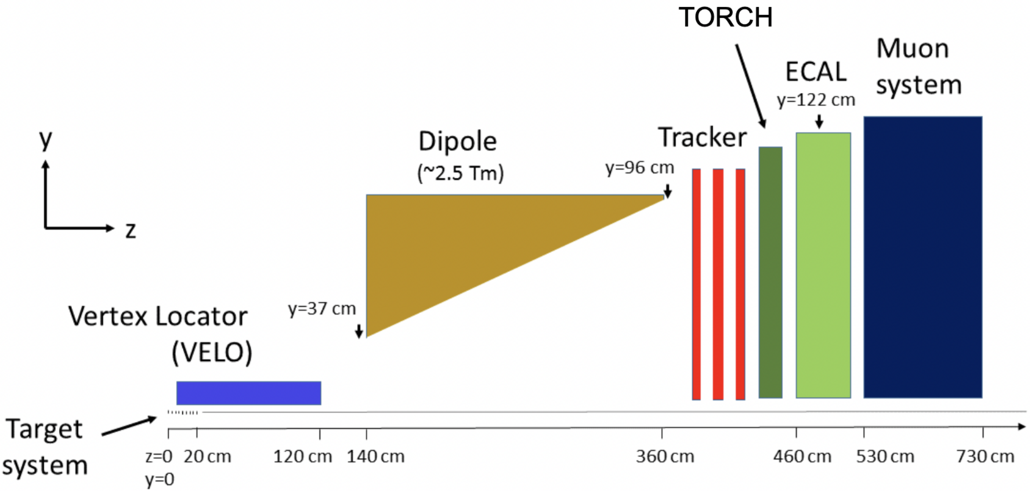

TauFV: opportunity for flavor physics @ SPS

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TauFV: ultimate τ and charm factory

TauFV puts forward **a concept of a high-precision fixed-target flavor experiment**

Latest documented status: input to the EPPSU

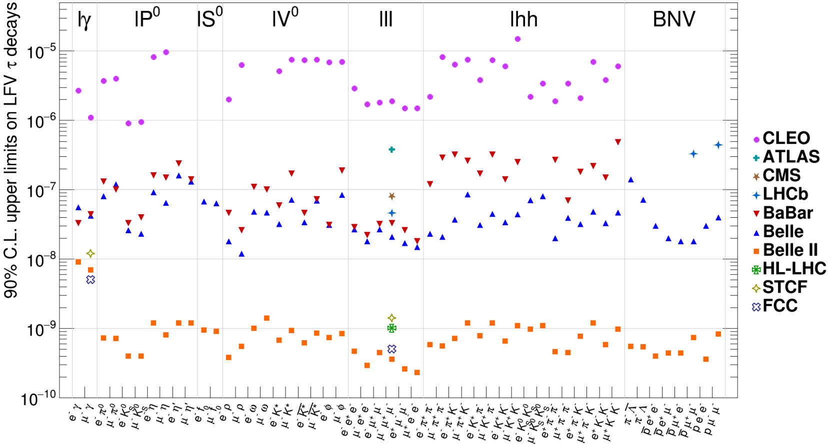
- TauFV: a fixed-target experiment to search for flavour violation in tau decays

Key characteristics in this proposal:

- located 100 m upstream of the proposed BDF with a separate target
- operates synergistically with the main user:
  - takes 2% of the proton beam
- aims at collecting 4×10^{18} PoT in 5 years
- leads to 10^{16} D and D_s mesons, 8×10^{13} taus from $D_s^- \to \tau^- \overline{\nu}_\tau$, 10^{19} kaons
  - $\tau \to 3\mu$ physics case is used as a demonstrator
  - its acceptance is order or magnitude larger than proposed LHCb Upgrade II

Charged lepton flavor violation in tau decays

$\tau \to 3\ell$ searches – the most stringent upper limits on charged lepton flavor violation



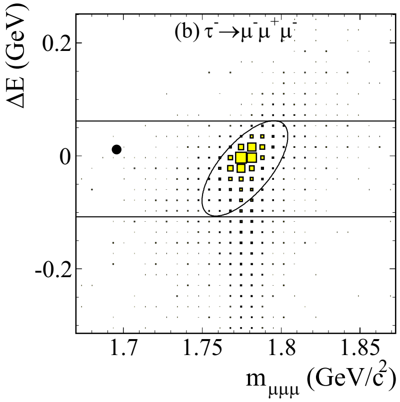
Belle II is the leader in projected sensitivity, expecting 3.6×10^{-10} with 50/ab

arXiv:2203.14919

$\tau \to 3\mu$: e^+e^- vs hadron machines

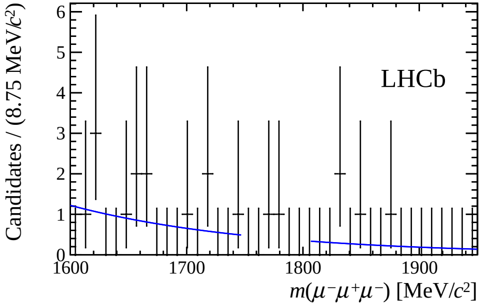
Belle@e^+e^-: $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$

- bkg-free search: tag on the other τ
- **single-event sensitivity**



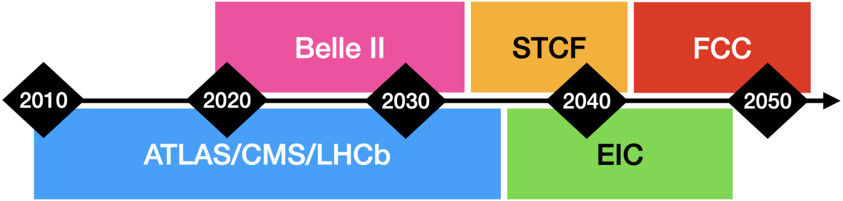
LHCb@pp: $\mathcal{B}(\tau \to 3\mu) < 4.6 \times 10^{-8}$

- irreducible $D_{(s)} \to 3\mu + X$ bkg
- search for a peak on top of bkg
- **need higher signal yield for same sensitivity**



arXiv:1001.3221 arXiv:1409.8548

$\tau \to 3\mu$: future prospects



Existing facilities:

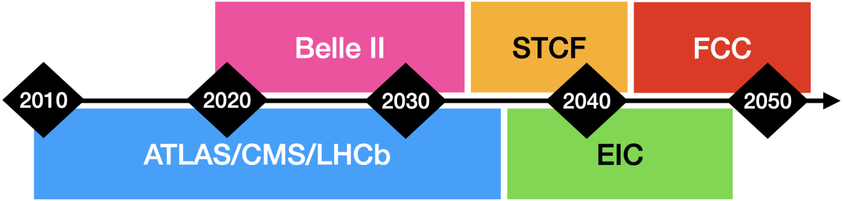
- Belle II@e^+e^-: 3.6×10^{-10}
- HL-LHC: ATLAS, CMS, LHCb envision $\mathcal{O}(10^{-9})$ – **the only hadron machine**

Proposed facilities:

- Super τ-charm facility (STCF), e^+e^- collider in China – 1.4×10^{-9} per year, or 1.4×10^{-10} @ 10 years
- FCC-ee: $\mathcal{O}(10^{-10})$

arXiv:2203.14919

$\tau \to 3\mu$: future prospects



	Observed Limits			Expected Limits		
$\tau^- \to$	Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
$\mu^-\mu^+\mu^-$	Belle	782 fb^{-1}	2.1×10^{-8}	Belle II	50 ab^{-1}	3.6×10^{-10}
	BaBar	468 fb^{-1}	3.3×10^{-8}			
	LHCb	3 fb^{-1}	4.6×10^{-8}	LHCb	300 fb^{-1}	$\mathcal{O}(10^{-9})$
	CMS	33 fb^{-1}	8.0×10^{-8}	CMS	3 ab^{-1}	3.7×10^{-9}
	ATLAS	20 fb^{-1}	3.8×10^{-7}	ATLAS	3 ab^{-1}	1.0×10^{-9}
				STCF	1 ab^{-1}	1.4×10^{-9}
				FCC-ee	150 ab^{-1}	$\mathcal{O}(10^{-10})$

arXiv:2203.14919

$\tau \to 3\mu$: opportunity at the SPS

Assuming 2% of 4×10^{18} PoT in 5 years, get 8×10^{13} $D_s \to \tau\nu$ decays, more than

- $\sim 10^2\times$ produced in LHCb in Runs 1&2
- $\sim 10^5\times$ produced in Belle

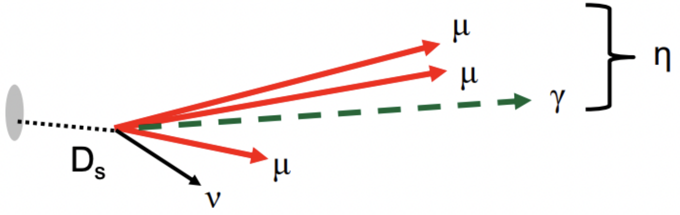
Assuming 10% total efficiency for $\tau \to 3\mu$ decays in TauFV, get for $\mathcal{B}(\tau \to 3\mu) = 10^{-10}$:

Experiment	Luminosity/PoT	Yield	UL (exp)
TauFV	4×10^{18}	800	$\mathcal{O}(10^{-10})$
Belle II	50 ab^{-1}	1	3.6×10^{-10}
LHCb Upgrade I	50 fb^{-1}	14	$\mathcal{O}(10^{-8})$
LHCb Upgrade II	300 fb^{-1}	84	$\mathcal{O}(10^{-9})$

Get into the competition on a not so long timeline!

Challenges: trimuon processes

Dominant background in the latest LHCb search:



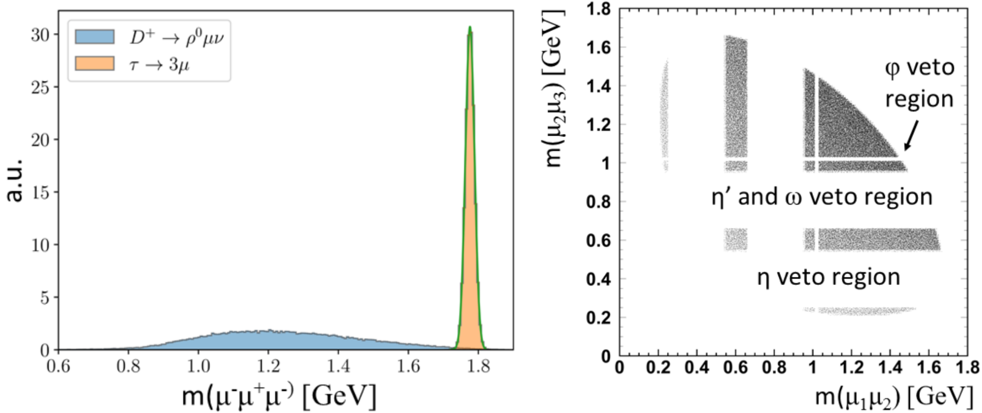
Other decays of D and D_s are likely to be a limiting factor to the final sensitivity.

Normalized to $D_s \to \eta(\mu\mu\gamma)\mu\nu$ ($\mathcal{B} \sim 10^{-5}$)

Decay channel	**Relative abundance**
$D_s \to \eta(\mu\mu\gamma)\mu\nu$	1
$D_s \to \varphi(\mu\mu)\mu\nu$	0.87
$D_s \to \eta'(\mu\mu\gamma)\mu\nu$	0.13
$D \to \eta(\mu\mu\gamma)\mu\nu$	0.13
$D \to \omega(\mu\mu)\mu\nu$	0.06
$D \to \rho(\mu\mu)\mu\nu$	0.05

Challenges: trimuon processes

Trimuons can be significantly/fully suppressed by setting vetos in the dimuon mass:



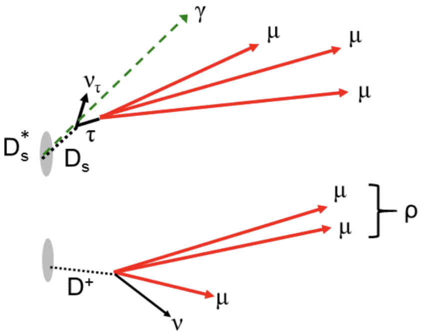
Flat phase space: 25% signal efficiency retained. Cons: $\tau \to 3\mu$ acceptance becomes model-dependent.

Other handles: ECAL

Need an excellent ECAL for:

- photon veto for η and η' modes
- photon tag to select $D_s^* \to D_s(\tau\nu)\gamma$

Can suppress all non-D_s backgrounds



Both energy resolution and timing in the ECAL are essential due to high pileup in the fixed-target environment

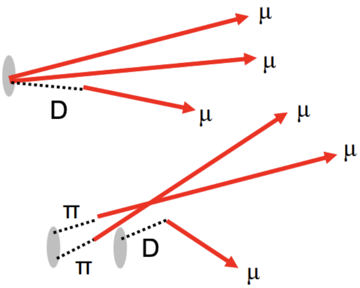
Challenges: combinatorial background

Includes the following sources:

- random matching of a dimuon vertex with a muon
- random matching of misID muons (e.g. decays in flight, punchtrough)

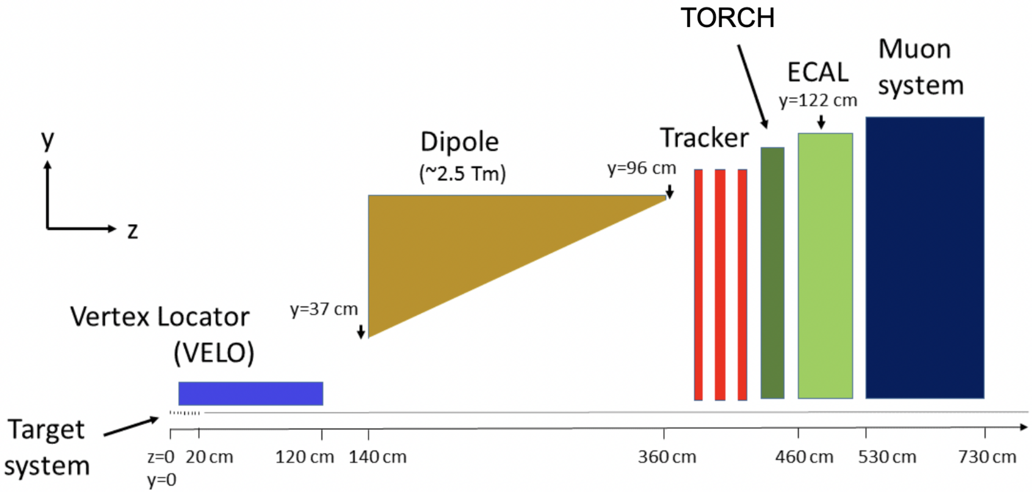
Can be suppressed with:

- high-quality vertex detector and low material budget at the τ production region
- good mass resolution allowing to veto known resonances
- timing information $\mathcal{O}(20\text{ps})$ and longer spill duration



Preliminary PYTHIA studies show that this background can be under control.

Possible detector layout



Angular acceptance: $20 \rightarrow 260$ mrad (geometrical efficiency $\sim 40\%$ for $\tau \rightarrow 3\mu$)

Bonuses of the excellent ECAL

- $\tau \to 3\mu$ is the most challenging mode
- $\tau^- \to \mu^+ e^- e^-$ and $\tau^- \to e^+ \mu^- \mu^-$ almost background-free, higher sensitivity
- $\tau^- \to e^- e^+ e^+$, $\tau^- \to \mu^- e^+ e^-$, $\tau^- \to e^- \mu^+ \mu^-$ can also be searched for

Plus various flavour physics with neutrals in the final state: photons or pions

Wider physics programme: charm physics

- huge sample of charm (e.g. $\sim 5 \times 10^{15}$ D^0) produced, $\times 10^5$ more than at Belle II
- similar to LHCb Upgrade II, and complementary in terms of soft ECAL objects

Excellent performance expected in highly wanted measurements:

- direct CPV in charged modes – exploit hadron ID from TORCH
- rare decays, e.g. $D^0 \to \mu\mu$
- indirect CPV studies

Soft ECAL based physics is very difficult at LHCb:

- CPV studies with neutrals, e.g. $D \to \pi\pi^0$
- CPV studies with radiative penguins, e.g. $D \to V\gamma$
- rare decays with neutrals, e.g. $D \to \gamma\gamma$ (10^{-8} in SM, just beyond Belle II reach)

Wider physics programme: strange physics

Expect to have 10^{19} kaons produced:

- can search for LFV kaon decays

$$K^+, K_S^0, K_L^0 \to (\pi)\mu e$$

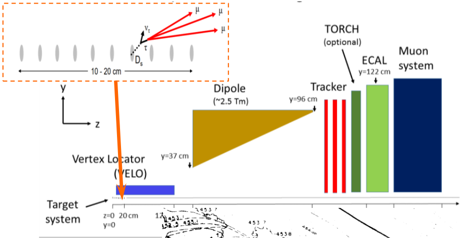
A potential to **to discover CPV in hyperon decay**:

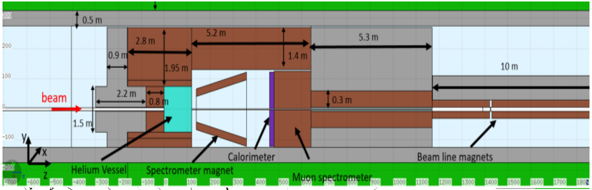
- expected to be 10^{-5} in the SM [Lee & Yang, PR 108 (1957) 1645,Perotti et al. PRD 99 (2019) 056008]
- can be probed at STCF in $J/\psi \to$ hyperon antihyperon decays but might be beyond sensitivity
- possible mode in TauFV

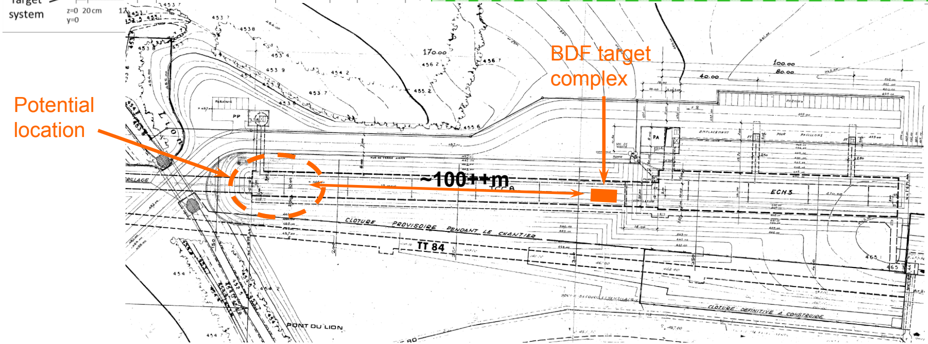
$$\Xi^- \to \Lambda\pi^-$$

Can search for many **rare or forbidden decays** [H-B Li, Front. Phys, 12 (2017) 121301]

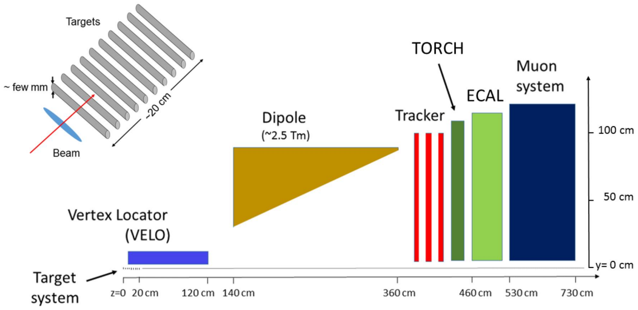
Possible location in ECN3







Target system and detector



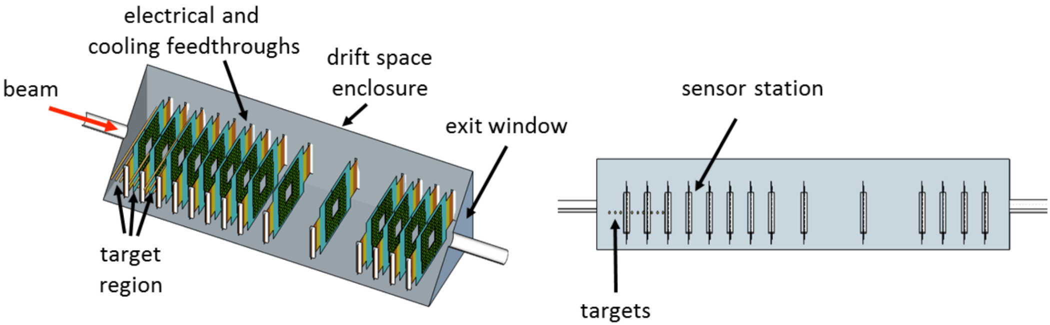
Wire target:

- skims small part of the beam
- no multiple scattering
- allows precise secondary vertex reconstruction

LHCb-like detector:

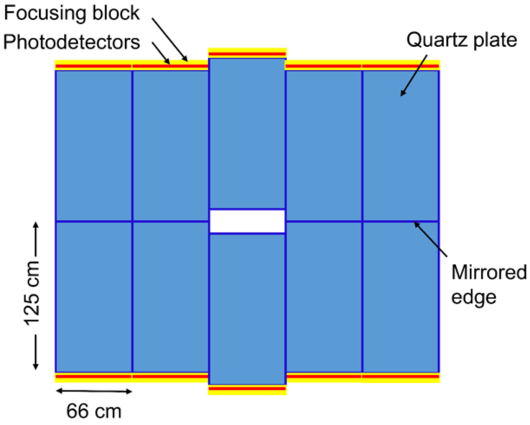
- technologies being developed for Upgrade 1b (LS3) and Upgrade II (LS4)
- high radiation tolerance and timing capabilities are essential

VELO: vertex locator



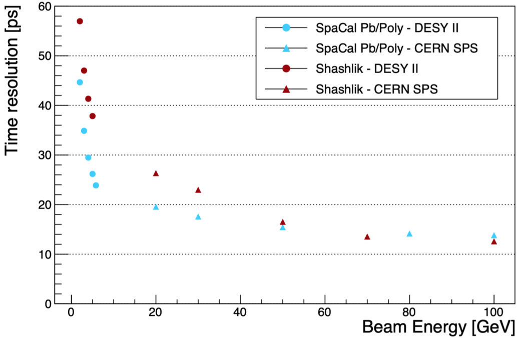
- hybrid pixel sensors (similar to already installed LHCb Upgrade I)
- mechanically simpler as no need to open or close the detector, no RF foil or vacuum
- aim for ~ 50 ps timing resolution per hit or ~ 20 ps per track

TORCH: Timing of Internally Reflected Cherenkov light



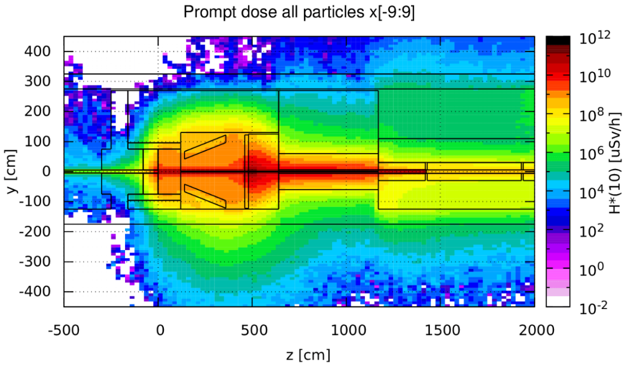
- hadron PID with time-of-flight measurements over large area
- target 70 ps resolution per photon leading to 10-15 ps per track
- demonstrator module has achieved $\sim 80\,\mathrm{ps}$
- very compact and intrinsically radiation hard

ECAL



- precise electron and photon measurement for decay tags and combinatorial bkg suppression
- R&D for LHCb: SPACAL design with GAGG crystal fibers and W(75%)/Cu(25%) absorber
- achieved energy resolution of $5 - 10\%/\sqrt{E[\mathrm{GeV}]}$
- timing resolution 15 ps above 30 GeV

Radiation hardness



- prompt dose rates: 2% of 4×10^{13} p / 7.2s
- the highest dose rates can be found in the region of the target, calorimeter, and muon spectrometer, reaching a few times 10^{11} μSv/h
- the facility should be designed such that interventions will be performed with remote handling systems

TauFV

- offers a possibility to study an unprecedented sample of τ, charm and strange hadrons:
  - more detailed simulation studies are required to get projected sensitivities
- relies on technologies developed for LHCb Upgrade II and pushes them further
- complements HL-LHC and SPS programmes and competes with other facilities