Some experimental aspects of

Flavor physics at CEPC

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09:05	**Potential in probes of new physics: rare hyperon decays vs. kaon decays** *25′* Speaker: Li-Sheng Geng (BUAA)
09:30	**Probing new physics with LFV Z decays at the CEPC** *25′* Speaker: Lorenzo Calibbi (Nankai University)
14:00	**Flavor Physics – An Experimental Review** *30′* Speaker: Abi Soffer (Tel Aviv U.)
14:30	**Analysis of Bc -> tau nu at CEPC** *20′* Speaker: Taifan Zheng (Nanjing University)
14:50	**Double-charm tetra-quark production at CEPC** *20′* Speaker: Mr. FuSheng Yu (IHEP)
15:10	**Flavor-changing charm decays illuminating dark photons at CEPC** *20′* Speaker: Jusak Tandean (Department of Physics National Taiwan University)
15:30	**Leptoquarks at future e^+ e^- colliders** *20′* Speaker: Andreas Crivellin (Zurich U.)
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tau physics

Higgs couplings

Flavor physics and CEPC

- Kaon experiments, LHCb, Belle II
  (I can't comment much)

Strangeness

- 10^{12} Z's: clearly the best facility for any Z study
- HL-LHC: 3 $ab^{-1} \sim 10^{11}$ Z's, but much less sensitive per Z
- Ensure lepton ID & b,c-tagging good enough to utilize the statistics

FV in Z

- Belle II, LHCb
- But some unique strengths for CEPC

B physics

- LHCb, Belle II, charm factory

Exotic hadrons

Charm decays

- Belle II, LHCb, ATLAS, CMS
- But some unique studies at the Z

NP with flavor

- Belle II

tau physics

- Clear CEPC territory
- Ensure good kaon ID for $H \to s\bar{s}$

Duarte-Campderros, Perez, Schlaffer, Soffer, [1811.09636]

Higgs couplings

b physics at CEPC

From Sébastien Descotes-Genon’s talk at the July 2019 workshop, Beijing:

CEPC and other flavour factories

Machine	CEPC (10^{12} Z)	Belle II (50 ab^{-1} + 5 ab^{-1} at $\Upsilon(5S)$)	LHCb (50 fb^{-1})	FCC-ee (150 ab^{-1})
Data taking	2030-2040	$\rightarrow$ 2025	$\rightarrow$ 2030	2035-2045
B^+	6×10^{10}	3×10^{10}	3×10^{13}	3×10^{11}
B^0	6×10^{10}	3×10^{10}	3×10^{13}	3×10^{11}
B_s	2×10^{10}	3×10^{8}	8×10^{12}	1×10^{11}
B_c	1×10^{8}	–	6×10^{10}	6×10^{8}
b baryons	10^{10}	–	10^{13}	10^{11}

CEPC will have similar B statistics to Belle II, but:

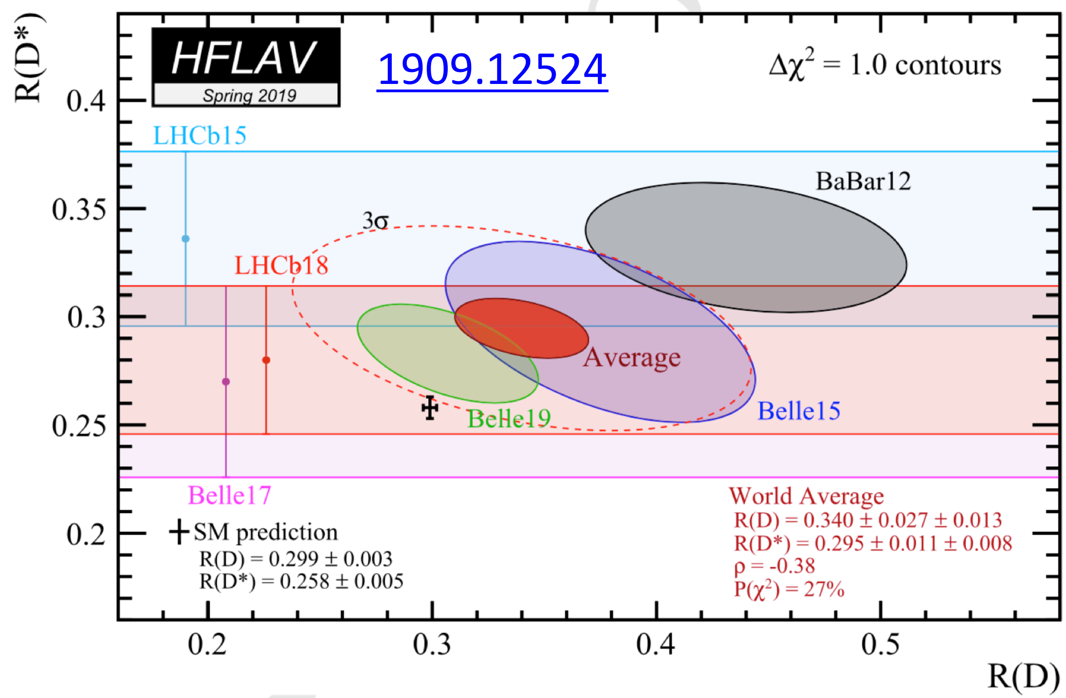
- Significantly later. Adding statistics won’t be relevant.
  - Belle II may also be upgraded by then, as will LHCb
- CEPC produces $ee \rightarrow b\bar{b}X$ like LHCb, not $ee \rightarrow B\bar{B}$ like Belle II
  - B production at CEPC isn’t so “clean”

(Semi)Tauonic b-hadron decays

- Measurements of

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)},$$
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

  are in ~3σ tension with the SM
- This might go away with new LHCb+Belle II results
- But still useful lab for probing new physics



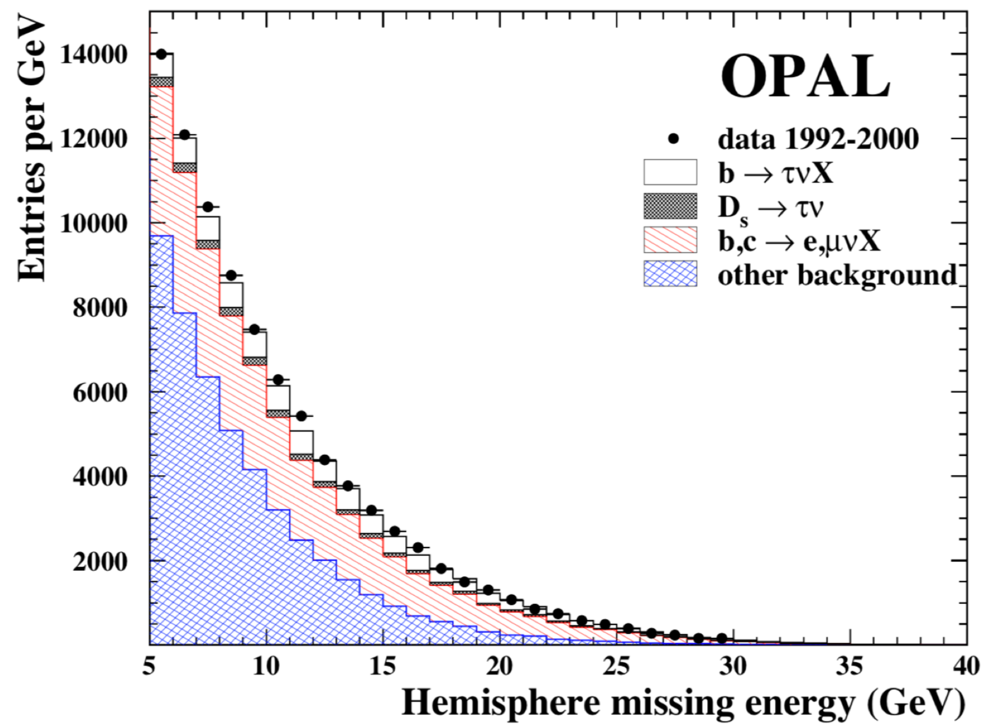
(Semi)Tauonic b-hadron decays

LEP demonstrated the capability.
E.g., OPAL (PLB 50, 1, hep-ex/0108031), $B \to \tau\nu X$:

- Divide the event into 2 hemispheres
- b-tag one hemisphere using vertexing: eff=47%, purity=92%
- Fit the missing energy in the other hemisphere

- Obtain a BR of $(2.78 \pm 0.18 \pm 0.51)\%$
- Similar precision by the other LEP experiments

- This is with ~4M Z→hadron events
- With 10^{12} Z's, $\sigma_{\text{stat}} \to 4{\times}10^{-4}$ % (!)



(Semi)Tauonic b-hadron decays

From control samples, $\propto 1/\sqrt{L}$

Mean b & c energy, from fragmentation models. Will be precisely measured at CEPC.

Greatly improved by B factories

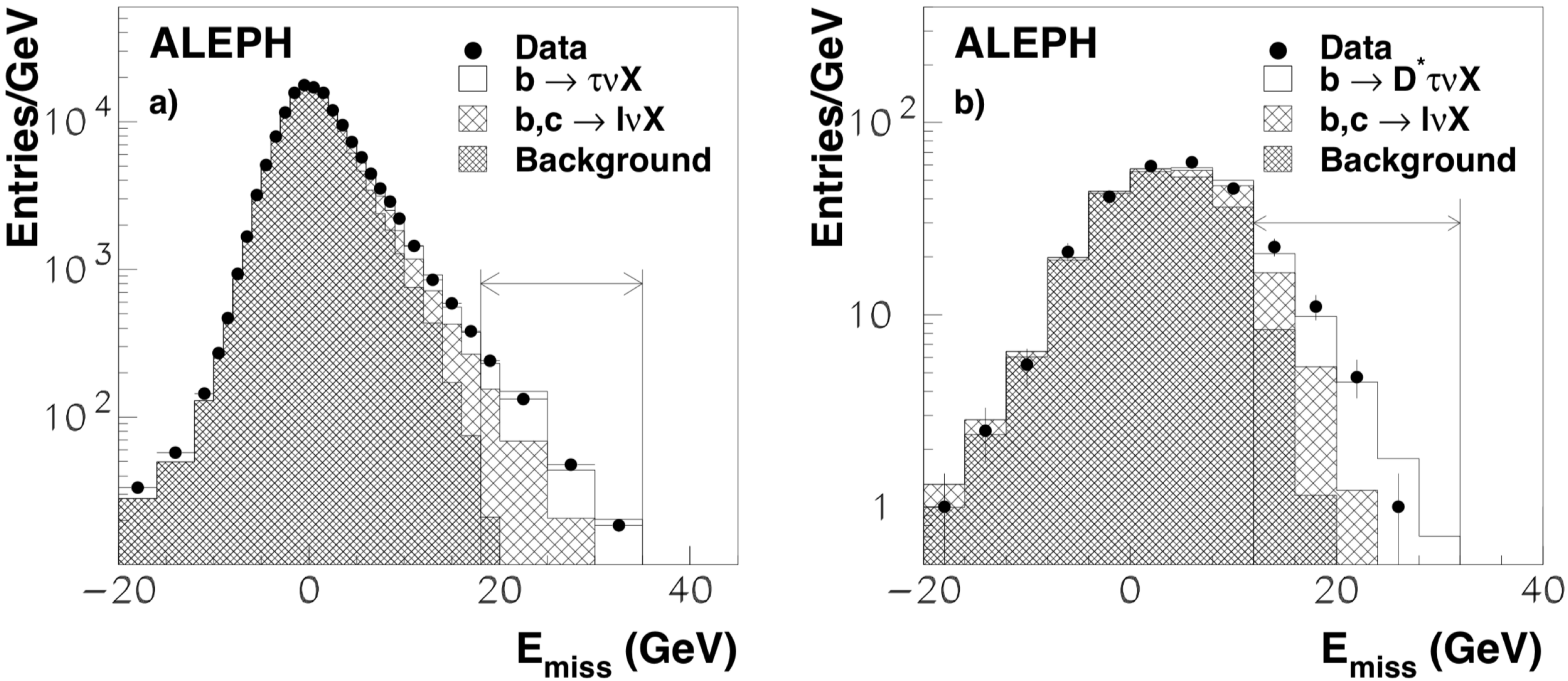
Note:

$$\sqrt{\frac{N_B(\text{Belle II})}{N_B(\text{CLEO})}} \sim 70$$

Source	$\Delta\text{BR}(\text{b} \to \tau^- \overline{\nu}_\tau \text{X})$
leptonic $E_{\text{miss}}^{\text{hemi}}$ description	-0.16%
hadronic $E_{\text{miss}}^{\text{hemi}}$ description	$+0.15\%$
tracking resolution	$\pm 0.04\%$
calorimeter resolution	$\pm 0.06\%$
b tagging efficiency	$\pm 0.04\%$
$\text{e}^\pm$ veto	$\pm 0.11\%$
$\mu^\pm$ veto	$\pm 0.07\%$
$\langle x_\text{b} \rangle = 0.702 \pm 0.008$ [26]	$\pm 0.33\%$
$\langle x_\text{c} \rangle = 0.484 \pm 0.008$ [26]	$\pm 0.04\%$
$\text{b} \to \tau^- \overline{\nu}_\tau \text{X}$ decay modelling	$\pm 0.03\%$
semileptonic b decay models	$\pm 0.26\%$
$\text{BR}(\text{b} \to \ell^- \overline{\nu} \text{X}) = (10.73 \pm 0.18)\%$ [9]	$\pm 0.08\%$
$\text{BR}(\text{b} \to \text{c or } \overline{c} \to \ell \nu \text{X}) = (9.69 \pm 0.51)\%$ [26]	$\pm 0.05\%$
$\text{BR}(\text{D}_\text{s}^- \to \tau^- \overline{\nu}_\tau) = (7.2 \pm 2.3)\%$ [27, 28]	$\pm 0.13\%$
$f(\text{b} \to \text{D}_\text{s}^-) = (18 \pm 5)\%$ [29]	$\pm 0.10\%$
Total systematic uncertainty	$\pm 0.51\%$

(Semi)Tauonic b-hadron decays

- ALEPH (hep-ex/0010022) also measured $\mathrm{Br}(b \to D^{*-}\tau^{+}\nu X) = (0.88 \pm 0.31 \pm 0.28)\%$
-



(Semi)Tauonic b-hadron decays

- At the Upsilon(4S), the 2 B's are not separated kinematically
  - B factories fully or partially reconstruct the other B in the event to reduce background and measure missing mass (called "Recoil B tagging")
  - Effective B-tagging efficiency is ~1%, compared with ~50% at LEP
- LHCb:
  - sensitivity to $(b \to D^{*-}\tau^{+}\nu)$ with 1-3 fb^{-1} is similar to those of BABAR and Belle with ~1 ab^{-1} (from published results)
  - With 50 fb^{-1}, expect sensitivity similar to that of Belle II with 50 ab^{-1}
  - Even with 300 fb^{-1}, sensitivity probably less than that of CEPC
- Improvements at CEPC wrt. LEP:
  - Better vertexing:
    - higher b-tag purity (other hemisphere)
    - higher signal purity from displaced B and tau vertex (used by LHCb)
  - Better calorimetry:
    - Better missing mass resolution

(Semi)Tauonic b-hadron decays

- There is a whole set of measurements:
  - Inclusive $b \to \tau\nu X$
  - $B \to D^{(*)}\tau\nu$, $B \to D^{**}\tau\nu$, $B^+ \to \tau\nu, B \to \pi/\rho\tau\nu$,
    $B_s \to K^{(*)}\tau\nu$ (requires some kaon ID),
    $B_c \to \psi\tau\nu$ (J/ψ done by LHCb), $B_c \to \tau\nu$ (Taifan Zheng's talk)
- Measure not only BRs, but q^2 distribution, polarizations
  - (Belle has already measured the tau polarization, with a 50% error)
- Interpretation ambiguity between exclusive and inclusive
  - E.g., hard to differentiate between $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\tau\nu\pi^0$
  - This also happens at LHCb with high lumi, and somewhat at Belle II
  - Resolving the ambiguity requires performing many exclusive measurements
    - E.g., Belle II can measure exclusive $B \to D\tau^-\bar{\nu}$, while CEPC has background from $B \to D\pi^0\tau^-\bar{\nu}$. CEPC might be able to use $B \to D\pi^+\tau\nu X$ + isospin to estimate its contribution, in addition to rejecting events with photons in the direction of the b jet.

What can we learn from these decays?

- If a large deviation from the SM is found by Belle II and LHCb:
  - CEPC would add more detailed information
- Otherwise
  - These are still interesting decays with NP sensitivity
  - The increased sensitivity of CEPC might be hard to interpret due to the inclusive/exclusive confusion
  - What are the theoretical limitations?

- See also Wolfgang Altmannshofer's talk regarding $B \to K\tau\tau$
  - This mode has the same benefits at CEPC as $B \to \tau\nu X$

Basic CP violation @ CEPC

- As an example, look at the CP parameter $\sin 2\beta$:
  - $0.687 \pm 0.028 \pm 0.012$ at BABAR with 450 M BB events
  - $0.84 \pm 1.0 \pm 0.16$ at ALEPH with 4M Z events
  - Naïve lumi scaling gives stat errors of 0.003 at Belle II and 0.002 at CEPC.

Belle II physics book 1808.10567 predicts 0.006 with realistic systematic evolution

- So CEPC could have similar sensitivity to Belle II
  - But significantly later

Potentially more interesting

- Can introduce sensitive CPV studies of semi-tauonic B decays
  - Aloni, Grossman, AS, 1806.04146
  - Duraisamy, Datta, 1302.7031
  - Hagiwara, Nojiri, Sakaki, 1403.5892
- These are difficult measurement
  - phase-space-dependent
  - require exclusive reconstruction
  - is there sufficient motivation in the absence of tension in $R(D^{(*)})$?

Perhaps also interesting

- Take advantage of the fact that in the SM, b quarks produced in Z decays are more left-handed ($c_L = -0.42, c_R = 0.08$), so they are polarized
- This could be useful for studying T-violating triple products in 3-body Λ_b decays, using the polarization direction (the b-jet direction) as one of the axes.
  - (The idea was conveyed to me by Yuval Grossman)
- Λ_c from $Z \to c\bar{c}$ could also be used, although the polarization is smaller for charm ($c_L = 0.35\ c_R = -0.15$) and one has to beware of Λ_c produced in b-hadron decays
- I don't have much more to say about it at this point, except to encourage theoretical work on measurement options and how they could be used to improve SM parameters or search for new physics.
- JHEP 11 067, 1505.02771 discusses using Λ_b decays to study polarization

Exotic hadrons, charm, tau

- CEPC charm and τ statistics ~ Belle II statistics
- Again, too late to be of particular interest

- τ already boosted enough at Belle II, so no advantage to large CEPC boost
- CEPC will have more precise vertexing & less multiple scattering
  - O(1) improvement

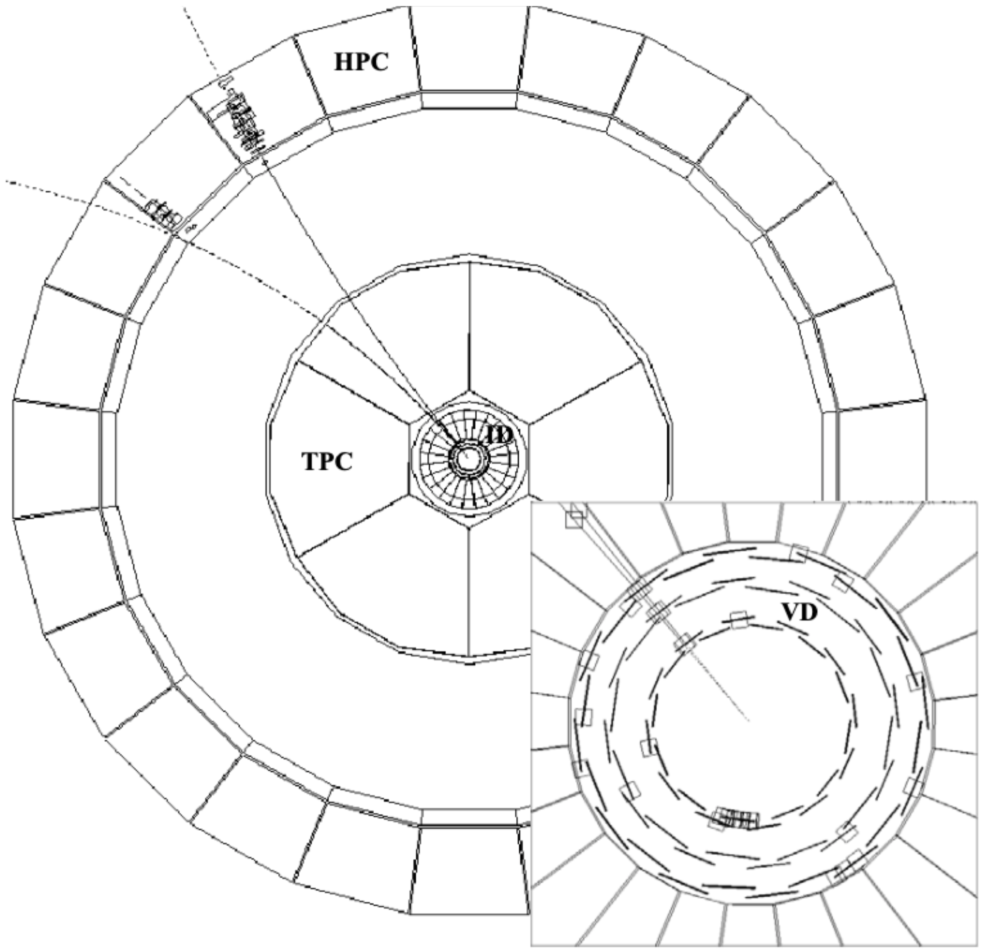
- Exotic hadrons: access to heavier states than Belle II
- But difficult to imagine beating LHCb's large cross section

New flavor-carrying particles: HNL

- Heavy neutral lepton:
  - DELPHI: Monojet search at various radii: very clean
  - Few 10^6 Z's

DELPHI: Z.Phys.C 74 (1997) 57, Z.Phys.C 75 (1997) 580 (erratum)

The single data event (probably $ee \to ee\nu\nu$)



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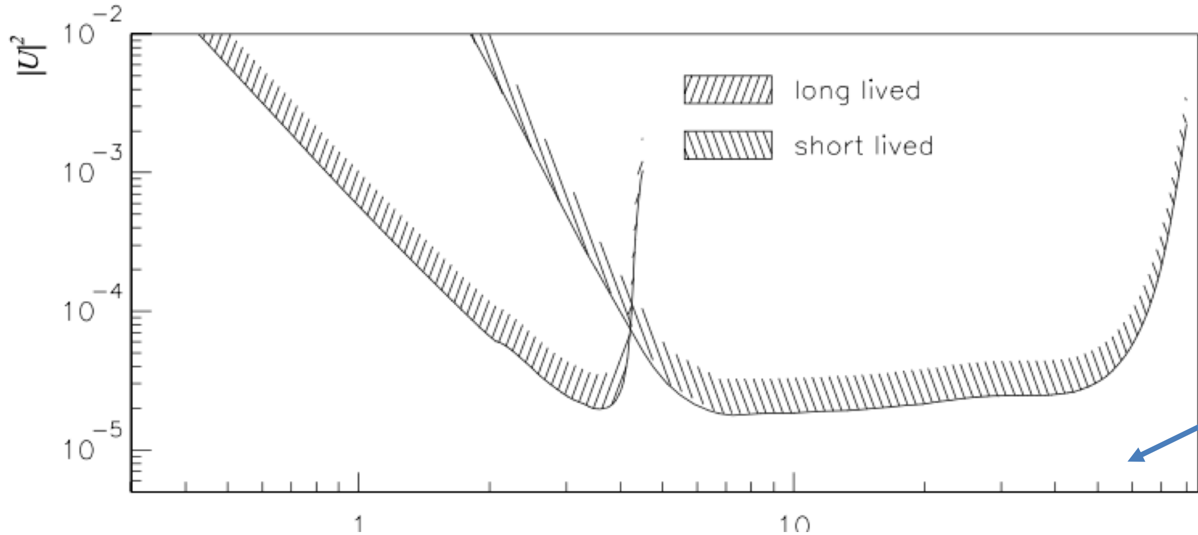
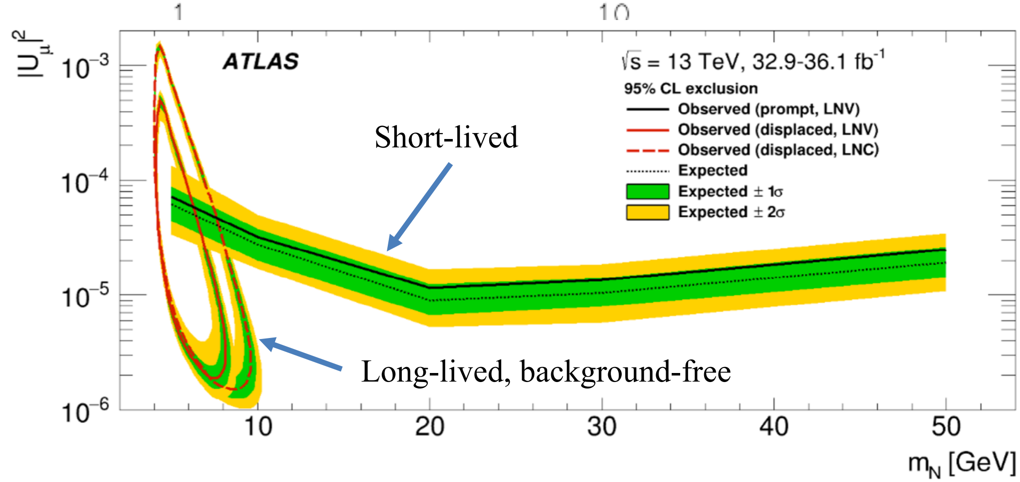
All flavors



Note different x scales

Mixing with ν_μ



Short-lived

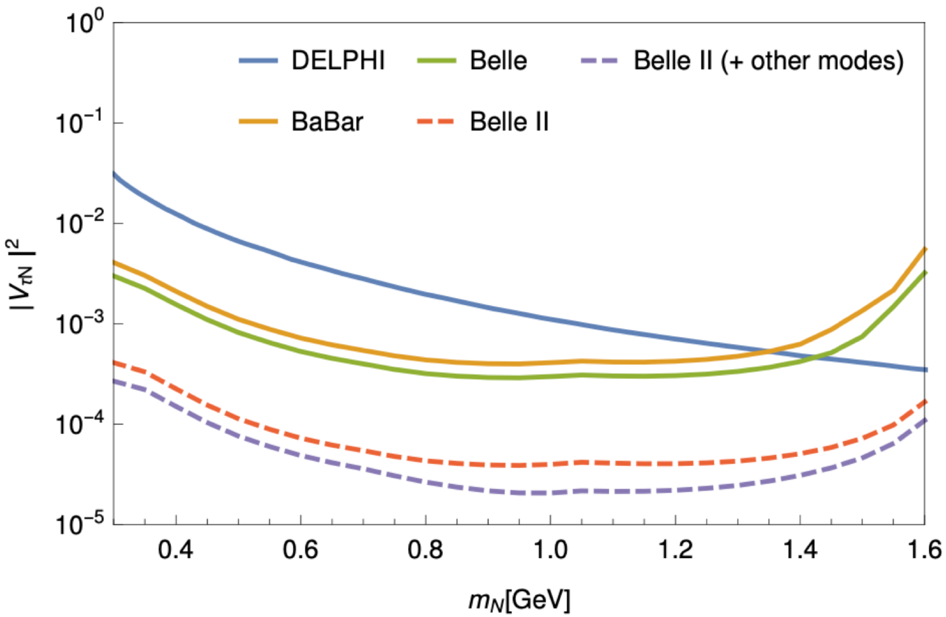
Long-lived, background-free

ATLAS:
JHEP 10 (2019) 265
1905.09787, 10^9 W's
~30 fb^{-1}

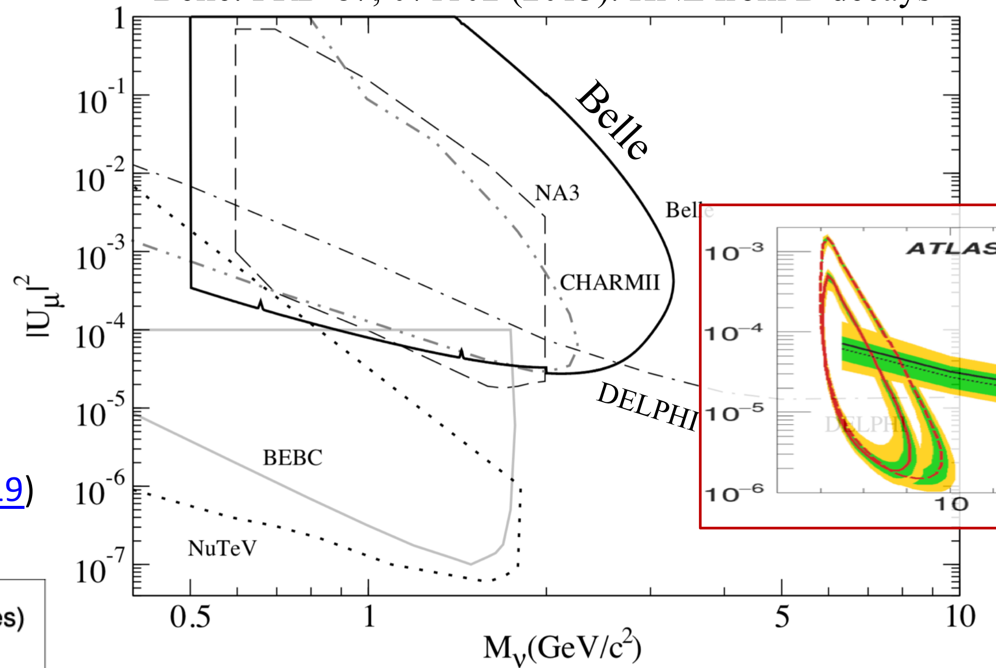
New flavor-carrying particles: HNL

Many experiments studied $|U_\mu|^2$
Only DELPHI probed $|U_\tau|^2$

B factories more sensitive to $|U_\tau|^2$
for $m_N < m_\tau$
(Dib, Helo, Nayak, Neil, Soffer, Zamora-Saa, 1908.09719)



Belle: PRD 87, 071102 (2013): HNL from B decays



But with ~ 10^5 more Z′s than DELPHI, CEPC will beat Belle II by O(10) assuming analysis is background dominated.

Summary

- CEPC is not likely to be competitive in
  - CP violation in hadron decays, charm, τ, exotic hadrons
    - But see talk by FuSheng Yu
- Will dominate in a few flavor-physics and related areas:
  - Anything directly related to Z decays (e.g., LFV, FCNC)
    - See talk by Lorenzo Calibbi
  - Tauonic and semi-tauonic b decays, particularly inclusive modes
    - See talks by Taifan Zheng and Wolfgang Altmannshofer
  - HNLs, both short- and long-lived, all neutrino-flavor mixings
    - See also talks by Andreas Crivellin and others
- Matching systematics with statistics will require excellent performance
  - b-tagging, c-tagging, lepton ID, kaon ID, spatial and energy resolutions