Search for massive neutrinos at LHCb and discovery potential of the FCC

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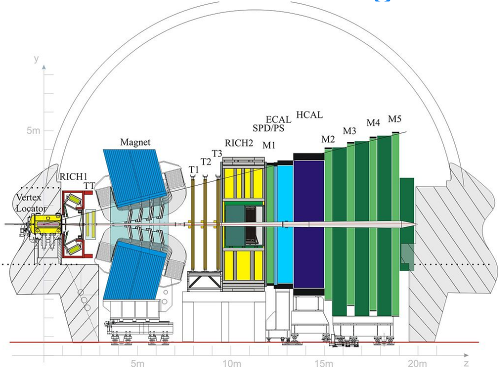
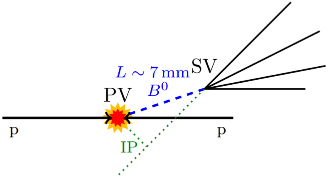
Outline

- $\Rightarrow$ LHCb detector and operations.
- $\Rightarrow$ Majorana neutrino search.
- $\Rightarrow$ Inflaton search in $B \to K^{*}\chi(\mu\mu)$.
- $\Rightarrow$ Hidden valley searches.

LHCb detector - tracking

Int. J. Mod. Phys. A30 (2015) 1530022





- Excellent Impact Parameter (IP) resolution ($20\ \mu\mathrm{m}$).
  $\Rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim\ 40$ fs.
  $\Rightarrow$ Good separation of primary and secondary vertices.
- Excellent momentum ($\delta p/p \sim 0.5 - 1.0\%$) and inv. mass resolution.
  $\Rightarrow$ Low combinatorial background.

LHCb detector - PID

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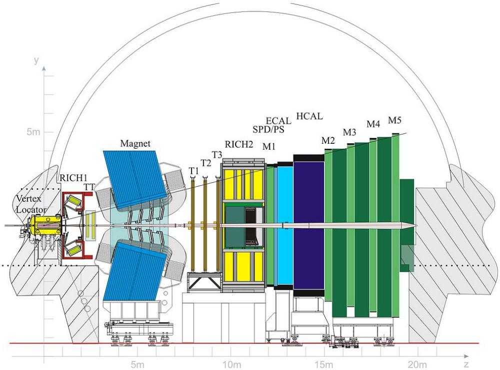
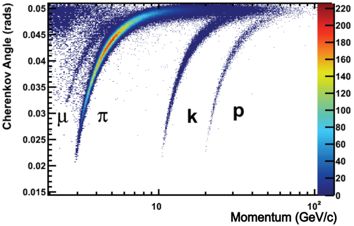
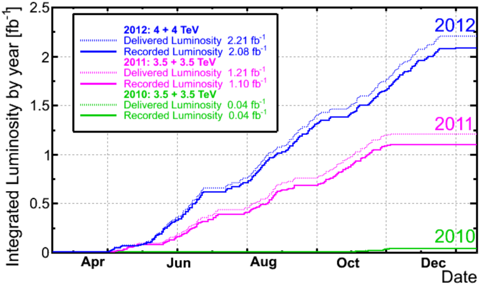
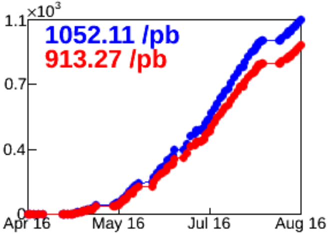




- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Good $K-\pi$ separation via RICH detectors, $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$.
  $\Rightarrow$ Reject peaking backgrounds.
- High trigger efficiencies, low momentum thresholds. Muons: $p_T > 1.76\mathrm{GeV}$ at L0, $p_T > 1.0\mathrm{GeV}$ at HLT1, $B \to J/\psi X$: Trigger $\sim 90\%$.

Data taken by LHCb

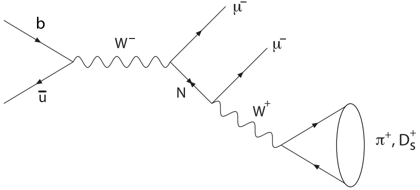




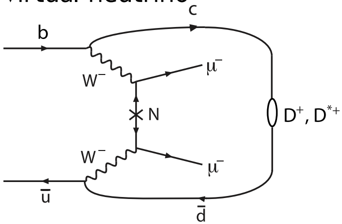
- In 2011 and 2012 LHCb has gathered $3\ \mathrm{fb}^{-1}$ of pp collisions.
- Got $1\ \mathrm{fb}^{-1}$ in 2016 already!
- The cross section are now two times bigger compared to Run1.

Majorana neutrinos in bottom decays

on-shell neutrino



virtual neutrino

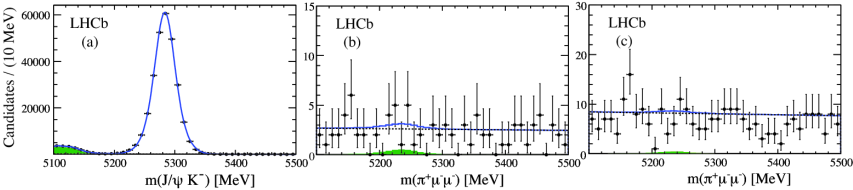


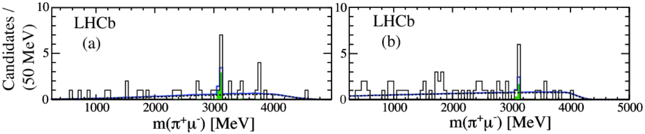
- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$
- $m_\mu + m_\pi < m_4 < m_B - m_\mu$

Diagram without mass restriction
Cabibbo favoured for $B \to D$
Analogous to double β decay.

On-shell Majorana neutrinos

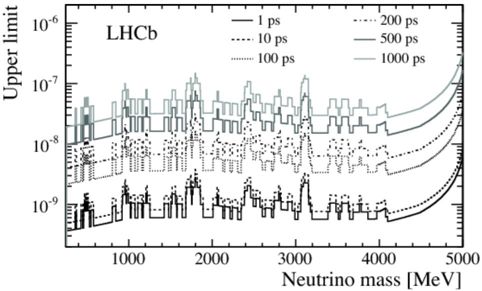
- $B^- \to \pi^+\mu^-\mu^-$ searched with full data set $3~\mathrm{fb}^{-1}$.
- Searches performed for two scenarios:
  - Short life-time neutrinos: $\tau_4 < 1ps$
  - Long life-time neutrinos: $\tau_4 \in (1, 1000)ps$

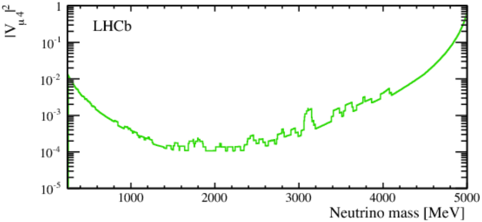




Phys. Rev. Lett. 112, 131802

On-shell Majorana neutrinos





- In absence of signal UL. were set.
- $Br(B^- \to \pi^+\mu^-\mu^-)$ in range 10^{-9}.
- Limits also set for the coupling $|V_{\mu 4}|^2$

$$Br(B^- \to \pi^+\mu^-\mu^-) = \frac{G_f^4 f_B^2 f_\pi^2}{128\pi\hbar}\tau_B m_B^5 |V_{ub}V_{ud}|^2 |V_{\mu 4}|^4 (1 - \frac{m_4^2}{m_B^2})\frac{m_4}{\Gamma_{N_4}}$$

Summary on Majorana neutrinos in B decays

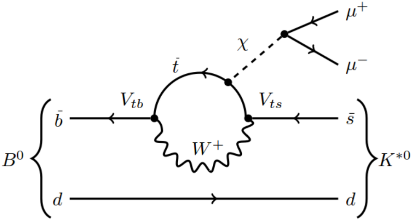
channel	limit		
$\mathcal{B}(B^- \to \pi^+ e^- e^-)$	$< 2.3 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^+ e^- e^-)$	$< 3.0 \times 10^{-8}$	@90 % CL	[a]
$\mathcal{B}(B^- \to K^{*+} e^- e^-)$	$< 2.8 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to \rho^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[b]
$\mathcal{B}(B^- \to D^+ e^- e^-)$	$< 2.6 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to D^+ e^- \mu^-)$	$< 1.8 \times 10^{-6}$	@90 % CL	[c]
$\mathcal{B}(B^- \to K^+ \mu^- \mu^-)$	$< 5.4 \times 10^{-7}$	@95 % CL	[d]
$\mathcal{B}(B^- \to D^+ \mu^- \mu^-)$	$< 6.9 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^{*+} \mu^- \mu^-)$	$< 2.4 \times 10^{-6}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D_s{}^+ \mu^- \mu^-)$	$< 5.8 \times 10^{-7}$	@95 % CL	[e]
$\mathcal{B}(B^- \to D^0 \pi^- \mu^- \mu^-)$	$< 1.5 \times 10^{-6}$	@95 % CL	[e]

[a] BaBar,Phys. Rev. D **85**, 071103 (2012)
[b] CLEO, Phys. Rev. D **65**, 111102 (2002)
[c] Belle, Phys. Rev. D **84**, 071106(R), (2011)
[d] LHCb, Phys. Rev. Lett. 108 101601 (2012)
[e] LHCb,Phys. Rev. Lett. (112) 131802 (2014)

$B \to K^* \chi(\mu\mu)$ search

- Search for displaced di-muon vertex coming form B meson.

$$B^0 \to K^* \chi(\mu^- \mu^+)$$



- If χ mixes with the Higgs and it is light:
  - $\Gamma(K \to \pi\chi) \propto m_t^4 \lambda^5$
  - $\Gamma(D \to \pi\chi) \propto m_b^4 \lambda^5$
  - $\Gamma(B \to K\chi) \propto m_t^4 \lambda^2$
- In addition; $K^* \to K^+ \pi^-$ helps in vertex reconstruction.
- High $\mathcal{B}(\chi \to \mu^- \mu^+)$.

$B^0 \to K^{*0}(\chi \to \mu^+\mu^-)$: motivation

Benchmark models:

1. *Inflaton*: arXiv:1403.4638
   - $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
   - $m_\chi < \mathcal{O}$(1 GeV),
   - $\mathcal{B}(B \to K\chi) \sim 10^{-6}$
2. *Axion portal*: Phys.Rev.D81(2010)034001
   - prompt decay are favourite
   - axion decay constant: $f_\chi \sim$ 1 - 3 TeV
   - $\mathcal{B}(\chi \to \mu\mu)$:
     - is dominant for $360 < m_\chi < 800$ MeV
     - $\sim \mathcal{O}(10^{-2})$ for 800 MeV $< m_\chi < 2m_\tau$

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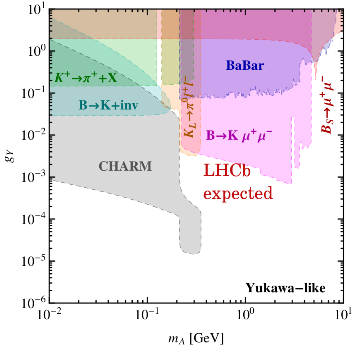
Existing experimental limit

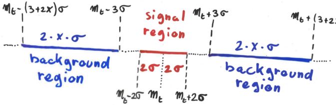


[JHEP 1503 (2015) 171]

$B^0 \to K^{*0}(\chi \to \mu^+\mu^-)$: strategy of the search

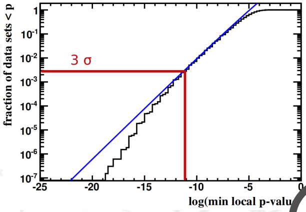
- Looking for di-muon resonance: [JINST 10(2015)P06002]
  - scan in step of $1/2\ \sigma_m(\chi)$

- Definition of search regions:
  - *signal*: $\mid m_{test} - m \mid < 2\sigma_m$
  - *background*:
    $3\sigma_m < \mid m_{test} - m \mid < (2x+3)\sigma_m$



- Background evaluation assume local linearity:
  - wide resonances are safe (small deviation from local linearity)
  - narrow resonances must be vetoed
  - $\mathcal{O}(10\%)$ deviations are allowed
    - $x = 5$ below the J/ψ mass
    - $x = 1$ above the J/ψ mass

- A global p-value is assigned from the minumum local p-value observed



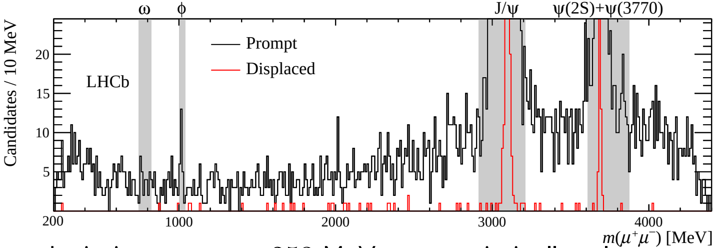
Selection

- Trigger on muons.
- Multivariate selection: $\mu\mathrm{BDT}$ JINST 8(2013)
  - $\mu\mathrm{BDT}$ ensures flat efficiency in lifetime of χ.
- Optimized on Punzi figure-of-merit:

$$P_a = \frac{S}{\frac{5}{2} + \sqrt{B}},$$

  with S and B are signal and background yields.
- Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{\mathrm{prompt}} \bigotimes \mathcal{L}^{\mathrm{displaced}}$
  - Prompt: $\tau < 3\sigma_\tau$
    $\mapsto$ SM background of $B^0 \to K^* \mu^- \mu^+$
  - Displaced: $\tau > 3\sigma_\tau$
    $\mapsto$ Almost background free.

Grey regions correspond to narrow SM di-muon resonances and are vetoed in the analysis



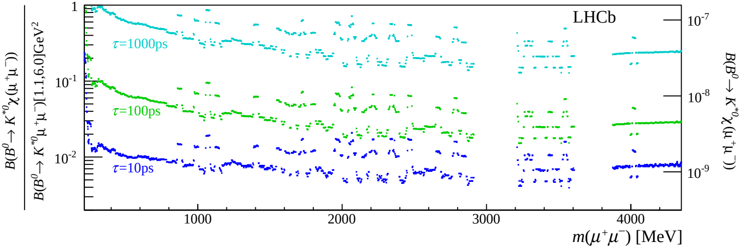
Largest deviation at $m_\chi = 253$ MeV, not statistically relevant:

- local p-value = 0.02

Exclusion limit

No deviation from the standard model is observed

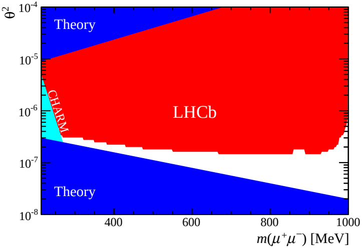
- We set a 95% CL upper limit as function of mass and lifetime of the new particle (in the LHCb accessible range)
- Lower lifetimes have better limit due to higher reconstruction efficiency
- The new particle is assumed to be a scalar



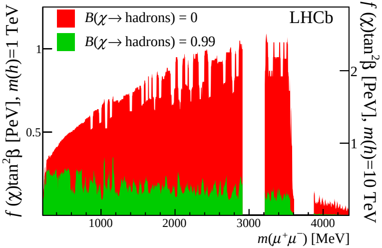
 Phys. Rev. Lett. 115, 161802 (2015)

Interpretation of the result in two specific model:

Inflaton model



Axion portal



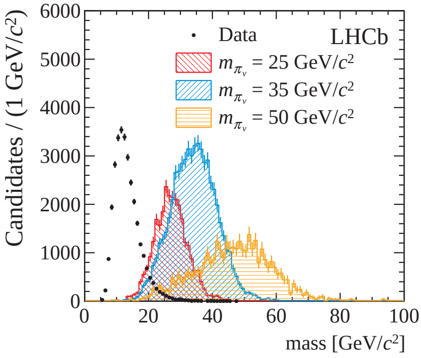
1. Able to exclude the large part of inflaton parameter space
2. Two exclusion limits are shown in the interpretation of the axion portal
   - χ dominantly decaying into muons
   - $\mathcal{B}(\chi \to \mu\mu) \sim \mathcal{O}(10^{-2})$ (when $\chi \to 3\pi$ becomes dominant)

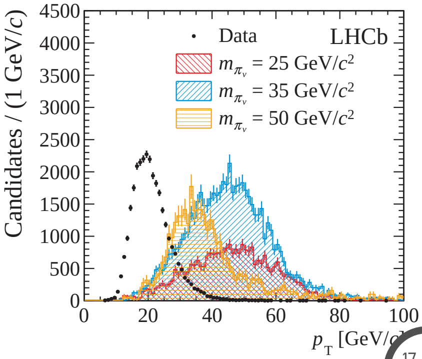
Hidden valley searches

- A possible extensions of the SM are models where the new particles have a small couplings to the SM particles.
- Such models are:
  - Lightest SUSY
  - B/LNV
  - Gravity mediated SUSY
  - Hidden Valleys
- LHCb have performed a search for π_ν particles that are pair produced from Higgs like SM particle.
- They have a long lifetime and decay to pair of jets.

Analysis strategy

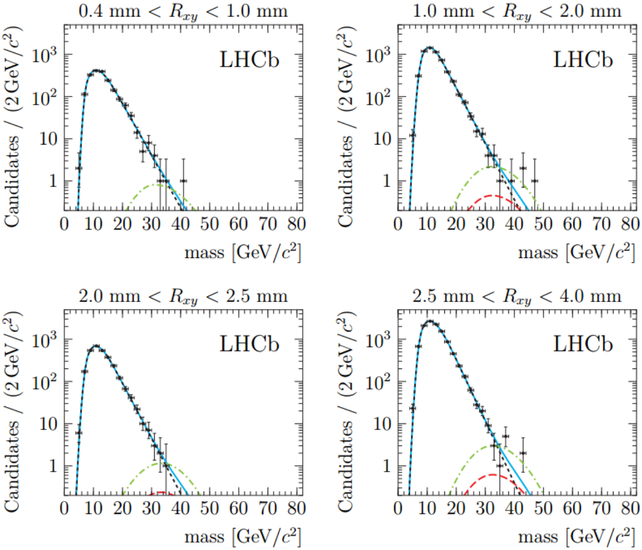
- Efficient trigger for long living particles.
- Reconstruction of two jets.
- MVA used for vertex search.
- Search performed in different regions of displaced vertexes (R_{xy}).
  - $0.4 < R_{xy} < 4$ mm, removes heavy flavour and material interaction backgrounds.





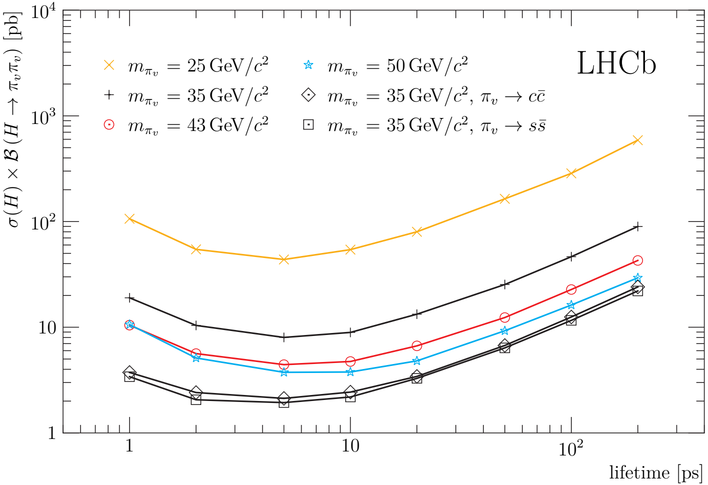
Di-jet distribution

Eur. Phys. J. C 75 (2015) 152



- Signal component fit result, Background component

Results



$m_{\pi_v} = 25\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 43\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 50\,\mathrm{GeV}/c^2$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2,\ \pi_v \to c\bar{c}$
$m_{\pi_v} = 35\,\mathrm{GeV}/c^2,\ \pi_v \to s\bar{s}$
LHCb
$\sigma(H) \times \mathcal{B}(H \to \pi_v\pi_v)$ [pb]
lifetime [ps]

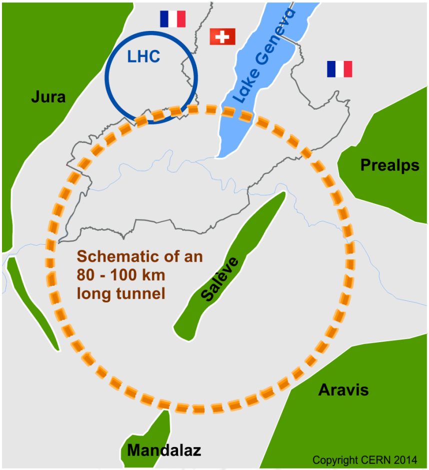
Conclusion

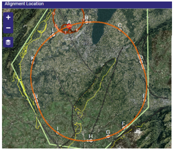
1. Three examples of displaced vertex searches for new physics have been presented, using the Run I LHCb data set
   - very clear new physics signature, SM background highly suppressed
   - more channels are going to be studied
2. Results are the most up-to-date exclusion limit on the processes
3. LHCb is able to exclude almost all the theoretical predicted parameter space of a specific Inflaton model

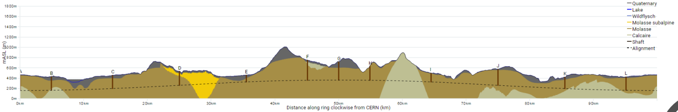
Future Circular Collider (FCC)

M.Benedikt, J. Osborne, C. Cook

- $p-p$ collider $\mathcal{O}(100\mathrm{TeV})$:
  - $16\ T$ in $100\ \mathrm{km}$ tunnel!!!
- The collider would benefit form existing CERN infrastructure.
- Before one reaches the technology for $\mathcal{O}(100\mathrm{TeV})$:
  - Collide e^+e^- with energy $90-400\ \mathrm{GeV}$.
  - The third option is the $p-e$ is also on the table.

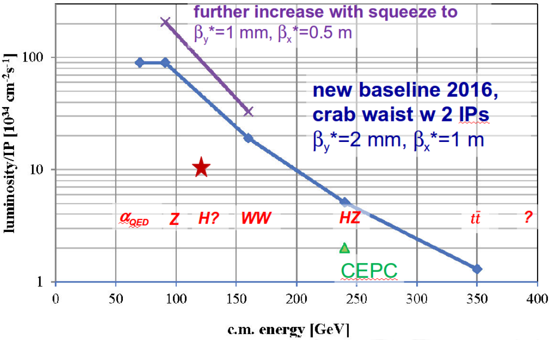






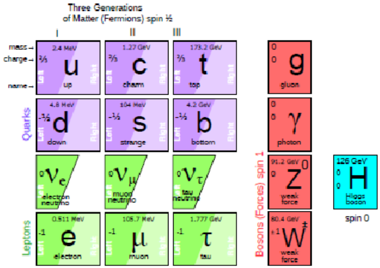
Why FCCee?

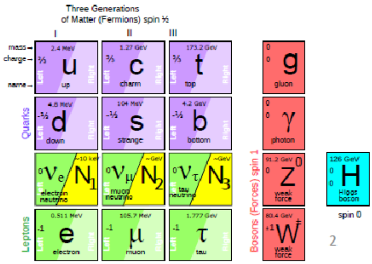
- FCCee is also a Z-factory!
- Current design produces 2.5×10^{12} Z peer year!
- We all love Z:
  - LFV: $Z \to \ell\ell'$.
  - $\mathcal{O}(10^{12}) \mathrm{b\bar{b}}$, flavour factory.



Sterile neutrinos

⇛ There are 3 missing pieces missing:





⇛ The neutrinos have masses (no one knows from where).

⇛ New degrees of freedom needed!

RHNS, at Z threshold

⇛ Production:

$$BR(Z \to \nu\nu_m) = 2 \times BR(Z \to \nu\bar{\nu}) \sum_i |U_{im}|^2 \left(1 - \frac{m_{\nu_m}^2}{m_Z^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{m_Z^2}\right)^2$$

RHNS, at Z threshold

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Decays

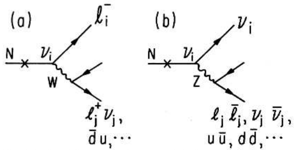


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay Lenght:

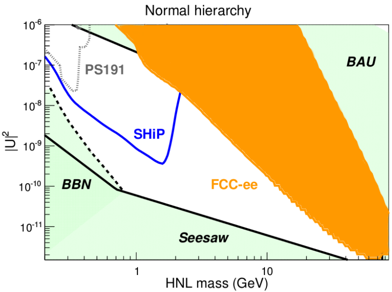
$$L = \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}[\mathrm{GeV/c^2}]\right)^6}$$

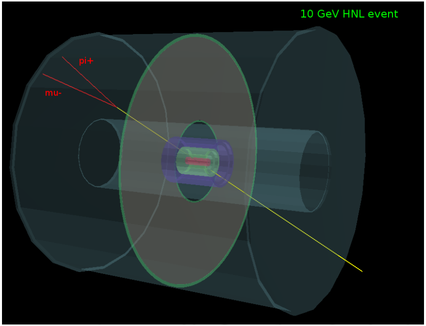
⇛ Possible backgrounds:

$$e^+e^- \to W^{*+}W^{*-}, Z(\nu\nu) + Z^*/\gamma$$

RHNS, at Z threshold

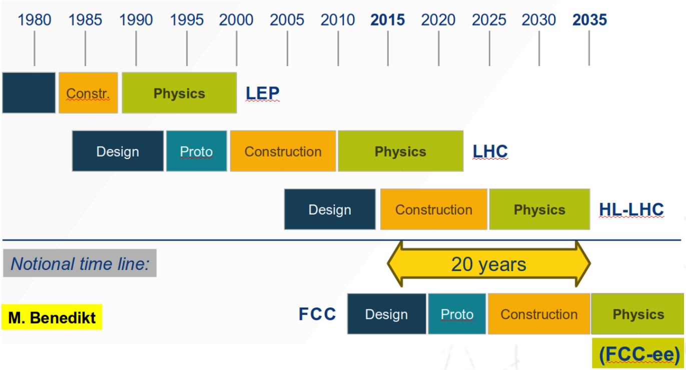
⇛ Expected sensitivity:





FCCee conclusions

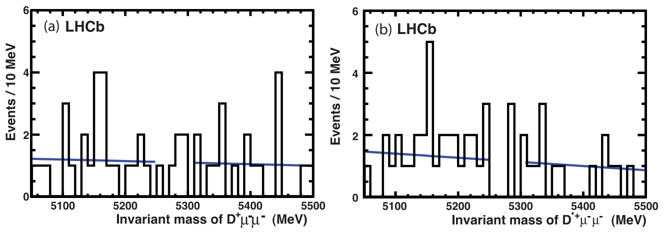
- $\Rightarrow$ FCCee is one of the future colliders that are on the table.
- $\Rightarrow$ I deal environment to do flavour physics!
- $\Rightarrow$ Can reach the $|U|^2$ up to 10^{-11}.
- $\Rightarrow$ Now is the right time to plan physics of 2035-2040:



Backup

Virtual Majorana neutrinos

$B^- \to D^+\mu^-\mu^-$ $\quad$ $B^- \to D^{*+}\mu^-\mu^-$



$\mathcal{B}(B^- \to D^+\mu^-\mu^-) < 6.9 \times 10^{-7}$
@ 95 % CL
Based on $0.41\ \mathrm{fb}^{-1}$ $7\ \mathrm{TeV}$ data.

$\mathcal{B}(B^- \to D^{*+}\mu^-\mu^-) < 2.4 \times 10^{-6}$
@ 95 % CL

`Phys. Rev.D85 (2012) 112004`

Long living charged particles like $\tilde{\tau}$

⇛ Long living particles can also be produced in the PV.

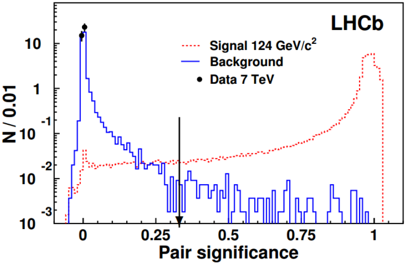
- This kind of particles would be produce in relatively low velocities and could be identified by their time -of-flight, dE/dx or in Cherenkov detectors.

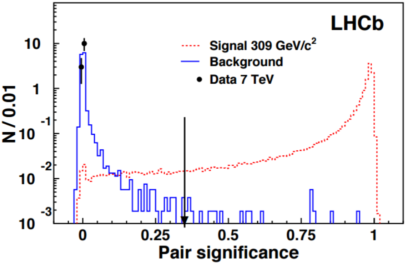
⇛ LHCb performed a search for long living $\tilde{\tau}$ particles.
⇛ $\tilde{\tau}^{+}\tilde{\tau}^{-}$ produced by Drell-Yan process.

$\tilde{\tau}$ analysis strategy

$\Rrightarrow$ Search performed $\tilde{\tau}$ in mass range of $124 - 309\ \mathrm{GeV}$.

$\Rrightarrow$ After the loose preselection to reduce normal Drell-Yan production.

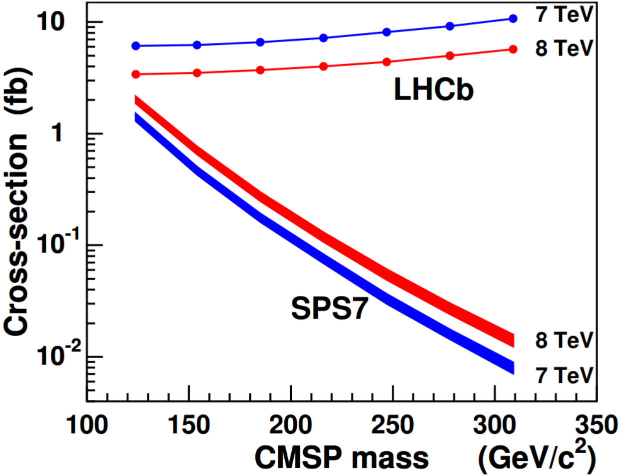


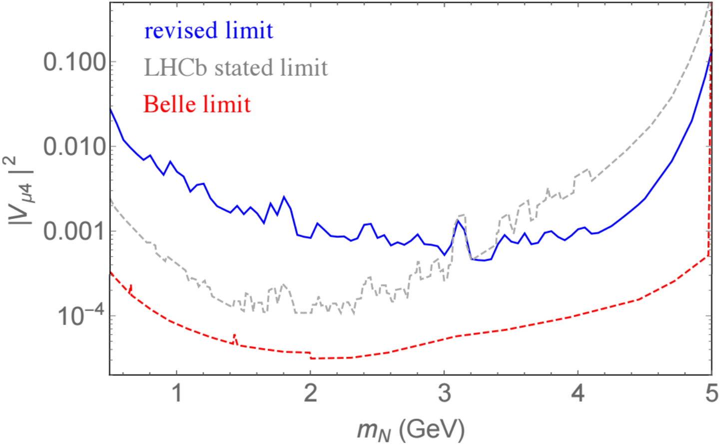


$\Rrightarrow$ After the preselection an Neural Net is trained based on Cherenkov detectors to calculate to further suppress the remaining background.

$\tilde{\tau}$ results

- No significant signal yield has been observed.
- $95\ \%$ upper limit has been set.




revised limit
LHCb stated limit
Belle limit
0.100
0.010
0.001
10^{-4}
$|V_{\mu 4}|^2$
1
2
3
4
5
m_N (GeV)