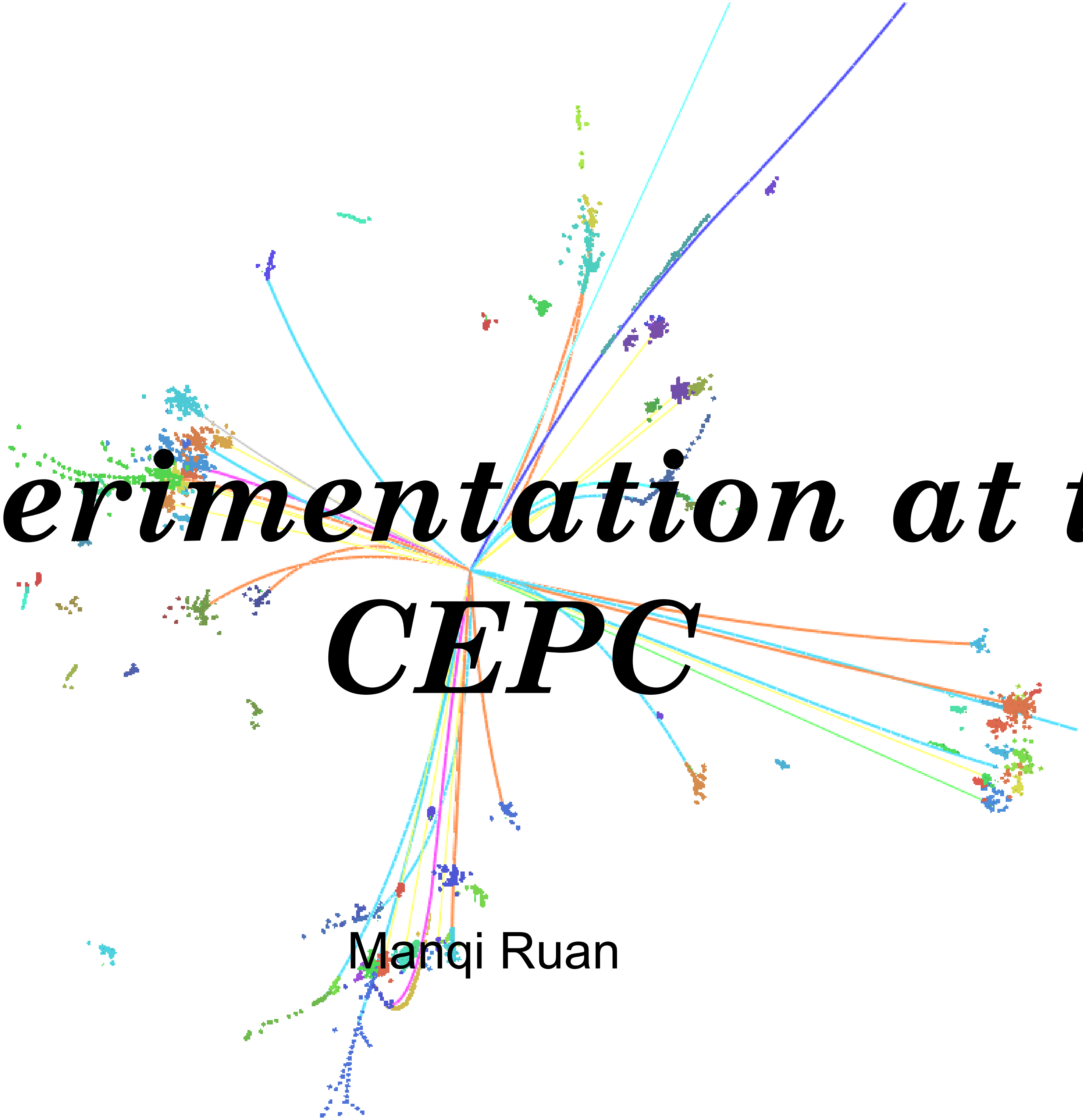
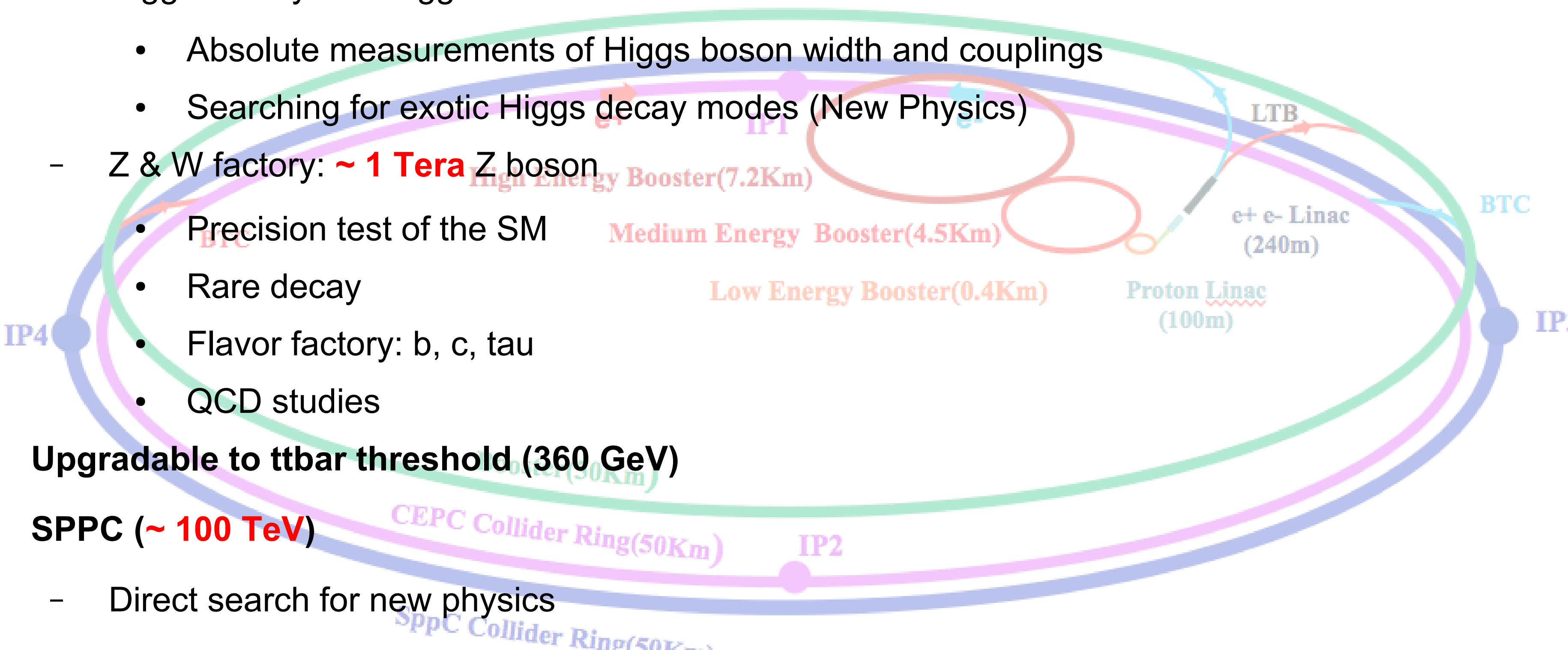


Experimentation at the CEPC

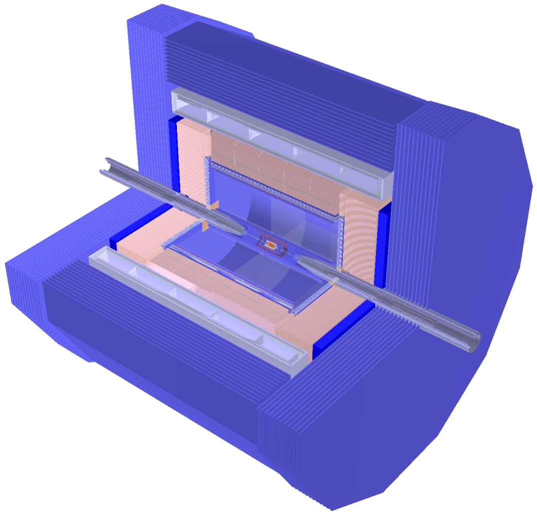
Manqi Ruan

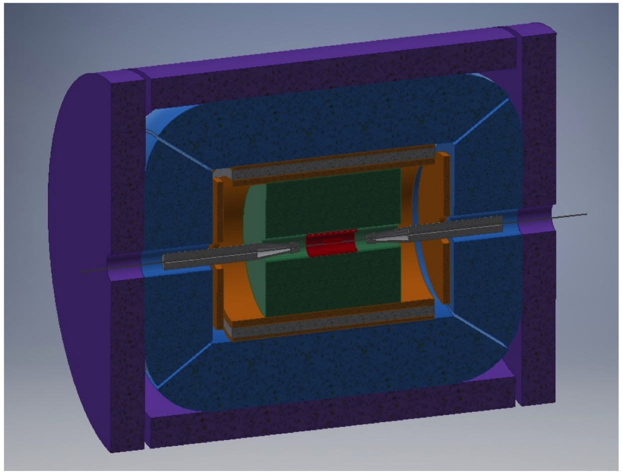
Key figures of the CEPC-SPPC

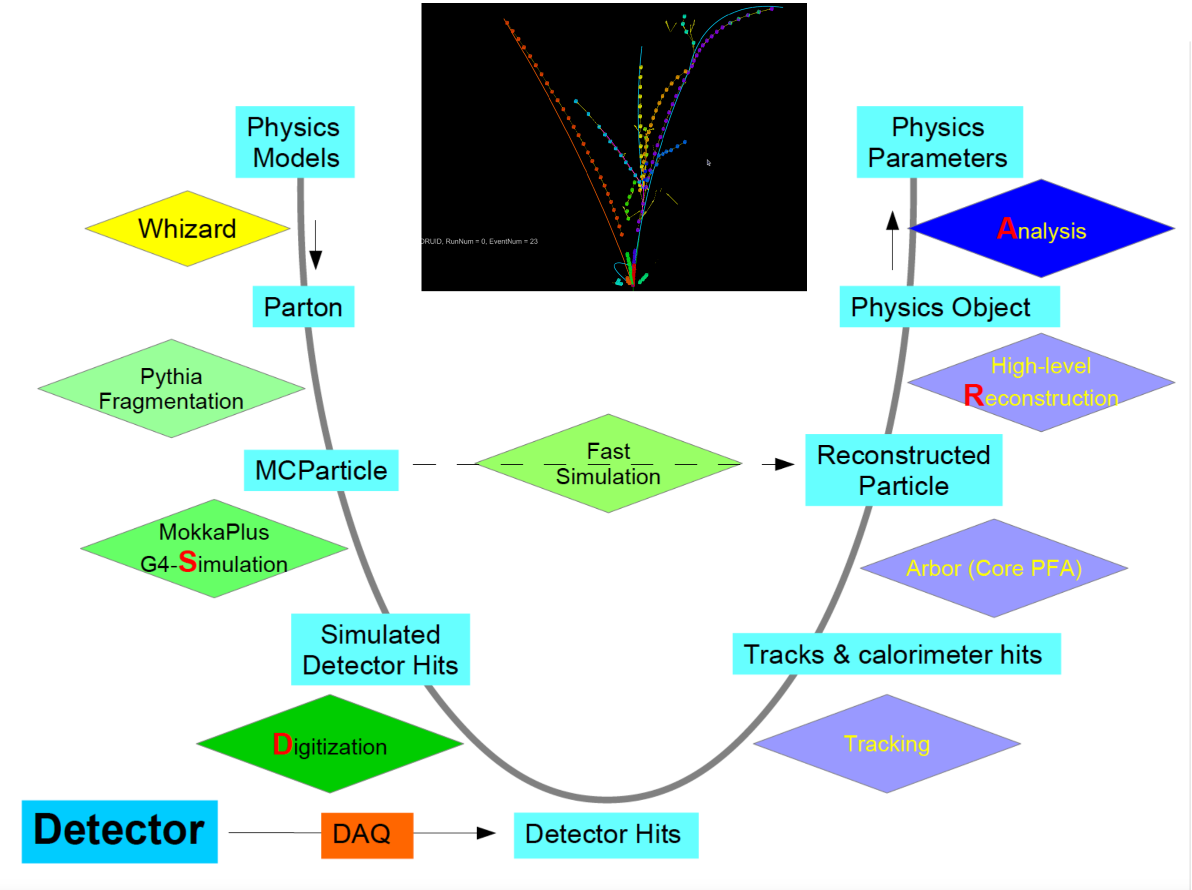


- **Tunnel ~ 100 km**
- **CEPC (90 – 240 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
    - Flavor factory: b, c, tau
    - QCD studies
- **Upgradable to ttbar threshold (360 GeV)**
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**

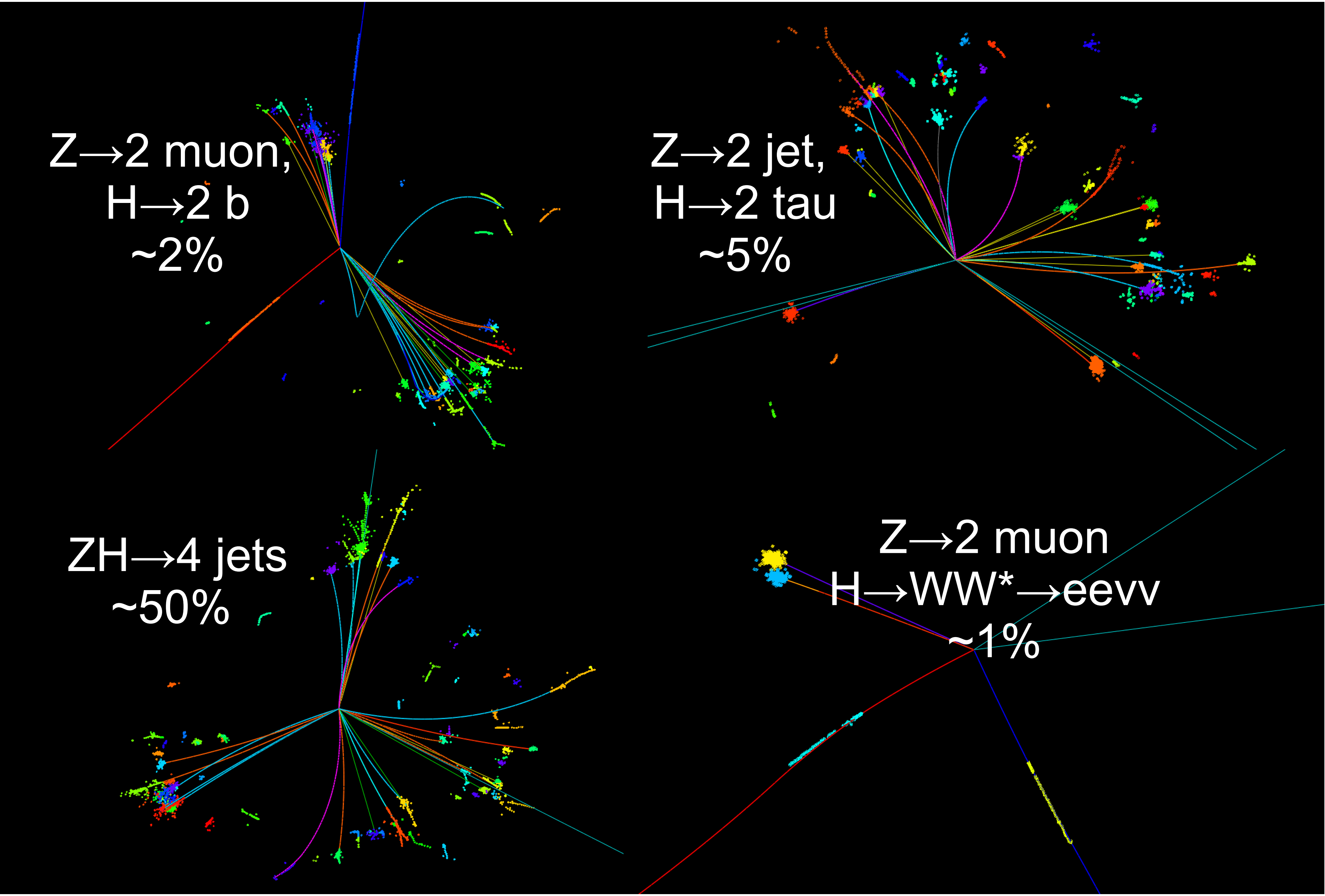
Detector & Software



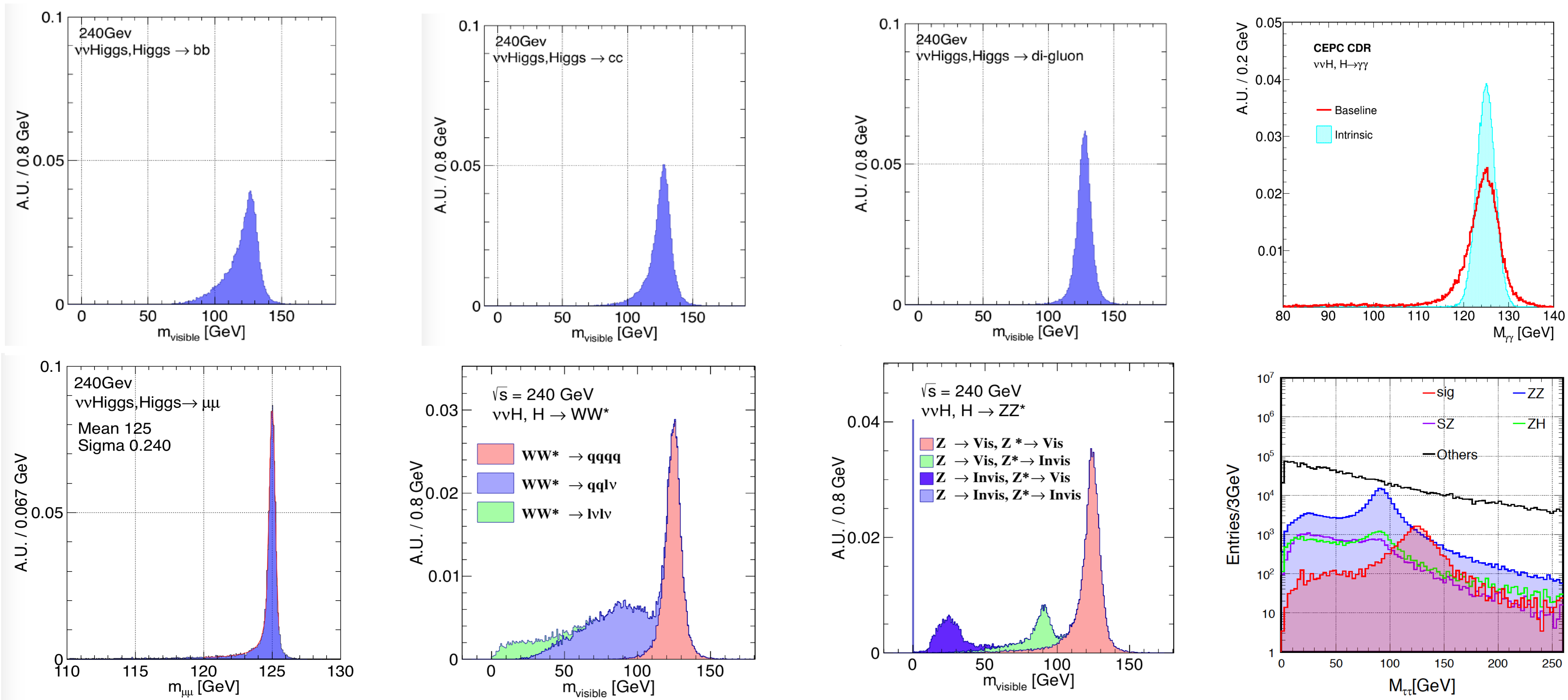




Full simulation reconstruction Chain with Arbor, iterating/validation with hardware studies


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%

Reconstructed Higgs Signatures

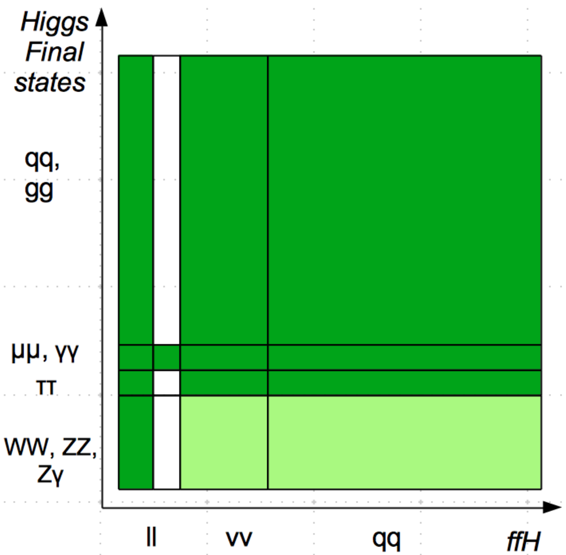


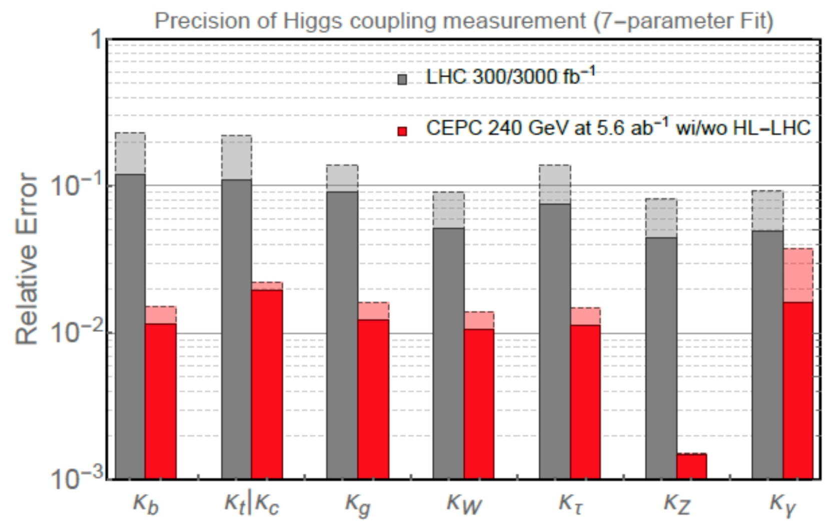
Clear Higgs Signature in all SM decay modes

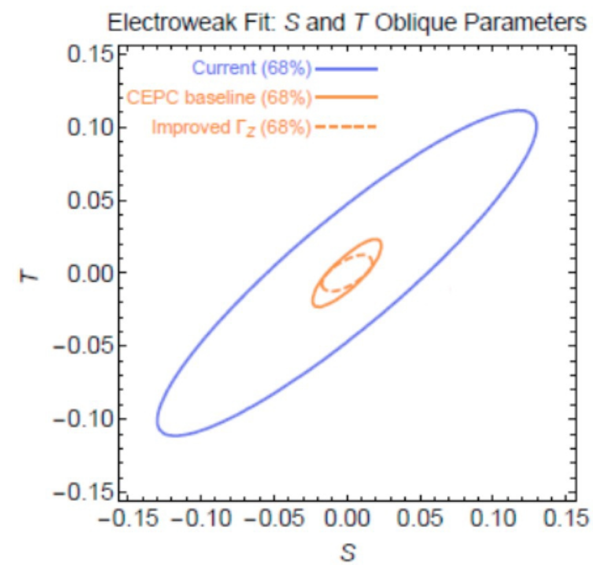
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

Right corner: di-tau mass distribution at qqH events using collinear approximation

Excellent physics potential







70 OVERVIEW OF THE PHYSICS CASE FOR CEPC

Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
BR($B_s \to ee$)	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \mu\mu$)	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \tau\tau$)	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
BR($B \to K^*\tau\tau$)	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
BR($B \to K^*\nu\nu$)	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
BR($B_s \to \phi\nu\bar{\nu}$)	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
BR($\Lambda_b \to \Lambda\nu\bar{\nu}$)	–	–	$\sim 10^{-6}$
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
BR($\tau \to 3\mu$)	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{BR(\tau \to \mu\nu\bar{\nu})}{BR(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
BR($Z \to \mu e$)	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
BR($Z \to \tau e$)	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
BR($Z \to \tau\mu$)	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Table 2.5: Order of magnitude estimates of the sensitivity to a number of key observables for which the tera-Z factory at CEPC might have interesting capabilities. The expected future sensitivities assume luminosities of 50 fb^{-1} at LHCb, 50 ab^{-1} at Belle II, and 3 ab^{-1} at ATLAS and CMS. For the tera-Z factory of CEPC we have assumed the production of 10^{12} Z bosons.

CEPC Accelerator TDR Design

2018 CDR Baseline Design

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	[illegible]	[illegible]	
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	[illegible]49.5/849.5/425.0	
Natural Chromaticity [illegible]	[illegible]	[illegible]	-491/-1161	-513/-1594
Betatr[illegible]	363.10 / 365.22			
S[illegible]	0.065	0.040	0.028	
H[illegible] (2 cell) (k[illegible]	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime† (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

† include beam-beam simulation and real lattice

2021 Improved Design

	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]/35
Bunch length (SR/total) [mm]	2.2/2.9	[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	[illegible]	[illegible]/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/[illegible]	[illegible]/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

67%⇑ (Higgs) **259%⇑** (Z)

CEPC TDR Parameters - 50MW upgrade

	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Bunch number	58	415	2162	19918
Bunch spacing [ns]	2640	385	154	15 (10% gap)
Bunch population [10^{10}]	20	14	13.5	14
Beam current [mA]	5.5	27.8	140.2	1339.2
Momentum compaction [10^{-5}]	0.71	0.71	1.43	1.43
Beta functions at IP ($\beta x/\beta y$) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance ($\varepsilon x/\varepsilon y$) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Betatron tune ν_x/ν_y	445.10/445.22	445.10/445.22	266.10/267.22	266.10/267.22
Beam size at IP ($\sigma x/\sigma y$) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Damping time (ms)	14/14/7	44/44/22	156/156/78	849.5/849.5/425.0
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters ($\xi x/\xi y$)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
Longitudinal tune νs	0.078	0.049	0.062	0.035
Luminosity per IP[10^{34}/cm^2/s]	0.83	8.3	26.6	191.7

From Prof. J. Gao

CEPC: operation scenario

- CEPC emphasize on the Higgs factory & Z factory
- Upgradable:
  - In energy: to 360 GeV
  - In SR beam power: 30 to 50 MW
- Tentative Operation Plan & Yields (2 IP, with 50 MW)
  - 2 year in Z: 100 ab^{-1}, 3 Tera $Z \rightarrow qq$ events
  - 1 year in W: 6 ab^{-1}, ~ 100 Million WW events
  - 10 year in Higgs: 20 ab^{-1}, 4 Million Higgs
  - ~ 5 years at top: 1 ab^{-1}, 0.5 Million ttbar events, 150 k Higgs

Challenge: Collision/Event Rate

- $Z \rightarrow qq$ event rate higher than 100 k Hz.

- Collision rate: can be comparable to that of LHC.
  - 2.6 ms for ttbar operation
  - 385/154 ns for Higgs/WW scan
  - 15 ns for Z pole

- Compatibility of the sub-detectors: especially
  - Feasibility of the TPC:
    - Track distortion & correction induced by even the primary ionization
  - Power pulsing is difficult... more efficient cooling + optimization?
  - DAQ: Triggerless mode, or at least software trigger (as LHCb upgrade)

Challenge: Beam condition

- Beam energy calibration
  - ~ 0.1 MeV at Z pole
  - ~ sub MeV at W threshold
  - ~ MeV at Higgs operation
  - ...with nature beam energy spread of ~ o(1E-3)

- Beam polarization monitoring
  - Transverse... (essential for the Resonance depolarization Method) and even longitudinal...

- Beam Luminosity Spectrum Monitoring, especially at top

Challenge: Forward region & MDI

- CEPC has very compact & difficult forward region design
  - Luminosity measurement requirement
    - At least 1E-4 for Z pole,
    - 1E-3 for W threshold scan, Higgs operation, and top runs
    - Micrometer level position stability & accuracy for Luminometer, et.al.
  - Very short L* (varies from 1.4 – 2 meter), but seems to be definitely installed inside the tracker volume
  - The beam background condition at the CEPC is yet to be quantified. While better flavor tagging performance strongly prefers small inner radius of the vertex system.

- Low material VTX system, with R_in as small as 20 mm, radiation hard...

Challenge: Solenoid

- To reach high luminosity at the Z pole operation, the B-Field of the main Solenoid shall not be higher than 2 Tesla
  - The beam X-angle (2*16.5 mrad) at the collision point induces correlations between the vertical & horizontal emittance..
  - Compared to 3 Tesla B-Field, 2 Tesla B-Field doubles the maximal Z pole luminosity

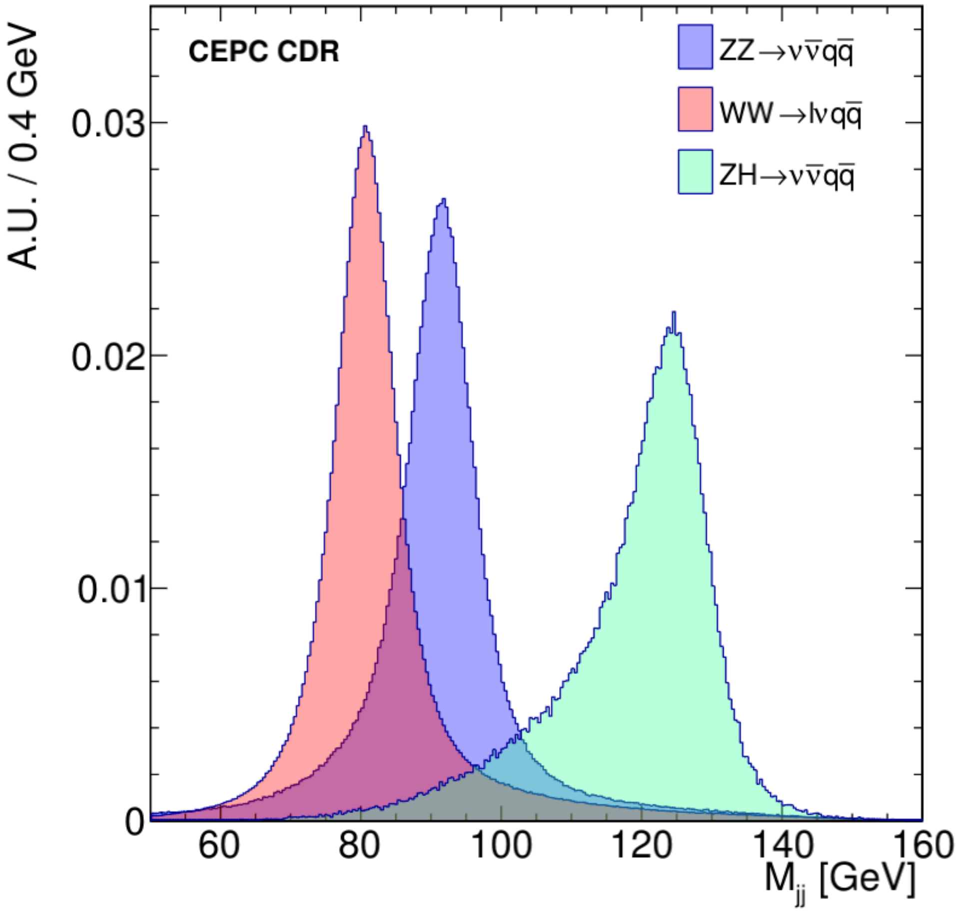
- However, a larger B-Field is strongly favored for Higher Energies.
  - Provide better momentum resolution, especially for the benchmark of Higgs to di-muon.
  - Constrains the beam background.

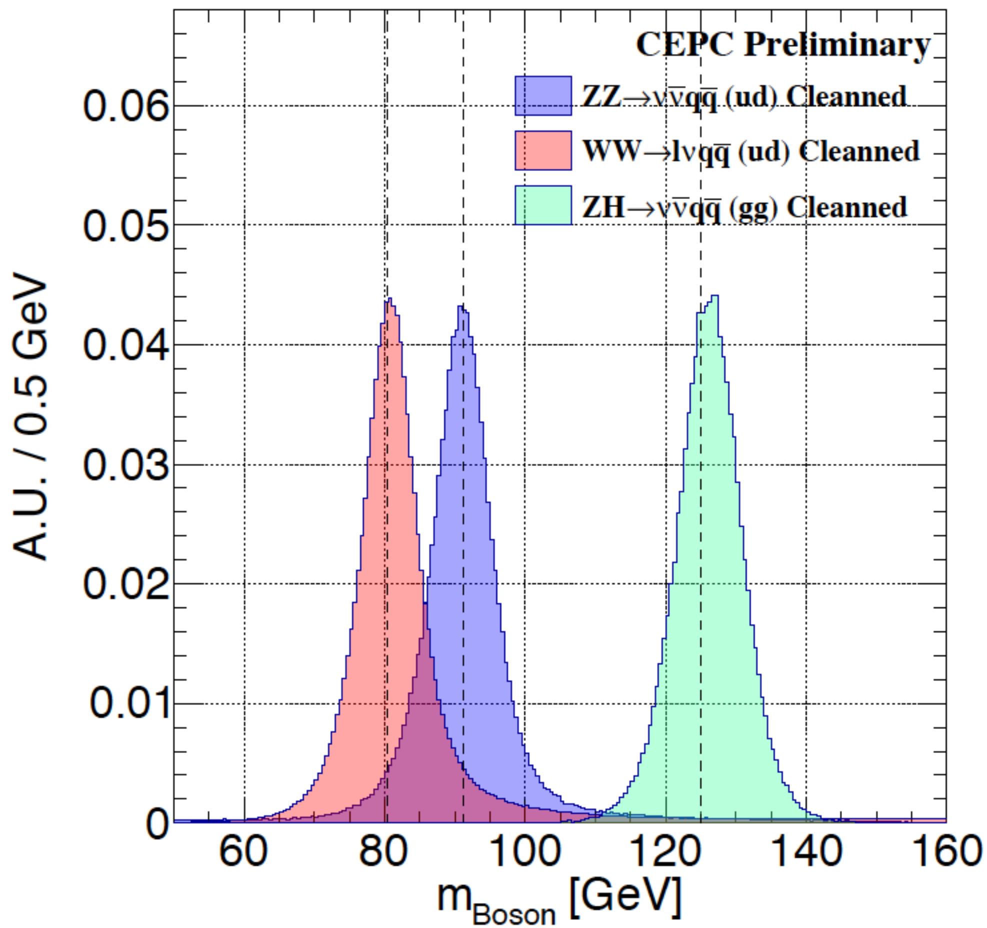
- Thus, a tunable Solenoid (2 to 3, or even higher) system, whose B-Field map can be monitored to a relative precision of 1E-4, and stable enough...

Performance requirement

- A clear separation of the final state particles
  - Identification of Physics Objects
    - Leptons, especially those inside jets
    - Composited objects:
      - With two/three final state particles: Pi-0, K-short, Lambda, Phi,Tau, D meson...
      - Jets
  - Improving the E/P resolution for composited objects, especially jets
- BMR (Boson Mass Resolution)
  - < 4% for Higgs measurements
  - Much demanding for Flavor Physics Measurements
- Pid: Pion & Kaon separation > 3-sigma
- Jet: Flavor Tagging & Charge Reconstruction
- Flavor Physics: requires good ECAL resolution

Massive Boson Separation





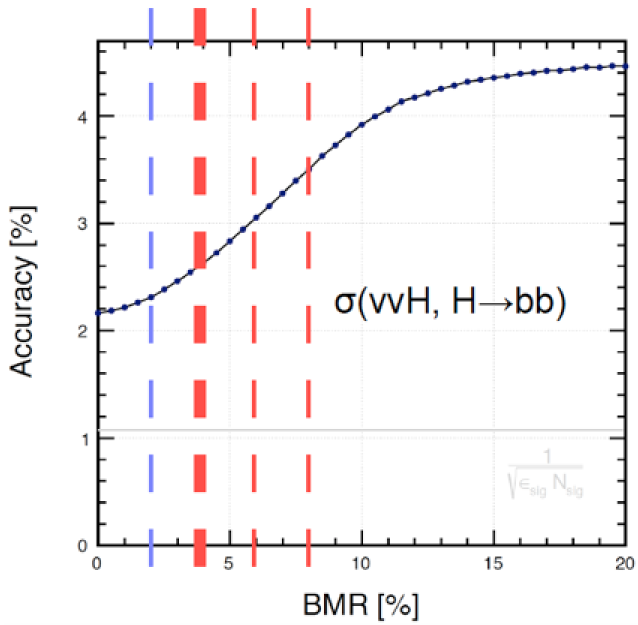
Peizhu Lai & CEPC CDR

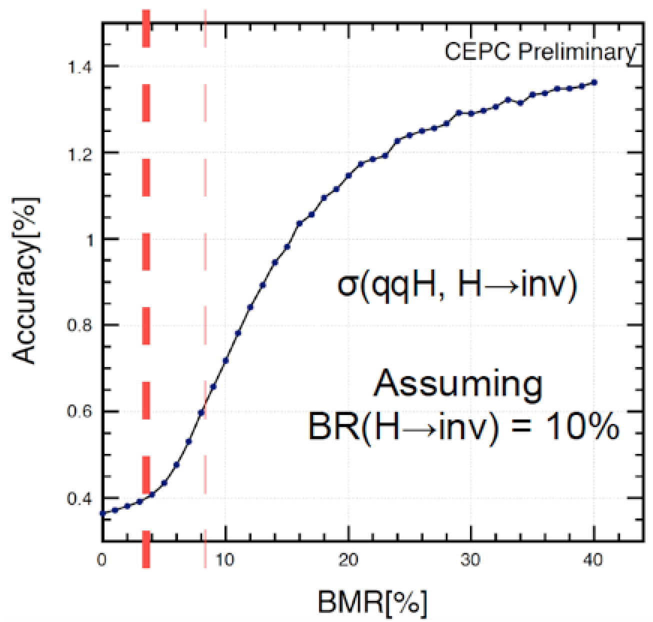
WW sample: using μνqq sample,
Plot: the visible mass without the muon

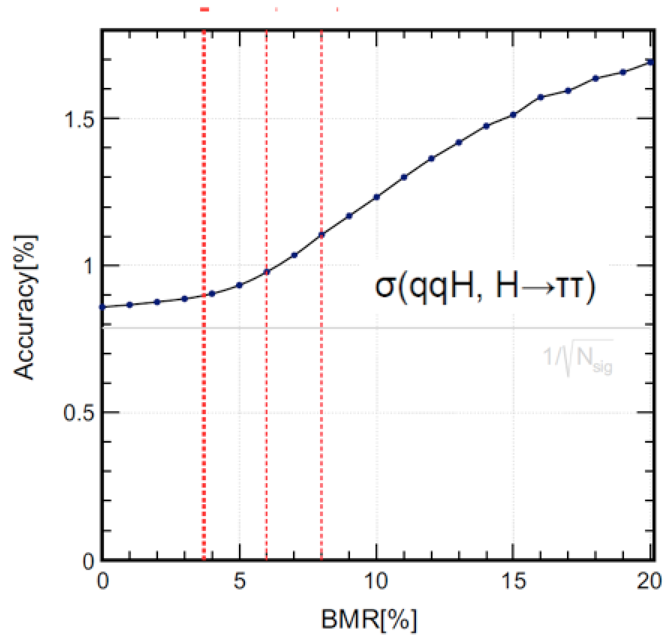
CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),

Eur. Phys. J. C (2018) 78: 426

BMR V.S. benchmark accuracy







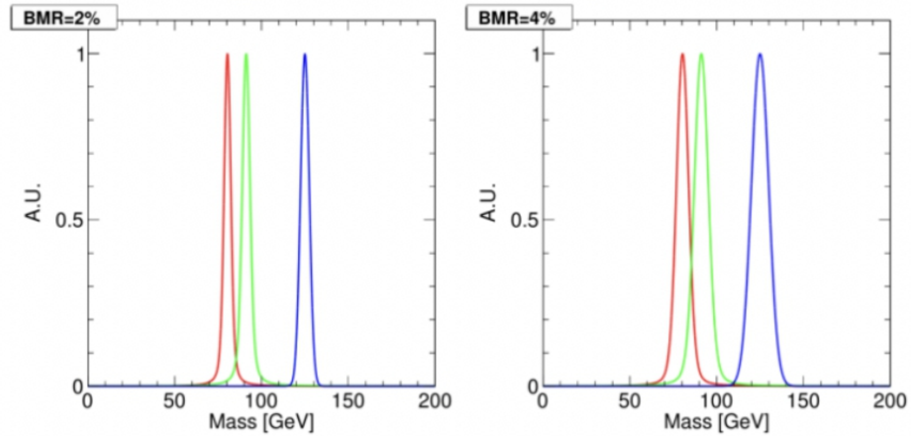
- Boson Mass Resolution: relative mass resolution of vvH, H→gg events
  - Free of Jet Clustering
  - Be applied directly to the Higgs analyses
- The CEPC baseline reaches 3.8%

	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(vvH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

Anticipated Higgs precisions at 20 + 1 iab

	240GeV, $20ab^{-1}$	360GeV, $1ab^{-1}$		
	ZH	ZH	ννH	eeH
any	**0.26%**	**1.4%**	\	\
$H \rightarrow bb$	**0.14%**	**0.9%**	**1.1%**	4.3%
$H \rightarrow cc$	**2.02%**	**8.8%**	**16%**	20%
$H \rightarrow gg$	**0.81%**	**3.4%**	**4.5%**	12%
$H \rightarrow WW$	**0.53%**	**2.8%**	**4.4%**	6.5%
$H \rightarrow ZZ$	**4.17%**	**20%**	**21%**	
$H \rightarrow \tau\tau$	**0.42%**	**2.1%**	**4.2%**	7.5%
$H \rightarrow \gamma\gamma$	**3.02%**	**11%**	**16%**	
$H \rightarrow \mu\mu$	**6.36%**	**41%**	**57%**	
$Br_{upper}(H \rightarrow inv.)$	**0.07%**	\	\	
$\sigma(ZH) * Br(H \rightarrow Z\gamma)$	**8.5%**	**35%**	\	
Width	**1.73%**	**1.10%**		

Scalar bosons with “tight” mass spectrum



- New resonances could be close to M_W, M_Z, M_H

cf. the 96 GeV excess at LHC, e.g. P. J. Fox and N. Weiner, JHEP **08** (2018), 025

- New resonances with spectrum $\delta m < M_Z - M_W$ possible.
- Difficult example: HEIDI Higgs

$$D_{HH}(q^2) = \left[q^2 + M^2 - \mu(q^2 + m^2)^{\frac{d-6}{2}}\right]$$

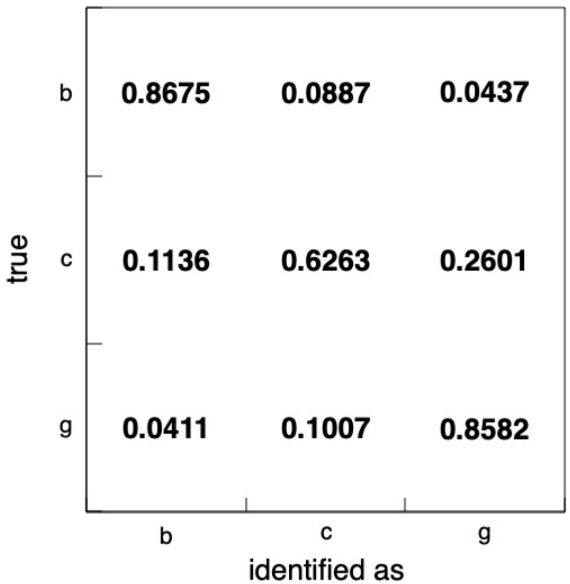
$\Rightarrow$ Test if the “Higgs signal” stems from a continuum.

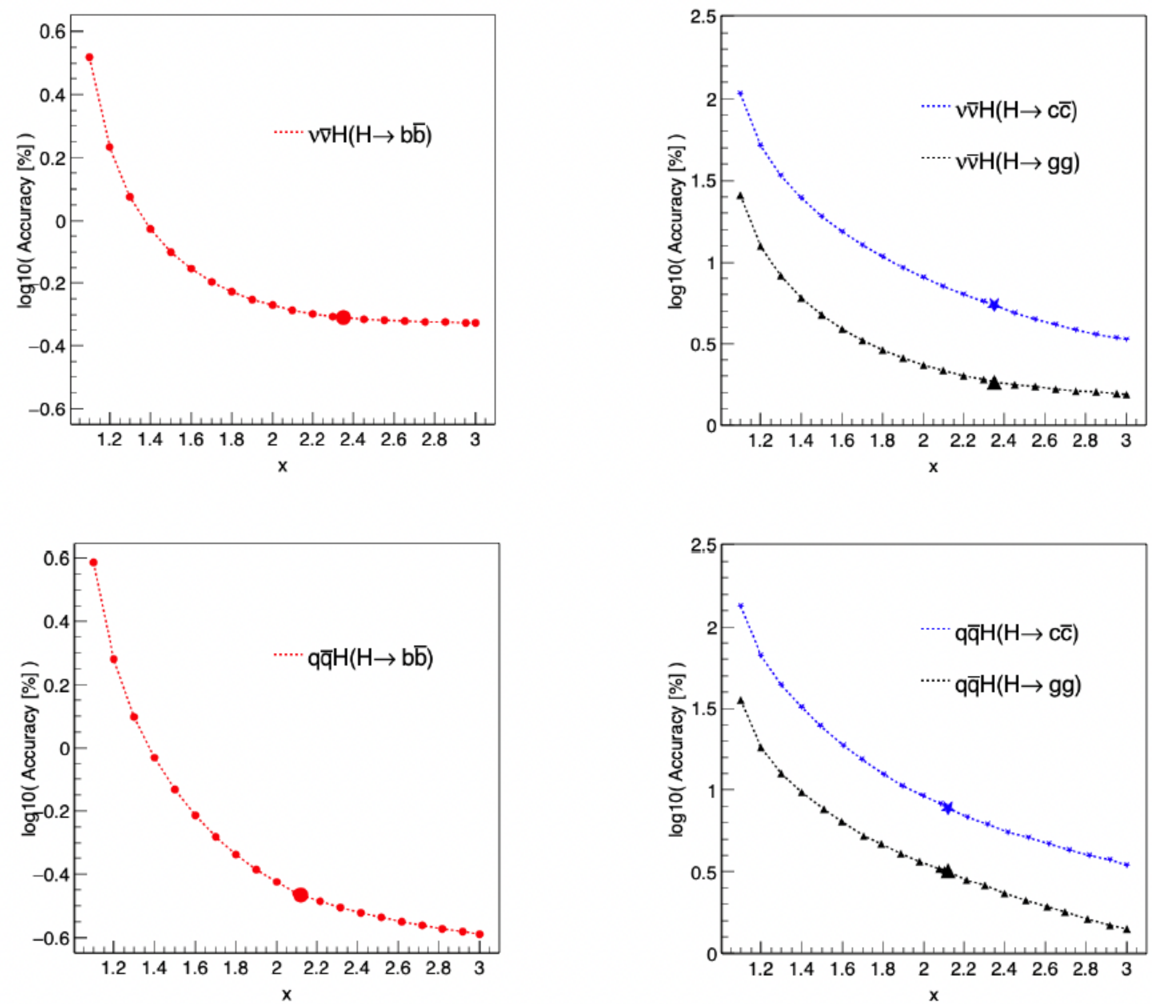
J. J. van der Bij and S. Dilcher, Phys. Lett. B **638** (2006), 234-238

- The Boson Mass Resolution should be as good as possible!

Find more info in <u>Oliver Fisher’s talk at CEPCWS2021</u>

Jet Flavor Tagging for Higgs measurement: good & significant potential to improve



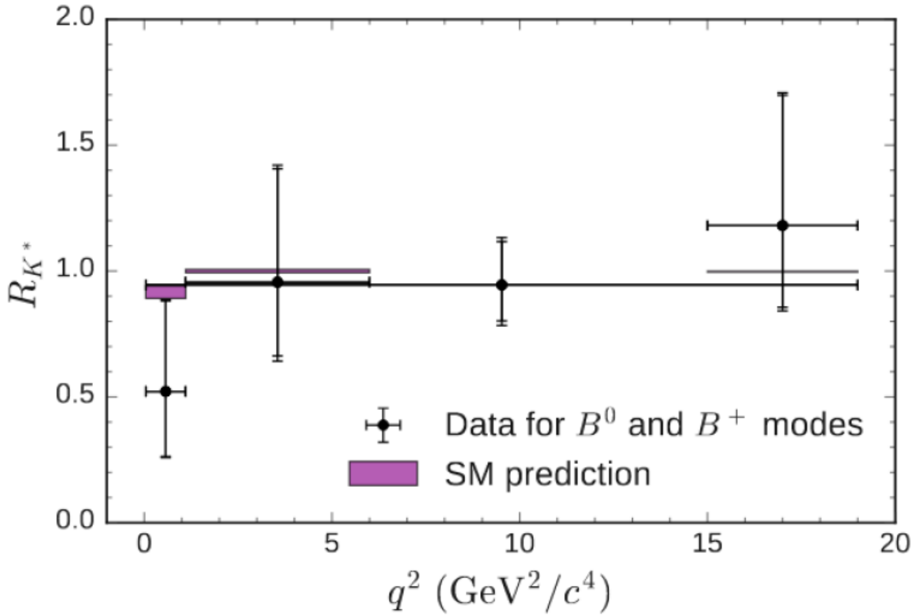


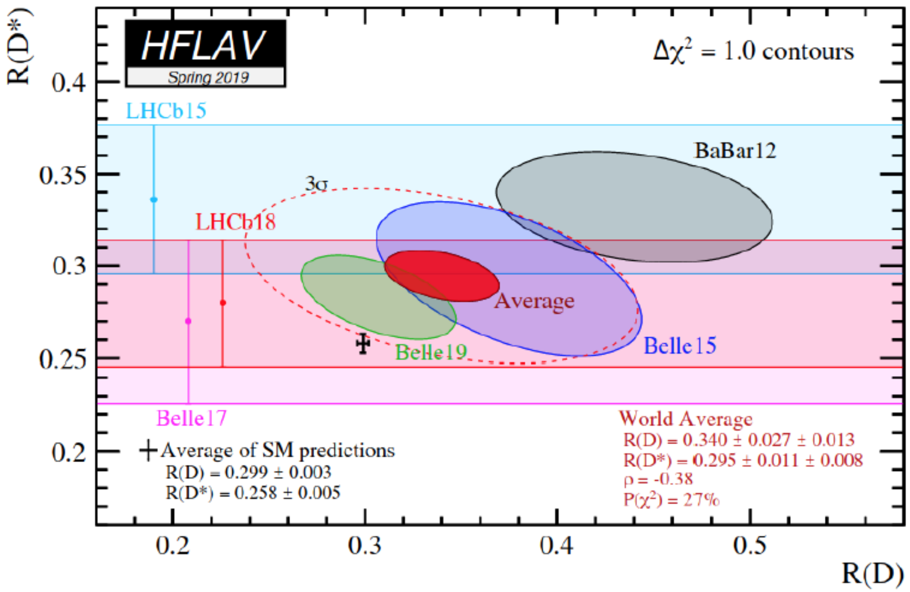
Compared to Baseline, Ideal FT improve the H->bb, cc, gg Measurements significantly. Especially at qqH channel. (up to 2 times.)

Flavor Physics @ Z pole

- Extremely rich physics & strong competition from Belle-II & LHCb
- Comparative advantages of a Tera-Z
  - V.S. BelleII, Access to particles heavier than Bs, large boost
  - V.S. LHCb, much lower yields (2 orders of magnitudes) Better Acceptance, better reconstruction of neutral final state (photon, missing energy, and even Klong, neutron) and Jet Charge
- Observations
  - For CP measurement, a Tera-Z can compete with LHCb @ HL-LHC thanks to the capability of precise Jet Charge measurements...
  - Brings lots of critical information on measurements with neutral final states...
  - Yet, Pid is essential.

B Anomalies Indicating LFUV

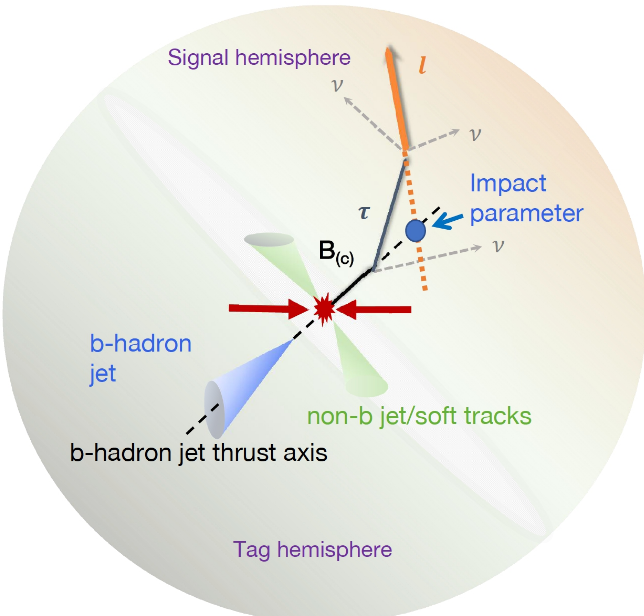


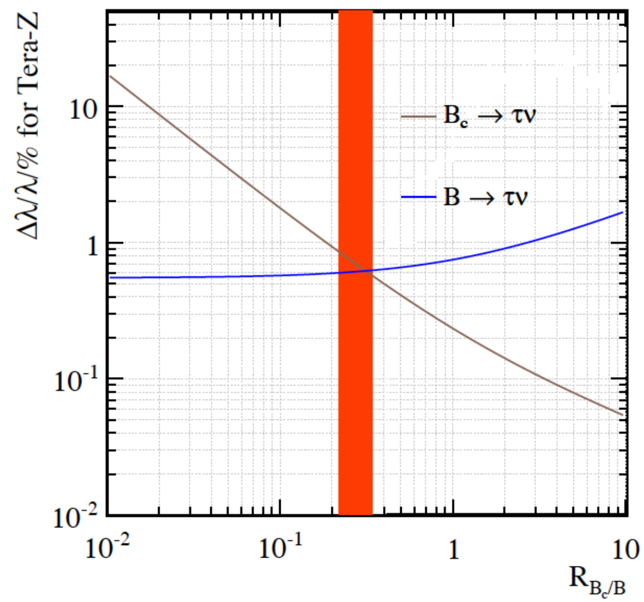


	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28	

[Tanabashi et al., 2018][Altmannshofer et al., 2018].

Bc→Tauv





Chinese Physics C Vol. 45, No. 2 (2021)

Analysis of $B_c \to \tau\nu_\tau$ at CEPC*

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Yeuk-Kwan E. Cheung(张若筠)[1] Manqi Ruan(阮曼奇)[4†]

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Abstract: Precise determination of the $B_c \to \tau\nu_\tau$ branching ratio provides an advantageous opportunity for understanding the electroweak structure of the Standard Model, measuring the CKM matrix element $|V_{cb}|$, and probing new physics models. In this paper, we discuss the potential of measuring the process $B_c \to \tau\nu_\tau$ with τ decaying leptonically at the proposed Circular Electron Positron Collider (CEPC). We conclude that during the Z pole operation, the channel signal can achieve five-σ significance with $\sim 10^9$ Z decays, and the signal strength accuracies for $B_c \to \tau\nu_\tau$ can reach around 1% level at the nominal CEPC Z pole statistics of one trillion Z decays, assuming the total $B_c \to \tau\nu_\tau$ yield is 3.6×10^6. Our theoretical analysis indicates the accuracy could provide a strong constraint on the general effective Hamiltonian for the $b \to c\tau\nu$ transition. If the total B_c yield can be determined to $O(1\%)$ level of accuracy in the future, these results also imply $|V_{cb}|$ could be measured up to $O(1\%)$ level of accuracy.

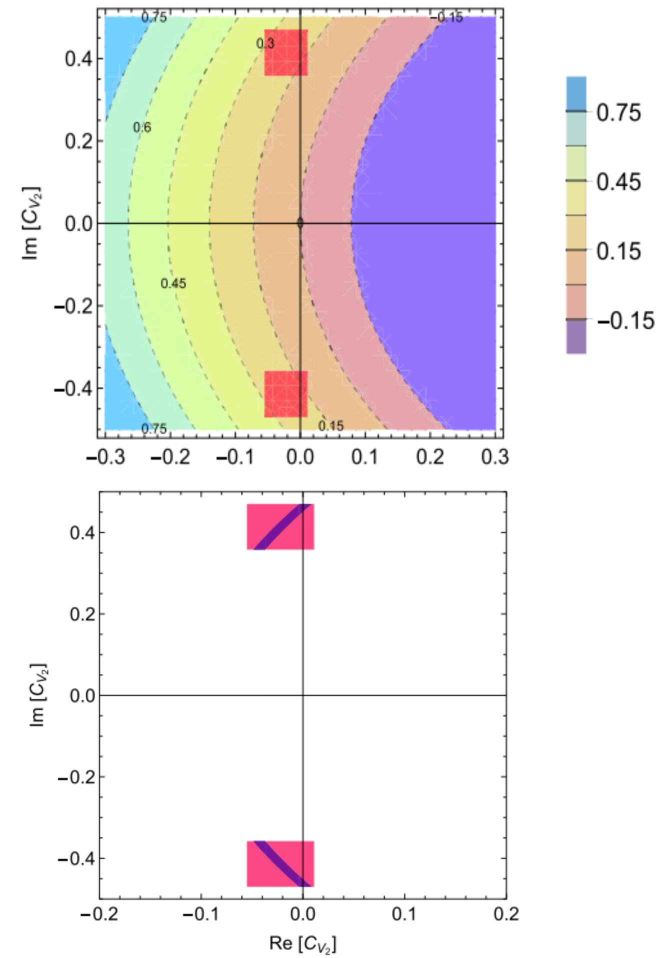
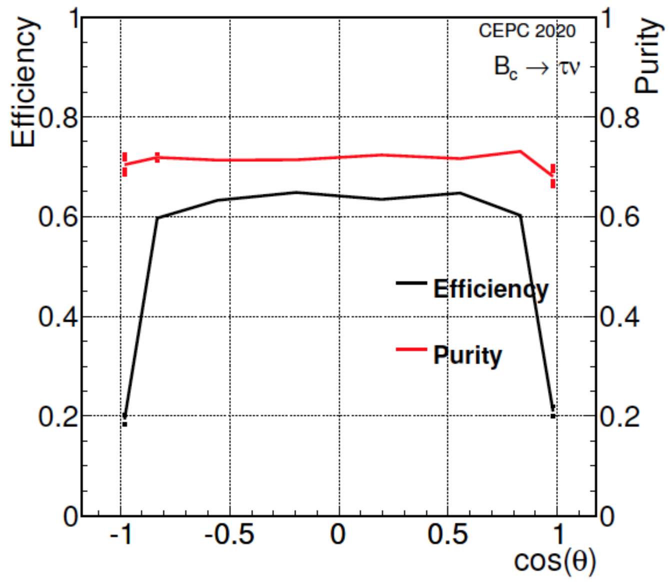
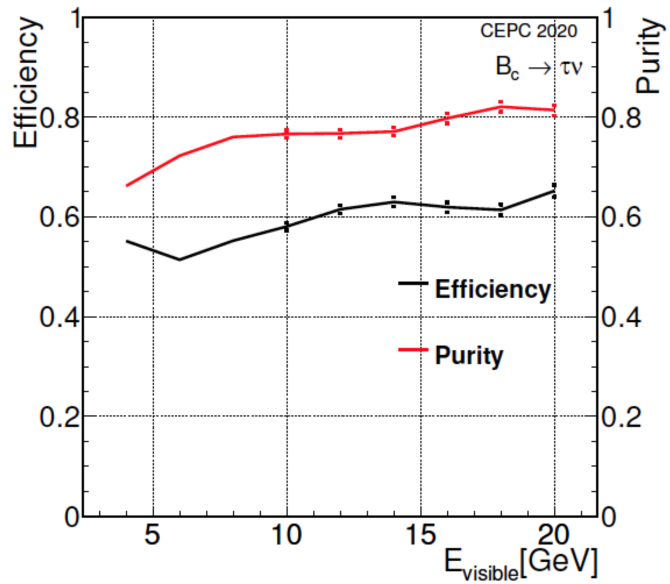


Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to 1%, the allowed region for C_{V_2} shrinks to the dark-blue regions.

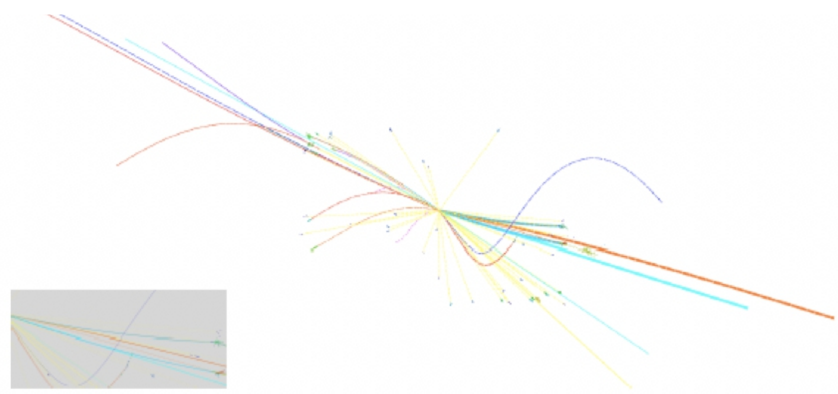
Z→bb, Bc→τν @ 91.2 GeV: eff ~ 60%, purity ~ 75%



(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

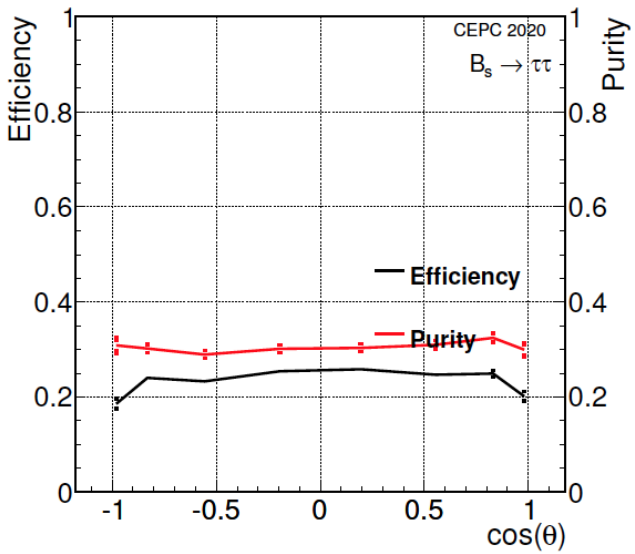


(b) Efficiency and purity performance along with visible energy

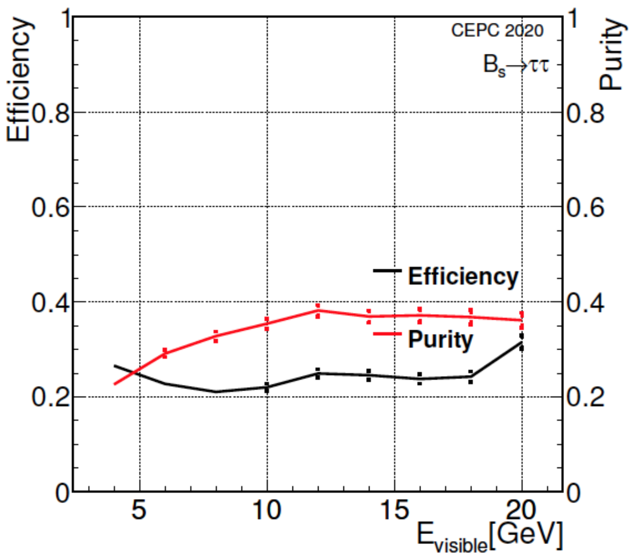


(c) $Z \to b\overline{b}, B_c \to \tau\nu$ with one hadronic dacay.

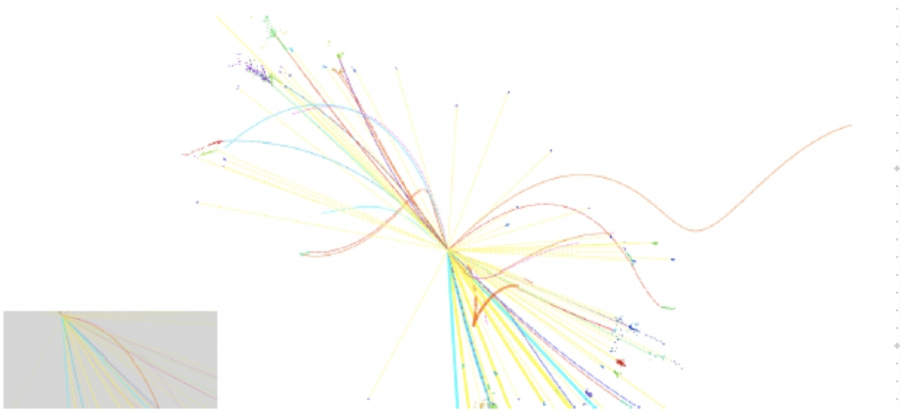
Z→bb, Bs→ττ @ 91.2 GeV: eff ~ 25%, purity ~ 30%



(a) Efficiency and purity performance along with polar angle θ, parameters fixed.



(b) Efficiency and purity performance along with visible energy



(d) $Z \to b\overline{b}, B_s \to \tau\tau$ with two hadronic decay mixed together.

Bs→Phi vv

https://arxiv.org/pdf/2201.07374.pdf

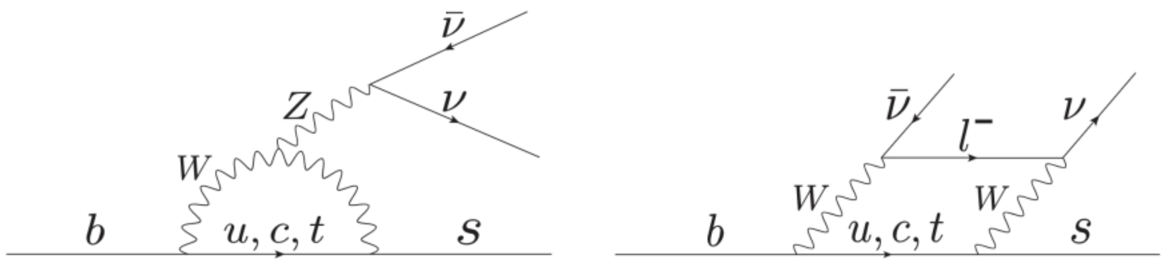
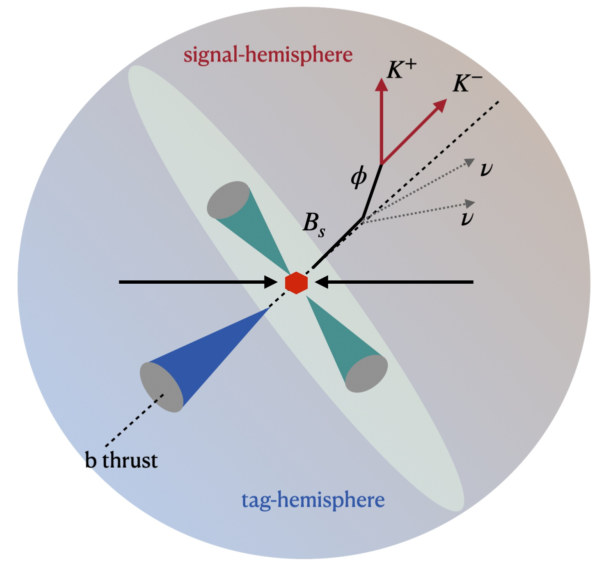
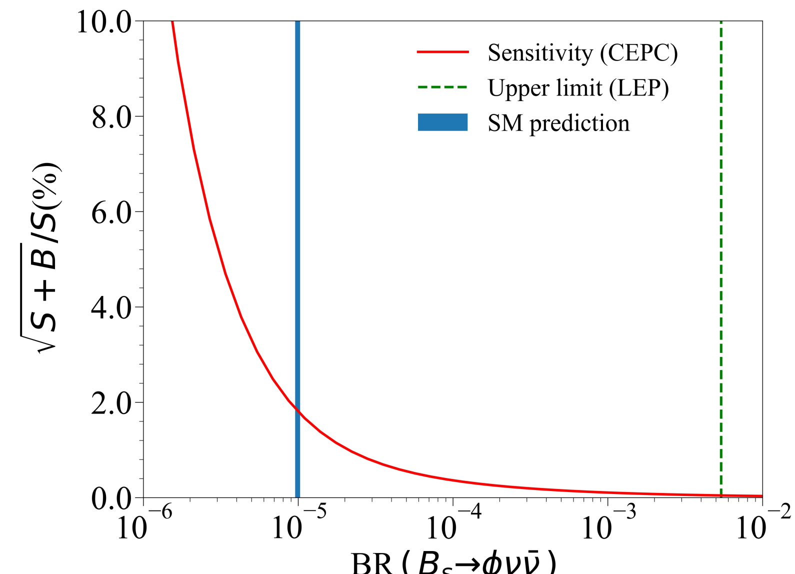


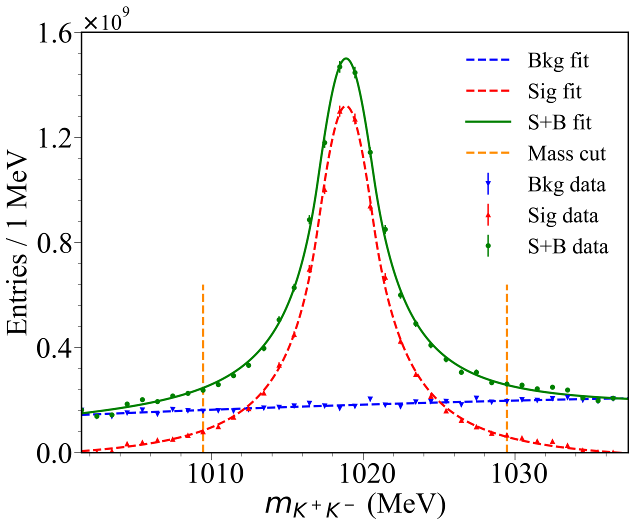
FIG. 1. The penguin and box diagrams of $b \to s\nu\bar{\nu}$ transition at the leading order.

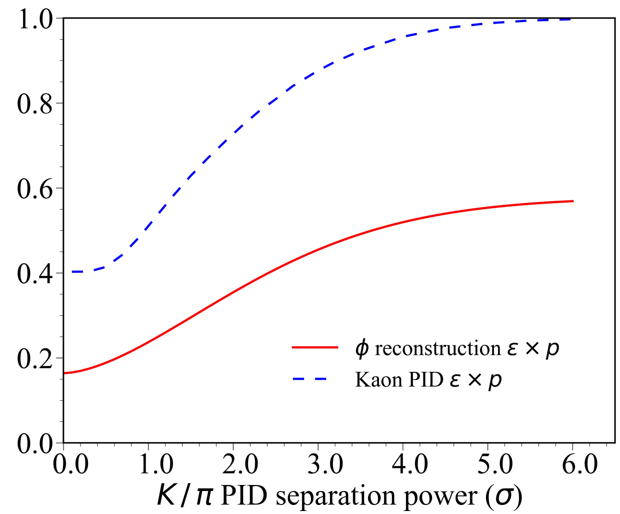


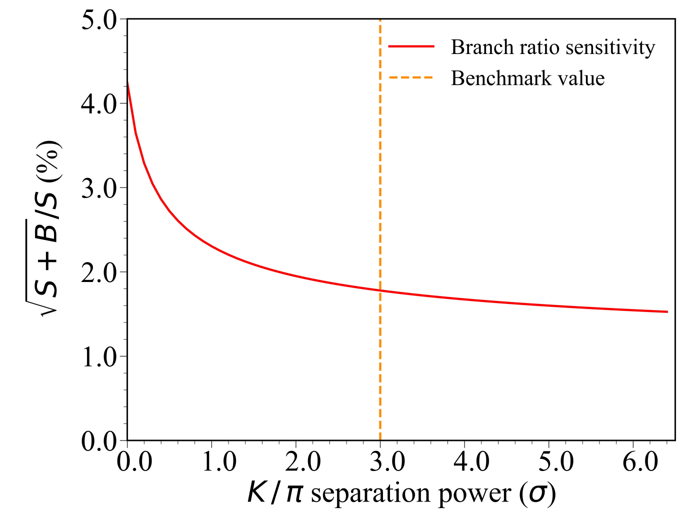


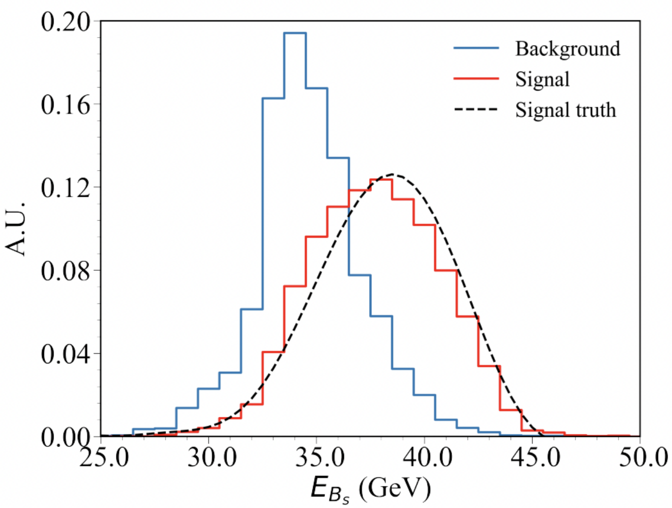
- Key ingredient to understand FCNC anomaly...
- Critical Physics Objects: Phi (and charged Kaon), 2nd VTX, Missing E/P, b-jet at opposite side
- Percentage level accuracy anticipated at Tera-Z

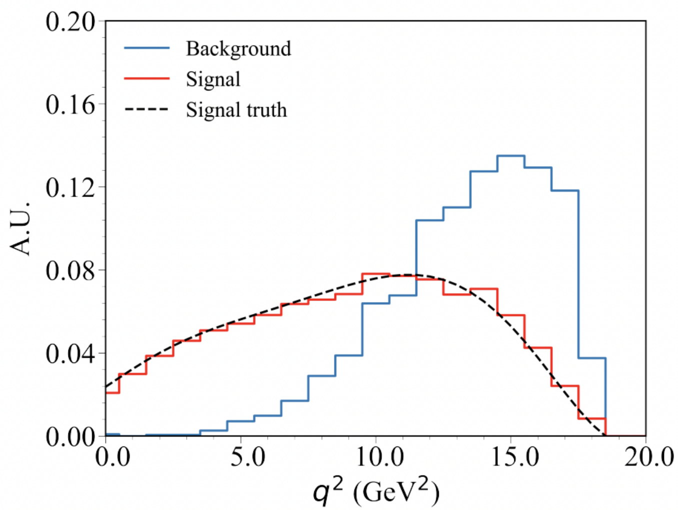
Bs→Phi νν











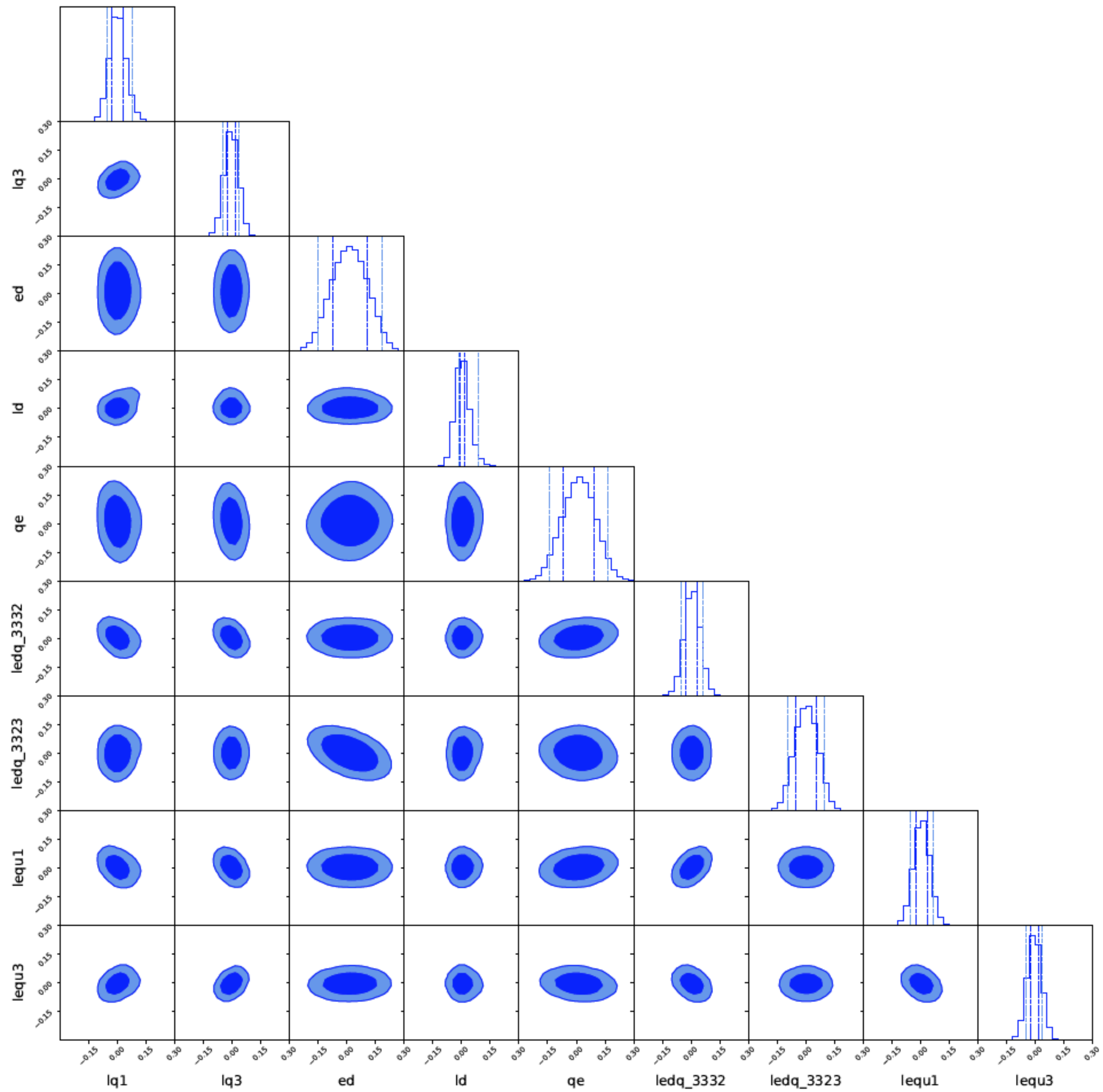
$$M_{\mathrm{tag}} = \sqrt{\left(\sum p_{\mathrm{tag}}^{\mathrm{vis}}\right)^2}\,,$$

$$M_{\mathrm{sig}}^{(i)} = \sqrt{\left(\sum p_{\mathrm{sig}}^{\mathrm{vis}} + p_{B_s}^{(i-1)} - p_\phi\right)^2}\,,$$

$$E_{B_s}^{(i)} = \frac{s + (M_{\mathrm{sig}}^{(i-1)})^2 - M_{\mathrm{tag}}^2}{2\sqrt{s}} - E_{\mathrm{sig}} + E_\phi\,,$$

$$(q^2)^{(i)} = (p_{B_s}^{(i-1)} - p_\phi)^2\,,$$

The separation power is defined as $2|\mu_\pi - \mu_K|/(\sigma_\pi + \sigma_K)$. Without loss of generality, we set $\sigma_\pi = \sigma_K$. Com-



Regular Article - Theoretical Physics | Open Access | Published: 09 June 2021

$b \to s\tau^+\tau^-$ physics at future Z factories

Lingfeng Li & Tao Liu

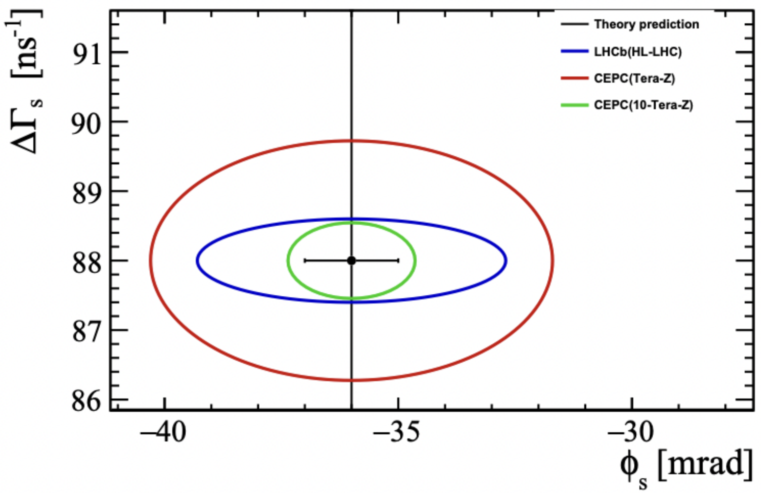
Journal of High Energy Physics **2021**, Article number: 64 (2021) | Cite this article

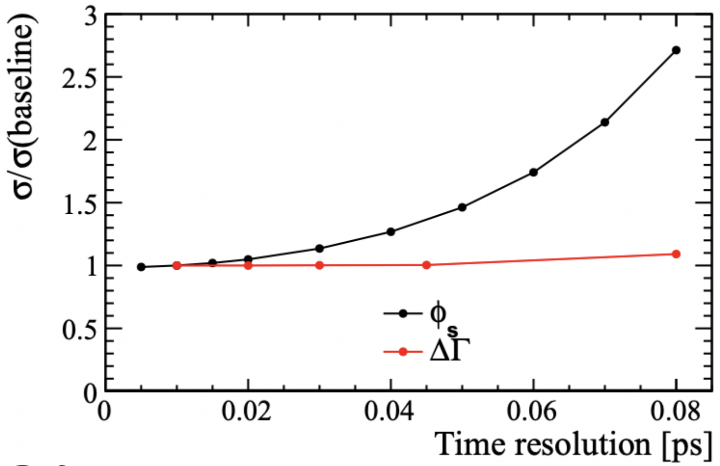
Preliminary: 9 effective channels:($R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, R_{Λ_c}, $B_c \to \tau\nu$, $B \to K\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $B^0 \to K\tau\tau$, $B^+ \to K^+\tau\tau$, $B_s \to \tau\tau$...)

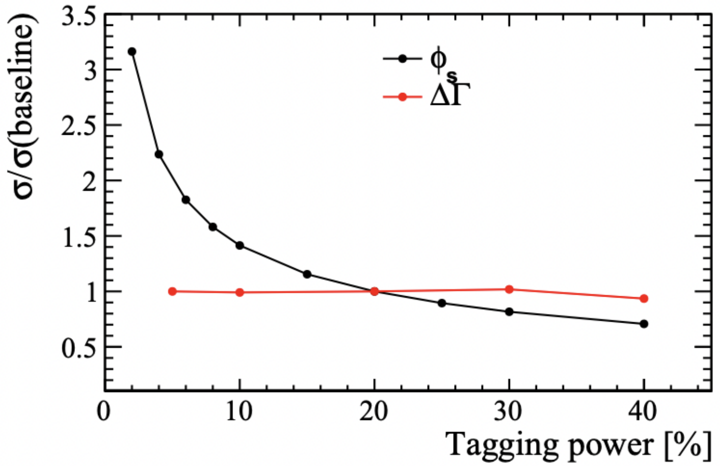
Dim-6 SMEFT basis at NP scale Λ=3 TeV.

Bs→Jpsi/Phi

	LHCb(HL-LHC)	CEPC(Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance×efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavour tagging	4.7%	20%	4.3
Time resolution $(\exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^{2\,2})$	0.52	1	1.92
scaling factor ξ	0.0014	0.0019	0.8
$\sigma(\phi_s)$	3.3 mrad	4.3 mrad	







Preliminary...

$B_s/B^0 \to 2$ pi0/eta

Preliminary...

$$A_{CP}\ (or\ C^{00}_{\pi\pi}) = \frac{\Gamma(B^0 \to \pi^0\pi^0) - \Gamma(\bar{B}^0 \to \pi^0\pi^0)}{\Gamma(B^0 \to \pi^0\pi^0) + \Gamma(\bar{B}^0 \to \pi^0\pi^0)}$$

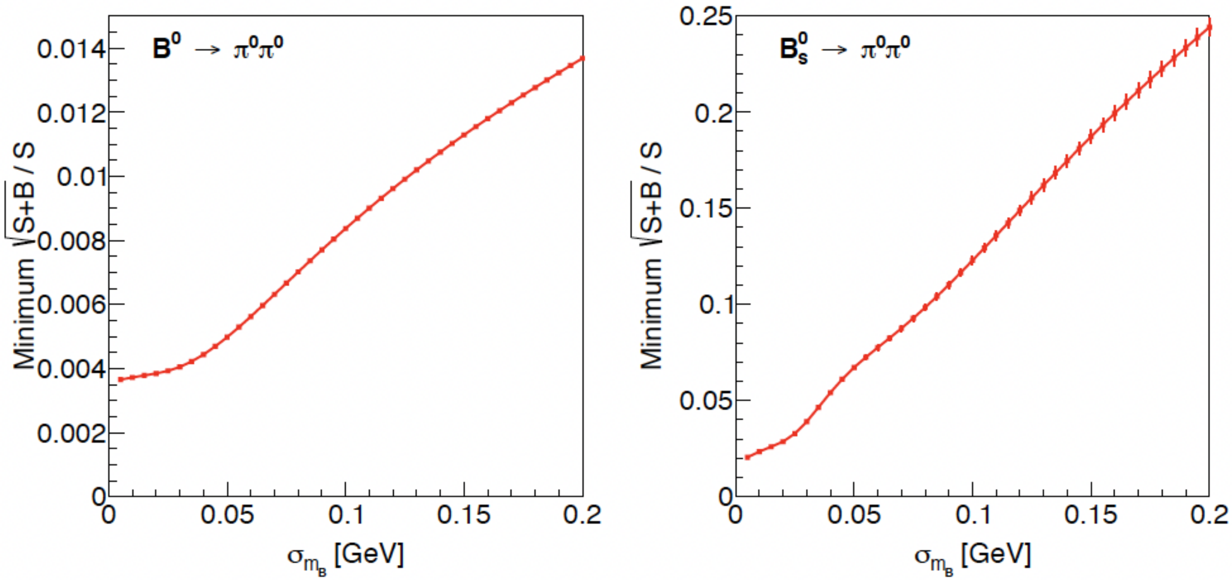
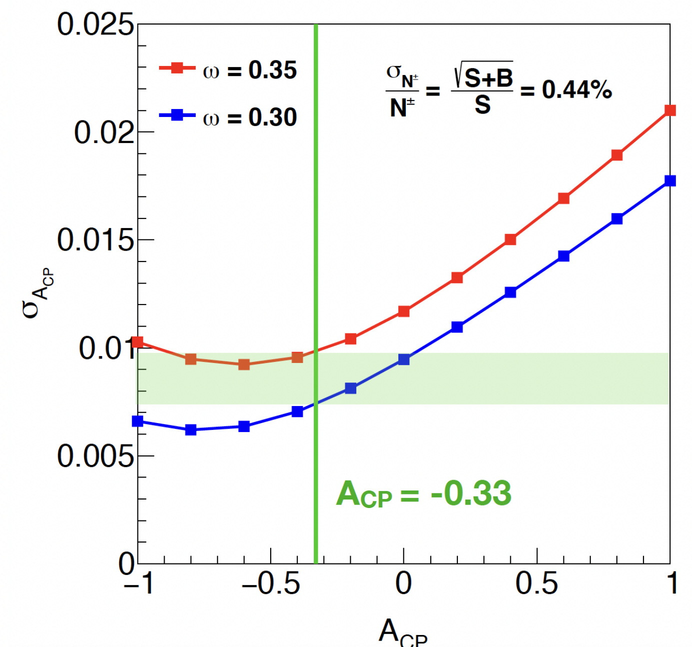


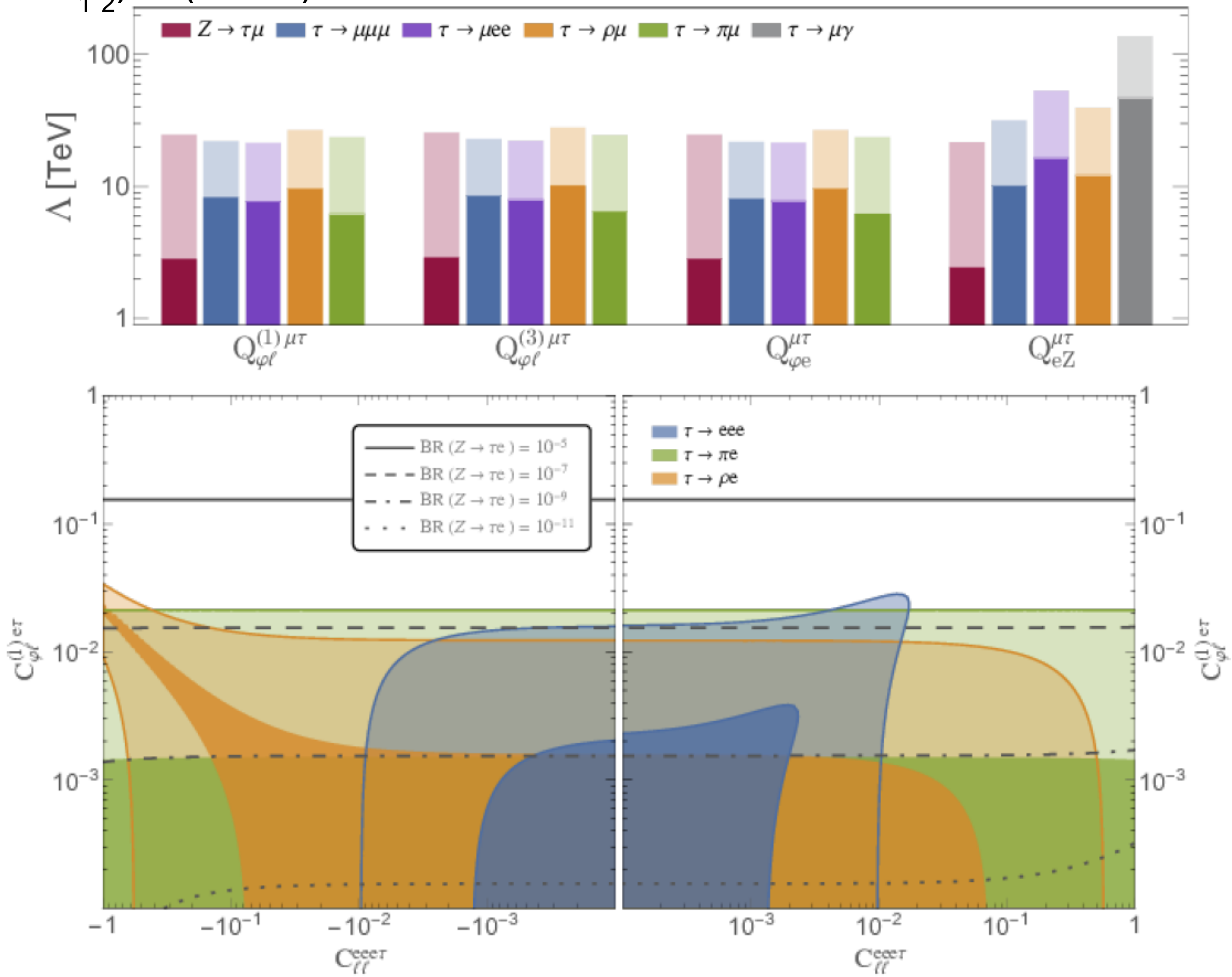
Figure 12: Accuracy of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) versus B mass resolution.



- Provide sub percentage level accuracies on B0->2 pi0, 40/5 times than current world average & Belle II anticipation, have a strong impact on the CKM angle (alpha measurements), discover the other three modes for the 1st time.
- Strongly Depends on the b-tagging performance (ILD is good enough) and the ECAL intrinsic resolution (provide 30 MeV mass resolution for B-meson... 5 times better than ILD ECAL)

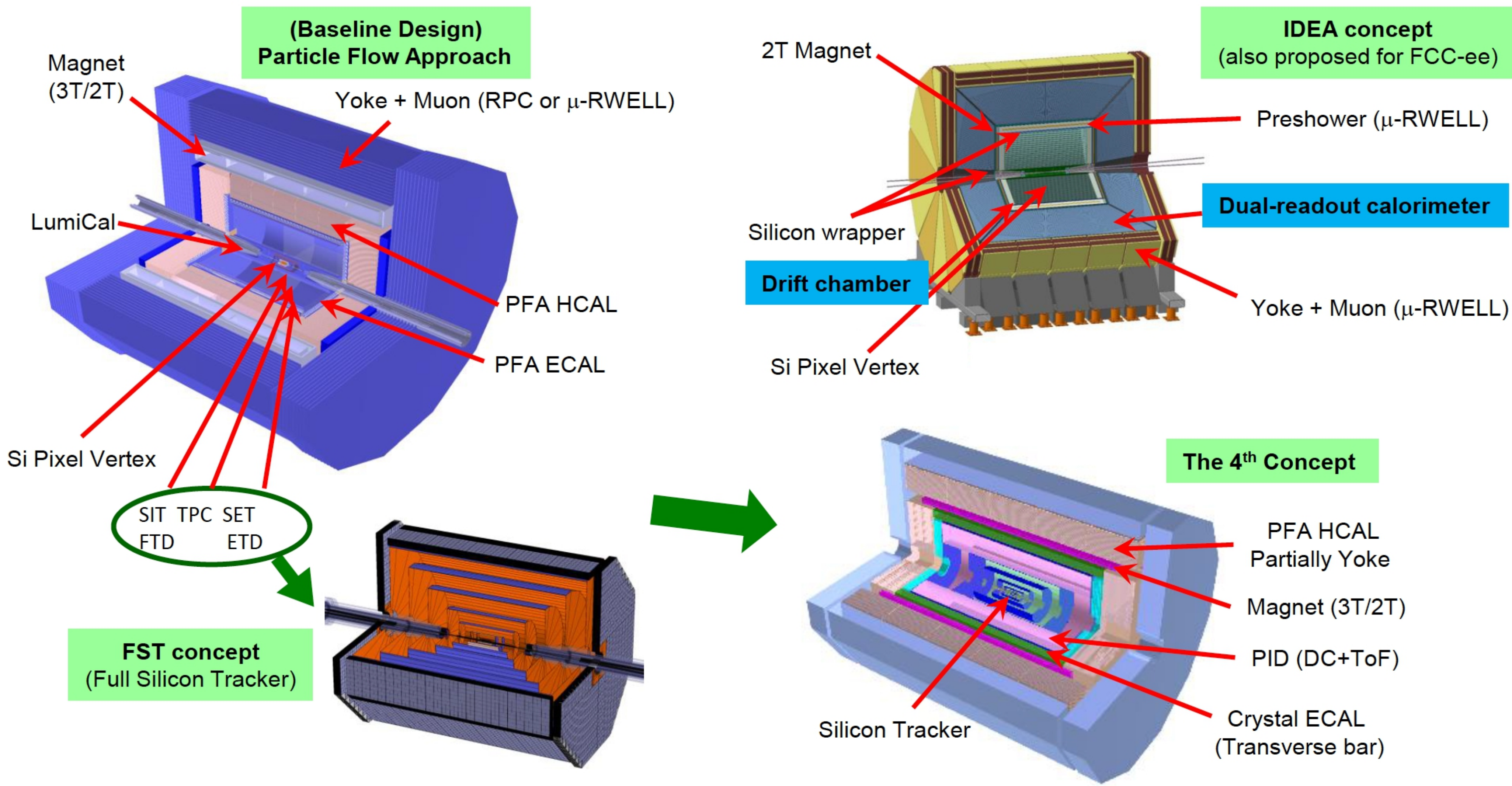
Lepton Flavor Violation (II)

Up limit of Br(Z→$l_1 l_2$)~o(1E-9)



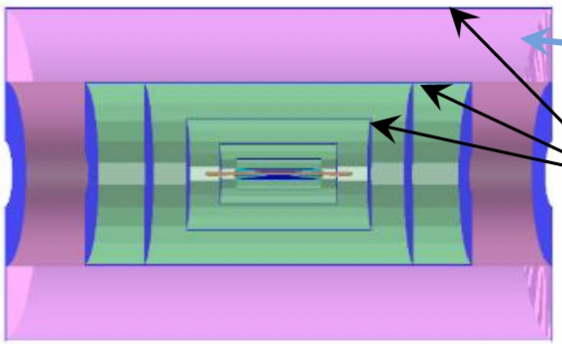
[Calibbi et al., 2021] 2107.10273

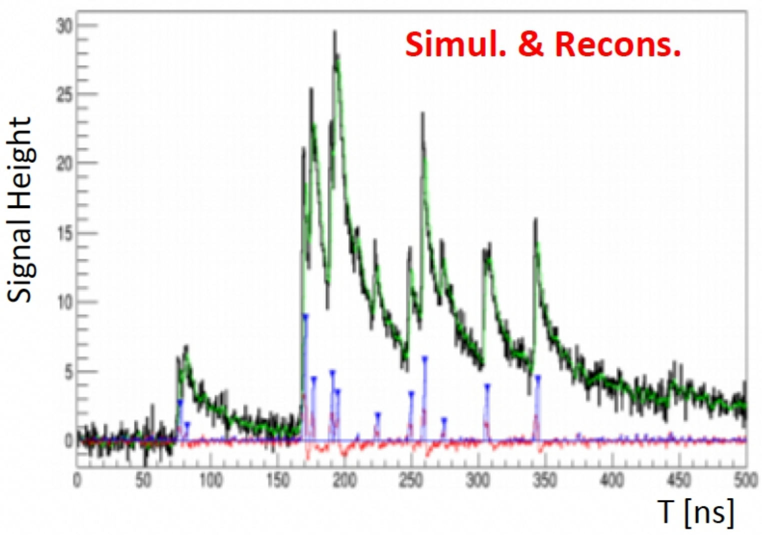
Conceptual Detector Designs

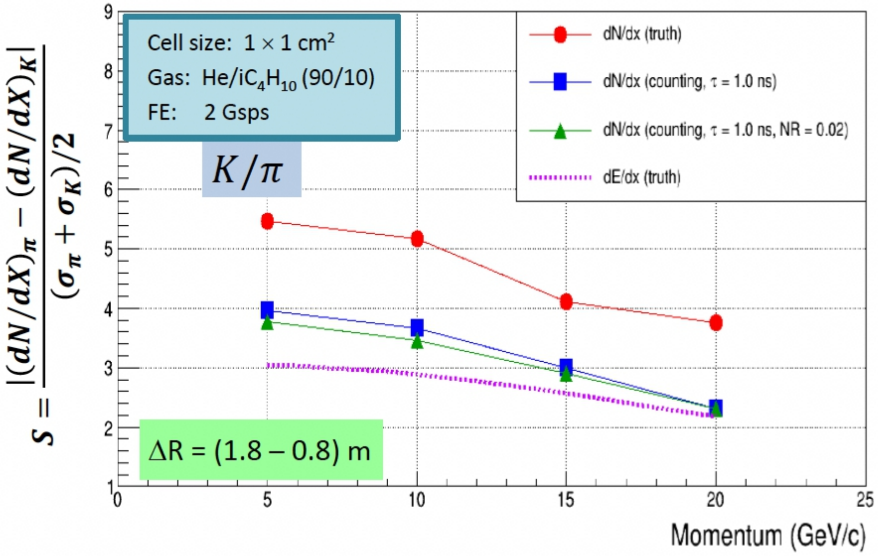


A Drift Chamber Optimized for PID

- Goal: 2σ π/K separation at P < ~ 20 GeV/c.
- Use the cluster counting method, or **dN/dx**, by measuring the number of primary ionizations.
- **It can be optimized specifically for PID**: larger cell size, no stereo layers, different gas mixture, …
- Garfield++ for simulation, realistic electronics, peak finding algorithm development.

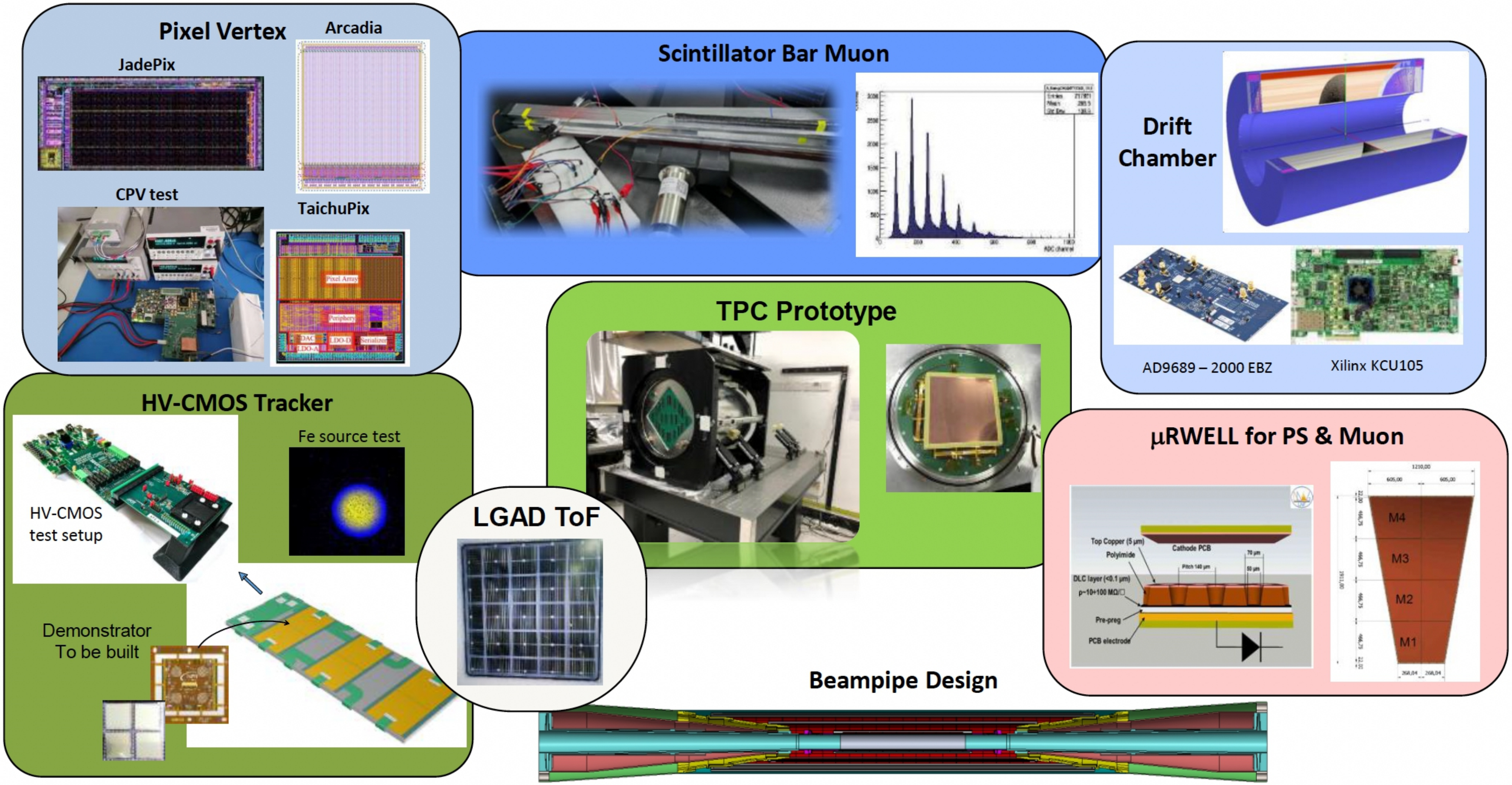






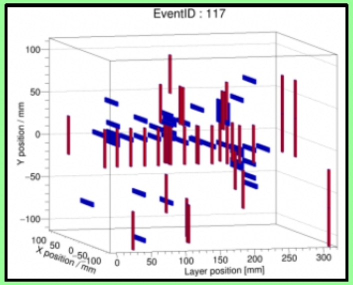
We are also analyzing the PID capability of Pixel TPC

Selection of Detector R&D’s

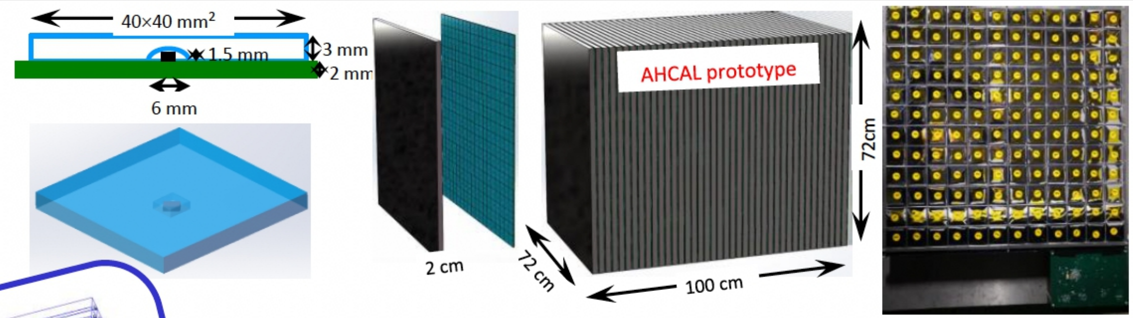


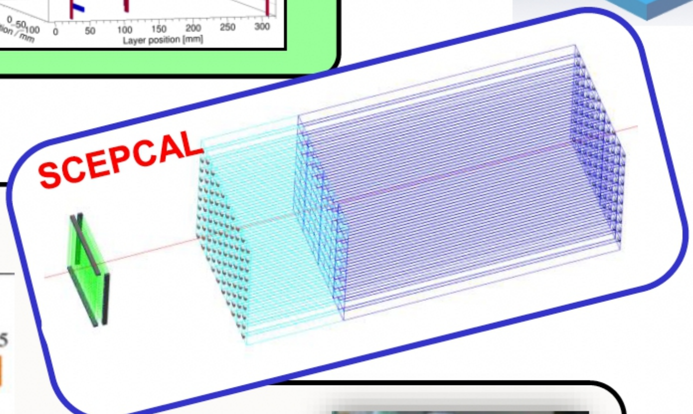
Selection of Detector R&D's

Prototype ScECAL

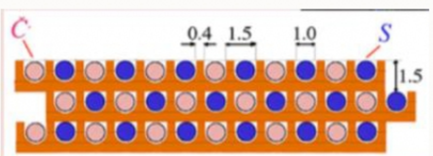


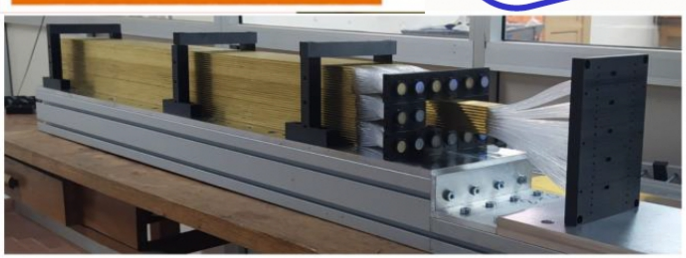
Scint-Steel HCAL

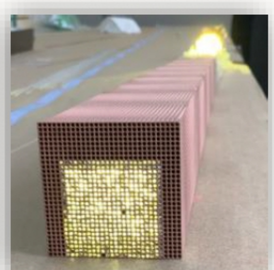


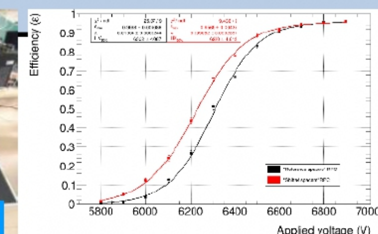


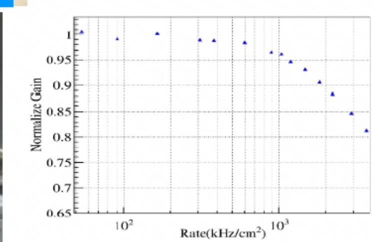
Dual Readout CAL











Summary

- CEPC, a precision & upgradable Higgs/W/Z factory, and a Discover machine!
  - 4 M Higgs, 100 Million – 1 Billion W, 1 Million Top, and 3 Tera Z.
  - For Higgs precision measurements, secures the precisions ~ 1 order of magnitude better compared to HL-LHC
  - Boost the precision on EW, etc, by at 1-2 orders of magnitudes.
  - Lots of opportunities for flavor physics & significant comparative advantages.
  - Strong physics cases for BSM & QCD

  ...
- Lots of challenges
  - High Rate (collision/event)
  - Difficult MDI & Integration
  - Solenoid with changeable B-Fields
  - Beam monitoring/calibration: Energy, Luminosity Spectrum, Polarization
  - ...

Summary

- On the performance side
  - Separation capability is critical for almost all the physics measurement using hadronic/semi-leptonic final state. Especially for the flavor measurement at Z pole, where critical physics objects need to be identified inside jets.
  - BMR shall be at least 4%, and better is better!
  - Improving the Jet Flavor Tagging has a significant impact on critical Higgs measurements.
  - Jet Charge measurement is a strong comparative advantages of Tera-Z
  - Good Pid is mandatory: pion-kaon separation shall be larger than 3-sigma
  - Better ECAL, Better tracking is always appreciated... especially for flavor measurements
  - ...
- Lots of R&D activities, including design of new detector concept, is on going.
- Enhance the collaboration is critical! Especially at this difficult time


...Peace！ ...

Back up

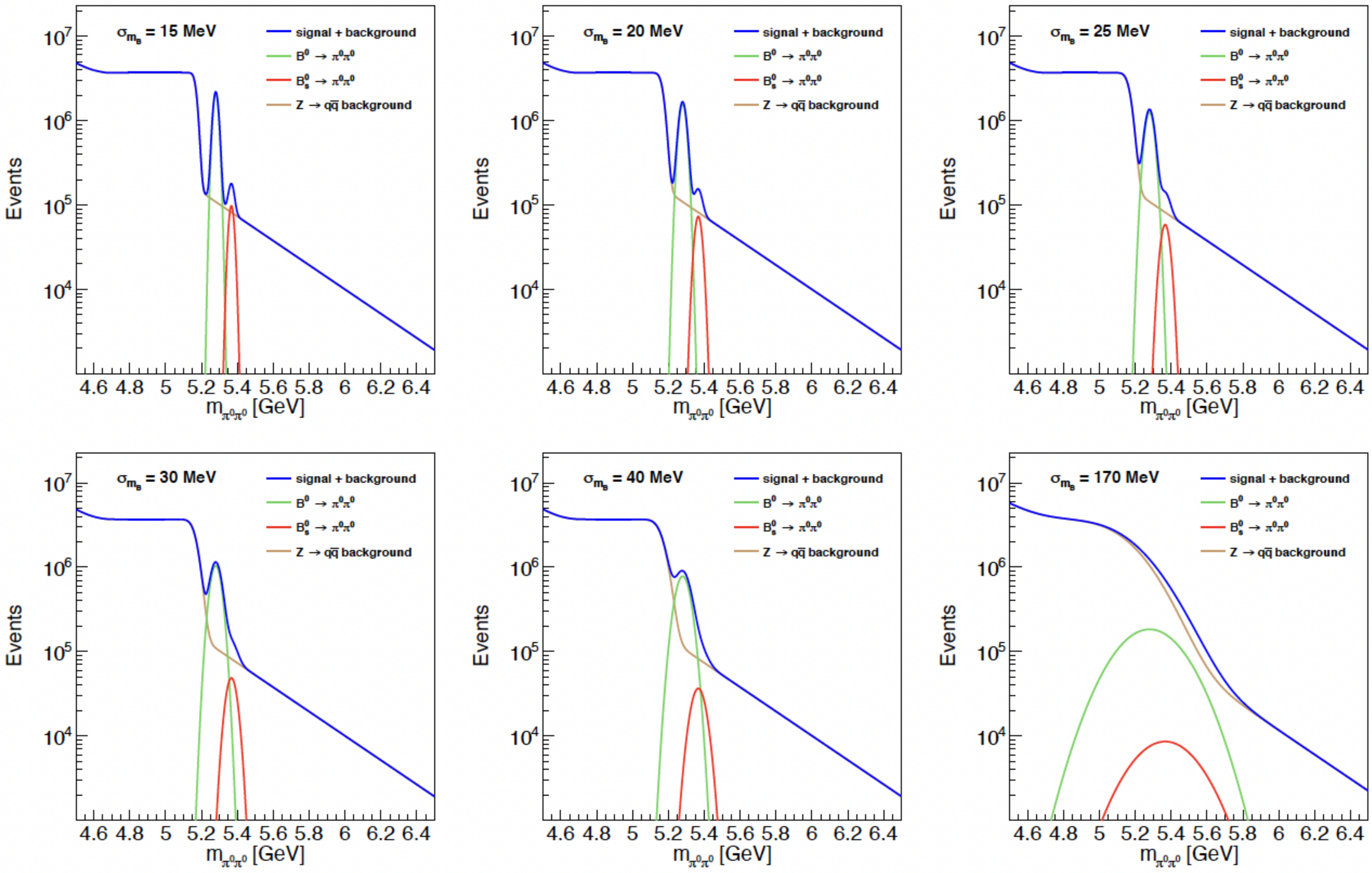
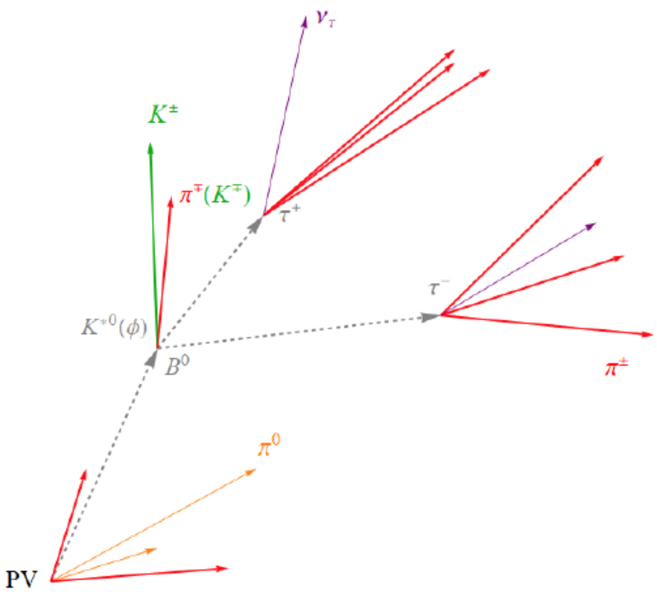


Figure 11: $m_{\pi^0\pi^0}$ distributions of $B^0 \to \pi^0\pi^0$, $B_s^0 \to \pi^0\pi^0$, and $Z \to q\bar{q}$ background at different B mass resolutions when applying CEPC baseline b-tagging.

LFU Test with $b \to s\tau\tau$ Measurements

More details in the published work (arXiv:2012.00665) [Li and Liu(2020)]

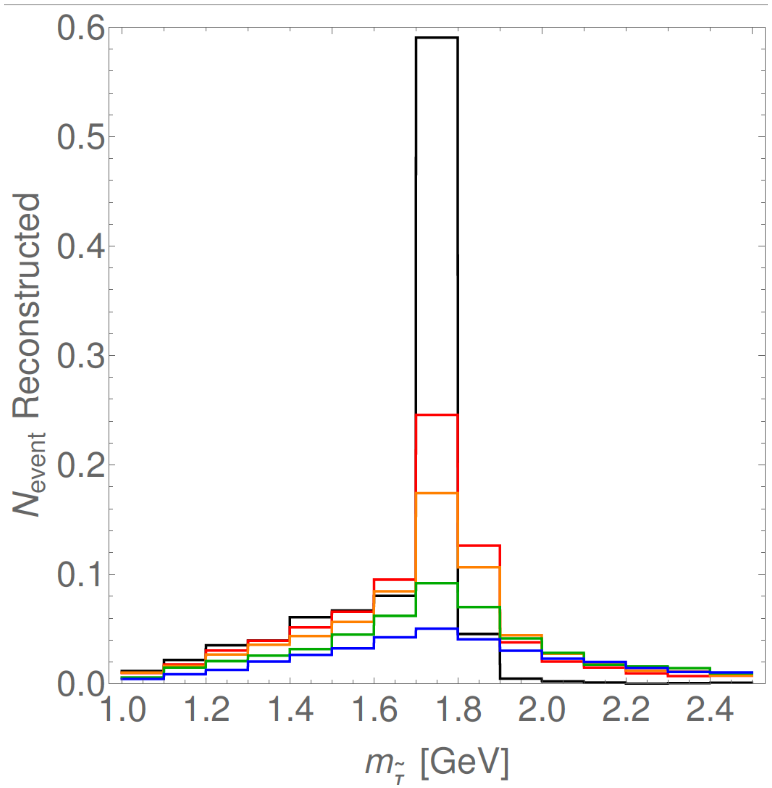


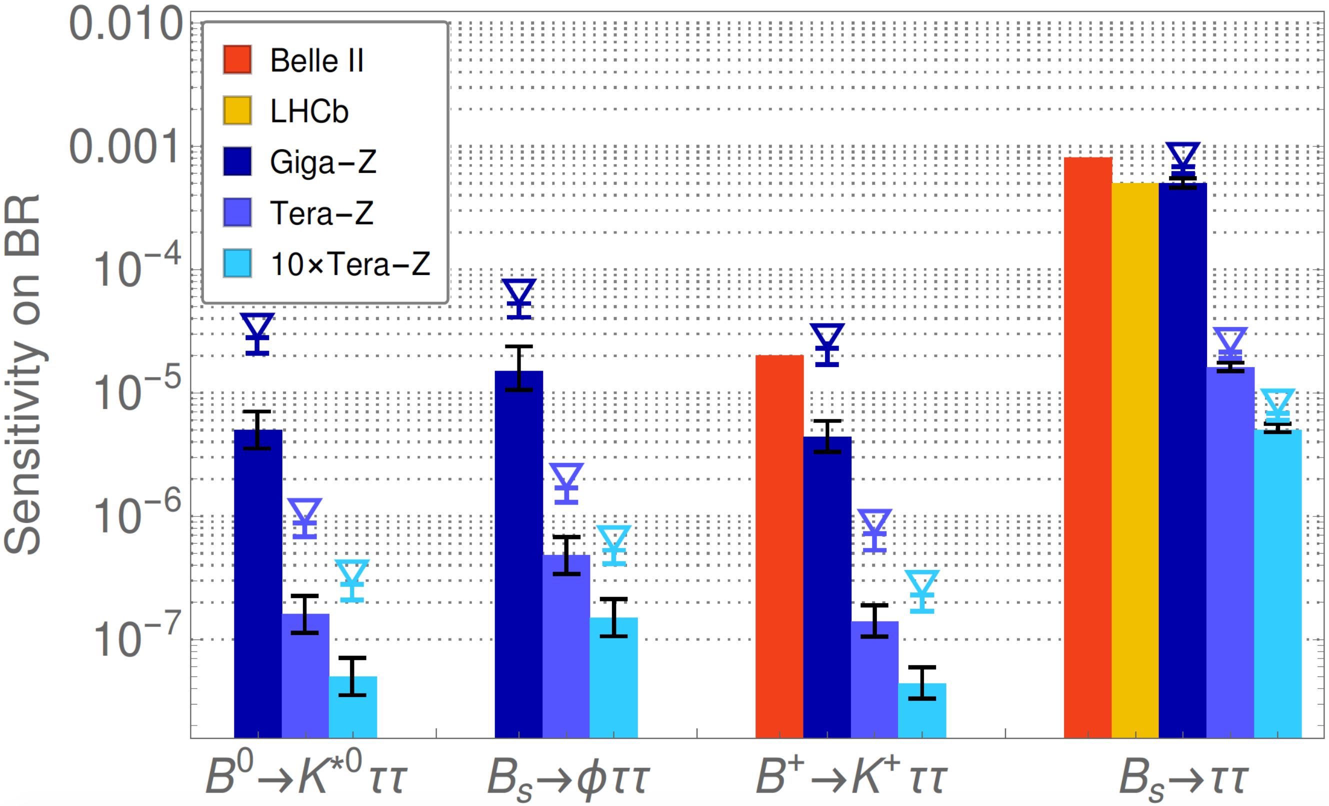
Use $\tau \to \pi^\pm\pi^\pm\pi^\mp\nu$ decay to locate each vertex

Fake 3π vertex from $D^\pm_{(s)} \to \pi^\pm\pi^\pm\pi^\mp + X$ decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.3%
	$c\tau = 87.0$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.6%
$D_s^\pm$	$m = 1.968$ GeV	$\tau^\pm\nu$	5.5%
	$c\tau = 151$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	0.6%
		$\pi^\pm\pi^\pm\pi^\mp 2\pi^0$	4.6%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	0.3%
		$\pi^\pm\pi^\pm\pi^\mp\phi$	1.2%
$D^\pm$	$m = 1.870$ GeV	$\tau^\pm\nu$	$< 0.12\%$
	$c\tau = 311$ μm	$\pi^\pm\pi^\pm\pi^\mp\pi^0$	1.1%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	3.0%

Sensitive to VTX Performance





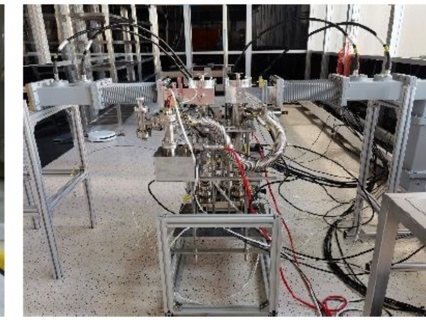
LINGFENG @ HKIAS

...
Contamination of D decay that mimics tau 3-prong decay;
reconstruction accuracy V.S final accuracy: ideal, 1, 2, 5, 10μm resolution
...

Beijing Huairou (4500m^2)

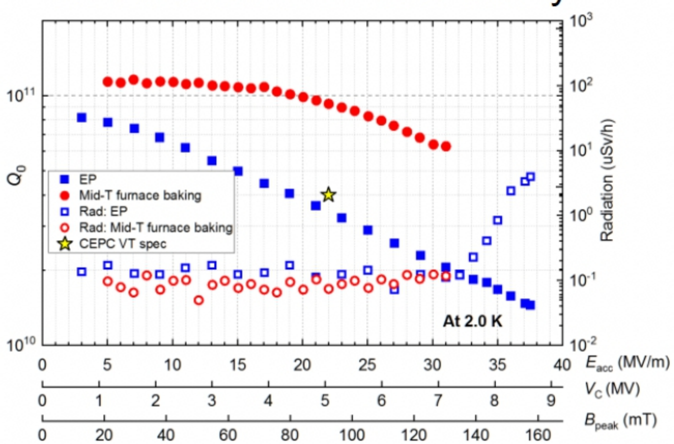






IHEP PAPS established in July 2021 Horizontal test stand, 1.3GHz 9cell cavities, and couplers...

CEPC 650 MHz 1-cell Cavity

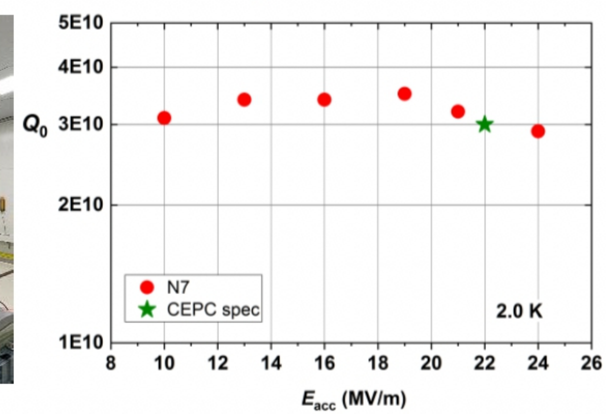


P. Sha et al., *Applied Sciences*. 2022; 12(2):546.

The 650Mhz 1-cell cavity's results (6.4E10@30MV/m, 1.5E10@37.5MV/m) have broken China's gradient record of low-frequency (<1 GHz) elliptical cavities.

World record Q of 650 MHz cavity at 30 MV/m.

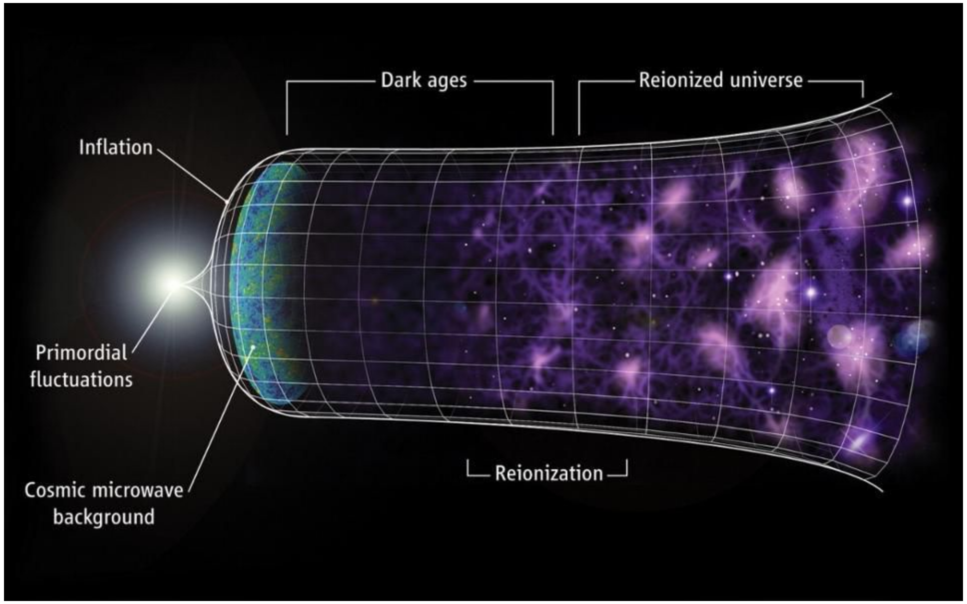
1.3 GHz High Q Mid-T Cavity Horizontal Test



Higgs: linked to many known unknowns of the SM

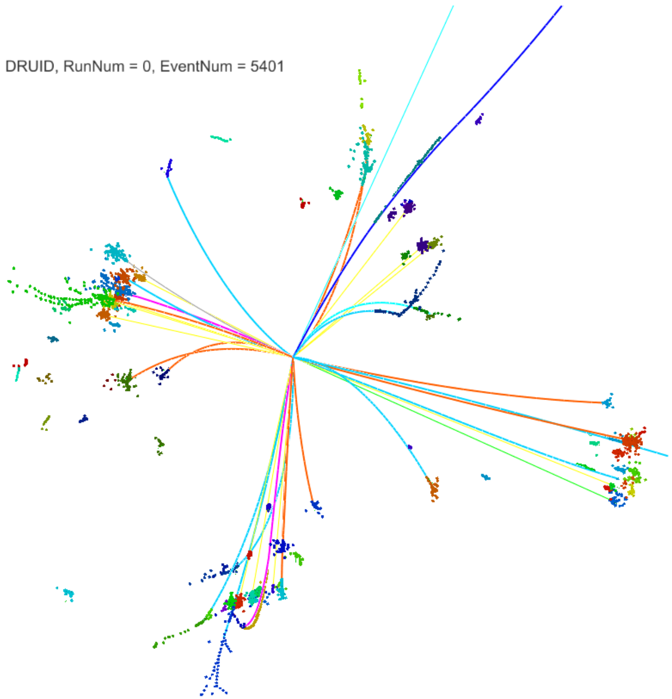
- Hierarchy: From neutrinos to the top mass, masses differs by 13 orders of magnitude
- Naturalness: Fine tuning of the Higgs mass
- Masses of Higgs and top quark: meta-stable of the vacuum
- Unification?
- Dark matter candidate?
- Not sufficient CP Violation for Matter & Antimatter asymmetry

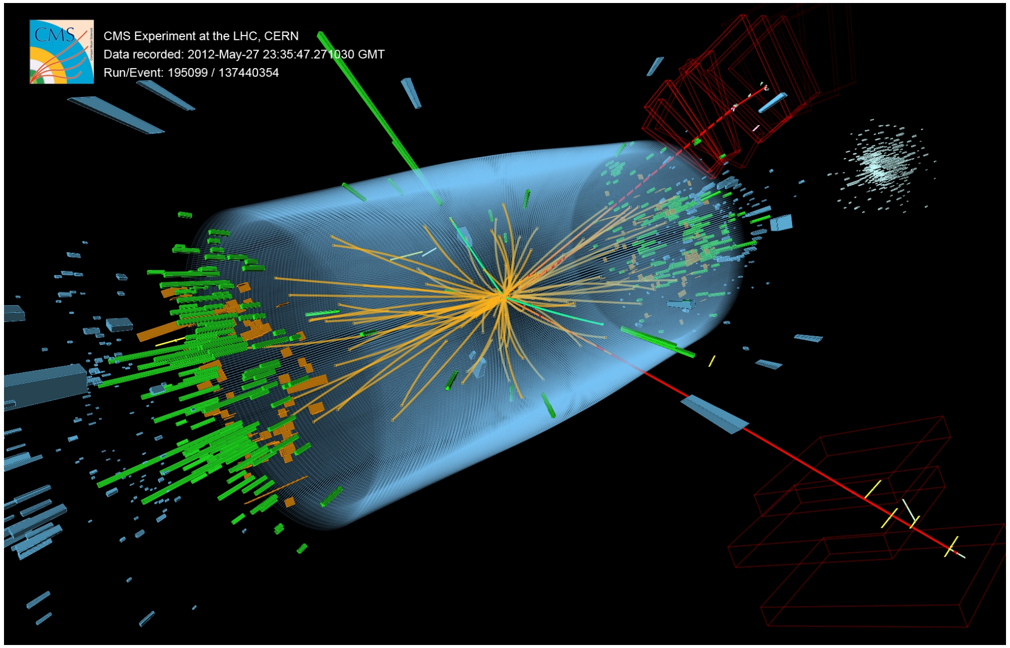
$$m_H{}^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023$$
$$-36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$$
$$= (125\ \text{GeV})^2\ !\ ?$$



- **Most issues related to Higgs**

Higgs measurement at e+e- & pp



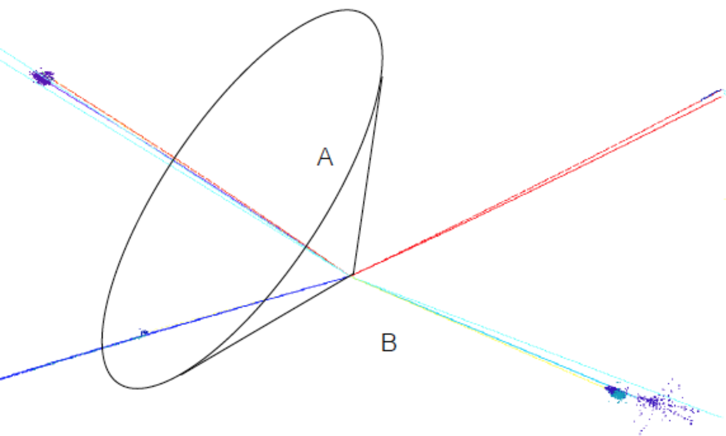


	Yield	efficiency	Comments
LHC	Run 1: 10^6 Run 2/HL: $10^{7\text{-}8}$	$\sim o(10^{-3})$	High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to g(ttH), and even g(HHH)
CEPC	10^6	$\sim o(1)$	Clean environment & Absolute measurement, Percentage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

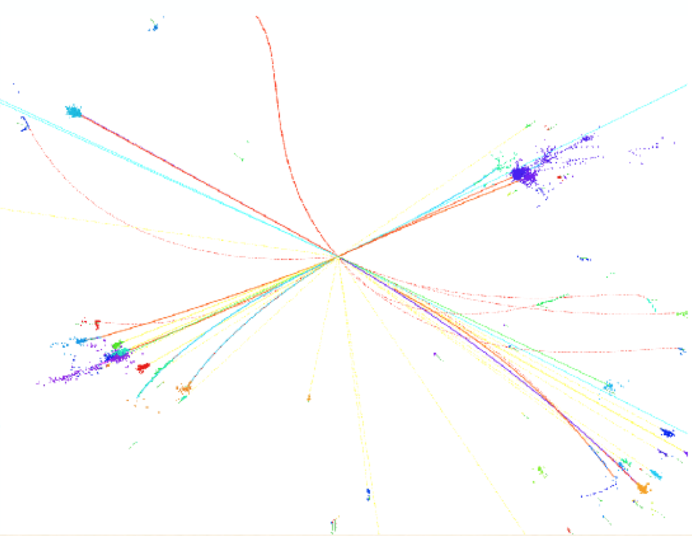
Complementary

Taus at the CEPC

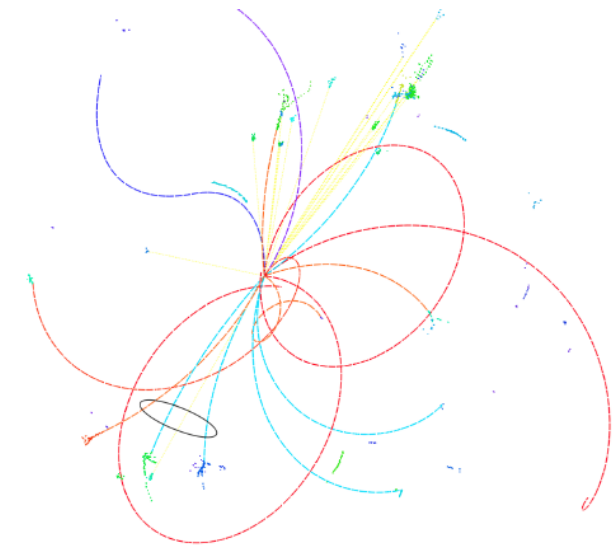
Leptonic:
ZH, $Z \to ll/\nu\nu$, $H \to \tau\tau$
$Z \to \tau\tau$



Semi-Leptonic:
ZH, $Z \to qq$, $H \to \tau\tau$
$WW \to \tau\nu qq$

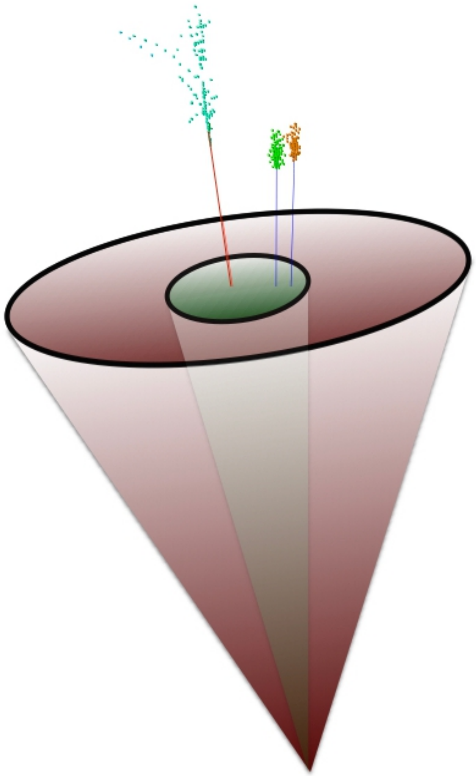


Full-Hadronic:
$Z \to qq \to \tau + X$

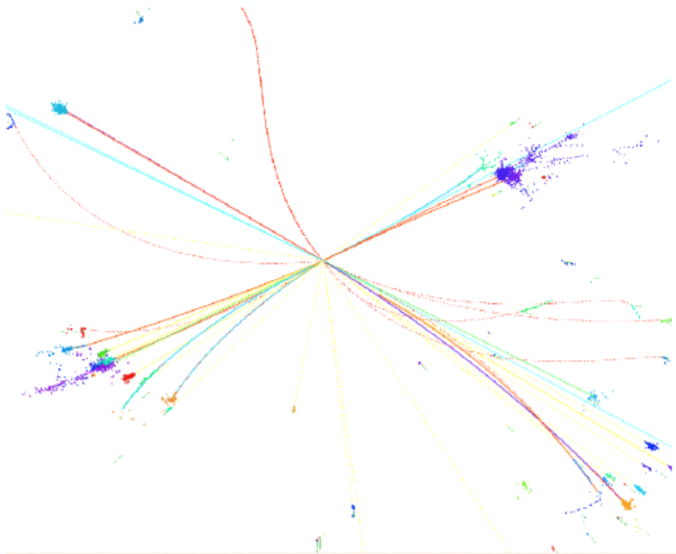


- Finding Tau
- Specify Tau decay product

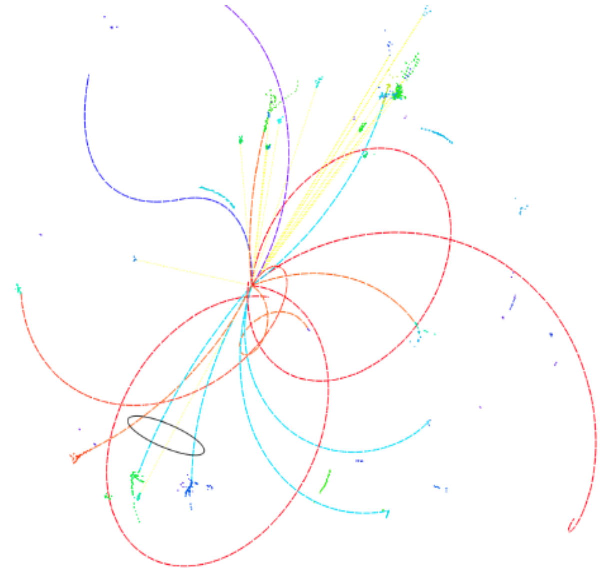
Taus at the CEPC



Semi-Leptonic:
ZH, Z→qq, H→ττ
WW→τνqq



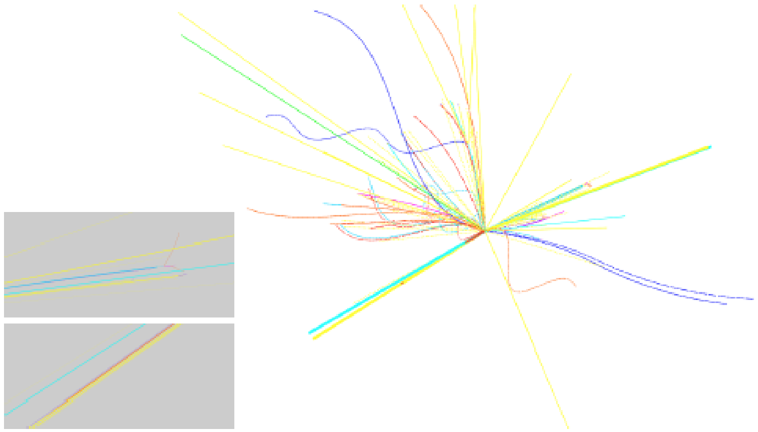
Full-Hadronic:
Z→qq→τ + X



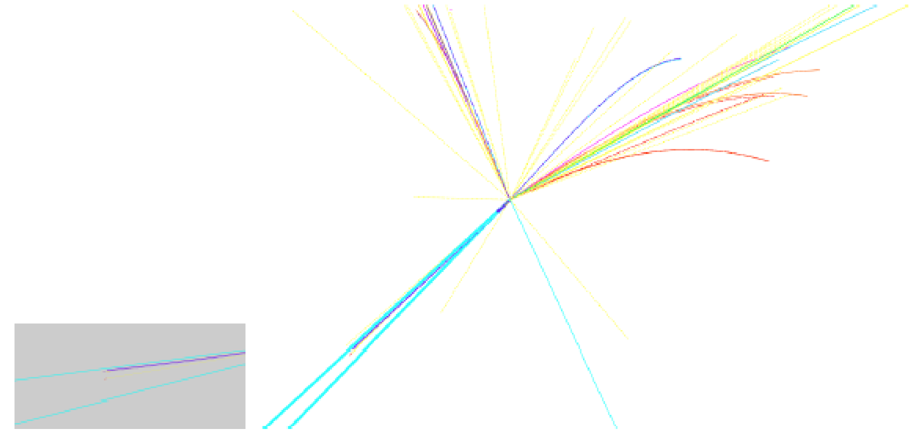
TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

TAURUS/Specify Tau decay product

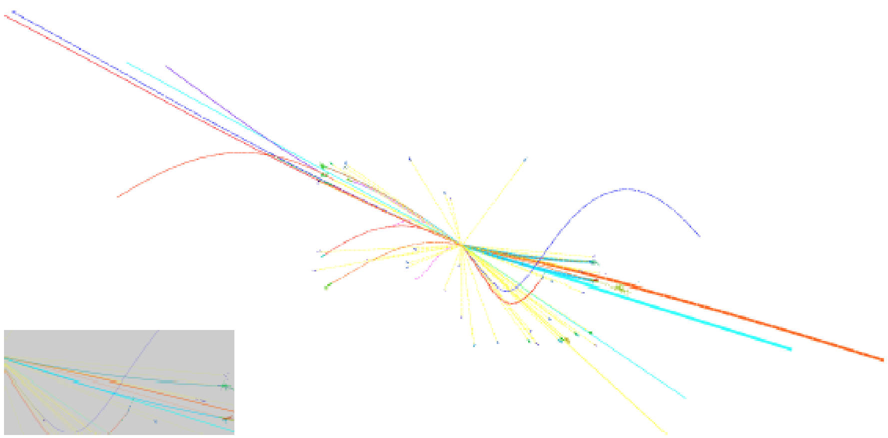
Benchmarks



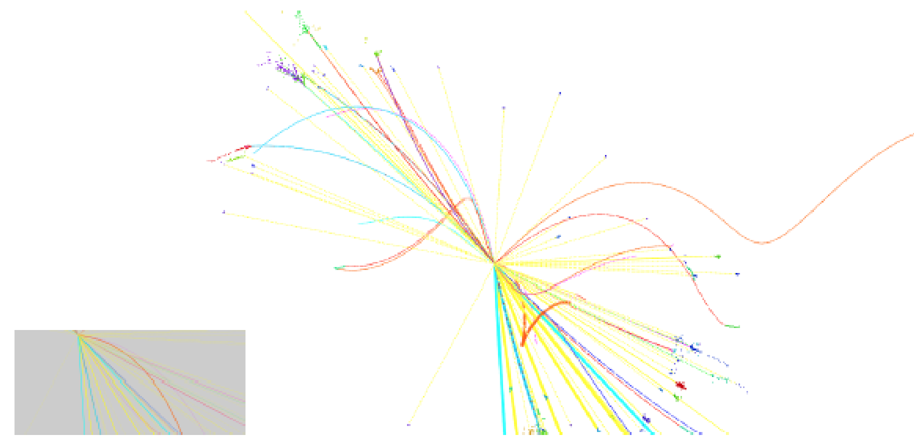
(a) $Z \to qq, H \to \tau\tau$ with two hadronic decay.



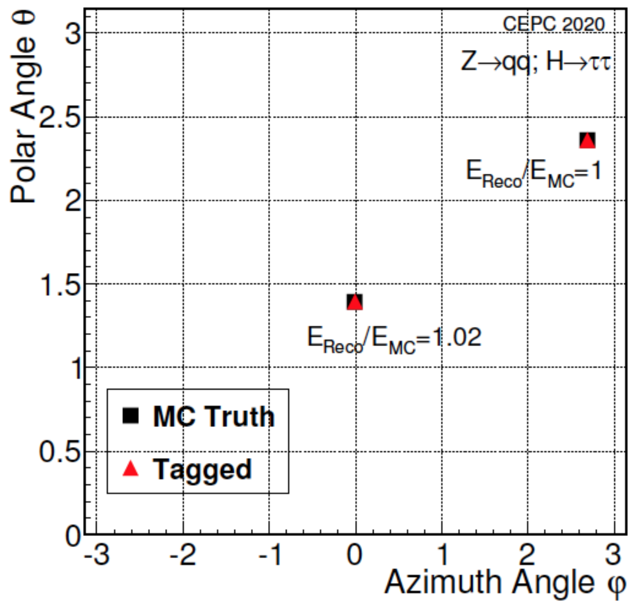
(b) $WW \to \tau\nu qq$ with one leptonic decay.



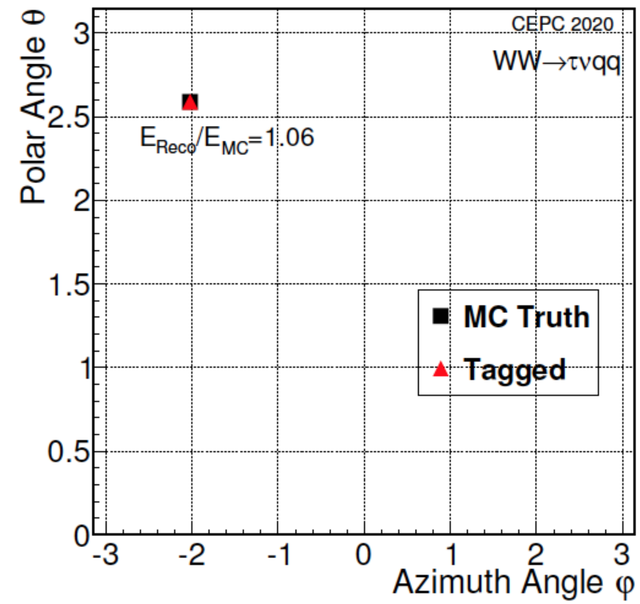
(c) $Z \to b\overline{b}, B_c \to \tau\nu$ with one hadronic dacay.



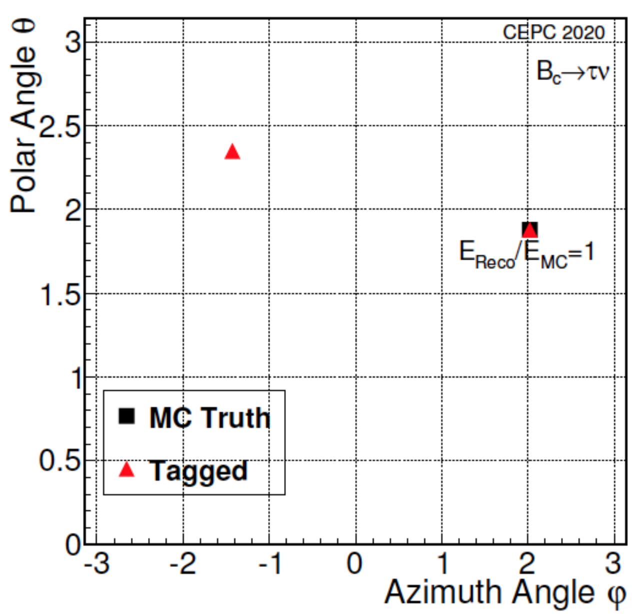
(d) $Z \to b\overline{b}, B_s \to \tau\tau$ with two hadronic decay mixed together.



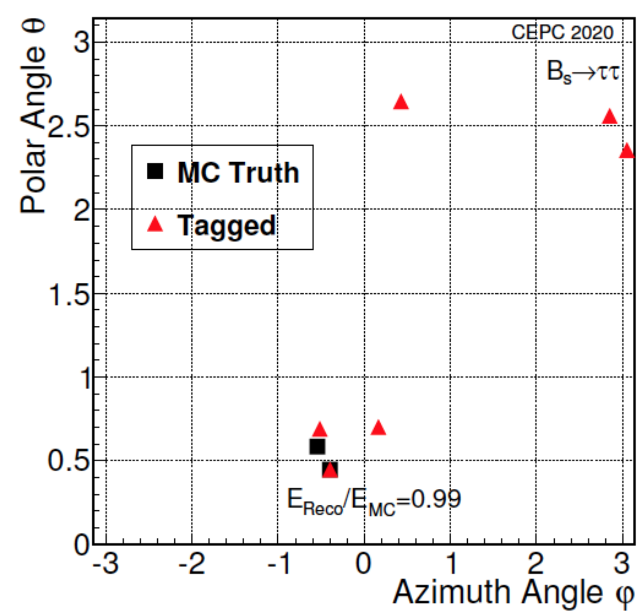
(a) $Z \to qq, H \to \tau\tau$, efficiency=1, purity=1



(b) $WW \to \tau\nu qq$, efficiency=1, purity=1

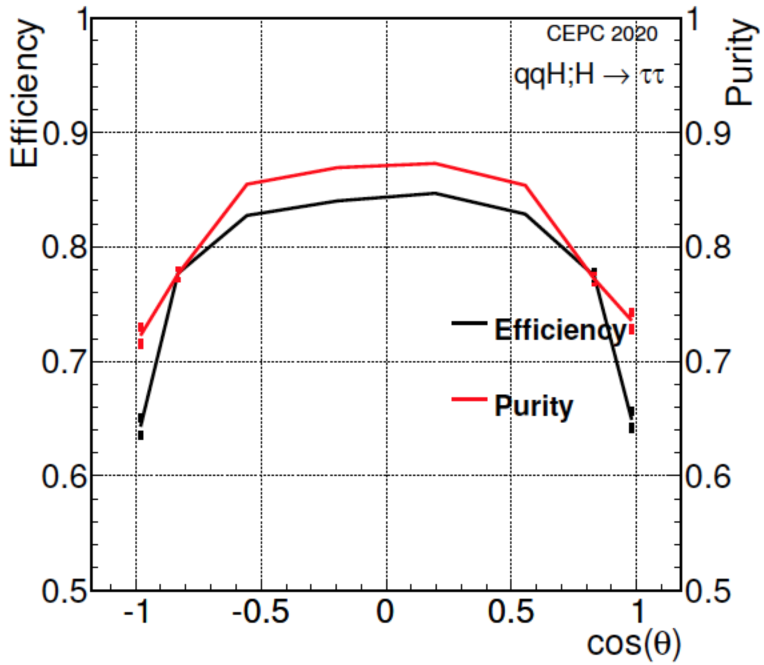


(c) $Z \to b\overline{b}, B_c \to \tau\nu$, efficiency=1, purity=0.5

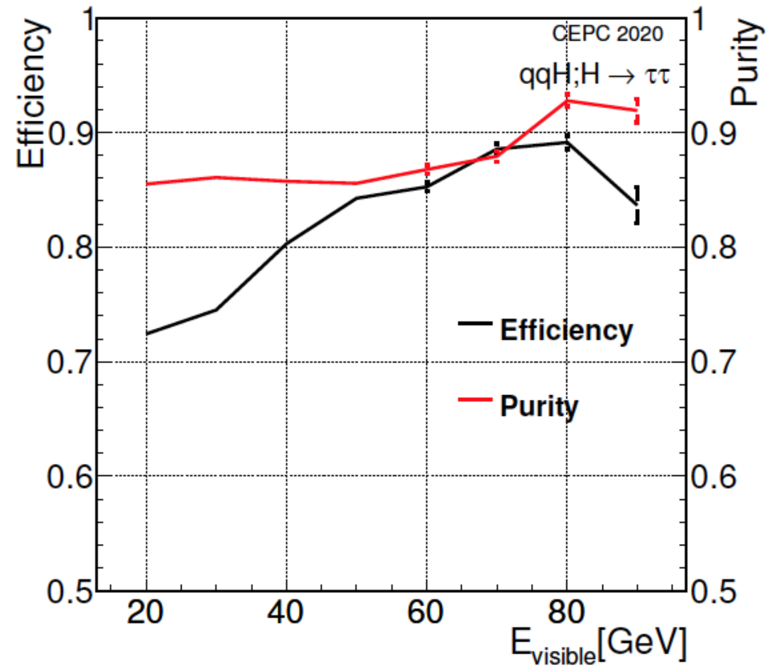


(d) $Z \to b\overline{b}, B_s \to \tau\tau$, efficiency=0.5, purity=0.167

qqH, H→ττ @ 240GeV: eff ~ 80%, purity ~ 85%

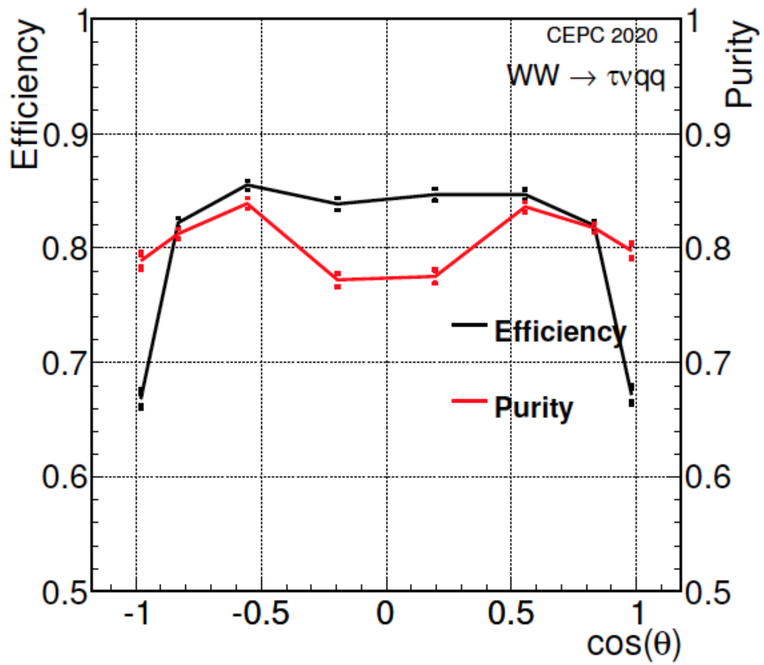


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

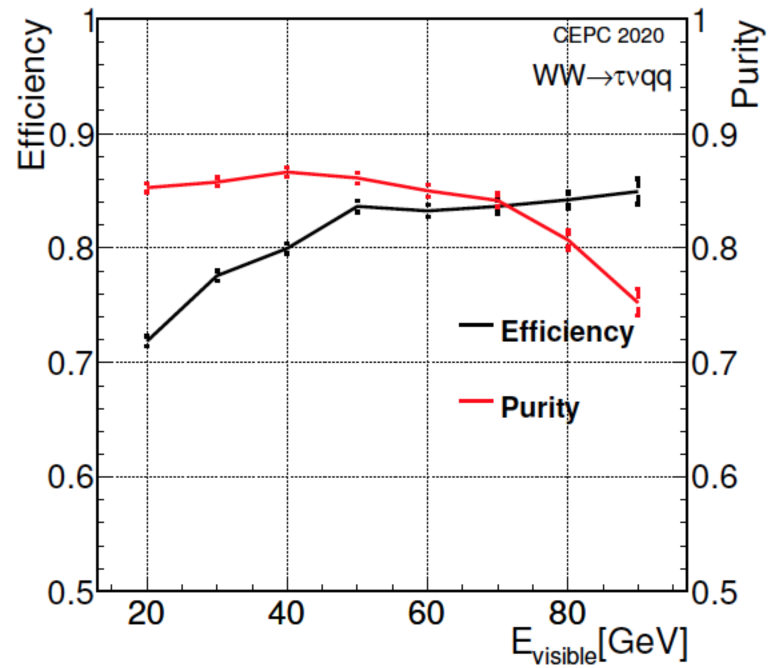


(b) Efficiency and purity performance along with visible energy. The performance above 80 GeV falls as a result of stringent cone selection.

WW→τνqq @ 240GeV: eff ~ 80%, purity ~ 85%

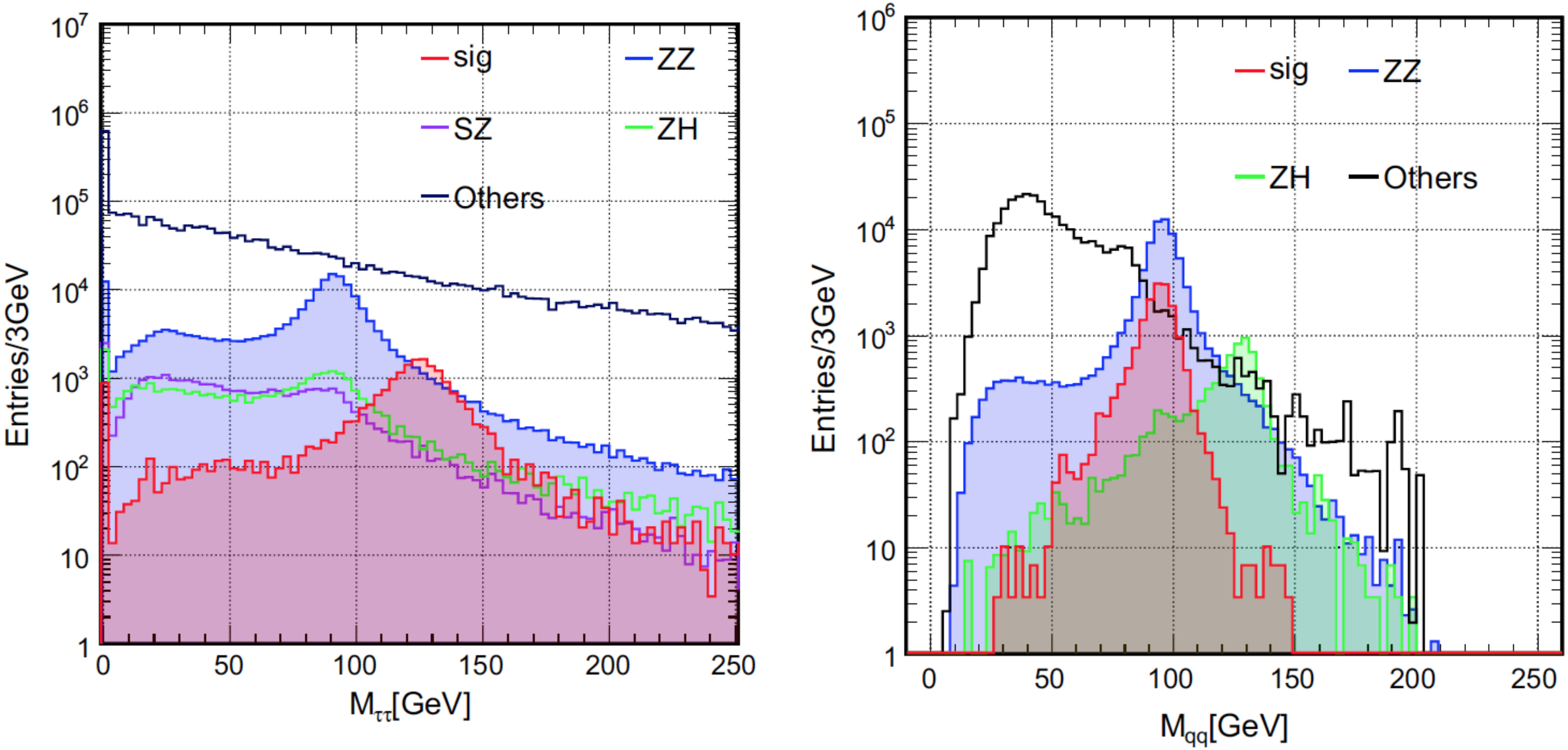


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.



(b) Efficiency and purity performance along with visible energy

Signal strength measurement of qqH, H→ττ @ 240 GeV



Invariant mass of di-tau: collinear approximation that assumes the neutrinos aligns with the direction of visible tau decay product

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

The measurement of the $H \to \tau\tau$ signal strength in the future e^+e^- Higgs factories

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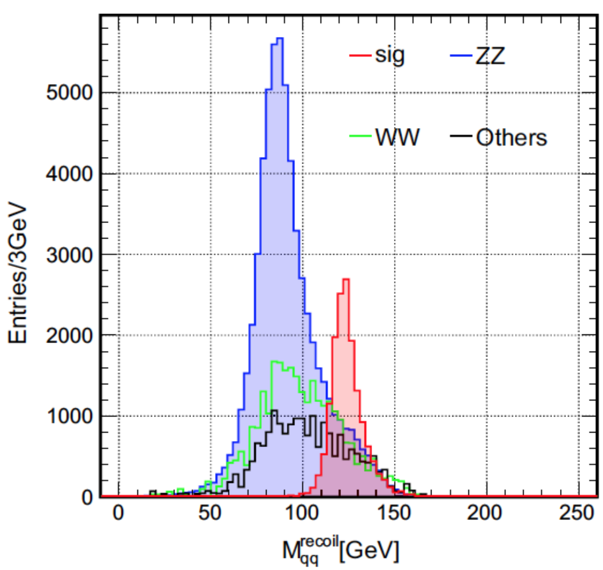
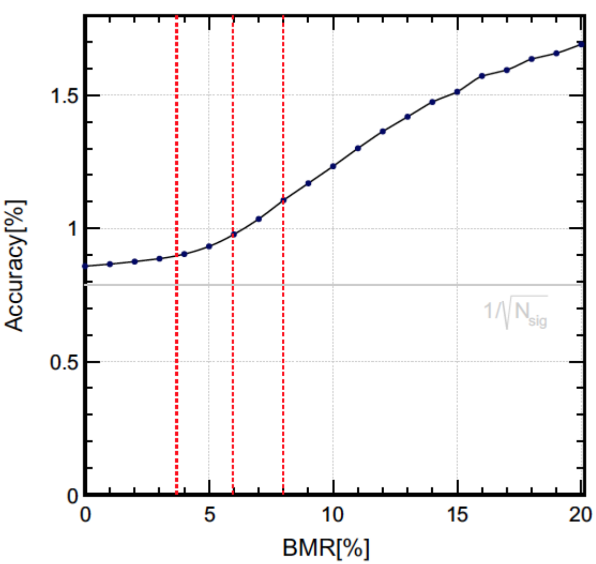
Table 9 Extrapolated accuracy $\delta(\sigma \times \mathrm{BR})/(\sigma \times \mathrm{BR})$ in the ILC 250 GeV (2000 fb^{-1})

	CEPC	ILC(L)	ILC(R)
Luminosity (ab^{-1})	5.6	2	2
Polarization (e^-, e^+)	–	(0.8, −0.3)	(−0.8, 0.3)
Total Higgs	1.18 M	0.60 M	0.40 M
Accuracy (%)	0.8	1.09	1.21





LFV from Z & Tau decays

Lorenzo Calibbi, 2107.10273

Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee exp.
$\mathrm{BR}(Z \to \mu e)$	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
$\mathrm{BR}(Z \to \tau \mu)$	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

Table 1: Current upper limits on LFV Z decays from LEP and LHC experiments and expected sensitivity of a Tera Z factory as estimated in [7] assuming 3×10^{12} visible Z decays.