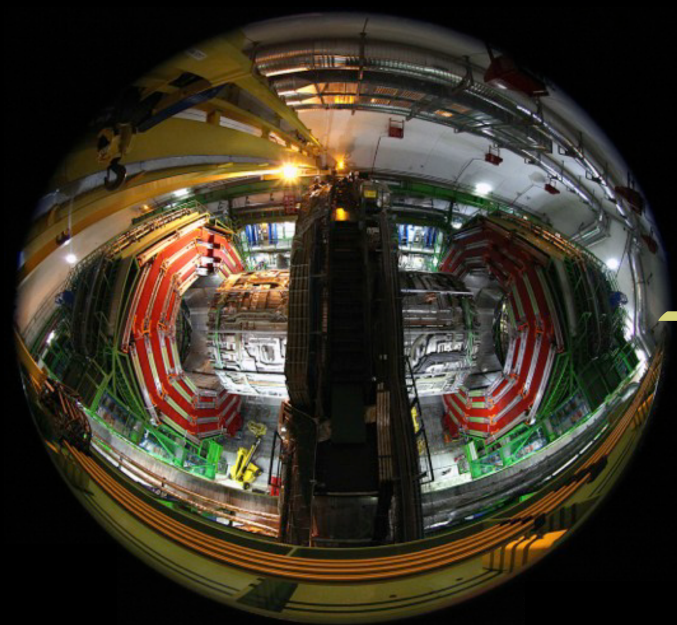

$H \to b\bar{b}$ at CMS

Caterina Vernieri
on behalf of the CMS collaboration

SCUOLA
NORMALE
SUPERIORE

ICHEP 2014 VALENCIA

37th INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS

2 - 9 - JULY - 2014 - VALENCIA

$H \rightarrow b\bar{b}$ at LHC

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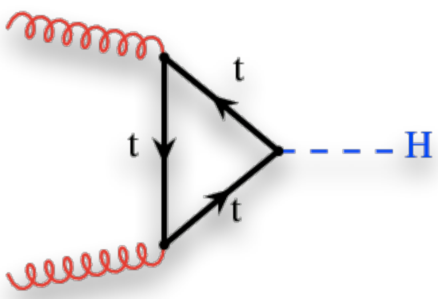

GF
87%

H → $b\bar{b}$ at LHC

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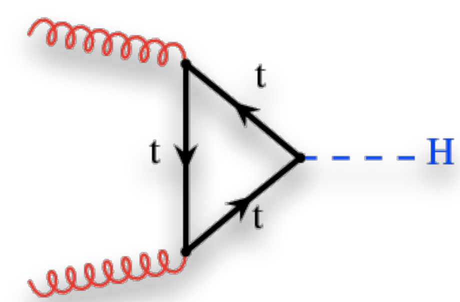

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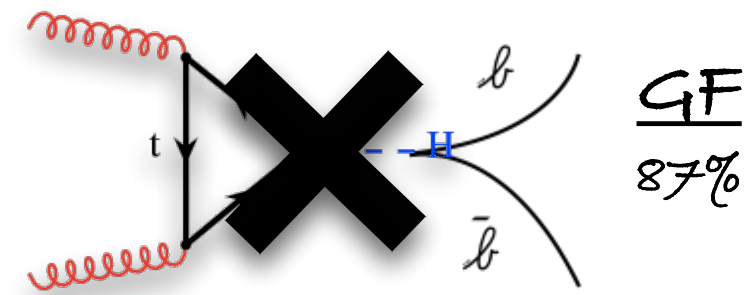

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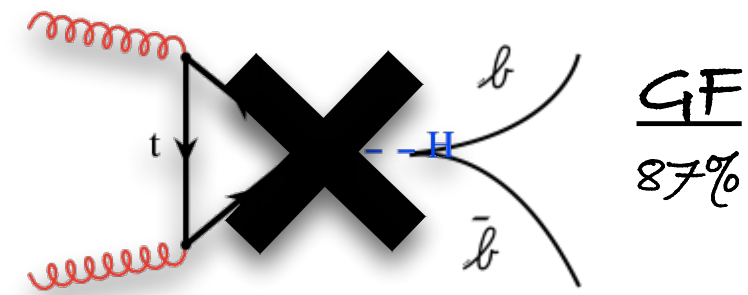

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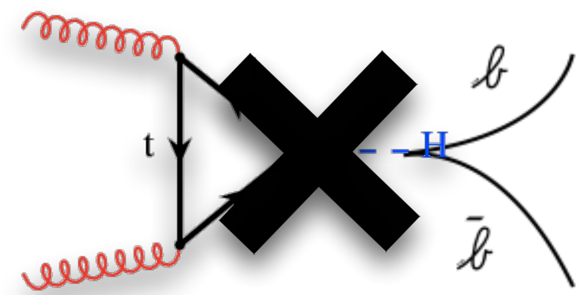

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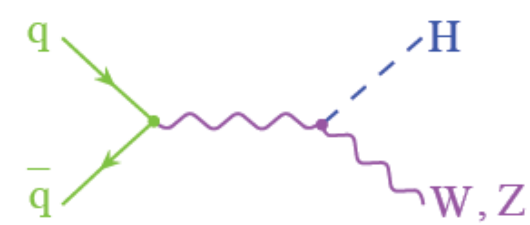

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5%

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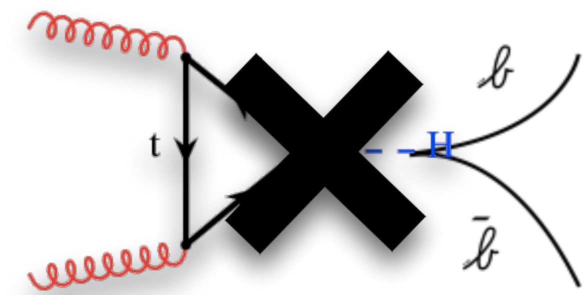

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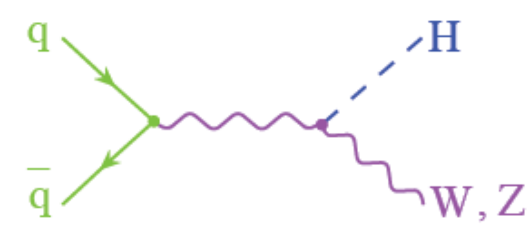

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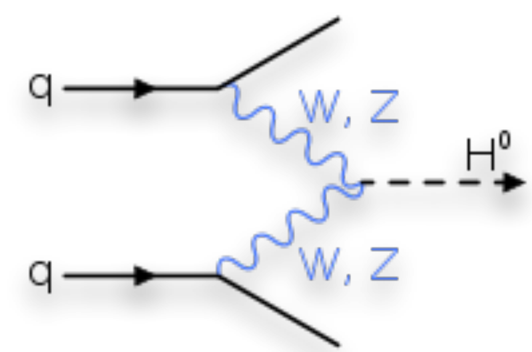

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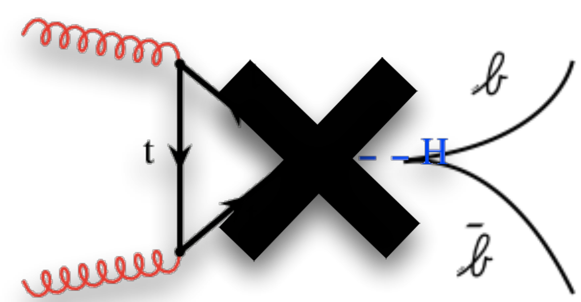

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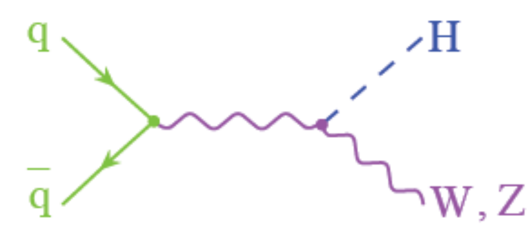

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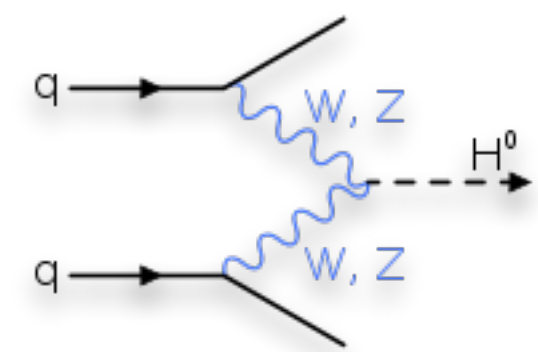
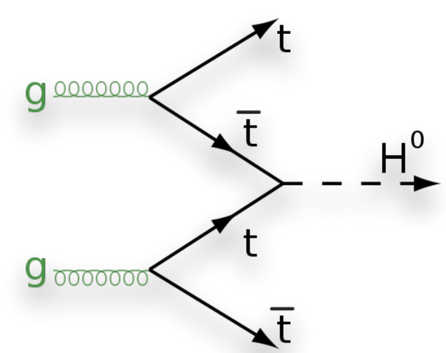


VBF
7%



ttH
0.6%

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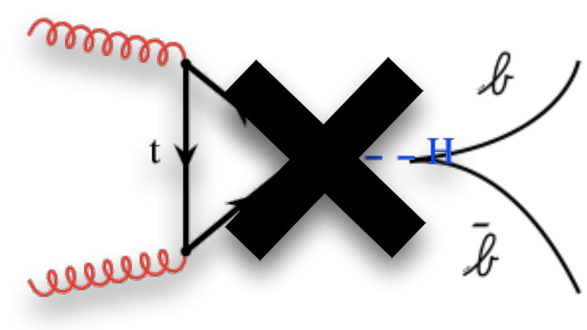

GF
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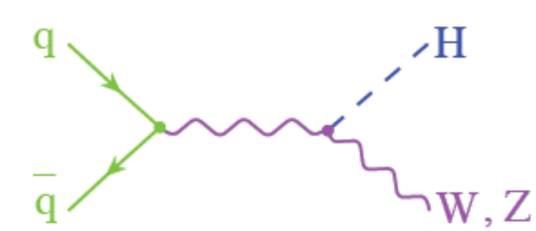

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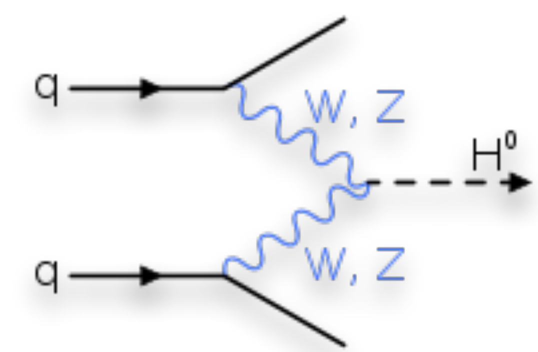
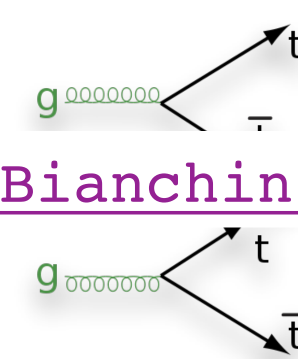
5%



VBF
7%

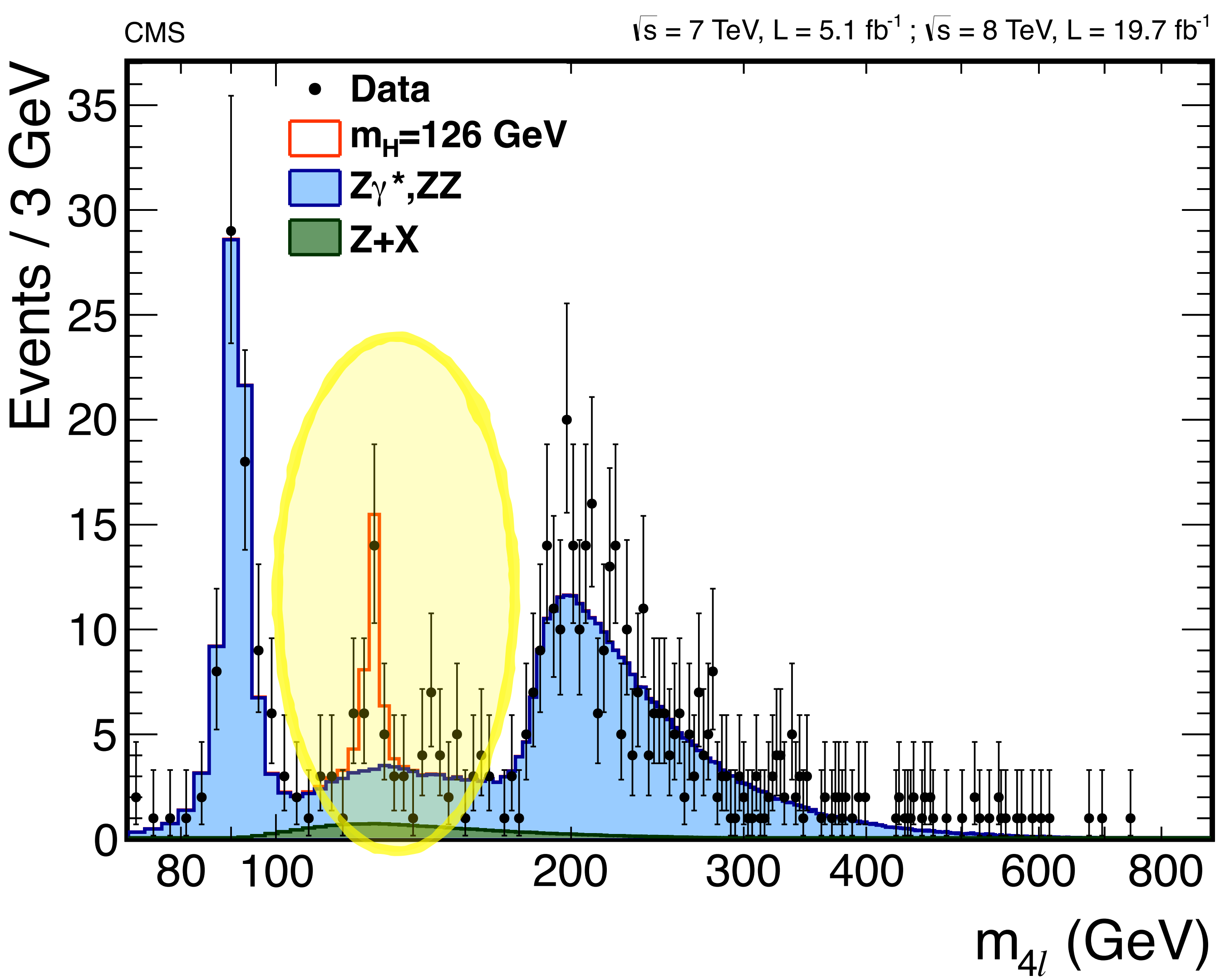


see Bianchini's talk

ttH
0.6%

Why so challenging?

Comparison with the discovery channel



	$H \to 4\ell$	$H \to b\bar{b}$
BR	0.013%	58%
mass resolution	1%	10%
signal efficiency	30%	1.3%
S/B	2	0.05

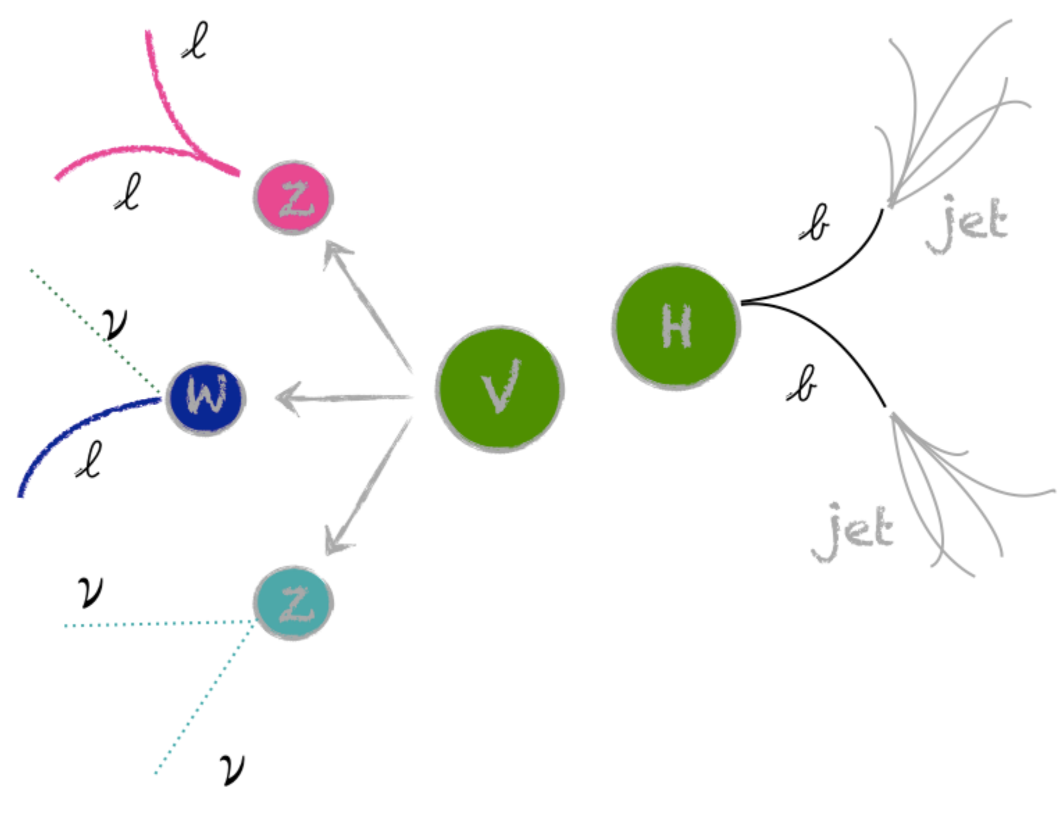
$H(b\bar{b})$ searches need:

- exploit all possible information from the event to improve S/B
- improve $m(b\bar{b})$ resolution

Quick look at the backgrounds

VH example

signal

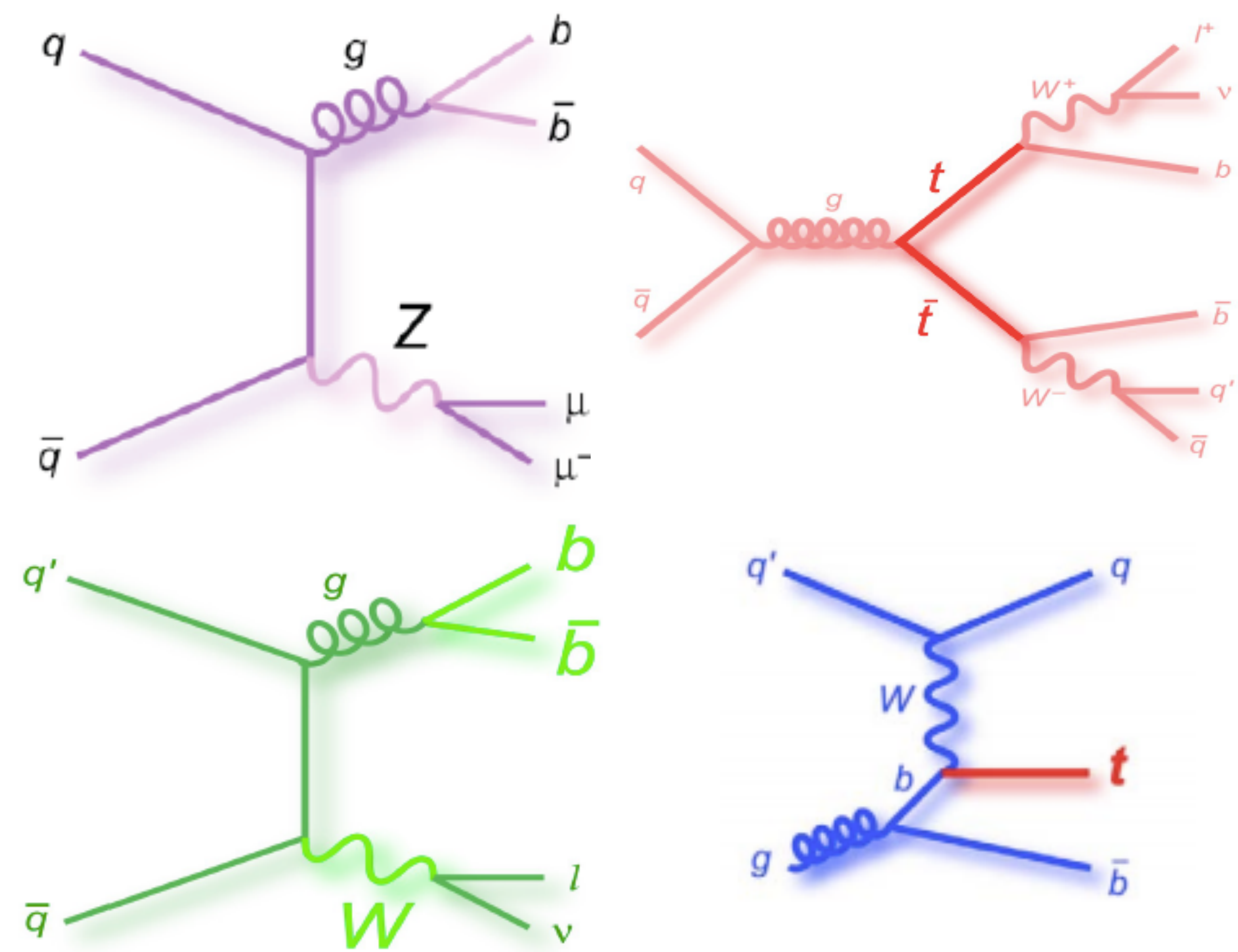


0-lepton (MET)

1-lepton [e,μ,τ]

2-OSSF leptons [ee,μμ]

irreducible backgrounds



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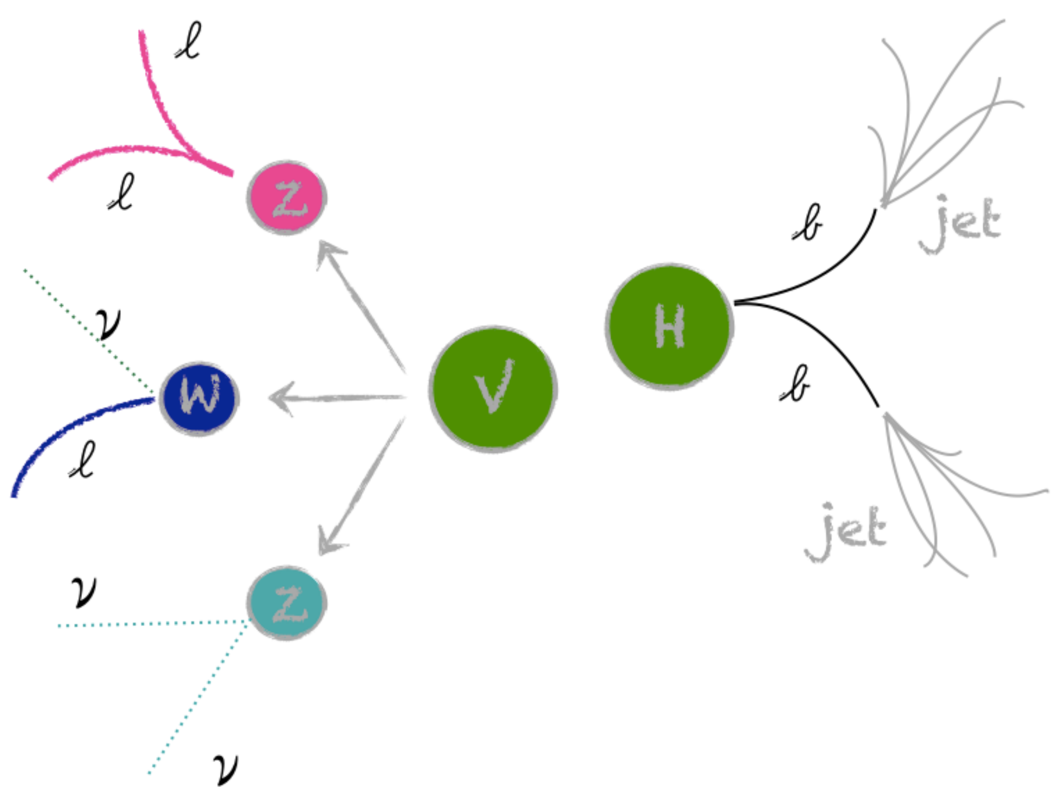

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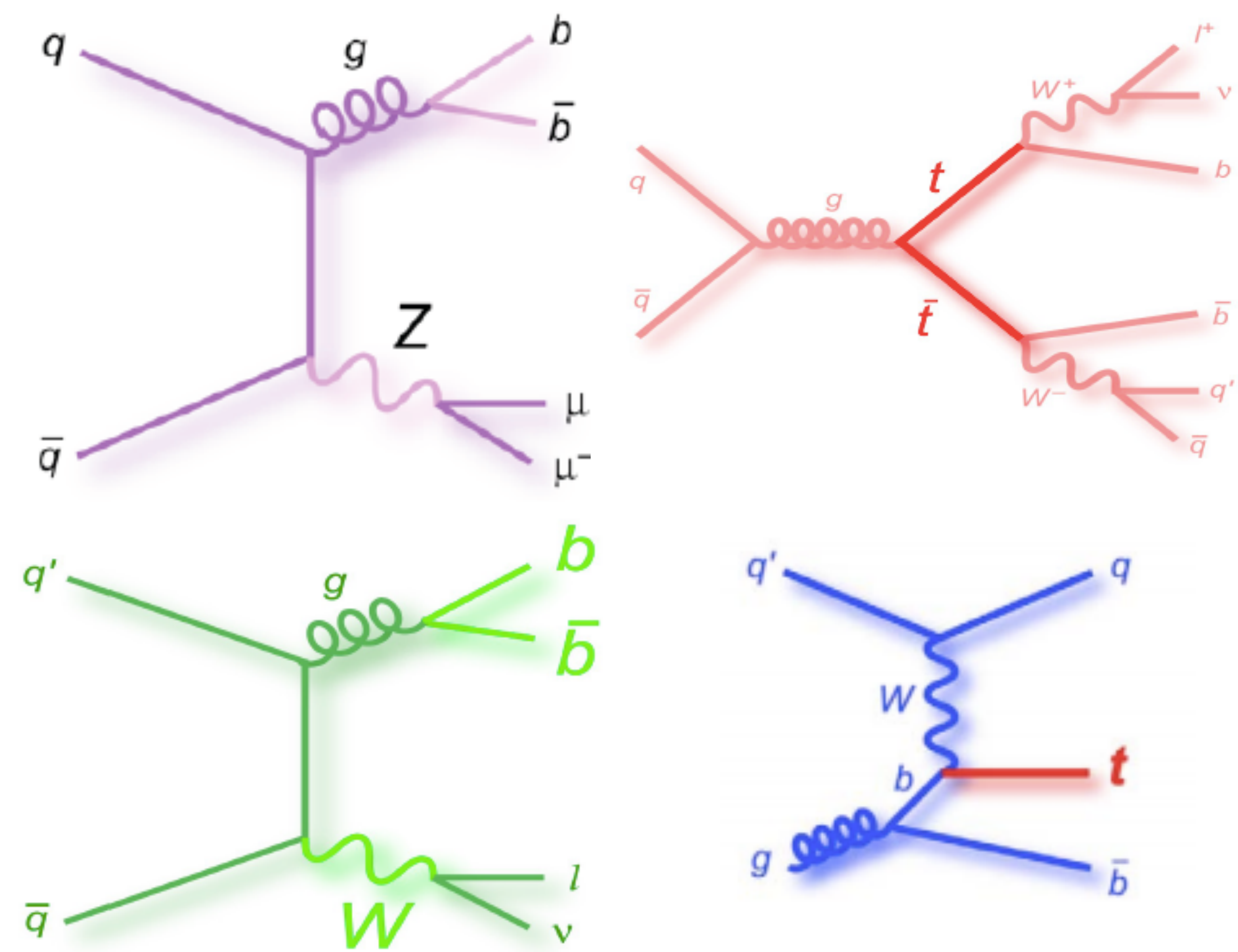

and diboson, of course

Quick look at the backgrounds

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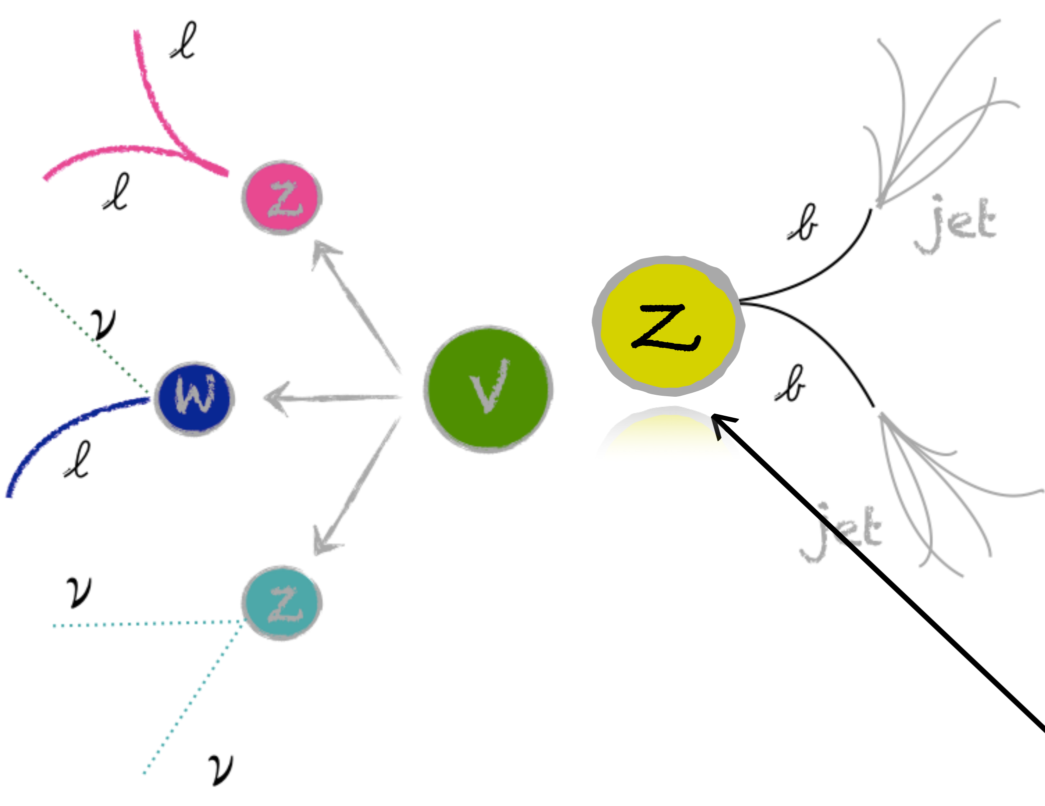

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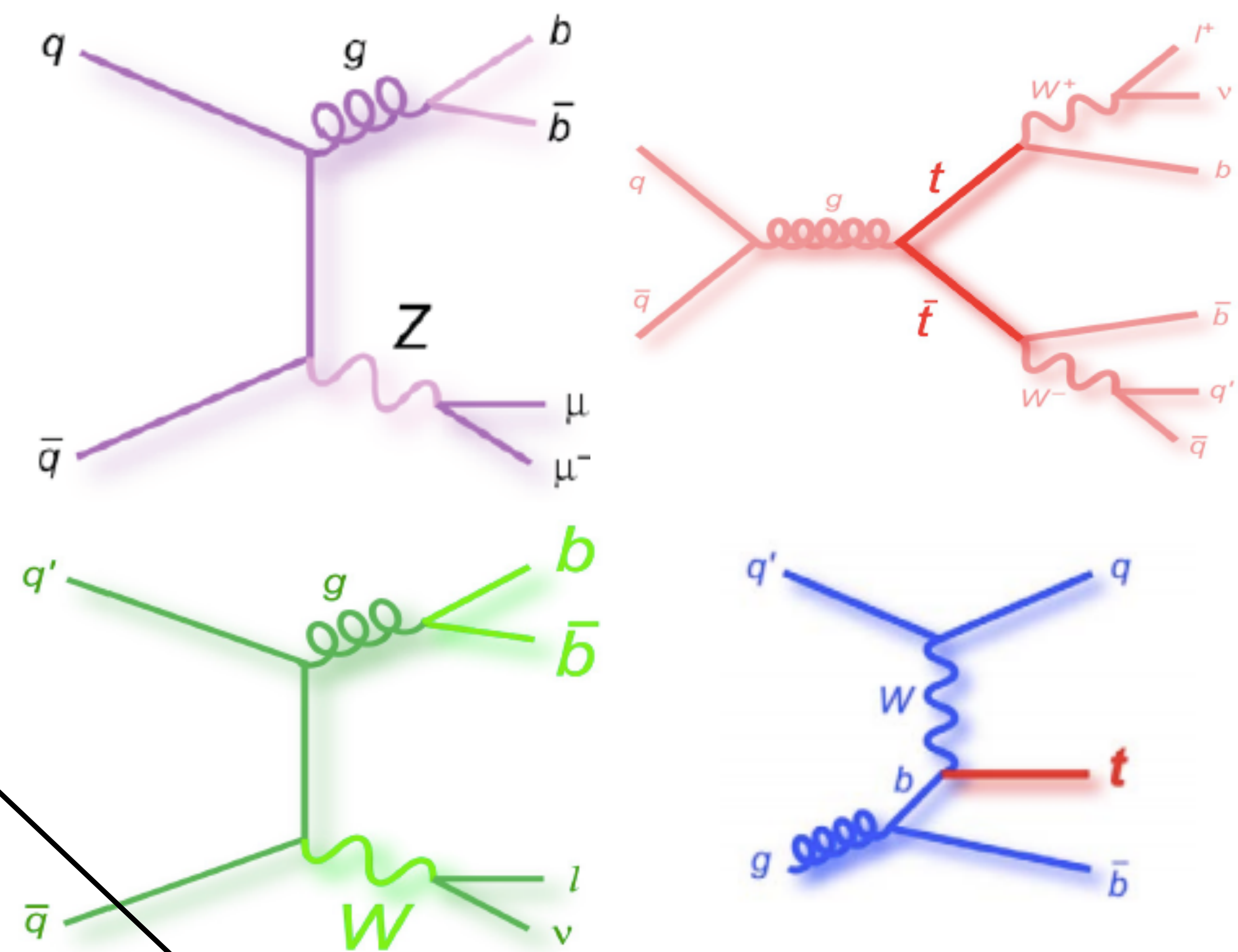

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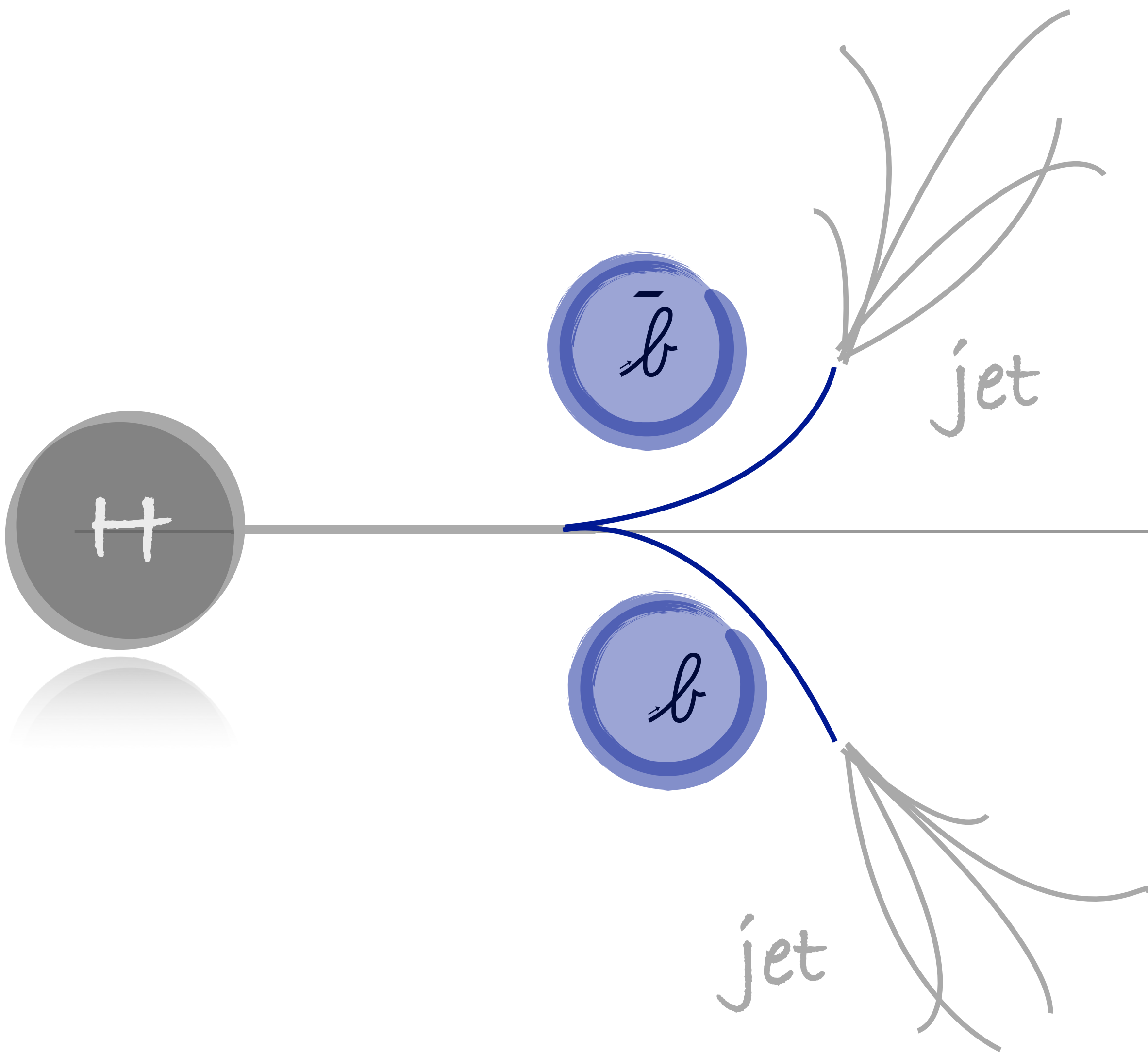


b-tagging

Combined Secondary Vertex

- The CSV through multivariate technique combines

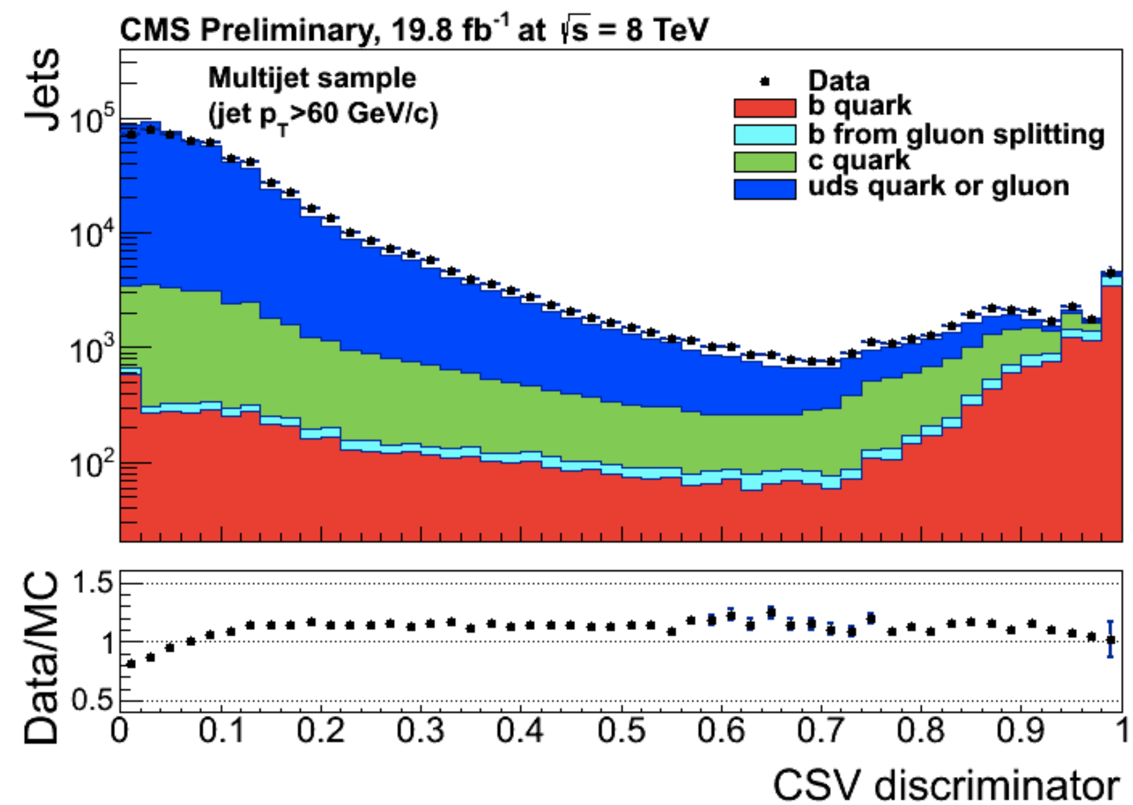
  Track information

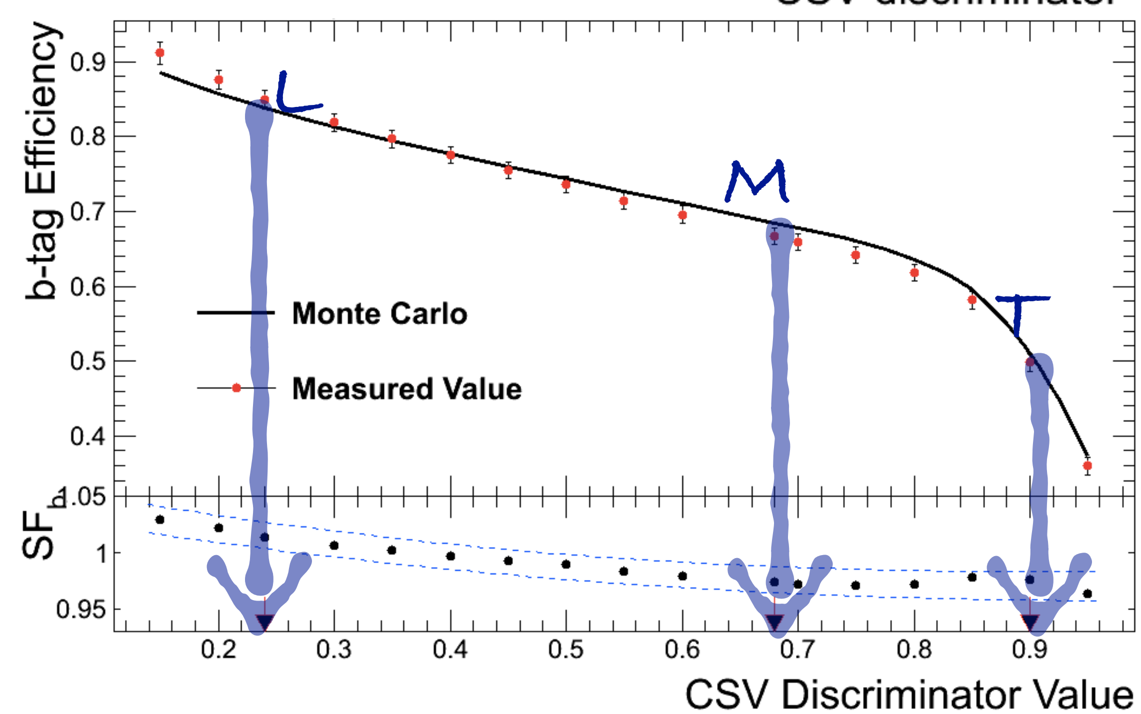
  - Impact parameter significance of the most energetic tracks

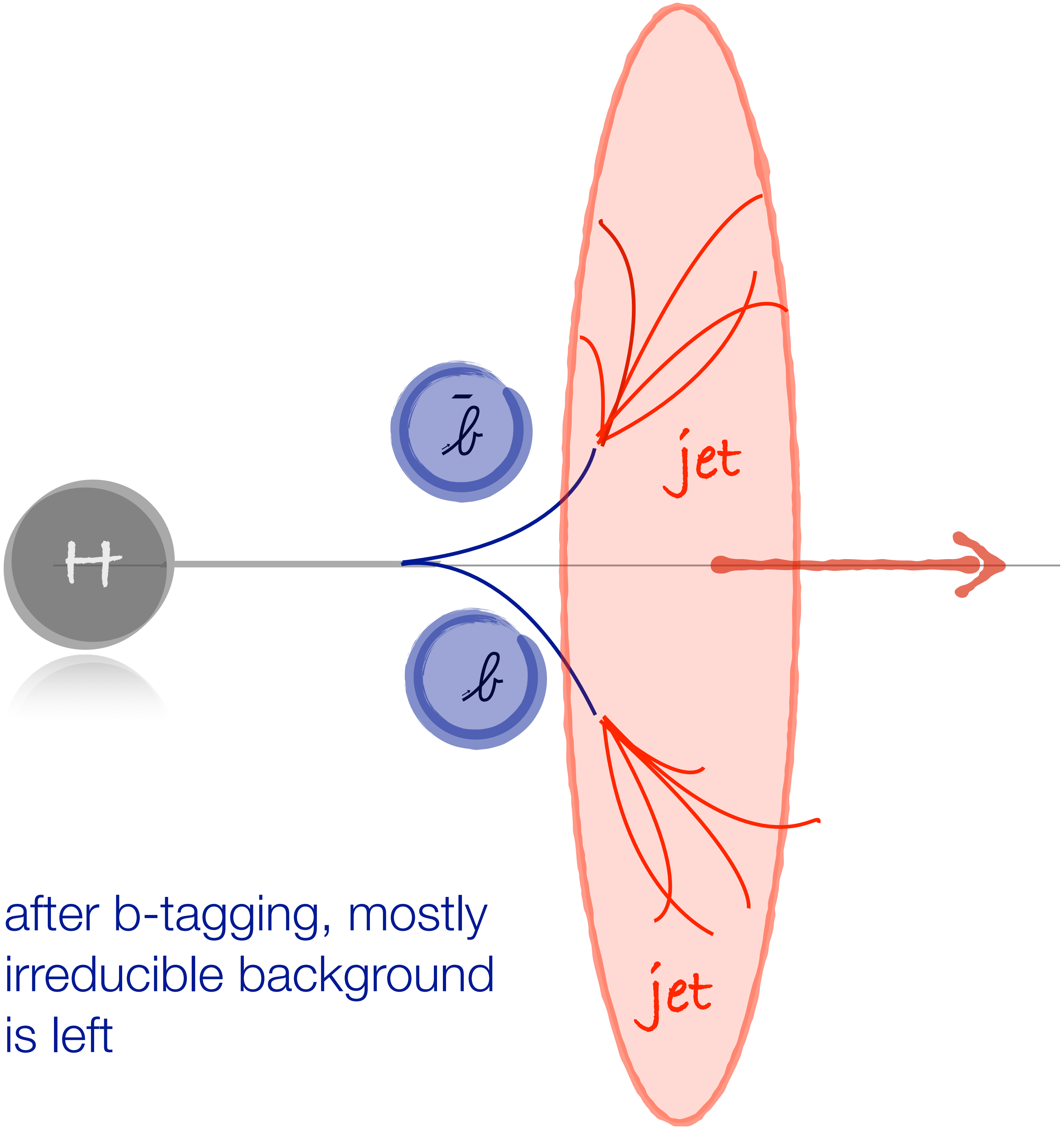
  Vertex information

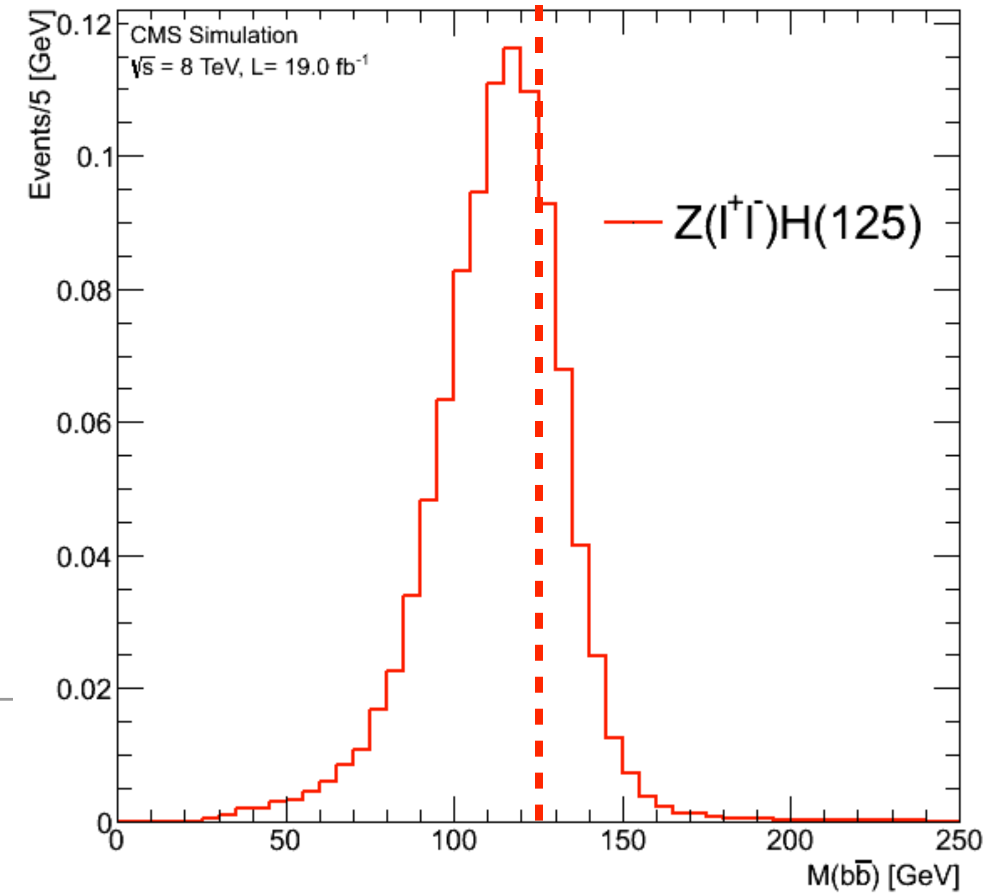
  - if available or pseudo vertex from displaced tracks

	b	c	light [%]
Loose	85	32	10
Medium	70	15	1
Tight	50	6	0.1









after b-tagging, mostly irreducible background is left

$m(b\bar{b})$ raw dijet resolution is ~ 10%

improvable to achieve a better signal discrimination

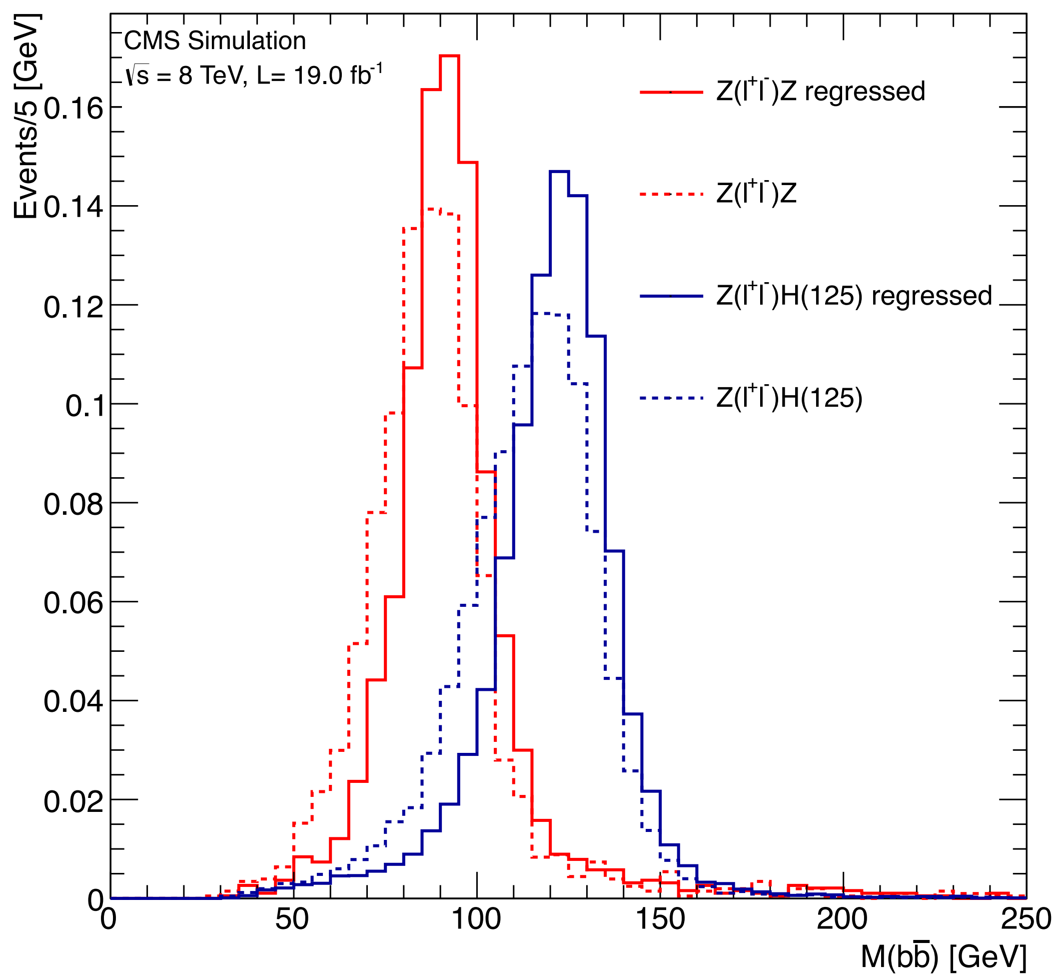
b-jet energy MVA regression

B.R. 35% $b \rightarrow l + \nu + X$

Multidimensional calibration targeting the jet p_T at generator level

✓ Basic kinematic and jet structure
✓ Secondary Vertex and soft lepton information
✓ MET related (as kinematic constraint)

✓Final resolution improves by 15-25%
✓The sensitivity increases by **10-20**%
✓The VZ/VH separation power improves



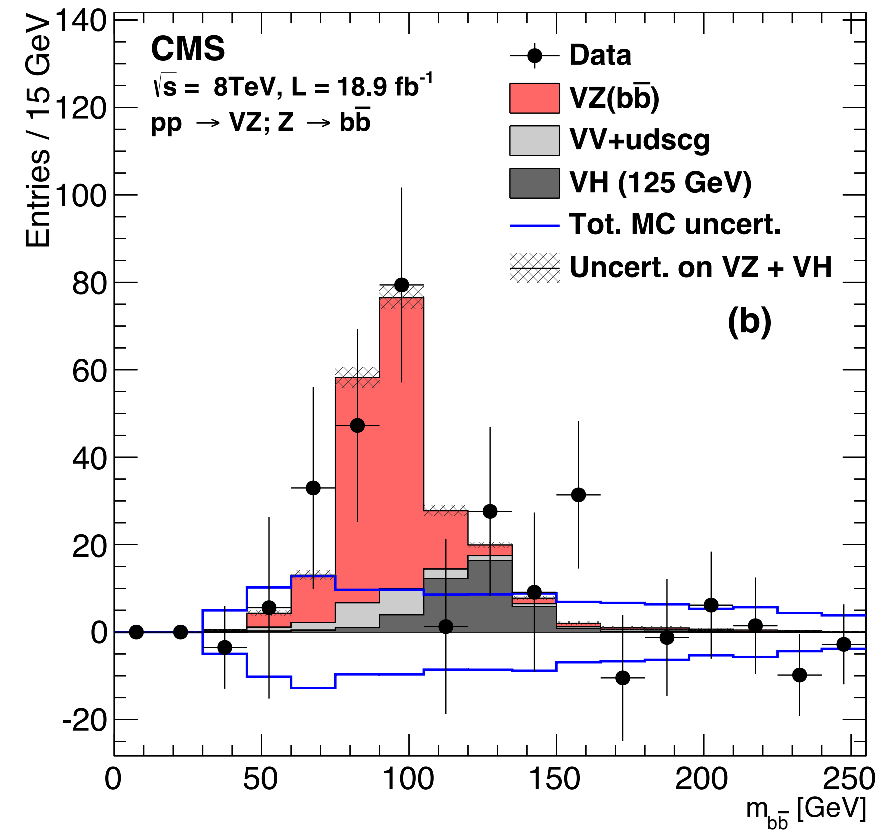
Validation on Data, Diboson

arXiv:1403.3047v1

submitted to the EPJ C

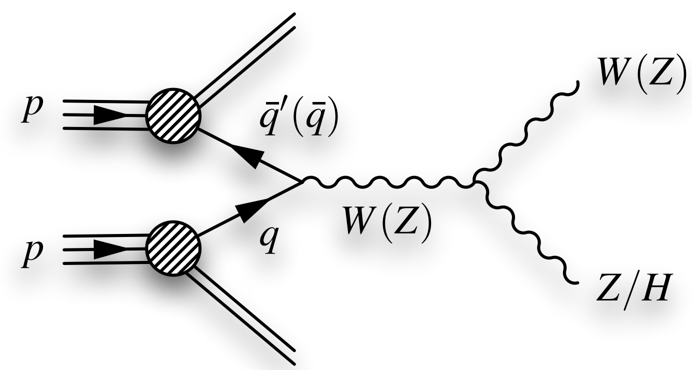
Diboson production in the $b\bar{b}$ final state

- Purest $b\bar{b}$ resonance
- A standard candle to validate the Higgs search



VZ,VH: same event topology

	$\sigma \cdot$BR at $\sqrt{s}$ =8 TeV [pb]		
bb	W($\ell\nu$)	Z($\ell\ell$)	Z($\nu\nu$)
Z	1.13	0.08	0.24
H	0.13	0.01	0.04



6.3σ, first observation of the VZ($b\bar{b}$) at an hadron collider

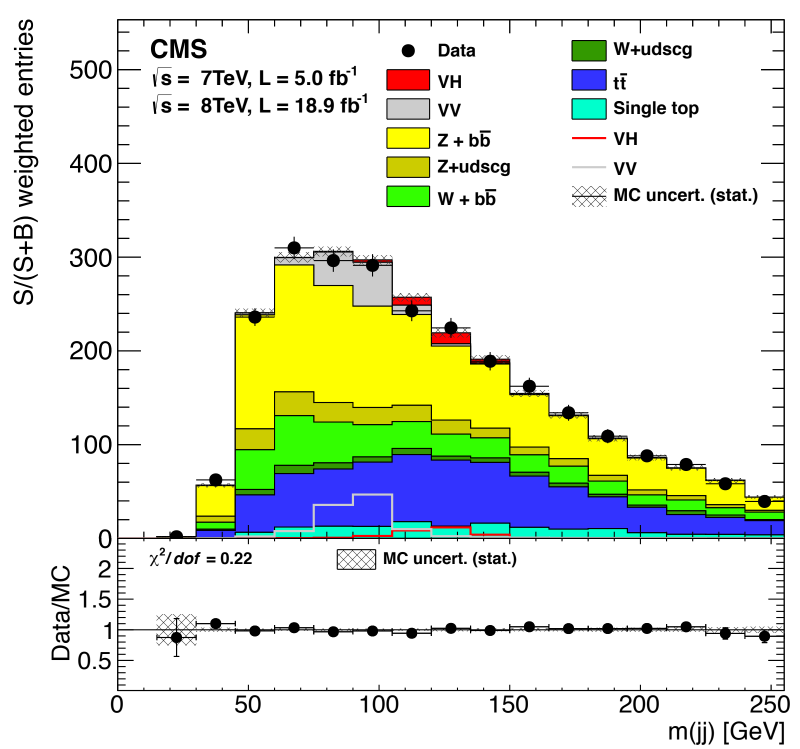
σ (pp → WZ) = 4.8 ± 1.4 (stat.) ± 1.1(syst.) pb

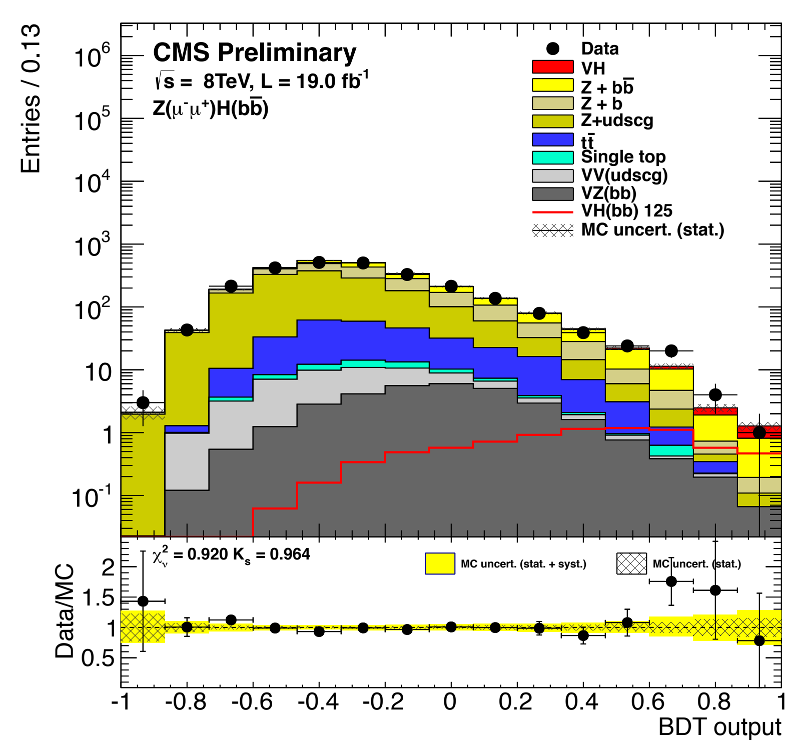
σ (pp → ZZ) = 0.90 ± 0.23(stat.) ± 0.16(syst.) pb

agreement with NLO MCFM prediction

VH, Key elements

- V boson is required to have high boost (~100 GeV) - categorization in $p_T(V)$ bins
  - multi-jet QCD background is highly suppressed
  - $m(b\bar{b})$ invariant resolution improved in this phase space
- Extract normalization for the dominant and irreducible backgrounds from the data
  V+0b/1b/2b and top pair production
- Use of a multivariate discriminant, BDT
  14 BDTs - shape analyses (for each lepton mode and boost category)





PHYSICAL REVIEW D **89,** 012003 (2014)

Search for the standard model Higgs boson produced in association with a *W* or a *Z* boson and decaying to bottom quarks

S. Chatrchyan *et al.**
(CMS Collaboration)

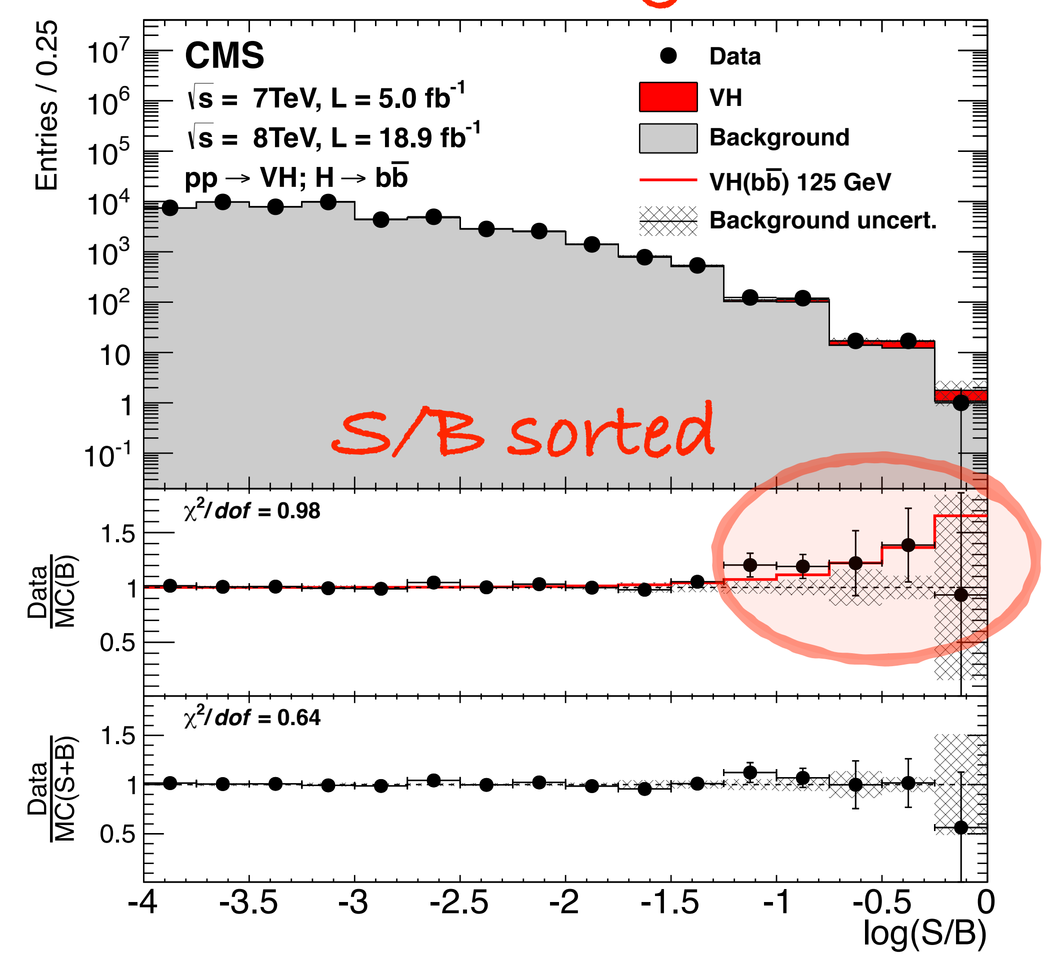
(Received 14 October 2013; published 21 January 2014)

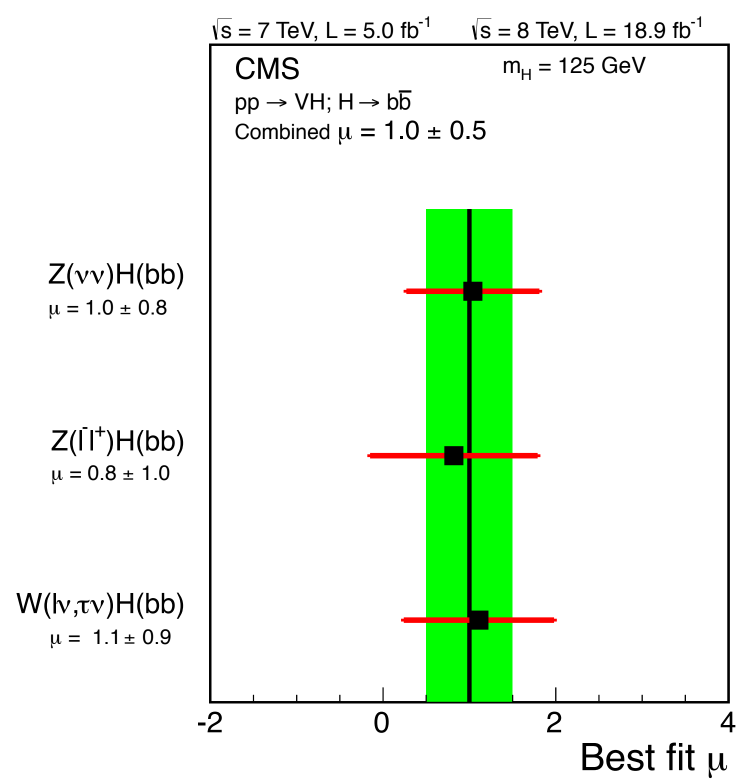
VH, Results

VH($b\bar{b}$) reported an excess of **2.1 σ** in agreement with SM H expectation at 125 GeV

	$\mu = \sigma/\sigma_{SM}$	exp. sign.
CMS	1.0 ± 0.5	2.1 σ
CDF	2.5 ± 1.0	1.3 σ
D0	1.2 ± 1.1	1.5 σ
D0+CDF	1.95 ± 0.75	1.9 σ
ATLAS	0.2 ± 0.9	1.6 σ

MVA analysis

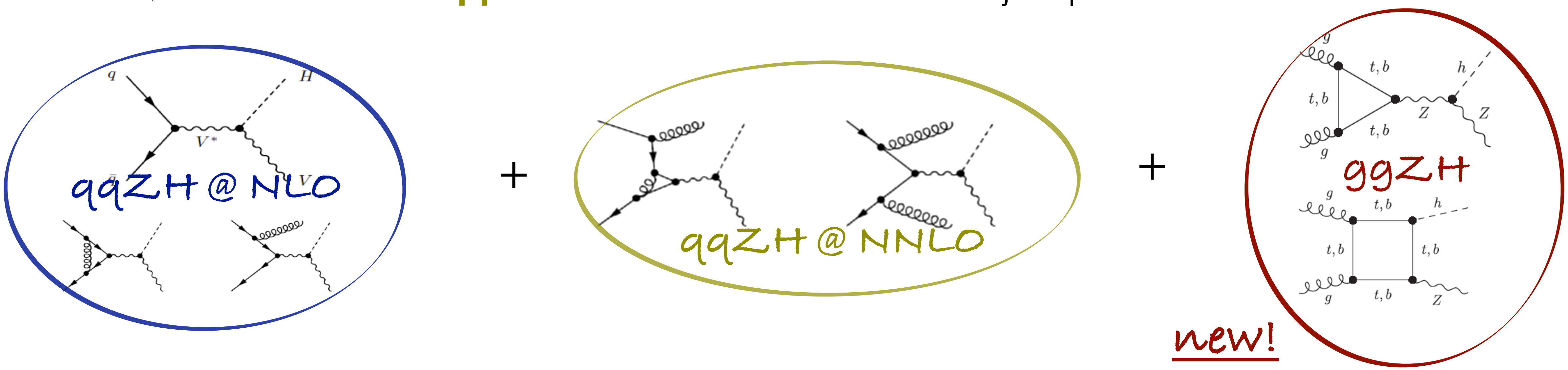




coupling results
<u>see CHEN's talk</u>

VH, ZH new theory cross section available

- ZH production at LHC is mostly **qqZH** (~95%)
- **NNLO** QCD corrections to **qqZH** are included in the VH result just presented

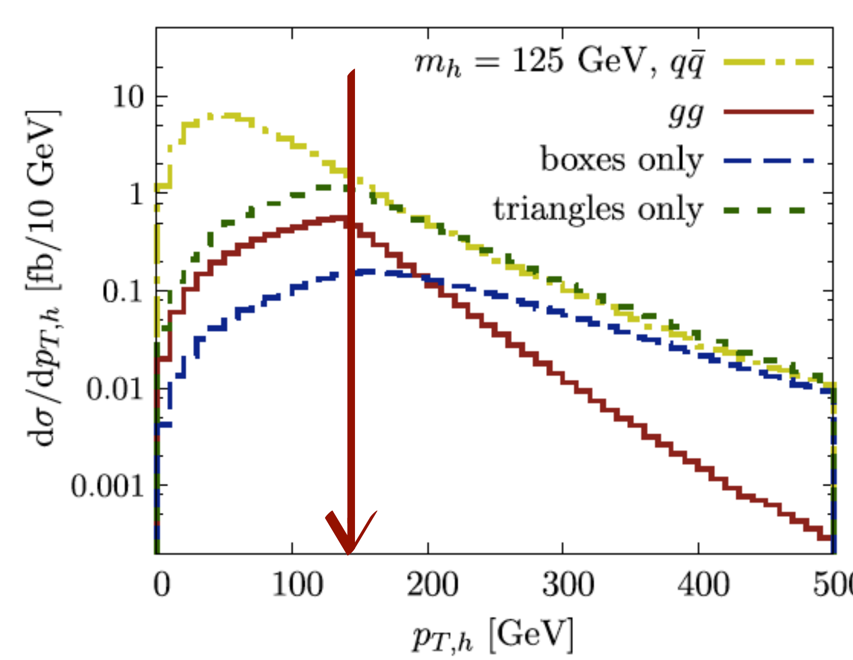


- **ggZH** calculations were not ready and not included
  - spectrum available - it peaks at $p_T(H) \sim 150$ GeV
  - σ corrections up to 30% at the highest p_T category
- Back of the envelope: folding in the corrected ZH p_T spectrum, combining with WH as is, overall VH theory prediction scales up by 10%

estimated effect:

roughly 10% decrease (increase) in μ (sensitivity)

PHYSICAL REVIEW D **89**, 013013 (2014)

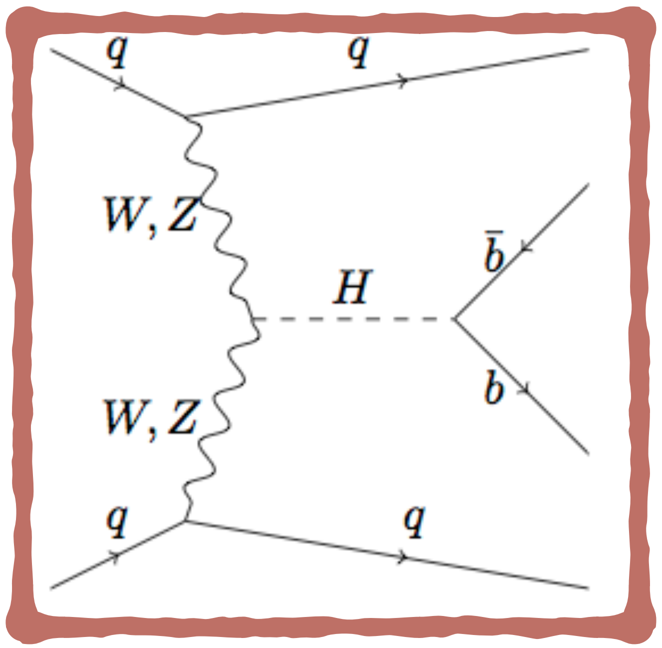


VBF

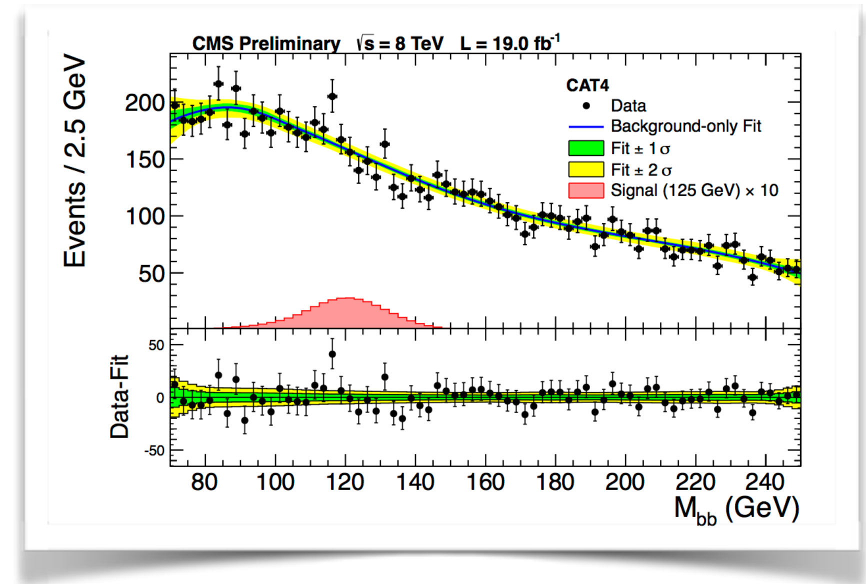
Search for the standard model Higgs boson produced in vector boson fusion, and decaying to bottom quarks

CMS-HIG-13-011

The CMS Collaboration



- 4 relatively hard jets
- jet flavor tagging
  - 2 central **b-jets**
  - 2 **light quark** jets (quark/gluon id)
- large m_{qq} and $\Delta\eta_{qq}$
- suppressed color flow between the $b\bar{b}$ and VBF jets

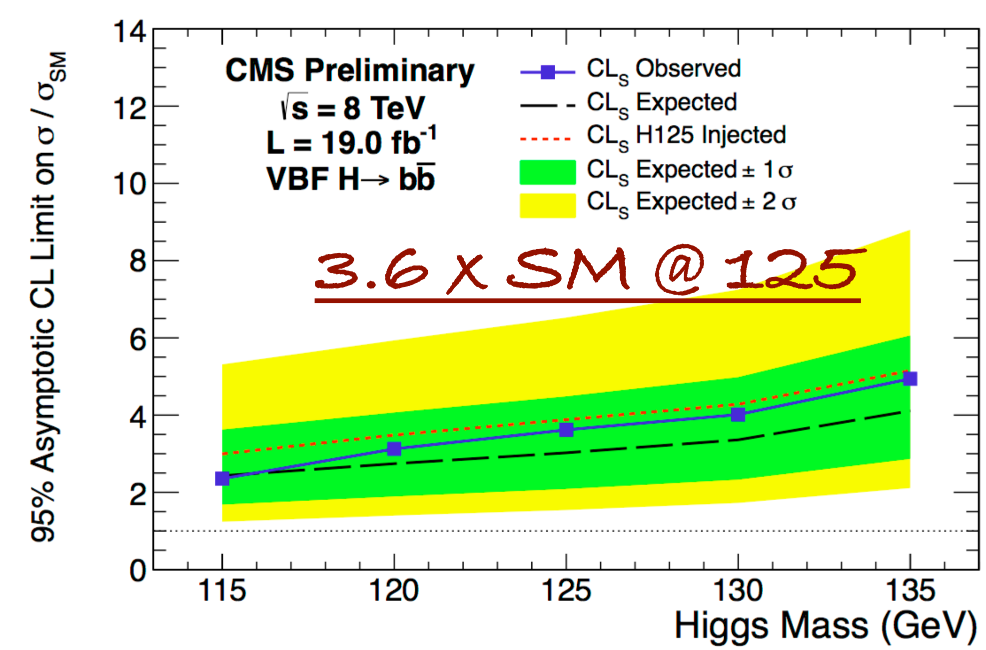


Key points:

1. A topological trigger on signal main properties
2. Neural Network - categorization in S/B bins
3. Fit the $m(b\bar{b})$ spectrum in each bin

work in progress

final results soon



Conclusion & Perspectives

CMS searches for H($b\bar{b}$) consistent with the SM prediction of a Yukawa structure

Evidence for H decaying to fermions

- $H \to \tau\tau$ and VH($b\bar{b}$), 3.8 σ (exp. 4.4 σ)
- see Steggemann's talk

An exciting program is expected to start at the LHC

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H→ $b\bar{b}$ evidence

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An exciting program is expected to start at the LHC

- $H \rightarrow b\bar{b}$ evidence
- Precision Measurement

Additional Material

b-jet energy regression, Validation on Data

Dijet balance in Z(ll)+ $b\bar{b}$ data

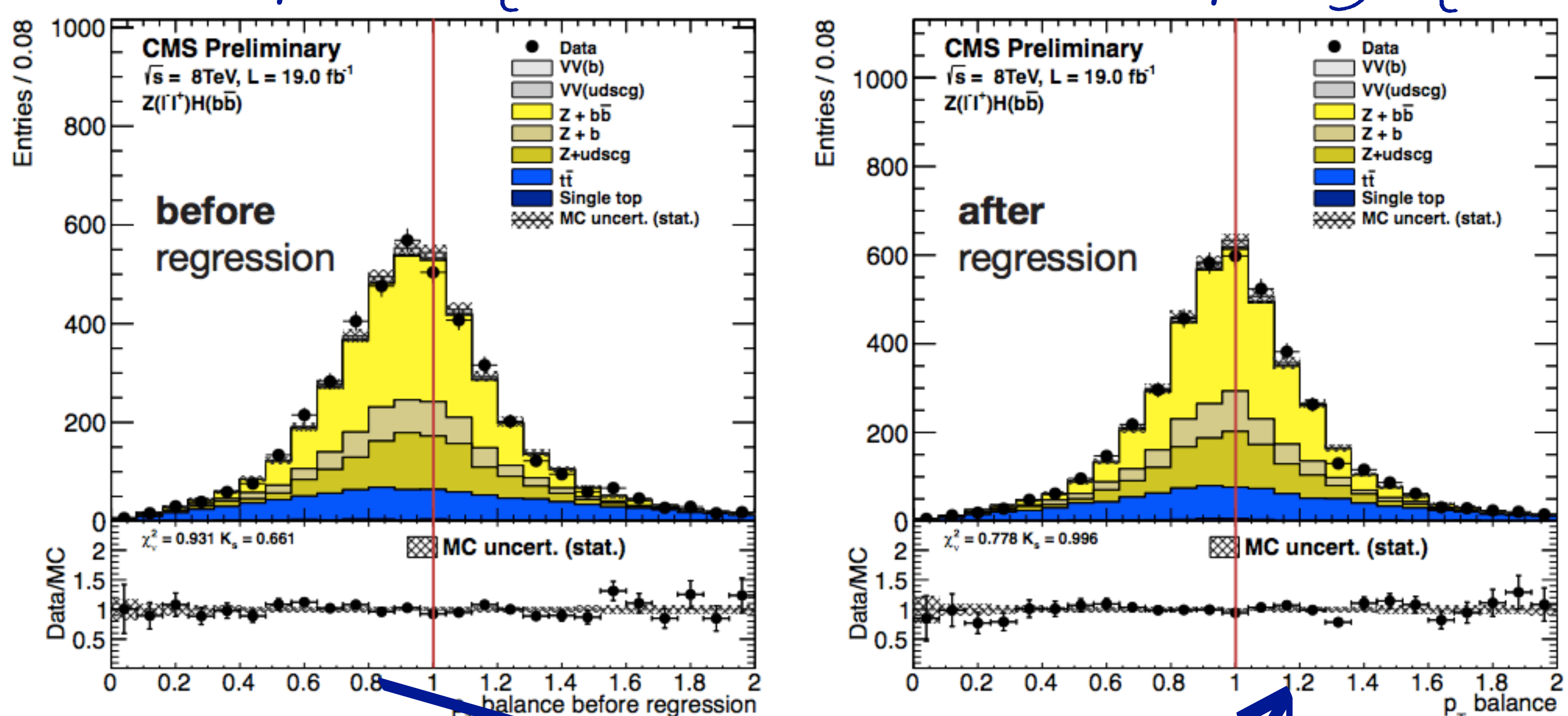
$$p_{T_{balance}} = \frac{p_T(jj)}{p_T(\ell\ell)}$$

An improved resolution and scale is observed

Data/MC agreement improves after regression

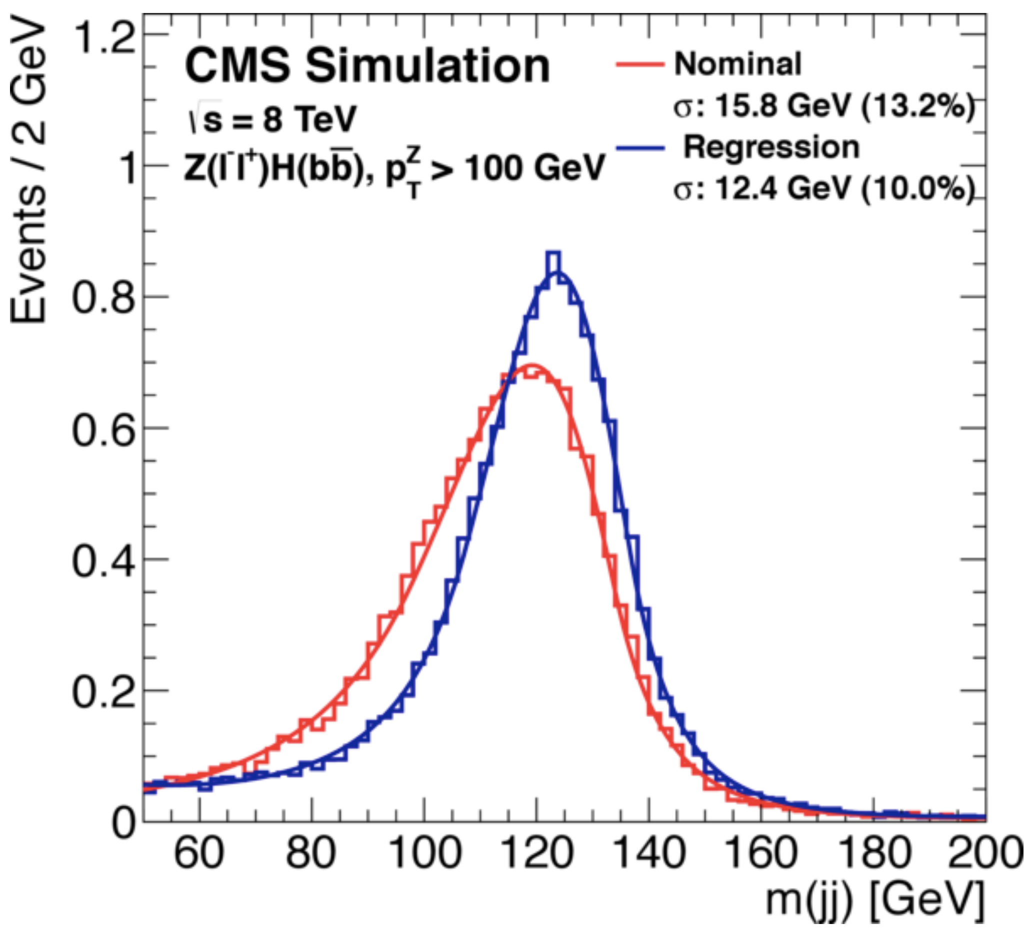
σ/μ=24.3%

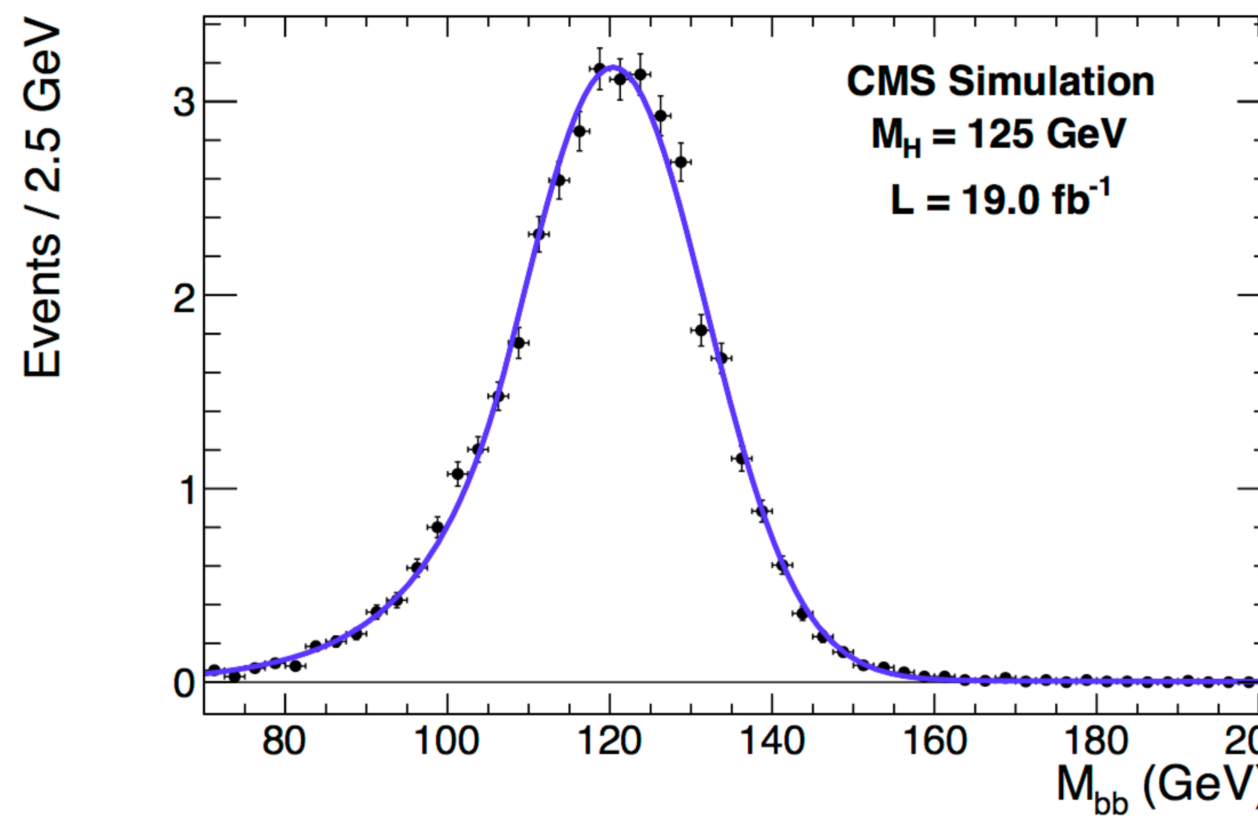
σ/μ= 19.5%



25% of improvement is found

Impact of the b-jet energy regression

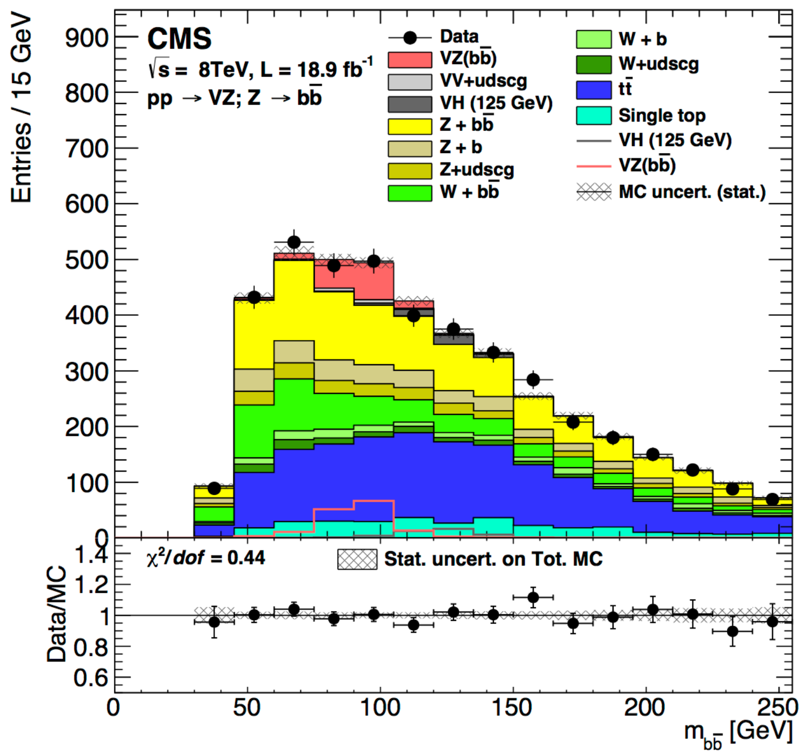


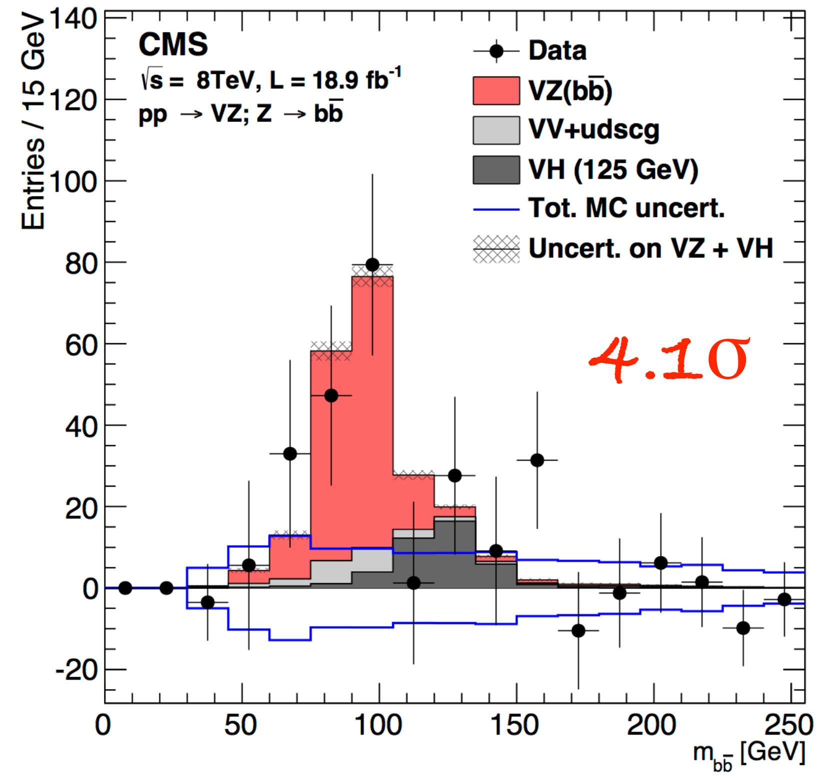


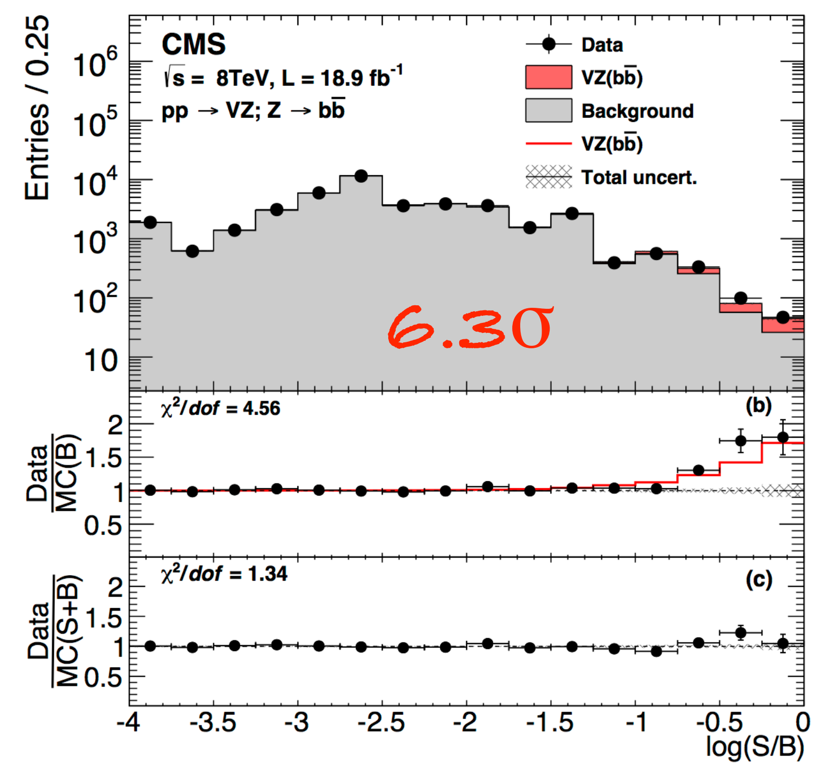
The resulting improvement in the Higgs mass resolution is **20%** (**Zll**), **15%** (**Zνν** and **Wlν**), **15%** (**VBF**)

(dependency on the event topology)

VZ, Strategy







Key points:

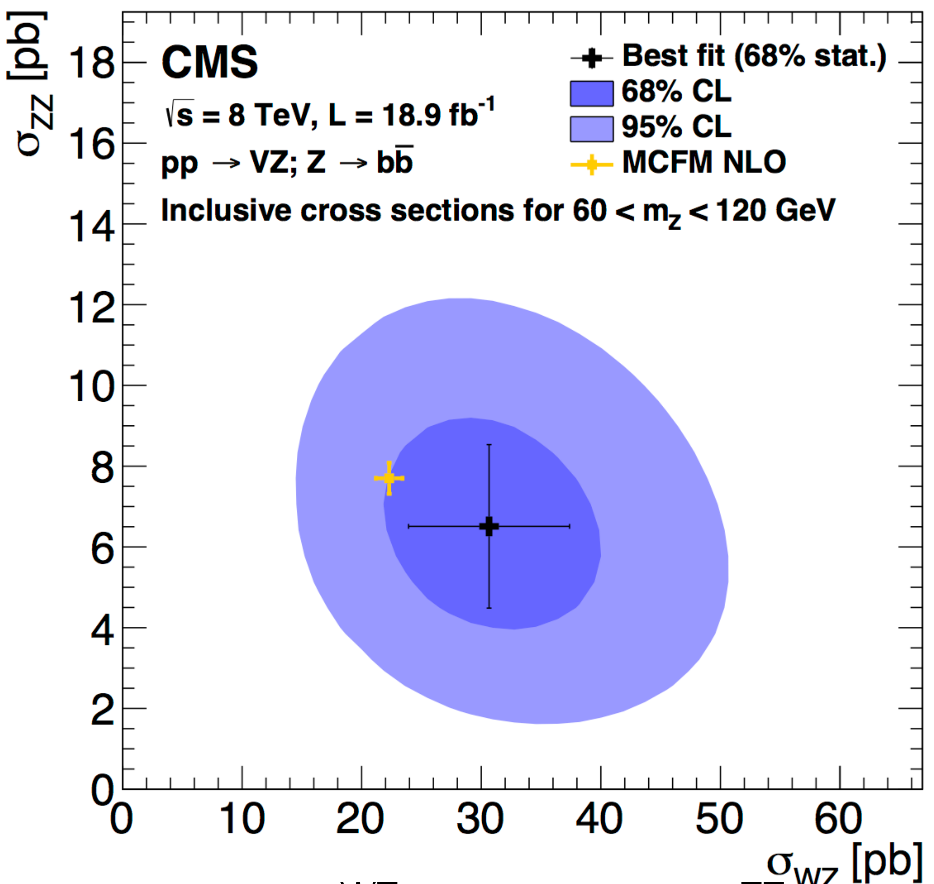
1. Extract normalization for the dominant backgrounds from the data V+0b/1b/2b and top pair production
2. A multivariate analysis, BDT
3. b-jet energy specific corrections (**regression**)

VZ, Systematic Uncertainties

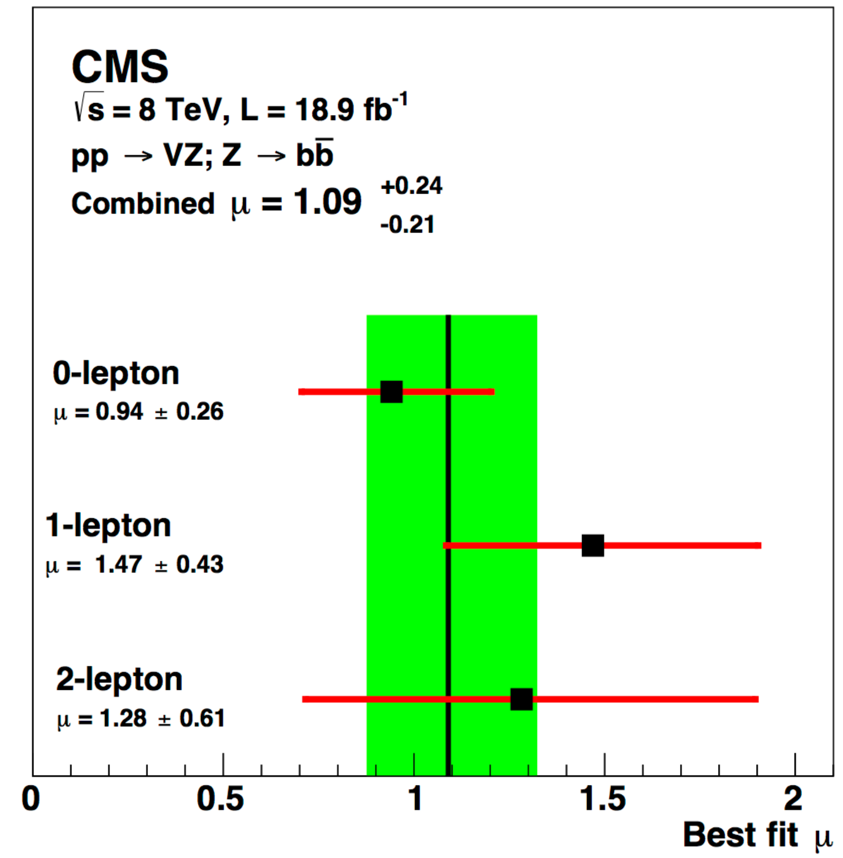
- Shape systematic
  - btag, JER, JES, trigger, generator modeling
- logNormal systematic
  - SF, signal cross section
- The systematics effect is in total of ~25% on the signal strength

Source	Type	Yield uncertainty (%) range	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Luminosity	norm.	4.4	12.3	4.4
Lepton efficiency and trigger	norm.	3	< 2	< 0.1
$Z \to \nu\bar{\nu}$ triggers	shape	3	< 2	< 0.1
Jet energy scale	shape	2–3	8.6	2.0
Jet energy resolution	shape	3–6	6.4	1.1
Missing transverse energy	shape	3	2.3	0.2
b-tagging	shape	3–15	8.7	2.0
Signal cross section (scale and PDF)	norm.	5	10.7	3.9
Monte Carlo statistics	shape	1–5	5.0	0.7
Backgrounds (data estimate)	norm.	10	10.6	3.6
Single-top and Higgs (MC estimate)	norm.	15	4.6	0.6
MC modeling (V+jets and $t\bar{t}$)	shape	10	2.7	1.1

VZ, Results



Best fit: μ^{WZ}=1.37 and μ^{ZZ} =0.85



μ with respect to LO MC rescaled to NLO

inclusive

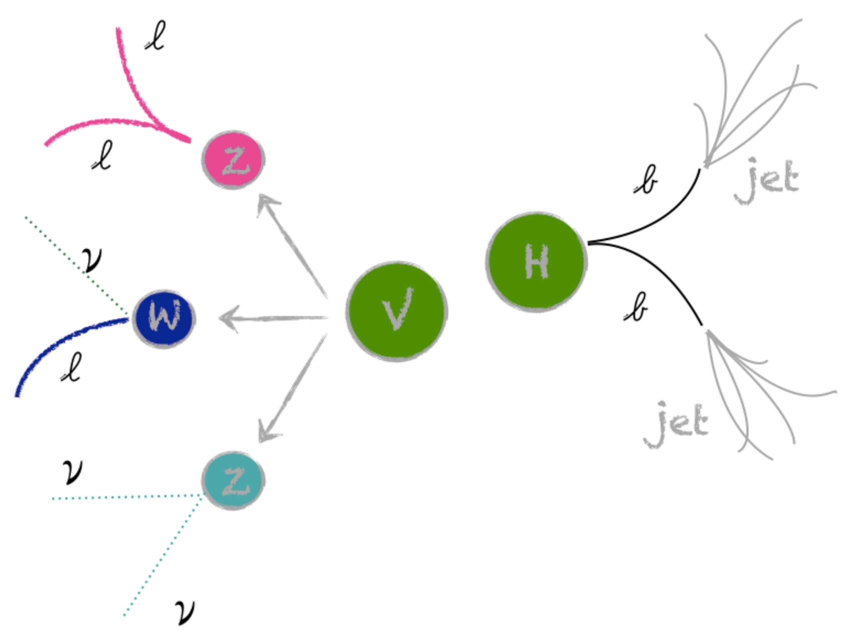
σ (pp→ZZ) = 6.5 ± 1.7 (stat.) ± 1.0 (syst.) ± 0.9 (th.) ± 0.2 (lum.) pb
σ (pp→WZ) = 30.7 ±9.3 (stat.) ± 7.1 (syst.) ± 4.1 (th.) ± 1.0 (lum.) pb

VH, Signal Topology

	Z→ll	W→lν	Z→νν	Z→ll	W→lν	Z→νν
Phys obj		p			ID,Iso	
PF muon	20, |η|<2.4	20, |η|<2.4	-	Tight muon, PF	Iso<0.12(dβ)	-
MVA electron	20, |η|<2.4	30, |η|<2.5	-	MVA 95	MVA80	-
HPS tau	-	40, |η|<2.1	-	-	LooseCIdβ>0.5	-
AK5 PF jets	20, |η|<2.4	30, |η|<2.4	80/30, |η|<2.4	Loose ID		Tight ID
Type I MET	-	45	100	-	-	

two isolated 20 GeV
e or μ with
75<M(ee,μμ)<105

one isolated 30 GeV
lepton
and additional missing
transverse energy (MET)



no isolated lepton and large MET

- (b)jets 20-30 GeV AK5 PFJets,
- The highest di-jet p_T combination in the event is selected.
- The CSV tagger is used to select the **b-jets**

VH, Background Estimate

The contributing backgrounds are :

• W/Z+jets splitted in **V+bb** and **V+udscg** • $t\bar{t}$ pair production (**$t\bar{t}$**)	Data-driven normalization to signal region
• Single top, WW	MC
• QCD multijet	Negligible

• Control regions (CR) for the main backgrounds: **V+bb**, **$t\bar{t}$**, **V+udscg** - are identified in data and used to adjust Monte Carlo estimates.

• A set of simultaneous fits is performed to the CR separately in each channel to obtain consistent data/MC scale factors.

Also a different fit among the different $p_T(V)$ categories except Z(ll) channel

•Based on CMS&Atlas studies events are split into 0/1/2b content at generator level.

•Electron and muons samples are fit simultaneously to determine average SF.

VH, Scale Factors

Process	$W(\ell\nu)$	$Z(\ell\ell)$	$Z(\nu\nu)$
Low			
W0b	$1.03 \pm 0.01 \pm 0.05$	–	$0.83 \pm 0.02 \pm 0.04$
W1b	$2.22 \pm 0.25 \pm 0.20$	–	$2.30 \pm 0.21 \pm 0.11$
W2b	$1.58 \pm 0.26 \pm 0.24$	–	$0.85 \pm 0.24 \pm 0.14$
Z0b	–	$1.11 \pm 0.04 \pm 0.06$	$1.24 \pm 0.03 \pm 0.09$
Z1b	–	$1.59 \pm 0.07 \pm 0.08$	$2.06 \pm 0.06 \pm 0.09$
Z2b	–	$0.98 \pm 0.10 \pm 0.08$	$1.25 \pm 0.05 \pm 0.11$
	$1.03 \pm 0.01 \pm 0.04$	$1.10 \pm 0.05 \pm 0.06$	$1.01 \pm 0.02 \pm 0.04$
Intermediate			
W0b	$1.02 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.04$
W1b	$2.90 \pm 0.26 \pm 0.20$	–	$2.08 \pm 0.20 \pm 0.12$
W2b	$1.30 \pm 0.23 \pm 0.14$	–	$0.75 \pm 0.26 \pm 0.11$
Z0b	–	–	$1.19 \pm 0.03 \pm 0.07$
Z1b	–	–	$2.30 \pm 0.07 \pm 0.08$
Z2b	–	–	$1.11 \pm 0.06 \pm 0.12$
	$1.02 \pm 0.01 \pm 0.15$	–	$0.99 \pm 0.02 \pm 0.03$
High			
W0b	$1.04 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.03$
W1b	$2.46 \pm 0.33 \pm 0.22$	–	$2.12 \pm 0.22 \pm 0.10$
W2b	$0.77 \pm 0.25 \pm 0.08$	–	$0.71 \pm 0.25 \pm 0.15$
Z0b	–	$1.11 \pm 0.04 \pm 0.06$	$1.17 \pm 0.02 \pm 0.08$
Z1b	–	$1.59 \pm 0.07 \pm 0.08$	$2.13 \pm 0.05 \pm 0.07$
Z2b	–	$0.98 \pm 0.10 \pm 0.08$	$1.12 \pm 0.04 \pm 0.10$
	$1.00 \pm 0.01 \pm 0.11$	$1.10 \pm 0.05 \pm 0.06$	$0.99 \pm 0.02 \pm 0.03$

All SFs are in good agreement across the different modes

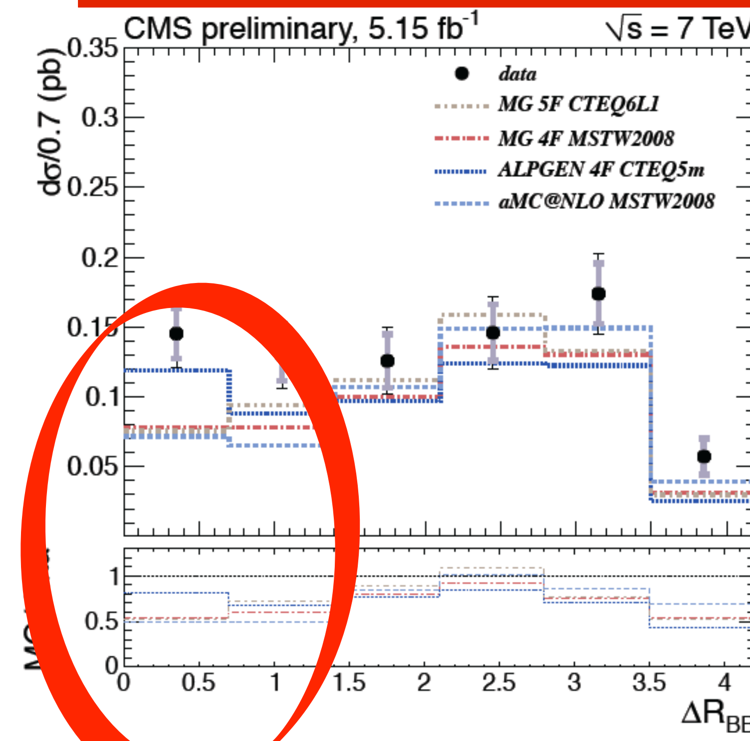
- The major part is close to 1
- V+1b is typically ~2, but:

- Not dominant background
- consistent with other CMS/Atlas studies

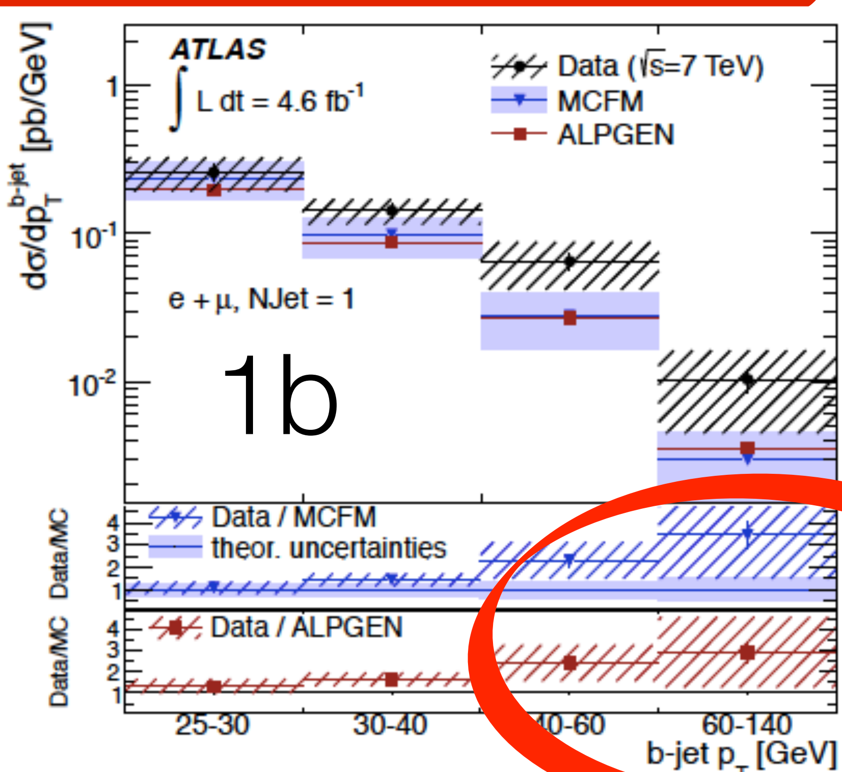
VH, 0/1/2 b splitting

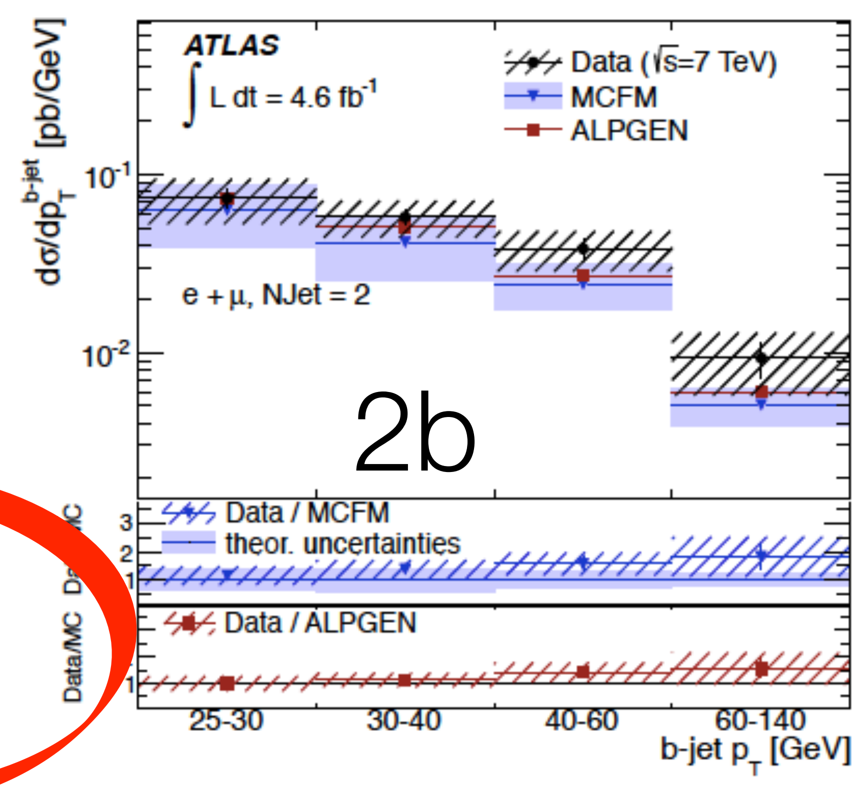
CMS, BB angular correlations,AN-11-179

Indication of gluon splitting, i.e. two b's end up in the same jet.
- SF(1b) ~ 2 is then motivated

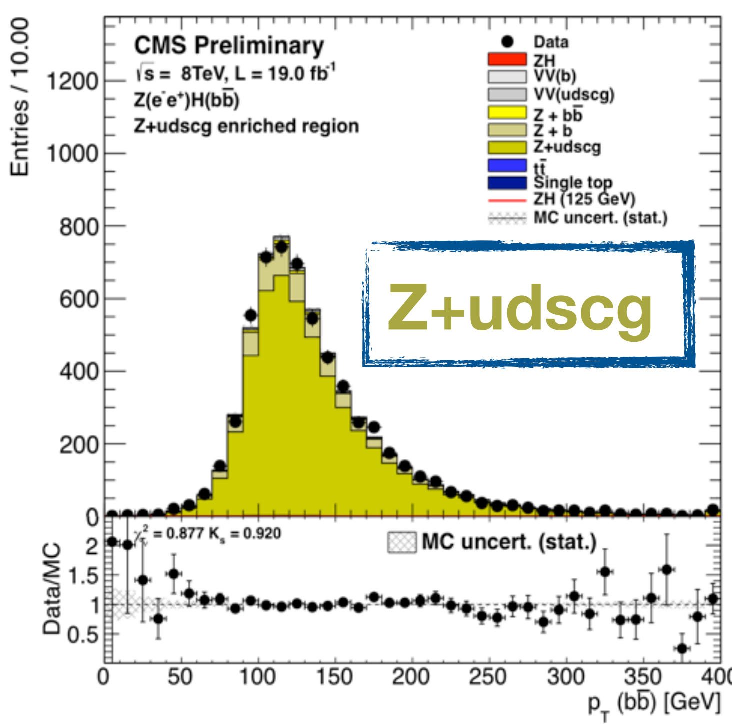


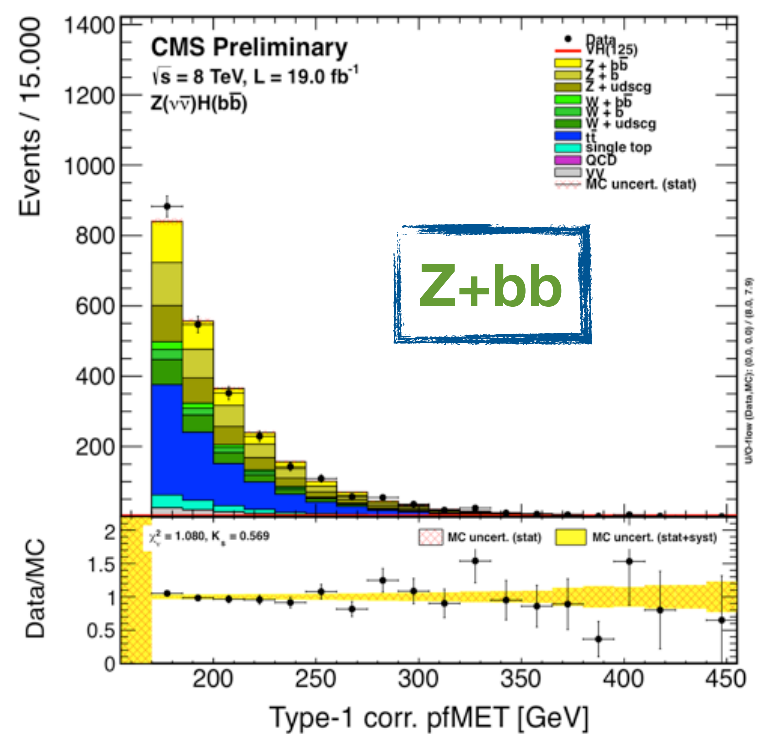
ATLAS, W+bjets xsec measurement
arXiv:1302.2929v1-13-069

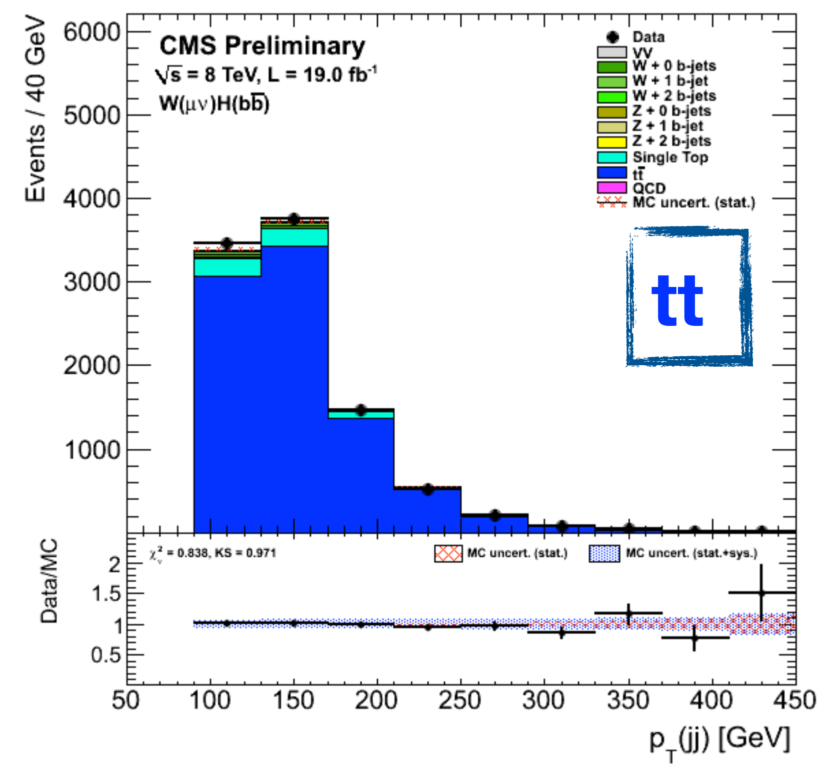


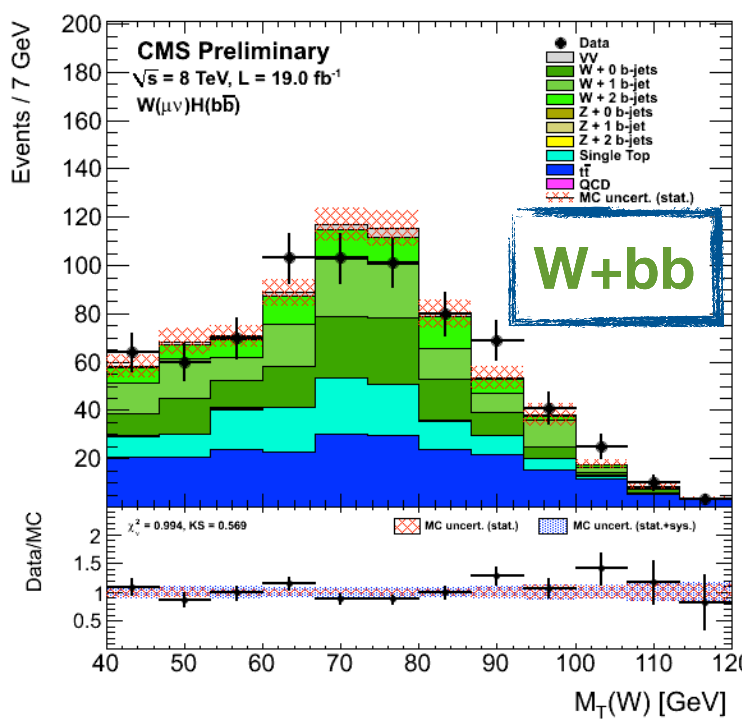


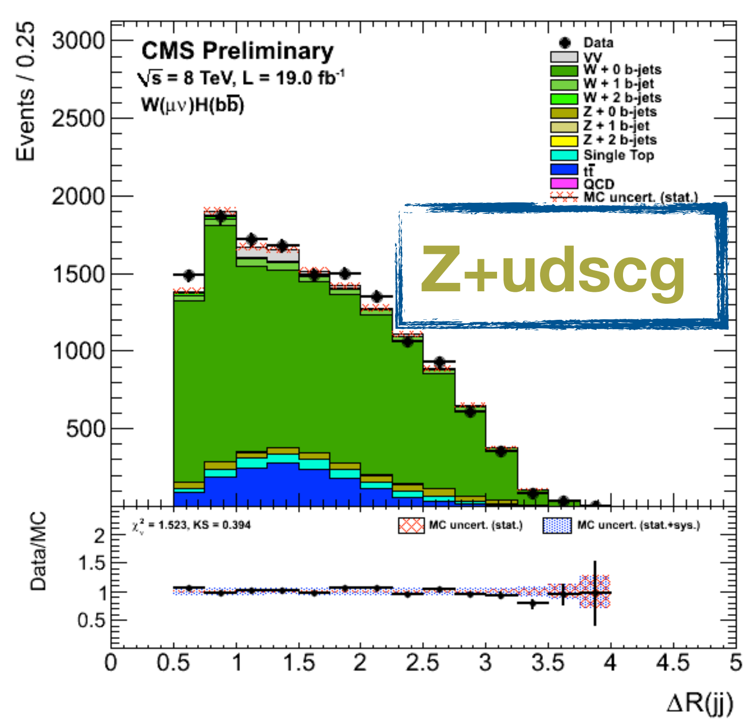
VH, Data/MC agreement











Good agreement in several control regions for all modes after applying SFs.

VH, Event Selections

Variable	$W(\ell\nu)Z$	$Z(\ell\ell)Z$	$Z(\nu\nu)Z$
$m_{\ell\ell}$	–	–	$75 < m_{\ell\ell} < 105$
$p_T(j_1)$, $p_T(j_2)$	> 30, > 30	> 20, > 20	> 60 > 30
$p_T(\mathrm{jj})$	> 100	–	> 110
$p_T(\ell)$	> 30	> 20	–
$p_T(\mathrm{V})$	$[100-130]$ (μ) $[100-150]$ (e) $[130-180]$ (μ) > 150 (e) > 180 (μ)	– $[100-150]$ > 150	$[100-130]$ $[130-170]$ > 170
$\mathrm{CSV}(j_1)$, $\mathrm{CSV}(j_2)$	CSVT, > 0.5	CSVM, > 0.5	CSVT, > 0.5
$\Delta\phi(\mathrm{V,H})$	> 2.95	–	> 2.95
$\Delta R(\mathrm{jj})$	–	$-(-, < 1.6)$	–
N_{aj}	$= 0$	–	$= 0$
N_{al}	$= 0$	–	$= 0$
$\mathrm{E_T^{miss}}$	> 45	$< 60.$	–
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{jet})$	–	–	$> 0.7\,(> 0.7, > 0.5)$
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{trkMET})$	–	–	< 0.5
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{lep})$	$< \pi/2$	–	–

- Subset of events used in the BDT analysis
  - Tighter selection in b-tagging and other additional selection
  - Different binning in boson-p_T
- For Z(ll) optimized on p_T (V), selecting different regions and then wrt the cut on dR($b\bar{b}$)

Variable	$W(\ell\nu)Z$	$Z(\ell\ell)Z$	$Z(\nu\nu)Z$
$m_{\ell\ell}$	–	$[75-105]$	–
$p_T(j_1)$, $p_T(j_2)$	> 30, > 30	> 20, > 20	> 60, > 30
$p_T(\mathrm{jj})$	> 100	–	> 100
$M(\mathrm{jj})$	< 250	$[40-250]$	< 250
$p_T(\ell)$	> 30	> 20	–
$p_T(\mathrm{V})$	$[100-130]$ (μ) $[100-150]$ (e) $[130-180]$ (μ) > 150 (e) > 180 (μ)	– – > 100	$[100-130]$ $[130-170]$ > 170
$\mathrm{CSV_{max}}$, $\mathrm{CSV_{min}}$	> 0.40, > 0.40	> 0.50, > 0.24	> 0.67, > 0.24
N_{aj}	–	–	< 2 (–,–)
N_{al}	$= 0$	–	$= 0$
$\mathrm{E_T^{miss}}$	> 80 (τ)	–	–
$\Delta\phi(\mathrm{V,H})$	–	–	> 2.0
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{jet})$	–	–	> 0.7 $(> 0.7, > 0.5)$
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{trkMET})$	–	–	< 0.5
pfMET significance	–	–	> 3 (–,–)
$\Delta\phi(\mathrm{E_T^{miss}}, \mathrm{lep})$	$< \pi/2$	–	–
Tightened Lepton Iso.	< 0.075 (–, –)	–	–

Final selection criteria optimized for each channel for the Higgs search in order to maximize signal efficiency

- Z/W selection plus loose b-tag requirements than for Mjj selection.

VH, BDT Training

- Separate BDTs trained in each channel and for each boost category
- **Inputs** used allow to exploit the complete kinematic information of the event.
- All variables are monitored in the CR, as well the outputs distribution

Variable
p_T(j): transverse momentum of each Z($b\bar{b}$) daughter
M(jj): dijet invariant mass
p_T(jj): dijet transverse momentum
p_T(V): vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Z($b\bar{b}$) daughter with largest CSV value
CSV_{min}: value of CSV for the Z($b\bar{b}$) daughter with second largest CSV value
$\Delta\phi(V, H)$: azimuthal angle between V and dijet
$\Delta\eta$(jj): difference in η between Z($b\bar{b}$) daughters
ΔR(jj): distance in η–ϕ between Z($b\bar{b}$) daughters
N_{aj}: number of additional jets
$\Delta\theta_{pull}$: color pull angle [2]
$\Delta\phi(E_T^{miss}$, jet): azimuthal angle between $E_T^{miss}$and the closest jet (only for Z($\nu\nu$))
$maxCSV_{aj}$: maximum CSV of the additional jets in an event (only for $Z(\nu\nu) and W(\ell\nu)$)
$min\Delta R(H, aj)$: mimimum distance between an additional jet and the Z($b\bar{b}$) candidate (only for Z($\nu\nu$) and W($\ell\nu$))
Angular variables: VZ system mass, Angle Z-Z*, Angle Z-l, Angle Z-jet (only for Z($\ell\ell$))

VH, Systematic Uncertainties

- Shape systematic
  - btag, JER, JES, trigger, generator modeling
- logNormal systematic
  - SF, signal cross section
- The systematics effect is in total of ~15% on the signal strength

Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Luminosity	norm.	2.2–2.6	<2	<0.1
Lepton efficiency and trigger (per lepton)	norm.	3	<2	<0.1
$Z(\nu\nu)H$ triggers	shape	3	<2	<0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top-quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

VBF, $m(b\bar{b})$ fit

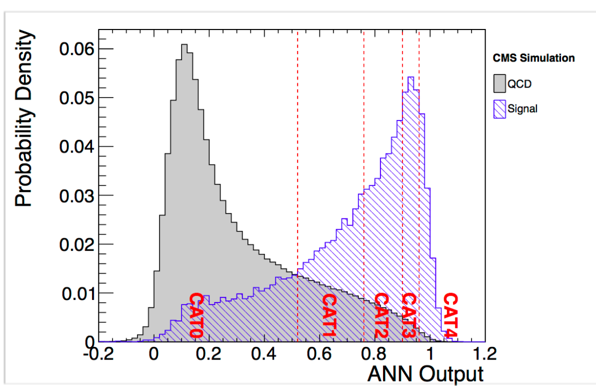
The most contributing backgrounds are :

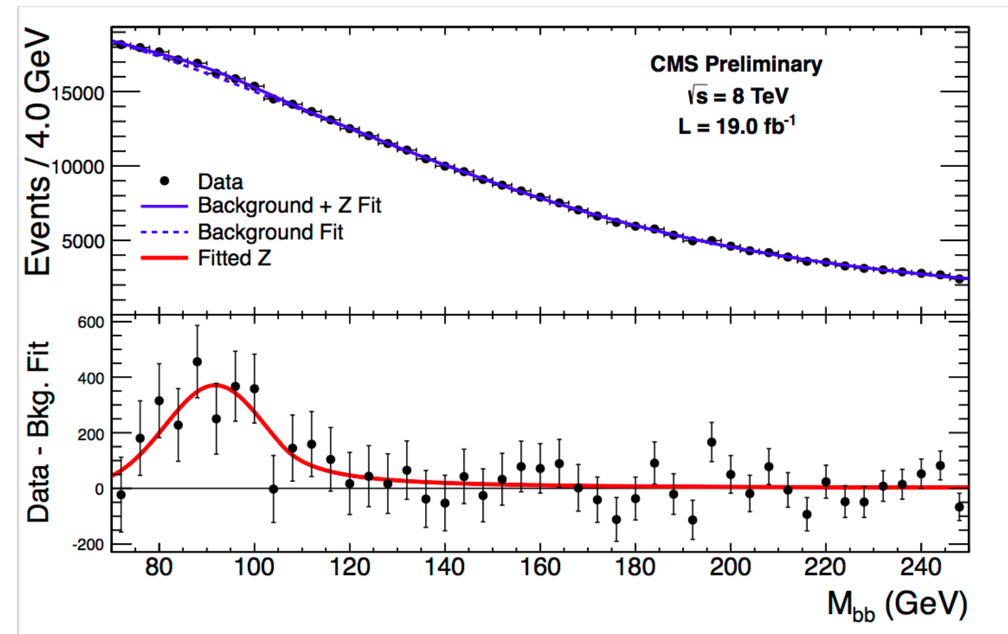
- Z+jets
- top

} MC normalization
shape model: crystal ball

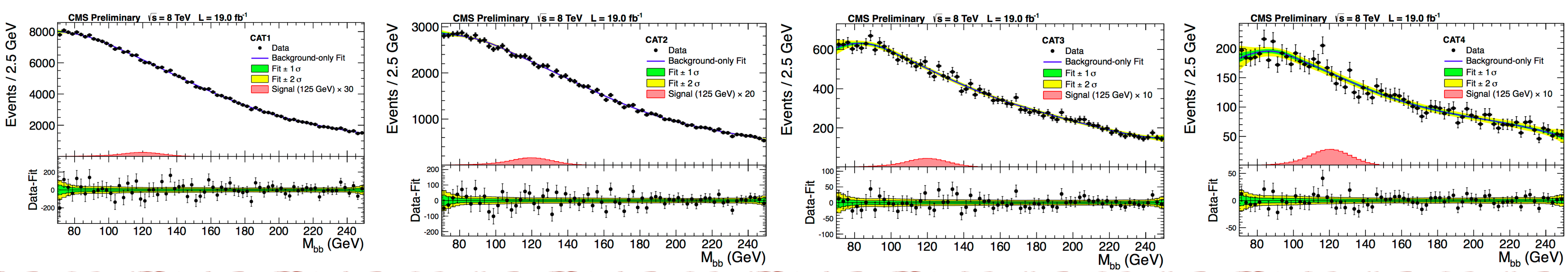
- QCD

} data driven normalization
shape model: Bernstein





fit procedure has been validated using the $Z(b\bar{b})$ signal



$H(b\bar{b})$ signal, separately for each category

ttH with the Matrix Element Method

CMS-HIG-14-010

see Bianchini's talk

- Analytical matrix element method for S/B separation
  - integrate over unreconstructed or poorly measured particles
  - ttH vs. ttbb
- Event categories through MEM classification
  - select 4 jets most likely to come from b quark hadronization
  - 4 event categories
- The $P_{s/B}$ is then computed as the ratio of ttH/ttb$\bar{b}$ probability density
- Combined fit to $P_{s/B}$ discriminant

$$\mu = 0.7 \pm 1.4$$

- 30% improvement on previous ttH(b$\bar{b}$) CMS analysis
  - less sensitive to tt+HF modeling

"SL Cat-1"	"SL Cat-3"	"SL Cat-2"	"DL"
$tt \rightarrow b\ell\nu\ bqq$	$tt \rightarrow b\ell\nu\ bqq$	$tt \rightarrow b\ell\nu\ bqq + g$	$tt \rightarrow b\ell\nu\ b\ell\nu$
all quarks reconstructed (+ *gluon(s)*)	all quarks *but one W-quark* reconstructed	all quarks *but one W-quark* reconstructed + ≥ *1 gluon(s)*	all quarks reconstructed