Universität Zürich[UZH]

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

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17th June 2014
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Outline

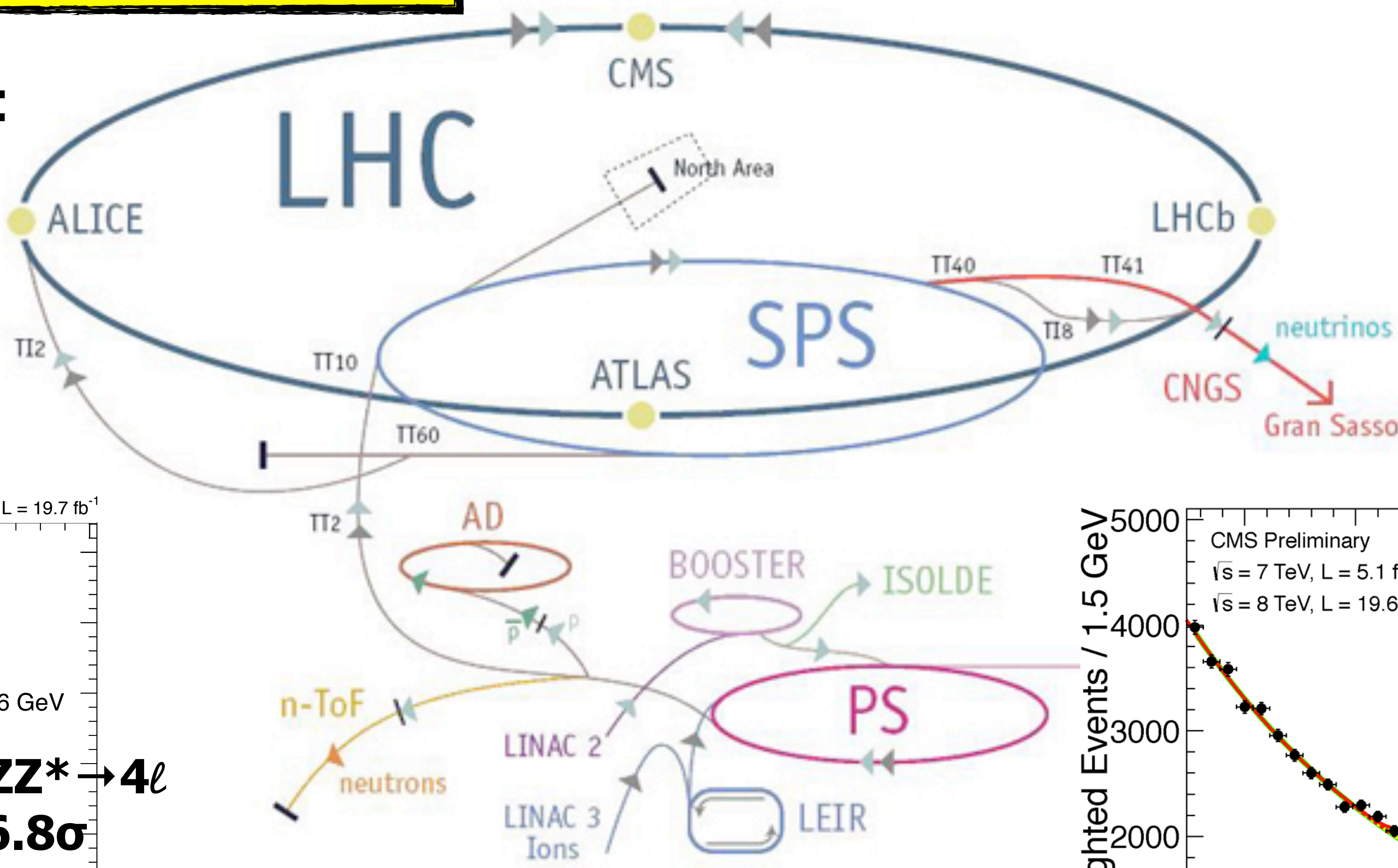
- **Analysis project:**
  - ★ Higgs at LHC
  - ★ Theoretical motivation: Beyond Standard Model
  - ★ Search for new spin-1 heavy resonance: W′ → lepton + boosted Higgs-jet
  - ★ The CMS Detector at LHC
  - ★ Analysis strategy outline: Higgs-tagging, b-tagging
  - ★ Rejection of the largest background
- **Hardware project:**
  - ★ CMS Pixel Detector
  - ★ Calibrations
  - ★ Phase I Upgrade
  - ★ System test setup at UZH

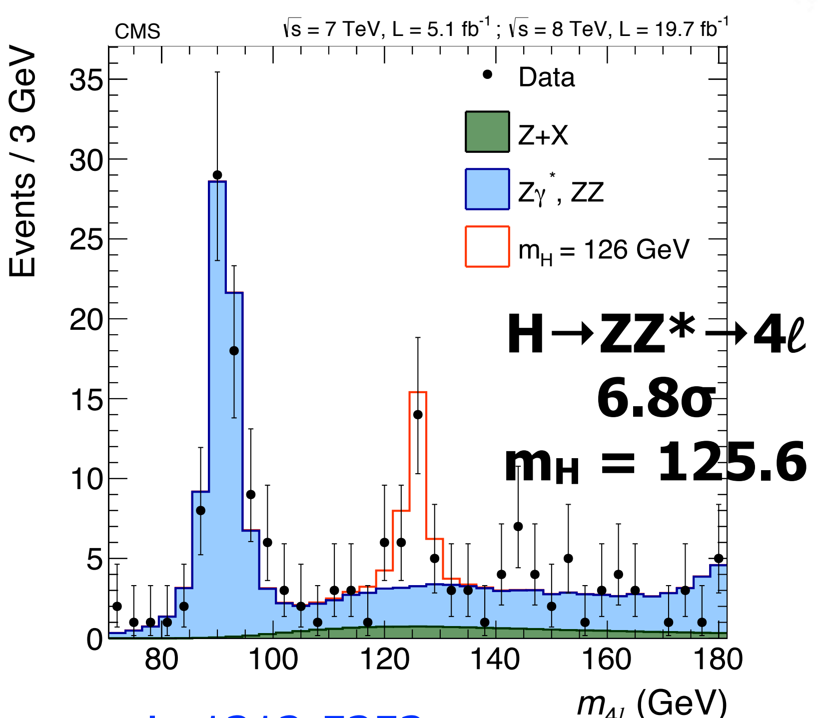
Higgs at LHC

Higgs boson discovered in proton-proton collision at √s = 7-8 TeV @ LHC!

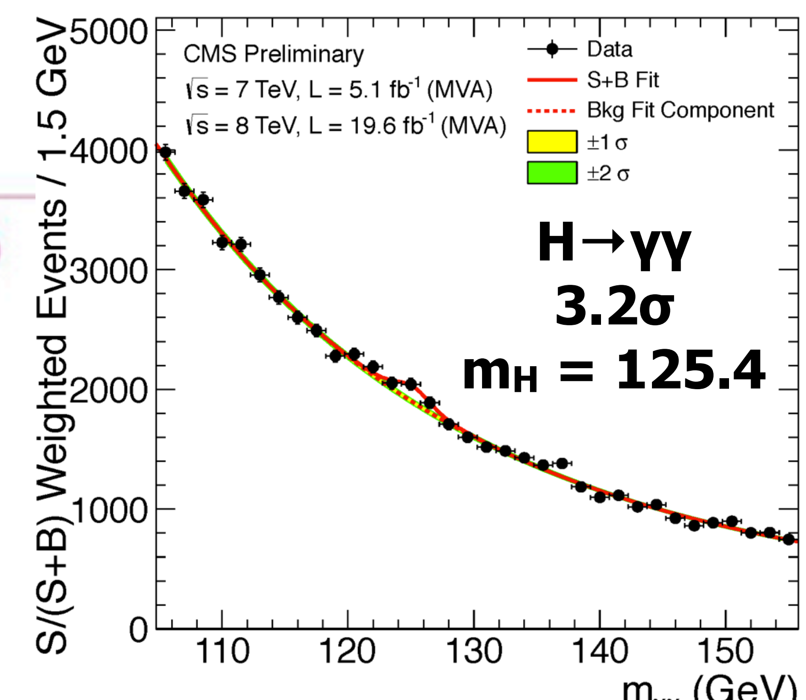
LHC machine parameters:
Design Luminosity: $\mathcal{L}$ = **10^{34}cm^{-2}s^{-1}**
Design center of mass energy: **√s = 14 TeV**

- Discovery channels:
  - ★ **H→γγ**
  - ★ **H→ZZ*→4ℓ**
  - ★ **H→WW*→2ℓ2ν**





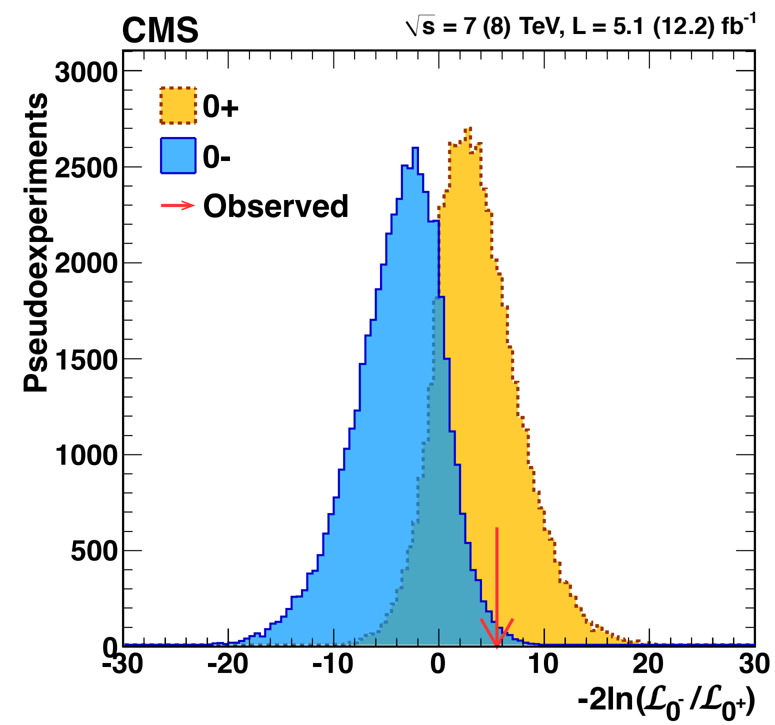
arxiv:1312:5353



arxiv: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 →



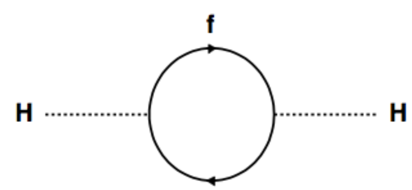
arxiv:1212:6639

- 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

- The Higgs mass gains quantum corrections from fermion loops



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

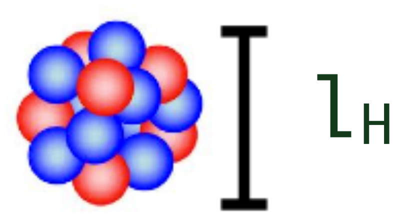
$$\delta M_H^2 = -2\frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

fine tuning: Λ ~ gravitational scale ~ M_{Planck} ~ 10^{18} 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



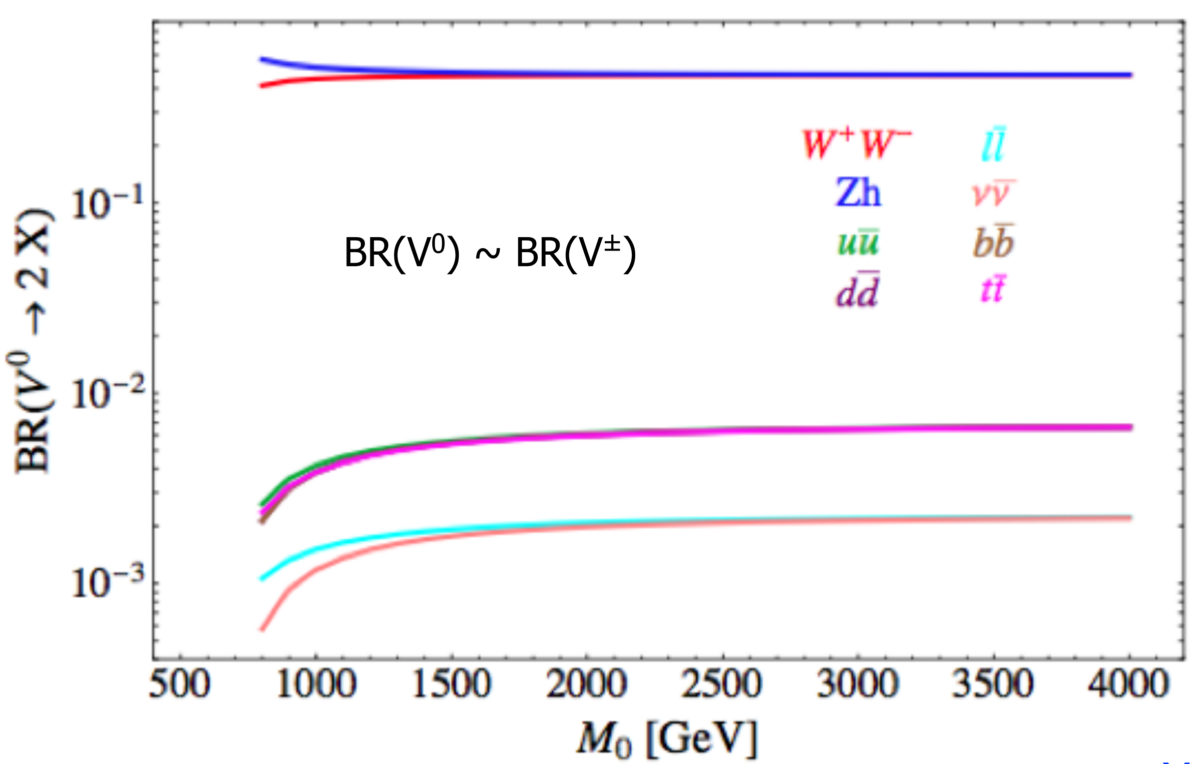
The hierarchy problem is solved:

- corrections to m_H screened at $1/l_H$

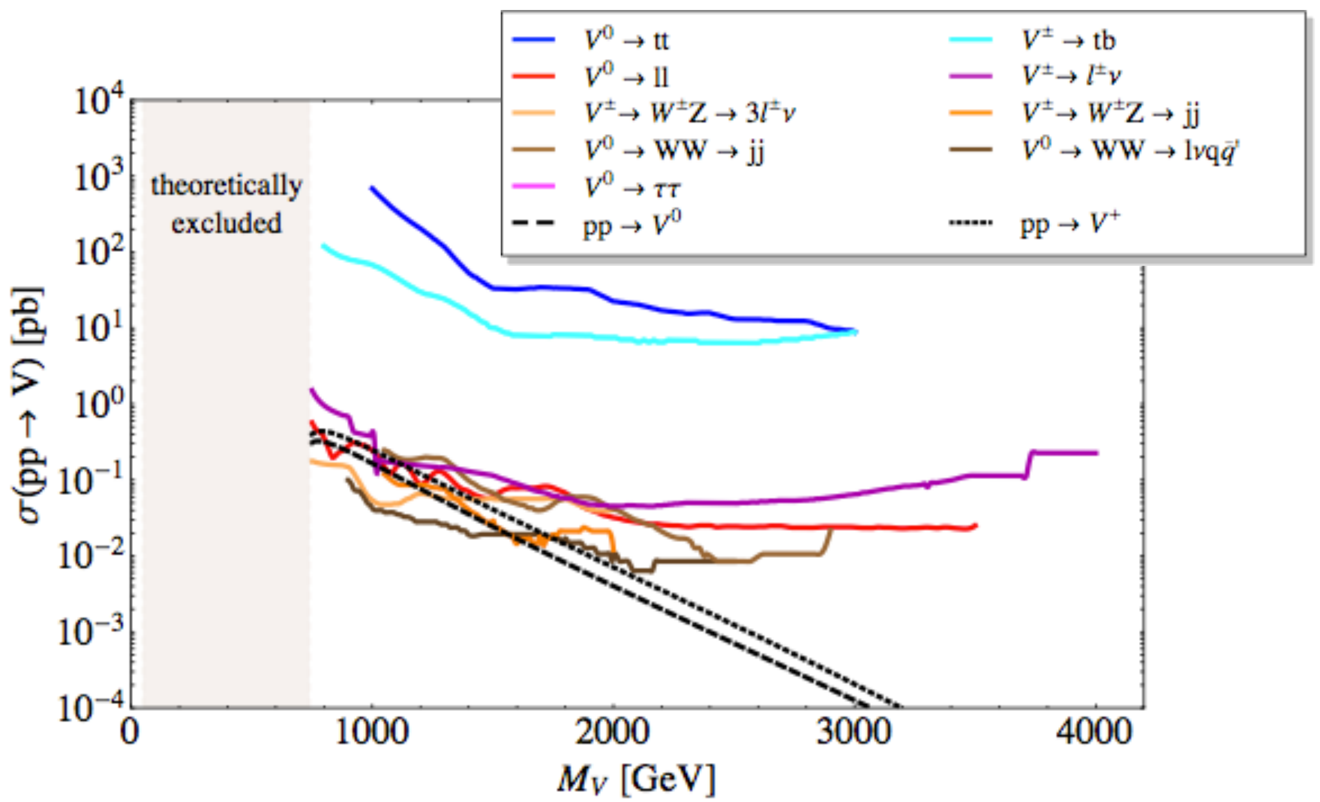
Z′ and W′: data & bounds

- 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 primarly to SM vector bosons (W,Z,Higgs)

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



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



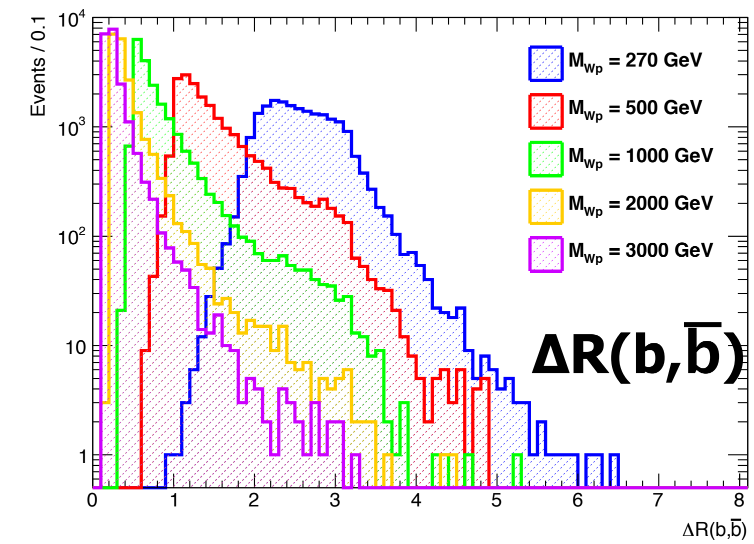
arXiv:1402.4431

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

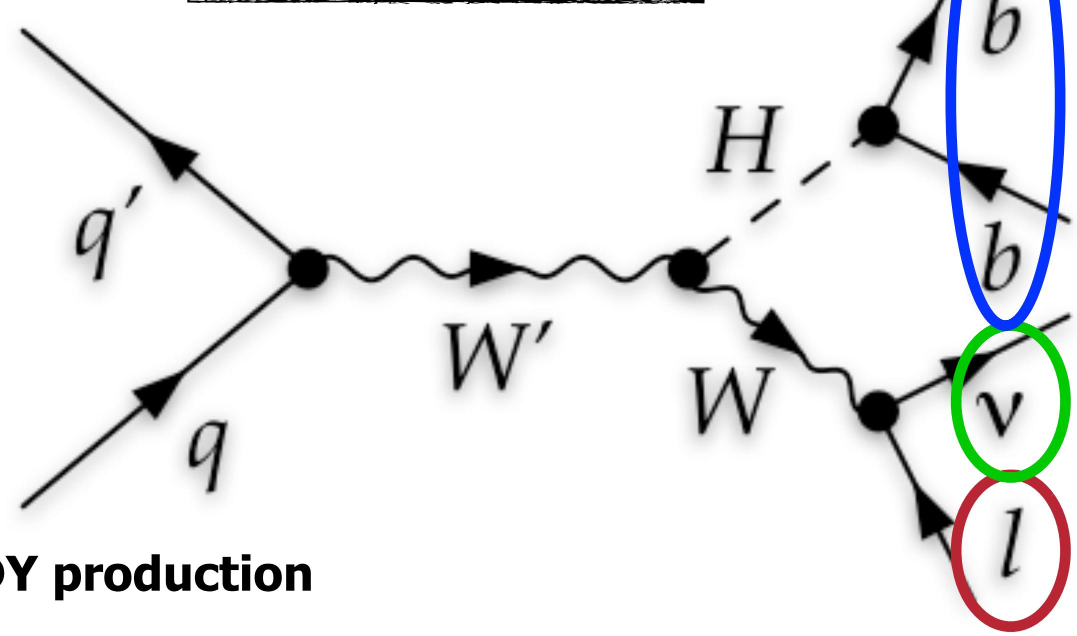
One of the first analyses attempting to look for exotic final state with a **Higgs boson**

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

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



boosted decay products

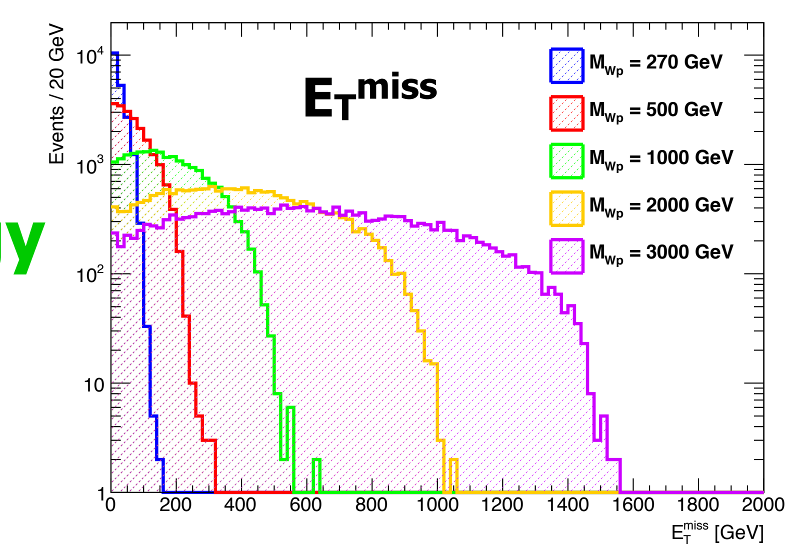


DY production

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

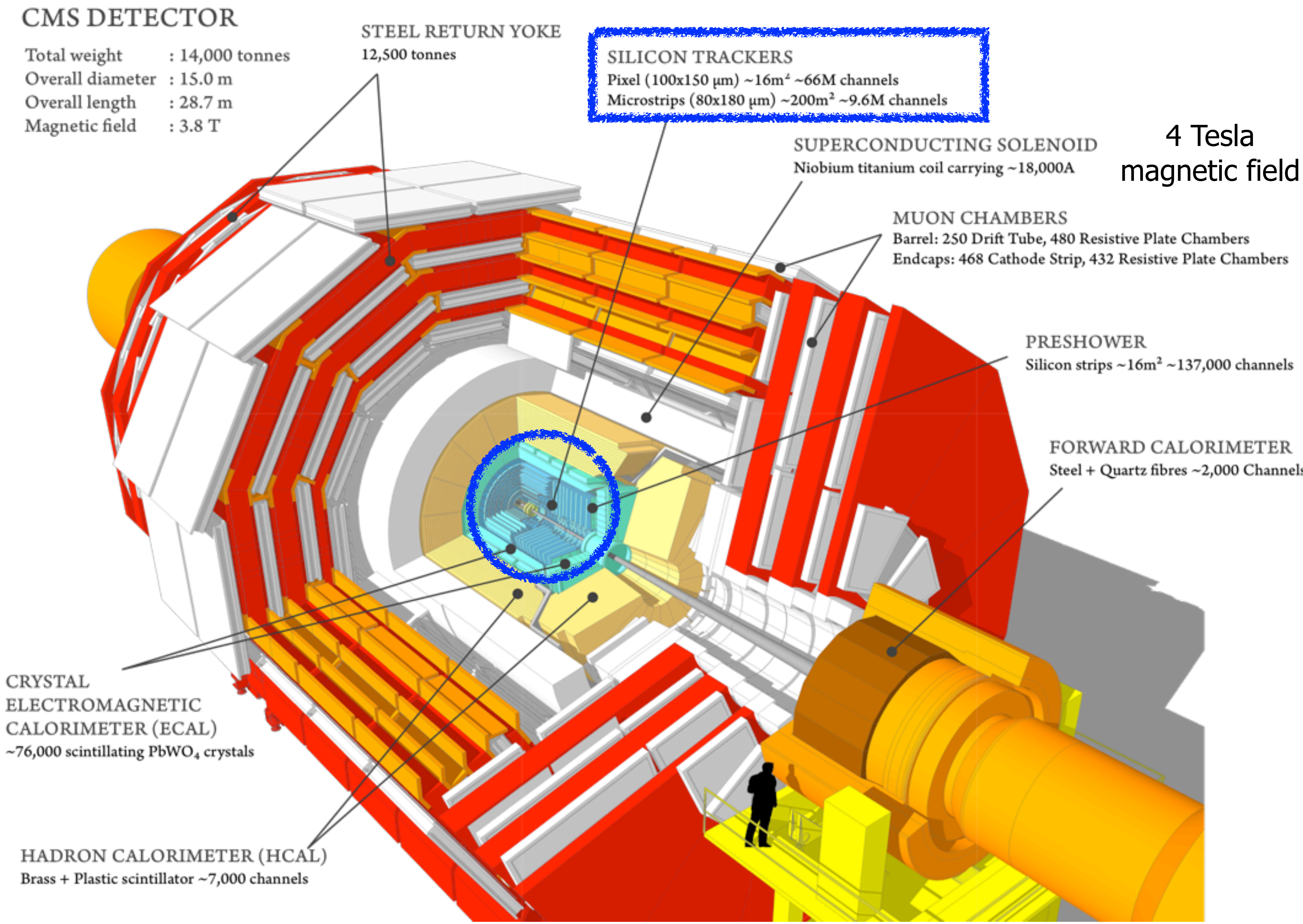
large missing transverse energy

One high p_T isolated lepton



CMS at LHC

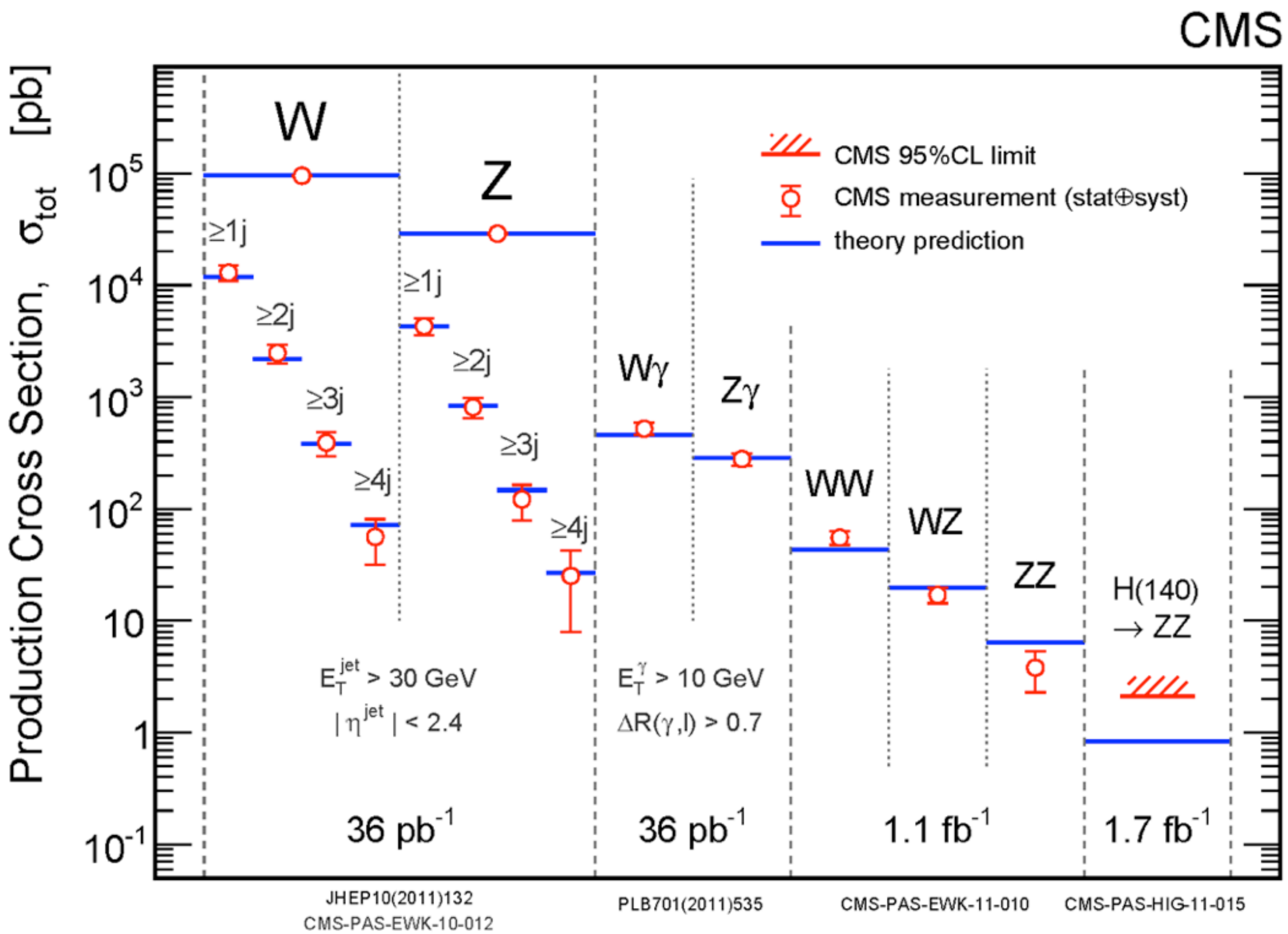
The CMS Pixel detector plays a central role in the identification of b-quarks present in the analysis final state



Backgrounds

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

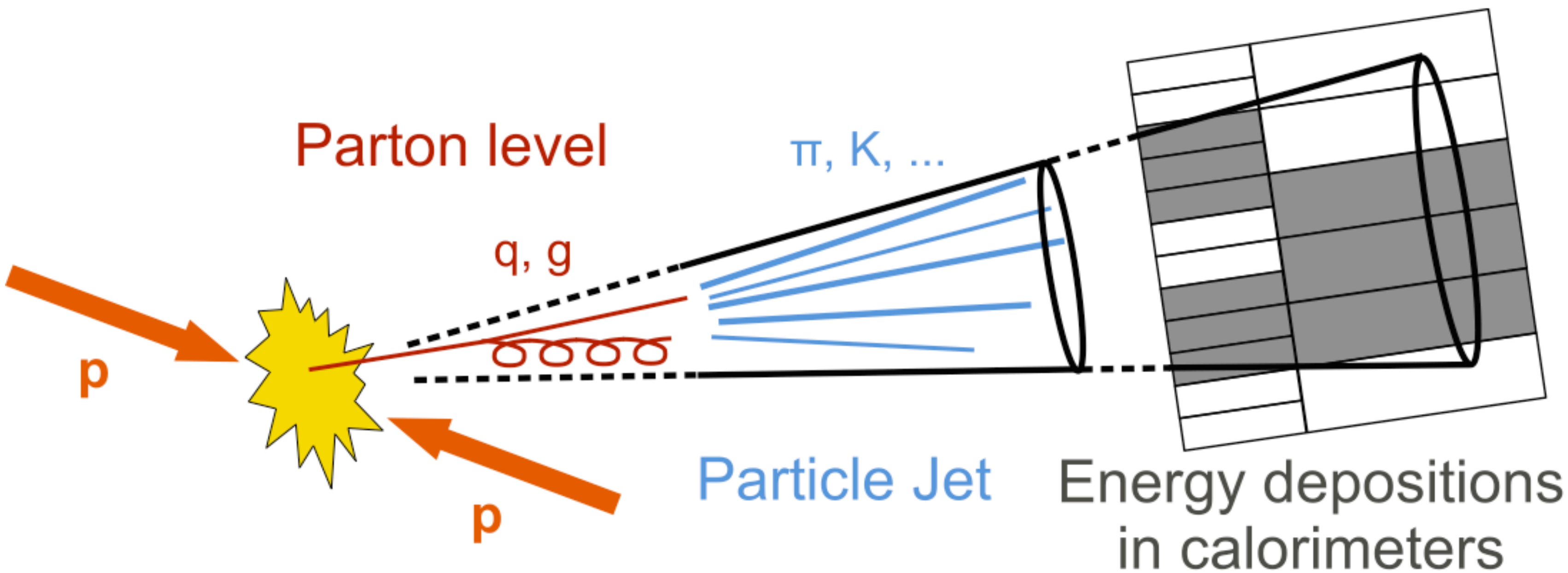
background	cross section (pb)
$W^\pm$ + jets	31314
$t\bar{t}$	225
Single top	80
W^+W^-	57
$W^\pm Z$	33
ZZ	8



arxiv:1201:4681

What are jets?

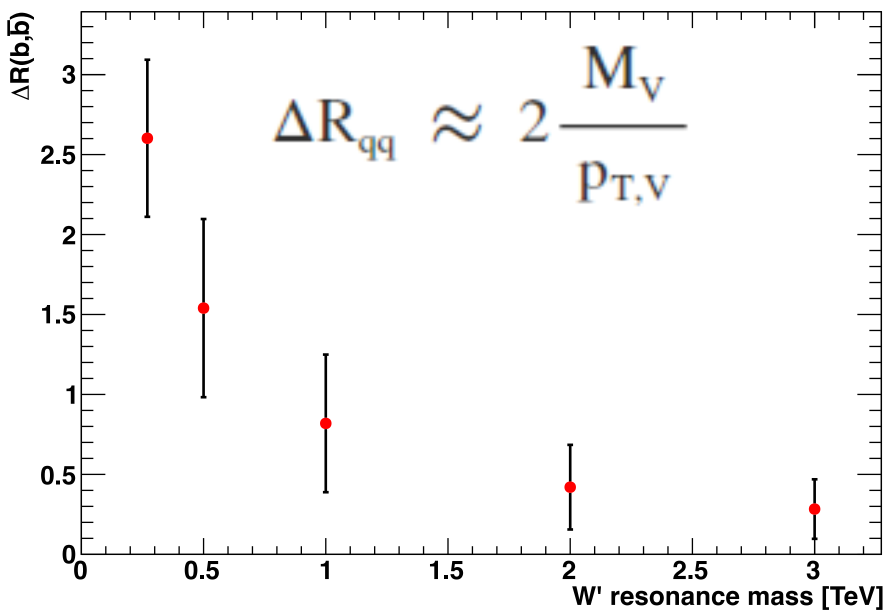
Collimated bunches of stable hadrons, originating from partons (quarks and gluons) after fragmentation and hadronization

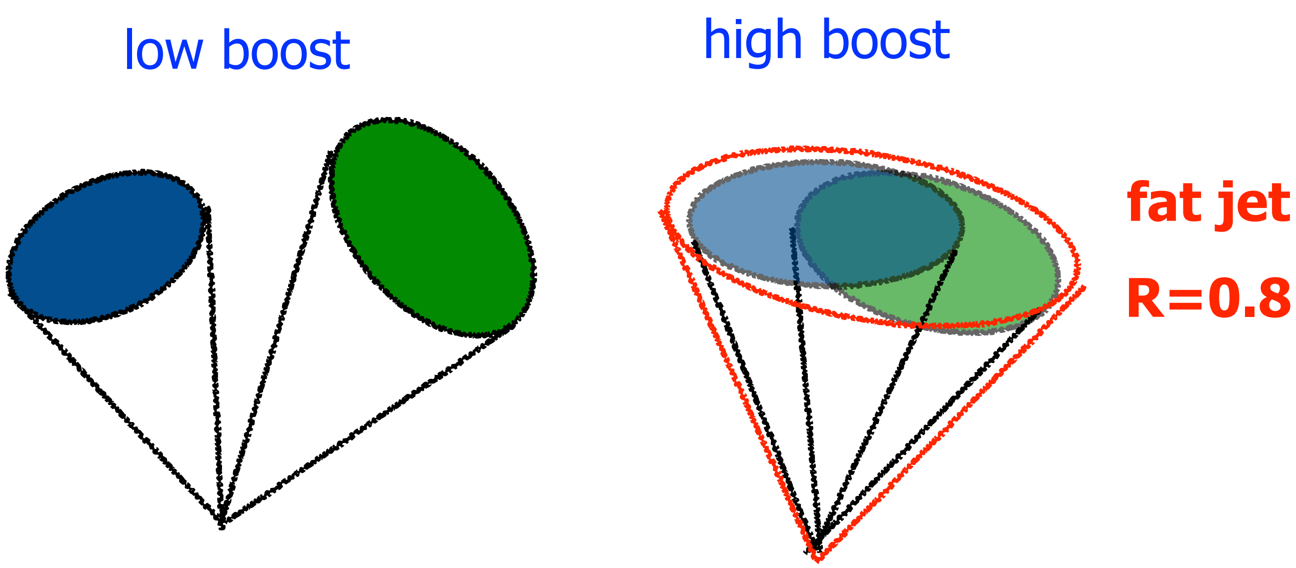


- the jet energies are collected by the two CMS calorimeters, ECAL and HCAL, and then clustered in jets
- then, the **CMS particle flow algorithm** links the calorimetric deposition to the tracks reconstructed in the tracker detector to form the charged hadrons that constitutes the jet and to give a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

Higgs-jet identification

- For large enough boost (depending on the resonance mass) the b-jets from the Higgs are expected to merge into a single jet: $\Delta R(b,\bar{b}) < 0.5$ for $M_{W'} > 2$ TeV





- **Strategy:** it is very important for boosted Higgs-tagging to be able to identify the substructure of the merged jet
  - the **Cambridge-Aachen jet clustering algorithm** has been shown to provide the best performance
- In order to cover a wider mass range a large-radius jet of R=0.8 (fat-jet) is used to identify the merged Higgs-jet

Jets clustering algorithms

- Construct the quantities:

$$d_{ij} = min(k_{T,i}^n, k_{T,j}^n)\frac{\Delta R_{ij}^2}{R^2}, d_{iB} = k_{T,i}^n$$

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

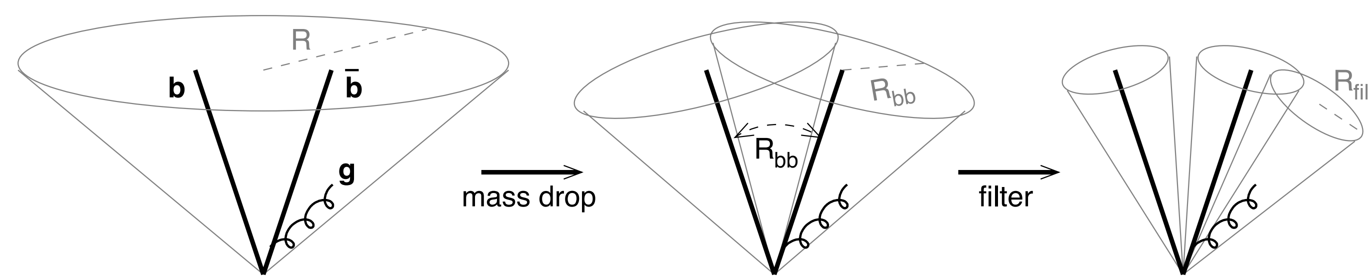
- Among the several algorithms proposed to identify jet substructure originating from heavy objects, the **jet pruning algorithm** has been shown to provide the best performance:
  - start from a large-radius jet (CA with R=0.8)
  - recluster the jet constituents and evaluate the hardness and angular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

hardness

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

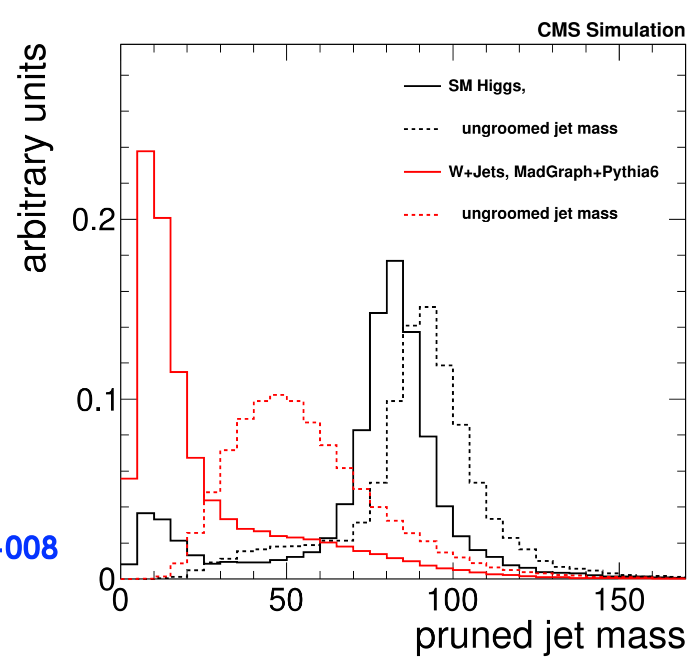
angular separation

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



  - remove the softest subjet if conditions are not satisfied

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

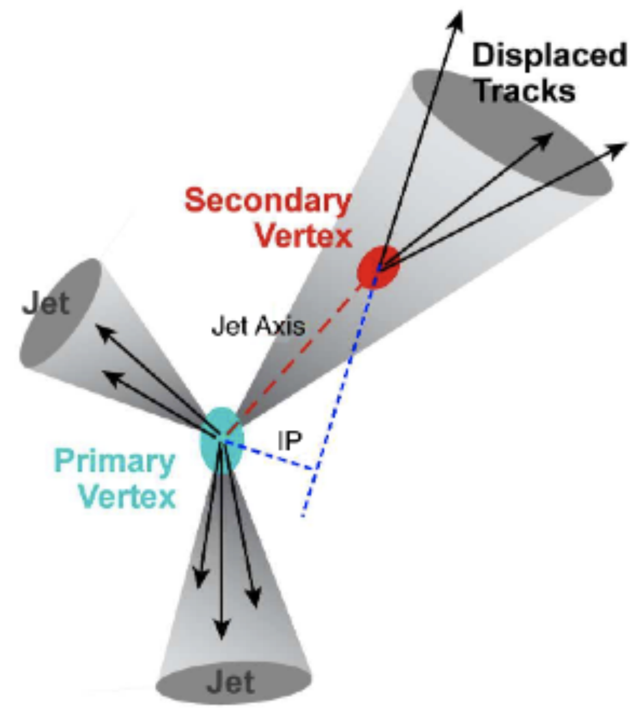


CMS-PAS-HIG-13-008

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

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**

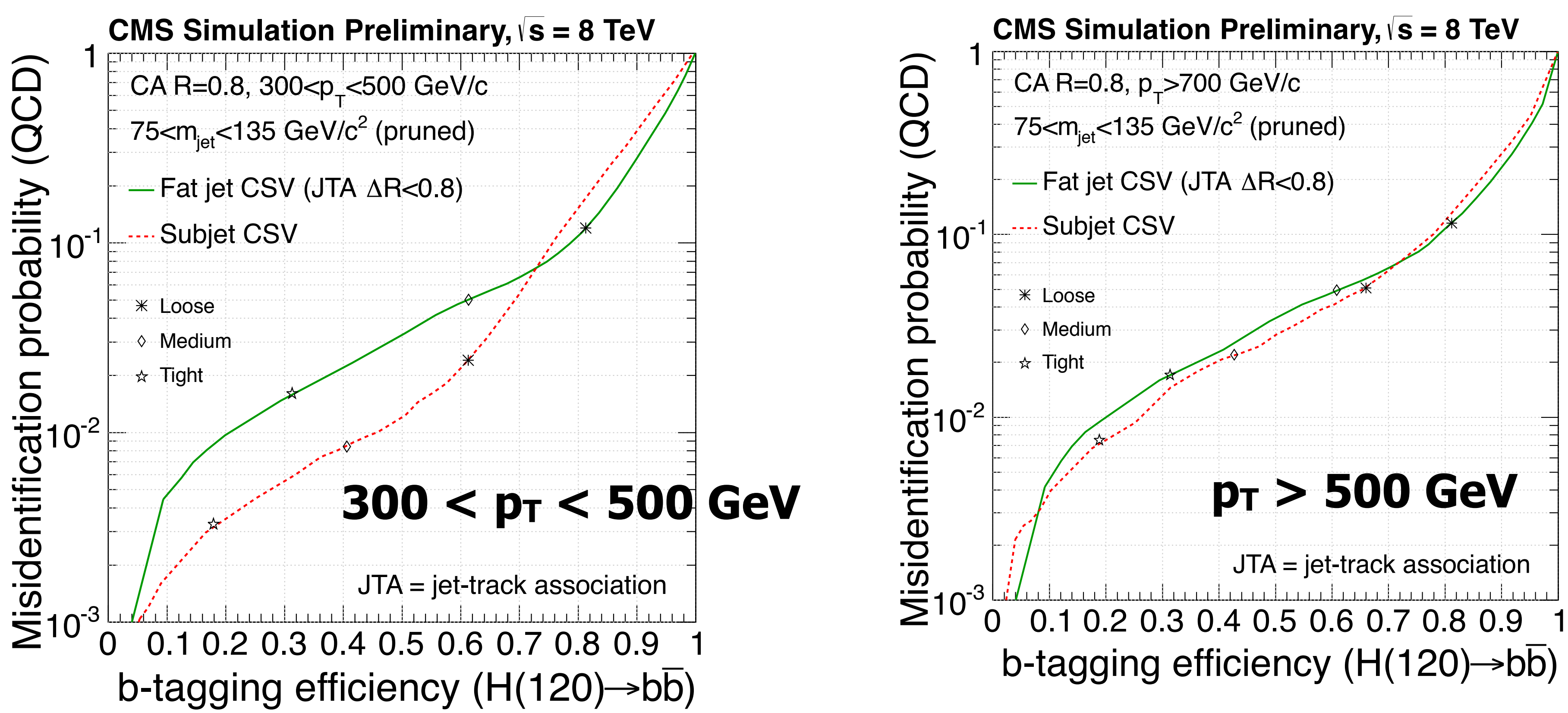
- The discriminant is used to apply a cut at different working points depending on the acceptance of light flavor jets:

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

Identifying jets with 2 b-quarks

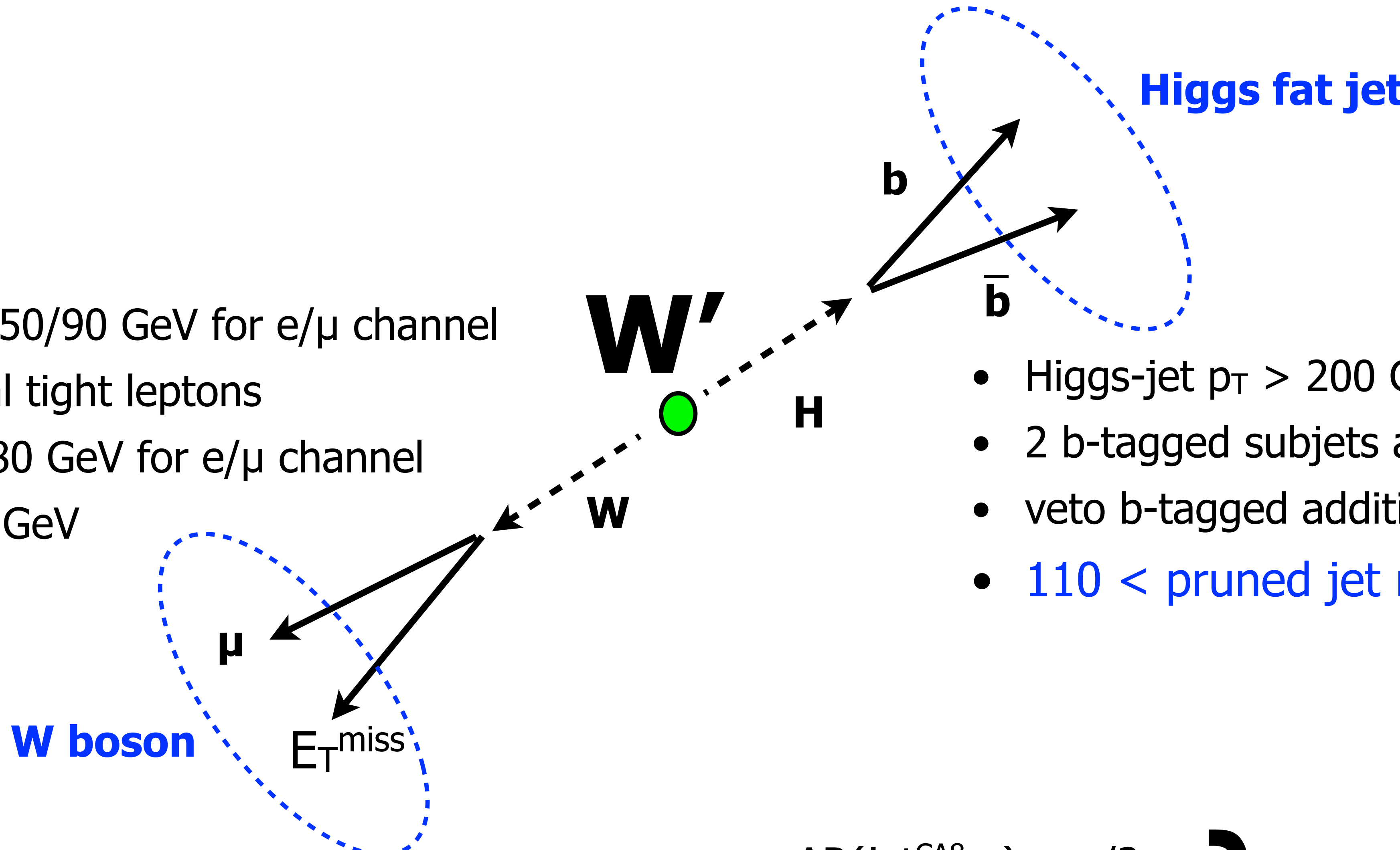
- Two b-tagging approach are currently used in CMS for boosted analysis:
  - application of b-tagging to fat jet
  - application of b-tagging to subjets reconstructed within the fat jet
- The **subjet b-tagging** approach has been shown to outperform the fat jet b-tagging in the largest part of the p_T range

subjet vs fat jet b-tagging



Event selections

- lepton p_T > 50/90 GeV for e/μ channel
- no additional tight 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 additional jets
- 110 < pruned jet mass < 135 GeV

the lepton from the W decay provides an efficient trigger path

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

} back-to-back topology

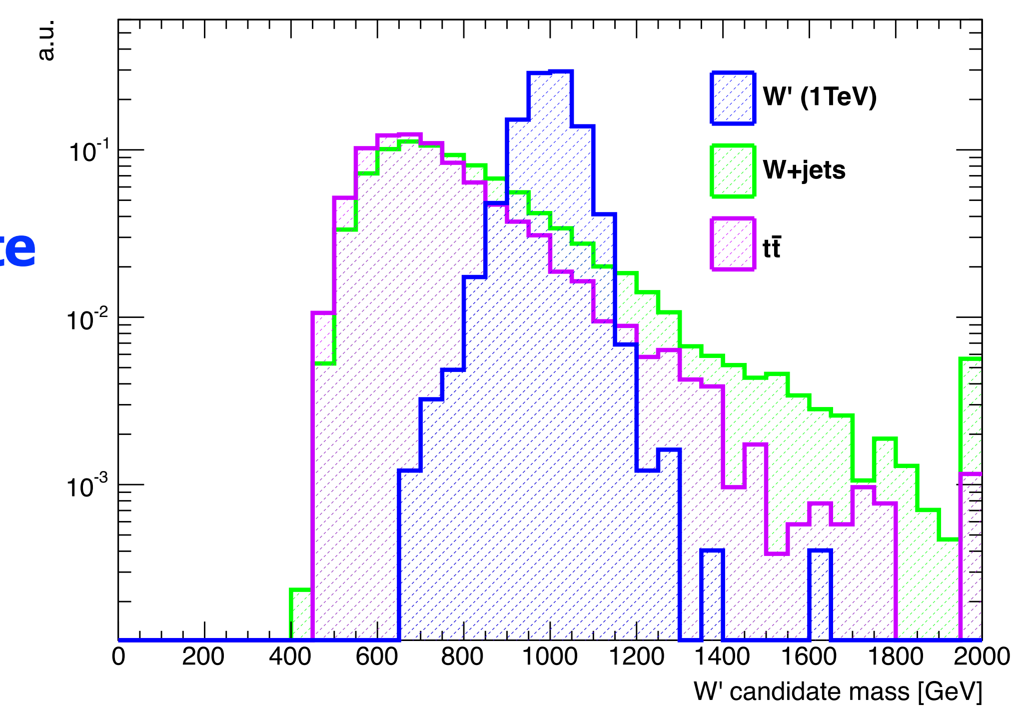
Reconstructing W' candidate

- Start from the reconstructed W→$\ell\nu$
- The W mass constraint is applied to extract the z component of the escaping neutrino

$$M_W^2 = (E_\mu + \sqrt{\mathbf{E}_T^{\mathrm{miss}\,2} + P_{z,\nu}^2})^2 - (\mathbf{P}_{T,\mu} + \mathbf{E}_T^{\mathrm{miss}})^2 - (P_{z,\mu} + P_{z,\nu})^2 = (80.4)^2$$

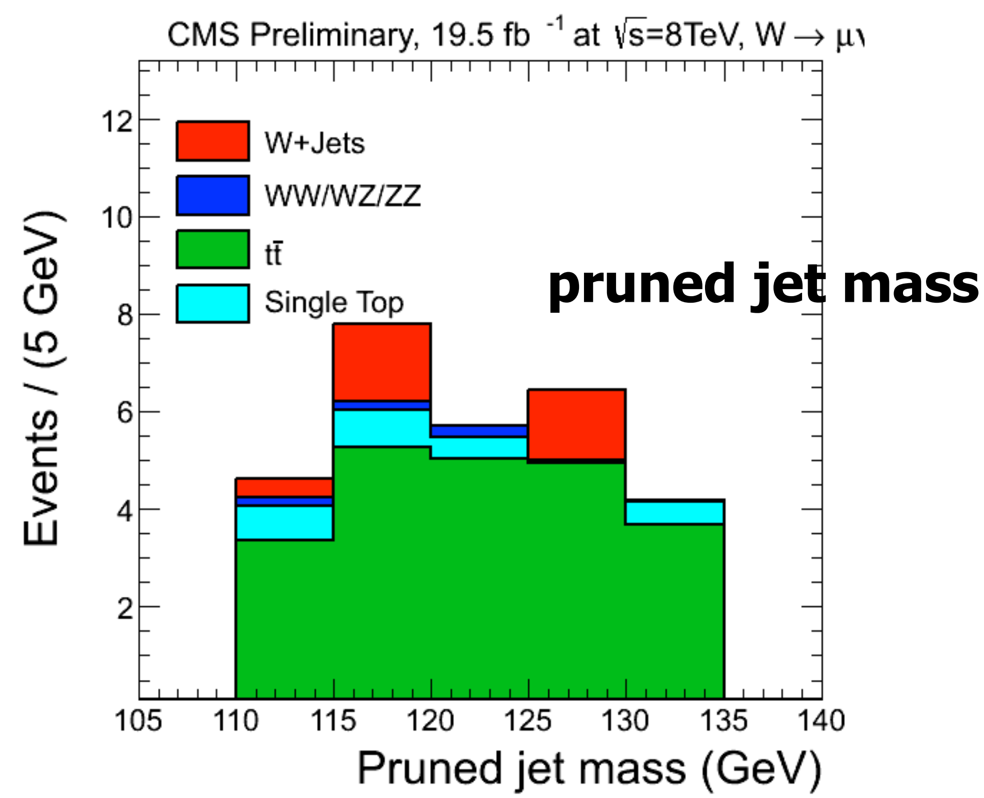
- the invariant mass of the **lepton+neutrino+Higgs-jet** system is computed

W' candidate mass

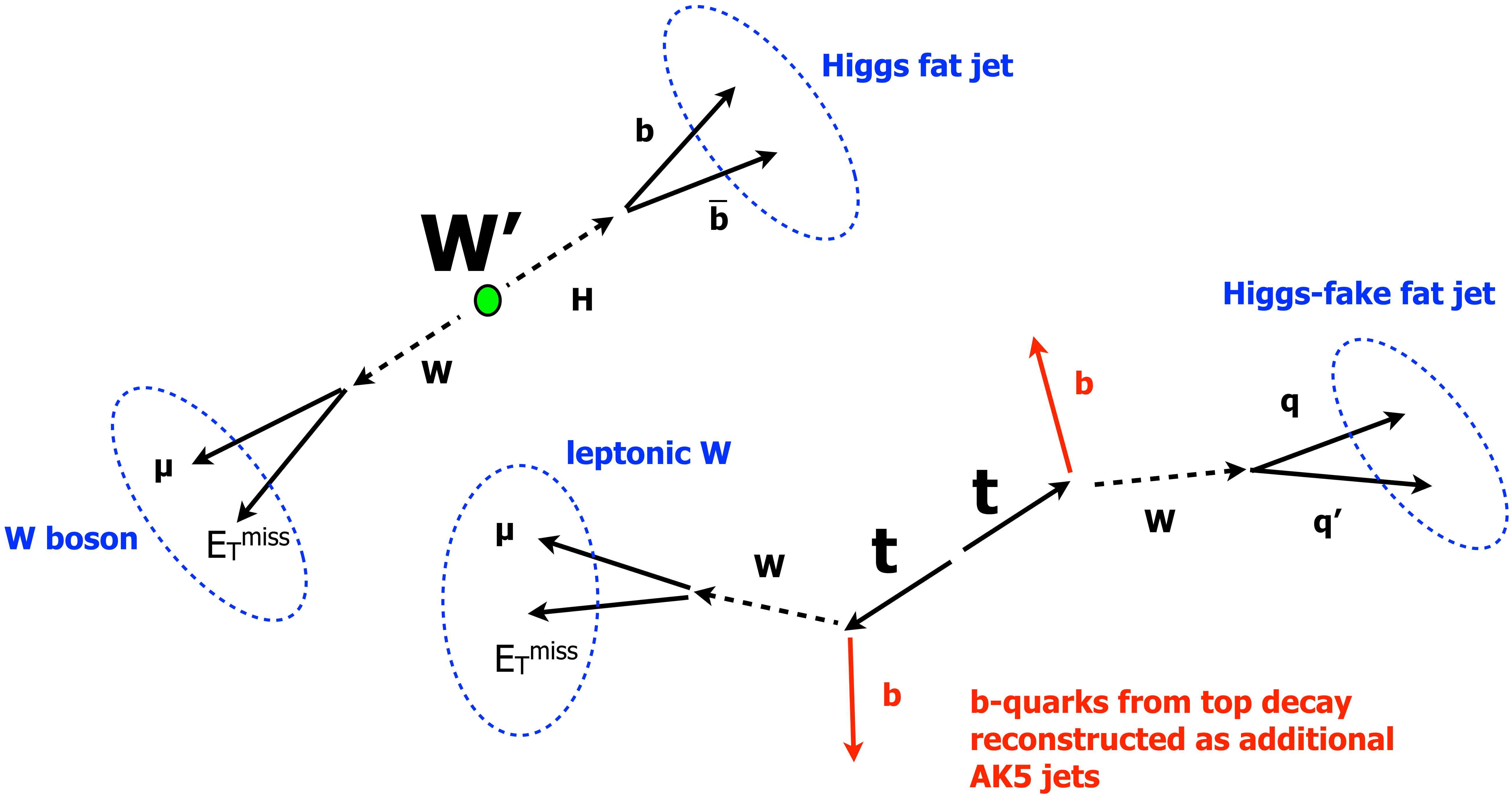


Largest background

- The ttbar process is the main source of background (~85%) in the pruned mass region containing the Higgs signal
- Currently focus on reducing this background:
  - understand the topology
  - estimate potential separation power
  - propose new selections

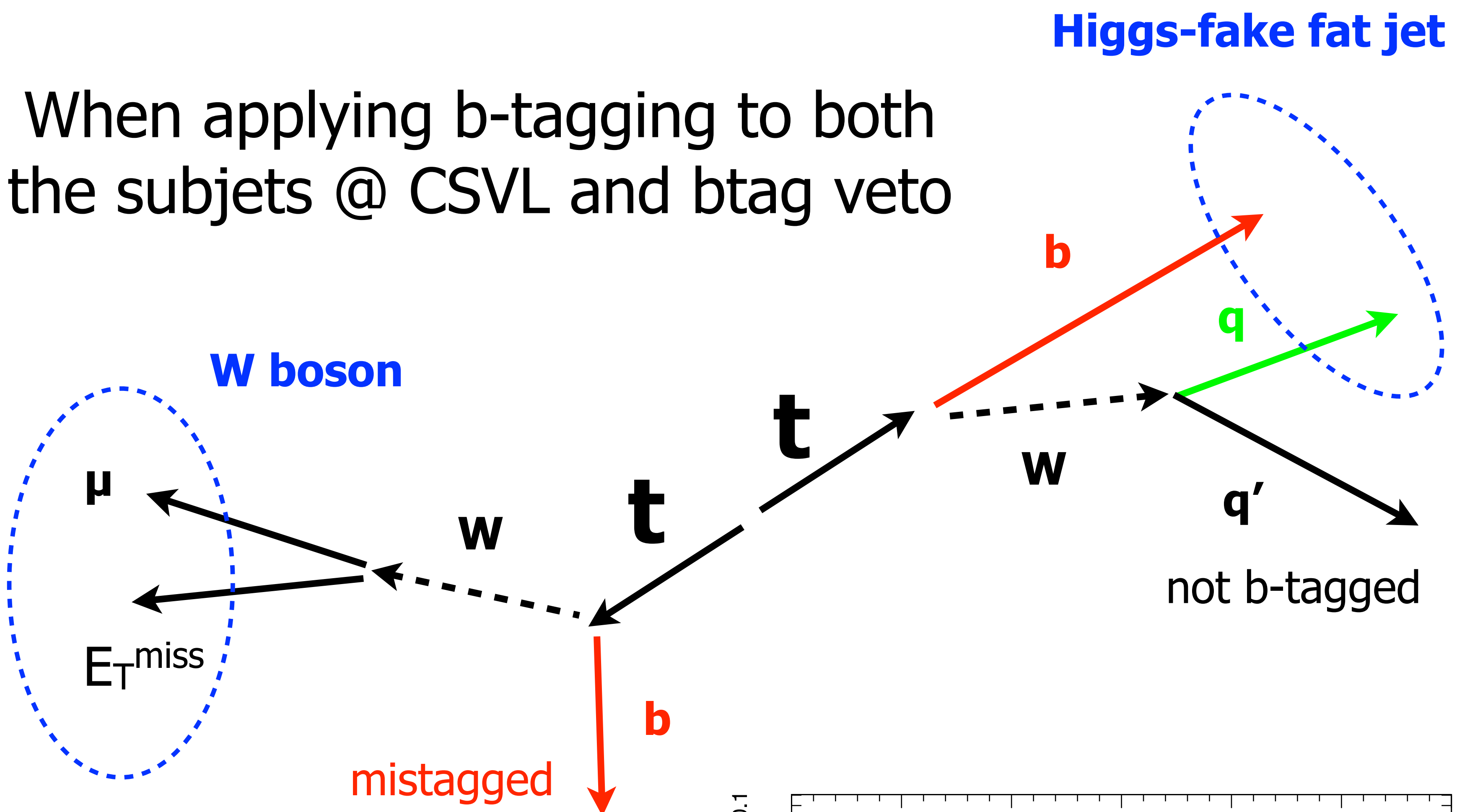


Comparing W' and ttbar

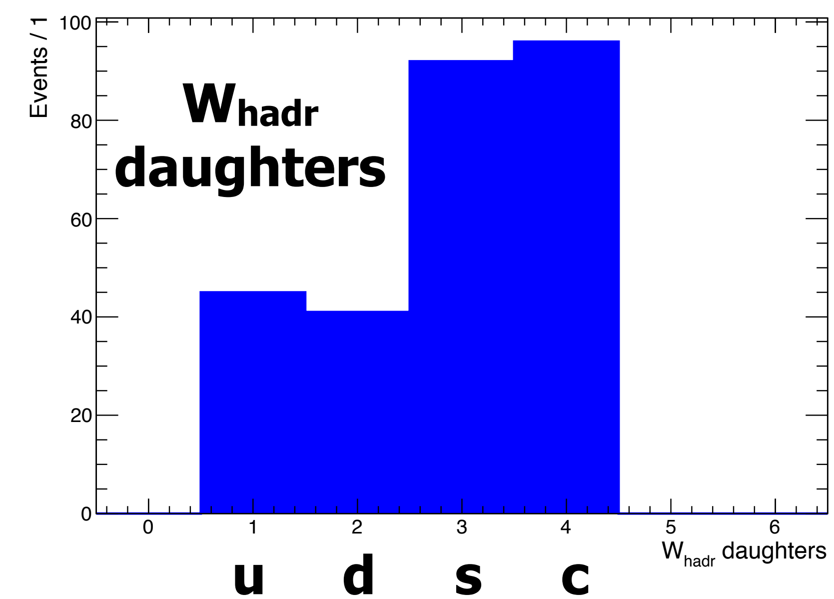


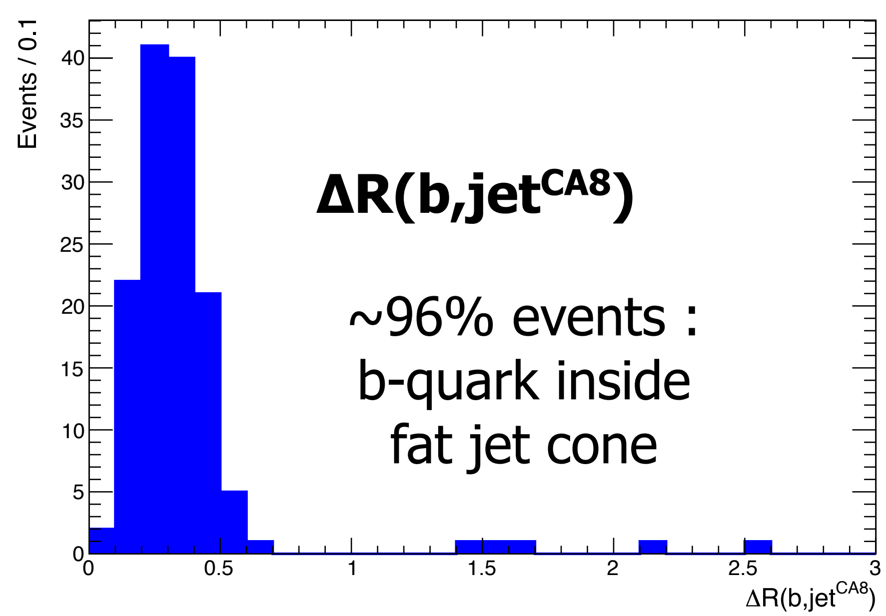
Comparing W' and ttbar

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



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

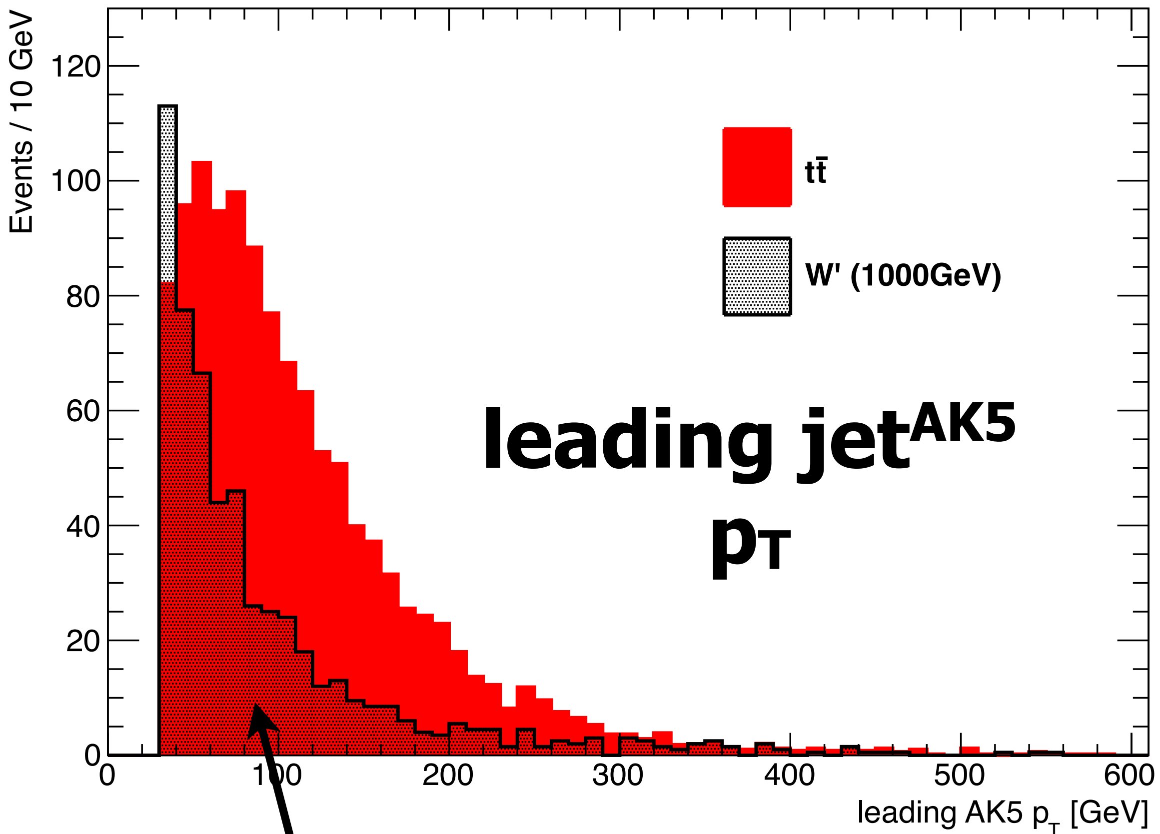




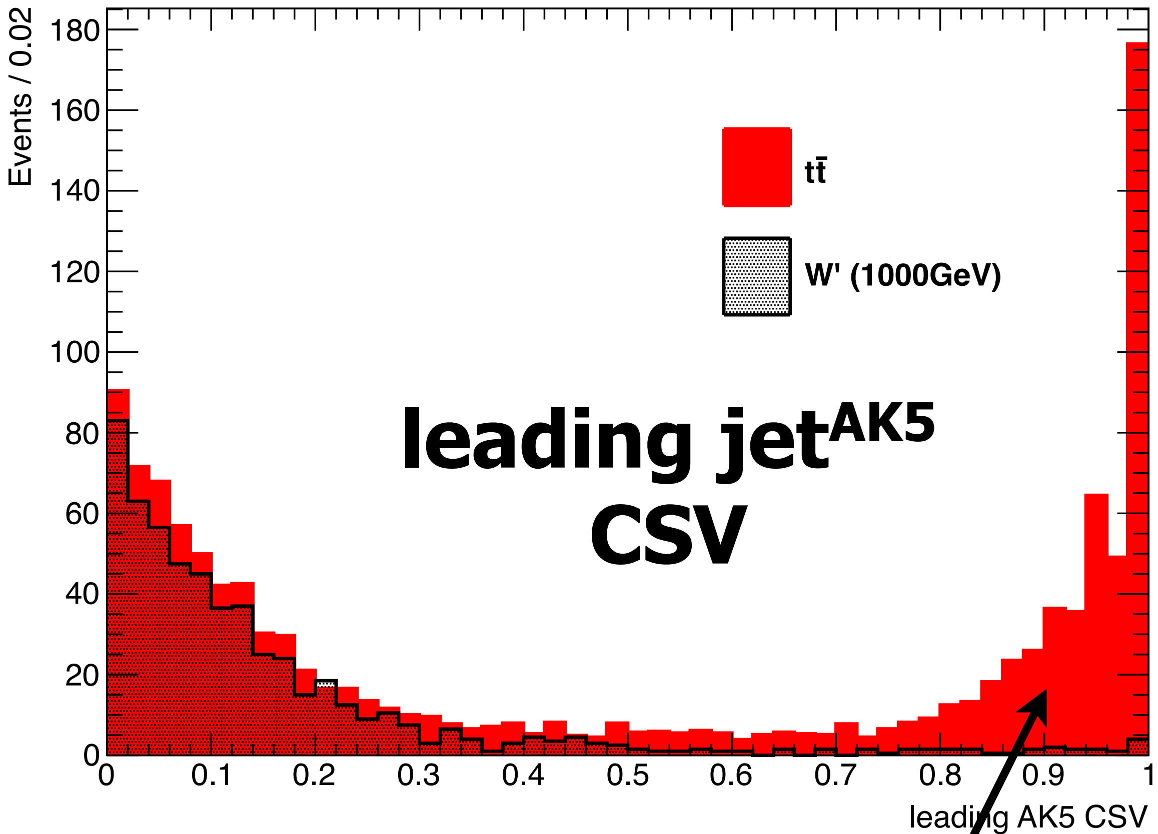
Strategy for ttbar rejection

- In order to take into account many variables and the correlations between them 100 **Boosted Decision Trees** are trained
- Boosting is one of the most popular learning technique used today and combines many weak learners to form a single strong one
- The training is done on both ttbar and W' events that pass all the selections excluding
  - b-tag veto
  - subjet b-tagging
- In order to gain more statistics a pruned jet mass region between **110-150 GeV** is considered where the ttbar background is larger compared to the W+jets
- Only **events with at least one additional AK5 jet** are used for the training

BDT input variables



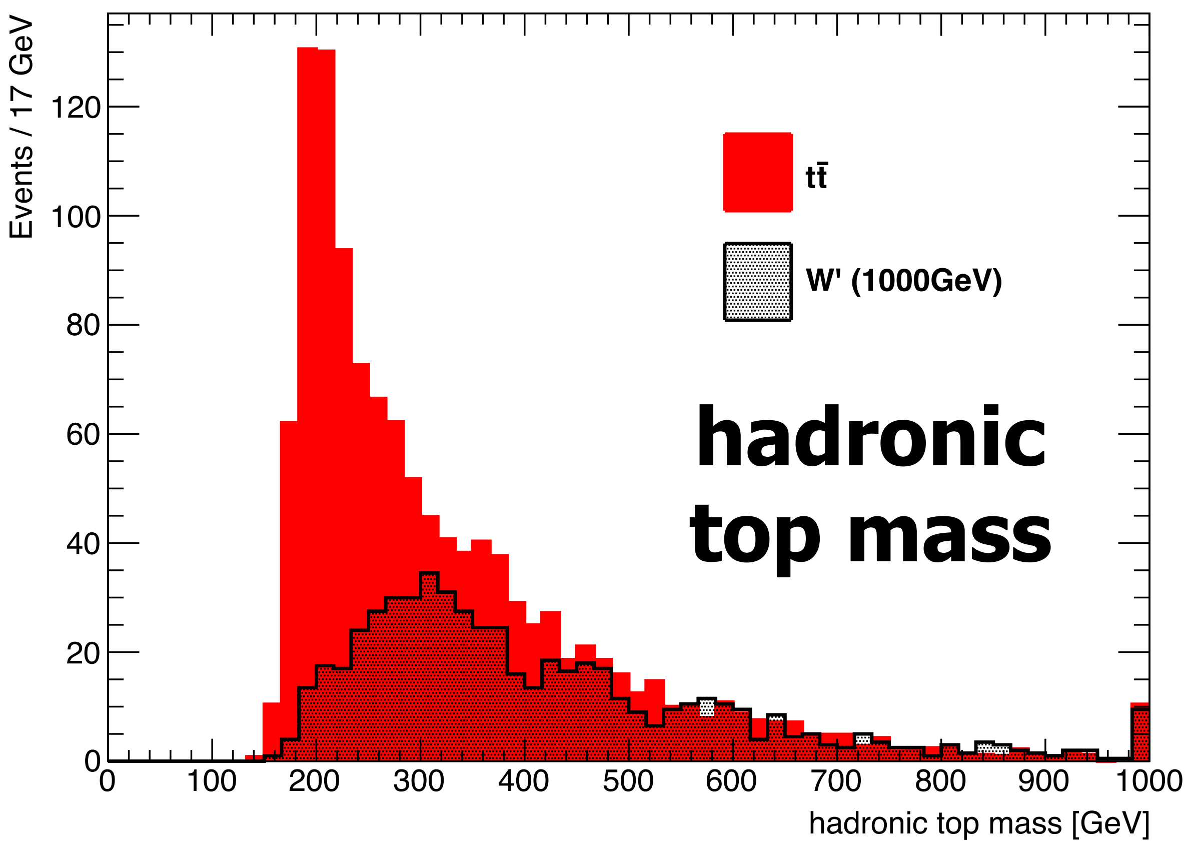
Signal: low p_T spectrum

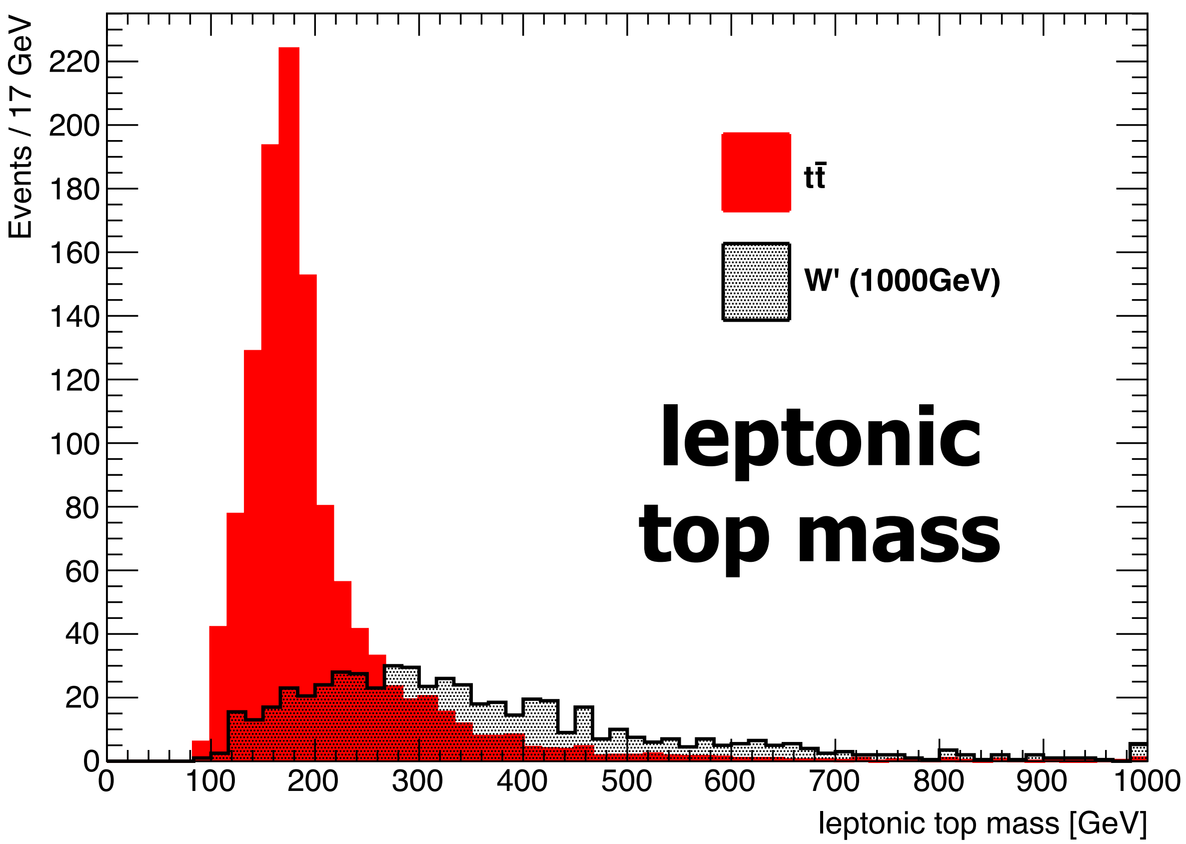


ttbar: b-tagged AK5 jets

BDT input variables

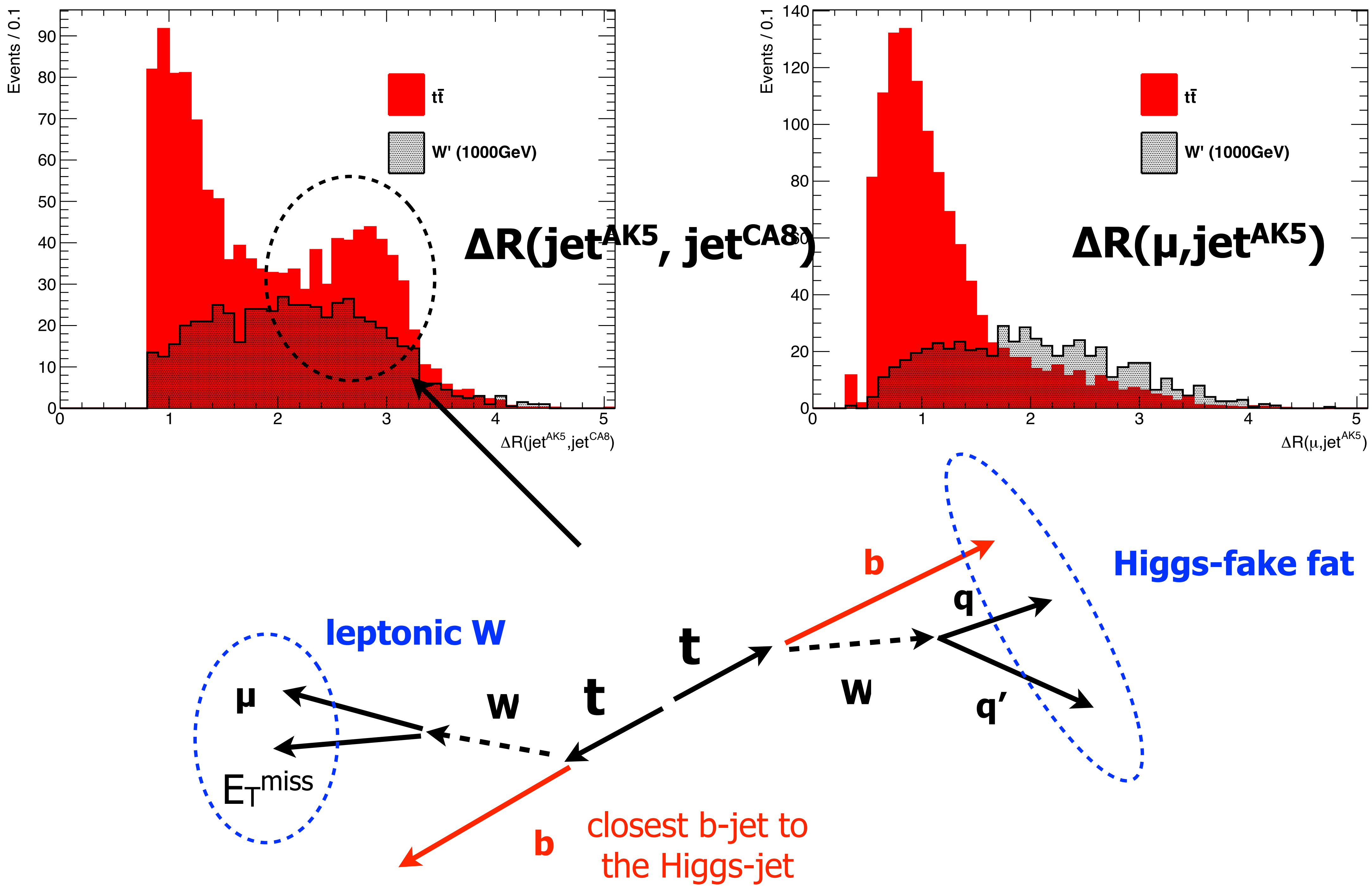
Found the best resolution on the top mass when computing it respect to the closest AK5 jet





BDT input variables

ΔR distributions of the closest AK5 jet to the lepton/CA8 Higgs-jet



Results on ttbar rejection

- After the training a BDT discriminant is computed for each event that passes the selections and a cut applied on it

veto	W' (1TeV)	TTbar	$\varepsilon_S/(1+\sqrt{B})$
btag veto	0.199 (896)	5.74e-5 (31.93)	0.0299
btag veto + (150 < leptonic top mass < 220 GeV || (150 < hadronic top mass < 300 GeV)	0.174 (781)	2.69e-5 (12.89)	0.0379
BDT < 0	0.183 (820)	1.91e-5 (10.64)	0.0429

- The BDT gives the best sensitivity in terms of signal efficiency and background rejection:
  - in addition to the simple b-tag veto, **cuts on the top masses** can improve the significance or xsec-limit of **~26%**
  - in addition to the simple b-tag veto, **cut on BDT** can improve the significance or xsec-limit of **~43%**

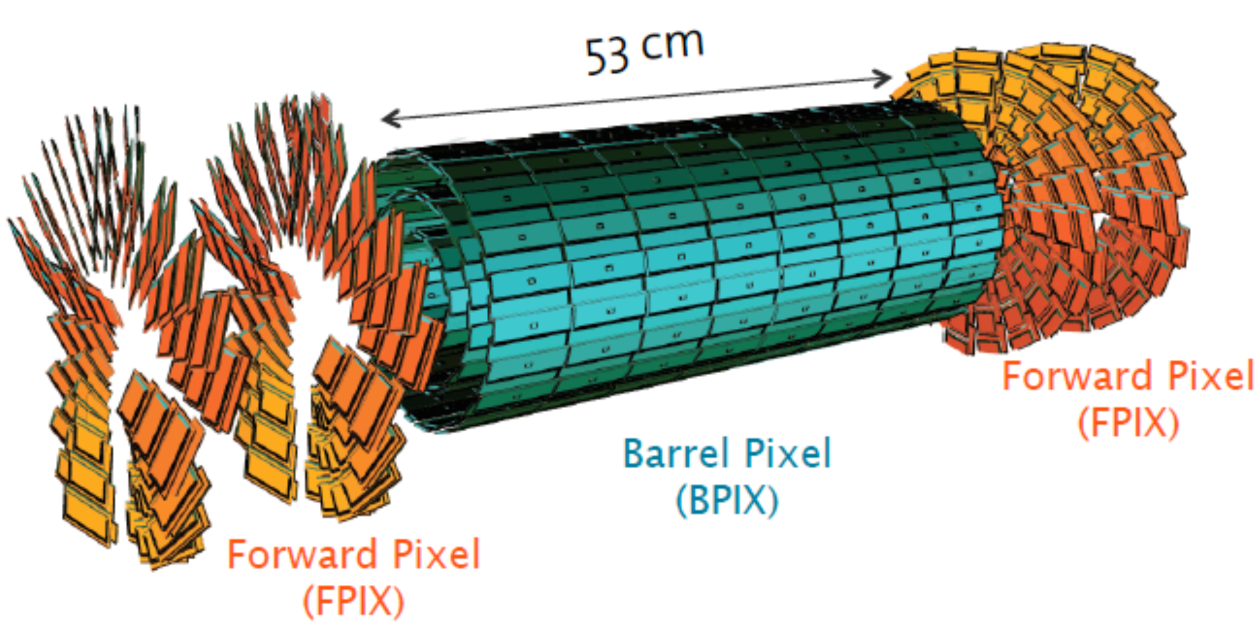
Conclusions about the analysis

- The W'→WH analysis is one of the first analyses attempting to look for exotic final state with a Higgs boson
- The procedures are presently being developed with the 8 TeV data in 2012
  - gain enough experience to repeat the study with the 13 TeV in 2015 when techniques for resolving boosted objects become even more important and when higher luminosities and beam energies will extend the mass reach
- The analysis strategy has been fully understood and all the required tools are now implemented in the analysis framework which I contribute to develop
- In particular, the new selections that I proposed for ttbar rejection have already been presented to the group and been accepted as a part of the analysis
  - the effect on the cross section limits are now under test
- The internal CMS analysis note has just been opened and will go soon for the approval!

Hardware project

The CMS Pixel Detector

- High precision tracking close to the interaction point to allow for reconstruction of primary vertex and secondary vertices of long lived particles
  - special role in the identification of b-quark jets which are in the W' physics analysis final state
- Pixel hits used for track seeding in track reconstruction
- This requires detectors with high spatial resolution, high granularity and minimum material



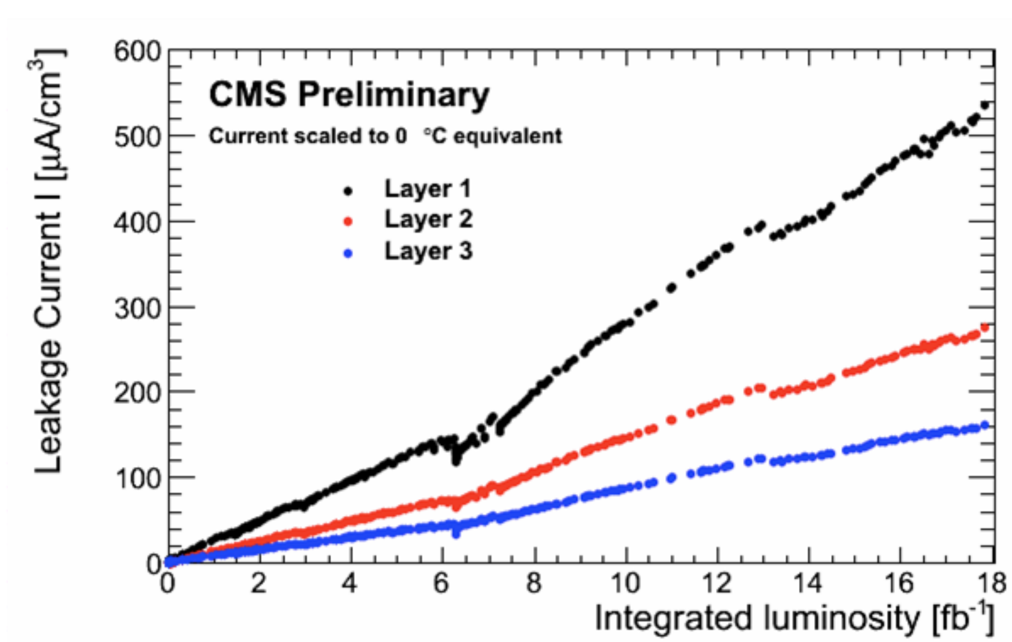
Barrel Pixel design:

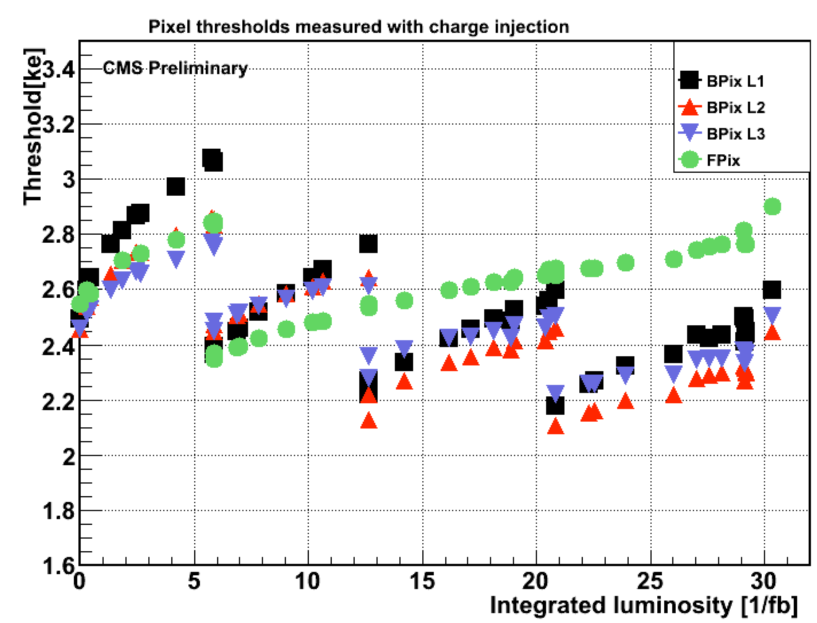
- 3 layers at 4,7 and 10 cm
- 768 modules
- 48M pixels of 100x150x285μm^3 size
- Analog charge measurement for each pixel
- $\sigma(r\Phi) \sim 13\mu m$
- $\sigma(z) \sim 28\mu m$

BPix maintenance

- The Pixel Detector was installed in 2008 and showed excellent performance during the LHC run

- subject to sever radiation damage
  - increase of the leakage current and of the bias voltage
  - charge trapping and signal degradation
  - changes in the pixel thresholds
- Several corrections are needed to guarantee correct operation:
  - currently contributing for calibrations aimed at finding optimal settings for the irradiated detector temporarily installed in the clean room of LHC-P5 (Cessy, France)

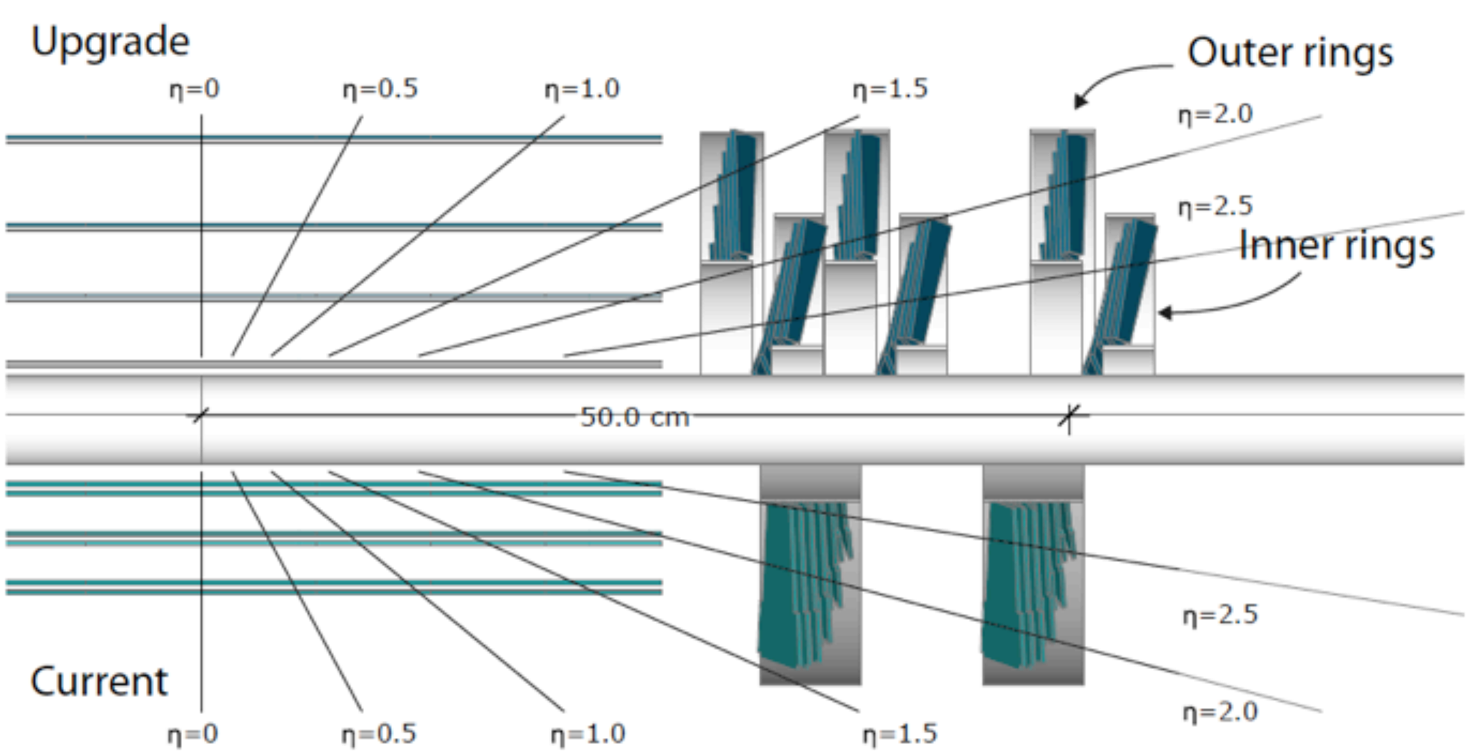


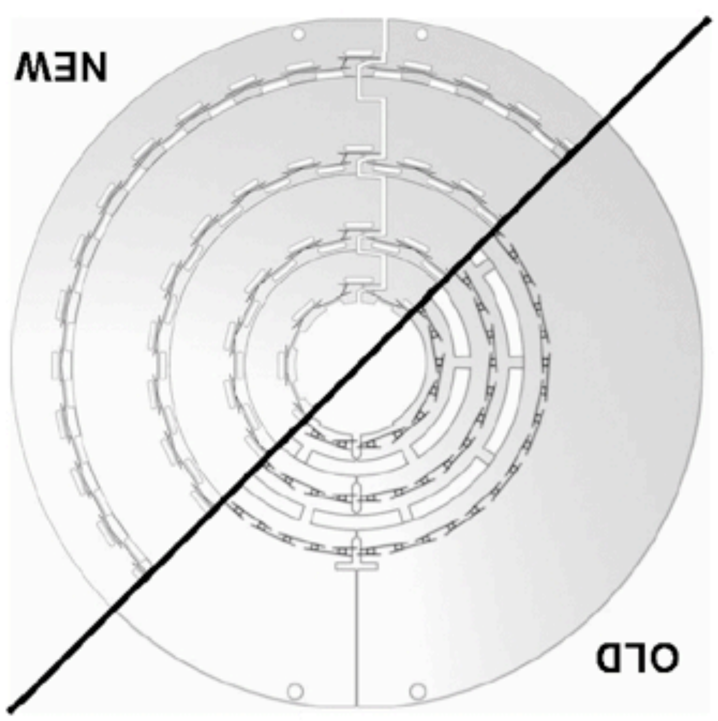


Phase I Pixel Detector Upgrade

- The current Pixel Detector is not designed for the expected LHC Run-II conditions of 2 x $10^{34}cm^{-2}s^{-1}$
- Need replacement to maintain and improve tracking performance
- Planned improvements:
  - Additional pixel layer
  - Innermost layer closer to the interaction point
  - Significantly less material
  - Faster front-end electronics to reduce dead-time

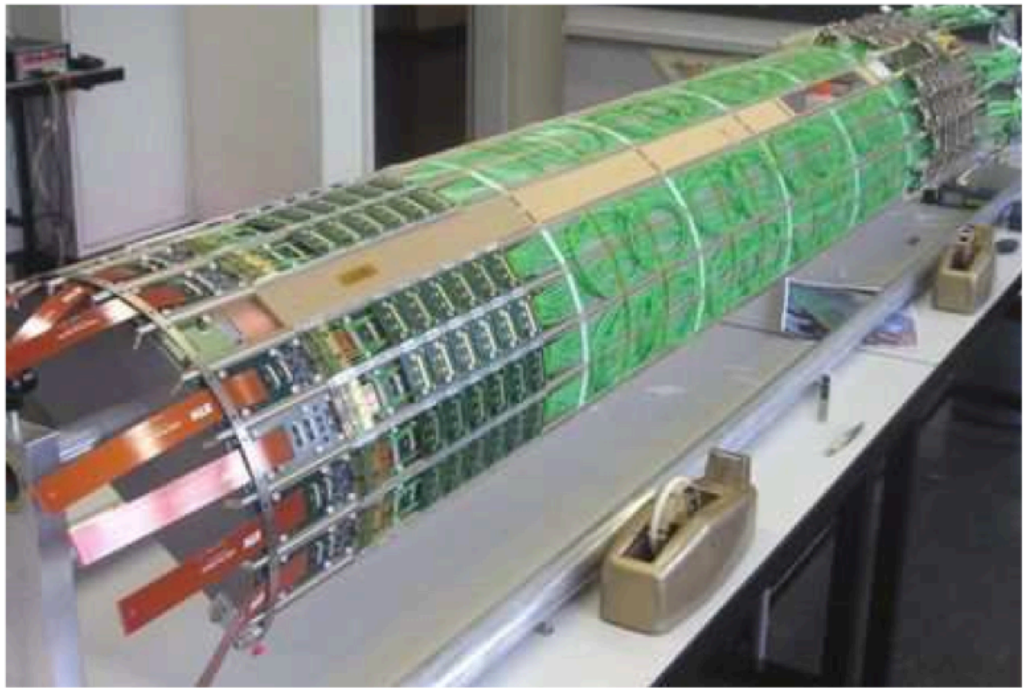
To be installed in winter shutdown 2016/2017

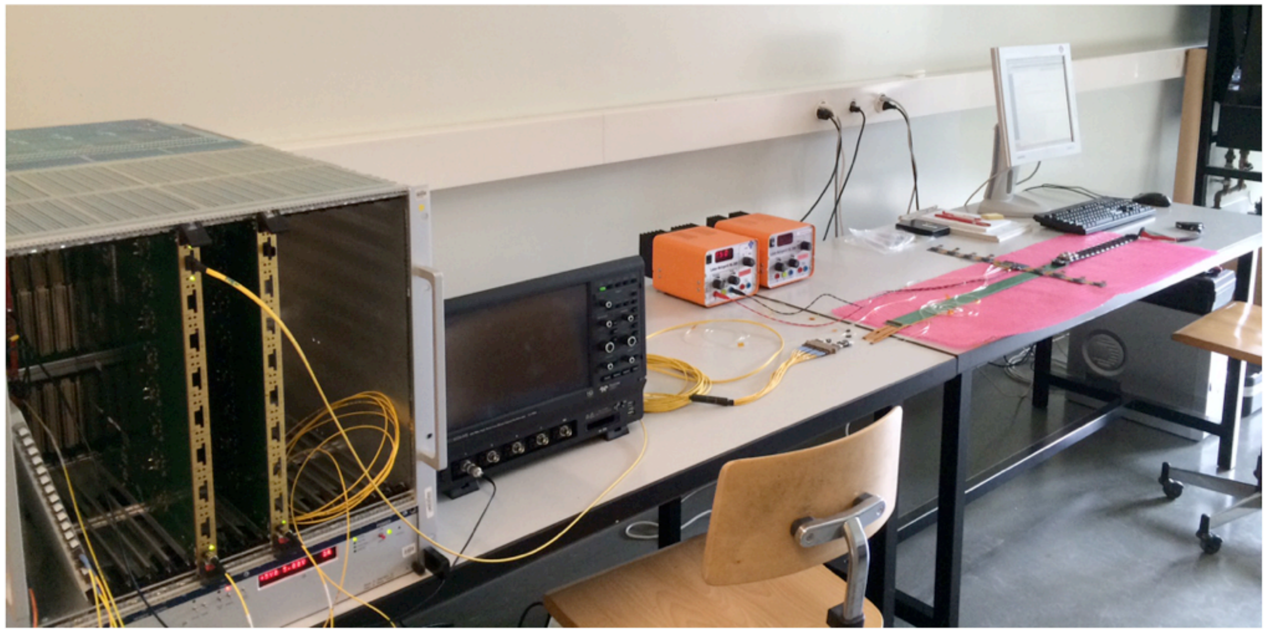




System test setup at UZH

- The current BPix consists of three 57 cm long layers of silicon pixel modules serviced by 2.2 m of **supply tubes** which transport cooling tubes, electrical power, and optical signals
- The University of Zurich designed and constructed the mechanical support structure, and designed, built, and tested the supply tubes





- We are now in charge of the phase I upgrade supply tubes and I am currently contributing in building the system test setup