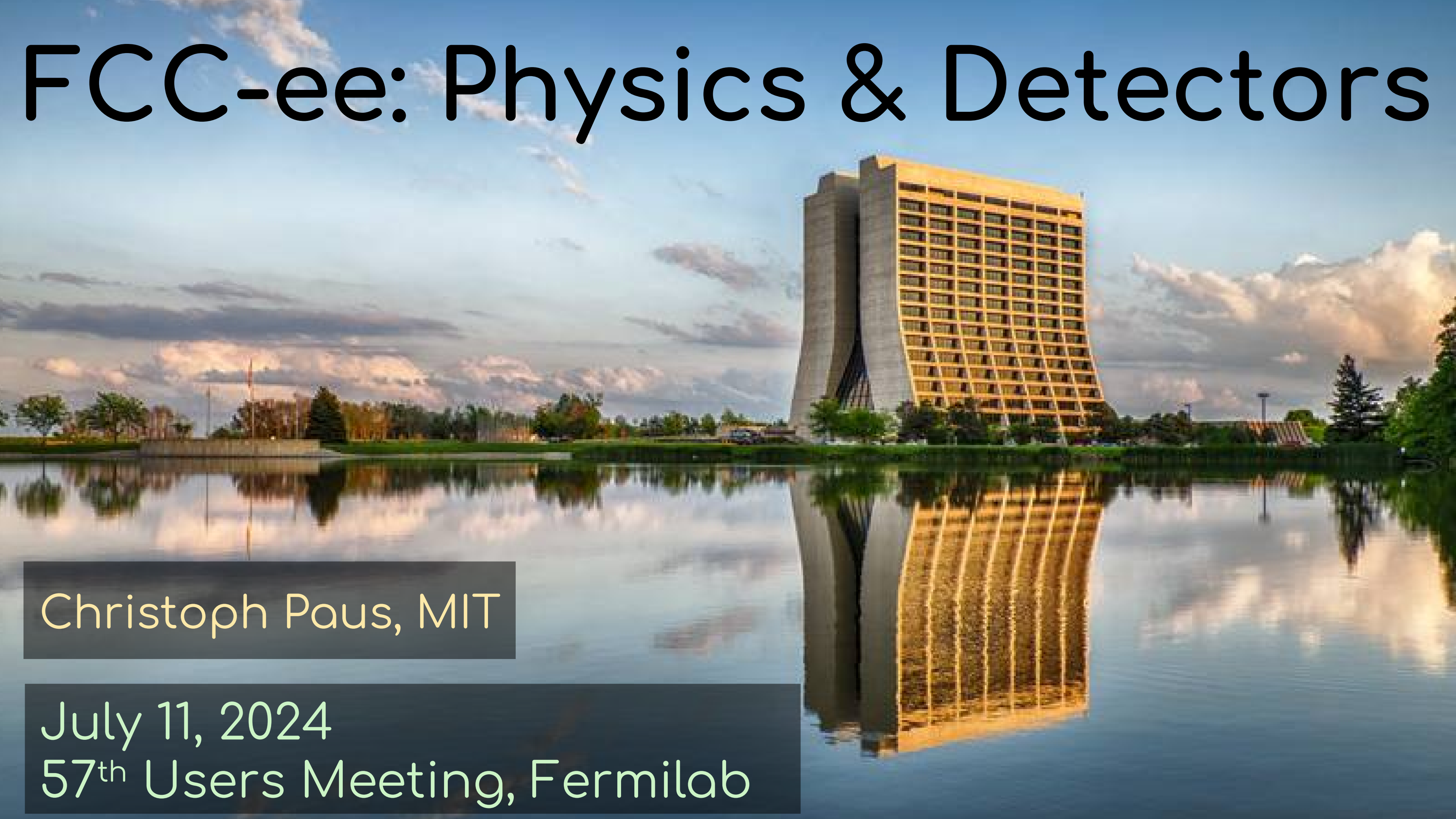
# FCC-ee: Physics & Detectors



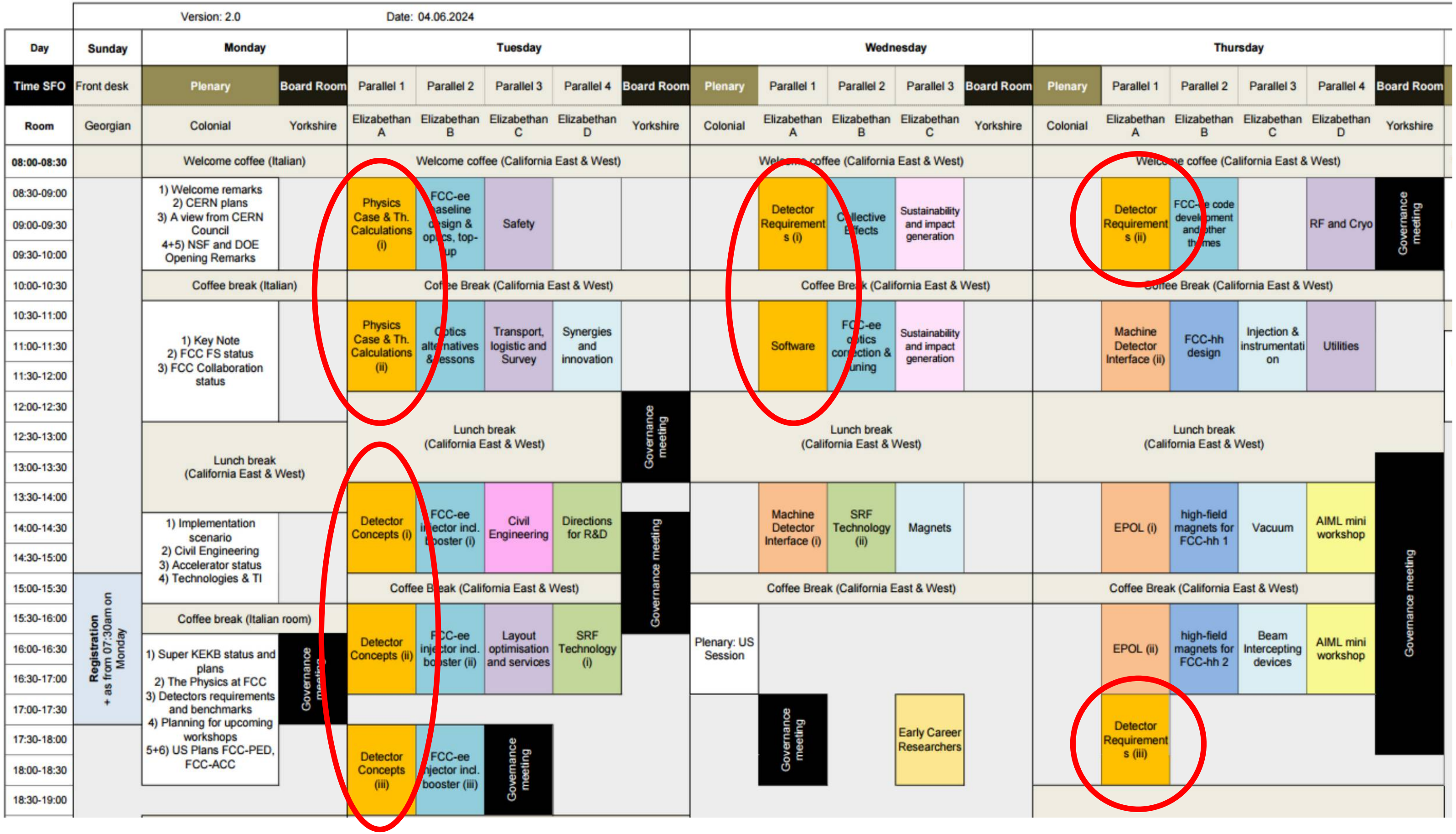
Christoph Paus, MIT

July 11, 2024
57th Users Meeting, Fermilab

# Reporting from June 2024 FCC Week in San Francisco

https://indico.cern.ch/event/1298458/timetable/

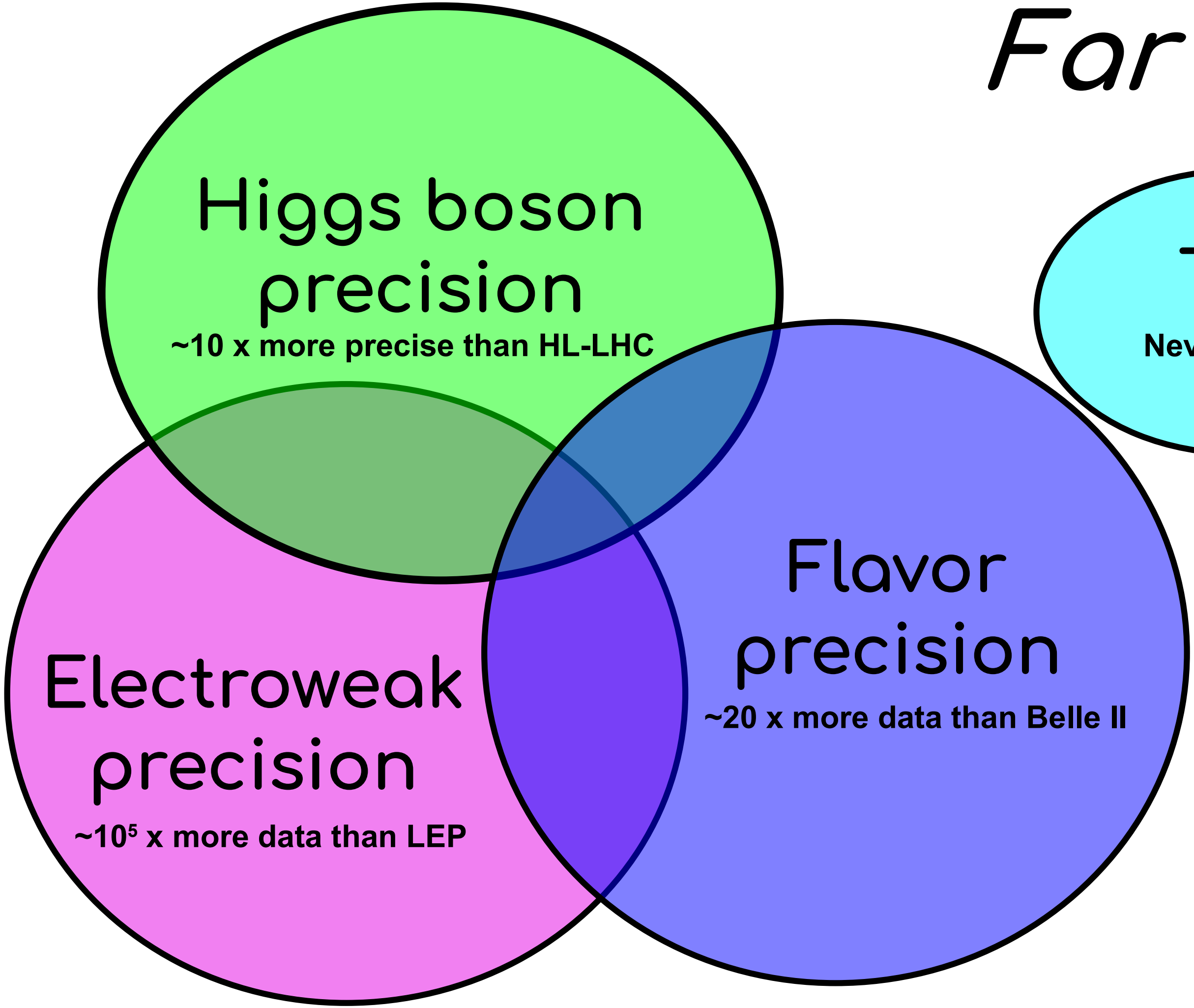
# *Parallel Presentations*



Version: 2.0 Date: 04.06.2024

| Day | Sunday | Monday | | Tuesday | | | | | Wednesday | | | | | Thursday | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time SFO | Front desk | Plenary | Board Room | Parallel 1 | Parallel 2 | Parallel 3 | Parallel 4 | Board Room | Plenary | Parallel 1 | Parallel 2 | Parallel 3 | Board Room | Plenary | Parallel 1 | Parallel 2 | Parallel 3 | Parallel 4 | Board Room |
| Room | Georgian | Colonial | Yorkshire | Elizabethan A | Elizabethan B | Elizabethan C | Elizabethan D | Yorkshire | Colonial | Elizabethan A | Elizabethan B | Elizabethan C | Yorkshire | Colonial | Elizabethan A | Elizabethan B | Elizabethan C | Elizabethan D | Yorkshire |
| 08:00-08:30 | | Welcome coffee (Italian) | | Welcome coffee (California East & West) | | | | | Welcome coffee (California East & West) | | | | | Welcome coffee (California East & West) | | | | | |
| 08:30-09:00 | | 1) Welcome remarks<br>2) CERN plans<br>3) A view from CERN Council<br>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 | | | 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 (Italian) | | Coffee Break (California East & West) | | | | | Coffee Break (California East & West) | | | | | Coffee Break (California East & West) | | | | | |
| 10:30-11:00 | | 1) Key Note<br>2) FCC FS status<br>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 | | | 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) | | | | Governance meeting | Lunch break (California East & West) | | | | | Lunch break (California East & West) | | | | | |
| 12:30-13:00 | | Lunch break (California East & West) | | | | | | | | | | | | | | | | | |
| 13:00-13:30 | | | | | | | | | | | | | | | | | | | Governance meeting |
| 13:30-14:00 | | | | Detector Concepts (i) | FCC-ee injector incl. booster (i) | Civil Engineering | Directions for R&D | | | Machine Detector Interface (i) | SRF Technology (ii) | Magnets | | | EPOL (i) | high-field magnets for FCC-hh 1 | Vacuum | AIML mini workshop | |
| 14:00-14:30 | | 1) Implementation scenario<br>2) Civil Engineering<br>3) Accelerator status<br>4) Technologies & TI | | | | | | Governance meeting | | | | | | | | | | | |
| 14:30-15:00 | | | | | | | | | | | | | | | | | | | |
| 15:00-15:30 | Registration + as from 07:30am on Monday | | | Coffee Break (California East & West) | | | | | Coffee Break (California East & West) | | | | | Coffee Break (California East & West) | | | | | |
| 15:30-16:00 | | Coffee break (Italian room) | | Detector Concepts (ii) | FCC-ee injector incl. booster (ii) | Layout optimisation and services | SRF Technology (i) | | Plenary: US Session | | | | | | EPOL (ii) | high-field magnets for FCC-hh 2 | Beam Intercepting devices | AIML mini workshop | |
| 16:00-16:30 | | 1) Super KEKB status and plans<br>2) The Physics at FCC<br>3) Detectors requirements and benchmarks<br>4) Planning for upcoming workshops<br>5+6) US Plans FCC-PED, FCC-ACC | Governance meeting | | | | | | | | | | | | | | | | |
| 16:30-17:00 | | | | | | | | | | | | | | | | | | | |
| 17:00-17:30 | | | | | | | | | | Governance meeting | | Early Career Researchers | | | Detector Requirements (iii) | | | | |
| 17:30-18:00 | | | | Detector Concepts (iii) | FCC-ee injector incl. booster (iii) | Governance meeting | | | | | | | | | | | | | |
| 18:00-18:30 | | | | | | | | | | | | | | | | | | | |
| 18:30-19:00 | | | | | | | | | | | | | | | | | | | |

# *Far away vision*



**Higgs boson precision**

~10 x more precise than HL-LHC

**Electroweak precision**

~$10^5$ x more data than LEP

**Flavor precision**

~20 x more data than Belle II

**Top**

Never produced in $e^+e^-$

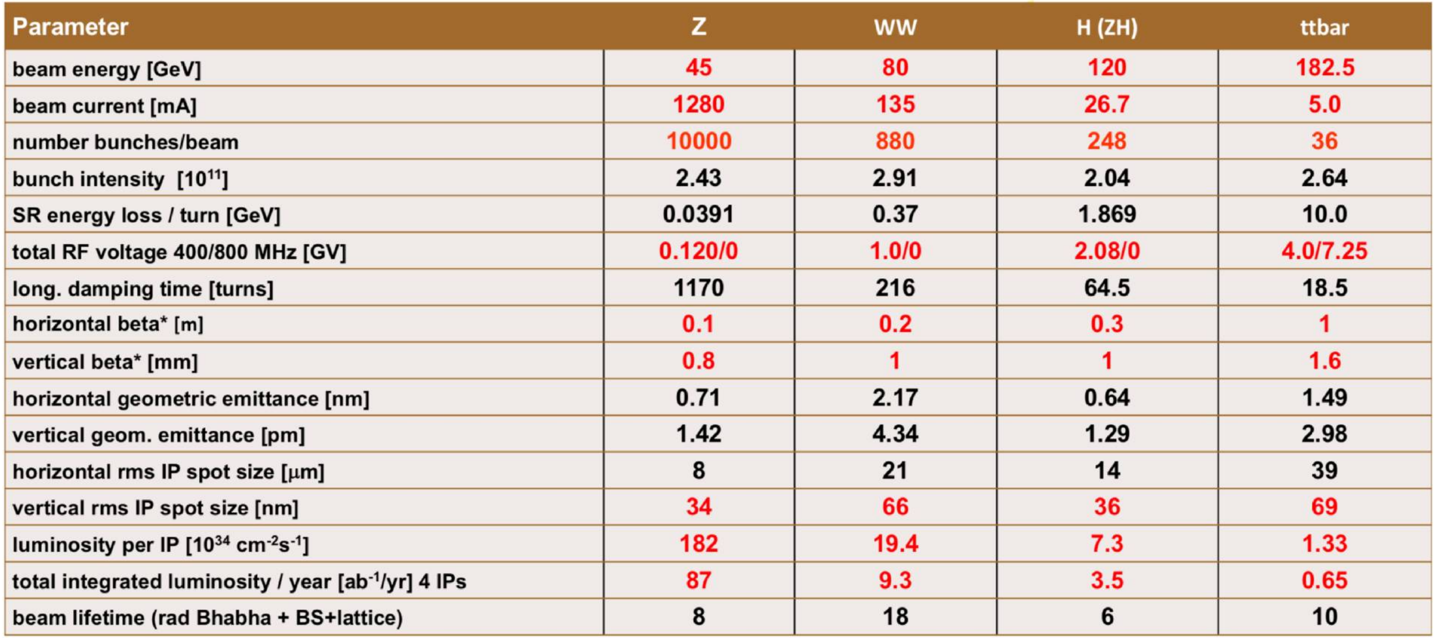
**New Physics**

‘Low mass’ and high luminosity

↓

Kind of ‘Intensity frontier’

# FCC-ee Specs



| Parameter | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| beam current [mA] | 1280 | 135 | 26.7 | 5.0 |
| number bunches/beam | 10000 | 880 | 248 | 36 |
| bunch intensity [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.64 |
| SR energy loss / turn [GeV] | 0.0391 | 0.37 | 1.869 | 10.0 |
| total RF voltage 400/800 MHz [GV] | 0.120/0 | 1.0/0 | 2.08/0 | 4.0/7.25 |
| long. damping time [turns] | 1170 | 216 | 64.5 | 18.5 |
| horizontal beta* [m] | 0.1 | 0.2 | 0.3 | 1 |
| vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| horizontal geometric emittance [nm] | 0.71 | 2.17 | 0.64 | 1.49 |
| vertical geom. emittance [pm] | 1.42 | 4.34 | 1.29 | 2.98 |
| horizontal rms IP spot size [μm] | 8 | 21 | 14 | 39 |
| vertical rms IP spot size [nm] | 34 | 66 | 36 | 69 |
| luminosity per IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | 182 | 19.4 | 7.3 | 1.33 |
| total integrated luminosity / year [ab$^{-1}$/yr] 4 IPs | 87 | 9.3 | 3.5 | 0.65 |
| beam lifetime (rad Bhabha + BS+lattice) | 8 | 18 | 6 | 10 |

From Fabiola's talk

Currently assessing
technical feasibility
of changing operation
sequence
(e.g. starting at ZH energy)

4 years
5 x $10^{12}$ Z
LEP x $10^5$

2 years
> $10^8$ WW
LEP x $10^4$

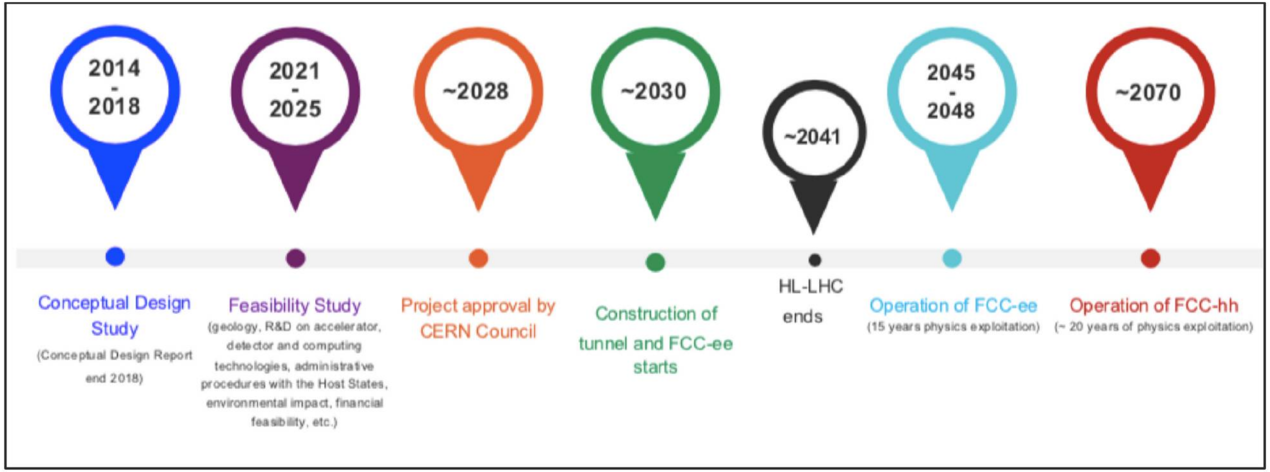
3 years
2 x $10^6$ H

5 years
2 x $10^6$ tt pairs

- ☐ x 10-50 improvements on all EW observables
- ☐ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ☐ x10 Belle II statistics for b, c, τ
- ☐ indirect discovery potential up to ~ 70 TeV
- ☐ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

# *FCC-ee Schedule*



2014 - 2018
Conceptual Design Study
(Conceptual Design Report end 2018)

2021 - 2025
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028
Project approval by CERN Council

~2030
Construction of tunnel and FCC-ee starts

~2041
HL-LHC ends

2045 - 2048
Operation of FCC-ee
(15 years physics exploitation)

~2070
Operation of FCC-hh
(~ 20 years of physics exploitation)

From Fabiola's talk

**1st stage collider FCC-ee**:
electron-positron collisions 90-360 GeV: electroweak and Higgs factory
**2nd stage collider FCC-hh**:
proton-proton collisions at ~ 100 TeV

"Realistic" schedule taking into account:

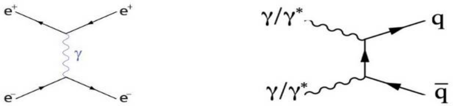
- ❑ past experience in building colliders at CERN
- ❑ the various steps of approval process: ESPP update, CERN Council decision
- ❑ HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

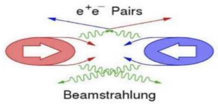
**Care should be taken when comparing to other proposed facilities, for which in most cases only the (optimistic) technical schedule is shown**. In particular, studies related to **territorial implementation** (surface sites, roads, connection to water and electricty, environmental impact, admin procedures, etc.), which for FCC are being carried out in the framework of the Feasibility Studies, **take years.**

# *Basic Detector Requirements*

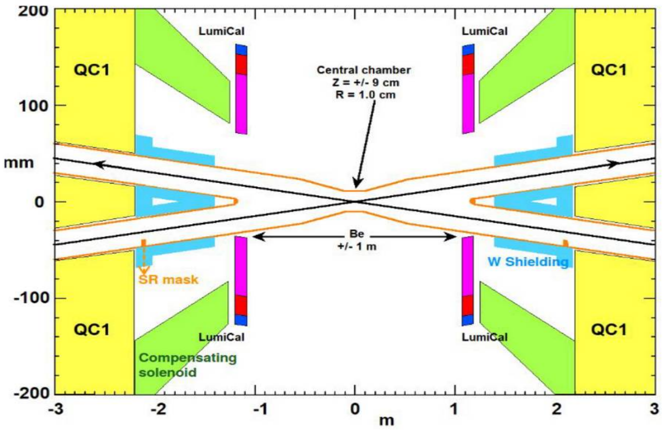
## Detector requirements - general considerations



- 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



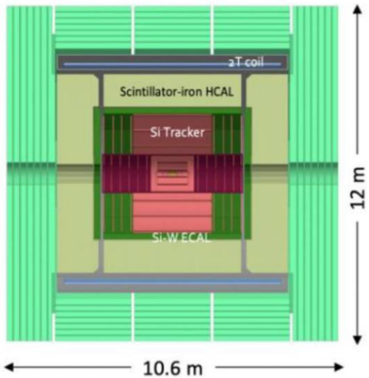
- **complex MDI:** last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
    - **limits the achievable track momentum resolution**
  - "anti"-solenoid
    - limits the acceptance to ~ 100 mrad

# *Basic Detector Designs*

## Detector Benchmarks

ALLEGRO

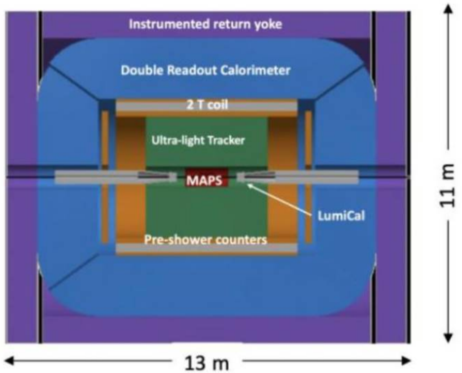
### CLD



- 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
  - $\sigma_p/p$, $\sigma_E/E$
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

CDR

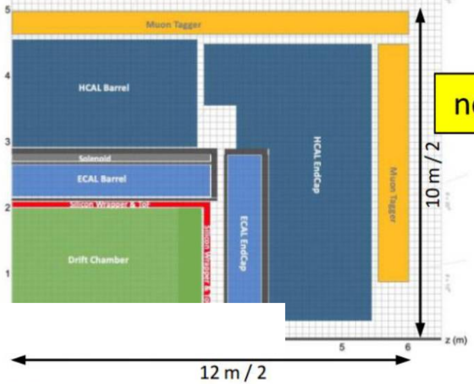
### IDEA



- 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, …

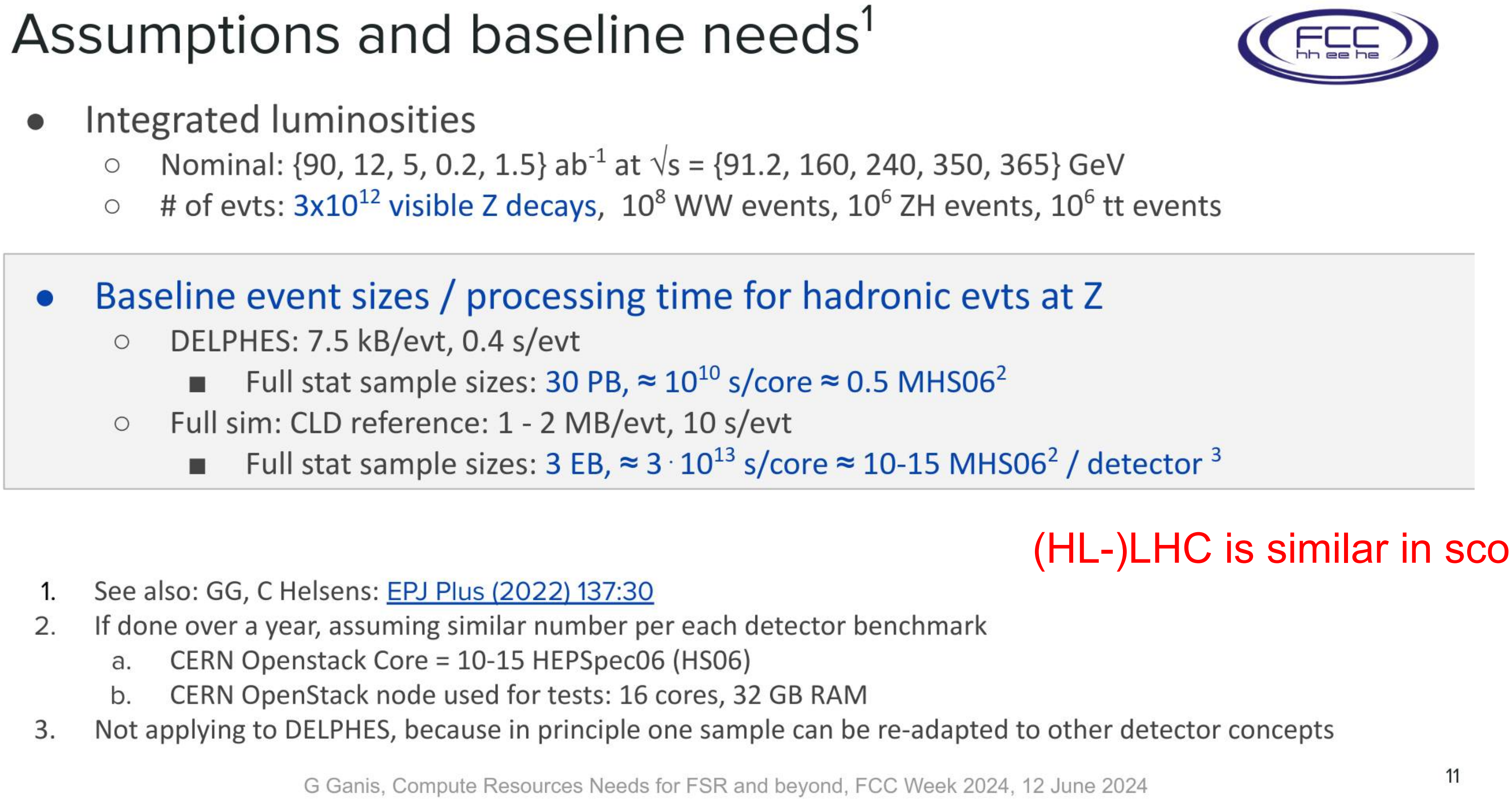
### Noble Liquid ECAL based

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

# 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: 3x$10^{12}$ 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]

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

G Ganis, Compute Resources Needs for FSR and beyond, FCC Week 2024, 12 June 2024

(HL-)LHC is similar in scope.

# Basic Measurements

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

Flavor

# B Physics to benchmark vertex

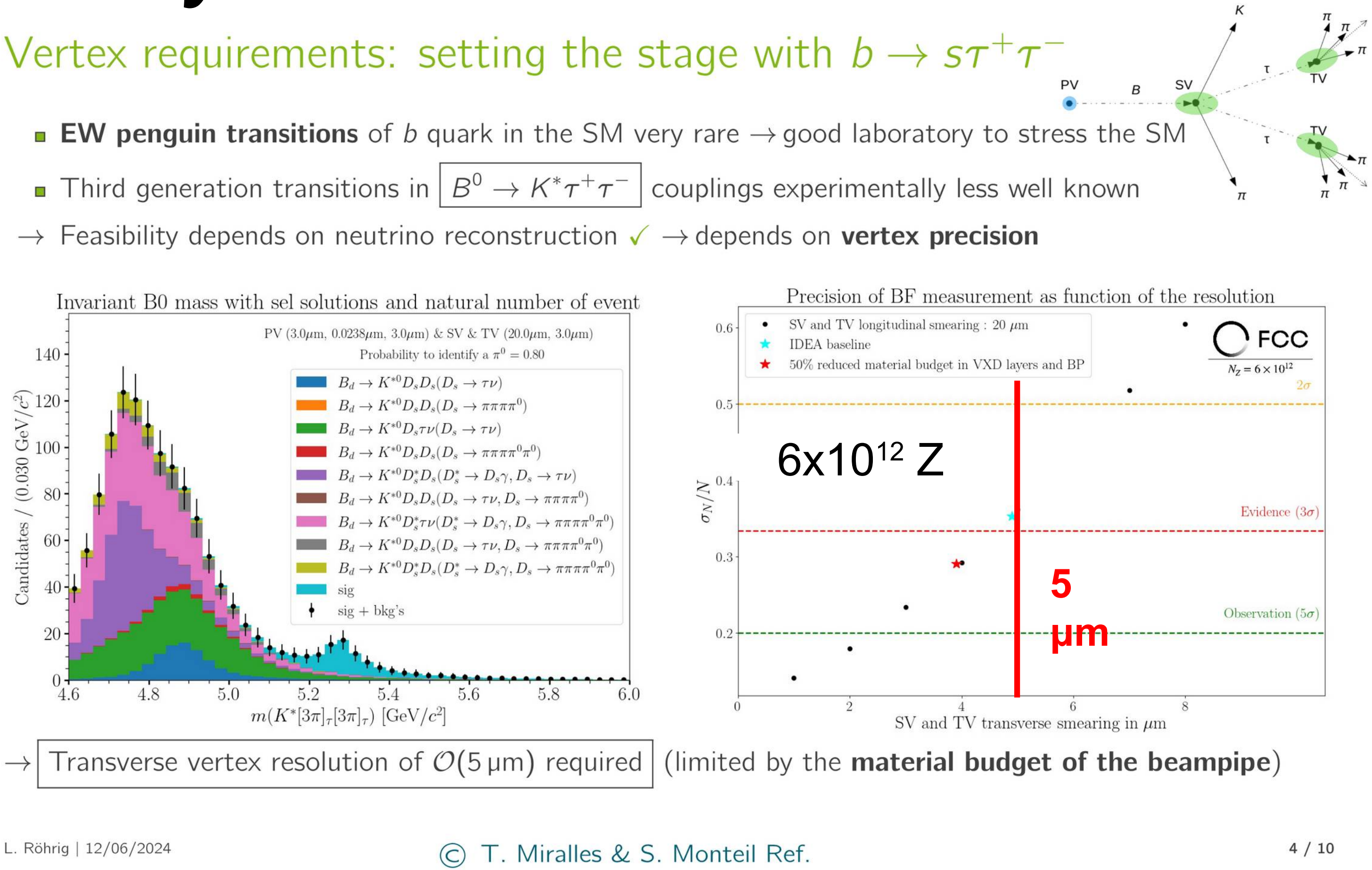
## Vertex resolution

- Requires

  **5 → 3 μm**

And BTW

- FCC-ee has ~20 times more b and tau pairs than Belle II
- 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 → good laboratory to stress the SM
- Third generation transitions in $\boxed{B^0 \to K^*\tau^+\tau^-}$ couplings experimentally less well known

→ Feasibility depends on neutrino reconstruction ✓ → depends on **vertex precision**

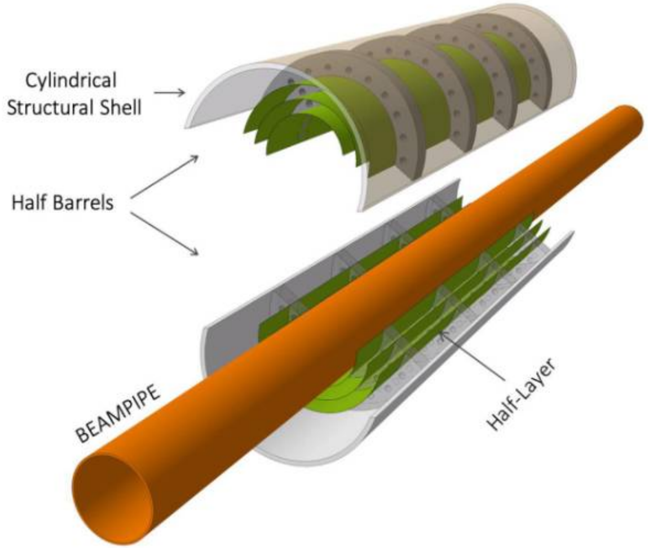
→ $\boxed{\text{Transverse vertex resolution of } \mathcal{O}(5\,\mu\text{m}) \text{ required}}$ (limited by the **material budget of the beampipe**)

© 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)*

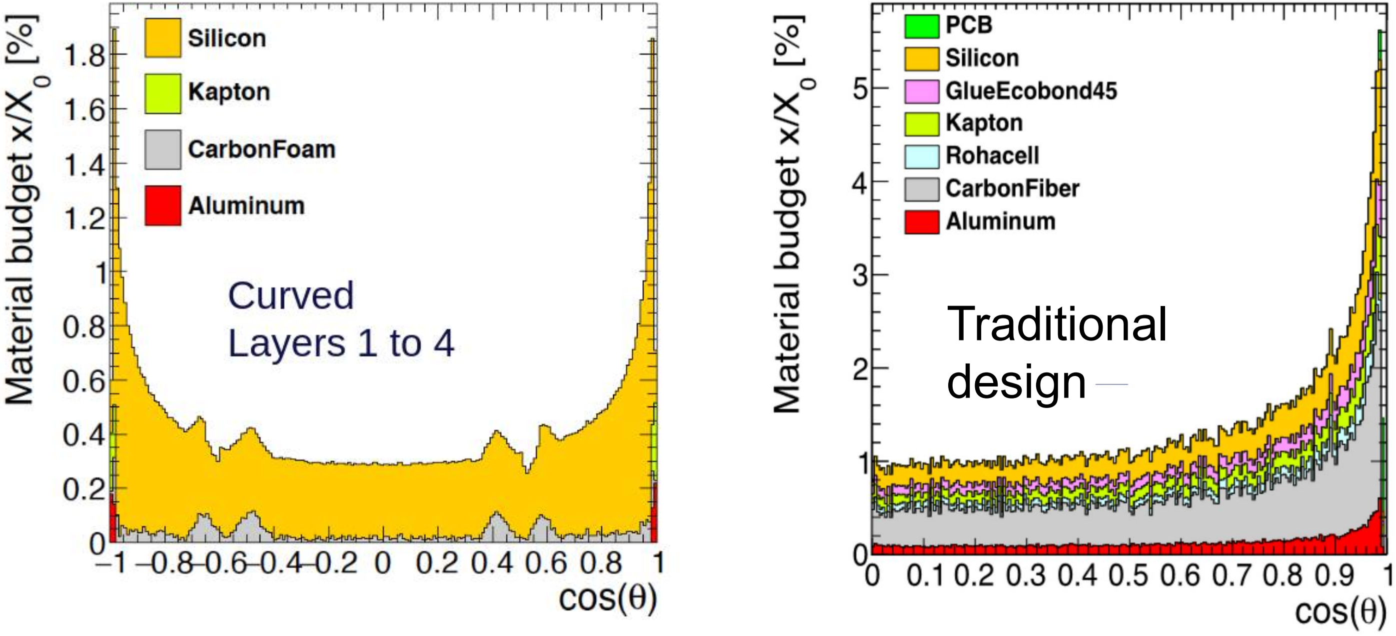
*After fruitful discussions with* ***C. Gargiulo, A. Junique, G. Aglieri Rinella, W. Snoeys***

# *Benchmark Vertex measurements*

## MAPS

- Workshop at CERN July 1-2 was a great event to hear what people are doing (*link*).

## Material budget inner vertex



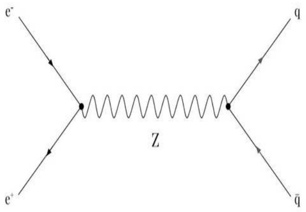
**~ 5 µm** resolution, but want to further improve

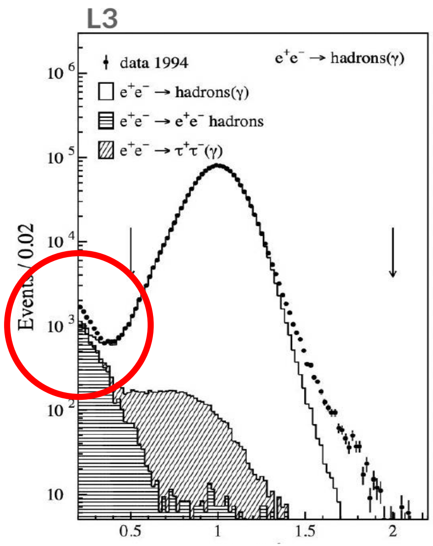
EW

# *Most copious process at FCC*

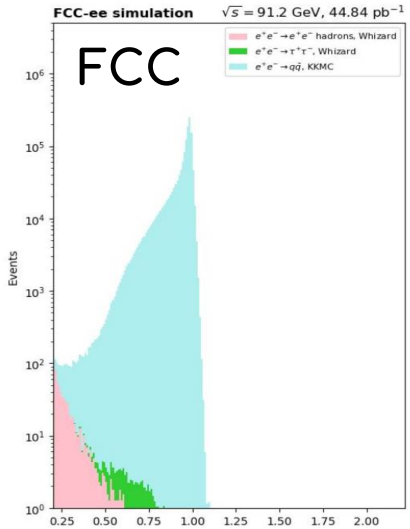
## $e^+e^- \rightarrow qq$

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

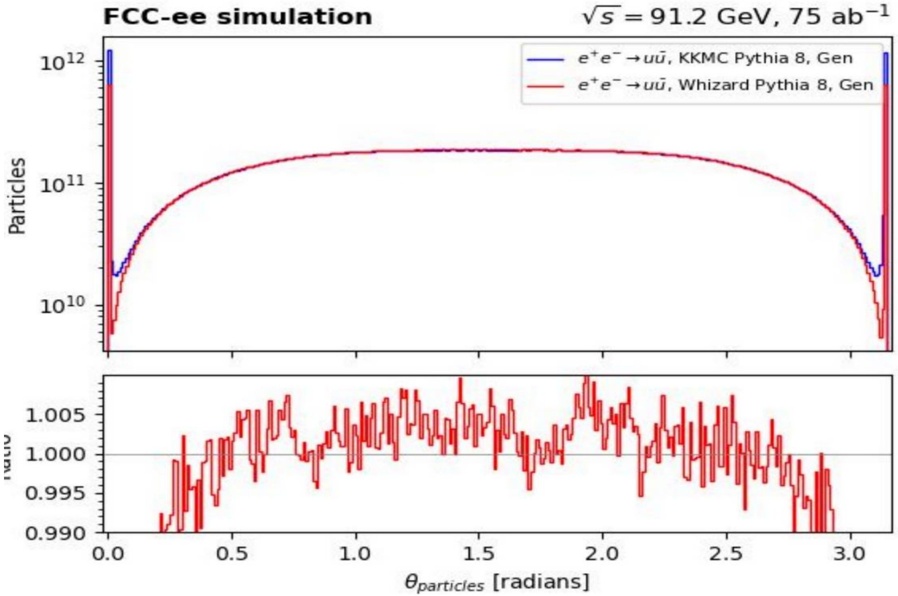


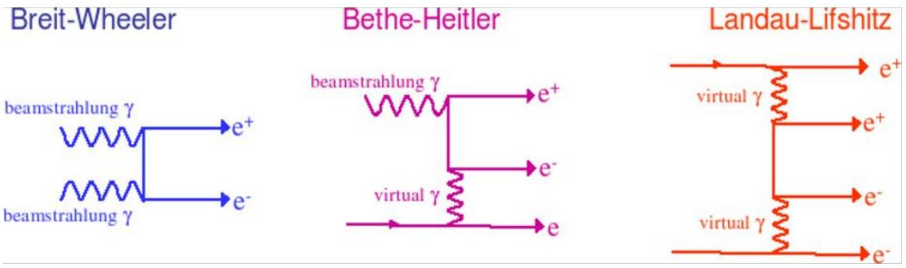


$E_{vis}/\sqrt{s}$



$E_{vis}/\sqrt{s}$





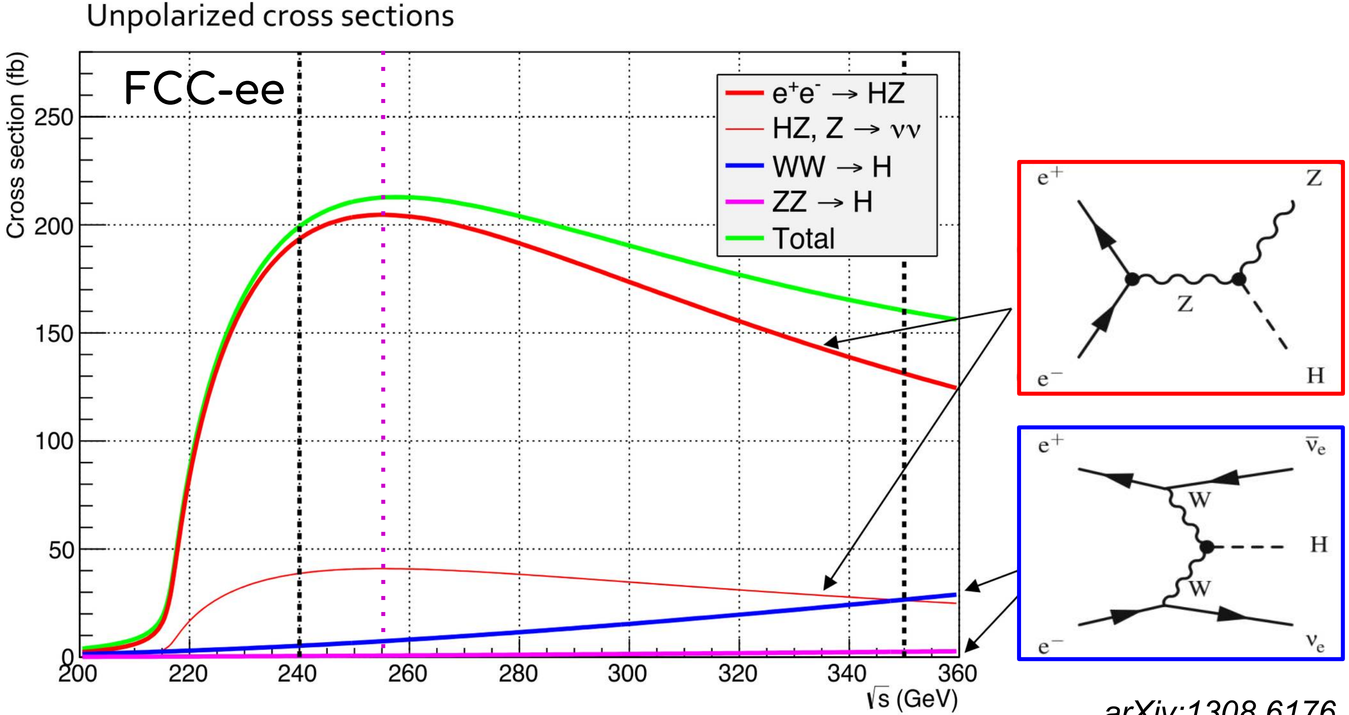
Higgs

# Higgs Physics at $e^+e^-$ Colliders

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

Vector boson fusion rises steadily, but is small

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



*arXiv:1308.6176*

Higgs

# *Higgs Physics at $e^+e^-$ Colliders*

## Leading strategy

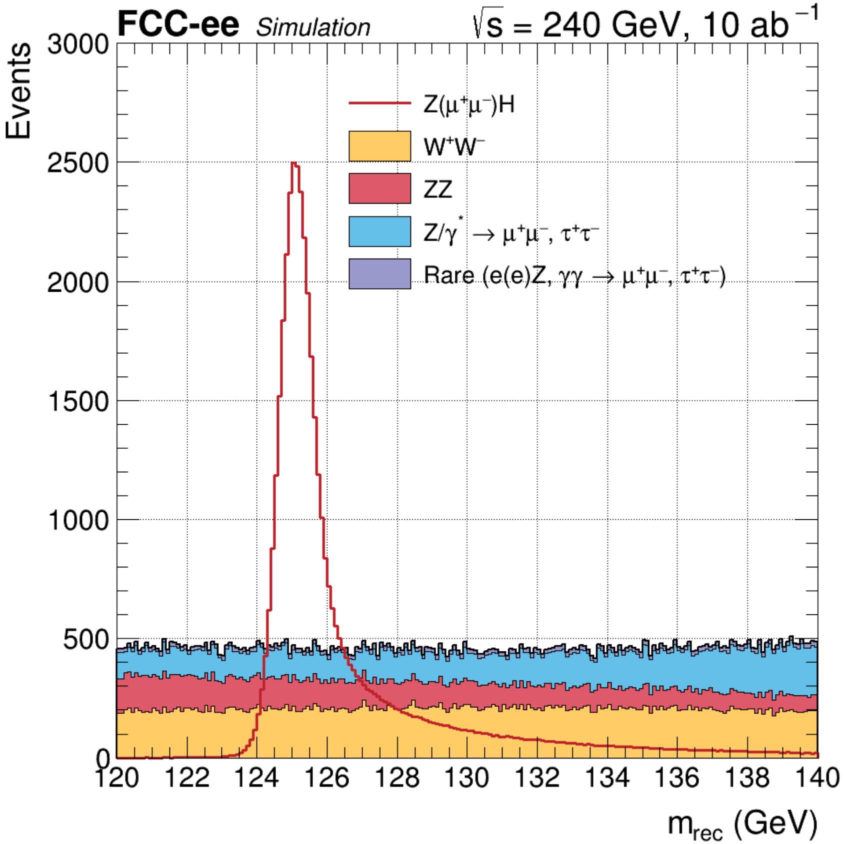
- Tag the Z boson (leptons or jets)
- Recoil mass peaks sharply at Higgs mass

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

- Direct Higgs reconstruction not required, model independent $\sigma_{ZH}$ 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

# Basic Higgs Properties

## Higgs mass

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

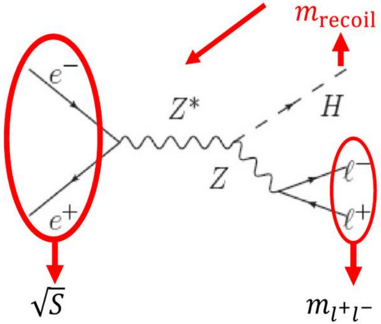
## Higgs mass

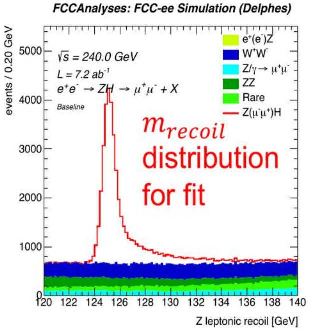
$\sqrt{s} = 240$ GeV
$L = 7.2ab^{-1}$

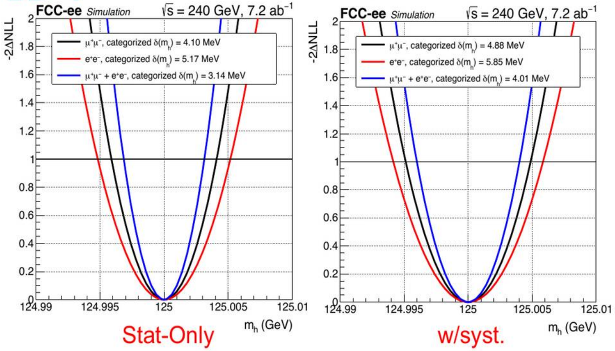
Gregorio Bernardi
Jan Eysermans
Ang Li
DOI 10.17181

- ❖ **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**

$$\boxed{m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2}$$







**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**

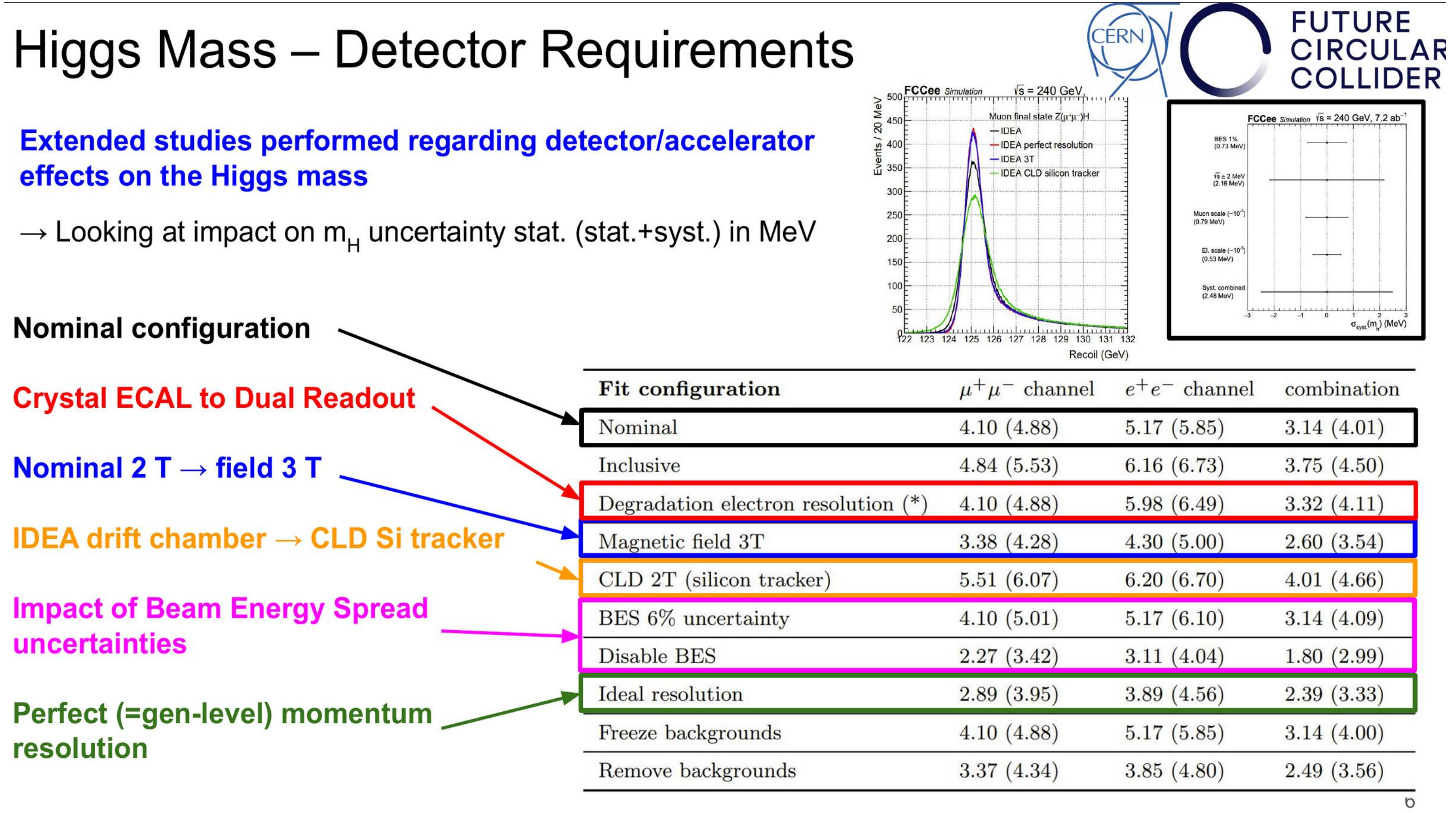
Higgs

# Basic Higgs Properties

## Higgs mass

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

  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**

**Crystal ECAL to Dual Readout**

**Nominal 2 T → field 3 T**

**IDEA drift chamber → CLD Si tracker**

**Impact of Beam Energy Spread uncertainties**

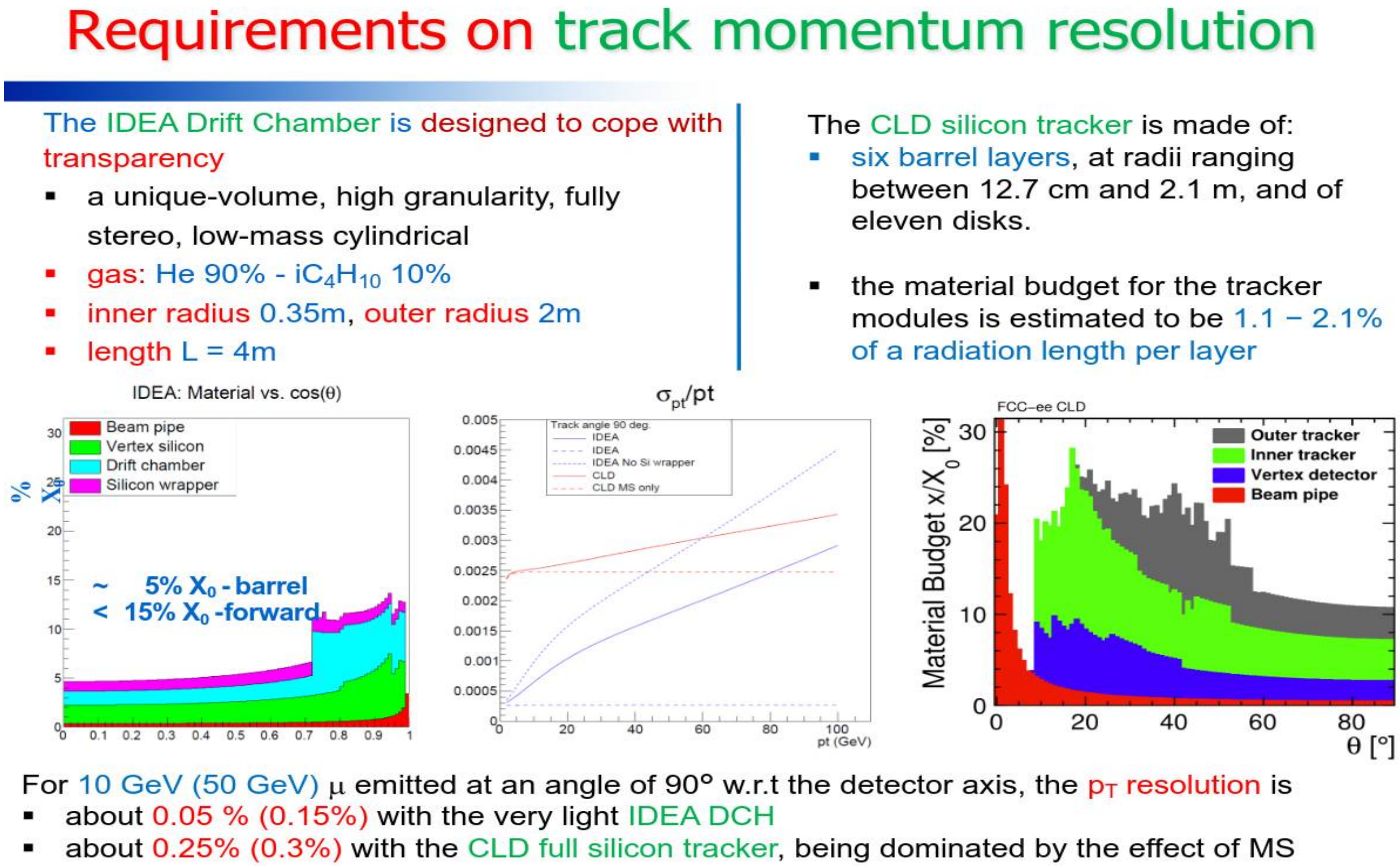
**Perfect (=gen-level) momentum resolution**

| 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

- Drift chamber is ultra 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
- Top never directly produced at lepton collider
- Hadron colliders have problematic definition of mass
- Theoretically much cleaner access at lepton colliders

## Top Threshold

**Current run plan at the top threshold**

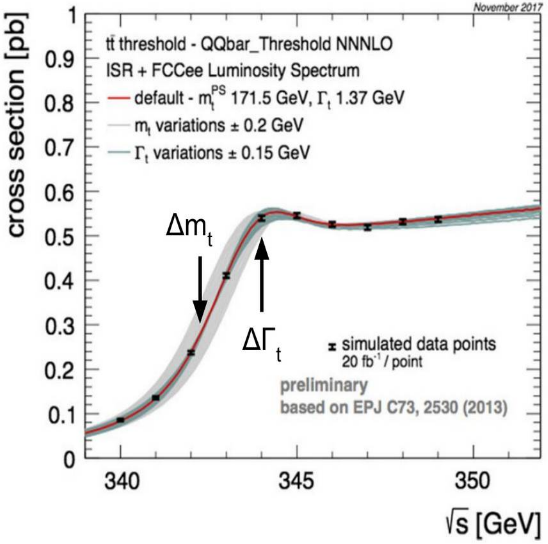
- 1 year threshold scan 340–350 GeV: total ~ 1.4 $ab^{-1}$
- 4 years at 365 GeV: total ~ 2.3 $ab^{-1}$

**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 → $\nu\nu$H): total cross-section, couplings, width



**→ $\Delta m_t$ (stat) ~ 17 MeV**

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

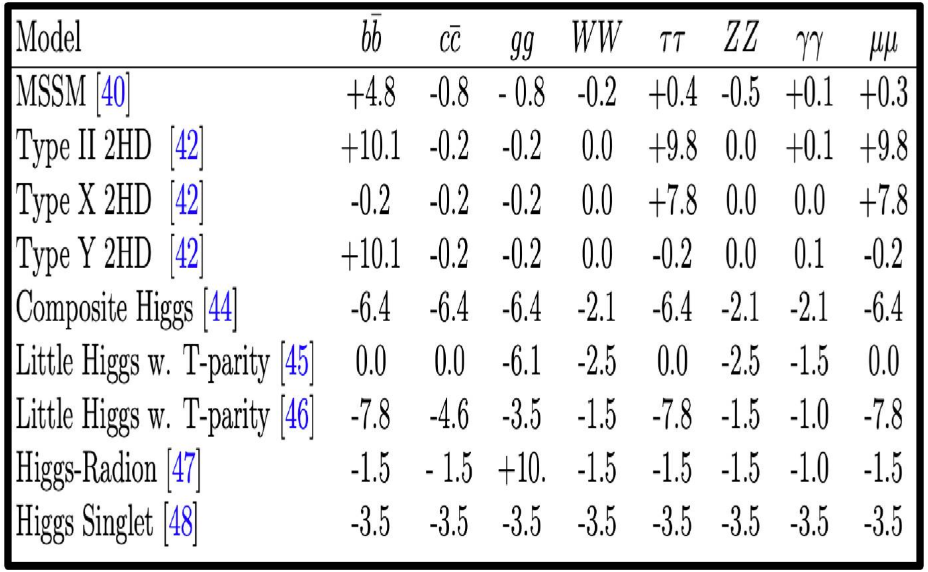
# *Higgs Couplings beyond the third generation fermions*

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

Higgs

# *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

$$\boxed{\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2(\mathrm{TeV})}}$$

e.g. Λ=1 (5)TeV→~5 (0.1)%

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

Loukas slide

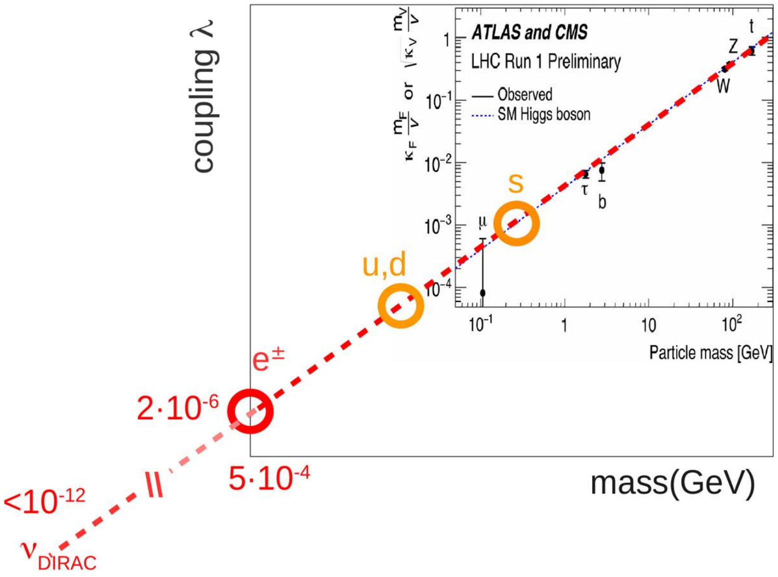
Higgs

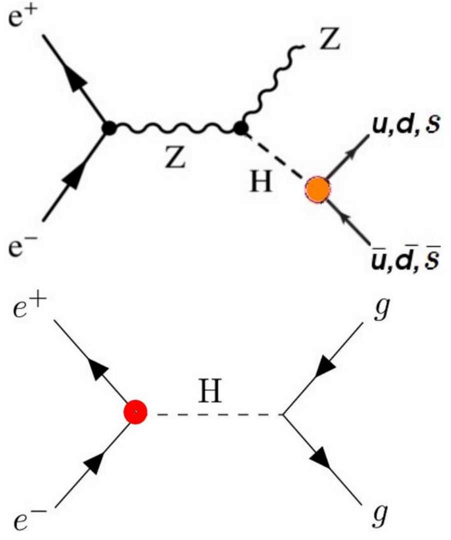
# *Higgs to first generation*

## Unresolved Higgs decay modes

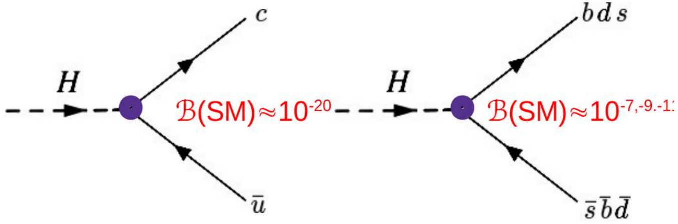
- Muons are only second generation seen
- Lighter fermions are very difficult

- 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?



Higgs

# *Hadronic final states dominate*

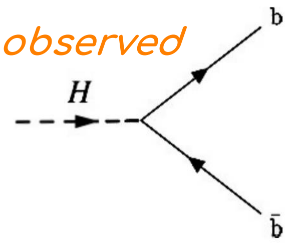
## Why is this important?

- 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!

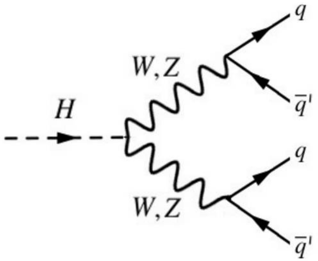
$\mathcal{B}$=57.7%

observed



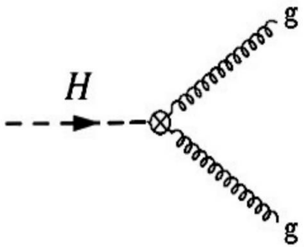
N(H)≈1.e6 @FCC-ee

$\mathcal{B}$=11%



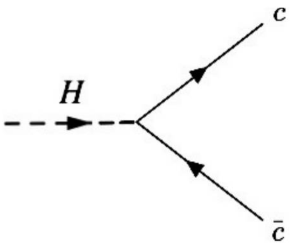
N(H)≈2.e5 @FCC-ee

$\mathcal{B}$=8.6%



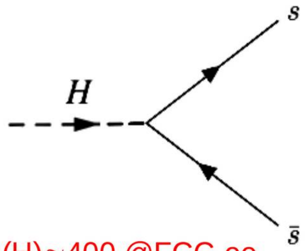
N(H)≈1.5e5 @FCC-ee

$\mathcal{B}$=2.9%



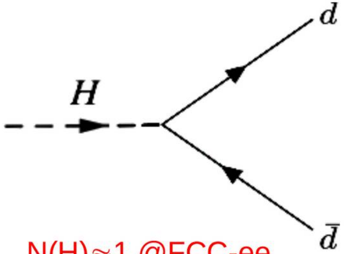
N(H)≈5.e4 @FCC-ee

$\mathcal{B}$=0.024%



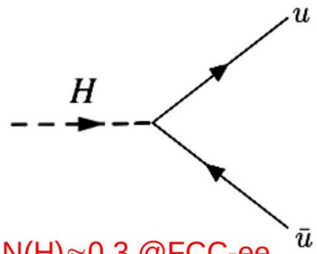
N(H)≈400 @FCC-ee

$\mathcal{B}=6\cdot10^{-7}$



N(H)≈1 @FCC-ee

$\mathcal{B}=1.4\cdot10^{-7}$



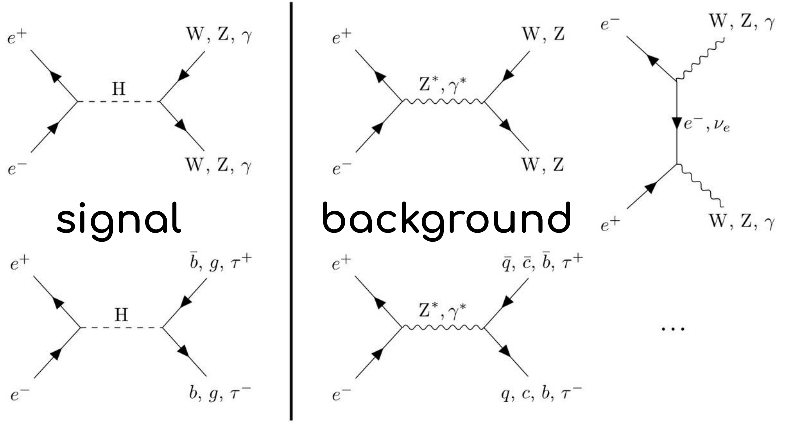
N(H)≈0.3 @FCC-ee

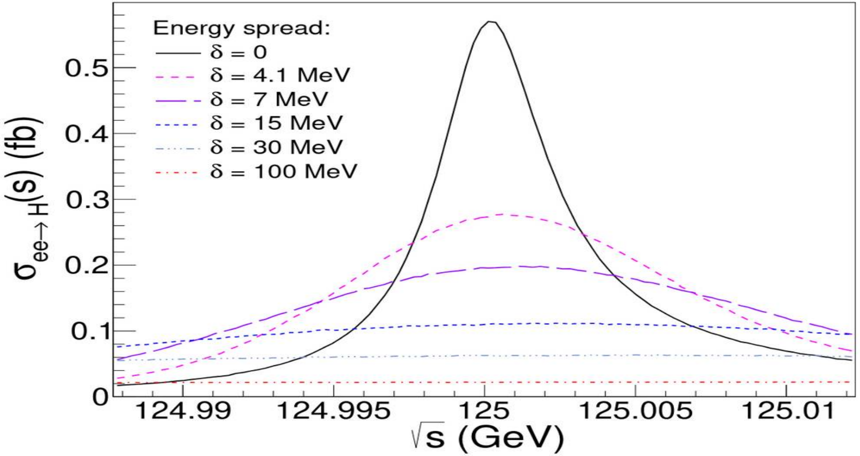
Higgs

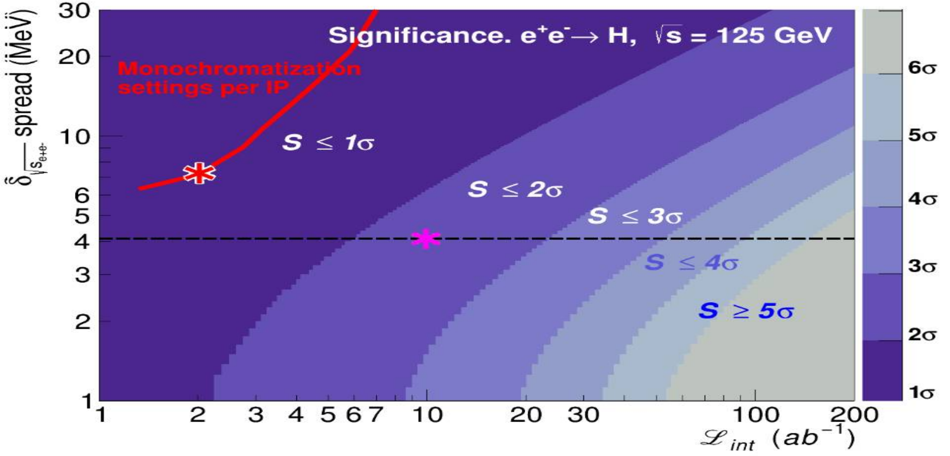
# *Higgs Electron Yukawa Coupling*

Measure $e^+e^- \rightarrow H \rightarrow e^+e^-$: how?

- $\Gamma_H$ is 4.1 MeV, measure $m_H$ at MeV level
- Dial collider $E_{CM}$ to $m_H$, *precisely!*
- 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

# 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?

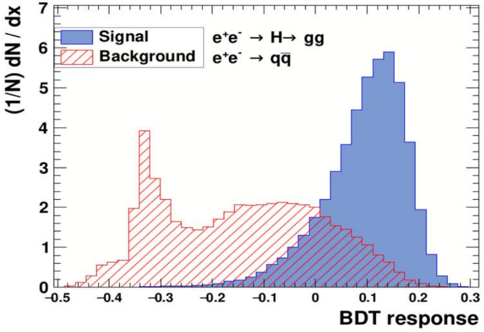
- No $e^+e^-$ background can generate 2 true gluon jets !
- Analysis performances assumed:

  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]



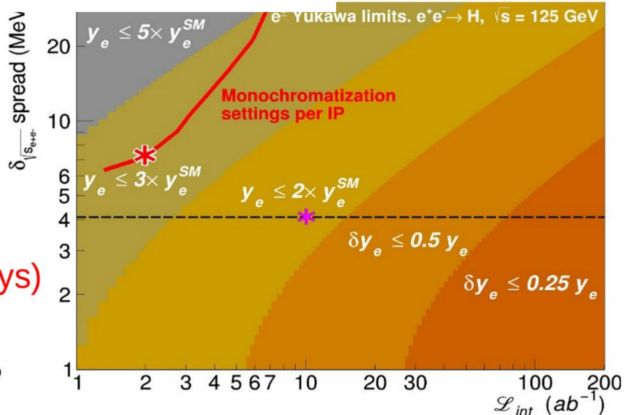
- BDT MVA result (removing jet vars. potentially already used in g-uds discrimination):

  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



Higgs

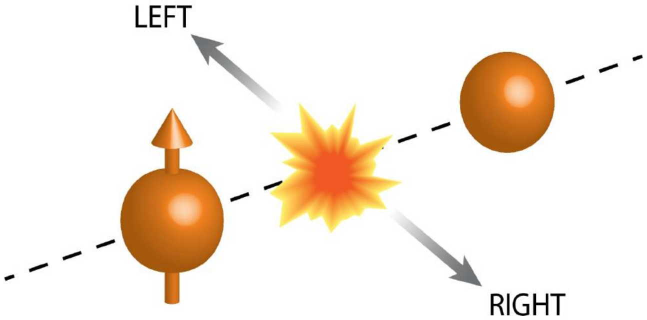
# $e^+e^-\rightarrow$*Higgs with polarized beams*

## 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$^{-}$):

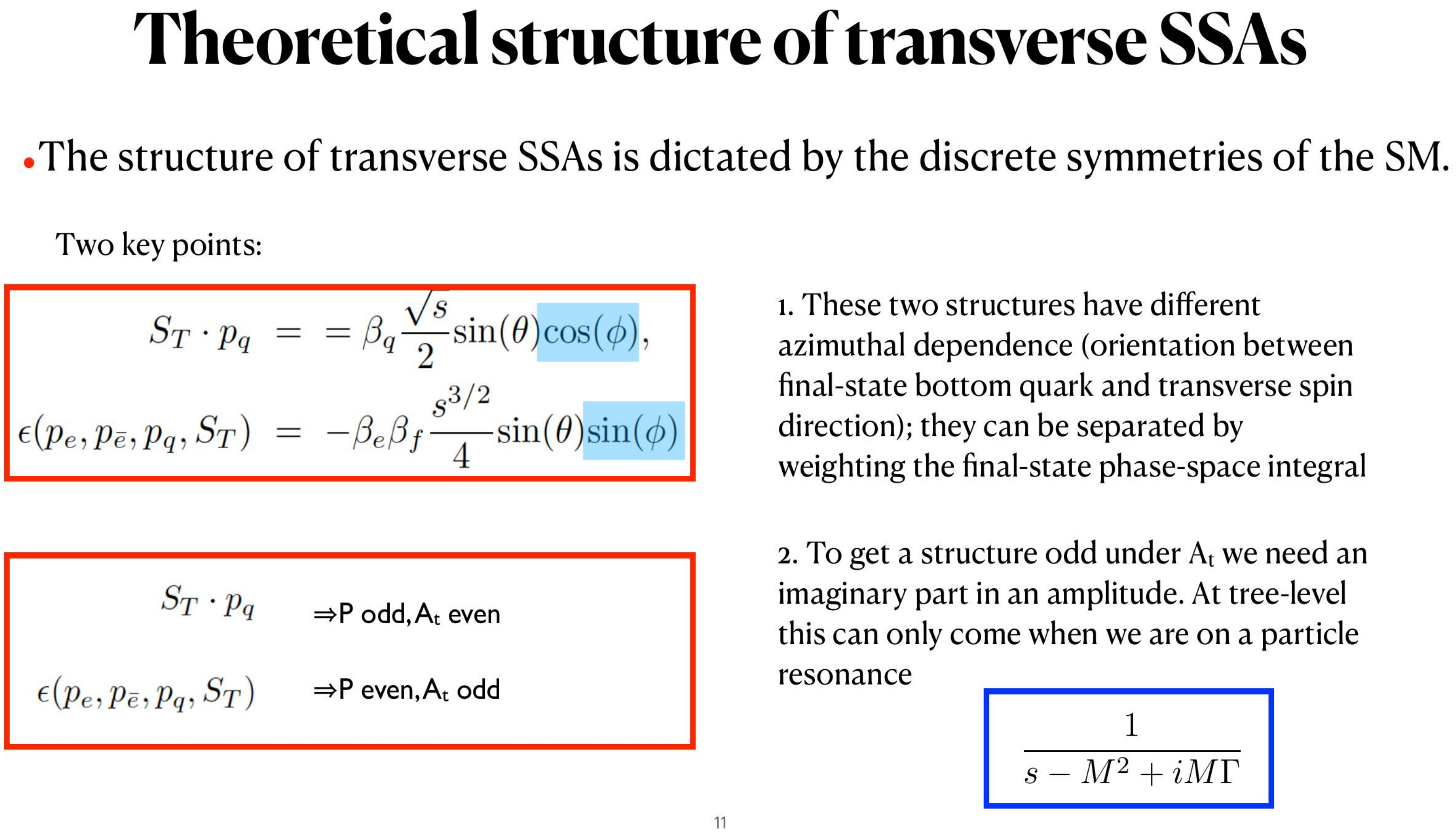
$$N = \frac{1}{2}(\sigma^{+-} - \sigma^{--})$$
$$D = \frac{1}{2}(\sigma^{+-} + \sigma^{--})$$

Higgs

# $e^+e^-\rightarrow$ *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

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

Higgs

# $e^+e^-\to$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.

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

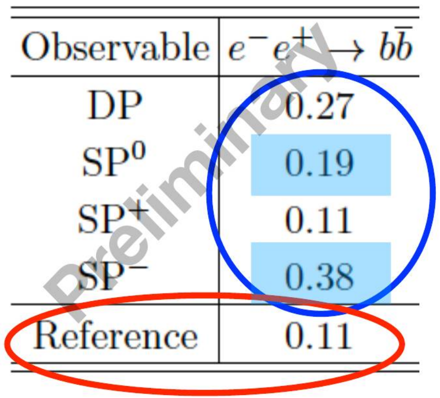
$$\begin{aligned}
R_{\gamma\gamma} &= 96e^4Q_e^2Q_q^2m_e(S_T\cdot p_q)(t-u)\\
R_{ZZ} &= 96m_e(S_p\cdot p_b)g_Z^4g_{ve}^2(g_{vq}^2+g_{aq}^2)(t-u)+192m_e(S_T\cdot p_q)g_Z^4g_{ve}g_{ae}g_{vq}g_{aq}s\\
R_{\gamma Z} &= 192e^2g_Z^2Q_eQ_qm_e(S_T\cdot p_b)g_{ve}g_{vq}(t-u)+96e^2g_Z^2Q_eQ_um_e(S_p\cdot p_q)g_{ae}g_{aq}s\\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

- Comes from the imaginary part of the Higgs propagator and is enhanced by a factor of **$M_H$/ $\Gamma_H$.**
- 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

Higgs

# $e^+e^-\rightarrow$Higgs with polarized beams

$b\bar{b}$



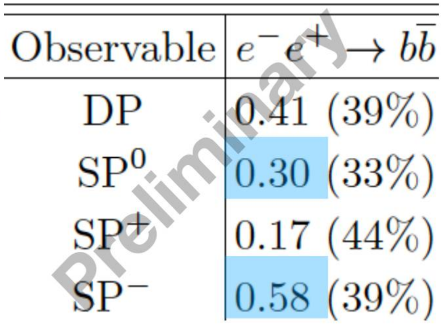
| Observable | $e^-e^+\to b\bar{b}$ |
|---|---|
| DP | 0.27 |
| $SP^0$ | 0.19 |
| $SP^+$ | 0.11 |
| $SP^-$ | 0.38 |
| Reference | 0.11 |

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

14

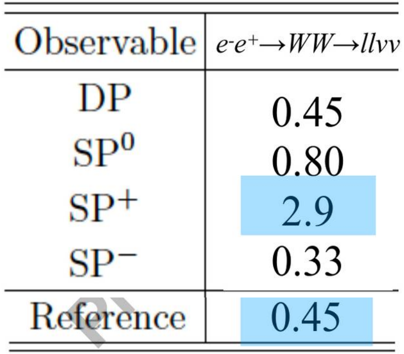
10 MeV from resonance invariant mass cut



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

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

$W^+W^-$



| 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**

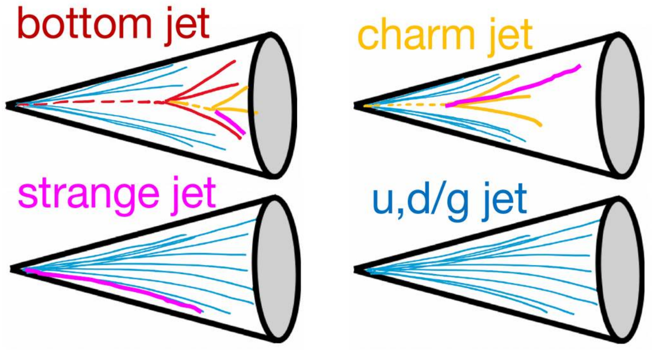
Higgs

# Tagging Challenge: Higgs→ss

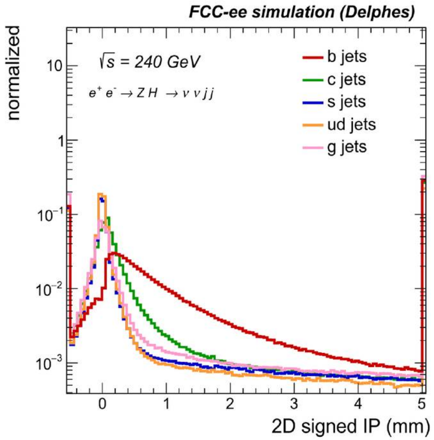
## Jet tagging

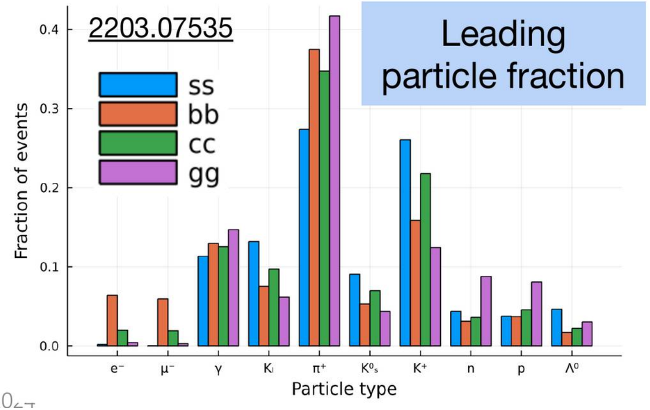
- Key to quarks and gluons
- Very different from LHC
- Huge Z and W boson decay samples to calibrate
- PID is crucial input
- Charm, strange gluon tagging works
- Seeing H→ ss is least obvious, but should be possible

**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 $dE/dx$,

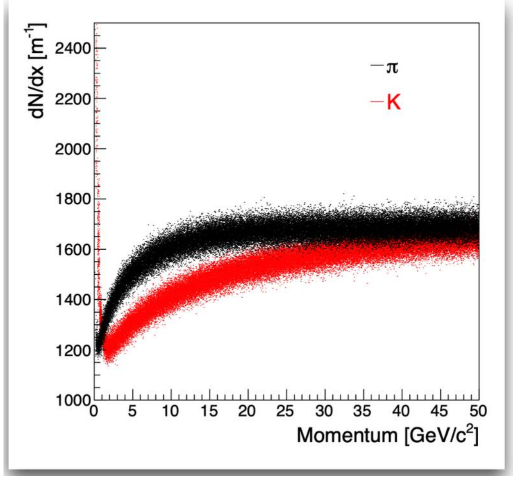
- Ionization cluster count or energy per path length
- Good separation in wide momentum range
- “Blind” region around 1 GeV
- Currently assume 2% resolution

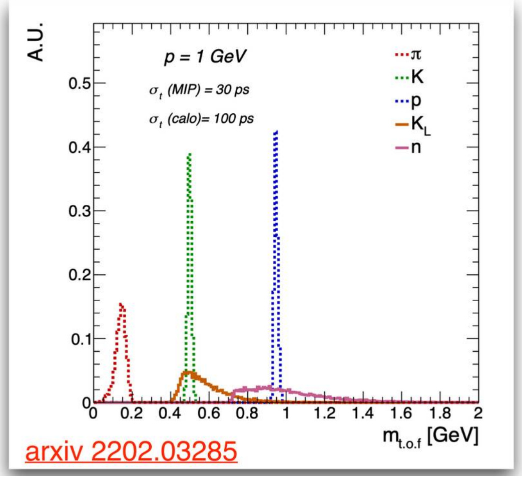
### Time of flight

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

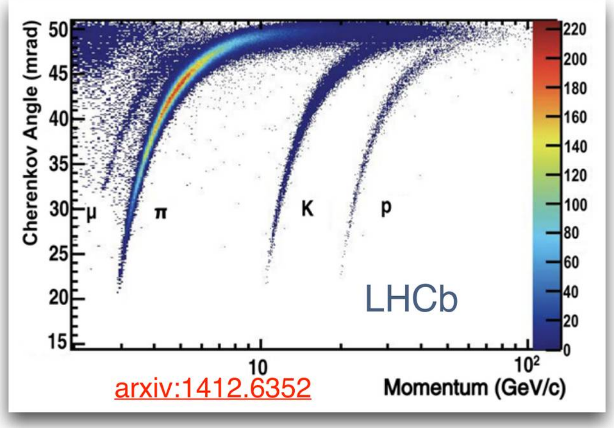
### RICH

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





arxiv 2202.03285

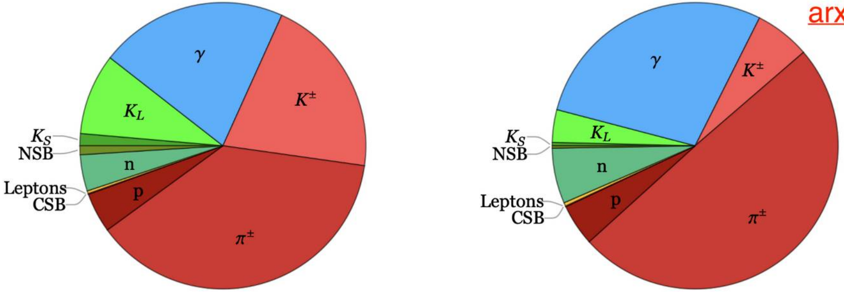


arxiv:1412.6352

# Tagging Challenge: strange

## Strange jet tagging

arxiv:2003.09517

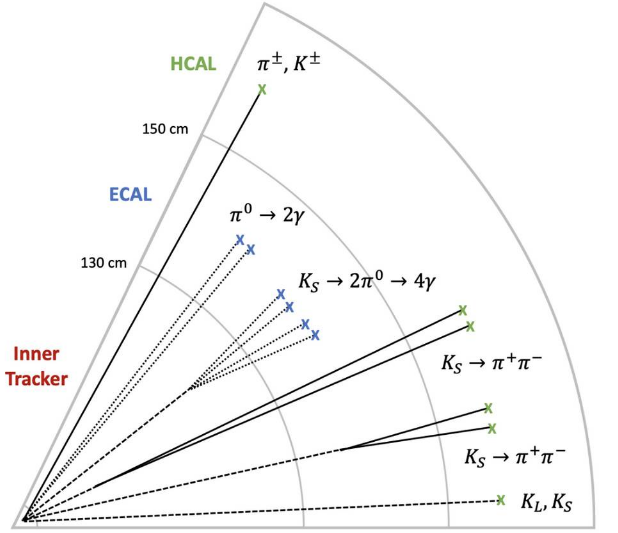


Momentum fraction

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

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

Not to scale



s-baryons $\Lambda, \Sigma, \Xi$ have $c\tau \approx 1 - 10$ cm

- Higher fraction of momentum carried by **kaons**
  - $K^+/\pi^+$ 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

Higgs

# *Tagging Challenge: Higgs→ss*

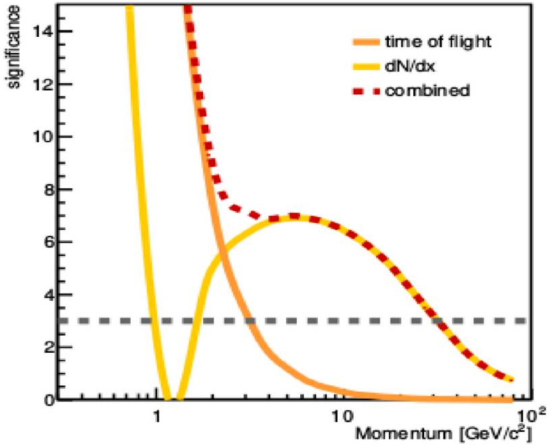
## Jet tagging

- 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]

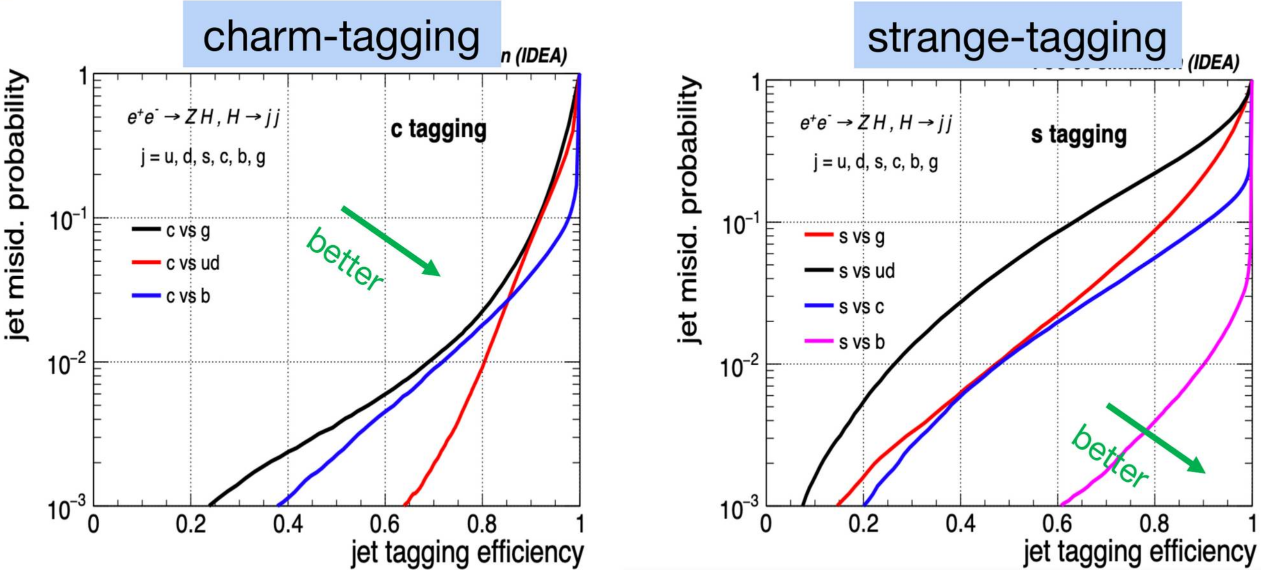
Higgs

# *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

## 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% |

Higgs

# *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

**$E_{CM}$ = 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 …

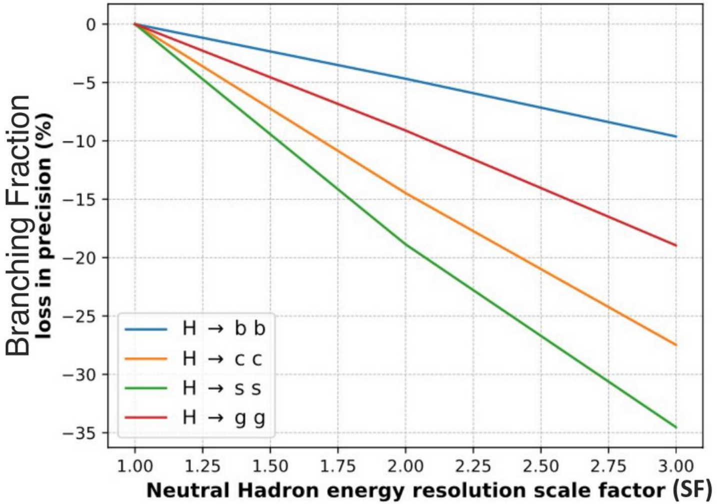
## Reconstruction of Higgs hadronic final states

(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 $\mathrm{H} \rightarrow \mathrm{s\bar{s}}$ 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

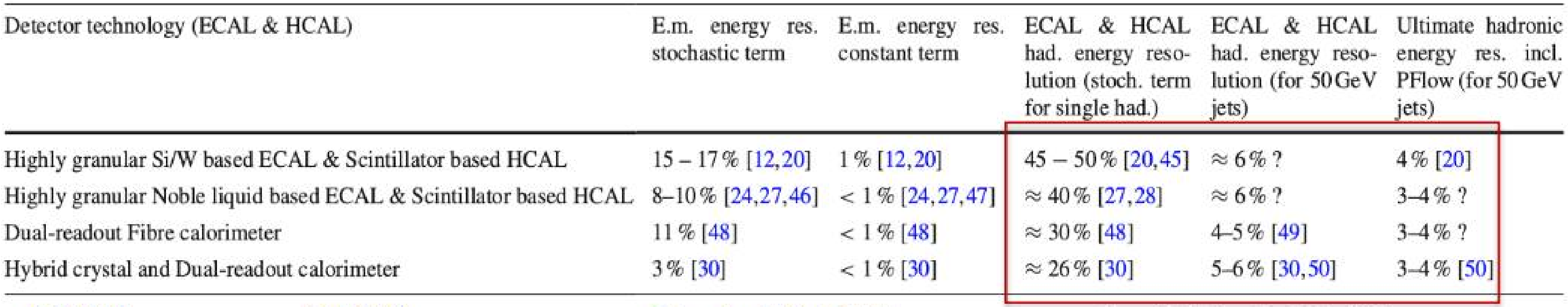
SF=1 ( dual readout calorimeter: **30%/√E** )
2 ( ATLAS type-calorimeter: **50%/√E** )
3 (CMS-type calorimeter: **100%/√E** )

# 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)*

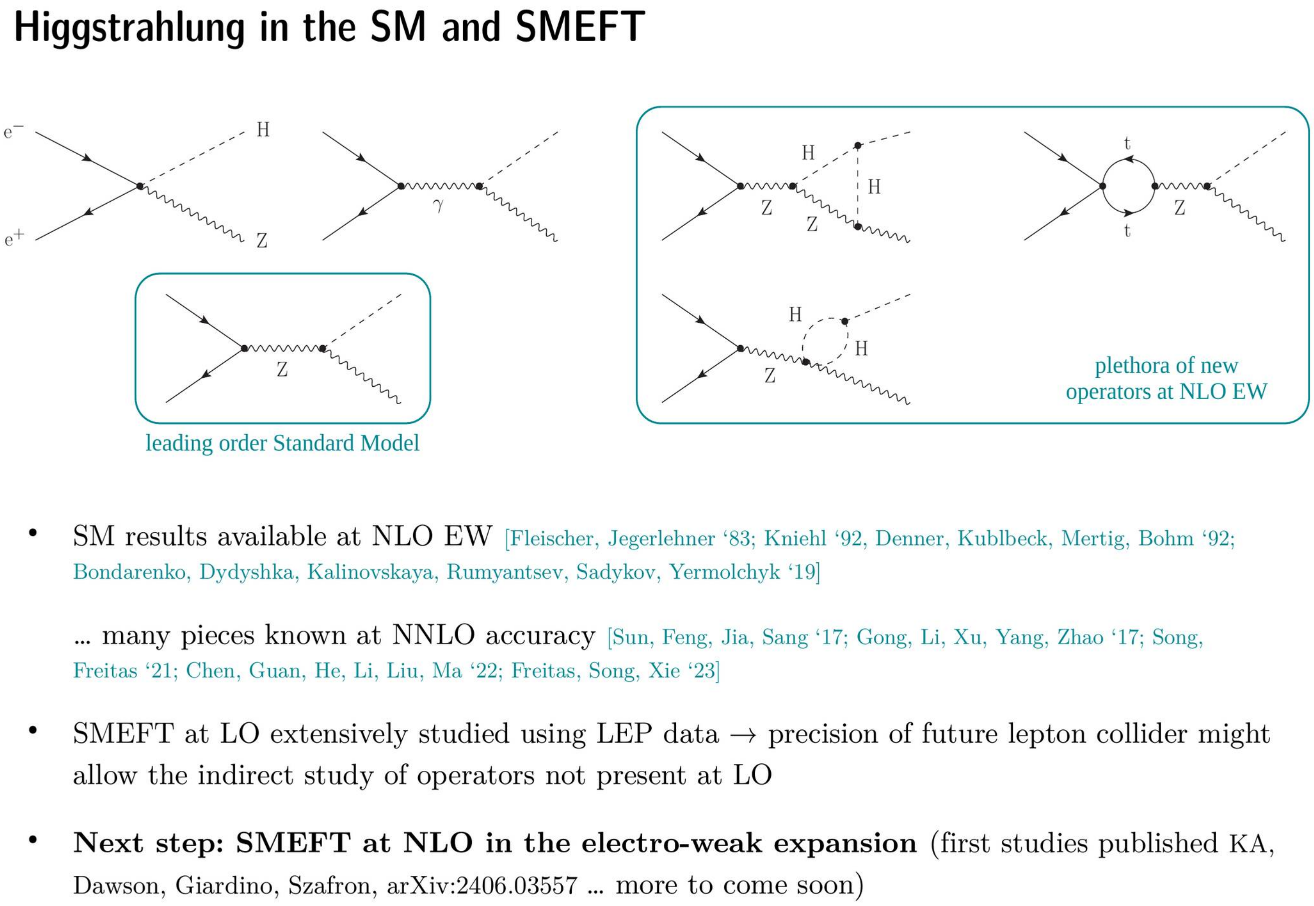
## *Generically beyond SM*

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

leading order Standard Model

plethora of new operators at NLO EW

- 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

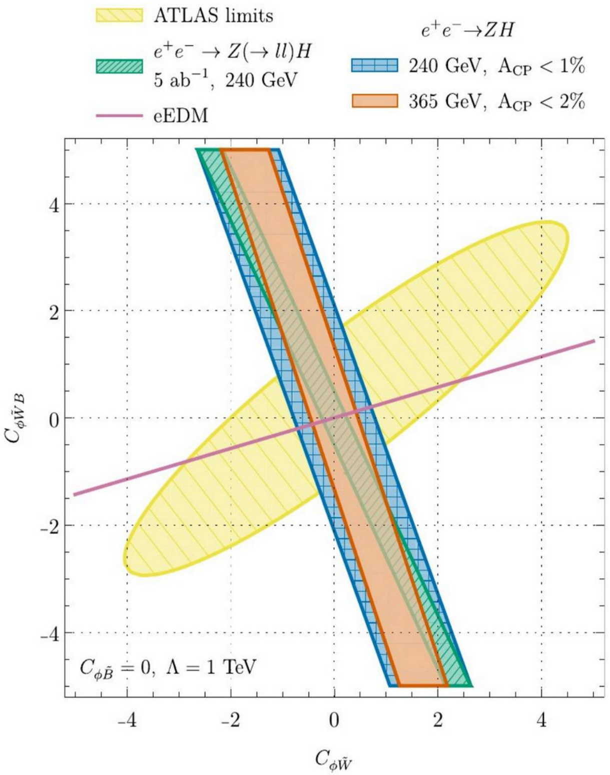
- Additional CP violating operators from NLO
- virtual corrections can develop imaginary contributions
- Instead of using full differential cross sections asymmetries should be sufficient
- LHC/FCC-ee complementary
- eEDM adds orthogonal very precise contribution

## 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

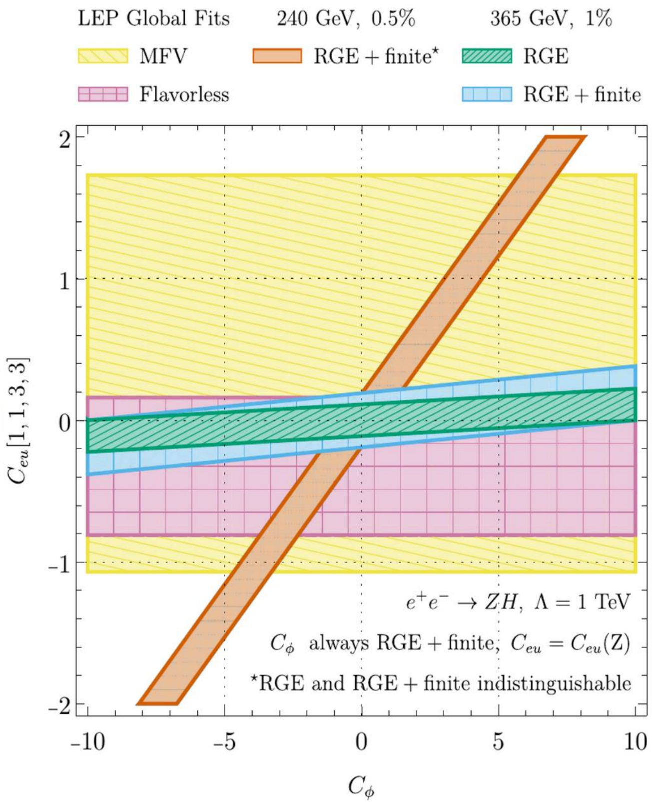
- Constraints on Higgs trilinear and electron-top coupling operators largely benefit from measurements at different $E_{CM}$
- Different contributions have different dependence on the $E_{CM}$

### Higgs Tri-linear and Top Quark Couplings

- Consider Higgs self-interaction $C_\phi$ 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 $\Delta_i$ only from exact higher order computations



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

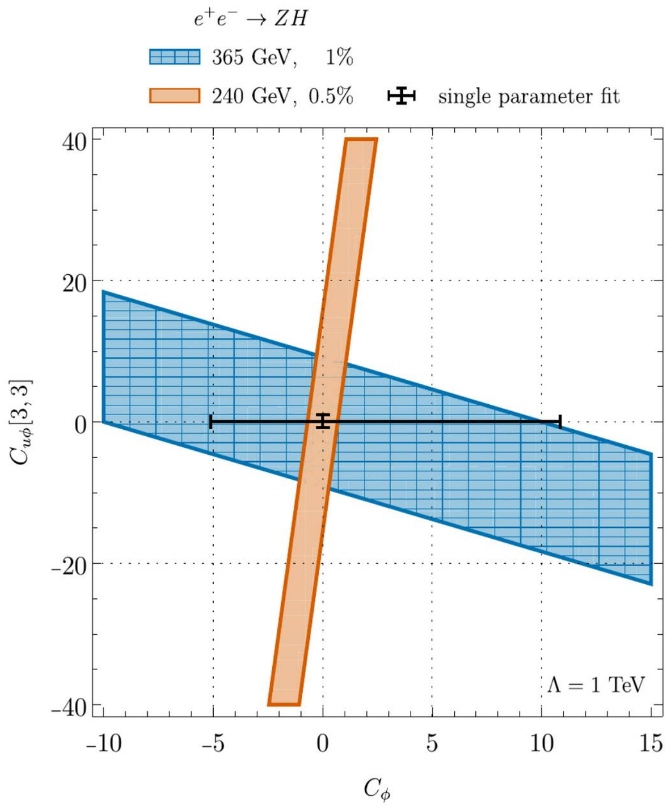
# *Precision measurements and SMEFT*

## 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 $C_\phi$ 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*

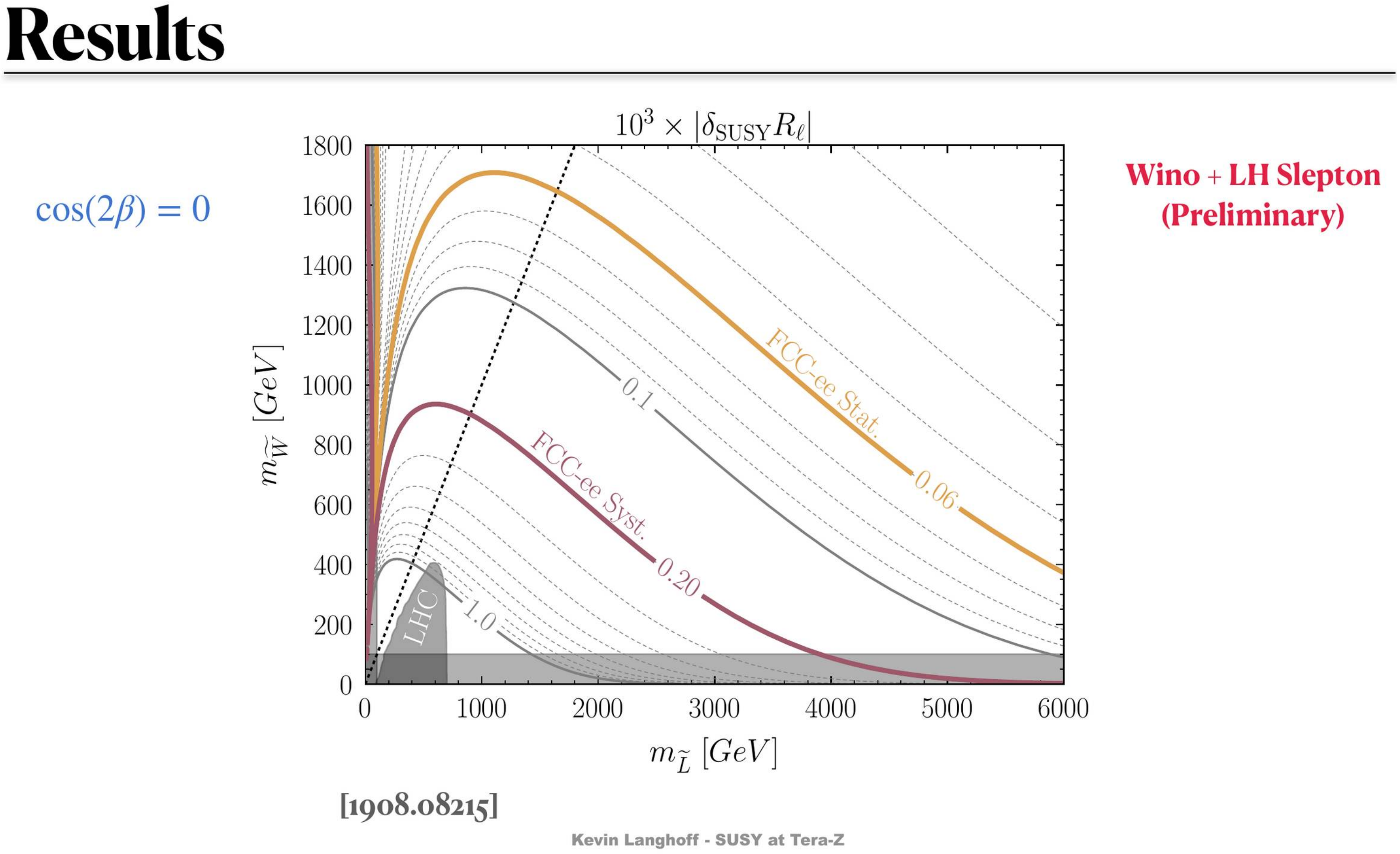
Kevin Langhoff, Chris Verhaaren, Zeynep Demiragli

New Physics

# *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]

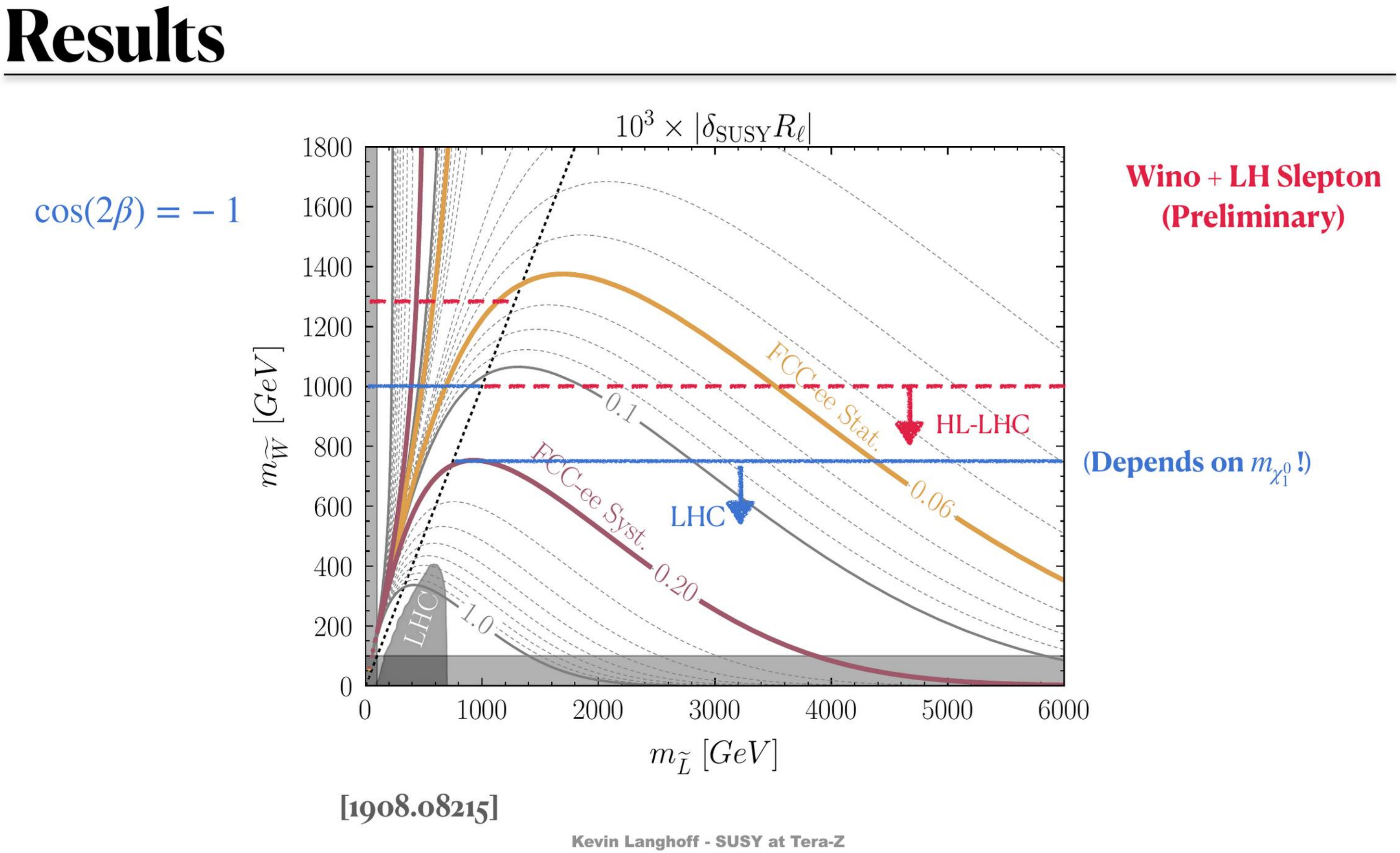
Kevin Langhoff - SUSY at Tera-Z

New Physics

# 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**

$\cos(2\beta) = -1$

**Wino + LH Slepton (Preliminary)**

**(Depends on $m_{\chi_1^0}$!)**

[1908.08215]

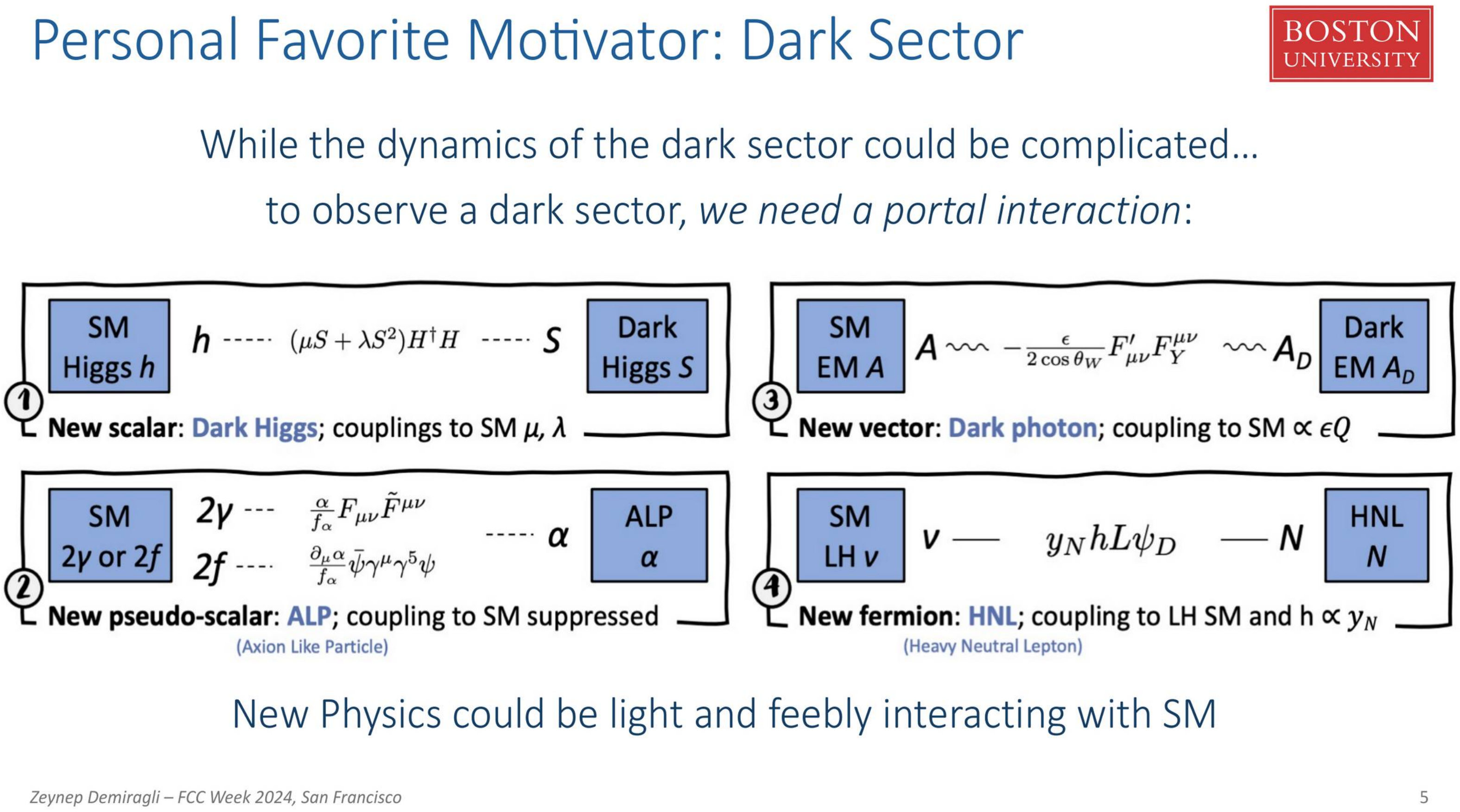
Kevin Langhoff - SUSY at Tera-Z

New Physics

# 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*:

① **SM Higgs** $h$ — $h$ ----- $(\mu S + \lambda S^2)H^\dagger H$ ----- $S$ — **Dark Higgs** $S$

**New scalar: Dark Higgs**; couplings to SM $\mu$, $\lambda$

③ **SM EM** $A$ — $A$ 〰 $-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}F_Y^{\mu\nu}$ 〰 $A_D$ — **Dark EM** $A_D$

**New vector: Dark photon**; coupling to SM ∝ $\epsilon Q$

② **SM** $2\gamma$ or $2f$ — $2\gamma$ --- $\frac{\alpha}{f_\alpha}F_{\mu\nu}\tilde{F}^{\mu\nu}$; $2f$ ---- $\frac{\partial_\mu\alpha}{f_\alpha}\bar{\psi}\gamma^\mu\gamma^5\psi$ ----- $\alpha$ — **ALP** $\alpha$

**New pseudo-scalar: ALP**; coupling to SM suppressed

(Axion Like Particle)

④ **SM LH** $\nu$ — $\nu$ —— $y_N h L \psi_D$ —— $N$ — **HNL** $N$

**New fermion: HNL**; coupling to LH SM and h ∝ $y_N$

(Heavy Neutral Lepton)

New Physics could be light and feebly interacting with SM

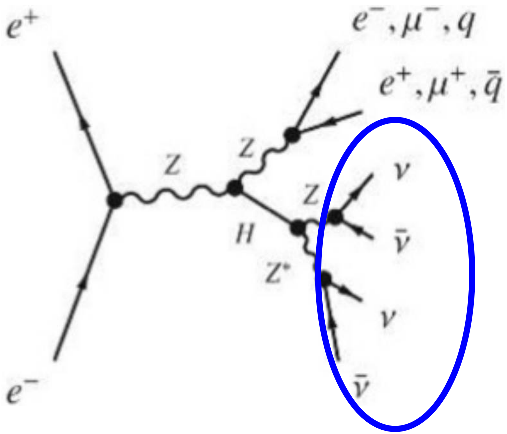
*Zeynep Demiragli – FCC Week 2024, San Francisco*

New
Physics

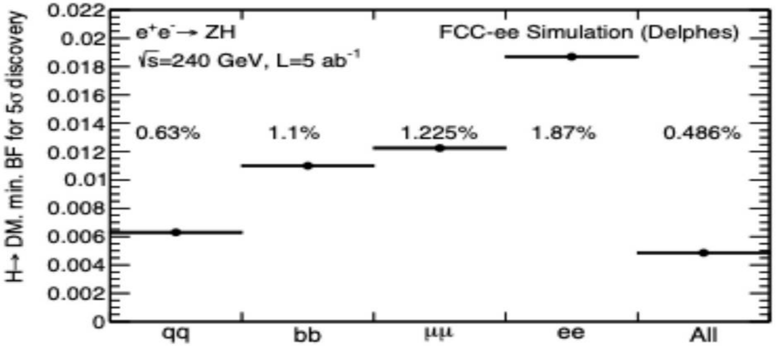
# Higgs Invisible Width

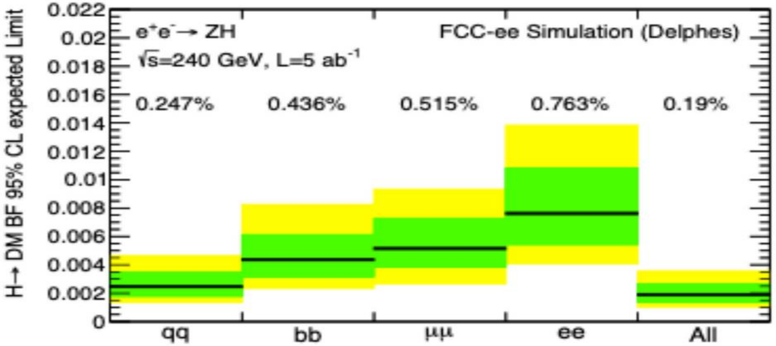
## Higgs boson: portal to dark world

- 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.

New Physics

# Dark Sector: Axion-Like Particles

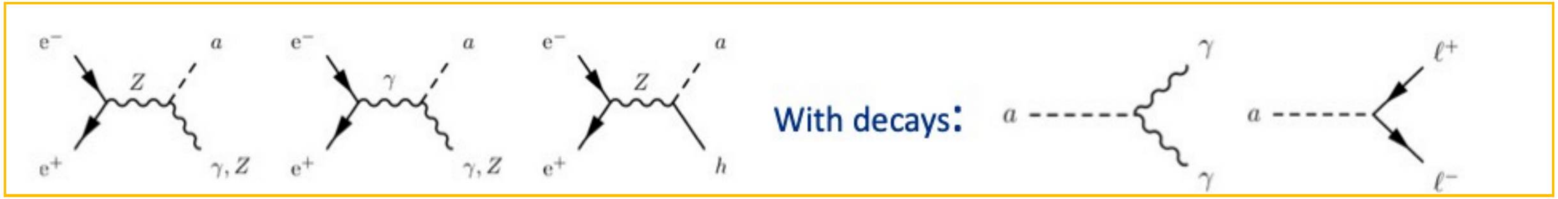
## Dark Sectors

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

## Case Study: Axion-like Particles

BOSTON UNIVERSITY

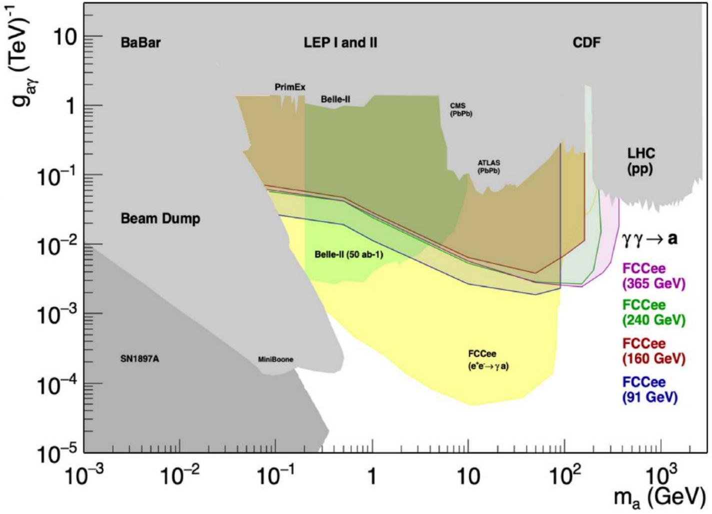
“Standard” approach:



With decays:

- ➢ $\gamma\gamma \to a$ extends current LHC limits for $m_a$ = 5 – 350GeV by 2(O) magnitude
- ➢ $e^+ e^- \to Z \to \gamma a$ 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*

New Physics

# Can the Z be a portal?

## Rare Z decays

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

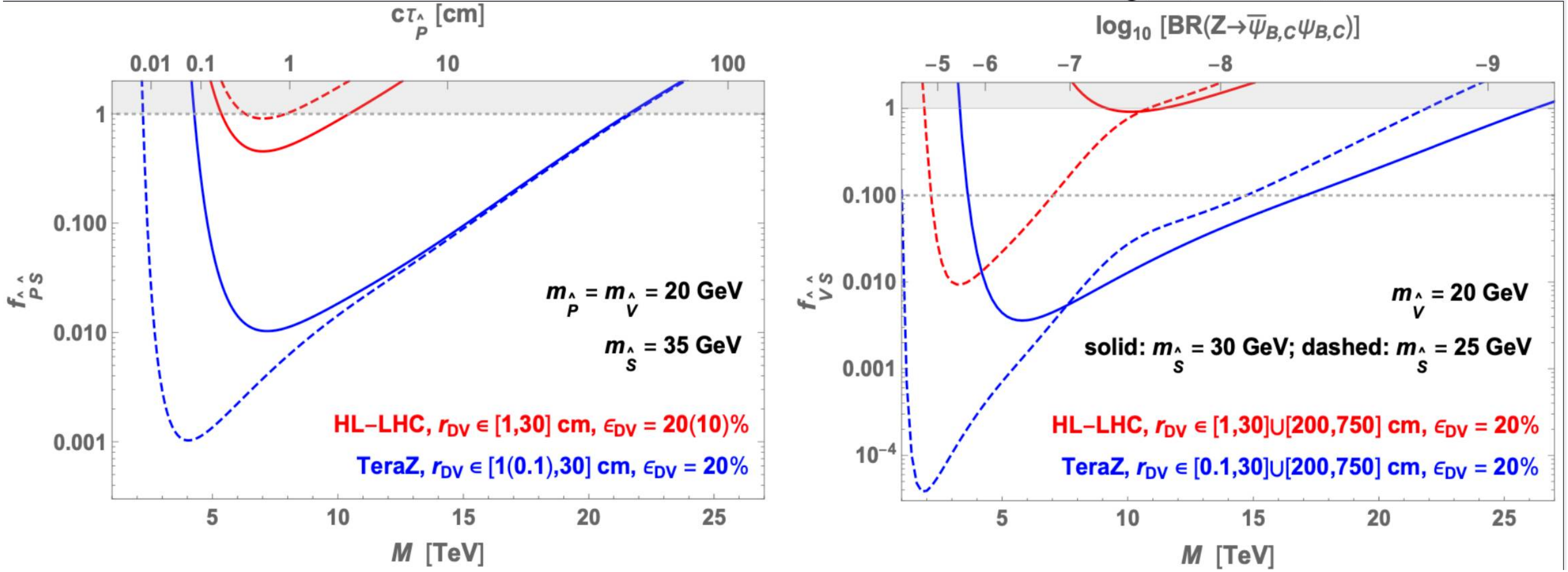
## Z-portal

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



New Physics

# *Sensitive to fractional charge?*

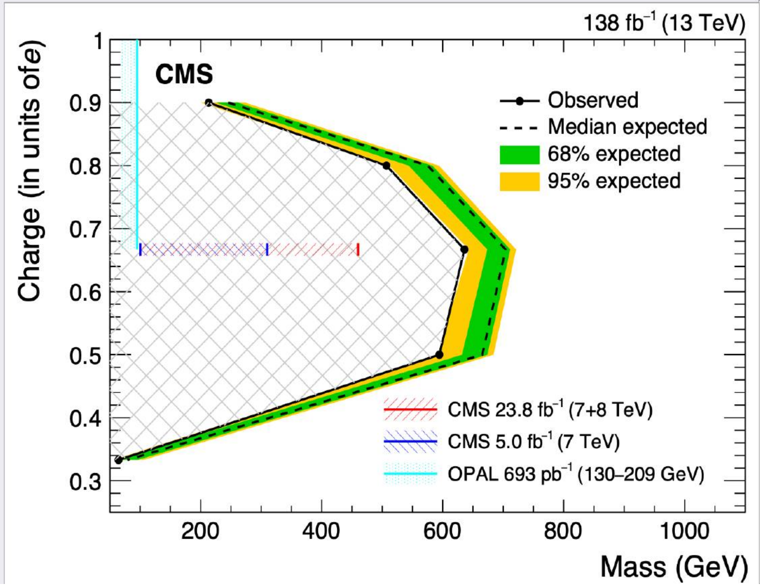
## GUT

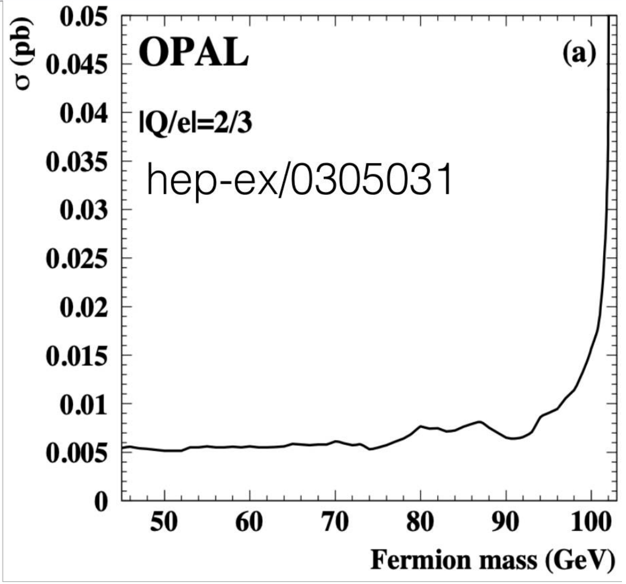
- Recent paper motivate GUTs with possible e/6 charges
- Can the FCC-ee make a contribution

## 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?





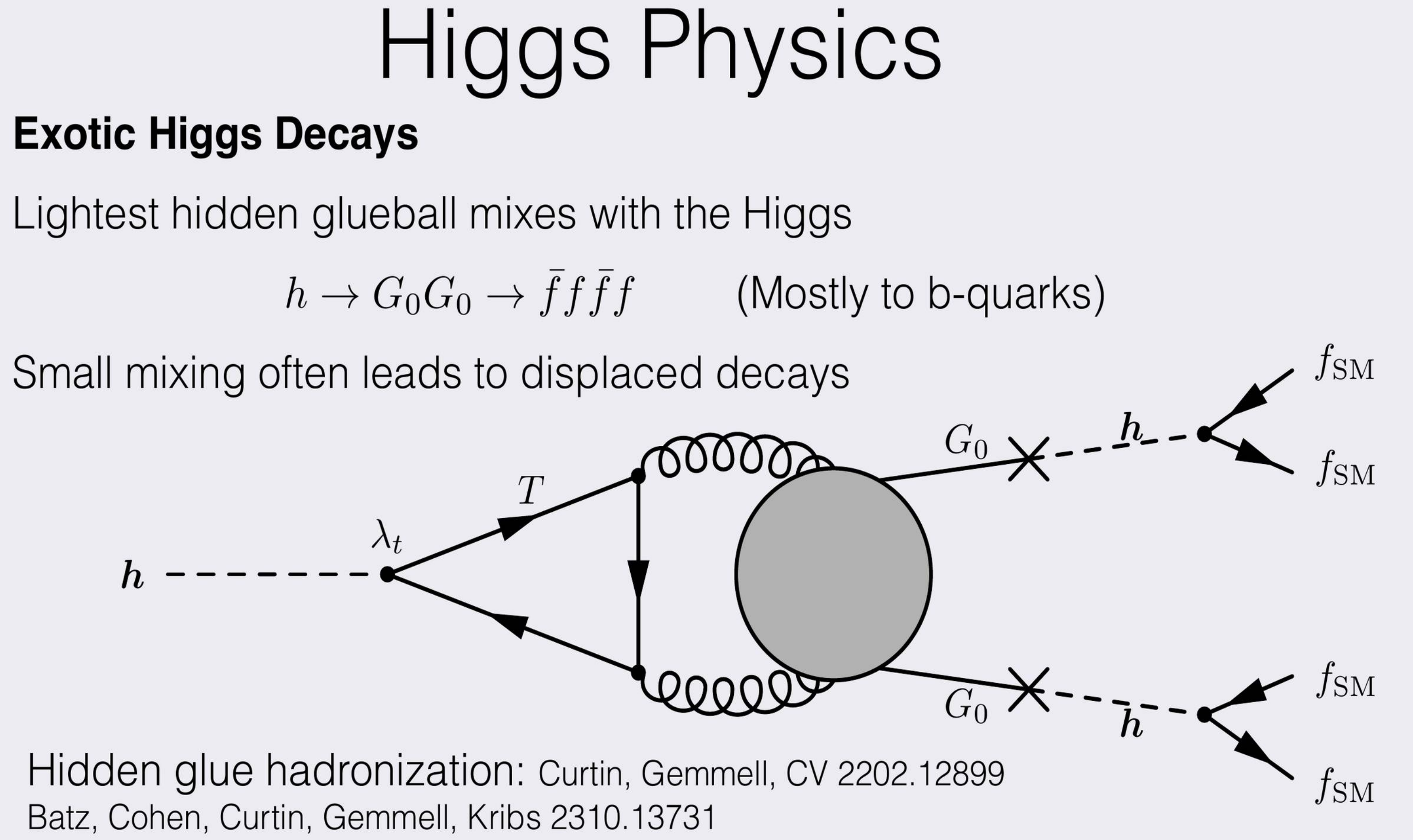
hep-ex/0305031

New Physics

# *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*

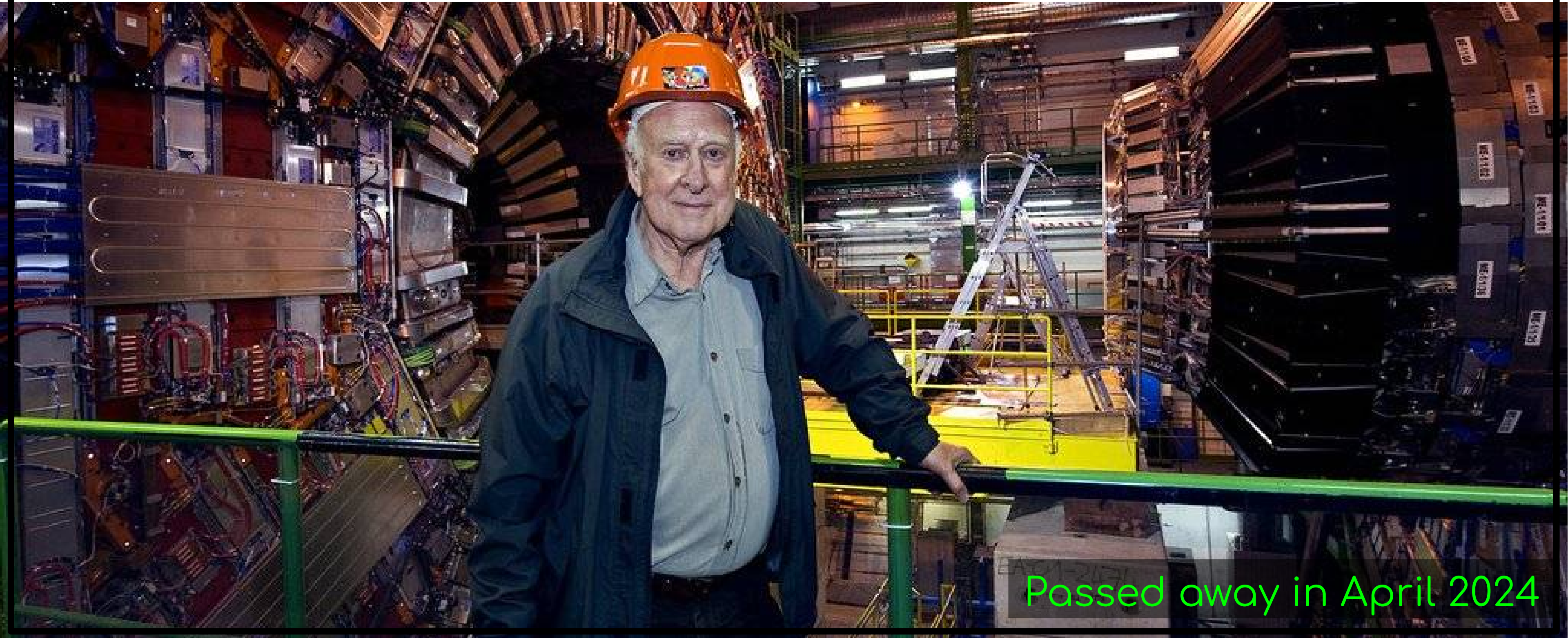
## Status

- FCC-ee produces ~2.2M Higgs bosons *in pristine conditions* and thus has a strong Higgs program (HL-LHC ~ 180M Higgses)
- There are extraordinary electroweak precison, flavor precision, top, 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*

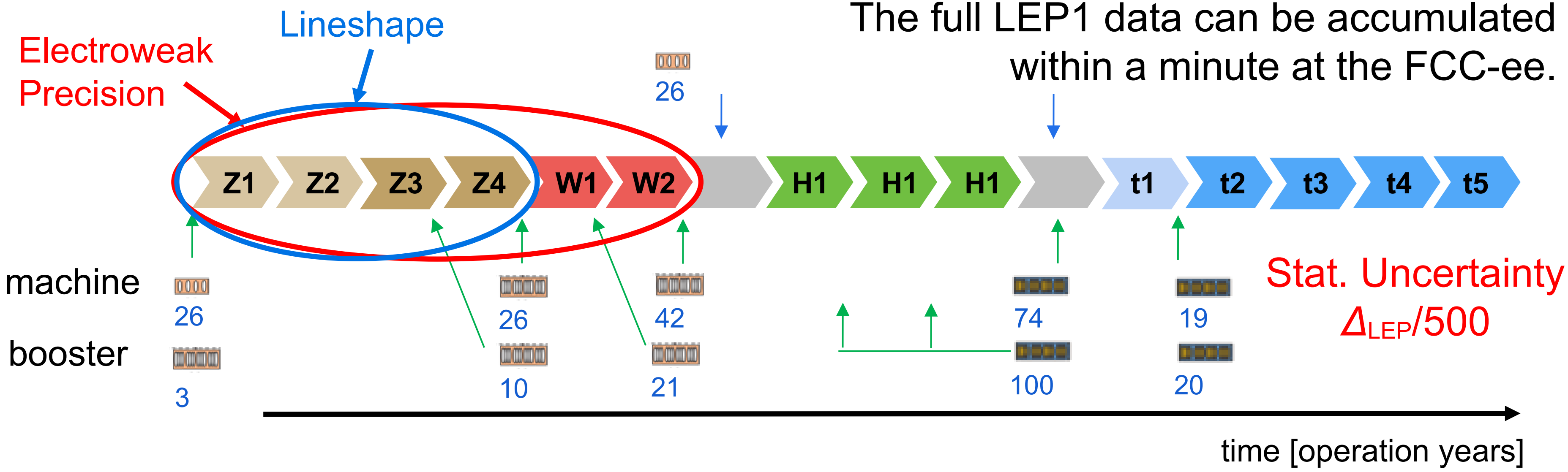
# FCC-ee: Physics & Detectors

July 11, 2024
57th Users Meeting, Fermilab

Christoph Paus, MIT

# *FCC-ee Schedule*

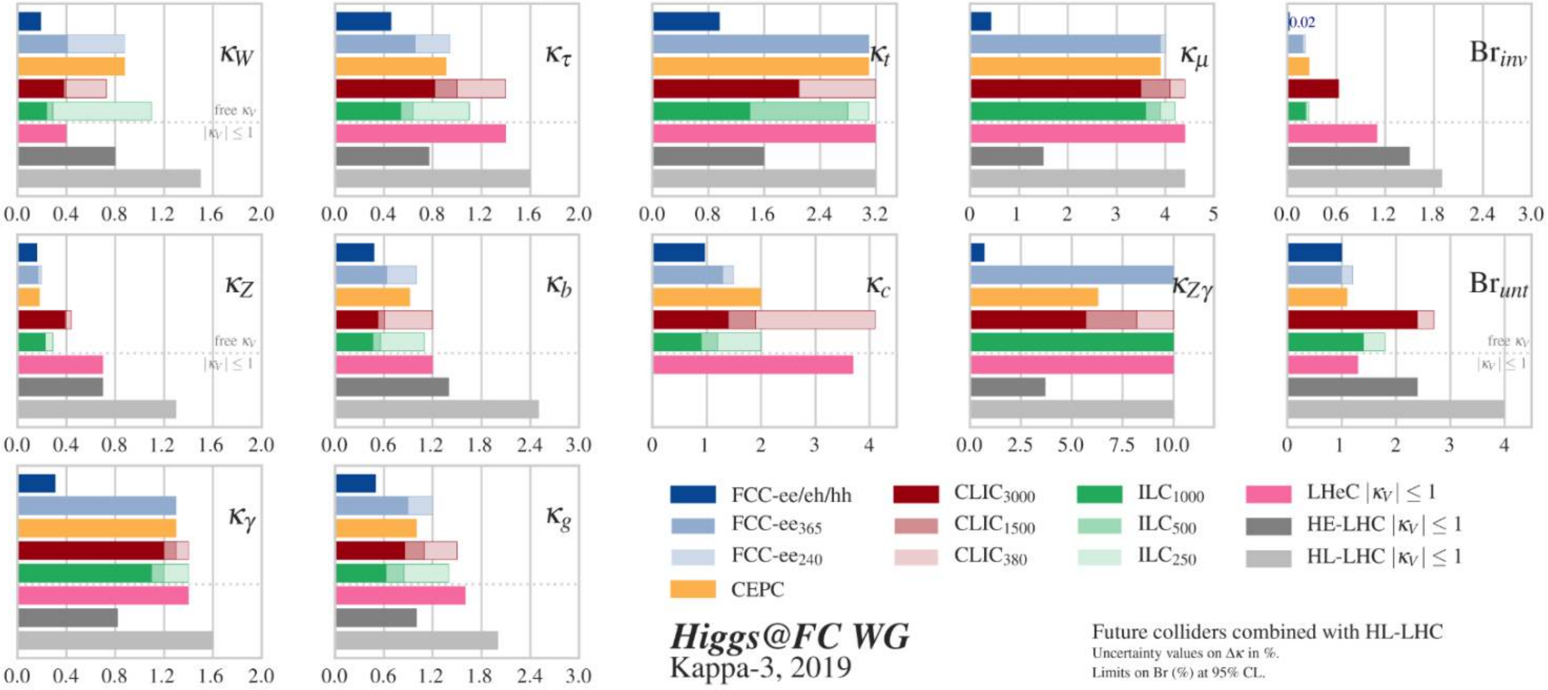
The full LEP1 data can be accumulated within a minute at the FCC-ee.



Stat. Uncertainty $\Delta_{\mathrm{LEP}}/500$

| 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 ($\mathrm{ab}^{-1}$) | 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<br>+<br>45k WW → H | $1.9\,10^{6}$ $t\bar{t}$<br>+330k HZ<br>+80k WW → H | |

# *Higgs Couplings Precision*



***Higgs@FC WG***
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

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

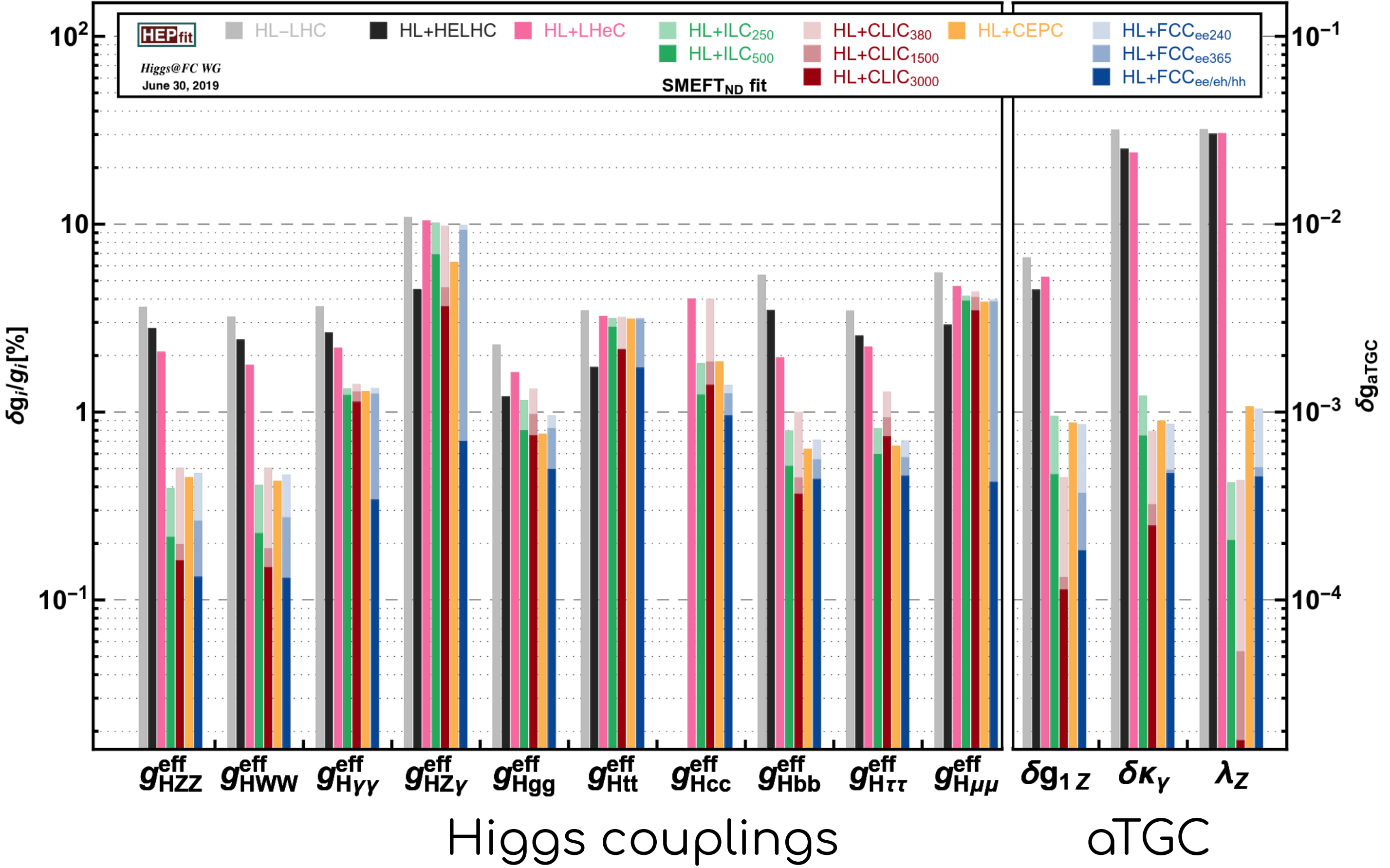
- Sensitivity to Higgs coupling is mostly around a percent
- Details of the uncertainties are dependent on the specific implementations

*arXiv:2206.08326*

# Higgs Couplings Precision

Sensitivity to deviations for

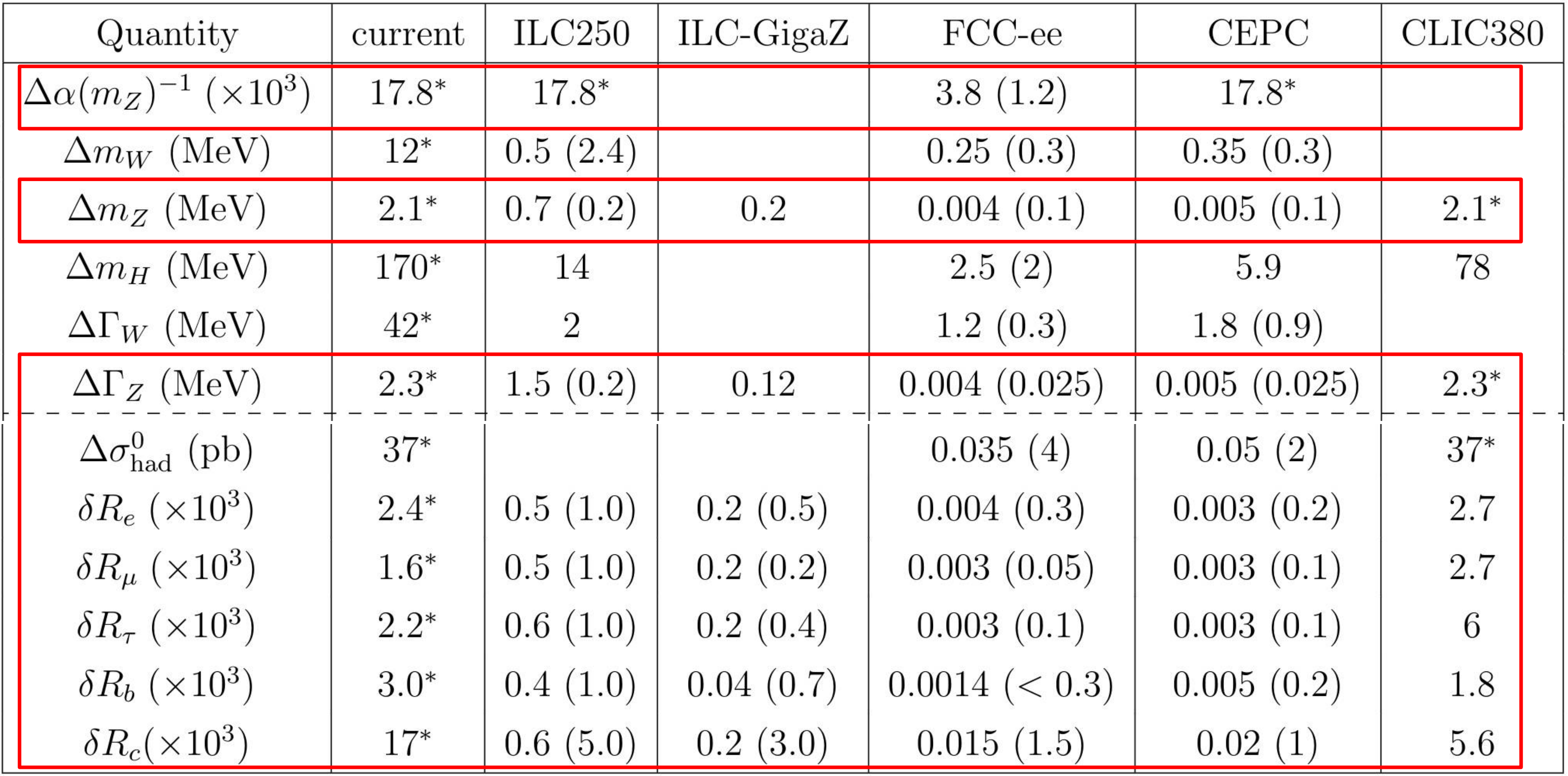
- Different effective Higgs couplings
- and aTGC



*arXiv:2206.08326*

# 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) | $17.8^*$ | |
| $\Delta m_W$ (MeV) | $12^*$ | 0.5 (2.4) | | 0.25 (0.3) | 0.35 (0.3) | |
| $\Delta m_Z$ (MeV) | $2.1^*$ | 0.7 (0.2) | 0.2 | 0.004 (0.1) | 0.005 (0.1) | $2.1^*$ |
| $\Delta m_H$ (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) | $2.3^*$ |
| $\Delta\sigma^0_{\mathrm{had}}$ (pb) | $37^*$ | | | 0.035 (4) | 0.05 (2) | $37^*$ |
| $\delta R_e$ ($\times 10^3$) | $2.4^*$ | 0.5 (1.0) | 0.2 (0.5) | 0.004 (0.3) | 0.003 (0.2) | 2.7 |
| $\delta R_\mu$ ($\times 10^3$) | $1.6^*$ | 0.5 (1.0) | 0.2 (0.2) | 0.003 (0.05) | 0.003 (0.1) | 2.7 |
| $\delta R_\tau$ ($\times 10^3$) | $2.2^*$ | 0.6 (1.0) | 0.2 (0.4) | 0.003 (0.1) | 0.003 (0.1) | 6 |
| $\delta R_b$ ($\times 10^3$) | $3.0^*$ | 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 |

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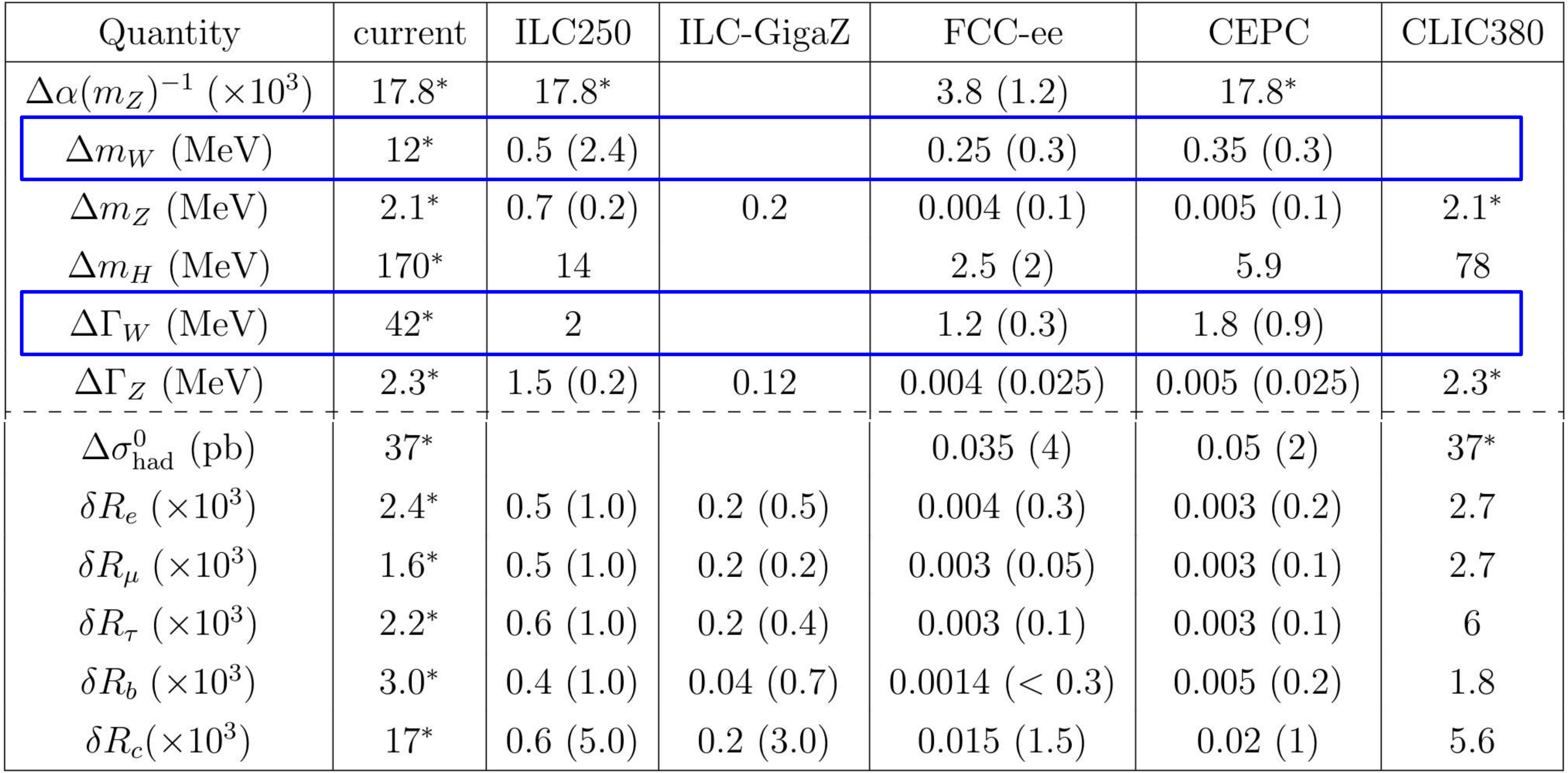
# *Lineshape Summary*

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* | |
| $\Delta m_W$ (MeV) | 12* | 0.5 (2.4) | | 0.25 (0.3) | 0.35 (0.3) | |
| $\Delta m_Z$ (MeV) | 2.1* | 0.7 (0.2) | 0.2 | 0.004 (0.1) | 0.005 (0.1) | 2.1* |
| $\Delta m_H$ (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* |
| $\Delta\sigma^0_{\mathrm{had}}$ (pb) | 37* | | | 0.035 (4) | 0.05 (2) | 37* |
| $\delta R_e$ $(\times 10^3)$ | 2.4* | 0.5 (1.0) | 0.2 (0.5) | 0.004 (0.3) | 0.003 (0.2) | 2.7 |
| $\delta R_\mu$ $(\times 10^3)$ | 1.6* | 0.5 (1.0) | 0.2 (0.2) | 0.003 (0.05) | 0.003 (0.1) | 2.7 |
| $\delta R_\tau$ $(\times 10^3)$ | 2.2* | 0.6 (1.0) | 0.2 (0.4) | 0.003 (0.1) | 0.003 (0.1) | 6 |
| $\delta R_b$ $(\times 10^3)$ | 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 |

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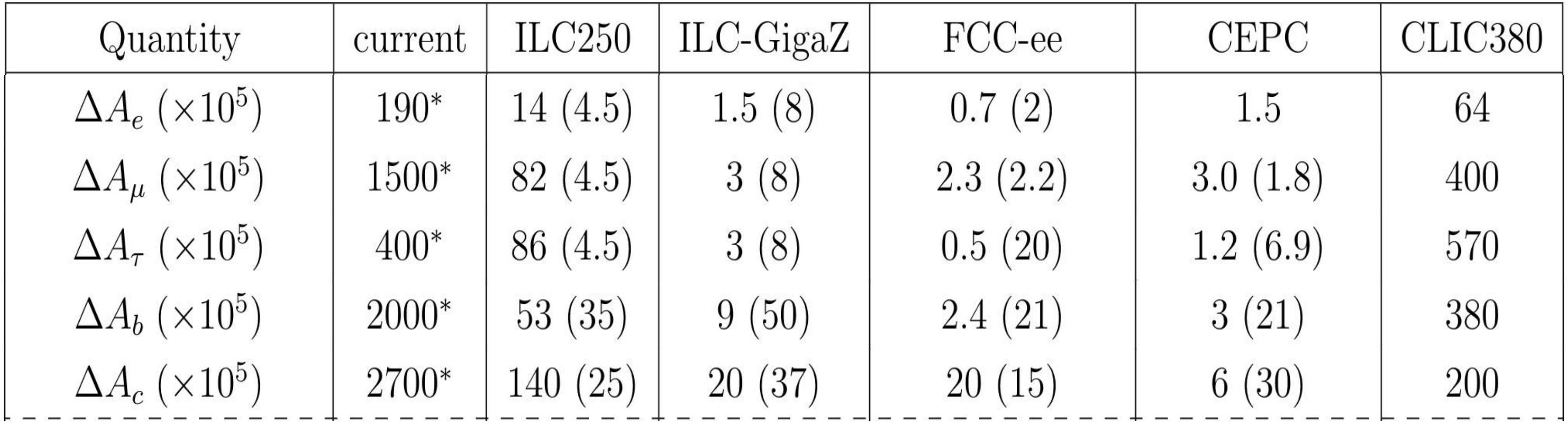
# *Asymmetry Summary*



| Quantity | current | ILC250 | ILC-GigaZ | FCC-ee | CEPC | CLIC380 |
|---|---|---|---|---|---|---|
| $\Delta A_e$ ($\times 10^5$) | $190^*$ | 14 (4.5) | 1.5 (8) | 0.7 (2) | 1.5 | 64 |
| $\Delta A_\mu$ ($\times 10^5$) | $1500^*$ | 82 (4.5) | 3 (8) | 2.3 (2.2) | 3.0 (1.8) | 400 |
| $\Delta A_\tau$ ($\times 10^5$) | $400^*$ | 86 (4.5) | 3 (8) | 0.5 (20) | 1.2 (6.9) | 570 |
| $\Delta A_b$ ($\times 10^5$) | $2000^*$ | 53 (35) | 9 (50) | 2.4 (21) | 3 (21) | 380 |
| $\Delta A_c$ ($\times 10^5$) | $2700^*$ | 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

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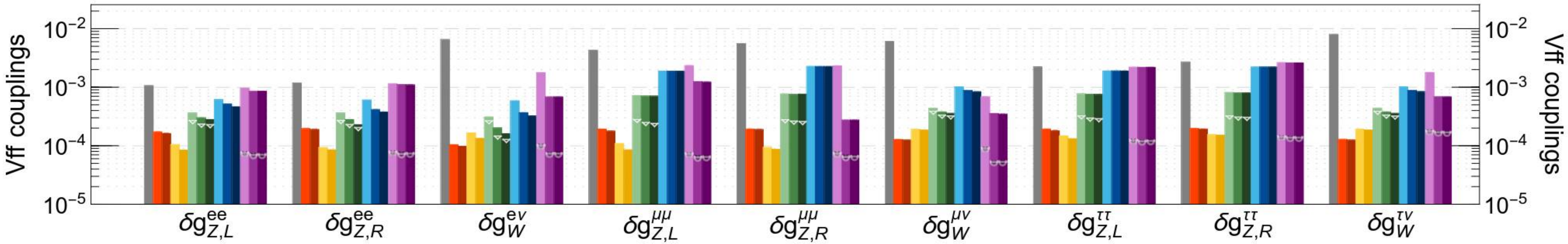
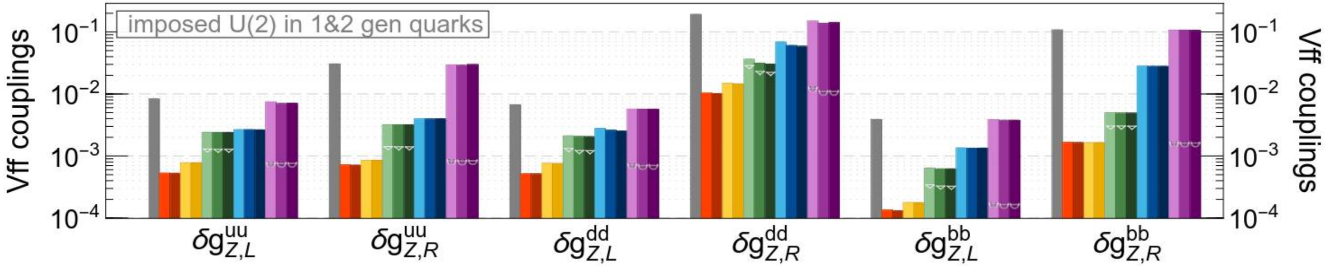
# *Global Fit focus W/Z couplings*





Note logarithmic scale

## As expected

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

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