FLAVOR PHYSICS @ CEPC

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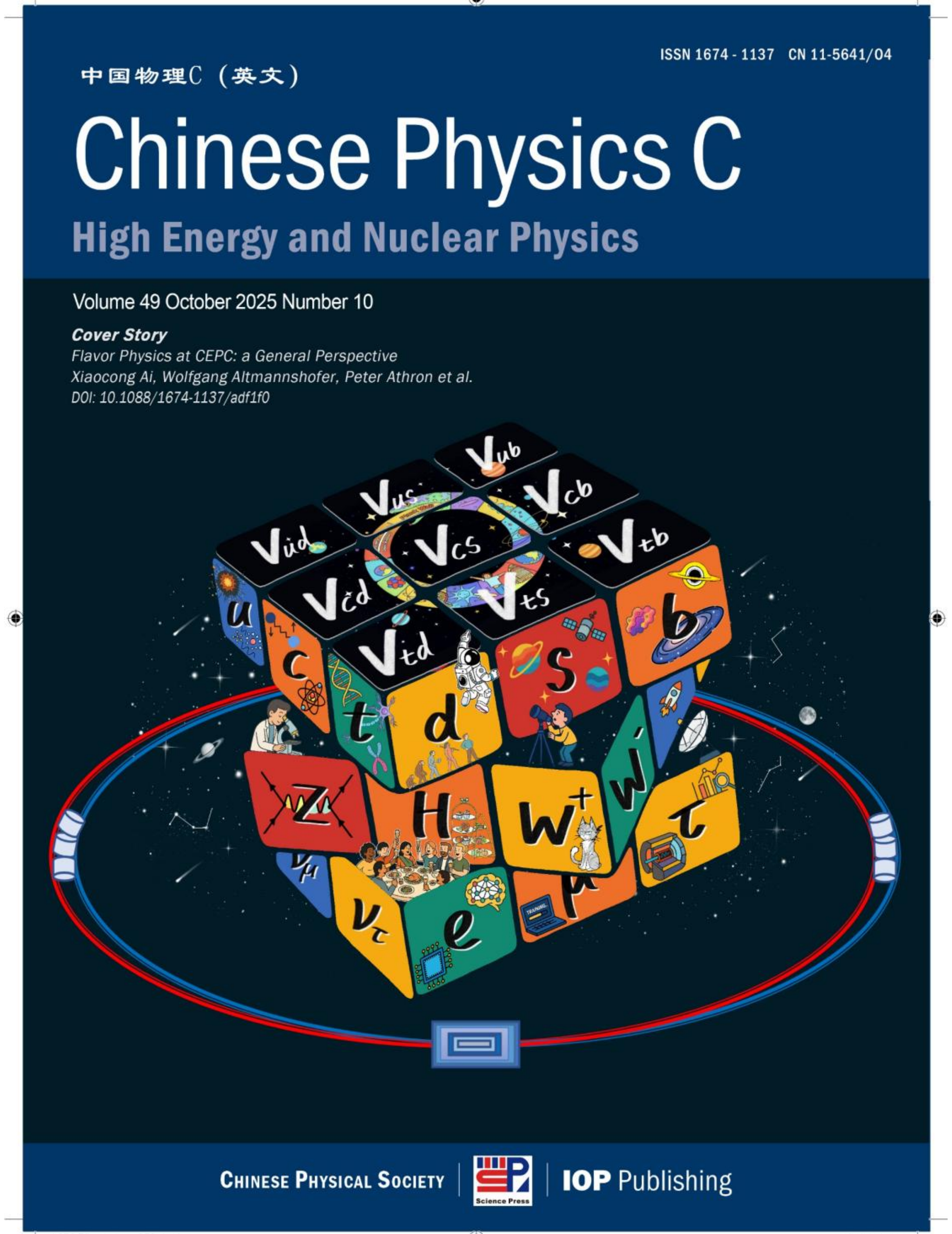
ICTP-AP, UCAS

Oct. 30, CLHCP, Xinxiang, Henan



*Also applies to FCC

*and partially ILC LEP3

Tera-Z

90 GeV

O(100) ab^{-1}

CEPC

Giga-W

160 GeV

O(10) ab^{-1}

Mega-HIGGS

240 GeV

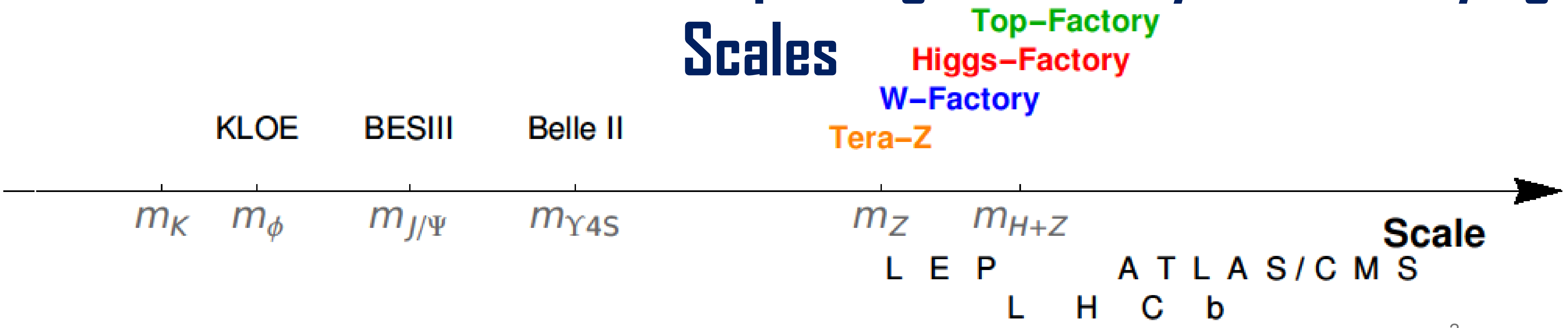
O(10) ab^{-1}

~100/π km

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, per IP)	191.7	26.7	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6.9	21.6	1
Event yields	4.1×10^{12}	2.1×10^{8}	4.3×10^{6}	0.6×10^{6}

- Massive Statistics
- Heavy/Exotic Hadrons
- Boosted final States
- Clean Environment
- EW scale Probes

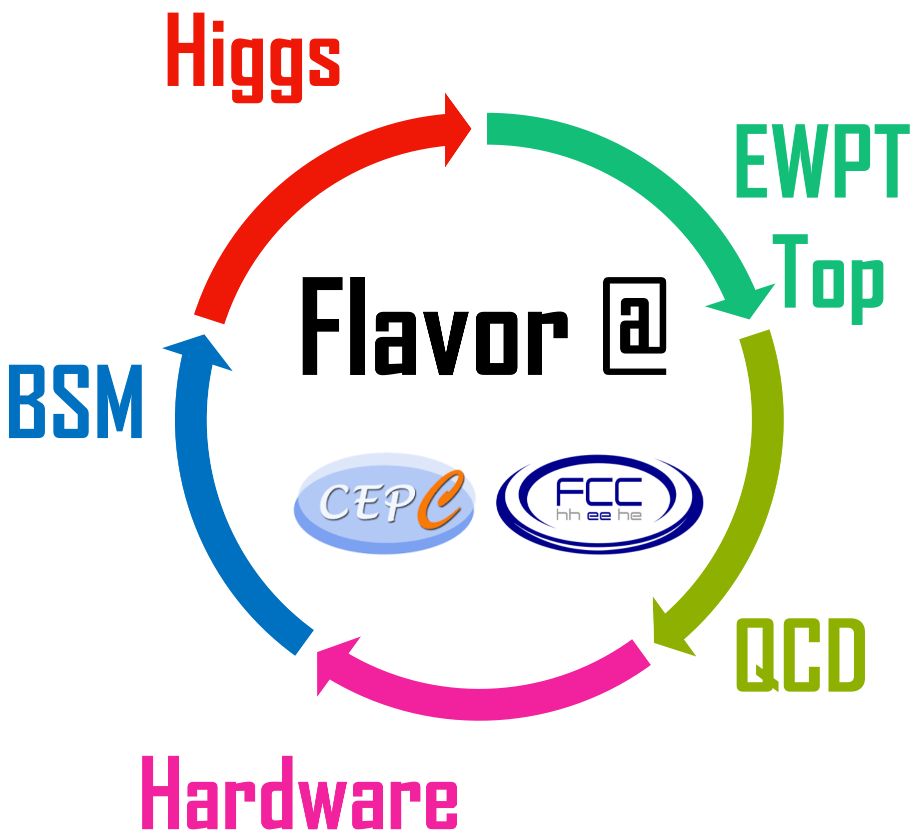
Inspecting Flavor Physics at Varying Scales



Flavor in the Big Picture

- ❑ Origin of flavor hierarchy?
- ❑ CP violation phases from Yukawa?

- ❑ Origin of matter? understand lepton and baryon numbers
- ❑ Light dark matter?
- ❑ (Remaining) flavor anomalies?



- ❑ Flavor physics beyond the Tera-Z phase?
- ❑ Common need in τ phys.

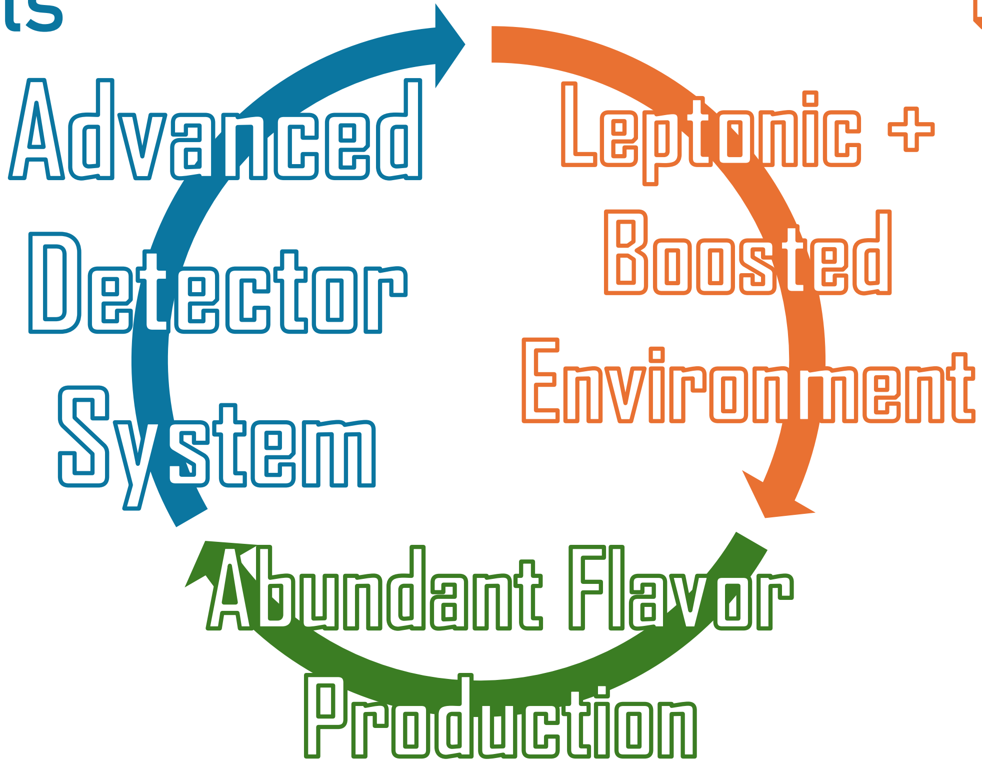
- ❑ How does asymptotic freedom work with flavor?
- ❑ New formalism beyond the conventional meson-baryon picture?
- ❑ Use a plethora of data to improve hadronization

- ❑ Most demanding field:

We need better tracker, E(H)CAL, electronics… everything!

- ❑ Lepton ID
- ❑ π/K/p separation
- ❑ Precise ECAL
- ❑ Displaced signals

- ❑ Multipe soft tracks
- ❑ Neutrinos & BSM
- ❑ Neutral Particles (photon/π^0/η…)



- ❑ Including heavy species: Bc, baryons, exotics…
- ❑ Rare modes

Particle	CEPC (TDR)
B^0, $\bar{B}^0$	4.8×10^{11}
$B^\pm$	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	1.2×10^{11}
$B_c^\pm$	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	1×10^{11}
D^0, $\bar{D}^0$	8.3×10^{11}
$D^\pm$	4.9×10^{11}
$D_s^\pm$	1.8×10^{11}
$\Lambda_c^\pm$	6.2×10^{10}
$\tau^+\tau^-$	1.2×10^{11}

Flavor physics at the CEPC: a general perspective*

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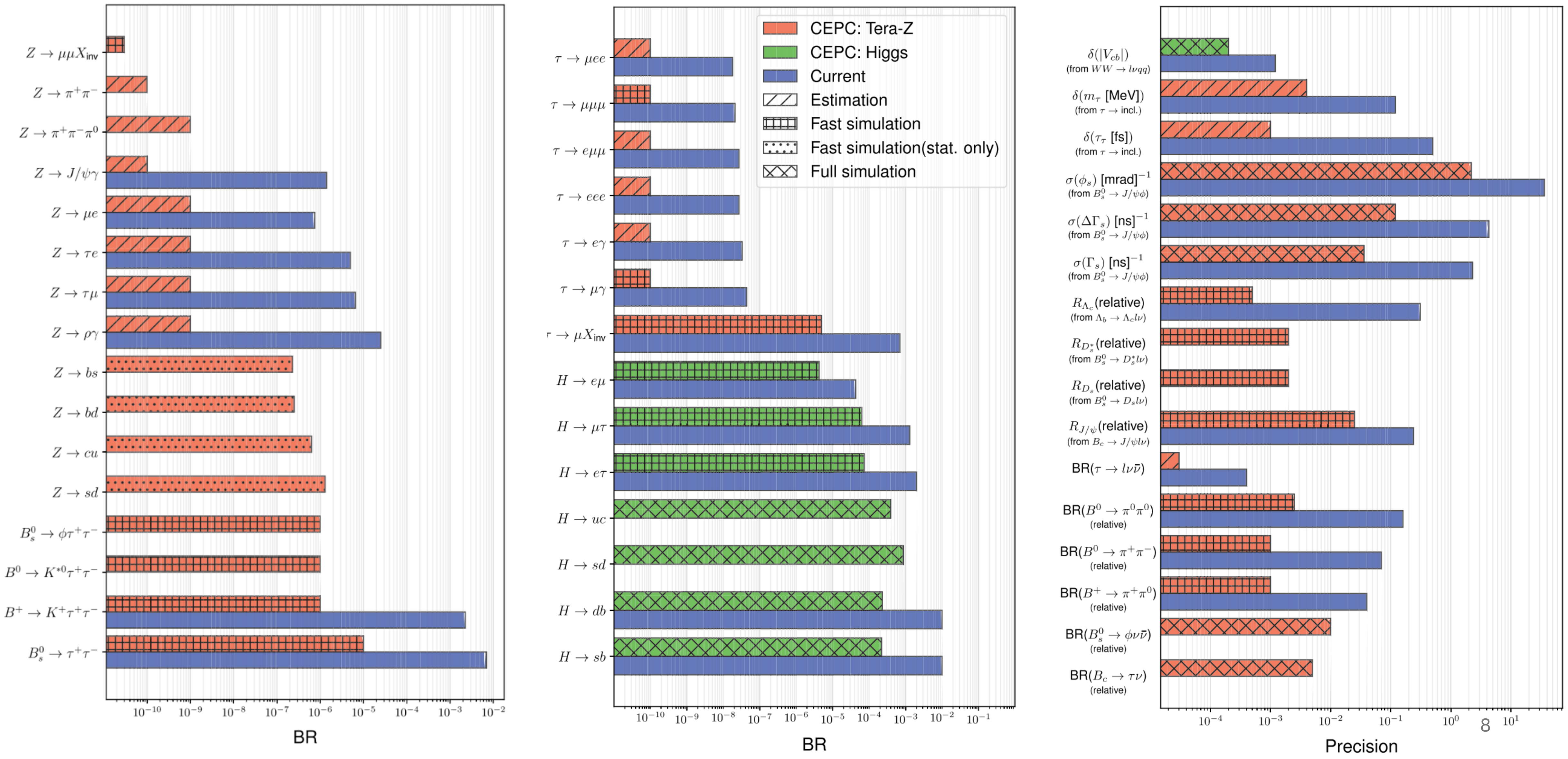
Timeline of Document

07/21 – 04/23	04/23 – 07/23	07/23-11/24	12/24	01/25-Soon
❑ Initiation of white paper, material collection	❑ First draft finished,	❑ Internal review by domestic & international collegues	❑ Appears on arXiv	❑ Finalization, editing for CPC publication (cover paper)

Higgs White Paper: 1810.09037
Accelerator TDR: 2312.14363
New Physics White Paper: 2505.24810

Physics Summary



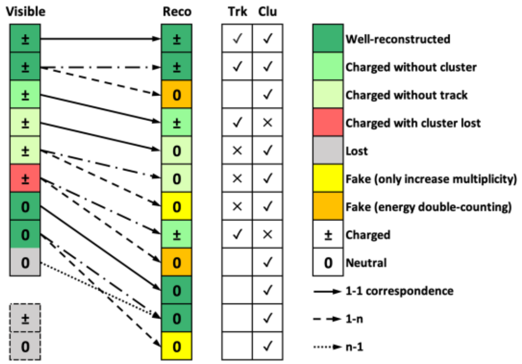
Detector Performance

High ECAL energy resolution, reaching $3\%/E^{0.5}$ with a crystal ECAL design

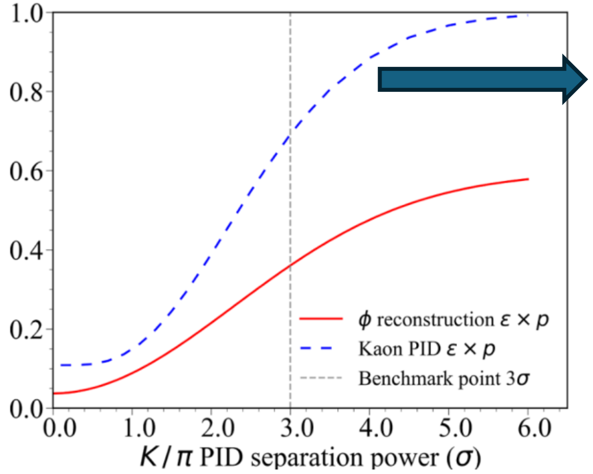
Item	CDR [2]	4^{th} concept [42]	Comments
Basic Performance			
Acceptance	$\lvert\cos\theta\rvert < 0.99$ [2]		
Threshold	200 MeV [43, 44]	100 MeV	For tracks & photons
Beam energy spread	$\mathcal{O}(0.1\%)$ [2]		
Tracker momentum resolution	$\mathcal{O}(0.1\%)$ [2]		
ECAL energy resolution	$17\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]	$3\%/\sqrt{E(\text{GeV})}$ [32]	
HCAL energy resolution	$60\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]	$30\%/\sqrt{E(\text{GeV})}$ [45]	
Vertex resolution	10–200 μm [2]	5–100 μm	
Jet energy resolution	3–5% [2, 46]		For 20–100 GeV
$\ell - \pi$ mis-ID	$< 1\%$ [47]		In jet, $\lvert\vec{p}\rvert > 2$ GeV
$\pi - K$ separation	$> 2\sigma$ [2]	$> 3\sigma$ [36]	In jet, $\lvert\vec{p}\rvert > 1$ GeV, TOF+dE/dx
Flavor Physics Benchmarks (Depending on the Above)			
$\sigma(m_{H,W,Z})$	3.7% [2]		Hadronic decays
b-jet efficiency×purity	$\sim 86\%$ [33]		In Z hadronic decays
c-jet efficiency×purity	$\sim 64\%$ [33]		In Z hadronic decays
b-jet charge tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	$\sim 37\%$ [33]		
c-jet charge tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	$\sim 58\%$ [33]		
π^0 efficiency×purity	$\gtrsim 70\%$ [44]	$\gtrsim 80\%$ [32]	In Z hadronic decays, $\lvert\vec{p}_{\pi^0}\rvert > 5$ GeV
K_S^0, Λ efficiency	60%-85% [48]		In Z hadronic decays, all tracks
τ efficiency×purity	70% [49]		In $WW \to \tau\nu q\bar{q}'$, inclusive
τ mis-ID	$\mathcal{O}(1\%)$ [49]		In $WW \to \tau\nu q\bar{q}'$, inclusive

High tagging power for b & c

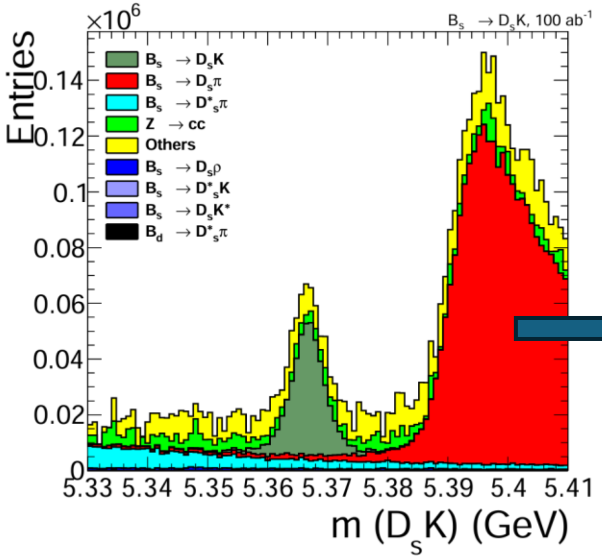
Advanced PID & Calorimeter Resolution

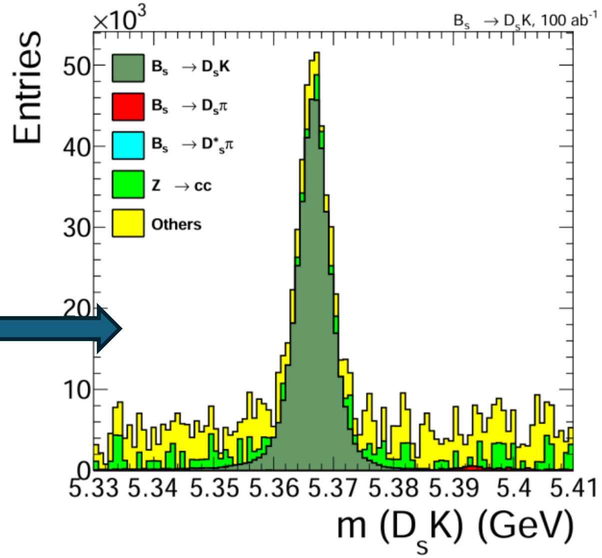


Reaching better K-π separation



dE(dN)/dx + TOF + HGCAL



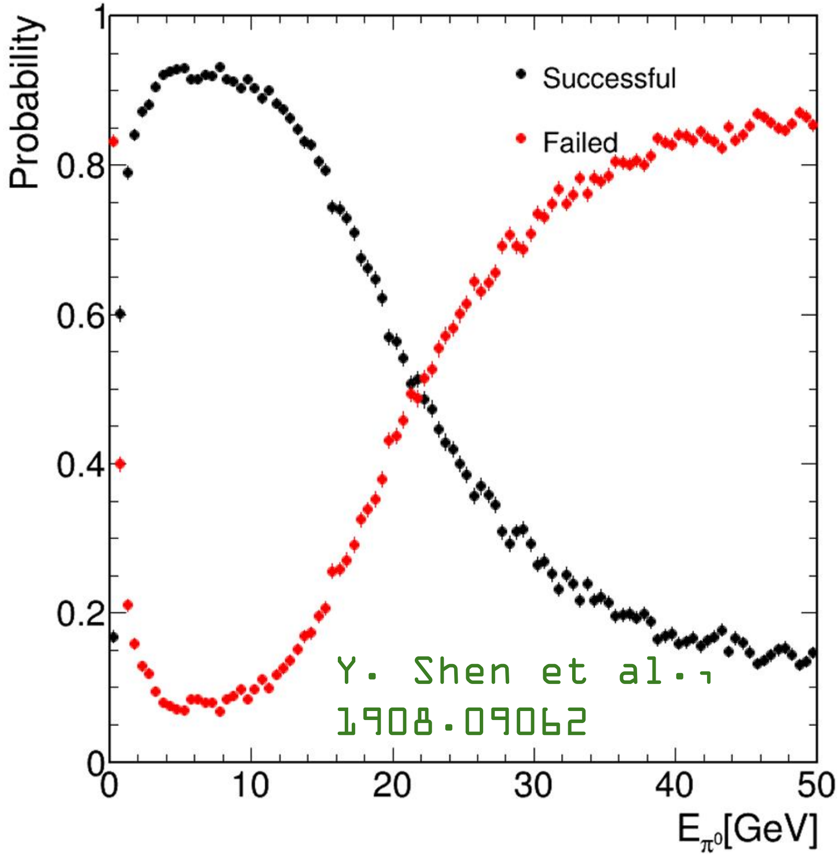


Y. Wang et al., 2411.06939

True \ Predicted	$e^\pm$	$\mu^\pm$	$\pi^\pm$	$K^\pm$	$p/\bar{p}$	γ	K_L^0	n	$\bar{n}$	others
$e^\pm$	0.999	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\mu^\pm$	0.000	0.985	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\pi^\pm$	0.000	0.019	0.977	0.003	0.000	0.000	0.000	0.000	0.000	0.000
$K^\pm$	0.000	0.001	0.003	0.985	0.011	0.000	0.000	0.000	0.000	0.000
$p/\bar{p}$	0.000	0.000	0.001	0.012	0.979	0.000	0.000	0.000	0.000	0.008
γ	0.000	0.000	0.000	0.000	0.000	0.973	0.003	0.004	0.000	0.020
K_L^0	0.000	0.000	0.000	0.000	0.000	0.007	0.756	0.070	0.048	0.119
n	0.000	0.000	0.000	0.000	0.000	0.003	0.083	0.803	0.027	0.084
$\bar{n}$	0.000	0.000	0.000	0.000	0.000	0.003	0.052	0.026	0.796	0.123
others	0.000	0.000	0.000	0.000	0.000	0.014	0.025	0.095	0.011	0.854

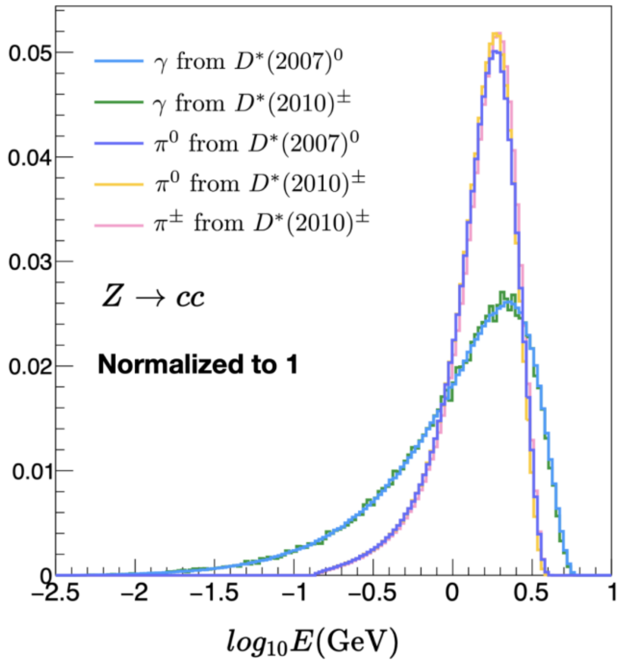
Boosted Final States

High boost leads to harder final states and better PID & time resolution

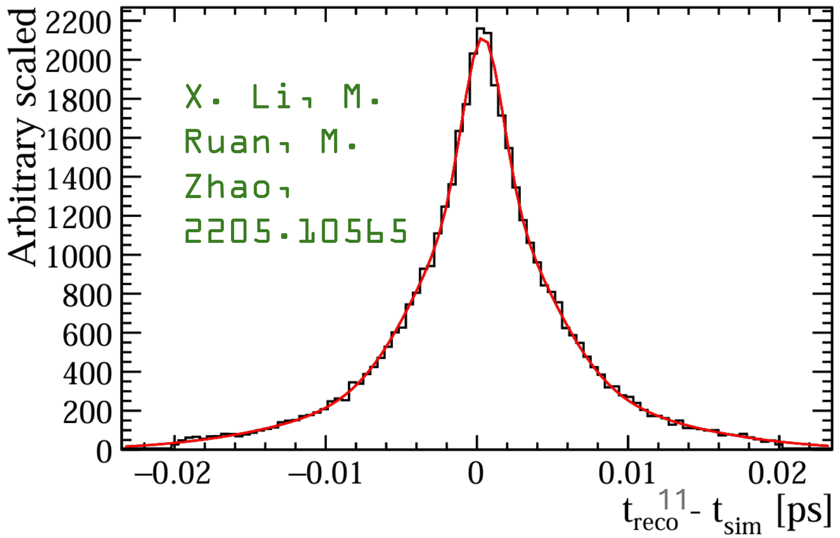


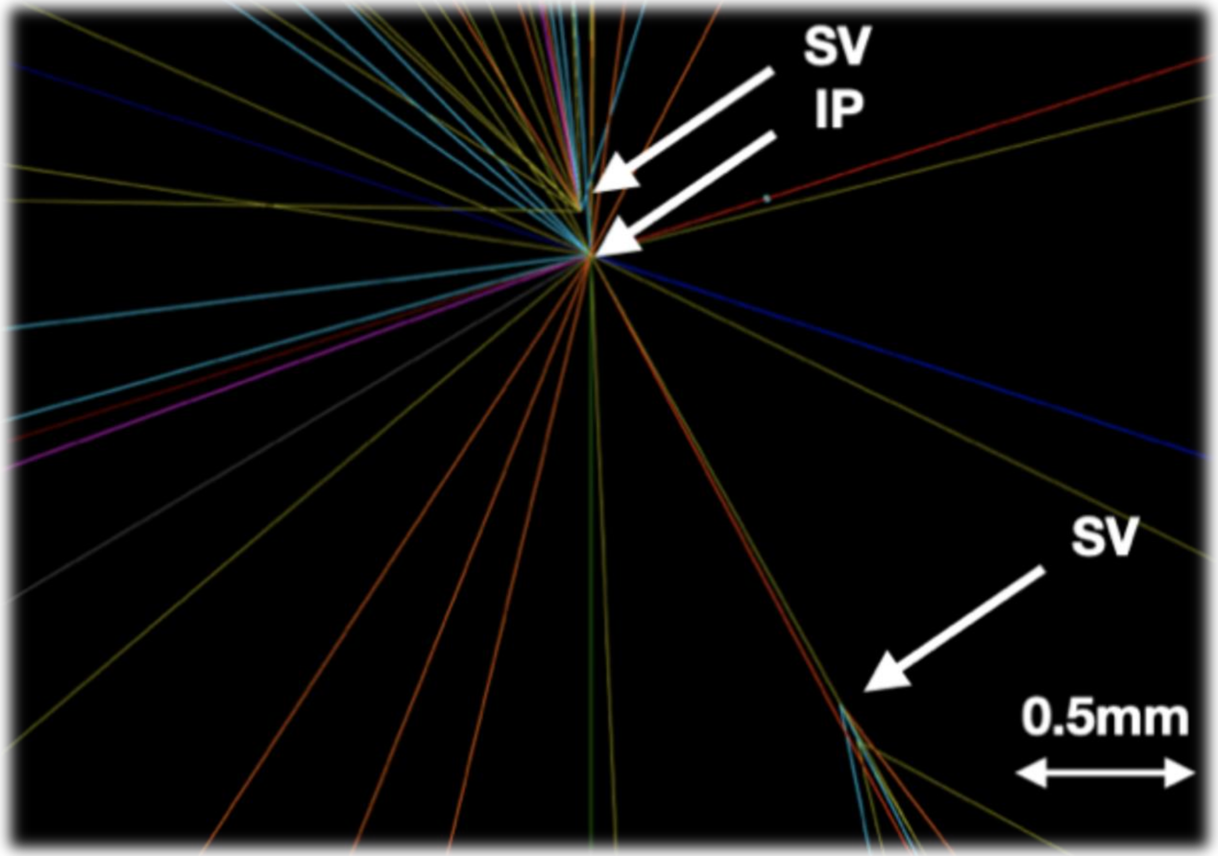
- π^0 @ baseline detector, eff. >60% in the range relevant to flavor phys.

- Soft particles from D* decays become harder



- Longer decay length + tracking, <O(10) fs resolution possible



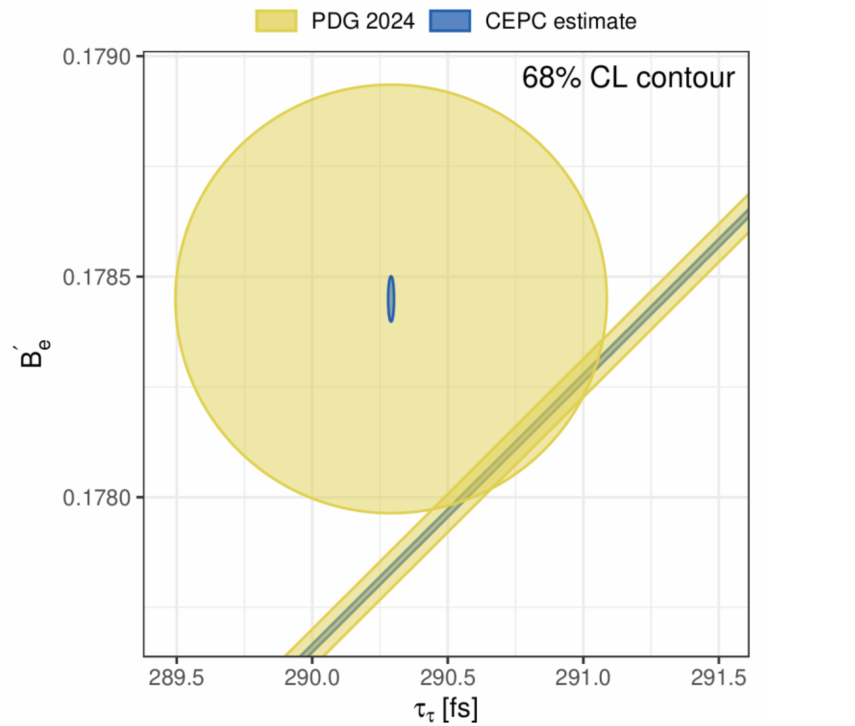


Approach I: Hadrons from the Z Factory (Exclusive)

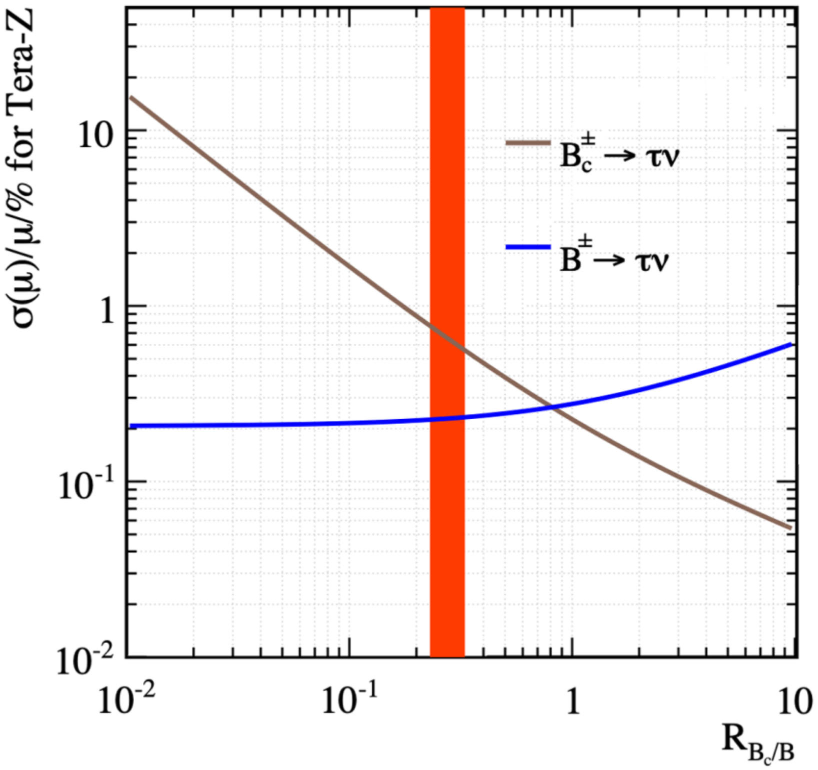
Precision Measurements

- Remains to be updated: $\Delta m_{d/s}$, $\Delta\Gamma_{d/s}$, $\tau(\Xi_b, \Omega_b \ldots)$, $f_{\text{hadron}} \ldots\ldots$

- Tau mass, lifetime and LFUV in leptonic tau decays

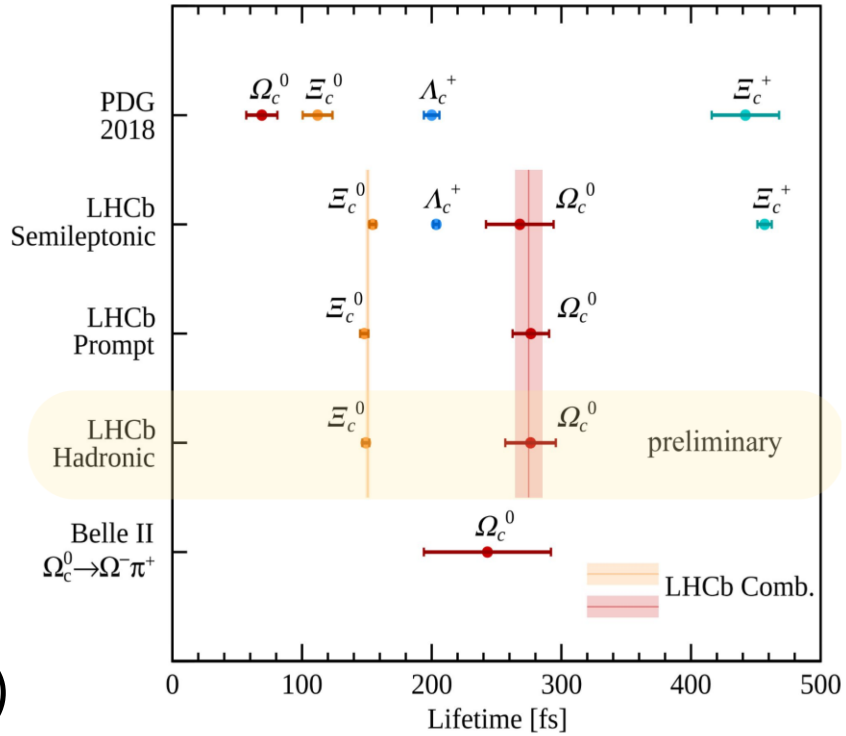


Measurement	Current	Belle II	FCC	CEPC prelim.
Lifetime [sec]	$(2903 \pm 5) \times 10^{-16}$		$\pm 6 \times 10^{-18}$	$\pm 7 \times 10^{-18}$
$BR(\tau \to e\nu\bar{\nu})$	$(17.82 \pm 0.04)\%$		$\pm 0.003\%$	$\pm 0.003\%$
$BR(\tau \to \mu\nu\bar{\nu})$	$(17.39 \pm 0.04)\%$		$\pm 0.003\%$	$\pm 0.003\%$
m_τ [MeV]	1776.93 ± 0.09		± 0.0016 (stat.) ± 0.018 (syst.)	
$BR(\tau \to \mu\mu\mu)$	$< 2.1 \times 10^{-8}$	3.6×10^{-10}	1.4×10^{-11}	10^{-10}
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	6.9×10^{-9}	1.2×10^{-9}	10^{-10}

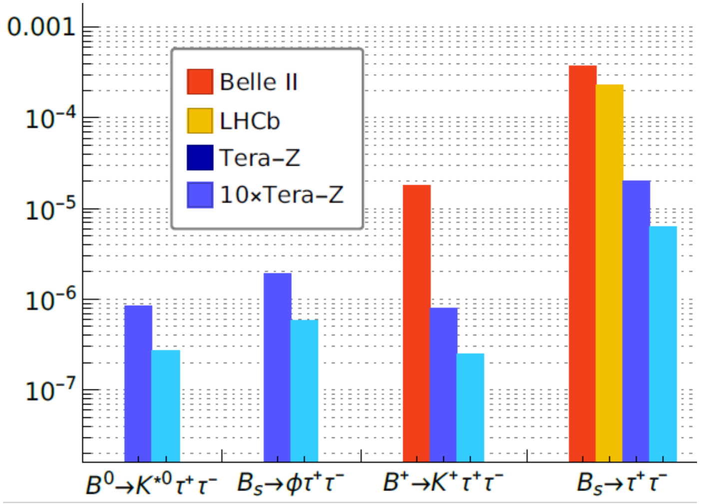


- Semileptonic decays of b-haadrons (BR, dσ, CPV)

- Charm (baryon) lifetime issues: update/cross checks



Rare Decays

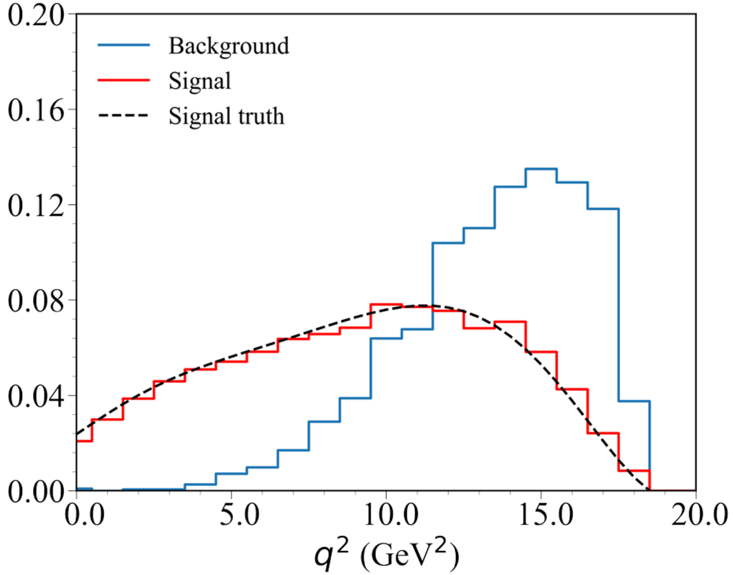


- FCNC $bs\tau\tau$ transitions: reaching the SM predictions

J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva, 1705.11106; LFL, T. Liu, 2012.00665

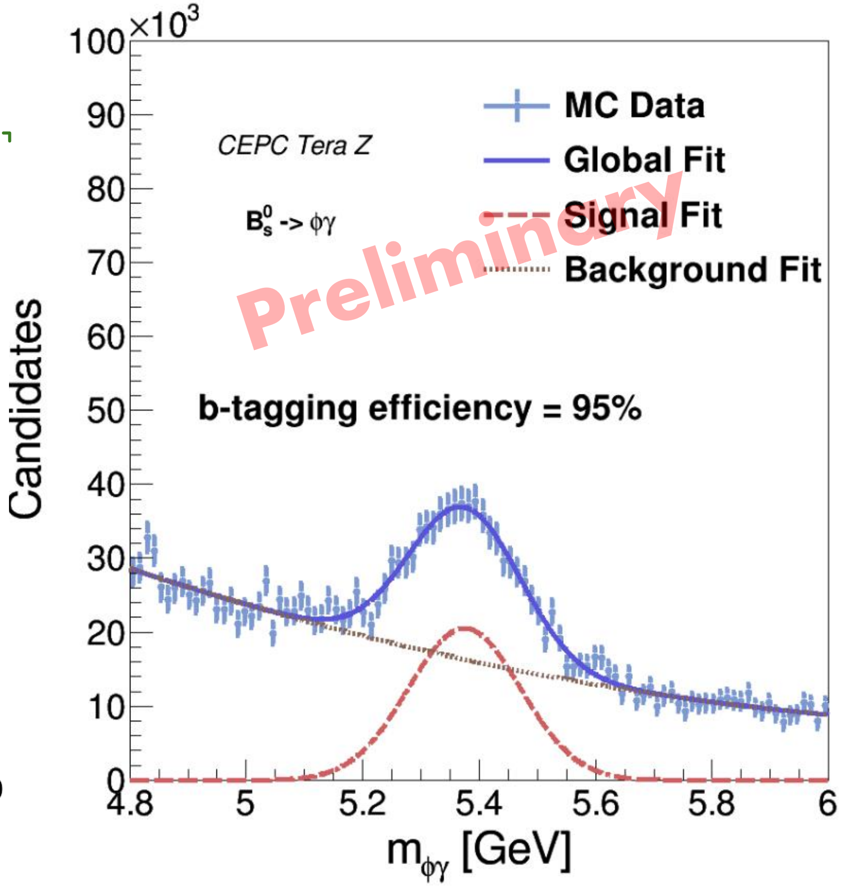
- Analogy: FCNC $bs\nu\nu$ transitions, reconstruct the invisible q^2

LFL, M. Ruan, Y. Wang, Y. Wang, 2207.07374, Y. Amhis, M. Kenzie, M. Reboud and A. R. Wiederhold, 2309.11353

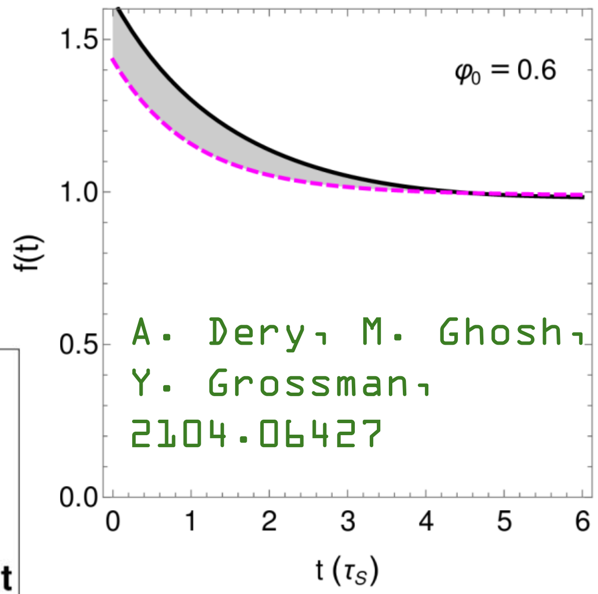


- Light lepton modes:

T. H. Kwok, Z. Polonsky, V. Lukashenko, J. Aebischer , B. Kilminster, 2506.08089; M. Bordone, C. Cornella, J. Davighi, 2503.22635;



- Rare neutral kaon decays (e.g. $K \to \mu\mu$) and the oscillation:



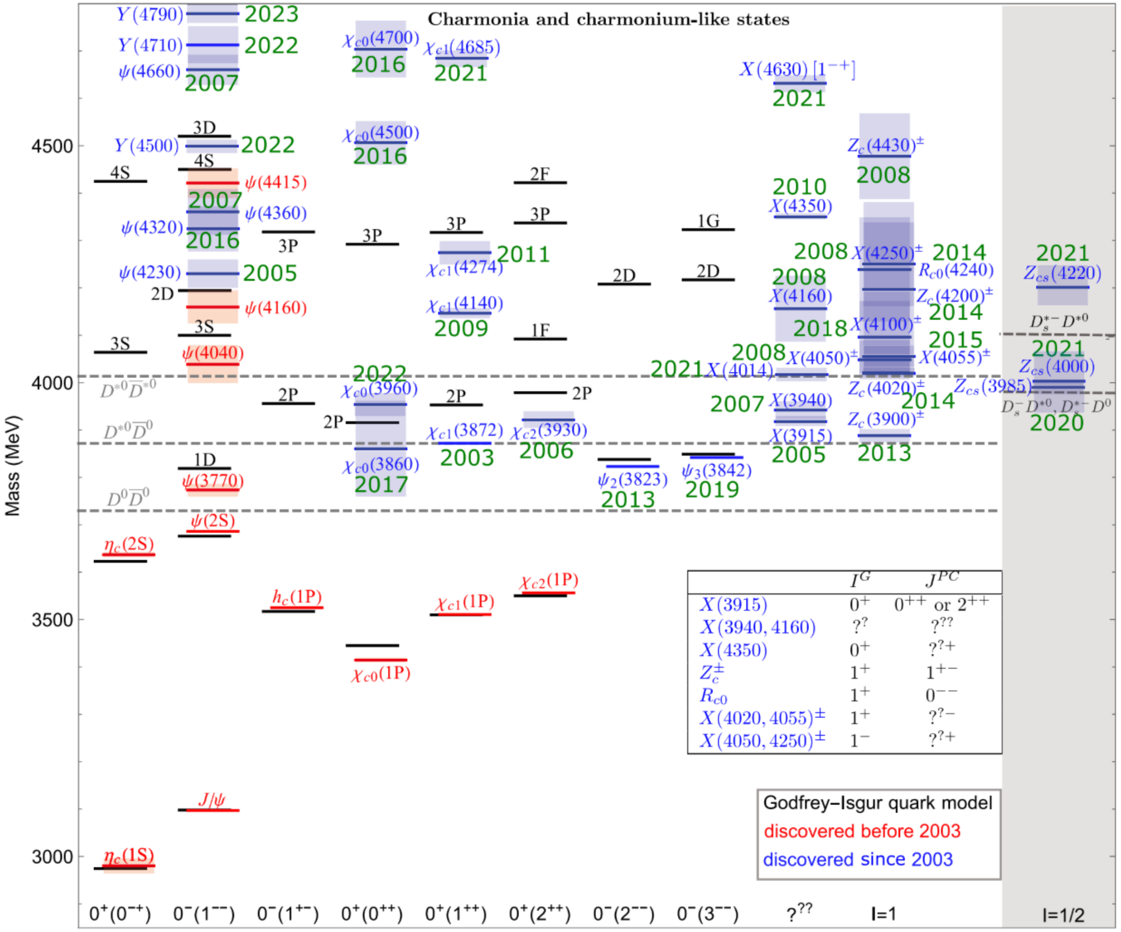
A. Dery, M. Ghosh, Y. Grossman, 2104.06427

- Radiative decays ($B_s \to \phi\gamma$)

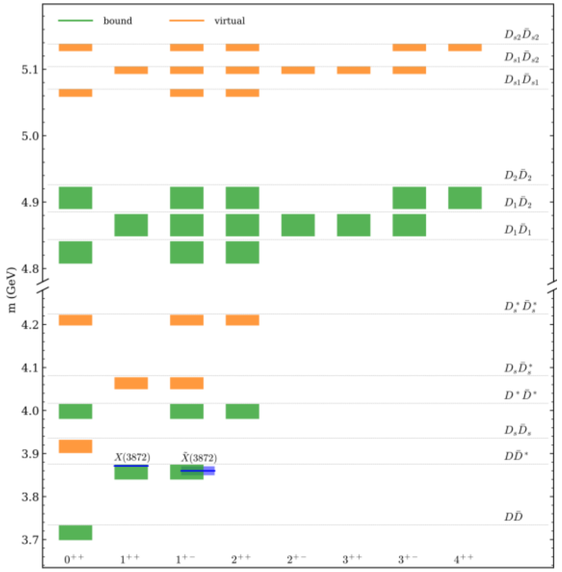
H.Y. Wang et al, in prep

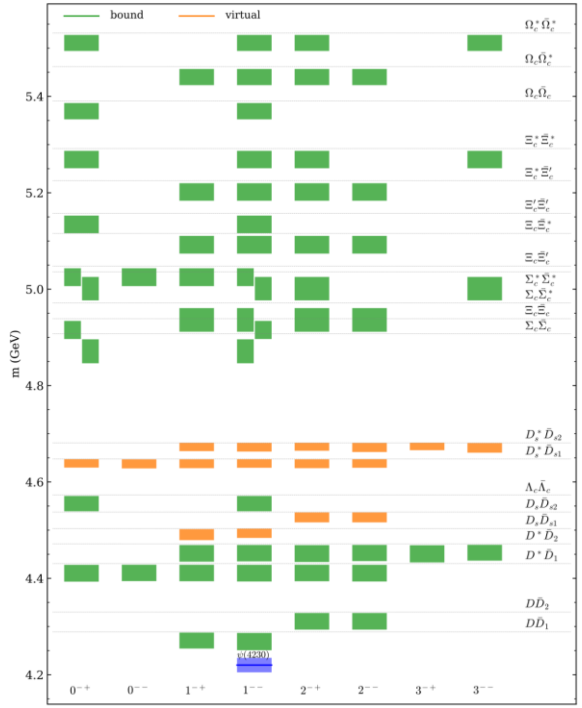
Spectroscopy in Meson Decays

F. K. Guo, C. Hanhart, U. G. Meissner, Q. Wang, Q. Zhao, B. S. Zou, 2018
X.K. Dong, F.K. Guo, B.S. Zou, 2021



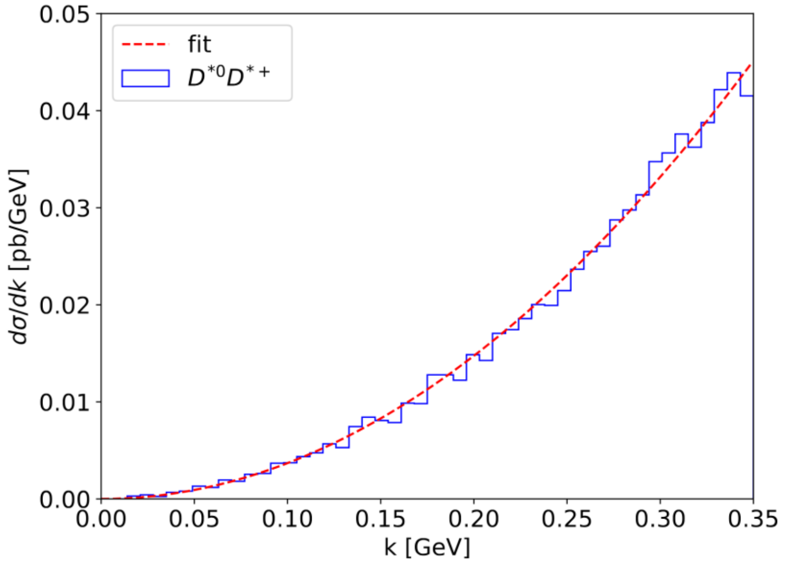
- A lot of “exotic” states discoverted, to be understood better, need more high-quality data





Spectroscopy from Z Decays

Z. S. Jia, G. Li, P. P. Shi and Z. H. Zhang, 2405.02619



- Relative momentum between D* mesons when pair produced from Z decay

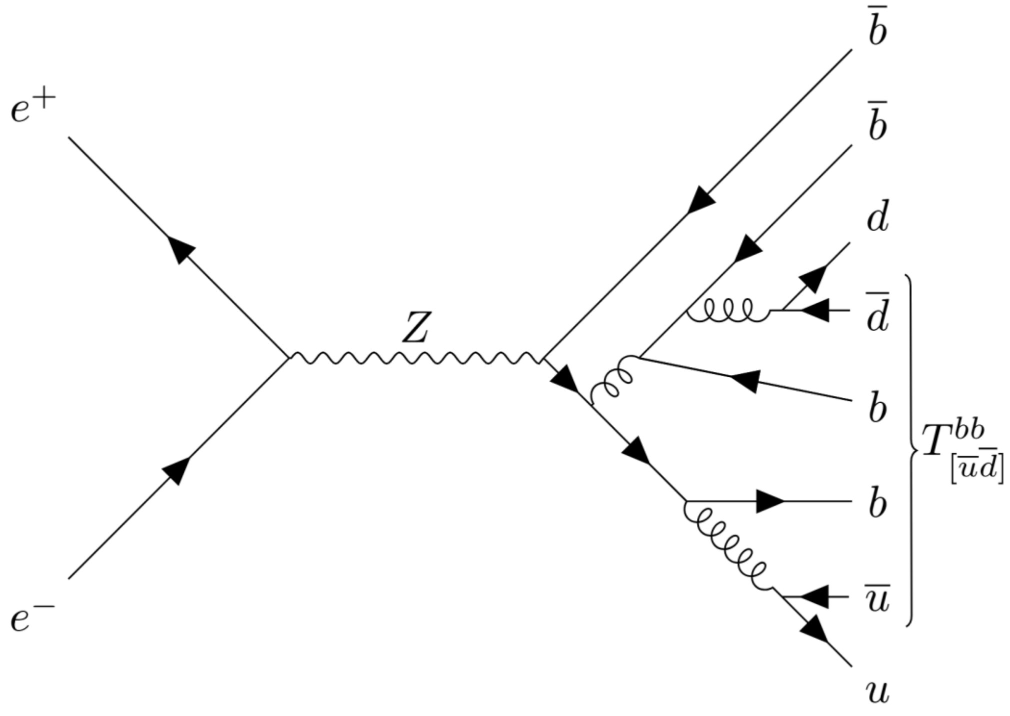
- Expected Yield: $O(10^5 - 10^7)$ for tetraquarks

Γ_{13} $\quad b\bar{b}b\bar{b}$ $\quad (3.6 \pm 1.3) \times 10^{-4}$

- 4b/ 2b2c/ 4c tetraquarks
- Doubly heavy-flavored baryons
- Related to B_c physics

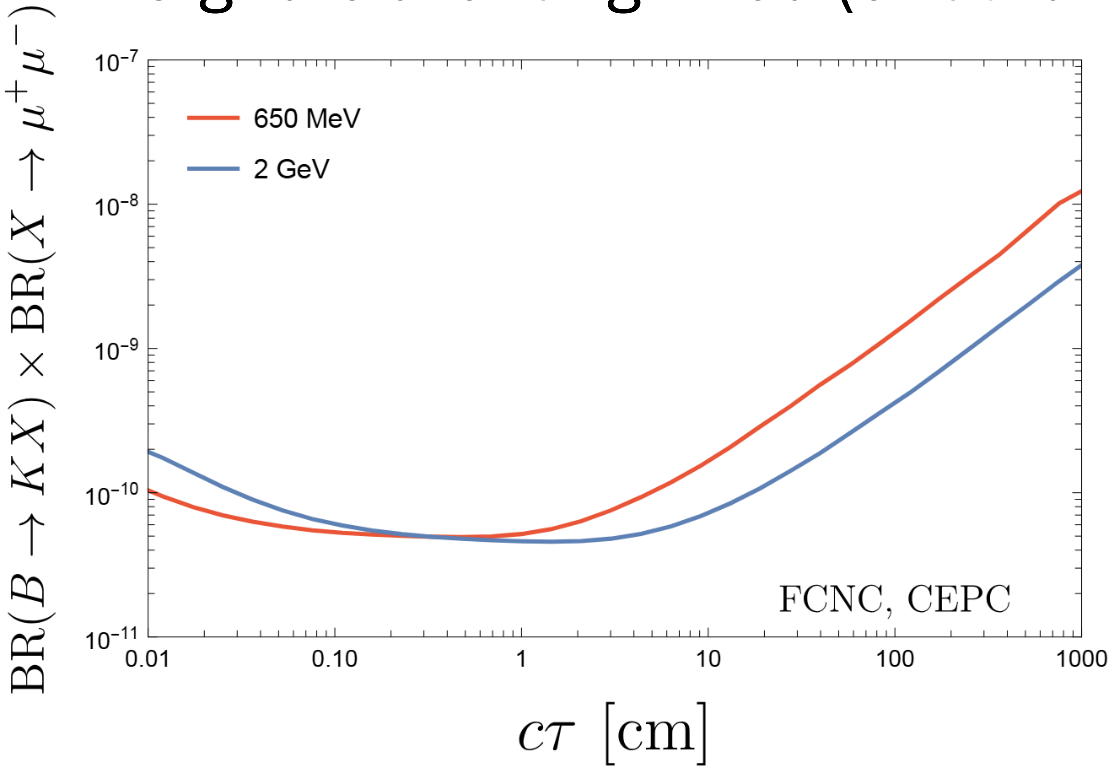
T. Zheng, J. Xu, L. Cao, D. Yu, W. Wang, 2007.08234; Y. Amhis, M. Hartmann, C. Helsens, D. Hill and O. Sumensari, 2105.13330; X. Zuo, M. Fedele, C. Helsens, D. Hill, S. Iguro, M. Klute, 2305.02998;

- ……



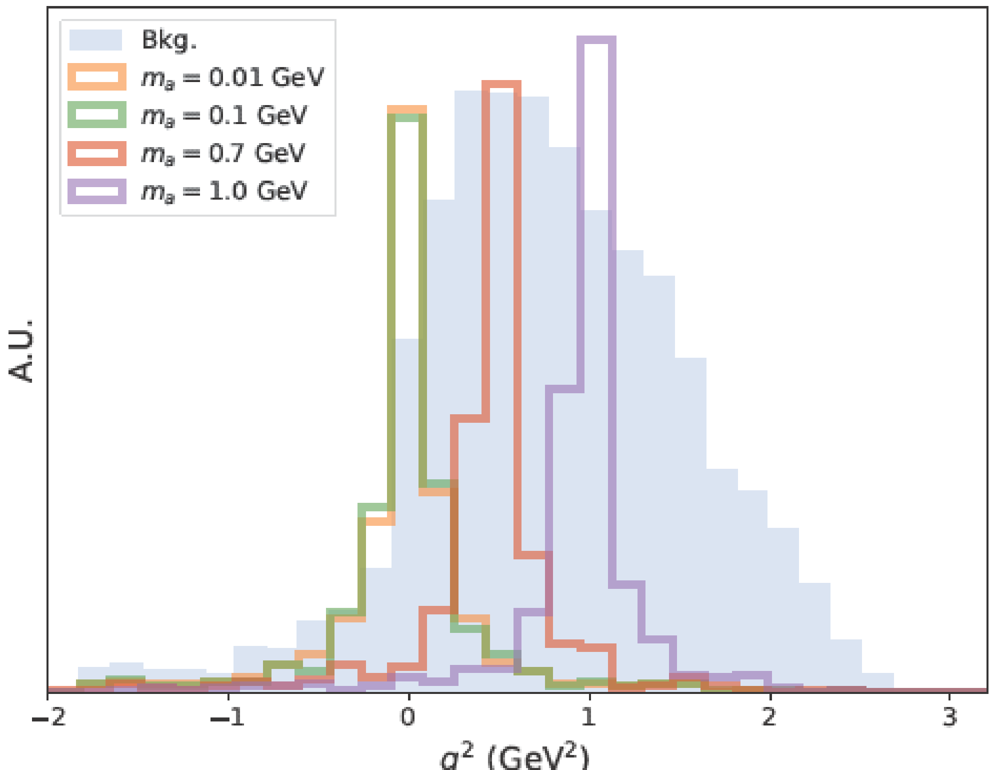
New Physics from Flavor

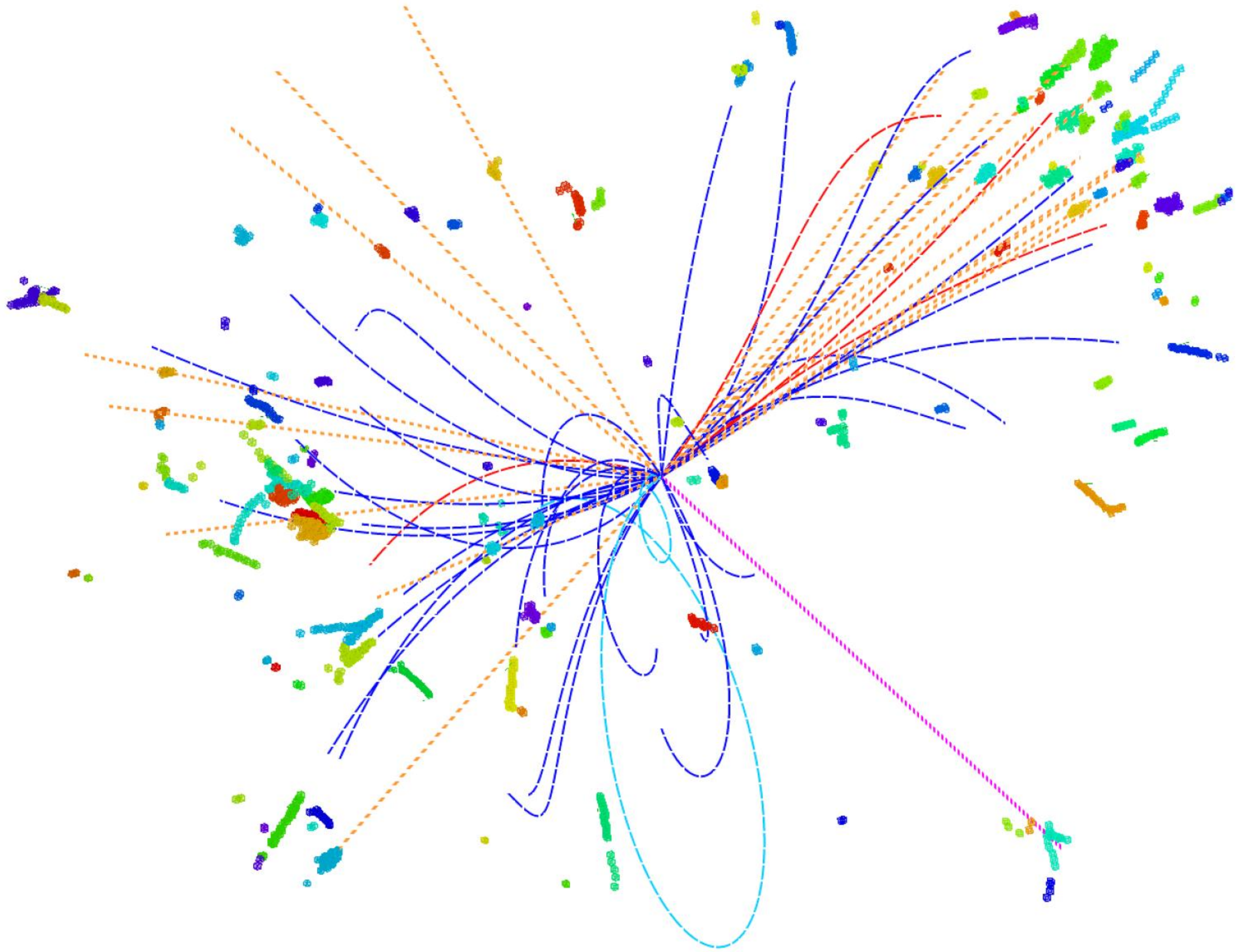
- Signals are invisible (similar to neutrinos)
- Signals are long-lived (shouldn't surprise flavor physicists)



❑ FCNC b s+X decays w/ long-lived BSM final states (down to 10^{-10} level)

❑ Tau decay to lepton + invisible X





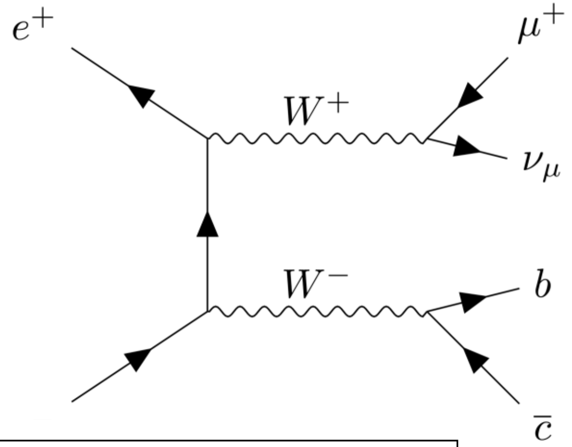
Approach II: Phenomena from the EW Scale (Often inclusive)

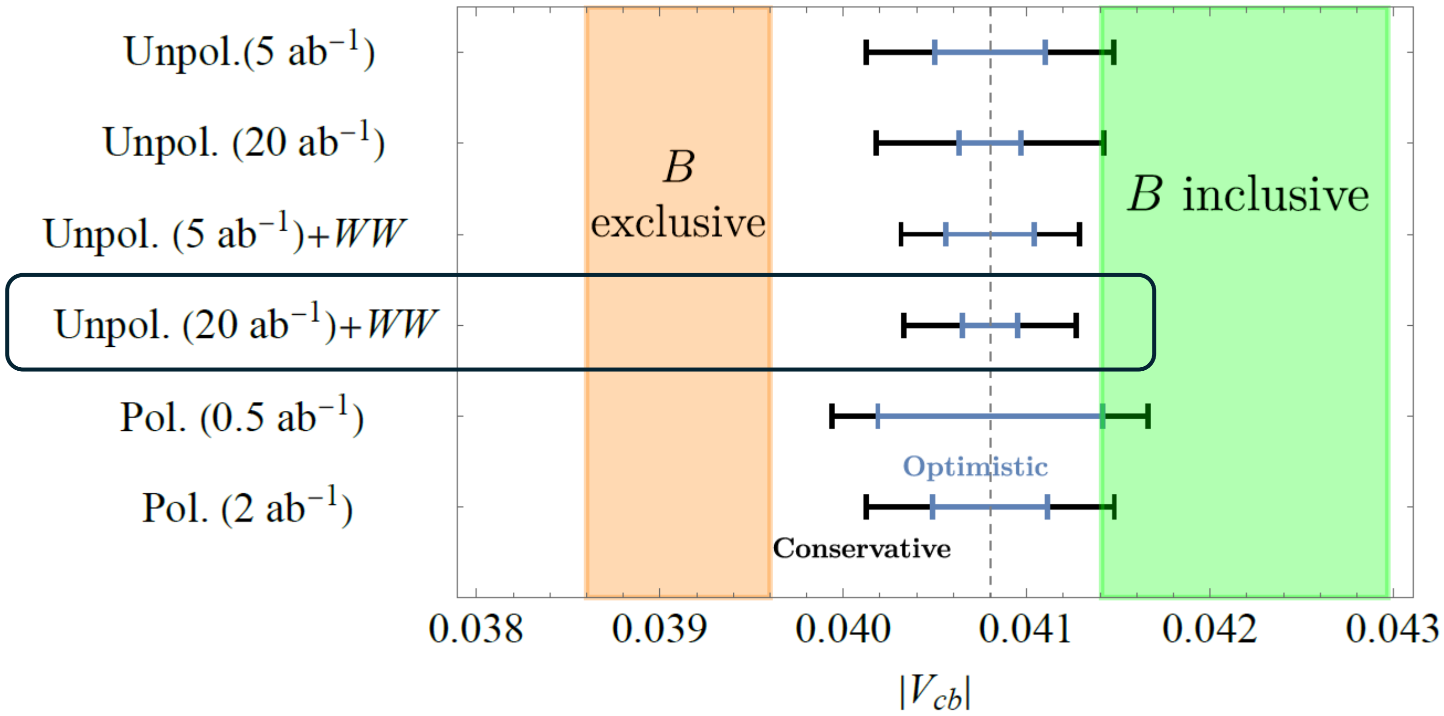
CKM from WW Decays

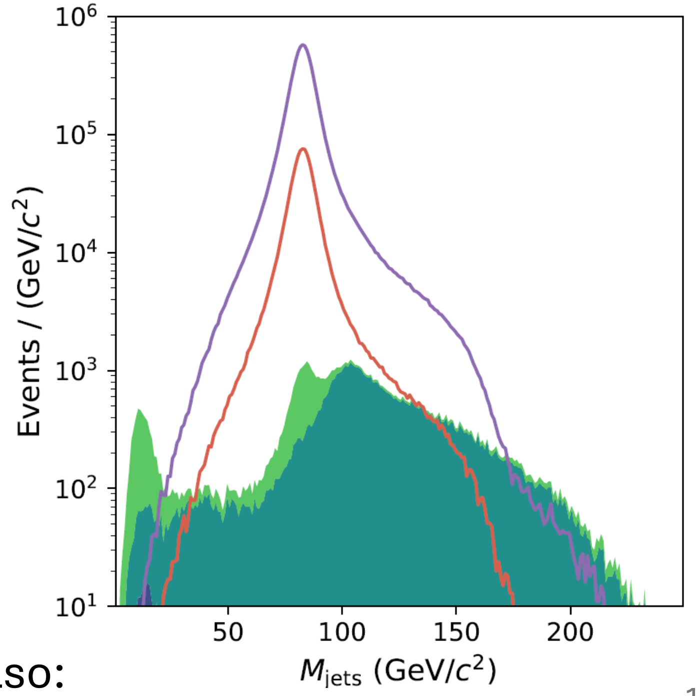
H. Liang, LFL, Y. Zhu, X. Shen and M. Ruan, 2406.01675

- The Higgs factory mode provides leading WW statistics

$$R_{cb} \equiv \frac{\Gamma(W \to cb)}{\sum \Gamma(W \to qq')} \simeq \frac{|V_{cb}|^2}{2}$$







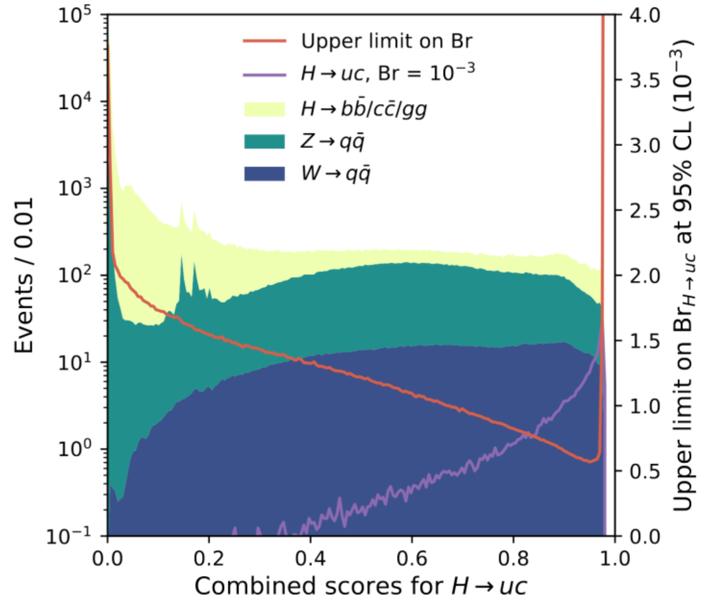
See also:

D. Marzocca, M. Szewc, M. Tammaro, 2024

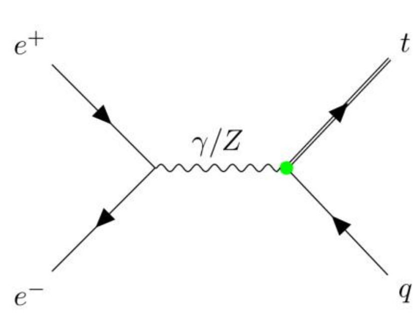
EW Scale FCNC Decays

FCNC/cLFV Z Decays

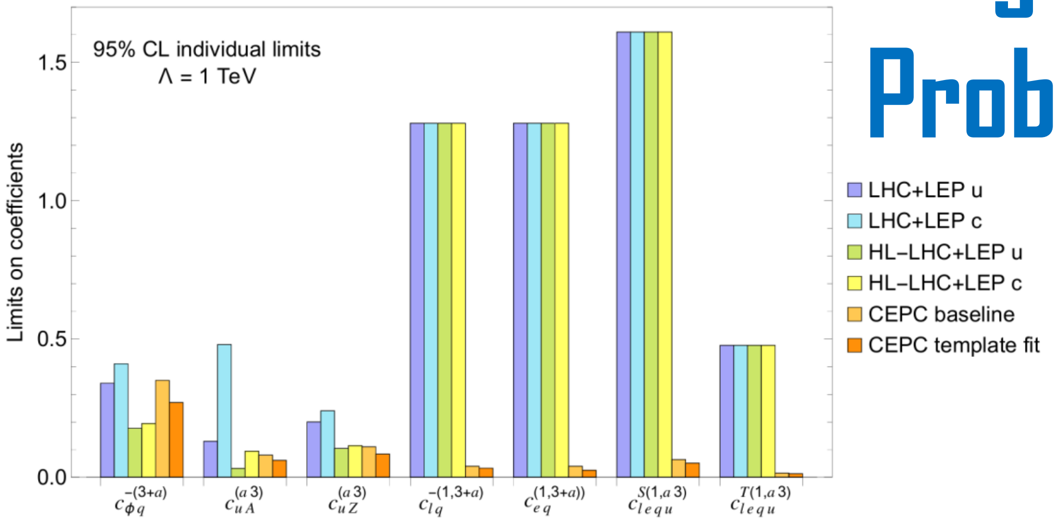
Measurement	Current	HL-LHC	FCC	CEPC prelim.
$\mathrm{BR}(Z \to \tau\mu)$	$< 6.5 \times 10^{-6}$	1.4×10^{-6}	10^{-9}	10^{-9}
$\mathrm{BR}(Z \to \tau e)$	$< 5.0 \times 10^{-6}$	1.1×10^{-6}	10^{-9}	
$\mathrm{BR}(Z \to \mu e)$	$< 2.62 \times 10^{-7}$	5.7×10^{-8}	$10^{-8} - 10^{-10}$	10^{-9}

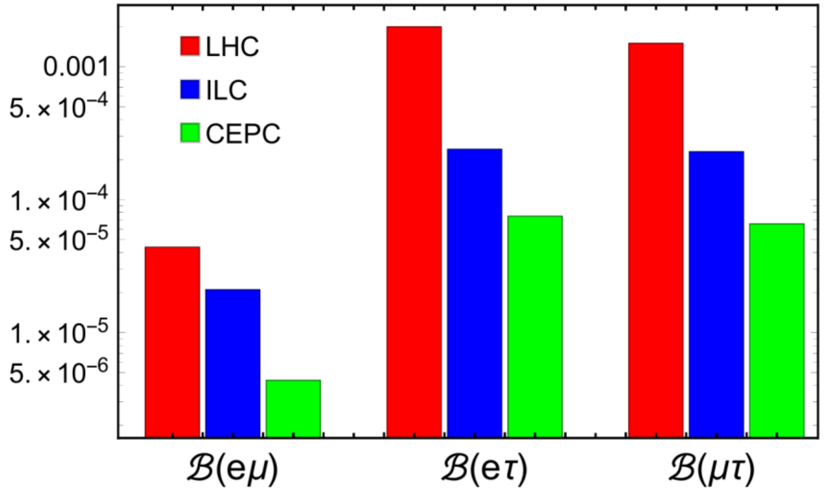


$\mathrm{BR}\ (h \to cu) < 4 \times 10^{-4}$



Single-Top Probing FCNC





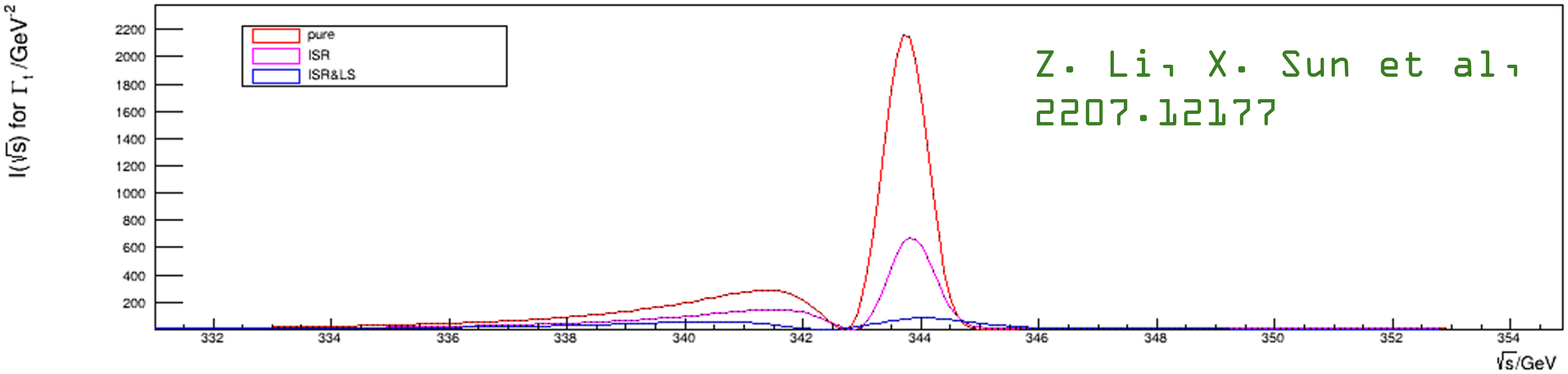
Higgs Decays

More Chances

- H/W/Z exclusive (radiative) hadronic decays

Measurement	SM Prediction	Current Limits [165]	CEPC prelim.
$\mathrm{BR}(Z \to \pi^+\pi^-)$	$(8.3 \pm 0.5) \times 10^{-13}$ [239]	–	$\mathcal{O}(10^{-10})$
$\mathrm{BR}(Z \to \pi^+\pi^-\pi^0)$	–	–	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(Z \to J/\psi\gamma)$	$(8.02 \pm 0.45) \times 10^{-8}$ [237]	$< 1.4 \times 10^{-6}$	$10^{-9} - 10^{-10}$
$\mathrm{BR}(Z \to \rho\gamma)$	$(4.19 \pm 0.47) \times 10^{-9}$ [237]	$< 2.5 \times 10^{-5}$	

- Precision toponium?



Summary

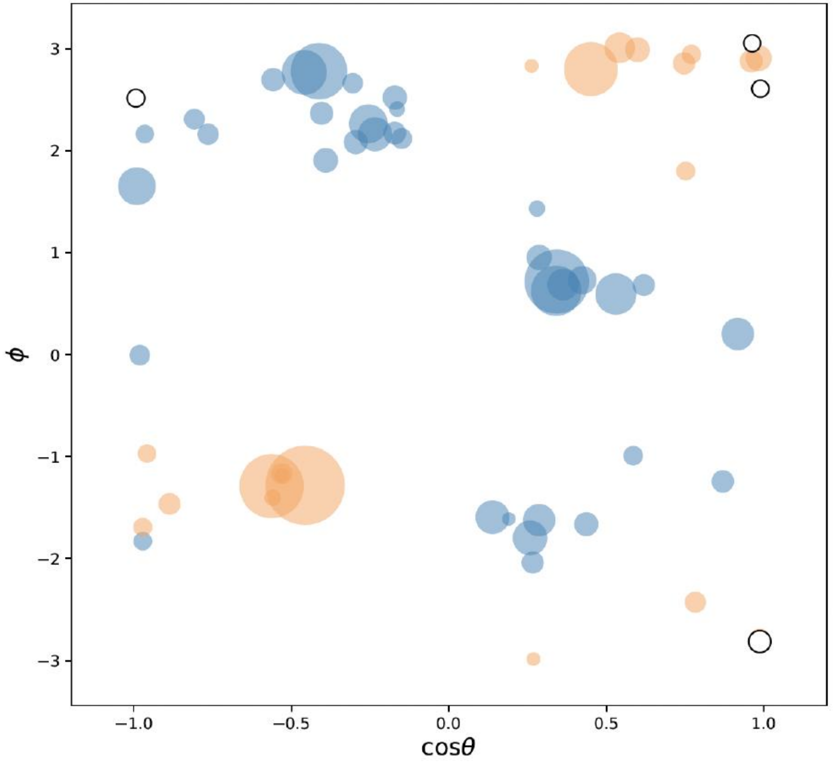
❖ **Current Stage:**

- ❑Future Z/W/Higgs factories are ideal places to study flavor physics
- ❑Complementary probes at the EW scale or even higher
- ❑Current result are of phase one, will move on to phase two study in the future

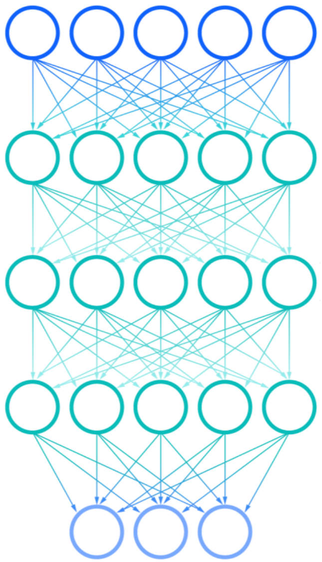
❖ **Message to the Community:**

- ❑Need to find the most advantageous/innovative observables for various flavor physics questions
- ❑Welcome to consider Tera-Z projections in your future works

The Upcoming ML Advantage: Progress in New Structures



- ❑ Jet clustering with color-singlet identification (Transformer)

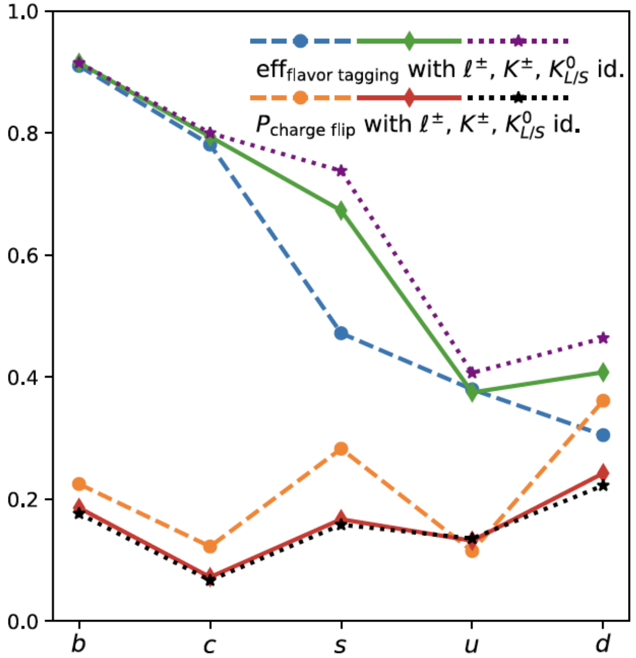


- ➢ResNet
- ➢PFN
- ➢ParticleNet
- ➢ParT
- ➢LorentzNet
- ➢L-GATr
- ➢PELICAN
- ➢MIParT
- …….

LFL, Y. Y. Li, T. Liu and S. J. Xu, 2004.15013; F. A. Dreyer, H. Qu, 2012.08526; A. Bogatskiy, T. Hoffman, D. W. Miller, J. T. Offermann, 2211.00454; Y. Wu, K. Wang, C. Li, H. Qu and J. Zhu, 2407.08682; H. Qu, L. Gouskos, 1902.08570; H. Qu, C. Li, S. Qian, 2202.03772

- ❑ New frontier of jet-tagging performance

H. Liang, M. Ruan, Y. Zhu et al., 2309.13231 & 2310.03440

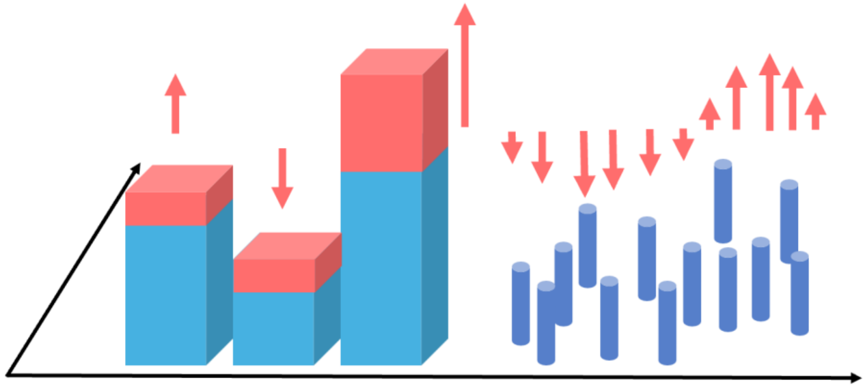


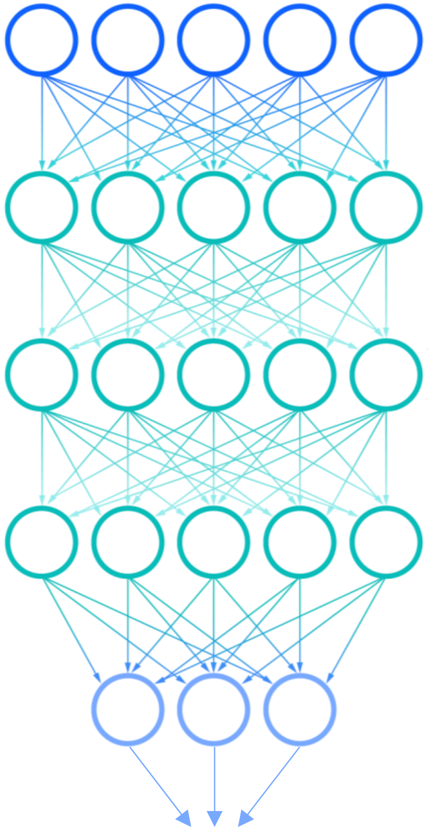
The Upcoming ML Advantage: New Strategies

Simulation based inference (SBI):

looking for EFT from all possible distributions

J. Brehmer, F. Kling, I. Espejo, K. Cranmer, 1907.10621; Chen, Glioti, Panico, Wulzer, 2007.10356; Ambrosio, Hoeve, Madigan, Rojo, Sanz, 2211.02058; R. Mastandrea, B. Nachman, T. Plehn, 2405.15847, Shengdu Chai, Jiayin Gu, LFL, 2401.02474





$$L = F(x_i, l_i) + \alpha(x_i) + \ldots$$

Update the strategy

Update the information input

Update the regulators/ agumentation

Anomaly detection:

Looking for unexpected phenomena with minimal assumptions

T. Cheng, J. F. Arguin, J. Leissner-Martin, J. Pilette and T. Golling, 2007.01850; G. Kasieczka, B. Nachman, M. D. Schwartz and D. Shih, 2007.14400; J. A. Raine, S. Klein, D. Sengupta and T. Golling, 2203.09470 ……