Status of the CEPC Flavor Physics White Paper (Phase I)

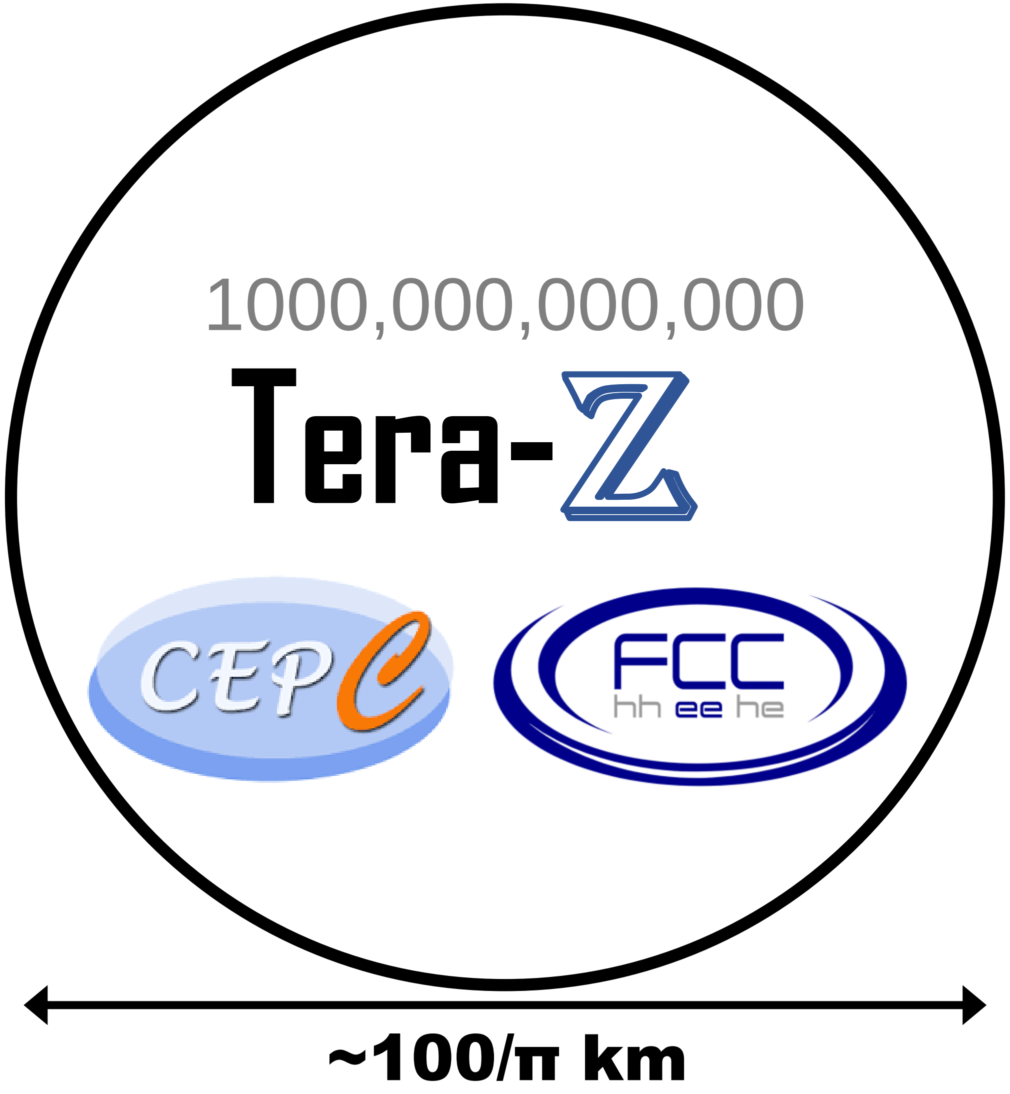
1000,000,000,000+

Or Flavor Physics at Tera - Z+

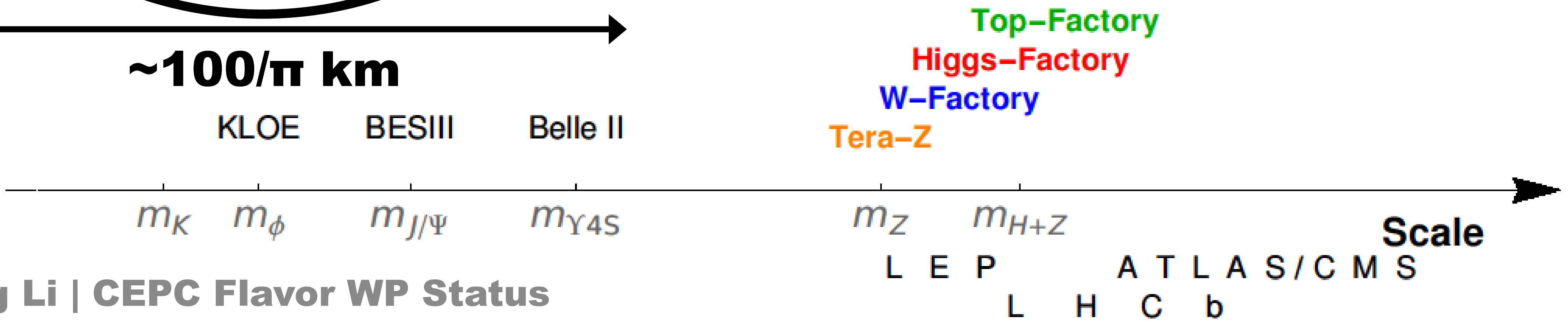
Lingfeng Li Brown University

Jul. 4, 2023

The 2023 international workshop on the CEPC



- Clean lepton collider (good for ν, γ, τ, e … Big advantages vs. hadronic ones)
- O(10^{11+}) b/c/τ (> B-factory of 50 ab^{-1})
- Generates all kinds of hadrons (B_c, Λ_b, T_{bb}…)
- Large energy (20-45 GeV) and boost for precision measurements
- Most advanced tech. infused detectors



1000,000,000,000

× 4 - 10⁺

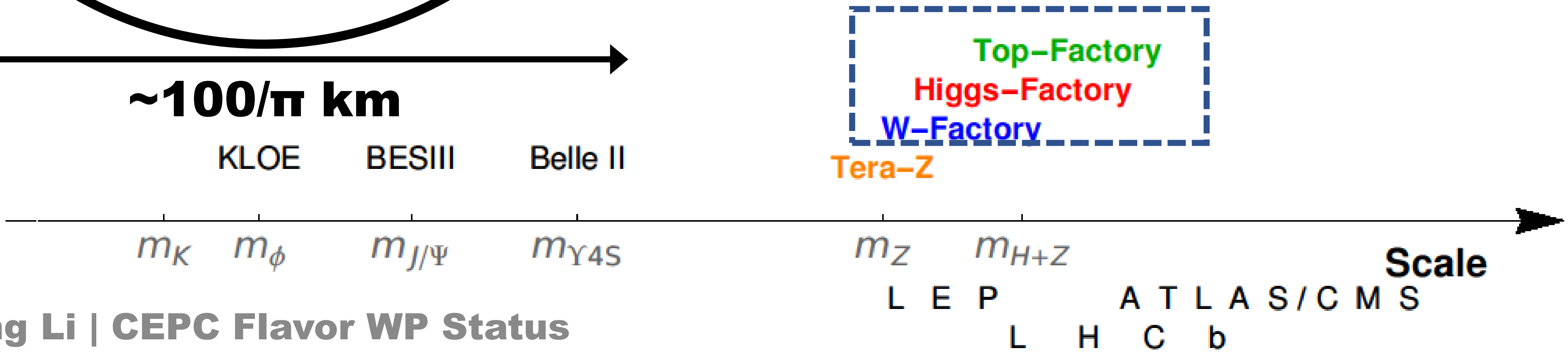
Tera-Z+

CEPC | FCC

~100/π km

- Higher luminosity as the accelerator design keeps upgrading
- ≥ 2 interaction points and various detectors

Flavor physics also need energy larger than 91 GeV



A Brief History

Flavor Phase II (+)
Cover the whole map?

Flavor Phase I

Further testing B anomalies & cLFV & ....

CP properties
Precision Flavor
Detector Performance...

B anomalies & charged lepton flavor violation (cLFV)

Before the CDR

Recognizing the advantages
Leptonic transitions

Status and Timeline

2019- Apr./23	Apr./23 – Jun./23	Jun./23 – Jul./23	Jul./23- Aug./23	Aug./23 Sep./23
❑ Initiation of white paper, material collection (by Haibo Li et al.)	❑ Drafting	❑ First draft finished, internal review	❑ External review by experts	❑ Preprint Publish

Cornerstones at CEPC

- Neutrinos
- Neutrals (photon/π^0/η…)
- Rare modes
- BSM states

Lepton Collider, Very Clean

Advanced Technology

- Leptons
- Flavor Tagging
- $b \to c \to \tau$ cascade
- Long-lived particles

$m_Z \gg m_f$ Abundant Energy

- Boost: O(fs) time scales
- Heavy Species: Bs, Bc, Λb, exotics…
- Multiple soft tracks

- Neutrinos
- Neutrals (photon/π^0/η…)
- Rare modes
- BSM states

Lepton Collider, Very Clean

- Overall Z = 4
- Full trigger rate: O(100) kHz
- Beam energy spread: O(0.1%)
- Beam transverse speared: O(1) μm

Advanced Technology

- ❑ Leptons
- ❑ Flavor Tagging
- ❑ b→c →τ cascade
- ❑ Long-lived particles

- ➢ PID techinques as dE/dx & time of flight
- ➢ Transervese vertex resolution of O(10) μm
- ➢ New ECAL designs

- Average boost of b ≈ 5-7, > 25 for τ
- Possibility to produce rare heavy states
- Unique opportunities from W/H/top modes

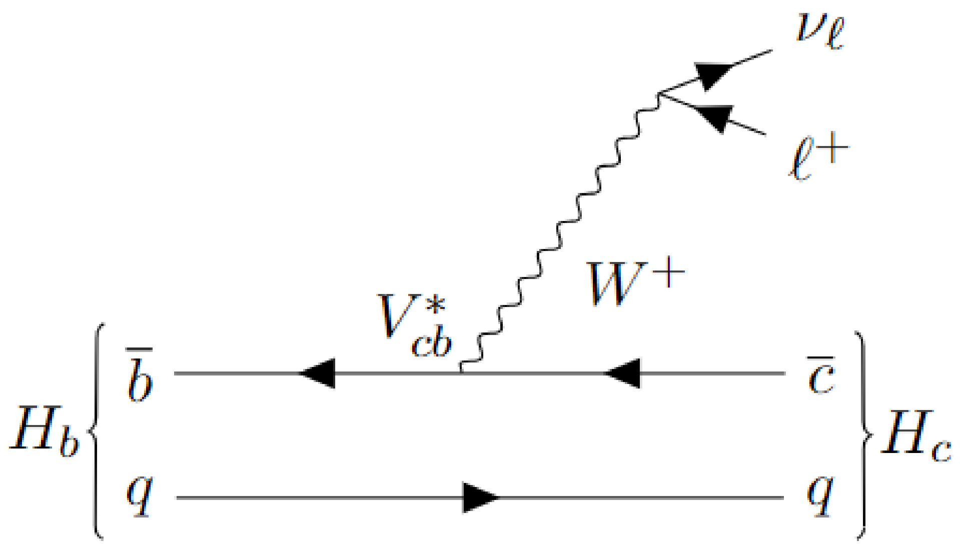
$m_Z \gg m_f$
Abundant Energy

- Boost: O(fs) time scales
- Heavy Species: Bs, Bc, Λb, exotics…
- Multiple soft tracks

Particle	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$			5.2×10^{11}
$D^\pm$			2.2×10^{11}
$D_s^\pm$			8.8×10^{10}
$\Lambda_c^\pm$			5.5×10^{10}
$\tau^\pm$	4.5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)		1.2×10^{11}

Item	Baseline [1]	Objective	Comments
Basic Performance			
Acceptance	$\lvert\cos\theta\rvert < 0.99$ [1]		
Threshold	200 MeV [37, 38]	100 MeV	For tracks & photons
Beam energy spread	$\mathcal{O}(0.1\%)$ [1]		
Tracker momentum resolution	$\mathcal{O}(0.1\%)$ [1]		
ECAL energy resolution	$17\%/\sqrt{E} \oplus 1\%$ [1]	$3\%/\sqrt{E}$ [31]	
HCAL energy resolution	$60\%/\sqrt{E} \oplus 1\%$ [1]		
Vertex resolution	10–200 μm [1]		
Jet energy resolution	3–5% [1, 39]		For 20–100 GeV
$\ell - \pi$ mis-ID	$< 1\%$ [40]		In jet, $\lvert\vec{p}\rvert > 2$ GeV
$\pi - K$ separation	$> 2\sigma$ [1]	$> 3\sigma$ [34]	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% [1]		Hadronic decays
b-jet efficiency×purity	$\sim 70\%$ [1]		In Z hadronic decays
c-jet efficiency×purity	$\sim 40\%$ [1]		In Z hadronic decays
b-jet charge tagging $\epsilon_{\text{eff}} = \epsilon(1-2\omega)^2$	-	15–25% [33, 41]	For B_s
π^0 efficiency×purity	$\gtrsim 70\%$ [38]	$\gtrsim 80\%$ [31]	In Z hadronic decays, $\lvert\vec{p}_{\pi^0}\rvert > 5$ GeV
K_S^0, Λ , D efficiency	60%-85% [42]		In Z hadronic decays, all tracks
τ efficiency×purity	70% [43]		In $WW \to \tau\nu q\bar{q}'$, inclusive
τ mis-ID	$\mathcal{O}(1\%)$ [43]		In $WW \to \tau\nu q\bar{q}'$, inclusive

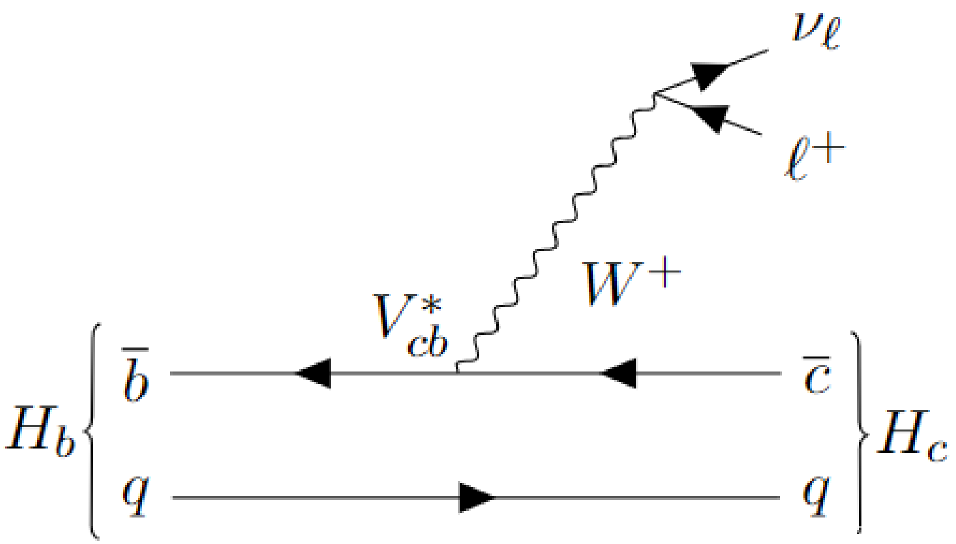
Indirect Discovery with Flavor Physics



$$\Gamma_{\rm SM} \sim \frac{G_F^2 m_f^5}{192\pi^3} \times \text{const} \propto \frac{m_f^5}{m_W^4}$$

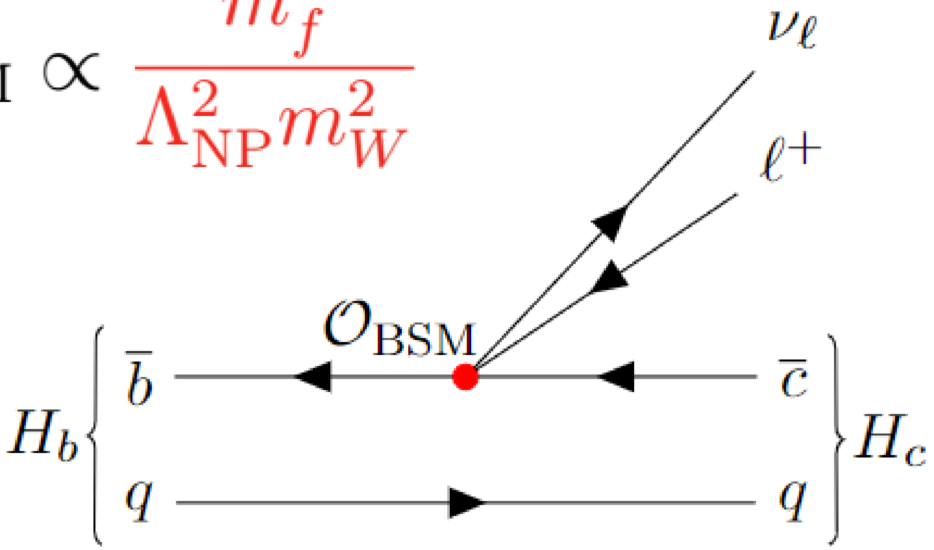
The amplitude of flavor physics in the SM is ALREADY suppressed by the EW scale → Many flavored states are long-lived

Indirect Discovery with Flavor Physics



$$\Gamma_{\rm BSM} \propto \frac{m_f^5}{\Lambda_{\rm NP}^2 m_W^2}$$

vs.

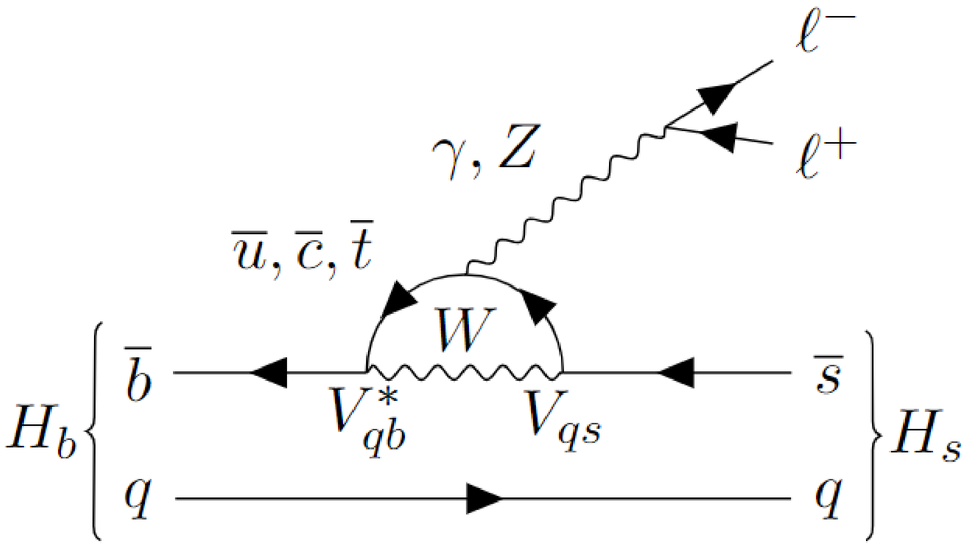


$$\Lambda_{\rm NP}^{\rm SL} \sim (G_F |V_{cb}| \delta_{\rm SL})^{-\frac{1}{2}} \sim (1.5\ {\rm TeV}) \times \delta_{\rm SL}^{-\frac{1}{2}}$$

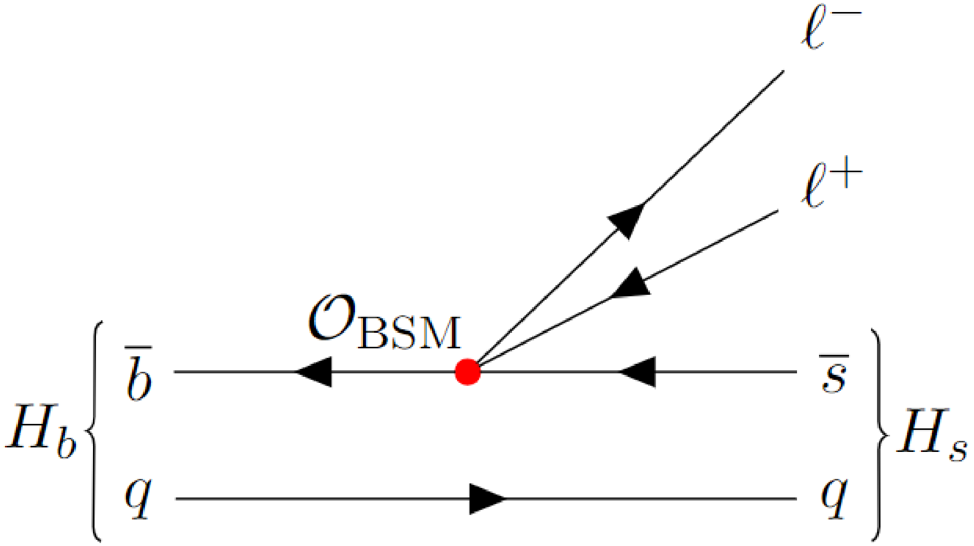
e.g., a 1% level precision = probing a scale of 15 TeV*

*: certainly depends on the way of interpretation

Indirect Discovery with Flavor Physics



vs.



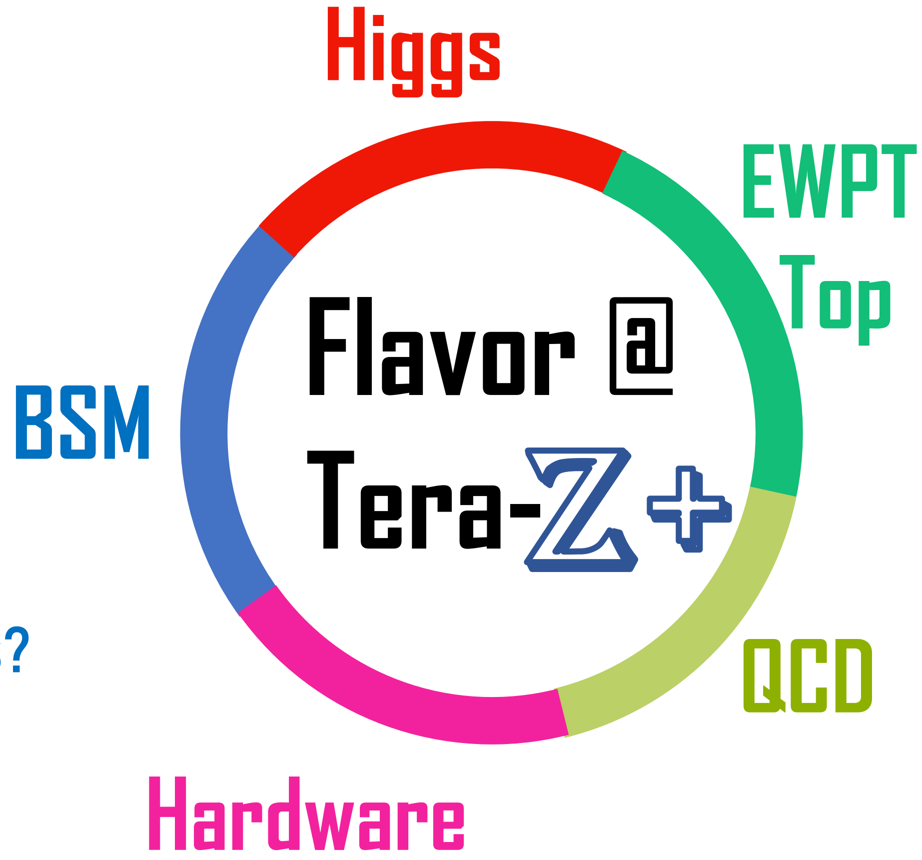
For SM process suppressed by a loop, the same relative precision means a even higher scale*

$$\Lambda_{\rm NP}^{\rm rare} \sim \left(\frac{\alpha}{4\pi}\frac{m_t^2}{m_W^2}G_F|V_{tb}V_{ts}^*|\delta_{\rm rare}\right)^{-\frac{1}{2}} \sim (30\ \text{TeV}) \times \delta_{\rm rare}^{-\frac{1}{2}}$$

*: still depends on your UV theory in mind

Support the CEPC Project

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



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

- ❑ Origin of matter? understand lepton and baryon numbers
- ❑ Light dark matter?
- ❑ Lepton Flavor Universality anomalies?

- ❑ 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!

The Purpose of the Flavor Physics White Paper (Phase I)

- To summarize the known results in an organized way
- To provide guidance and recommendation for studies in the next phase
- To resonate on relevant programs (e.g. flavor phys. @ FCC-ee)

Major Challenges

- Excessive statistics, data flow, and precision goals require **understanding and control** of experimental systematics (otherwise the projections will be very wrong)
- Recognize the **most valuable** analyses for CEPC, even overlooked ones
- Incorporate the appropriate **theory** (not always available)

Flavor Physics at CEPC: a General Perspective

- > 60 pages, > 200 refs.
- > XX original studies, > YY initiated by local groups, > ZZ contributed to CEPC
- > XXX Detector studies

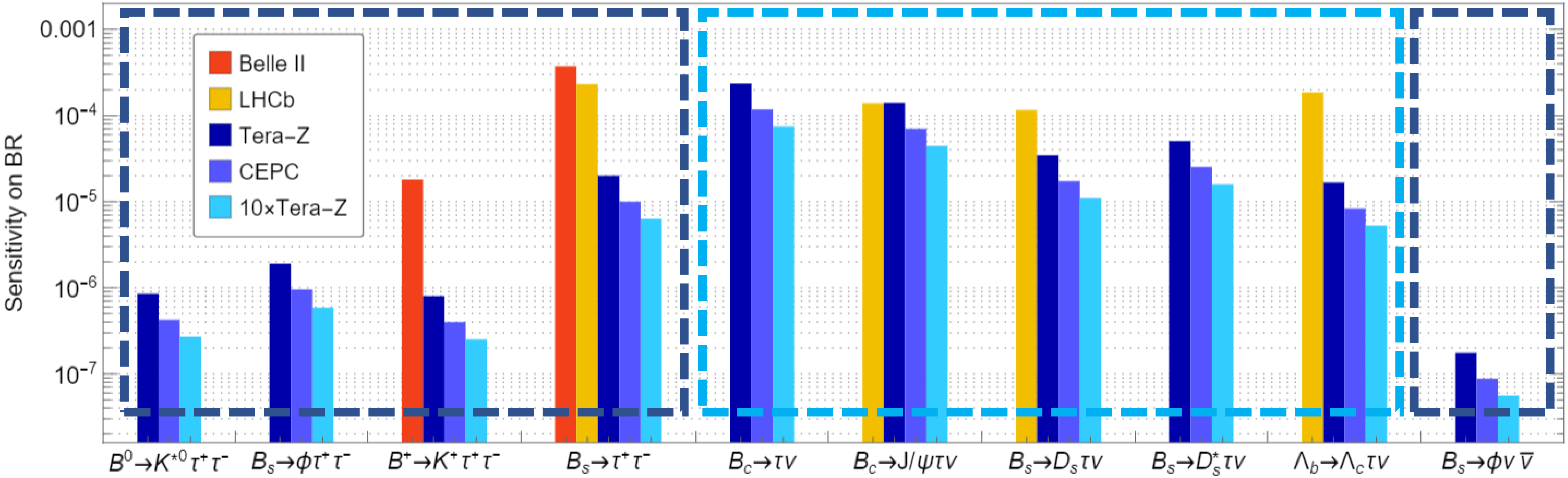
4 FCNC-mediated Rare b Decays

4.1 Dilepton Modes

4.2 Neutrino Modes

4.3 Radiative Modes

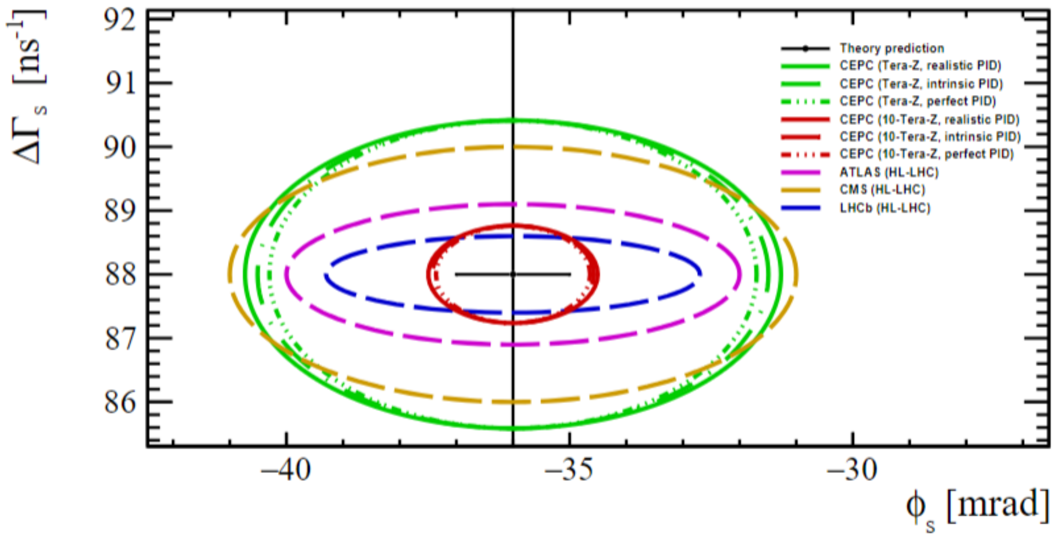
R(D) & R(D*) @ LHCb	C108, 物理楼	Jibo HE et al. 08:30 - 08:50
theoretical review of R(D) and R(D*)	C108, 物理楼	Ryotaro Watanable 08:50 - 09:10
global fit of b to s l+ l- decays	C108, 物理楼	Fanrong Xu 09:10 - 09:30
LFU/LFV review	C108, 物理楼	Lorenzo Calibbi et al. 09:30 - 09:55

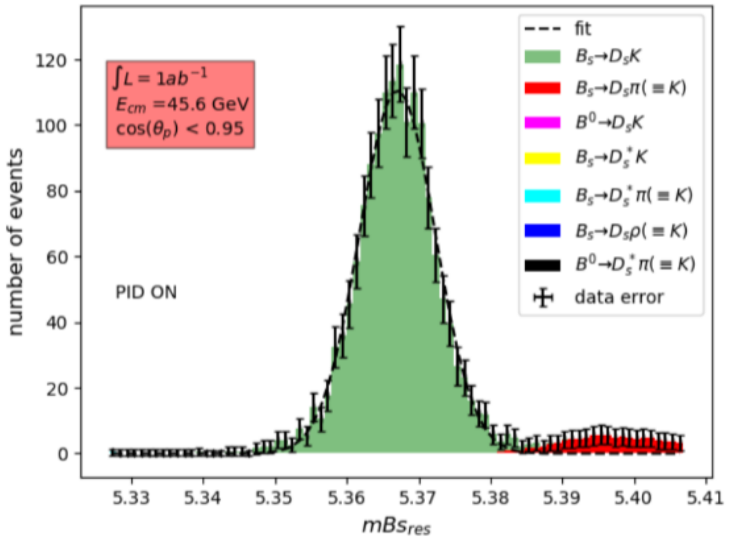


Benchmark studies predict promising precisions

3 FCCC-mediated Semileptonic and Leptonic b Decays

5 CP Asymmetry in b Decays





Progress in both time-dependent and time time-integrated benchmarks

B0 to pipi @CEPC	*Yuexin Wang*	*C108, 物理楼*	14:00 - 14:15
Bs->Jpsi Phi @CEPC	*Mingrui Zhao*	*C108, 物理楼*	14:15 - 14:30
Time dependent measurement (LHCb/Belle II)	*Peilian LI*	*C108, 物理楼*	15:50 - 16:10
T-odd CP violation	*Qin Qin*	*C108, 物理楼*	16:10 - 16:30
Double-mixing CP violation	*Yin-Fa Shen*	*C108, 物理楼*	16:30 - 16:50
Partial-wave CP violation	*zhenhua zhang*	*C108, 物理楼*	16:50 - 17:10

6 Global Symmetry Tests in Z and b Decays

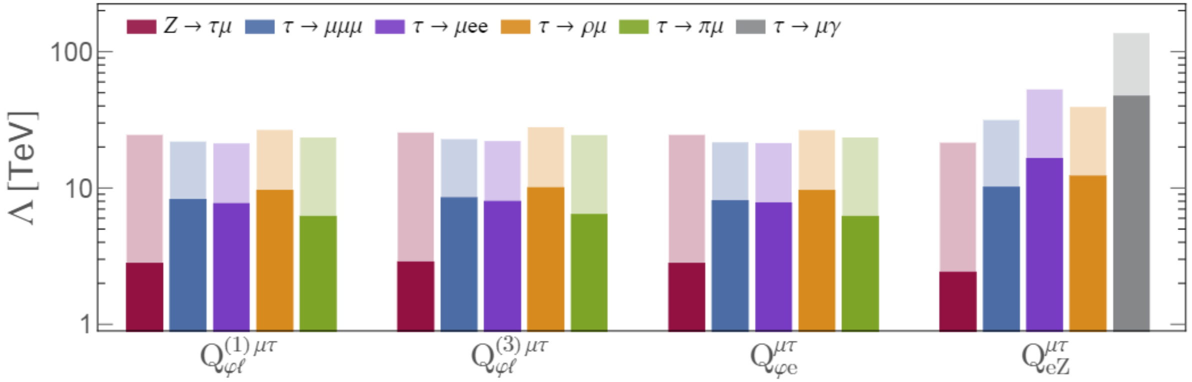
Measurement	Current [101–103]	FCC [104]	CEPC prelim.	Comments
$\mathrm{BR}(Z \to \tau\mu)$	$< 6.5 \times 10^{-6}$	$\mathcal{O}(10^{-9})$	same [105]	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 5.0 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	1×10^{-9} [106]	PID limited

Flavor violating Higgs and Z decays — *Prof. Michele Tammaro*
C108, 物理楼 — 15:20 - 15:40

LFU/LFV review — *Lorenzo Calibbi et al.*
C108, 物理楼 — 09:30 - 09:55

Probing Lepton Flavor Violation at Circular Electron-Positron Colliders — *Wolfgang Altmannshofer*
C108, 物理楼 — 10:45 - 11:05

Low-multiplicity τ/lepton phenomenology is better known in the last few years



LFU/LFV In tau decays — *Alberto Lusiani*
C108, 物理楼 — 14:25 - 14:45

Theoretical review on Physics with Tau — *Zhihui Guo*
C108, 物理楼 — 14:45 - 15:05

Belle II at Tau Physics/mass — *Yubo Li et al.*
C108, 物理楼 — 15:05 - 15:25

EFTs of Weakly-Interacting Light Particle and Their phenomenology in Flavor Physics — *Huayang Song*
C108, 物理楼 — 15:25 - 15:45

Tau physics at BES III — *涛 罗*
C108, 物理楼 — 15:45 - 16:05

Measurement	Current [134]	FCC [104]	CEPC prelim. [105]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		0.1× the ALEPH systematics
$m(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to \mu\mu\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to eee)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		

8 τ Physics

8.1 LFV τ Decays

8.2 LFU Tests in τ Decays

8.3 Hadronic τ Decays and Other Opportunities

7 Charm and Strange Physics

Charm physics measurement at LHCb	*Liang Sun*	
C108, 物理楼	10:55 - 11:15	
Charm physics measurement at BES III	*Prof. Baiqian Ke*	
C108, 物理楼	11:15 - 11:35	
DiPion distribution amplitudes and the semileptonic decays of strange charm meson	*Prof. Shan Chen*	
C108, 物理楼	11:35 - 11:55	

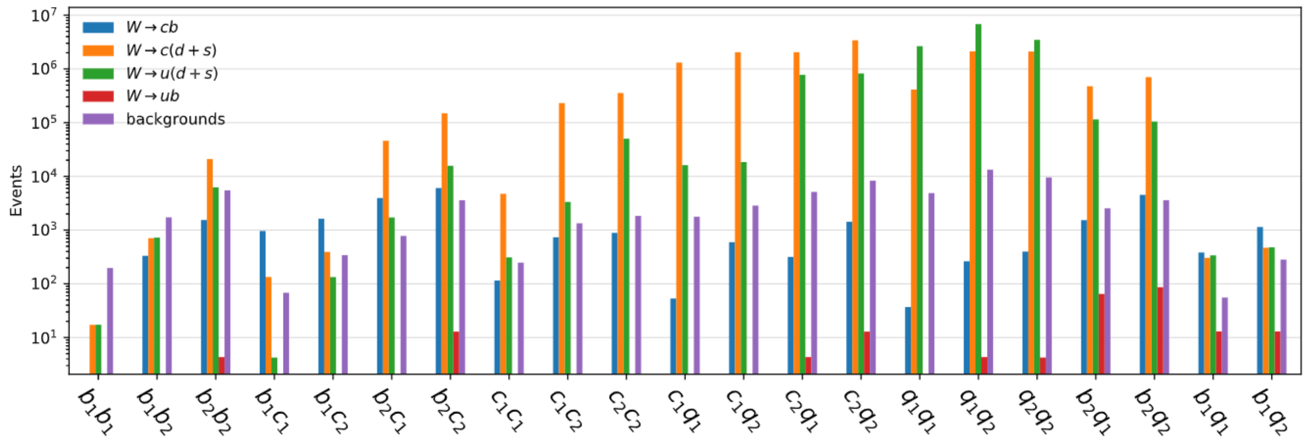
Rare Kaon decays	*Avital Dery*
C108, 物理楼	09:55 - 10:15

9 Flavor Physics beyond Z Pole

9.1 Exclusive Hadronic Decays of Heavy SM Bosons

9.2 $|V_{cb}|$ and W Decays

Measurement	Current Limit [134]	CEPC prelim.	Comments
$\mathrm{BR}(Z \to \pi^+\pi^-)$	-	$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\mathrm{track}})$ limited, good PID
$\mathrm{BR}(Z \to \pi^+\pi^-\pi^0)$	-	$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$\mathrm{BR}(Z \to J/\psi\gamma)$	$< 1.4 \times 10^{-6}$	$10^{-9} - 10^{-10}$	$\ell\ell\gamma$+$\tau\tau\gamma$ bkg
$\mathrm{BR}(Z \to \rho\gamma)$	$< 2.5 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(p_{\mathrm{track}})$ limited

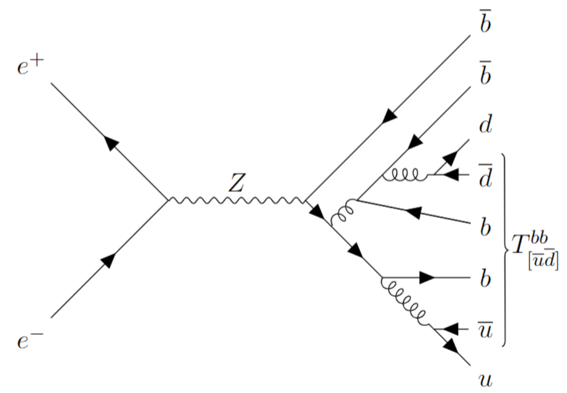


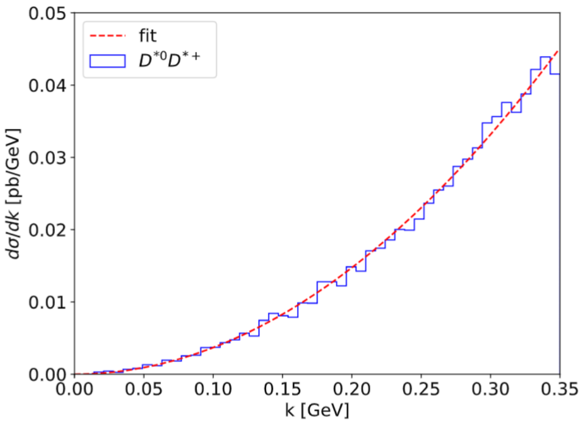
Contributions from phases beyond Tera-Z are non-trivial

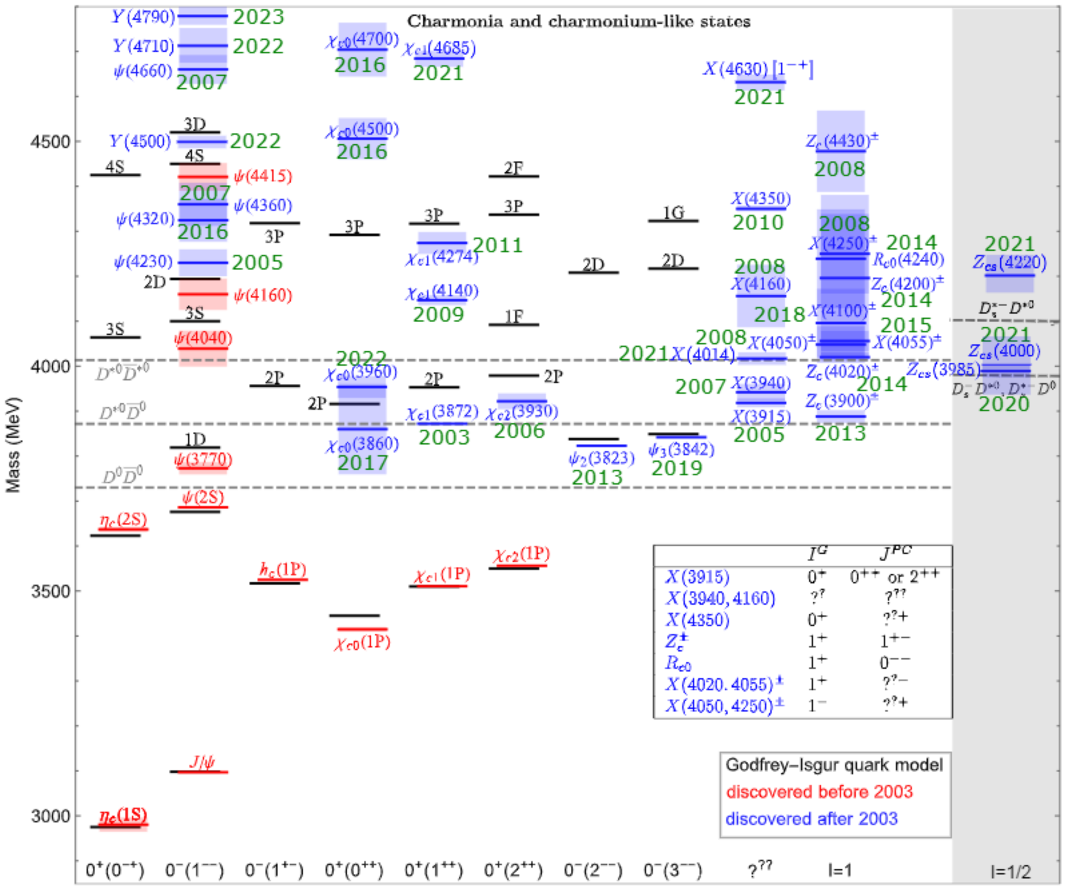
FCNC & Rare deacy of Higgs measurements at CEPC	*Hao Liang et al.*
C108, 物理楼	14:30 - 14:55

Production of heavy hadrons from Z & Higgs decays (NRQCD)	*Xuchang Zheng*
C108, 物理楼	16:55 - 17:15
Top FCNC	*Liaoshan Shi*
C108, 物理楼	17:15 - 17:35
Measurement of energy correlators at the CMS	*meng xiao*
C108, 物理楼	17:35 - 17:55

10 Spectroscopy and Exotics







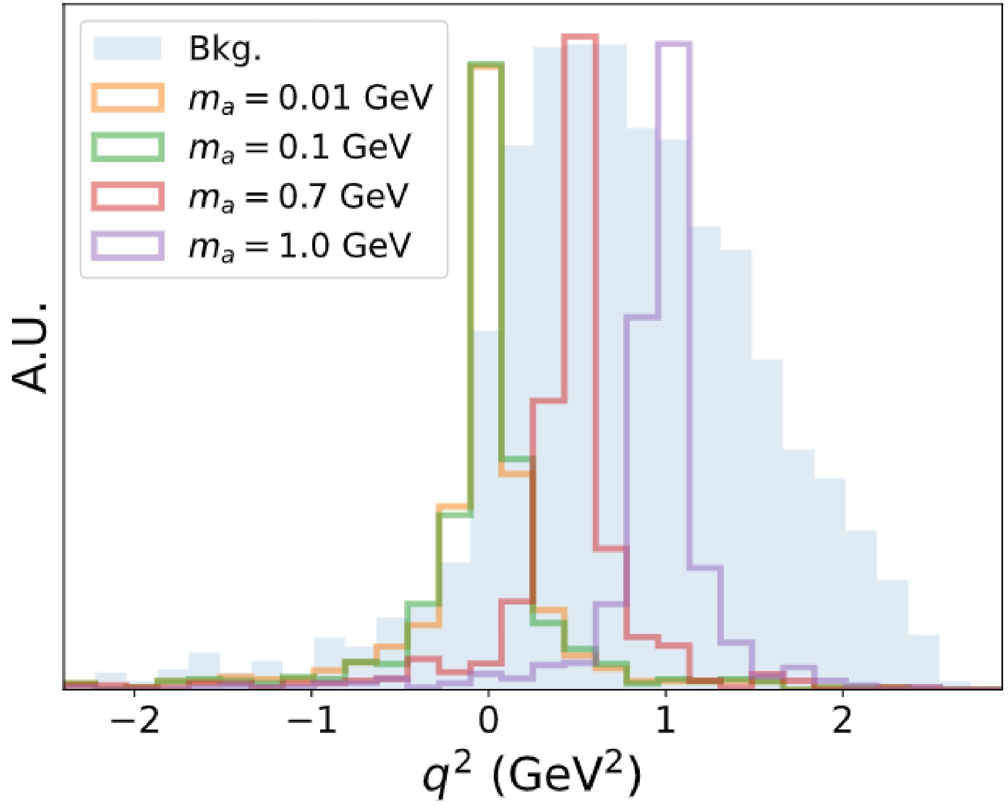
Very rich physics and a lots of potential discoveries

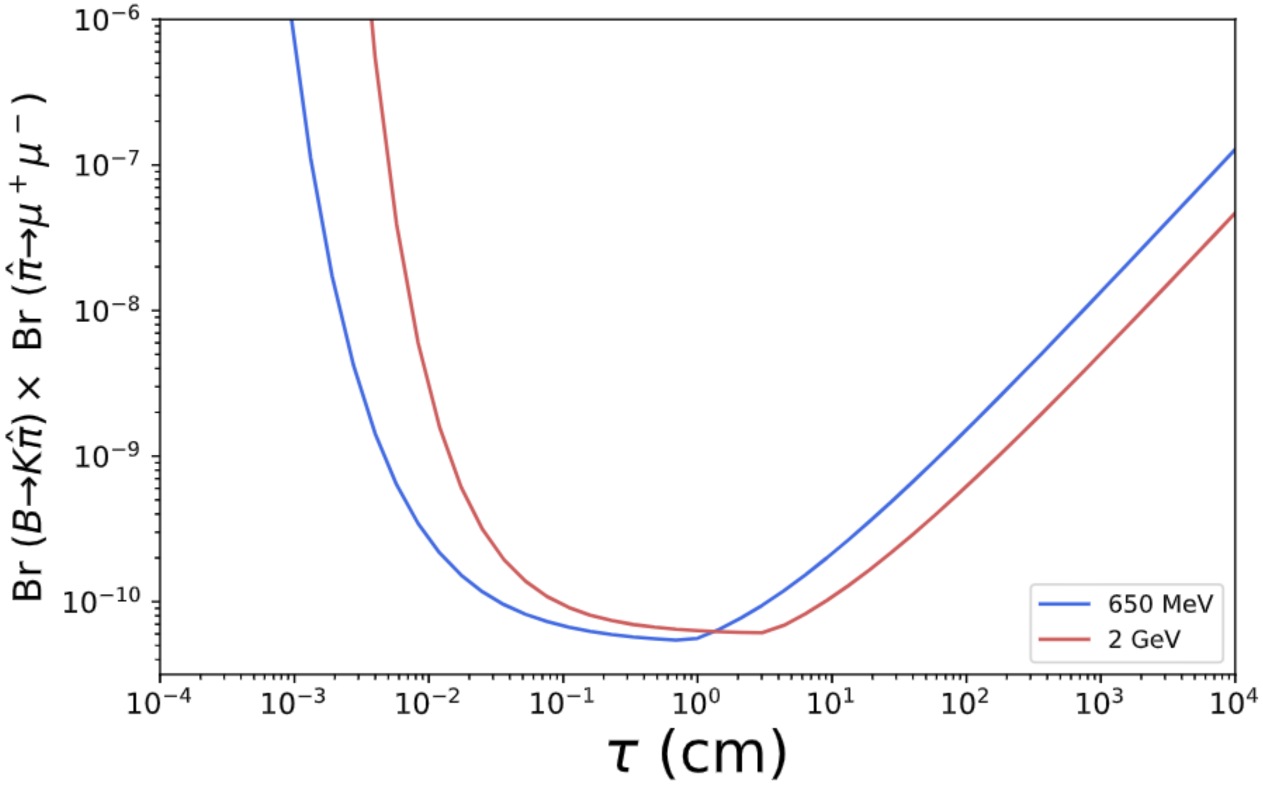
Exotics experimental status		*yanxi zhang*
C108, 物理楼		16:10 - 16:35
Production of doubly heavy hadrons (NRQCD)		*Hong-Hao Ma*
C108, 物理楼		16:35 - 16:55
Production of heavy hadrons from Z & Higgs decays (NRQCD)		*Xuchang Zheng*
C108, 物理楼		16:55 - 17:15

11 Light BSM States from Heavy Flavors

11.1 Lepton Sector

11.2 Quark Sector





BSM From Tau decay	Lingfeng Li
C108, 物理楼	14:00 - 14:25

Tau/B/C FCNC to LLP	Xuhui Jiang
C108, 物理楼	17:40 - 18:00

Flavor Phase II

Theory, simulation, and analysis for (exotic) hadron productions

A global analysis of CEPC impacts on the CKM elements and CP properties

Complete the map of LFU/LFV with b and τ decays

Fill the relevant gap in charm and strange physics

Build stronger connections with Higgs/EW/top/BSM physics

Flavor Phase I

Summary

- Flavor program at CEPC is a healthy/urgent need
- The white paper (phase I) is ready for external review
- More flavor physicists are encouraged to join
- https://www.overleaf.com/project/64a546abdc3477d097714c94

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

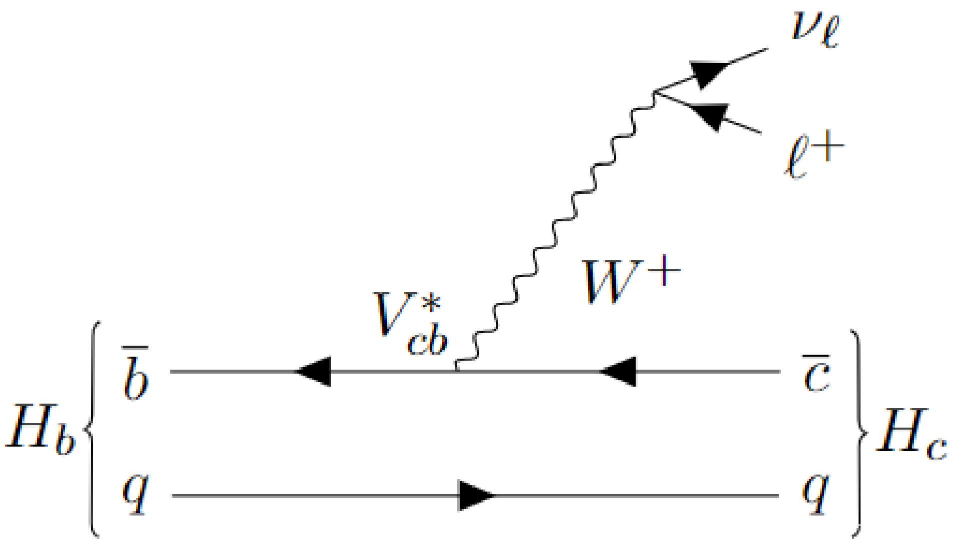
Backup Slides

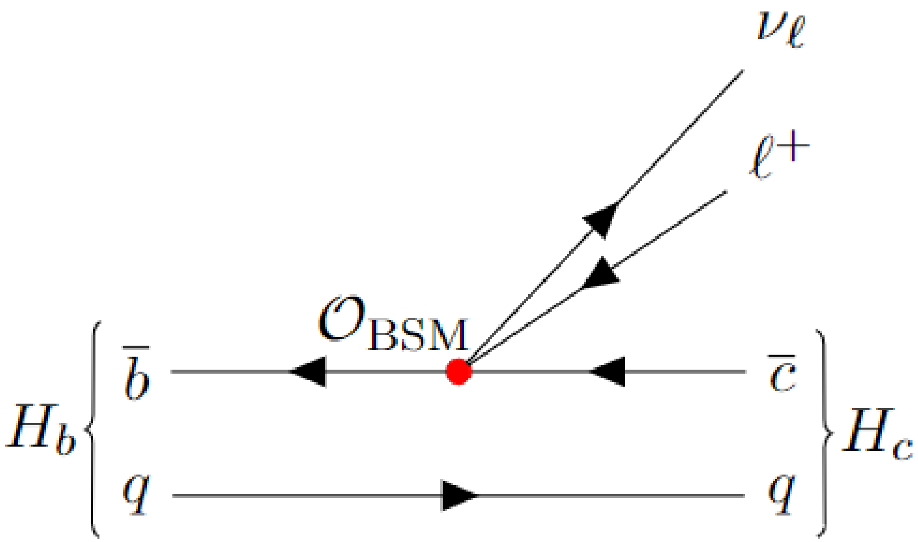
3 Charged Current Semileptonic and Leptonic b Decays

3.1 Theoretical Interpretation

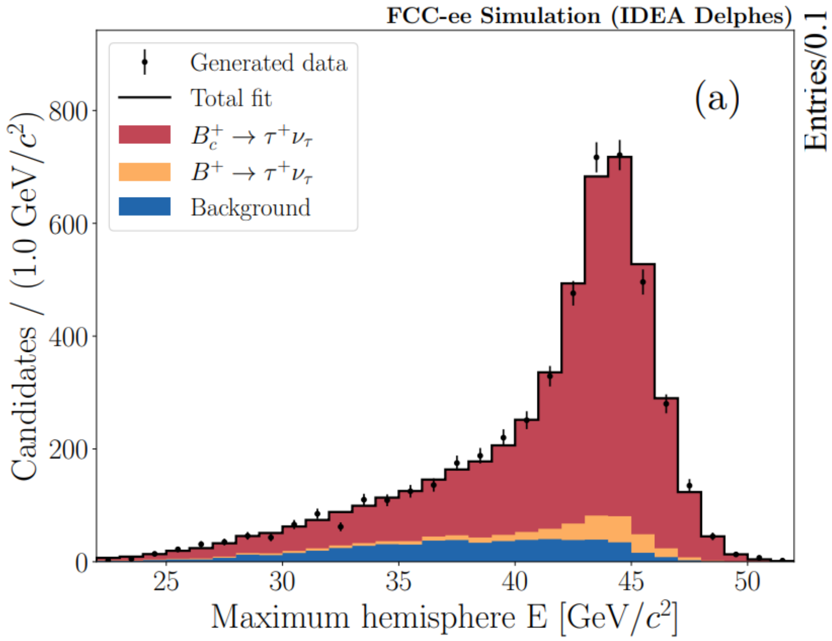
3.2 Recent Progress and Directions to be Explored

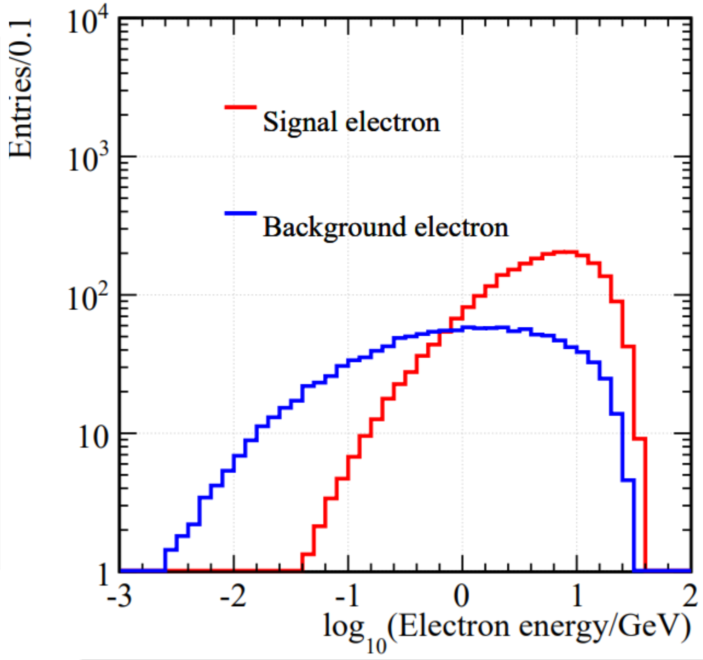
- Anomalies indicating lepton flavor universality violation
- Potential for $|V_{cb}|$ & $|V_{ub}|$ extraction
- CP asymmetries are clean
- Potentially probe higher scales of new physics

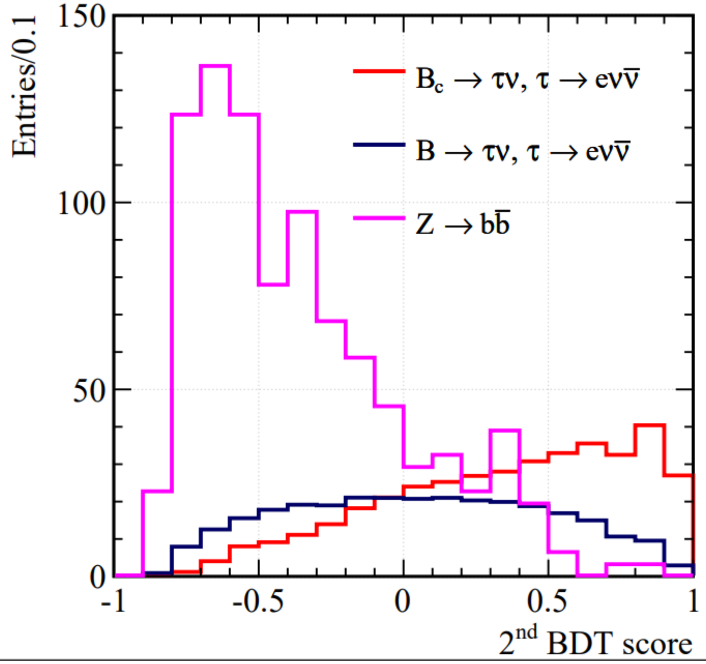




$B_c \to \tau\nu$ measurement, unique at CEPC





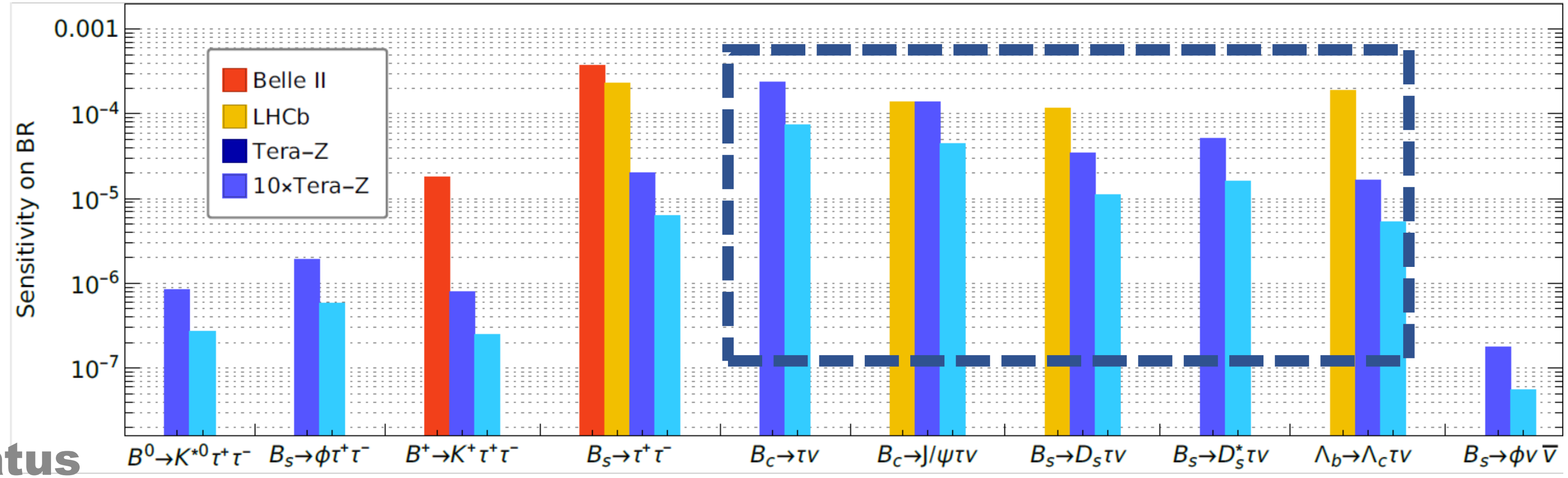


Y. Amhis, M. Hartmann, C. Helsens D. Hill, O. Sumensari 2105.13330

T. Zheng, J. Xu, L. Cao, D. Yu, W. Wang et al., 2007.08234

LFU tests with various transition types

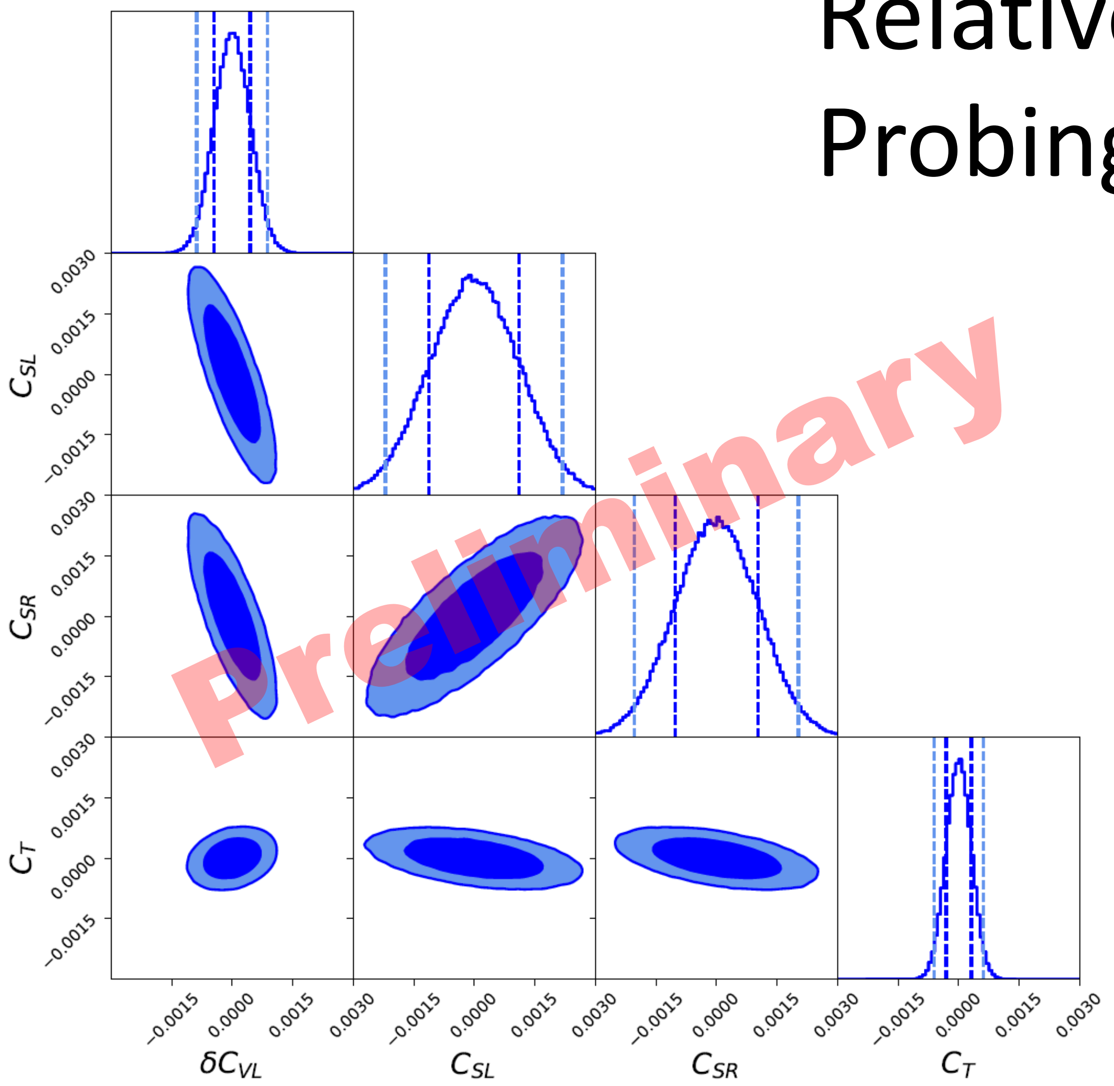
See Anson Kwok’s talk



Section Summary and Suggestions

Relative precisions $\lesssim$ O(1%) achieved

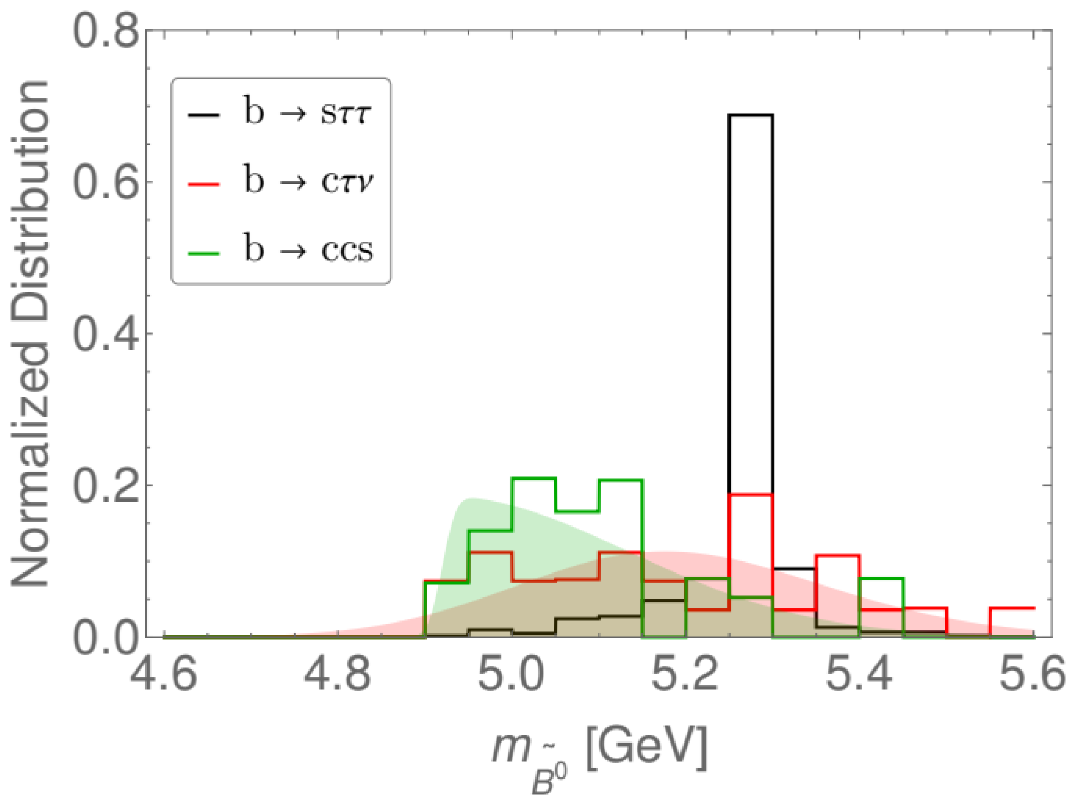
Probing multi-TeV scales already



Recommended future steps:

- Differential measurements (polarimetry, asymmetry …)
- Extend the search on more final states
- Evaluate electron modes with electron PID

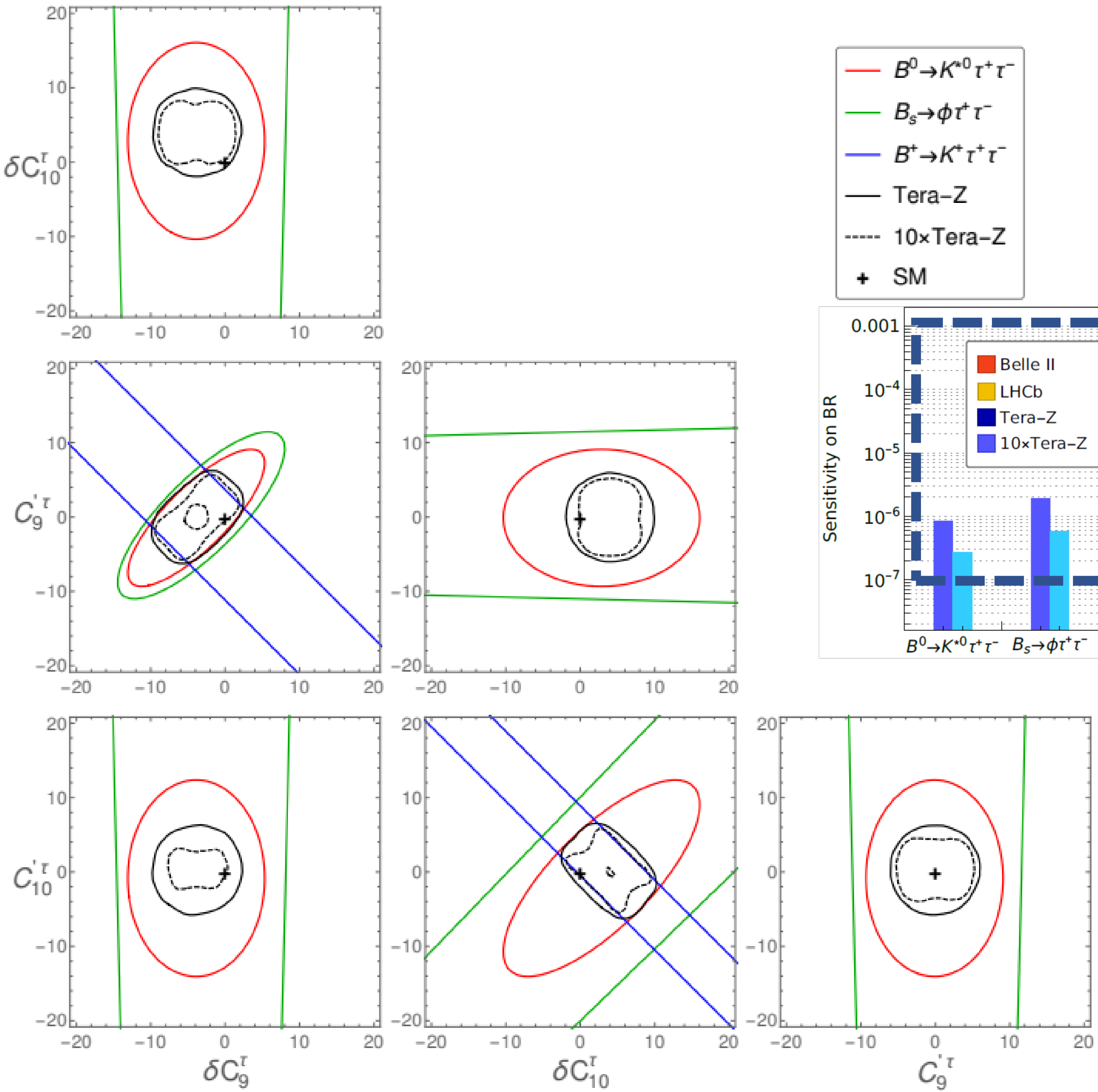
J. F. Kamenik, S. Monteil, A. Semkiv, L. V. Silva 1705. 11106
LL, T. Liu, 2012.00665



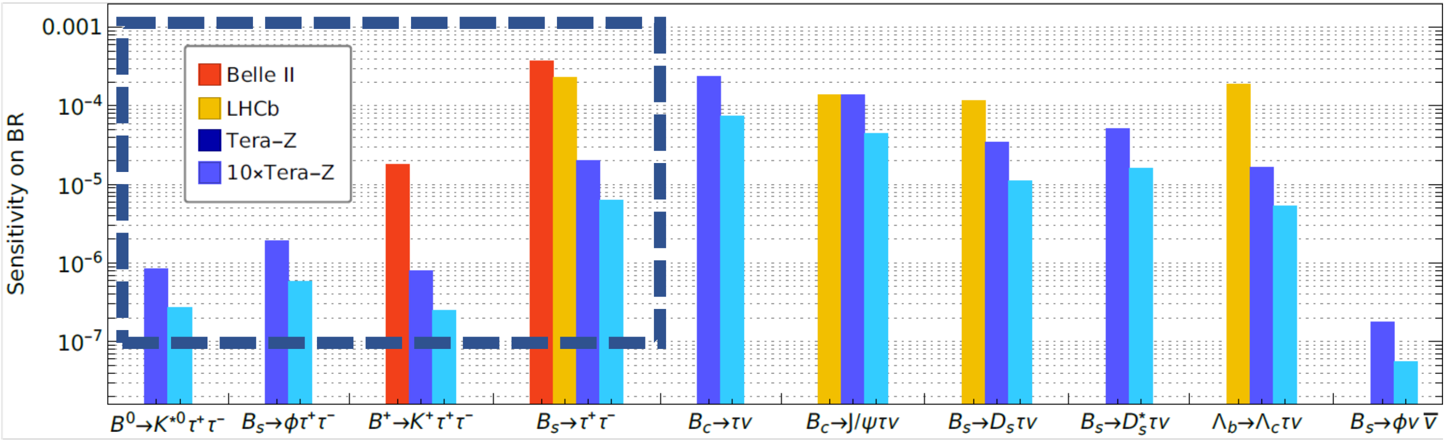
- Partially motivated by B anomalies
- Rare decays, sensitive to BSM and probe multi-TeV

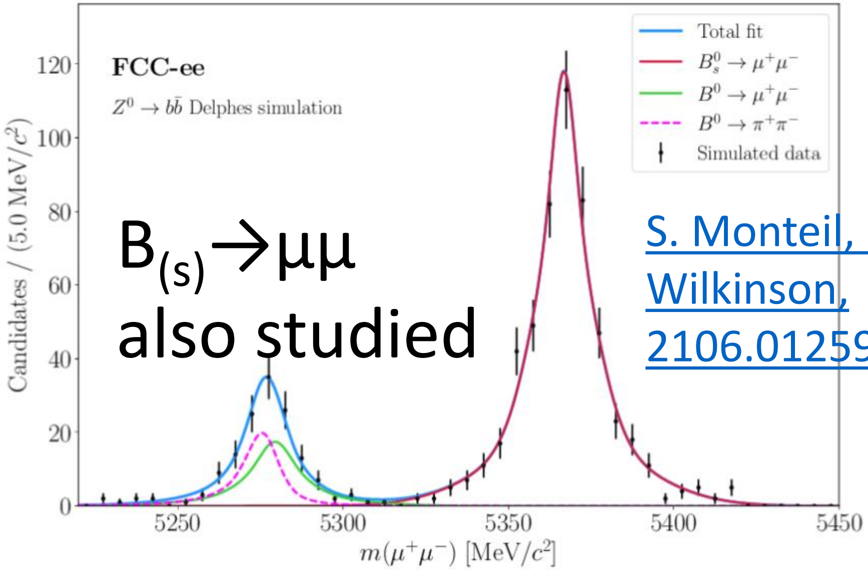
$$\Lambda_{\rm NP} \simeq \left(\frac{\alpha}{4\pi}\frac{m_t^2}{m_W^2}G_F|V_{tb}V_{ts}^*|\delta_{\rm rare}\right)^{-\frac{1}{2}} \simeq (30\ {\rm TeV}) \times \delta_{\rm rare}^{-\frac{1}{2}}$$

See also:
S. Descotes-Genon, S. Fajfer, J. Kamenik, M. Novoa-Brunet 2208.10880



- The LFU test via b→sττ rare decay are most studied
- Flagship channel for CEPC

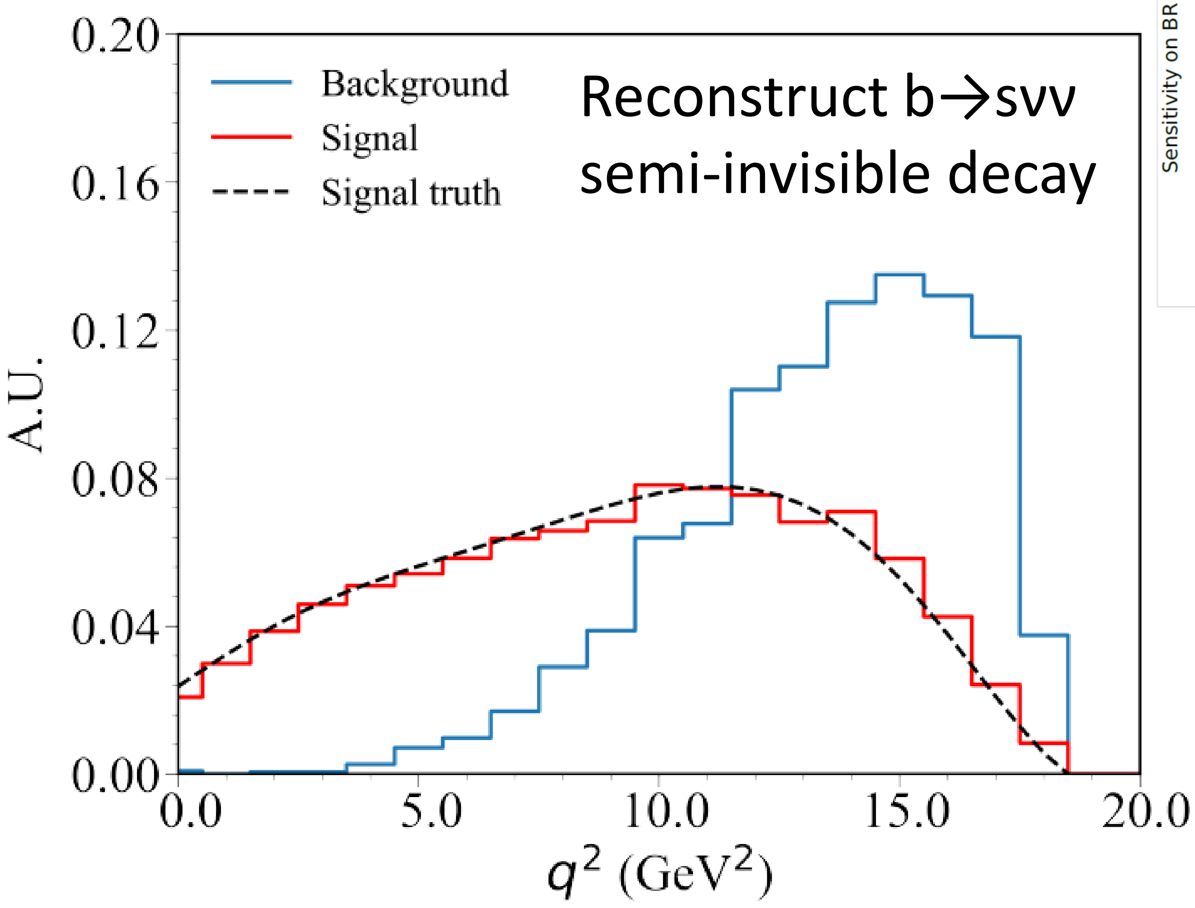




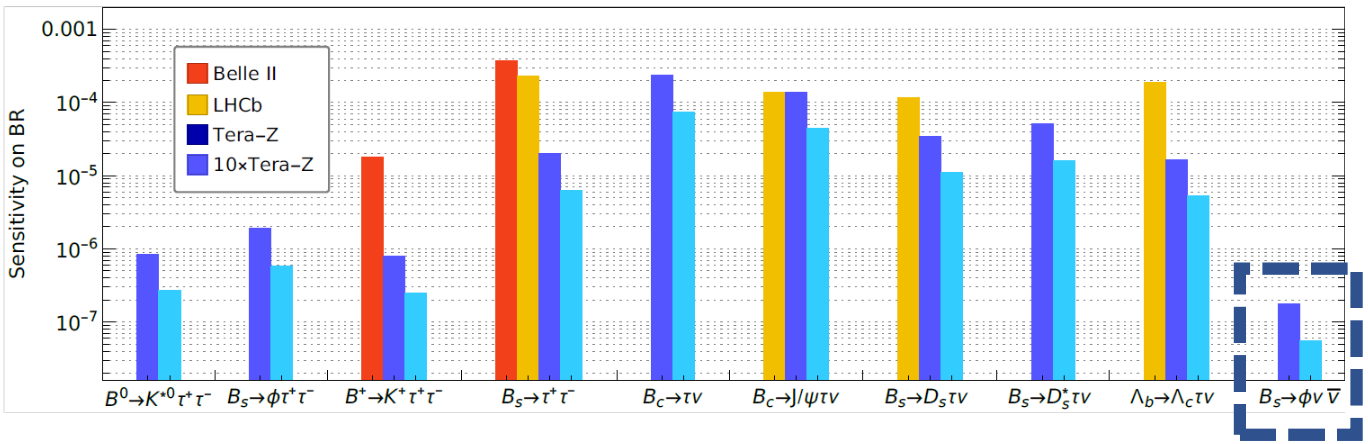
$B_{(s)} \to \mu\mu$ also studied

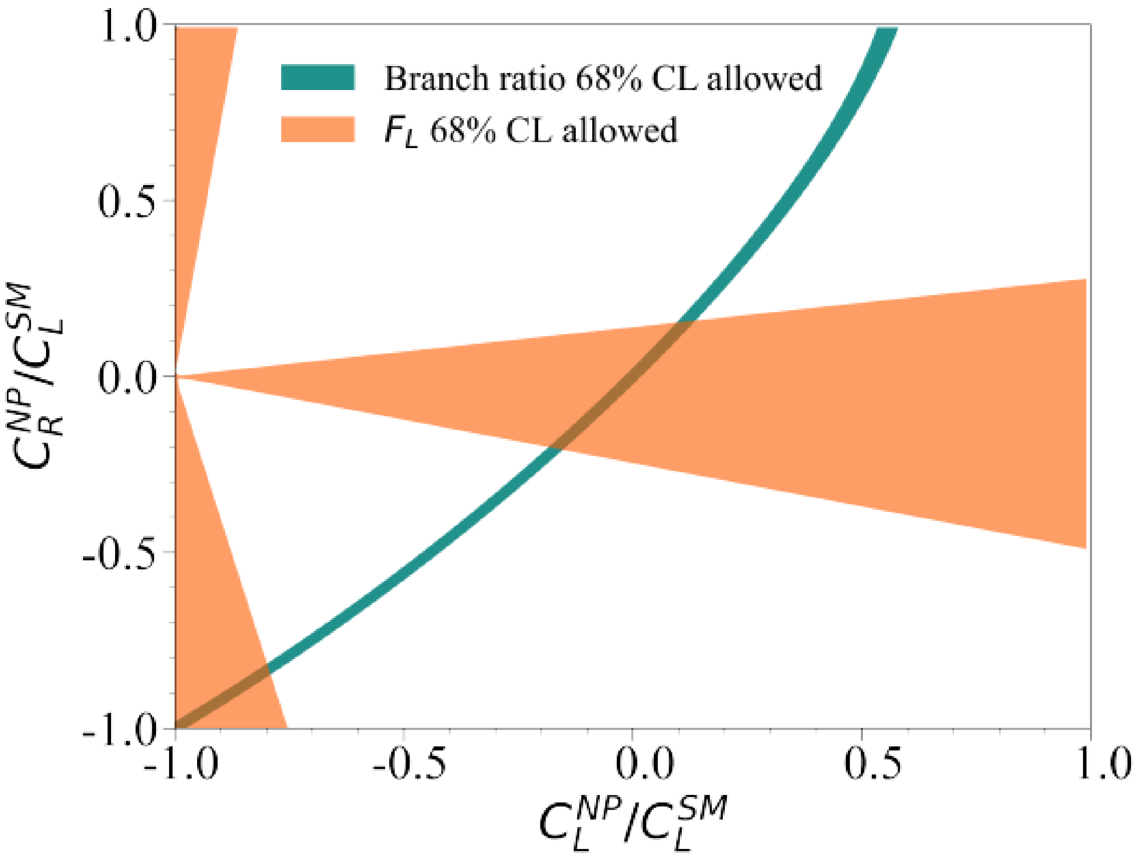
[S. Monteil, G. Wilkinson, 2106.01259]

4.3 Neutrino Modes



Reconstruct b→sνν semi-invisible decay





LL, M. Ruan, Y. Wang, Y. Wang, 2201.07374

See also:

S. Descotes-Genon, S. Fajfer, J. Kamenik, M. Novoa-Brunet 2208.10880

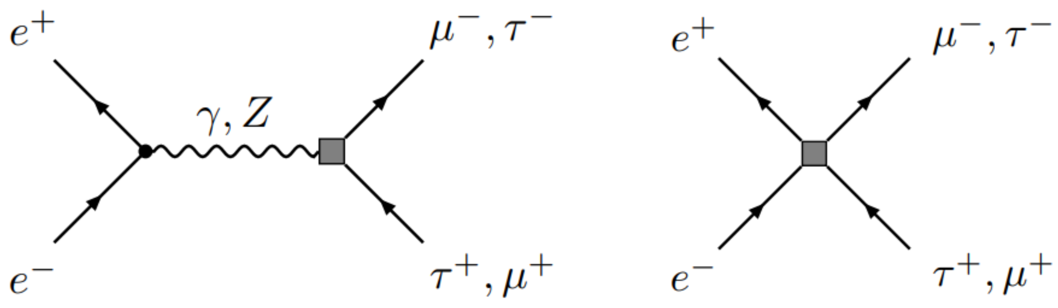
- Most decays are rare (BR < 10^{-5}).
- Relative precisions vary from $O(10^{-2}$ -1) determined by final states, probing multi-TeV already
- Unique advantages at CEPC

Section Summary and Suggestions

- Benchmark studies for (double) radiative decays with proper ECAL simulations
- Modes of heavy hadrons like Λ_b
- Systematically dominated e vs. μ LFU tests

6 Testing SM Global Symmetry with Flavor

- lepton flavor, lepton number and baryon number are conserved in flavor physics
- Clear sign of new physics if violation observed



W. Altmannshofer, P. Munbodh, T. Oh, 2305.03869

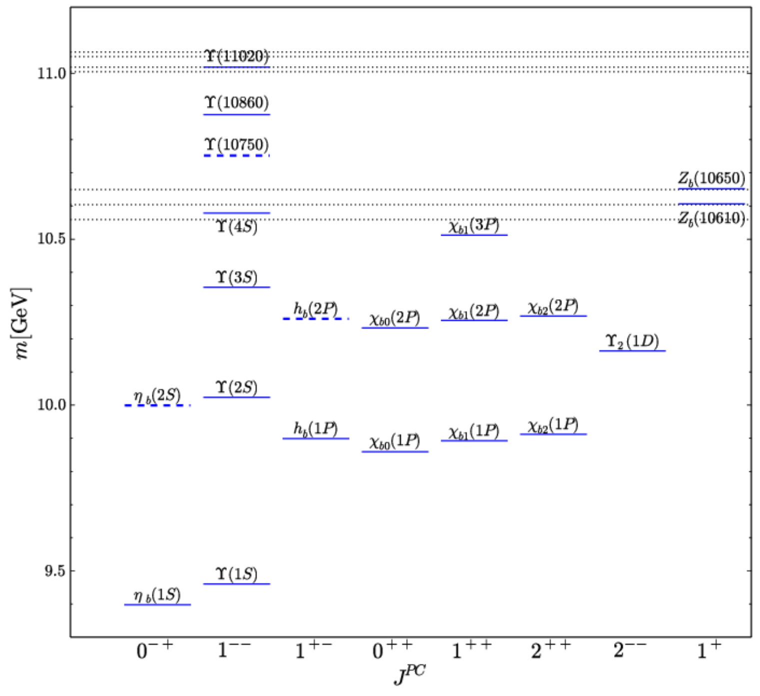
$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{x_c}_{\rm bkg}$ [10^{-6}]	$N_{\rm bkg}$	σ [ab]
91.2 (Z-pole)	50	0.92	1.35	1.53	6400 ± 80	55
87.7 (off-peak)	25	0.92	1.33	1.46	350 ± 20	27
93.9 (off-peak)	25	0.92	1.37	1.59	620 ± 25	35
160 (WW)	6	0.99	1.89	2.49	3 ± 2	17
240 (ZH)	20	1.20	2.60	4.42	7 ± 3	6.6
360 ($t\bar{t}$)	1	1.41	3.74	8.61	0.3 ± 0.5	72

BR($Z \to \tau\mu$) limit down to 10^{-9}
Also from runs of higher E_{cm}

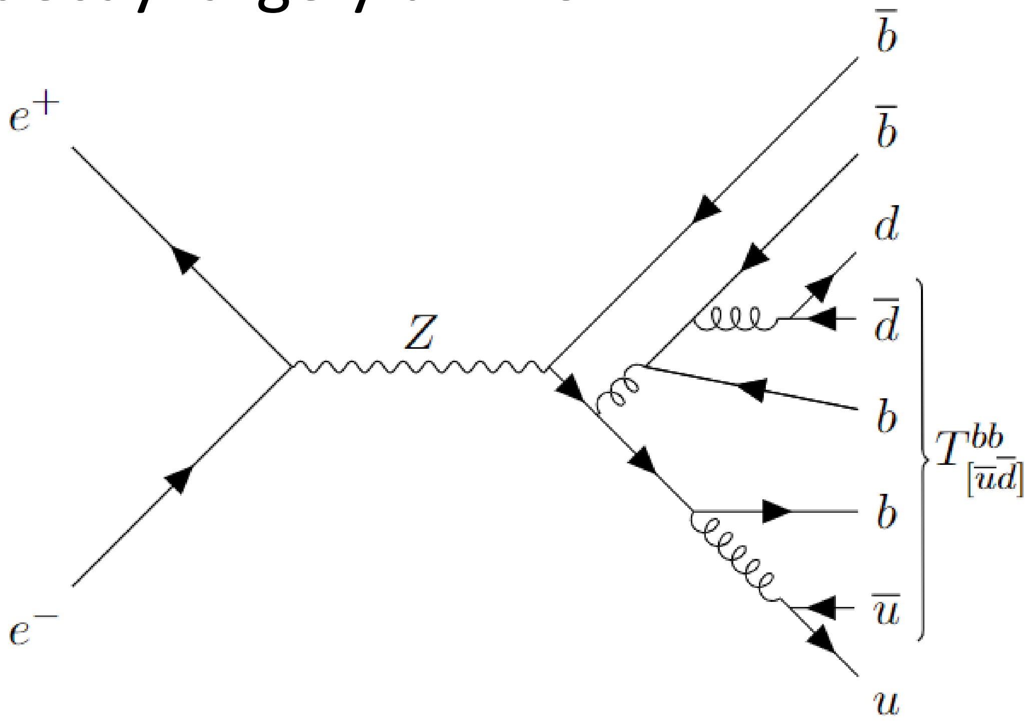
Recommendations:

- Need studies on lepton and baryon number violation in the next phases

7 Spectroscopy and Exotics



- A lot of states, guaranteed DISCOVERY at CEPC?
- Z→bbbb, bbcc, cccc processes may give rise to highly exotic species
- Production & decay largely unknown



Recent studies on production of tetraquarks & doubly-flavored baryons J. Niu, J. Li, H. Bi, H. Ma, 2305.15362 A. Ali, A.Y. Parkhomenko, Q. Qin, W. Wang, 1805.02535

Recommendations:

- More theory inputs for simulation
- Analysis framework to be developed

8 Charm and Strange Physics

Γ_9	$(u\,\overline{u} + c\,\overline{c})/2$	$(11.6 \pm 0.6)\%$
Γ_{10}	$(d\,\overline{d} + s\,\overline{s} + b\,\overline{b})/3$	$(15.6 \pm 0.4)\%$

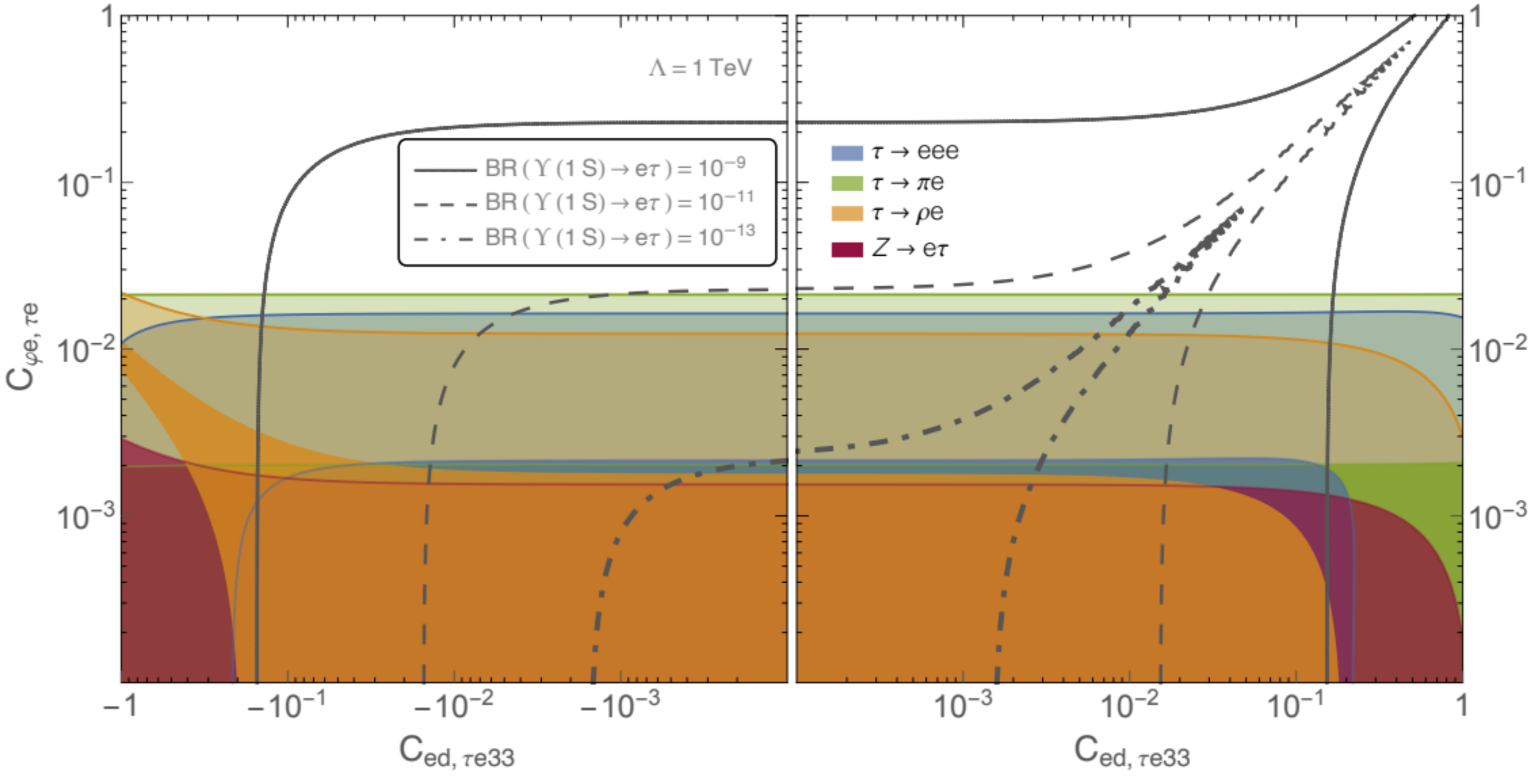
- Z decay also produces a lot of c and s quarks
- More s quarks ($K^{(*)}$,Λ…) produced by QCD
- Also building blocks of b physics

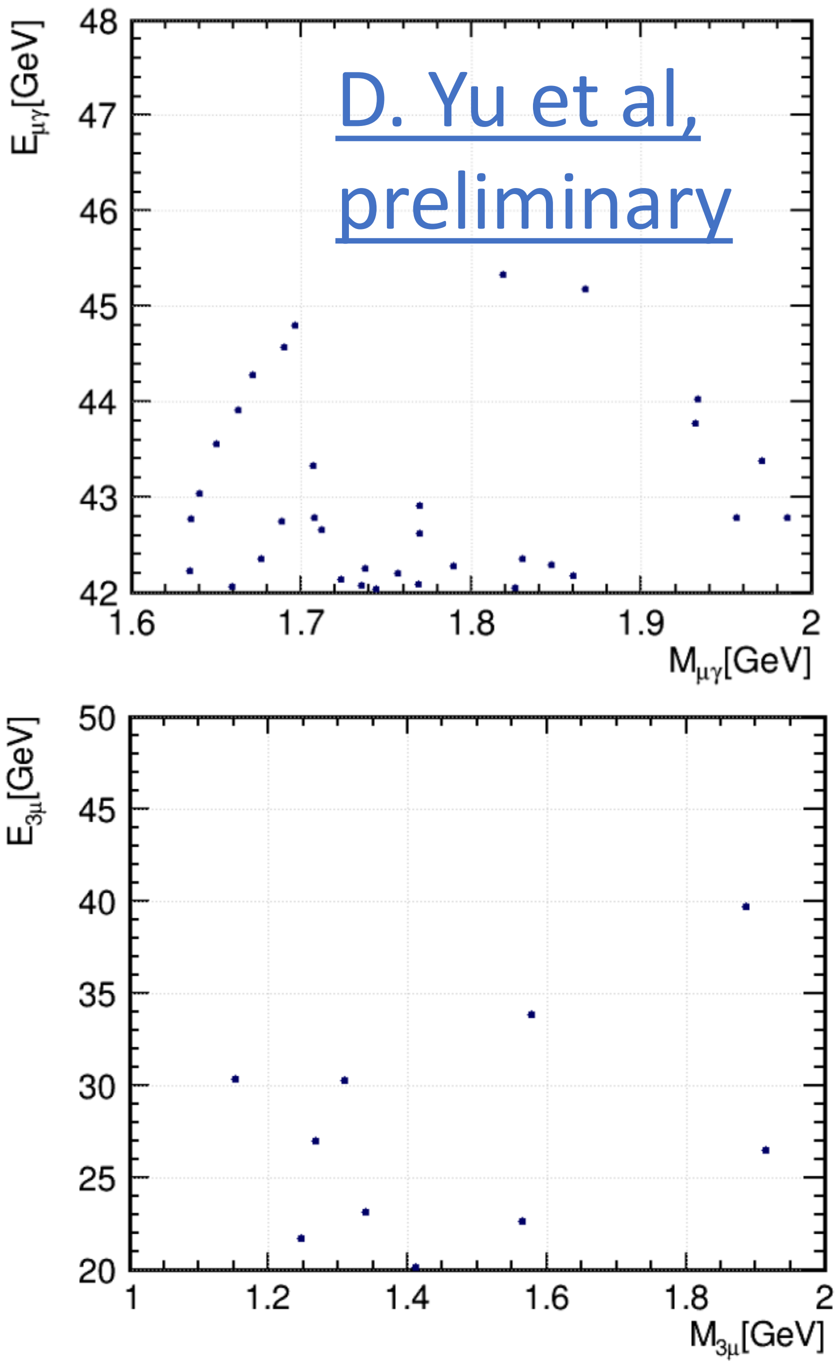
Recommendations:

- Have a charm physics program in parallel to bottom ones in the next phase
- Focus on K_S and Λ rare decays, e.g. $K_S \to \mu\mu(+\gamma)$, complementary to future kaon factories

9 τ Physics

- A most powerful tau machine
- Essential for EW and QCD in precision
- Most studies focus on exotic decays





L. Calibbi, T. Li, X. Marcano, M.A. Schmidt, 2207.10913
L. Calibbi, X. Marcano, J. Roy, 2107.10273 M. Dam, 2107.12832

Section Summary and Suggestions

Measurement	Current [104]	FCC [102]	Tera-Z Prelim. [105]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell\nu\bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		$0.1\times$ the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_\gamma)$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_\gamma)$ limited

M. Dam, 1811.09408

- More exotic τ decay modes
- Hadronic τ decay for f_K, V_{us}, and α_s (m_τ)
- τ polarimetry/asymmetry at the Z pole for extracting EWPO

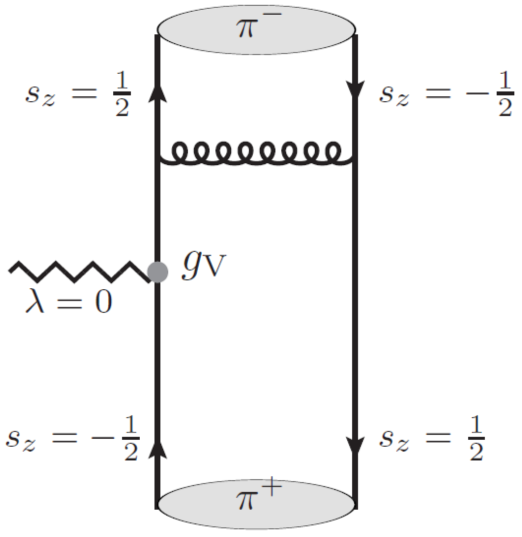
10 Flavor Physics at Higher Energies

10.1 Exclusive Hadronic Decays of Heavy SM Bosons

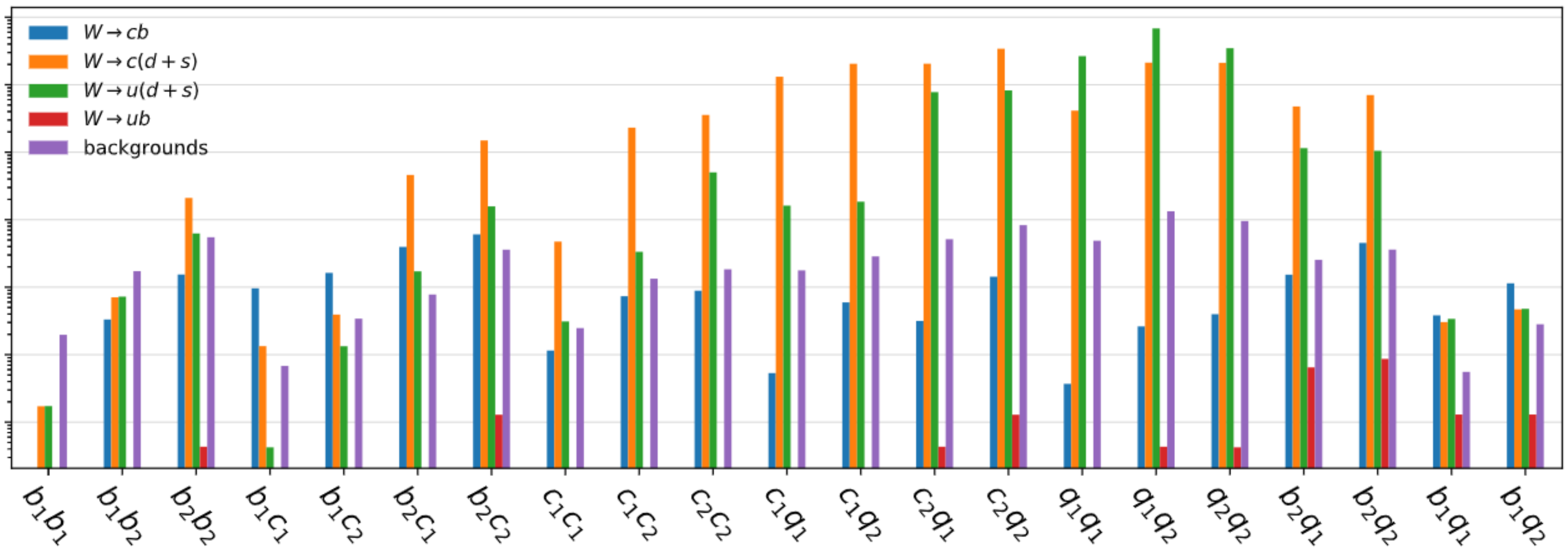
10.2 $|V_{cb}|$ measurement from on-shell W Decays

10.3 Other Possibilities

See Hao Liang's talk



(a) $Z \to \pi^+\pi^-$



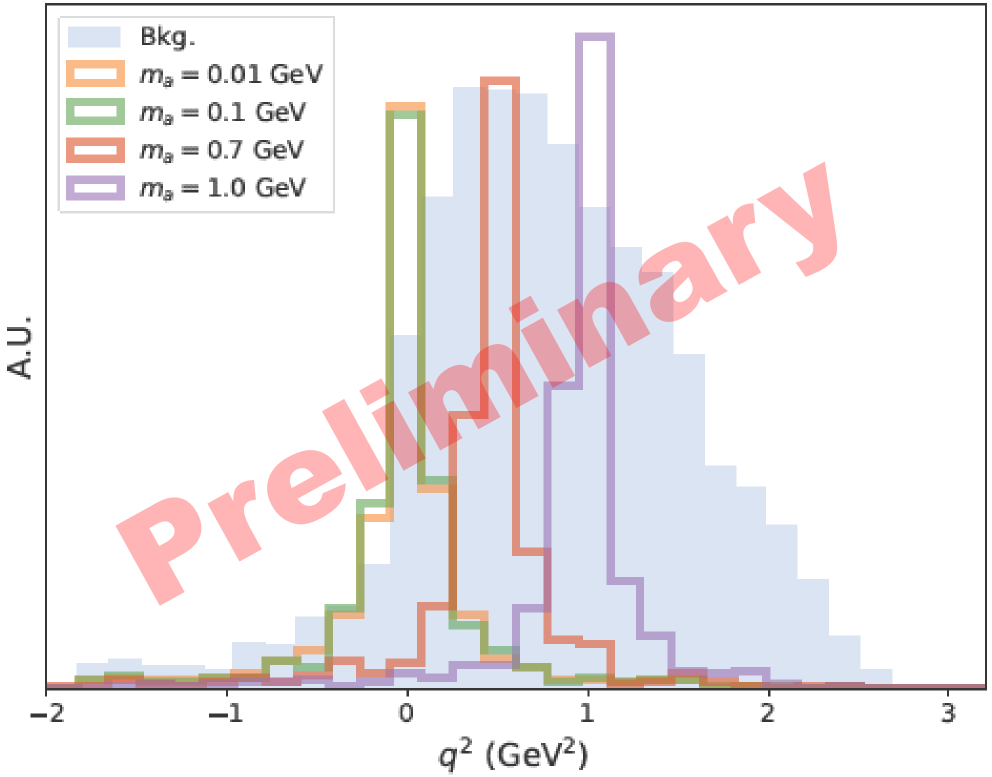
Current Recommendation:

❖Flavored hadronization, also crucial for EW & Higgs

11 Production of BSM States from Heavy Flavor Decays

11.1 Light BSM states produced via their coupling with leptons

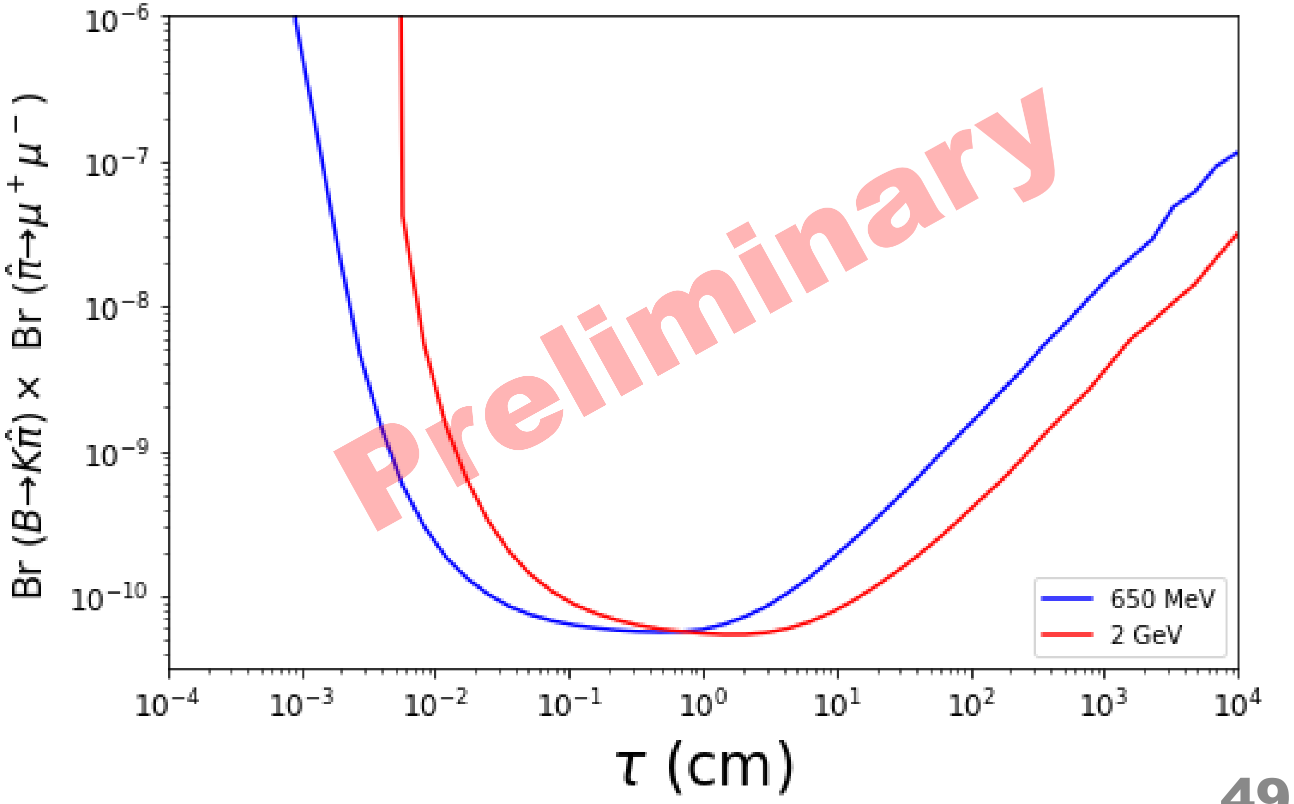
11.2 Light BSM states produced from FCNC quark decays



Dark sector from τ decays

Anson Kwok et al., in prep

Long lived particle from B FCNC rare decays Xuhui Jiang et al., in prep.



5 Hadronic b Decays and CP Violation Measurements

5.1 Theoretical Interpretation (preliminary)

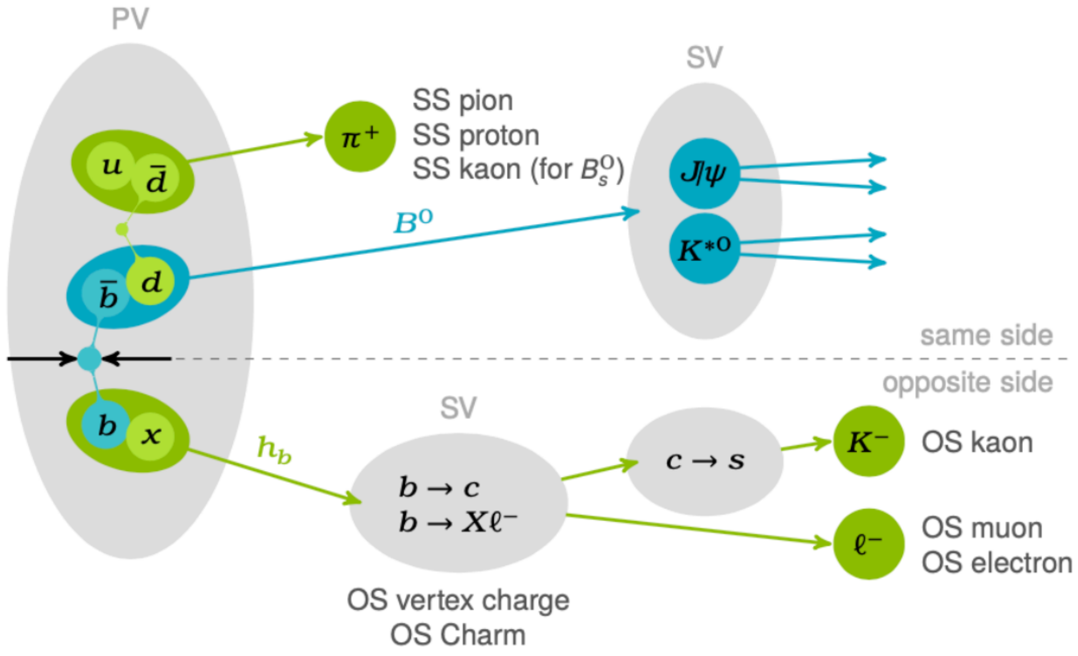
5 Measuring CP Asymmetries

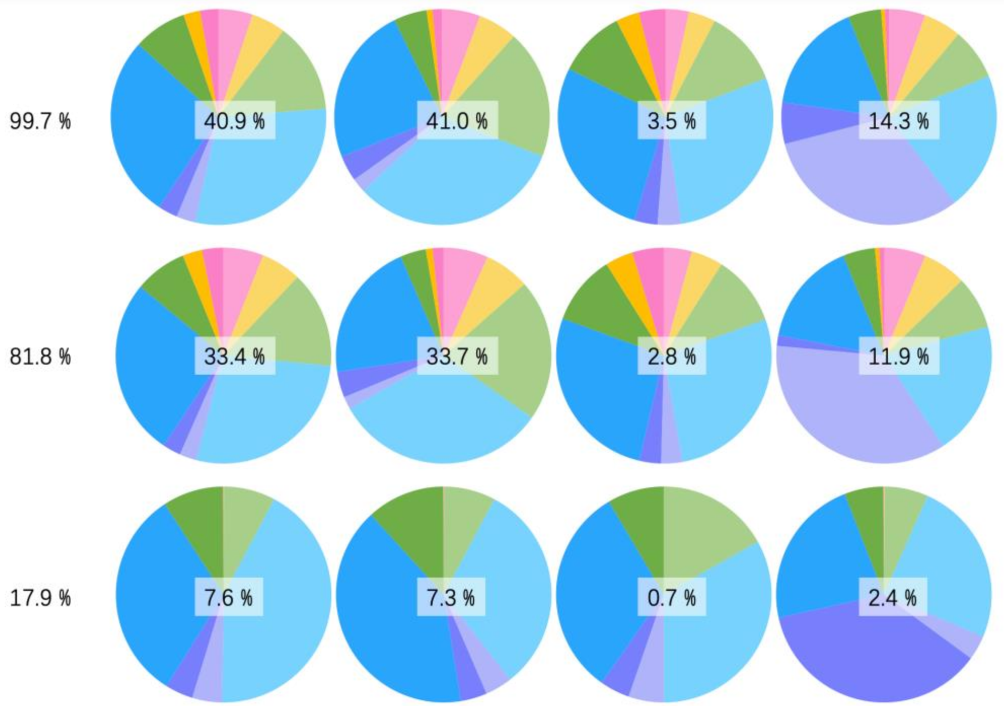
Taken from HFLAV2019

Flavor Tagging

$$\epsilon_{\text{eff}} = \epsilon(1 - 2\omega_{\text{mistag}})^2$$

Effective tagging power @ LEP ~ 20%, expected to improve further @ CEPC (vs. ~5% @LHCb & ~35% @ Belle II)

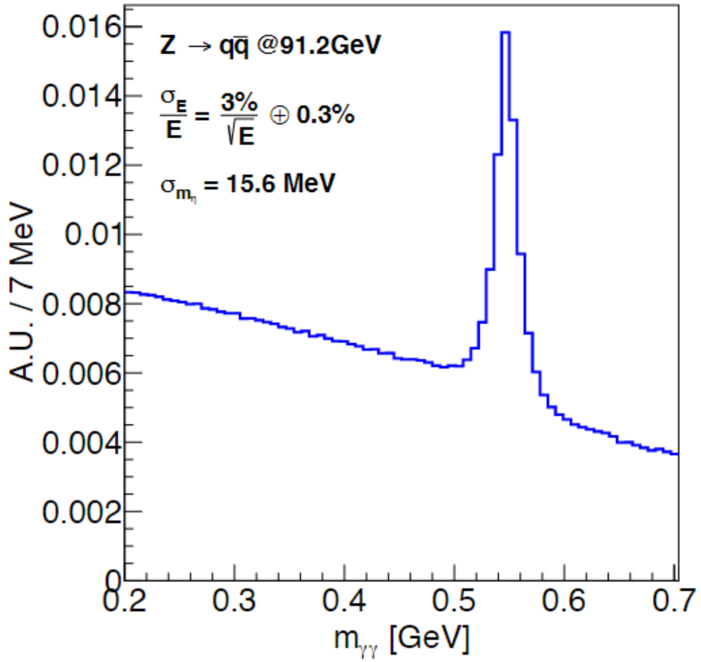


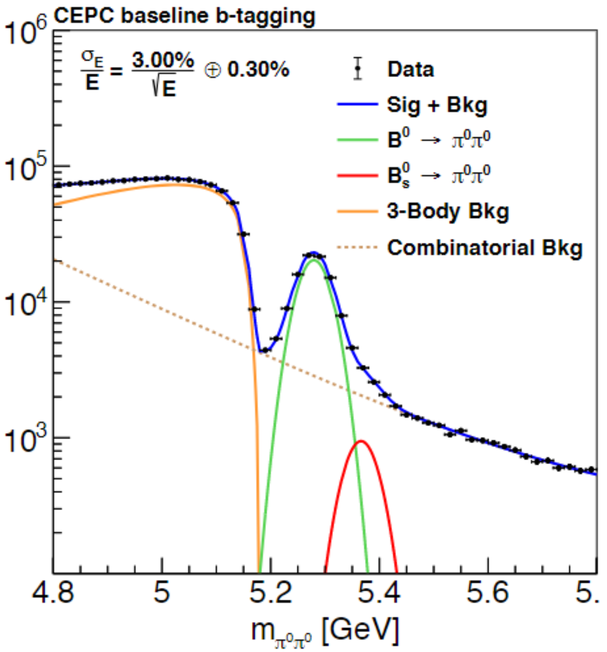


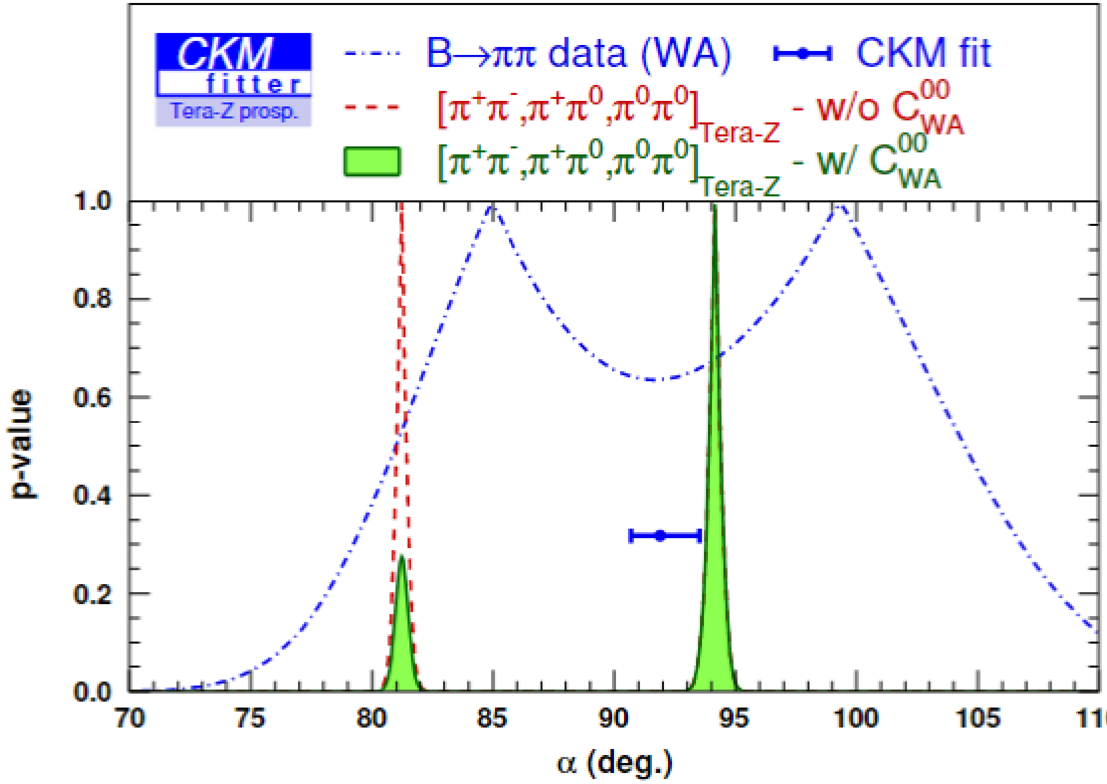
Tagging strategys are similar to LEP and LHCb

Preliminary study on going

Time-Integrated CP Asymmetry







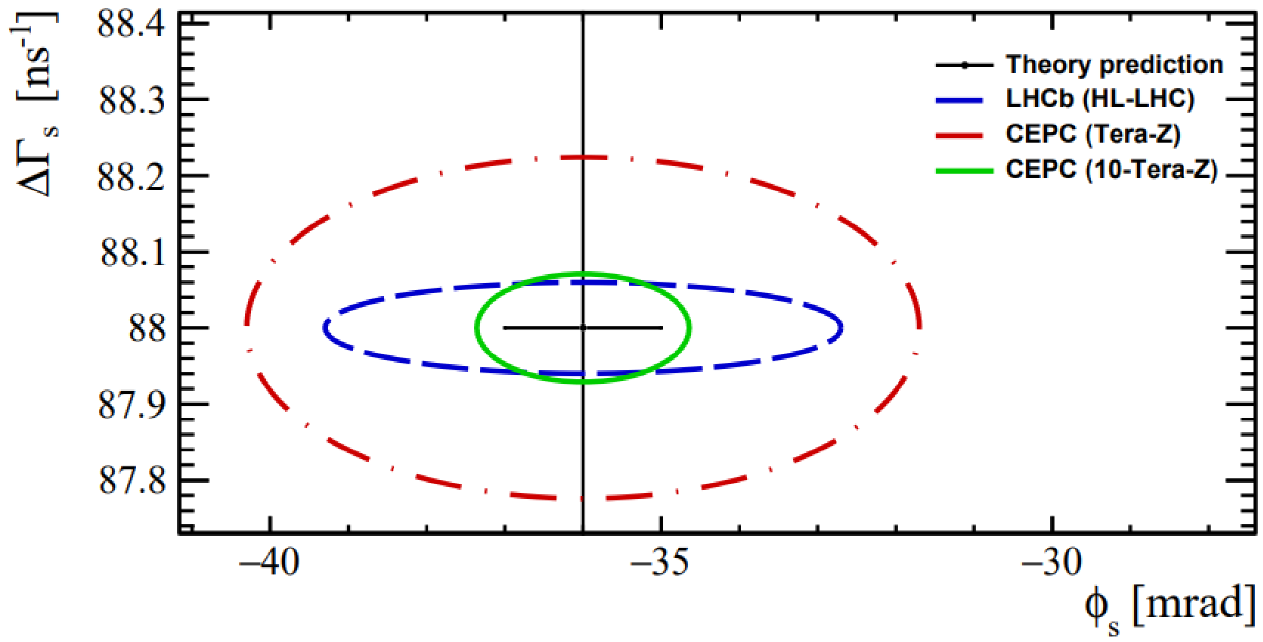
[Y. Wang, S. Descotes-Genon, O. Deschamps, LL, S. Chen, Y. Zhu, M. Ruan]

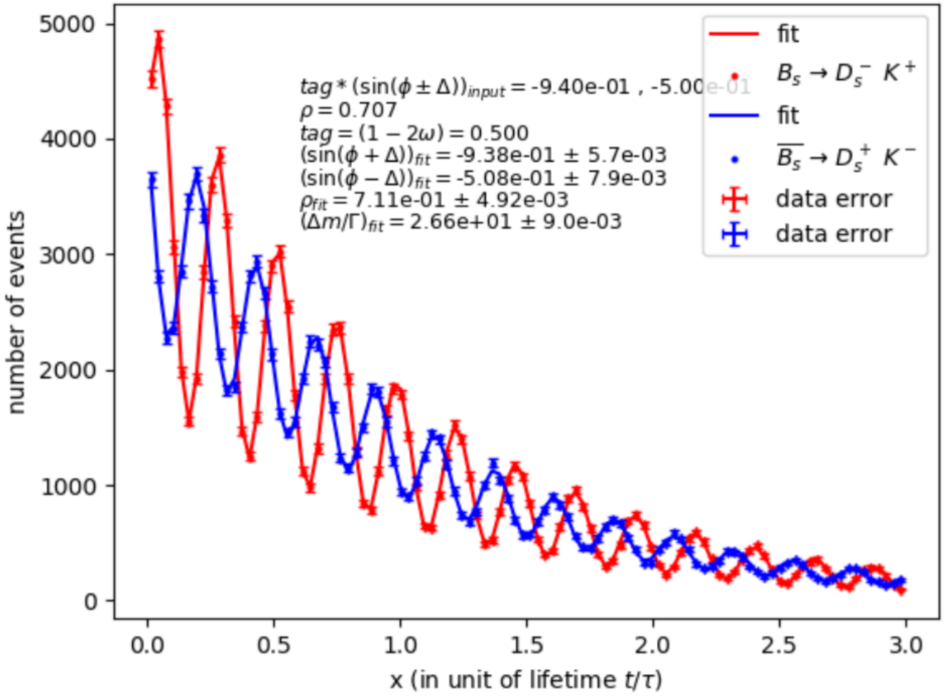
See also: [J. Charles, S. Descotes-Genon, Zoltan Ligeti, S. Monteil, M. Papucci, K. Trabelsi, L. Silva, 2006.04824]

Measure CKM α down to 0.4 deg by $B \to \pi^0\pi^0 \to 4\gamma$

But only if ECAL is crystal

Time-Dependent CP Asymmetry





X. Li, M Ruan, M. Zhao, 2205.10565

Angle β_s measurement by time-dependent $B_s \to J/\psi\phi \to \mu\mu KK$

See also R. Aleksan, L. Oliver, 2205.07823

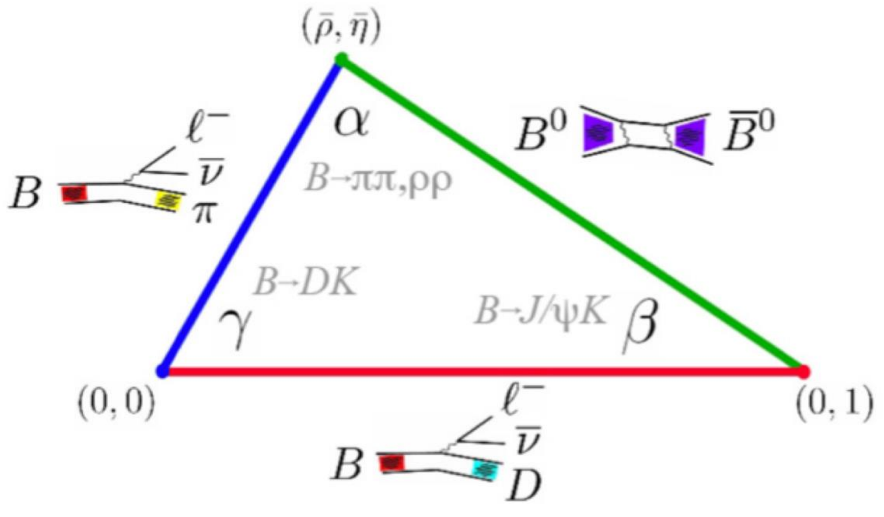
Time-dependent measurement of $B \to DK$ to give α_s and β_s, helpful to fix the value of angle γ

R. Aleksan, L. Oliver, E. Perez, 2107.02002

R. Aleksan, L. Oliver, E. Perez, 2107.05311

Potential Advantages?

- Asymmetry closer to LHCb instead of B factories
- Time resolution and PID
- Access to heavier b-hadrons



- We certainly want a CEPC version
- Need many more experiment and theory inputs
- Move on to the next phase