Jet tagging as a tool for measuring Higgs couplings at O(0.1%) precision & H→ss

Loukas Gouskos (Brown University)

FCC Week, June 2024

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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)%

Introduction

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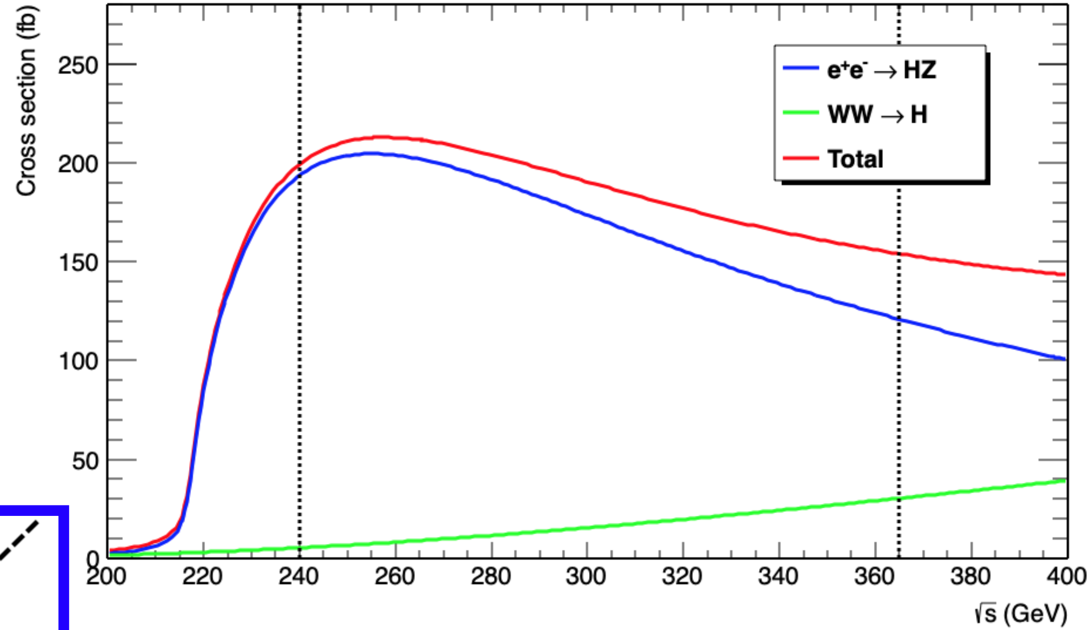
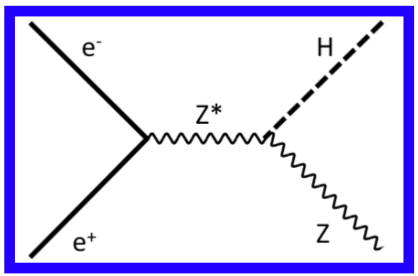
e.g. Λ=1 (5)TeV→~5 (0.1)%

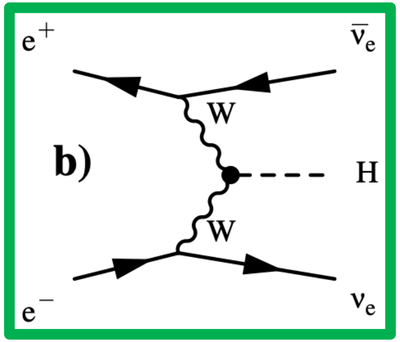
- HL-LHC:
  - Direct searches: O(5) TeV
  - H-couplings:
    - Bosons/ 3rd-Gen fermions @ few %
    - 2nd Gen fermions: maybe evidence of H→cc
    - Self-coupling~50%
- Future e^+e^- collider:
  - Measure H-couplings at O(0.1)% level

Higgs production @ e+e-



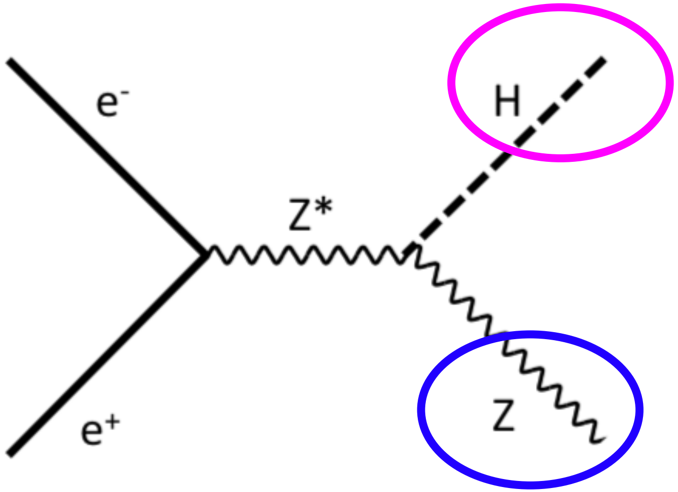


E_{CM} ~240 GeV:
ZH production dominates



E_{CM}~365 GeV:
Hνν becomes important

General strategy



Higgs boson reconstruction:
- particular focus on had. decays
  [e.g., → bb/cc/gg; ss (?) ..]

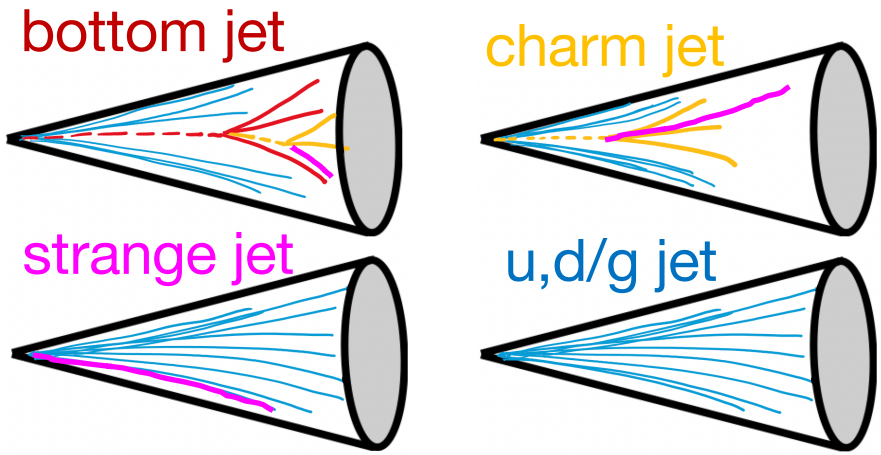
Z boson reconstruction:
- Explore several decay modes
- Recoil mass

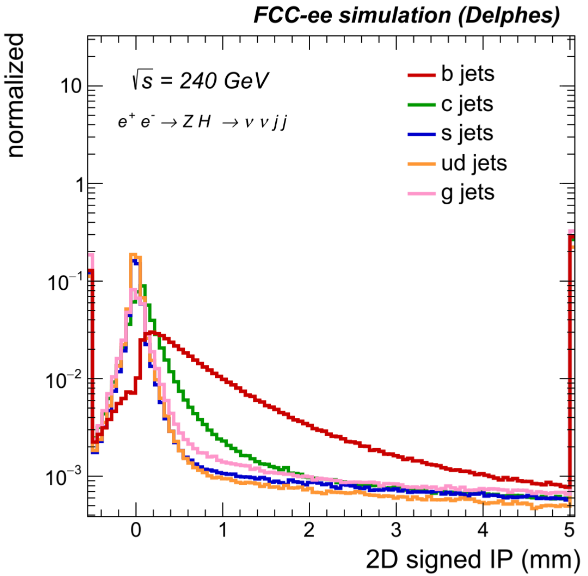
BR(H→hadrons) ~ 80%
BR(Z→hadrons) ~ 70%

- Key:
  - Optimal identification ("tagging") of hadronic decays
    - Simultaneously across different flavors
  - "In-situ" constrain of BKG uncertainties to better than O(1%)

Jet tagging

Basics





- Bottom/charm tagging
  - Large lifetime
  - Displaced vertices/tracks
  - Non-isolated e/μ

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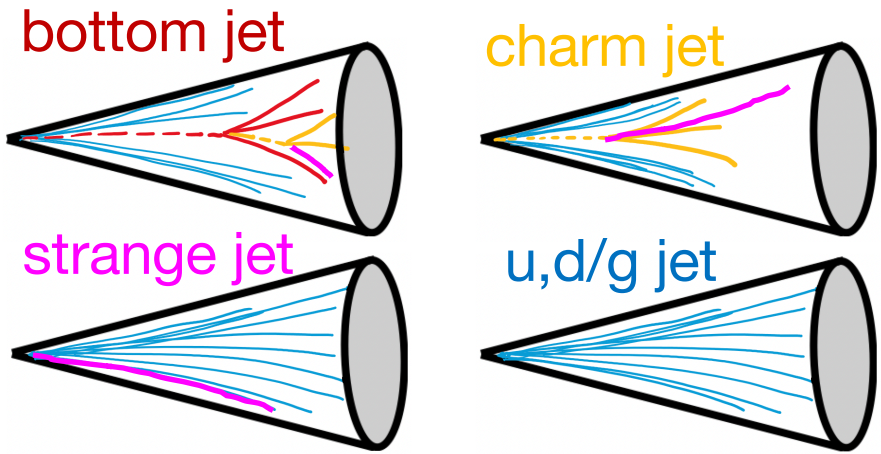
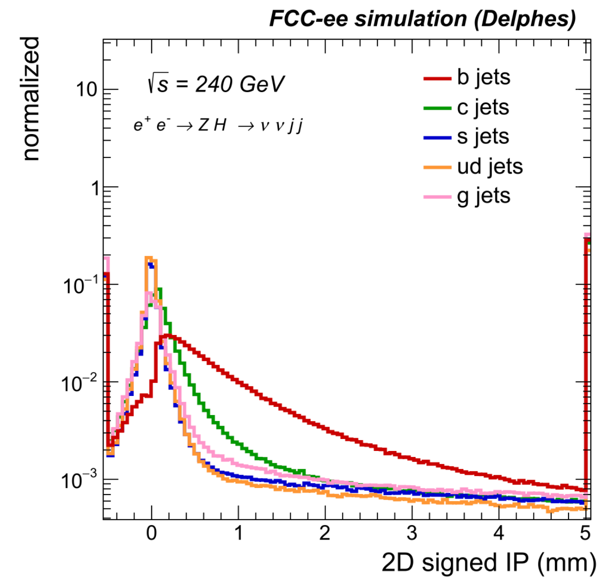
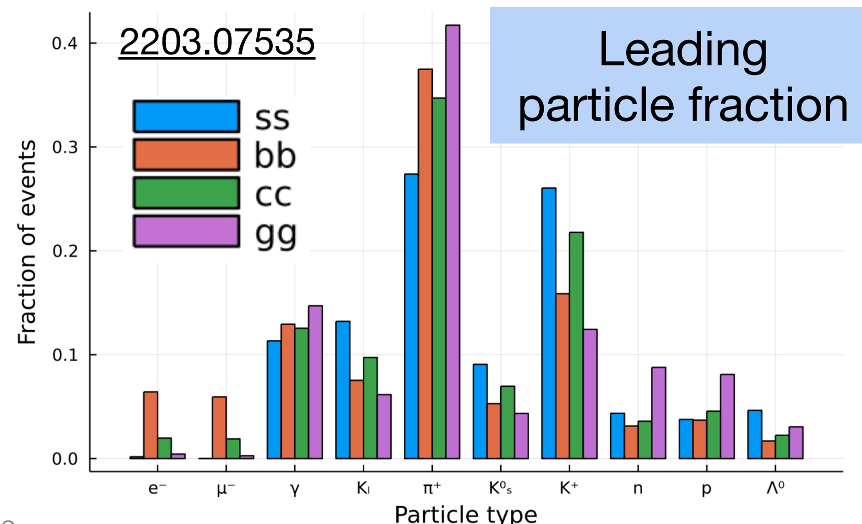


- Bottom/charm tagging
  - Large lifetime
  - Displaced vertices/tracks
  - Non-isolated e/μ
- Strange tagging
  - Enhanced Kaon fraction
  - Large momentum fraction

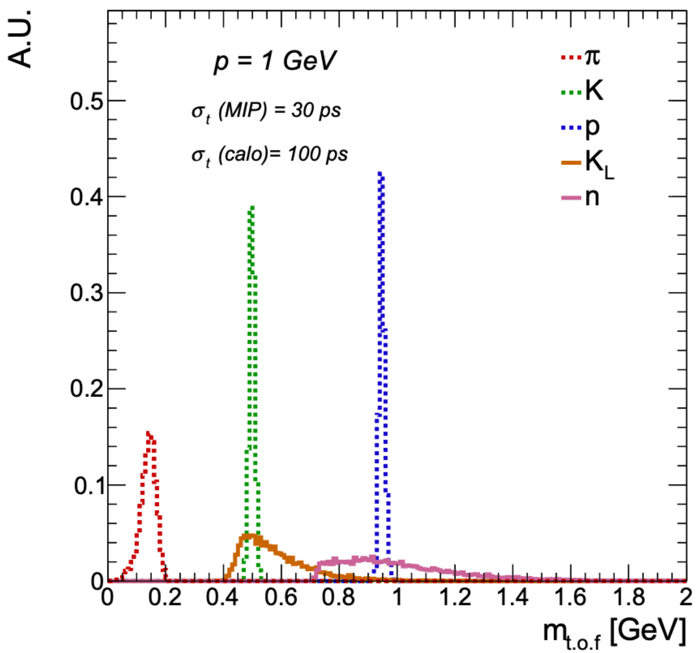




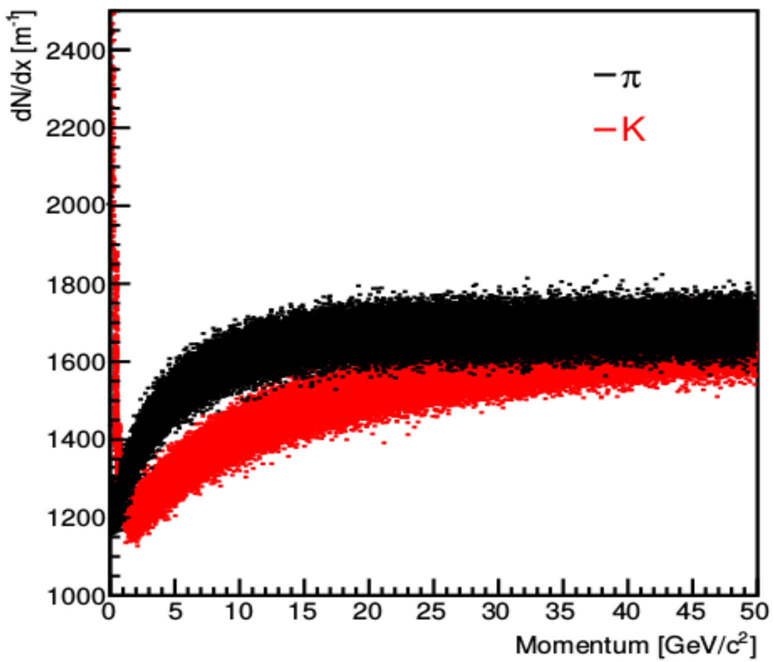
Strange tagging: Particle ID

- Big effort to design optimal PID detectors and algorithms to exploit their full potential [e.g., ECFA H→ss team, Wiki]
  - IDEA detector:

Timing layer (TOF)



Drift Chamber (dN/dx)



Strange tagging: Particle ID

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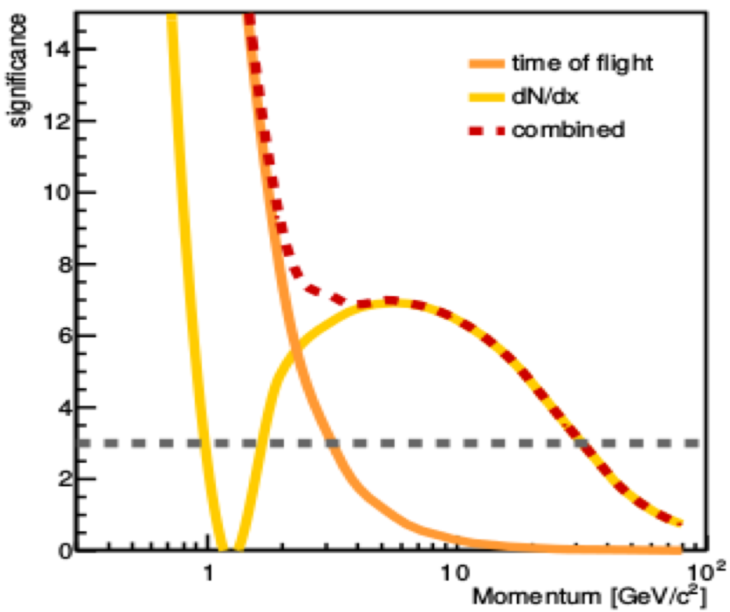
  - IDEA detector:

TOF + dN/dx



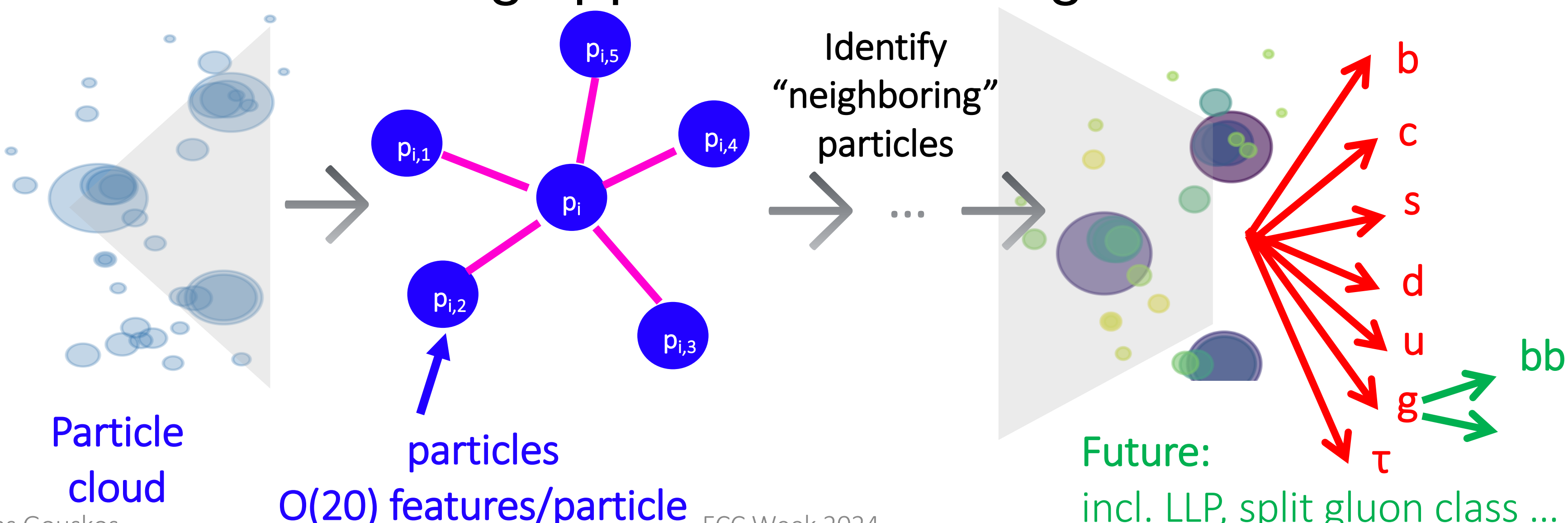
Achieve 3σ π/K separation for up to ~30 GeV momenta

But:
We need to carefully access impact of detector proposals to the full Higgs [and not only] physics program in general [more later]

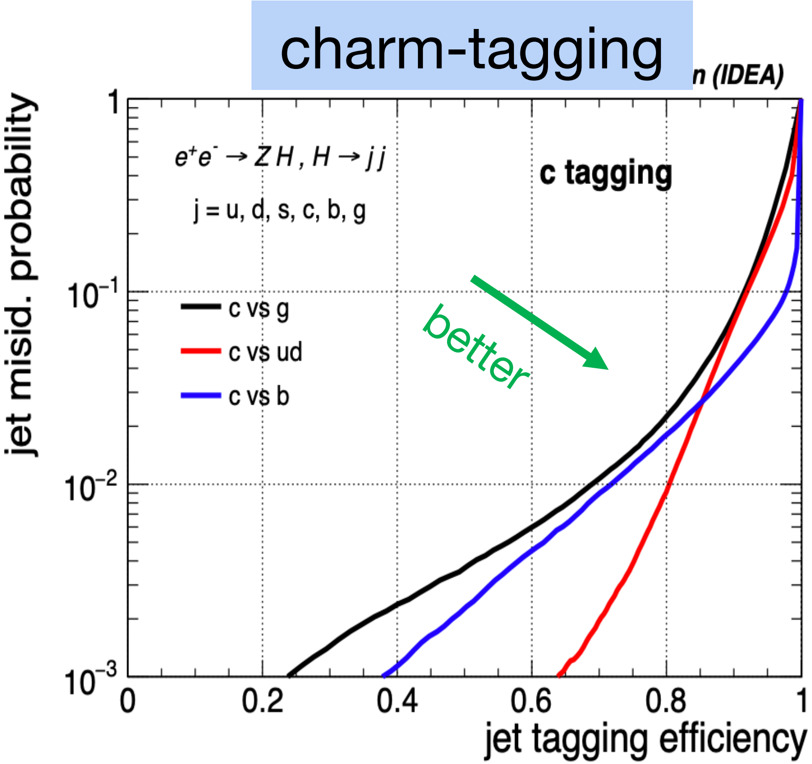
Jet tagging

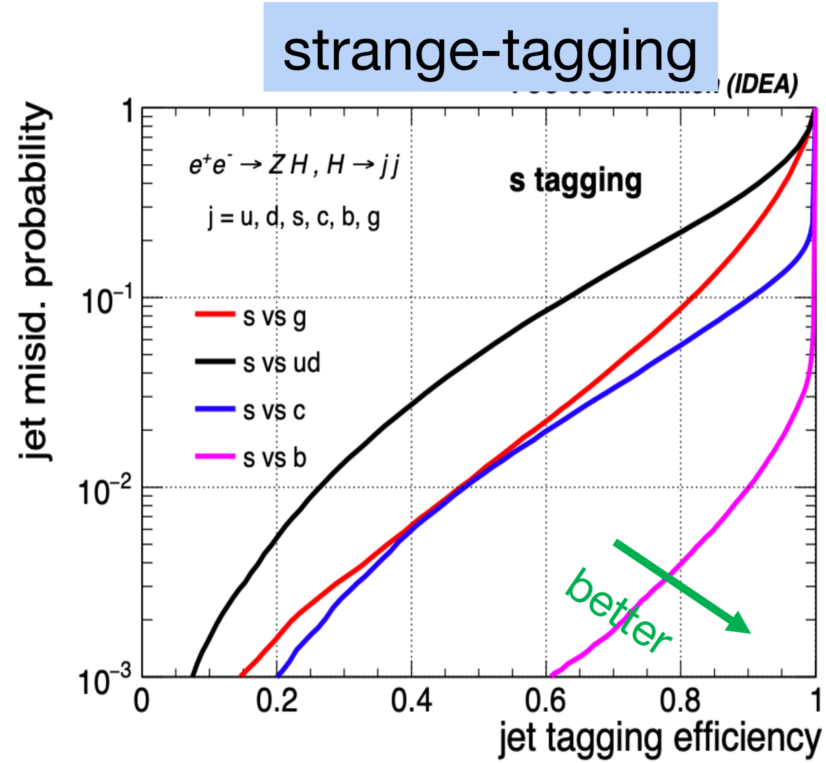
PRD 101 056019 (2020)
EPJ C 82 646 (2022)

- Jet representation: Particle cloud (i.e., ParticleNet)
  - 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





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

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

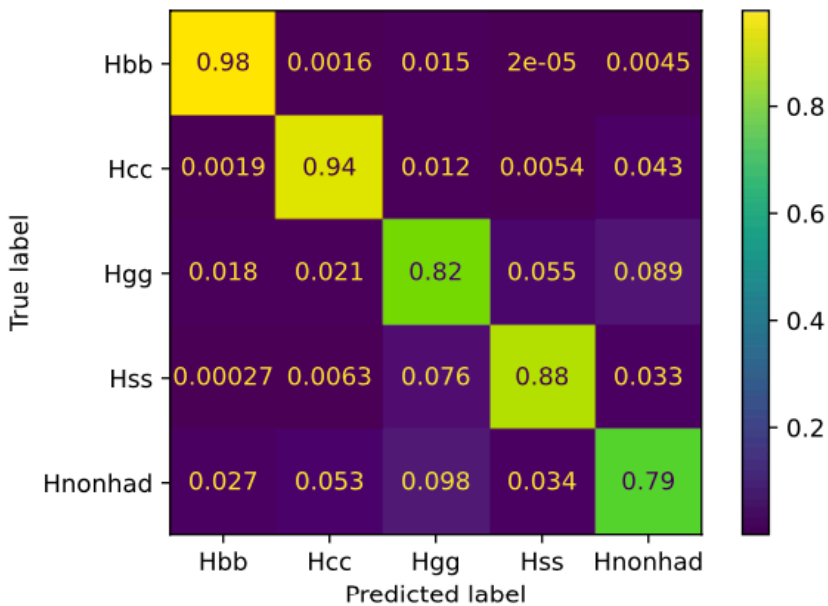
ZH analysis

- **Three analysis channels**
  - Z(→LL)H, Z(→vv)H, Z(→quarks)H
- **Similar strategy across channels**
  - Categorize events using ParticleNet score [bb, cc, ss, gg, ..]
  - Signal extraction: Fit m_H simultaneously across analysis categories

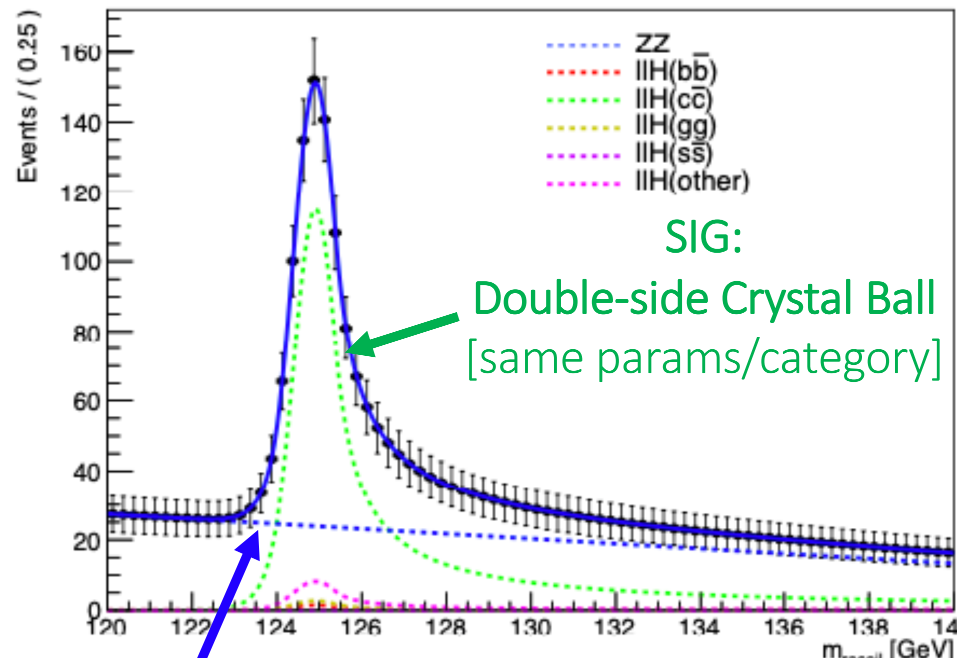
Z(→e⁺e⁻/μ⁺μ⁻)H channel

- Clean but small signal acceptance
  - Key: disentangle Higgs decays

Event categorization



Z(→LL)H(→cc) category



SIG:
Double-side Crystal Ball
[same params/category]

BKG:
1^{st} order polynomial

Simultaneous m_{rec} fit in all categories

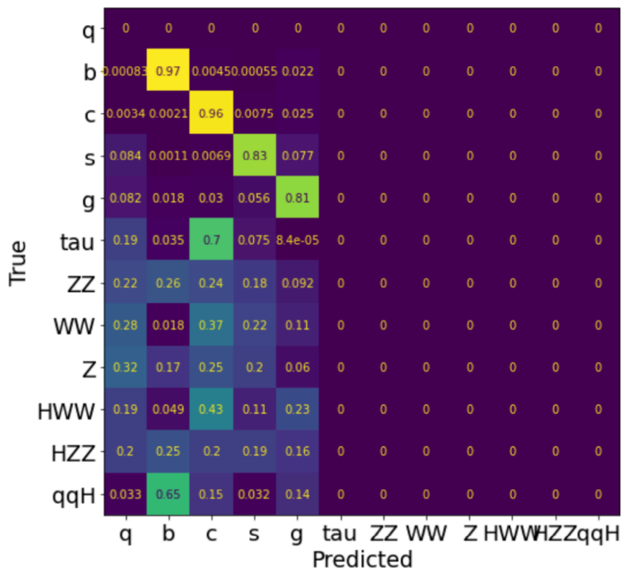
- NN-based evt-level disc.
  - PNet scores+Evt info

Z(→νν)H channel

- More signal, but larger and more complex BKGs

Event categorization

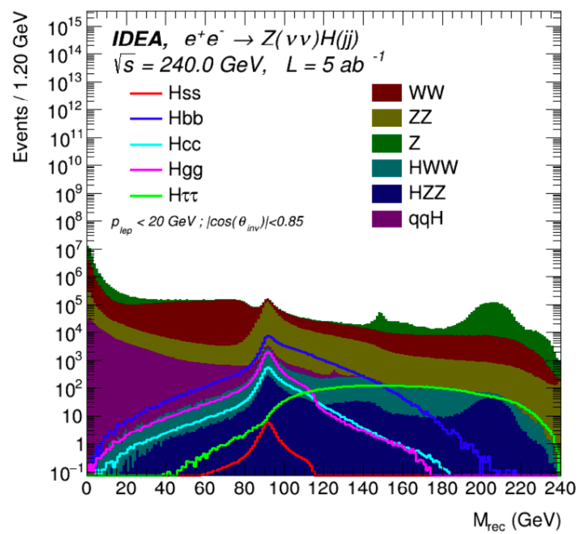
- Sum ParticleNet scores of 2 jets
  - e.g. scores: b_1b_2, c_1c_2, s_1s_2, …
- Largest ∑: Characterize event
  - Subcategories based on S/B



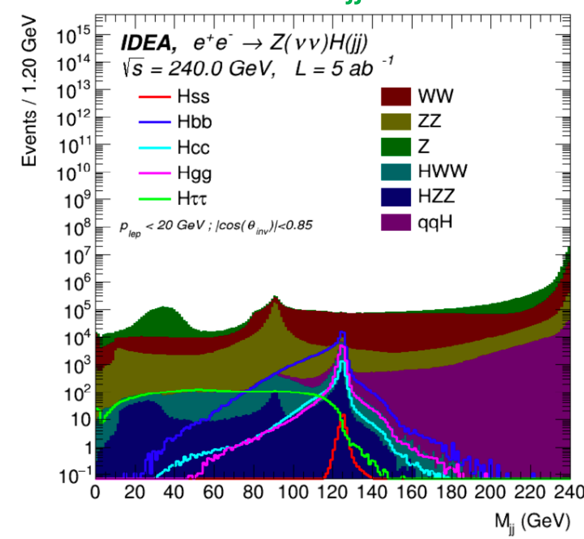
SIG-vs-BKG discrimination

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

m_{rec}

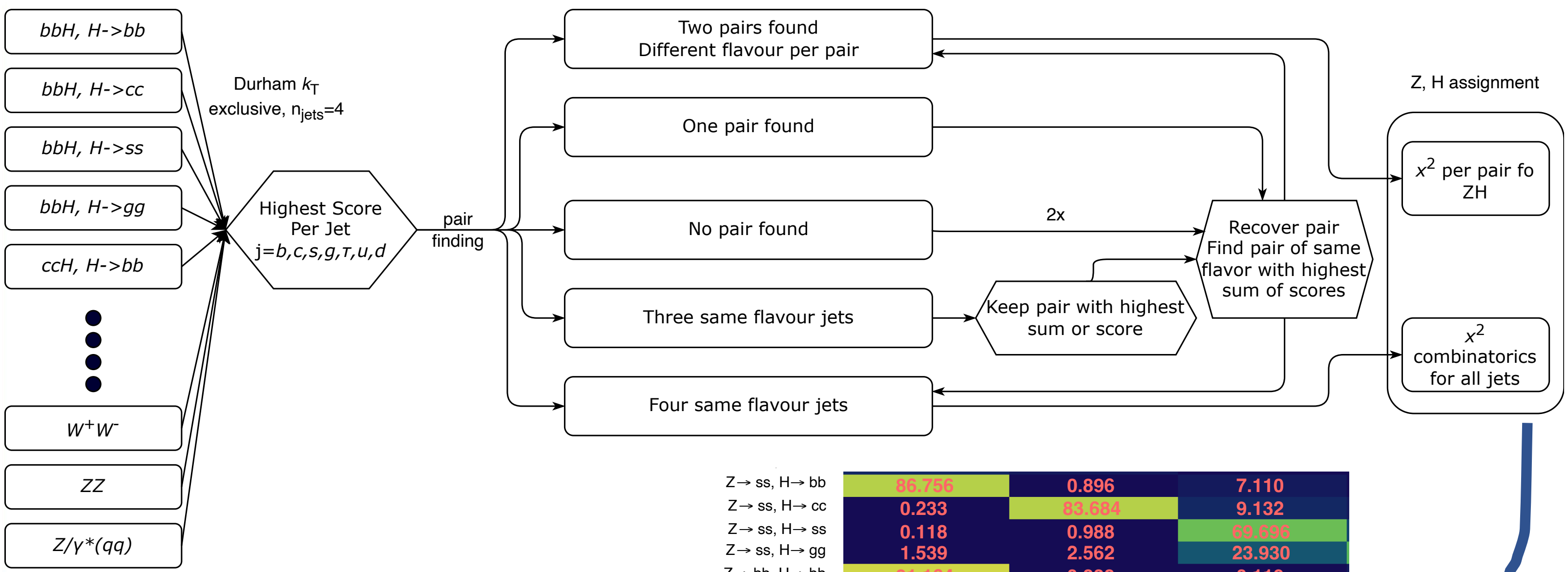


m_{jj}



Z(→qq)H channel

- Largest signal acceptance, but.. jets
  - Challenge: Jet-pairing



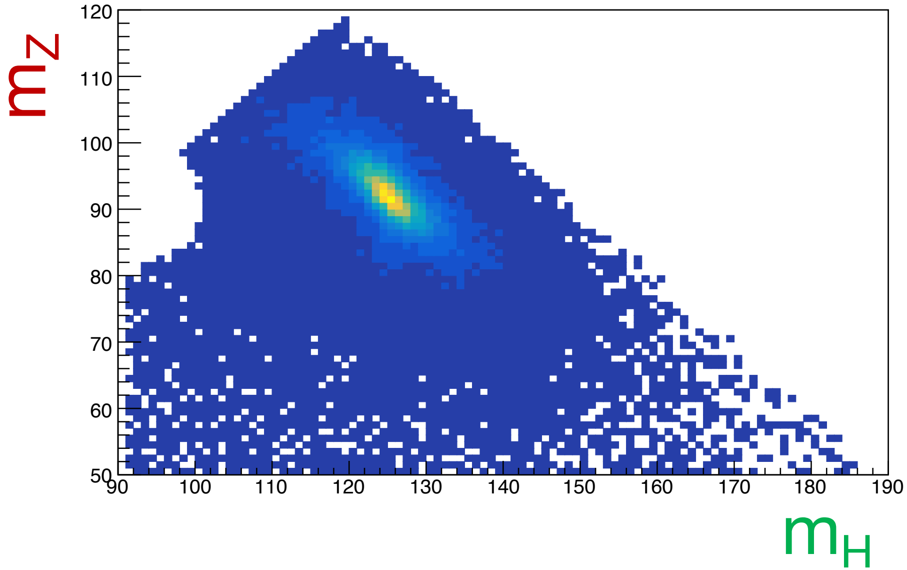
	B	C	S
Z→ ss, H→ bb	86.756	0.896	7.110
Z→ ss, H→ cc	0.233	83.684	9.132
Z→ ss, H→ ss	0.118	0.988	69.696
Z→ ss, H→ gg	1.539	2.562	23.930
Z→ bb, H→ bb	91.164	0.838	0.119
Z→ bb, H→ cc	21.445	74.468	0.435
Z→ bb, H→ ss	26.049	1.672	56.704
Z→ bb, H→ gg	41.832	2.477	2.828
Z→ qq, H→ bb	87.019	0.952	1.018
Z→ qq, H→ cc	0.228	84.564	1.869
Z→ qq, H→ ss	0.117	0.711	61.448
Z→ qq, H→ gg	1.656	2.528	6.760
Z→ cc, H→ bb	83.264	13.426	0.104
Z→ cc, H→ cc	0.515	89.881	1.014
Z→ cc, H→ ss	0.234	25.228	58.423
Z→ cc, H→ gg	1.457	39.152	3.254

Z(→qq)H channel (II)

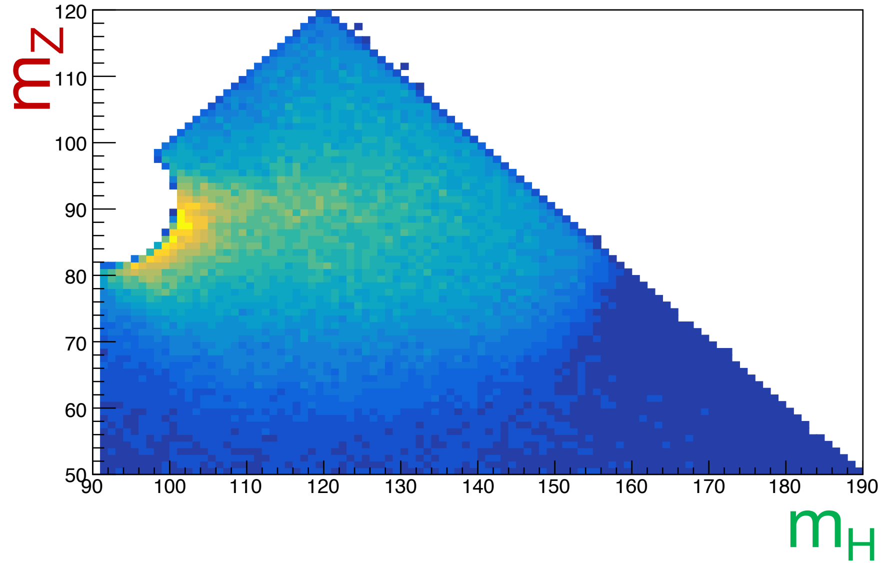
- Similar strategy for signal extraction
  - Bump hunt in m_Z & m_H simultaneously in all categories

Z(→bb)H(→bb) category

Signal



ZZ BKG



Results @240 GeV

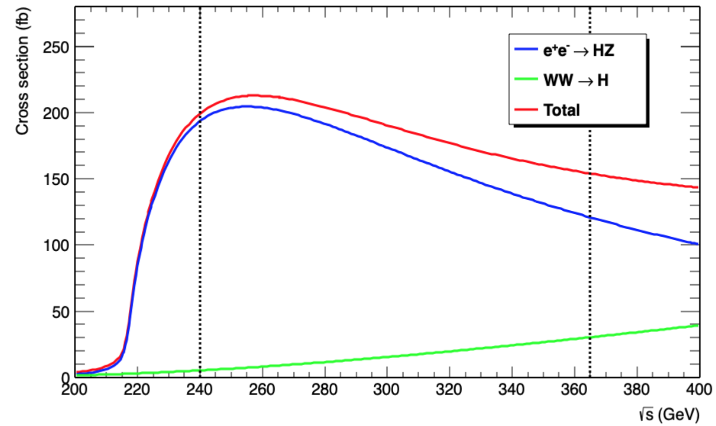
E_{CM} = 240 GeV [10.8 ab^{-1}, 4 IP]

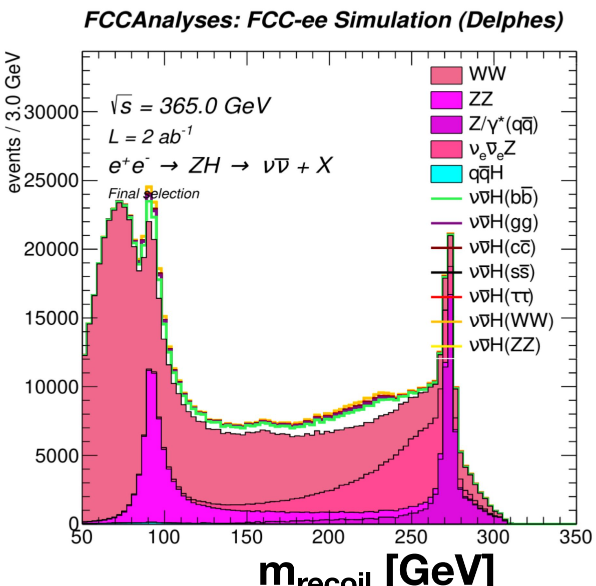
Decay mode	Z(→LL)H(→jj) [%]	Z(→vv)H(→jj) [%]	Z(→jj)H(→jj) [%]	Combination
H→bb	0.55	0.24	0.20	0.15
H→cc	3.35	1.77	2.38	1.20
H→ss	280	93	296	80
H→gg	1.86	0.75	1.63	0.65

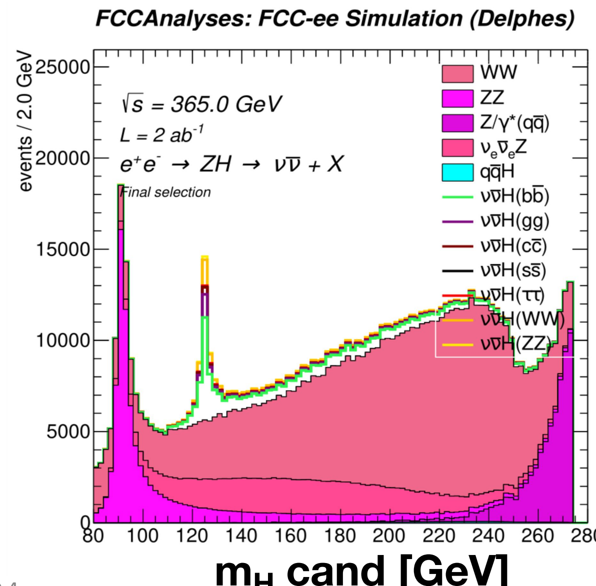
- Details
  - Signal & most BKGs: free floating parameters [correlated across categories]
  - Systematics: Signal 0.1%, BKG 5% [constrained to <1%]

Results @365 GeV [hot-off-the-press]

- Similar strategy to 240 GeV
  - Tuning of event-level variables
  - WWH & ZH are fitted with a shared signal strength parameter
    - Focus on BR determination







Results @365 GeV [hot-off-the-press]

E_{CM} = 365 GeV [2.3 ab^{-1}, 4 IP]

Decay mode	Z(→LL)H(→jj) [%]	Z(→vv)H(→jj) [%]	Z(→jj)H(→jj) [%]	Combination
H→bb	1.23	0.68	0.52	0.39
H→cc	8.20	3.95	4.68	2.83
H→ss	1153	214	664	201
H→gg	4.24	2.51	4.15	1.92

- Modest increase in sensitivity O(10%)
  - but: Jet tagger has never seen this regime [poor performance]
- Expect significant improvement

Instead of summary

- Meet physics goals
  - Improve precision by O(10) wrt HL-LHC
  - Extend to couplings that are [probably] impossible at the HL-LHC (charm, strange ?)

Opportunity to **fully establish second generation** charged fermions!
→ Impossible at the HL-LHC/hadron colliders

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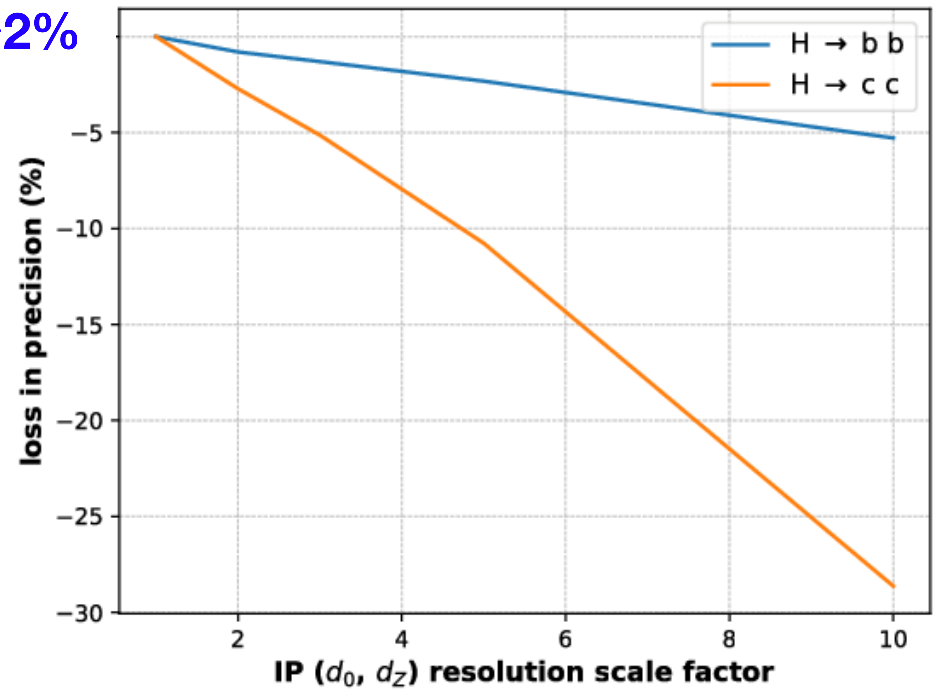
Opportunity to **fully establish second generation** charged fermions!
→ Impossible at the HL-LHC/hadron colliders

- In parallel: Lot's of effort on detector design
  - What's the most optimal way?
    - optimal: e.g., performance, cost, risk, ..
- This analysis: Framework to access impact of detector proposals to the **full** Higgs physics program

Impact of detector configuration: H→cc

Pixel detector

Optimal:
δ(BR(H→cc))~2%



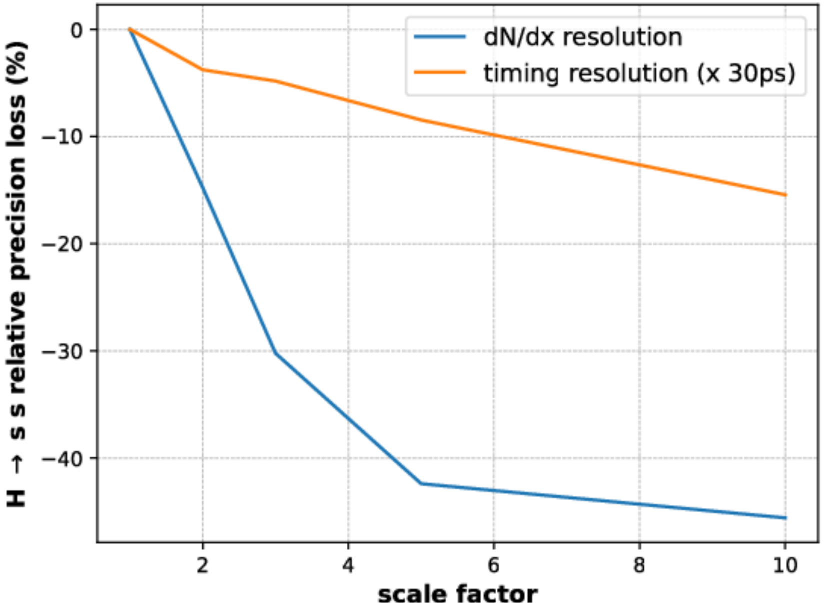
Pessimistic:
δ(BR(H→cc))~2.7%

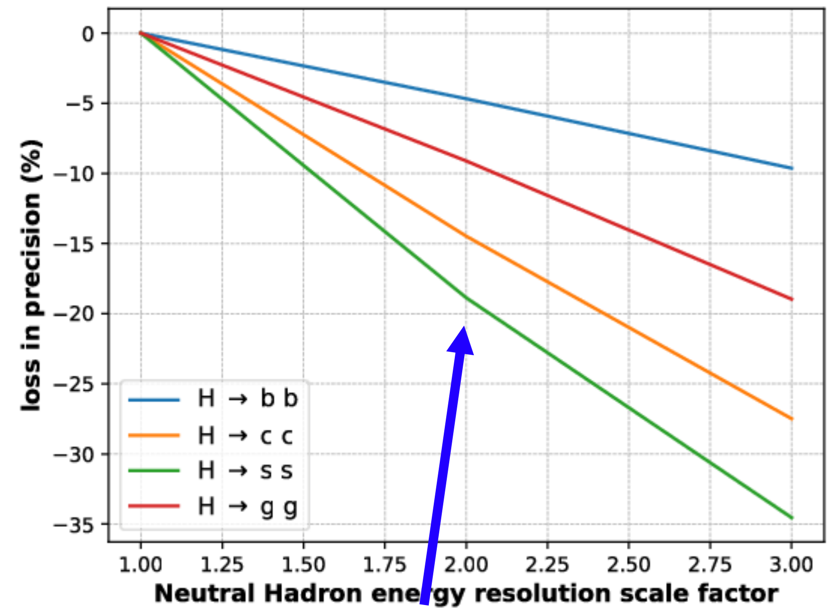
- FastSim based [need to repeat using FullSim]

Impact of detector configuration: H→ss

Optimal: δ(BR(H→ss))~100% **PID**

Optimal: δ(BR(H→ss))~100% **Calorimetry**





Pessimistic: δ(BR(H→ss))~140%

Pessimistic: δ(BR(H→ss))~120%

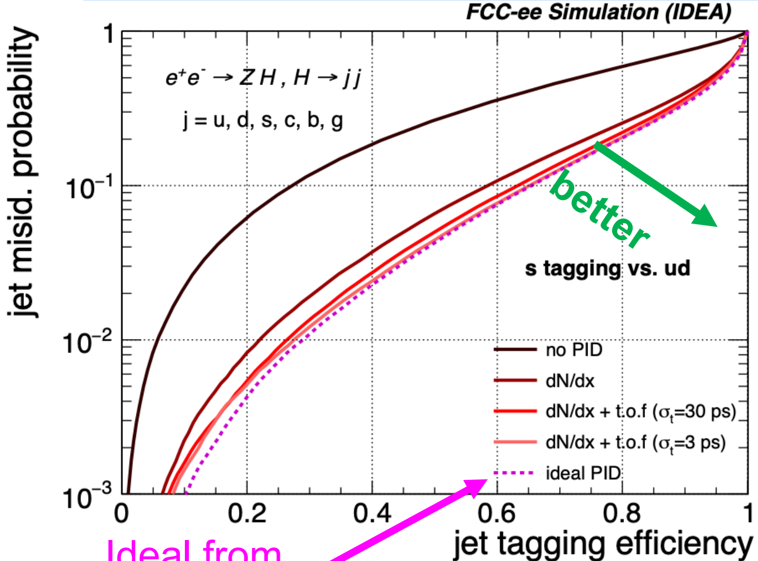
- Should systematically access impact of detector developments in physics benchmarks

Extra slides

Impact of detector configurations

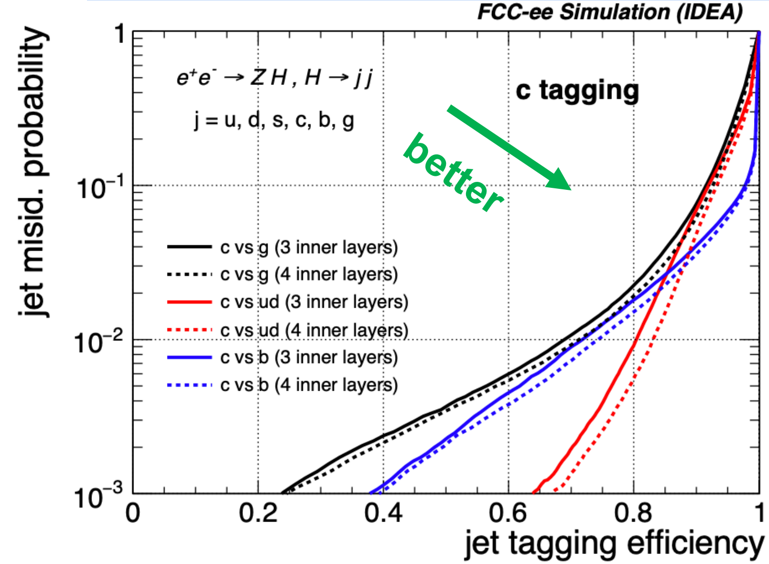
[EPJ C 82 646 (2022)]

strange-tagging (timing)



Ideal from MC

charm-tagging [PIX layer]



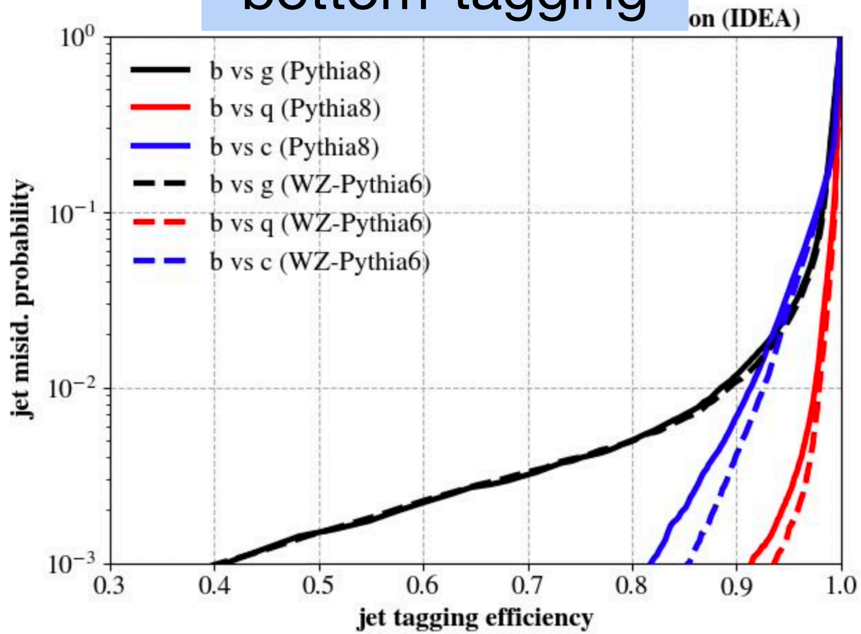
dN/dx brings most of the gain
additional gain w/ TOF (30ps)
→TOF (3ps): marginal improvement

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

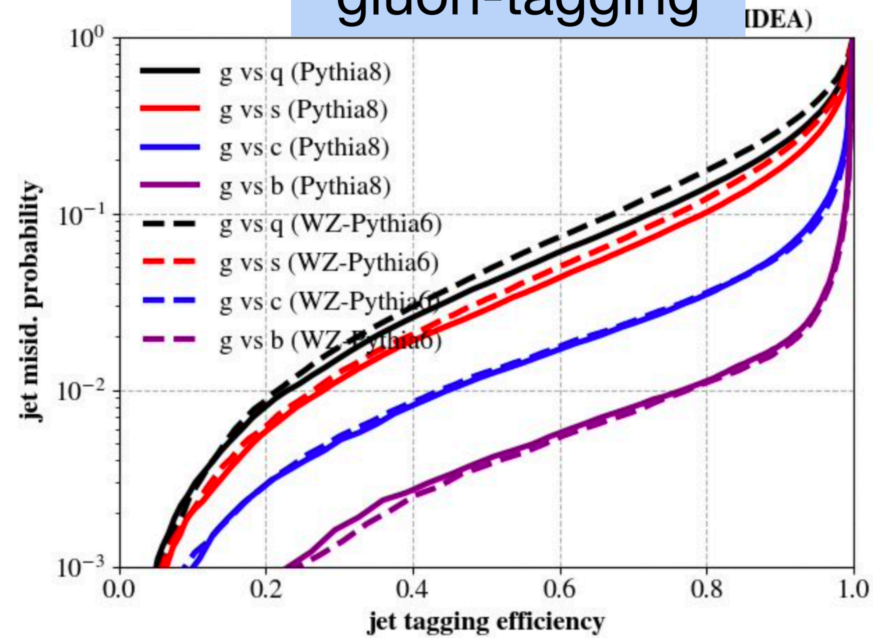
Jet tagging: robustness

- 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

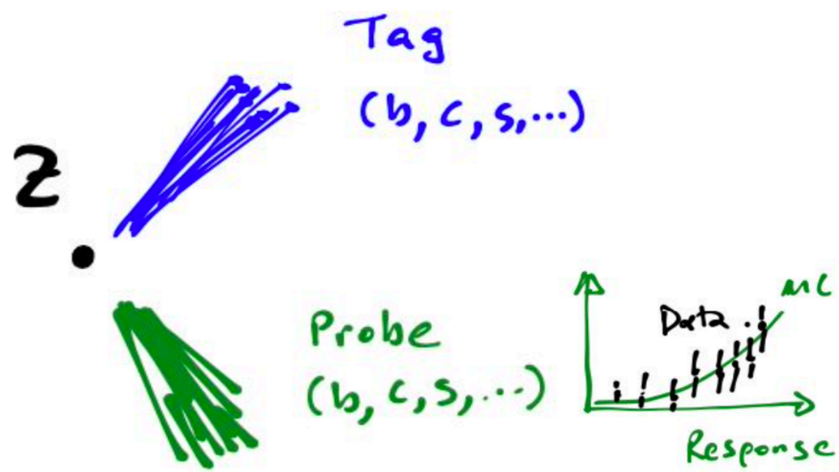
[still many tricks to reduce the dependence]

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

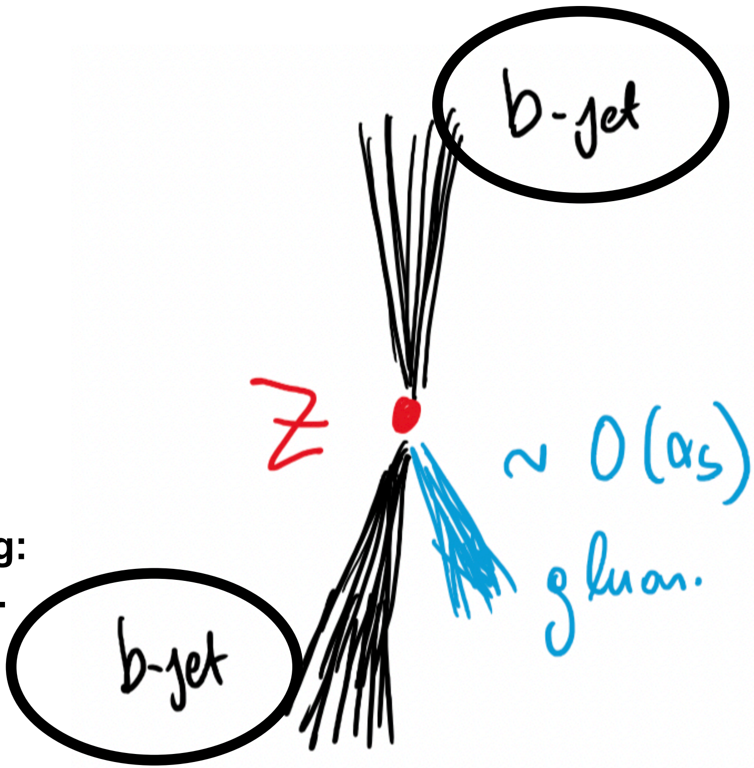
WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

- 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