# Higgs couplings to hadrons and invisible particles

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# Physics motivation

- **LHC results:** do not concretely point to any BSM scenario/mass scale
- HL-LHC: Direct searches: reach O(5-10) TeV regime
  Higgs-couplings: few%, self-coupling ~50%
- Which precision?

Ref

BSM O(1TeV): Impact on H-couplings

| Model | $b\bar{b}$ | $c\bar{c}$ | $gg$ | $WW$ | $\tau\tau$ | $ZZ$ | $\gamma\gamma$ | $\mu\mu$ |
|---|---|---|---|---|---|---|---|---|
| MSSM [40] | +4.8 | -0.8 | - 0.8 | -0.2 | +0.4 | -0.5 | +0.1 | +0.3 |
| Type II 2HD [42] | +10.1 | -0.2 | -0.2 | 0.0 | +9.8 | 0.0 | +0.1 | +9.8 |
| Type X 2HD [42] | -0.2 | -0.2 | -0.2 | 0.0 | +7.8 | 0.0 | 0.0 | +7.8 |
| Type Y 2HD [42] | +10.1 | -0.2 | -0.2 | 0.0 | -0.2 | 0.0 | 0.1 | -0.2 |
| Composite Higgs [44] | -6.4 | -6.4 | -6.4 | -2.1 | -6.4 | -2.1 | -2.1 | -6.4 |
| Little Higgs w. T-parity [45] | 0.0 | 0.0 | -6.1 | -2.5 | 0.0 | -2.5 | -1.5 | 0.0 |
| Little Higgs w. T-parity [46] | -7.8 | -4.6 | -3.5 | -1.5 | -7.8 | -1.5 | -1.0 | -7.8 |
| Higgs-Radion [47] | -1.5 | - 1.5 | +10. | -1.5 | -1.5 | -1.5 | -1.0 | -1.5 |
| Higgs Singlet [48] | -3.5 | -3.5 | -3.5 | -3.5 | -3.5 | -3.5 | -3.5 | -3.5 |

$$\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2(\mathrm{TeV})}$$

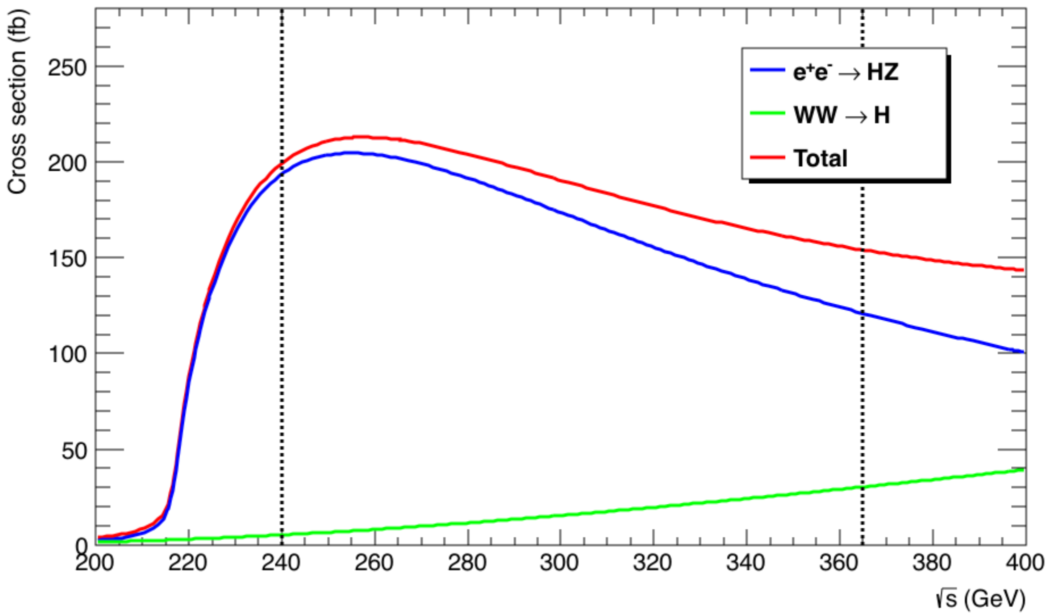
e.g. Λ=1 (5)TeV→~5 (0.1)%

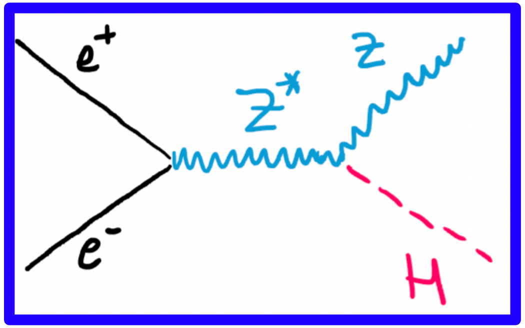
- HL-LHC cannot guarantee definite answers to the open questions
- Begs for Higgs factory → $e^+e^-$

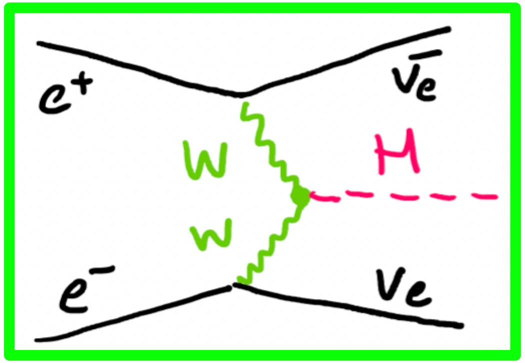
## Outline:

- Strategy and tools for Higgs measurements
- Higgs couplings to “visible” particles
- Higgs couplings to “invisible” particles
- Detector requirements
- Summary

# Higgs production at FCC-ee



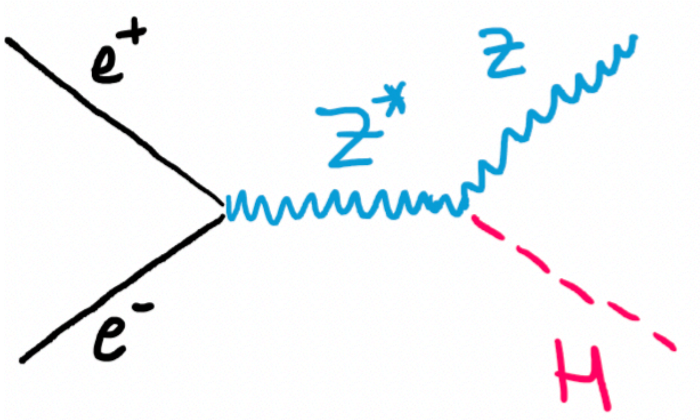



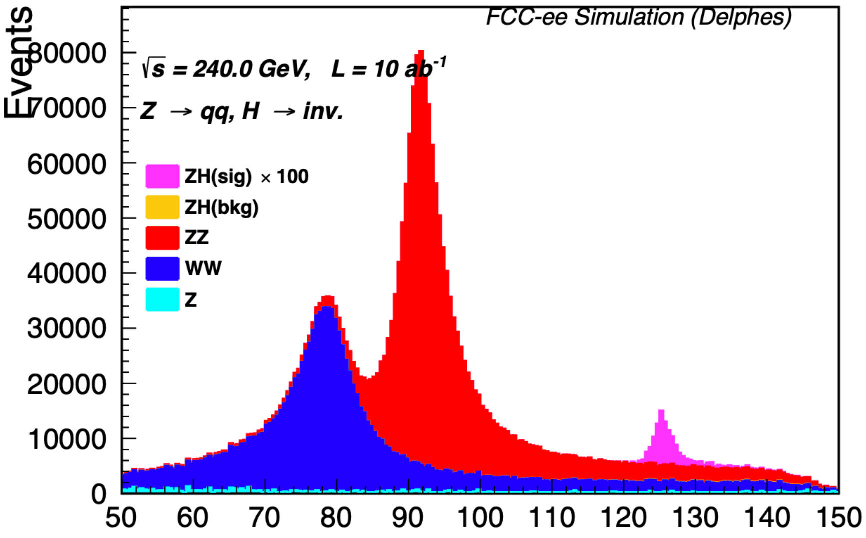




**Focus at ZH production:** 2M Higgs [4IP]
- Clean environment
- Small BKGs [compared to hadron colliders]

# General strategy

Z boson reconstruction:
- explore several decay modes
- recoil mass




$$M_{\rm rec} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

# General strategy

**Z boson reconstruction:**
- explore several decay modes
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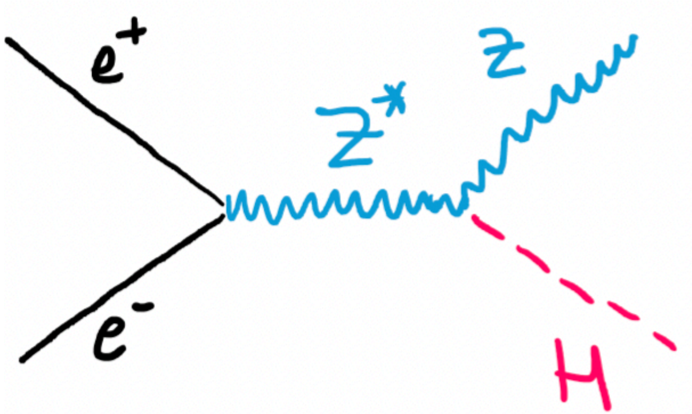
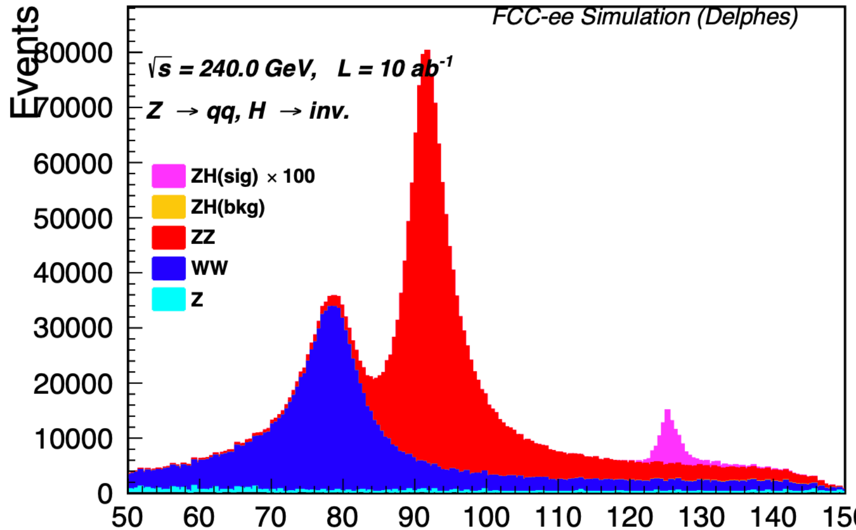



**Higgs boson reconstruction:**
- jet clustering
- jet flavor identification




$$M_{\rm rec} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

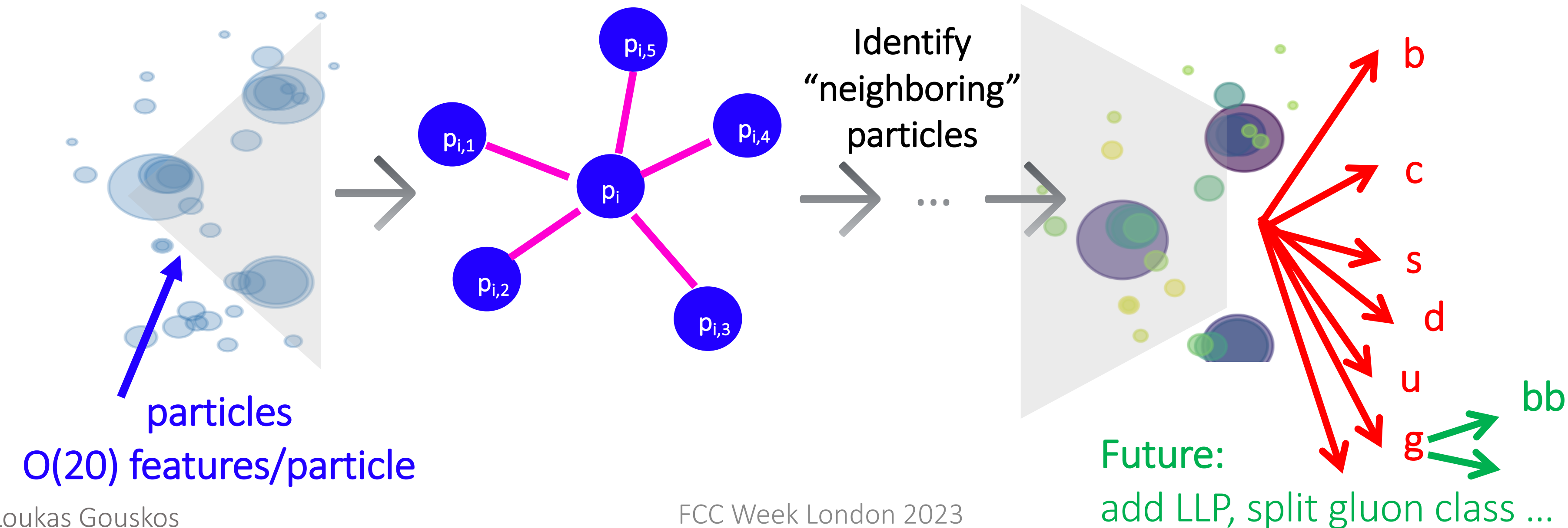
BR(H→hadrons) ~ 80%
BR(Z→hadrons) ~ 70%

**Optimal reconstruction of hadronic final states essential**

# Jet Flavour identification ("tagging")

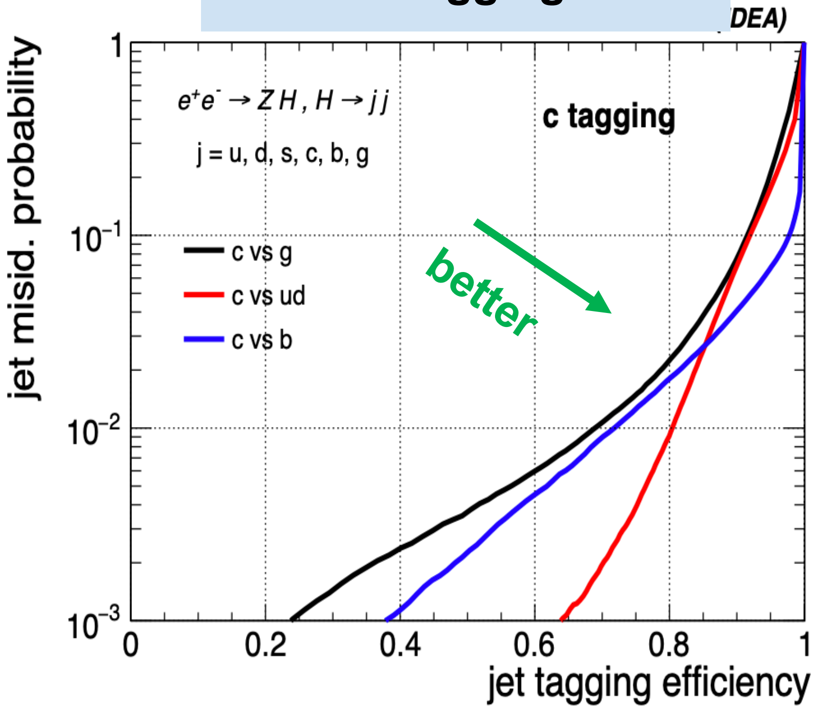
H. Qu and LG
PRD 101 056019 (2020)
F. Bedeschi, M. Selvaggi, LG
EPJ C 82 646 (2022)

- Jet representation: Particle cloud
  - i.e. unordered set of particles
- Network architecture: Graph Neural Networks
  - Particle cloud represented as a graph
    - particles: vertices of graph; interactions b/w particles: edges of graph
- Hierarchical learning approach: local → global structures

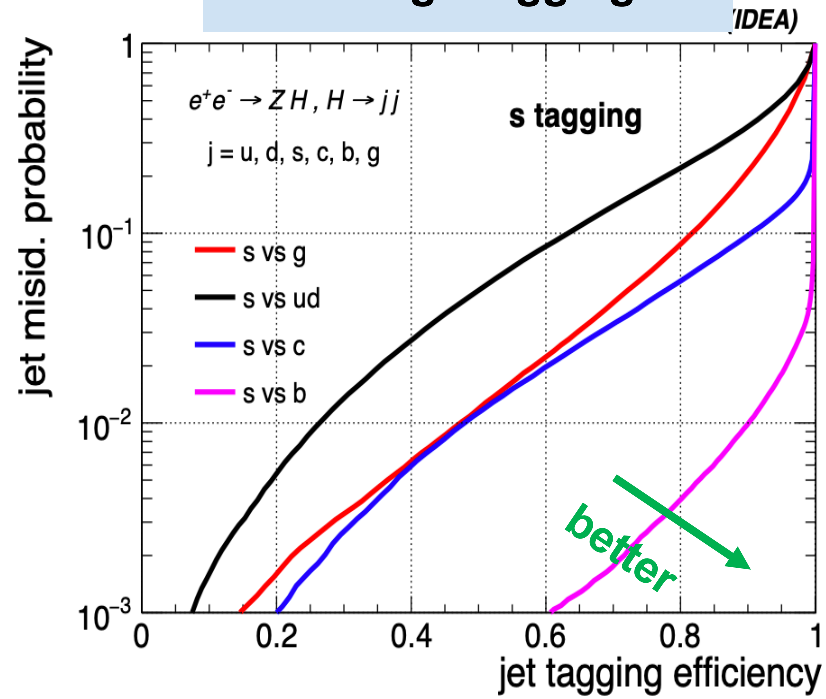


# Jet tagging: Performance

## c-tagging




## strange-tagging




| WP | Eff (c) | Mistag (g) | Mistag (ud) | Mistag (b) |
|---|---|---|---|---|
| Loose | 90% | 7% | 7% | 4% |
| Medium | 80% | 2% | 0.8% | 2% |

| WP | Eff (s) | Mistag (g) | Mistag (ud) | Mistag (c) | Mistag (b) |
|---|---|---|---|---|---|
| Loose | 90% | 20% | 40% | 10% | 1% |
| Medium | 80% | 9% | 20% | 6% | 0.4% |

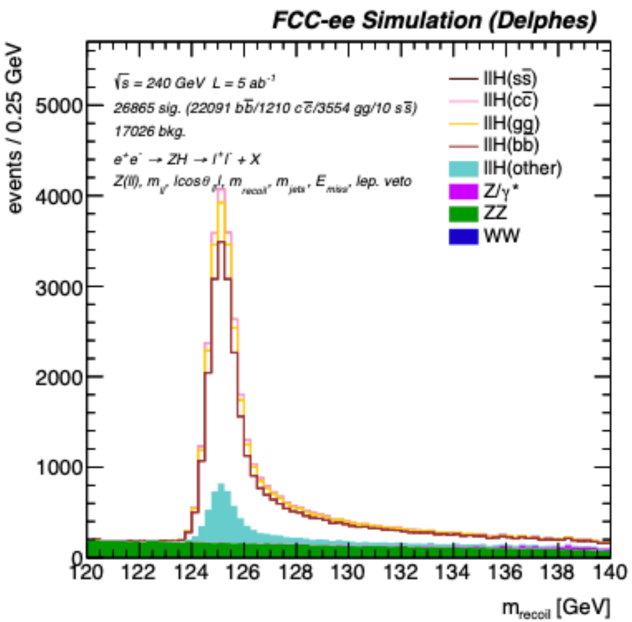
# H-Couplings to visible particles

- Analysis channels
  - Z(→LL)H: clean but smaller signal acceptance
  - Z(→vv)H: good compromise b/ signal acceptance and purity
  - Z(→hadrons)H: Largest signal acceptance, but.. jets [work in progress]

- Study all possible Higgs decay modes
  - Currently: bb, cc, ss, gg, ττ
    - work on going: uu, dd, + off diagonal terms

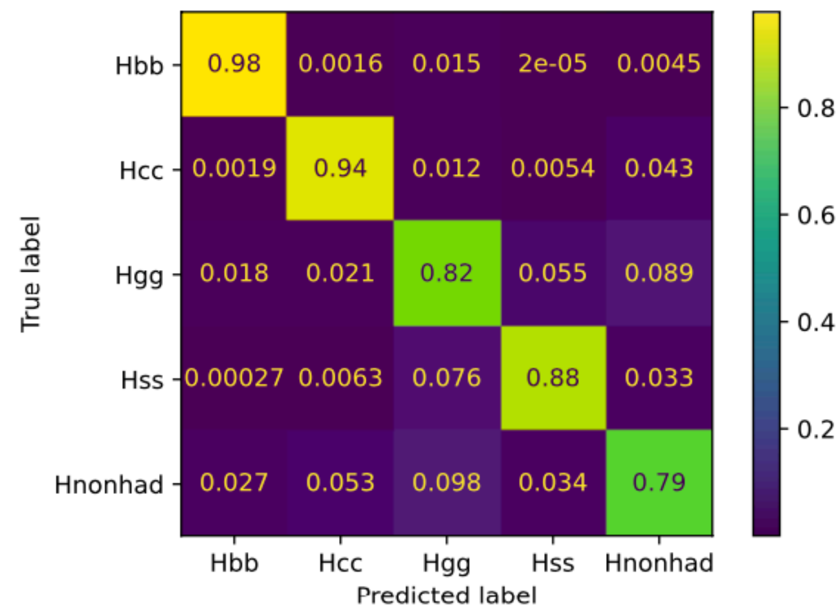
# Z(→LL)H channel

- Baseline: $N_L$=2, $N_j$=2
  - $m_{LL}$ ($m_{jj}$) consistent with $m_Z$ ($m_H$)
  - $d_{23}$ > 2, $d_{34}$ > 1.5




- Main [non-Higgs] BKGs: ZZ
  - Key: disentangle Higgs decay modes

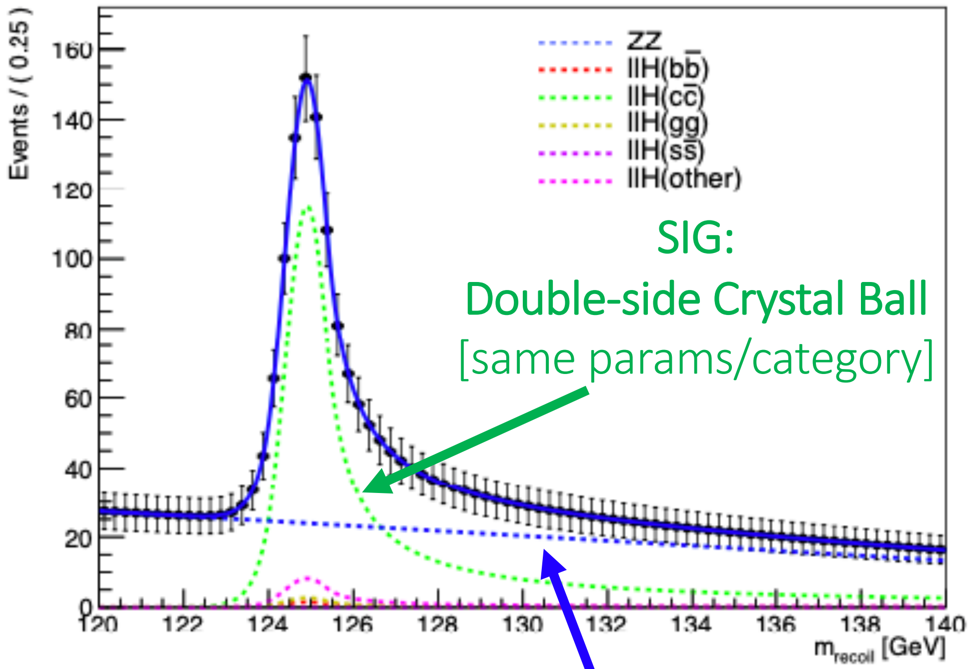
- Event-level discrimination with NN:
  - Inputs:
    - ParticleNet-ee scores / jet
    - Event-level: d23, d34, $p_{miss}$, $m_{jj}$
  - Multiclass output



# Z(→LL)H channel (II)

- Fit $m_{rec}$ simultaneously in all categories

Z(→LL)H(→cc) category




- Systematics: 5% on BKG
  - uncorrelated b/w categories
- Free-floating signal strength

Results @10 $ab^{-1}$

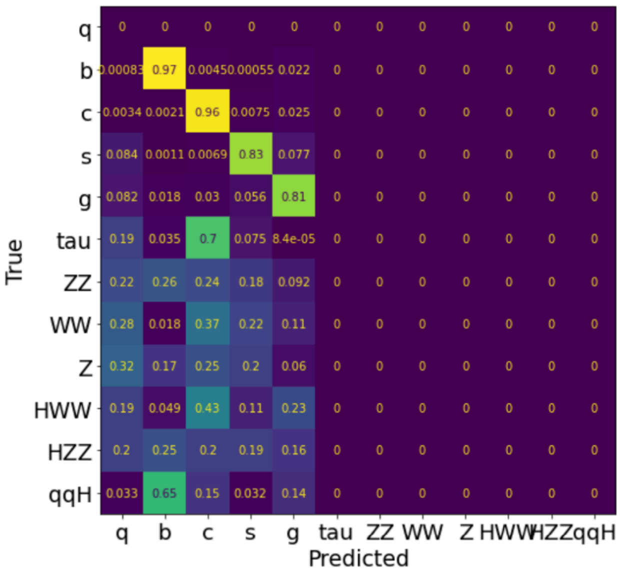
| Z(→LL)H(→qq) | bb | cc | ss | gg |
|---|---|---|---|---|
| δμ/μ (%) | 0.6 | 3.5 | 290 | 1.5 |

# Z(→νν)H channel

- Similar strategy: but larger and more complex BKGs

## Event categorization

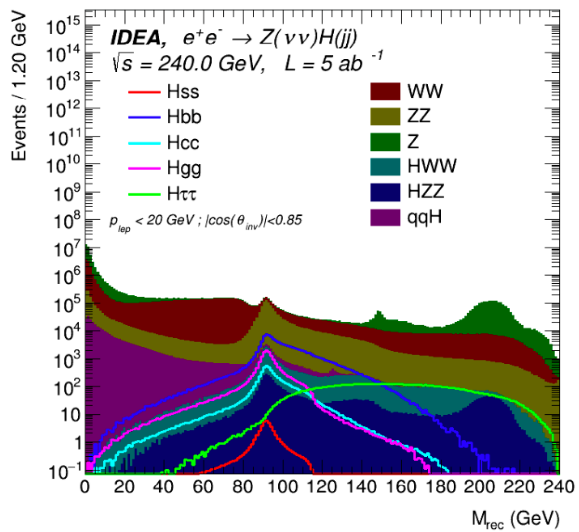
- Sum ParticleNet scores of 2 jets
  - e.g. scores: $b_1b_2$, $c_1c_2$, $s_1s_2$, …
- Largest ∑: Characterize event
  - Subcategories based on S/B



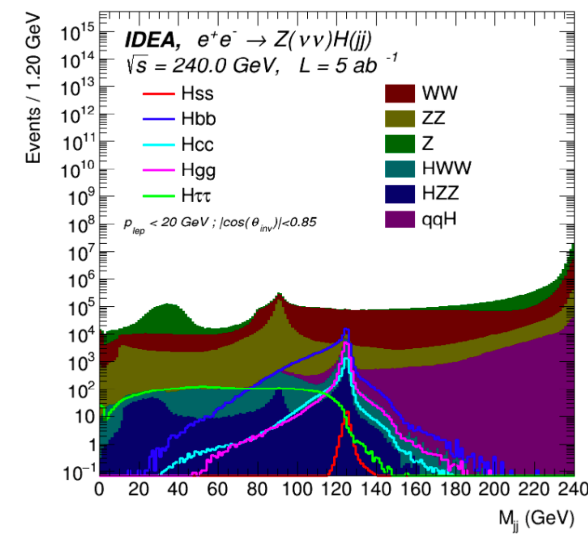

## SIG-vs-BKG discrimination

- Different SIG and BKGs shapes in $m_{rec}$ & $m_{jj}$
- Bump hunt in 2D
  - simultaneous fit in all categories

$m_{rec}$




$m_{jj}$



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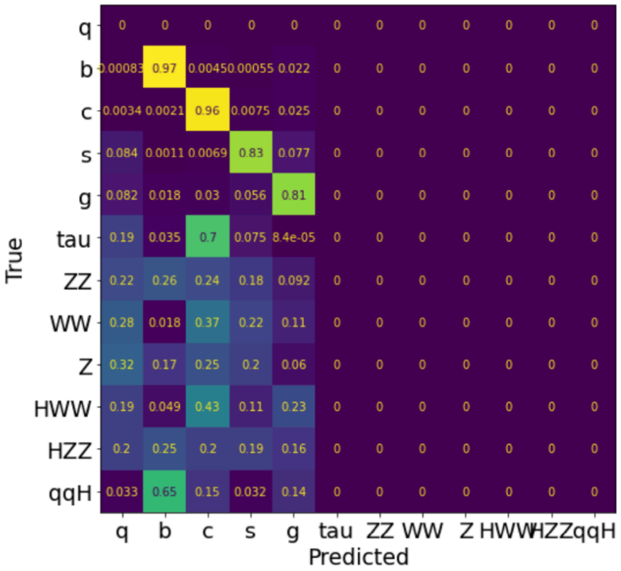



## Results @10 $ab^{-1}$

**Systematics:**

- 5 (0.1)% BKG (SIG)
  - uncorrelated b/w processes
    BKG: constrained to O(1)%
- Limited MC statistics

| Z(→vv)H(→qq) | bb | cc | ss | gg |
|---|---|---|---|---|
| δμ/μ (%) | 0.3 | 2.1 | 100 | 0.8 |

***$|BR_{H\rightarrow ss}|$<1.3**

2x better compared to the 2L channel
All-had channel: effort started

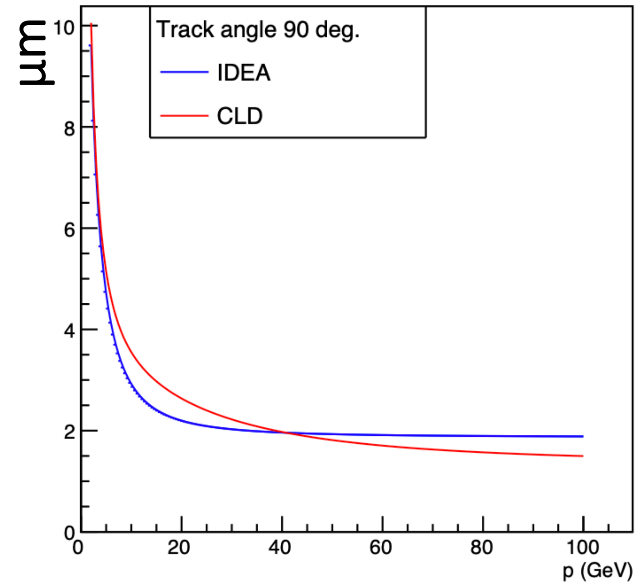
# Impact of detector performance

- Neutral Hadron energy resolution
  - relevant for all H decays modes

$$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}} \oplus \frac{5\%}{E} \oplus 1\%$$

- Impact parameter resolution (d0, dz)
  - relevant for H→bb, H→cc
- dN/dX resolution:
  - relevant for H→ss
- Timing resolution (nominal = 30 ps)
  - relevant for H→ss

$d_0$ resolution

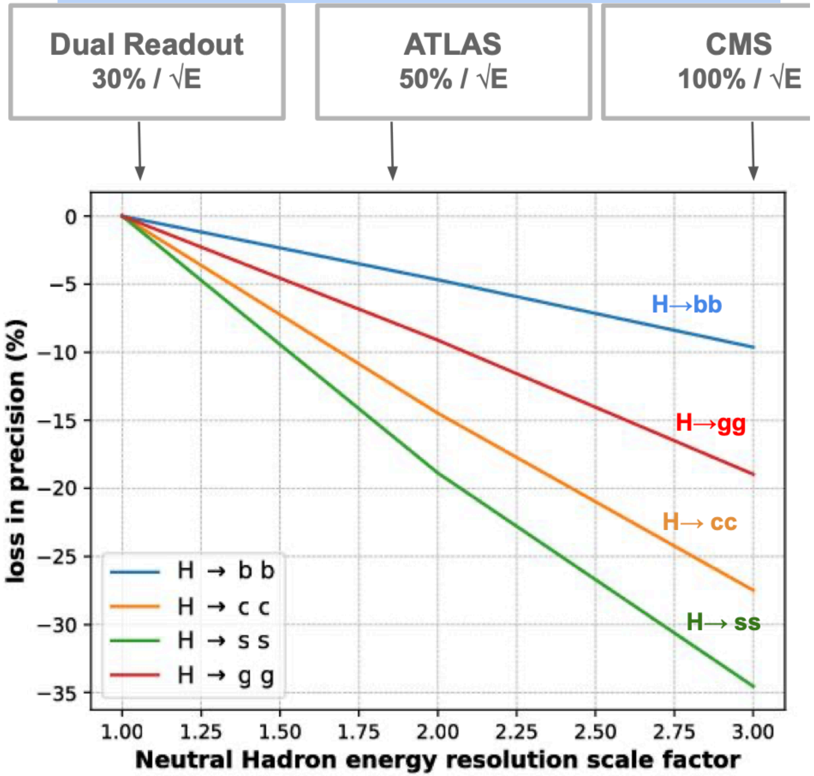



NB: Impact pessimistic
→ no retraining of jet identification algorithm performed

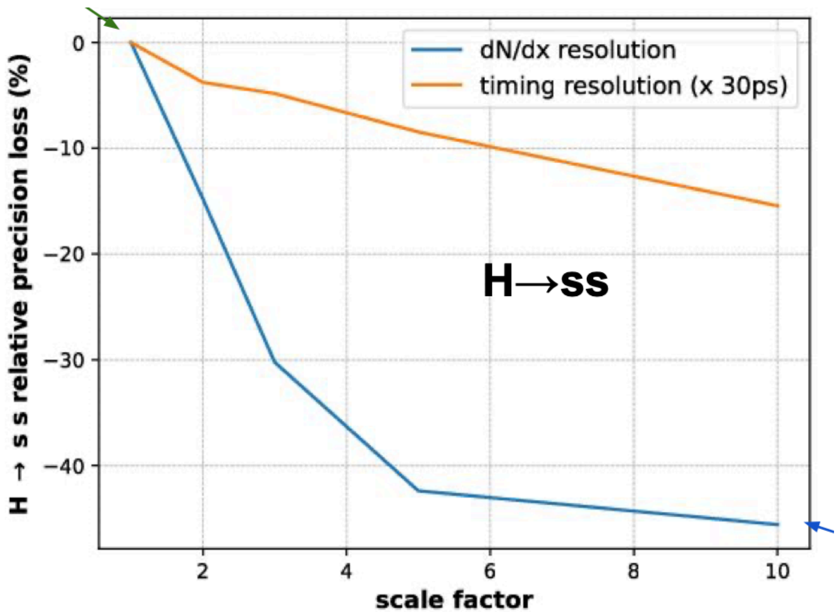
Details: M. Selvaggi talk

# Impact of detector performance (II)

## Neutral Hadron resolution




## PID



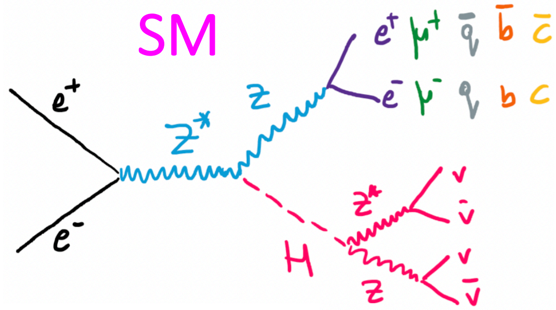

Hadronic resolution critical

Powerful PID essential for H-strange coupling

Details: M. Selvaggi talk

# H-Coupling to invisible particles

- Portal to Dark Matter (DM)
  - DM only via Higgs decays (?)
  - SM: BR($H \rightarrow ZZ^{*} \rightarrow \nu\nu\nu\nu$) ~0.1%
    - Goal: reach neutrino floor with FCC-ee



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  - DM only via Higgs decays (?)
  - SM: BR(H→ZZ*→νννν) ~0.1%
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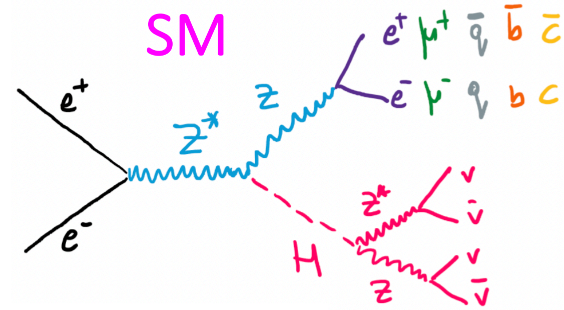
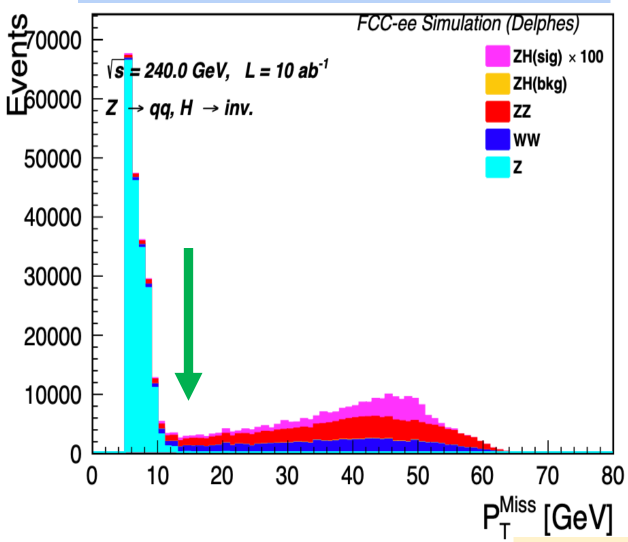
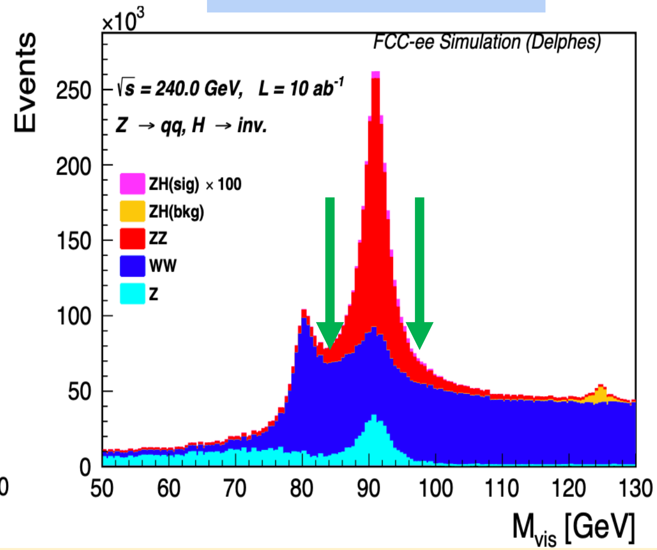
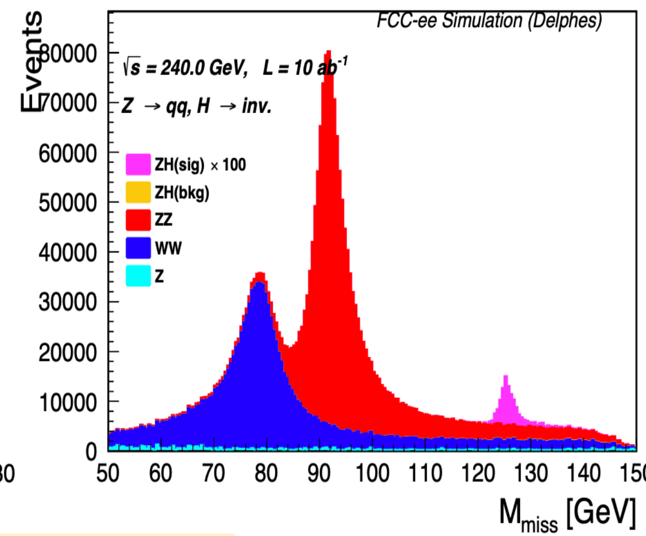



- Analysis strategy: Categorize based on Z decays modes

| Missing momentum | Z boson part | Signal extraction |
|---|---|---|



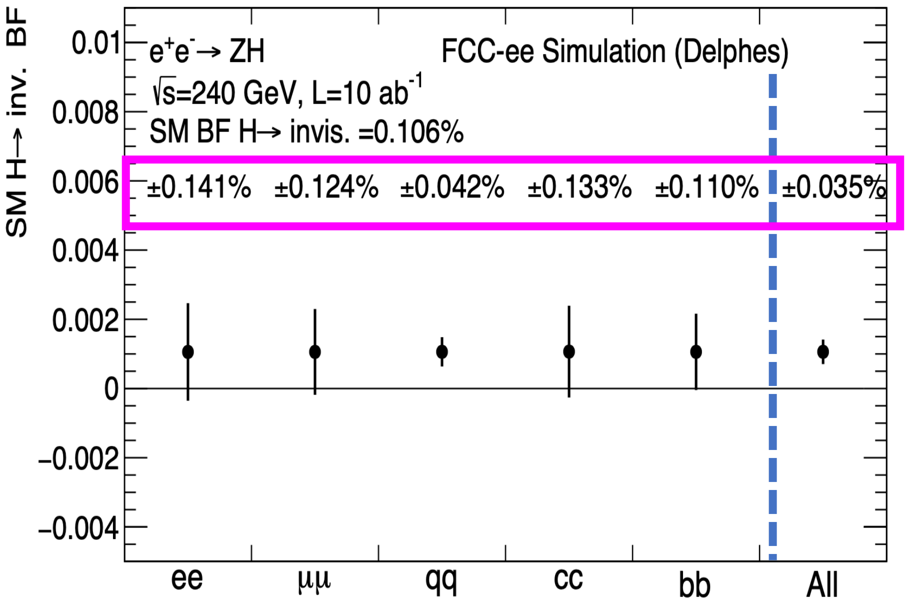




Simultaneous fit in all analysis categories

# H-Coupling to invisible particles (II)

## SM H→inv reach




**FCC-ee:** Measure SM BR(H→inv)
w/~35% uncertainty
[Driven by hadronic channels]

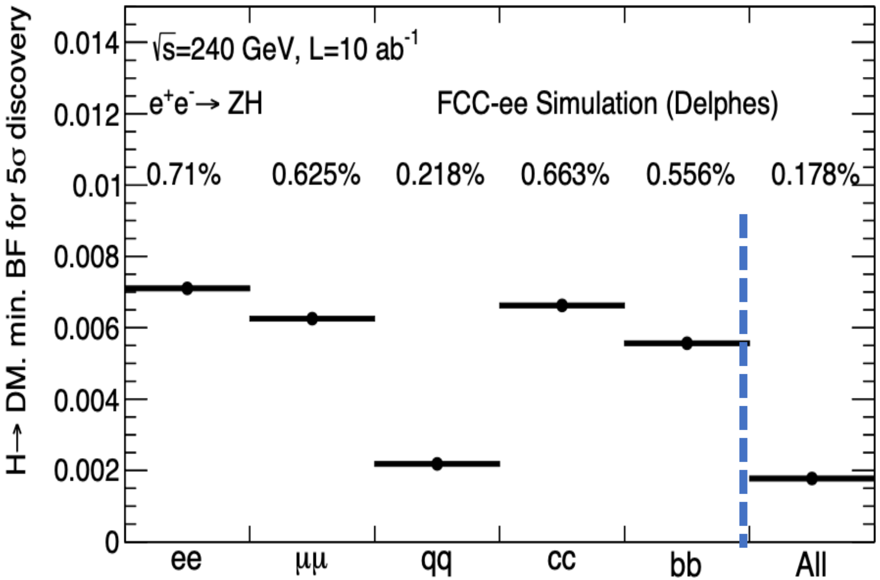
**LHC:** Upper limit BR(H→inv) ~10-15%

## Impact of detector perf.

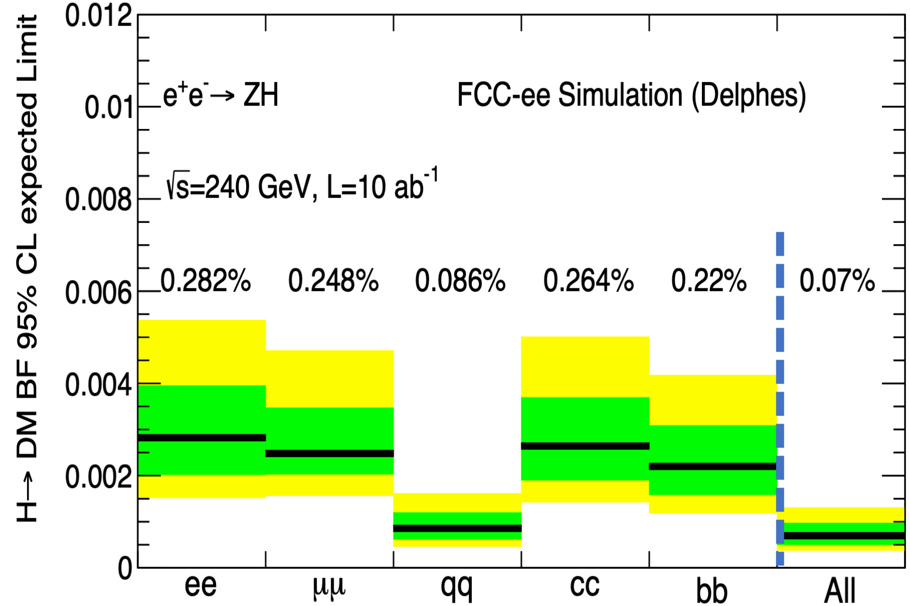
- **5% poorer Had. resolution:** ~80% increase in H→inv unc.
- **5% poorer Lept. resolution:** ~% effect in sensitivity

# H-Coupling to invisible particles (III)

5σ discovery potential




Upper limit on BR(H→DM)




**Discover:** BR(H→DM)~0.18%
**Exclude:** BR(H→DM) ~0.07%

# Summary

- **Unique situation:** no clear direction of where to look for New Physics
  - but strong reasons to believe exists

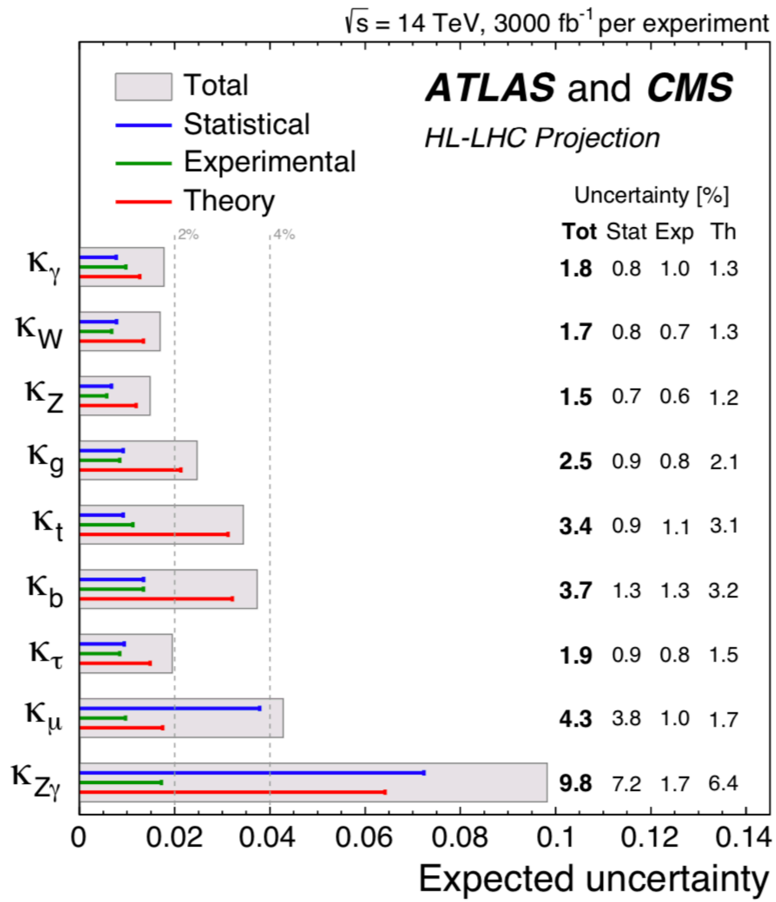
- **Major priority:** Exhaustively study the Higgs boson
  - Full analysis: H→fermions/gluons/invisible at the ZH threshold
    - Understanding detector requirements
    - State-of-the-art jet flavor tagging algorithm developed and implemented in FCCSW
      - use-case: beyond Higgs couplings
- O(10) improvement wrt HL-LHC:
  - e.g. H→ fermions/gluons: O(1%) or better; H→ZZ→4v with 35% unc

- Still, lot's of room for ingenuity in several fronts
  - e.g. establish H-strange and H-electron couplings,
    exploration of additional channels, detector design, ..

# Additional material

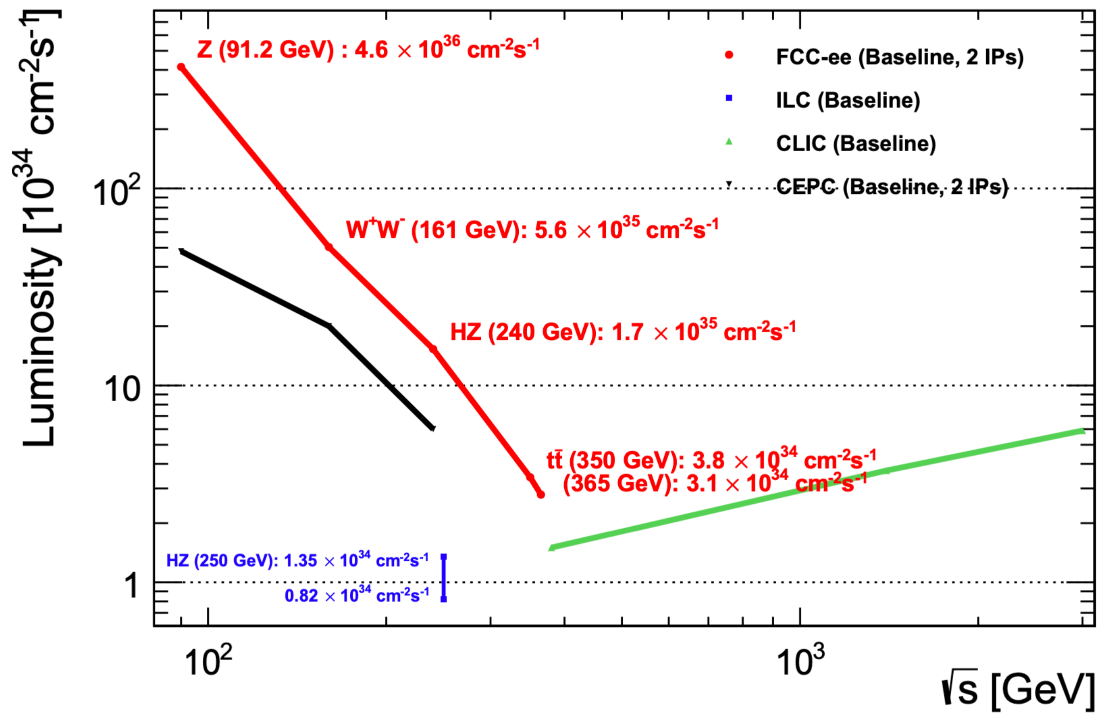
# Physics motivation

HL-LHC



# In a nutshell

- e+e-: Different strategies
  - different luminosity and $E_{CM}$ scenarios
  - FCC-ee/CEPC:
    - Study Z, W, H and top with unprecedented precision
      - e.g. $10^{12}$ Z, 1M H
  - CLIC/ILC:
    - Rich Higgs program
    - Direct access to HH




- Ultimate goal: O(100 TeV) pp collider
  - FCC-hh/SppC: use same tunnel constructed for FCC-ee/CepC

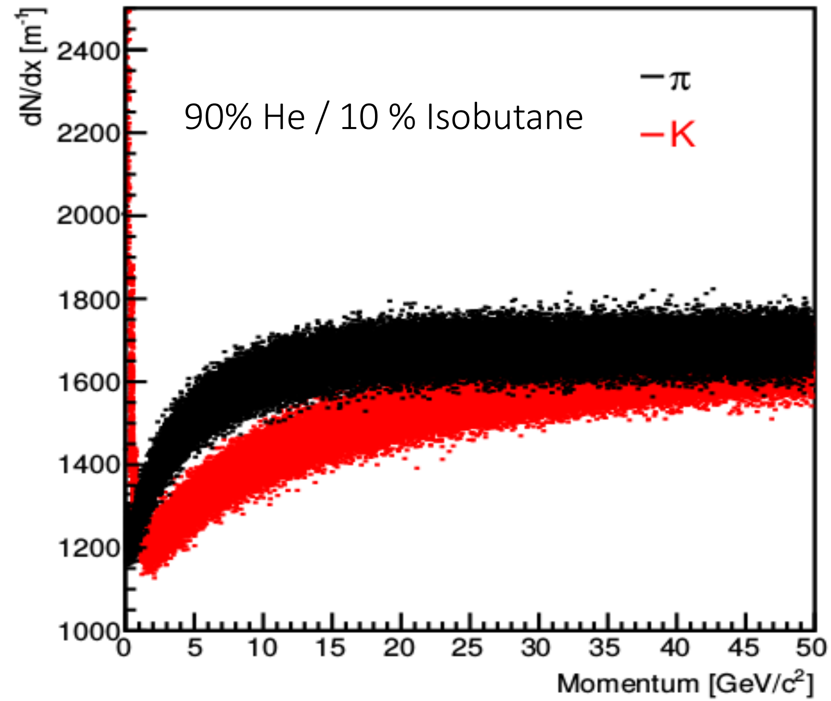
Today: Discuss results from FCC-ee

# Particle ID: Cluster counting (dN/dx)

- Count number of primary ionization clusters along track path
- Avoids large Landau flukes
- Requires high granularity
- module added in Delphes

```
##################
# Cluster Counting
##################

module ClusterCounting ClusterCounting {

  add InputArray TrackSmearing/tracks
  set OutputArray tracks

  set Bz $B

  ## check that these are consistent with DCHCANI/DCHNANO parameters in TrackCovariance module
  set Rmin $DCHRMIN
  set Rmax $DCHRMAX
  set Zmin $DCHZMIN
  set Zmax $DCHZMAX

  # gas mix option:
  # 0:  Helium 90% - Isobutane 10%
  # 1:  Helium 100%
  # 2:  Argon 50% - Ethane 50%
  # 3:  Argon 100%

  set GasOption 0

}
```

**IDEA detector:**



# Particle ID: TOF

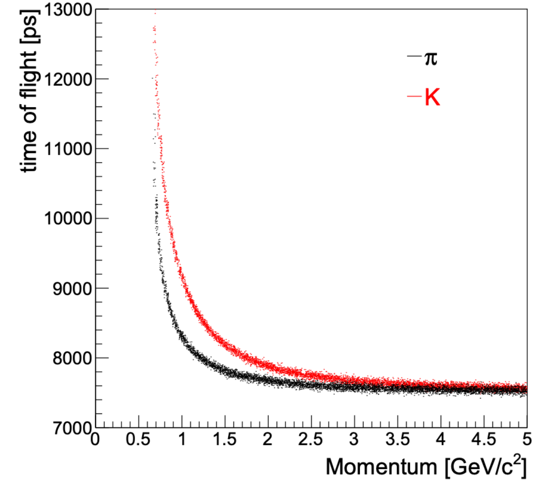
- Good K/π separation at low-momenta:

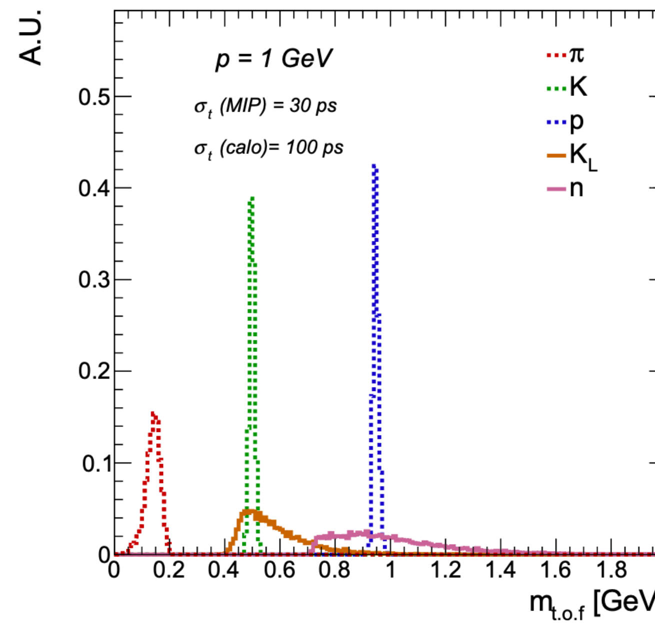
$$t_{\text{flight}} \equiv t_{\text{F}} - t_{\text{V}} = \frac{L}{\beta} = \frac{L\sqrt{p^2 + m^2}}{p}$$

- Assumption on vertex time [crucial for highly displaced $K_s$]

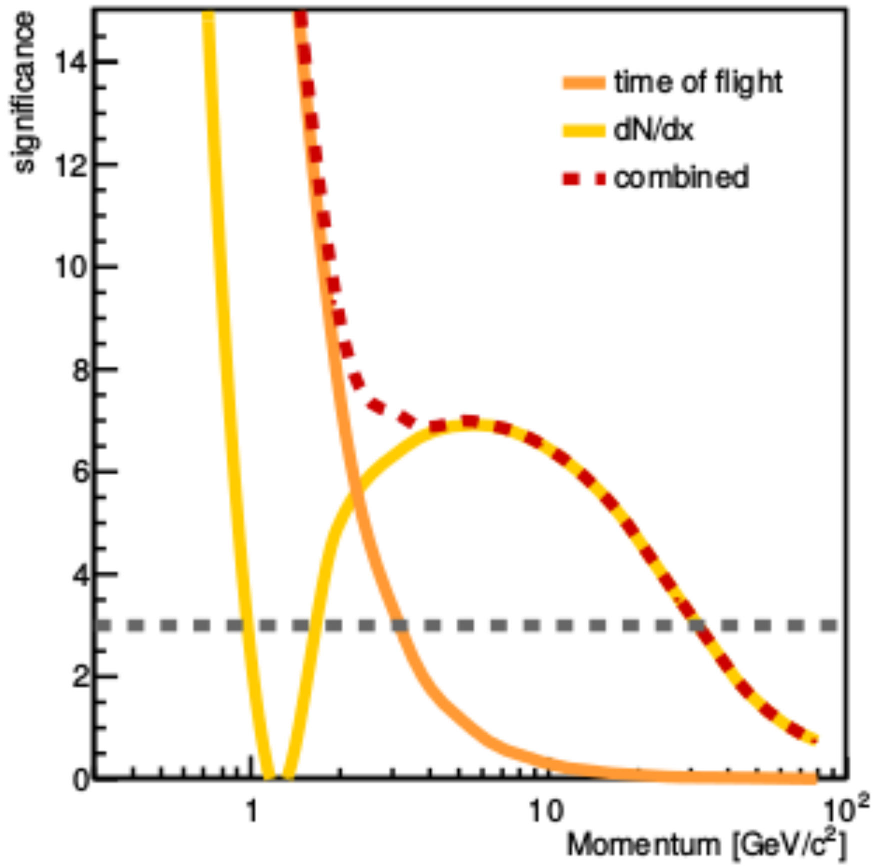
```
########################################
#   Time Of Flight Measurement
########################################

module TimeOfFlight TimeOfFlight {
  set TrackInputArray TimeSmearing/tracks
  set VertexInputArray TruthVertexFinder/vertices

  set OutputArray tracks

  # 0: assume vertex time tV from MC Truth (ideal case)
  # 1: assume vertex time tV = 0
  # 2: calculate vertex time as vertex TOF, assuming tPV=0

  set VertexTimeMode 2
}
```

$$t_{\text{V}} = \frac{r_{\text{V}}}{\beta_{\text{V}}}$$



# ParticleID: Combined

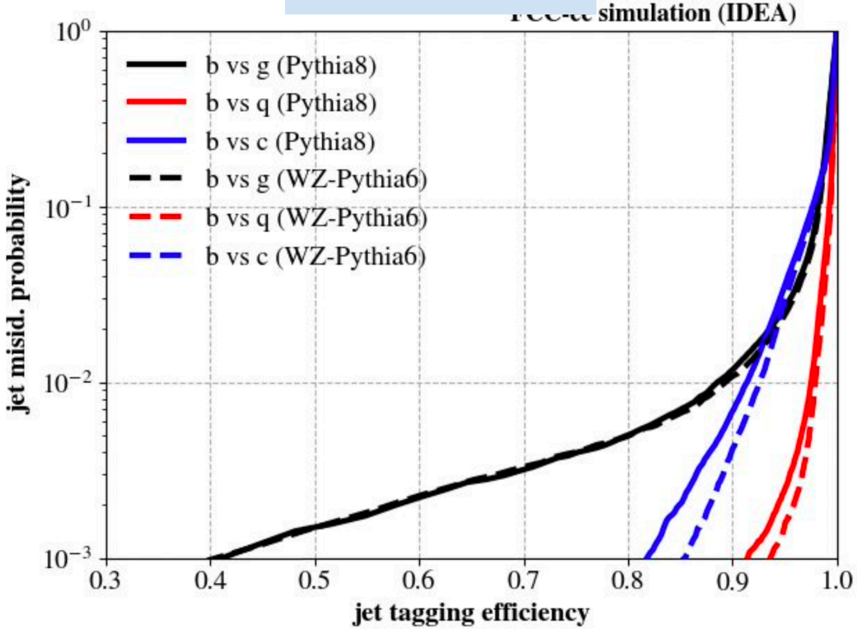



3σ K/π separation for tracks w/ p<30 GeV

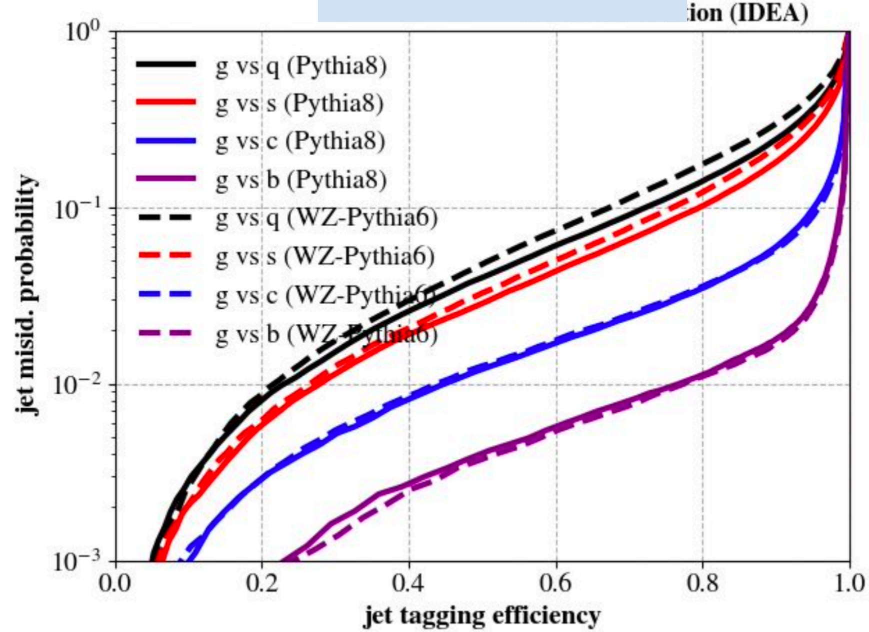
# Robustness

- ParticleNet-ee: trained with Pythia8 samples
  - tested on Pythia 8 [solid lines]
  - tested on WZ-Pythia 6 [dashed lines]

**b-tagging**




**gluon -tagging**




Modest dependence

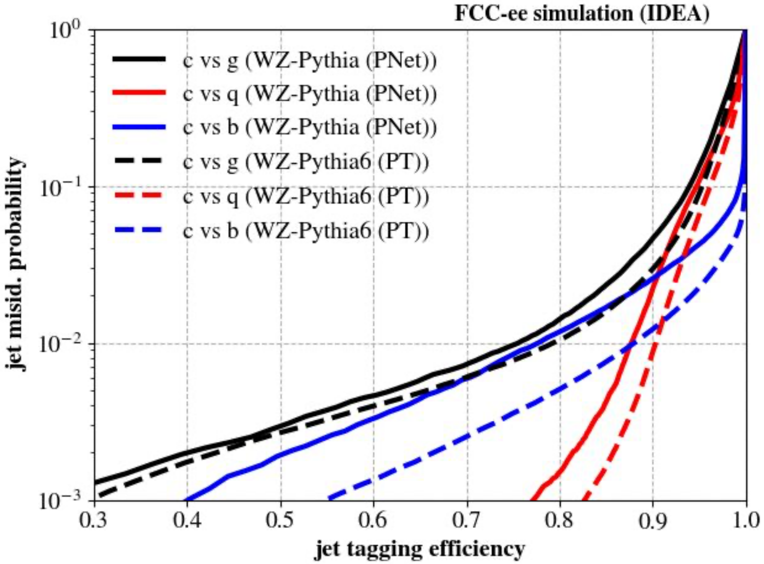
[still many tricks in the bag to reduce the dependence]

# Pushing the limits further

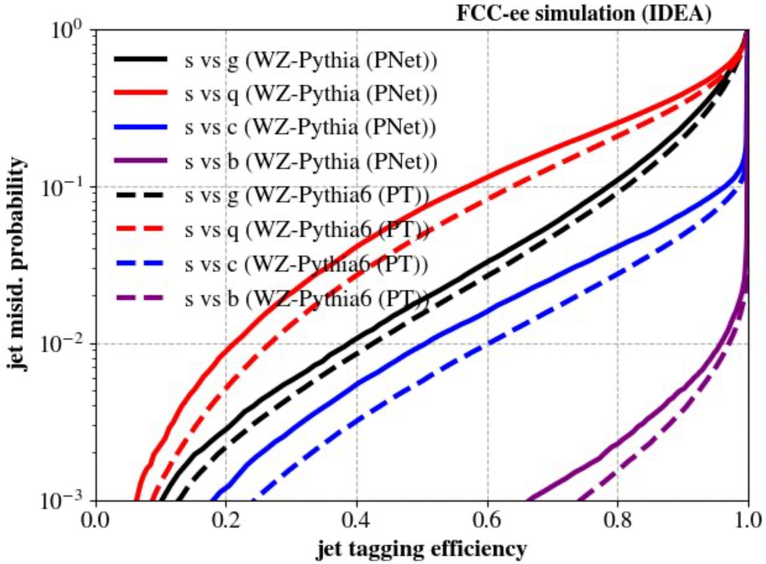
- Move to a fully connected graph: Particle transformer

based on:
H. Qu, C. Li, S. Qian
ICML 2022
For FCCee: D. Garcia

**c-tagging**



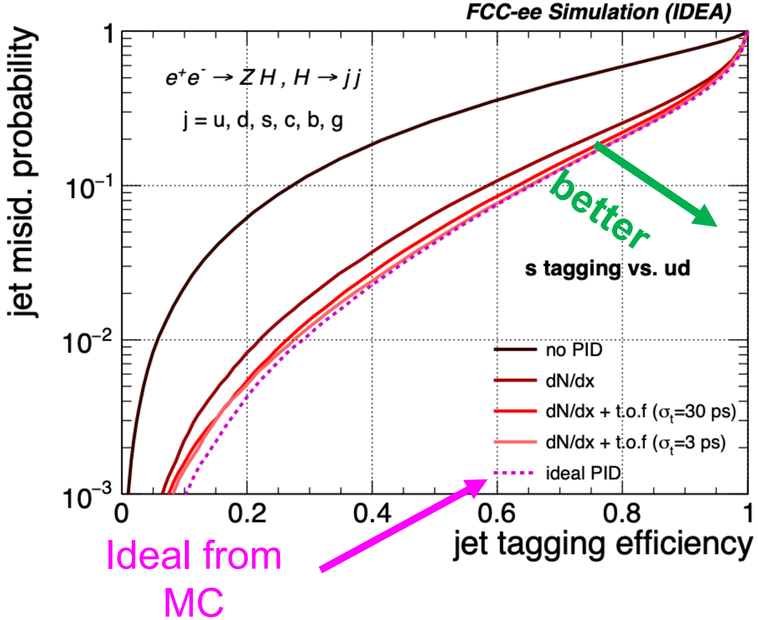

**strange-tagging**



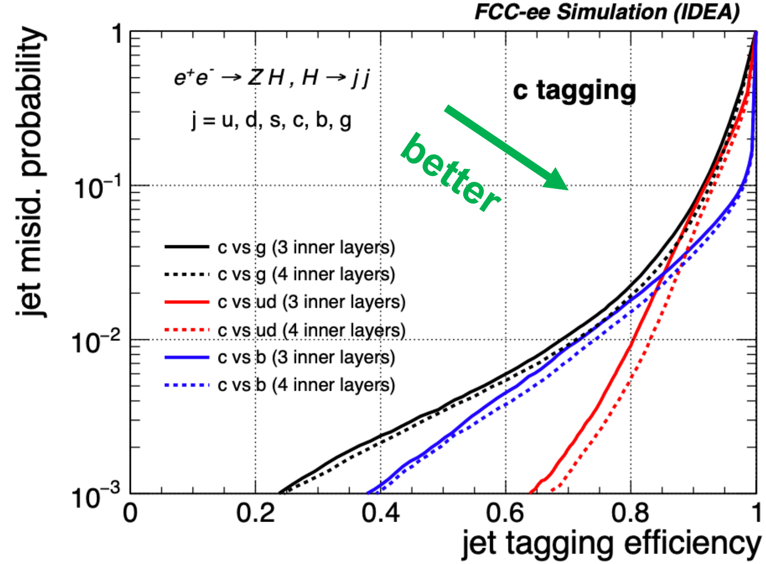

Improvement: up to 2x in BKG rejection

# Impact of detector configurations

## Strange tagging [PID]



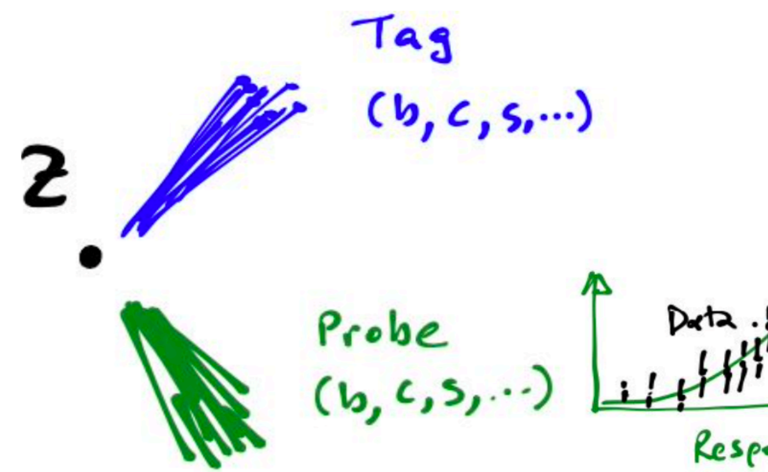

## c-tagging [PIX layers]




- dN/dx brings most of the gain additional gain w/ TOF (30ps)
  - TOF (3ps): marginal improvement
  - dN/dX + TOF(30ps) ~ perfect PID
- Additional pixel layer:
  - 2x improved BKG rejection in c-tagging
  - marginal/no improvement in b-tagging

# Improving robustness

- Current development relies solely on MC
  - Full control of class definition, lot's of [MC] data [~2M jets/ jet flavor]
    - but: MC != Data; potentially lead to large uncertainties
    - NB: it's also not Full SIM ..




- Another route: Use data
  - [Obvious] advantage: much smaller syst unc.
- How: Tag-and-probe @ Z pole
  - First: Tag one of the two jets with high purity
    - e.g. by using a pretrained MC-based algo
  - Then: create a training sample using the 2nd jet (probe).

**FCC-ee @ Zpole**

| $Z \to$ hadrons | ~70% | $0.7 \times 10^6$ M |
|---|---|---|
| $\to$ uu/cc | ~12%/flavor | $8.4 \times 10^4$ M/ flavor |
| $\to$ dd/ss/bb | ~15%/flavor | **$1.1 \times 10^5$ M/ flavor** |

# Improving robustness (II)

- Take into account tagging performance [& mistag rates]
  - NB: Each class does not have to be 100% pure on specific jet flavor or have the same population

**Best case: b-tagging**

| WP | Eff (b) | Mistag (g) | Mistag (ud) | Mistag (c) |
|---|---|---|---|---|
| Loose | 90% | 2% | 0.1% | 2% |
| Medium | 80% | 0.7% | <0.1% | 0.3% |

**"Worst" case: s-tagging**

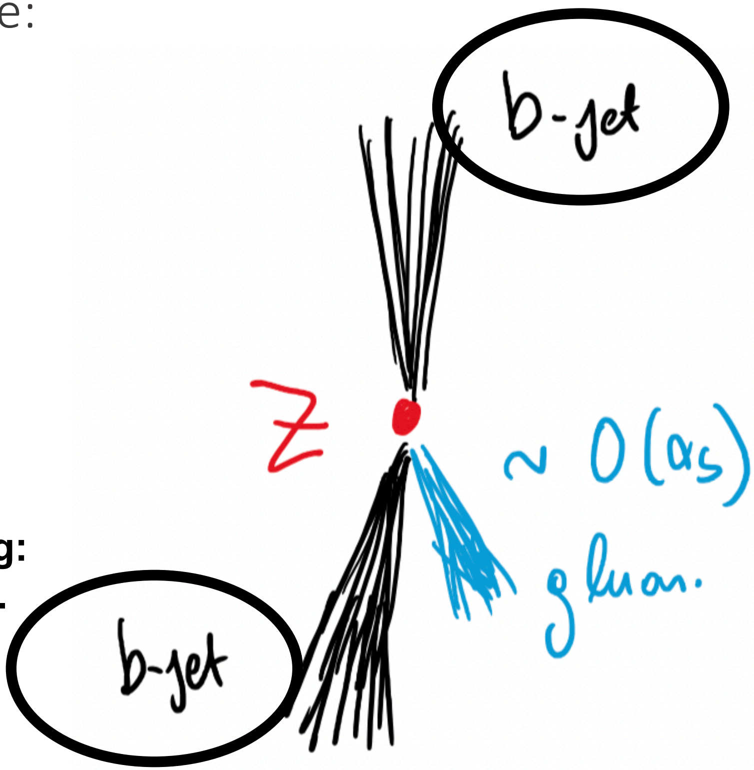
| WP | Eff (s) | Mistag (g) | Mistag (ud) | Mistag (c) | Mistag (b) |
|---|---|---|---|---|---|
| Loose | 90% | 20% | 40% | 10% | 1% |
| Medium | 80% | 9% | 20% | 6% | 0.4% |

**Much larger training sample than what used for the MC-based training sample**

- Back-of-the-envelope: Training sample @ Zpole
  - bottom jets: ~$1\text{x}10^5$ M, strange jets: ~$8.8\text{x}10^4$ M
    - all other jet flavors in between

# Gluon tagging using data?

- Challenging... topic of discussion and brainstorming
  - For instance:




b-tagging:
~90% eff.

b-tagging:
~90% eff.

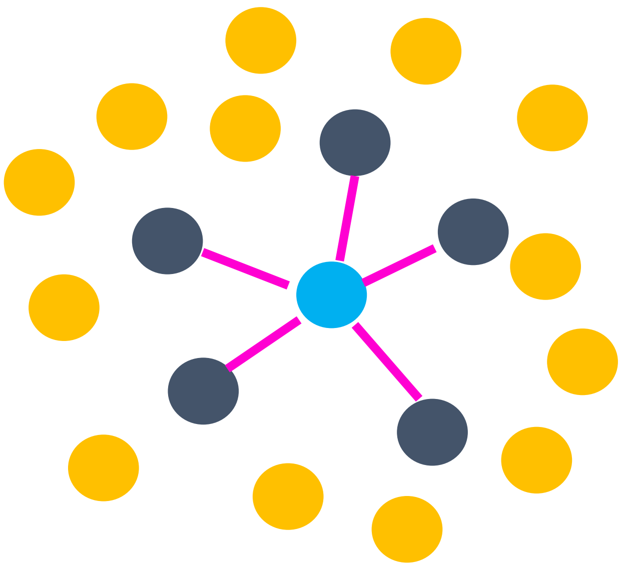
- 3rd jet is a gluon: O(1-10%) depending on momentum, angle
- Still more than enough for developing the gluon-category

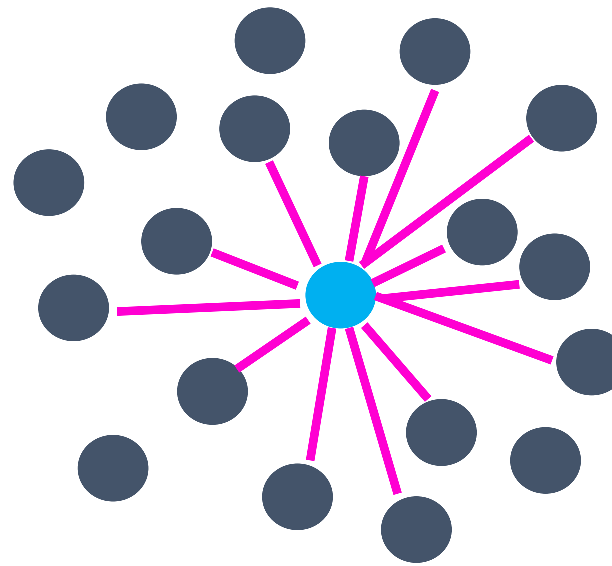
To be tested

# Pushing the limits further

based on:
H. Qu, C. Li, S. Qian
ICML 2022

**ParticleNet-EE** → **ParticleTransformer**



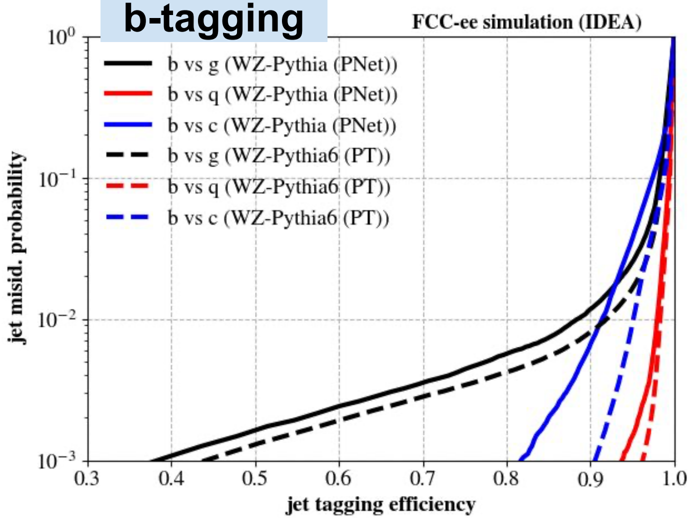


**Use the *k*-nearest particles**
[*k*=8 for ParticleNet-EE]

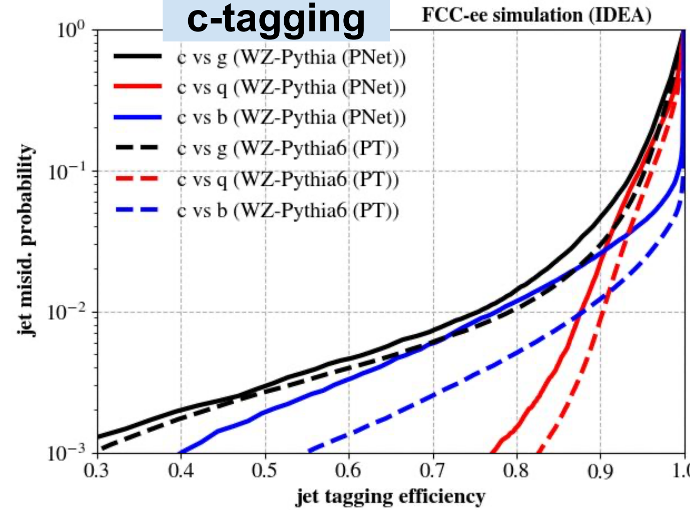
- **Fully connected graph**
- **Include per-particle-pair properties more directly**

# Pushing the limits further (II)

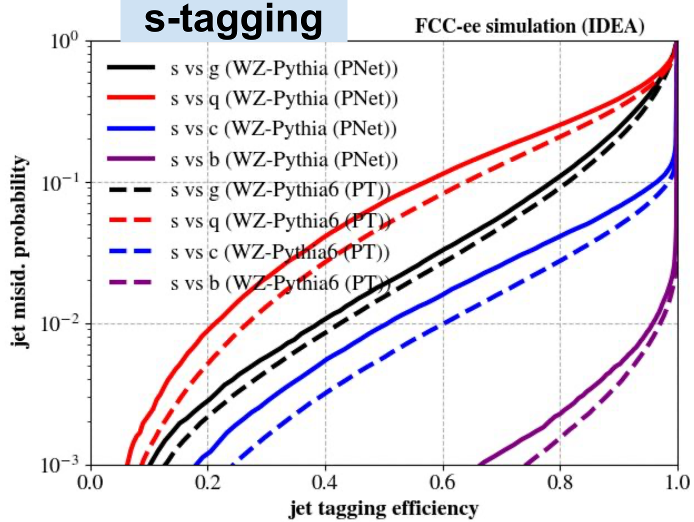
b-tagging



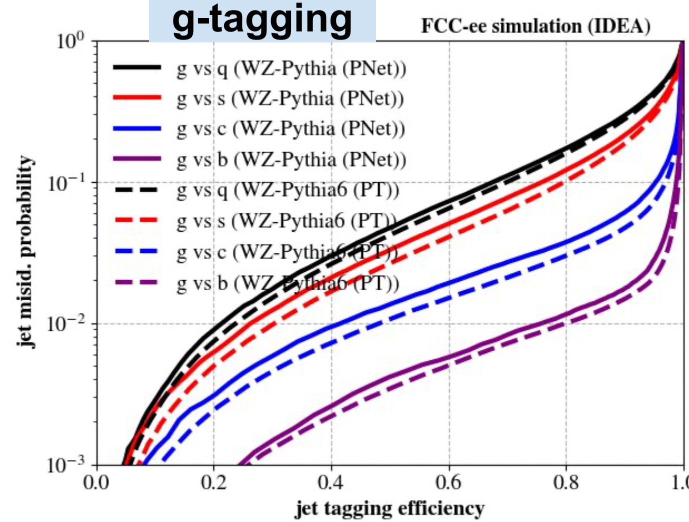

c-tagging




s-tagging

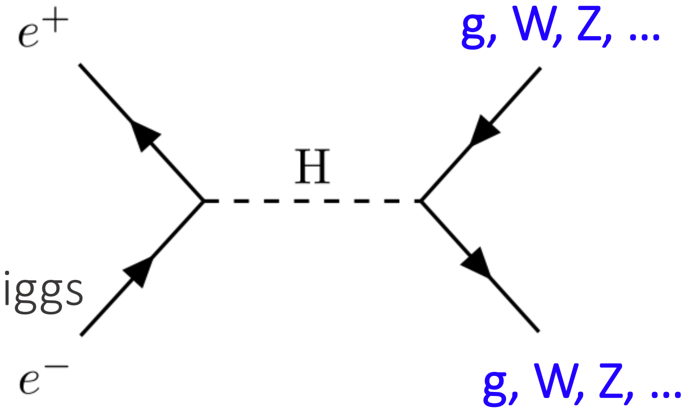



g-tagging

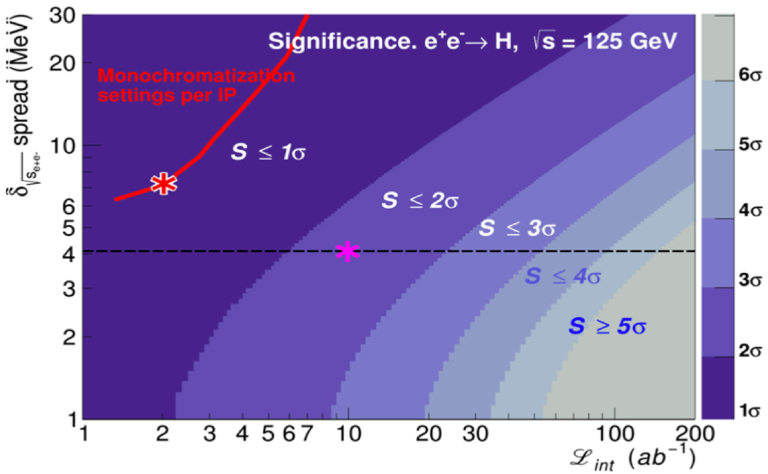


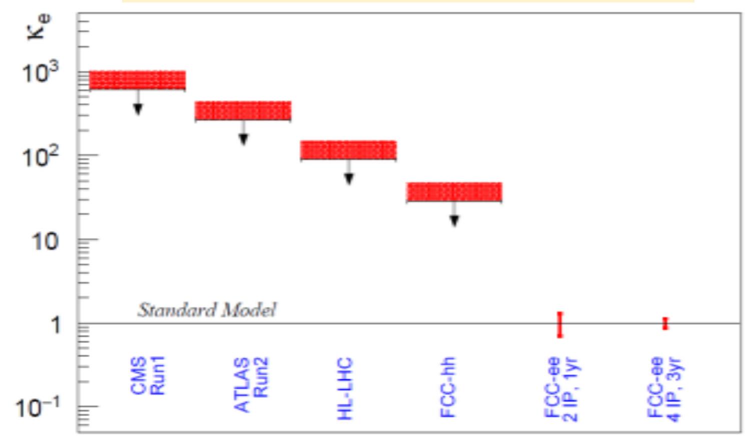
# Unique at FCC-ee: H→ee

- Extremely challenging: BR(H→ee) ~$10^{-9}$
- FCC-ee: Resonant Higgs production
  - tiny signal (1.64 fb) vs. huge BKGs
  - but: huge luminosity: 20 $ab^{-1}$/year/IP → 30K Higgs
- Key points:
  - Beam spread (~MeV) → monochromatization
  - Precise $m_H$ → from ZH run

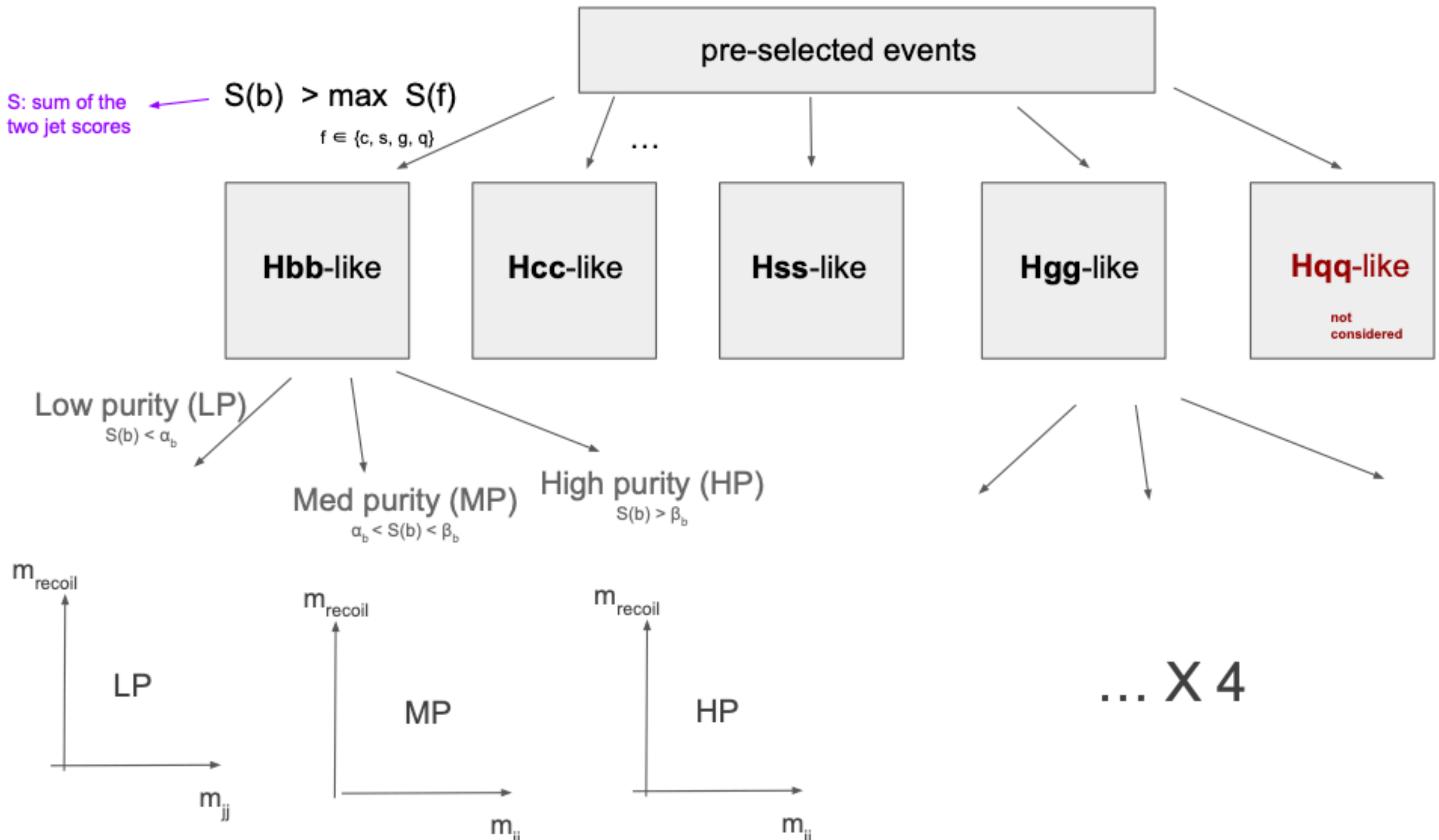



- 1 year, 2 IPS: **2σ**
- 3 years, 4 IPS: **$\kappa_e$ @15%**

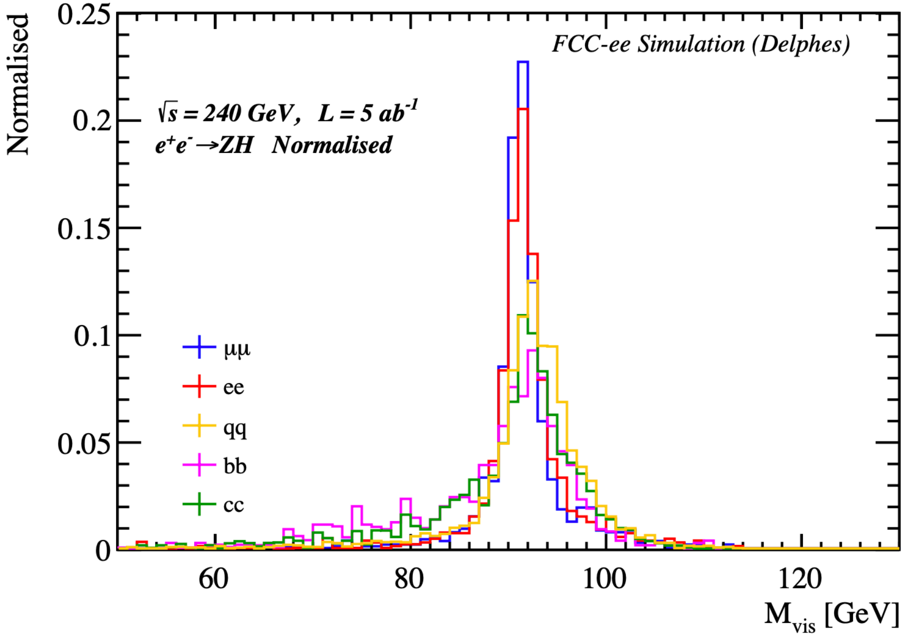


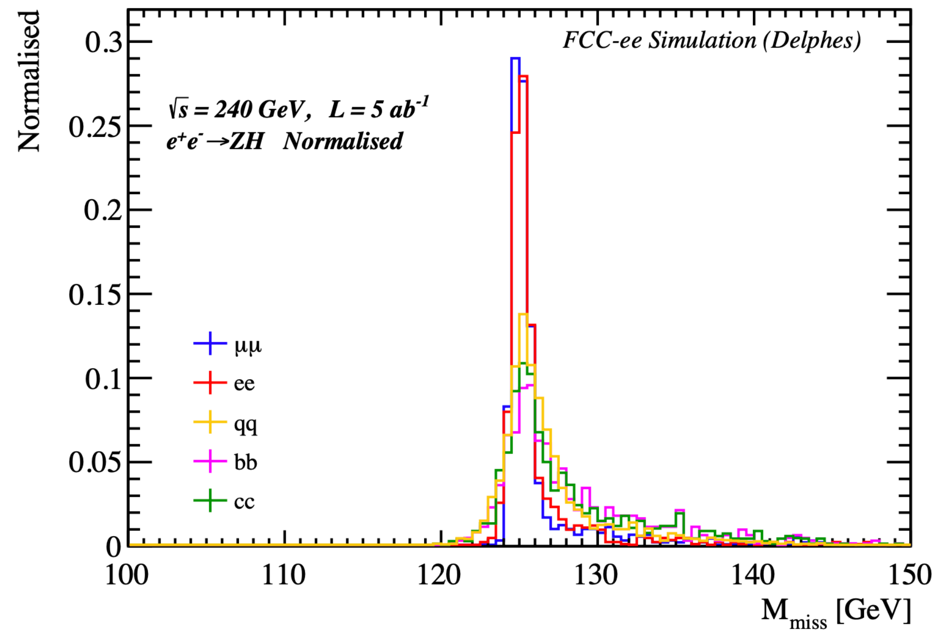
# Putting pieces together



# H→inv



Normalised
FCC-ee Simulation (Delphes)
√s = 240 GeV, L = 5 ab-1
e+e- →ZH Normalised
μμ
ee
qq
bb
cc
M_vis [GeV]

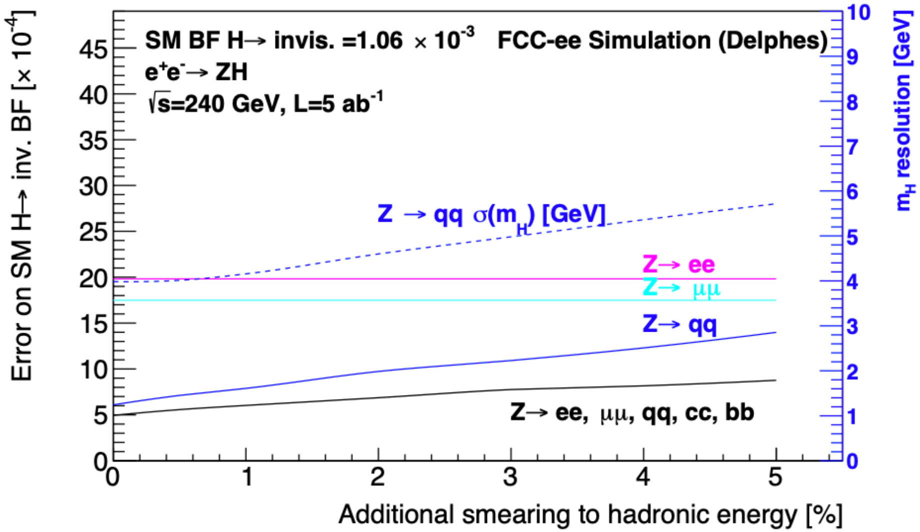



Normalised
FCC-ee Simulation (Delphes)
√s = 240 GeV, L = 5 ab-1
e+e- →ZH Normalised
μμ
ee
qq
bb
cc
M_miss [GeV]

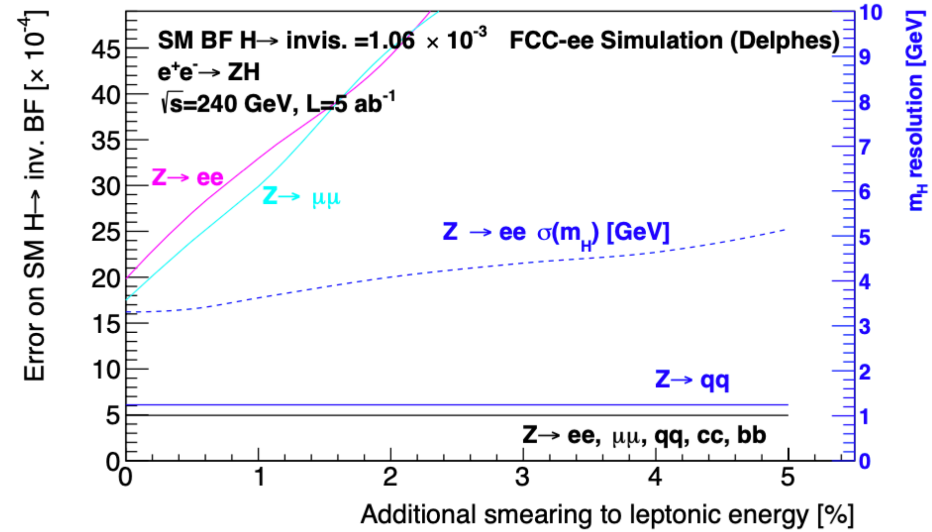
# H-Coupling to invisible particles (III)

- Impact of detector performance

**Hadronic resolution**




**Leptonic resolution**




**Powerful hadronic resolution is essential**

-5% poorer HAD resolution: ~80% larger unc. in H→inv