Universität Zürich[UZH]

Search for new heavy bosons with b-tagged jets in the boosted regime with the CMS detector

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University of Zurich

Higgs at LHC

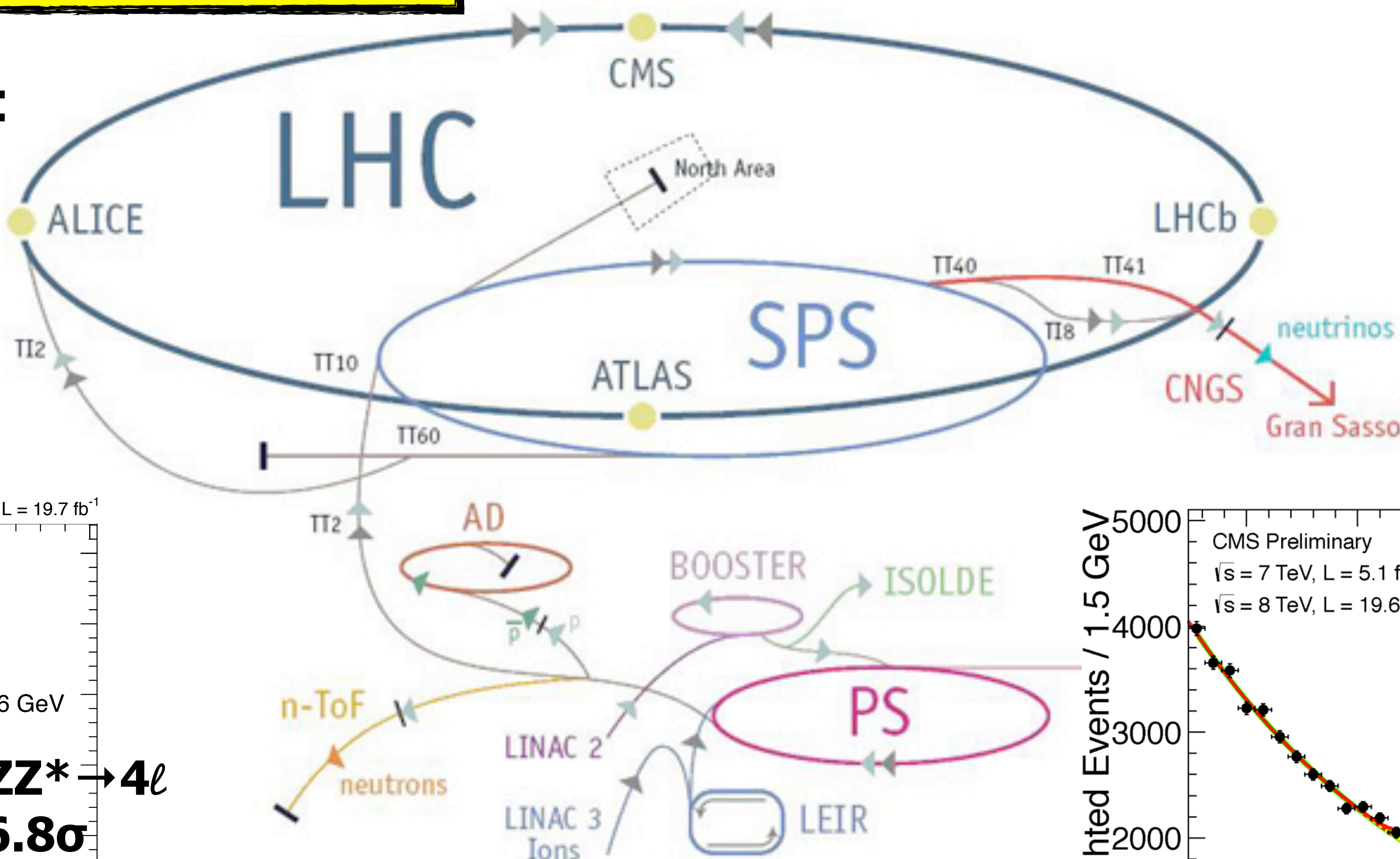
Higgs boson discovered in proton-proton collision at $\sqrt{s}$ = 7-8 TeV @ LHC!

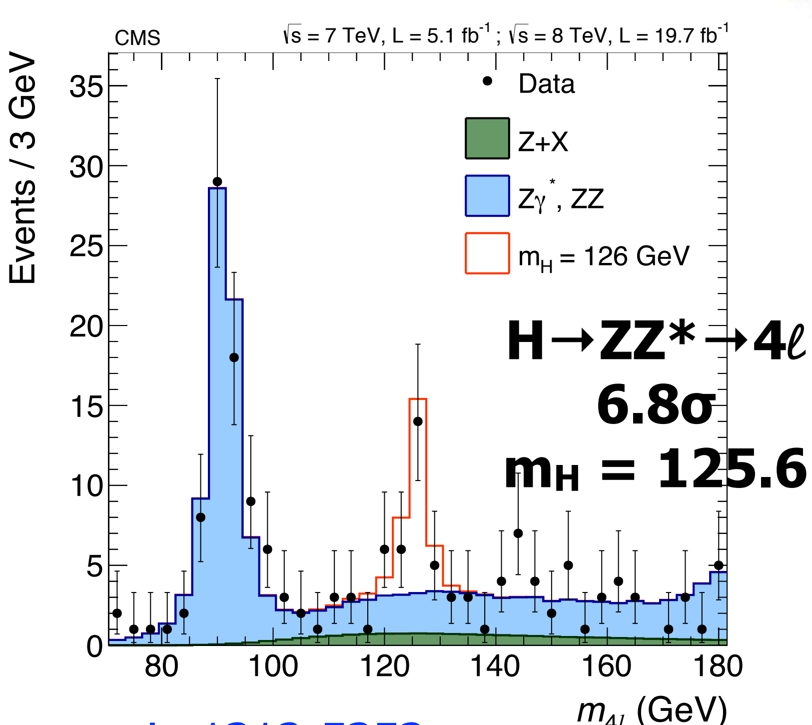
LHC machine parameters:

Design Luminosity: $\mathcal{L}$ = **$10^{34} cm^{-2}s^{-1}$**

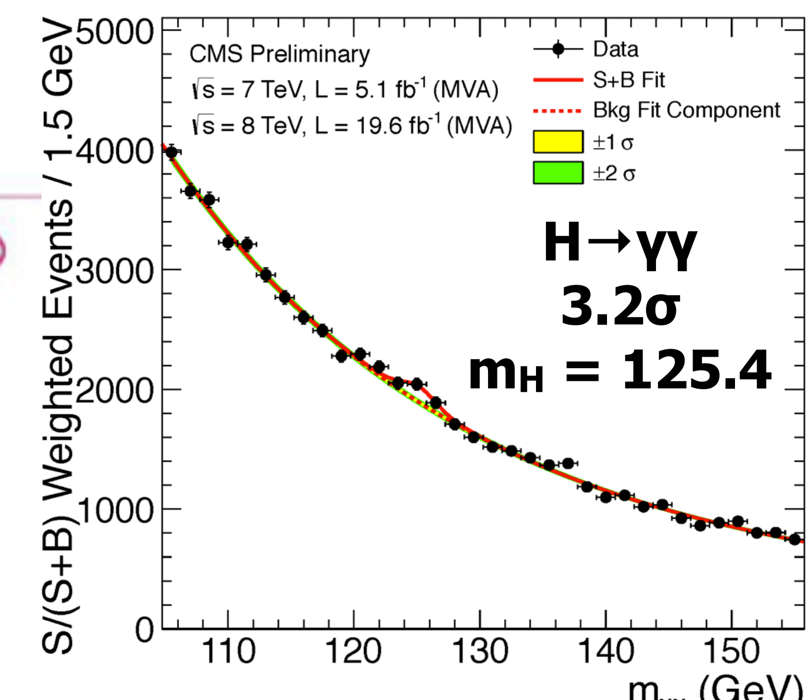
Design center of mass energy: **$\sqrt{s}$ = 14 TeV**

- Discovery channels:
  - ★ **$H \to \gamma\gamma$**
  - ★ **$H \to ZZ^* \to 4\ell$**
  - ★ **$H \to WW^* \to 2\ell 2\nu$**





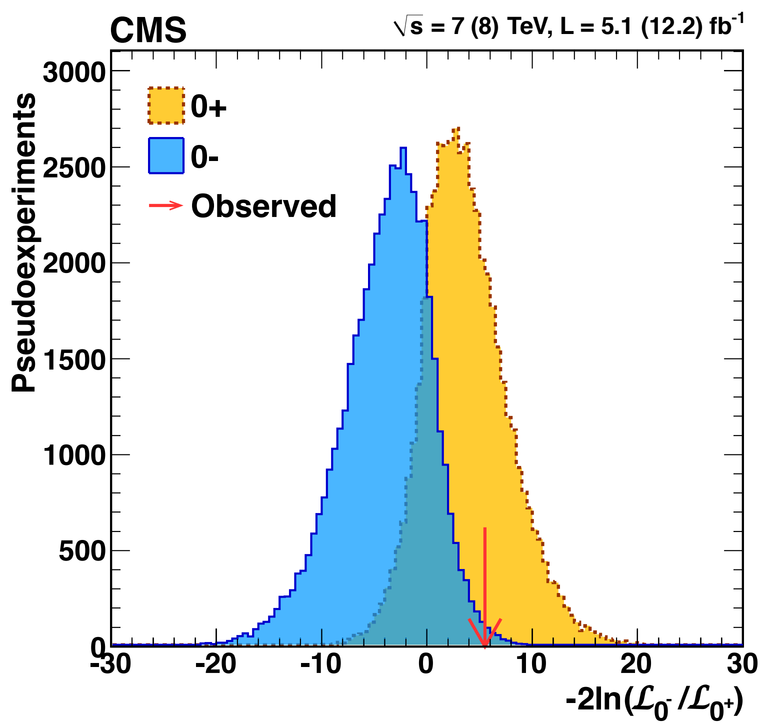
[arxiv:1312:5353](https://arxiv.org/abs/1312.5353)



[arxiv:1305:3654](https://arxiv.org/abs/1305.3654)

Is it SM-Higgs?

- Whether or not the new particle is a SM Higgs boson remains to be seen
- Two approaches:
  - study Higgs properties: coupling to fermions and bosons, spin and parity
  - search for new physics Beyond Standard Model
- The Higgs boson has already been measured to be compatible with the hypothesis of spin 0 and positive parity as predicted by the SM →



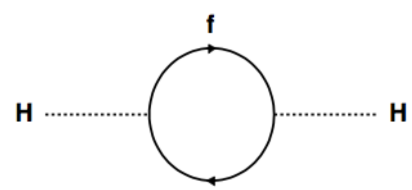
arxiv:1212:6639

- Nevertheless, the search for new physics is strongly motivated by the several limitations of the SM:
  - **higgs mass stability**
  - dark matter and dark energy
  - gravitational force
  - ...

Beyond Standard Model

The Higgs mass stability problem (hierarchy)

- The Higgs mass gains quantum corrections from fermion loops



M_H^2 (125 GeV) = $M_0^2 + \delta M_H^2$

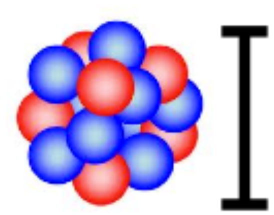
$$\delta M_H^2 = -2\frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

fine tuning: Λ ~ gravitational scale ~ M_{Planck} ~ 10^{19} GeV

- If new physics at the TeV scale exists the cut-off Λ is set by the scale of the new dynamics ... Λ ~ 1 TeV

The composite Higgs model

Higgs as a composite state of an enlarged global symmetry of a new strong dynamics



l_H

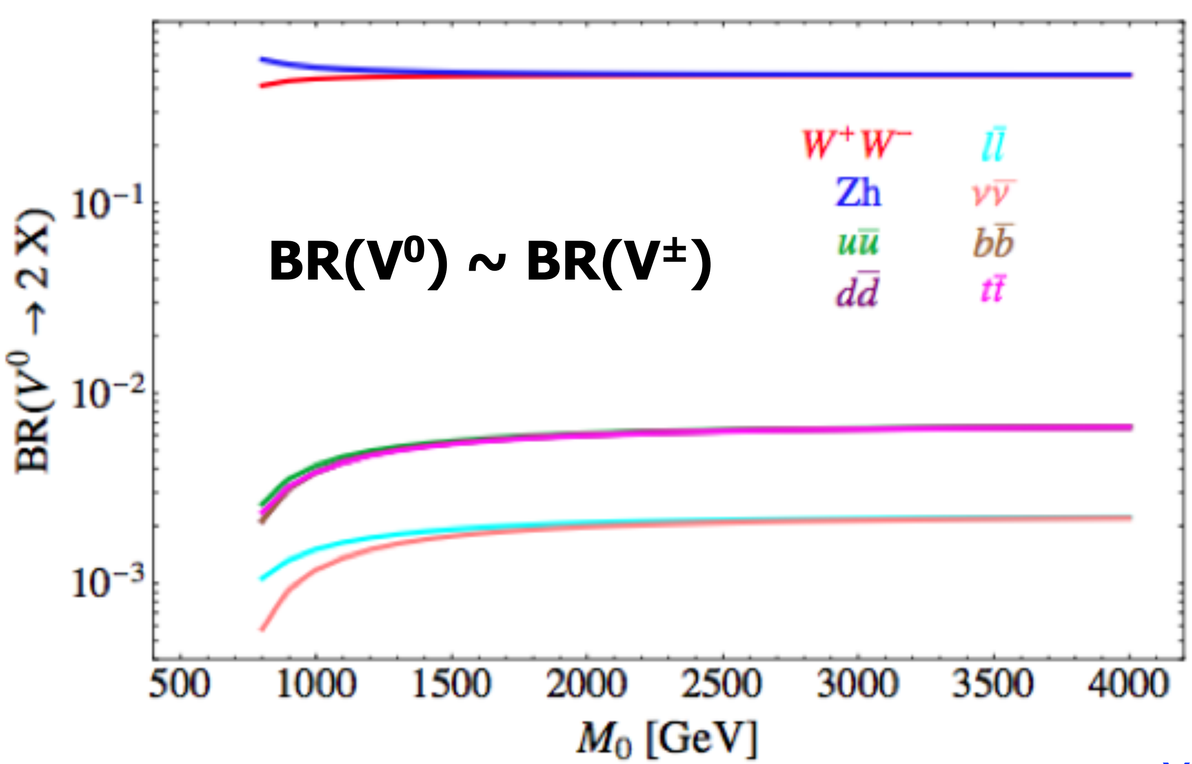
The hierarchy problem is solved:

- corrections to m_H screened at $1/l_H$

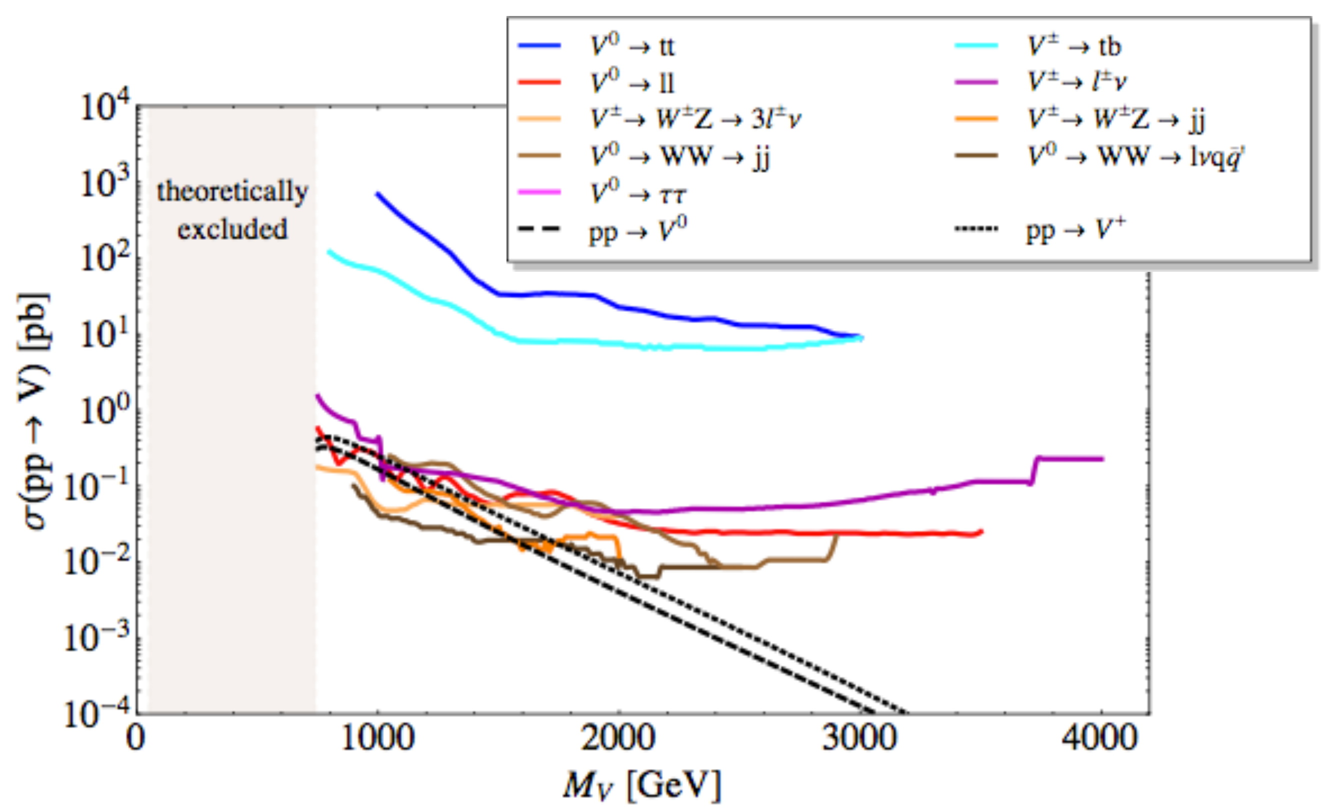
Z′ and W′: data & bounds

- The composite Higgs boson couples to the SM particles and to new heavier gauge bosons, such as **Z′** and **W′**, with masses in the TeV region
  - in this scenario the neutral (V^0) and the charged ($V^\pm$) heavy resonances decay primarily to SM vector bosons or to the composite Higgs

Branching Ratios for the two body decays of the neutral vector V^0 (Z′)



Bounds on the production cross sections in pp collisions @ 7-8 TeV



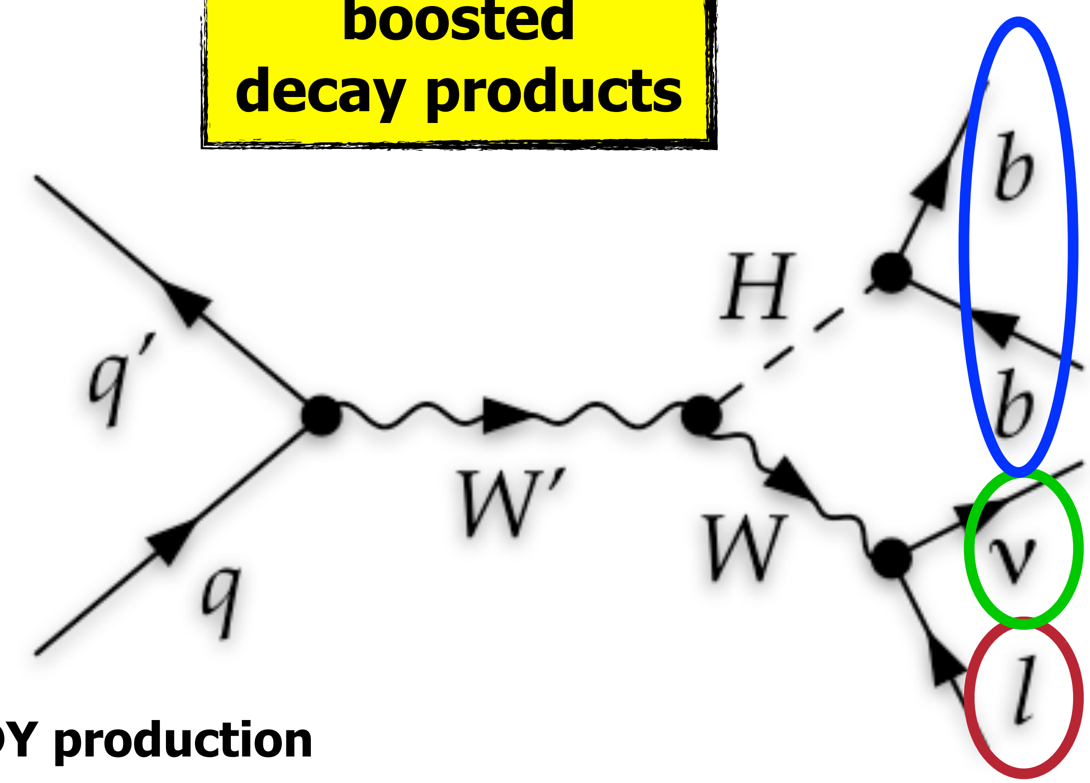
arXiv:1402.4431

W′ signal: **W′ → WH → $\ell\nu b\bar{b}$**

H → $b\bar{b}$ dominant Higgs decay mode : BR~56%

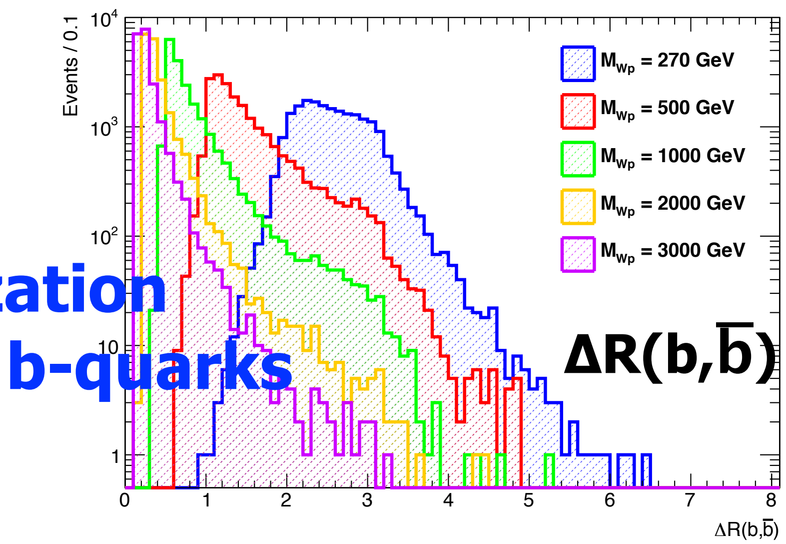
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

boosted decay products

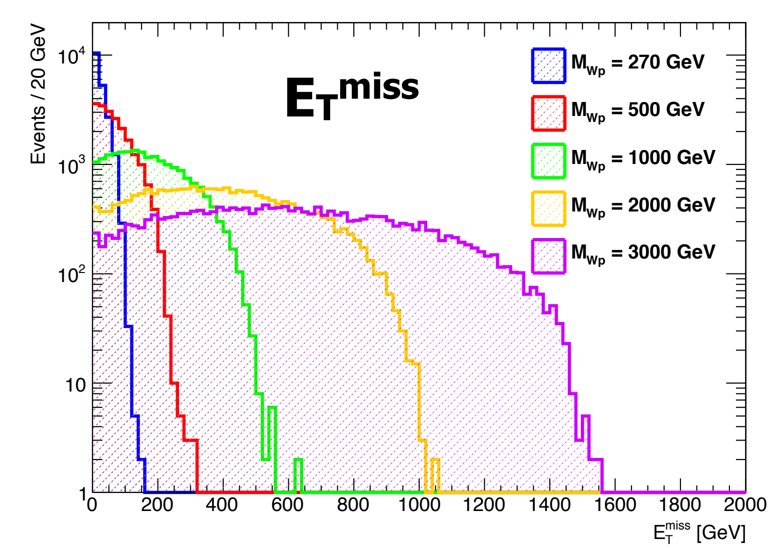


DY production

one high p_T jet from the hadronization of two collimated b-quarks



large missing transverse energy



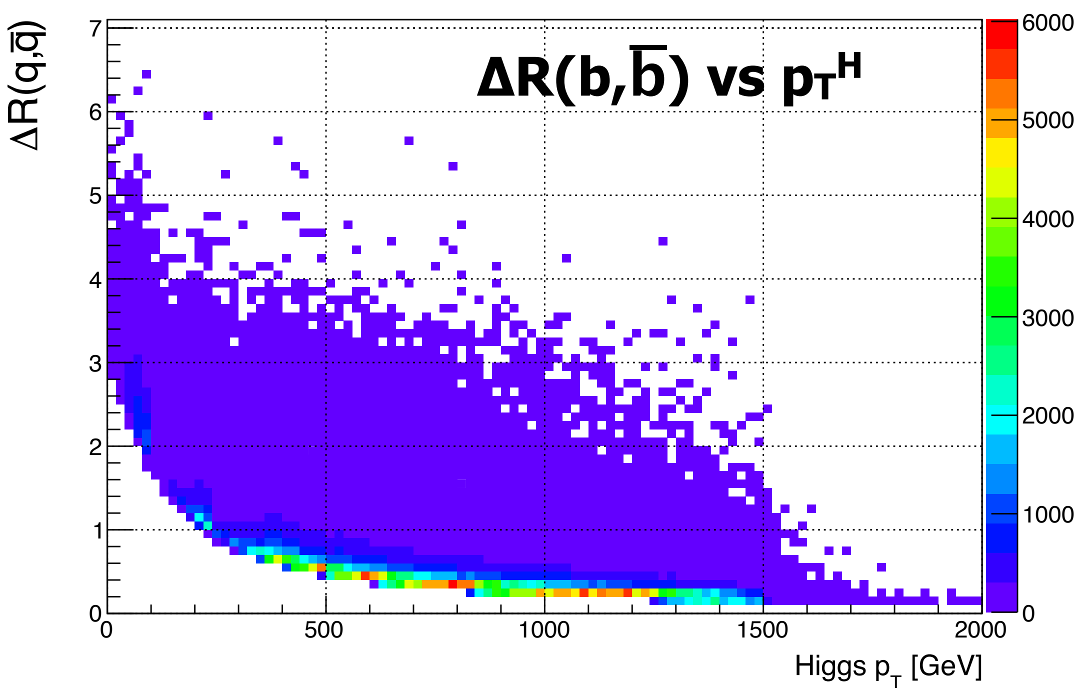
One high p_T isolated lepton

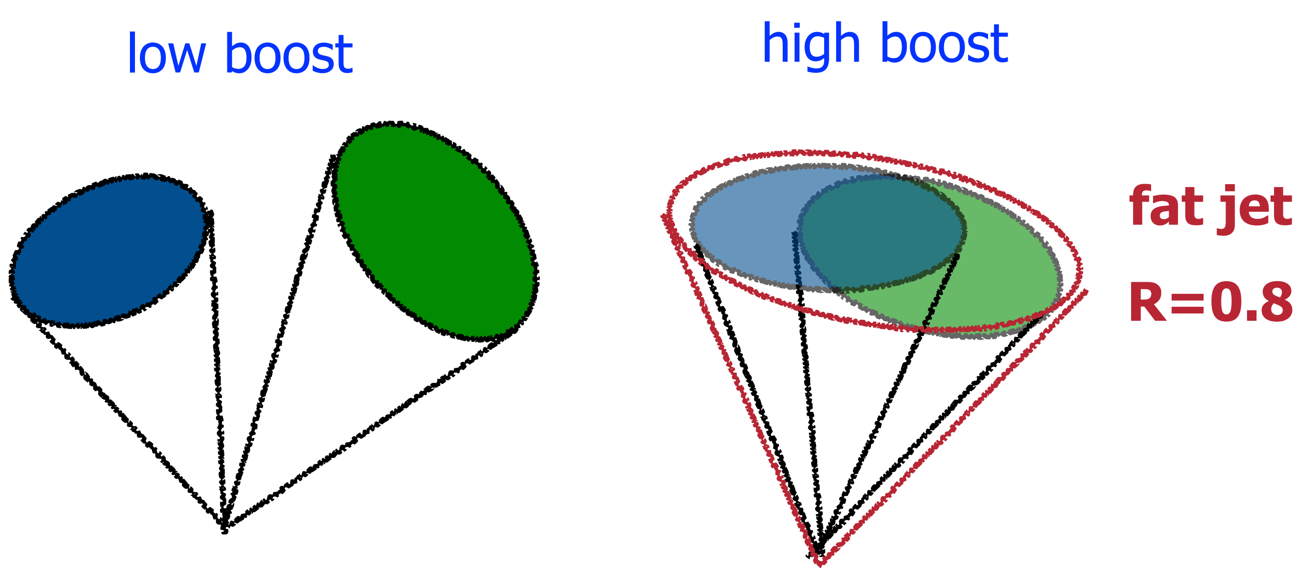
ℓ = electron, muon

E_T^{miss} measures the energy imbalance in the plane transverse to the colliding proton beams

Higgs-jet identification

- In X→WH events the Lorentz factor γ (boost factor) of the Higgs is ≈ $M_X/2M_H$
- For large γ the b-quarks from the Higgs will be predominantly emitted with small $\Delta R \approx 2M_H/p_T^H$: $p_T^H \sim 350$ GeV for $M_X = 0.8$ TeV → $\Delta R < 0.7$ in ~60% of the events

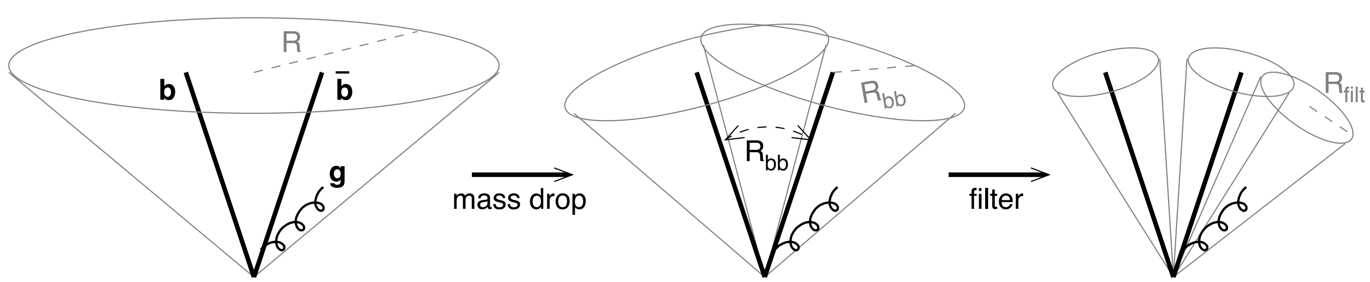




- **Strategy:** it is very important for boosted Higgs-tagging to be able to identify the substructure of the merged jet

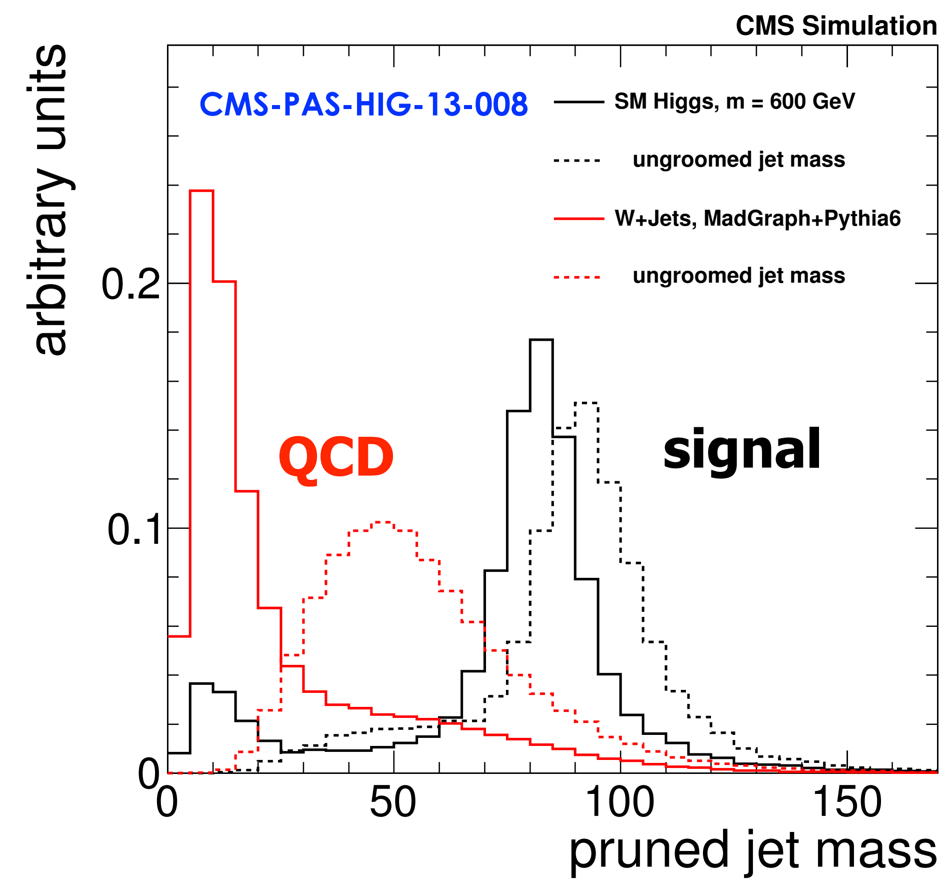
Enhancing jet substructure

- Among the several algorithms proposed to identify jet substructure originating from heavy objects, the **jet pruning algorithm** has been shown to provide the best performance
- The algorithm removes particles with background-like QCD radiation while keeping the particles from the quarks originating in Higgs decay
- Pruning the jet mass gives improved discrimination power by suppressing background jet masses to zero while preserving the signal jet mass near the Higgs mass



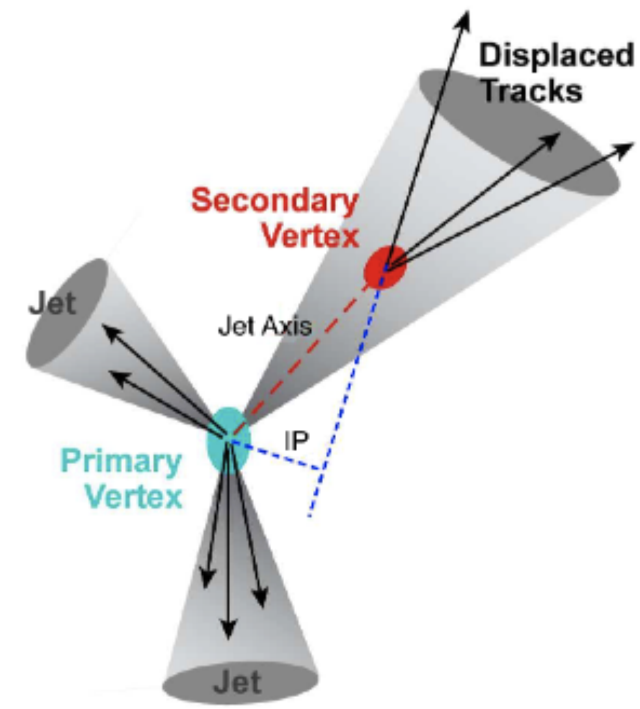
single-jet mass distribution for a heavy resonant signal and for the background

before pruning - - - - - -
after pruning ———



Identifying b-jets

- Large lifetime of B-hadrons (~1.5ps)
  - observable flight distance (~450 μm)
  - secondary vertex displaced from the primary vertex
- Large multiplicity of charged particles in the final state
- Large mass
  - charged particle tracks incompatible with the primary vertex
  - high impact parameter



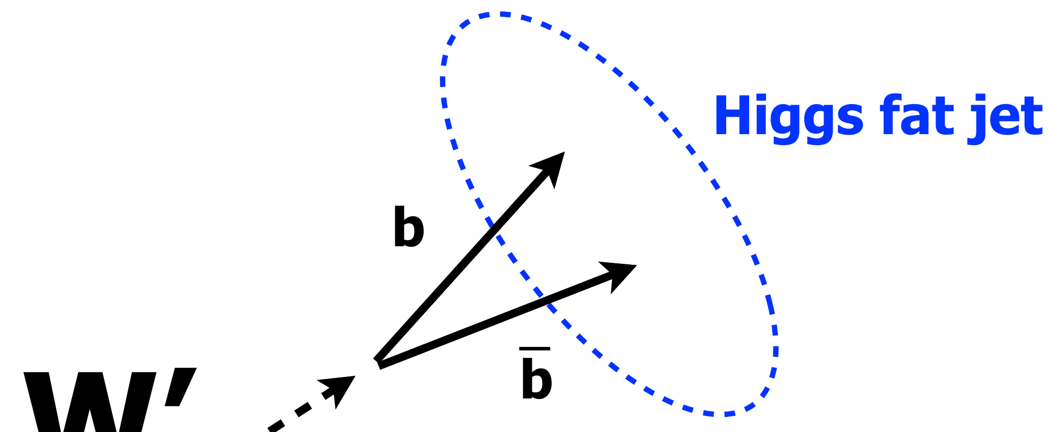
➜ All these information are combined in the CMS default b-tagging algorithm to identify jets coming from b-quarks: **Combined Secondary Vertex**

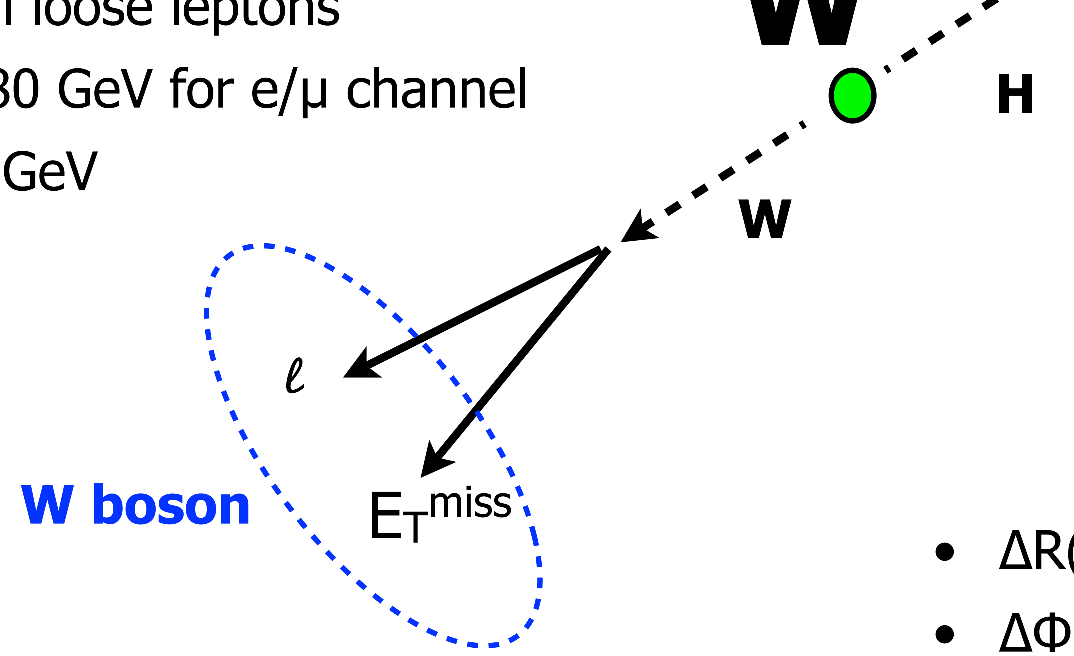
- The algorithm is trained to discriminate light from heavy/b flavor
- The discriminant is used to apply a cut at different working points depending on the acceptance of light flavor jets:

Loose : 10% - Medium : 1% - Tight : 0.1%

Event selections

- lepton p_T > 50/90 GeV for e/μ channel
- no additional loose leptons
- E_T^{miss} > 50/80 GeV for e/μ channel
- W p_T > 200 GeV





- Higgs-jet p_T > 200 GeV
- 2 b-tagged subjets at CSVL
- veto b-tagged extra jets
- 110 < pruned jet mass < 135 GeV

the lepton from the W decay provides an efficient trigger path

- $\Delta R(\text{jet}^{CA8}, \ell) > \pi/2$
- $\Delta\Phi(\text{MET}, \text{jet}^{CA8}) > 2$
- $\Delta\Phi(\text{jet}^{CA8}, W) > 2$

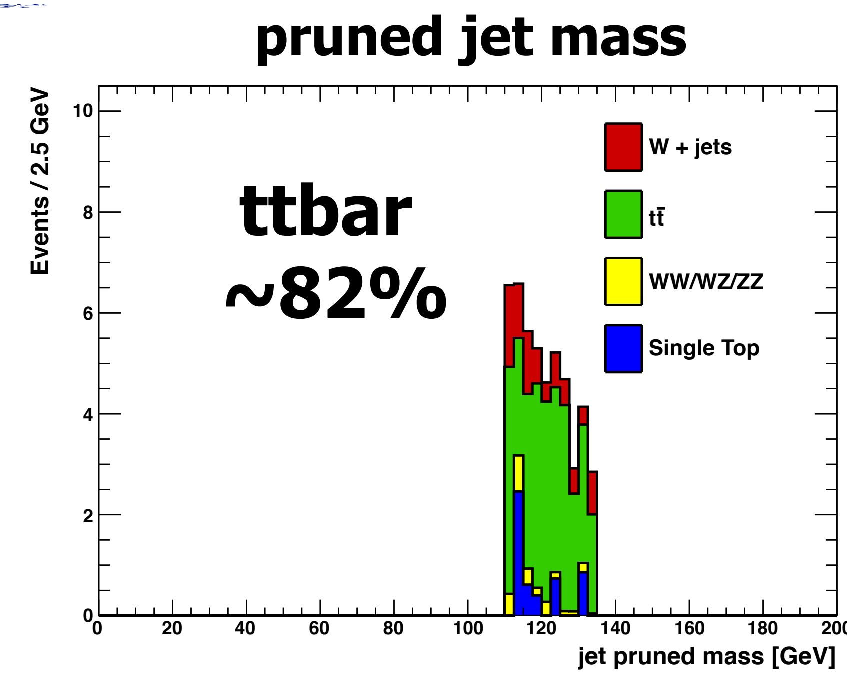
} back-to-back topology

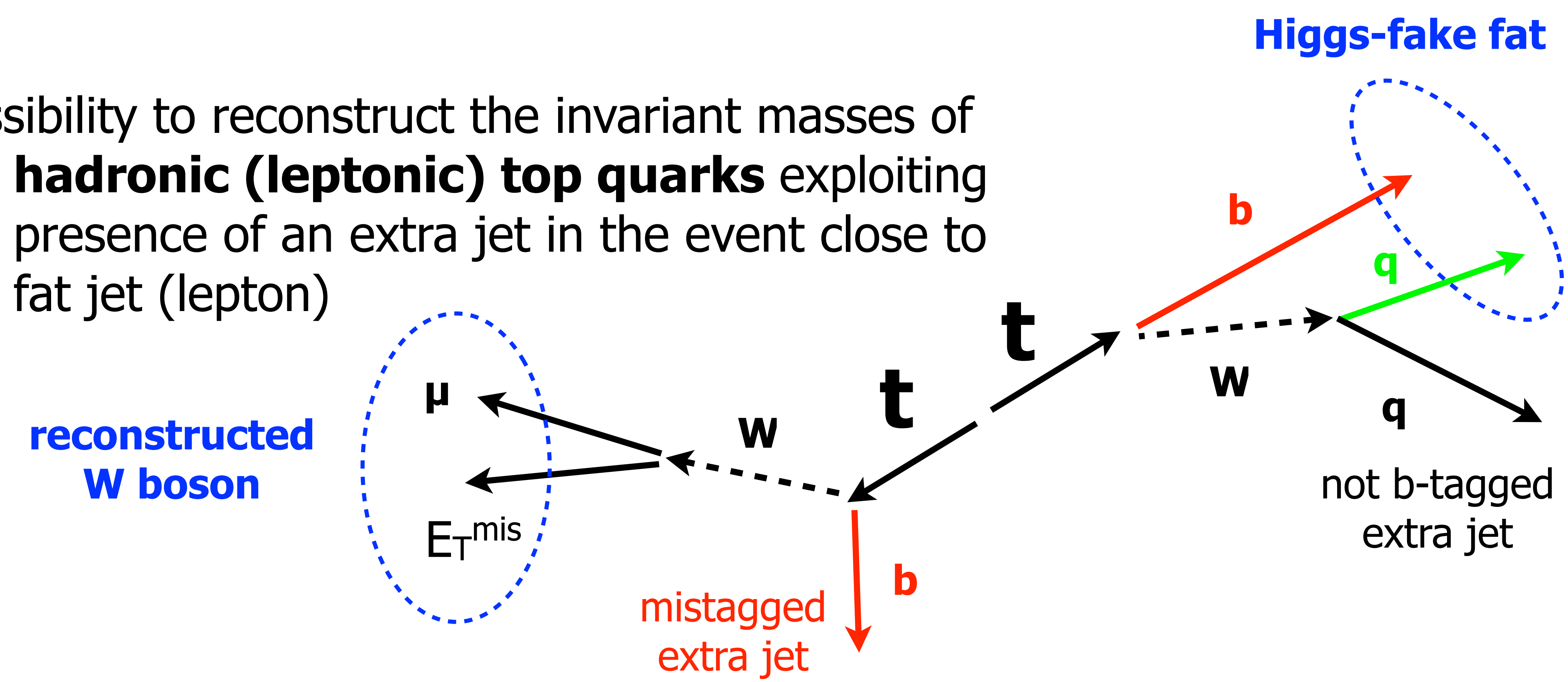
Main backgrounds with signal-like signature ➜ lepton+E_T^{miss}+jet

$t\bar{t}$, W+jets, single top, WW/WZ/ZZ

$t\bar{t}$ background rejection

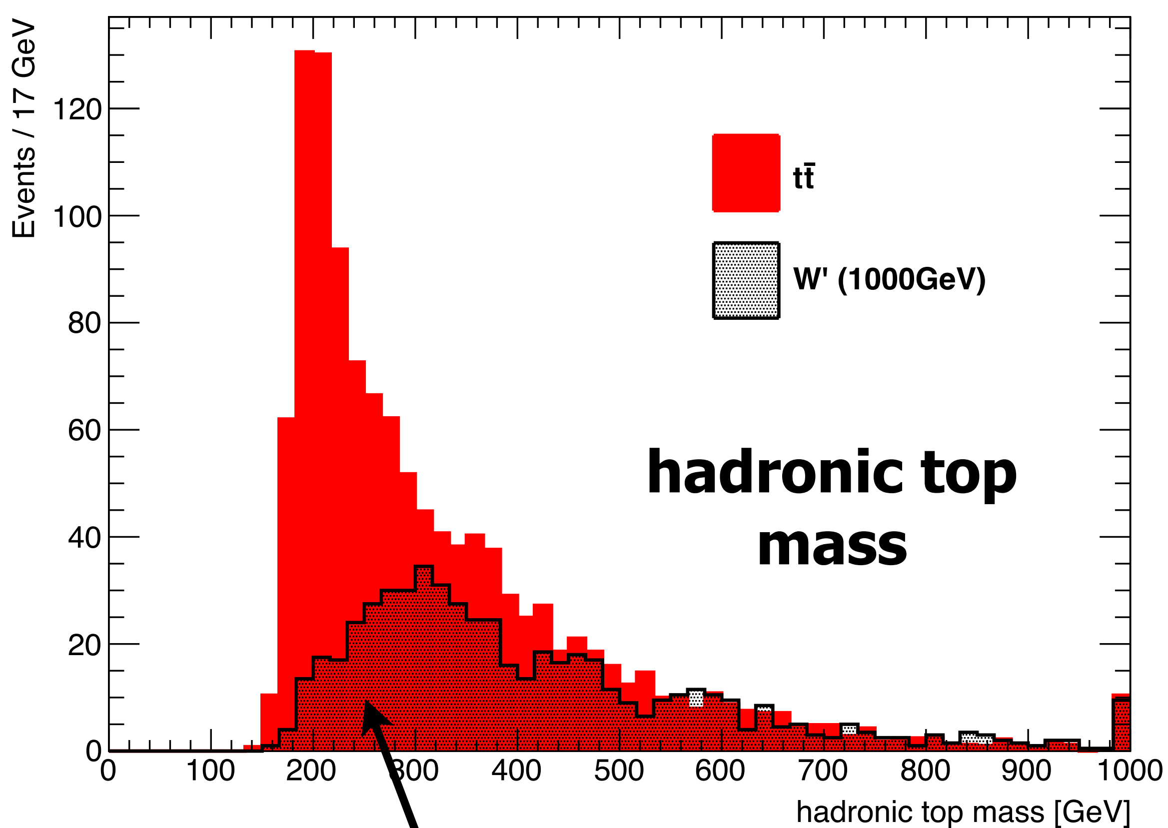
- The ttbar process is the main source of background (~82% after full selection) in the pruned jet mass signal region [110-135] GeV
- Two real Ws: one decaying in leptons and the other in hadrons
- Two b-quarks → veto on number of extra b-tagged jets
- Possibility to reconstruct the invariant masses of the **hadronic (leptonic) top quarks** exploiting the presence of an extra jet in the event close to the fat jet (lepton)



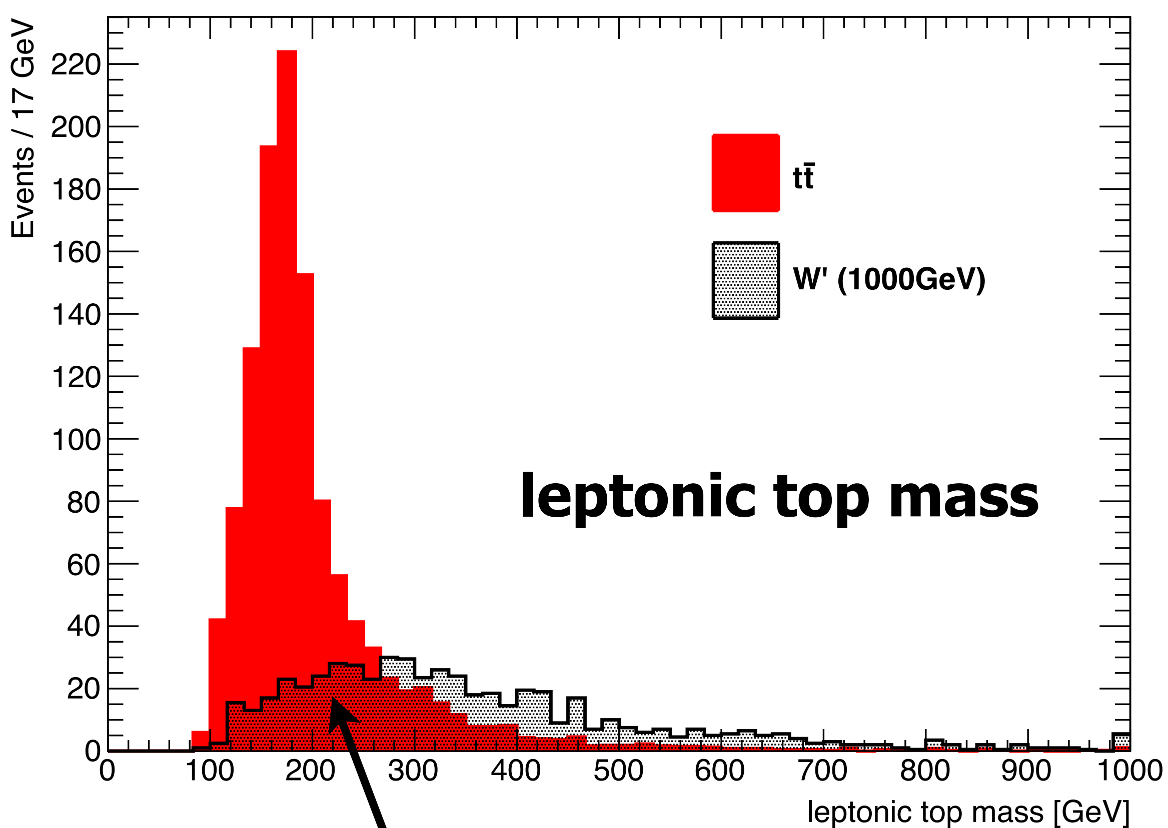


$t\bar{t}$ background rejection

- Different shapes of the hadronic and leptonic top masses for signal and ttbar
- A veto on the top masses is introduced to further suppress ttbar events
- Reject events with reconstructed leptonic or hadronic top mass compatible with top quark mass



reject events with
hadronic top mass in [160-280] GeV



reject events with
leptonic top mass in [120-240] GeV

Reconstructing W' candidate

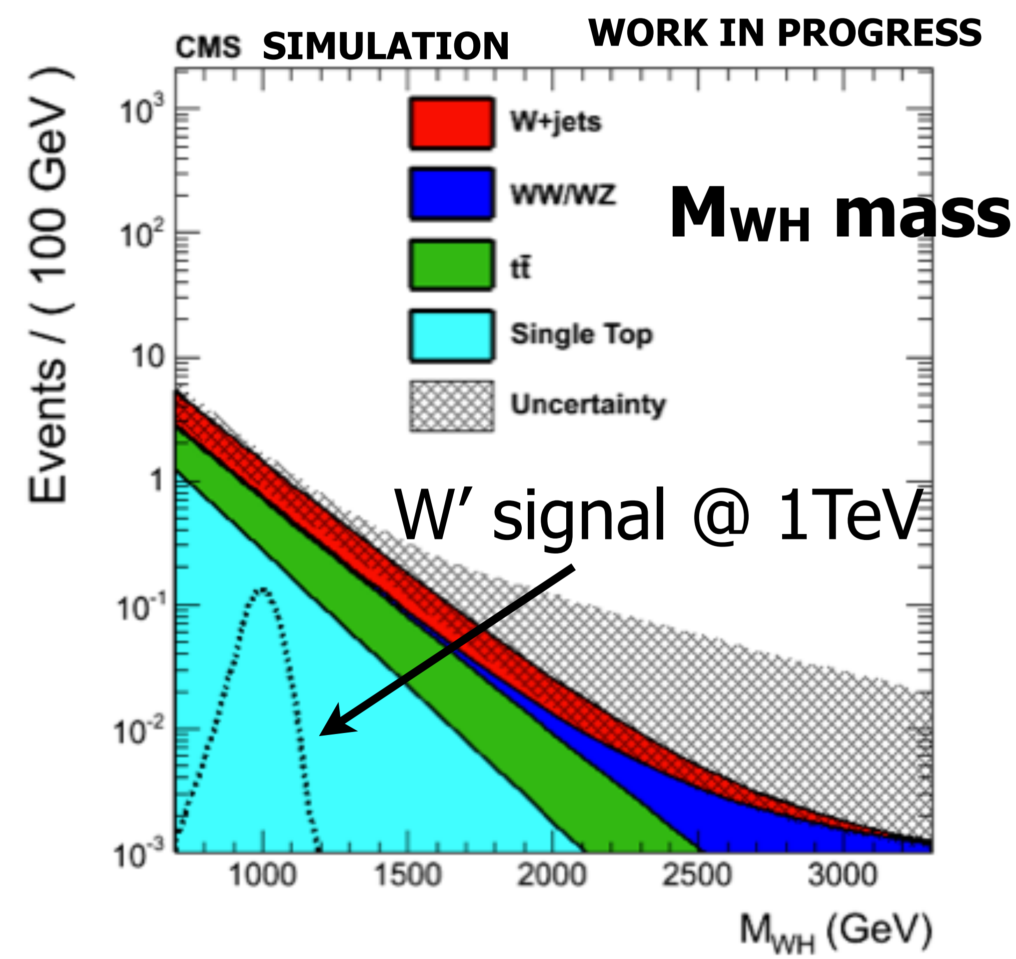
- **Reconstruct W→lv candidates**: the longitudinal component of the neutrino momentum, $p_{z,v}$, is calculated solving the second-order equation that makes use of the known W mass

$$(E_\ell + \sqrt{{\mathbf{E}_T^{miss}}^2 + p_{z,\nu}^2})^2 - (\mathbf{p}_{T,l} + \mathbf{E}_T^{miss})^2 - (p_{z,l} + p_{z,\nu})^2 = M_W^2 = (80.4)^2 \qquad (1)$$

- Once the leptonic W is reconstructed, the invariant mass of the W plus Higgs-jet candidate is computed to give the resonance invariant mass

Bump "hunt" in jet+lepton final state

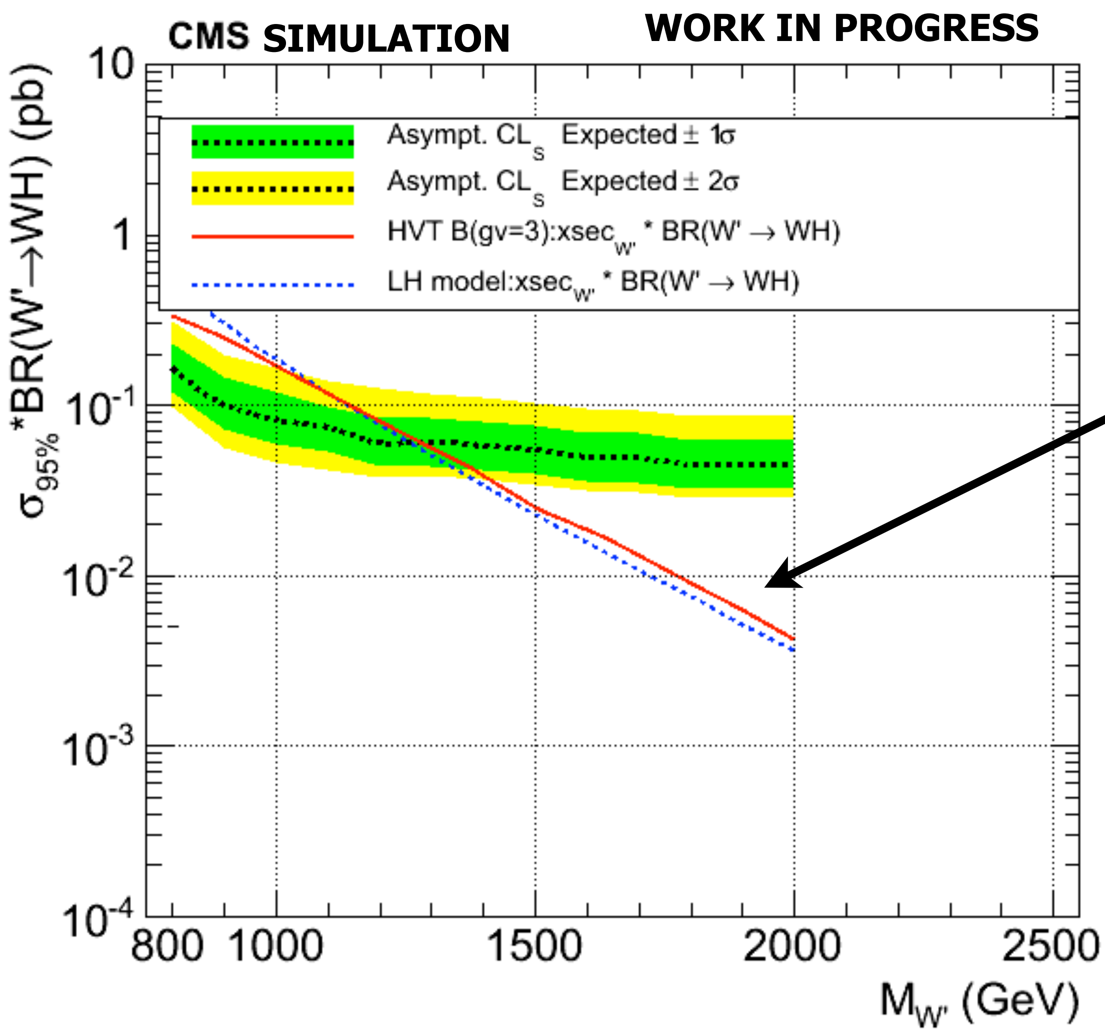
Search for resonances on top of a smoothly falling background



Expected upper limits

- Set **model independent** limits on the production cross-section of a resonance decaying to WH as a function of the resonance mass using the predicted data in 19.7fb-1 of integrated luminosity at 8 TeV

$\sigma(pp \to W') \times BR(W' \to WH)$



Predictions from composite Higgs models

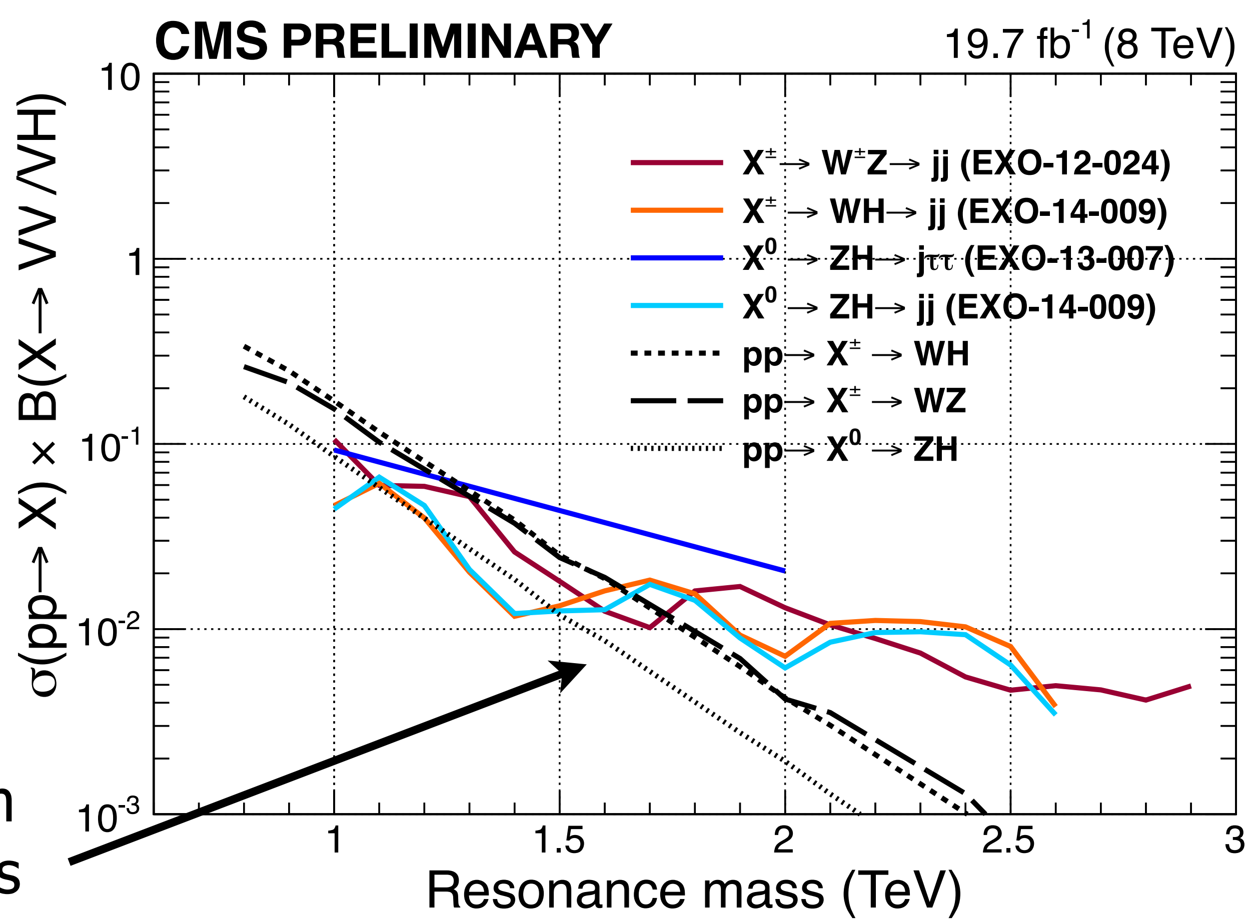
Expected exclusion up to $M_{W'}$~1.3 TeV

Exotic searches

- Other CMS analyses have already performed model independent searches for narrow heavy spin-1 resonances $X^{0/\pm}$ decaying into di-bosons (VV/VH) in different final states
- Efforts are currently spent to compare and combine the results in a common simplified benchmark model which reproduces a large class of explicit models
- In particular, a chosen set of parameters of the model reproduces the Composite Higgs model in which the searches into di-bosons final state can set more constraining limits

Comparison of the observed limits set on $\sigma(pp\rightarrow X) \times BR(X\rightarrow VV/VH)$ by di-bosons searches in CMS in 19.7fb^{-1} of integrated luminosity at 8 TeV in 2012

Predictions from composite Higgs model



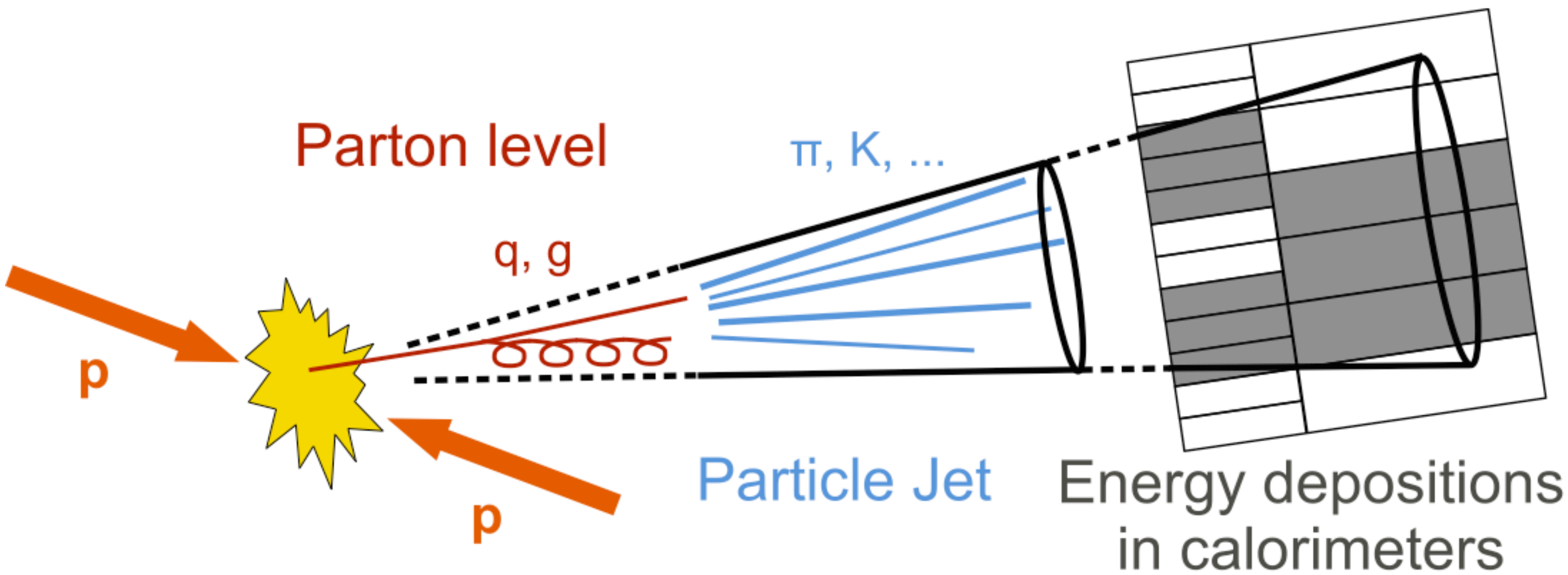
Conclusions

- Presented a strategy for a model independent search for a heavy resonance decaying into a W boson and a Higgs boson with boosted $W \rightarrow l\nu$ and $H \rightarrow bb$
- Higgs-jet identification against the SM background requires the use of jet substructure techniques
  - jet pruning
  - subjets b-tagging
- The procedures have already been validated in other CMS resonance searches with the 8 TeV data in 2012
  - no excess of events observed in the signal regions
  - upper limits interpreted in a common simplified model setting an exclusion up to ~1.7 TeV
- The experience gained from this study will be crucial with the 13 TeV data in 2015 when techniques for resolving boosted objects become even more important and when higher luminosities and beam energies will extend the mass reach

Back up

What are jets?

Collimated bunches of stable hadrons, originating from partons (quarks and gluons) after fragmentation and hadronization



- the jet energies are collected by the two CMS calorimeters, ECAL and HCAL, and then clustered in jets
- then, the **CMS particle flow algorithm** links the calorimetric deposition to the tracks reconstructed in the tracker detector to form the charged hadrons that constitutes the jet and to give a better measurement of the jet transverse momentum

Jets clustering algorithms

- Construct the quantities:

$$d_{ij} = min(k^n_{T,i}, k^n_{T,j})\frac{\Delta R^2_{ij}}{R^2}, d_{iB} = k^n_{T,i}$$

k_{Ti} = transverse momentum of the i-th particle
ΔR_{ij} = transverse distance between particle i and j in the (eta,phi) plane
R = scaling factor that defines the jet cone radius
d_{iB} = distance between particle i and the beam

- compute all distances d_{ij} and d_{iB}, find the smallest:
  - if smallest is d_{ij}, combine (sum 4-momenta) the two particles i and j, update distances, proceed finding next smallest
  - if smallest is d_{iB}, particle i is a final jet and is removed from the list
- The parameter **n** of the algorithm governs the power of the energy in respect to the geometrical scales
  - **n=2 - kT algorithm**
  - **n=0 - Cambridge-Aachen algorithm**
  - **n=-2 - anti-kT algorithm**

anti-kT with R=0.5 default algorithm used in CMS for Higgs analysis (AK5 jets)

Starting from a Cambridge-Aachen jet and undoying the jet clustering step-by-step yields to its decomposition in intermediate clusters, defined as **"subjets"**

Enhancing jet substructure

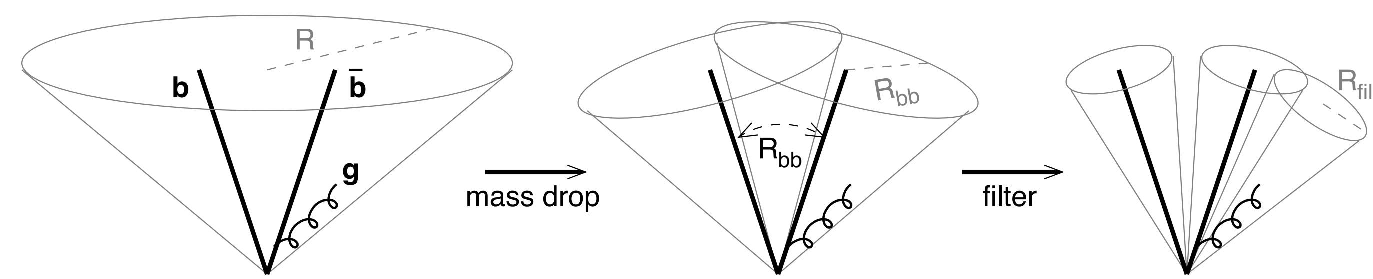
- Among the several algorithms proposed to identify jet substructure originating from heavy objects, the **jet pruning algorithm** has been shown to provide the best performance:
  - start from a large-radius jet (Cambridge Aachen with R=0.8)
  - recluster the jet constituents and evaluate the hardness and angular separation of the last recombination

hardness

$$z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,JET}} > 0.1$$

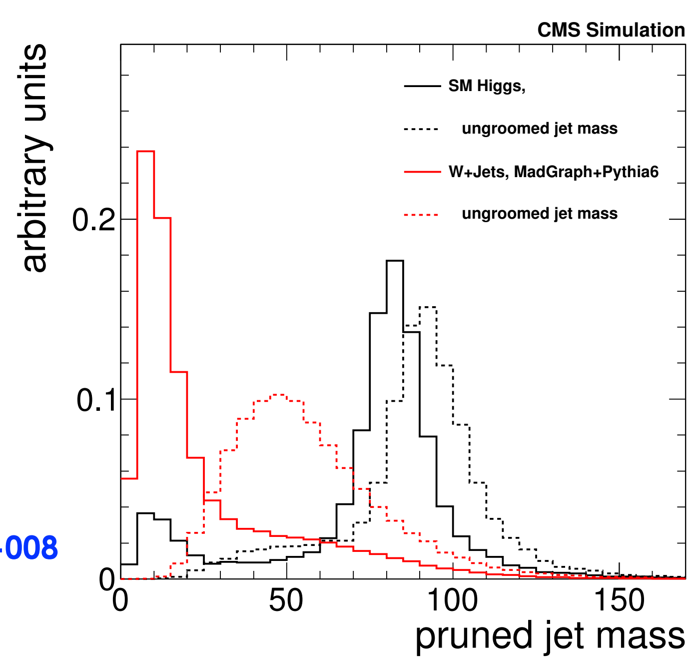
angular separation

$$\Delta R < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



  - remove the softest subjet if conditions are not satisfied

- The procedure removes soft and large-angle radiation from QCD jets produced with W



CMS-PAS-HIG-13-008

Pruning the jet mass gives improved discrimination power by suppressing background jet masses to zero while preserving the signal jet mass near the Higgs mass

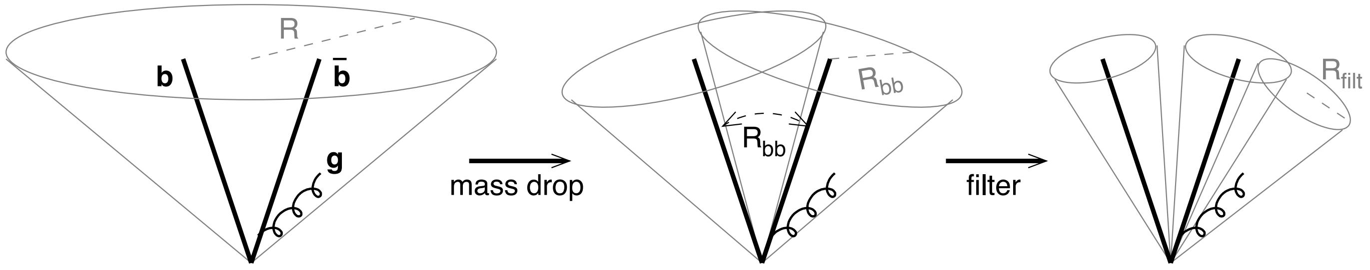
Enhancing jet substructure

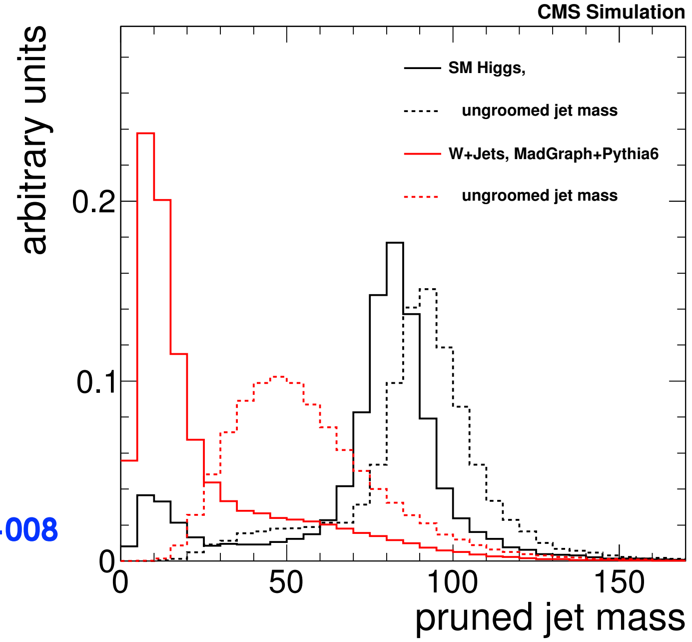
hardness

$$z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,JET}} > 0.1$$

angular separation

$$\Delta R < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



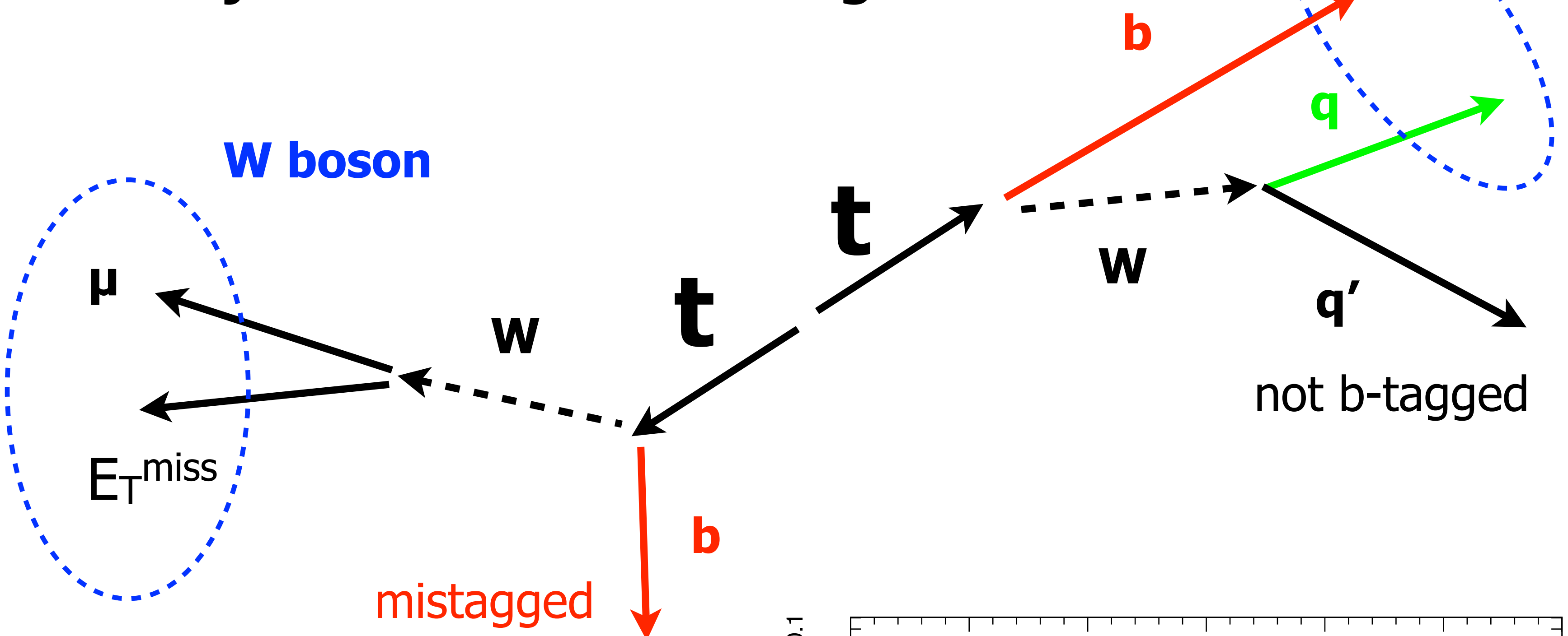


CMS-PAS-HIG-13-008

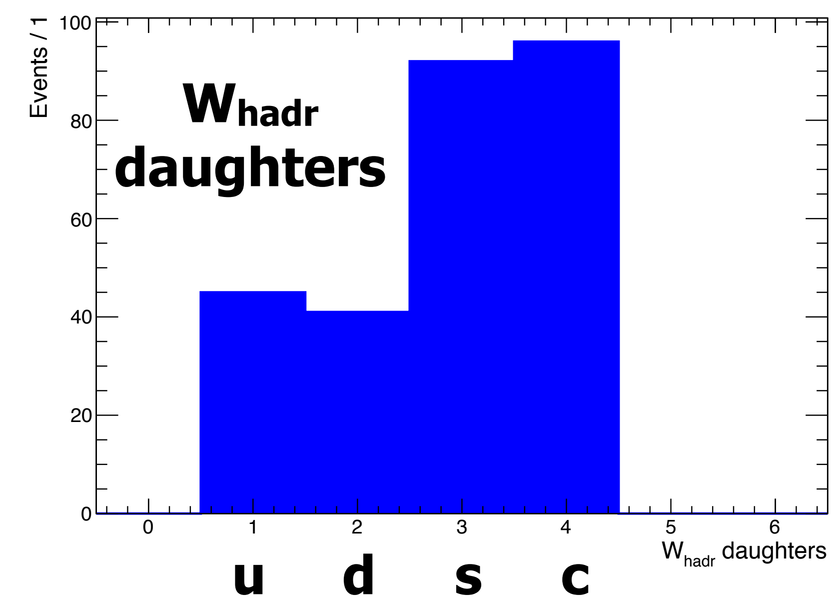
Pruning the jet mass gives improved discrimination power by suppressing background jet masses to zero while preserving the signal jet mass near the Higgs mass

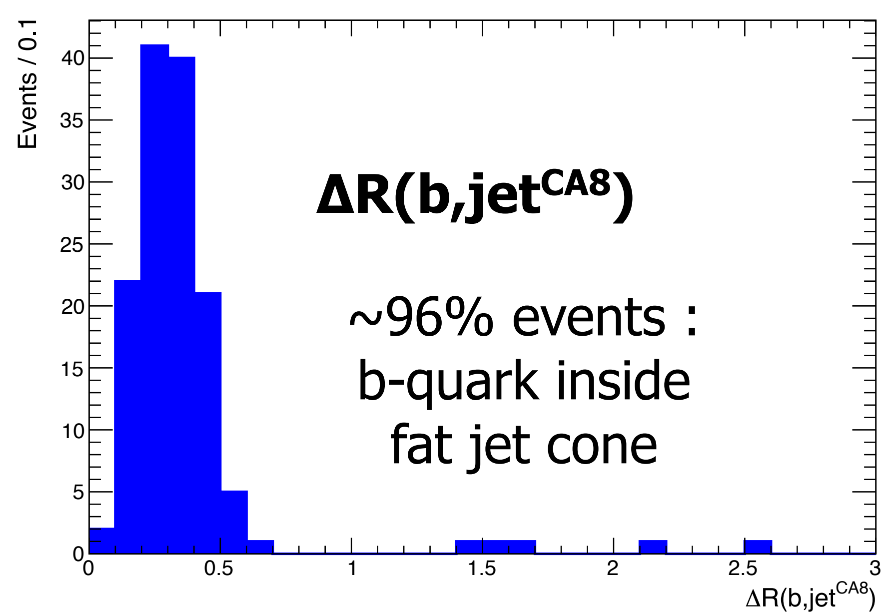
Comparing W' and ttbar

When applying b-tagging to both the subjets @ CSVL and btag veto



~70% events
q = c-quark
higher mistagging probability





W’ models

- **Simplified Model for heavy vector triplets (HVT)**
  - https://indico.cern.ch/event/309326/contribution/0/material/slides/0.pdf
  - model tested in ATLAS-PH-EP-2014-094 for WZ in the leptonic channel
  - the couplings to fermions and gauge bosons are defined in terms of the 3 parameters g_V, c_F and c_H:

    g : $SU(2)_L$ gauge coupling

    - coupling to fermions → $g^2 c_F / g_V$
    - coupling to Higgs and to vector bosons → $g_V c_H$

    dominant BRs into di-bosons

    fermionic decays suppressed

  - Depending on the parameter g_V:
    - Model A: weakly coupled vector resonances arise from an extension of the SM gauge group → $g_V \lesssim 3$
    - **Model B:** the heavy vector triplet is produced in a strongly coupled scenario, for example in a Composite Higgs model → $g_V \gtrsim 3$

W' models

Little Higgs

- https://indico.cern.ch/event/322109/contribution/5/material/slides/0.pdf (Qiang)
- model tested in ATLAS-PHYS-2004-001 for WH and ZH
- the couplings of W' depend on a single parameter: **the θ angle**
  - coupling to fermions → **-cotθ**
  - coupling to vector bosons → **-cot2θ**
- is a composite Higgs model which can be easily interpreted in the Model B of the HVT

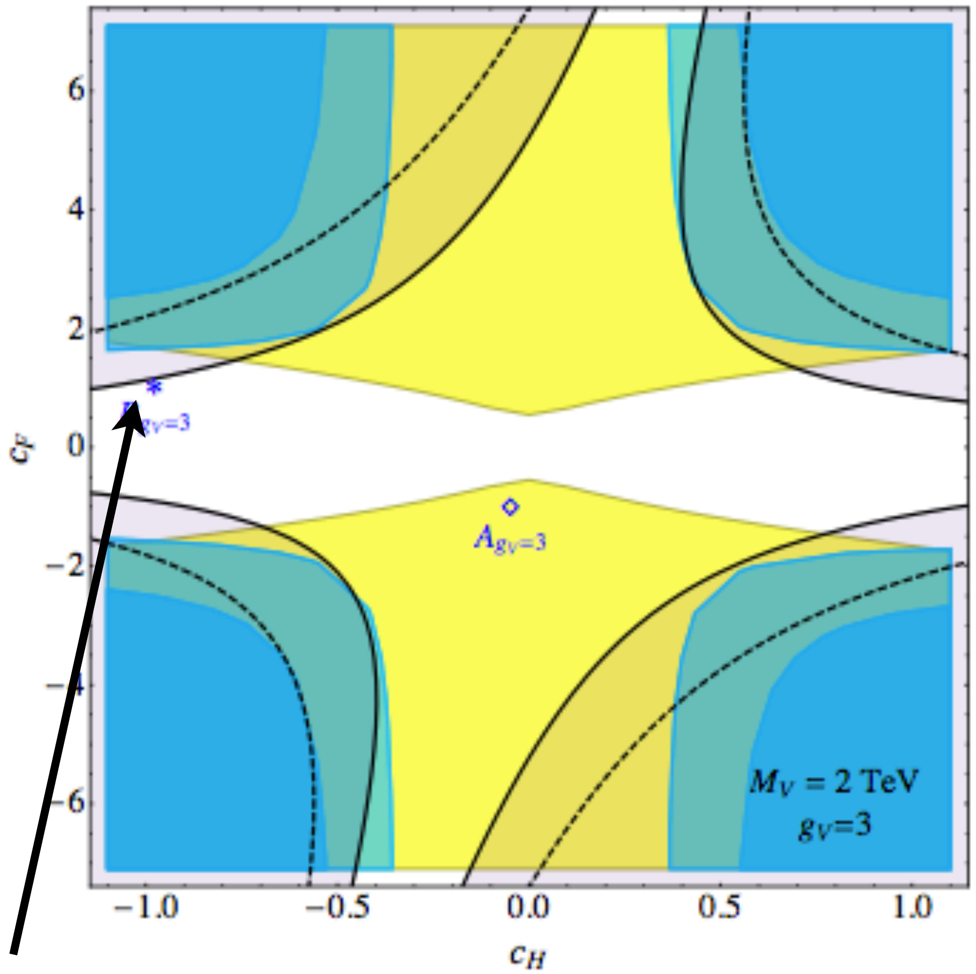
$$WWH: \ \frac{i}{2} g^2 v\, g_{\mu\nu} \quad \longrightarrow \quad WW'H: \ x * \frac{i}{2} g^2 v\, g_{\mu\nu} + O(v^2/f^2)$$

$$Wu_L d_L: \ \frac{i}{\sqrt{2}} g \gamma_\mu V_{ud} \quad \longrightarrow \quad W'u_L d_L: \ y * \frac{i}{\sqrt{2}} g \gamma_\mu V_{ud} + O(v^2/f^2)$$

Model	x	y
LH	-cot2θ	-cotθ
HVT	$c_H g_V/g$	$c_q g/g_V$

W' models

allowed and excluded regions in the (c_F, c_H) plane for M_V=2 TeV and g_V = 3



arxiv.1402.4431

black: constraints coming from EWPT

- solid: strict 95% CL bound
- dashed: obtained enlarging the bound by a factor of two

blue: exclusion from the CMS WZ→3lν and WZ→jj analysis

yellow: exclusion from the CMS $l^+\nu$ analysis

Model B

$g_V = 3$
$c_F = 0.5$
$c_H = -1$

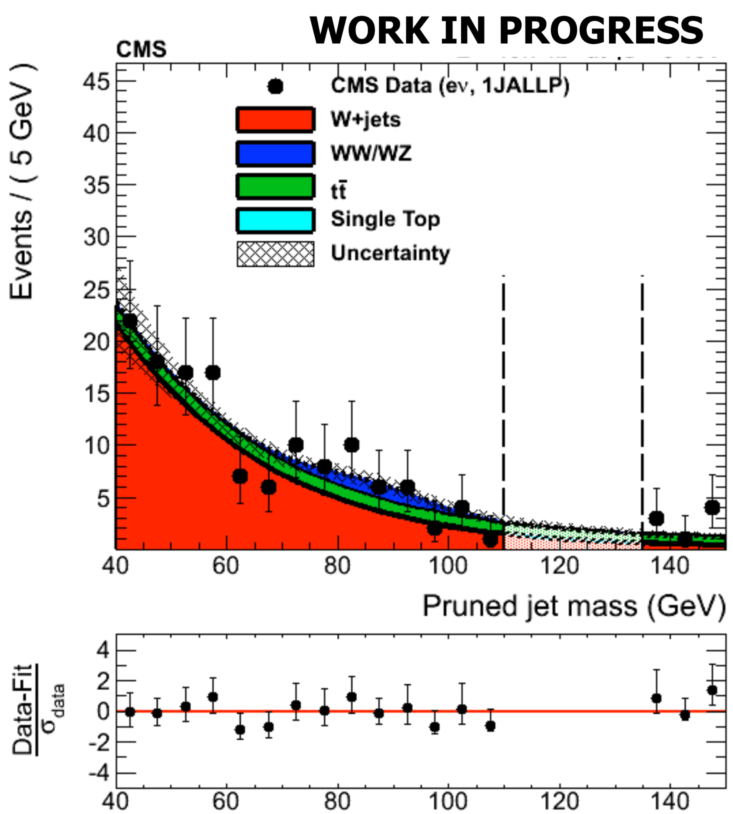
→

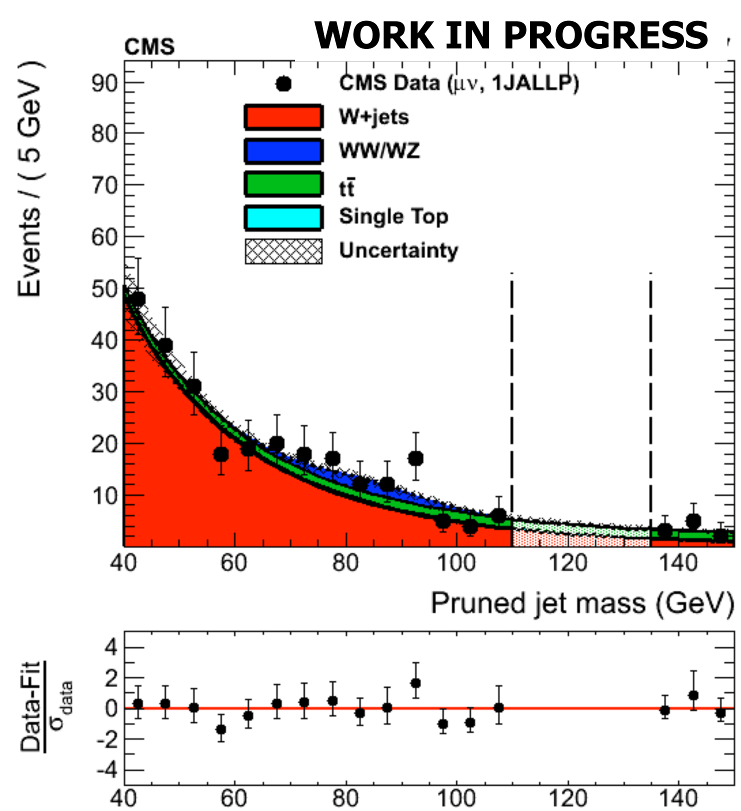
Little Higgs

$\cot\theta = -0.1$
$\cot 2\theta = 4.6$

Expected yields

- Analyzed LHC 2012 data corresponding to 19.7fb^{-1} of integrated luminosity
- W+jets background estimated in pruned jet mass signal region fitting the data in sidebands region
  - low sideband : [40-110] GeV - high sideband : [135-150] GeV
- Other background : normalization from the MC





process	electron channel	muon channel
ttbar	3.51 ± 0.46	7.96 ± 0.60
W+jets	5.54 ± 0.20	10.40 ± 0.24
VV	3.01 ± 0.33	0.68 ± 0.05
Single Top	0.35 ± 0.11	0.22 ± 0.05
Tot expected data	12.41 ± 0.61	19.26 ± 0.65