VH(bb) and the search for boosted ggH(bb) in CMS

Martin Kwok (Brown University)

on behalf of CMS collaboration

QCD@LHC 2019, Buffalo NY
18 July, 2019

PhysRevLett.121.121801 Phys. Rev. Lett. 120.071802

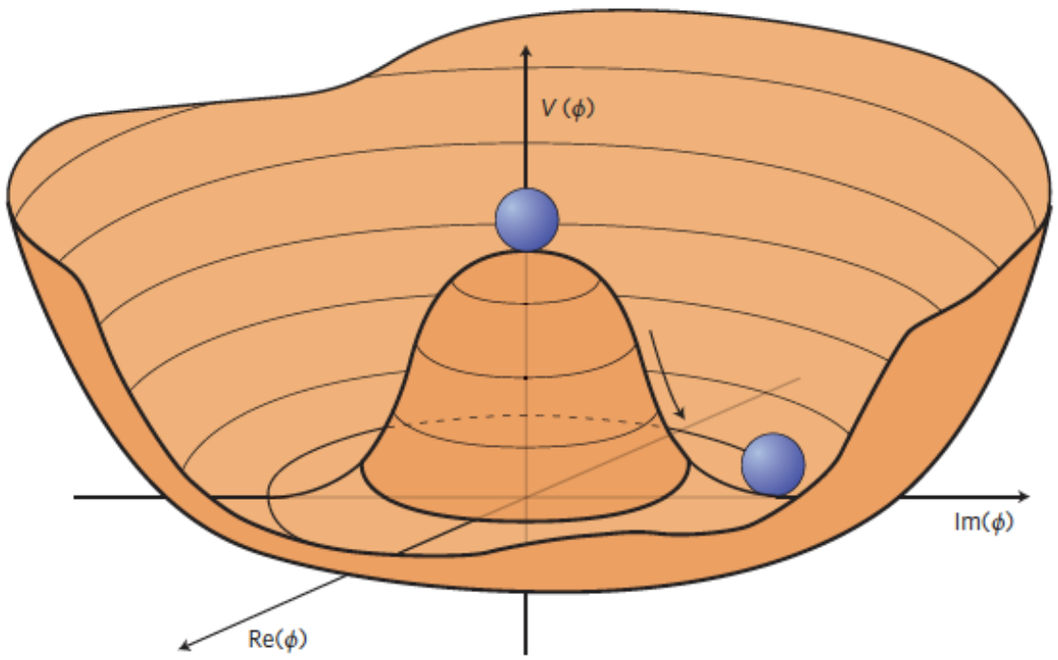
Why Higgs to bb?

- Higgs gives mass to elementary particles via two different mechanisms
- Higgs to bb is a **direct** test of mass generation to the charged fermion sector.

EWSB

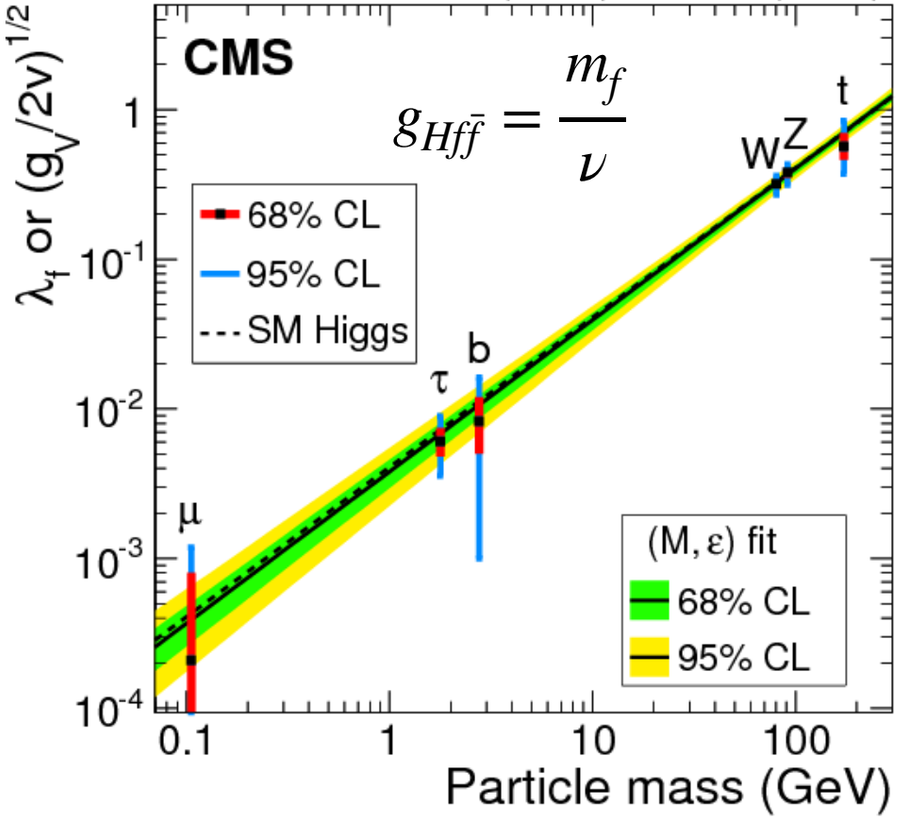
$$\mathscr{L}_{Higgs} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$



Yukawa coupling

$$\mathscr{L}_{Yukawa} = -\hat{h}_{d_{ij}} \bar{q}_{L_i} \Phi d_{R_j} - \hat{h}_{u_{ij}} \bar{q}_{L_i} \Phi u_{R_j} - \hat{h}_{l_{ij}} \bar{l}_{L_i} \Phi e_{R_j}$$

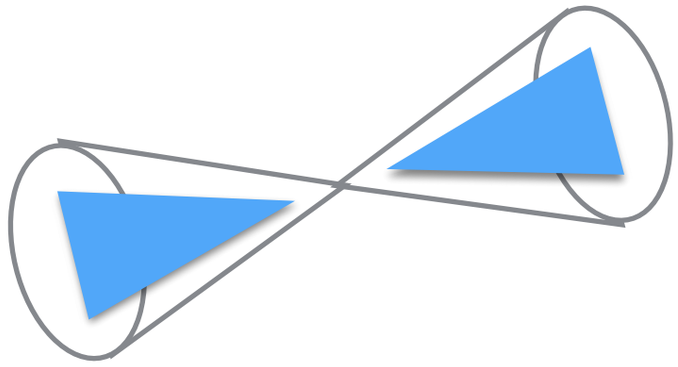


Eur. Phys. J. C 75 (2015) 212

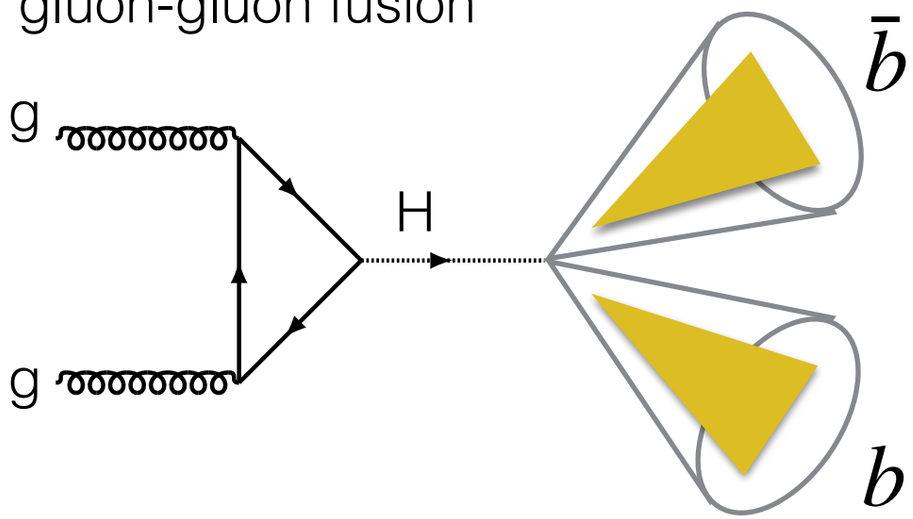
Experimental challenges

Overwhelming background at LHC: QCD dijet events

QCD dijet ~O(mb)

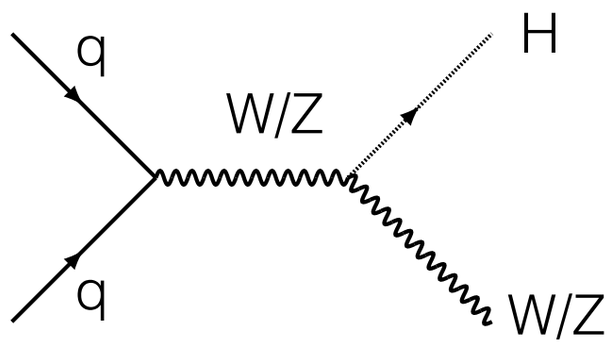


gluon-gluon fusion



~48 pb

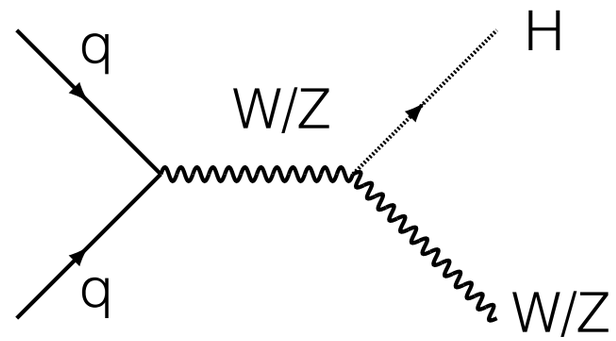
VH production



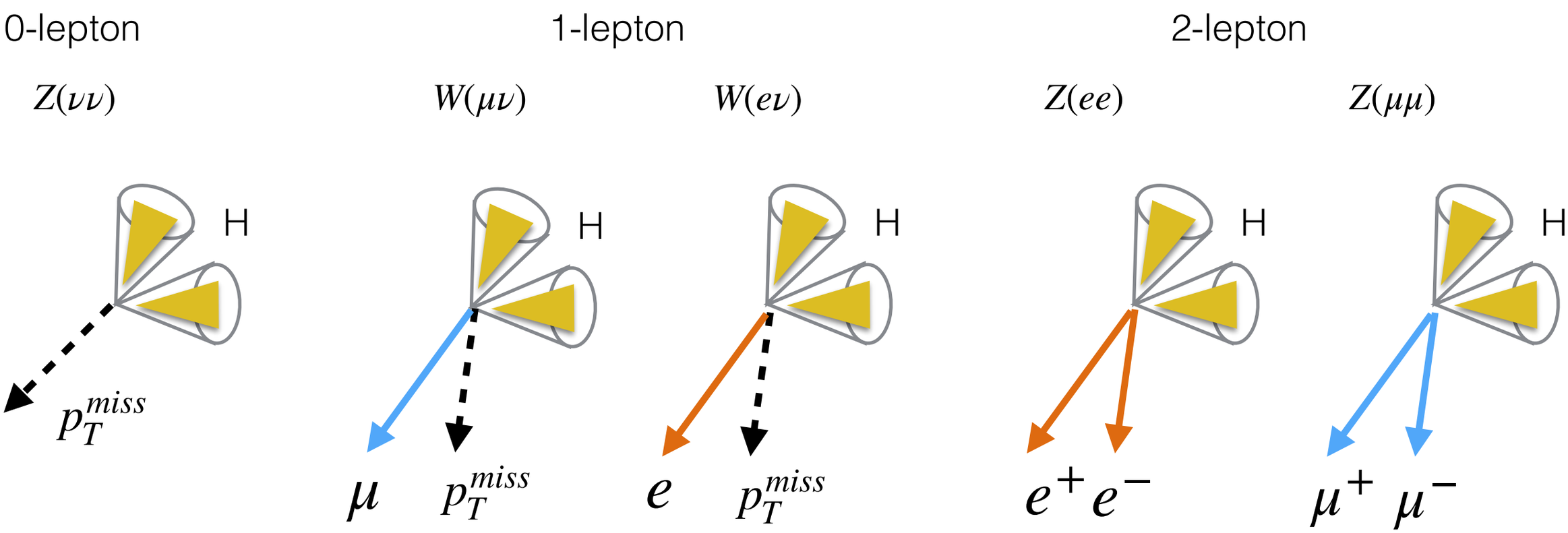
~2.2 pb

CERN Yellow Report 4

Analysis strategy



- At the cost of lower cross section,
  an associated vector boson gives many handles to reject backgrounds.
- 5 different final states depending decay modes
- To maximise the sensitivity,
  machine learning techniques helped from various aspects.



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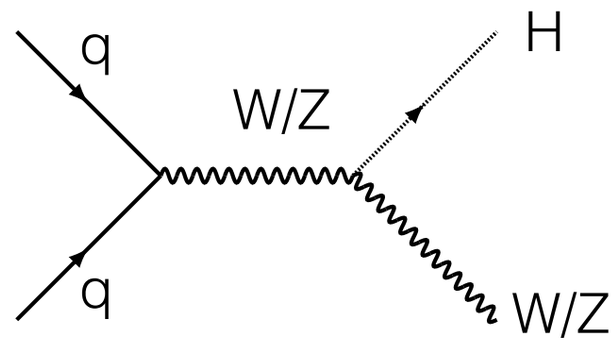
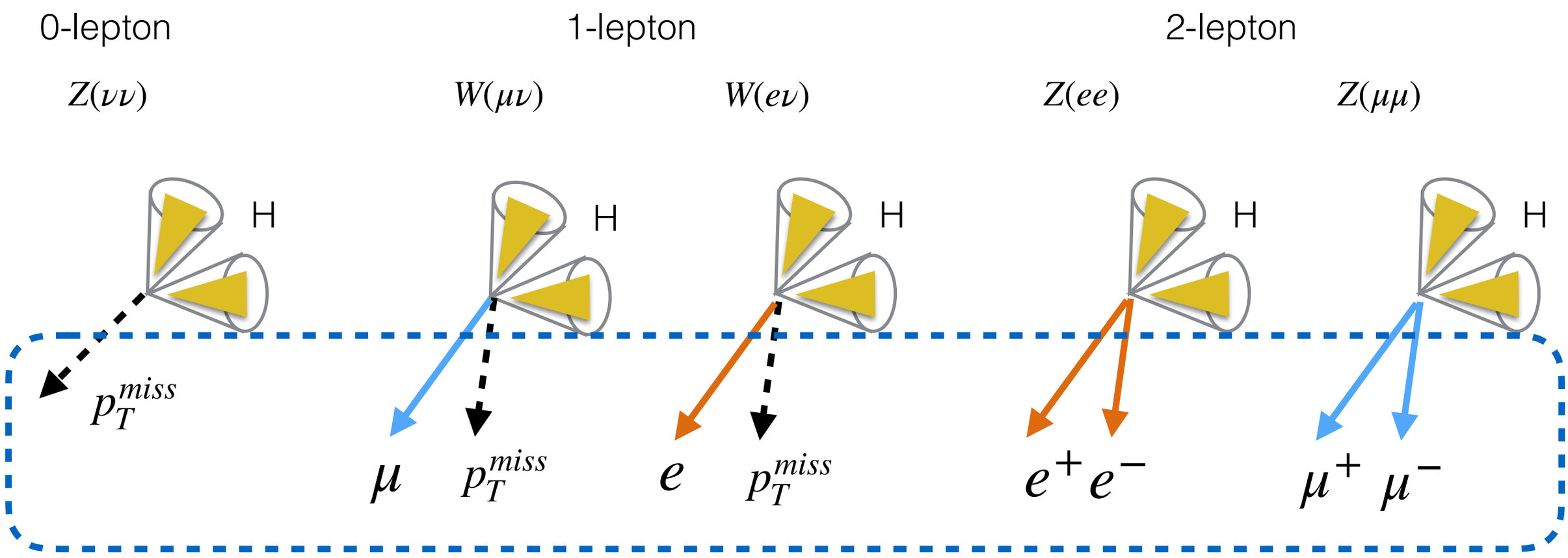


W/Z selection Background rejection, Triggering

Higgs candidate reconstruction

Signal extraction with full event information



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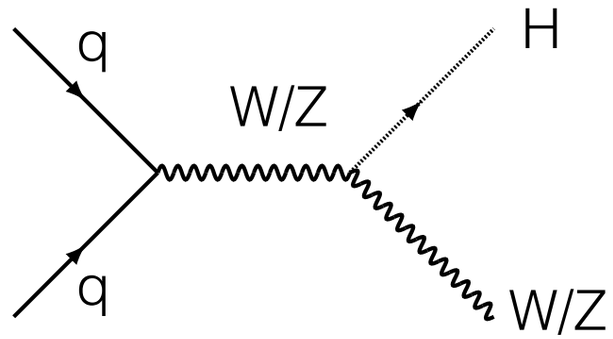

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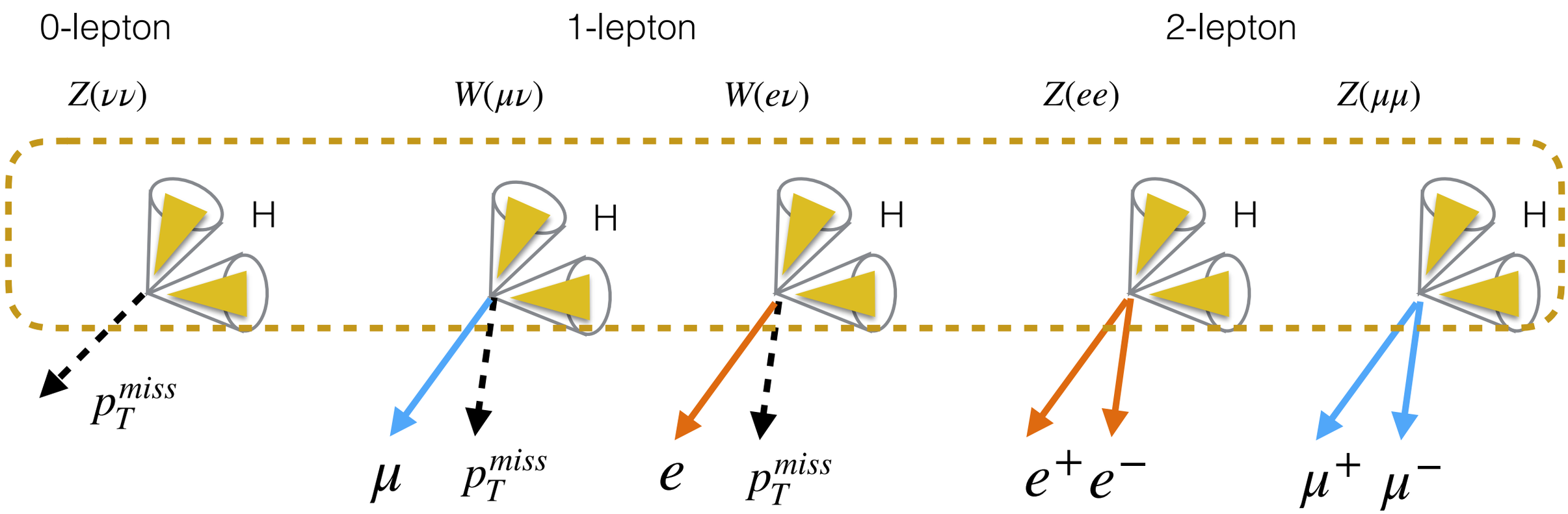

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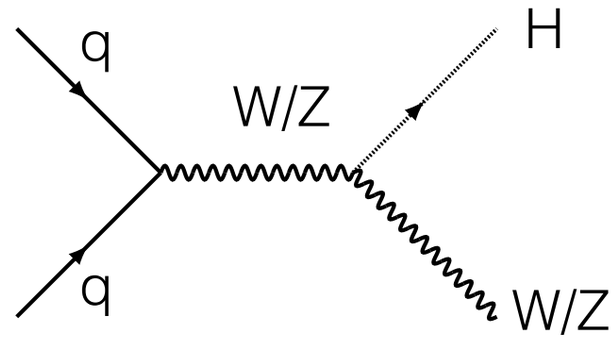

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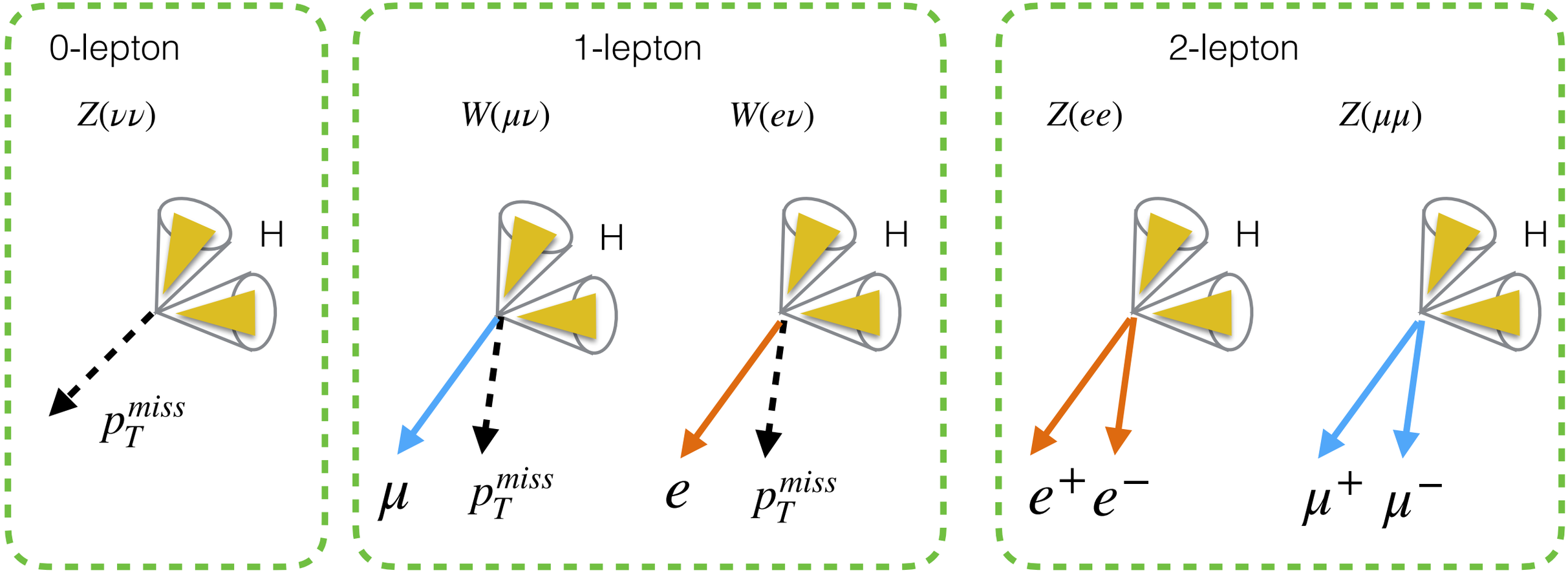
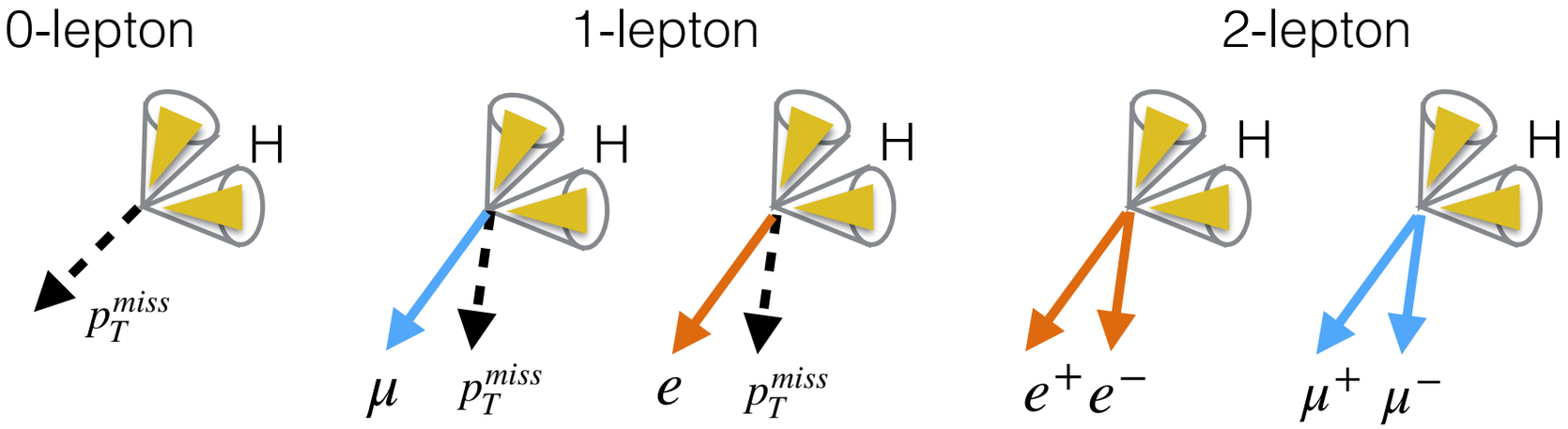


W/Z selection



- W/Z momentum can be reconstructed in the final states

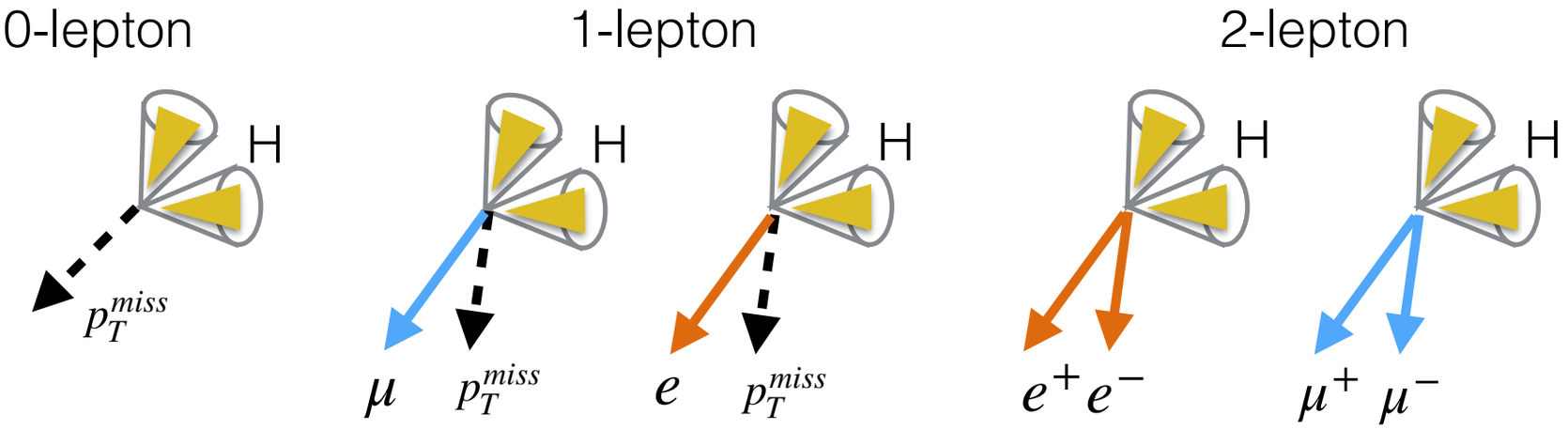
$$p_T(V) = p_T^{miss} \qquad p_T(V) = p_T^{miss} + p_T(l) \qquad p_T(V) = p_T(ll), m_{ll} \in [75-105] \text{ GeV}$$

- All backgrounds are substantially reduced by requiring large pT(V)

$$p_T(V) > 170 \text{ GeV} \qquad p_T(V) > 150 \text{ GeV} \qquad p_T(V) \in (50,150] \cup (150,\infty) \text{ GeV}$$

- Remaining background are estimated with dedicated control regions (CR)

W/Z selection



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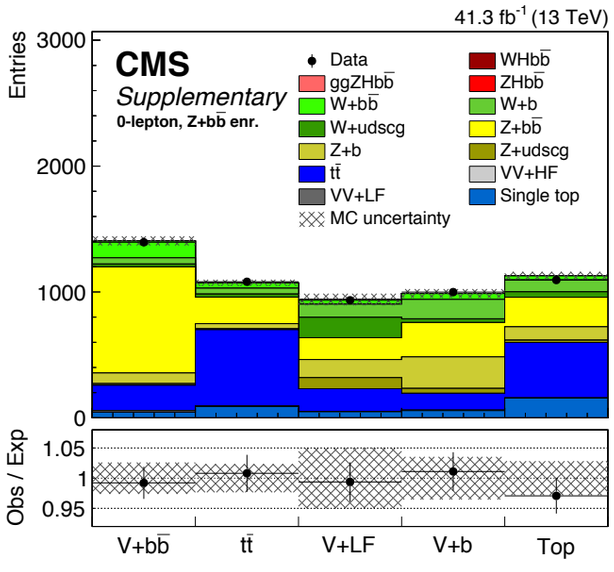
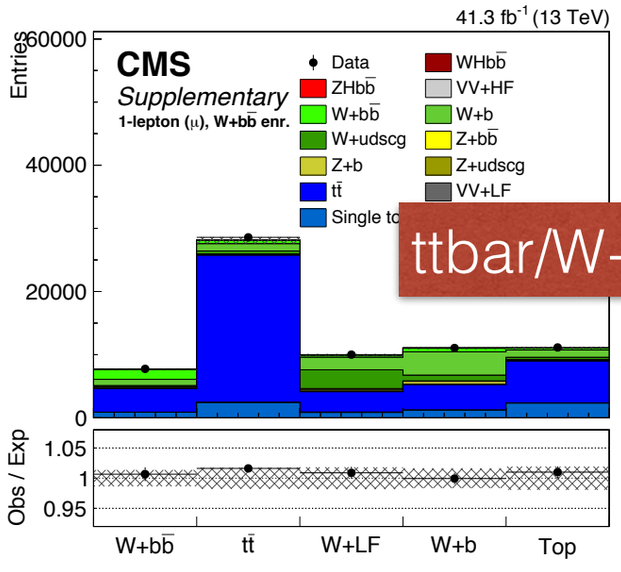
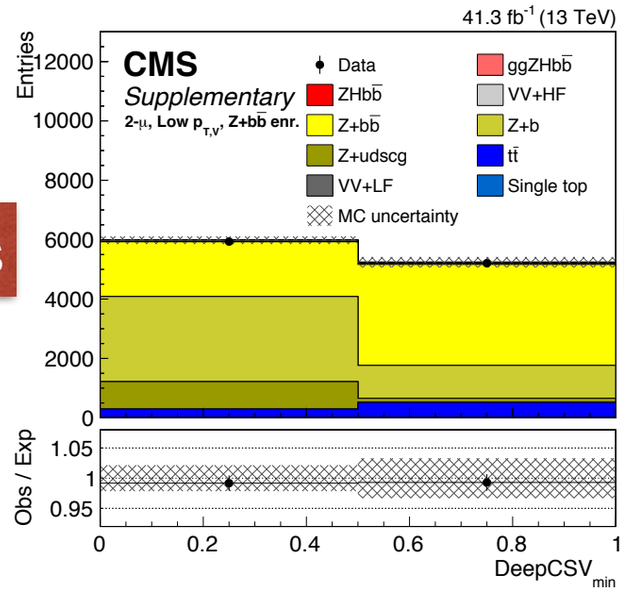




ttbar/W+jets



Z+Jets

Higgs reconstruction

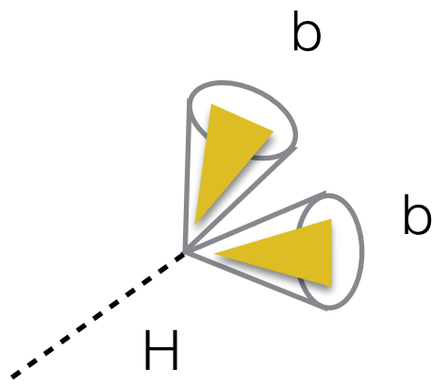
b-tagging

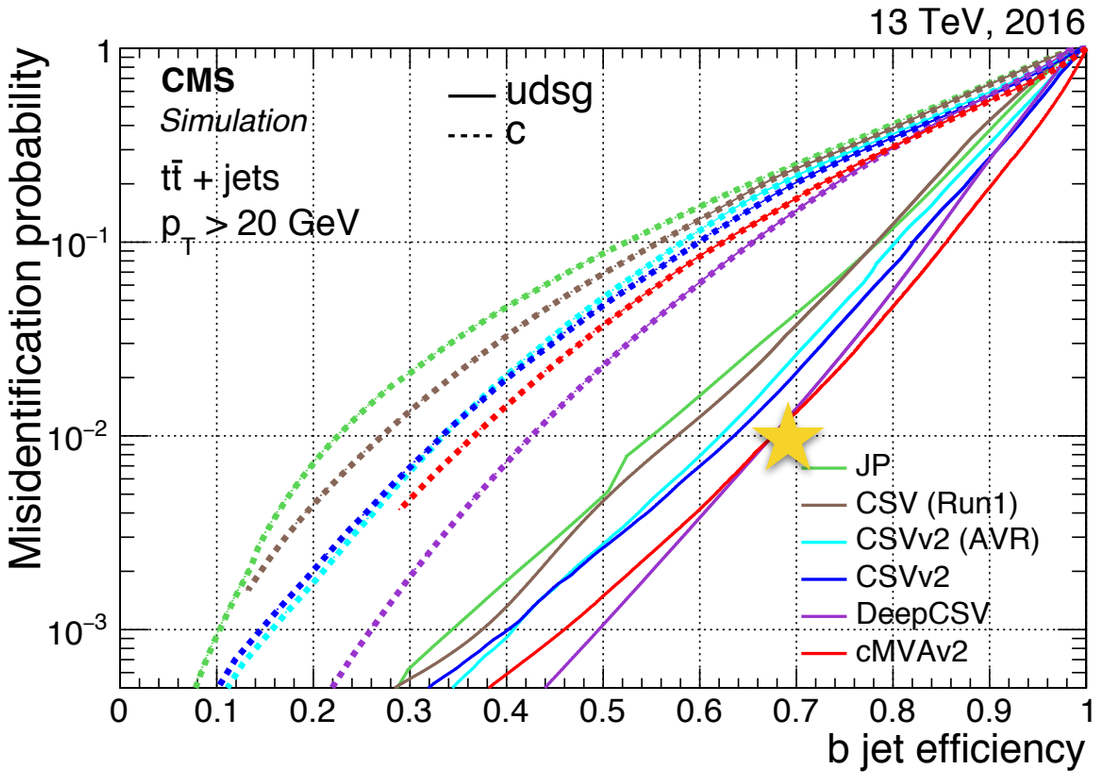
Higgs mass resolution

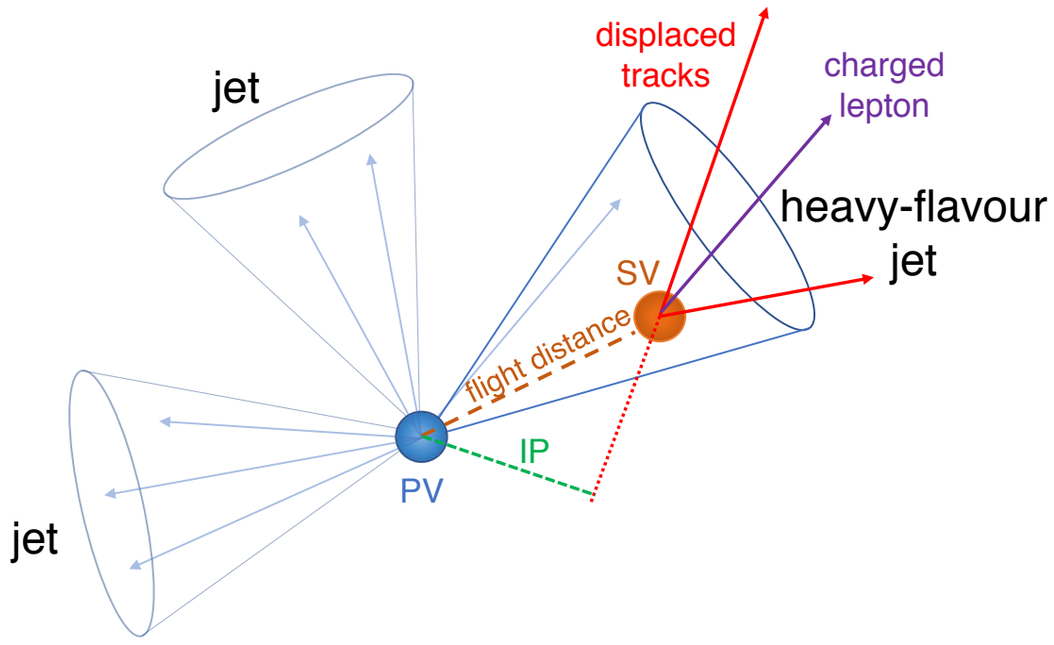
Improved b-tagging with DNN

arXiv:1712.07158v2

- Higgs candidate is reconstructed with the 2 jets with highest b-tagging score
- **10-20%** better performance w.r.t Run1 due to
  - Extra pixel layer installed for 2017 data-taking period
  - Improved machine learning architecture:
    Deep Neural Network(DNN)
  - More input variables: track variables up to 6 tracks

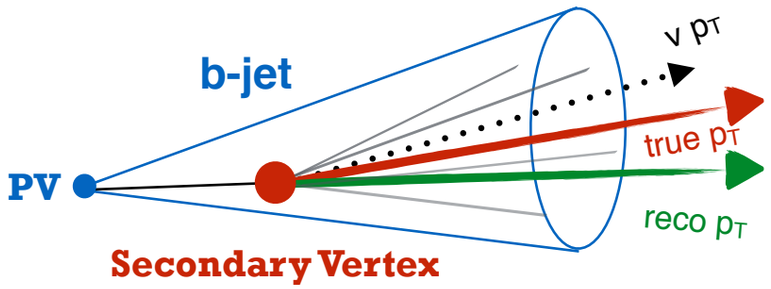






DNN based b-jet regression

- b-jets resolution is generally worse than light(quark/gluon) jets
- Dedicated DNN to correct for mis-measured energy due to escaping neutrino



Jet kinematics

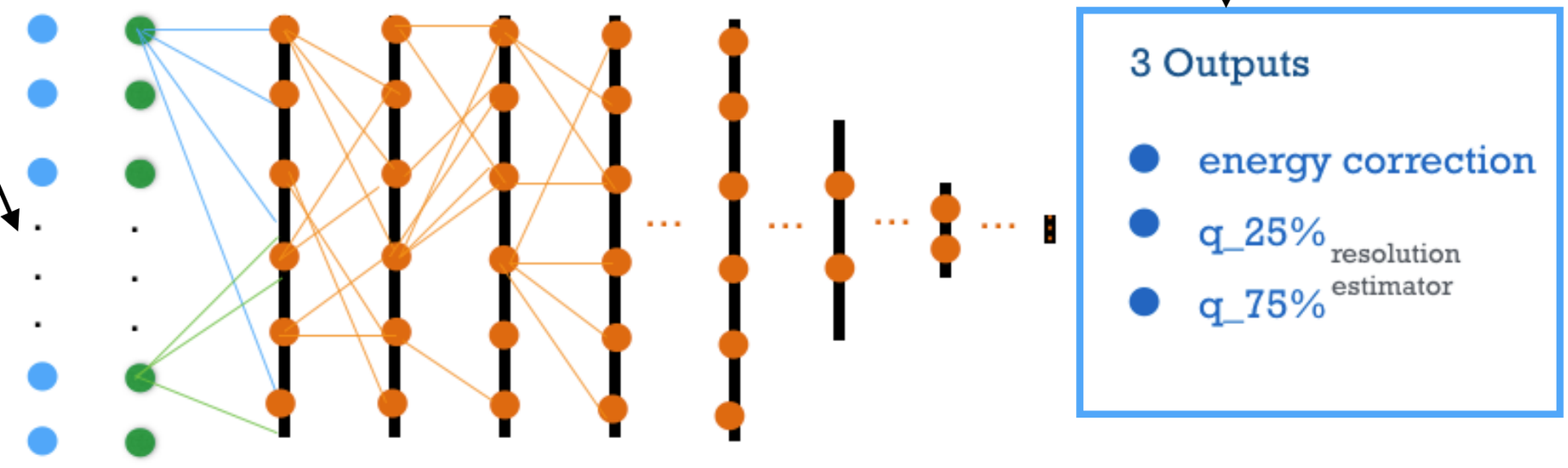
Jet energy fractions binned in radius

Jet constituent multiplicity

SV, Jet pT relative to soft-lepton

Per-jet resolution estimator

~double improvement on m_{jj}



DNN based b-jet regression

VHbb(supplymentary)

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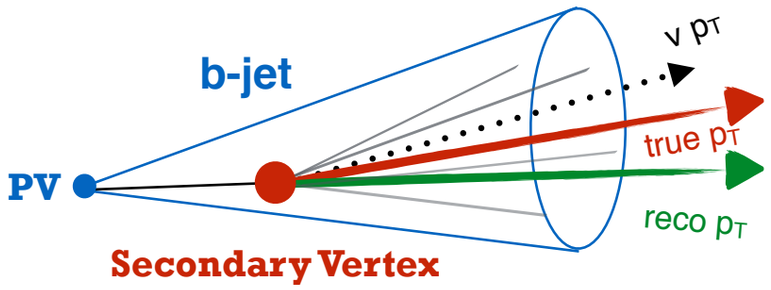
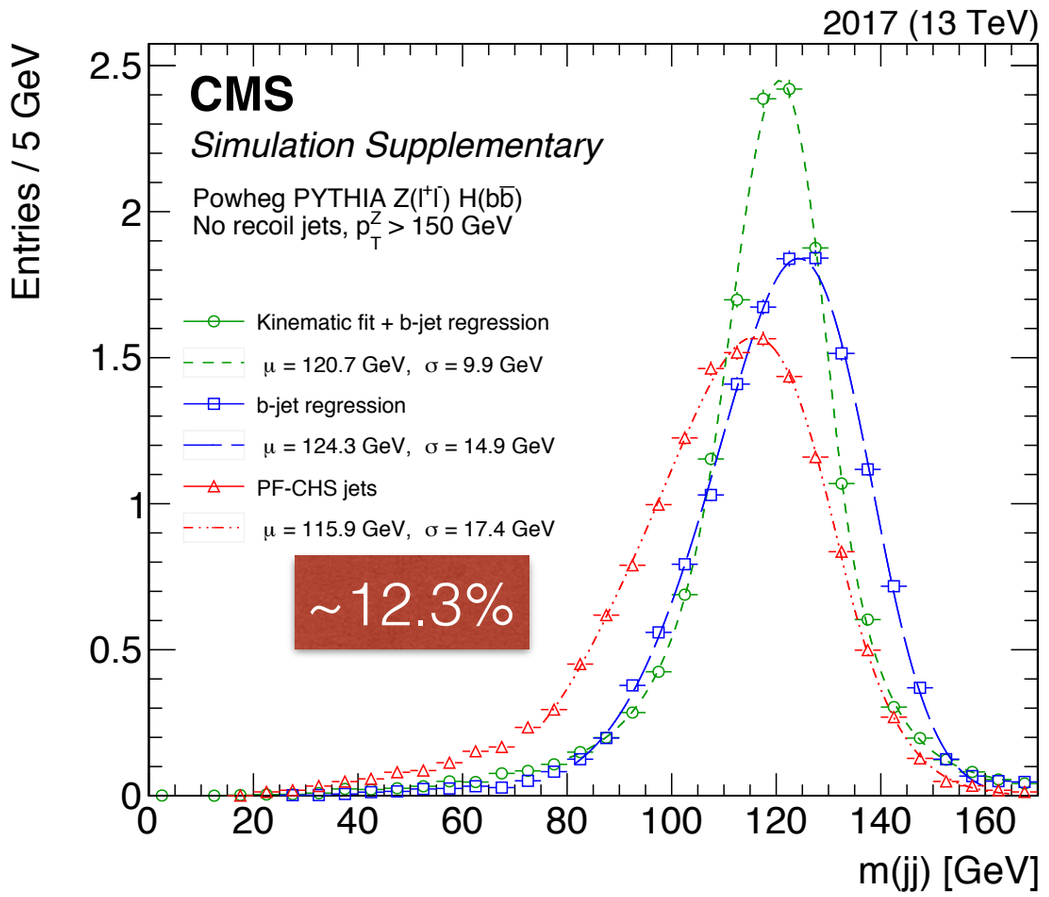


Significant improvement on jet mass resolution

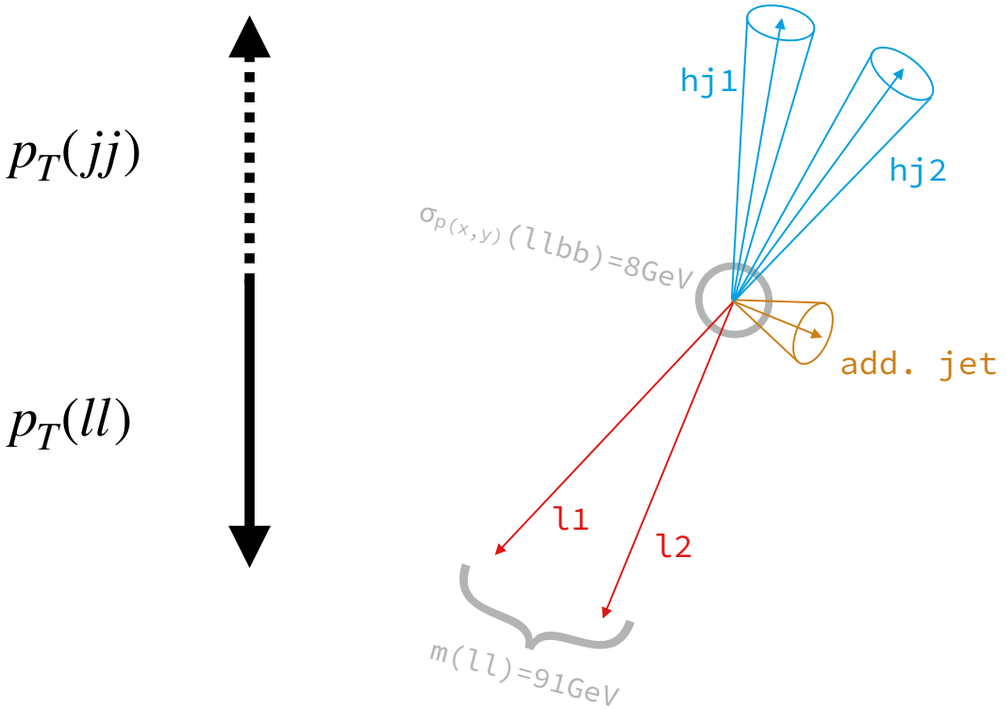
	Before regression	After regression
$\sigma/\mu(\%)$	~15%	~12%



Kinematic fit

VHbb(supplymentary)

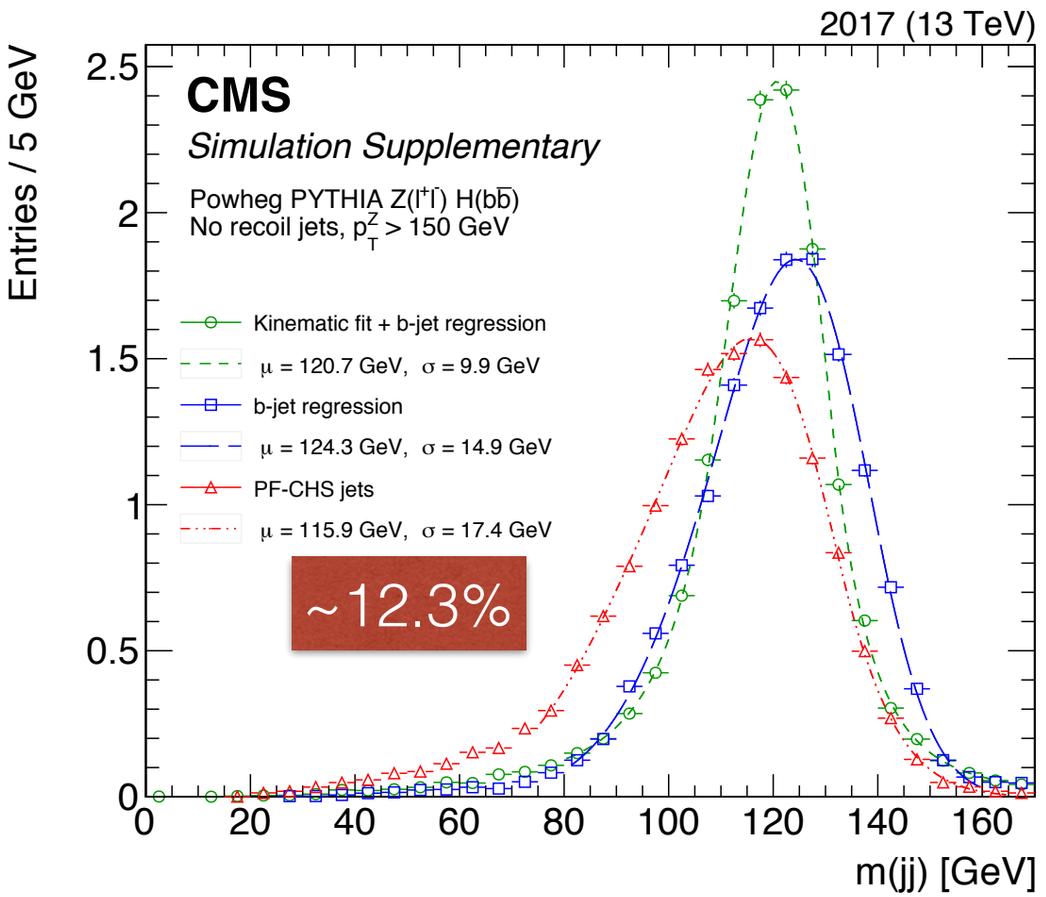
2-lepton channel: Further improve jet mass resolution with kinematic fit



- leptons have better momentum resolution than jets
- No intrinsic missing momentum
- Fit lepton and jet momentum within uncertainty

Significant improvement on jet mass resolution

	Before regressio	After regression	kin. fit
$\sigma/\mu(\%)$	~15%	~12%	~10%



Signal extraction with DNN

PhysRevLett.121.121801

- Invariant mass is the most intuitive variable
- Other variables may have some sensitivity as well:

$$p_T(V),\ \Delta R(j1,j2),\ N_j,\ \text{DeepCSV}$$

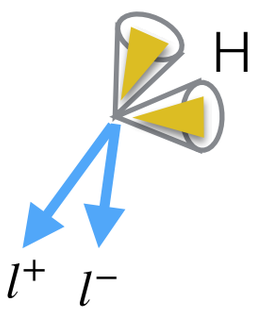
- Highly correlated => Maximise sensitivity with DNN

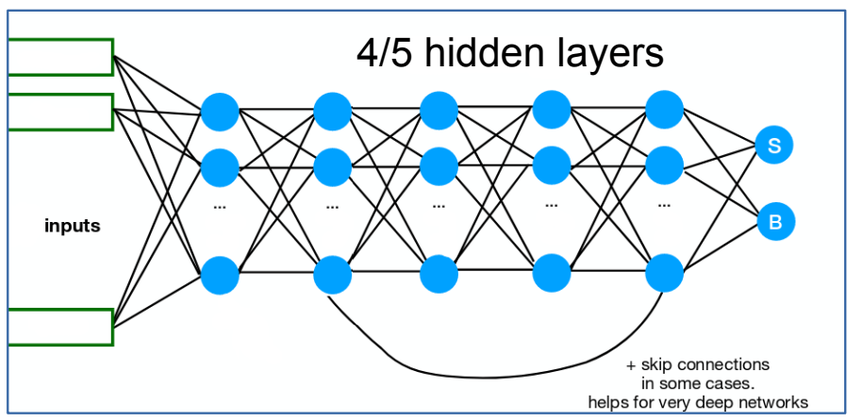
S.R.

0-lep: $m_{jj} \in [60,160]$ GeV

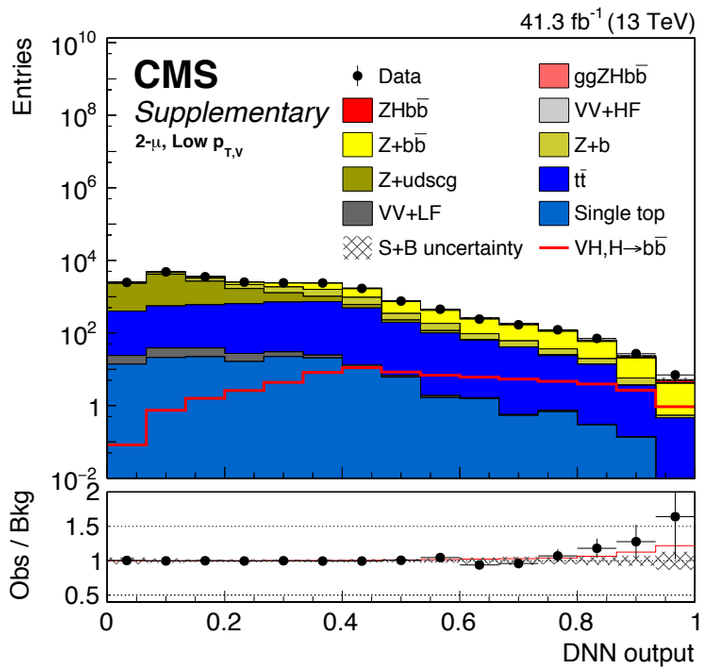
1,2-lep: $m_{jj} \in [90,150]$ GeV

2-leptons





DNN score



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- Other variables may have some sensitivity as well:

$$p_T(V), \Delta R(j1,j2), N_j, \text{DeepCSV}$$

- Highly correlated => Maximise sensitivity with DNN
- Separate DNNs in each channel.

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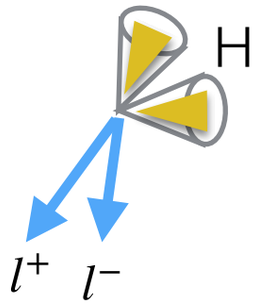
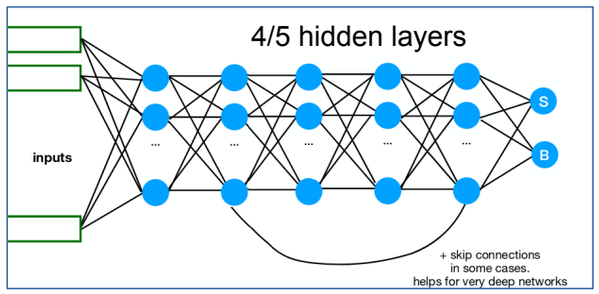
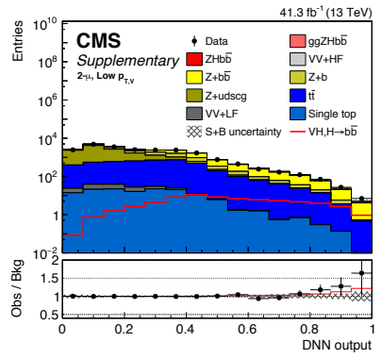
DNN score

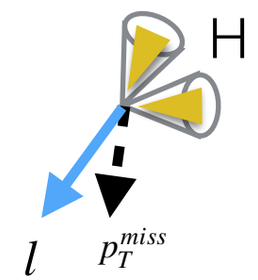
2-leptons

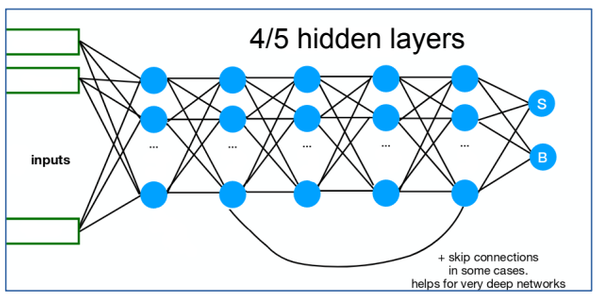


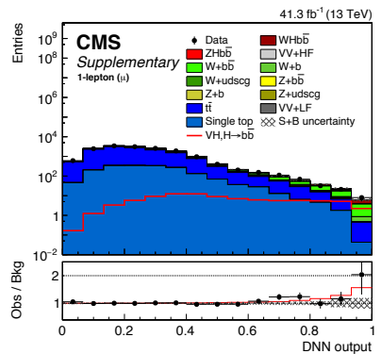




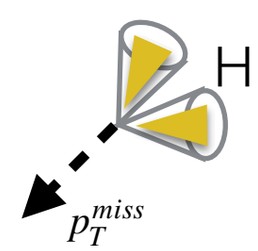
1-lepton

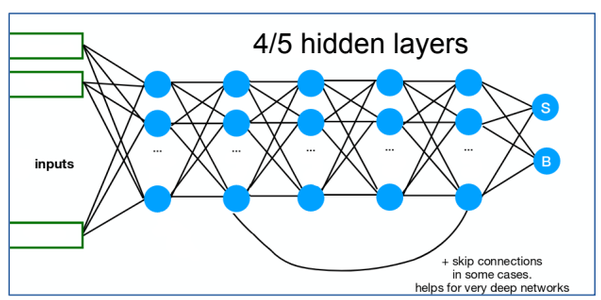


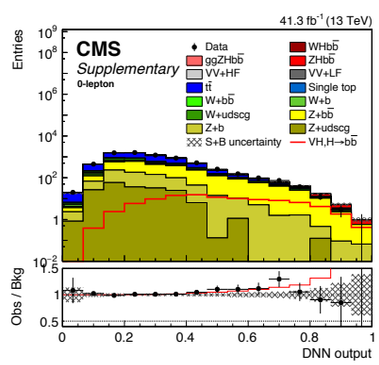




0-lepton



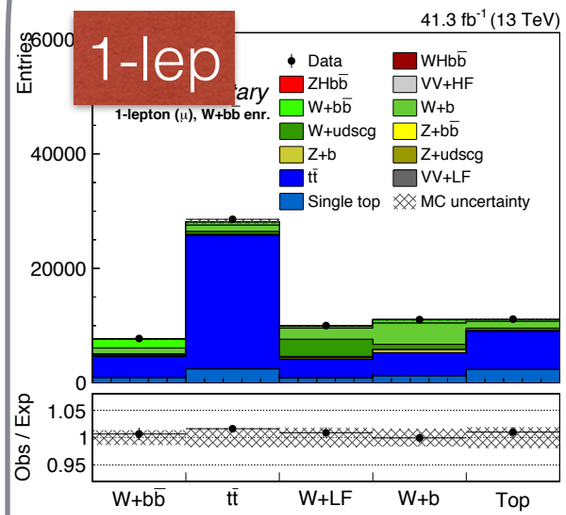


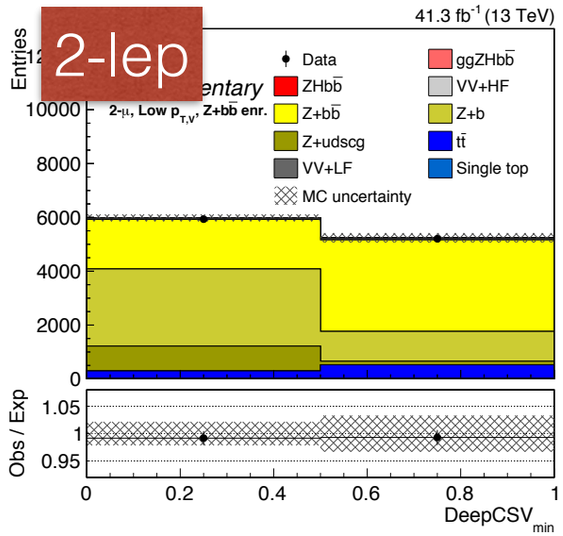


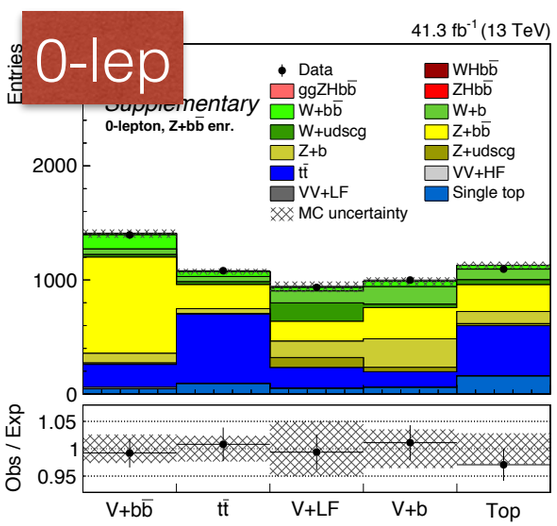
Signal extraction with DNN

- Fit simultaneously all control regions and signal regions.
- Allow normalisations of **$t\bar{t}$** , **W+b(b)**, **Z+b(b)** backgrounds to float independently in each channel.

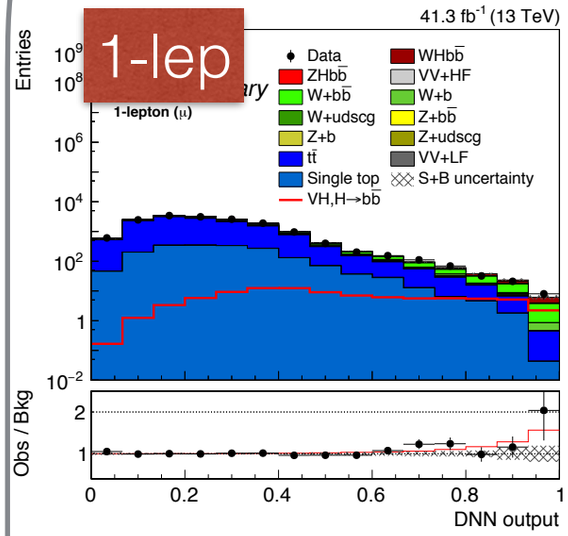
Control Regions

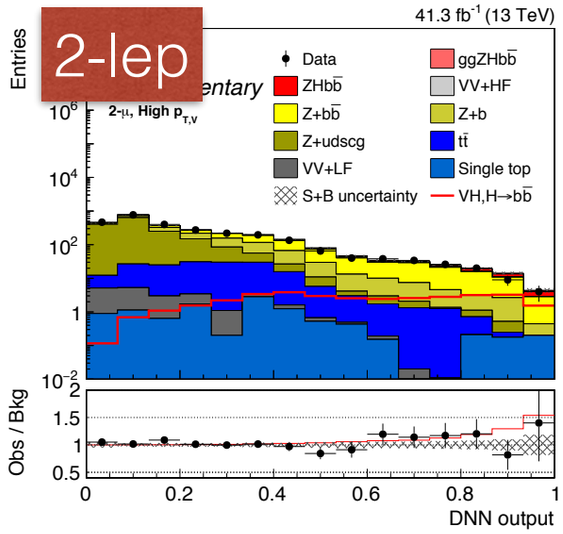


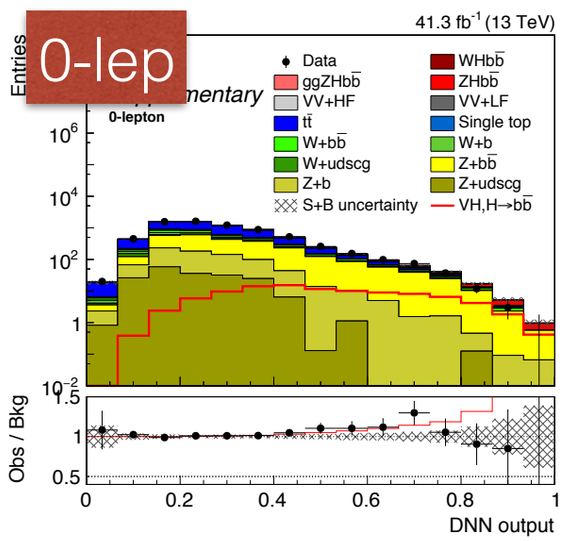




Signal Regions - DNN





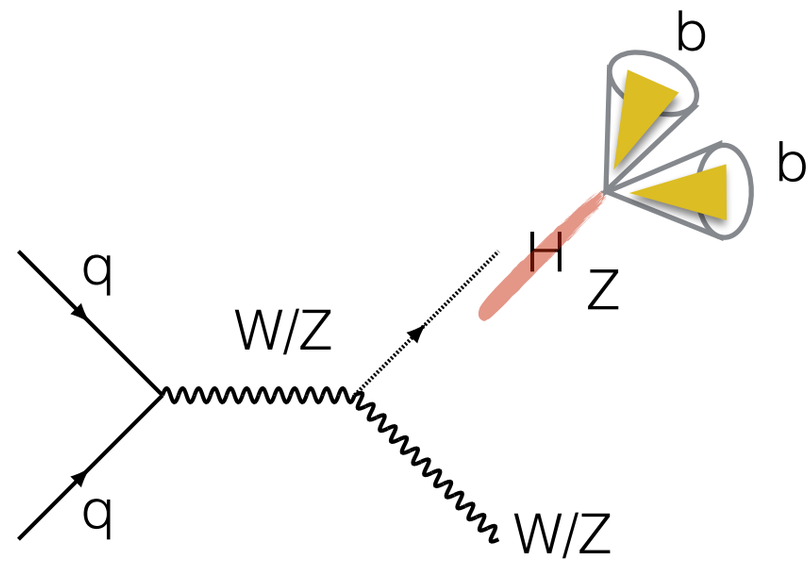


VZ(bb) Validation

VHbb(supplymentary)

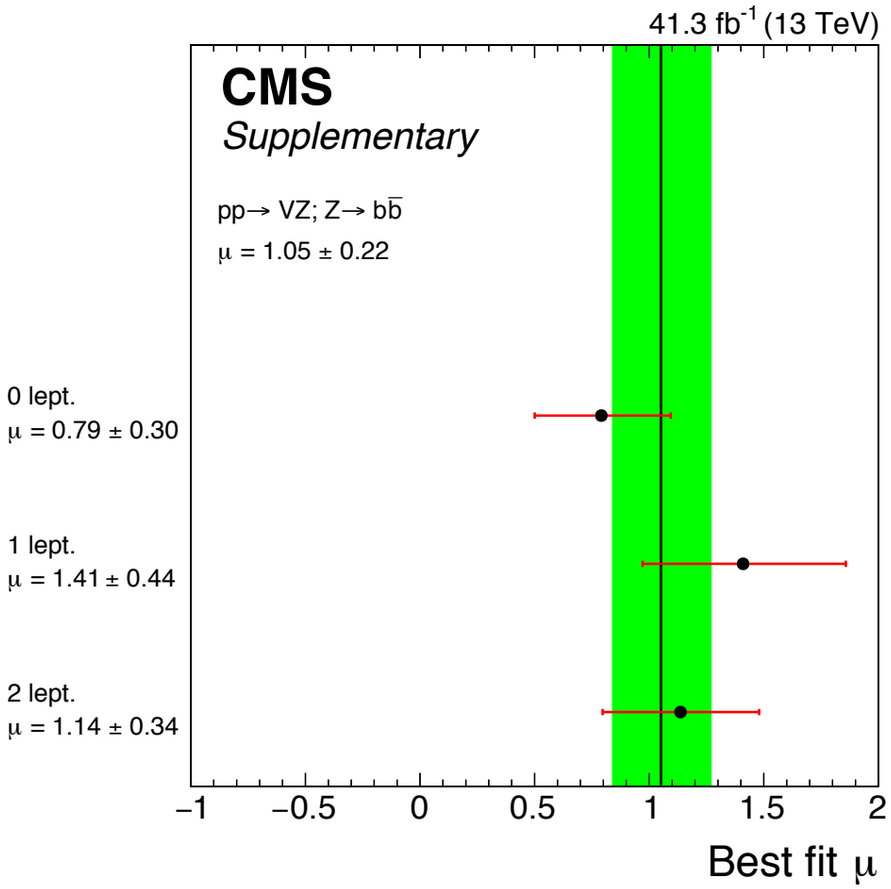
- Same final state and similar kinematic as VH
  - Standard Candle!
- Minimal changes to analysis strategy

	VH(bb)	VZ(bb)
mass	$m_{jj} \in [90,150]$ GeV	$m_{jj} \in [60,160]$ GeV
Signal	VH(bb)	VZ(bb)
Background	VZ(bb)	VH(bb)



Observed (Expected) = 5.2 (5.0) sigma

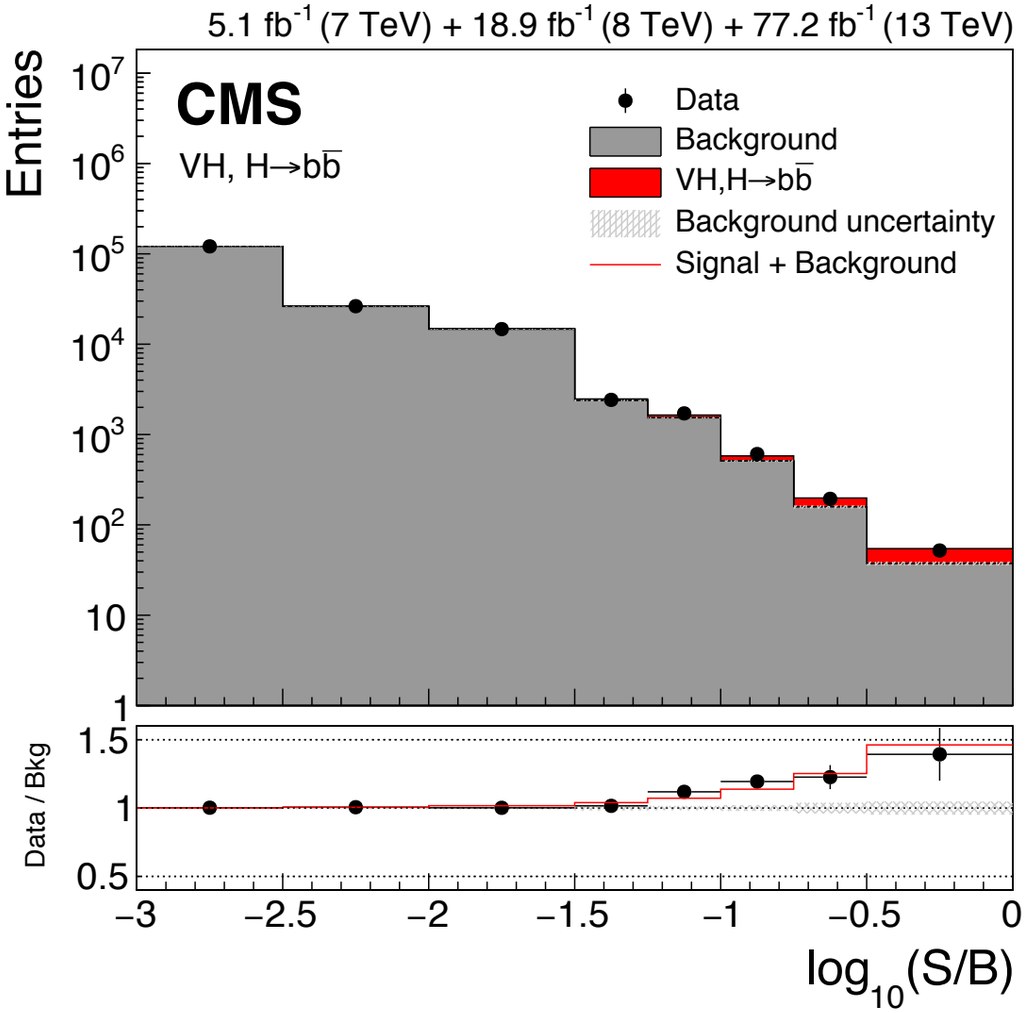
$$\mu_{Zbb} = 1.05 \pm 0.22$$



Results

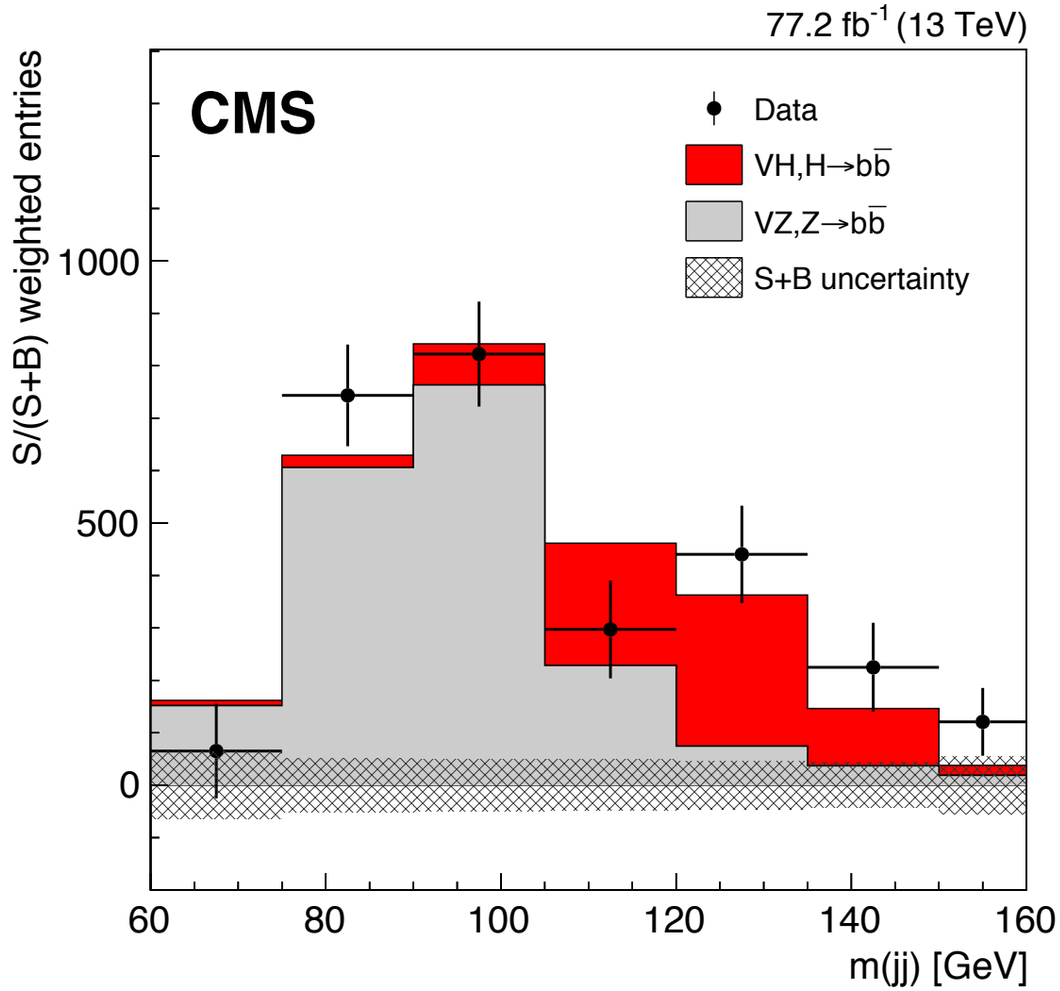
Fit with DNN distribution

More sensitive, but no mass peak



Fit with di-jet mass distribution

Less sensitive, but visible mass peak



Reaching 5 sigma

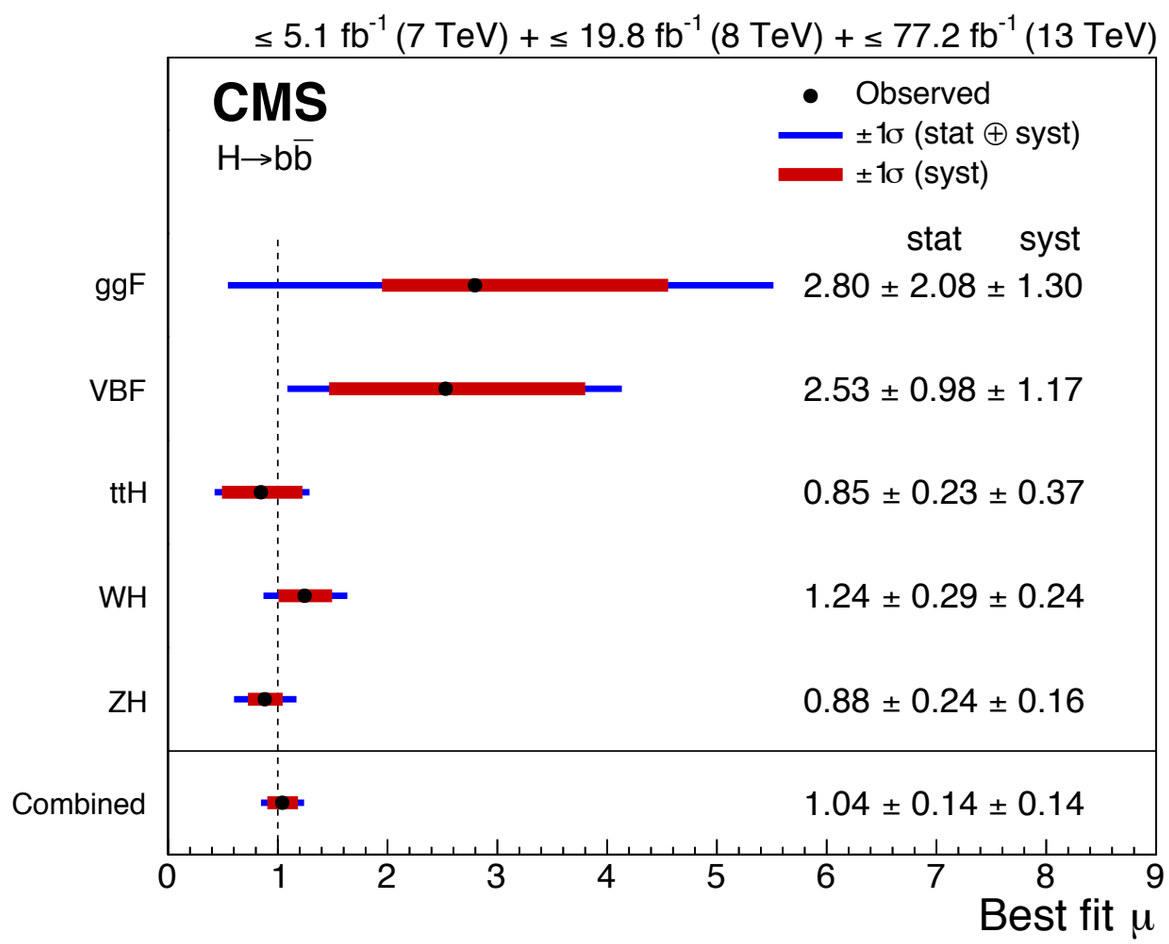
ttH Observation paper

- 2017 analysis has the best sensitivity 3.3(3.1) sigma obs.(exp.)
- Run 1 + Run 2 VH(bb) = 4.9 (4.8) sigma
- Combine with ttH and other analysis

Observed (Expected) = 5.6 (5.5) sigma

$$\mu_{Hbb} = 1.04 \pm 0.20$$

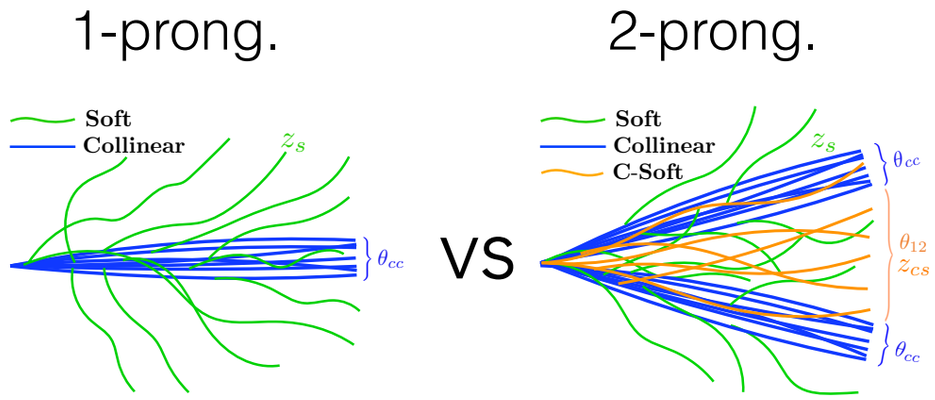
Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23



Why Boosted Higgs?

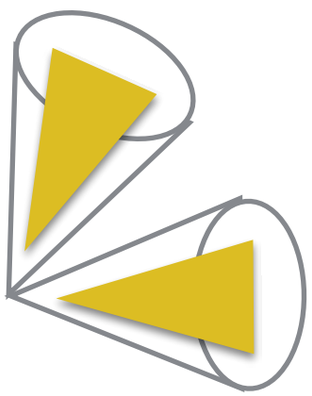
arXiv:1609.07483

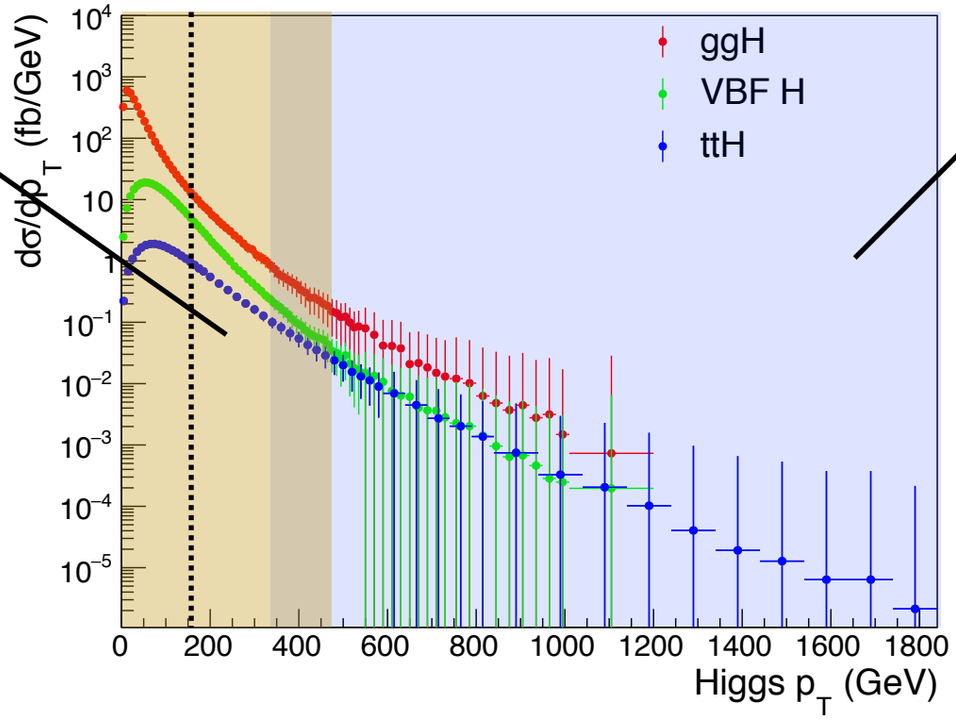
- Above ~400 GeV, two b-jets from Higgs starts to merge
- Exploit jet substructure to reject background
- Only possible with substantial understanding/development with jet substructures
- CMS pioneered a search into this new phase space



$$\Delta R(b\bar{b}) \sim 2m_H/p_T$$

two separated b-jets (R=0.4)





one merged double b-jet (R=0.8)

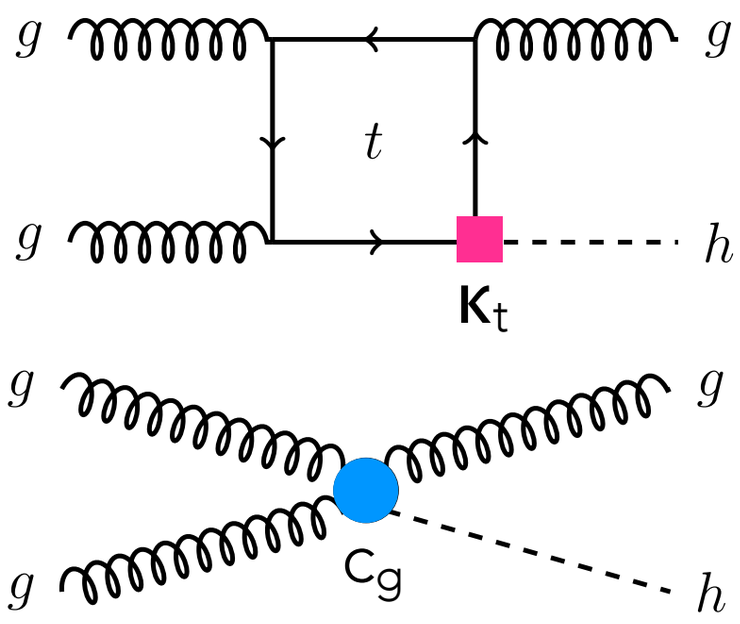
Why Boosted Higgs?

- New physics may show up as anomalous coupling.
- Inclusive production cross section alone cannot distinguish modification of κ_T and κ_g

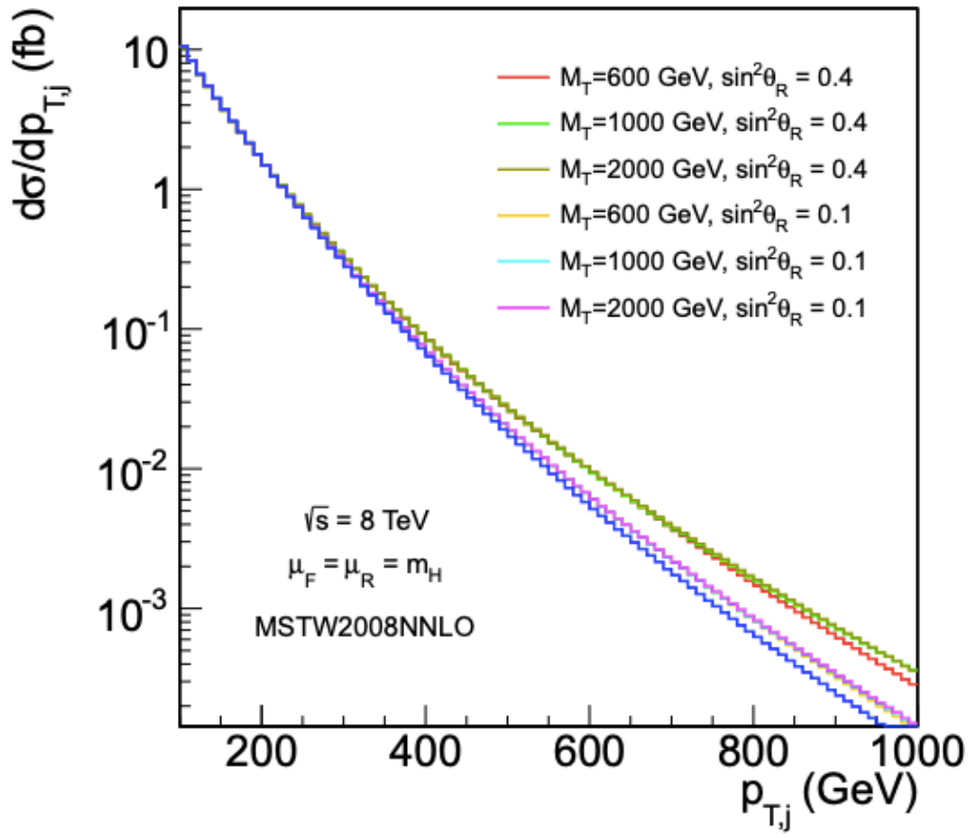
$$\sigma_{incl.}(\kappa_T, \kappa_g) \sim (\kappa_T + \kappa_g)^2 \times \sigma_{SM}$$

- Contribution could be sizeable at high pT!

arxiv:1312.3317

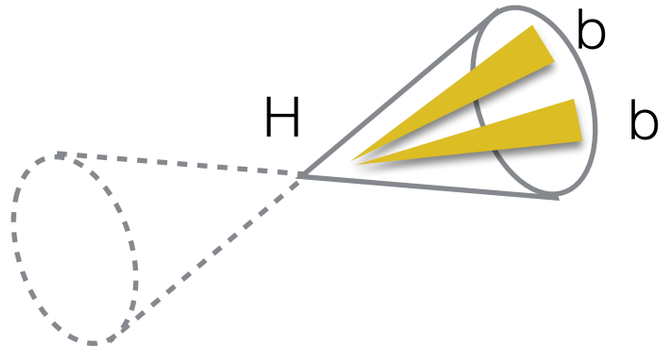


arxiv:1308.4771

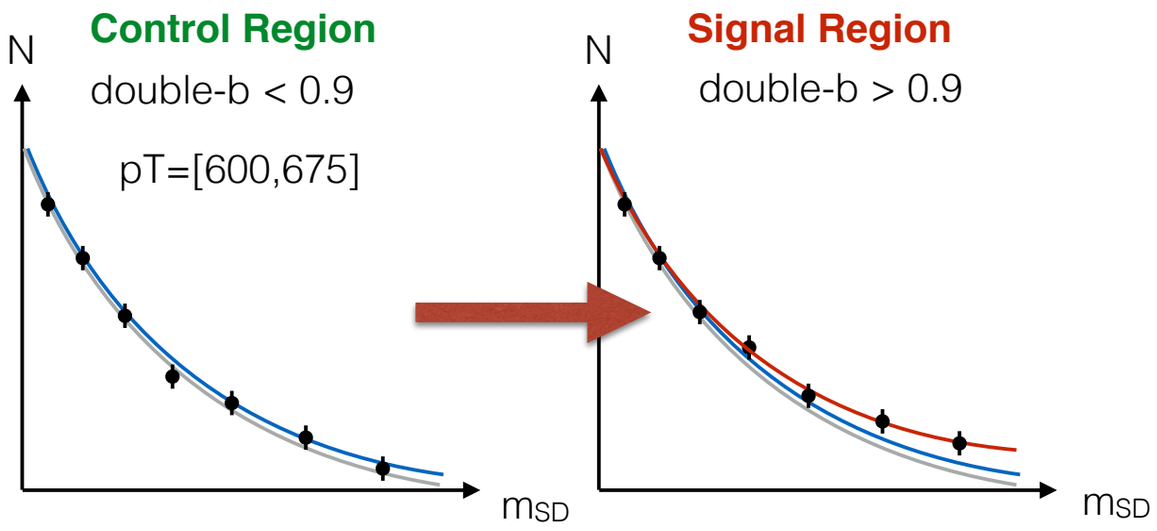


Analysis strategy

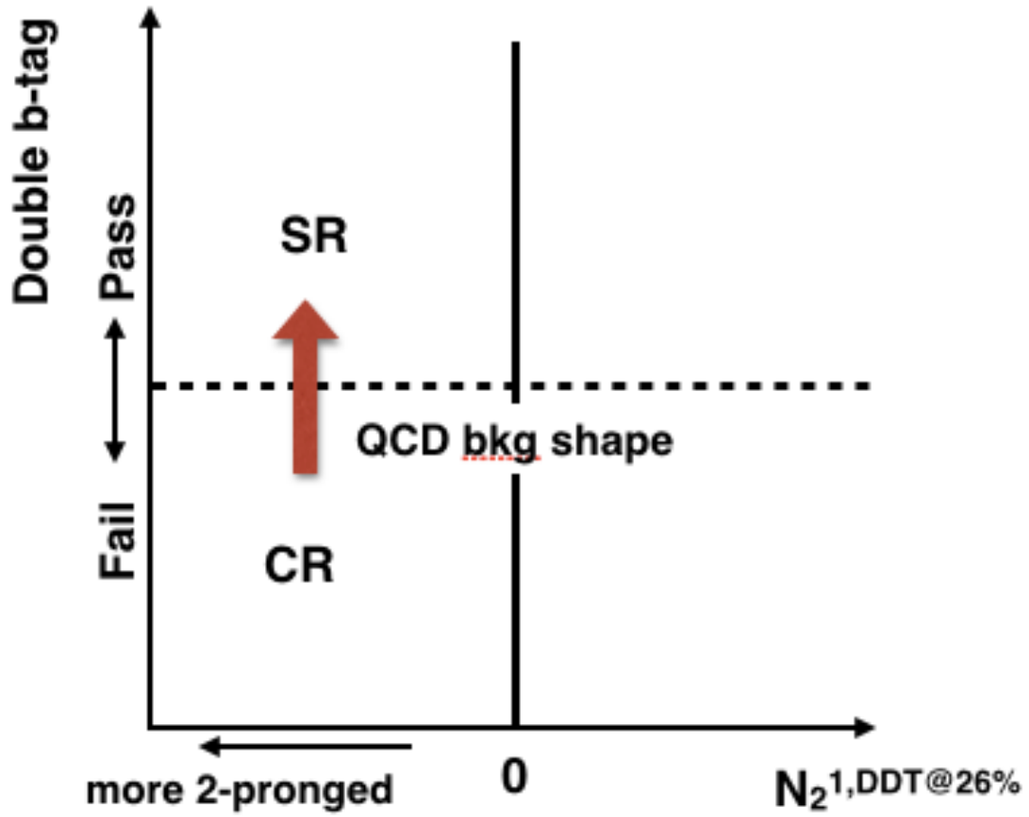
Boosted H to bb



- Two main handles to reject QCD background:
  Jet substructure : N_2
  Dedicated double-b tagging
- Look for excess on a ***smoothly falling*** QCD mass spectrum:
- Data-driven QCD background estimation
- Double-b tagging de-correlated with jet mass



For each (pT, mass) bin



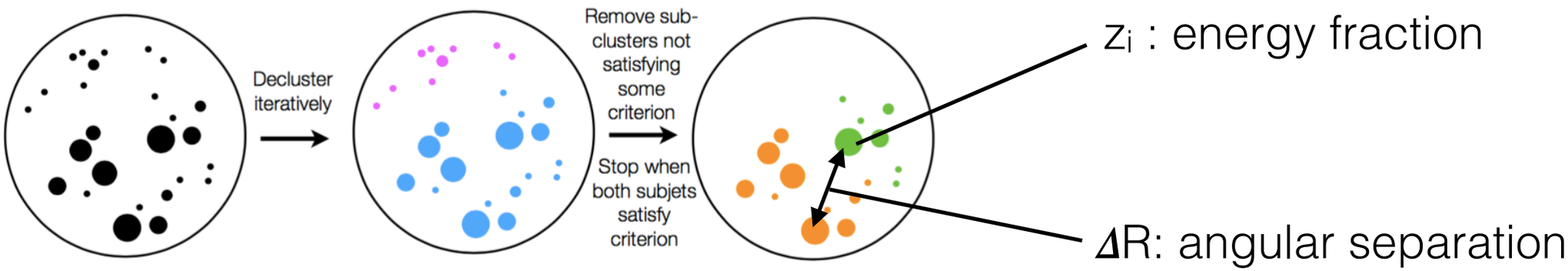
Jet substructure

[arXiv:1609.07483]

- Use generalised Energy Correlation Function(ECF) to identify 2-prong substructure
- N_2 : Ratio of 3-point over 2-point correlation functions (smaller N_2 for more 2-prong)

$$N_2^{\beta=1} = \frac{{}_2e_3^\beta}{({}_1e_2^\beta)^2}$$

- ☑ Theoretically motivated
- ☑ IRC safe
- ☑ No subjet axes



soft-drop jet grooming algorithm

Jet substructure decorrelation

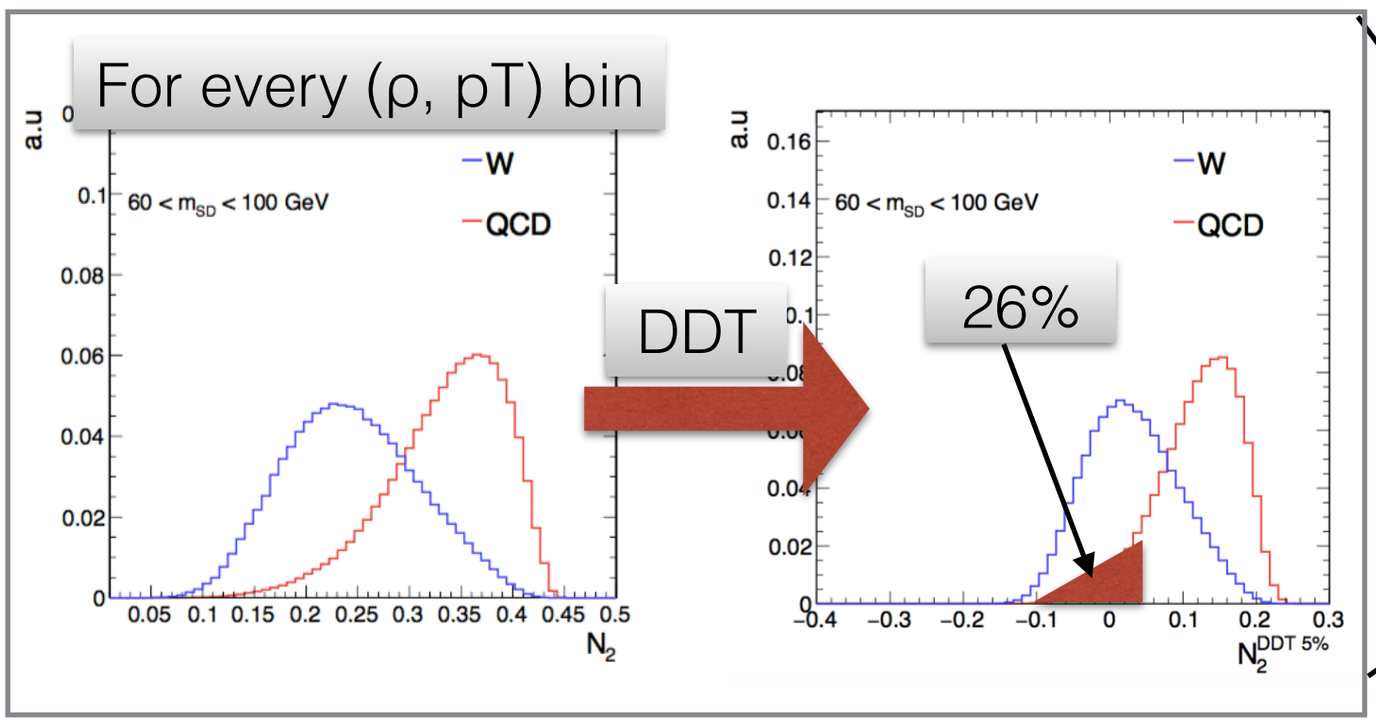
See Cristina's talk for more

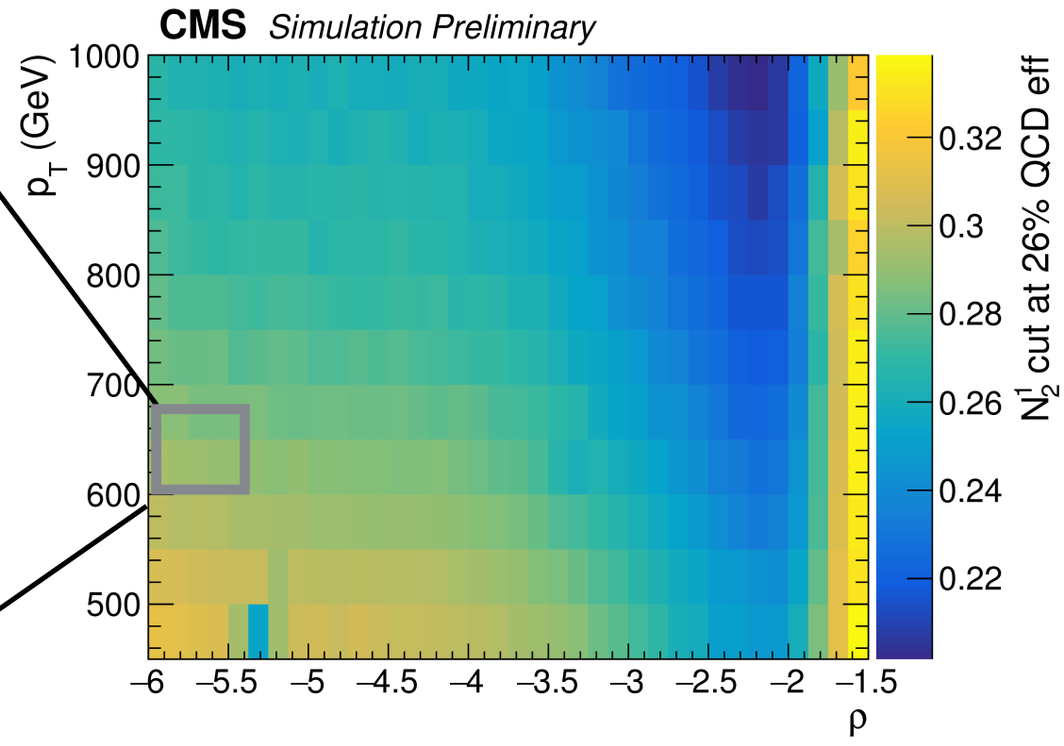
- Substructure variables are **highly correlated** with jet mass.
- Take QCD MC, define

$$N_2^{1,DDT}(\rho, p_T) = N_2(\rho, p_T) - N_2^{(\epsilon=X\%)}(\rho, p_T)$$

- By construction, $N_2^{1,DDT} < 0$ has constant efficiency of QCD and does not sculpt mass spectrum.

[HIG-PAS-17-010]





2D Map of DDT transformation

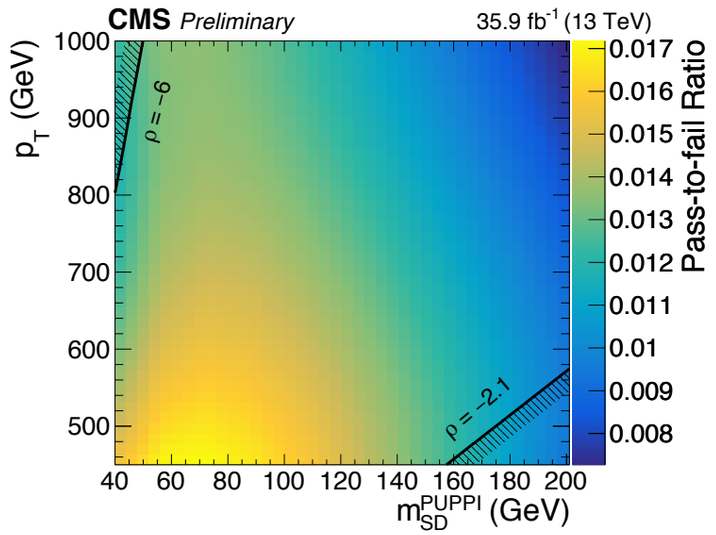
Data driven background

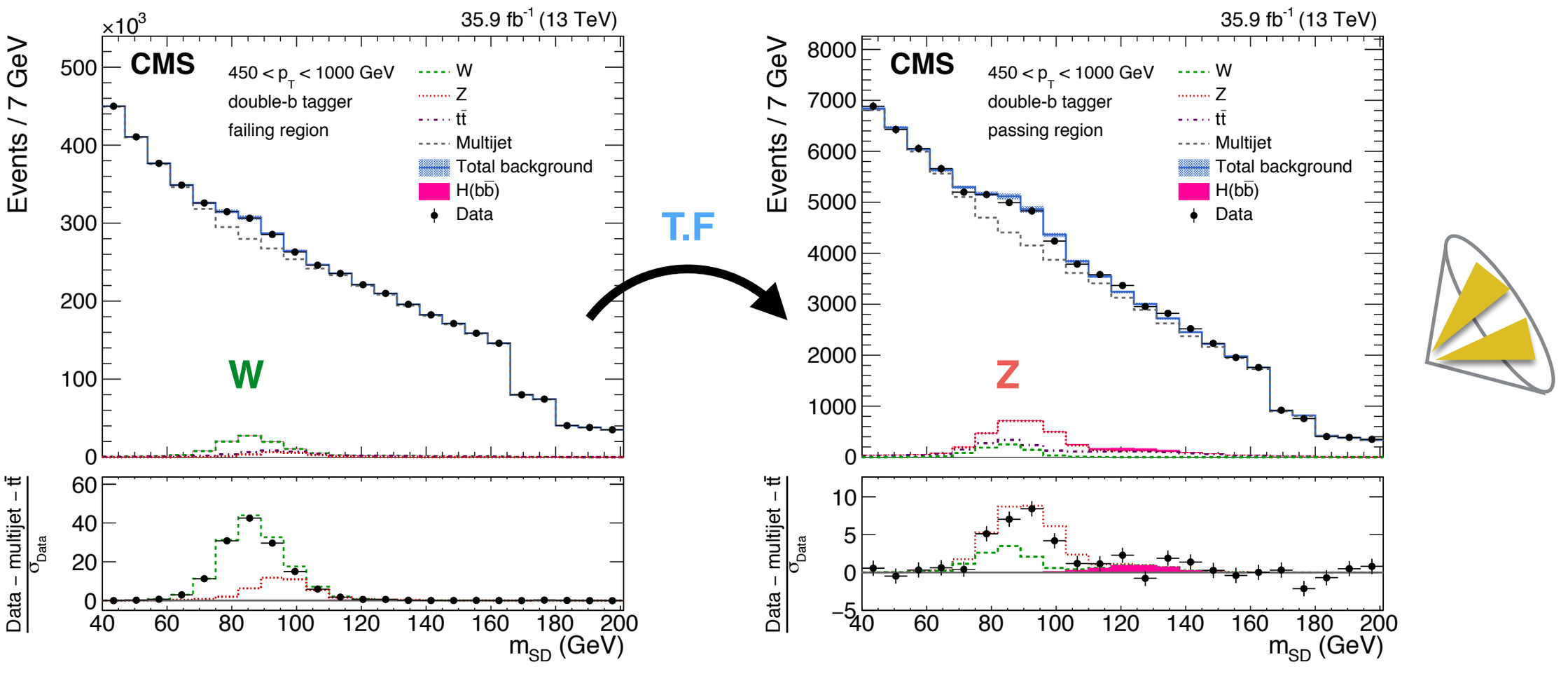
Boosted H to bb [HIG-PAS-17-010]

- Residue shape difference
  due to data/MC is fitted with a smooth transfer function

$$N(\rho, p_T|\text{pass}) = N(\rho, p_T|\text{fail}) \times \mathcal{F}(\rho, p_T)$$

- Simultaneously fit **Z(bb)**, **H(bb)** and **transfer function**

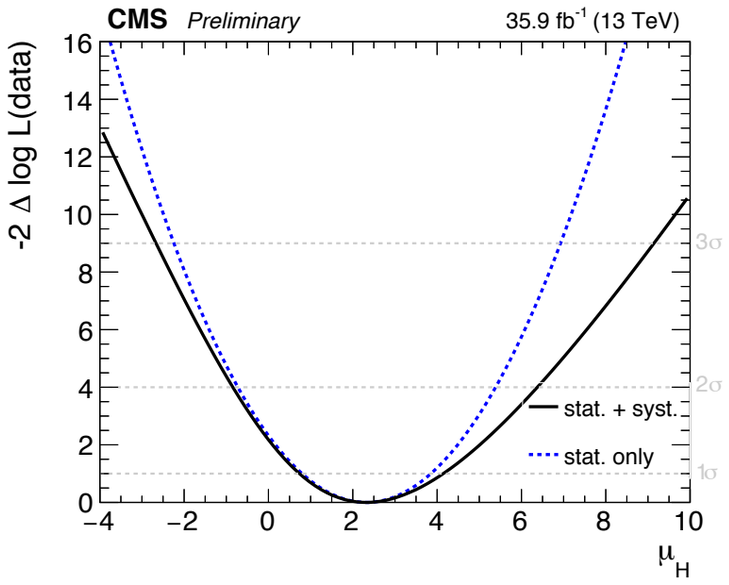


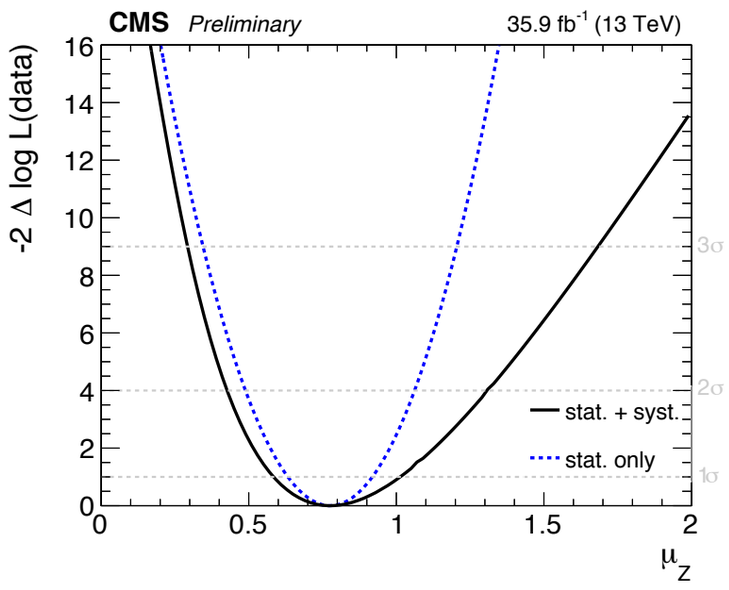


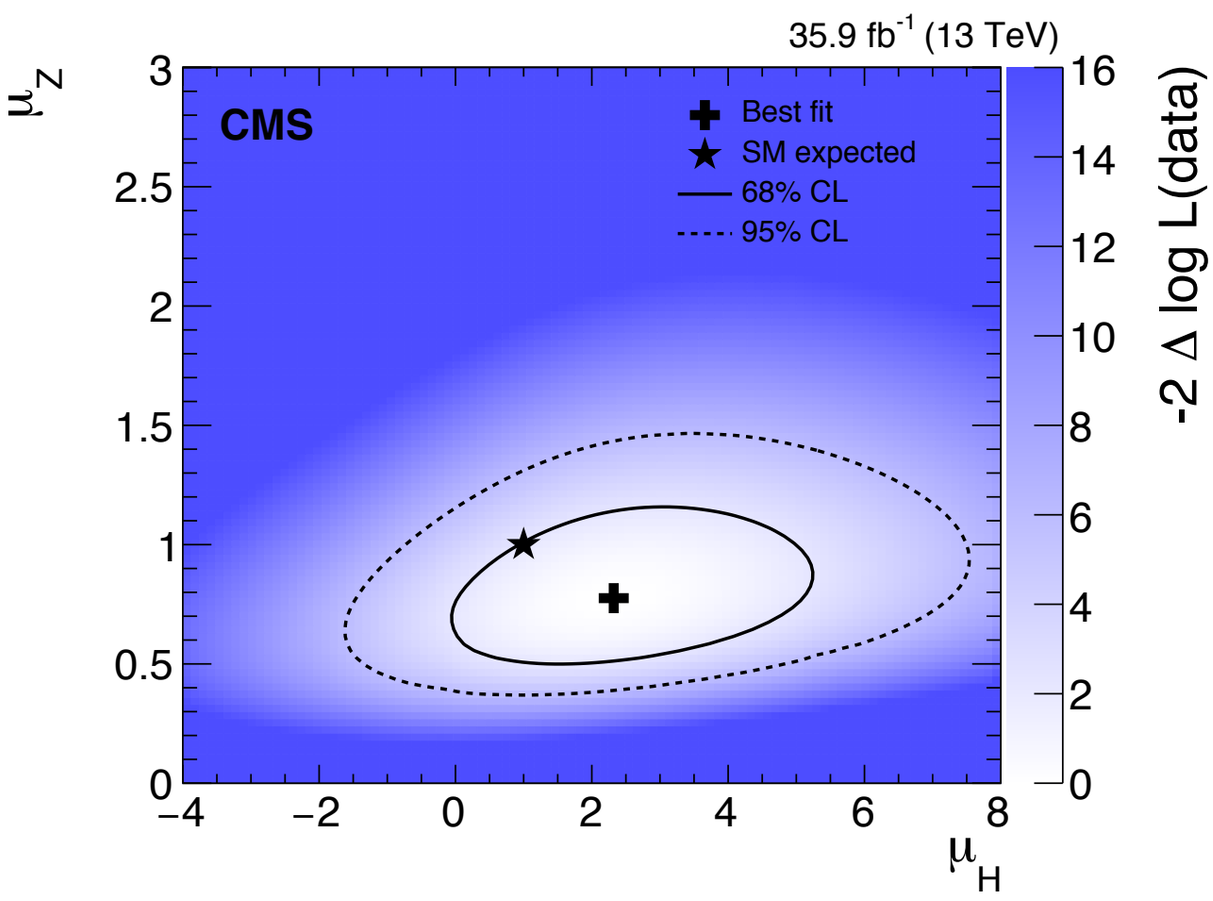
Results

Boosted H to bb

- With 2016 dataset, (<1/3 of full Run 2 data)
- Observed Z(bb) with 5.1 sigma (5.8 sigma expected)
- Observed H(bb) with 1.5 sigma (0.7 sigma expected)



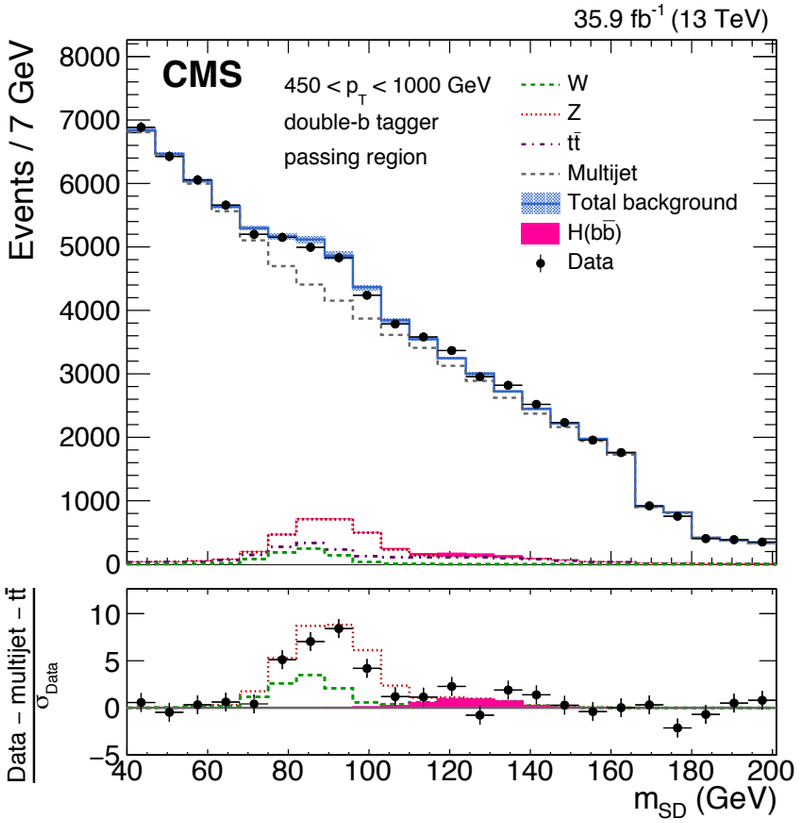




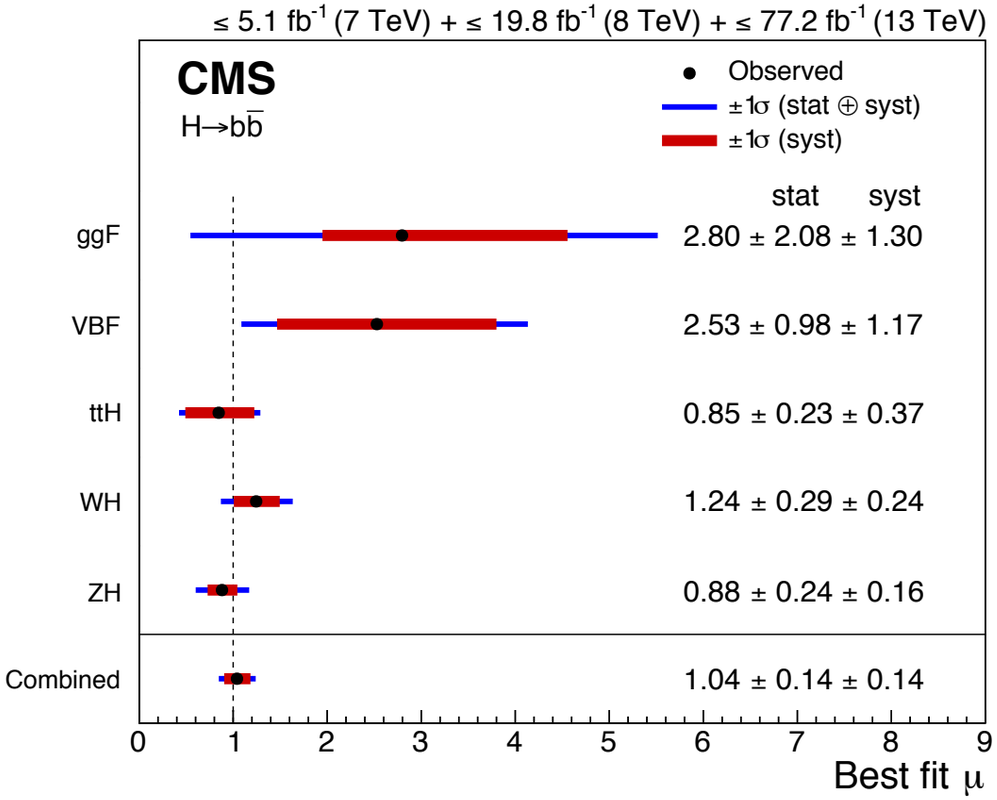
Summary

- H(bb) is observed with associated production modes VH, ttH
- Boosted topology opens up possibility for probing ggF production
  - Updating with better double-b tagger + full Run 2 data
- Next goal: VH(cc) and ggH(cc)

Phys. Rev. Lett. 120 (2018) 071802



PhysRevLett.121.121801



Summary

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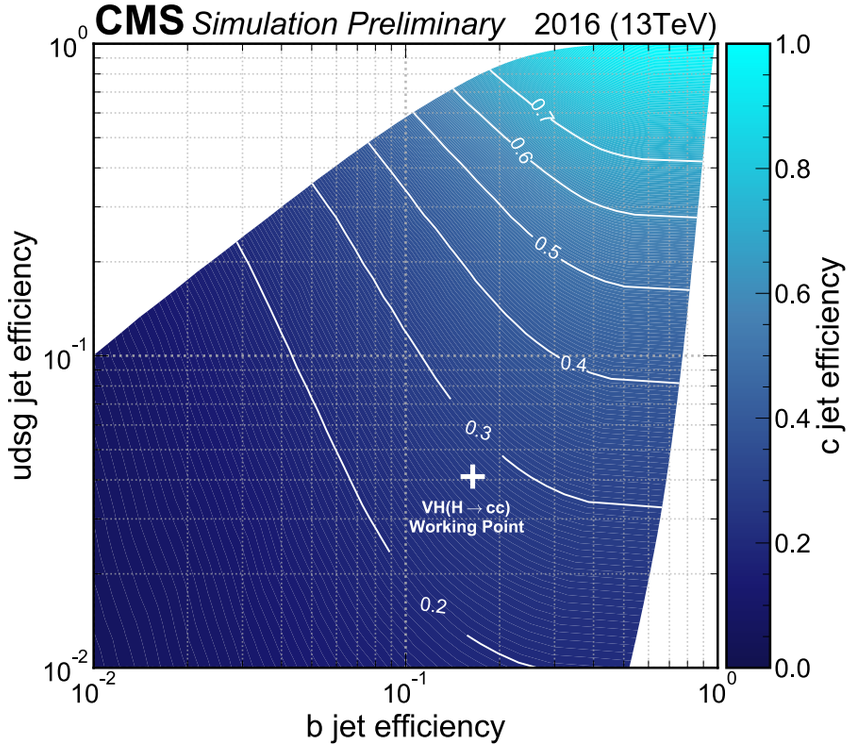
Stay tuned for updates!

CMS-PAS-HIG-18-031



VH(cc)

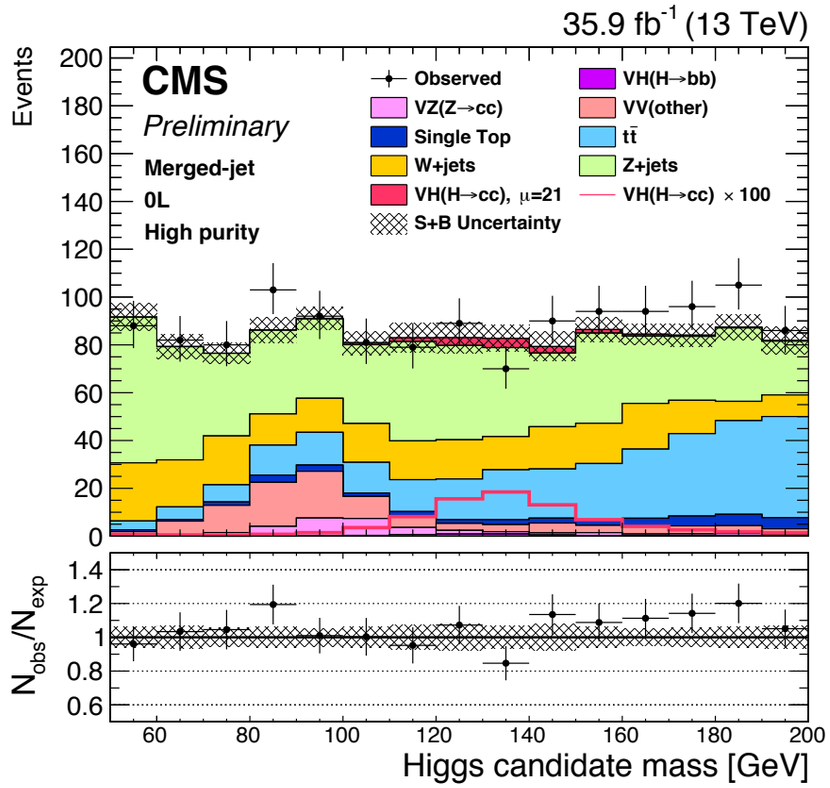
$$\frac{\sigma_{VH(H\to c\bar{c})}}{\sigma^{SM}_{VH(H\to c\bar{c})}} < 70(37^{+16}_{-10})$$

VZ(cc)

$$\mu_{VZ(Z\to c\bar{c})} = 0.55^{+0.86}_{-0.84}$$

$$\sigma_{VZ(Z\to c\bar{c})} = 0.7(1.3)$$

0-lep, 2016 dataset

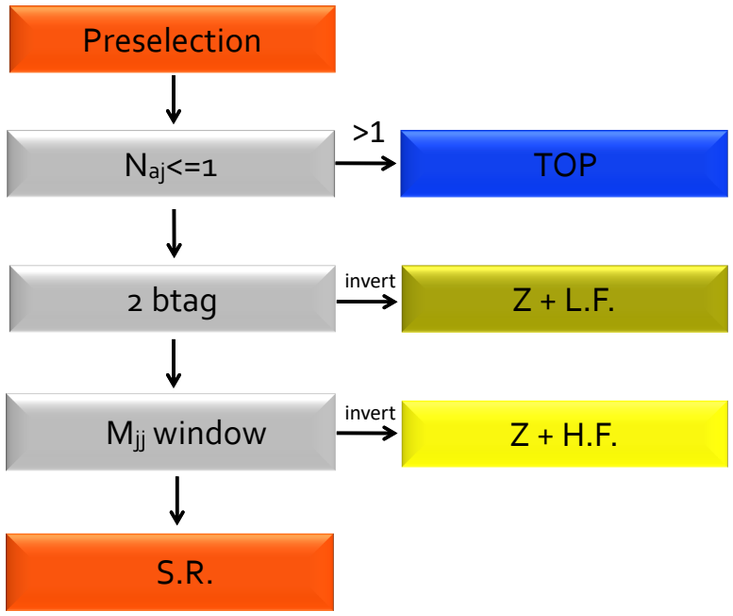


Additional materials

VH(bb) control regions

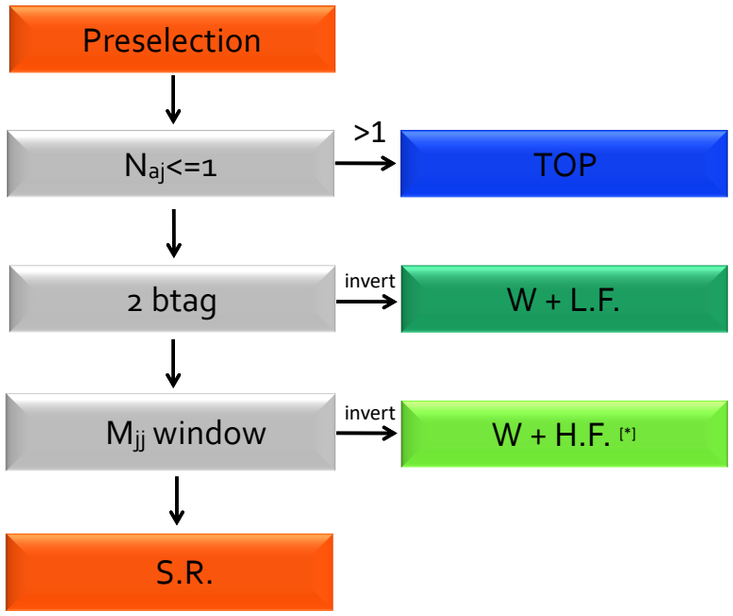
- Control regions are mutually exclusive with each others
- Defined using properties of on
  Higgs side (b-tagging) or vetos of extra jets

0-lepton channel



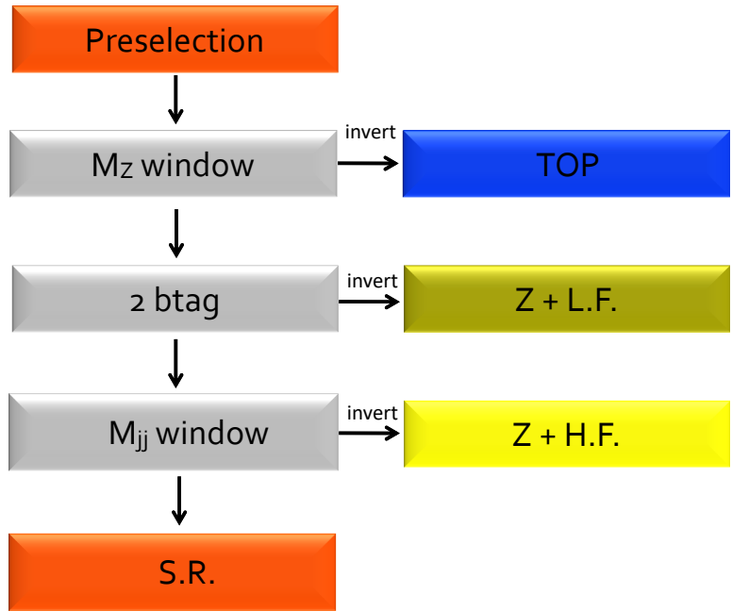
[*] W+L.F and W+H.F taken from 1-lepton analysis

1-lepton channel



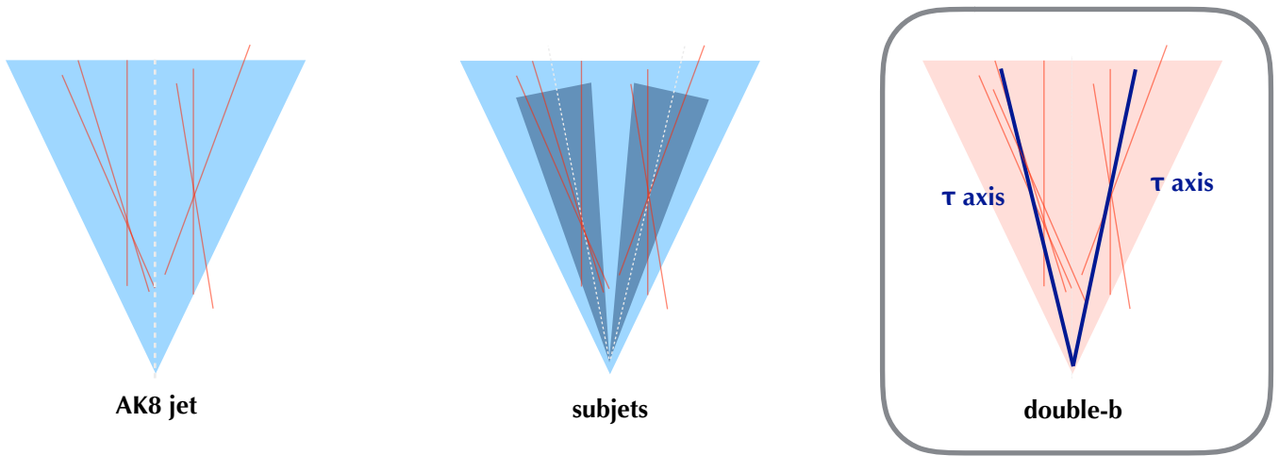
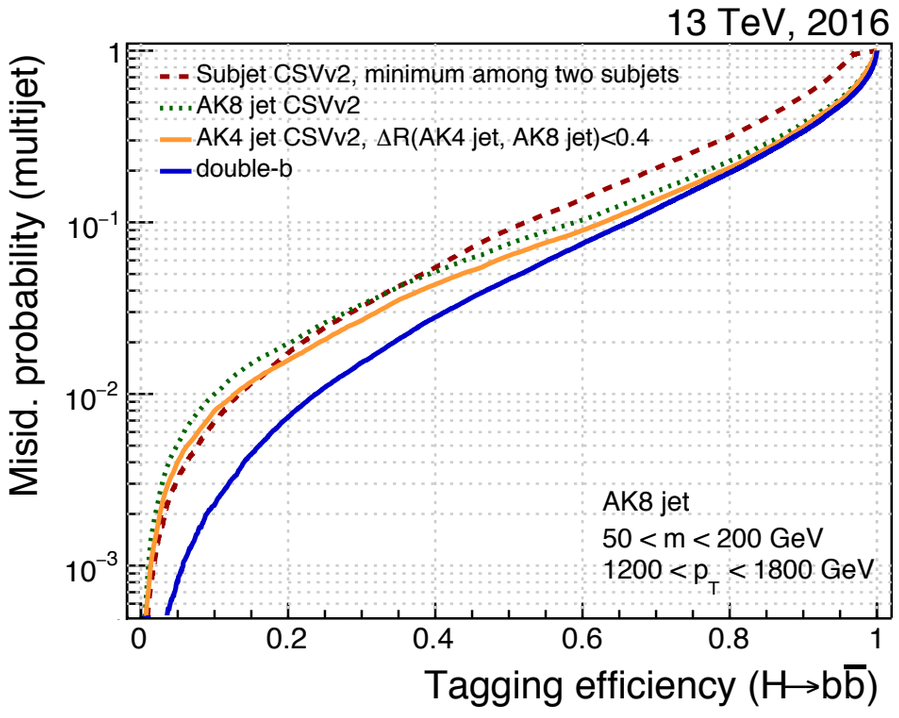
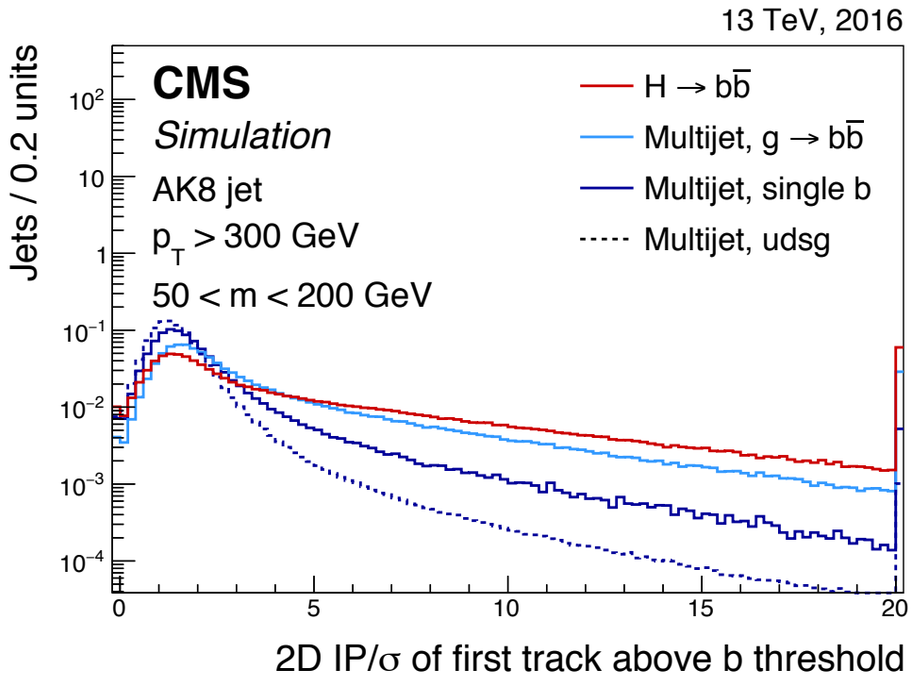
[*] W+H.F splitted in high and low mass

2-lepton channel



Double-b tagger

JINST 13(2018) P05011



- Combines tracking and vertexing information in a boosted decision tree(BDT) with 27 input observables
- Input variables are chosen to carefully to have no strong dependence on mSD or pT