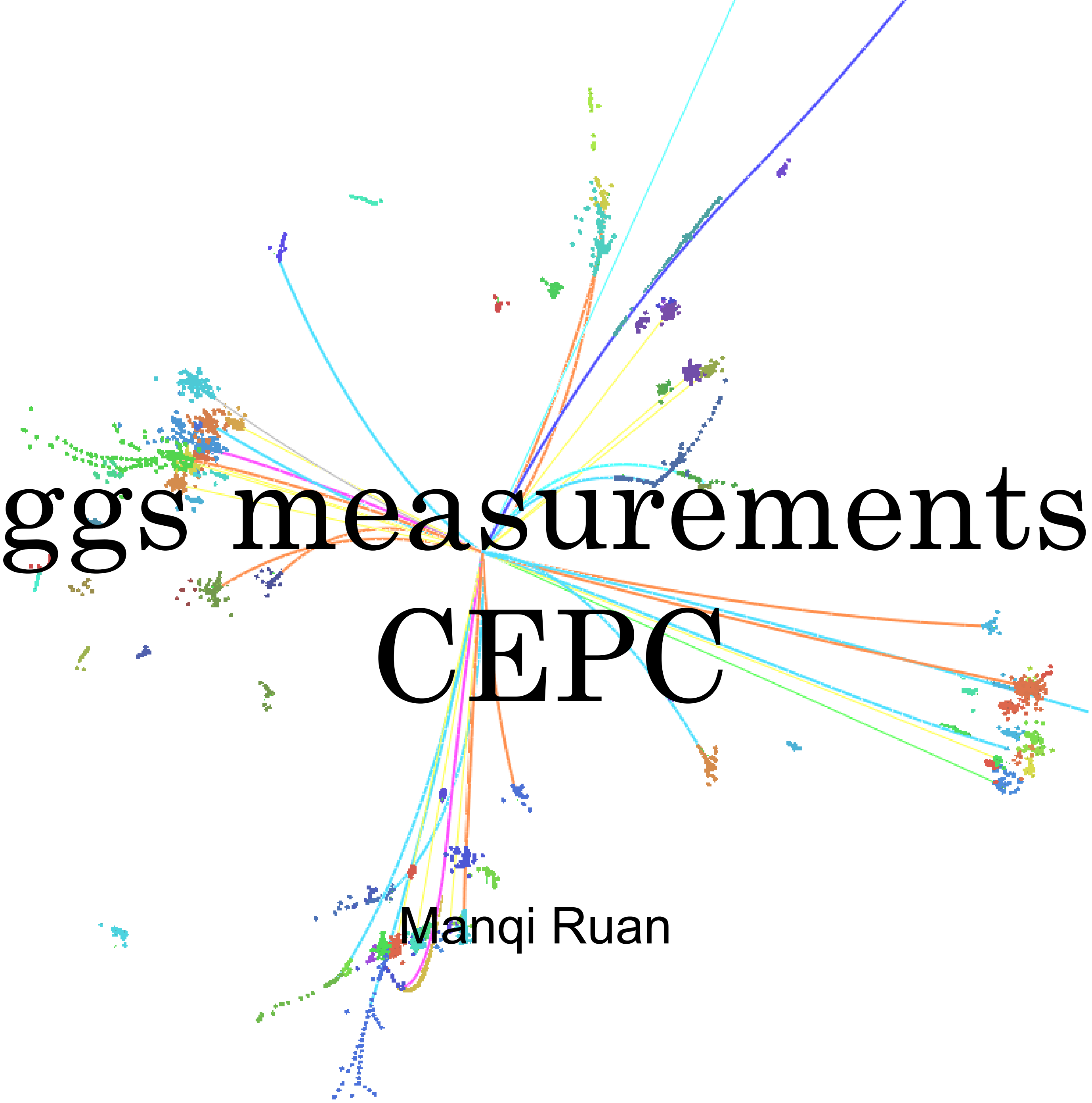


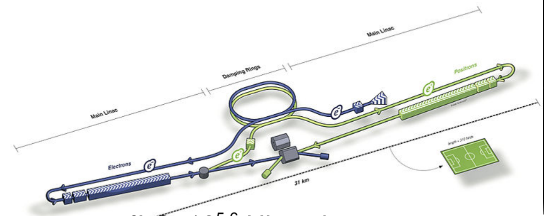
Higgs measurements at CEPC

Manqi Ruan

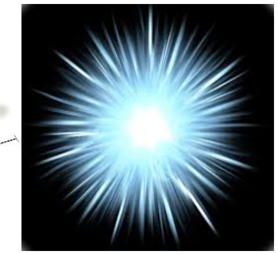

Higgs...

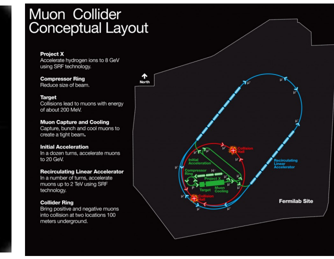
Higgs factories

LHC, 1 M Higgs boson in Run 1
$10^{7\text{-}8}$ Higgs boson in future operation,
pp @ 7, 8, 13, 14 TeV

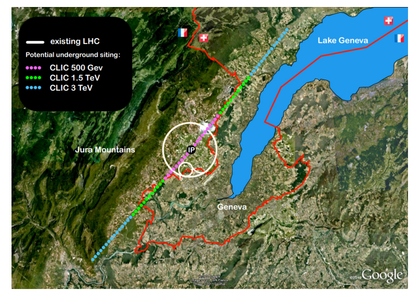


ILC, $10^{5\text{-}6}$ Higgs boson,
e+e- @ 250, 500 GeV & 1 TeV

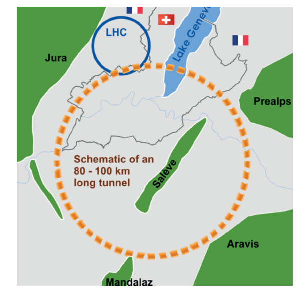




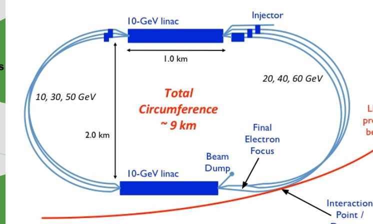
Photon/Muon collider, $10^{4\text{-}5}$ Higgs @ 126 GeV



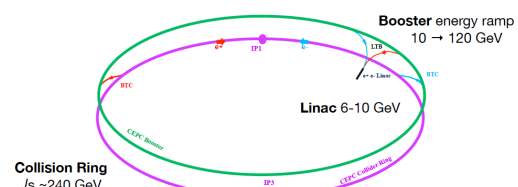
CLIC, $10^{5\text{-}6}$ Higgs boson,
e+e- @ 500 GeV - 3 TeV

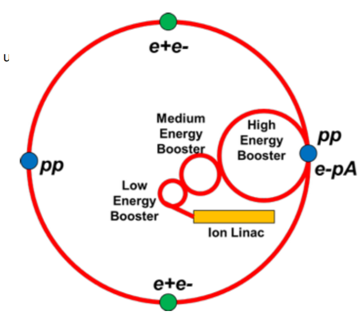


FCCee, 2M Higgs
FCChh, $10^{9\text{-}10}$ Higgs



LHeC, 10^5 Higgs
60GeV e to 7 TeV p



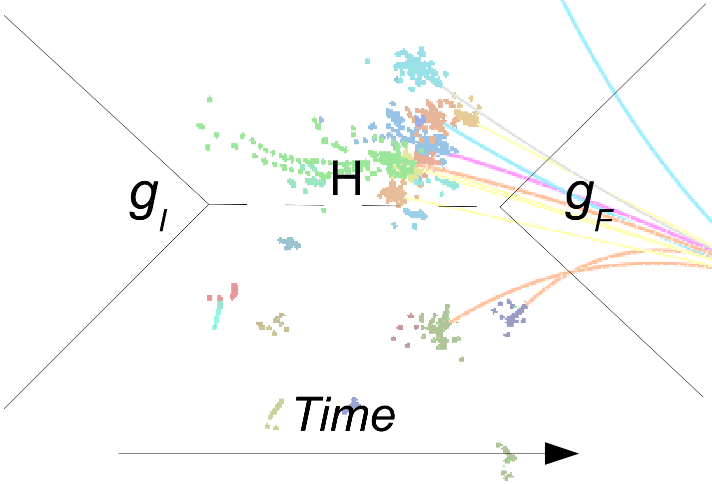


CEPC, 1 M Higgs @ 240-250 GeV
SPPC, $10^{9\text{-}10}$ Higgs @ 100 TeV

○ ○ ○

Now *Future*

Higgs Measurements



At any Higgs factory, we can measure

- *Event rates with specified generation/decay mode:*

  $\sigma(I \rightarrow H \rightarrow F) \sim g_I^2 Br(H \rightarrow \text{Final State}) \sim g_I^2 g_F^2 / \Gamma_{total}$

- *Differential distributions: operator, quantum numbers*

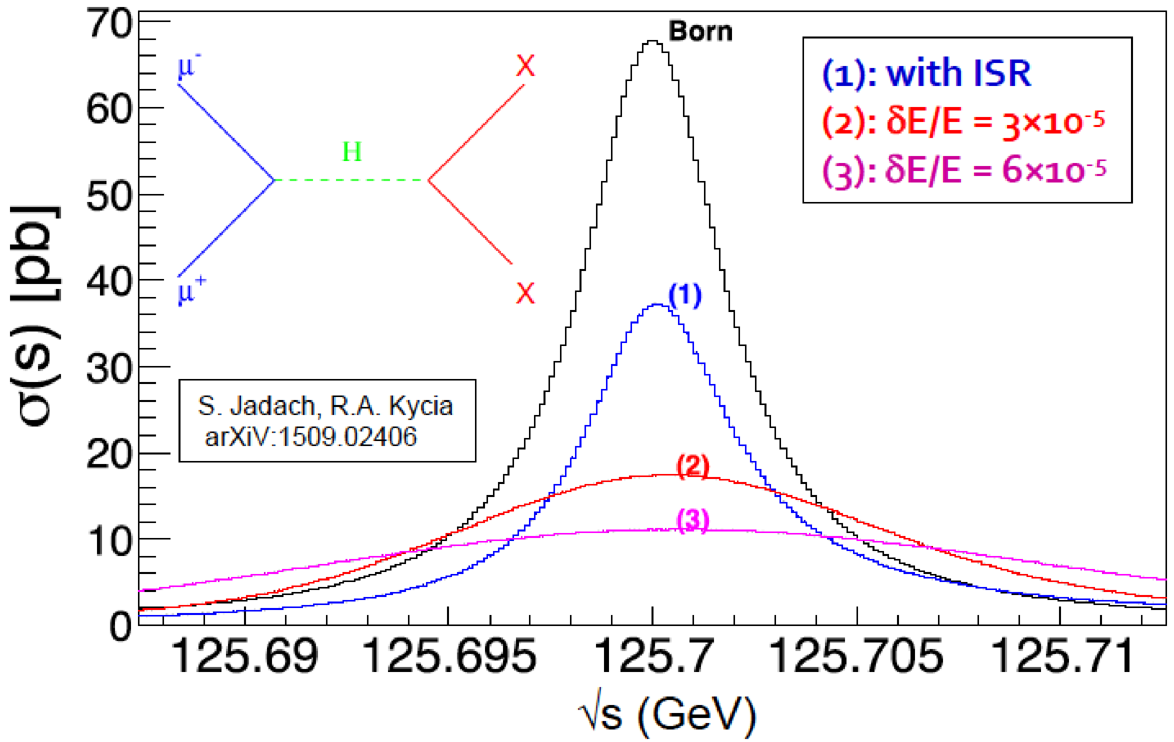
Besides:

Inclusive cross section measurement of Higgsstralung processes at electron-positron Collider: σ(ZH)

Higgs width scan at muon collider

Higgs boson production (2)

- **Muons are heavy, unlike electrons: $m_\mu/m_e \sim 200$**
  - Large direct coupling to the Higgs boson: $\sigma(\mu^+\mu^- \rightarrow H) \sim 40{,}000 \times \sigma(e^+e^- \rightarrow H)$
  - Much less synchrotron radiation, hence potentially superb energy definition
    - $\delta E/E$ can be reduced to $3\text{-}4 \times 10^{-5}$ with more longitudinal cooling
      - → Albeit with equivalent reduction of luminosity: $2 - 8 \times 10^{31}\ cm^{-2}s^{-1}$



- $\sigma(\mu^+\mu^- \rightarrow H) \sim 15$ pb (ISR often forgotten…)
- $200 - 800\ pb^{-1}$ / yr
- 3000 – 12000 Higgs / yr

Reminder: At FCC-ee 400,000 to 800,000 Higgs/yr

Not quite there, even with factor 10

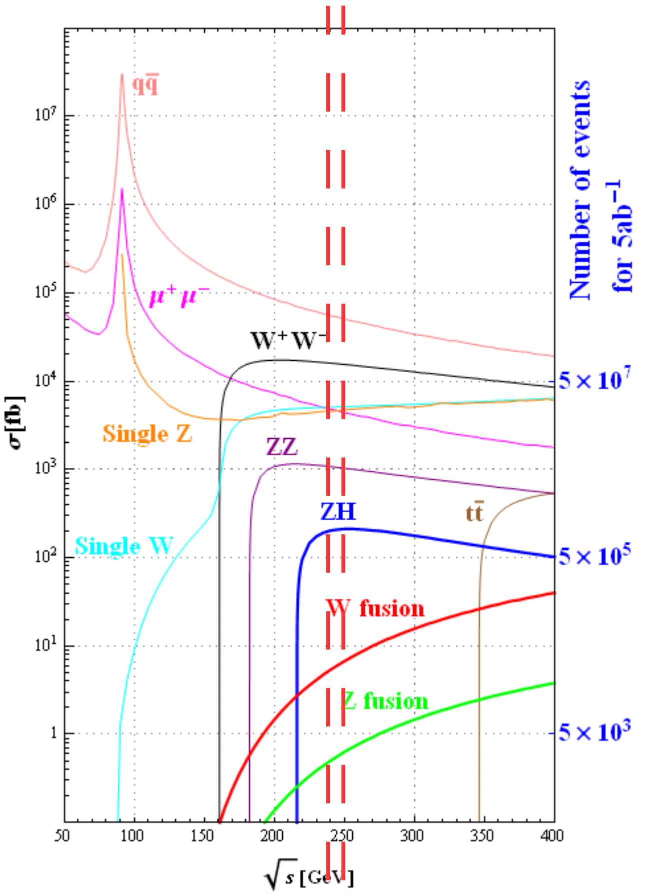
Patrick Janot

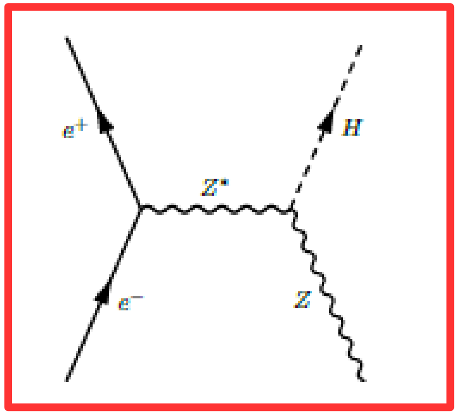
FCC-ee Higgs mini-workshop
24 Sept 2015

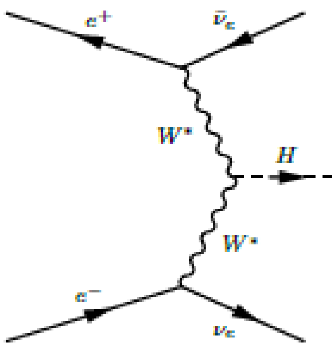
8

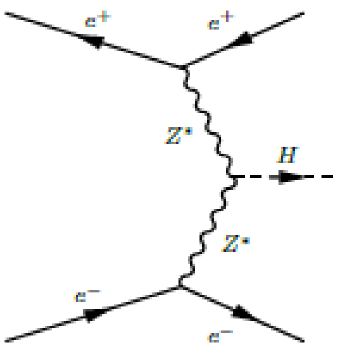
$\delta\Gamma_H$: expected to be Measured to 170 keV at muon Collider...

Higgs program at CEPC









Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

σ(ZH), determined model independently from **recoil mass method**

Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H->X))

Derive: Higgs width, branching ratios & absolute value of coupling constants

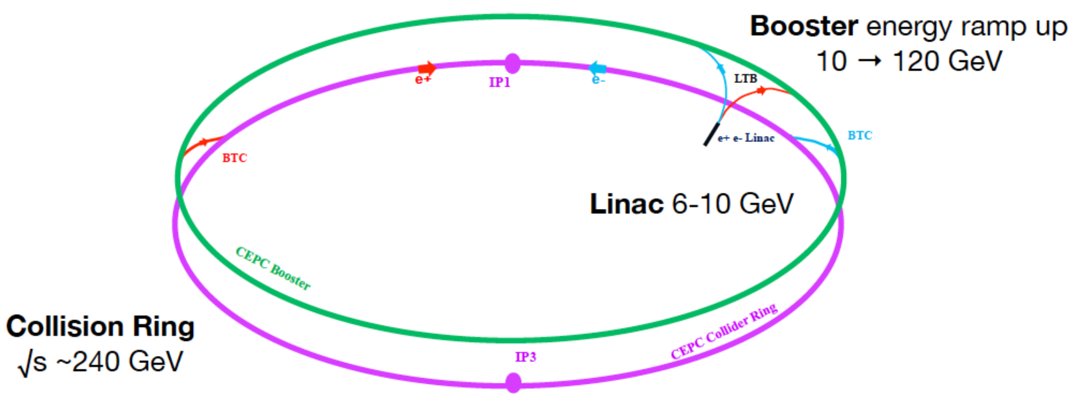
Determine absolute Higgs couplings at e+e- collider

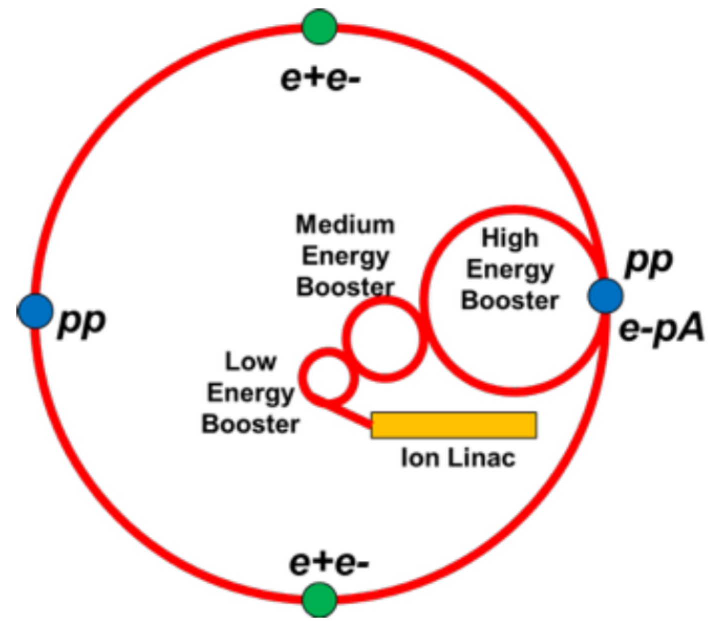
- σ(ZH), measured from recoil mass method
- Event rates, measured by tagging specified generating & decay mode:
  - σ(ZH)*Br(H→X)
  - σ(ννH, eeH)*Br(H→X)

σ(ZH)

- Absolute Higgs width can be calculated, from:
  - σ(ZH) & σ(ZH)*Br(H→ZZ) ~ $g^4(HZZ)/\Gamma_{Higgs}$
  - σ(ZH)*Br(H→bb), σ(ννH)*Br(H→bb), σ(ZH)*Br(H→WW), σ(ZH)
- Combine the Branching ratio measurement & Width measurements, the coupling between Higgs boson and its decay products can be measured...
  - Γ_{higgs} and Br(H→X) ~ $g^2(HXX)/\Gamma_{Higgs}$

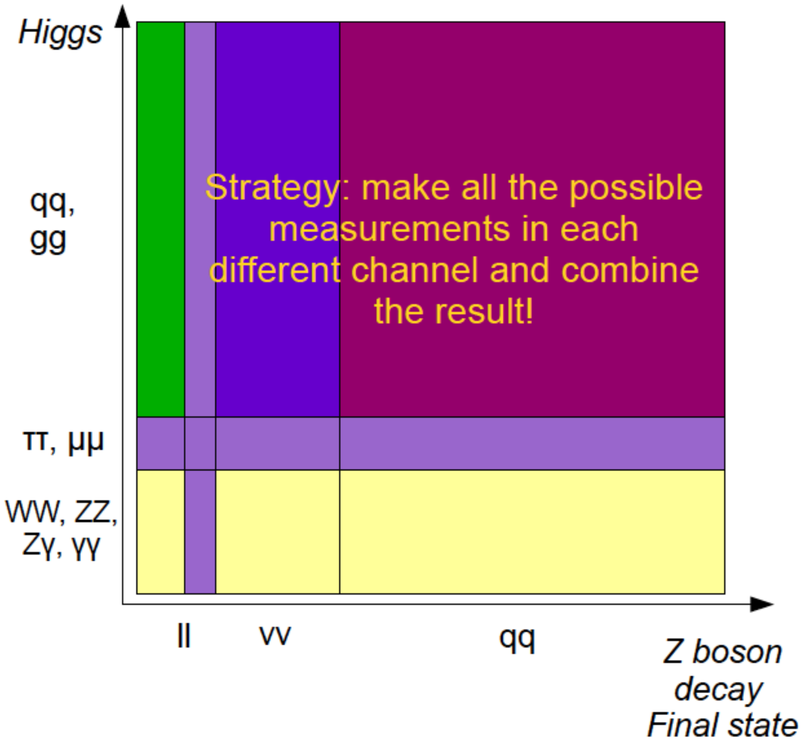
CEPC-SPPC

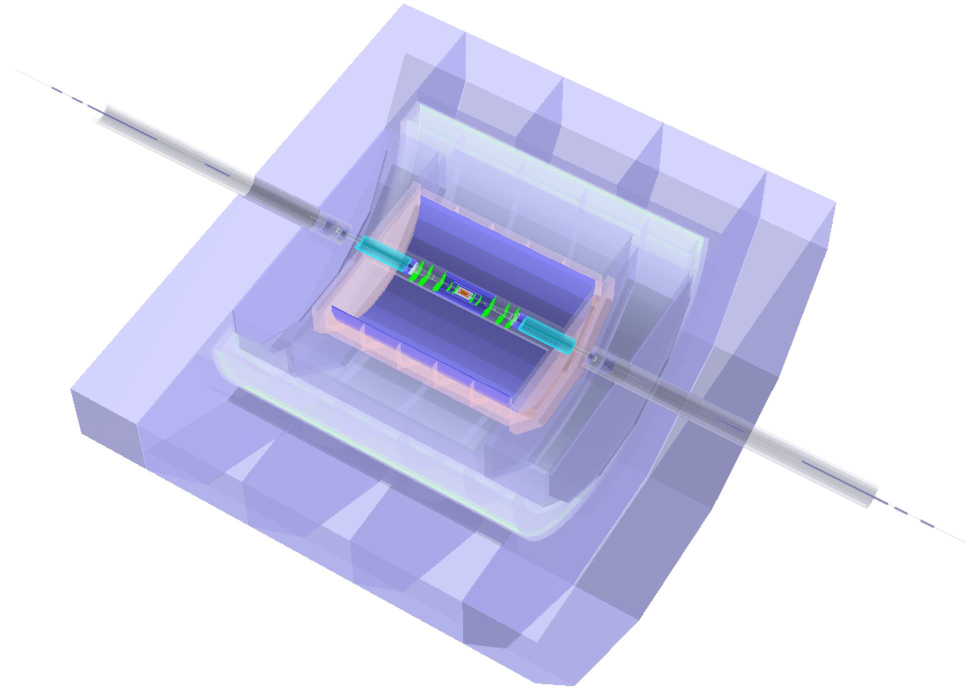




- Electron-positron collision phase
  - Higgs factory: collision at ~240 - 250 GeV center-of-mass energy, Instant luminosity ~ $2*10^{34}$ $cm^{-2}s^{-1}$, 1M clean Higgs event at 2 IP over 10 years
  - Z pole operation for precise EW measurement
- Proton-Proton collision phase
  - center-of-mass energy constrained by tunnel circumference and high-field dipole
  - Peak luminosity ~ $1*10^{35}$ $cm^{-2}s^{-1}$ (*ArXiv: 1504.06108, discussion on needed Luminosity*)
- Tunnel circumference: 54 km in the baseline design. Longer tunnel to be evaluated.

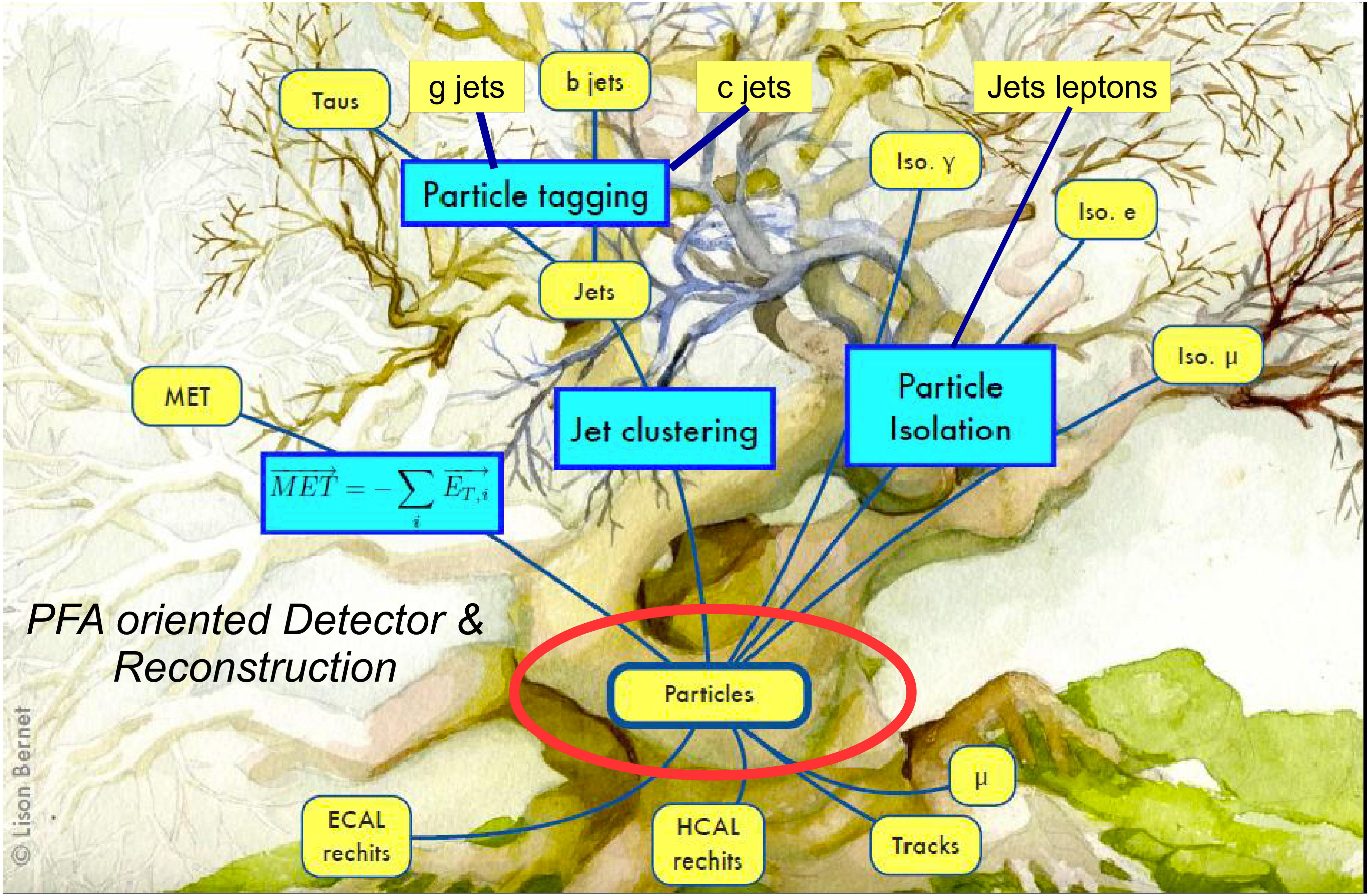
CEPC Conceptual detector, developed from ILD



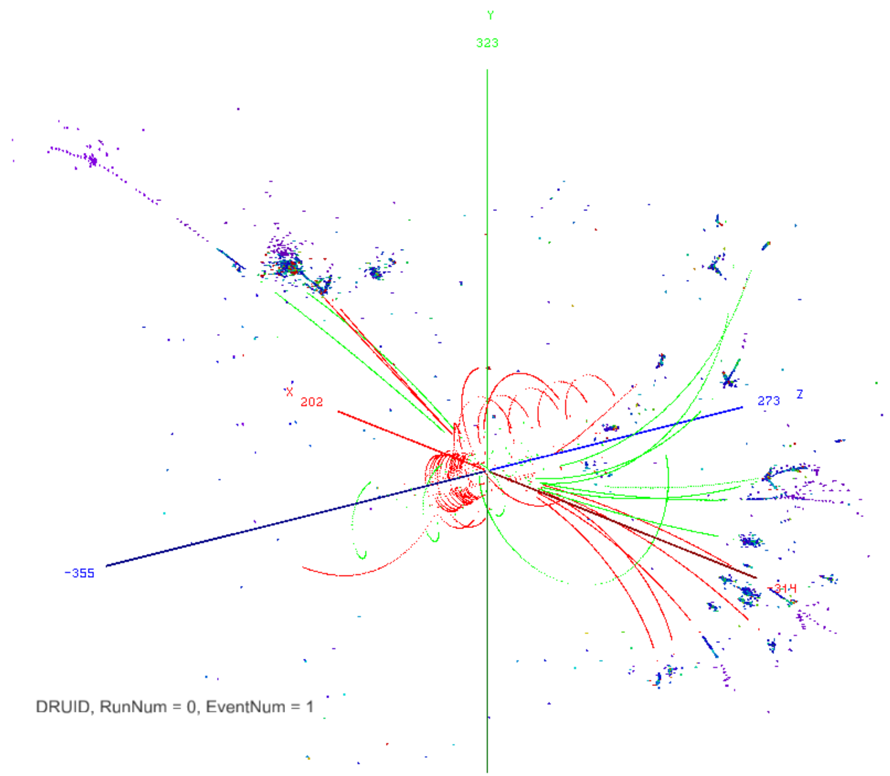


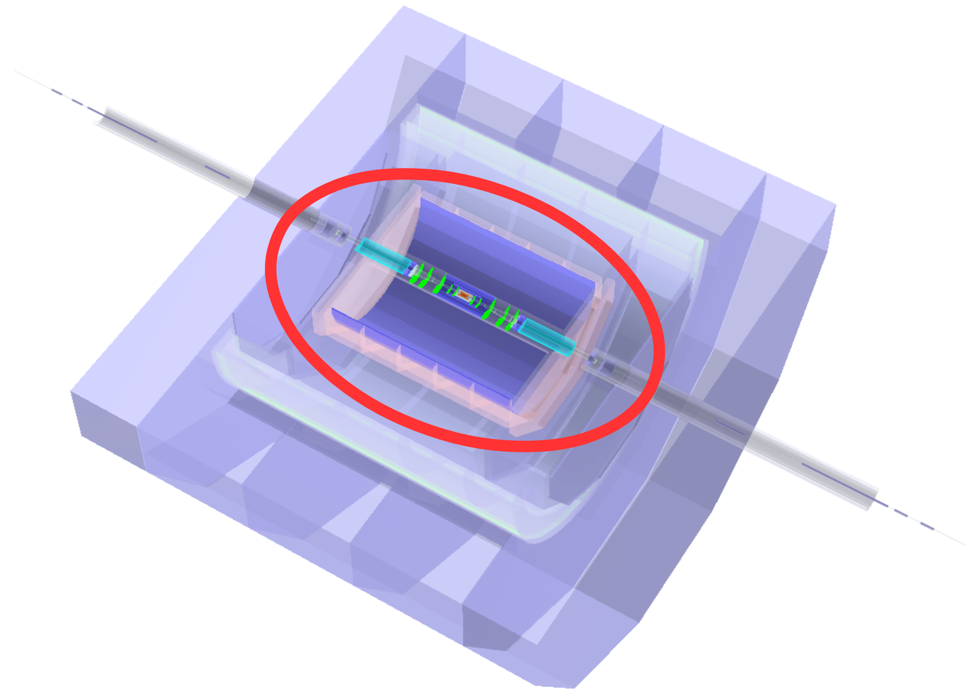
A detector reconstruct all the physics object (lepton, photon, tau, Jet, MET, ...) with high efficiency/precision

High Precision VTX located close to IP: b, c, tau tagging
High Precision Tracking system: $\delta(1/Pt) \sim 2*10^{-5}(GeV^{-1})$
PFA oriented Calorimeter System ($\sim o(10^{8})$ channels): Tagging, ID, Jet energy resolution, ect



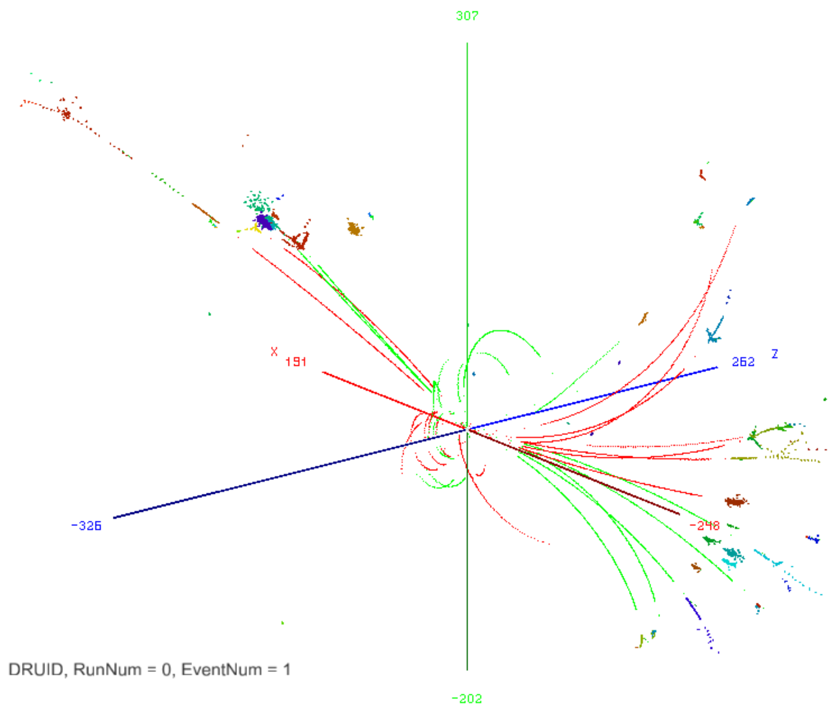
Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
Iso. μ
MET
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
© Lison Bernet
μ
ECAL rechits
HCAL rechits
Tracks



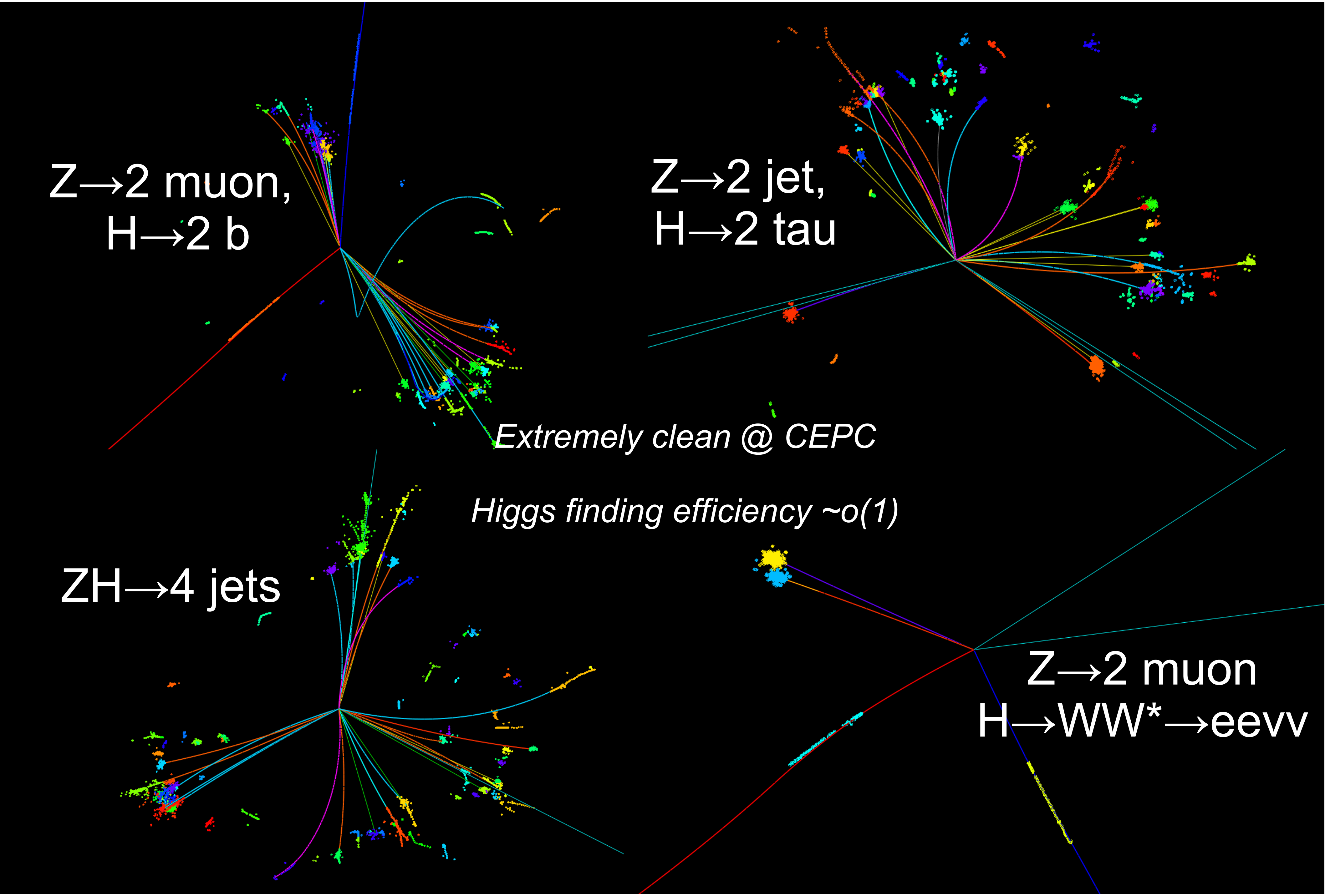


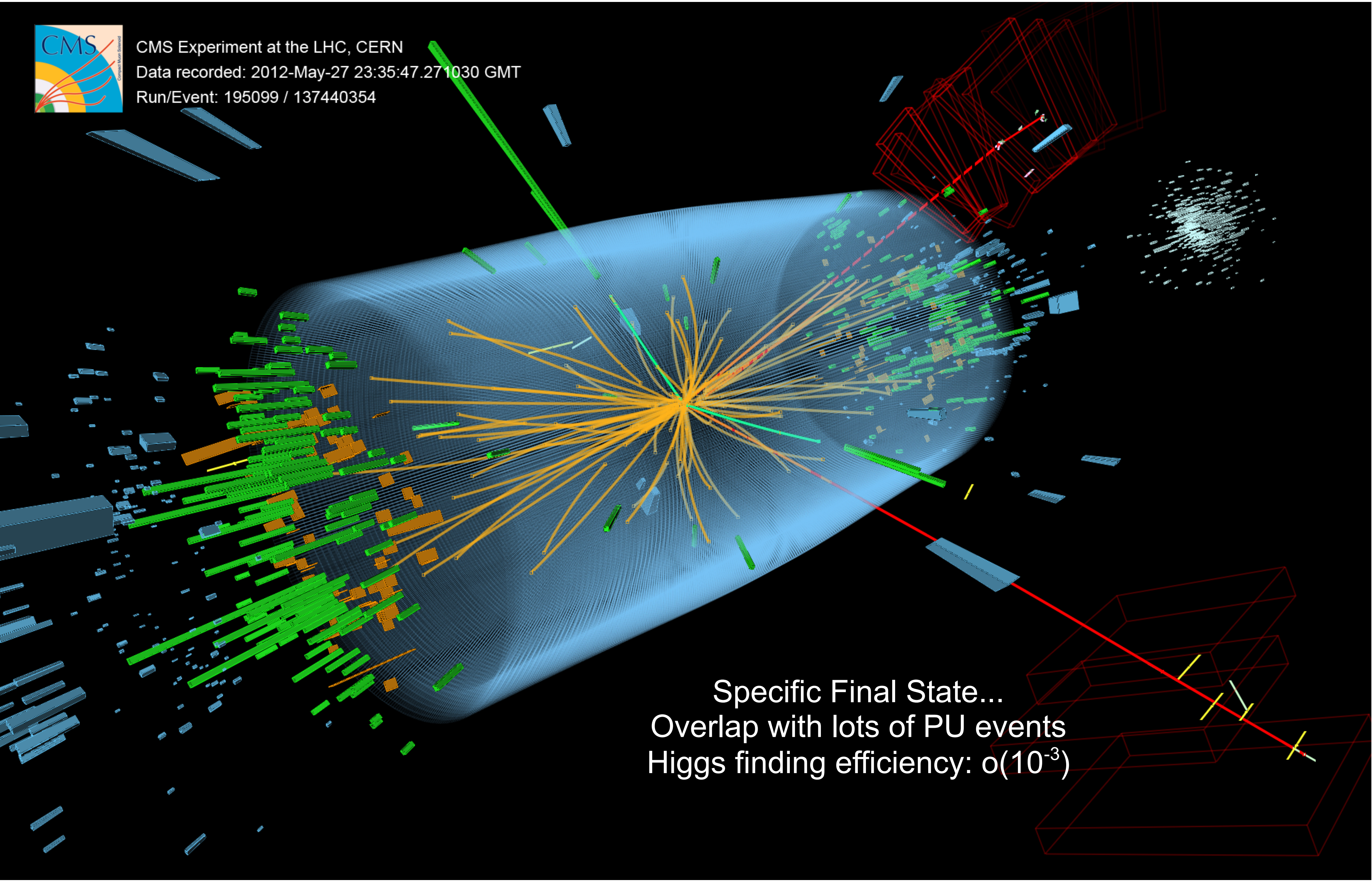
From Hits to Final State Particles

Goal: ... Access the origin of every detector hit ...

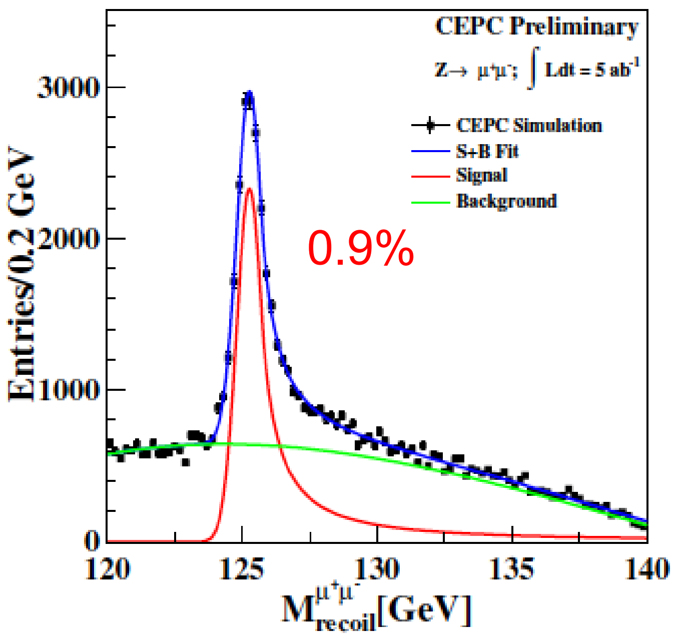


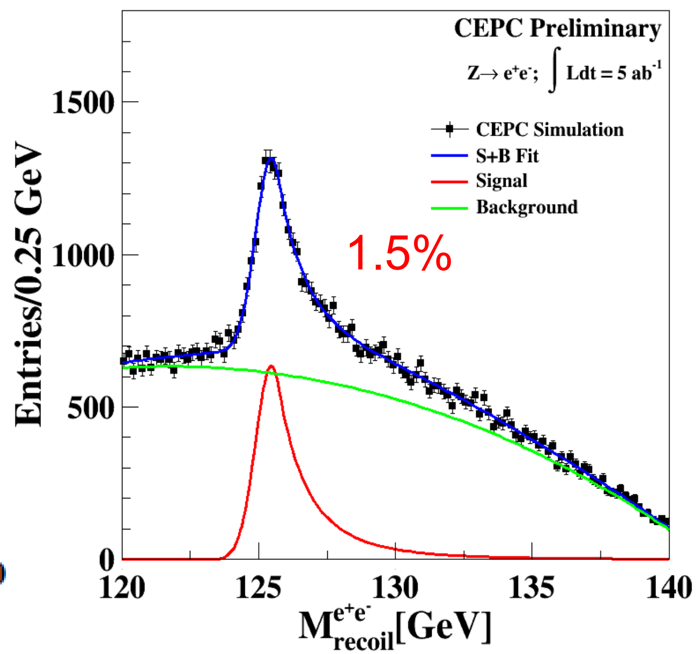
See the talk of Gang: simulation & reconstruction at CEPC

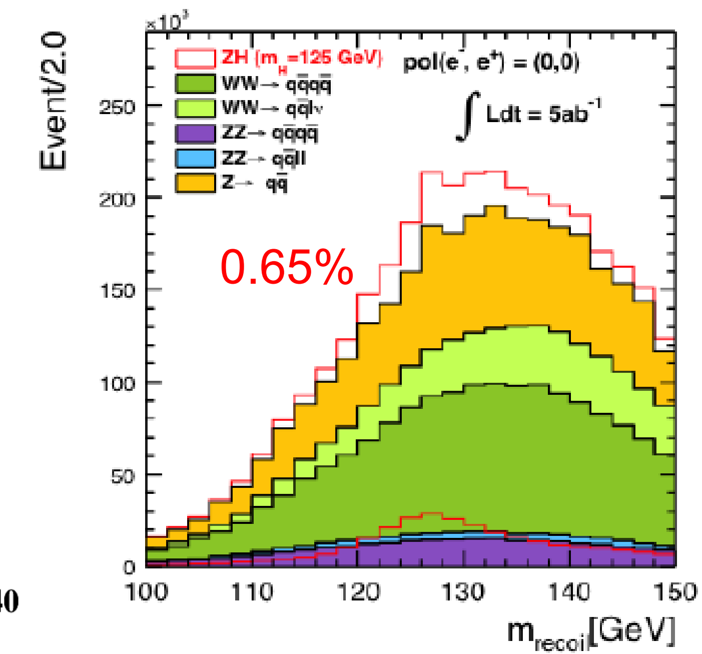

Z→2 muon,
H→2 b
Z→2 jet,
H→2 tau
Extremely clean @ CEPC
Higgs finding efficiency ~o(1)
ZH→4 jets
Z→2 muon
H→WW*→eevv


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
Specific Final State...
Overlap with lots of PU events
Higgs finding efficiency: o(10^-3)

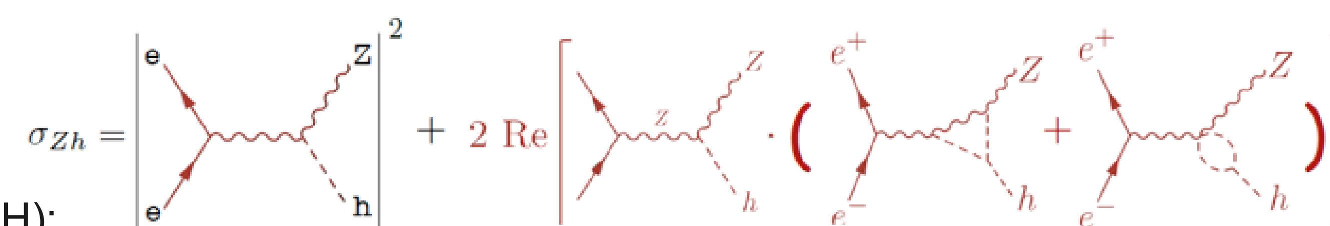
Model-independent measurement of σ(ZH)







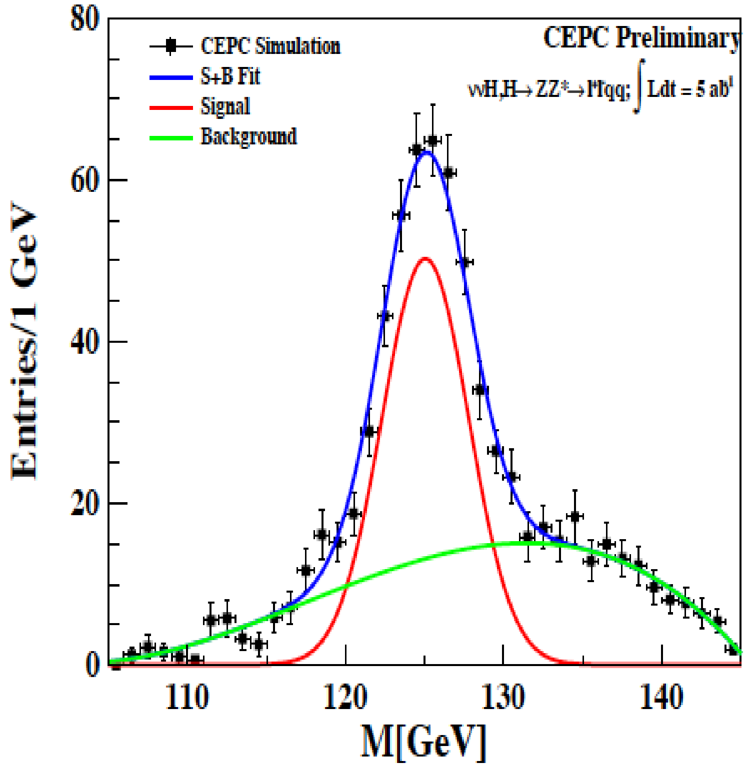
- Recoil mass method. Combined precision:
  δσ(ZH)/σ(ZH) = 0.5% -
  δg(HZZ)/g(HZZ) = 0.25%
- In-direct measurement on g(HHH): ~60% in 7 para fit and ~ 70% in 10 para fit

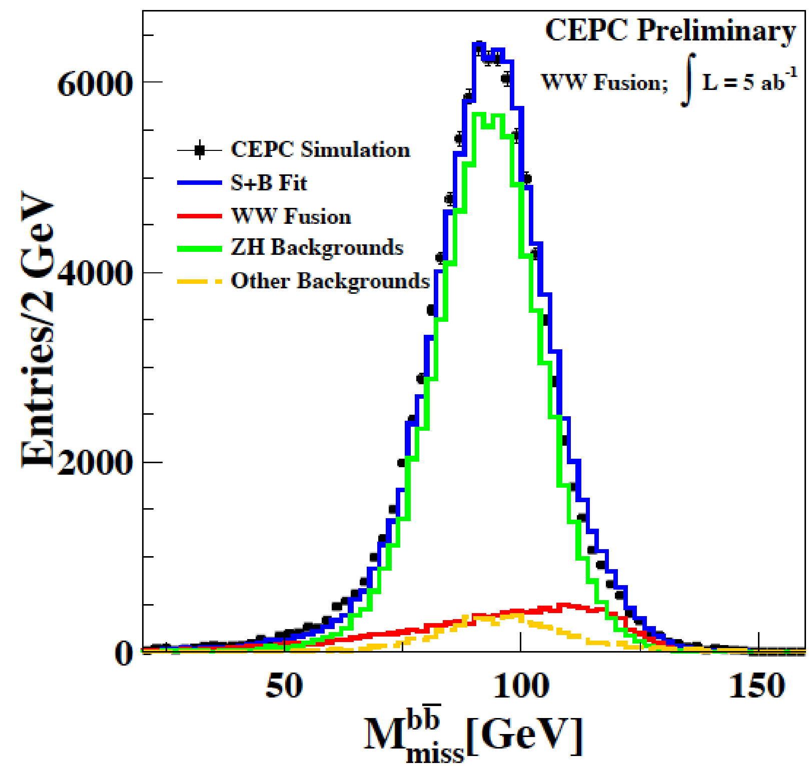


$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$

- *M. McCullough, 1312.3322*

Higgs width measurement



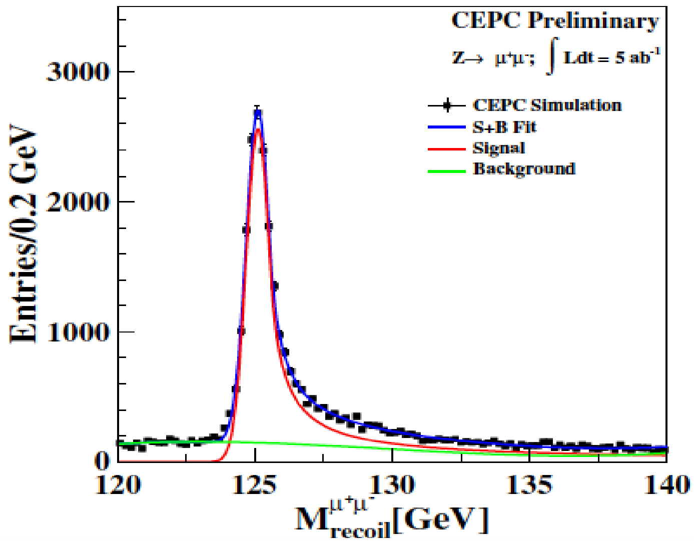


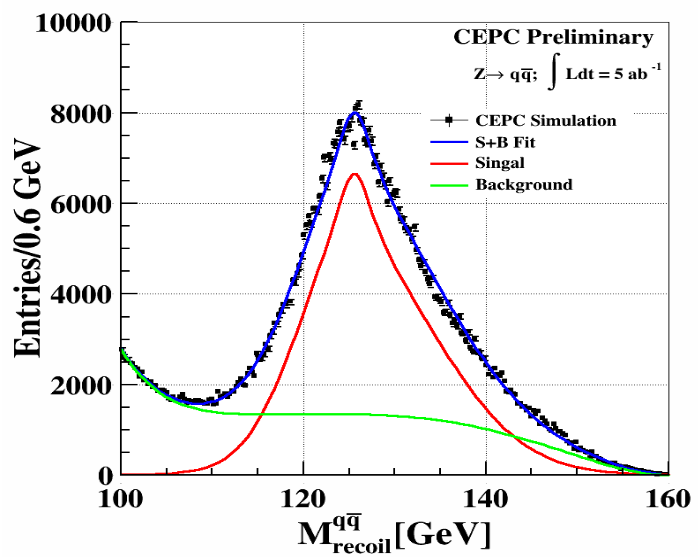
Br(H->ZZ): relative error of 5.8% achieved by combing of a limited set of final states. Extrapolation of TLEP result leads to 4.3% relative error

σ(vvH)*Br(H->bb): relative error of 2.8%

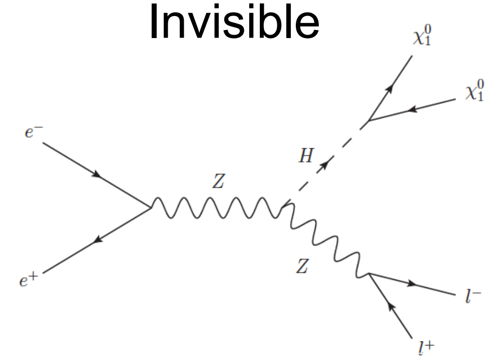
A combined accuracy of 2.8% for the Higgs total width measurements

Higgs invisible/exotic decays

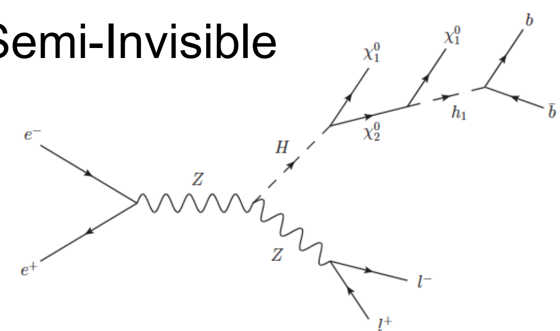




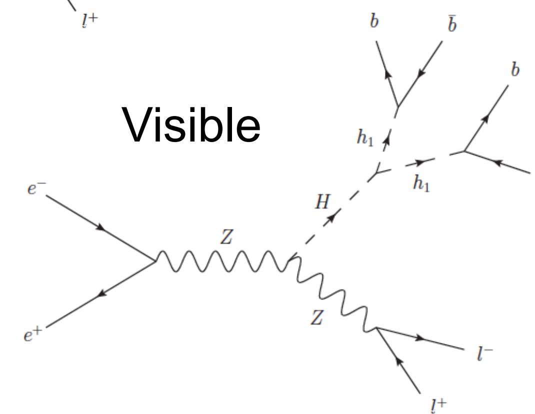
Invisible



Semi-Invisible



Visible

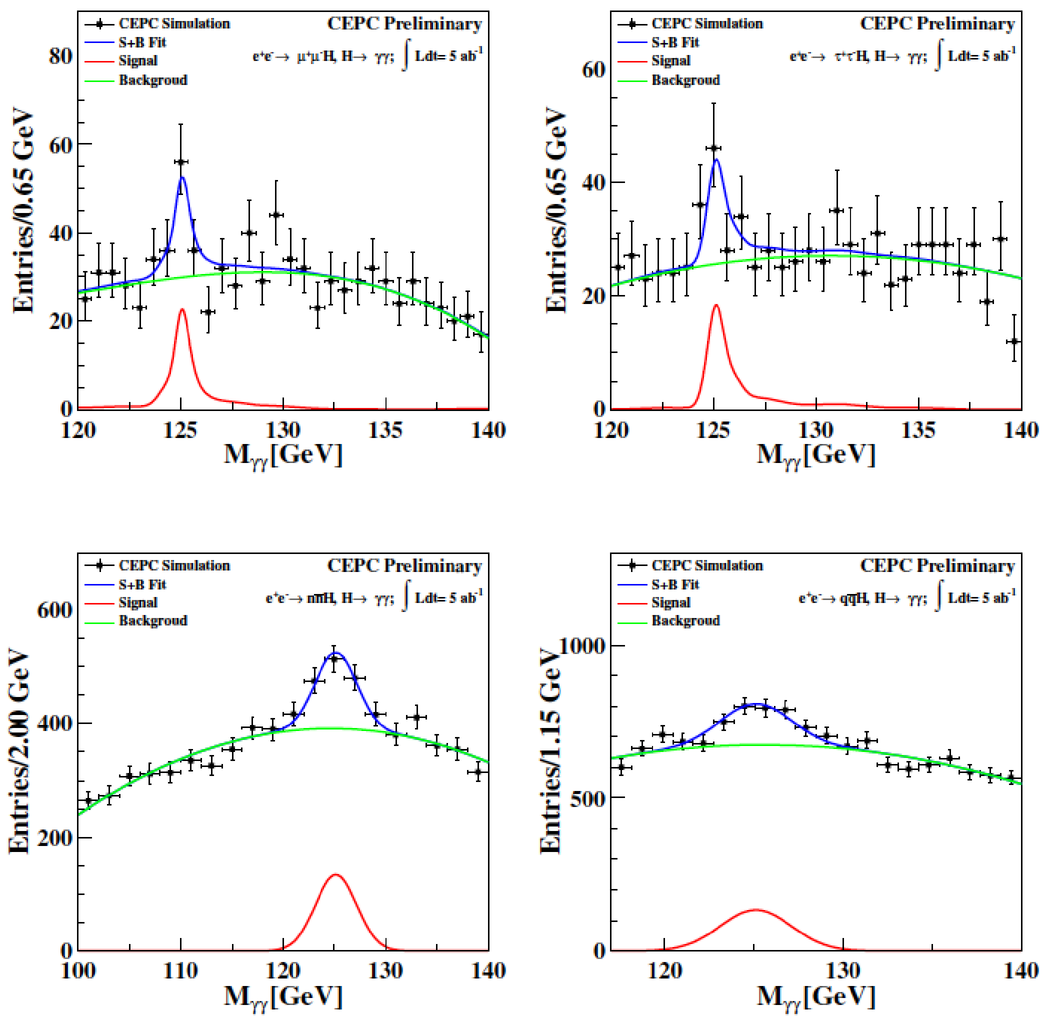


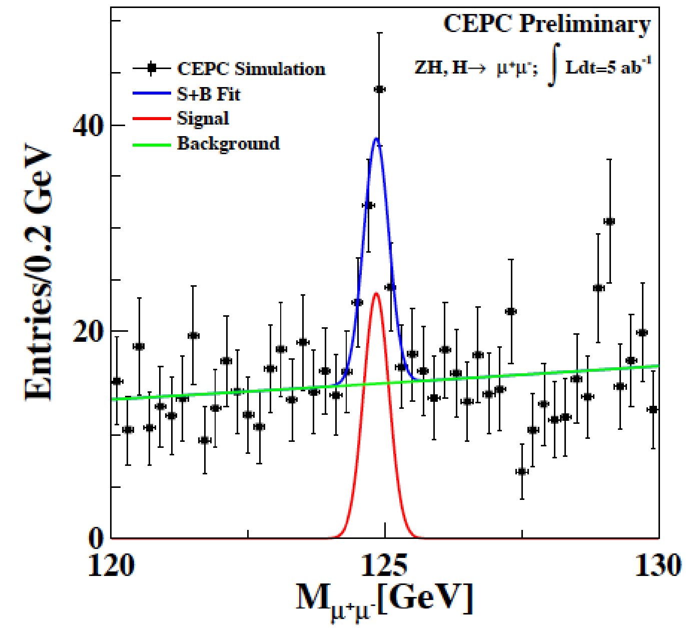
Constrain the final state recoil to Z boson: probe the Higgs invisible/exotic decays

Br(H->inv) are limited to 0.28% at 95% CL

Several benchmark exotic decay verified: 5-sigma deviation expected at Br(H->exo) of 0.1%

Higgs rare decay





Br(H→γγ):
photon identification efficiency
& ECAL intrinsic resolution

Br(H→μμ):
Muon identification & Track
Momentum resolution

Event rate & Branching ratio measurements

Table 3.12 Estimated precisions of Higgs boson property measurements at the CEPC. All the numbers refer to relative precision except for M_H and $\mathrm{BR}(H \to \mathrm{inv})$ for which ΔM_H and 95% CL upper limit are quoted respectively.

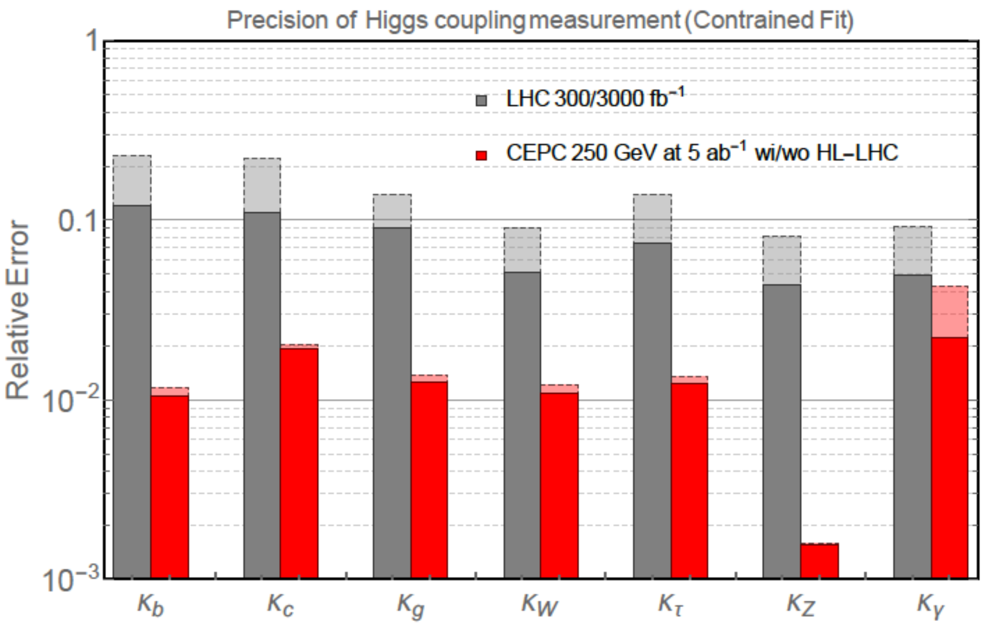
ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
5.9 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to bb$	0.28%	0.57%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

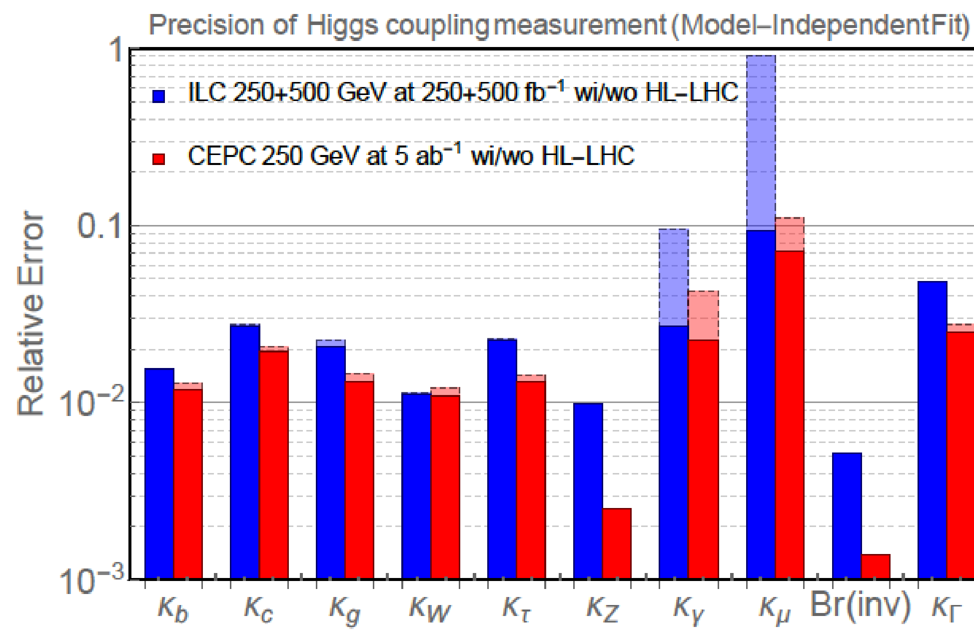
Global fit and interpretation

- Higgs couplings to fermions and gauge bosons predicted by the Standard Model (SM): $g(hff;\mathrm{SM})$ and $g(hVV;\mathrm{SM})$; deviations from the SM couplings parameterised as:

$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})}, \kappa_V = \frac{g(hVV)}{g(hVV;\mathrm{SM})}$$



Model dependent fit



Model in-dependent fit

HL-LHC expectation: ATL-PHYS-PUB-2014-016

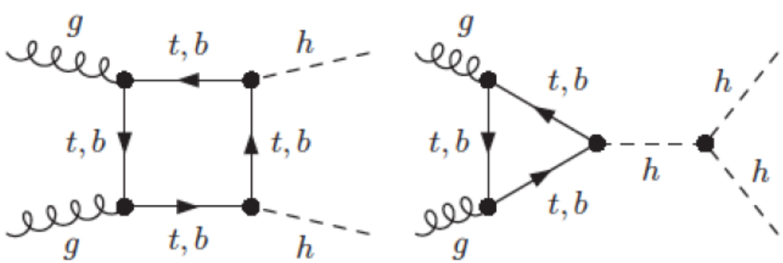
At SPPC

o(10^{9-10}) Higgs

Event rates measured at pp collision $\sigma \cdot BR(X \to H \to Y) = \sigma_X \frac{\Gamma_Y}{\Gamma_{tot}}$

Complementary to CEPC result: better access/interpretation to rare decay/generation...

Direct access to g(HHH) & g(Htt) and better access to Higgs rare decays

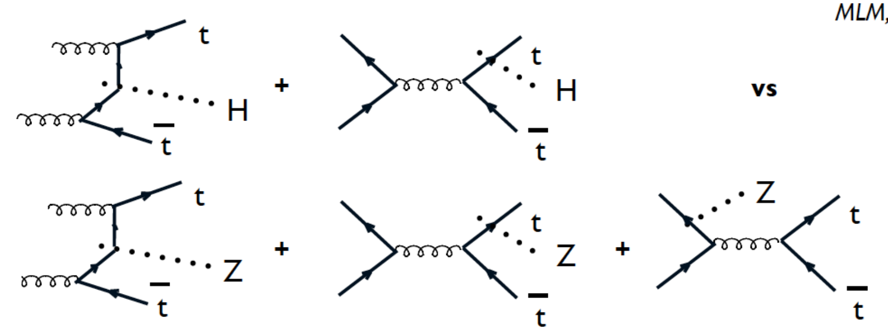


	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

ArXiv: 1310.8361 [hep-ex]

ttH/ttZ as a precision probe of the top Yukawa coupling

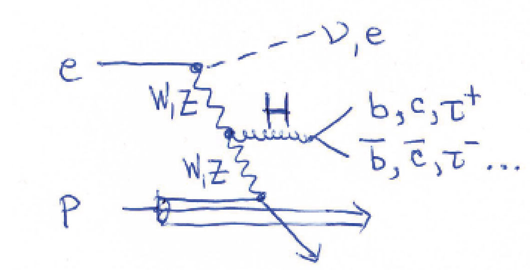
MLM, Frederix

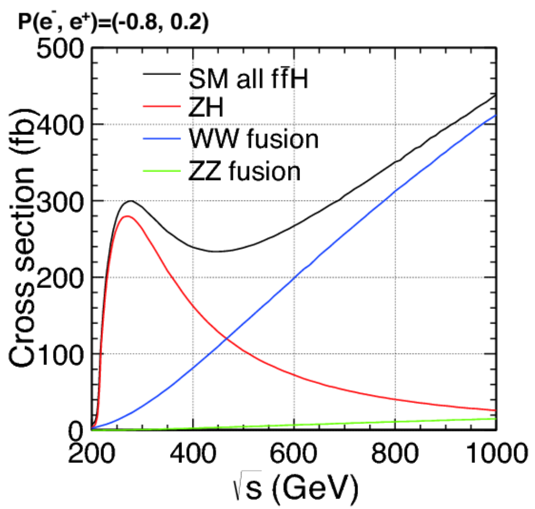


	δσ(ttH)	δσ(ttZ)	δ[σ(ttH)/σ(ttZ)]
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

Complementary between CEPC and others

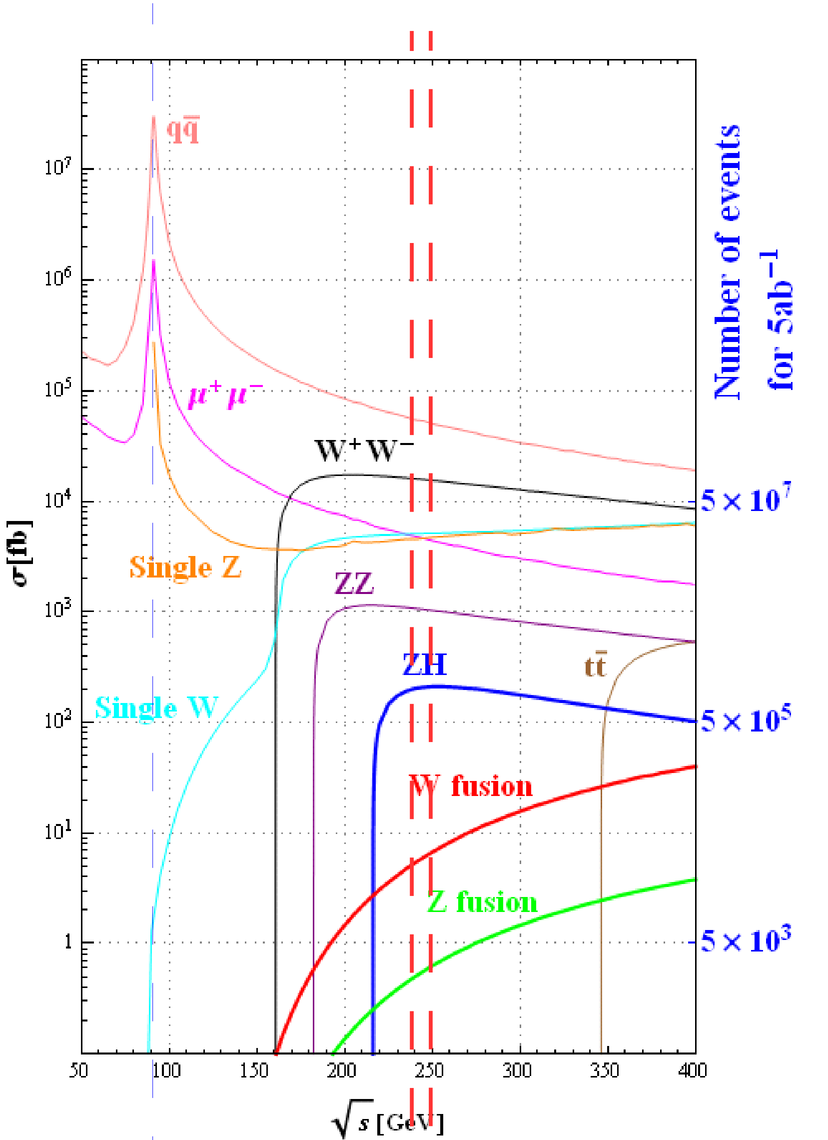
- CEPC + pp colliders
  - *Enhance rare decay measurements, better g(Hγγ) & g(Hμμ) measurements*
  - *Better interpretation of Higgs rare generation measurements*
  - *Access to g(Htt) & g(HHH)*
- CEPC + LHeC
  - *Improve the width measurement*
- CEPC + ILC/CLIC
  - *Improve the width measurement*

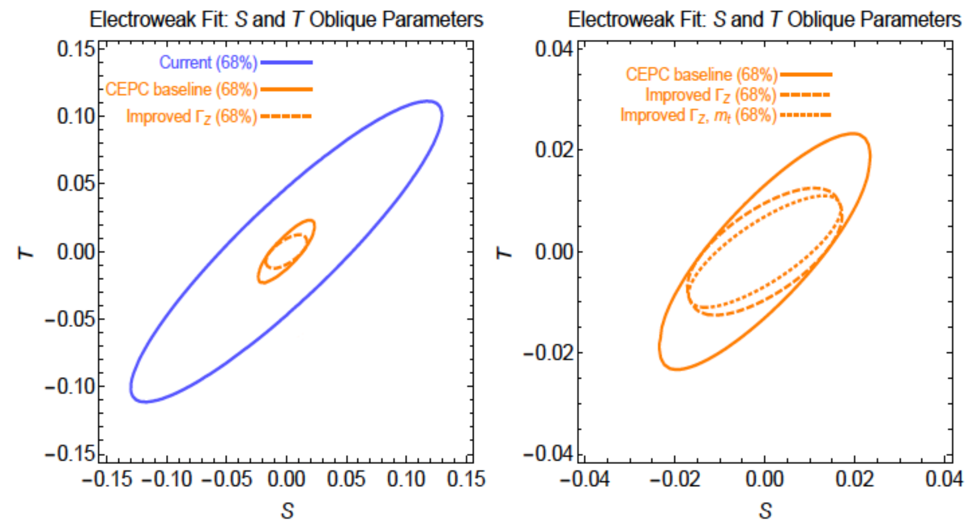




- *Absolute Higgs coupling measurements need the input from e+e- or muon collider. The Higgs total width can be measured to 2.8% at CEPC; better than that of muon collider*

EW@CEPC



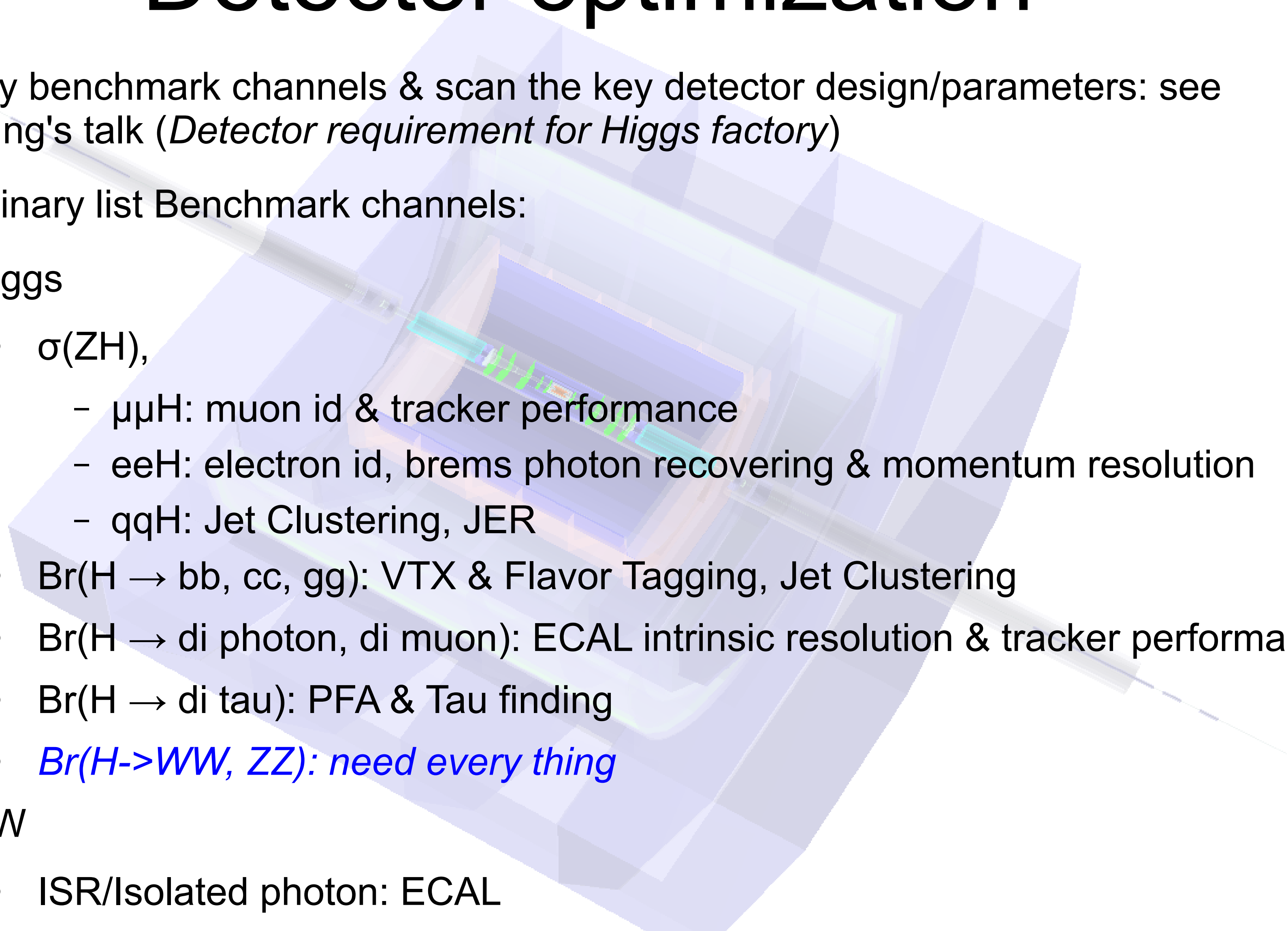


- EW precision measurements with significantly reduced uncertainties:

$$R_b, A_{FB}^b, \sin\theta_W^{eff}, m_Z, m_W, N_\nu \cdots$$

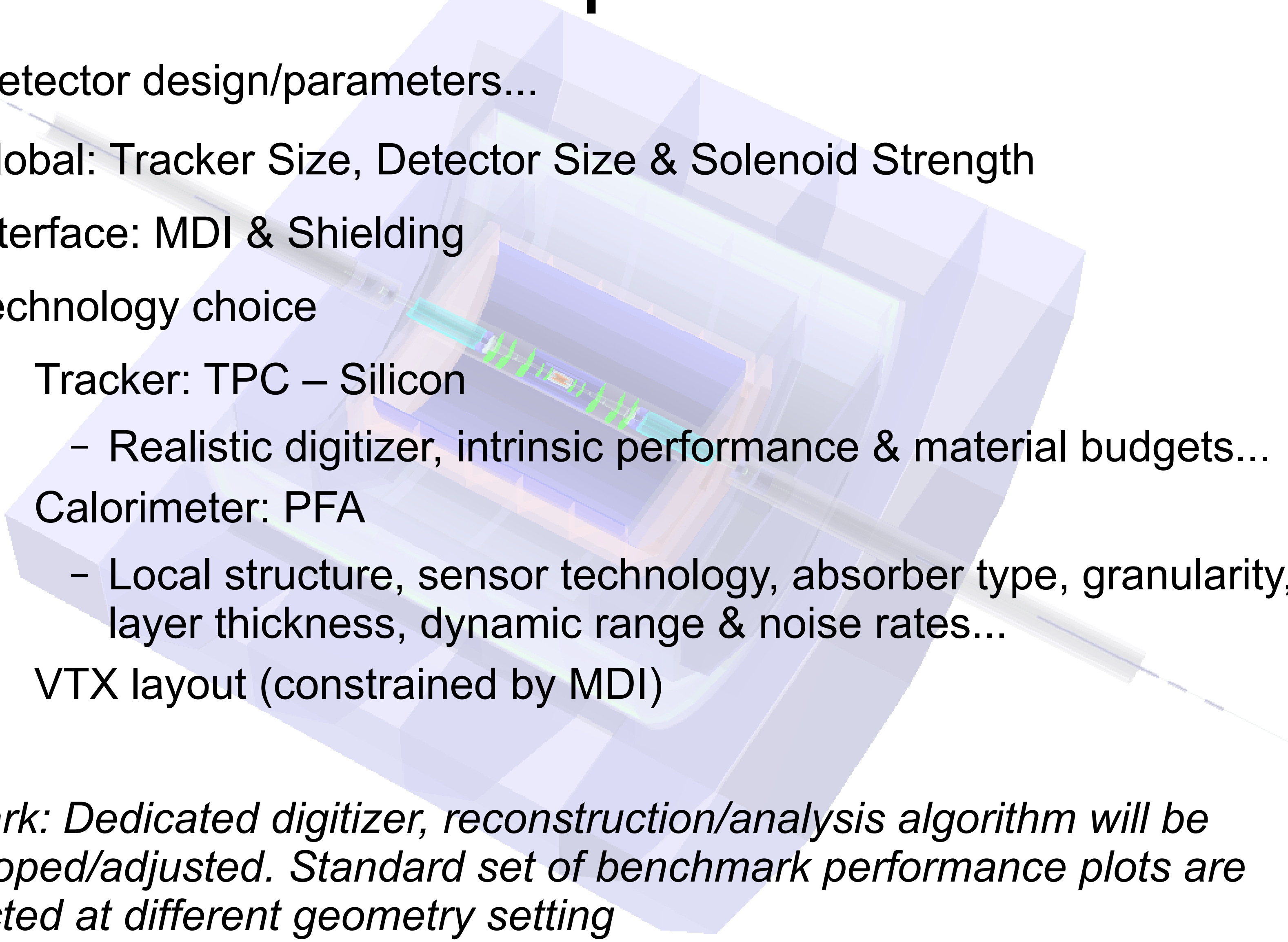
	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [23]	$\pm 1.0 \times 10^{-4}$ [24]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [25]	$\pm 4.7 \times 10^{-5}$ [26]
m_Z [GeV]	91.1875 ± 0.0021 [27]	$\pm \mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [28] $\pm 0.5_{\rm th}$ [26]	$\pm 0.2_{\rm exp} \pm 0.5_{\rm th}$ [29, 30]
m_h [GeV]	125.14 ± 0.24 [26]	$< \pm 0.1$ [26]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [23] $\pm 0.004_{\rm th}$ [31]	$(\pm \mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [31]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [27]	$(\pm \mathbf{2.3}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [32]
Γ_Z [GeV]	2.4952 ± 0.0023 [27]	$(\pm \mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [33]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [27]	$\pm \mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [27]	$\pm \mathbf{0.007}$

Detector optimization



- Specify benchmark channels & scan the key detector design/parameters: see Jianming's talk (*Detector requirement for Higgs factory*)
- Preliminary list Benchmark channels:
  - Higgs
    - σ(ZH),
      - μμH: muon id & tracker performance
      - eeH: electron id, brems photon recovering & momentum resolution
      - qqH: Jet Clustering, JER
    - Br(H → bb, cc, gg): VTX & Flavor Tagging, Jet Clustering
    - Br(H → di photon, di muon): ECAL intrinsic resolution & tracker performance
    - Br(H → di tau): PFA & Tau finding
    - *Br(H->WW, ZZ): need every thing*
  - EW
    - ISR/Isolated photon: ECAL
    - Afb(B): Jet lepton
    - ...

Detector optimization



- Key detector design/parameters...
  - Global: Tracker Size, Detector Size & Solenoid Strength
  - Interface: MDI & Shielding
  - Technology choice
    - Tracker: TPC – Silicon
      - Realistic digitizer, intrinsic performance & material budgets...
    - Calorimeter: PFA
      - Local structure, sensor technology, absorber type, granularity, layer thickness, dynamic range & noise rates...
    - VTX layout (constrained by MDI)

- *Remark: Dedicated digitizer, reconstruction/analysis algorithm will be developed/adjusted. Standard set of benchmark performance plots are expected at different geometry setting*

Summary

- CEPC-SPPC: precision measurement of the Higgs boson at electron-positron machine and search for New Physics at ~100 TeV pp collisions
  - CEPC provides
    - **absolute** measurements to the Higgs couplings.
    - **σ(ZH)**, invisible/exotic branching ratios, Total Width
    - Rich EW & flavor programs
  - SPPC: naturalness, dark matter, electro-weak phase transition, etc
- Synergies between e+e- & other facilities, especially e+e- & pp collider
- Current focus: physics performance & detector optimization

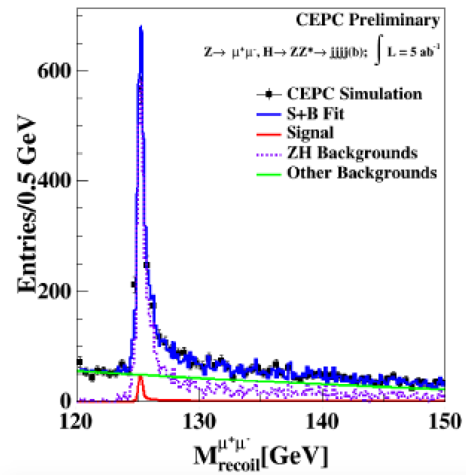
Your ideas & Help: more than welcome!

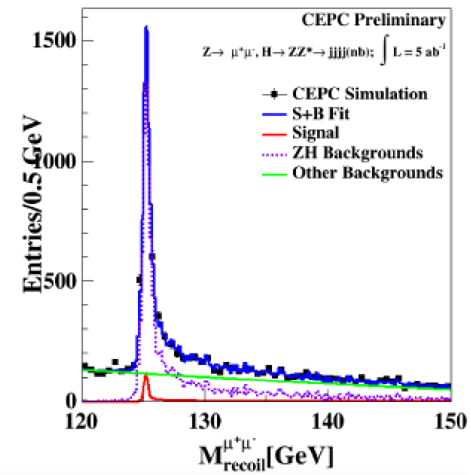
Thank you

Br(H->ZZ*) measurement: preliminary

	Z->ll	taus	vv	qq
ZZ*->4q	888	444	2.64k	9.24k
2v + 2q	508	254	1.51k	5.29k
2l + 2q	170	85	508	1778
4v	73	36	216	756
2l + 2v	49	24	145	508
4l	8	4	24	86
X + tau	120	60	356	1246

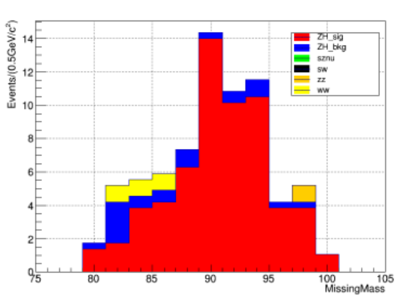
- ZH->ZZZ*->μμjjjj   precision: 48.3%





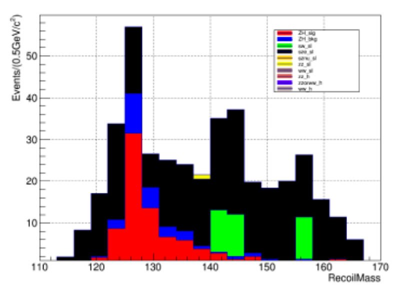
- ZH->ZZZ*->μμvvjj

11.2%



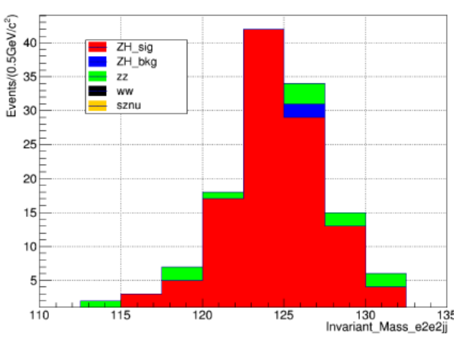
ZH->ZZZ*->eevvjj

19.1%

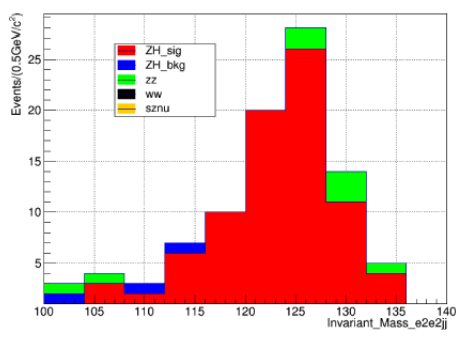


- ZH->ZZZ*->vvμμjj/vvjjμμ

ZZZ*->vvμμjj:9.7%



ZZZ*->vvjjμμ:11.7%



Higgs measurements at e+e- & proton colliders

	Productivity	Finding efficiency	Remarks
LHC	Run 1: 10^6 Run 2/HL: 10^{7-8}	~o(10^{-3})	Lots of Pile Up; Large theoretical/systematic uncertainties. Access to signal strength in major decay channels; Access to g(HHH)/g(Htt).
CEPC	10^6	~o(1)	**Absolute** measurements in very clean environment; o(0.1%) accuracy on key observable (g(HZZ)); Excellent precision to **total width, invisible/exotic decay ratios**; Indirect constrain to g(HHH)/g(Htt);
SPPC	10^{9-10}	?	Good access to Higgs rare decay/generation, g(HHH)/g(Htt),

High complementarity between electron-positron & pp colliders

Scan of the SM Higgs resonance (5)

- Summary of precision measurements (after ~10 years of running)

Error on	μμ Collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

Not sure of the practical use of such a precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

The SM Higgs coupling to muons is *the* added value of a μμ collider *

These Higgs couplings are *only* measured at ee colliders *

* pp colliders have their say, too

- FCC-hh best for g_{HHH} and g_{ttH} , perhaps $g_{H\mu\mu}$; FCC (ee, hh) for rare decays
  - BR(H→ μμ) can also be measured with % precision at FCC-hh. (Will be already 10% after LHC.)

Patrick Janot

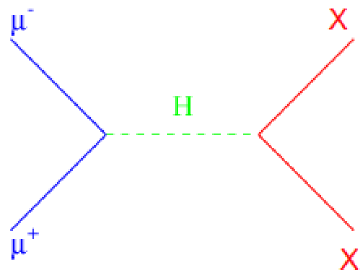
FCC-ee Higgs mini-workshop
24 Sept 2015

17

Scan of the SM Higgs resonance (1)

Resonant production

$$\sigma(\mu^+\mu^- \to H^0) = \frac{4\pi\Gamma_H^2 Br(H^0 \to \mu^+\mu^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2}$$



Major background: $\mu^+\mu^- \to Z/\gamma^* \to XX$

- Convoluted with
  - Beam energy spectrum
  - Initial state radiation (ignored in most studies)
- The measurement of the lineshape gives access to
  - The Higgs mass, m_H
  - The Higgs width, Γ_H
  - The branching ratio into $\mu^+\mu^-$, BR($H \to \mu\mu$)
    - → Hence, the coupling of the Higgs to the muon, $g_{H\mu\mu}$
  - Some branching fractions and couplings, with exclusive decays

SAPPHIRE & LHeC

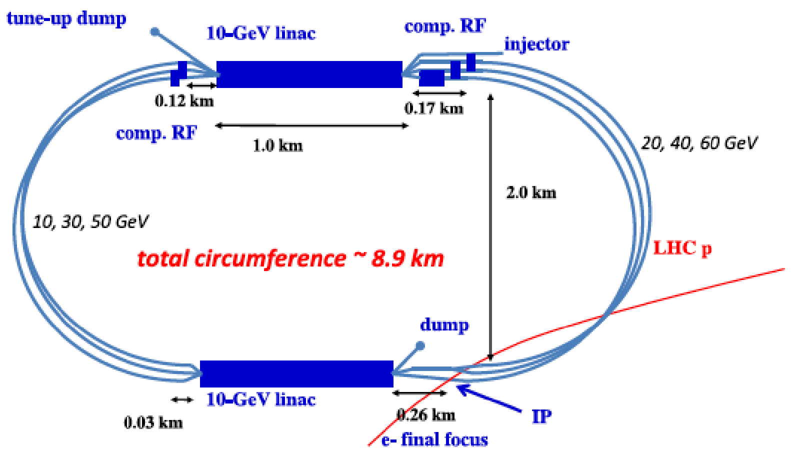


Figure 1: LHeC ERL layout including dimensions.

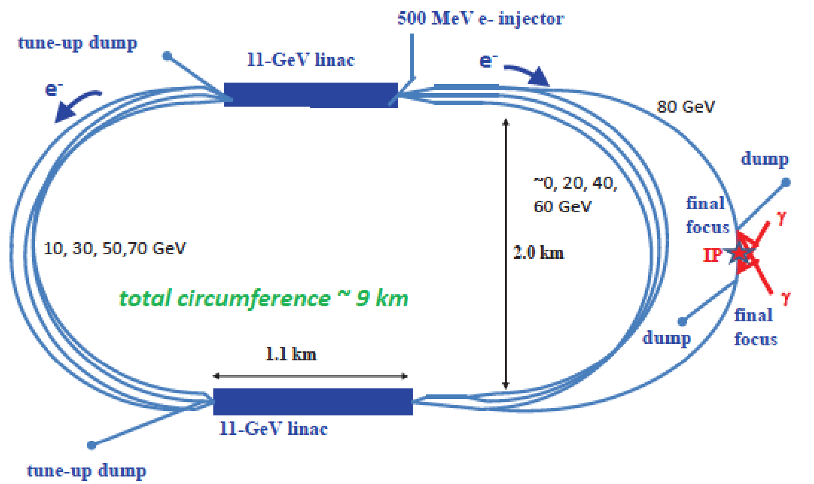
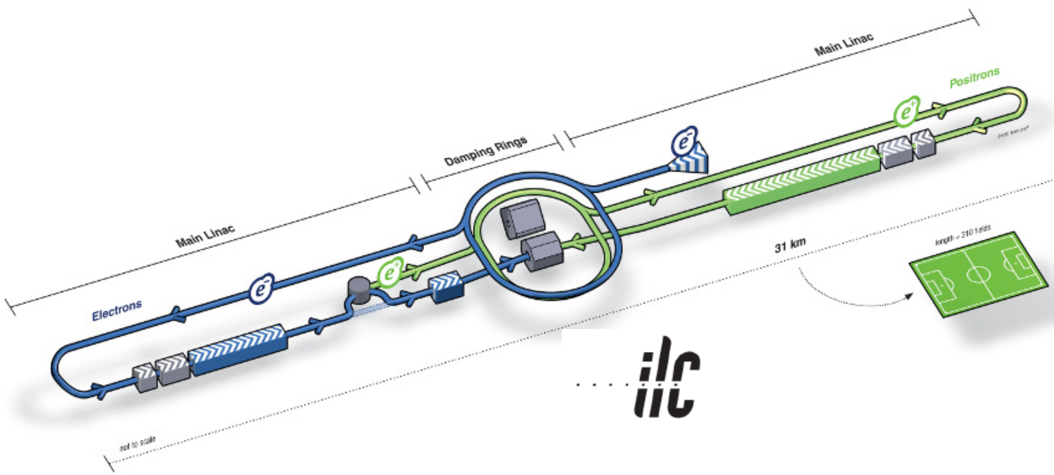


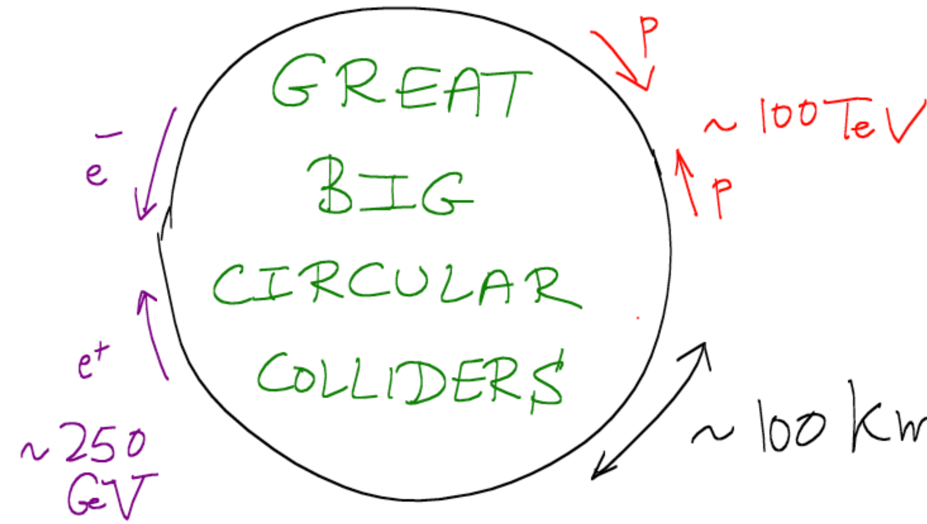
Figure 2: Sketch of a layout for a $\gamma\gamma$ collider, "SAPPHiRE," based on the LHeC recirculating SC linacs [8].

Table 3: LHeC Higgs factory comparison (where 1 year is taken to be 10^7 s at design luminosity).

machine	LHeC	LHeC-HF	SAPPHiRE
luminosity [10^{34} cm^{-2}s^{-1}]	0.1 (ep)	2 (ep)	0.06 ($\gamma\gamma$ $>$ 125 GeV)
cross section	$\sim$200 fb	$\sim$200 fb	$>$1.7 pb
no. Higgs/yr	2k	40k	$>$10k

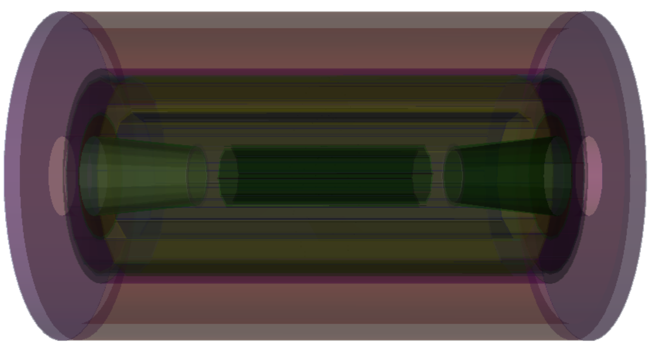
e^-e^+ Higgs factory: Linear or Circular

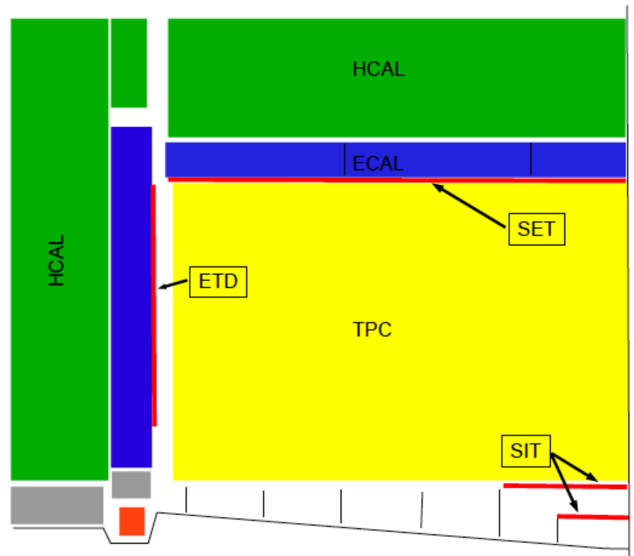


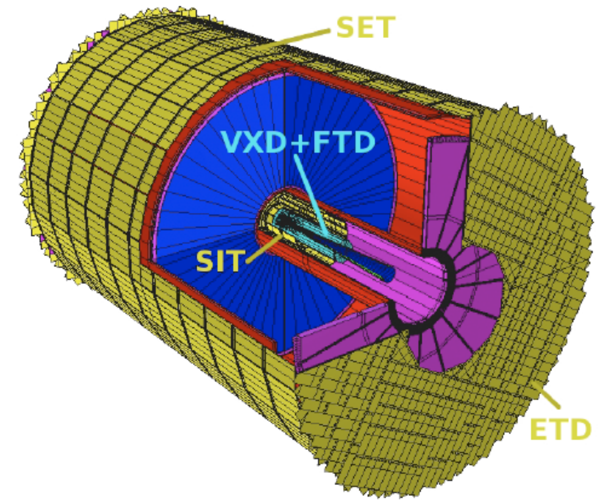


	Linear: ILC, CLIC	Circular: FCC, CEPC
Pro	C.o.M energy can be upgraded to 1-3 TeV Longitudinal polarized beam Power pulsed detector	Cost-efficient, component-mature technology Multiple interaction point High luminosity & beam quality
Con	Expensive Single interaction point, might need push-pull	Center of mass energy limited in e^+e^- phase (but can be upgraded to ~ 100 TeV in pp phase) No beam polarization at high energy No power pulse

Vertex & Silicon Tracking at ILD



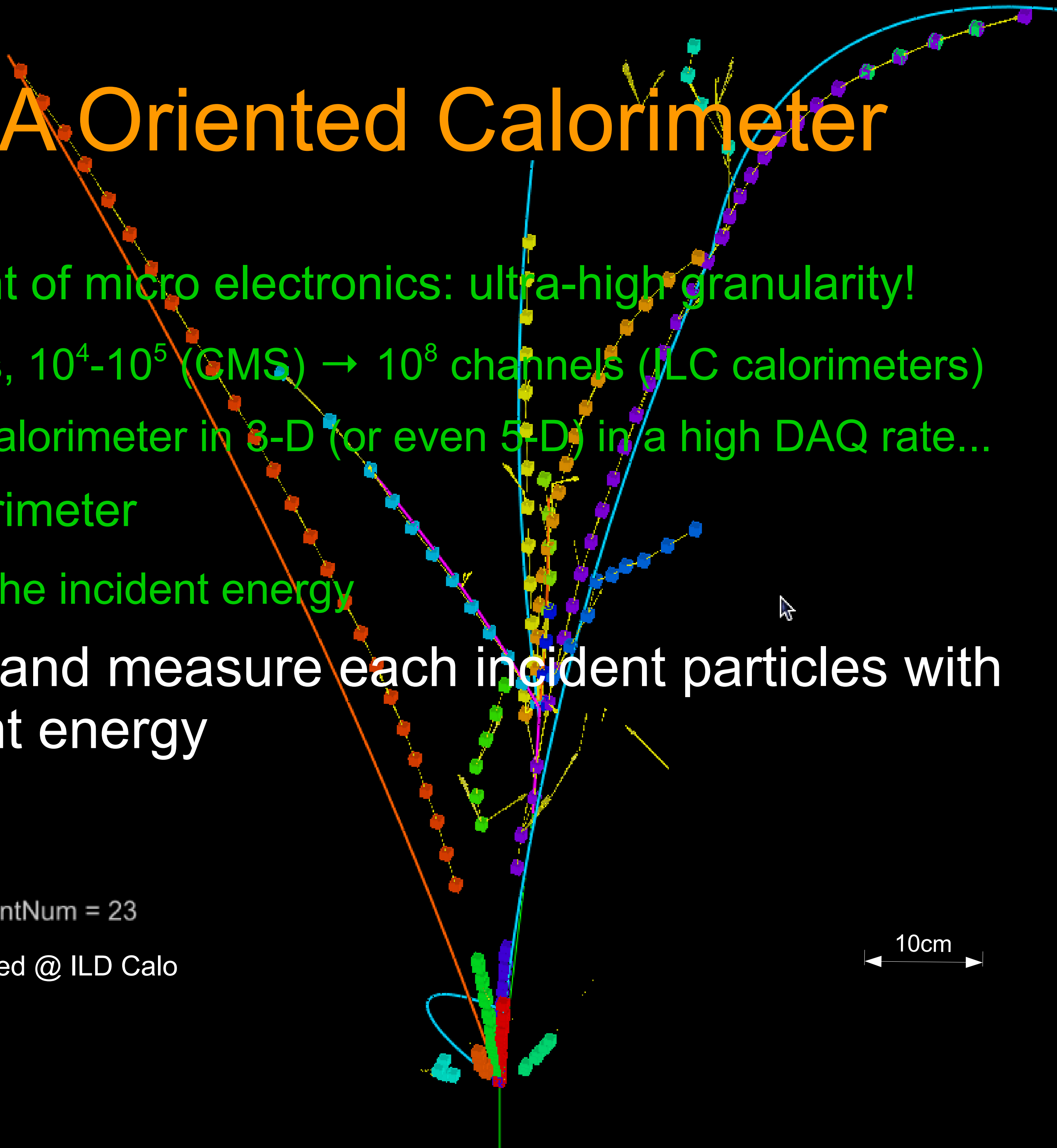




- VTX: Inner most layer Radius: ~15 mm, Spatial resolution: ~ 5 μm
- Massive usage of silicon pixel/strips in the tracking system & VTX: ensures good accuracy in Impact parameter & momentum measurement

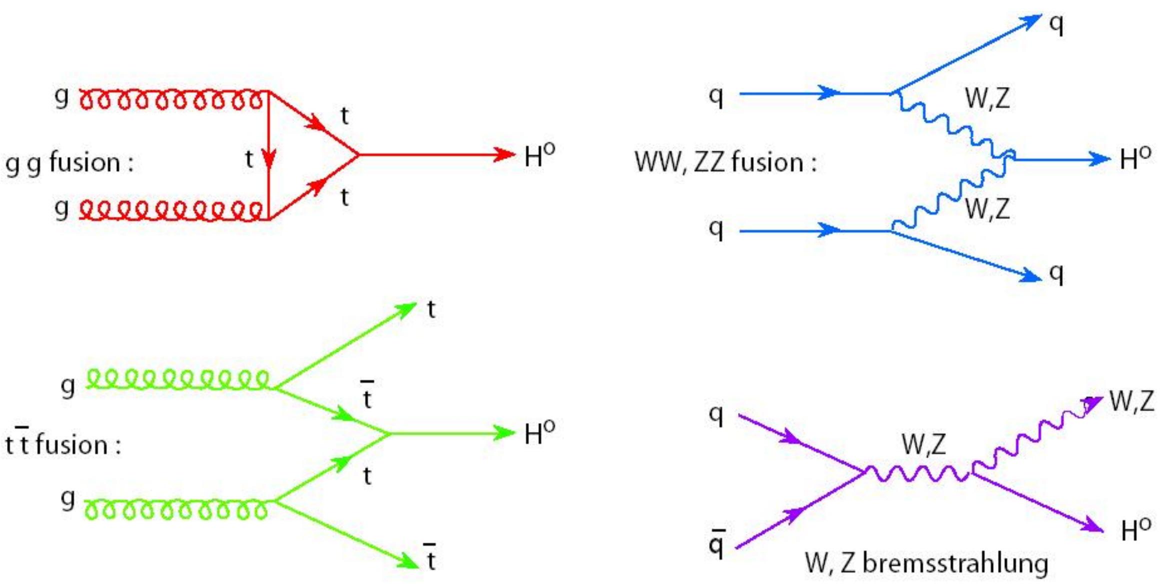
PFA Oriented Calorimeter

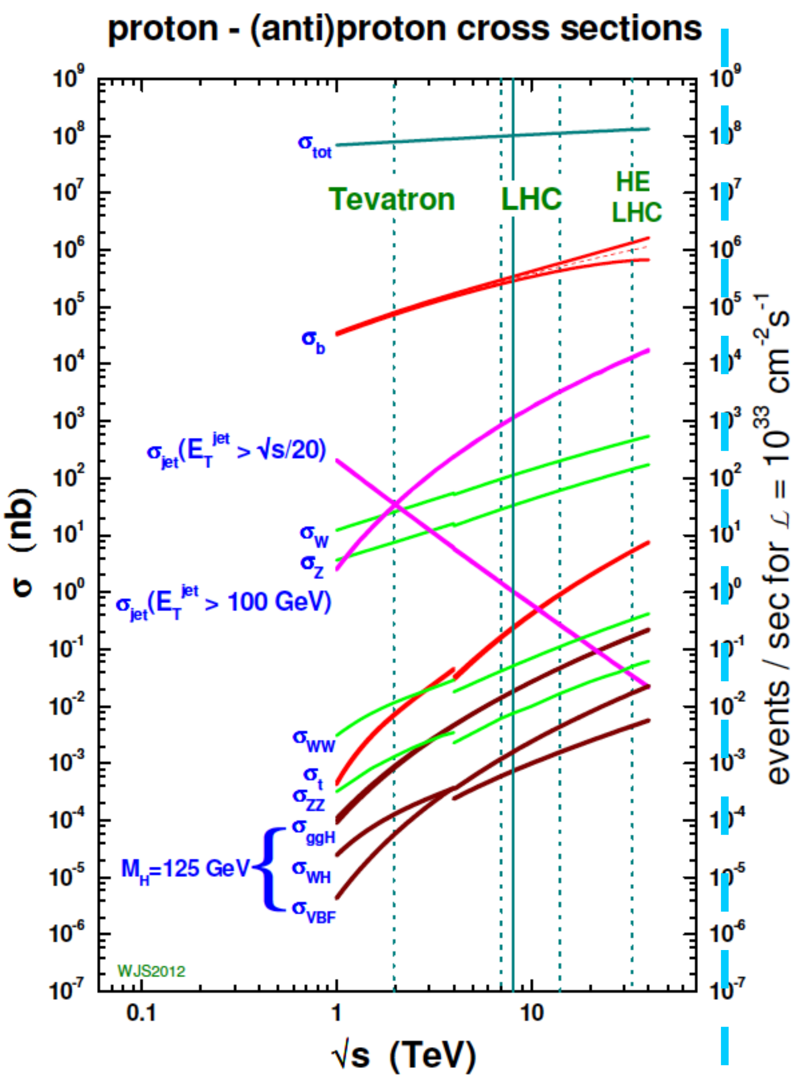
- Development of micro electronics: ultra-high granularity!
  - #channels, 10^4-10^5 (CMS) → 10^8 channels (ILC calorimeters)
  - Imaging calorimeter in 3-D (or even 5-D) in a high DAQ rate...
- Role of calorimeter
  - Measure the incident energy
  - Identify and measure each incident particles with sufficient energy



20 GeV Klong reconstructed @ ILD Calo

Higgs @ LHC





PP collider: High productivity but low finding efficiency
~already 10^6 Higgs in Run 1 data...

Higgs signal: found via the decay final states.

$$\sigma(AA \to H \to BB) \sim g^2(HAA)g^2(HBB)/\Gamma_{total}$$