Flavor Physics on Z pole at CEPC

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Talks in this workshop

- **Flavor opportunities at a Z factory in CEPC** Emmanuel Stamou
- **Studies of τ decays into two mesons** Sergi GONZÀLEZ-SOLÍS
- **Bs->K*tautau analysis at the future e+e- collider** Simon Wehle
- **Tau finding performance study at CEPC** Zhigang Wu
- **Search for $Bc \rightarrow \tau \nu$** Fenfen An
- **Lepton Flavor Violation** Michael Schmidt

My apologies if I missed your flavor talk.

Flavor productions on Z peak

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	[a]	(3.3632 ± 0.0042) %	
Γ_2	$\mu^+\mu^-$	[a]	(3.3662 ± 0.0066) %	
Γ_3	$\tau^+\tau^-$	[a]	(3.3696 ± 0.0083) %	
Γ_4	$\ell^+\ell^-$	[a,b]	(3.3658 ± 0.0023) %	
Γ_5	$\ell^+\ell^-\ell^+\ell^-$	[c]	(3.5 ± 0.4) $\times 10^{-6}$	S=1.7
Γ_6	invisible	[a]	(20.000 ± 0.055) %	
Γ_7	hadrons	[a]	(69.911 ± 0.056) %	
Γ_8	$(u\overline{u}+c\overline{c})/2$		(11.6 ± 0.6) %	
Γ_9	$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ± 0.4) %	
Γ_{10}	$c\overline{c}$		(12.03 ± 0.21) %	
Γ_{11}	$b\overline{b}$		(15.12 ± 0.05) %	
Γ_{12}	$b\overline{b}b\overline{b}$		(3.6 ± 1.3) $\times 10^{-4}$	
Γ_{13}	ggg		$<$ 1.1 %	CL=95%

We still miss many rare Z decays: $Z \to b\bar{b}l^+l^-, \ \ c\bar{c}l^+l^-,$

List of flavor physics in CDR

Talk on Monday by Emmanuel Stamou

Production at different experiements

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

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

Talk on Monday by Emmanuel Stamou

Production at different experiements

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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 $\Upsilon(4S))$	

LHCb produce huge charm hadrons

$$\sigma(pp \to c\bar{c}) = (2369 \pm 3 \pm 152 \pm 118)\mu b @ 13TeV$$

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

CEPC @ Z pole will be a tau factory

Talk on Monday by Emmanuel Stamou

Highlights in CDR

FCNC processes: genes (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)	$\sim 10^{-8} - 10^{-10}$

Talk on Monday by Emmanuel Stamou

Preliminary framework for white paper

1 Introduction
- 1.1 Overview of CEPC
- 1.2 Flavor physics to be addressed at CEPC
- 1.3 Overview of this book

2 Leptonic and semileptonic b-hadron decays
- 2.1 Introduction
- 2.2 Pure leptonic decays
- 2.3 Semileptonic decays and lepton universality
- 2.4 CKM matrix elements

3 b-hadronic decays and CPV in b-sector
- 3.1 Bs decay
- 3.2 Bc production and decay
- 3.3 Lambda_b and other b-baryons

Preliminary framework

4 Rare and forbidden b-hadron decays

- 4.1 Introduction
- 4.2 Rare Leptonic decays
- 4.3 Flavor-changing b --> s l+l- and b --> d l+l- transitions
- 4.4 Lepton-flavor, Lepton-number and baryon-number violating decays
- 4.5 Radiative decays
- 4.6 Decay with missing energy b-> s \nu \nu_bar
- 4.7 Summary

5 Charm physics

(a short chapter to briefly discuss charm mesons and baryons)

- 5.1 Opportunity on Charmed mesons
- 5.2 Opportunity on Charmed baryons

Preliminary framework

6 Exotic hadron and Spectroscopy with heavy flavors

- 6.1 Introduction
- 6.2 Tetraquark and pentaquark states (with heavy quarks)
- 6.3 Doubly heavy baryons in charm and beauty
- 6.4 Production of conventional heavy quarkonium
- 6.5 Summary

7 Tau Physics

- 7.1 Introduction
- 7.2 Tau decays
- 7.3 Lepton Universality in tau decay
- 7.4 cLFV in tau decays
- 7.5 CPV in tau decay and production
- 7.6 g-2_tau and EDM
  - 7.6.1 Anomalous magnetic moment of the tau
  - 7.6.2 Electric Dipole Moment of the tau
  - 7.6.3 Weak Dipole Moments of the
- 7.7 Summary

Preliminary framework

8 Z decays with heavy flavors

8.1 Leptonic Z decays

8.2 Z hadronic decays

8.3 cLFV Z decays

$$Z \to l^+ l'^-, \;\; 4leptons, \;\; b\bar{b}l^+l^-$$

9 Two photon physics with heavy flavors , and ISR physics with heavy flavor

10 Summary and Conclusion

10.1 Sensitivity to key observables and physics reach in flavor

10.2 Comparison with Belle II, Phase-II ATLAS and CMS, and LHCb

10.3 Summary

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

LNV processes at Z peak

LNV signals of Majorana neutrinos:

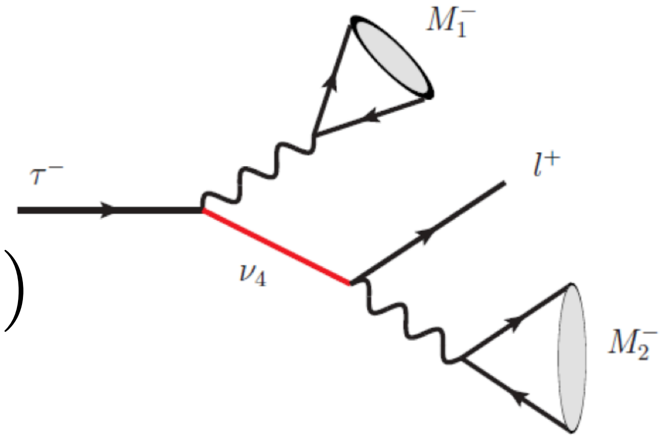
$B^+/D^+ \to h^- l^+ l^+ (h = hadron)$

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

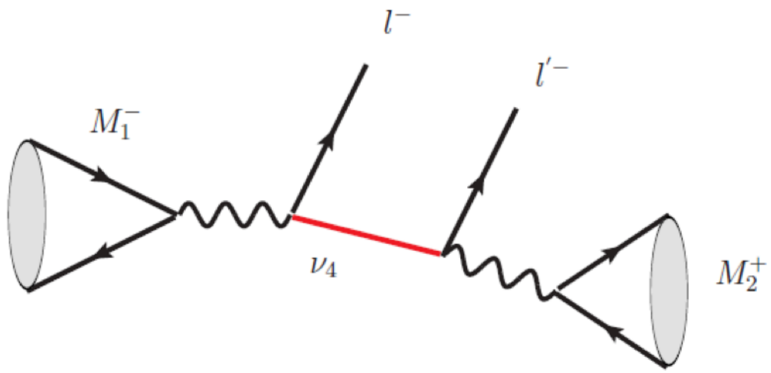
$Z^0 \to h_1^- h_2^- l^+ l^+$

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

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



- 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

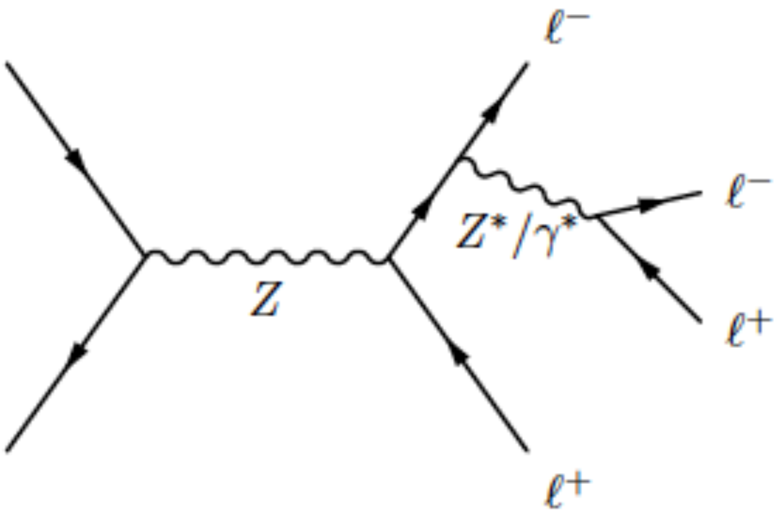
LNV signals of Majorana neutrinos:	**CEPC**	**Belle-II**
$B^+/D^+ \to h^- l^+ l^+ (h = hadron)$	10^{-10}	10^{-10}
$B^0/D^0 \to h_1^- h_2^- l^+ l^+ (h = hadron)$	10^{-10}	10^{-10}
$Z^0 \to h_1^- h_2^- l^+ l^+$	10^{-11}	
$\tau^\pm \to l^\mp h_1^\pm h_2^\pm$	10^{-10}	10^{-9}
$\tau^\pm \to \nu_\tau l^\pm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

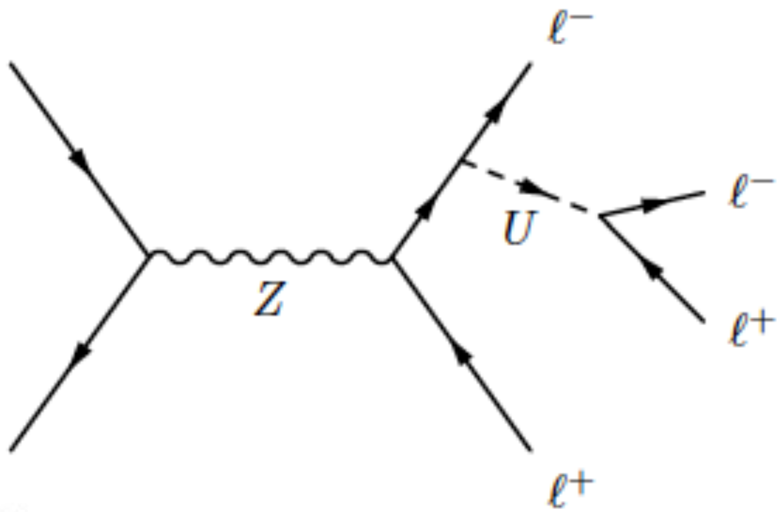
- Very light neutrinos $\to \langle m_{ll'} \rangle = \Sigma_i U_{il} U_{l'i} m_i$,
- Very heavy neutrinos $\to \Sigma_k V_{lk} V_{l'k} / m_k$,
- Resonant neutrinos $\to \Sigma_k V_{lk} V_{l'k} m_k / \Gamma_N$

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

Probe New physics in Z four-body decays

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





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

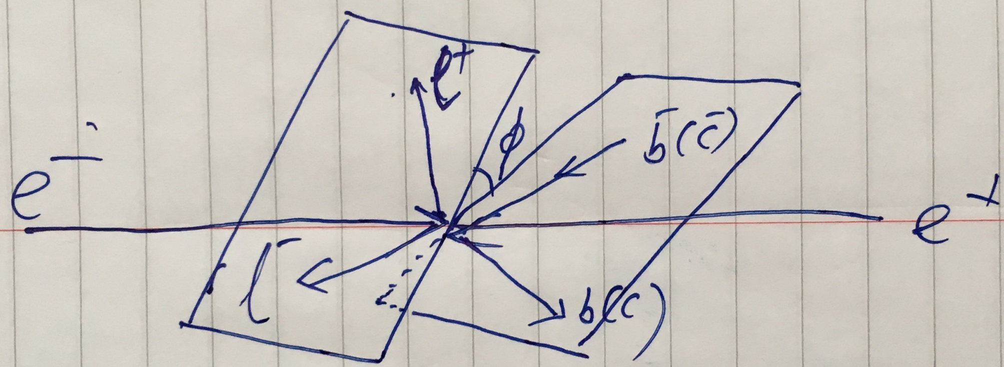
U could be scalar or vector boson

arXiv:1805.05791

CPV in Z decays

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

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



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

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

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

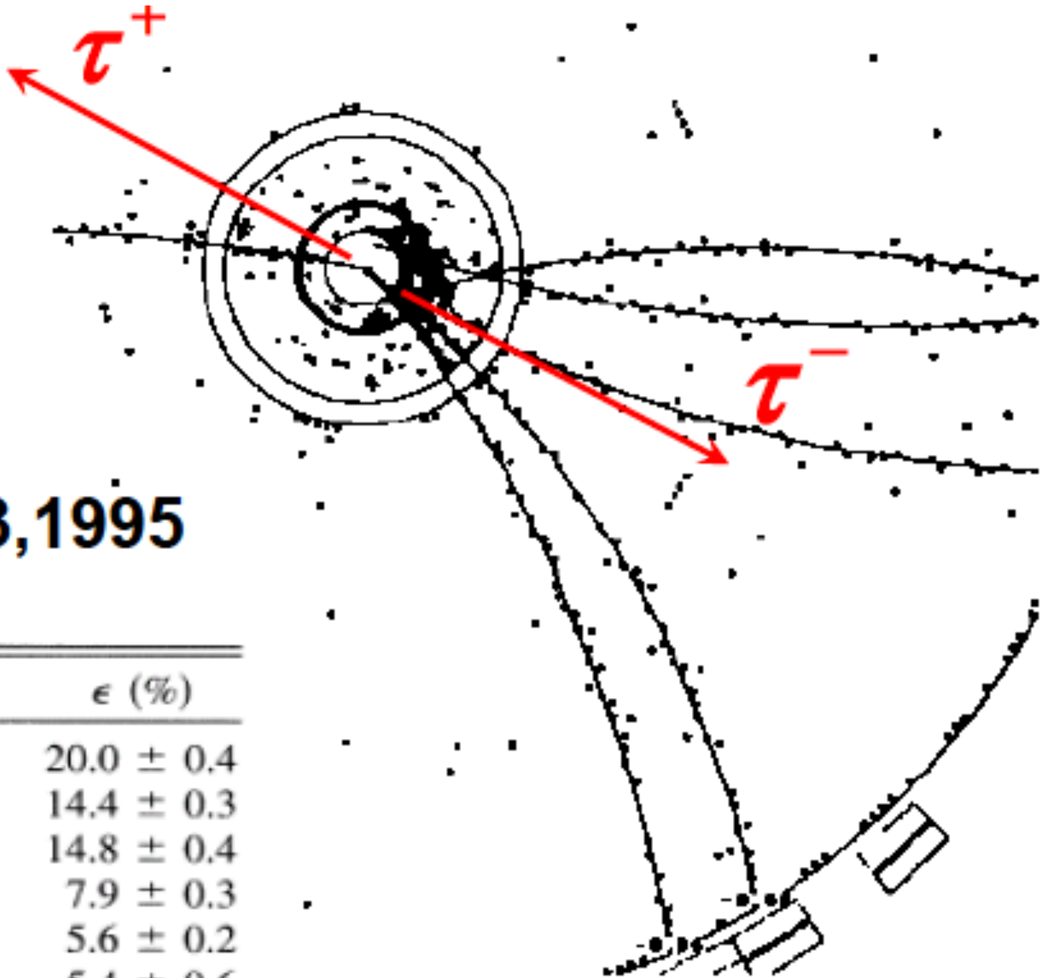
Ecm～10.6 GeV

Tau 对之间任意粒子的夹角均大于90°。

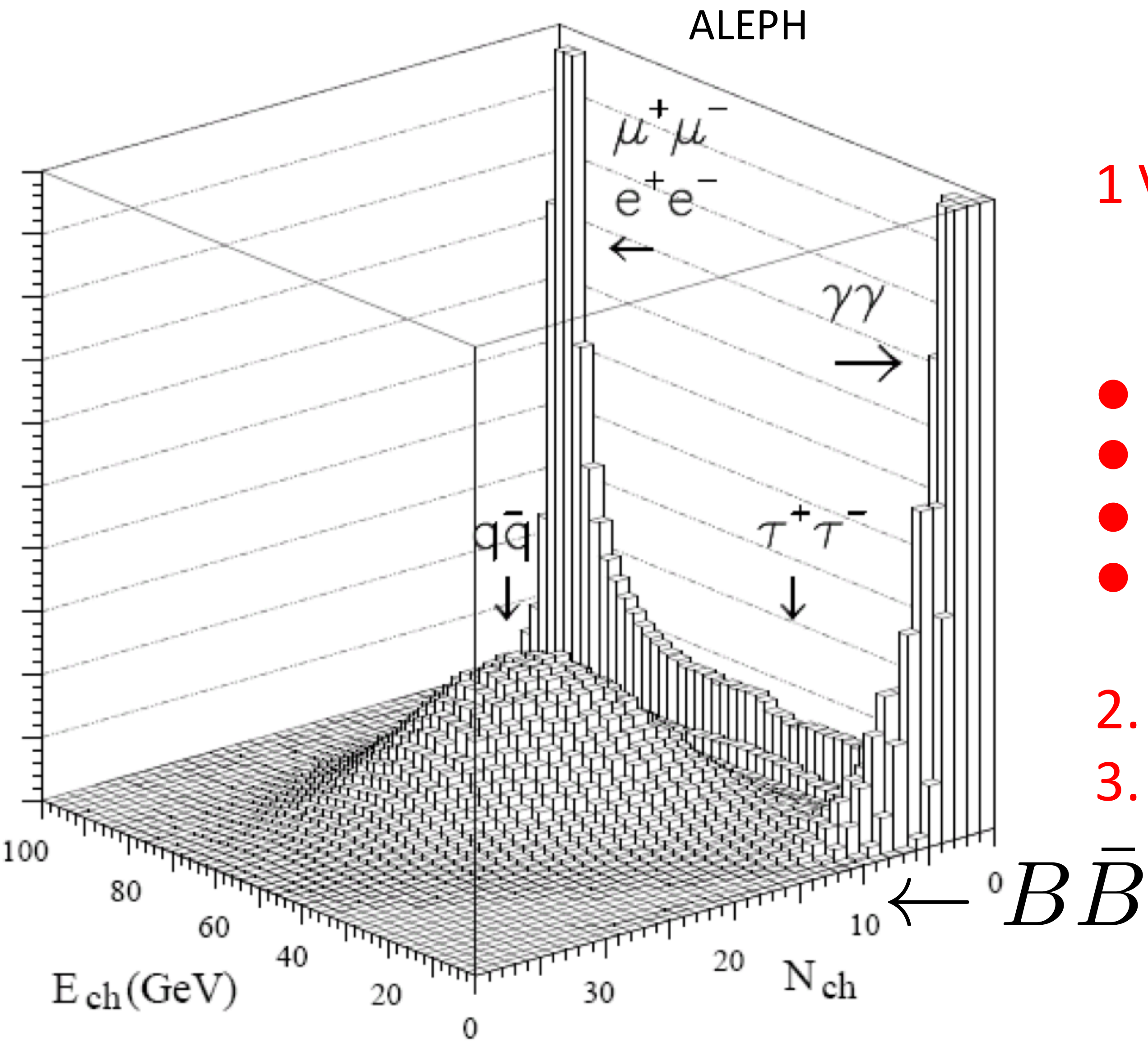
CLEO

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



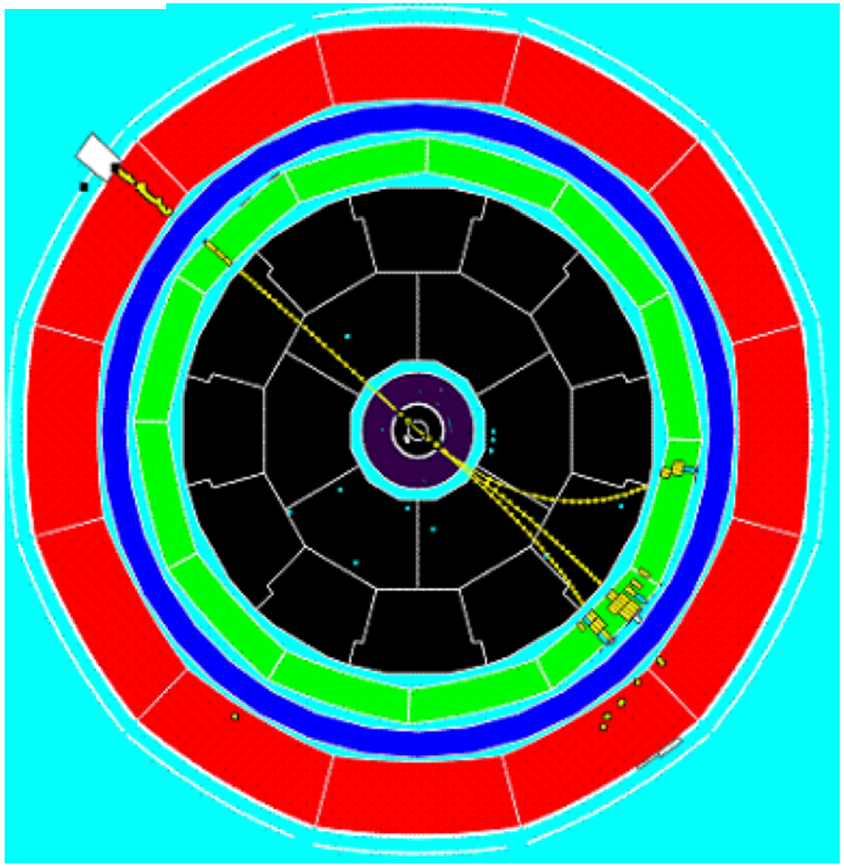
1 Very clean $\tau\tau$ events can be selected with very simple selection criteria.

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

2. Subtract background
3. Classify all the events

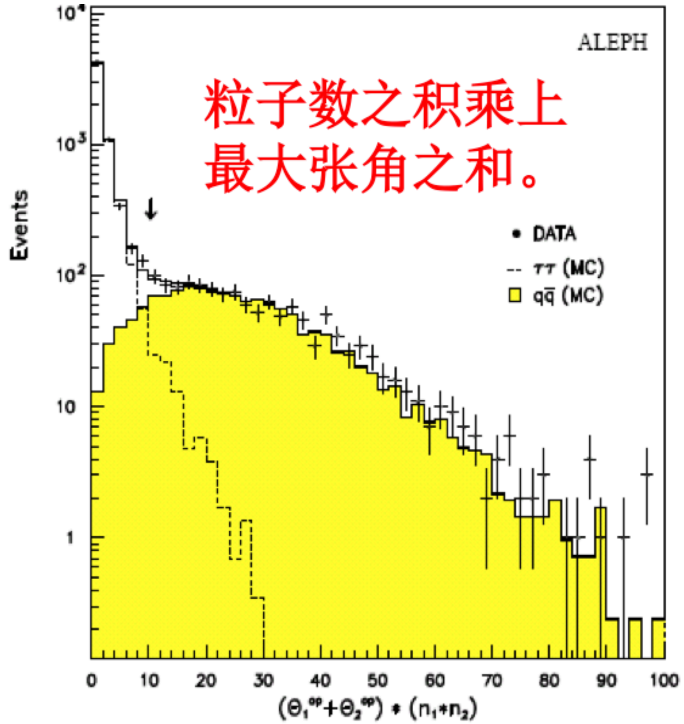
tau lepton reconstruction at Z-peak

ALEPH



Ecm≈91 GeV

Z.Phys.C70:579-608,1996



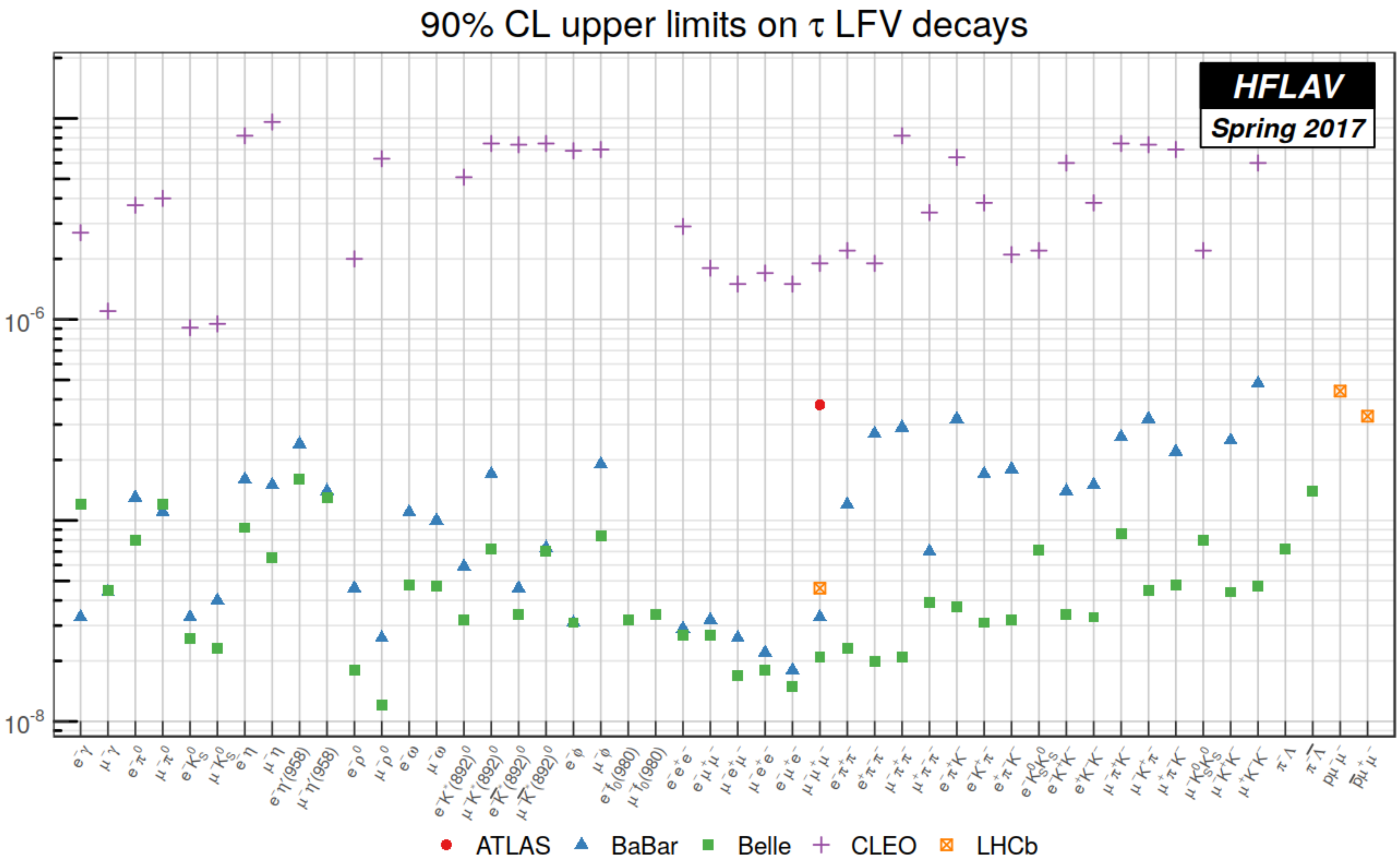
Physics processes	Efficiency (%)	Contamination (%)
$Z^0 \to \tau^+\tau^-$	78.84 ± 0.13	
Bhabha		0.15 ± 0.03
$Z^0 \to \mu^+\mu^-$	丢失的效	0.07 ± 0.02
$\gamma\gamma \to e^+e^-$		0.07 ± 0.02
$\gamma\gamma \to \mu^+\mu^-$	率是因几	0.08 ± 0.02
four-fermion		0.14 ± 0.02
cosmic rays	何造成的	0.02 ± 0.01
$Z^0 \to q\bar{q}$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

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: ~10^{-6}-10^{-7}
- Electric Dipole Moment of the tau: Re(d_{tau}) ~ 10^{-19} e cm
- Weak Dipole Moments of the tau (Z and W coupling)

cLFV in tau decays

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



Heavy quarks @ Z peak

Two key issues: *CP* violation and rare *b*-decays (FCNC)

LHCb sees all species of *b*-particles (and charm in abundance) and is especially good at rare decays with muons and fully charged decay modes. However less efficient for electrons, neutrals, missing energy, hadronic multibody decays.

Belle II should explore deeply/widely 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.

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.

$$B_s \to \phi\tau\tau \qquad B_s \to \eta\mu\mu$$

$$B_s \to \eta'\tau\tau \qquad B_s \to \eta'\mu\mu$$

$$B^0 \to K^{(*)}\tau\tau \qquad B^0 \to \pi^0\mu\mu$$

$$B^0 \to \pi^0\tau\tau \qquad B^0 \to \eta\mu\mu$$

$$B^+ \to K^{+(*)}\tau\tau \qquad B \to h\nu\bar{\nu}$$

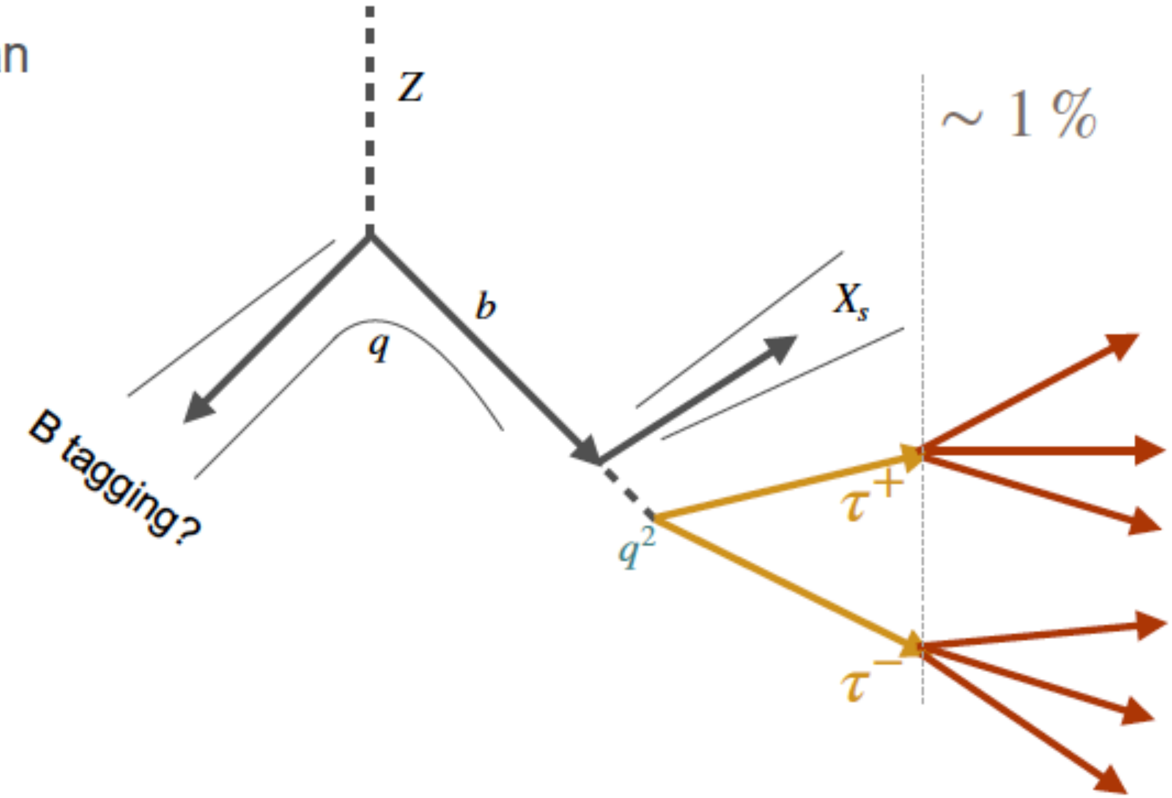
B/Bs → (K*) tau tau

Reconstruction Methods

Talk by Simon Wehle

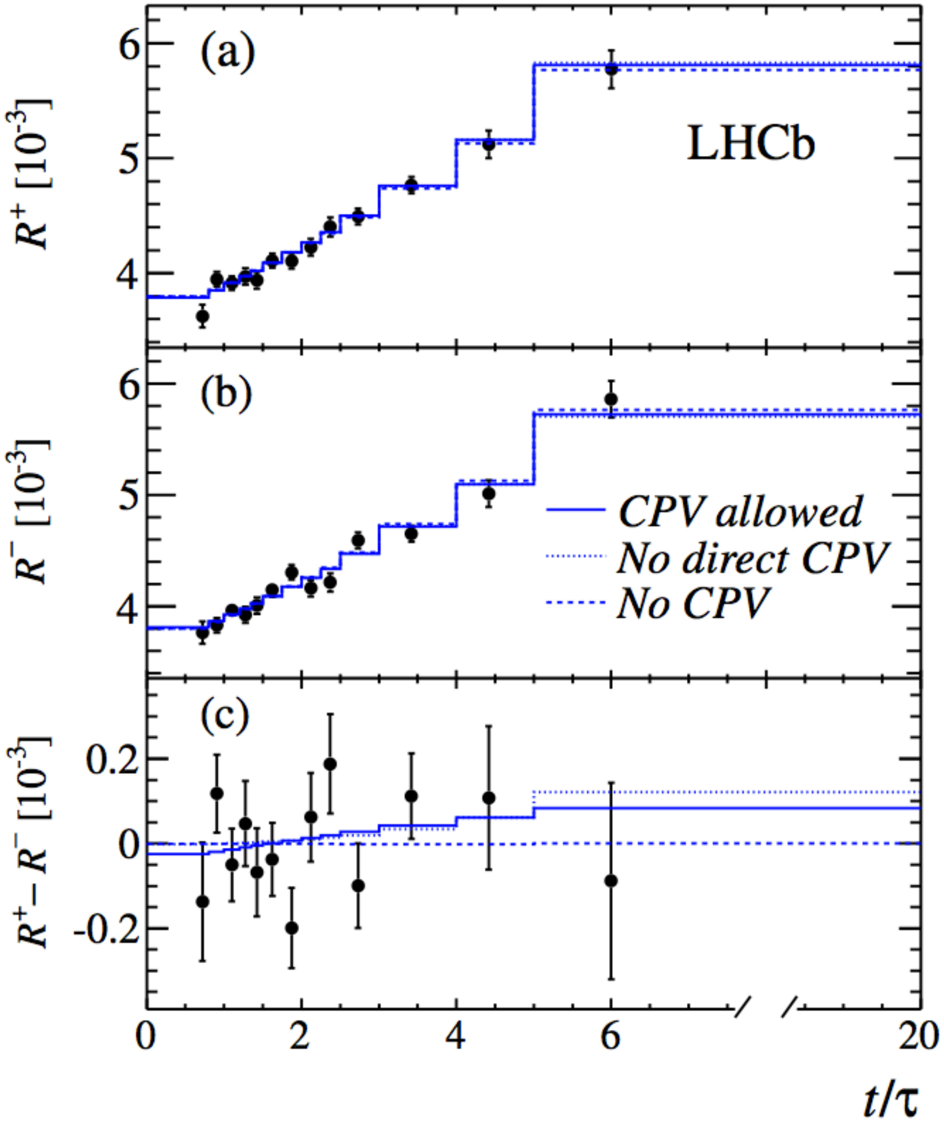
Inclusive

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

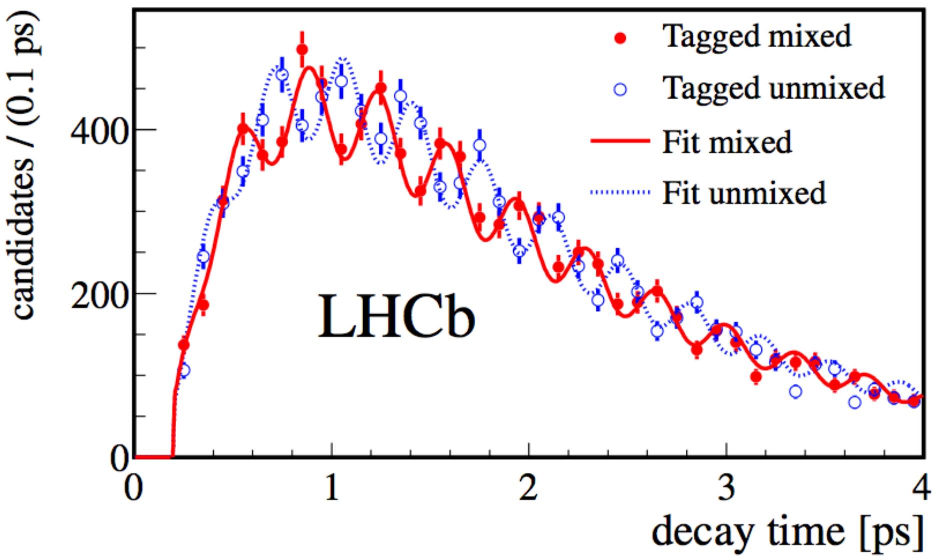


Time resolution

D^0 mixing



Bs mixing



$$\sigma_t/\tau_D < 1$$

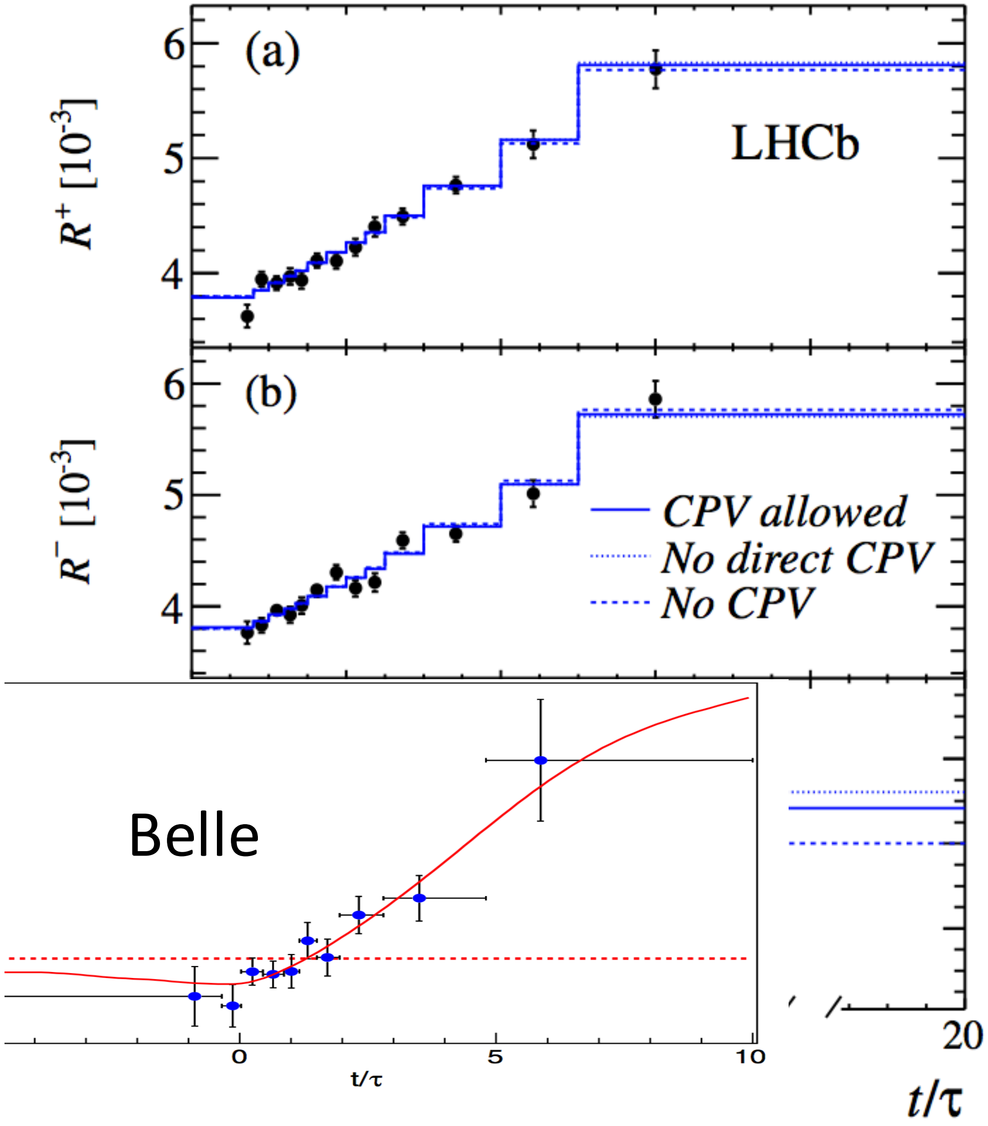
$$\sigma_t \sim 0.25ps(Belle)$$

$$\sigma_t \sim 0.040ps(LHCb)$$

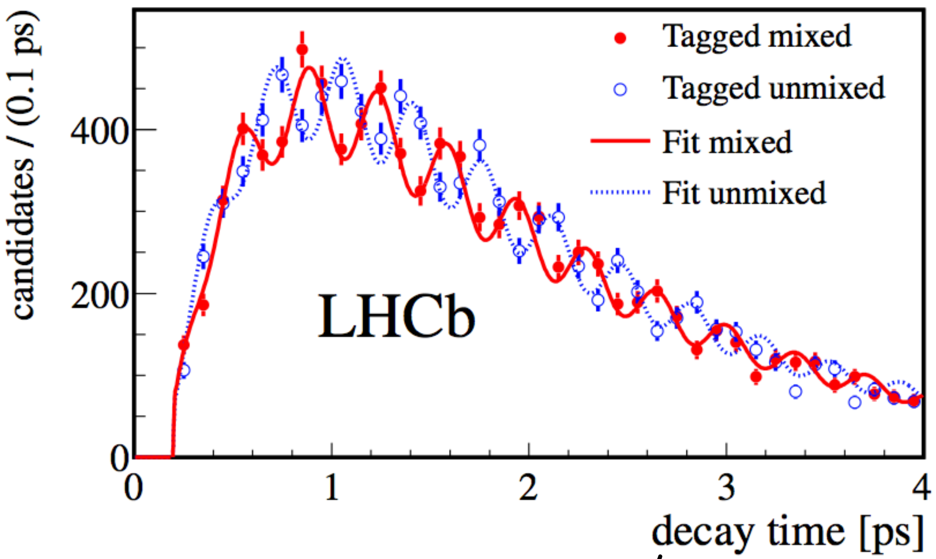
CEPC: σ~ 0.030-0.050 ps

Time resolution

D^0 mixing



Bs mixing



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CEPC: σ~ 0.030-0.050 ps

Time-dependent CPV in Bs→J/$\psi\phi$

Bc production at Z pole

Efforts from LEP: OPAL PLB420 157 ; DELPH PL B398 207; ALEPH: PL B402 213

OPAL 1998 $$\mathcal{B}(Z \to B_c + X) = \frac{(3.8^{+5.0}_{-2.4} \pm 0.5) \times 10^{-5}}{\mathcal{B}(B_c \to J/\psi\pi^+)}$$

PRD85(2012)094015 , LO NRQCD prediction:

$$\sigma(e^+e^- \to Z \to B_c + b + \bar{c}) = (5.19^{+6.22}_{-2.42})pb$$

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

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

Event generator on Z peak: arXiv:1305.4828

Study of Bc decays @ Z peak

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

< 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

$B_c \to B_s + anything$

$B_c \to J/\psi + anything$

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

Stable doubly heavy Tetraquark

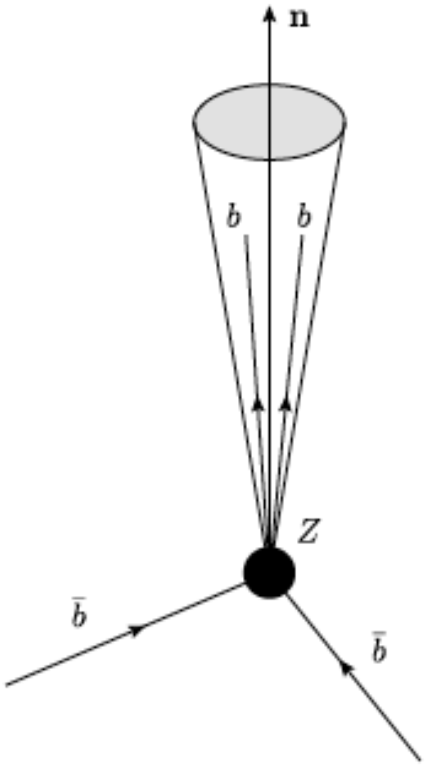
- $bb\bar{q}\bar{q}'$: PLB 782(2018) 412

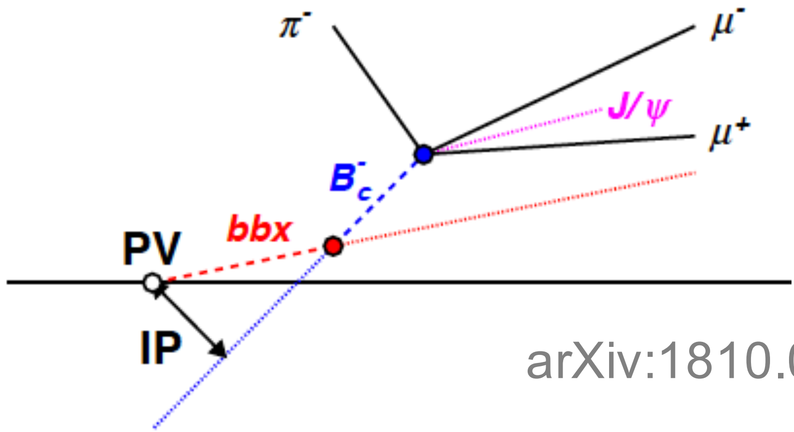
$$\mathcal{B}(Z \to bb\bar{b}\bar{b}) = (3.6 \pm 1.3) \times 10^{-4}$$ LEP 98

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

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

PRL 119(2017)20
PRD90(2014) 094007





arXiv:1810.06657

Requirement

- For charged tracks
  - Good momentum measurement
  - Good π/K separation (PID for tracks up to 40 GeV?)
  - Good vertex: TDCPV, lifetime, background suppression
- For $\gamma/\ \pi^{0}$
  - Good geometric coverage
  - Very fine granularity with longitudinal readout
  - Good energy resolution and angular resolution
  - Very low photon energy threshold: < 200 MeV

Plan and manpower

- Tau physics

  1) "Passemar, Emilie" <epassema@indiana.edu>

  2) Wolfgang Altmannshofer, Emmanuel Stamou
- B/Bs/Bc/Lambda_b

  1) Yuehong Xie (LHCb, 华中师大)

  2) Emmanuel Stamou and Wolfgang Altmannshofer

  3) Fenfen An (IHEP), Soeren Prell (IA state Univ.) Exp.

  4) Jianchun Wang (IHEP, LHCb)
- Hadron spectroscopy and charm

  1) Fusheng Yu (Lanzhou Uni.) Theory

  2) Fengkun Guo (ITP) Theory

  3) Wei Wang (SHJTU) Theory

  3) Hai-Bo Li (IHEP)
- CKM fitter

  1) "Sébastien Descotes-Genon

  2) Jerome Charles jerome.charles@cpt.univ-mrs.fr
- New Physics → cLFV

  1) cLFV in Z decays : "Lorenzo Calibbi" <calibbi@itp.ac.cn>

You are very welcome to join us!

Summary

- Understand the experimental precision：

  rare decays of *c*- and *b*-hadrons and CP violation at 10^{12} *Z factory;*

  precision tau physics with 10^{12} *Z.*

- Examine the physics reach of lepton flavor violating processes and neutrino-related Physics unique to the CEPC.
- Examine the relevance of a dedicated PID (π / K / p separation) detector.
- Unique place for the tau decays and b-hadron taunic decays.
- Do we need a comprehensive paper on flavor physics?

Thank you!