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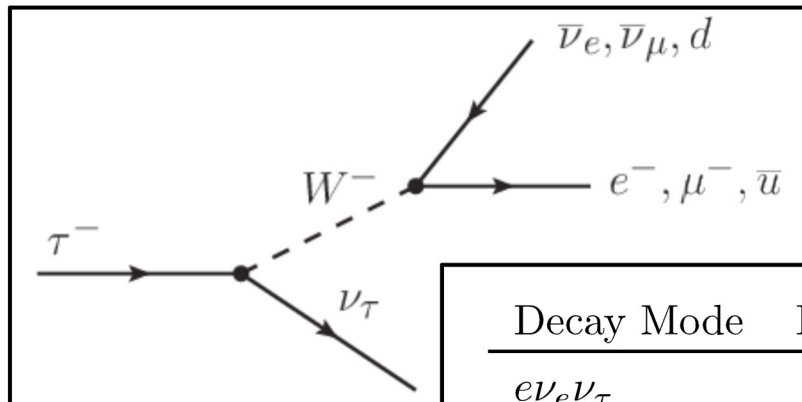
# From the analysis of the observed Higgs boson coupling structure to the search for more Higgs bosons

– Higgs boson analyses in the di- $\tau$  final state –

**Roger Wolf**  
23. Mai 2019

# $\tau$ -leptons & LHC Higgs physics

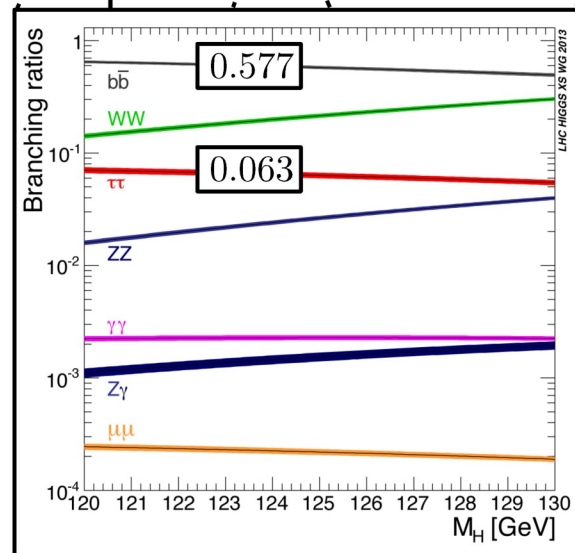
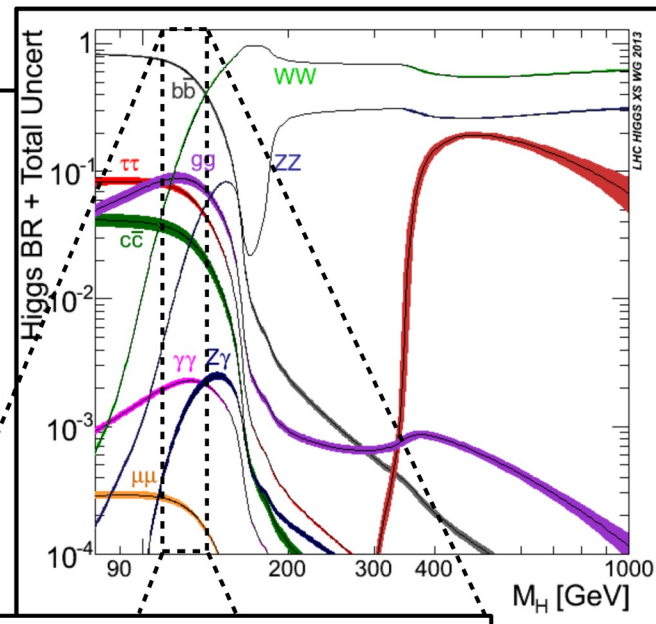
- With 1.77 GeV the **heaviest known lepton**.



Decay Mode	BR [%]
$e\nu_e\nu_\tau$	17.83
$\mu\nu_\mu\nu_\tau$	17.41
1-prong $\nu_\tau$	37.10
3-prong $\nu_\tau$	15.20

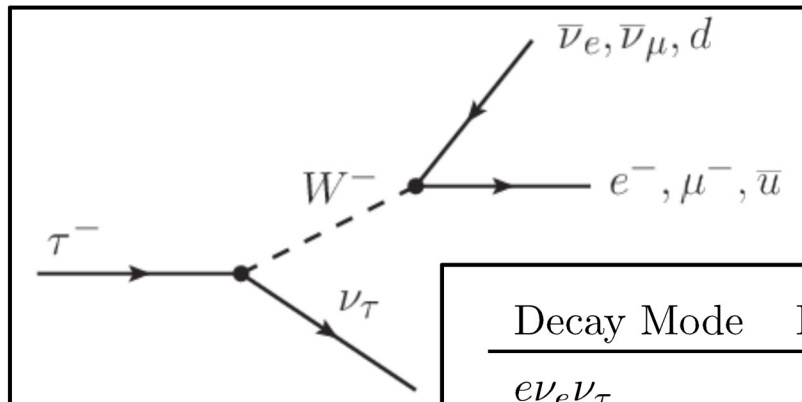
- One of the **big five** in the investigation of the Higgs sector @ low mass.

	Channel	Resolution	S/B
$\kappa_{HVV} = \frac{2m_V^2}{v}$	$H \rightarrow \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
	$H \rightarrow ZZ$	1-2%	$\mathcal{O}( > 1)$
	$H \rightarrow WW$	20%	$\mathcal{O}(1)$
$\kappa_{Hff} = \frac{m_f}{v}$	$H \rightarrow b\bar{b}$	10%	$\mathcal{O}(0.1)$
	$H \rightarrow \tau\tau$	15%	$\mathcal{O}(0.1)$



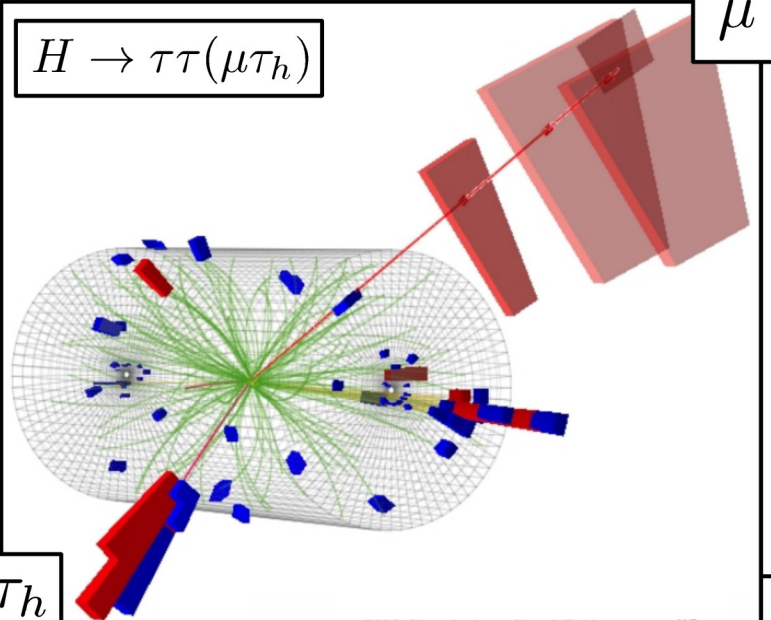
# Di- $\tau$ final state

- High mass allows for **decays into hadrons**:



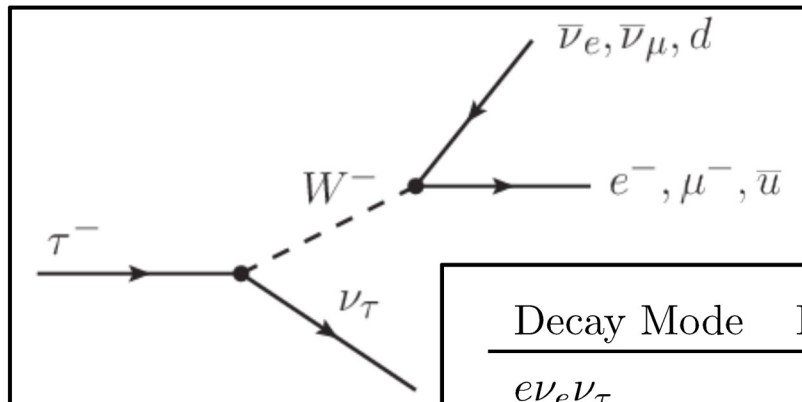
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$H \rightarrow \tau\tau(\mu\tau_h)$



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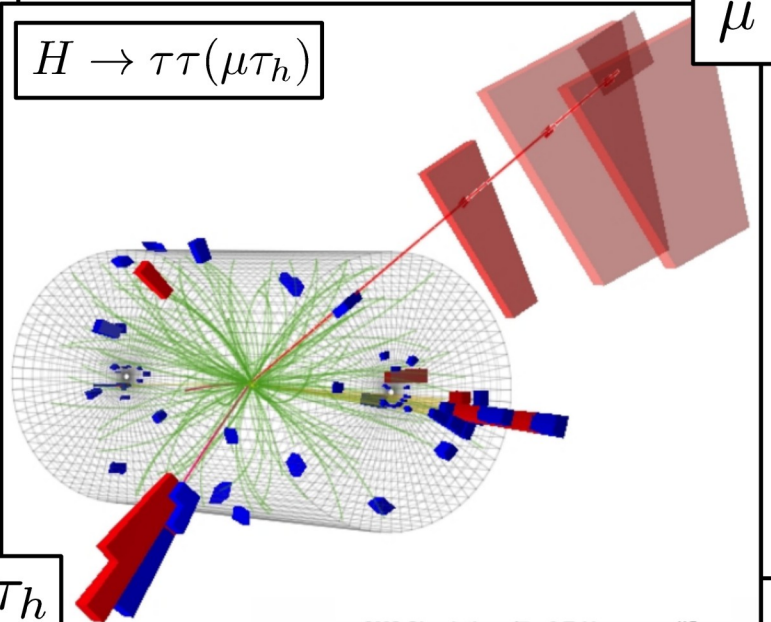
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~90% of all di- $\tau$  final states contain at least one  $\tau_h$ .

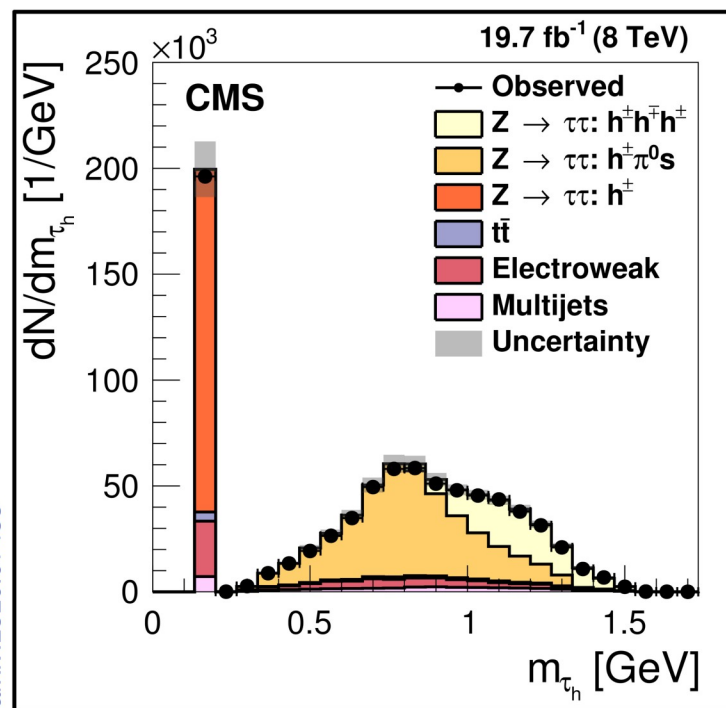
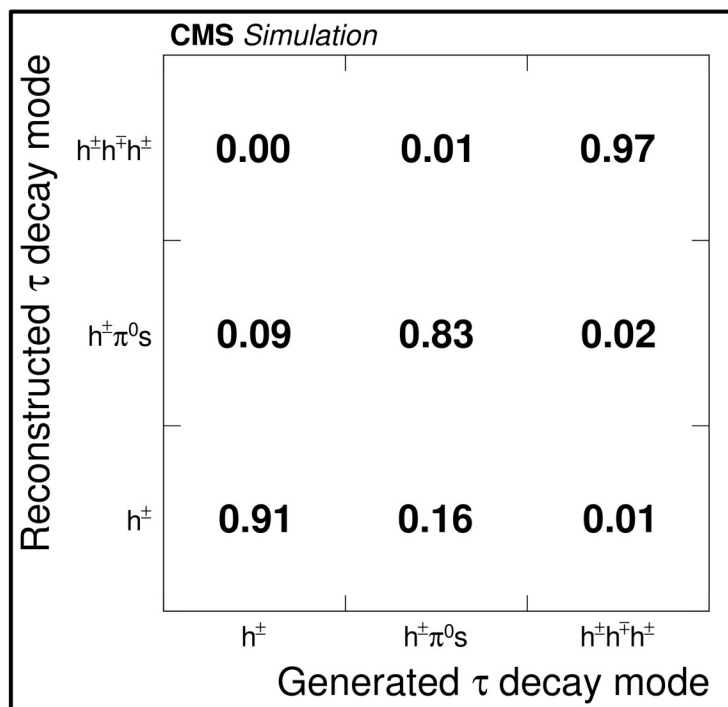
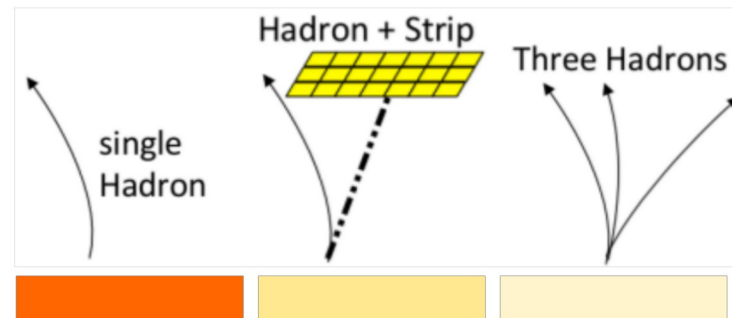
$H \rightarrow \tau\tau(\mu\tau_h)$





# Hadronic $\tau$ -decays

- Start from anti- $k_T$  clustered jets of particle flow objects with opening parameter of 0.4.
- Require **one or three high  $p_T$  charged hadrons** ( $\rightarrow$  prongs).

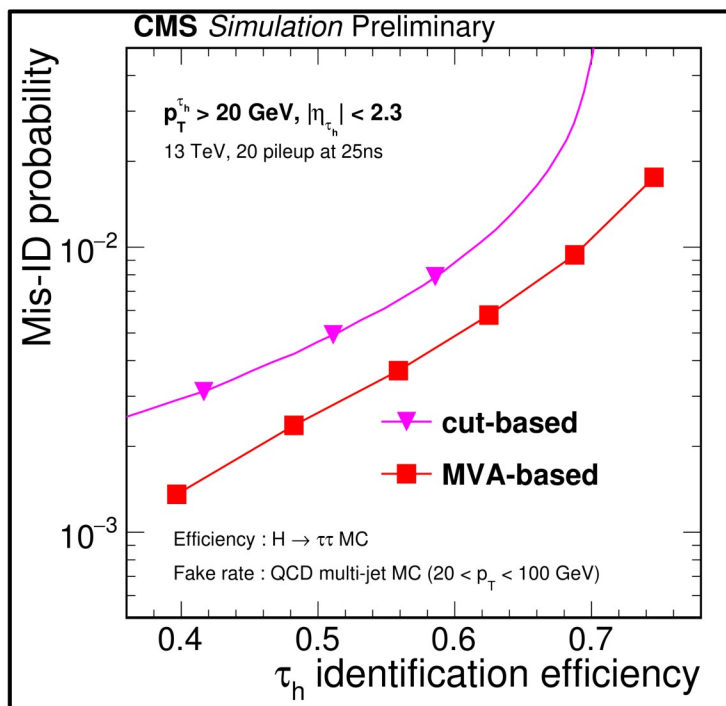


arxiv:1510.07488

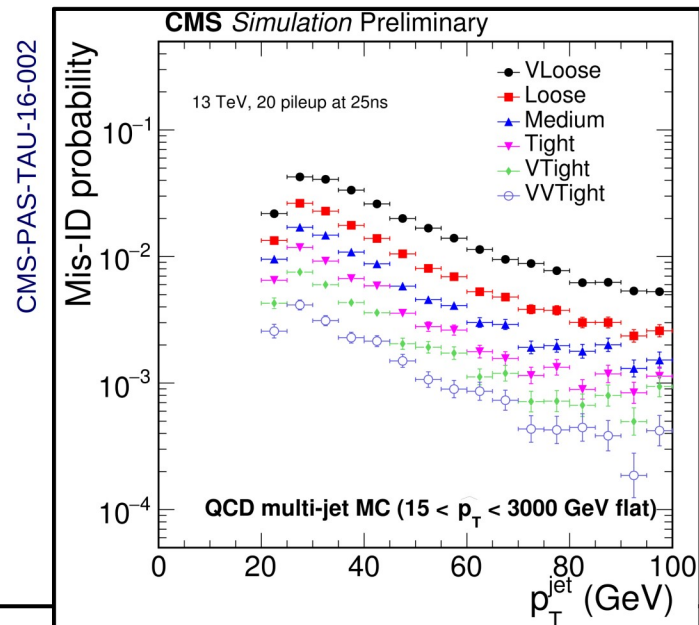
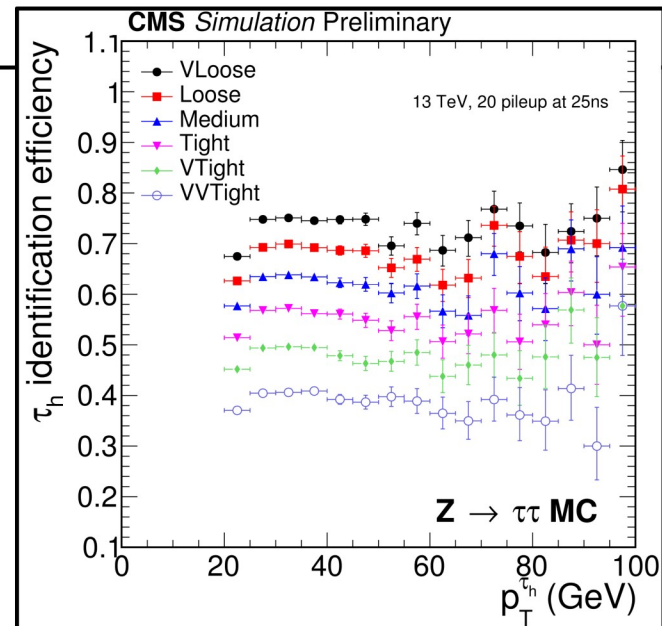
- Apply ID criteria to increase purity.

# $\tau_h$ -Identification

- **MVA based  $\tau_h$ -identification:** energy deposits close to  $\tau$ -candidate + impact parameter information on prongs.
- Discrimination against muons and electrons.

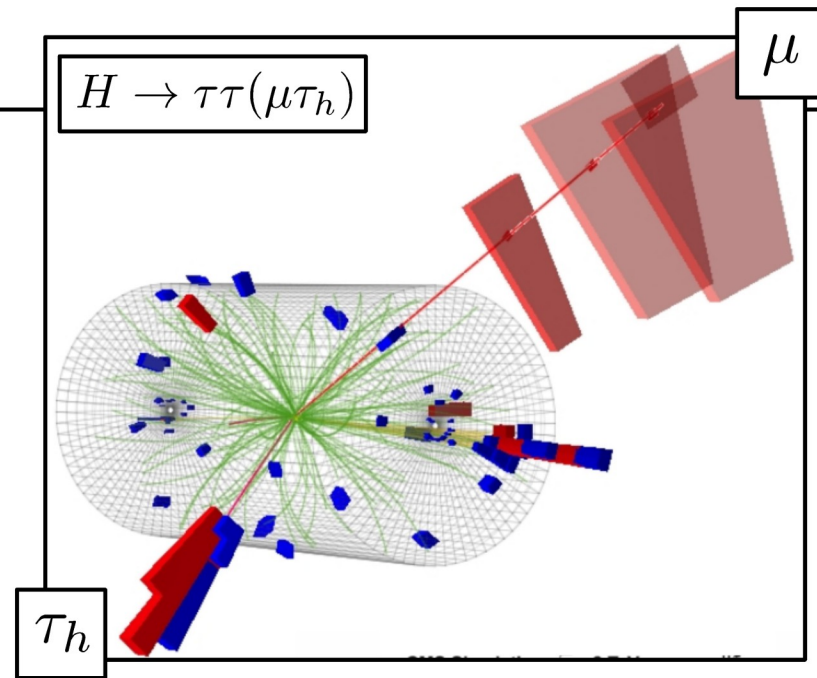
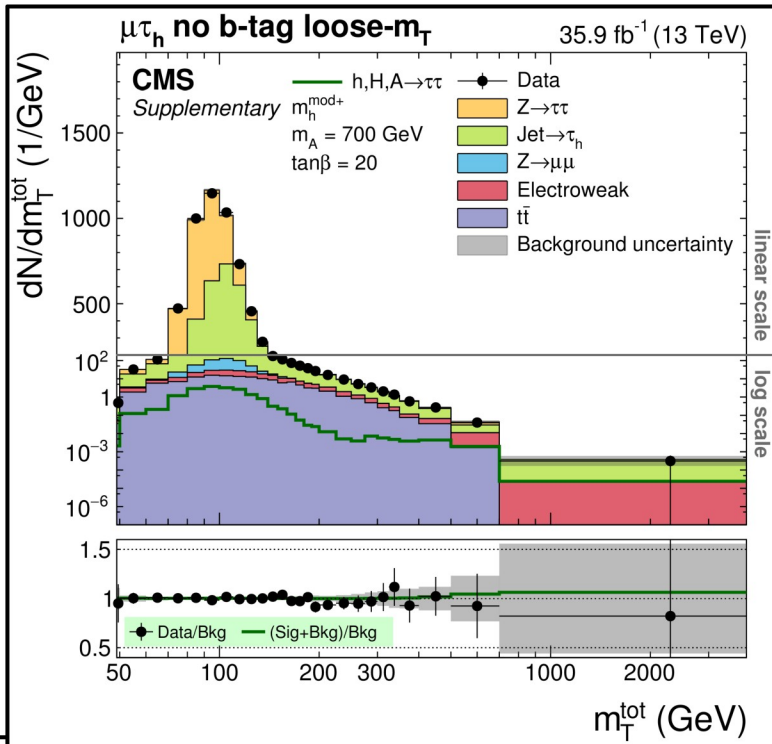


- Predefined working points used in analyses.



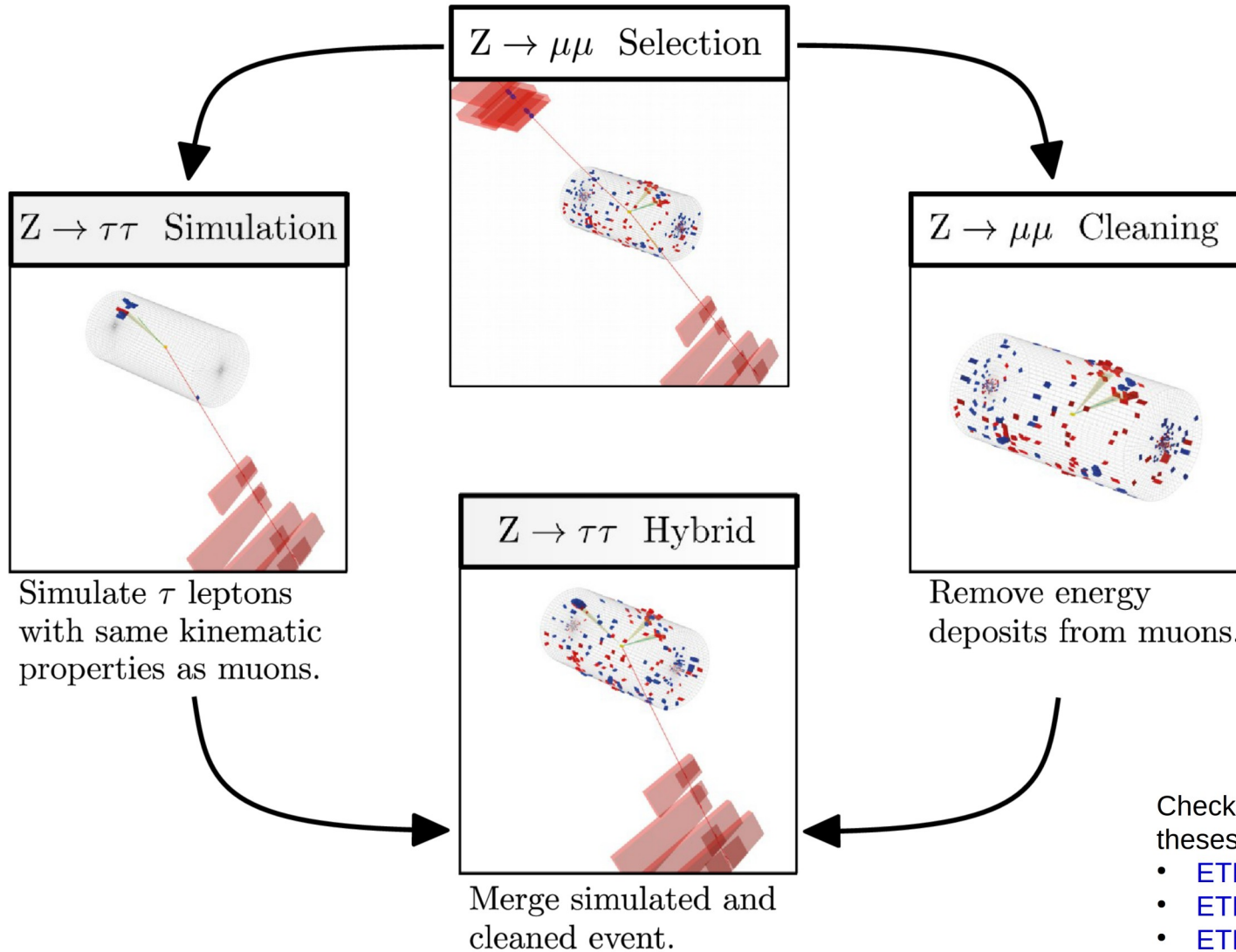
# Di- $\tau$ final state

- Search for **2 isolated high  $p_T$  leptons** ( $e, \mu, \tau_h$ ).
- Reduce obvious backgrounds, control what can't be reduced.
- Reconstruct discriminating variable, related to di- $\tau$  final state.



# $\tau$ -embedding

arxiv:1903.01216



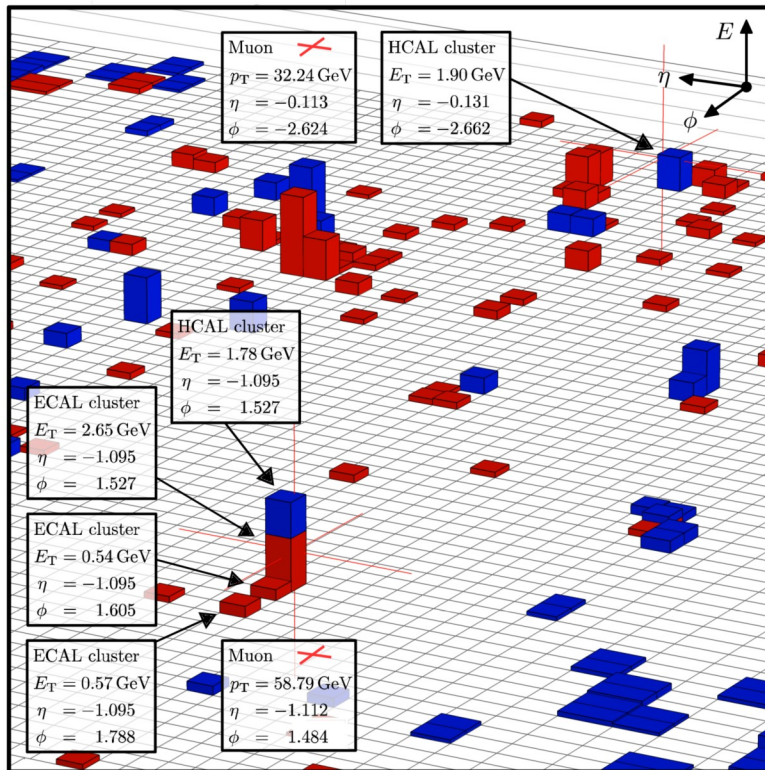
Check the following theses for more details:

- [ETP-KA/2016-23](#)
- [ETP-KA/2017-31](#)
- [ETP-KA/2018-11](#)
- [ETP-KA/2019-05](#)

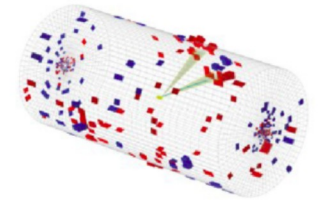
# $\tau$ -embedding

 $Z \rightarrow \mu\mu$  Cleaning

Before:



arxiv:1903.01216

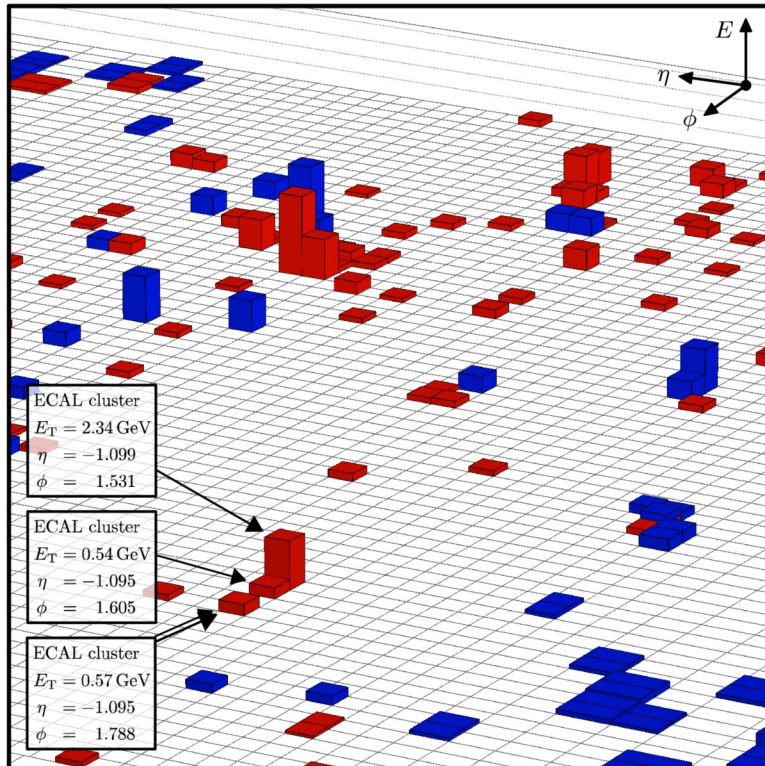




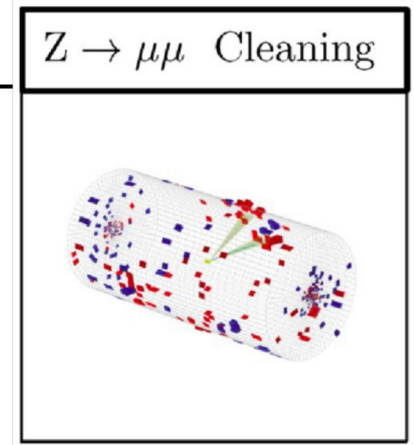
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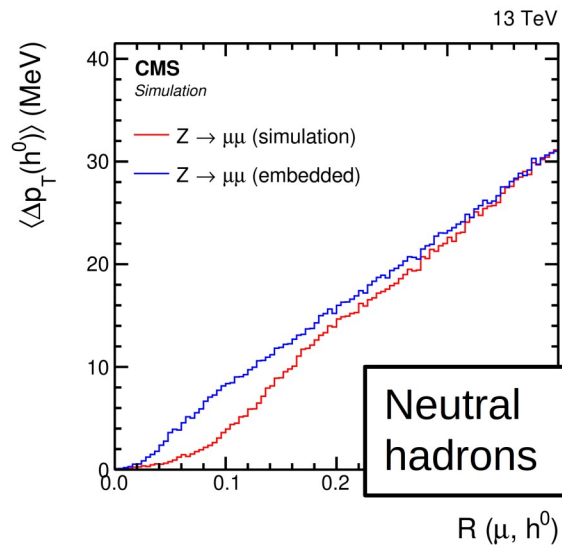
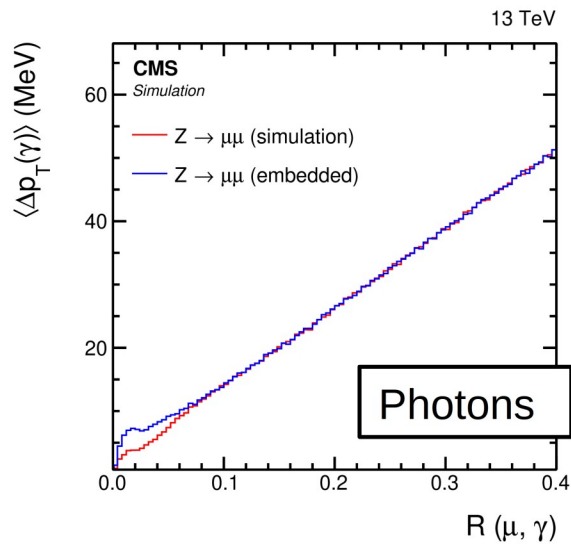
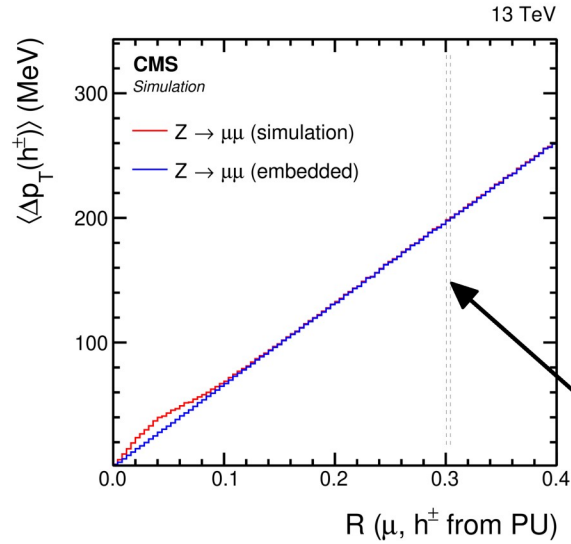
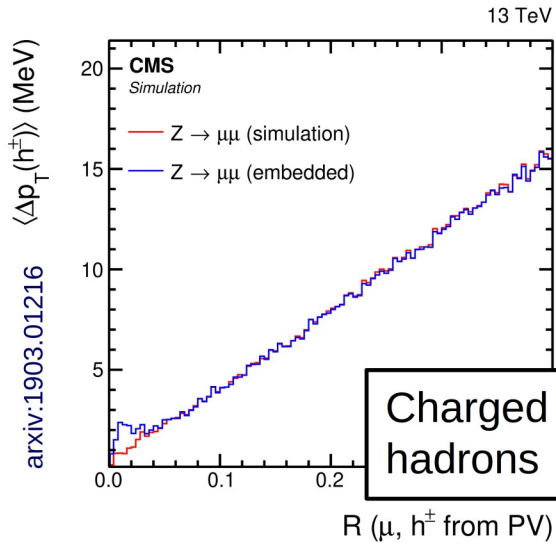
After:



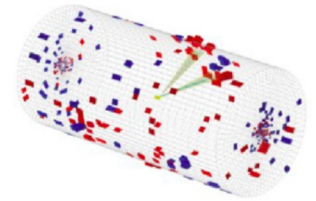
arxiv:1903.01216



# $\mathcal{T}$ -embedding



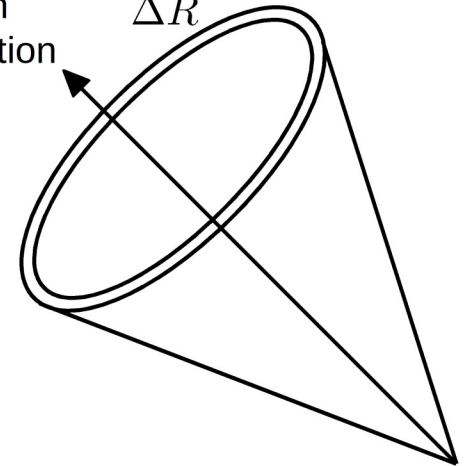
$Z \rightarrow \mu\mu$  Cleaning



Control particle flux close to  $\mu$  to level of **140 MeV**

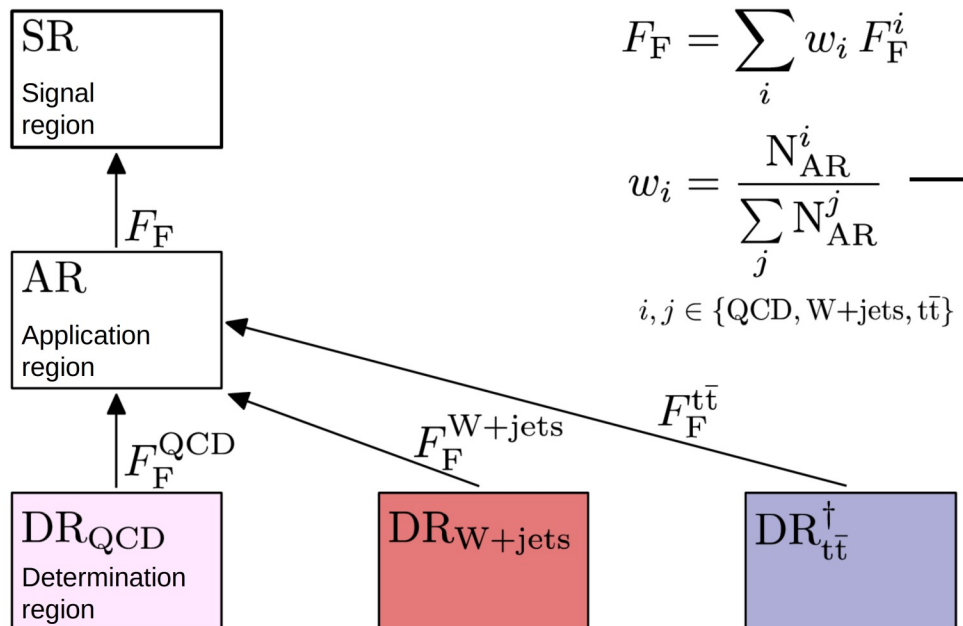
Muon direction

$\Delta R$





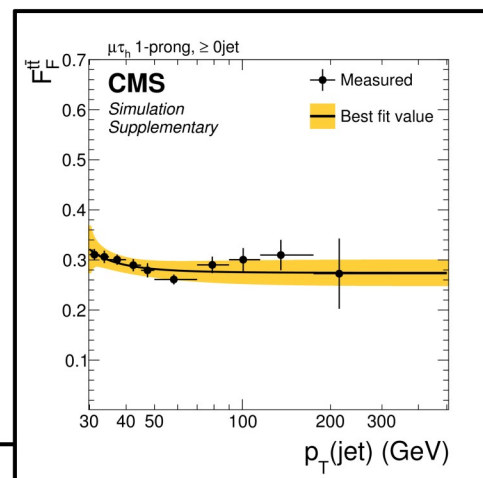
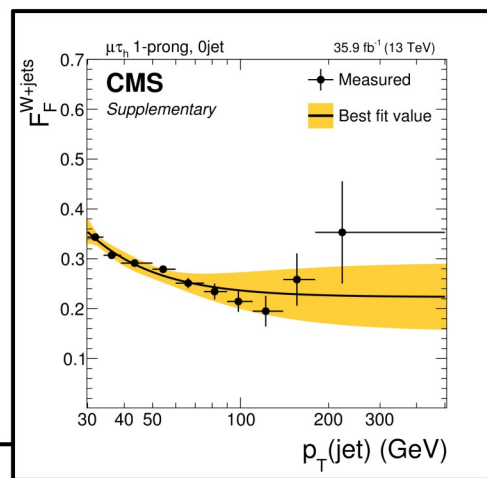
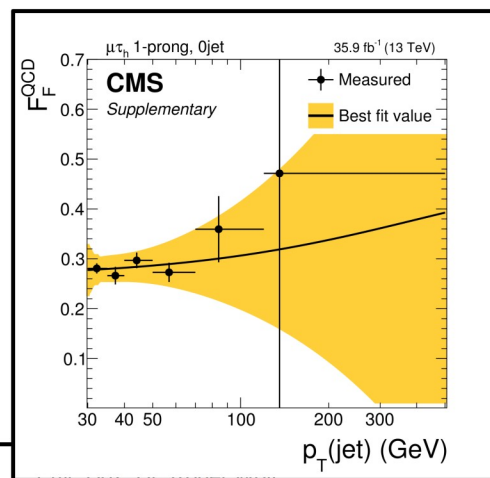
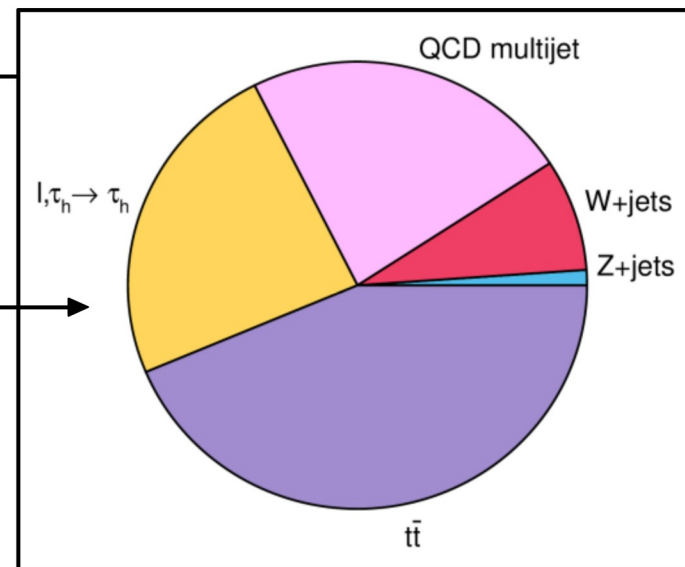
# Fake factor (FF) method



$$F_F = \sum_i w_i F_F^i$$

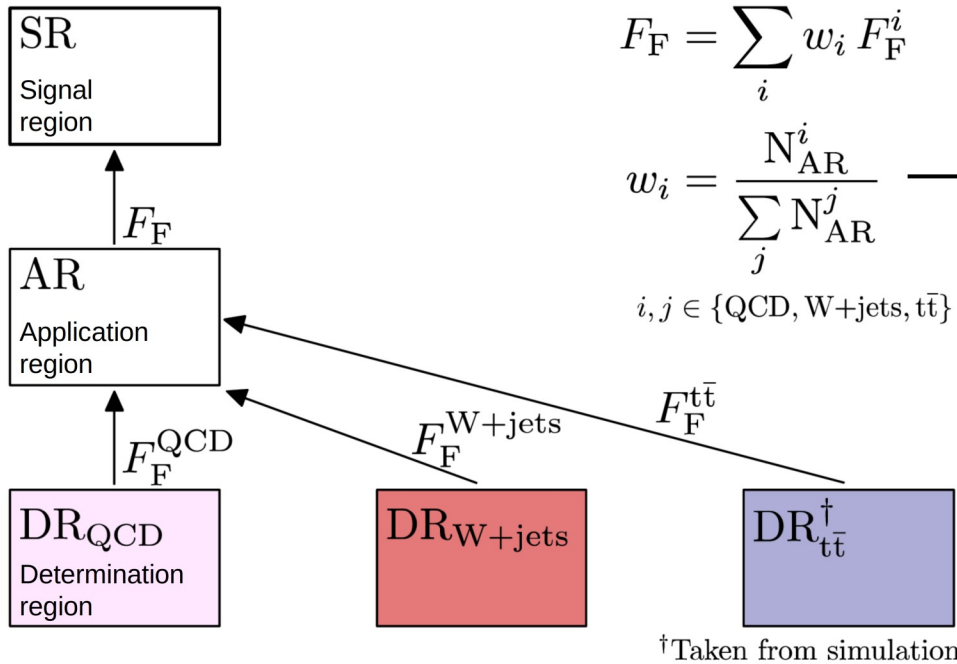
$$w_i = \frac{N_{AR}^i}{\sum_j N_{AR}^j}$$

$$i, j \in \{QCD, W+jets, t\bar{t}\}$$



JHEP 09 (2018) 007

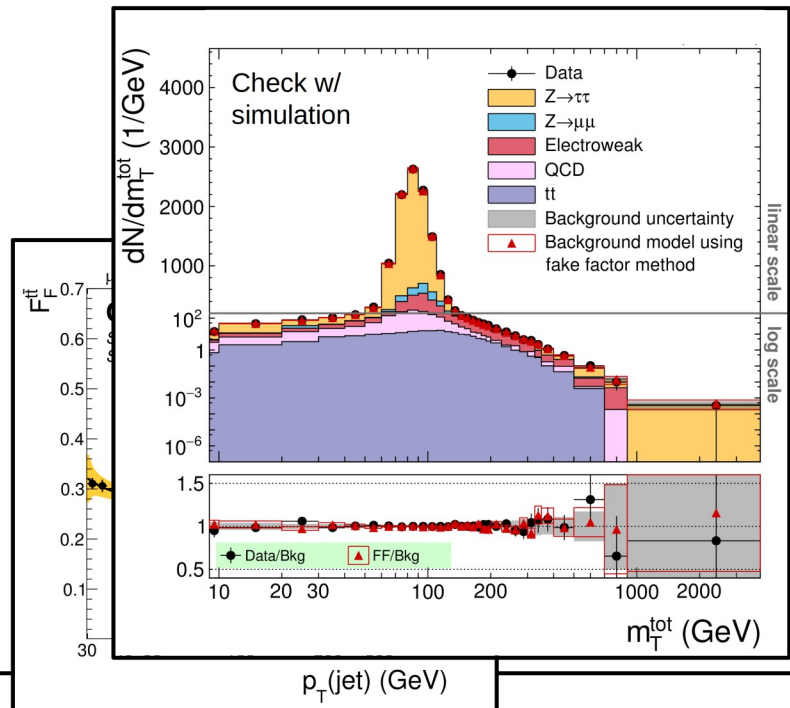
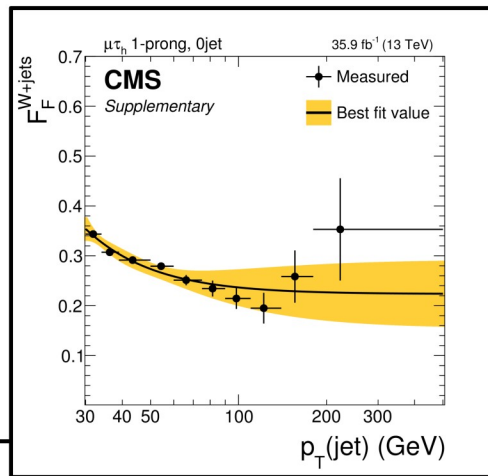
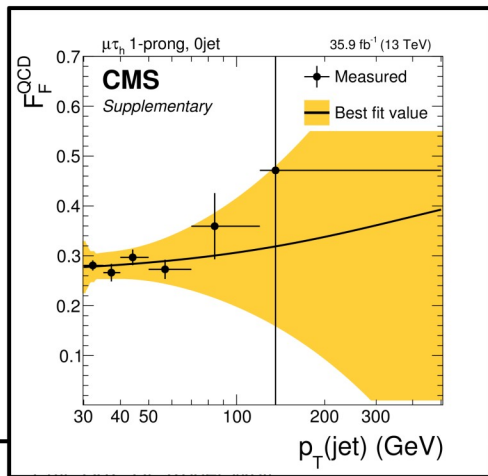
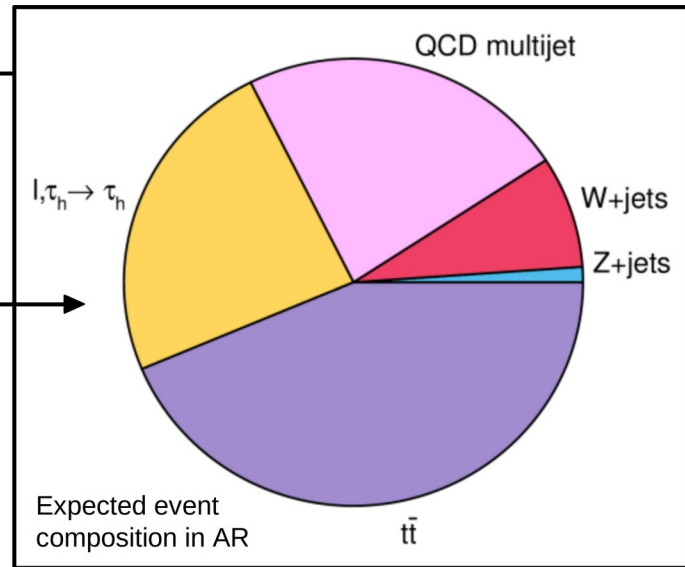
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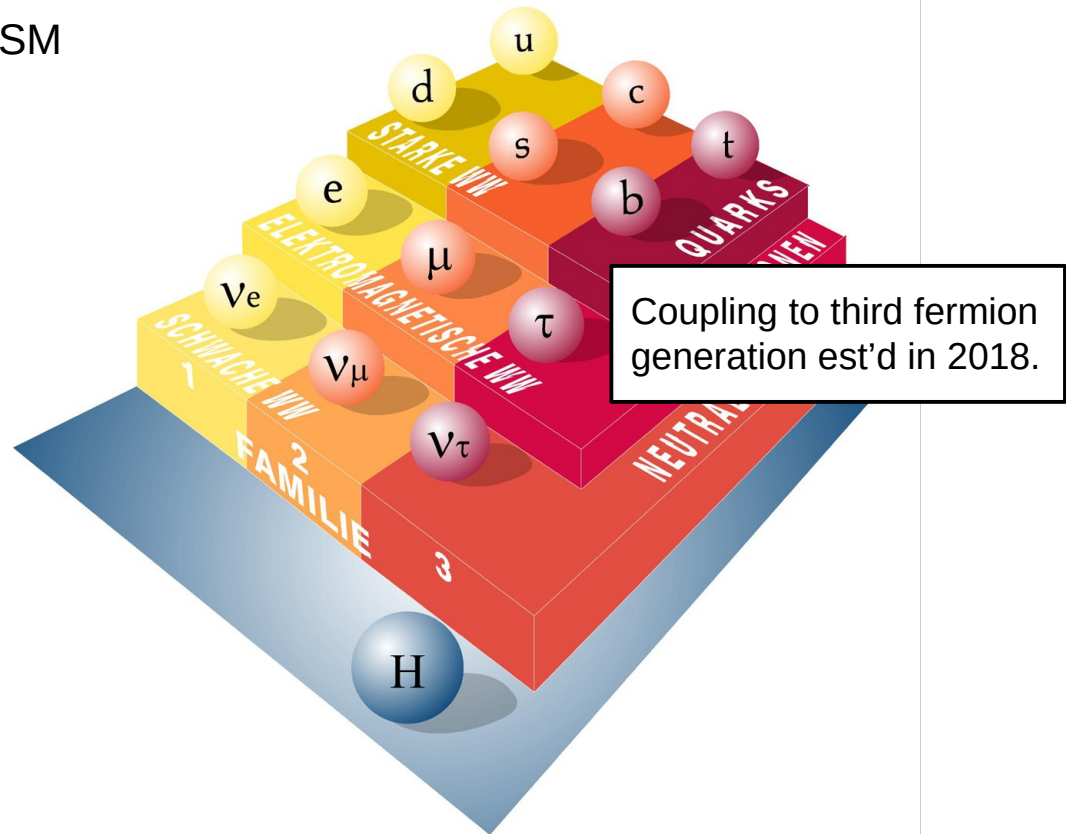
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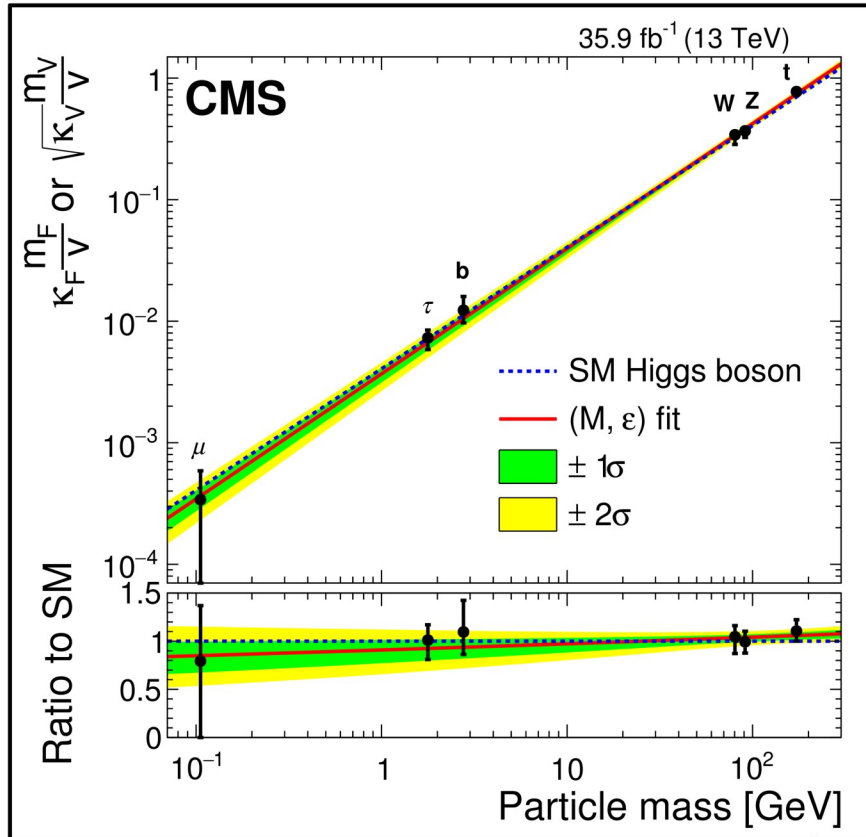
# SM $H \rightarrow \tau\tau$ analysis

- Undoubted that what we observe at 125 GeV is a Higgs boson.
- Measurement scope:
  - Investigate **coupling** structure.
  - Check for **deviations** from the SM expectation.

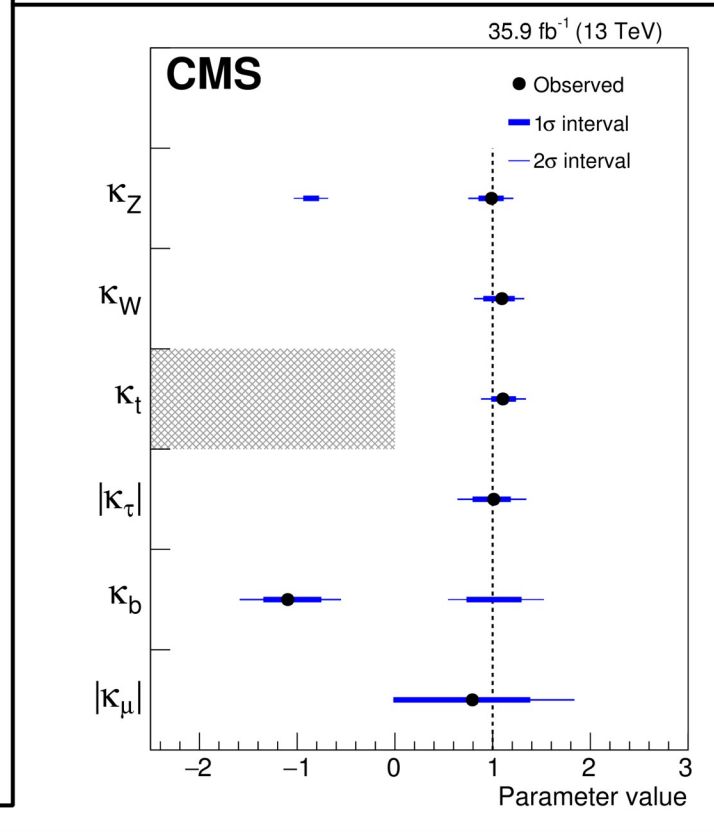


# Higgs coupling structure

- Part of classic analysis of **rate measurements** in production modes & final states.



arxiv:1809.10733



**BUT:** new physics has influence on kinematic distributions.

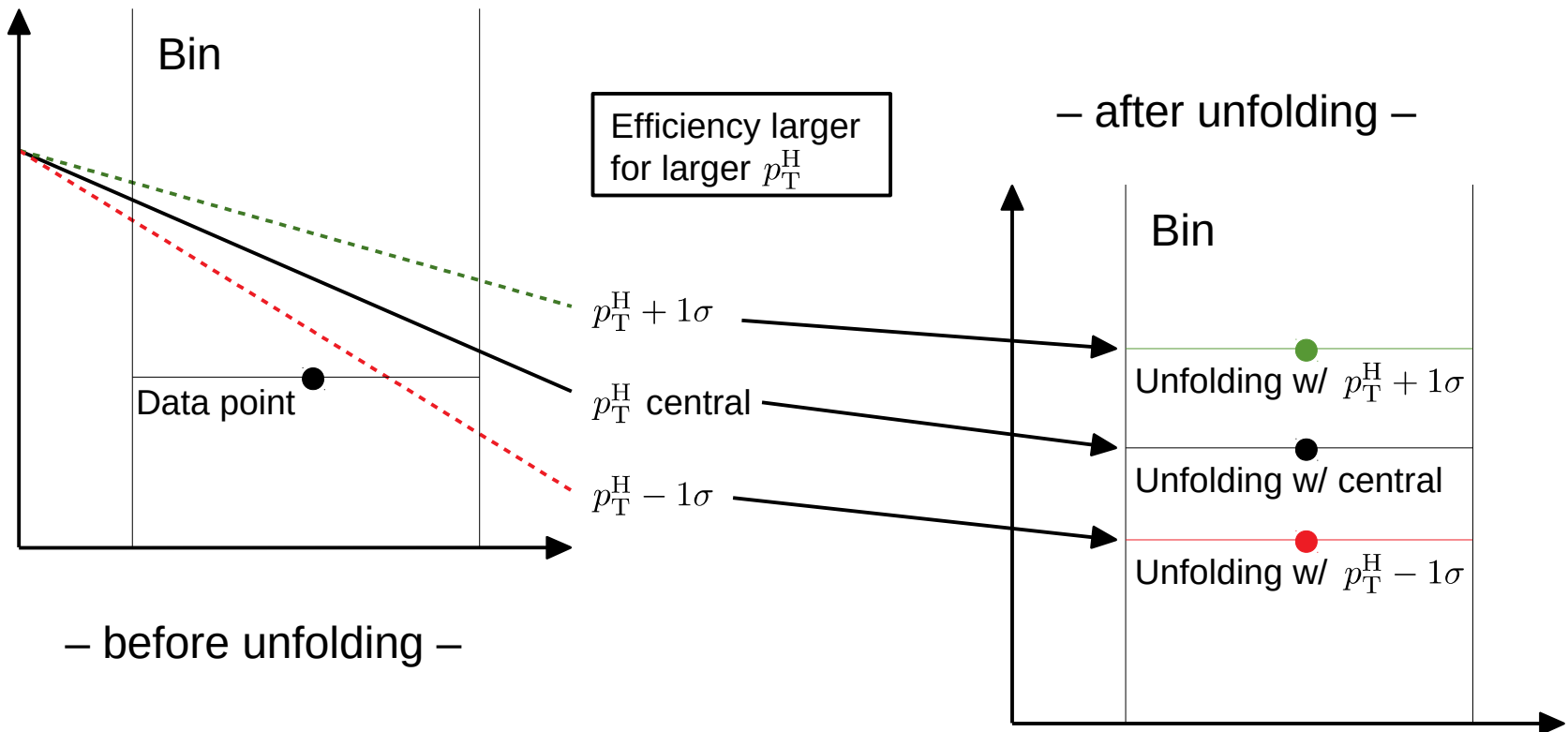
# Simplified template cross section (STXS)

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- Define common phase space regions based on pseudo-observable objects and quantities:
  - Convention to allow for **combination** of final states and across experiments.
  - Kinematic bins help to reduce **influence of theory uncertainties** (e.g. in  $p_T^H$  or  $N_{\text{Jet}}$ ) on measurement.

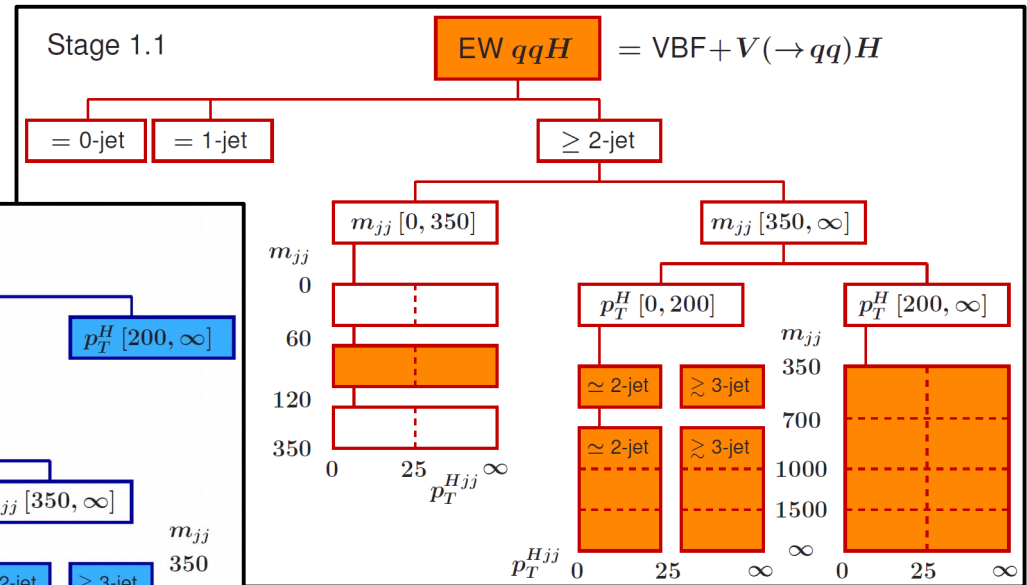
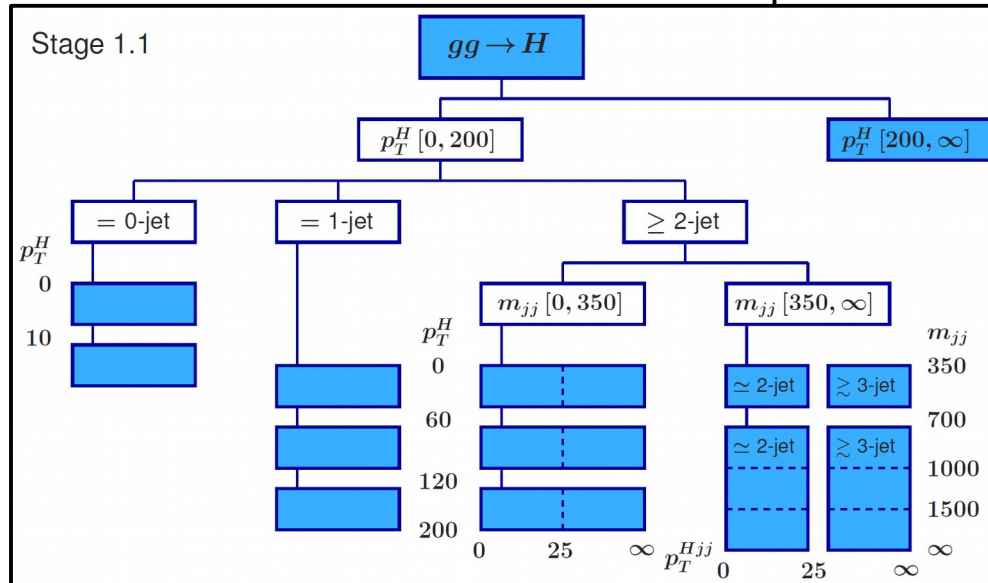
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# Simplified template cross section (STXS)

- Defined for analysis of LHC Run-2 data by LHC HXSWG:





# Template vs. fiducial cross section

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## Simplified template cross section (STXS):

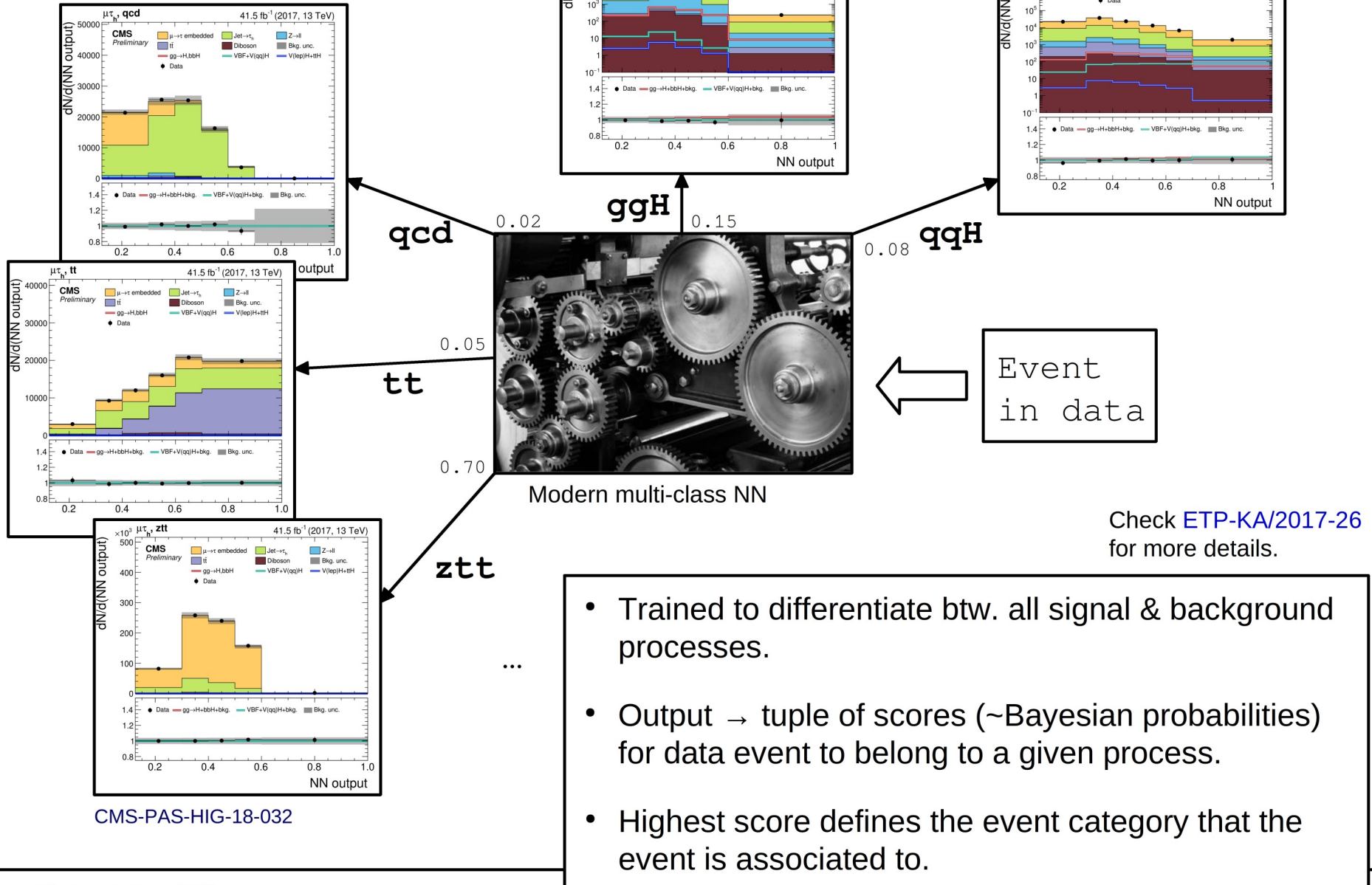
- E.g. Higgs production in VBF & gluon fusion.



## Fiducial cross section:

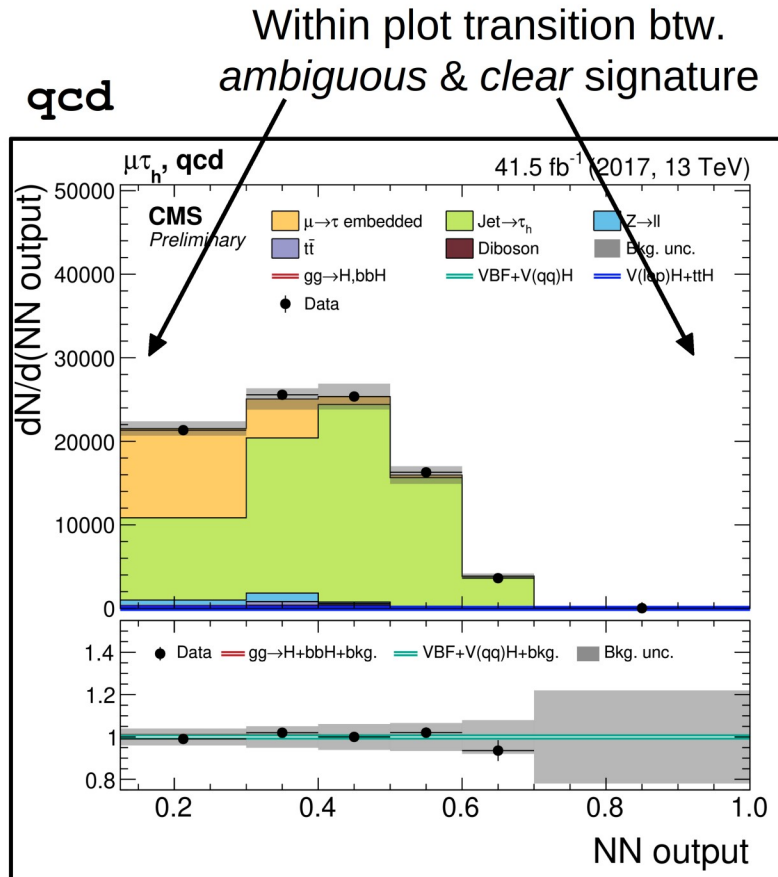
- Obey detector acceptance and stick to measurable quantities.
- E.g. Higgs production in association w/ two jets w/  $m_{jj} > 350$  GeV.

# Event classification

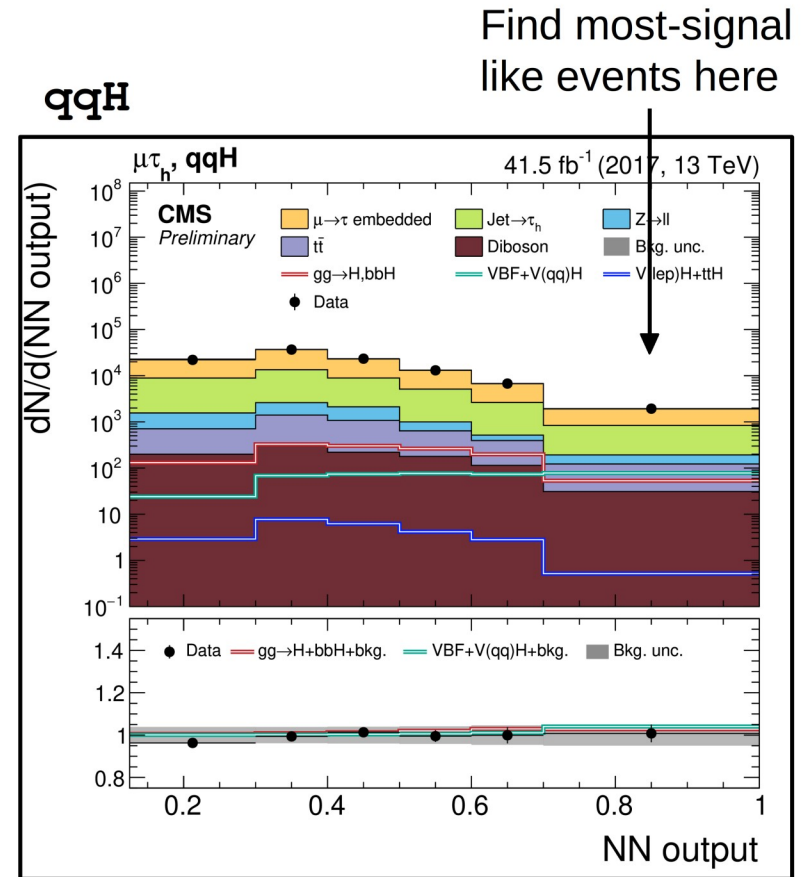


# Signal extraction

- Signal derived from **maximum likelihood fit** to NN output of each event category.
- Pure background categories help to constrain backgrounds in signal categories.



CMS-PAS-HIG-18-032



# NN inputs

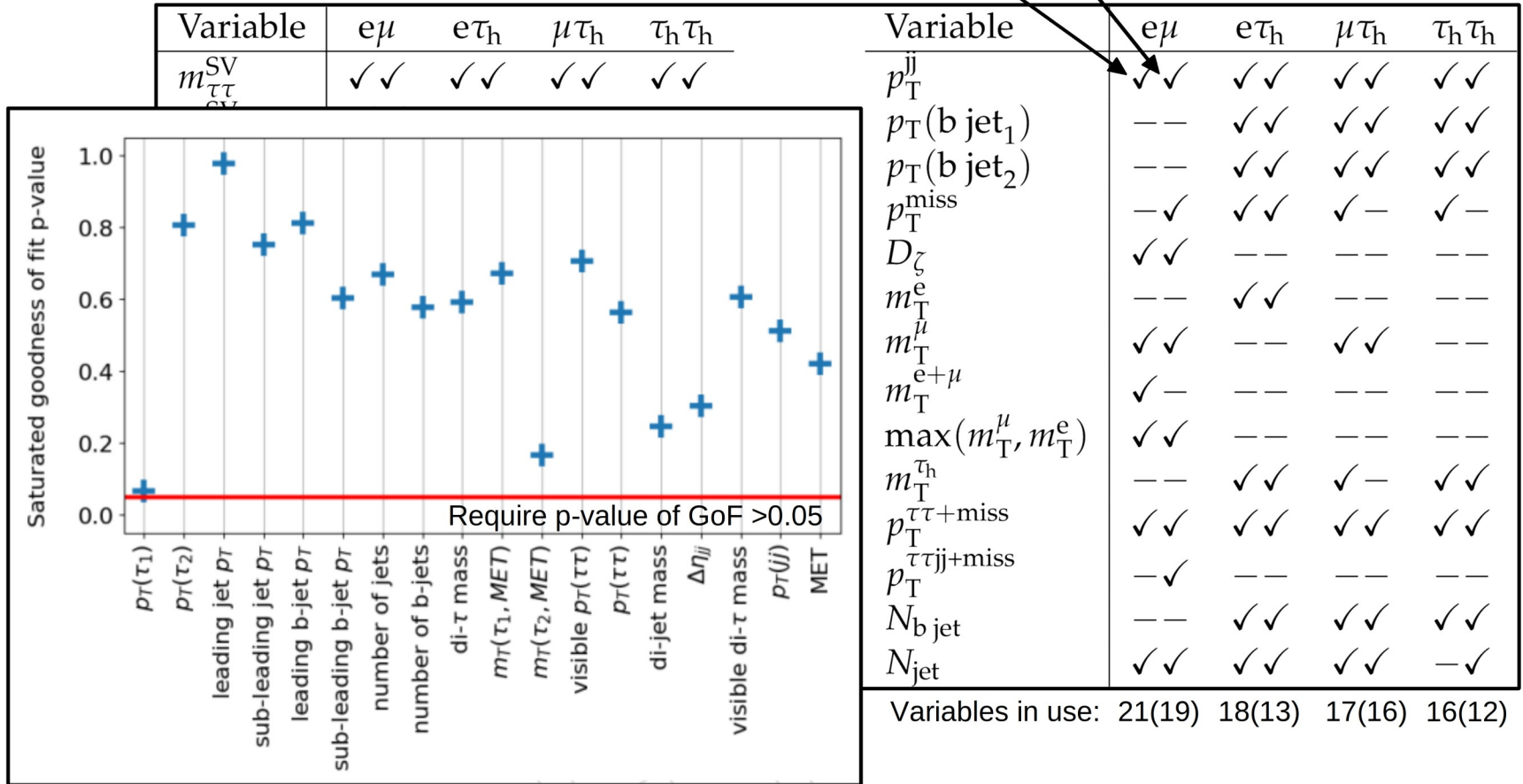
- Use one NN for each final state and separated btw. 2016 & 2017 (→ **8 NNs**):

Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}^{SV}$	✓✓	✓✓	✓✓	✓✓	$p_T^{jj}$	✓✓	✓✓	✓✓	✓✓
$m_{T\tau\tau}^{SV}$	✓✓	---	---	---	$p_T(\text{b jet}_1)$	---	✓✓	✓✓	✓✓
$p_{T\tau\tau}^{SV}$	✓✓	---	---	---	$p_T(\text{b jet}_2)$	---	✓✓	✓✓	✓✓
$m_{vis}$	✓-	✓-	✓-	✓✓	$p_T^{miss}$	-✓	✓✓	✓-	✓-
$p_T^{vis}$	✓✓	✓✓	✓-	✓-	$D_\zeta$	✓✓	---	---	---
$p_T^{\tau_1}$	---	---	✓-	✓✓	$m_T^e$	---	✓✓	---	---
$p_T^{\tau_2}$	✓-	✓✓	✓✓	✓-	$m_T^\mu$	✓✓	---	✓✓	---
$\Delta R^{e\mu}$	✓✓	---	---	---	$m_T^{e+\mu}$	✓-	---	---	---
$p_T(\text{jet}_1)$	✓✓	✓✓	✓✓	✓-	$\max(m_T^\mu, m_T^e)$	✓✓	---	---	---
$\eta(\text{jet}_1)$	✓-	---	---	---	$m_T^{\tau_h}$	---	✓✓	✓-	✓✓
$p_T(\text{jet}_2)$	✓✓	✓✓	✓✓	✓✓	$p_T^{\tau\tau+miss}$	✓✓	✓✓	✓✓	✓✓
$\eta(\text{jet}_2)$	✓-	---	---	---	$p_T^{\tau\tau jj+miss}$	-✓	---	---	---
$m_{jj}$	✓✓	✓✓	✓✓	✓✓	$N_{b\text{ jet}}$	---	✓✓	✓✓	✓✓
$\Delta\eta_{jj}$	✓✓	✓✓	✓✓	✓✓	$N_{\text{jet}}$	✓✓	✓✓	✓✓	-✓

Variables in use: 21(19) 18(13) 17(16) 16(12)

# NN inputs

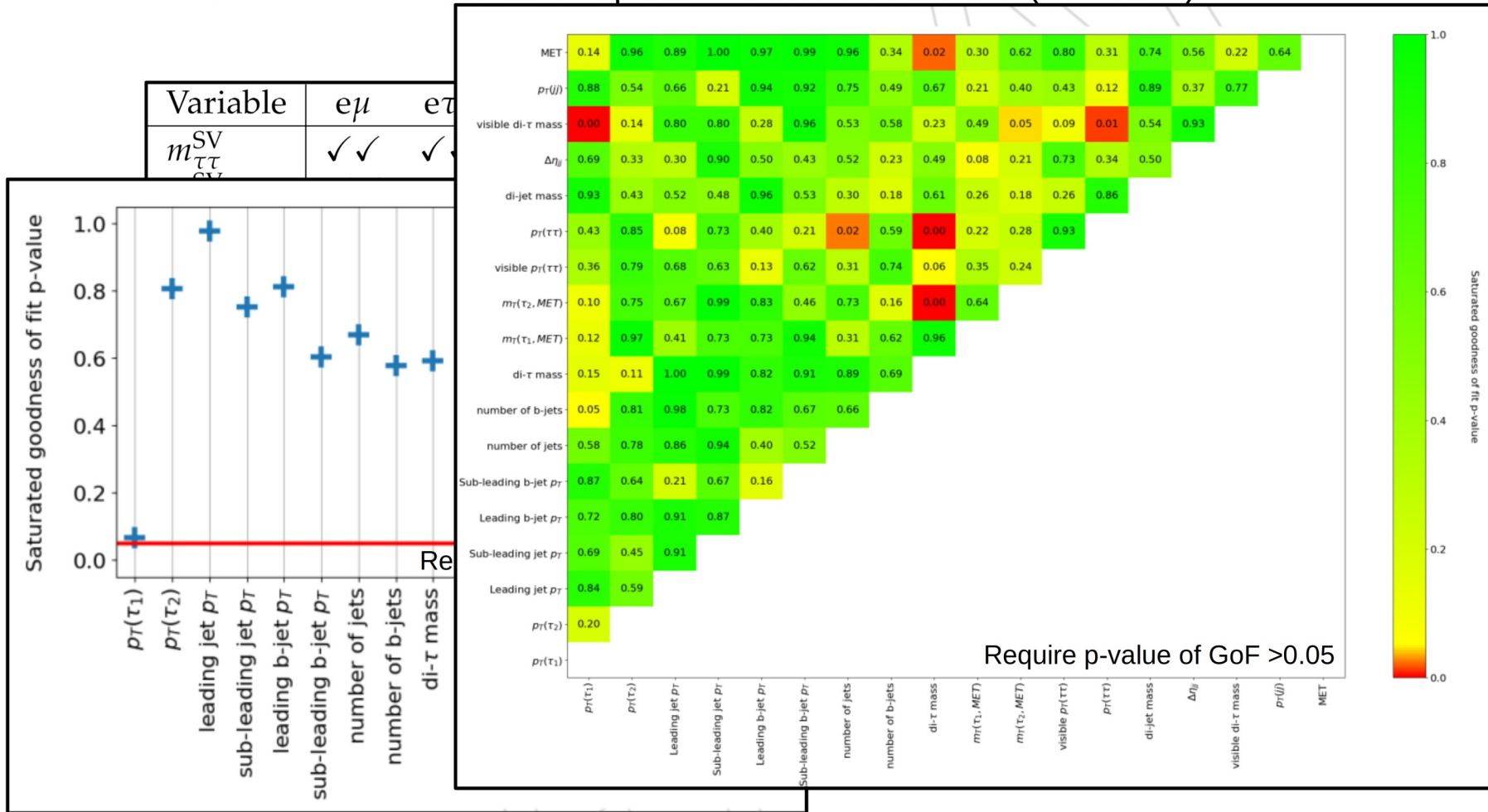
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Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d...

# NN inputs

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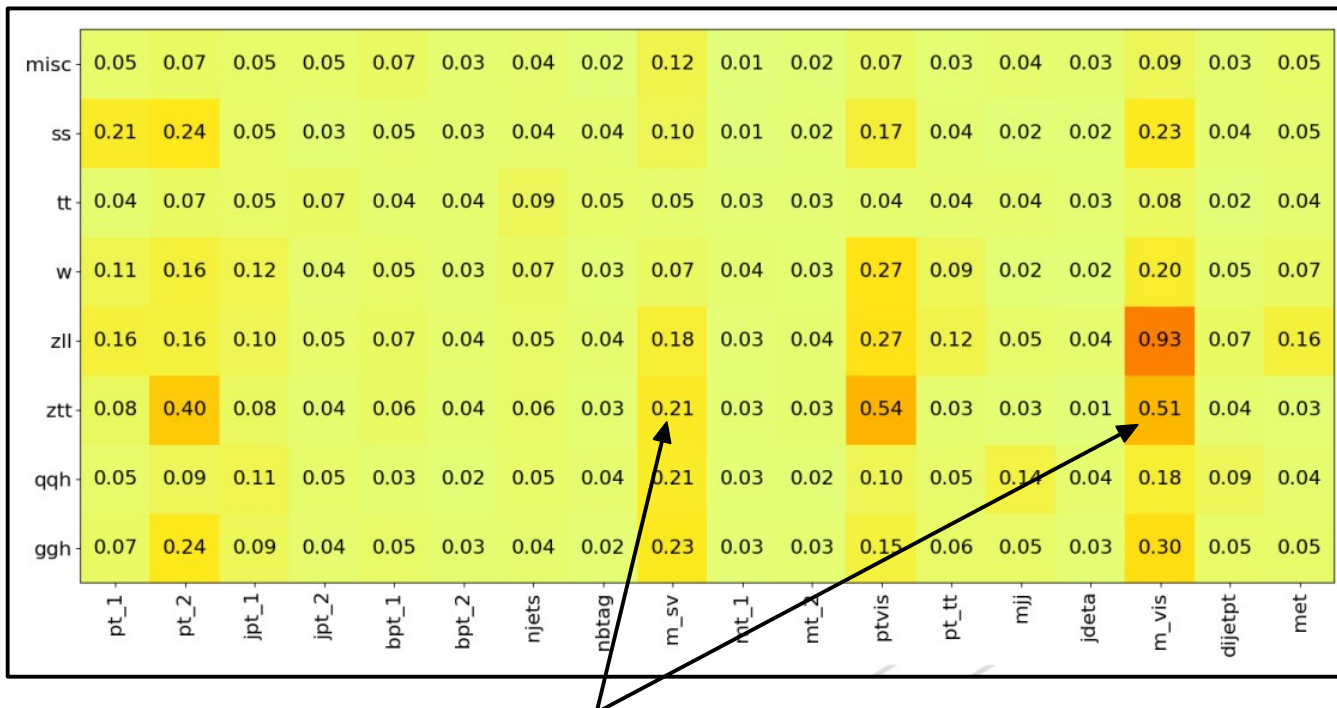


Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d... & 2d.



# “Unboxing” the NN

- Decipher what the NN is doing using a Taylor expansion of the full NN output function.  
**Impact analysis** like on LEP likelihood, but here on NN output function.



Note that all values >0 are allowed.

Relative size of number indicates how sensitive the NN output is on the given input.



# “Unboxing” the NN

- Decipher what the NN is doing using a Taylor expansion of the full NN output function.  
Impact analysis like on LEP likelihood, but here on NN output function.

misc	0.05	0.07	0.05	0.05	0.07	0.03	0.04	0.02	0.12	0.01	0.02	0.07	0.03	0.04	0.03	0.09	0.03	0.05					
ss	0.21	0.24																					
tt	0.04	0.07																					
w	0.11	0.16																					
zll	0.16	0.16																					
ztt	0.08	0.40																					
qqh	0.05	0.09																					
ggh	0.07	0.24																					
	pt_1	pt_2																					
	ggh	qqh	ztt	zll	w	tt	ss	misc															
m_vis	m_vis	1.50	m_vis	m_vis	0.44	pt_2	pt_vis	1.14	m_vis	m_vis	7.58	m_vis	m_vis	0.83	m_vis	m_vis	0.16	m_vis	m_vis	0.56	m_vis	m_vis	0.23
pt_vis	m_vis	0.58	m_vis	m_vis	0.39	pt_vis	pt_vis	1.06	m_vis	m_vis	1.29	pt_2	pt_vis	0.43	m_vis	m_vis	0.11	pt_2	pt_vis	0.42	m_vis	m_vis	0.22
pt_vis	pt_vis	0.50	m_vis	m_vis	0.39	pt_vis	m_vis	0.90	pt_vis	m_vis	1.28	pt_vis	pt_vis	0.42	njets	0.09	pt_2	m_vis	0.34	m_vis	m_vis	0.20	
pt_2	m_vis	0.48	m_vis	pt_vis	0.26	m_vis	pt_vis	0.85	m_vis	met	1.01	pt_vis	m_vis	0.41	pt_2	m_vis	0.08	pt_vis	m_vis	0.34	m_vis	pt_vis	0.14
pt_2	pt_vis	0.48	m_vis	m_vis	0.21	pt_1	pt_vis	0.67	m_vis	0.89	pt_2	m_vis	0.29	jpt_1	jpt_1	0.08	pt_1	pt_vis	0.33	m_vis	0.13		
m_vis	m_vis	0.45	m_vis	dijetpt	0.20	pt_2	m_vis	0.63	pt_tt	m_vis	0.88	pt_vis	0.28	pt_2	0.08	pt_vis	pt_vis	0.32	pt_2	pt_vis	0.12		
m_vis	pt_vis	0.33	pt_vis	dijetpt	0.18	pt_2	m_vis	0.62	pt_1	m_vis	0.87	pt_1	pt_vis	0.27	pt_vis	m_vis	0.08	pt_1	pt_2	0.28	pt_vis	m_vis	0.11
pt_1	pt_vis	0.31	m_vis	m_vis	0.17	m_vis	m_vis	0.60	pt_1	m_vis	0.73	m_vis	m_vis	0.26	m_vis	m_vis	0.07	pt_1	m_vis	0.26	pt_vis	m_vis	0.11
m_vis	0.29	pt_2	m_vis	0.16	pt_vis	0.57	m_vis	dijetpt	0.72	jpt_1	pt_vis	0.25	jpt_2	0.07	m_vis	pt_vis	0.25	pt_2	pt_2	0.24	pt_1	pt_vis	0.09
pt_1	m_vis	0.29	pt_vis	m_vis	0.16	m_vis	m_vis	0.55	jpt_1	pt_vis	0.63	m_vis	pt_vis	0.22	jpt_1	0.07	pt_2	pt_2	0.23	pt_2	pt_1	pt_vis	0.09
m_vis	met	0.26	pt_vis	pt_vis	0.16	m_vis	m_vis	0.52	pt_vis	pt_vis	0.62	pt_vis	pt_tt	0.21	m_vis	m_vis	0.06	pt_2	pt_2	0.21	pt_1	pt_vis	0.09
m_vis	m_vis	0.24	m_vis	dijetpt	0.15	pt_2	pt_2	0.52	pt_1	pt_vis	0.49	m_vis	0.20	pt_2	pt_2	0.06	m_vis	0.21	jpt_1	pt_vis	0.09		
pt_tt	m_vis	0.24	m_vis	m_vis	0.15	m_vis	m_vis	0.45	mjj	m_vis	0.49	pt_tt	m_vis	0.18	m_vis	pt_vis	0.06	pt_1	0.21	m_vis	0.09		
jpt_1	pt_vis	0.23	dijetpt	dijetpt	0.14	pt_2	0.40	pt_2	pt_vis	0.47	pt_2	0.18	pt_2	0.18	pt_2	0.06	m_vis	m_vis	0.20	pt_vis	0.08		
jpt_1	m_vis	0.23	jpt_1	dijetpt	0.13	jpt_1	pt_vis	0.32	mt_2	m_vis	0.39	pt_2	pt_2	0.17	jpt_1	jpt_2	0.06	pt_1	pt_1	0.19	m_vis	dijetpt	0.08
pt_2	pt_2	0.22	pt_2	pt_vis	0.13	pt_1	pt_2	0.31	m_vis	pt_vis	0.36	m_vis	met	0.17	pt_vis	pt_vis	0.06	pt_2	m_vis	0.18	pt_1	m_vis	0.07
pt_vis	pt_tt	0.19	m_vis	met	0.12	pt_vis	met	0.29	jdet	m_vis	0.32	pt_vis	met	0.16	m_vis	met	0.13	pt_1	m_vis	0.13	pt_2	0.07	
m_vis	dijetpt	0.19	jpt_1	jpt_1	0.12	jpt_1	m_vis	0.27	bpt_1	m_vis	0.32	pt_1	pt_2	0.16	pt_1	pt_2	0.05	m_vis	m_vis	0.13	jpt_1	m_vis	0.07
pt_2	m_vis	0.18	jpt_1	m_vis	0.12	pt_vis	pt_tt	0.27	pt_vis	0.30	pt_2	m_vis	0.14	pt_1	m_vis	0.05	pt_vis	met	0.12	bpt_1	0.07		
pt_vis	dijetpt	0.18	pt_1	m_vis	0.12	nbt	pt_vis	0.26	bpt_2	m_vis	0.30	njets	pt_vis	0.13	pt_1	pt_vis	0.05	pt_1	met	0.12	pt_2	pt_2	0.07
pt_1	pt_2	0.17	jpt_1	0.11	bpt_1	pt_vis	0.25	pt_vis	pt_tt	0.30	pt_2	pt_tt	0.13	pt_2	jpt_1	0.05	m_vis	met	0.12	jpt_1	jpt_1	0.07	
pt_vis	met	0.16	jpt_1	m_vis	0.11	pt_1	pt_1	0.25	pt_1	pt_1	0.29	pt_vis	dijetpt	0.13	pt_2	m_vis	0.05	jpt_1	m_vis	0.11	pt_1	pt_2	0.06
pt_1	m_vis	0.15	pt_tt	m_vis	0.11	njets	pt_vis	0.24	m_vis	m_vis	0.29	m_vis	dijetpt	0.13	pt_tt	m_vis	0.05	pt_vis	pt_tt	0.11	pt_vis	dijetpt	0.06
pt_vis	0.15	pt_vis	0.11	m_vis	0.23	pt_vis	met	0.28	jpt_1	jpt_1	0.13	nbt	0.05	pt_tt	m_vis	0.11	jpt_1	0.06					
jpt_1	m_vis	0.15	mjj	m_vis	0.10	pt_1	m_vis	0.23	jpt_2	m_vis	0.28	pt_2	jpt_1	0.12	m_vis	0.04	pt_2	jpt_1	0.11	m_vis	pt_tt	0.06	
mjj	m_vis	0.14	pt_2	0.10	m_vis	dijetpt	0.22	jpt_1	pt_vis	0.27	pt_1	pt_1	0.12	jpt_1	m_vis	0.04	pt_vis	dijetpt	0.11	m_vis	met	0.06	
bpt_1	pt_vis	0.14	pt_2	m_vis	0.09	pt_2	pt_tt	0.19	nbt	m_vis	0.26	bpt_1	pt_vis	0.12	pt_vis	0.04	bpt_1	pt_vis	0.10	met	0.06		
pt_1	pt_1	0.14	dijetpt	0.09	bpt_2	pt_vis	0.18	pt_vis	dijetpt	0.26	pt_tt	0.12	jpt_1	dijetpt	0.04	jpt_1	m_vis	0.10	m_vis	dijetpt	0.06		
njets	m_vis	0.13	m_vis	pt_tt	0.09	pt_2	jpt_1	0.18	pt_2	0.25	pt_1	0.12	m_vis	dijetpt	0.04	njets	pt_vis	0.10	pt_vis	pt_tt	0.06		
njets	pt_vis	0.13	m_vis	mjj	0.09	m_vis	pt_tt	0.17	pt_1	m_vis	0.23	jpt_1	0.12	pt_tt	0.04	m_vis	0.10	jpt_2	m_vis	0.06			
pt_2	jpt_1	0.13	pt_1	pt_vis	0.09	pt_2	bpt_1	0.17	pt_2	m_vis	0.23	jpt_1	m_vis	0.12	pt_2	njets	dijetpt	0.10	bpt_2	m_vis	0.05		
bpt_1	m_vis	0.12	mjj	0.08	pt_tt	m_vis	0.16	m_vis	dijetpt	0.21	nbt	pt_vis	0.11	pt_2	pt_tt	0.04	pt_1	jpt_1	0.09	pt_1	pt_1	0.05	
jpt_1	jpt_1	0.12	pt_2	0.08	jpt_1	m_vis	0.16	m_vis	met	0.19	m_vis	met	0.11	pt_vis	dijetpt	0.04	nbt	pt_vis	0.09	pt_tt	m_vis	0.05	
m_vis	dijetpt	0.11	m_vis	met	0.08	pt_2	njets	0.15	pt_1	m_vis	0.19	pt_1	m_vis	0.11	pt_1	pt_1	0.04	pt_2	pt_tt	0.09	pt_vis	met	0.05
pt_2	pt_tt	0.11	pt_tt	0.08	jpt_1	jpt_1	0.15	pt_1	met	0.18	jpt_2	pt_vis	0.10	bpt_1	0.04	pt_2	dijetpt	0.08	pt_2	jpt_1	0.05		
mt_2	m_vis	0.11	jpt_2	dijetpt	0.08	pt_1	nbt	0.15	njets	pt_vis	0.17	pt_1	jpt_1	0.10	njets	m_vis	0.04	pt_2	njets	0.08	njets	pt_vis	0.05
jpt_2	m_vis	0.11	bpt_2	m_vis	0.08	pt_2	met	0.15	pt_2	jpt_1	0.17	pt_1	met	0.09	jpt_1	hjets	0.04	pt_1	pt_tt	0.08	bpt_1	pt_vis	0.05
nbt	pt_vis	0.11	jpt_1	mjj	0.08	pt_1	dijetpt	0.14	nbt	pt_vis	0.17	pt_2	met	0.09	pt_1	m_vis	0.04	pt_2	met	0.08	jpt_2	0.05	
jpt_2	pt_vis	0.10	jpt_2	m_vis	0.08	m_vis	met	0.14	jpt_2	pt_vis	0.17	njets	m_vis	0.09	pt_1	0.04	jpt_2	pt_vis	0.08	m_vis	met	0.05	
bpt_2	m_vis	0.10	jpt_1	jpt_2	0.07	m_vis	met	0.13	bpt_1	pt_vis	0.16	mjj	m_vis	0.09	mjj	0.04	pt_2	bpt_1	0.08	jpt_1	jpt_2	0.05	
jdet	m_vis	0.10	mjj	dijetpt	0.07	pt_2	dijetpt	0.13	mt_1	m_vis	0.16	bpt_1	m_vis	0.09	bpt_2	0.04	pt_1	dijetpt	0.08	jpt_1	dijetpt	0.05	
m_vis	met	0.10	m_vis	jdet	0.07	pt_1	met	0.13	jpt_1	m_vis	0.16	jpt_1	dijetpt	0.08	pt_1	jpt_1	0.04	njets	m_vis	0.08	jpt_2	m_vis	0.05
jpt_1	0.09	jpt_2	m_vis	0.07	pt_1	jpt_1	0.13	pt_1	jpt_1	0.15	pt_2	njets	0.08	met	0.04	pt_1	nbt	0.08	0.08	njets	0.05		
m_vis	pt_tt	0.09	pt_2	jpt_1	0.07	bpt_1	m_vis	0.12	pt_1	pt_1	0.14	pt_2	pt_vis	0.08	jpt_2	m_vis	0.08	jpt_2	jpt_2				
pt_2	dijetpt	0.09	njets	m_vis	0.07	m_vis	dijetpt	0.12	jpt_1	jpt_1	0.14	jpt_2	m_vis	0.08	pt_1	met	0.08	pt_1	met				
nbt	m_vis	0.09	jdet	m_vis	0.07	bpt_2	m_vis	0.12	pt_2	pt_tt	0.14	m_vis	0.08	pt_1	met	0.08	pt_2	met					
pt_2	njets	0.09	jpt_1	njets	0.07	njets	m_vis	0.12	met	0.14	pt_2	dijetpt	0.08	pt_2	dijetpt	0.08	pt_2	pt_2					
pt_1	jpt_1	0.09	njets	pt_vis	0.07	jpt_2	pt_vis	0.12	pt_2	met	0.13	jpt_1	njets	0.08	jpt_2	njets							

Also this can be done in 2d.  
And that way one can learn a lot about the NN task and how it is solved.

# How well can the NN do?

- Confusion matrix tells how well the NN can **identify each individual process**:
- In this representation: all columns normalized to unity.
- 72% of all **qqH** events can be identified as such.
- Assess success of NN by comparison to random association (prob.  $1/8=12.5\%$ ).

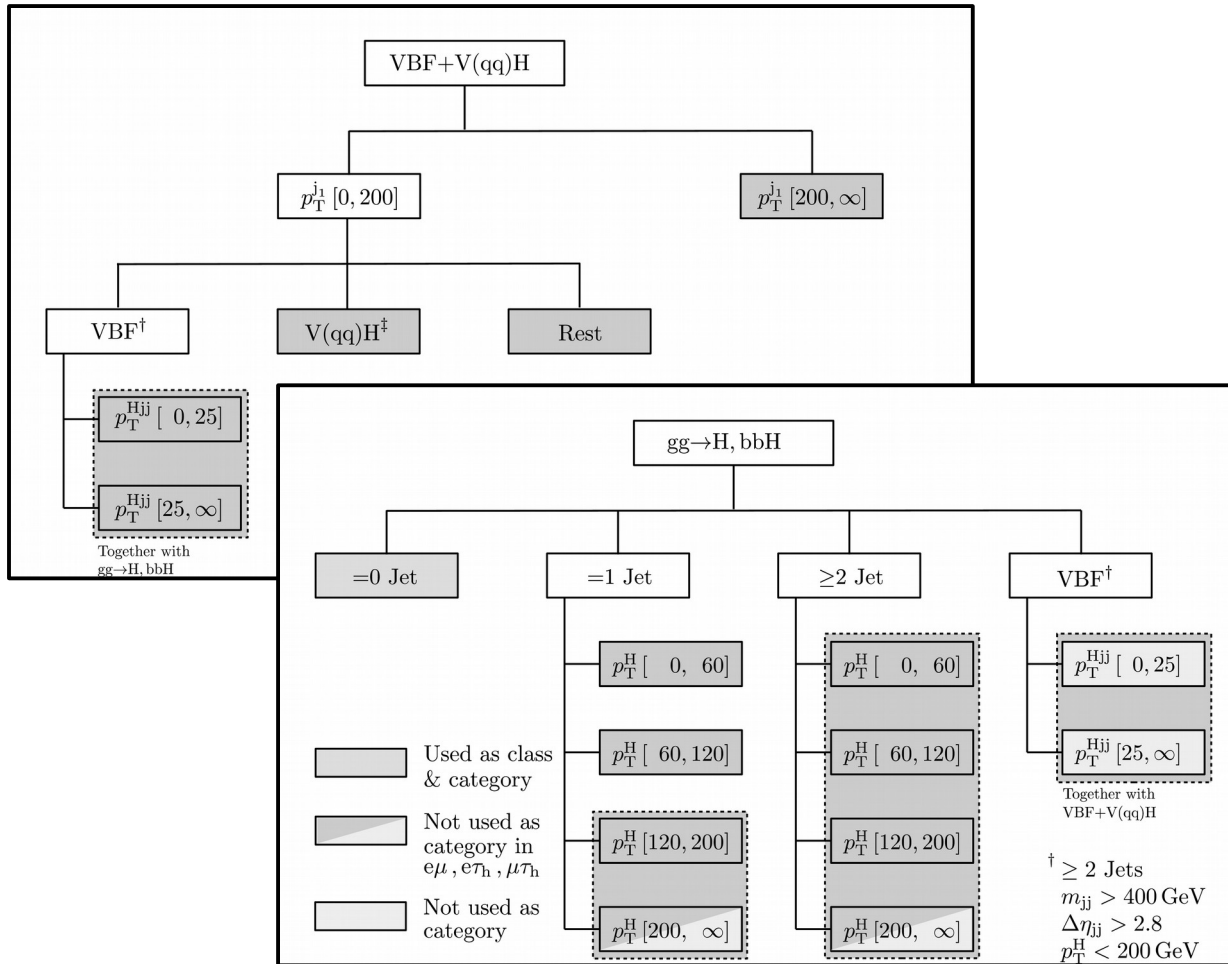
*CMS Simulation Preliminary*

		$\mu\tau_h$ (2017)							
NN predicted event class	ggH	0.27	0.08	0.08	0.07	0.01	0.05	0.11	0.08
	qqH	0.21	0.72	0.07	0.06	0.06	0.12	0.05	0.06
	ztt	0.23	0.06	0.63	0.26	0.01	0.09	0.14	0.18
	qcd	0.02	0.01	0.02	0.17	0.02	0.06	0.04	0.13
	tt	0.01	0.04	0.01	0.06	0.75	0.23	0.01	0.02
	misc	0.02	0.04	0.06	0.07	0.14	0.28	0.02	0.09
	zll	0.17	0.03	0.08	0.13	0.00	0.04	0.53	0.14
	wj	0.07	0.02	0.06	0.19	0.02	0.13	0.10	0.31
			ggH	qqH	ztt	qcd	tt	misc	zll
		True event class							

CMS-PAS-HIG-18-032

# STXS classification

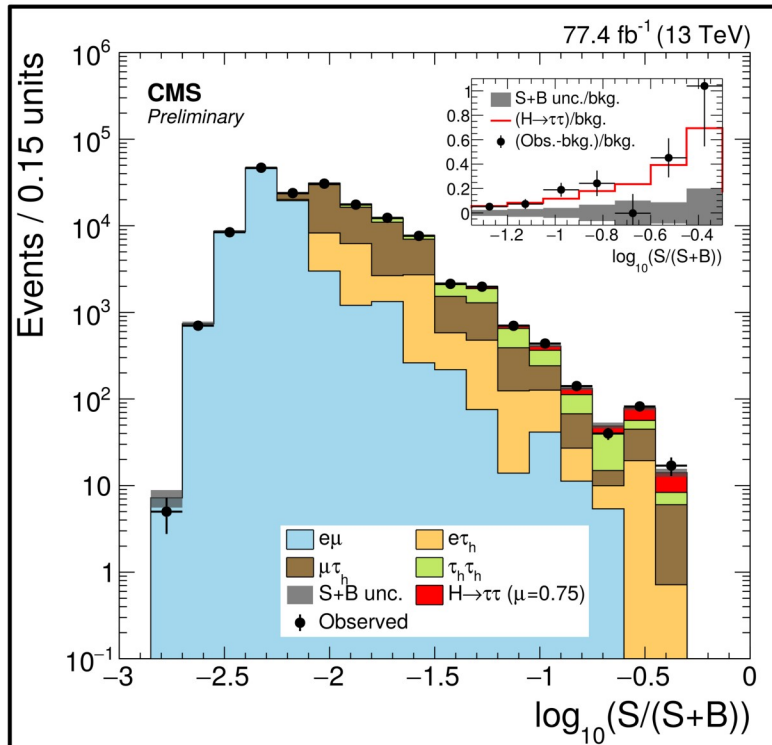
- After classification of  $ggH$  and  $qqH$  events are split into STXS bins, based on selection requirements on theory-related quantities after reconstruction:



CMS-PAS-HIG-18-032

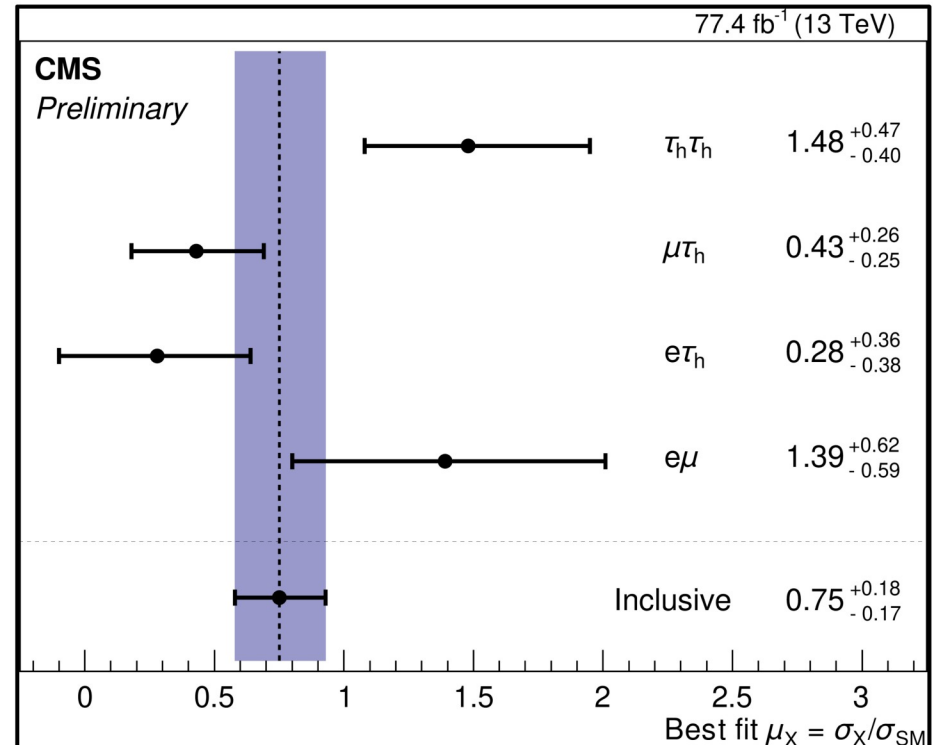
# Results (inclusive)

Inclusive signal (sorted by  $\log(S/(S+B))$ )



CMS-PAS-HIG-18-032

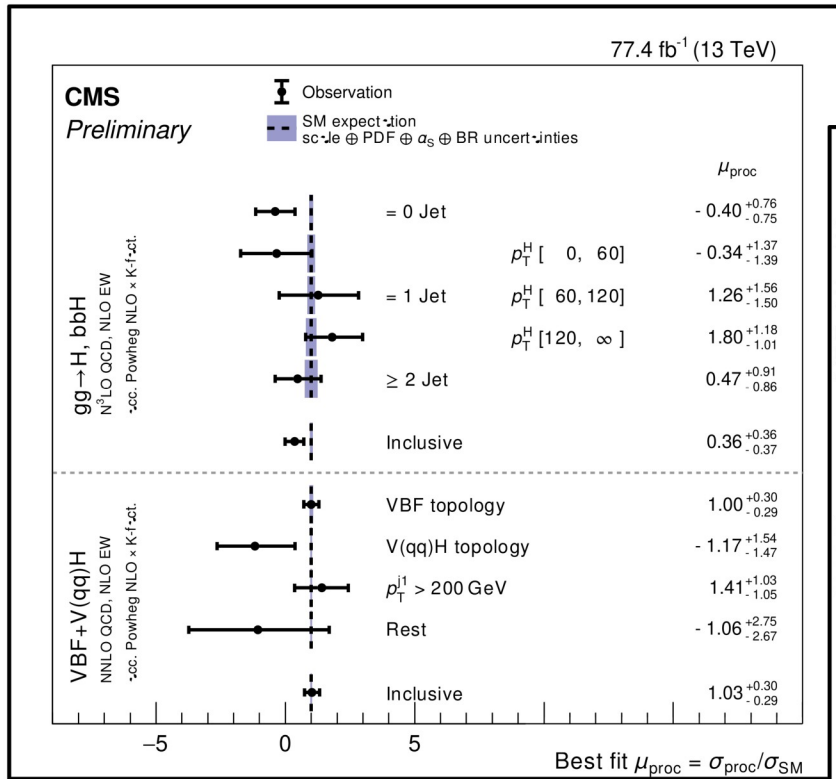
Signal strength: (top) split by final state and (bottom) inclusive



- **Clear signal** seen, though a bit on the low side, compared to other Higgs decay modes.

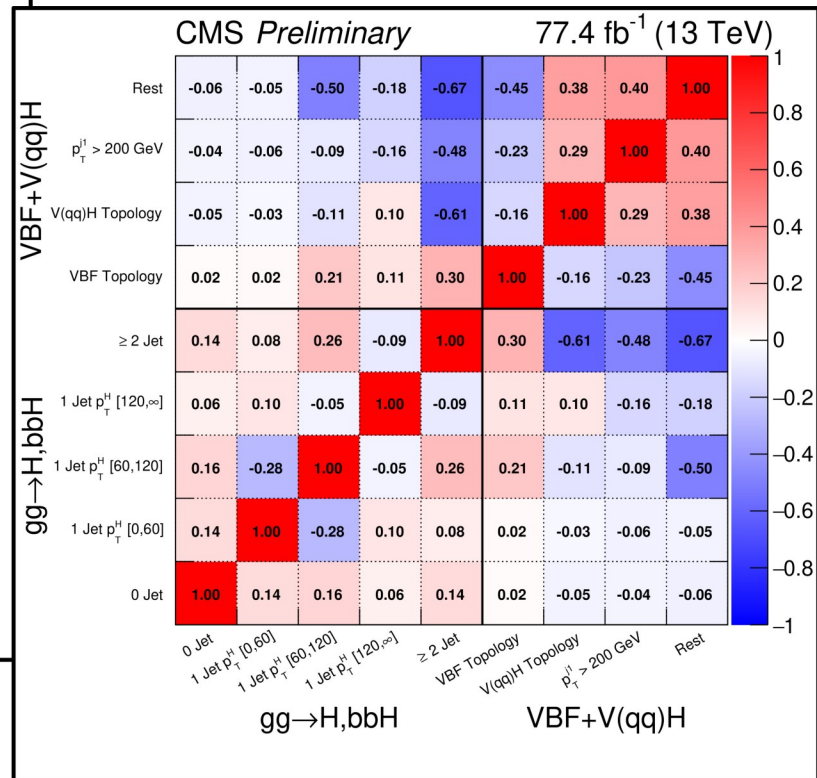
# Results (STXS)

- More **differential** measurement in 9 predefined STXS bins:



STXS bins

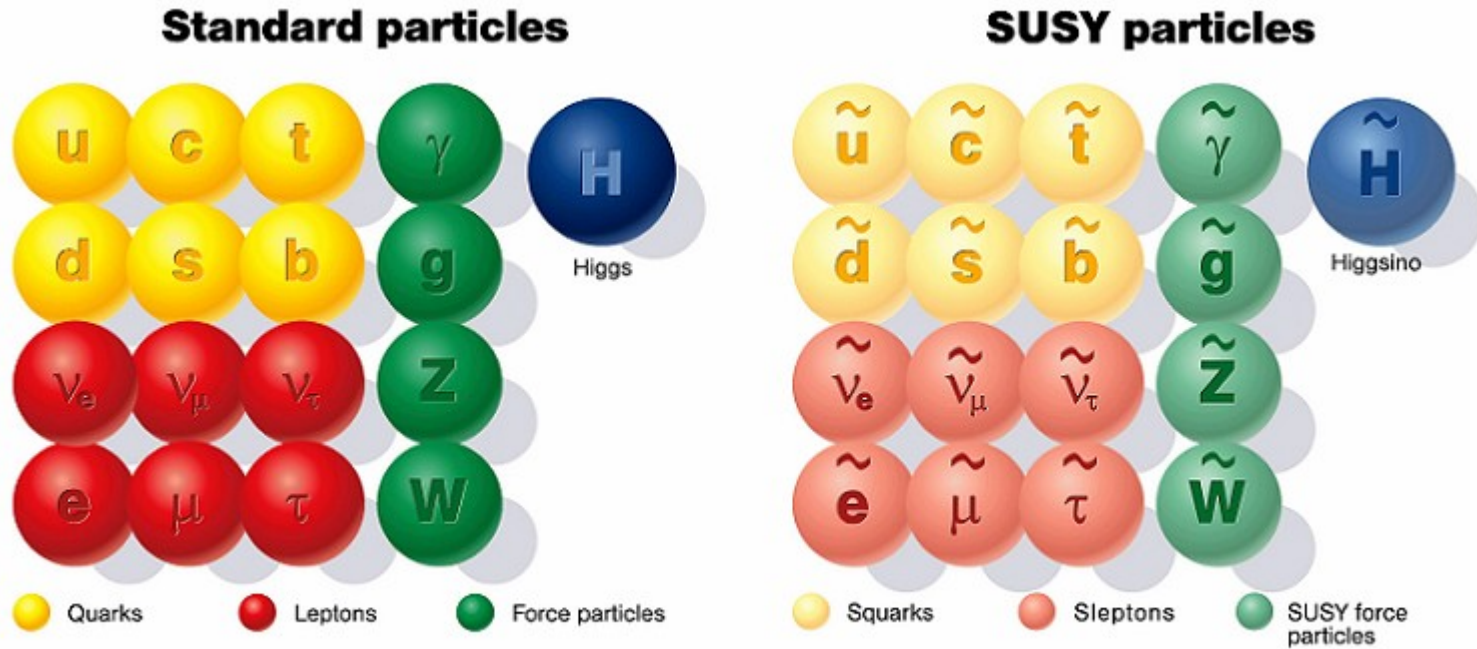
CMS-PAS-HIG-18-032



Correlation matrix



# MSSM $H \rightarrow \tau\tau$ analysis (\*)



(\*) as proxy for a well motivated Two Higgs Doublet Model (2HDM) extension of the SM.

# Higgs sector in SUSY

NB: w/o CP-violation in the SUSY Higgs sector.

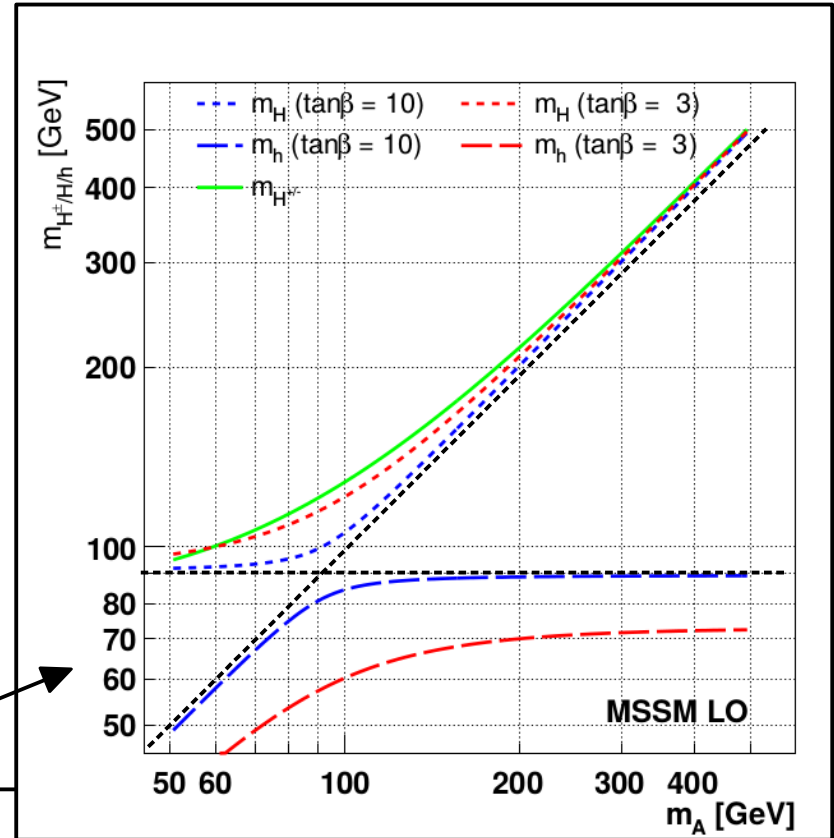
- SUSY requires @ least 2 Higgs doublets (2HDM type-II) → **five Higgs bosons**:

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u : \text{VEV}_u$$

$$\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}, \quad Y_{\phi_d} = -1, \quad v_d : \text{VEV}_d$$

$$N_{\text{ndof}} = 8 \quad - \underbrace{3}_{W, Z} = \underbrace{5}_{H^\pm, H, h, A}$$

- Strict mass requirements imposed by symmetry
- At tree level two free parameters:  $m_A$ ,  $\tan \beta = v_u/v_d$ .



$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H, h}^2 = \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta} \right)$$

$$\tan \alpha = \frac{-(m_A^2 + m_Z^2) \sin 2\beta}{(m_Z^2 - m_A^2) \cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}$$

$\alpha$  : angle between  $H$  and  $h$  in mass matrix



# $m_h$ and $\tan \beta$ in the MSSM

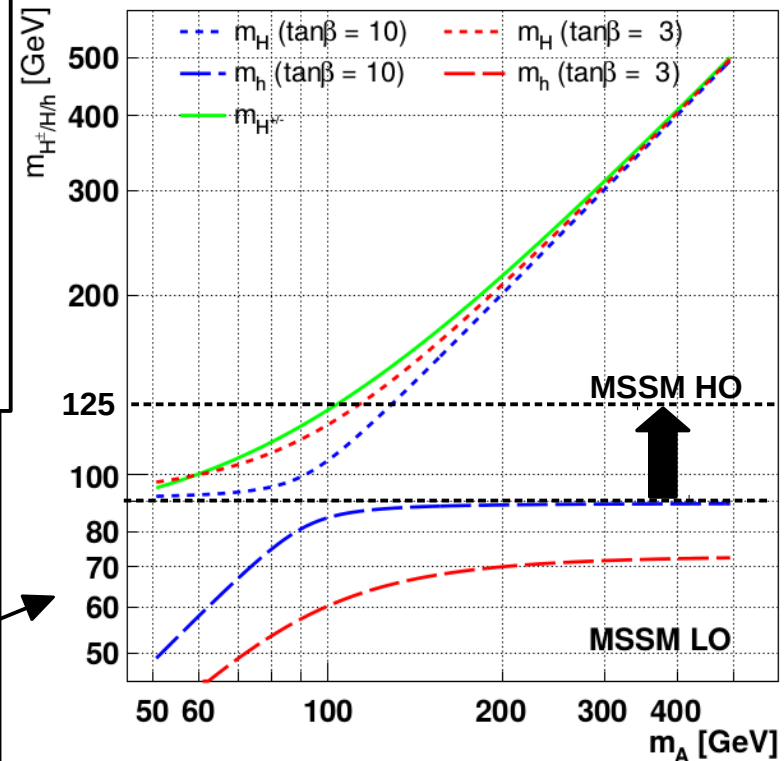
NB: w/o CP-violation in the SUSY Higgs sector.

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \Delta_{\text{rad}}$$

$$\Delta_{\text{rad}} = \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left( \ln \left( \frac{m_{\tilde{t}}^2}{m_t^2} \right) + \frac{X_t^2}{m_{\tilde{t}}^2} \left( 1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right)$$

- +30% of  $m_h$  due to higher order corrections.
- Following factors help to increase  $m_h$ : large  $m_t$ , large  $m_{\tilde{t}}$ , large  $X_t$ , large  $\tan \beta$ .

$$X_t = m_t (A_t - \mu \cot \beta)$$



$$m_{H^{\pm}}^2 = m_A^2 + m_W^2$$

$$m_{H, h}^2 = \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta} \right)$$

$$\tan \alpha = \frac{-(m_A^2 + m_Z^2) \sin 2\beta}{(m_Z^2 - m_A^2) \cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}$$

$\alpha$  : angle between  $H$  and  $h$  in mass matrix

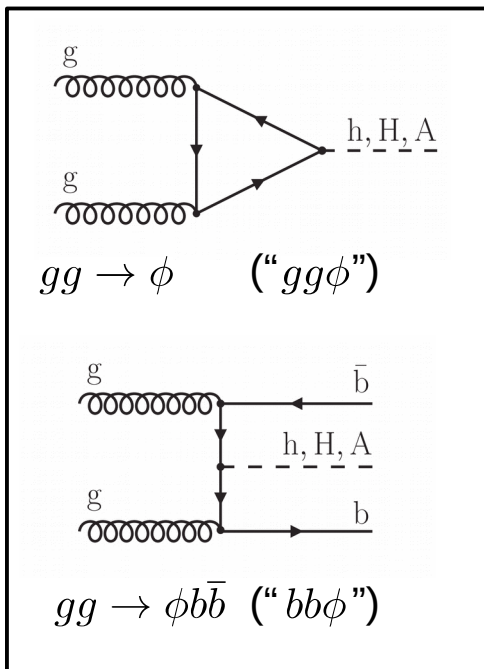
# Down-type fermions in the MSSM

NB: w/o CP-violation in the SUSY Higgs sector.

	$g_{VV}$	$g_{uu}$	CP-odd part of coupling.	$g_{dd}$	
$A$	—	$\gamma_5 \cot \beta$		$\gamma_5 \tan \beta$	← Relative to corresponding couplings to a SM Higgs boson.
$H$	$\cos(\beta - \alpha) \rightarrow 0$	$\sin \alpha / \sin \beta \rightarrow \cot \beta$		$\cos \alpha / \cos \beta \rightarrow \tan \beta$	
$h$	$\sin(\beta - \alpha) \rightarrow 1$	$\cos \alpha / \sin \beta \rightarrow 1$		$-\sin \alpha / \cos \beta \rightarrow 1$	

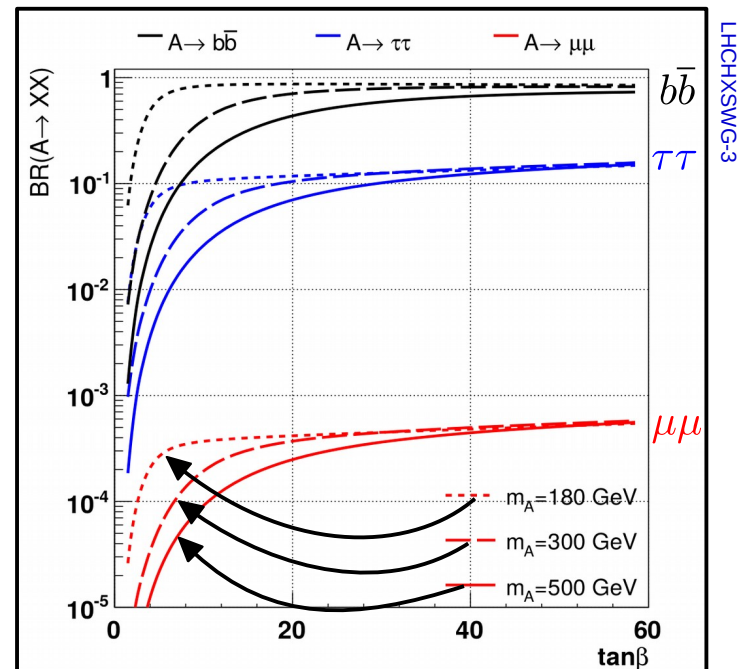
For  $m_A \gg m_Z$ :  $\alpha \rightarrow \beta - \pi/2$  (coupling  $A/H$  to down-type fermions enhanced by  $\tan \beta$ ).

## Production modes:



**X**

## Decay channels: $m_h^{\text{mod+}}$



# Additional event information/categorization

- Exploiting high mass of di- $\tau$  final state (via  $m_T$ ) and increased coupling to b quarks (via b-tag).
- Apart from this stay **more simplistic** with event categorization w.r.t SM analysis.

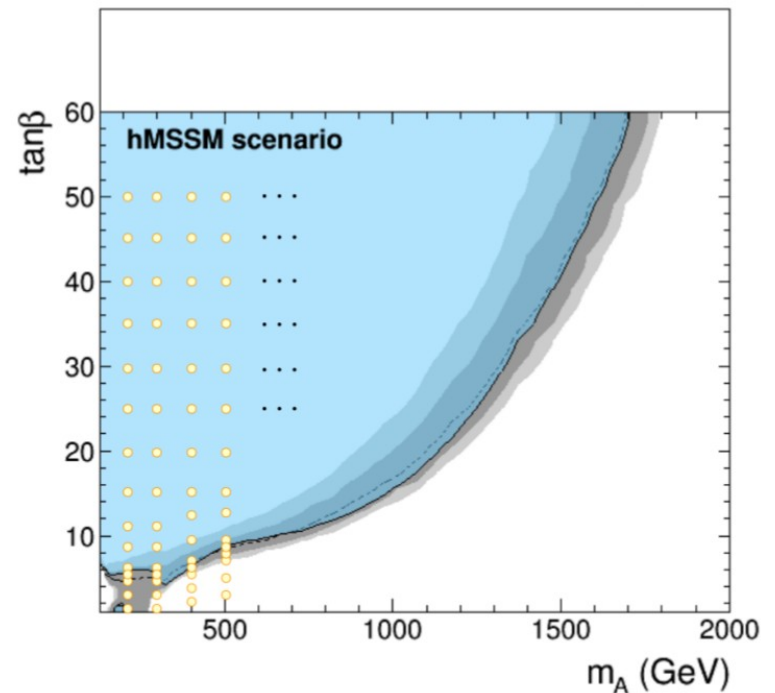
	No b-tag			b-tag		
$H \rightarrow \tau\tau \rightarrow e\mu$	Low- $D_\zeta$	Medium- $D_\zeta$	High- $D_\zeta$	Low- $D_\zeta$	Medium- $D_\zeta$	High- $D_\zeta$
$H \rightarrow \tau\tau \rightarrow e\tau_h$	Loose- $m_T$		Tight- $m_T$	Loose- $m_T$		Tight- $m_T$
$H \rightarrow \tau\tau \rightarrow \mu\tau_h$	Loose- $m_T$		Tight- $m_T$	Loose- $m_T$		Tight- $m_T$
$H \rightarrow \tau\tau \rightarrow \tau_h\tau_h$						
$Z \rightarrow \mu\mu$						
$t\bar{t}(e\mu)$						
				Signal region (SR)		
				Control region		

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Control regions used for in situ determination of normalization and partially shapes of backgrounds in ML fit used for statistical inference of the signal.

# Signal modeling

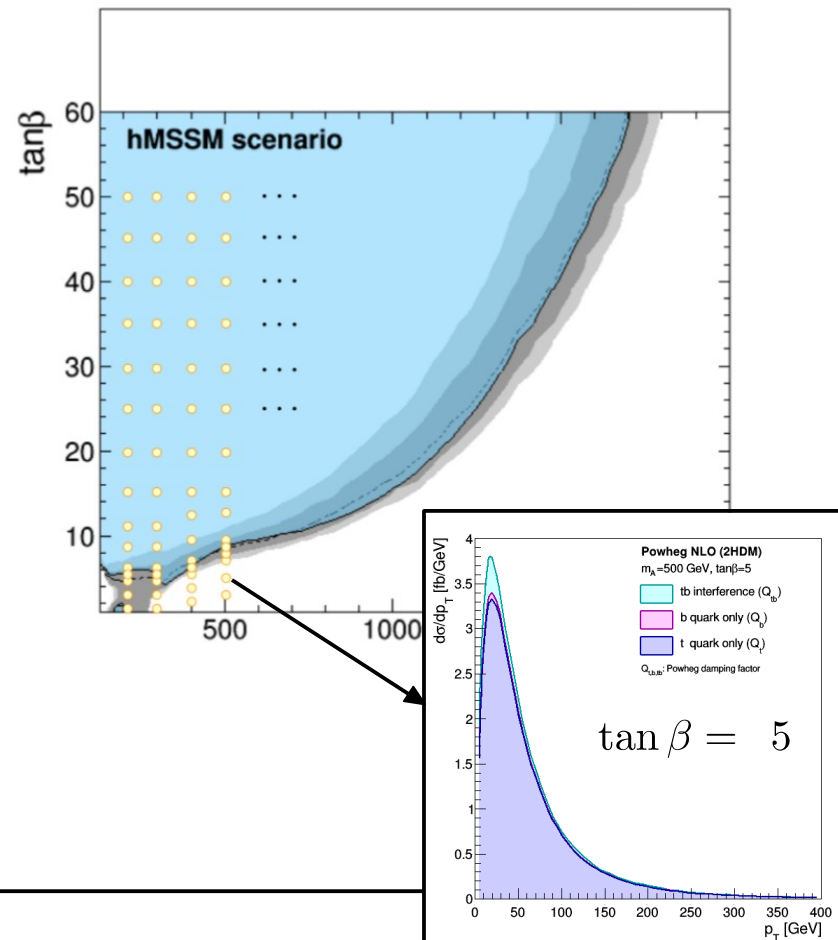
**Test MSSM vs SM hypothesis:** allows for well defined statistical problem, even when reaching sensitivity to the 125 GeV Higgs boson.



- Typical scan to determine exclusion contours in specific models.
- Determine CLs in each point in parameter space to obtain limit at significance level  $\alpha$ .

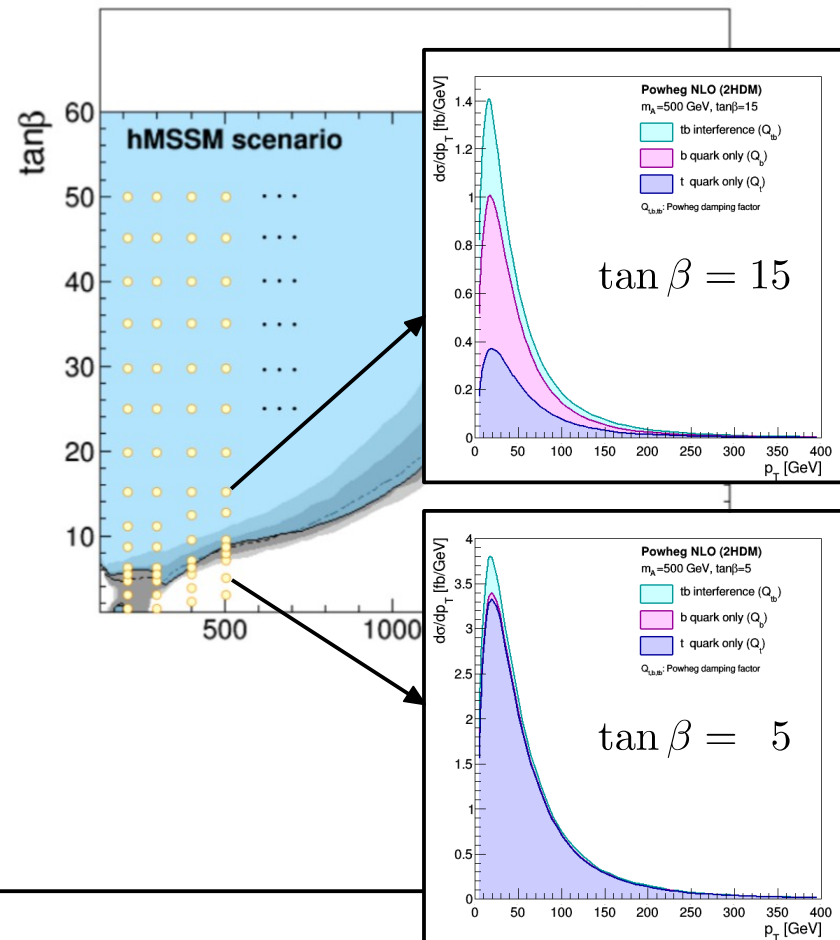
# Signal modeling

- $p_T(A, H, h)$  @ NLO QCD + PS  $\rightarrow$  **multiscale problem.**
- Plus: b contribution varies as a function of  $\tan\beta$ .



# Signal modeling

- $p_T(A, H, h)$  @ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of  $\tan\beta$ .

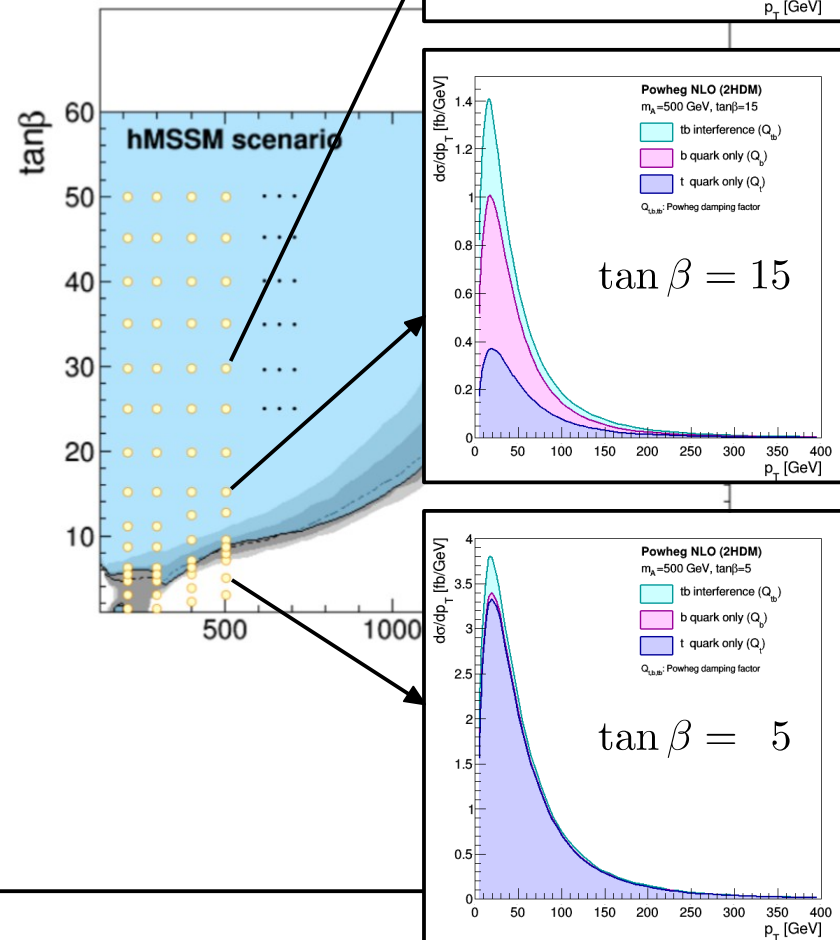




# Signal modeling

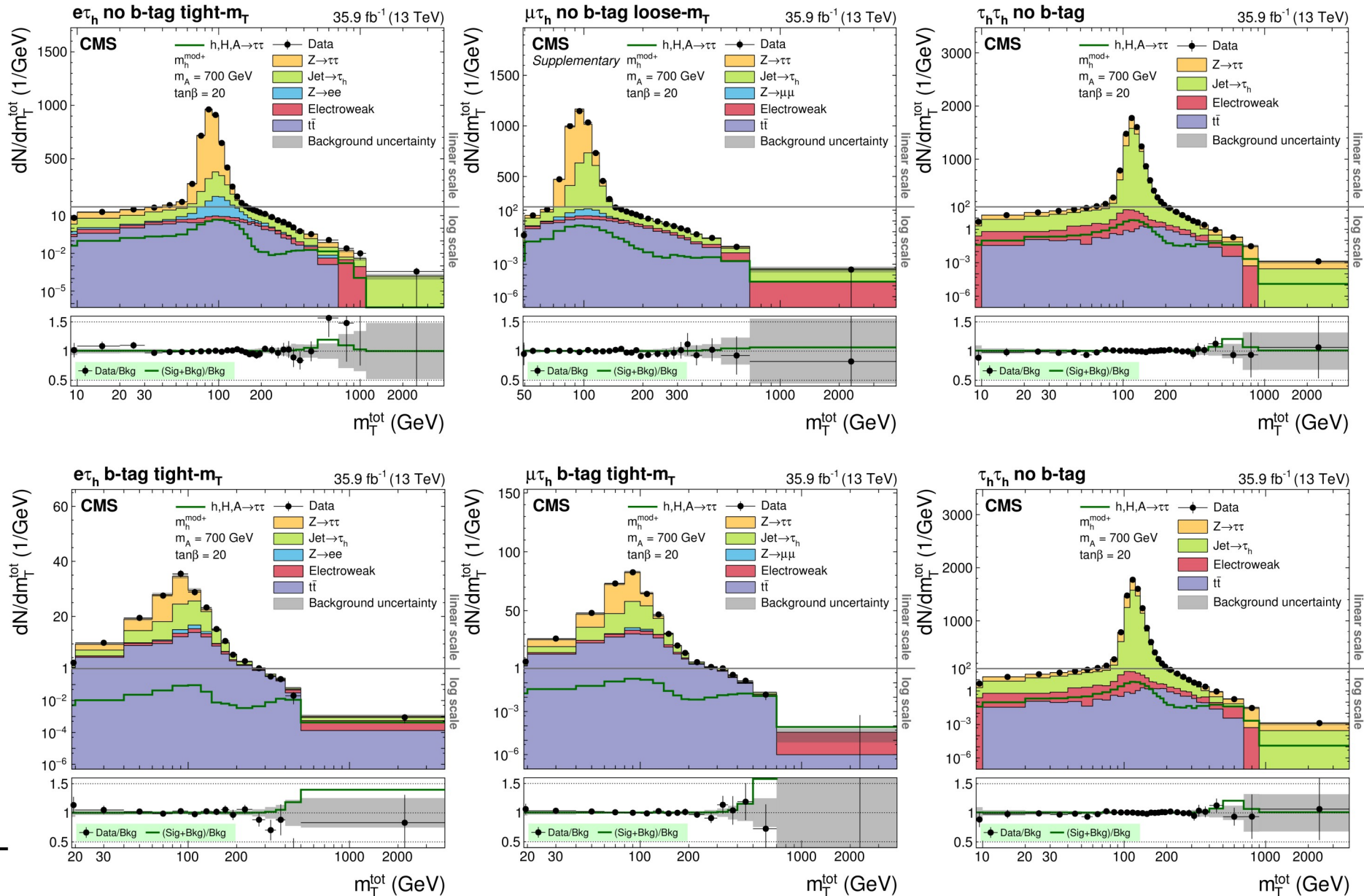
- $p_T(A, H, h)$  @ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of  $\tan\beta$ .

Change in  $p_T(A, H, h)$   
implies change in  
signal acceptance.



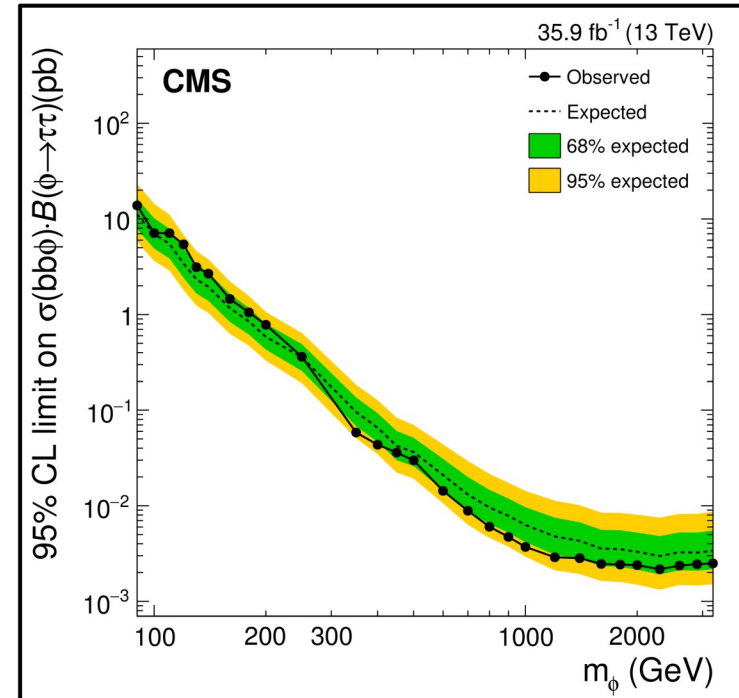
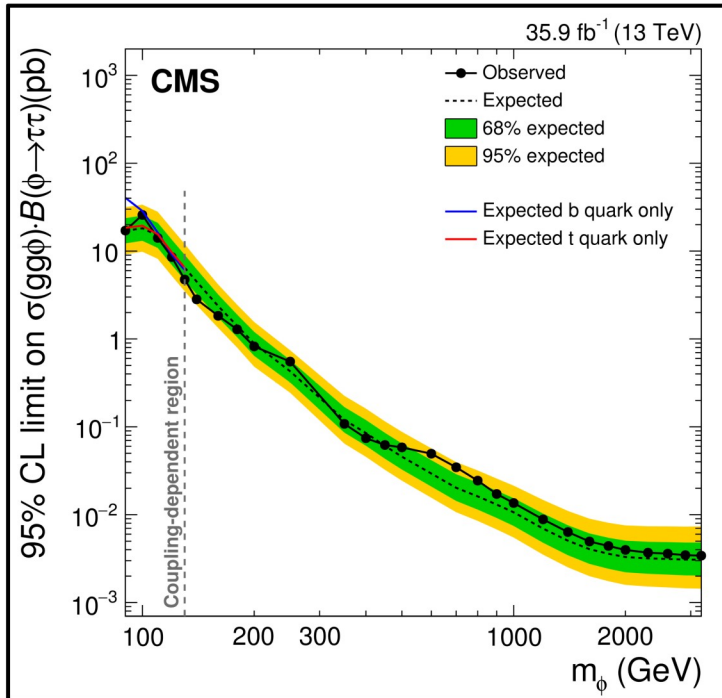


Shown are the most sensitive categories with an MSSM  $m_h^{\text{mod}+}$  hypothesis w/  $m_A = 700$  GeV and  $\tan\beta = 20$  fitted to the data.



# Model independent limits

- Narrow width approximation, two parameters of interest,  $\mu_{gg\phi}$  and  $\mu_{bb\phi}$ .

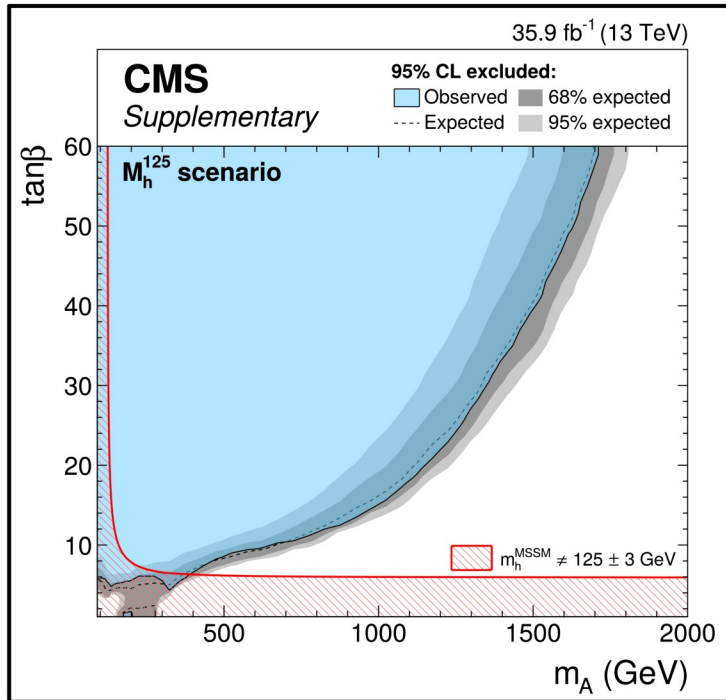


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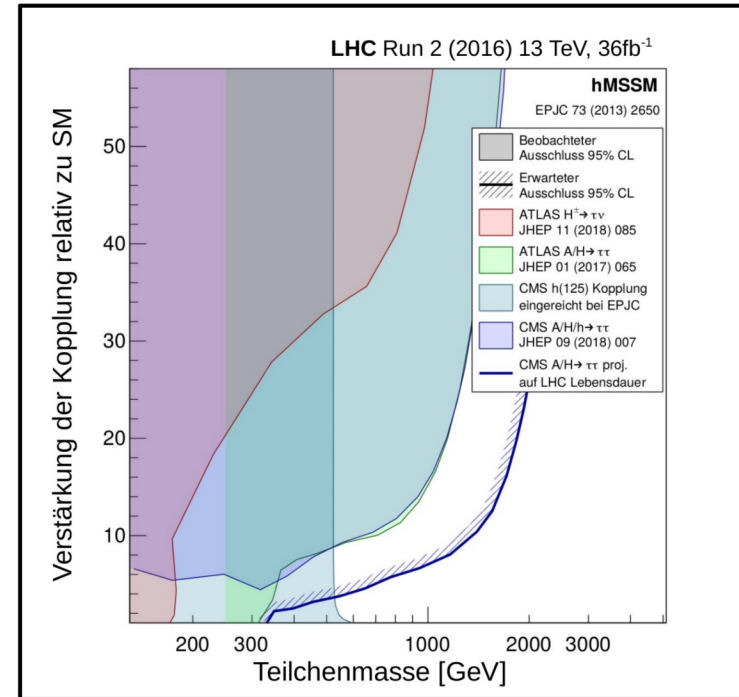
- No deviation beyond  $2\sigma$  found.
- Cross checks discussed e.g. in [ETP-KA/2017-21](#) and [ETP-KA/2017-31](#).

# Model dependent exclusion contours

- In predefined **benchmark models**:



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- In general parameter space is explored down to  $\tan\beta \gtrsim 6$  for  $m_A \lesssim 250 \text{ GeV}$  and up to  $m_A \leq 1600 \text{ GeV}$ .



# Summary

---

- $\text{Di-}\tau$  is one of the **most interesting final states** in the Higgs physics program of the LHC.
  - Best access to Higgs boson **couplings to fermions**.
  - **Large event yields**, reasonably well accessible (e.g. for studies of specific production modes, like VBF).
  - Most interesting final state to **search for extensions** of the SM Higgs sector.
- CMS had a very successful start in analyzing the LHC Run-2 data.
- KIT has a significant contribution to everything that has been shown.
- We are looking forward to analyze the full LHC Run-2 data.



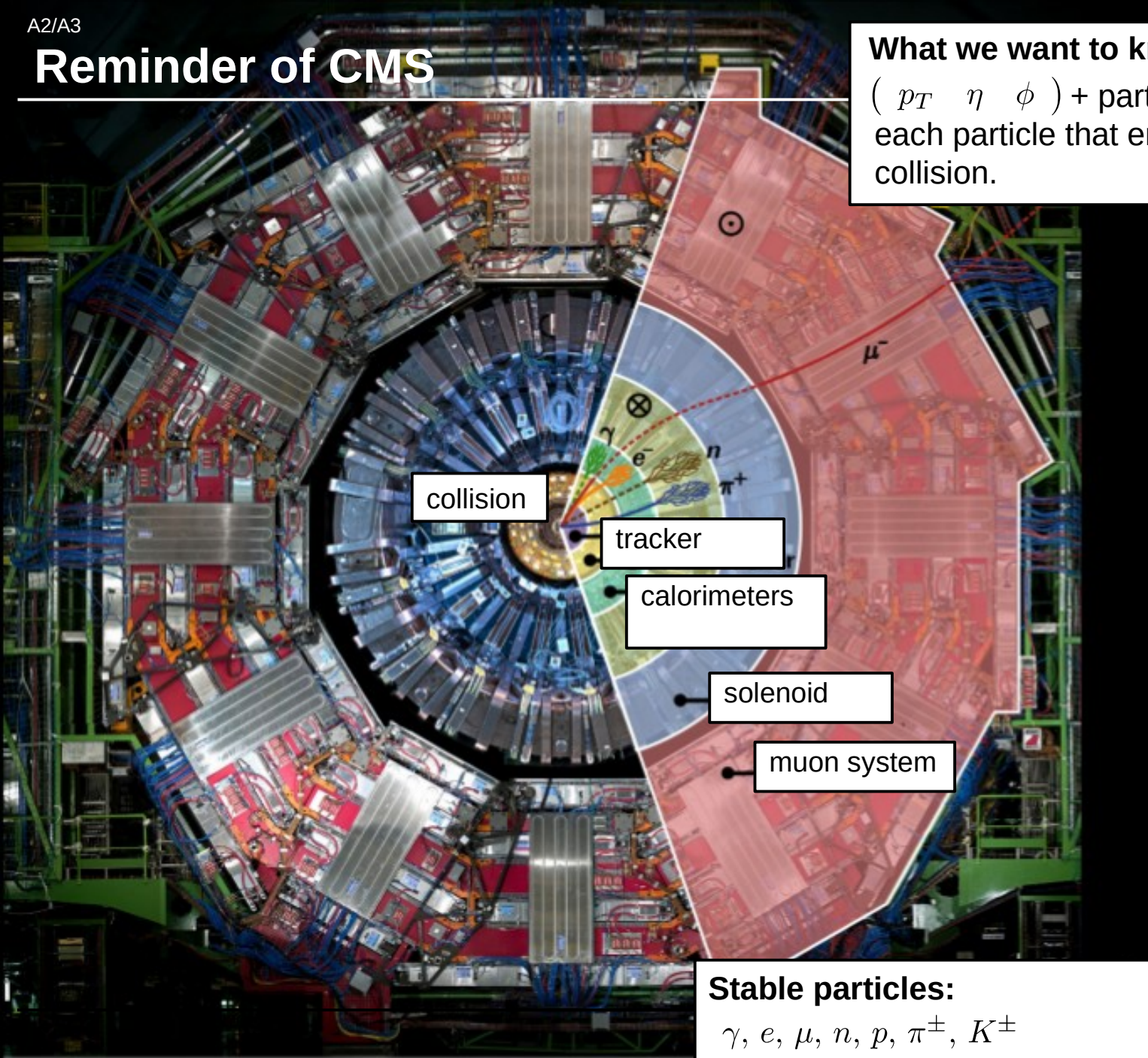
# Backup

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# Reminder of CMS

**What we want to know:**

$( p_T \quad \eta \quad \phi ) +$  particle type (m) from each particle that emerges the collision.

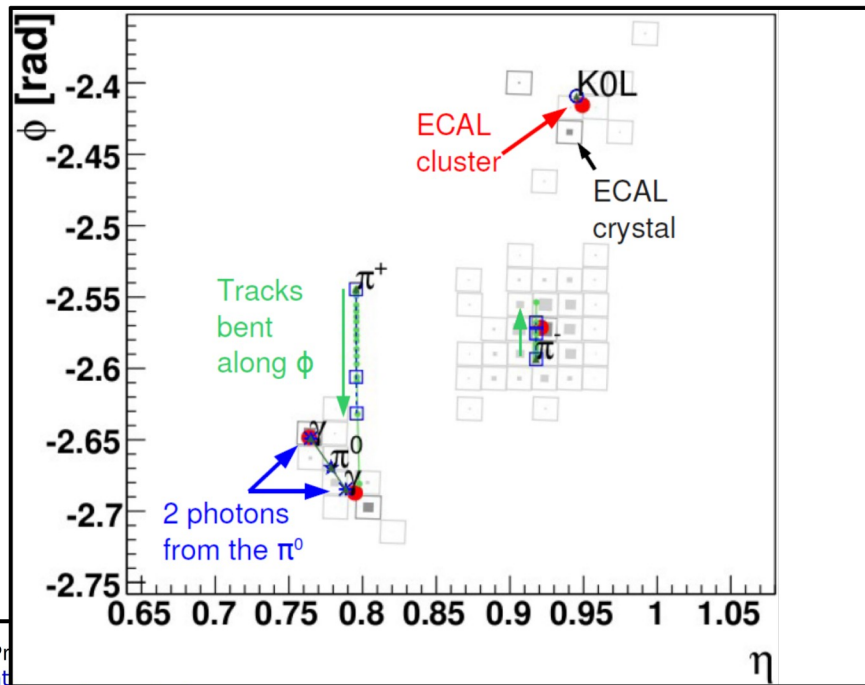
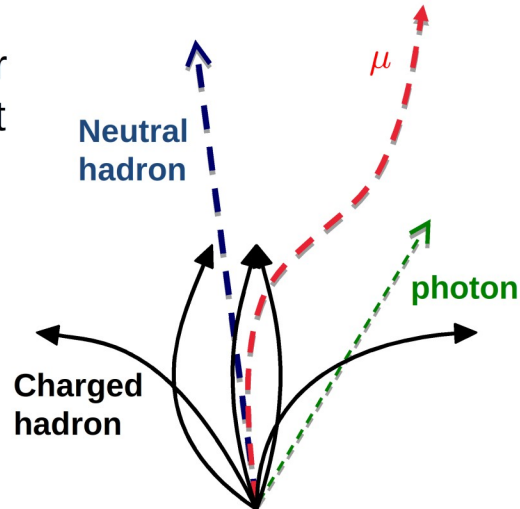


**Stable particles:**

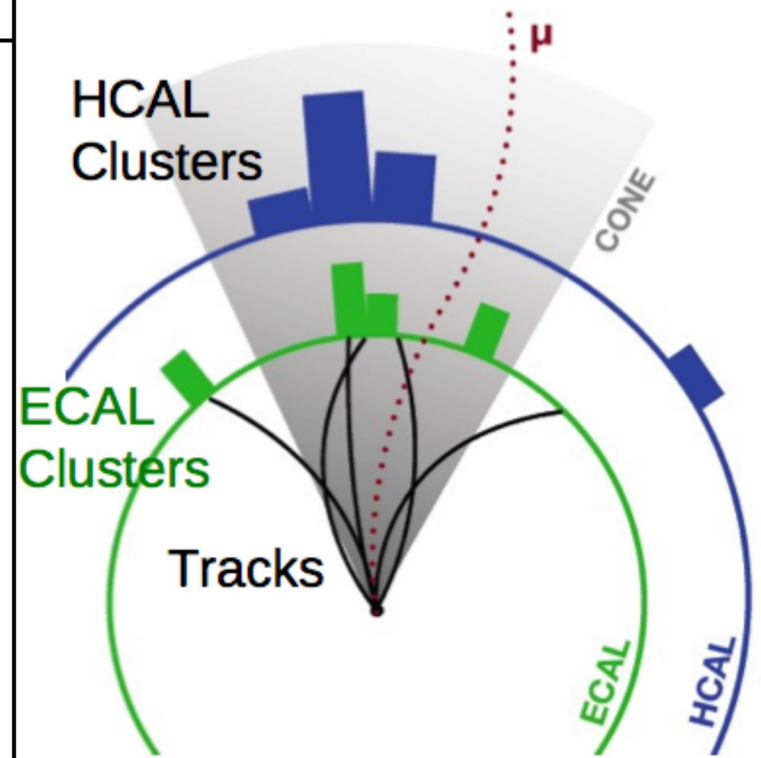
$\gamma, e, \mu, n, p, \pi^\pm, K^\pm$

# Particle reconstruction @ CMS

- Combine all energy deposits in the detector to obtain a unique event description.



## Particle Flow:

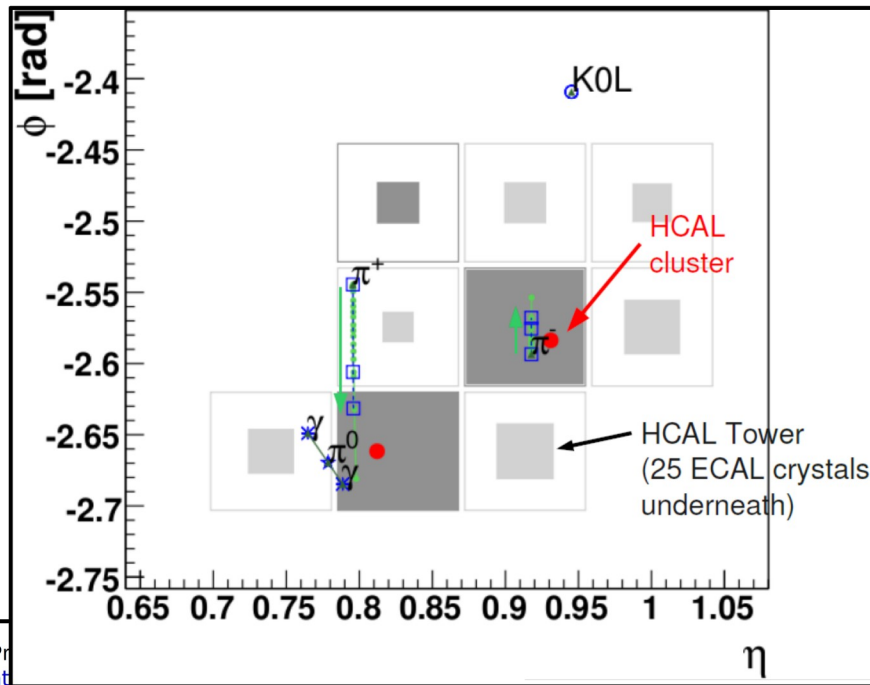
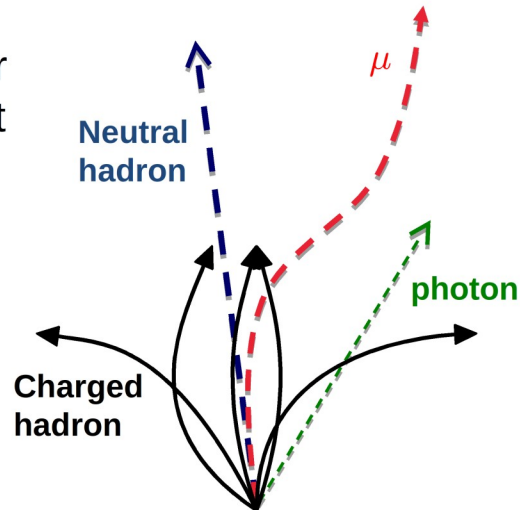


- Unambiguous list of stable particles: muons, electrons, photons, charged & neutral hadrons.

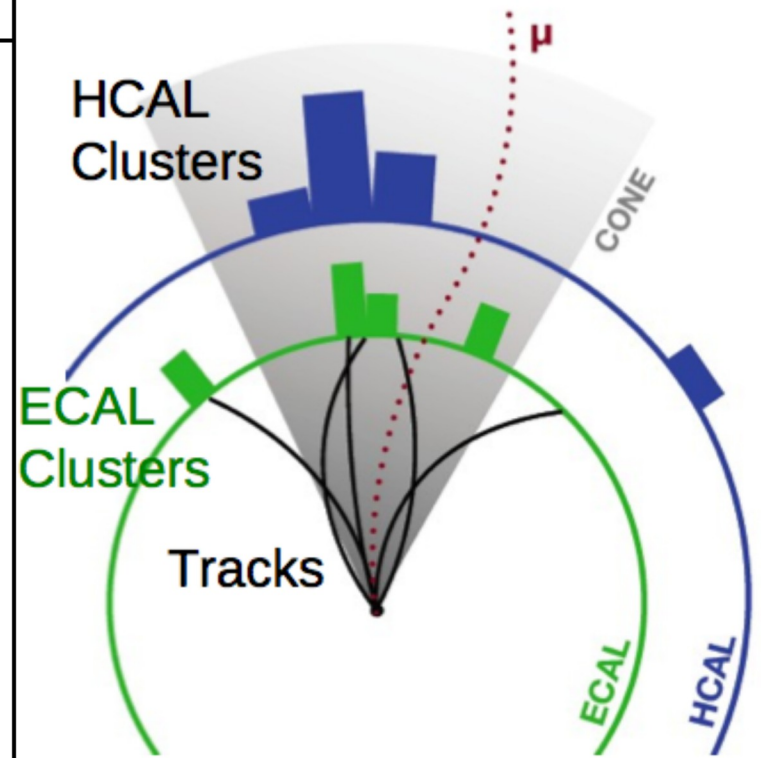


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