Physics Summary

June 10-14, 2024
FCC Week, San Francisco

Christoph Paus, MIT

Parallel Presentations

Monday		Tuesday					Wednesday						
Plenary	Board Room	Parallel 1	Parallel 2	Parallel 3	Parallel 4	Board Room	Plenary	Parallel 1	Parallel 2	Parallel 3	Board Room	Plenary	Parallel
Colonial	Yorkshire	Elizabethan A	Elizabethan B	Elizabethan C	Elizabethan D	Yorkshire	Colonial	Elizabethan A	Elizabethan B	Elizabethan C	Yorkshire	Colonial	Elizabeth A
Welcome coffee (Italian)		Welcome coffee (California East & West)					Welcome coffee (California East & West)					We	
1) Welcome remarks 2) CERN plans 3) A view from CERN Council 4+5) NSF and DOE Opening Remarks		Physics Case & Th. Calculations (i)	FCC-ee baseline design & optics top-up	Safety				Detector Requirements (i)	Collective Effects	Sustainability and impact generation			Detecto Requirem s (ii)
Coffee break (Italian)		Coffee Break (California East & West)					Coffee Break (California East & West)					C	
1) Key Note 2) FCC FS status 3) FCC Collaboration status		Physics Case & Th. Calculations (ii)	Optics alternatives & lessons	Transport, logistic and Survey	Synergies and innovation			Software	FCC-ee optics correction & tuning	Sustainability and impact generation			Machin Detecto Interface
Lunch break (California East & West)		Lunch break (California East & West)				Governance meeting	Lunch break (California East & West)					(C	
1) Implementation scenario 2) Civil Engineering		Detector Concepts (i)	FCC-ee injector incl. booster (i)	Civil Engineering	Directions for R&D	meeting		Machine Detector Interface (i)	SRF Technology (ii)	Magnets			EPOL (

Parallel Presentations

Version: 2.0 Date: 04.06.2024

Time SFO / Room	Sunday – Front desk (Georgian)	Monday – Plenary (Colonial)	Monday – Board Room (Yorkshire)
08:00-08:30		Welcome coffee (Italian)	
08:30-09:00		1) Welcome remarks 2) CERN plans 3) A view from CERN Council 4+5) NSF and DOE Opening Remarks	
09:00-09:30			
09:30-10:00			
10:00-10:30		Coffee break (Italian)	
10:30-11:00		1) Key Note 2) FCC FS status 3) FCC Collaboration status	
11:00-11:30			
11:30-12:00			
12:00-12:30			
12:30-13:00		Lunch break (California East & West)	
13:00-13:30			
13:30-14:00			
14:00-14:30		1) Implementation scenario 2) Civil Engineering 3) Accelerator status 4) Technologies & TI	
14:30-15:00			
15:00-15:30	Registration + as from 07:30am on Monday		
15:30-16:00		Coffee break (Italian room)	
16:00-16:30		1) Super KEKB status and plans 2) The Physics at FCC 3) Detectors requirements and benchmarks 4) Planning for upcoming workshops 5+6) US Plans FCC-PED, FCC-ACC	Governance meeting
16:30-17:00			
17:00-17:30			
17:30-18:00			
18:00-18:30			
18:30-19:00			

Time SFO	Tuesday – Parallel 1 (Elizabethan A)	Parallel 2 (Elizabethan B)	Parallel 3 (Elizabethan C)	Parallel 4 (Elizabethan D)	Board Room (Yorkshire)
08:00-08:30	Welcome coffee (California East & West)				
08:30-09:00	Physics Case & Th. Calculations (i)	FCC-ee baseline design & optics, top-up	Safety		
09:00-09:30					
09:30-10:00					
10:00-10:30	Coffee Break (California East & West)				
10:30-11:00	Physics Case & Th. Calculations (ii)	Optics alternatives & lessons	Transport, logistic and Survey	Synergies and innovation	
11:00-11:30					
11:30-12:00					
12:00-12:30	Lunch break (California East & West)				Governance meeting
12:30-13:00					
13:00-13:30					
13:30-14:00	Detector Concepts (i)	FCC-ee injector incl. booster (i)	Civil Engineering	Directions for R&D	
14:00-14:30					Governance meeting
14:30-15:00					
15:00-15:30	Coffee Break (California East & West)				
15:30-16:00	Detector Concepts (ii)	FCC-ee injector incl. booster (ii)	Layout optimisation and services	SRF Technology (i)	
16:00-16:30					
16:30-17:00					
17:00-17:30					
17:30-18:00	Detector Concepts (iii)	FCC-ee injector incl. booster (iii)	Governance meeting		
18:00-18:30					
18:30-19:00					

Time SFO	Wednesday – Plenary (Colonial)	Parallel 1 (Elizabethan A)	Parallel 2 (Elizabethan B)	Parallel 3 (Elizabethan C)	Board Room (Yorkshire)
08:00-08:30	Welcome coffee (California East & West)				
08:30-09:00		Detector Requirements (i)	Collective Effects	Sustainability and impact generation	
09:00-09:30					
09:30-10:00					
10:00-10:30	Coffee Break (California East & West)				
10:30-11:00		Software	FCC-ee optics correction & tuning	Sustainability and impact generation	
11:00-11:30					
11:30-12:00					
12:00-12:30	Lunch break (California East & West)				
12:30-13:00					
13:00-13:30					
13:30-14:00		Machine Detector Interface (i)	SRF Technology (ii)	Magnets	
14:00-14:30					
14:30-15:00					
15:00-15:30	Coffee Break (California East & West)				
15:30-16:00	Plenary: US Session				
16:00-16:30					
16:30-17:00					
17:00-17:30		Governance meeting		Early Career Researchers	
17:30-18:00					
18:00-18:30					
18:30-19:00					

Time SFO	Thursday – Plenary (Colonial)	Parallel 1 (Elizabethan A)	Parallel 2 (Elizabethan B)	Parallel 3 (Elizabethan C)	Parallel 4 (Elizabethan D)	Board Room (Yorkshire)
08:00-08:30	Welcome coffee (California East & West)					
08:30-09:00		Detector Requirements (ii)	FCC-ee code development and other themes		RF and Cryo	Governance meeting
09:00-09:30						
09:30-10:00						
10:00-10:30	Coffee Break (California East & West)					
10:30-11:00		Machine Detector Interface (ii)	FCC-hh design	Injection & instrumentation	Utilities	
11:00-11:30						
11:30-12:00						
12:00-12:30	Lunch break (California East & West)					
12:30-13:00						
13:00-13:30						Governance meeting
13:30-14:00		EPOL (i)	high-field magnets for FCC-hh 1	Vacuum	AIML mini workshop	
14:00-14:30						
14:30-15:00						
15:00-15:30	Coffee Break (California East & West)					
15:30-16:00		EPOL (ii)	high-field magnets for FCC-hh 2	Beam Intercepting devices	AIML mini workshop	
16:00-16:30						
16:30-17:00						
17:00-17:30		Detector Requirements (iii)				
17:30-18:00						
18:00-18:30						
18:30-19:00						

Physics&Detector Summary

June 10-14, 2024
FCC Week, San Francisco

Christoph Paus, MIT

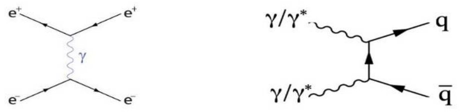
Basic Detector Requirements

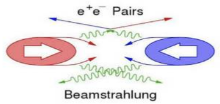
Detector requirements - general considerations

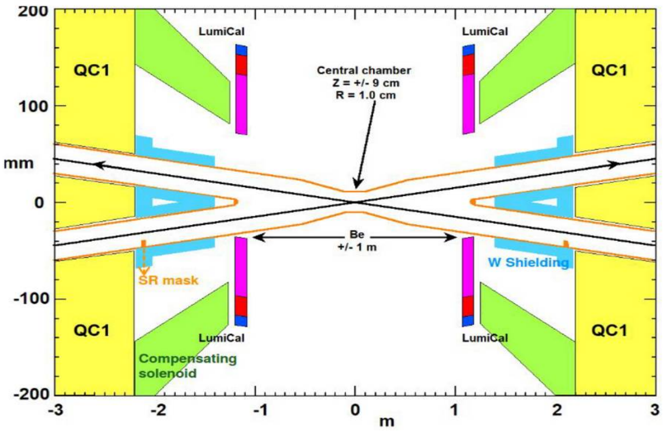
- Requirements for Higgs and above have been studied to some extent by LC:
  - we want a detector that is able to withstand a **large dynamic range**:
    - in energy ($\sqrt{s}$ = 90 - 365 GeV)
    - in luminosity (L = 10^{34} - 10^{36} cm^2/s)

- 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







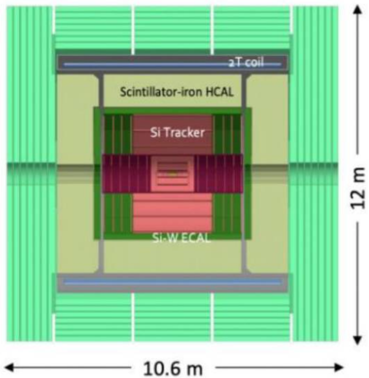
Basic Detector Designs

Detector Benchmarks

ALLEGRO

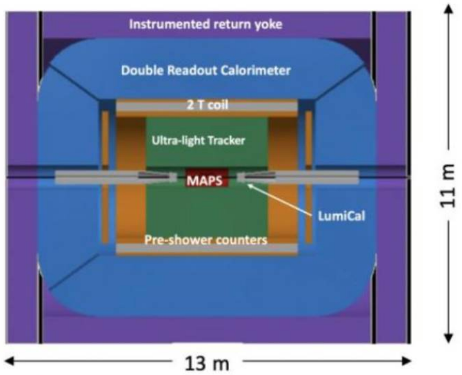
CLD	IDEA	Noble Liquid ECAL based

CLD



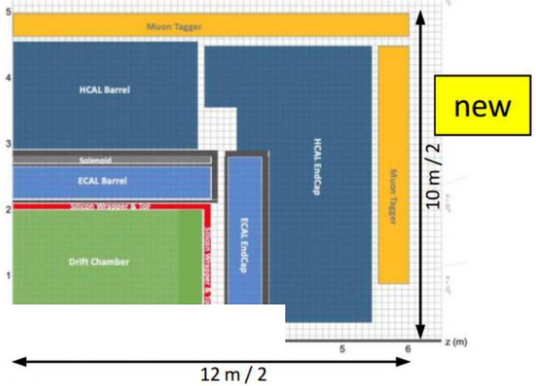
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, 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



- 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

Computing / Software are crucial ingredient

Assumptions and baseline needs[1]

- Integrated luminosities
  - Nominal: {90, 12, 5, 0.2, 1.5} ab^{-1} at $\sqrt{s}$ = {91.2, 160, 240, 350, 365} GeV
  - # of evts: 3×10^{12} visible Z decays, 10^{8} WW events, 10^{6} ZH events, 10^{6} tt events

- Baseline event sizes / processing time for hadronic evts at Z
  - DELPHES: 7.5 kB/evt, 0.4 s/evt
    - Full stat sample sizes: 30 PB, ≈ 10^{10} s/core ≈ 0.5 MHS06[2]
  - Full sim: CLD reference: 1 - 2 MB/evt, 10 s/evt
    - Full stat sample sizes: 3 EB, ≈ $3 \cdot 10^{13}$ s/core ≈ 10-15 MHS06[2] / detector [3]

LHC is similar in scope.

1. See also: GG, C Helsens: EPJ Plus (2022) 137:30
2. If done over a year, assuming similar number per each detector benchmark
   a. CERN Openstack Core = 10-15 HEPSpec06 (HS06)
   b. CERN OpenStack node used for tests: 16 cores, 32 GB RAM
3. Not applying to DELPHES, because in principle one sample can be re-adapted to other detector concepts

Help is always welcome in computing/software!

Basic Measurements

Marina Nogueria, Ang Li, Michele Selvaggi,
Lars Röhrig, Fabrizio Palla, Nicola De Filippis

B Physics to benchmark vertex

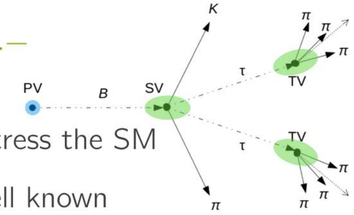
Vertex resolution

- Requires **5 µm**

And BTW

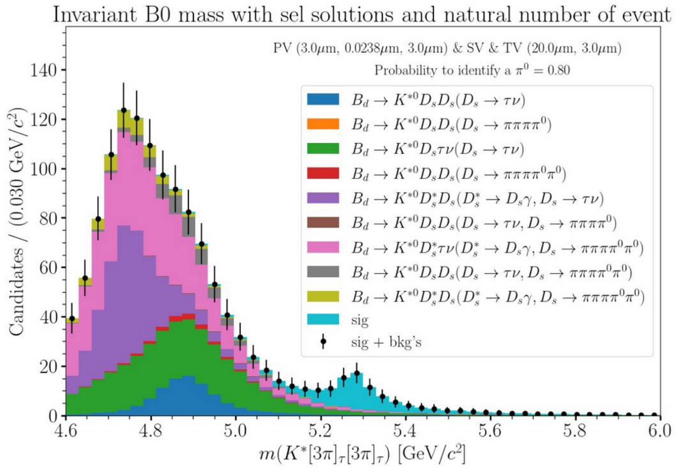
- FCC-ee has ~20 times more b and tau pairs than BelleII
- And the b/tau pairs are boosted

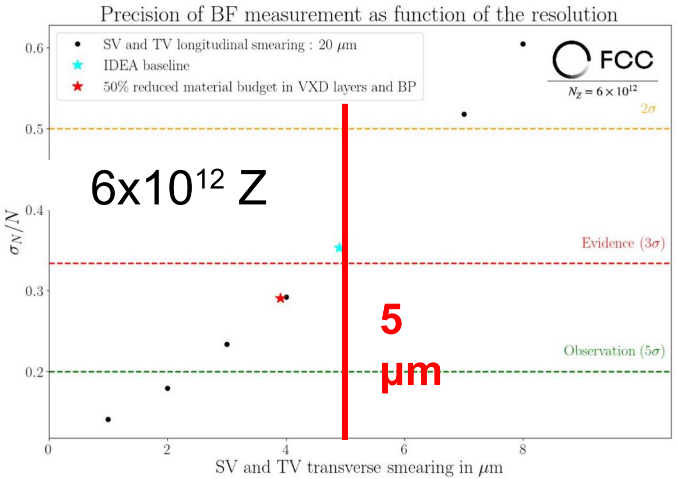
Vertex requirements: setting the stage with $b \to s\tau^+\tau^-$



- **EW penguin transitions** of b quark in the SM very rare $\to$ good laboratory to stress the SM
- Third generation transitions in $B^0 \to K^*\tau^+\tau^-$ couplings experimentally less well known

$\to$ Feasibility depends on neutrino reconstruction ✓ $\to$ depends on **vertex precision**





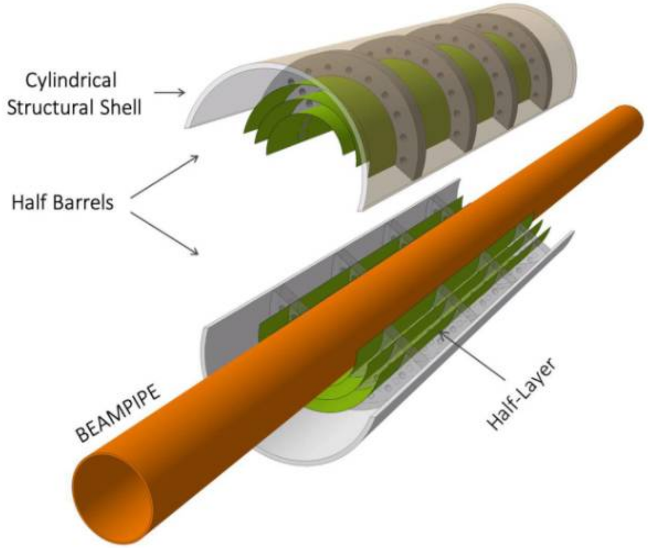
$\to$ Transverse vertex resolution of $\mathcal{O}(5\,\mu m)$ required (limited by the **material budget of the beampipe**)

© T. Miralles & S. Monteil Ref.

Benchmark Vertex measurements

MAPS

- Come to the workshop at CERN July 1/2



- A mini-workshop on vertex detector technologies (including system integration and mechanical aspects) will be held at CERN on July 1 and 2, with a lot of discussions:

  https://indico.cern.ch/event/1417976/

Lightweight layout using an ALICE ITS3 inspired design

(~0.05 % X/X_0 *material budget per layer – 5 times less than the Mid-Term one)*

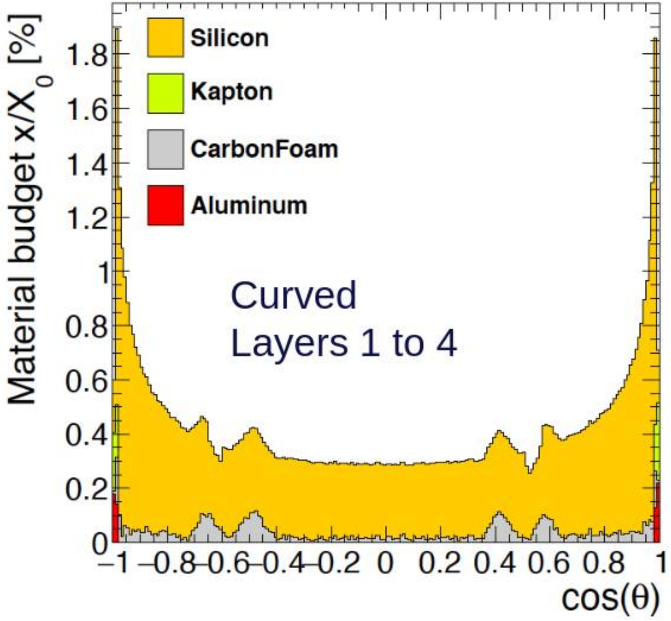
After fruitful discussions with ***C. Gargiulo, A. Junique, G. Aglieri Rinella, W. Snoeys***

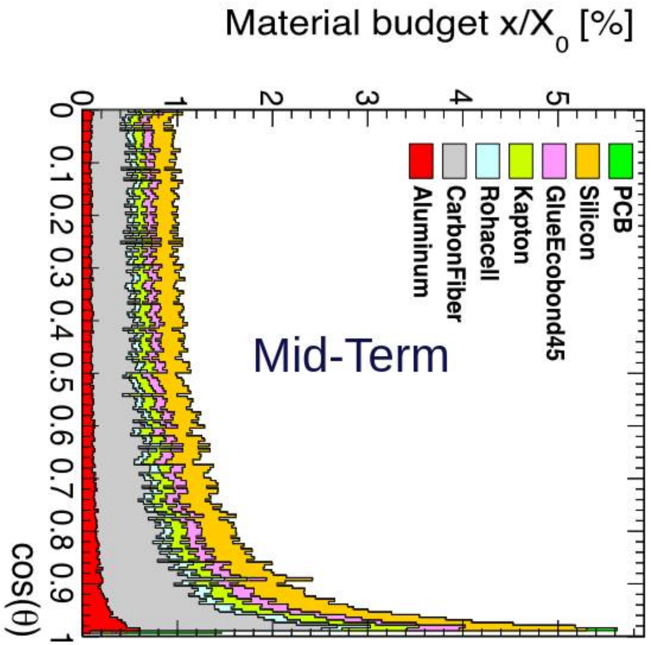
Benchmark Vertex measurements

MAPS

- Come to the workshop at CERN July 1/2

Material budget inner vertex



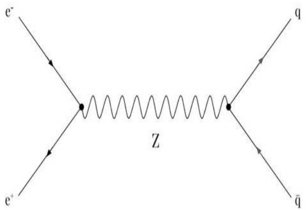


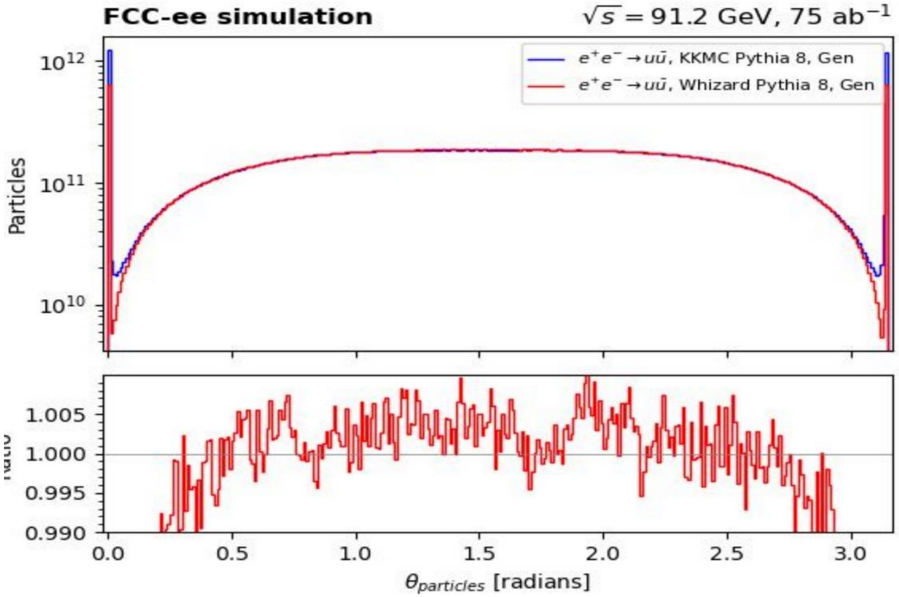
~ 5 μm resolution

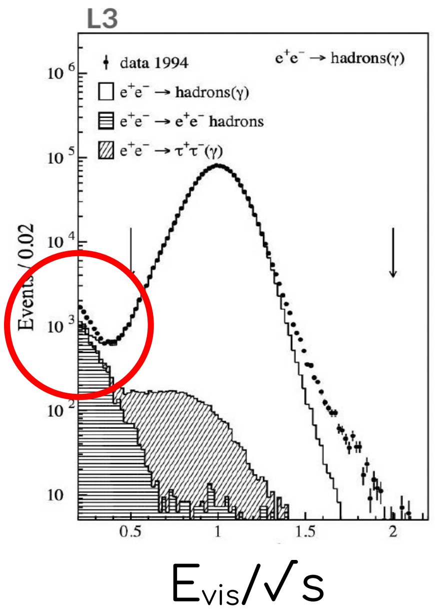
Most copiously recorded process at FCC

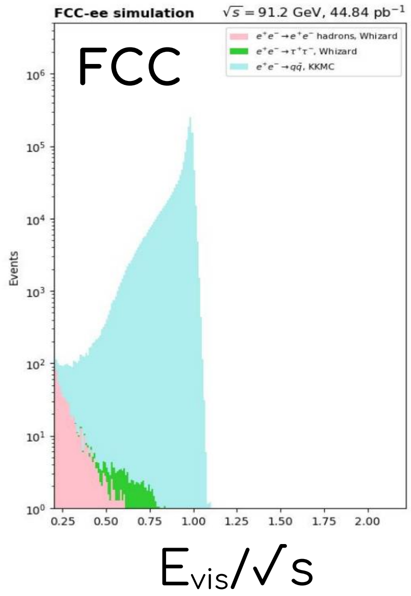
$e^+e^- \to qq$

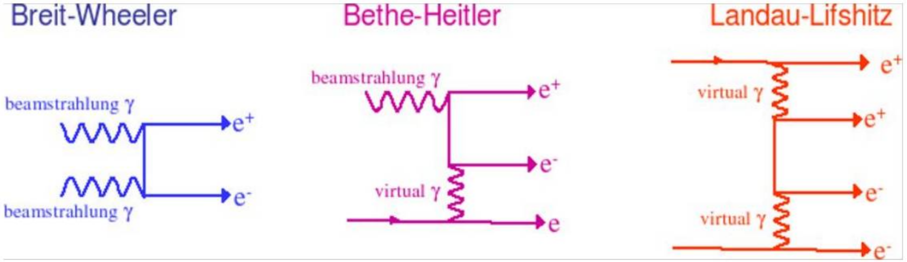
- Most basic MC needs work
- Acceptance not precise
- Beam and two photon background poorly modelled











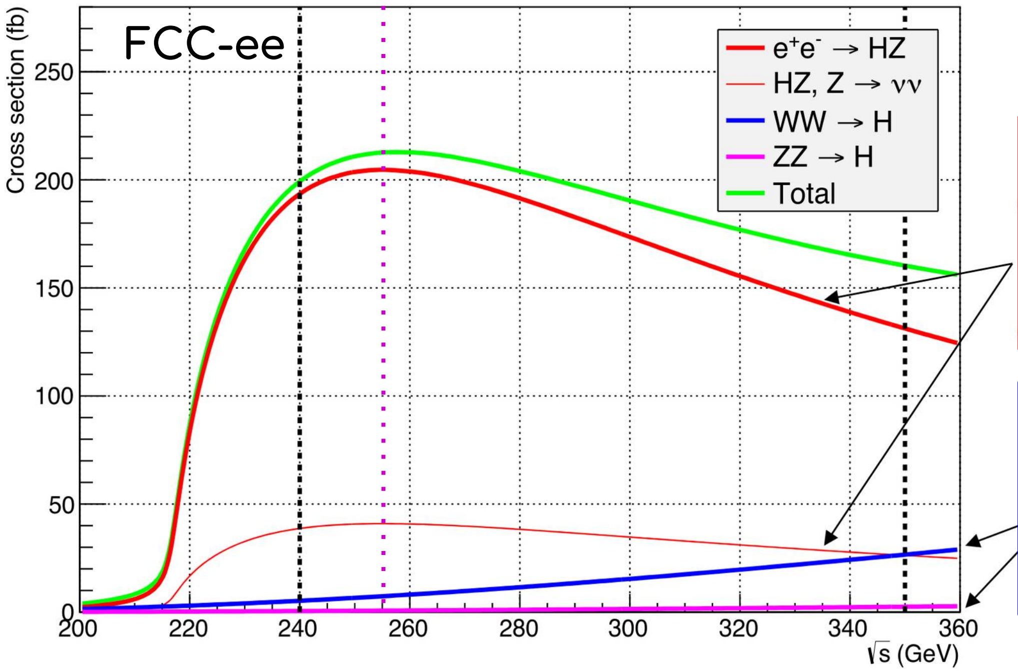
Higgs Physics at e^+e^- Colliders

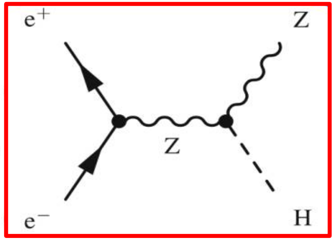
ZH Threshold turns on at 91 + 125 GeV = 216 Ge
reaches a maximum at around 255 GeV

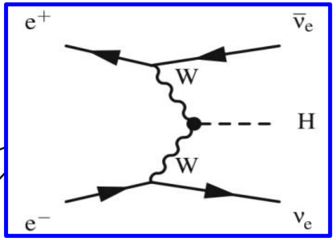
Vector boson fusion rises steadily but is small

FCC-ee: most Higgses at 240 GeV for FCC-ee considering lumi profile

Unpolarized cross sections







arXiv:1308.6176

Higgs Physics at e^+e^- Colliders

Leading strategy

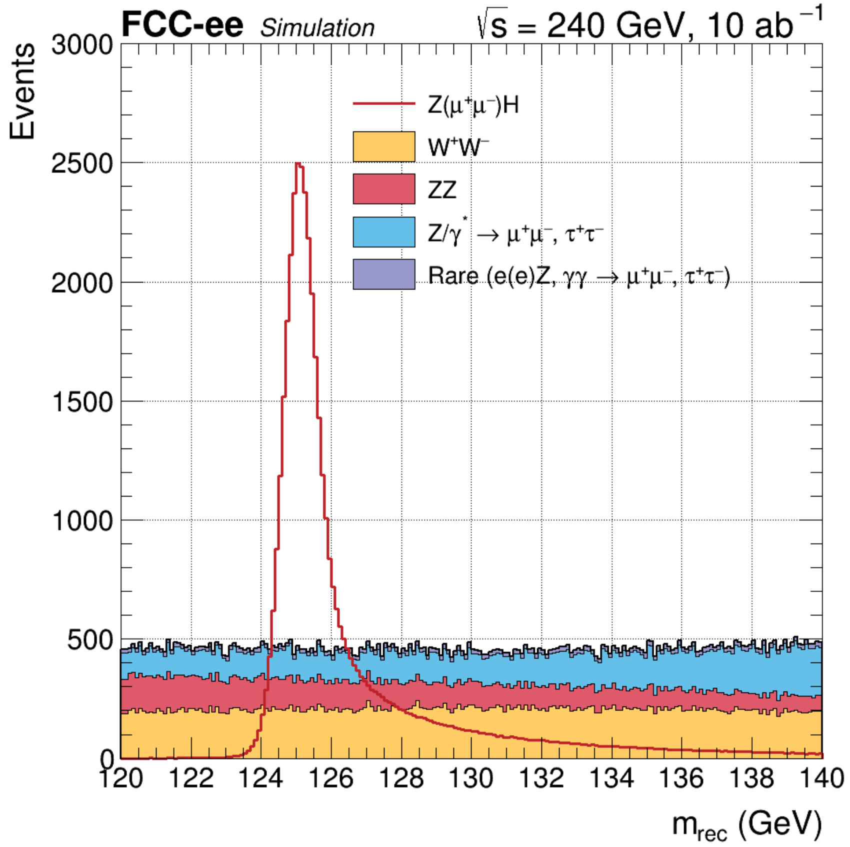
- Tag the Z boson (leptons or jets)
- Recoil mass peaks sharply at Higgs mass

$$m^2_{recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \approx m^2_H$$

- Direct Higgs reconstruction not required, model independent σ_{ZH} measurement
- Dominant background: WW, ZZ and Z/γ*

Challenges

- Detectors: resolution, tracking, vertexing, timing, angular
- Flavour tagging for Higgs couplings
- Jet reconstruction algorithms



This plot does not work at hadron colliders.

Basic Higgs Properties

Higgs mass

- Basic SM parameter
- Not a limiting factor for radiative corrections
- Essential for producings Higgs directly $e^+e^- \to H$
- Widths 4.1 MeV

Higgs mass

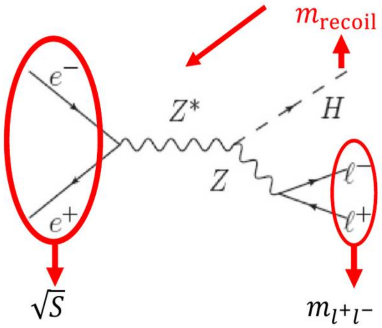
$\sqrt{s} = 240$ GeV
$L = 7.2ab^{-1}$

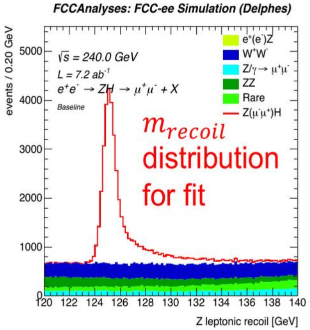
Gregorio Bernardi
Jan Eysermans
Ang Li

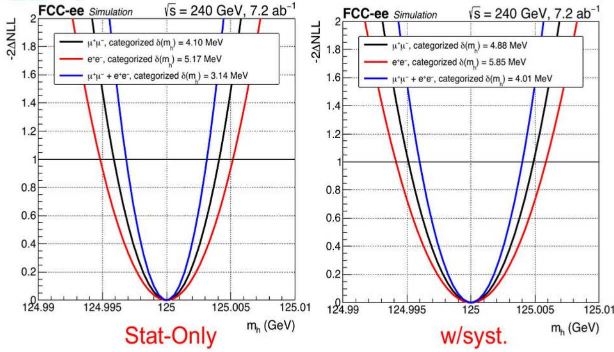
DOI 10.17181

- Current best from LHC $\delta m_H \sim 100$ MeV
- At FCC-ee, Higgs mass will reach MeV level accuracy, ($\Gamma_H \sim 4.1$ MeV)
- Electron and Muons final states: $e^+e^- \to ZH \to l^+l^- + XX$, ($Z \to \mu^+\mu^-, e^+e^-$)
- M_{recoil} from the Z production without measuring the Higgs production final state

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







Higgs mass, Fit with analytic shape

- Signal Shape: 2 Crystal-Ball with Gaussian core
- Backgrounds modelled as polynomial (3rd order)
- Signal and background injected in Combine, m_H as POI

Uncertainty Stat-Only, and w/ systematics:

- Higgs mass: 3.1 MeV → 4.0 MeV

Dominant Syst. Unc. :

Centre-of-mass with ~ 2 MeV

Basic Higgs Properties

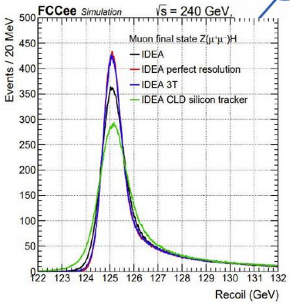
Higgs mass

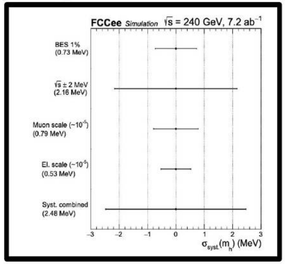
- Basic SM parameter
- Not a limiting factor for radiative corrections
- Essential for producings Higgs directly $e^+e^- \to H$
- Widths 4.1 MeV

Higgs Mass – Detector Requirements

Extended studies performed regarding detector/accelerator effects on the Higgs mass

→ Looking at impact on m_H uncertainty stat. (stat.+syst.) in MeV





Nominal configuration → Nominal

Crystal ECAL to Dual Readout → Degradation electron resolution

Nominal 2 T → field 3 T → Magnetic field 3T

IDEA drift chamber → CLD Si tracker → CLD 2T (silicon tracker)

Impact of Beam Energy Spread uncertainties → BES 6% uncertainty / Disable BES

Perfect (=gen-level) momentum resolution → Ideal resolution

Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	4.10 (4.88)	5.17 (5.85)	3.14 (4.01)
Inclusive	4.84 (5.53)	6.16 (6.73)	3.75 (4.50)
Degradation electron resolution (*)	4.10 (4.88)	5.98 (6.49)	3.32 (4.11)
Magnetic field 3T	3.38 (4.28)	4.30 (5.00)	2.60 (3.54)
CLD 2T (silicon tracker)	5.51 (6.07)	6.20 (6.70)	4.01 (4.66)
BES 6% uncertainty	4.10 (5.01)	5.17 (6.10)	3.14 (4.09)
Disable BES	2.27 (3.42)	3.11 (4.04)	1.80 (2.99)
Ideal resolution	2.89 (3.95)	3.89 (4.56)	2.39 (3.33)
Freeze backgrounds	4.10 (4.88)	5.17 (5.85)	3.14 (4.00)
Remove backgrounds	3.37 (4.34)	3.85 (4.80)	2.49 (3.56)

Momentum resolution

Minimal material matters

- TDC is very light
- Silicon detectors could be as light?
- Larger radius improves resolution ...
- Higher magnetic field improves resolution: 2T to 3T improves momentum 50% and mass by 14%

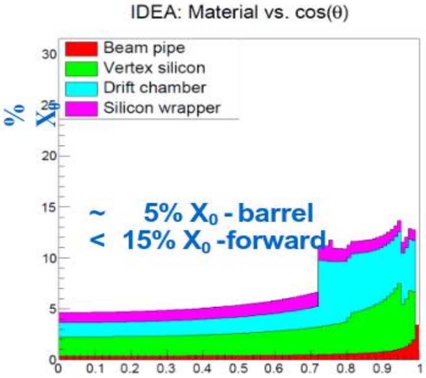
Requirements on track momentum resolution

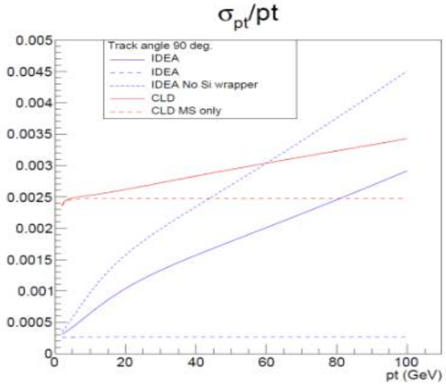
The IDEA Drift Chamber is designed to cope with transparency

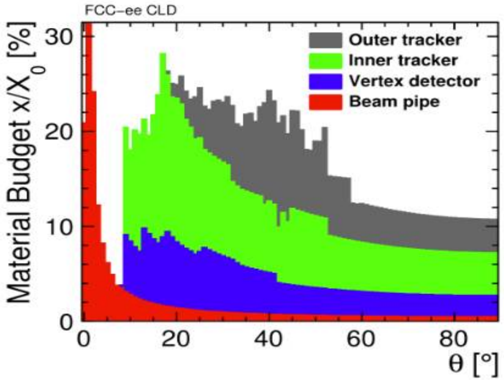
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius 0.35m, outer radius 2m
- length L = 4m

The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 – 2.1% of a radiation length per layer







For 10 GeV (50 GeV) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

- about 0.05 % (0.15%) with the very light IDEA DCH
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

Basic Top Properties

Top mass

- Basic SM parameter
- Hadron colliders have problemtic definition of mass
- Theoretically much cleaner access at lepton colliders

Top Threshold

Current run plan at the top threshold

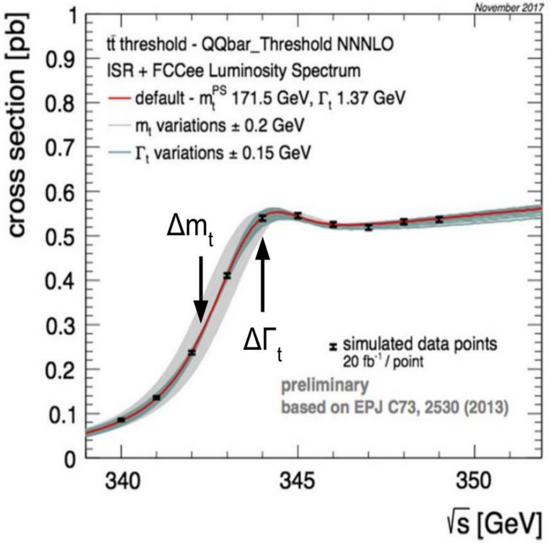
- 1 year threshold scan 340–350 GeV: total ~ 1.4 ab^{-1}
- 4 years at 365 GeV: total ~ 2.3 ab^{-1}

Threshold scan to extract the Top mass and width (similar as WW)

- Relative large uncertainty on top mass (+/- 0.5 GeV from HL-LHC)
- Need to constrain shape in optimal way
- Possible to constrain backgrounds (below) and ttH (above)
- Multipoint scan in 5 GeV window [340, 345], each ~ 25 /fb to be studied

At 365 GeV, with 2.3 ab^{-1}

- Top properties
- Higgs properties ($ee \rightarrow \nu\nu H$): total cross-section, couplings, width



→ **Δm_t (stat) ~ 17 MeV**

→ **$\Delta\Gamma_t$ (stat) ~ 45 MeV**

Higgs Couplings beyond the third generation fermions

David d’Enterria, Francis Petriello, Loukas Gouskos, Michele Selvaggi,
Daniel Elvira, Xunwu Zuo

Why measure Higgs couplings?

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)%

- 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

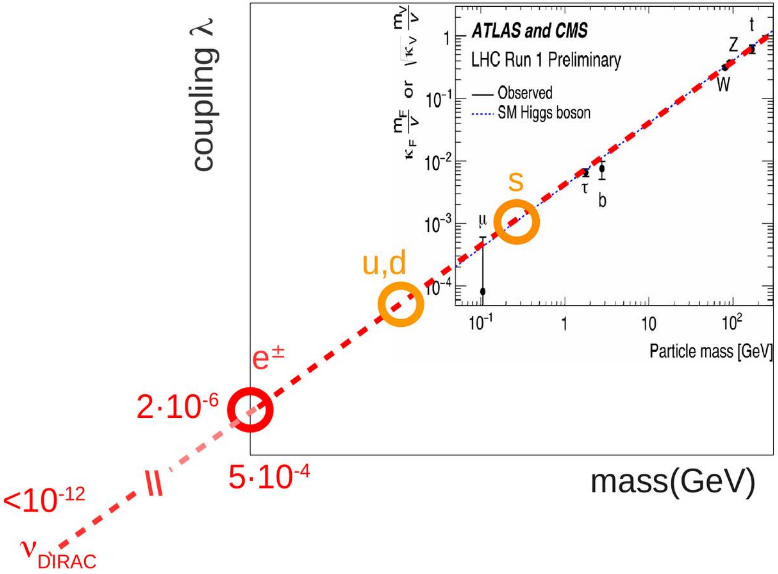
Loukas slide

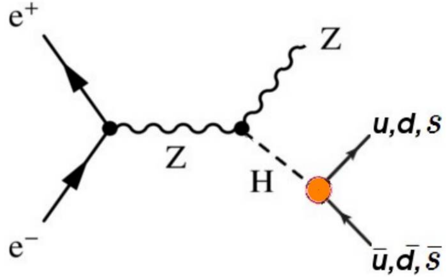
Higgs to first generation

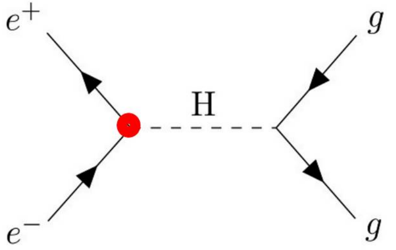
Unresolved Higgs decay modes

- Muons are only second generation seen
- Lighter fermions are very difficult

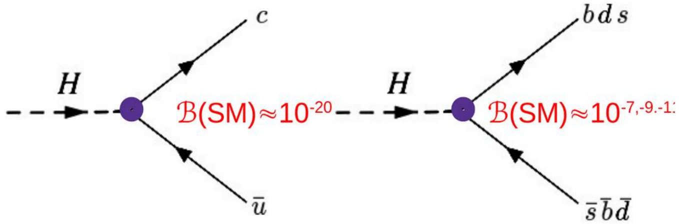
- Do the lightest fermions (u,d,s,e) acquire their masses through their Higgs (Yukawa) couplings?







- Does the Higgs boson mediate H→qq' FCNCs at tree level?

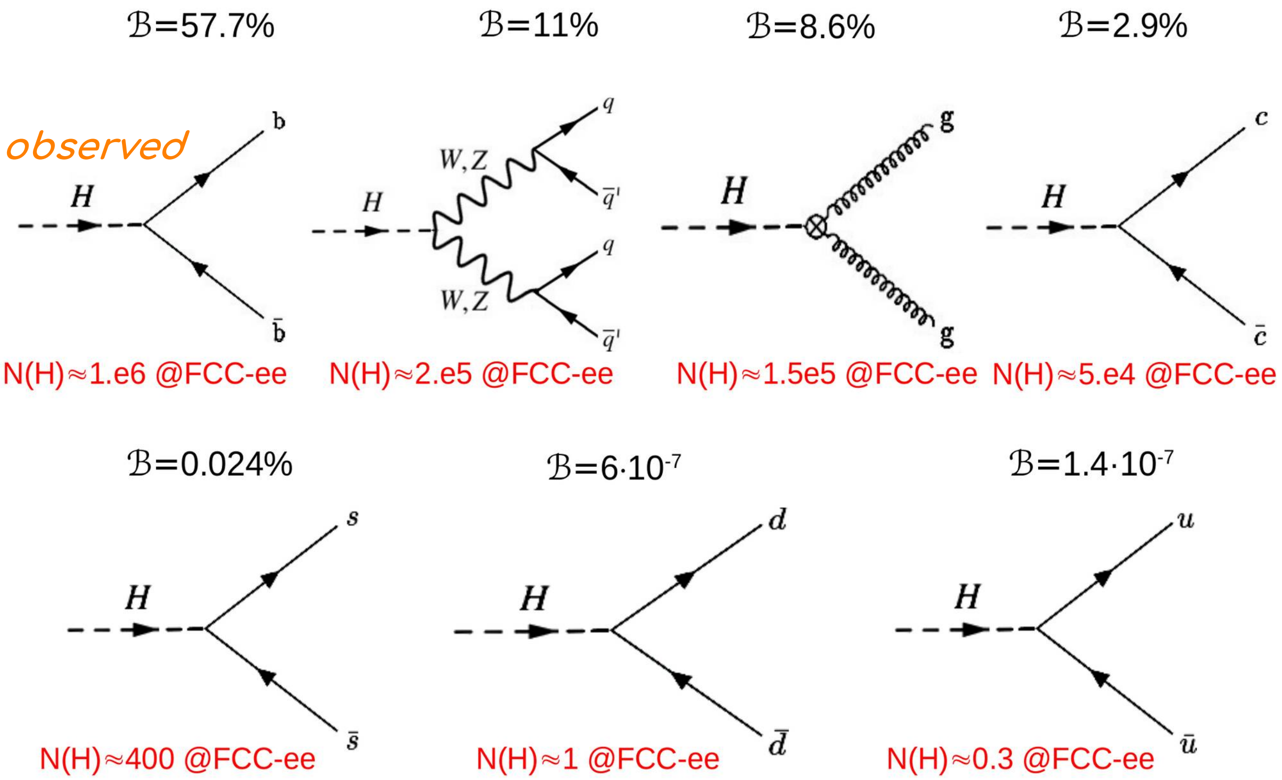


Hadronic final states dominate

Why is this important?

- At LHC those are often hopeless – background
- FCC-ee offers cleaner environment, more handles and data calibration

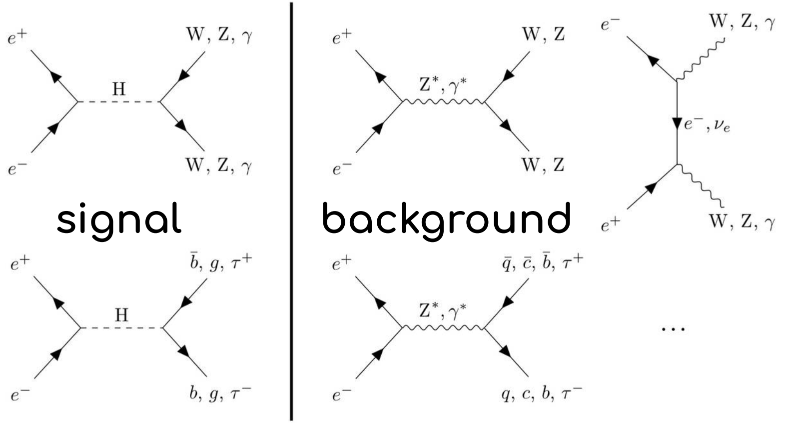
■ 80% of the Higgs decays are fully hadronic. Mostly measurable at FCC-ee!

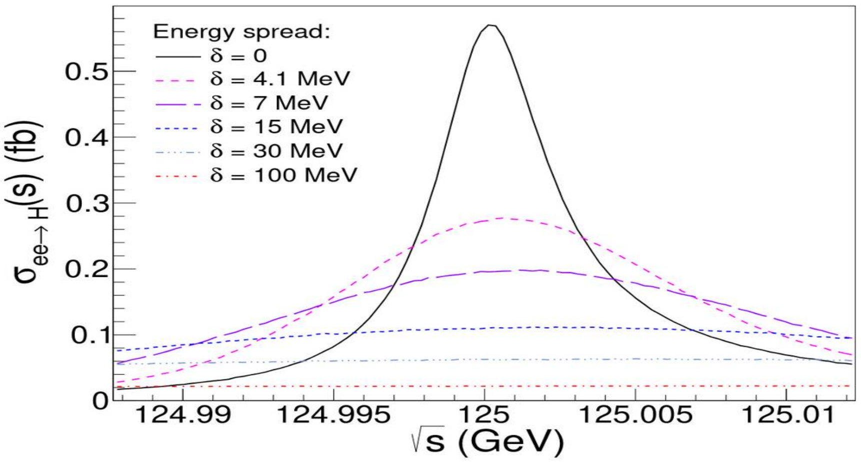


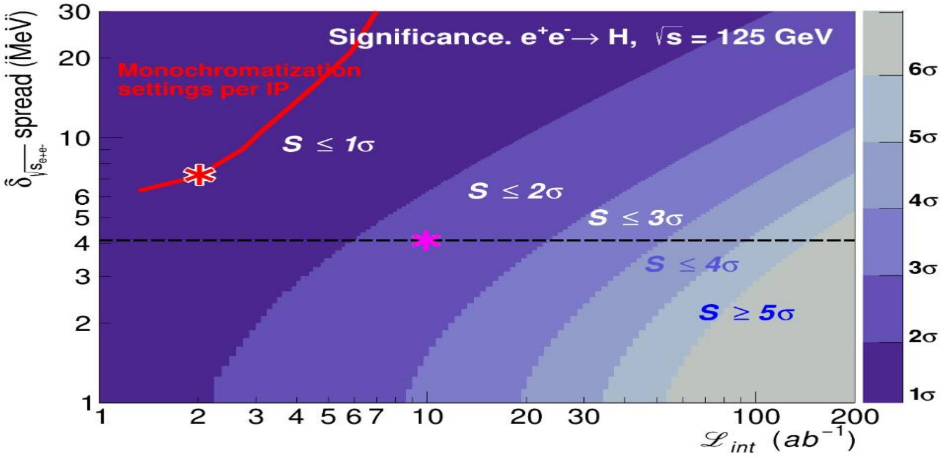
Higgs Electron Yukawa Coupling

Measure e+e- → H → e^+e^-: how?

- Γ_H is 4.1 MeV, measure m_H at MeV level
- Dial collider E_{CM} to m_H
- Monochromatize energy: ~ 4 MeV spread
- Signal is tiny and background is very large
- 1.3 std significance per IP and per year







arXiv:2107.02686

Higgs to gluon gluon

Gluon tagging

- Major progress in tagging makes it feasible
- H→gg has no continuum background
- But can we distinguish well enough between u,d,s and gluons?

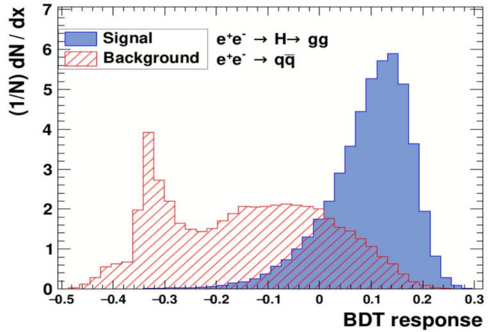
- No e^+e^- background can generate 2 true gluon jets !
- Analysis performances assumed:

  2 gluon-tagged jets (with 70% effic. each)
  u,d,s mistagging rate: ~1%

  Challenging, but not impossible (see next)

  Retains 50% of $\sigma(H\rightarrow gg)$ = 24 ab signal

[DdE,Poldaru/Wojcik arXiv:2107.02686]



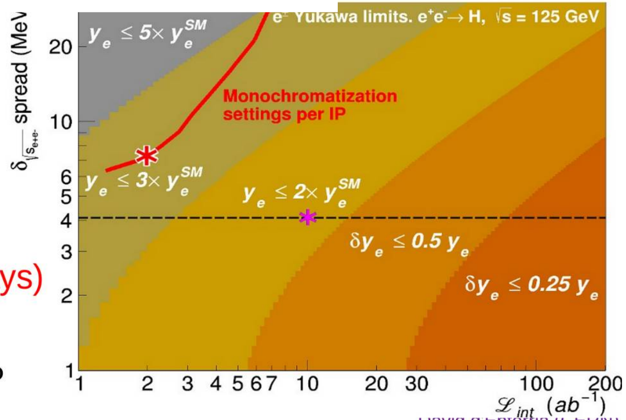
- BDT MVA result (removing jet vars. potentially already used in g-uds discrimination):

  Signal reduction ~50%
  Backgd. reduction: x17

- For $\mathcal{L}_{int}$=10 ab^{-1} :

  $S/\sqrt{B} = 55/\sqrt{2500} \approx 1.1$
  Significance ≈ 1.1σ (1.3σ, other decays)

  With current best monochromatization:
  $y_e < 2.5 \times y_{e,SM}$ (95% CL) per year & per IP



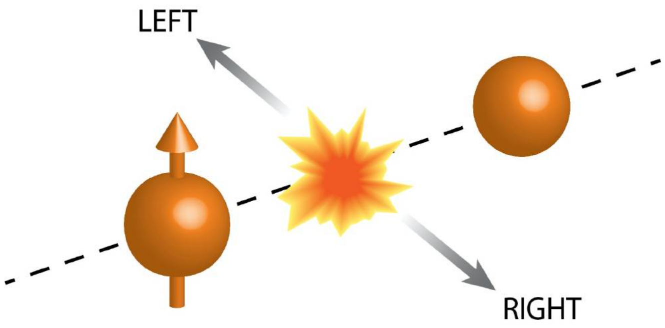
$e^+e^- \to$ *Higgs with polarized beams*

Beam polarization

- Transverse is more obvious
- 80% not unreasonable
- Longitudinal much less clear
- Needs polarimeter: expensive
- Can work: 30%?

Transverse spin asymmetries

- The idea is to use transverse spin asymmetries to increase the sensitivity to the electron Yukawa coupling. We consider the following observables in our study.



$$A = \frac{N}{D}$$

Electron polarized, positron unpolarized (SP^0):

$$N = \frac{1}{2}(\sigma^{+0} - \sigma^{-0})$$
$$D = \frac{1}{2}(\sigma^{+0} + \sigma^{-0})$$

Electron transversely polarized, positron longitudinally polarized (DP):

$$N = \frac{1}{4}(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--})$$
$$D = \frac{1}{4}(\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--})$$

Electron transversely polarized, positron longitudinally polarized (SP^+):

$$N = \frac{1}{2}(\sigma^{++} - \sigma^{-+})$$
$$D = \frac{1}{2}(\sigma^{++} + \sigma^{-+})$$

Electron transversely polarized, positron longitudinally polarized (SP^-):

$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$
$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

$e^+e^-\to$Higgs with polarized beams

Single Spin Asymmetry

- Imaginary part in amplitude: interference
- Requires resonance (Higgs)

Theoretical structure of transverse SSAs

- The structure of transverse SSAs is dictated by the discrete symmetries of the SM.

Two key points:

$$S_T \cdot p_q = = \beta_q \frac{\sqrt{s}}{2} \sin(\theta) \cos(\phi),$$

$$\epsilon(p_e, p_{\bar{e}}, p_q, S_T) = -\beta_e \beta_f \frac{s^{3/2}}{4} \sin(\theta) \sin(\phi)$$

1. These two structures have different azimuthal dependence (orientation between final-state bottom quark and transverse spin direction); they can be separated by weighting the final-state phase-space integral

$S_T \cdot p_q$ ⇒P odd, A_t even

$\epsilon(p_e, p_{\bar{e}}, p_q, S_T)$ ⇒P even, A_t odd

2. To get a structure odd under A_t we need an imaginary part in an amplitude. At tree-level this can only come when we are on a particle resonance

$$\frac{1}{s - M^2 + iM\Gamma}$$

$e^+e^-\to$Higgs with polarized beams

Origin

- ZH interference
- Does not work for H→gg
- Term is proportional to mass!
- Azimuthal structure is different!

Application to the ee→bb process

- Study the structure of the asymmetry numerator (DP in this example). Three diagrams contribute at tree-level: s-channel photon, Z-boson, and Higgs exchange.

$$N = \frac{1}{2s}\int d\text{LIPS}\left\{\frac{R_{\gamma\gamma}}{s^2} + \frac{R_{ZZ}}{(s-M_Z^2)^2} + \frac{R_{\gamma Z}}{s(s-M_Z^2)} + \frac{R_{\gamma H}(s-M_H^2)}{s[(s-M_H^2)^2+M_H^2\Gamma_H^2]} + \frac{R_{ZH}(s-M_H^2)+I_{ZH}M_H\Gamma_H}{(s-M_Z^2)[(s-M_H^2)^2+M_H^2\Gamma_H^2]}\right\}$$

$$\begin{aligned}
R_{\gamma\gamma} &= 96e^4Q_e^2Q_q^2 m_e(S_T\cdot p_q)(t-u)\\
R_{ZZ} &= 96m_e(S_p\cdot p_b)g_Z^4g_{ve}^2(g_{vq}^2+g_{aq}^2)(t-u)+192m_e(S_T\cdot p_q)g_Z^4g_{ve}g_{ae}g_{vq}g_{aq}s\\
R_{\gamma Z} &= 192e^2g_Z^2Q_eQ_qm_e(S_T\cdot p_b)g_{ve}g_{vq}(t-u)+96e^2g_Z^2Q_eQ_um_e(S_p\cdot p_q)g_{ae}g_{aq}s\\
R_{\gamma H} &= -96e^2Q_eQ_qy_ey_q(S_T\cdot p_q)m_q\\
R_{ZH} &= -96g_Z^2g_{ve}g_{vq}y_ey_q(S_T\cdot p_q)s\\
I_{ZH} &= -192g_Z^2g_{ae}g_{vq}y_ey_qm_q\epsilon(p_e,p_{\bar{e}},p_q,S_T).
\end{aligned}$$

- Comes from the imaginary part of the Higgs propagator and is enhanced by a factor of $\mathbf{M_H/\Gamma_H}$.
- All terms are suppressed **linearly** by the electron mass; this structure is directly proportional to the electron Yukawa couplings
- Can be isolated due to its different azimuthal structure, which follows from the discussion on the previous slide

$e^+e^- \to$ Higgs with polarized beams

$b\bar{b}$

Observable	$e^- e^+ \to b\bar{b}$
DP	0.27
SP^0	0.19
SP^+	0.11
SP^-	0.38
Reference	0.11

Preliminary

Definite improvement using transverse polarization; further improvement if the second beam can be longitudinally polarized

Obtained using unpolarized cross section; in good agreement with $S/\sqrt{B}$=0.13 in 2107.02686

10 MeV from resonance invariant mass cut

Observable	$e^- e^+ \to b\bar{b}$
DP	0.41 (39%)
SP^0	0.30 (33%)
SP^+	0.17 (44%)
SP^-	0.58 (39%)

Preliminary

Second column gives polar angle cut in terms of percentage of phase spaced removed

14

W^+W^-

Observable	$e^-e^+ \to WW \to ll\nu\nu$
DP	0.45
SP^0	0.80
SP^+	2.9
SP^-	0.33
Reference	0.45

Over a factor of 6 improvement if P_T,P_L)=(80,30)% can be obtained

Obtained using unpolarized cross section; $S/\sqrt{B}$=0.53 in 2107.02686, likely due to use of BDT rather than simple cuts

Quoted are significance of the signal.

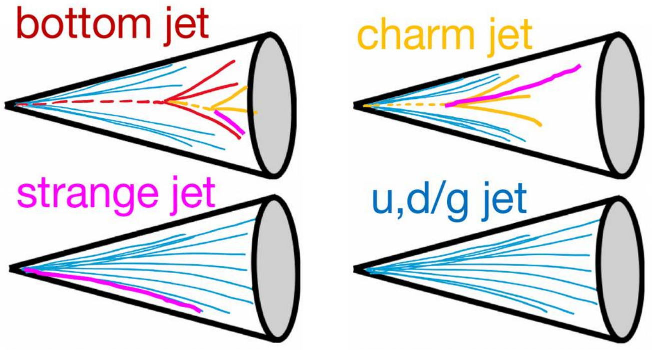
Major improvements of up to factors of 6 possible for bb and WW

Tagging Challenge: Higgs→ss

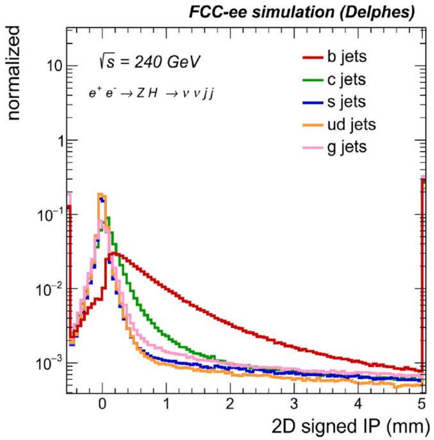
Jet tagging

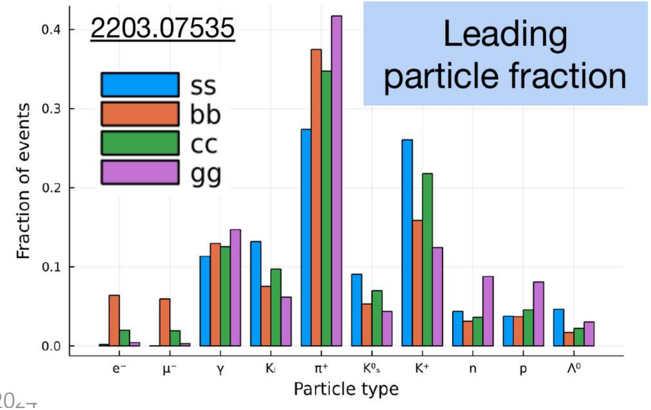
- Key to quarks and gluons
- Very different from LHC
- Huge Z and W boson decay samples to calibrate
- PID is crucial input
- Charm, strange gluon tagging works
- Seeing H→ ss is least obvious, but should be possible

Basics



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



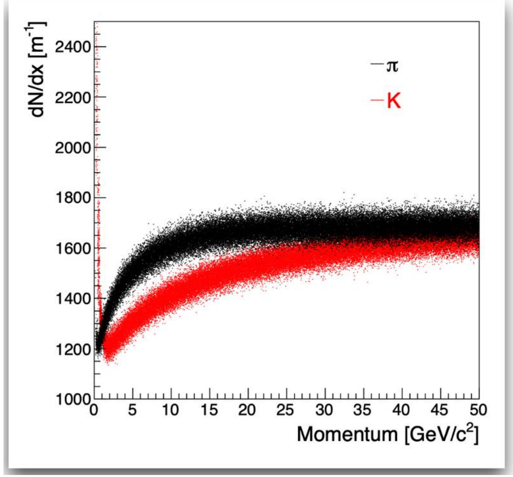


Strange Tagging needs PID

Handles for PID

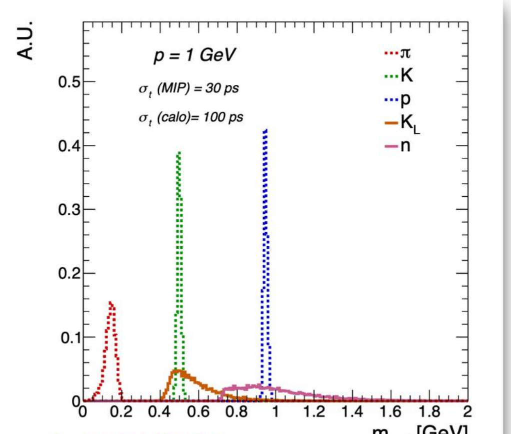
dN/dx or dE/dx,

- Ionization cluster count or energy per path length
- Good separation in wide momentum range
- "Blind" region around 1 GeV
- Currently assume 2% resolution



Time of flight

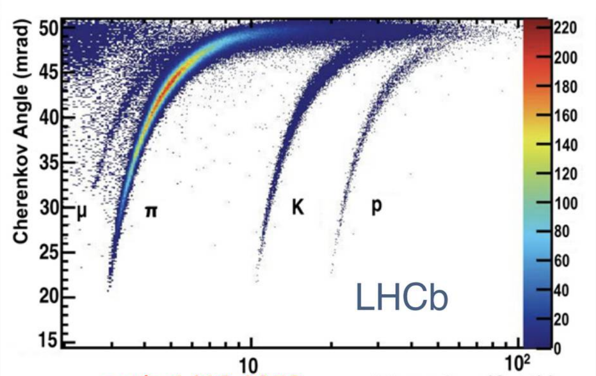
- Good separation at low momentum (~1 GeV)
- Requires ~100 ps resolution to cover PID ~1 GeV
- Current studies assume 30 ps resolution



arxiv 2202.03285

RICH

- Good separation in a wide momentum range
- Need enough radiation length for good PID

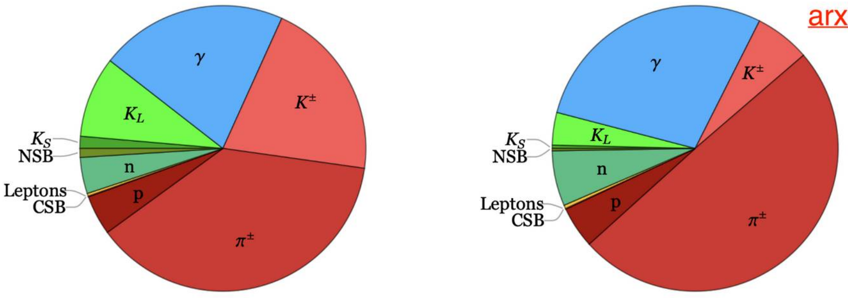


arxiv:1412.6352

Tagging Challenge: strange

Strange jet tagging

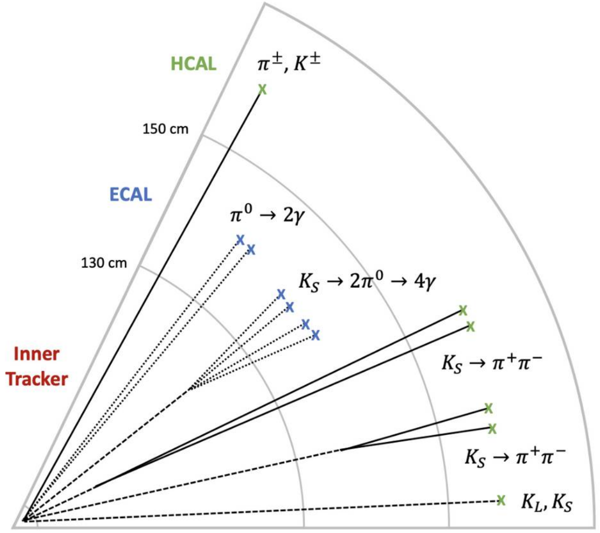
arxiv:2003.09517



Momentum fraction

Strange $p_T = 45\,\mathrm{GeV}$ Down $p_T = 45\,\mathrm{GeV}$

Not to scale



s-baryons Λ, Σ, Ξ have $c\tau \approx 1 - 10$ cm

- Higher fraction of momentum carried by **kaons**
  - K^+/π^+ separation is the key
- Neutral kaons and s-baryons are long-lived
  - $c\tau(b/c) \approx 0.5$ mm, $c\tau(s) \approx 50$ mm
  - Requirement on vertexing, see talk by L. Roerig

Tagging Challenge: Higgs→ss

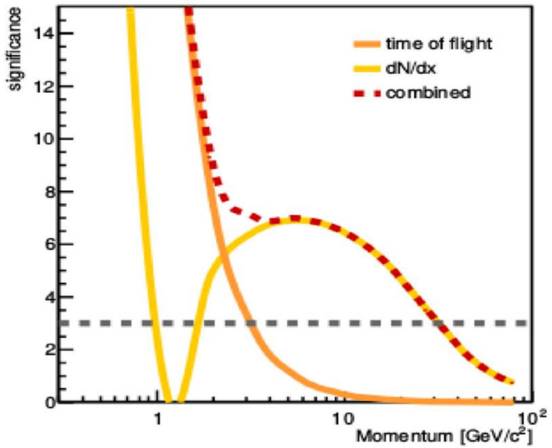
Jet tagging

- Key to quarks and gluons
- Very different from LHC
- Huge Z and W boson decay samples to calibrate
- PID is crucial input
- Charm, strange gluon tagging works
- Seeing H→ ss is least obvious, but should be possible

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:

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]

Tagging Challenge: Higgs→ss

Jet tagging

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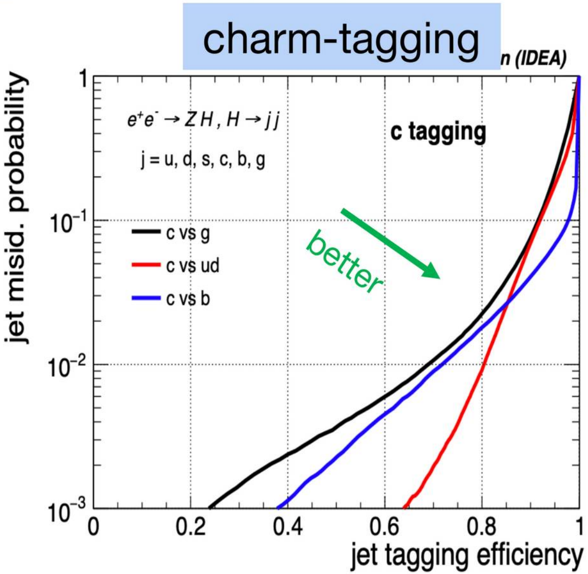
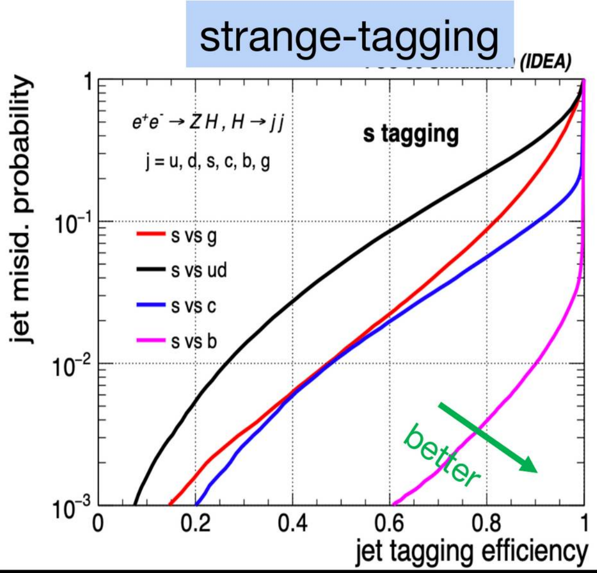
- Very different from LHC
- Huge Z and W boson decay samples to calibrate
- PID is crucial input
- Charm, strange gluon tagging works
- Seeing H→ ss is least obvious, but should be possible

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%

Tagging Challenge: Higgs→ss

Jet tagging

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- Very different from LHC
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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

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

Calorimeter resolution matters ...

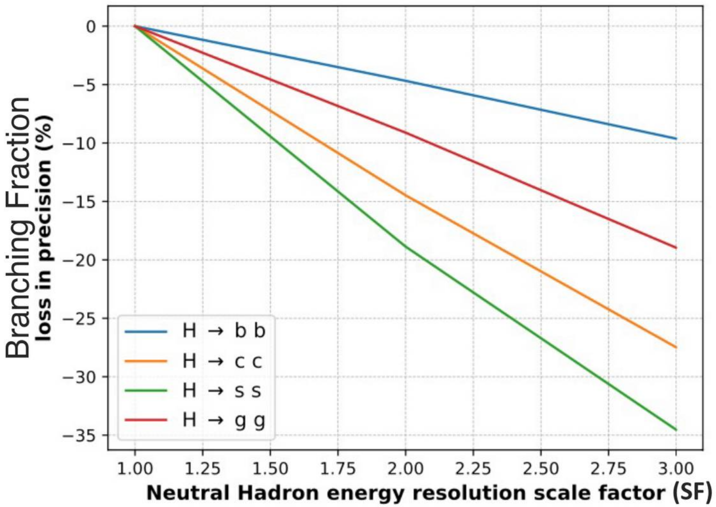
Reconstruction of Higgs hadronic final states

(Case study 1)

FUTURE CIRCULAR COLLIDER

Higgs → 2 jets signal ID in HZ events relies on the calorimeter (and vertex detector) performance:
Mass resolution of Higgs and recoil system, flavor tagging efficiency

Study to measure impact of variation in neutral hadron resolution by a factor of 2 (3) with respect to the baseline) on H → jet-jet, with jet = b, c, s, g, with Z → lepton-lepton



Precision of $H \rightarrow s\bar{s}$ degrades by 20% (35%)

- A bit larger than similar degradation in the number of ionization clusters per unit length (*dN/dx*) – IDEA gas chamber (*dN/dx* provides particle ID)

The effect the Hcc, Hgg, Hbb couplings is smaller

- Increases as the s/b decreases

SF=1 (dual readout calorimeter: **30%/√E**)
2 (ATLAS type-calorimeter: **50%/√E**)
3 (CMS-type calorimeter: **100%/√E**)

Calorimeter technologies match

Single particle, jet, and invariant mass resolution

FUTURE CIRCULAR COLLIDER

Expected energy resolution for the different technologies: measurements when available, otherwise obtained from (DELPHI) simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [20,45]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8–10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3–4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4–5 % [49]	3–4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5–6 % [30,50]	3–4 % [50]

IDEA [48]
JINST 15 C06015

CLD [20]
LCD-Note-2019-001

Calos for FCC-hh [27]
CERN-FCC-PHYS-2019-0003

Crystal Calos for FCs [30]
J. Instrum. **15**, P11005–P11005 (2020)

Traditionally, the physics drivers for the "ultimate" ~3-4% PFlow jet energy resolution

- High efficiency for W/Z/H boson mass separation
- Separation of boosted objects (at higher energies)

SMEFT (at NLO)

Generically beyond SM

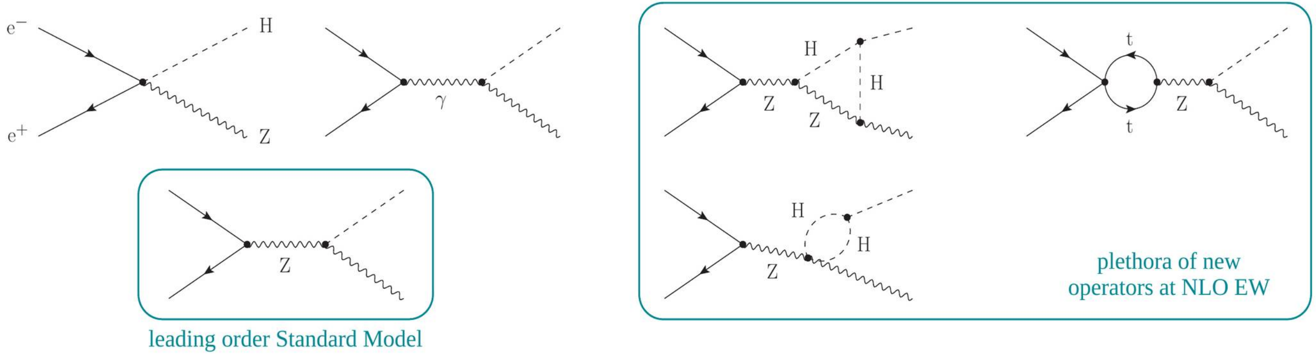
Konstantin Asteriadis

Precision measurements and SMEFT

SMEFT @ NLO

- Well studied on LEP data but LO only
- NLO opens up number of new operators
- Precision from FCC-ee is essential

Higgstrahlung in the SM and SMEFT



- SM results available at NLO EW [Fleischer, Jegerlehner '83; Kniehl '92, Denner, Kublbeck, Mertig, Bohm '92; Bondarenko, Dydyshka, Kalinovskaya, Rumyantsev, Sadykov, Yermolchyk '19]

  ... many pieces known at NNLO accuracy [Sun, Feng, Jia, Sang '17; Gong, Li, Xu, Yang, Zhao '17; Song, Freitas '21; Chen, Guan, He, Li, Liu, Ma '22; Freitas, Song, Xie '23]

- SMEFT at LO extensively studied using LEP data → precision of future lepton collider might allow the indirect study of operators not present at LO

- **Next step: SMEFT at NLO in the electro-weak expansion** (first studies published KA, Dawson, Giardino, Szafron, arXiv:2406.03557 ... more to come soon)

Precision measurements and SMEFT

SMEFT @ NLO

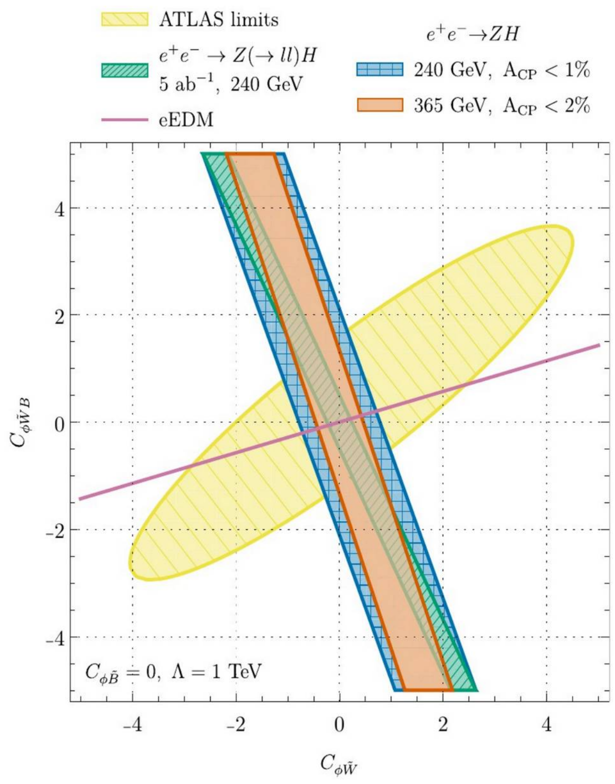
- Additional CP violating operators from NLO
- virtual corrections can develop imaginary contributions
- Instead of using full differential cross sections asymmetries should be sufficient
- LHC/FCC-ee complementary
- eEDM adds orthogonal very precise contribution

CP Violation in Higgstrahlung

- Define CP violating asymmetry

$$A_{\mathrm{CP}} = \frac{\sigma(\cos\theta < 0) - \sigma(\cos\theta > 0)}{\sigma_{\mathrm{SM,NLO}}}$$

- Expected precision for the total cross section at FCC-ee might be as low as ~ 0.5% at 240 GeV (365 GeV ~ 1%) → Assume half the precision
- Consider $C_{\phi\tilde{W}}$ and $C_{\phi\tilde{W}B}$ (other Wilson coefficients set to 0)
- Limits from H → 4 lepton decay at LHC [ATLAS, JHEP 05, 105 (2024)]
- Strong limits from electron electric dipole moment (eEDM) that also depends on SMEFT coefficients [ACME, Nature 562, 355 (2018)]
- Potential limits through angular observables [JHEP 03, 050 (2016)]



[KA, Dawson, Giardino, Szafron, arXiv:2406.03557]

Precision measurements and SMEFT

SMEFT @ NLO

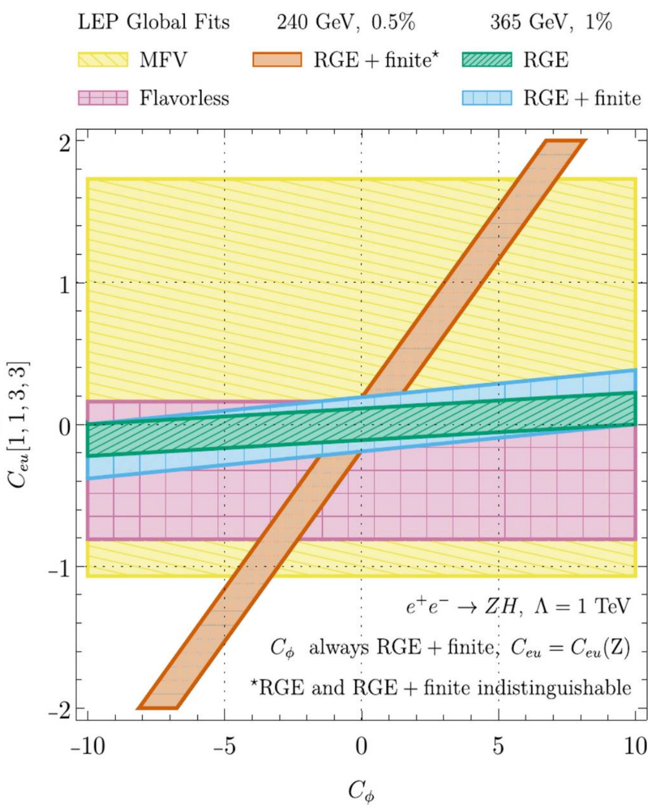
- Constraints on Higgs trilinear and electron-top coupling operators largely benefit from measurements at different E_{CM}
- Different contributions have different dependence on the E_{CM}

Higgs Tri-linear and Top Quark Couplings

- Consider Higgs self-interaction C_ϕ and electron-top 4-fermion operator $C_{eu}[1,1,3,3]$
- SMEFT Wilson coefficients are regulated in $\overline{\text{MS}}$ → Scale dependent contributions $\bar{\Delta}_i$ can be obtained from RGE evolution [Jenkins, Manohar, Trott '13 '14; Alonso, Jenkins, Manohar, Trott '14]

$$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{SM,NLO}}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2}\left\{\Delta_i + \bar{\Delta}_i \log\frac{\mu^2}{s}\right\}$$

- Finite contributions Δ_i only from exact higher order computations



[KA, Dawson, Giardino, Szafron, arXiv:2406.03557]

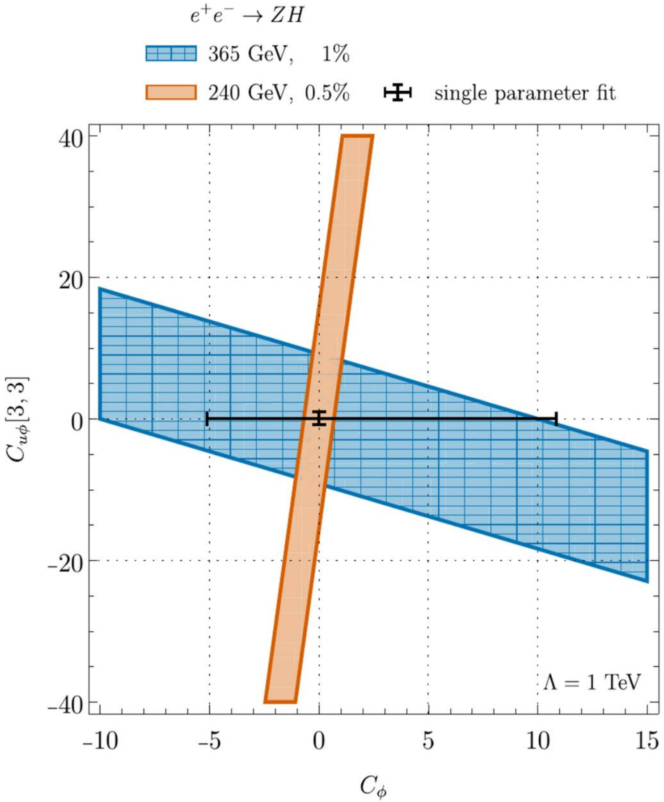
Precision measurements and SMEFT

SMEFT @ NLO

- Systematic framework and evaluating all different operators
- SMEFT community is catching up and will join the fun

Higgs Tri-linear and Top Quark Couplings

- Consider Higgs self-interaction C_ϕ and anomalous top-Yukawa coupling $C_{u\phi}[3,3]$
- Single parameter limits from global fit to LHC Higgs data [JHEP 04, 279 (2021)] and HH searches [ATLAS, arXiv:2404.05498]
- **Measurement at two energy scales complementary**



[KA, Dawson, Giardino, Szafron, arXiv:2406.03557]

Beyond the Standard Model Physics

Kevin Langhoff, Chris Verhaaren, Zeynep Demiragli

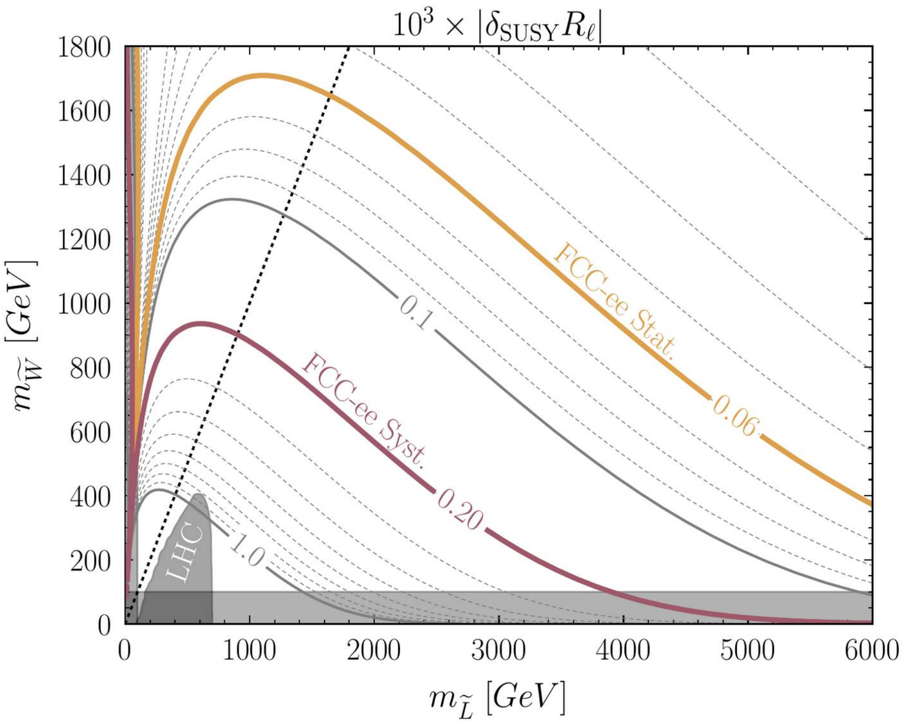
SUSY has still open phase space

SUSY

- For certain areas of the phase space there is still room
- Careful with older plots as the LHC might do better than indicated but … there is room

Results

$\cos(2\beta) = 0$



Wino + LH Slepton
(Preliminary)

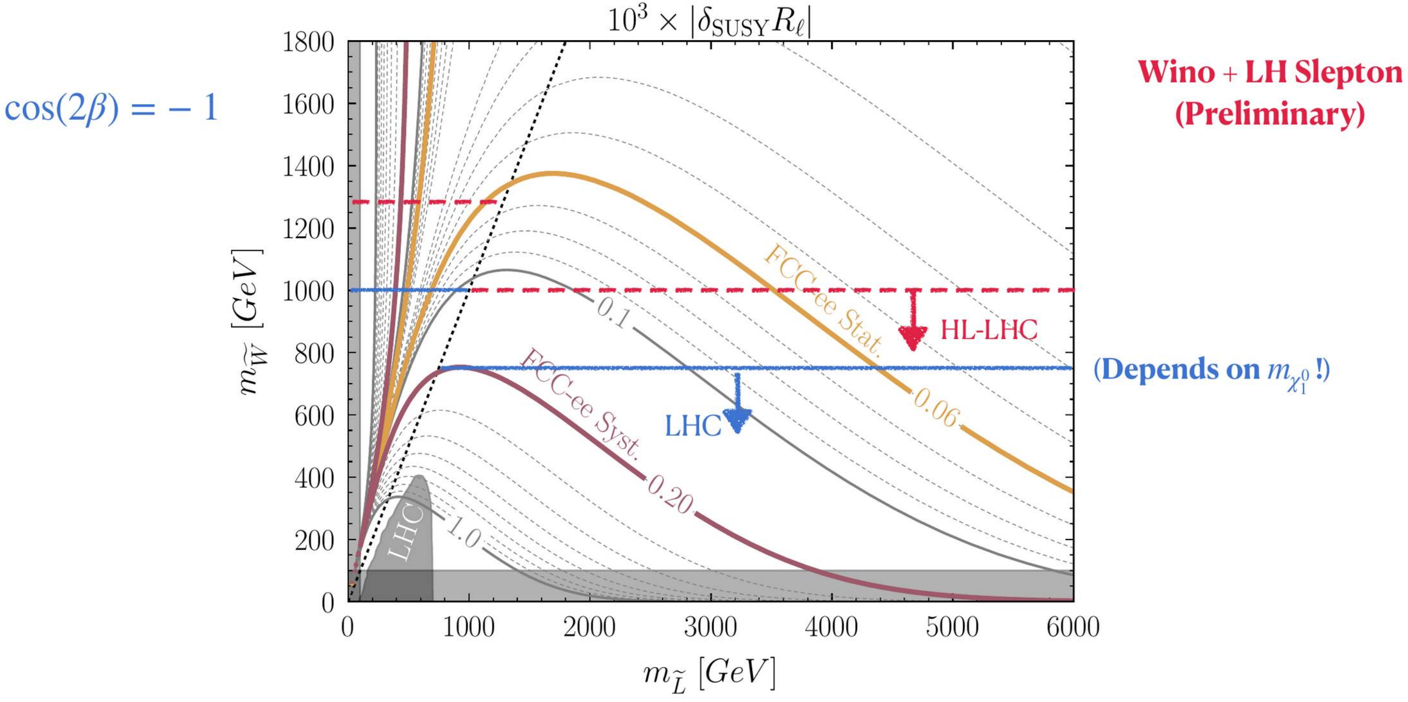
[1908.08215]

SUSY has still open phase space

SUSY

- LHC might do better than indicated but … there is room
- Systematic uncertainties at FCC-ee are very important
- Theorists need to review the options, experimentalist the uncertainties

Results



[1908.08215]

Dark Sector: Axion-Like Particles

Dark Sectors

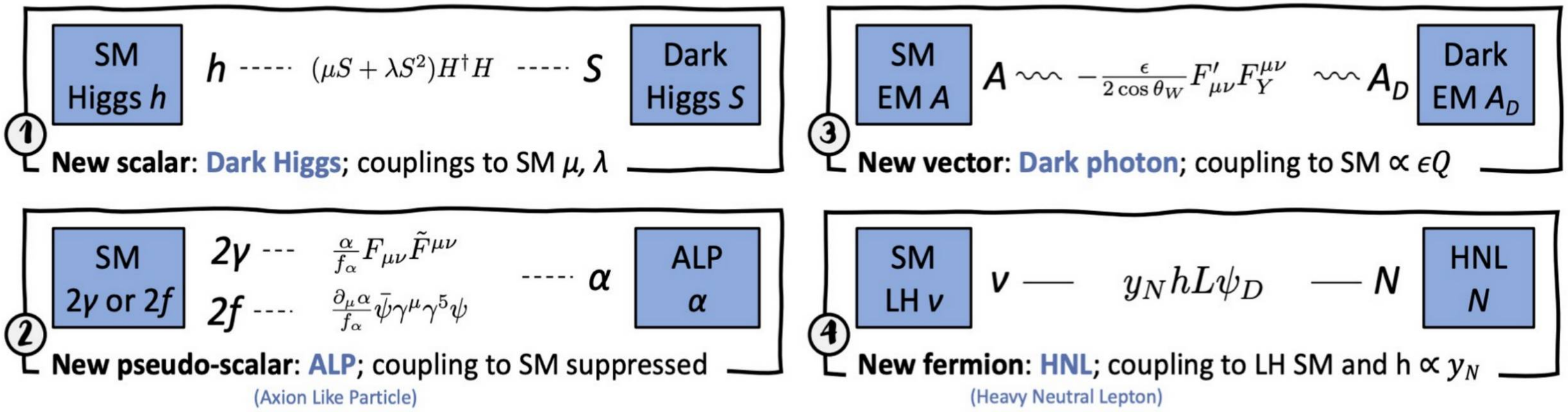
- Going to lower energy from LHC
- → use the event counts and look for lower masses: intensity frontier

Personal Favorite Motivator: Dark Sector

BOSTON UNIVERSITY

While the dynamics of the dark sector could be complicated…

to observe a dark sector, *we need a portal interaction*:

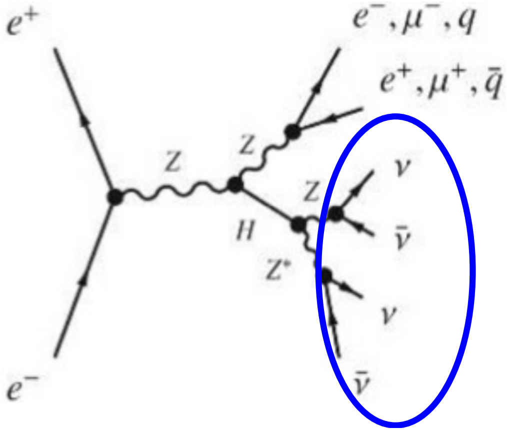


New Physics could be light and feebly interacting with SM

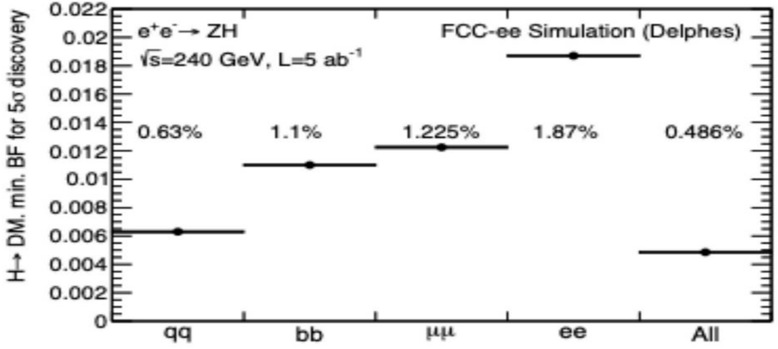
Higgs Invisible Width

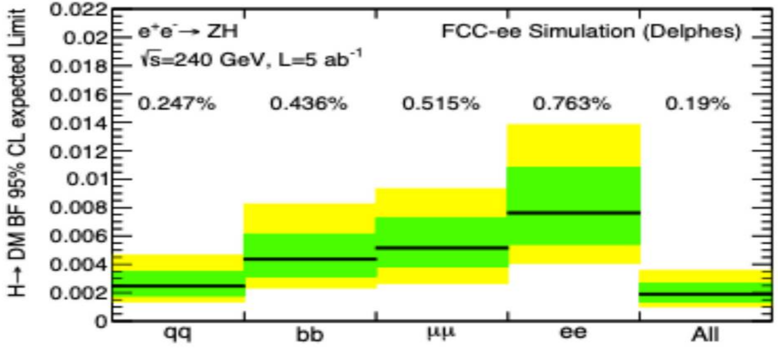
Higgs boson: portal to dark world

- Use recoil and require nothing else
- Measure H→ZZ→νννν
- Then remove as SM background
- SM precision 0.1%; NP at BF of 0.5%



Invisible decay products





Recent work (FCC MIT Workshop) compares CLD full sim and CLD & IDEA Delphes fast sim.

- ➢ Efficiency is ~identical for IDEA and CLD fast simulations!
- ➢ Electron eff is worse for full sim than for fast sim & Muon eff is very similar for full & fast sim.

Dark Sector: Axion-Like Particles

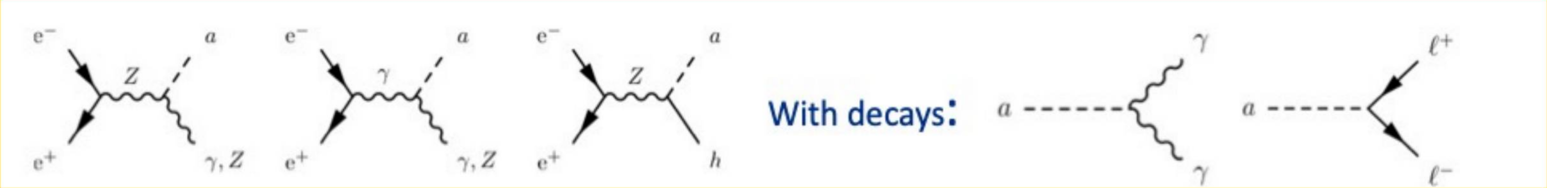
Dark Sectors

- Going to lower energy from LHC
- → use the event counts and look for lower masses: intensity frontier

Case Study: Axion-like Particles

BOSTON UNIVERSITY

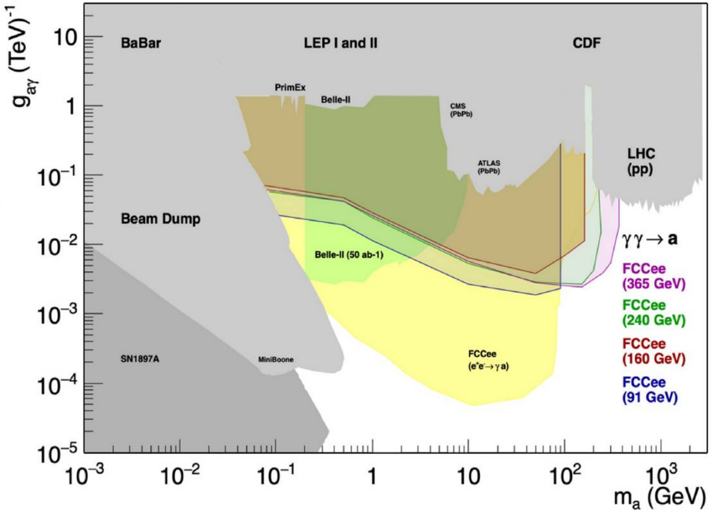
"Standard" approach:



➢ $\gamma\gamma \rightarrow a$ extends current LHC limits for m_a = 5 – 350GeV by 2(O) magnitude

➢ $e^+ e^- \rightarrow Z \rightarrow \gamma a$ extends current LHC limits for m_a = 0.1 – 90 GeV by 3(O) magnitude

For low ALP mass, sophisticated detectors & techniques are needed to isolate the overlapping photons



Zeynep Demiragli – FCC Week 2024, San Francisco

Can the Z be a portal?

Rare Z decays

- Not only the Higgs can be a portal
- Z resonance holds potential for exotic decays

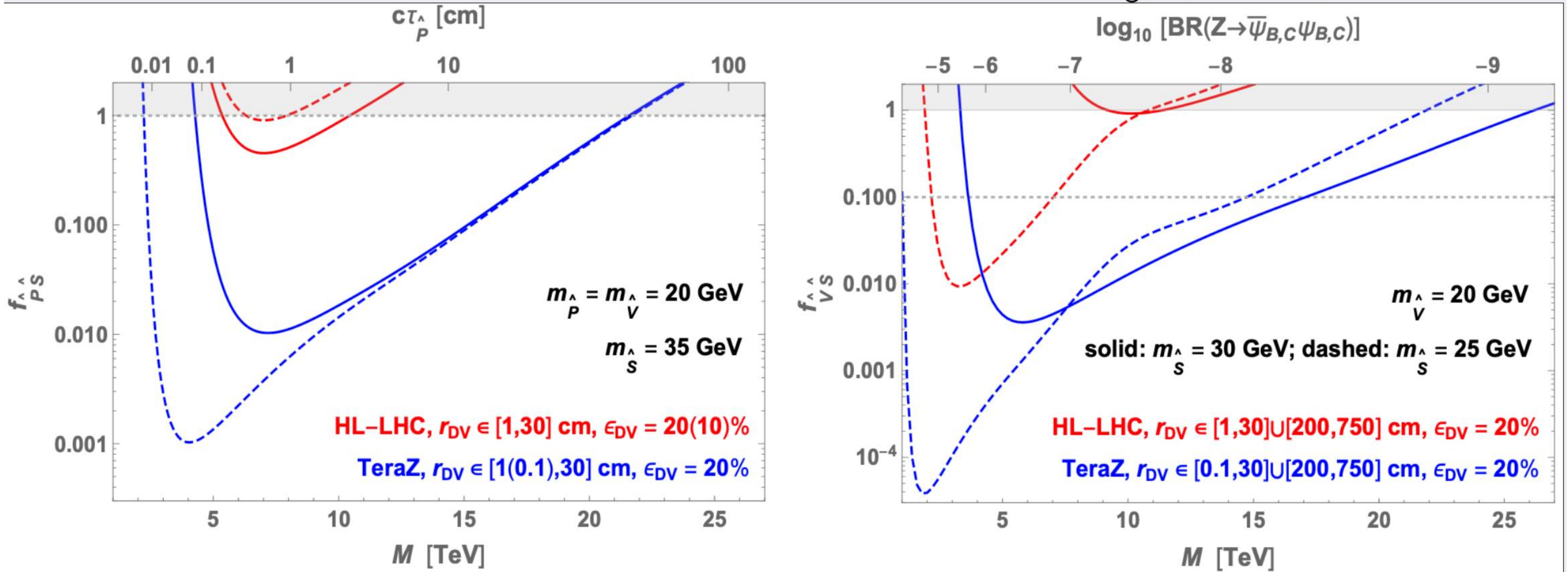
Z-portal

Fraction of Z decays to hidden sector that are XY final state: f_{XY}

Grey lines motivated benchmarks

See that FCC-ee has impressive reach

Cheng, Li, Salvioni, CV 1906.02198



Sensitive to fractional charge?

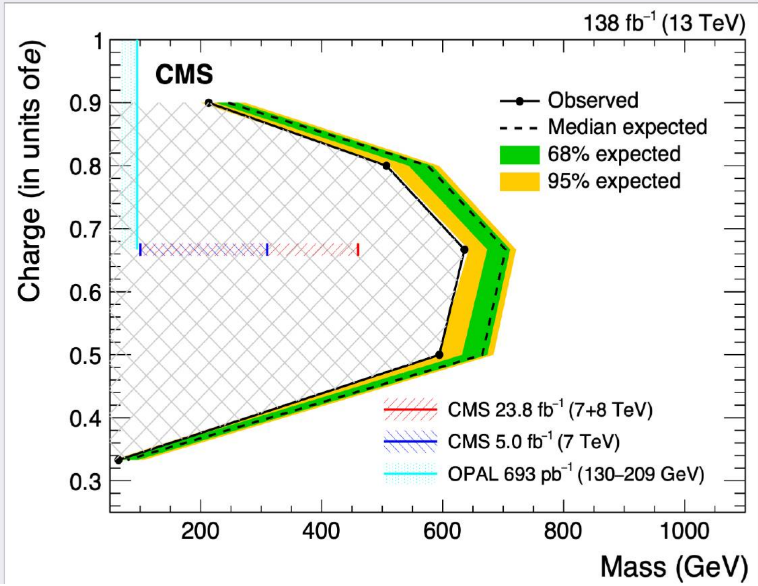
GUT

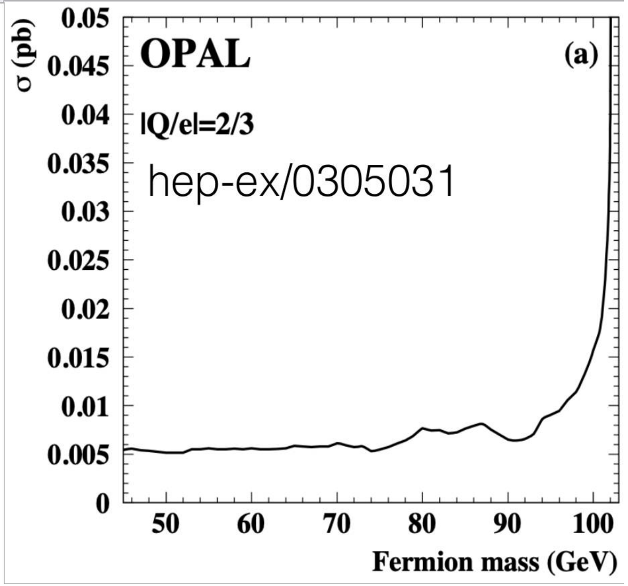
- Recent paper motivate GUTs with possible e/6 charges
- Can the FCC-ee make a contribution

Fractionally Charge Particles

Not clear that the charge e/6 target can be probed at the LHC

Can the FCC-ee make a comprehensive search/discovery up to the top-quark mass?





Higgs and Glueballs?

Comments

- Glueball searches are hard at the LHC
- The excess in bbbb final states will be hard to distinguish from the background

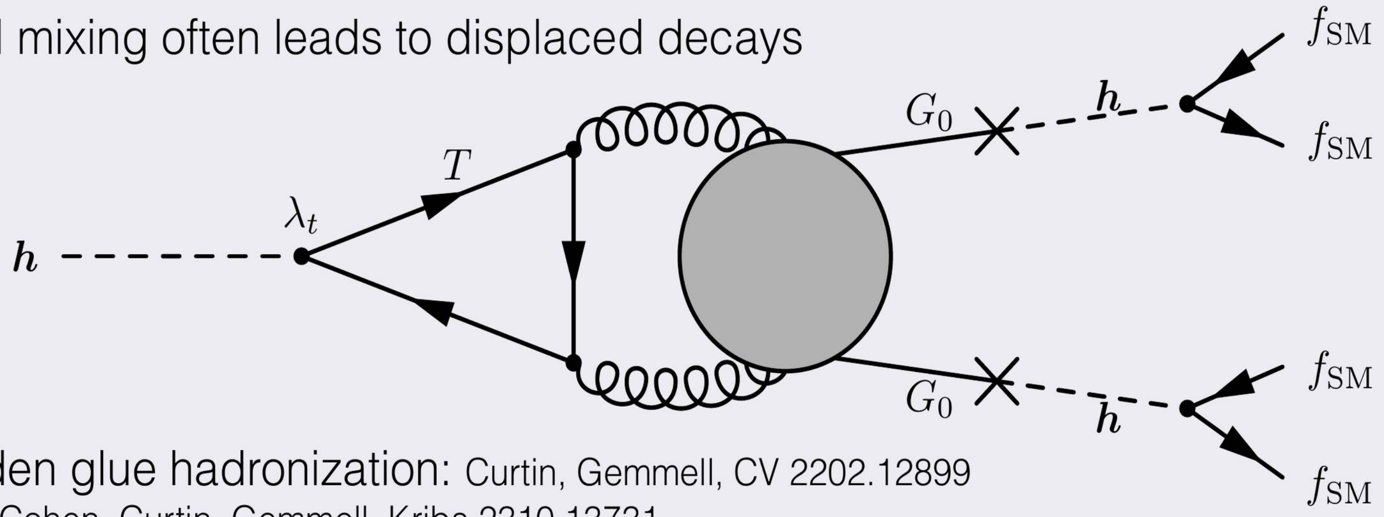
Higgs Physics

Exotic Higgs Decays

Lightest hidden glueball mixes with the Higgs

$$h \to G_0 G_0 \to \bar{f} f \bar{f} f \qquad \text{(Mostly to b-quarks)}$$

Small mixing often leads to displaced decays



Hidden glue hadronization: Curtin, Gemmell, CV 2202.12899
Batz, Cohen, Curtin, Gemmell, Kribs 2310.13731

Conclusions

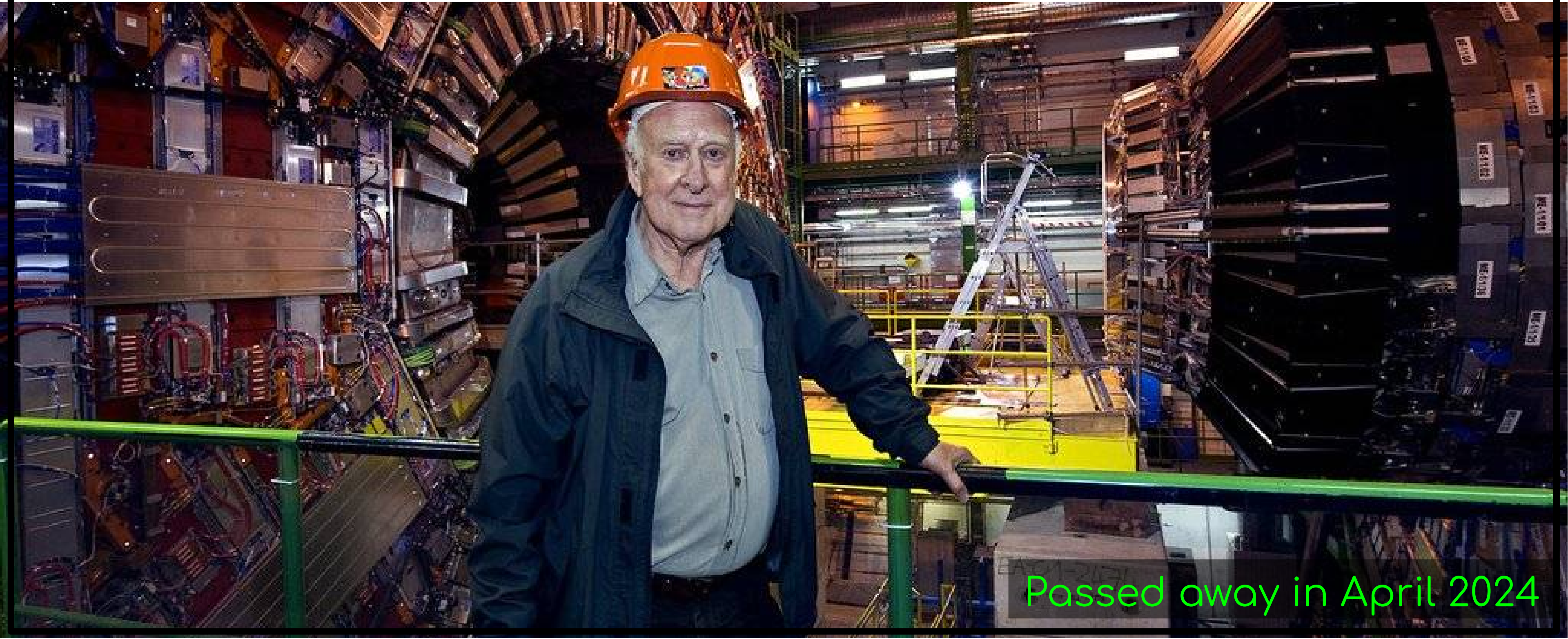
Status

- FCC-ee produces ~2.2M Higgs bosons in pristine conditions and thus has a strong Higgs program
- There are extraordinary electroweak precison, flavor and BSM programs
- Detector design ideas exist and match the requirements
- New ideas for even better solutions are being investigated

Work that needs doing

- Work on systematics and the theory is essential
- New detector technology should be supported
- Detector integration is starting to move into focus

R.I.P. Peter Higgs



Passed away in April 2024

More

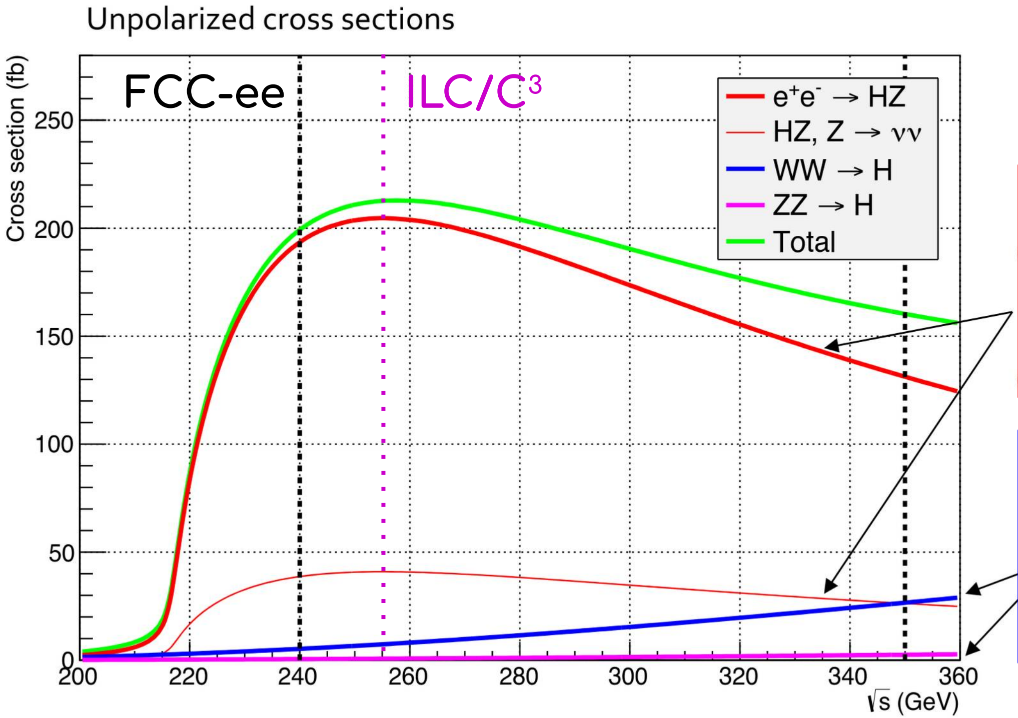
Higgs Physics at e^+e^- Colliders

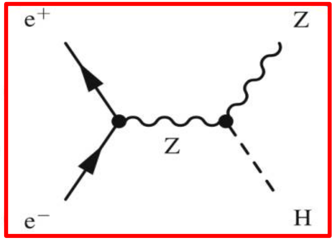
ZH Threshold turns on at 91 + 125 GeV = 216 Ge
reaches a maximum at around 255 GeV

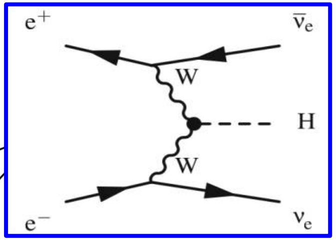
Vector boson fusion rises steadily but is small

FCC-ee: most Higgses at 240 GeV for FCC-ee considering lumi profile

ILC/C[3] best at peak







arXiv:1308.6176

Higgs Physics at e^+e^- Colliders

Leading strategy

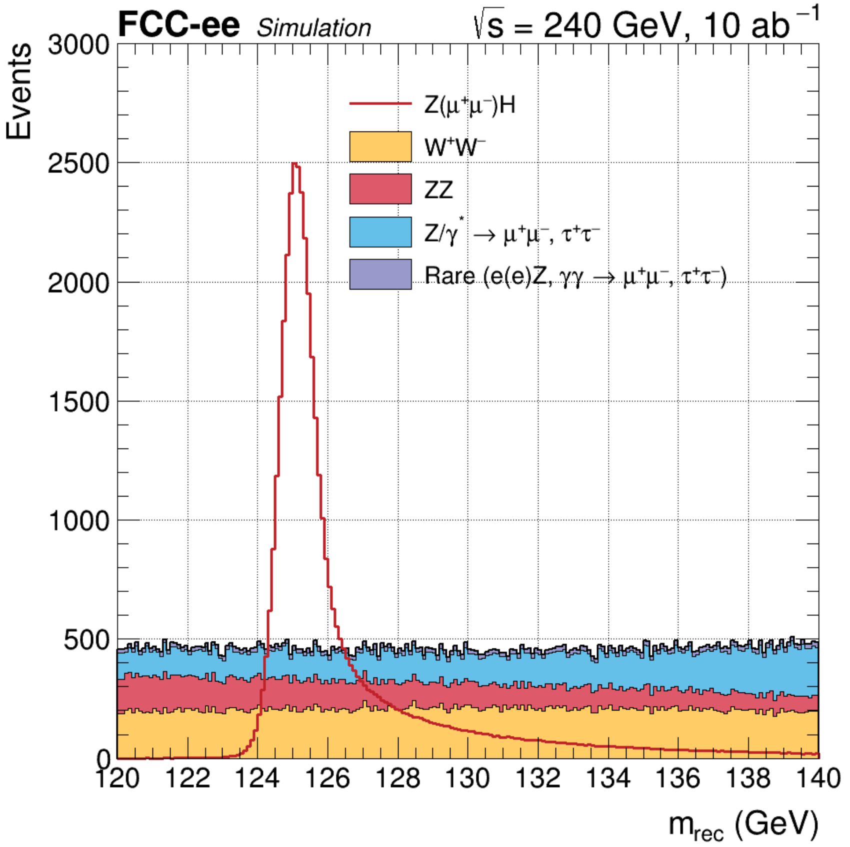
- Tag the Z boson (leptons or jets)
- Recoil mass peaks sharply at Higgs mass

$$m^2_{recoil} = \left(\sqrt{s} - E_{ff}\right)^2 - p^2_{ff}$$
$$= s + m^2_Z - 2E_{ff}\sqrt{s} \approx m^2_H$$

- Direct Higgs reconstruction not required, model independent σ_{ZH} measurement
- Dominant background: WW, ZZ and Z/γ*

Challenges

- Detectors: resolution, tracking, vertexing, timing, angular
- Flavour tagging for Higgs couplings
- Jet reconstruction algorithms

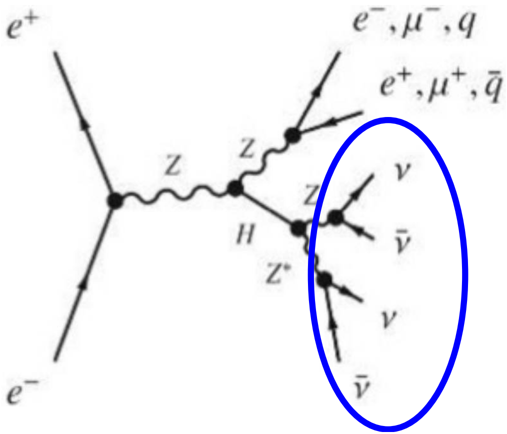


This plot does not work at hadron colliders.

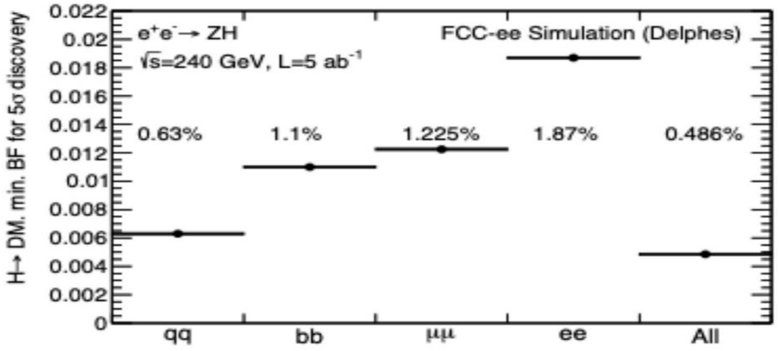
Higgs Invisible Width

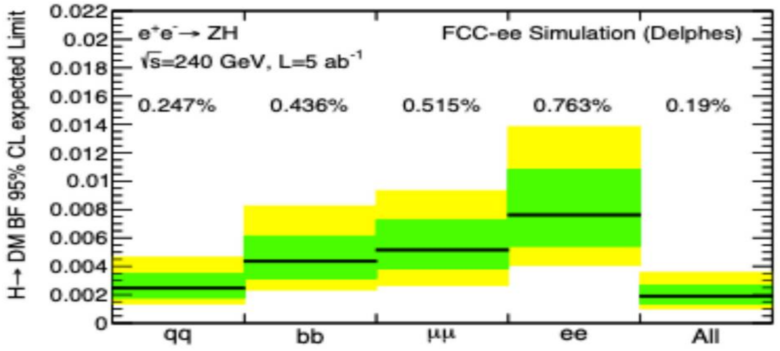
Higgs boson: portal to dark world

- Use recoil and require nothing else
- Measure H→ZZ→νννν
- Then remove as SM background



Invisible decay products





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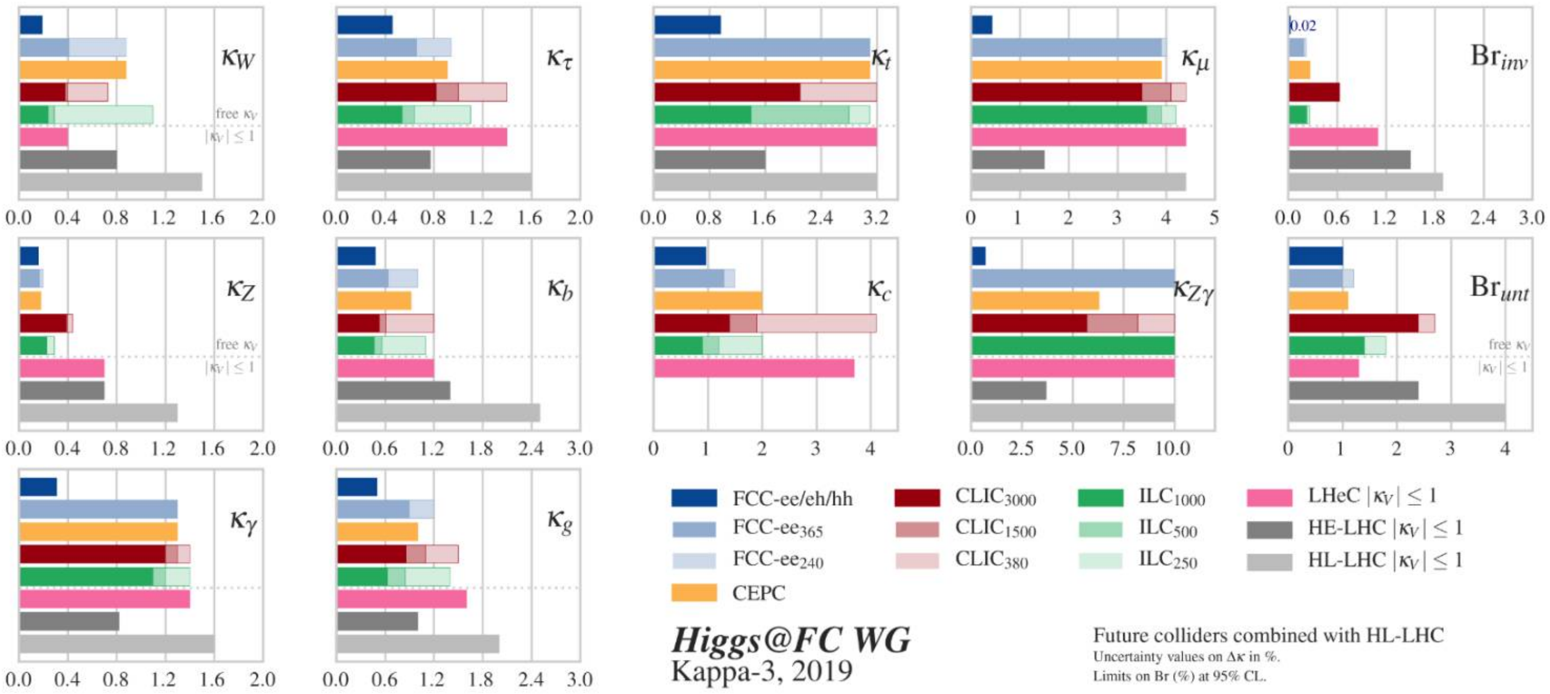
- ➢ Efficiency is ~identical for IDEA and CLD fast simulations!
- ➢ Electron eff is worse for full sim than for fast sim & Muon eff is very similar for full & fast sim.

Higgs Couplings Precision



Not very dependent on the e^+e^- option

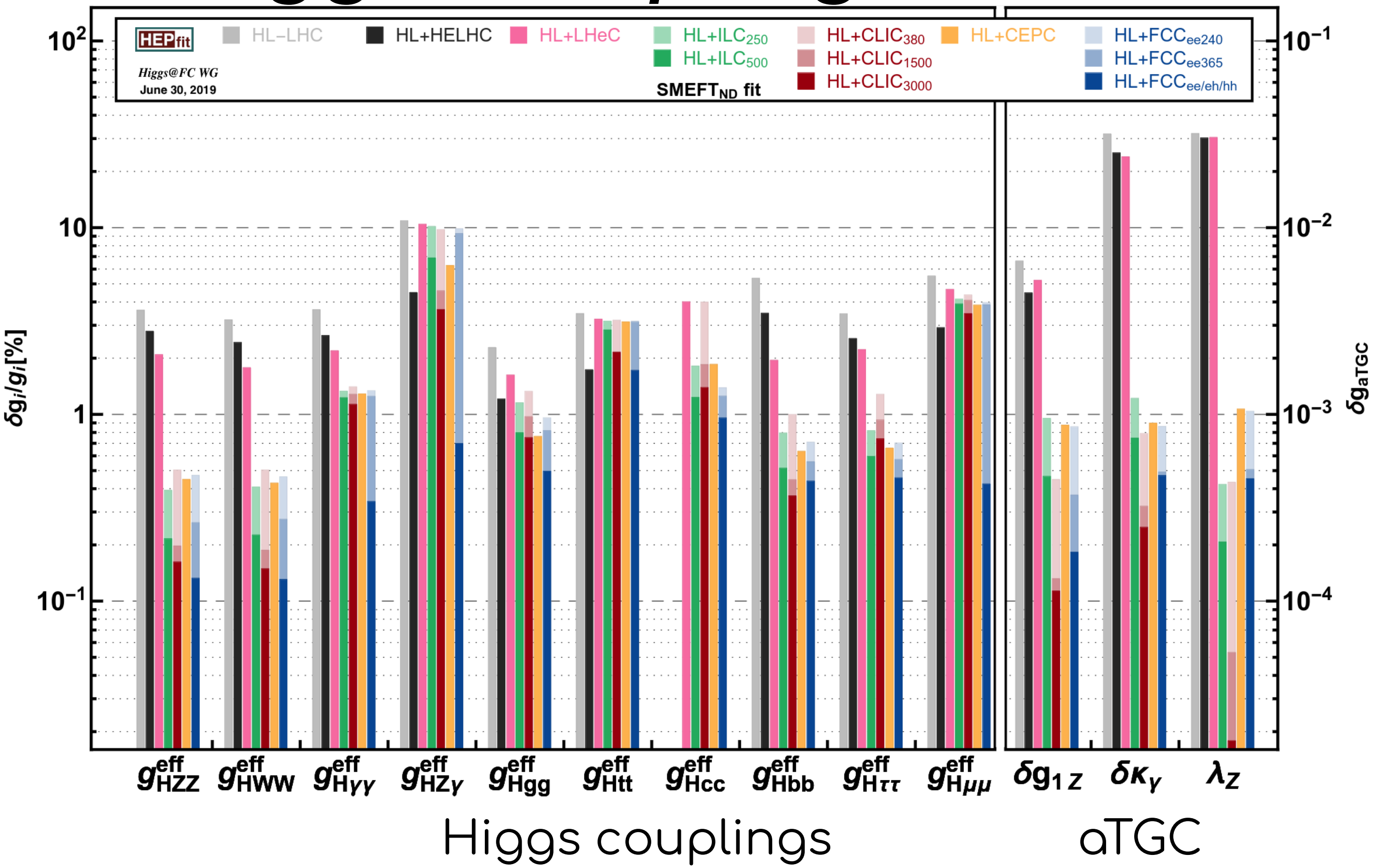
- Sensitivity to Higgs coupling is mostly around a percent
- Details of the uncertainties are dependent on the specific implementations

arXiv:2206.08326

Higgs Couplings Precision

Sensitivity to deviations for

- Different effective Higgs couplings
- and aTGC

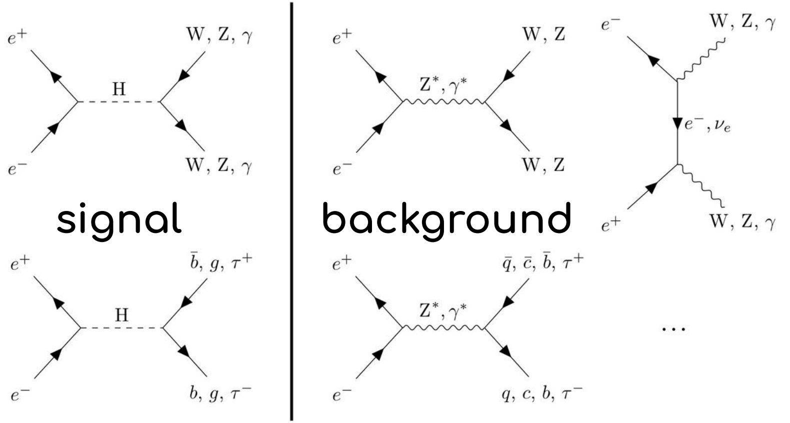


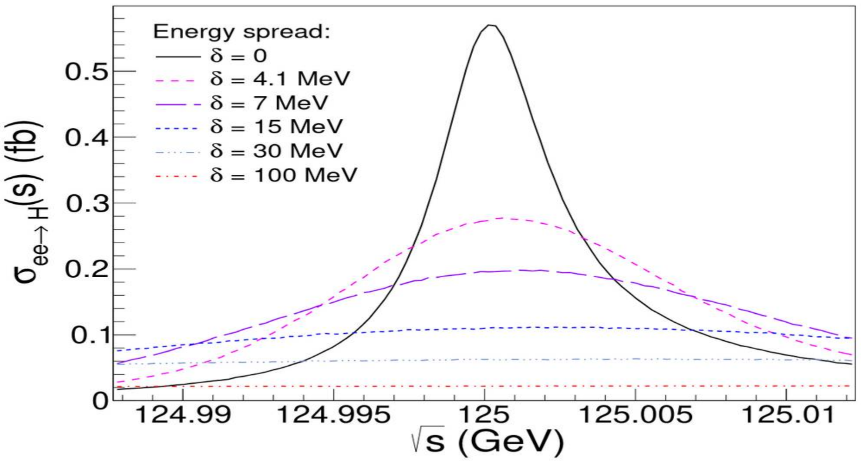
arXiv:2206.08326

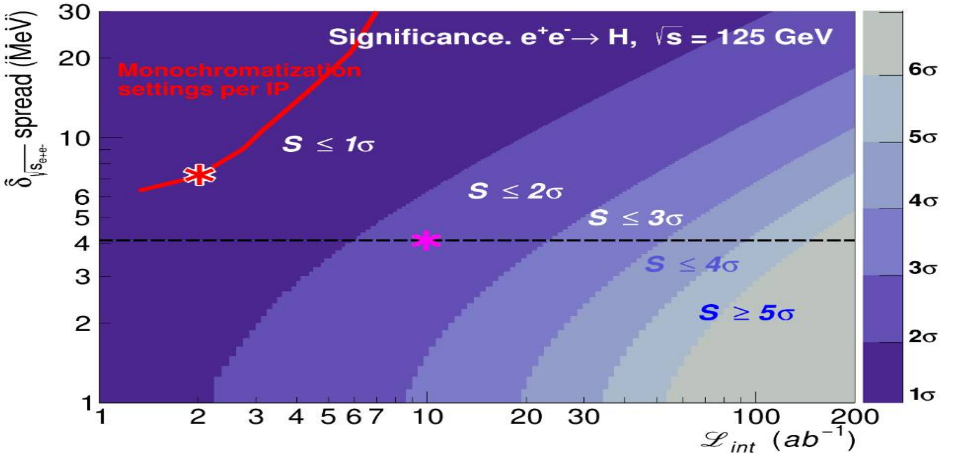
Higgs Electron Yukawa Coupling

Measure e+e- → H →e^+e^-: how?

- Γ_H is 4.1 MeV, measure m_H at MeV level
- Dial collider E_{CM} to m_H
- Monochromatize energy: ~ 4 MeV spread
- Signal is tiny and background is very large
- 1.3 std significance per IP and per year

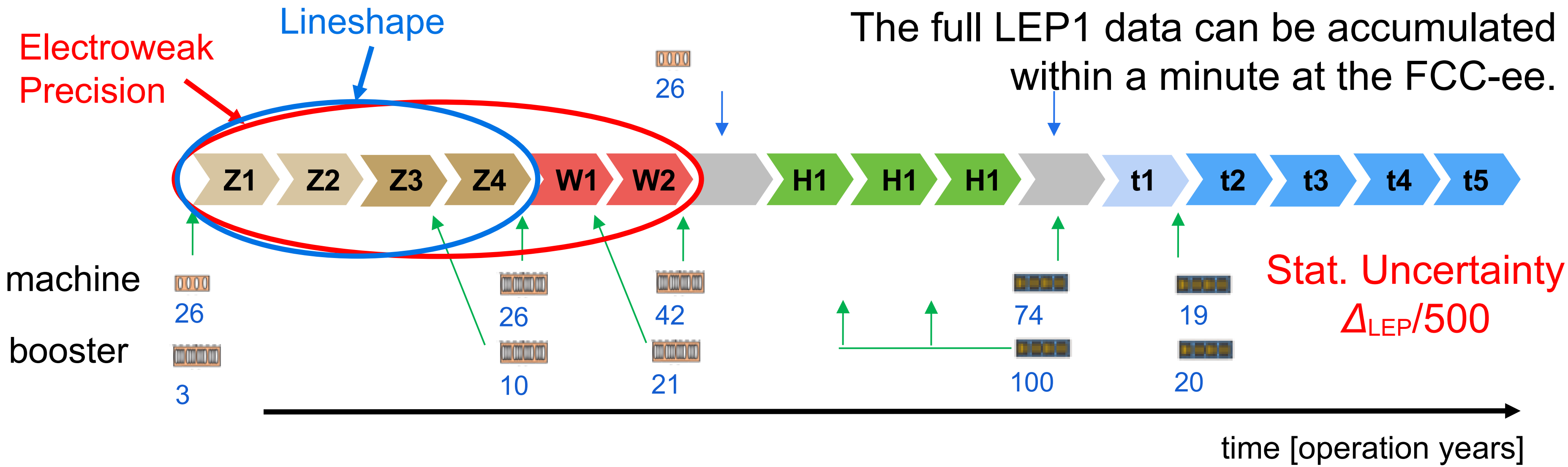






arXiv:2107.02686

‘Circular Electroweak Opportunity’



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW $\to$ H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW $\to$ H	

Lineshape Summary

Z pole run

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
$\Delta\sigma^0_{\rm had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e $(\times 10^3)$	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ $(\times 10^3)$	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ $(\times 10^3)$	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b $(\times 10^3)$	3.0*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
$\delta R_c (\times 10^3)$	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

arXiv:2206.08326

Lineshape Summary

WW threshold run

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8^*	17.8^*		3.8 (1.2)	17.8^*	
Δm_W (MeV)	12^*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1^*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1^*
Δm_H (MeV)	170^*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42^*	2		1.2 (0.3)	1.8 (0.9)	
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δR_μ $(\times 10^3)$	1.6^*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ $(\times 10^3)$	2.2^*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b $(\times 10^3)$	3.0^*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
$\delta R_c (\times 10^3)$	17^*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

arXiv:2206.08326

Asymmetry Summary

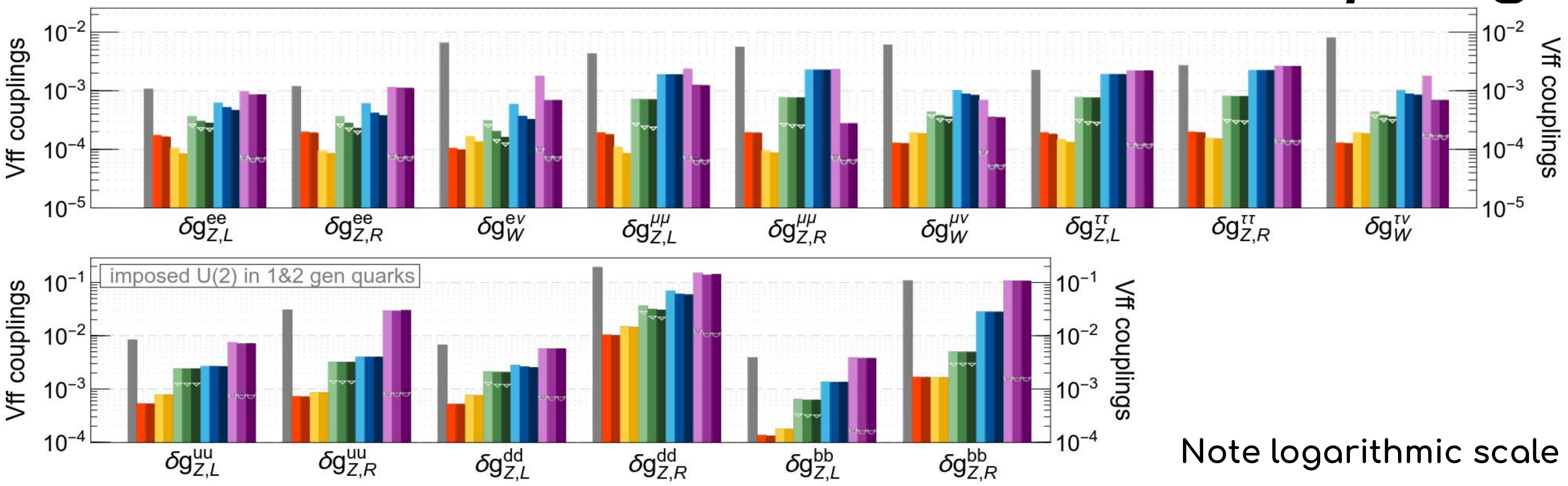
Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (6.9)	570
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	200

A few points to note

- Z pole running creates substantially improved precision for all 'LEP' measurements by close to 3 orders of magnitude (statistically speaking)
- Major work for experimental and theory community to bring that precision to bear

arXiv:2206.08326

Global Fit focus W/Z couplings



Note logarithmic scale

As expected

- Precision on couplings of W and Z bosons to fermions is more competitive at circular collider

arXiv:2206.08326