Flavor Physics @ CEPC
a survey

Based on:
Oxford meeting, April, 2019
Peking University, July, 2019
IHEP CEPC meeting, Nov. 2019

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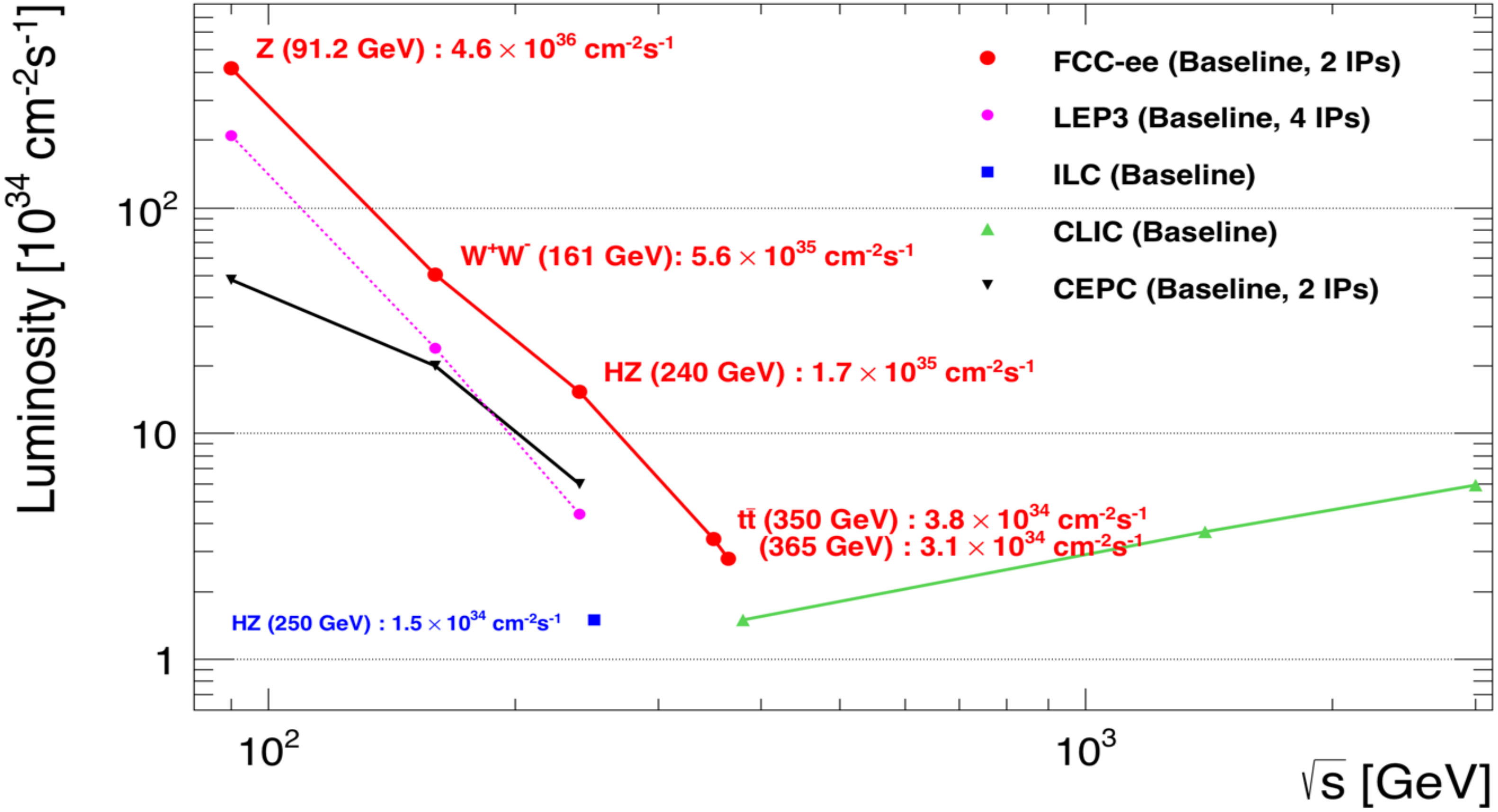
Luminosities

From A. Blondel: Oxford



Z peak	E_{cm} : 91 GeV	10^{12}	e+e- → Z	LEP x 10^5
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 10^3
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	N/A
$t\bar{t}$ threshold	E_{cm} : 350 GeV	??	e+e- → $t\bar{t}$	N/A

Flavors Production at different experiments

Particle	@ Tera-Z	@ Belle II		@ LHCb
b hadrons				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ 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}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

Huge amount of charmed hadrons more than trillions

Hadrons contain double heavy quarks can be produced at CEPC and LHCb .

Key probes with flavors

- *CP* violation in quark and lepton sectors

  CPV in B/Bs/D/Ds/Bc mesons

  CPV in b-baryon and c-baryon decays

  CPV in tau production and decays,

  tau EDM

- FCNC processes:

  rare *b*-decays , rare charm,

  cLFV in tau decays

  FCNC in Z decays

- Measurements of Polarization, Forward-backward asymmetries, etc.

New hadron spectroscopy @ Z pole

Leading experiments on Heavy quarks

LHCb sees all species of *b*- and c-particles, and is especially good at rare decays with muons and fully charged decay modes.

However less efficient for electrons, neutrals, missing energy.

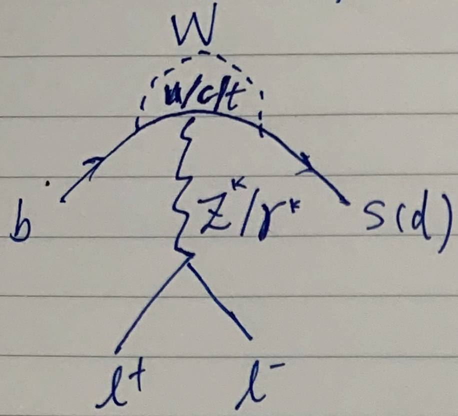
The backgrounds are complicated for a hadron machine.

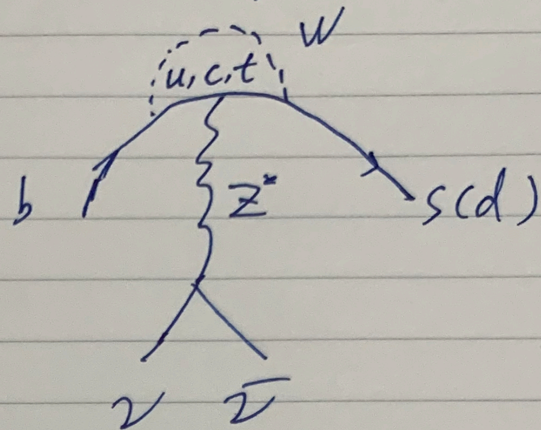
Belle II should explore deeply the B_d and B_u meson systems.

Might also runs above the Υ(5S) threshold but can't resolve the oscillation and TD CPV of B_s meson, and cannot do Bc and b-baryons.

DATE : ..../......./.......

FCNC : "New" in loop





$l = e, \mu, \tau$

$B^0 \to K^{(*)} l^+ l^-$
$B_s \to \phi\, l^+ l^-$ } 10^{-6}

$B_c^+ \to D_s^{(*)+} l^+ l^-$

$B^0 \to l^+ l^-$ 10^{-10}

$B_s \to l^+ l^-$ $BR(\mu^+\mu^-) \sim 10^{-9}$

$\Lambda_b \to \Lambda^{(*)} l^+ l^-$ } 10^{-6}

$B^0 \to K^{(*)} \nu \bar{\nu}$
$B_s \to \phi\, \nu \bar{\nu}$
$\Lambda_b \to \Lambda \nu \bar{\nu}$ } $10^{-6} \sim 10^{-7}$

$B_c^+ \to D_s^+ \nu \bar{\nu}$

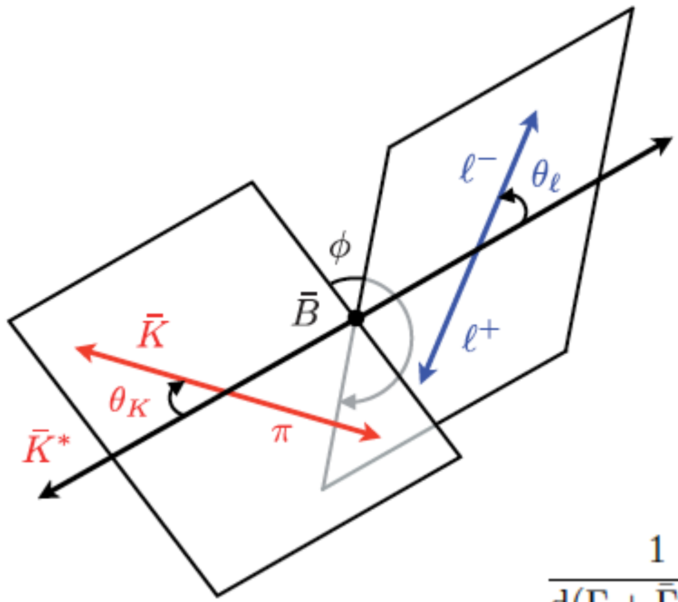
$B^0 \to \nu \bar{\nu}$
$B_s^0 \to \nu \bar{\nu}$ } zero

Highlights: rare decays

FCNC processes: DNA for new physics

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

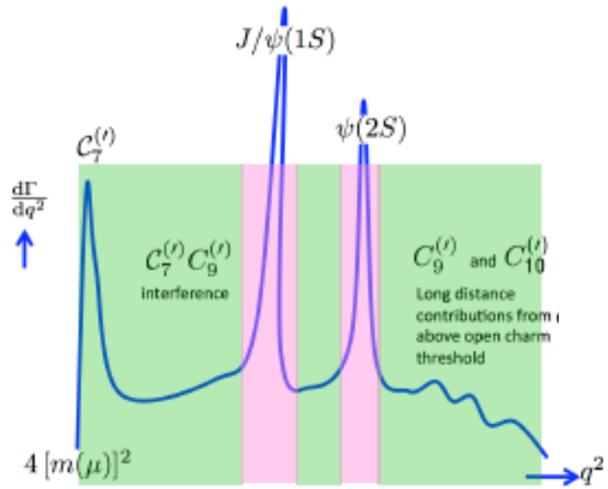
Angular analysis: $B^0 \rightarrow K^* \mu^+ \mu^-$



Rich information in the angular analysis

1) Polarizations
2) Forward-backward asymmetry
3) Access to amplitudes of K*
4) Access to Wilson coefficients
5) 8 observables in the fit

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$



Local tension is still there

LHCb: arXiv:2003.04831

$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$

Run1+2016: 2.5σ

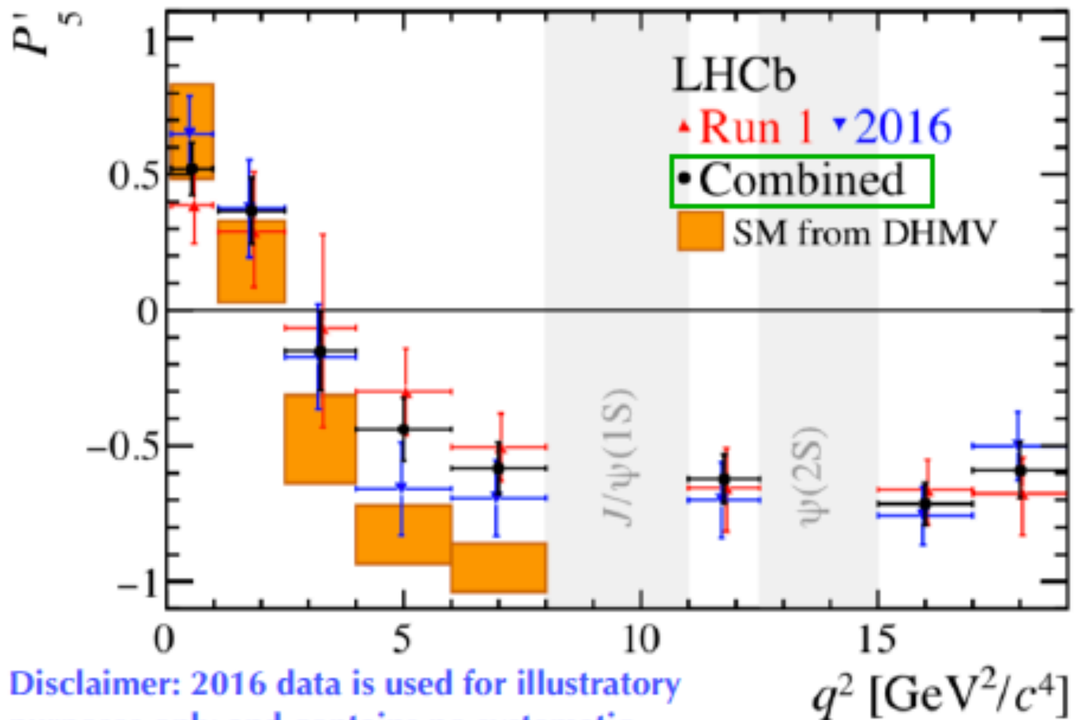
Run1 only: 2.8σ

$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$

Run1+2016: 2.9σ

Run1 only: 3.0σ

Theory predictions from JHEP 12 (2014) 125, JHEP 09 (2010) 089,



Disclaimer: 2016 data is used for illustratory purposes only and contains no systematic uncertainties or bias and coverage corrections

b→s $\tau^+\tau^-$ at CEPC

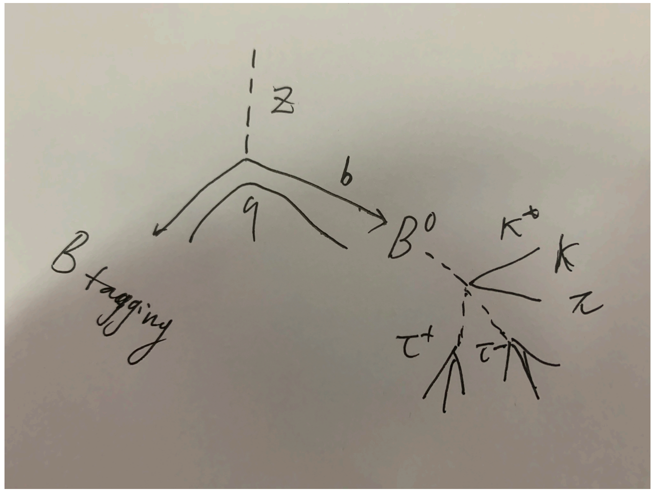
PhysRevLett.120.181802
Phys. Rev. D **93**, 034005
Phys. Rev. D **96**, 053006

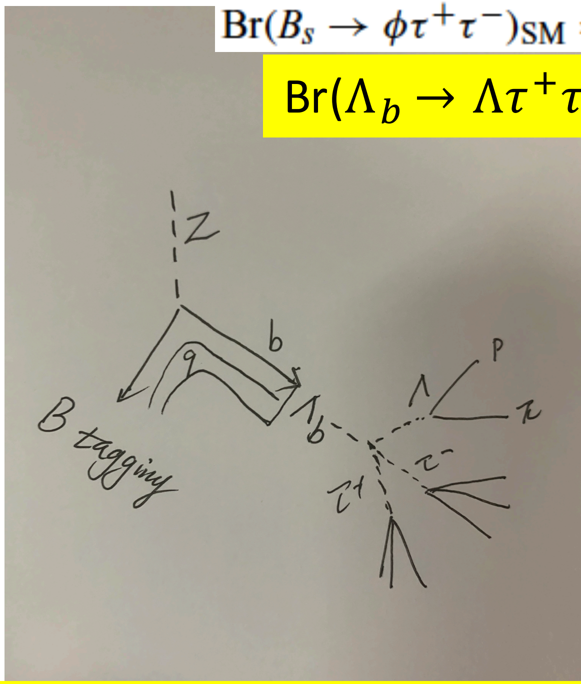
- Performance of mass resolution of mu+mu-
- Background?
- tauonic decay modes: B→K*$\tau^+\tau^-$,

  $\Lambda_b \to \Lambda\tau^+\tau^-$
- Invisible modes: B→K* $\nu\bar{\nu}$?

$$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)_{\mathrm{SM}} = (1.22 \pm 0.10) \cdot 10^{-7},$$
$$\mathrm{Br}(B^0 \to K^0\tau^+\tau^-)_{\mathrm{SM}} = (1.13 \pm 0.09) \cdot 10^{-7},$$
$$\mathrm{Br}(B^+ \to K^{*+}\tau^+\tau^-)_{\mathrm{SM}} = (0.99 \pm 0.12) \cdot 10^{-7},$$
$$\mathrm{Br}(B^0 \to K^{*0}\tau^+\tau^-)_{\mathrm{SM}} = (0.91 \pm 0.11) \cdot 10^{-7},$$
$$\mathrm{Br}(B_s \to \phi\tau^+\tau^-)_{\mathrm{SM}} = (0.73 \pm 0.09) \cdot 10^{-7},$$

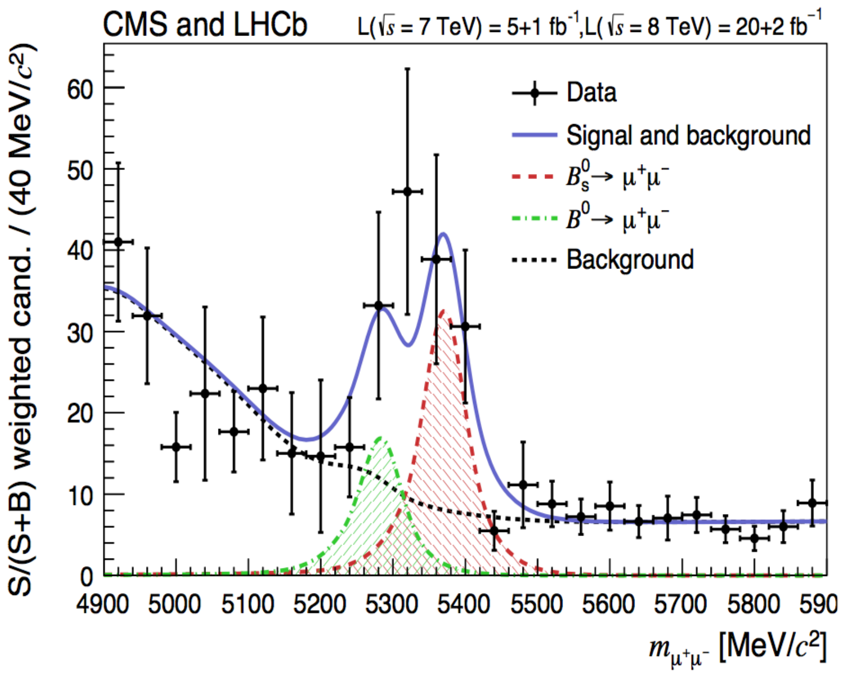
$$\mathrm{Br}(\Lambda_b \to \Lambda\tau^+\tau^-) = 2\times10^{-7}$$

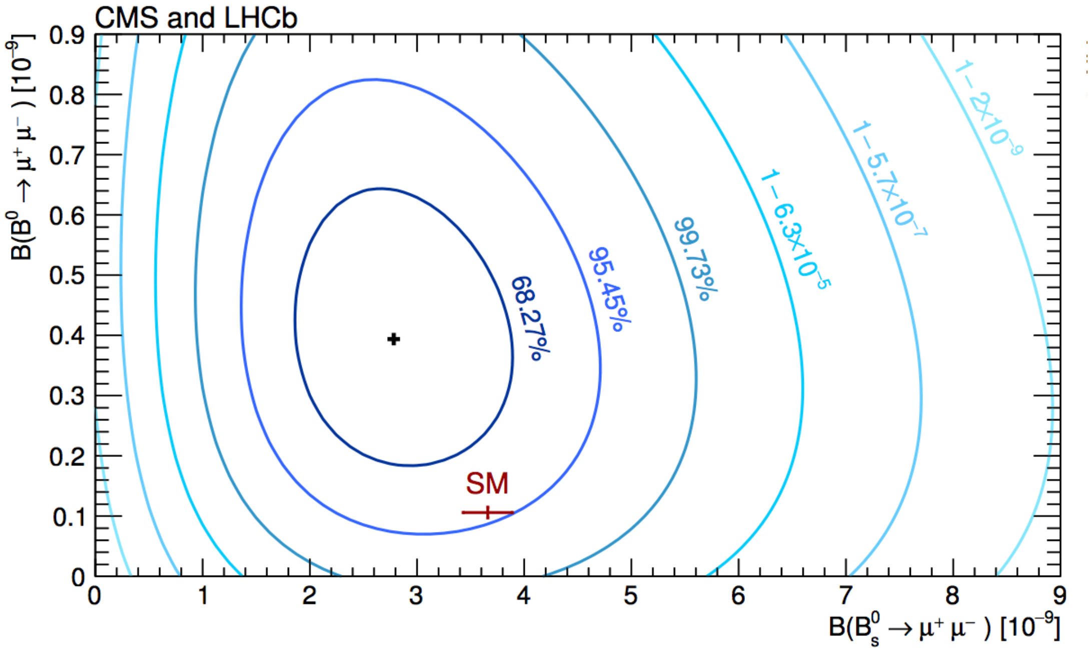




Discovery potential of New Physics: FCNC

FCNC:　pure leptonic decays





LHCb and CMS, arXiv:1411.4413

$$B(B^0 \to \mu\mu) = (3.94^{+1.58+0.31}_{-1.41-0.24}) \times 10^{-10} (3.2\sigma)$$

$$B(B_s \to \mu\mu) = (2.79^{+0.66+0.26}_{-0.60-0.19}) \times 10^{-10} (6.2\sigma)$$

$$B(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

$$B(B_s \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-10}$$

Theory: Bobeth et al. PRL 112(2014)101801

FCNC： pure tauonic decays

C. Bobeth et al., Phys. Rev. Lett. **112**, 101801 (2014)

$$\mathrm{Br}(B_s \to \tau^+\tau^-)_{\mathrm{SM}} = (7.73 \pm 0.49) \cdot 10^{-7},$$

$$\mathrm{Br}(B_d \to \tau^+\tau^-)_{\mathrm{SM}} = (2.22 \pm 0.19) \cdot 10^{-8}.$$

BelleII cannot reach SM predictions.

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–

Detailed study at CEPC should be done.

b→s $\nu\bar{\nu}$ at CEPC

- SM predicts rates of $b \to s\nu\bar{\nu}$ decays at the level of few $\times 10^{-6}$

  (e.g. WA, Buras, Straub, Wick 0902.0160; Buras, Girrbach, Niehoff, Straub 1409.4557)

- SM rates of $B \to K^{(*)}\nu\bar{\nu}$ can be observed at Belle II.

Observables	Belle $0.71\,\text{ab}^{-1}$ ($0.12\,\text{ab}^{-1}$)	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\text{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\text{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%

(Belle II Physics Book 1808.10567)

b→s $\nu\bar{\nu}$ at CEPC

- In addition to $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$, CEPC can also access $B_s \to \phi\nu\bar{\nu}$ and $\Lambda_b \to \Lambda\nu\bar{\nu}$

- Combined study of

  $B \to K\nu\bar{\nu}$ (pseudo-scalar to pseudo-scalar)

  $B \to K^*\nu\bar{\nu}$ and $B_s \to \phi\nu\bar{\nu}$ (pseudo-scalar to vector)

  $\Lambda_b \to \Lambda\nu\bar{\nu}$ (spin 1/2 to spin 1/2)

  can be used to determine the chirality structure of the short distance interactions.

b→s $\nu\bar{\nu}$ at CEPC

- Naive expectation:

  Sensitivities for $B \to K^{(*)}\nu\bar{\nu}$ should be at least as good as Belle II.

  At Belle II the recoiling B needs to be fully reconstructed
  $\to$ big hit in efficiencies. Not neccessary at CEPC.

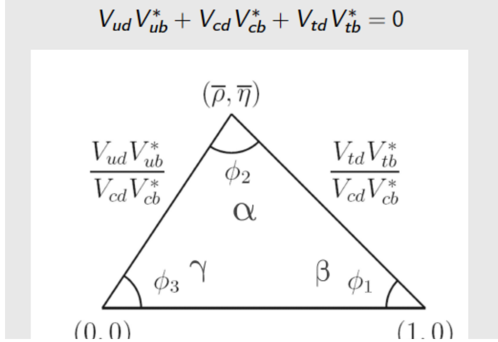
  At CEPC similar sensitivities for $B_s \to \phi\nu\bar{\nu}$ and $\Lambda_b \to \Lambda\nu\bar{\nu}$ as well.
  (not accessible at Belle II).

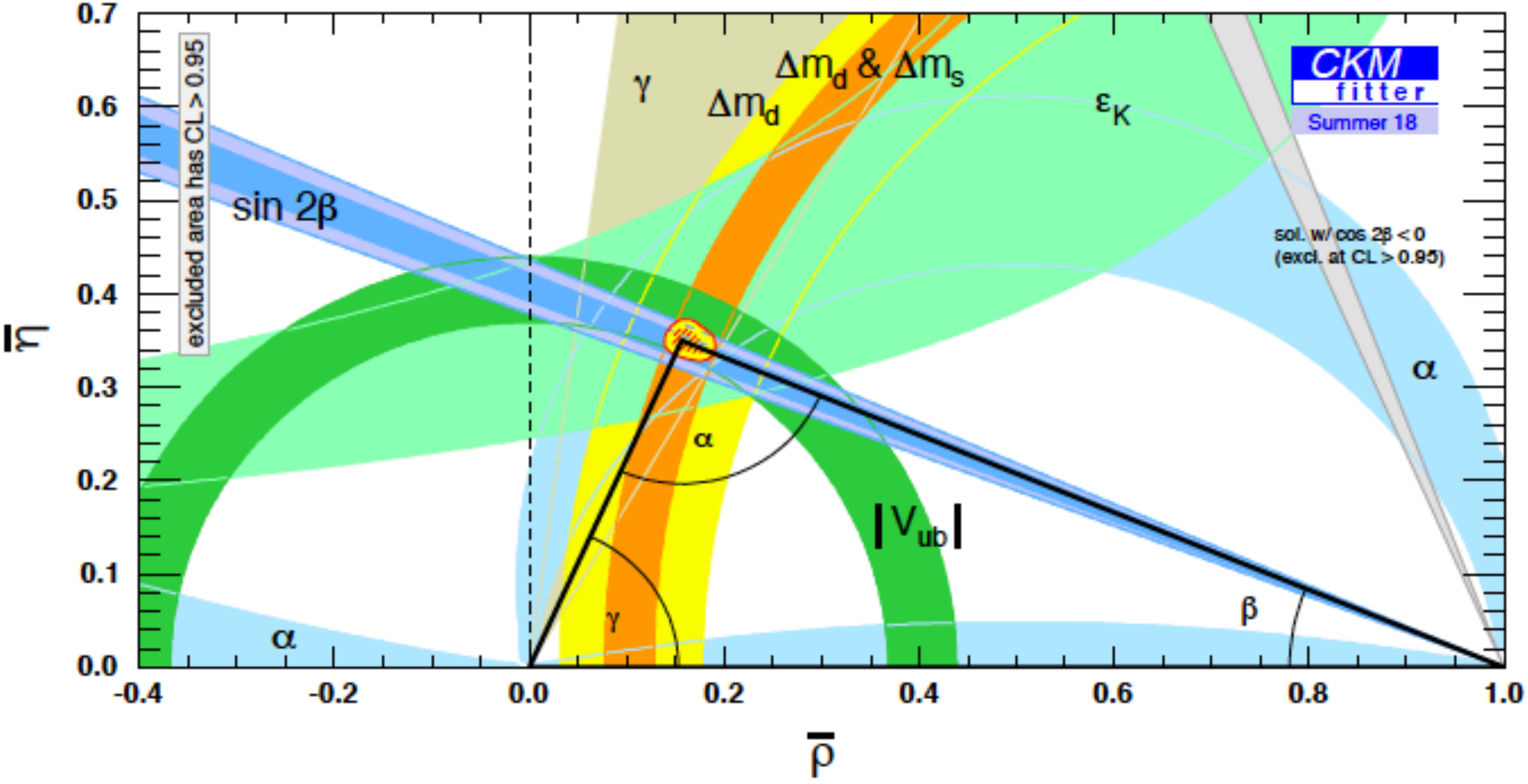
- Signature of $B \to K\nu\bar{\nu}$: single charged track + missing energy.
- Study is under way to estimate the CEPC sensitivity.

- for the K^*, ϕ final states, one can get the B vertex from the decays $K^* \to K\pi$, $\phi \to KK$.

$\Rightarrow$ might further improve the sensitivities.

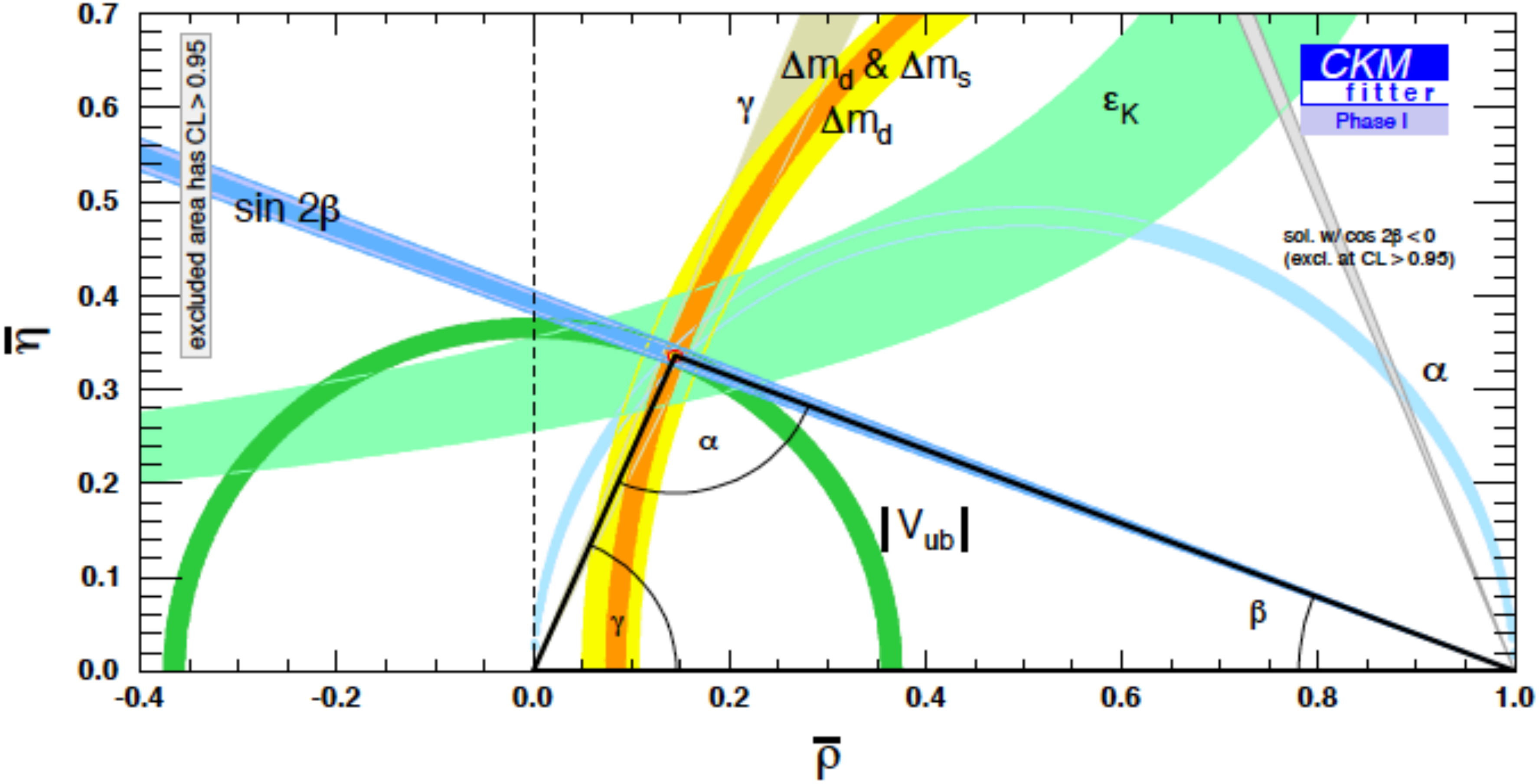
CKM and CPV





Summer 2018

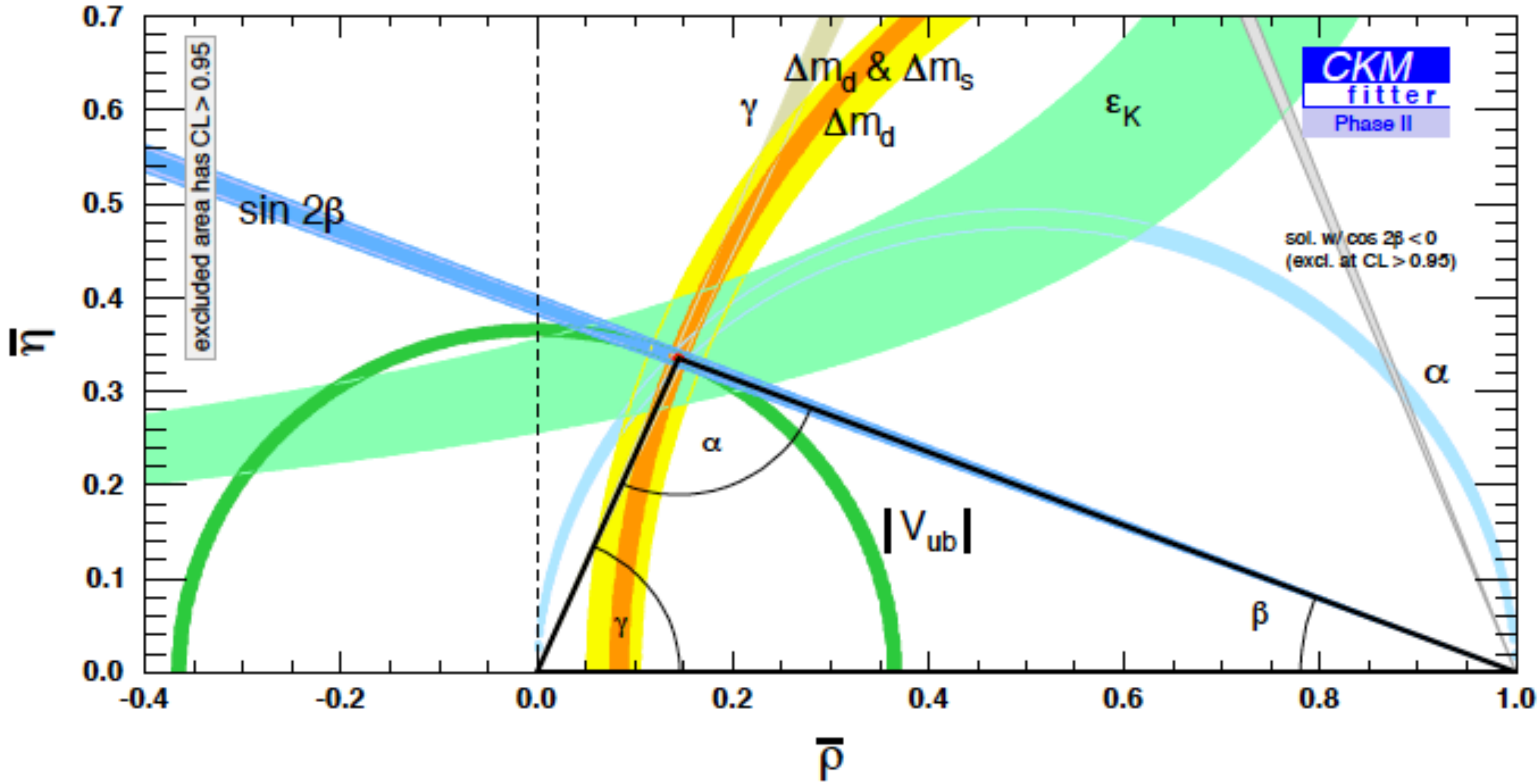
Phase-I



Phase 1 ($\simeq$ 2025)

LHCb 27 fb^{-1}, CMS/ATLAS 300 fb^{-1}, Belle II 50 ab^{-1}

Phase-II



Phase 2 ($\simeq$ 2035)

LHCb 300 fb^{-1}, CMS/ATLAS 3000 fb^{-1}, Belle II 50 ab^{-1}

Improvement on CKM matrix

	Summer 18	Current	Phase I	Phase II
A	0.0129	0.0120	0.0058	0.0057
λ	0.0002	0.0007	0.0004	0.0004
$\bar{\rho}$	0.0085	0.0085	0.0027	0.0018
$\bar{\eta}$	0.0083	0.0087	0.0024	0.0015
$\lvert V_{ub} \rvert$	0.000076	0.000096	0.000027	0.000023
$\lvert V_{cb} \rvert$	0.00073	0.00070	0.00026	0.00025
$\lvert V_{td} \rvert$	0.00017	0.00014	0.00006	0.00006
$\lvert V_{ts} \rvert$	0.00068	0.00054	0.00026	0.00025
$\sin 2\beta$	0.012	0.015	0.004	0.003
α (°)	1.4	1.4	0.4	0.3
γ (°)	1.3	1.3	0.4	0.3
β_s (rad)	0.00042	0.00042	0.00012	0.00010

Current = Summer 18 with perfect agreement of inputs with SM

Beauty hadrons @CEPC

	CEPC (10^{12} Z)	Belle II (50 ab^{-1} @$\Upsilon(4S)$ & 5 fb^{-1} @$\Upsilon(5S)$)	LHCb (50 fb^{-1})
$B^{\pm}/B^0$	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	10^{8}	-	6×10^{10}
b baryons	10^{10}	-	10^{13}

CEPC vs. Belle II: access to B_s, B_c, Λ_b; much larger boost, resulting in better reconstruction of $D_{(s)}$ and τ vertices (this helps fighting background without tagging the 2nd B). However the energy of the initial meson/baryon is unknown.

CEPC vs. LHCb: lower yields but cleaner environment, lower background; much better access to final states with neutrals (photons, π^0 ...).

Possibly best $b \to c$ and $b \to u$ channels @CEPC

$B \to \tau\nu$: extraction of $|V_{ub}|$ and test of NP; BR at the level of 10^{-4}.
$B \to D^{(*)}\tau\nu$ and $B_s \to D_s^{(*)}\tau\nu$: test LFU/LFV NP in $b \to c$ by taking the ratio with the corresponding $(\mu, e)\nu$ channels; BR at the level of 10^{-2}.
$B \to \pi(\rho)\tau\nu$ and $B_s \to K^{(*)}\tau\nu$: same as above, for $b \to u$; BR at the level of 10^{-5}.
$B_c \to \eta_c, J/\Psi\ell\nu$: extraction of $|V_{cb}|$; BR at the level of 10^{-2}.
$B_c \to \eta_c, J/\Psi\tau\nu$: again test LFU/LFV BP in $b \to c$; BR at the level of 10^{-2}.
All these channels need further work to compare CEPC performance wrt LHCb.

$B_c \to \tau\nu$: extraction of $|V_{cb}|$ and test of NP; BR at the level of 10^{-2}.
$B_c \to \tau\nu$ is presumably impossible at LHCb: a golden channel for CEPC ?

Inclusive versions of the above channels are also interesting complementary measurements that cannot be performed at a hadron collider.

Bc decays

- The B_c is largely uncharted territory.
- Several decay modes are "seen" at the LHC, but no well established normalization mode exists

The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\overline{b} \to B_c)$.

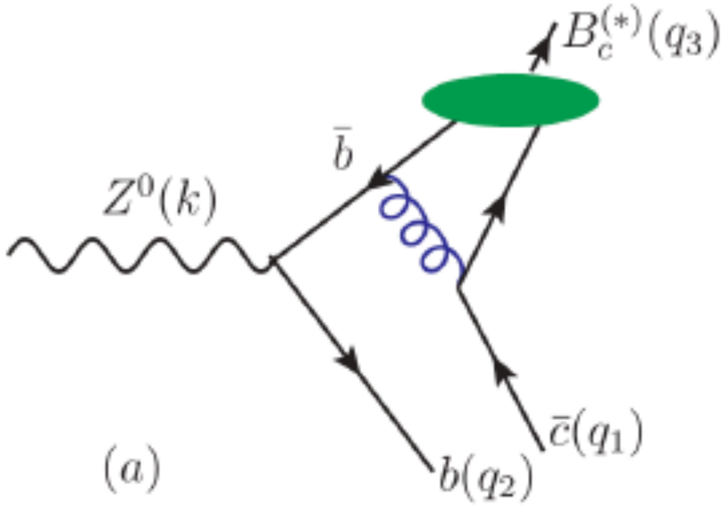
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	$(8.1 \pm 1.2) \times 10^{-5}$		
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$			
Γ_3	$J/\psi(1S)\tau^+\nu_\tau$			
Γ_4	$J/\psi(1S)\pi^+$	seen		
Γ_5	$J/\psi(1S)K^+$	seen		
Γ_6	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen		
Γ_7	$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$	90%
Γ_8	$J/\psi(1S)K^+K^-\pi^+$	seen		
Γ_9	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen		
Γ_{10}	$\psi(2S)\pi^+$	seen		
Γ_{11}	$J/\psi(1S)D^0K^+$	seen		
Γ_{12}	$J/\psi(1S)D^*(2007)^0K^+$	seen		
Γ_{13}	$J/\psi(1S)D^*(2010)^+K^{*0}$	seen		
Γ_{14}	$J/\psi(1S)D^+K^{*0}$	seen		
Γ_{15}	$J/\psi(1S)D_s^+$	seen		
Γ_{16}	$J/\psi(1S)D_s^{*+}$	seen		
Γ_{17}	$J/\psi(1S)p\overline{p}\pi^+$	seen		
Γ_{18}	$\chi_c^0\pi^+$	$(2.4\ ^{+0.9}_{-0.8}) \times 10^{-5}$		
Γ_{19}	$p\overline{p}\pi^+$	not seen		
Γ_{20}	D^0K^+	$(3.8\ ^{+1.2}_{-1.0}) \times 10^{-7}$		

Bc production at Z pole

- B_c has not been seen at LEP.

- Theory predictions suggest $\mathrm{BR}(Z \to B_c + X)$ could be as large as $\sim 10^{-4}$
  (e.g. Braaten et al. hep-ph/9305206,
  Deng et al. 1009.1453,
  Yang et al. 1305.4828)

$\Rightarrow$ up to $\sim 10^8$ B_c mesons from 10^{12} Z bosons



$$\mathcal{B}(Z \to B_c + b + \bar{c}) : \ 10^{-4}$$

For recent review on Bc production at Z : arXiv:1701.04561

Event generator on Z peak: arXiv:1305.4828

Bc→ $\tau\nu$

- Hard for LHCb, not reachable for Belle II, $Br(B_c \to \tau^- \bar{\nu}_\ell) = O(2\%)$
- Two lattice determinations
  - $f_{B_c} = 427 \pm 6$ MeV (McNeile et al. 2012)
  - $f_{B_c} = 434 \pm 15$ MeV (Colquhoun et al. 2015)
- Original constraint for $|V_{cb}|$ (helping solve discrepancy)

$$\mathrm{BR}(B_c \to \tau\nu) : \mathrm{BR}(B_c \to \mu\nu) : \mathrm{BR}(B_c \to e\nu) = m_\tau^2 : m_\mu^2 : m_e^2$$

$B^- \to \tau\nu$

- Already studied (but difficult, many backgrounds) at Babar and Belle, measured at $Br(B \to \tau\nu) = (1.09 \pm 0.24) \times 10^{-4}$
- Many lattice determinations with FLAG average (2+1 flavours): $f_B = 192 \pm 4.3$ MeV

Bc→ $\tau\nu$ and B → $\tau\nu$ are background each other ?

Bc decays @ Z peak

$B_c \to \tau^+ \nu_\tau$ 3% PLB 414 (1997) 130

< 10% from LEP1 PRD 96(2017)075011

$B_c \to J/\psi l^+ \nu_l$ 1.36% PRD 68(2003)094020

$B_c \to J/\psi \pi^+$ 6.4×10^{-4} PRD90(2014) 094007

$B_c \to B_s \pi^+$ 10% Estimated based on LHCb measuremnt PRD 94(2016) 034036

$B_c \to B_s + anything$

$B_c \to J/\psi + anything$

$$R = \frac{\mathcal{B}(B_c \to J/\psi \tau \nu)}{\mathcal{B}(B_c \to J/\psi l \nu)}$$

Exciting new spectroscopy awaiting discovery

- narrow exotics with $Q\bar{Q}$: BESIII &LHCb Belle
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$ molecules

– *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450)$ $\Rightarrow$ photoproductior
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$

- doubly charmed baryon found exactly where predicted
  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !
- $cc\bar{c}\bar{c}$ @ 6,192$\pm$25 MeV, $bb\bar{b}\bar{b}$ @ 18,826$\pm$25 MeV $\Rightarrow 4\ell$
- quark-level analogue of nuclear fusion

Calculation of tetraquark $bb\bar{u}\bar{d}$ mass

From Marek CEPC Peking meeting 2019

build on accuracy of the Ξ_{cc} mass prediction

$$V(bb) = \frac{1}{2}V(\bar{b}b)$$

to obtain lowest possible mass, assume:

- $bb\bar{u}\bar{d}$ in S-wave
- $\bar{u}\bar{d}$: $\mathbf{3_c}$ "good" antidiq., S=0, I=0 (it's the lightest one)

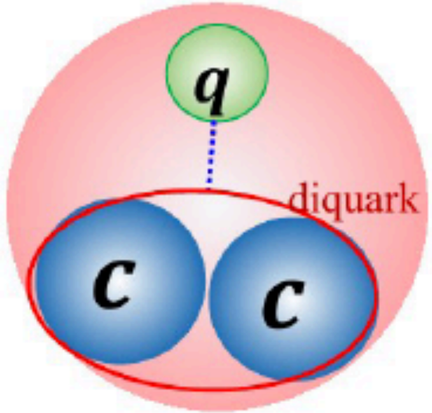
$\Rightarrow$ bb must be $\bar{3}_c$; Fermi stats: spin 1

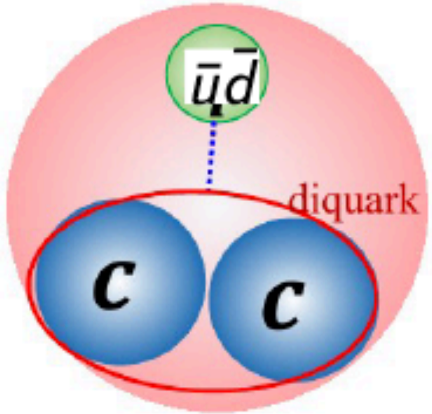
$(bb)_{S=1}\,(\bar{u}\bar{d})_{S=0} \Rightarrow J^P = 1^+$.

$\Rightarrow$ $(bb)\,(\bar{u}\bar{d})$ very similar to bbq baryon:

$q \leftrightarrow (\bar{u}\bar{d})$

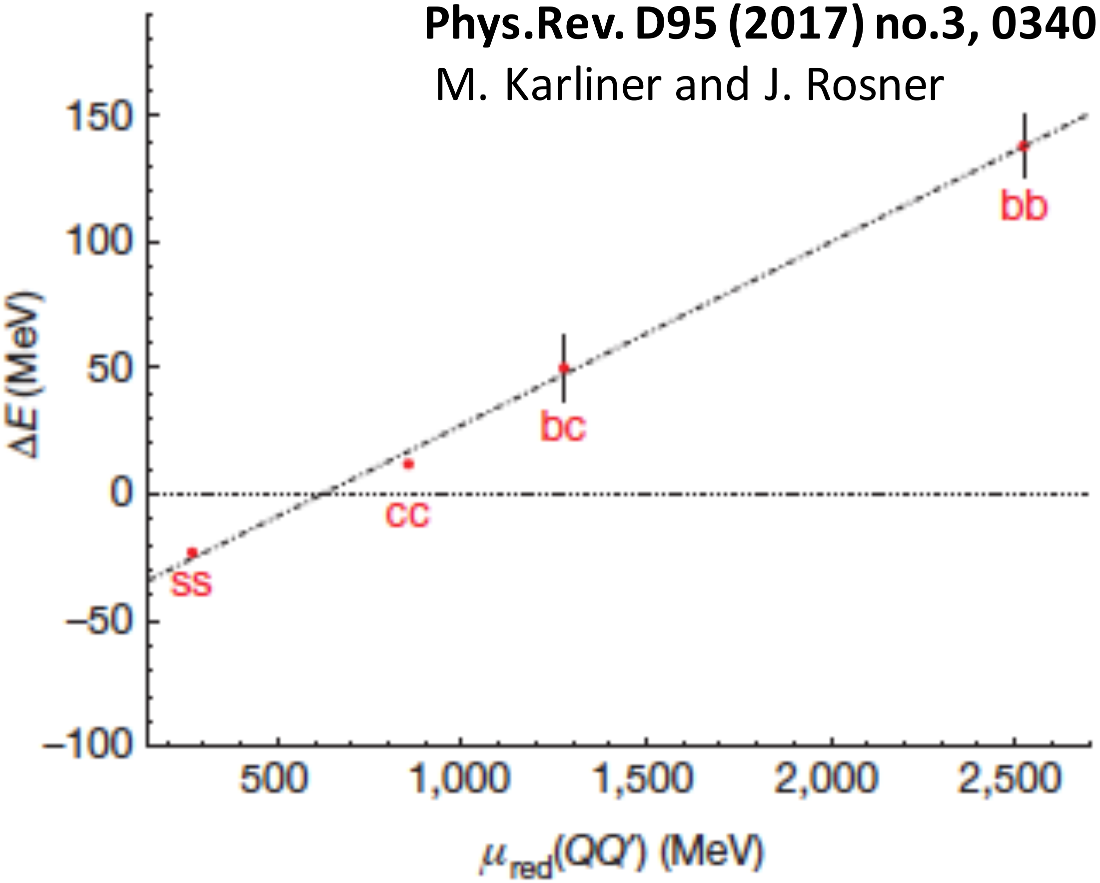
bbq baryon





M. Karliner, Heavy exotics   CEPC, PKU, Beijing, 2 July 2019   44

Nature 551 (2017) 89
Phys.Rev.Lett. 119 (2017) no.20, 202001
Ann.Rev.Nucl.Part.Sci. 68 (2018) 17-44
Phys.Rev. D95 (2017) no.3, 034011
M. Karliner and J. Rosner



(bb)q
(bb)(qq)
(bc)q
(bc) (qq)
(cc)q
(cc)(qq)
(ss)q
(ss)qq

Figure 2 | The energy release ΔE in the quark-level fusion reactions $\Lambda_Q\Lambda_{Q'} \rightarrow \Xi_{QQ'}N$, where $Q, Q' \in \{s, c, b\}$, plotted against the reduced masses of the doubly heavy diquarks, $\mu_{red}(QQ')$. The dot-dashed line denotes the linear fit: $\Delta E = -44.95 + 0.0726\mu_{red}$. The error bars denote the uncertainty of the theoretical predictions.

Tetraquark production

$$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lesssim \sigma(pp \to \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

$$\left.\begin{array}{l} \{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d} \end{array}\right\} \quad \begin{array}{ccc} P(\bar{u}\bar{d}) & \lesssim & P(q) \\ \mathbf{3}_c & & \mathbf{3}_c \end{array}$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
with much more $\int \mathcal{L} dt$

$bb\bar{u}\bar{d}$ decay channels

(a) "standard process" $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$.

$(bb\bar{u}\bar{d}) \to D^0\bar{B}^0\pi^-,\ D^+B^-\pi^-$

$(bb\bar{u}\bar{d}) \to J/\psi K^-\bar{B}^0,\ \ J/\psi\bar{K}^0B^-$.

$(bb\bar{u}\bar{d}) \to \Omega_{bc}\,\bar{p},\ \ \Omega_{bc}\,\bar{\Lambda}_c,\ \ \Xi^0_{bc}\,\bar{p},\ \ \Xi^0_{bc}\,\bar{\Lambda}_c$

In addition, a rare process where *both* $b \to c\bar{c}s$,

$(bb\bar{u}\bar{d}) \to J/\psi J/\psi K^-\bar{K}^0$.

striking signature: $2J/\psi$-s from same 2ndary vertex

(b) The W-exchange $b\bar{d} \to c\bar{u}$

e.g. $(bb\bar{u}\bar{d}) \to D^0B^-$.

M. Karliner, Heavy exotics CEPC, PKU, Beijing, 2 July 2019

$T(bb\bar{u}\bar{d})$ Summary

From Marek CEPC Peking meeting 2019

- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifesty exotic stable hadron
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$, $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
  7134 $\pm$ 13 MeV, 11 MeV below $\bar{B}^0D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
  3882 $\pm$ 12 MeV, 7 MeV above the D^0D^{*+}

Inclusive signature of (bbx): displaced B_c

T. Gershon & A. Poluektov JHEP 1901 (2019) 019

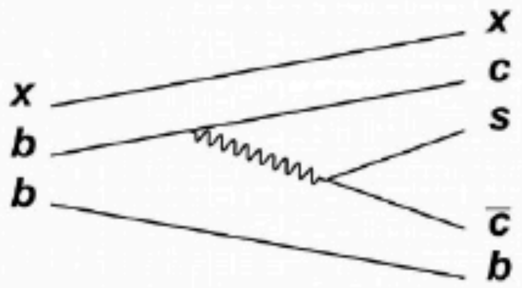
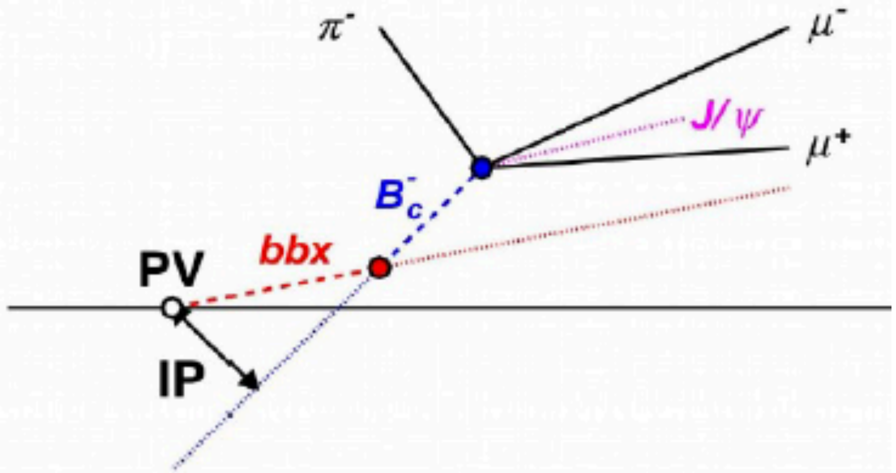


Diagram for production of a B_c^- meson from a double beauty hadron decay.



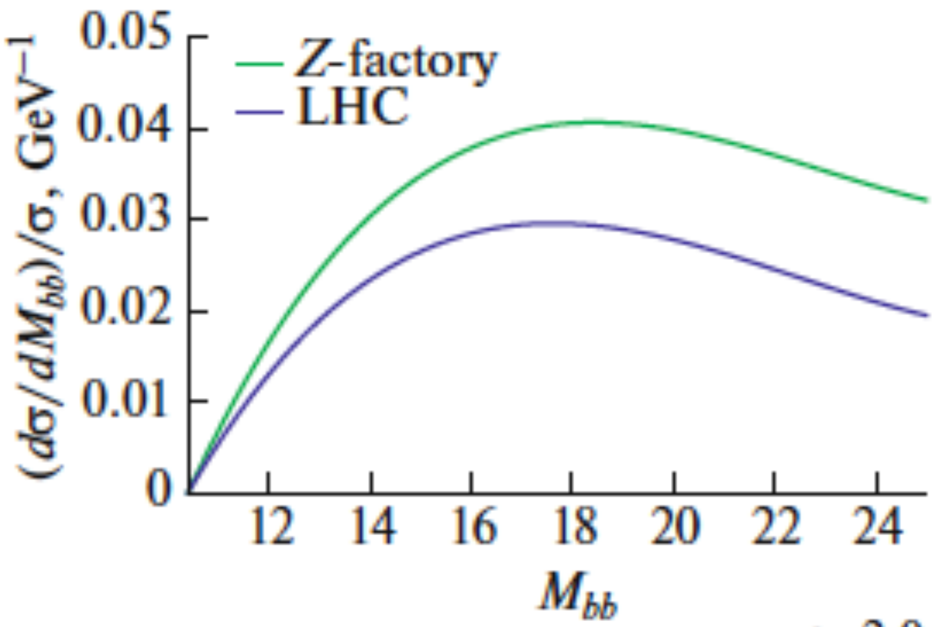
$\mathcal{O}(1\%)$ of all B_c-s @LHC come from bbx

- major enhancement of eff. bbx rate
- bbq or $bb\bar{u}\bar{d}$?

incl. $\sigma(bbx)$:
heavy ions $\gg$ pp

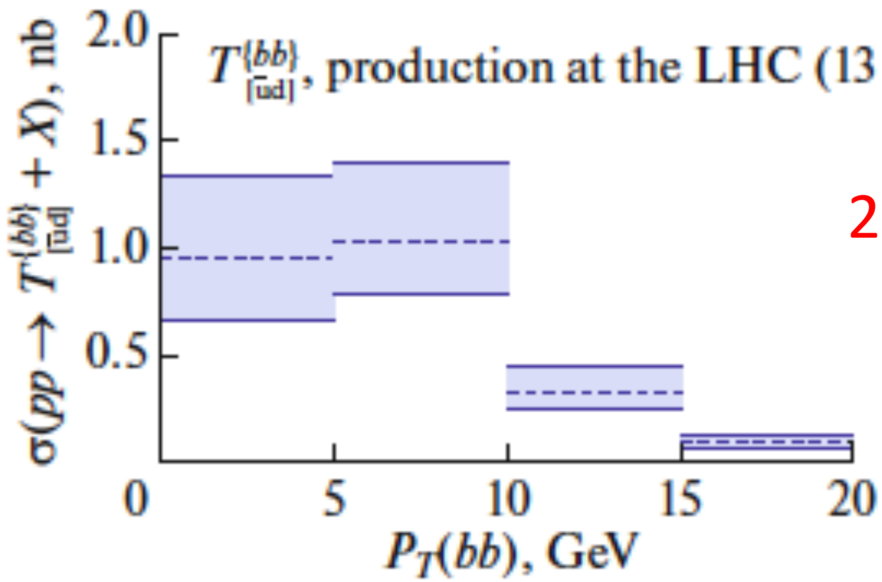
$\Rightarrow$ displaced B_c @ALICE & RHIC !

Productions: doubly heavy Tetraquark



Phys.Part.Nucl.Lett.
16 (2019) no.5, 481-485

A. Ali A.Ya. Parkhomenko , Q. Qin ,W. Wang



2.8 nb

Access to doubly heavy Tetraquark at CEPC

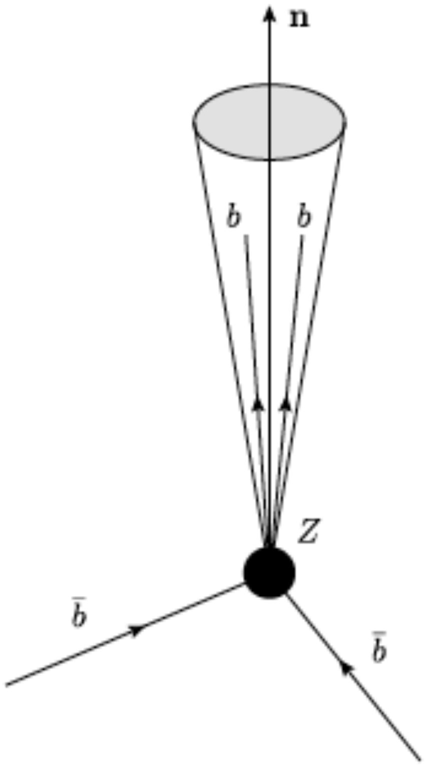
- $bb\bar{q}\bar{q}'$: PLB 782(2018) 412

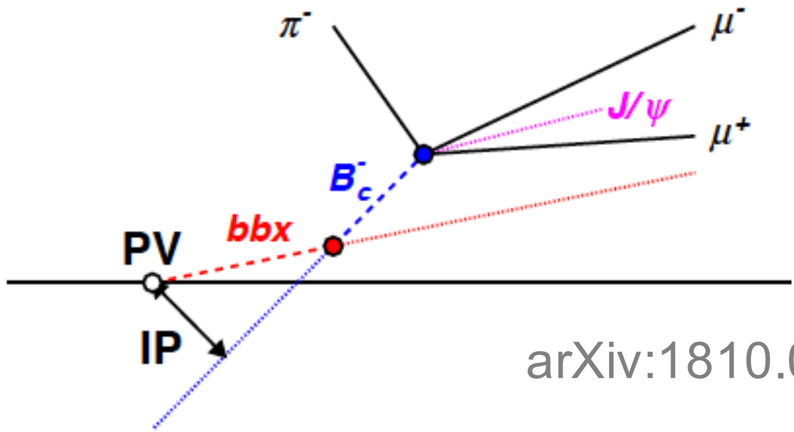
$$\mathcal{B}(Z \to bb\bar{b}\bar{b}) = (3.6 \pm 1.3) \times 10^{-4}$$ LEP 98

$$\mathcal{B}(Z \to T^{bb}_{\bar{q}\bar{q}'} + \bar{b}\bar{b}) = (1.2^{+1.0}_{-0.3}) \times 10^{-6}$$

$$\tau(T^{bb}_{\bar{q}\bar{q}'}) : \quad 300 - 800 fs$$

PRL 119(2017)20
PRD90(2014) 094007





arXiv:1810.06657

Thresholds for $Q\bar{Q}'$ molecular states

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a]Ignoring annihilation of quarks. [b]Plus other charge states when $I \neq 0$.
[c]Based on isospin-averaged masses. [d]Thresholds differ by 27.6 MeV.

M. Karliner, Heavy exotics CEPC, PKU, Beijing, 2 July 2019

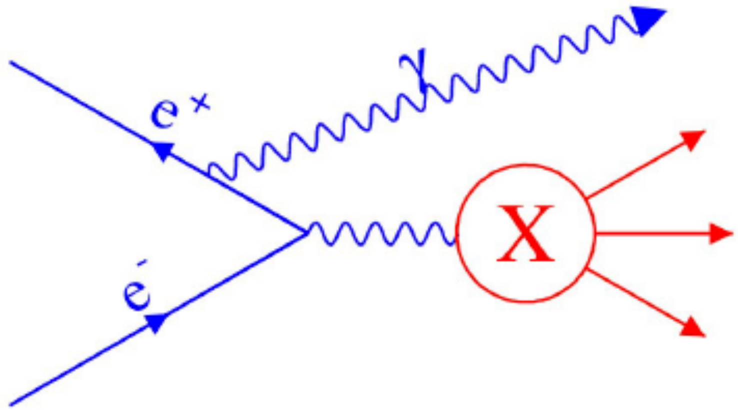
ISR Physics: access to different thresholds

CEPC: $\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1}

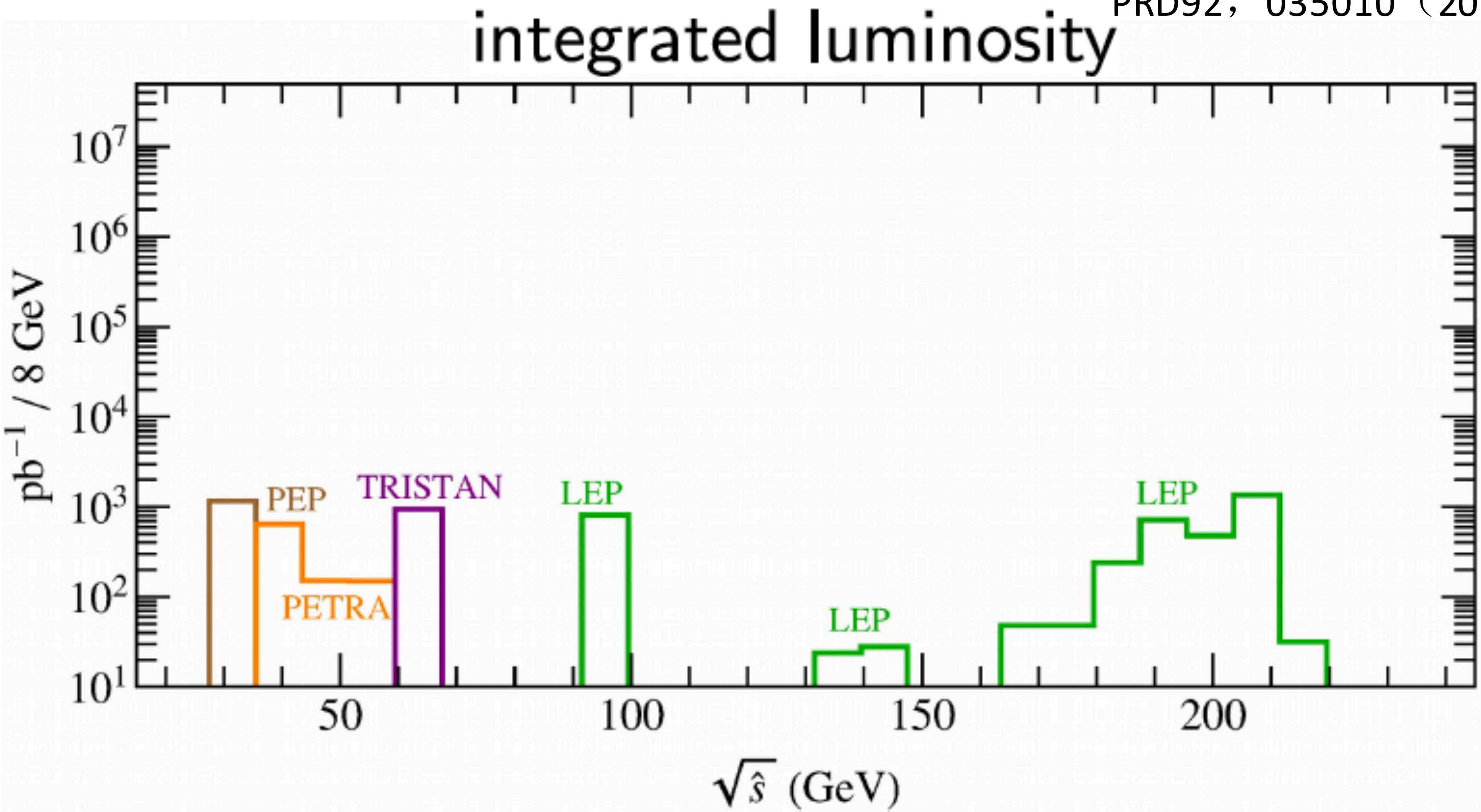
with rad. ret. can explore

interesting physics

significantly *below* design E_{CM}.



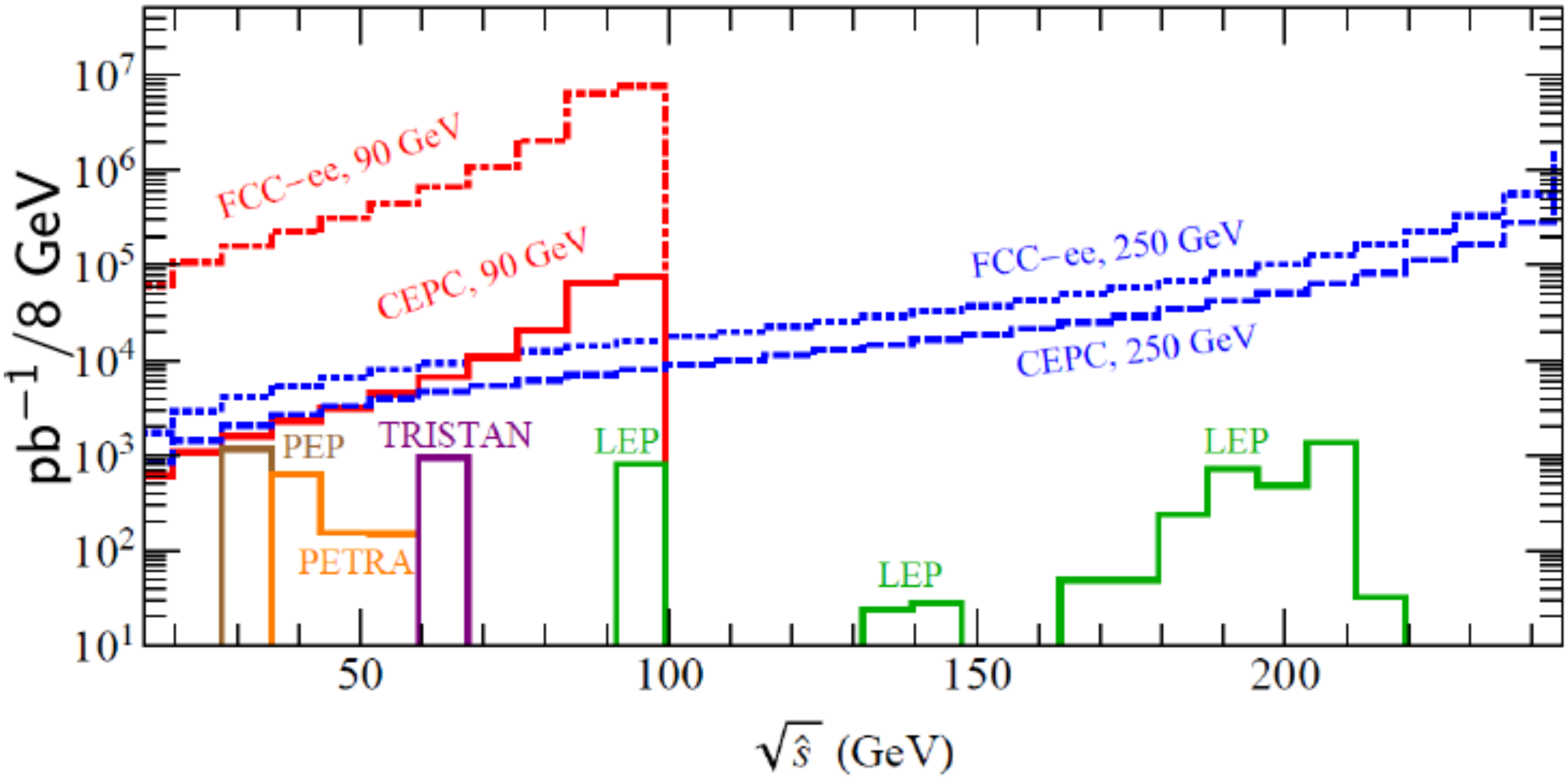
PRD92，035010（2015）



gaps left by PEP, PETRA, TRISTAN and LEP

PRD92，035010（2015）

integrated luminosity



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

interesting thresholds for heavy flavor production in e^+e^-

PRD92，035010（2015）

Final state	Threshold (MeV)
$B\bar{B}$	10559
$B\bar{B}^*$	10605
$B^*\bar{B}^*$	10650
$B_s\bar{B}_s$	10734
$B_s\bar{B}_s^*$	10782
$B_s^*\bar{B}_s^*$	10831
$B_{s0}\bar{B}_s^*$	11132–11193[a]
$\Lambda_b\bar{\Lambda}_b$	11239
$B_c\bar{B}_c$	12551
$B_c\bar{B}_c^*$	12619–12635[b]
$B_c^*\bar{B}_c^*$	12687–12719[b]
$\Xi_{bc}\bar{\Xi}_{bc}$	13842–13890[c]
$\Xi_{bb}\bar{\Xi}_{bb}$	20300–20348[c]

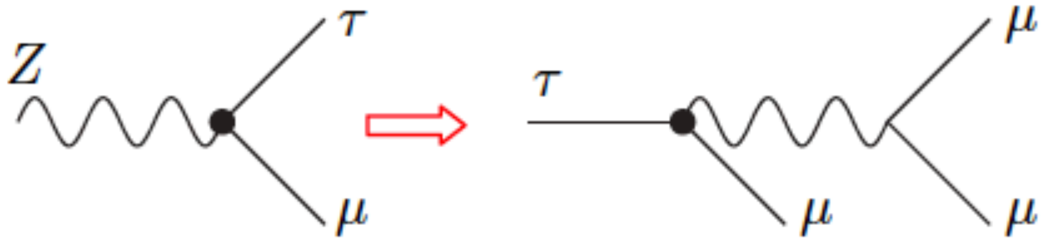
Belle-II energy

FCNC： cLFV in Z decays

Lorenzo 2019

4×10^6 Z → LEP bounds	LHC bounds
no candidates → $\mathrm{BR}(Z\to\mu e)<1.7\times10^{-6}$	$\mathrm{BR}(Z\to\mu e)<7.5\times10^{-7}$ ← 8 TeV, 20/fb
Z→ττ bg. → $\mathrm{BR}(Z\to\tau e)<9.8\times10^{-6}$	$\mathrm{BR}(Z\to\tau e)<5.8\times10^{-5}$ ← 13 TeV, 36/fb
$\mathrm{BR}(Z\to\tau\mu)<1.2\times10^{-5}$	$\mathrm{BR}(Z\to\tau\mu)<1.3\times10^{-5}$ ← 8+13 TeV comb.
OPAL '95, DELPHI '97	ATLAS '14, '18

- LHC searches limited by backgrounds (in particular $Z\to\tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- CEPC can definitely reach better sensitivities
- Severe indirect constraints from low-energy LFV observables, e.g.:



Is Z LFV still interesting?

FCNC： cLFV in Z decays

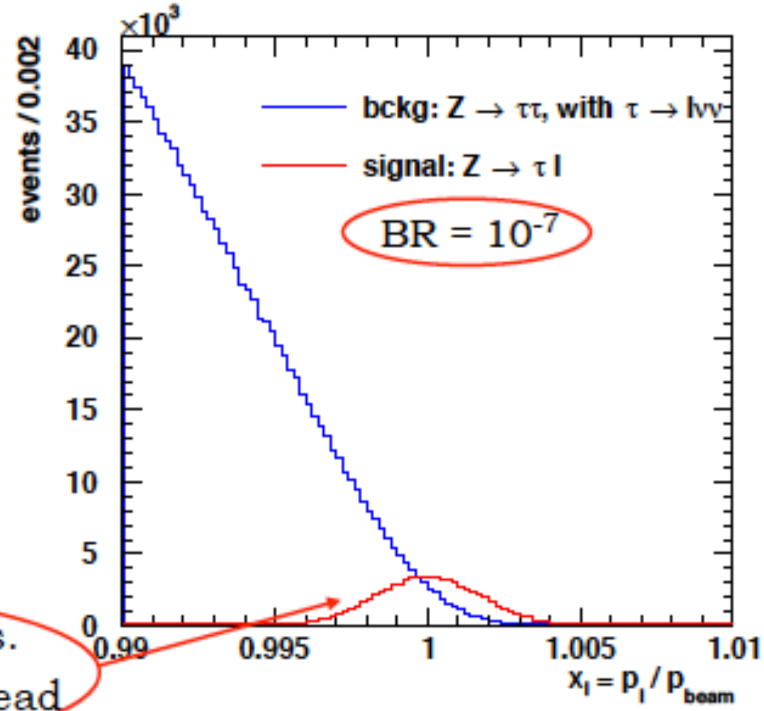
FCC physics opportunities
Eur. Phys. J. C (2019) 79:474

- $Z \to \ell\tau$:

To avoid mis-id, select one hadronic $\boldsymbol{\tau}$ (>3 prong, or reconstructed excl. mode)

Main background from $Z \to \boldsymbol{\tau\tau}$ (with one leptonic $\boldsymbol{\tau}$ decay)

Simulated signal & background:



~10^{-3} momentum res.
& ~10^{-3} collision E spread

Sensitivity:
$\mathrm{BR}(Z \to \ell\tau) \sim 10^{-9}$

Z LFU tests

Universality presently tested at the per-mil level

LEP exps/SLD combination hep-ex:0509008

$$\frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

(1.7×10^7 Z decays at LEP + 6×10^5 Z decays with polarised beams at SLC)

- Very important test in view of the LFU anomalies in B decays
- With 10^{12} Z, CEPC has no problem of statistics
- Can systematics (lepton-id efficiencies? what else?) be controlled so as to measure BRs with e.g. 10^{-4} precision?

⇨ We need your input!

(Q: *Is any EW precision expert studying this?*)

Lorenzo
Peking University
2019

Z WG outlook

Lorenzo
Peking University
2019

Ideal wish list:

LFV: Study of the muon mis-id for μ-e

Signal & background study for ℓ-τ

LFU: Estimate of the achievable precision given the systematics

Personal (more *realistic*) view:

$Z \to \mu e$ is a nice process *but*

barring extreme tuning indirect bounds overwhelming

(sensitivity on $\mu \to e$ LFV will improve > ×1000 within a decade!)

For $Z \to \ell\tau$ we can readapt FCC-ee simulation

The priority should be to focus Z LFU assessment!

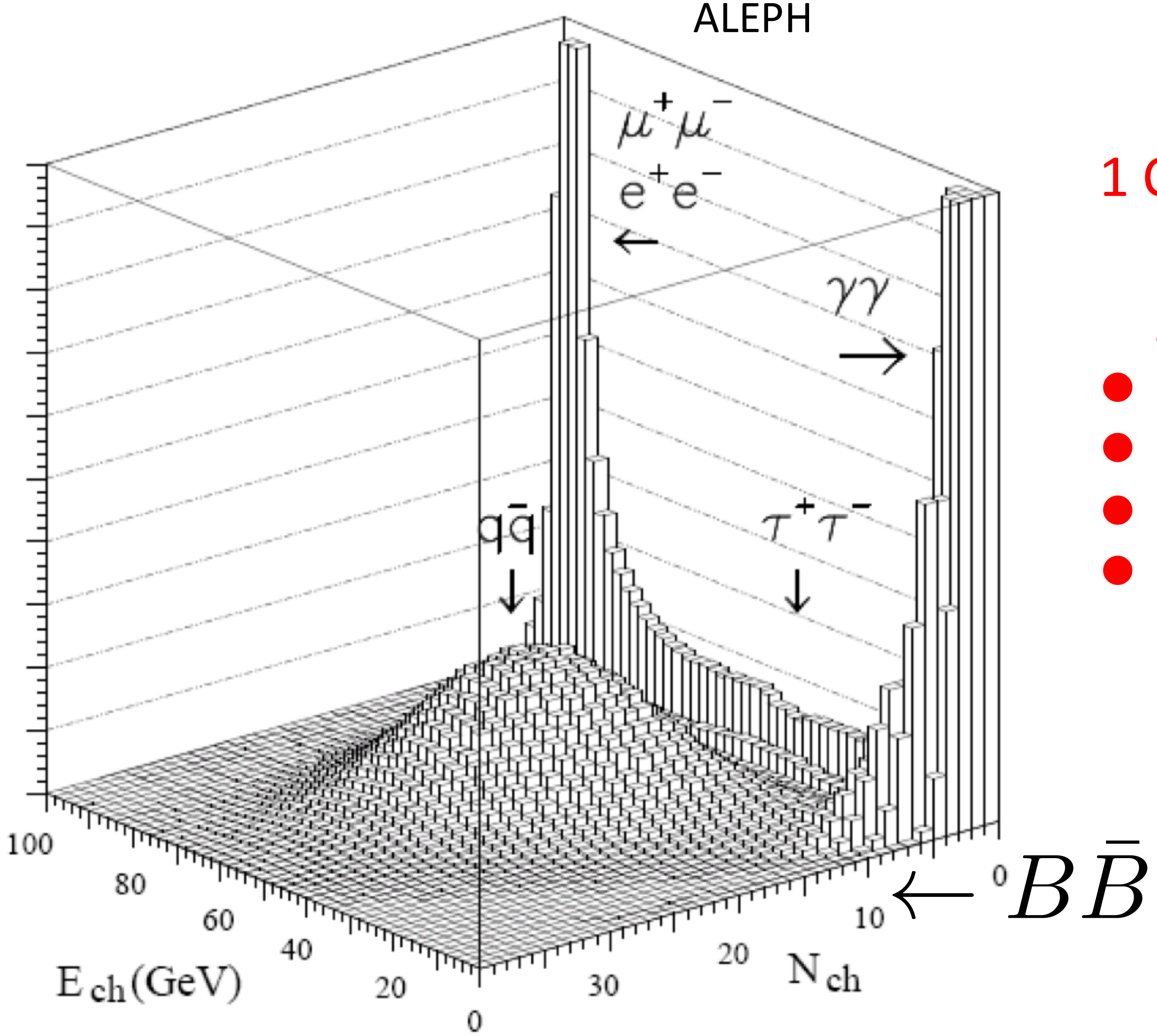
tau lepton at Z peak

Advantage of tau experiment at Z peak:

- Large production cross-section (1.5 nb)
- Strong boost, decay length: 2 mm
- Back-to-back event topology, 80% efficiency
- Background clean
- Good lepton and K_L ID

Disadvantage: K/pi ID is challenge

tau lepton reconstruction @ Z peak

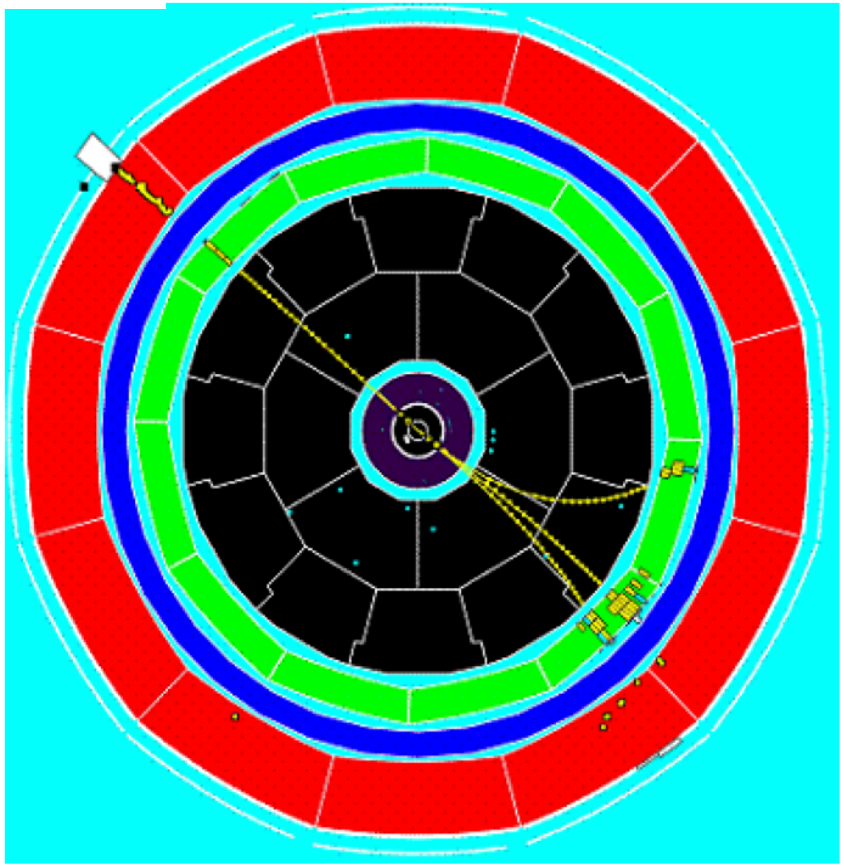


1 Clean $\tau\tau$ events can be selected with very simple selection criteria:

- Low track multiplicity
- Back-to-back
- Low invariant mass
- Total energy not very small

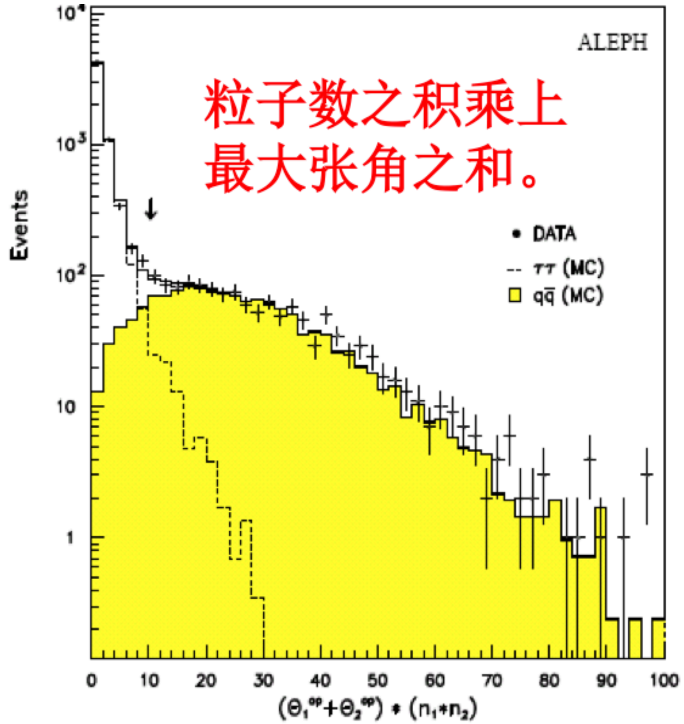
tau lepton reconstruction at Z-peak

ALEPH



Ecm≈91 GeV

Z.Phys.C70:579-608,1996



Physics processes	Efficiency (%)	Contamination (%)
$Z^0 \to \tau^+\tau^-$	78.84 ± 0.13	
Bhabha		0.15 ± 0.03
$Z^0 \to \mu^+\mu^-$		0.07 ± 0.02
$\gamma\gamma \to e^+e^-$		0.07 ± 0.02
$\gamma\gamma \to \mu^+\mu^-$		0.08 ± 0.02
four-fermion		0.14 ± 0.02
cosmic rays		0.02 ± 0.01
$Z^0 \to q\bar{q}$		0.31 ± 0.09

丢失的效率是因几何造成的

Belle: 10% efficiency

Requirement

- For charged tracks
  - Good momentum measurement
  - Good π/K separation (PID for tracks up to 30GeV?)
  - Good vertex: lifetime, background suppression
- For γ/π^0
  - Good geometric coverage
  - Fine granularity with longitudinal readout
  - Good energy resolution and angular resolution
  - Low photon energy threshold: < 200 MeV

τ Data Samples

ALEPH:	$3.3 \cdot 10^5$ reconstructed τ decays	
BaBar / Belle:	$1.4 \cdot 10^9$ $\tau^+\tau^-$ pairs	
Belle-II:	$4.6 \cdot 10^{10}$ $\tau^+\tau^-$ pairs	
SτCF:	$2.1 \cdot 10^{10}$ $\tau^+\tau^-$ pairs	(10^8 near threshold)

Proposed Super Tau-Charm

A. Pich @ Future Tau-Charm Factory '18

CEPC potential as a "Tera-Z factory":

$$\mathrm{BR}(Z \to \tau^+\tau^-) \simeq 3.4\%$$

$$10^{12}\ Z \quad \Longrightarrow \quad 3 \times 10^{10}\ \tau^+\tau^-$$

Tau physics @ Z pole

tau properties: lifetime, mass,

(g-2)_tau (10^{-6}-10^{-7}), EDM (10^{-19} e cm)

Weak Dipole Moments

Tau: CPV (10^{-4})

tau decay measurements

Lepton Universality test (LUT)

charged Lepton flavor violation (cLFV) (10^{-10})

Vus

branching fractions (10^{-5})

hadron spectral function

Tau LFU： prospects

M. Dam @ Tau '18 & 1811.09408

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.005	0.12	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.005	< 0.040	Vertex detector alignment
$B(\tau \to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	No estimate; possibly 0.003	Efficiency, bkg, Particle ID
$B(\tau \to \mu\nu\nu)$ [%]		17.39 ± 0.05			

$(g_\tau/g_{e\mu}) = 1.0020 \pm 0.0013$
$[g_{e\mu} = g_e = g_\mu$ assuming $g_e = g_\mu]$

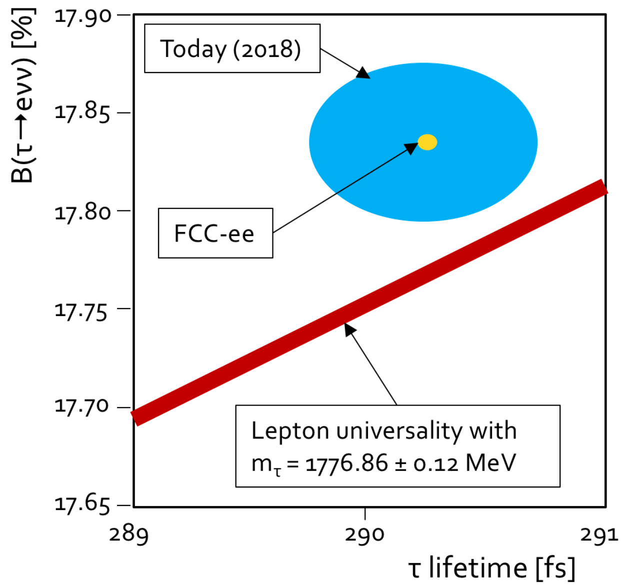
$\Delta(g_\tau/g_{e\mu})$ contributions

input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.178%	0.089%
τ_τ	0.172%	0.086%
m_τ	0.007%	0.017%
total		0.125%

best measurements

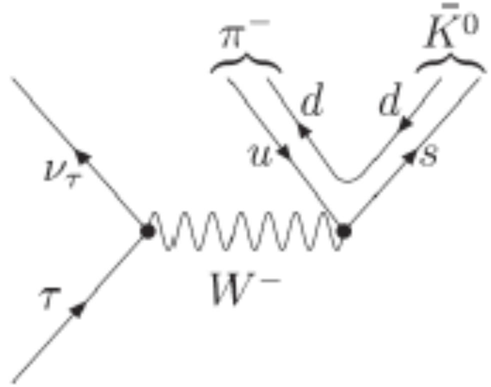
$\mathcal{B}'_{\tau\to e}$	ALEPH
τ_τ	Belle
m_τ	BES III

- $\mathcal{B}'(\tau \to e\bar{\nu}\nu) = \text{average of} \begin{cases} \mathcal{B}(\tau \to e\bar{\nu}\nu) \\ \mathcal{B}(\tau \to \mu\bar{\nu}\nu)\cdot f_{\tau e}/f_{\tau\mu} \end{cases}$
- $$\frac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)\tau_\mu}{\mathcal{B}(\mu \to e\bar{\nu}\nu)\tau_\tau} = \frac{g_\tau^2}{g_{e\mu}^2}\,\frac{m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^\tau}{m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}$$
- $$\left(\frac{g_\tau}{g_{e\mu}}\right)^2 = \frac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)}{\mathcal{B}(\mu \to e\bar{\nu}\nu)}\,\frac{\tau_\mu}{\tau_\tau}\,\frac{m_\mu^5}{m_\tau^5}\,\frac{f_{\mu e} R_\gamma^\mu R_W^\mu}{f_{\tau e} R_\gamma^\tau R_W^\tau}$$



CEPC？ Systematic uncertainties under control?

CPV in tau decay



$$A_Q = \frac{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}$$

$$= |p|^2 - |q|^2 \quad \approx (0.36 \pm 0.01)\%$$ in the SM

Bigi & Sanda'05
Grossman & Nir'11

$$|K_S^0\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$$

$$|K_L^0\rangle = p|K^0\rangle - q|\bar{K}^0\rangle$$

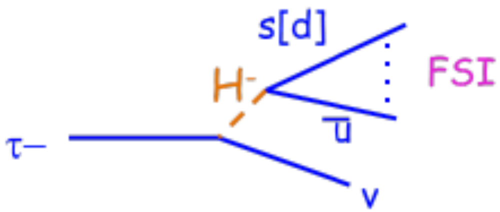
$$\langle K_L | K_S \rangle = |p|^2 - |q|^2 \simeq 2\mathrm{Re}(\varepsilon_K)$$

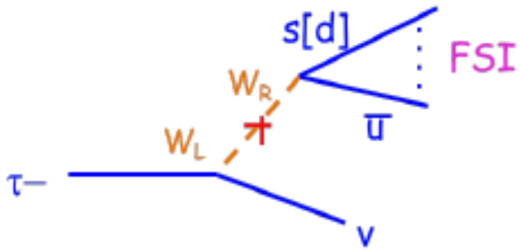
Experimental measurement : *BaBar'11*

$$A_{Q\,\mathrm{exp}} = \left(-0.36 \pm 0.23_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}\right)\%$$

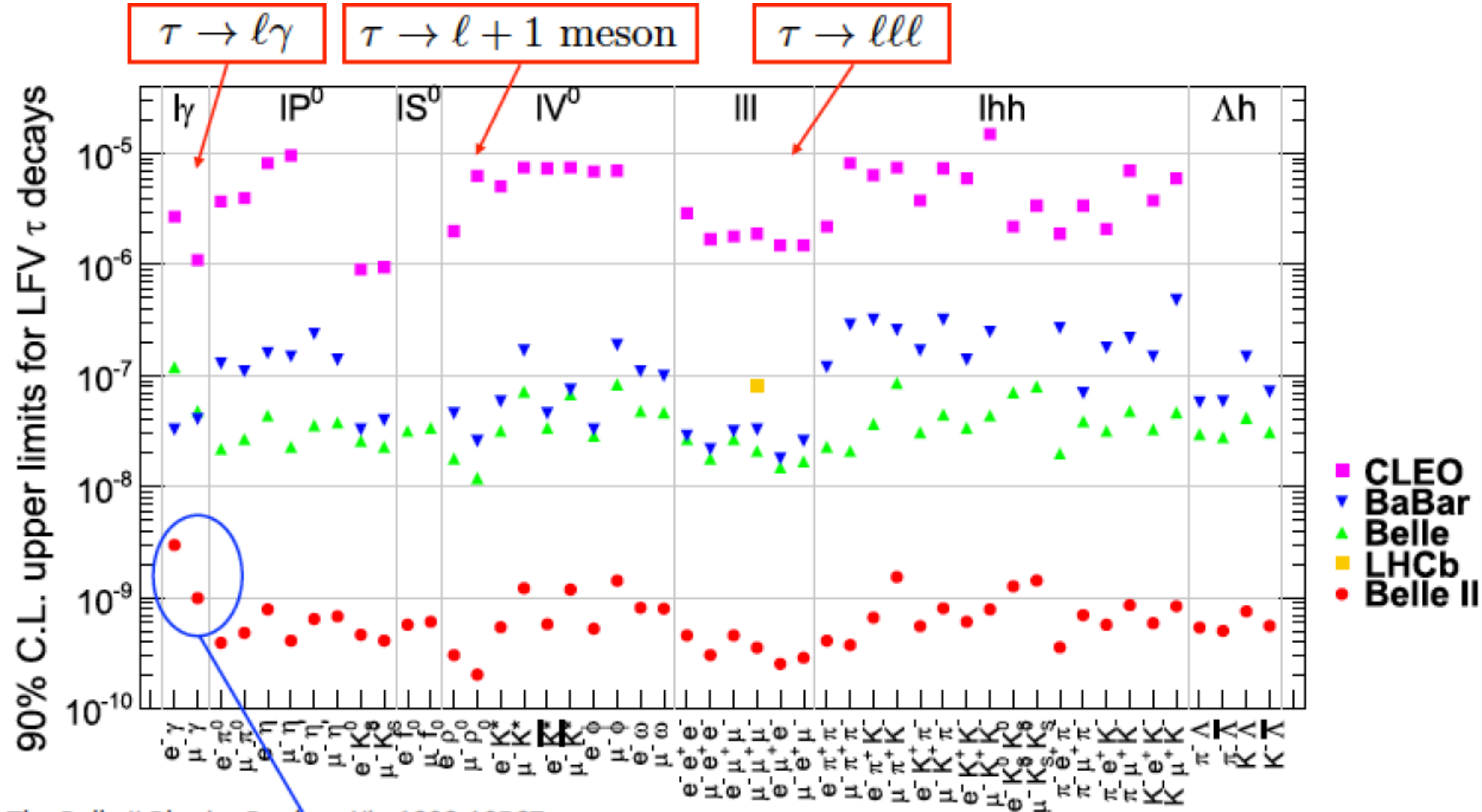
⇨ **2.8σ** from the SM!

New Physics : charged Higgs
W_L-W_R mixing …





Charged Lepton Flavor violation?



The Belle II Physics Book arXiv:1808.10567

Radiative modes affected by ISR photon background:

Expected sensitivity too optimistic?

CEPC: $\tau \to \mu\gamma$ 10^{-9} ? $\tau \to \mu\,\mu\,\mu$ 10^{-10}?

Call a white paper in last December 2018

By Prof. Yi-Fang Wang

Flavor Physics at CEPC

IHEP-Physics-Report-CEPC-2018-12-11-v0.0

Working Group and Conveners

Chapter One: Introduction	Conveners: Marek Karliner, Luciano Maiani, Jonathan Rosner, Abner Soffer, Lian-Tao Wang	N/A
Chapter Two: Leptonic and semileptonic b-hadron decays	Conveners: Sebastien Descotes-Genon , Jeorme Charles, Abner Soffer,Florian Bernlochner, Bob Kowalewski	Very preliminary version
Chapter Three: b-hadronic decays and CP violation	Conveners: I.I. Bigi, Chao-Qiang Geng, Abner Soffer, Yue-Hong Xie	N/A
Chapter Four: Rare and forbidden b-hadron decays	Conveners: Wolfgang Altmannshofer, Soeren A. Prell, Emmanuel Stamou	Very preliminary version
Chapter Five: Charm physics	Conveners: Chun-Hui Chen, Hai-Yang Cheng, Marek Karliner, Jonathan Rosner	**Well-done preliminary version**
Chapter Six: Exotic hadron and Spectroscopy with heavy flavors	Conveners: Marek Karliner, Luciano Maiani, Jonathan Rosner, Wei Wang	N/A
Chapter Seven: τ Physics	Conveners: Emilie Passemar, Emmanuel Stamou, Lorenzo Calibbi	**Preliminary version**
Chapter Eight: Flavor physics in Z decays	Conveners: Wolfgang Altmannshofer, Lorenzo Calibbi	Very preliminary version
Chapter Nine: Two photon and ISR physics with heavy flavors	Conveners: Igor Boyko, Vladimir Bytiev, Alexey Zhemchugov, Lian-Tao Wang	**Well-done preliminary**
Chapter Ten: Summary and Conclusion	Conveners: Lorenzo Calibbi, Hai-Bo Li, Manqi Ruan, Abner Soffer, Jian-Chun Wang	N/A

Summary

- Understand the experimental precision with 10^{12} *Z:*

  rare decays of tau, *c*- and *b*-hadrons;

  CP violation*;*

  precision tau physics;

- Examine the relevance of a dedicated PID (π / K / p separation) detector.

Thank you!

Back up slides

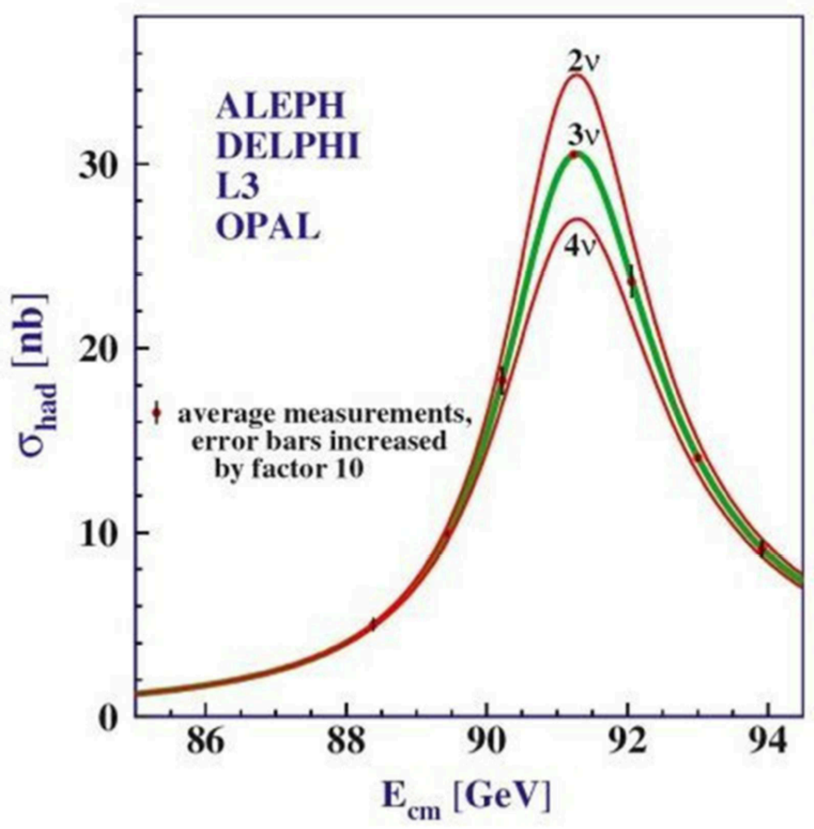
Flavour at the Z: the lepton Physics Case

Direct search: $$n_\nu = (\frac{\Gamma_{inv}}{\Gamma_{lept}})^{meas} / (\frac{\Gamma_{inv}}{\Gamma_{lept}})^{SM}$$

$$n_\nu = 2.9840 \pm 0.0082$$ LEP

0.004 CEPC

Limited by uncertainty due to calculation of Bhabha scattering. Improved by a factor of 2-3 at CEPC



Direct search: one year run at E=105 GeV

$$n_\nu = (\frac{e^+e^- \to \gamma Z_{inv}}{e^+e^- \to \gamma Z_{lept}})^{meas} / (\frac{\Gamma_{inv}}{\Gamma_{lept}})^{SM}$$

$$\Delta n_\nu = \pm 0.0008$$

Blondel, Graverinib, Serrab, Shaposhnikov arXiv:1411.5230

Flavor at the *Z*: the lepton physics

A high-luminosity *Z* factory with 10^{12} *Z* allows us to search for new physics in the leptonic Z decays:

$$e^+e^- \to Z \to \nu N$$
$$N \to l^+ l'^- \nu, q\bar{q}' l, q\bar{q}\nu$$

Blondel, Graverinib, Serrab, Shaposhnikov arXiv:1411.5230

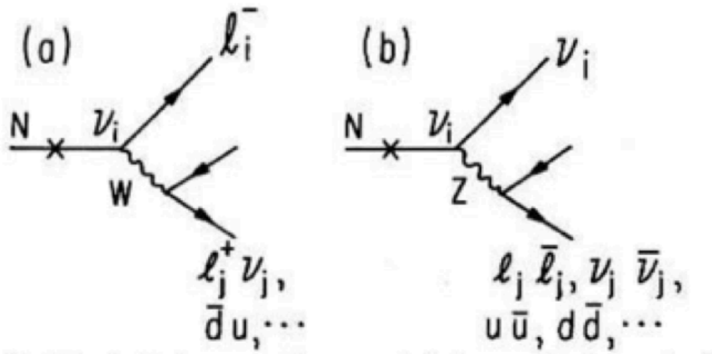


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

LNV processes to identify Majorana neutrinos Sensitivity: 10^{-11} at CEPC.

$$e^+e^- \to Z \to NN \to l^+l^+h^-h^- + c.c.$$

Z decays: cLFV

- Lepton Flavor-violating *Z* decays in the SM with lepton mixing are typically:

$$B(Z \to \mu e) \sim B(Z \to \tau e) \sim 10^{-54} \quad B(Z \to \tau\mu) \sim 10^{-60}$$

- Any observation of such a decay would be an indisputable evidence for New Physics.
- Current limits at the level of ~10^{-6} (from LEP and recently ATLAS, *e.g*. DELPHI, Z. Phys. C73 (1997) 243 ATLAS, CERN-PH-EP-2014-195 (2014))
- The CEPC high luminosity *Z* factory would allow to gain up to five orders of magnitude …

A. Abada et al. arXiv:1412.6322

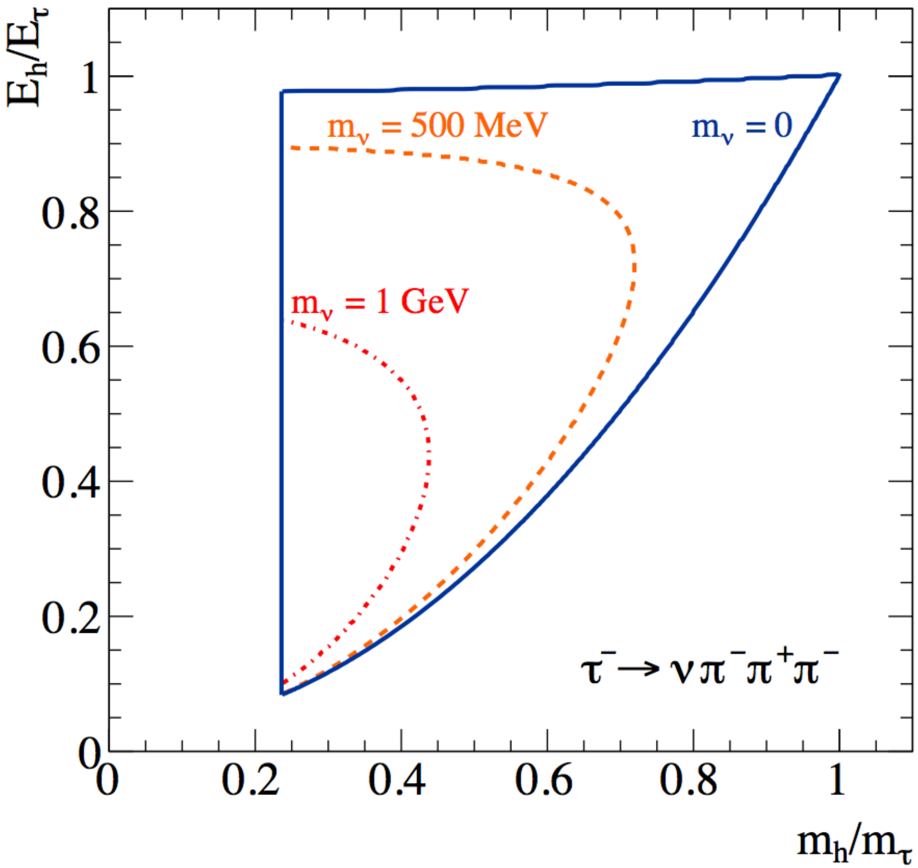
S. Davidson et al. JHEP 1209 (2012) 092

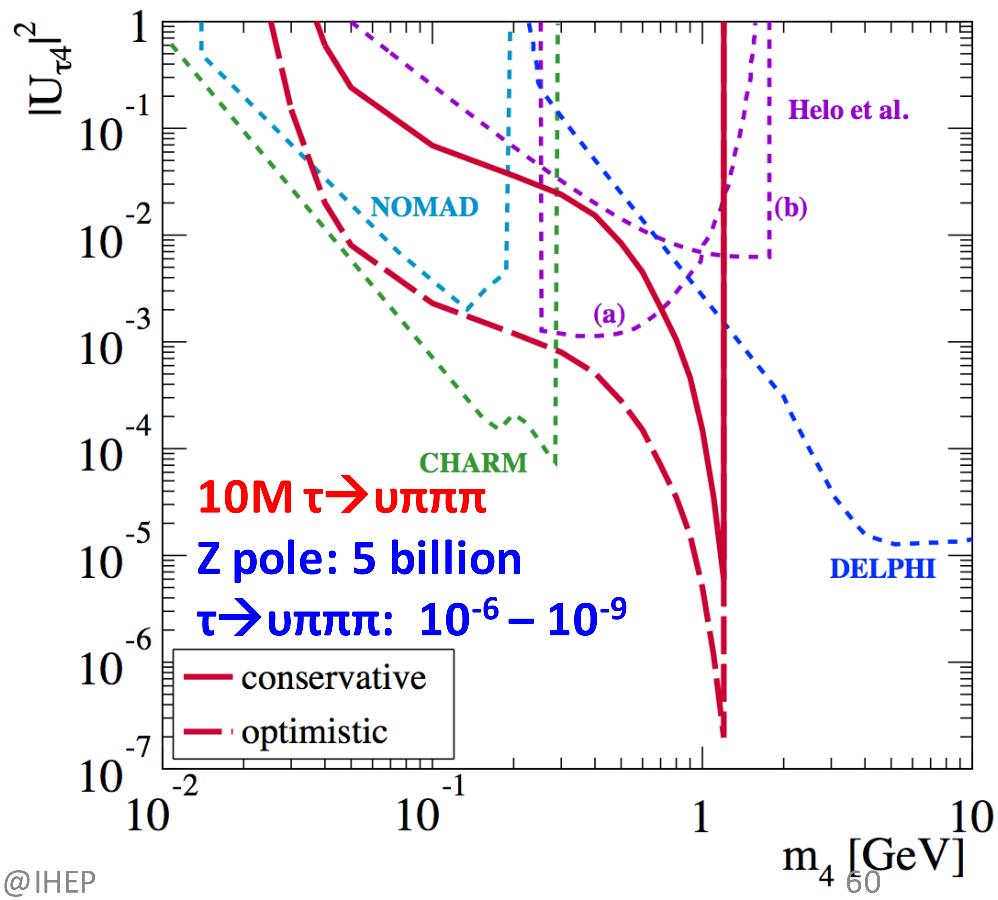
Kinematics of τ decays: heavy neutrinos

arXiv:1412.4785

$e^+e^- \to \tau^+\tau^-$ **at Z pole with known $E_\tau = E_{beam}$**
must understand well the ISR effects

$$\frac{d\Gamma_{tot}(\tau^- \to \nu h^-)}{dm_h dE_h} = \left(1 - |U_{\tau 4}|^2\right) \frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu = 0} + |U_{\tau 4}|^2 \frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu = m_4}$$





LNV processes at Z peak

LNV signals of Majorana neutrinos:

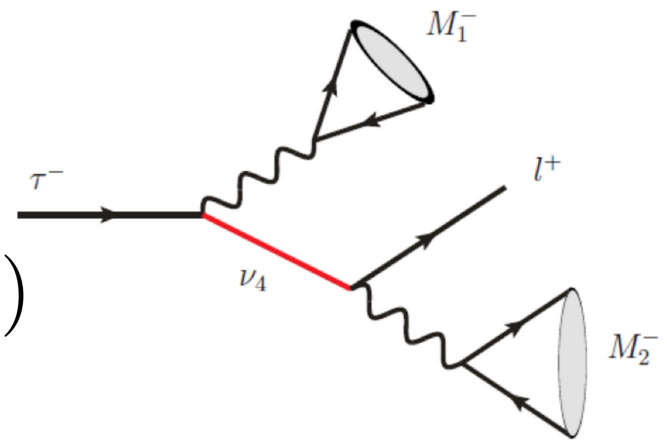
$$B^+/D^+ \to h^- l^+ l^+ (h = hadron)$$

$$B^0/D^0 \to h_1^- h_2^- l^+ l^+ (h = hadron)$$

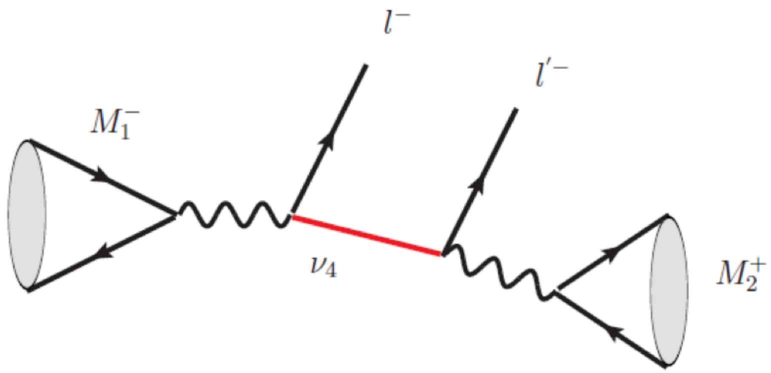
$$Z^0 \to h_1^- h_2^- l^+ l^+$$

$$\tau^\pm \to l^\mp h_1^\pm h_2^\pm$$

$$\tau^\pm \to \nu_\tau l^\pm l^\pm h_1^\mp$$



- Very light neutrinos $\to \langle m_{ll'} \rangle = \Sigma_i U_{il} U_{l'i} m_i$,
- Very heavy neutrinos $\to \Sigma_k V_{lk} V_{l'k} / m_k$,
- Resonant neutrinos $\to \Sigma_k V_{lk} V_{l'k} m_k / \Gamma_N$



Atre, Han, Pascolie and Zhang JHEP 0905,030(2009)

LNV processes at Z peak

LNV signals of Majorana neutrinos:

	CEPC	Belle-II
$B^+/D^+ \to h^- l^+ l^+ (h = hadron)$	10^{-10}	10^{-10}
$B^0/D^0 \to h_1^- h_2^- l^+ l^+ (h = hadron)$	10^{-10}	10^{-10}
$Z^0 \to h_1^- h_2^- l^+ l^+$	10^{-11}	
$\tau^\pm \to l^\mp h_1^\pm h_2^\pm$	10^{-10}	10^{-9}
$\tau^\pm \to \nu_\tau l^\pm l^\pm h_1^\mp$	10^{-10}	10^{-9}

- Very light neutrinos $\to \langle m_{ll'} \rangle = \Sigma_i U_{il} U_{l'i} m_i$,
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Atre, Han, Pascolie and Zhang JHEP 0905,030(2009)

LNV meson decays: current limits

$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}			
$K^+ \to \pi^- \mu^+ \mu^+$	3.0×10^{-9}	PDG		
$K^+ \to \pi^- e^+ \mu^+$	5.0×10^{-10}			
$D^+ \to \pi^- e^+ e^+$	1.9×10^{-6}	$D_s^+ \to \pi^- e^+ e^+$	4.1×10^{-6}	
$D^+ \to \pi^- \mu^+ \mu^+$	2.0×10^{-6}	$D_s^+ \to \pi^- \mu^+ \mu^+$	14×10^{-6}	
$D^+ \to \pi^- e^+ \mu^+$	2.0×10^{-6}	$D_s^+ \to \pi^- e^+ \mu^+$	8.4×10^{-6}	BABAR1
$D^+ \to K^- e^+ e^+$	0.9×10^{-6}	$D_s^+ \to K^- e^+ e^+$	5.2×10^{-6}	
$D^+ \to K^- \mu^+ \mu^+$	10×10^{-6}	$D_s^+ \to K^- \mu^+ \mu^+$	13×10^{-6}	
$D^+ \to K^- e^+ \mu^+$	1.9×10^{-6}	$D_s^+ \to K^- e^+ \mu^+$	6.1×10^{-6}	
$B^+ \to \pi^- e^+ e^+$	2.3×10^{-8} BABAR2	$B^+ \to D^- e^+ e^+$	2.6×10^{-6} Belle	
$B^+ \to \pi^- \mu^+ \mu^+$	10.7×10^{-8} BABAR2	$B^+ \to D^- \mu^+ \mu^+$	1.8×10^{-6} Belle	
	$4.0 \times 10^{-9} LHCb$		6.9×10^{-7} LHCb	
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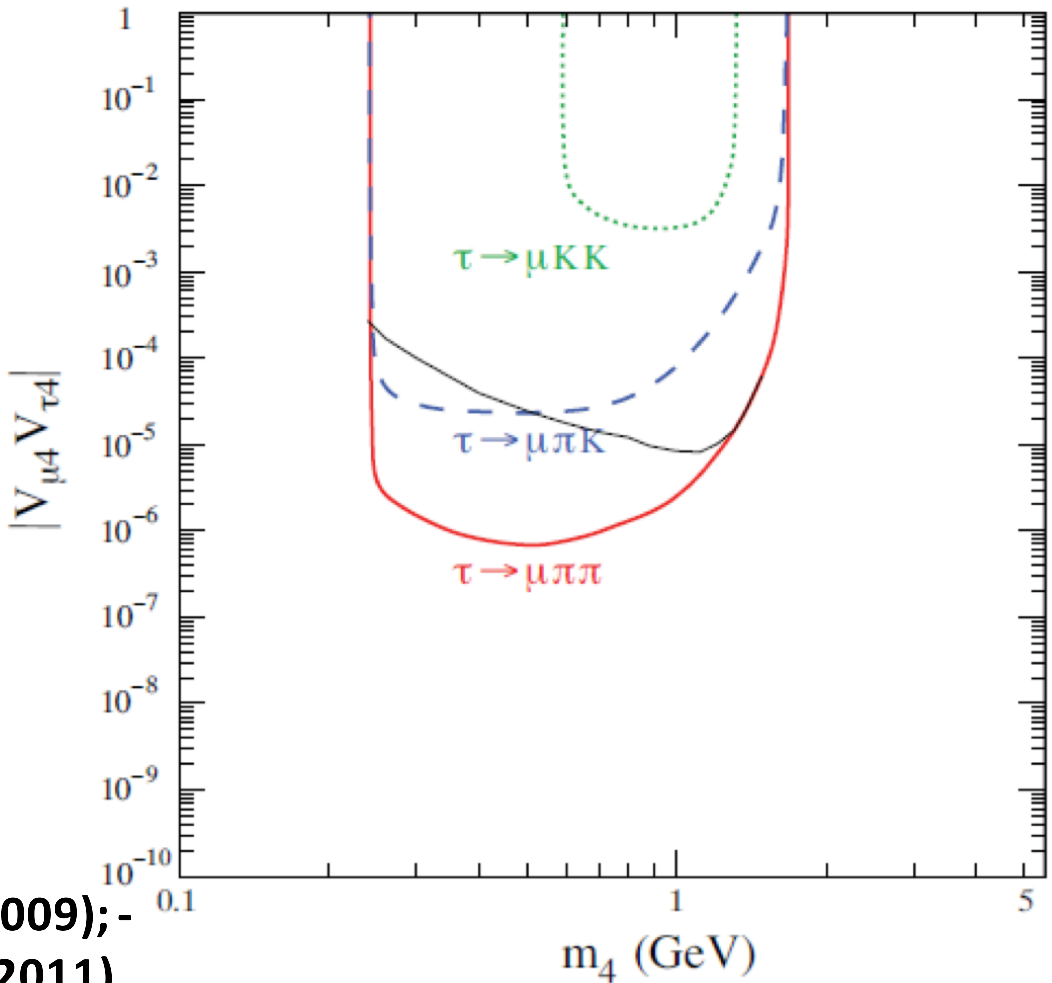
$B^+ \to K^- e^+ \mu^+$	2.0×10^{-6} BABAR2			

BABAR1: J. P. Lees et al, PRD 84, (2011)
BABAR2: J. P. Lees et al, arXiv: 1202.3650
Belle: O. Seon et al, PRD 84 (2011)
LHCb: R. Aaij et al, PRL 104 (2011), arXiv: 1201.5600 LHCb, PRL 112,131802 (2014)

LNV τ data: current limit

Belle: PLB 682, 355 (2010), (90 % C.L.).

	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^+\pi^-\pi^-$	8.8
$\tau^- \to e^+\pi^-K^-$	6.7
$\tau^- \to e^+K^-K^-$	6.0
$\tau^- \to \mu^+\pi^-\pi^-$	3.7
$\tau^- \to \mu^+\pi^-K^-$	9.4
$\tau^- \to \mu^+K^-K^-$	9.6



Atre, Han, Pascoli & Zhang, JHEP 0905, (2009); - Helo, Kovalenko and Schmidt, NPB 853, (2011)

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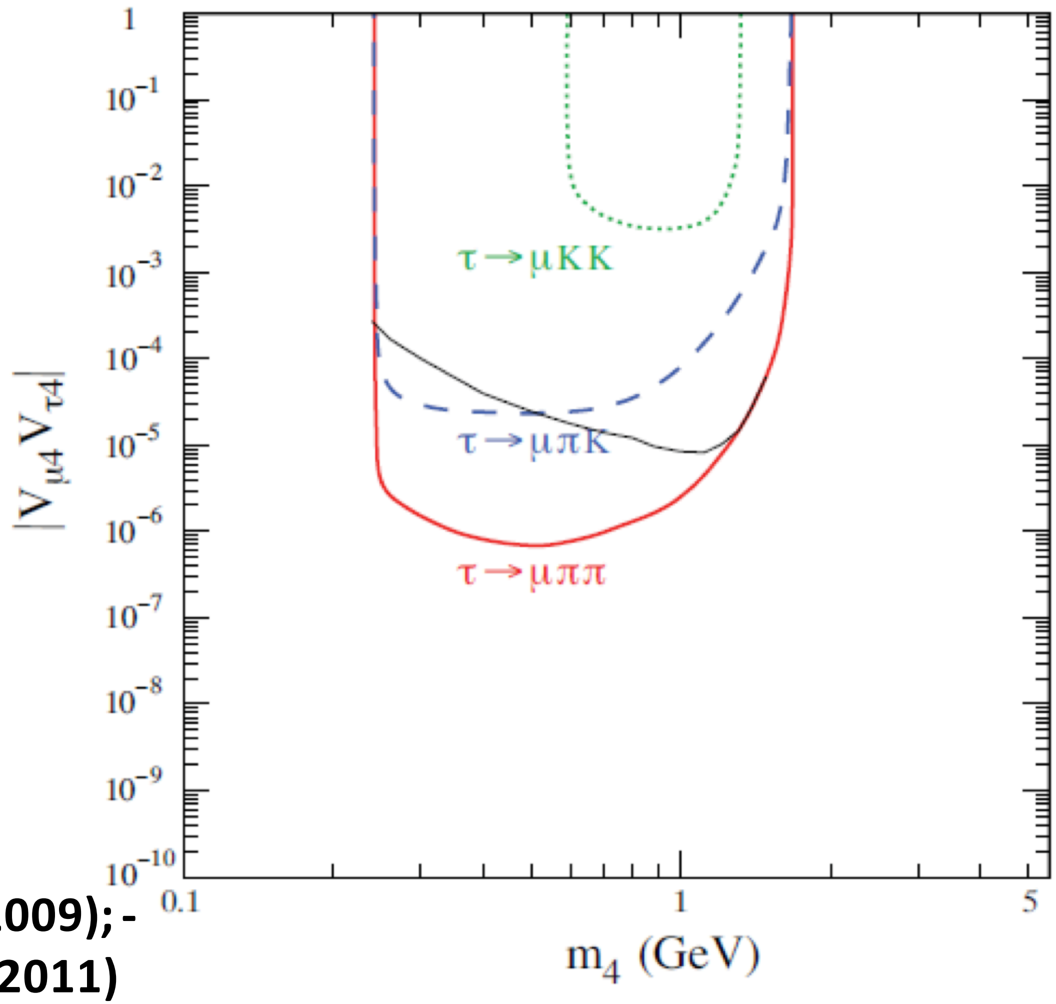
$\tau^- \to \mu^+K^-K^-$	9.6



Atre, Han, Pascoli & Zhang, JHEP 0905, (2009); - Helo, Kovalenko and Schmidt, NPB 853, (2011)

tau lepton at Z peak

Advantage of tau experiment at Z peak:

- Large production cross-section (1.5 nb)
- Strong boost, decay length: 2 mm
- Back-to-back event topology, 80% efficiency
- Clean background
- Good lepton and K_L ID

Disadvantage: K/pi ID is challenge

Tau lepton at Belle-II

- Low cross section and back-to-back
- Relatively short decay length : 0.25 mm
- High background from qqbar and B decays
- Good pi/K PID and Ks reconstruction
- Limited K_L reconstruction
- Low efficiency for high multiplicity

tau lepton reconstruction at Belle

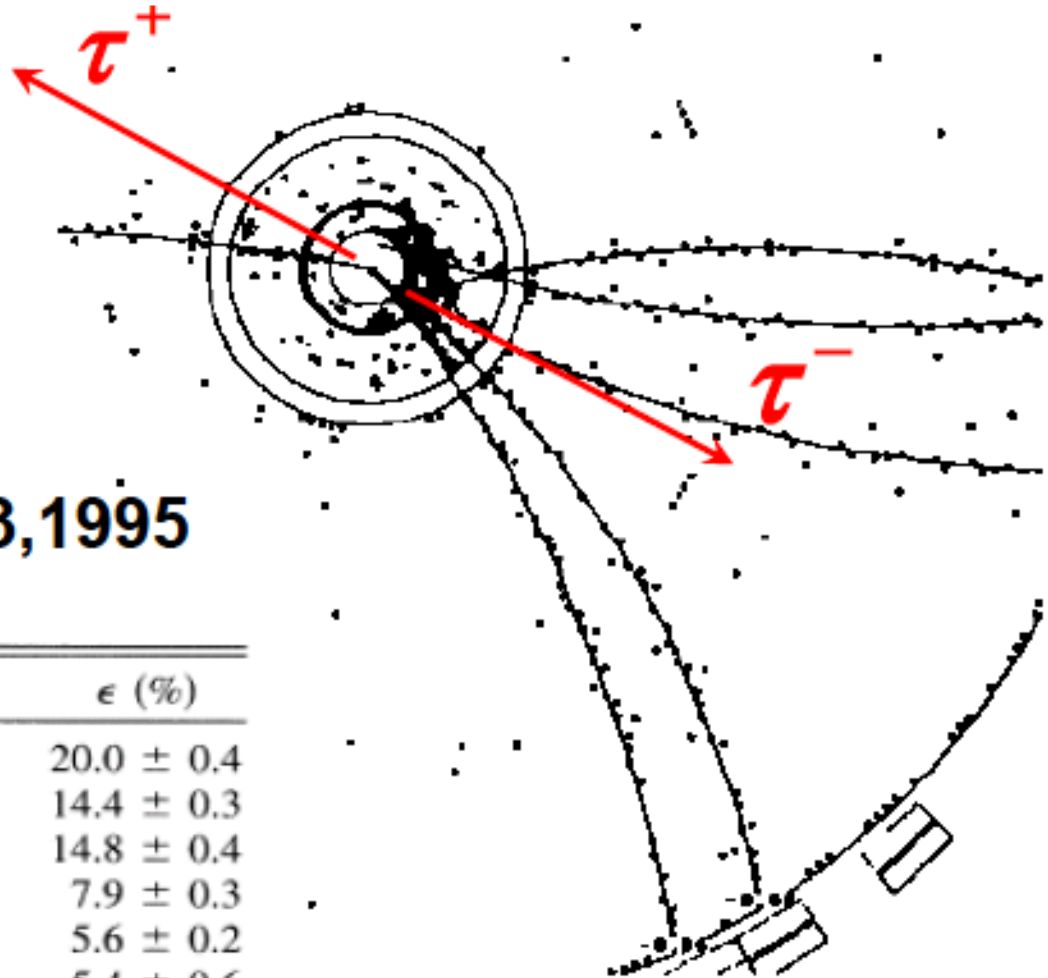
Ecm～10.6 GeV

Tau 对之间任意粒子的夹角均大于90°。

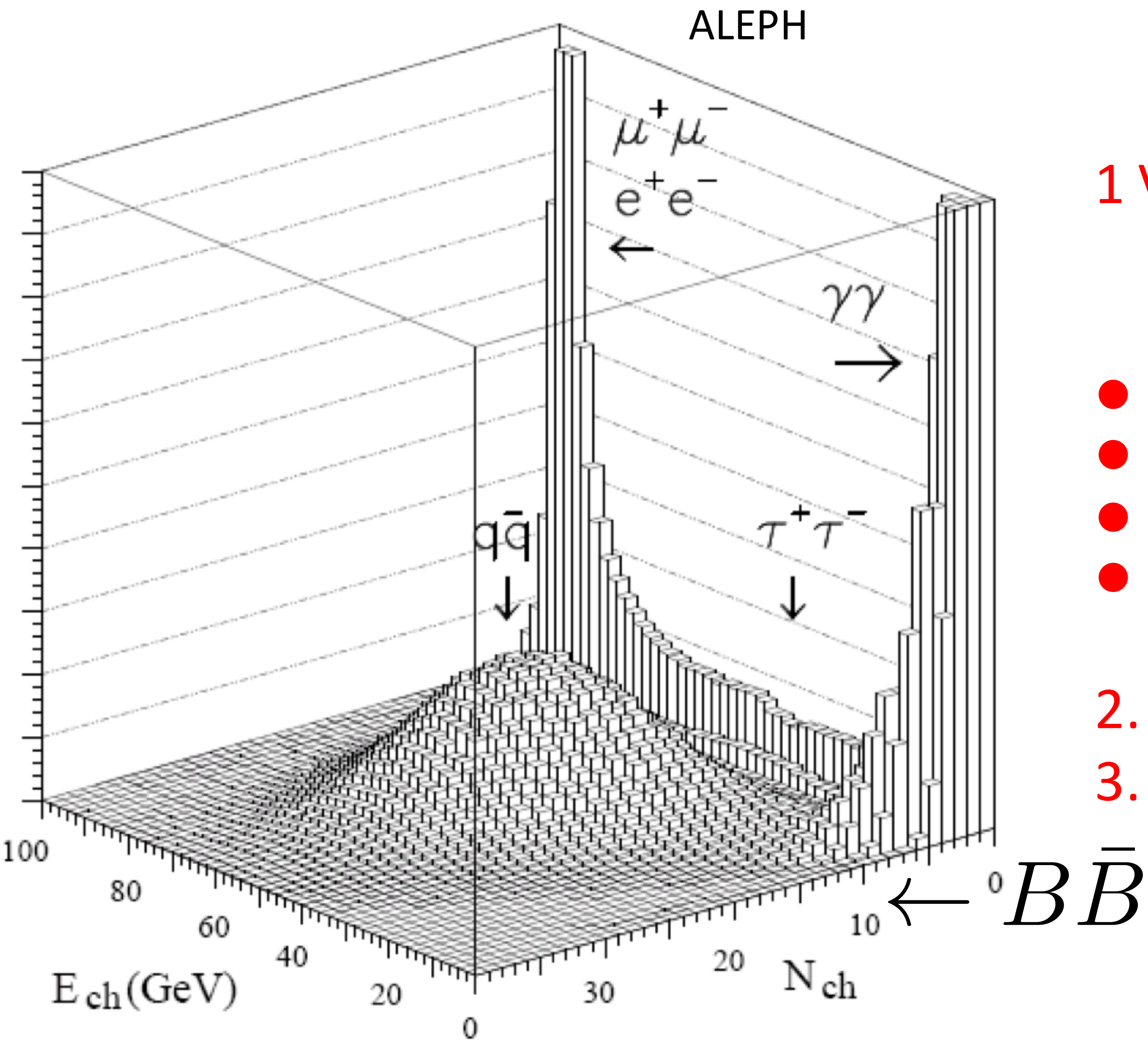
CLEO

Phys.Rev.Lett.75:3809-3813,1995

Sample	N_d	f_b^{τ} (%)	$f_b^{q\bar{q}}$ (%)	ϵ (%)
e-$3h$	18815	7.5 ± 0.2	0.2 ± 0.2	20.0 ± 0.4
μ-$3h$	13985	12.8 ± 0.2	0.3 ± 0.3	14.4 ± 0.3
$3h$-$3h$	4877	16.8 ± 1.3	6.5 ± 1.3	14.8 ± 0.4
e-$3h\pi^0$	3227	4.5 ± 0.4	0.3 ± 0.3	7.9 ± 0.3
μ-$3h\pi^0$	2335	10.3 ± 0.4	0.7 ± 0.7	5.6 ± 0.2
$3h$-$3h\pi^0$	1681	13.6 ± 0.6	12.3 ± 1.4	5.4 ± 0.6



tau lepton reconstruction @ Z peak



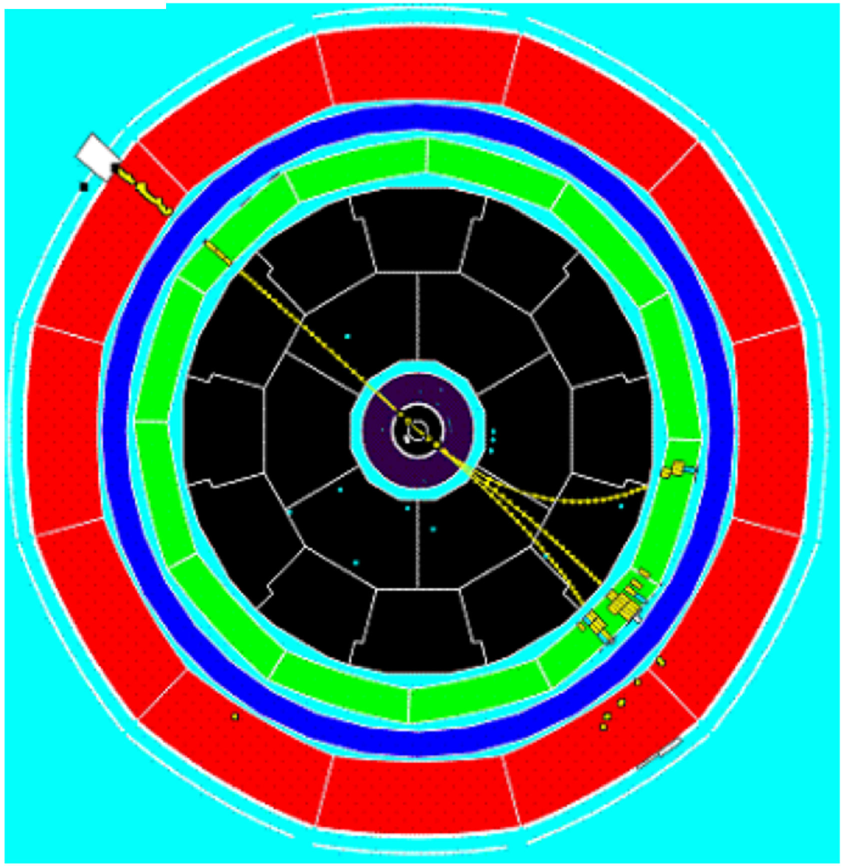
1 Very clean $\tau\tau$ events can be selected with very simple selection criteria.

- Low track multiplicity
- Back-to-back
- Low invariant mass
- Total energy not very small

2. Subtract background
3. Classify all the events

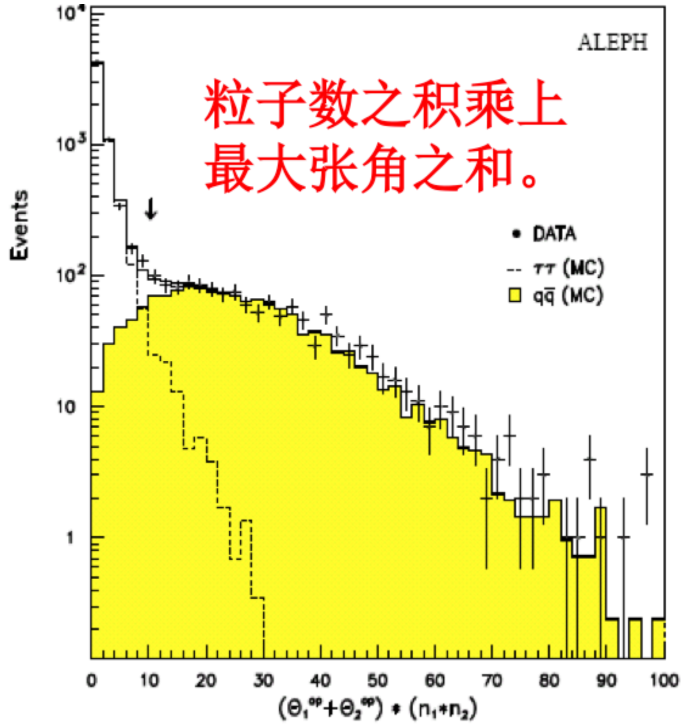
tau lepton reconstruction at Z-peak

ALEPH



Ecm≈91 GeV

Z.Phys.C70:579-608,1996



Physics processes	Efficiency (%)	Contamination (%)
$Z^0 \to \tau^+\tau^-$	78.84 ± 0.13	
Bhabha		0.15 ± 0.03
$Z^0 \to \mu^+\mu^-$		0.07 ± 0.02
$\gamma\gamma \to e^+e^-$		0.07 ± 0.02
$\gamma\gamma \to \mu^+\mu^-$		0.08 ± 0.02
four-fermion		0.14 ± 0.02
cosmic rays		0.02 ± 0.01
$Z^0 \to q\bar{q}$		0.31 ± 0.09

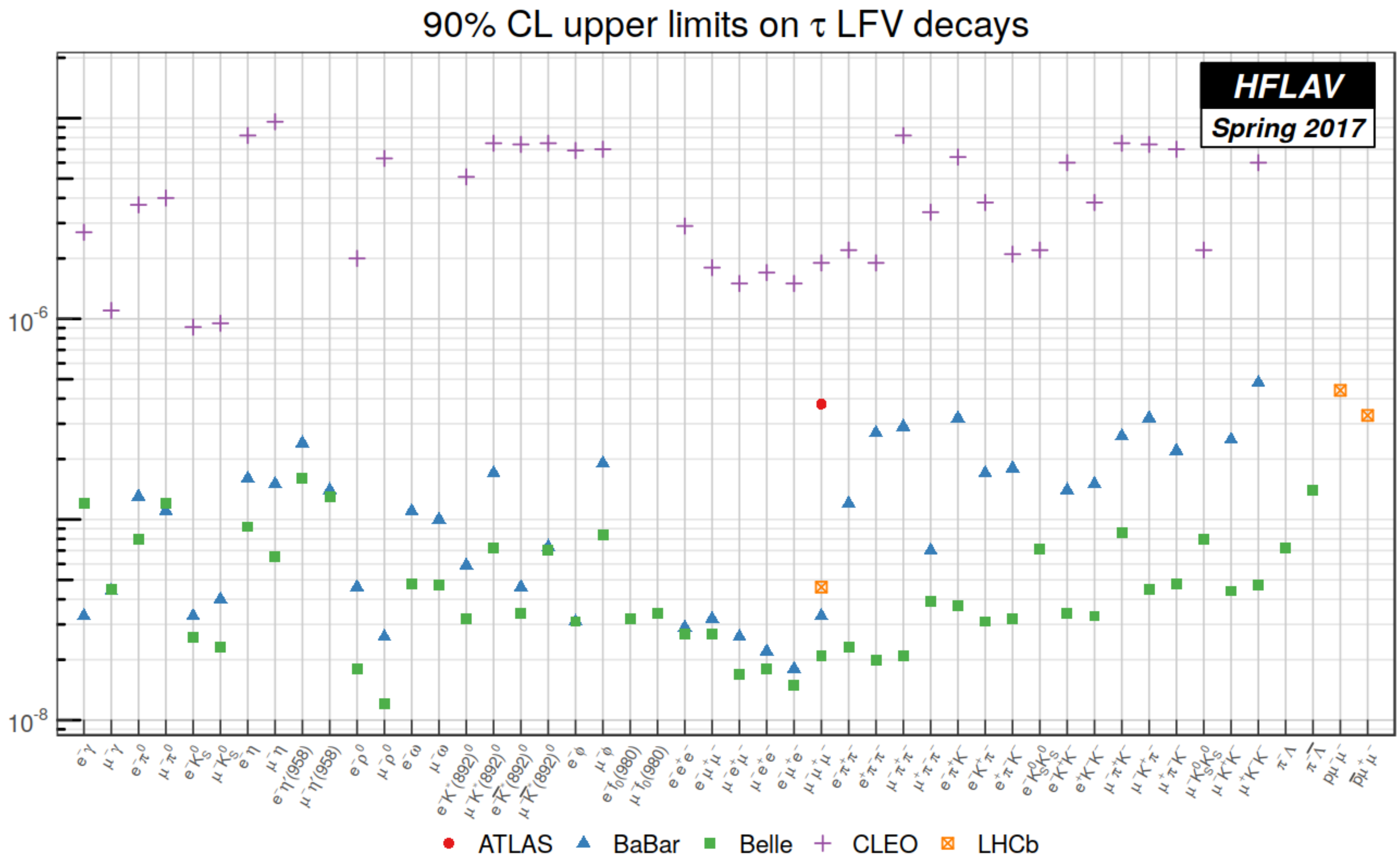
丢失的效率是因几何造成的

List of tau physics @ Z peak

- High precision tau decays rates (uncertainty: 10^{-5})
- Vus, tau life time, tau coupling, αQCD etc.
- Rare: cLFV, LNV …
- CPV in tau production and decay (10^{-4})
- Anomalous magnetic moment of the tau: $\sim 10^{-6}$ - 10^{-7}
- Electric Dipole Moment of the tau: $Re(d_{tau}) \sim 10^{-19}$ e cm
- Weak Dipole Moments of the tau (Z and W coupling)

cLFV in tau decays

6 × 10^{10} τ pairs on Z pole at CEPC→ reach at 10^{-9}-10^{-10}



Heavy quarks @ Z peak

b-hadron productions at CEPC and Belle-II

b-hadron species	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	22.0×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	22.0×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	5.4×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	4.8×10^{10}	—	—

- The production rate of Bc meson is small, $10^6 - 10^7$ Bc mesons are expected from NRQCD

- In the first class of Λ_b decays one gets $p\pi^-$, $p\pi^-\pi^0$, pK^-K^0, ΛK^-, $p\pi^-\pi^+\pi^-$, $p\pi^-K^+K^-$, $p\pi^-\bar{K}^0K^0$, etc.

  In the second class one probes pK^-, $pK^-\pi^0$, $pK_S\pi^-$, ΛK^+K^- etc.

- Ξ_b^- decays lead to $\Lambda^0\pi^-$, $\Lambda^0\pi^-\pi^0$ etc. and Λ^0K^-, $\Lambda^0K^-\pi^0$, $\Lambda^0\bar{K}^0\pi^-$ etc.

  For Ξ_b^0 decays one probes FS about $\Sigma^+\pi^-$, $\Lambda^0\pi^+\pi^-$ etc. and Σ^+K^-, $\Lambda^0\pi^+K^-$ etc.

- For obvious reasons we list only first class of Ω_b^-, namely $\Xi^0\pi^-$, Ω^-K^0.

Heavy quarks @ Z peak

Likely unique to CEPC:

1) Any leptonic or semileptonic decay mode involving *Bs, Bc* or *b*-baryon, including electrons and taus.
2) Any decay mode involving *Bs, Bc* or *b*-baryon with neutrals.
3) Multibody (means 4 and more) hadronic *b*-hadron decays.

$B_s \to \phi\tau\tau$	$B_s \to \eta\mu\mu$
$B_s \to \eta'\tau\tau$	$B_s \to \eta'\mu\mu$
$B^0 \to K^{(*)}\tau\tau$	$B^0 \to \pi^0\mu\mu$
$B^0 \to \pi^0\tau\tau$	$B^0 \to \eta\mu\mu$
$B^+ \to K^{+(*)}\tau\tau$	$B \to h\nu\bar{\nu}$

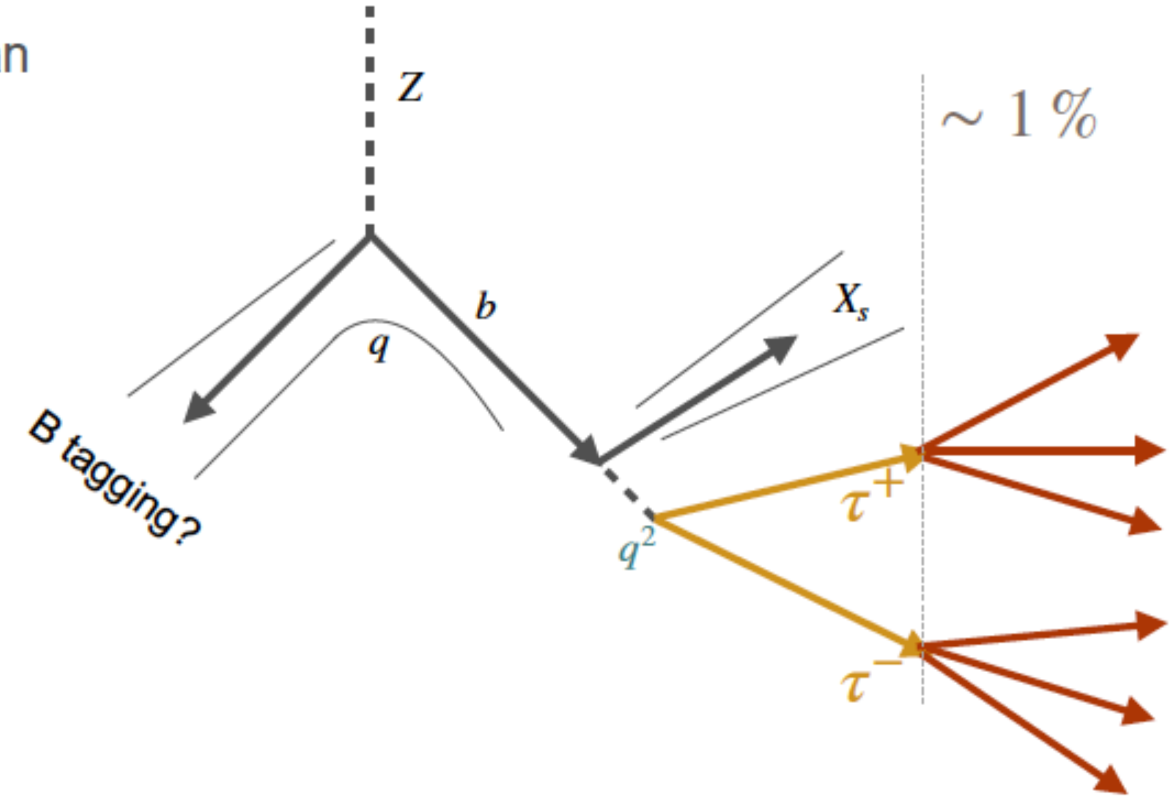
B/Bs → (K*) tau tau

Reconstruction Methods

Inclusive

Talk by Simon Wehle

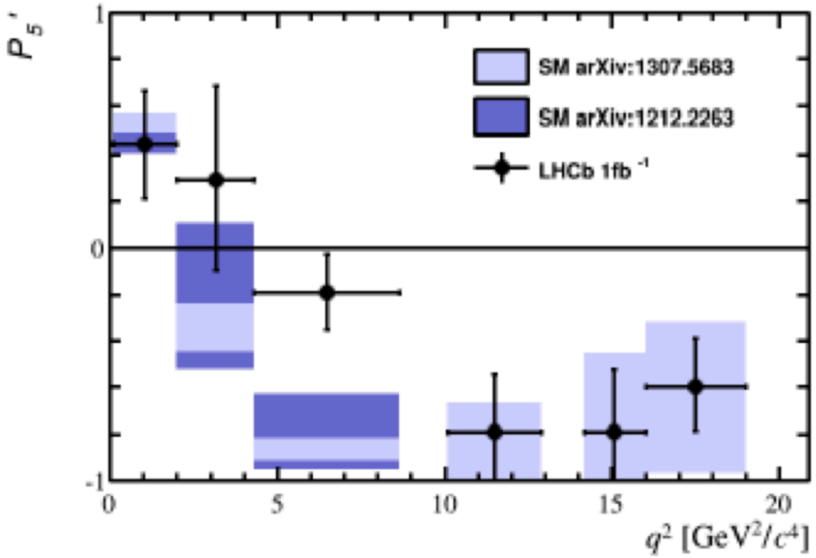
- Inclusive decays offer very clean theoretical observables
- Important benchmarks:
  - Kaon identification
  - K_S finding
- Possible problems
  - difficult to estimate spectator



Flavors at the Z: EW penguins

	$3\,\text{fb}^{-1}$ (7+8 TeV)	2015	CEPC	LHCb Upgrade
$B^0 \to K^{*0}\mu^+\mu^-$	$2.6\text{k}^\dagger$	$1.4 - 2.1\text{k}$	20k	34 k
$B^+ \to K^+\mu^+\mu^-$	4746 ± 81	$2.6 - 3.9\text{k}$	10k	61.6 k
$B^+ \to \pi^+\mu^+\mu^-$	100	$50 - 80$	1000	1280
$B^+ \to K^+e^+e^-$ $(1 < q^2 < 6)$	256^{+25}_{-23}	$140 - 210$	10k	3320

†with enlarged q^2 windows for $3\,\text{fb}^{-1}$ analysis



LHCb update and CEPC will improve it by a factor of 3-4 after 2028. Theoretical uncertainty is in the same level.

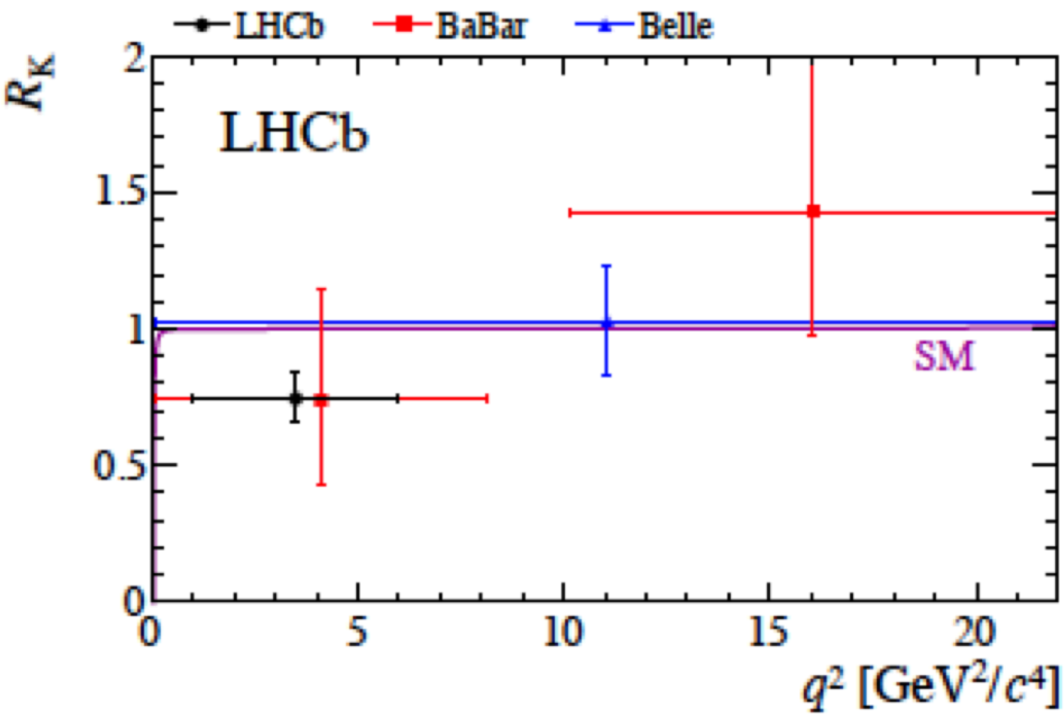
At CEPC we can search for:

$B_s \to \eta\mu\mu$	$B_s \to \phi\tau\tau$
$B_s \to \eta'\mu\mu$	$B_s \to \eta'\tau\tau$
$B^0 \to \pi^0\mu\mu$	$B^0 \to K^{(*)}\tau\tau$
$B^0 \to \eta\mu\mu$	$B^0 \to \pi^0\tau\tau$
$B \to h\nu\bar{\nu}$	$B^+ \to K^{+(*)}\tau\tau$

Flavor at the Z: EW penguins

Lepton universality

$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$



Consistent with SM within 2.6 σ

R_K is theoretical extremely clean:

$R_K = 1 + O(10^{-4})$

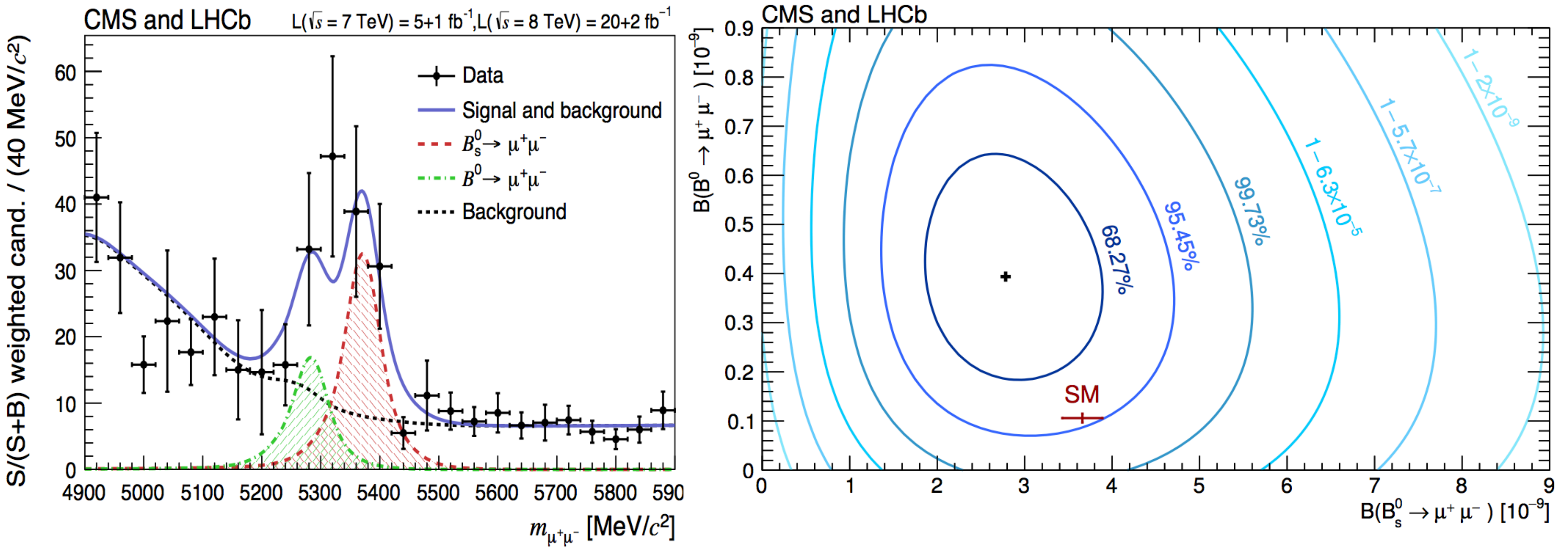
CEPC reach: (2-4) %

LHCb, PRL 113 (2014) 151601

Belle, PRL 103 (2009) 171801

Babar, PRD 86 (2012) 032012

Flavors at the Z: EW & Higgs penguins



LHCb and CMS, arXiv:1411.4413

$$B(B^0 \to \mu\mu) = (3.94^{+1.58+0.31}_{-1.41-0.24}) \times 10^{-10} (3.2\sigma)$$

$$B(B_s \to \mu\mu) = (2.79^{+0.66+0.26}_{-0.60-0.19}) \times 10^{-10} (6.2\sigma)$$

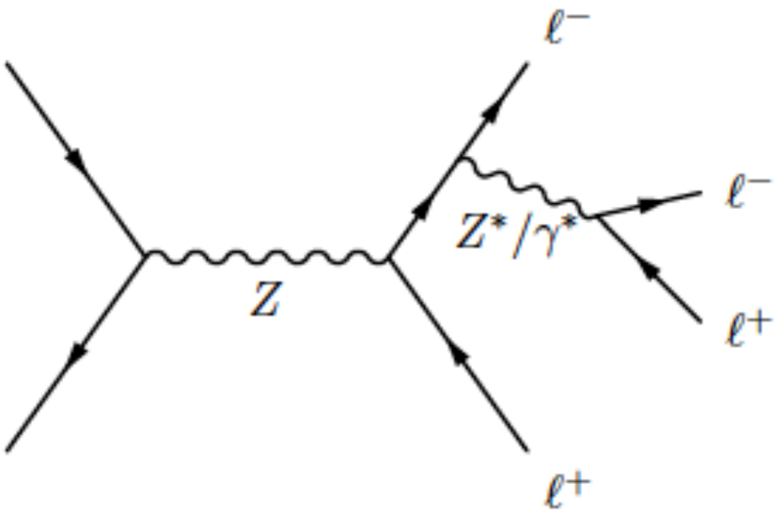
$$B(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

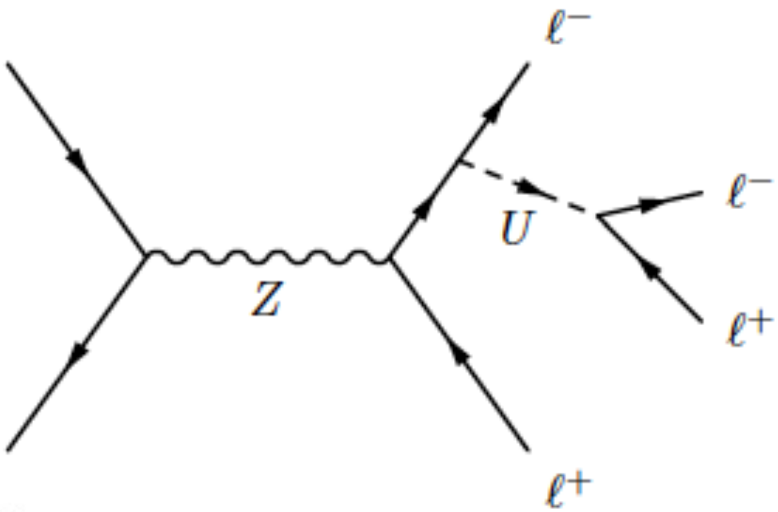
$$B(B_s \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-10}$$

Theory: Bobeth et al. PRL 112(2014)101801

Probe New physics in Z four-body decays

Example: $Z \to b\bar{b}l^+l^-,\ \ l^+l^-l'^+l'^-$





$$Z \to l^+l^-l^+l^-$$

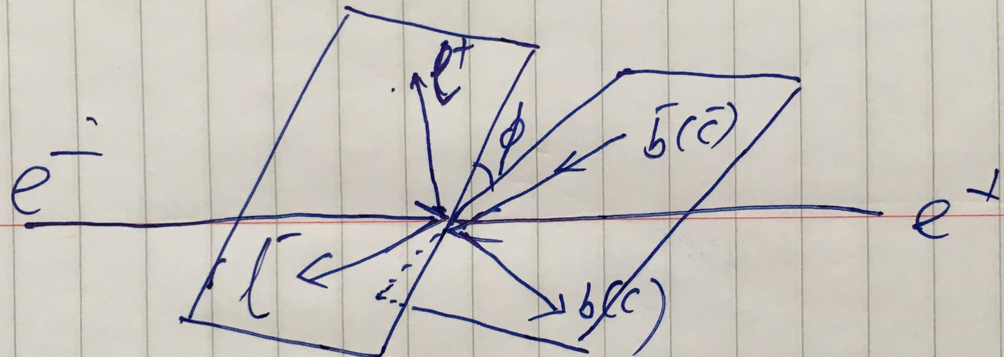
U could be scalar or vector boson

arXiv:1805.05791

CPV in Z decays

$$\mathcal{B}(Z \to b\bar{b}l^+l^-) \approx 10^{-5} - 10^{-6}$$

$$Z \to b\bar{b}\,l^+l^-, \quad Z \to l'^+l'^-l^+l^+$$



$$T \text{ odd}: \quad (\vec{P}_{\bar{b}} \times \vec{P}_b)\cdot\vec{P}_{l^-}, \quad (\vec{P}_{l^+} \times \vec{P}_{l^-})\cdot\vec{P}_b$$

$$A = \frac{N(\cos\phi\cdot\sin\phi > 0) - N(\cos\phi\cdot\sin\phi < 0)}{N(\cos\phi\cdot\sin\phi > 0) + N(\cos\phi\cdot\sin\phi < 0)}.$$