ECFA Higgs/Top/EW Workshops

Dirk Zerwas (DMLab)

ESPPU Session at the IRN Terascale Meeting

November 13, 2024

- Introduction
- Physics Analysis Tools
- Physics
- Summary/Outlook

DARK MATTER LAB

cnrs

DESY.

GSI

KIT
Karlsruher Institut für Technologie

Introduction

2020: ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at **future Higgs *(added top and EW)* factories** to gather. ECFA supports **a series of workshops** with the aim to share challenges and expertise, to **explore synergies in their efforts** and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).

WG1: Physics Potential

- Juan Alcaraz/Patrick Koppenburg
- James Wells/Jorge de Blas
- Jenny List
- Fabio Maltoni

WG2: Physics Analysis Tools

- Patrizia Azzi
- Fulvio Piccinini
- Dirk Zerwas

WG3: Detector R&D (set up post DRD)

- Mary-Cruz Fouz
- Giovanni Marchiori
- Felix Sefkow

Workshops:

- 2021: Kickoff in ZOOM
- 2022: 1st workshop in DESY
- 2023: 2nd workshop in Paestum
- 2024: 3rd workshop in Paris

Activities:

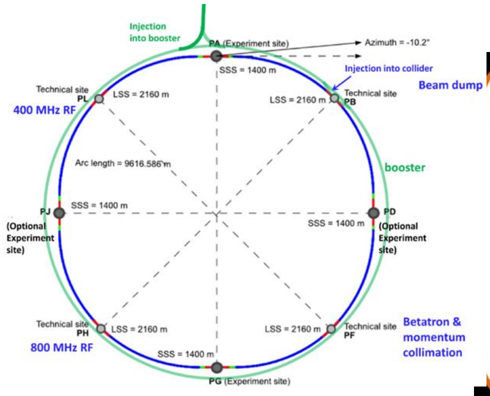
- WG3 interface and relationship with DRD (talk in its own right, not covered here)
- WG2 Topical and focus meetings
- WG1 (and all): ECFA topics
- WG1-2-3: A Report

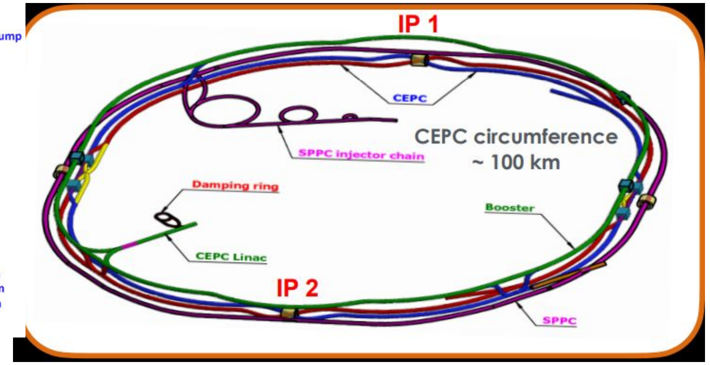
Machines/Proposals by derivative

Circular:

- 90km (FCC), 100km (CEPC)
- √s=90-365GeV
- Tera-Z

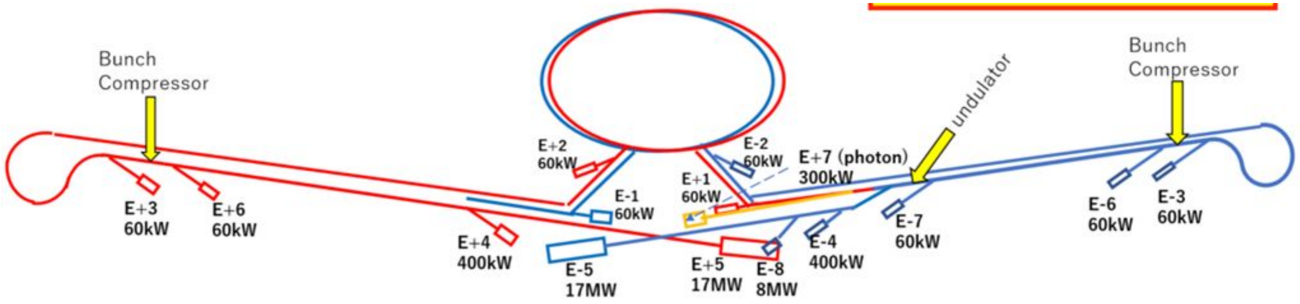
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter x_x / x_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11





Linear

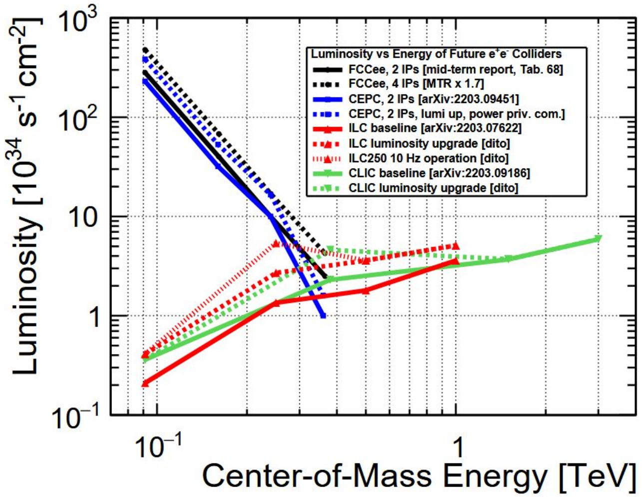
- 27 km
- √s=90-550GeV
- Giga-Z



Central messages:

- Strength of circular low(er) E lumi
- Strength of linear high(er) E lumi
- Luminosity != Luminosity (polarisation)
- 2nd gen Attobarn machines
- √s is √s (to first order)

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	$10^{34}cm^{-2}s^{-1}$	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	f_{rep}	Hz	5	5
Bunches per pulse	n_{bunch}	1	1312	2625
Bunch population	N_e	10^{10}	2	2
Linac bunch interval	Δt_b	ns	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	961
Average beam power	P_{ave}	MW	5.3	10.5
RMS bunch length	σ_z^*	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %
Site AC power	P_{site}	MW	111	128
Site length	L_{site}	km	20.5	20.5



Technologies

- ILC
- CLIC
- C^3
- HALHF

Physics Analysis Tools

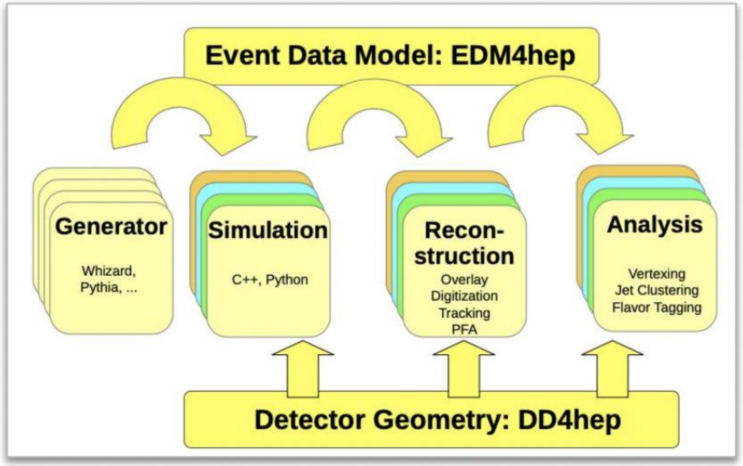
- Monte Carlo generators for e+e- precision EW, Flavour, Higgs, and top physics,
- Luminosity measurements
- Software framework
- Fast simulation and the limitations of such techniques
- Full Simulation
- Track and vertex reconstruction algorithms
- Jet algorithms / jet reconstruction
- Particle-flow reconstruction and global event description
- Requirements on particle identification
- Flavour tagging algorithms
- Importance of timing information
- Constrained fit
- *Coffee*
- *Tea*
- *Donuts*
- *eclair au chocolat*

SOFTWARE ECOSYSTEM

GENERATORS

SIMULATION

RECONSTRUCTION



KEY4HEP Ecosystem:

- EDM4HEP
- Geometry DD4HEP
- Gaudi
- DIRAC
- ILCSOFT
- FCC
- CEPCSW
- ACTS….

Adopted by ECFA(well…), CEPC, C^3, FCC, ILC :

- Interoperability of algorithms
- comparisons and improvements

Generators

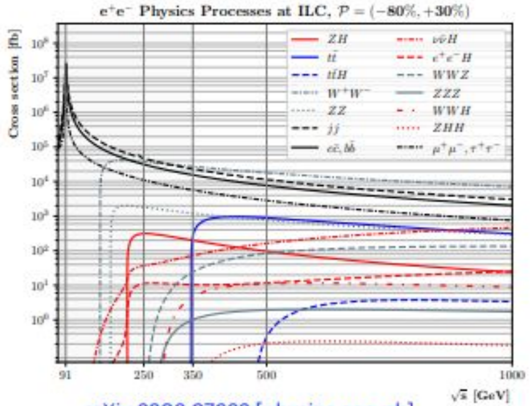
LEP era generators:
- Pythia
- Herwig
- KKMC
- Babayaga, BHLUMI (specialized)

LHC era generators (automation):
- Madgraph
- Sherpa

Modern e+e- era generators:
- Whizard
- CIRCE (specialized)

Goal:
- Update and extend

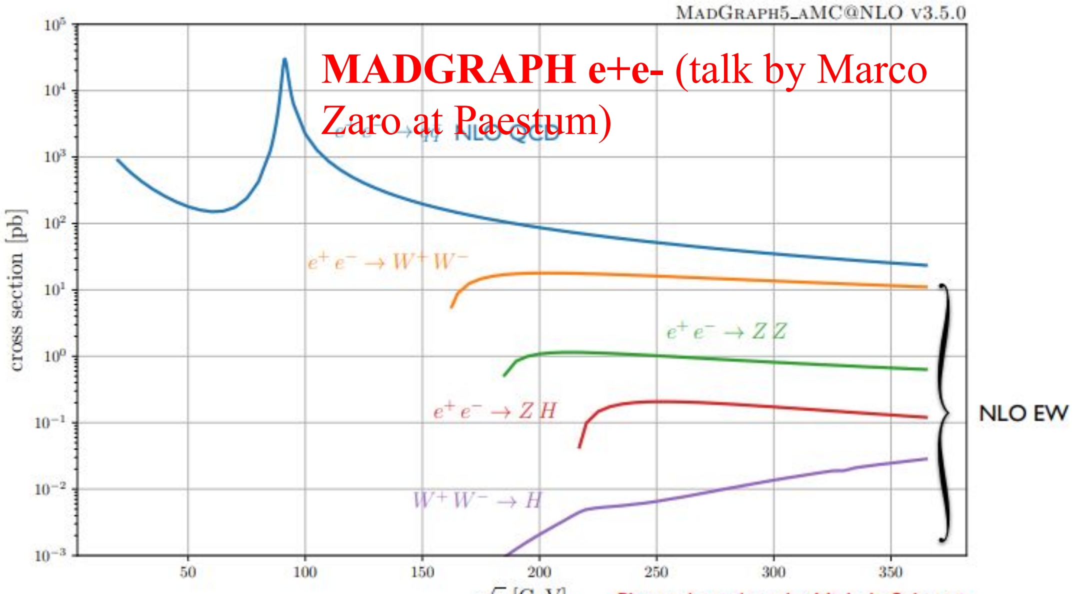
Whizard e+e- (talk by Reuter@LCWS2024)



arXiv:2203.07622 [physics.acc-ph]

Beamstrahlung:
- high density of bunches leads to strong fields
- machine dependent (Guinea Pig)
- Input to Generators (MADGRAPH, Whizard)
- Provide a consistent set for all machines

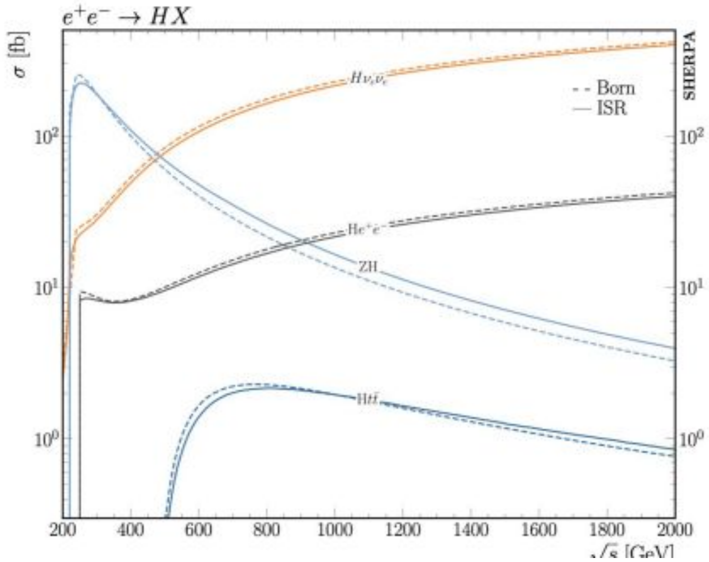
MADGRAPH e+e- (talk by Marco Zaro at Paestum)



Plot and numbers by Michele Selvaggi

QED:
- ePDF, QED Parton Shower and Yennie-Frautchi-Suura resummation
- Some generators use ePDF (thought we got rid of this, but no….)

SHERPA e+e- (talk by Daniel Reichelt at Paris)

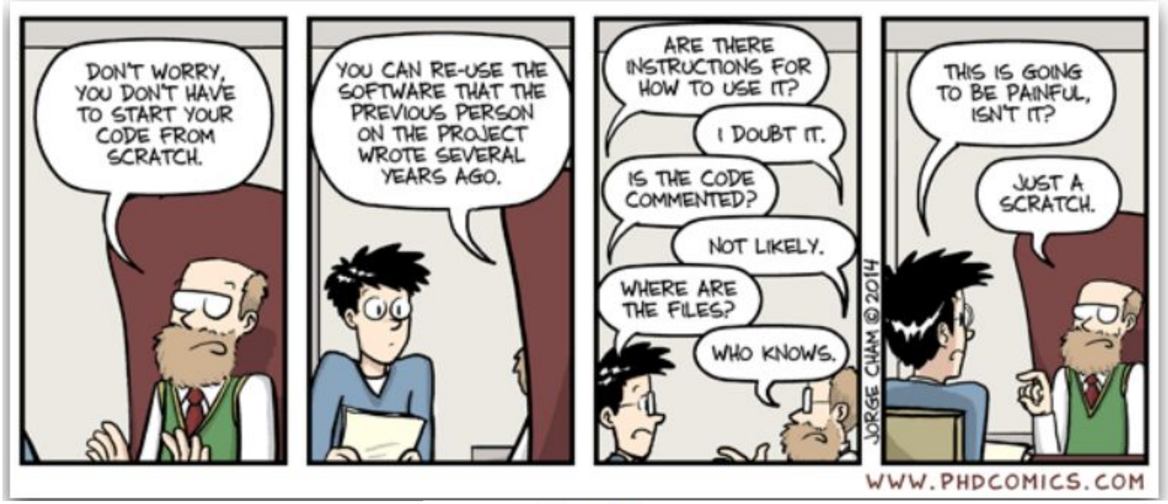


Alan Price (Cracovie) in Paris

Generators: Configuration

Attobarn data with N^nLO under control:

- many generators claim the same precision (differing approaches)
- needs high precision in generation
- first step: cross section
- second step: differential distributions
- Technical Benchmarks



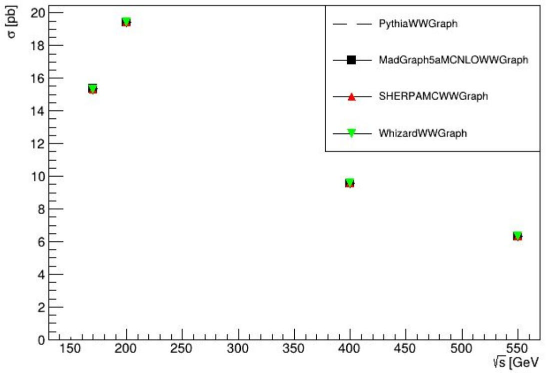

```
Generators:
  - Sherpa
  - Whizard
  - Madgraph
  - KKMC
  - Pythia

OutputFormat: hepmc3
OutDir: Run-Cards
Events: 10000
EventMode: unweighted

SqrtS: 91.2
Model: SM
ISRMode: 0

Processes:
  Muon:
     Final: [13, -13]
     Order: [2,0]

  Tau:
     Final: [15, -15]
     Order: [2,0]

Sherpa:
  Run:
    EW_SCHEME: 3


ParticleData:
  23:
    mass: 91.1876
    width: 2.4952
```

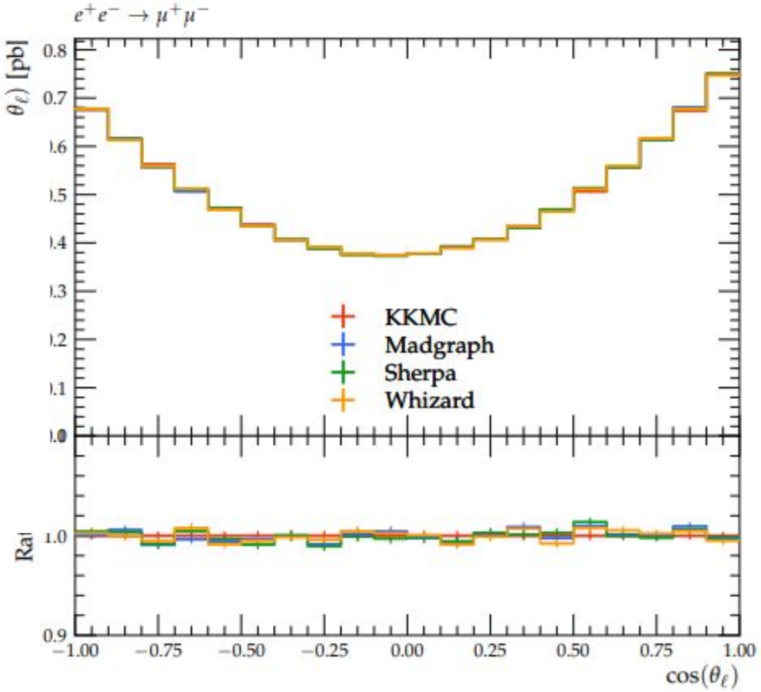
k4GeneratorsConfig in KEY4HEP:

- define process
- define generators
- generates datacards for the generators
- generates run script in KEY4HEP

behind the scenes:

- converter HEPMC/LHE to EDM4HEP
- interface to Pythia for MADGRAPH
- PythiaRunnner with PhaseSpace cuts
- lots of subtle effects (started with 10% deviations!!)

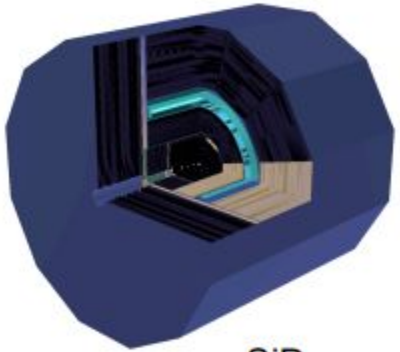




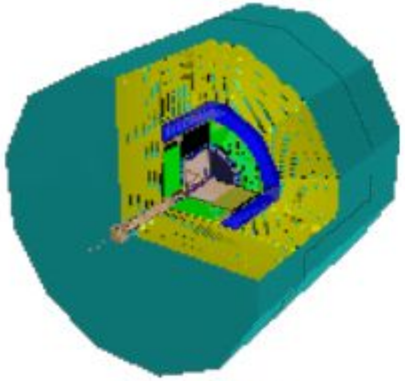
Physics Analysis Tools: Concepts

KEY4HEP contains DD4HEP:

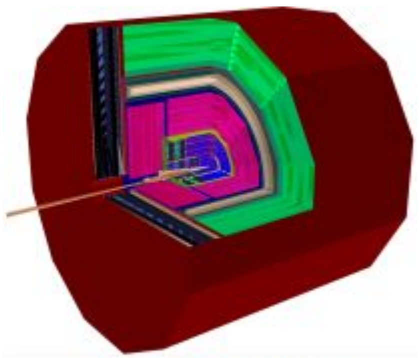
- geometry definitions of detectors
- residing in the same framework
- enabling assembly of via detector exchange



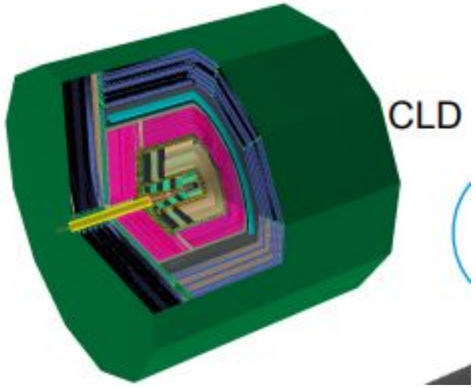
SiD



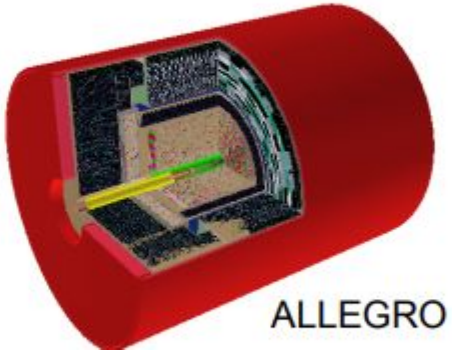
ILD



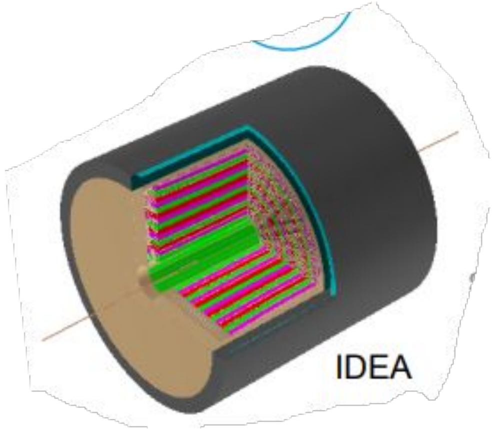
CLICdet



CLD

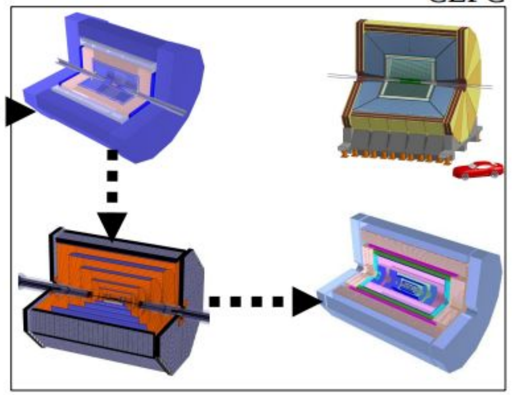


ALLEGRO



IDEA

CEPC



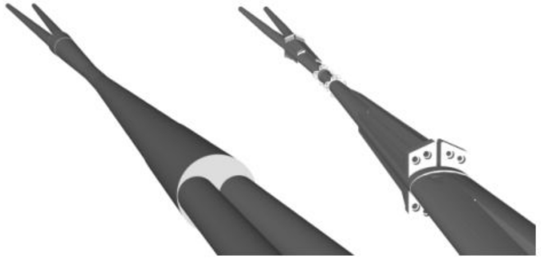
Linear and Circular World:

- concepts defined initially for a specific machine, now options
  - ILD, CLICdet, CLD
  - ILD, ILD@FCC
  - New concepts IDEA, Allegro

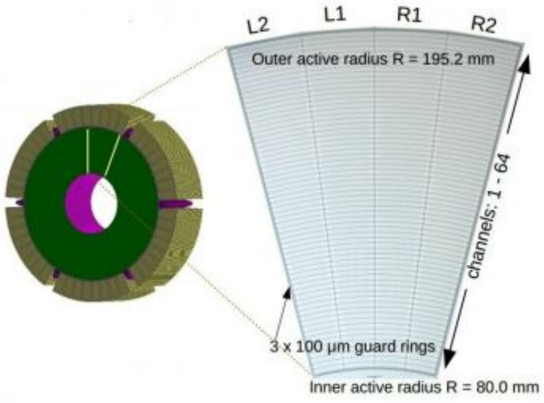
Physics Analysis Tools: Simulation Geometry

Shared MachineDetectorInterface (MDI):

- FCC
- ILD@FCC



SiW Lumimeter for ILC, FCC and CEPC:



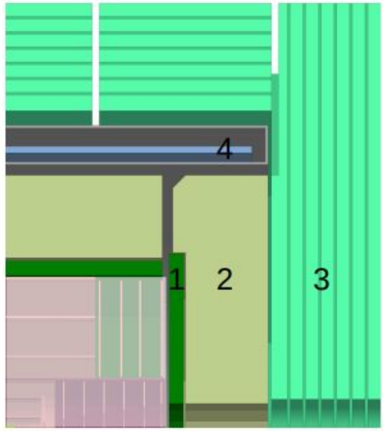
Lumimeter geometry

Tracking:

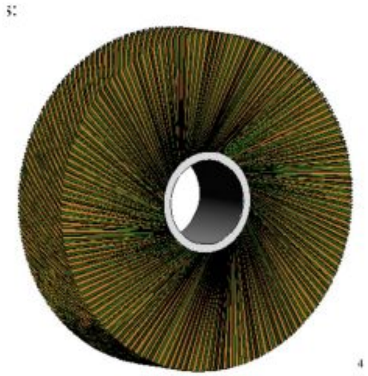
- Si+Gaseous (TPC or Drift Chamber IDEA)
- Si+Si

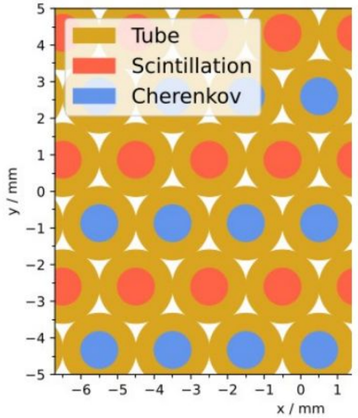
Calo:

- Calo Type 1: SiW with concurrent simulation of two HCALs
- Calo Type 2: Noble Liquid+TileCal
- Calo Type 3: Dual readout (scintillation+cerenkov)



Muon chambers RPC
ParticleID ARCH (before Calo)





General move to full simulation:

- tremendous effort by all groups
- necessary for detailed understanding of performance
- enabled by exchangeability of subdetectors (devil is in the details)

Physics Analysis Tools: Reconstruction

Tracking reconstruction:

- ILD (cellular automatons+kalman extrapolation)
- Conformal (CLIC)
- ACTS (in progress)

Clustering:

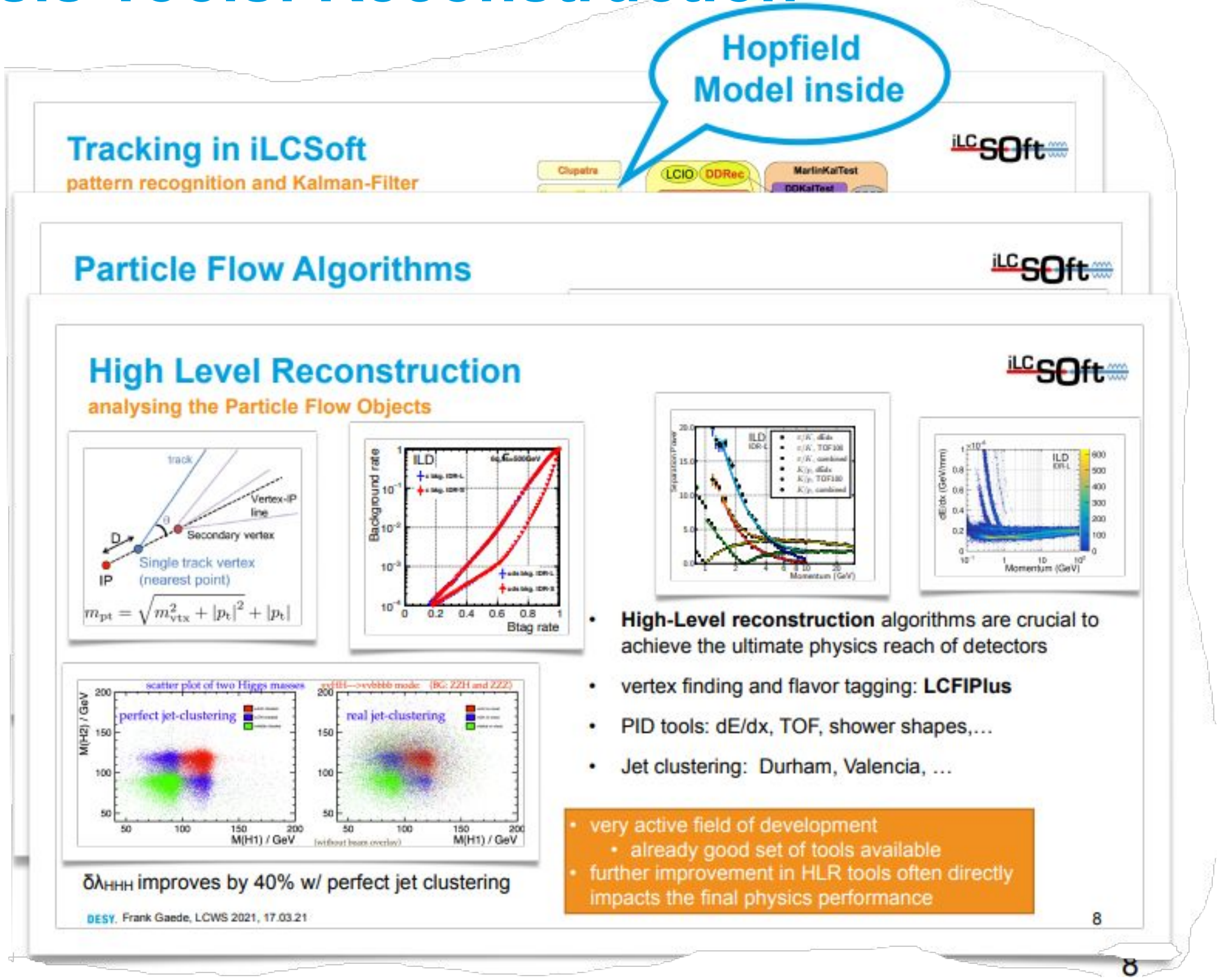
- CLUE alg (energy density based from HGCAL)

Particle Flow:

- ARBOR (LLR and CEPC)
- Pandora aka new CERN DG
- ML/AI (on simplified events)
- changes the optimization from single detector to concept

High Level:

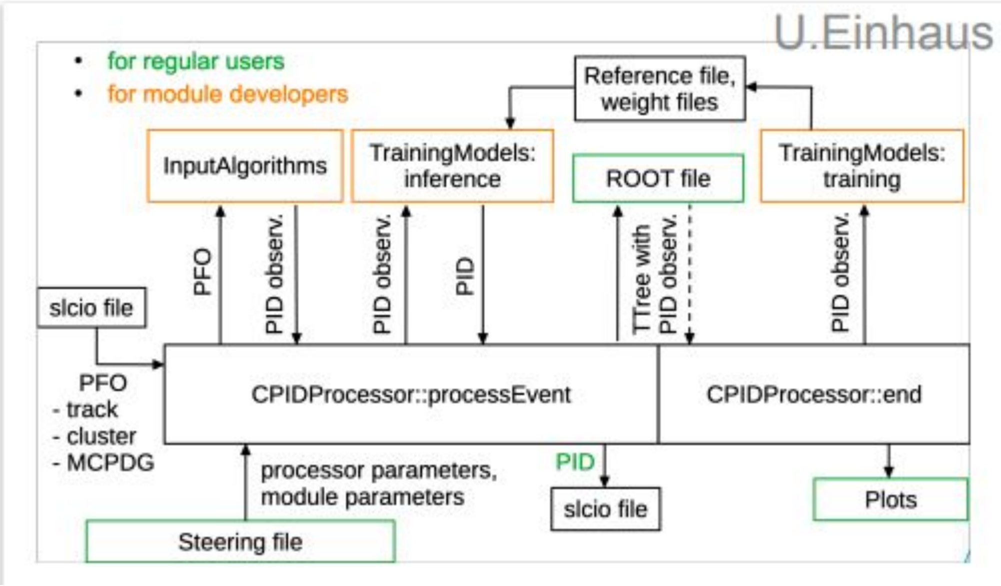
- Particle ID
- Vertexing
- Flavour tagging
- jet reconstruction (Fastjet)

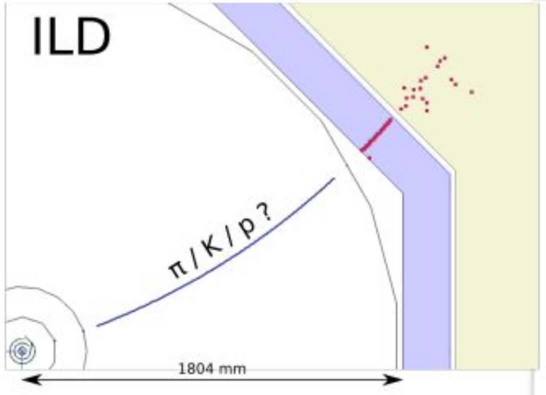


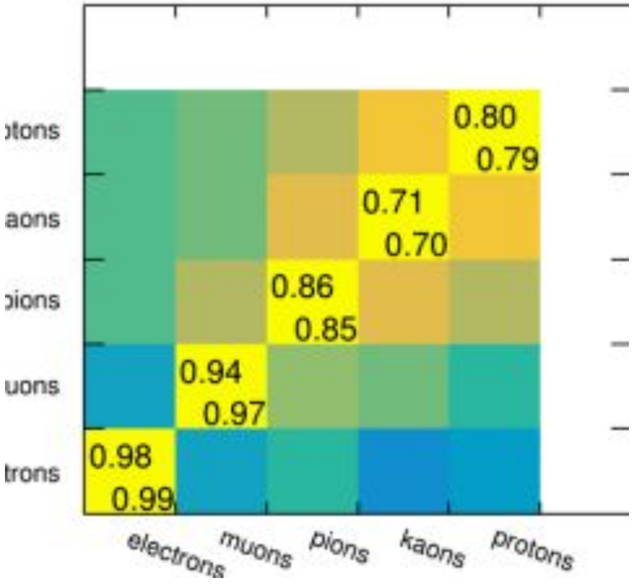
Charged Particle ID

Comprehensive charged particle identification:

- ParticleFlowID
- Dedicated Lepton ID
- dE/dx (TPC)
- TimeOfFlight
- Cluster Counting (drift chamber)







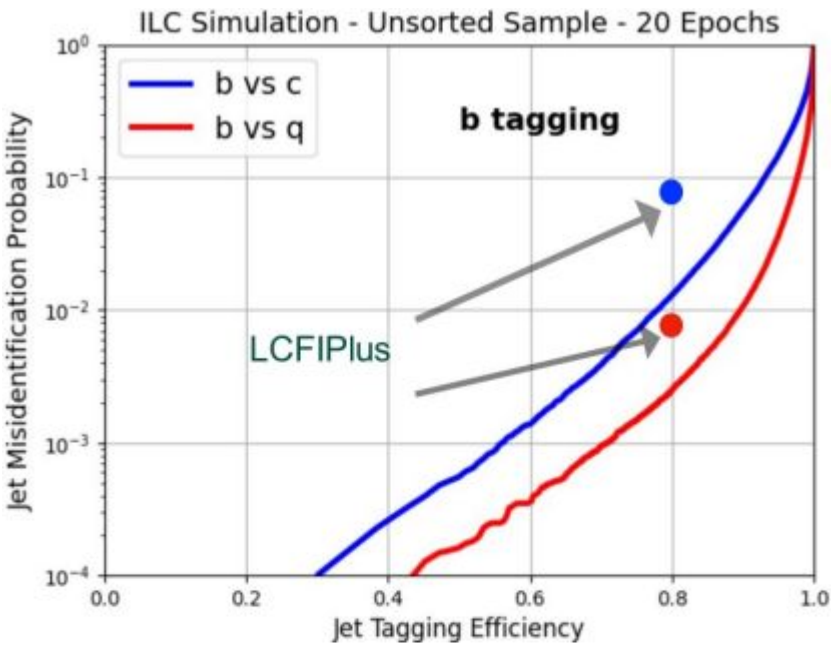
Allows for use:

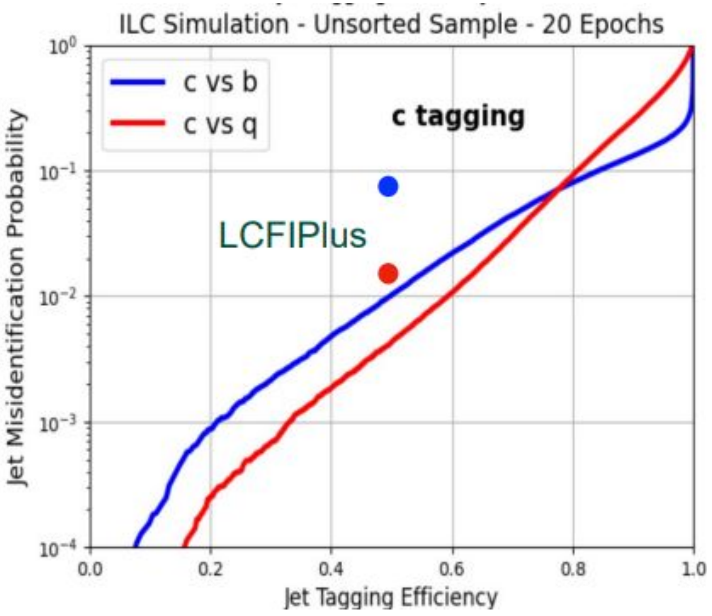
- use as is
- new training
- adding algorithms etc
- interface to be moved to EDM4HEP

Tagging

Particle Transformer (a nice example of cross project collaboration):

- developed for FCC (circular) based on ParticleNet
- discussions on input variables, training etc
- moved to newer and more performant ParticleTransformer
- clear improvement on the old standard (DNN etc) LCFIPlus





Many algorithms being tested and developed in various degrees of maturity

Combining with CPID:

- strange tagging

	s-tag 80% eff.	
Method	g-bkg acceptance (%)	d-bkg acceptance (%)
ILD full sim. CPID	25.7	42.7
ILD full sim. Truth PID	23.2	38.0
FCC 1M (PID+tof)	20.3	29.6

Some questions under study:

- performance improves "limitless" with statistics….TBC

Physics

Higgs Factories all study:

- Higgs: mass, branching ratios, couplings, angular distributions
- top quark: mass, couplings
- electroweak: Z boson, W boson
- All together via EFT
- with varying "emphasis"=luminosity/polarisation…

ECFA Topics:

- Bring together circular, linear and LHC
- choose topics where joint work is useful

- HtoSS: $e^+e^- \to Zh$: $h \to ss$
- ZHang: ZH angular distributions and CP studies
- Hself: Determination of the Higgs self-coupling
- Wmass: Mass and width of the W boson
- WWdiff: Full studies of WW and evW
- TTthresh: Top threshold - detector-level studies of $e^+e^- \to t\bar{t}$
- LUMI: Precision luminosity measurement
- EXscalar: New exotic scalars
- LLPs: Long-lived particles
- EXtt: Exotic top decays
- CKMWW: CKM matrix elements with on-shell and boosted W decays
- BKtautau: $B^0 \to K^{0*}\tau^+\tau^-$
- TwoF: EW precision - 2-fermion final states
- BCfrag/Gsplit: Measurement of b- and c-fragmentation functions and hadronisation rates and measurement of gluon splitting to bb / cc

Physics: Luminosity

Motivation:

- Precise absolute measurements need precise luminosity measurements

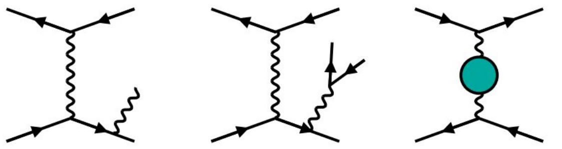
Small Angle Bhabha Scattering (SABS):

- Advantages: large rate, well-understood (LEP)
- Challenges: metrology requirements (μm scale), beam–beam and beam–final-state particle interactions, beam energy systematics, hadronic vacuum polarization uncertainty in theory calculation
- Recent work: (updated) metrology requirements for ILC and CEPC
- Generators and calculation precision (lots of fun)
- Estimate the impact of new physics: yes we can

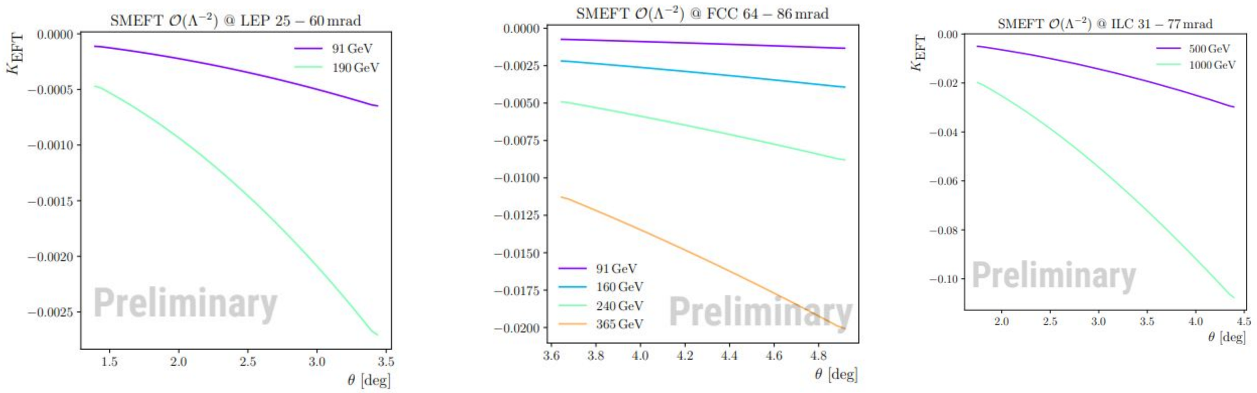
$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SM+new} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \left[1 + \frac{c_8\ s^2}{8\pi\alpha\Lambda^4}\ \sin^2\theta\right]$$

Two Photon Production:

- Advantages: smaller non-perturbative theory effects, no deflection of outgoing photon
- Challenges: smaller rate, large SABS background, few existing MC generators
- high-granularity calorimeter and/or mini-tracker for improvement e+/e- angle measurements and e/γ separation
- Effect of new physic, can be "measured"



	Photonic	Light pairs	Vacuum Pol.	Total
LEP 1999 18-52 mrad	0.030% $\mathcal{O}(\alpha^2 L \oplus \alpha^3 L^3)$	0.030%	0.040%	0.061%
2018 18-52 mrad		0.010% G. Montagna et al.	0.013% F. Jegerlehner	0.038%
2018 64-86 mrad	0.030% $\mathcal{O}(\alpha^2 L \oplus \alpha^3 L^3)$	0.010%	0.014%	0.097%
FCC-ee Forecast	0.011% $\mathcal{O}(\alpha^3 L^2 \oplus \alpha^4 L^4)$	0.005%	0.006%	0.01% Goal

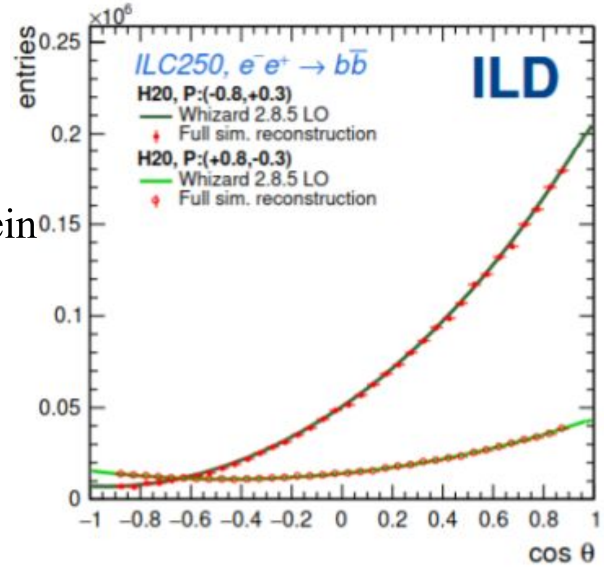


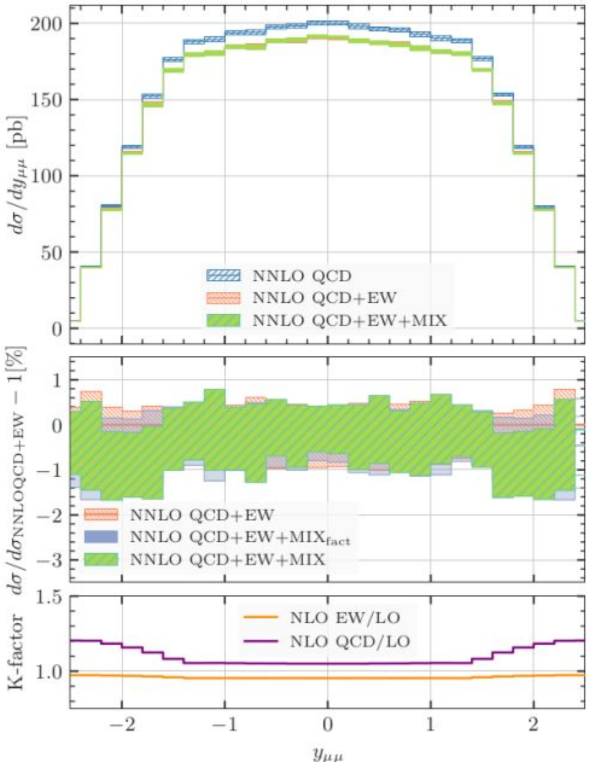
P.Ucci in Paris (Babayaga)

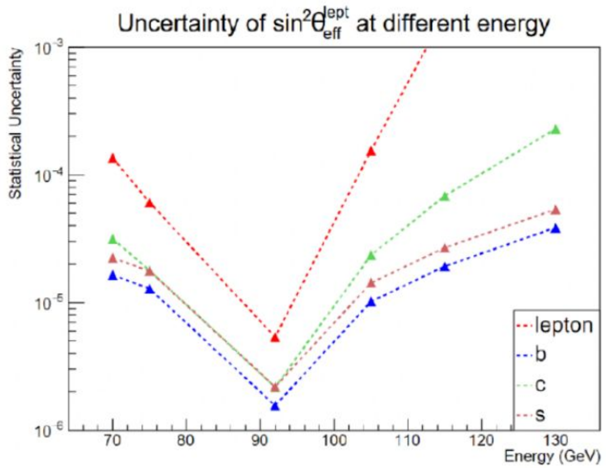
Physics: Electroweak

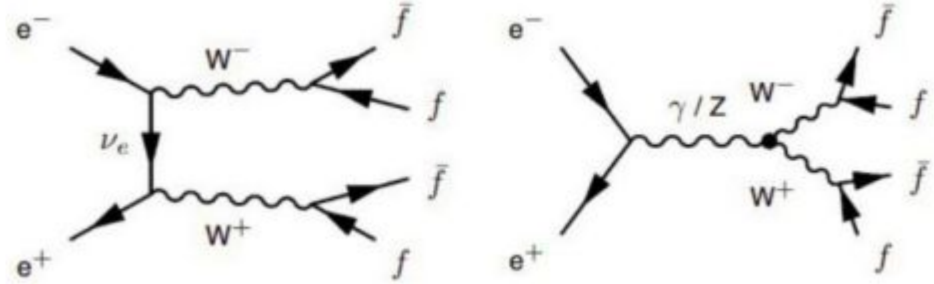
Two fermion measurements:

- simple
- high statistics
- difficult
- super playground for loopVerein
- needs extremely good tagging
- sin^2theta stat 10^-6!





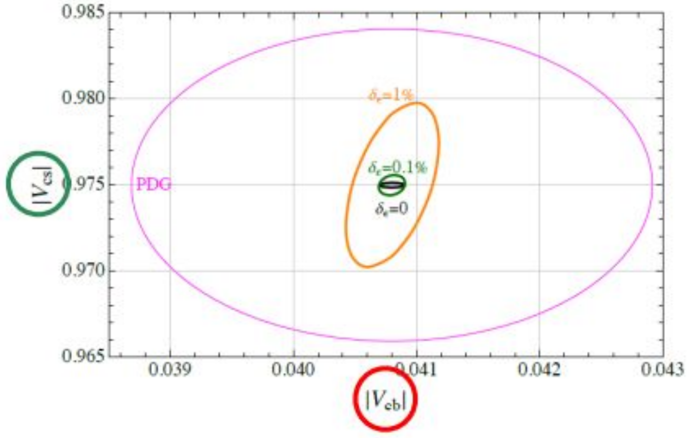




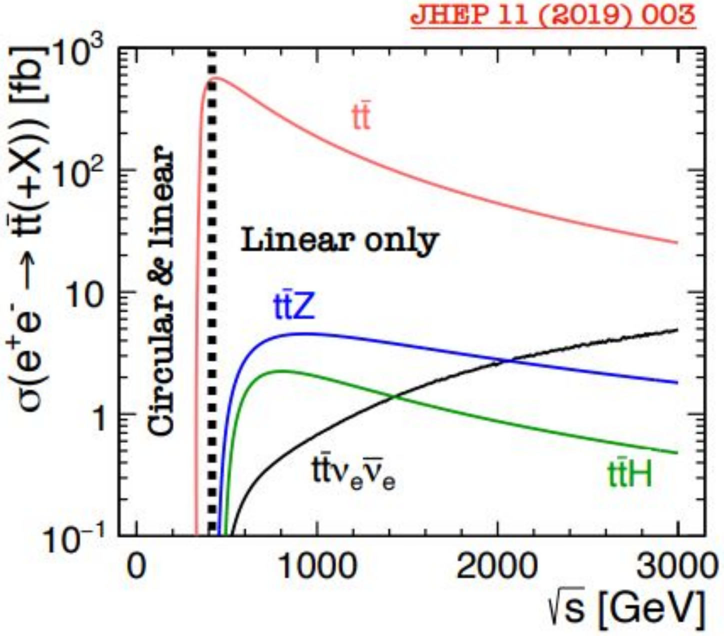
W access to CKM matrix element:

- access to Vcb and Vcs
- high statistics: 100 M events at any collider
- difficult: needs extremely good tagging

$W^- \to$	$\bar{u}d$	$\bar{u}s$	$\bar{u}b$	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$
BR	31.8%	1.7%	4.5×10^{-6}	1.7%	31.7%	5.9×10^{-4}
N_{ev}	64×10^6	3.4×10^6	900	3.4×10^6	63×10^6	118×10^3
$\delta^{th}_{V_{ij}}$	0.0063 %	0.027 %	1.7 %	0.027 %	0.0063 %	0.15 %



Physics: Top

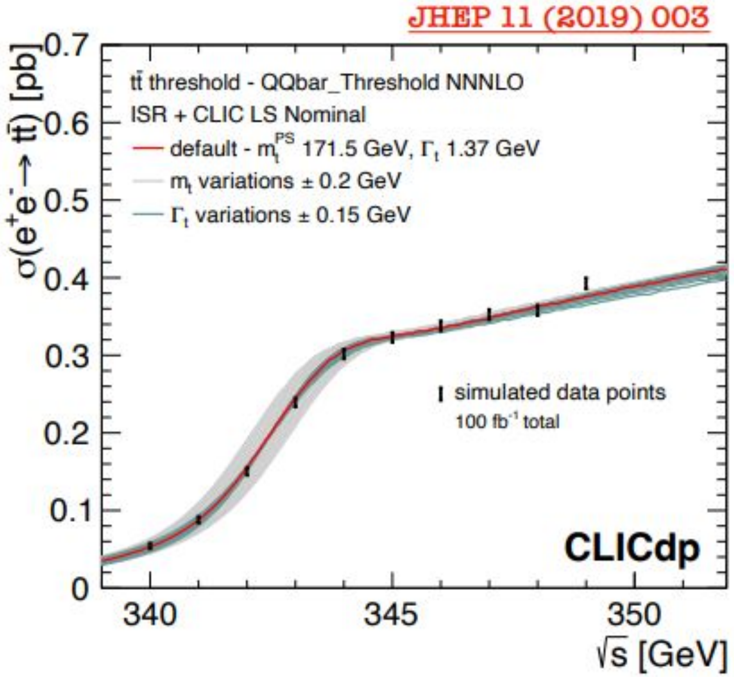


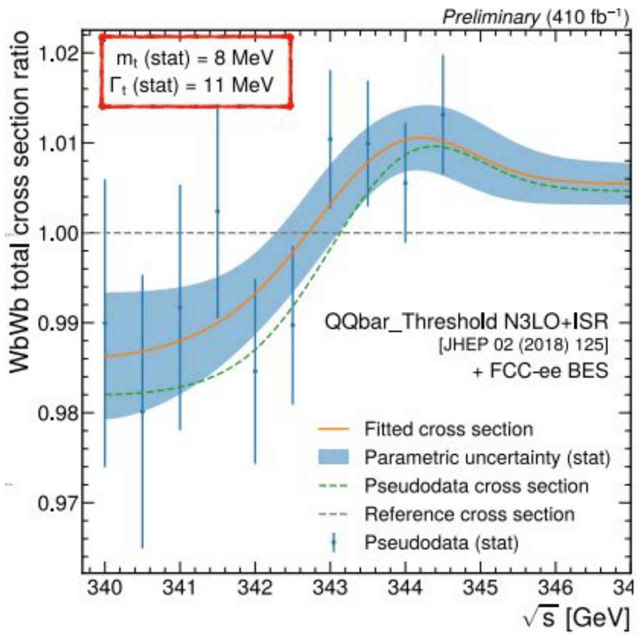
Physics motivation:

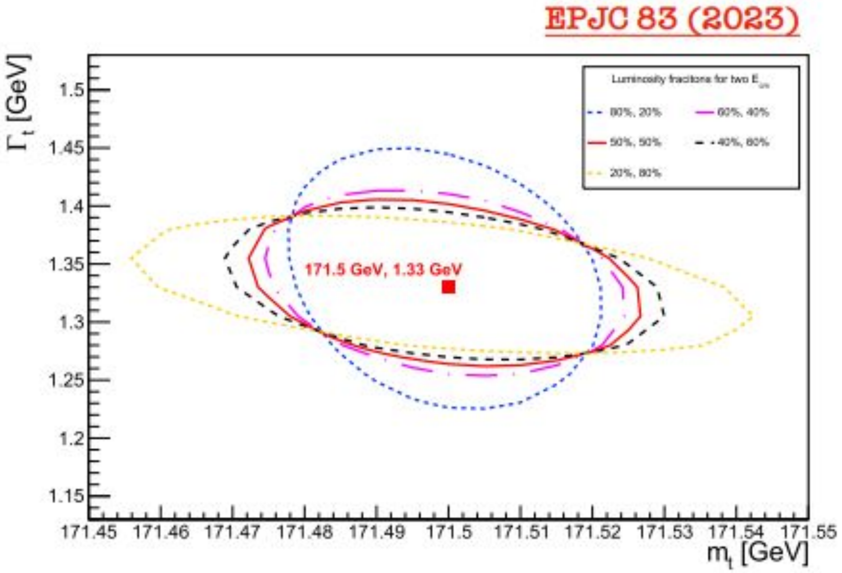
- Internal consistency of the SM with Higgs mass mass and W boson mass
- Stability of the Electroweak vacuum at the Planck scale

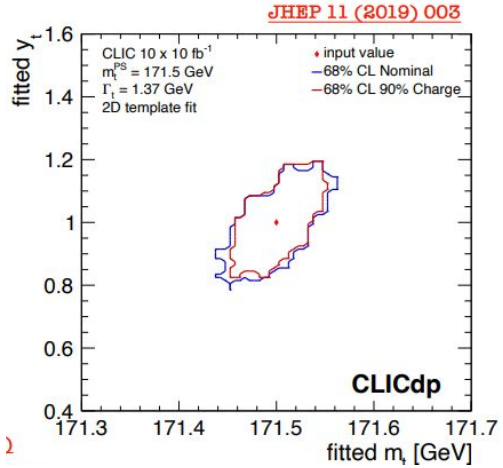
Measuring the top quark mass:

- Turn-on curve at threshold
- cross section measurement
- depends on width, yukawa (direct or indirect), αS, scales…..
- expect 10 MeV (stat) to ~ 100MeV including scheme translation error

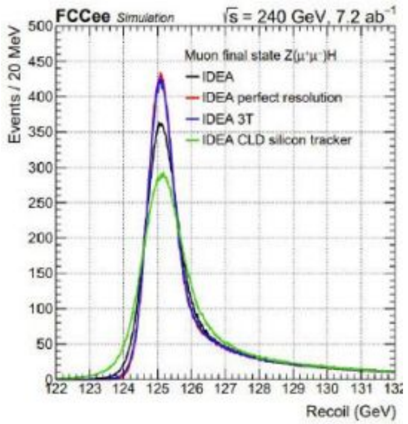


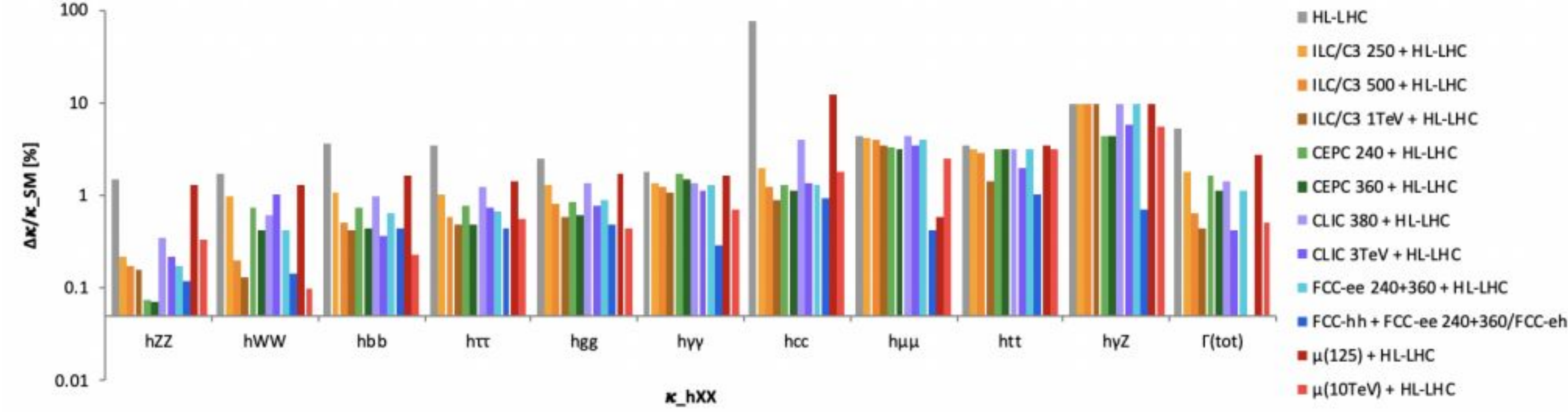






Physics: Higgs





Measurement of the mass:

- high precision with recoil mass (Z to electrons and muons) ~3MeV
- Implications for detectors…(Tracking resolution, B-field,...)

- Nominal configuration
- Crystal ECAL to Dual Readout
- Nominal 2 T → field 3 T
- IDEA drift chamber → CLD Si tracker
- Impact of Beam Energy Spread
- Perfect (=gen-level) momentum resolution

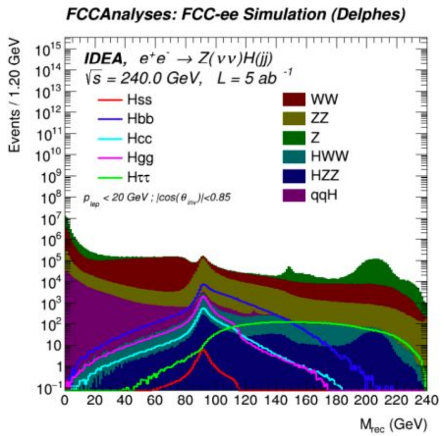
Final state	Muon	Electron	Combination
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Categorized	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution			3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	3.92(4.79)	4.95(5.92)	3.07(3.98)
Disable BES	2.11(3.31)	2.93(3.88)	1.71(2.92)
Ideal resolution	3.12(3.95)	3.58(4.52)	2.42(3.40)
Freeze backgrounds	3.91(4.74)	4.95(5.67)	3.07(3.96)
Remove backgrounds	3.08(4.13)	3.51(4.58)	2.31(3.45)

Physics motivation:

- detect hints for BSM

Measurement of BRs:

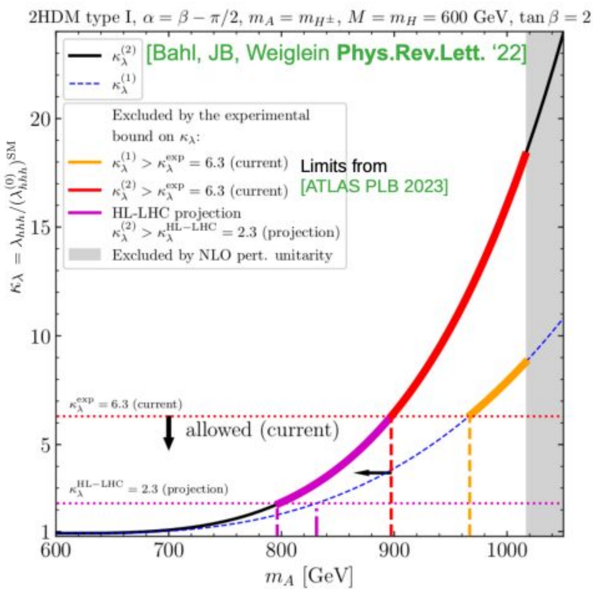
- complete picture: HWW, HZZ, Hgg, Hbb, Hcc,...
- Htt (depends on √s)



BR Higgs to strange:

- strangeness taggers
- definition (theory Dalitz)
- it's tough but with ab-1 colliders….

Physics: Higgs self coupling

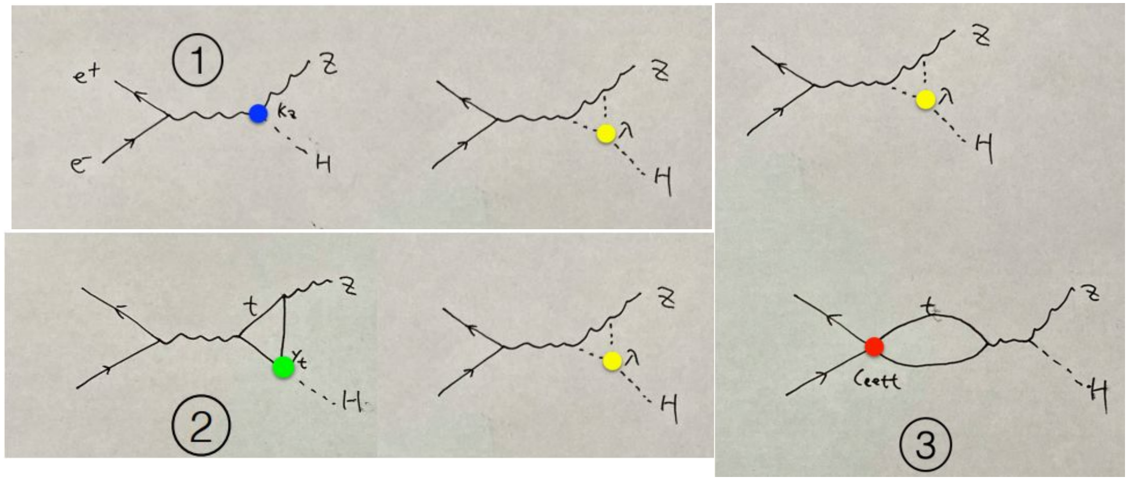


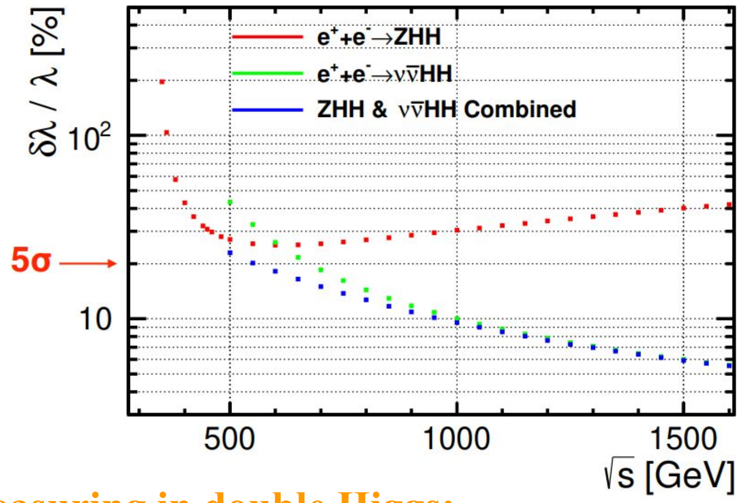
Measuring the HHH coupling:

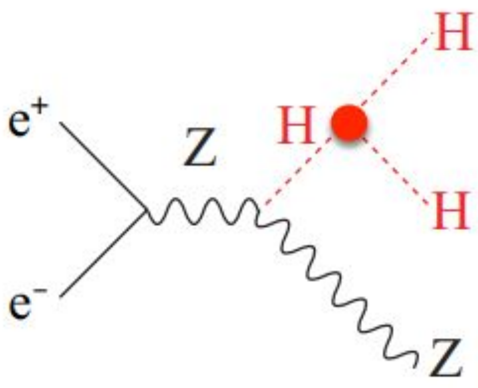
- understand the form of the Higgs potential
- information UV complete models

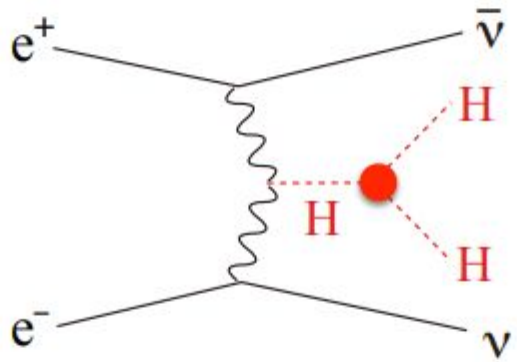
Measuring via RCs in single Higgs:

- ZH coupling
- top Yukawa
- four fermions
- new operators calculated
- needs a complete description at (N)LO









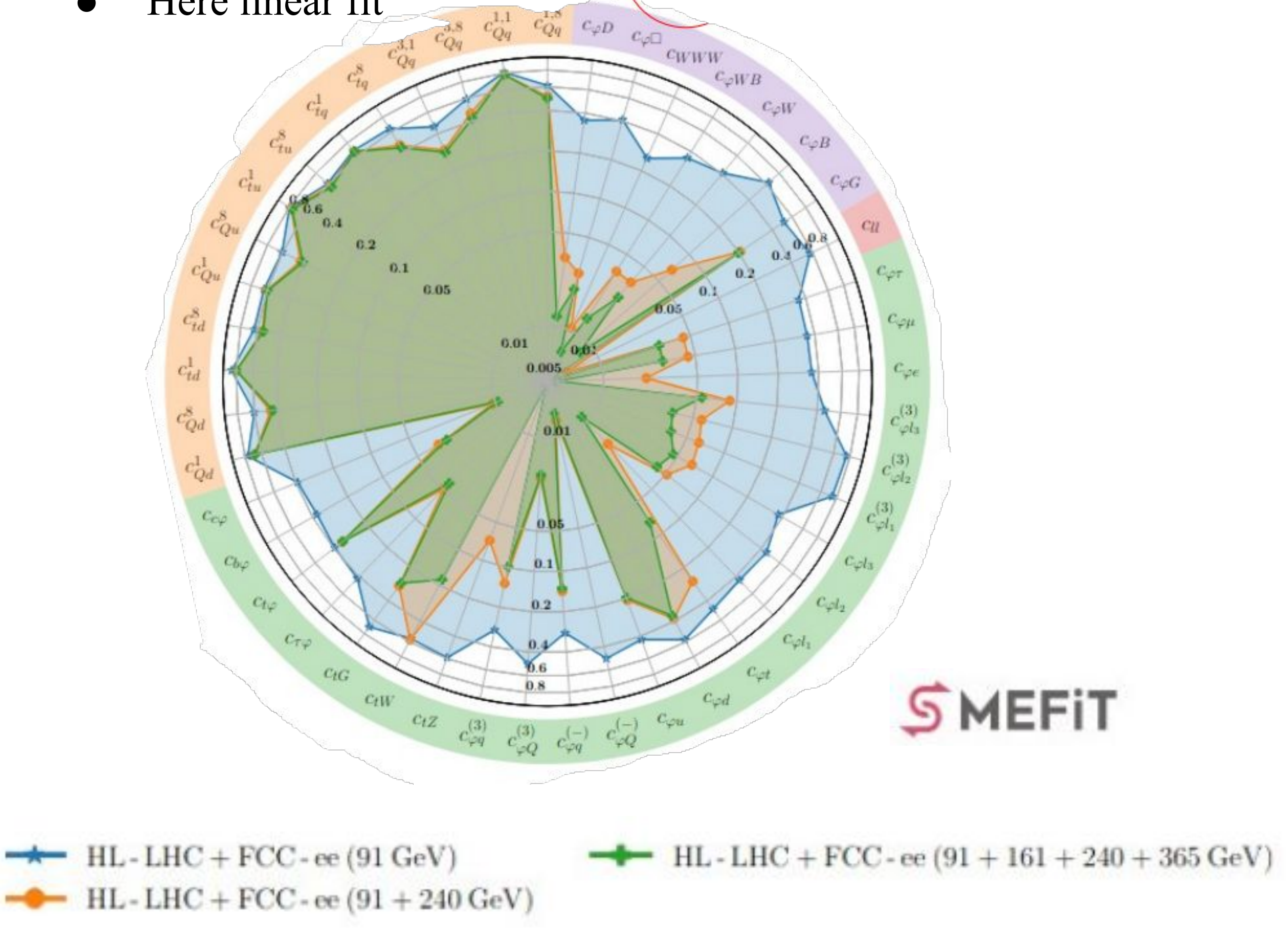
Measuring in double Higgs:

- analysis improvements
- two processes instead of 1 (important at 550GeV)

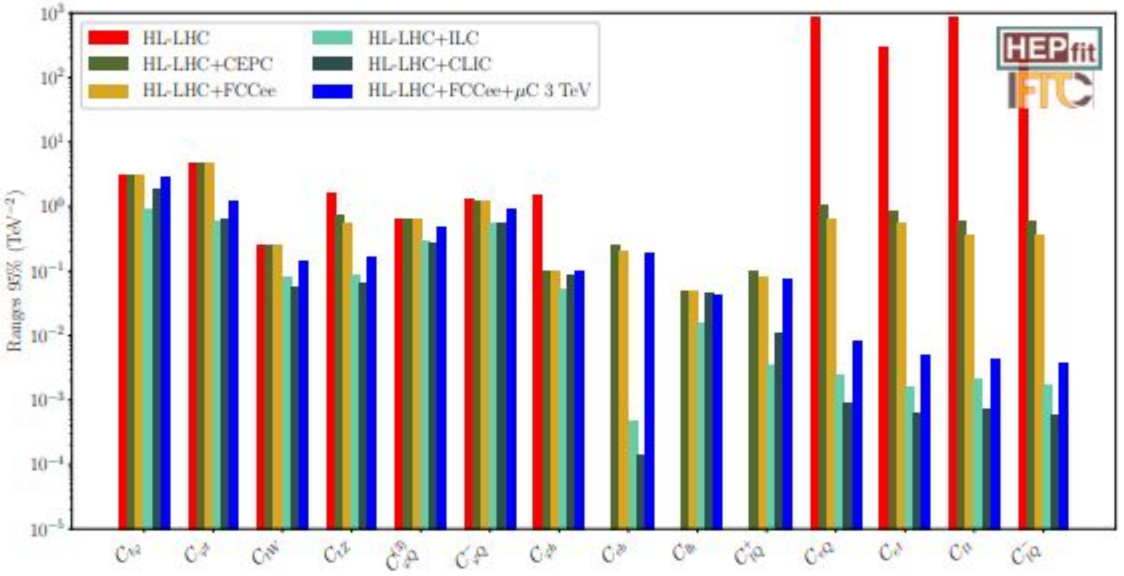
Physics: Global Interpretations

Global view of the field or a subfield:

- Higgs: push towards SMEFT at NLO (precision….)
- Here linear fit



Electroweak interactions of the top quark:



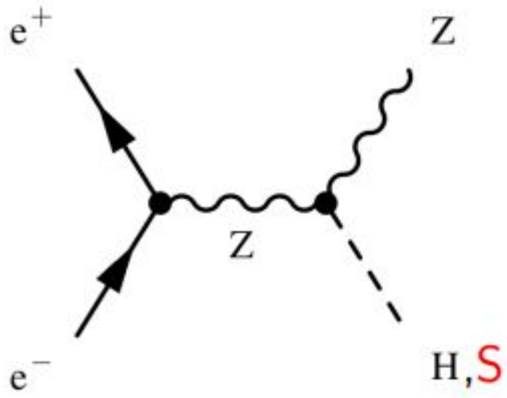
Take away:

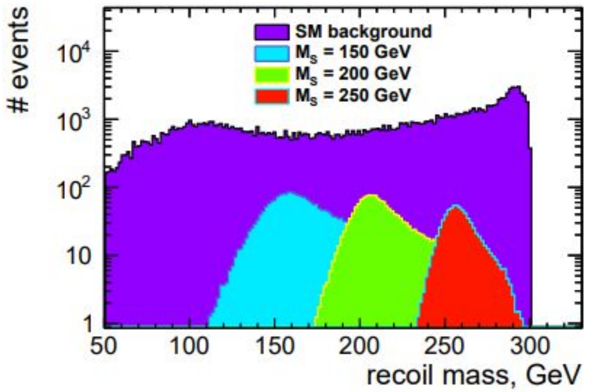
- Strong improvement on most SMEFT parameters in Higgs and top
- Four quark operators unconstrained
- Precise radiography of the heaviest particles

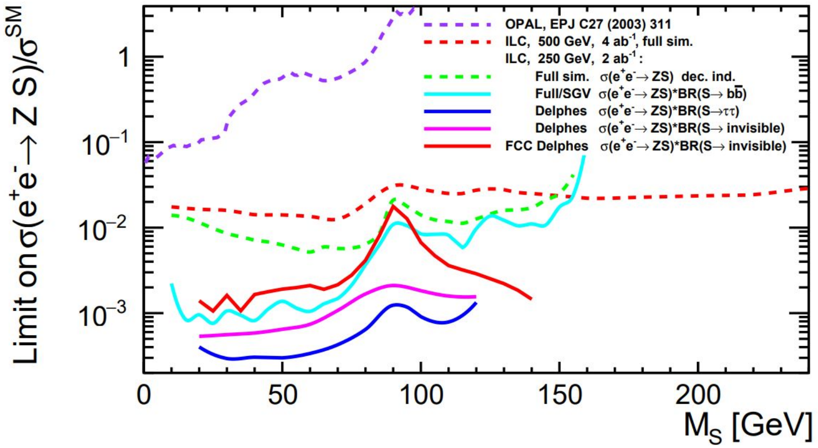
Physics: Searches

New Scalars

- 380 GeV eg μμ+S
- initial state fully known
- recoil mass
- best at rest





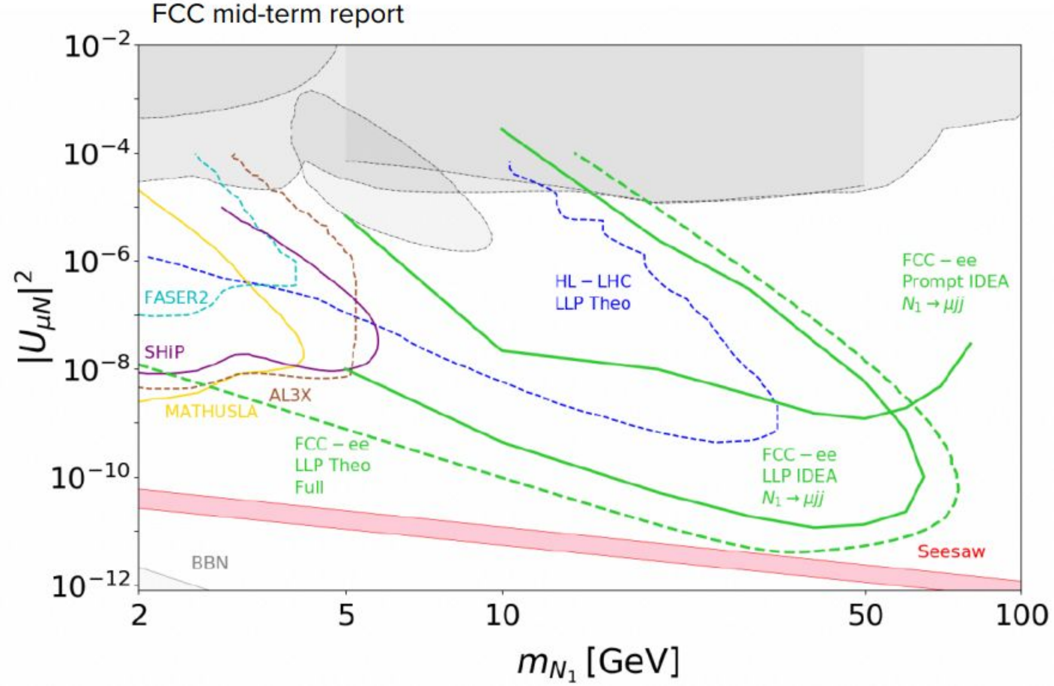


Expected limits

- several channels studied
- improves on LEP
- with full sim
- with SGV
- with fast sim

Long Lived Particles (LLP):

- Heavy Neutral Lepton
- Z →HNL+charged lepton
- HNL → jj
- Prompt Decay (IDEA)
- LLP (IDEA)



Sensitivity (FCCee)

- masses < mZ
- large stat allows to probe weak couplings

Summary/Outlook

Summary:

- **Exciting prospects for electron-positron Higgs/Top/EW factories:**
  - **Developing SW**
  - **Developing algorithms**
  - **Physics studies**
- **Good collaboration across projects enabled by the KEY4HEP Eco-system**
- **Intense discussions and exchange on Higgs/Top/Electroweak topics**
- **Did not come as far as we wanted due to the schedule change (-9months)**

Outlook:

- Full draft end of November
- Iterations until December/January
- Approval by PECFA Q1/2025
- EOA: March 31, 2025

Thank you:

- **ECFA chair Karl Jakobs for the support**
- **WG coordinators for collaboration and help in putting together the presentation**
- **the speakers at the DESY/Paestum/Paris workshops from whose slides I compiled the talk :)**