ZH->jjjj

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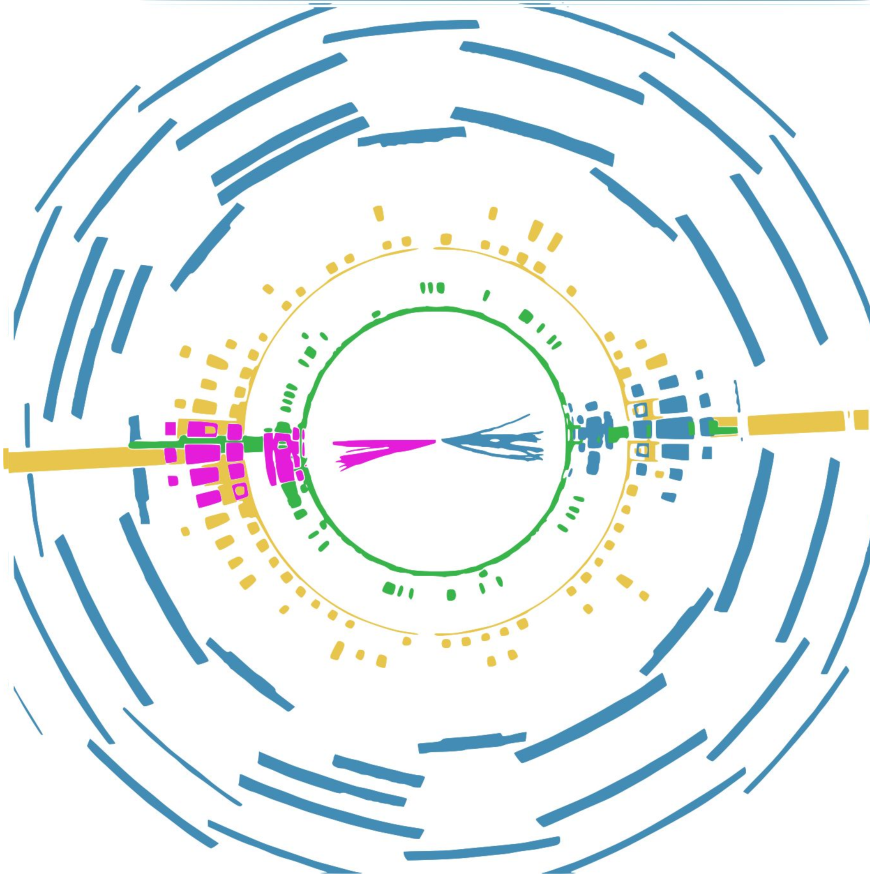
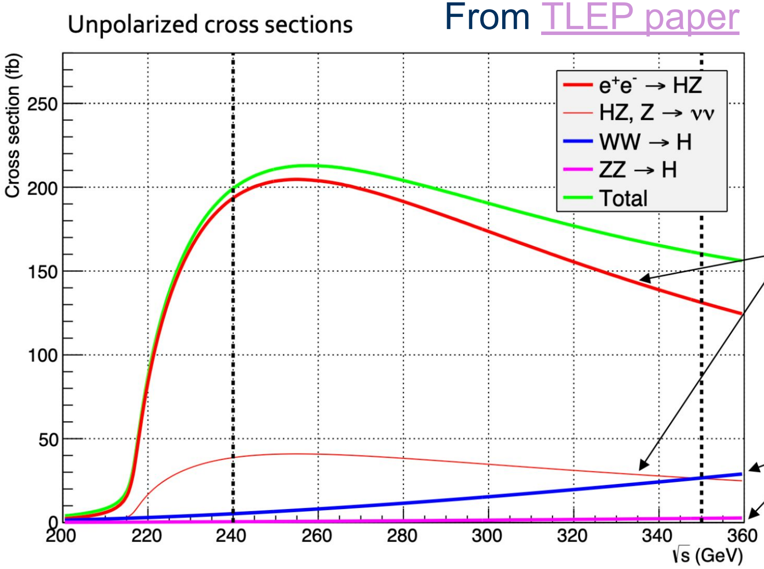


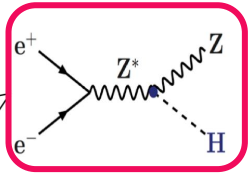
Brookhaven National Laboratory

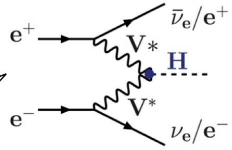
FUTURE CIRCULAR COLLIDER

Introduction

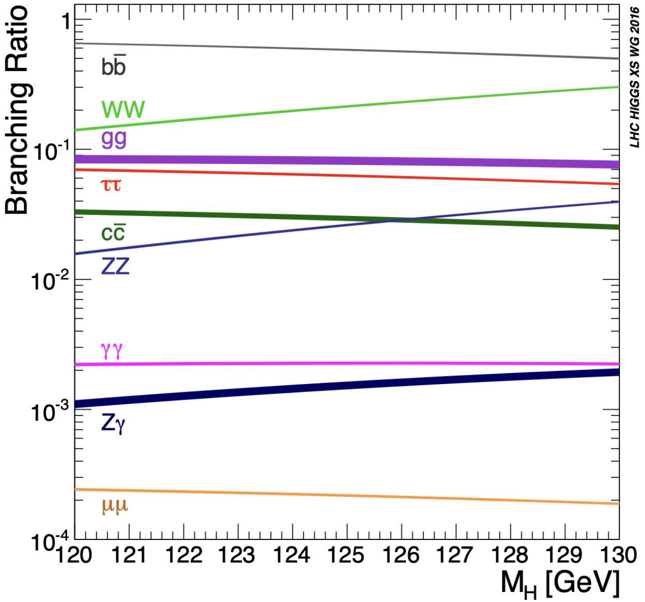
From TLEP paper







From Handbook of LHC Higgs cross sections



- ZH leading Higgs production mode
  - + All hadronic decay has the largest branching fraction
  - - Jet combinatorics, flavour identification
- Abundance of Higgs produced @ √s = 240 GeV
  - Focus on IDEA Detector

Samples Considered

- **IDEA Detector**
  - Delphes fast sim
- **Winter2023 Samples**
  - /eos/experiment/fcc/ee/jet_flavour_tagging/winter2023/wc_pt_7classes_12_04_2023
- **Jet Clustering**
  - N = 4 Durham k_T exclusive algorithm
- **ParticleNet jet tagger**
  - fccee_flavtagging_edm4hep_wc
- Build on ZH(full hadronic) analysis presented in Annecy by George [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)**

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 jet!

Lepton cuts

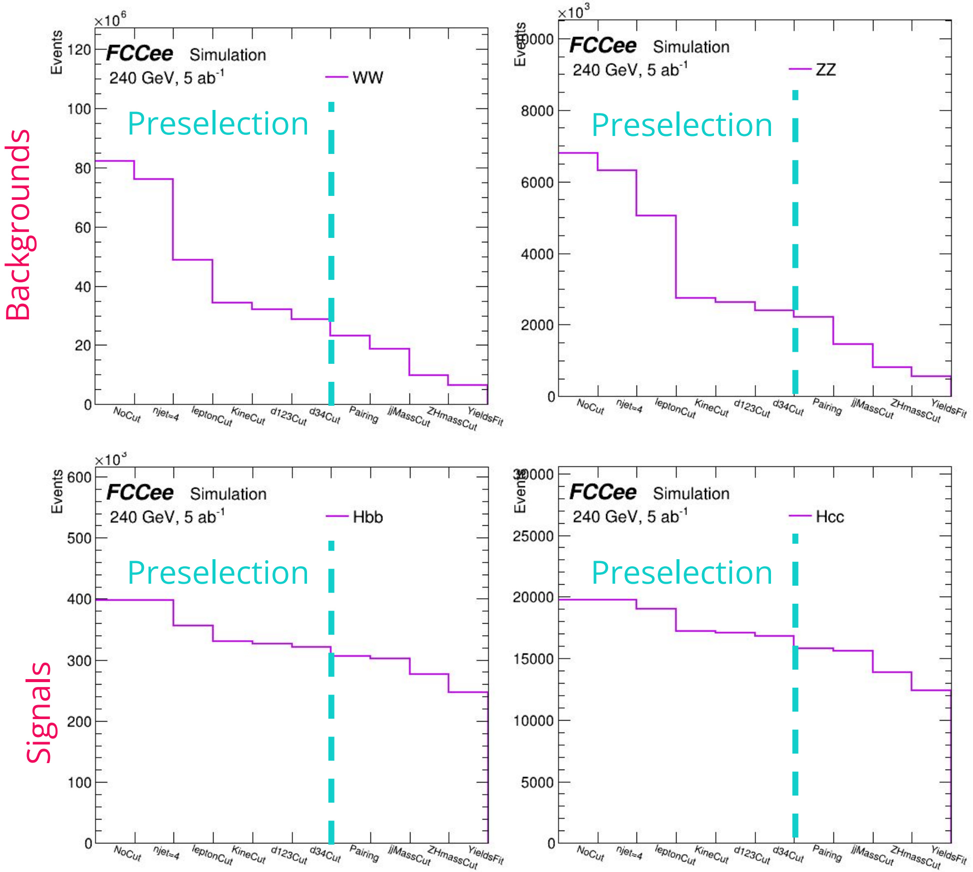
- <= 2 muons and electrons
- Leading muon and electron pT < 20 GeV

Visible Energy

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

d_{ij} Cuts

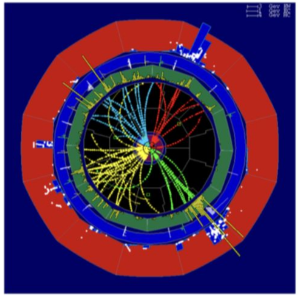
- $15000 < d_{12} < 58000$
- $400 < d_{23} < 18000$
- $100 < d_{34} < 6000$



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

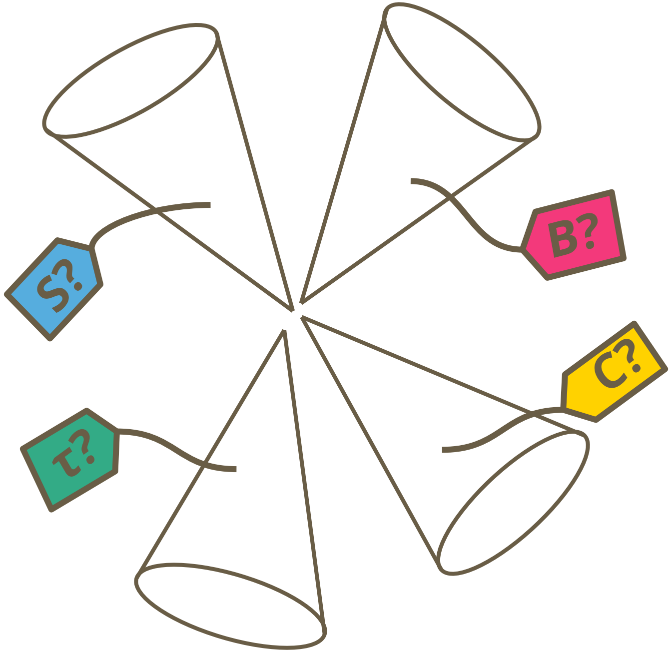
A lot of Z are available anyway to calibrate and align everything

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]

TOSS EVENT

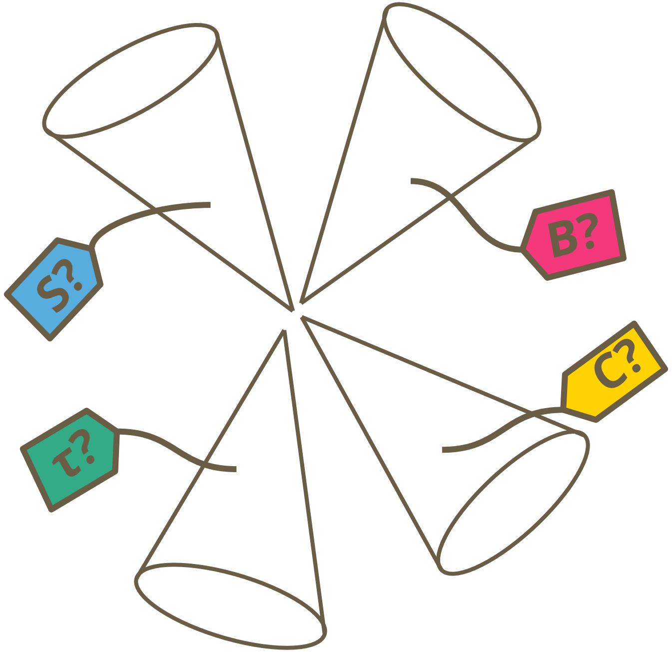
Jet “tagging”



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
- NOT traditional flavour tagging
  - Maximum flavour score ~ flavor of jet
  - Sums of same flavour scores for jet pairs ~ flavour of jet pair

Jet pairing



Each jet has a maximum tagger score from a different flavour

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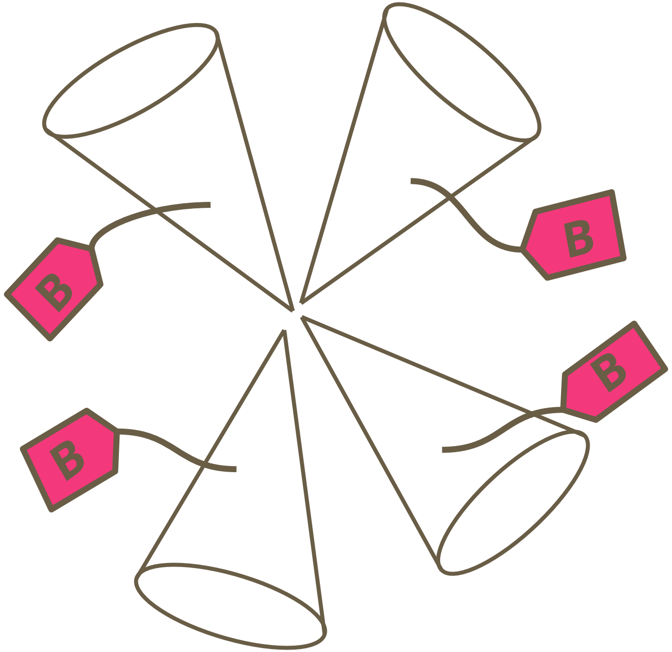
TOSS EVENT

Jet pairing



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

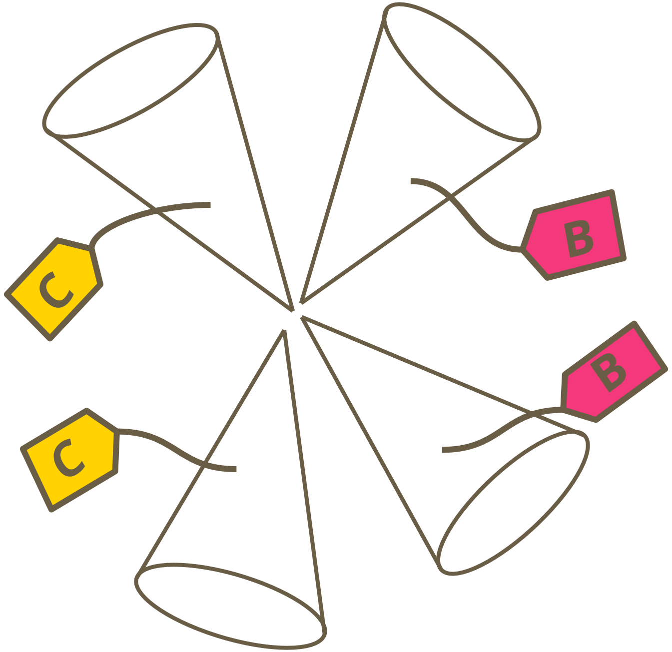
Finding the H&Z candidates

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!

Jet pairing

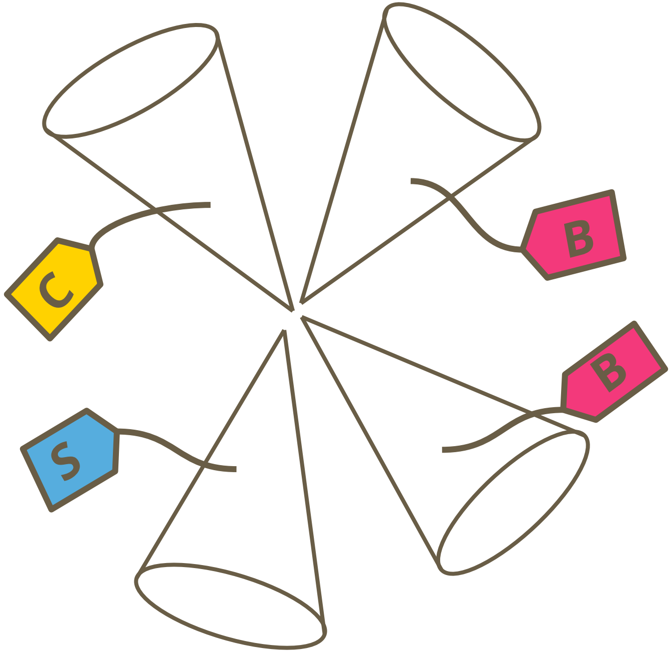


CASE 2: Two jet pairs with same maximum score from the same flavour, but different flavour of the pairs

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

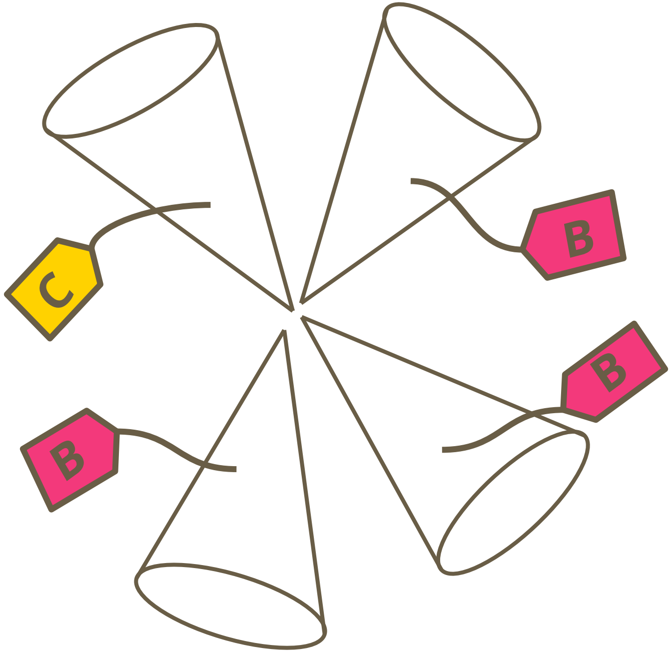
Recover second pair:

- 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: [check code]

- 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

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

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

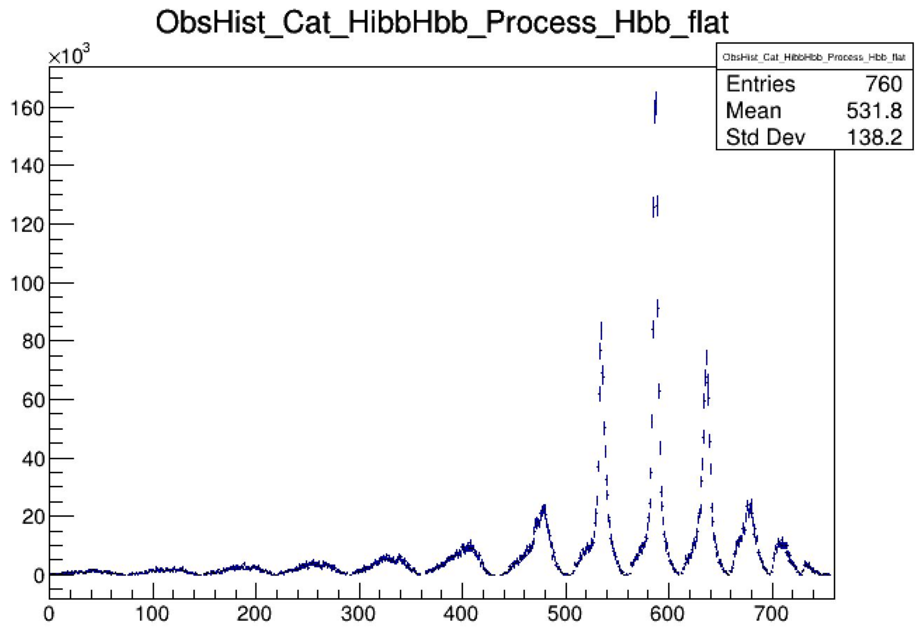
Mass window

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

Reject events identified/contain as:

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

Categorization



Unfolded 2D $m_{jj,H}$ - $m_{jj,Z}$ mass plane

Hbb signal in the high purity Z(bb)H(bb) category

- 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))
- 36 Categorised in total!
- + 1 GeV binning in $m_{jj,H}$
- + 5 GeV binning in $m_{jj,Z}$

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.

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

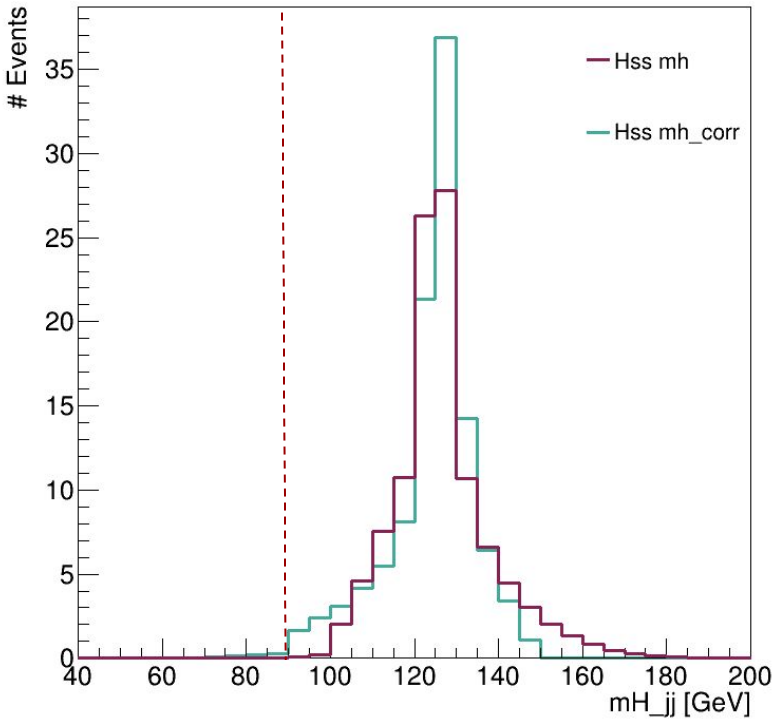
Maximize $L(\kappa_\lambda, \theta)$ by holding μ_{xx} fixed and fitting the model.

Nuisance parameters

Best-fit coupling

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

Yet another correction to $m_{jj,H}$



- Besides the energy correction to the jets based on COM
- After all selection:
  - $mH\_jj\_corr = mH\_jj + mZ\_jj - mZ_{truth}$
- As before fit mH_jj_corr against mZ_jj

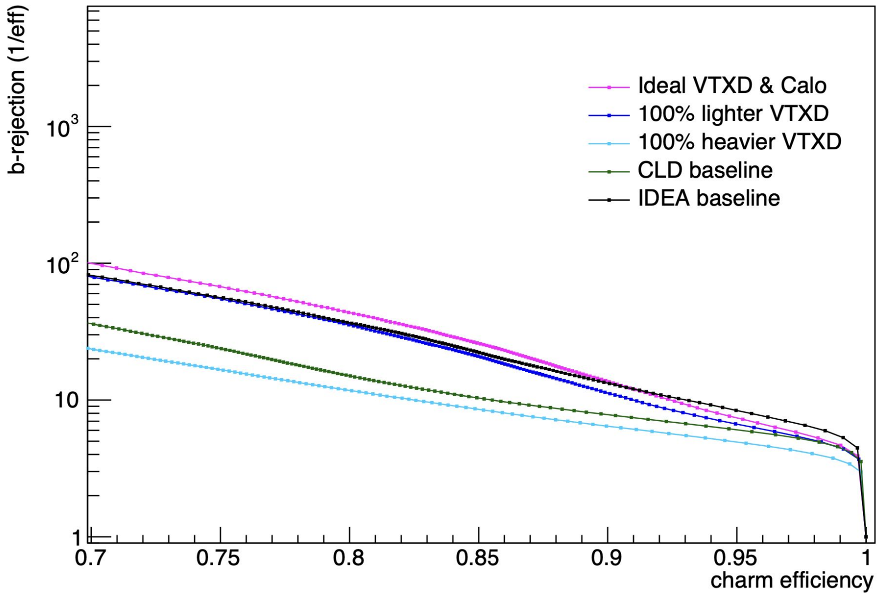
68% CL precision / variation	μ_{Hbb}	μ_{Hcc}
BASE	±0.3	±3.9
Base (fit Mh_jj_corr_Mz_jj	±0.3	±3.9

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



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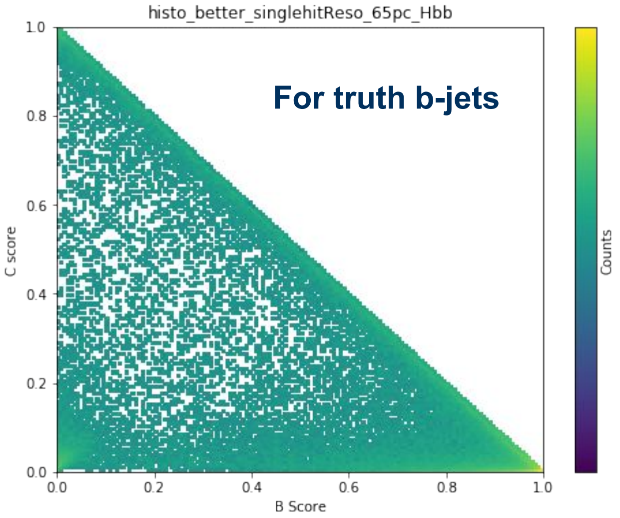
Approximating the impact on tagging

Propagating the impact of retraining the tagger:

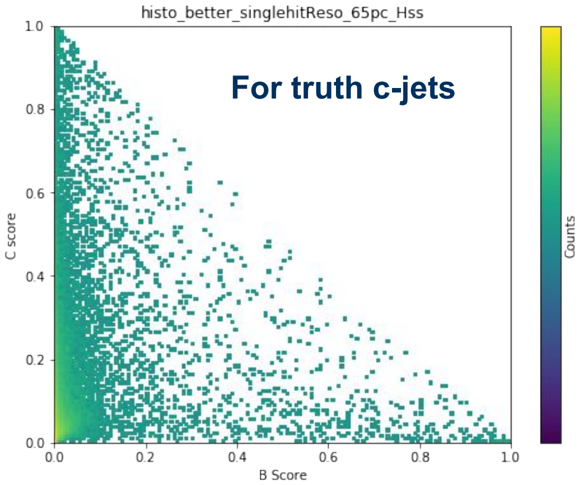
- Account only for impact on **b-,c- and s-score**
- Histo per jet flavour (4x) per detector variation **[Thanks Andrea!]**
  - Sample from histogram to update the b- c- and s-score score
    - Depends on the jet truth label!



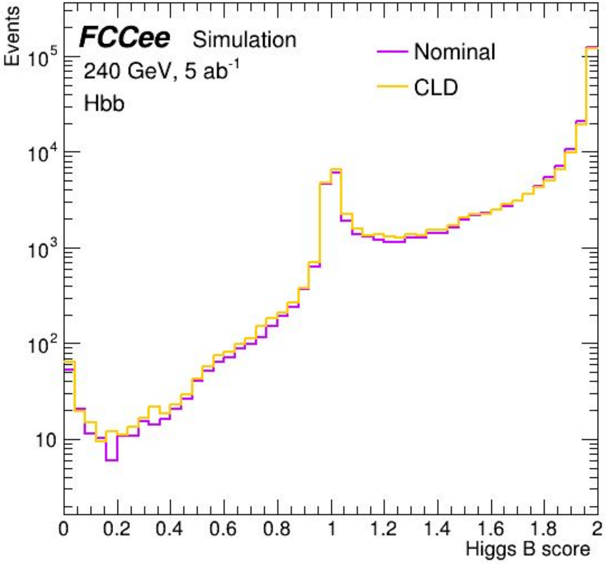
Drawbacks of the strategy

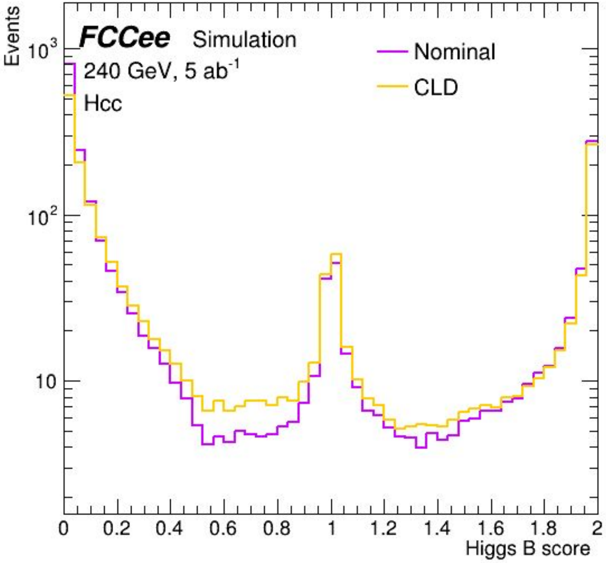
- Jet truth labelling not optimal
  - 88% accuracy in Z(qq)H(bb) samples [**Thanks Jan E.!**]
  - Does not tag gluon jets
- Ignoring some correlations
  - Correlation of the b-,c-, s- score to u/d, gluon score neglected

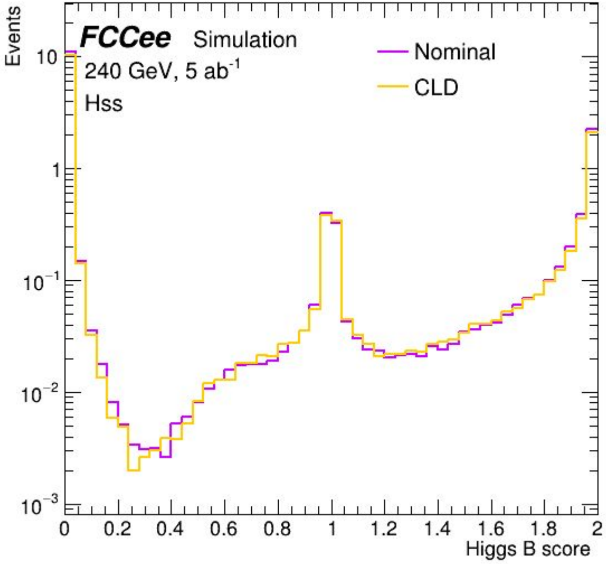
* Older tagger training, tau's not included



Impact on the analysis - Higgs B score

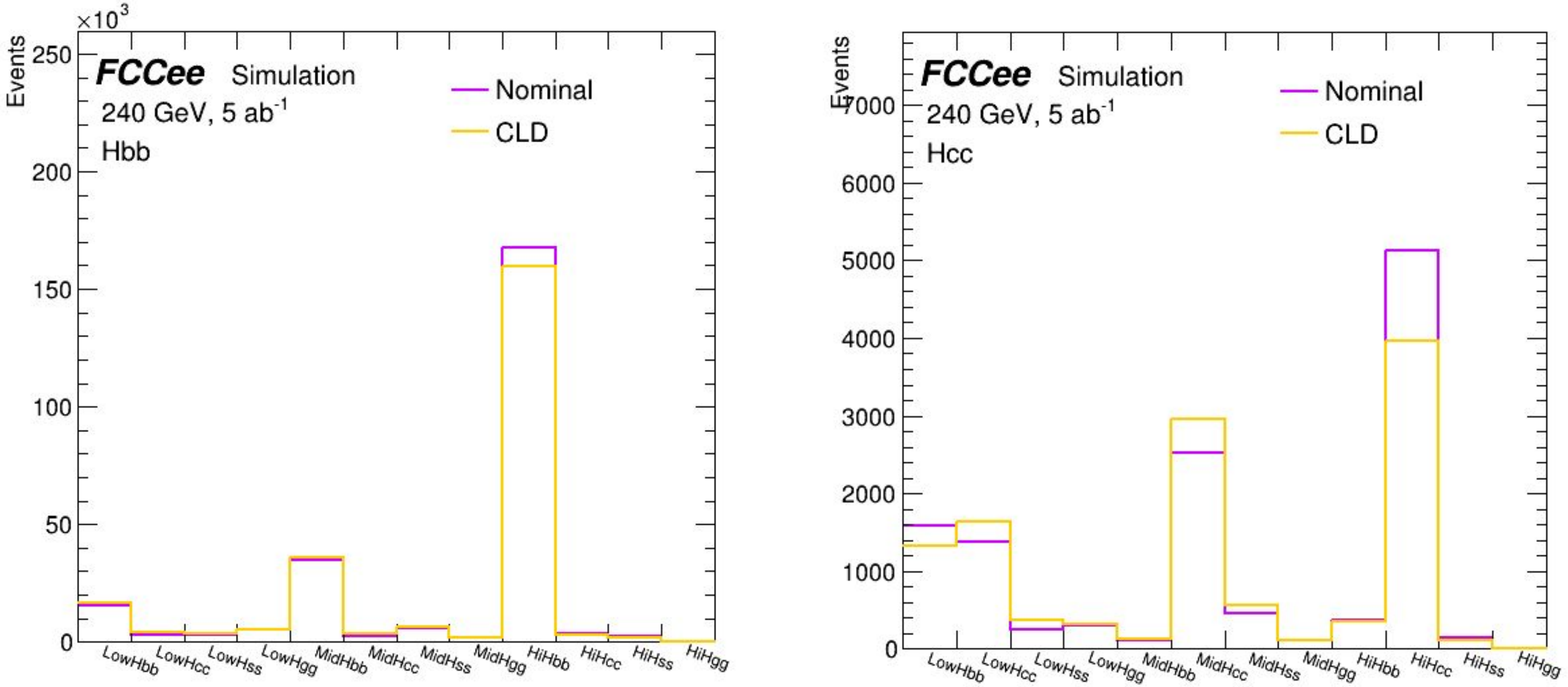




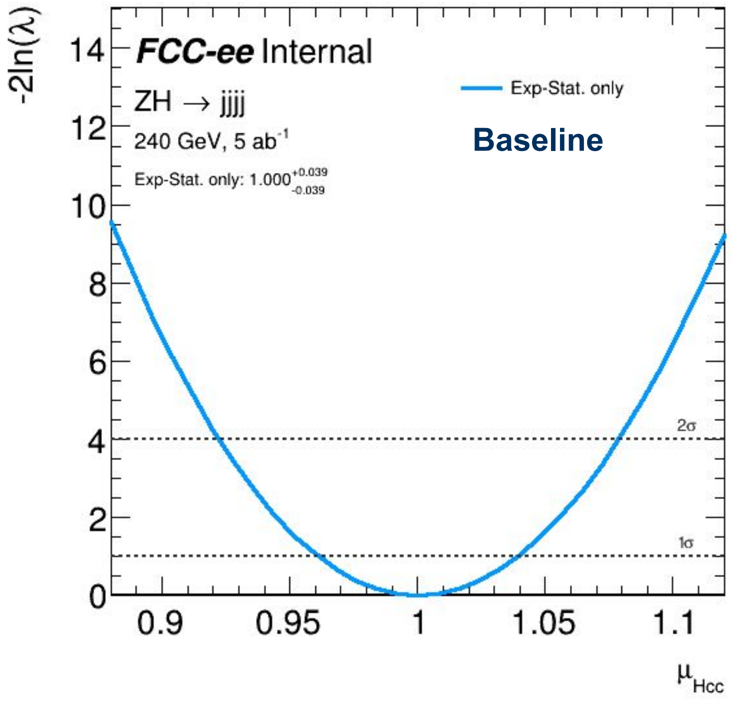


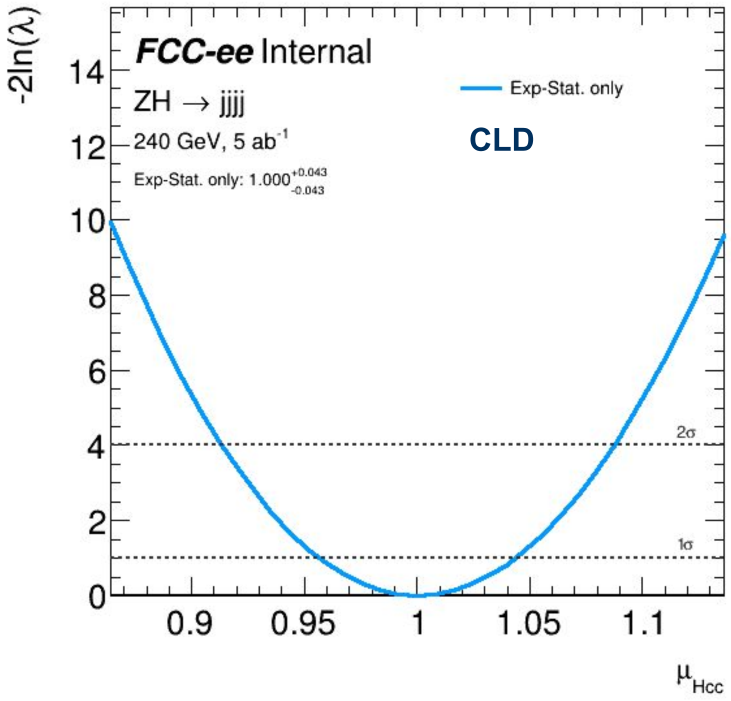
Truth H->bb jets flavour: The hit in performance of the tagger has the largest effect on the Higgs C-score. Smaller c-jet rejection leads to a larger Higgs C score.

Impact on the analysis - Migration between fit categorise



Likelihood scans - μ_{Hcc}





Largest change in expected precision on μ_{Hcc} observed when the tagger is re-trained with the CLD simulation.

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 $\boldsymbol{\mu}_{Hgg}$ as expected
  - G-score not varied nor truth gluon jet score corrected
- Largest impact on $\boldsymbol{\mu}_{Hcc}$ 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%

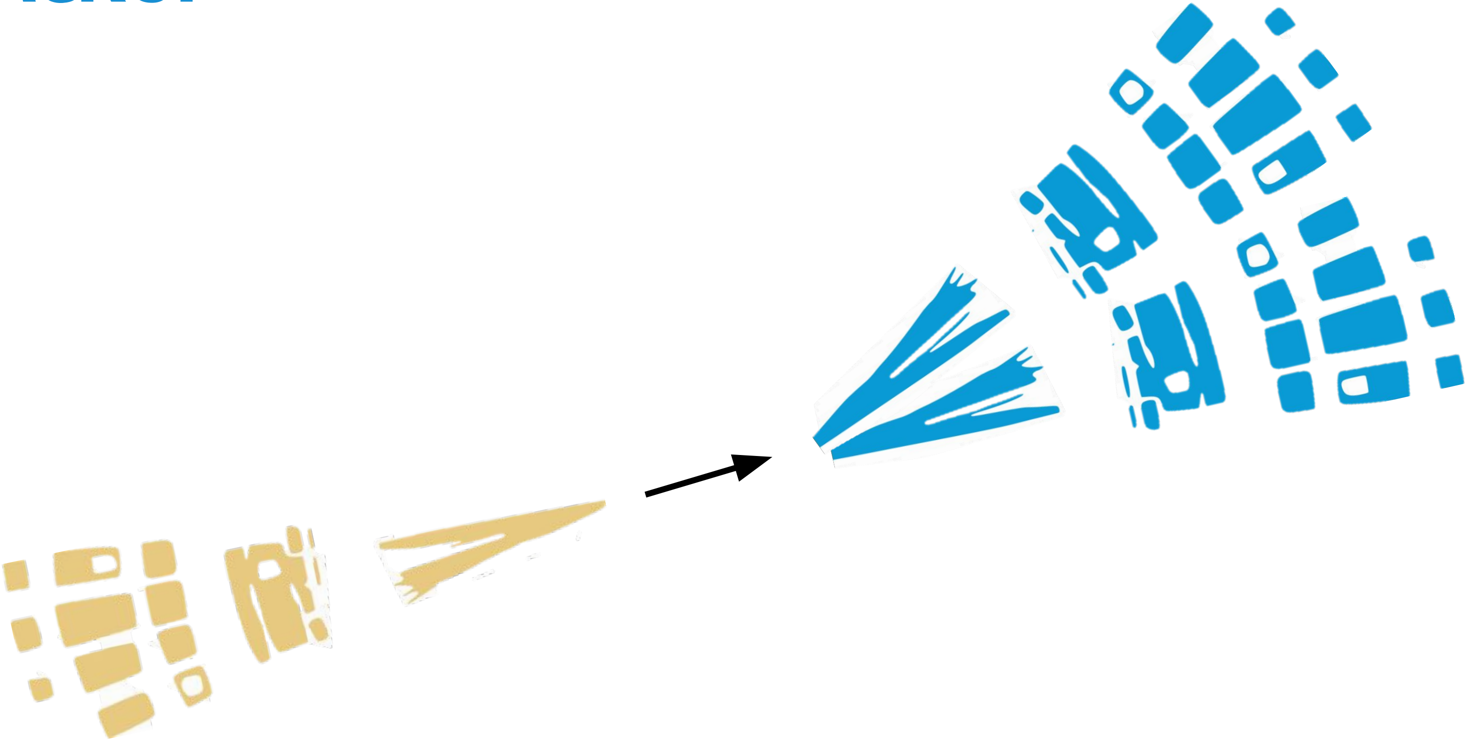
Conclusion

- Correction of the reconstructed Higgs mass does not significantly improve the expected precision on μ_{Hxx}
  - mH_jj_corr = mH_jj + mZ_jj - mZ_{truth}
- First look at the impact of flavour tagging given different detector layouts
  - Partricle net retrained for various detector layouts
  - Changes in tagger performance propagated to the ZH->jjjj analysis
    - Sever approximation taken to have a quick estimation of the impact
      - Determine how big of a change in the tagging performance is worth rerunning the whole analysis chain
  - The analysis roubouts
    - Very small impact on the expected μ_{Hxx} precision measurement

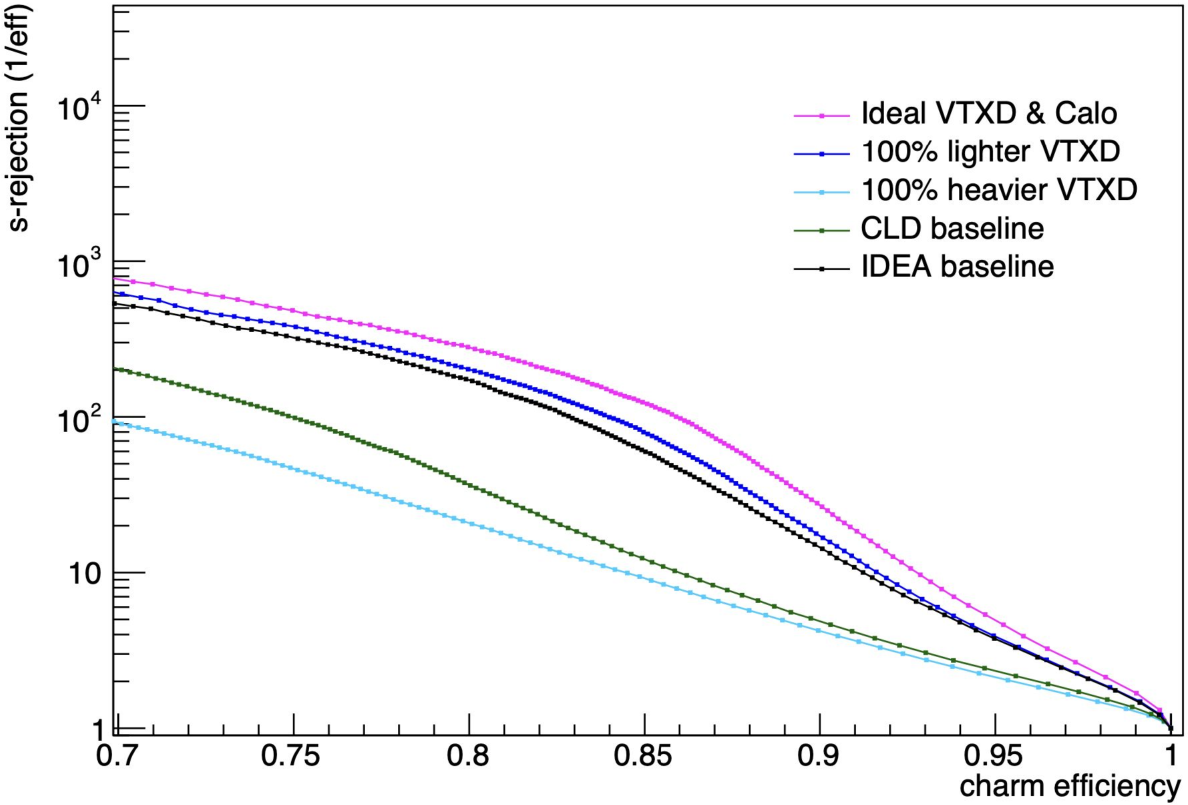
Next Steps

- Consider different jet clustering strategies
  - Will have a summer student working on it for ~ 8 weeks
- Optimize analysis strategy
  - Still some space to push for more precise $\boldsymbol{\mu}_{Hxx}$ measurements
- Future parametrize impact of various detector layout
  - Evaluate re-trained tagger without approximations
  - Jet mass resolution
- Combine with Z(vv)H(jj) and Z(jj)H(jj)

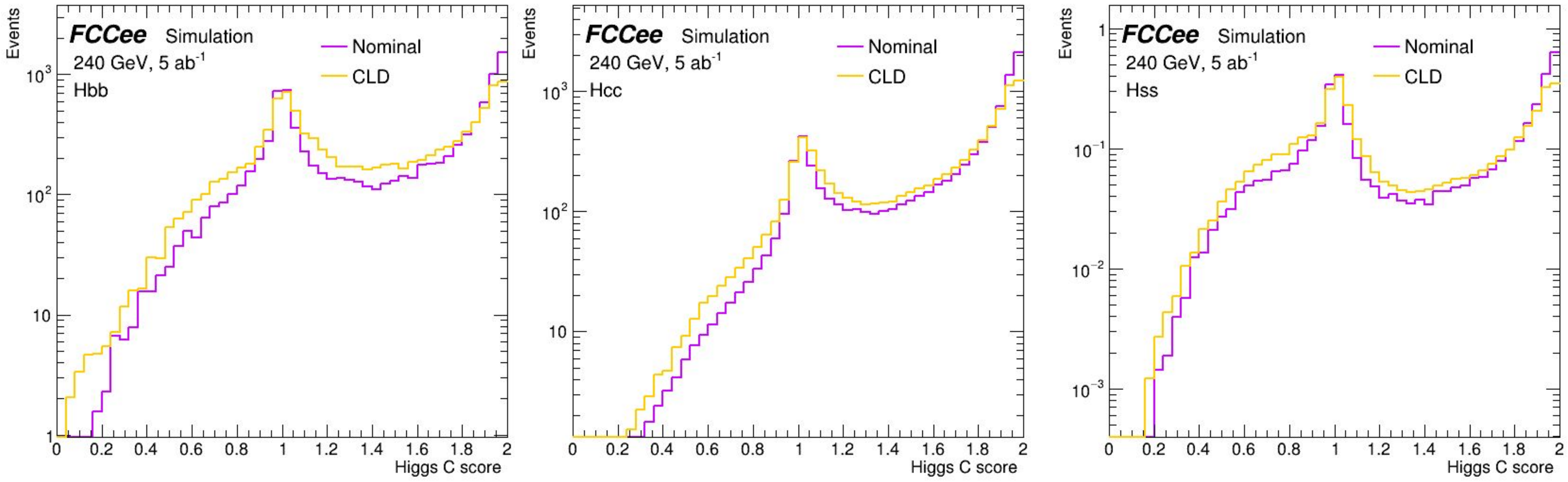
BACKUP



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]

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Migration of ZZ events