Status of H→bb and H→cc search with full Run 2

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Introduction

Goal of my thesis: “Inclusive H⟶bb and H⟶ cc searches at LHCb with the full Run 2 (5.4 fb^{-1})”

- DNN-based jet flavour tagging to separate b vs c vs (u,d,s,g)
  - Inputs are not only SV variables. Global quantities of the jet and features of charged and neutral particles in the jet are also considered
  - Three outputs: probabilities to be a b, c, or light jet
  - $P_b+P_c+P_q=1$
- Significance calculated in the invariant mass range [66,146] GeV (5.4 fb^{-1}) is 0.15
  - expected number of data: 31 M
  - expected number of Higgs in bb events: 840

$$S_b = \frac{N_{H\to bb}}{\sqrt{N_{data}}}$$

- Significance not enough to measure H⟶bb and H⟶cc cross section
  - limit on the production cross section will be set on the inclusive H⟶bb and H⟶ cc production cross sections and prospects for Yukhawa couplings at HL-LHC

Analysis Strategy

- Model of the bb (cc) QCD background for the H⟶bb (H⟶ cc) search:
    - Define a signal region (SR) and a control region (CR) on **data** by applying requirements on the DNN output:
        - Signal region, signal is expected: both jets in the final state are identified as b quarks;
        - Control region, mixed flavour in order to not have resonances: events that have the same kinematic characteristics as SR, but one quark is identified as b (c) quark, the other as light quark.
    - Transfer Function calculated from the Monte Carlo QCD bb or cc samples + correction function
- Fit to the di-jet invariant mass distribution
- Set of upper limits on inclusive production cross sections with CLs method
- Evaluation of the systematic uncertainties

Data and Monte Carlo samples

- Run II data-taking in the year 2016, center of mass energy 13 TeV
- Events used are those that pass the HLT2 lines: *HLTQEEJetsDiJetSVSV* and *HLTQEEJetsDiJetSV* (prescaled)
  - *HLTQEEJetsDiJetSVSV*: for both jets p_T>17 GeV, SV in jet cone
  - *HLTQEEJetsDiJetSV*: events with two reconstructed jets, at least one with SV
- Stripping lines required are *StrippingHLTQEEJetsDiJetSVSV* and *StrippingHLTQEEJetsDiJetSV* that store events where HLT2 lines are true. Tot integrated luminosity 1.6 fb^{-1} for both samples.
- Monte Carlo: H⟶bb, H⟶cc, Z⟶bb, Z⟶cc, QCD (bb,cc,qq)
- **Selection requirements**: P_T>20 GeV, 2.2 < η< 4.2, |Δφ| > 1.5, one of the two jets L0Chain TOS and HLT1Chain TOS

Monte Carlo requirements	H⟶bb	H⟶cc	Z⟶bb	Z⟶cc
Selection requirements+ **both jets SV-tagged**	11%	1.4%	14%	1.1%
Selection requirements+ **at least one jet SV-tagged**	30%	13%	34%	10%

- L0Chain TOS:
  L0HadronDecision_TOS || L0MuonDecision_TOS || L0PhotonDecision_TOS || L0DiMuonDecision_TOS || L0ElectronDecision_TOS || L0MuonEWDecision_TOS || L0JetPhotonDecision || L0JetPhotonDecision
- HLT1Chain TOS:
  Hlt1TrackMVADecision_TOS || Hlt1TwoTrackMVADecision_TOS || Hlt1TrackMuonDecision_TOS || Hlt1TrackMVATightDecision_TOS || Hlt1TwoTrackMVATightDecision_TOS ||Hlt1DiMuonHighMassDecision_TOS || Hlt1DiMuonLowMassDecision_TOS ||Hlt1SingleMuonHighPTDecision_TOS || Hlt1DiMuonNoL0Decision_TOS;

$H \rightarrow bb$: signal region

- Region where the signal is expected
- DNN P_b and P_q requirements tuned to maximize the significance in the SVSV data sample $S_b = \frac{N_{H\rightarrow bb}}{\sqrt{N_{data}}}$

$$N_{sign} = \mathcal{L} \cdot \sigma_{th} \cdot A \cdot \epsilon$$

$$\mathcal{L} = 1644.16 \text{ pb}^{-1}$$

ϵ includes the selection efficiencies, the cut on the DNN probability

- Maximum significance reached when both jets have $P_b>0.25$

Requirements	$P_b>0.25$ on both jets
$N_{H\rightarrow bb}$	257
N_{Data}	2.1e+07
Purity ($N_{H\rightarrow bb}/N_{Data}$)	1.3e-05
Significance	0.057

Purity and significance calculated in the entire mass spectrum

$H \rightarrow bb$: control region

- The goal is to have a data sample with enough data statistics while minimizing the number of signal events
- This search is done both in SVSV and in SVjet samples
- Different criteria have been studied to choose the best working point:
  - Significance minimization
  - Purity minimization $N_{H\rightarrow bb}/N_{Data}$
  - **$F=N_{H\rightarrow bb}/(N_{Data})^{3/2}$ minimization** (the idea was to increase the data statistics while keeping purity close to the minimum)
- Statistics higher in the SVSV sample, but SV+jet sample offers higher purity (less signal contamination in the CR)

Working point SR	P_b>0.25 on both jets
N_{Data}	2.1e+07
Purity	1.3e-05
Significance	0.057

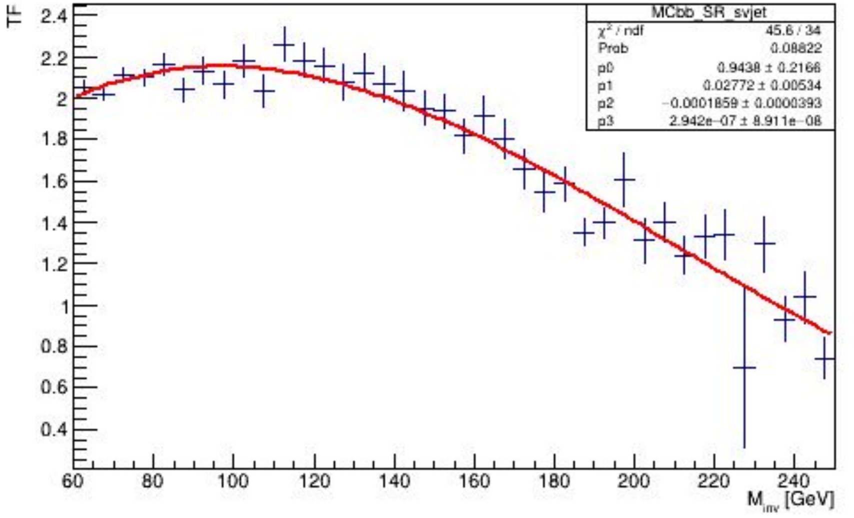
Working Point **SVSV**, CR
P_b>0.25 on one jet P_b< 0.25 on the other jet
N data: 3.23e+06
Significance: 0.009
Purity: 5e-06
F: 2.7e-09

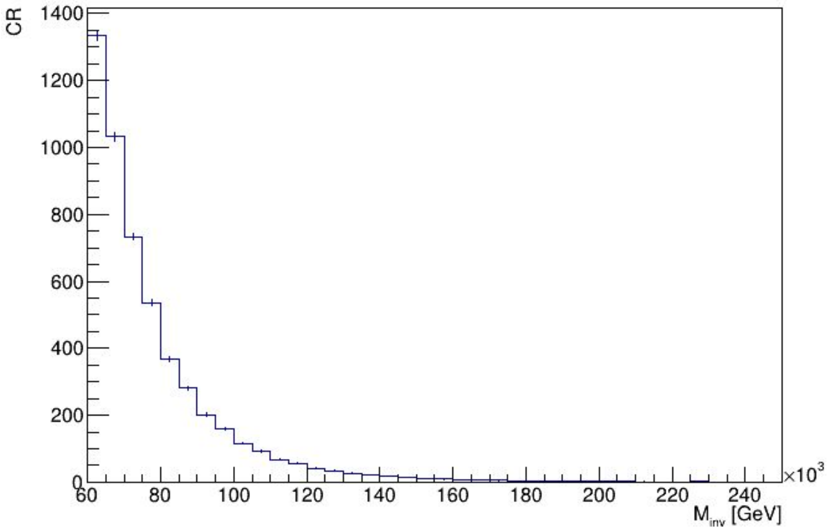
Working point **SV+jet**, CR
P_b>0.25 on the jet with SV, P_b< 0.22 on the other jet
N data: 1.1e+06 (with pre-scaling)
Significance: 0.02
Purity: 2.2e-06
F: 2.1e-10

Transfer Function fit Range [60,250] GeV

- QCD bb background sample used to calculate the Transfer Function as a function of the dijet invariant mass

$$\mathrm{TF} = \frac{n_{events,SR}}{n_{events,CR}}$$

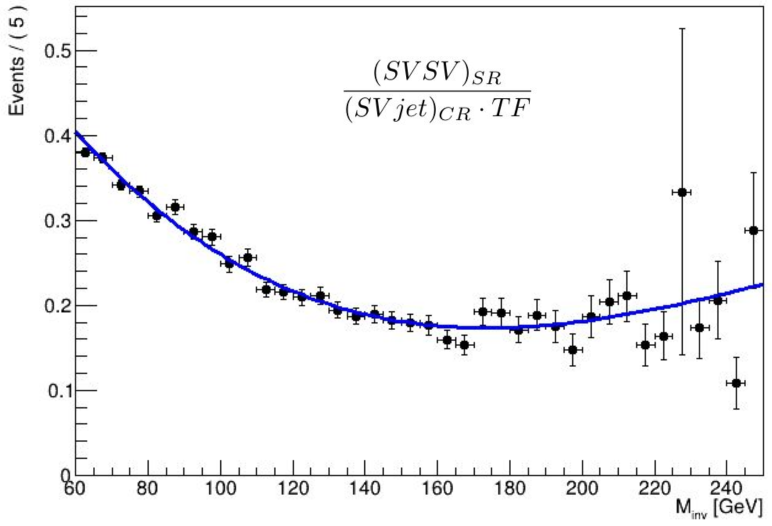




H →bb: full fit model

- Model to fit data in SVSV Signal Region, range [60,250] GeV:
  - H→bb, Z→bb, H→cc, Z→cc distributions from Monte Carlo
  - QCD background modeled as data in CR x TF (with CR and TF built from with SVjet samples)
  - Correction function (shape: Bernstein function)
- Determination of the proper number of coefficients of the Bernstein function: F-test
  - decide whether or not to reject the lower polynomial degree in favor of the higher polynomial degree
  - Bernstein polynomial degree: 4

- Correction function initial parameters: calculated by fitting a small portion of data
- Parameters of the correction function left free to vary in the fit to data
- N_{data} and N_{Hbb} left free in the fit to data

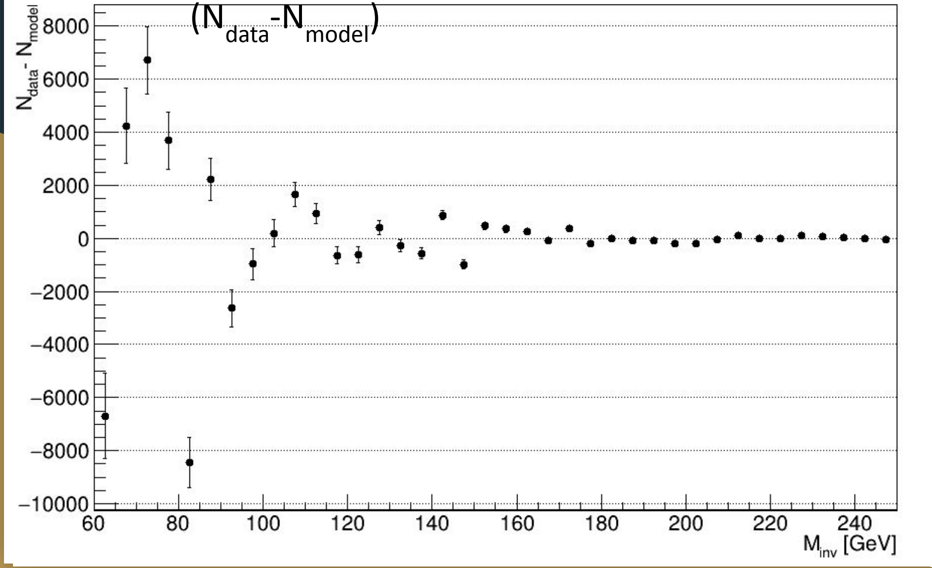


Fit to data results: H to bb

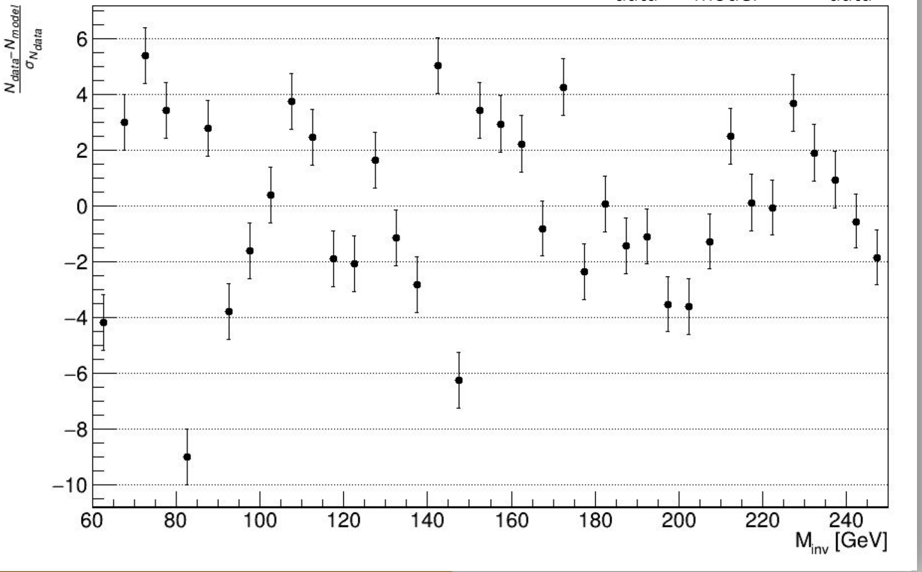
- Results on signal and background left blind

```
Error on Higgs: 3257.03
x0: 6.59769 +/- 0.573768
x1: 1.49541 +/- 0.132015
x2: 2.84324 +/- 0.250394
x3: 3.14267 +/- 0.279535
```

Residual: $(N_{data}-N_{model})$

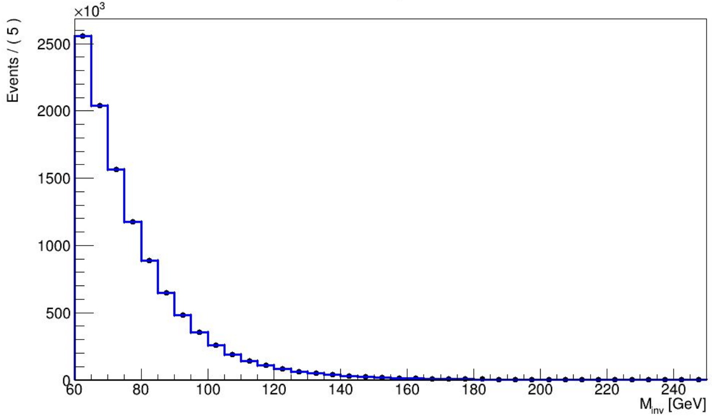


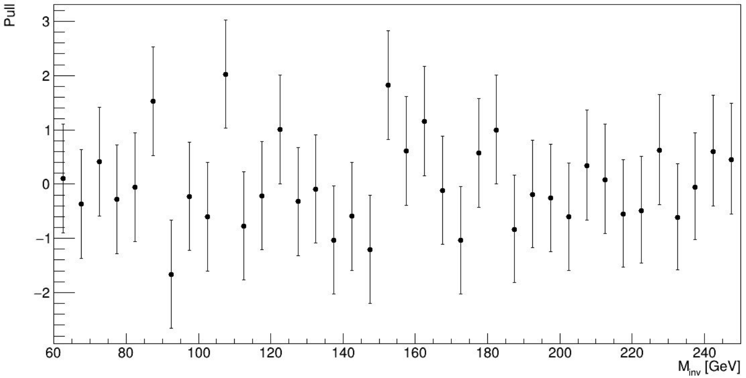
Pull: $(N_{data}-N_{model})/\sqrt{N_{data}}$

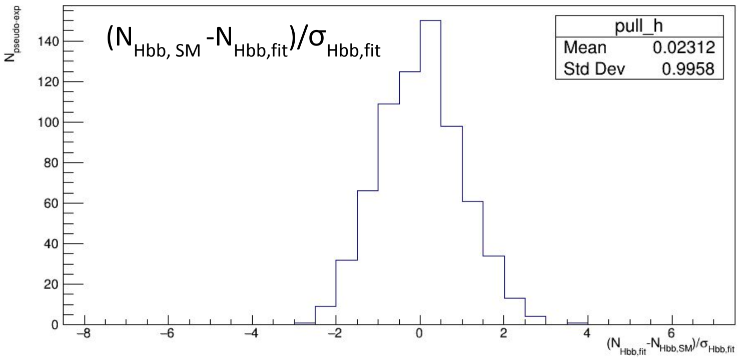


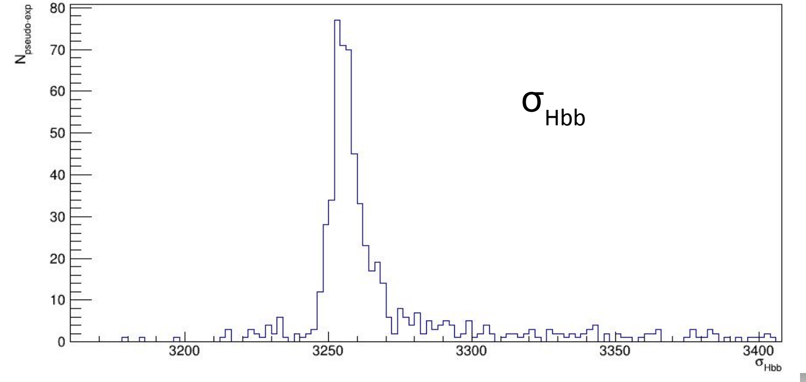
Monte Carlo fit validation

- Monte Carlo pseudo-experiment done with the Bern-4 correction function
- Initial values taken from the fit to data and then left free to vary in the fit

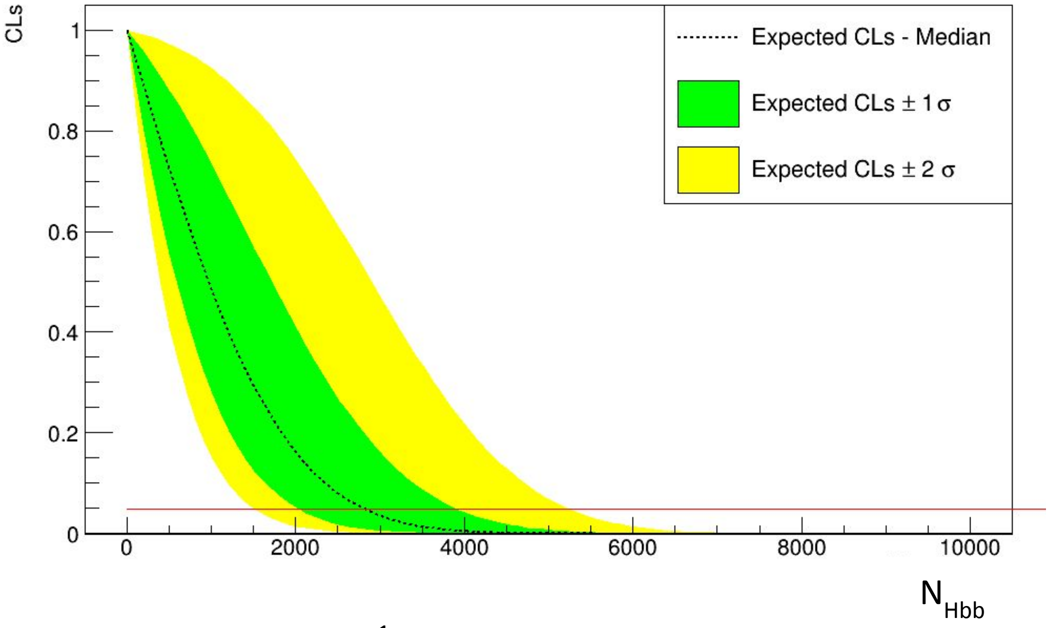








Expected Upper Limit on H to bb



Expected limit at 95% C.L.: 2807 in 1.6 fb^{-1} -> 12 x SM

Expected limit at 95% C.L. in 5.4 fb^{-1} (full Run 2) -> 6 x SM

Expected limit at 95% C.L. in 50 fb^{-1} (full Run 3+4) -> 2 x SM

Expected limit at 95% C.L. in 300 fb^{-1} (HL-LHC) -> 0.9 x SM

Signal and Control region H to cc

- Run II data-taking in the year 2016, center of mass energy 13 TeV, tot integrated luminosity 1.6 fb^{-1}
- Trigger: *HLTQEEJetsDiJetSVSV* and *HLTQEEJetsDiJetSV* (prescaled), *StrippingHLTQEEJetsDiJetSVSV* and *StrippingHLTQEEJetsDiJetSV*
- Monte Carlo: H→bb, H→cc, Z→bb, Z→cc, QCD (bb,cc,qq)
- **Selection requirements**: P_T>20 GeV, 2.2 < η< 4.2, |Δφ| > 1.5, one of the two jets L0Chain TOS and HLT1Chain TOS

- **SIGNAL REGION**: DNN P_c and P_q requirements tuned to maximize the significance in the SVSV data sample
- Maximum significance: both jets have P_c>0.15

Signal region	**P_c>0.15** on both jets
$N_{H\to cc}$	1.8 (entire mass spect)
N_{Data}	4 M (entire mass spect)
Purity ($N_{H\to cc}/N_{Data}$)	5.0e-07 (entire mass spect)
Significance	0.0008 (entire mass spect)

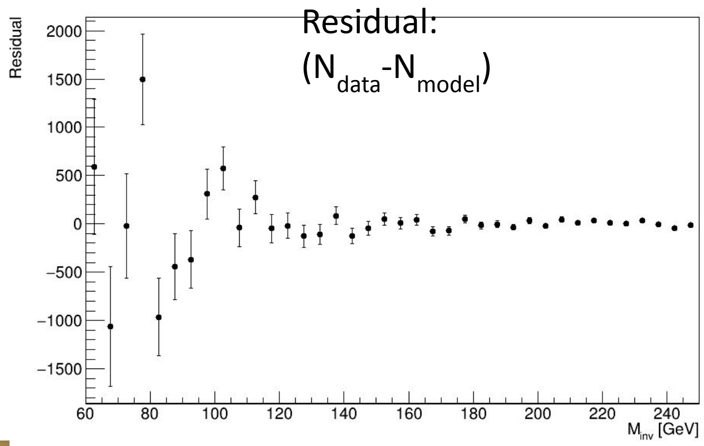
- **CONTROL REGION:** the goal is to have a data sample with enough data statistics while minimizing the number of signal events
- This search is done both in SVSV and in SVjet samples
- Low data statistics in the SV+jet sample, the SVSV is used

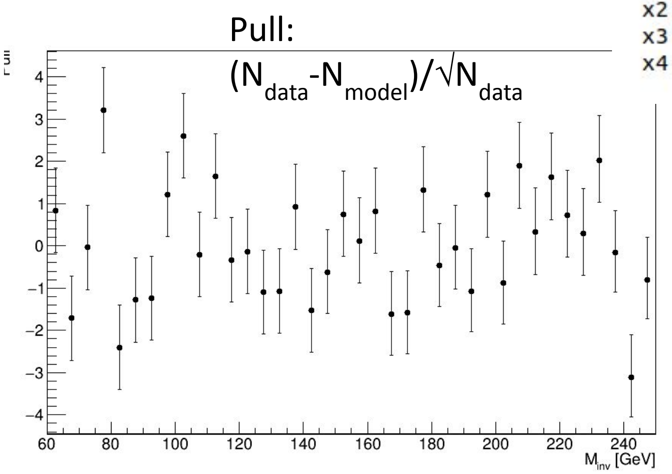
Control region	Minimum Signif. and purity
Cuts on P_c	**P_c>0.15 on one jet** **P_c< 0.02 on the other jet**
N data	4.5e+06
Significance	2.4e-05
Purity	1.1e-08

Fit to the SVSV signal region

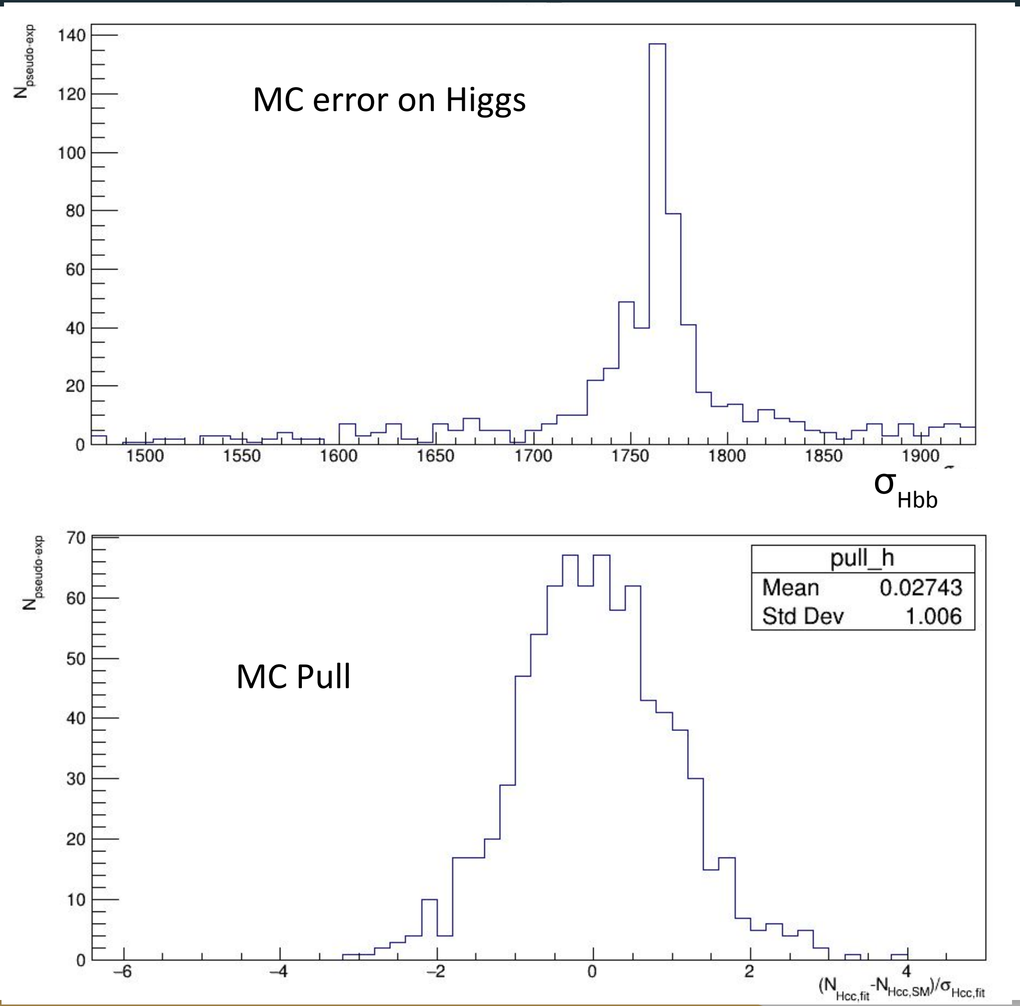
- Model to fit invariant mass distribution of data selected *HLTQEEJetsDiJetSVSV* Signal Region:
  - $H \to bb$, $Z \to bb$, $H \to cc$, $Z \to cc$ distributions from Monte Carlo
  - QCD background modeled as:
    - data SVSV in CR x Transfer Function (TF) determined using invariant mass distribution of Monte Carlo QCD bb and cc samples
    - Correction function (shape: Bernstein polynomial 5 coefficients)
- Correction function initial parameters: calculated by fitting a small portion of data and are left free in the fit to the full dataset
- N_{data} and N_{Hcc} left free in the fit to data

```
Error on Higgs to cc: 1798.69
x0: 4.98278 +/- 0.574746
x1: 4.72565 +/- 0.554297
x2: 8.11861 +/- 0.970454
x3: 7.00158 +/- 0.924254
x4: 6.85781 +/- 0.817415
```

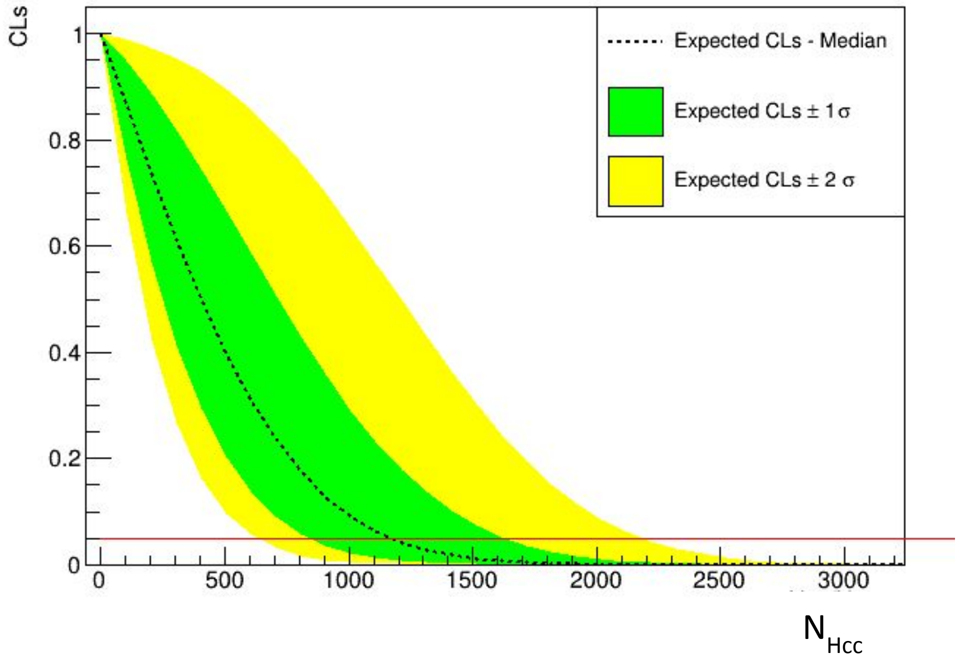




Monte Carlo fit validation H to cc



Expected Upper Limit on H to cc



L=1.6fb^{-1}: 1174 -> 665x SM

Scaling with luminosity:

L=5.6 fb^{-1} -> 356 x SM

L=50 fb^{-1} -> 116 x SM

L=300 fb^{-1} -> 47 x SM

Improvements to the H to cc significance

Upper limit roughly scales with the inverse of the Higgs significance S

- How much the significance increases without requiring SV, only DNN
  - Trigger line and stripping line with two jets required (Hlt2: Hlt2JetsDiJet and Stripping: FullDiJetsLine, total prescale: 1.3e-05)
  - Same selection requirements of the analysis: P_T>20 GeV, 2.2 < η< 4.2, |Δφ| > 1.5, one of the two jets L0Chain TOS and HLT1Chain TOS
  - DNN P_c and P_q optimized to maximize the significance

S (dijets): 0.0011

S (SVSV): 0.0008

Factor: 1.4

- C.o.m. will pass from 13 TeV to 14 TeV: $f = \frac{S(14TeV)}{S(13TeV)} = \frac{N_H(14TeV)}{N_H(13TeV)}\sqrt{\frac{N_{bkg}(13TeV)}{N_{bkg}(14TeV)}}$

$$\frac{N_{bb}(14TeV)}{N_{bb}(13TeV)} = \frac{(\sigma_{bb}\cdot A)(14TeV)}{(\sigma_{bb}\cdot A)(13TeV)} = 1.17+/-0.06$$

$$\frac{N_{qq}(14TeV)}{N_{qq}(13TeV)} = \frac{(\sigma_{qq}\cdot A)(14TeV)}{(\sigma_{qq}\cdot A)(13TeV)} = 1.21+/-0.13$$

$$\frac{N_{H}(14TeV)}{N_{H}(13TeV)} = \frac{(\sigma_{H}\cdot A)(14TeV)}{(\sigma_{H}\cdot A)(13TeV)} = 1.13+/-0.08$$

Factor~ 1

- Scaling factors for mixed flavour background are compatible with the bb and qq samples

Prospects on H to cc

*LHCb-CONF-2016-006
**https://agenda.infn.it/getFile.py/access?contribId=36&sessionId=4&resId=0&materialId=slides&confId=12253

- Final prospect for the upper limit on the inclusive Higgs cross section at HL-LHC, taking into account DNN improvement:

$$\frac{BR(H \to c\bar{c})}{BR_{SM}(H \to c\bar{c})} < 33$$

- V + H_0 (⟶ cc) limit: 6400xSM at 8 TeV in (*)
- From (**) limit recast for the H to cc cross section with the Higgs produced in association with a W/Z
  - V + H_0 (⟶ cc) limit: **50xSM** without any improvement in the analysis and the detector at HL-LHC
  - V + H_0 (⟶ cc) limit: **13xSM** with improvement in the c-tagging (best IP resolution) at HL-LHC
  - V + H_0 (⟶ cc) limit: **5-10xSM** with improvement in the c tagging and analysis at HL-LHC

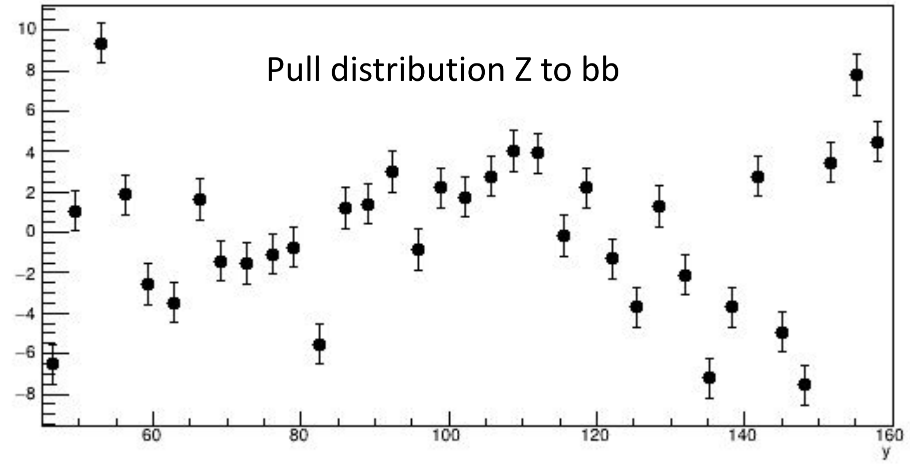
- With the improvement on c-tagging applied to the inclusive production, the 33xSM limit could become **~8.6xSM**

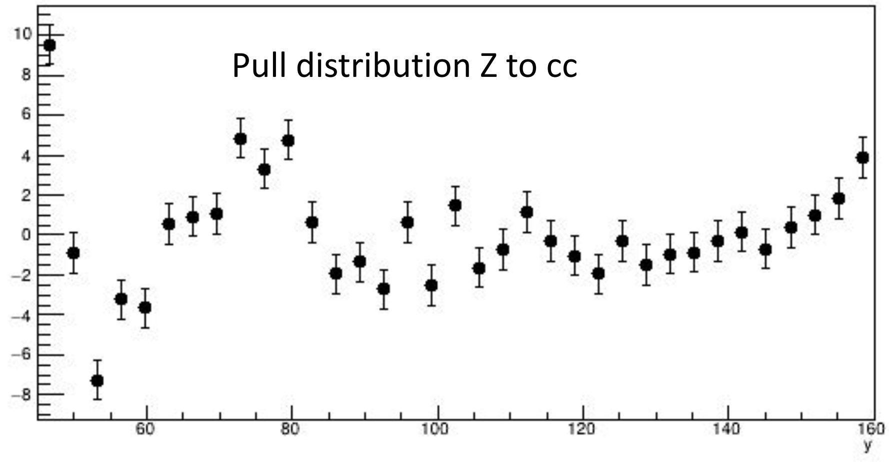
Z to bb and Z to cc fit

- Simultaneous fit of the Z to bb and Z to cc in the two signal regions, mass range [45,160] GeV:
  - One common signal strength parameter between the two fits for the Z to bb and one for the Z to cc
  - Number of data left free in the fit
  - The correction functions : Bernstein function with 4 coefficients for the cc and Bernstein function with 6 coefficients for bb

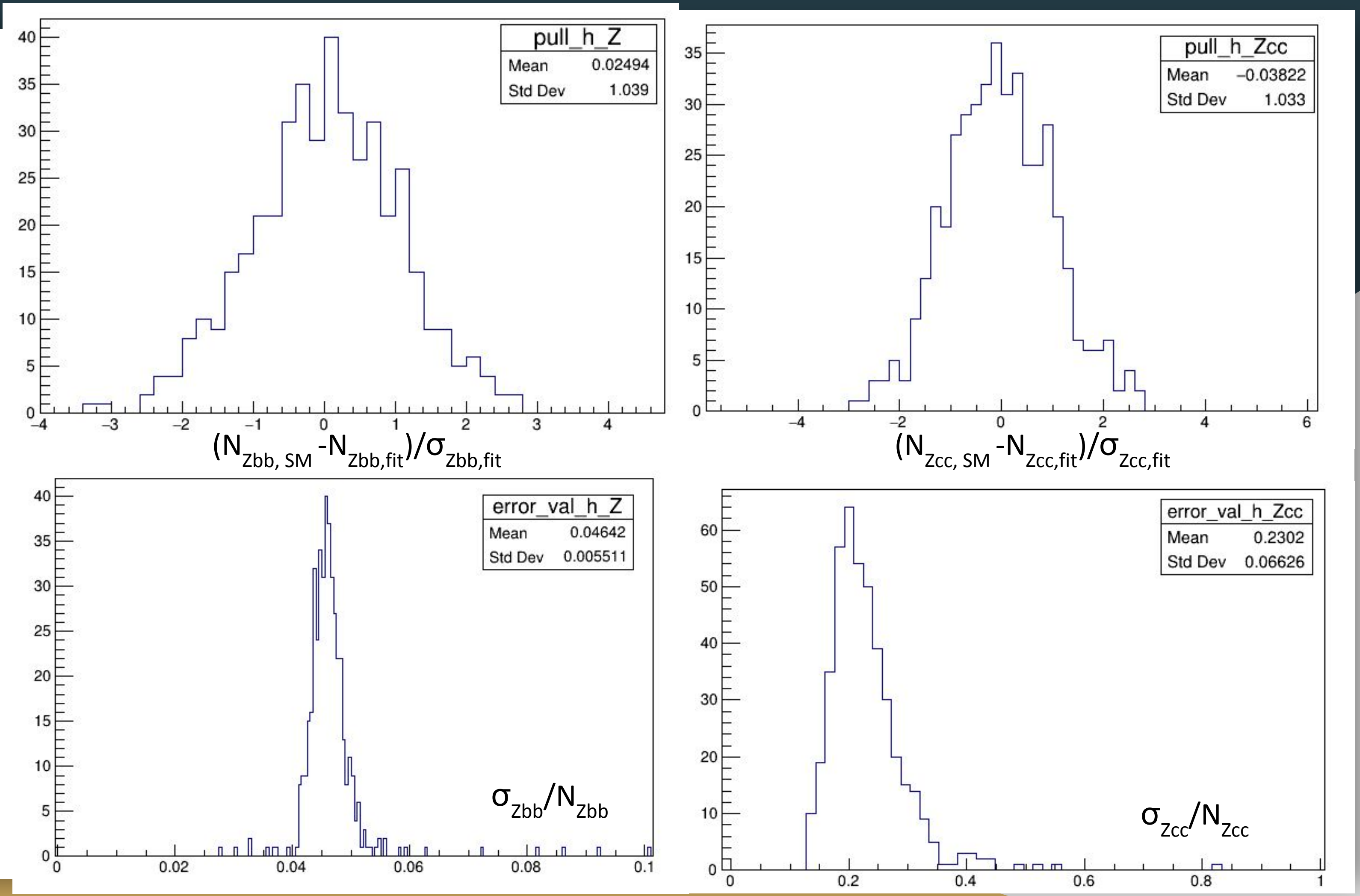
Z to bb signal strength:
6.5e-01 +/- 4.74e-02

Z to cc signal strength:
1.6e+00 +/- 2.26e-01





Monte Carlo



pull_h_Z
Mean 0.02494
Std Dev 1.039
$(N_{Zbb, SM} - N_{Zbb,fit})/\sigma_{Zbb,fit}$
pull_h_Zcc
Mean −0.03822
Std Dev 1.033
$(N_{Zcc, SM} - N_{Zcc,fit})/\sigma_{Zcc,fit}$
error_val_h_Z
Mean 0.04642
Std Dev 0.005511
σ_{Zbb}/N_{Zbb}
error_val_h_Zcc
Mean 0.2302
Std Dev 0.06626
σ_{Zcc}/N_{Zcc}

Current focus

- Calculation of systematic uncertainties started:
  - Systematic on correction function
    - to be added in limit calculation
  - Systematic on SV tagging:
    - Effects on limit to be determined

H to cc:

Modelling the correction with Bernstein poly, 5 coeff:
$L=1.6fb^{-1}$: 1174 -> 667x SM

Modelling the correction with Bernstein poly, 6 coeff
$L=1.6fb^{-1}$: 1171.9 -> 666x SM

	N Z in cc	N Z in bb	N H in cc	N H in bb
No Corr	15338	191391	2,1	265
Corr+1 sigma	18404	236841	2,2	353
Corr	15263	204406	1,7	302
Corr-1 sigma	12416	174431	1,3	258

jet p_T (GeV)	jet η	b jets	c jets
10–20	2.2–4.2	0.89 ± 0.04	0.81 ± 0.09
20–30	2.2–4.2	0.92 ± 0.07	0.97 ± 0.09
30–50	2.2–4.2	1.06 ± 0.08	1.04 ± 0.09
50–100	2.2–4.2	1.10 ± 0.09	0.81 ± 0.15

Next steps

- Complete the systematics and efficiency correction calculation:
  - Strategy defined for the calculation of some systematics: Control Region statistics, signal contamination in CR, DNN efficiency
  - For the others I will follow the same strategy that are explained in the analysis note “Measurement of differential $b\bar{b}$ and $c\bar{c}$ cross sections in the forward region of pp collisions at $\sqrt{s}$ = 13 TeV”: Jet Energy Correction, Jet Energy Scale, Jet Identification, Trigger…

TIMELINE

- by the end of August:
  - complete the systematics (upload results on the H to cc paper from time to time)
  - write the introduction chapters (detector, Higgs, event reconstruction)
- since September: apply to Z to bb and Z to cc fit, write the analysis

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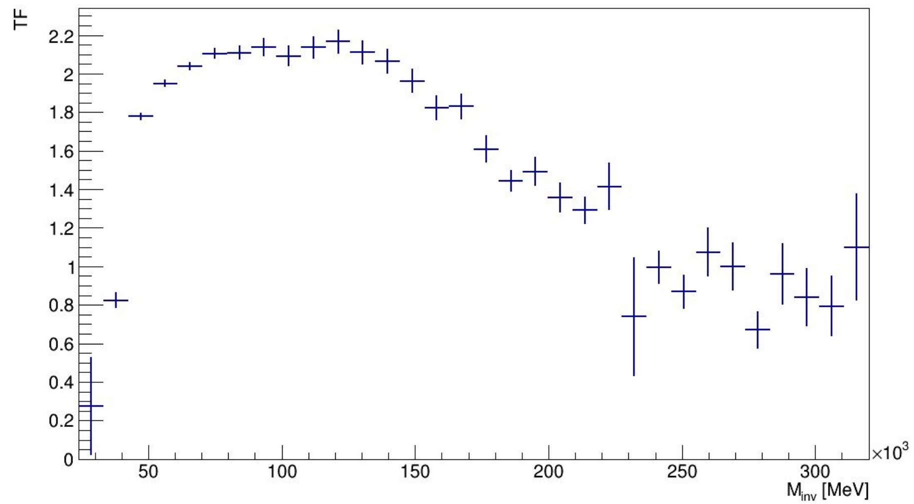
References

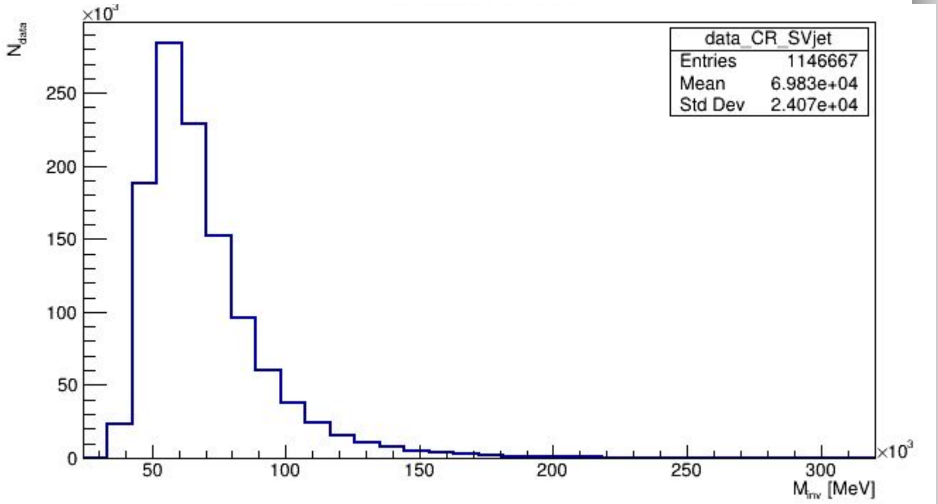
BACKUP

H →bb: transfer function SVjet

- QCD bb background sample used to calculate the Transfer Function as a function of the dijet invariant mass

$$\mathrm{TF} = \frac{n_{events,SR}}{n_{events,CR}}$$



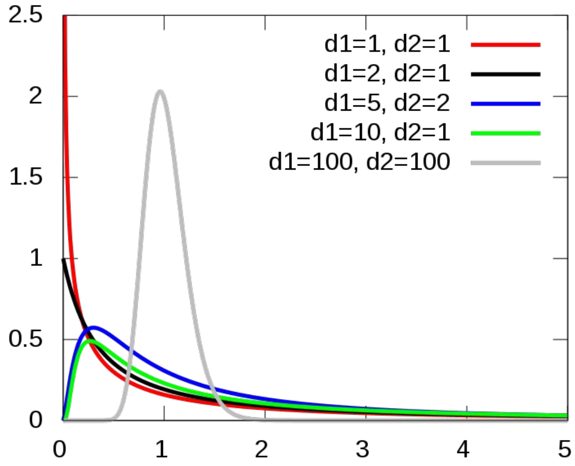


F-test

1. Define a larger **full model**. ("larger," with more parameters.)
2. Define a smaller **reduced model**. ("smaller," with fewer parameters.)
3. Use an ***F*-statistic** to decide whether or not to reject the smaller reduced model in favor of the larger full model
    a. Size of the test: alpha=0.05
    b. Null hypothesis: additional parameter is useless
    c. Null hypothesis always pertains to the reduced model, the alternative hypothesis always pertains to the full model.
    d. F is distributed as a Fisher-Snedecor distribution
    e. Calculate the F statistic from data ("Ftest") and p as 1-FDistI(Ftest,p2-p1,N-p2)
    f. reject the null hypothesis if p < alpha

$$F = \frac{\dfrac{\sum_i (y_i - f_1(x_i))^2 - \sum_i (y_i - f_2(x_i))^2}{p_2 - p_1}}{\dfrac{\sum_i (y_i - f_2(x_i))^2}{n - p_2}}$$

f1: reduced model
f2: full model
p1: N parameters in f1
p2: N parameters in f2
N: Nbins

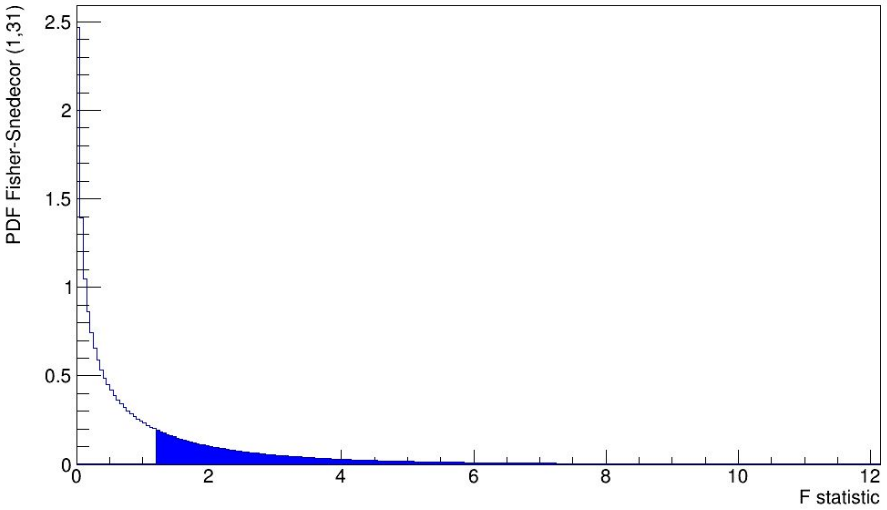


Fisher test H to bb

1-FDistI(Ftest,p2-p1,N-p2)

F value Bernst(degree 2 vs 3): 305
F value Bernst(degree 3 vs 4): 772
F value Bernst(degree 4 vs 5): 1.19

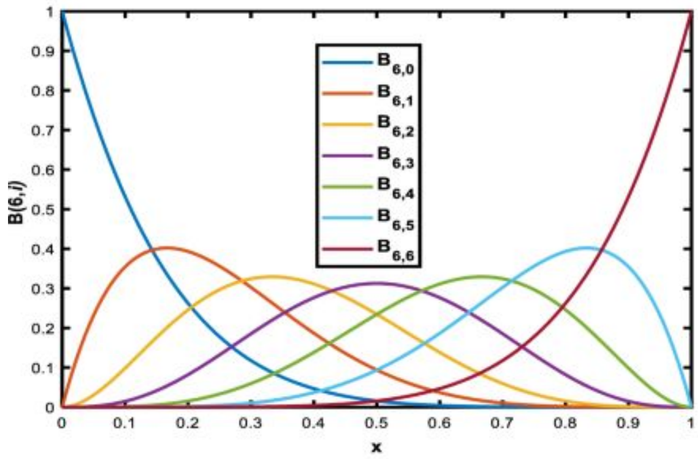
p value Bernst(degree 2 vs 3): 1.1e-16
p value Bernst(degree 3 vs 4): 1.1e-16
p value Bernst(degree 4 vs 5): 0.3



Bernstein polynomial

$$PDF(x, c_0, \ldots, c_n) = \mathcal{N} \cdot \sum_{i=0}^{n} c_i \cdot B_{i,n}(x).$$

$$B_{i,n}(x) = \binom{n}{i} x^i \cdot (1-x)^{n-i}$$



$$B_{6,0} = (1-x)^6$$

$$B_{6,1} = 6\,x(1-x)^5$$

$$B_{6,2} = 15\,x^2(1-x)^4$$

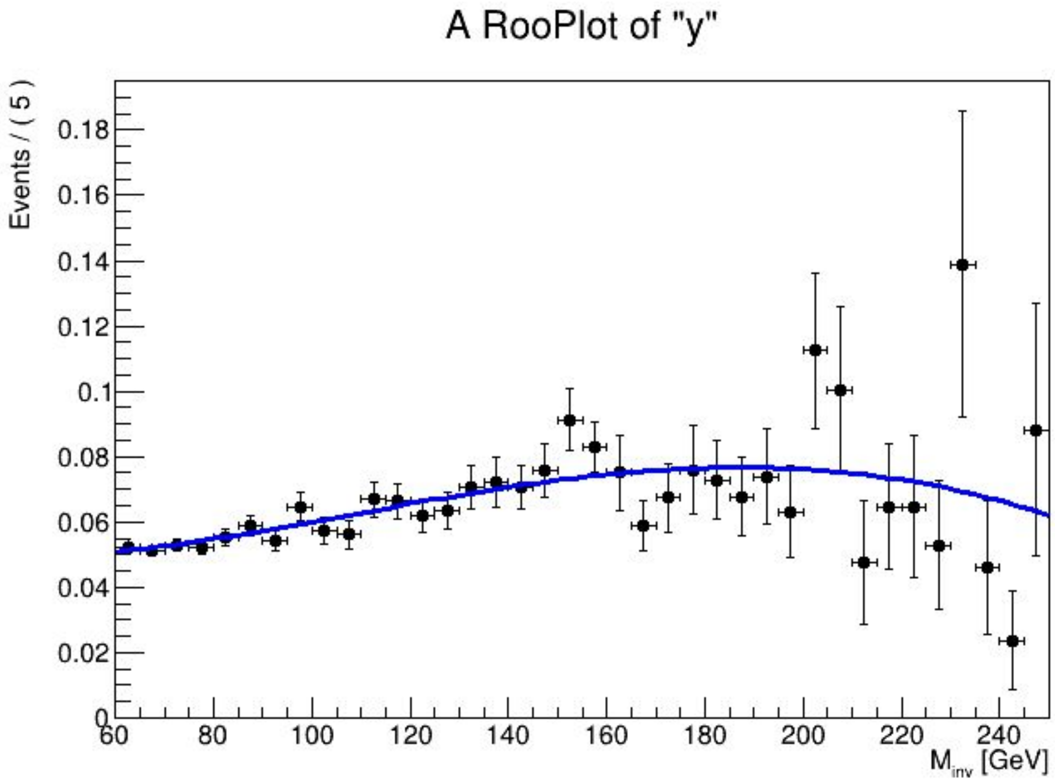
$$B_{6,3} = 20\,x^3(1-x)^3$$

$$B_{6,4} = 15\,x^4(1-x)^2$$

$$B_{6,5} = 6\,x^5(1-x)$$

$$B_{6,6} = x^6$$

Correction function H to cc

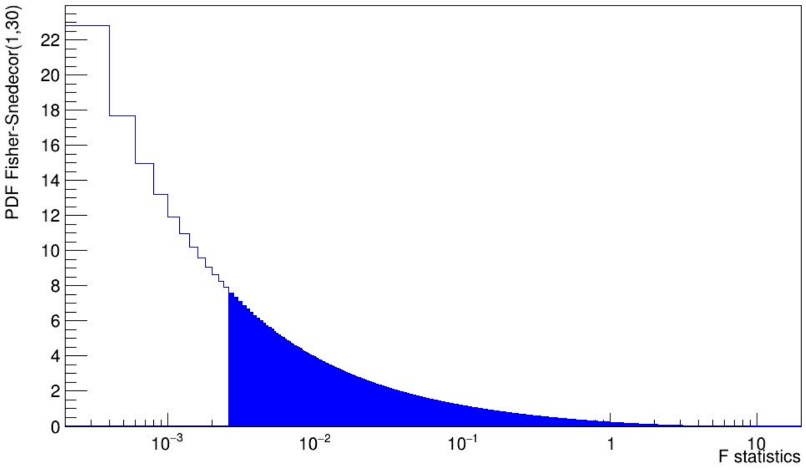


$$\frac{(SVSV)_{SR}}{(SVjet)_{CR} \cdot TF}$$

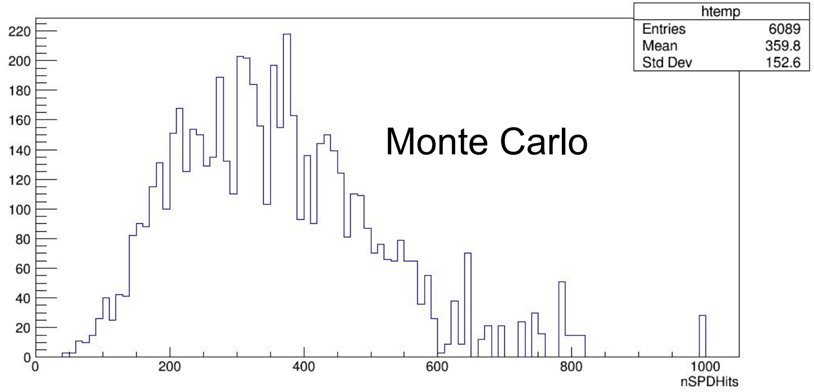
Fisher test H to cc

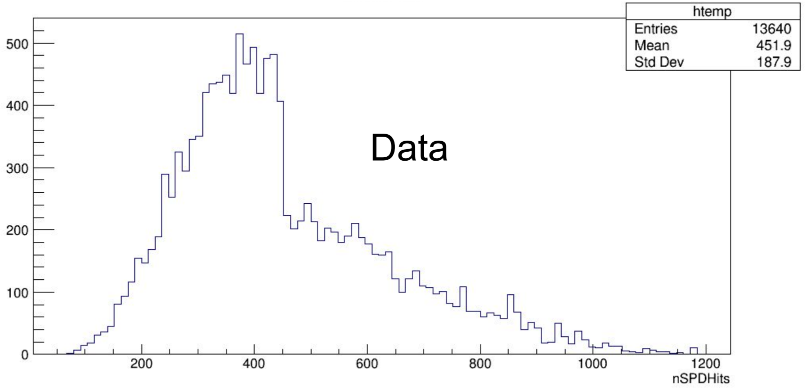
F value Bernst(degree 2 vs 3): 68.1678
F value Bernst(degree 3 vs 4): 52.7894
F value Bernst(degree 4 vs 5): 17.9335
F value Bernst(degree 5 vs 6): 0.00553859

p value Bernst(degree 2 vs 3): 1.55447e-09
p value Bernst(degree 3 vs 4): 2.95368e-08
p value Bernst(degree 4 vs 5): 0.00018944
p value Bernst(degree 5 vs 6): 0.941169



Global Event Cut





PT Higgs and Z