Higgs physics and detector requirements

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Introduction

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

1708.08912

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

e.g. Λ=1 (5)TeV→~5 (0.1)%

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1708.08912

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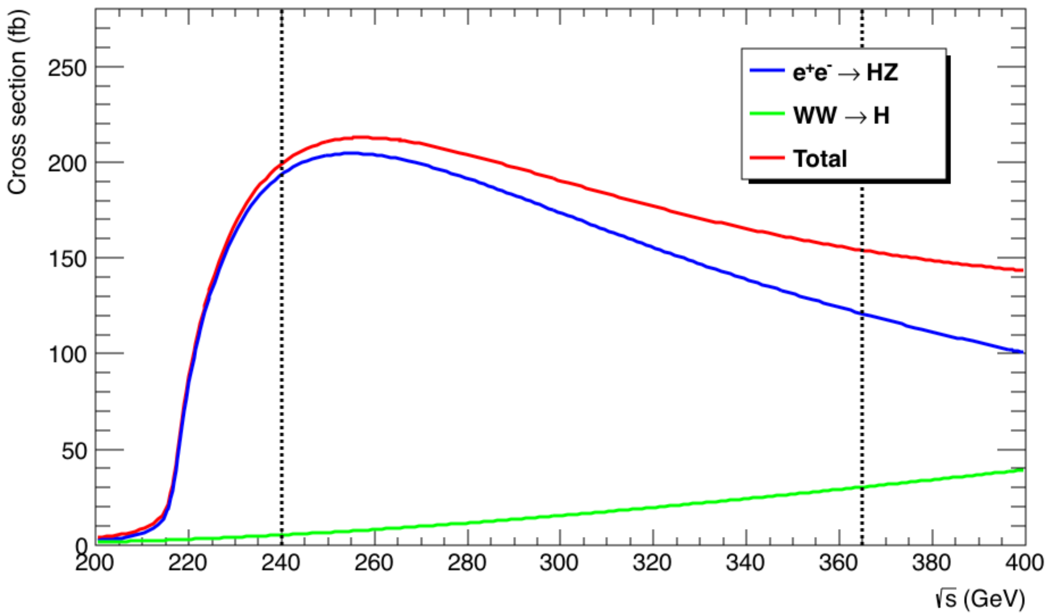
e.g. Λ=1 (5)TeV→~5 (0.1)%

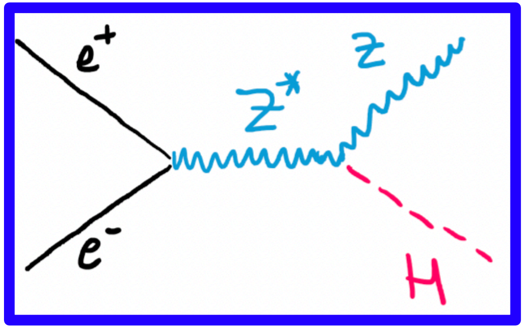
- HL-LHC:
  - Direct searches: O(5) TeV
  - H-couplings: few%, self-coupling~50%
- Future e^+e^- collider:
  - Measure H-couplings at O(0.1)% level

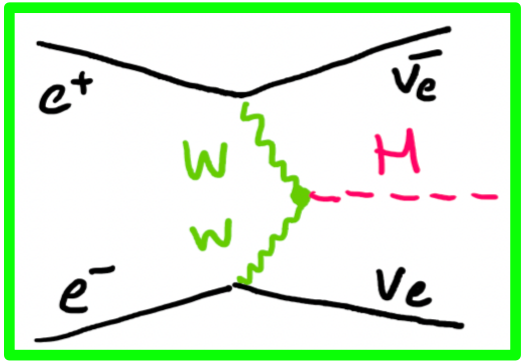
Outline:

- What we can do with FCC-ee (in H-couplings)
  - Strategy and tools
- How we can reach these results [teasers]
  - Detector requirements
  - Physics objects/tagging
- Summary

Higgs production at FCC-ee



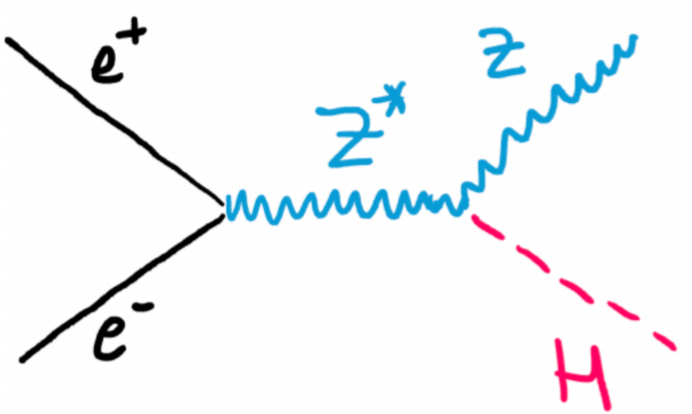


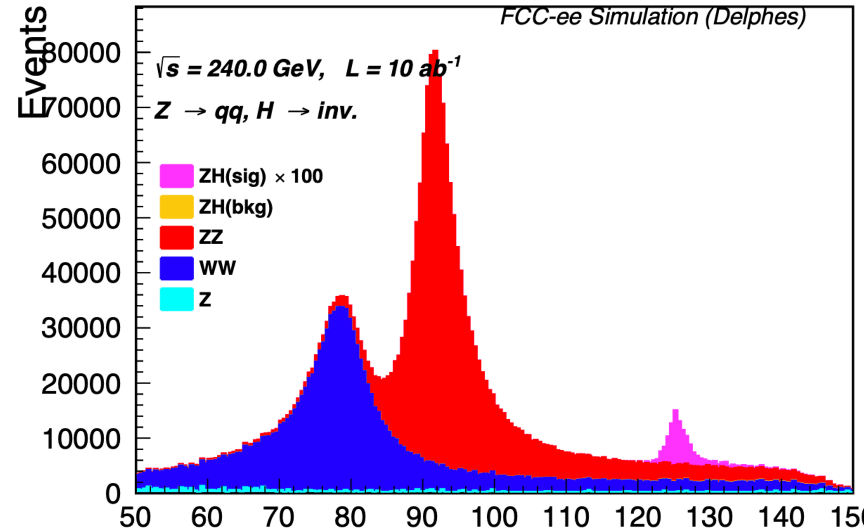


Focus at ZH production@240 GeV : 2M Higgs [4IP]
→Effort on exploring CM~360 GeV just started

General strategy

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





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

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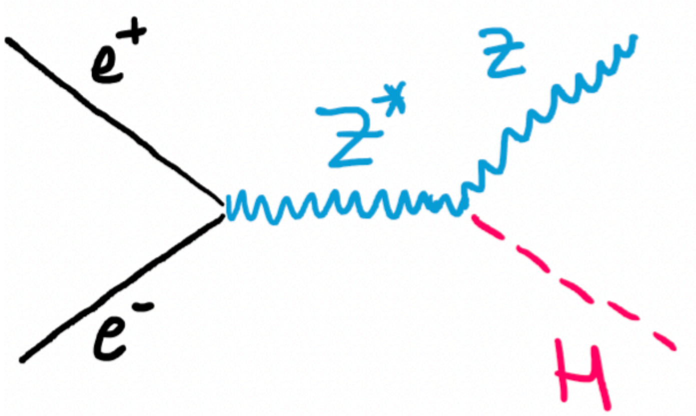
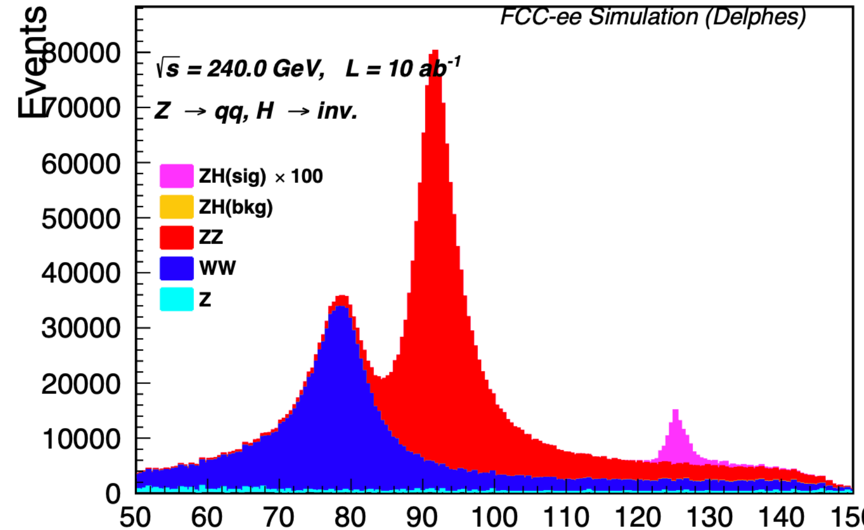




$$M_{\mathrm{rec}} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

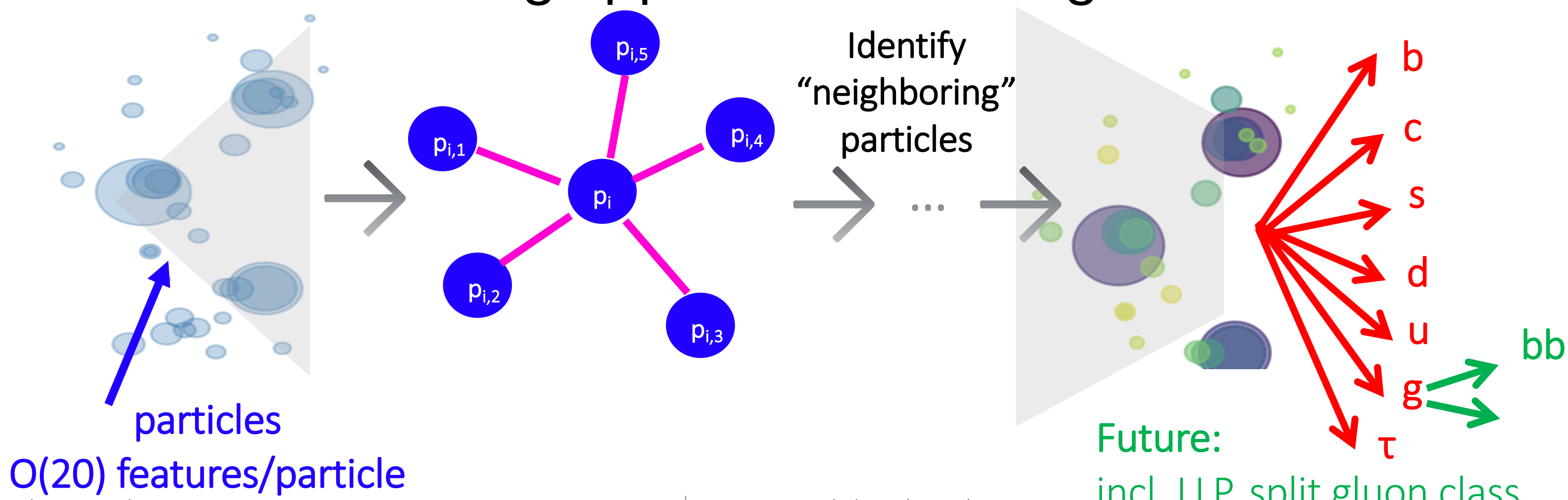
Higgs boson reconstruction:
- as many as possible decay modes

BR(H→hadrons) ~ 80%
BR(Z→hadrons) ~ 70%
Optimal reconstruction and ID ("tagging") of hadronic final states essential

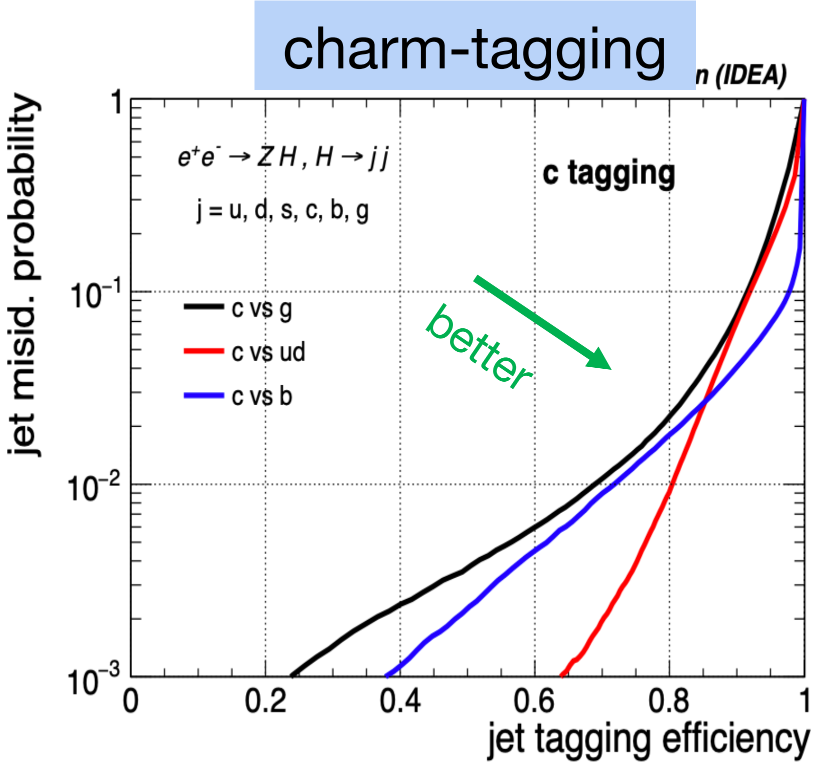
Jet tagging

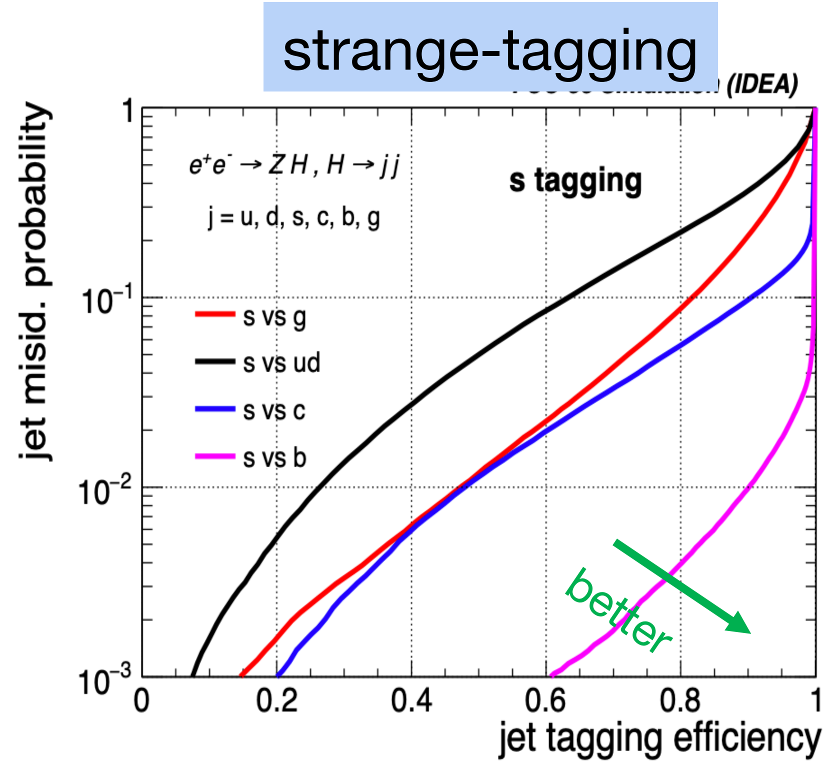
PRD 101 056019 (2020)
EPJ C 82 646 (2022)

- 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**
- Hierarchical learning approach: local → global structures



Jet tagging: Performance





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

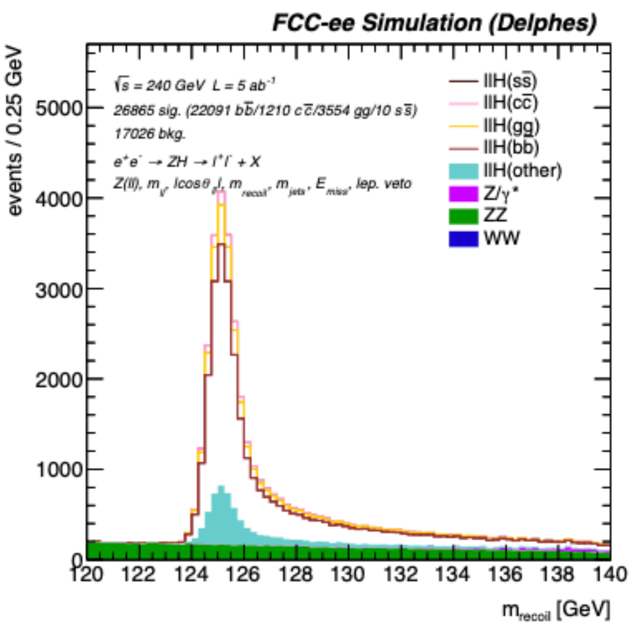
WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

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
    - details in Iza's talk later today
- Study all possible Higgs decay modes
  - Currently: bb, cc, ss, gg, ττ
    - work on going: uu, dd, + off diagonal terms

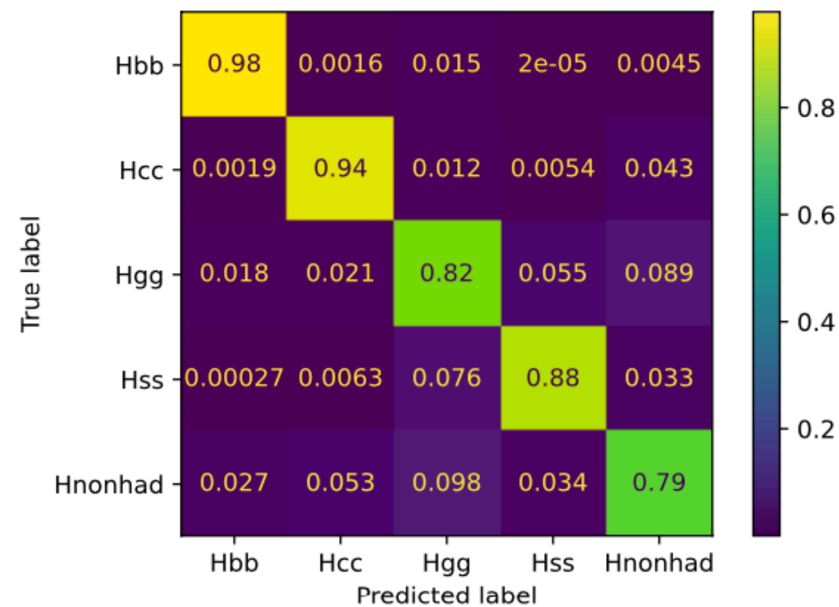
Z(→e^+e^-/$\mu^+\mu^-$)H channel

- Baseline: N_L=2, N_j=2
  - m_{LL} (m_{jj}) consistent w/ m_Z (m_H)



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

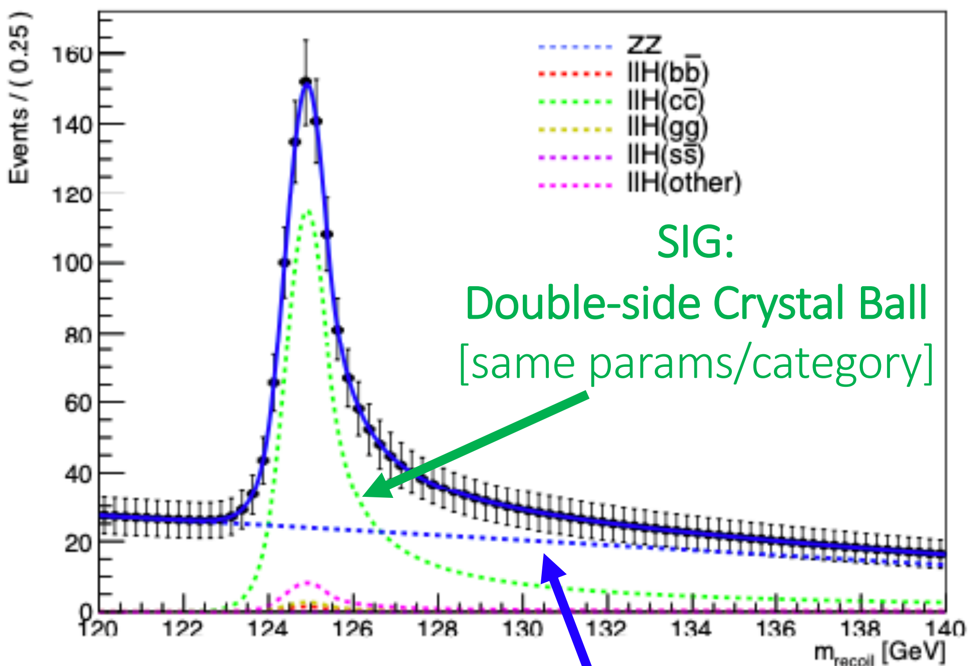
- NN-based evt-level discrim.
  - Inputs:
    - ParticleNet-ee scores / jet
    - Evt-level info
  - Multiclass output



Z(→e⁺e⁻/μ⁺μ⁻)H channel (II)

- Fit m_{rec} simultaneously in all categories

Z(→LL)H(→cc) category



BKG:
1st order polynomial

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

Results @5 ab^{-1}

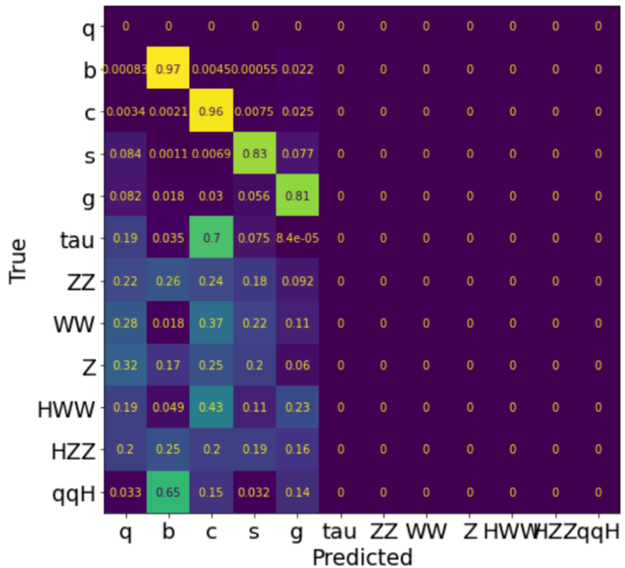
Z(→LL)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.8	4.9	410	2.7

Z(→νν)H channel

- More signal, but larger and more complex BKGs

Event categorization

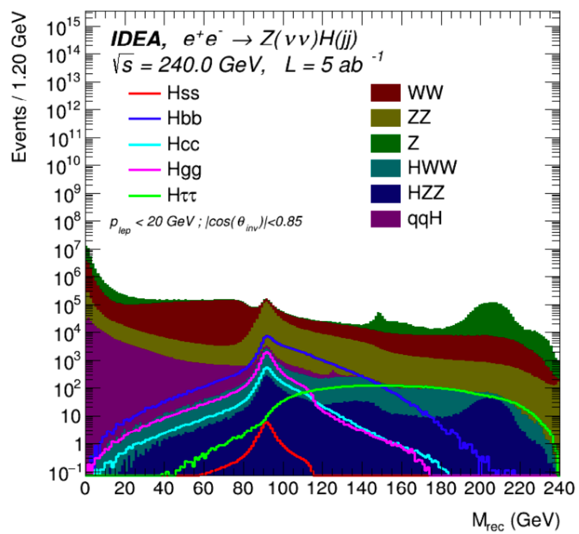
- Sum ParticleNet scores of 2 jets
  - e.g. scores: b_1b_2, c_1c_2, s_1s_2, …
- Largest ∑: Characterize event
  - Subcategories based on S/B



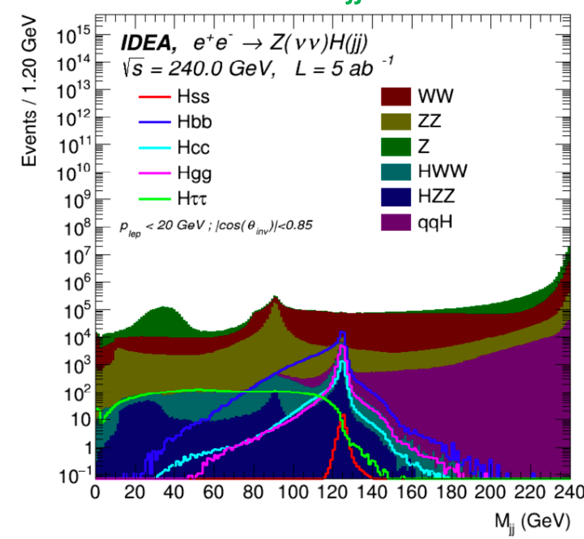
SIG-vs-BKG discrimination

- 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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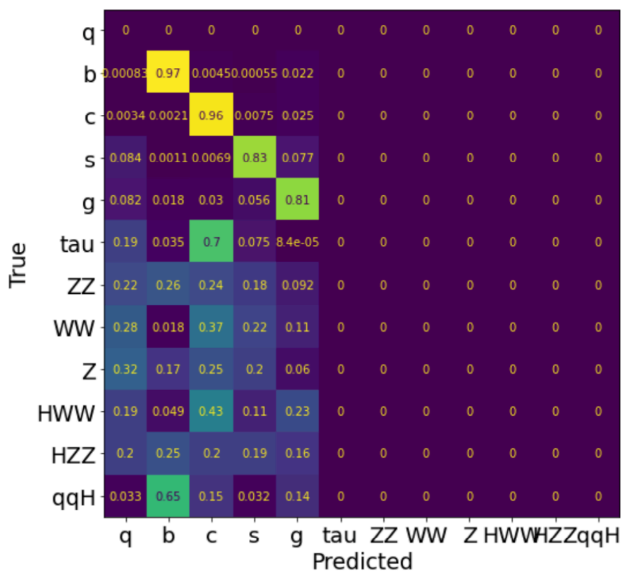

Results @5 ab^{-1}

Systematics:

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

Z(→νν)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.4	2.6	137	1.1

2x better compared to the 2L channel
Also: All-had channel [I. Veliscek talk]

Big picture

- [Very] Preliminary combination ($5ab^{-1}$)

Final state	Z(ll)H(jj) [%]	Z(vv)H(jj) [%]	Z(jj)H(jj) [%]	Comb. [%]
$H \rightarrow bb$	0.81	0.36	0.3	0.22
$H \rightarrow cc$	4.93	2.6	3.5	1.92
$H \rightarrow gg$	2.73	1.1	2.4	0.94
$H \rightarrow ss$	410	137	436	124

Big picture

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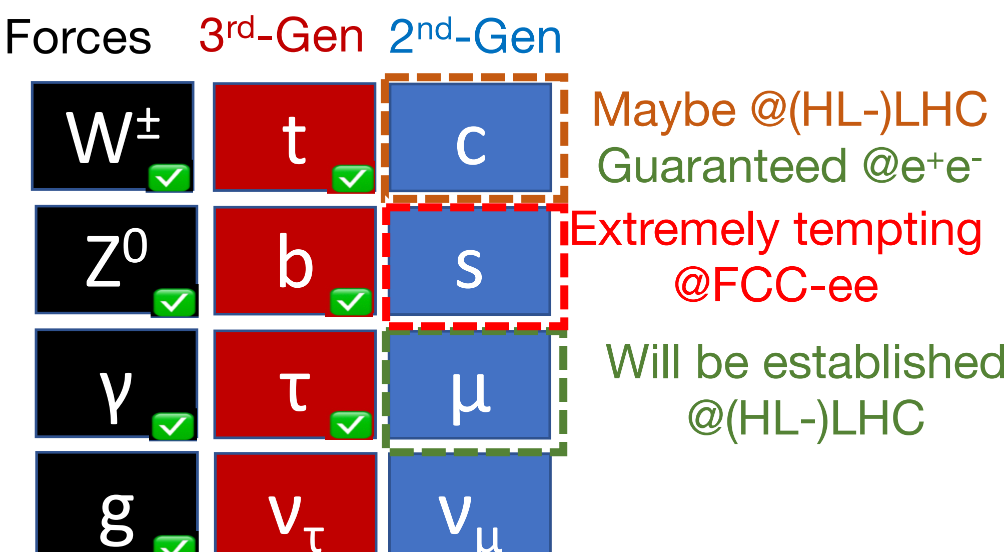


Potential to complete
2nd-Gen Yukawa couplings

How to get there?

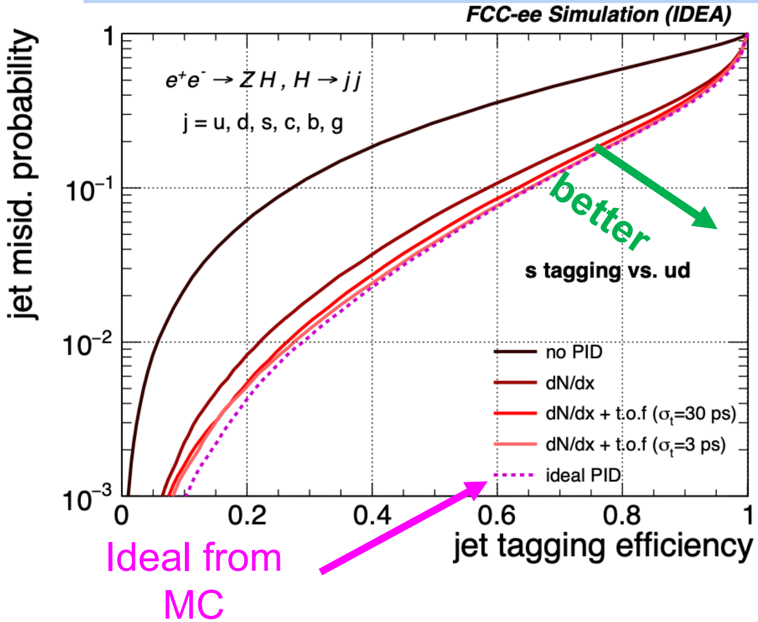
Detector design

- What's the most optimal way?
  - optimal: e.g., performance, cost, risk, ..

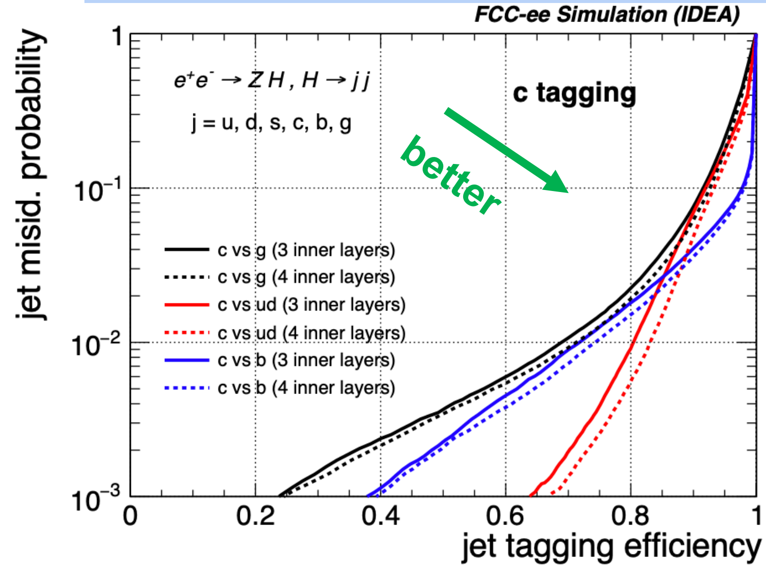
Impact of detector configurations

EPJ C 82 646 (2022)

strange-tagging (timing)



charm-tagging [PIX layer]



dN/dx brings most of the gain
additional gain w/ TOF (30ps)
→TOF (3ps): marginal improvement

Additional PIX layer:
→ 2x improved BKG rej. in c-tag
→ Marginal/no improvement in b-tag

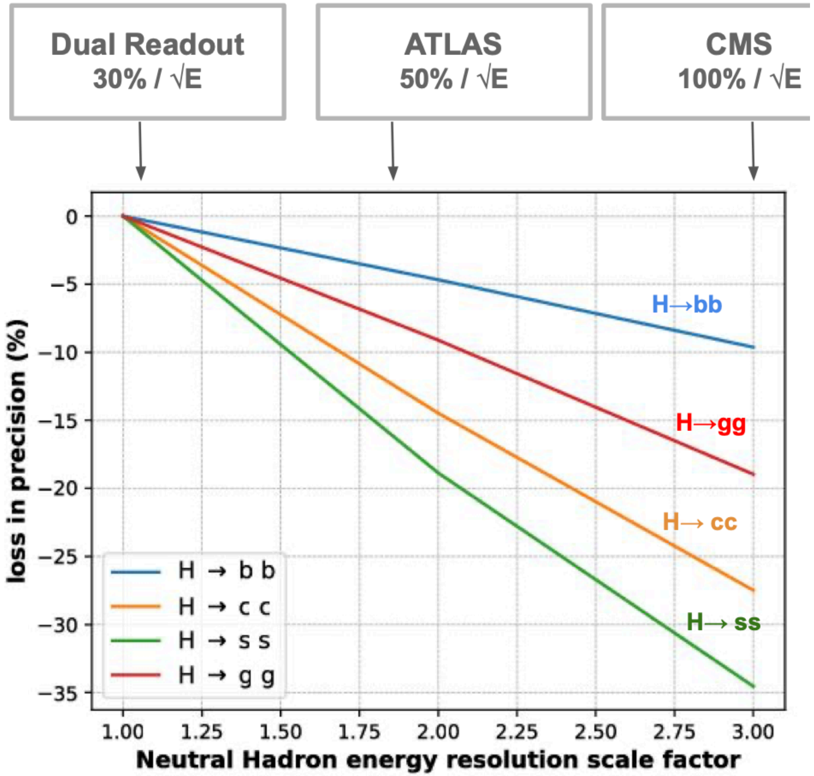
- More results: A. Sciandra's talk

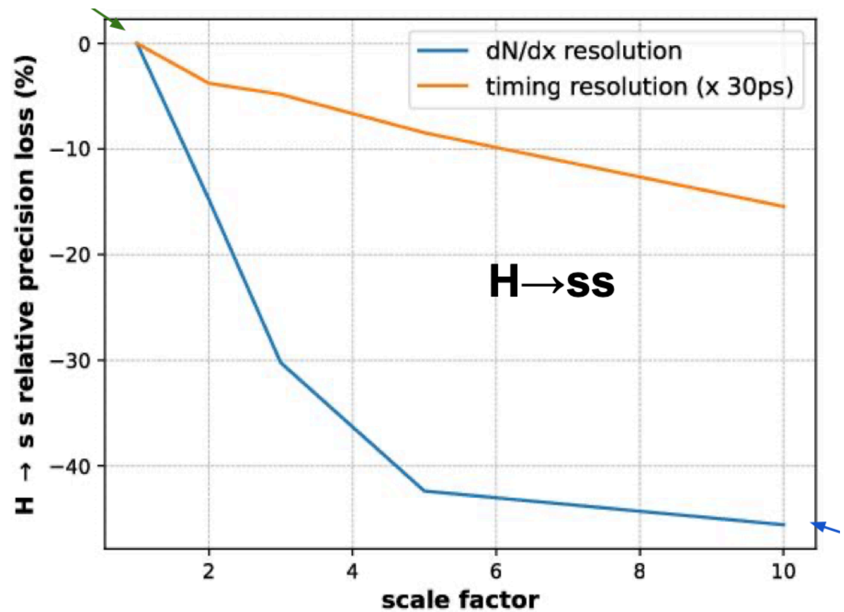
Impact of detector performance

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

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

Impact of detector performance





- Need to carefully access impact of detector proposals to the Higgs physics program in general

Analysis front: Systematics

Results @5 ab^{-1}

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

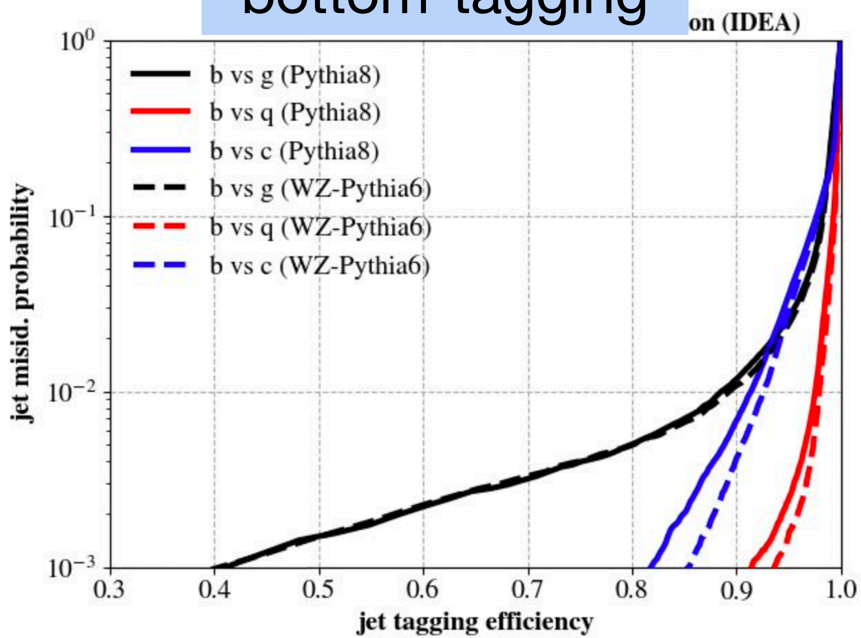
Need excellent control of systematic [EXP+TH] uncertainties

Z(→vv)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.4	2.6	137	1.1

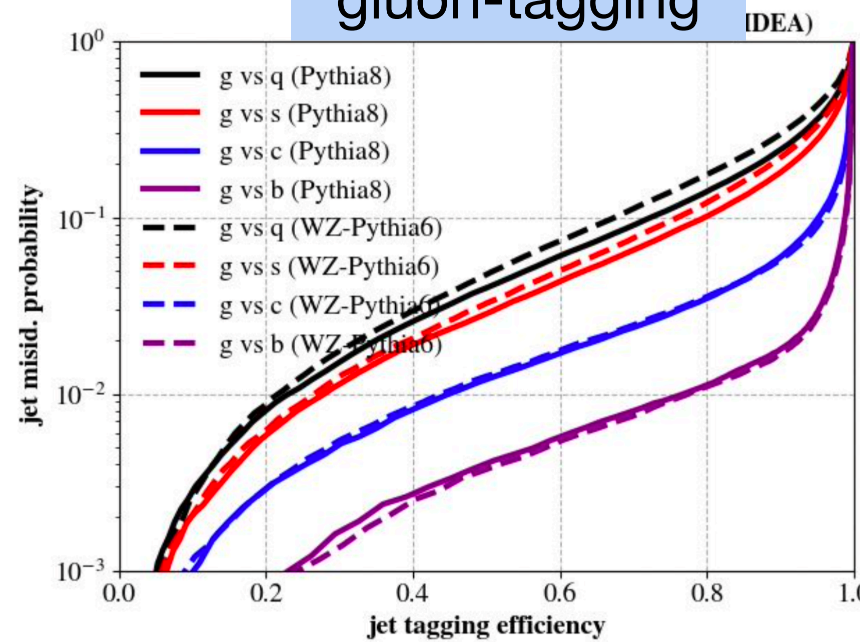
Jet tagging: robustness

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

bottom-tagging



gluon-tagging



Modest dependence

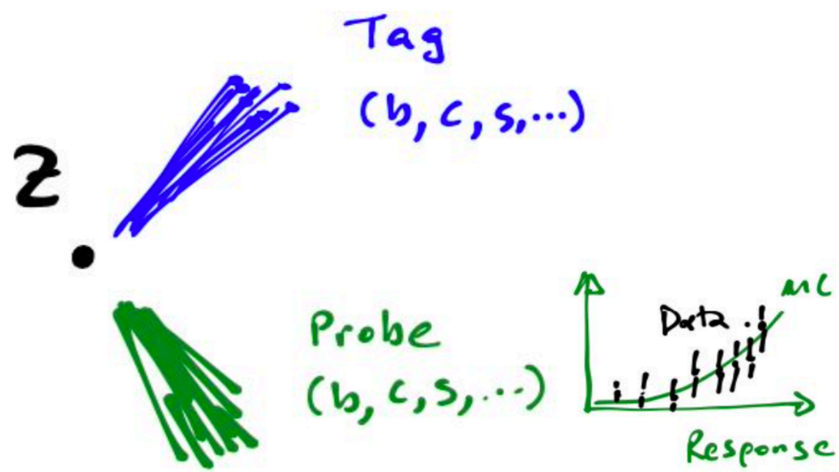
[still many tricks to reduce the dependence]

Improving robustness

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

Improving robustness: The Z-pole

- Another route: **collision 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→hadrons	~70%	0.7×10^6 M
→ uu/cc	~12%/flavor	8.4×10^4 M/ flavor
→ dd/ss/bb	~15%/flavor	1.1×10^5 M/ flavor

Improving robustness

- Take into account tagging performance [& mistag rates]

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

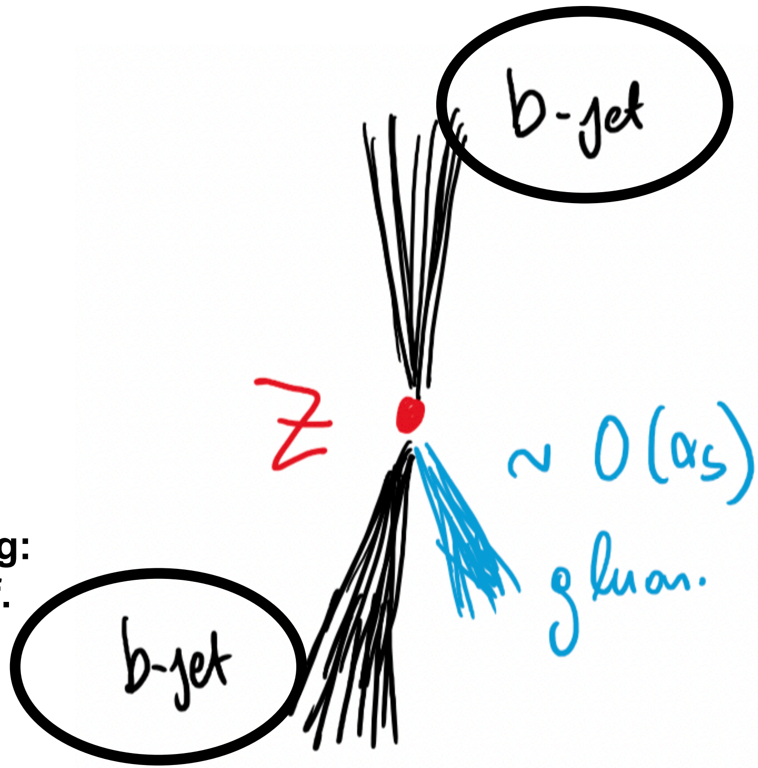
WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

- Back-of-the-envelope: Training sample @ Zpole
  - **bottom jets:** ~1x10^5 M, **strange jets:** ~8.8x10^4 M
    - all other jet flavors in between
  - Much larger training sample than what used for the MC-only development

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

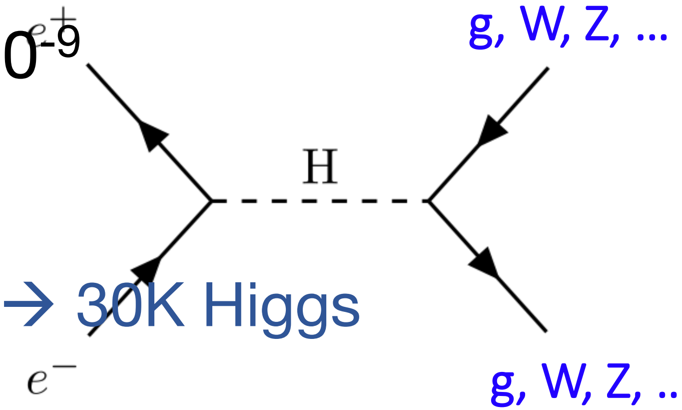
To be tested

Summary

- FCC-ee [full program] is a powerful machine for Higgs physics [and not only]
  - Potential to reach O(0.1)% precision in H-coupling measurements
- Far from “over-subscribed”; steep learning curve ☺
  - Physics object reconstruction
    - Performance: incl. secondary vertices
    - Robustness: architecture design, data-driven @ Zpole, gluon-tagging, ..
  - Detector design/performance
    - Fast and reliable workflow → test different design configurations
      - hand-in-hand with the detector design teams

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: **κ_e @15%**