# Higgs Physics at the FCC

## experimental overview

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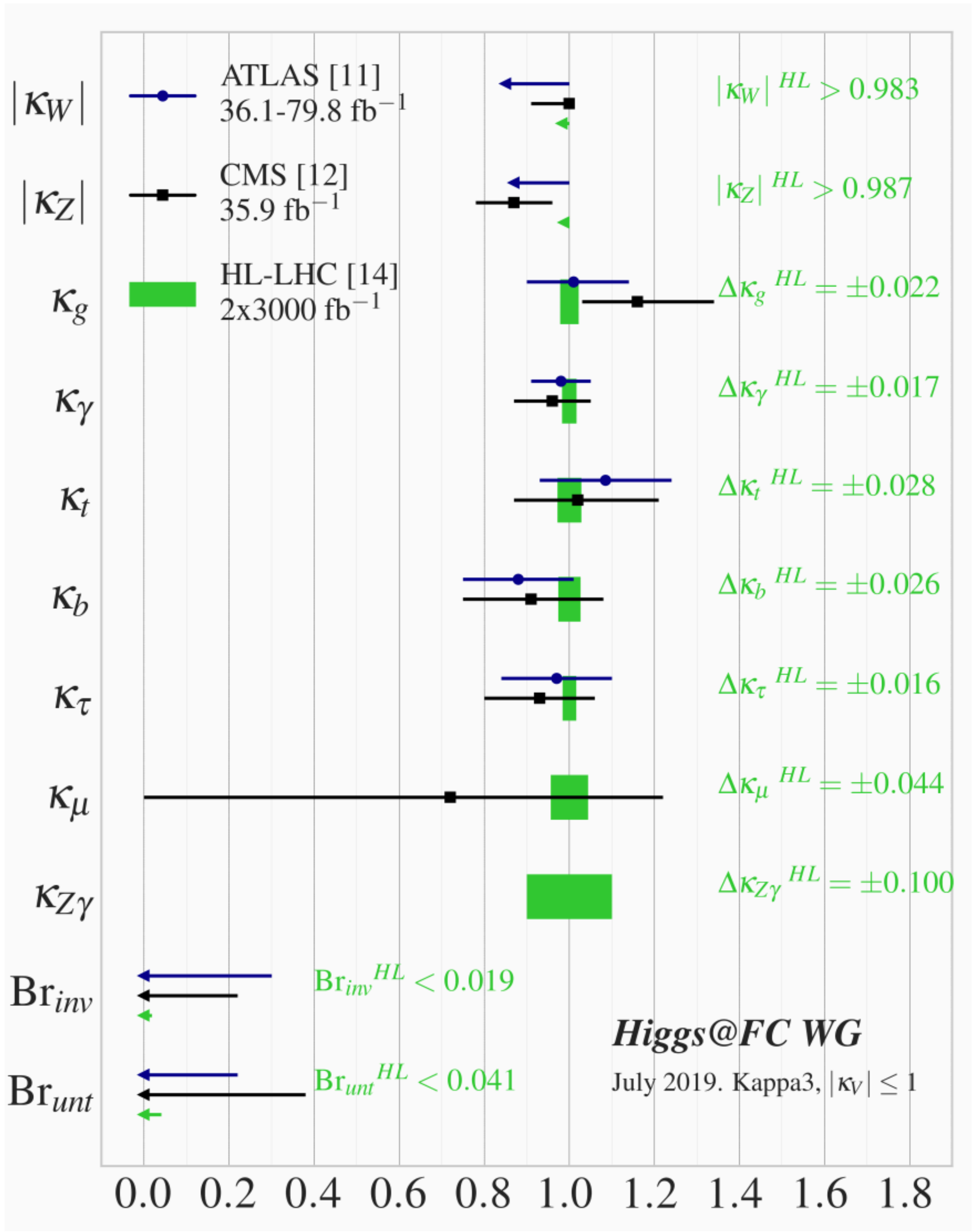
CERN

FCC Pheno Physics  '23 CERN

# Higgs at HL-LHC

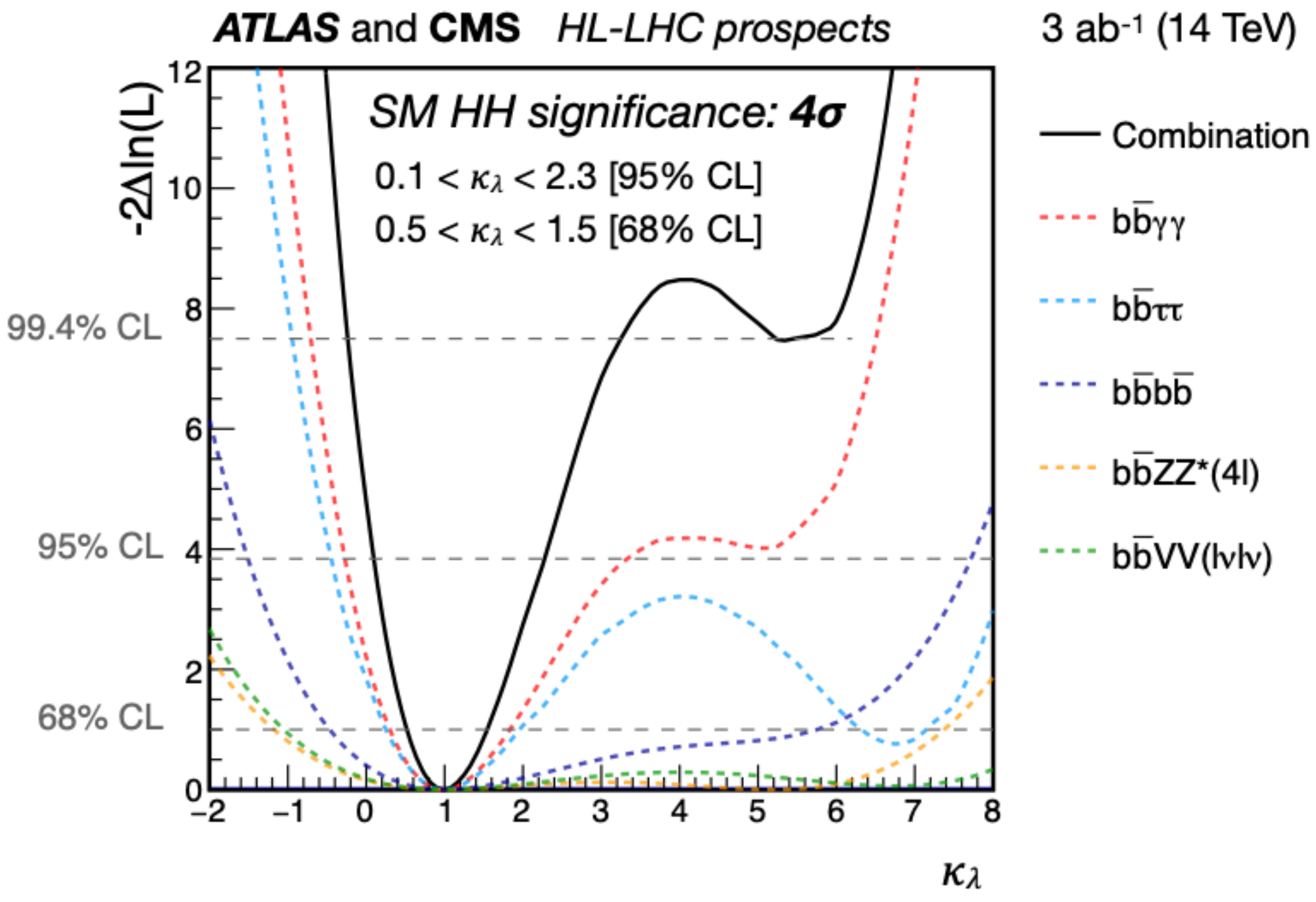



~ 1%

~ 2-3%

~ 5%

~ 10%

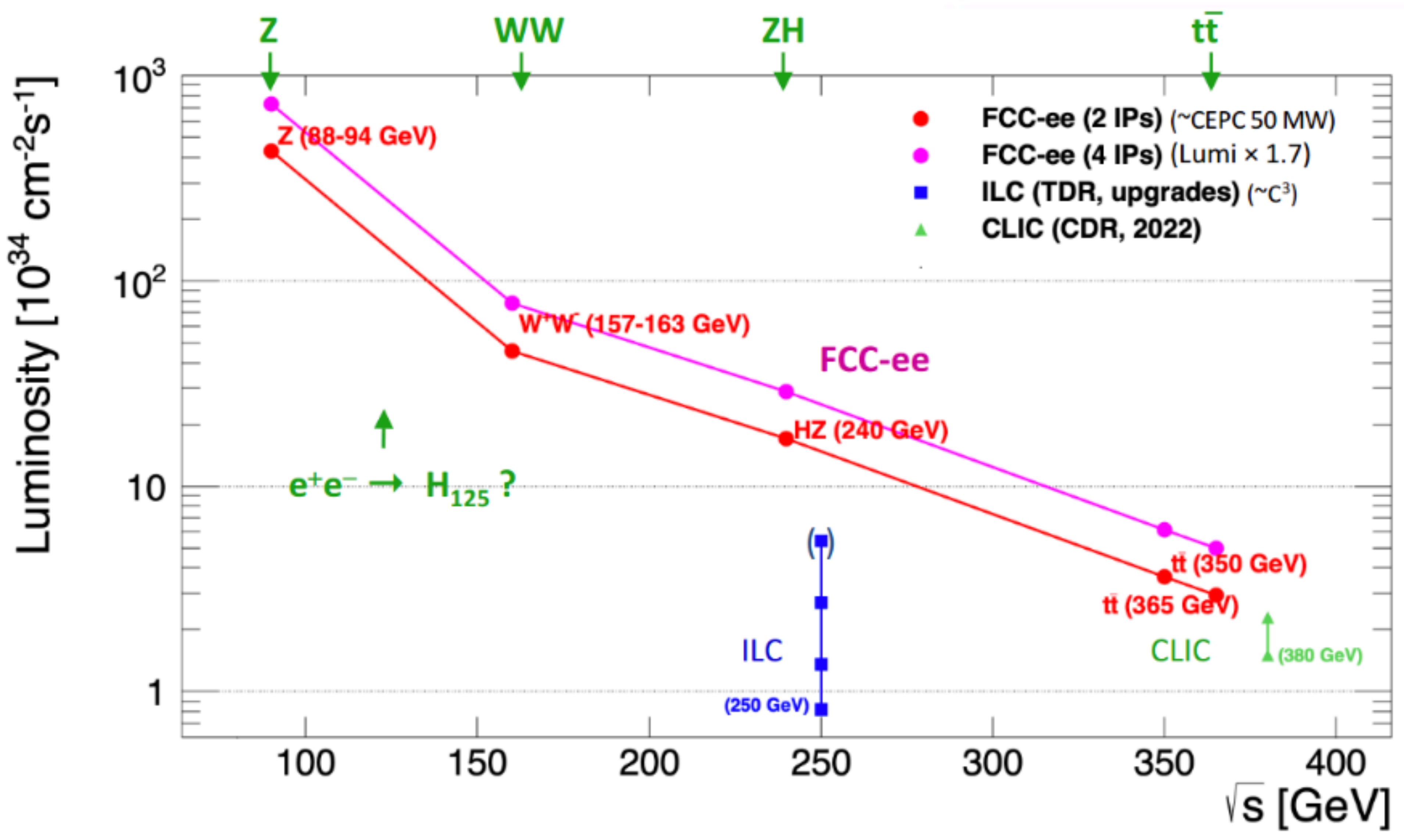



Need to go beyond the LHC precision measurements:

- Model independence, Higgs width
- Light couplings (charm, muon)
- Invisible decays

- Self-coupling(s)
- BSM Higgs

# FCC-ee program




15 (20?) years of operations

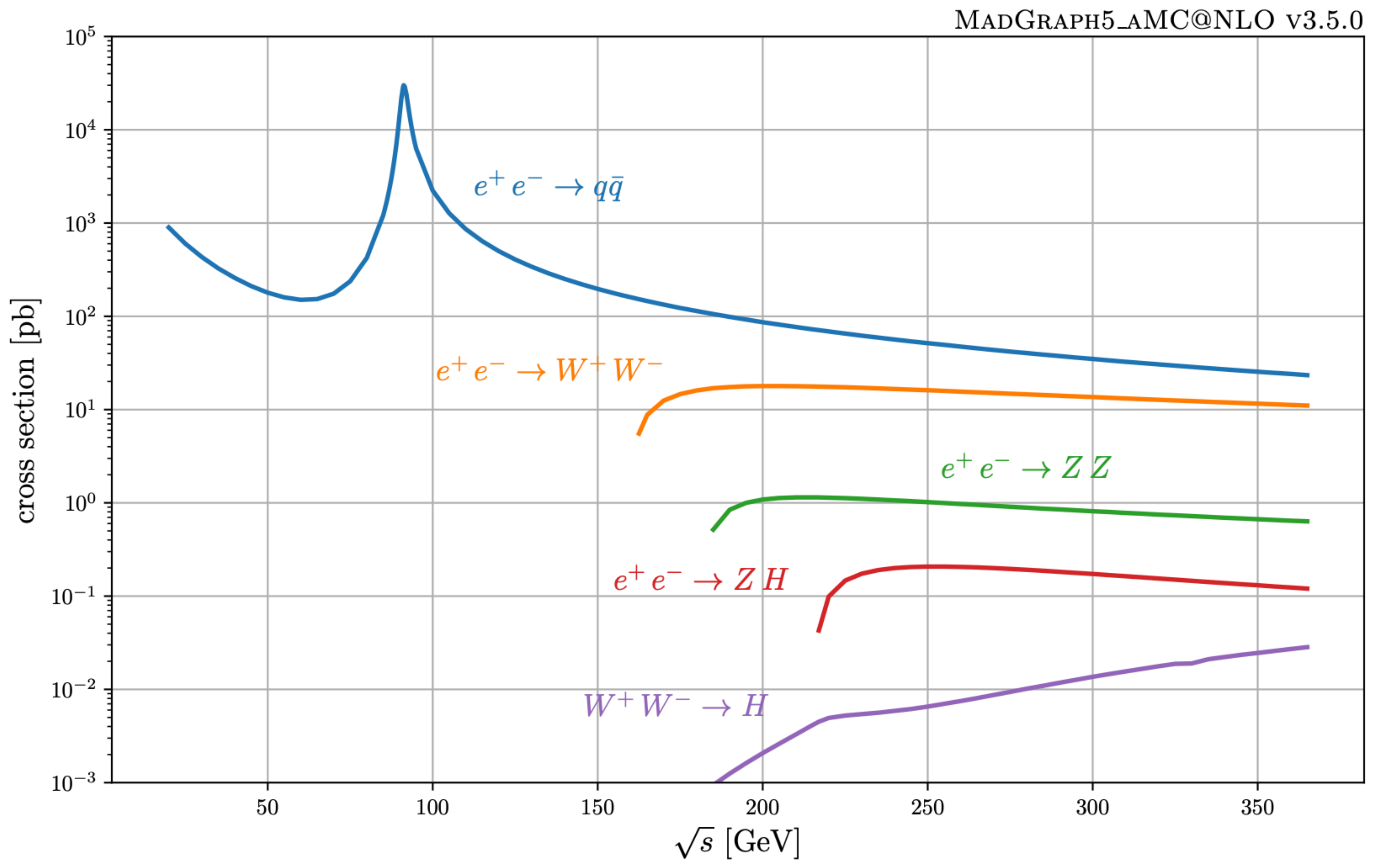
| | Z pole | ? H pole ? | WW | ZH | ttbar |
|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | 88 - 91 - 94 | 125 | 157 - 161 | 240 | 350 - 365 |
| Lumi / IP [$10^{34}$ cm$^2$ s$^{-1}$] | 182 | 80 | 19.4 | 7.3 | 1.33 |
| Int. lumi / 4IP [ab$^{-1}$ / yr] | 87 | 38 | 9.3 | 3.5 | 0.65 |
| $N_{years}$ | 4 | 5 | 2 | 3 | 5 |
| $N_{events}$ | 8 Tera | 8 K | 300 M | 2 M | 2 M |

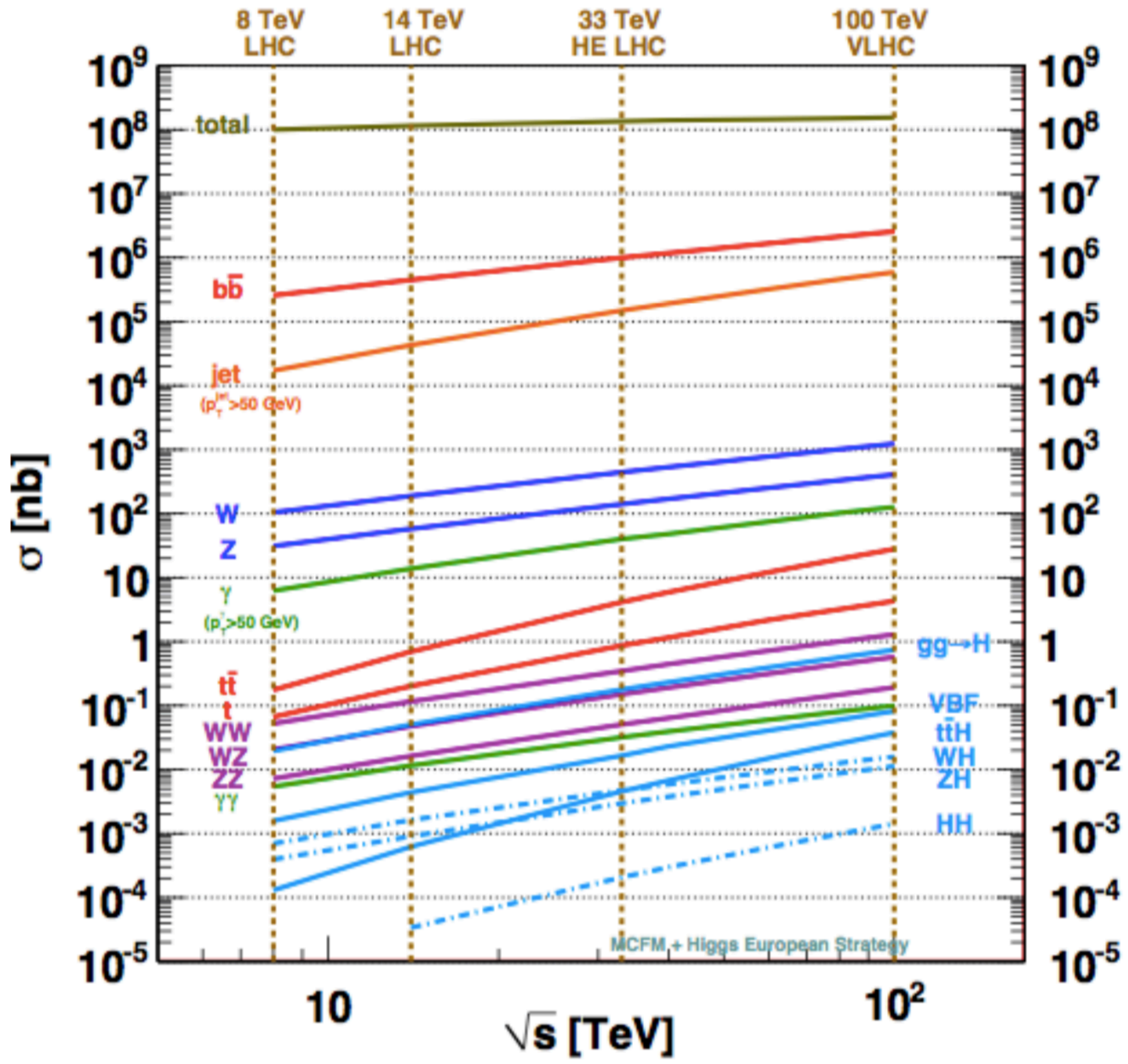
Exquisite luminosity allows for ultimate precision:

- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day

# Physics processes

- Physics background are "small" in $e^+e^-$
  - s-channel ~ 1/s
  - t-channel ~ log s



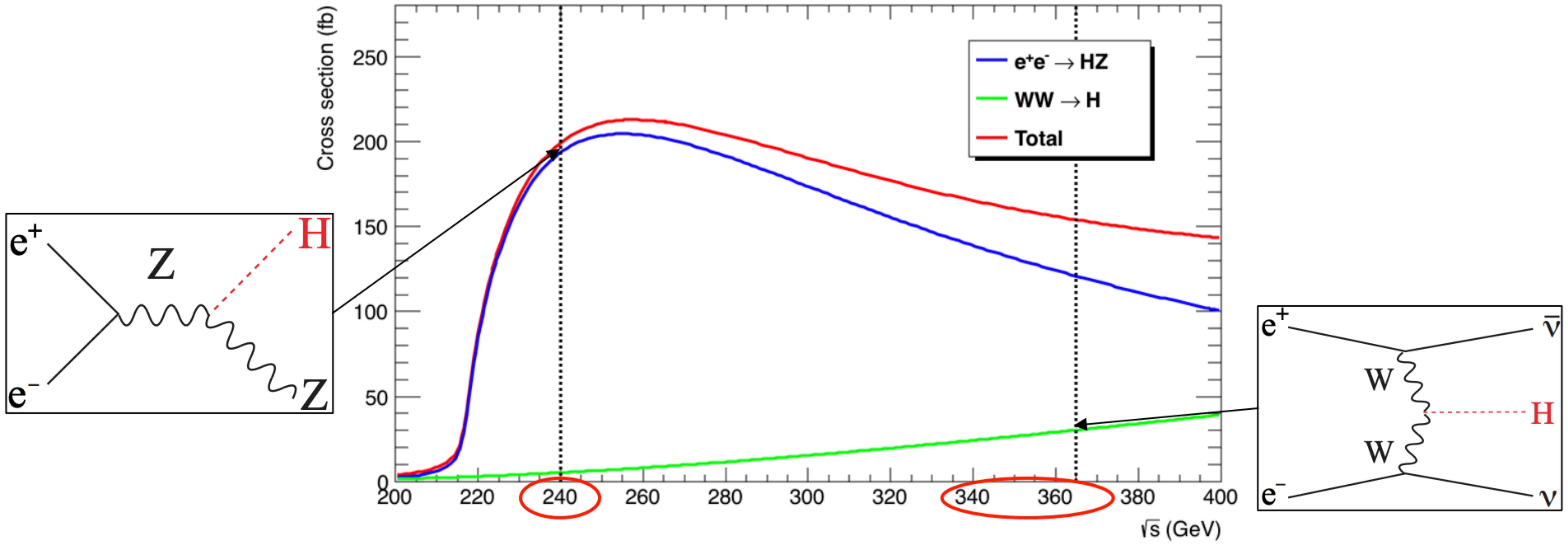

S/B **$10^{-2}$ at $e^+e^-$** **$10^{-10}$ at hadron colliders**

FCC-ee offers ideal environment for Higgs physics

large rates ( > 1e6 )
clean exp. environment (no UE, Pile-up, low event rate)
Large S/B (no QCD background)
Energy, momentum constraints

# Higgs at the FCC-ee

- production mechanisms
  - Higgs-strahlung
  - VBF




4IP

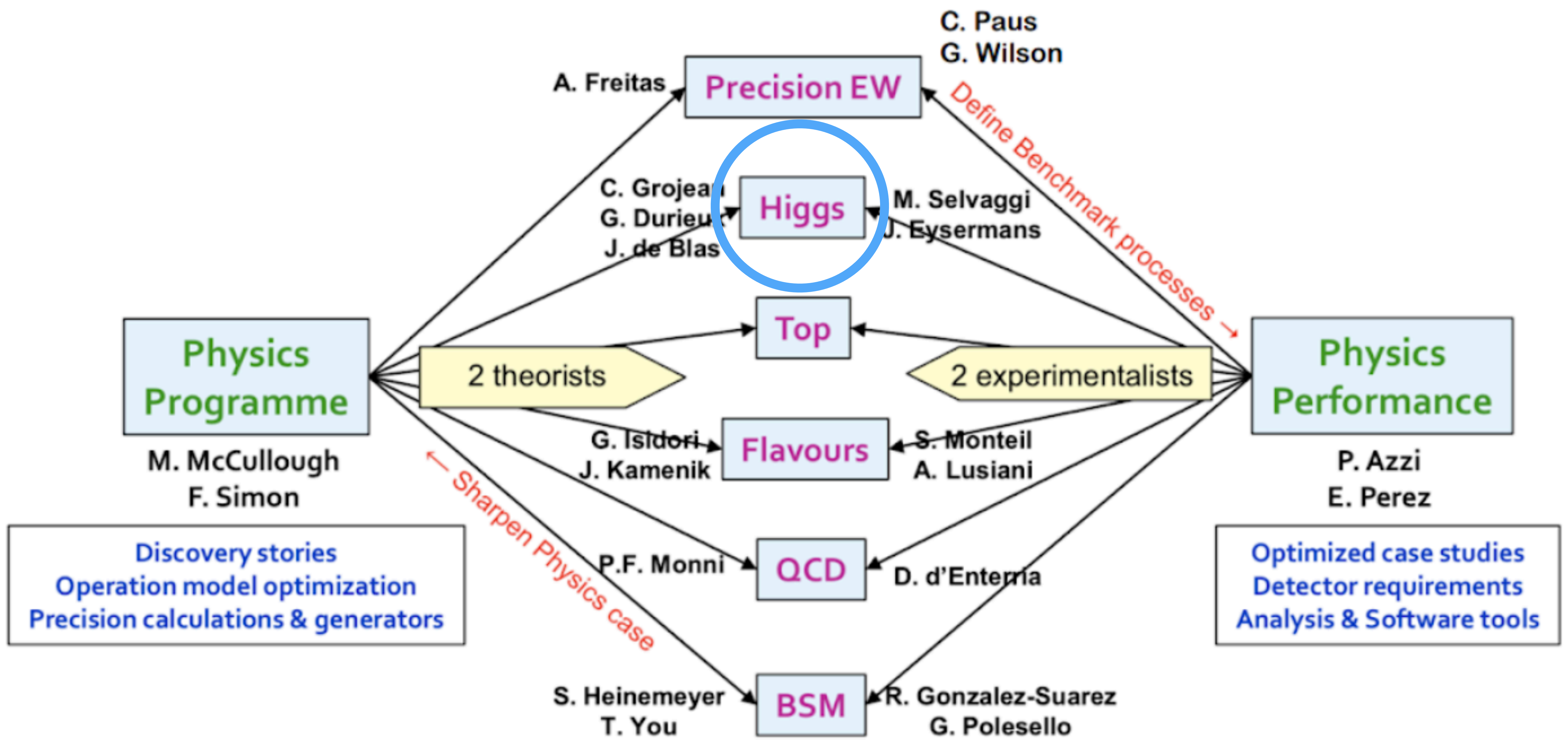
| | $L = 10\ ab^{-1}$ | $L = 3\ ab^{-1}$ |
|---|---|---|
| | $ZH = 2 \times 10^6$ | $ZH = 50 \times 10^5$ |
| | $VBF = 4 \times 10^4$ | $VBF = 10^5$ |

Note on systematic uncertainties

- integrated lumi ~ 0.01%
- tagging efficiency, BES < 1%
- TH < 1% (no PDFs, )

# Overview of Higgs analyses

- Intrinsic properties
  - mass
  - ZH cross section (decay mode independent)
  - width
- Higgs couplings
  - vector bosons
  - jets
    - bb/cc/gg/ss
  - self-coupling (FCC-ee/hh)
  - electron (production)
  - taus
  - rare (μμ/γγ/Zγ)
  - FCNCs




**Goal:** establish the detector requirements that maximise the Higgs physics potential

- as part of the FCC Feasibility Study, to be completed by the end of 2025
- Mid-term review of feasibility study in 2023

# Overview of (ongoing) Higgs analyses

- H→ hadrons
  - Z(ll) H (Marchiori - APC)
  - Z(vv)H (Del Vecchio, Gouskos, Marchiori, MS - CERN )
- Z → X H→ anything (recoil)
  - Z→ ll/jj :
    - xsec, mass (Eysermans, Bernardi, Li - MIT, Paris)
    - self-coupling (Salerno/Portales, Lemmon - LLR/Liverpool/Brookhaven )
- H→ invisible (Mehta, Rompotis - Liverpool)
- ee→ H (d'Enterria, Guntam - CERN/Hamburg)

# Overview of (new) Higgs analyses

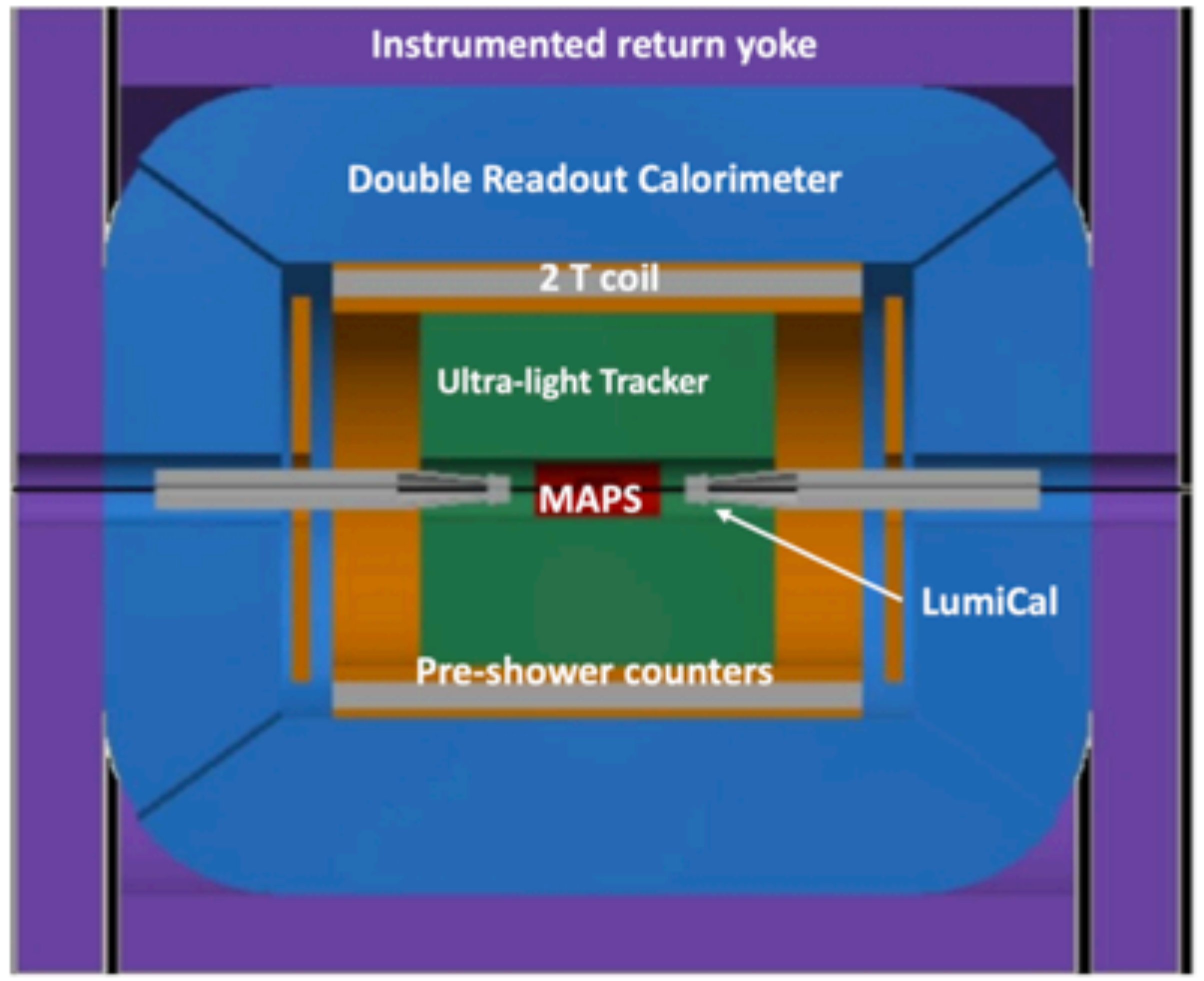
- H→ hadrons
  - Z(jj) H (Iakovidis - BNL)
- H→ ZZ* - width
  - llvvjj/vvjjjj (Nicolas Morange, Ines combe - IJClab)
  - 6j (Aman Desai)
- H→ ττ (Maria Cepeda, CIEMAT)
- H→ μμ,γγ (Siminiuc, Torres, Eysermans - MIT)

# Detector description and samples

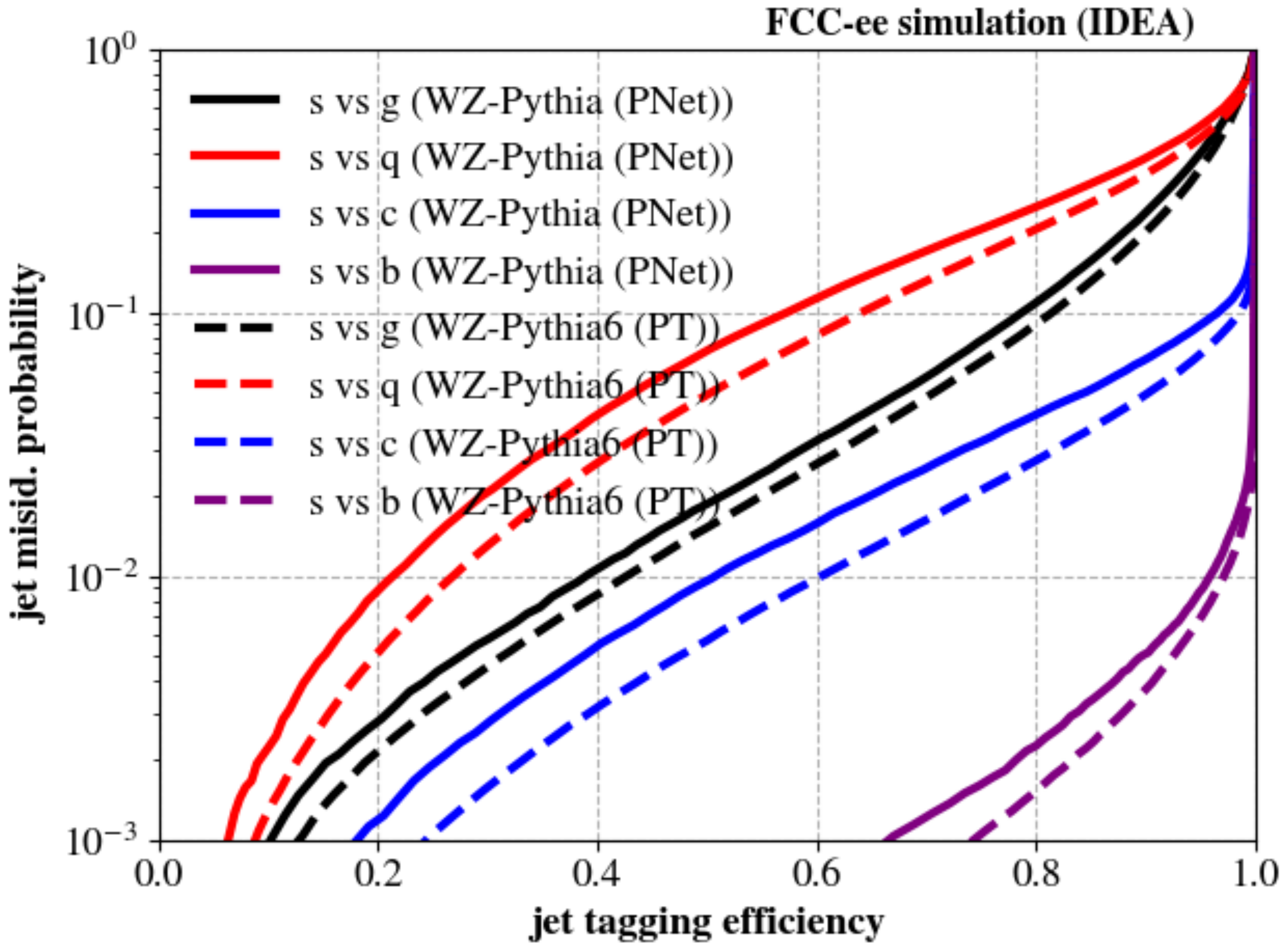
- Detector simulation baseline:
  - IDEA with Delphes
    - full track covariance reconstruction
    - particle ID (timing, charged energy loss)
    - jet tagging using Weaver/Particle NET
      - Flavors: g/b/c/s/light/tau

- Recent updates:
  - "Realistic" electron description
    - including brem recovery
  - smaller beampipe
  - ECAL crystal for better ele/photon performance

- Samples:
  - Wizard3+ Pythia6
  - Pythia8

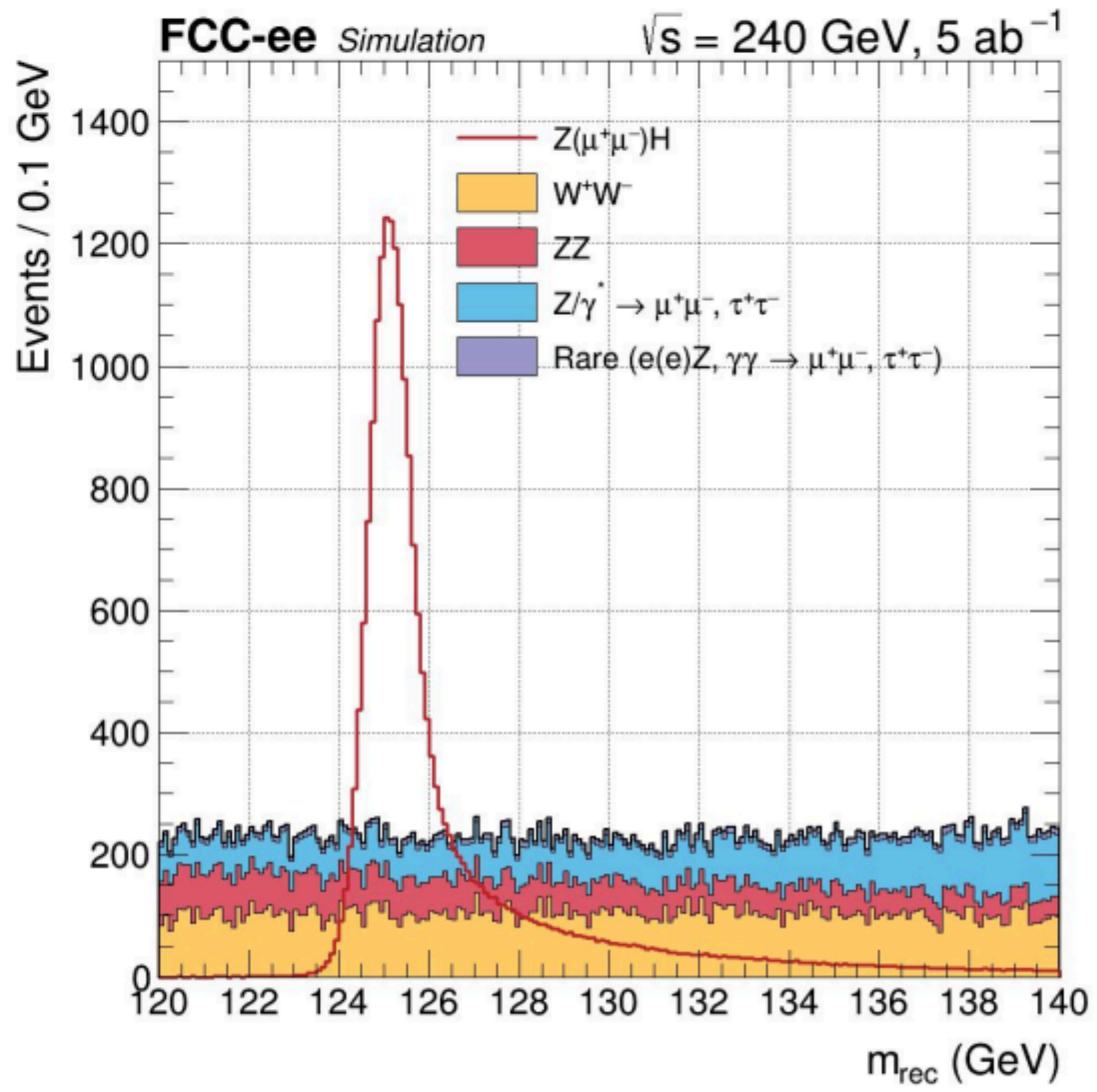


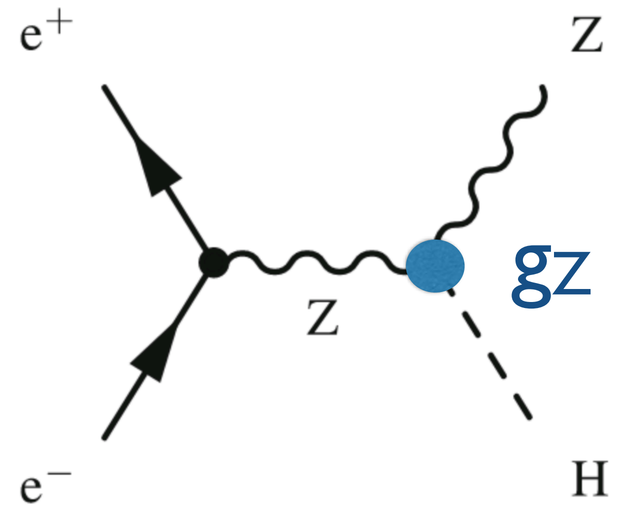

IDEA




http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/winter2023/Delphesevents_IDEA.php

# FCC-ee recoil method




Higgs recoil mass measurement → ZH production cross section:

- $10^6$ Higgs produced @ FCC-ee
  - rate ~ $\mathbf{g_Z}^2$ → $\delta g_Z/g_Z$ ~ 0.2 %
- Then measure ZH → ZZZ
  - rate ~ $\mathbf{g_Z}^4 / \mathbf{\Gamma_H}$ → $\delta\Gamma_H / \Gamma_H$ ~ 1 %
- Then measure ZH → ZXX
  - rate ~ $\mathbf{g_Z}^2 \mathbf{g_X}^2 / \mathbf{\Gamma_H}$ → $\delta g_X/g_X$ ~ 1 %

Precise knowledge of center of mass allows for:

- tag the Z by reconstructing pair of leptons
- reconstruct the the recoil mass

$$m^2_{\text{recoil}} = s - 2\sqrt{s}E_{\text{di-lepton}} + m^2_{\text{di-lepton}}$$

Provides absolute and **model independent** measurement of $g_Z$ coupling in e+e-

Bernardi, Li

# Z(ll)H cross-section measurement

## Goals:

- O(<%) on cross-section

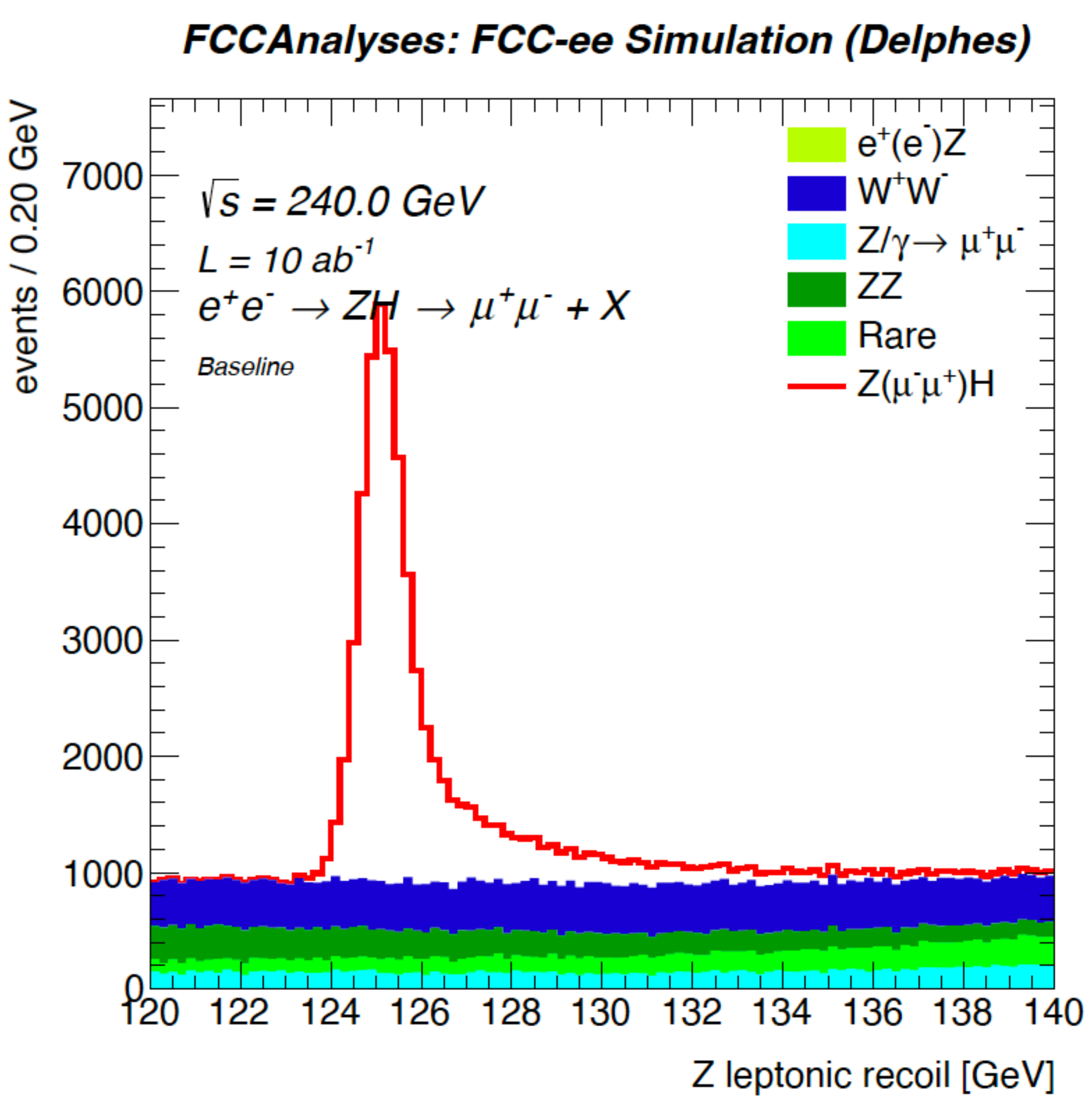
## Event selection:

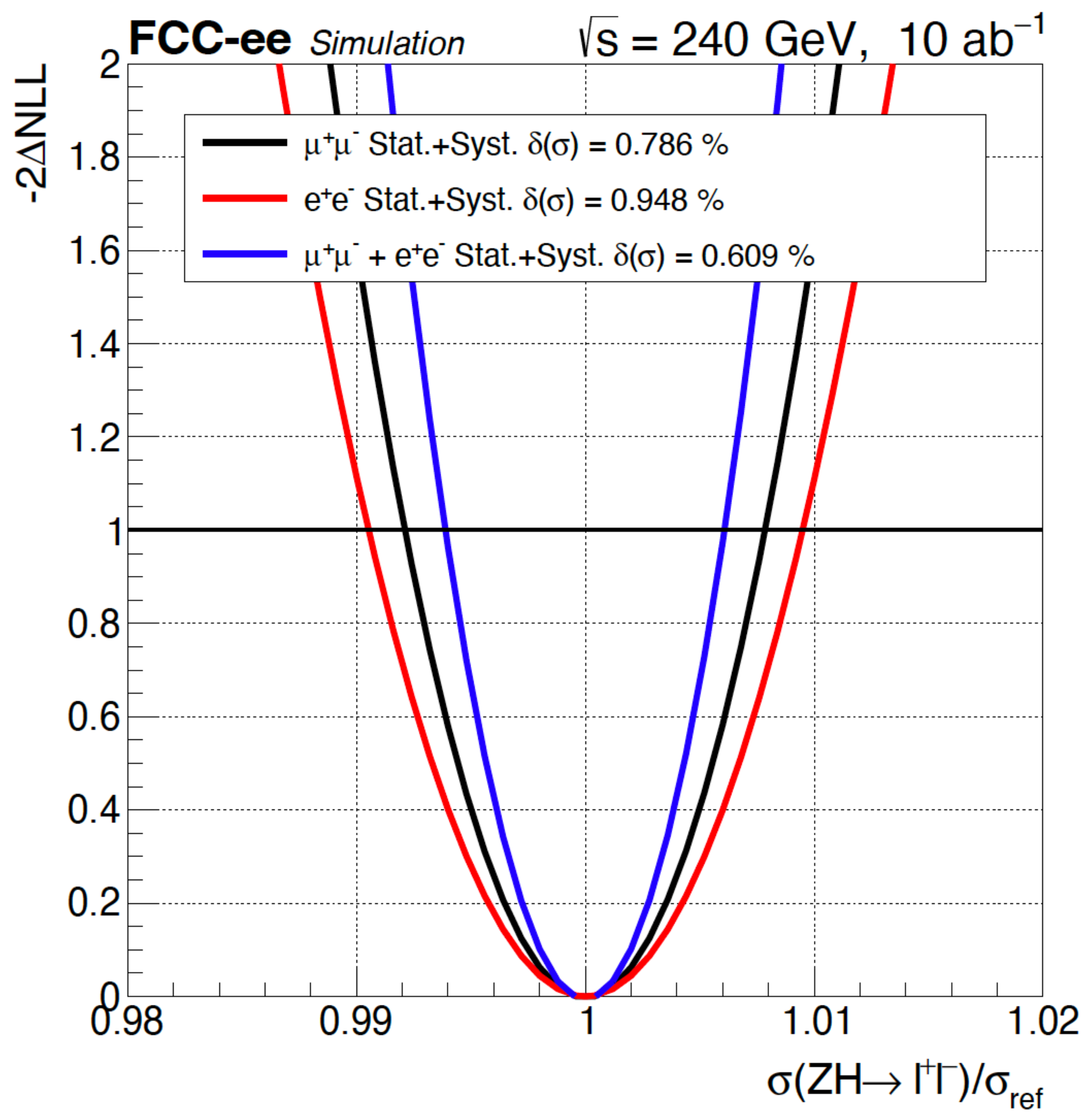
- at least 2 leptons
- tight $m_Z$ selection [86,96] GeV
- $p(\mu\mu) > 20,70$ GeV

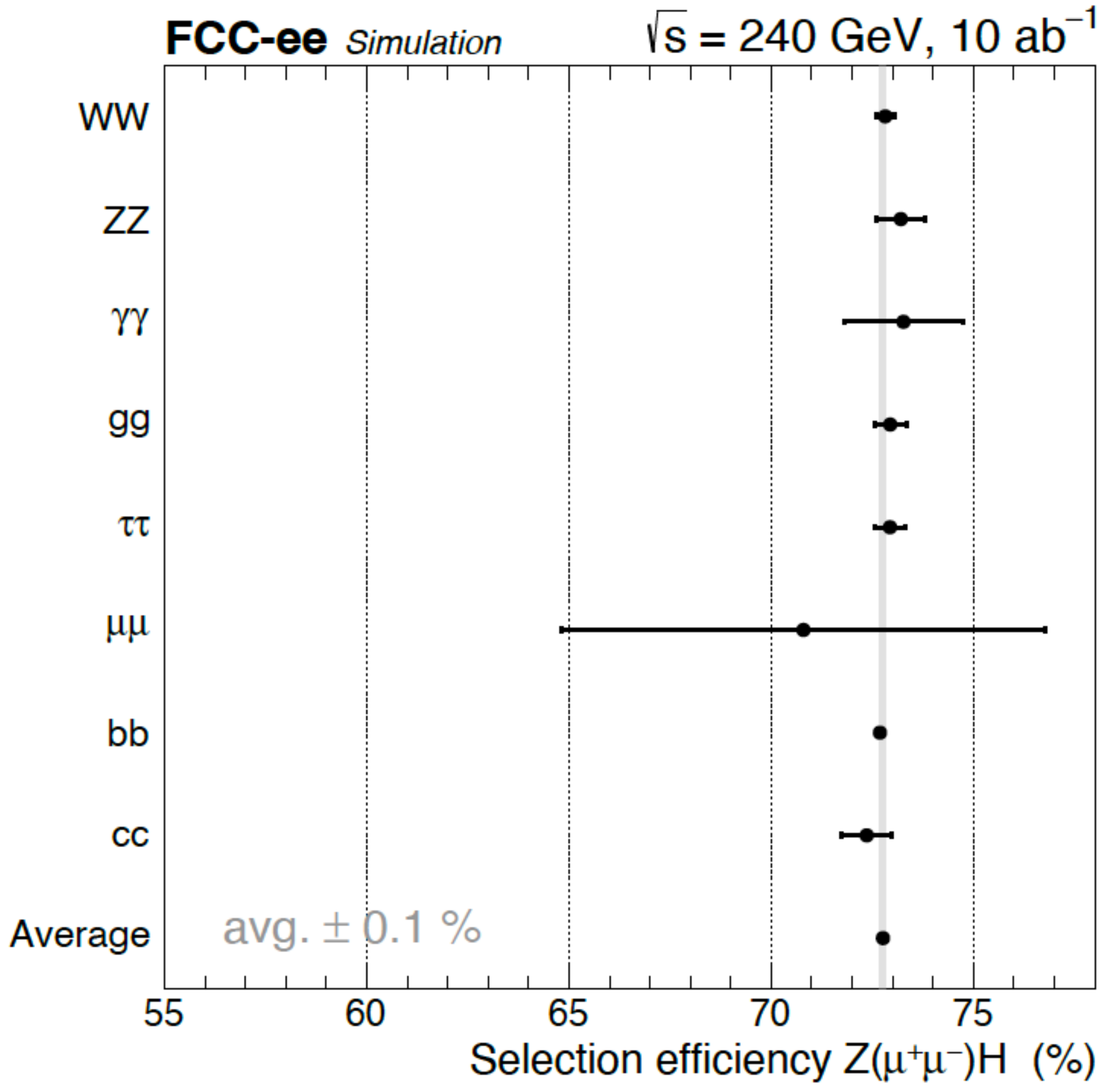
## Cross-section:

$\delta\sigma_{ZH} \sim 0.6\%$

- BDT to optimise selection in a model independent way



# Higgs mass measurement

Jan Eysermans

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

- Why measure Higgs mass:
  - input for the EW precision fit
  - O(10 MeV) need for permil precision of $g_Z$, $g_W$, $g_{Z\gamma}$
  - O($\Gamma_H$ = 4 MeV) to measure electron Yukawa

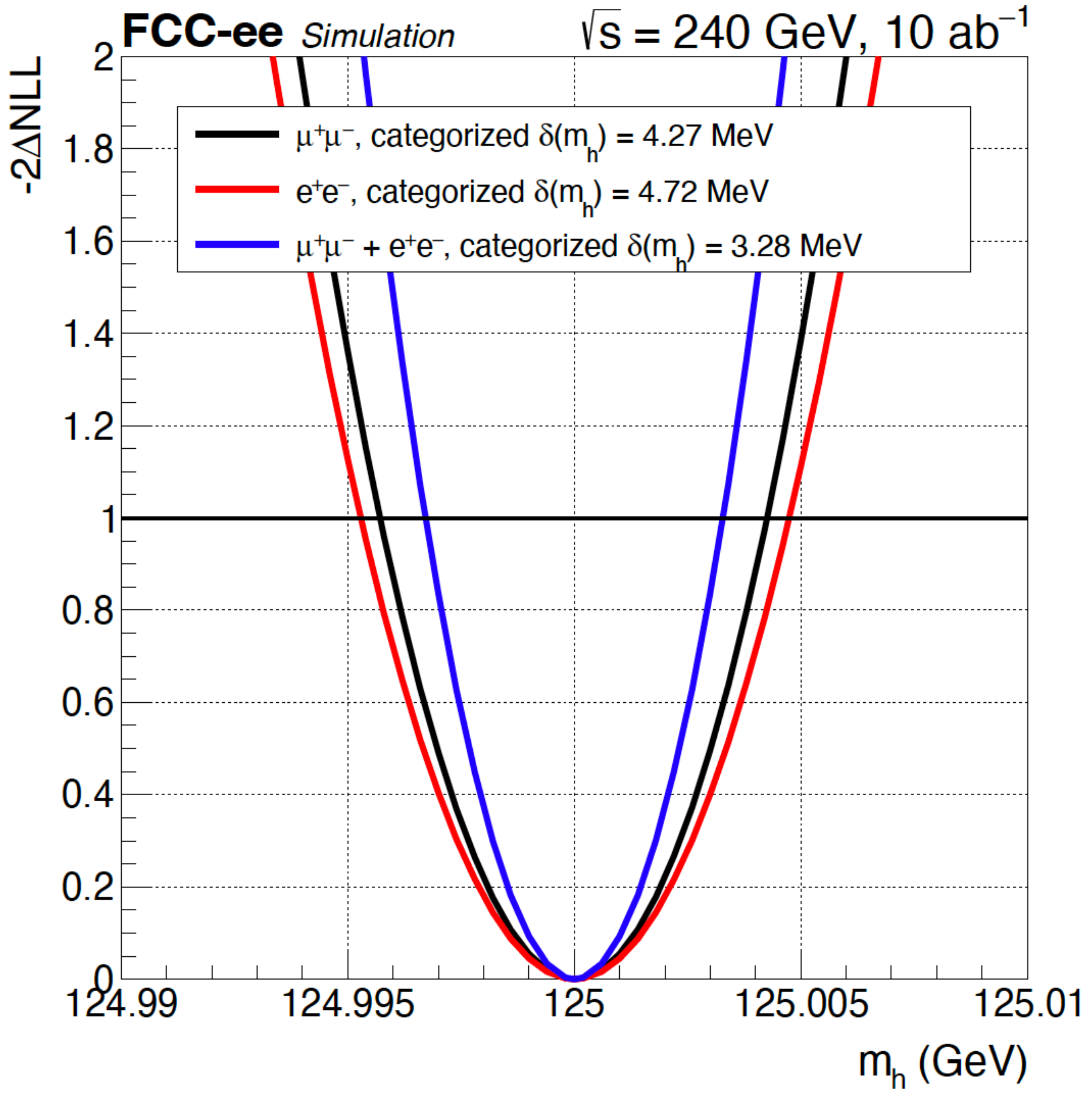
Event selection (common with sec):

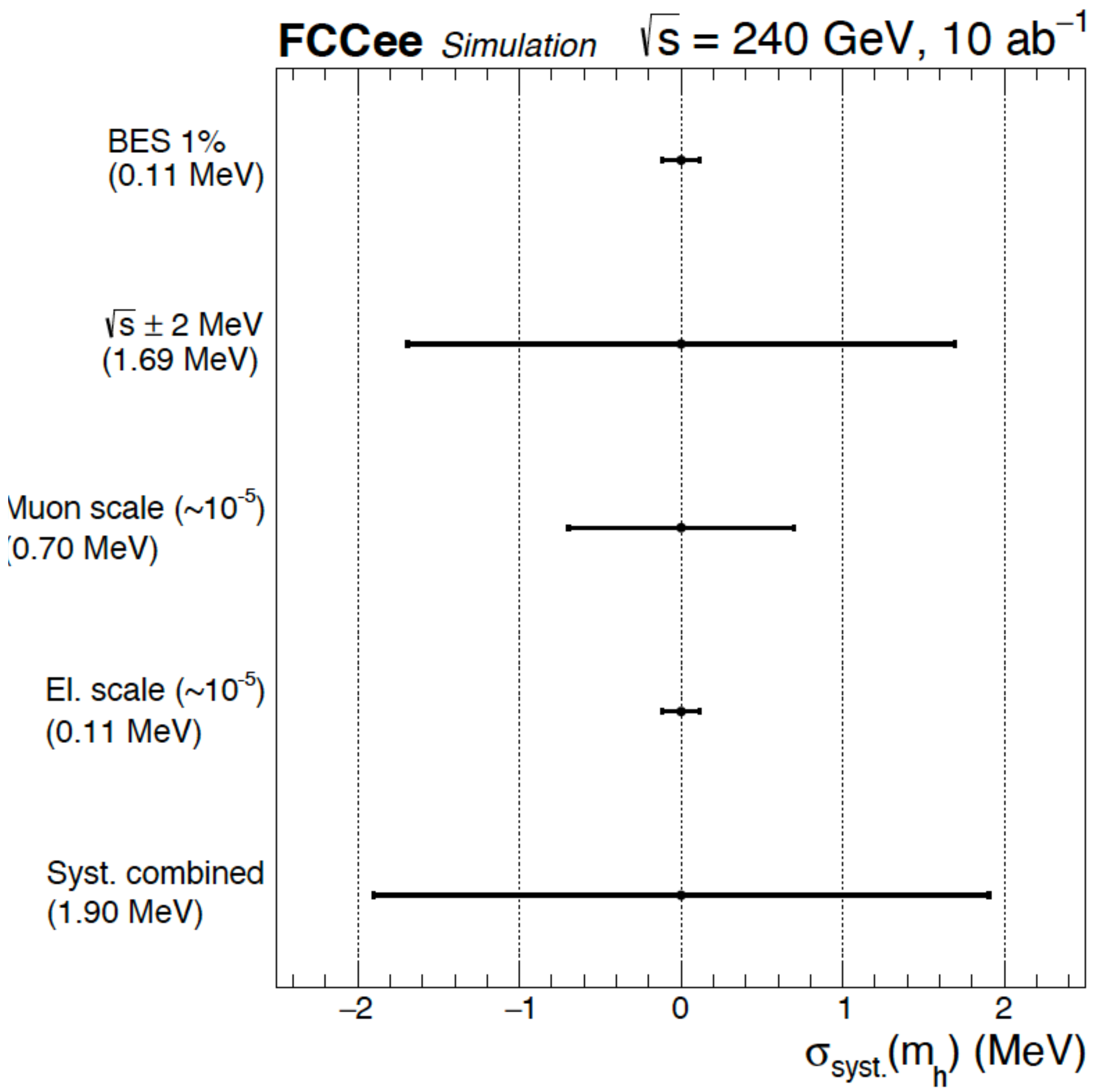
- at least 2 leptons
- tight $m_Z$ selection [86,96] GeV
- p(μμ) > 20,70 GeV
- measurement differential in θ

Systematics:

- Beam energy spread ~ **2e-03 (~200 MeV)**
- C.O.M energy ~ **2e-05 (~2 MeV)**
- Lepton scale ~ **2e-05**
- ISR ~ t.b.d

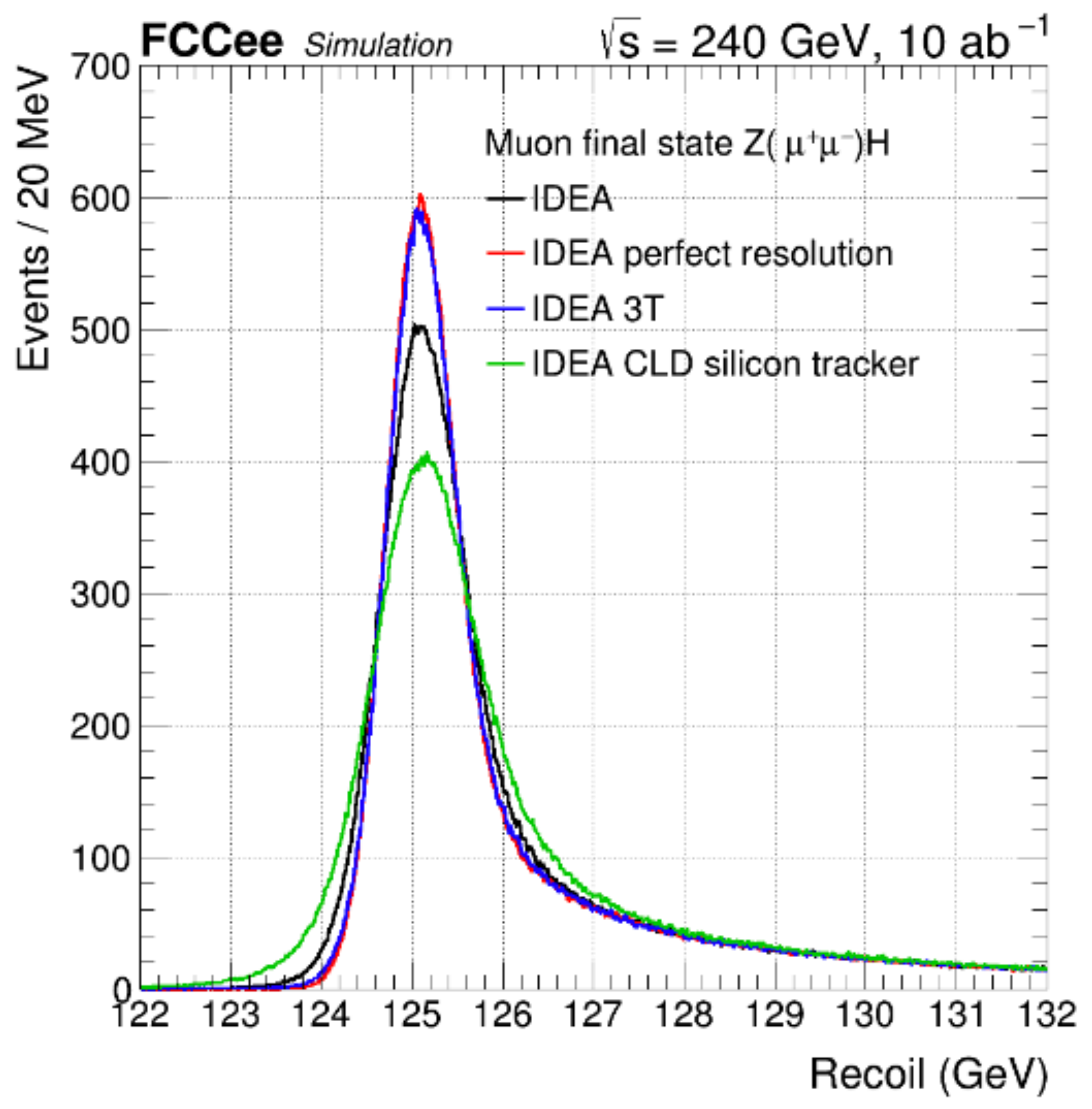
in situ from ee→ffɣ events

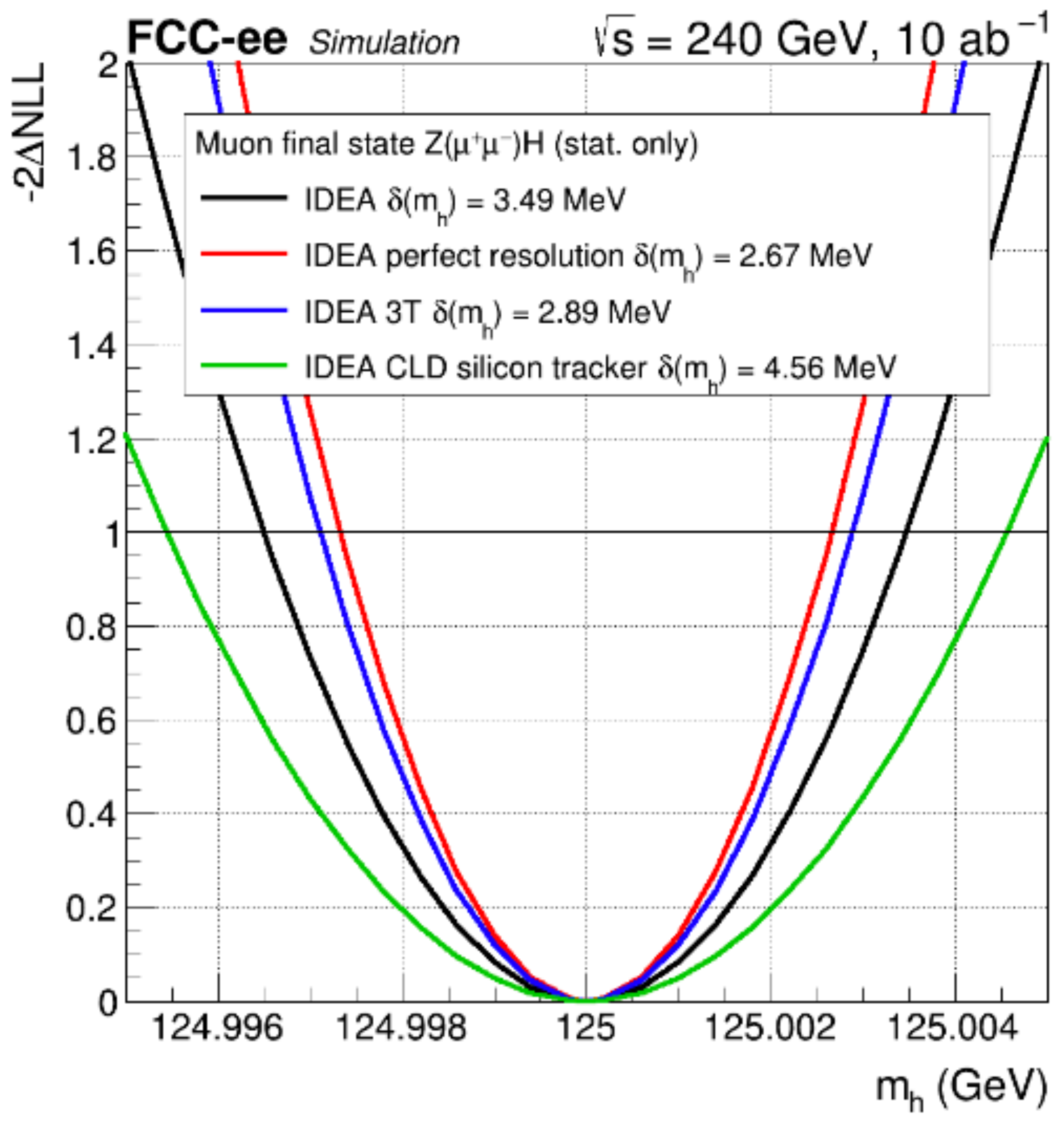


# Higgs mass measurement (detector sensitivity)

Jan Eysermans




**using μμ channel**

| tracking system | $\Delta m_H$ (MeV) stat.only | $\Delta m_H$ (MeV) stat + syst |
|---|---|---|
| **IDEA 2T** | **3.49** | **4.27** |
| **Perfect** | **2.67** | **3.44** |
| **IDEA 3T** | **2.89** | **3.97** |
| **CLD 2T** | **4.56** | **5.32** |

~150 MeV
in ATLAS/CMS

- sensitivity dominated by the Z(μμ) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if > beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
  - multiple-scattering limit < BES
    - for CLD ~ 30% above
      - **transparent** tracker is key

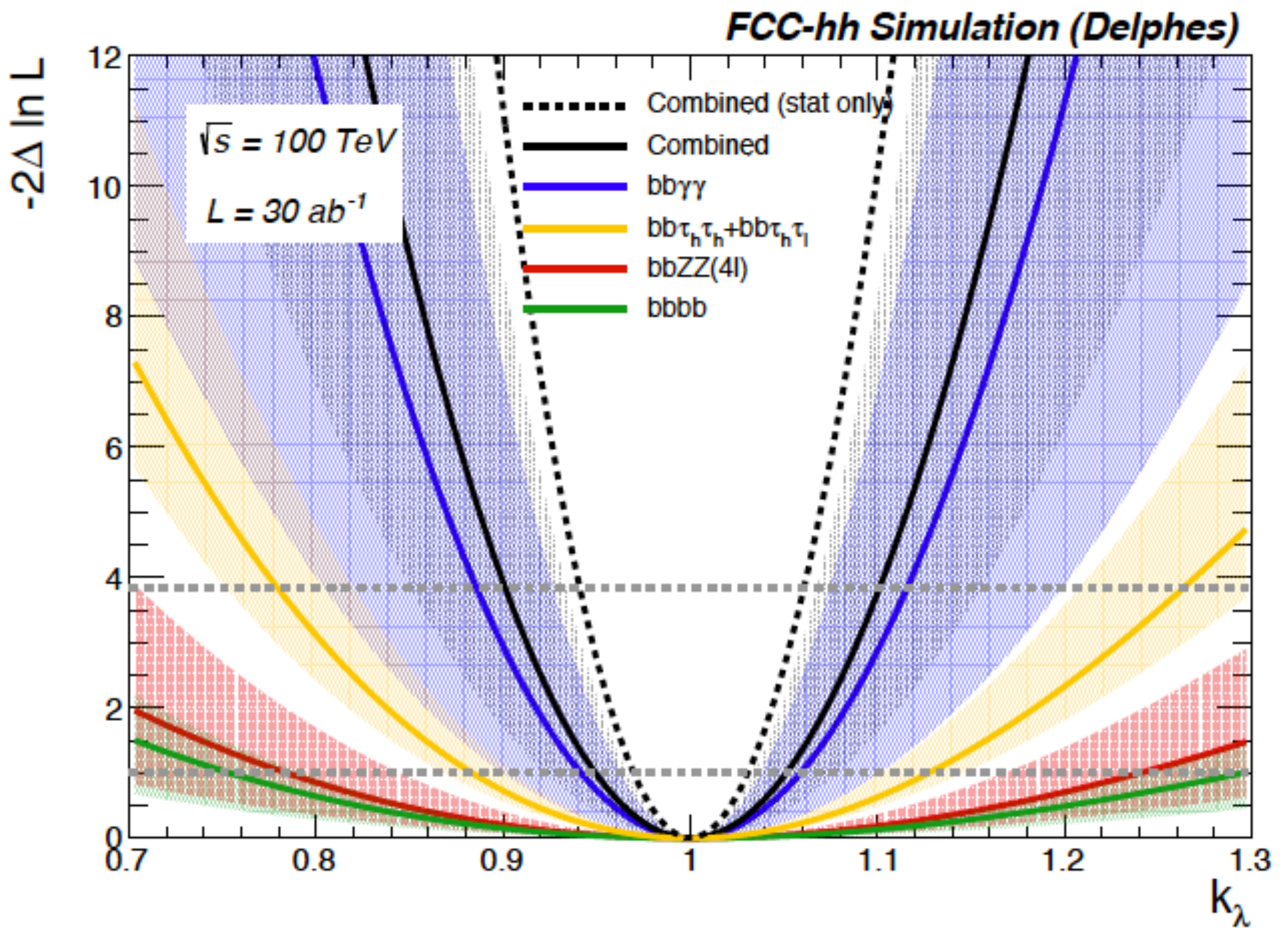
| **Fit configuration** | $\mu^+\mu^-$ channel | $e^+e^-$ channel | combination |
|---|---|---|---|
| Nominal | 3.49 (4.27) | 4.38 (4.72) | 2.67 (3.28) |
| Inclusive | 4.11 (4.79) | 5.26 (5.73) | 3.19 (3.89) |
| Degradation electron resolution (*) | 3.49 (4.27) | 5.09 (5.70) | 2.82 (3.66) |
| Magnetic field 3T | 2.89 (3.79) | 3.59 (4.38) | 2.20 (3.27) |
| CLD 2T (silicon tracker) | 4.56 (5.32) | 4.93 (5.48) | 3.26 (3.99) |
| BES 6% uncertainty | 3.49 (4.35) | 4.38 (5.00) | 2.67 (3.42) |
| Disable BES | 1.92 (3.15) | 2.52 (3.46) | 1.50 (2.70) |
| Ideal resolution | 2.67 (3.44) | 3.29 (3.94) | 2.02 (2.96) |
| Freeze backgrounds | 3.49 (4.27) | 4.38 (4.72) | 2.67 (3.27) |
| Remove backgrounds | 2.86 (3.69) | 3.26 (3.47) | 2.11 (2.64) |

# Higgs self-coupling

Salerno, Portales

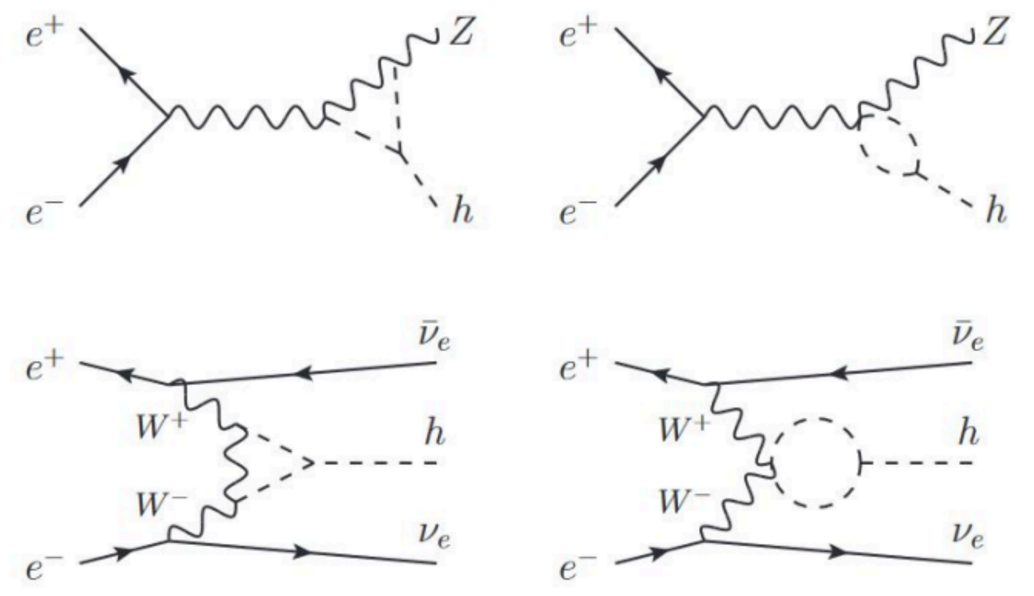
%-level precision only at the FCC-hh

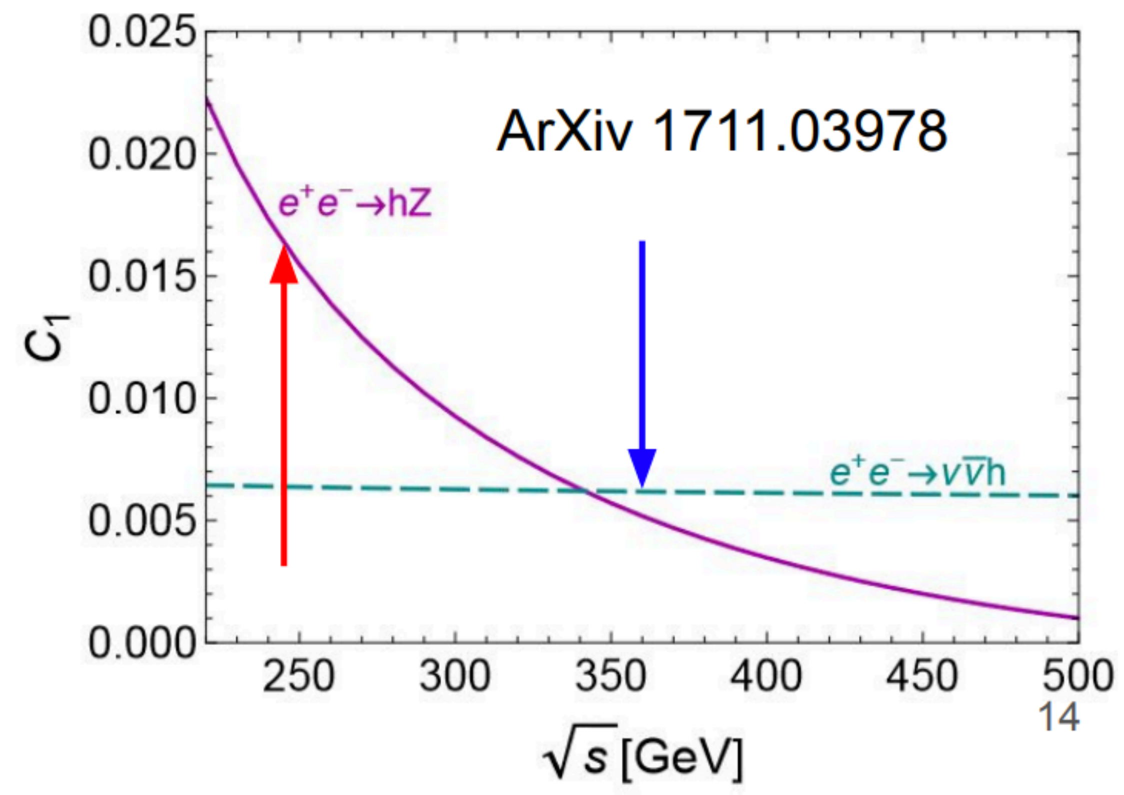
| @68% CL | scenario I | scenario II | scenario III |
|---|---|---|---|
| bbγγ | 3.8 | 5.9 | 10.0 |
| bbττ | 9.8 | 12.2 | 13.8 |
| bbbb | 22.3 | 27.1 | 32.0 |
| comb. | 3.4 | 5.1 | 7.8 |



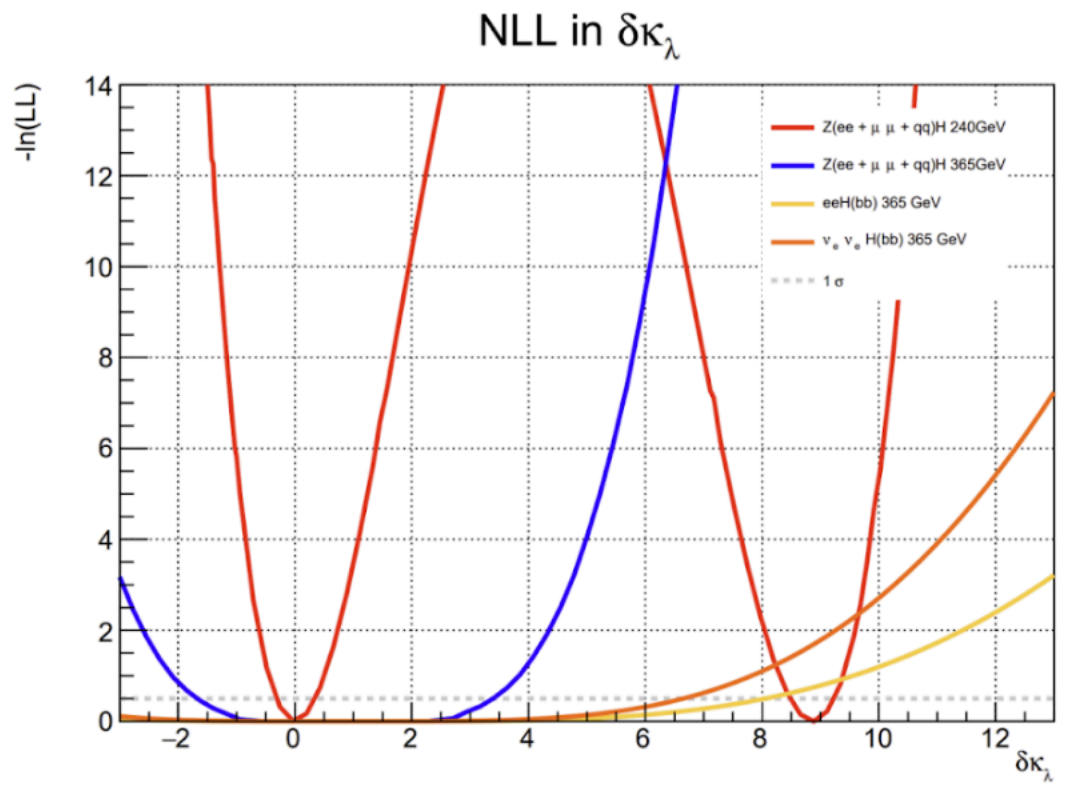

New effort started (new channel/extended parameter space/ revisited detector performance)

FCC-ee:
from radiative corrections to ZH/VBF single H production
(√s=240, 365 GeV)





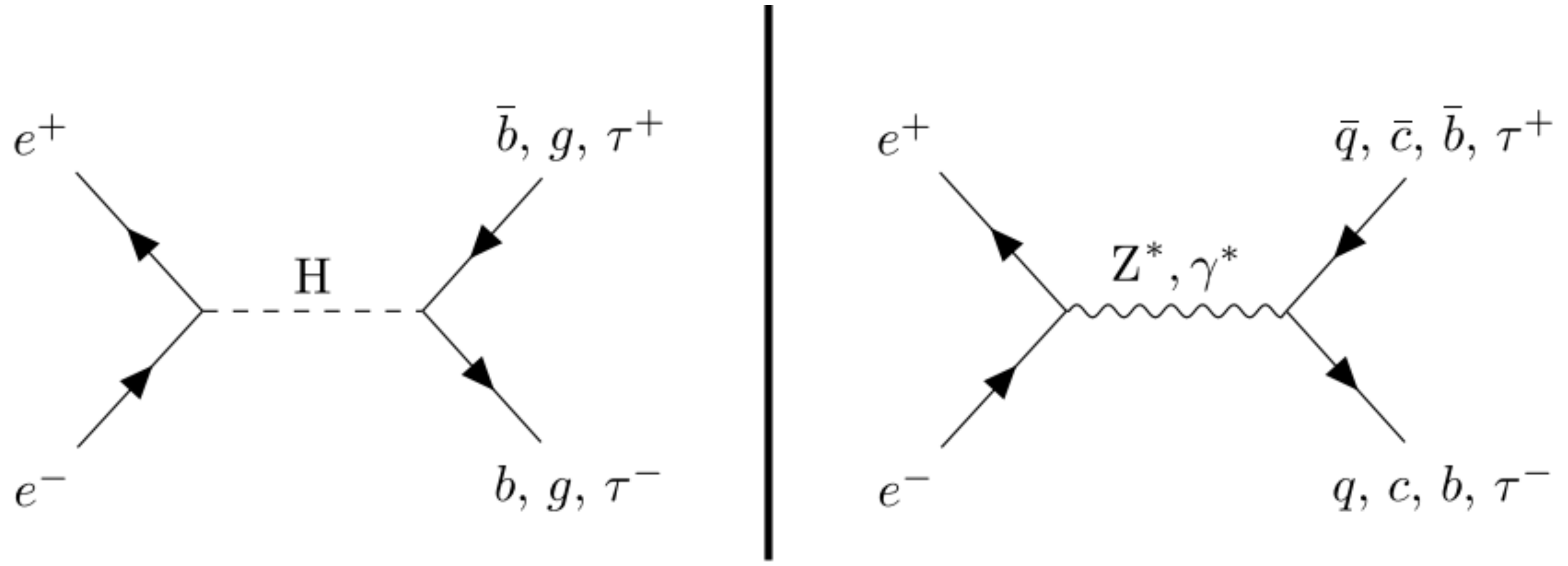

experimental analysis

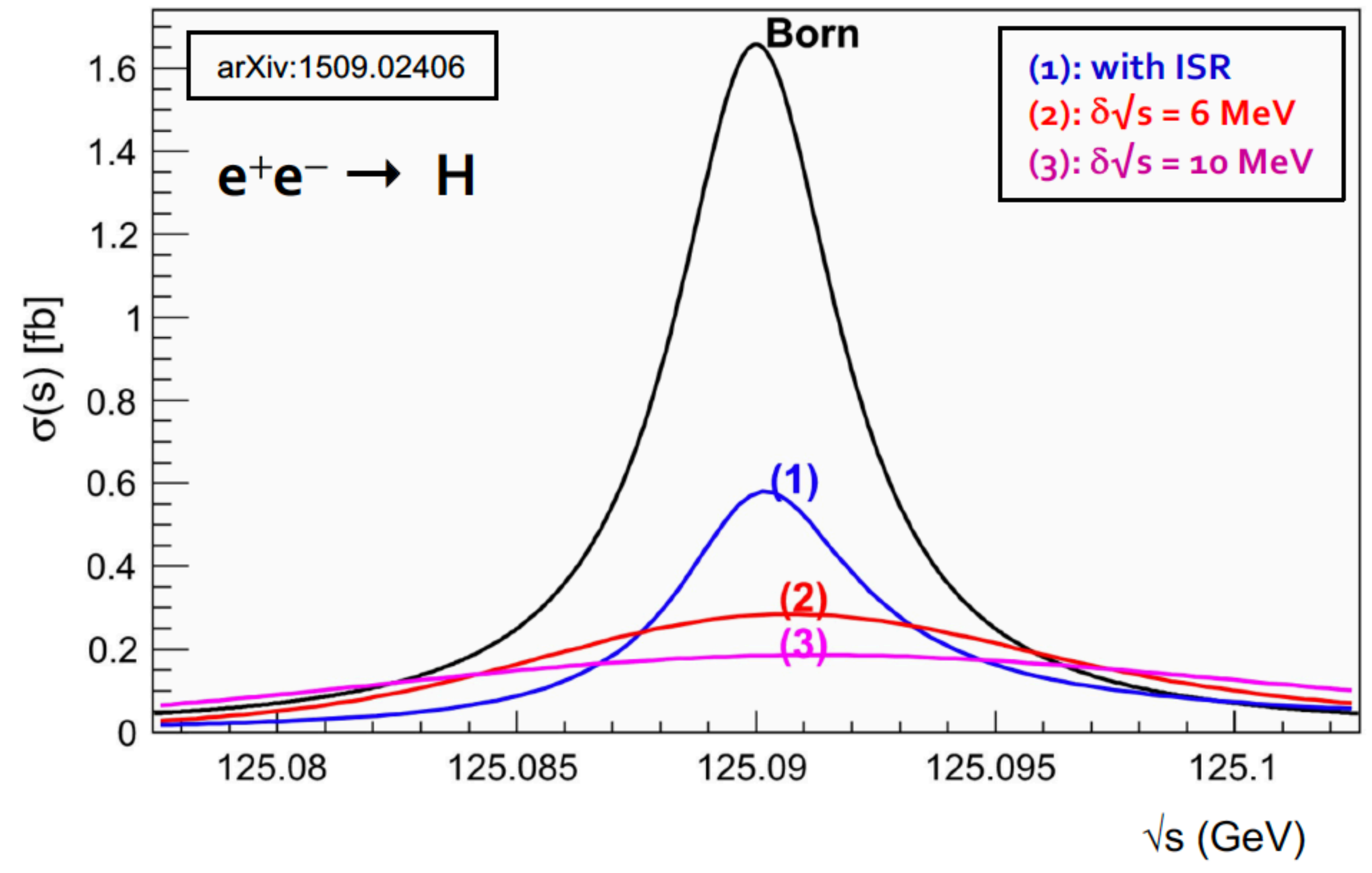



- state of the art fit to self-coupling precision:
  - 19% κλ alone vs 33% full (EFT projected) with 2IPs
  - 14% κλ alone vs 24% full (EFT projected) with 4IPs

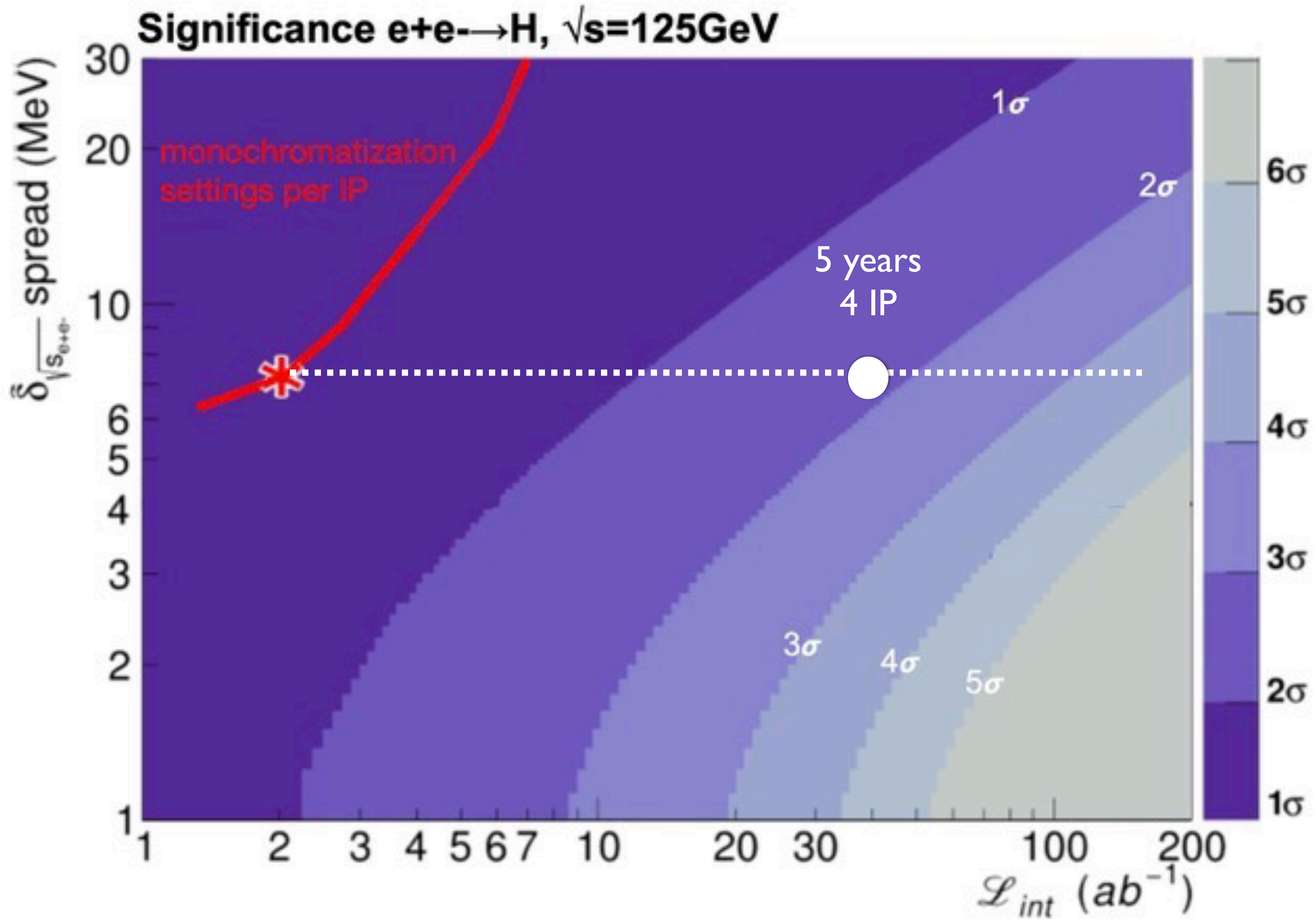
# Electron Yukawa

D'Enterria



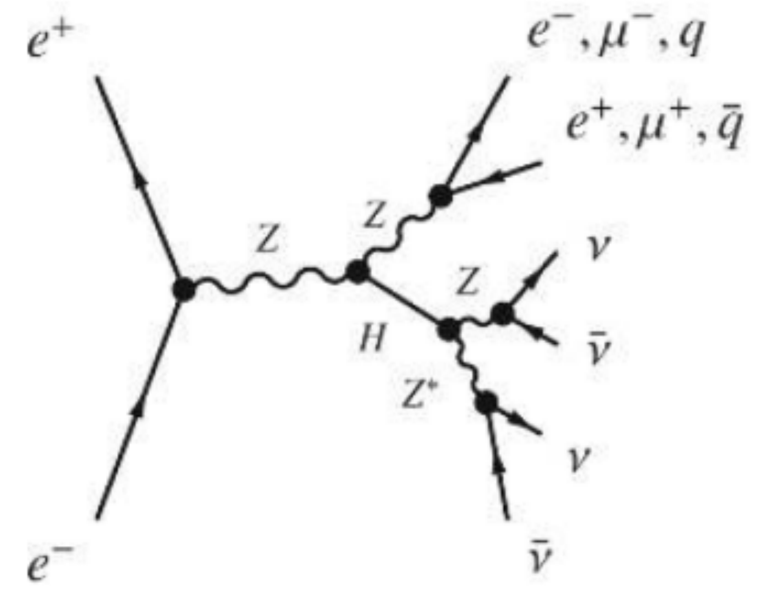

- s-channel production with beam mono-chromatisation at $\sqrt{s}$ = 125 GeV
  - ISR+FSR leads to 40% + with beam spread ~ $\Gamma_H$ another 45% ($\sigma$ ~ 280 $ab^{-1}$)
    - plus potentially uncertainty on the Higgs mass
    - can hope for ~ 2σ with 5 years and 4 IPs
      - potentially improve with exclusive ee→gg(cc)

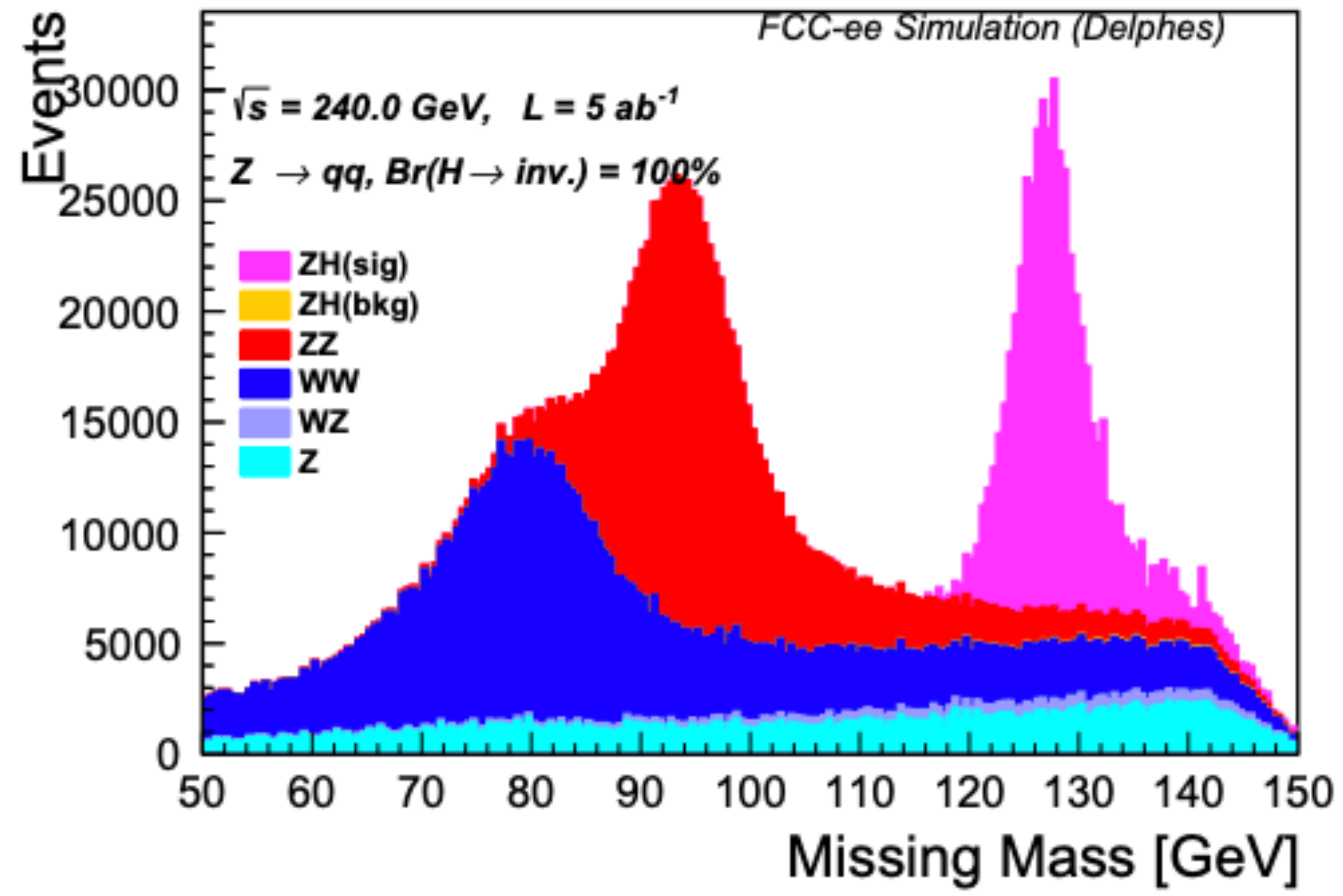



**effort has re-started using HWW decay mode**

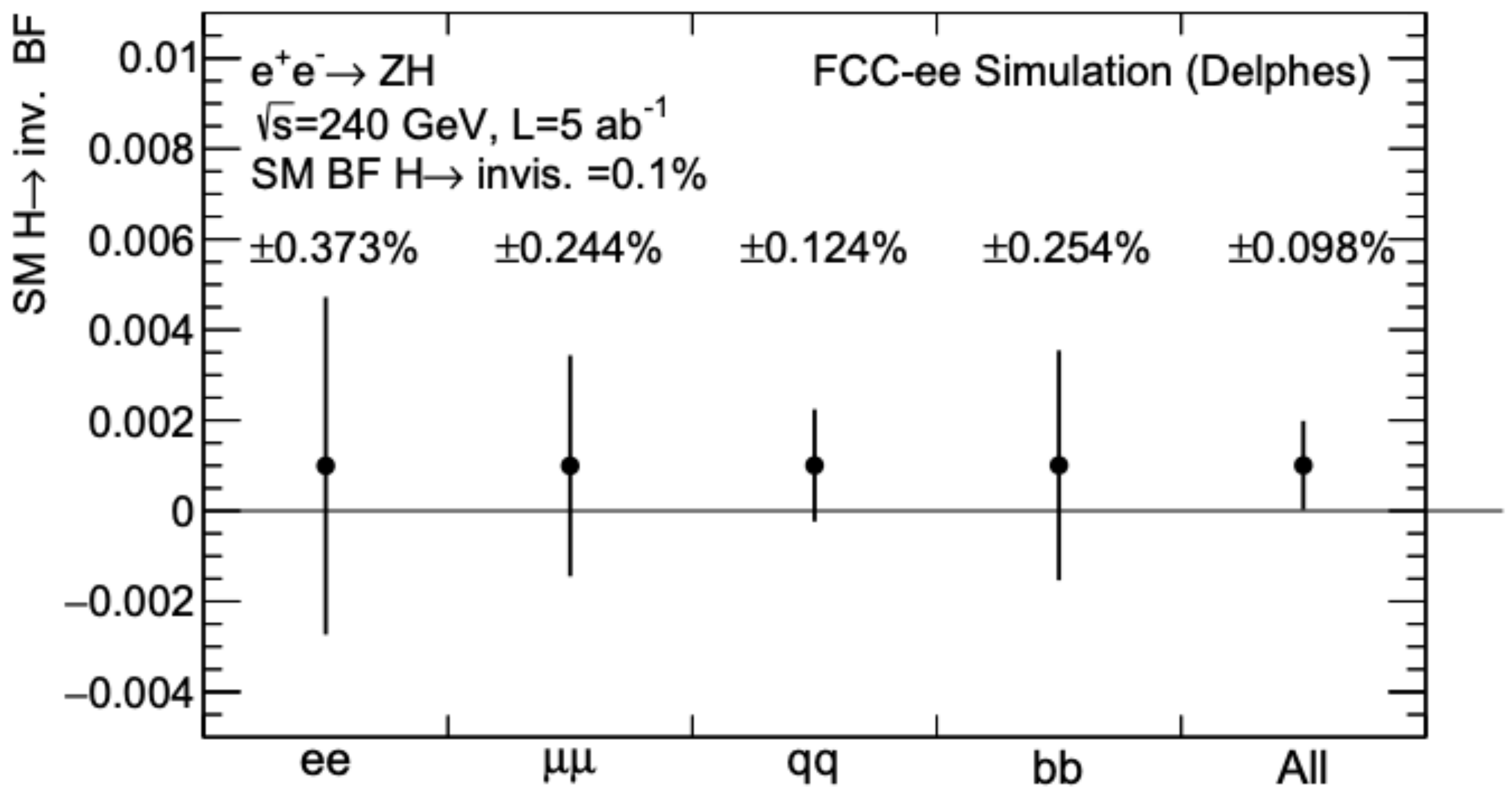
# Higgs to invisible

Mehta, Rompotis




- Higgs could be a portal to dark matter or other new physics
- In the SM B(H→inv) ~ $10^{-3}$
- Use recoil method to reconstruct the Higgs
  - potential to improve 1 order of magnitude compared to LHC

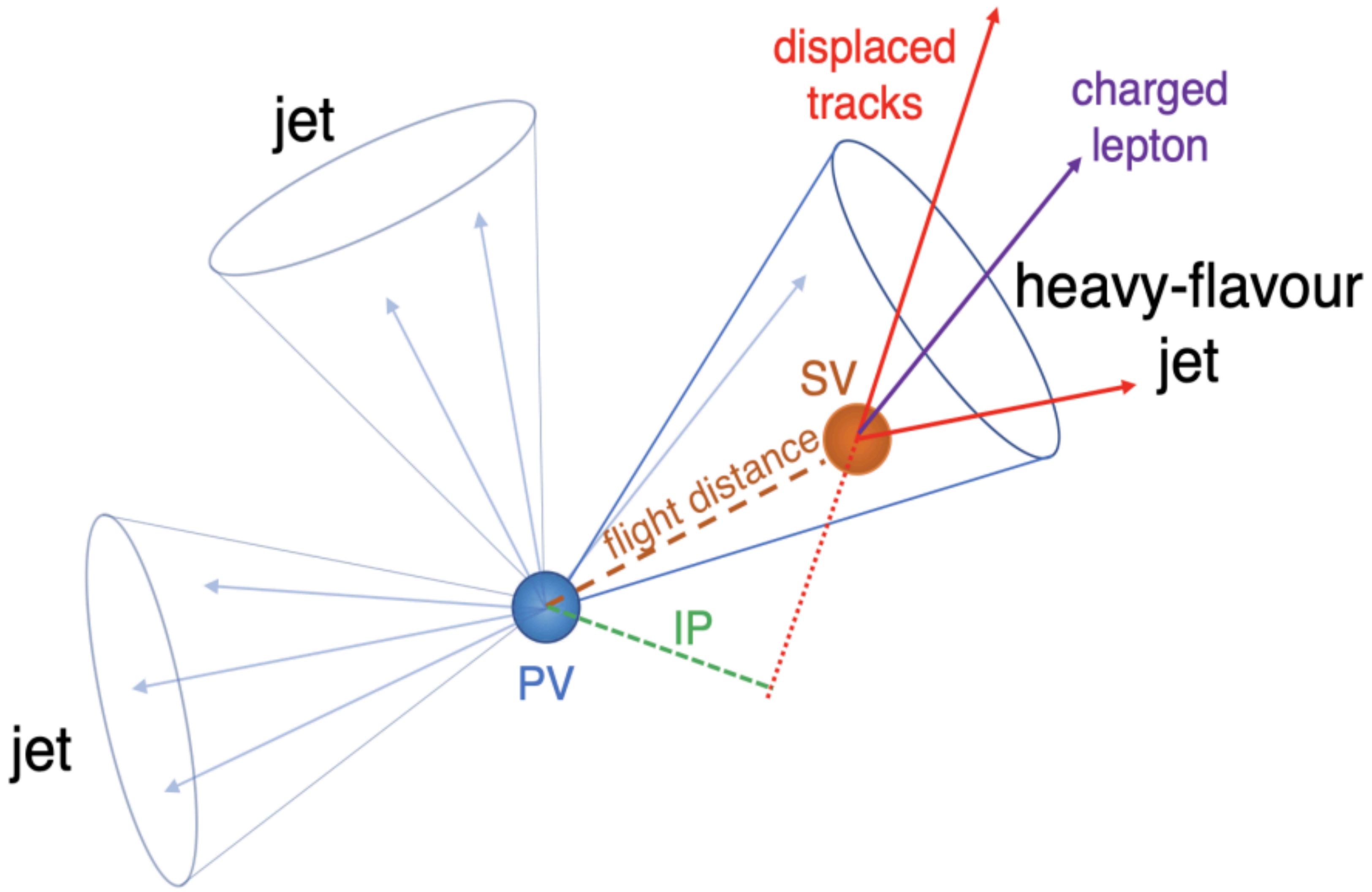



- Event selection:
  - Split events into exactly 2e, 2μ and 0 e+μ (bb/qq)
  - Reconstruct Z from 2 leptons or $M_{vis}$
  - Reconstruct $M_{miss}$ from all visible particles
  - Use distribution of $M_{miss}$ in likelihood fit

~ 100% sensitivity on SM BR(H→inv)

# Flavor tagging

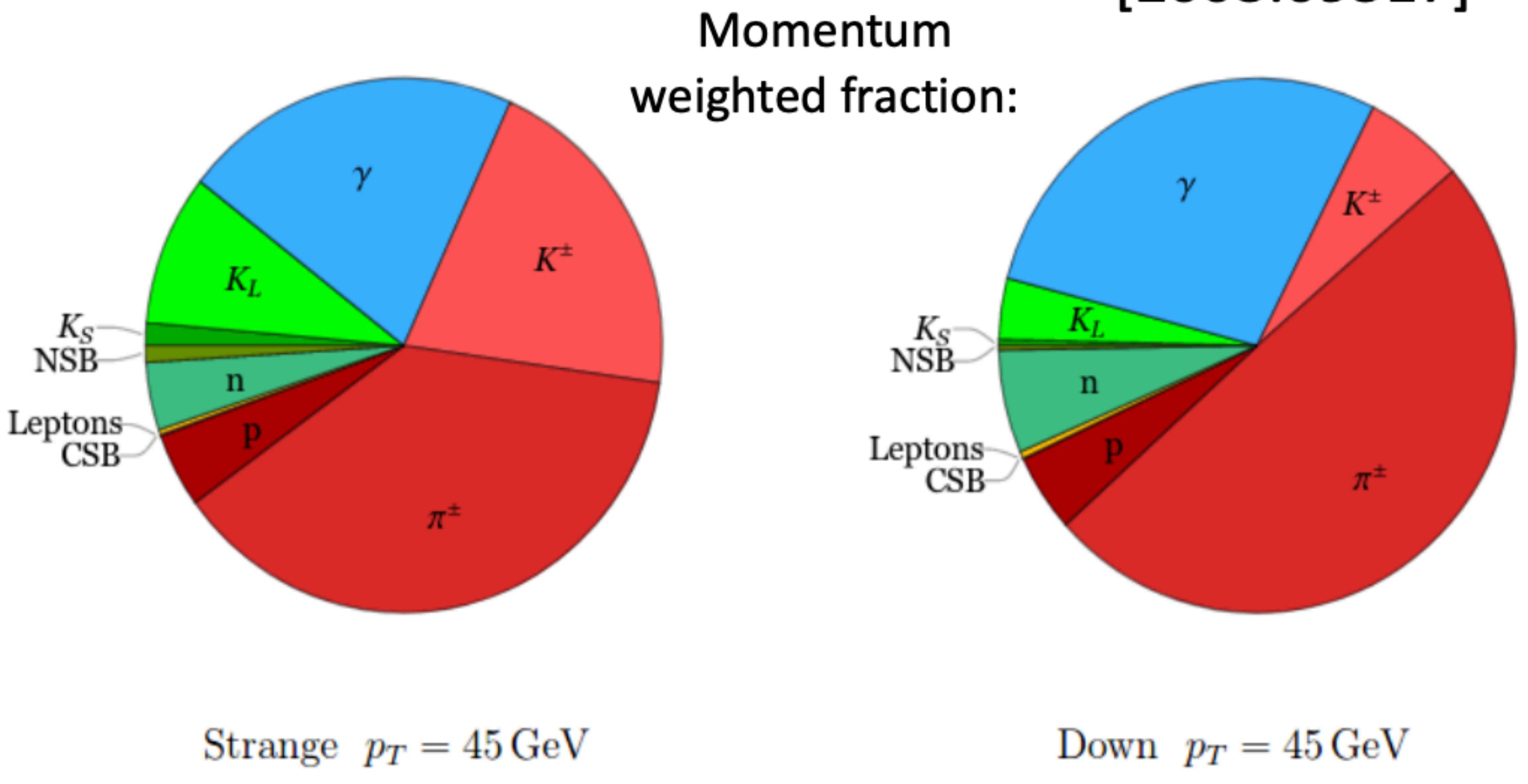
**bottom/charm-tagging**




- Large lifetime
- Displaced vertices/tracks
- Large track multiplicity
- non-isolated e/μ

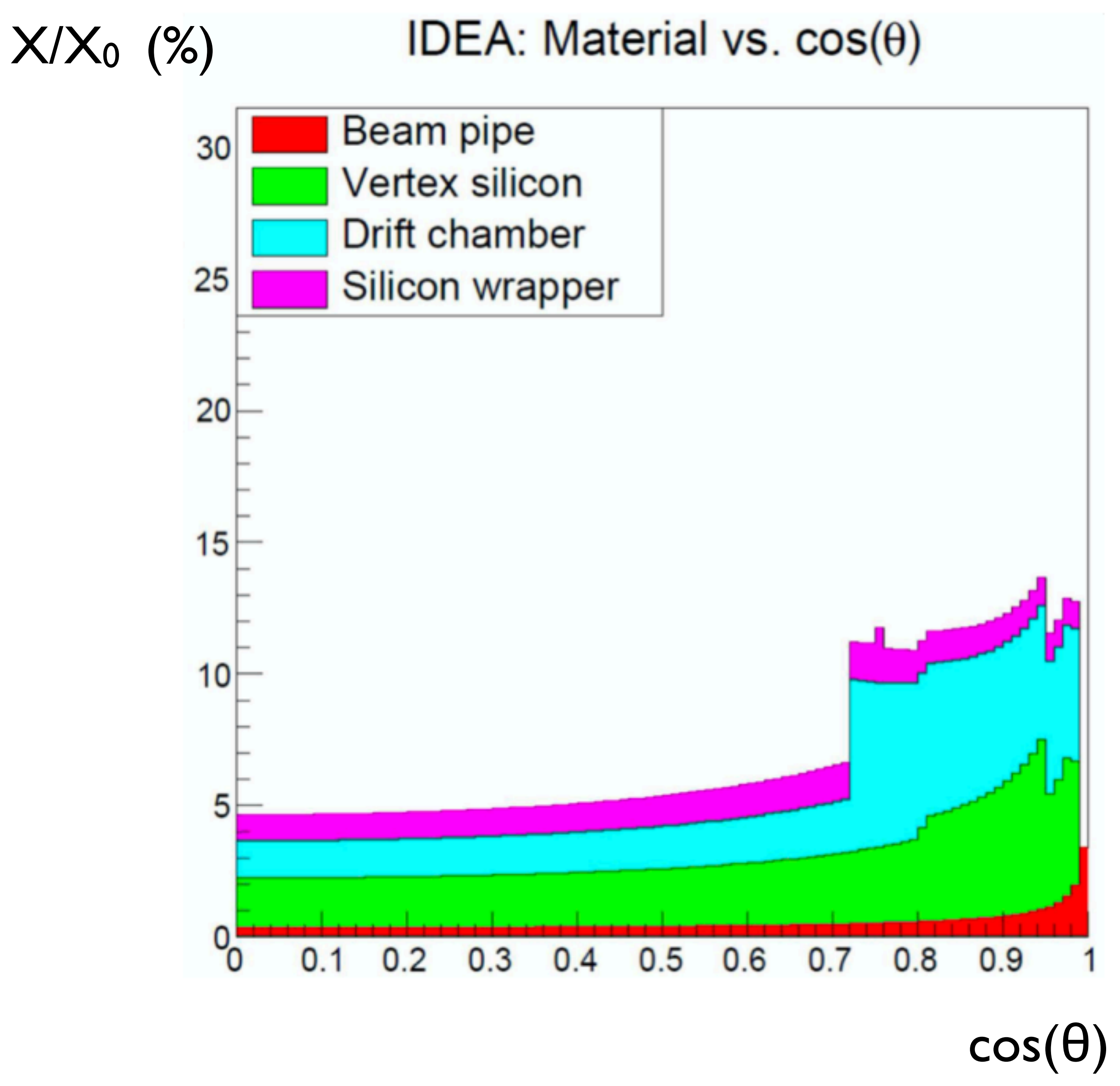
**strange-tagging**

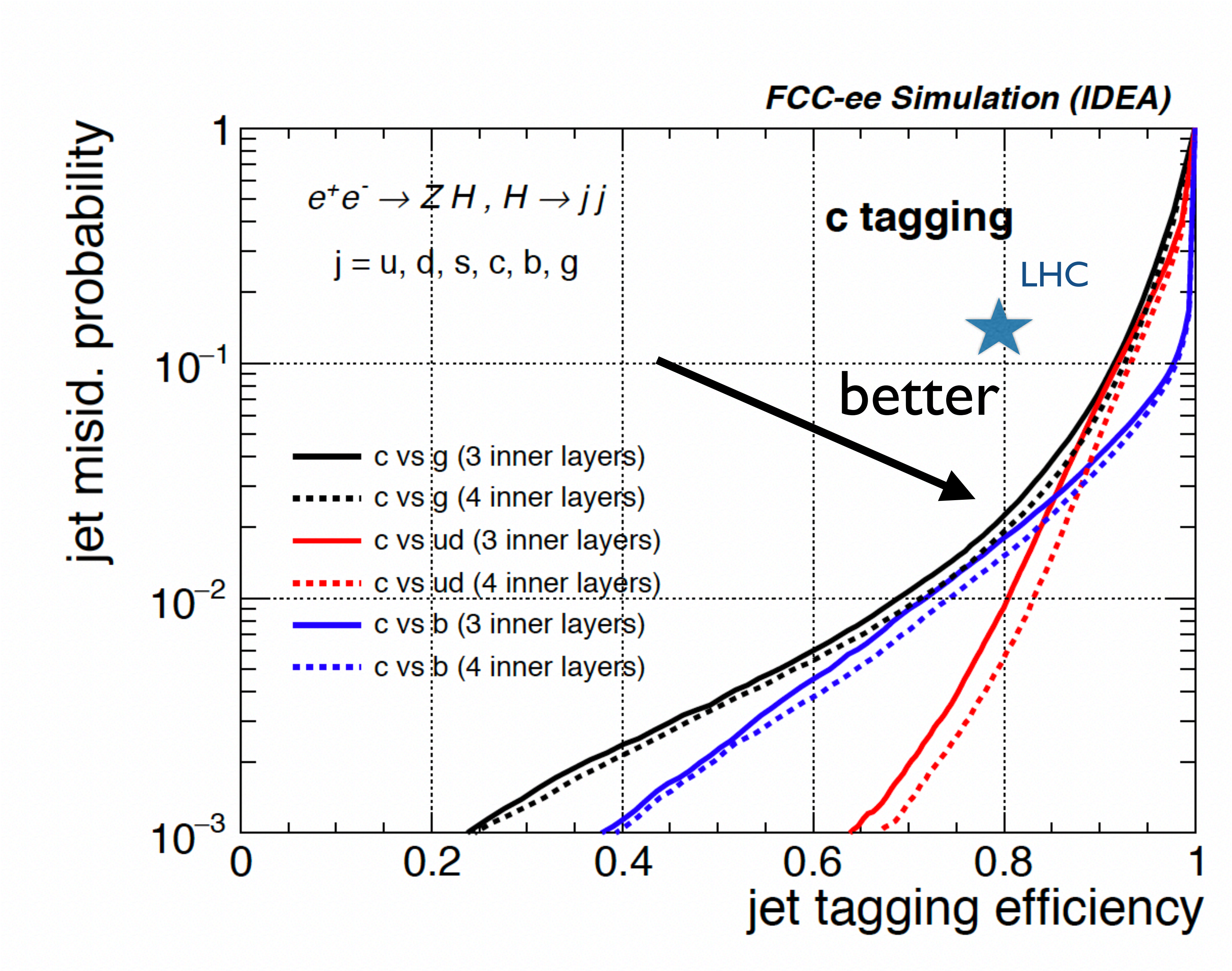
[2003.09517]

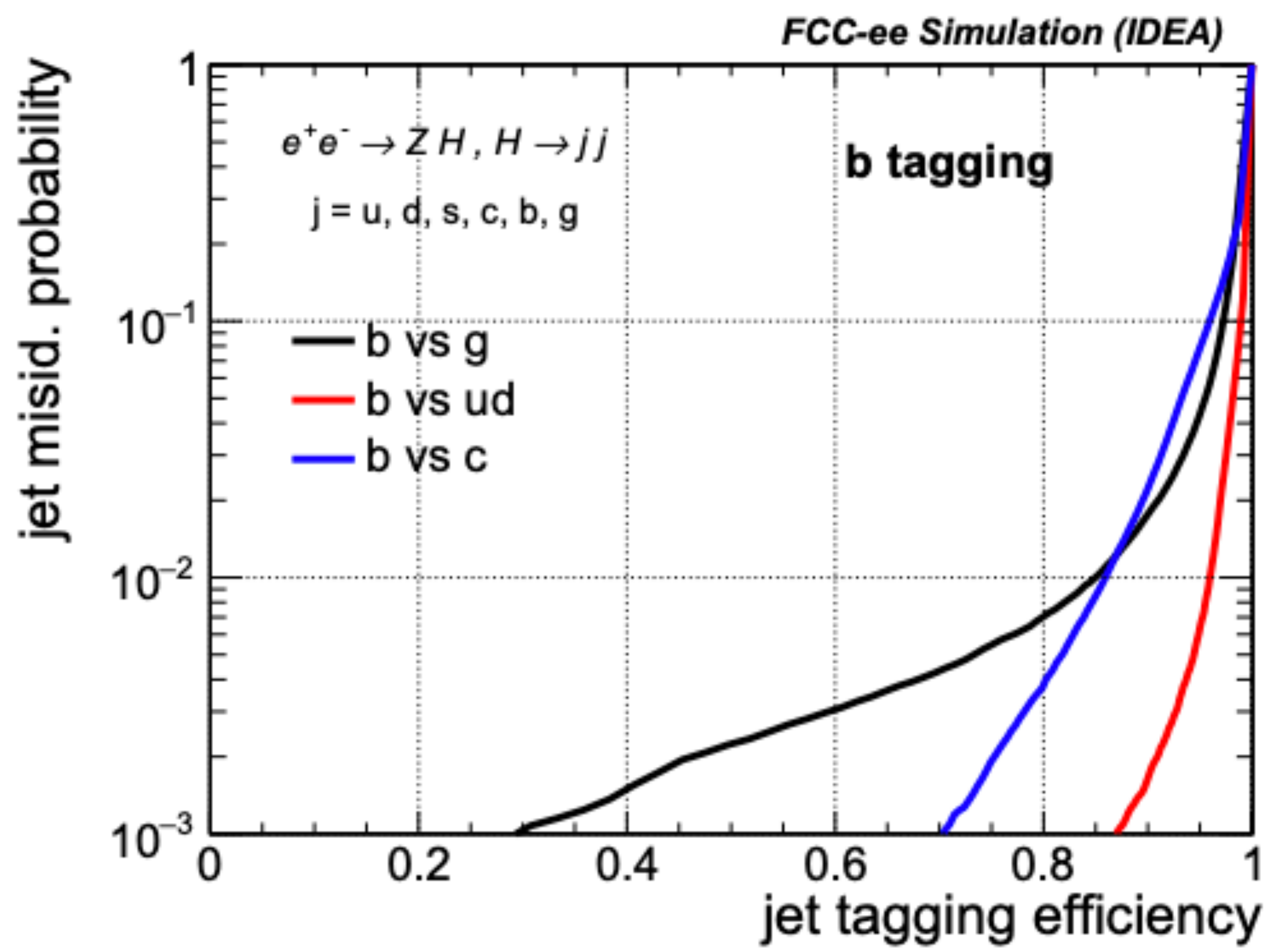



- Large Kaon content
  - Charged Kaon as track:
    - K/pi separation
  - Neutral Kaons:
    - $K_S \to \pi\pi$, $K_L$

# Flavor tagging



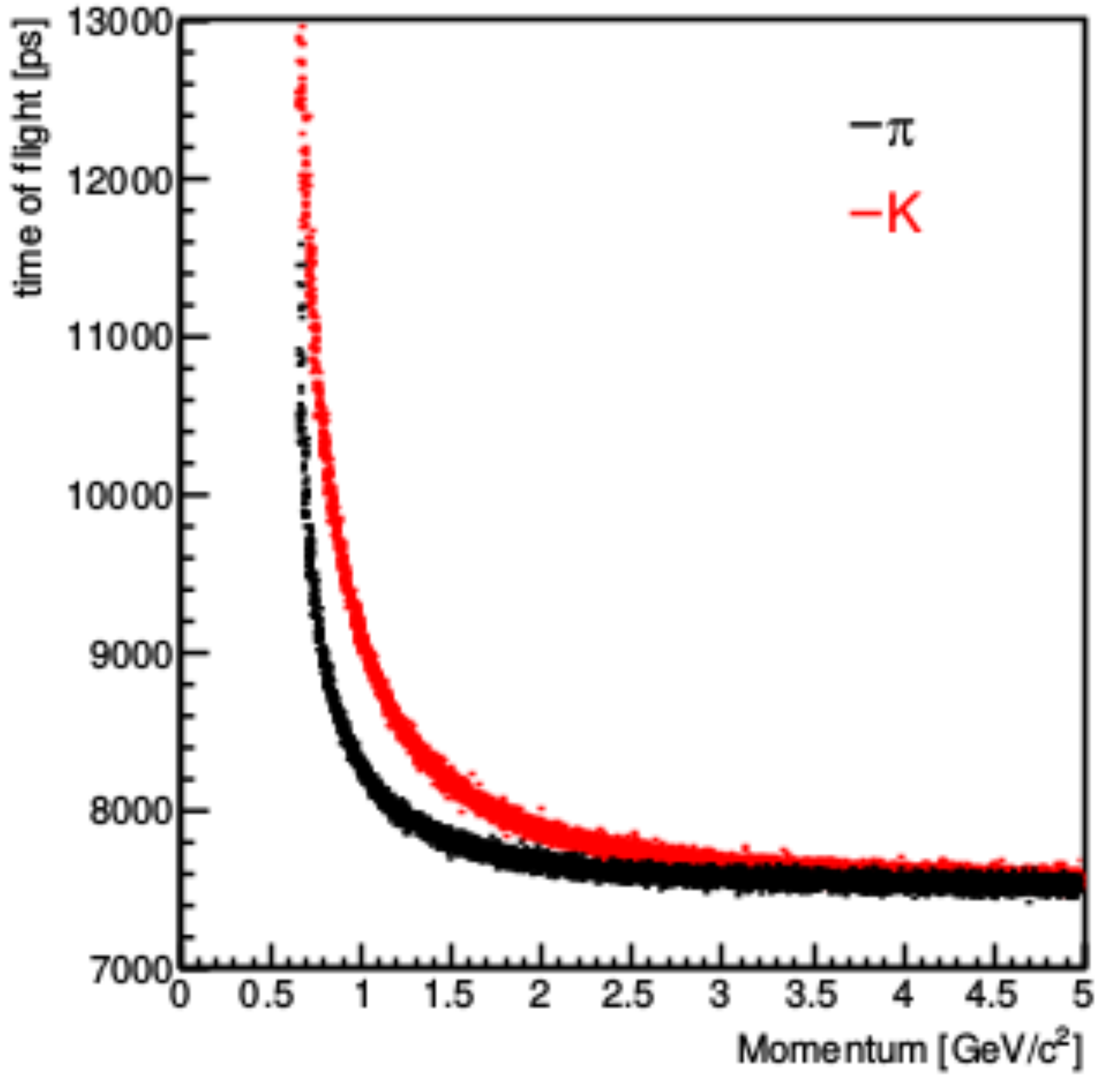



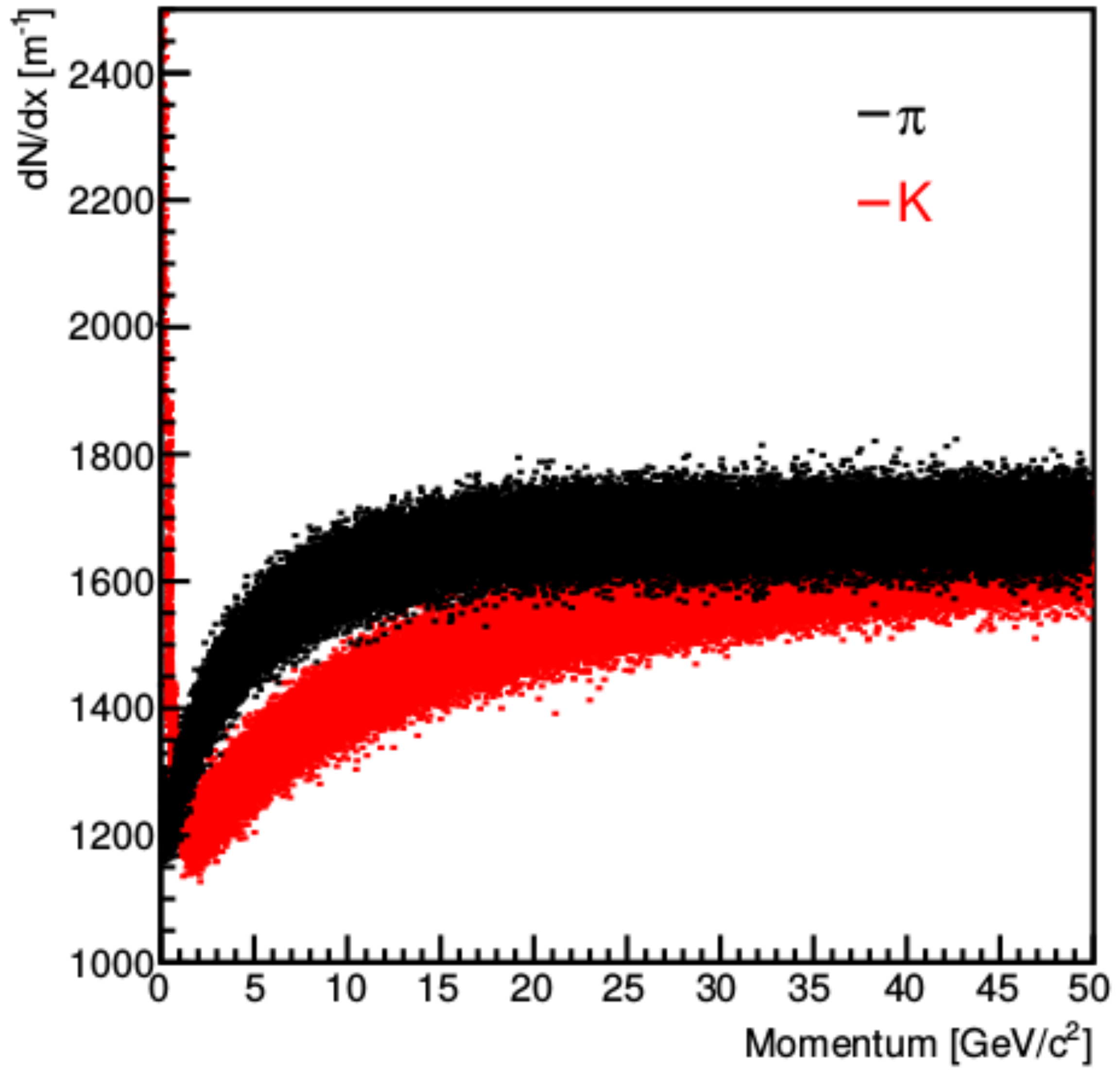



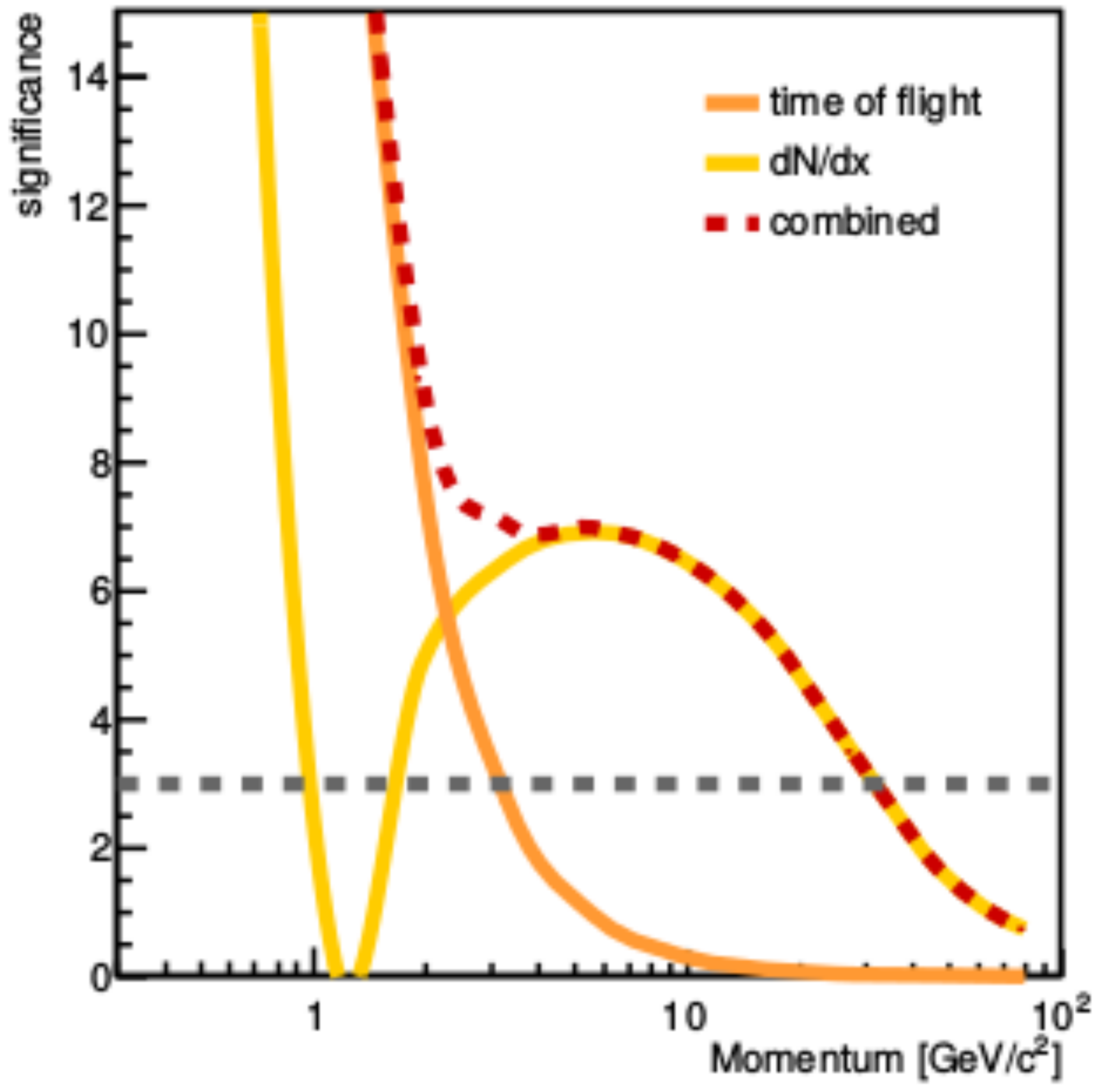

Light tracker, first measurement layer close to IP:

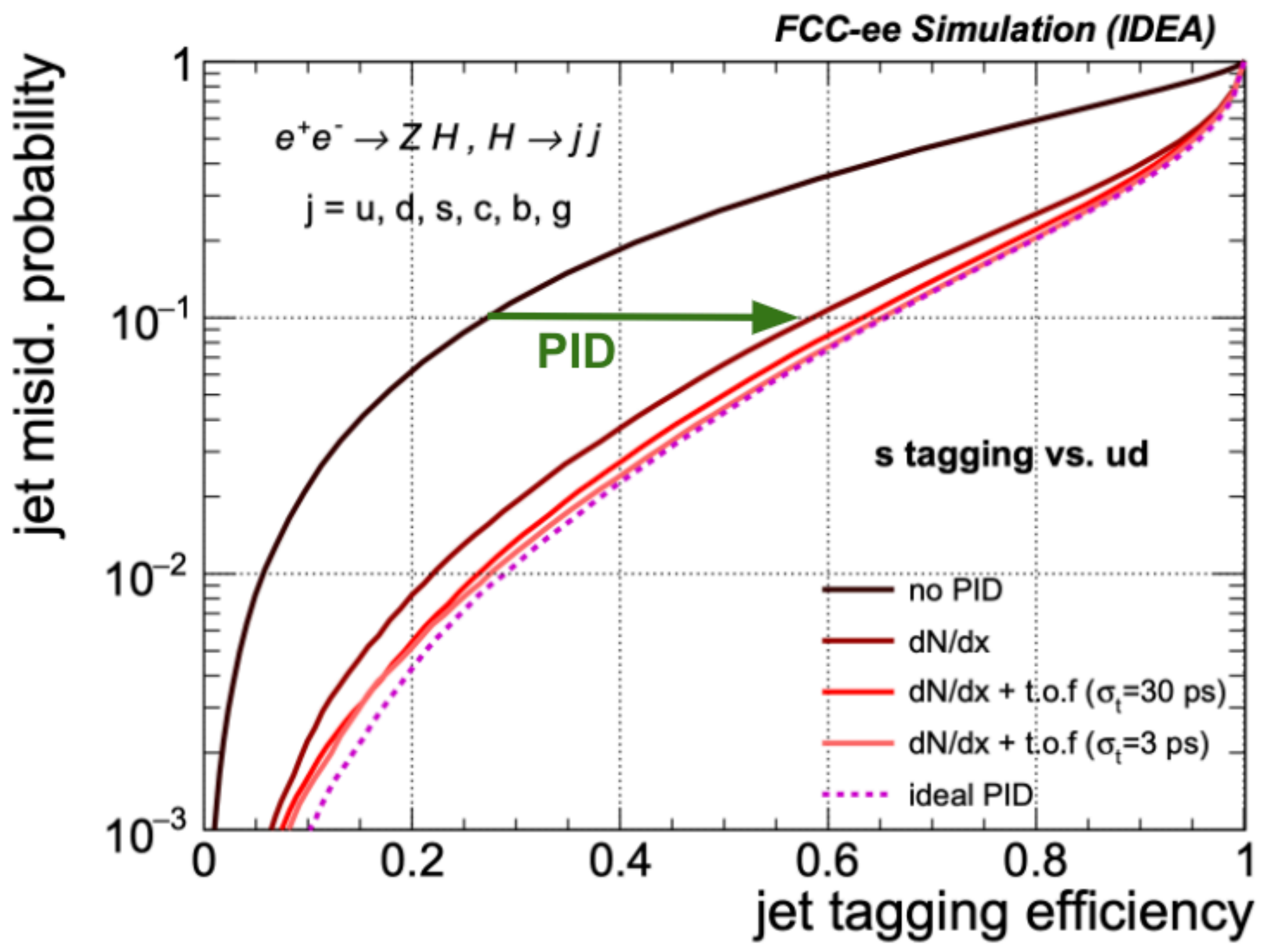
- excellent b/c-tagging performance
  - crucial to measure and to isolate clean H→bb/cc/gg samples

# Particle ID




- Particle Id for **strange** jet identification:
  - ToF at low momenta
  - dN/dX at high momenta
- Possible to measure strange Yukawa at FCC-ee ?

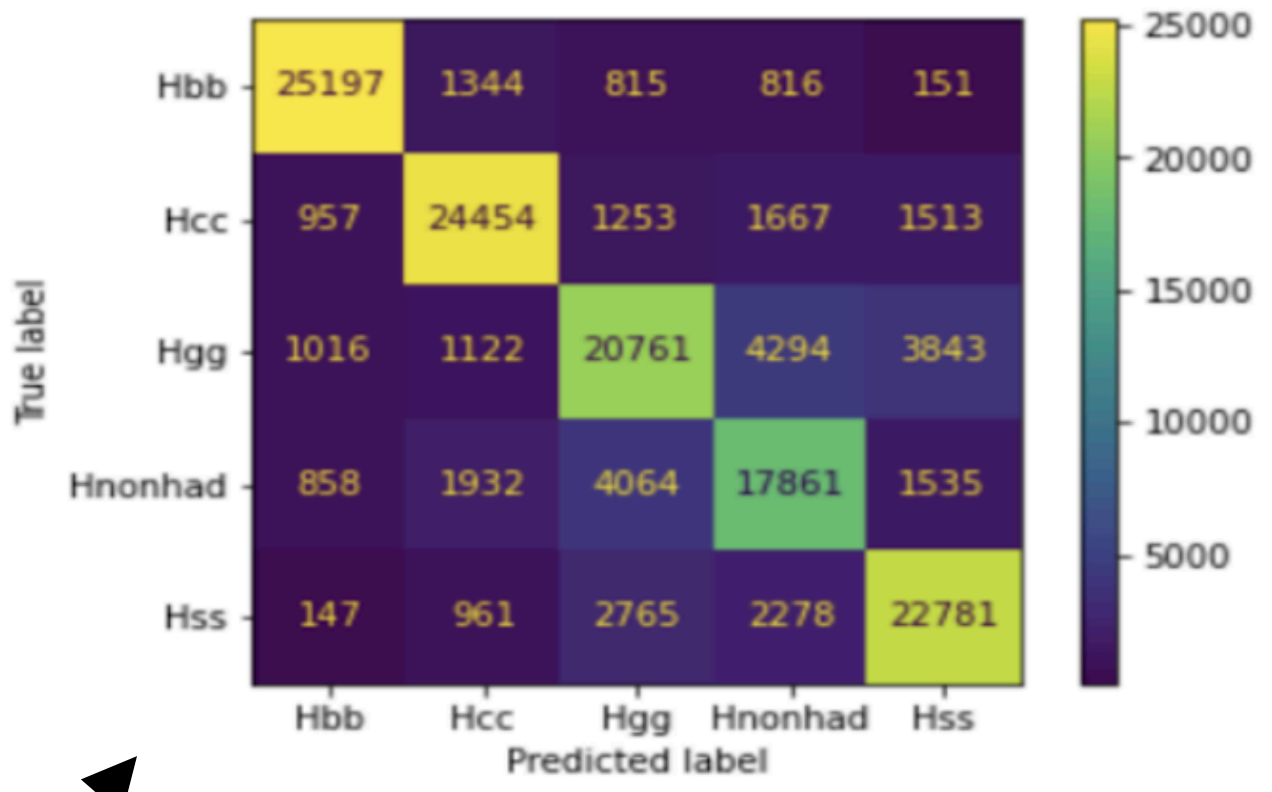
# Higgs to hadrons (Z(LL))

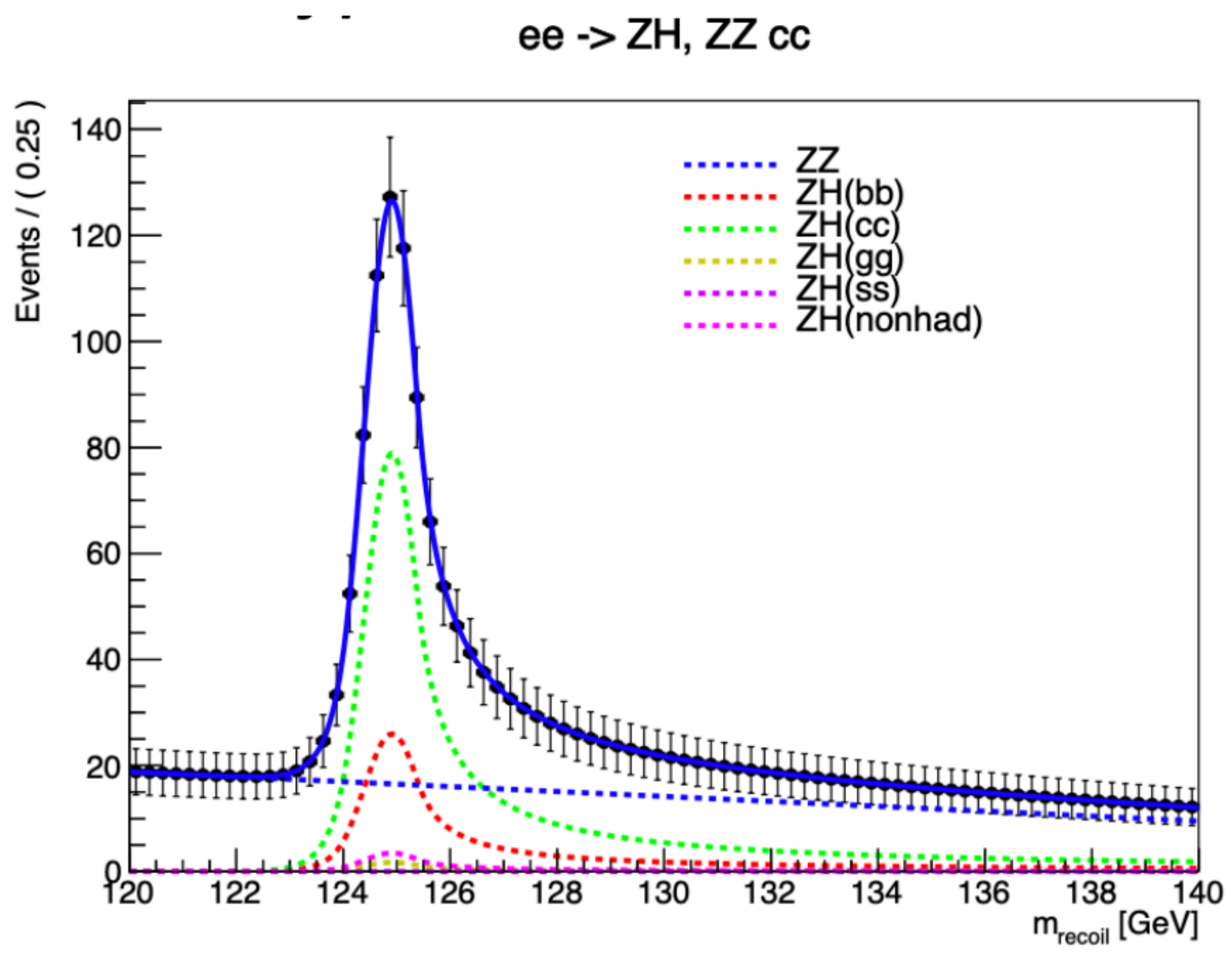
G. Marchiori (Friday)

Marchiori, Maloizel

- ee → ZH → l l j j
  - j = b, c, s, g
- Event pre-selection:
  - build recoil mass

one $Z(\ell\ell)$ candidate
$m_{\ell\ell}$ in 81–101 GeV
$|\cos\theta_{\ell\ell}| < 0.8$
$m_{\text{recoil}}$ in 120–140 GeV
$m_{jj}$ in 100–140 GeV
$p_{\text{miss}} < 30$ GeV
no leptons with $p > 25$ GeV
$d_{23} > 2$, $d_{34} > 1.5$, $d_{45} > 1.0$




Results @10 $ab^{-1}$

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

- Final selection and signal extraction:
  - multi-score BDT using jet tagger output to maximise purity in
    - bb/cc/ss/gg/other final states
  - simultaneous un-binned fit on $m_{\text{recoil}}$ on 4/5 signal strength modifiers POIs

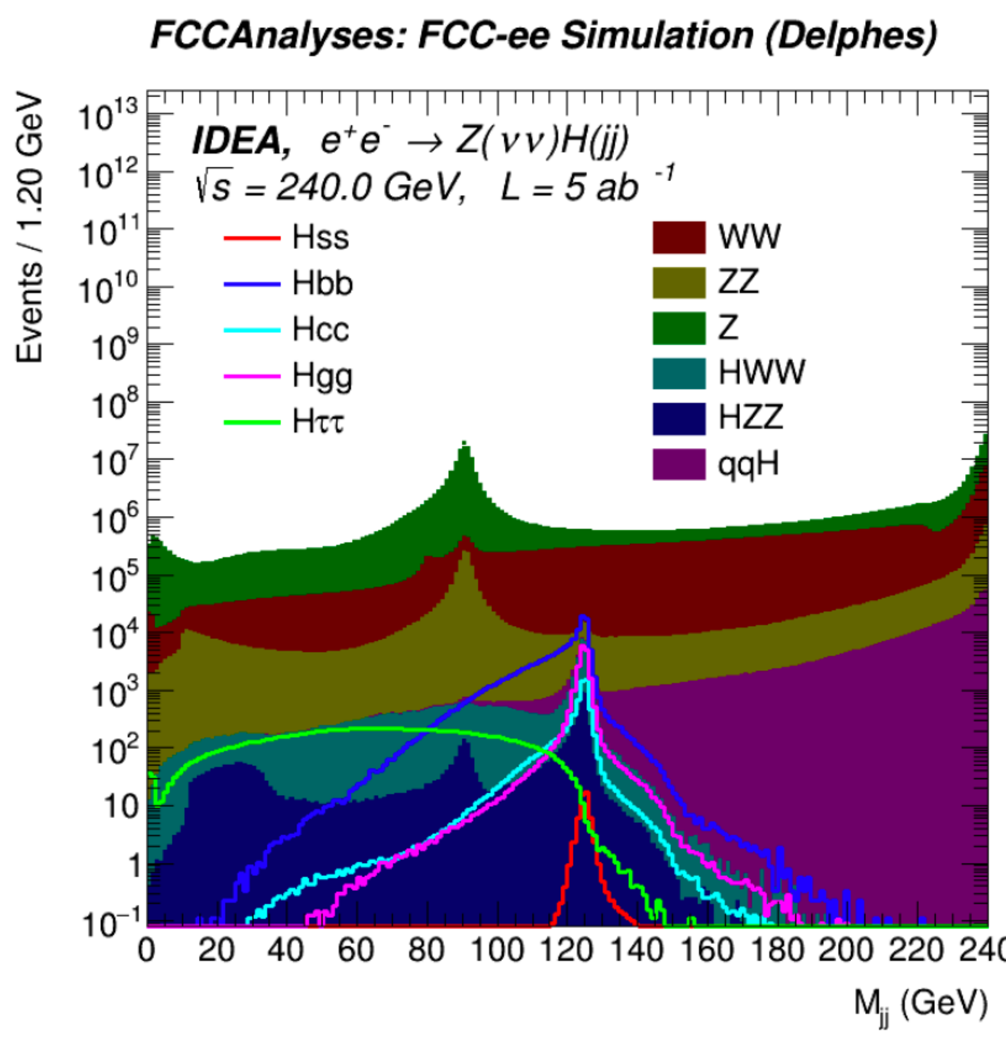
# Higgs to hadrons (Z(vv))

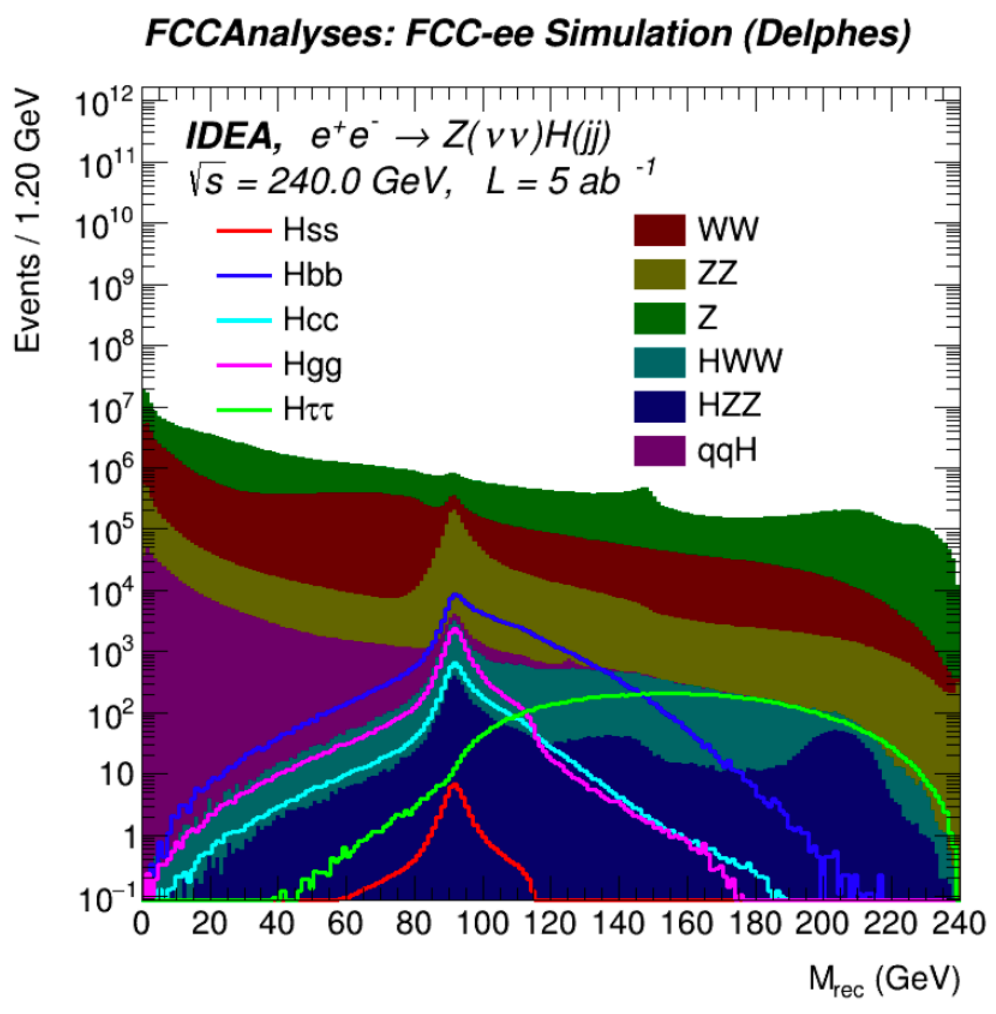
Del Vecchio, Gouskos, MS

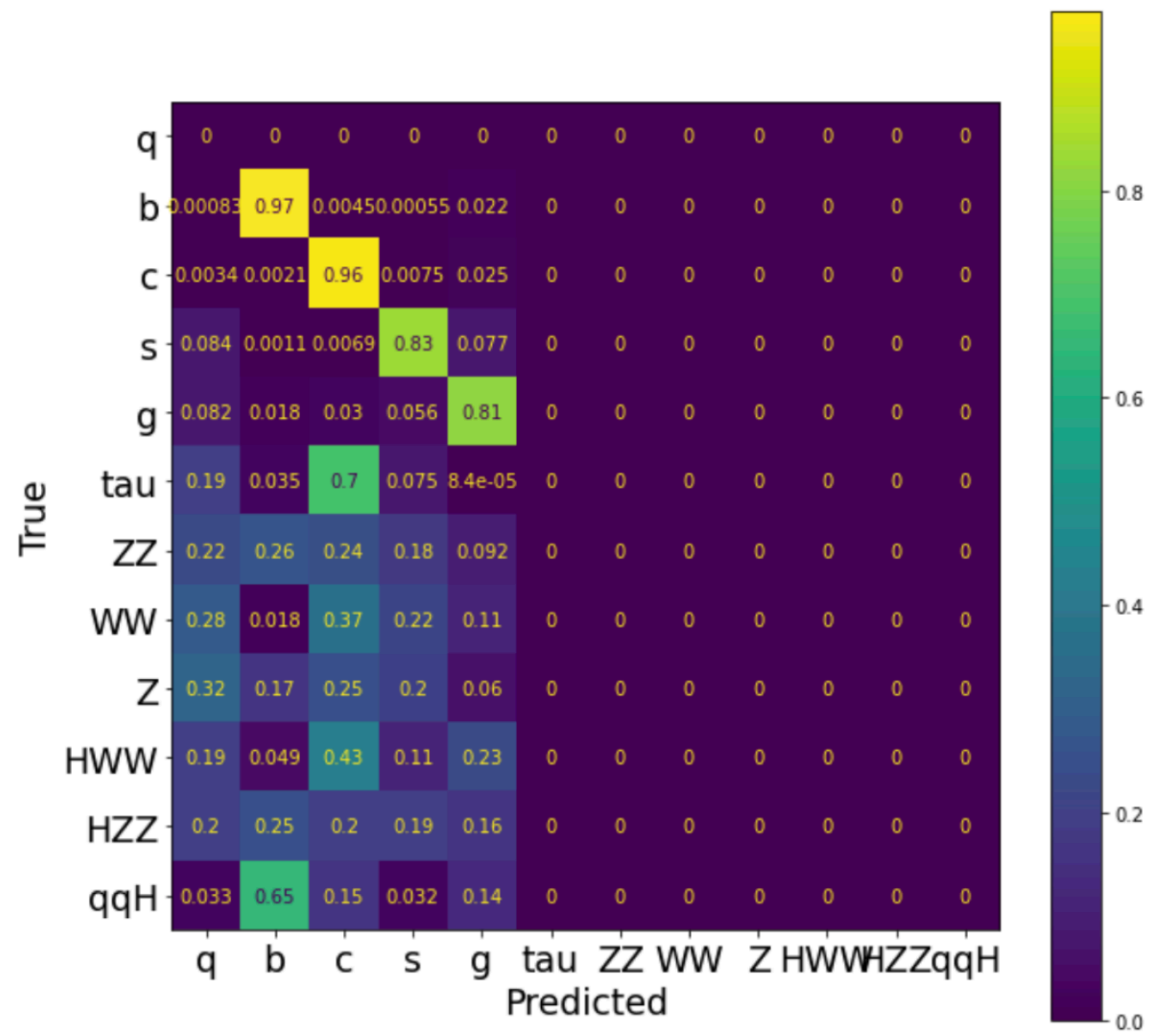
- ee → ZH → vv j j
  - j = b, c, s, g

| Final States | Cross-section [pb] | BR(H) | BR(Z) | Expected Yields |
|---|---|---|---|---|
| *signal* | | | | |
| $Z(\nu\nu)H(uu/dd)$ | 0.201868 | | 0.2 | |
| $Z(\nu\nu)H(bb)$ | 0.201868 | 0.571 | 0.2 | $1.34 \cdot 10^5$ |
| $Z(\nu\nu)H(cc)$ | 0.201868 | 0.0291 | 0.2 | $6.68 \cdot 10^3$ |
| $Z(\nu\nu)H(ss)$ | 0.201868 | $2.50 \cdot 10^{-4}$ | 0.2 | 55 |
| $Z(\nu\nu)H(gg)$ | 0.201868 | 0.0853 | 0.2 | $1.89 \cdot 10^4$ |
| $Z(\nu\nu)H(\tau\tau)$ | 0.201868 | 0.0626 | 0.2 | $1.45 \cdot 10^4$ |
| *background* | | | | |
| $ZZ$ | 1.35899 | - | - | $6.79 \cdot 10^6$ |
| $WW$ | 16.4385 | - | - | $8.22 \cdot 10^7$ |
| $Z$ | 52.6539 | - | - | $2.63 \cdot 10^8$ |
| $Z(\nu\nu)H(WW)$ | 0.201868 | | 0.2 | $4.97 \cdot 10^4$ |
| $Z(\nu\nu)H(ZZ)$ | 0.201868 | | 0.2 | $6.10 \cdot 10^3$ |
| $Z(q\bar{q})H$ | 0.201868 | | | $6.82 \cdot 10^5$ |

- Strategy:
  - Event preselection
    - lepton veto (orthogonalise)
  - build bb/cc/ss/gg orthogonal enriched categories using max sum of jet scores



# Higgs to hadrons (Z(νν))

Del Vecchio, Gouskos, MS

- ee → ZH → νν j j
  - j = b, c, s, g

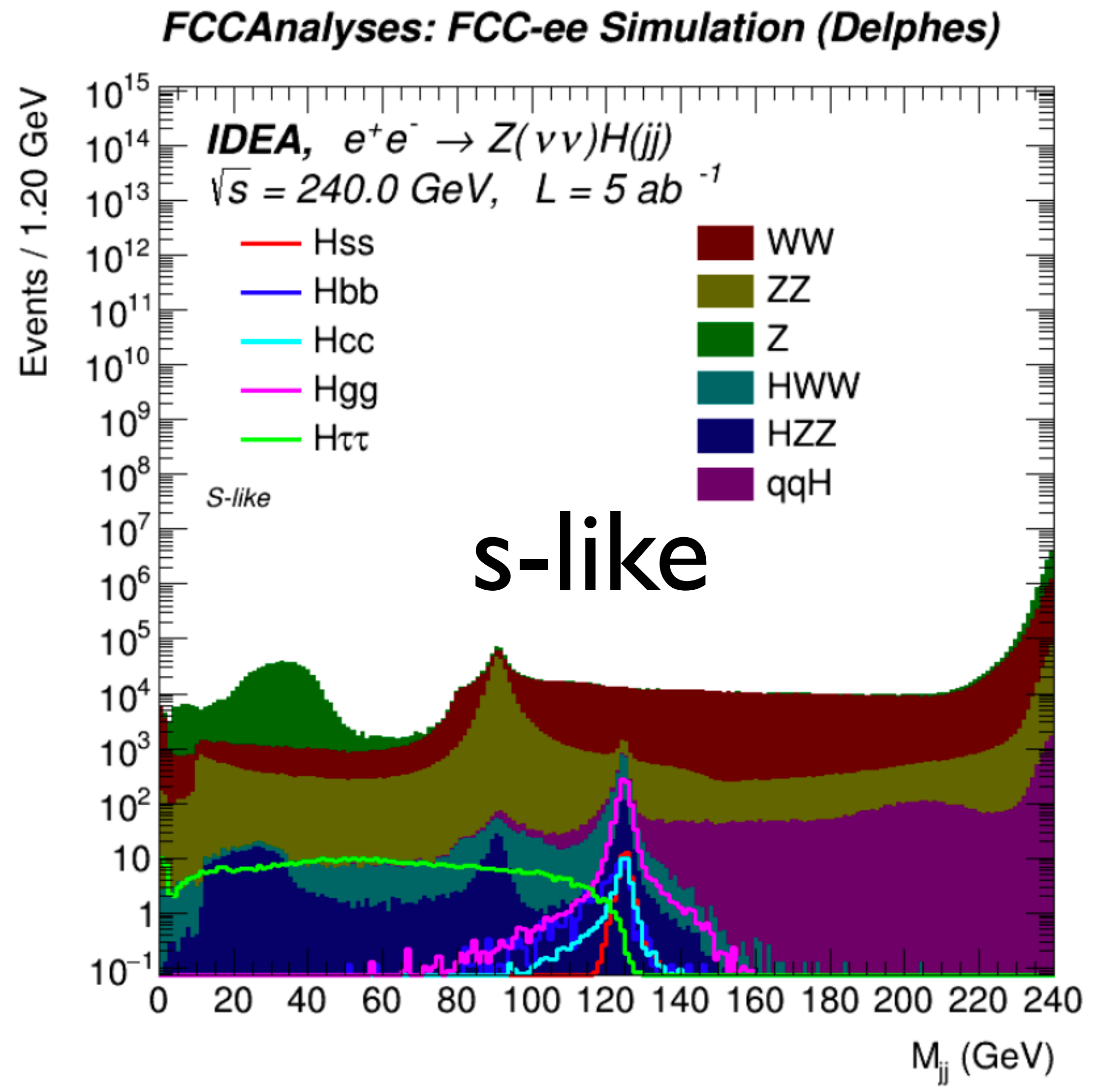
- Strategy (continued):
  - for each signal category (bb/cc/ss/gg)
    - define LP/MP/HP categories based on $s(j_1) + s(j_2)$
  - perform a 2D ($m_{jj}$ , $m_{recoil}$) template fit on each of the 3x4 categories

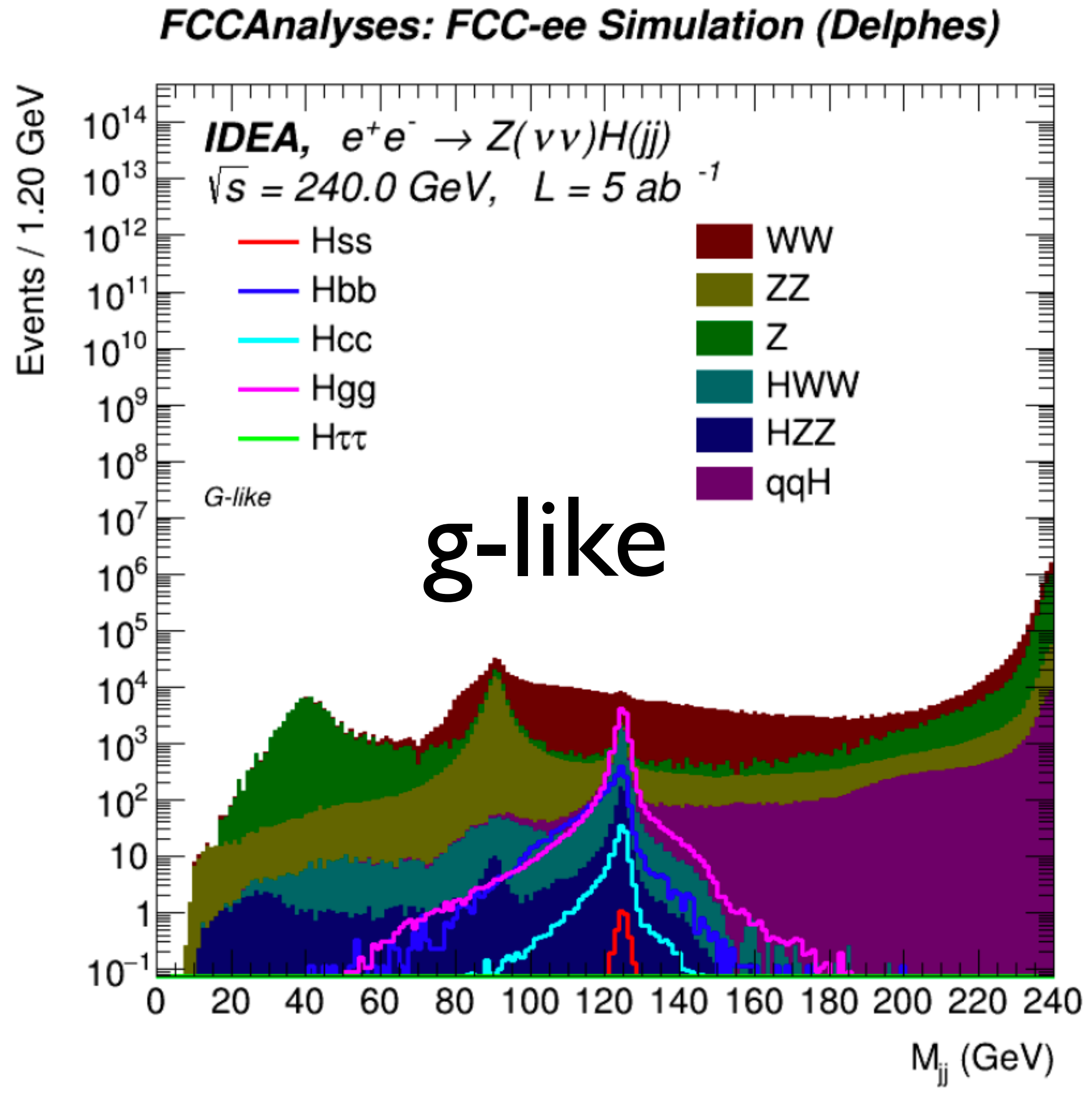
Achievable precision:

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

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

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



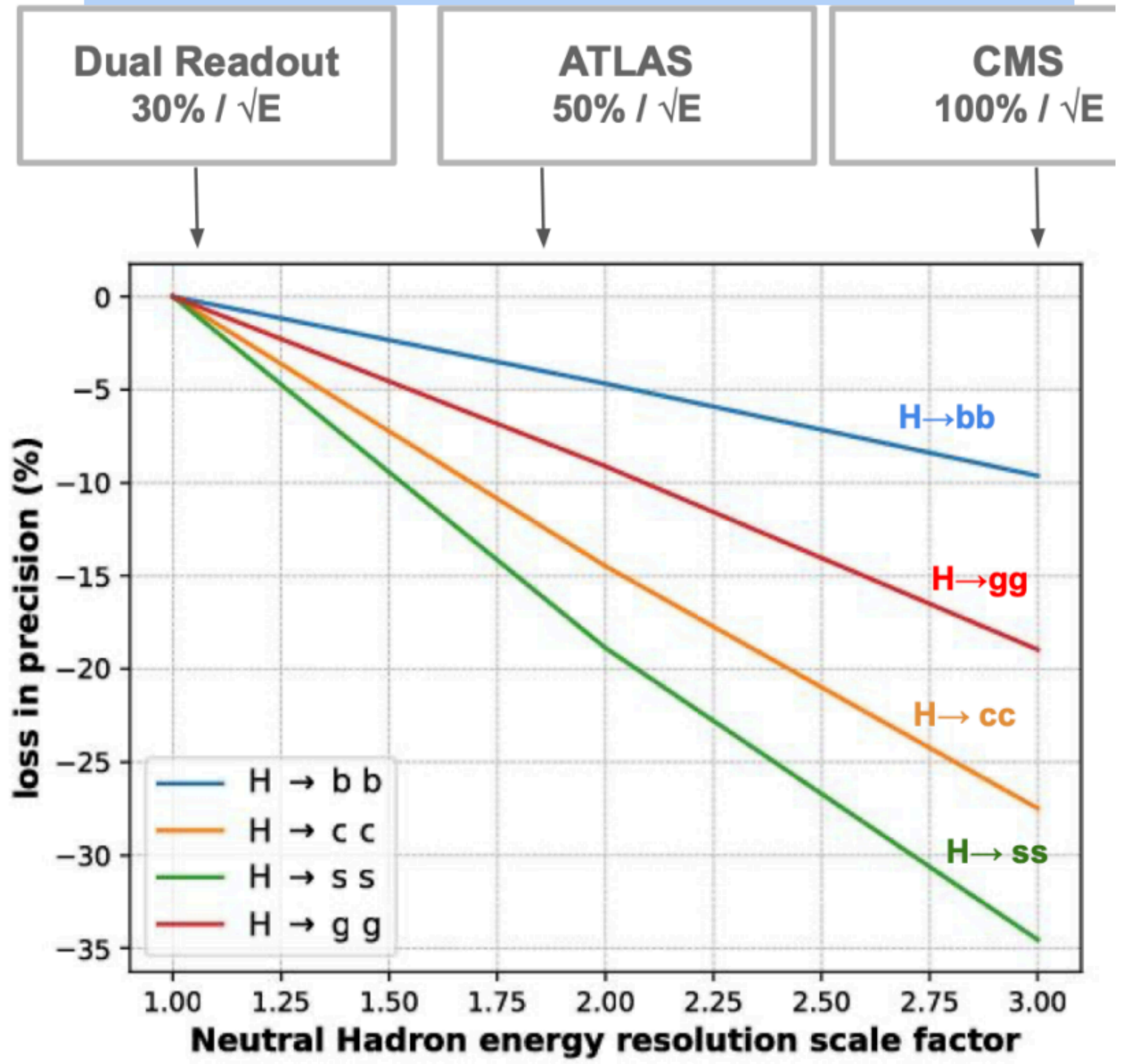

~ strange Yukawa to 50% precision seems possible …

can the fully hadronic (4j) channel help?

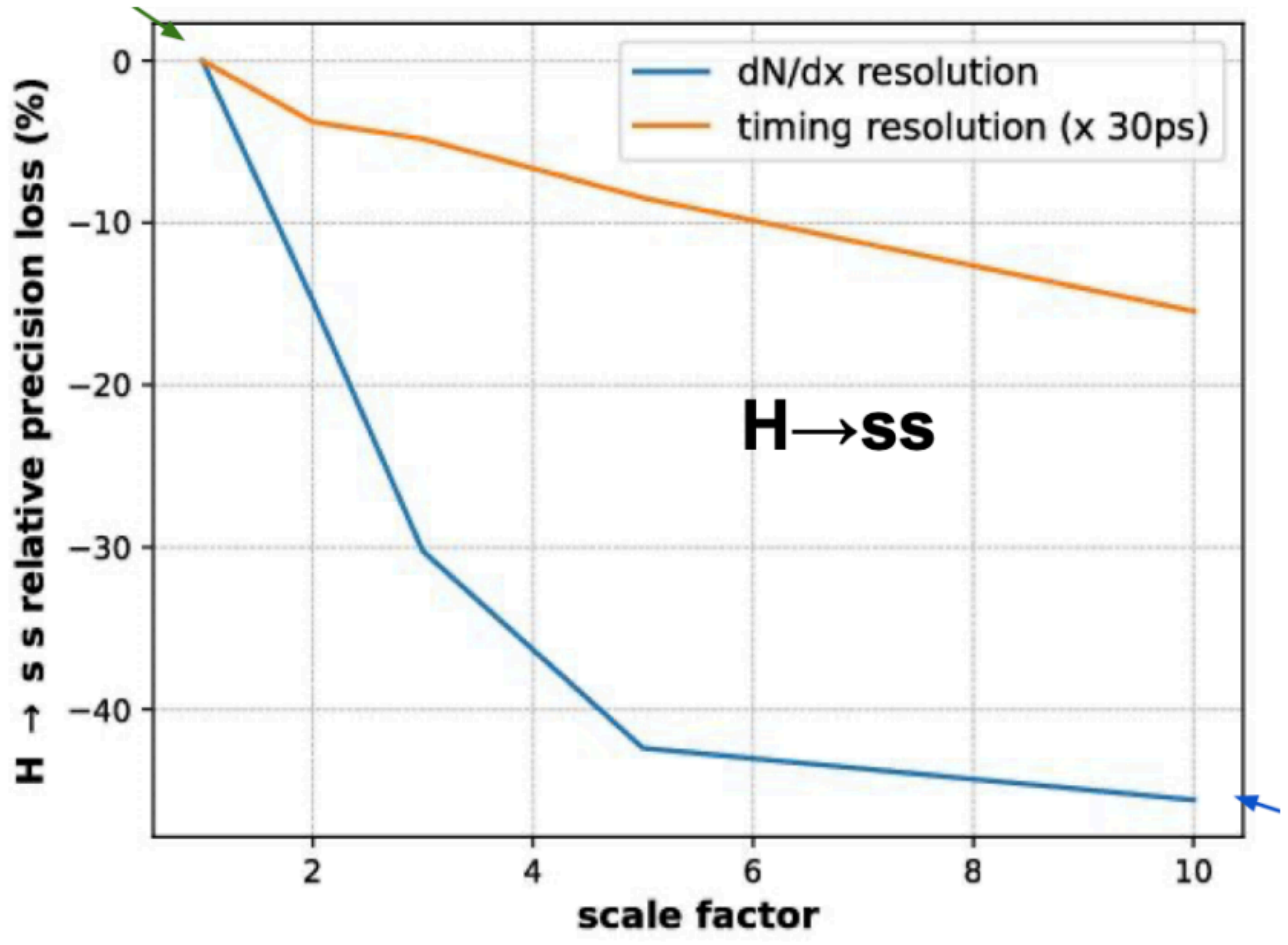
# H→jj (detector requirements)

j=b,c,s,g

Neutral Hadron resolution




PID




**Maximise physics output in Higgs physics:**

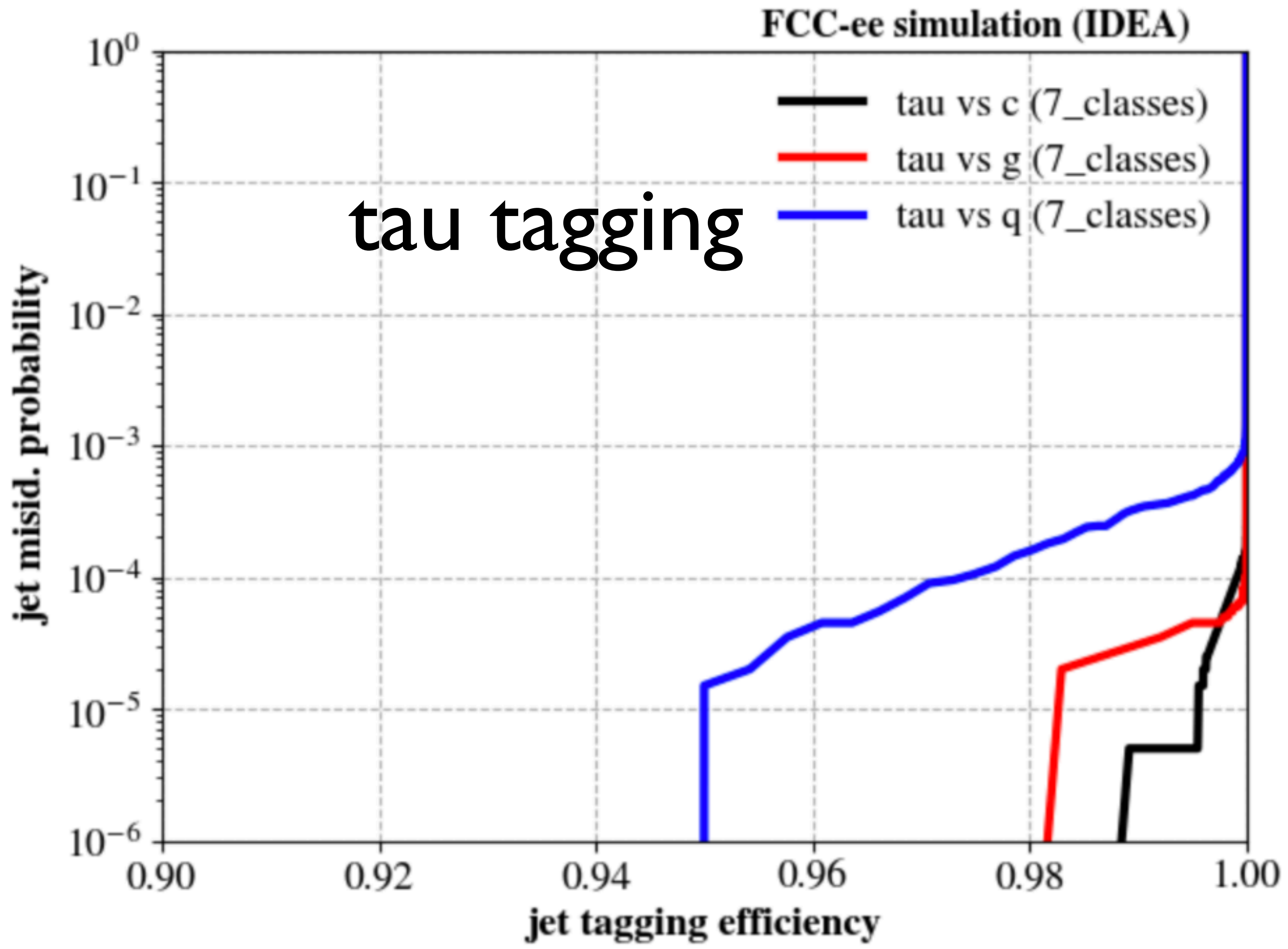
- **Hadronic resolution** critical for all H→jj
- Powerful **PID** (K/π) essential for **strange Yukawa**

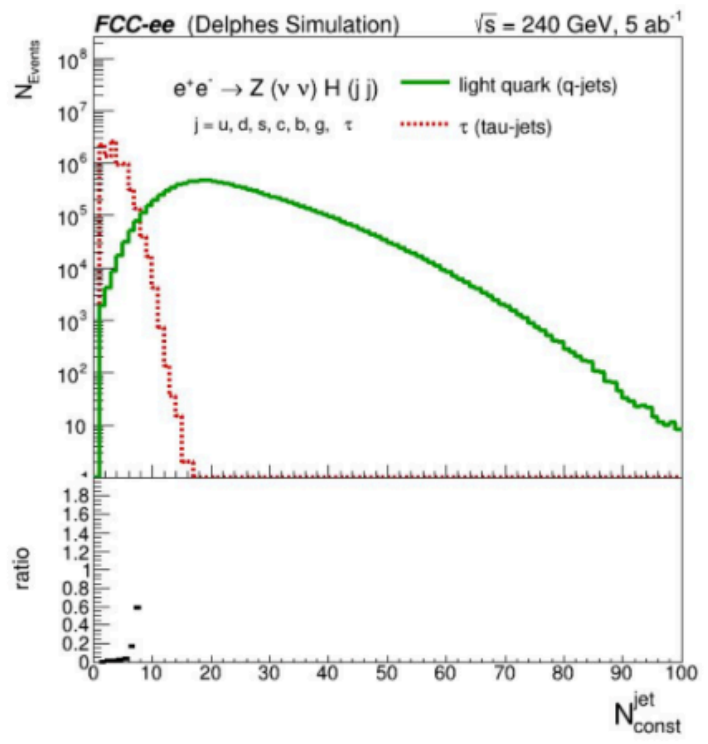
# Recent highlights

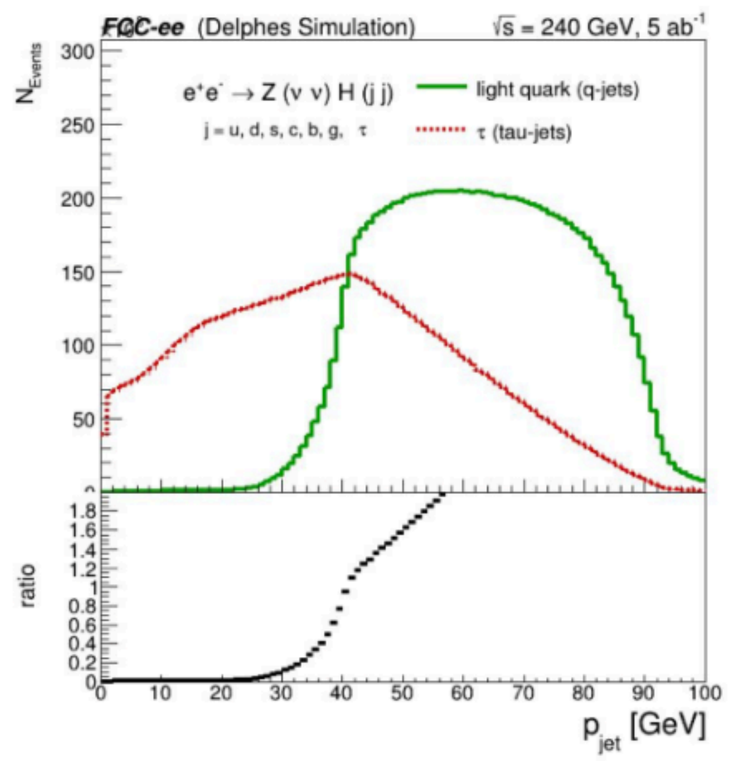
WORK IN PROGRESS

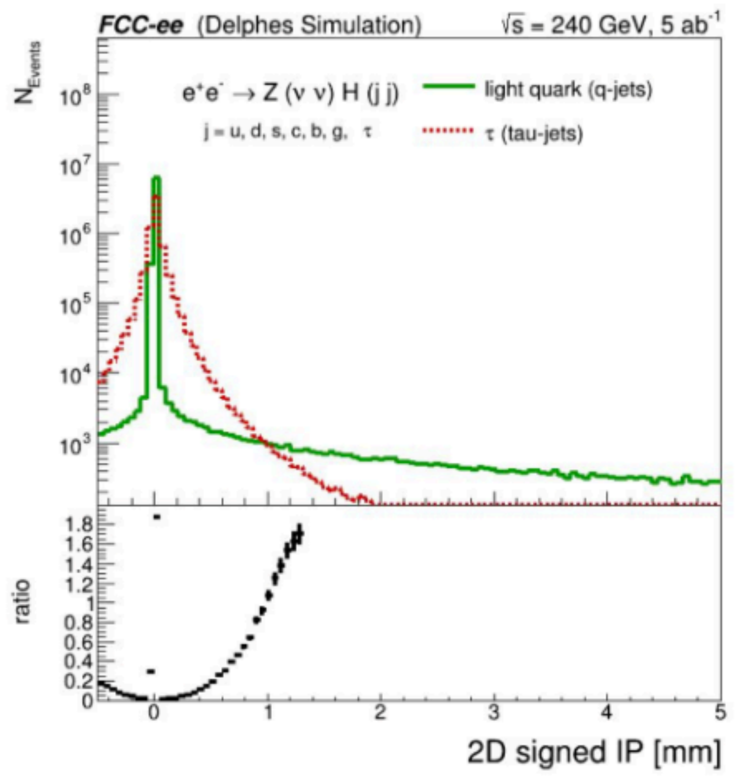
# Tagger update (tau)

Dolores Garcia



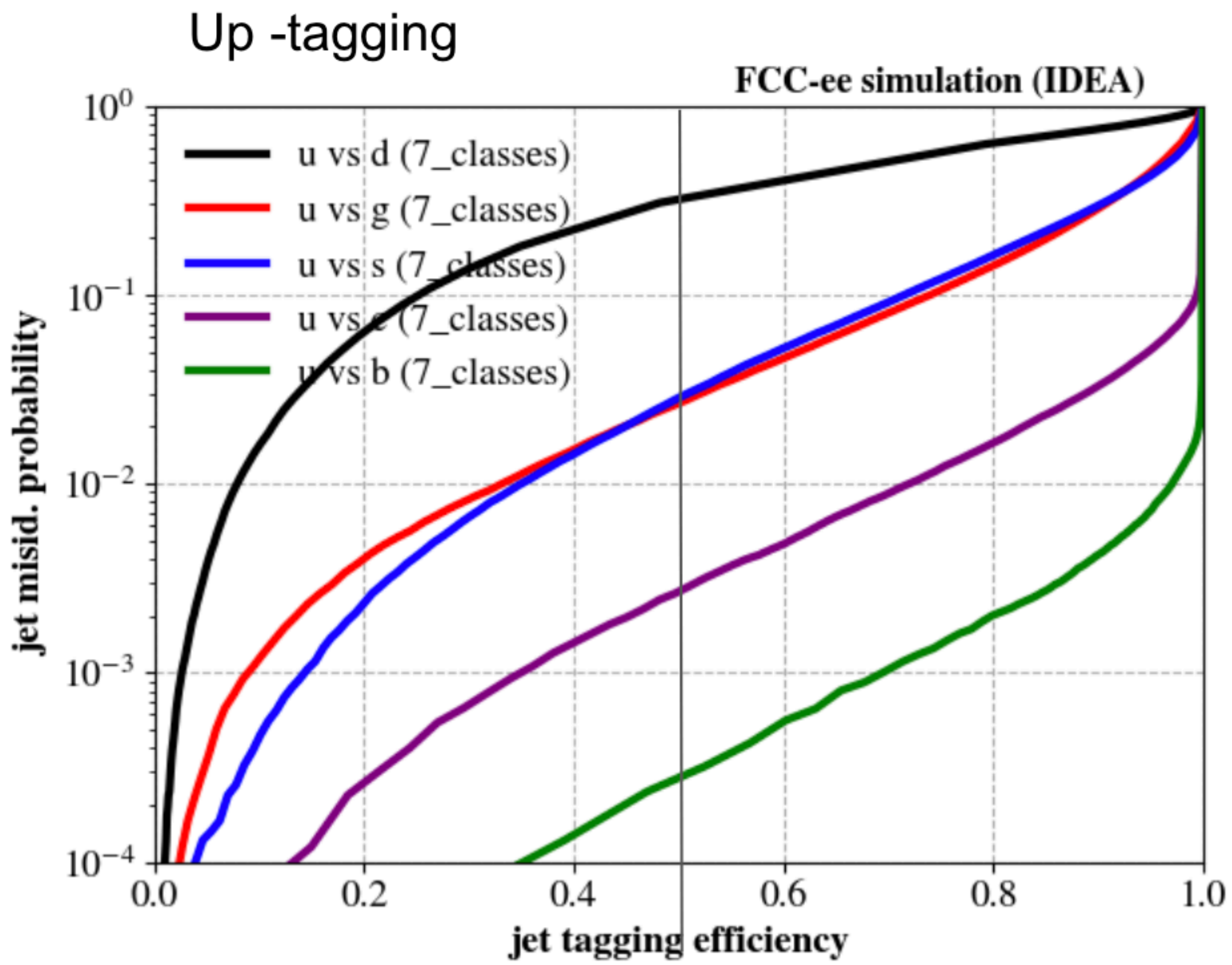

- Extremely high purity with virtually no signal loss seems achievable:
  - $10^{-3}$ bkg rejection for free

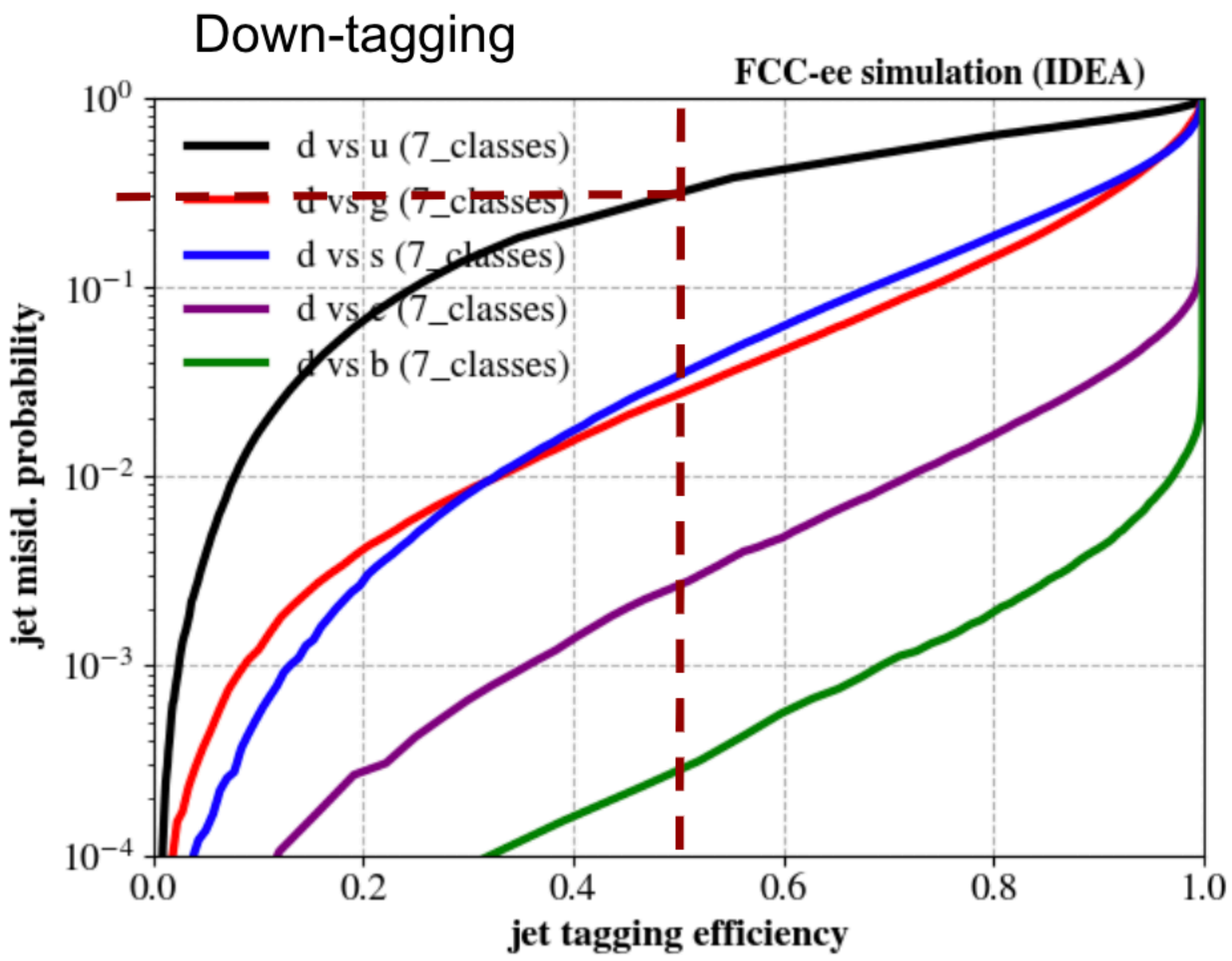
- Low multiplicity:
  - Using very large radius effective
  - No color connection between taus in the events
    - No soft fragmentation hadrons "between" the taus
    - Very low multiplicity

- Other handles:
  - missing momentum
  - displacement
  - High mom leptons

# Tagger (Up/Down)






- Up vs Down discrimination seems possible thanks to jet charge
- 30% bkg eff at 50% signal (better than random coin toss)

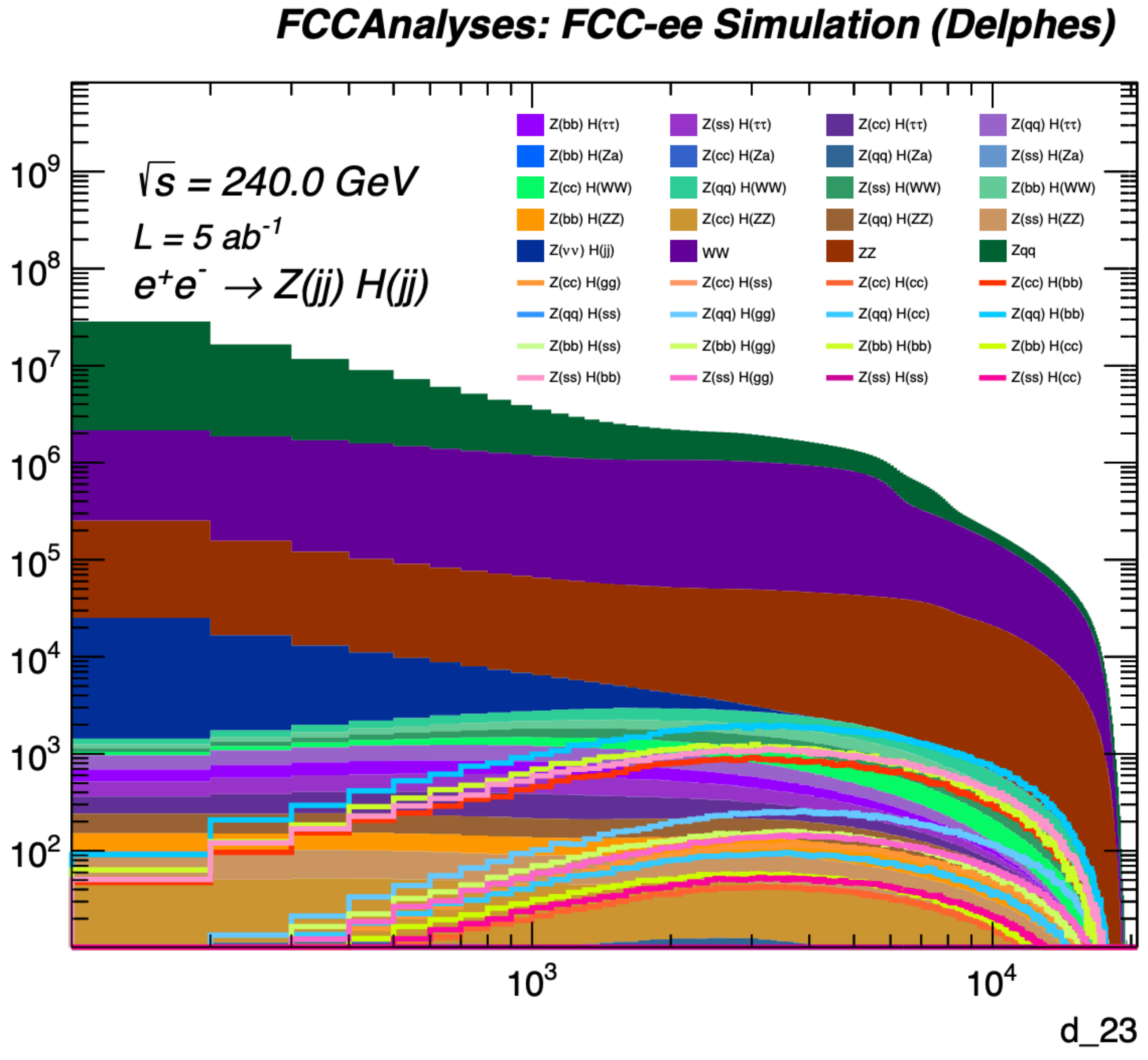
# ZH→4j

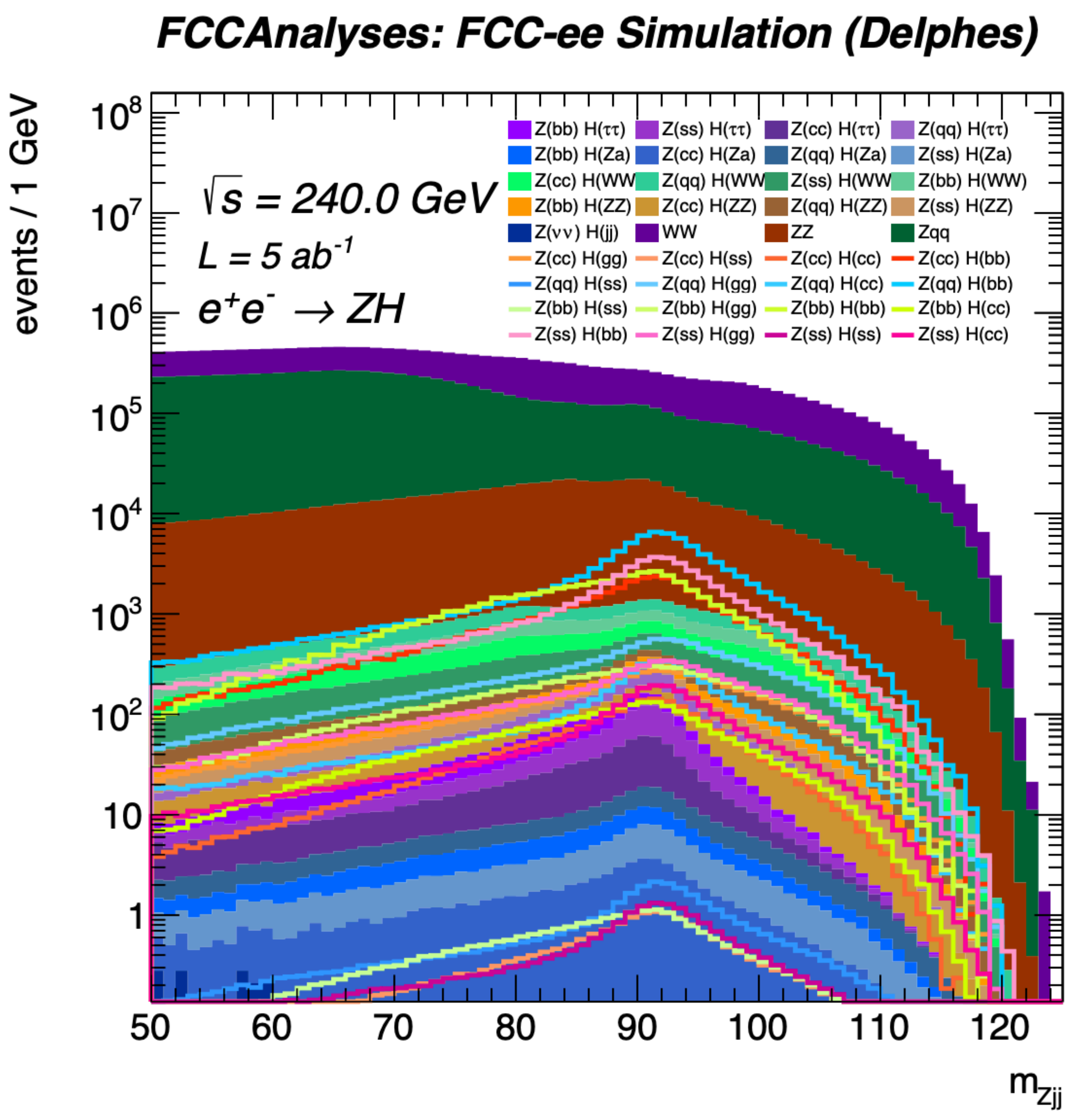
Iakovidis

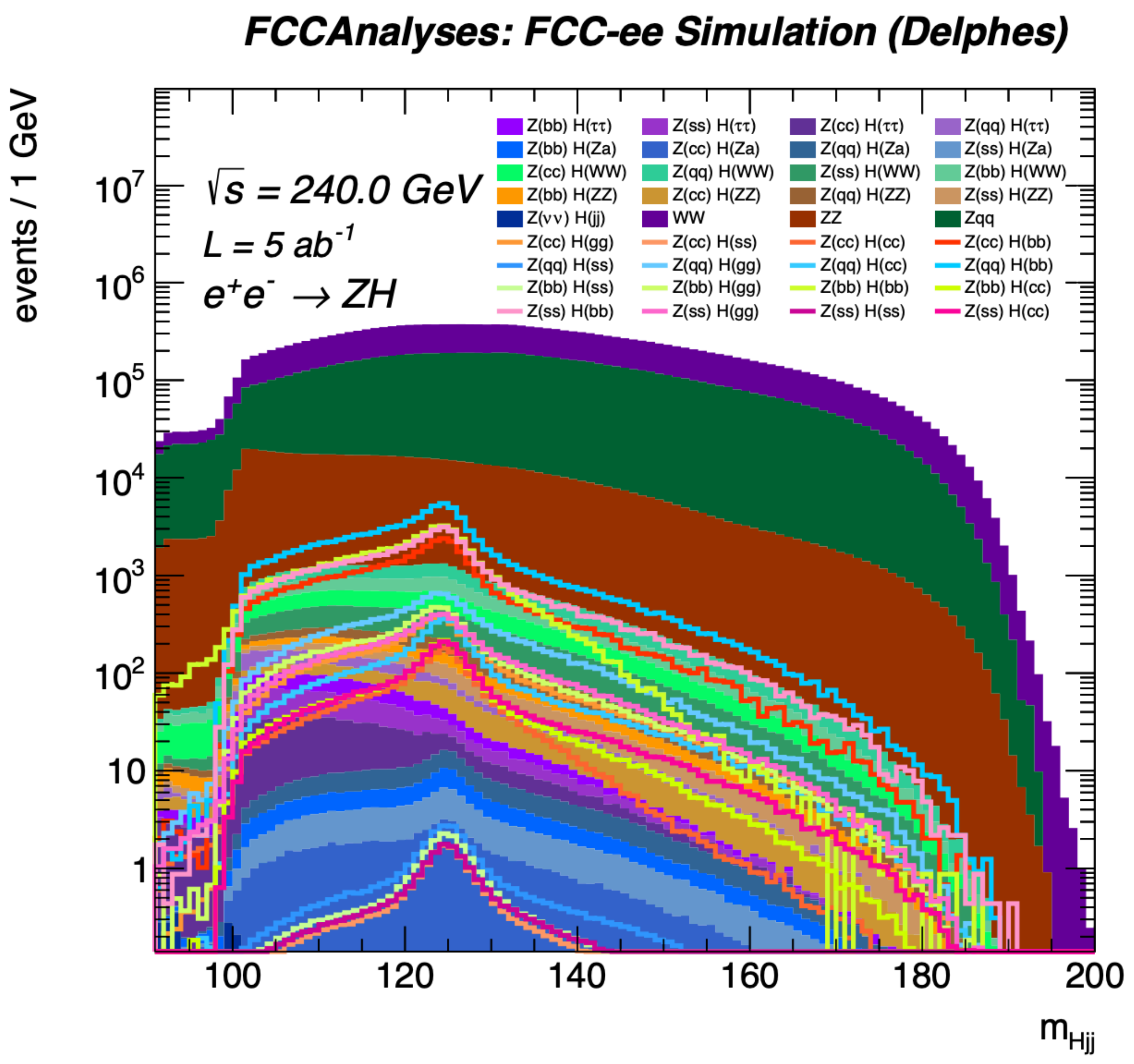
- Largest stat channel
  - very complex final state
    - Combinatorics
    - 15 signal regions?
- Handles:
  - can use E/p constraints to improve mass resolution (kin. Fit )
  - Jet merging scales

| | H → gg | H → bb | H → cc | H → ss | H → qq |
|---|---|---|---|---|---|
| Z → bb | | | | | |
| Z → cc | | | | | |
| Z → ss | | | | | |
| Z → qq | | | | | |

- Strategy:
  - N = 4 exclusive jet clustering
  - use tagger to classify final state
  - color singlet clustering?



# ZH→ZZZ*

Combe, Morange

- $\mathrm{BR}(H \to ZZ^*) \sim 2.64\%$

$\mathrm{N}_{\text{expected } ZH(ZZ^*) \text{ events}} \sim 25000$

$3^3$ = 27 final states
(x4 if jet flavour)

Z(ll)Z(vv)Z*(jj) $\sim 9\%$

Z(ll)Z(jj)Z*(vv) $\sim 17\%$

Z(vv)Z(ll)Z*(jj) $\sim 8.7\%$

**Fit results** *(uncertainty on H(ZZ*) cross section)*

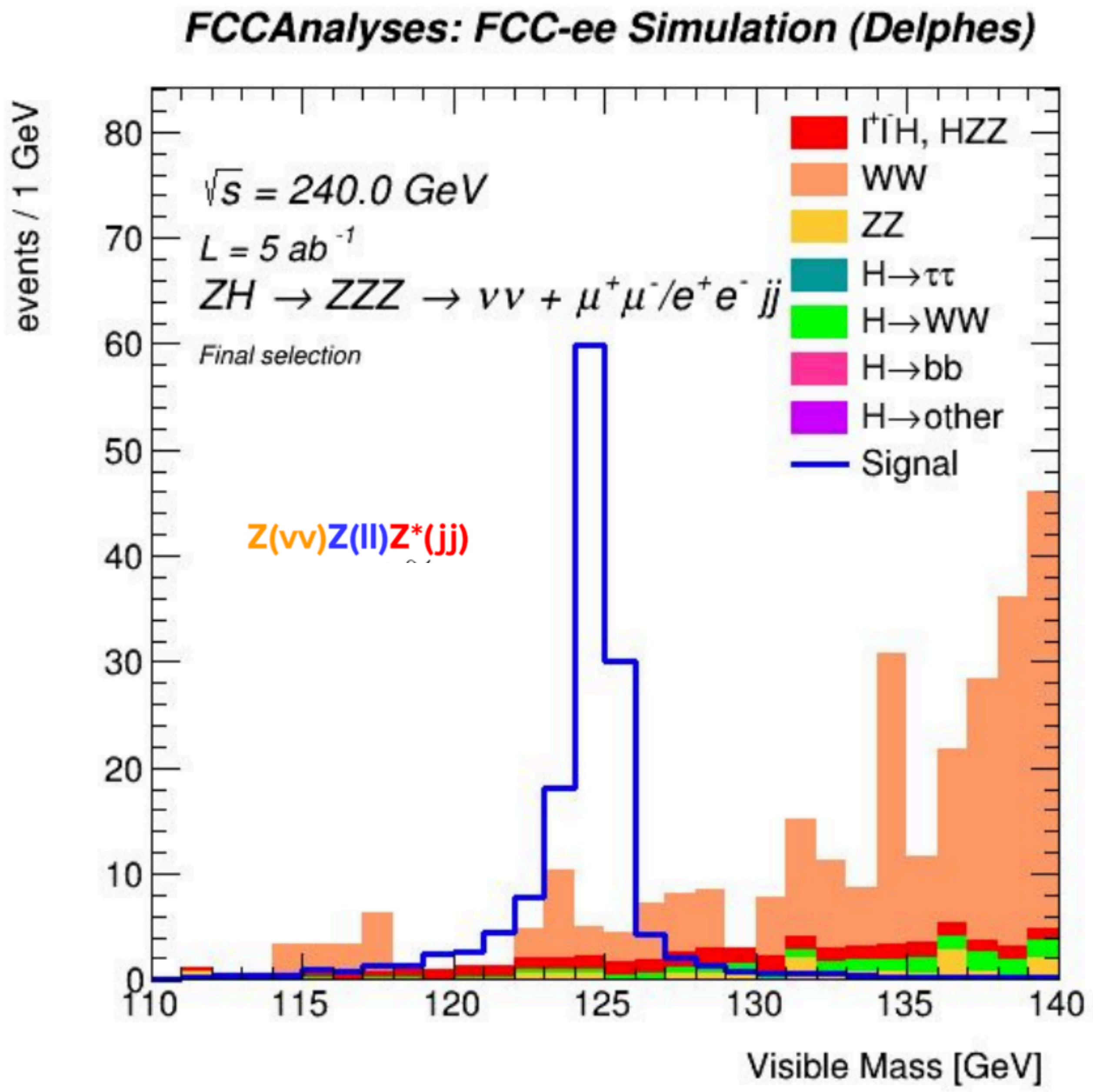
COMBINE

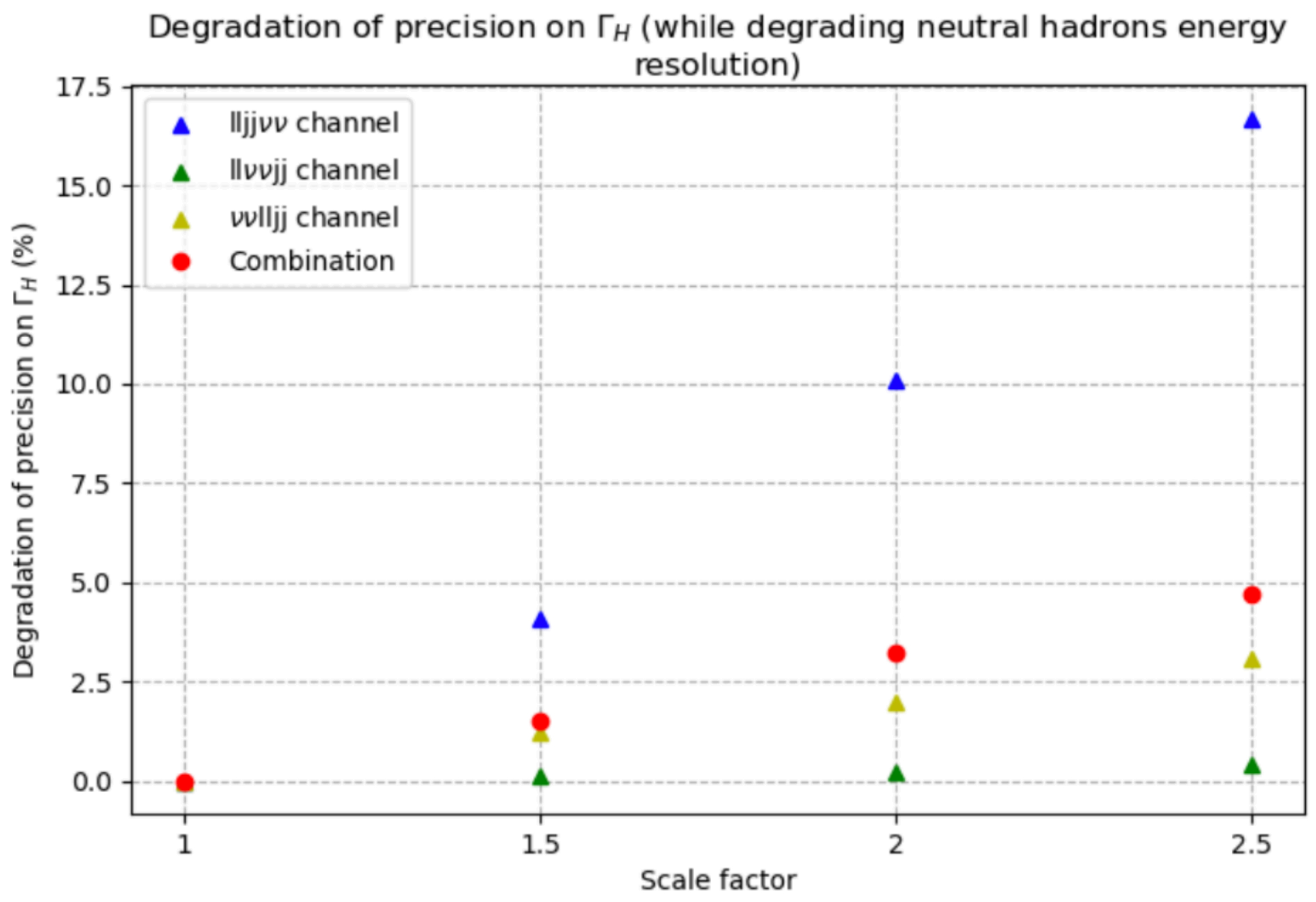
$r = 1 \pm 0.066$

Included systematics :
- H(WW*) normalisation : 5%
- ZZ normalisation : 10%

- Fully **hadronic** final states => more statistics but **complicated combinatorics**
- Fully **leptonic** => **fewer** statistics
- **Mixes** of leptons and/or neutrinos and/or jets => better **balance** to

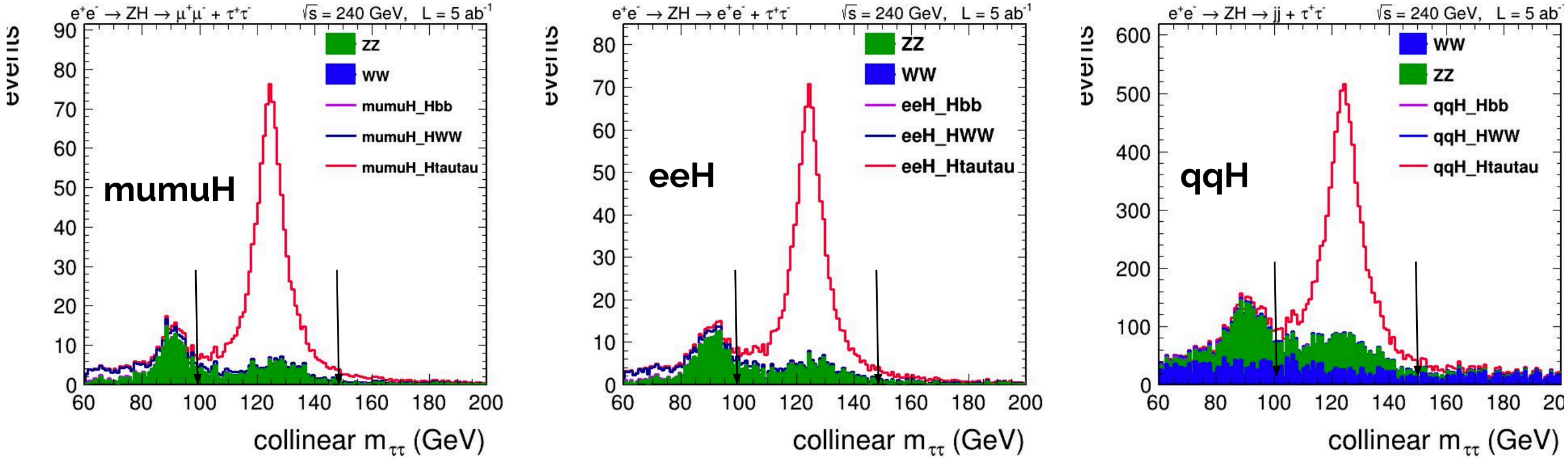
only 3 final states considered
stay tuned for more …



# H→ττ

Cepeda




Restricting the results to the Collinear Mass range: 100 to 150 GeV

| | | TauTau | MuTau | ETau | HTauTau |
|---|---|---|---|---|---|
| Z→QQ | Signal | 2741 | 1875 | 1917 | 6533 |
| | Bg | 1142 | 939 | 1060 | 3141 |
| Z→MuMu | Signal | 456 | 203 | 214 | 873 |
| | Bg | 63 | 66 | 55 | 184 |
| Z→EE | Signal | 440 | 206 | 201 | 847 |
| | Bg | 71 | 57 | 62 | 190 |

Assuming only stat uncertainty on the signal (no bg uncertainty, no syst): ~>~8253 events in 5ab-1 → 1.1% uncertainty on $\Delta(\sigma_{ZH}$*Br(H→ττ)) . **Assuming 10ab-1 , 0.78% .**

# H→μμ/γγ

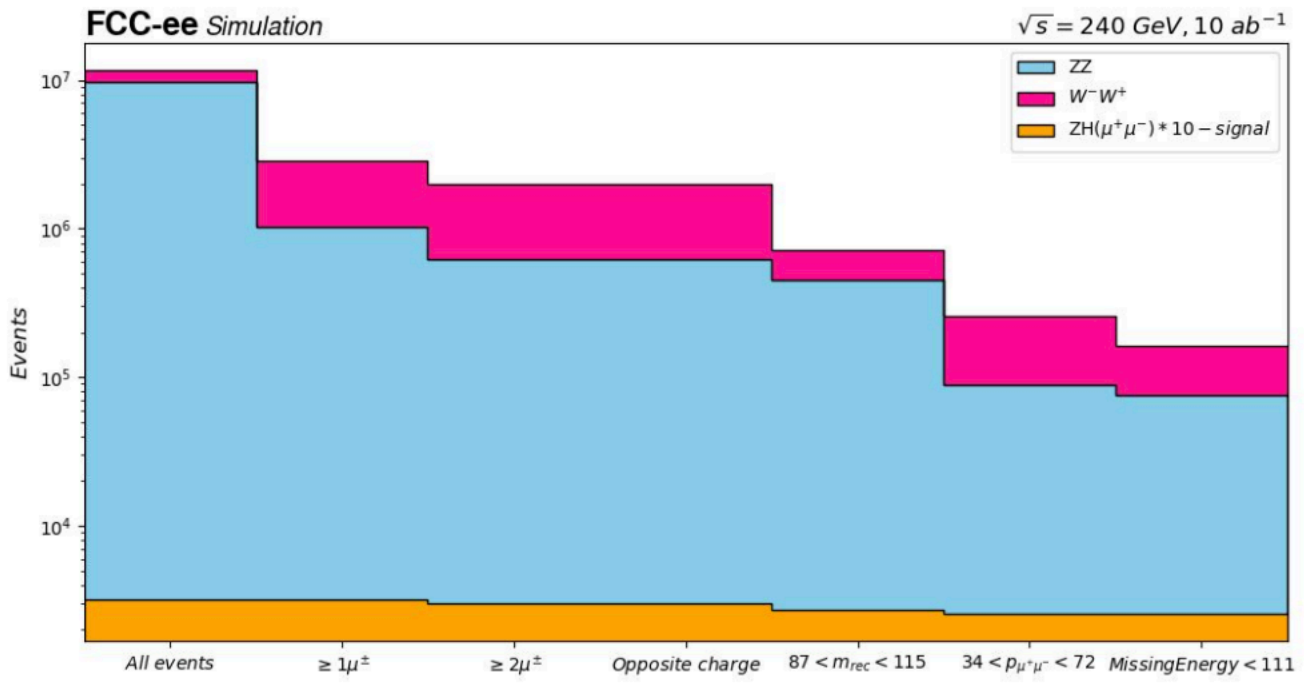
## can improve by categorising vs Z decay

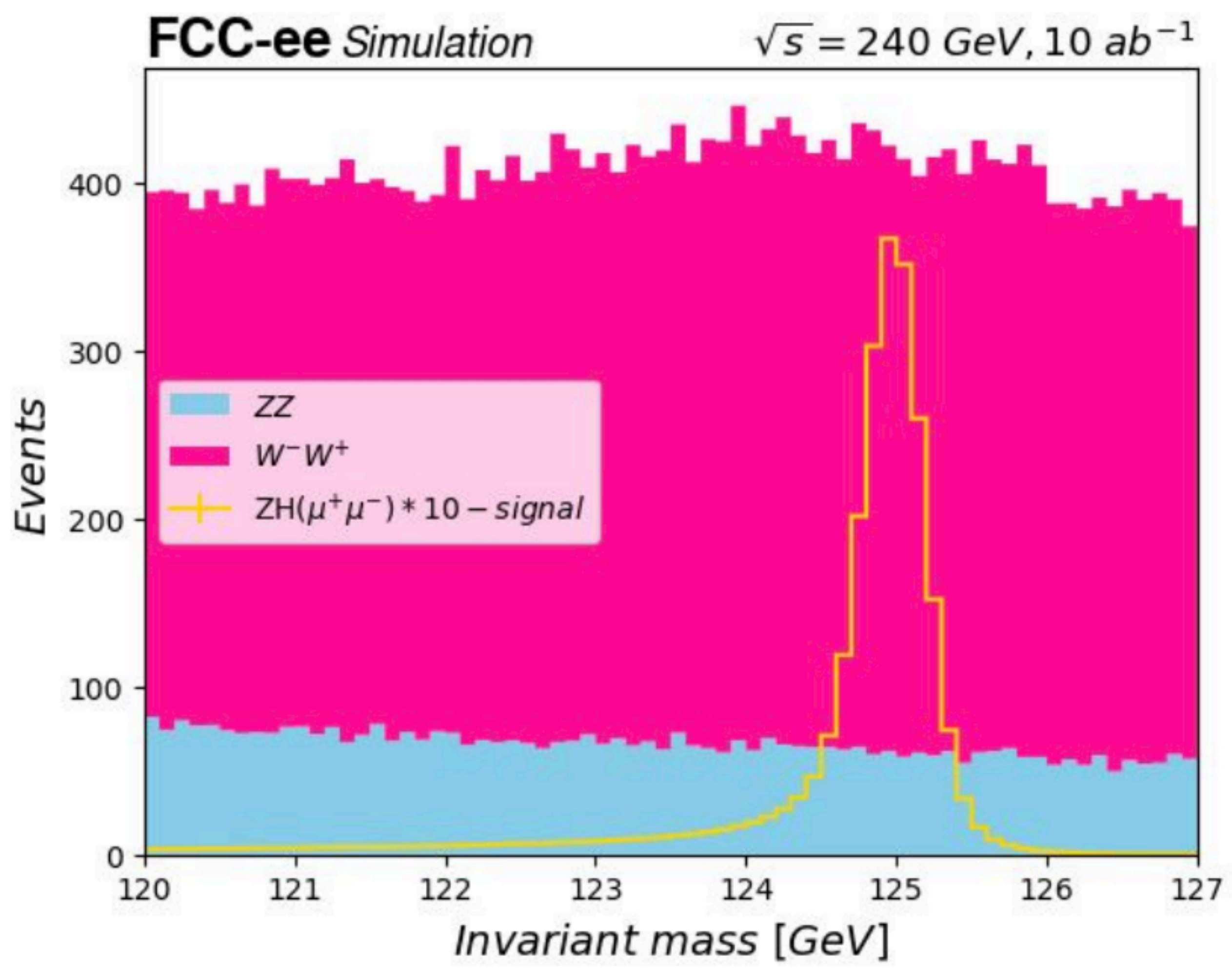
Siminius

### Preselection cuts

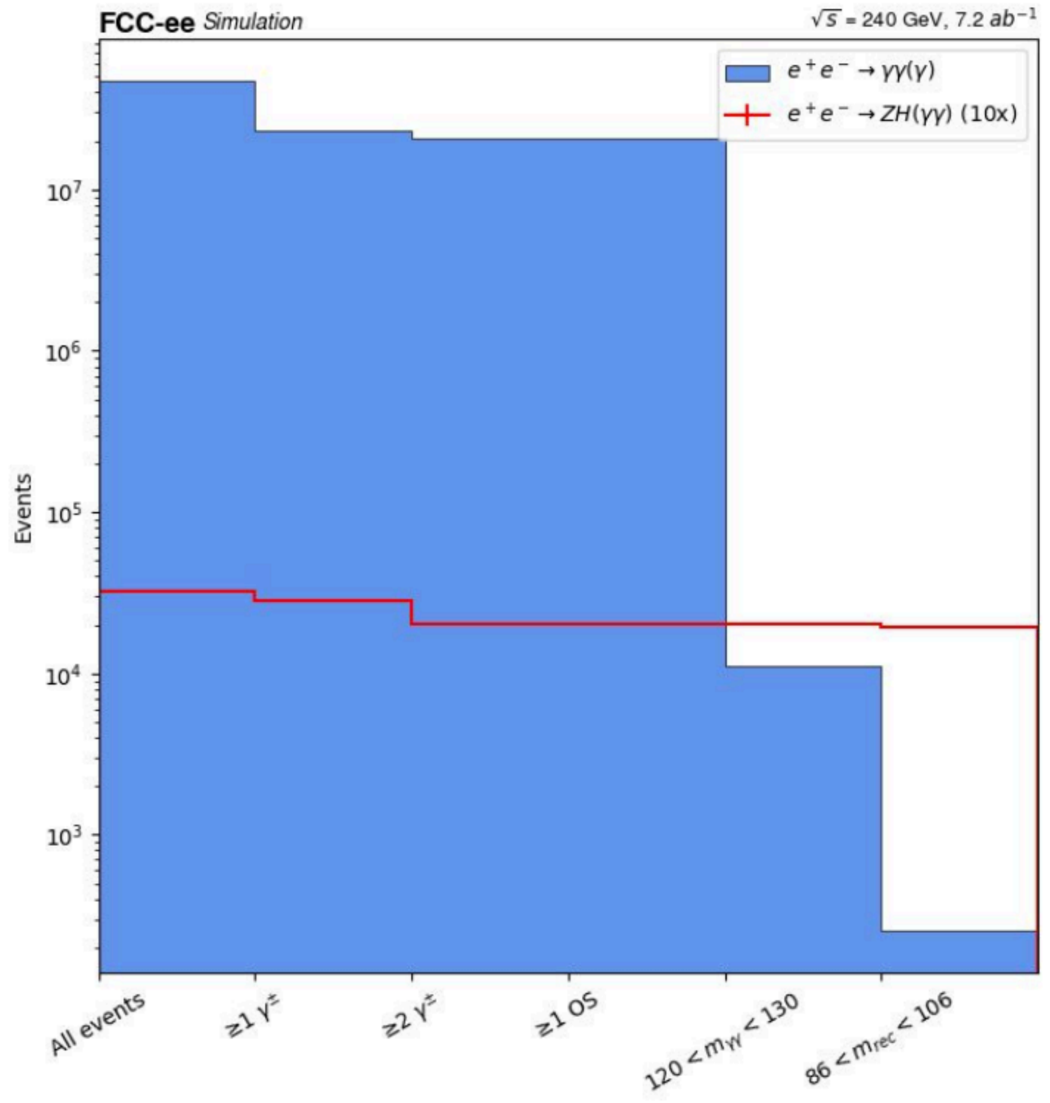
1. Muon momentum threshold of 25 GeV (definition of a good muon);
2. At least two muons;
3. Opposite charge for the muons.

μμ




Torres




**CUTS AND FILTERS**

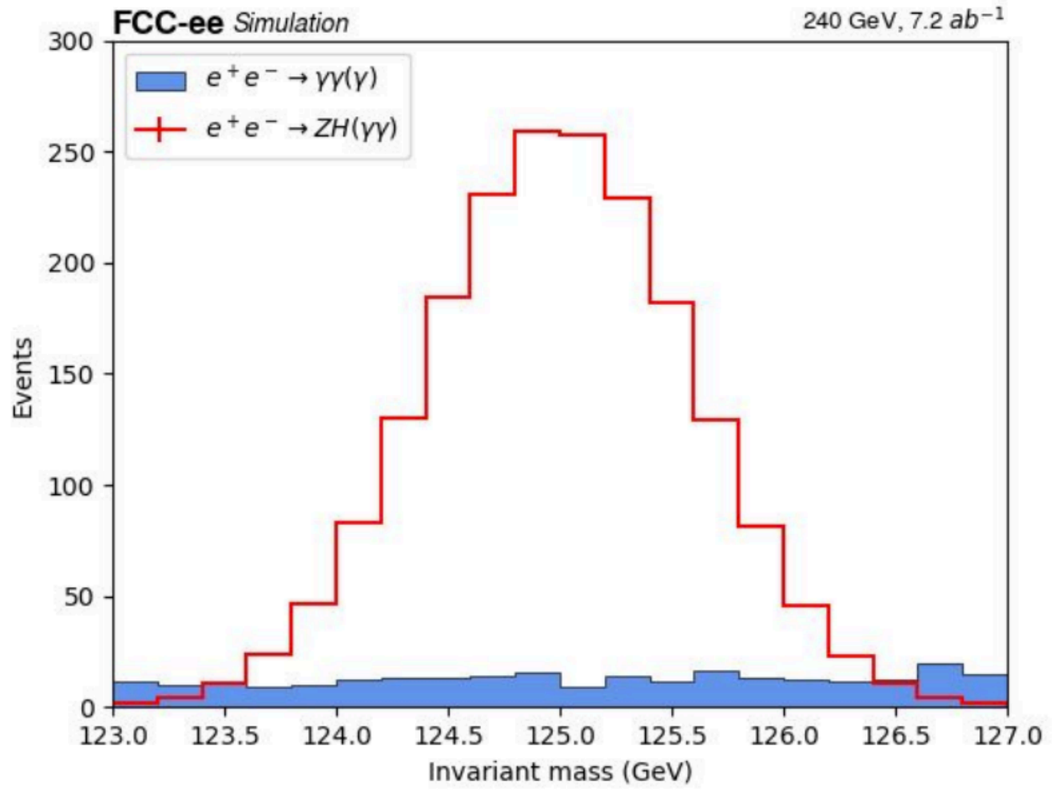
**Object definition**

- Momentum over 40 GeV
- $|\cos\theta_\gamma|$ under .76

**Events cuts**

- Cut 1: at least one photon
- Cut 2 : at least two photons
- Cut 3: at least one resonance with $m_{\gamma\gamma}$ close to 125 GeV
- Cut 4 : 123 < $m_{\gamma\gamma}$ < 127
- Cut 5: 80 < $m_{inv}$ < 111

γγ




The uncertainty on the signal strength is 2.7 %

# Conclusions & outlook

- Monthly informal meetings (next July 24th)
- Many new results will come soon:
  - all ZH(jj) including FCNCs and light (u,d,s)
  - rare decays ($\gamma\gamma$,$\mu\mu$)
  - HZZ, H$\tau\tau$
- Uncovered areas:
  - Higgs rare decays (Z$\gamma$)
  - Higgs Width missing channels (HWW/HZZ)
    - Higgs @365 GeV
  - Higgs CP
  - ….
- Global fit

**FCC-ee Higgs conveners**

**Performance**

Michele Selvaggi, Jan Eysermans

**Programme**

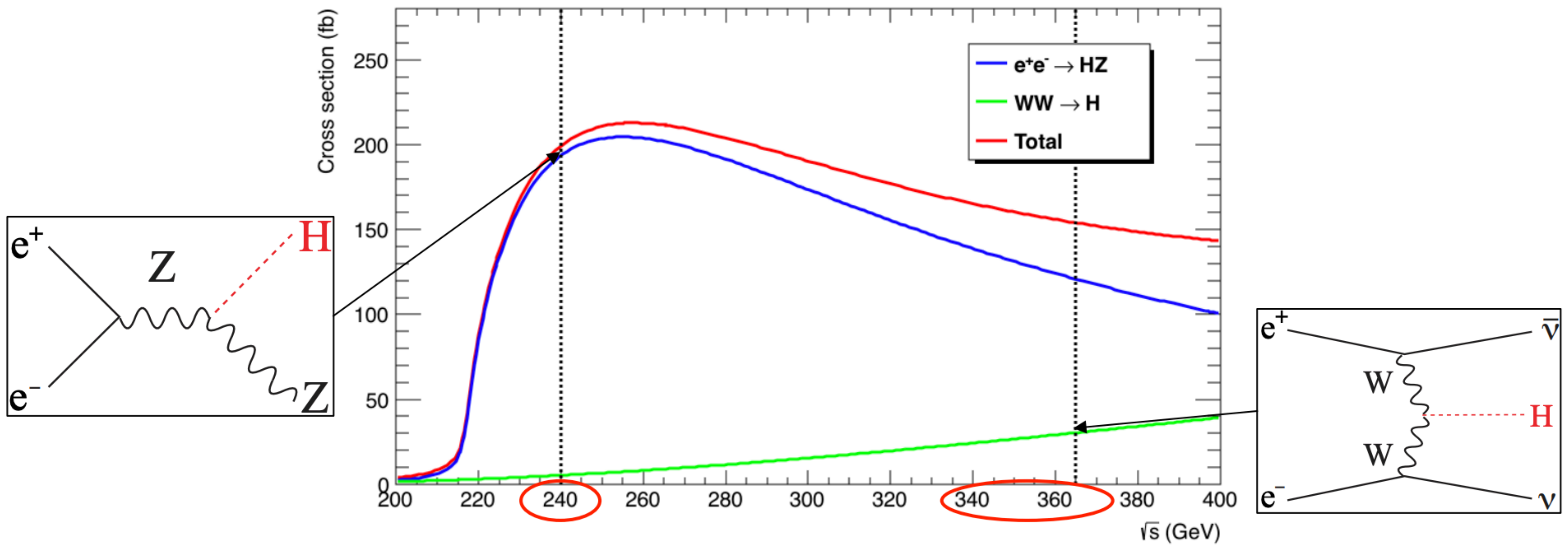
Gauthier Durieux, Christophe Grojean, Jorge De Blas Mateo

FCC-PED-PhysicsGroup-Higgs@cern.ch

Join the effort for an exciting future !

# Backup

# FCC-ee Higgs couplings (part II)




WW fusion added value

- ννH → ννbb ~ $g_W^2\ g_b^2\ /\ \Gamma_H$
  - ννbb / ( ZH(bb) ZH(WW) ~ $g_Z^4\ /\ \Gamma_H$ = R
    - $\Gamma_H$ precision at 1%
- Then do ννH →ννWW ~ $g_W^4\ /\ \Gamma_H$
  - R / ννWW ~ $g_W^4\ /\ g_Z^4$
    - $g_W$ precision to few permil

Running at the top does not simply add statistics
it exploits complementary production mode to improve constraints

BR expected precision with 2 IPs

| $\sqrt{s}$ (GeV) | 240 | | 365 | |
|---|---|---|---|---|
| Luminosity (ab$^{-1}$) | 5 | | 1.5 | |
| $\delta(\sigma BR)/\sigma BR$ (%) | HZ | $\nu\bar{\nu}$ H | HZ | $\nu\bar{\nu}$ H |
| H → any | ±0.5 | | ±0.9 | |
| H → $b\bar{b}$ | ±0.3 | ±3.1 | ±0.5 | ±0.9 |
| H → $c\bar{c}$ | ±2.2 | | ±6.5 | ±10 |
| H → gg | ±1.9 | | ±3.5 | ±4.5 |
| H → $W^+W^-$ | ±1.2 | | ±2.6 | ±3.0 |
| H → ZZ | ±4.4 | | ±12 | ±10 |
| H → $\tau\tau$ | ±0.9 | | ±1.8 | ±8 |
| H → $\gamma\gamma$ | ±9.0 | | ±18 | ±22 |
| H → $\mu^+\mu^-$ | ±19 | | ±40 | |
| H → invis. | < 0.3 | | < 0.6 | |

For 4 IPs, expect:
x 1.7 luminosity / statistics
x 1.3 in expected precision

Abundant statistics and high precision for:
- bb/cc/gg/WW

Limited for:
- rare decays μμ,γγ, Zγ
- HH

# Conclusions & outlook

| FCC-ee parameters | | Z | WW | ZH | ttbar |
|---|---|---|---|---|---|
| √s | GeV | 88 - 94 | 157.2 - 162.5 | 240 | 350-365 |
| Inst. Lumi / IP | $10^{34}$ $cm^2$ $s^{-1}$ | 182 | 19.4 | 7.3 | 1.33 |
| Integrated lumi / 4IP | $ab^{-1}$ / yr | 87 | 9.3 | 3.5 | 0.65 |
| N bunches/beam | - | 10 000 | 880 | 248 | 36 |
| bunch spacing | ns | 30 | 340 | 1 200 | 8 400 |
| L* | m | 2.2 | 2.2 | 2.2 | 2.2 |
| crossing angle | mrad | 30 | 30 | 30 | 30 |
| vertex size (x) | µm | 5.96 | 14.7 | 9.87 | 27.3 |
| vertex size (y) | nm | 23.8 | 46.5 | 25.4 | 48.8 |
| vertex size (z) | mm | 0.4 | 0.97 | 0.65 | 1.33 |
| vertex size (t) | ps | 36.3 | 18.9 | 14.1 | 6.5 |
| Beam energy spread | % | 0.132 | 0.154 | 0.185 | 0.221 |