

# Studies of heavy flavors physics at a future $e^+e^-$ collider

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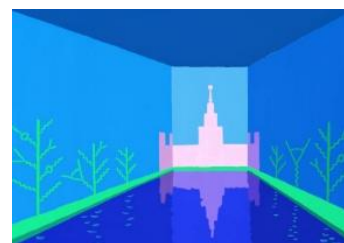
**Outline:**

**Future  $e^+e^-$  Collider(s)**

**CEPC detector(s) performance**

**Benchmark heavy flavors measurements**

**Summary**



# Projects of future high-energy electron-positron colliders

	<b>2048+</b>	<b>2035+</b>	<b>Missed?</b>	<b>2050+</b>
	FCC-ee	CEPC	ILC	CLIC
Species	$e^+e^-$	$e^+e^-$	$e^+e^-$	$e^+e^-$
Beam energy $E_b$ (GeV)	46, 120, 183	46, 120, 180	125, 250	190, 1500
Circumference or length (km)	90.66	100	20.5, 31	11, 50
Interaction regions	4	2	1	1
Est. integrated luminosity per experiment ( $\text{ab}^{-1}/\text{year}$ )	17, 0.6, 0.15	15, 0.65, 0.07	0.2, 0.3	0.1, 0.6
Peak lumi. $\mathcal{L}/\text{IP}$ ( $10^{34}\text{cm}^{-2}\text{s}^{-1}$ )	140, 5.0, 1.25	115, 5.0, 0.5	1.4, 1.8	1.5, 6

## CEPC operation scenario

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 ( $10^{34}\text{cm}^{-2}\text{s}^{-1}$ , per IP)	191.7	26.7	8.3	0.83
Integrated luminosity ( $\text{ab}^{-1}$ , 2 IPs)	100	6.9	21.6	1
Event yields	$4.1 \times 10^{12}$	$2.1 \times 10^8$	$4.3 \times 10^6$	$0.6 \times 10^6$

**First**

**Last**

## CEPC vs LEP

Operation mode	$Z$ factory	$WW$ threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
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	LEP (CERN)
Physics start date	1989
Physics end date	2000
Maximum beam energy (GeV)	100 - 104.6
Delivered integrated luminosity per experiment ( $\text{fb}^{-1}$ )	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV
Luminosity ( $10^{30}\text{cm}^{-2}\text{s}^{-1}$ )	24 at Z peak 100 at > 90 GeV

$0.2\text{ fb}^{-1}$  vs  $100\text{ ab}^{-1}$

$\sim 10^5$  more data at CEPC

# b, c, $\tau$ yields at colliders

arXiv:2412.19743 [hep-ex]

Particle	BESIII	Belle II (50 ab <sup>-1</sup> on $\Upsilon(4S)$ )	LHCb (300 fb <sup>-1</sup> )	CEPC (4×Tera-Z)
$B^0, \bar{B}^0$	-	$5.4 \times 10^{10}$	$3 \times 10^{13}$	$4.8 \times 10^{11}$
$B^\pm$	-	$5.7 \times 10^{10}$	$3 \times 10^{13}$	$4.8 \times 10^{11}$
$B_s^0, \bar{B}_s^0$	-	$6.0 \times 10^8$ (5 ab <sup>-1</sup> on $\Upsilon(5S)$ )	$1 \times 10^{13}$	$1.2 \times 10^{11}$
$B_c^\pm$	-	-	$1 \times 10^{11}$	$7.2 \times 10^8$
$\Lambda_b^0, \bar{\Lambda}_b^0$	-	-	$2 \times 10^{13}$	$1 \times 10^{11}$
$D^0, \bar{D}^0$	$1.2 \times 10^8$	$4.8 \times 10^{10}$	$1.4 \times 10^{15}$	$8.3 \times 10^{11}$
$D^\pm$	$1.2 \times 10^8$	$4.8 \times 10^{10}$	$6 \times 10^{14}$	$4.9 \times 10^{11}$
$D_s^\pm$	$1 \times 10^7$	$1.6 \times 10^{10}$	$2 \times 10^{14}$	$1.8 \times 10^{11}$
$\Lambda_c^\pm$	$0.3 \times 10^7$	$1.6 \times 10^{10}$	$2 \times 10^{14}$	$6.2 \times 10^{10}$
$\tau^+ \tau^-$	$3.6 \times 10^8$	$4.5 \times 10^{10}$		$1.2 \times 10^{11}$

CEPC vs LHCb : (-) smaller production yields

(+) much cleaner environment

(+) precisely known  $v_s$

(+) smaller beam spot size

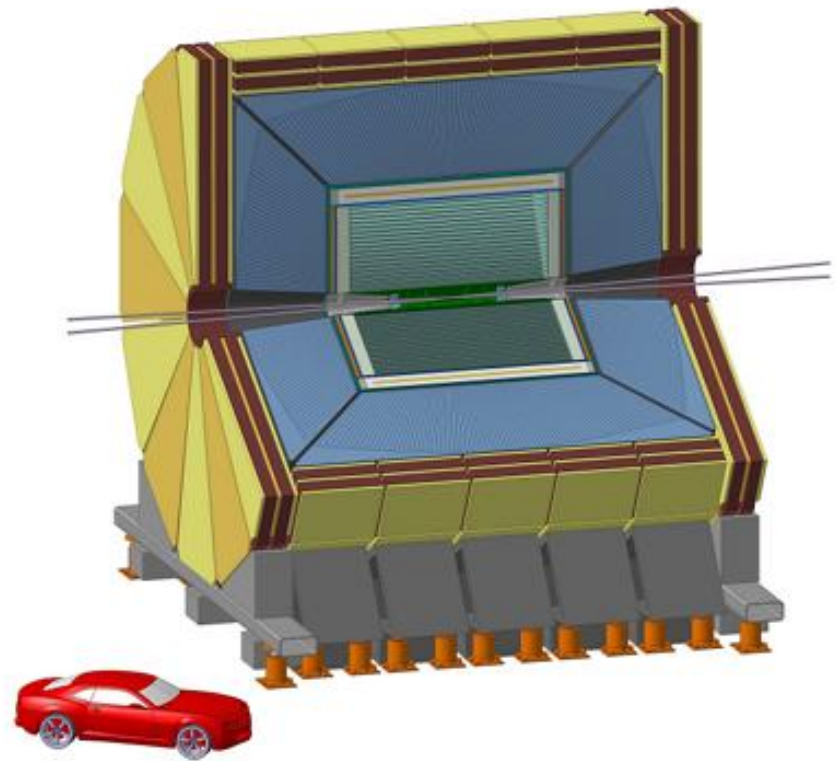
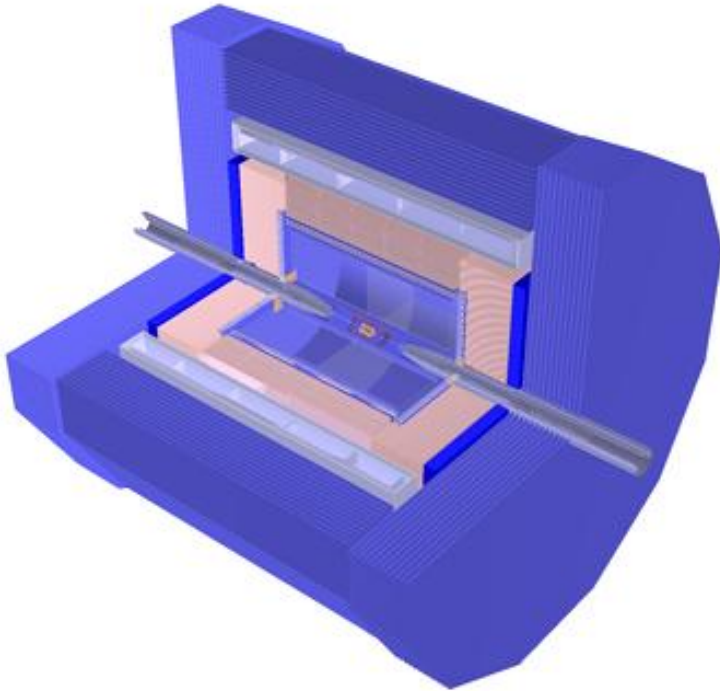
## Beam size, bunch length, and crossing angle at different operation modes of the CEPC

Operation mode	$Z$ factory	$WW$ threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Beam size $\sigma_x$ ( $\mu\text{m}$ )	6	13	14	39
Beam size $\sigma_y$ ( $\mu\text{m}$ )	0.035	0.042	0.036	0.113
Bunch length (total, mm)	8.7	4.9	4.1	2.9
Crossing angle at IP (mrad)		33		

# CEPC / FCC-ee detectors

CDR, arXiv:1811.10545 [hep-ex]

IDEA, arXiv:2502.21223  
[physics.ins-det], Snowmass 21



Innovative Detector for E+e-  
Accelerator (IDEA)

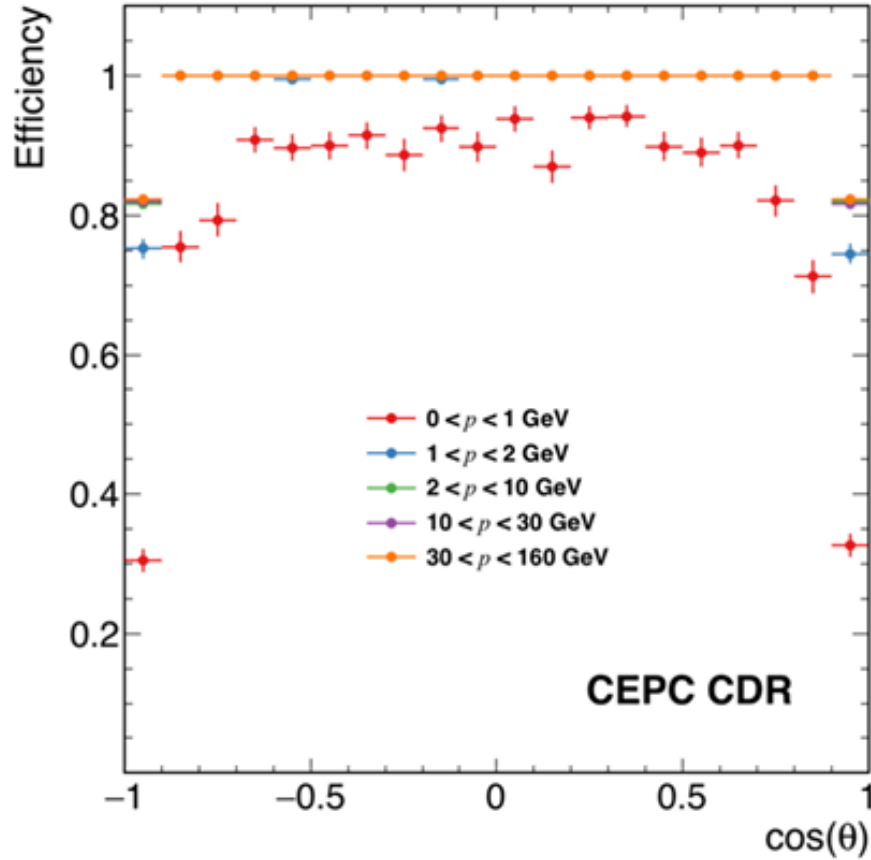
# Expected CEPC detector performance

arXiv:2412.19743 [hep-ex]

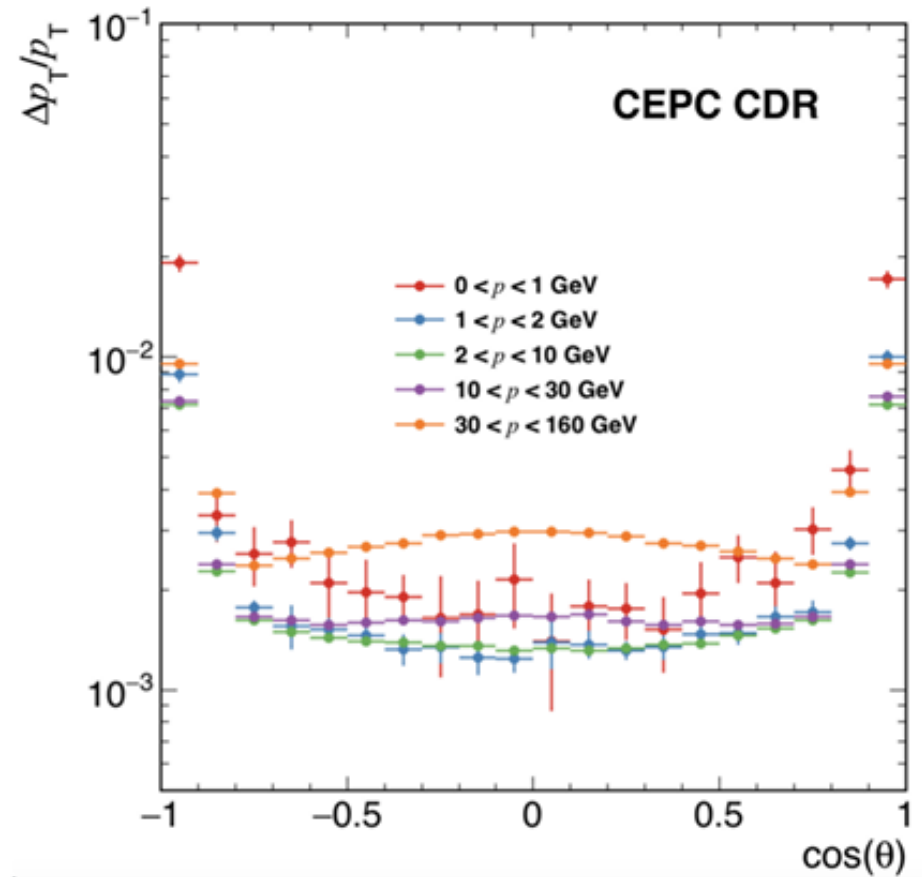
Item	CDR [2]	Objective	Comments
Basic Performance			
Acceptance	$ \cos\theta  < 0.99$ [2]		
Threshold	200 MeV [42, 43]	100 MeV	For tracks & photons
Beam energy spread	$\mathcal{O}(0.1\%)$ [2]		
Tracker momentum resolution	$\mathcal{O}(0.1\%)$ [2]		
ECAL energy resolution	$17\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]	$3\%/\sqrt{E(\text{GeV})}$ [32]	
HCAL energy resolution	$60\%/\sqrt{E(\text{GeV})} \oplus 1\%$ [2]		
Vertex resolution	10–200 $\mu\text{m}$ [2]		
Jet energy resolution	3–5% [2, 44]		For 20–100 GeV
$\ell - \pi$ mis-ID	$< 1\%$ [45]		In jet, $ \vec{p}  > 2$ GeV
$\pi - K$ separation	$> 2\sigma$ [2]	$> 3\sigma$ [36]	In jet, $ \vec{p}  > 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 $\times$ purity	$\sim 86\%$ [33]		In $Z$ hadronic decays
$c$ -jet efficiency $\times$ 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]		
$\pi^0$ efficiency $\times$ purity	$\gtrsim 70\%$ [43]	$\gtrsim 80\%$ [32]	In $Z$ hadronic decays, $ \vec{p}_{\pi^0}  > 5$ GeV
$K_S^0, \Lambda$ efficiency	60%-85% [46]		In $Z$ hadronic decays, all tracks
$\tau$ efficiency $\times$ purity	70% [47]		In $WW \rightarrow \tau\nu q\bar{q}'$ , inclusive
$\tau$ mis-ID	$\mathcal{O}(1\%)$ [47]		In $WW \rightarrow \tau\nu q\bar{q}'$ , inclusive

# Expected CEPC detector performance

## Track reconstruction efficiency

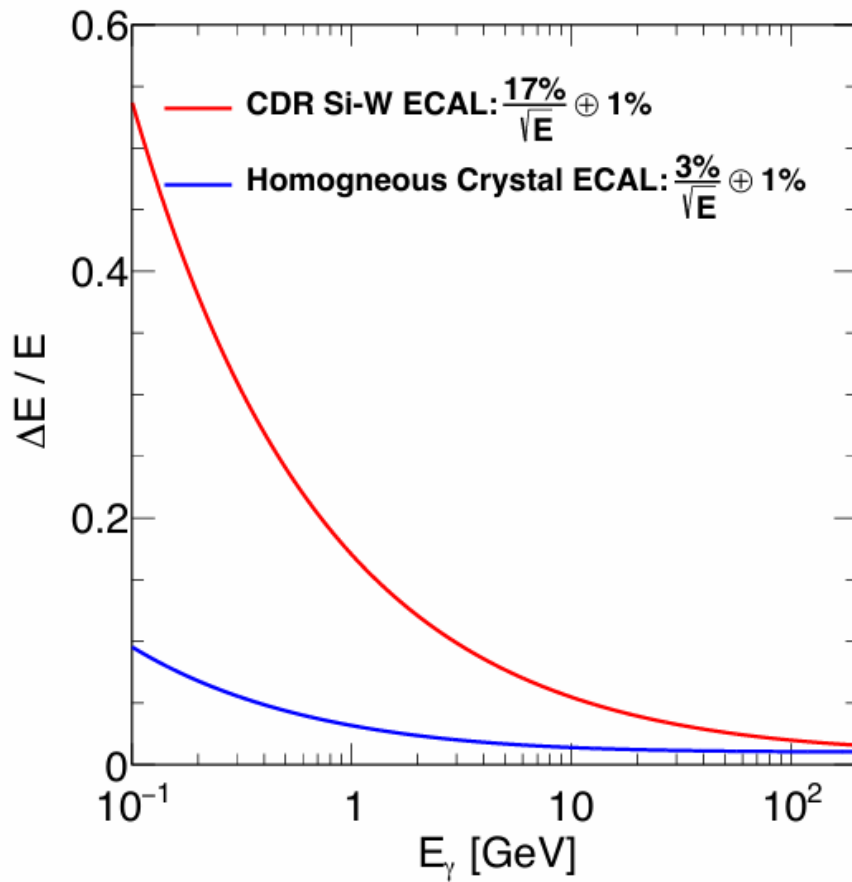


## Track momentum resolution

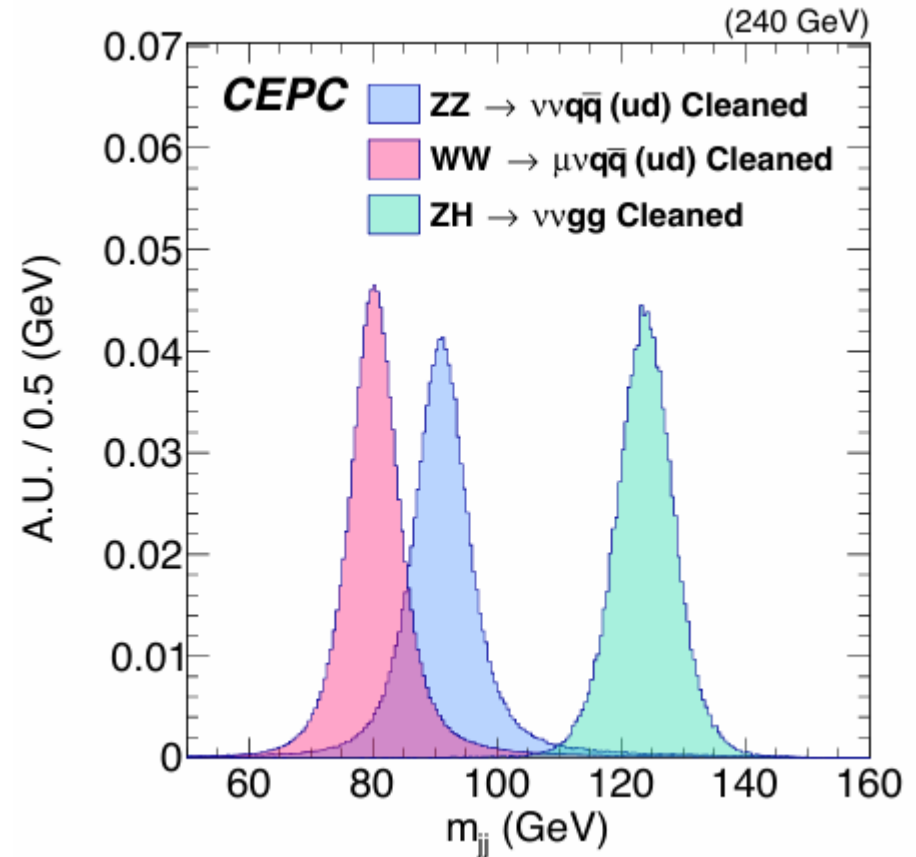


# Expected CEPC detector performance

## Photon energy resolution

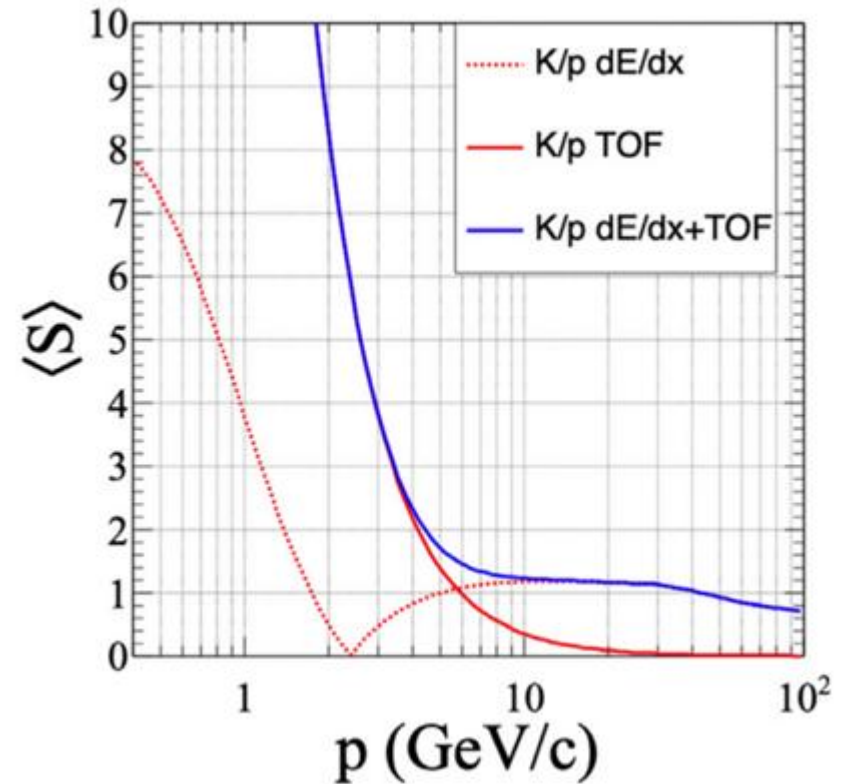
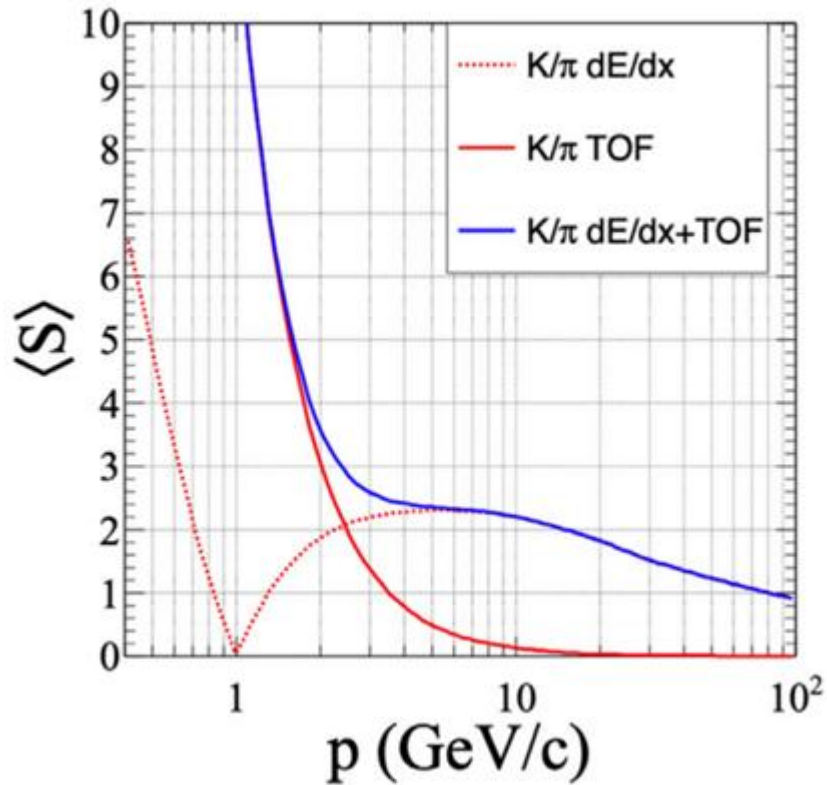


## Dijet boson masses



# Expected CEPC detector performance

arXiv:2209.14486 [physics.ins-det]

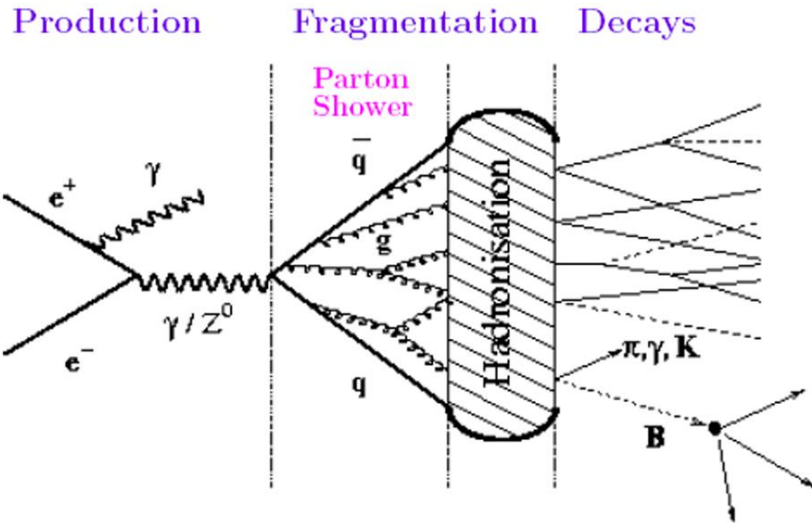


$$S_{AB} = \frac{|O_A - O_B|}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

# Benchmark heavy-flavor measurements

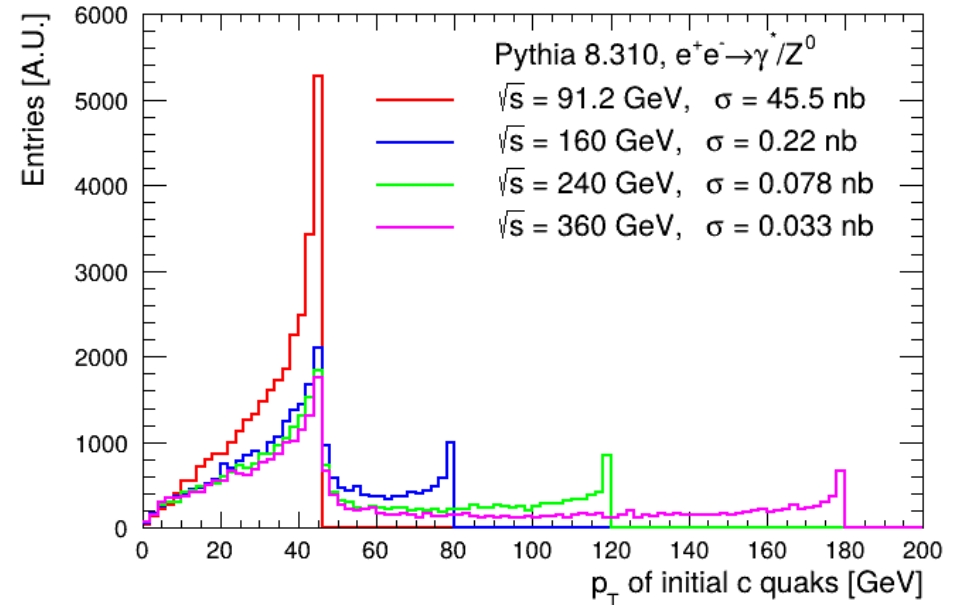
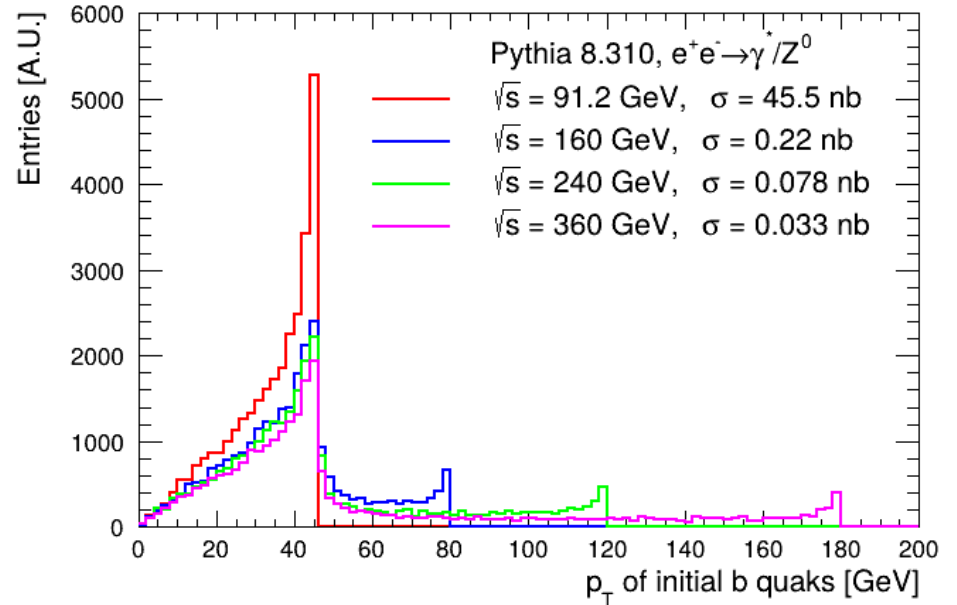


# HQ production and fragmentation at CEPC



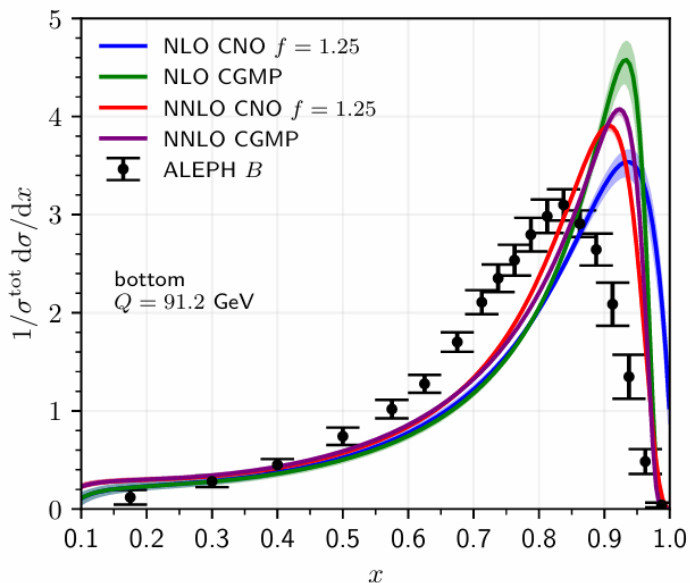
## Production issues:

- Parton showers at different  $\sqrt{s}$
- Gluon splitting
- HQ in  $e\gamma$  DIS ( $\gamma$  PDF)
- HQ in  $\gamma\gamma$  ( $\gamma$  PDF)



# HQ production and fragmentation

arXiv:2312.12519 [hep-ph]



Fragmentation functions tuning for various perturbative cores: FONLL, NNLO, GM-VFNS

arXiv:1404.3888 [hep-ph]

$H_c$	ALEPH [9] $f(c \rightarrow H_c)$ [%]	DELPHI [10,14] $f(c \rightarrow H_c)$ [%]	OPAL [11,12] $f(c \rightarrow H_c)$ [%]
$D^0$	$55.3 \pm 1.6 \pm 3.4$	$53.4 \pm 1.5 \pm 2.2$	$58.2 \pm 4.0^{+3.9}_{-3.6}$
$D^+$	$23.4 \pm 0.8 \pm 1.3$	$22.2 \pm 0.7 \pm 0.9$	$22.8 \pm 2.9^{+1.6}_{-2.0}$
$D_s^+$	$9.1 \pm 1.5 \pm 0.5$	$9.7 \pm 0.9 \pm 0.5$	$7.1 \pm 1.9 \pm 0.9$
$\Lambda_c^+$	$5.8 \pm 0.6 \pm 0.3$	$6.4 \pm 1.3 \pm 0.7$	$3.5 \pm 1.6 \pm 0.6$
$D^{*+}$ , rate	$23.3 \pm 1.0 \pm 0.9$	$24.1 \pm 0.6 \pm 0.9$	$23.0 \pm 0.4 \pm 0.9$
$D^{*+}$ , double-tag	–	$25.7 \pm 1.5 \pm 0.6$	$22.4 \pm 1.4 \pm 1.4$

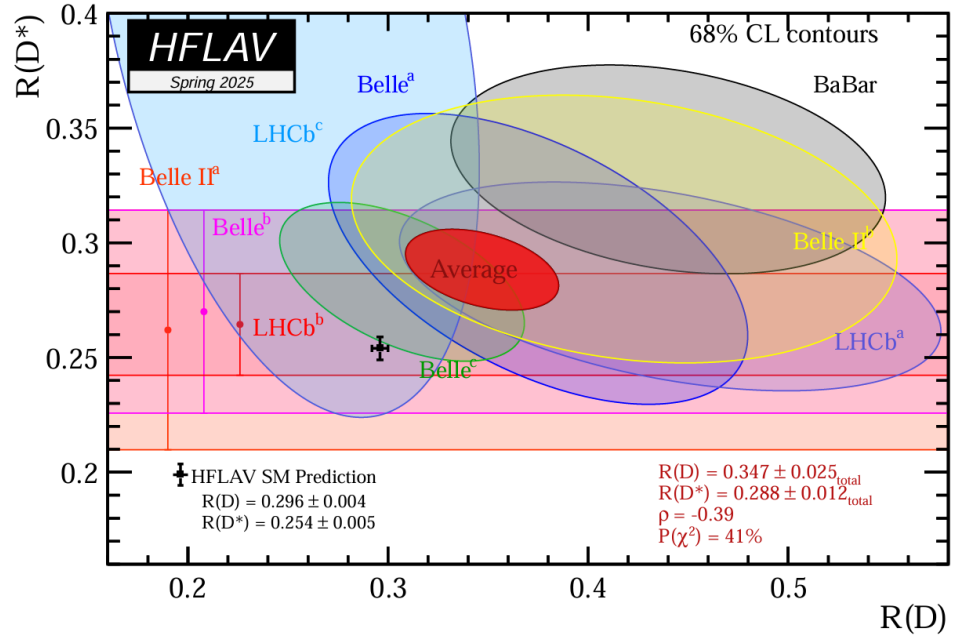
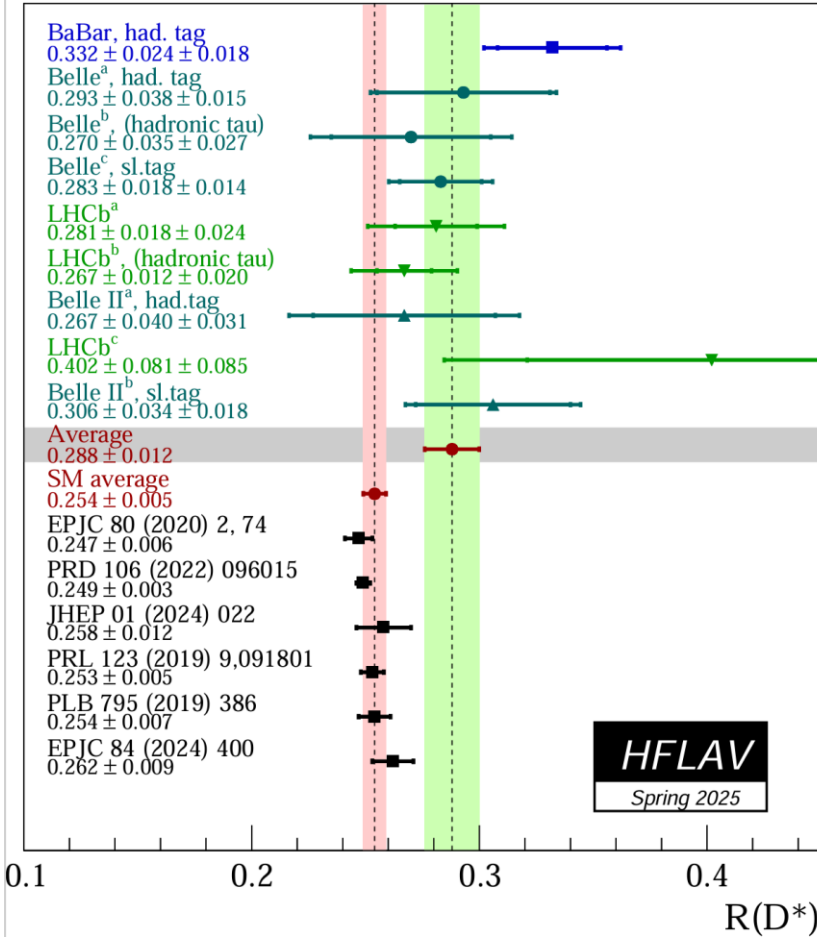
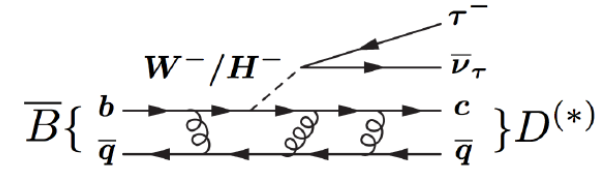
Fragmentation fractions extraction

# FCCC Semileptonic and Leptonic b-Hadron Decays

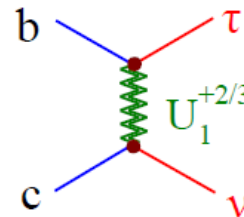
Process	Observable
$b \rightarrow cl\nu$	$R_{H_c}(R_{J/\psi}, R_{D_s^{(*)}}, R_{\Lambda_c})$
$B_c \rightarrow \tau\nu$	$ V_{cb} $
$B \rightarrow \tau\nu$	$ V_{ub} $

# Lepton Flavour Universality (Violation?)

$$R_{D^*} = \frac{\Gamma(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\Gamma(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$



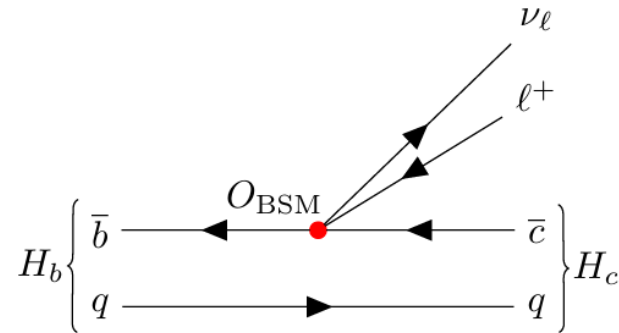
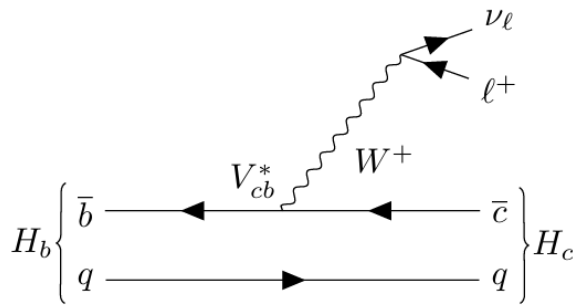
$3.77 \sigma$



# FCCC Semileptonic b-Hadron Decays

arXiv:2212.02433 [hep-ph]

$$R_{H_c} = \frac{\text{BR}(H_b \rightarrow H_c \tau \nu_\tau)}{\text{BR}(H_b \rightarrow H_c \ell' \nu_{\ell'})}$$



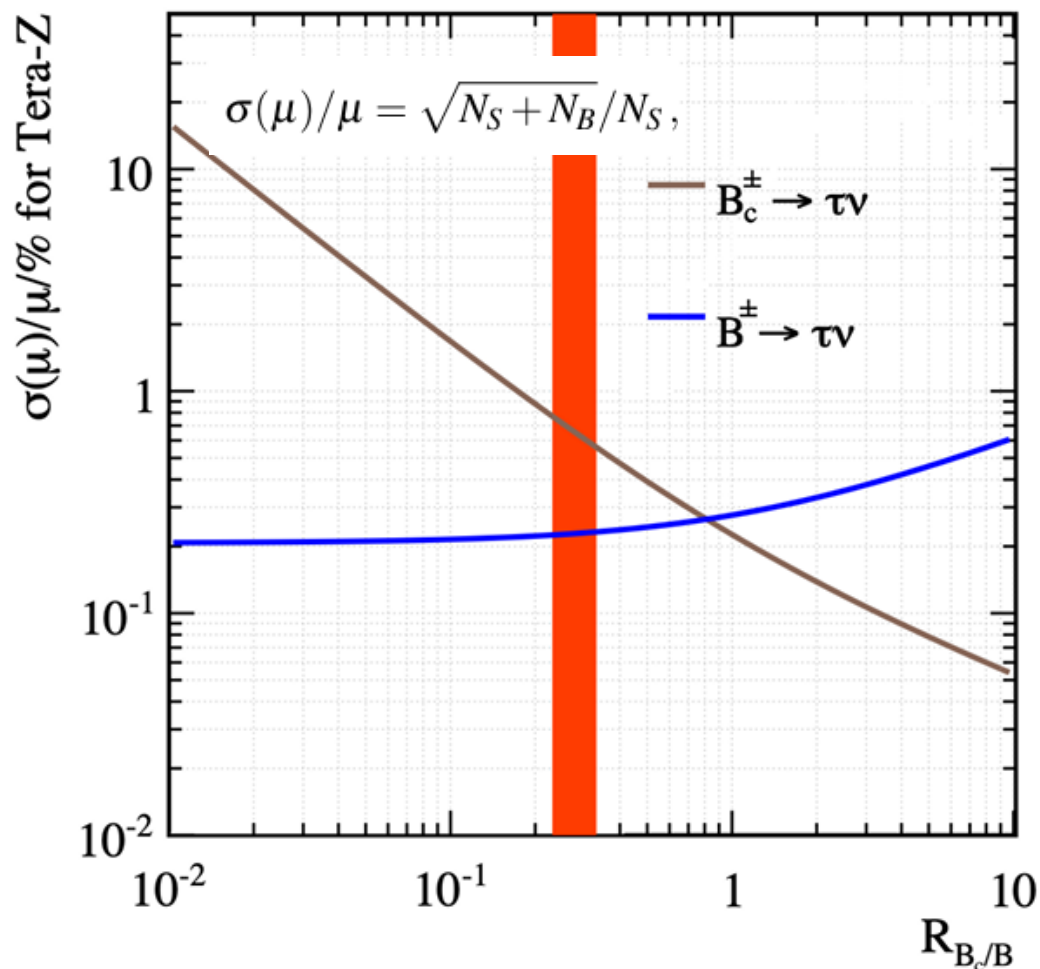
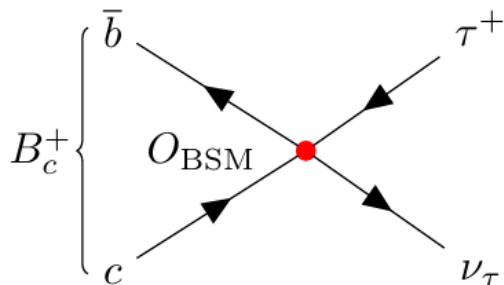
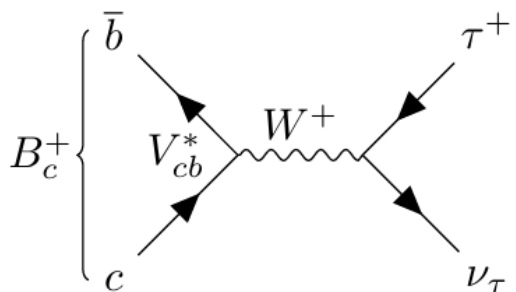
$R_{H_c}$	SM Value	Tera-Z	$4 \times \text{Tera-Z}$	$10 \times \text{Tera-Z}$
$R_{J/\psi}$	0.289	$4.3 \times 10^{-2}$	$2.1 \times 10^{-2}$	$1.4 \times 10^{-2}$
$R_{D_s}$	0.393	$4.1 \times 10^{-3}$	$2.1 \times 10^{-3}$	$1.3 \times 10^{-3}$
$R_{D_s^*}$	0.303	$3.3 \times 10^{-3}$	$1.6 \times 10^{-3}$	$1.0 \times 10^{-3}$
$R_{\Lambda_c}$	0.334	$9.8 \times 10^{-4}$	$4.9 \times 10^{-4}$	$3.1 \times 10^{-4}$

# FCCC Leptonic b-Hadron Decays

arXiv:2007.08234 [hep-ex]

Relative precision of measuring the  $B_c^\pm \rightarrow \tau\nu$  rate

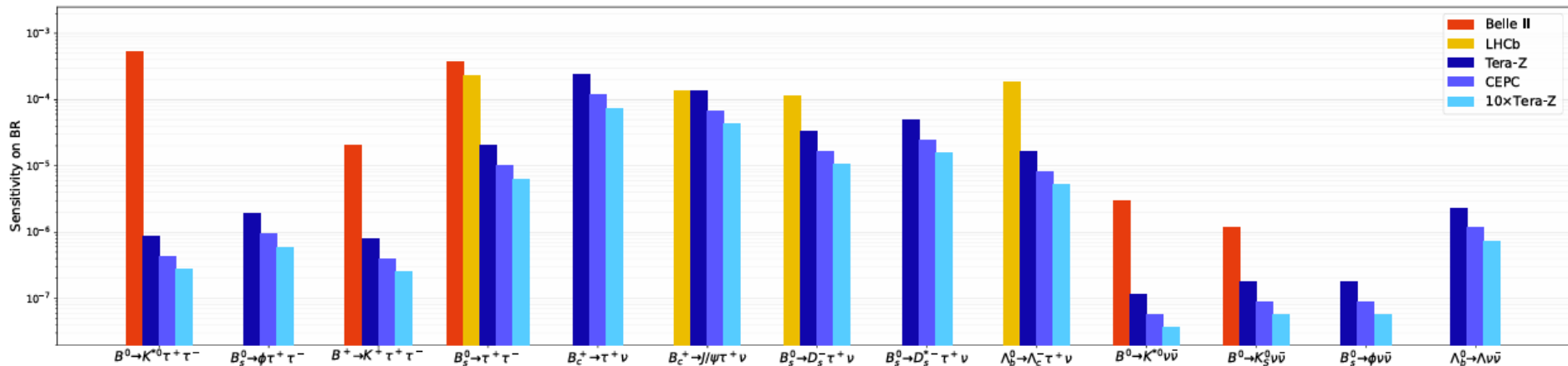
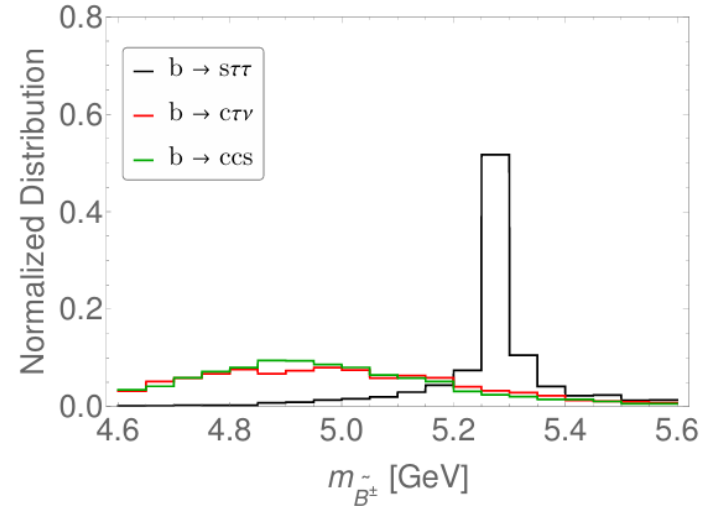
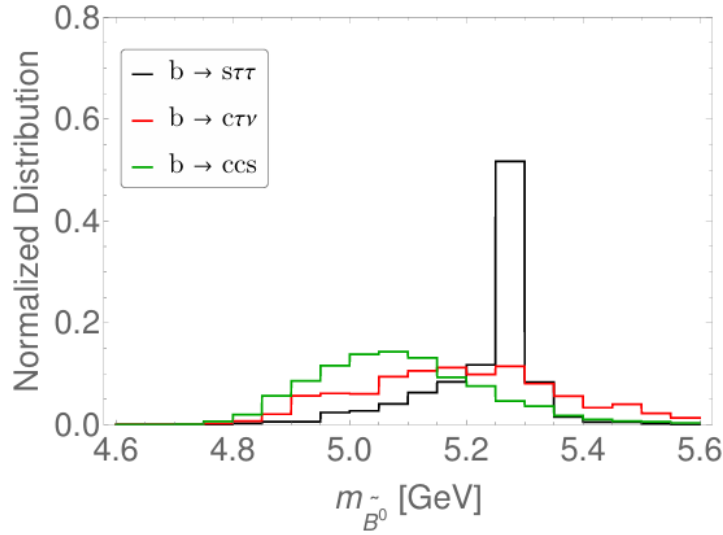
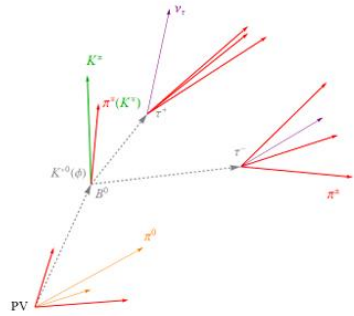
$$B_c^+ \rightarrow \tau^+ \nu_\tau$$



$$R_{B_c/B} \equiv N(B_c^\pm \rightarrow \tau\nu)/N(B^\pm \rightarrow \tau\nu)$$

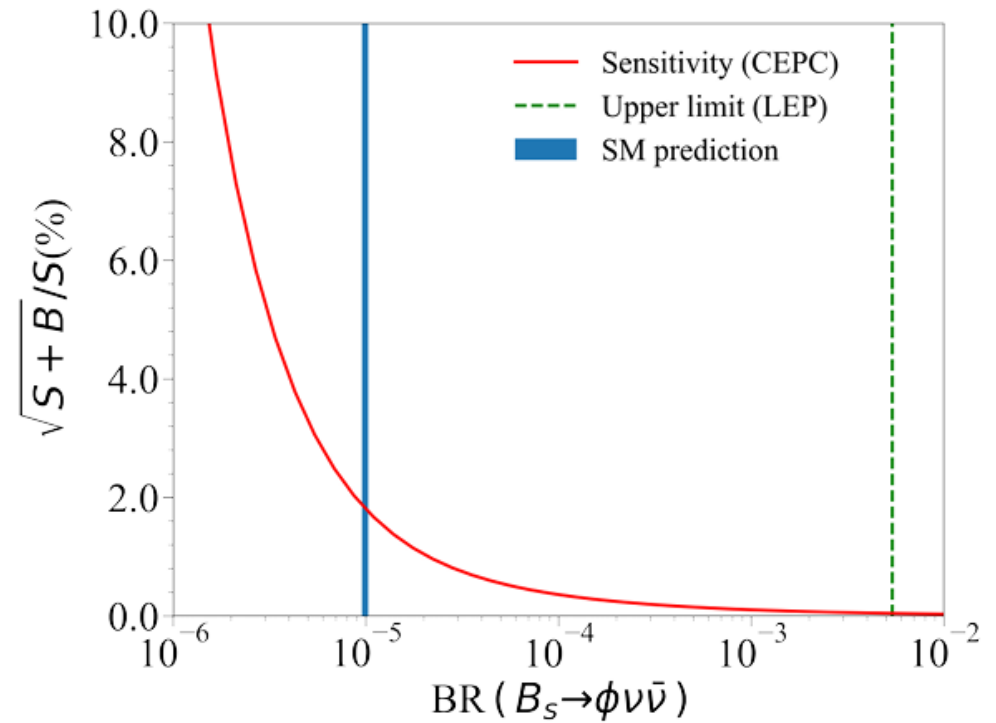
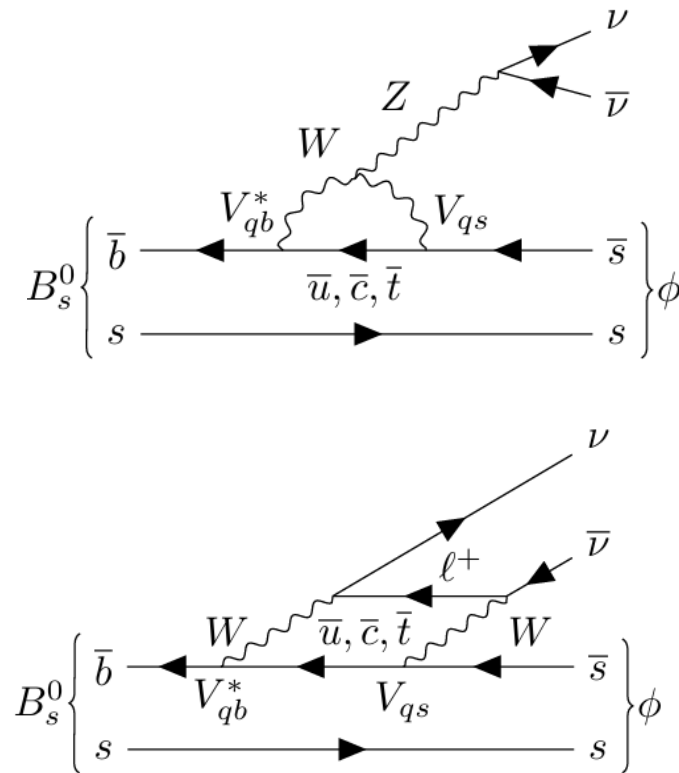
# FCNC b-Hadron Decays: Di-lepton modes

arXiv:2012.00665 [hep-ph]



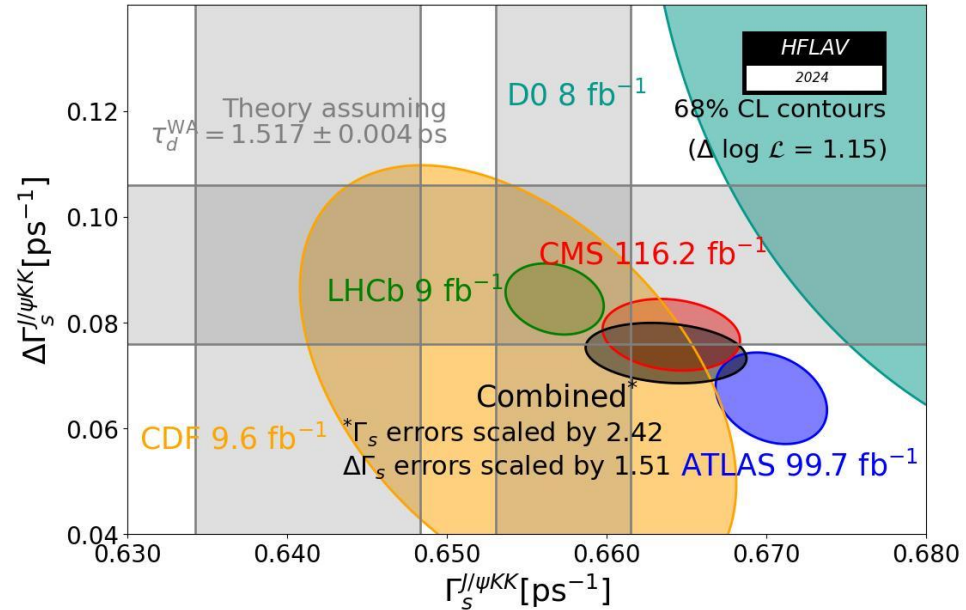
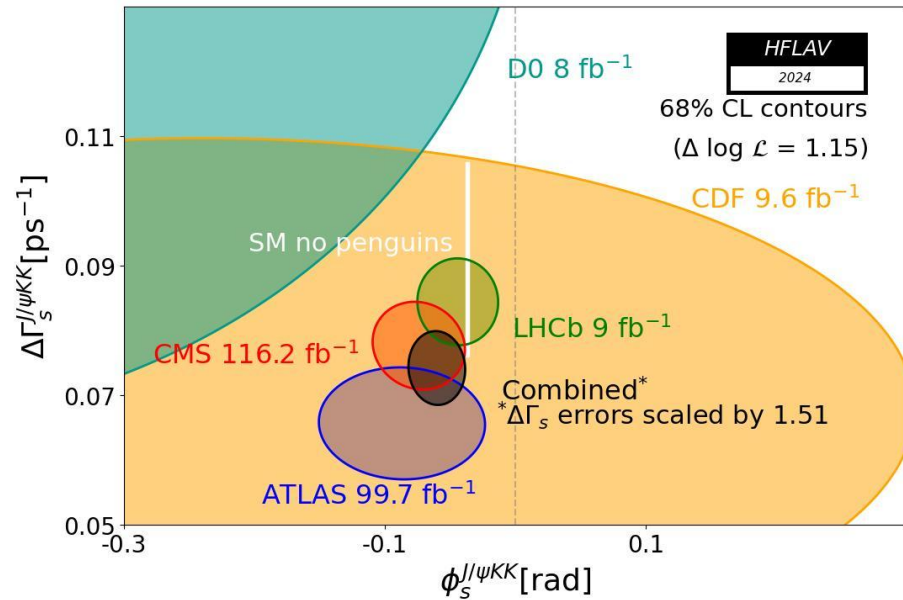
# FCNC b-Hadron Decays: Di-lepton modes

arXiv:2201.07374 [hep-ph]



# CP Violation in b-Hadron Decays

$$B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi(\rightarrow K^+ K^-)$$



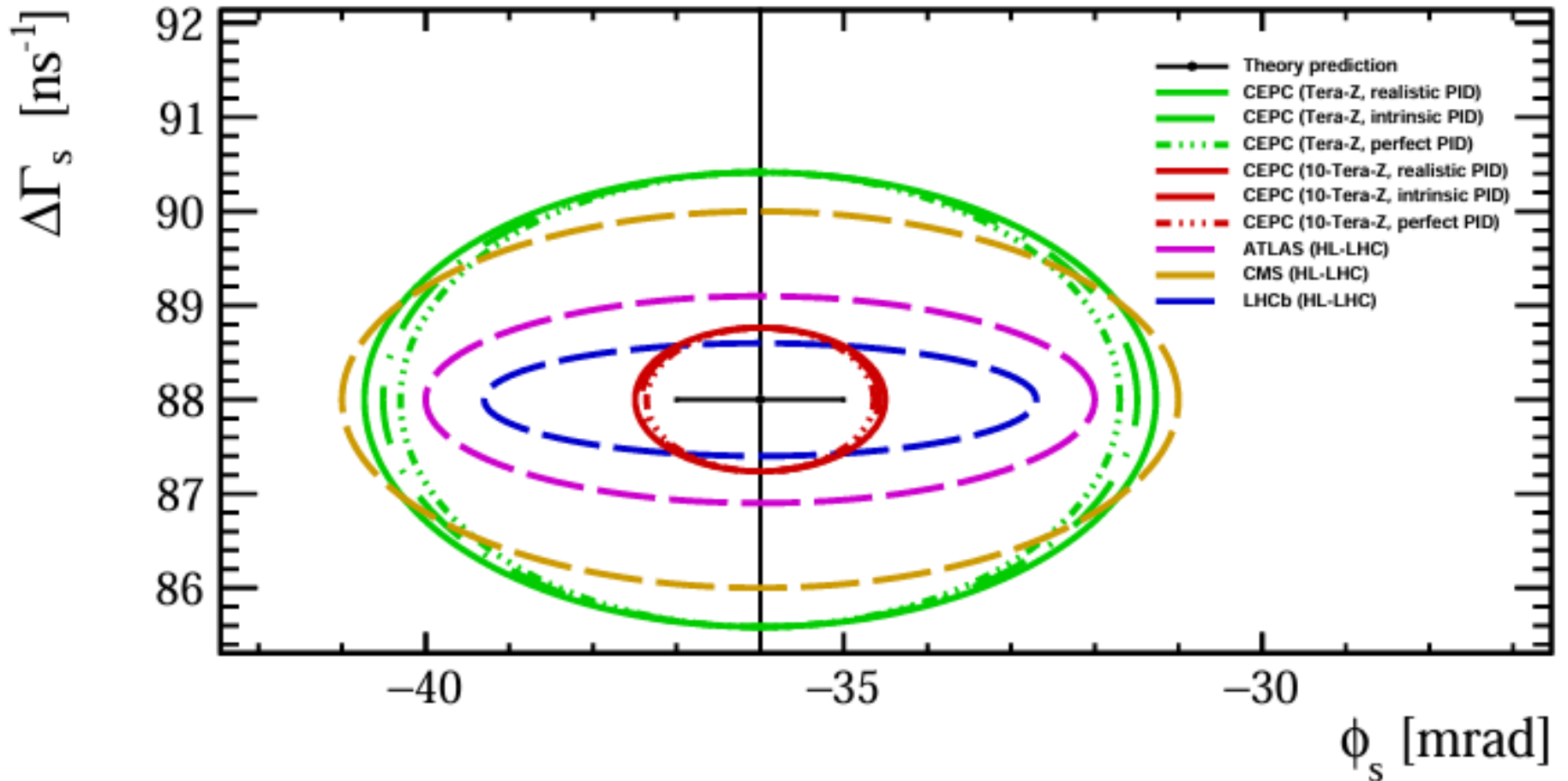
$$\phi_s \simeq -2\beta_s = -0.0367 \pm 0.0010 \text{ (Ufit)}$$

$$\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

# CP Violation in b-Hadron Decays

$$B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi(\rightarrow K^+ K^-)$$

arXiv:2205.10565 [hep-ex]



## below open-flavor threshold

PDG Name	Former Name	$m$ (MeV)	$\Gamma$ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$h_c(1P)$		$3525.37 \pm 0.14$	$0.78^{+0.30}_{-0.27}$	$0^-(1^{+-})$	$\psi(2S) \rightarrow \pi^0 X$ $p\bar{p} \rightarrow X$ $e^+e^- \rightarrow \pi\pi X$	$\gamma\eta_c(1S)$ hadrons (see listings)	2004	YES
$\psi_2(3823)$	$X(3823)$	$3823.51 \pm 0.34$	$< 2.9$	$0^-(2^{--})$	$B \rightarrow KX$ $e^+e^- \rightarrow \pi^+\pi^-X$	$\gamma\chi_{c1}(1P)$ $\pi^+\pi^-J/\psi(1S)$	2013	YES
$B_c^+$		$6274.47 \pm 0.32$	stable	$0(0^-)$	$\bar{p}p \rightarrow X\dots$ $pp \rightarrow X\dots$	$\pi^+J/\psi(1S)$ (see listings)	2007	YES
$B_c^+(2S)$		$6871.2 \pm 1.0$	?	$0(0^-)$	$pp \rightarrow X\dots$	$B_c^+\pi^+\pi^-$	2014	YES
$\eta_b(1S)$		$9398.7 \pm 2.0$	$10^{+5}_{-4}$	$0^+(0^{-+})$	$\Upsilon(2S, 3S) \rightarrow \gamma X$ $h_b(1P, 2P) \rightarrow \gamma X$	hadrons (see listings)	2008	YES
$h_b(1P)$		$9899.3 \pm 0.8$	?	$0^-(1^{+-})$	$\Upsilon(10860) \rightarrow \pi^+\pi^-X$ $\Upsilon(3S) \rightarrow \pi^0 X$ $\Upsilon(4S) \rightarrow \eta X$ $T_{bb}^-(10610)^+ \rightarrow \pi^+ X$ $T_{bb}^-(10650)^+ \rightarrow \pi^+ X$	$\gamma\eta_b(1S)$	2011	YES
$\eta_b(2S)$		$9999.0^{+4.5}_{-4.0}$	$< 24$	$0^+(0^{-+})$	$h_b(2P) \rightarrow \gamma X$	hadrons	2012	NO
$\Upsilon_2(1D)$		$10163.7 \pm 1.4$	?	$0^-(2^{--})$	$\Upsilon(3S) \rightarrow \gamma\gamma X$ $\Upsilon(10860) \rightarrow \pi^+\pi^-X$	$\gamma\gamma\Upsilon(1S)$ $\pi^+\pi^-\Upsilon(1S)$	2004	YES
$h_b(2P)$		$10259.8 \pm 1.2$	?	$0^-(1^{+-})$	$\Upsilon(10860) \rightarrow \pi^+\pi^-X$ $T_{bb}^-(10610)^+ \rightarrow \pi^+ X$ $T_{bb}^-(10650)^+ \rightarrow \pi^+ X$	$\gamma\eta_b(1S, 2S)$	2011	YES
$\chi_{b1}(3P)$		$10513.42 \pm 0.67$	?	$0^+(1^{++})$	$pp \rightarrow X\dots$	$\gamma\Upsilon(1S, 2S, 3S)$	2011	YES
$\chi_{b2}(3P)$		$10524.02 \pm 0.78$	?	$0^+(2^{++})$	$pp \rightarrow X\dots$	$\gamma\Upsilon(3S)$	2011	YES

Where is  $B_c^{*+}$  ?

## near open-flavor threshold

PDG Name	Former Name	$m$ (MeV)	$\Gamma$ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c1}(3872)$	$X(3872)$	$3871.64 \pm 0.06$	$1.19 \pm 0.21$	$0^+(1^{++})$	$B \rightarrow KX$ $p\bar{p} \rightarrow X\dots$ $pp \rightarrow X\dots$ $e^+e^- \rightarrow \gamma X$	$\pi^+\pi^- J/\psi(1S)$ $3\pi J/\psi(1S)$ $D^{*0}\bar{D}^0$ $\gamma J/\psi(1S)$ $\gamma\psi(2S)$ $\pi^0\chi_{c1}(1P)$	2003	YES
$T_{cc}(3875)$		$3874.83 \pm 0.11$	$0.410^{+0.172}_{-0.175}$	$?(?^?)$	$pp \rightarrow X\dots$	$D^0D^0\pi$	2022	NO
$T_{c\bar{c}1}(3900)$	$Z_c(3900)$	$3887.1 \pm 2.6$	$28.4 \pm 2.6$	$1^+(1^{+-})$	$\psi(4230) \rightarrow \pi^- X$ $\psi(4230) \rightarrow \pi^0 X$	$\pi^+ J/\psi(1S)$ $\pi^0 J/\psi(1S)$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$T_{c\bar{c}s1}(4000)$	$Z_{cs}(4000)$	$3980 - 4010$	$5 - 150$	$\frac{1}{2}(1^+)$	$e^+e^- \rightarrow KX$ $B^+ \rightarrow \phi X$	$D_s D^* + D_s^* D$ $K^+ J/\psi(1S)$	2021	NO
$T_{c\bar{c}}(4020)$	$Z_c(4020)$ $X(4020)$	$4024.1 \pm 1.9$	$13 \pm 5$	$1^+(?^?^-)$	$\psi(4230, 4360) \rightarrow \pi^- X$ $\psi(4230, 4360) \rightarrow \pi^0 X$	$\pi^+ h_c(1P)$ $\pi^0 h_c(1P)$ $(D^* \bar{D}^*)^+$ $(D^* \bar{D}^*)^0$	2013	YES
$T_{c\bar{c}s1}(4220)$	$Z_{cs}(4220)$	$4216^{+49}_{-38}$	$233^{+110}_{-90}$	$\frac{1}{2}(1^+)$	$B^+ \rightarrow \phi X$	$K^+ J/\psi(1S)$	2021	NO
$T_{b\bar{b}1}(10610)$	$Z_b(10610)$	$10607.2 \pm 2.0$	$18.4 \pm 2.4$	$1^+(1^{+-})$	$\Upsilon(10860) \rightarrow \pi^- X$ $\Upsilon(10860) \rightarrow \pi^0 X$	$\pi^+ \Upsilon(1S, 2S, 3S)$ $\pi^0 \Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B\bar{B}^*)^+$	2011	YES
$T_{b\bar{b}1}(10650)$	$Z_b(10650)$	$10652.2 \pm 1.5$	$11.5 \pm 2.2$	$1^+(1^{+-})$	$\Upsilon(10860) \rightarrow \pi^- X$	$\pi^+ \Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B^* \bar{B}^*)^+$	2011	YES

What about  $T_{bb}$  and  $T_{bc}$  ?

# Spectroscopy and Exotics

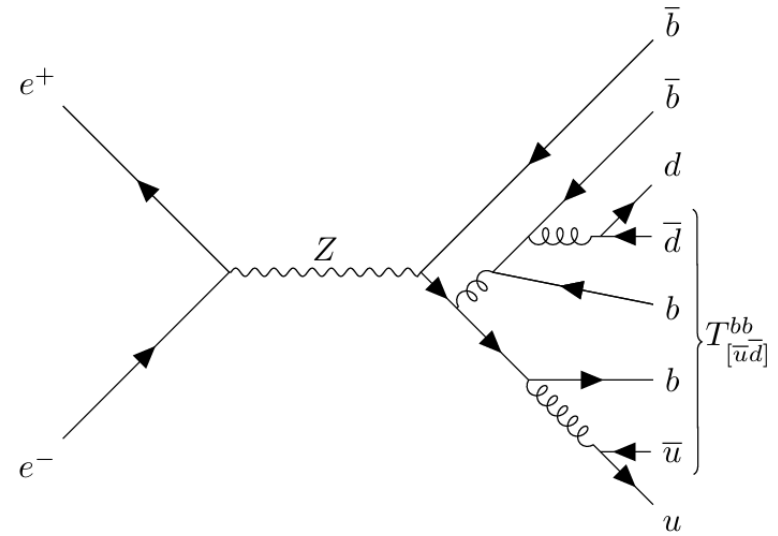
arXiv:2412.19743 [hep-ex]

$(\bar{b}c)$  spectroscopy ( $Z \rightarrow b\bar{b}c\bar{c}$ )

$T_{bb}$  production in  $Z \rightarrow b\bar{b}b\bar{b}$

Doubly-heavy baryons

Pentaquarks



# Physics of $\tau$ leptons and LFV $Z^0$ decays

D.Yu et al., preliminary

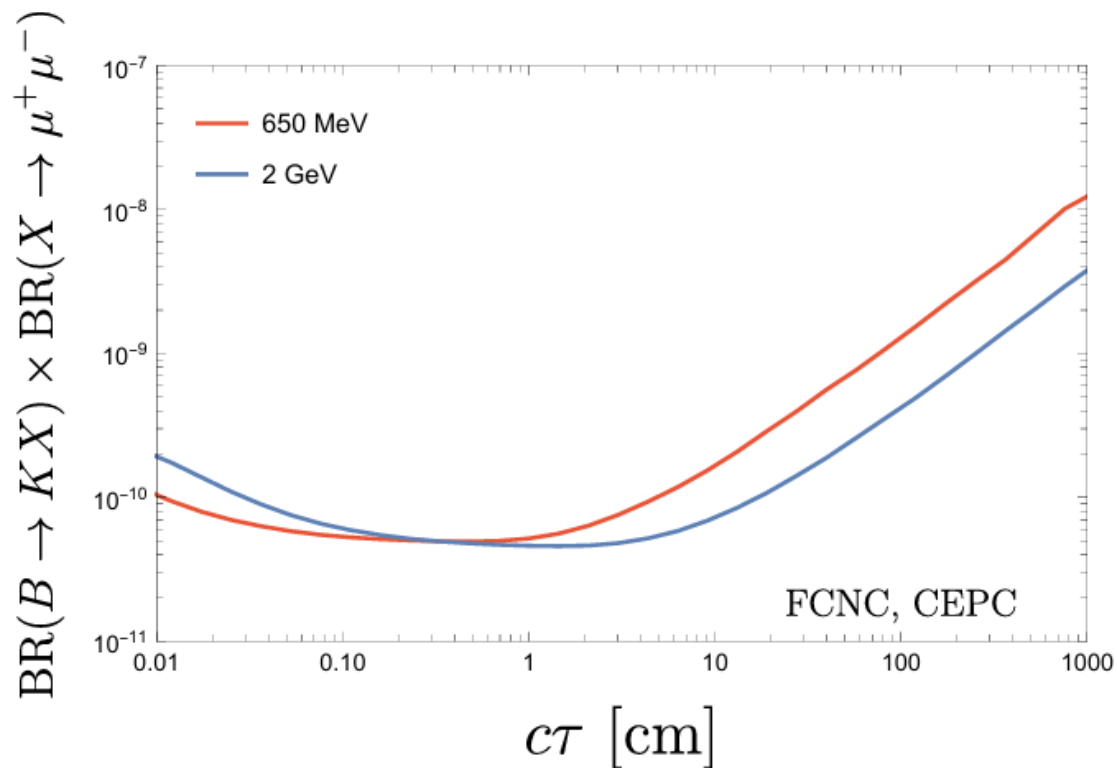
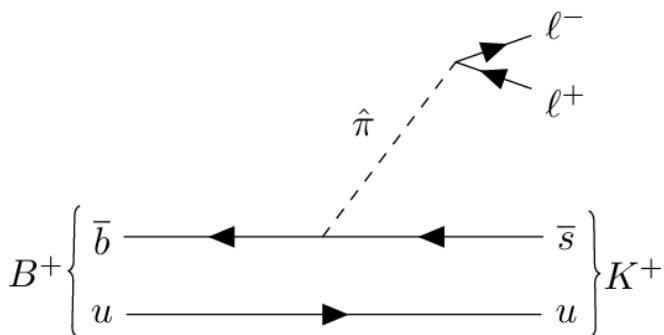
Measurement	Current	Belle II	FCC	CEPC prelim.
Lifetime [sec]	$(2903 \pm 5) \times 10^{-16}$		$\pm 6 \times 10^{-18}$	$\pm 7 \times 10^{-18}$
$\text{BR}(\tau \rightarrow e\nu\bar{\nu})$	$(17.82 \pm 0.04)\%$		$\pm 0.003\%$	$\pm 0.003\%$
$\text{BR}(\tau \rightarrow \mu\nu\bar{\nu})$	$(17.39 \pm 0.04)\%$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

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

# Searches for light BSM states

## Light dark pion

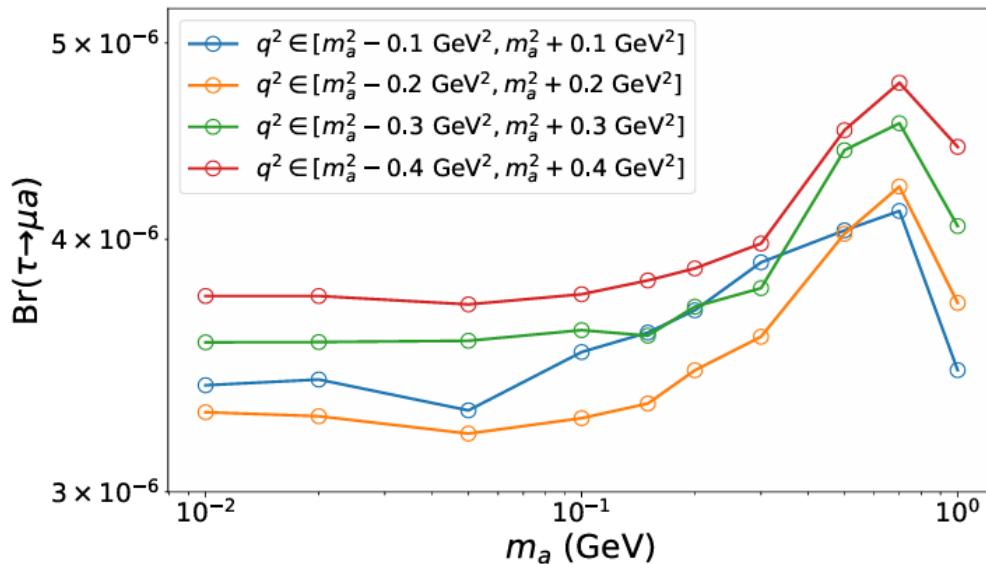
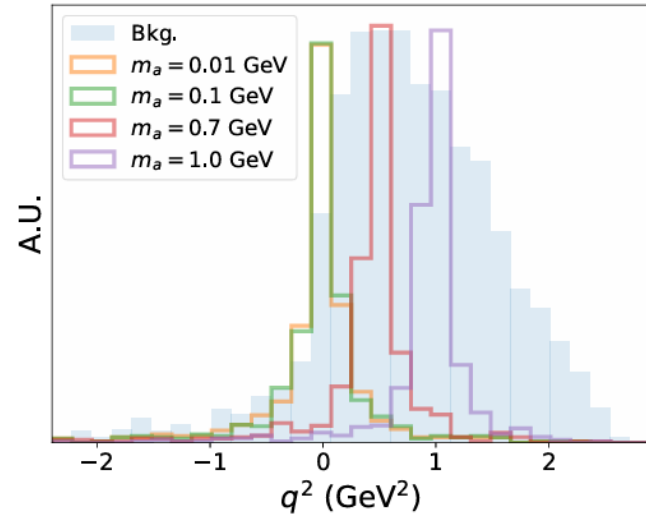
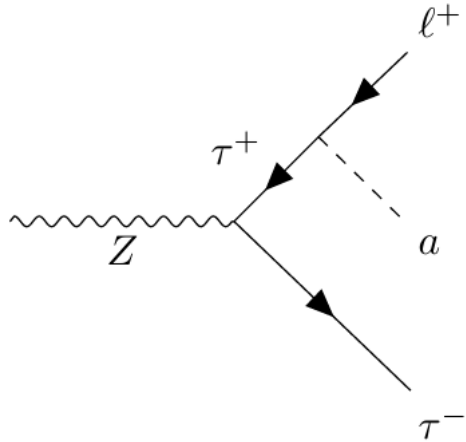
T.H.Kwok et al., preliminary



# Searches for light BSM states

## ALP

T.H.Kwok et al., preliminary



$$q^2 \equiv (p_\tau - p_\mu)^2$$

$$Z \rightarrow \tau(\rightarrow \mu a)\tau(\rightarrow 3\pi\nu)$$

# Summary

Future  $e^+e^-$  collider will provide unique opportunities for studies of heavy flavor physics

**All areas of heavy quarks physics will be covered:**

- specific HQ production and fragmentation characteristics
- FCCC and FCNC in b-decays
- CP violation in B and D decays
- spectroscopy and Exotics
- physics of  $\tau$  leptons and LFV  $Z^0$  decays
- searches for light new physics in B and  $\tau$  decays
- ....

**Hundreds young physicists will be needed to work at CEPC**

contacts : [gladilin@sinp.msu.ru](mailto:gladilin@sinp.msu.ru)

# Backup

## ▶ Leptoquarks

Which (tree-level) mediators can generate the effective operators required for by the EFT fit? Not many possibilities...

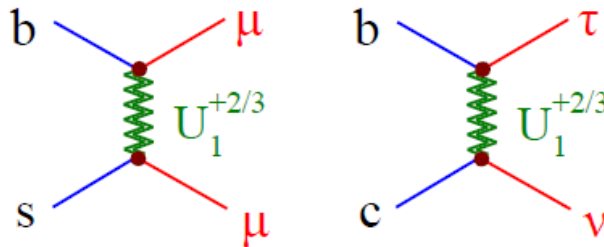
✓ We do observe “large” NP effects in semileptonic operators

\* What we do not see is in NP in (→ *additional loop suppression*):

Four-quarks ( $\Delta F=2$ )  
Four-leptons ( $\tau \rightarrow \mu \nu \nu$ )

➔ **Leptoquarks**

Among the (few) LQ options, there is one outstanding case:



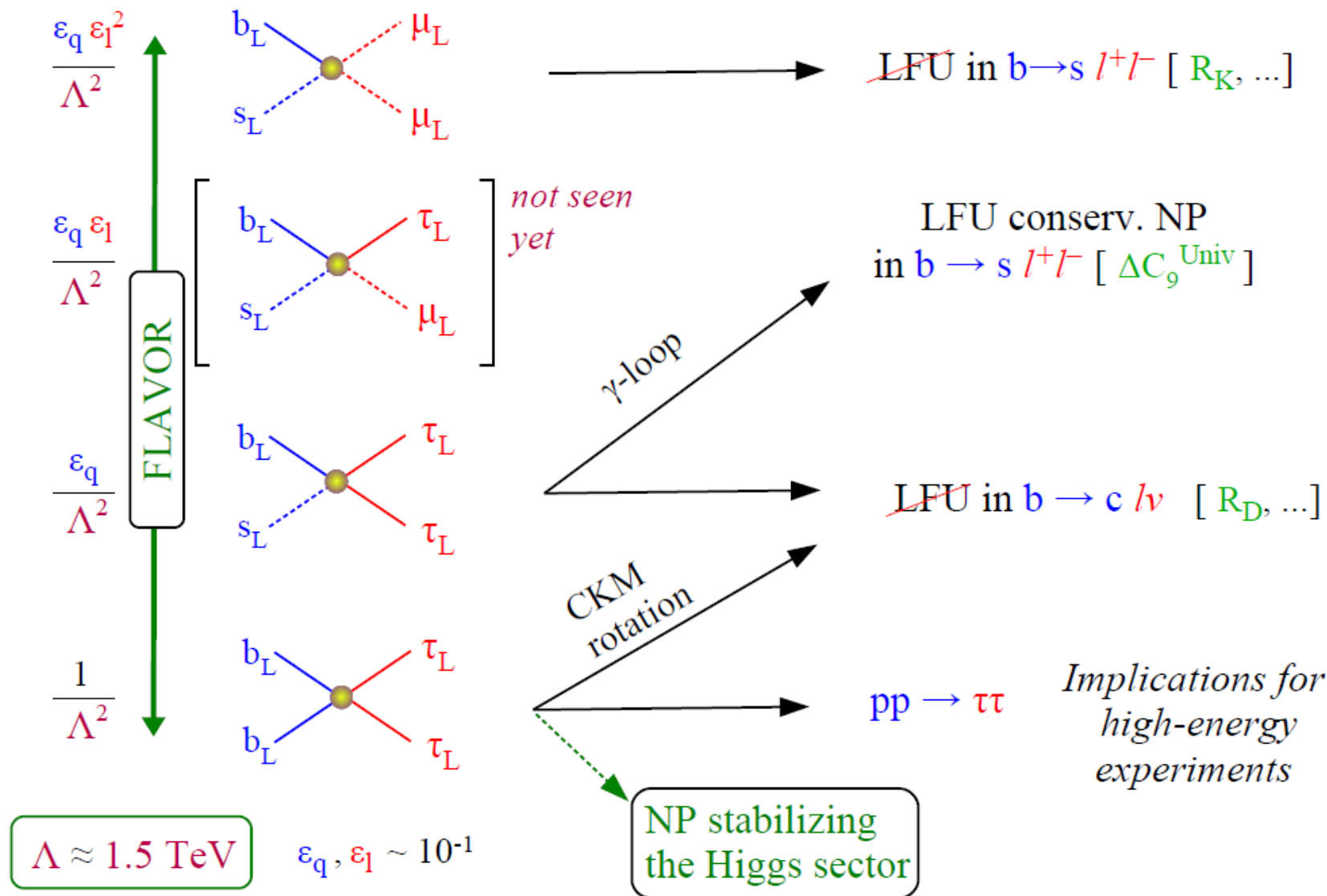
- ➔ mediator:  $U_1$
- ➔ flavor structure:  $U(2)^n$
- ➔ UV completion:  $SU(4)$

Barbieri, GI,  
Pattori, Senia '15

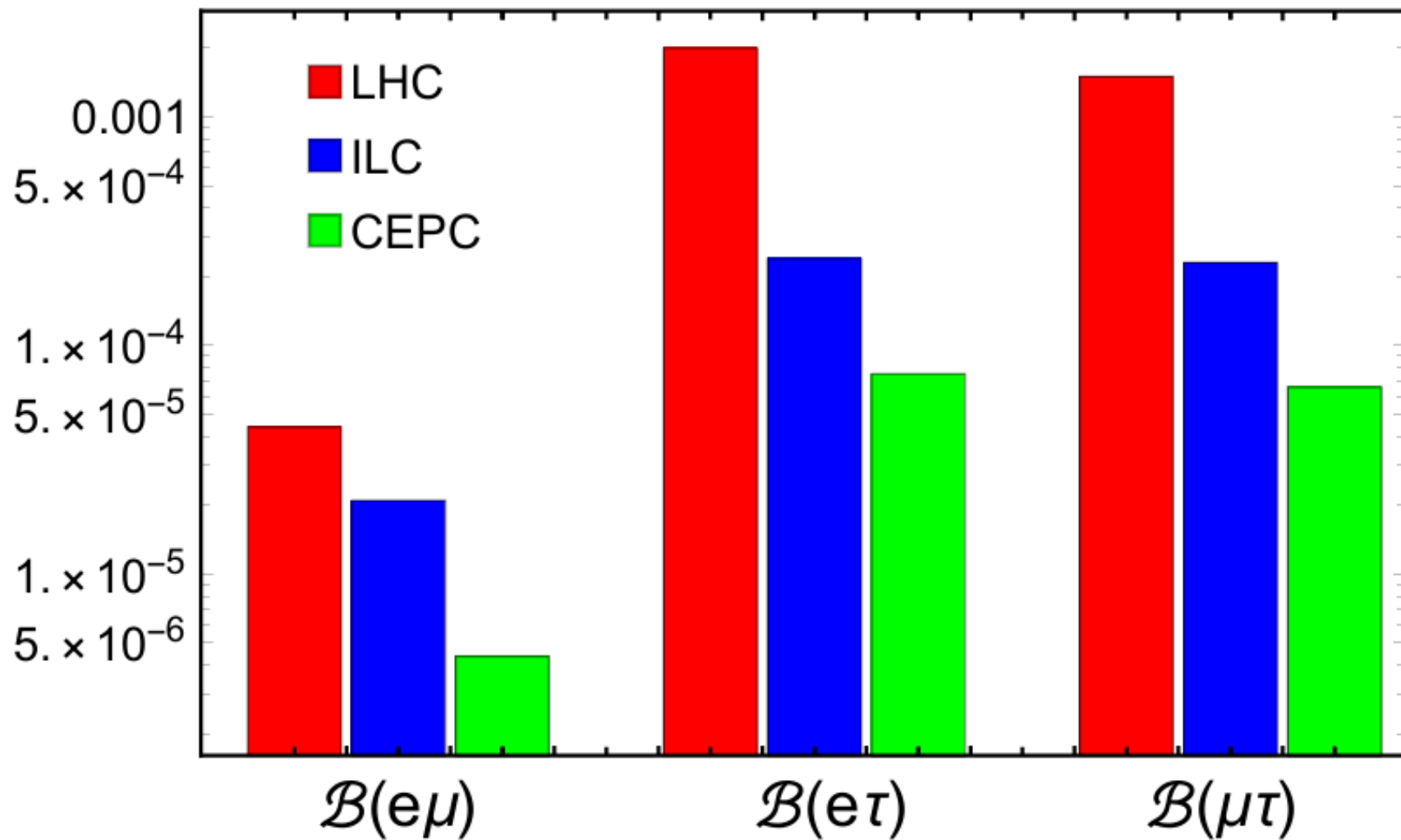
*We identified this path back in 2015, as a motivated simplified model...*

*...after 7 years, this is one of the very few options still in place for combined explanations & we understood much better its possible UV completion*

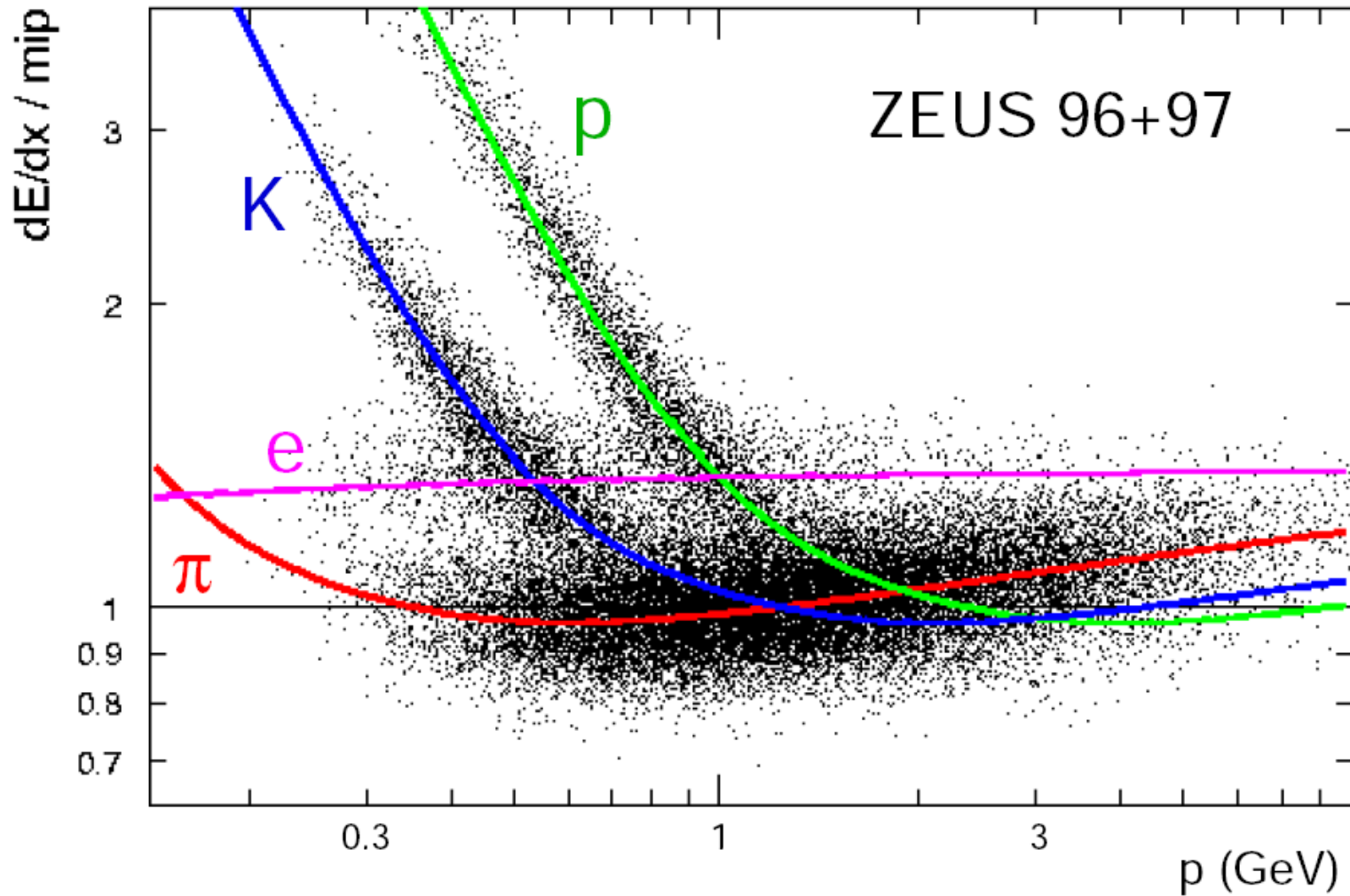
► The B-physics anomalies



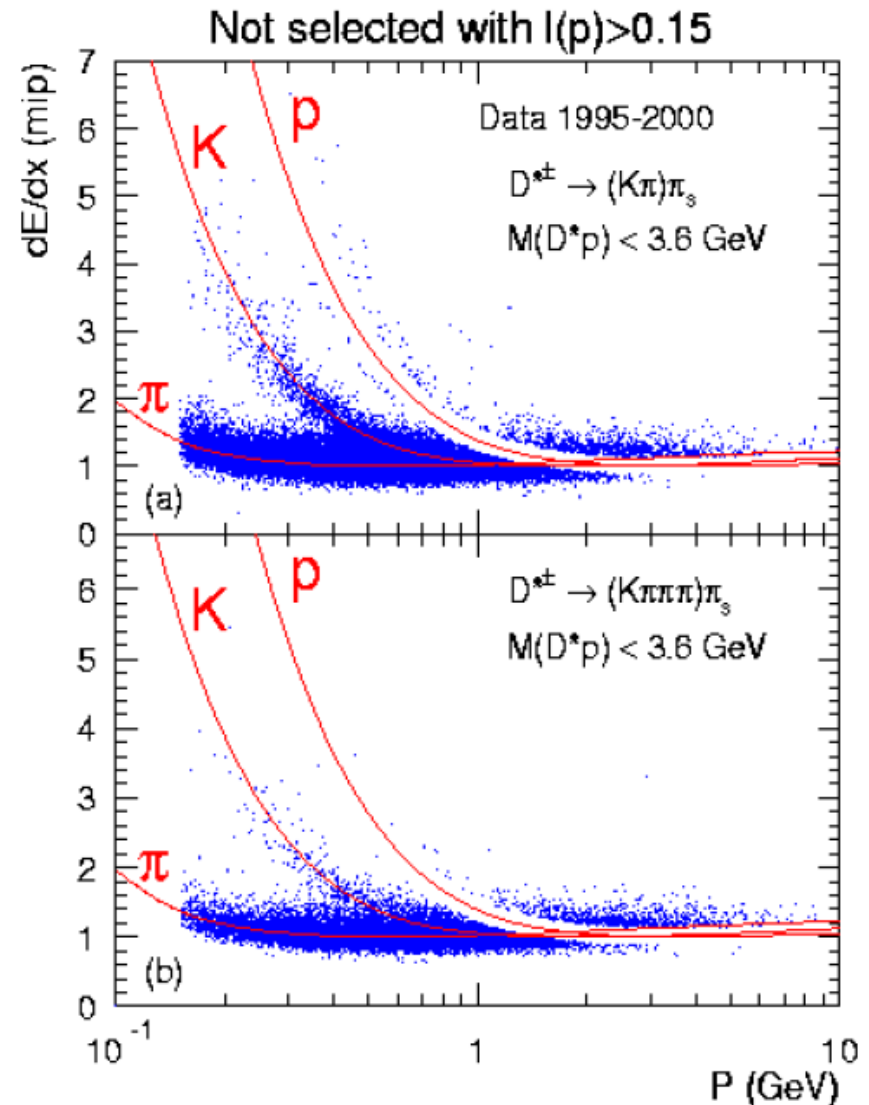
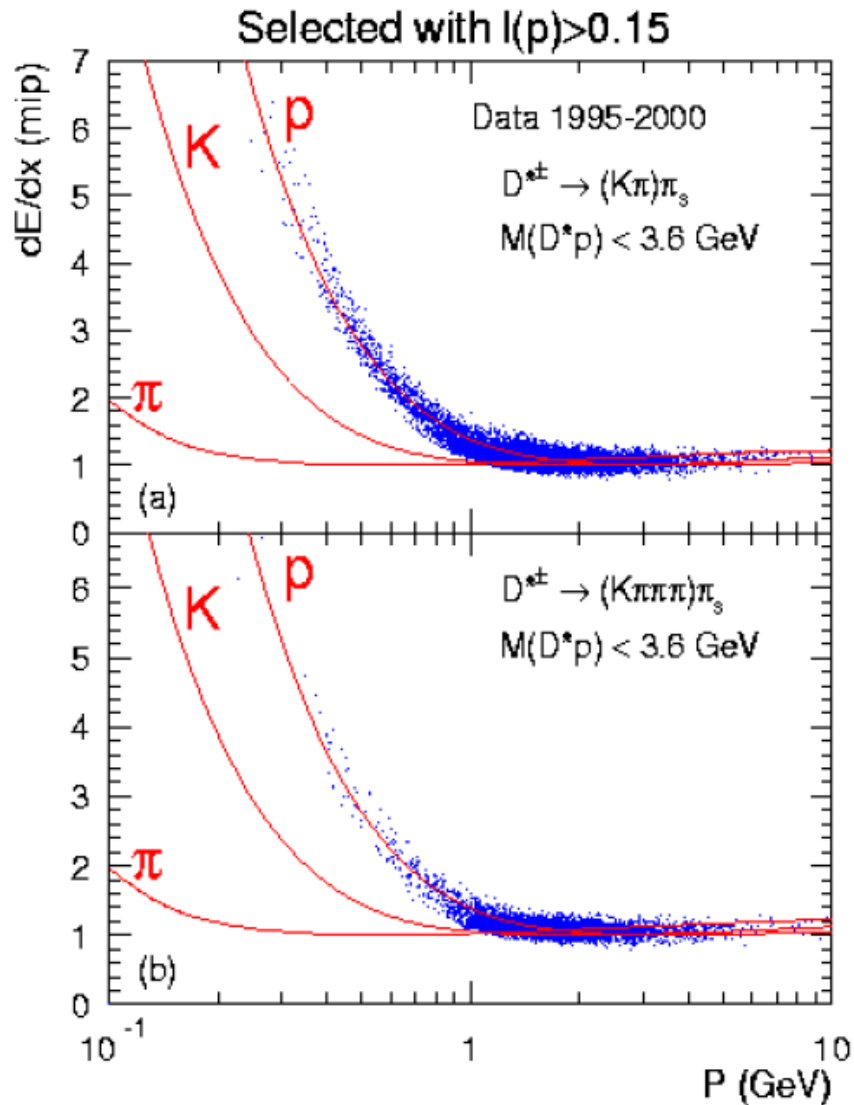
# Flavor-Violating Higgs Boson Decays



# Particle Identification (PID)



$dE/dx$  proton selection was tuned in  $\Theta_c^0$  analysis :

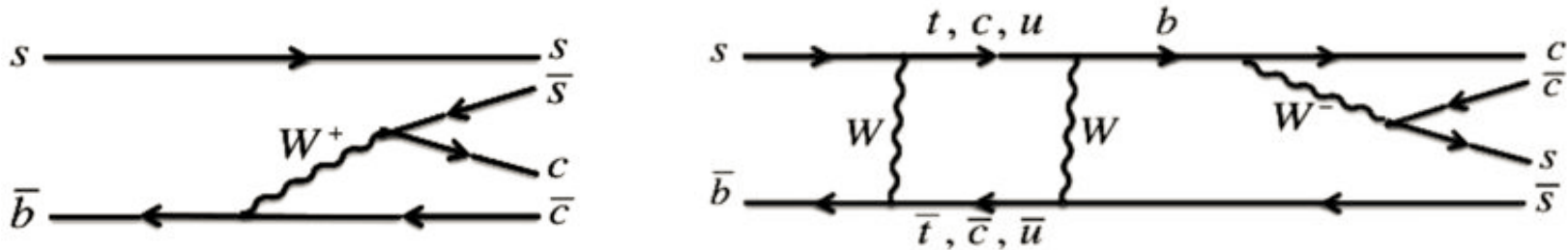


# Measurements of CP violation with $B_s \rightarrow J/\psi\phi$

The time evolution of  $B_s$  meson mixing is characterized by

- ✓ the mass difference  $\Delta m_s$  of the heavy ( $B_H$ ) and light ( $B_L$ ) mass eigenstates
- ✓ the CP-violating mixing phase  $\varphi_s$
- ✓ the width difference of  $\Delta\Gamma_s = \Delta\Gamma_L - \Delta\Gamma_H$

Interference between the  $B_s$  decays amplitudes to the CP eigenstates  $J/\psi\phi$  or via mixing gives rise to a measurable CP violating phase  $\varphi_s$



SM:

$$\phi_s \simeq -2\beta_s = -0.0363_{-0.0015}^{+0.0016} \text{ rad} \quad \beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.087 \pm 0.021 \text{ ps}^{-1}$$

New Physics could modify  $\varphi_s$  and  $\Delta\Gamma_s / \Delta m_s$  If new particles contributes to box diagrams

$PS \rightarrow VV$  decay gives orbital angular momentum  $L = 0, 1$  or  $2$

$L = 0$  or  $2$  are CP-even  
 $L = 1$  is CP-odd

PDG Name	Former Name(s)	$m$ (MeV)	$\Gamma$ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\psi_3$ (3842)		$3842.71 \pm 0.20$	$2.79 \pm 0.62$	$0^-(3^{--})^*$	$pp \rightarrow X...$	$D\bar{D}$	2019	YES
$\chi_{c0}$ (3860)		$3862^{+48}_{-35}$	$201^{+177}_{-106}$	$0^+(0^{++})$	$e^+e^- \rightarrow J/\psi(1S)X$	$D\bar{D}$	2017	NO
$\chi_{c0}$ (3915)	$X$ (3915), $Y$ (3940)	$3922.1 \pm 1.8$	$20 \pm 4$	$0^+(0/2^{++})$	$B \rightarrow KX$	$\omega J/\psi(1S)$	2004	YES
$\chi_{c2}$ (3930)	$\chi_{c2}(2P)$ , $Z$ (3930)	$3922.5 \pm 1.0$	$35.2 \pm 2.2$	$0^+(2^{++})$	$e^+e^- \rightarrow e^+e^-X$	$D\bar{D}$	2005	YES
$X$ (3940)		$3942^{+9}_{-8}$	$37^{+27}_{-17}$	$?^?(?^{??})$	$e^+e^- \rightarrow J/\psi(1S)X$	$D\bar{D}^*$	2007	NO
$T_{c\bar{c}}$ (4050)	$Z_1$ (4050) $X$ (4050)	$4051^{+24}_{-43}$	$82^{+51}_{-28}$	$1^-(?^{?+})$	$\bar{B}^0 \rightarrow K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$T_{c\bar{c}}$ (4055)	$Z_c$ (4055) $X$ (4055)	$4054 \pm 3$	$45 \pm 13$	$1^+(?^{?-})$	$e^+e^- \rightarrow \pi^-X$	$\pi^+\psi(2S)$	2015	NO
$T_{c\bar{c}}$ (4100)	$X$ (4100)	$4096^{+27}_{-30}$	$152^{+83}_{-68}$	$1^-(?^{??})$	$\bar{B}^0 \rightarrow K^-X$	$\pi^+\eta_c(1S)$	2018	NO
$\chi_{c1}$ (4140)	$Y$ (4140)	$4146.5 \pm 3.0$	$19^{+7}_{-5}$	$0^+(1^{++})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2009	YES
$X$ (4160)		$4153^{+23}_{-21}$	$136^{+60}_{-35}$	$?^?(?^{??})$	$e^+e^- \rightarrow J/\psi(1S)X$	$D^*\bar{D}^*$	2007	NO
$T_{c\bar{c}1}$ (4200)	$Z_c$ (4200)	$4196^{+35}_{-32}$	$370^{+99}_{-149}$	$1^+(1^{+-})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2014	NO
$\psi$ (4230)	$Y$ (4230) $Y$ (4260)	$4222.1 \pm 2.3$	$49 \pm 7$	$0^-(1^{--})$	$\bar{B}^0 \rightarrow K^-X$	$J/\psi(1S)\pi^+$	2014	NO
					$e^+e^- \rightarrow X$	$\pi^+\pi^-J/\psi(1S)$	2015	YES
						$\omega\chi_{c0}(1P)$		
						$\pi^+\pi^-h_c(1P)$		
						(see listings)		
$T_{c\bar{c}0}$ (4240)	$Z_c$ (4240) $R_{c0}$ (4240)	$4239^{+48}_{-21}$	$220^{+118}_{-88}$	$1^+(0^{--})$	$\bar{B}^0 \rightarrow K^-X$	$\pi^+\psi(2S)$	2014	NO
$T_{c\bar{c}}$ (4250)	$Z_2$ (4250) $X$ (4250)	$4248^{+185}_{-45}$	$177^{+321}_{-72}$	$1^-(?^{?+})$	$\bar{B}^0 \rightarrow K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$\chi_{c1}$ (4274)	$Y$ (4274)	$4286^{+8}_{-9}$	$51 \pm 7$	$0^+(1^{++})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2011	YES
$X$ (4350)		$4350.6^{+4.7}_{-5.1}$	$13^{+18}_{-10}$	$0^+(?^{?+})$	$e^+e^- \rightarrow e^+e^-X$	$\phi J/\psi(1S)$	2009	NO
$\psi$ (4360)	$Y$ (4360)	$4374 \pm 7$	$118 \pm 12$	$0^-(1^{--})$	$e^+e^- \rightarrow X$	$\pi^+\pi^-\psi(2S)$	2007	YES
$T_{c\bar{c}1}$ (4430)	$Z_c$ (4430)	$4478^{+15}_{-18}$	$181 \pm 31$	$1^+(1^{+-})$	$\bar{B}^0 \rightarrow K^-X$	$\pi^+\pi^-J/\psi(1S)$	2007	YES
						$\pi^+\psi(2S)$		
						$\pi^+J/\psi(1S)$		
$\chi_{c0}$ (4500)	$X$ (4500)	$4474 \pm 4$	$77^{+12}_{-10}$	$0^+(0^{++})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2017	NO
$X$ (4630)		$4626^{+24}_{-111}$	$174^{+137}_{-78}$	$0^+(?^{?+})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2021	NO
$\psi$ (4660)	$Y$ (4660), $X$ (4660)	$4641 \pm 10$	$72^{+13}_{-11}$	$0^-(1^{--})$	$e^+e^- \rightarrow X$	$\pi^+\pi^-\psi(2S)$	2007	YES
						$A_1^+ \bar{A}_1^-$		
						$D_s^+ D_{s1}(2536)$		
$\chi_{c1}$ (4685)		$4684^{+15}_{-17}$	$126^{+40}_{-44}$	$0^+(1^{++})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2021	NO
$\chi_{c0}$ (4700)	$X$ (4700)	$4694^{+16}_{-5}$	$87^{+18}_{-10}$	$0^+(0^{++})$	$B^+ \rightarrow K^+X$	$\phi J/\psi(1S)$	2017	NO
$T_{c\bar{c}\bar{c}}$ (6900)	$X$ (6900)	$6899 \pm 12$	$153 \pm 29$	$0^+(?^{?+})$	$pp \rightarrow X...$	$J/\psi(1S)J/\psi(1S)$	2020	NO
$\Upsilon$ (10753)		$10752.7^{+5.9}_{-6.0}$	$36^{+18}_{-12}$	$?^?(1^{--})$	$e^+e^- \rightarrow X$	$\pi\pi\Upsilon(1S, 2S, 3S)$	2019	NO
$\Upsilon$ (10860)	$\Upsilon(5S)$	$10885.2^{+2.6}_{-1.6}$	$37 \pm 4$	$0^-(1^{--})$	$e^+e^- \rightarrow X$	$B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}(\pi)$	1985	YES
						$\pi\pi\Upsilon(1S, 2S, 3S)$		
						$\pi^+\pi^-h_b(1P, 2P)$		
						$\eta\Upsilon(1S, 2S)$		
						$\pi^+\pi^-\Upsilon(1D)$		
						(see listings)		
$\Upsilon$ (11020)	$\Upsilon(6S)$	$11000 \pm 4$	$24^{+8}_{-6}$	$0^-(1^{--})$	$e^+e^- \rightarrow X$	$B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}(\pi)$	1985	YES
						$\pi\pi\Upsilon(1S, 2S, 3S)$		
						$\pi^+\pi^-h_b(1P, 2P)$		
						(see listings)		

above open-flavor threshold

