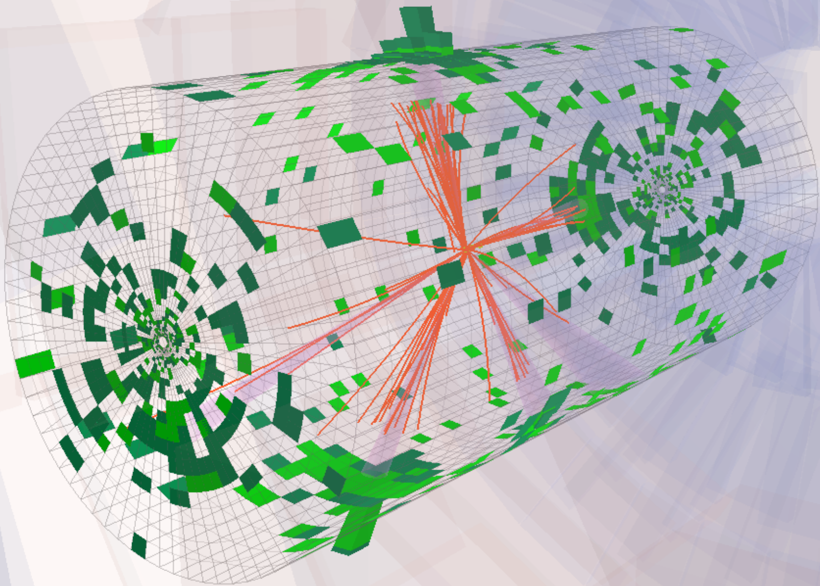
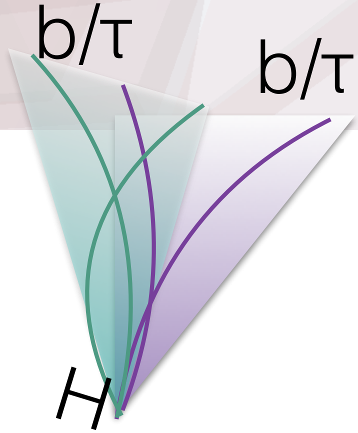
Boosting the Higgs boson



Higgs couplings 2018
Tokyo
Nov. 27, 2018



Ben Kilminster
Physik Institut

University of Zurich UZH

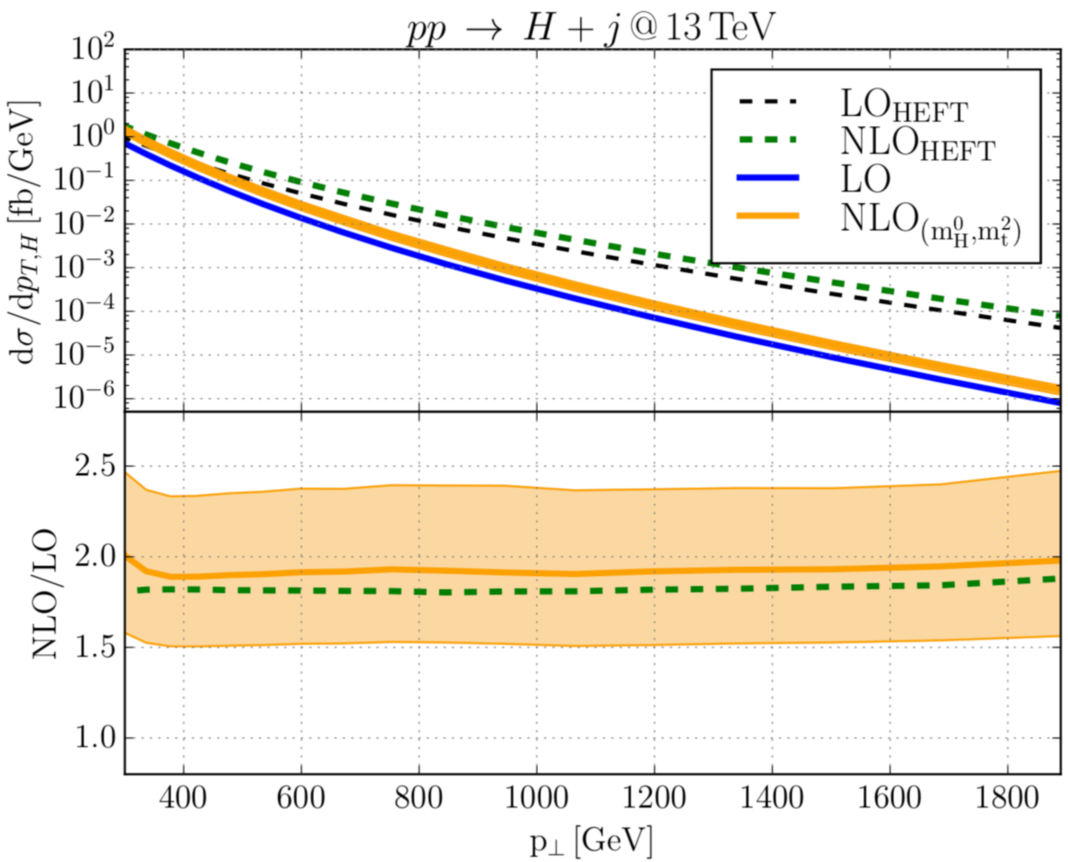
Boosted Higgs bosons

- **Can improve sensitivity of SM Higgs measurements**
  - At high Higgs P_T > 200 GeV
    - $H \rightarrow bb$, $H \rightarrow \tau\tau$ can benefit from analysis of unresolved jets
    - At higher P_T, $H \rightarrow ZZ/WW \rightarrow$ qqqq can also benefit
- **Can be used as a tool to search for BSM physics**
  - Radions, RS Bulk Gravitons
  - Composite Higgs
  - New vector triplets ($W^{\pm\prime}$, Z')
  - Portal to dark matter (2HDM)

SM Higgs boson at high P_T

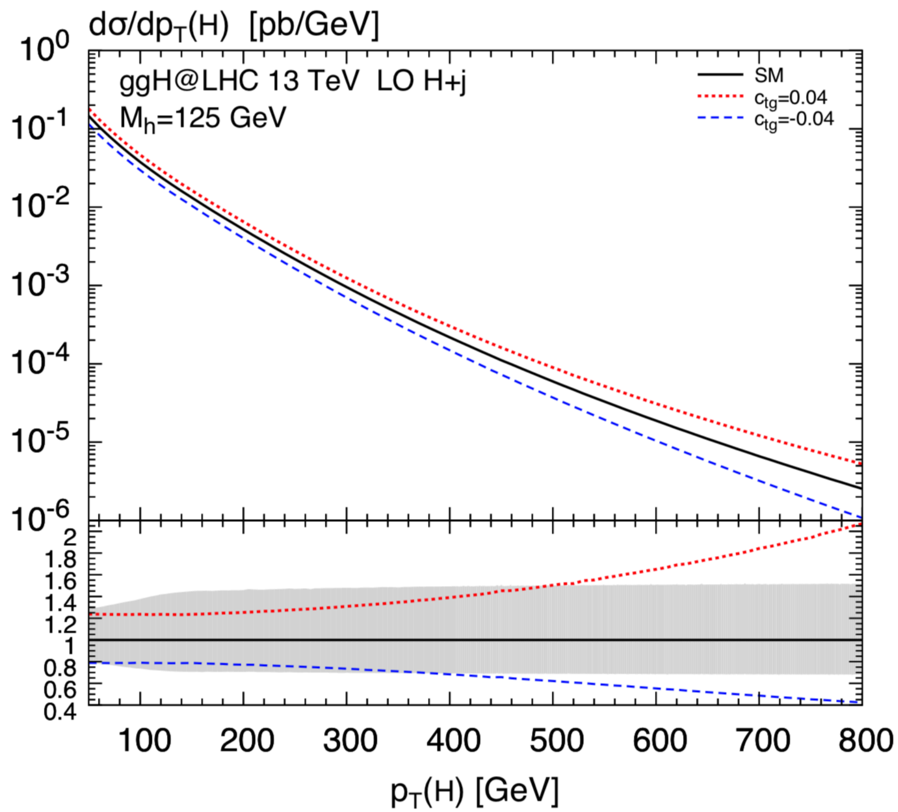
- SM theory shape is remarkably stable wrt higher orders at high P_T
- May provide a way to identify new physics that enters at high P_T

SM predictions



PLB 1801.08226, and see Jonas Lindert's talk yesterday

BSM example : SMEFT with deviations in chromomagnetic operator



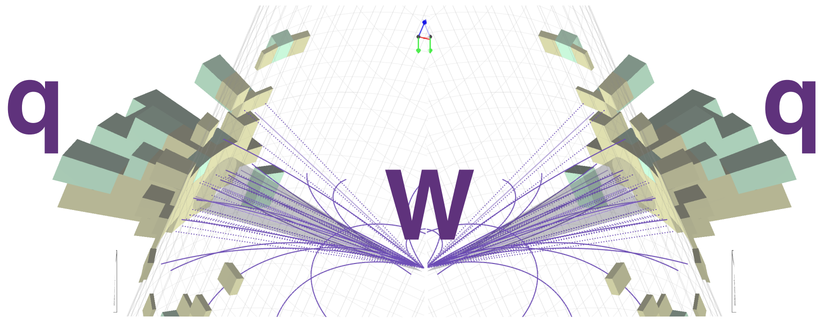
Eur.Phys.J, 1806.08832

- **See later slides on our experimental techniques to probe this …**

Focus of this talk

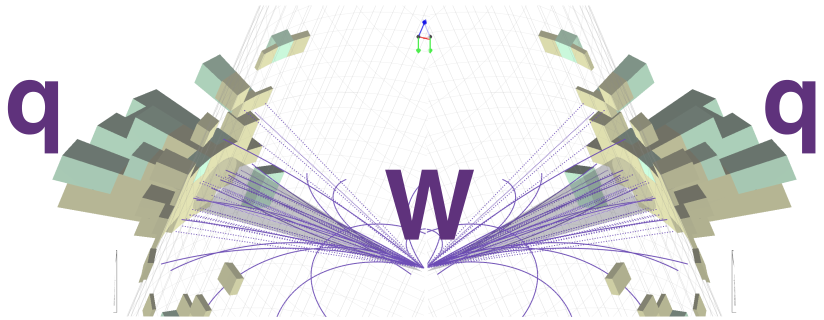
- **Boosted Analyses and techniques used in :**
  - BSM : $X \rightarrow VV \rightarrow qqqq$ (ATLAS)
  - BSM : $X \rightarrow HH \rightarrow \tau\tau bb$ (CMS)
  - BSM : $H \rightarrow bb$ +dark matter (ATLAS)
  - SM : $gg \rightarrow H \rightarrow bb$ (CMS)
- **Boosted boson techniques, mainly …**
  - V(qq)-tagging vs. H(bb)-tagging
  - Track+Calorimeter techniques (ATLAS)
  - Track jets for b-tagging (ATLAS)
  - Double-b tagging (CMS)
  - $H \rightarrow \tau\tau$ tagging (CMS)
- **BSM searches currently driving experimental techniques at high P_T**

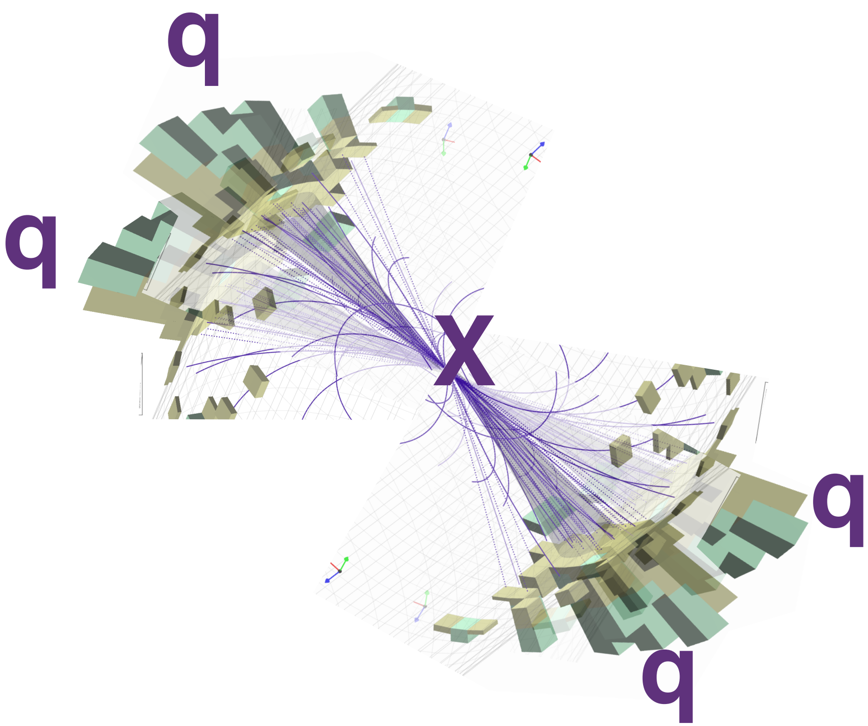
Measuring a boson-jet



- At low P_T, a boson (W,Z,H) decaying to two quarks looks like 2 jets
  - Ie., $W \rightarrow qq$
  - $\overline{P}_W \sim 0$

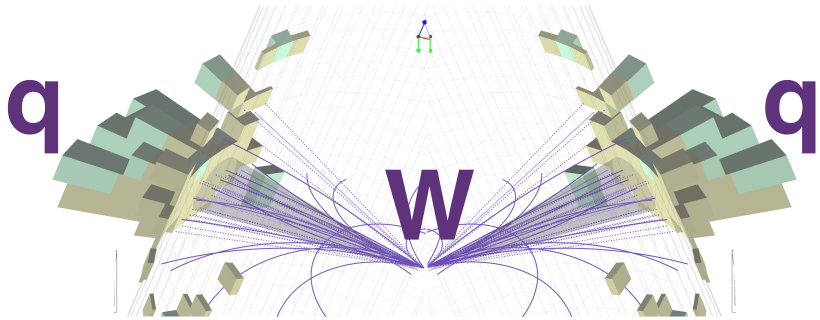
Measuring a boson-jet



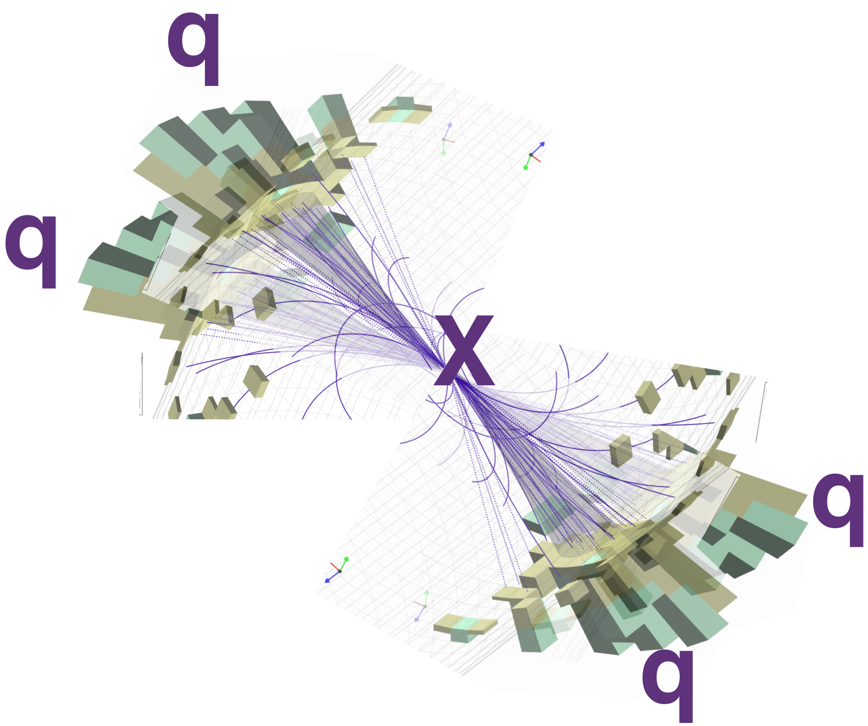


- At low P_T, a boson (W,Z,H) decaying to two quarks looks like 2 jets
  - Ie., $W \rightarrow qq$
  - $\overline{P}_W \sim 0$

Measuring a boson-jet

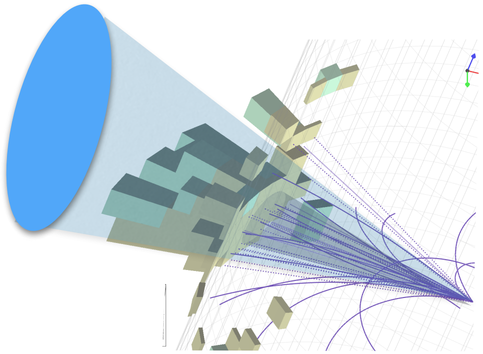


- At low P_T, a boson (W,Z,H) decaying to two quarks looks like 2 jets
  - Ie., W→qq
  - $\bar{P}_W \sim 0$

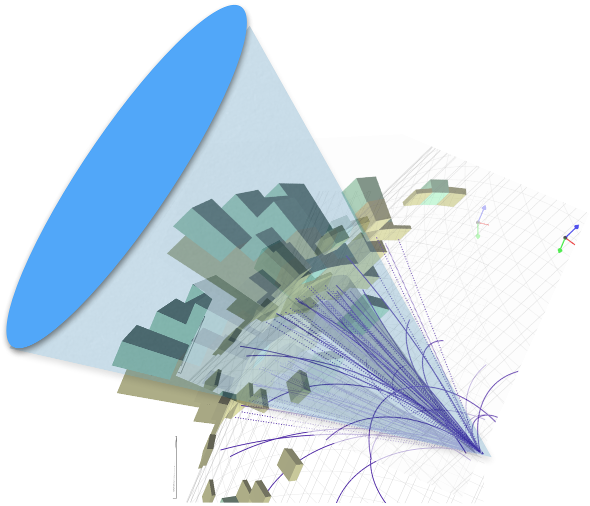


- But in heavy particle decays, two quarks become merged
  - Ie., X→WW→qq+qq
  - Mass of X → Momentum of W's
  - W's are said to be Lorentz "boosted"
  - Quarks are essentially massless
  - Merging when $M_X / M_W > 10$
    - Ie, somewhere around ~ 1 TeV

Quark-jets vs. boson-jets

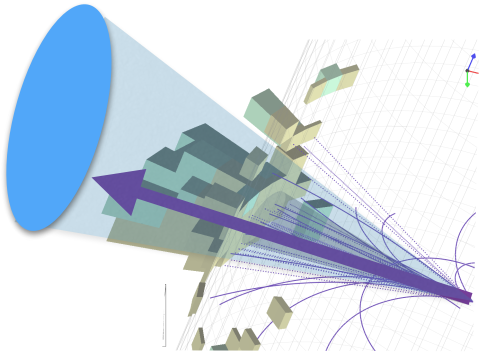


- **Quark jets :**
  - **Smaller cone**

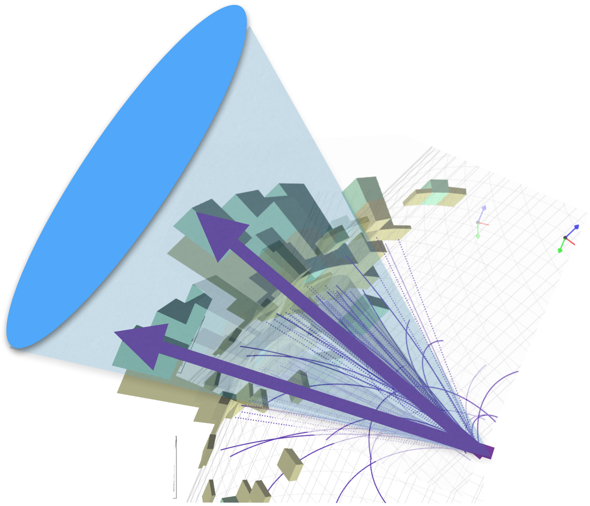


- **Boson-jets :**
  - **Larger cone**

Quark-jets vs. boson-jets

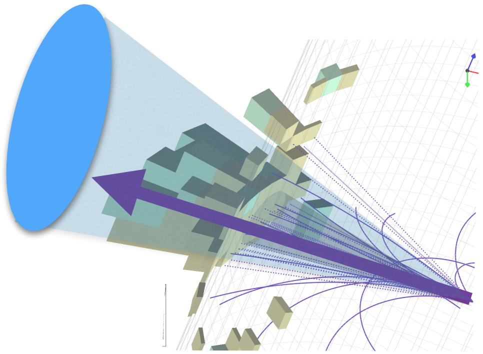


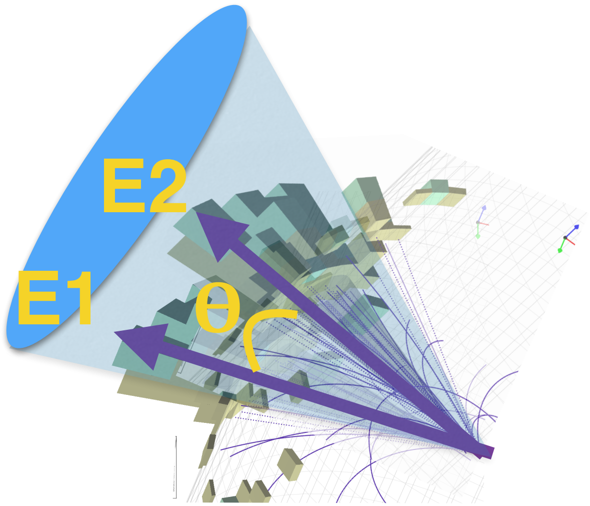
- **Quark jets :**
  - **Smaller cone**
  - **Jet collimated over single axis**



- **Boson-jets :**
  - **Larger cone**
  - **Jet collimated over two axes**

Quark-jets vs. boson-jets





$M^2 \sim E1 \cdot E2(1-\cos\theta)$

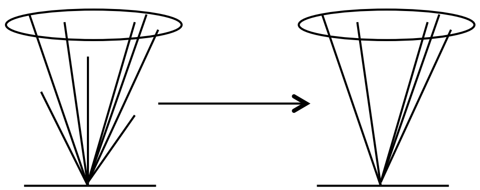
- **Quark jets :**
  - **Smaller cone**
  - **Jet collimated over single axis**
  - **Mass of jet ~ 0 GeV**
- **Boson-jets :**
  - **Larger cone**
  - **Jet collimated over two axes**
  - **Mass of jet ~ boson mass ~ 100 GeV**

Grooming jets

Many algorithms used : trimming, pruning, soft drop …

Goal :

Removing soft, high angle emissions

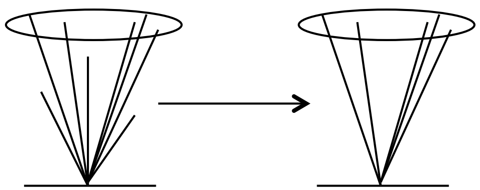


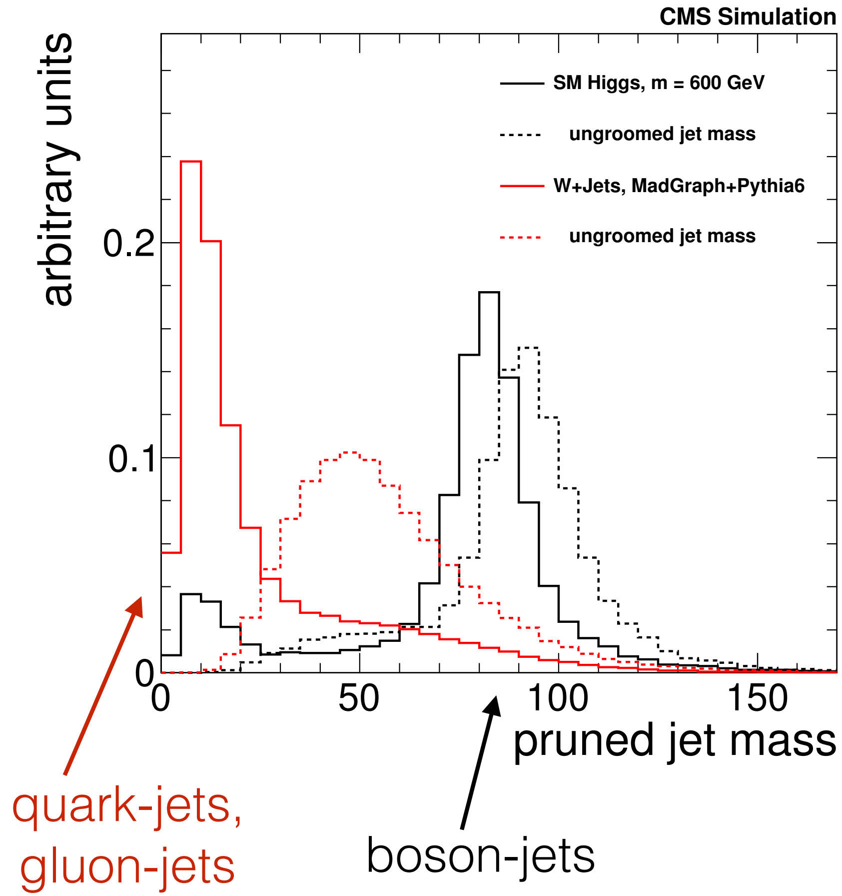
Grooming jets

Many algorithms used : trimming, pruning, soft drop …

Goal :

Removing soft, high angle emissions



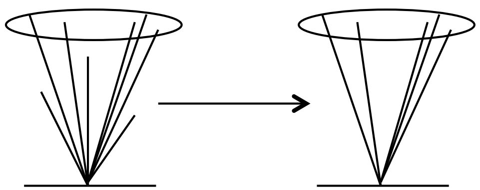


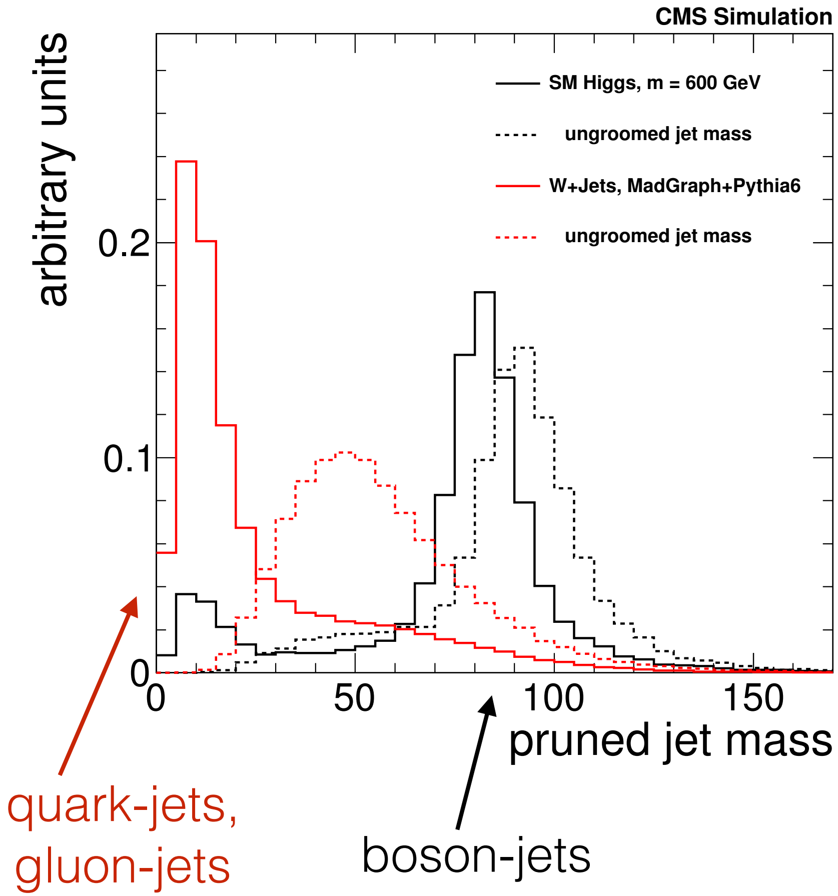
Grooming jets

Many algorithms used : trimming, pruning, soft drop …

Goal :

Removing soft, high angle emissions





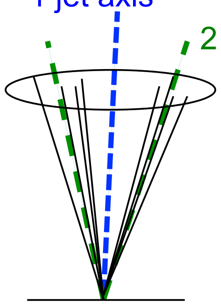
Improves discrimination between quark-jets and boson-jets

Sub-jet finding

We calculate a sum of:

(P_T *angular distance to axis)

for each energy deposit in cone



Then compare ratio of 2-axis sum to 1-axis sum

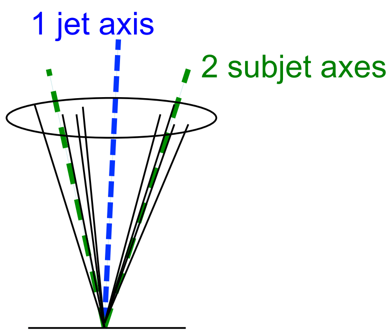
"$\tau_{21} = \tau_2/\tau_1$"

Sub-jet finding

We calculate a sum of:

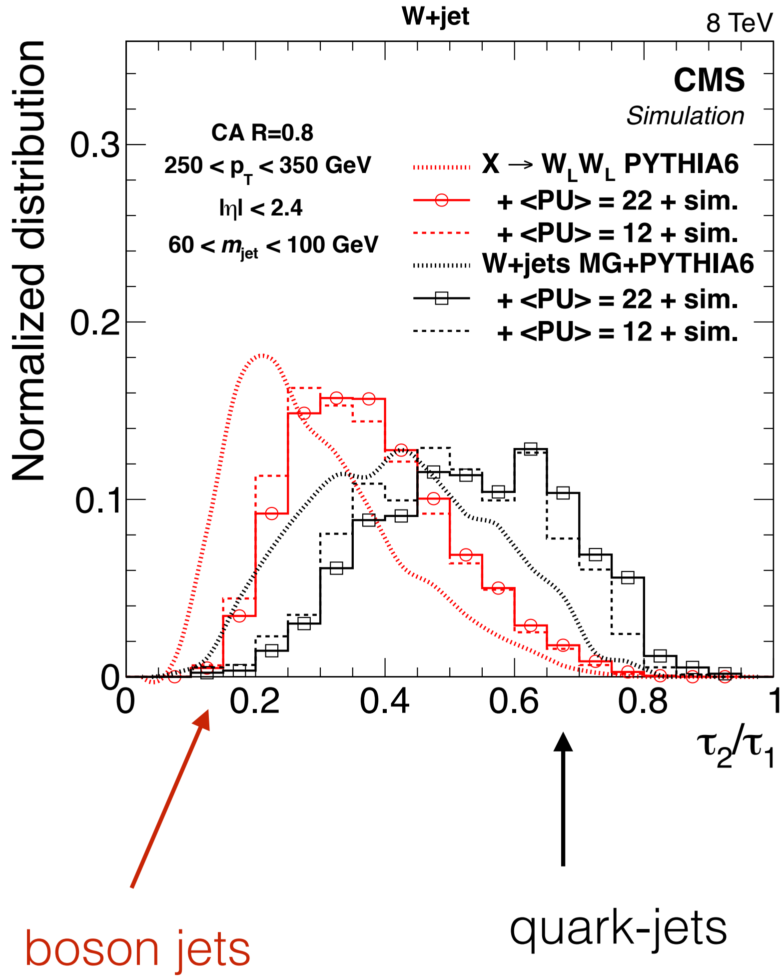
(P_T *angular distance to axis)

for each energy deposit in cone



Then compare ratio of 2-axis sum to 1-axis sum

"$\tau_{21} = \tau_2/\tau_1$"

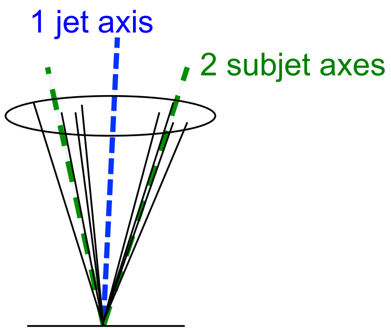


Sub-jet finding

We calculate a sum of:

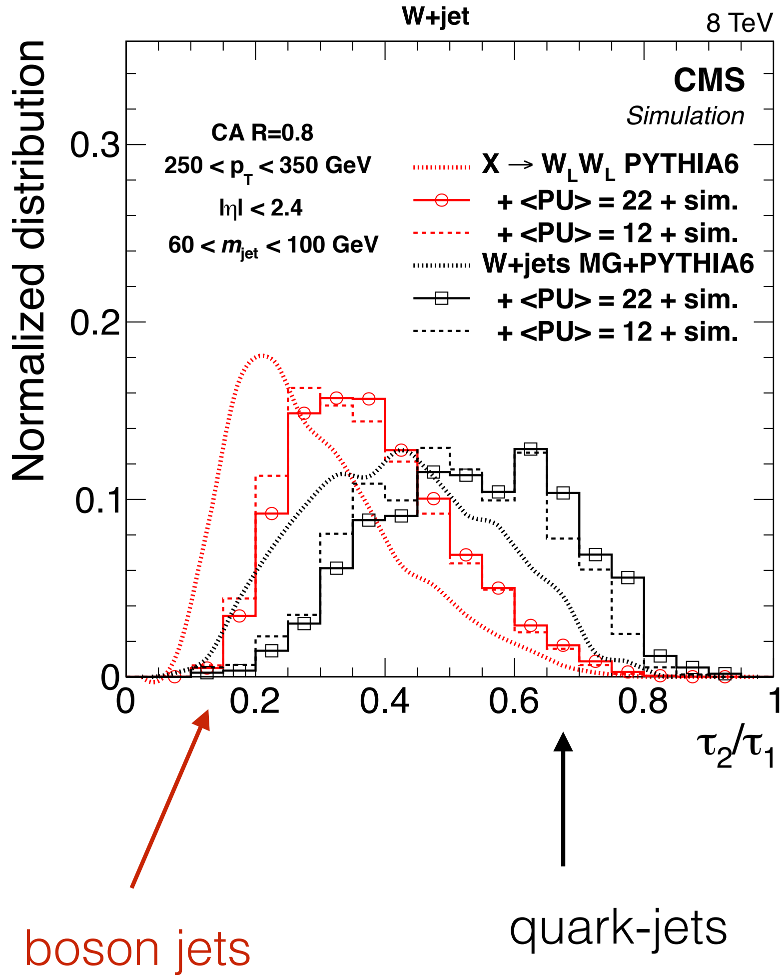
(P_T *angular distance to axis)

for each energy deposit in cone



Then compare ratio of 2-axis sum to 1-axis sum

"$\tau_{21} = \tau_2/\tau_1$"

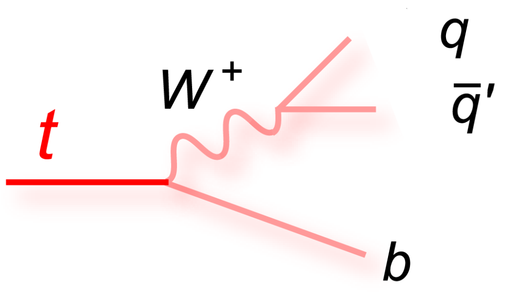


Helps further isolate boson-jets from background

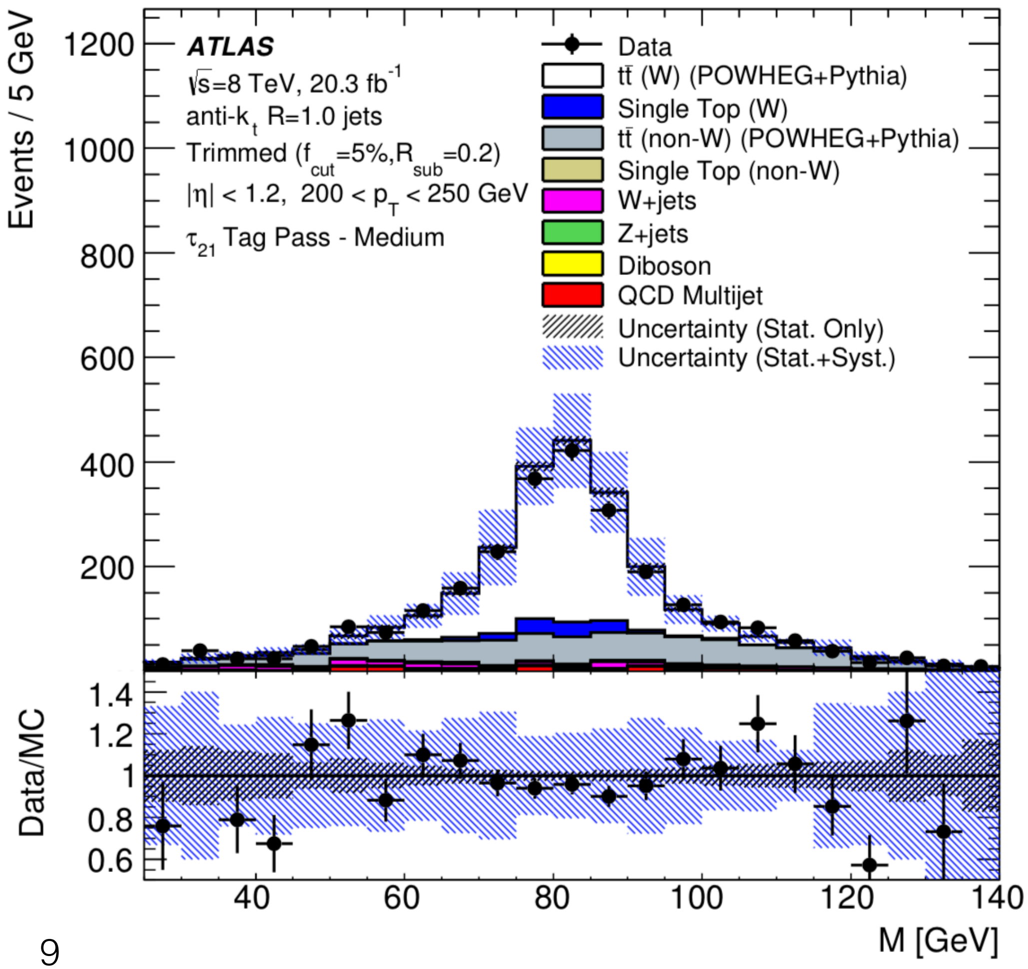
Does this all work ?

- Luckily, we have a way of testing these :
  - jet mass
  - pruning/trimming
  - sub-jet finding

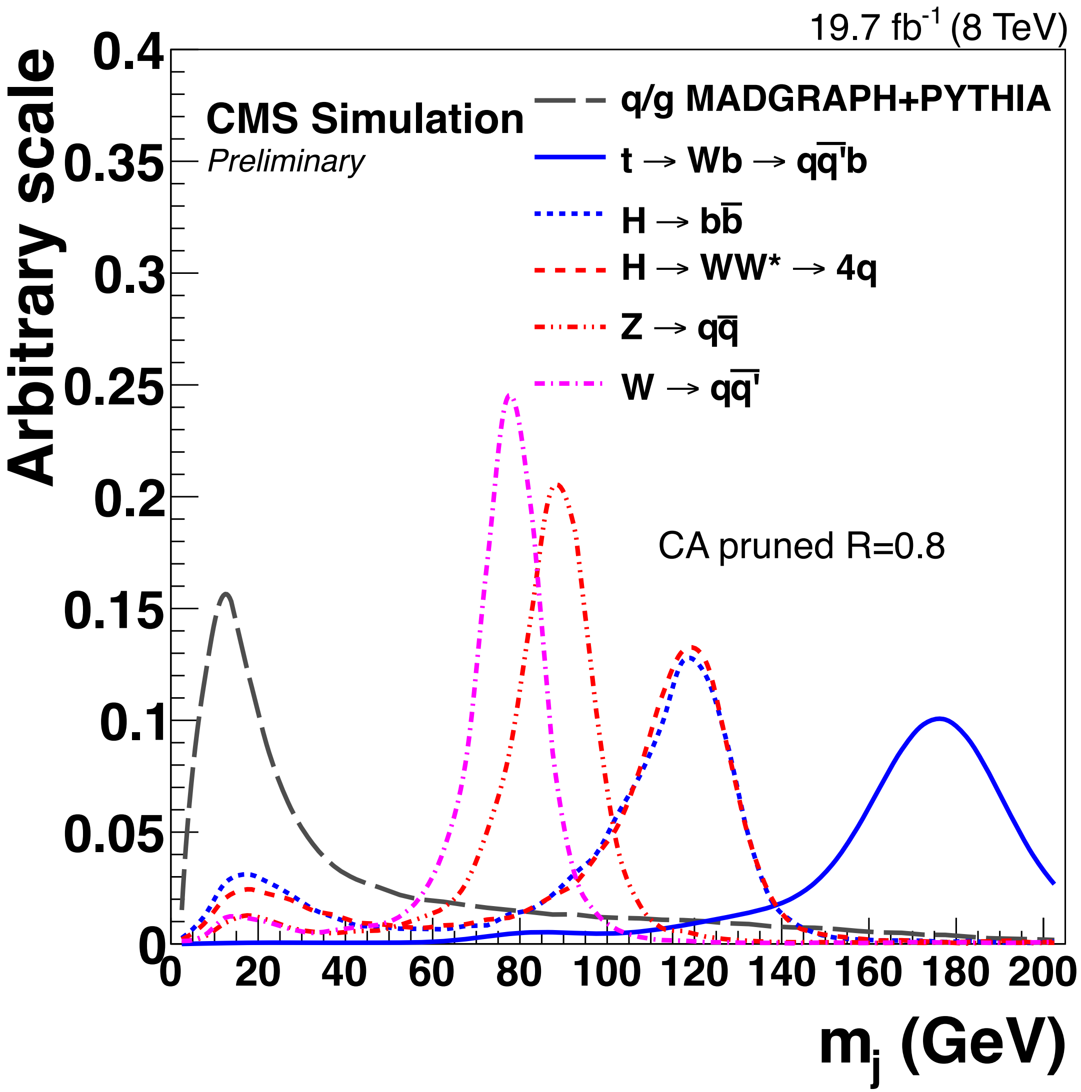
- The standard model process of top quark decay gives standard candle



Example from ATLAS : Identifying boosted W boson from top-quark decays



So we know we can disentangle W-jet, Z-jet, and H-jet through jet mass



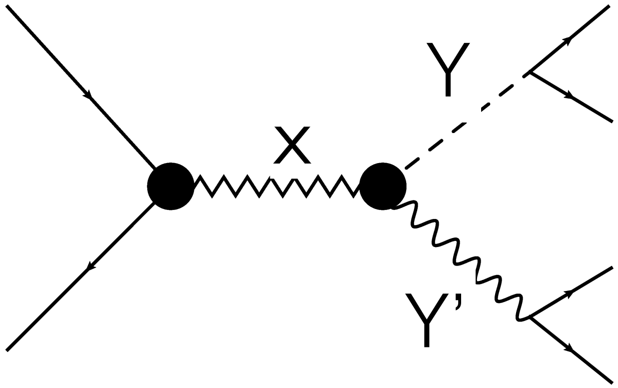
Diboson resonances

Extra dimensions

Composite Higgs

Extended gauge symmetry
(more Z' and W' bosons)

Signature is TeV-mass diboson resonance X



X is a new BSM particle at TeV-scale
Y is a W, Z, or H boson

Keep in mind for the rest of this talk :
The boson P_T being probed in a diboson search is ~ half the mass of X

ATLAS new particle flow for V-tagging

- **Standard : Locally calibrated (LC) topo-clusters** [Eur. Phys. J., 1603.02934]

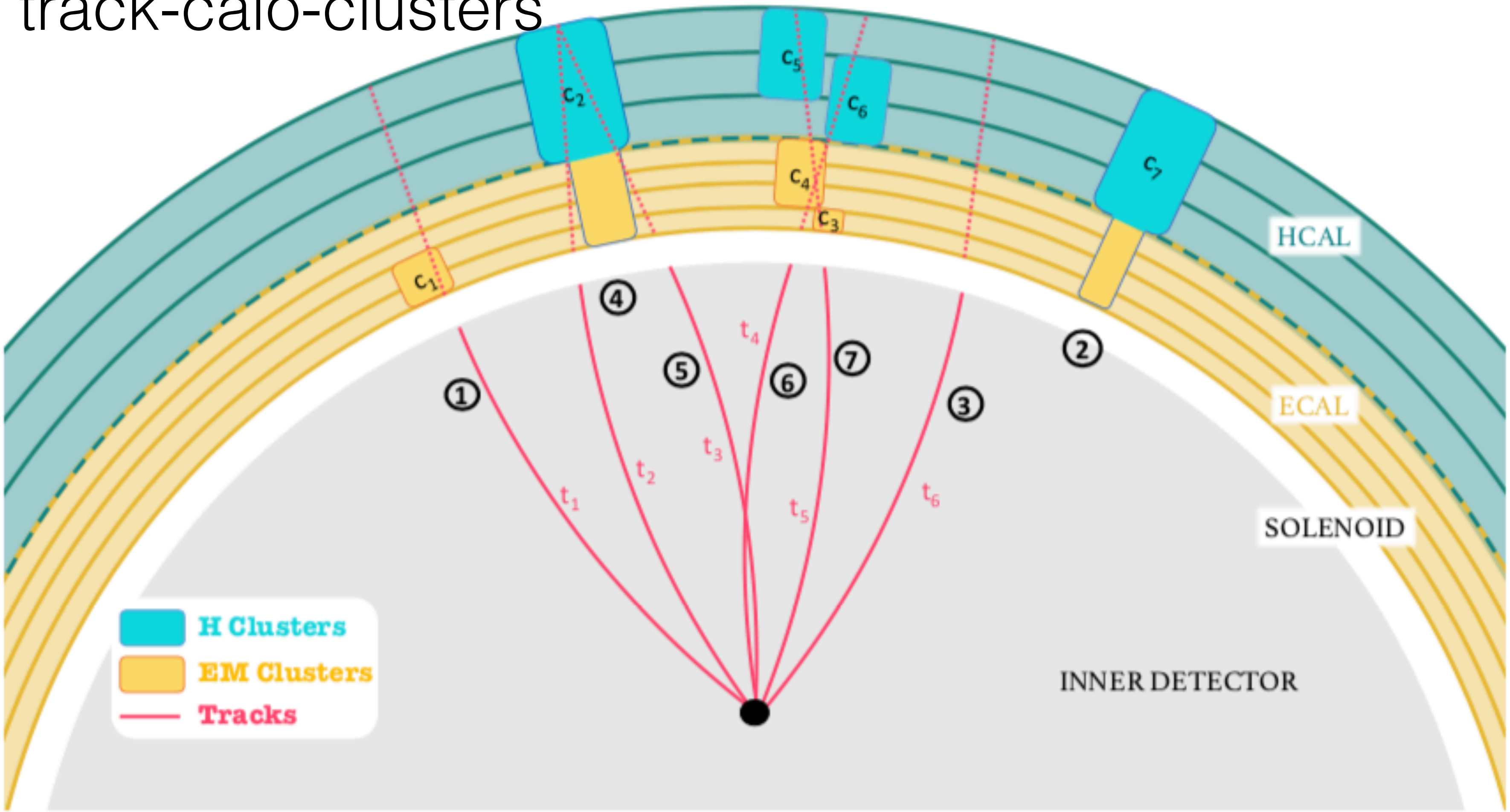
+ Excellent jet energy resolution based on noise-suppressed calorimeter cell clustering

- Granularity of calorimeter insufficient to resolve angular separation from highly-boosted hadronic decays

- **New : Track-Calo cluster (TCC) algorithm** [ATL-PHYS-PUB-2017-15]
  - Combined TTCs (clusters matched to primary-vertex tracks)
    - Robust against pile-up (remove combined TTC if matched to PU vertex)
    - Yields improved angular resolution from tracks
  - Neutral TTCs (clusters not matched to tracks)
    - Not robust against pile-up
- **Followed by trimming procedure** [JHEP 0912.1342]
  - remove pile-up and soft radiation inside large cone

ATLAS : new TCC jets

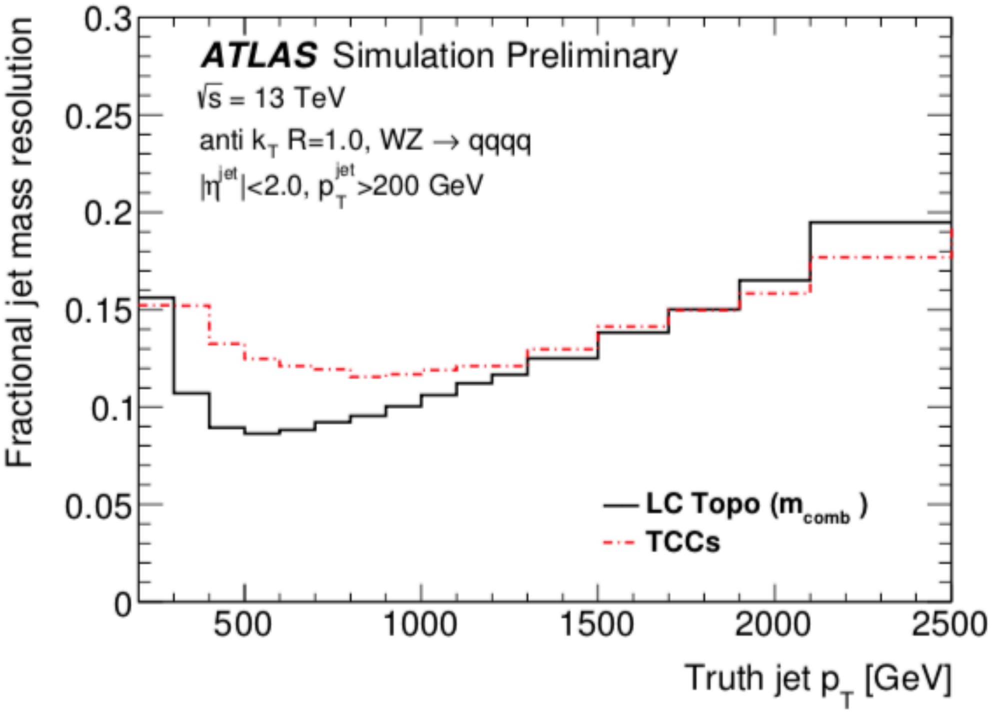
TCC : track-calo-clusters



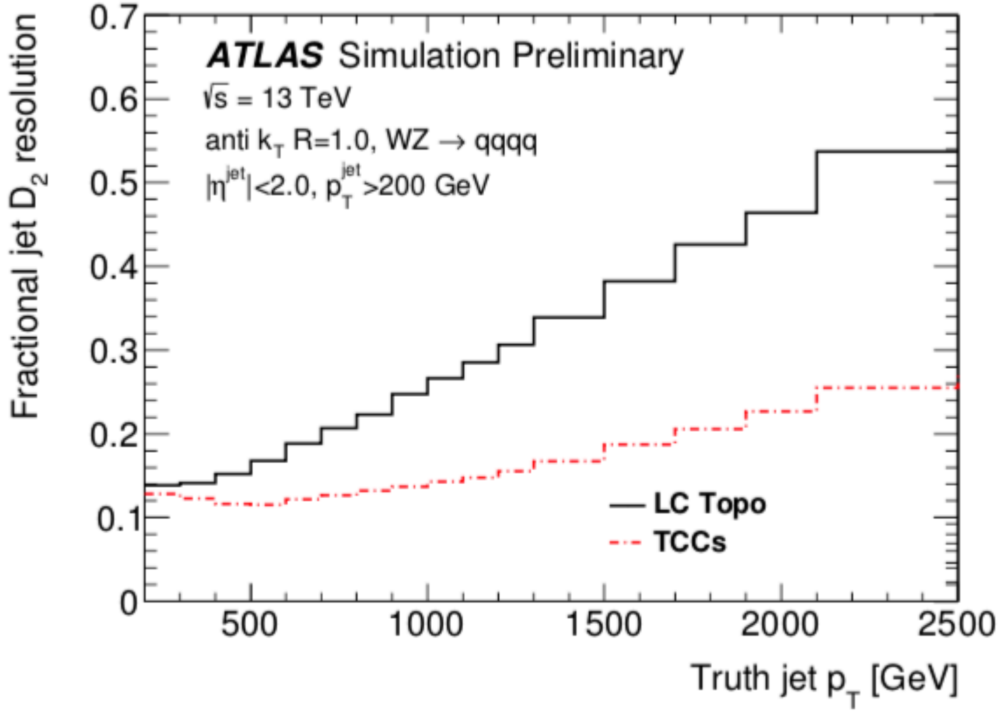
[description at ATL-PHYS-PUB-2017-15]

Performance of new algorithm

ATL-PHYS-PUB-2017-15



(a) Mass



(b) D_2

- While jet mass resolution is not better below P_T of 2 TeV , the resolution of variable D_2, useful for boson tagging does greatly improve

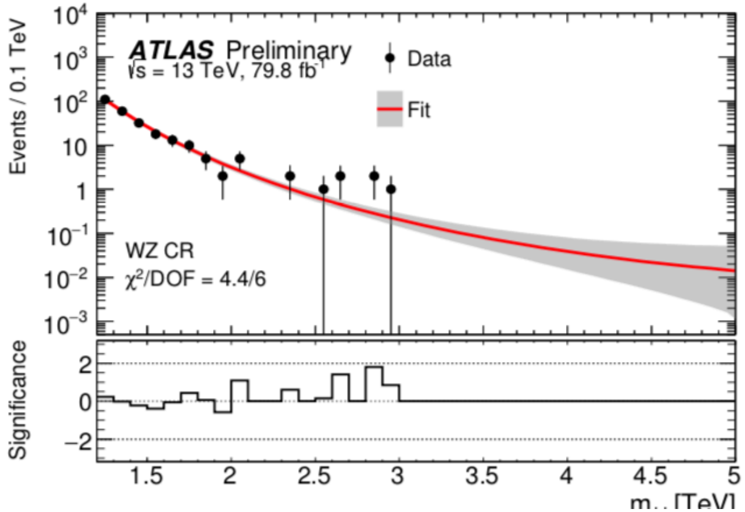
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

Ratio of 3 and 2-point energy correlation functions

[1409.6298, 1305.0007]

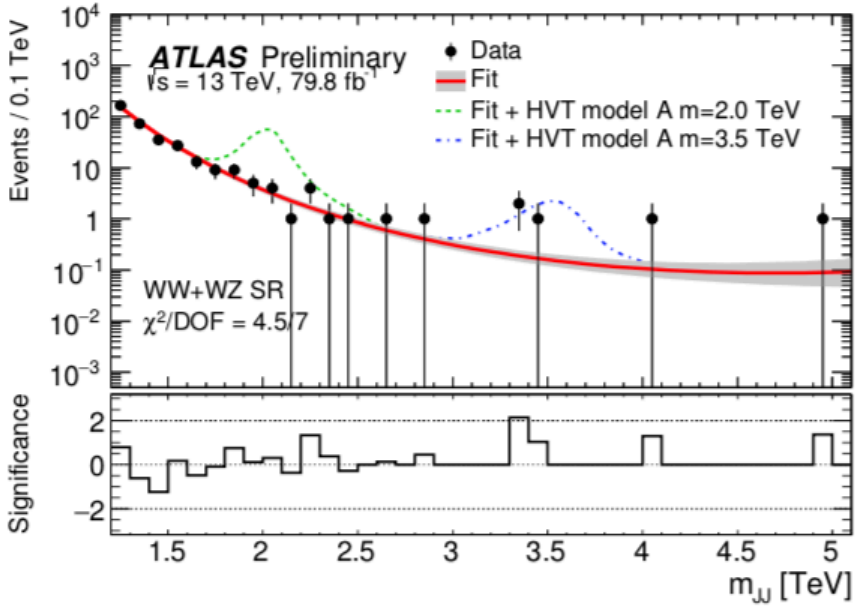
Results on VV search

[ATLAS-CONF-2018-016]

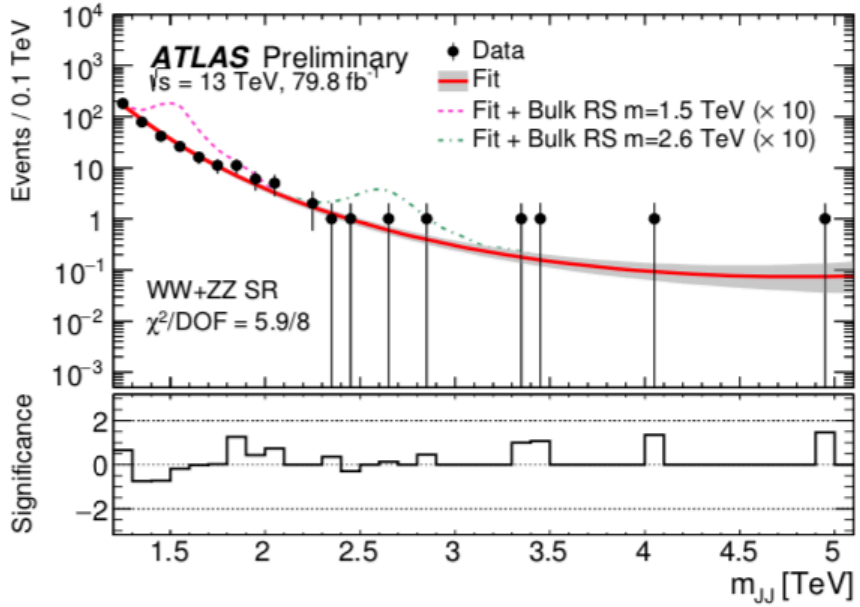


Control region

Signal regions



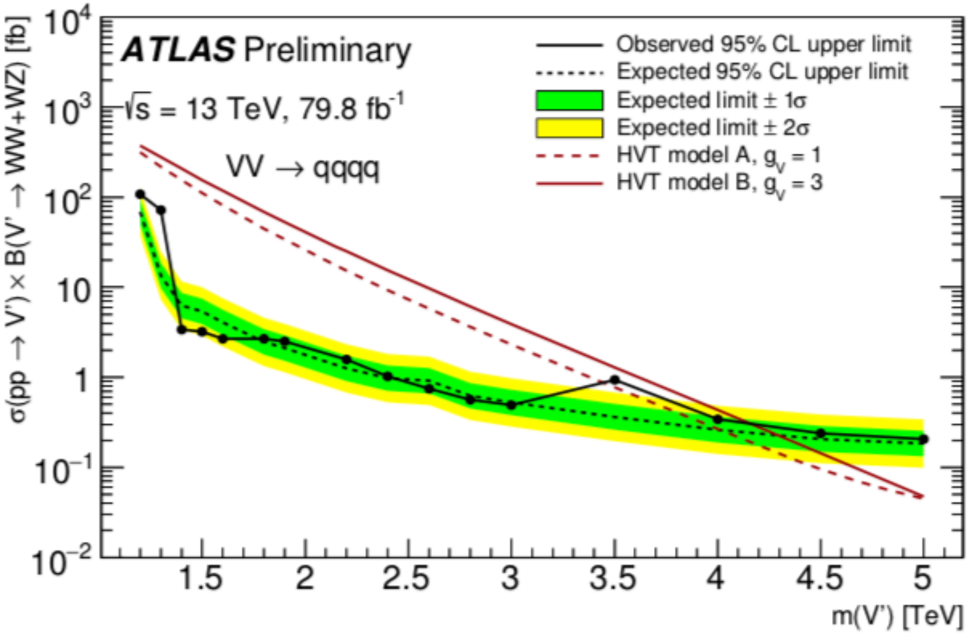
(a) $WZ + WW$ selection



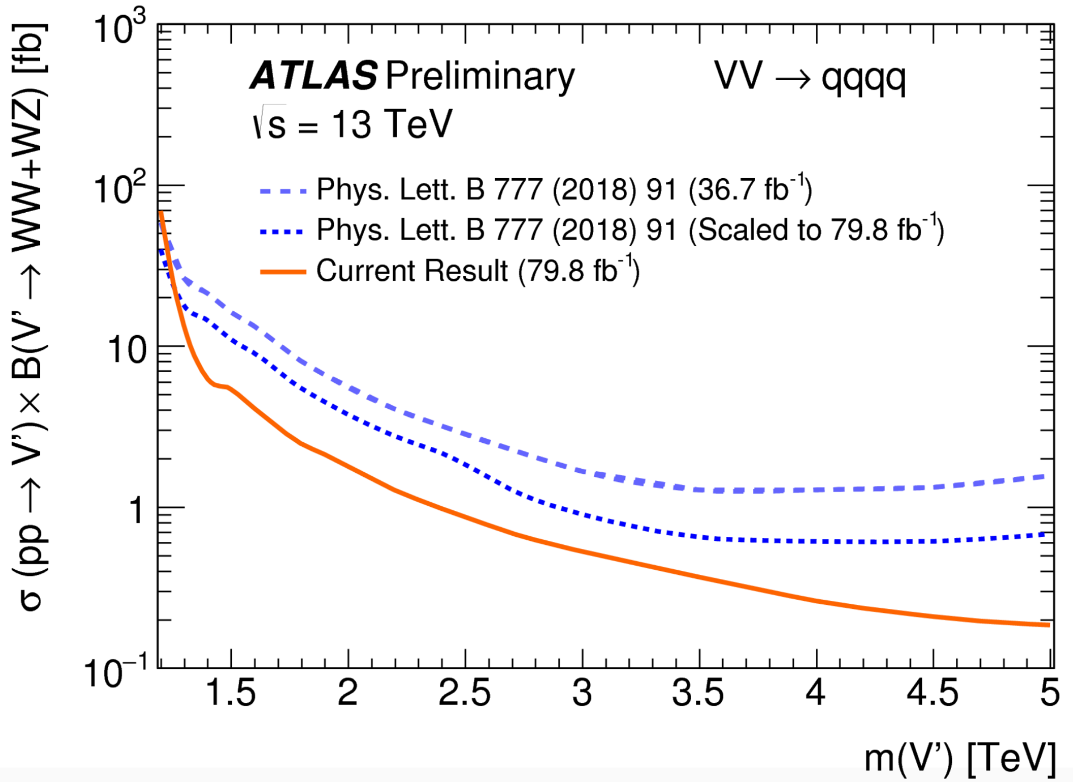
(b) $WW + ZZ$ selection

Note : Data out to $P_T > 2$ TeV

Resonance interpretation



(a) HVT $V' \to WW + WZ$

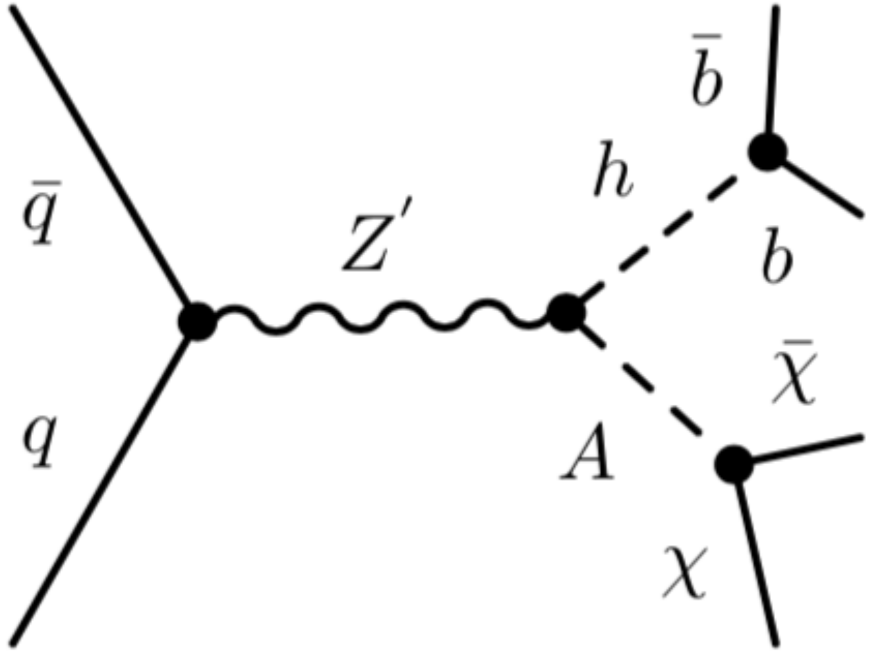


Note : Limits out to boson P_T > 2 TeV

Huge gains with new TCC tagger

[ATLAS-CONF-2018-016]

Higgs portal to DM



- Signature b-jet(s) opposite MET

ATLAS: variable-Radius track jets

- Difficult to identify boosted b-jet pairs that are merged
  - Standard algorithm, Fixed-radius (FR) jets less effective at high PT
  - New algorithm, Variable-radius (VR) track jets
    - Radius parameter decreases with jet PT

$$R \rightarrow R_{\mathrm{eff}}(p_{\mathrm{T}}) \approx \frac{\rho}{p_{\mathrm{T}}}$$

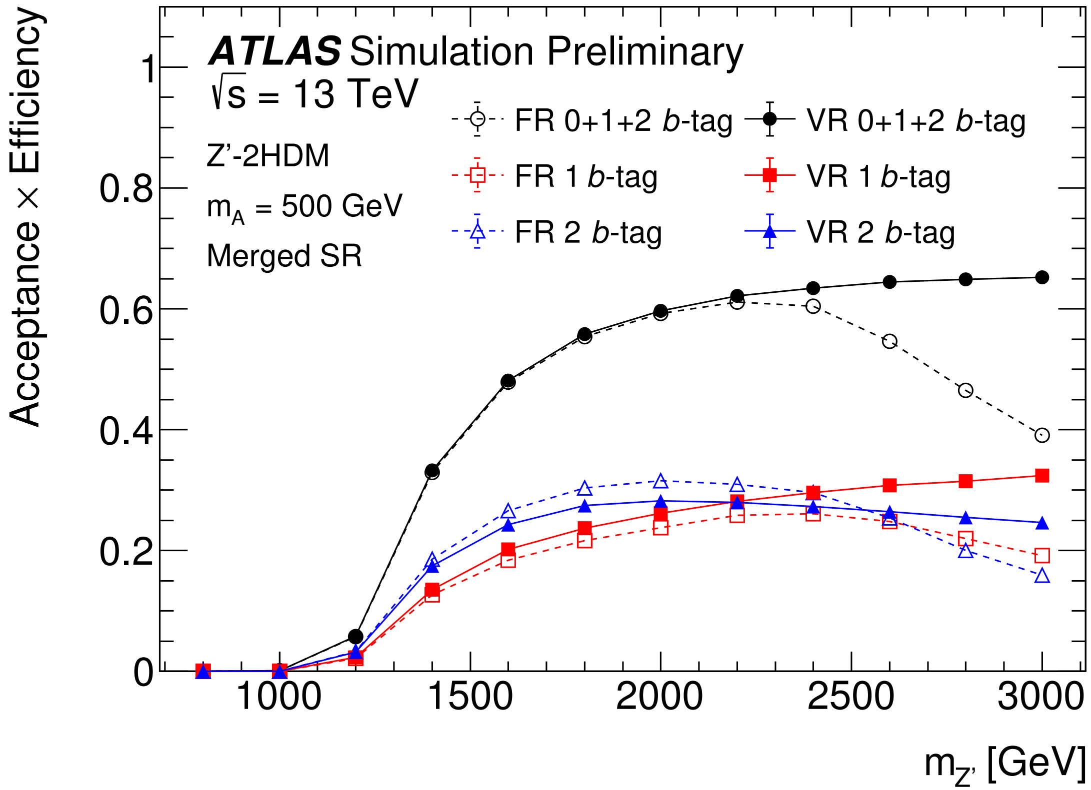
ρ determines how jet-radius scales with jet P_T

Optimized to get :

$\rho = 30$ GeV, $R_{\min} = 0.02$ and $R_{\max} = 0.4$

Identifying B hadrons in fat jets

- VR track jets improve significantly the efficiency for high PT H➞bb tagging (Mass above 2 TeV)

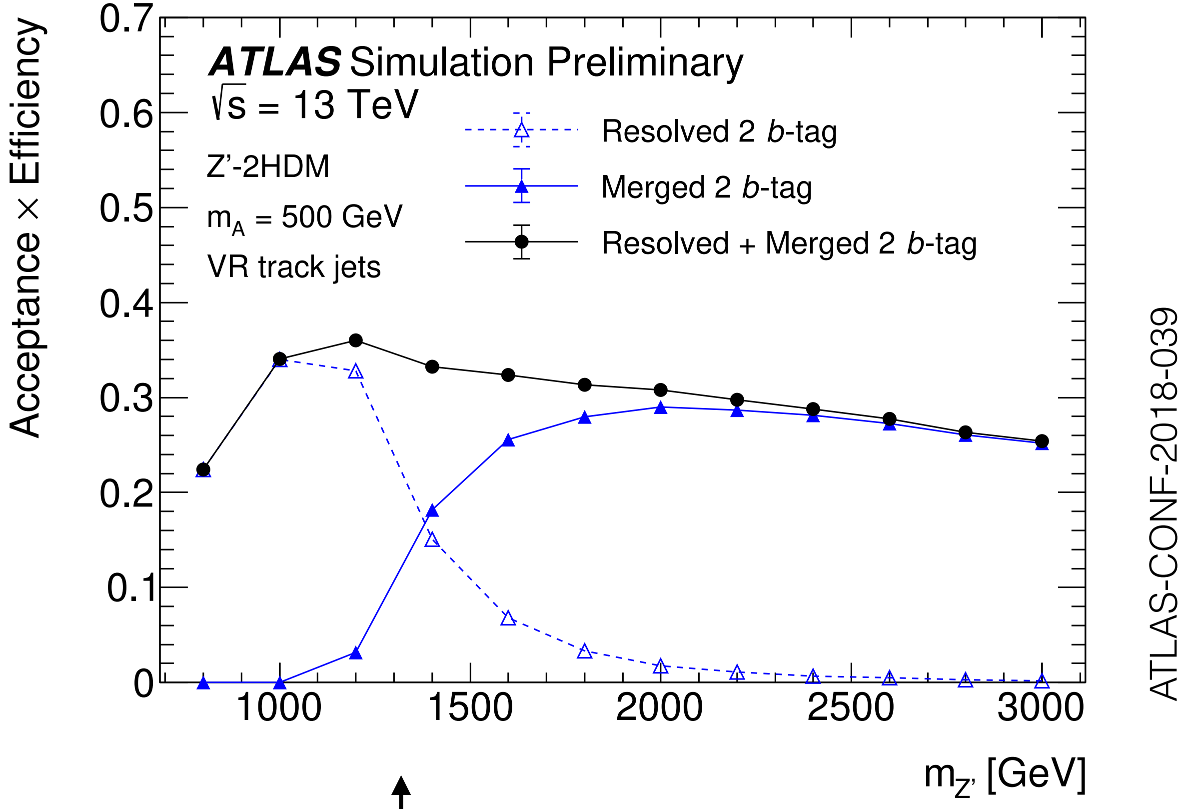


ATLAS-CONF-2018-039

Reconstructing Higgs-jet

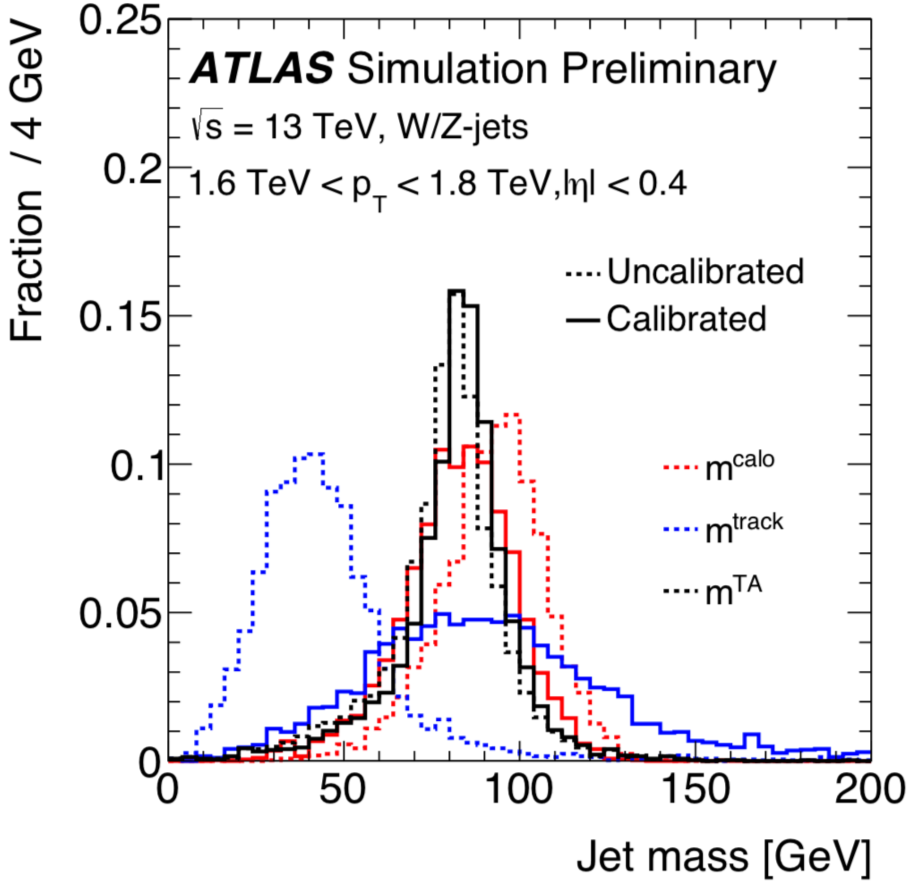
- Gain of using fat jets between 1 and 2 TeV

Jets groomed
Calibrated to particle level



Changeover for boson P_T 500-1000 GeV

Track-assisted jet mass



Calo-jet with track correction

$$m^{\mathrm{TA}} = \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}} \times m^{\mathrm{track}}$$

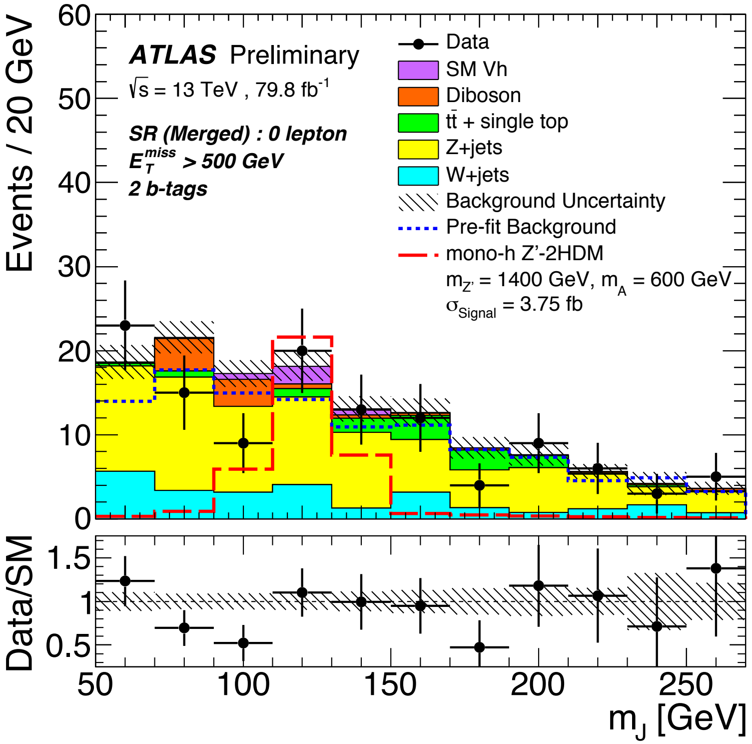
Improves jet mass resolution

→ Improves S/sqrt(B) for boson signal at high P_T

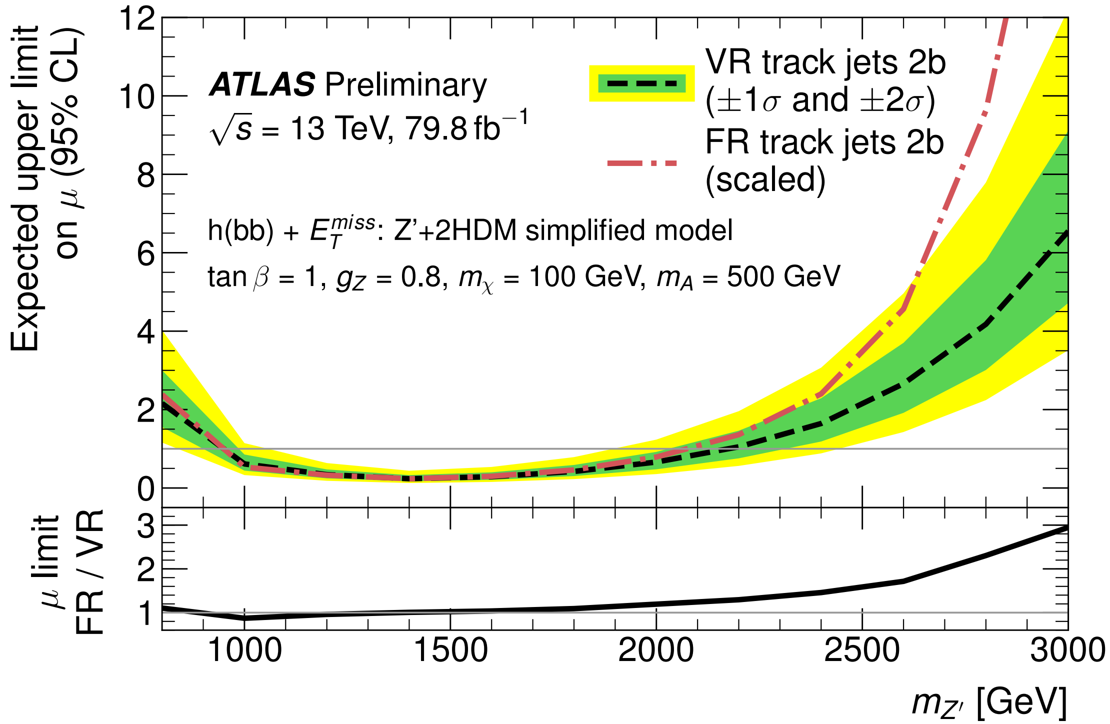
Results on H+DM

ATLAS-CONF-2018-039

ATL-CONF-2018-051



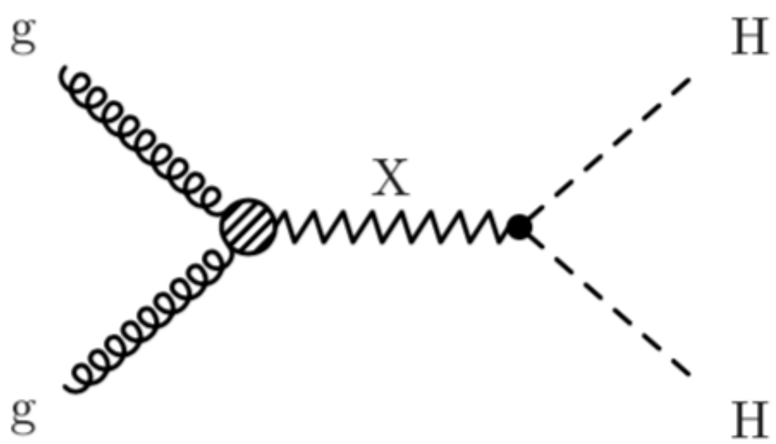
Higgs-Jet mass used to search for signal (and set limits)

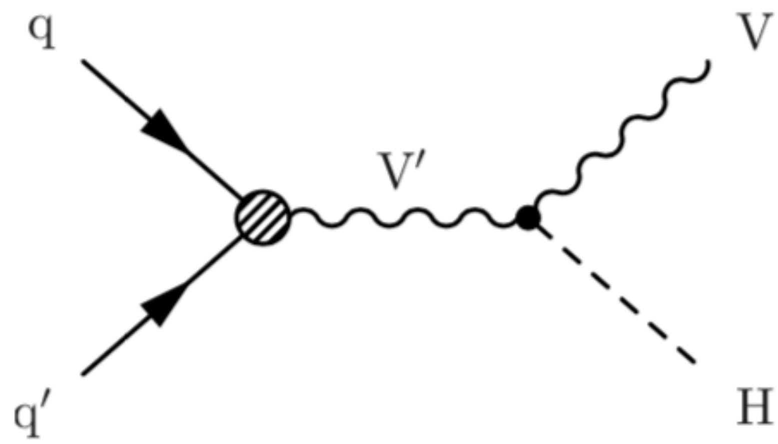


Clear gain from VR jets clear Mass above 2 TeV, (boson P_T > 1 TeV)

boosted HH➞bbττ

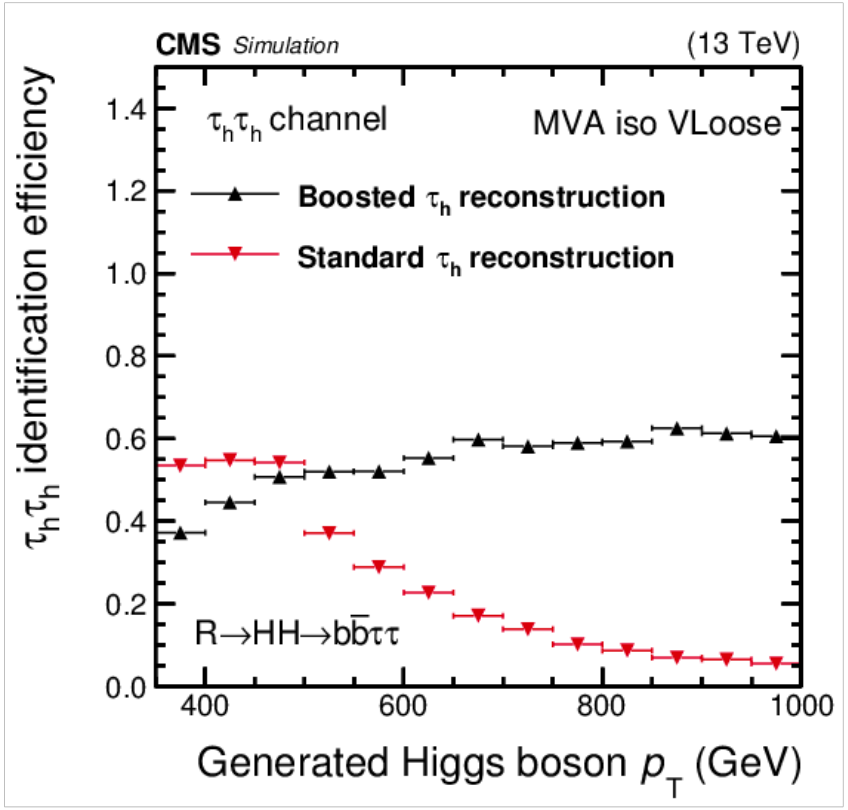
- Motivated by models :
    - X = Spin-2 Bulk graviton, Spin-0 radion
    - Heavy vector boson, V’ = Z’, W’

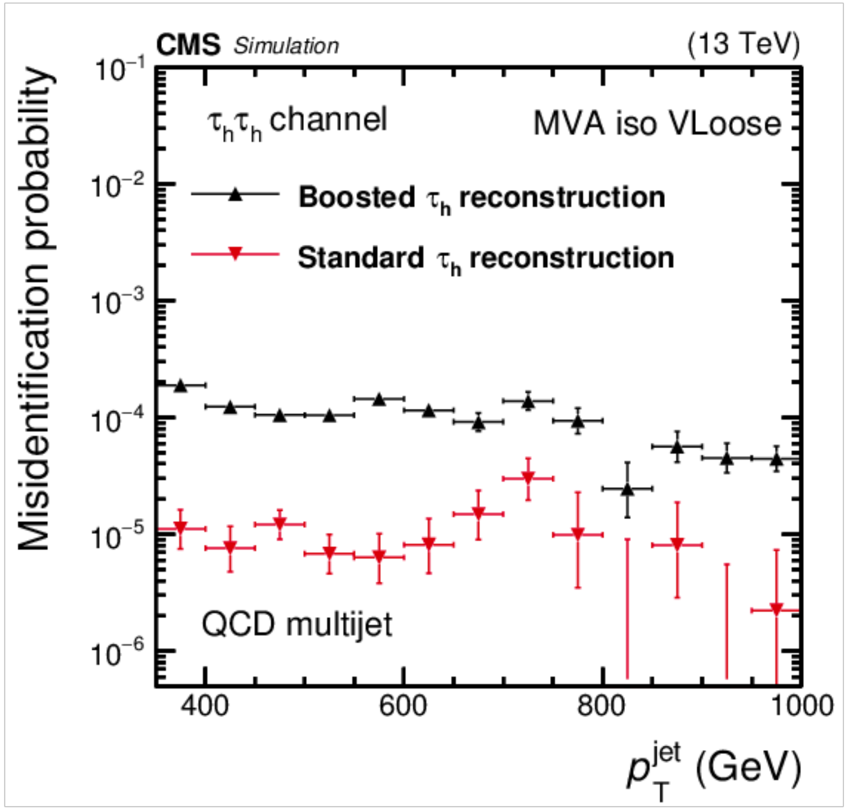




boosted H→ττ identification

1. τ pair algorithm starts with CA8 jets
2. Reverses final step of clustering
3. Applies standard τ ID techniques (HPS) to identify hadronic taus with some modifications on isolation

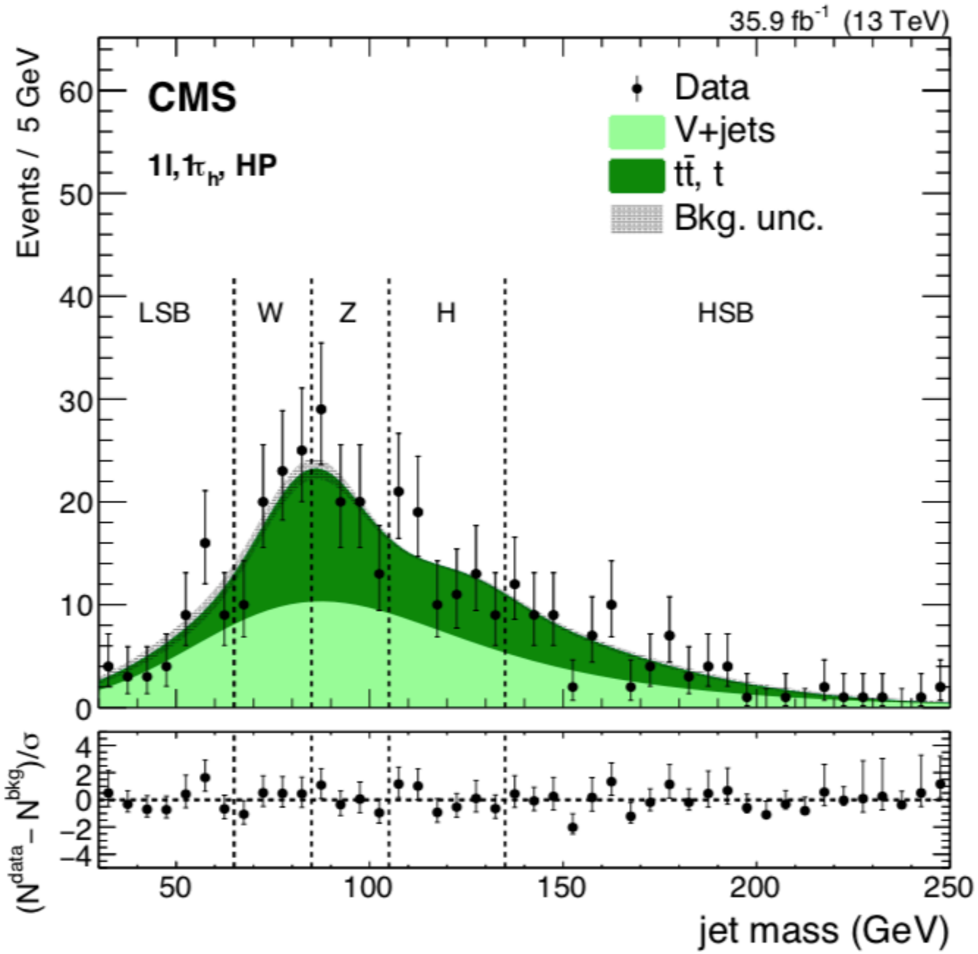




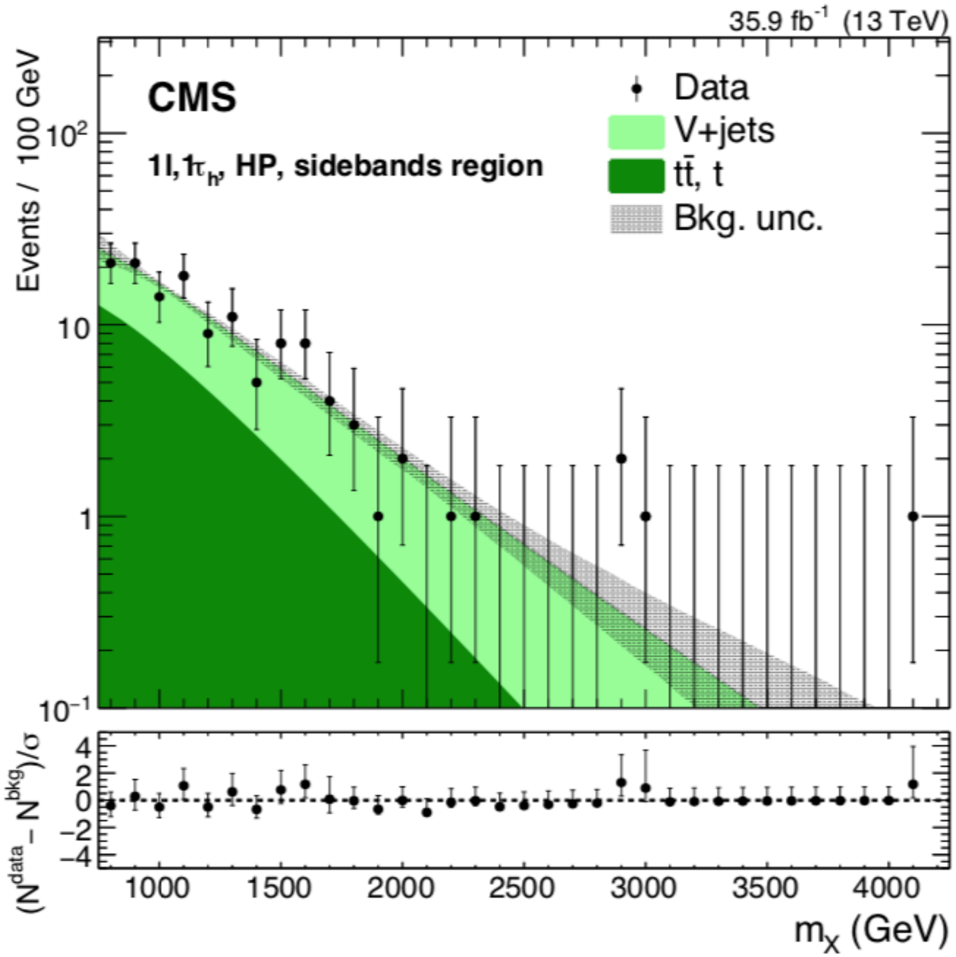
JINST 1809.02816

HH→bbττ data

Jet mass



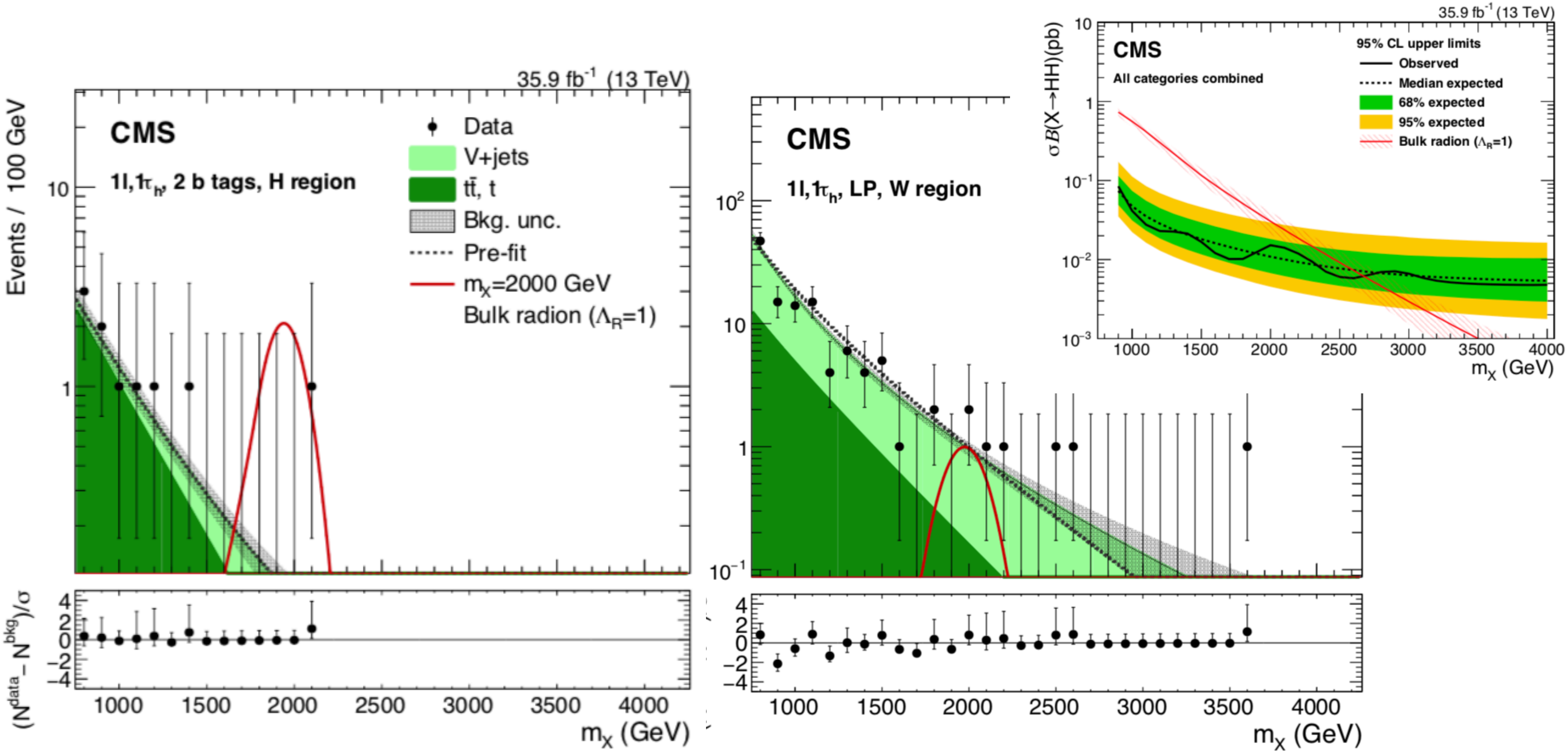
Diboson mass in sidebands



JHEP 1808.01365

Note : Data out to Higgs P_T ~ 2 TeV

HH→bbττ results



Note : Data out to Higgs P_T >1 TeV —> Set limits on new particles up to 4 TeV

boosted SM $H \rightarrow bb$

Conventional wisdom

- Largest sources of Higgs bosons
  - Leading Higgs boson branching ratios
    1. $H \to bb$ (57%)
    2. $H \to WW$ (22%)
  - Leading Higgs boson production mechanisms
    1. ggH (44 pb)
    2. VBF H (3.7 pb)

➡ Most signal comes from $gg \to H \to bb$ (25 pb)

➡ However, bb background is large (560 ub : 10^7 bigger !) [1]

➡ **CW : despite being our biggest source of Higgs bosons, $gg \to H \to bb$ impossible !**

[1] LHCb PRL 1612.05140

But, is there a way to find $gg \rightarrow H \rightarrow bb$?

Perhaps by identifying high P_T bosons, where S/B is more favorable

Get inspiration from searches for new physics decaying to boosted Higgs bosons

Ingredients to gg+ISR → boosted H →bb

1. Start with AK8 jets

2. Apply PUPPI to remove pileup

    1. Fix P_T and η problems introduced

3. Trim jets & apply soft-drop to remove soft, wide-angle emissions to get jet mass - make corrections to get correct mass scale

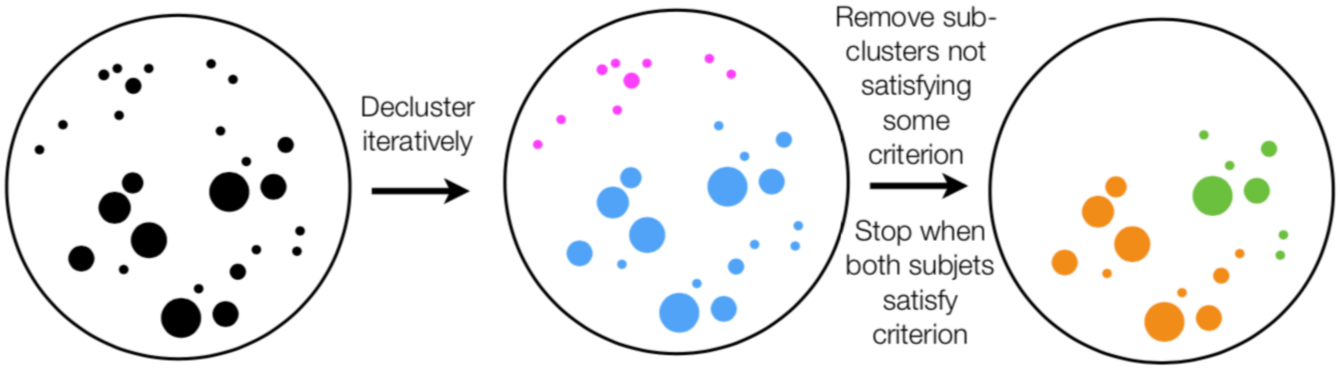
4. Use ρ variable to remove difficult events to model

5. Calculate N_2^1 variable from 2-point and 3-point energy correlation functions

6. Transform $N_2^1 \rightarrow N_2^{1,DDT}$ to flatten effect of QCD, and make cut

7. Select events based on double-b tagger

Soft-Drop

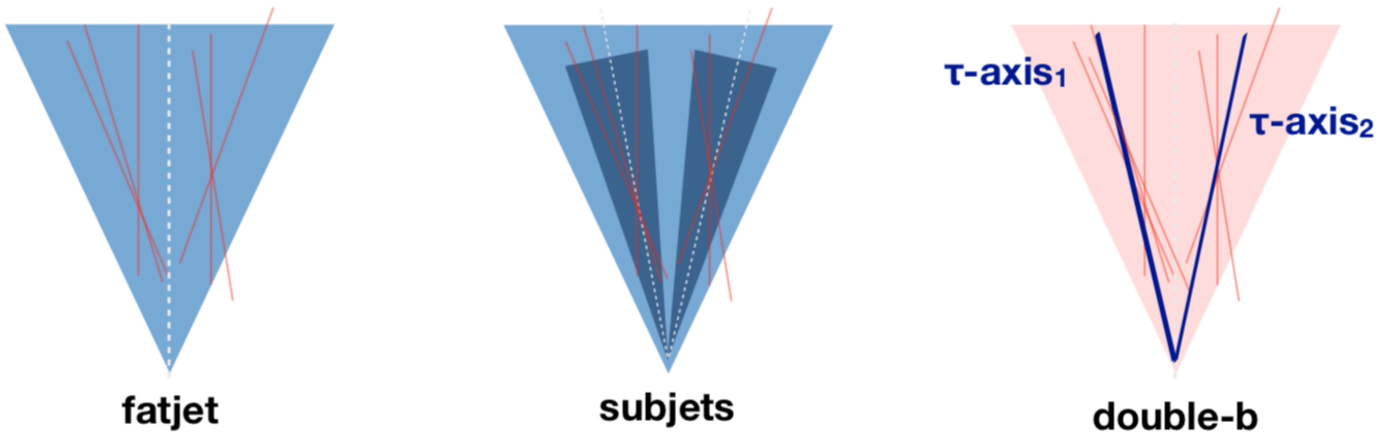


$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

CMS: $z_{cut} = 0.1$, $\boldsymbol{\beta} = 0$

For β = 0, case corresponds to so-called modified mass-drop tagger" (mMDT) [1307.0007, 0802.2470]

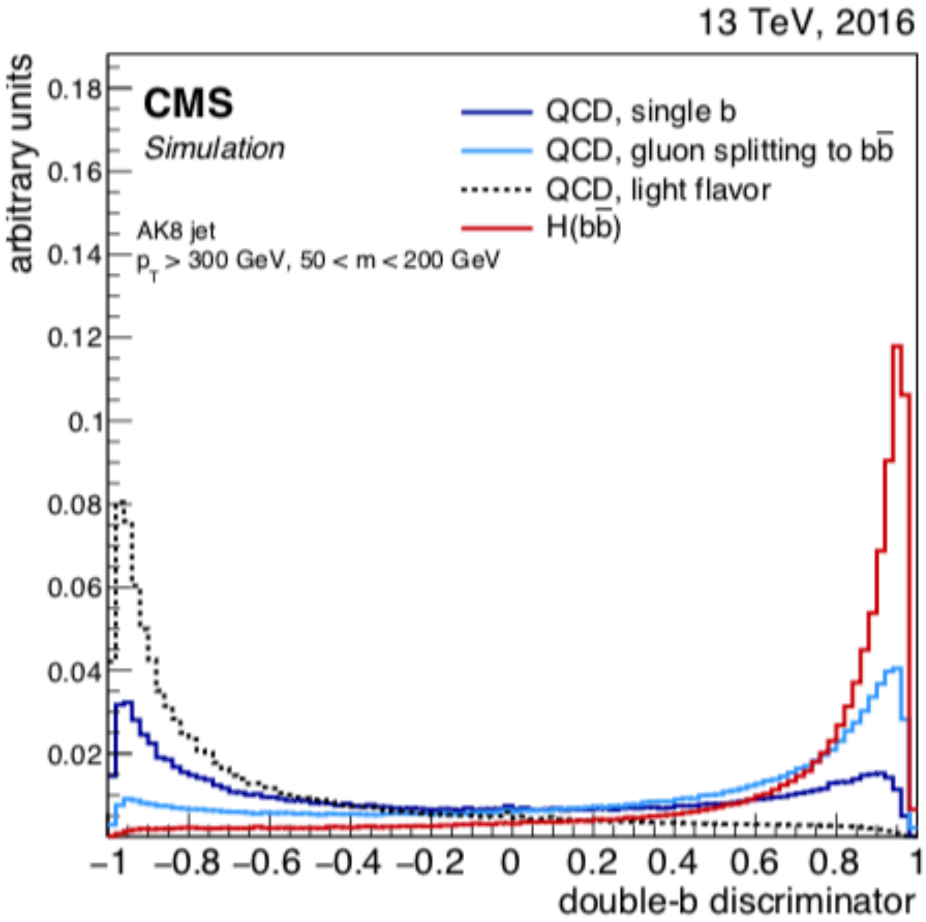
Double b-tagger

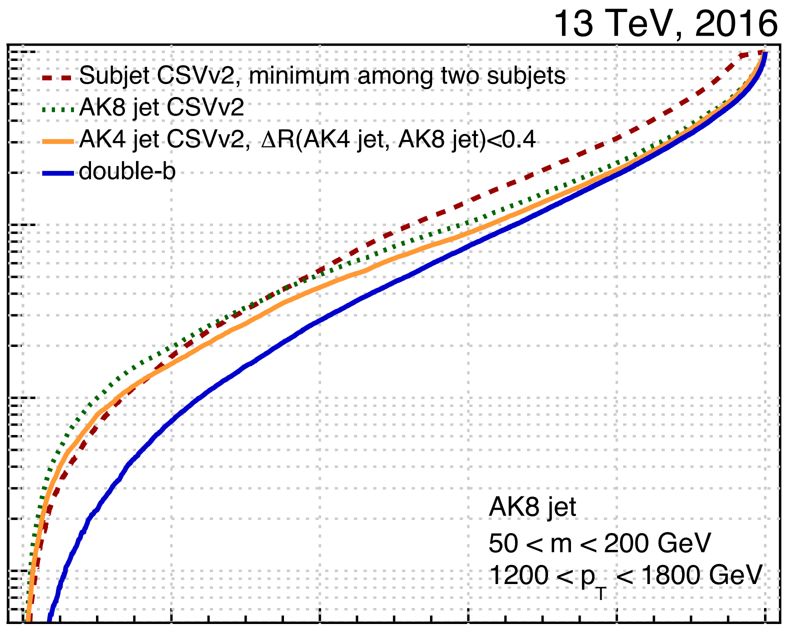


1. The two τ_2 axes matched to secondary vertices using IVF algorithm (Inclusive Vertex Finder) runs on tracks, independent of jets

2. Then, combination of 2nd vtx info and impact parameters of tracks used to define MVA double-b tagger

Tagging jets with 2 b quarks





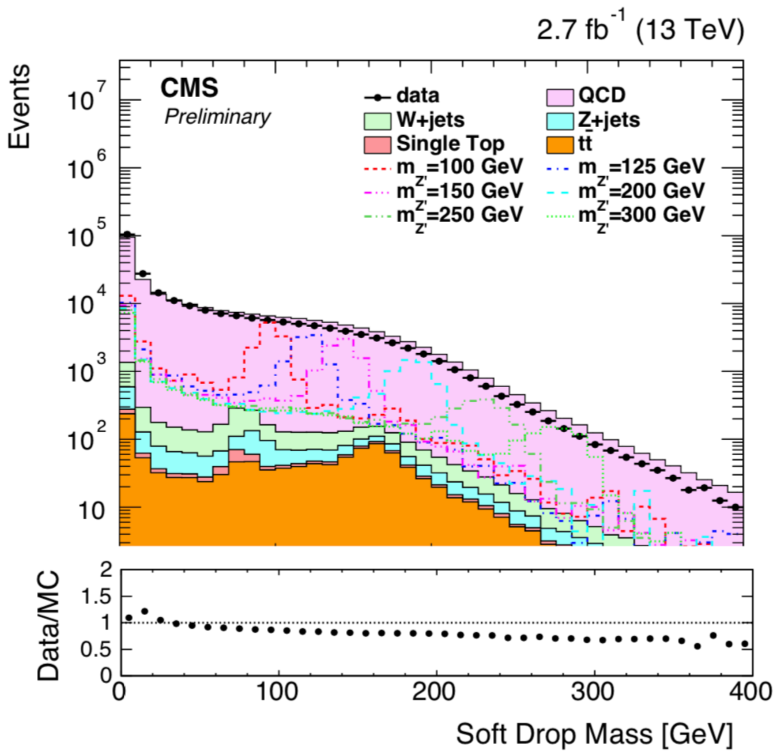
[CMS PAS BTV-15-002]

Modeling of jet mass

PRL 1709.05543

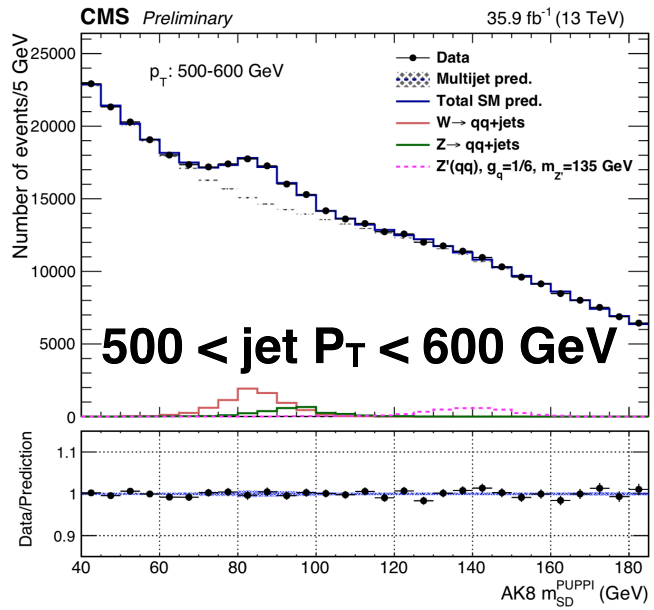
Previously:

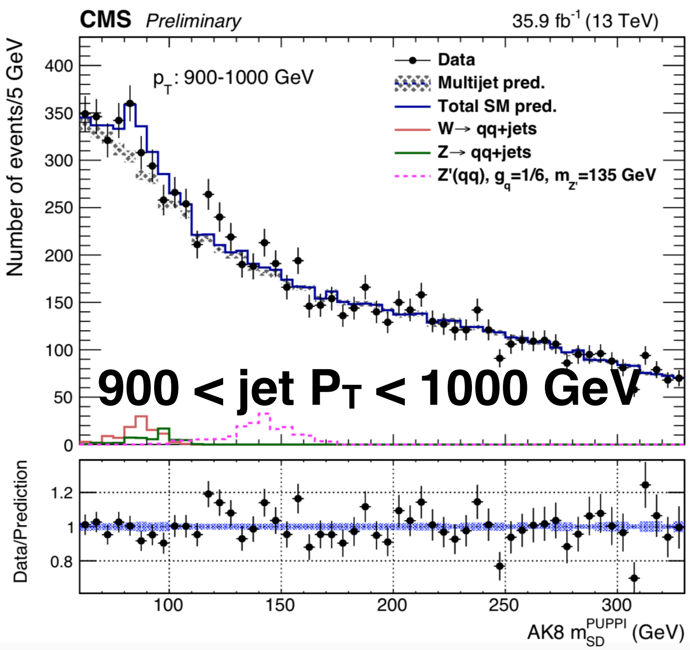
- poor modeling of jet mass
- many parameters to describe fit
- hard to model correctly for all boson P_T



(Can discuss from backups how better modeling is obtained at low and high P_T)

Now : Better fit of mass, across P_T



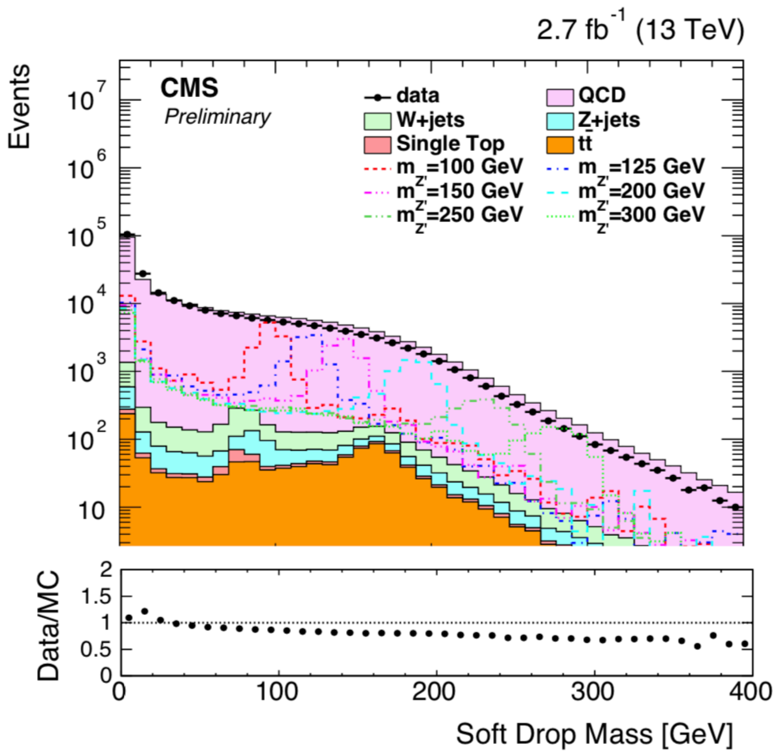


Modeling of jet mass

PRL 1709.05543

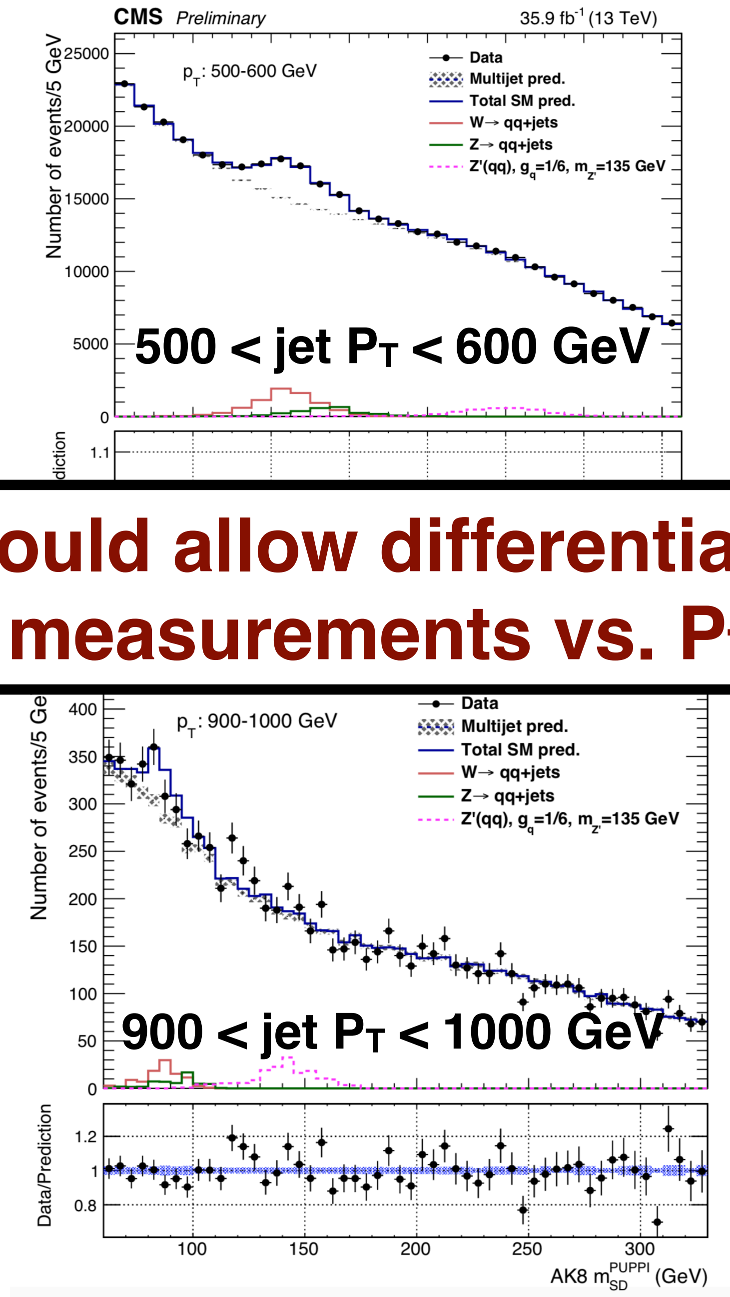
Previously:

- poor modeling of jet mass
- many parameters to describe fit
- hard to model correctly for all boson P_T



(Can discuss from backups how better modeling is obtained at low and high P_T)

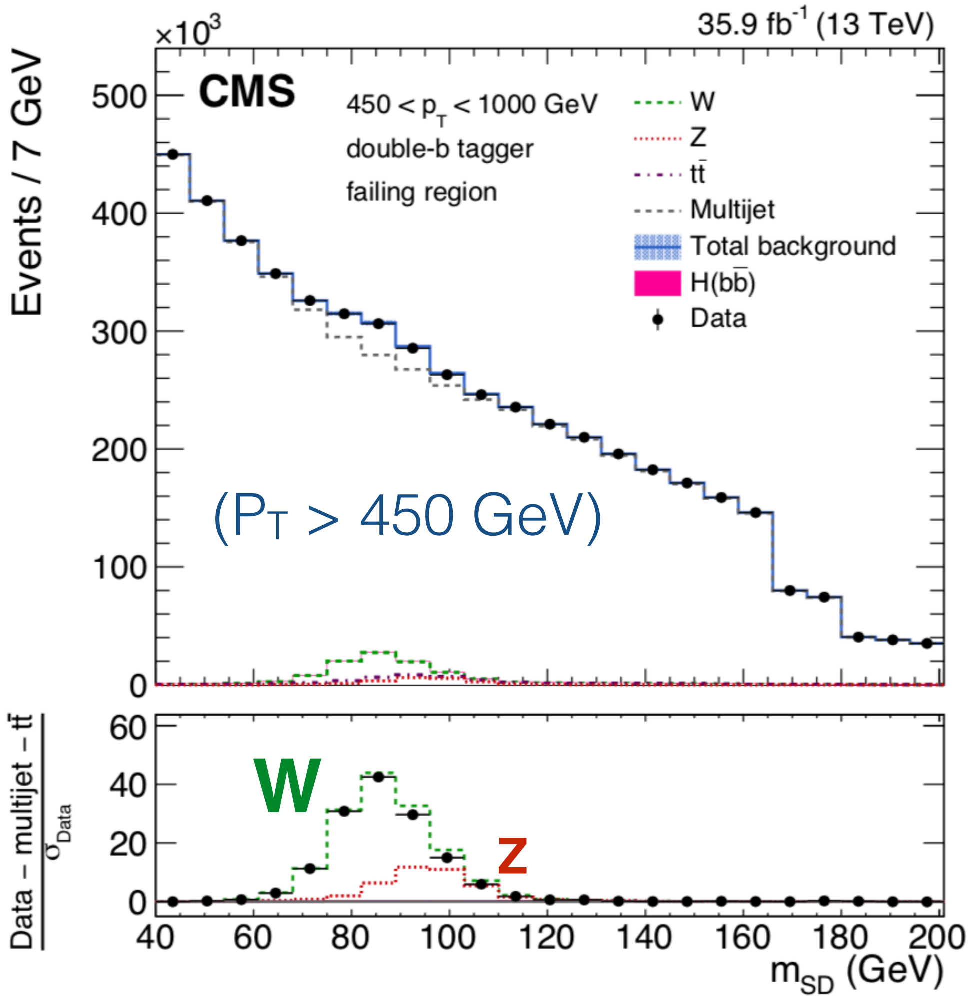
Now : Better fit of mass, across P_T



This could allow differential Higgs measurements vs. P_T

gg→H→bb results

PRL 1709.05543



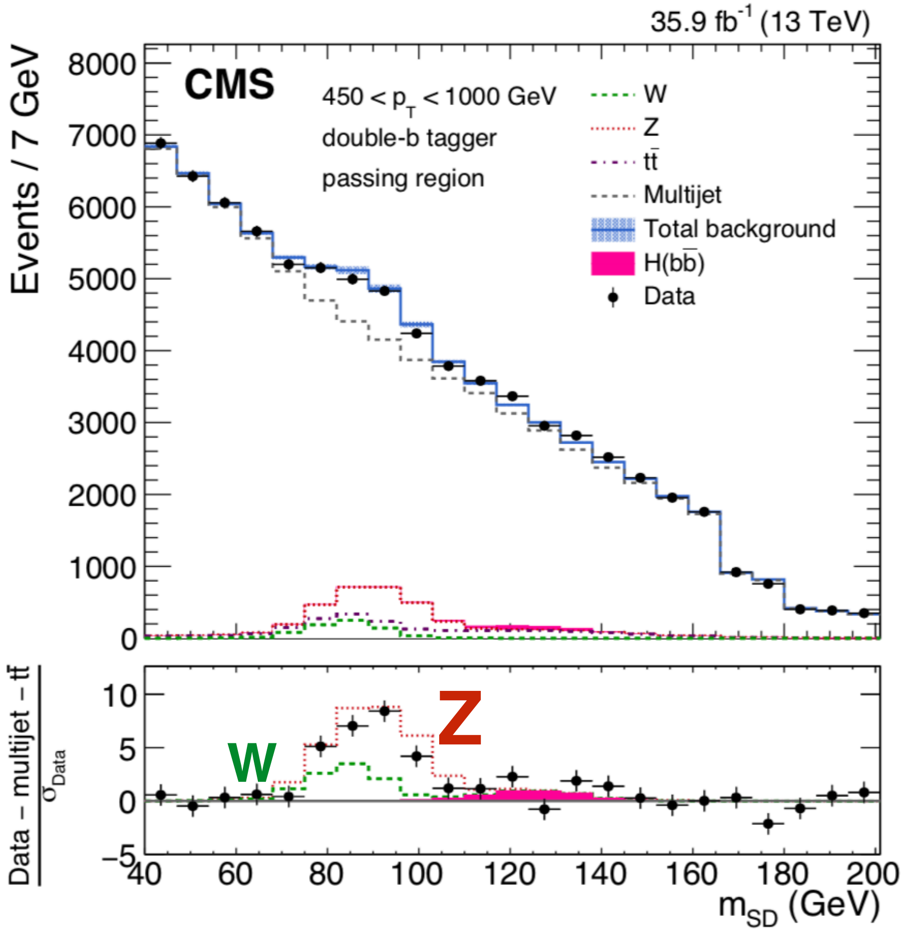
Jet mass

First, consider events failing the double b-tagger

→ **Mainly sensitive to W+jet**

gg→H→bb

PRL 1709.05543



1) **Measurement of Z→ bb**

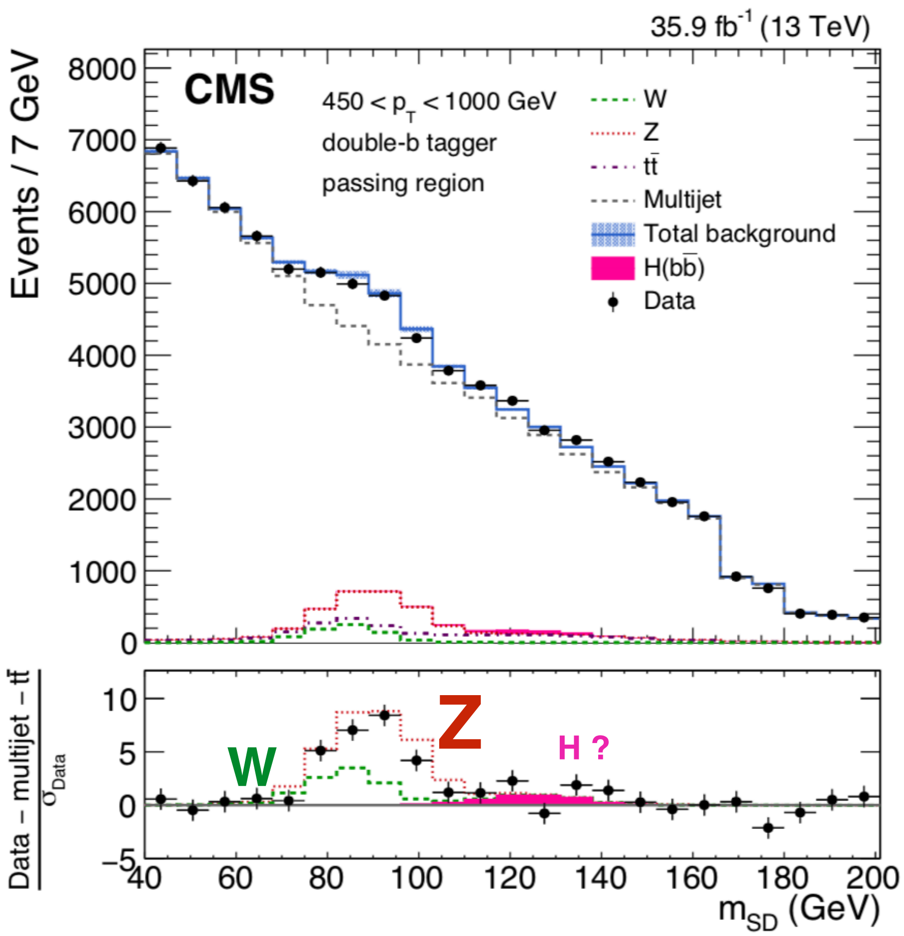
(for Z P_T > 450 GeV)

Expected Z(bb) significance : 5.8σ

Observed H(bb) significance : 5.1σ

gg→H→bb

PRL 1709.05543



1) **Measurement of Z→ bb**

(for Z P_T > 450 GeV)

Expected Z(bb) significance : 5.8σ

Observed H(bb) significance : 5.1σ

2) Search for H→bb

(for H P_T > 450 GeV)

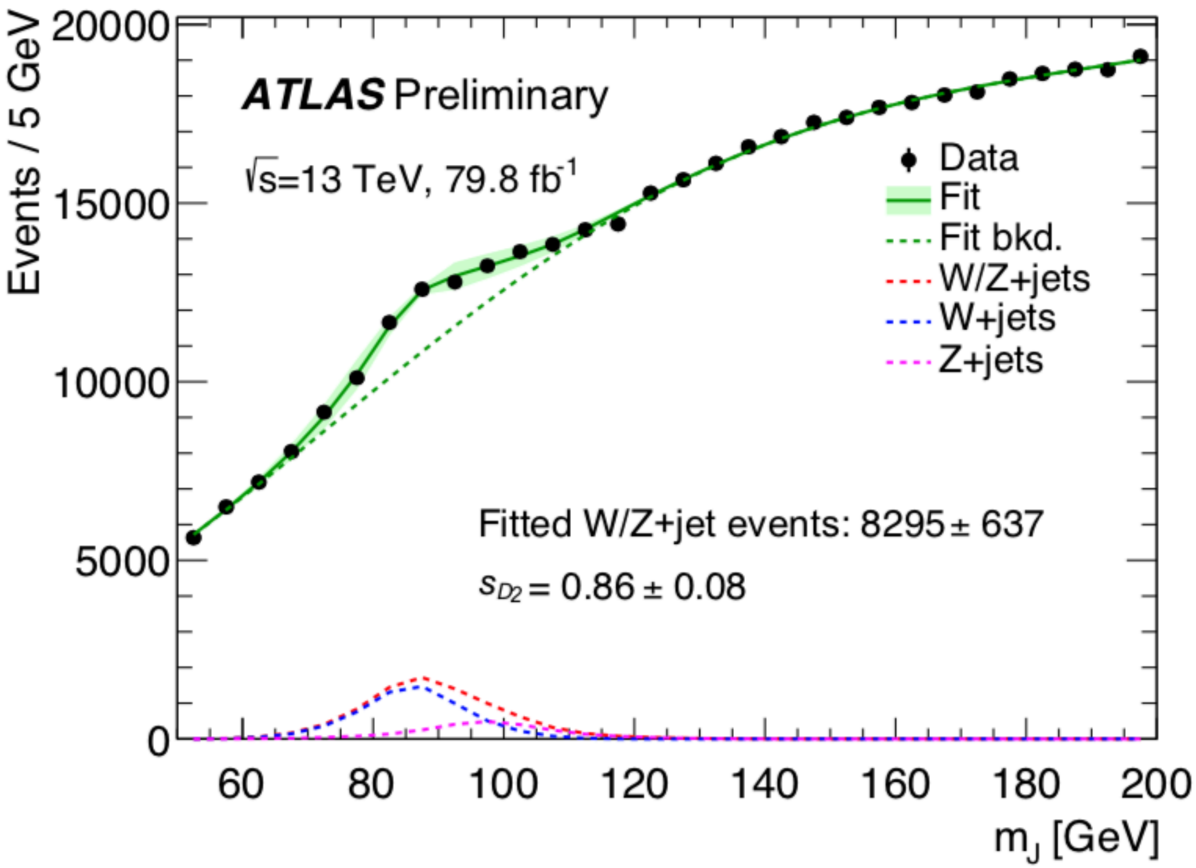
Expected H(bb) sig. : 0.7σ

Observed H(bb) sig. : 1.5σ 🍀

"Measurement" : σ/SM = $2.3^{+1.8}_{-1.6}$

$$74 \pm 48\,(\text{stat})^{+17}_{-10}\,(\text{syst})\,\text{fb}$$

Identifying bosons above QCD



[ATLAS-CONF-2018-016]

For lead jet P_T > 600 GeV

Boson-tagging based on D_2 only

Results make us wonder, could we see H➞bb this way also ?

Summary

- **Presented techniques for identifying high P_T bosons**
  - Boosted W-jet and Z-jet
  - Boosted jets of H(bb) & H(ττ)
- **Can be used to probe for new physics** (heavy vector bosons, radions, bulk gravitons, dark matter, 2HDM, etc.)
- **Can be a tool for SM measurements** (as in gg+ISR→H→bb) not previously thought possible …
  - **Should we be recasting our boosted measurements and searches as differential wrt Higgs jet P_T ?**

Description of techniques and acronyms

- **Hadronic jets**
  - **AK** : Jets clustered with sequential anti-Kt algorithm [0802.1189]
  - **C/A jets** : jets sequentially clustered with Cambridge/Aachen algorithm only uses angular separation to build up successive jets [9907280]
  - **PF** : Particle Flow jets - technique at CMS to combined measurements from calorimeters, trackers, muon detectors to get particles, used for jet clustering [1706.04965]
  - **TCC** : Track-Calo Clusters - technique at ATLAS to combined tracking and calorimeter information, used for jet clustering [ATL-PHYS-PUB-2017-15]
  - **N^1_2** : variable with ratio of 2-point and 3-point energy correlations within jet, used to find boson-jets [1609.07483]
  - **SD (Soft-Drop)** : algorithm for removing soft wide-angle radiation from jet [1402.2657]
  - **jet trimming, pruning** : algorithms for removing small QCD-like emissions from within a jet [0912.1342]
  - **PUPPI** : pileup per particle identification algorithm (CMS) for removing particles likely to be pile-up from jets [1407.6013]
  - **ρ** $= \log(m^2/p_T^2)$: a variable for defining a dimensionless scale for QCD jets, whose distribution varies little over P_T [1307.0007]
  - **DDT** : Designed Decorrelated tagger - a transform of N^1_2 that flattens out the efficiency for QCD jets, uses ρ & p_T [1603.00027]
  - **τ_{21} : N-subjettiness**, τ_1 represents how much a jet seems to have a 1-prong shape, τ_2 is how much it has a 2-prong shape, etc. The variable τ_{21} is the ratio τ_2 to τ_1 such that small τ_{21} means a jet is more likely to have a 2-prong structure [1011.2268]

Description of techniques and acronyms

- **B-tagging Higgs jets**
  - **VR track jets** : Variable-radius track jets (dependent on P_T) used at ATLAS for B-tagging within large-cone jets [theory 0903.0392, ATLAS implementation ATL-PHYS-PUB-2016-013]
  - **Double B-tagger** : MVA based tagger, used at CMS for tagging Higgs boson, starts with IVF (Inclusive Vertex Finder) that finds secondary vertices in tracks independent of jets, matches to sub-jets from τ_{21} algorithm, and considers variables like impact parameter [CMS-PAS-BTV-15-002]

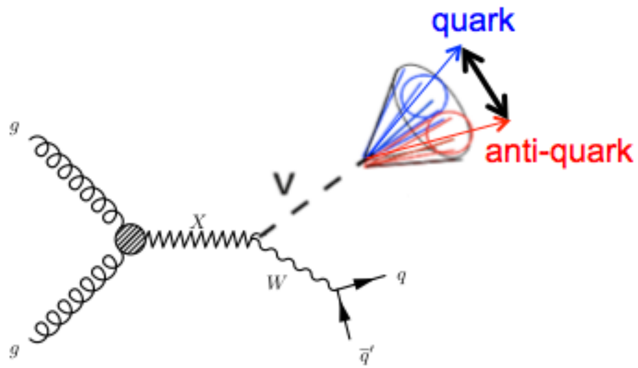
Description of techniques and acronyms

- **Tau identification**
  - **SVFit : algorithm for calculating di-tau invariant mass based on MET and visible products [1104.1619]**
  - **boosted tau lepton ID : CMS techniques for identifying tau leptons in sub-jets of large-R jets [CMS-DP-2016-038]**

Backup

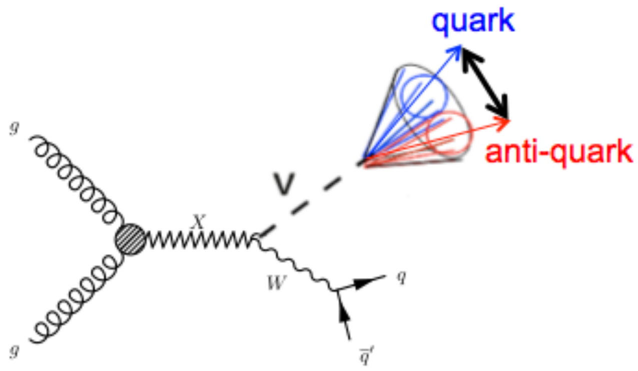
When do we need a boost ?

X ➞ V V ➞ q + q (where V = W/Z, applies to H)



When do we need a boost ?

X → V V → q + q (where V = W/Z, applies to H)



$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}} \approx 2\frac{M_V}{\frac{1}{2}M_X}$$

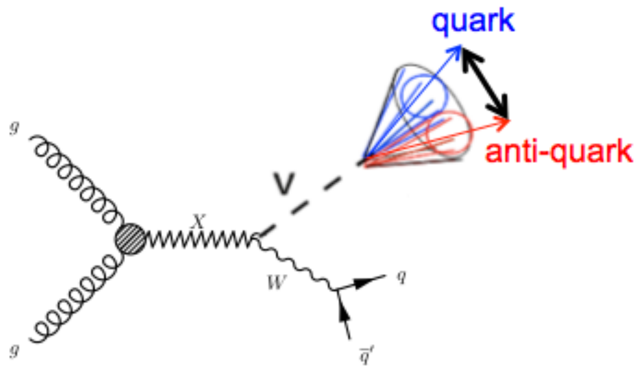
$$M_X = \frac{4M_V}{dR(q,q)}$$

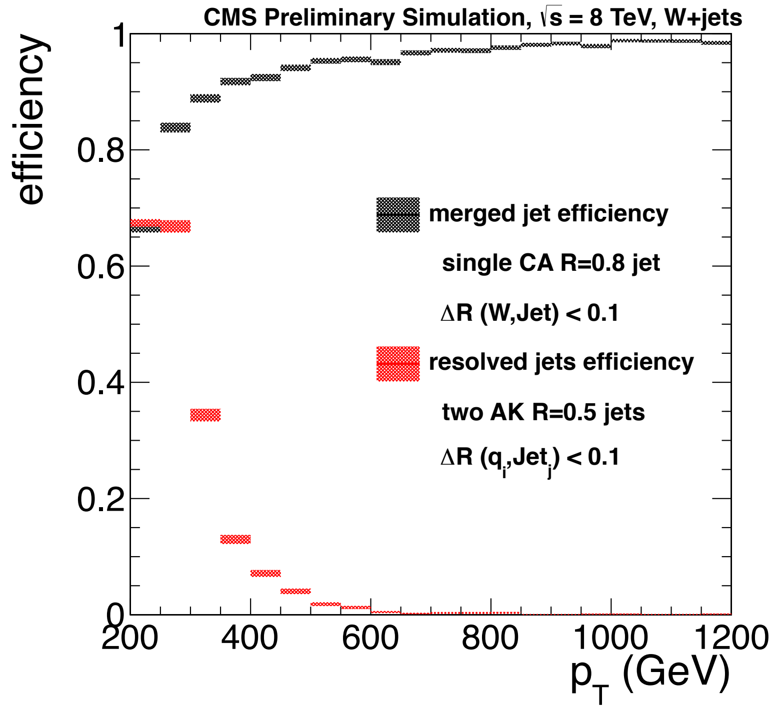
dR(q,q) = 0.5 → $M_X = 8^*M_V$ = 650 - 1000 GeV (W - H)

dR(q,q) = 0.2 → $M_X = 12^*M_V$ = 950 - 1500 GeV (W - H)

When do we need a boost ?

X ➞ V V ➞ q + q (where V = W/Z, applies to H)





$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}} \approx 2\frac{M_V}{\frac{1}{2}M_X}$$

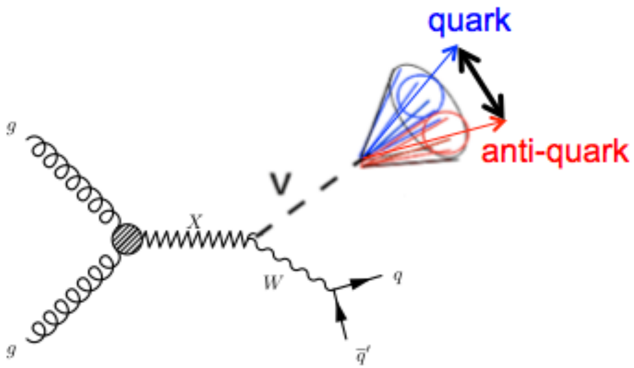
$$M_X = \frac{4M_V}{dR(q,q)}$$

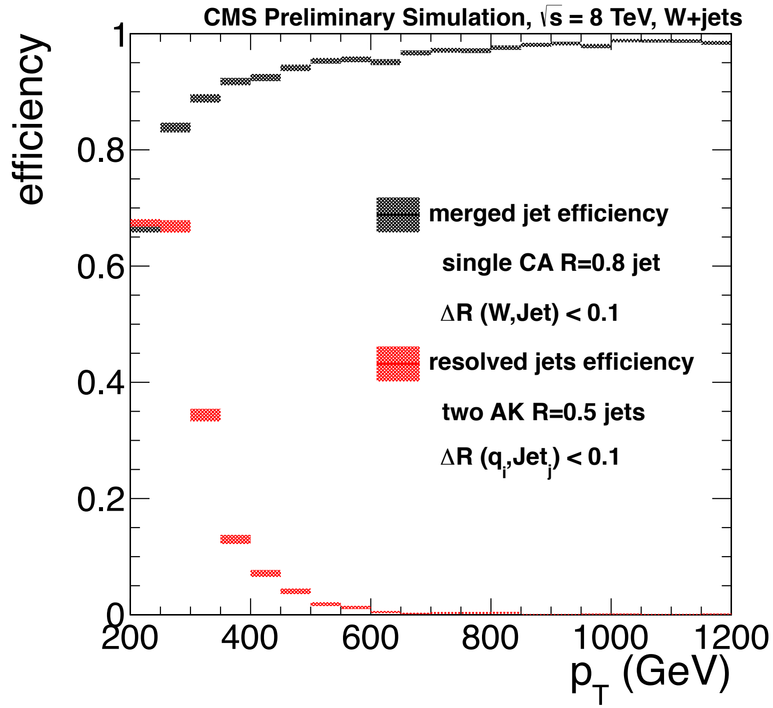
dR(q,q) = 0.5 ➞ $M_X = 8*M_V$ = 650 - 1000 GeV (W - H)

dR(q,q) = 0.2 ➞ $M_X = 12*M_V$ = 950 - 1500 GeV (W - H)

When do we need a boost ?

X ➞ V V ➞ q + q (where V = W/Z, applies to H)





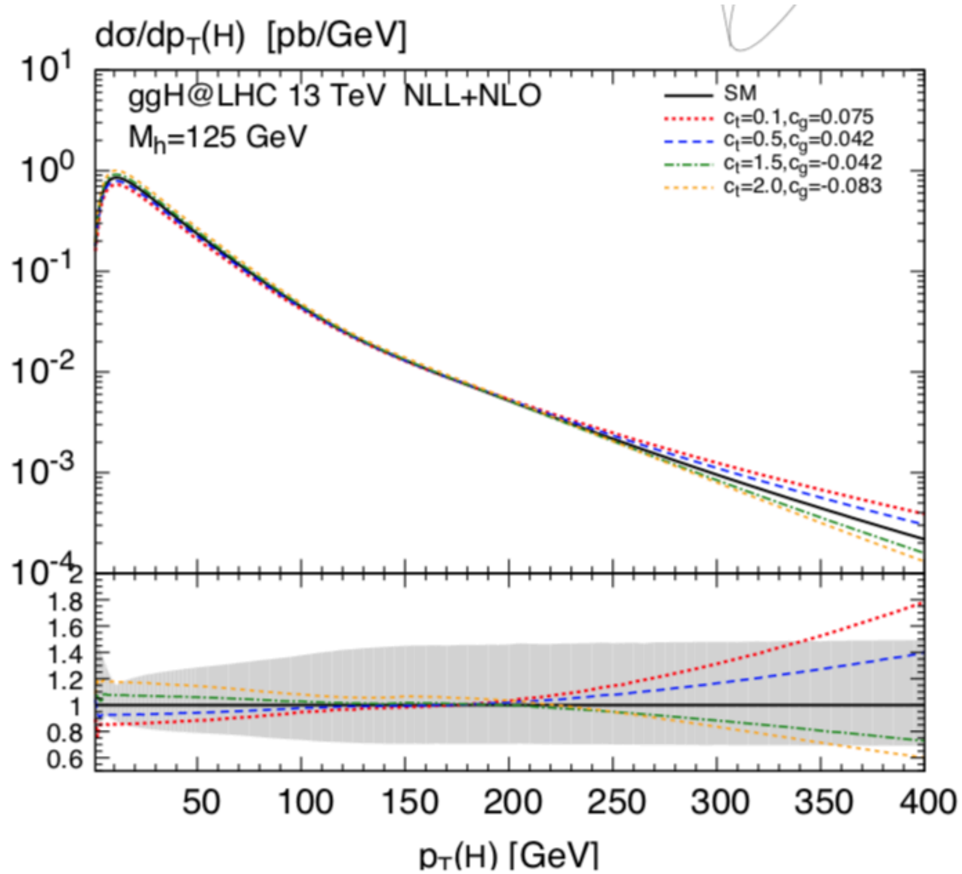
$$\Delta R_{qq}^{\min} \approx \Delta \theta_{qq}^{\min} \approx 2 \frac{M_V}{p_{T,V}} \approx 2 \frac{M_V}{\frac{1}{2} M_X}$$

$$M_X = \frac{4 M_V}{dR(q,q)}$$

dR(q,q) = 0.5 ➞ $M_X = 8^*M_V$ = 650 - 1000 GeV (W - H)
dR(q,q) = 0.2 ➞ $M_X = 12^*M_V$ = 950 - 1500 GeV (W - H)

M_X
< 600 GeV : two resolved cone 0.5 jets
600 - 1000 GeV : wise to consider both boosted and resolved quarks
> 1000 GeV : cone of 0.8 captures sub-jets

New physics in Higgs P_T



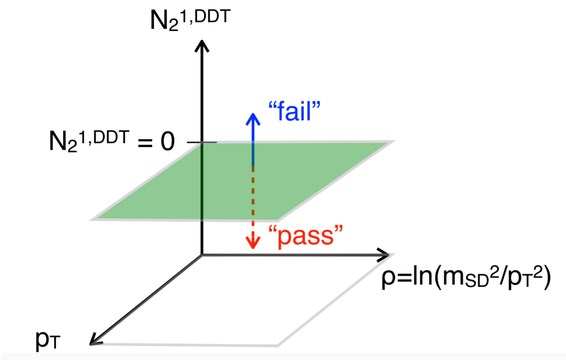
Improved background estimate for high-P_T Higgs with $N_2^{1,DDT}$

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

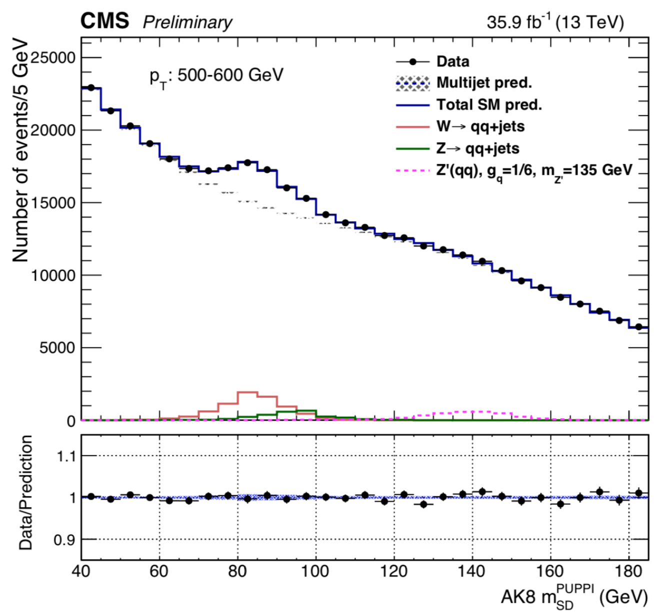
DDT = Designed decorrelated tagger

$N_2^{1,DDT} = N_2^1 - N^1_{2\,(26\%)}$, where $N^1_{2\,(26\%)}$ is the 26th percentile of the N_2^1 distribution in simulated QCD events as a function of ρ and p_T. This ensures that the selection $N_2^{1,DDT} < 0$ yields a constant QCD background efficiency of 26% across the entire ρ and p_T range considered in

Use QCD data to model signal region by selecting events which fail a cut on $N_2^{1,DDT}$



Better fit of mass, across P_T

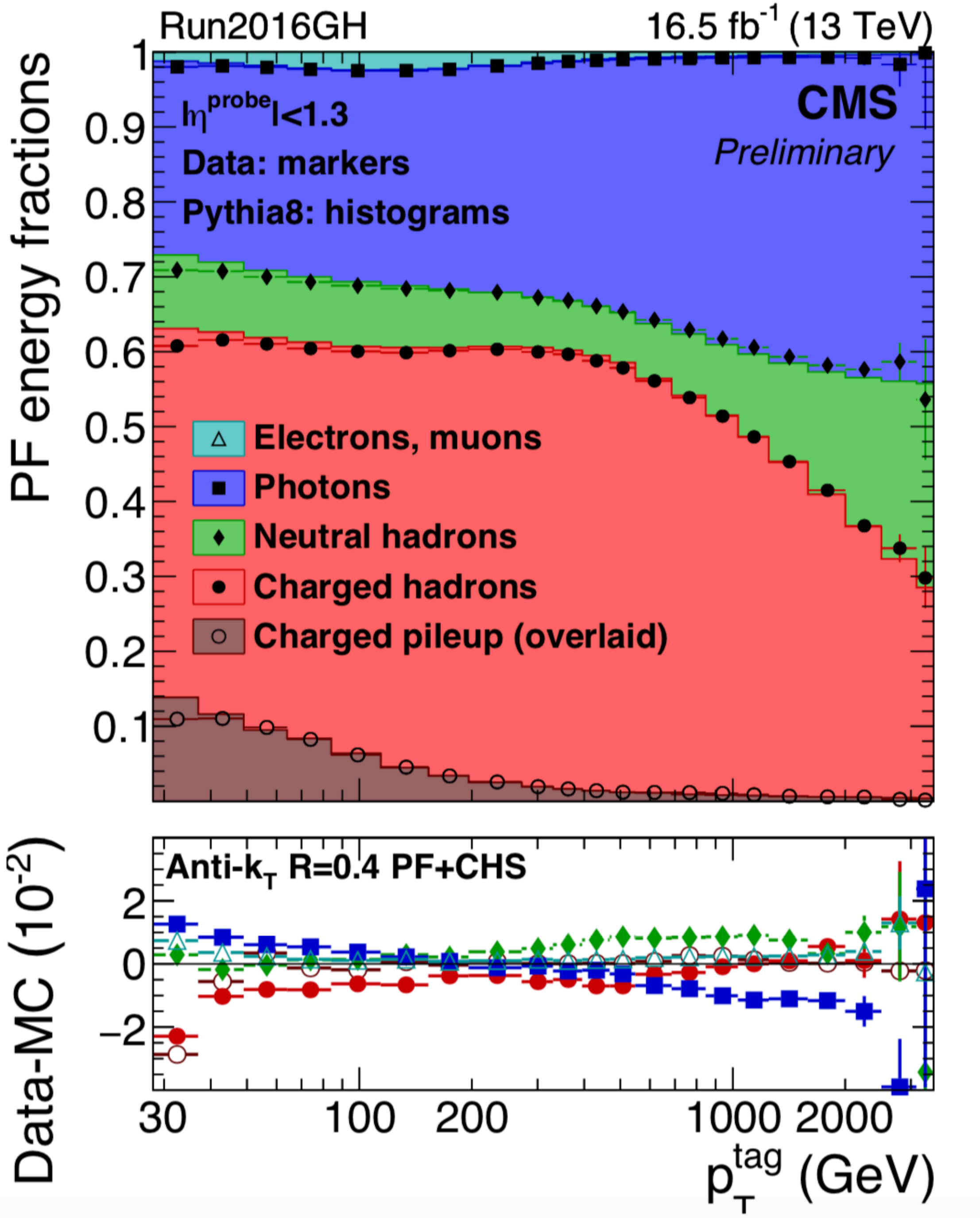


Modeled vs. jet ρ, P_T

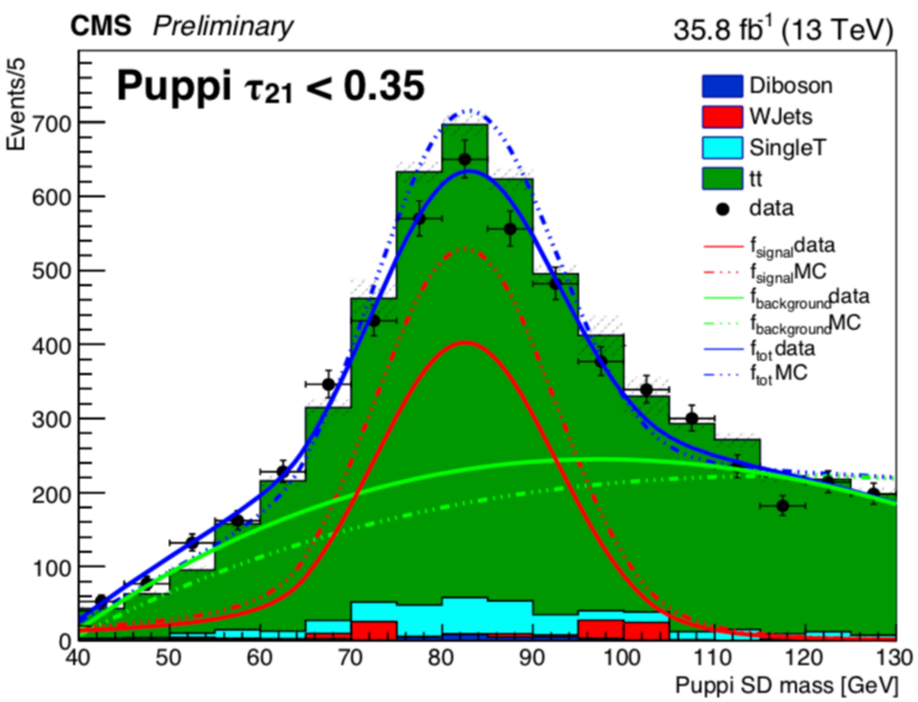
$$p^{QCD}_{pass}(m_{SD}, p_T) = \mathcal{F}(\rho(m_{SD}, p_T), p_T) \times p^{QCD}_{fail}(m_{SD}, p_T)$$

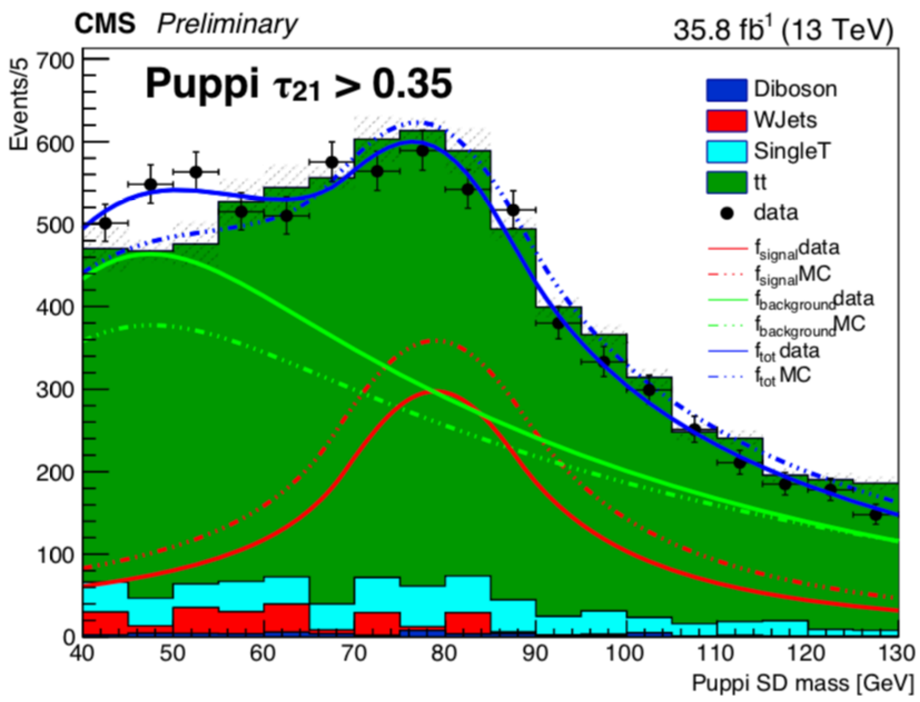
More info PRL 1709.05543

CMS particle flow

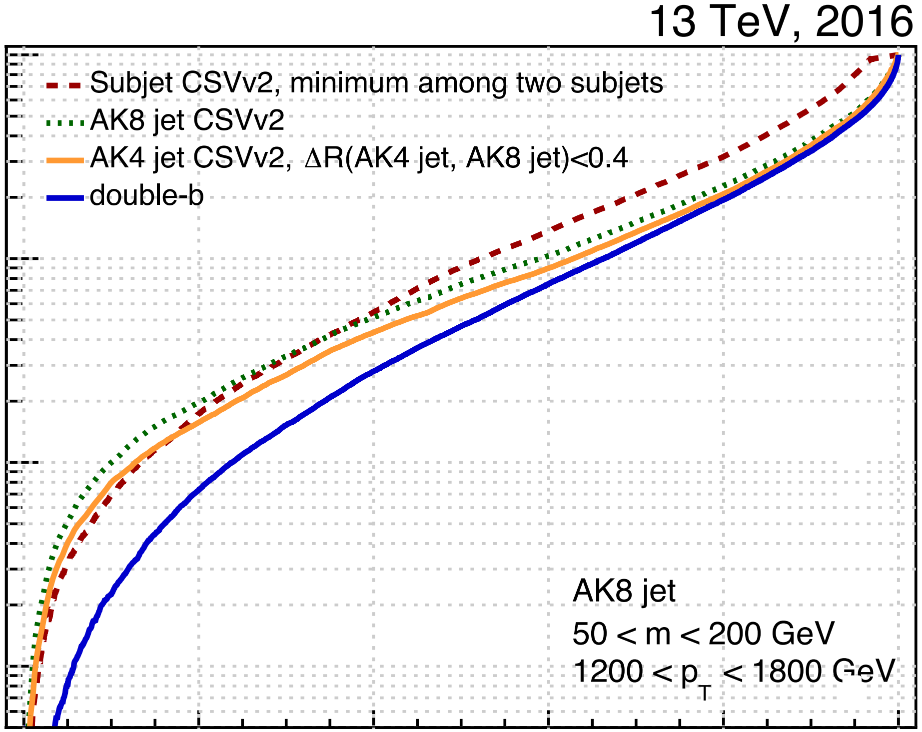


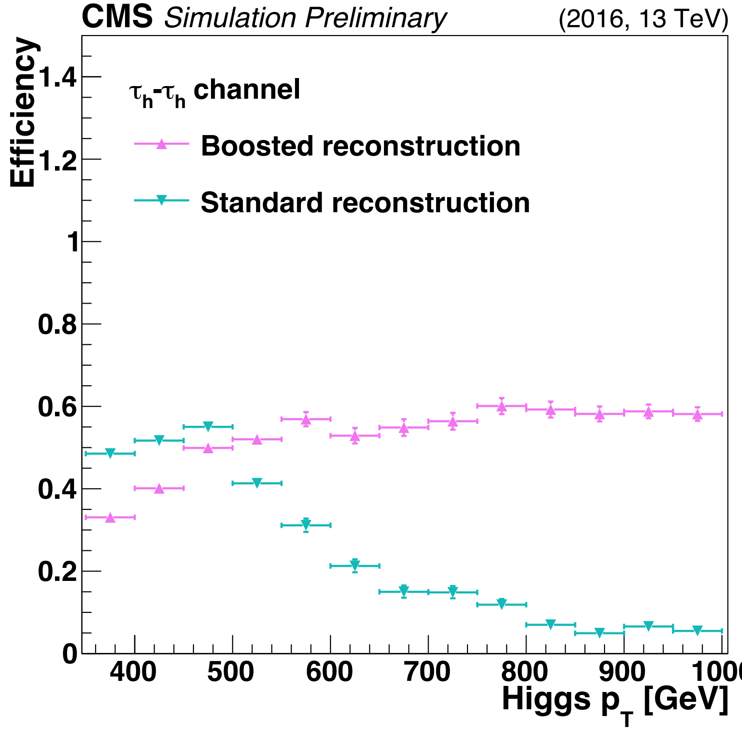
PUPPI+soft drop W-tagging in top events

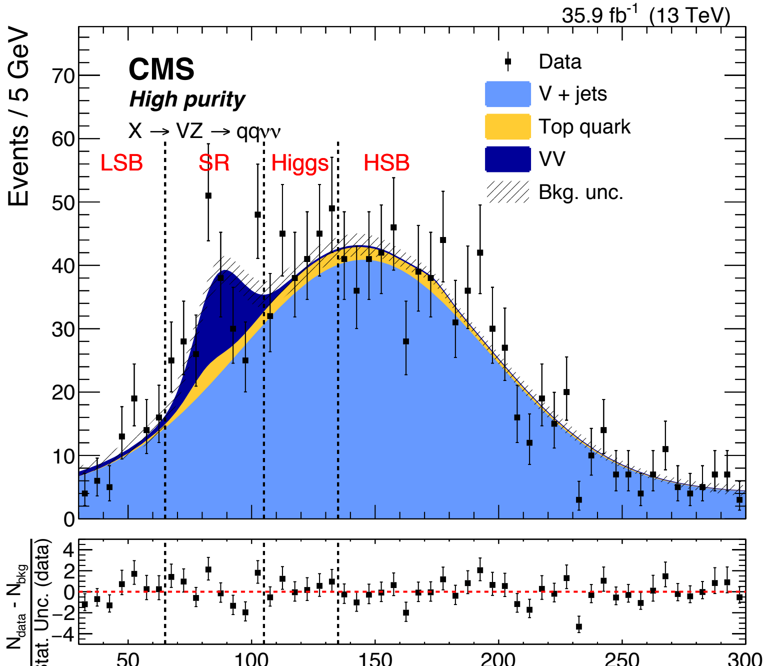


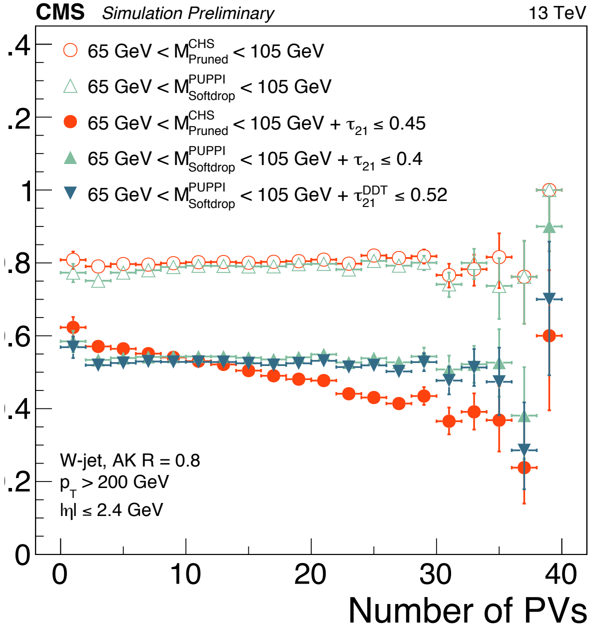


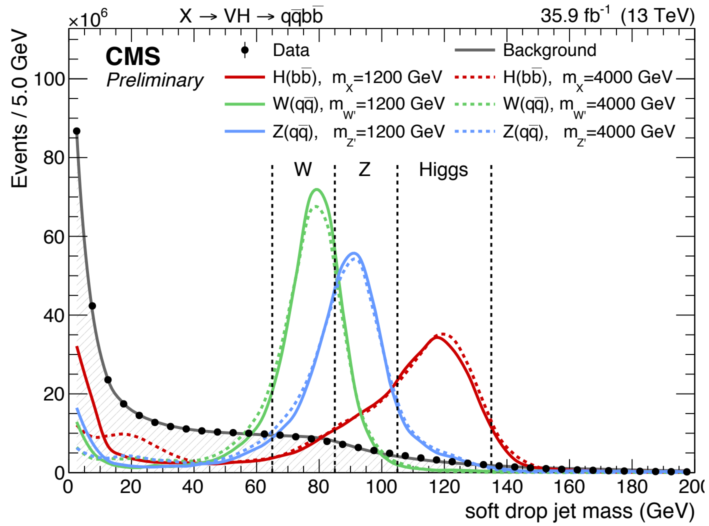
Some backup plots CMS



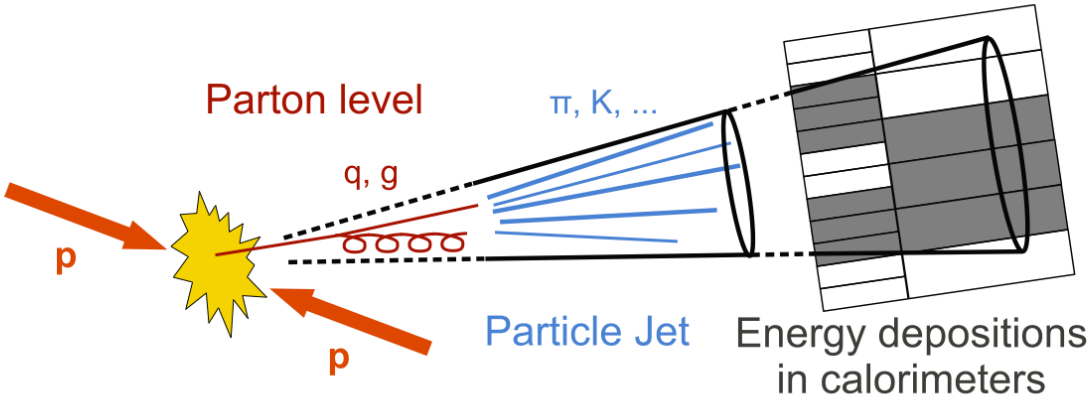




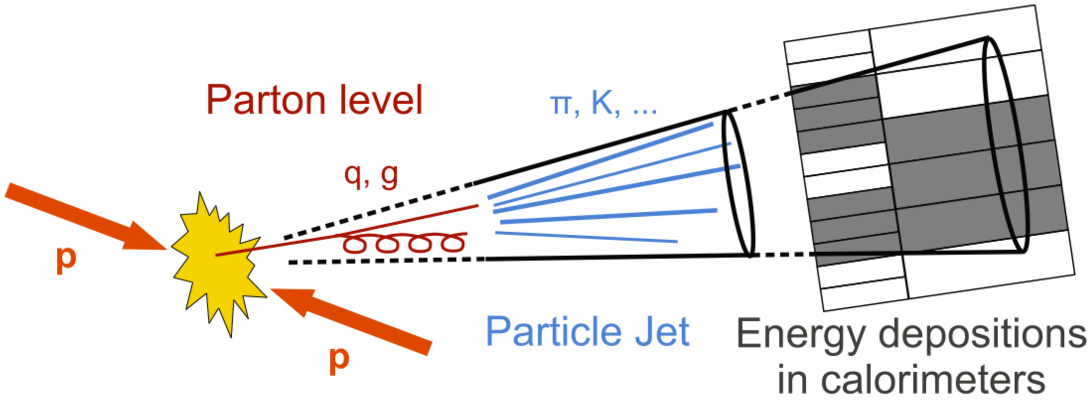


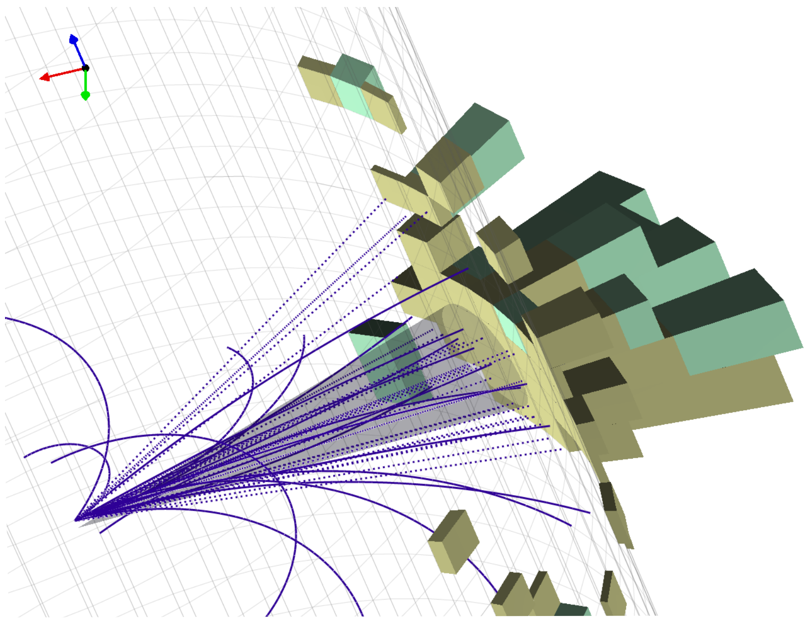


Measuring a normal quark jet

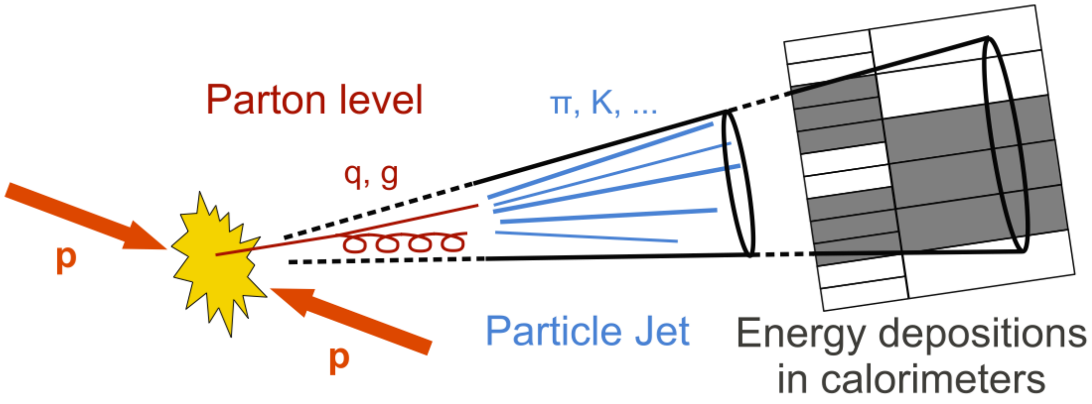


Measuring a normal quark jet

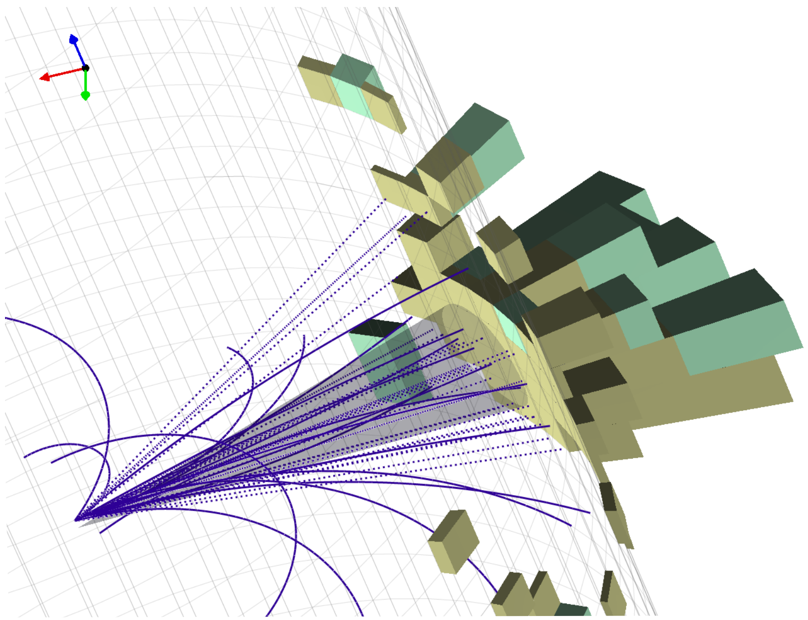




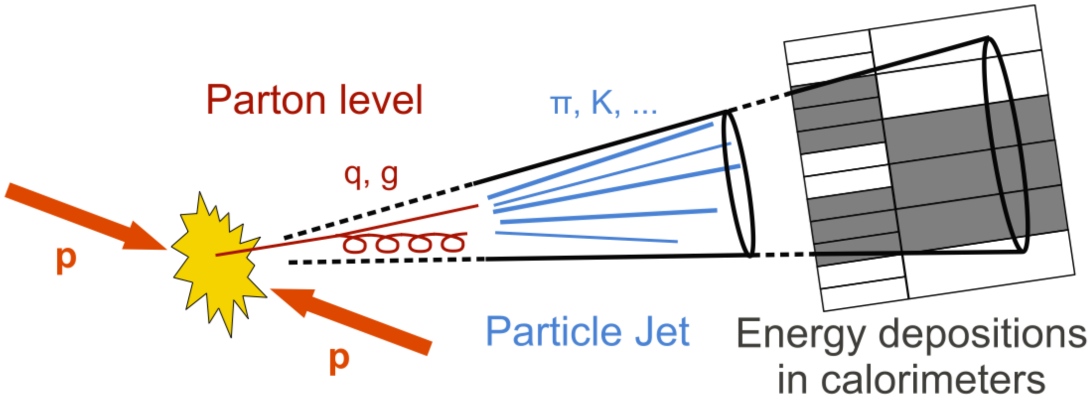
Measuring a normal quark jet



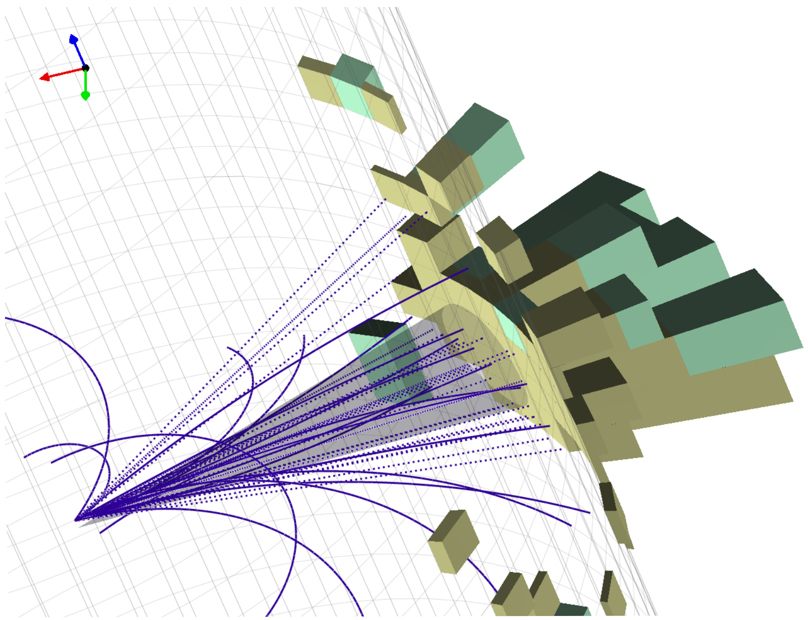
- **2/3 of jet momentum from charged particles**
  - **Bend in 3.8 T B-field (CMS)**
  - **Produce ionization in tracker**
    - **determine momentum precisely from curvature >~1%**



Measuring a normal quark jet

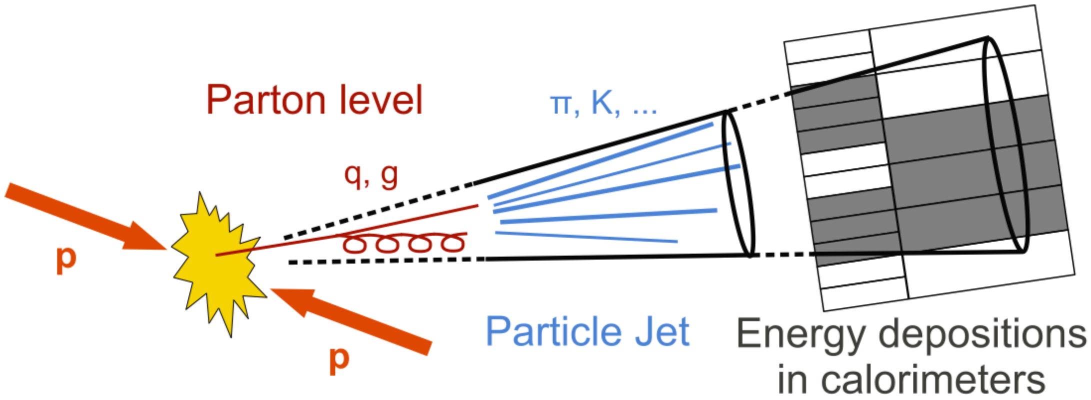


- 2/3 of jet momentum from charged particles
  - Bend in 3.8 T B-field (CMS)
  - Produce ionization in tracker
    - determine momentum precisely from curvature >~1%

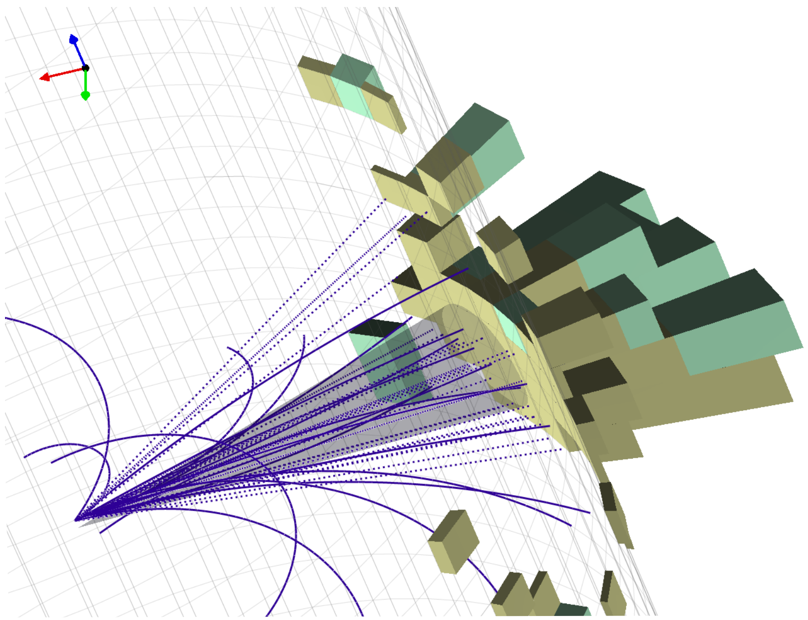


- 1/3 of jet momentum from neutral particles
  - 2/3 of which are photons that shower EM
    - Produce scintillation light within 20 cm crystal calorimeter (ECAL)
    - Precise energy measurement from light ~> 1%
  - 1/3 of which are neutral hadrons
    - Produce extended nuclear shower in 100 cm brass-sampling scintillator hadronic calorimeter (HCAL)
    - Poor energy measurement ~20%

Measuring a normal quark jet



- 2/3 of jet momentum from charged particles
  - Bend in 3.8 T B-field (CMS)
  - Produce ionization in tracker
    - determine momentum precisely from curvature >~1%



- 1/3 of jet momentum from neutral particles
  - 2/3 of which are photons that shower EM
    - Produce scintillation light within 20 cm crystal calorimeter (ECAL)
    - Precise energy measurement from light ~> 1%
  - 1/3 of which are neutral hadrons
    - Produce extended nuclear shower in 100 cm brass-sampling scintillator hadronic calorimeter (HCAL)
    - Poor energy measurement ~20%

Using all 3 detectors, we measure quark-jet energies to 10%

BACKUP

In the resolved regions, events with at least two small-R jets are considere
required to be b-tagged. The Higgs-boson candidate is reconstructed from
least one of these two jets has to have a p_{T} above 45 GeV. The scalar sum
of the highest-p_{T} additional jet, if present, has to be larger than 63% of the
event to reject $t\bar{t}$ events. In order to reduce backgrounds from multijet ev
between the two jets forming the Higgs candidate is restricted to below 1
must be less than 1.8. The Higgs candidate has to be separated from th
object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance has to fulfil $S > 16$. For events with two (th
sum of the first two (three) jets has to be greater than 120 (150) GeV. In co
first all central jets are considered, then forward jets, each set of jets ordere

The merged-region selection requires the presence of at least one large-R
jets associated with the leading large-R jet are required to be b-tagged a
separation cut as described in Sec. 4.2. Events that contain one or more
the large-R jet are rejected. The p_{T} of the leading large-R jet is required
scalar sum of the transverse momenta of the leading large-R jet and all sm
the contribution from $t\bar{t}$ events.

4.1.3 Variable-radius track jets

The VR track jets are reconstructed from inner detector tracks using the anti-k_t algorithm. The considered tracks are required to have $p_{\mathrm{T}}^{\mathrm{track}} > 0.5$ GeV and $|\eta| < 2.5$. In addition, the tracks must have at least 7 hits in total in the SCT and pixel detectors, and no more than one hit shared by multiple tracks in the pixel detector. If no hit is observed in an active detector element where one is expected, this is referred to as a missing hit. Tracks are required to have no more than one missing hit in the pixel detector and no more than two missing hits in the SCT detector. The longitudinal impact parameter $|z_0 \sin(\theta)|$ is required to be less than 3 mm with respect to the primary vertex to reduce the pile-up contri
efficiency in selecting tracks from the hard-scatter vertex.

The main feature of the VR jet reconstruction is the p_{T} dependence of the jet ra

$$\mathrm{R} \rightarrow \mathrm{R}_{\mathrm{eff}}(p_{\mathrm{T}}) \approx \frac{\rho}{p_{\mathrm{T}}}$$

where the parameter ρ determines how the effective jet radius scales with the p
the jet finding procedure. Two additional parameters R_{min} and R_{max} are used t
and an upper cut on the jet radius. The optimal values of these three parameter
double b-tagging over a wide mass range have been found to be: $\rho = 30$ GeV, R
[69].

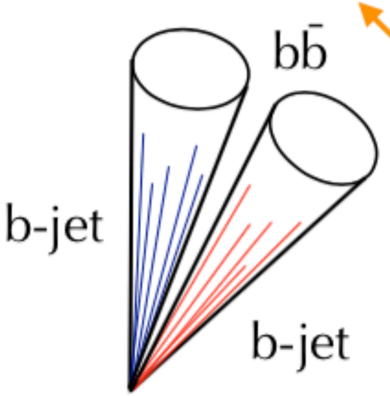
In Figure 2, the gain in sele
illustrated. Figure 2(a) show
for events with $E_{\mathrm{T}}^{\mathrm{miss}} > 50$
that the mass of the Higgs candidate lies between 70 and 140 GeV, as a function of $m_{Z'}$. In particular
selection requires at least two track jets associated to the large-R jet, and a minimum angular separa
of the two leading track jets as described in Sec. 4.2. The efficiency is calculated only considering H
decays to b-quarks. Open symbols and dashed lines mark the efficiencies obtained when using fixed-ra
(FR) track jets with a radius parameter of 0.2, while filled symbols and solid lines correspond to the u
VR track jets. The effect is shown separately for b-tag multiplicities of 1 (square markers) and 2 (triang
markers). In addition, the combined acceptance from events with 0, 1 or 2 b-tagged jets is drawn
circular markers. It is considerably higher for VR track jets in the region above 2.5 TeV, as events
often fail the requirement of more than one track jet in the case of FR jets. The increase in accept
for both 1- and 2-b-tag events is also most pronounced for $m_{Z'}$ above 2.5 TeV, corresponding to the la
ts to a factor of about 1.7 for events with two b-tags
tive efficiencies of 1 and 2 b-tagged events norma
track jets, which shows similar b-tagging efficie
ent in signal acceptance originates from the impr
by the combined acceptance (line with filled cir

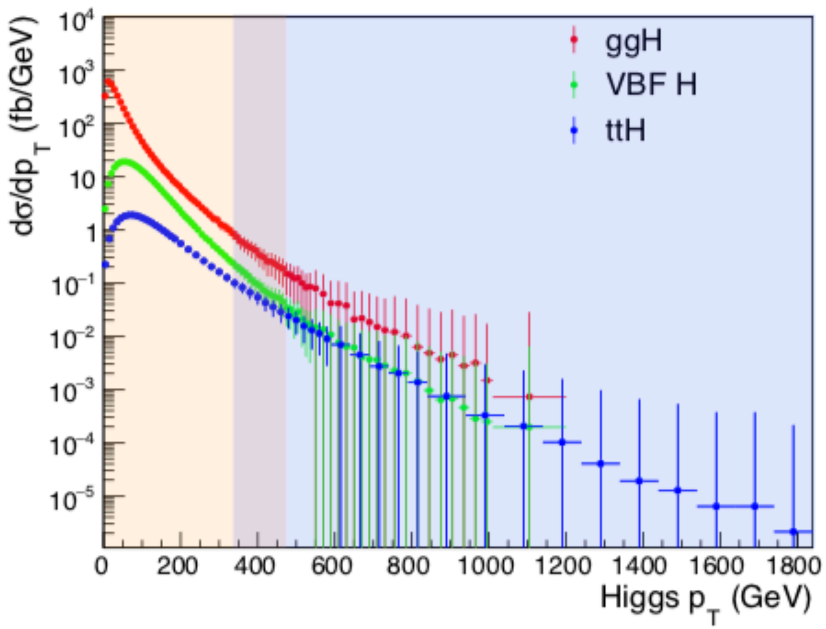
Below 2.5 TeV, a higher efficiency for identifying two b-jets is obtained with FR track jets. This is due to the fact that in this regime, often more than two jets are reconstructed with the VR jet algorithm, and the two highest-p_{T} jets are not always the b-jets [69]. Thus, when considering only the two highest-p_{T} track jets, the efficiencyis smaller for VR compared to FR track jets. It is possible to recover this signal efficiency by considering the three highest-p_{T} jets [69], but in the search presented here this was found to also increase the background contamination to a level that led to an overall decrease in sensitivity. Therefore, only the two highest-p_{T} VR track jets are used in this analysis. Even though the signal efficiency is higher for FR track jets below 2.5 TeV, the use of the VR algorithm provides a better signal to background ratio. In particular, including events containing only one b-tagged jet leads only to a marginal improvement in sensitivity when using VR track jets. Since the background modelling in such events is more challenging, they are not included in the result presented here, but are shown for illustration in Figure 2. More detailed studies and the potential inclusion of such events in the search are left for future work.

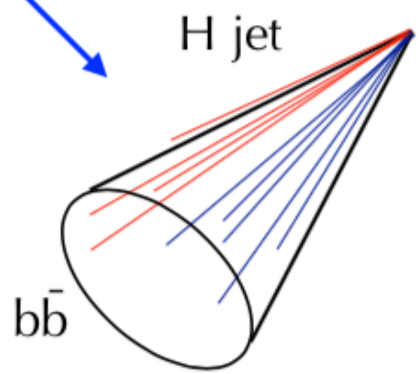
$\Delta R(b\bar{b}) \sim 2m_H/p_T$

two separated b-jets (R=0.4)

one merged double b-jet (R=0.8)

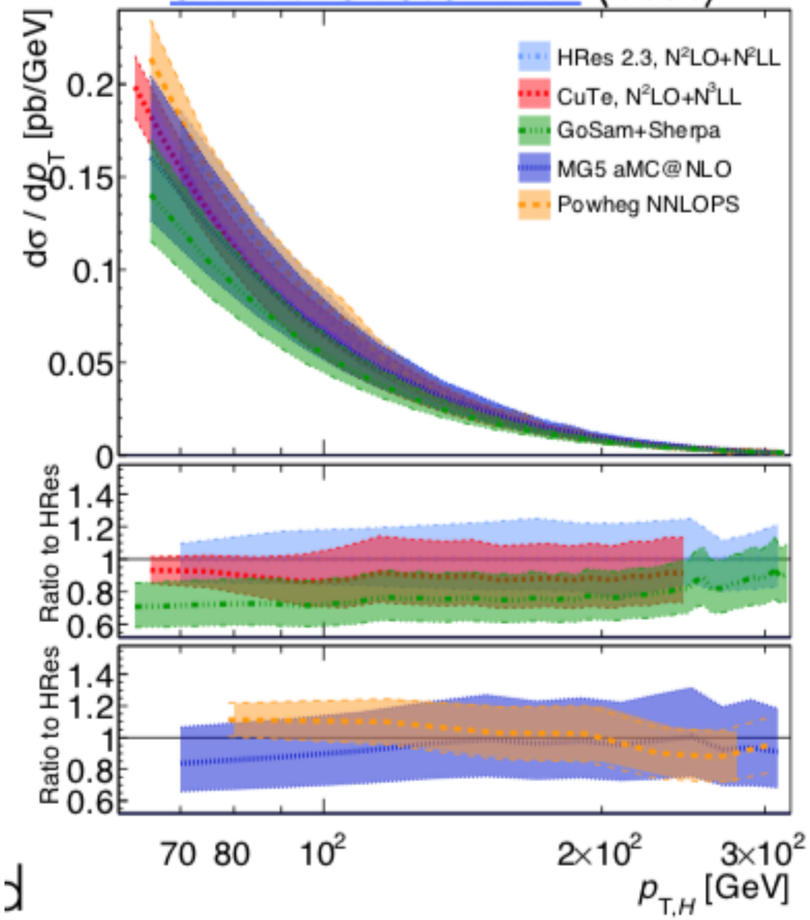




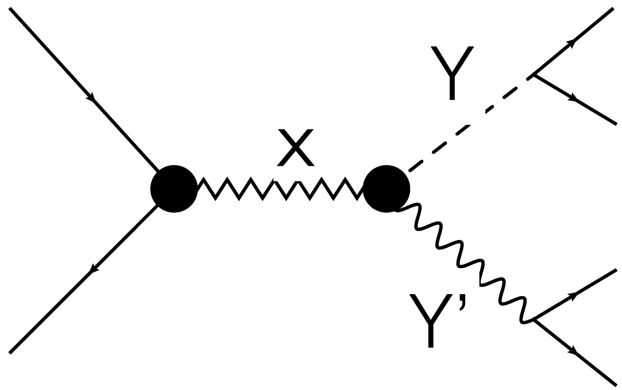


Higgs PT modeling

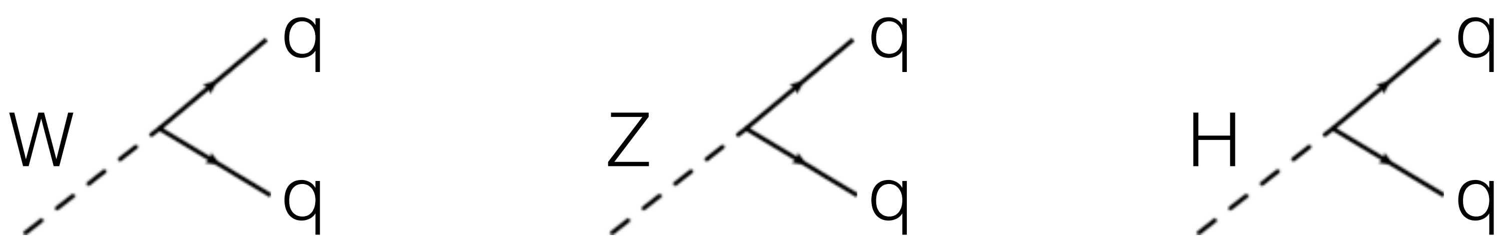
arXiv:1610.07922 (YR4)



Heavy resonances decaying to two bosons

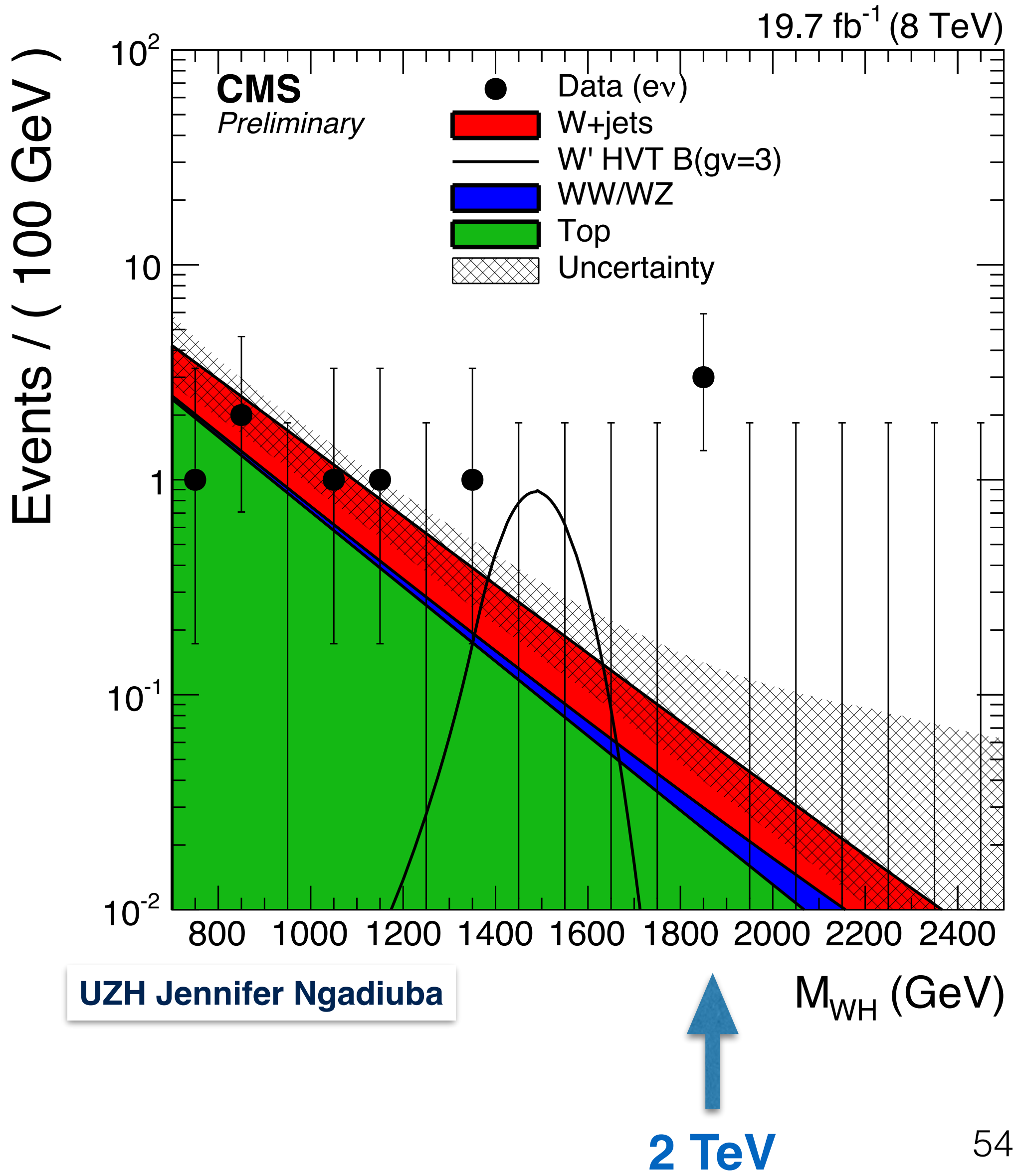


- These two bosons Y={W,Z,H} each mostly decays to quarks

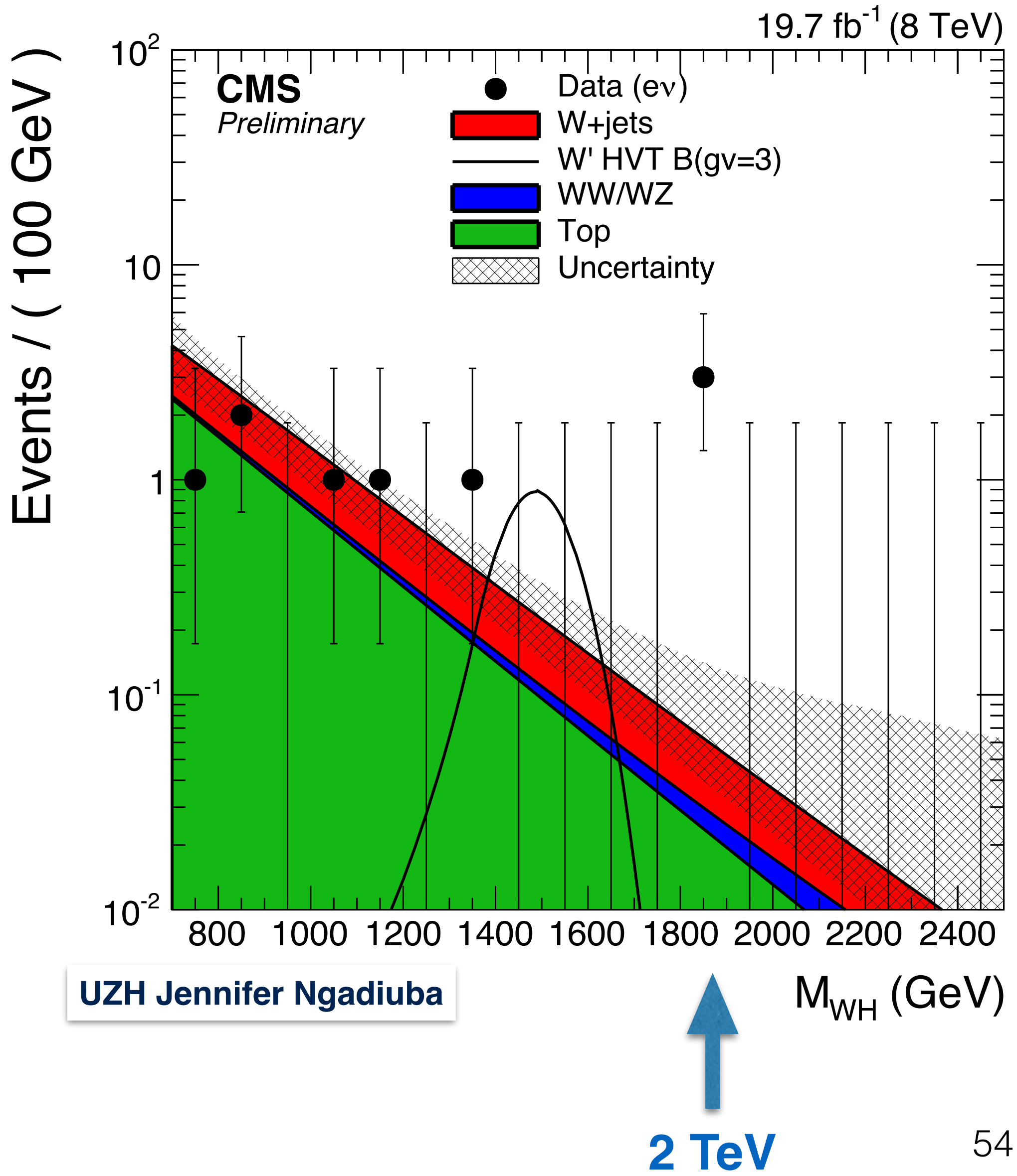


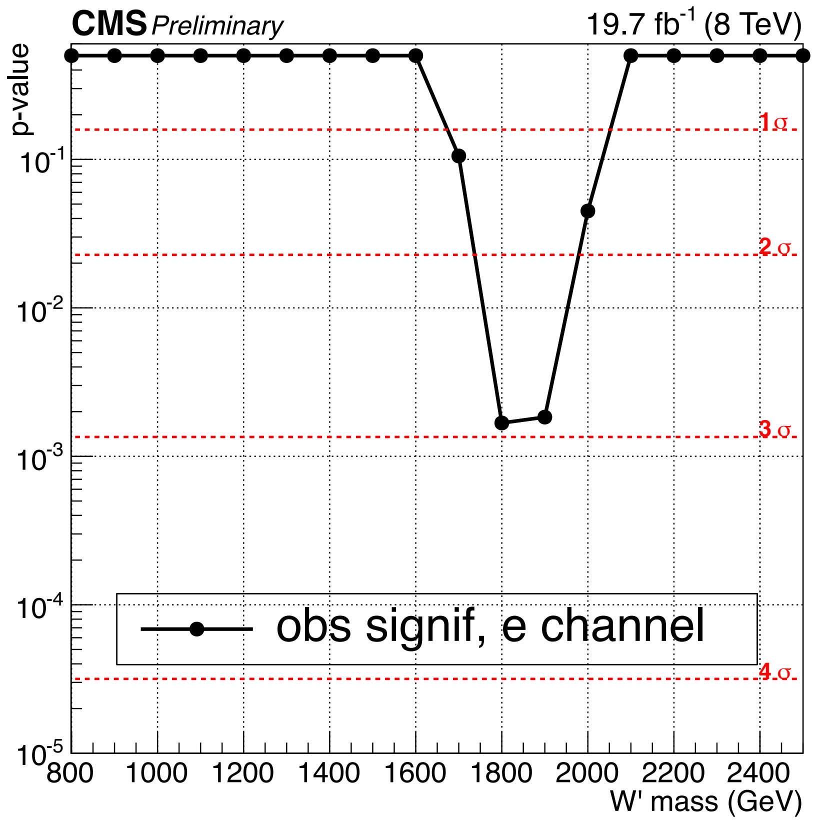
So we just need controlled way to make TeV-mass scale heavy resonances and then look for quarks in our detector

In spring 2015, while studying 2012 LHC data



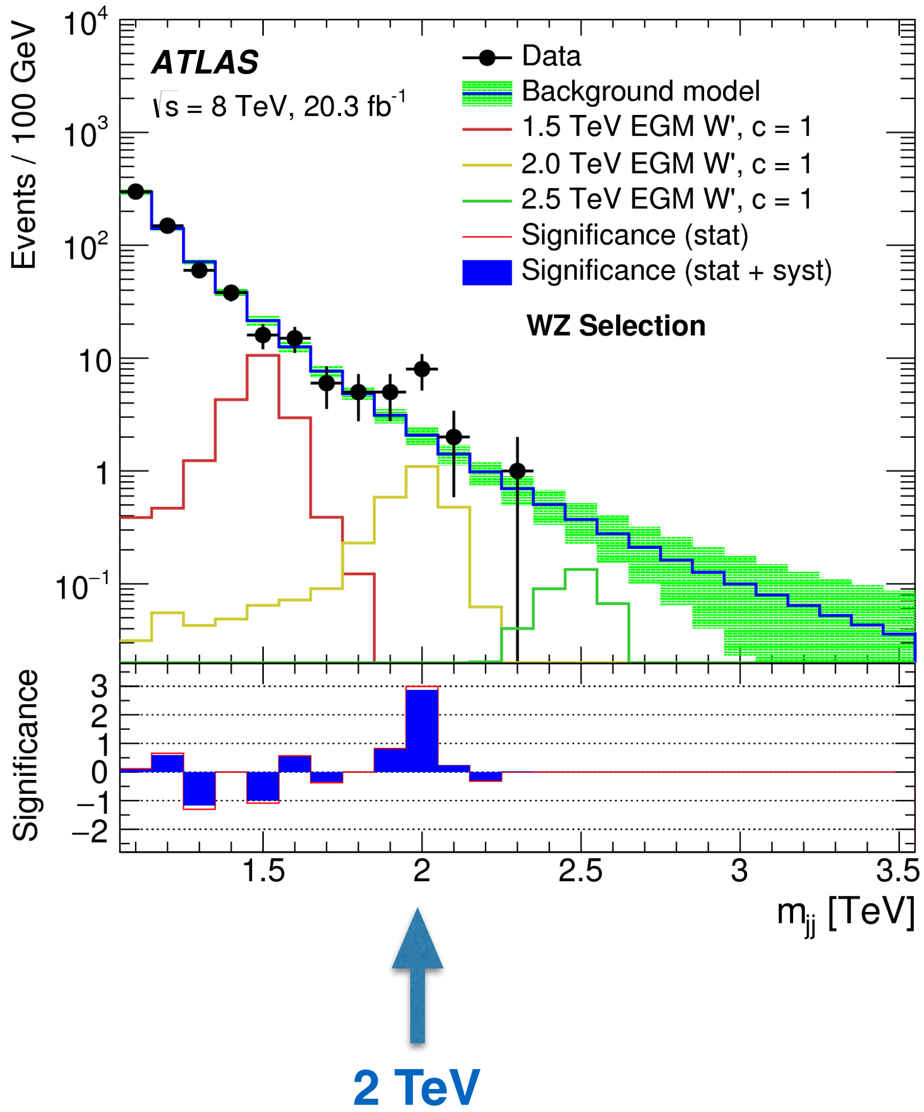
In spring 2015, while studying 2012 LHC data





But fluctuations like this are expected some times

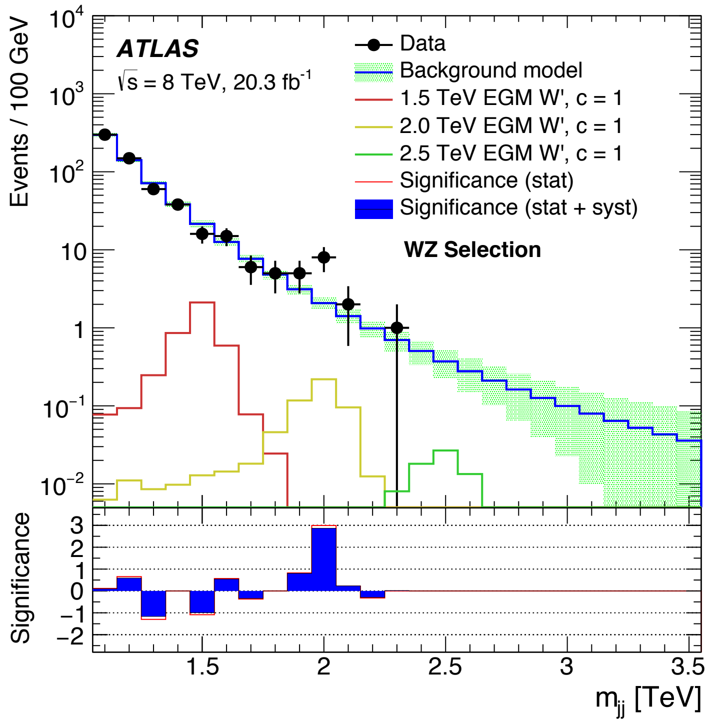
In summer 2015, things got more interesting

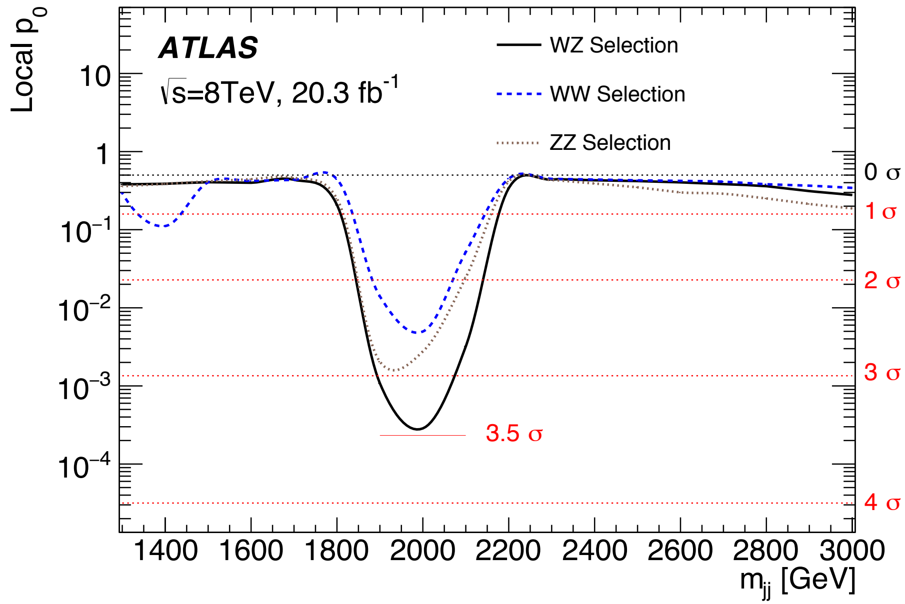


- Another bump at 2 TeV found by ATLAS analyzing the 2012 data

ATLAS 2 TeV bump in 2012 data

X→VV→JJ

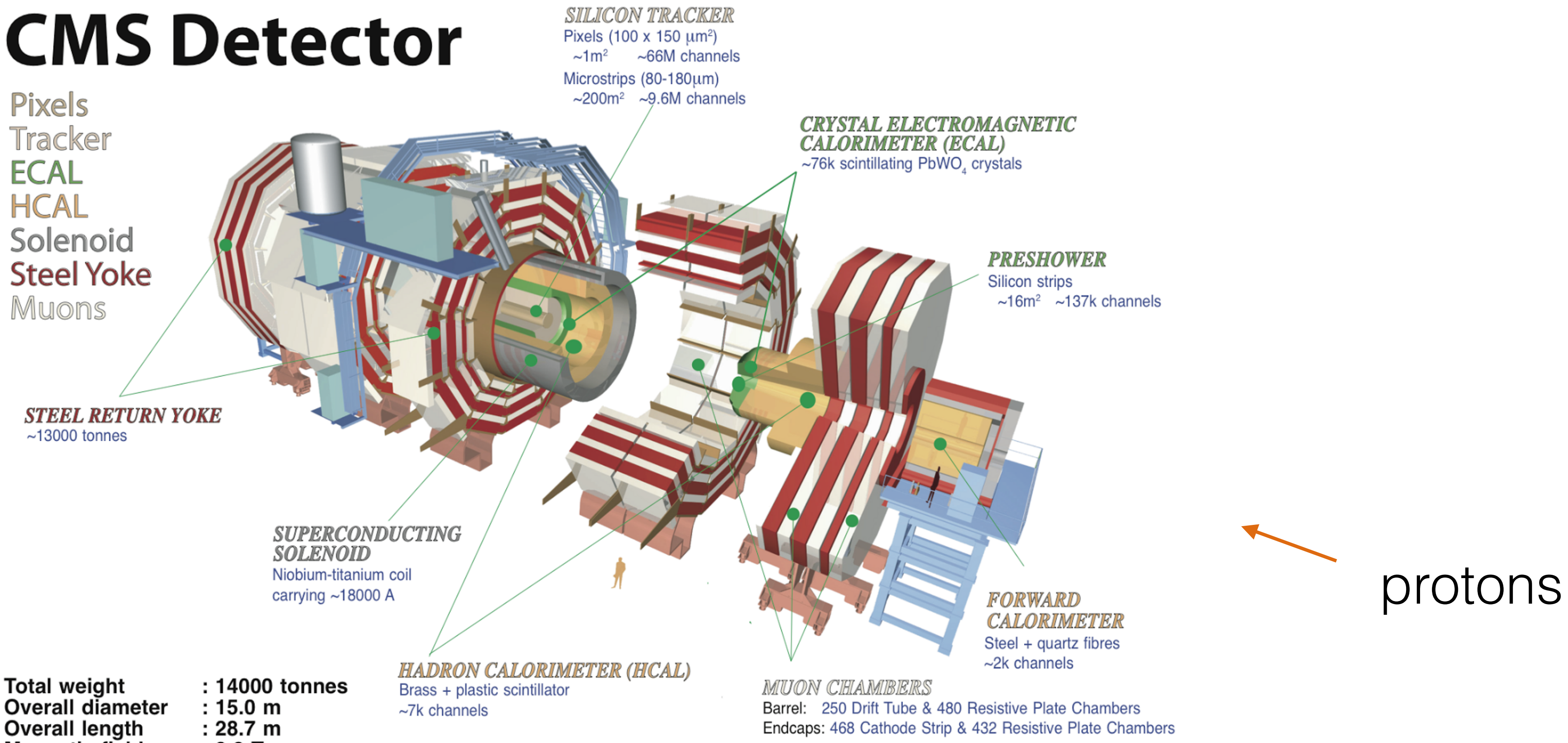





protons
protons


protons
E = mc²
&
QFT
protons

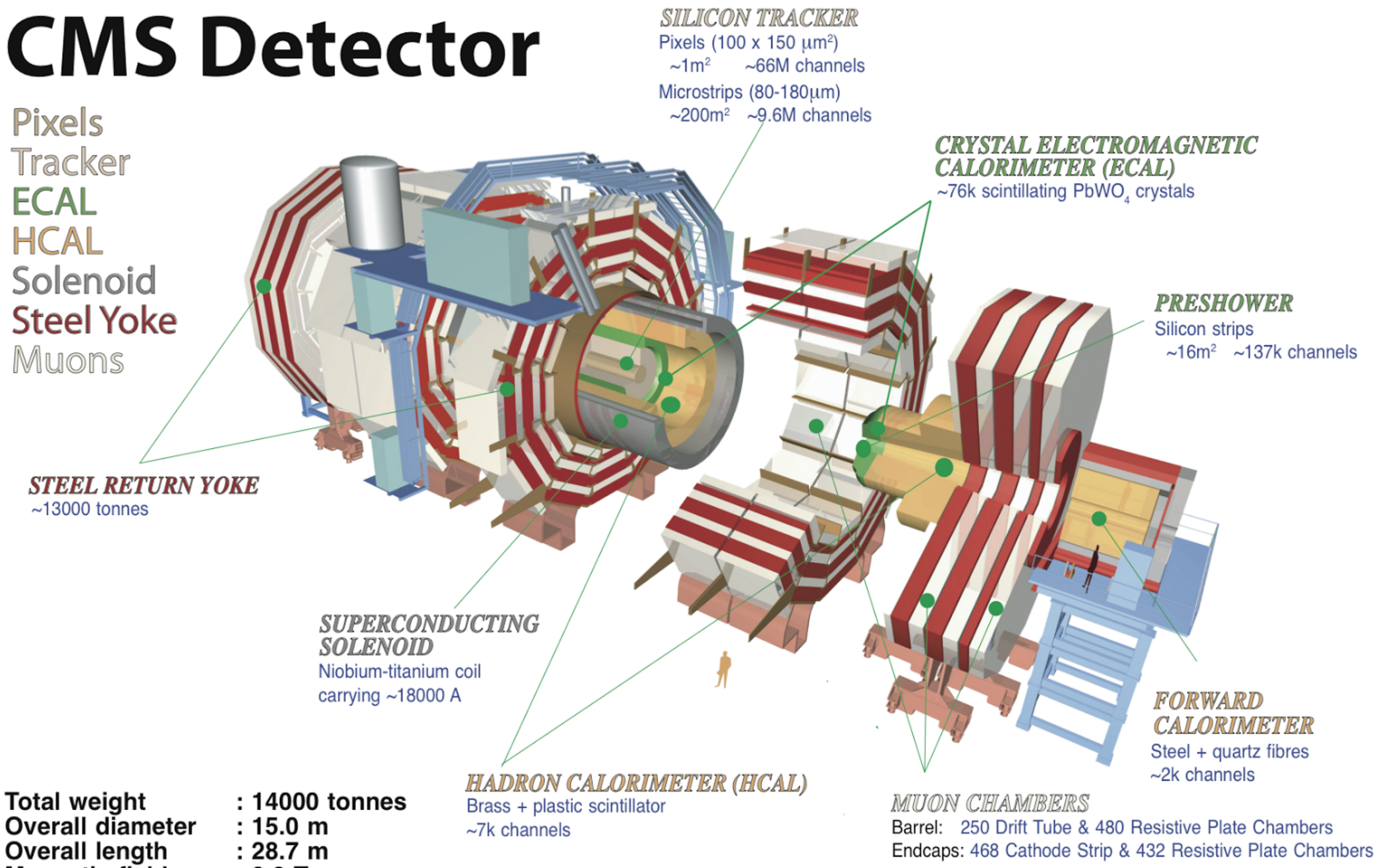
CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

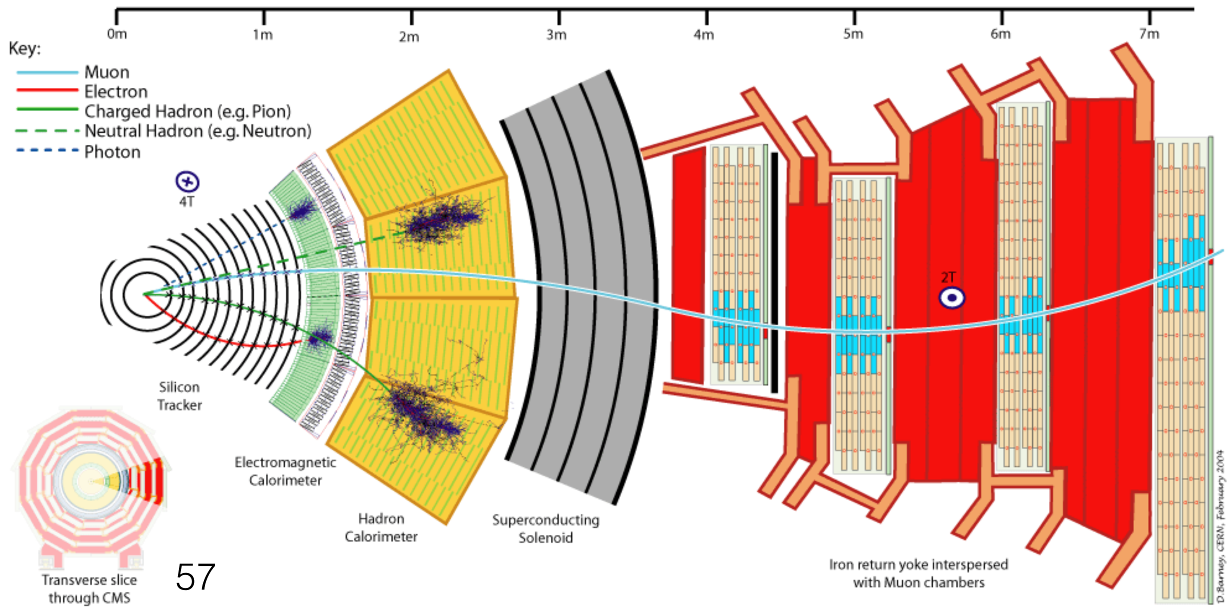


Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

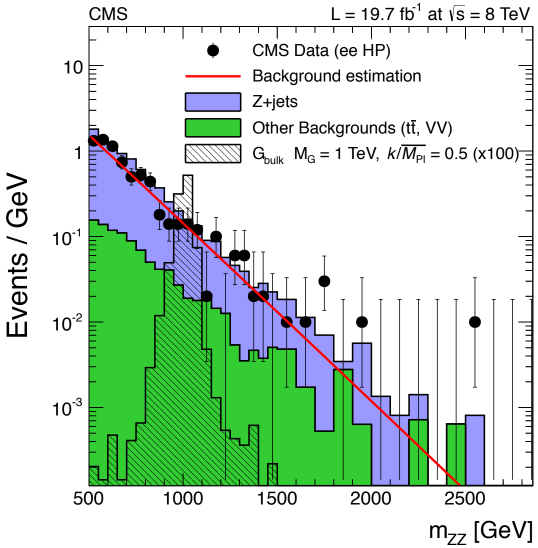
protons

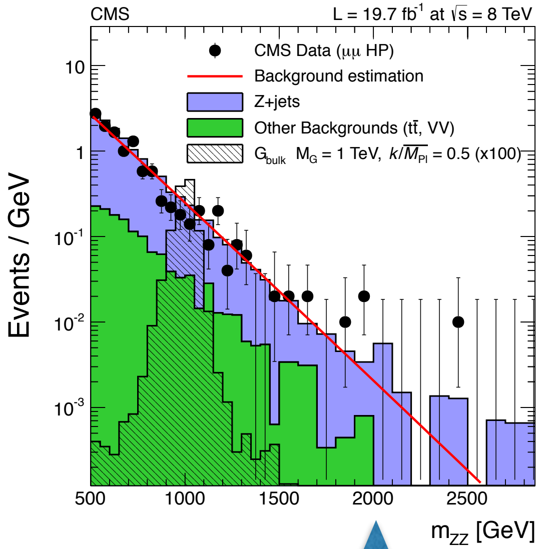
protons

⊗ ⊙



Other 2012-data diboson resonance searches





UZH Dr. Andreas Hinzmann

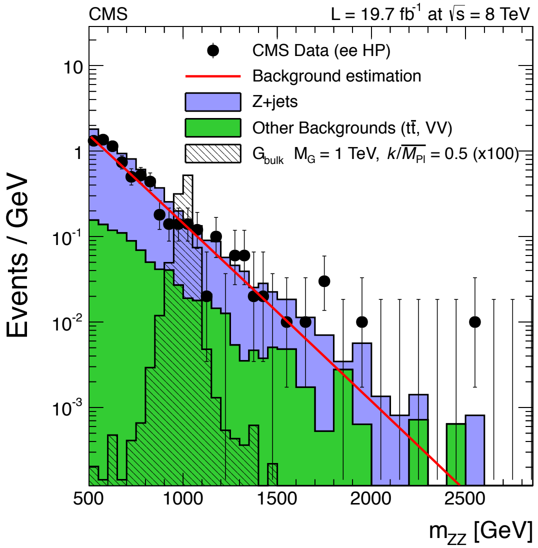
2 TeV

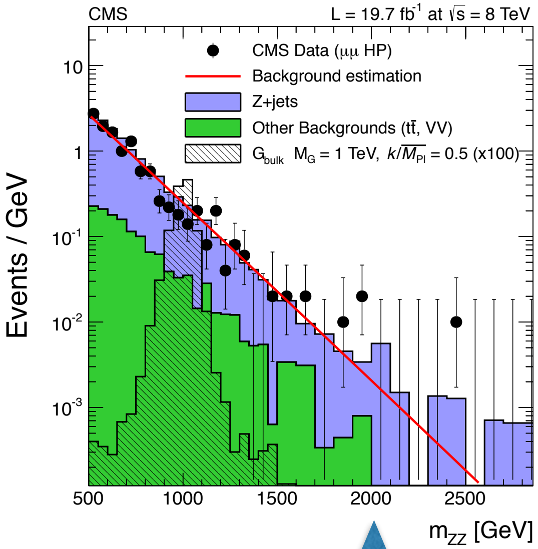
2 TeV

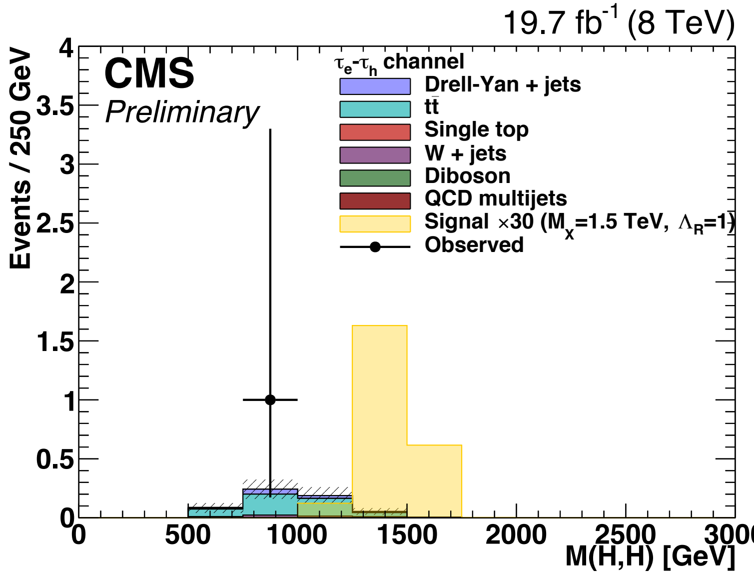
JHEP 08 (2014) 173

JHEP 08 (2014) 174

Other 2012-data diboson resonance searches





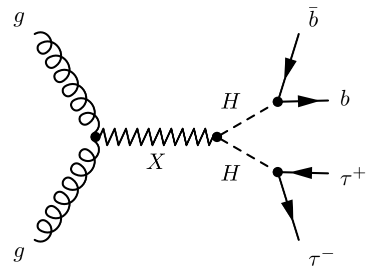


2 TeV

UZH Dr. Andreas Hinzmann

2 TeV

UZH Camilla Galloni

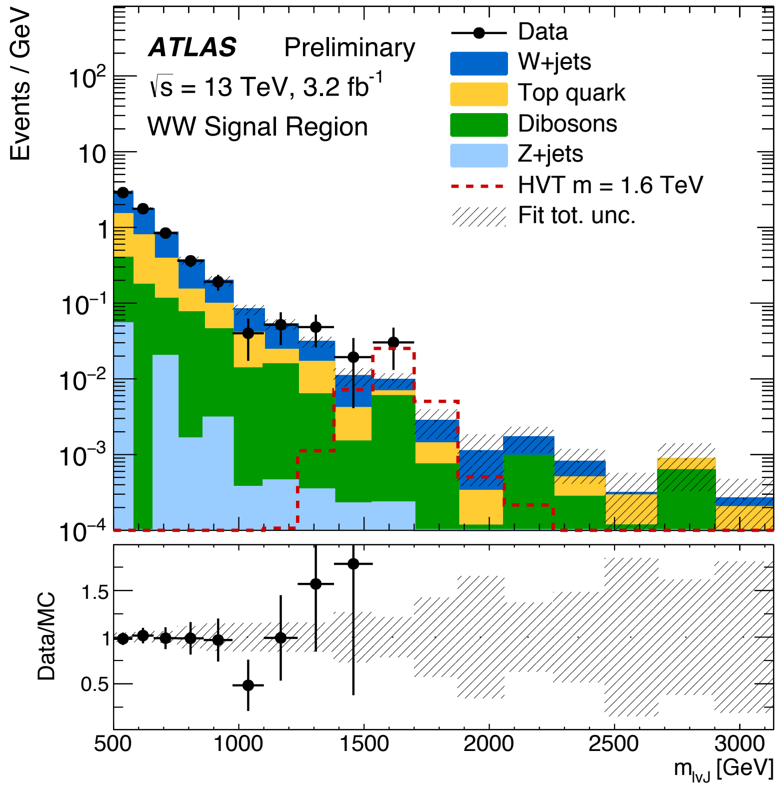


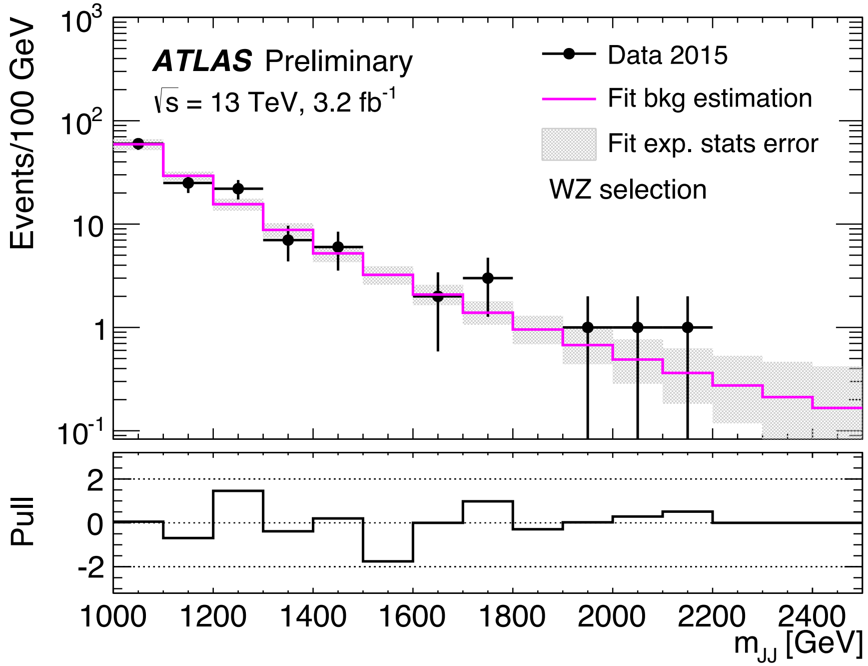
JHEP 08 (2014) 173

JHEP 08 (2014) 174

Extremely difficult boosted topology

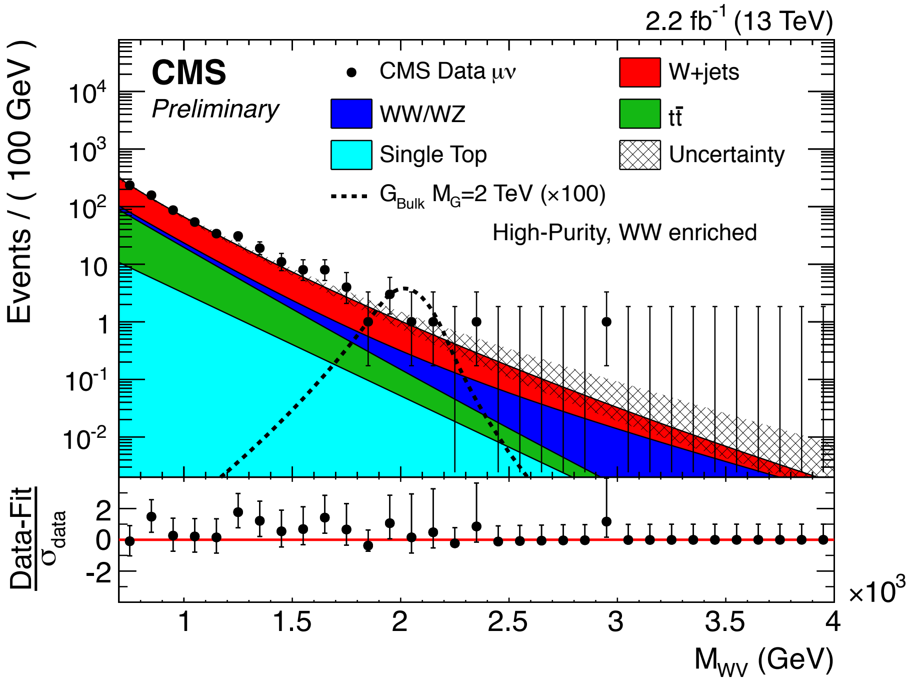
ATLAS new 2015 data search results



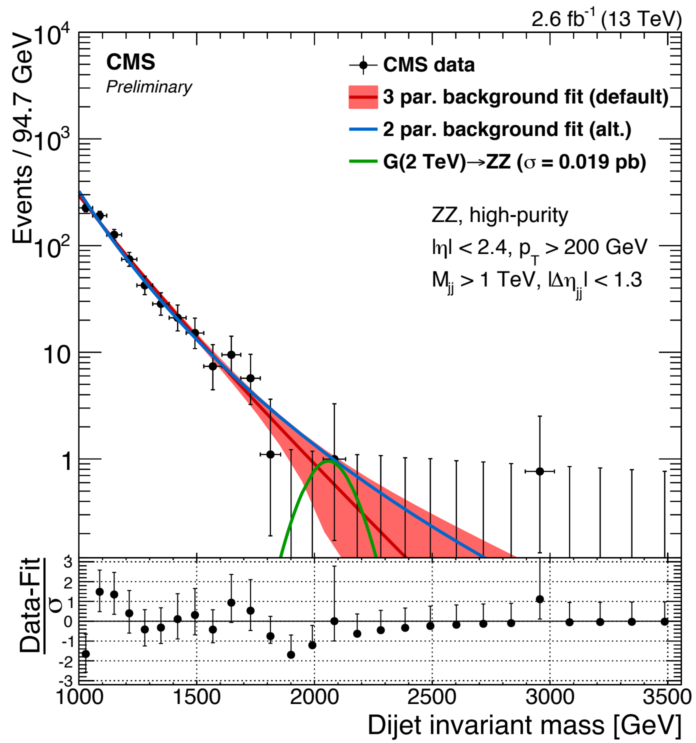


- Nothing at 2 TeV
- Statistical fluctuations as expected

CMS 2015 data search results

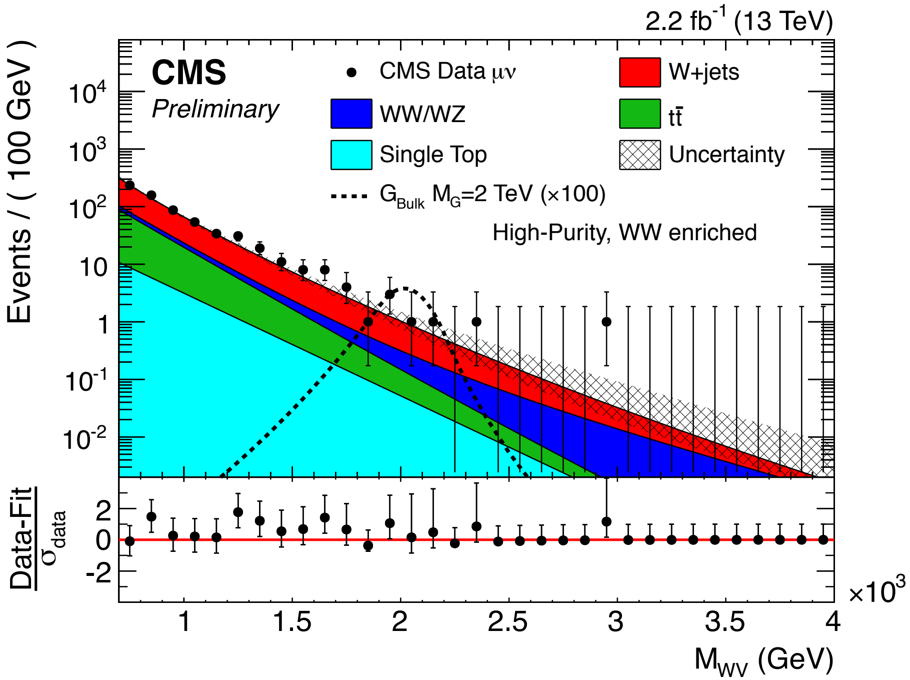


UZH Jennifer Ngadiuba

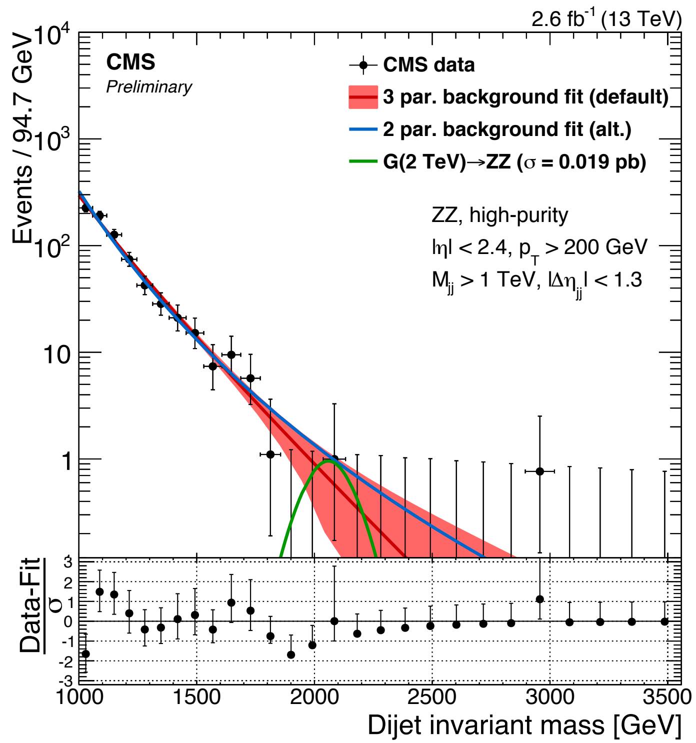


UZH Thea Årrestad

CMS 2015 data search results



UZH Jennifer Ngadiuba

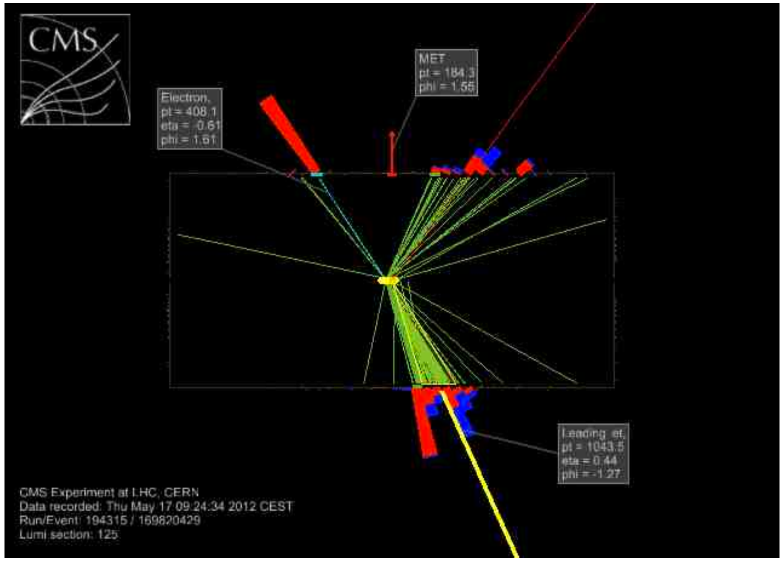


UZH Thea Årrestad

- Nothing obvious at 2 TeV
- Statistical fluctuations as expected
- 3 TeV excess more interesting than 2 TeV
  - (combined ~2σ local fluctuation)

$X \rightarrow WH \rightarrow l\nu bb$

CMS EXO-14-010



MET = 185 GeV

Ele P_T = 400

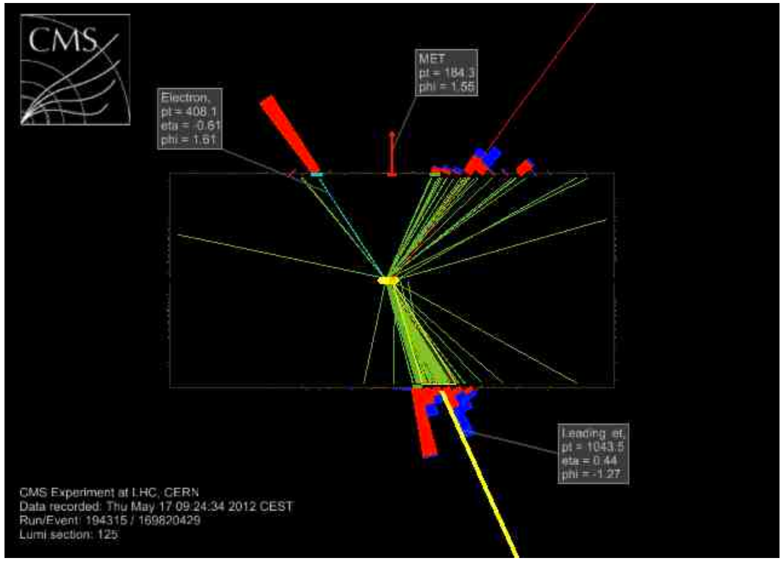
Jet P_T = 1.08 TeV

M_J = 124

M_X = 1.81 TeV

X →WH→lvbb

CMS EXO-14-010



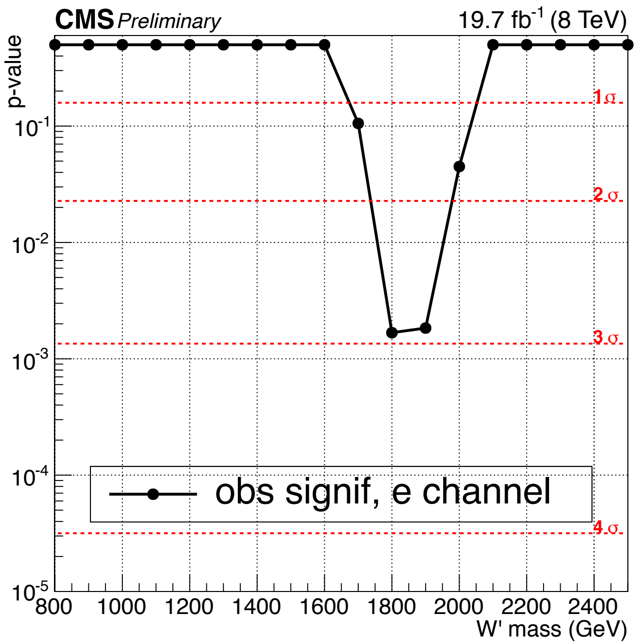
MET = 185 GeV

Ele P_T = 400

Jet P_T = 1.08 TeV

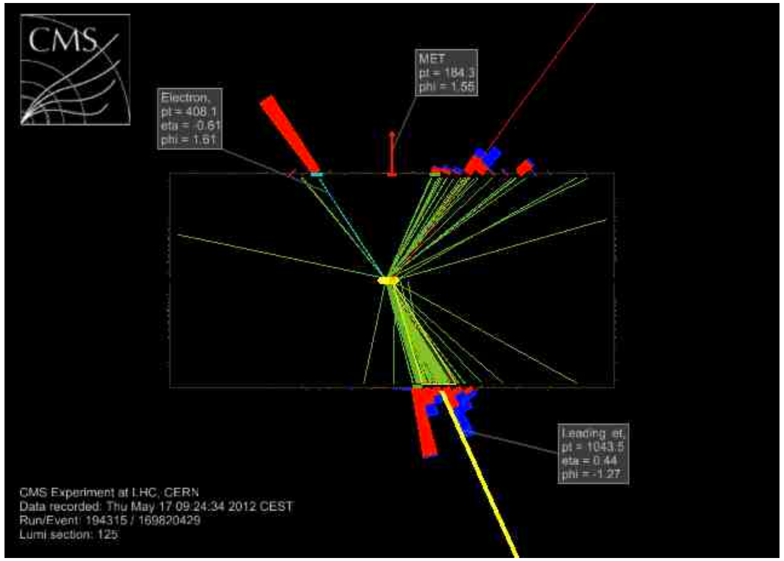
M_J = 124

M_X = 1.81 TeV



X →WH→lνbb

CMS EXO-14-010



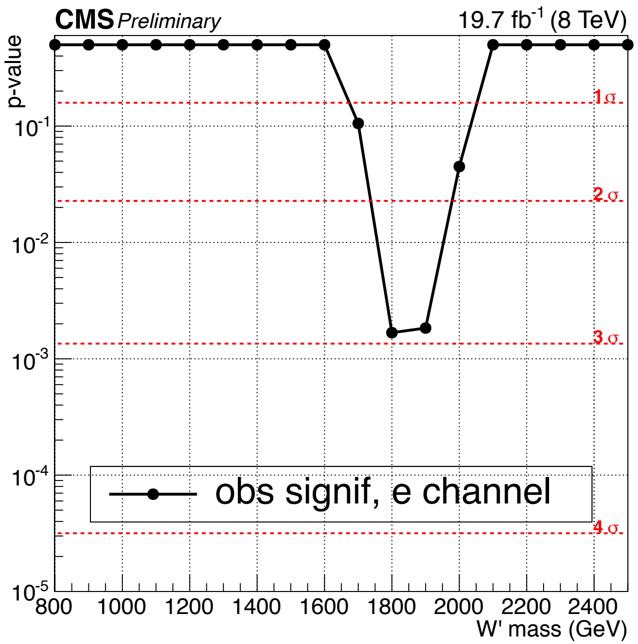
MET = 185 GeV

Ele P_T = 400

Jet P_T = 1.08 TeV

M_J = 124

M_X = 1.81 TeV



→ but not seen in muons