Towards defining an optimal detector for Higgs hadronic final states

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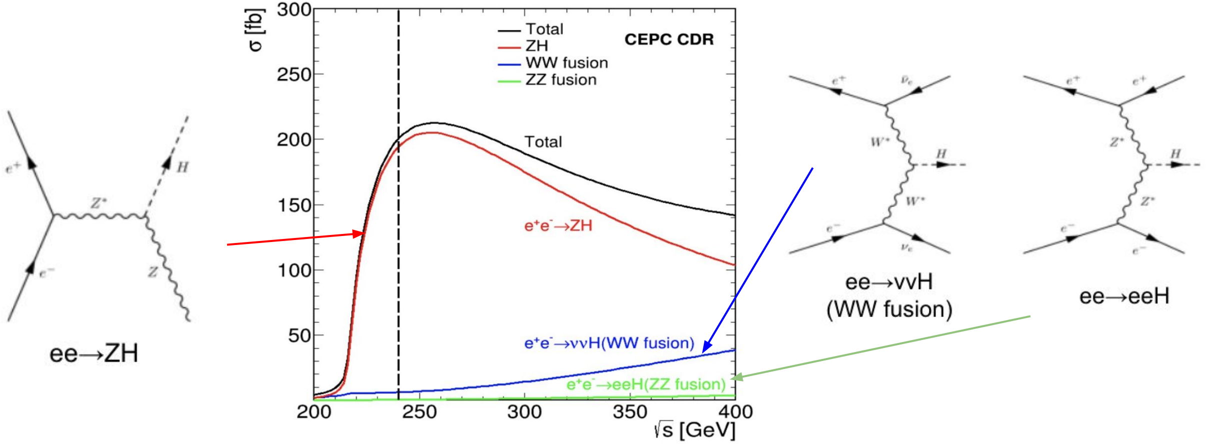
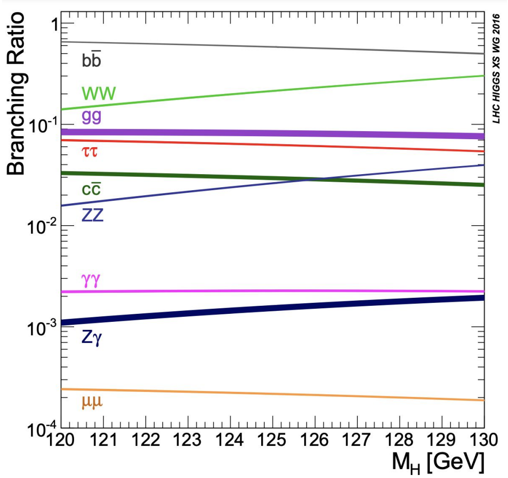
Outline

- Higgs (hadronic) measurements at the ZH pole
- Detector design optimisation
- Hadronic object identification
  - $H \rightarrow$ bb, cc, gg, ss
- Higgs $\rightarrow$ hadron visible mass, energy resolution
  - $Z \rightarrow$ Hadrons, $H \rightarrow$ Invisible

Introduction

- **ZH production** mode dominant
- vvH, eeH sub-dominant
- ee→H





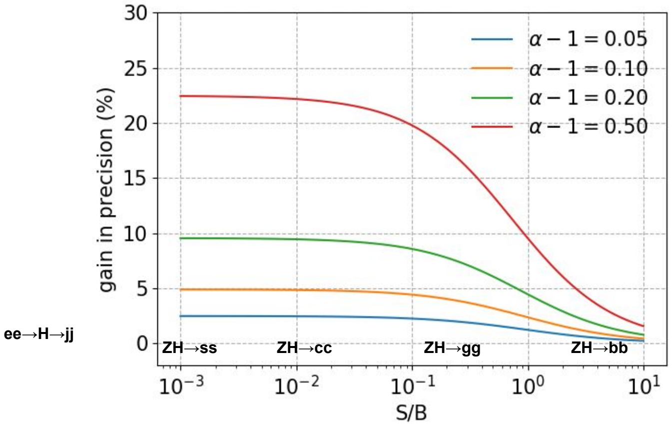
Large hadronic branching fractions:

- BR(H → hadrons) > 0.80
  - BR(H→bb + cc + gg) ~ 0.70
- BR(Z → jj) ~ 0.70

Achieving **optimal performance** on hadronic final states is crucial to the FCC-ee physics programme

Goal

- which **detector design maximises** expected precision for H → gg, bb, cc, ss final states ?
  - final state object flavour jet tagging
    - b,c - tagging vertexing detector
    - strange: PID (ToF, dNdx, Rich)
  - visible energy (mass) reconstruction:
    - **resolution** is crucial, in particular for **rare channels**
      - If S << B , improve resolution by α → improve precision by $\sqrt{\alpha}$
        - e.g. H → ss
      - If S ~ B , improve resolution by α → precision by $\sqrt{(2\alpha / (\alpha+1))}$
        - e.g. H → bb



Hadronic resolution

Energy/Mass resolution in ideal particle flow

visible energy/mass

Consider ee → ZH → νν **j j**

$$\sigma^2(E_{\text{vis}}) = \sum_{i\in \text{tr}} \sigma^2_{\text{tr}}(E^{(i)}_{\text{tr}}) + \sum_{i\in\gamma} \sigma^2_{\text{ecal}}(E^{(i)}_{\gamma}) + \sum_{i\in \text{nh}} \sigma^2_{\text{hcal}}(E^{(i)}_{\text{nh}})$$

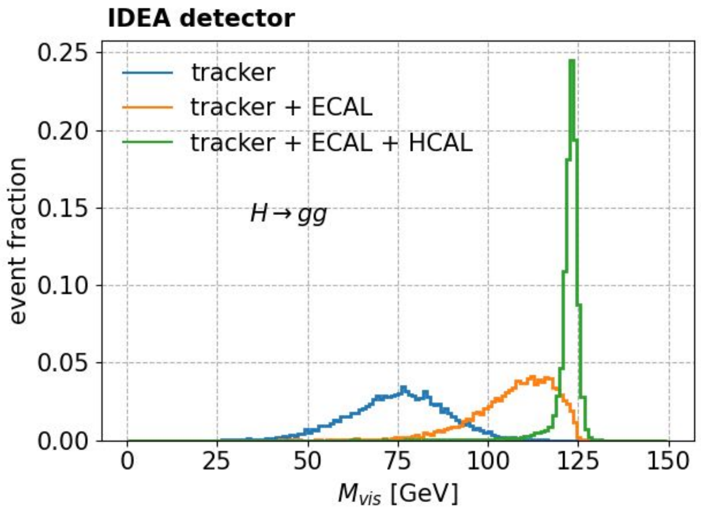
65% 25% 10%

Neglect track resolution, and assume only stochastic calo contribution:

$$\sigma^2(E_{\text{vis}}) = S^2_{\text{ecal}} \sum_{i\in\gamma} E^{(i)}_{\gamma} + S^2_{\text{hcal}} \sum_{i\in} E^{(i)}_{\text{nh}}$$

25% 10%

$$\sigma^2(E_{\text{vis}}) = (f_\gamma S^2_{\text{ecal}} + f_{\text{nh}} S^2_{\text{hcal}}) E_{\text{vis}}$$



→

$$\sigma(E_{\text{vis}}) = \sqrt{\sigma^2_{\text{ecal}} + \sigma^2_{\text{hcal}}}$$

$$\sigma_{\text{ecal}} = S_{\text{ecal}} \sqrt{f_\gamma E_{\text{vis}}}$$

$$\sigma_{\text{hcal}} = S_{\text{hcal}} \sqrt{f_{\text{nh}} E_{\text{vis}}}$$

Ideal Particle Flow
Energy/Mass resolution

$$\sigma(E_{\text{vis}}) = \sqrt{\sigma_{\text{ecal}}^2 + \sigma_{\text{hcal}}^2}$$

$$\sigma_{\text{ecal}} = S_{\text{ecal}} \sqrt{f_\gamma E_{\text{vis}}}$$

$$\sigma_{\text{hcal}} = S_{\text{hcal}} \sqrt{f_{\text{nh}} E_{\text{vis}}}$$

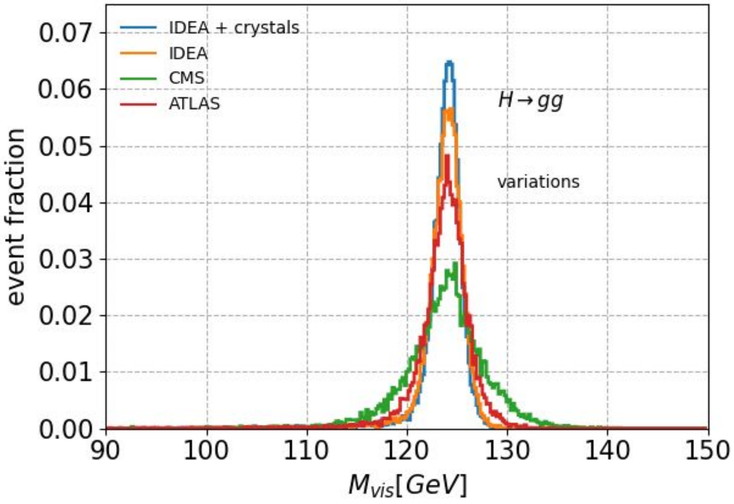
Resolution [GeV]	Crystal Cu/Brass (CMS)	LAr TileCal (ATLAS)	Dual Readout	Dual Readout +Crystal
S_{ECAL}	5%	10%	10%	5%
S_{HCAL}	100%	50%	30%	30%
σ_{ECAL}	0.3 GeV	0.6 GeV	0.6 GeV	0.3 GeV
σ_{HCAL}	3.7 GeV	1.8 GeV	1.1 GeV	1.1 GeV
σ	3.7 GeV	1.9 GeV	1.2 GeV	1.1 GeV

- Assuming an ideal Particle Flow, HCAL dominates the hadronic resolution
- Assumes:
    - all available energy is reconstructed
    - no particle overlap

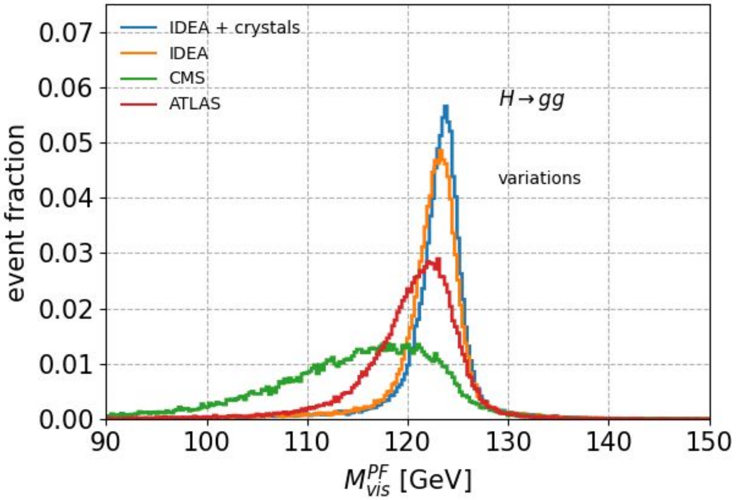
Ideal PF → "realistic" PF

<u>note</u>: no jet clustering

Ideal Particle Flow



Delphes Particle-flow

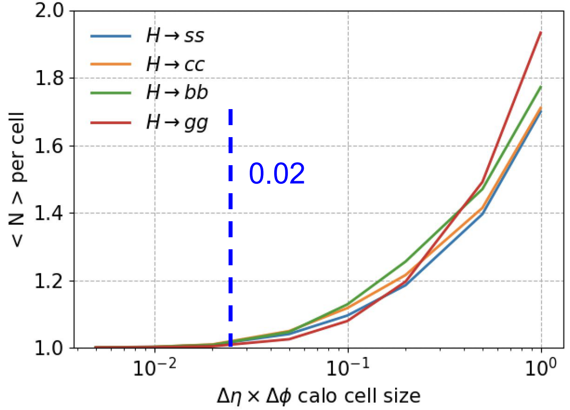


- **inefficient tracks** reconstructed as neutral hadrons
- low momentum **photons / neutral hadrons inefficiencies**
- **fake neutral hadrons / photons** from particle flow
- **overlapping photons/neutral hadrons** reconstructed as neutral hadrons

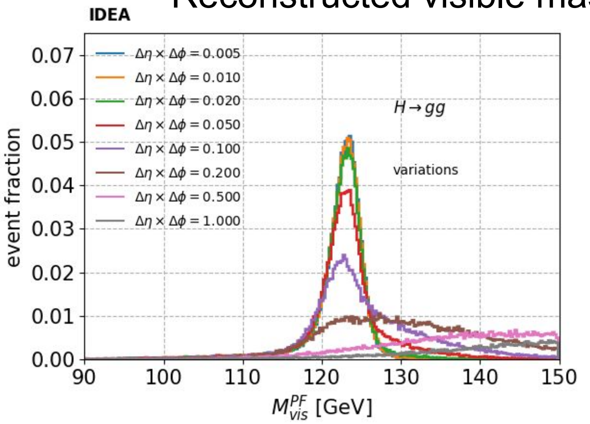
Resolution [GeV]	Crystal Cu/Brass (CMS)	LAr TileCal (ATLAS)	Dual Readout	Dual Readout +Crystal
σ(IDEAL)	3.7 GeV	1.9 GeV	1.2 GeV	1.1 GeV
σ(DELPHES)	6.9 GeV	3.5 GeV	2.2 GeV	2.1 GeV

Granularity

<N> particles per cell

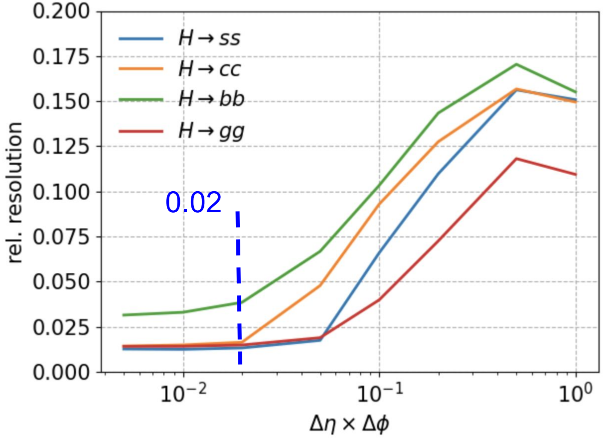


Reconstructed visible mass

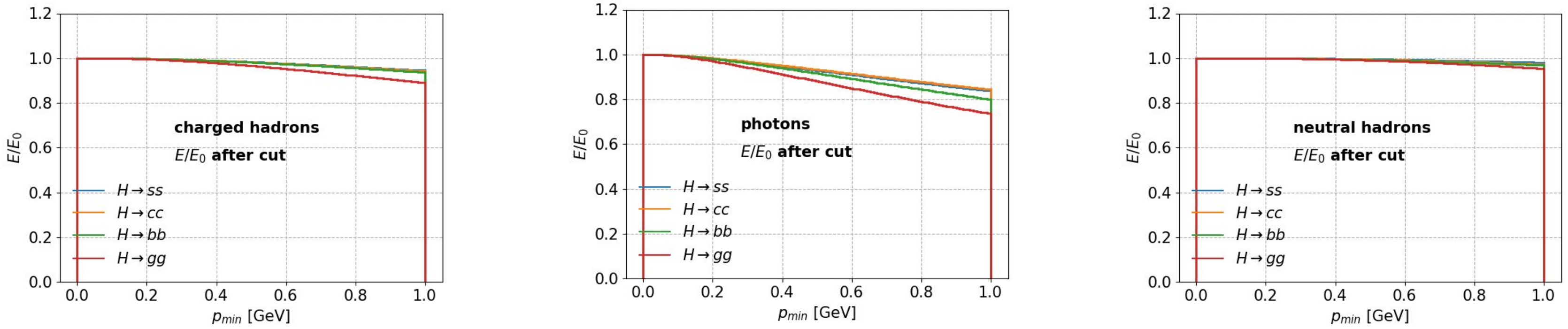


- As expected granularity impacts mass resolution considerably (loss in angular resolution)
- Θ ~ 0.02 angular resolution seems sufficient
  - caveats:
    - assuming the same scale for a transverse shower size
    - particle-flow not re-tuned for coarser granularities

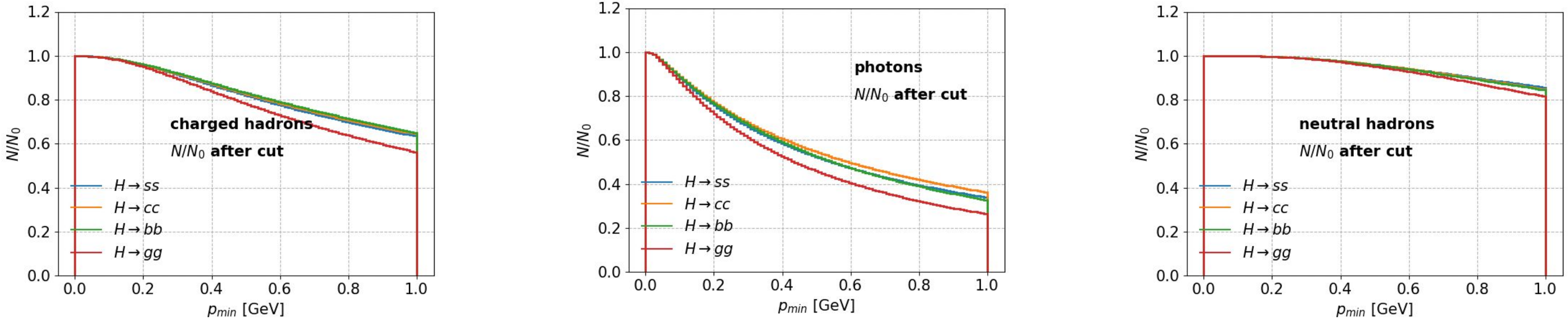
mass resolution vs granularity



Higgs hadronic decays component spectra

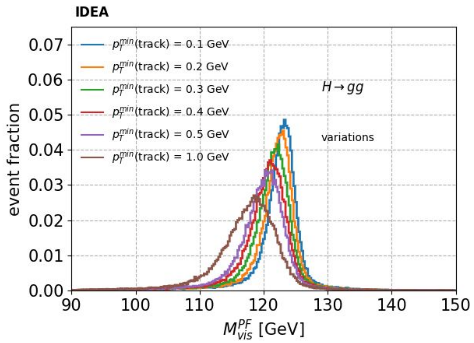


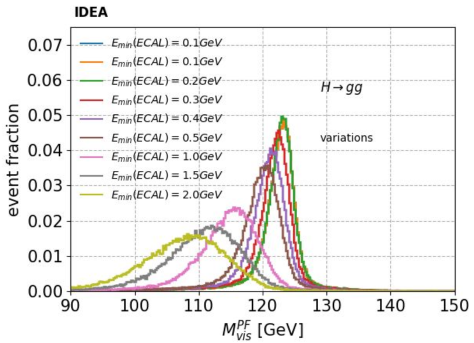
How much visible energy/multiplicity at low momenta ?

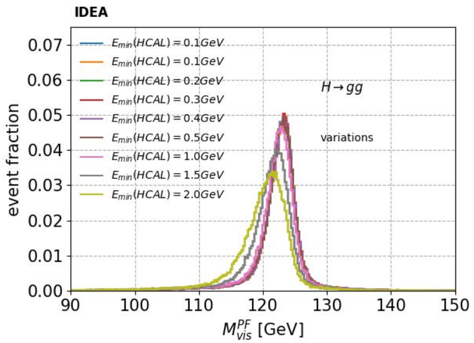


- Neutral Hadrons are harder: HCAL mass resolution should not suffer from low threshold
- Photons are the softest (in particular in H→gg), mass resolution should degrade substantially if p < 200 MeV not reconstructed

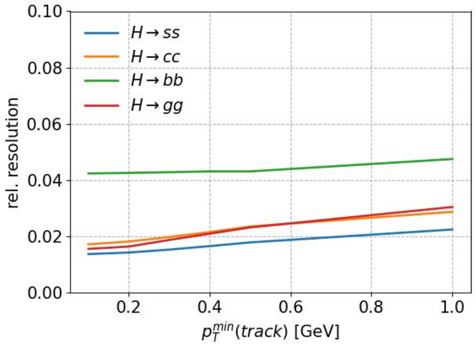
Higgs hadronic decays component spectra

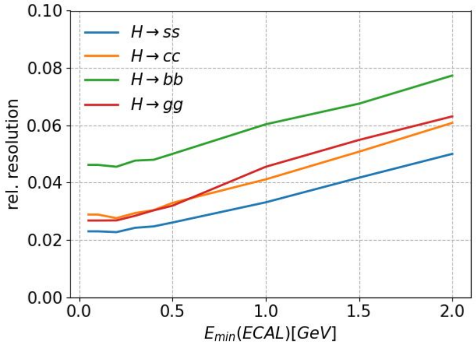


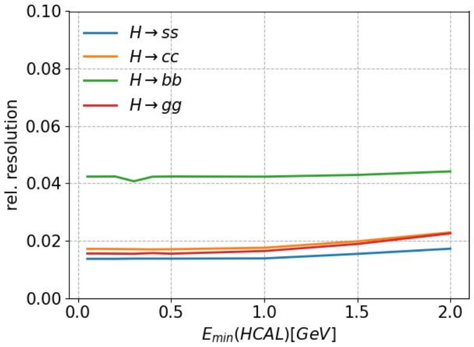




How much visible energy/multiplicity at low momenta ?







- Neutral Hadrons are harder: HCAL mass resolution should not suffer from low threshold
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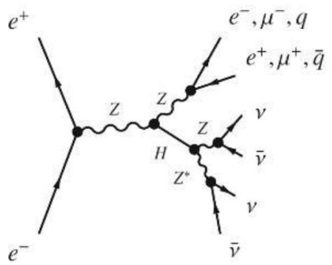
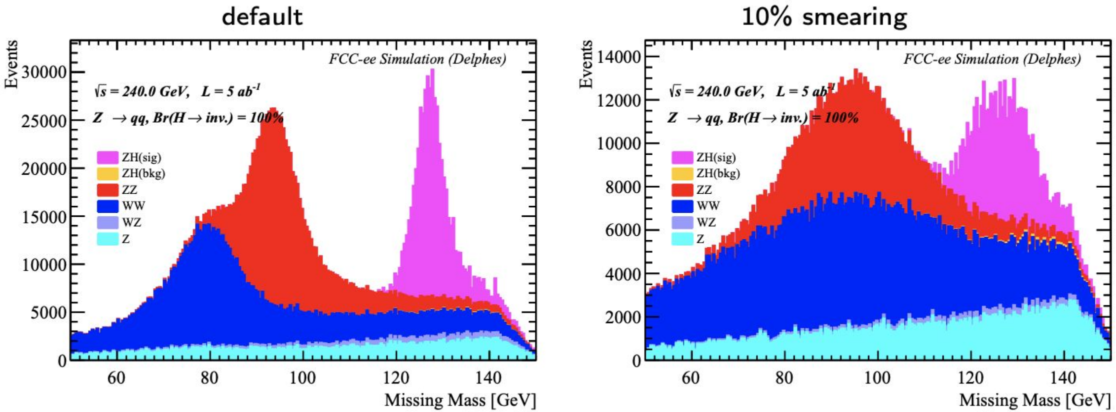
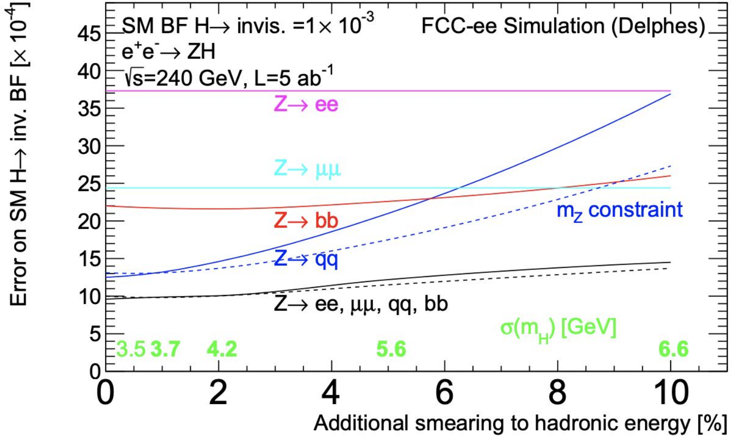
H→ invisible







- smearing has a large impact on qq channel
- can be reduced with Z mass constraint
- overall impact is small due to leptonic channels

Heavy flavour tagging

HF tagging - b/c tagging

- Large lifetime
  - b (c) decay length: ~5 (2-3) mm for ~50 GeV boost
- Large track multiplicity
  - ~5 (~2) charged tracks/decay
- Non-isolated e/μ
  - ~20 (10)% in B (C) decays

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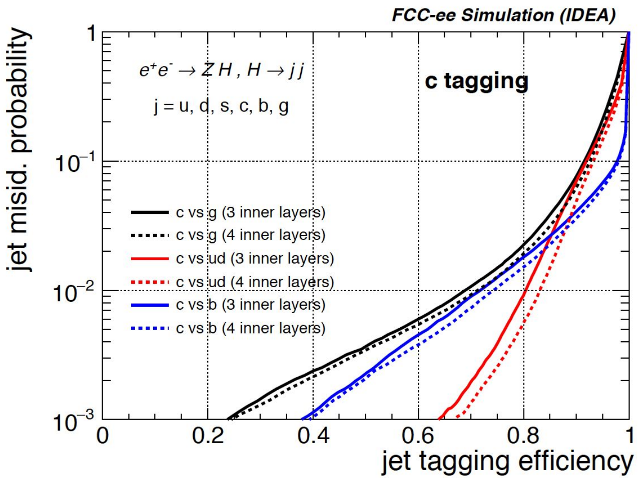
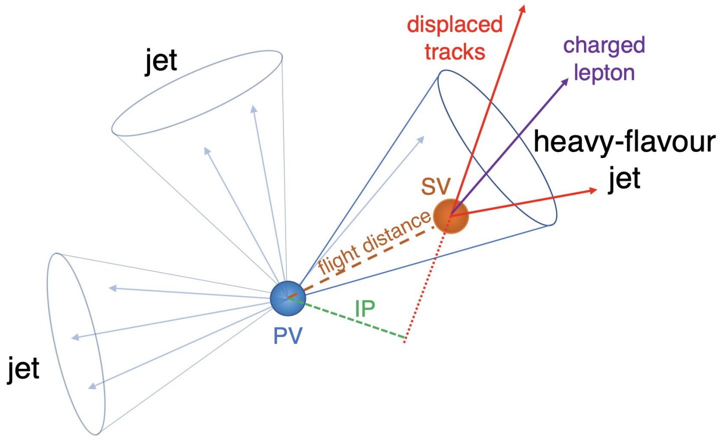


x2 light quark rejection with additional pixel layer at 1 cm from IP



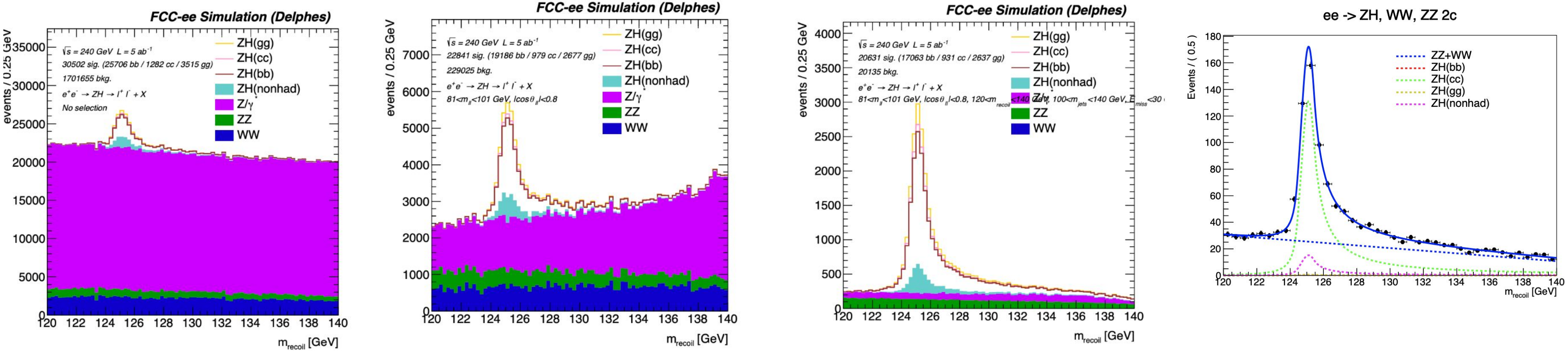
Detector constraints:

Need power pixel/tracking detectors

- excellent IP resolution
  - first pixel closest to IP
  - lightest tracker

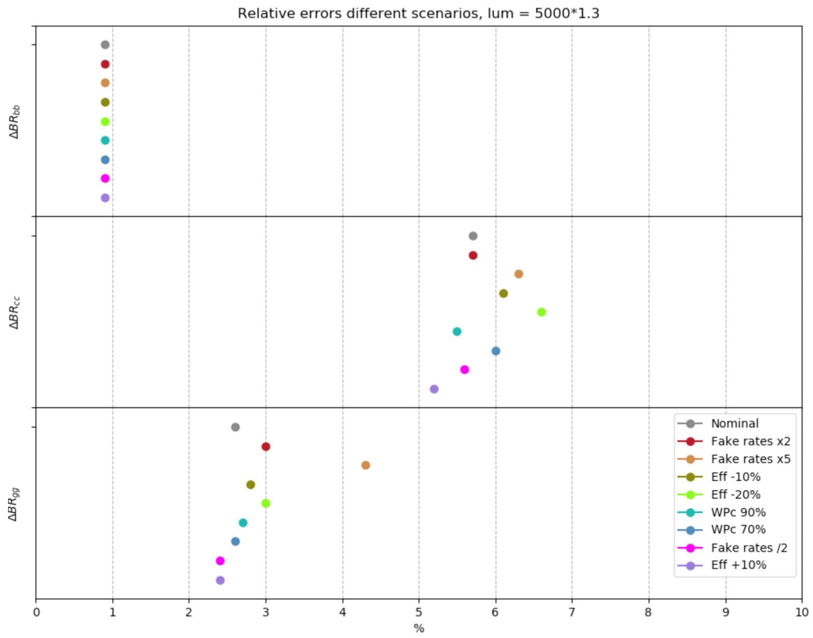
H→ bb/cc/gg

After reconstruction *After Z selection* *After recoil, jets, Emiss selection*



- Events are **classified in mutually orthogonal categories** based on the number of b-, c- and g-tags (2c category also requires < 2b tags)
- **Simultaneous S+B fit to the recoil mass** of the event categories
    - Background model: simple functions (polynomials, exponentials) with floating parameters in each category
    - Signal model: double-sided Crystal Ball with same parameters in each category
    - Non-hadronic BR is fixed to SM prediction (assume to measure it precisely with other channels) - though some constraining power from 0b0c0g category

H→ bb/cc/gg



Expected precision using only the Z→ ll channel

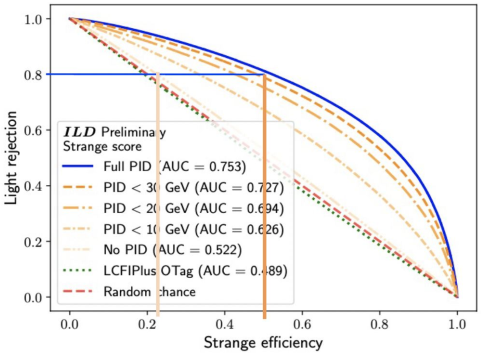
Results with various tagging performance/WP scenarios (lum +30%)

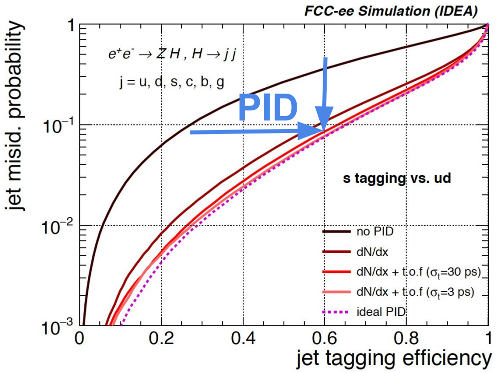
Strategy	ΔBR_{bb} (rel., %)	ΔBR_{cc} (rel., %)	ΔBR_{gg} (rel., %)
Nominal	0.9	5.7	2.6
Fake rates x2	0.9	5.7	3.0
Fake rates x5	0.6	6.3	4.3
Eff -10%	0.9	6.1	2.8
Eff -20%	0.9	6.6	3.0
WPc 90%	0.9	5.5	2.7
WPc 70%	0.9	6.0	2.6
Fake rates /2	0.9	5.6	2.4
Eff +10%	0.9	5.2	2.4

- H→ bb very **pure in all sensitive categories** (2 btags, 1btag)
  - barely affected by variations (nor in fake rate nor from tagging efficiency)
- H→ cc / gg are fairly sensitive to detector performance assumption

HF tagging - Strange tagging

- Charged Kaon as track:
  - K/pi separation
- Neutral Kaons:
  - $K_S \rightarrow \pi\pi$
    - Displaced 2 track vertex
    - 4 photons
  - K_L TOF vs n ?





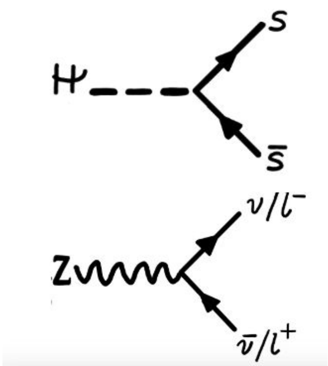
Detector constraints:

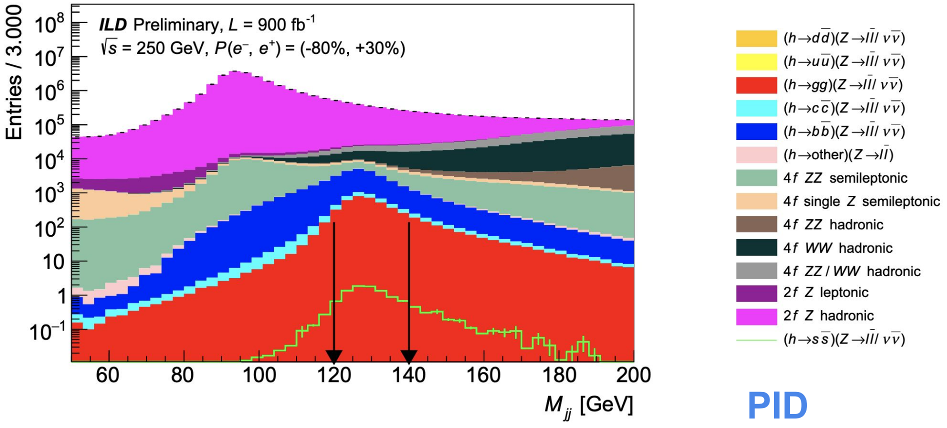
- Excellent PID:
  - Low momentum (p<5 GeV):
    - timing detectors
  - High momentum (p>5 GeV)
    - charged energy loss (gas/silicon)
    - cherenkov

- 2.5x increase in tagging efficiency with PID
- x10 reduction in light mistag rate

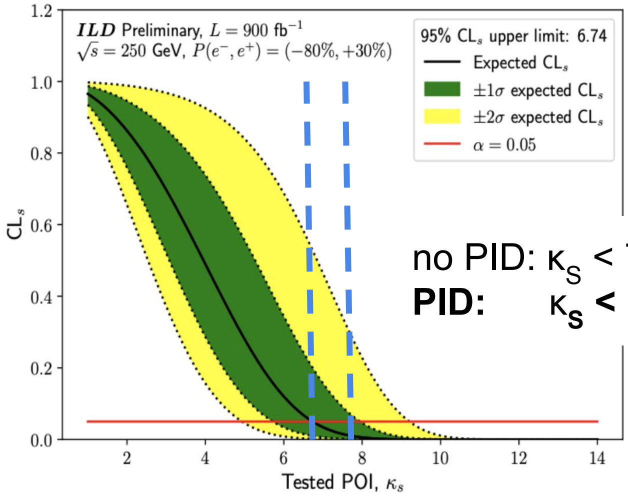
- No need for K/pi separation > 30 GeV
- 30 ps timing sufficient for low momentum K/pi separation

Higgs to strange





PID ←



no PID: κ_S < 7.8
PID: κ_S < 6.7

- BR(H→ ss) = BR (H→ cc) $(m_s/m_c)^2$ ~ 2.3 10^{-4}
- Expect: 200 H→ss events
- Large backgrounds:
  - Other hadronic Higgs decays
    - 600k H→bb, 100k H→gg, 30k H→cc,
  - The most challenging BKG is ZZ with one Z off-shell ~125 GeV

- **Particle ID crucial to reduce other Z/H→ jj backgrounds**
- Optimal hadronic mass resolution for irreducible Z→ ss

Conclusions

Higgs precision (in hadronic final states), relies on:

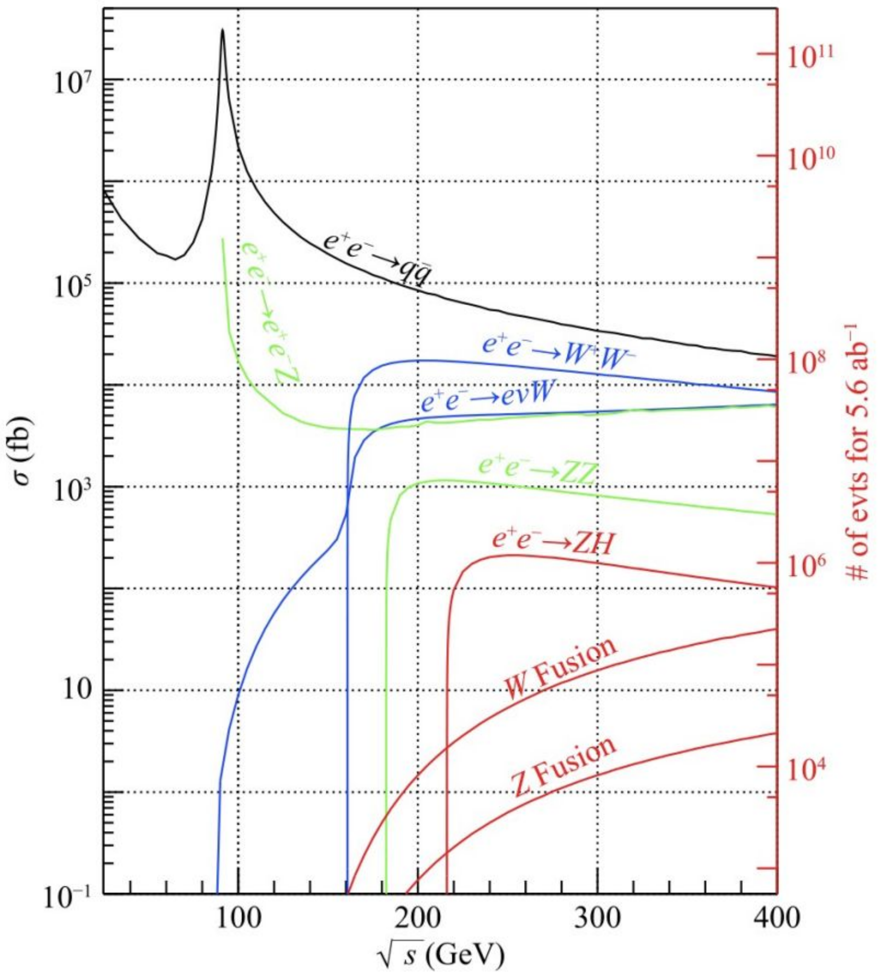
- efficient tagging of hadronic final states directly affects Higgs precision.
    - b/charm tagging relies on light tracker (minimise MS), excellent IP resolution
    - strange tagging relies on PID:
        - low momentum TOF
        - High momentum dNdx/RICH

- ability to reconstruct visible mass with high resolution:
    - with Ideal Particle Flow HCAL (angular/energy resolution) limits the H→ hadrons mass resolution:
        - DR (crystals) $\gtrsim$ DR > ATLAS > CMS
        - H→ hadron particle content mostly of soft particles (in particular in H → gg):
            - it is important to reconstruct low momentum particles (p~ 100-200 MeV), in particular photons from π^0
                - need low material budget in front of ECAL (timing detector? cryostats)
                - low electronic noise
        - Charged particle reconstruction efficiency is also crucial (missed ch. hadron → hcal)

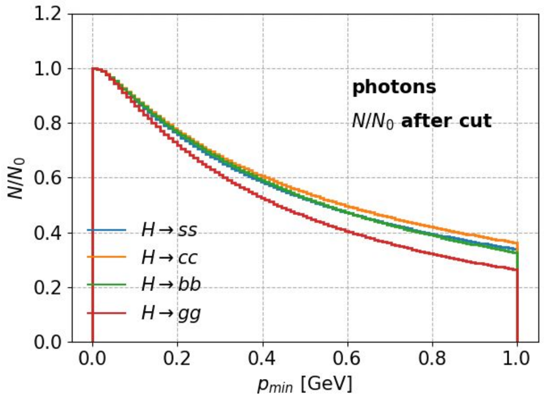
    - Is 1-2% mass resolution/visible energy resolution seems to be a fundamental limit

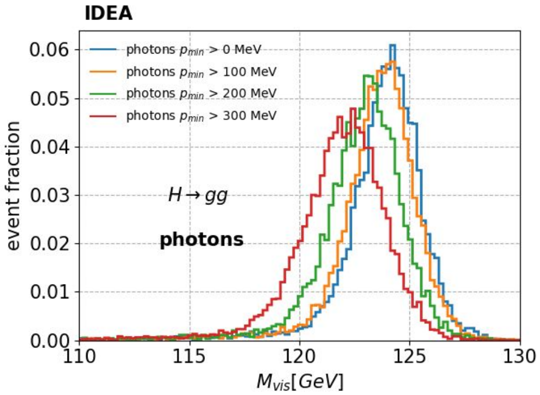
Backup

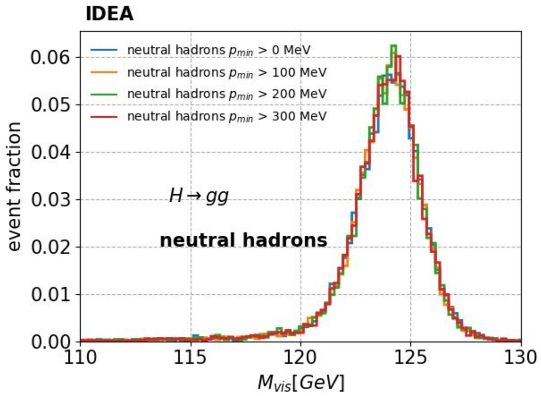
Backgrounds



Backgrounds







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