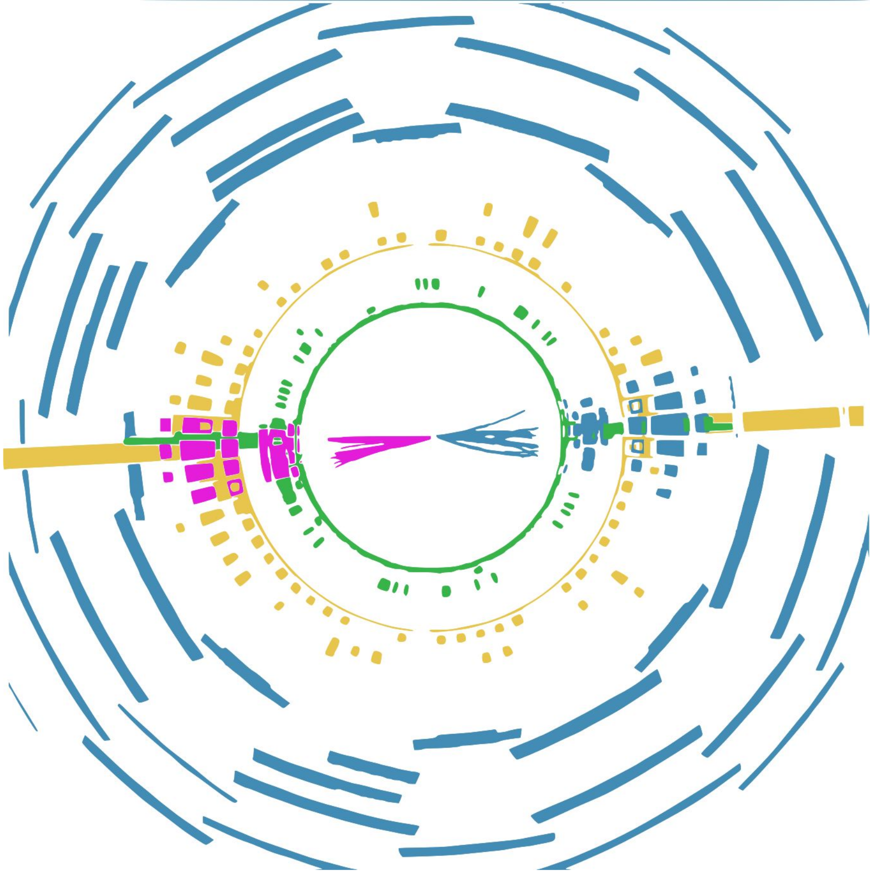
Impact of changes in the flavour tagger performance on the Higgs coupling measurements in ZH fully hadronic final states at the FCCee



Iza Veliscek

Contributions from: Haider Abidi, Viviana Cavaliere, Jan Eysermans, George Iakovidis, Loukas Gouskos, Andrea Sciandra, Michele Selvaggi

3rd ECFA Workshop

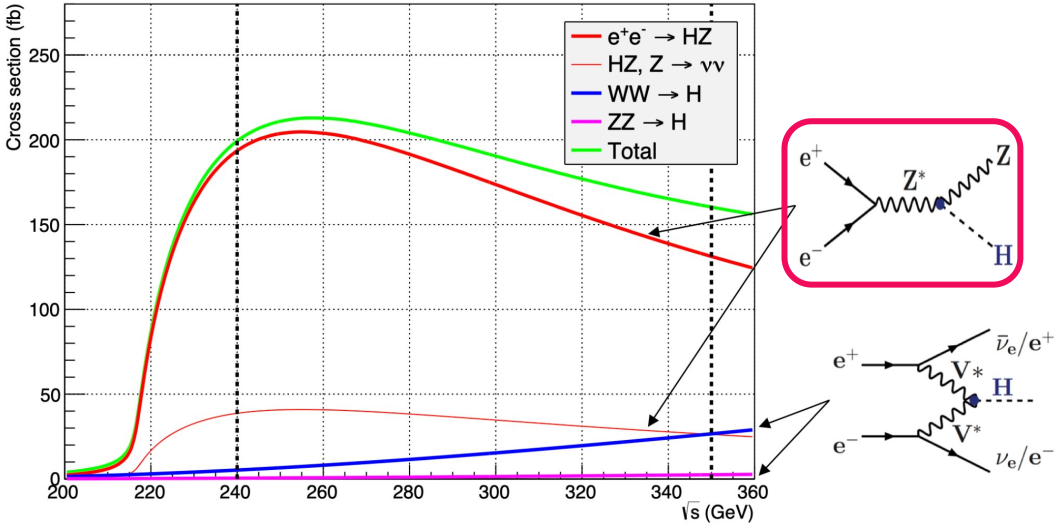
9-11 October 2024

Brookhaven National Laboratory

FUTURE CIRCULAR COLLIDER

Introduction

Unpolarized cross sections   From TLEP paper



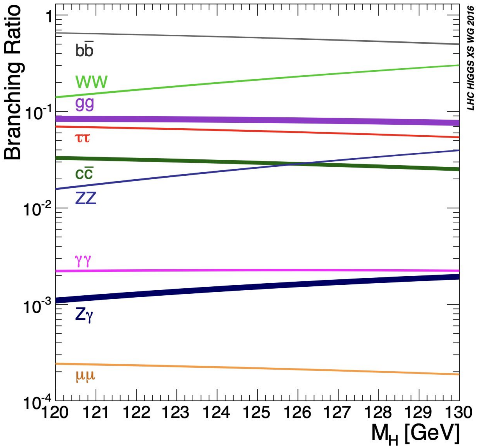
Performance of the flavour tagging algorithms depends on the detector properties.

The goal is to determine the impact of flavor tagging performance on the Higgs coupling measurements.

- **ZH leading Higgs production mode**
  - \+ All hadronic decay has the largest branching fraction
  - \- Jet combinatorics, flavour identification
- Abundance of Higgs produced

  @ √s = 240 GeV
  - ~2 000 000 ZH events

Handbook of LHC Higgs cross sections



Some technicalities

- **IDEA Detector**
  - Delphes fast sim
- **Jet Clustering**
  - N = 4 Durham k_T exclusive algorithm
- **ParticleNet jet tagger** [trained by A. Sciandra]
  - See 2202.03285 for details on the flavor tagger
- Build on ZH(full hadronic) analysis

  presented in Annecy by **G. Iakovidis**

  [slides]

Background:

- **WW**
- **ZZ**
- **Zqq**
- **Z(bb/cc/ss/qq/)H(tautau)**
- **Z(bb/cc/ss/qq/)H(WW)**
- **Z(bb/cc/ss/qq/)H(ZZ)**
- **Z(bb/cc/ss/qq/)H(Z/ɣ*)**
- **nunuH(jj)**
- **Missing Z(bb/cc/ss/qq/)H(qq)**
  - **Negligible impact !**

Signals:

- **Z(bb/cc/ss/qq/)H(bb)**
- **Z(bb/cc/ss/qq/)H(cc)**
- **Z(bb/cc/ss/qq/)H(ss)**
- **Z(bb/cc/ss/qq/)H(gg)**

Analysis setup

Preselection

- Exactly 4 jets!

Lepton cuts

- <= 2 muons and electrons
- Leading muon and electron p_T<20 GeV

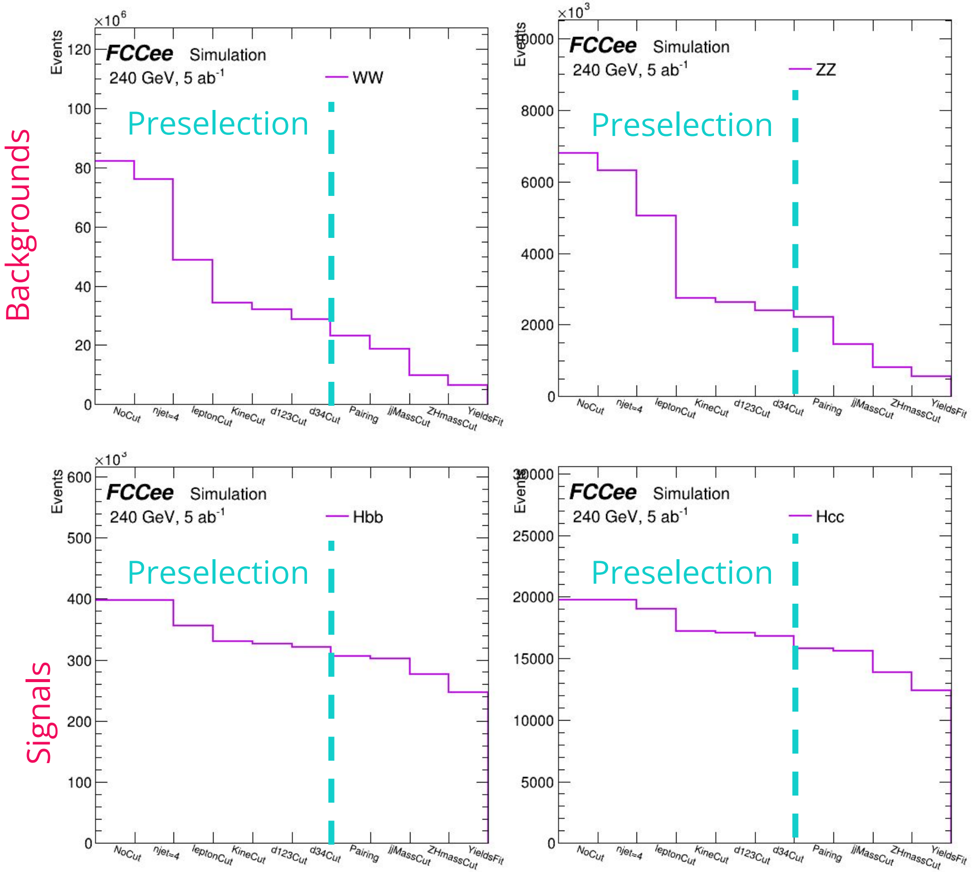
Visible Energy

- Visible m > 150 GeV
- Visible E > 150 GeV
- 0.15 <Visible θ < 3.0

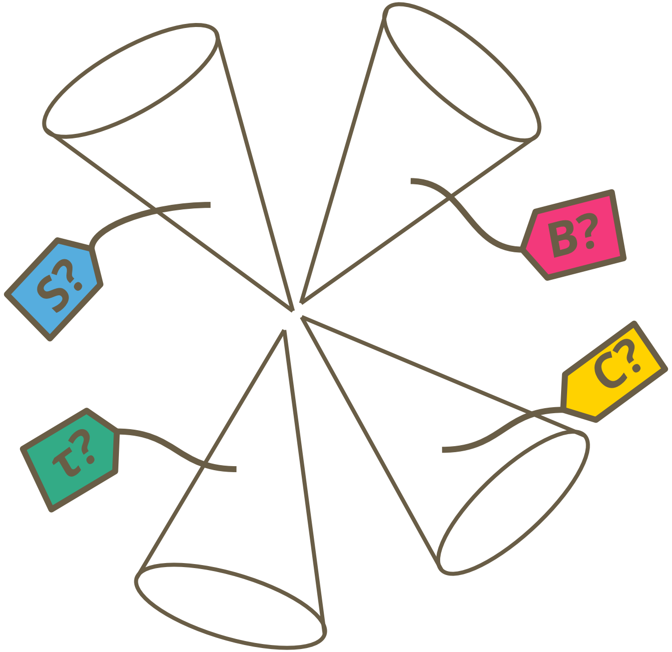
d_{ij} Cuts

- $15000 < d_{12} < 58000$
- $400 < d_{23} < 18000$
- $100 < d_{34} < 6000$

* $d_{ij} = 2 \min(E^2_i , E^2_j)(1 - \cos \theta_{ij})$, distance measure between jet i & j used by clustering



Jet “tagging”

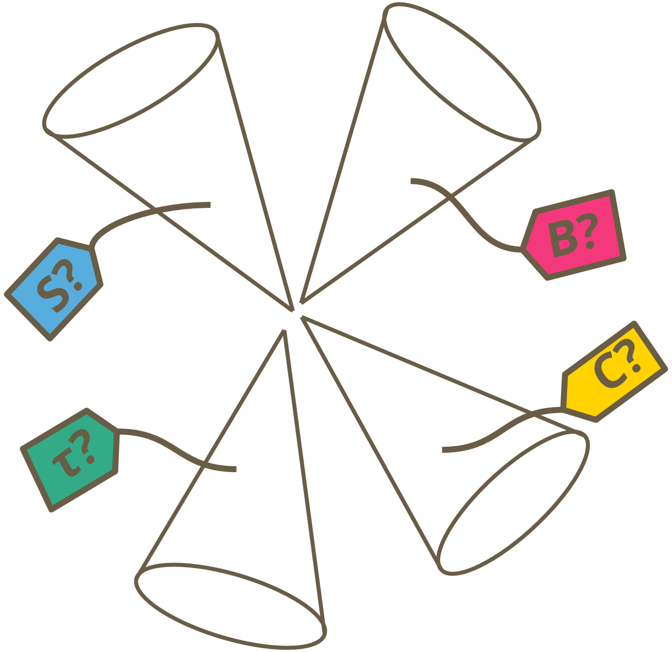


ParticleNet jet tagger

- Scores provided for the “flavours”:
  - B, C, S, g, τ, U, D
    - q: U,D
- Scores ~ probability jet is of flavour X
- Flavour tagging
  - Maximum flavour score ~ flavor of jet
  - Sums of same flavour scores for jet pairs ~ flavour of jet pair

  * Note - no fixed working point used, different than in ATLAS or CMS

Jet pairing

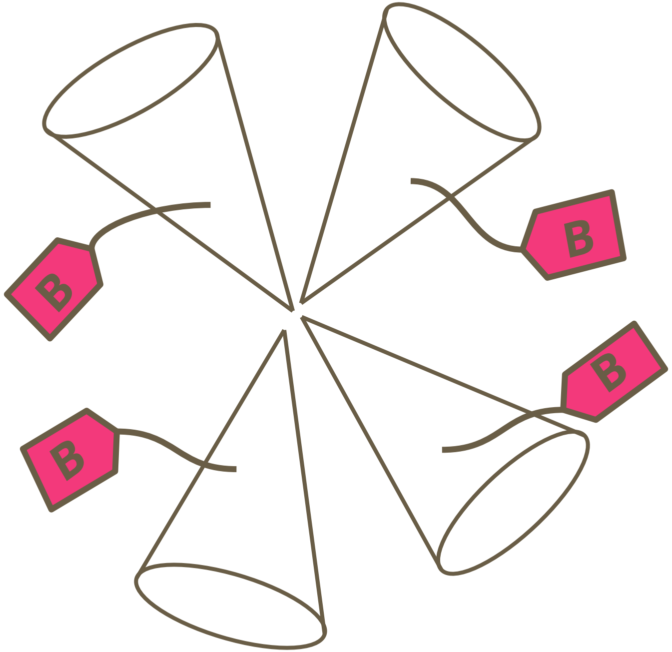


Each jet has a maximum tagger score from a different flavour

-

TOSS EVENT

Jet pairing



CASE 1: All jets have the maximum score from the same flavour

Finding the H&Z candidates

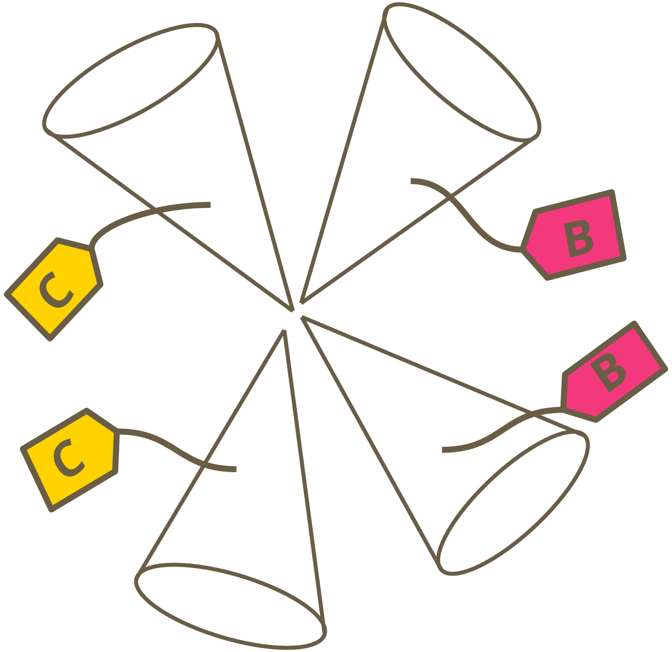
Consider all possible jet pairs

- $\chi_H = (m_{ij} - m_{H,true})^2$
- $\chi_Z = (m_{lk} - m_{Z,\,true})^2$
- $\chi_{comb} = \chi_H + \chi_Z$

The jet paring that gives the **minimum** $\boldsymbol{\chi_{comb}}$ is chosen!

FUTURE CIRCULAR COLLIDER

Jet pairing

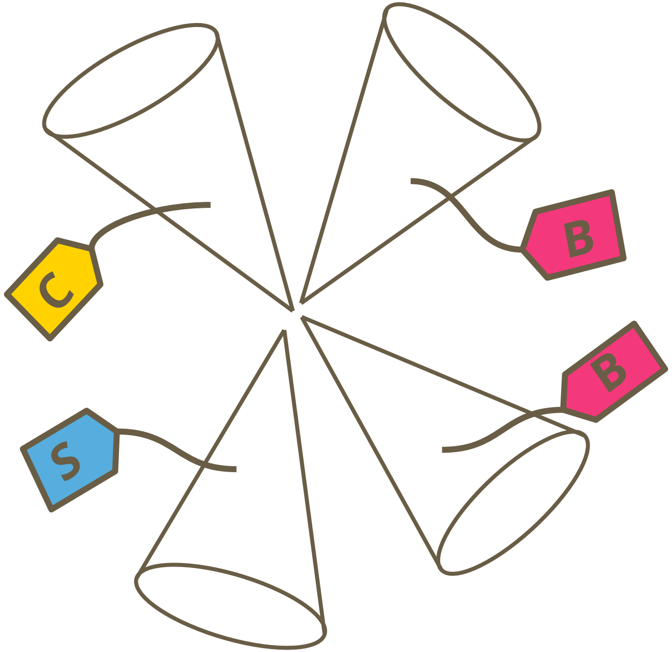


CASE 2: Two jet pairs with same maximum score from the same flavour, but different flavour of the pairs

Finding the H&Z candidates

- Jet paired, if they have the same flavour maximum score
- Z candidate: Pair with minimum $\chi_Z=(m_{lk} - m_{Z,\ true})^2$

Jet pairing



CASE 3: Two jets with maximum score from the same flavour form a pair

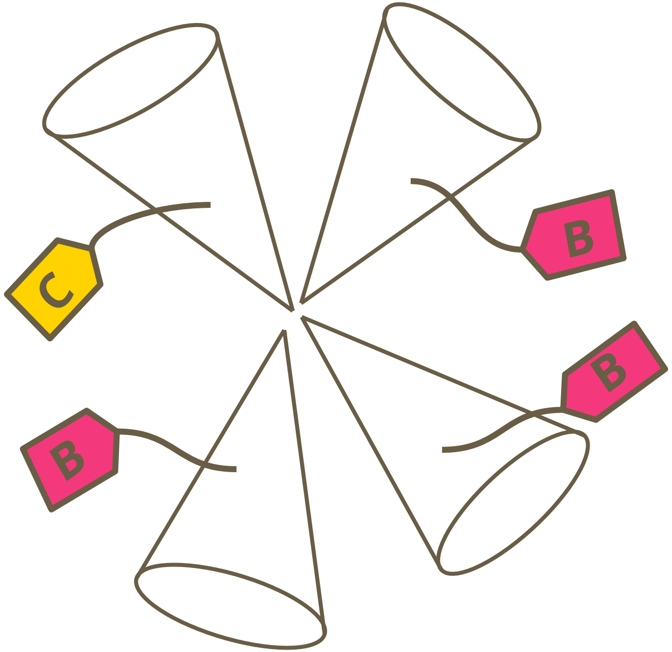
Recover second pair:

- Consider all sums of tagger scores
  - **Max**($\sum_{ij}$Bscore, $\sum_{ij}$Cscore, $\sum_{ij}$Sscore, …)
    - Determines the flavour of the pair

Finding the H&Z candidates

- Same flavour pairs (Case 1)
  - Min($\chi_{comb}=\chi_H+\chi_Z$)
- Different flavour pairs (Case 2)
  - Min($\chi_Z=(m_{lk} - m_{Z,\ true})^2$

Jet pairing



CASE 4: Three jets with maximum score from the same flavour

Recover first pair:

- Maximum tagger score sum
  - **Max**($\sum_{ij}$Bscore, $\sum_{ik}$Bscore, $\sum_{jk}$Bscore, …)
    - Determines the flavour of the 1st pair

Recover second pair:

- Consider all sums of tagger scores
  - **Max**($\sum_{ij}$Bscore, $\sum_{ij}$Cscore, $\sum_{ij}$Sscore, …)
    - Determines the flavour of the pair

Finding the H&Z candidates

- Same as for Case 3

A few more cuts

WW & ZZ rejection

$$\sqrt{(m_{z_{jj}} - m_W)^2 + (m_{H_{jj}} - m_W)^2} > 10$$

$$\sqrt{(m_{z_{jj}} - m_Z)^2 + (m_{H_{jj}} - m_Z)^2} > 10$$

Mass window

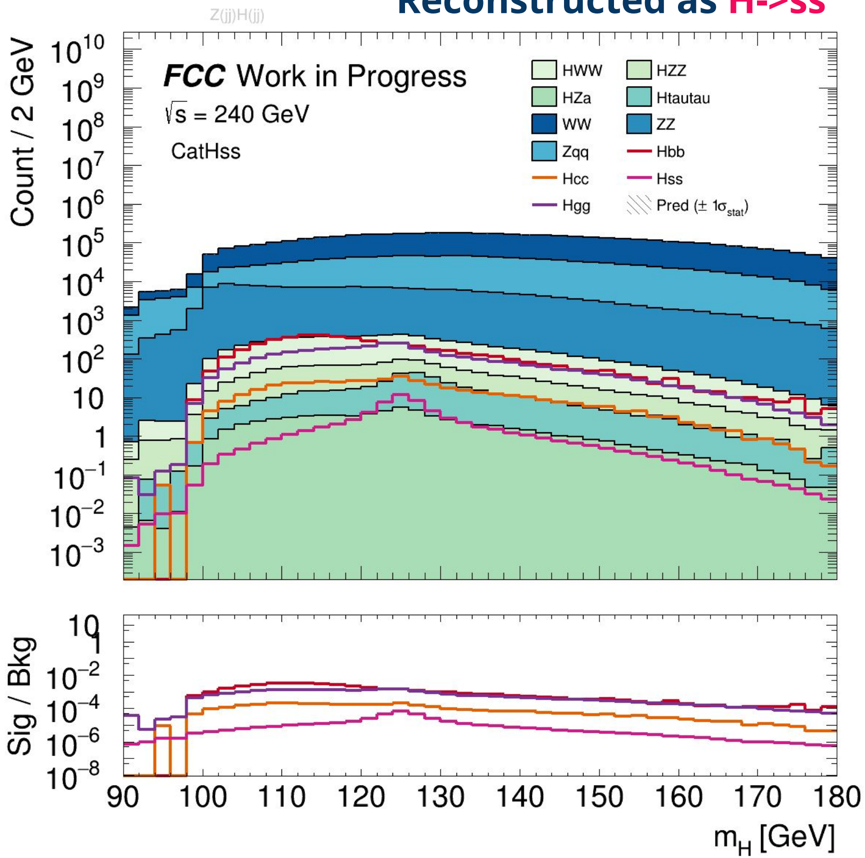
$$50 < m_{Z_{jj}} < 125\,\text{GeV}, m_{H_{jj}} > 90\,\text{GeV}$$

After flavour tagging and Z&H identification reject events reconstructed as:

- H->ττ
- H->qq, q=u,d
- Z->ττ
- Z->gg

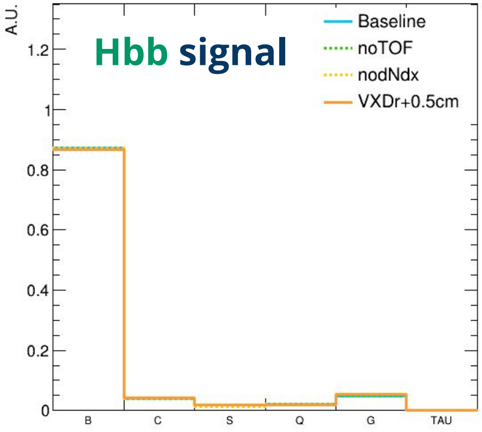
*Jet energies are recomputed from jet directions & energy-momentum conservation

Reconstructed as H->ss

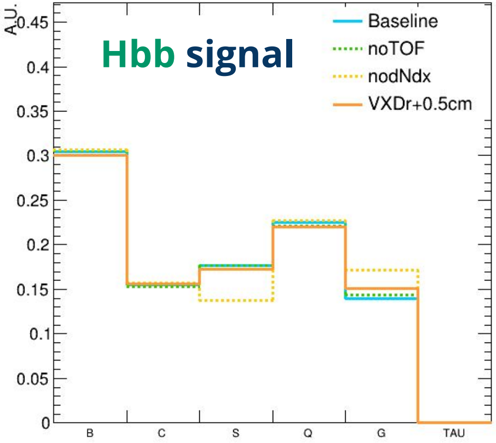


Categorization

H candidate



Z candidate

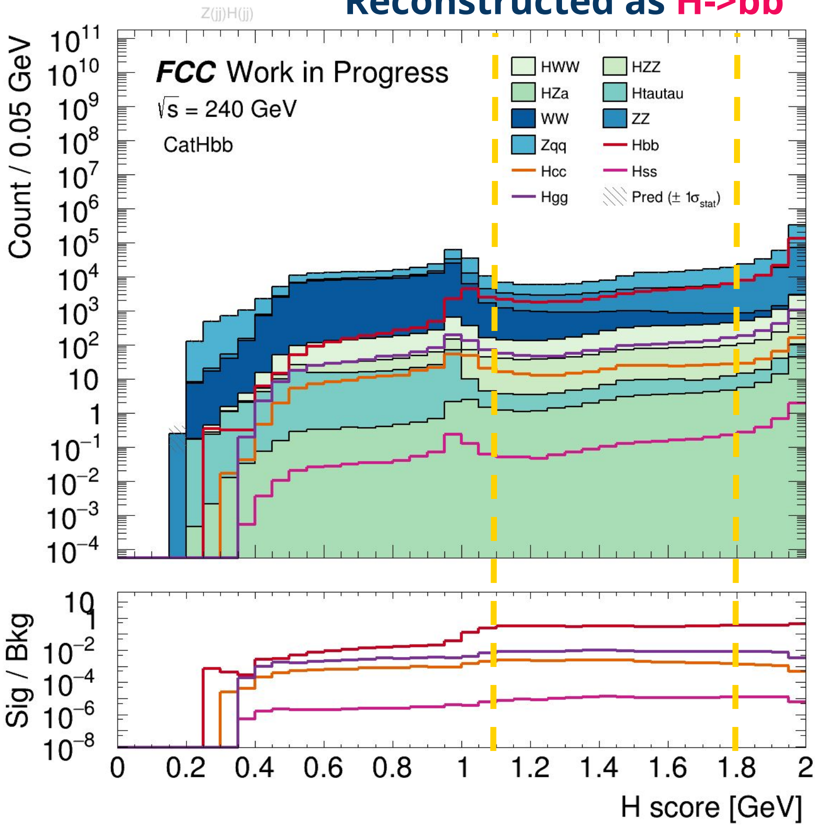


Hbb signal categorized according to the flavour tagged. Additional split according to H flavour score in fit (purity)

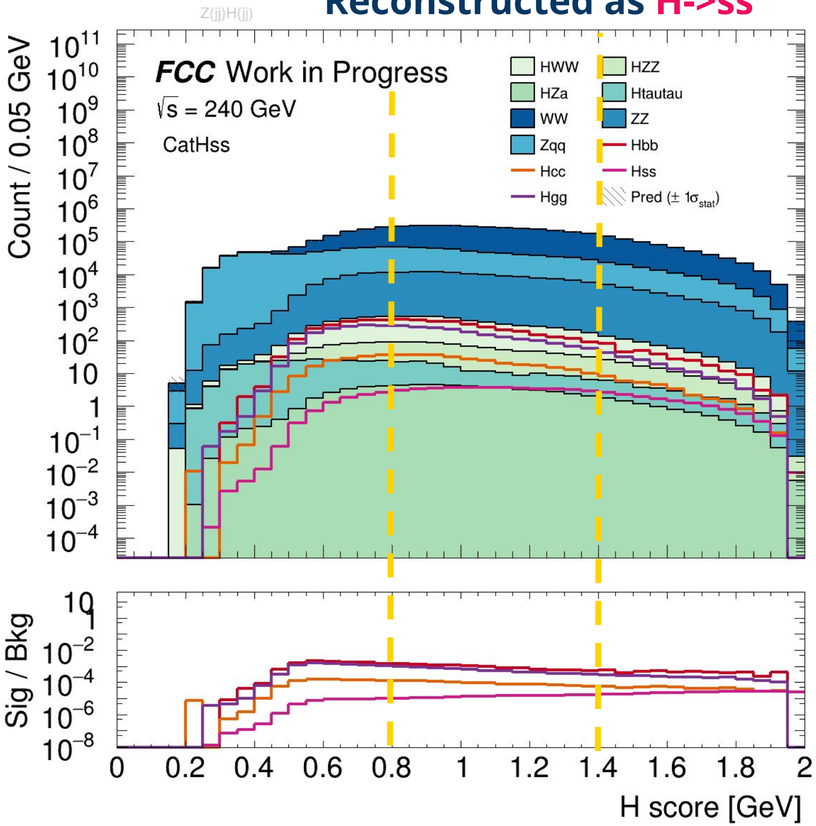
- Categorize by H->j_1j_2 decay
  - Categorize by Z->j_3j_4 decay
  - Additionally by H flavour score
    - **Purity category :**
      - High (>1.8 (1.4 for Hss))
      - Mid(1.1 (0.8) < score < 1.6 (1.4) (Hss cut in ())
      - Low (<1.1 (0.8 for Hss))
- 48 Categorised in total!
- + 1 GeV binning in $m_{jj,H}$
- + 5 GeV binning in $m_{jj,Z}$

H score determining the purity categories

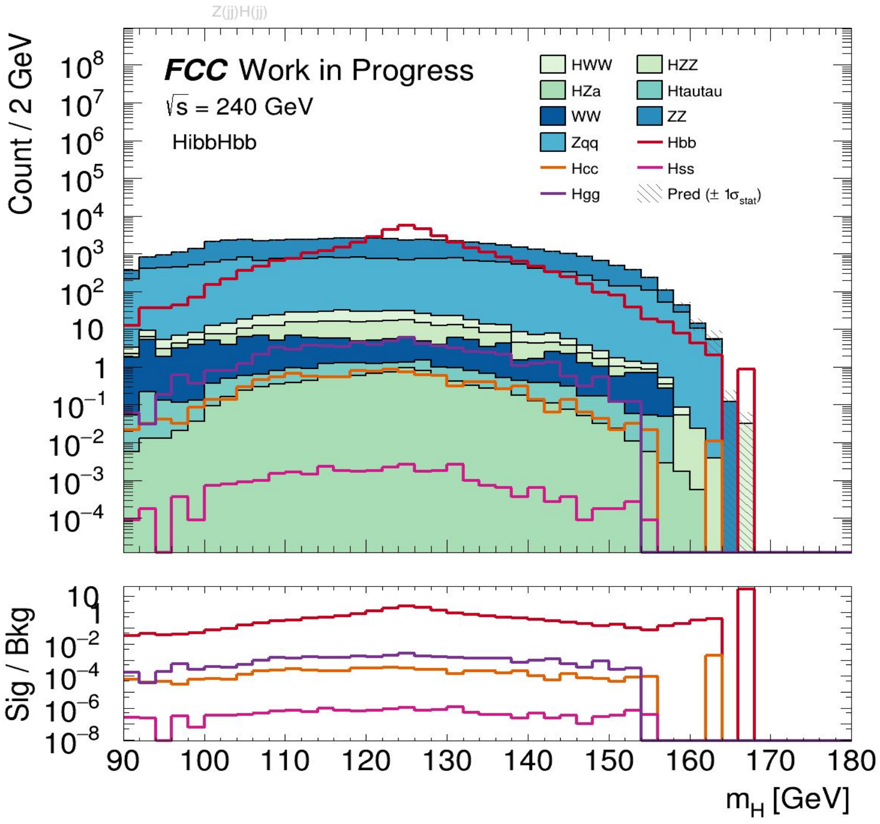
Reconstructed as H->bb

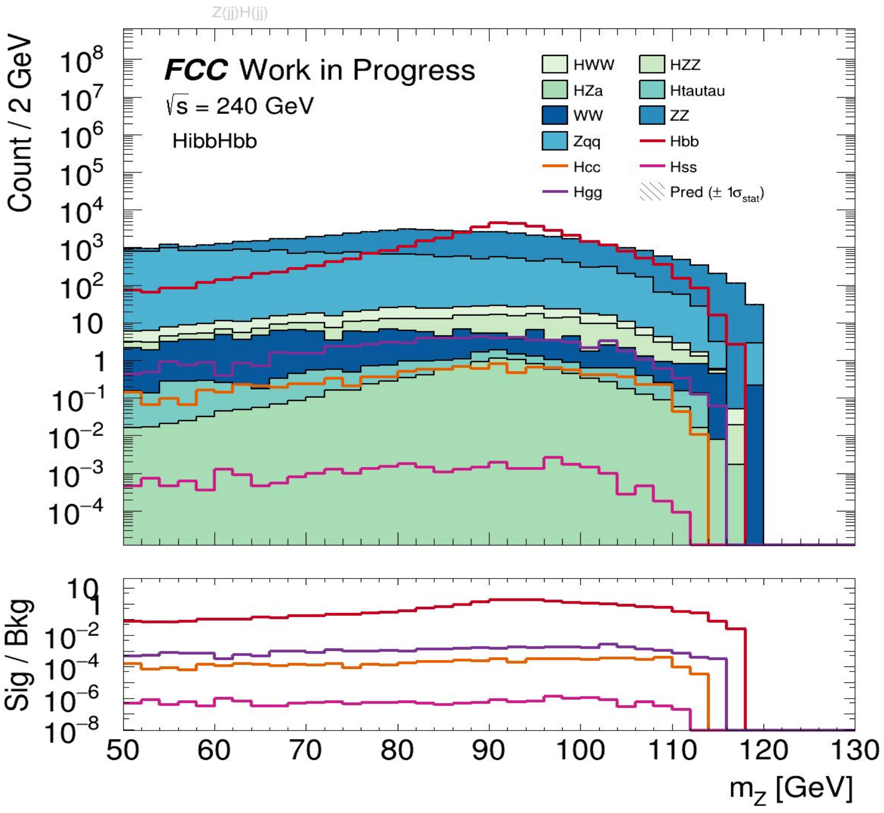


Reconstructed as H->ss



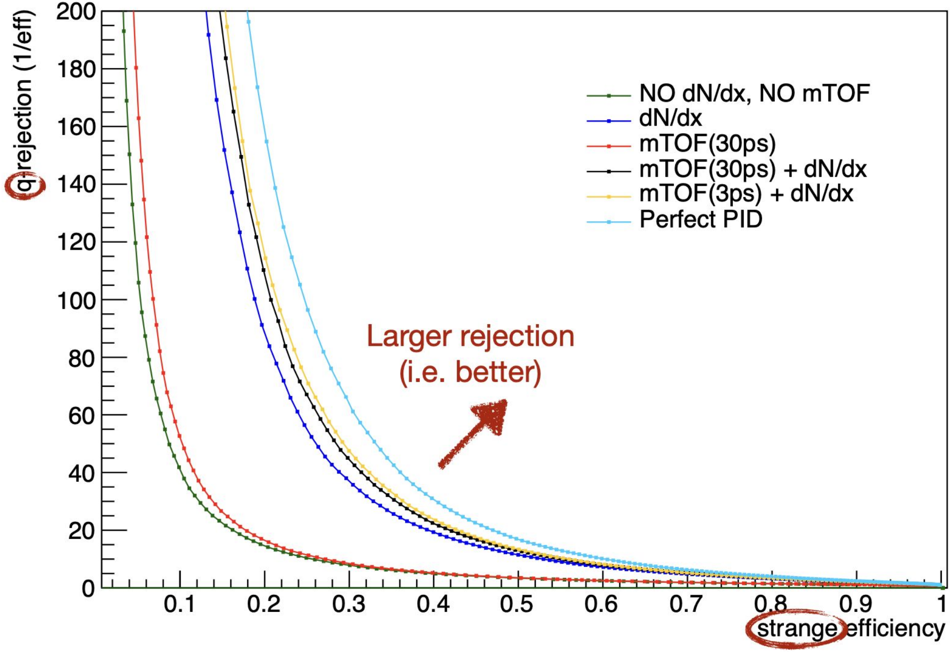
Categorization - High purity ZbbHbb category





Reminder - Flavour Tagging & PID

by Andrea Sciandra

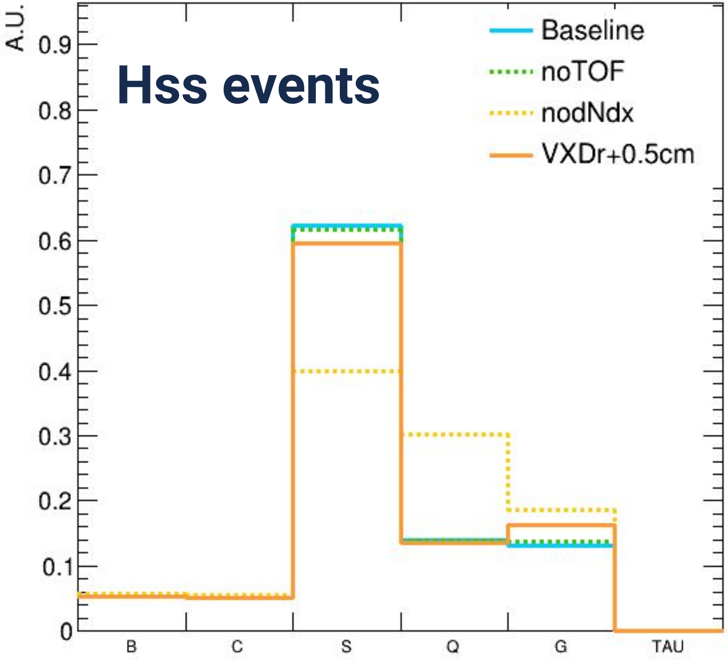


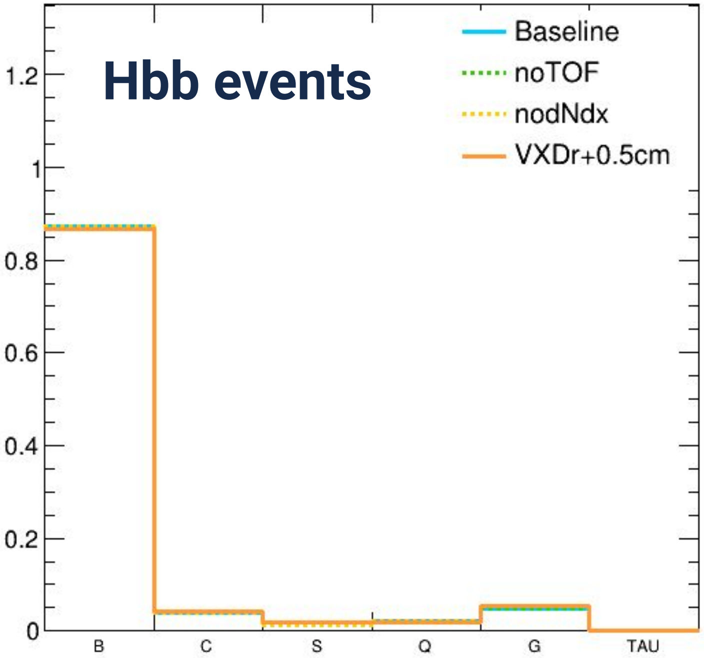
Will only show biggest changes in tagger's performance

- **Baseline** = baseline IDEA detector concept
- **No TOF** (time of flight, dNdX on the plot)
- **No dNdx** (cluster counting)

*Initial studies shown that number of pixel layers and pixel-detector material budget have a negligible impact on the analysis

Robustness of flavour tagging strategy





Very little migration between the flavour categories

Summing the flavour scores and not rejecting events with low flavour scores guarantees the robustness of flavour tagging

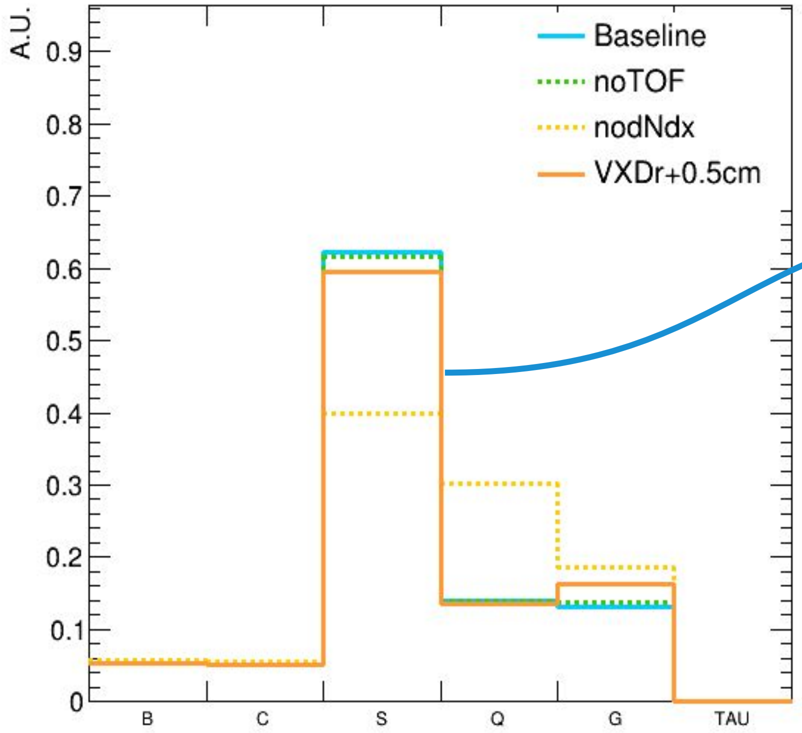
Missing dNdx information notably impacts flavour categorization

- **Strange** tagging impacted the most
- Expected from ROC curves

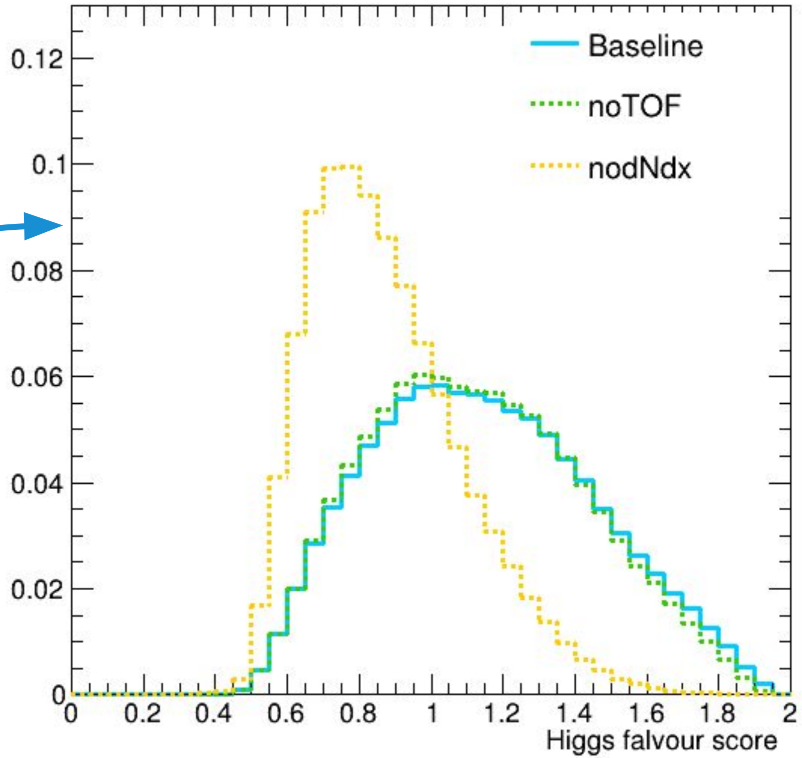
*True also for the backgrounds [see backup slide 26]

Impact on strange tagging

Categorization of Hss events



Hss events identified as H->ss



* Re-optimized Hss category definition for no dNdx case

Impact on the ZH fully hadronic analysis

Removing PID information

- TOF no significant impact on tagging
- Significant impact from removing dNdX information on Hss coupling
  - x1.6 worse measurement precision at 68% CL

Tracker variations considered

- **No notable change in the limits** from 65% Worse single hit resolution, 50% Heavier VXD, no intermediate layer, VTXD layers R + 0.5cm
  - Note - nominal simulation used only tagger training changed

VARIATION	68% CL precision			
	μ_{Hbb}	μ_{Hcc}	μ_{Hgg}	μ_{Hss}
Baseline	**±0.3%**	**±4.2%**	**±2.8%**	**+674% -669%**
Relative change compared to baseline ($\mu_{variation}/\mu_{baseline}$)				
No TOF	x1.3	x1.02 (upper limit only)	x1	x1.03
No dNdX	x1.3	x1.07	x1.07	**x1.6**
VXDR +500µm	x1.3	x0.98 (lower limit only)	x1.04	x1

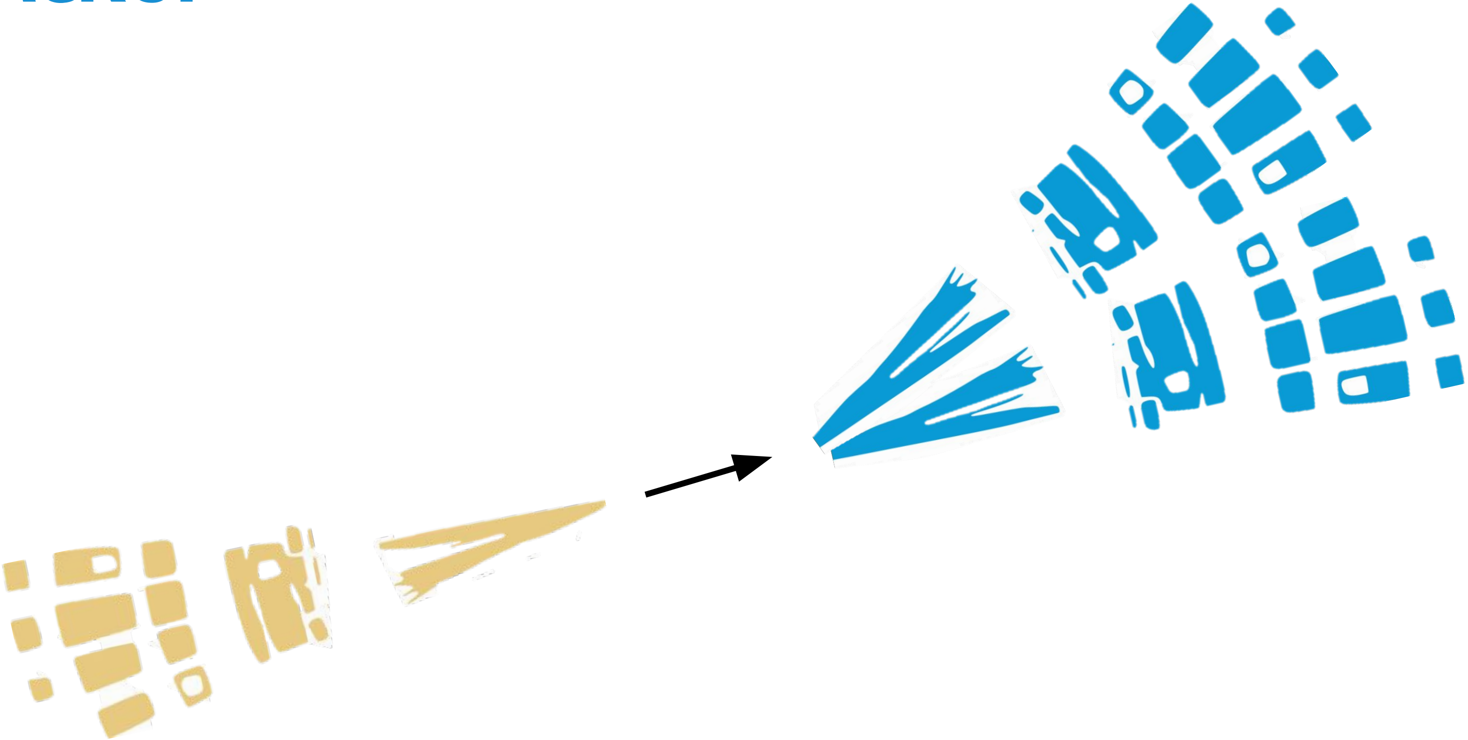
Conclusions

- Cluster information (**dNdx**) is crucial and has a significant impact on the sensitivity of the measurements
  - Without the number of cluster information **x1.6** worse precision on **Hss coupling**!
- **Hbb coupling** measurement gets slightly worse for all detector variations considered
- Very small changes in the measurements of **Hcc & Hgg couplings**
- Changing the tracker does not impact the fully hadronic ZH analysis significantly
  - Could be an underestimation as flavour tagging strategy might be too robust
  - Caveat - Only change the flavour tagging training not IDEA simulation

Ongoing effort

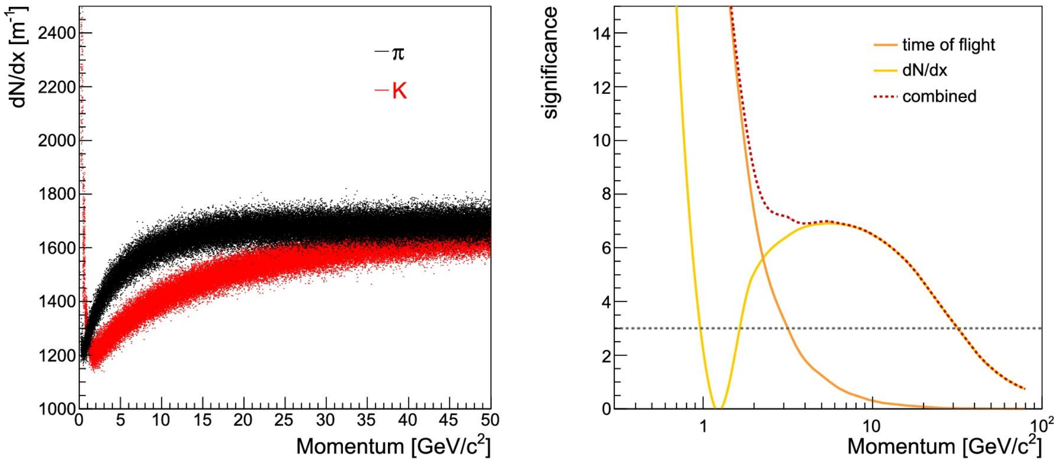
- See the impact on the Z($\nu\nu$)H(jj)
  - Most sensitive channel
  - Samples available with considering different detector geometry
- Extract the impact on the Higgs self-coupling measurement from the ZH analysis

BACKUP

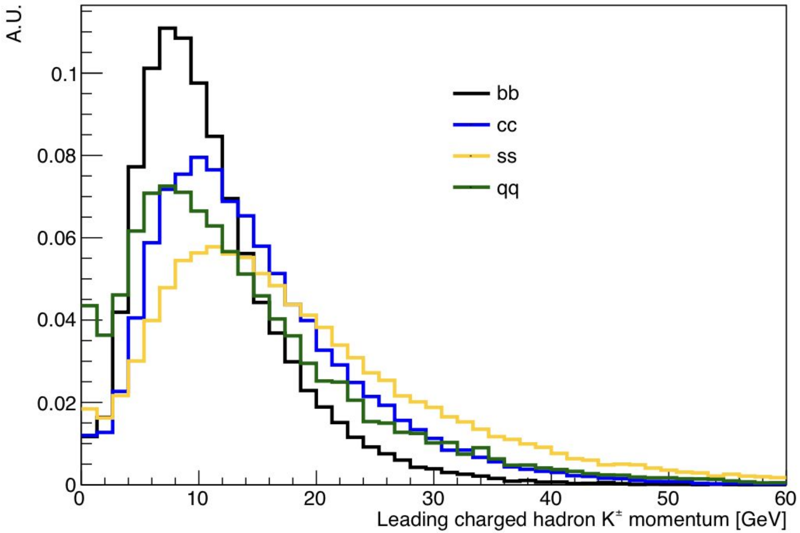


Identifying Kaons

by Andrea Sciandra



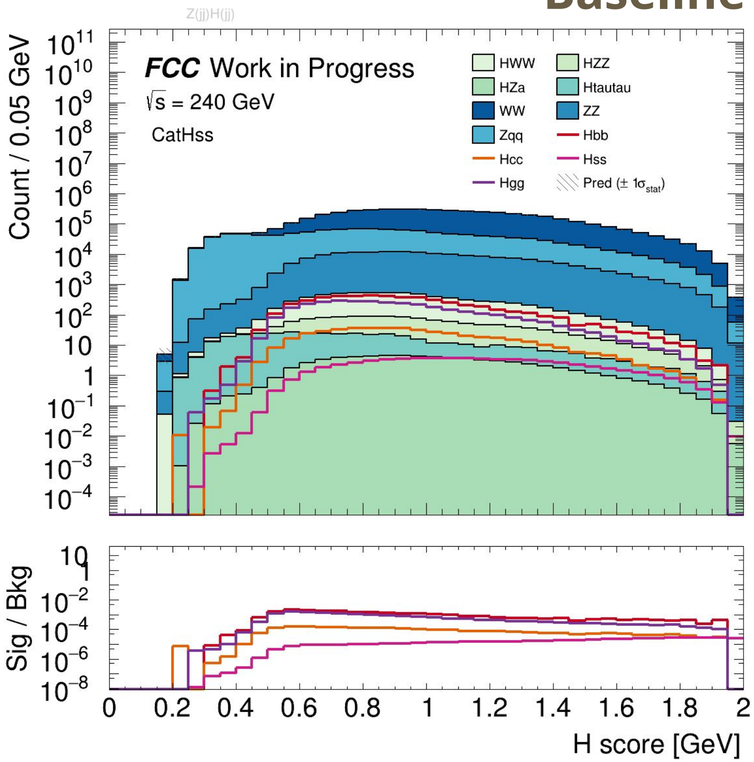
(a) (b)



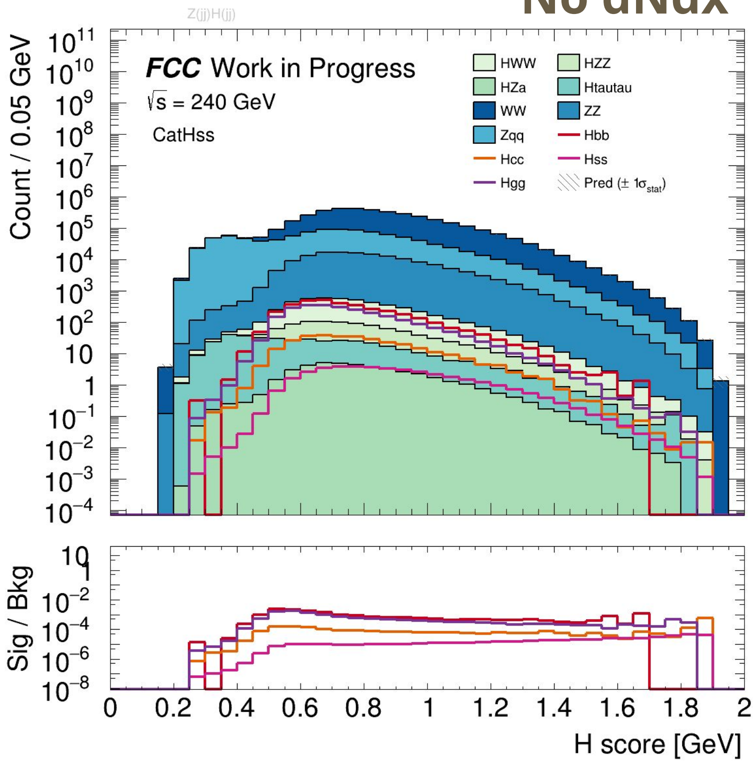
From: Bedeschi, F., Gouskos, L. & Selvaggi, M. Jet flavour tagging for future colliders with fast simulation. *Eur. Phys. J. C* **82**, 646 (2022). https://doi.org/10.1140/epjc/s10052-022-10609-1

H score in the H->ss categorise

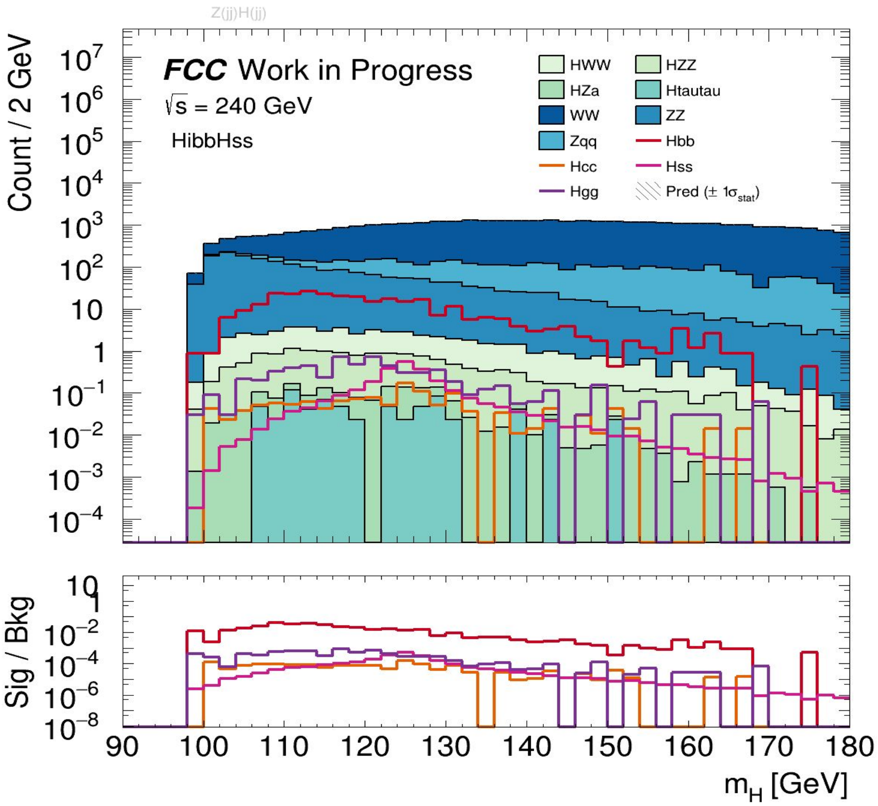
Baseline

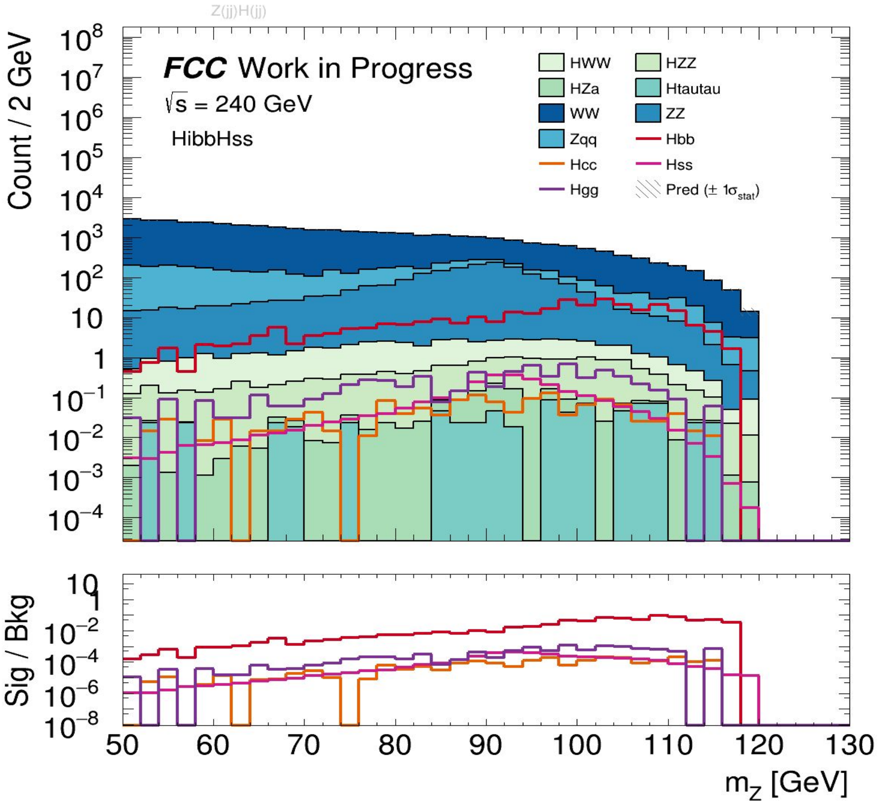


No dNdx

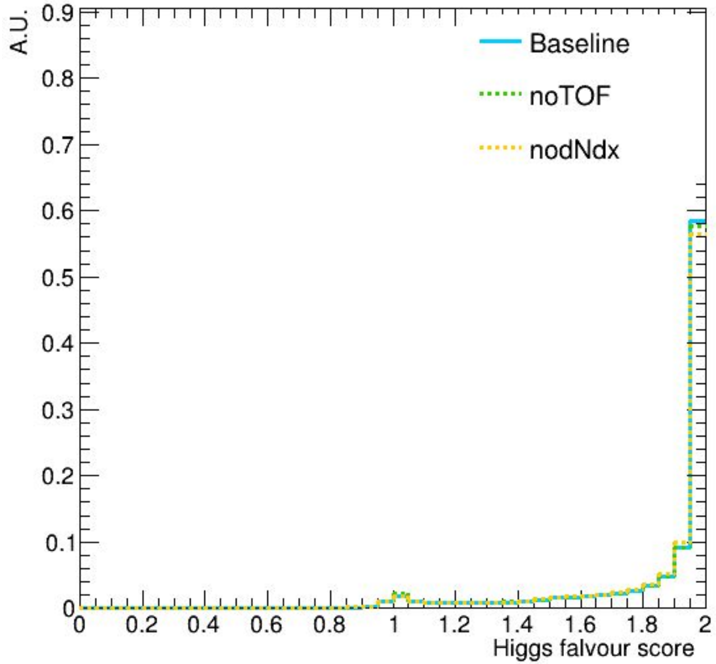


Categorization- High purity ZbbHss category





Reconstructed H->bb decays

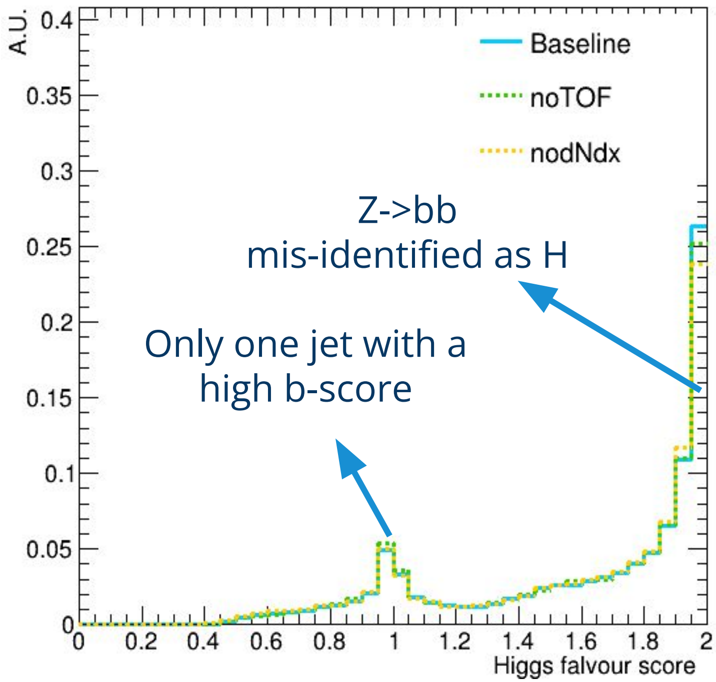


Hbb signal events identified as H->bb

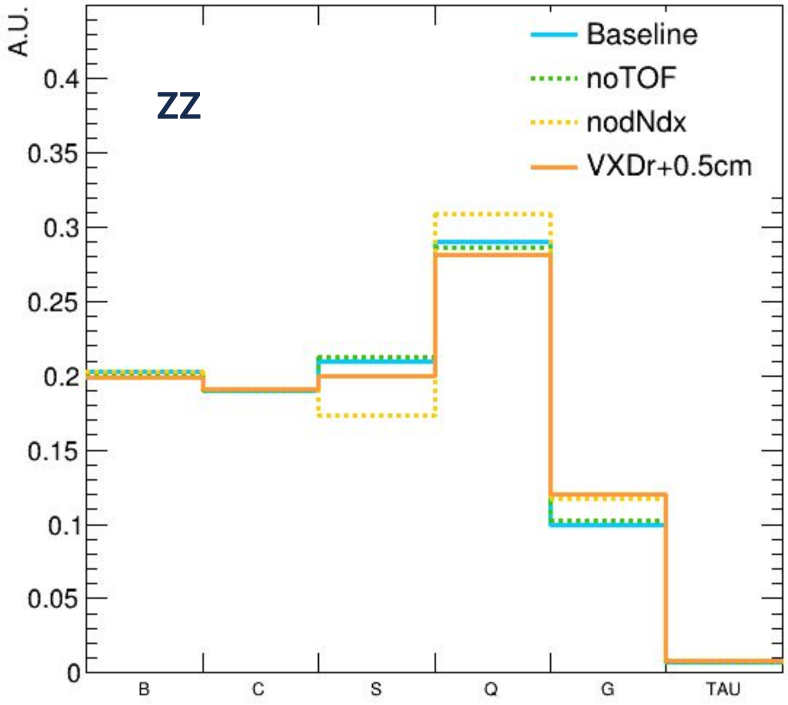
- Very high b-score
- Negligible change between different taggerc

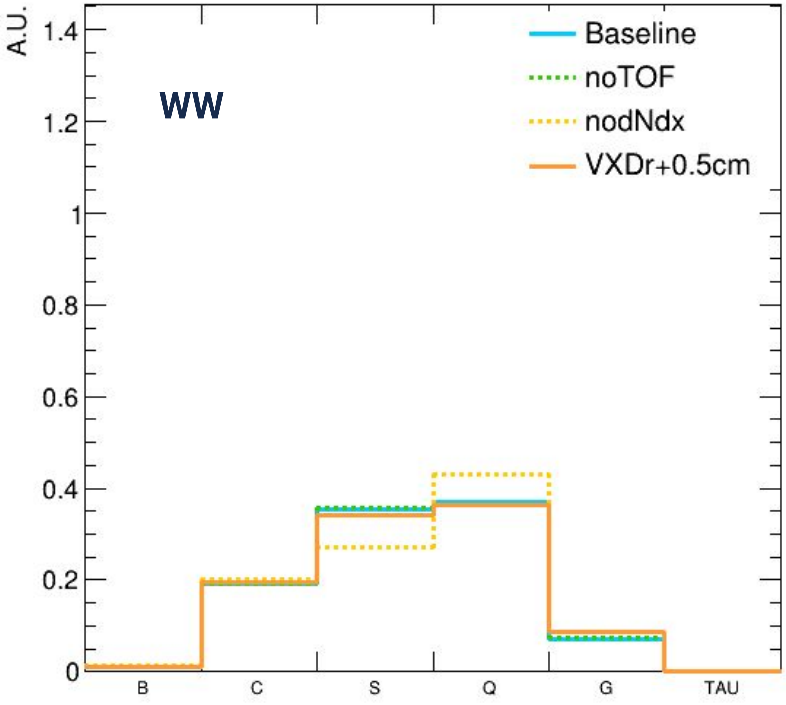
- No significant change in H score distributions of background event

Hgg events identified as H->bb



Robustness of flavour tagging strategy





FUTURE CIRCULAR COLLIDER

Likelihood scan

- **Asimov** (expected) **data = SM = background estimation + SM signal**
  - How compatible are different μ_{xx} to the asimov data set, i.e. how sensitive are we?
  - Compare the **test statistic (λ)** of the different μ_{xx} on this dataset.

$$\lambda(\mu_{xx}) = -2\, ln\left(\frac{L(\mu_{xx}, \hat{\hat{\theta}})}{L(\bar{\mu}_{xx}, \hat{\theta})}\right)$$

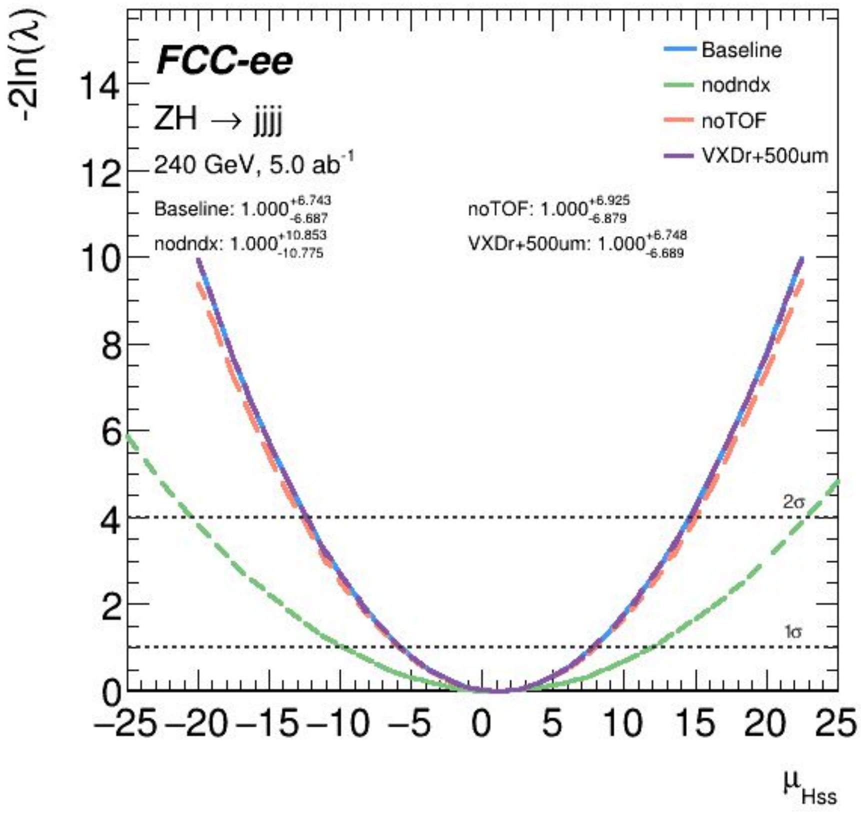
Maximize $L(\kappa_\lambda, \theta)$ by holding μ_{xx} fixed and fitting the model.

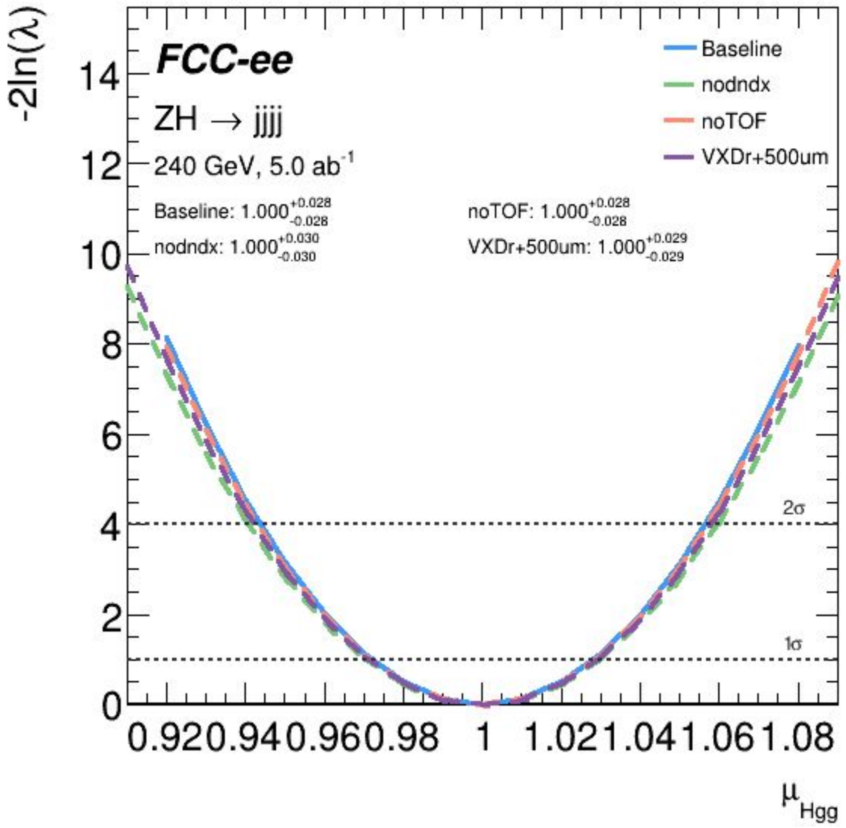
Nuisance parameters

Best-fit coupling

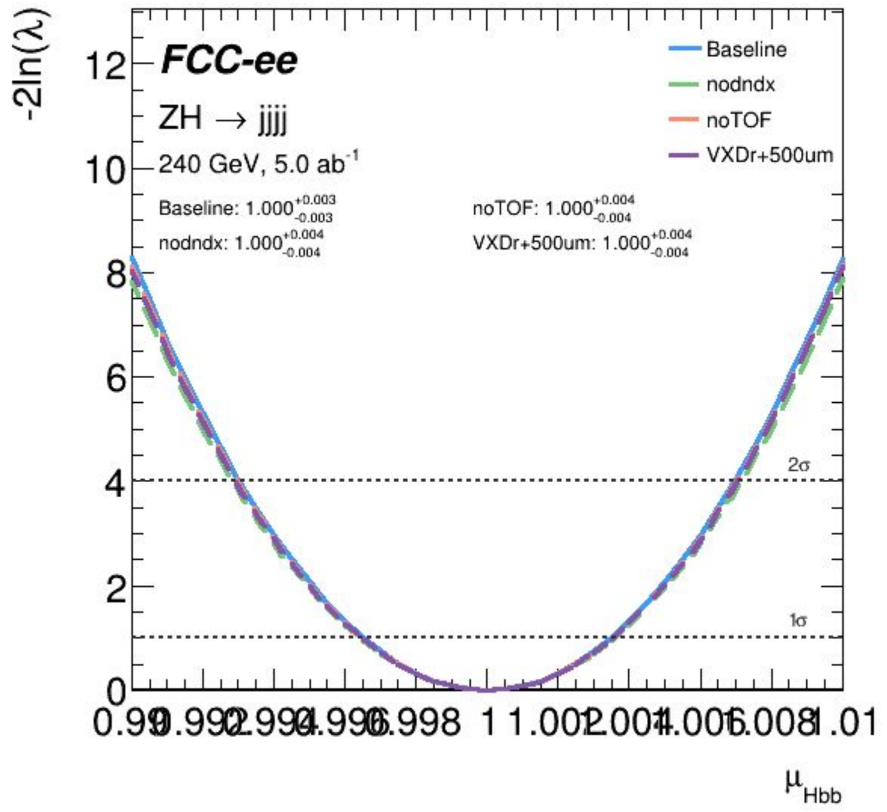
Find μ_{xx} that maximizes ***L*** for the data, i.e. let μ_{xx} vary in a global fit.

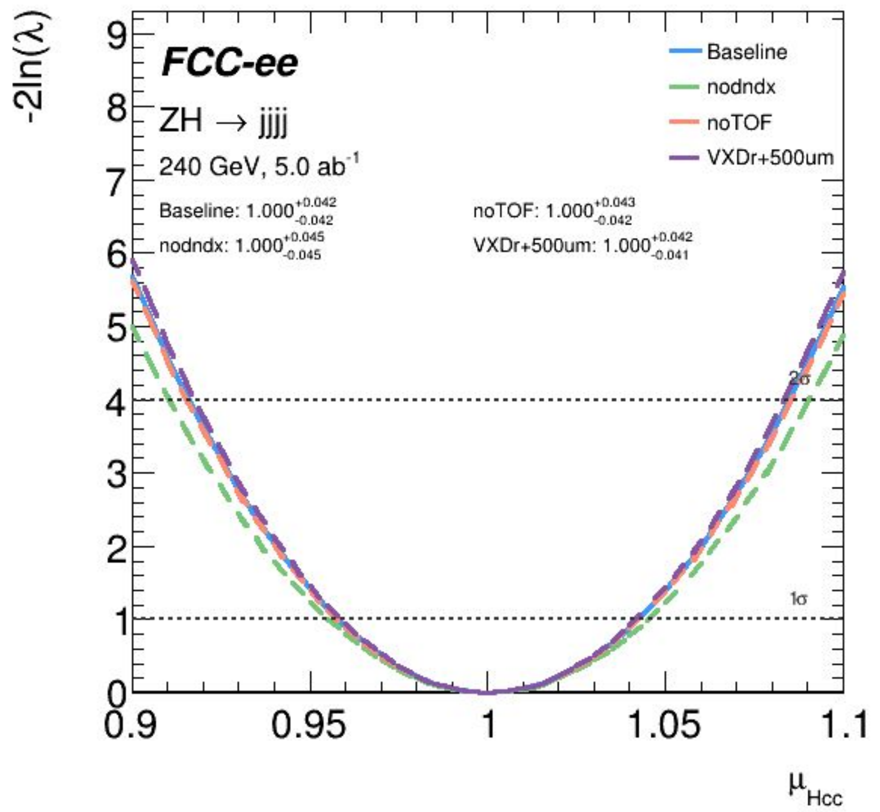
Impact on the ZH fully hadronic analysis [NLL scnas]



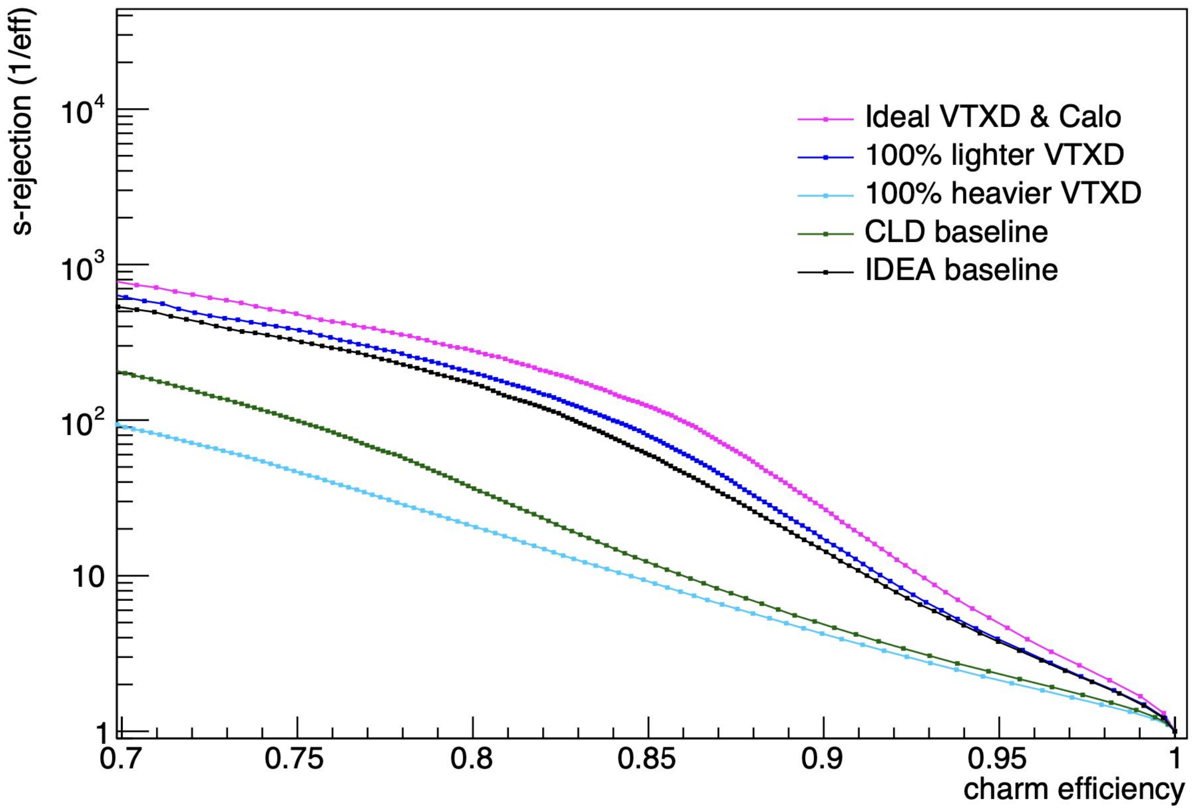


Impact on the ZH fully hadronic analysis [NLL scnas]

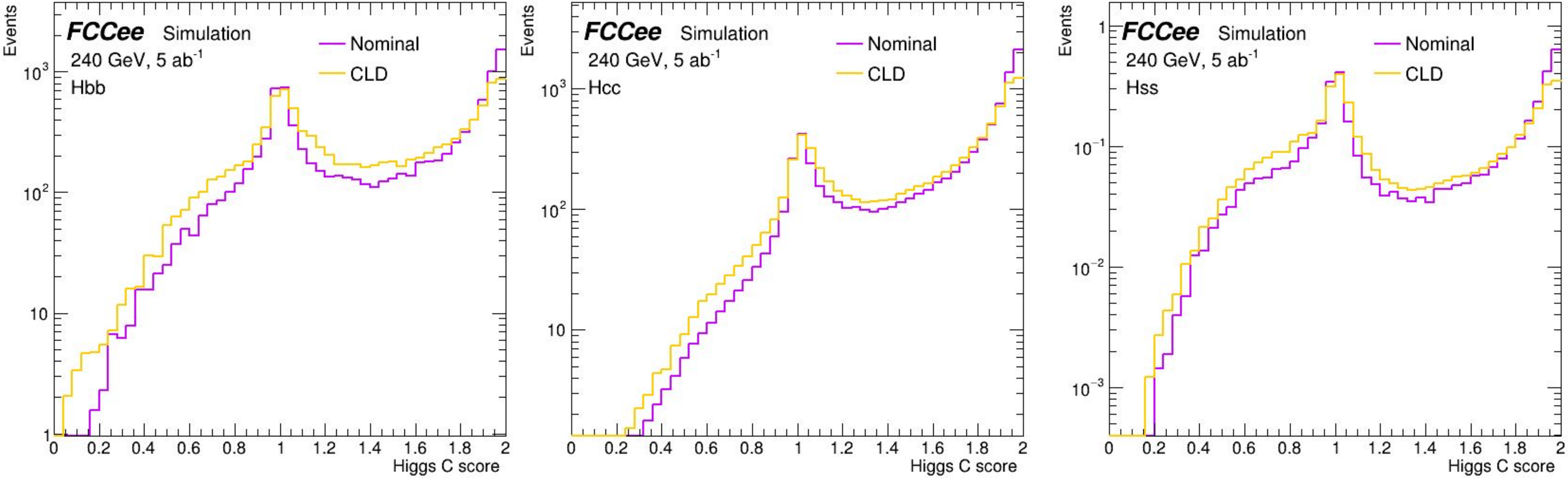




Tagger performance

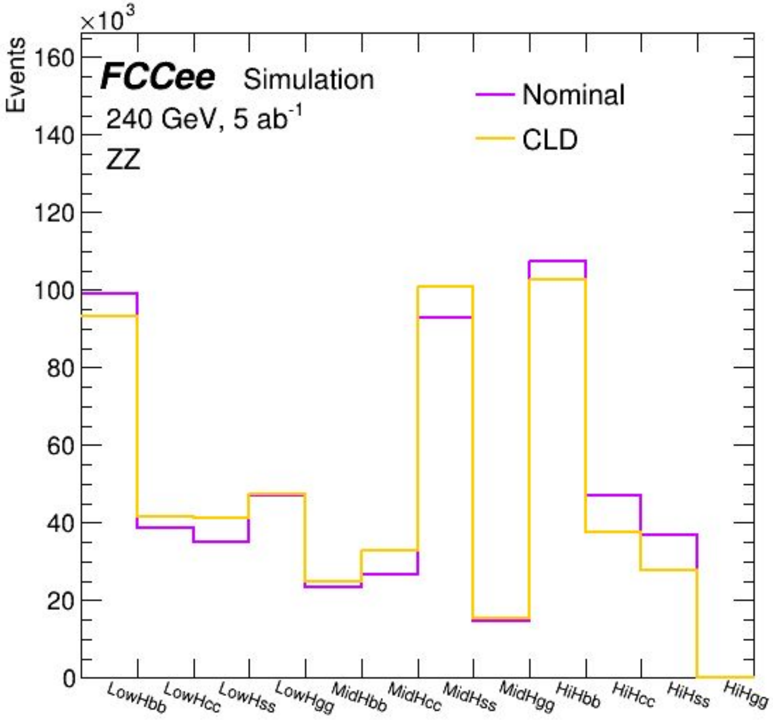


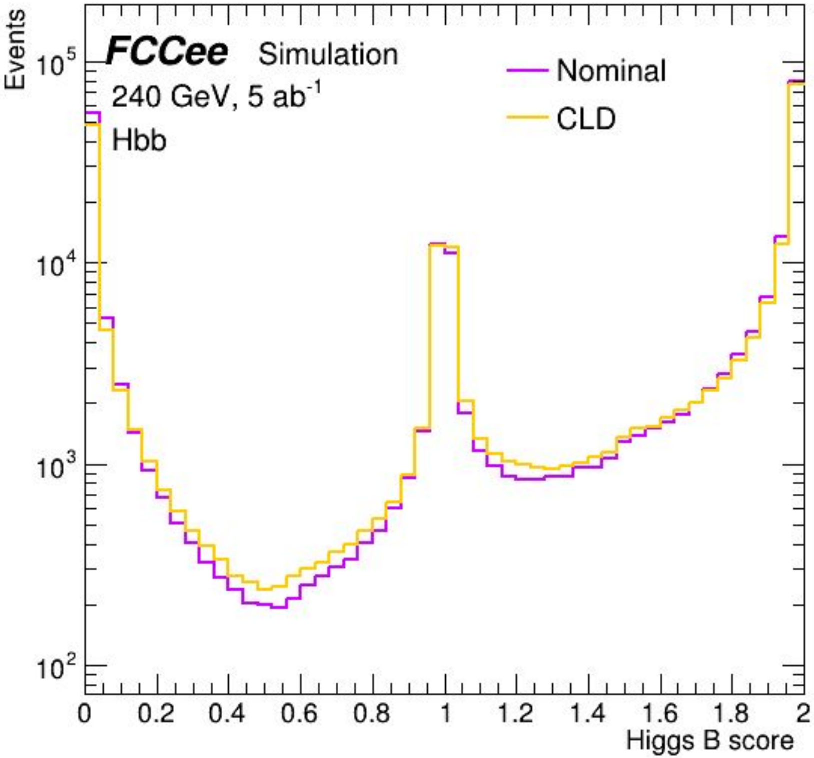
Impact on the analysis - Higgs C score



Truth H->cc jets flavour: The better rejection of the Nominal tagger is reflected in a higher fraction of truth H->cc events, with a very high Higgs C score. [see next slide]

Migration of ZZ events





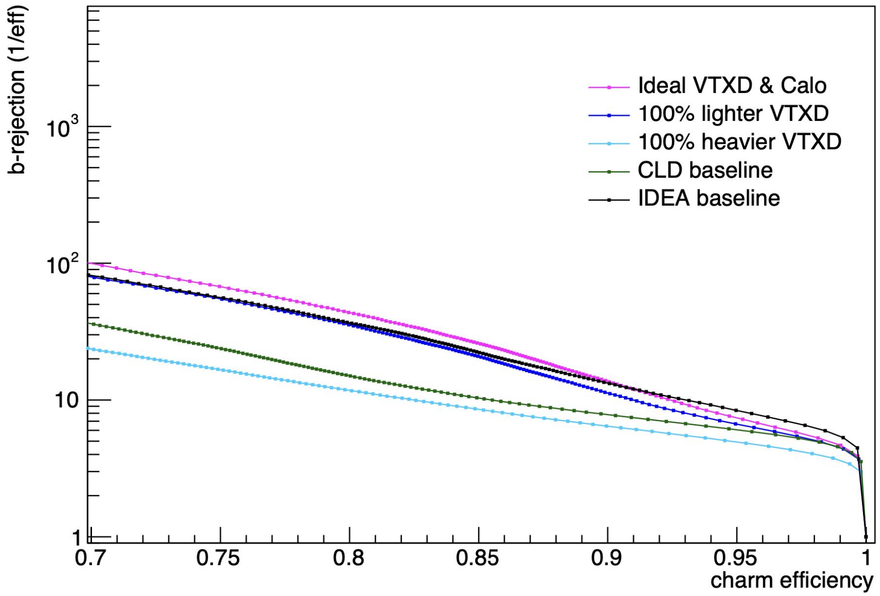
FUTURE CIRCULAR COLLIDER

IDEA tracker variations: Approximating the impact of tagging performance on the analysis

Andrean re-trained tagger for different detectors [see Andrea' presentation]:

- **Baseline:** IDEA baseline
- **idealVXDCalo:**
  - Best material budget, hit resolution and calorimeter granularity
- **lighterVXD_100pc:**
  - ~ No material interaction (X_0>>1m)
- **heavierVXD_100pc:**
  - Super small radiation length (X_0<<1m)
- **CLD**
  - Fast sim of the CLD **o1_v01**

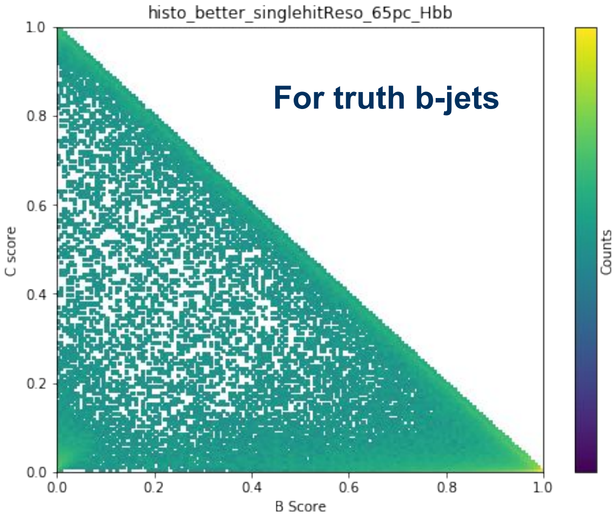
Plot from Andrea



Approximating the impact on tagging

Propagating the impact of retraining the tagger:

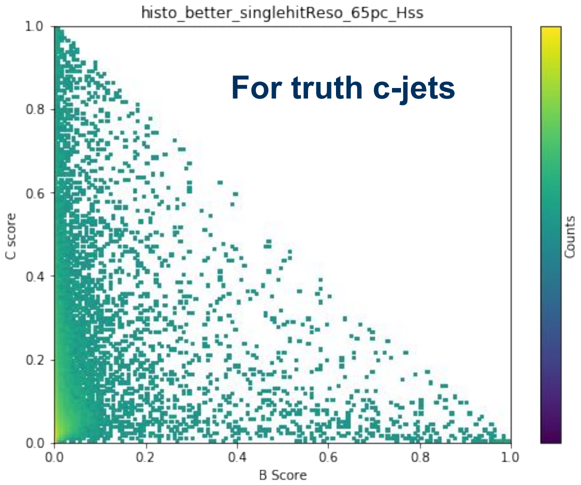
- Account only for impact on **b-,c- and s-score**
- Histo per jet flavour (4x) per detector variation **[Thanks Andrea!]**
  - Sample from histogram to update the b- c- and s-score score
    - Depends on the jet truth label!



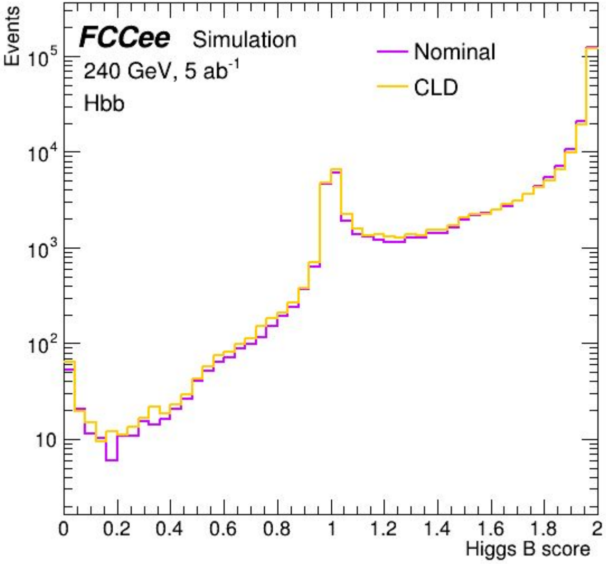
Drawbacks of the strategy

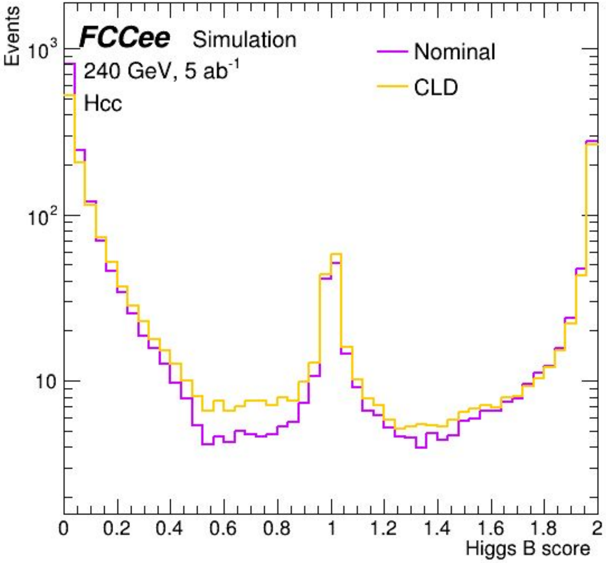
- Jet truth labelling not optimal
  - 88% accuracy in Z(qq)H(bb) samples [**Thanks Jan E.!**]
  - Does not tag gluon jets
- Ignoring some correlations
  - Correlation of the b-,c-, s- score to u/d, gluon score neglected

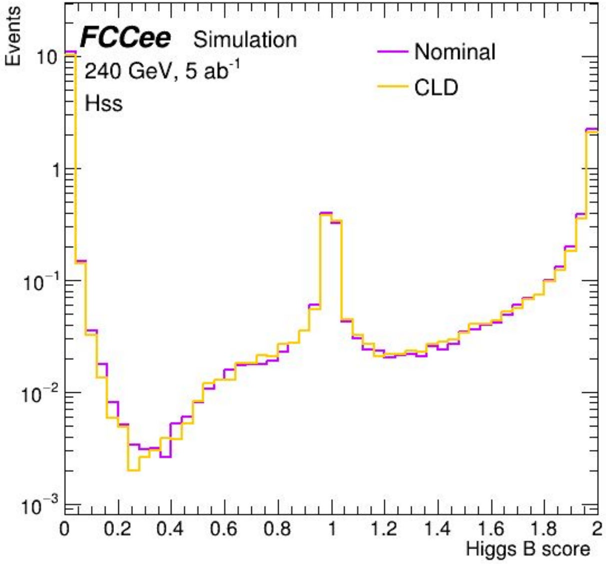
* Older tagger training, tau's not included



Impact on the analysis - Higgs B score

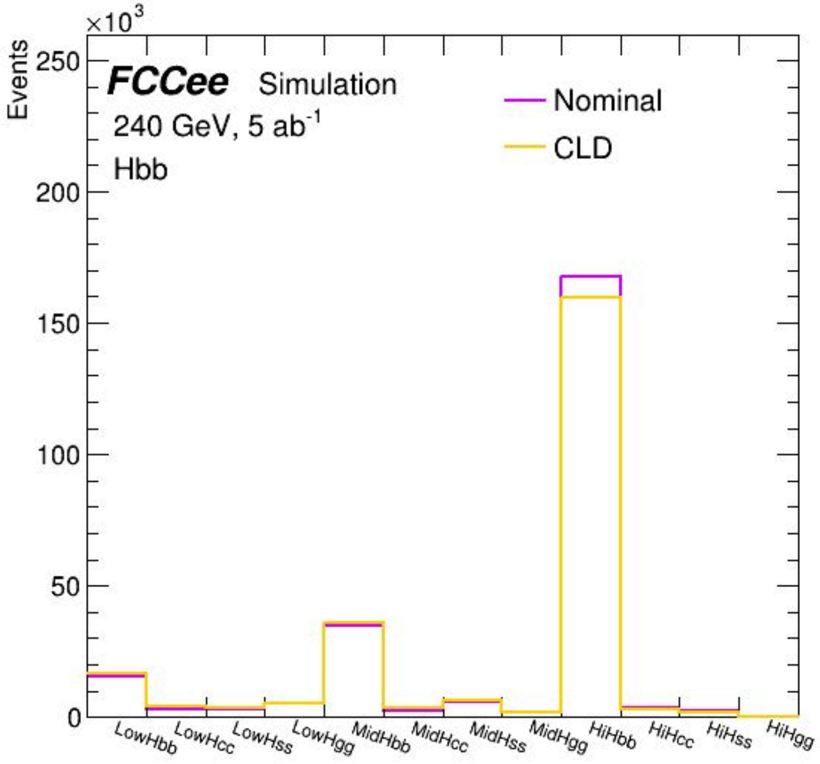


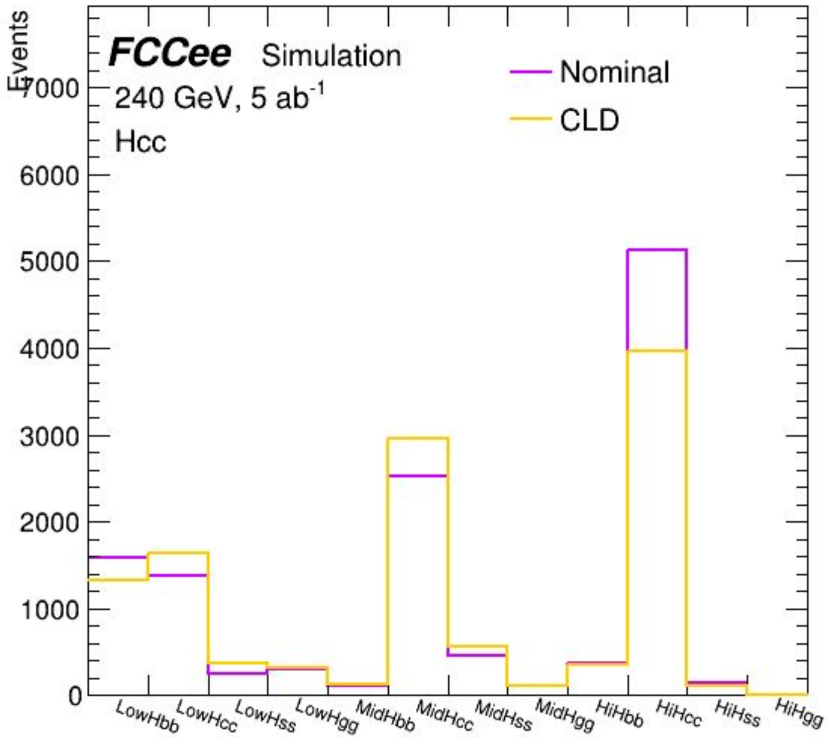




Truth H->bb jets flavour: The hit in performance of the tagger has the largest effect on the Higgs C-score. Smaller c-jet rejection leads to a larger Higgs C score.

Impact on the analysis - Migration between fit categories





Results

- **IDEA baseline very close to ideal vertex & calo detector**
- Robust analysis strategy
  - Small change in event selection
  - Main effect is migrates events between categories, dues to changes in performance
- No change in μ_{Hgg} as expected
  - G-score not varied nor truth gluon jet score corrected
- Largest impact on μ_{Hcc} w/ CLD trained tagger
- Caveats remainder!
  - Only approximate propagation of tagging effects
  - Ignored correlations of between b/c/s with g and light scores

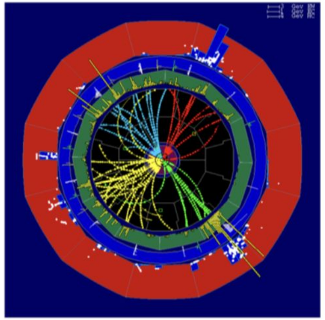
variation \ 68% CL precision	μ_{Hbb}	μ_{Hcc}
BASE	±0.3%	±3.9%
idealVXDCalo	±0.3%	+3.9% -3.8%
lighterVXD_100pc	±0.3%	±3.9%
heavierVXD_100pc	±0.4%	+4.6% -4.5%
CLD	±0.4%	±4.3%

Jet energy correction

Precision with e^+e^- colliders (4)

- Why are e^+e^- colliders the tool of choice for precision anyway ? (cont'd)
  - Electrons are leptons, i.e., elementary particles: no underlying event
    - Corollary: Final state has known energy and momentum: ($\sqrt{s}$, 0, 0, 0)
  - Example: an $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ candidate
    - Four jets in the event and nothing else
    - Total energy and momentum are conserved
      - ➨ $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
      - ➨ $P_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$
    - Jet directions ($\beta_i = p_i/E_i$) are very well measured

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



- Jet energies (or di-jet masses: m_W) determined analytically by inverting the matrix
  - ➨ No systematic uncertainty related to jet energy calibration

A lot of Z are available anyway to calibrate and align everything

Patrick Janot — Physics at Future Colliders 28-29 July 2016 — 7

- If any jet in event **E<0** OR **E>240** GeV [only a few percent of events] keep uncorrected value