Searches for long-lived particles at LHCb

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

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The LHC schedule

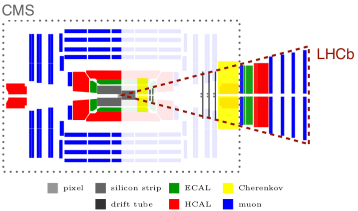
2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
			Run III						Run IV				Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE Phase I			$L = 2 \times 10^{33}$		LHCb Consolidation				$L = 2 \times 10^{33}$ 50 fb^{-1}		LHCb Ph II UPGRADE *		$L = 2 \times 10^{34}$ 300 fb^{-1}	
ATLAS Phase I Upgr			$L = 2 \times 10^{34}$		ATLAS Phase II UPGRADE				HL-LHC $L = 5 \times 10^{34}$		ATLAS		HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr			300 fb^{-1}		CMS Phase II UPGRADE						CMS		3000 fb^{-1}	
Belle II		5 ab^{-1}	$L = 8 \times 10^{35}$		50 ab^{-1}									

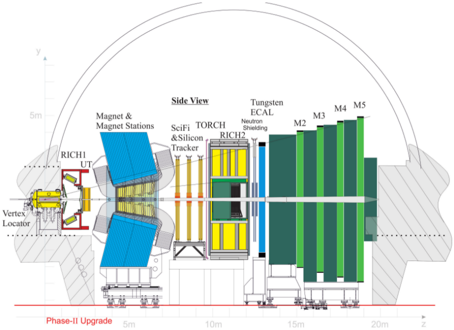
Phase-II LHCb Upgrade EoI: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2017-003]

- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Expect to collect 300 fb^{-1} by the end of (LHCb) Phase-II.
- Phase-II detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for LLP searches.

The LHCb experiment

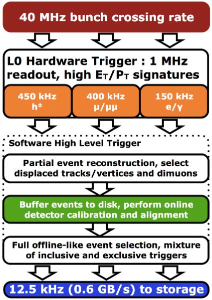
- Fully instrumented in $2 < \eta < 5$ (see comparison below) **[IJMP A30 (2015) 1530022]**
- Lower luminosity (1/8 of ATLAS/CMS during Run I) $\rightarrow$ **lower pileup**.
- **Particle identification** capabilities (RICH) and excellent **mass** resolution.
- Good **jet reconstruction**: **[JINST 10 (2015) P06013]**
  $\rightarrow$ Run I b(c)-tagging efficiency of 65(25)% – very reduced contamination (0.3%).
- **Will be even better for Phase-II** **[CERN-LHCC-2017-003]**



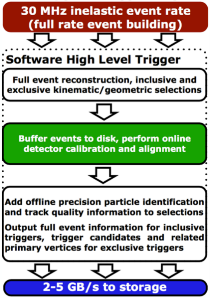


The LHCb trigger

- Very **soft** and **versatile** trigger system.
  - Hardware level L0:
    - $\rightarrow$ to be **removed** for Phase-I.
    - $\rightarrow$ **benefit for low mass searches.**
  - **Software level HLT:**
    - $\rightarrow$ Topological triggers on DV.
    - $\rightarrow$ **Online μ-ID and jets in turbo.**
  - **Turbo** (since 2015) lines:
    - $\rightarrow$ Full event reco can be saved.
    - $\rightarrow$ Any event part is **persisted.**
    - $\rightarrow$ Allow to work directly on them.

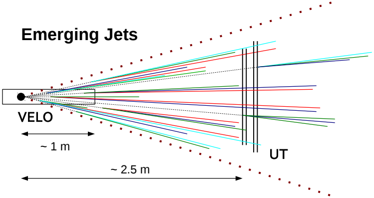


LHCb Run II

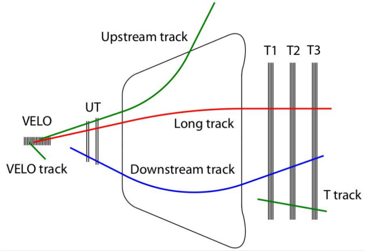


LHCb Phase-I

- Foreseen improvements for μ and e:
  - $\rightarrow$ μ reco down to $p_T \sim 80$ MeV/c (Run II).
  - $\rightarrow$ Dedicated $\mu\mu$ lines (efforts to also add e lines).
- **Trigger on emerging jets** (no pointing to PV):
  - $\rightarrow$ Characteristic of dark sector (shower) signatures.



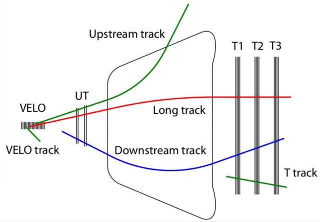
The LHCb reconstruction

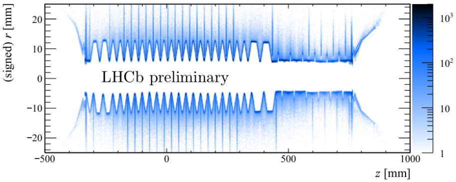


- **Downstream tracks:**
  - Reconstruction of LLP decaying beyond VELO.
  - Tracks with worse vertex and momentum resolution.
  - Trigger proposed on downstream tracks → better for LLP ($\leqslant$ 2 m) signatures.
  - Offline studies on-going **[LHCb-PUB-2017-005]**
- **Upstream tracks:**
  - Reconstruction of soft charged particles bending out of the acceptance.
  - New tracker (UT) – high granularity, closer to beam pipe.
  - Proposal to add magnet stations (MS) inside the magnet → improve low p resolution.

The LHCb reconstruction

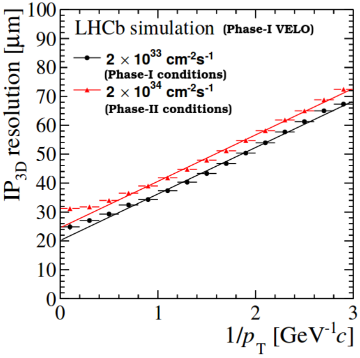
- **Long tracks:**
  - Excellent spatial and momentum resolution.
  - Crucial for LLP decaying within VELO (most of our LLP searches).
  - Presence of a **VELO envelope** (RF-foil) at $\sim$ 5 mm from beam:
    $\rightarrow$ Background dominated by heavy flavour below 5 mm.
    $\rightarrow$ Background dominated by **material interactions** above 5 mm.
  - Having a precise model of material interactions is crucial for LLP searches.
  - A **detailed material veto map** is used (paper in preparation):
    $\rightarrow$ Sensitivity **improvement** by **one** to **two** orders of magnitude.

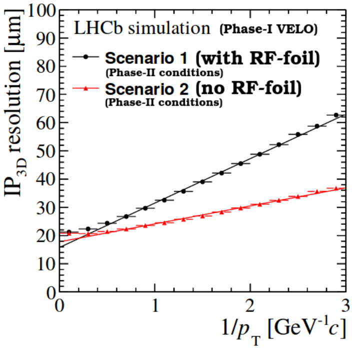




- **Phase-II VErtex LOcator:** **[CERN-LHCC-2017-003]**
  - Probably based on Phase-I VELO (silicon pixels).
  - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment.
  - But – 10x multiplicity, pile-up and radiation damage w.r.t. Phase-I.
  - **Possibility of removing RF-foil** for Phase-II:

    $\rightarrow$ better IP resolution + no material interactions.





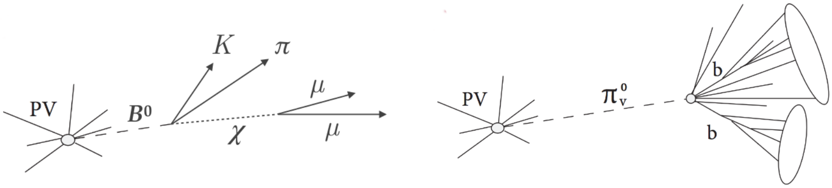
Direct searches for LLPs at LHCb

Unique coverage complementary to ATLAS/CMS:

- Soft trigger and forward acceptance → **lower masses** (few GeV/MeV for jets/leptons).
- Excellent vertexing capabilities → **lower lifetimes** (∼ 1 ps).

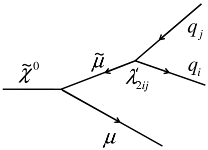
Exploit LHCb capabilities for direct searches:

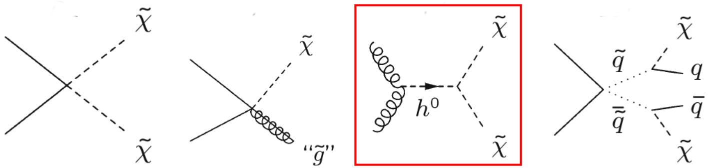
- Search for LLP produced in B and D decays → see talk tomorrow by Martino.
- Search for LLP produced in the *pp* collision → **this talk.**
- Measure detachment (∼ 0.1 ps) of LLP decaying into hadrons (+leptons) → future?
- Proposal for a compact sub-detector (CODEX-b) → see next talk by David.



Massive LLPs decaying to μ + jets

- **Massive LLP into μ + two quarks ($\rightarrow$ jets).**
- Signature sensitive to **several benchmark models:**
  - mSUGRA RPV neutralino,
  - Right-handed (Majorana) neutrinos,
  - Simplified MSSM topologies:

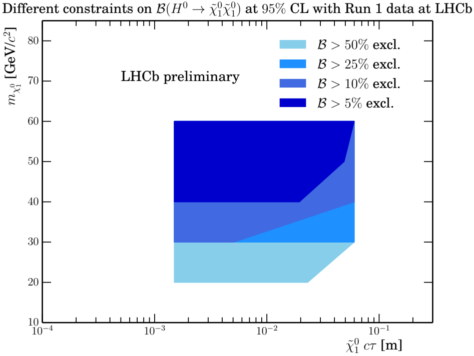


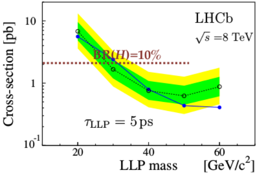


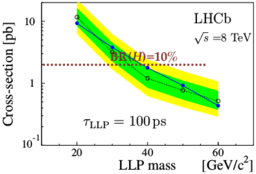
- One particular example: **decay of a Higgs-like particle** into two LLPs.
- Look for a **single displaced vertex** with several tracks + high p_T muon.
- Background dominated by $b\bar{b}$ events and material interactions.

Massive LLPs decaying to μ + jets

- Search with full Run I (3 fb^{-1}) LHCb data published. **[EPJC (2017) 77:224]**
- Results interpreted in $H^0 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ benchmark model:



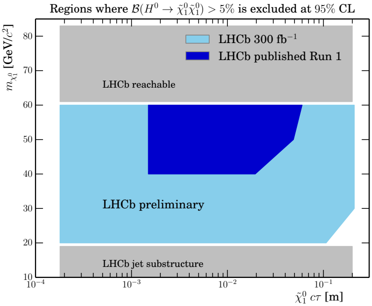


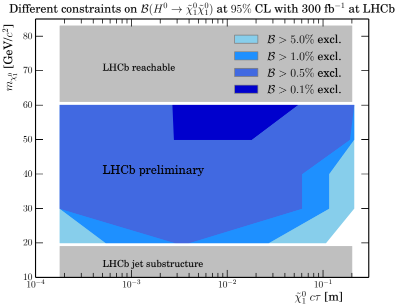


- Stringent limits – rejecting $\mathcal{B}(H^0 \rightarrow \chi\chi) >$10% down to 30 GeV/c^2 (5 ps).
- **No excess observed.**

Massive LLPs decaying to μ + jets

- Prospects for Phase-II → some **naive extrapolations** below:
  - Scale signal and background – consider increase of cross-sections,
  - Conservative assumptions for jet reco, trigger, and material interactions,
  - Optimistic assumptions for pile-up effect.

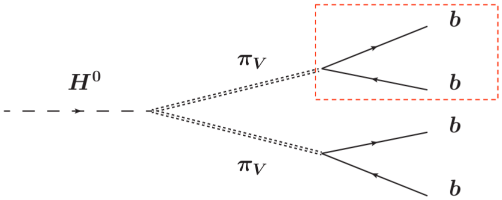




- Our main aim is to reach **lower masses** and **lower lifetimes.**
- **Removal of L0 trigger (Phase-I)** → much higher trigger efficiencies at the end!
- Jet reconstruction efficiencies **will be better for lower masses.**
- Expected a **better knowledge of material interactions** (or much less interactions!).

Massive LLPs decaying to jet pairs

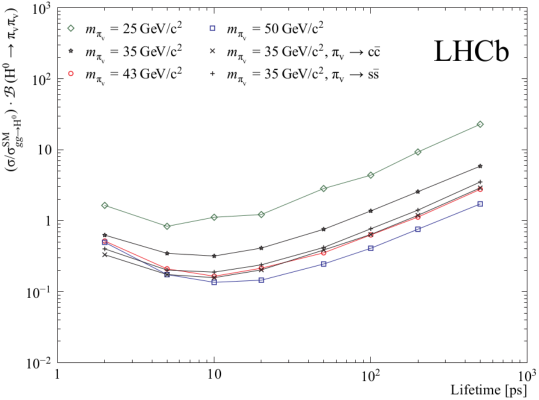
- Possible scenarios to accommodate this signature:
  - LSP in gravity mediated SUSY,
  - LSP in SUSY models with BNV or LNV,
  - **HV π_v decaying to $b\bar{b}$ – especially SM-like $H^0 \to \pi_v \pi_v$ production.**
- In most of the cases only one of the two π_v decays into the LHCb acceptance.
- Experimental signature is a **single displaced vertex** with two associated jets.



- Reconstruct the displaced vertex and find two associated jets.
- Use π_v detachment to discriminate between signal and background.
- Background dominated by $b\bar{b}$ events and material interactions.

Massive LLPs decaying to jet pairs

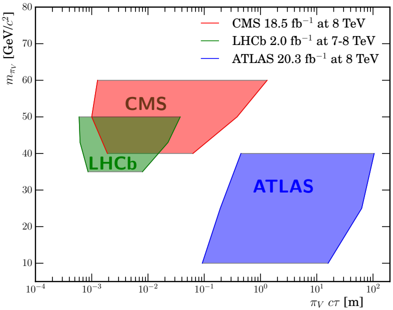
- Search with full LHCb Run I (3 fb^{-1}) dataset published **[LHCb-PAPER-2016-065]**
- Limits at 95% C.L. as a function of π_v lifetime for several π_v masses:



- **No excess found** – plan to analyse LHCb Run II + go to lower π_v masses.
  $\rightarrow$ Working on **new dedicated trigger lines for displaced jets.**
- Develop **jet substructure tools** to study multi-jets at lower masses.
- Develop a selection for emerging jets $\rightarrow$ confining HV (dark showers) **[arXiv:1708.05389]**

Massive LLPs decaying to jet pairs

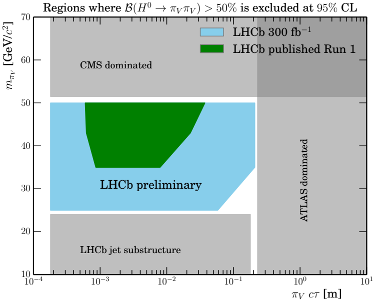
- Compare with recasted results from ATLAS and CMS (plot by M. Borsato):
  - CMS 18.5 fb^{-1} **[PRD 91 (2015) 012007]**, recast **[PRD 92 (2015) 073008]**
  - ATLAS 20.3 fb^{-1} **[PRD 92 (2015) 012010] [PLB 743 (2015) 15-34]**

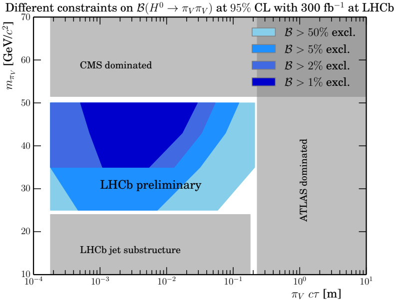


- Parameter space where $\mathcal{B}(H^0 \to \pi_v \pi_v) > 50\%$ is excluded at 95% C.L. is shown.
- Disclaimer: new 13 TeV results from CMS not included in the recast **[CMS-PAS-EXO-16-003]**
- Keep complementarity w.r.t. ATLAS and CMS in Phase-II searches.
- Consider similar strategy for lower masses as in the $h^0 \to \chi\chi \to$ hadrons search **[EPJC (2016) 76:664]**

Massive LLPs decaying to jet pairs

- Prospects for Phase-II $\rightarrow$ same naive assumptions as before:





- Again – our main aim is to reach **lower masses** and **lower lifetimes.**
- **Removal of L0 (Phase-I)** will be beneficial as well $\rightarrow$ access to lower jet masses.
- Higher pile-up in Phase-II:
  - Impact of pile-up on jet reconstruction efficiencies needs to be studied in much detail.
  - We have reasons to be optimistic – preliminary studies ongoing + ideas (see below).
- Some possible improvements to mitigate the effect of the increased pile-up:
  - Remove neutrals (more pile-up dependent) from jet reco (only charged tracks).
  - Consider ML techniques to seize pile-up contributions as in ATLAS and CMS.

Conclusions

- Expect to collect 300 fb^{-1} by the end of Phase-II.
- A **lot of potential in Phase-I triggers and VELO** $\rightarrow$ also **potential for Phase-II.**
- Ace up our sleeve $\rightarrow$ our complementarity w.r.t. other LHC experiments.
- Plenty of **prospects** from existing results and ideas of new searches:
  - LLP searches at **lower masses and lifetimes** $\rightarrow \pi_v$, $\tilde{\chi}^0_1$, RH neutrinos...
  - Develop **jet substructure tools** to study multi-jets at lower masses.
  - More **realistic models for HV** searches – dark showers (emerging jets).
  - e in final states – sensitive to lower masses (no sensitivity anywhere else at the LHC).
  - Fractional charge particles, monopoles, quirks – sensitivity studies needed.
- Encouraging **proposals** (increasing interest!) from the theory community:
  - Confining HV at LHCb **[arXiv:1708.05389]**
  - Soft bombs **[JHEP 08 (2017) 076]**
  - Rare Z decays to a hidden sector **[arXiv:1710.07635]**
- We are looking forward to new ideas $\rightarrow$ **do not hesitate to contact us!**

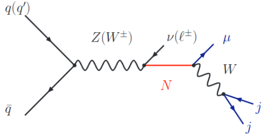
Is there anything beyond the Standard Model?

Thanks for your attention!

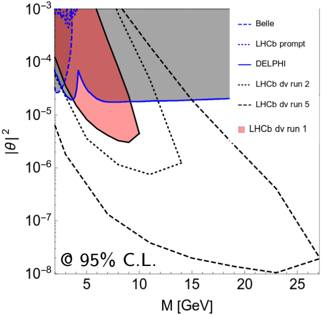
Backup

Massive LLPs decaying to μ + jets – recast

- Limits from this analysis recasted to look into sterile neutrinos **[arXiv:1706.05990]**



- Could we get best world-limit (5–10 GeV/c^2) with same kind of search?
- Dedicated search with Run II data **in preparation.**



Confining HV at LHCb [arXiv:1708.05389]

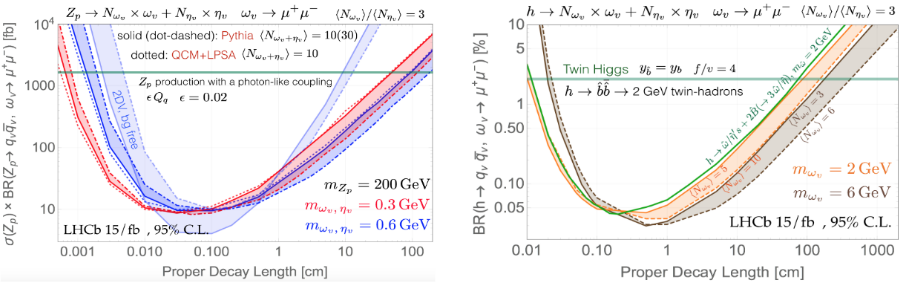


FIG. 1: Left panel: Z_p cross section reach. Green line: cross section for a photon-like coupling, suppressed by $\epsilon = 0.02$. Right panel: Projected upper bounds on BR($h \to$ twin bottom quarks) using the 1 DV search. This process produces lighter twin mesons $\hat{\omega}/\hat{\eta}$ followed by $\hat{\omega} \to \mu^+\mu^-$. Horizontal green line: prediction in a variation of the Fraternal Twin Higgs model (see text); in this context ω_v is a mixture of c' and s'. Green curve: reach for the corresponding decay topology (see text for details).

Confining HV at LHCb [arXiv:1708.05389]

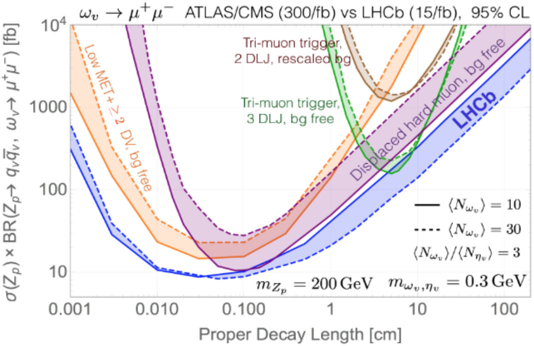


FIG. 2: Projected bounds from various ATLAS/CMS displaced muons search strategies, see text for details. The brown curve represents an extrapolation of a current analysis, while the green curve represents only a minor modification. The orange and purple projections have aggressive assumptions about backgrounds and will likely weaken following detailed detector simulations. The band widths correspond to $10 \leq \langle N_v\rangle \leq 30$. The blue band is derived from the LHCb search proposed in this work.

Confining HV at LHCb [arXiv:1708.05389]

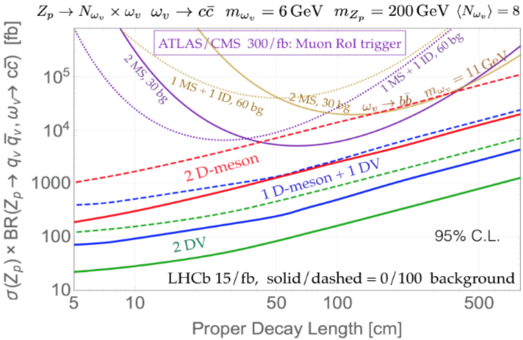
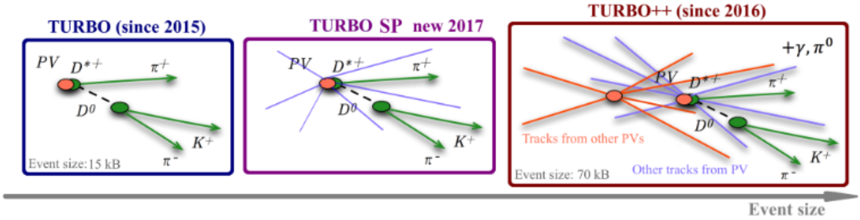
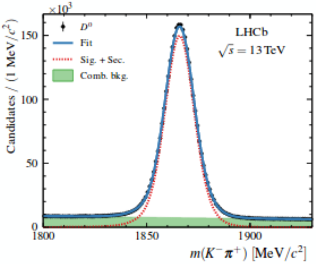


FIG. 3: Projected bounds from various displaced $c\bar{c}$ search strategies, see text. Purple curves: ATLAS/CMS reach estimate for DV decays into ≥ 5 charged tracks, with either two DV in the muon spectrometer (solid) or one DV in the inner detector and one in the muon spectrometer (dotted). Brown: analogous ATLAS/CMS reach for $\omega_v \to b\bar{b}$, $m_{\omega_v} = 11$ GeV.

[LHCb-TALK-2017-327] Turbo stream in Run II



- Turbo:
  - only exclusive decays (and nothing else) saved
- Turbo++ :
  - Full event reconstruction can be persisted
  - Variables such as isolation, objects for jets reconstruction, can be saved
- Turbo SP:
  - New intermediate solution between Turbo and Turbo++
  - Trigger candidate + subset of reconstruction saved



[JHEP03(2016)159]

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