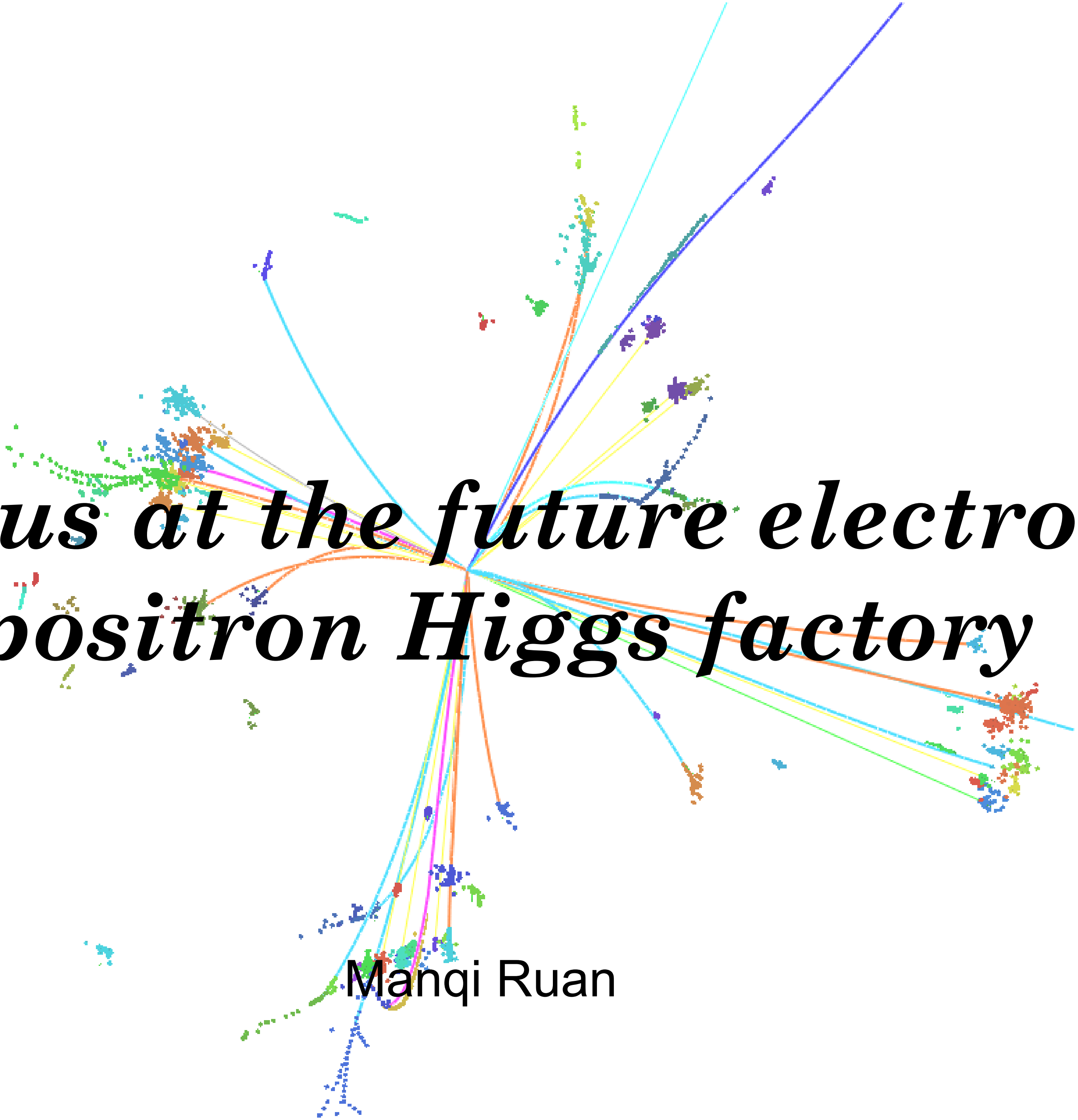


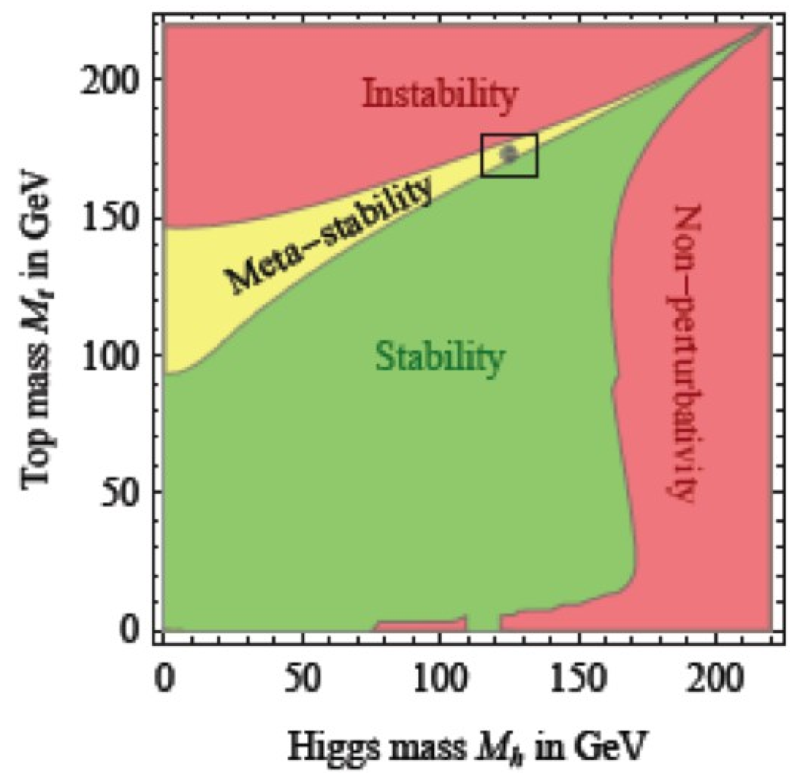
Taus at the future electron positron Higgs factory

Manqi Ruan

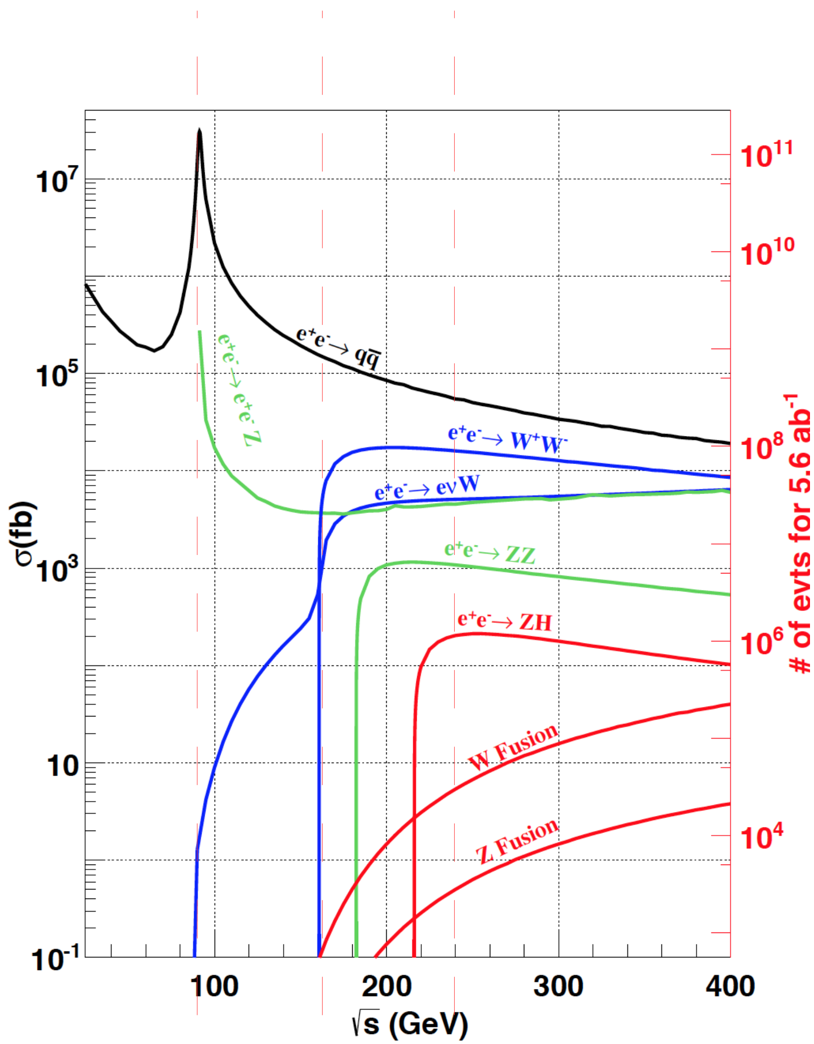
SM is **NOT** the end of story...

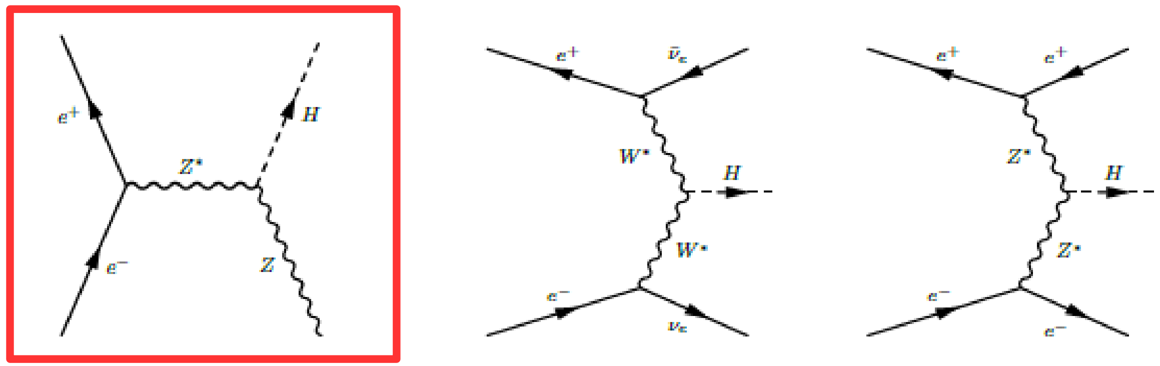
- **Naturalness?**
  - Fine tuning of the Higgs mass
- **Vacuum Stability?**
  - Masses of Higgs and top quark
- **Hierarchy?**
  - From neutrinos to the top mass, masses differs by 13 orders of magnitude
- **Unification?**
- **Dark matter?**
- **Baryogenisis?**
- **...**
- **Most issues related to Higgs**

$$m_H^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023$$
$$-36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$$
$$= (125\ \mathrm{GeV})^2\ !\ ?$$



Higgs @ electron positron collider





S/B ~ 1:100 – 1000

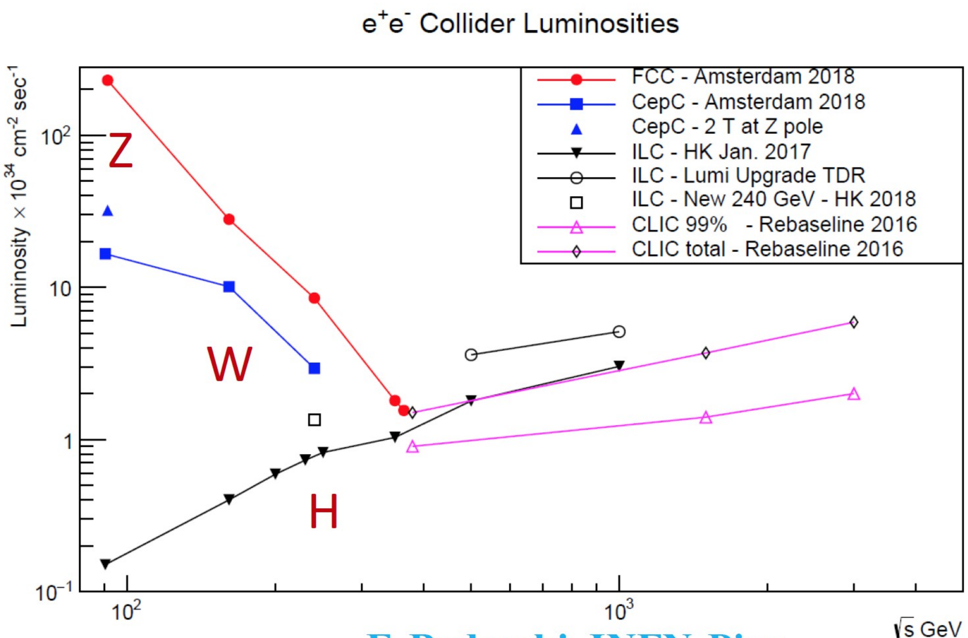
(7 orders of magnitudes better than HL-LHC)

Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H→X)), Diff. Distributions

Derive: Absolute Higgs width, branching ratios, couplings

The precision is roughly 1 order of magnitude better than HL-LHC

Electron Positron Higgs factories



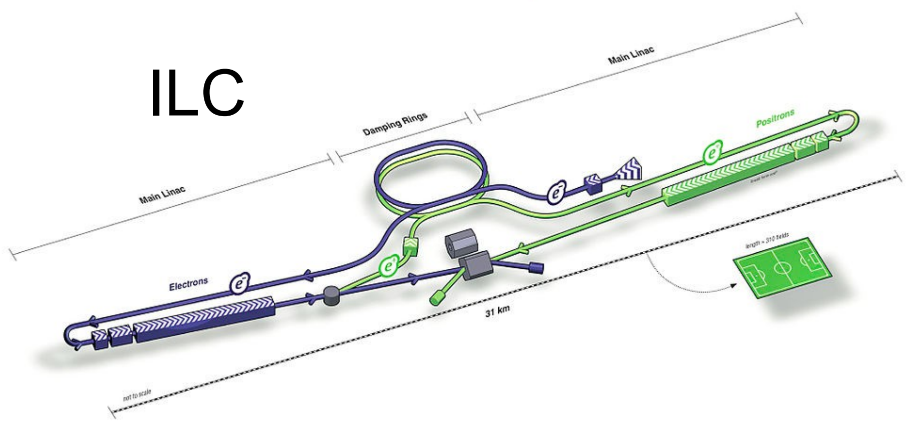
F. Bedeschi, INFN-Pisa

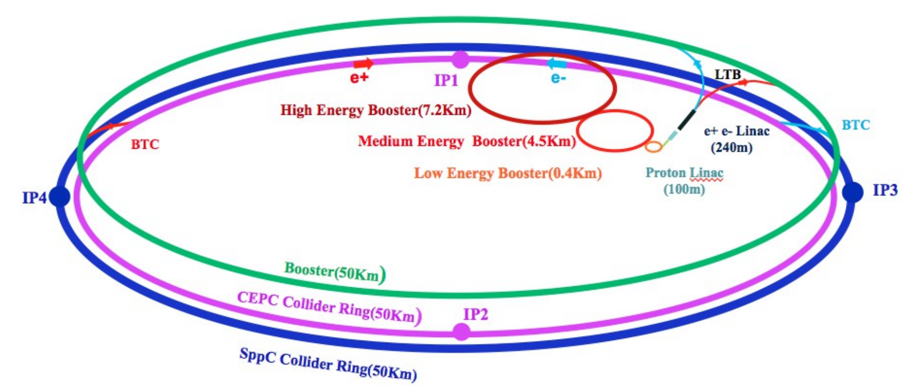
CEPC

Operation mode	Z factory	W threshold scan	Higgs factory
$\sqrt{s}$ (GeV)	91.2	158 - 172	240
L ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	16-32	10	3
Running time (years)	2	1	7
Integrated Luminosity (ab^{-1})	8 - 16	2.6	5.6
Higgs yield	-	-	10^6
W yield	-	10^7	10^8
Z yield	10^{11-12}	10^9	10^9

Table 3.2: Instantaneous and integrated luminosities at different values of center-of-mass energy ($\sqrt{s}$) and anticipated corresponding boson yields at the CEPC. The range of luminosities for the Z factory correspond to the two possible solenoidal magnetic fields, 3 or 2 Tesla.

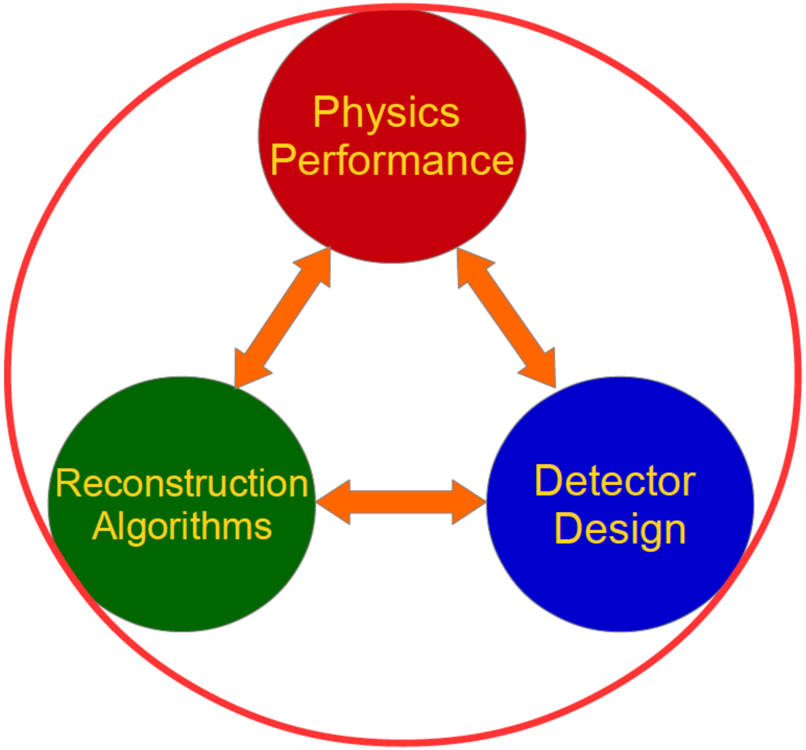
ILC





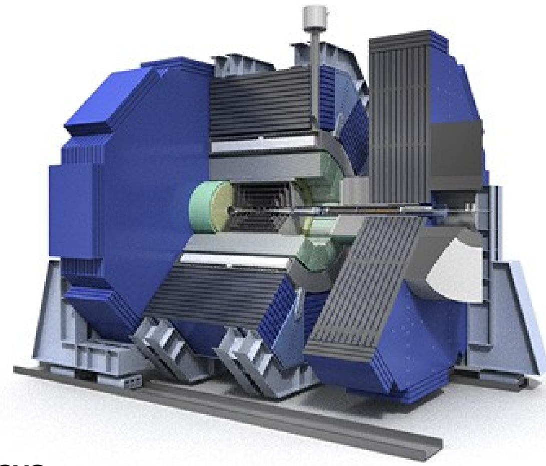
$H \to \tau\tau$ at CEPC/ILC

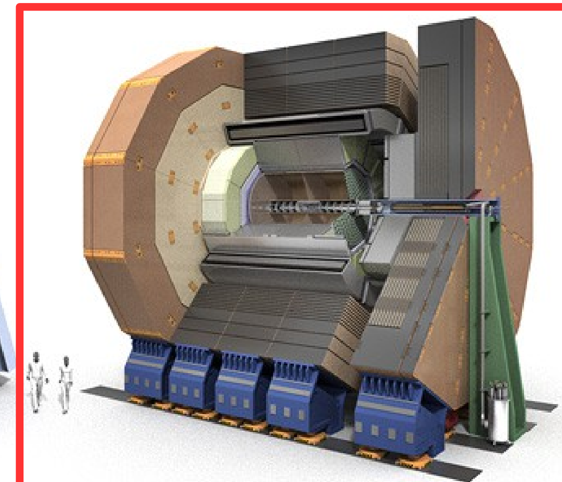
- Perfect Physics benchmark
  - Physics reach: High accuracy & Sensitive to NP
  - Detector design/optimization
    - Separation performance
    - Variety of physics objects, Depends on Tracker, Calorimeter & VTX...
- Physics analyses
  - $\mu(H \to \tau\tau)$ at CEPC (with 5 ab^{-1} ~ 1 Million Higgs at 240 GeV c.m.s)
  - $\mu(H \to \tau\tau)$ at ILC (with 2 ab^{-1} ~ 0.6 M Higgs at 250 GeV c.m.s)
  - Higgs CP measurement at the ILC

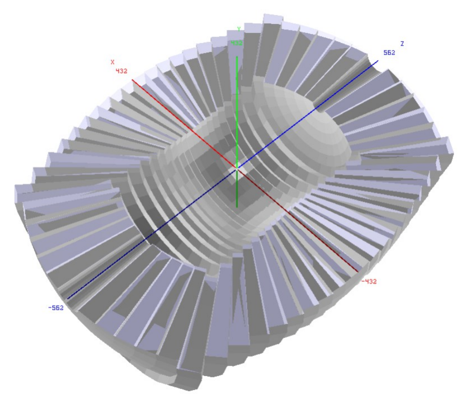


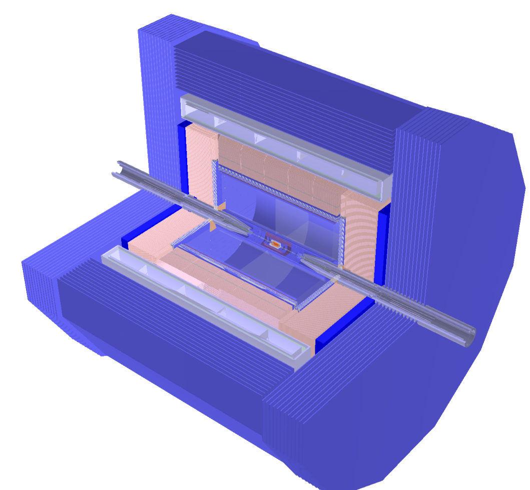
Detectors

- ILC: PFA Oriented design
  - **ILD**
  - SiD
- CEPC
  - Baseline: PFA Oriented Design
    - **ILD-like: APODIS**
    - SiD-like
  - Alternative: Dual Readout Calorimeter + Wire Chamber
- **ILD**: High Granularity Calorimeter + Time Projection Chamber

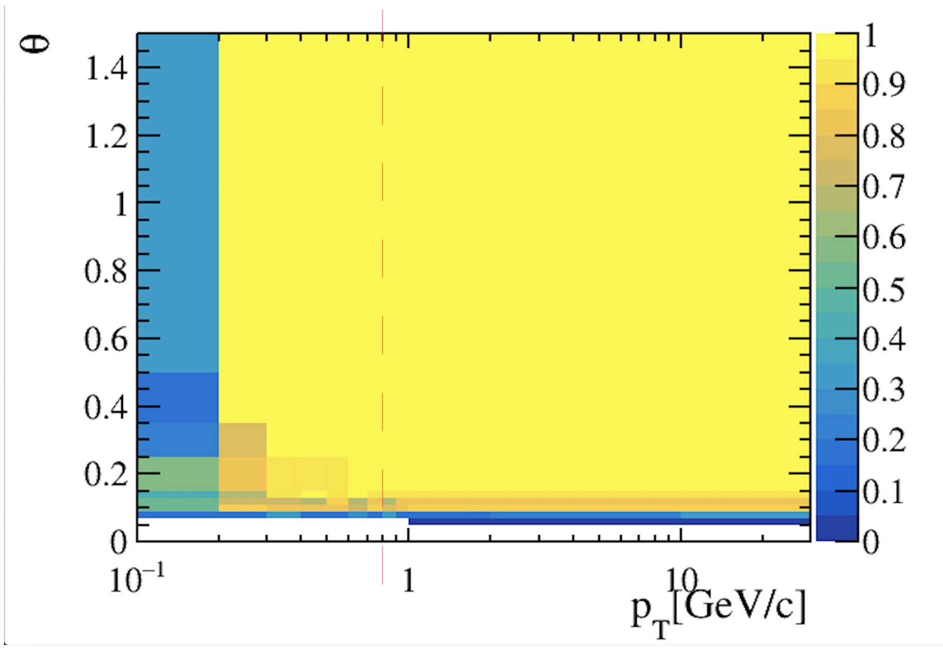


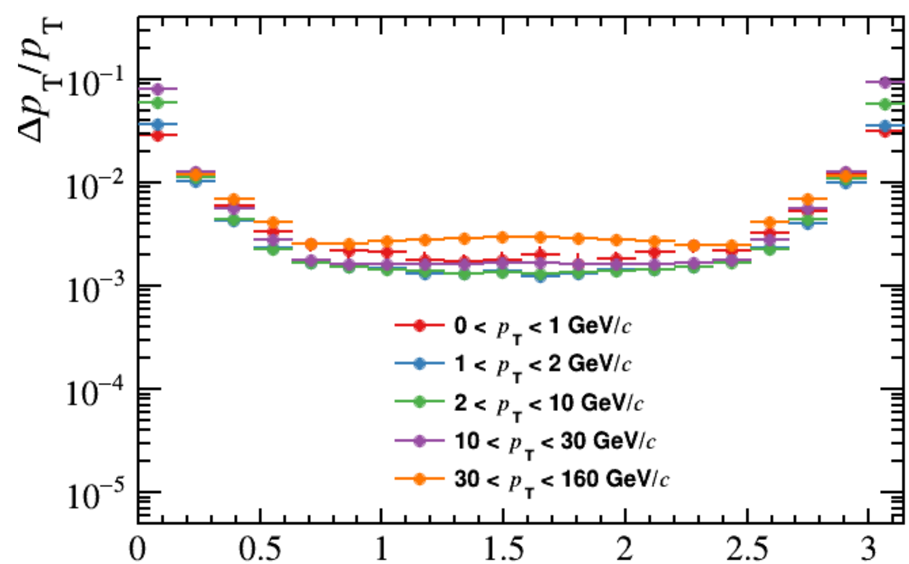


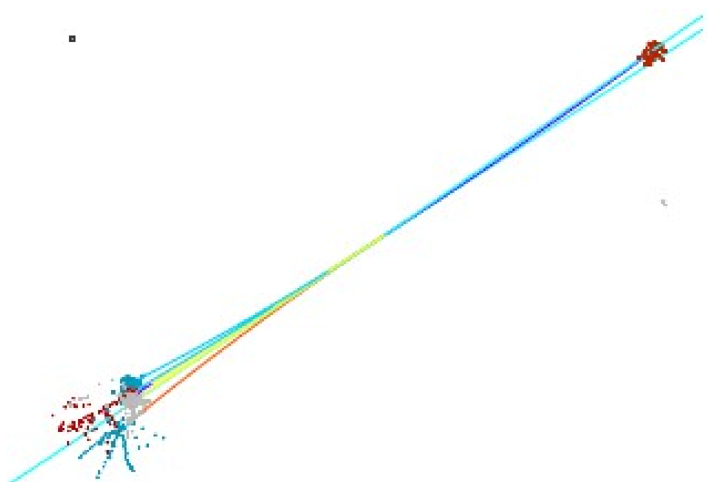


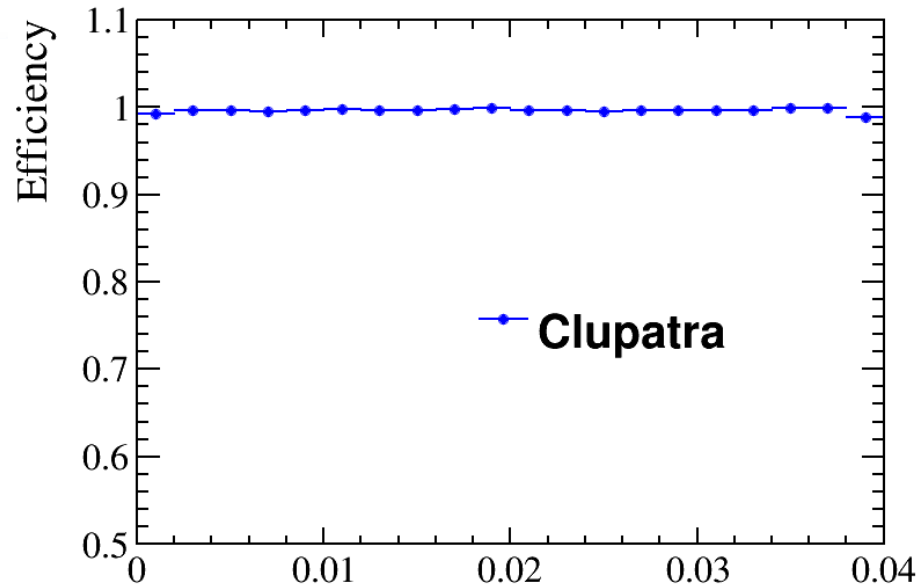


Tracking

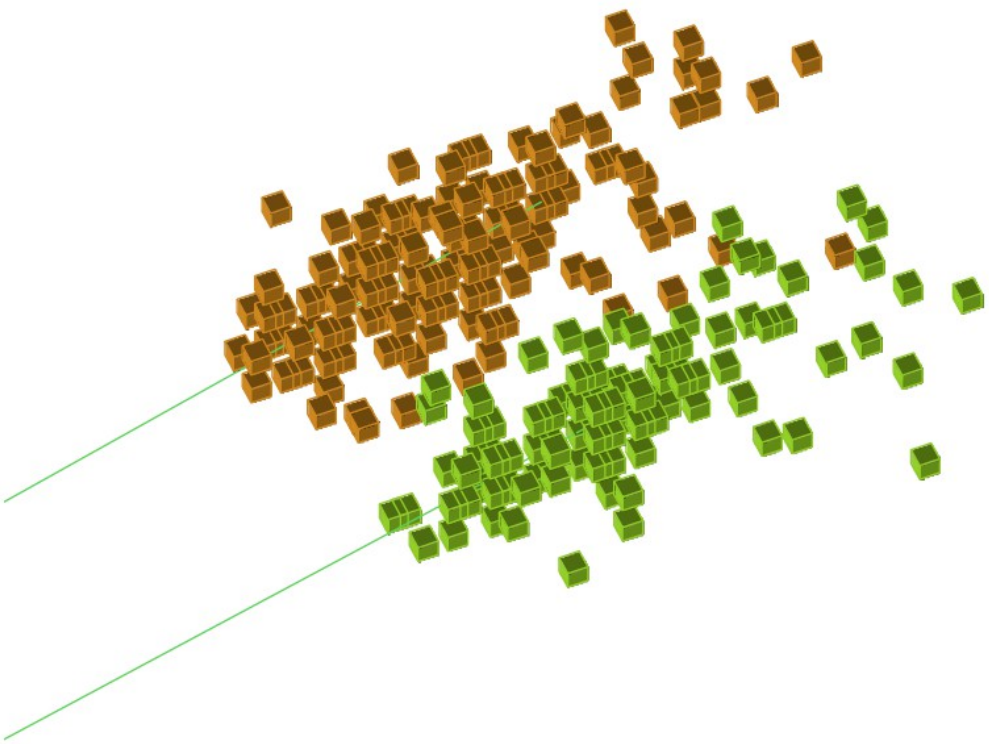

θ
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
p_T[GeV/c]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

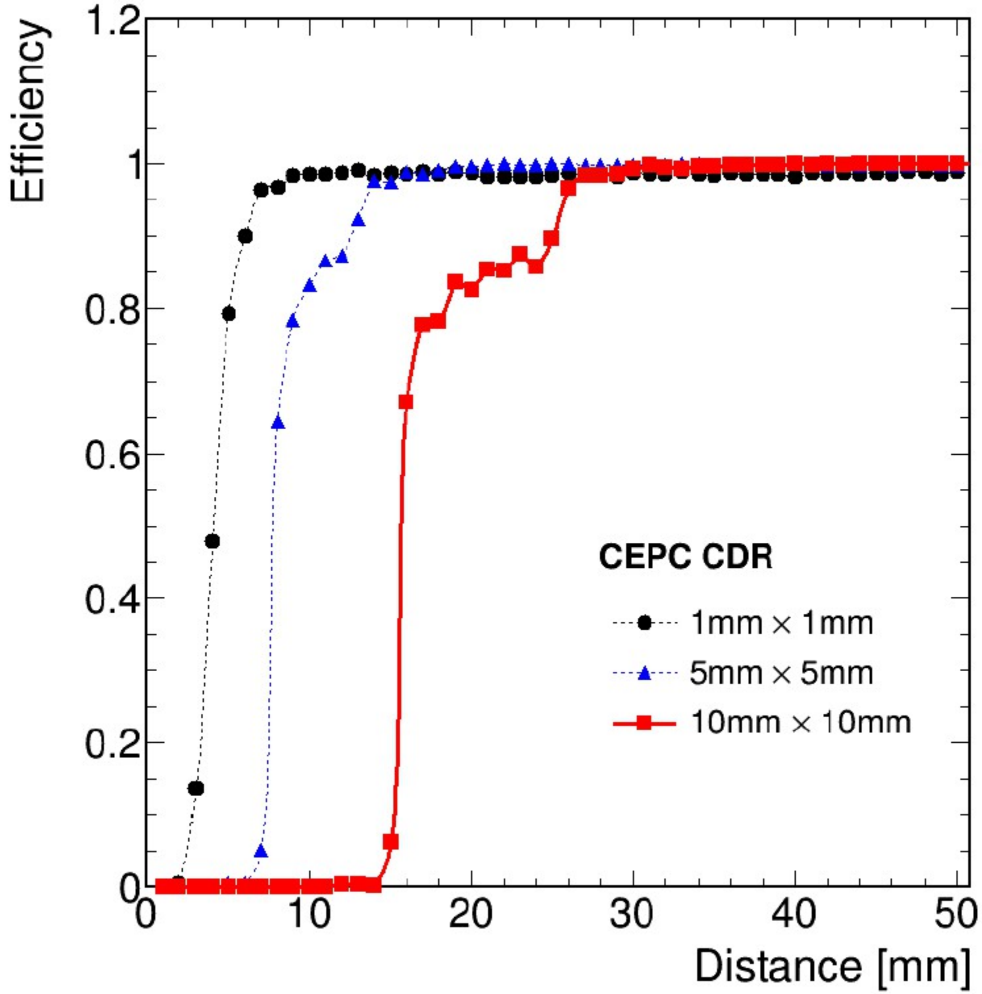

$\Delta p_T/p_T$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1
1.5
2
2.5
3
$0 < p_T < 1$ GeV/c
$1 < p_T < 2$ GeV/c
$2 < p_T < 10$ GeV/c
$10 < p_T < 30$ GeV/c
$30 < p_T < 160$ GeV/c




Efficiency
1.1
1
0.9
0.8
0.7
0.6
0.5
0
0.01
0.02
0.03
0.04
Minimal angle [rad]
Clupatra

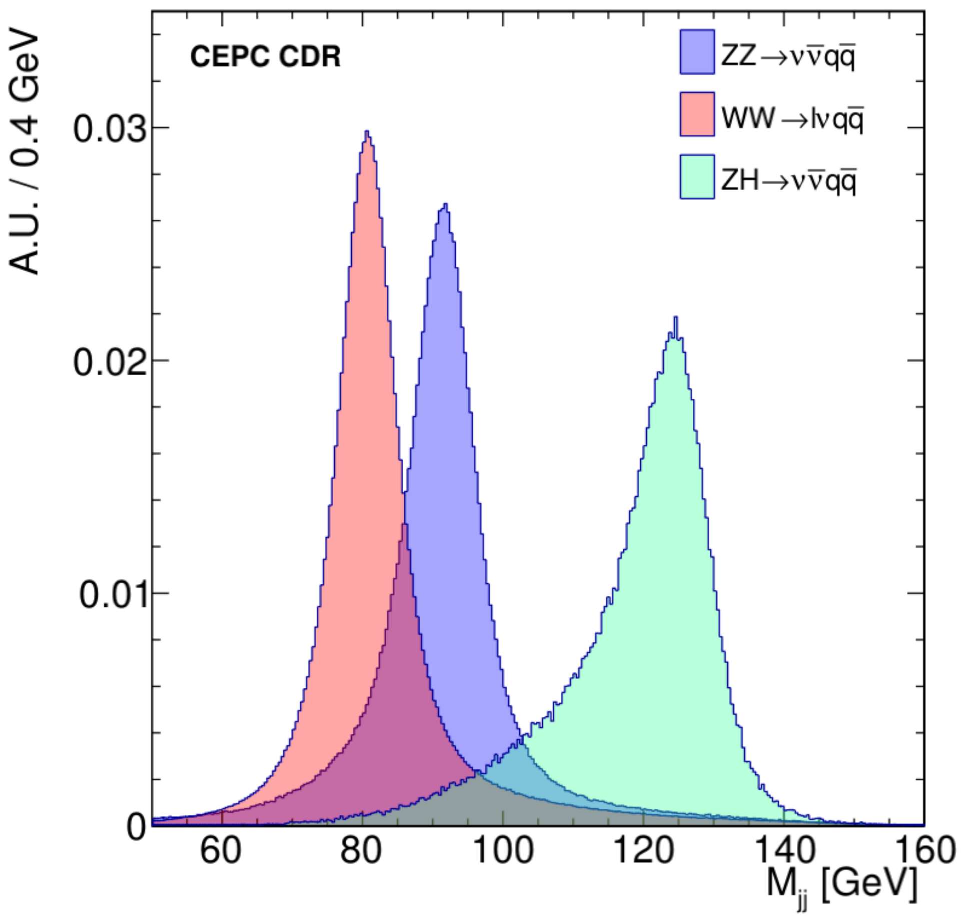
Clustering

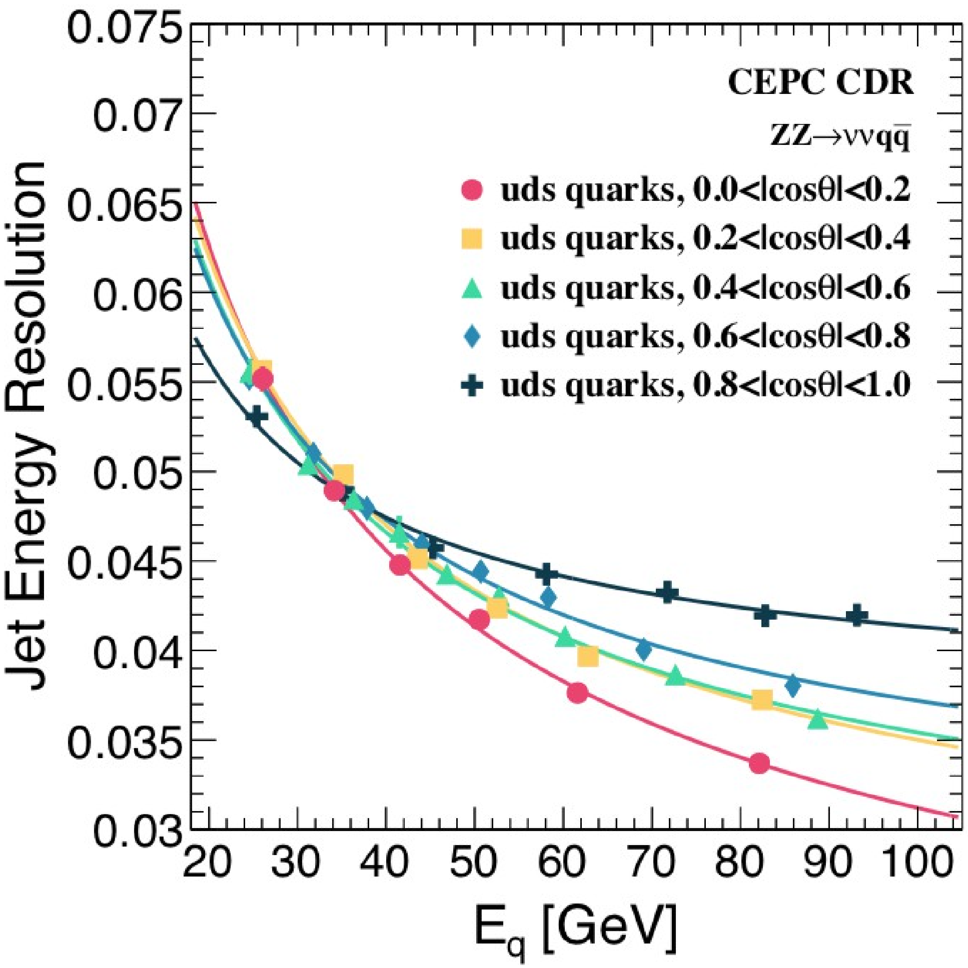




Critical energy to separate an evenly decay π_0: 30 GeV

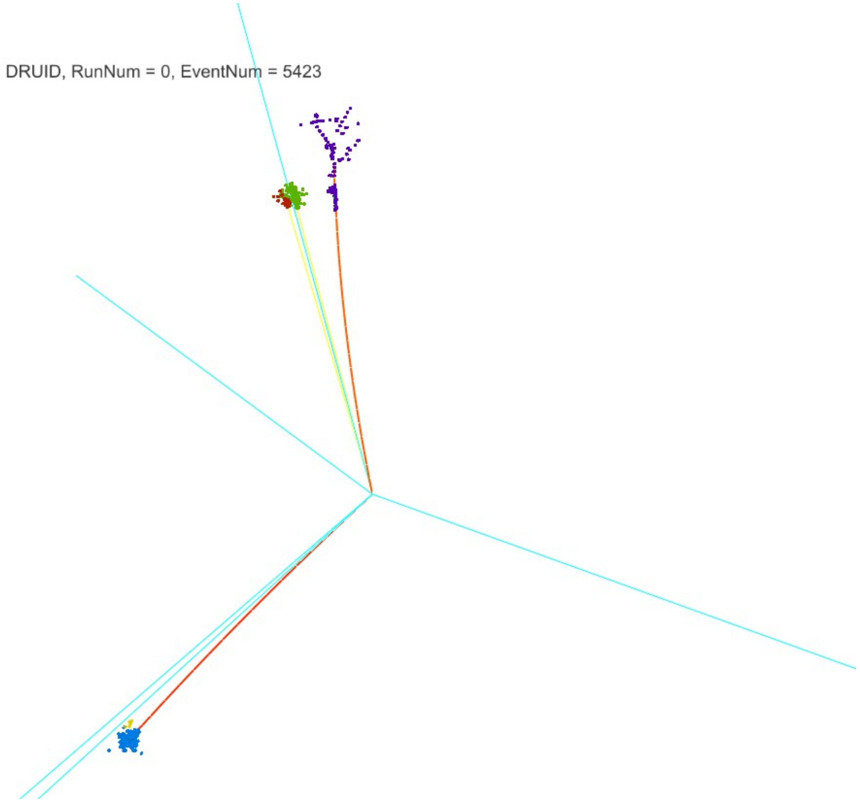
Jets

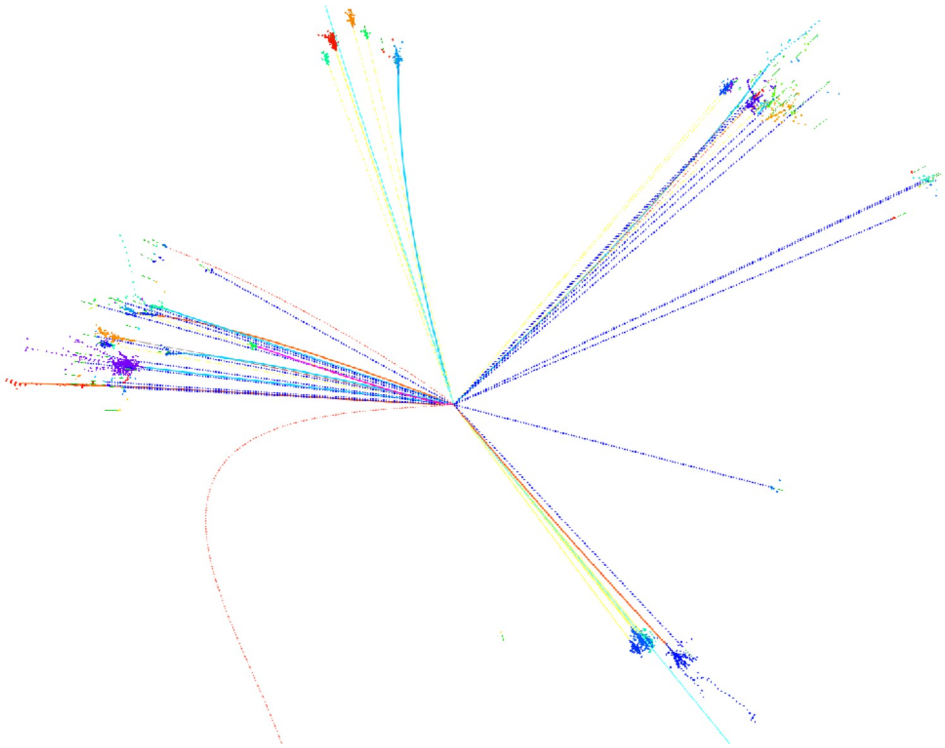




Amplitude ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
Depends on the Flavor, direction and jet energy
Superior to LHC experiments by 3-4 times

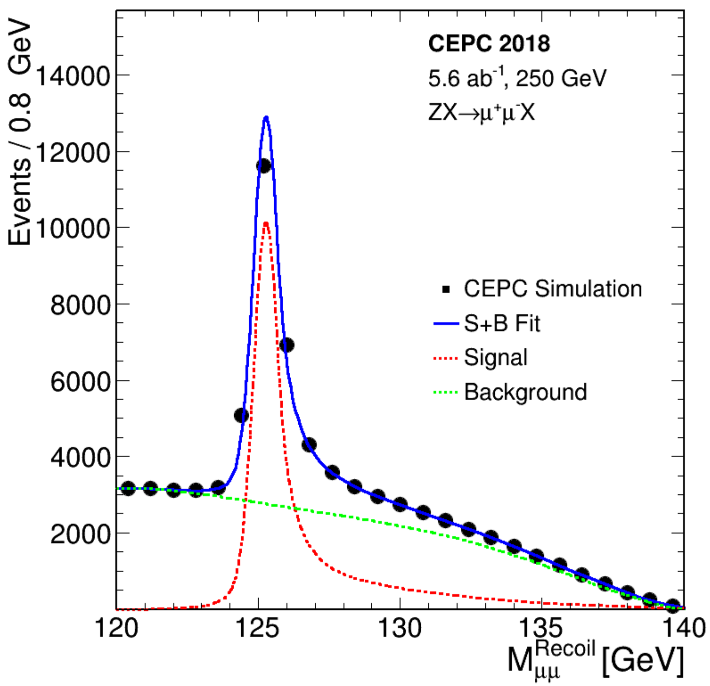
μ(H→ττ)

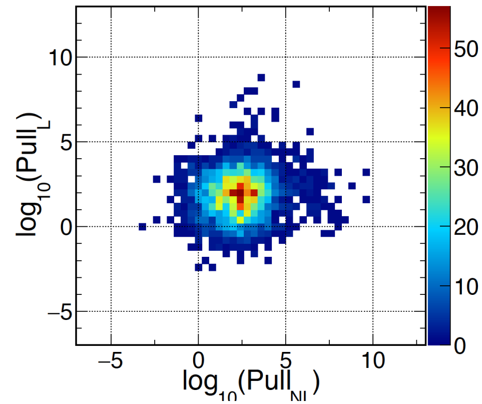


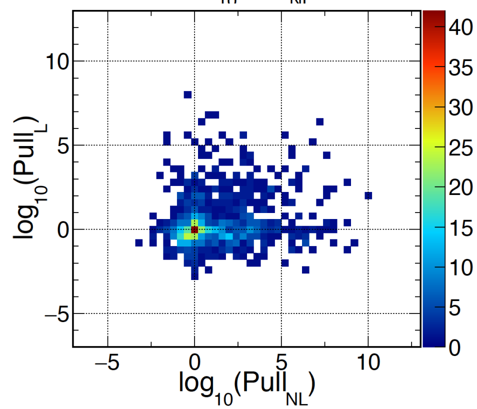


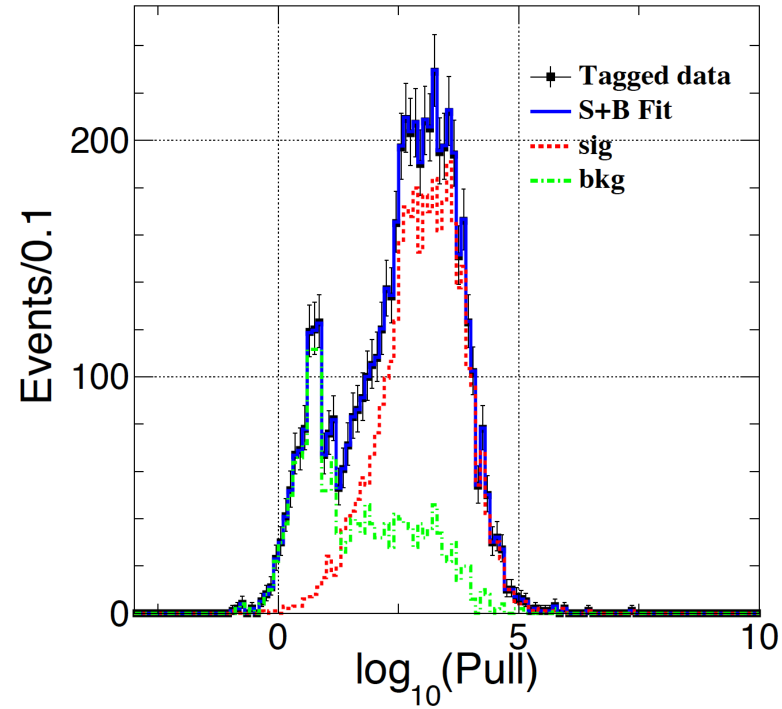
- Two classes of events with tau:
  - Leptonic events: i.e, llττ(ZZ/ZH), ννττ(ZZ/ZH/WW), Z→ττ;
  - Hadronic ones: i.e, ZZ/ZH→qqττ, WW→qqντ;

At Leptonic events



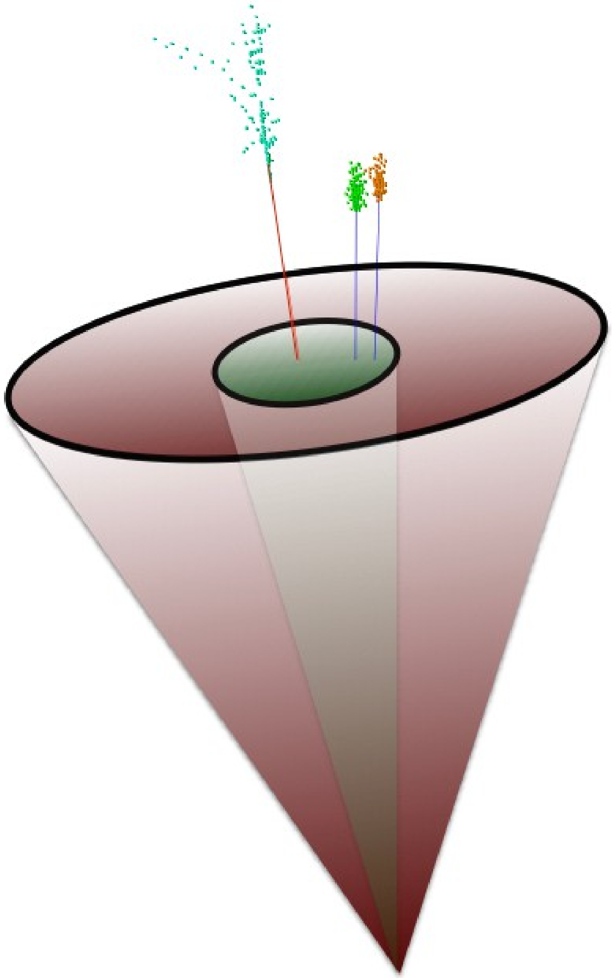


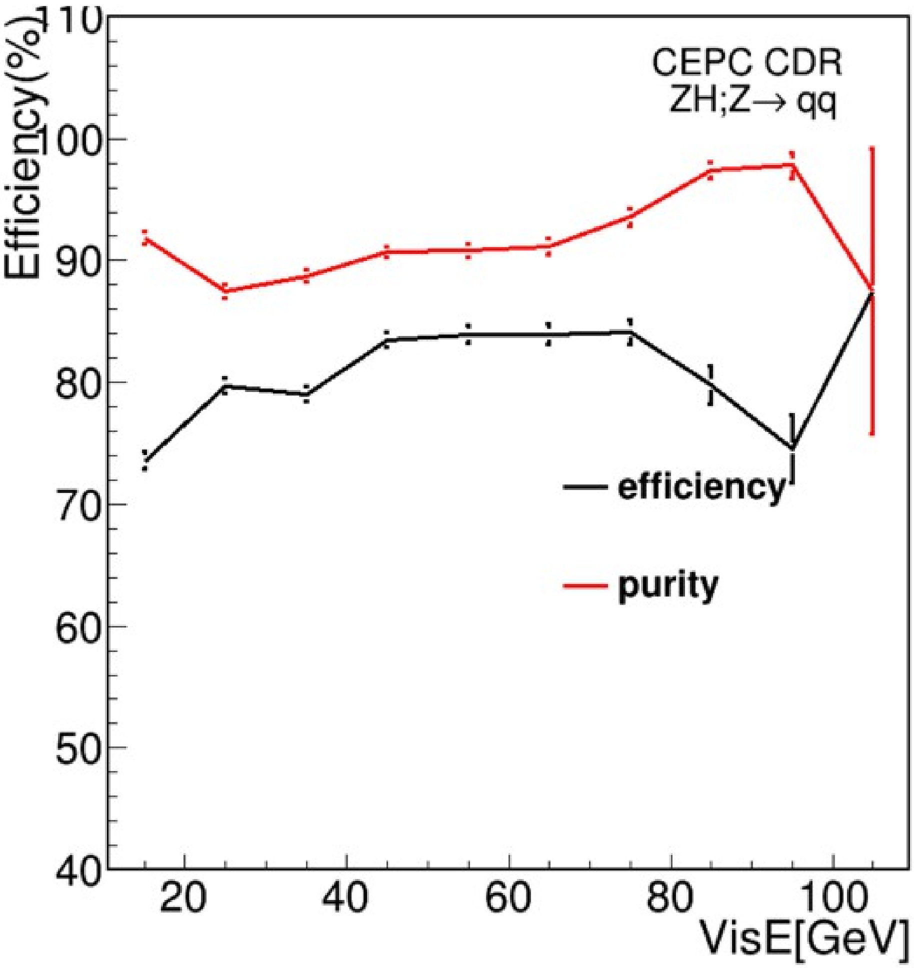




- ZH→μμττ
- Extremely powerful event selection: signal efficiency of ~90% - entire SM background reduced by 5 orders of magnitudes
- Isolated, energetic tracks are intentionally identified as tau candidates - to be distinguished by VTX measurement (impact parameter)

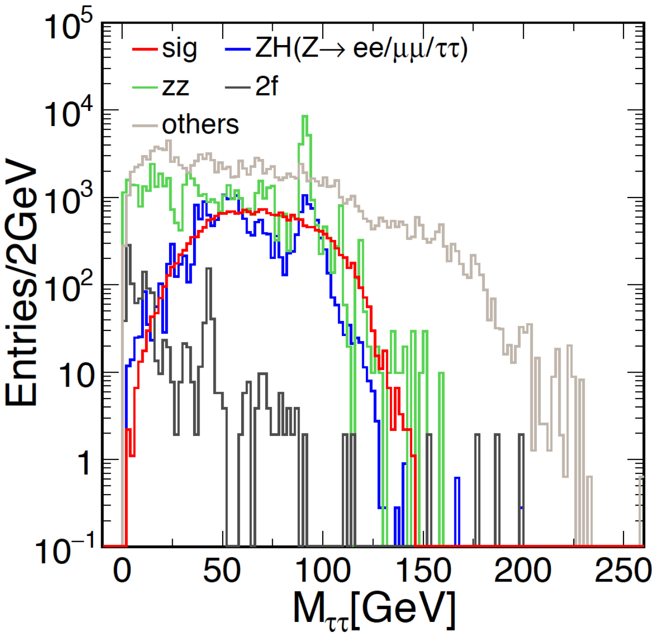
At hadronic events

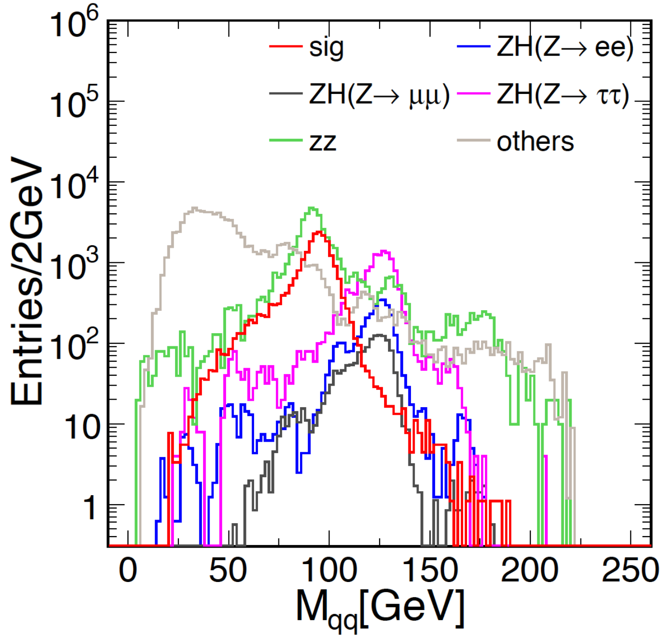


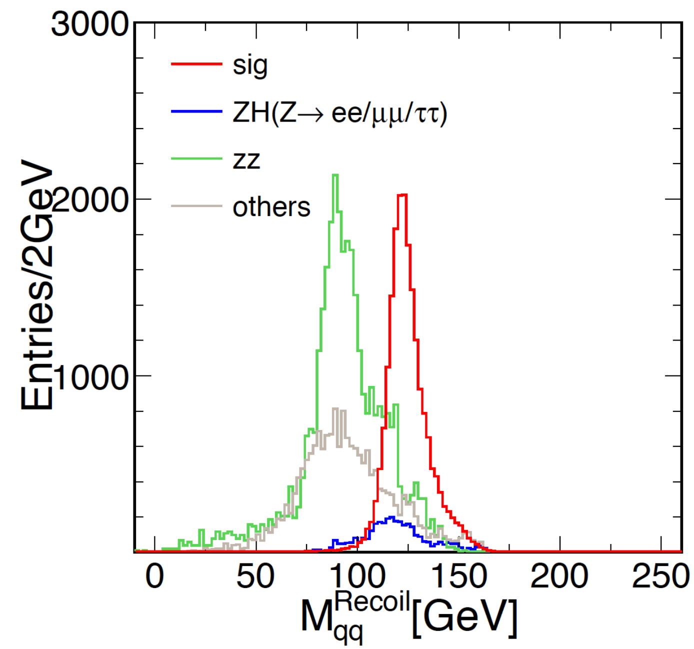


TAURUS (Tau ReconstrUction toolS) optimization in progress

Information from the ττ/qq system



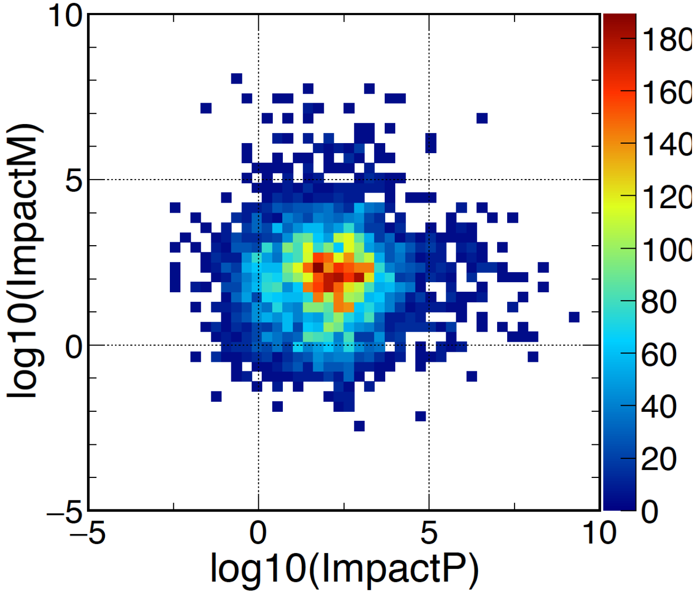


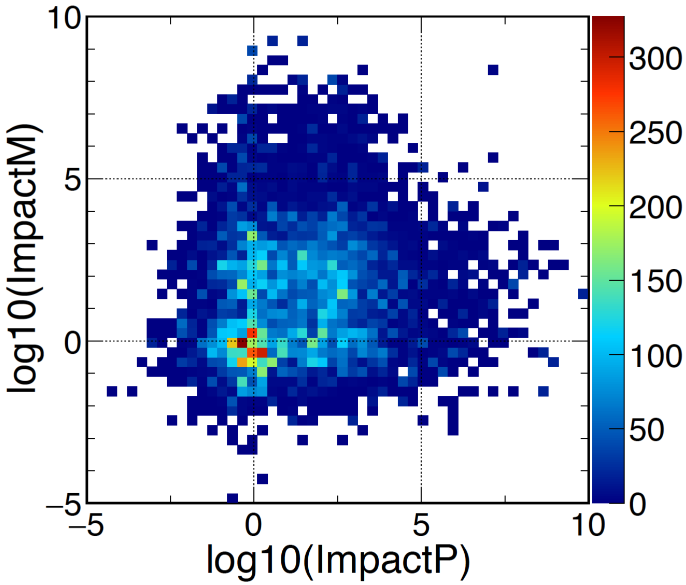


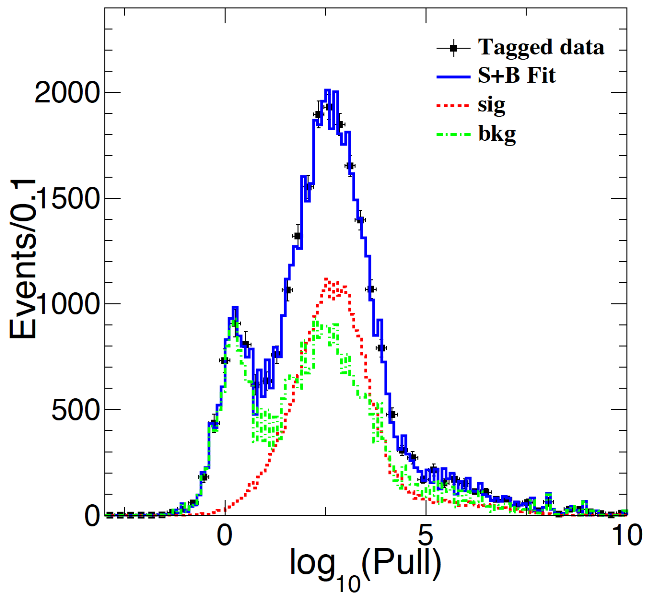
Event selection:
- Request a pair of tau;
- visible mass of di-tau pair;
- Invariant/recoil mass of di-jet;

	m_{jj}	$m_{jj\text{-recoil}}$
Signal: Z(qq)H(ττ)	91.2	125
Z(ττ)H(qq)	125	91.2
ZZ	91.2	91.2

And from the VTX...







vvH channel:

Lot of WW, ZZ backgrounds.

	BR ($H \to \tau\tau$)	$\delta(\sigma\times BR)/(\sigma\times BR)$
$\mu\mu H$	6.40	2.6%
eeH(extrapolated)	6.37	2.7%
$\nu\nu H$	6.26	2.7%
qqH	6.23	0.9%
combined	6.28	0.8%

Higgs boson coupling to τ τ

Eur. Phys. J. C75 (2015) no.12, 617

all studies with full simulation of ILD, all background processes, realistic reconstruction

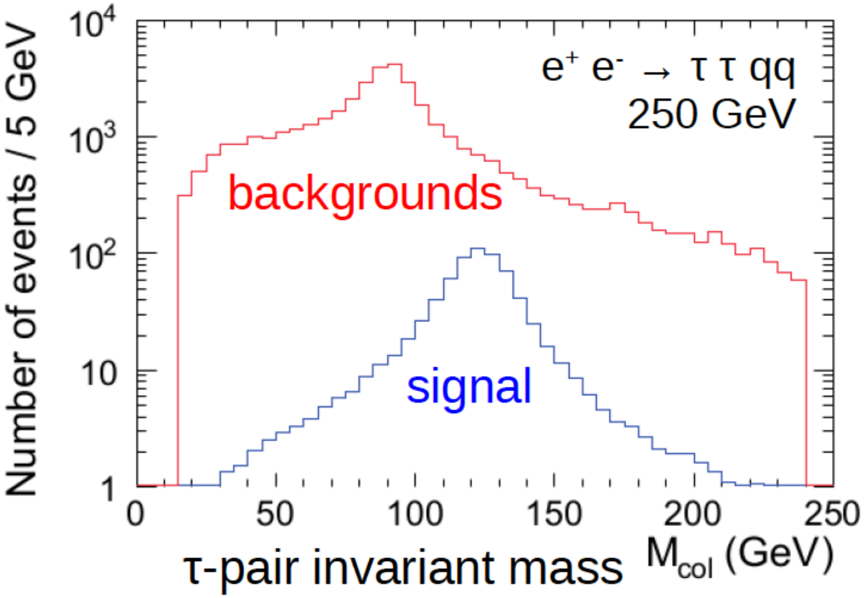
$e^+ e^- \rightarrow H Z \rightarrow \tau \tau + (ee, \mu \mu, q q)$

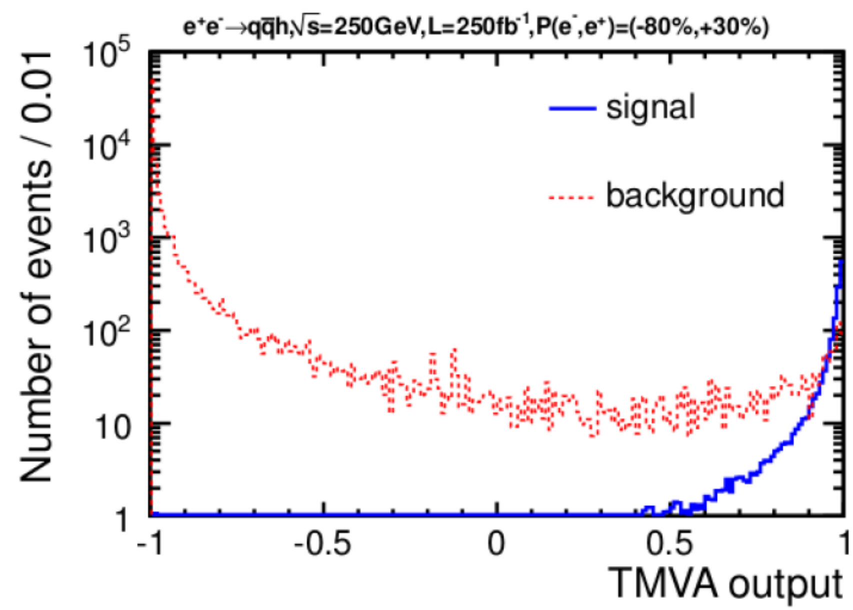
isolated narrow jets,
- 1 or 3 charged particles
- total jet charge ±1
- invariant mass < 2 GeV/c^2

various cuts to reduce backgrounds

colinear approximation to estimate
- momenta of ν from τ decay

final multivariate analysis [BDT]





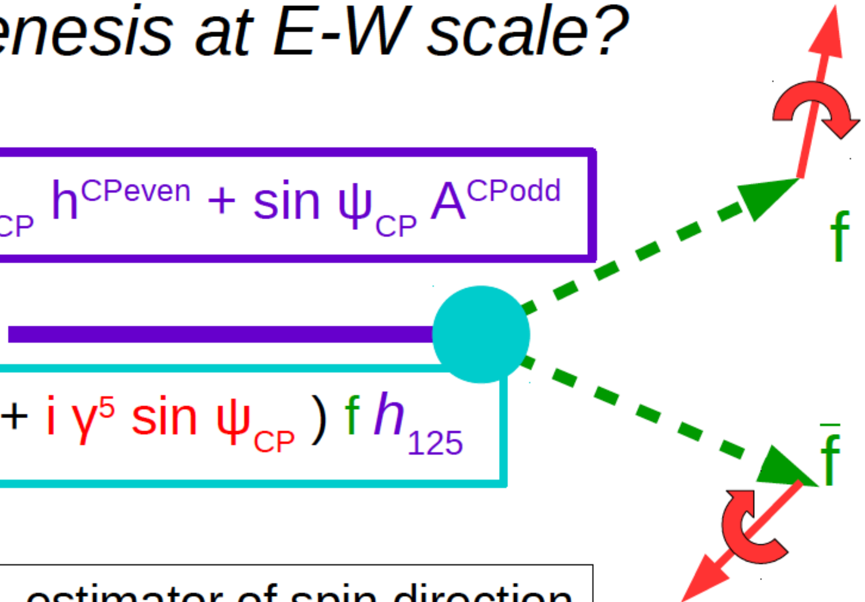
expected precision at ILC on
$\sigma(h) \cdot BR(h \rightarrow \tau \tau)$:
1.2 % [ILC250 / 2 ab^{-1}]
1.0 % [+ ILC500 / 4 ab^{-1}]

does Higgs → τ τ conserve CP ?

baryogenesis at E-W scale?

arXiv:1804.01241
to appear in PRD

$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$



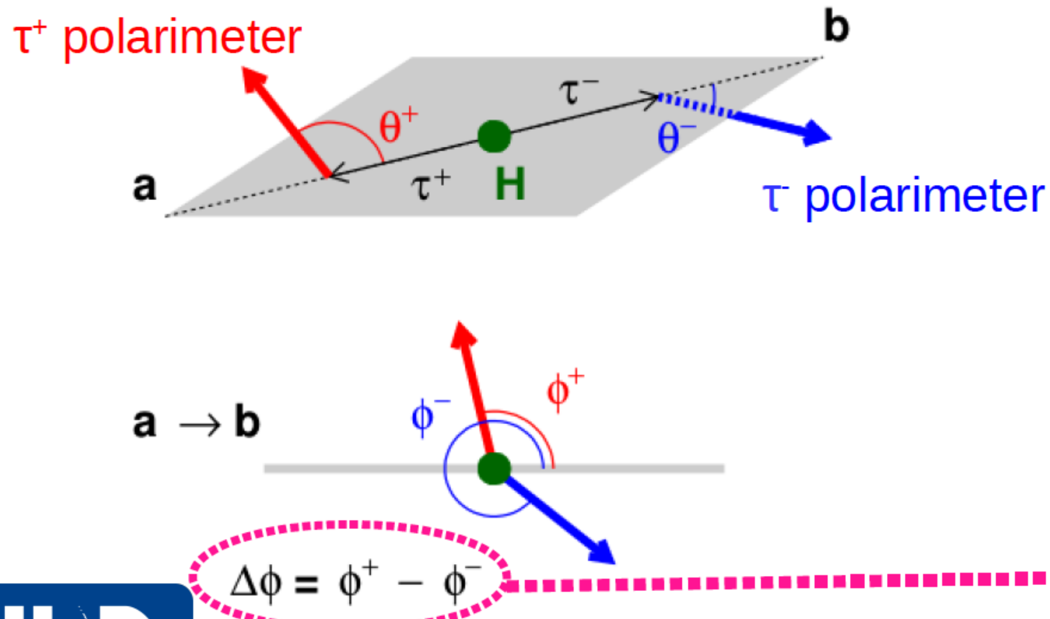
$g\, \bar{f}\, (\cos\psi_{CP} + i\, \gamma^5 \sin\psi_{CP})\, f\, h_{125}$

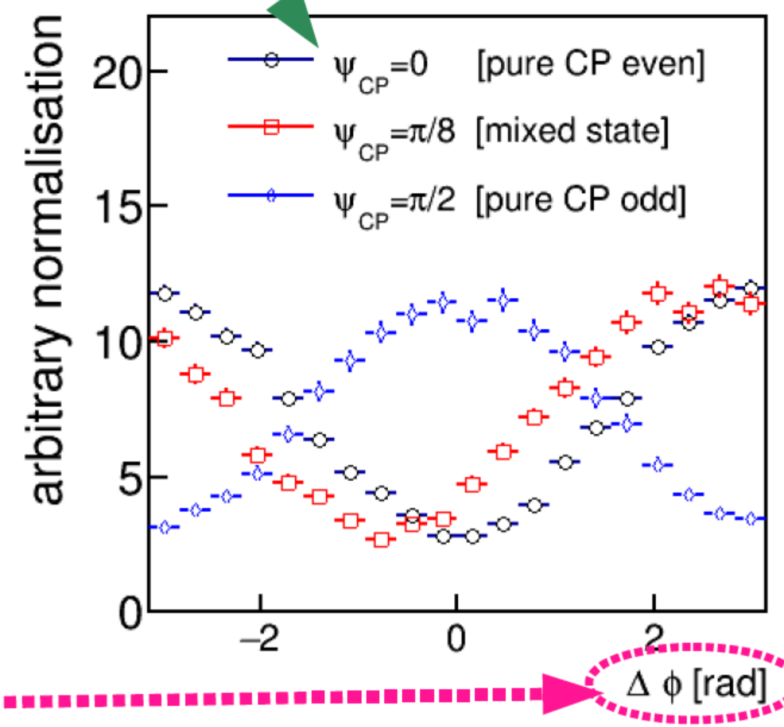
h is a spin 0 state:

$| f\ \bar{f} \rangle = |\uparrow\downarrow\rangle + e^{2i\,\psi CP} |\downarrow\uparrow\rangle$

[ψ_{CP} = 0 CP even,
$\pi/2$ CP odd]

"**polarimeter**" - estimator of spin direction from τ decay products





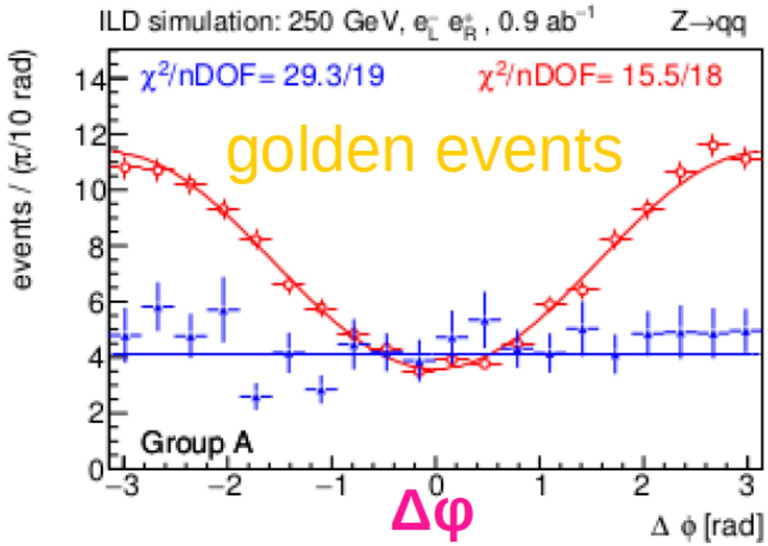
CP in h → τ τ : sensitivity

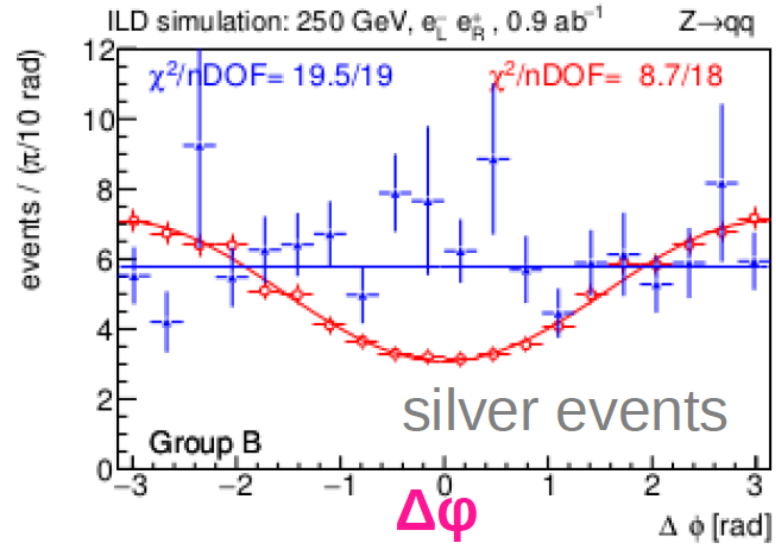
arXiv:1804.01241
to appear in PRD

signal background

$\tau^\pm \rightarrow \pi^\pm \nu$ [B.R.11%]

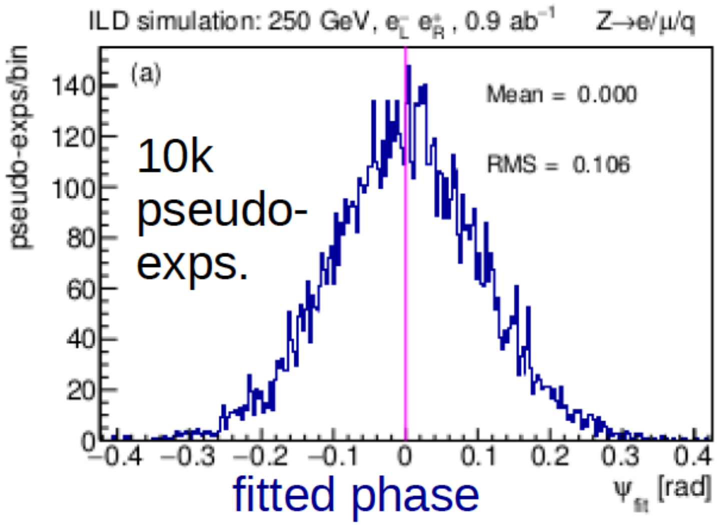
$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu$ [B.R. 26%]





signal: **phase** of Δφ distribution sensitive to CP
backgrounds: consistent with flat distribution

pseudo-experiments: simultaneous likelihood fit to Δφ distributions in all channels



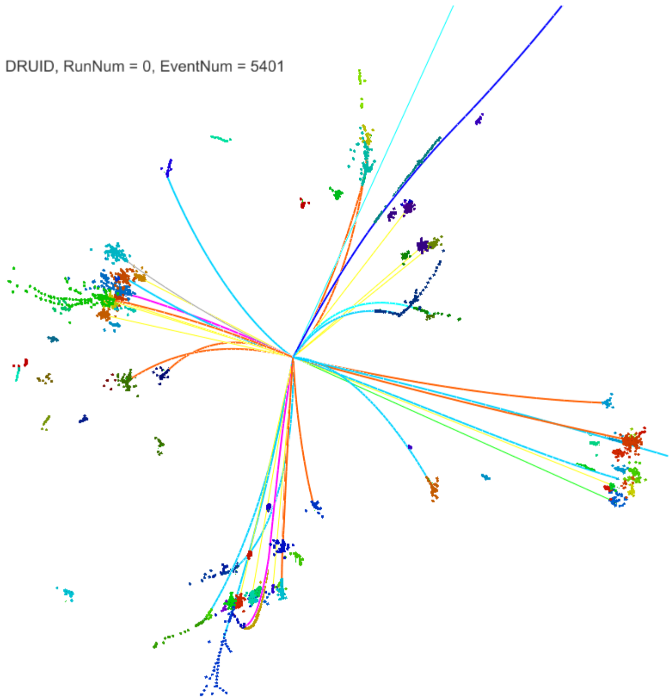
with 2 ab^{-1} @ ILC250, measure ψ_{CP} to **75 mrad** (4.3 deg)

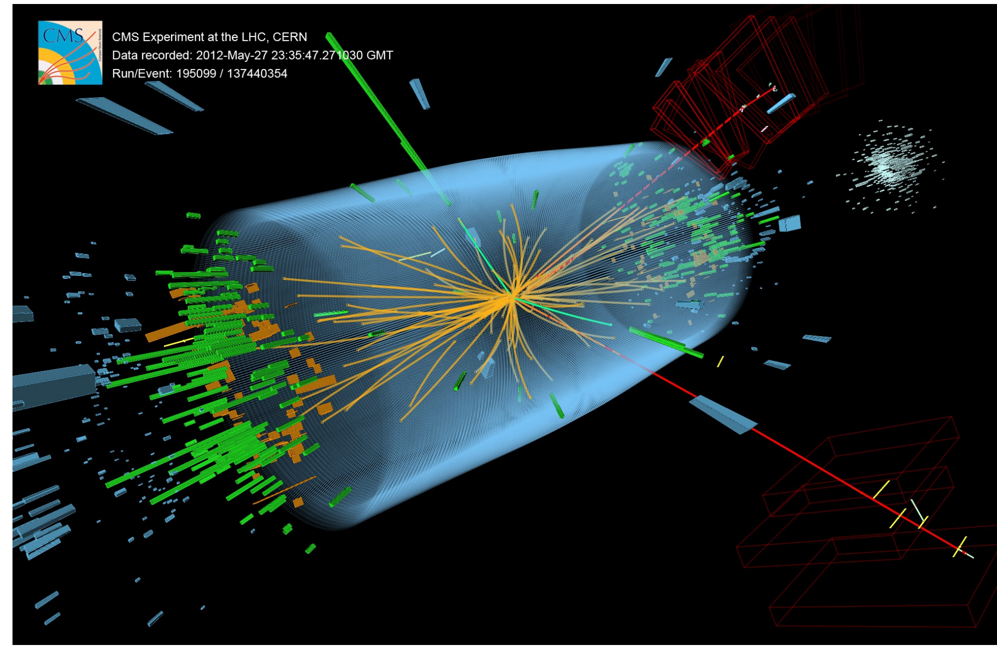
Summary

- An electron positron Higgs factory is crucial for future High energy physics exploration – multiple proposals
- The $H \rightarrow \tau\tau$ is an excellent benchmark for the physics potential and detector design study
- The $\mu(H \rightarrow \tau\tau)$ can be measured to o(1%) accuracy at CEPC/ILC...
  - CEPC: 0.8% with 1 Million Higgs boson; Cut based analysis that combines the information from di-tau, di-jet, and VTX system.
  - ILC: 1.2% with 0.6 Million Higgs, MVA based analysis.
- The CP phase can be measured to an accuracy of ~ 4 degree at ILC
- Intriguing physics with taus at future electron positron Higgs factories, lots of other benchmarks to be explored – **Your idea/help is more than welcome!**

Backup

Higgs measurement at e+e- & pp

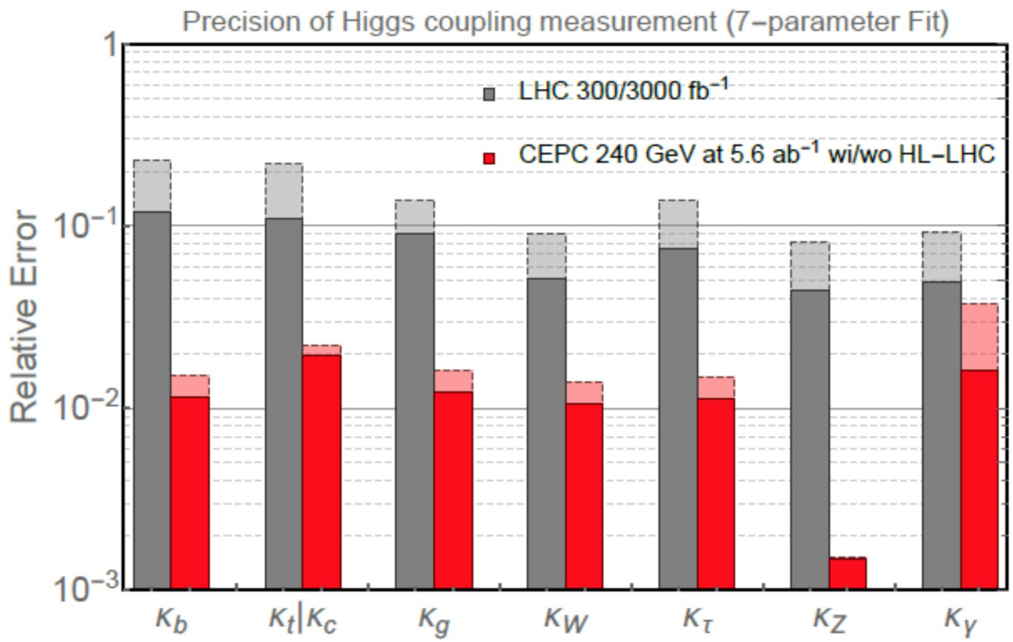


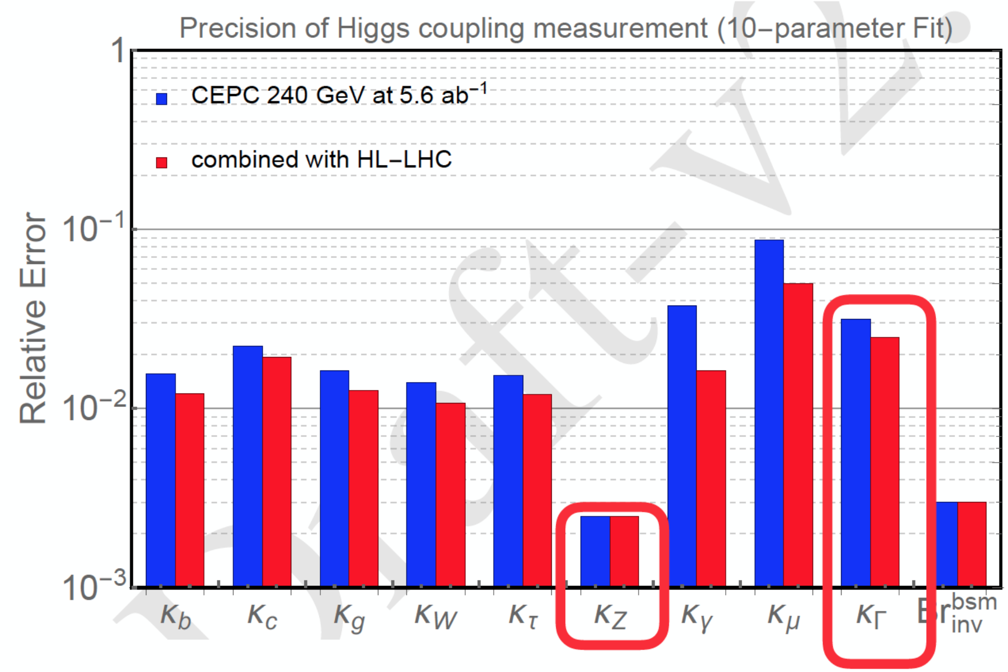


	Yield	efficiency	Comments
LHC	Run 1: 10^6 Run 2/HL: 10^{7-8}	~o(10^{-3})	High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to g(ttH), and even g(HHH)
CEPC	10^6	~o(1)	Clean environment & Absolute measurement, Percentage level accuracy of Higgs width & Couplings

Complementary

Higgs coupling measurements





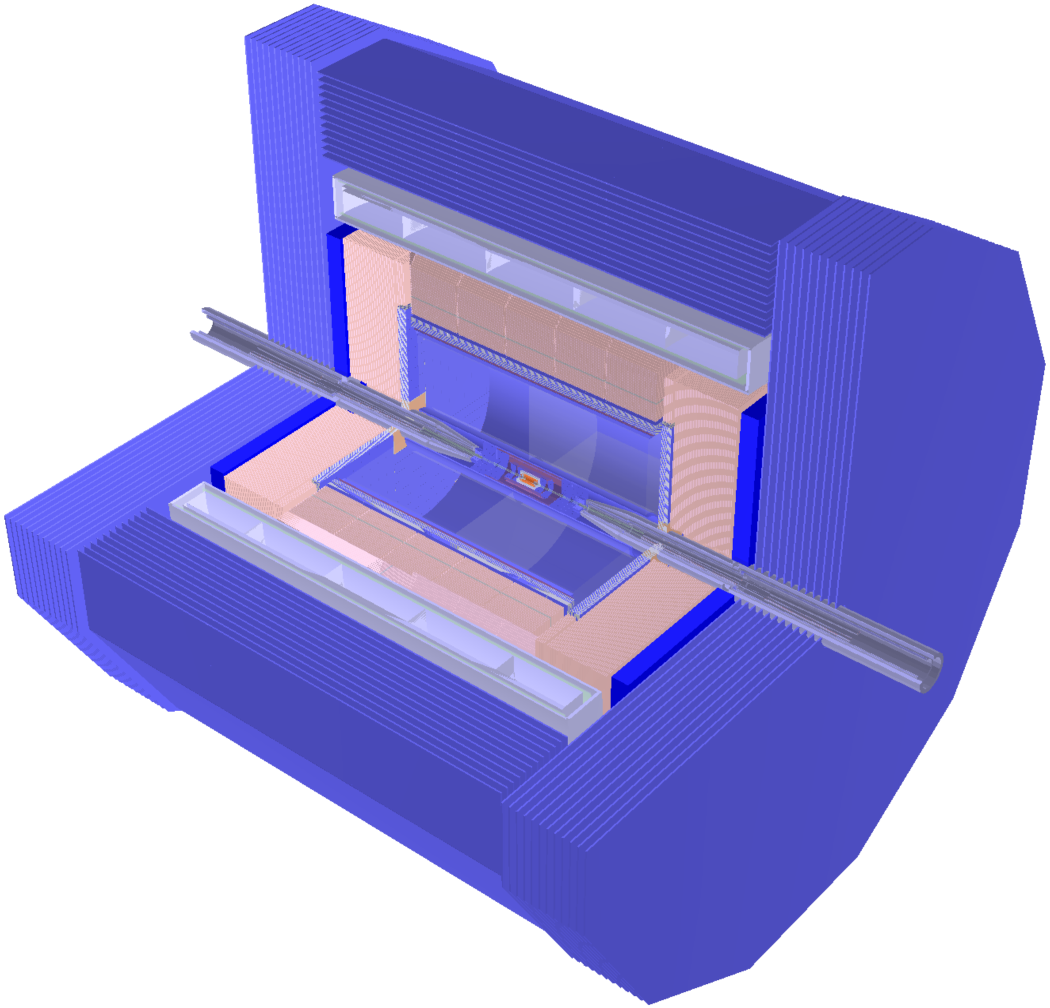
Full simulation on measurement with Event Counting

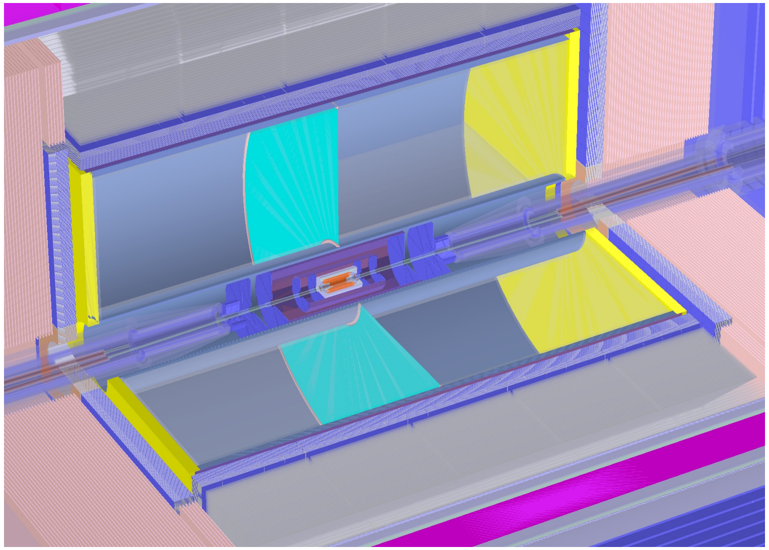
Comparing to HL-LHC: accuracy improved by 1 order of magnitude

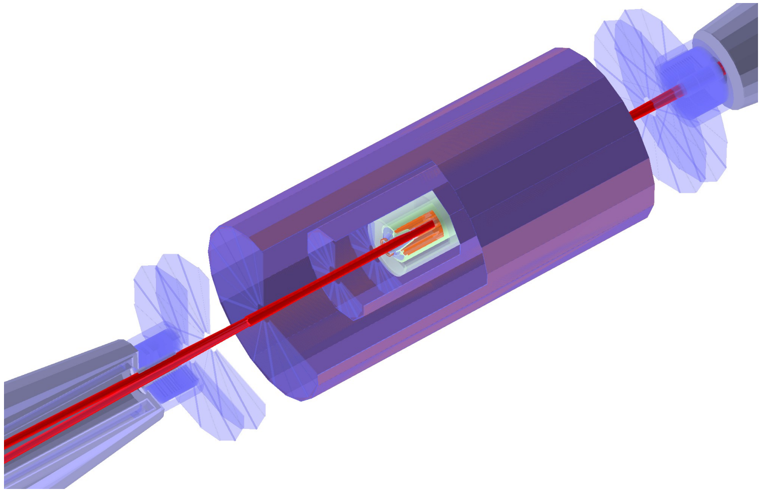
Combined with HL-LHC: several measurement can be significantly improved

To be covered: Differential Measurements, etc.

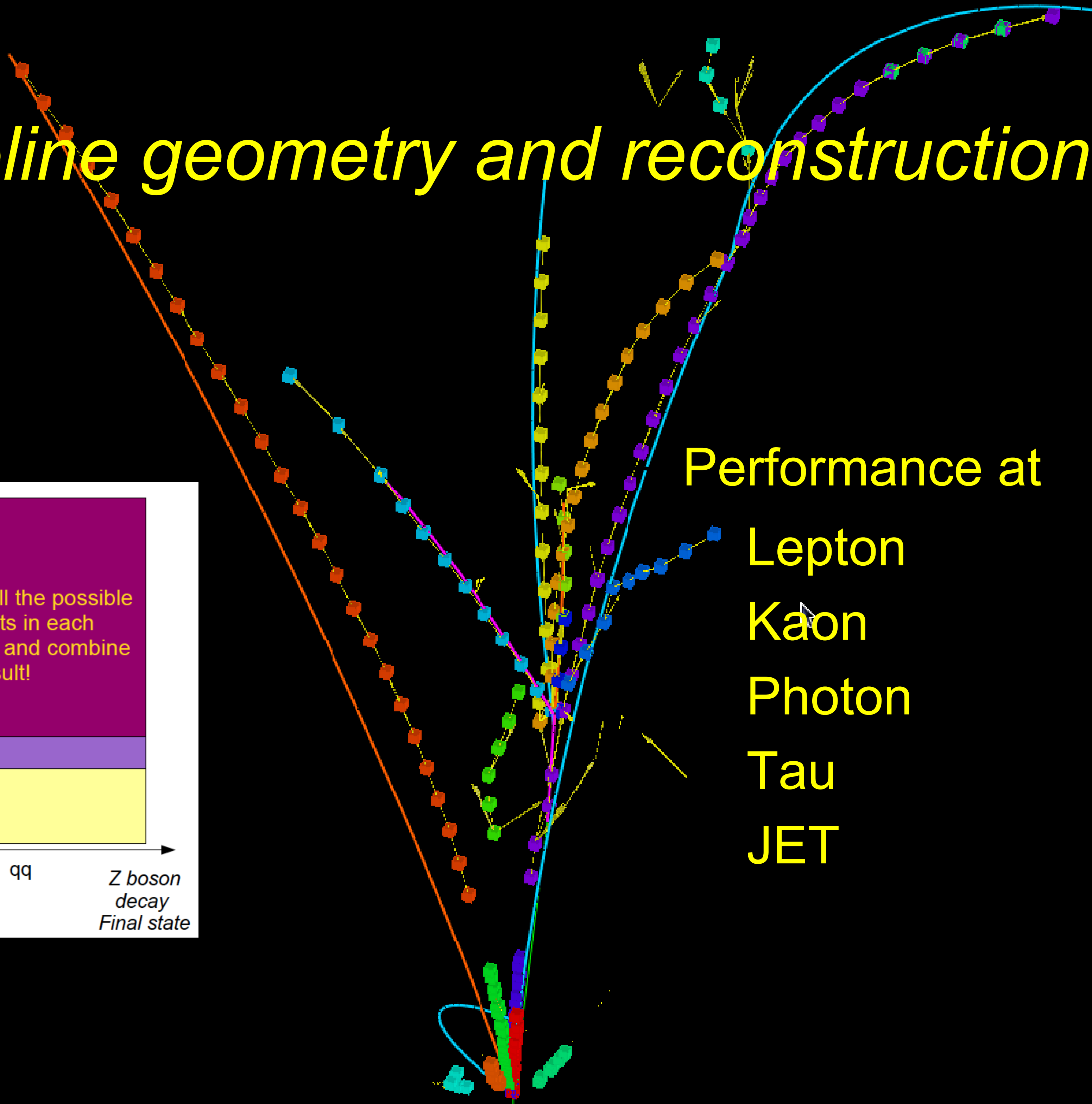
Baseline detector Geometry





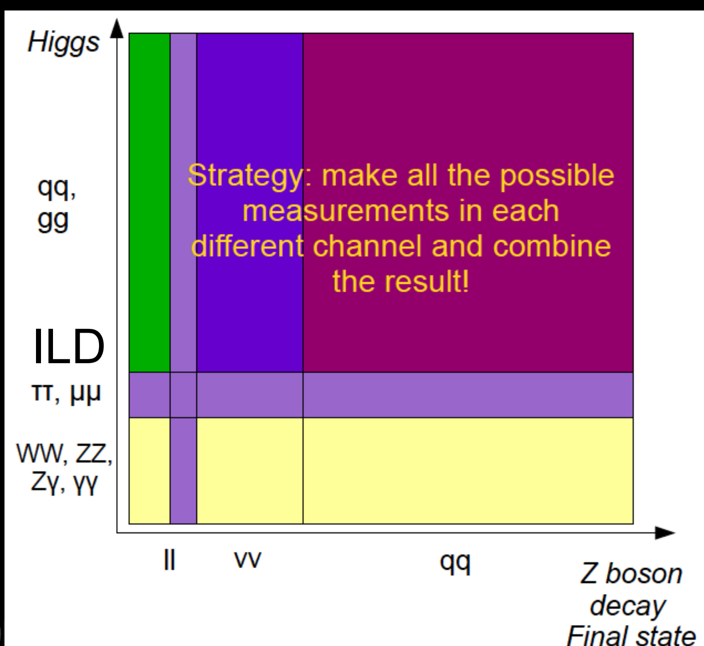


Baseline geometry and reconstruction



Performance at

- Lepton
- Kaon
- Photon
- Tau
- JET



The optimization of the Vertex

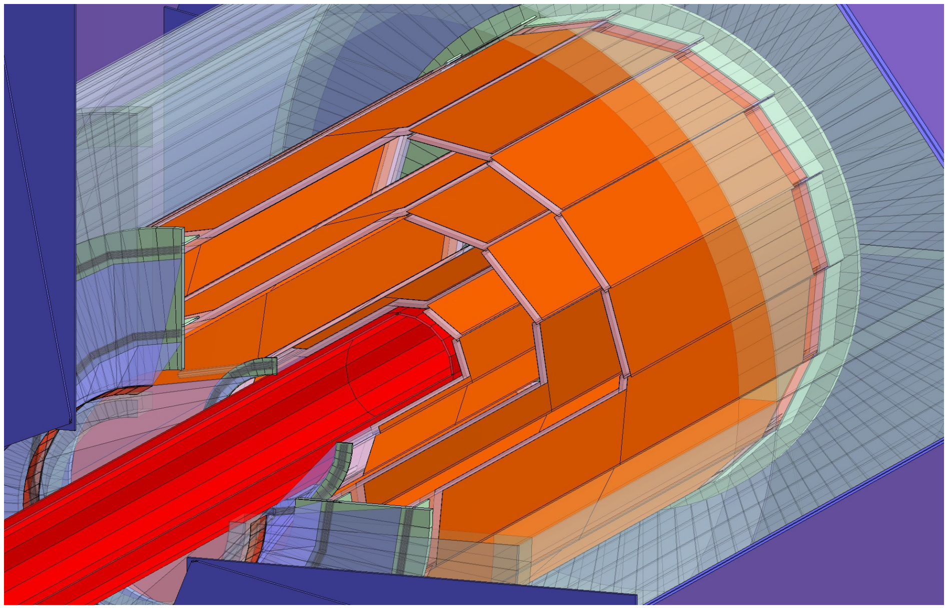


Table 1. Design parameters of the CEPC vertex system.

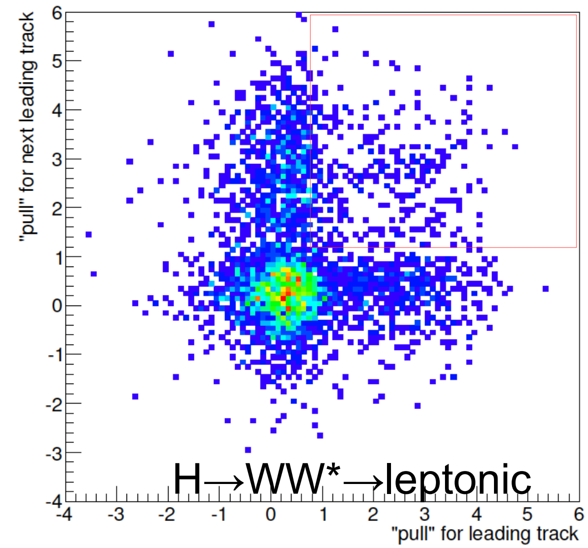
	R(mm)	$\mid Z \mid$(mm)	$\sigma(\mu m)$	material budget
Layer 1	16	62.5	2.8	0.15%/X_0
Layer 2	18	62.5	6	0.15%/X_0
Layer 3	37	125.0	4	0.15%/X_0
Layer 4	39	125.0	4	0.15%/X_0
Layer 5	58	125.0	4	0.15%/X_0
Layer 6	60	125.0	4	0.15%/X_0

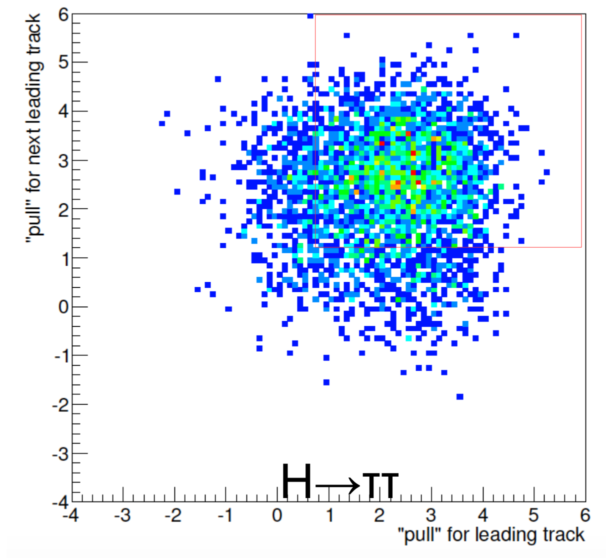
Table 2. Reference geometries

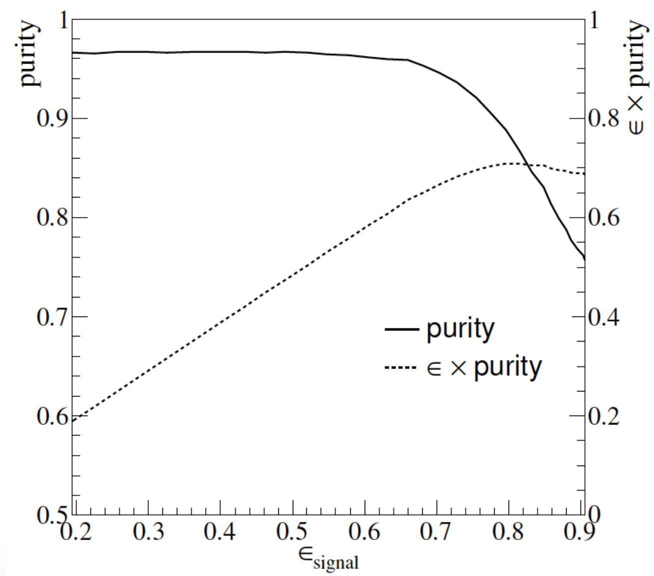
	Scenario A (Aggressive)	Scenario B (Baseline)	Scenario C (Conservative)
Material per layer/X_0	0.075	0.15	0.3
Spatial resolution/μm	1.4 - 3	2.8 - 6	5 - 10
R_{in}/mm	8	16	23

Zhigang & Dan: *g(Hττ)* at μμH

	$\mu\mu H\tau\tau$	$\mu\mu H$ inclusive bkg	ZZ	WW	single$W$	single$Z$	$2f$
total generated	2292	33557	5711445	44180832	15361538	7809747	418595861
after preselection	2246	32894	122674	223691	0	86568	1075886
$N_{Trk}(A/B) < 6$ & $N_{Ph}(A/B) < 7$	2219	1039	2559	352	0	9397	25583
BDT>0.78	2135	885	484	24	0	157	161
efficiency	93.15%	2.63%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%





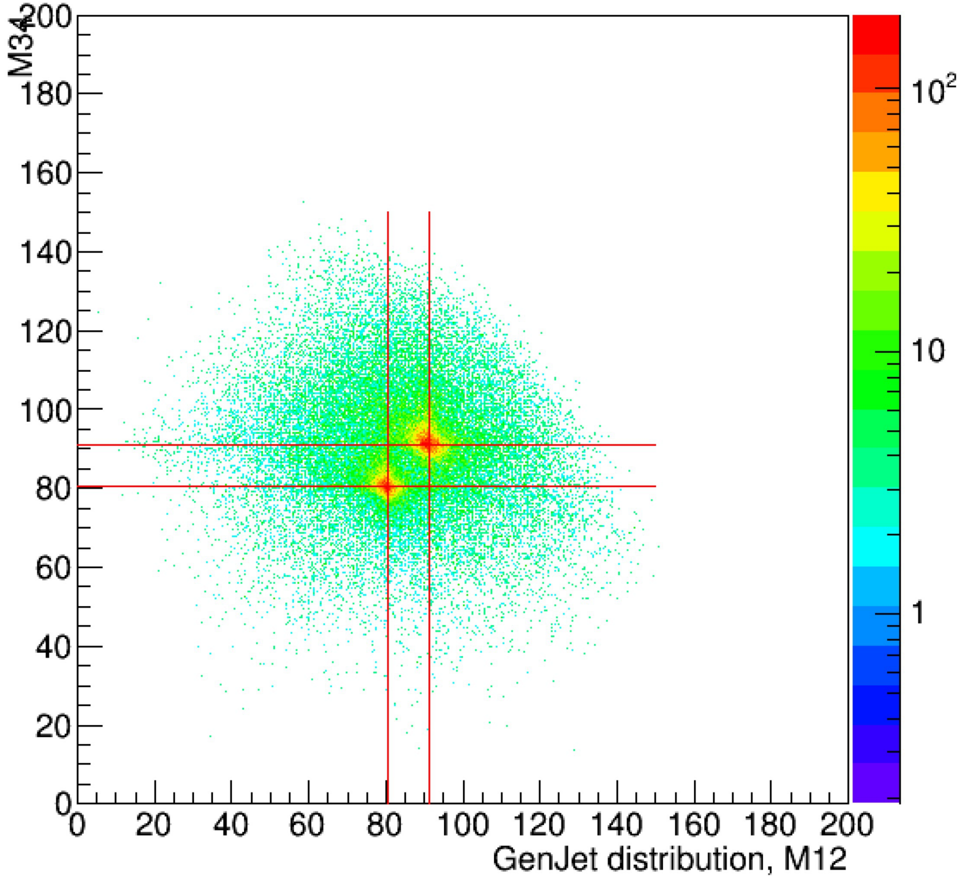


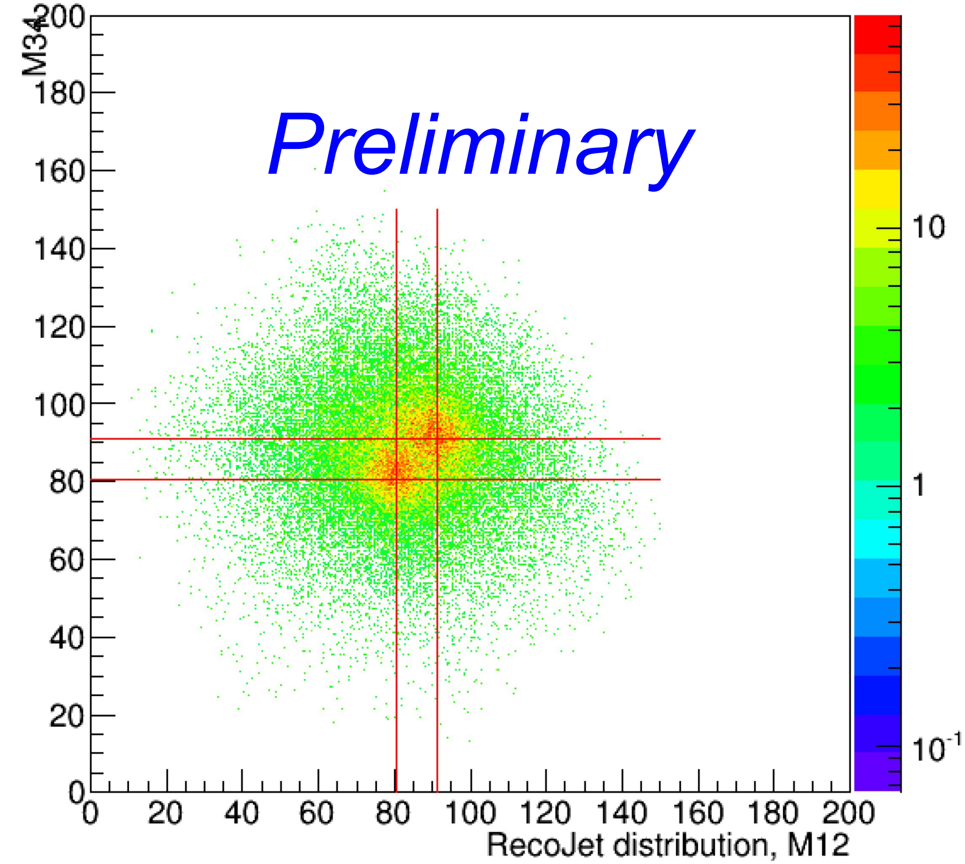
situations	best	baseline	worst
$\epsilon \cdot$ purity	0.77 ± 0.01	0.71 ± 0.01	0.68 ± 0.01

Worst: ALICE ITS parameter
Best: 2 times more aggressive w.r.t baseline
In inner Radius, Material & resolution

Conclusion: in this benchmark channel, VTX is sensitive but not crucial

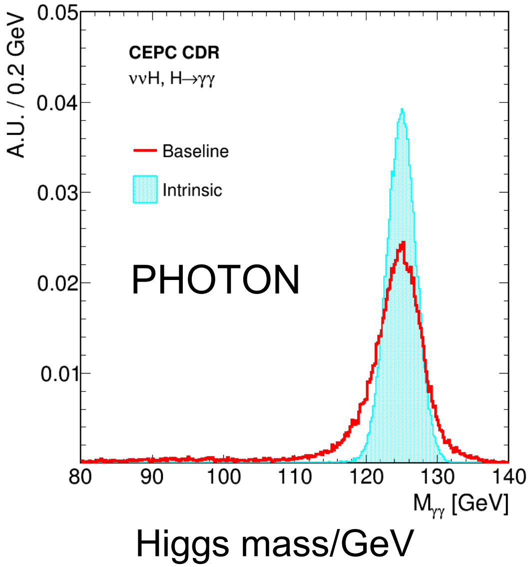
WW/ZZ→4 jet event separation at full reconstruction

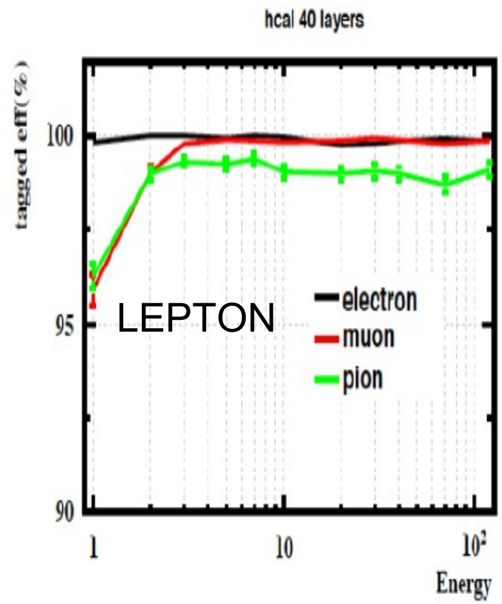


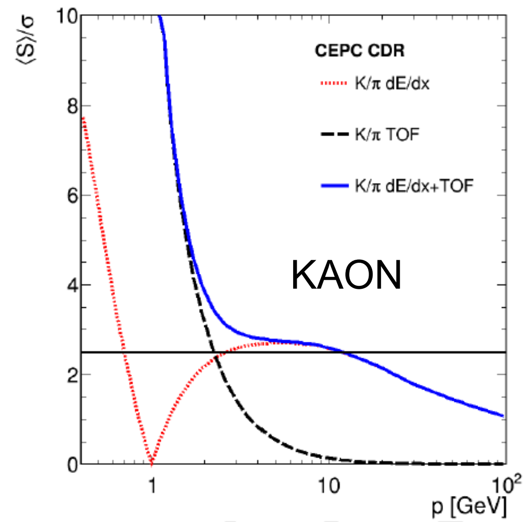


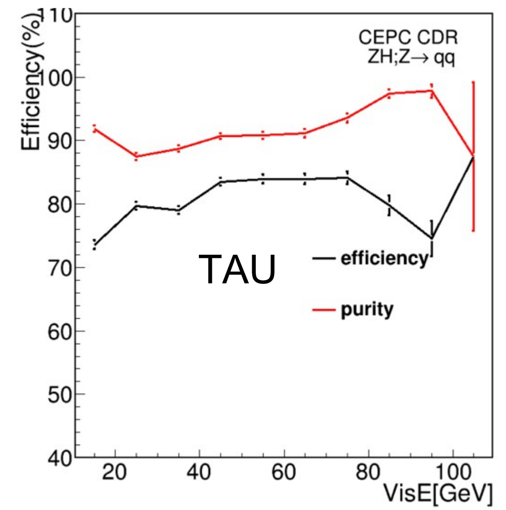
Inclusive WW/ZZ sample at 240 GeV c.m.s., each with 15k statistic
Jet Clustering effect is very significant
With realistic Jet Clustering and Arbor Reconstruction: WW/ZZ **can be separated**

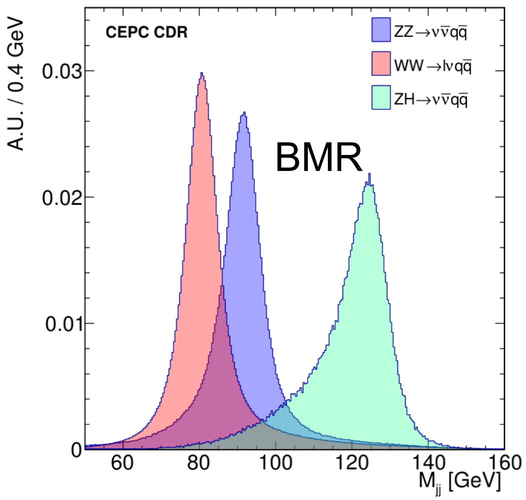
Physics Objects

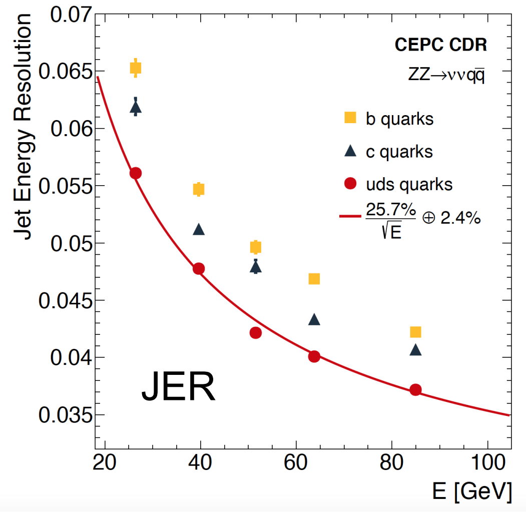


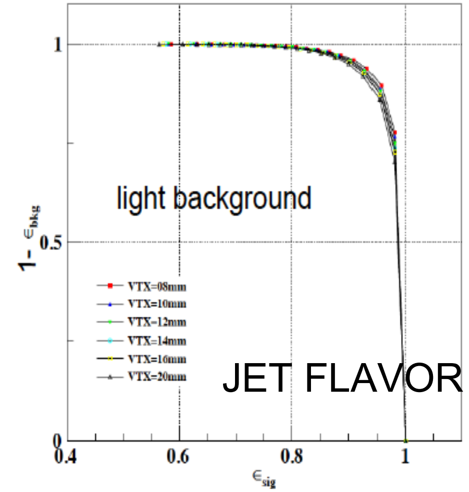


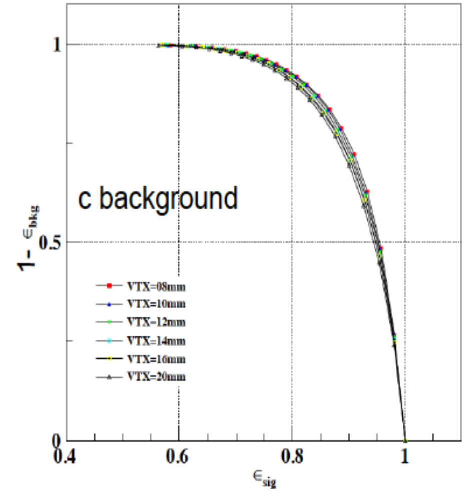




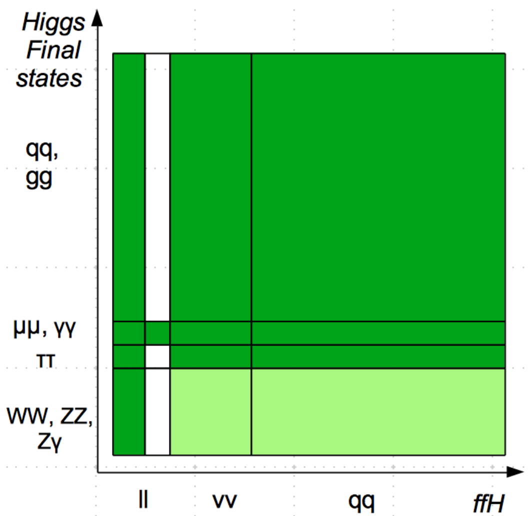


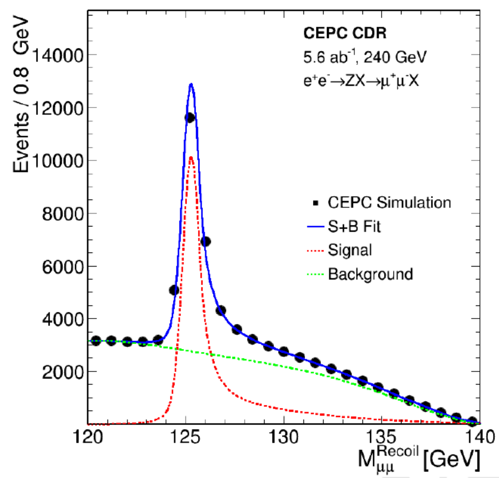


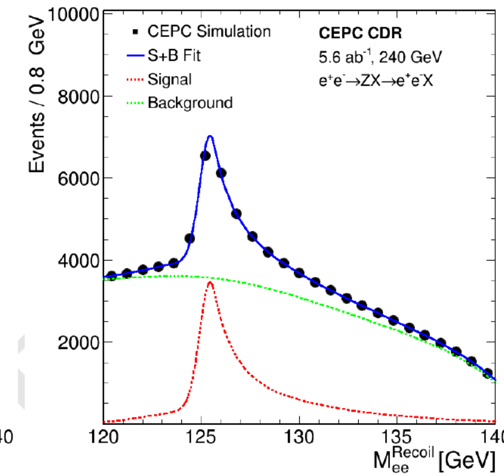




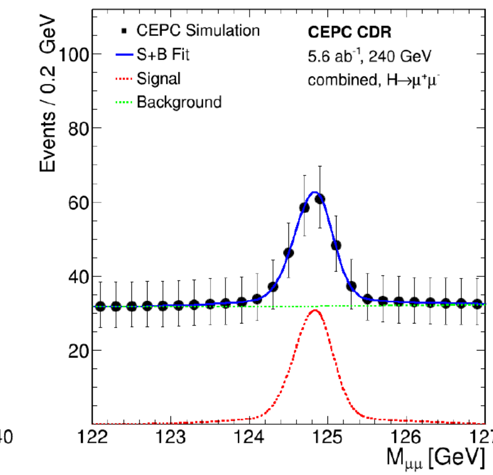
Higgs benchmark analyses



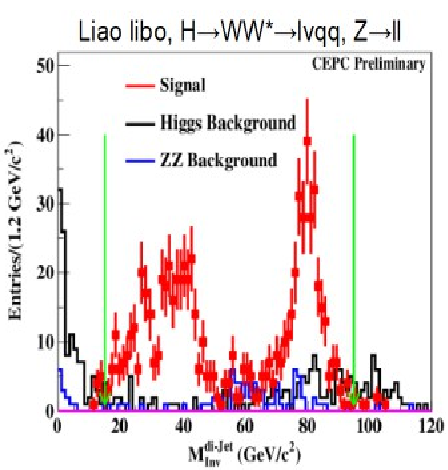




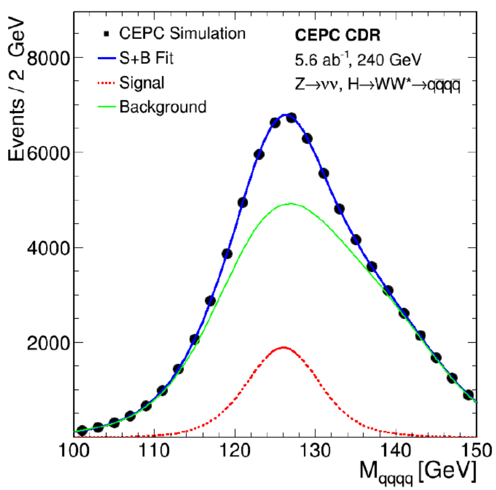
σ(ZH) measurements



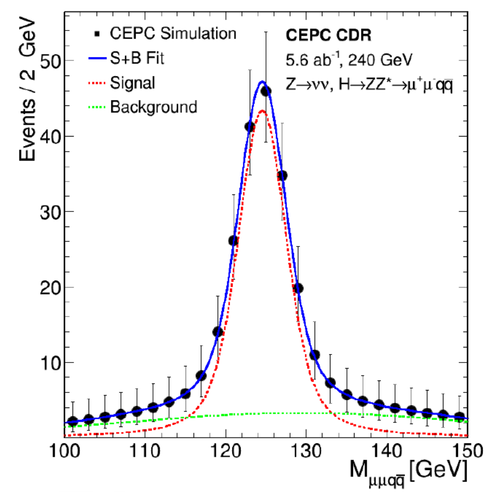
Br(H→μμ)



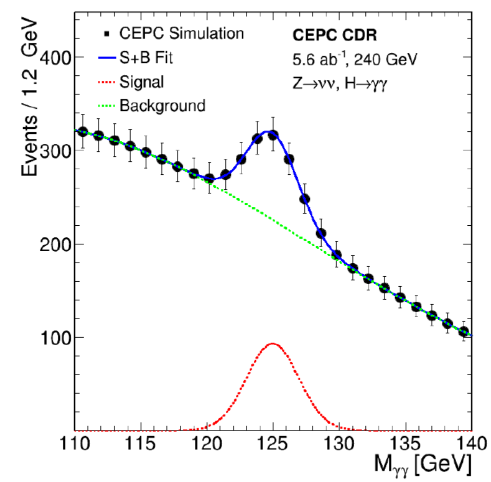
Br(H→WW)



σ(ννH)*Br(H→bb)



Br(H→ττ)



Br(H→γγ) (Asimov)

Jet Energy Scale

- JES ~ with 1% of the unity (without correction)
- Larger JES Observed at
  - Leading jets (correlated with energy)
  - Overlap/endcap region (Larger confusion term)
- *JES ~ with 0.1% of unity anticipated after correction (geometry/energy dependent)*