

---

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects  
28<sup>th</sup> April - 2<sup>nd</sup> May 2014, Warsaw, Poland



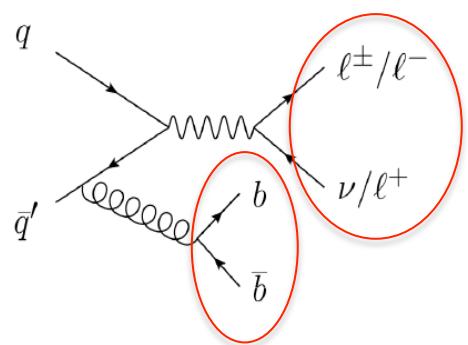
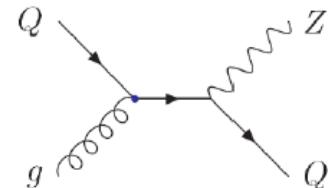
Associated production of heavy flavour final state and vector  
boson V and search for V+H(bb) at CMS

Roberto Castello (UC Louvain CP3, FNRS)  
on behalf of CMS collaboration

---

# Why associated production with heavy flavour?

$V+jets$  ( $V=W,Z$ ) topology provides excellent testing ground for perturbative QCD prediction and MC technique

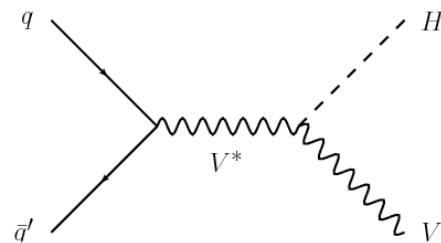


Experimentally focusing on  $V$  leptonic decays (clean signature in the detector) and jets from heavy quarks or hadrons (secondary vertex ‘footprint’)

- ❖ **W+c**: probing strange quark content of proton
- ❖ **W+bb**: agreement w/ theory in  $bb$  phase space
- ❖ **Z+b's**: kinematics and x-section comparison w/ theory

And also... a key background for searches of “new” physics:

- ❖ SM scalar boson searches:  $VH(bb)$
- ❖ BSM physics processes, e.g.  $H \rightarrow Z(l\bar{l})A(bb)$

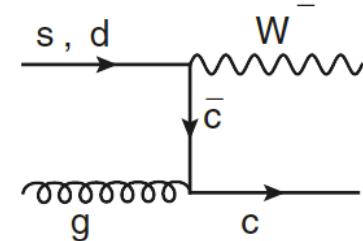


---

$$pp \rightarrow W + c + X$$

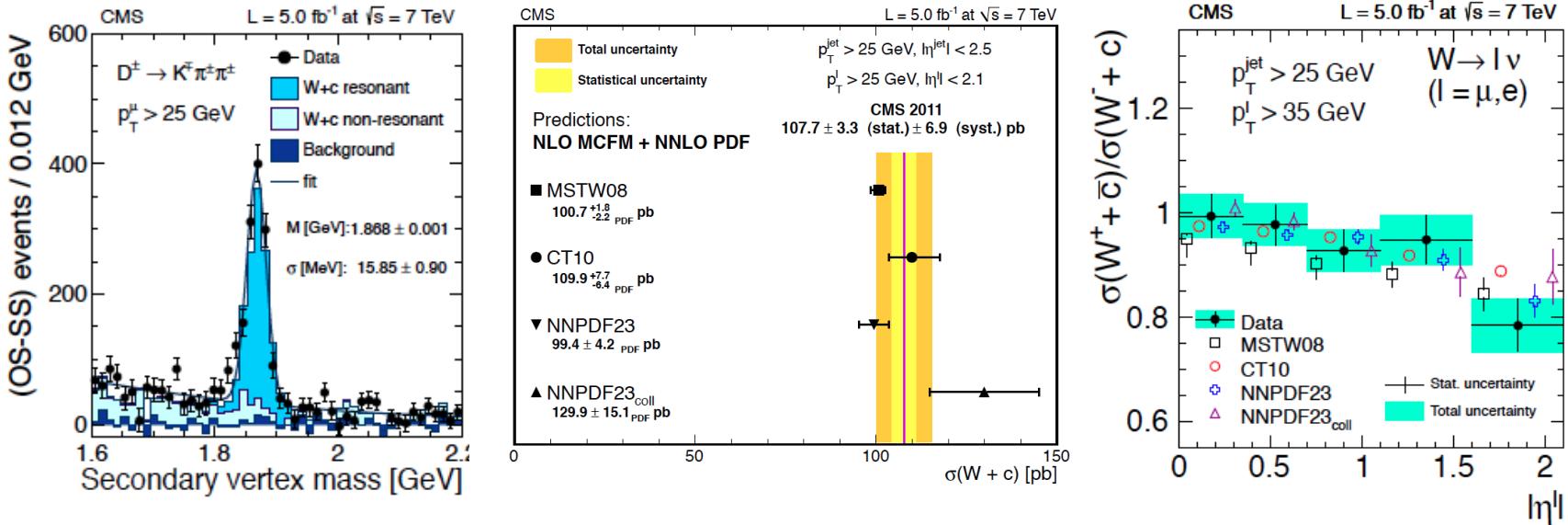
Process sensitive to the proton strange content

Production at LHC dominated by  $sg \rightarrow W+c$  ( $dg$  are Cabibbo-disfavored)



[JHEP 02 (2014) 013]

- ◆ Key property: opposite sign (OS) nature of  $W^+ + \bar{c}$  production (SS subtracted)
- ◆  $c$ -quark tagging through  $D^+$ ,  $D^*(\rightarrow D^0\pi^\pm)$  and leptonic decay (well-identified muon)
- ◆ Signal: fitting resonant component of the SV mass
- ◆ Cross section ratio as a function of lepton  $\eta$ : asymmetry + probing a wide range of  $x$



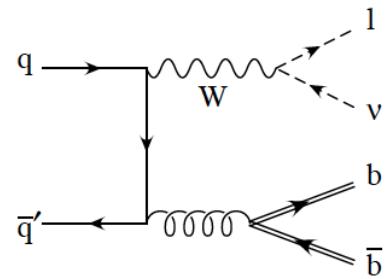
Good agreement with theoretical predictions at NNLO

$$R_c^\pm = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = \frac{(N_{OS}^+ - N_{SS}^+)}{(N_{OS}^- - N_{SS}^-)}$$

---

$$pp \rightarrow W + bb$$

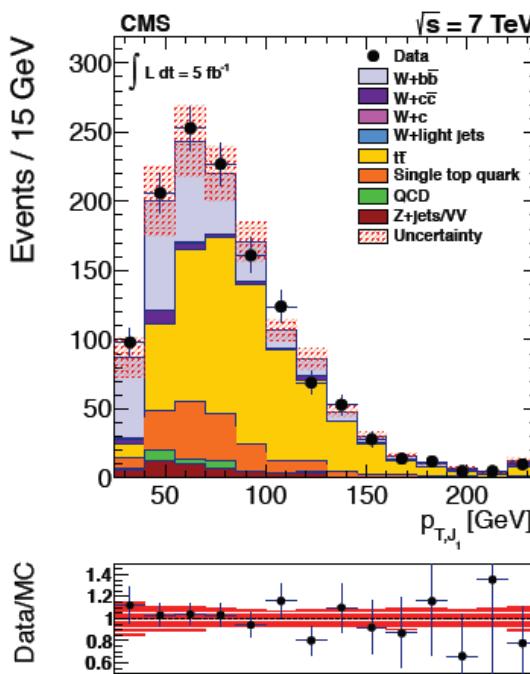
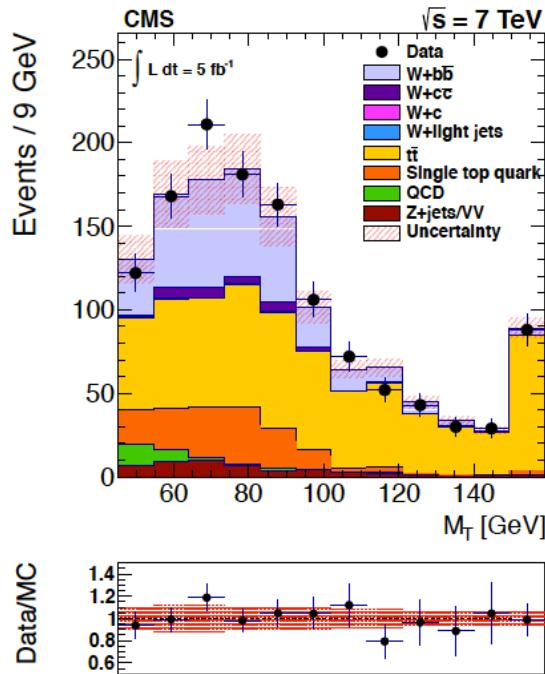
Production of  $W$  together with central  $b$ -jets  
Historical disagreement between data and experiment ( $W+b+X$ )



[CMS-SMP-12-026, submitted to PLB]

## Selection and signal extraction

- ◆ First measurement in exclusive  $b\bar{b}$  phase space:
  - ❖ two well separated  $b$ -jets (+ veto on extra-jets), one isolated lepton,  $MT > 45$  GeV
- ◆ Dominant background from  **$t\bar{t}$  pairs** and **single top** quarks production



- ◆ Yields from simultaneous ML fit
  - ❖ leading jet  $p_T$  in signal region (two  $b$ -tagged jets)
  - ❖  $M_{jj}$  in control region (4 jets / 2  $b$ -tagged, for  $t\bar{t}$  bkg)



## Experimental

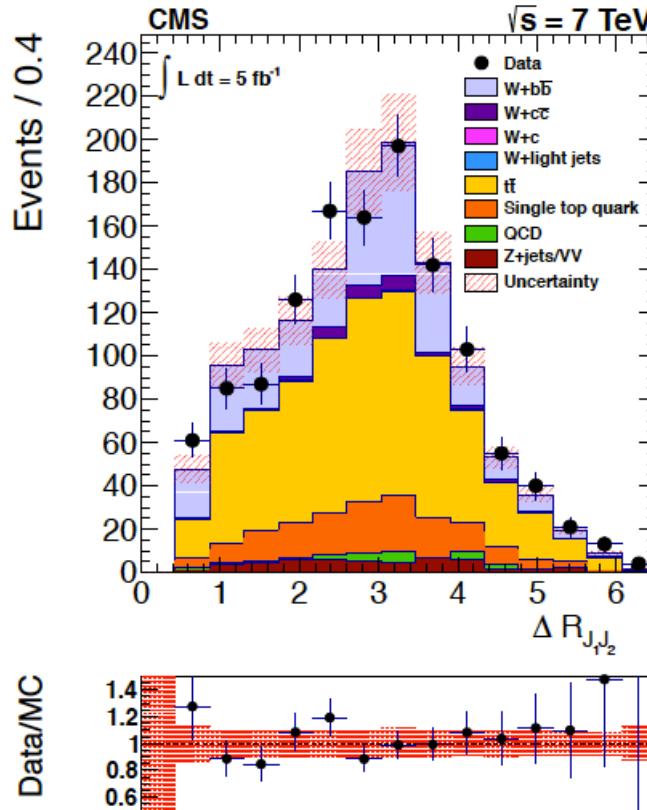
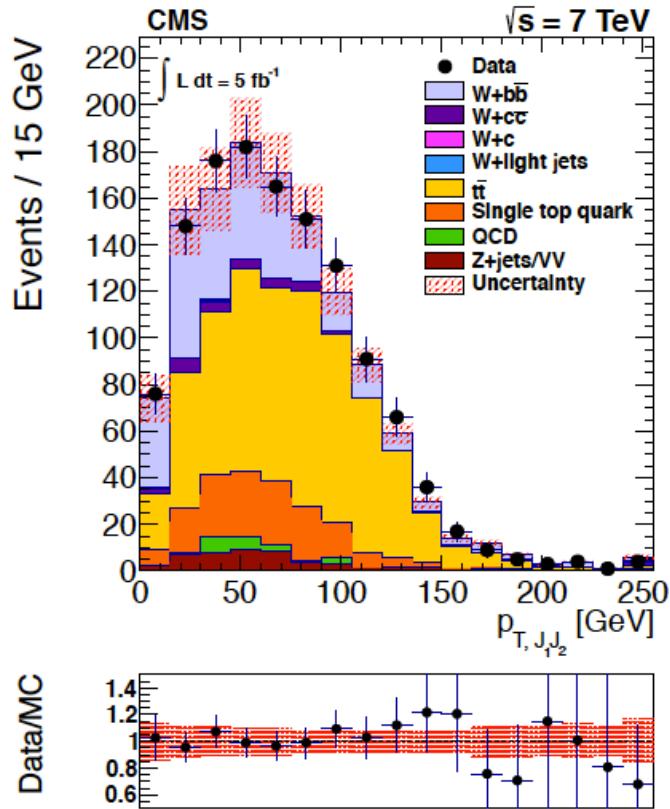
$\sigma(W(\mu\nu)+bb) = 0.53 \pm 0.05 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.06 \text{ (theo.)} \pm 0.01 \text{ (lum.) pb}$   
acceptance:  $pT(\mu) > 25 \text{ GeV}$ ,  $|\eta(\mu)| < 2.1$ ,  $MT(\mu\nu) > 45 \text{ GeV}$ ,  $pT(b) > 25 \text{ GeV}$ ,  $|\eta(b)| < 2.4$

- ◆ Experimental syst. uncertainties: b-tagging (~6% per jet) and jet-energy (1-3%)

## Theoretical

- ◆ MCFM(NLO) at parton-jet level predicts  $\sigma(W(\mu\nu)+bb) = 0.52 \pm 0.03 \text{ pb}$ 
  - ❖ Hadronization correction factor:  $C_{b \rightarrow B} = 0.92 \pm 0.01$
  - ❖ DPS contribution ~15% :  $(\sigma_W \times \sigma_{bb}) / \sigma_{\text{eff}} = 0.08 \pm 0.05$  ( $\sigma_{\text{eff}}$  from arXiv:1301.6872 )
- ◆ Final MCFM:  $\sigma(W(\mu\nu)+bb) = 0.55 \pm 0.03 \text{ (MCFM)} \pm 0.01 \text{ (hadr.)} \pm 0.05 \text{ (DPS) pb}$

Measured agrees within  $1\sigma$  with MCFM predictions



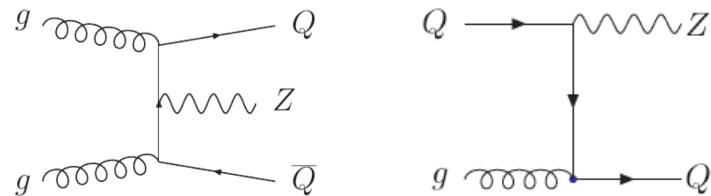
Remarkable agreement with MadGraph 5F (not observed in  $W+>=1b$ )

---

$$pp \rightarrow Z + (b)b + X$$

Comparing different schemes and calculations describing this SM process

Kinematics: Z boson transverse momentum, bb angular correlations



4-flavor: hep-ph/1106.6019

5-flavor: hep-ph/0312024

[CMS-SMP-13-004, submitted to JHEP]  
[JHEP, 12 (2013) 039]

# Selection and background evaluations

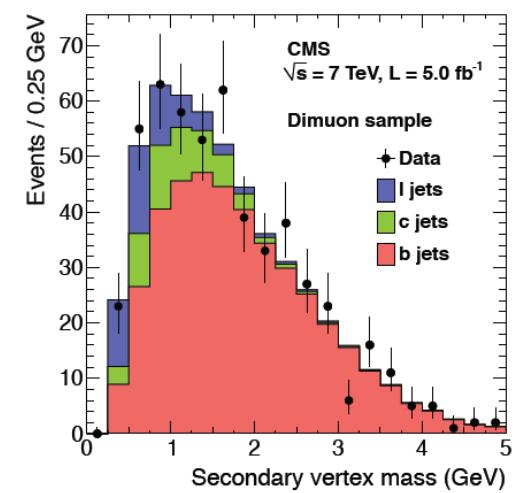
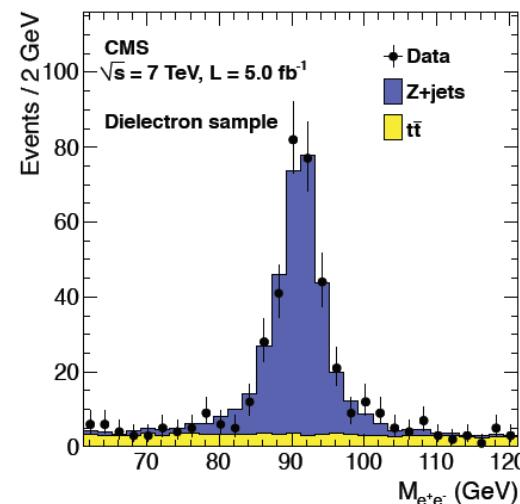
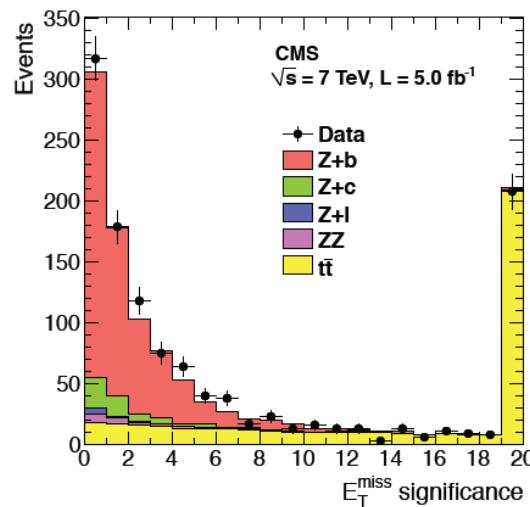
## Top production:

- Reduced via  $ME_T / \sigma(ME_T) < 10$  and  $76 < M(l\bar{l}) < 106$  GeV
- Measured via fit to  $M(l\bar{l})$

## Z + light/charm jets:

- Reduced by flight distance significance
- Data driven estimate with two 1D template fits to SV mass distributions

**Diboson (ZZ):** from MC, normalized to data using CMS cross section ZZ measurement



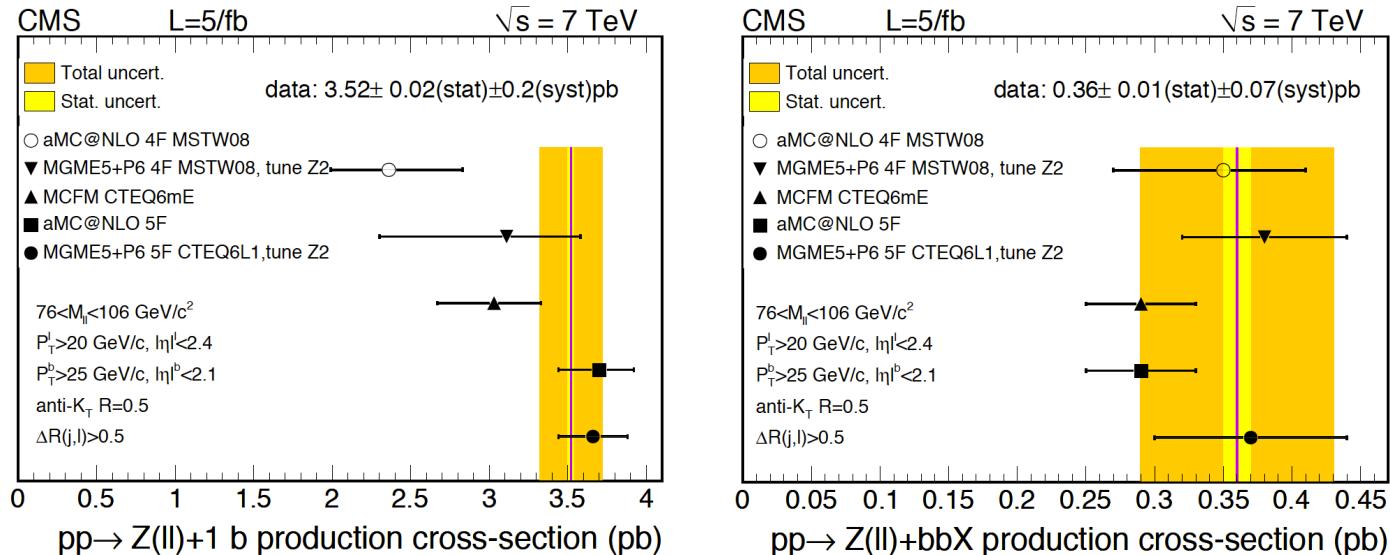
Selection	$P_b^{Z+1b}$	$f_{t\bar{t}}^{Z+1b}$	$N_{ZZ}^{Z+1b}$
$Z(\mu\mu)+1b\text{-jet}$	$(53.7 \pm 1.1)\%$	$(5.2 \pm 0.7)\%$	$73 \pm 24$
$Z(ee)+1b\text{-jet}$	$(55.0 \pm 1.3)\%$	$(5.0 \pm 0.7)\%$	$56 \pm 19$

	$P_b^{Z+2b}$	$f_{t\bar{t}}^{Z+2b}$	$N_{ZZ}^{Z+2b}$
$Z(\mu\mu)+2b\text{-jets}$	$(75.1 \pm 6.4)\%$	$(13.0 \pm 1.9)\%$	$12 \pm 4$
$Z(ee)+2b\text{-jets}$	$(74.1 \pm 7.3)\%$	$(14.0 \pm 2.3)\%$	$8 \pm 3$

- Unfolding of the b-jet multiplicity from reconstructed to hadron level
- Background subtraction and efficiency correction in different bins

$$\begin{pmatrix} \sigma(Z + 1b) \\ \sigma(Z + 2b) \end{pmatrix} = \frac{1}{\mathcal{L}} \times E_r^{-1} \times E_l^{-1} \times E_b^{-1} \times E_m^{-1} \times \begin{pmatrix} N_{sig}^{Z+1b} \\ N_{sig}^{Z+2b} \end{pmatrix}$$

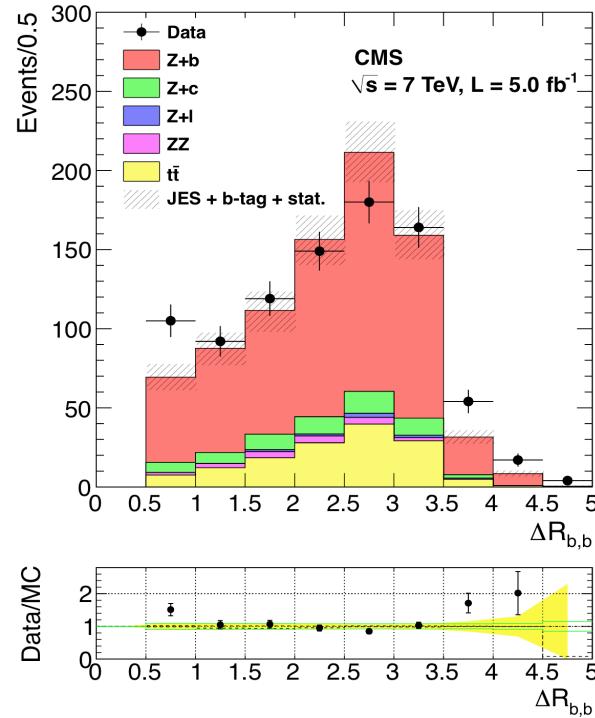
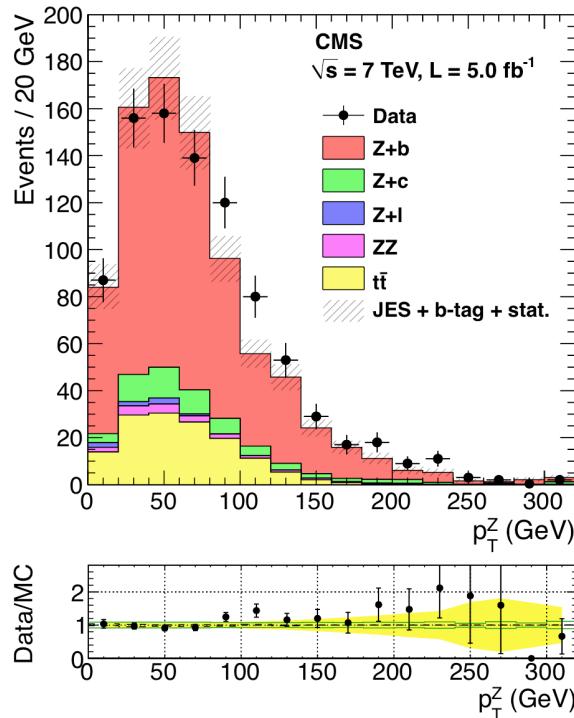
- Measured values dominated by systematics (b-purity  $\sim 3\text{-}15\%$  and b-tagging  $\sim 3\text{-}9\%$ )



Agreement with 5F and up to  $2\sigma$ -discrepancy with 4F and MCFM predictions

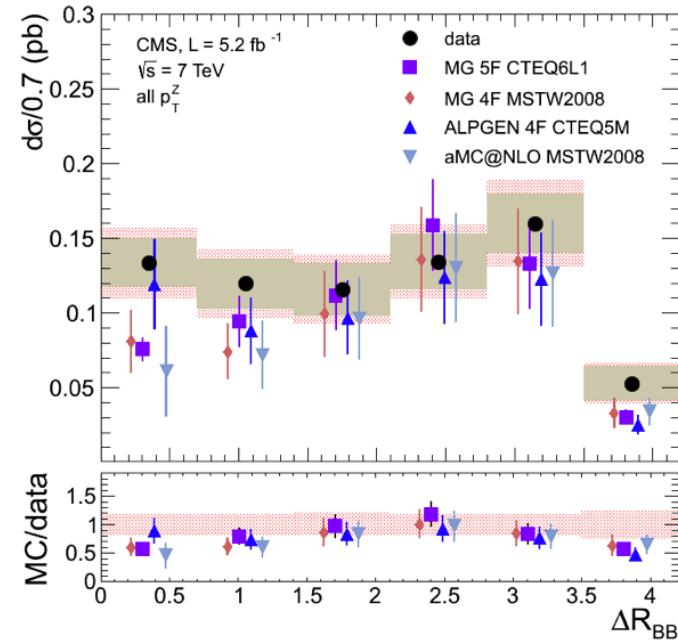
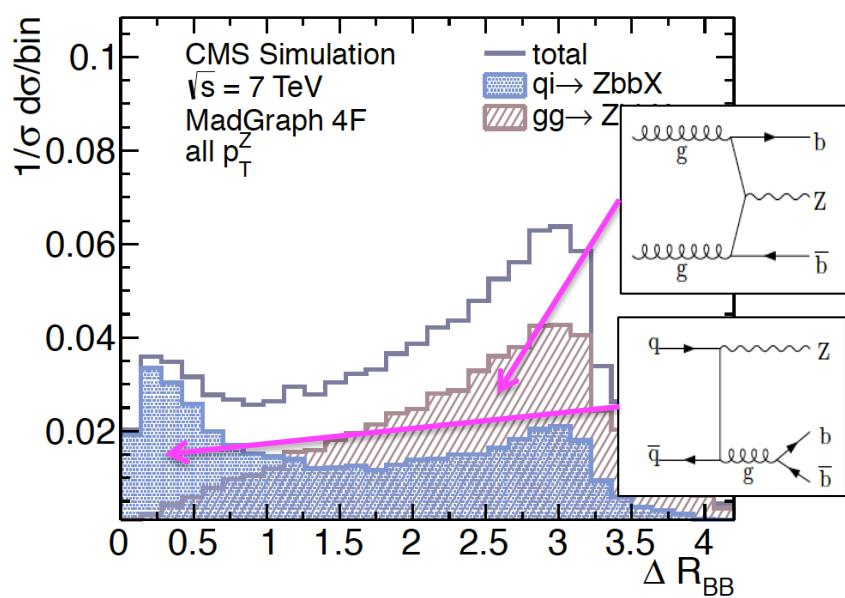
## Observables of interest for searches:

- ❖  $M(bb)$ ,  $\Delta\Phi(Z,bb)$ : well agreement with simulation
- ❖  $pT(Z)$ : tension when compared to MadGraph 5F predictions (also observed in  $Z+b$ )
- ❖  $\Delta R(bb)$ : tensions in the collinear regime, also confirmed by  $Z+B$ -hadrons measurement



Tension observed in  $pT$  and angular separation of the jets

- ◆ Low  $\Delta R(bb)$  regime:
  - ❖ interesting for searches ( $pp \rightarrow \phi_1 \rightarrow Z\phi_2$ ,  $M\phi_1 \gg M\phi_2$ ) and strong lever for QCD testing
- ◆ A different technique is applied:
  - ❖ no usage of jet cone definition, no angular limitation  $\rightarrow \Delta R < 0.5$
  - ❖ Inclusive Vertex Finder, exploiting tracking on displaced decay vertices of B hadrons

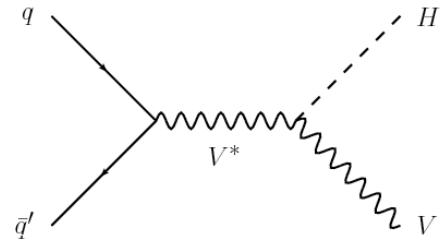


Tension at  $\Delta R \rightarrow 0$ , best agreement with AlpGen

---

$$pp \rightarrow V + H(bb)$$

Boosted kinematics regime: pT and angular resolution  
Irreducible background from SM processes involving  $V+HF$  final state

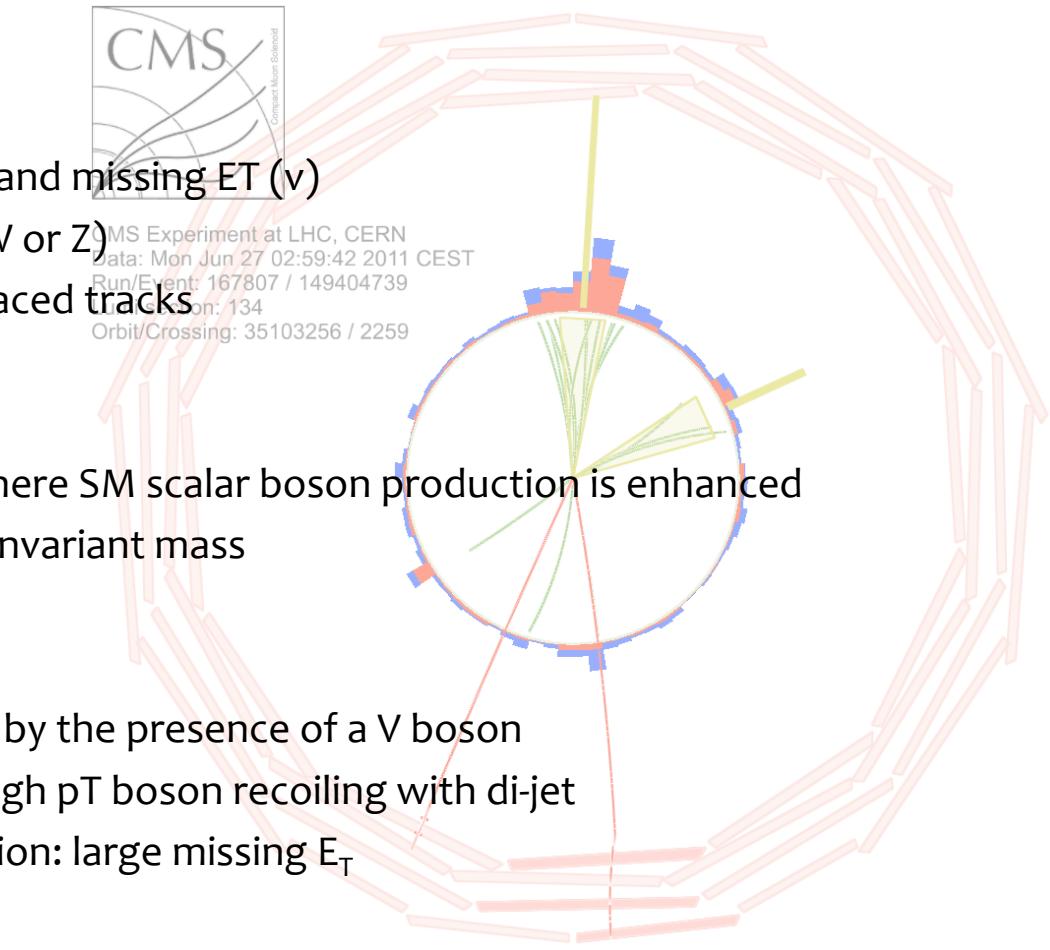


[Phys.Rev. D 89, 012003 (2014)]

## The VH(bb) topology: signal and backgrounds

Characterizing the event:

- ◆ trigger based on (di-) leptons and missing ET ( $\nu$ )
- ◆ Presence of a vector boson (W or Z)
- ◆ b-jets identified through displaced tracks



Signal handles:

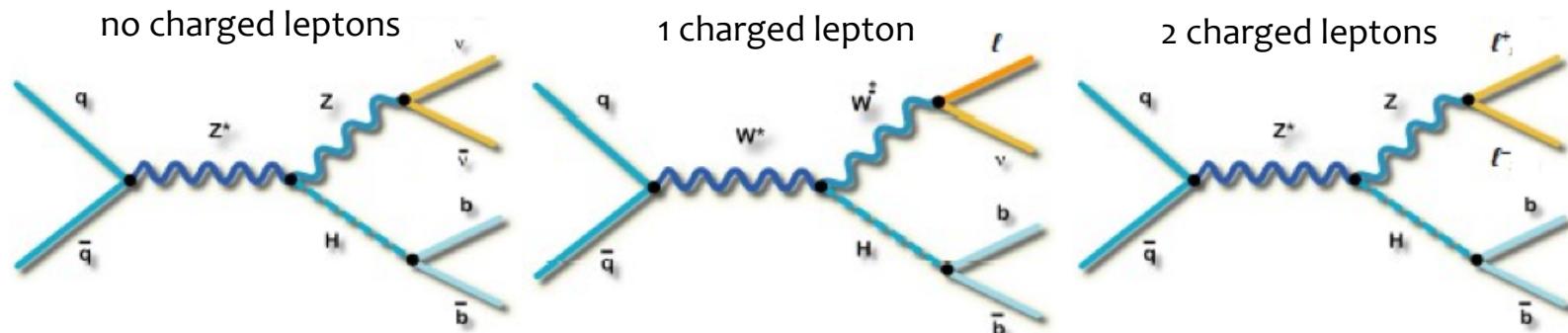
- ◆ Exploit the high pT regime, where SM scalar boson production is enhanced
- ◆ Look for excess in bb system invariant mass

Background handles:

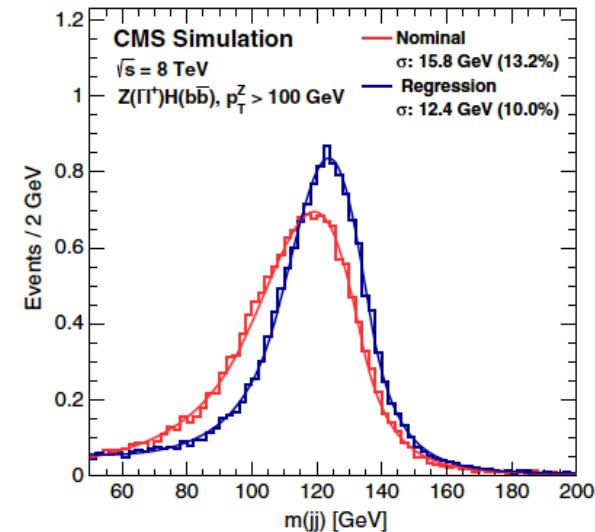
- ◆ QCD background: suppressed by the presence of a V boson
- ◆ W/Z+jets: reduced requiring high pT boson recoiling with di-jet
- ◆ Single and paired top production: large missing  $E_T$

*more details on CMS Higgs fermionic decay in J.Vizan talk tomorrow*

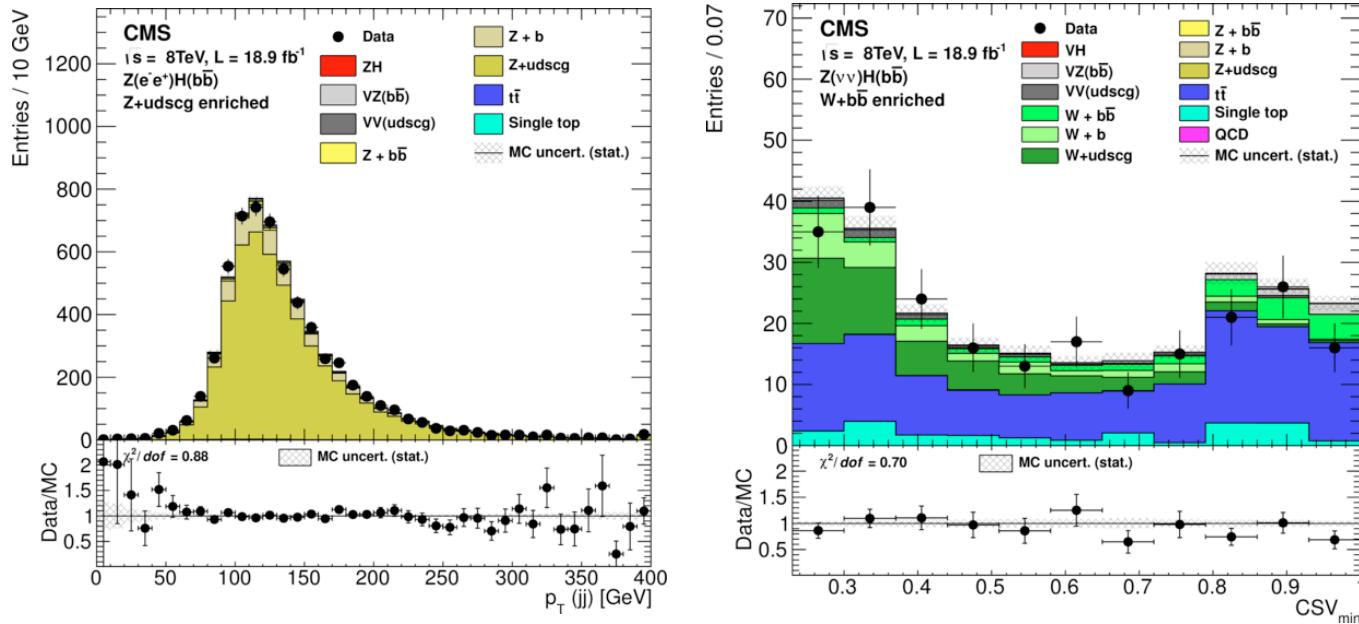
# The VH(bb) analysis strategy in a nutshell



- ◆ Decay modes:  $W(e\nu/\mu\nu/\tau\nu)H(bb)$  and  $Z(ee/\mu\mu/\nu\nu)H(bb)$
- ◆ Large  $V$  boost required to reduce SM backgrounds:
  - ❖ Up to 3 categories per channel based on  $pT(V)$
- ◆ Energy regression per-b-jet improves  $M_{bb}$  resolution (15%)
- ◆ Backgrounds:
  - ❖  $V+jets$  and  $t\bar{t}$  normalized from control regions in data
- ◆ BDT methods to separate signal and background
- ◆ Extract S and B from a fit to composite BDT distribution

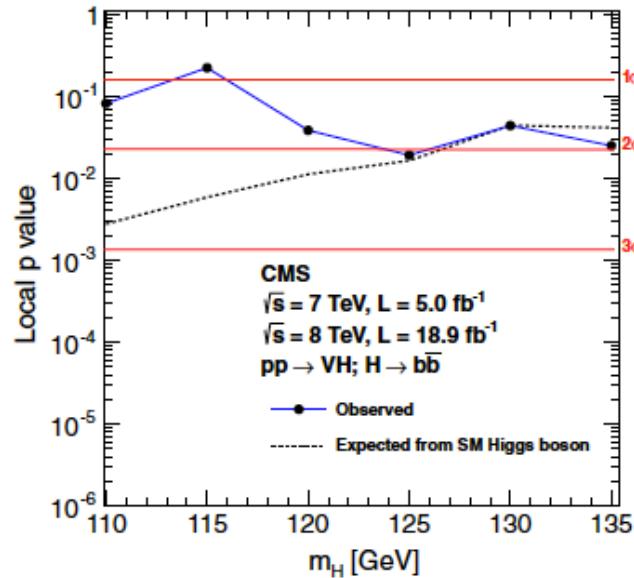
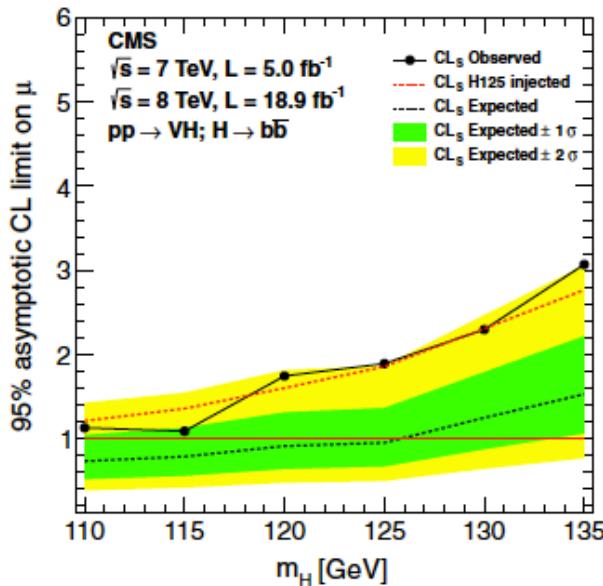


- ◆ Validating distributions in input to BDT
- ◆ Obtain scale factors (SF) for background modeling:
  - ❖ accounting for cross section discrepancies + potential residual differences in physics objects
- ◆ Associated production is categorized: V+ucsdg/ V+b/V+bb



- ◆ All SF found to be compatible with 1, except  $SF_{V+b} \sim 2$ :
  - ❖ Possible mis-modeling in generator parton shower of  $g \rightarrow b\bar{b}$ , already seen in V+b

- ◆ Single distribution of S/B: observed excess consistent w/ SM scalar boson expectation
- ◆ Limit from simultaneous fit of all channels and categories



- ◆ At 125 GeV observed (expected) 95% CL upper limit is 1.89 (0.95) the SM expectations
- ◆ p-values: significance of the observed (expected) excess is 2.1 $\sigma$  (2.1 $\sigma$ )
- ◆ All channels consistent with SM scalar boson with  $m_H = 125$  GeV:
  - ◆ Combined best-fit for signal strength  $\mu = 1.0 \pm 0.5 \times \text{SM}$

- ◆ Measurement of SM processes involving V+HF in final state:
  - ❖ Excellent test of QCD prediction
  - ❖ Tension in key-observable may have direct impact in search for new physics
- ◆ CMS provided solid results for Z+b(b), W+bb, W+c:
  - ❖ for different jet multiplicities
  - ❖ Cross sections overall in agreement ( $\sim 2\sigma$  discrepancy in Z+b w.r.t. 4F predictions)
  - ❖ Tensions in comparisons of Z+b(b) kinematics :  $p_T(Z)$  and  $\Delta R(b,b)$
- ◆ V+HF is main background for new physics (e.g  $H \rightarrow bb$ ) produced in association with V
  - ❖ Large Z boost required to reduce the background:  $p_T$  should be well reproduced by MC
  - ❖ SM backgrounds: normalization corrects for possible discrepancies in the cross section
  - ❖ Significance of the observed excess in VH(bb) is  $2.1\sigma$  ( $2.1\sigma$  expected)

More data and comparison with different calculations might shed more light on the observed remaining tension

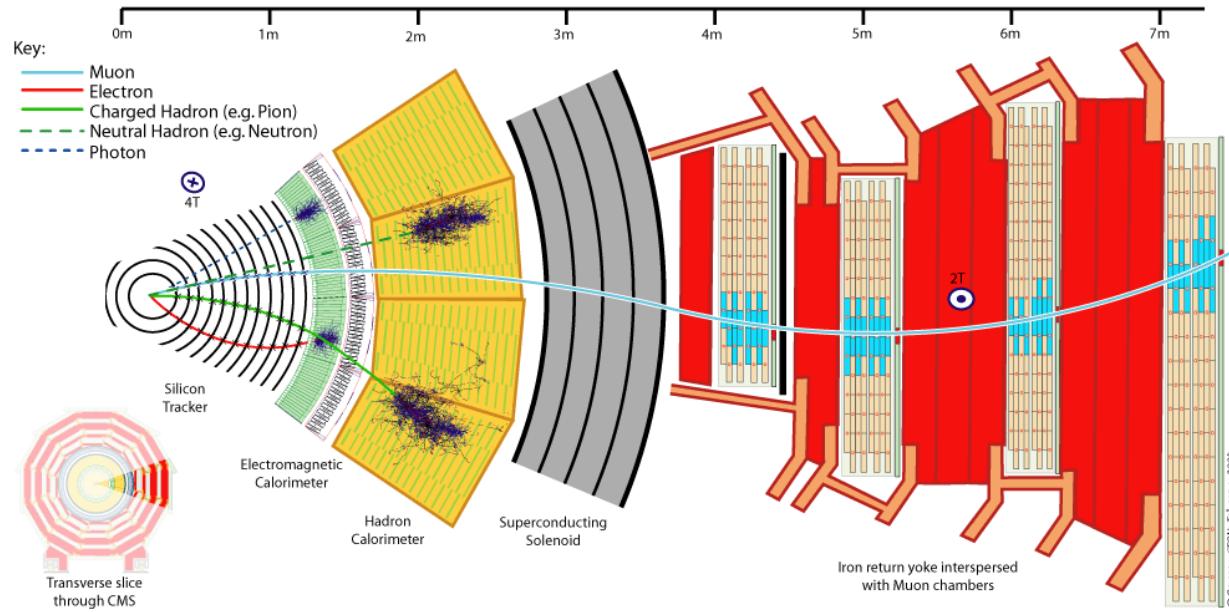


---

BACKUP

# The tool: a Compact Muon Solenoid

- From particle reconstruction: muons, electrons, hadrons (charged and neutral), photons



... to physics objects: muons, electrons, jets, photons

- Excellent detector performance:
  - Track-finding efficiency is more than 99%
  - Transverse momentum resolution:  $\sigma(p_T)/p_T = 1.5 - 3\%$  for tracks of  $p_T \sim 100$  GeV
  - Energy resolution for electrons and photons:  $\sigma(E)/E \sim 1\%$

# The Z(l<sup>l</sup>) + bb event

## Tools for tagging b-quark jets

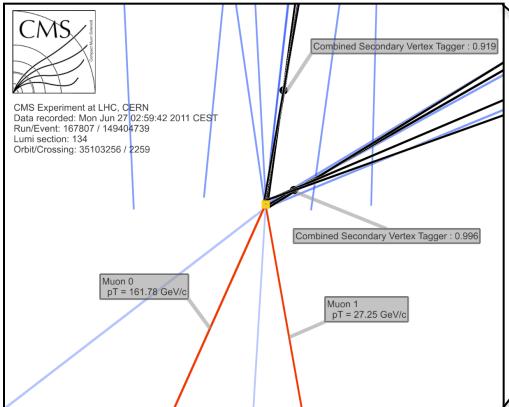
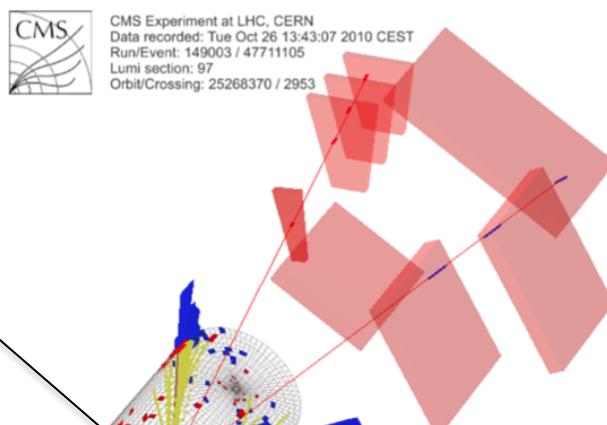
- Presence of B-hadron
- Sizeable lifetime  $\beta\gamma\tau \sim 5\text{mm}$   
→ secondary vertex
- Several algorithms based on IP sig., SV mass, MVA
- Working points (efficiency vs. purity)

## Missing Transv. Energy (MET)\*

- Presence of ν
- Significance:  $\text{ME}_T / \sigma(\text{ME}_T)$

## Leptons: electrons, muons

- Triggering the event (di-lept.)
- ParticleFlow reco + ID
- $\mu$ : tracker+muon fit
- $e$ : tracks+ECAL clusters
- Isolation criteria



## Jets

- ParticleFlow anti-k<sub>T</sub> ( $R = 0.5$ )
- Energy calibration applied

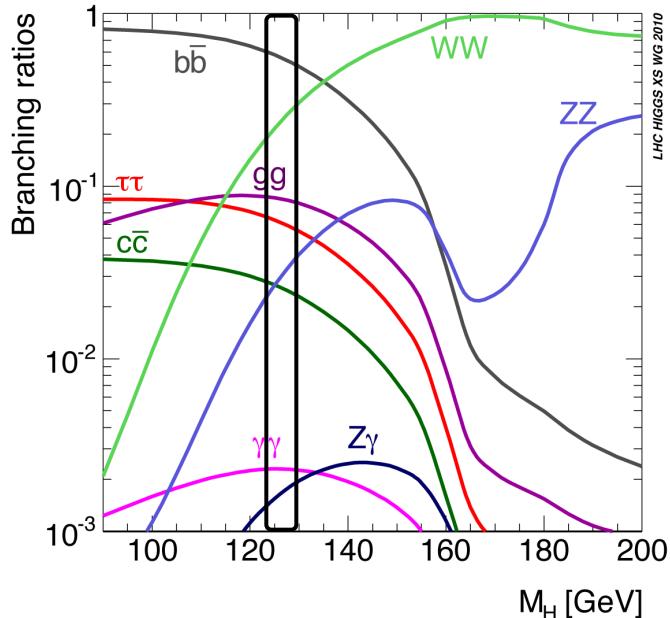
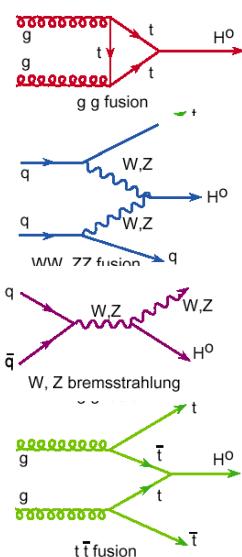
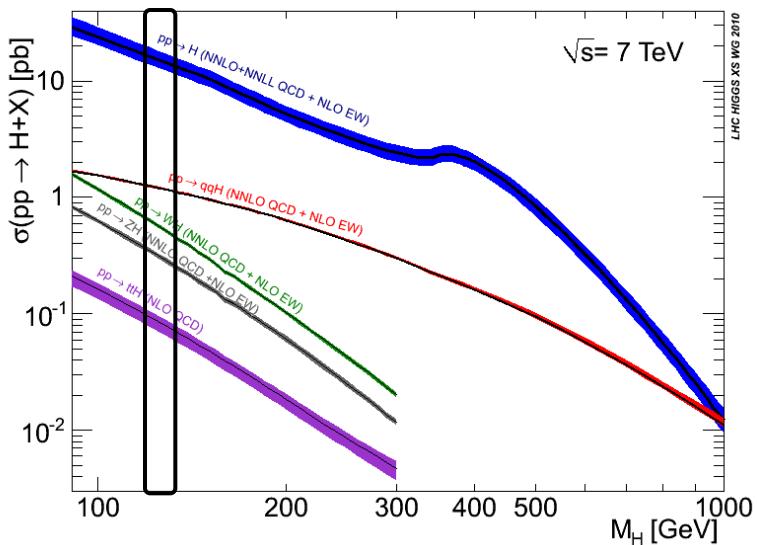
## Phase space

- Leptons:  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.4$
- Jets:  $p_T > 25 \text{ GeV}$ ,  $|\eta| < 2.1$
- jet-lepton separation:  $\Delta R(l, \text{jet}) > 0.5$
- di-lepton invariant mass:  $76 < m(l^l) < 106 \text{ GeV}$

\* For background events

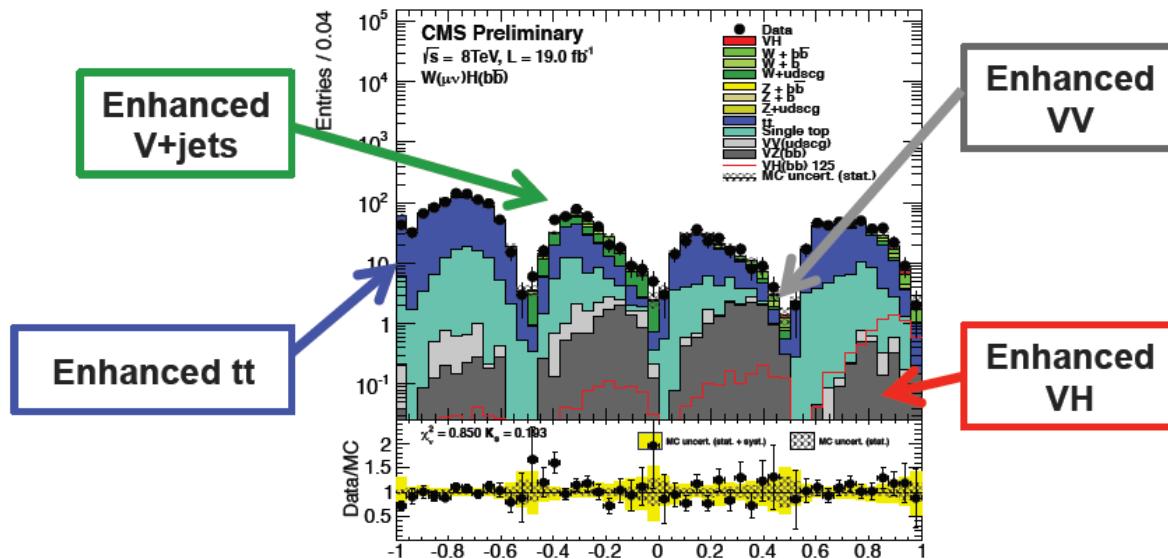
# Higgs production and decay modes at LHC

- ◆ Gluon fusion production mode dominates at LHC
- ◆  $H \rightarrow bb$  is the favored decay mode, but suppressed by large QCD
  - ❖  $\sigma_{bb}(\text{QCD}) \sim 10^7 \sigma_{bb}(\text{H} \rightarrow bb)$



Need to search for  $H \rightarrow bb$  in associated production (VBF, VH, ttH)

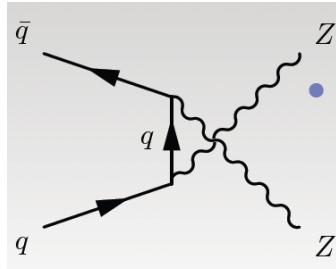
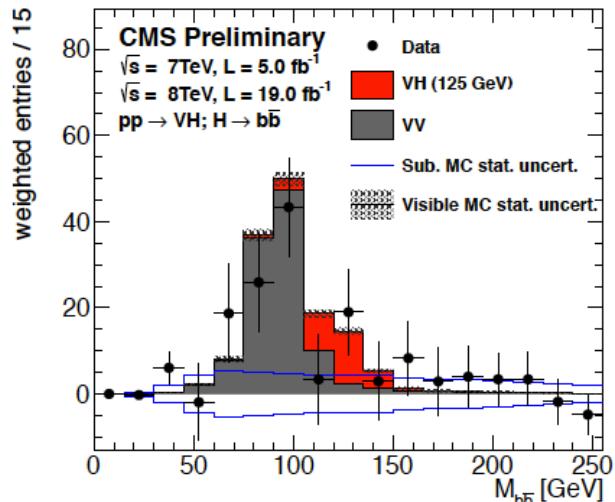
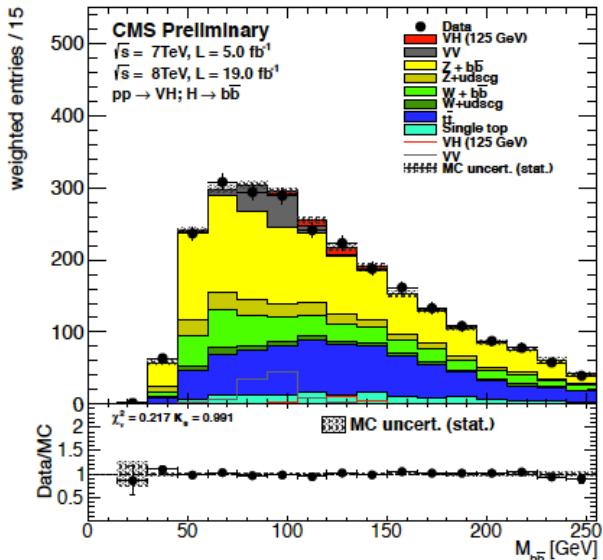
- ◆ Inputs:
  - ❖ kinematics and topological properties of candidate bb pair and vector boson ( $p_T$ ,  $\Delta\phi(V,jj)$ )
  - ❖ b-tagging discriminators of selected jets
- ◆ Sequential BDTs : **tt vs VH | VJ vs VH** (after passing tt) | **VV vs VH** (after passing VJ)
- ◆ Event categorization based on output of the specific BDTs (*à la CDF*)



- ◆ Mapped into main BDT, trained to separate signal from all backgrounds
- ◆ Fitting the main BDT distribution for extracting the signal and background shape

## Results fitting the $M_{bb}$ mass

- ◆ Combine mass distributions in all channels and categories
- ◆ Excess visible once all bkg, but VV, subtracted
- ◆ 95% CL upper limit:  
exp. 1.4, obs. 2.0



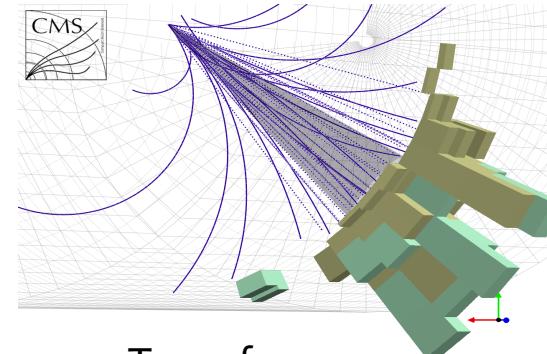
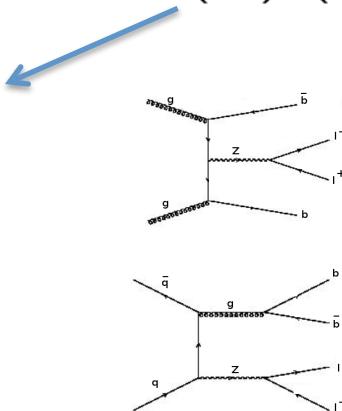
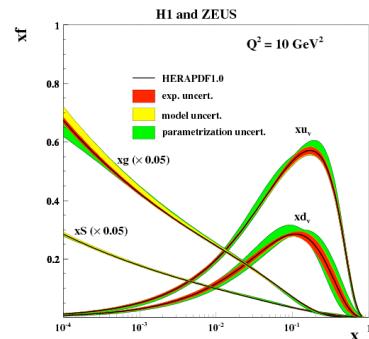
	<b>BDT VZ(bb)</b>
Exp. Sig	<b><math>6.3 \sigma</math></b>
Obs. Sig	<b><math>7.5 \sigma</math></b>
$\mu$	<b><math>1.19^{+0.27}_{-0.23}</math></b>

- ◆ Testing the consistency of di-boson production rate with SM expectation
- ◆ Validation of the background estimate

# An alternative approach: the Matrix Element (ME)

- ◆ An alternative event by event method exploiting kinematics embedded in the LO matrix element of the process under investigation:  $|M(p)|^2$
- ◆ Based on weight computation

$$P(x^{vis}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 f(x_1) f(x_2) \int d\phi |M(p)_\alpha|^2 W(p^{vis}, p)$$



- ◆ Integration done using MadWeight [[arXiv:1007.3300v2](https://arxiv.org/abs/1007.3300v2)]

Method already in use: top mass and tt bkg in Zb cross section