Detector Requirements from Physics

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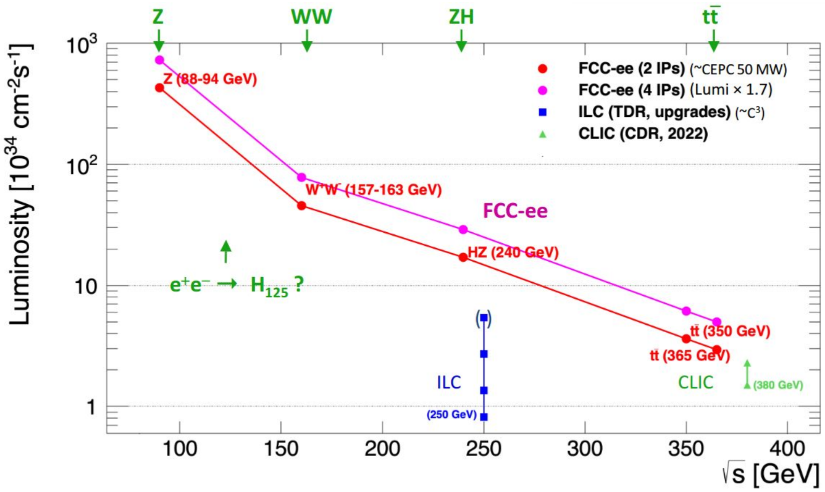
FCC Week - London

June 5th, 2023

A few general considerations



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:

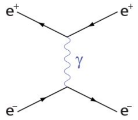
- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day

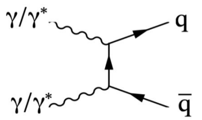
Detector requirements - general considerations

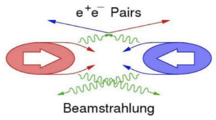
- Requirements for Higgs and above have been studied to some extent by LC:
  - have to be revised by FCC-ee
  - we want a detector that is able to withstand a large dynamic range:
    - in energy ($\sqrt{s}$ = 90 - 365 GeV)
    - in luminosity (L = 10^{34} - 10^{36} cm^2/s)

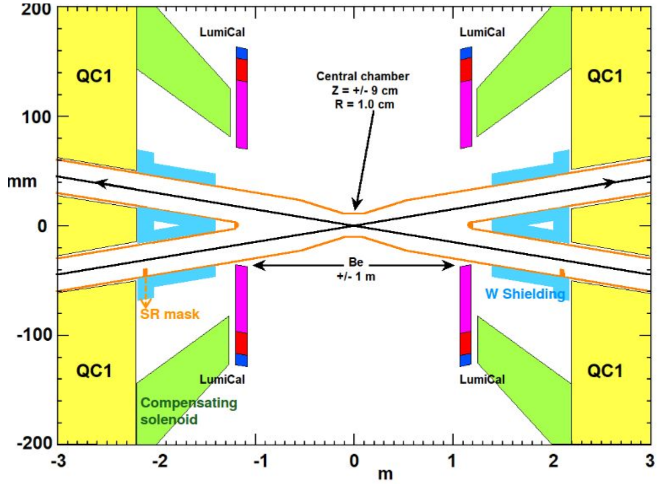
- most of the machine induced limitations are imposed by the Z pole run:
  - large collision rates ~ 33 MHz and continuous beams
    - no power pulsing possible
  - large event rates ~ 100 kHz
    - fast detector response / triggerless design challenging (but rewarding)
    - high occupancy in the inner layers/forward region (Bhabha scattering/γγ hadrons)
  - beamstrahlung

- complex MDI: last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
    - limits the achievable track momentum resolution
  - “anti”-solenoid
    - limits the acceptance to ~ 100 mrad





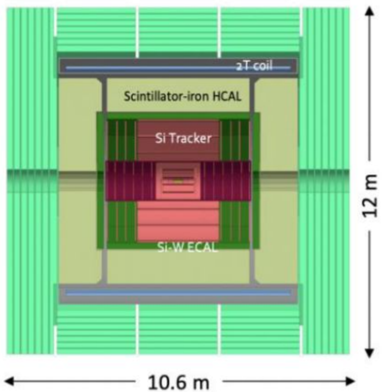




Detector concepts

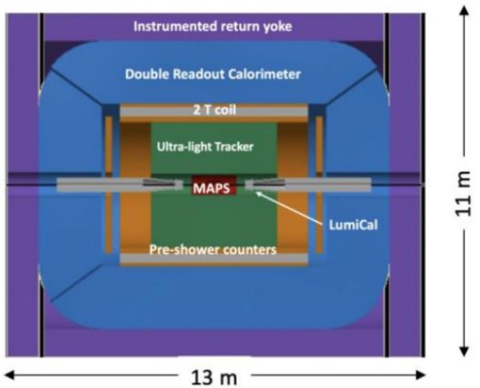
see Detector sessions (Thursday 11:30AM, 2:30PM)

CLD



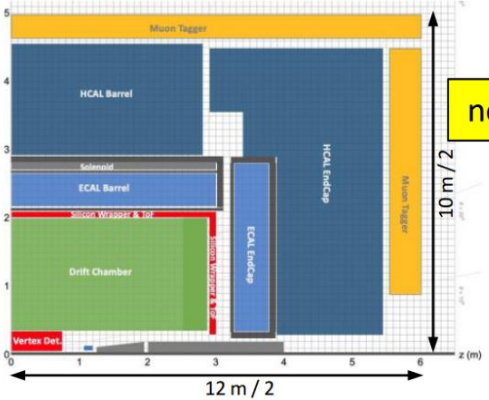
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based



new

- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

Physics landscape at the FCC-ee

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/*τ* factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \rightarrow \tau\, \nu$
$B_s \rightarrow D_s\, K/\pi$
$B_s \rightarrow K^* \tau\, \tau$
$B \rightarrow K^*\, \nu\, \nu$
$B_s \rightarrow \varphi\, \nu\, \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, *τ* pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector requirements at the FCC-ee

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
“boosted” B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

BSM
feebly interacting particles

Large decay volume

High radial segmentation
- tracker
- calorimetry
- muon

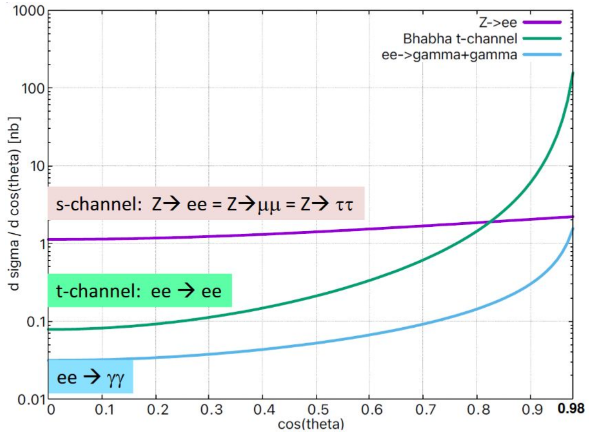
impact parameter resolution for large displacement

triggerless

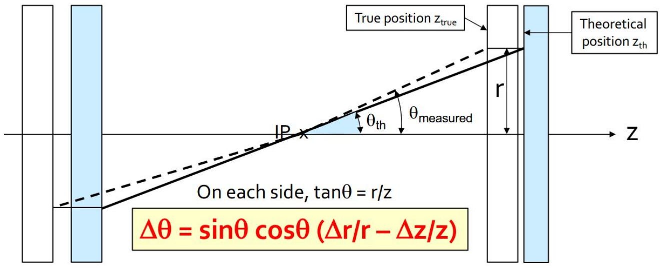
Highlights from recent activities

Luminosity/acceptance

see P. Janot (wed. tbc)



- Precise knowledge of the **geometrical acceptance** required by
  - R^Z_ℓ measurement (as limiting systematics)
  - absolute luminosity measurement at Z pole, required by
    - peak Z cross section (σ_0)
- At LEP, via Bhabha scattering at low angle, here we require 10^{-5} precision (for point-to-point), 10^{-4} being absolute target
  - un-matched by theoretical calculations
  - use **ee → γγ** process as an alternative, rarer but cleaner TH
- To match stat. precision ($2x10^{-5}$)
  - must know **$\Delta\theta_{min}$ ~ 10 μrad**
    - equivalent to **Δr ~ 30 μm**, **Δz ~ 80 μm** at θ = 20° and z = 2.6m
      - challenging design requirement !!

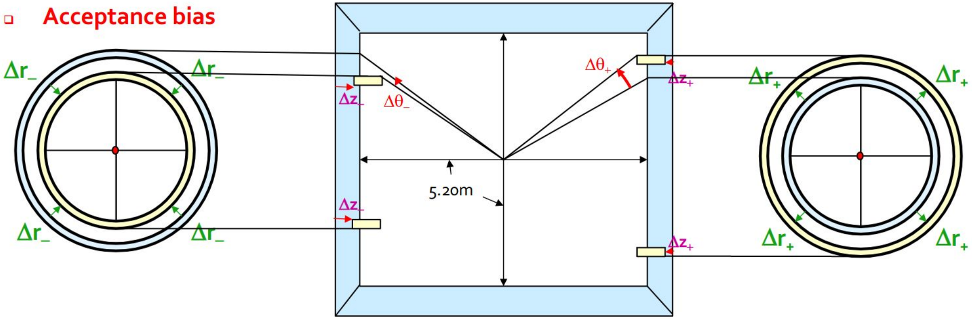


Luckily, it turns out could be measured in situ!

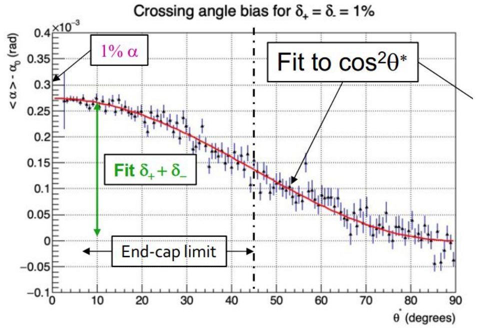
Luminosity/acceptance

see P. Janot (wed. tbc)

- Acceptance bias



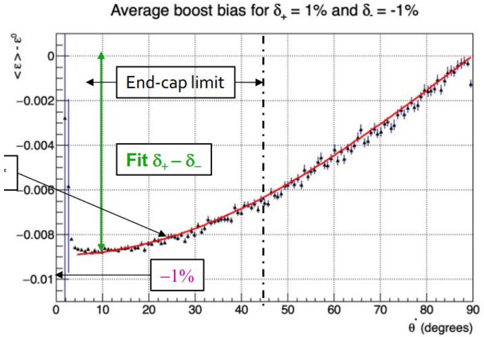
$$\Delta\theta_{\pm} = \delta_{\pm}\sin\theta_{\pm}\cos\theta_{\pm}\ with\ \delta_{\pm} = \left[\frac{\Delta r_{\pm}}{r_{\pm}} - \frac{\Delta z_{\pm}}{z_{\pm}}\right]$$



$$\Delta\alpha(\theta^*) \approx \frac{\alpha}{2}\cos^2\theta^* \times (\delta_+ + \delta_-)$$

measuring outgoing 4-momenta of photons

- energy/momentum conservation, allows:
  - **solve** for the crossing-angle **α** and the beam energy asymmetry **ε** on an **event-by-event** basis
  - extract potential bias from the known dependency of **α** and **ε** with the bias



can measure av. radius and z to **Δr ~ 2 μm**, **Δz ~ 10 μm**
→ **x10 better than needed to match stat. Precision**
(assuming **0.5 mm position resolution** for photons)

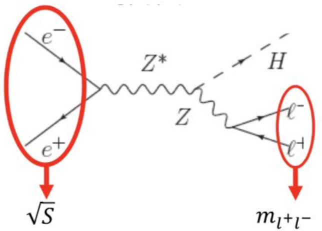
$$\Delta\varepsilon(\theta^*) \approx -\frac{\cos\theta^*}{2} \times (\delta_+ - \delta_-)$$

This in-situ calibration technique could be used to determine lumiCal acceptance
(with low angle Bhabha, 1.6 μm tolerance needed, for 10^{-4} lumi meas.)

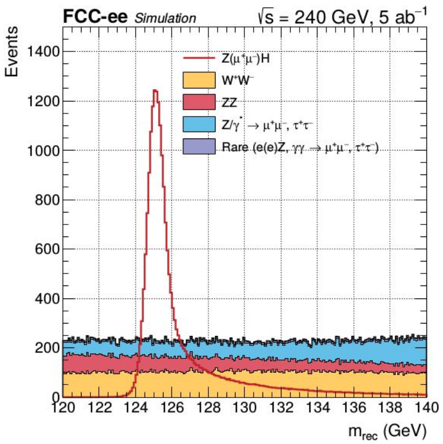
Track Momentum resolution

see J. Eysermans, L. Portales (wed.)

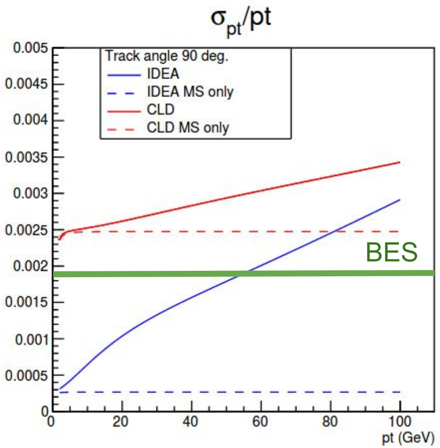
- **Higgs mass** and **ZH production cross-section** can be extracted from the **recoil mass distribution**



$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

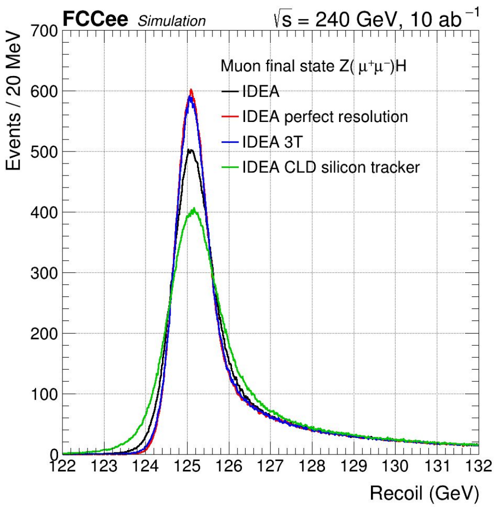


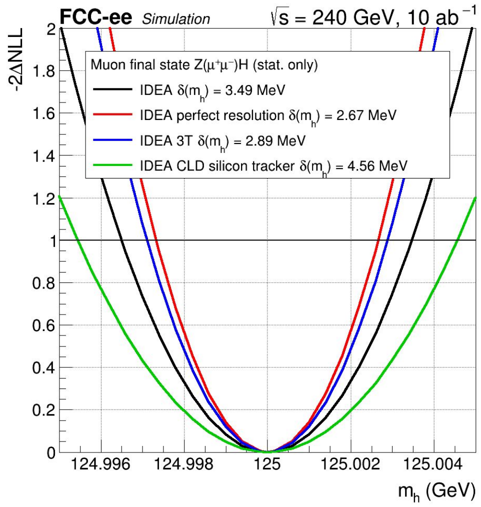
- sensitivity dominated by the Z(μμ) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if > beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
  - multiple-scattering limit < BES
    - for CLD ~ 30% above
      - **transparent**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



Track Momentum resolution

see J. Eysermans, L. Portales (wed.)





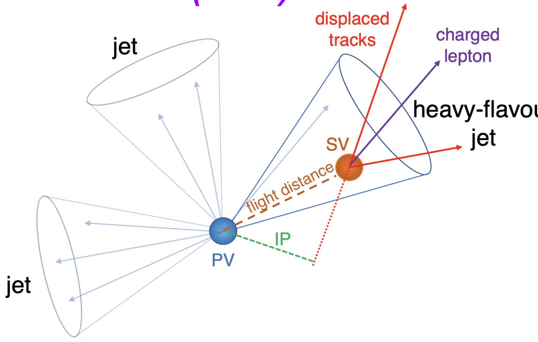
using μμ channel

tracking system	Δm_H (MeV) stat.only	Δm_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**

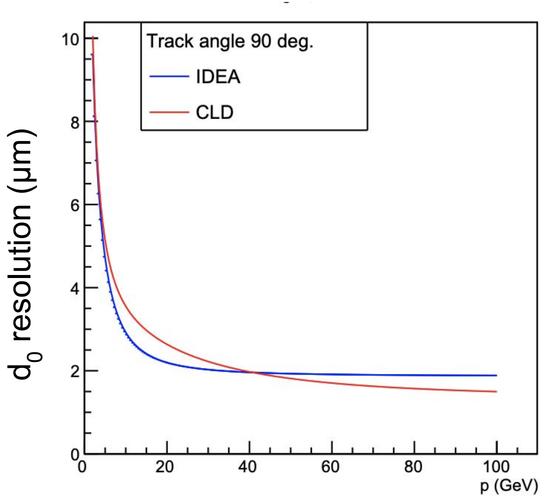
- we want to get down to **$\Delta m_H \sim \Gamma_H \sim$ 4 MeV** to allow for electron Yukawa at √s = 125 GeV
- as expected, tracking resolution highly impacts m_H precision
- light tracker/ **high B field** highly preferable

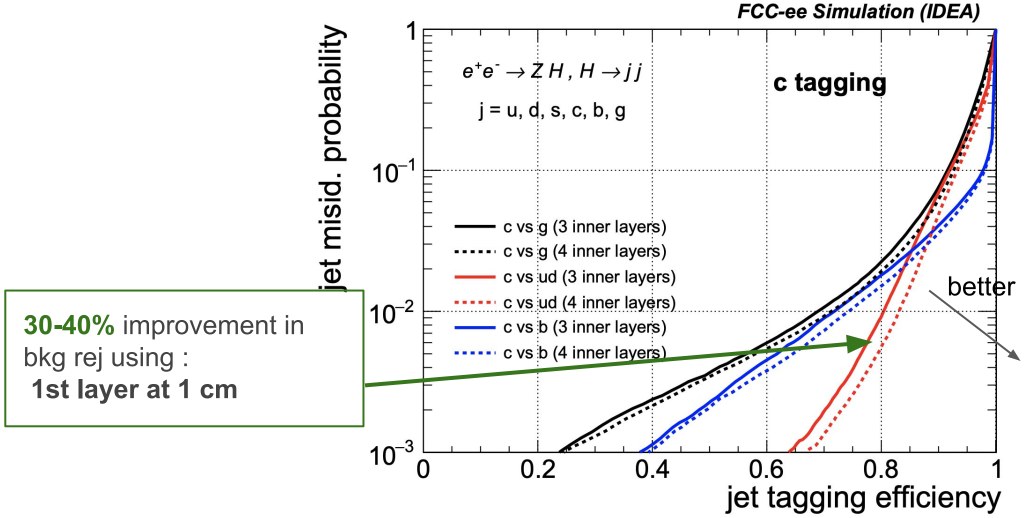
Track impact parameter resolution and vertexing

see J. Eysermans, L. Gouskos (wed.)



- **Impact parameter resolution** major driver of jet **charm** and **bottom** jet identification
  - B (D) mesons travel a finite decay length 500 (150) μm
- precise IP determination driven by:
  - single point resolution
  - **radial distance of first tracking layer** from the interaction point (at large momentum)
    - need small radius beam-pipe
  - material budget X/X_0 (at low p)

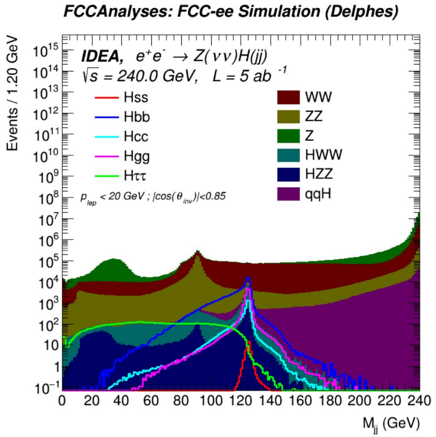




Track impact parameter resolution and vertexing

see J. Eysermans, L. Gouskos (wed.)

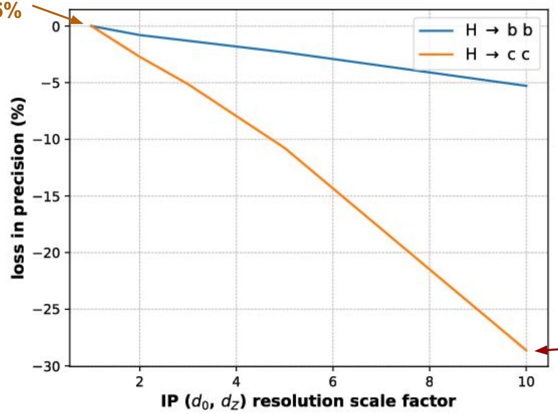
- BR(H→jj) jj = **bb**, **cc** precision rely on excellent displaced track reconstruction
- Z(ll - vv - jj)H(jj)
  - sensitivity driven by Z(vv)H so far
    - large “jet” background from WW, ZZ, Z



nominal expected precision (%) in vvH channel

$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to s\bar{s}$	$H\to gg$
0.28 %	**2.05 %**	**100 %**	**0.85 %**

nominal performance: δμ(Hcc) = 2.05%



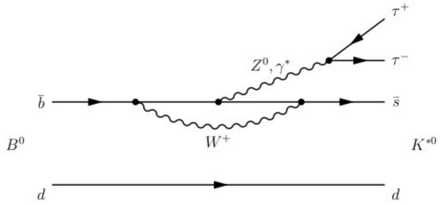
pessimistic performance: δμ(Hcc) = 2.64%

worse IP resolution impact **H→cc** vs **H→bb** due to smaller displacement and smaller S/B

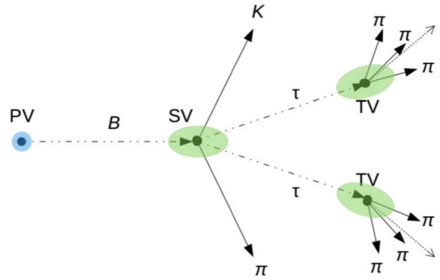
Effort on the fully hadronic channel has started

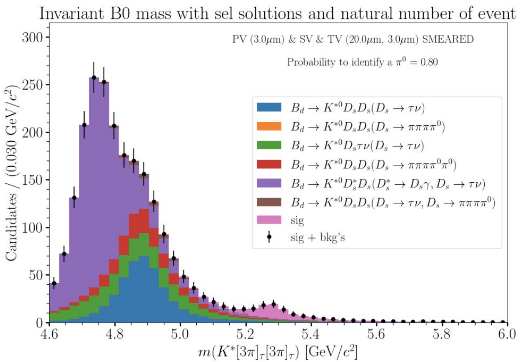
Track impact parameter resolution and vertexing

see T. Miralles (wed.)

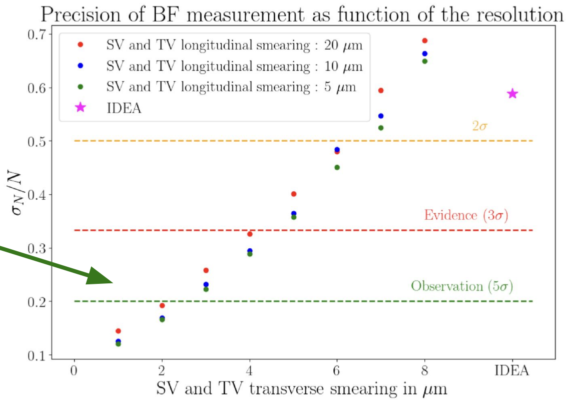


- $B_s \rightarrow K^* \tau\, \tau$ important channel to study **LFU** in **b→s transitions**
  - focusing on 3-prong τ decays
- very rich signature with :
  - 8 visible particles (1K, 7π)
  - 1 secondary vertex and tertiary vertices
- very complex analysis: many **backgrounds** and **combinatorics**
- $B_s \rightarrow K^* \tau\, \tau$ sensitivity driven by **vertex resolution** to make maximal use of kinematic constraints





5σ observation with **2 μm** vertex resolution

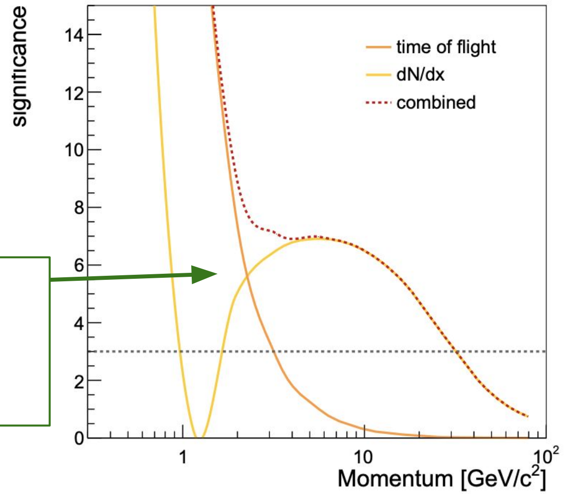


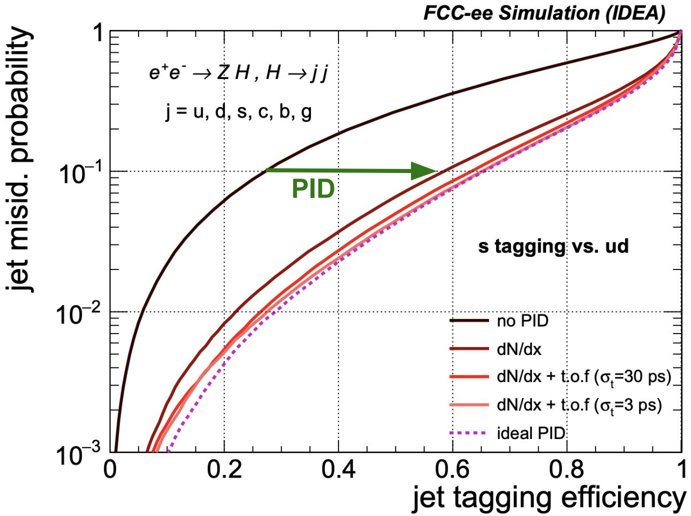
Charged hadron particle identification (K/π/p discrimination)

see L. Gouskos, A. Tolosa Delgado, M. Kenzie (wed.)
R. Forty (thursday)

- PID crucial ingredient of
  - flavor physics measurements: $B_s \rightarrow D_s K$, $B \rightarrow K^* \nu \nu$, $B_s \rightarrow \varphi \nu \nu$ …
  - **strange quark** jet identification ($H \rightarrow ss$, V_{ts}, V_{cs}, $H \rightarrow bs$, FCNCs ..)
  - e/π separation at level of 10^{-5} required for $\tau \rightarrow e$ (calorimetry)
- Toolbox:
  - High momentum dE/dx (**dN/dx**) - Cherenkov detectors (**RICH**)
  - Low momentum: **Time of flight**

ToF + dNdx/Cherekov = PID for p < 30 GeV





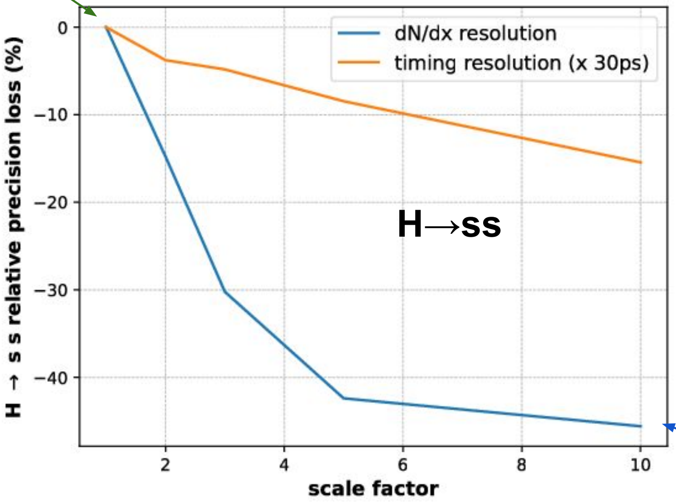
Charged hadron particle identification (K/π/p discrimination)

see L. Gouskos (wed.)

expected precision on BR(H→ss) ~100%
with 10 ab^{-1} (only using ννH channel)

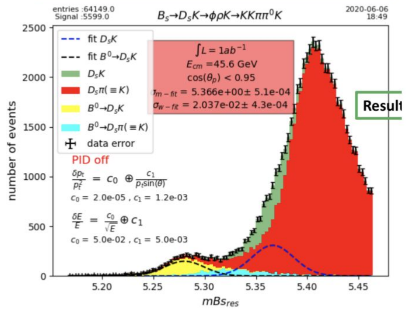
PID performance: **dN/dx > timing** resolution

ominal performance: δμ(Hss) = 100%



degraded dN/dx resolution: δμ(Hss) = 140%

Very good ECAL, no PID

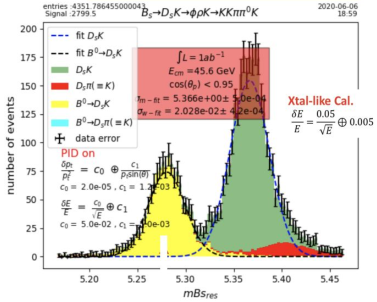


$B_s \to D_s K$

PID

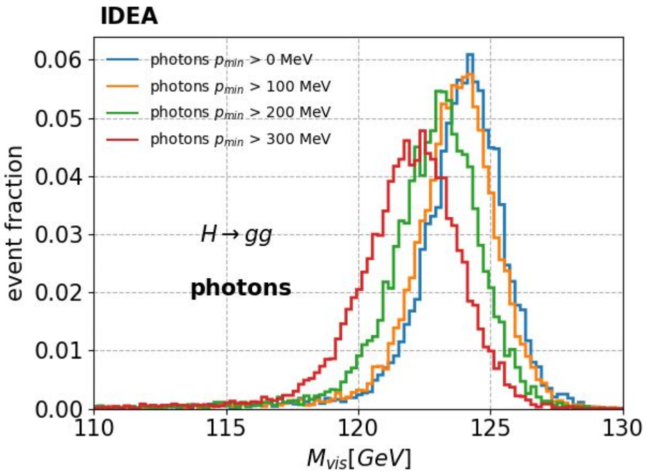
removes
$B_s \to D_s\ \pi$
background

With “standard” PID



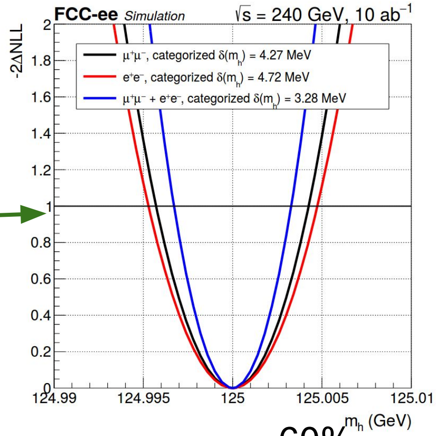
ECAL : electron/photon reconstruction

- many flavor physics benchmarks: $B_s \to D_s K$, $B_0 \to \pi^0 \pi^0$, $B_s \to K^* \tau \tau$ ..
- put stringent requirements on ECAL performance, both resolution and granularity:
  - soft π^0 ECAL resolution is a must (e.g crystal) AND low X_0 material in front
  - for boosted π^0 granularity required (τ decays)
- High momentum prompt photon $H \to \gamma\gamma$, ALPs
- ECAL granularity resolution needed for efficient brem recovery (and low X_0 tracker)



Low energy photons content from π^0 (in particular for $H \to gg$)

Z(ee) channel improves m_H precision



ECAL granularity and resolution needed for efficient brem recovery → 60% improvement vs standalone tracking

Jet resolution and particle-flow

Consider ee → ZH → νν **j j** → visible energy/mass

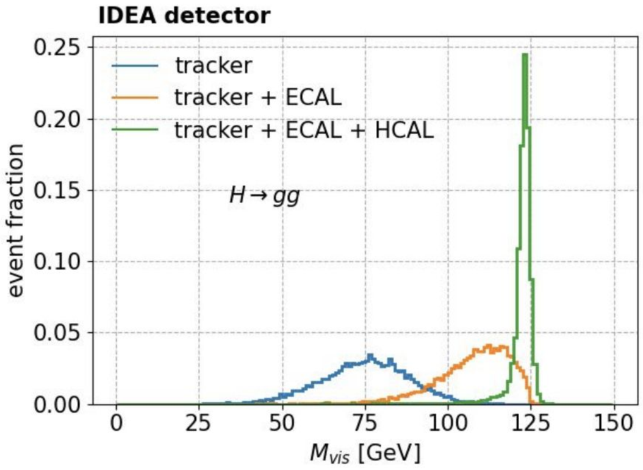
$$\sigma^2(E_{\rm vis}) = \sum_{i\in {\rm tr}} \sigma^2_{\rm tr}(E^{(i)}_{\rm tr}) + \sum_{i\in\gamma} \sigma^2_{\rm ecal}(E^{(i)}_{\gamma}) + \sum_{i\in {\rm nh}} \sigma^2_{\rm hcal}(E^{(i)}_{\rm nh})$$

65% 25% 10%

25% 10%

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

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



with a **perfect Particle-flow** algorithm:

- jet energy energy resolution is dominated by **neutral hadron (HCAL) resolution**

with a **realistic Particle-flow** algorithm:

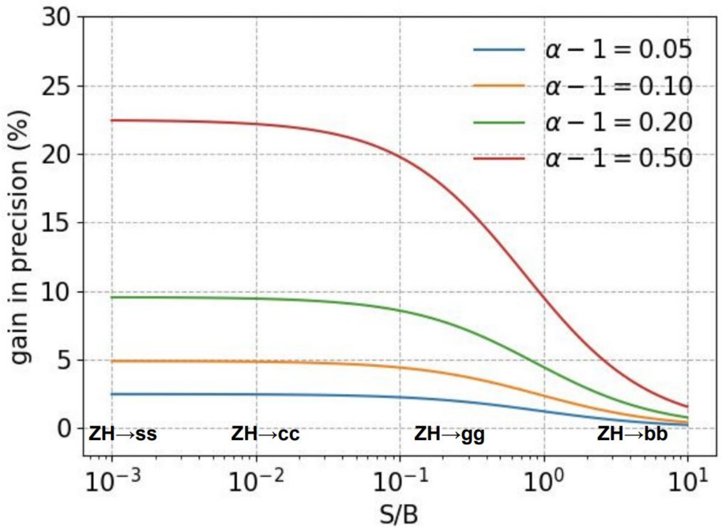
- granularity and thresholds matter

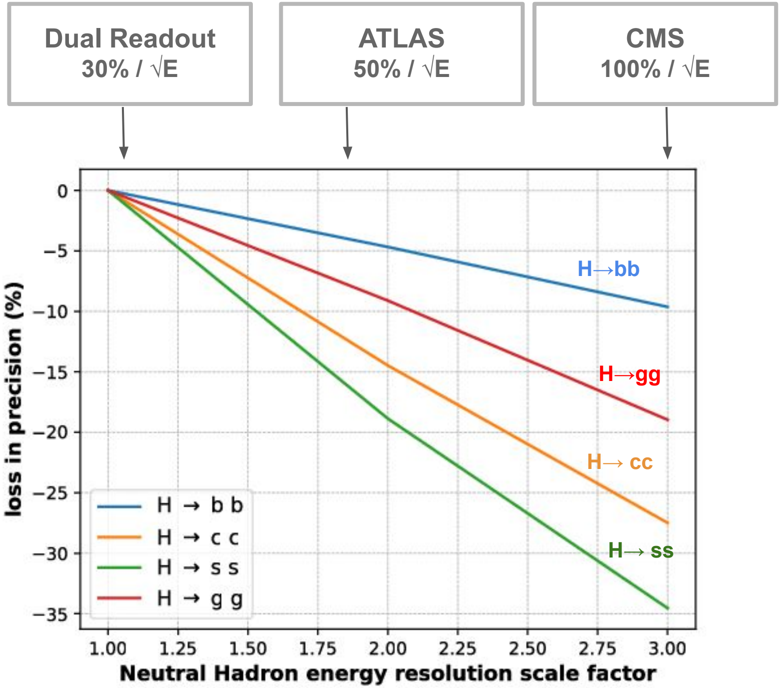
HCAL and jets -- Higgs hadronic final states

see L. Gouskos (wed.)

Largest gain from JER expected for S/B << 1:

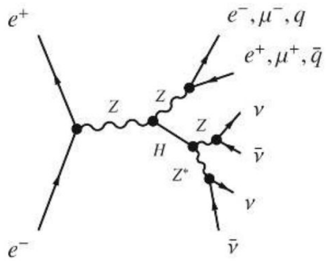
If relative improvement **α**, expect √**α** increase in precision

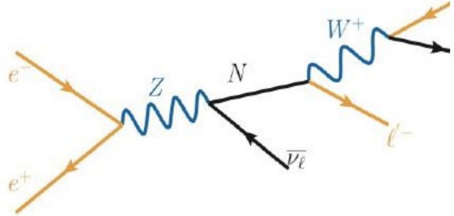




Observe less degradation than expected, studies will have to be repeated with full simulation

HCAL and jets

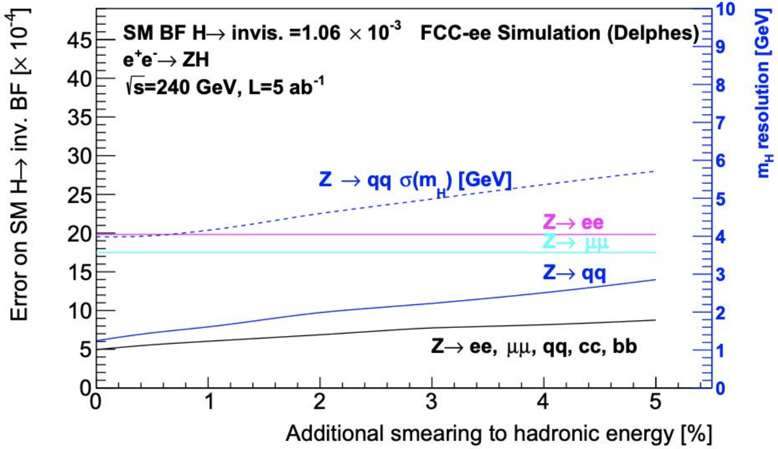


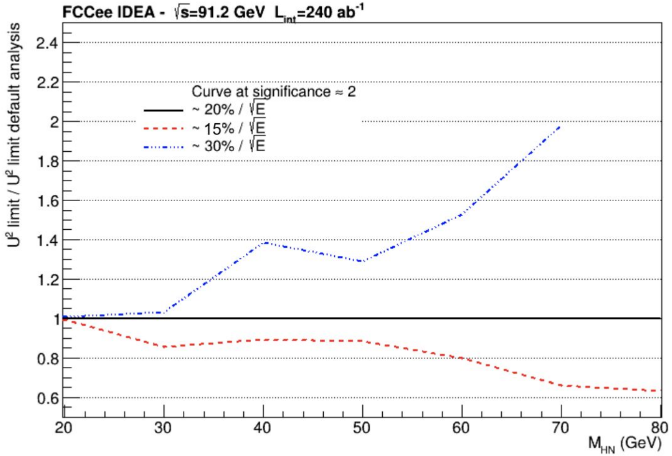


see L. Portales (wed.)

H→ invisible

HNLs → μqq prompt final state
reconstruct visible mass





sizable impact of JER on Z→qq channel
offset by Z→ll channel at large smearings

sizable impact of JER

see S. Williams, N. Valle (wed.)

Summary

- To fully exploit its physics potential:
  - precise alignment
  - small radius vertex detector for good IP resolution
  - low material
  - precise and granular calorimetry
  - excellent hadronic calorimetry

- The FCC-ee will provide MANY clean events, given its large luminosity, but
  - high rates
  - complex MDI

- Many case studies NOT discussed here to be undertaken:
  - Higgs FCNCs, rare decay channels, at 365 GeV
  - Top properties and FCNCs
  - EWK Z / WW energies tight req (yet to be fully explored)
  - Taus (see Alberto Lusiani ‘s talk Wed)

Backup

FCC-ee conditions

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