Search for heavy resonances decaying into a pair of boosted bosons in the $\tau^{-}\tau^{+}q\bar{q}$ final state at CMS

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Theory Motivation

The Standard Model is a successful theory describing the fundamental interactions of matter constituents

However some issues still need to be addressed: hierarchy problem, unification of interactions, etc…

Many New Physics (NP) Scenarios have been proposed:

new symmetries and properties -> new particles have been introduced

- Standard Model extensions
- Extra Dimensions Model

- Beyond the Standard Model searches of new resonances:
  - Low mass searches (up to 1 TeV)
  - High mass searches (1 TeV - 2.5 TeV) -> **Boosted regime**

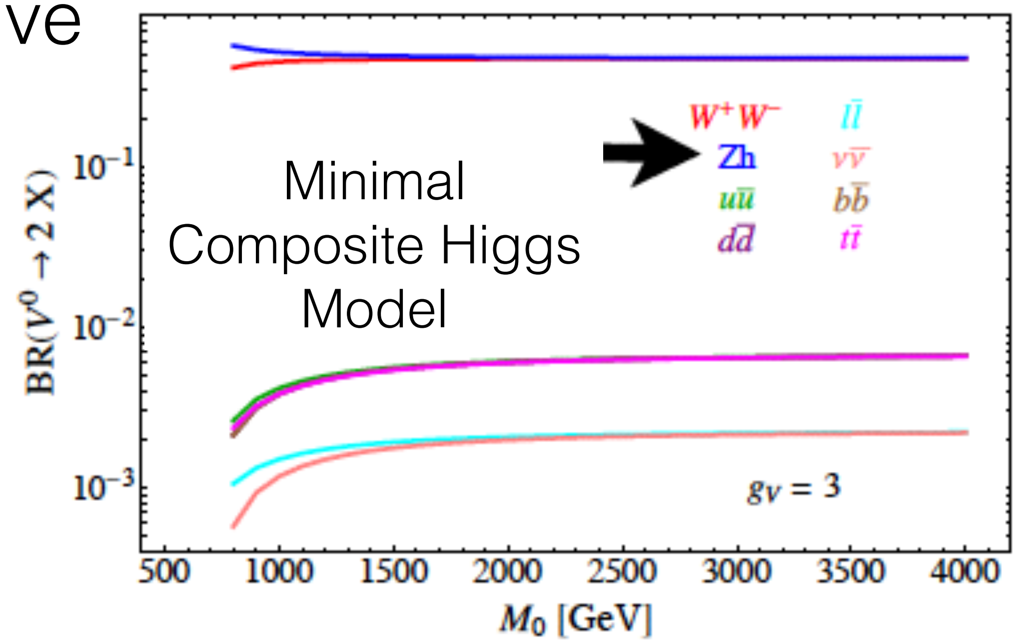
First searches for high mass narrow resonances in the $\tau^-\tau^+$ qq final state

ZH Search: Benchmark model

- New Physics searches adopting a Simplified Model strategy

arXiv:1402.4431

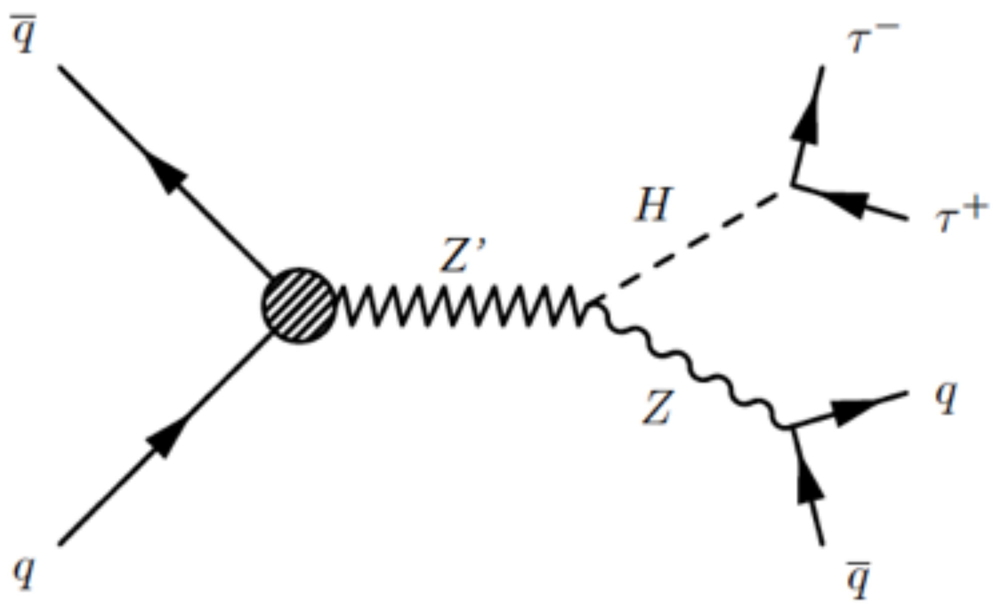
- Heavy Vector Triplets model predicts 3 massive gauge bosons: Z' and W'$^{\pm}$
- Phenomenological Lagrangian with only the relevant couplings and the mass parameters



$$\begin{aligned}\mathcal{L}_V = & -\frac{1}{4} D_{[\mu}V^a_{\nu]} D^{[\mu}V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \\ & + i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F \\ & + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu}V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW}\, \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu\end{aligned}$$

- g_V gauge coupling of the new interaction
- c_H, c_L, c_q, c_3, couplings to the H, leptons, light and third family quarks
- m_V resonance mass parameter

ZH Signal topology

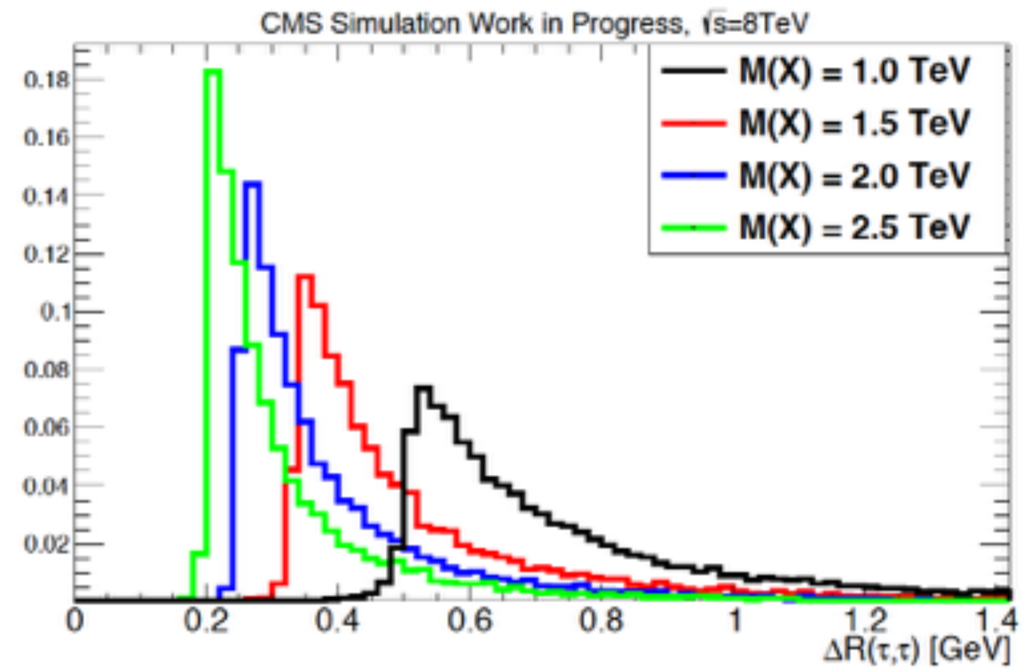


Final state with:

- two tau leptons from the Higgs decay
- two quarks from the Z boson decay

Heavy vector boson search starting from **$m_{Z'}$ > 1TeV**:

- H and Z very boosted
- the final products can be really collimated
- H boson: boosted tau reconstruction requires modification in the lepton ID
- Z boson: reconstruction through substructure study



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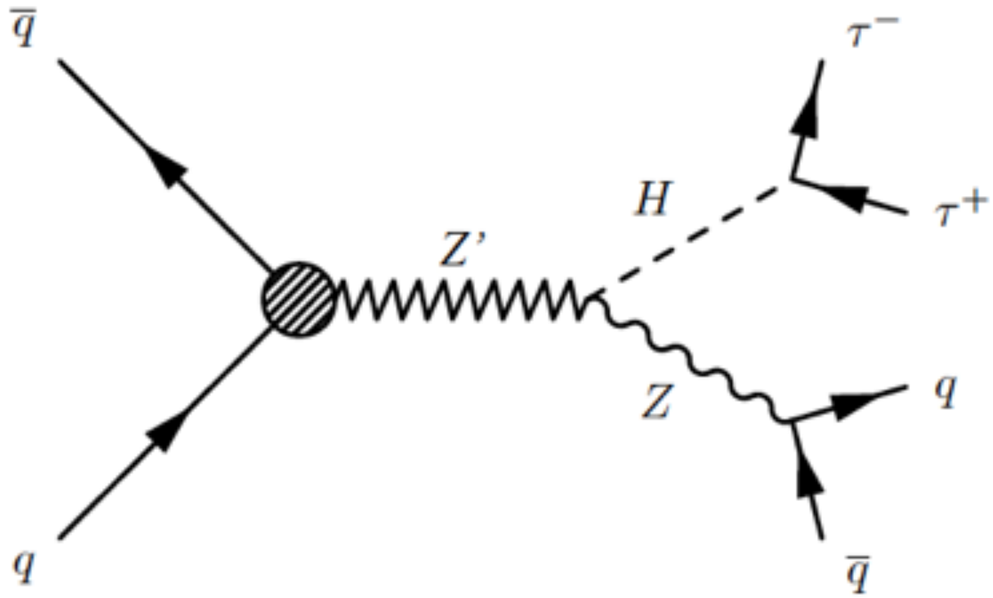
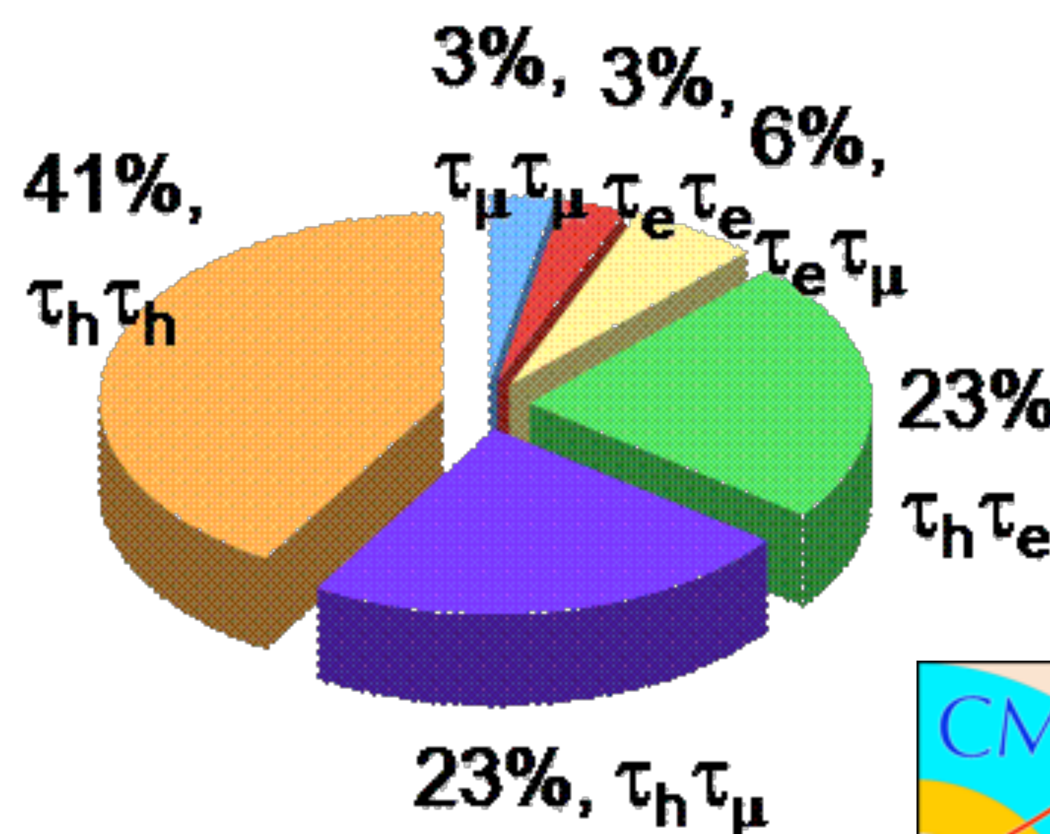


Final state with:

- two tau leptons from the Higgs decay
- two quarks from the Z boson decay

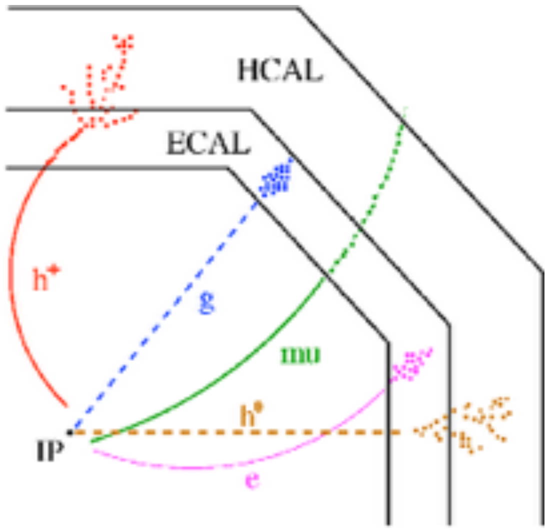
Six possible final states, depending on the τ decay:

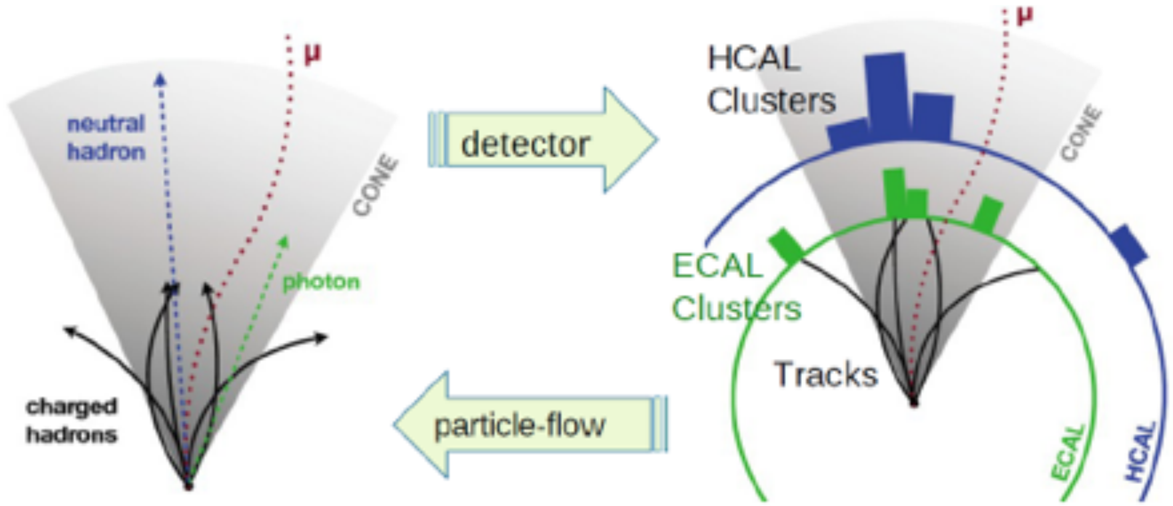
- Fully leptonic channel:
  - $\tau\tau \to \mu\mu$ 4v, $\tau\tau \to \mu e$ 4v, $\tau\tau \to ee$ 4v
- Semi-leptonic channel:
  - $\tau\tau \to$ nh μ 3v, $\tau\tau \to$ nh e 3v
- All hadronic channel:
  - $\tau\tau \to$ 2 nh 2v



Object Identification

- Particle Flow Algorithm — all the information from the sub detectors are combined to reconstruct all particles in the collisions :
    - charged and neutral hadrons, photons, electrons, muons
- Particles are used to identify jets, tau and MET





Missing Transverse Energy (MET) for the presence of escaping neutrinos:

- Computed as the negative sum of all the reconstructed particles momenta in the event
- Various Corrections: Jet energy correction and X-Y corrections

Object Identification: Z-jet

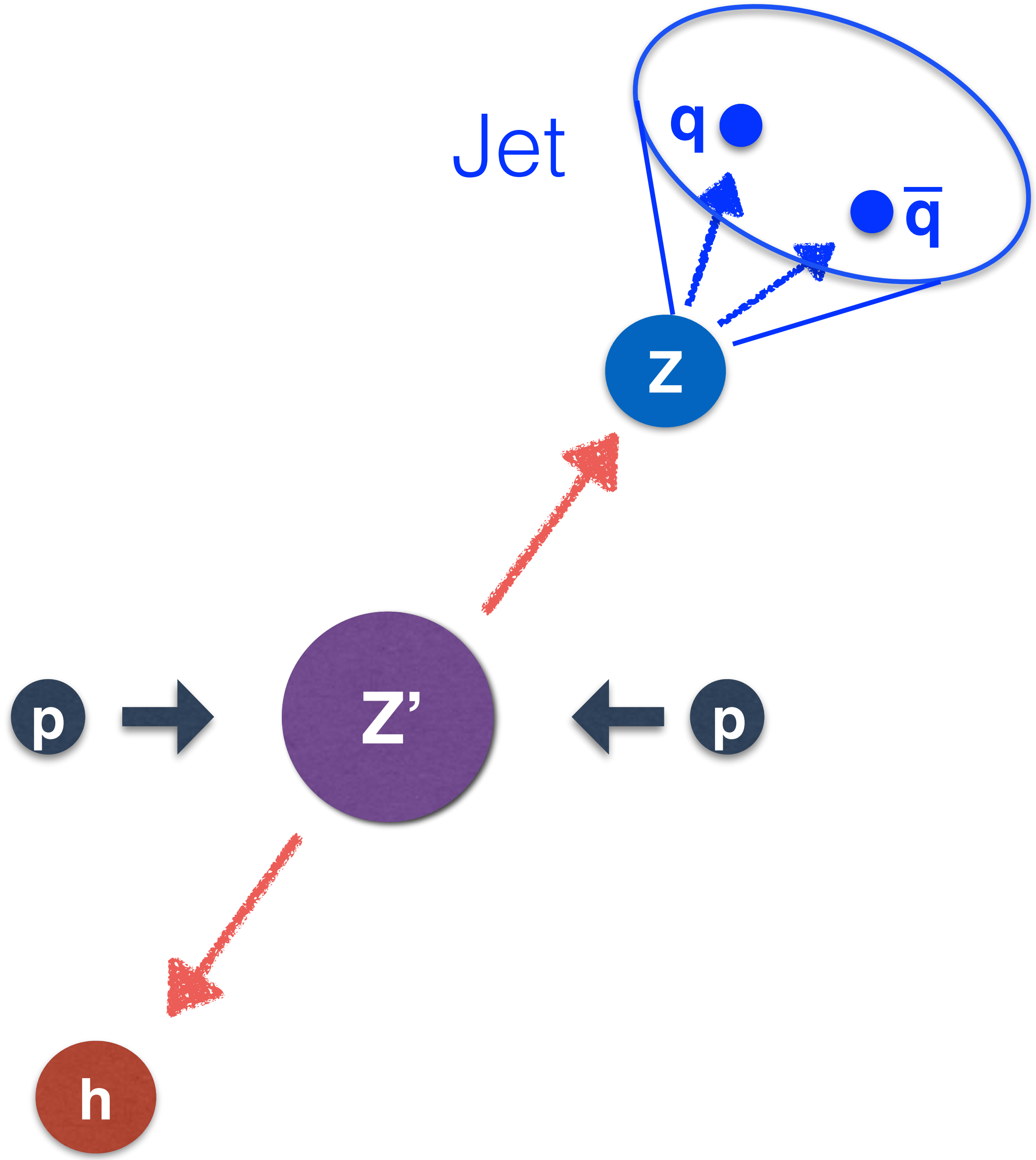
The Z boson is reconstructed as <u>one single energetic massive fat jet</u> (R = 0.8) for the merging of the two jets coming from the quarks hadronization → $p_T > 400$ GeV to match the trigger requirements

Pruning technique: removes the soft and large angle emitted radiation inside the jet

(70 GeV < m(pruned jet) < 110 GeV

Jet substructure: jet track topology is analyzed to see the number of subjets

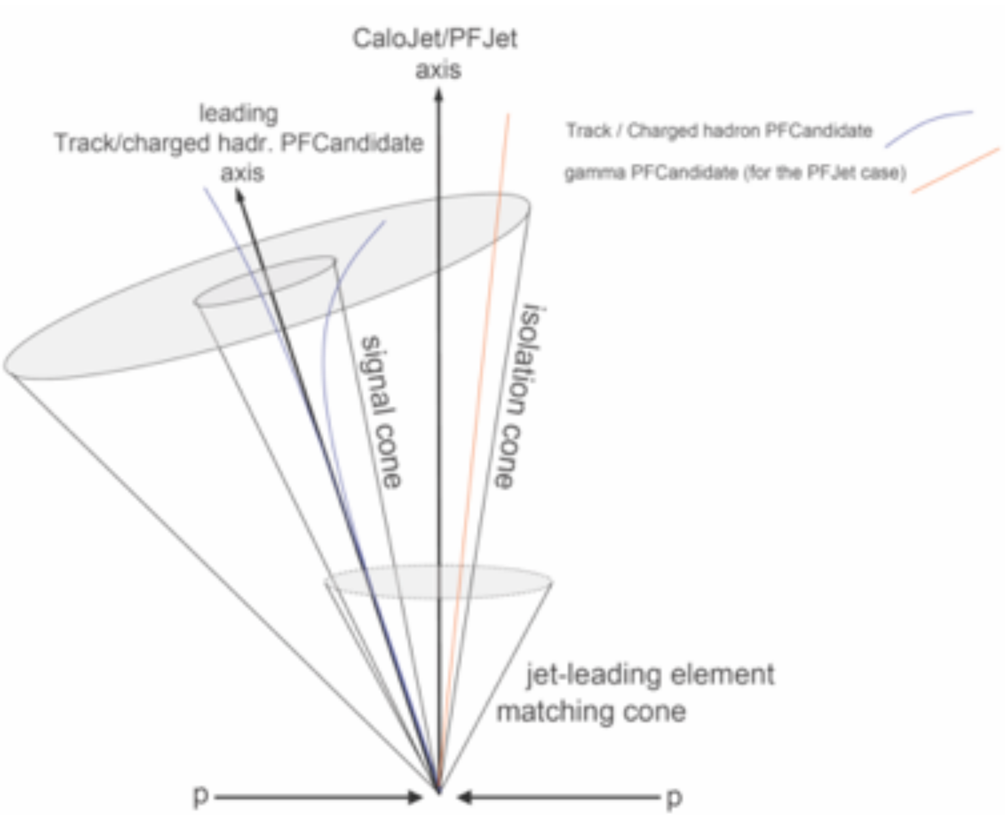
N-subjettiness $\tau_{21} < 0.75$

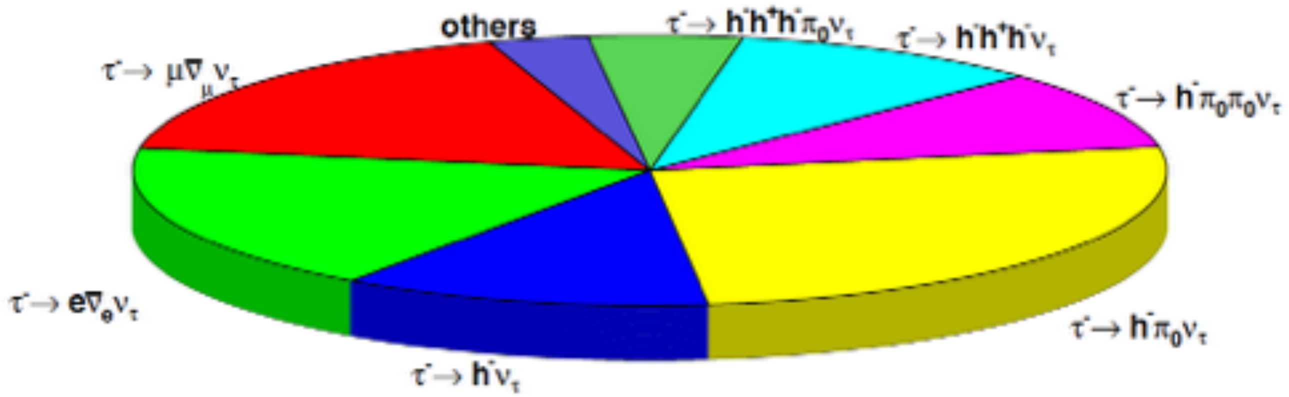


Object Identification: taus

Hadronic taus: starting from a PF jet

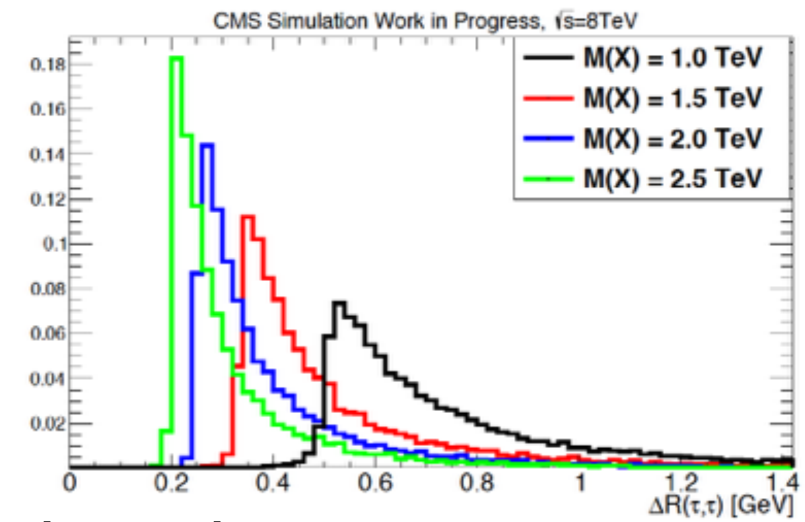
- Cut based and MultiVariate identification discriminants :
    - Decay mode finding: tau lepton decay signature
    - Isolation: used to reject QCD jets
    - Muon rejection
    - Electron rejection



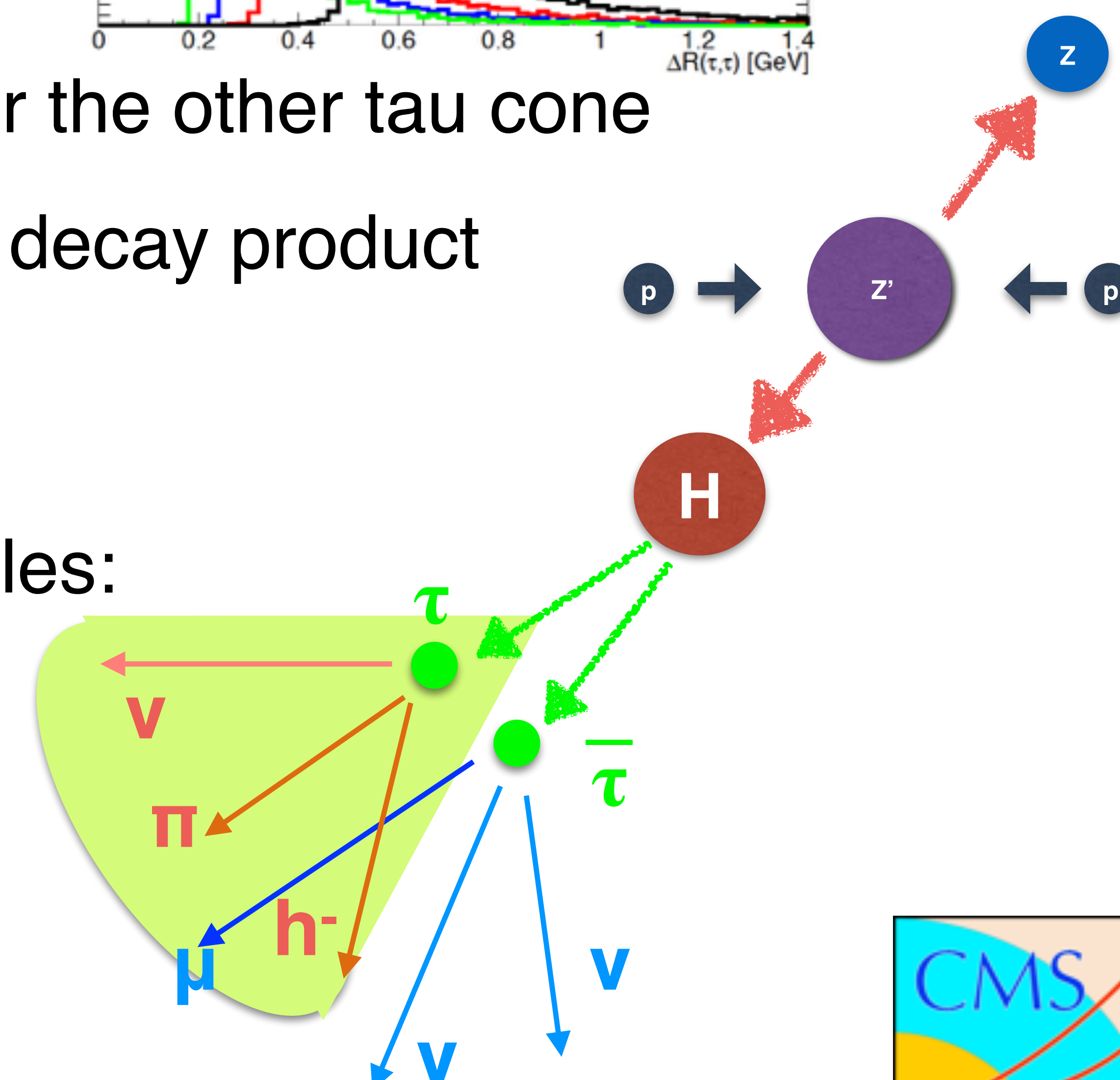


Boosted regime

- Higgs decay products very collimated



- Tracks coming from a tau decay may enter the other tau cone and be considered by PF as an additional decay product



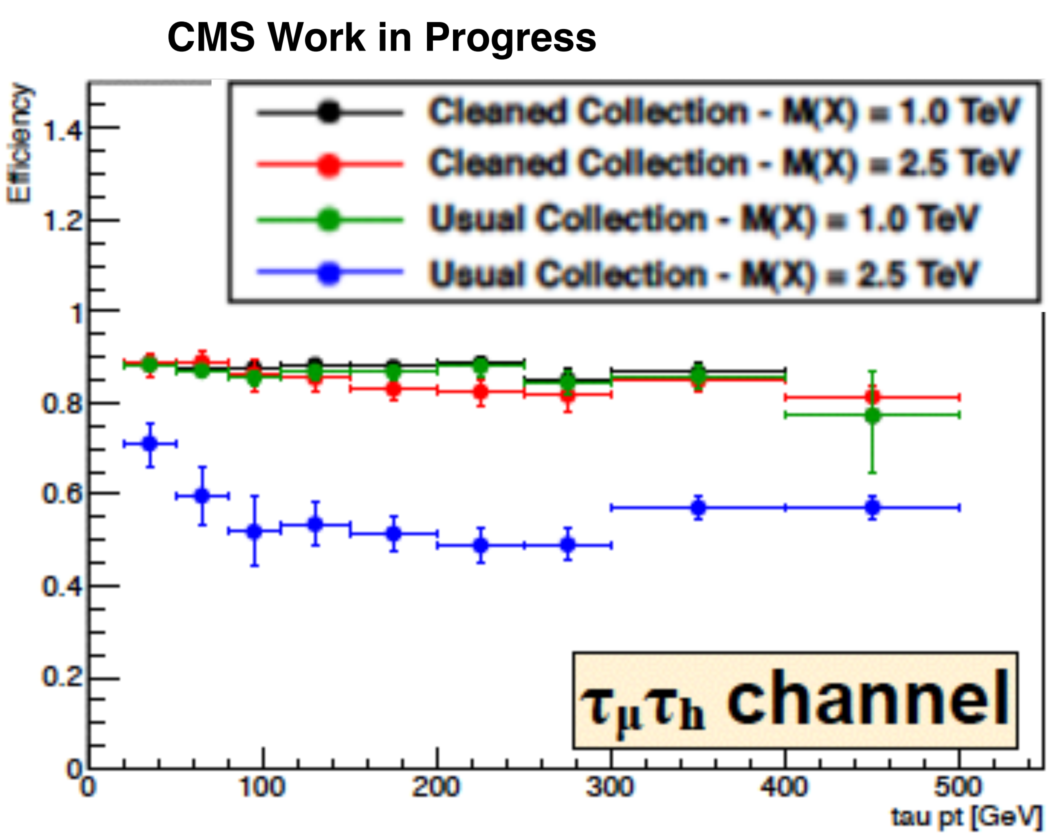
- Challenge in the identification of the particles:
    - hadronic tau reconstruction
    - lepton isolation

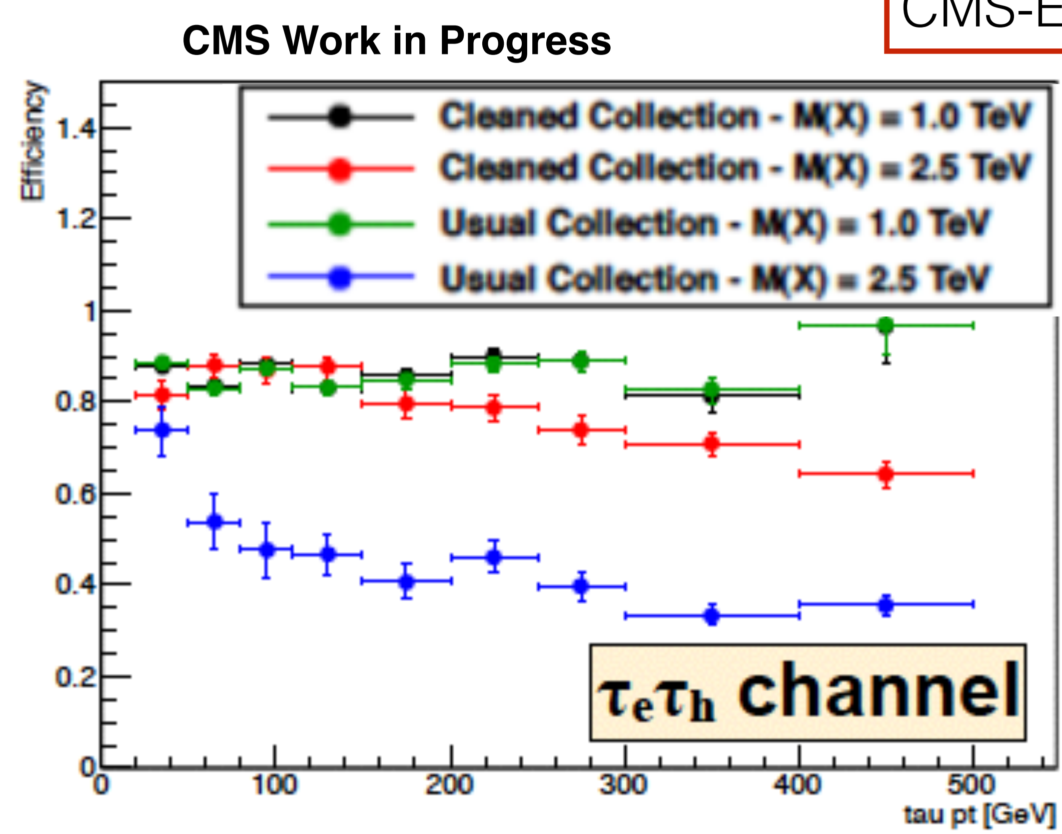
Hadronic tau reconstruction

Jet cleaning procedure: → PF Tau Producer

- electrons and muons identified with loose requirements inside the jet cone
- removed from the Jet constituents

CMS-EXO-13-007



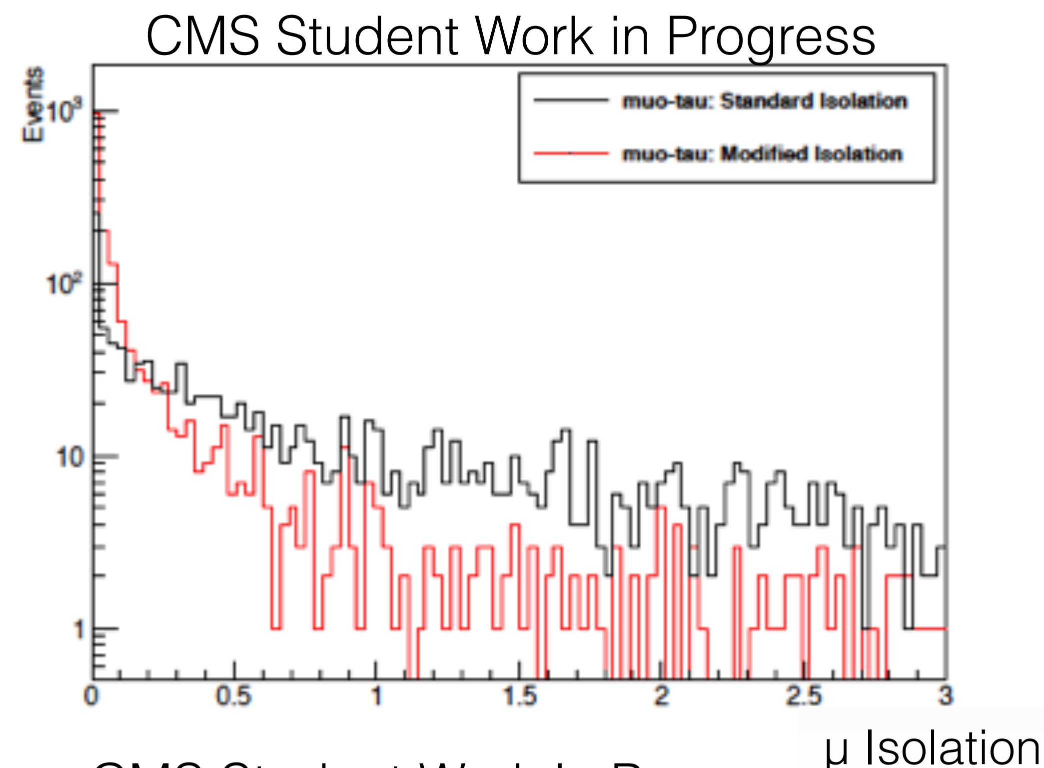


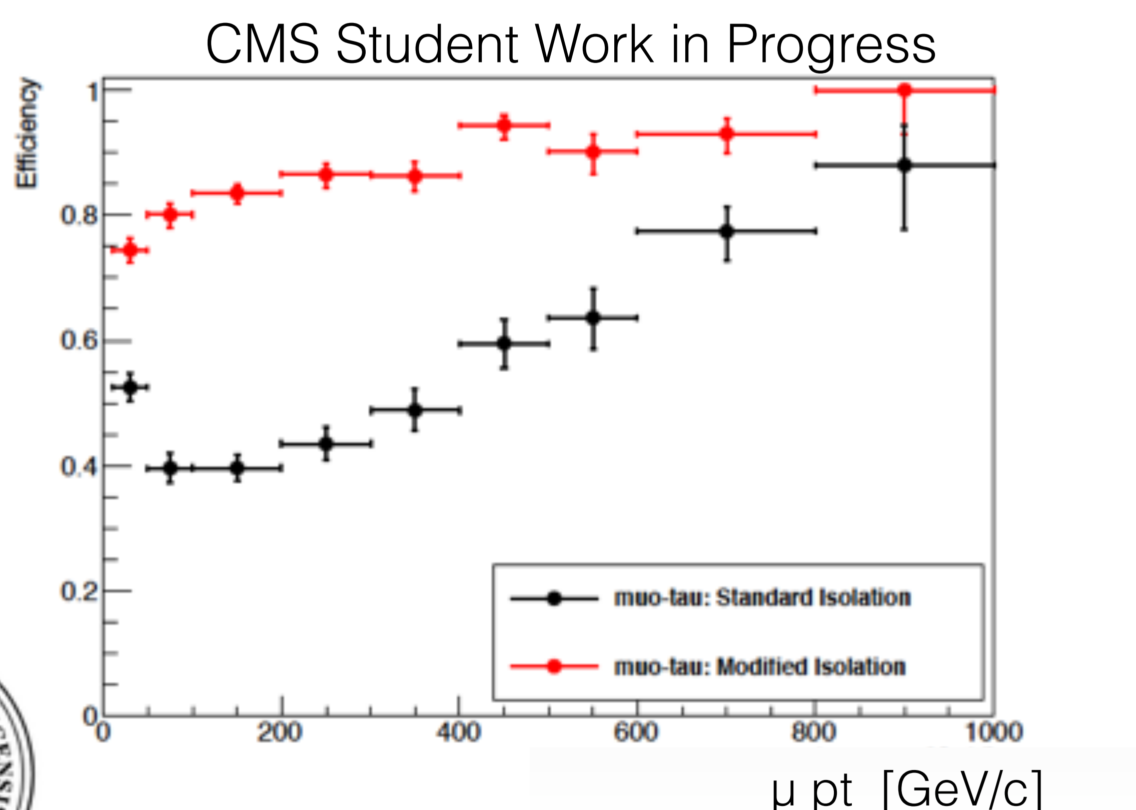
$$\epsilon = \frac{DEN\ \ \&\ \ PassAllDMs}{\Delta R(\tau_{reco},\tau_{gen})<0.4\ \&\ pT(\tau_{reco,gen})>20}$$

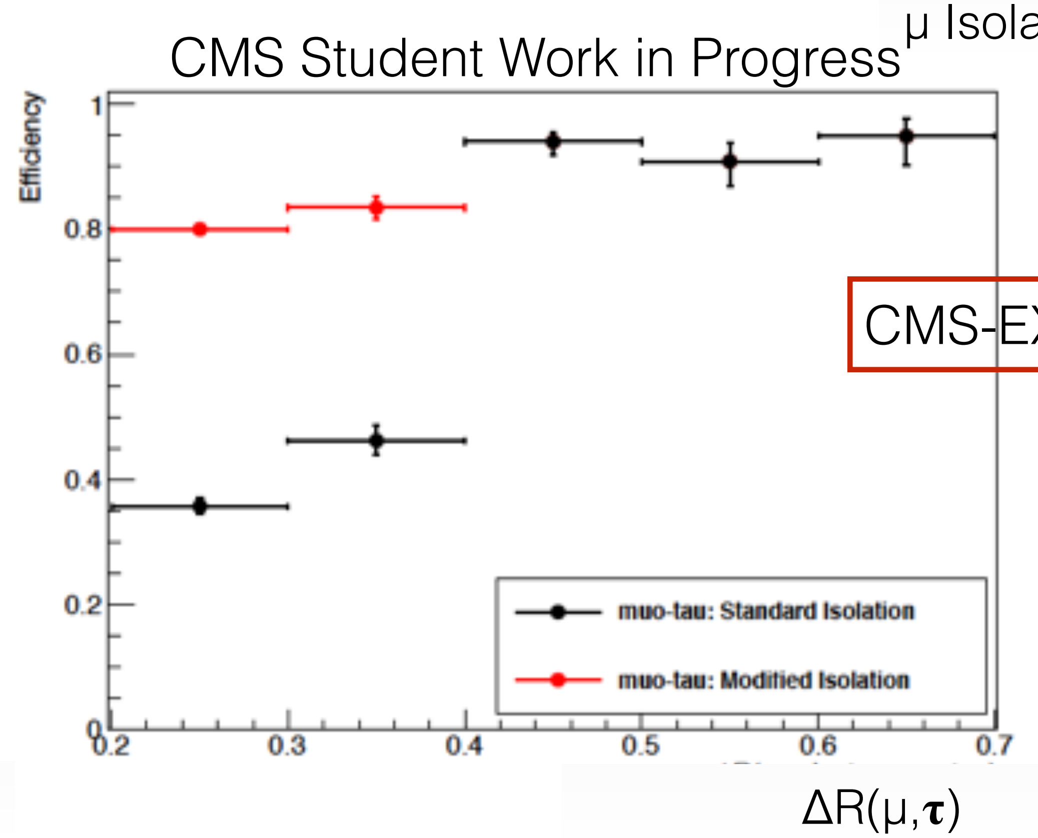
Lepton Isolation

New algorithm for lepton isolation:

- hadronic tau in the lepton isolation cone
- tau is fully identified (IDs)
- the PF constituents removed from the lepton isolation deposits





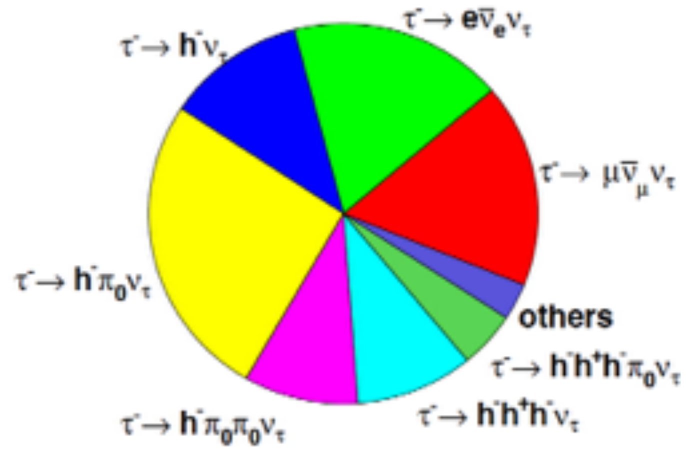


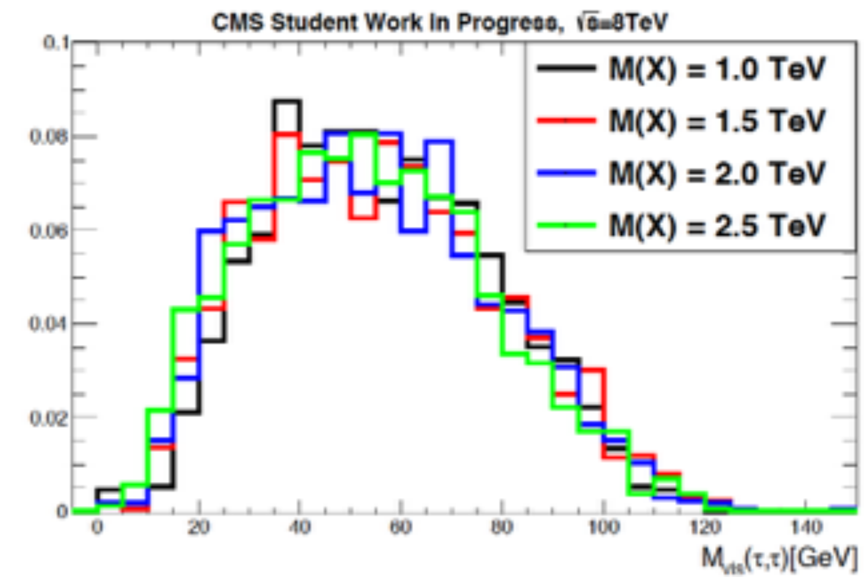
CMS-EXO-13-007

H $\rightarrow \tau\tau$ reconstruction

Neutrinos in the final state

→ Challenge in kinematics reconstruction

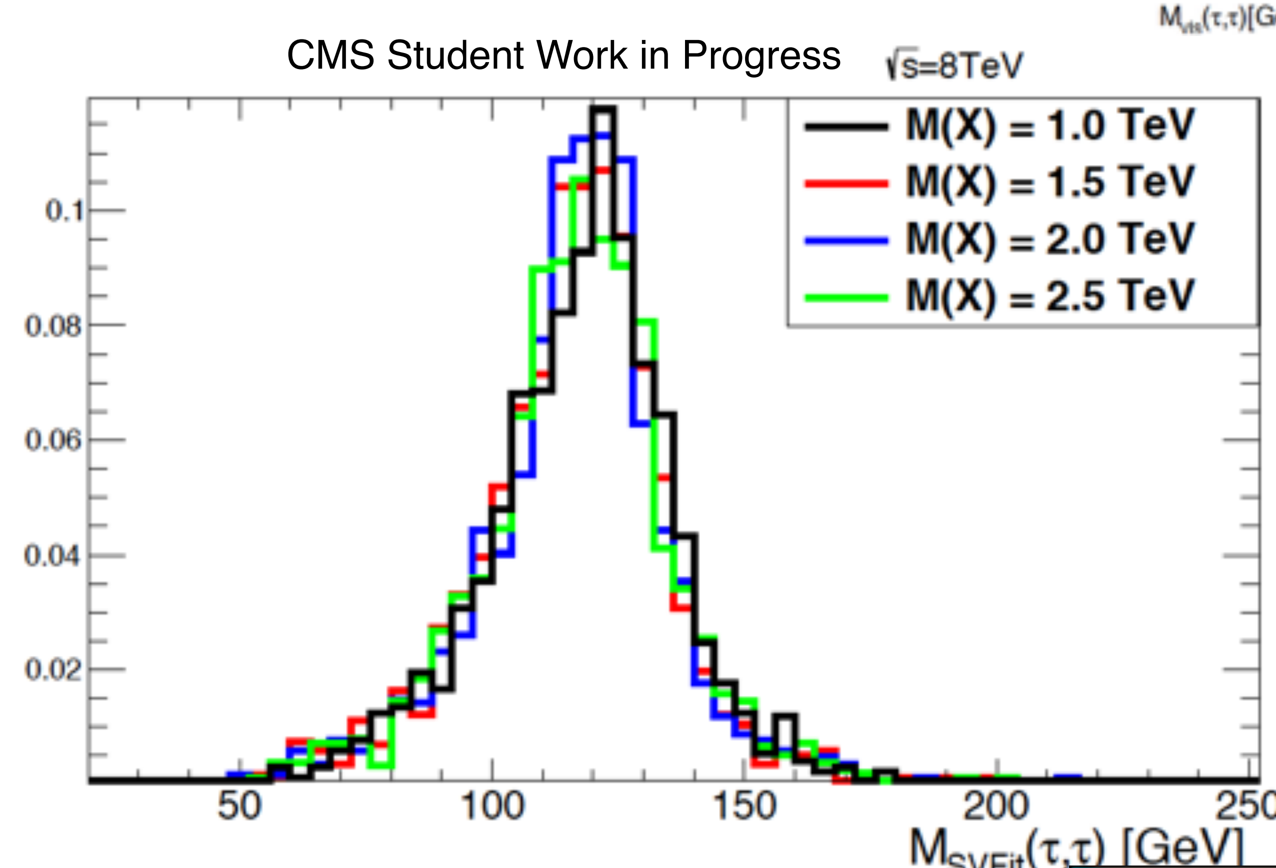




SVFit tool: algorithm for taus invariant system reconstruction

arXiv:1401.5041

- Probability model:
  - measured METx and METy
  - the tau decay visibile kinematics
  - the MET resolution
- Marginalized likelihood function on an event-by-event basis



Higgs mass reconstructed for all the resonance masses

Event Selection

Fully/Semi leptonic channel:

$p_T(\tau_1 + \tau_2)_{SVFit} > 100$ GeV

Fully hedronic channel:

$\Delta\phi(\tau, MET) < 1.5$

$\Delta\phi(z\text{-jet}, MET) > 2$

Z-jet side:

$p_T > 400$ GeV

$M_{pruned} \in [70,110]$ GeV

N-subjettiness $\tau_{21} < 0.75$

Additional requirements:

b-jet Veto: b-jets tagged using CSV loose WP, jet is required to have $\Delta R(\text{jet,lep}) > 0.5$ and $\Delta R(\text{jet,Z-jet}) > 0.5$

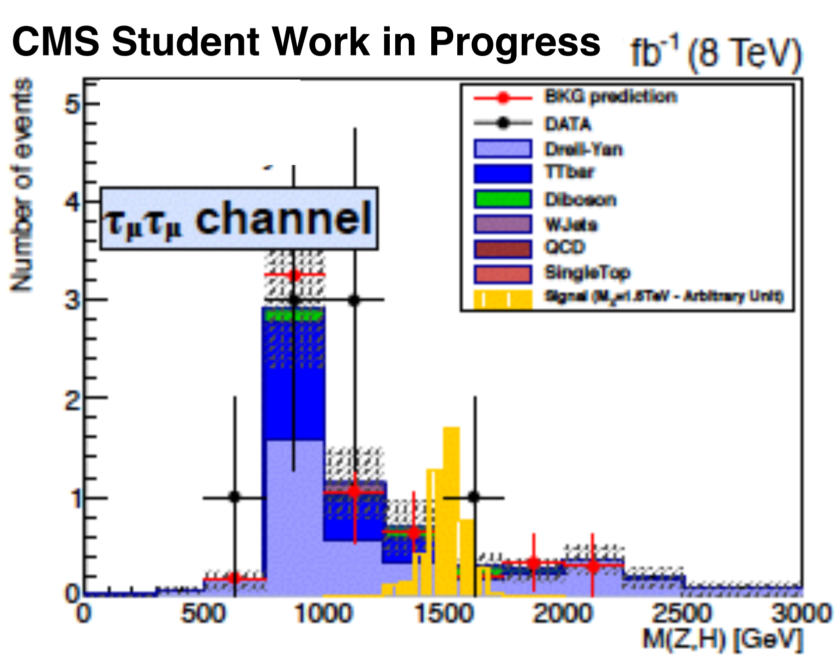
Selection	ee, $\mu\mu$, eμ channels	$\mu\tau_{had}$, eτ_{had} channels	$\tau_{had}\tau_{had}$ channel
E_T^{miss}	> 100 GeV	> 50 GeV	> 80 GeV
$p_{T,\ell}^{leading}$	-	> 35 GeV	> 50 GeV
$N_{b-\text{tagged jet}}$	$= 0$	$= 0$	-
$\Delta R_{\ell\ell}$	< 1.0	< 1.0	< 1.0
$m_{\tau\tau}$	-	-	105-180 GeV

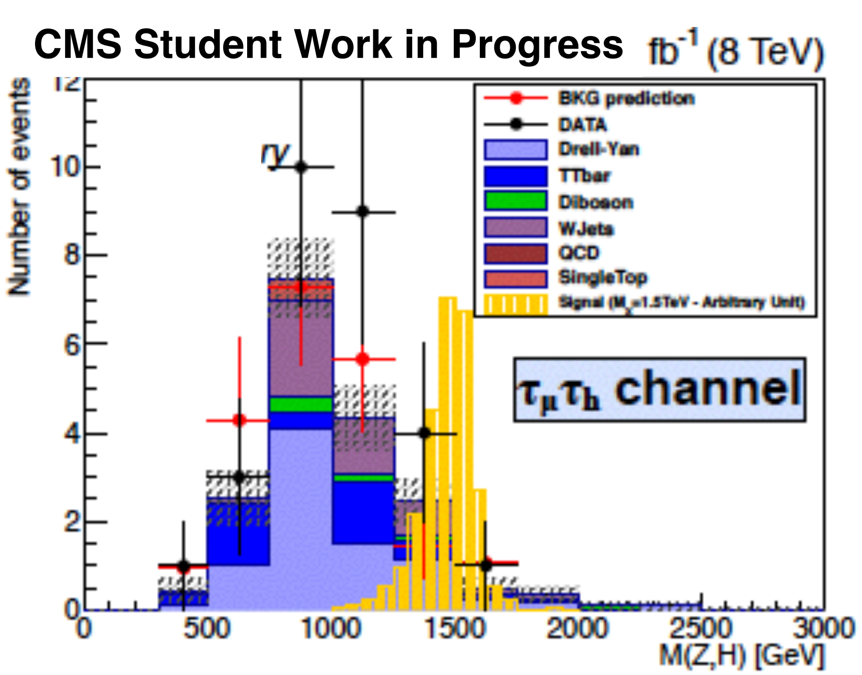
Background Estimation

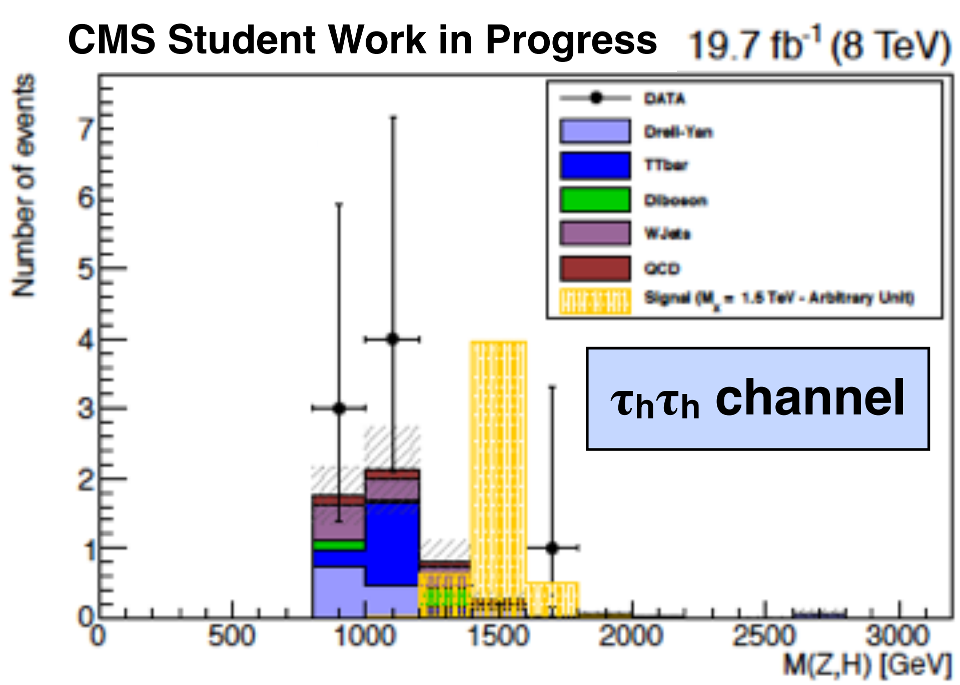
Background estimation strategy varies accordingly to the tau decay channels

- Different background composition: Drell Yan, top pair production, W+ jets..

- Data driven estimation procedure



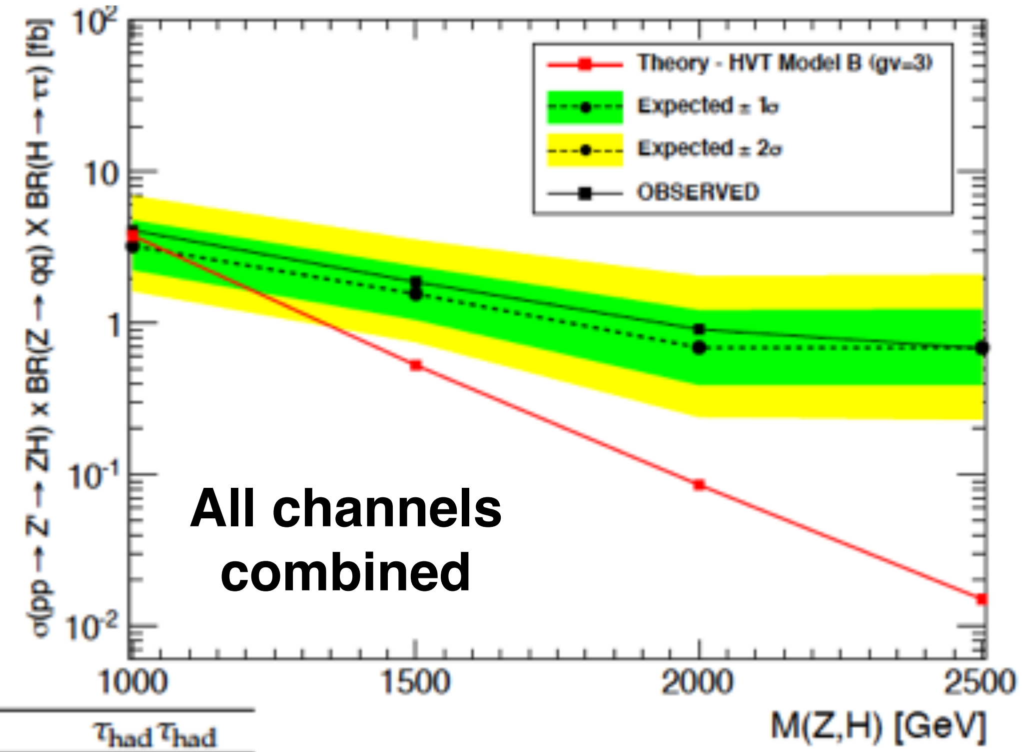




Results

No deviation from the background prediction is observed in data

Upper limits on the production cross section of a new resonance decaying into ZH bosons is set



	Mass	$\tau_e\tau_e$	$\tau_\mu\tau_\mu$	$\tau_e\tau_\mu$	$\tau_e\tau_{had}$	$\tau_\mu\tau_{had}$	$\tau_{had}\tau_{had}$
$\varepsilon_{sig}(\%)$	1.0 TeV	17 ± 2	38 ± 2	24 ± 1	21.2 ± 0.6	29.3 ± 0.7	18.2 ± 0.5
	1.5 TeV	30 ± 2	53 ± 2	42 ± 2	29.2 ± 0.8	38.1 ± 0.9	29.0 ± 0.7
	2.0 TeV	28 ± 2	56 ± 3	39 ± 2	31.1 ± 0.8	39.2 ± 0.9	31.9 ± 0.7
	2.5 TeV	27 ± 2	42 ± 2	37 ± 2	26.8 ± 0.8	37.0 ± 0.8	30.0 ± 0.7
N_{bkg}	1.0 TeV	1.2 ± 1.2	2.0 ± 0.9	1.7 ± 1.0	9.5 ± 3.5	7.6 ± 2.2	
	1.5 TeV	0.4 ± 0.4	0.9 ± 0.4	0.07 ± 0.04	4.3 ± 1.8	2.6 ± 0.9	$6.1^{+3.2}_{-2.5}$
	2.0 TeV	< 0.5 at 68% CL	0.7 ± 0.4	< 0.4 at 68% CL	0.1 ± 0.1	< 0.4 at 68% CL	
	2.5 TeV	< 2.1 at 68% CL	0.3 ± 0.1	< 0.3 at 68% CL	0.18 ± 0.05	< 0.5 at 68% CL	
$N_{observed}$	1.0 TeV	2	5	2	2	13	
	1.5 TeV	0	1	0	2	5	8
	2.0 TeV	0	0	1	0	0	
	2.5 TeV	0	0	0	0	0	

Resonance production cross section in a range between 0.7 and 4.1 fb are excluded at 95% confidence level

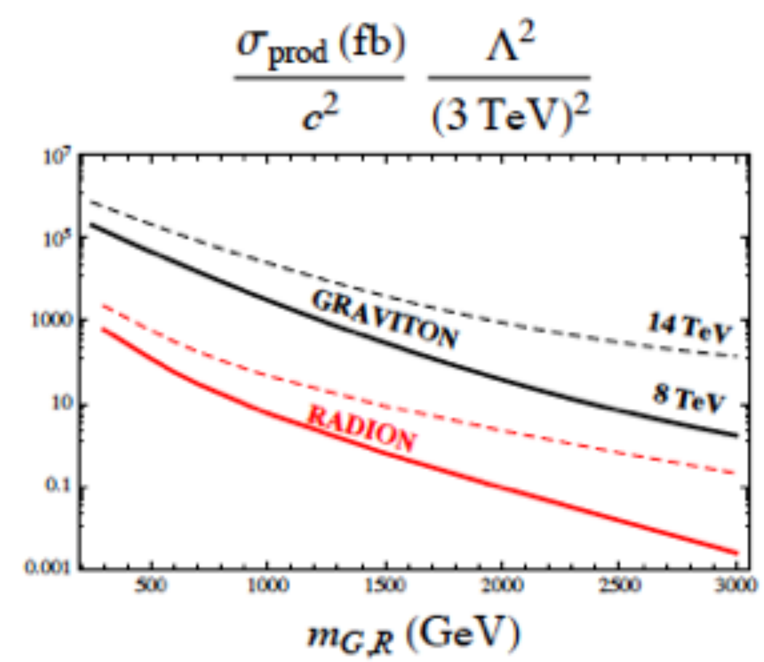
Other searches outlook: HH

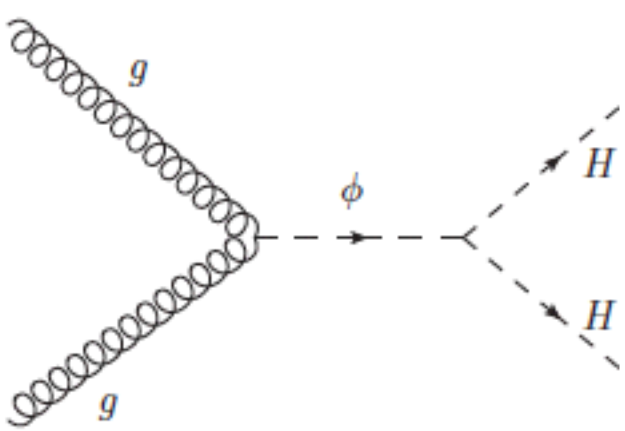
Extend the search of heavy resonances also to other final states and theoretic models

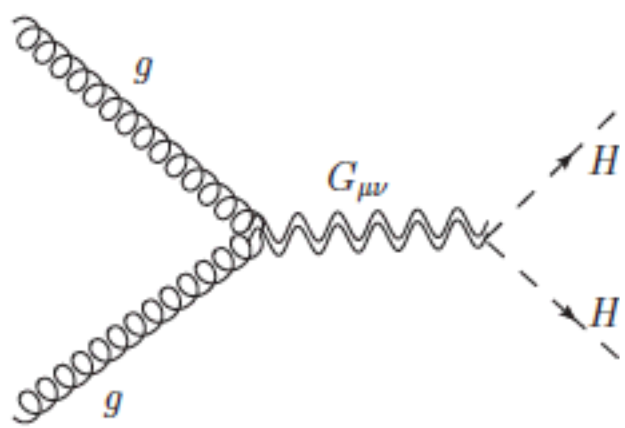
Warped extra-dimension model:

arXiv: 1303.6636

- Explains hierarchy between the Electroweak and the Planck scales
- Non trivial geometry a fifth extra dimension
- Higgs pair production by:
  - spin 2 particle (Kaluza-Klein (KK) Graviton)
  - scalar particle (Radion)

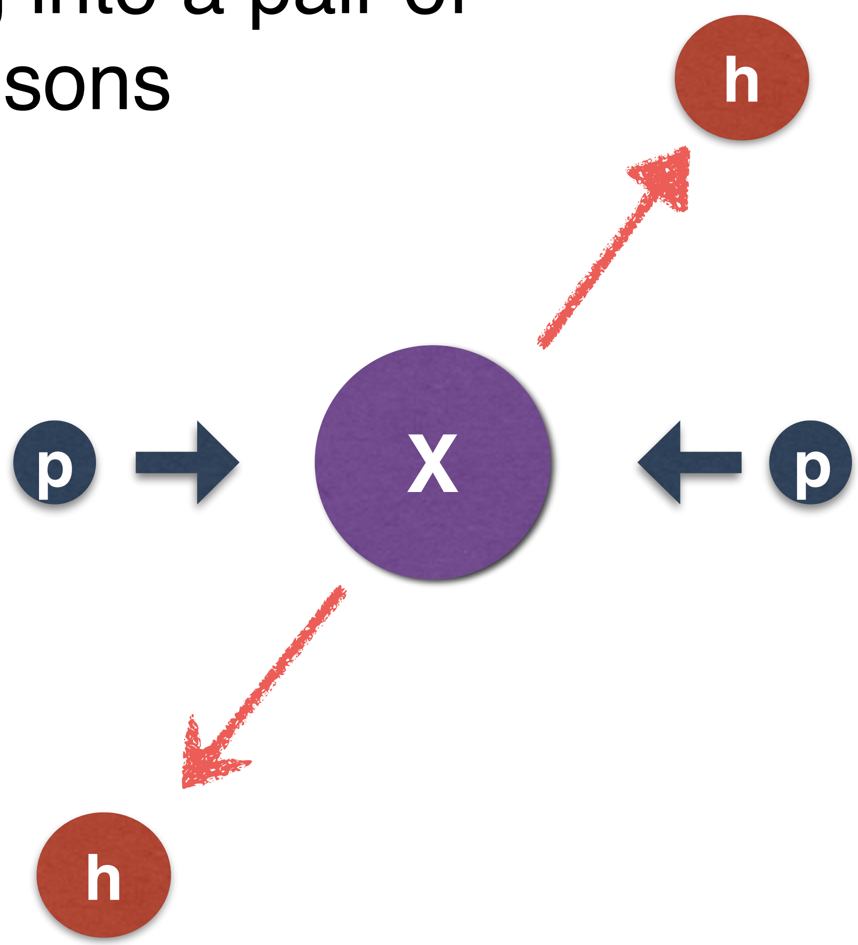




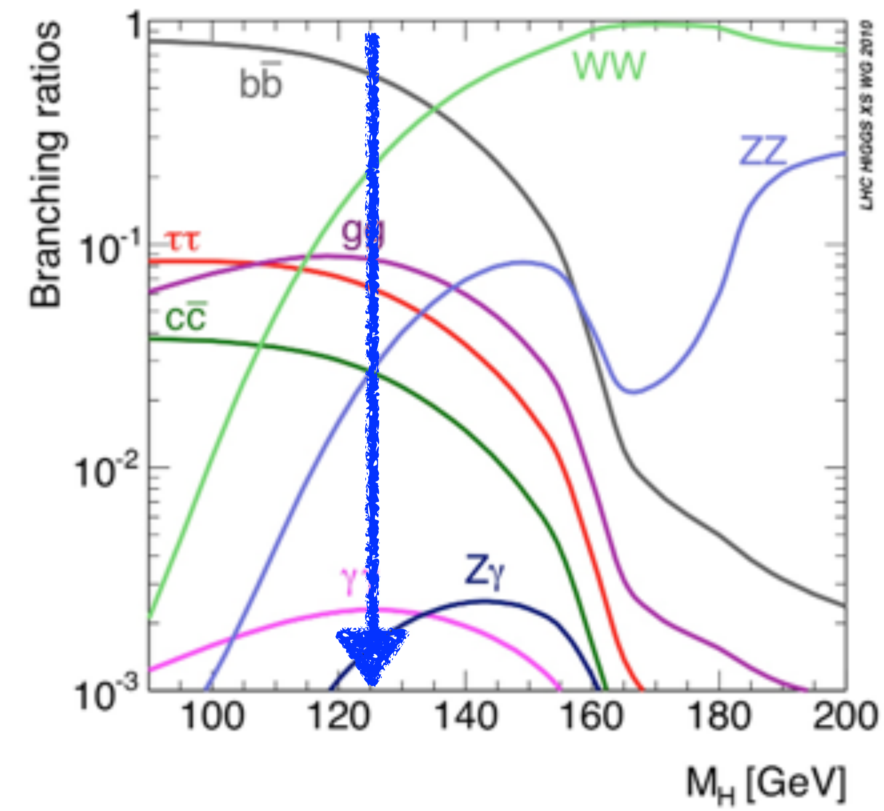


Search strategy

- Radion or Graviton decaying into a pair of Higgs bosons



Strategy



- *High statistics*
- *Purity of the signal*

Search strategy

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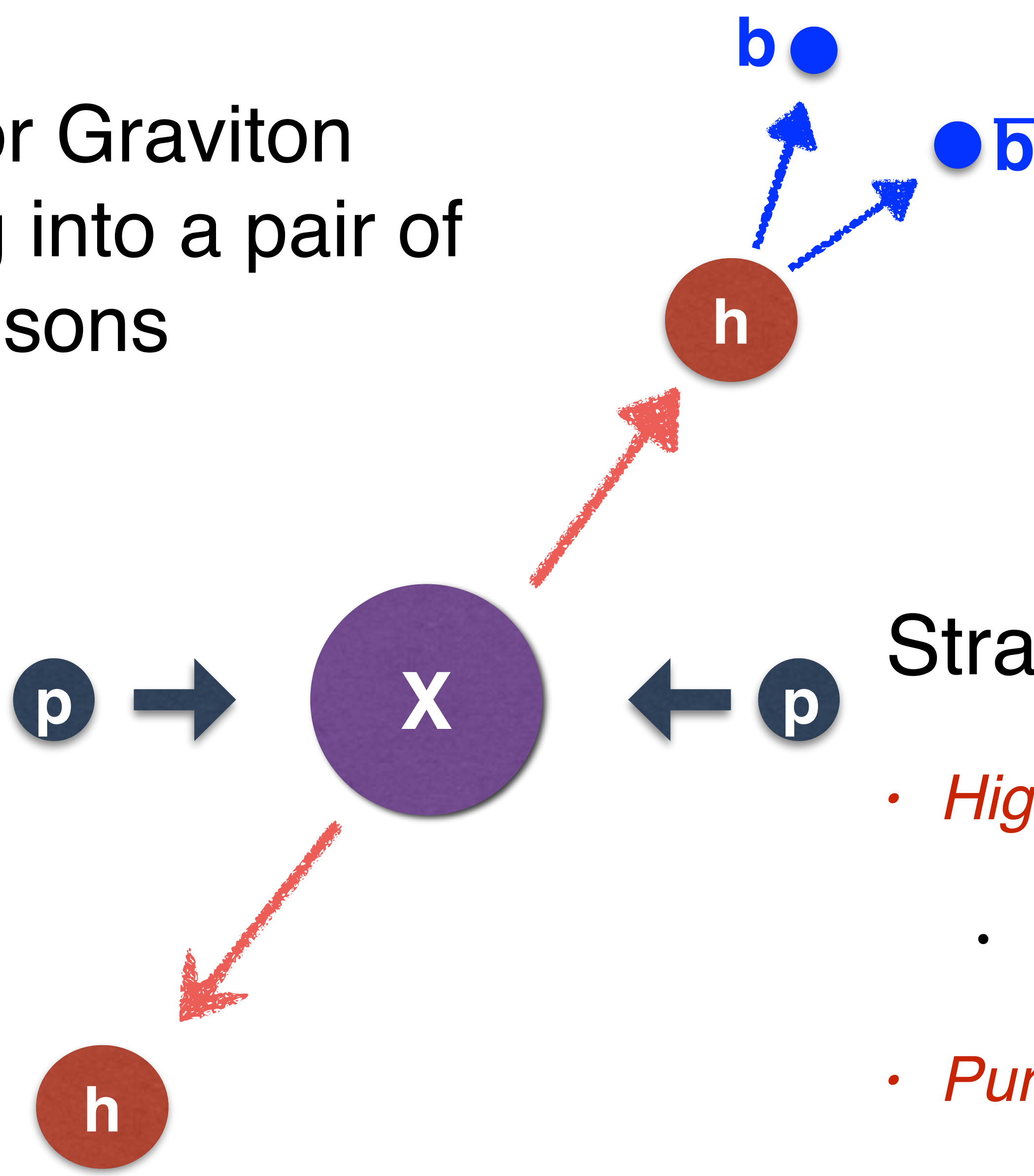

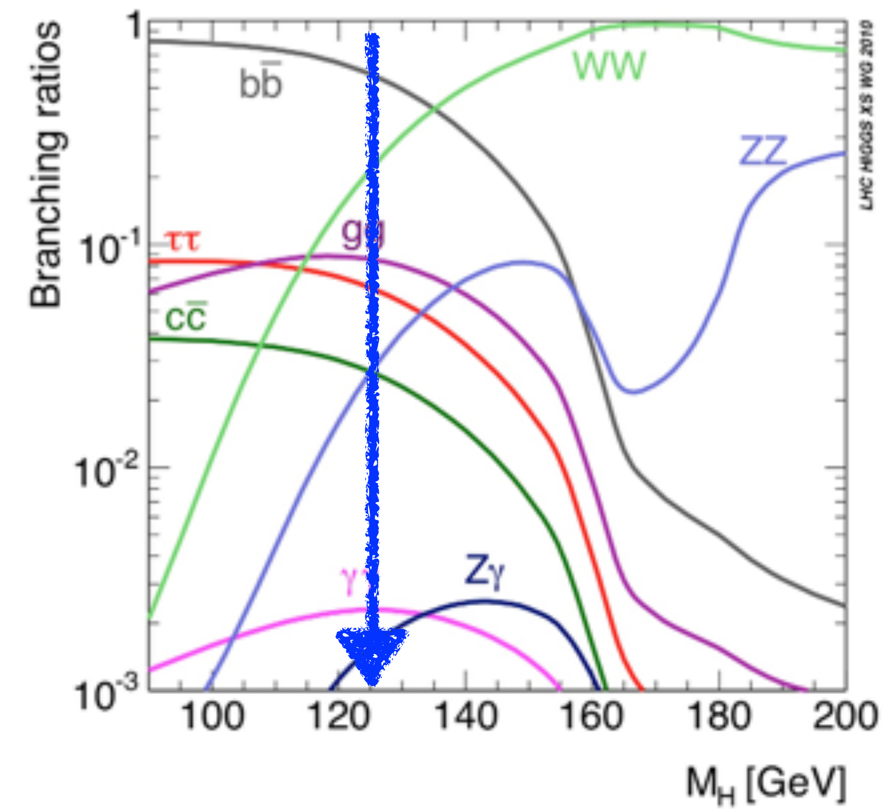

Strategy

- *High statistics*
  - High branching ratio: $H \rightarrow b\bar{b}$(~60%)
- *Purity of the signal*

Search strategy

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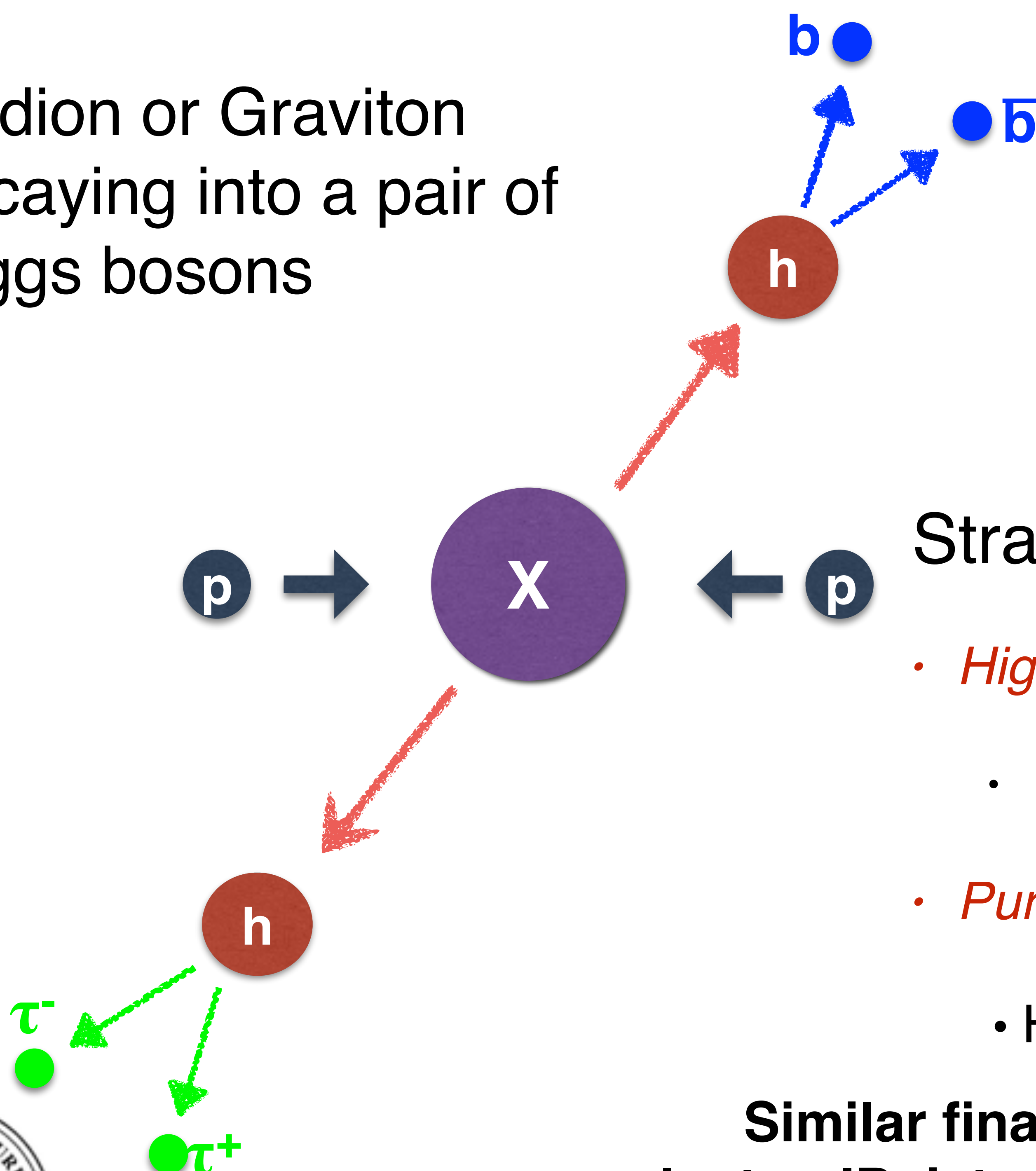

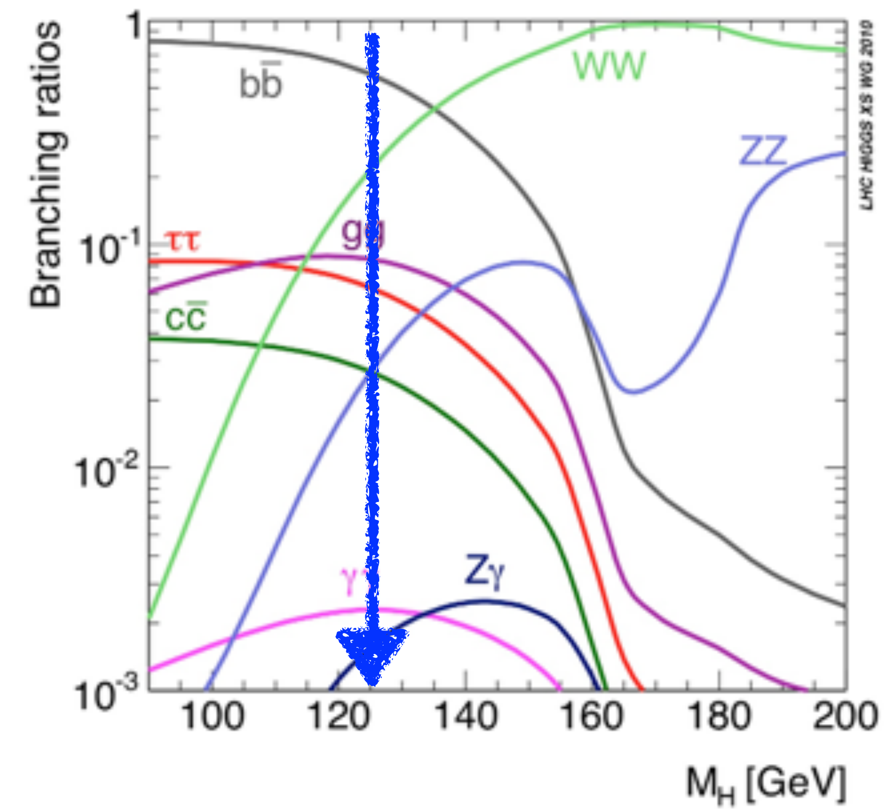

Strategy

- *High statistics*
  - High branching ratio: $H \rightarrow b\bar{b}$ (~60%)
- *Purity of the signal*
  - $H \rightarrow \tau^- \tau^+$ (~7%)

Similar final state wrt ZH analysis: lepton ID, jet substructure and b-tagging

Conclusions

- The first search for a high mass narrow resonances decaying into Z and H bosons has been performed
  - Heavy resonances ⇒ highly boosted bosons
    - Jets with merged tau leptons or b quark pairs are most common for Higgs decays, but experimentally very challenging
    - Algorithms have been developed for the physics object and the event reconstruction

- Searching for physics BSM predicting HH resonances, e.g. Composite Higgs or Extra Dimension models
  - First time we look for such high mass resonances in Higgs pairs

Analysis of 8 TeV data well underway!

Stay tuned for the next run at 13/14 TeV!

Back up

Search strategy

- Radion or Graviton decay into a pair of Higgs bosons
- Channel HH-> $\tau\tau bb$
  - *High breaching ratio*
  - *The presence of tau leptons can help discriminate against QCD Multi-jet background.*
- Many possible final states depending on the tau lepton decay mode:
  - Fully leptonic: $\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow e\nu\nu$
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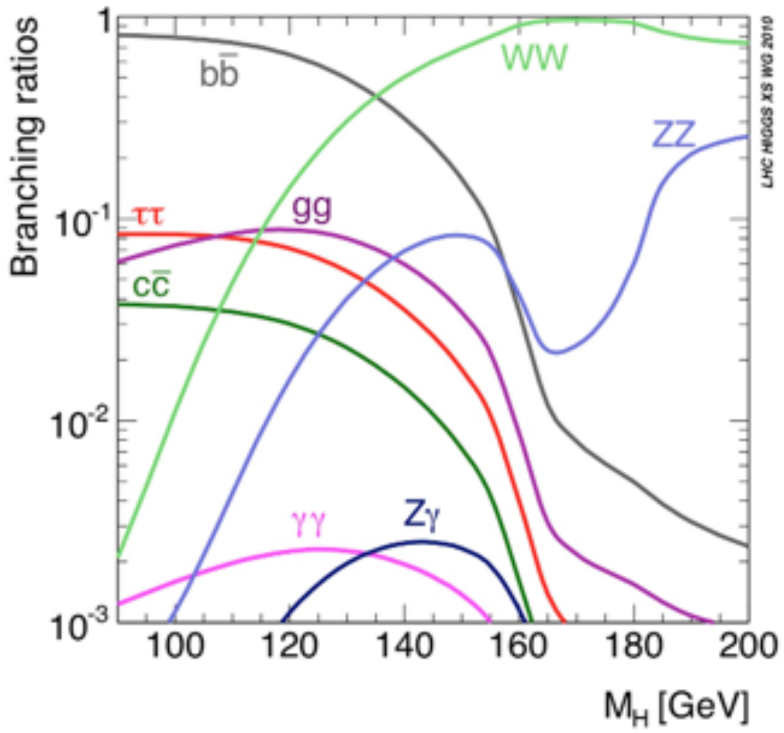
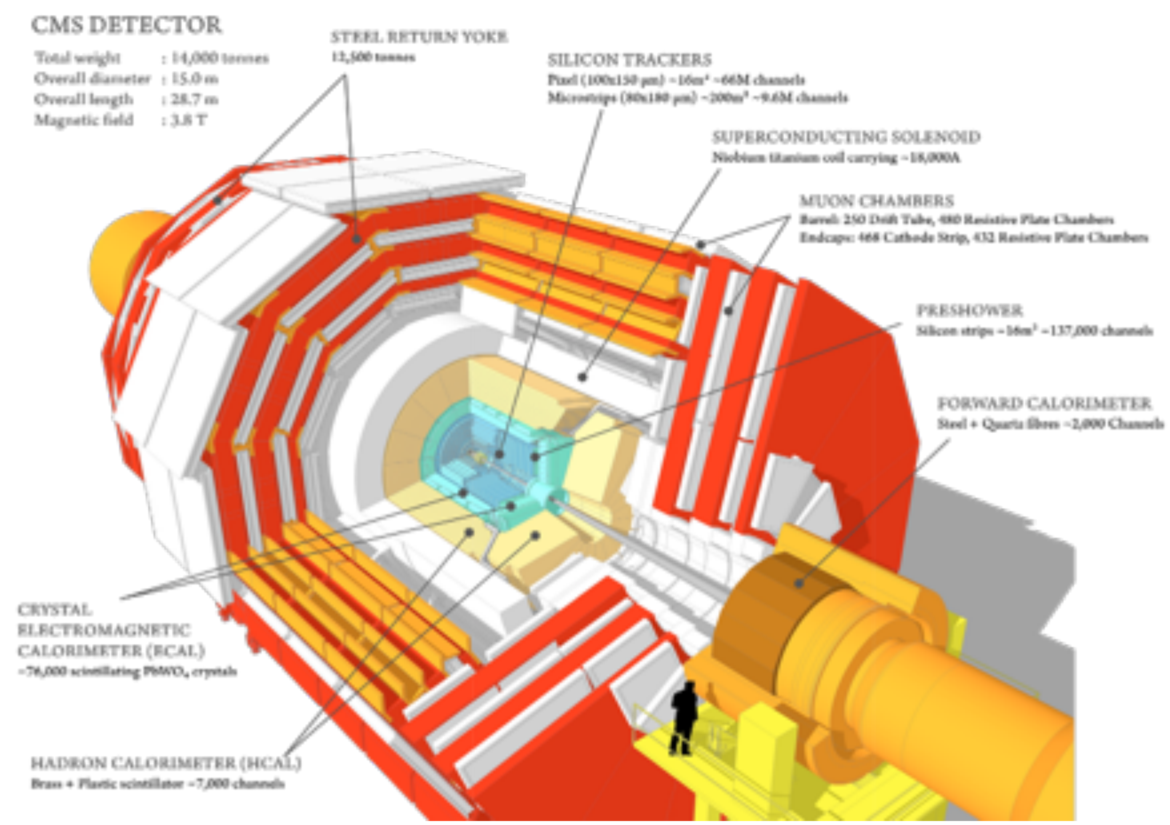
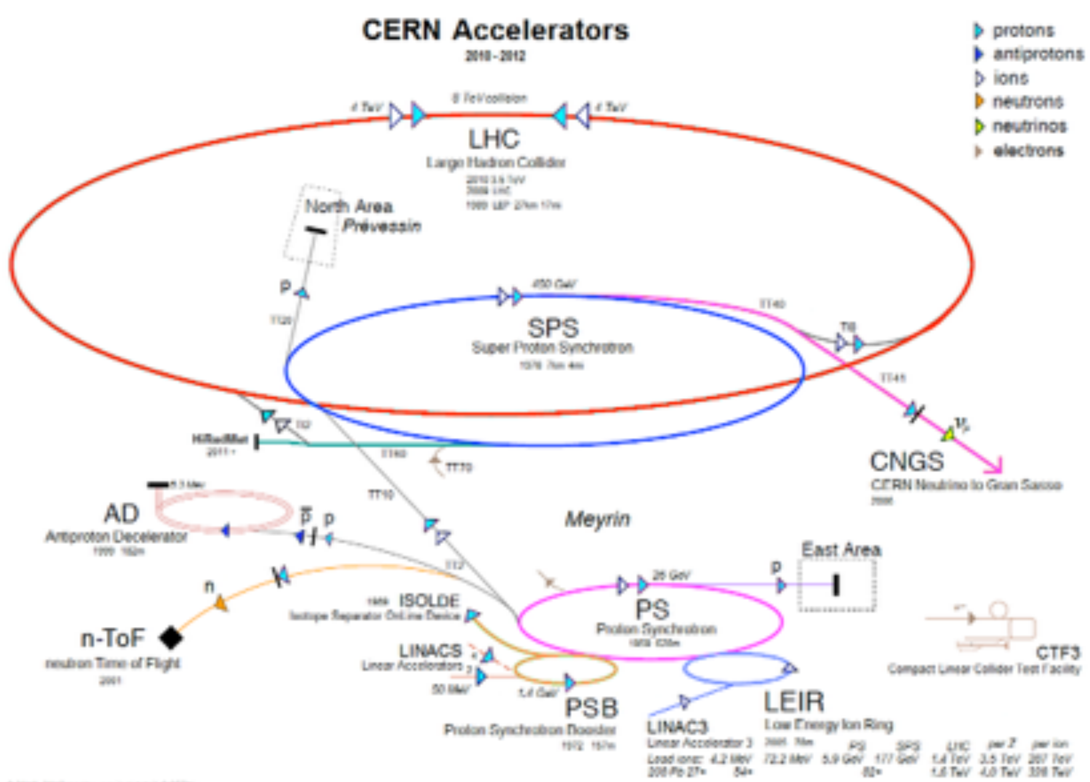


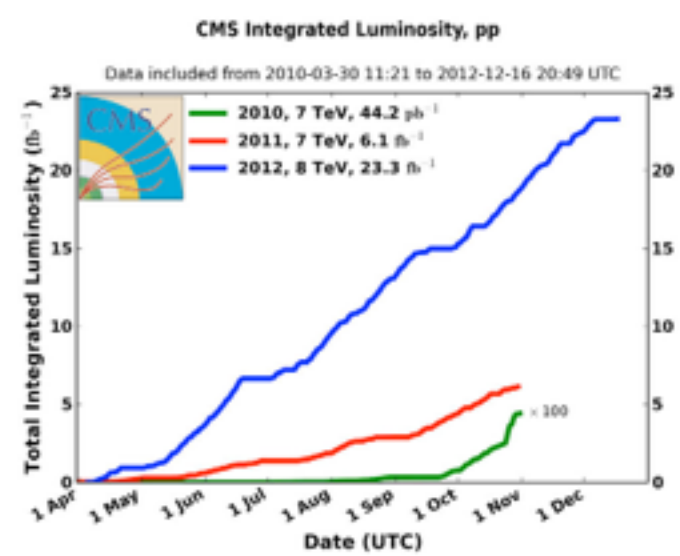
Decay channel	BR(%)
τ^-	17.36
	17.85
τ^-	11.6
τ^-	26.0
τ^-	9.5
τ^-	9.8
τ^-	4.8
others	3.1

LHC and CMS

- Heavy particles production require high energy.
- LHC 8 TeV of energy in the center of mass reference frame
- CMS detector for particle identification



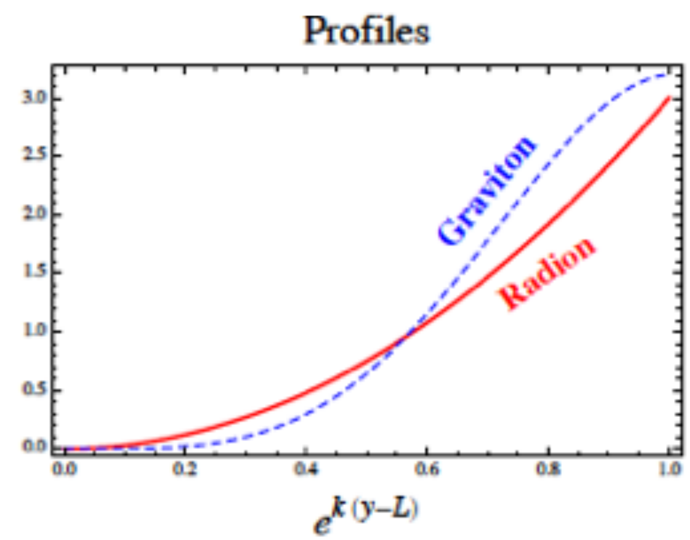




Higgs Pair Production

arXiv: 1303.6636

- Metric due to the fifth extra dimension $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

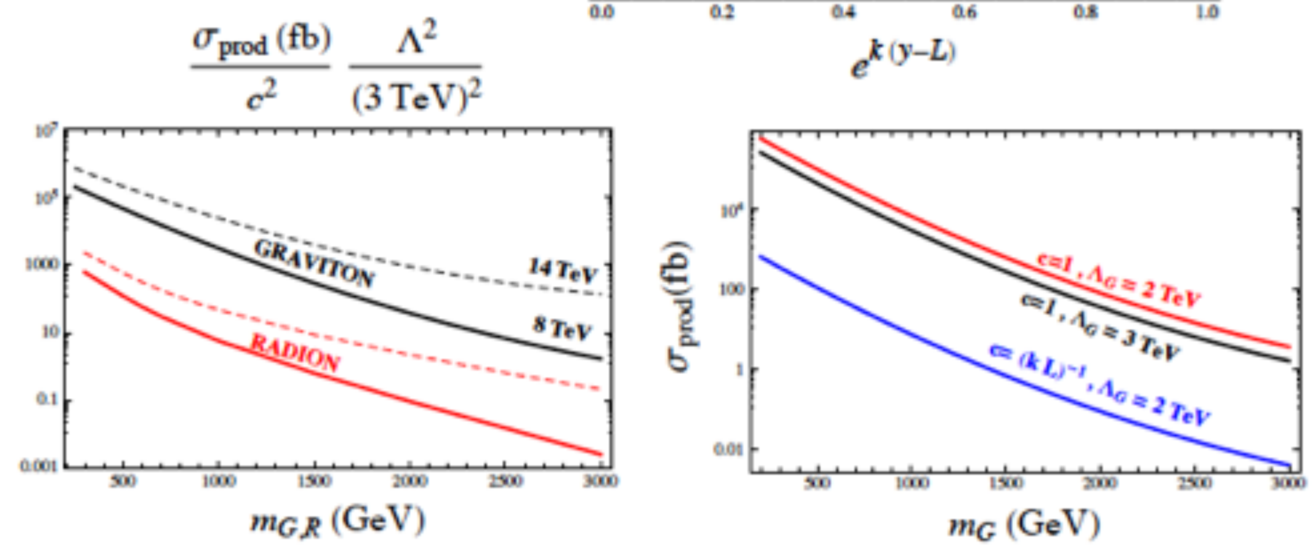


$$g_{\mu\nu} = e^{-2ky}\eta_{\mu\nu} \to e^{-2(ky+F(x,y))}\left(\eta_{\mu\nu} + G_{\mu\nu}(x,y)\right)$$

$$F(x,y) \propto e^{2ky}\,\phi(x) \qquad G^{(1)}_{\mu\nu}(x,y) \propto e^{2ky}\,J_2\left(e^{2ky}\frac{m_G}{k}\right)\,G^{(1)}_{\mu\nu}(x)$$

- Localization of the fields

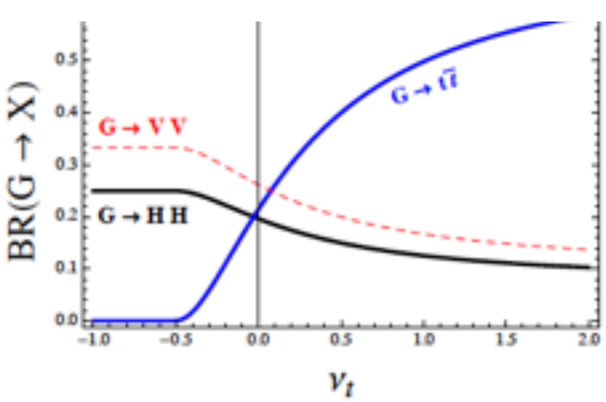
- Coupling to SM fields



$$\mathcal{L} = -\frac{c_i}{\Lambda_G}G^{\mu\nu(1)}T^i_{\mu\nu} - \frac{d_i}{\Lambda_\phi}\phi T^{\mu i}_{\mu}$$

RS1 scenario: $c_H =$ all the other $c_i \simeq \mathcal{O}(1)$

Bulk RS scenario: $c_H \simeq c_{Z,W,t} \simeq \mathcal{O}(1) \simeq (kL)\,c_{\gamma,g} \gg c_{u,d,\ell}\ldots$



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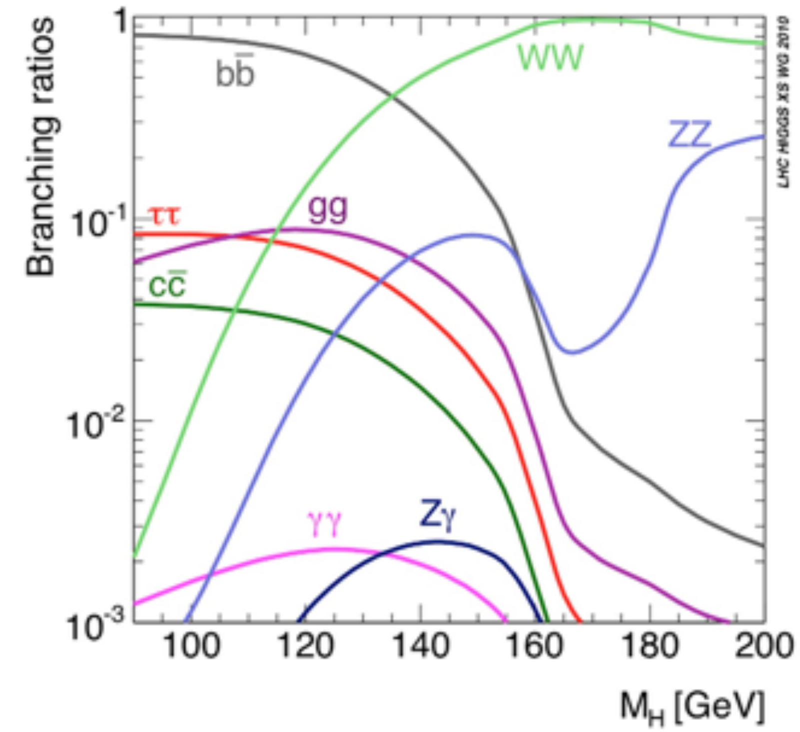

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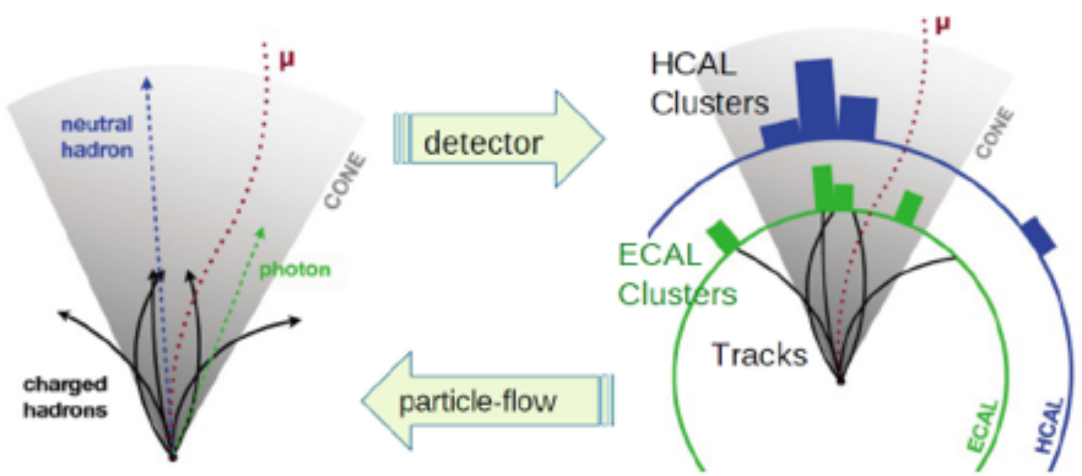
PF particle Identification

- Particle Flow: all the information from the sub detectors are combined to reconstruct all particles in the collisions

- Particles are identified in mutually exclusive categories: charged and neutral hadrons, photons, electron and muons.

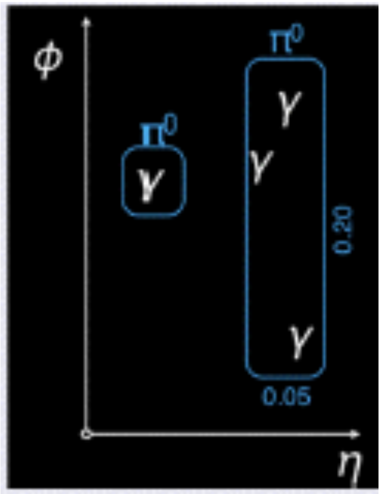
- Particles are used to identify jets, tau and MET



- Algorithms have been developed to reconstruct the tau hadron decay:
    - HPS

PF Tau Identification

- Starting from a PF Jet, special attention is given to photon conversion in the tracker, since the bending of electron positron can broaden the photon signature in the ϕ



- A strip of $\Delta\eta = 0.05$ and $\Delta\phi = 0.2$ is centered around the most energetic electromagnetic particle in the jet
- Other electromagnetic particles in the strip are considered and added to the four momentum.
- Strips with $p_T > 1$ GeV/c are combined to the hadrons to reconstruct the Tau hadronic decay mode

Strips and hadrons ($\pi^{\pm}$, $K^{\pm}$) are combined to reconstruct the main decay topologies:

- Single hadron (for $h^- \nu_\tau$ and $h^- \pi^0 \nu_\tau$);
- One hadron + 1 or 2 strips (for $h^- \pi^0 \nu_\tau$);
- Three hadrons (for $h^- h^+ h^- \nu_\tau$).

The other decay modes are reconstructed via the previous topologies.

- All hadrons and strips have to be within a cone of $\Delta R = (2.8 \text{ GeV/c}) / p_T^{(Tau\_h)}$
- The tau 4-vector has to be in a cone of $\Delta R = 0.1$ from the Jet axis
- The mass of the composite system has to be compatible with ρ(770 MeV) (2 hadrons) or a_1 (>=3 hadrons 1200 MeV)

Searches at low mass (<1TeV)

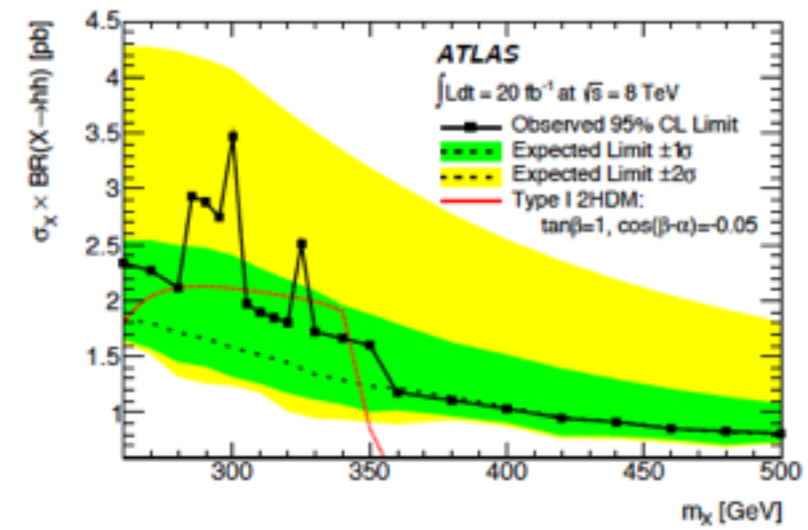
CMS (CMS PAS HIG-13-032):

hh ->gamma gamma bb final state.
The search for a new particle X is performed in the range 260 < mX < 1100 GeV.
Upper limits at 95%confidence-level are extracted on new particles production cross-section.
WED Radion is observed (expected) to be excluded with masses below 0.97 TeV (0.88 TeV).

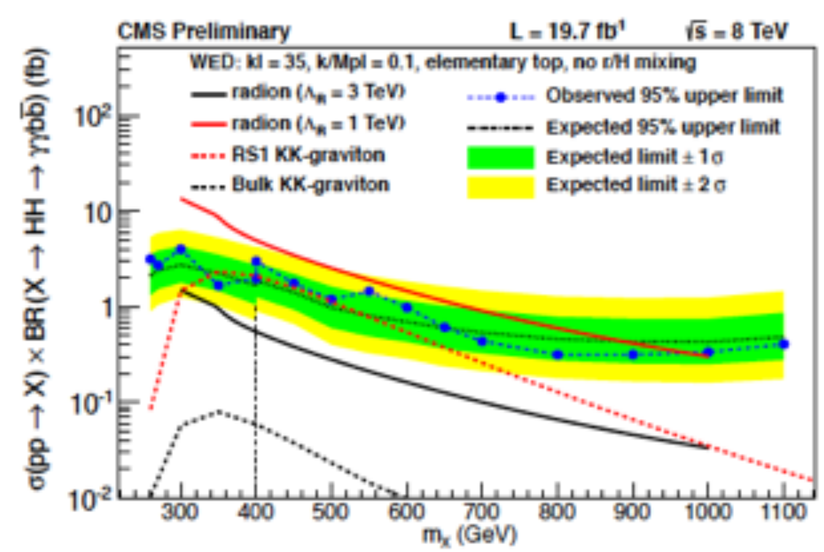
ATLAS(arXiv:1406.5053):
hh ->gamma gamma bb final state.
A 95% confidence level upper limit on the cross section times branching ratio of non-resonant production is set at 2.2 pb, while the expected limit is 1.0 pb.
The corresponding limit observed for a narrow resonance ranges between 0.8 and 3.5 pb as a function of its mass.

ATLAS (ATLAS-CONF-2014-005):
G*->hh ->bbbb final state.

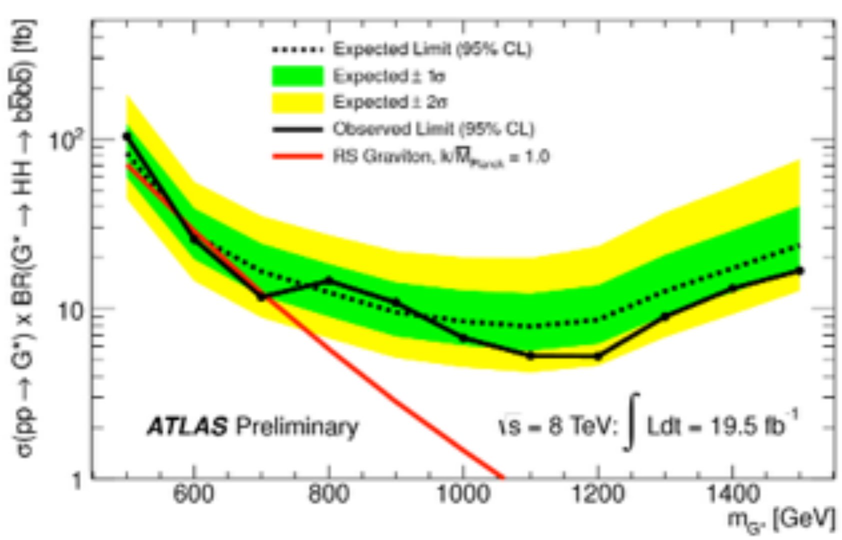
arXiv:1406.5053



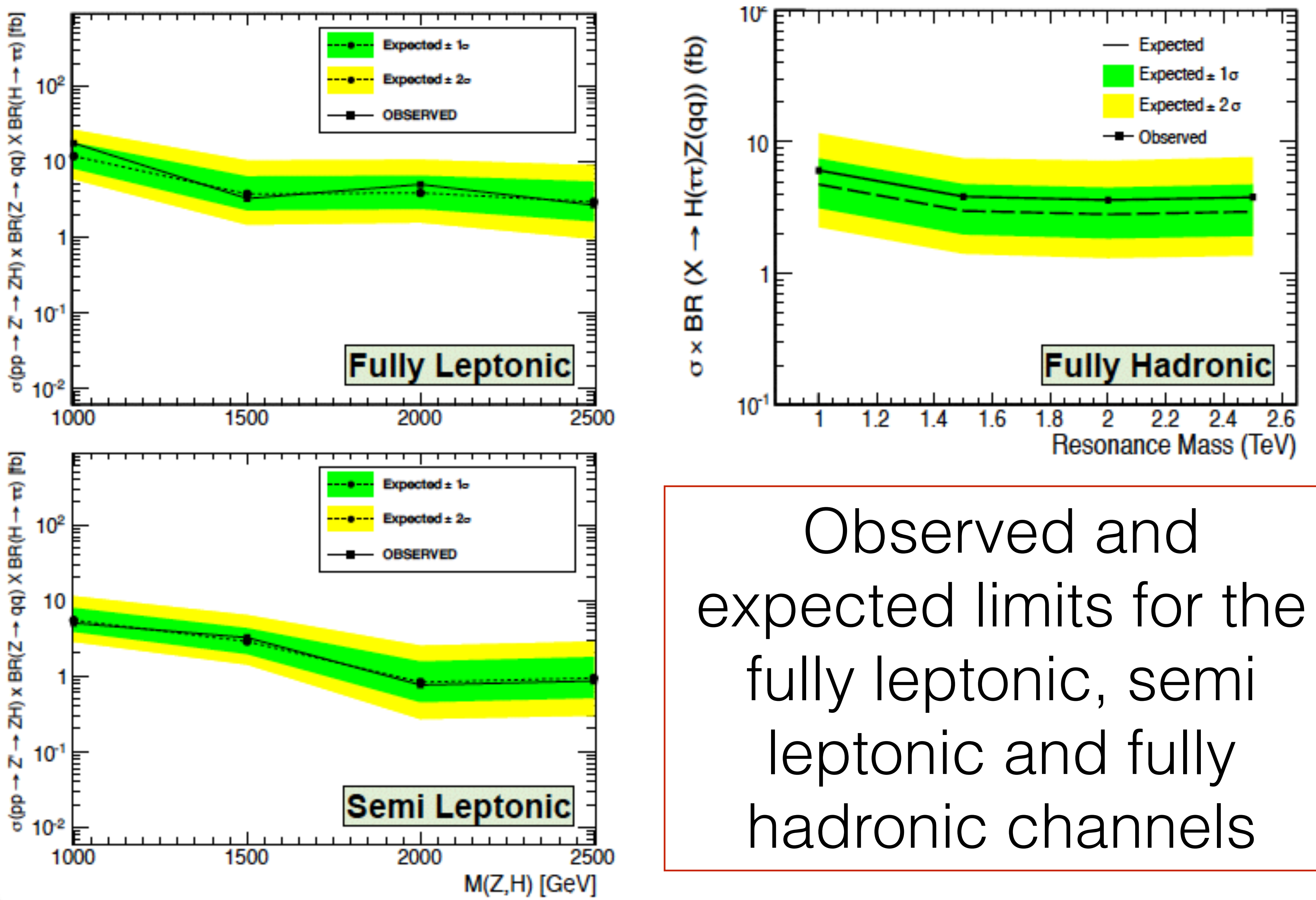
CMS PAS HIG-13-032



ATLAS-CONF-2014-005

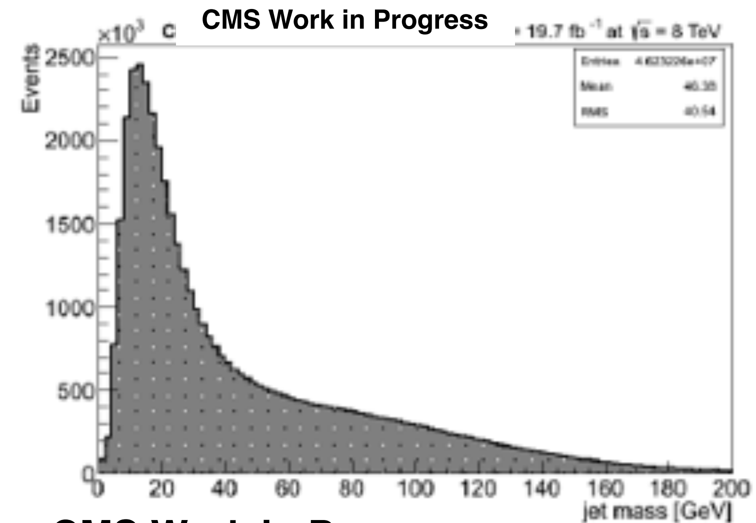


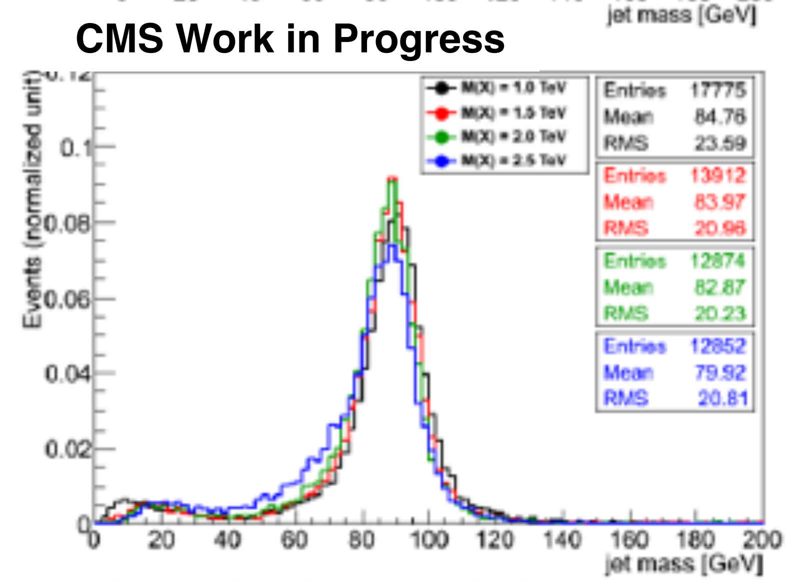
Results



Observed and expected limits for the fully leptonic, semi leptonic and fully hadronic channels

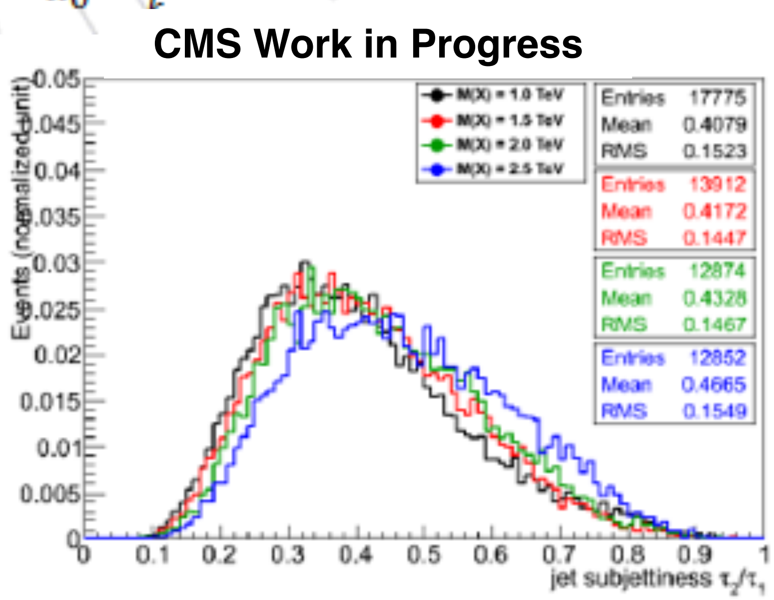
Jet reconstruction

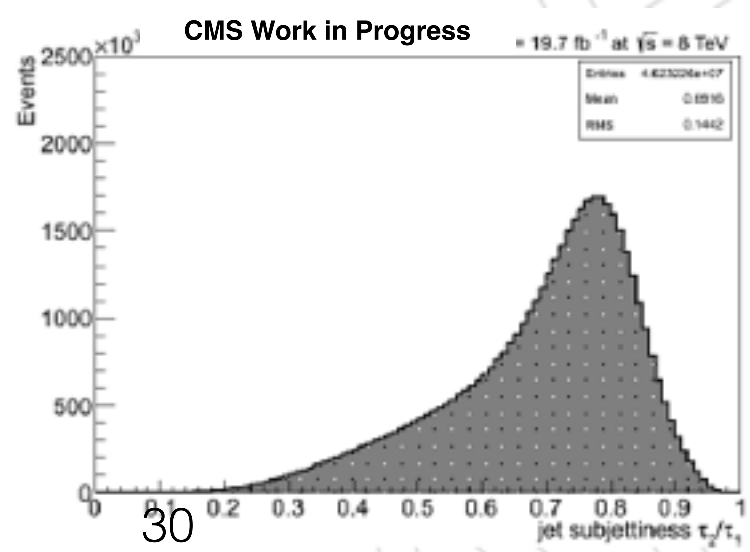




- Reconstruction of the hadronically decaying boson
- Analysis of the substructure of the jets for discriminating wrt QCD jets
  - Main idea: set of requirements during the jet clustering algorithm to “prune” the jet, i.e. to remove constituents that are at large angles or soft.
  - N-subjettiness helps discriminate between a jet that has 2 subjets or a jet that doesn’t have substructures

$$\tau_N = \frac{1}{d_0} \cdot \sum_k [p_{T_k} \cdot min(\Delta R_{1,k}, \Delta R_{2,k}, ...\Delta R_{N,k})]$$





Background evaluation Method

- Fully leptonic channel: DY is the main background source
- Alpha-ratio method:

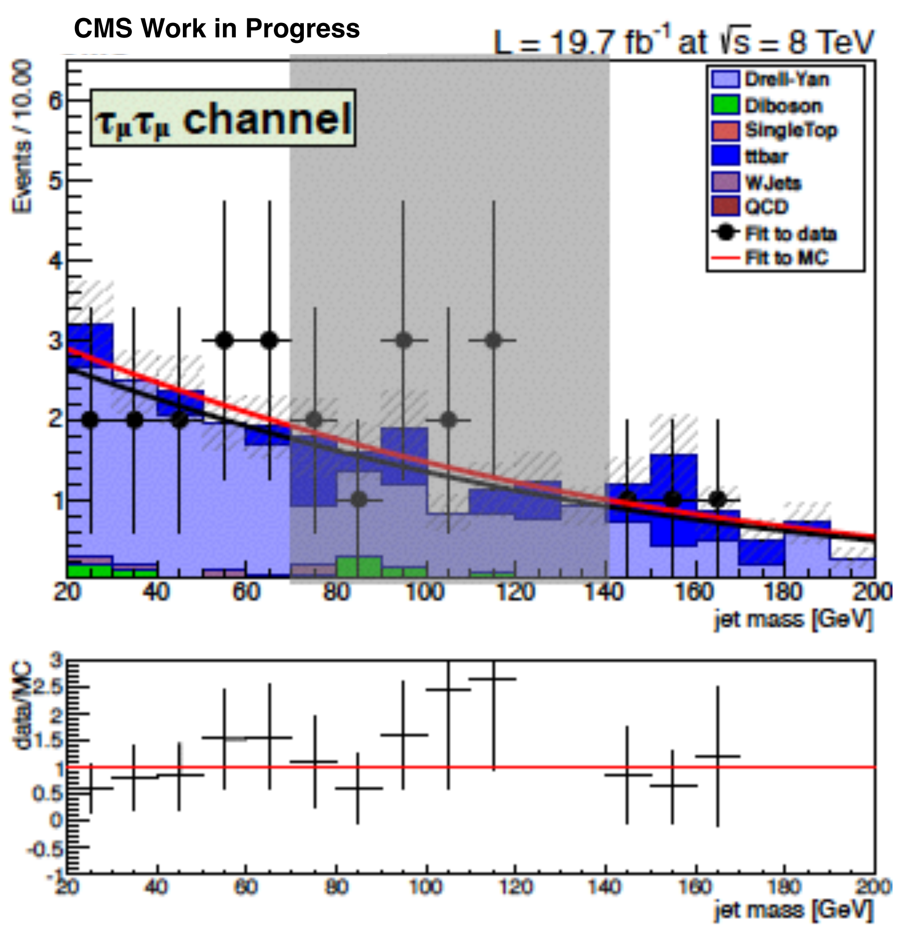
$$N_{bkg}(M_{ZH}) = \mathcal{N} \cdot N_{sb}(M_{ZH}) \cdot \alpha(M_{ZH})$$

- where:
  - $\mathcal{N}$ = normalization found in data
  - N_{sb} (M_{HZ}) is the number of events in the sideband in data
  - $\alpha(M_{HZ})$ is ratio between the MC bkg events in the signal and sideband region
- Sideband defined:
  - ✓ events with $\tau_{21} < 0.75$ and 20 < M(pruned jet) < 70 GeV || M(pruned jet) > 140 GeV
  - ✓ events with $\tau_{21} > 0.75$ and M(pruned jet) > 20 GeV

Background evaluation Method

- Fully leptonic channel:

$$N_{bkg}(M_{ZH}) = \mathcal{N} \cdot N_{sb}(M_{ZH}) \cdot \alpha(M_{ZH})$$



- Fit the pruned jet mass distribution in the MC in [20,200]GeV with the the function

$$F(x) = e^{Ax} \cdot \frac{1+\mathrm{erf}((x-B)/C)}{2}$$

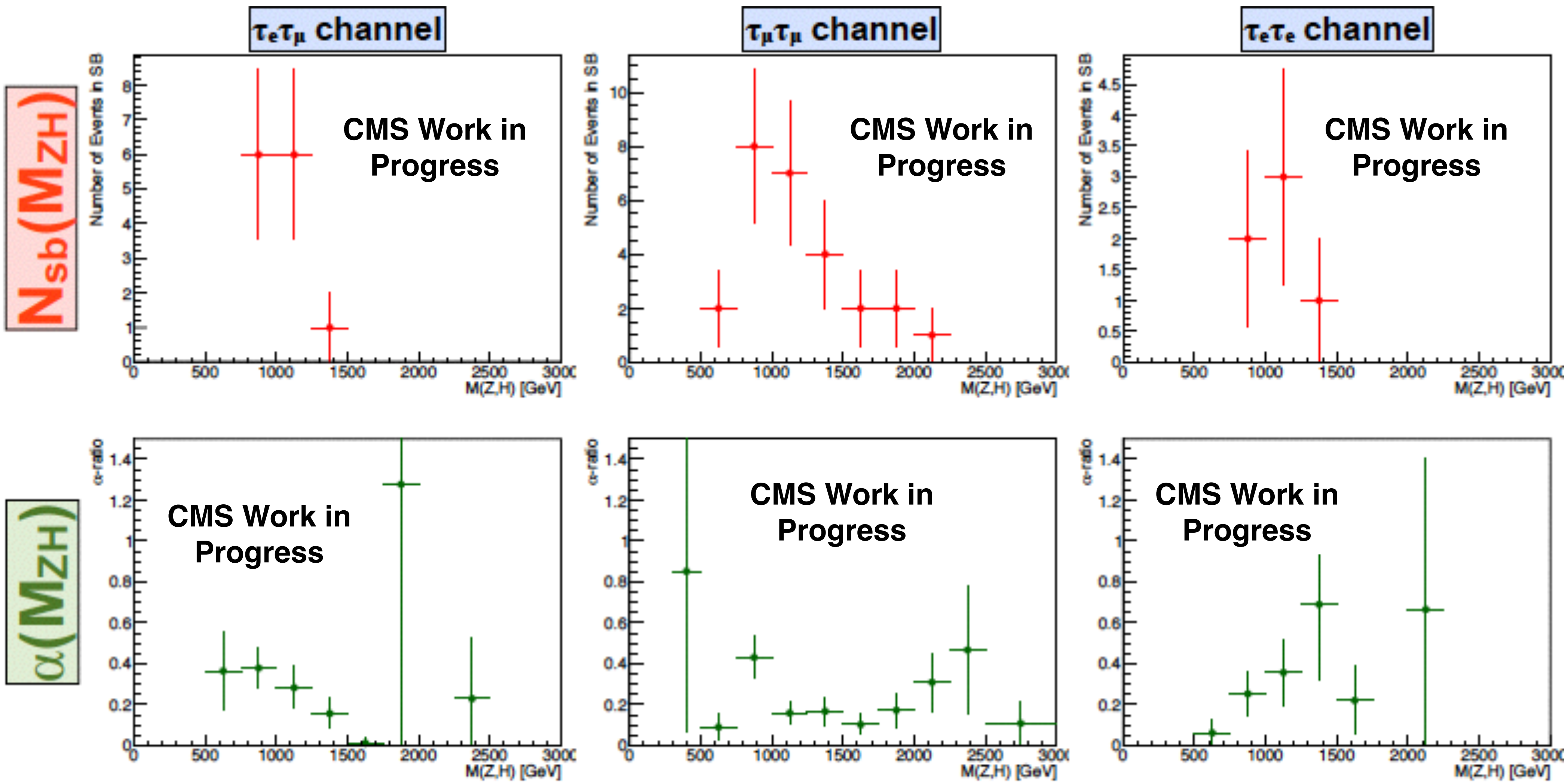
- Fit data in the range [20,70] + [140,200] with the shapes found before,leaving the normalization unconstrained

- Extrapolate the number of events in the signal region [70,100] GeV

Background evaluation Method

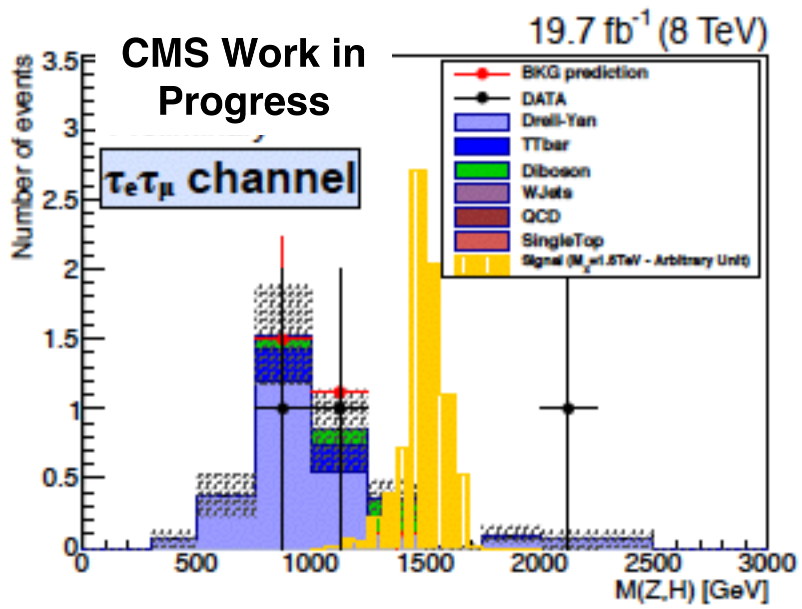
- Fully leptonic channel:

$$N_{bkg}(M_{ZH}) = \mathcal{N} \cdot N_{sb}(M_{ZH}) \cdot \alpha(M_{ZH})$$



Background evaluation Method

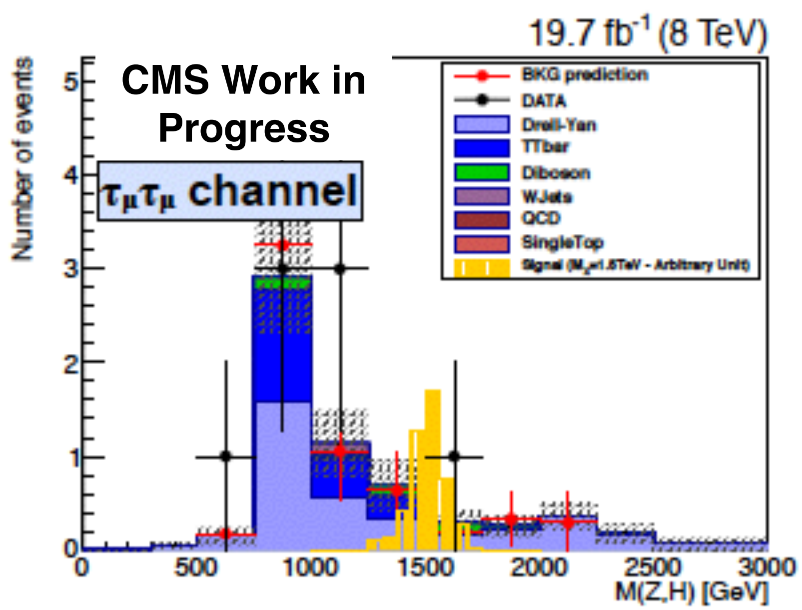
- Fully leptonic channel:

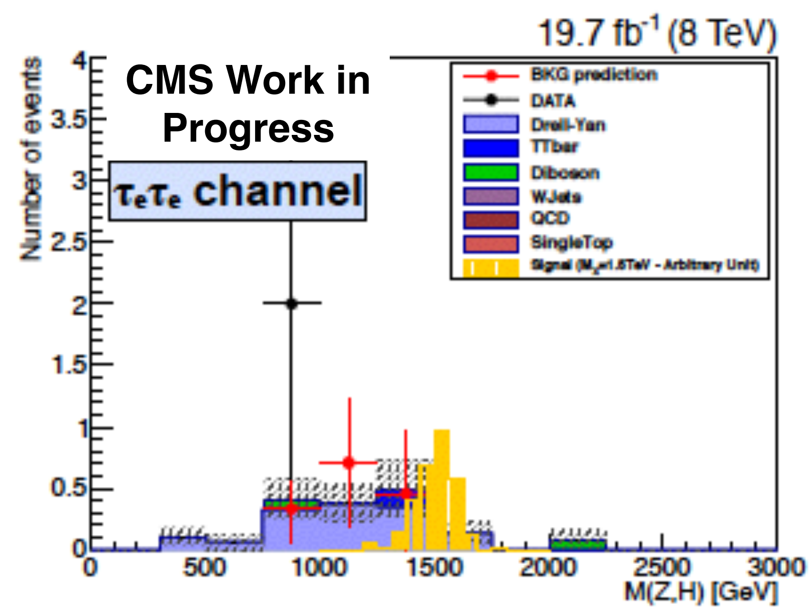


RESULTS

CMS Work in Progress

Channel	$e\mu$	$\mu\mu$	ee
BKG prediction	2.7 ± 1.0	5.9 ± 1.5	1.5 ± 0.7
BKG in MC	3.4 ± 0.5	6.1 ± 0.8	1.7 ± 0.4
DATA	3	8	2

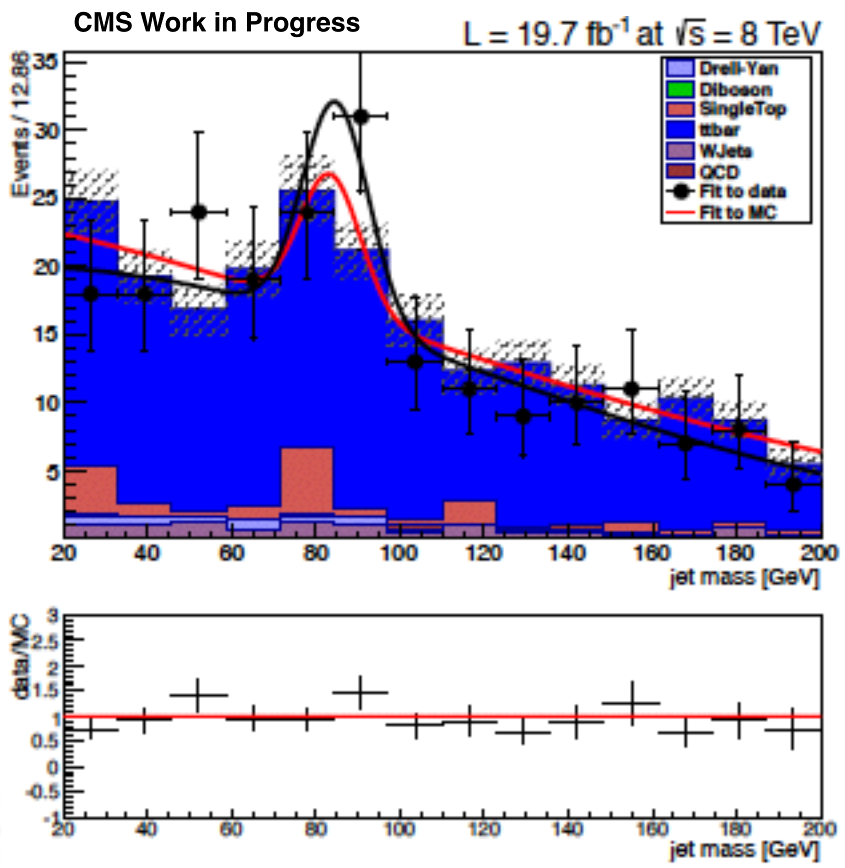




Background evaluation Method

- Semi leptonic channel: DY is the main background source
- Alpha-ratio method as before but with the ttbar contribution fixed.
- Top events normalization estimated in a ttbar enriched control sample (at least a b-tagged jet-CSVM)
- Fit of the pruned mass distribution using the function

$$F_{t\bar{t}}(x) = N(\text{non-peaking}) \cdot e^{Ax} \cdot \frac{1+\text{erf}((x-B)/C)}{2} + N(\text{peaking}) \cdot Gauss(D, E)$$

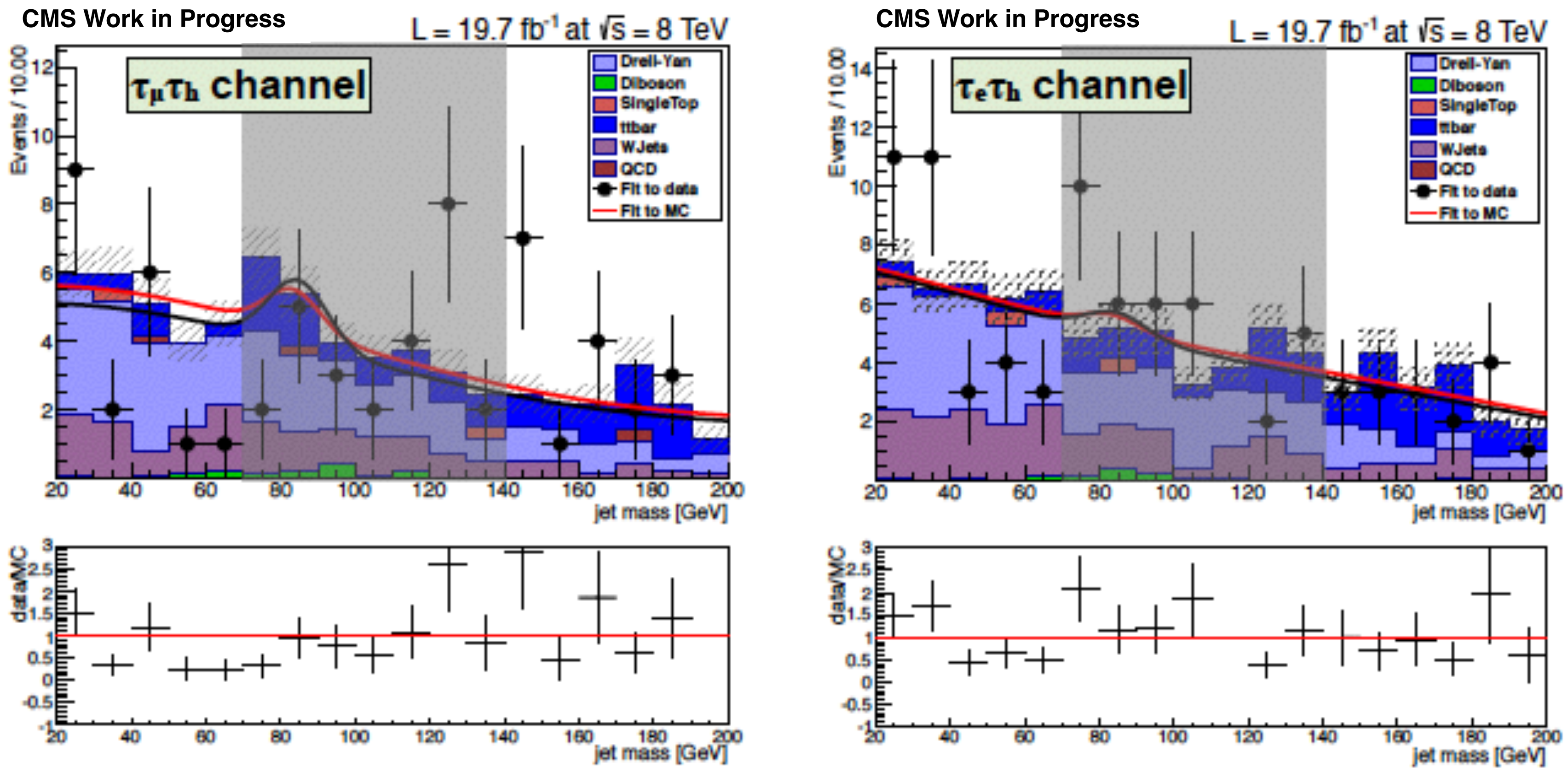


- The two SFs are found as the ratio between data and MC of the normalization of the two functions

	$\tau_\mu\tau_h$	$\tau_e\tau_h$
SF(peak)	1.8 ± 1.3	1.7 ± 2.1
SF(NO peak)	0.9 ± 0.1	0.9 ± 0.1

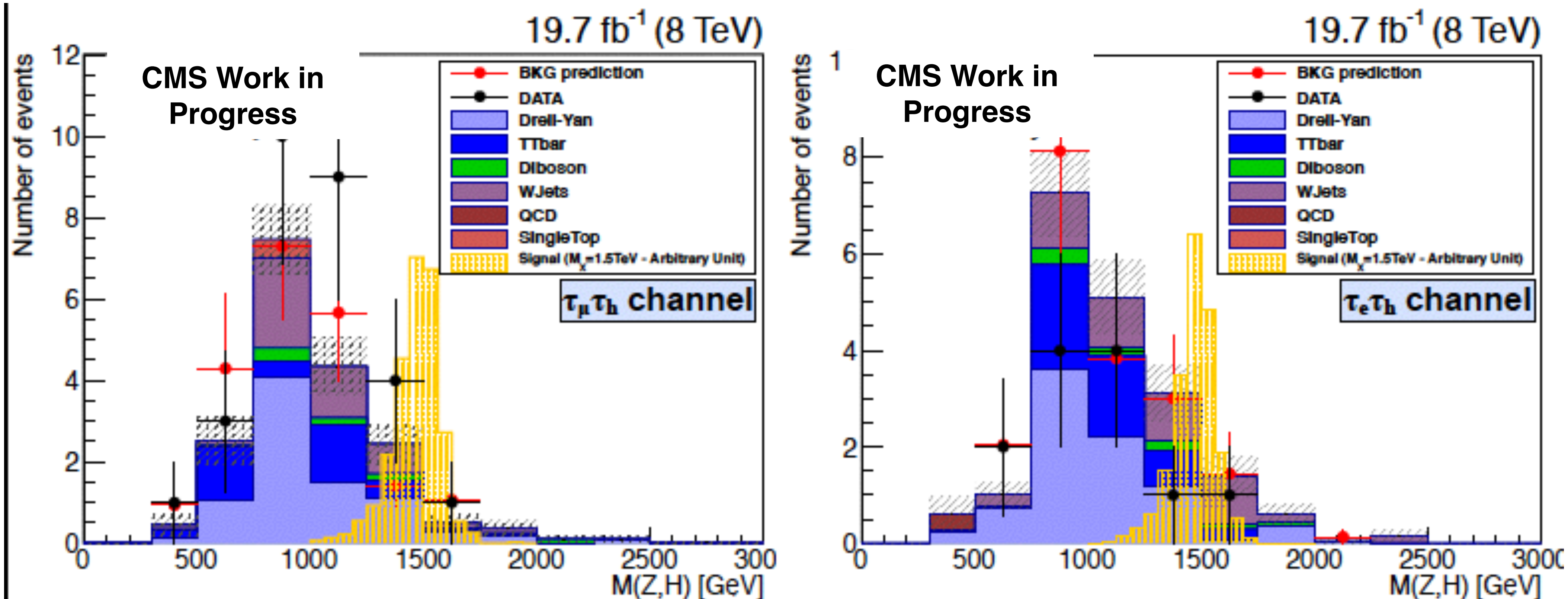
Background evaluation Method

- Semi leptonic channel:



Background evaluation Method

- Semi leptonic channel:



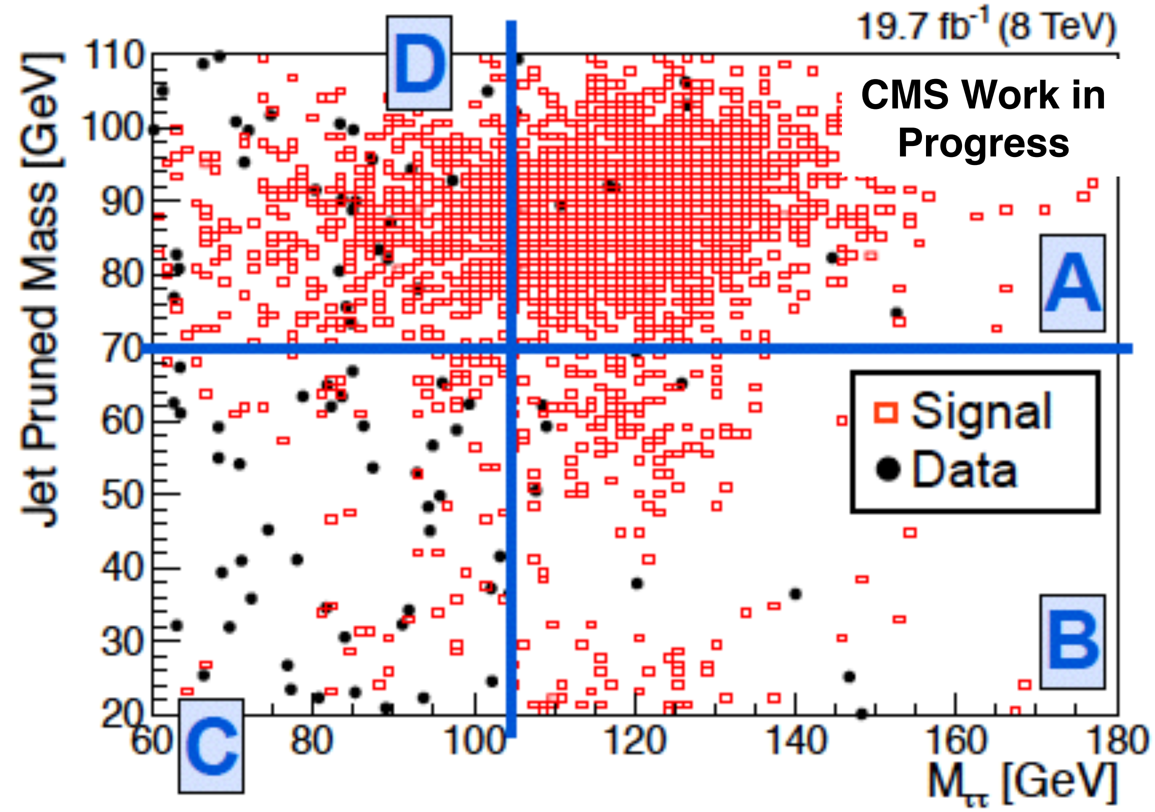
CMS Work in Progress

RESULTS

Channel	$\mu\tau_h$	$e\tau_h$
BKG prediction	20.7 ± 3.7	18.6 ± 5.6
BKG in MC	18.3 ± 1.4	19.3 ± 1.5
DATA	28	12

Background evaluation Method

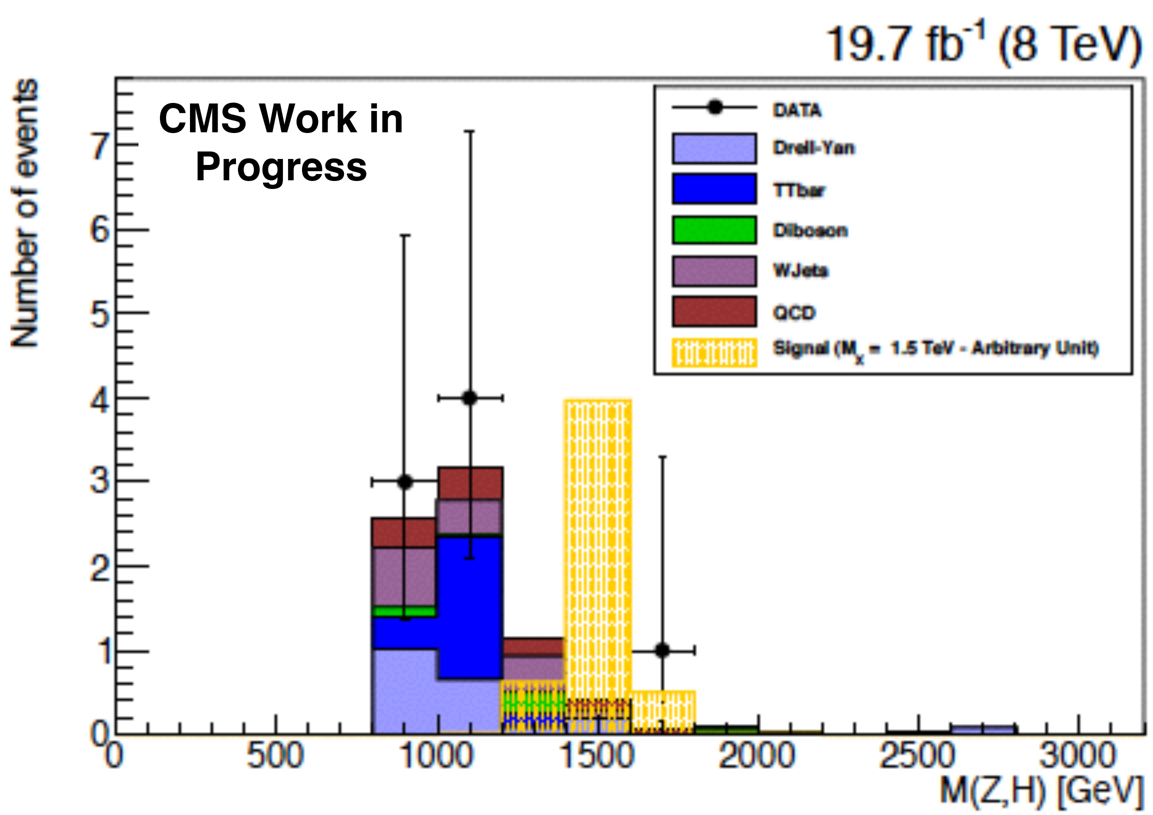
- Fully hadronic channel:
  - ABCD Method:
  - M $_{pruned}$ and M$\tau\tau$ from SVFit are used: uncorrelated variables
    - Number of background events evaluated through:



$$N(A) = N(D) \cdot \frac{N(B)}{N(C)}$$

Background evaluation Method

- Fully hadronic channel:



RESULTS

CMS Work in Progress

Regions	Events in Data - Original
NB	$9.0^{+4.1}_{-2.9}$
NC	43^{+8}_{-7}
ND	29^{+6}_{-5}
NA(estimate)	$6.1^{+3.2}_{-2.5}$
Observed A	8

Systematics

- The largest systematics are the ones due to the background evaluation
- When the number of events is evaluated from a control sample the distribution for Nbkg is a Gamma function

$$n = \alpha \cdot N \qquad \Gamma(n) = \frac{(n/\alpha)^N}{\alpha N!} e^{-n/\alpha}$$

CMS Work in Progress

	1.0 TeV	1.5 TeV	2.0 TeV	2.5 TeV
$\tau_e\tau_\mu$	8	1	0	0
$\tau_\mu\tau_\mu$	10	6	3	1
$\tau_e\tau_e$	3	1	0	0
$\tau_\mu\tau_h$	26	11	0	0
$\tau_e\tau_h$	23	11	2	1
$\tau_h\tau_h$	29			

Number of events in the sideband

The **other two systematics associated to the background estimation** method for the **fully and semi leptonic channels** are:

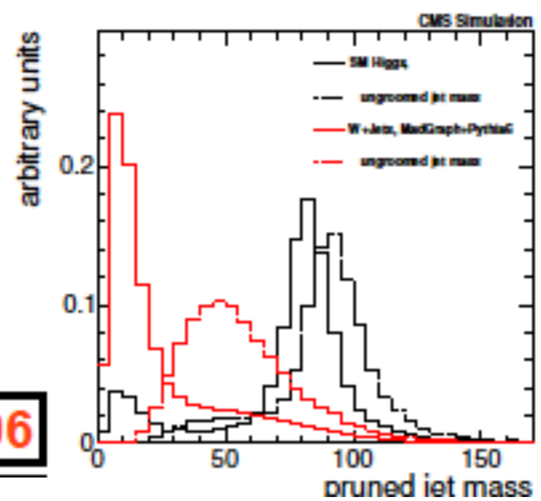
✓ **statistical error on the alpha ratio**

✓ **statistical error on normalization factor**

Pruning

- Developed by ***S.Ellis et al***: **[Phys. Rev. n D80 (2009)]**
- Main idea ➙ add a set of requirements during the clustering algorithm
  ➙ ***to prune the jet***: remove constituents that are at large angles or soft
- **Starting point**: jets clustered with CA algorithm and distance parameter of 0.8
- Steps of the algorithm:
  1. **rerun** the clustering sequence
  2. **two more requirements** are asked:

- $z_{ij} \equiv \frac{min(p_T^i, p_T^j)}{p_T^p} > z_{cut}$ → remove **soft** particles
- $\Delta R_{ij} < \alpha \cdot m_{jet}/p_T^{jet}$ → remove **large angle** particles



ref. CMS PAS JME-13-006