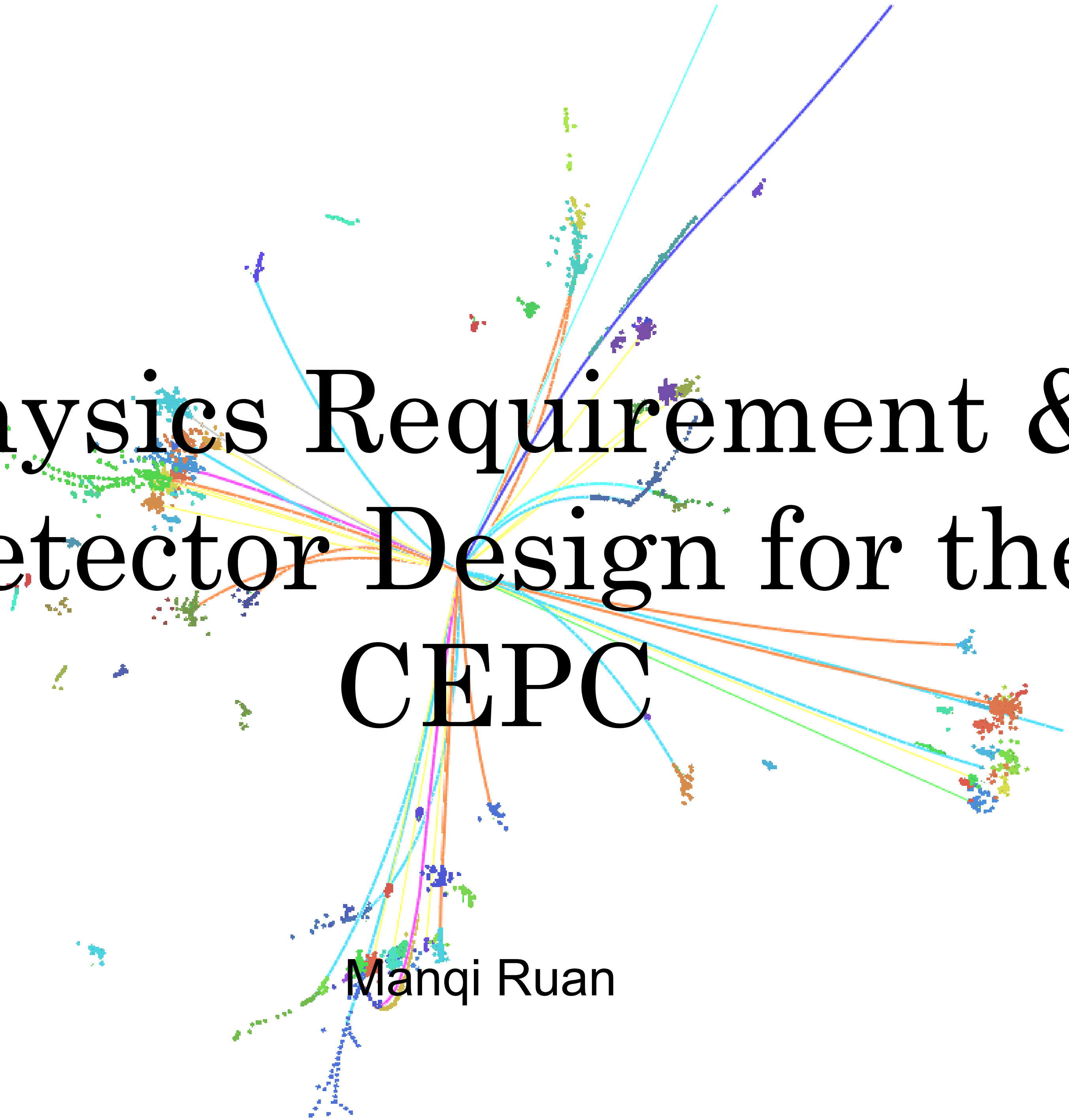
Physics Requirement & Detector Design for the CEPC

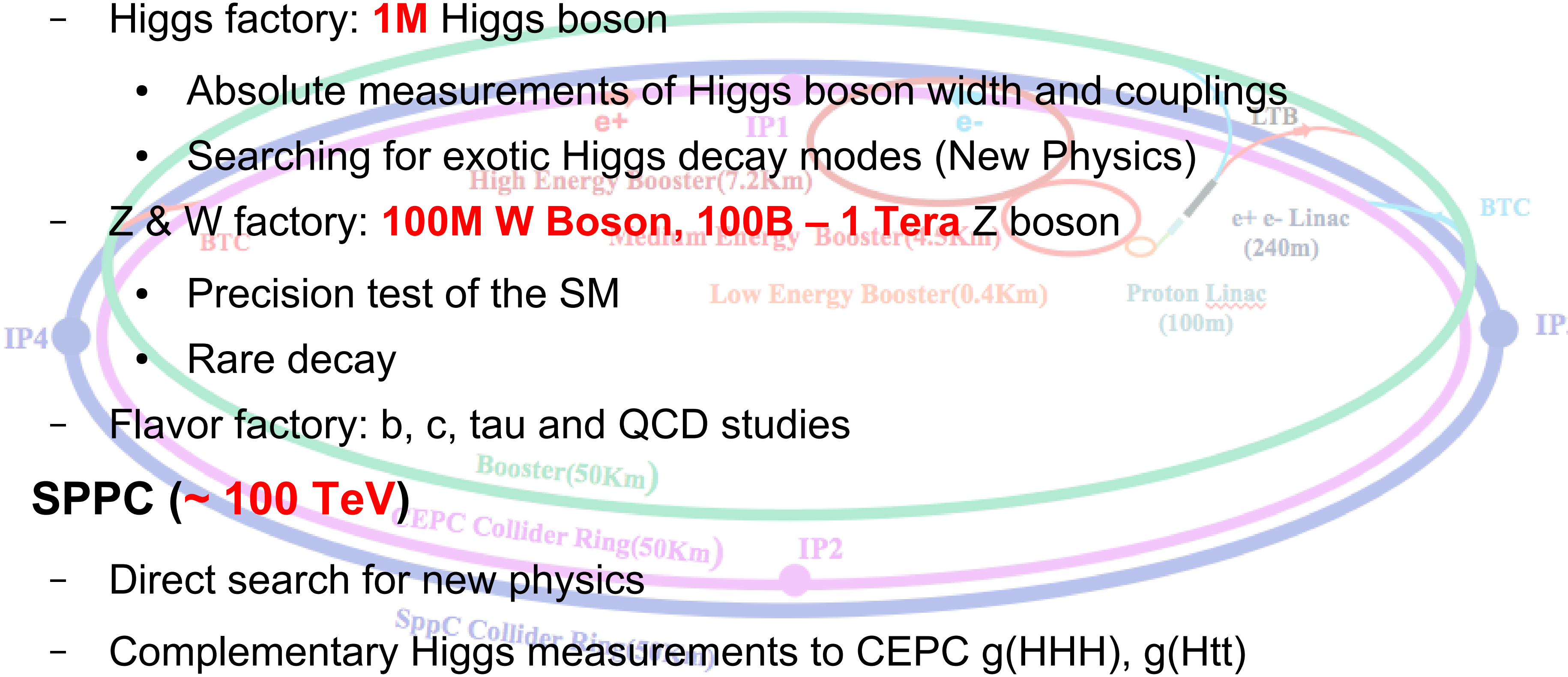


Manqi Ruan

提纲

- CEPC：物理及其对探测器的性能需求
- CPEC CDR 基线探测器：
  - 思路、构造，
  - 其探测器性能、及其对需求的满足
- 新设计
  - 关键问题
- 小结

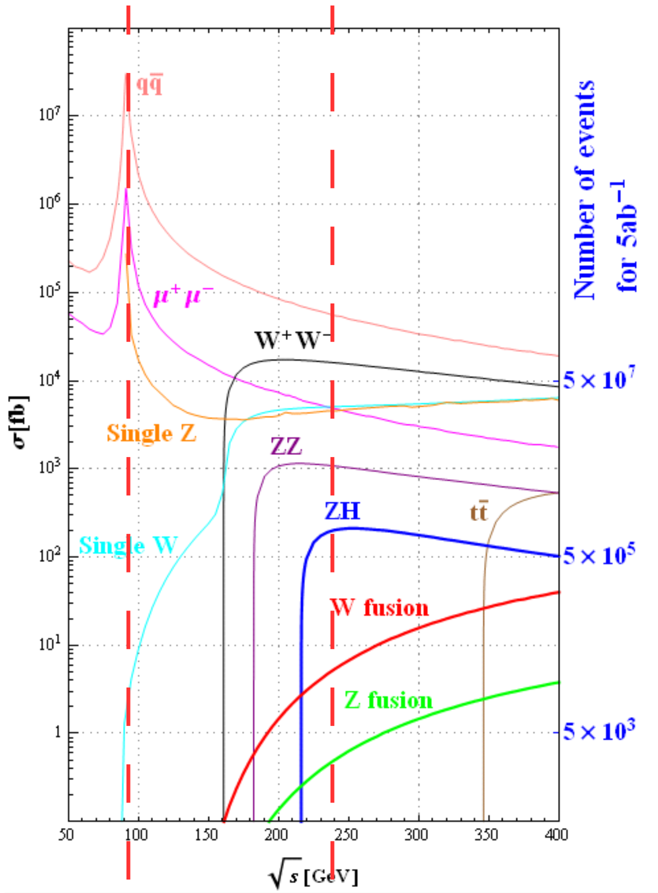
Science at CEPC-SPPC

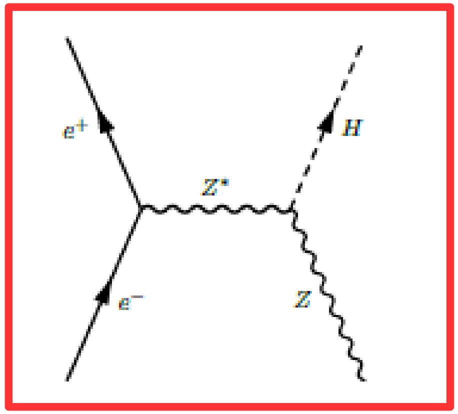


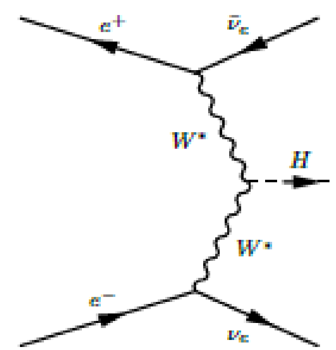
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **100M W Boson, 100B – 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**

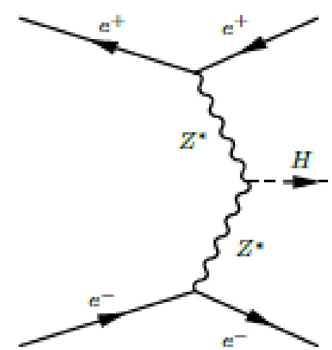
Complementary

Higgs @ CEPC





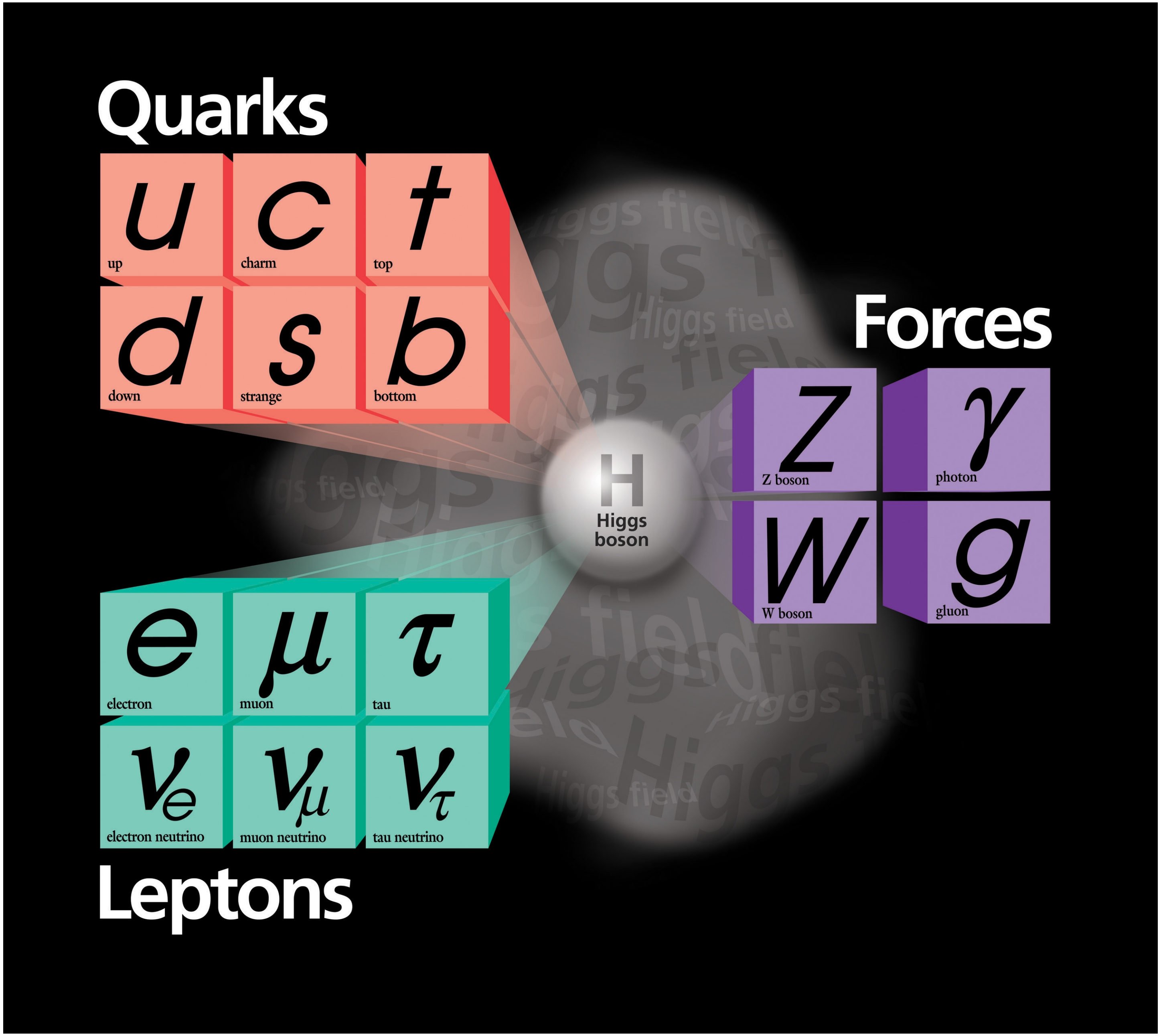




Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

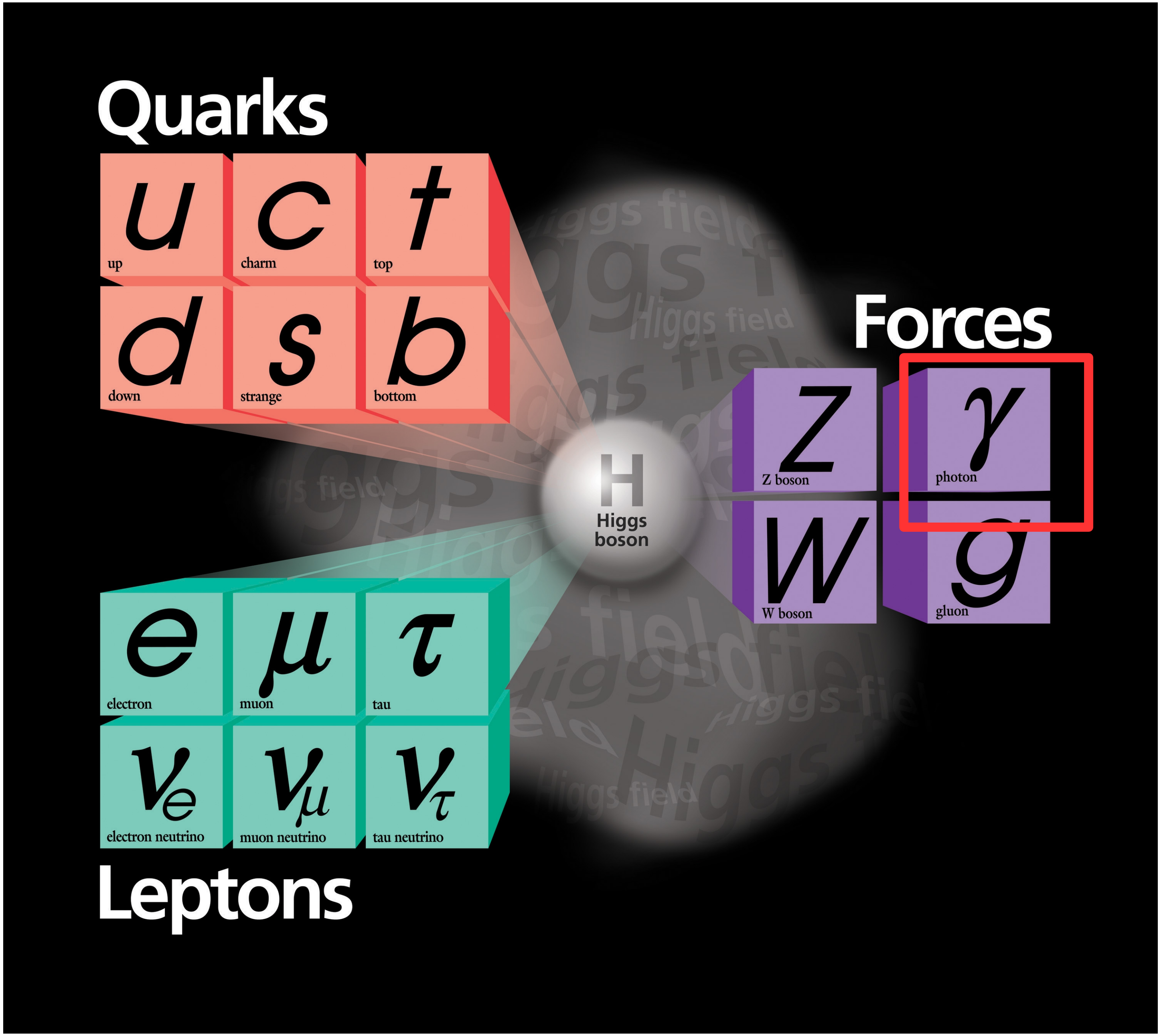
Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H→X)), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings



Key Physics Object (High Level)

- Leptons (electron & muon)
- Tau
- Photon (and pi-0, etc)
- Charged stable hadron
  - Pion, Kaon, Proton, ...
- Neutral Hadron
  - Klong, neutron...
- Jet: with flavor and charge
- Missing energy/momentum



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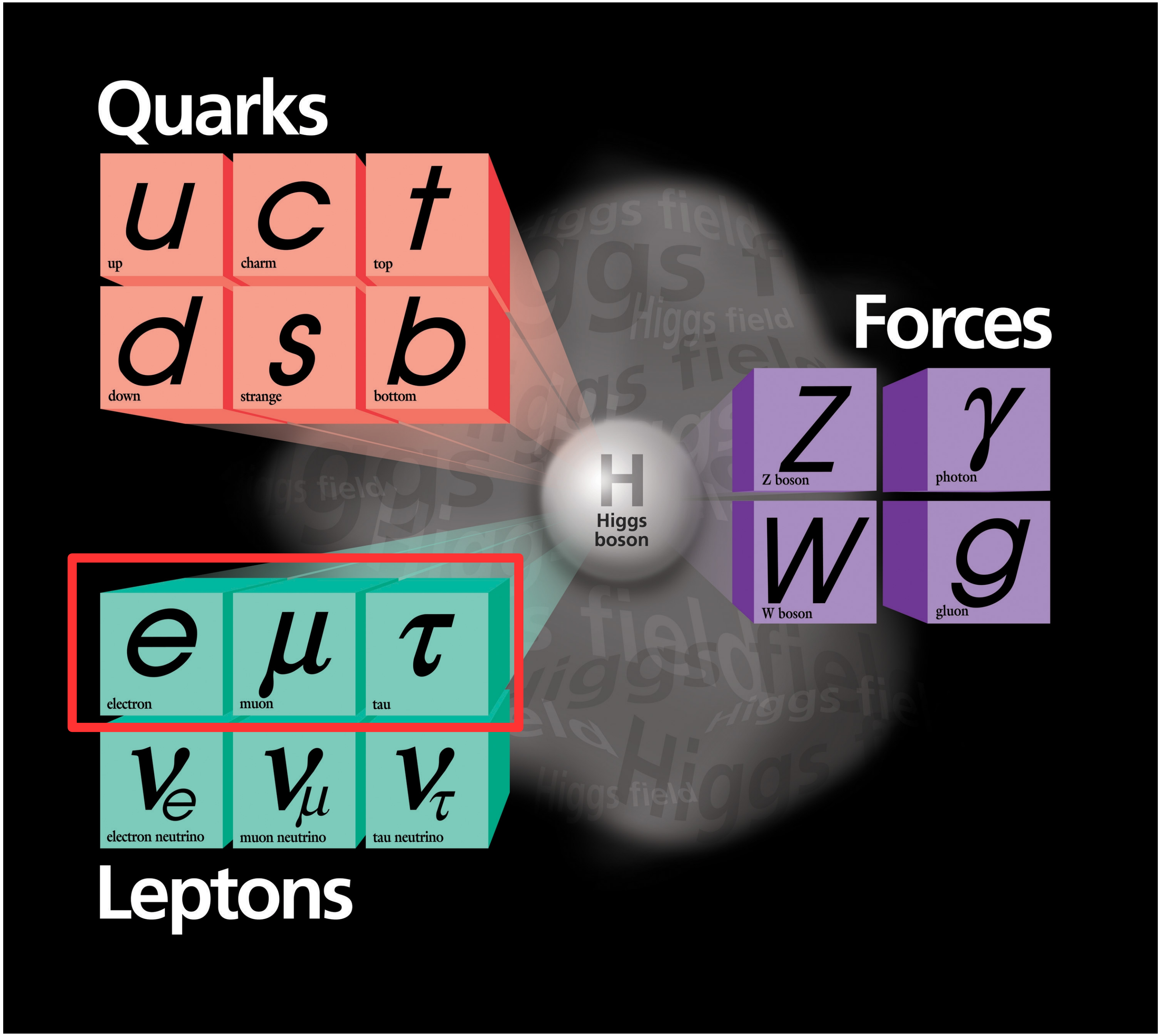

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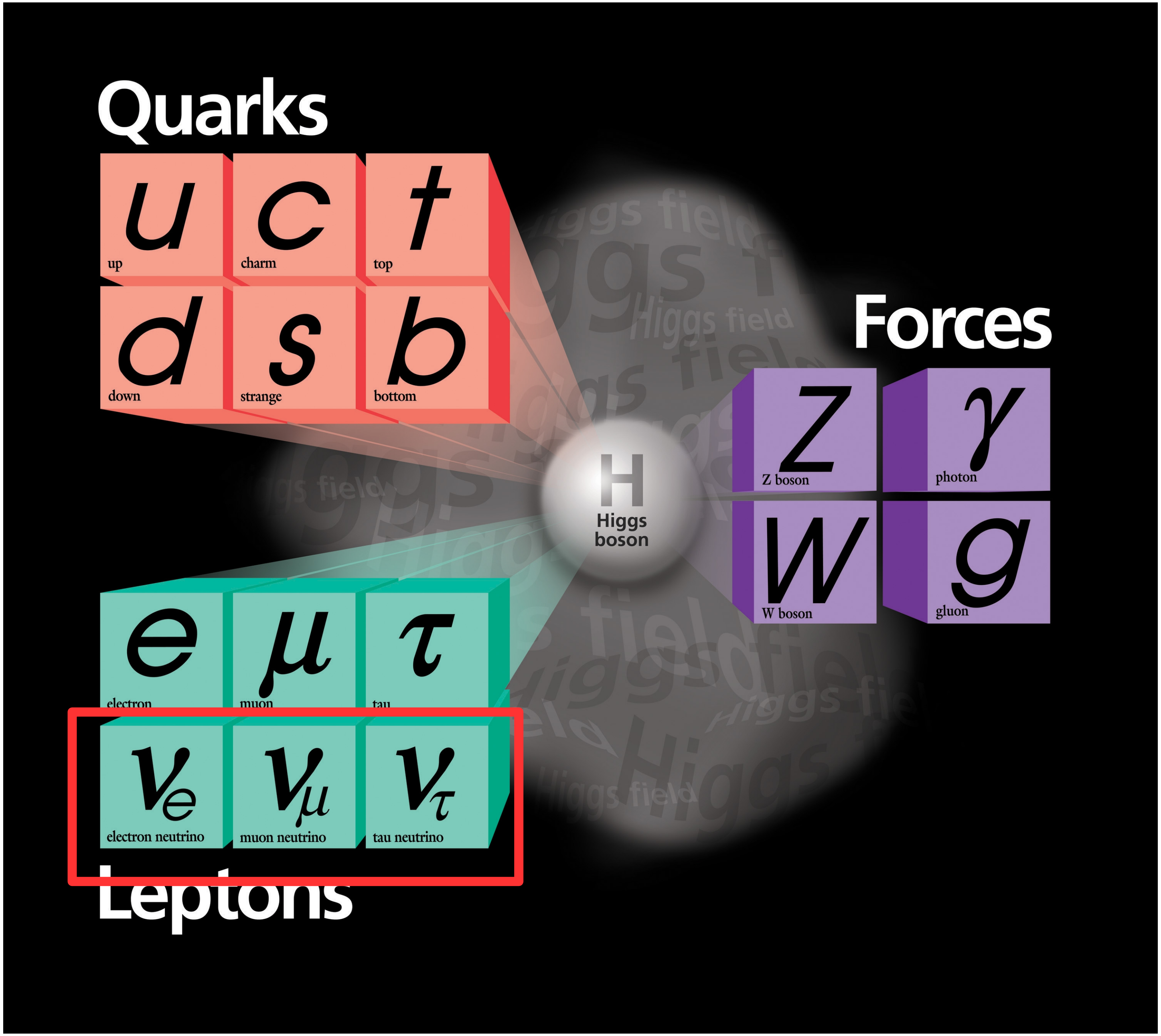

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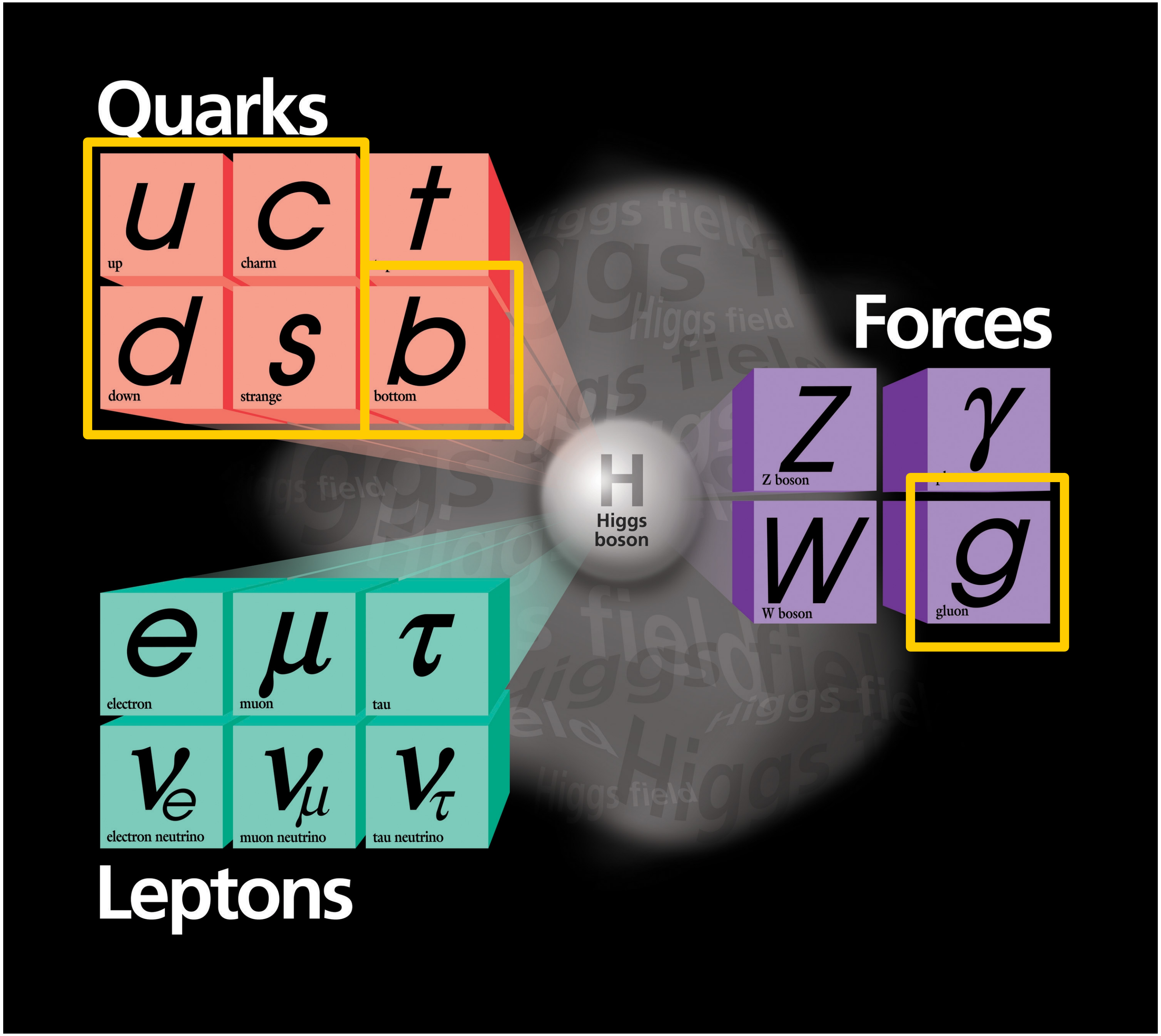

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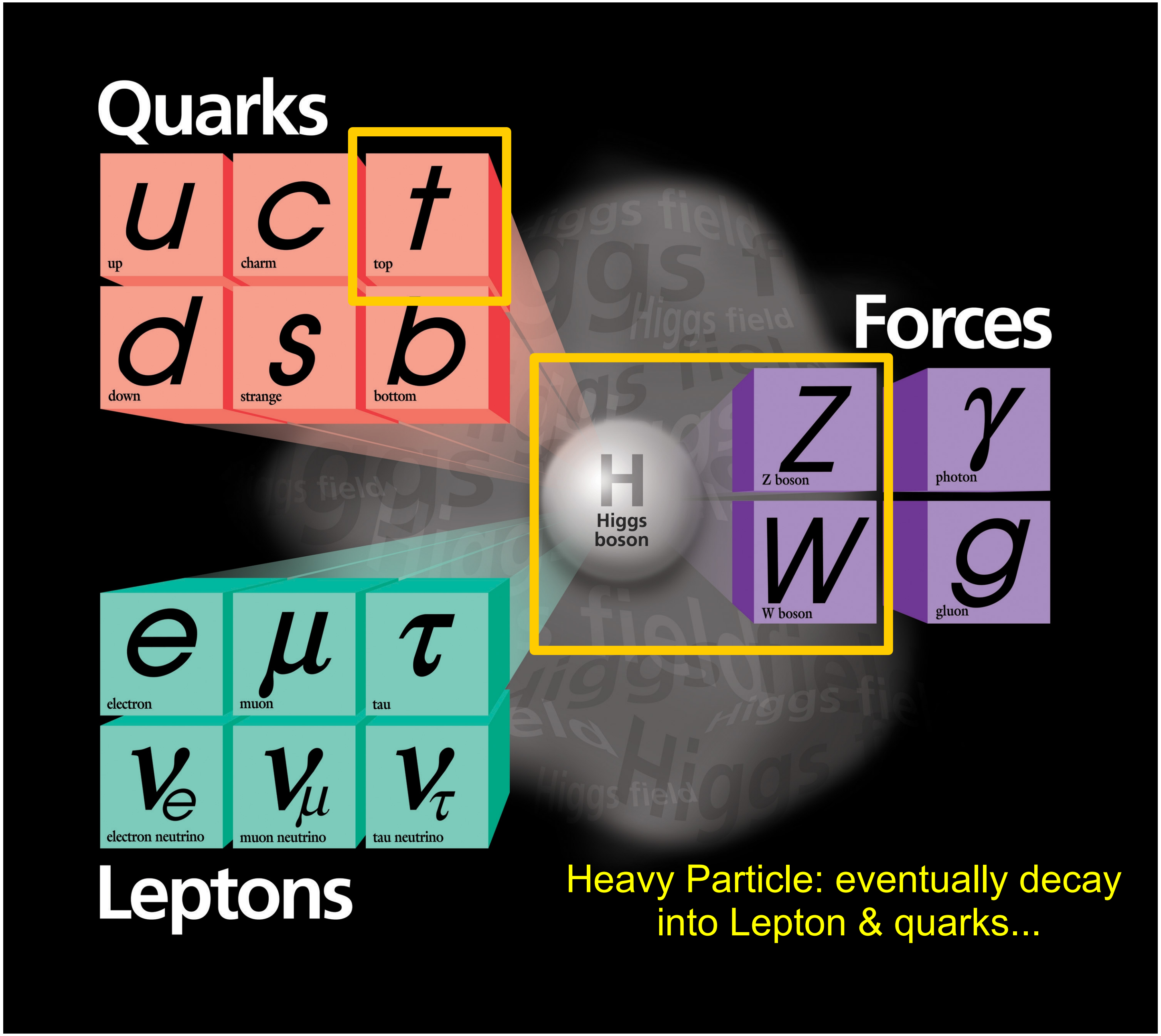

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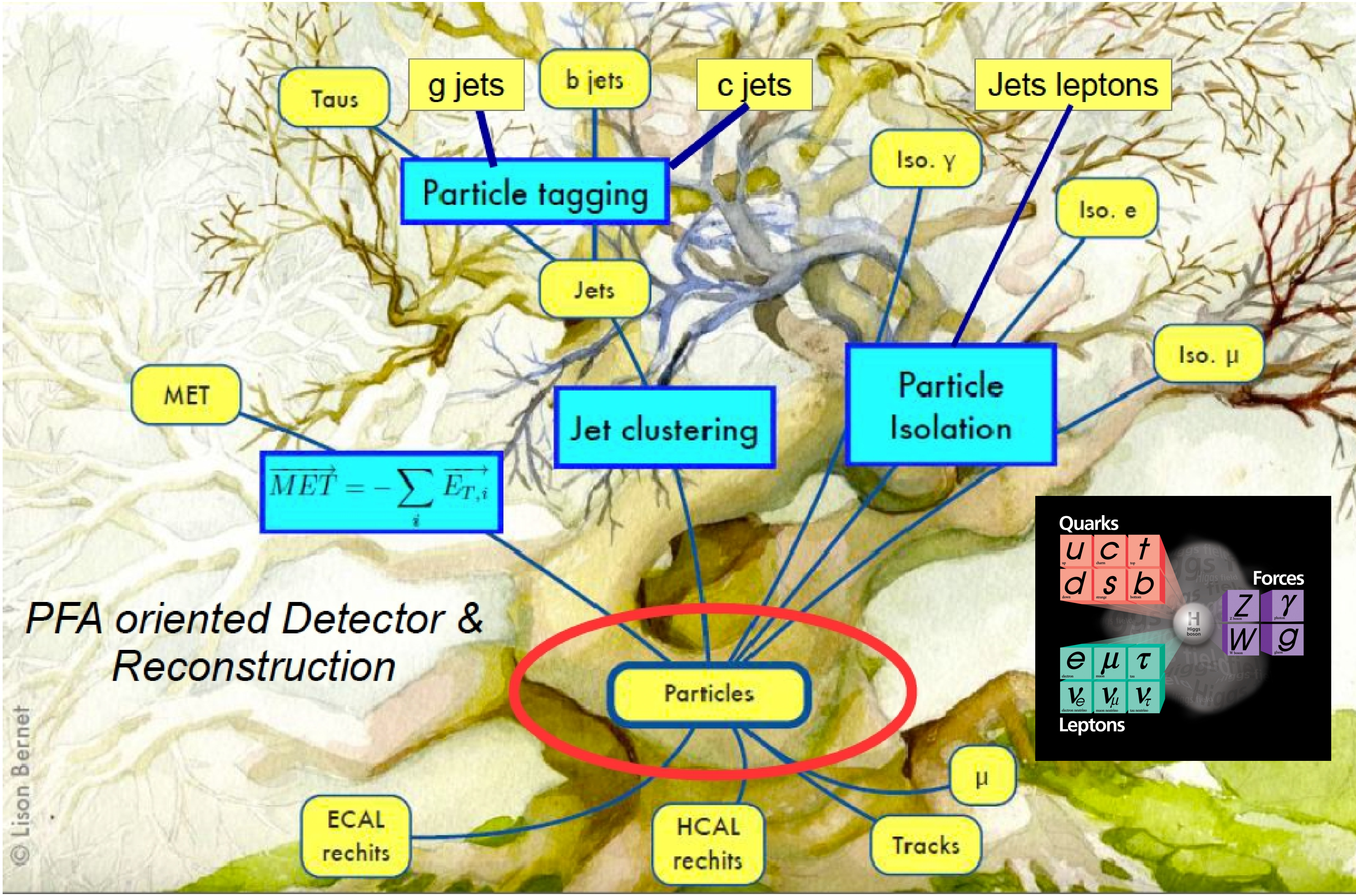
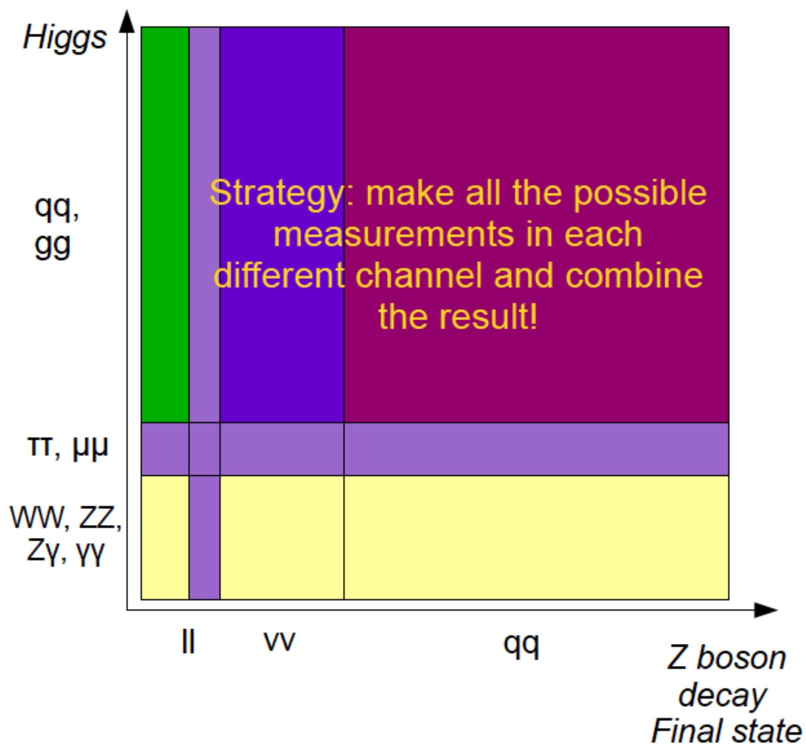
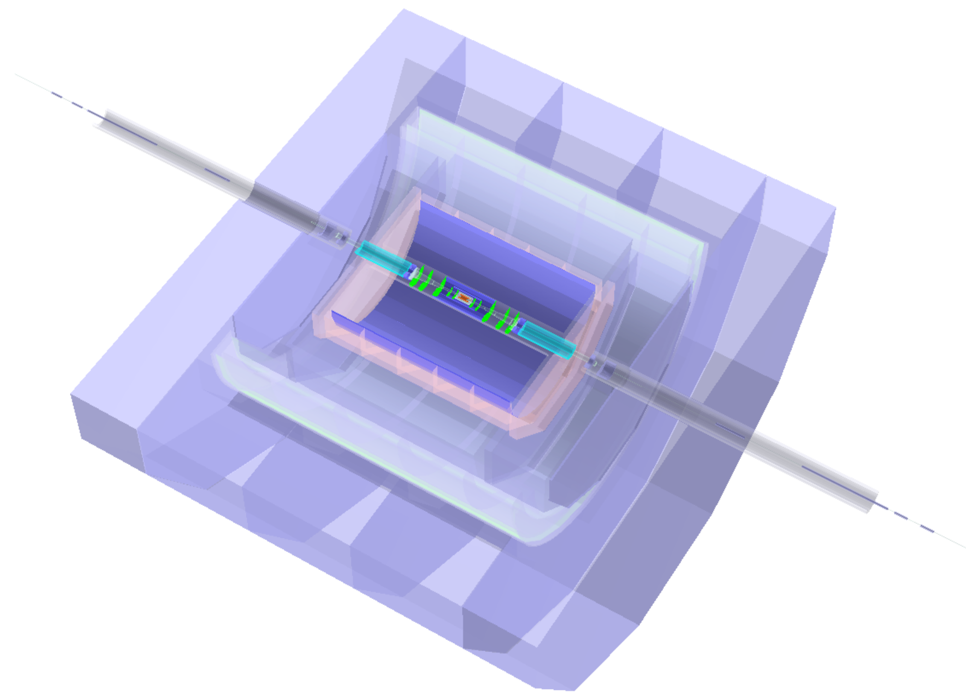
Key requirement

- Identify the key physics objects & measure them precisely
- Higgs (at c.m.s = 240 GeV)
  - 97% of Higgs events has jets in their final state...
  - Together with many other objects (lepton, photo, tau, missing energy-momentum...)
- Z (at c.m.s = 91.2 GeV)
  - 70% of Z decay into 2-jets: Finding the correct combination of final state particles inside jet
  - 10% decays into electron, muon & tau (and their anti-particles)
  - 20% goes invisible


Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
MET
Jet clustering
Particle Isolation
Iso. μ
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
μ
ECAL rechits
HCAL rechits
Tracks
© Lison Bernet
Quarks
u c t
d s b
Forces
Z γ
W g
H
e μ τ
ν_e ν_μ ν_τ
Leptons

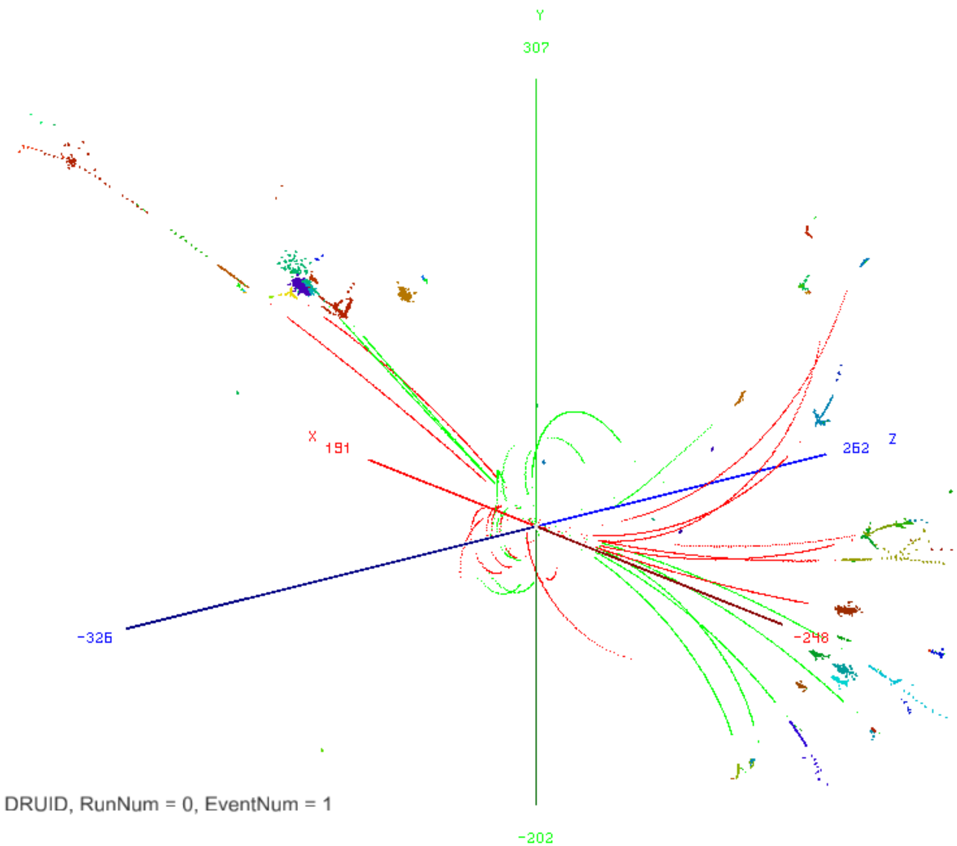
CEPC Conceptual detector

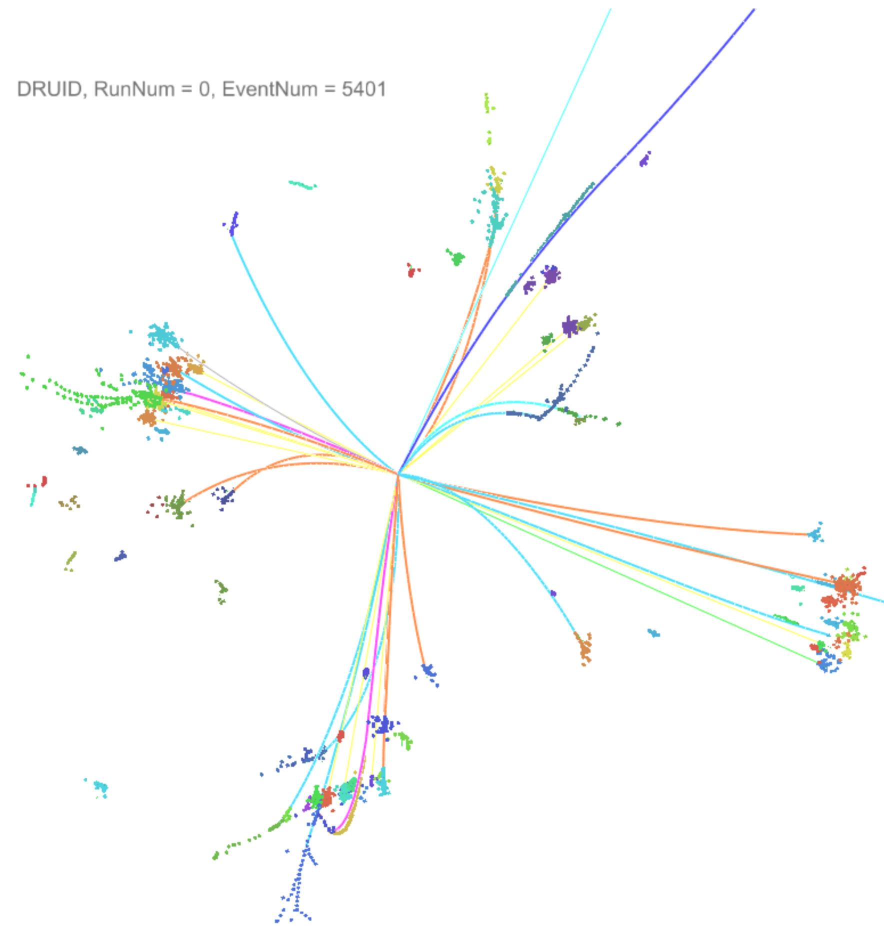




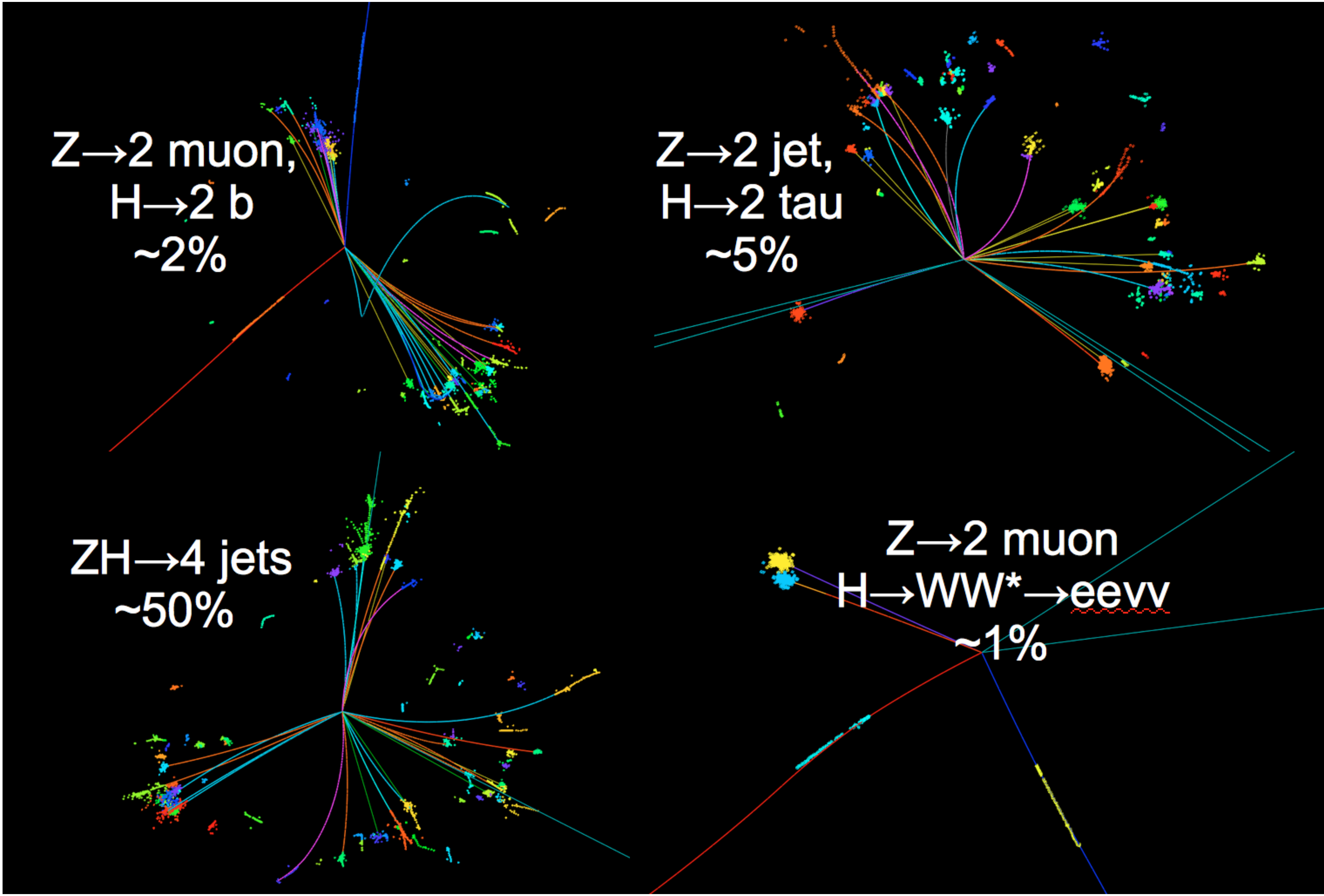
A detector reconstruct all the physics object (lepton, photon, tau, Jet, MET, ...) with high efficiency/precision

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 (~o(10^8) channels): Tagging, ID, Jet energy resolution, ect

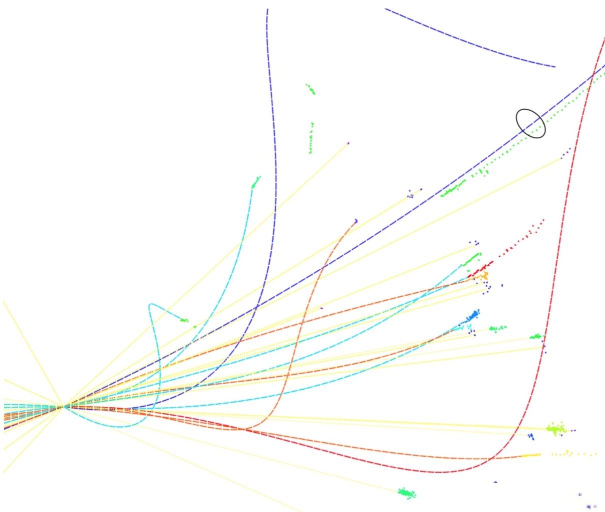


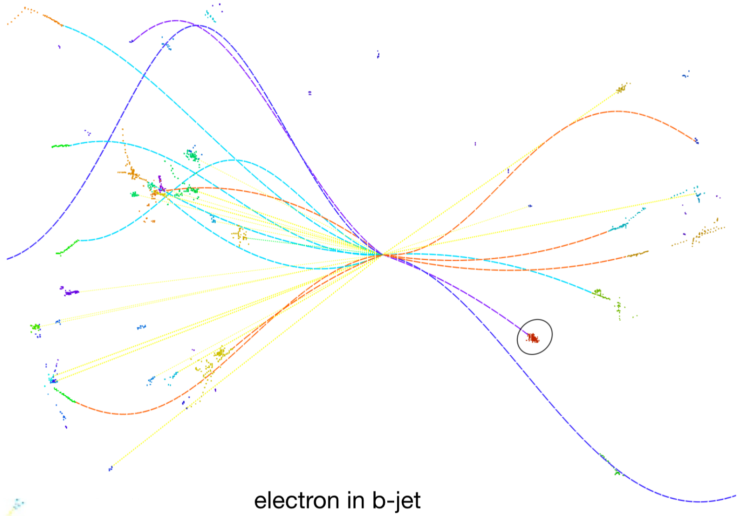


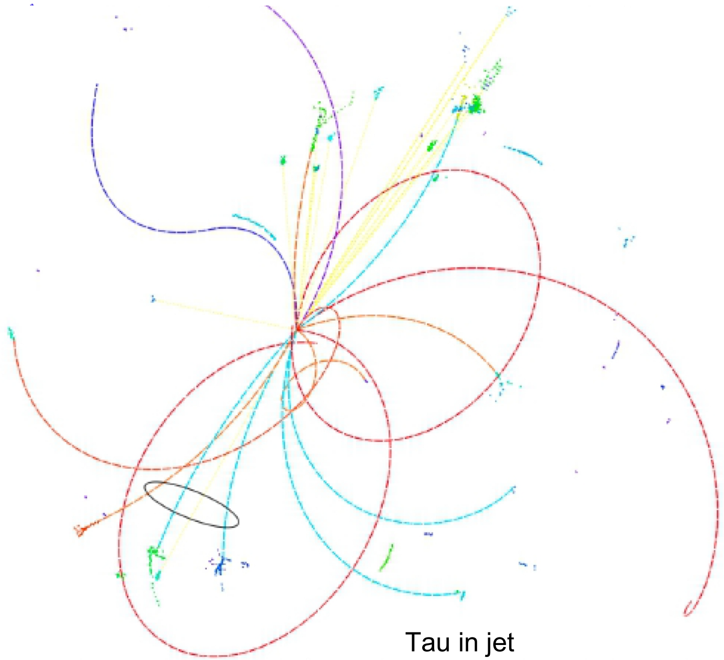
Sim Higgs @ CEPC


Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~1%

At Z pole...


muon in b-jet


electron in b-jet


Tau in jet

Key requirement

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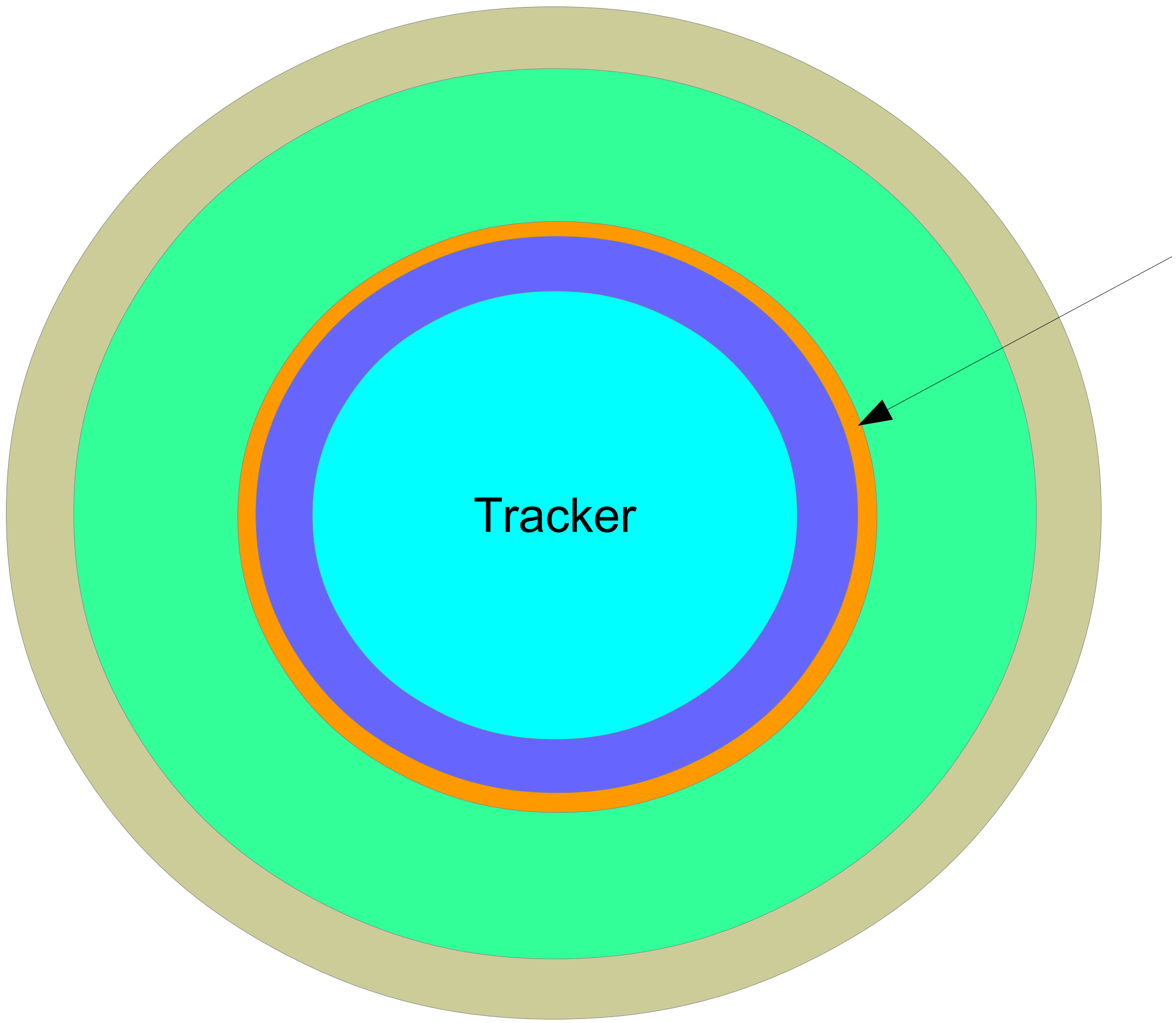
- Higgs (at c.m.s = 240 GeV)
  - 97% of Higgs events has jets in their final state...
  - Together with many other objects (lepton, photo, tau, missing energy-momentum...)
- Z (at c.m.s = 91.2 GeV)
  - 70% of Z decays into 2-jets: Finding the correct combination of final state particles inside jet
  - 10% of Z decays into leptons
  - 20% goes invisible

PFA Oriented concept



Dedicated ToF
Or
ECAL Layer with TDC
Equipped Chips

delta(T) ~ 50 ps

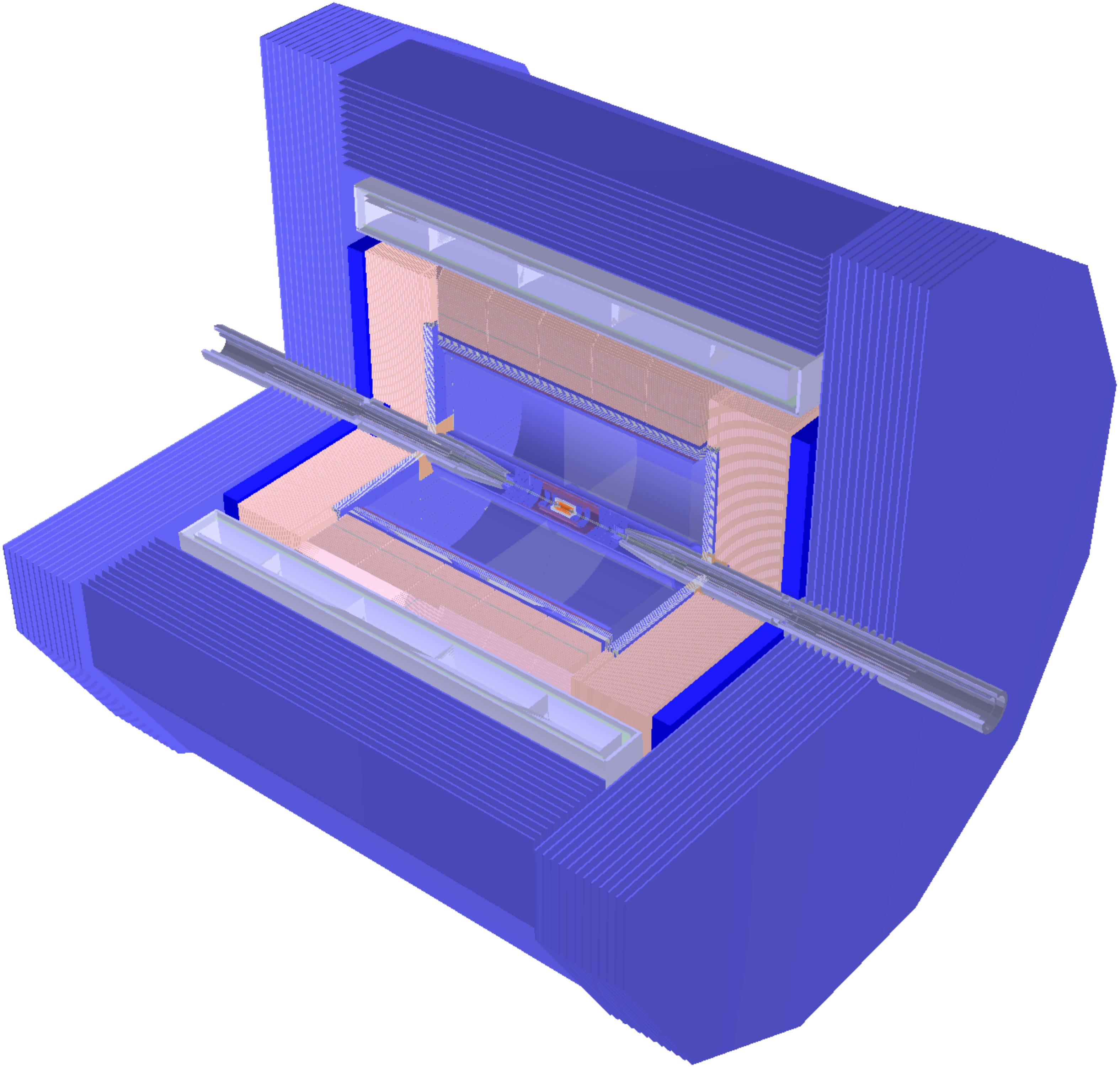
To balance the efficiency &
Purity of time measurement...

Tracker, TPC: R = 1.8 m

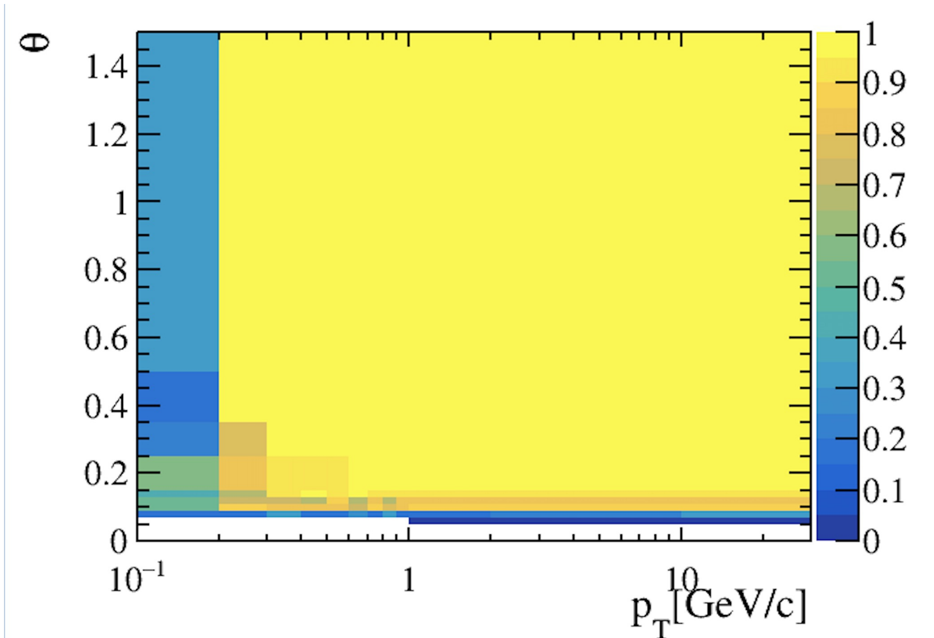
ECAL: 84-90 mm W

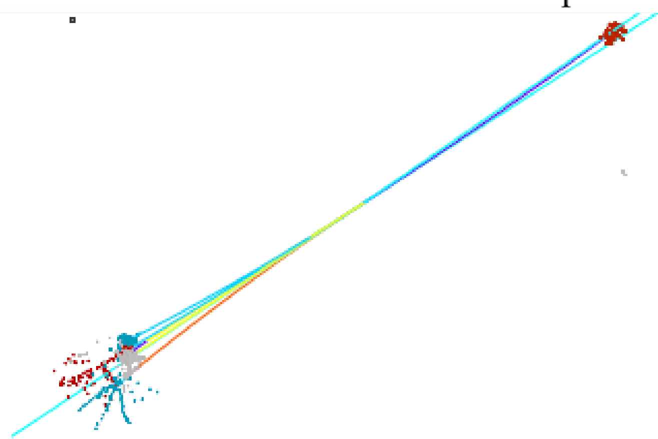
HCAL: ~1000 mm Iron

Solenoid (3T) + Yoke

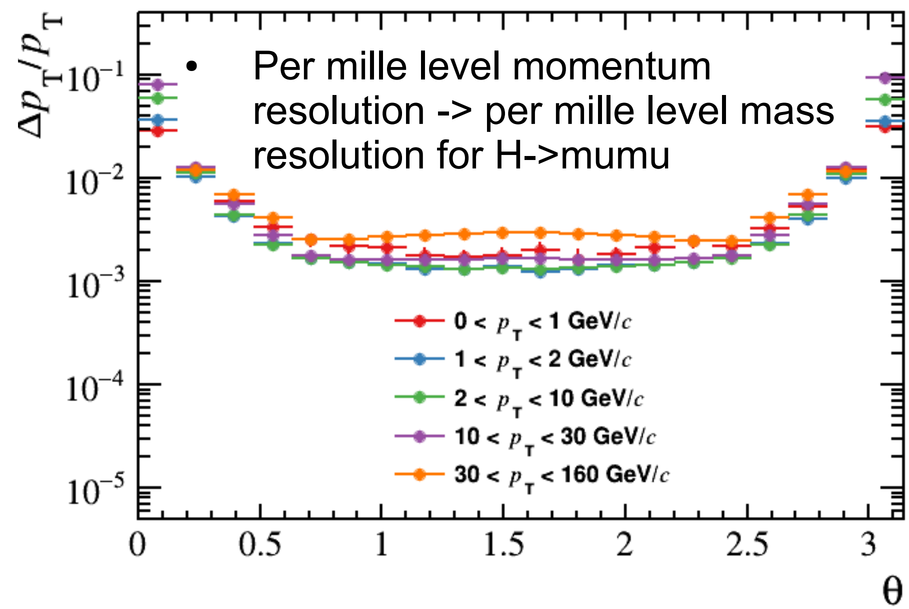


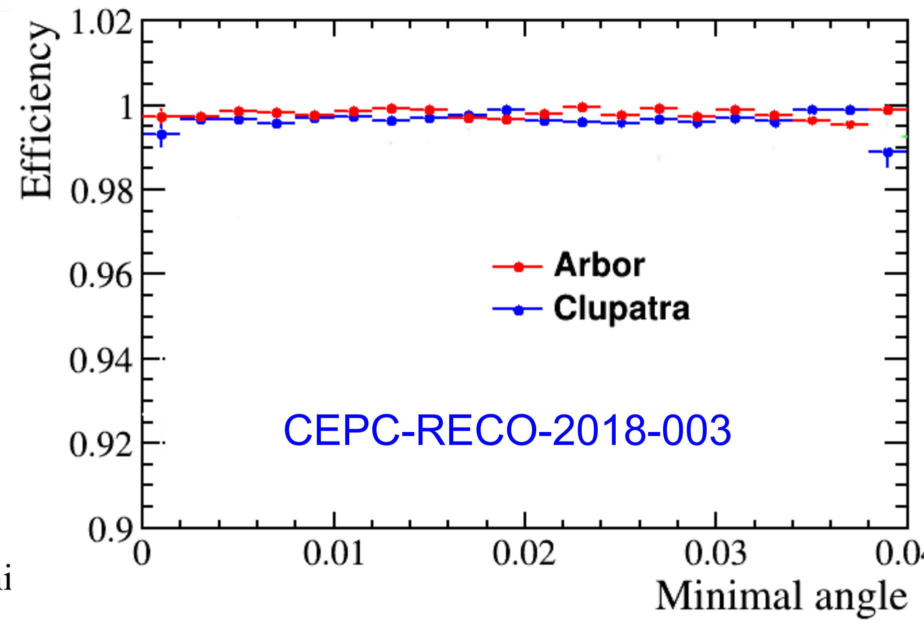
Tracking



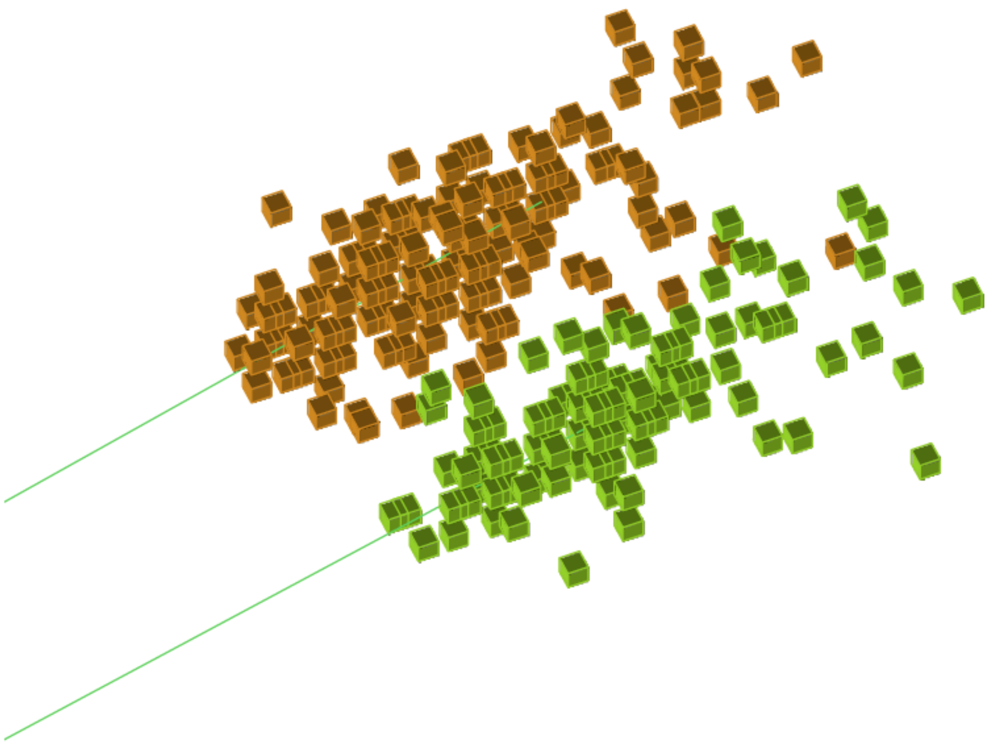


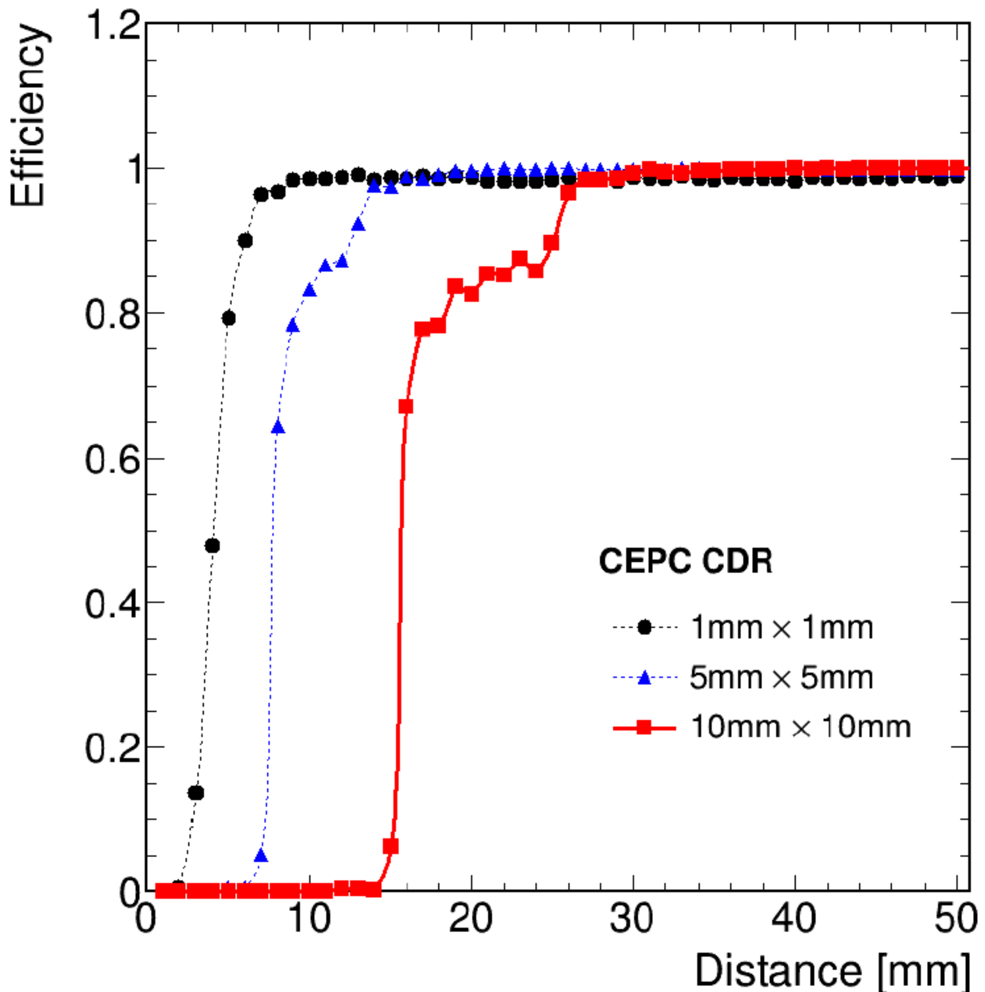
Mingrui Zhao. CEPC CDR





Clustering - Separation

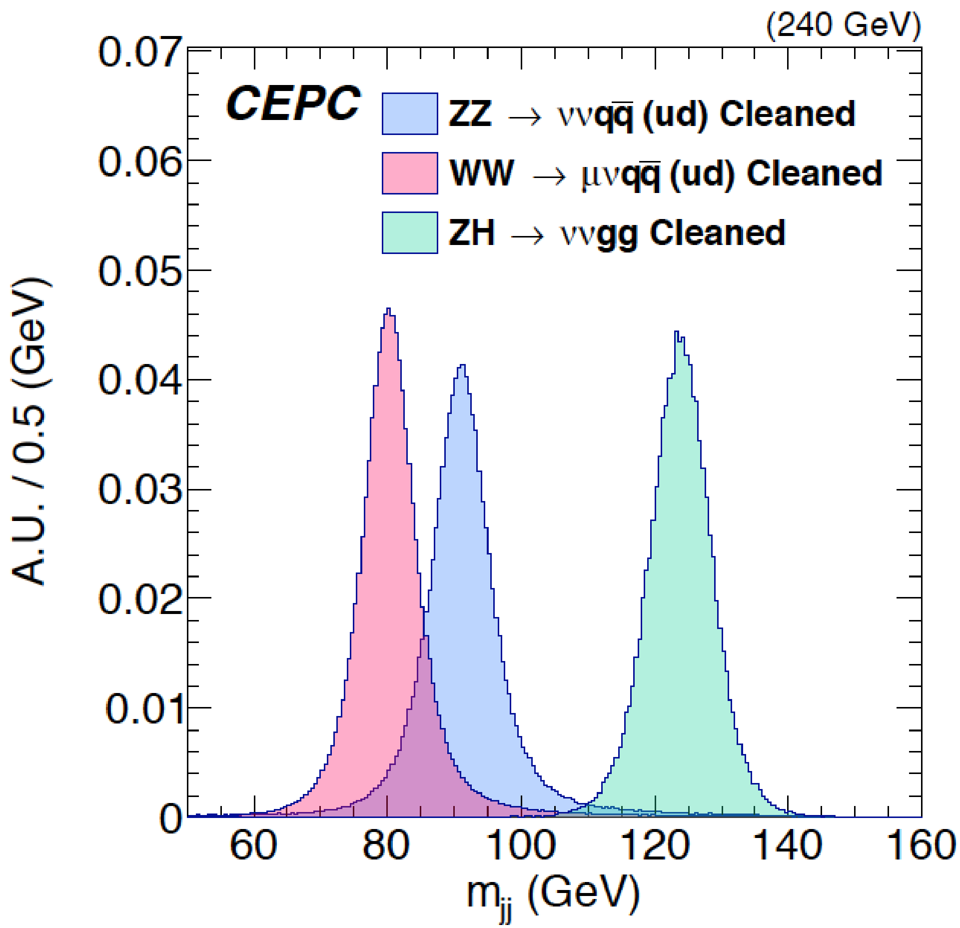




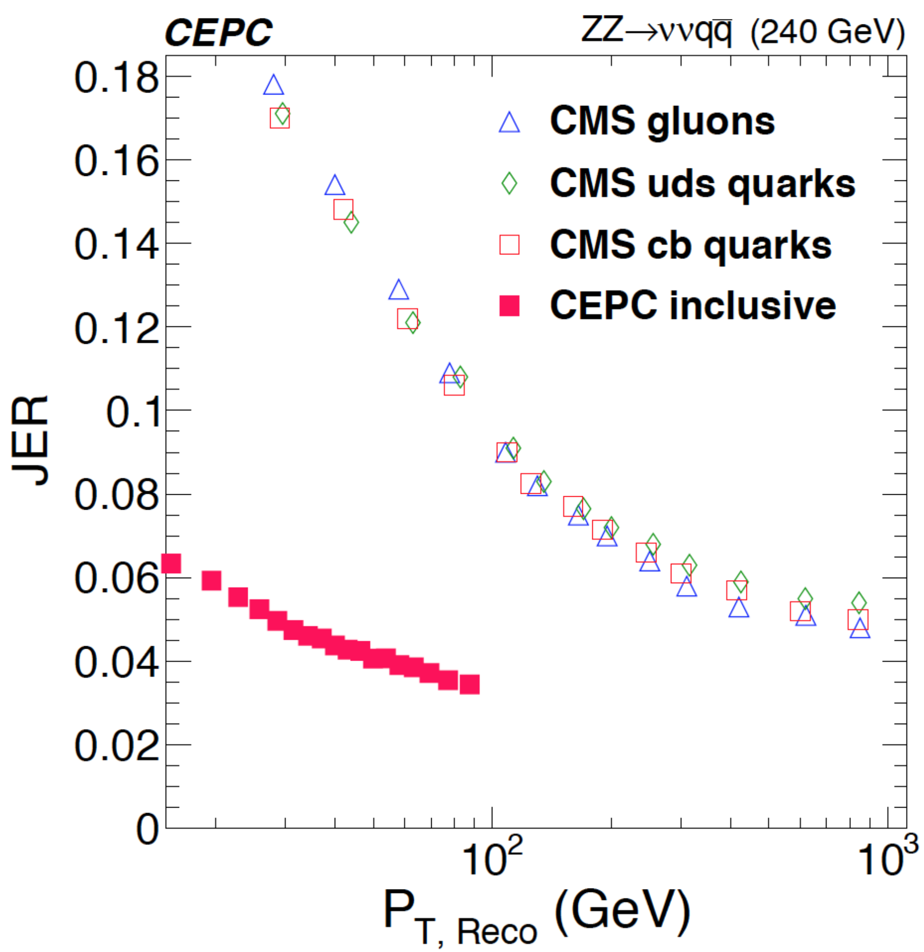
Critical energy to separate an evenly decay π_0: 30 GeV

Hang Zhao. CEPC CDR

Jets

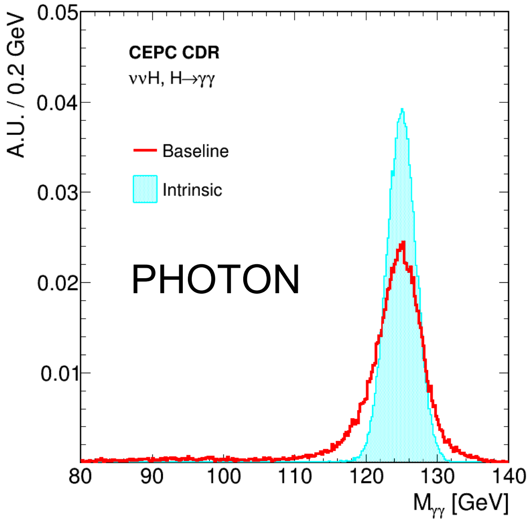


(240 GeV)
CEPC
ZZ → ννqq̄ (ud) Cleaned
WW → μνqq̄ (ud) Cleaned
ZH → ννgg Cleaned
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
A.U. / 0.5 (GeV)
60
80
100
120
140
160
m_jj (GeV)

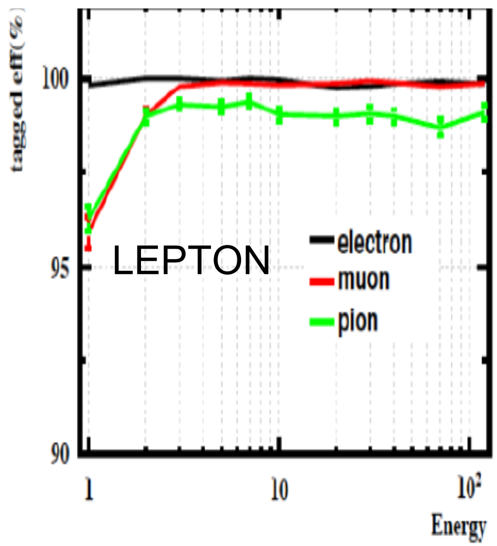


CEPC
ZZ→ννqq̄ (240 GeV)
CMS gluons
CMS uds quarks
CMS cb quarks
CEPC inclusive
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
JER
10^2
10^3
P_T, Reco (GeV)

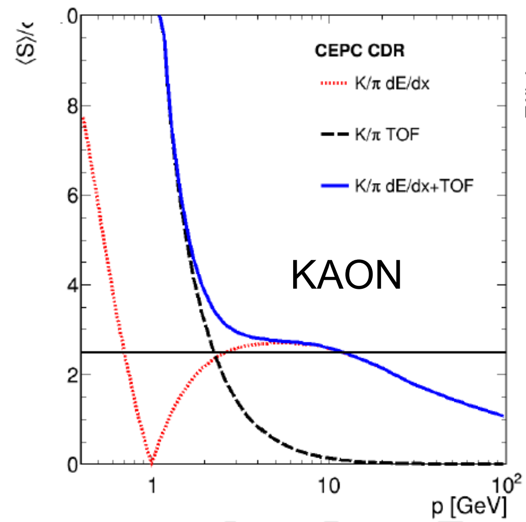
Physics Objects

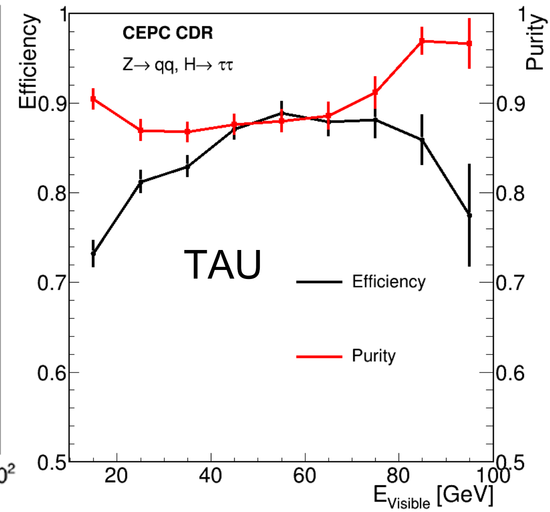


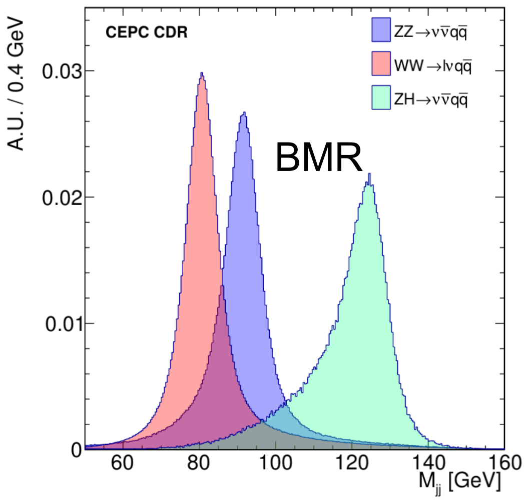
Eur. Phys. J. C (2017) 77: 591

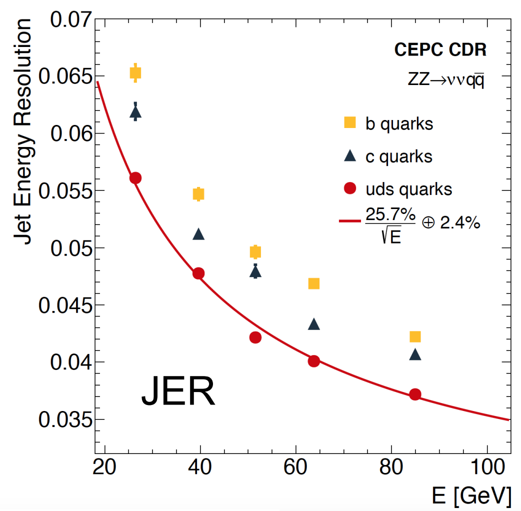


Eur. Phys. J. C (2018) 78:464









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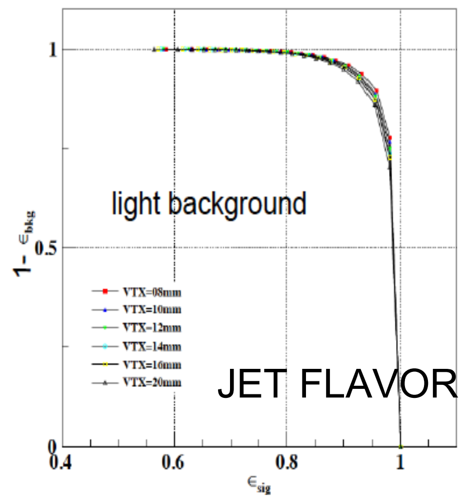
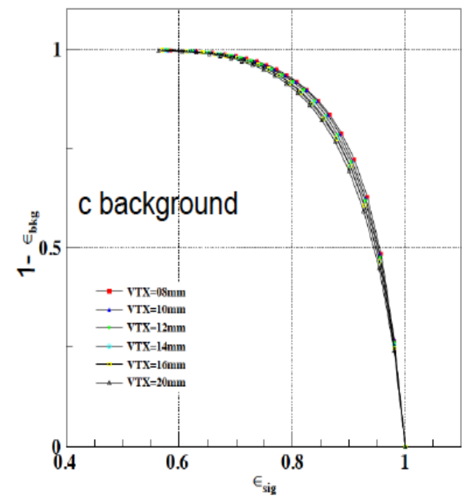
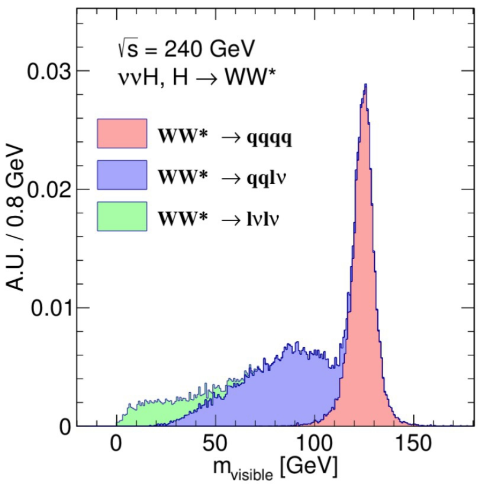
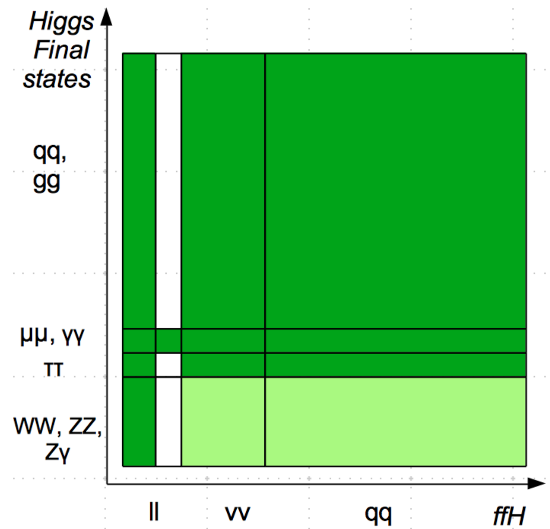
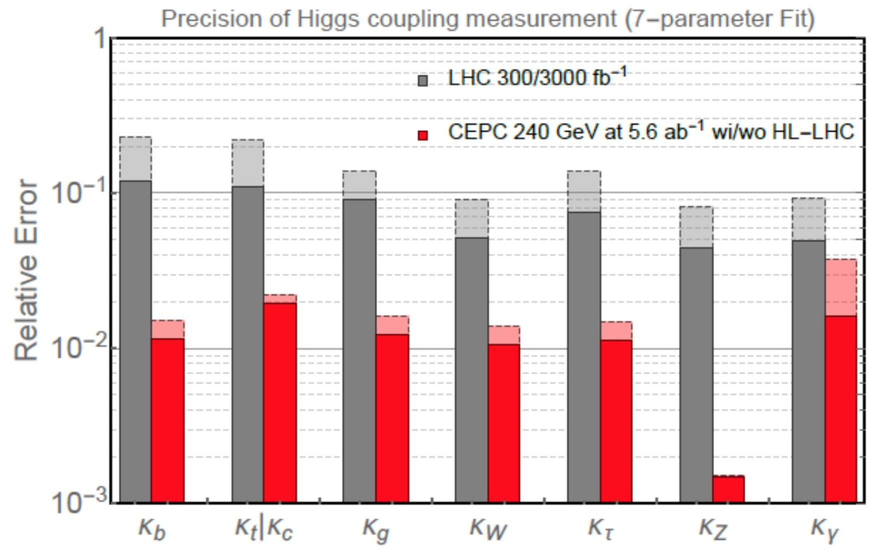


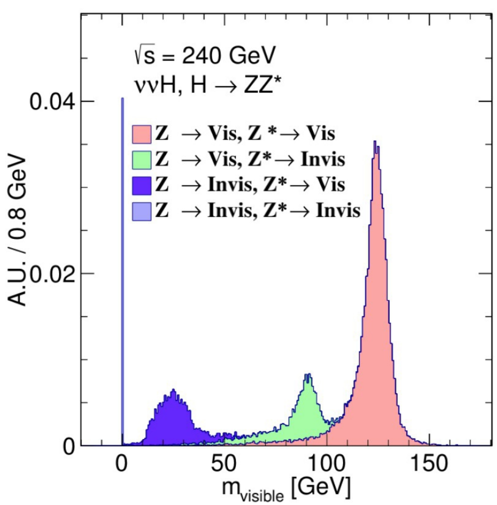


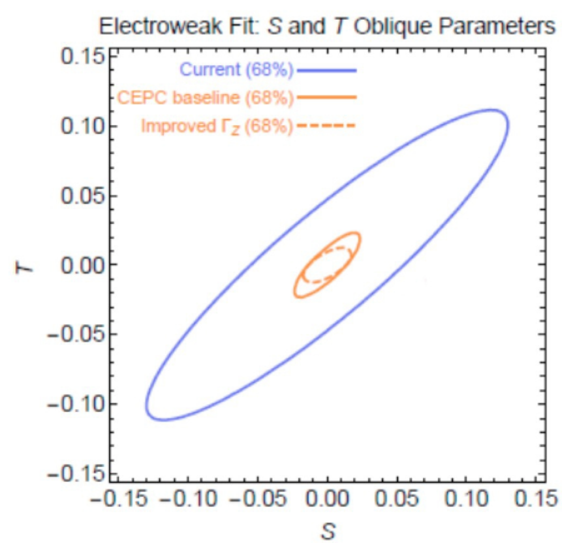
Applied on Higgs physics, et.al











Precision Higgs Physics at CEPC

Initial assessments of Higgs physics potential at the CEPC based on the white paper (to be submitted)

Chinese Physics C Vol. XX, No. X (201X) 010201

Precision Higgs Physics at the CEPC*

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Haifeng Li[12] Liang Li[10] Shu Li[10,11] Tong Li[12] Qiang Li[3] Hao Liang[4,6] Zhijun Liang[4]
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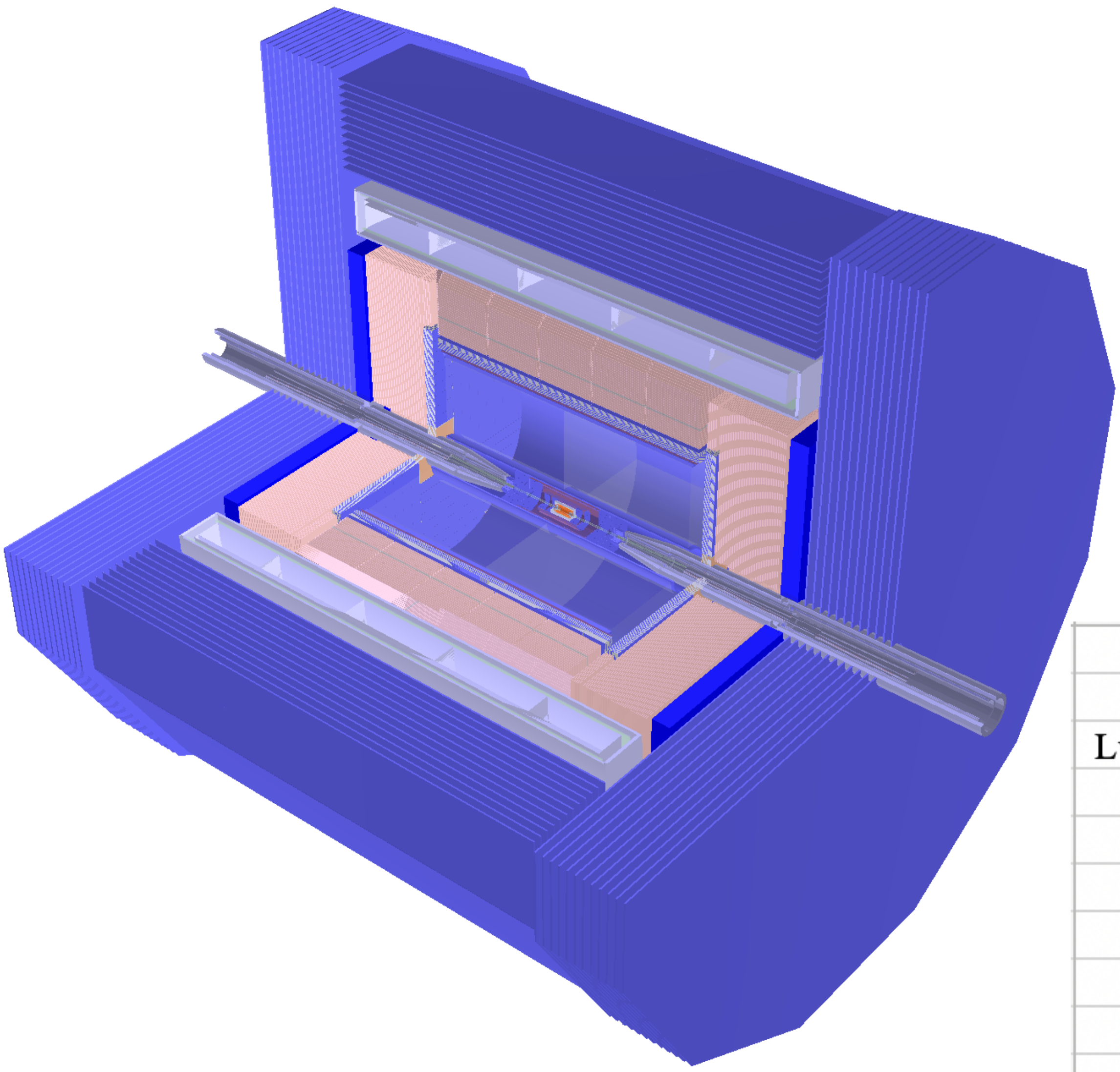
Bruce Mellado[17] Xin Mo[4] Mila Pandurovic[16] Jianming Qian[22] Zhuoni Qian[18]
Nikolaos Rompotis[20] Manqi Ruan[4] Alex Schuy[30] Lian-You Shan[4] Jingyuan Shi[9] Xin Shi[4]
Shufang Su[23] Dayong Wang[3] Jing Wang[4] Lian-Tao Wang[25] Yifang Wang[4,6] Yuqian Wei[4]
Yue Xu[5] Haijun Yang[10,11] Weiming Yao[26] Dan Yu[4] Kaili Zhang[4,6] Zhaoru Zhang[4]
Mingrui Zhao[2] Xianghu Zhao[4] Ning Zhou[10]

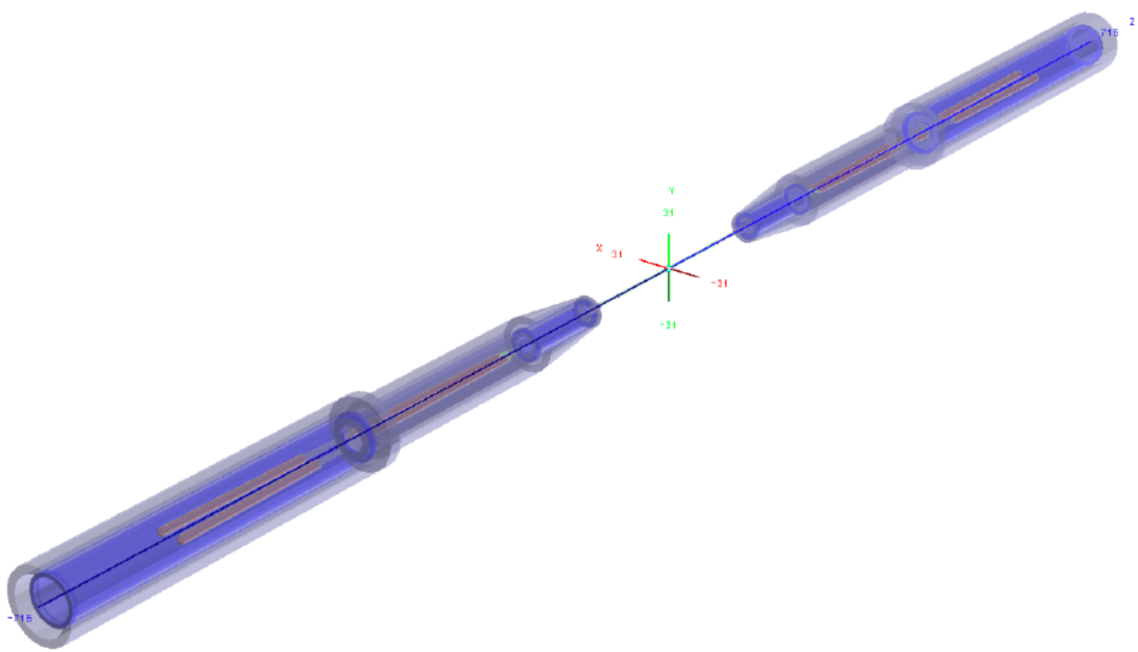
https://arxiv.org/pdf/1810.09037.pdf

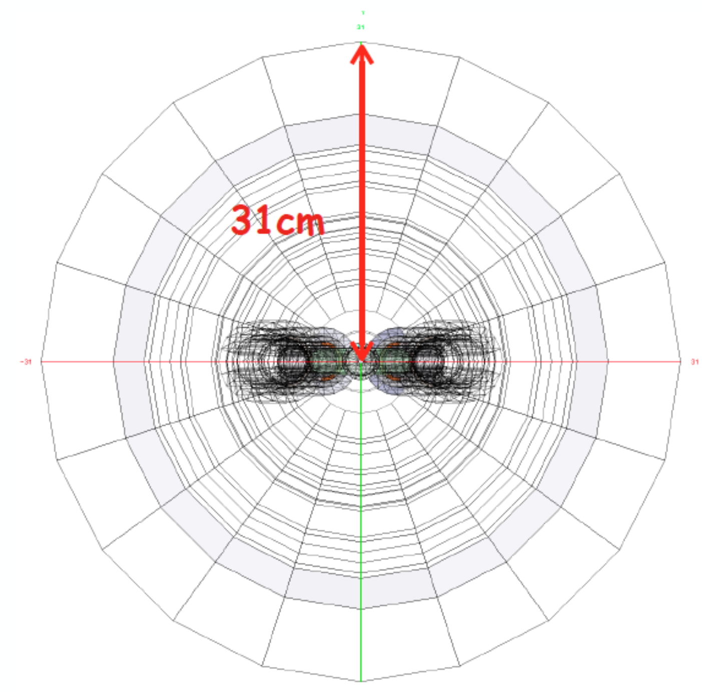


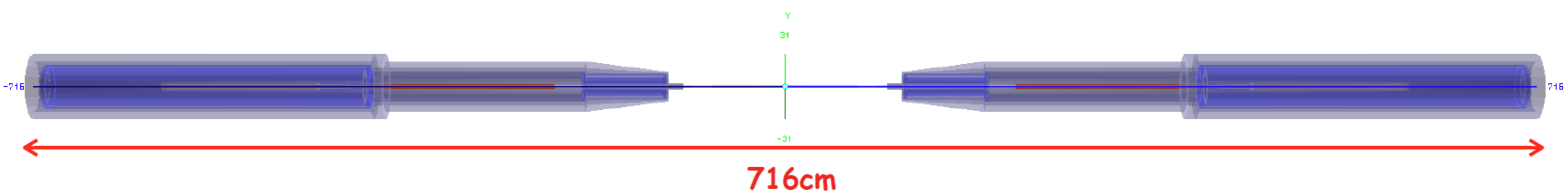
	mass (kg)	mass (ton)
MDI	11,909.85	11.91
LumiCal	118.46	0.12
VXD	0.85	0.00
SIT	15.70	0.02
SET	259.62	0.26
FTD	3.21	0.00
TPC	1,750.47	1.75
Ecal	161,489.50	161.49
Hcal	906,668.80	906.67
Yoke	12,685,708.80	12,685.71
Magnet	262,841.11	262.84

MDI mass: 11.91ton

MDI

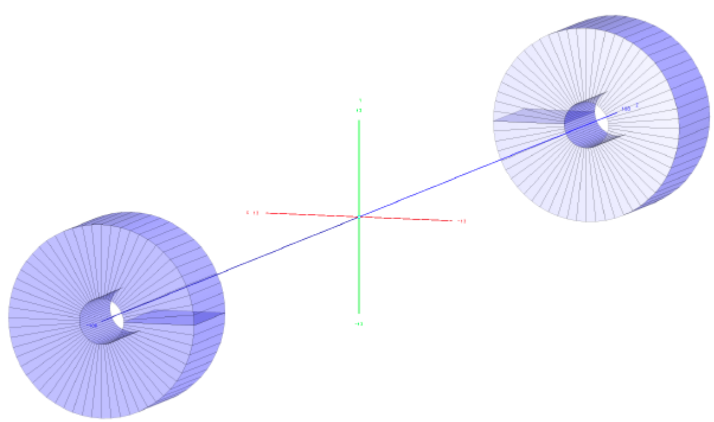


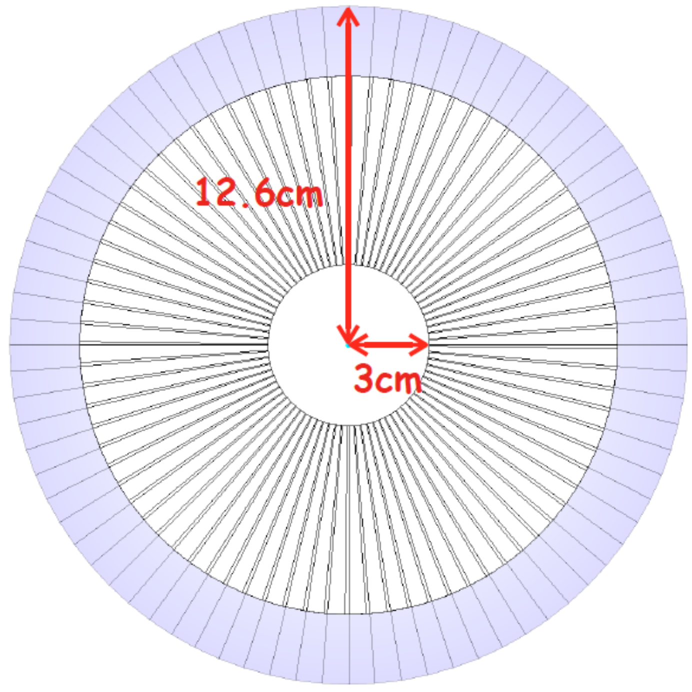


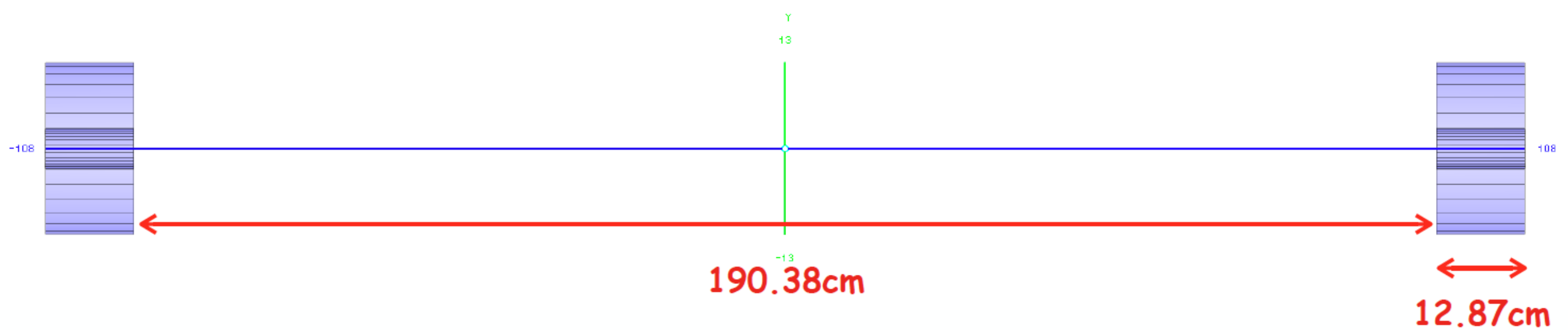


LumiCal mass: 118.46kg

LumiCal

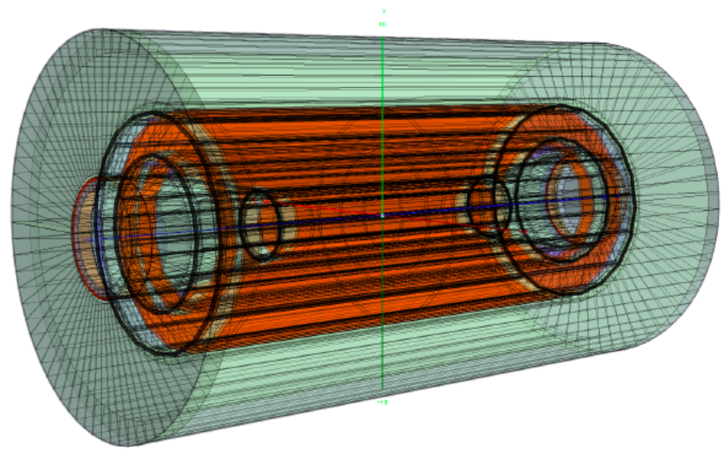


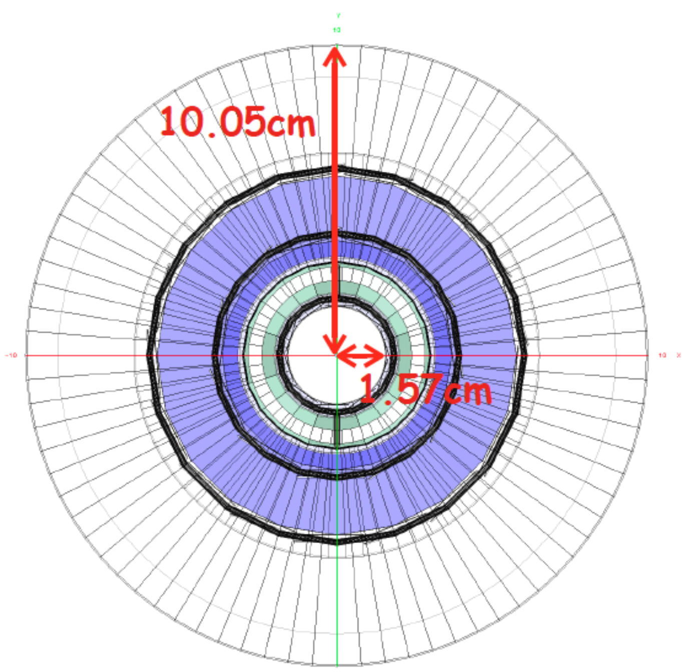


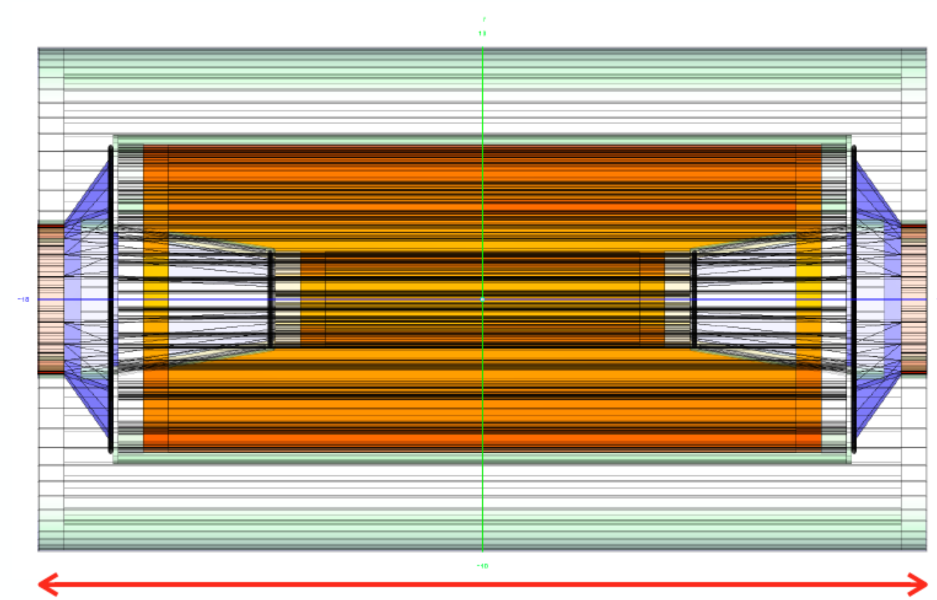


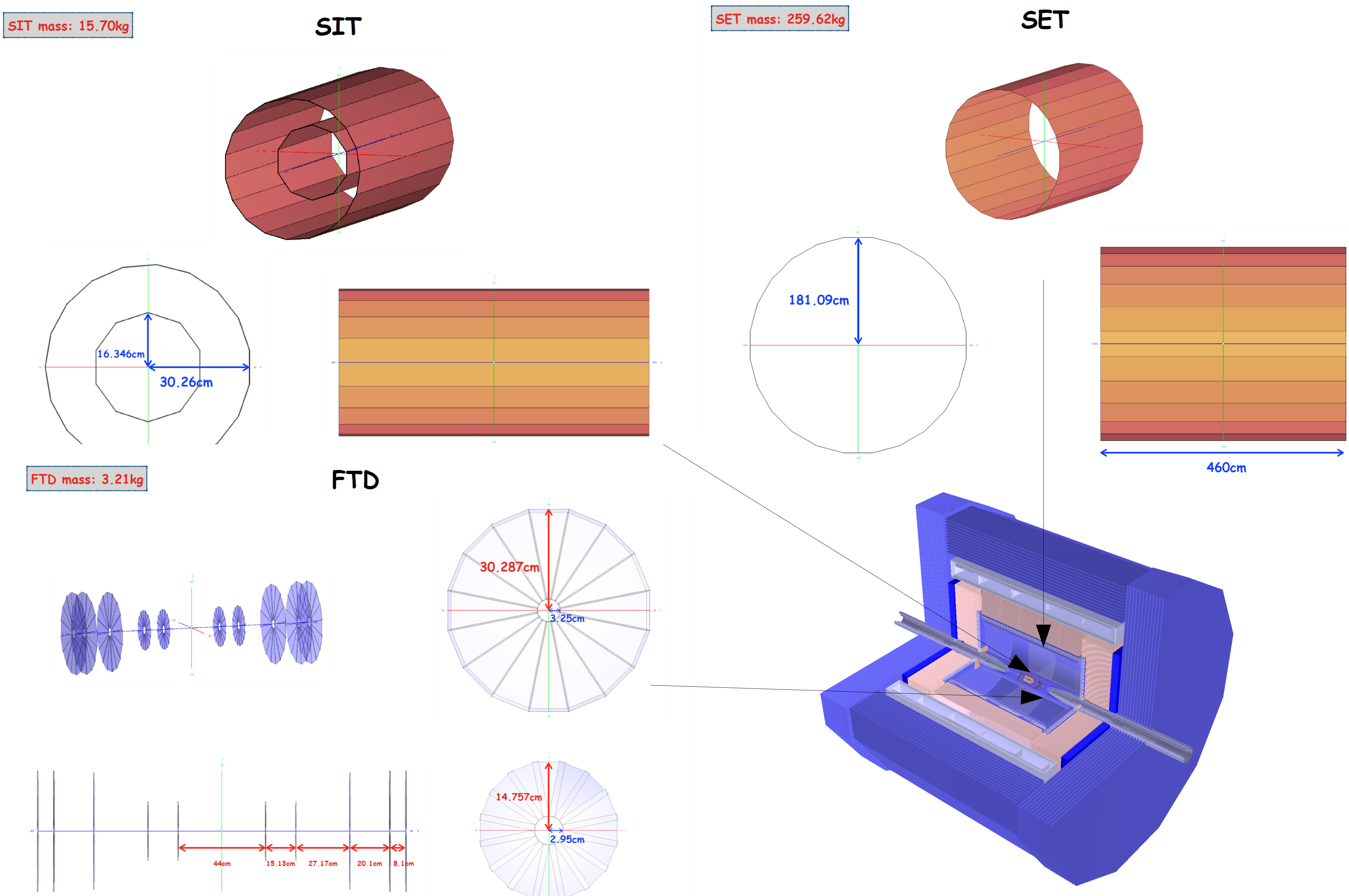
VXD mass: 0.85kg

VXD



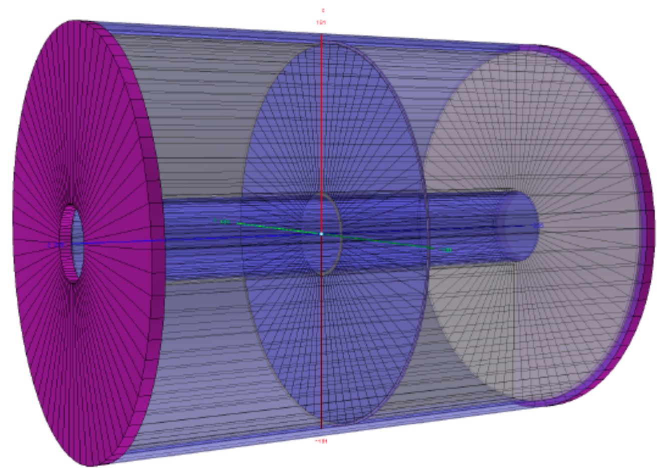


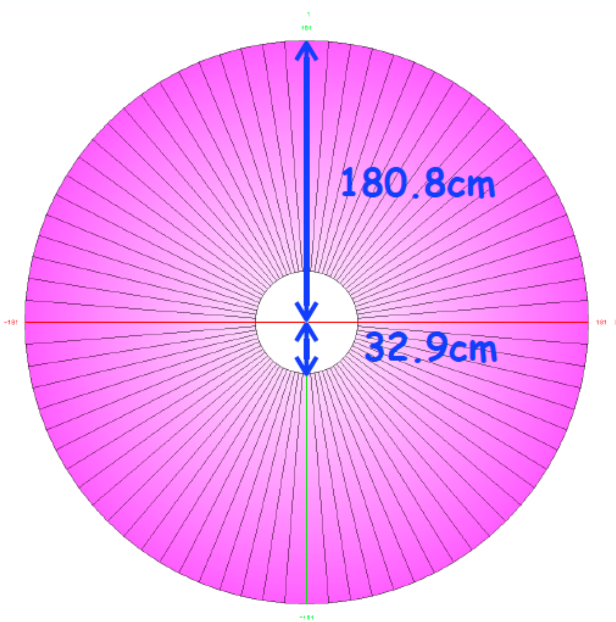


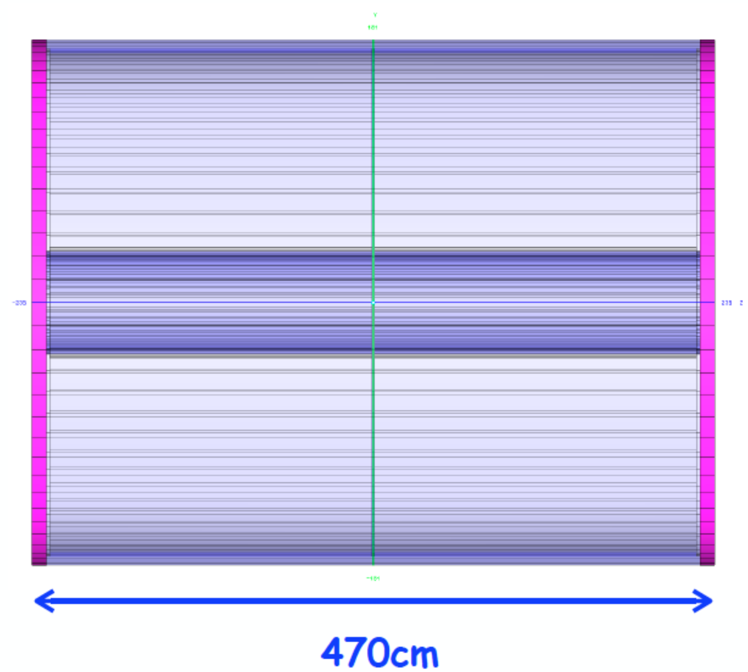

SIT mass: 15.70kg
SIT
SET mass: 259.62kg
SET
16.346cm
30.26cm
181.09cm
460cm
FTD mass: 3.21kg
FTD
30.287cm
3.25cm
14.757cm
2.95cm
44cm
15.13cm
27.17cm
20.1cm

TPC mass: 1.75ton

TPC

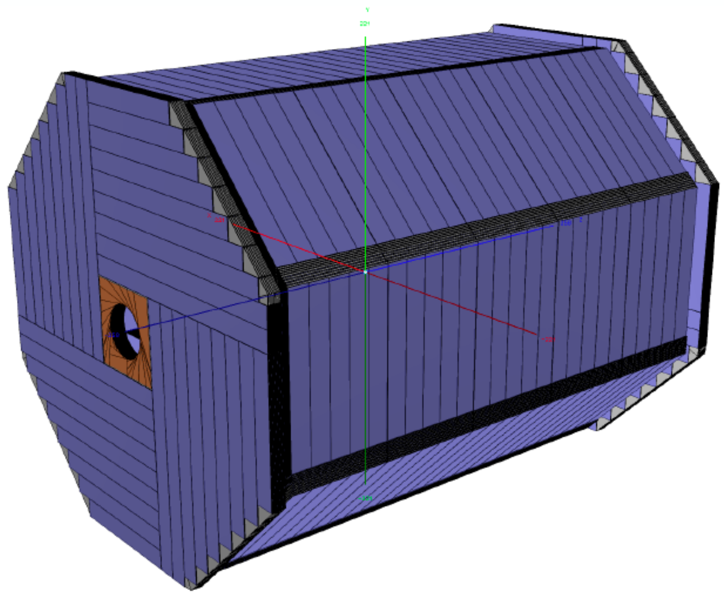


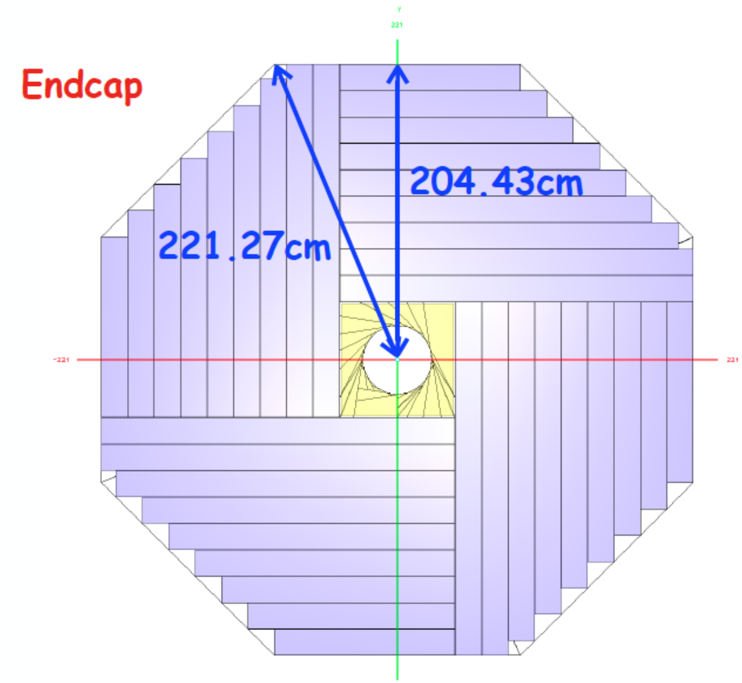


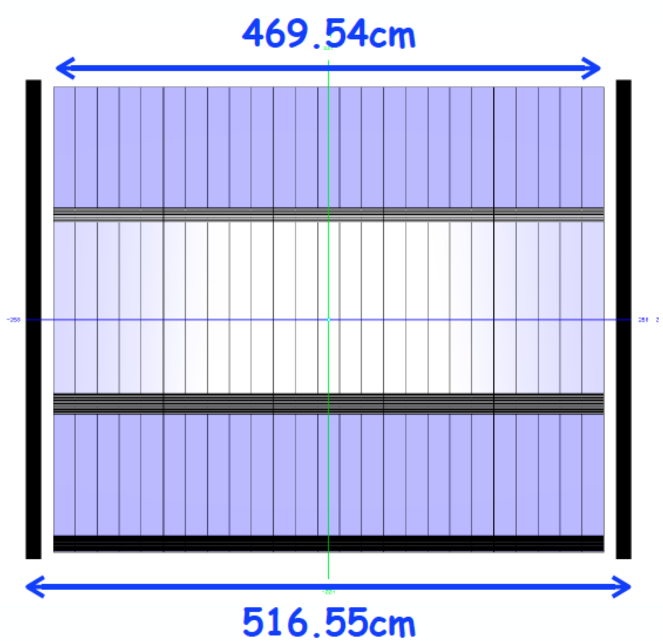


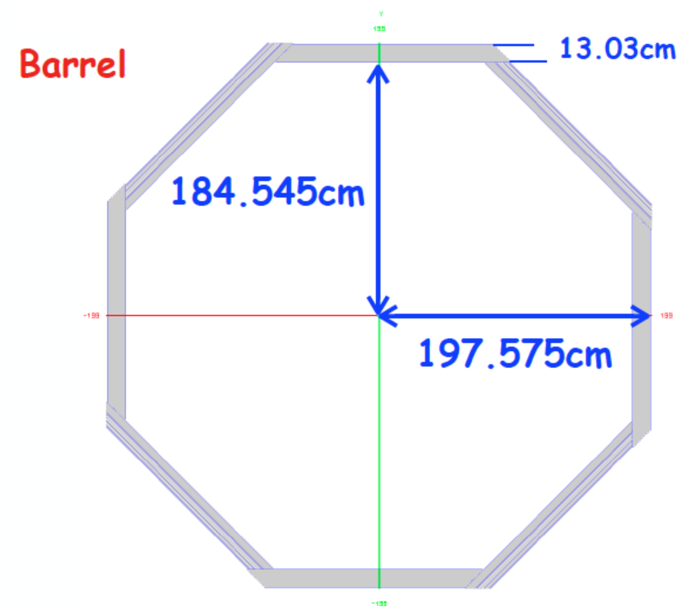
Ecal mass: 161.49ton

Ecal



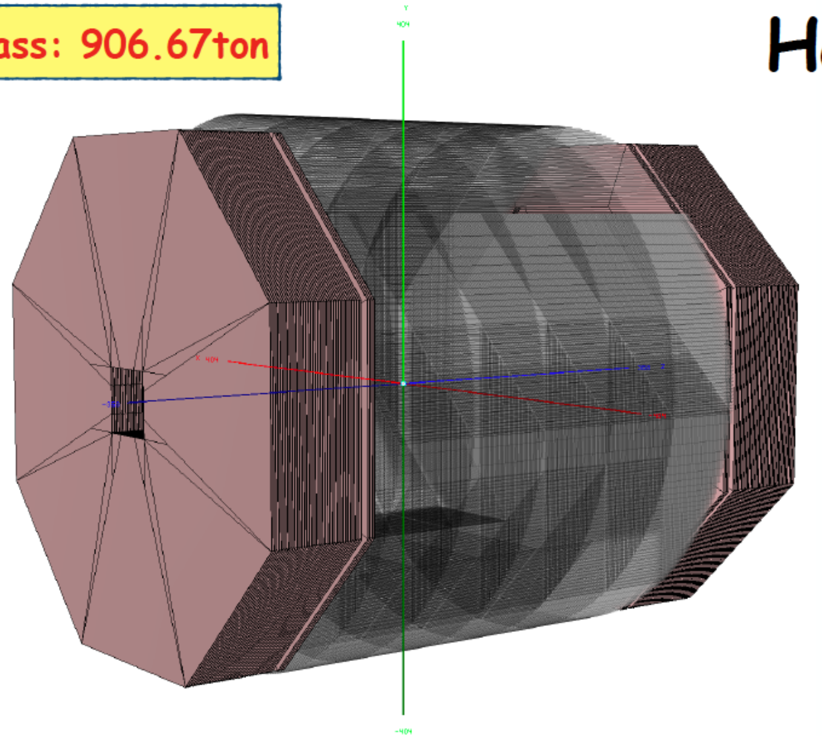


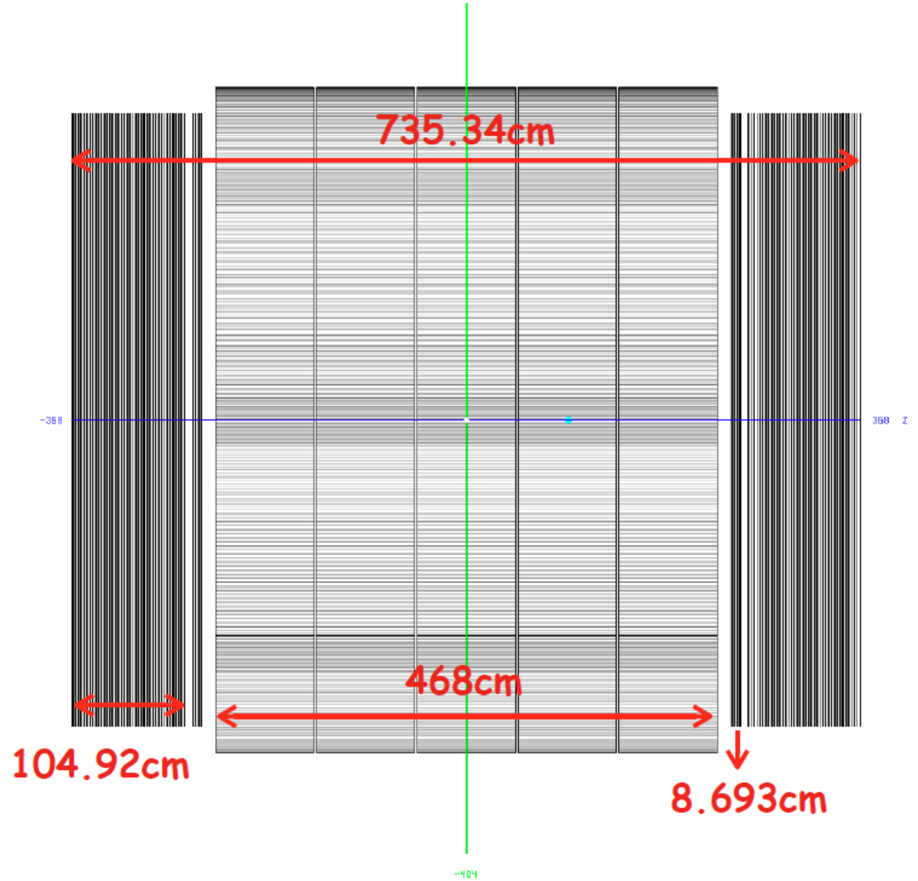




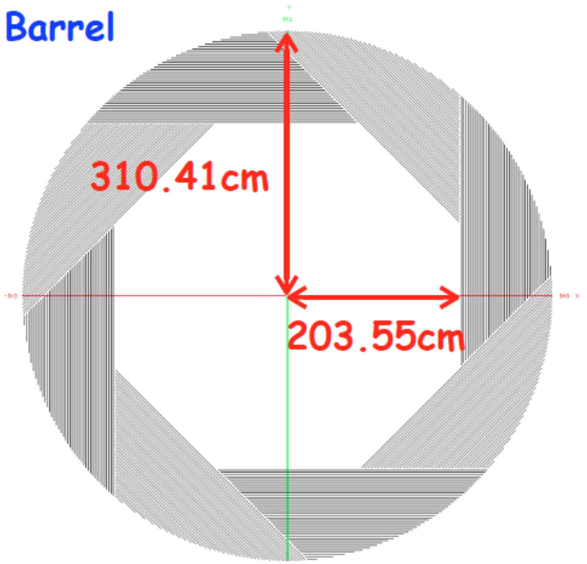
Hcal

Hcal mass: 906.67ton

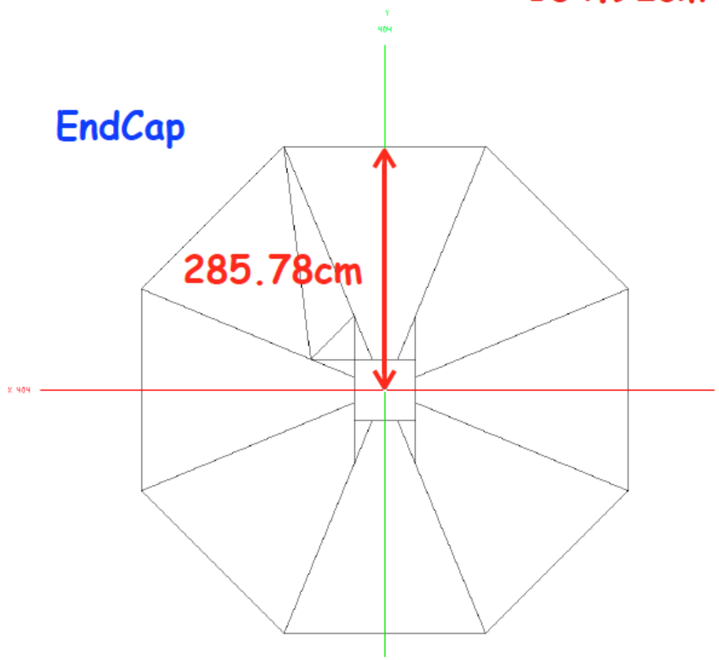




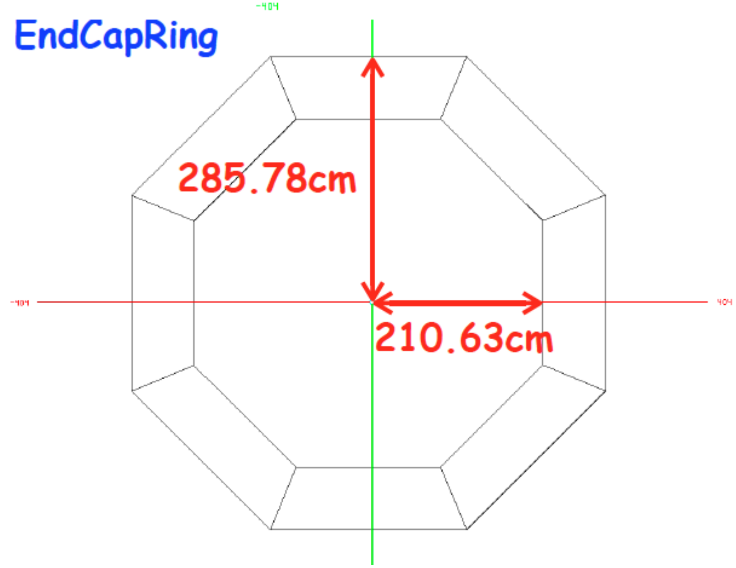
Barrel



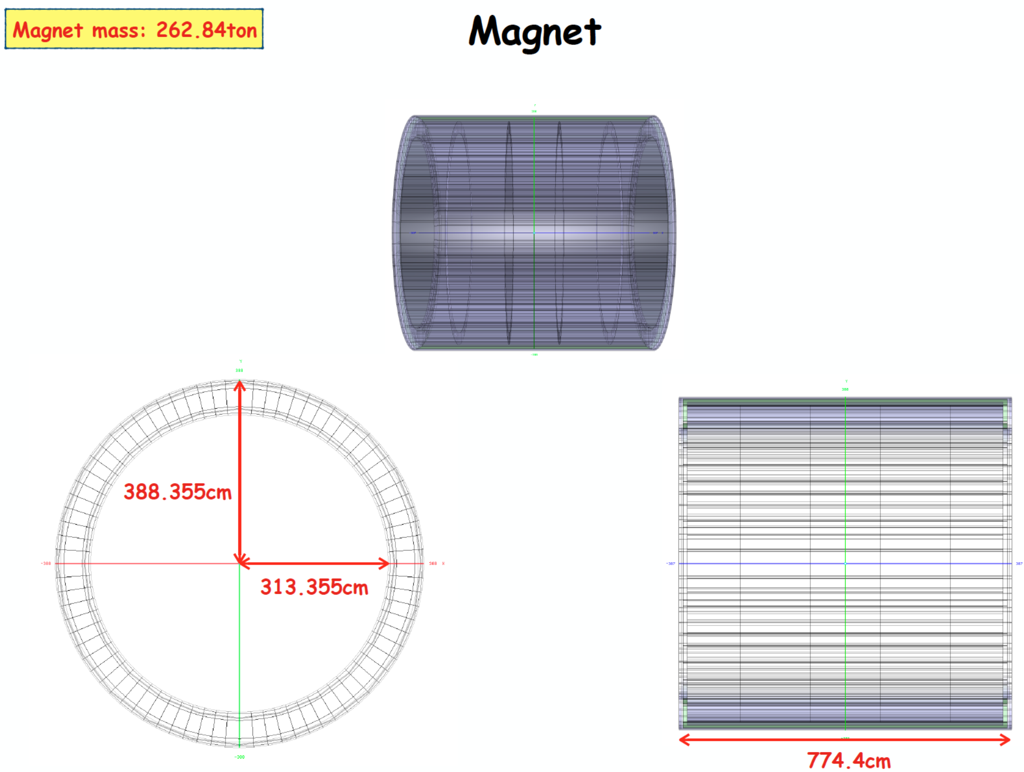
EndCap

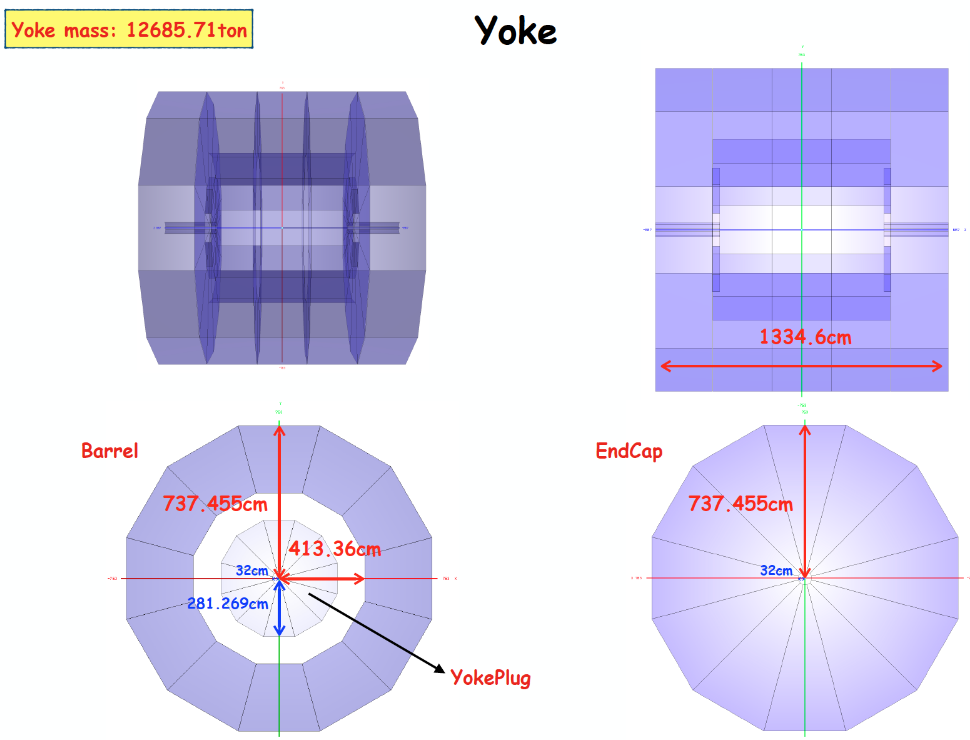


EndCapRing



Magnet + Yoke


Magnet mass: 262.84ton
Magnet
388.355cm
313.355cm
774.4cm

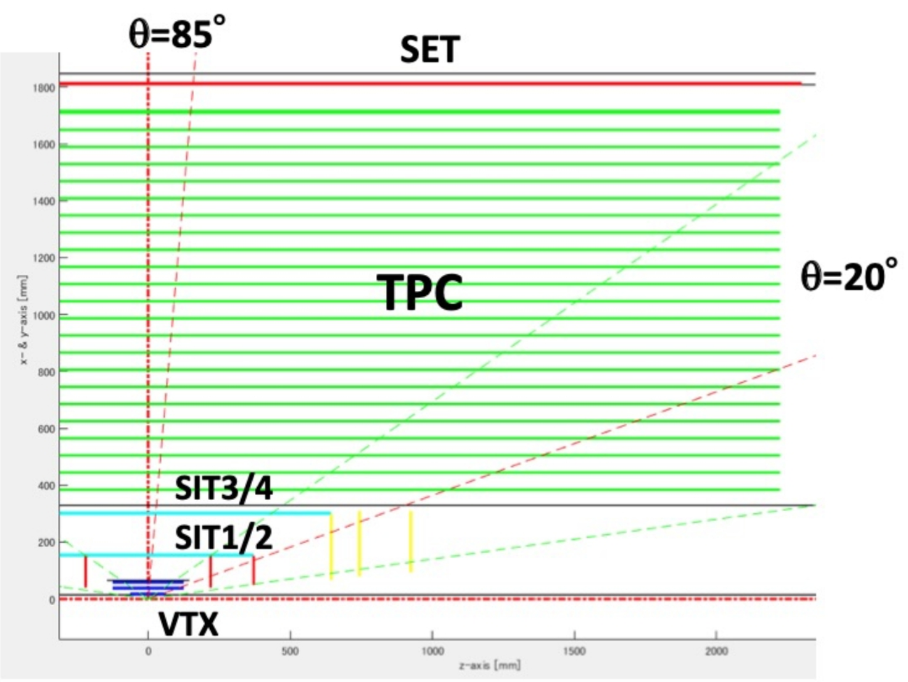

Yoke mass: 12685.71ton
Yoke
1334.6cm
Barrel
737.455cm
413.36cm
32cm
281.269cm
YokePlug
EndCap
737.455cm
32cm

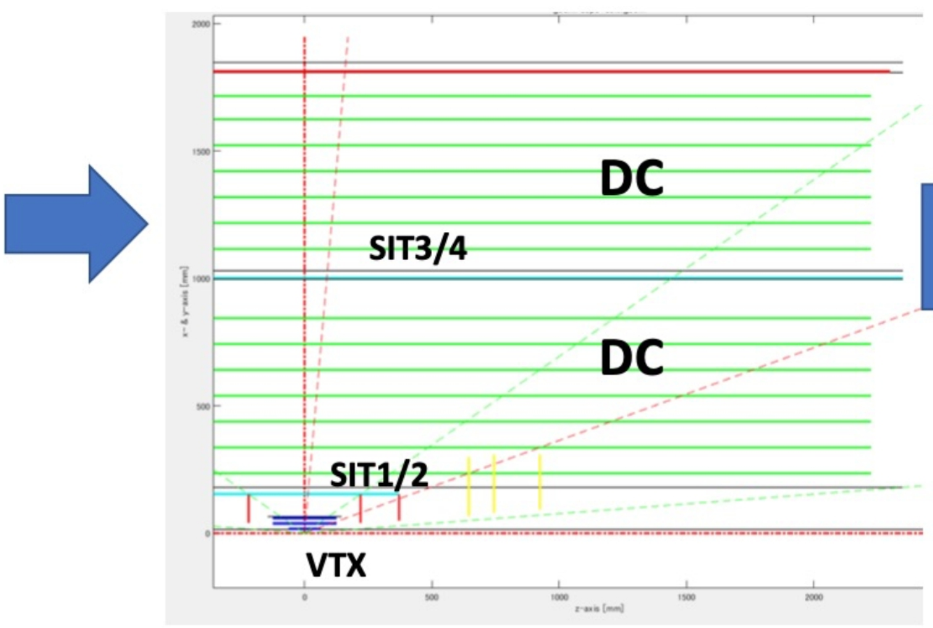
New design

- PFA Oriented Baseline
  - Excellent object finding + Jet reconstruction: fulfills the core physics requirement
  - EM resolution is not really good...
  - Very demanding DAQ + Electronic system
  - TPC might be difficult at Tera-Z operation, also difficult for mechanism & integration
- New design
  - Crystal ECAL；
  - Wire Chamber: cluster counting give good dE/dx measurements...
  - Thin Magnet between ECAL & HCAL, while HCAL serve as part of the Yoke

CEPC Silicon + Drift Chamber Tracker: v1.0

- Based on the baseline Silicon + TPC
- Replace TPC layers with two drift chamber layers
  - SIT 3&4 set at R=1.0m / larger cell size of DC than TPC

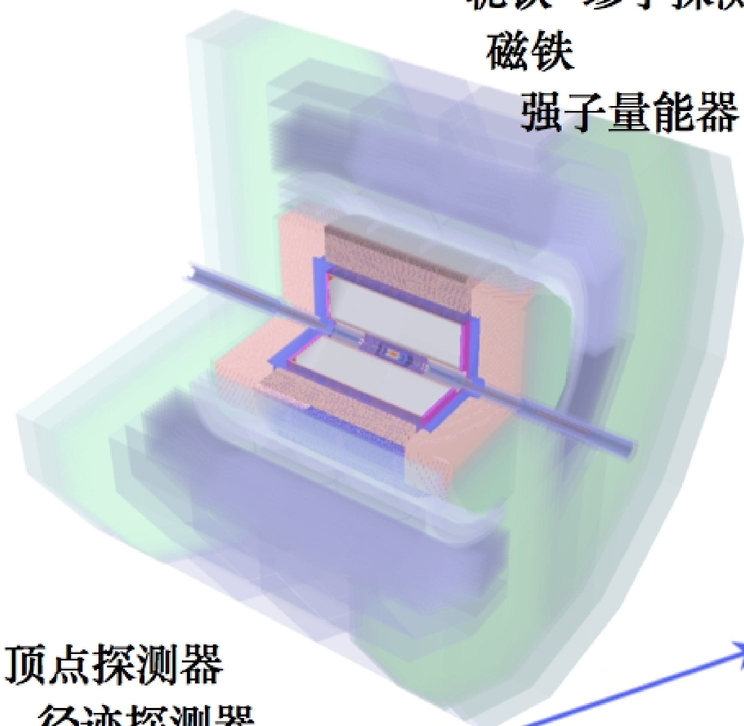




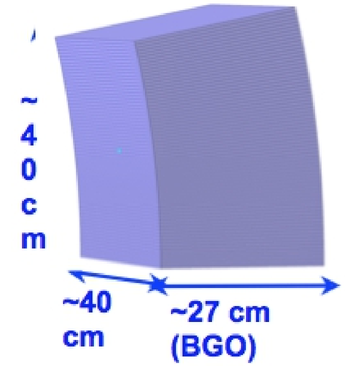
SIT 3,4 @ R=1.0m

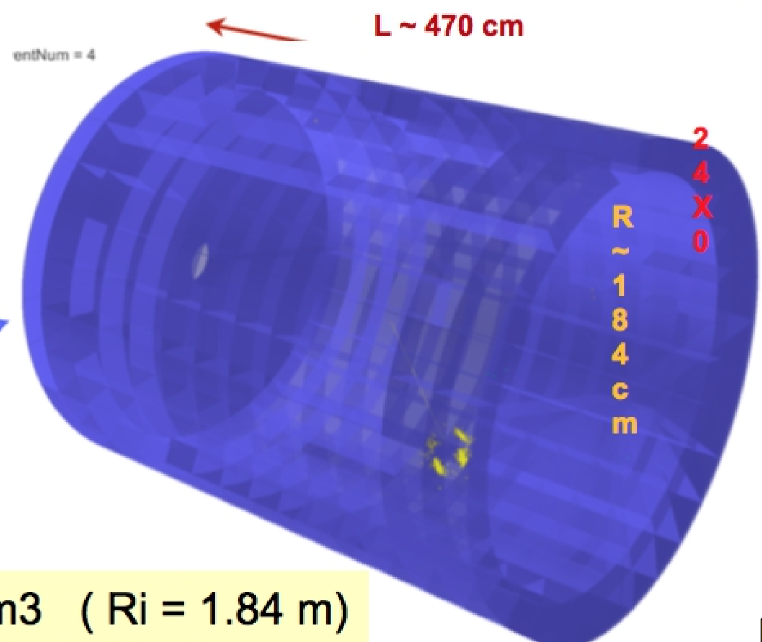
CEPC电磁量能器

轭铁+缪子探测器
磁铁
强子量能器

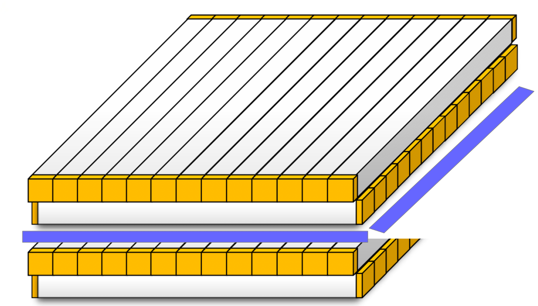


顶点探测器
径迹探测器
电磁量能器



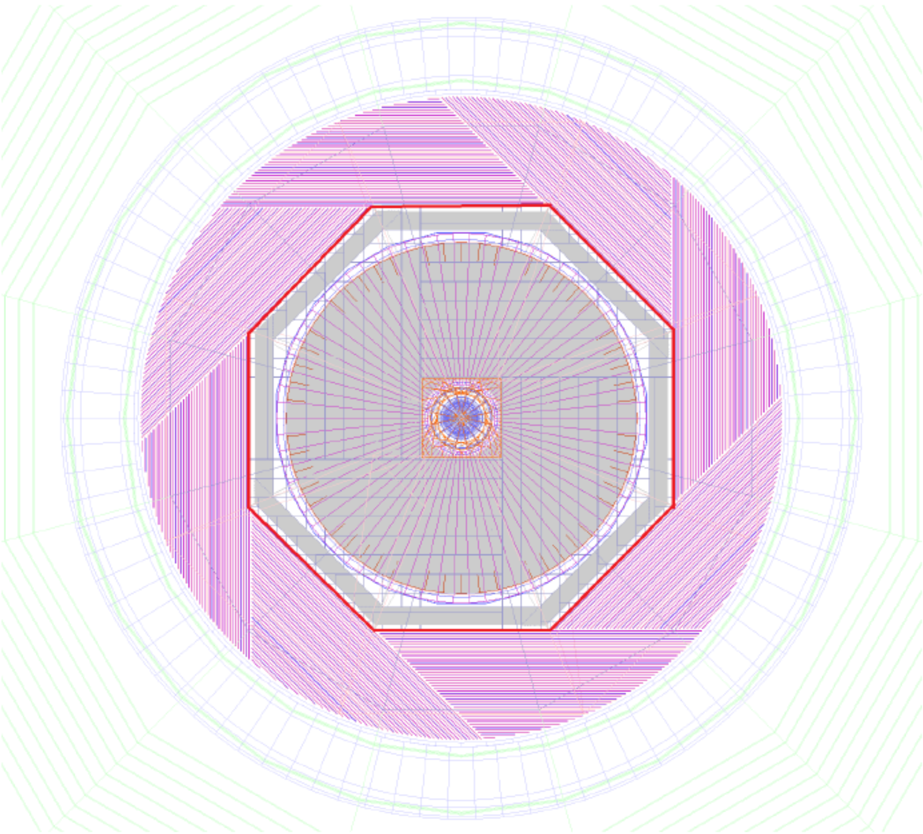


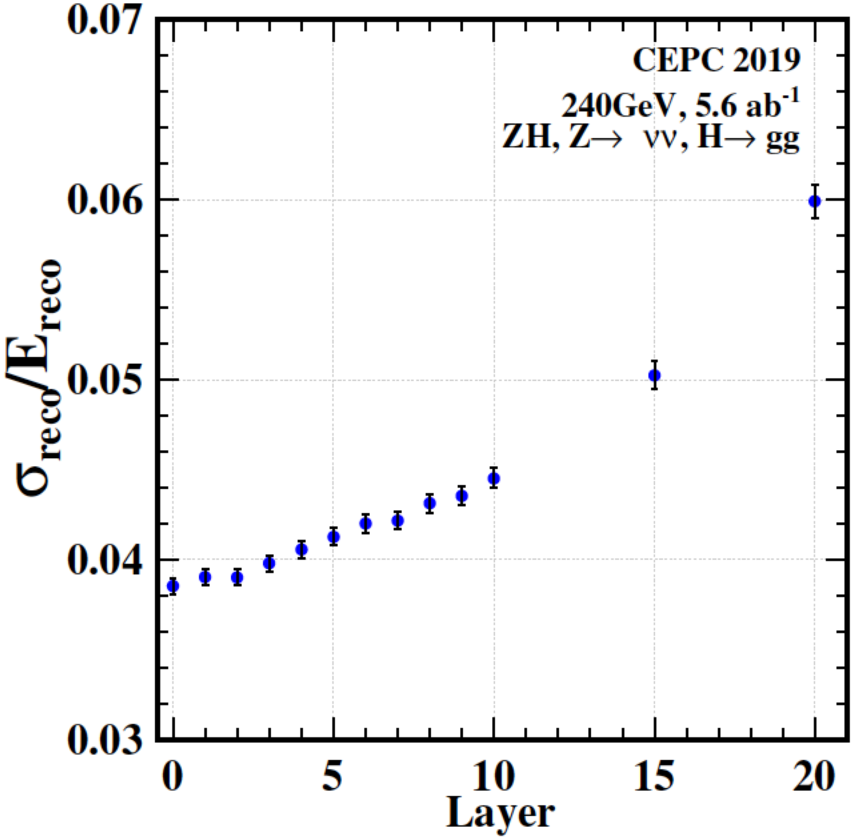
所需晶体 ~ 23.3 m3 （Ri = 1.84 m）
~ 15.5 m3（Ri = 1.50 m）



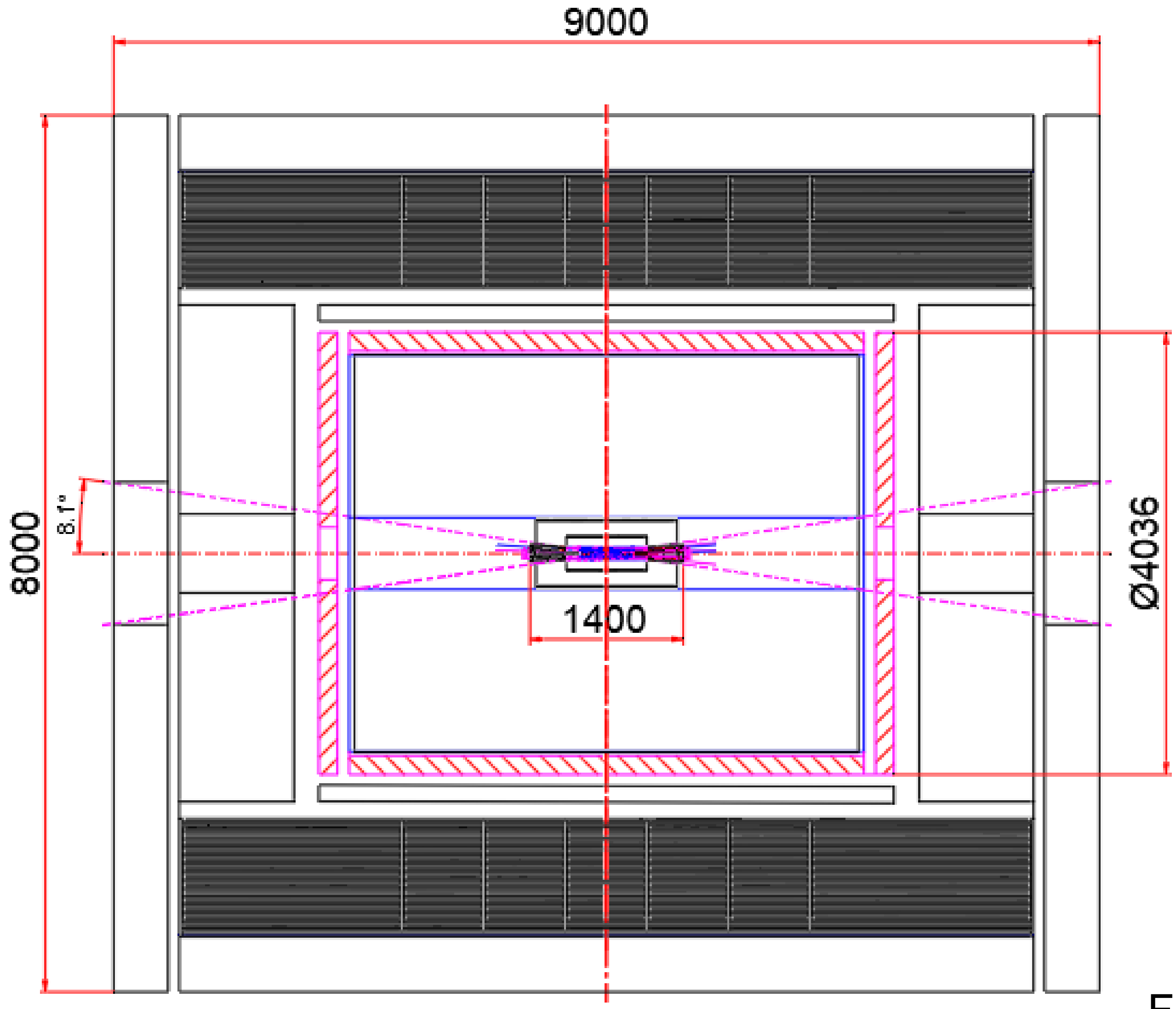
彼此垂直的晶体条 + Silicon Layers with 1*1cm granularity...

Yoke




CEPC 2019
240GeV, 5.6 ab^{-1}
ZH, Z→ νν, H→ gg
σ_{reco}/E_{reco}
Layer
0.07
0.06
0.05
0.04
0.03
0
5
10
15
20

A preliminary layout...



From Prof. Ji

New design: Key questions

- Wire Chamber: Geometry to reach the requirement (of dE/dx resolution)?
- Wire Chamber + Silicon: Geometry to reach the momentum resolution
- ECAL
  - Compatibility with PFA & Reconstruction
  - Material budget for tracker
- Yoke
  - Material budget allowance (~ o(10) cm Iron)
  - Thickness?
  - Physics requirement for special physics: i.e., Long Lived Particle search
- General:
  - Intergratibility & Support
  - MDI
  - Mechanics, Cooling - Power, DAQ - Electronics

Summary

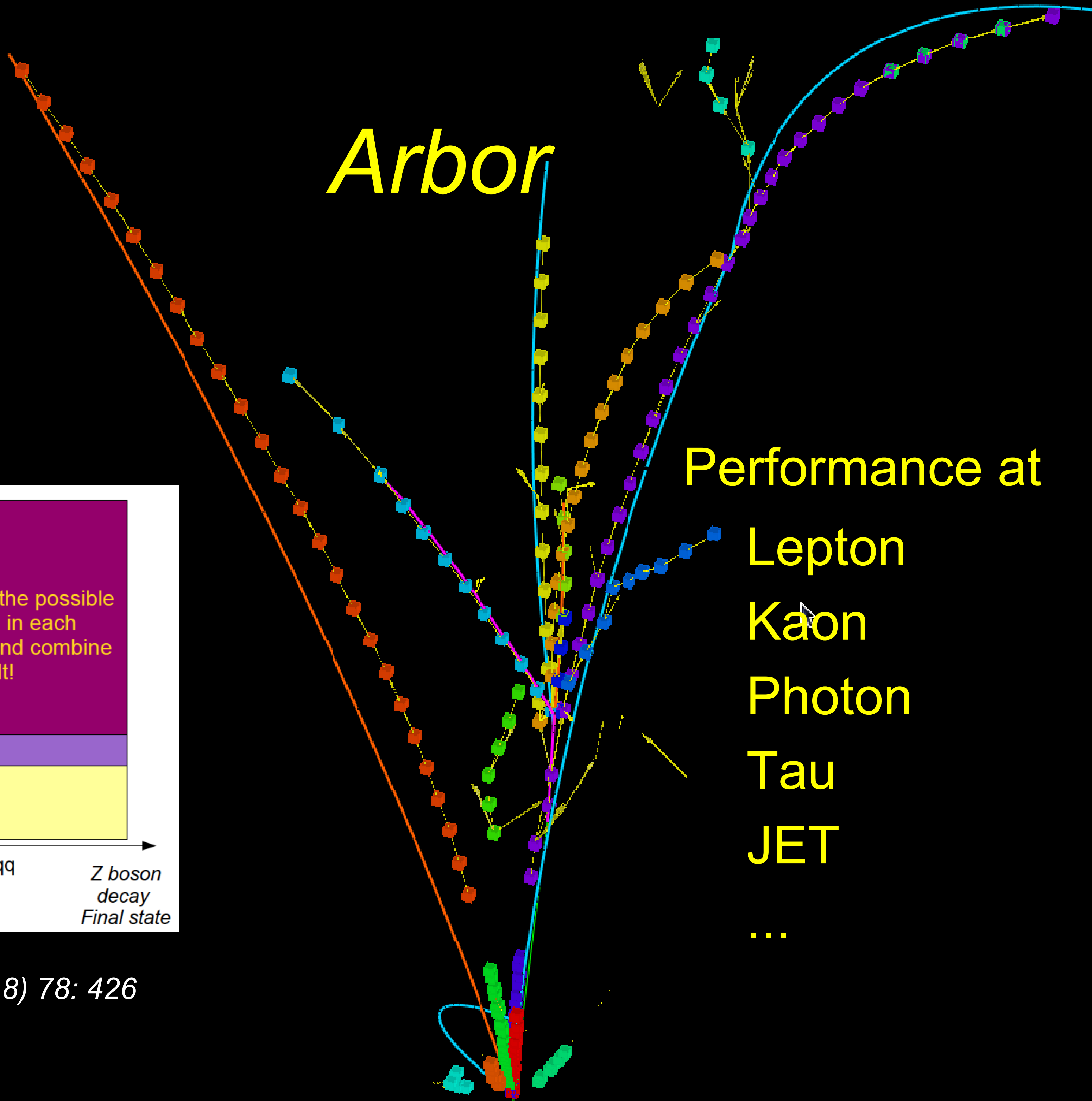
- CEPC: a promising Higgs/Z factory, clear requirement on the detector performance
- PFA Oriented baseline: fulfill the core CEPC physics requirements (object + jet); but has some shortages...
- To overcome these shortage, new designs are proposed, with many critical questions to be answered
- Mechanics is critical!
  - W.r.t CDR: Targeting the critical MDI part & significantly improved the Yoke
  - Many Challenges ahead, towards the new designs.
- Next step: my suggestion –
  - Mechanics: Exercise with Magnet between E/HCAL
  - Physics: answer critical questions & converge to a physics design of the new concept(s)

Backup

Summary

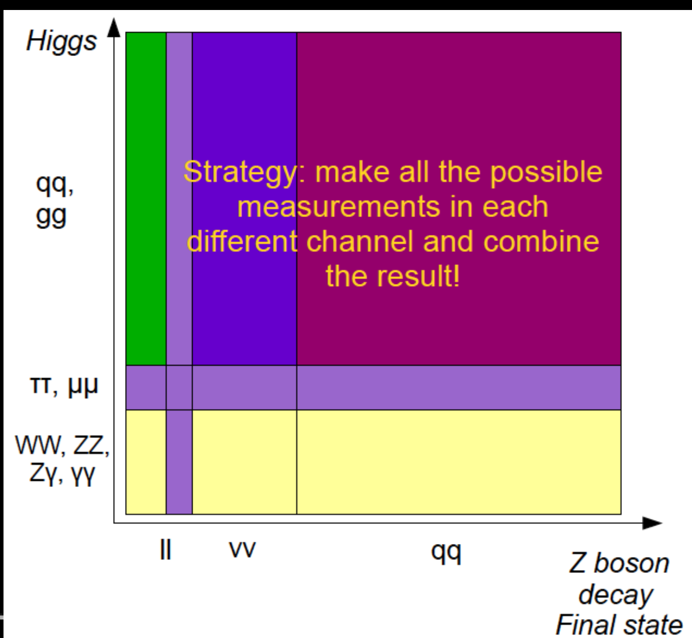
- Higgs, portal to unknown
- CEPC, an electron-positron Higgs factory & an precision EW machine
  - o(0.1-1%) level accuracy in absolute measurement of Higgs Branching ratio and couplings
  - Higgs total width measured to 2.8%
  - Good access to SM Higgs rare decays (μμ, γγ, Zγ)
  - Higgs exotic decays, limited to better than 0.1% level
  - EW Program significantly enhance the access to the New Physics
  - Highly complementary to pp machine
- Simulation study: toward a better understanding of its Physics potential
  - Good understanding toward absolute Higgs coupling measurement
  - Toward detector optimization & measurement with detector optimizations

Arbor



Performance at

- Lepton
- Kaon
- Photon
- Tau
- JET
- ...



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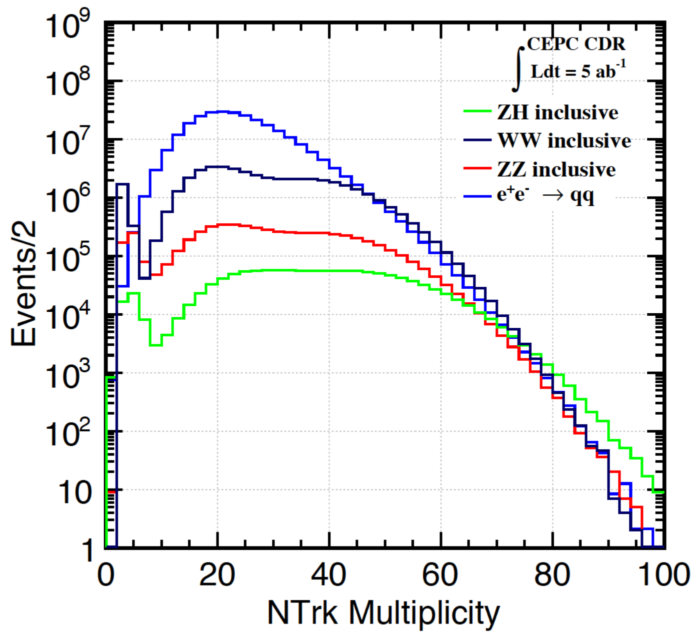
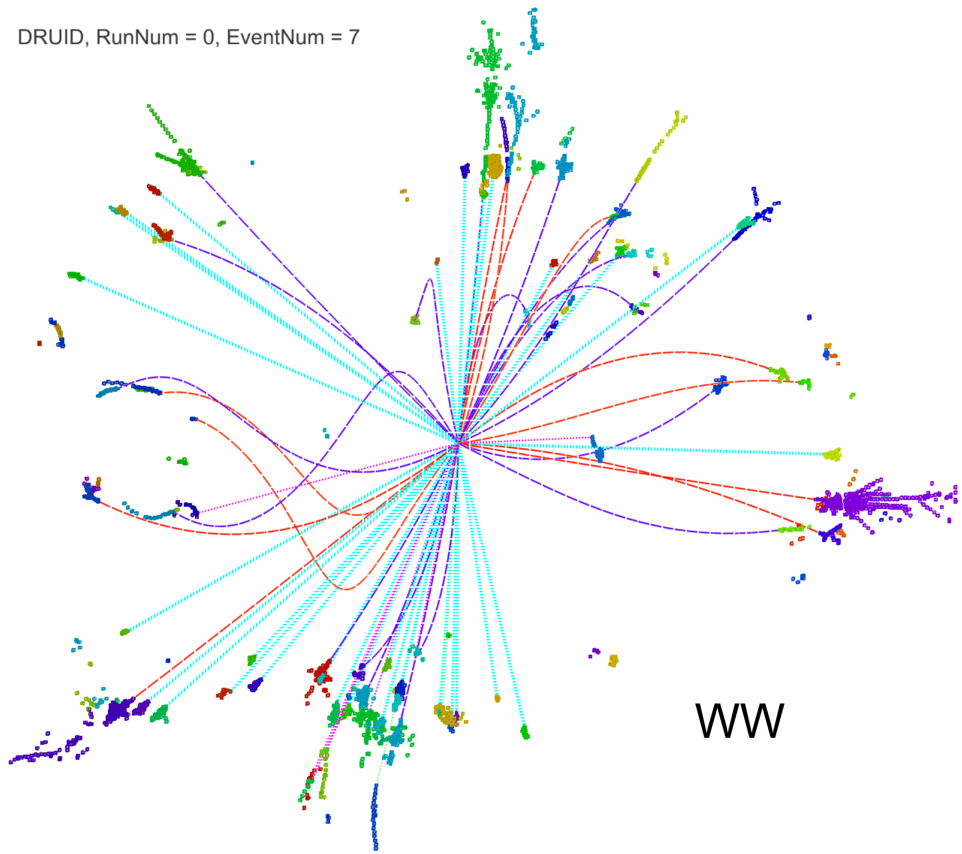
Parameters

	CEPC_v1 (~ ILD)	Optimized (Preliminary)	Comments
Track Radius	1.8 m	>= 1.8 m	Requested by Br(H->μμ) measurement
B Field	**3.5 T**	**3 T**	**Requested by MDI**
ToF	**-**	**50 ps**	**Requested by pi-Kaon separation at Z pole**
ECAL Thickness	84 mm	84(90) mm	84 mm is optimized on Br(H->γγ) at 250 GeV; 90mm for bhabha event at 350 GeV
ECAL Cell Size	5 mm	10 – 20 mm	Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation
ECAL NLayer	30	20 – 30	Depends on the Silicon Sensor thickness
HCAL Thickness	**1.3 m**	**1 m**	-
HCAL NLayer	**48**	**40**	Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV.

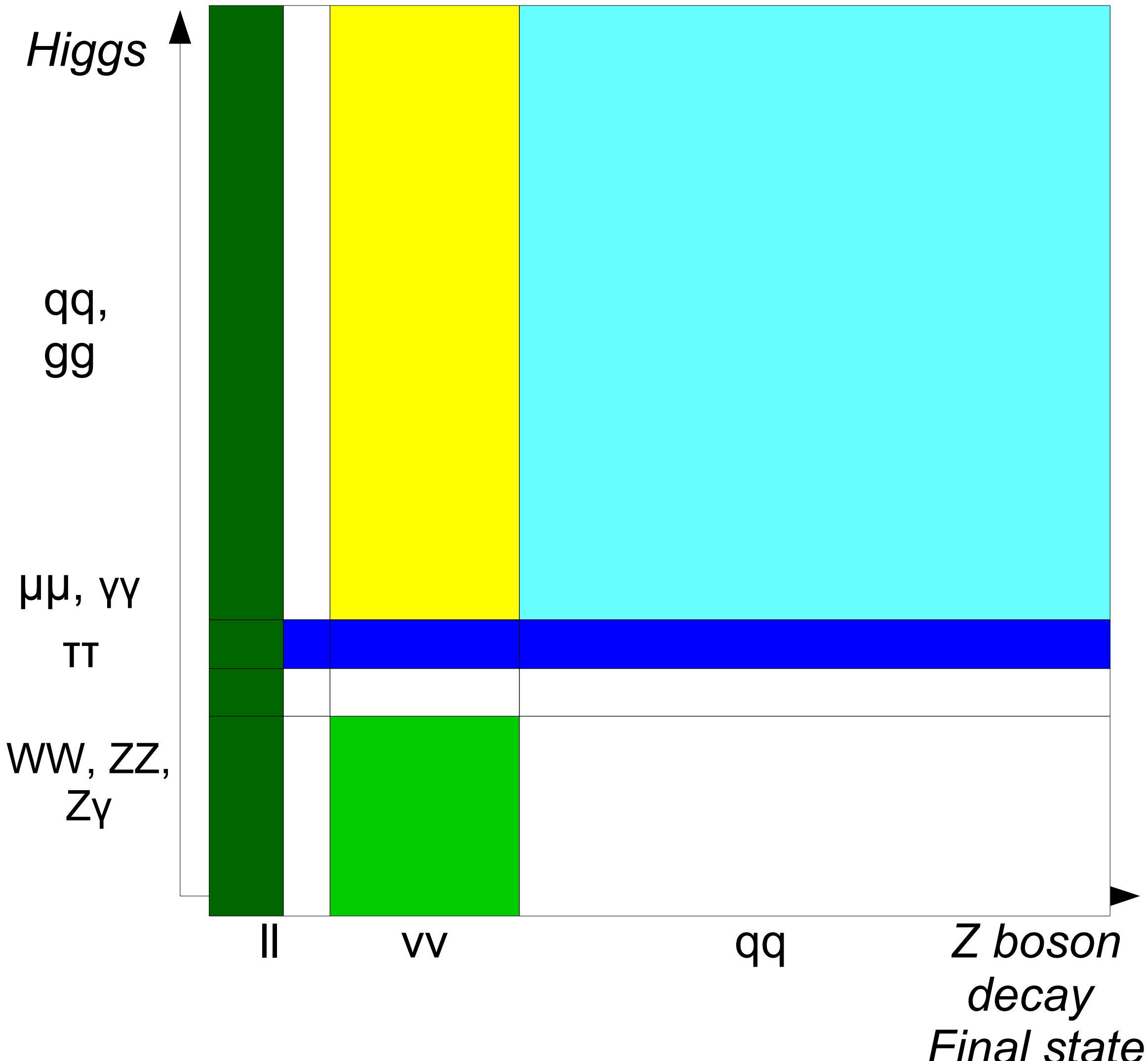
Color Singlet identification: Full hadronic WW-ZZ separation, an example





- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response

Benchmark measurements: Higgs



Lepton & Momentum resolution: Br = 6.7%

Flavor Tagging & JER: Br = 14%

Composition of Jet/MET, lepton: Br = 4%

Jet Clustering: Br = 50%

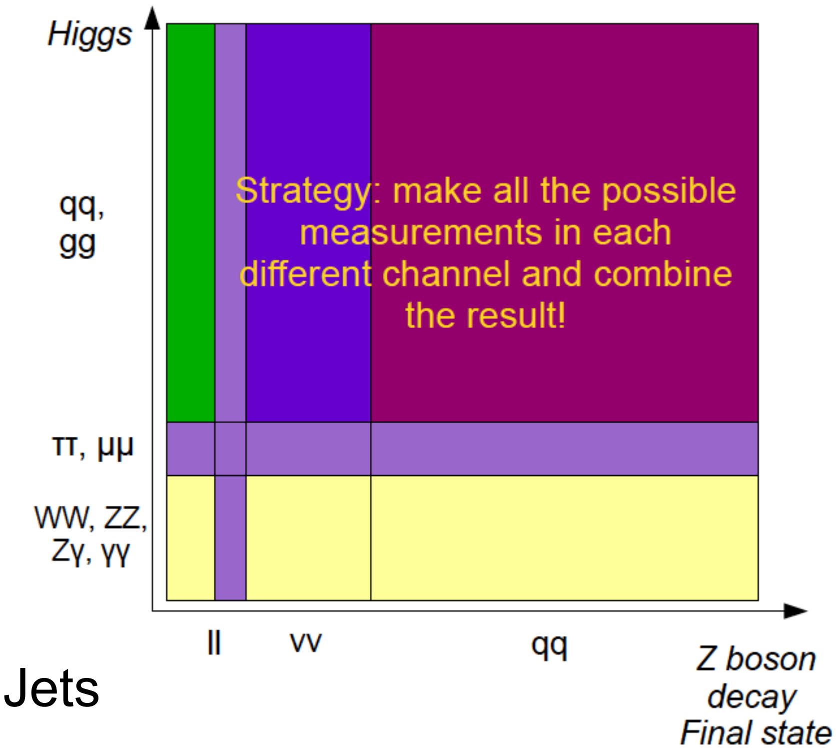
Photon/ECAL: Br = 0.2%

qqH, H->inv. MET & NP: SM Br = 0.1%

EW, Br(tau->X) @ Z pole: Separation

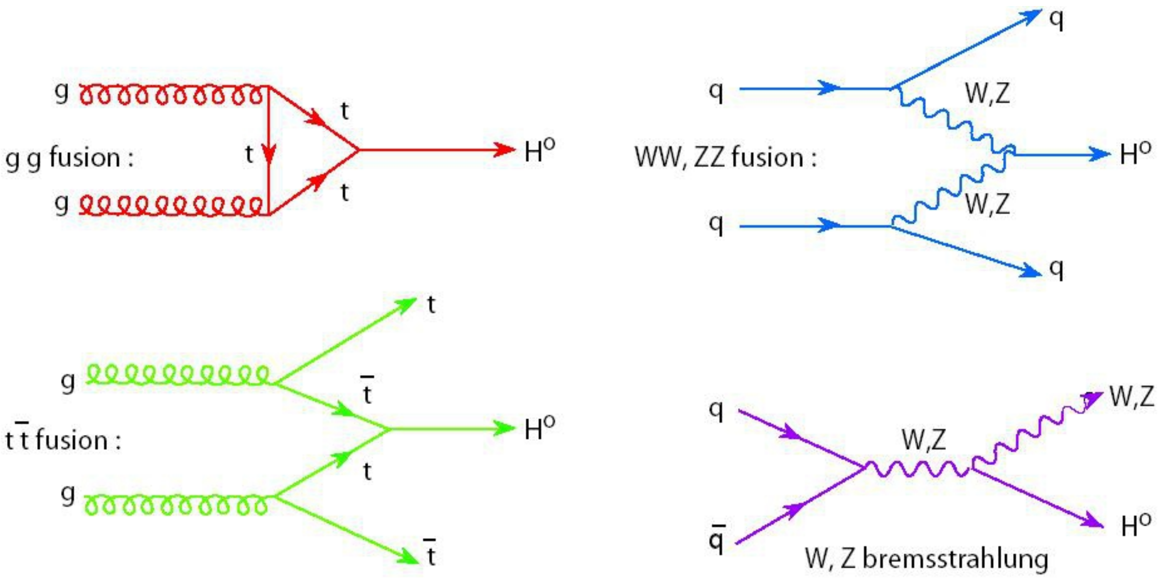
Jets at the Higgs Signal

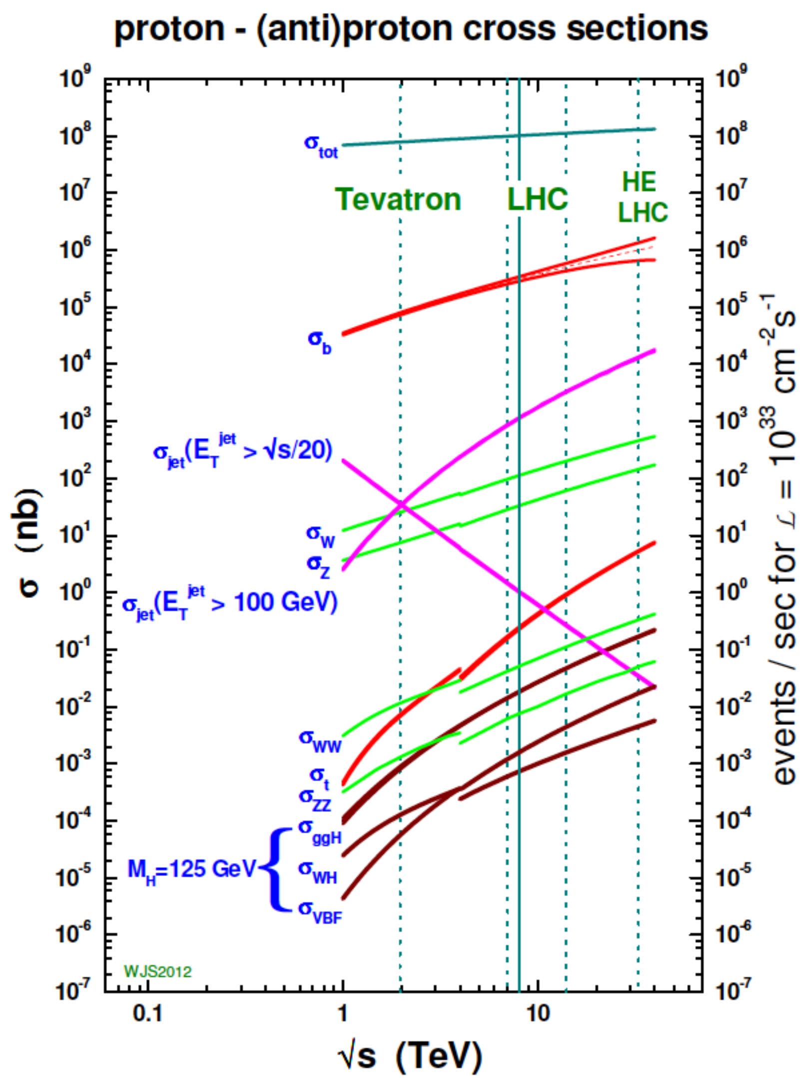
- SM Higgs
  - **0 jets: 3%**
    - Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)
  - **2 jets: 30%**
    - Z→qq, H→0 jets.
    - Z→ll, νν; H→2 jets.
    - Z→ll, νν; H→WW/ZZ→semi-leptonic.
  - **4 jets: 59%**
    - Z→qq, H→2 jets.
    - Z→ll, νν; H→WW/ZZ→4 jets.
  - **6 jets: 8%**
    - Z→qq, H→WW/ZZ→4 jets.



- 97% of the SM Higgsstrahlung Signal involves Jets

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.

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