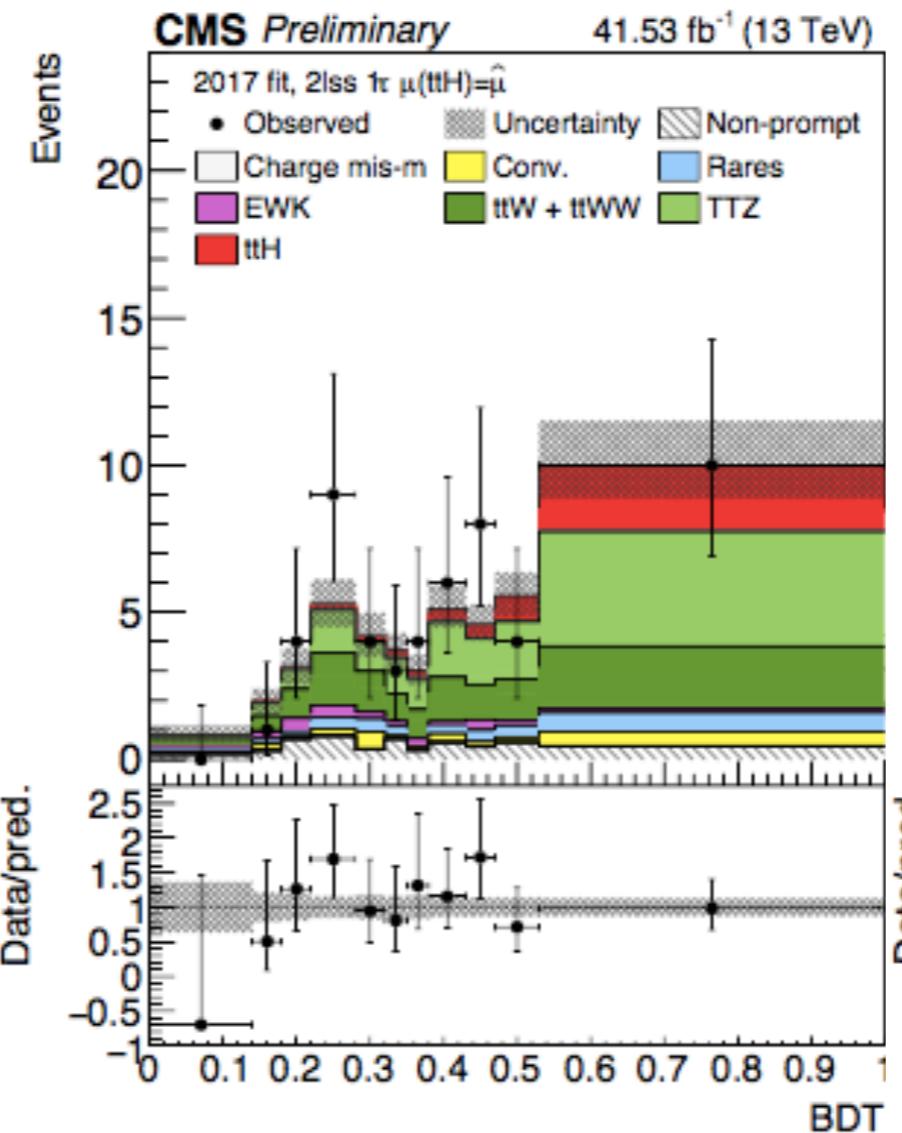
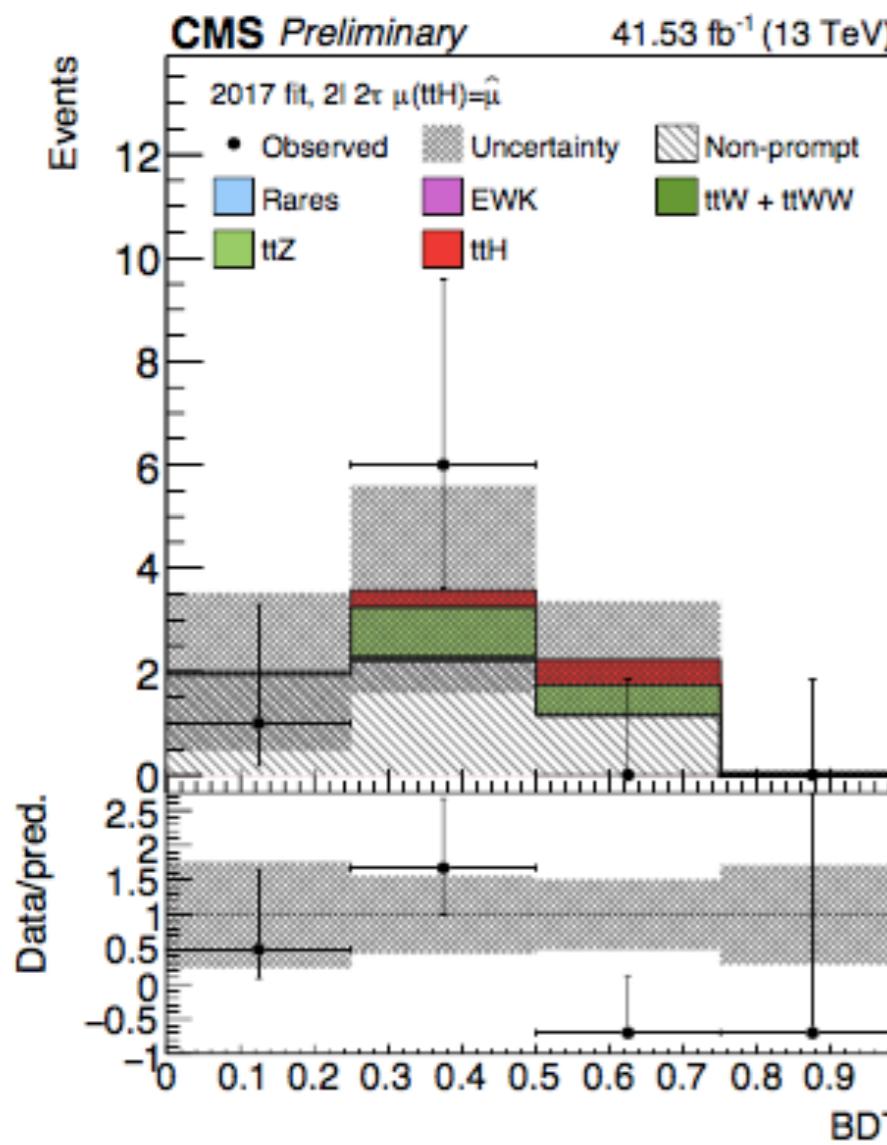
# Signal extraction: BDT

[HIG-18-019](#)

2l + 2 $\tau_h$

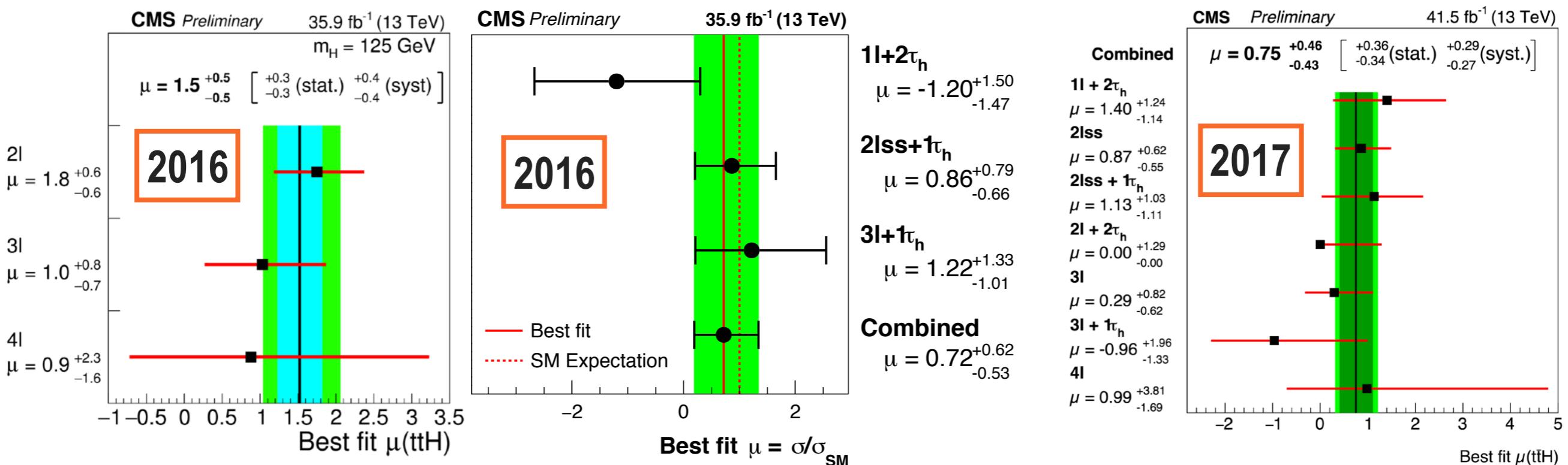
2lss + 1 $\tau_h$

3l + 1 $\tau_h$



# Latest results

Year	Final state	Docs.	Signal strength	Significance
2016	Purely leptonic channels	<a href="#">HIG-17-004</a>	$\mu = 1.5^{+0.5}_{-0.5} [{}^{+0.3}_{-0.3} (\text{stat}) {}^{+0.4}_{-0.4} (\text{syst})]$	$3.3\sigma$ obs. ( $2.5\sigma$ exp.)
	Channels with hadronic $\tau$ 's	<a href="#">HIG-17-003</a>	$\mu = 0.72^{+0.62}_{-0.53}$	$1.4\sigma$ obs. ( $1.8\sigma$ exp.)
	Combination leptons + hadronic $\tau$ 's	<a href="#">HIG-17-018</a>	$\mu = 1.23^{+0.45}_{-0.43} [{}^{+0.26}_{-0.25} (\text{stat}) {}^{+0.37}_{-0.35} (\text{syst})]$	$3.2\sigma$ obs. ( $2.8\sigma$ exp.)
2017	Channels with leptons and hadronic $\tau$ 's	<a href="#">HIG-18-019</a>	$\mu = 0.75^{+0.46}_{-0.43} [{}^{+0.36}_{-0.34} (\text{stat}) {}^{+0.29}_{-0.27} (\text{syst})]$	$1.7\sigma$ obs. ( $2.9\sigma$ exp.)
	Combination 2016+2017		$\mu = 0.96^{+0.34}_{-0.31}$	$3.2\sigma$ obs. ( $4.0\sigma$ exp.)

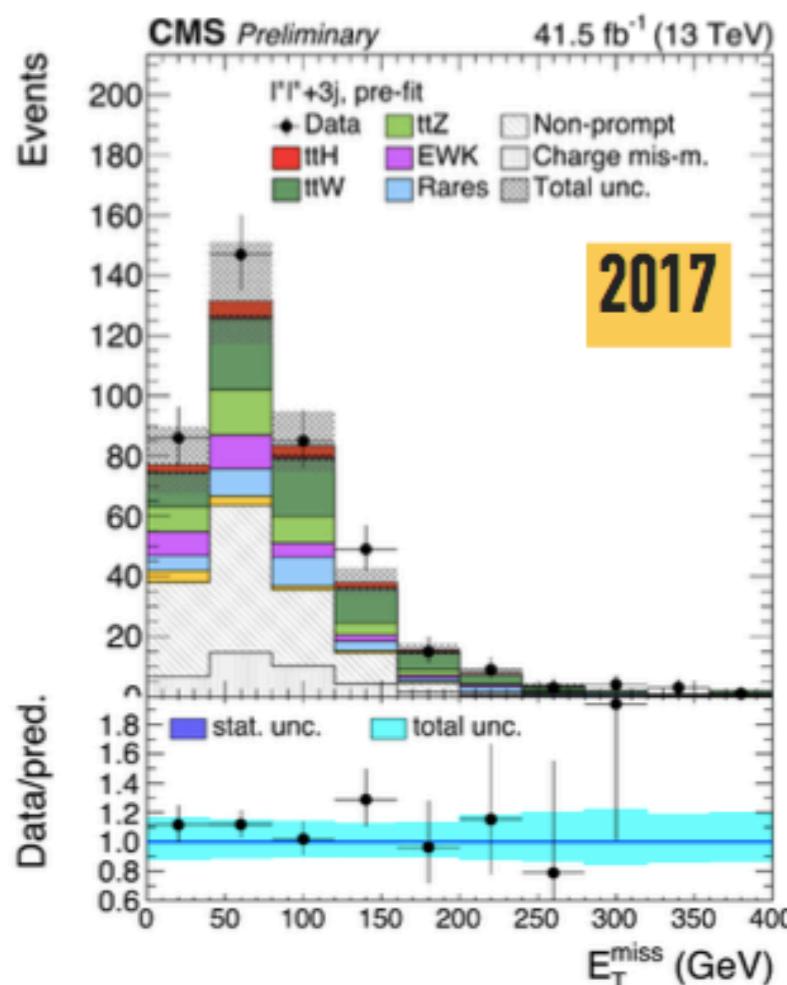


# Control regions

[HIG-18-019](#)

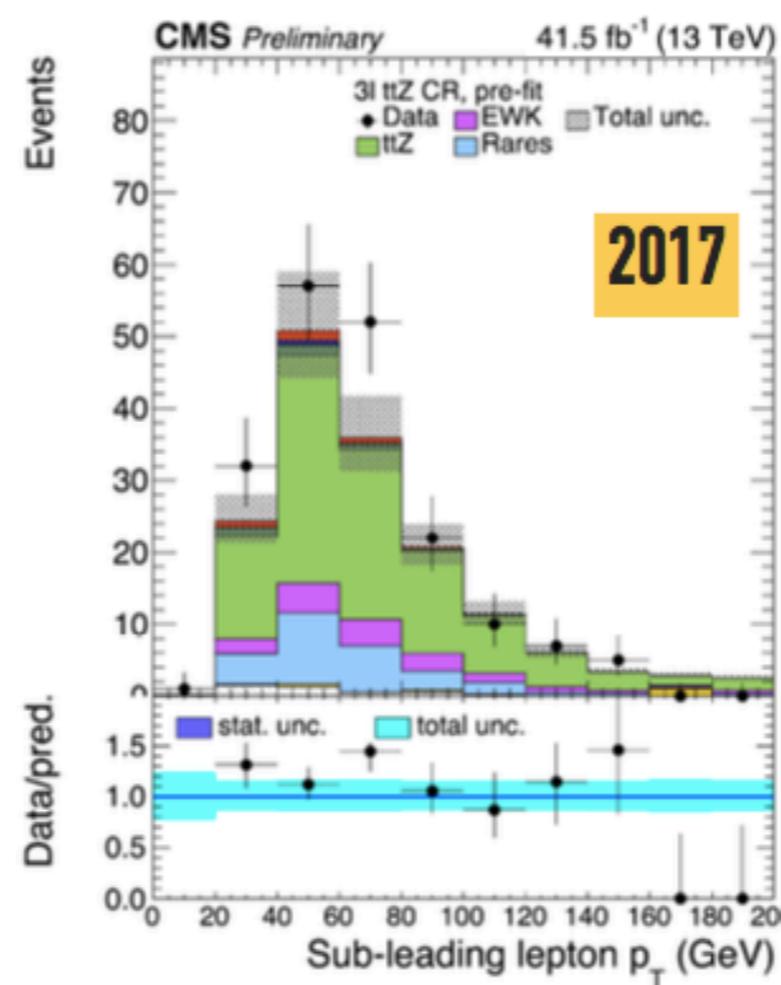
ttW(W) and ttZ floating in the final fit, constrained from data thanks to the inclusion of dedicated CRs.

**ttW**



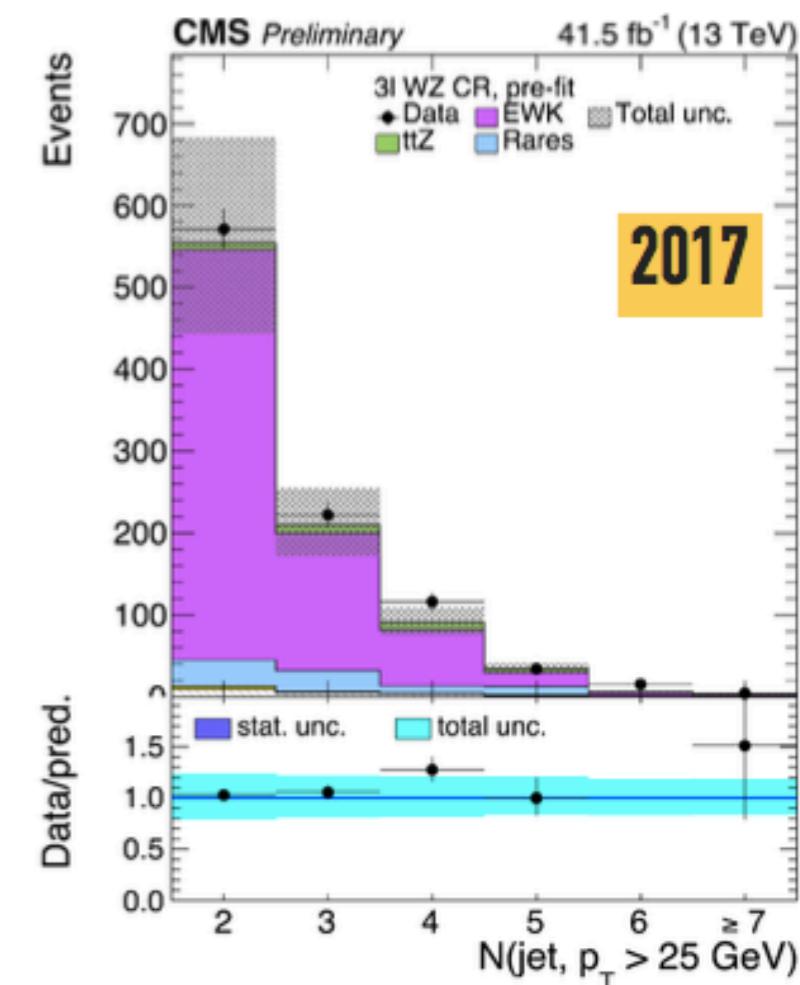
Same as 2lss SR,  
with exactly 3 jets

**ttZ**



Same as 3l SR,  
inverting the Z veto

**WZ**

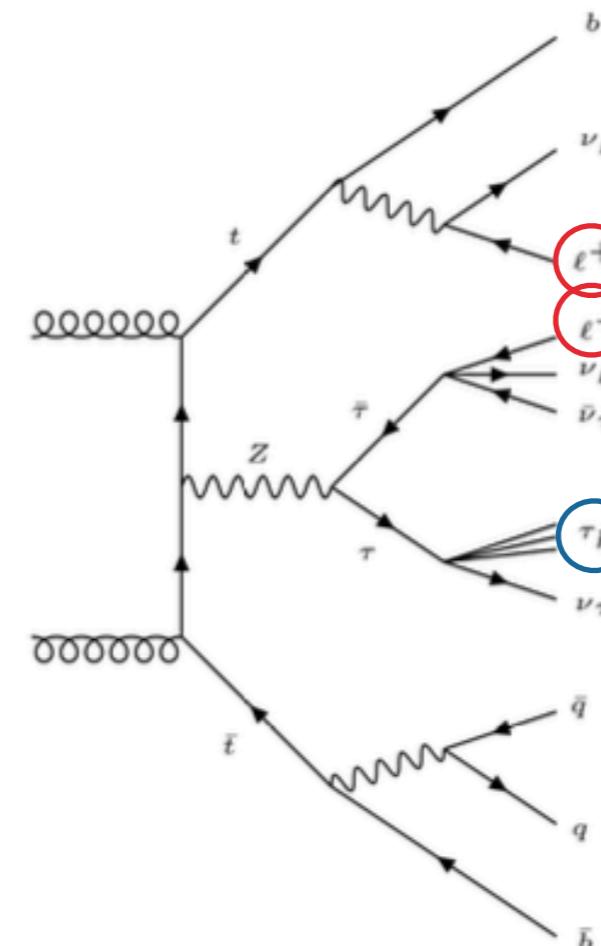
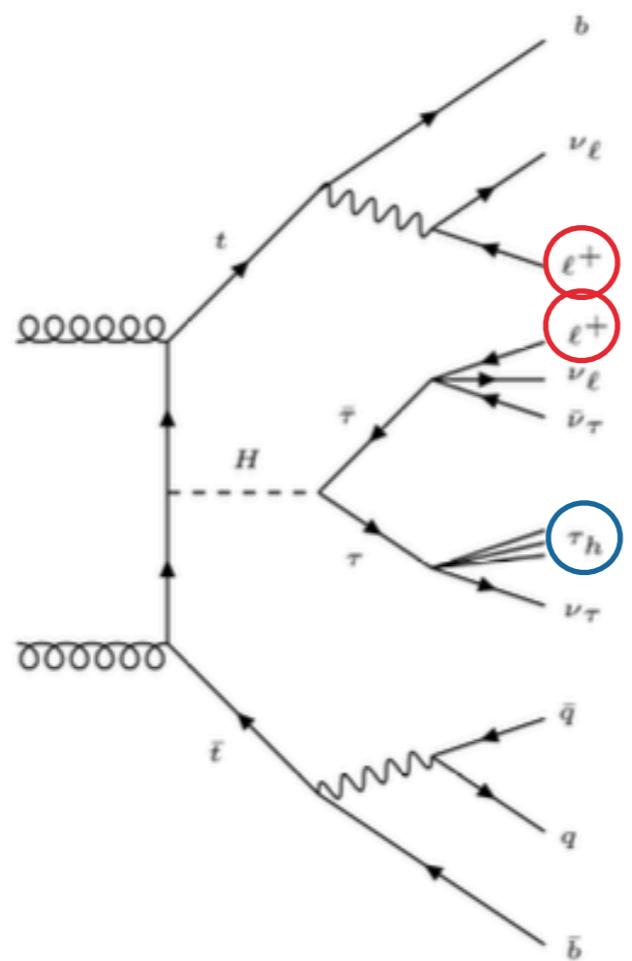


Same as 3l SR,  
with 0 b-jets and  
inverting the Z veto

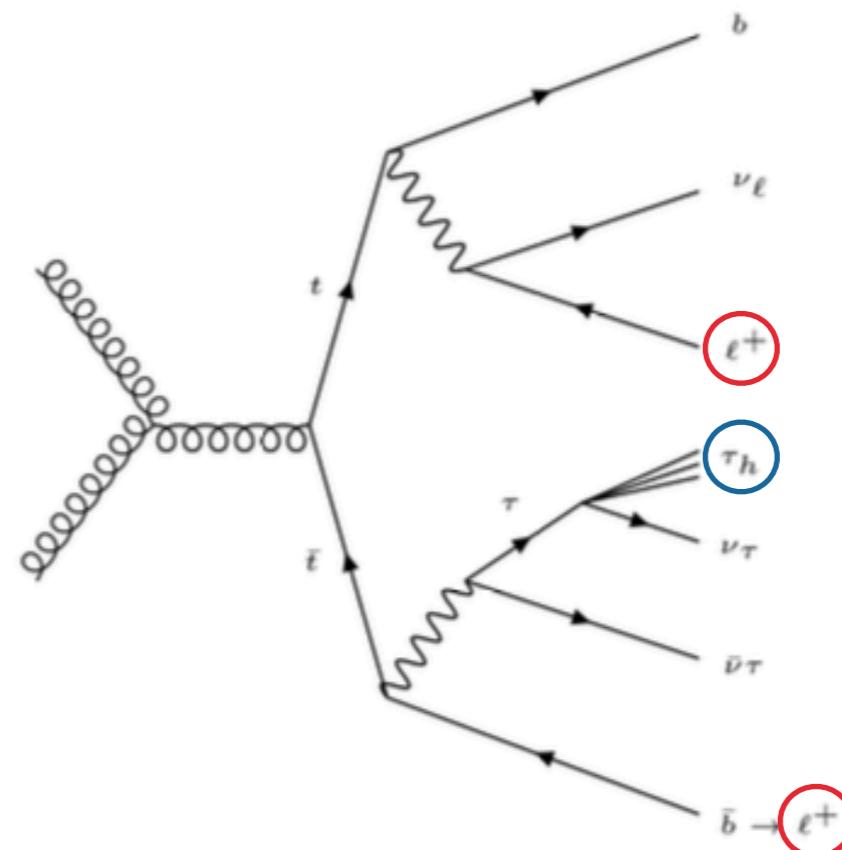
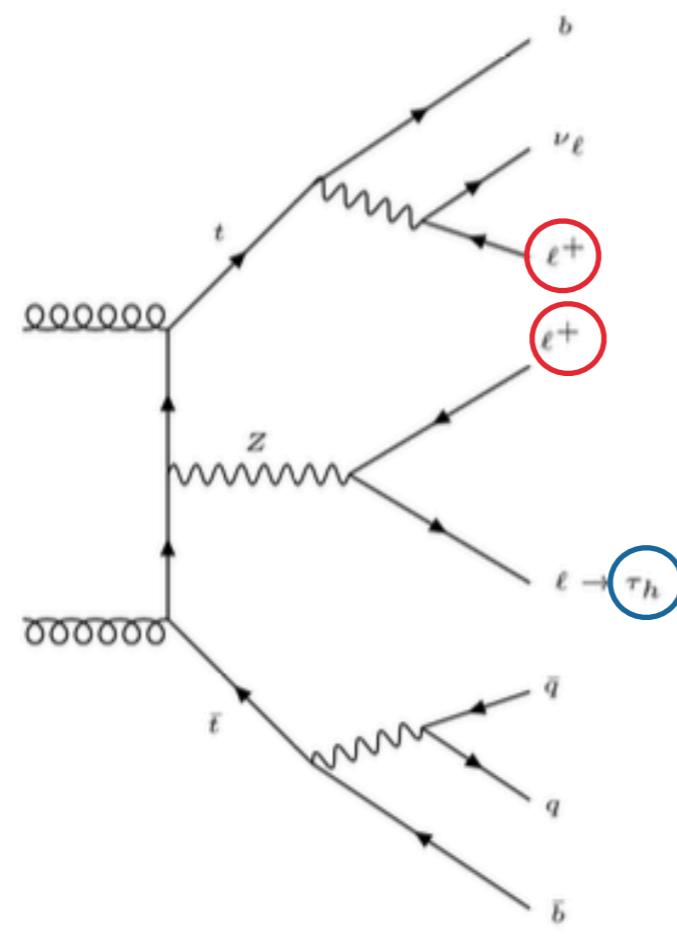
# HYPOTHESIS

[HIG-17-003](#)

Signal hypothesis  
 $t\bar{t}H \ H \rightarrow \tau\tau$



Background hypothesis  
 $t\bar{t}Z \ Z \rightarrow ll$



Background hypothesis  
 $t\bar{t}Z \ Z \rightarrow \tau\tau$

# MEM

[HIG-17-003](#)

- Resolution of the detector and reconstruction techniques.
- Obtained from **MC simulation**.
- Relates the parton-level variables  $\underline{x}$  to the set of observables  $\hat{\mathbf{y}}$  (with hat):

## Quarks associated to jets

Jet direction perfectly measured

$$W(\hat{\mathbf{y}}||\mathbf{x}) = \prod_{q \in \mathcal{A}} \delta(\hat{\vec{e}}_j - \vec{e}_q) T_j(\hat{p}_{Tj} | p_{Tq}, \eta_q) \prod_{q \notin \mathcal{A}} A_q(p_{Tq}, \eta_q)$$

$$\prod_{\pi} \delta(\hat{\vec{\pi}} - \vec{\pi}) T_h(\hat{\pi} | \tau_h) \prod_l \delta(\hat{\vec{l}} - \vec{l}) T_\ell(\hat{\ell} | \tau_\ell) T_{E_T}(\hat{\vec{\rho}}_T | \vec{P}_T)$$

Momentum of visible decay products from hadronic  $\tau$  perfectly measured

Transfer function hadronic  $\tau \rightarrow$  measured visible decay products

## Hadronic $\tau$ decays

Transfer function quark  $\rightarrow$  measured jet

## Quarks not associated to jets

Probability that not jet is reconstructed given the kinematics of the quark

Momentum of charged leptons perfectly measured

Transfer function leptonic  $\tau \rightarrow$  measured visible decay products

## Leptonic $\tau$ decays

Transfer function measured opposite recoil  $\rightarrow$  recoil

$$\vec{\rho}_T = \sum_{\ell, \tau_h, j} \vec{p}_T + \vec{E}_T^{miss}$$

$$P_T = \sum_{\tau, p} \vec{p}_T$$

## Missing transverse energy

# Observation of the ttH process

