Long-lived new particles at present and future colliders

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Colliding Pizza Seminar
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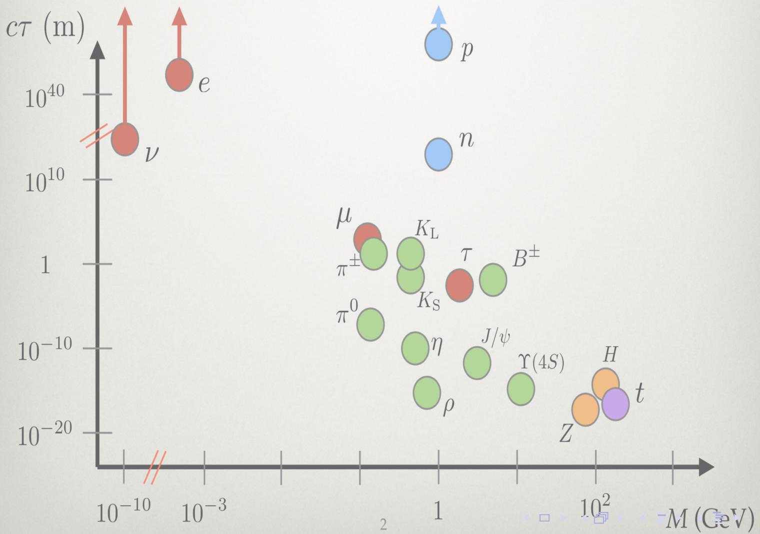
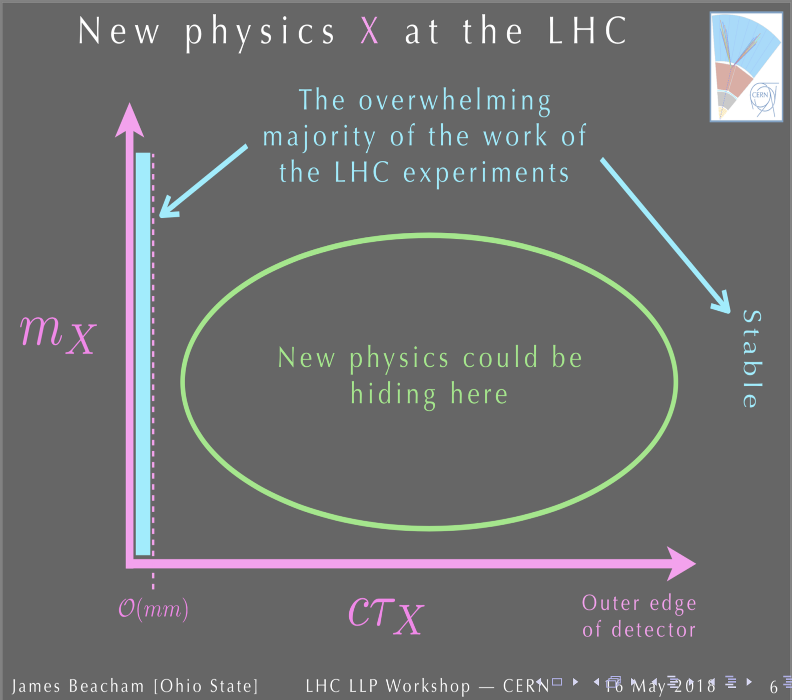
Disclaimer:
Next two slides borrowed from J. Beacham and B. Shuve.

Long-Lived Particles in the SM

- The world is **full** of long-lived particles




New physics X at the LHC
The overwhelming majority of the work of the LHC experiments
m_X
New physics could be hiding here
Stable
$\mathcal{O}(mm)$
$c\tau_X$
Outer edge of detector
James Beacham [Ohio State]
LHC LLP Workshop — CERN
16 May 2018
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Particle lifetime

- Proper lifetime of particle i (lifetime in its own restframe)

$$\tau_i^{\text{proper}}[s] = 1/\Gamma_i \times 6.58 \times 10^{-25}$$

  Γ_i (in GeV) is the total decay width.
  $\Rightarrow$ Small $\Gamma_i \Leftrightarrow$ long lifetime
- Example 1, charged muon:
  - Decay channel $\mu \to \nu_\mu \, e \, \nu_e$, $\Gamma_\mu \propto g_W^4 (m_\mu/m_W)^4 m_\mu$
  - Lifetime $\sim 2 \times 10^{-6}$ s.
- Example 2, neutron:
  - Decay channel $n \to p \, e \, \nu_e$, $\Gamma_n \propto g_W^4 (\Delta m/m_W)^4 \Delta m$
  - $\Delta m = m_n - m_p$
  - n lifetime ~ 850 s.
- Example 3, Z boson:
  - Total decay width $\Gamma_Z = 2.1876$ GeV.
  - Z lifetime $\sim 3 \times 10^{-25}$ s.

Laboratory lifetime

- Experiments measure the laboratory lifetime, τ^{lab}.

$$\tau^{\text{lab}} = \gamma\beta\tau^{\text{proper}}$$

- Relativistic velocity: $\gamma\beta = \sqrt{E^2 - m^2}/m \sim E/m$
- Example 4, cosmic muons:
  - production $\sim$ 15 km above ground.
  - Most of them have $E \geq 10$ GeV.
  - Decay length: $c\,\tau_\mu^{\text{lab}} \geq 57$ km.
- Large E/m enhances accessibility of short proper lifetimes...
  ... but it suppresses long ones!

(LHC experiments 'see' displaced vertices from many SM particles.)

Decay probability

- LLP produced at origin & propagates until it decays.
- Decay governed by the probability distribution:

$$D_{\rm decay}[t] = \exp[-t/\tau^{\rm lab}]$$

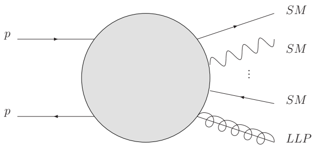
- The probability for LLP to decay between the times t_1 and t_2:

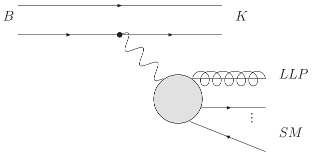
$$P_{\rm decay}[t_1, t_2, \tau^{\rm lab}] = \frac{1}{\tau^{\rm lab}} \int_{t_1}^{t_2} D_{\rm decay}[t] dt$$

- Can be translated to distances via the velocity βc $(c = 3 \times 10^8 m/s)$
- Simplification if $\tau^{\rm lab} \gg t_1,\ t_2$:

$$P_{\rm decay} \approx (t_2 - t_1)/\tau_{\rm lab}$$

LLP production at the LHC



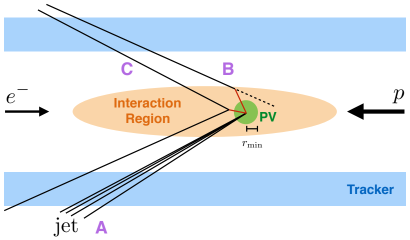


- Strongly model dependent.
- Direct, from the beams: $pp \rightarrow$ LLP $+X$, X SM particle(s).
- Indirect, from decays:
  - SM mesons.
  - W or Z bosons on the mass shell.
  - Top quark.

Relevant properties

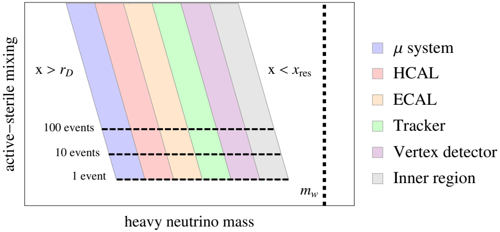
- Production cross section $\Rightarrow$ Total number of LLP.
- LLP Momentum spectrum.
  $\Rightarrow$ NOT (only) P_t!
  $\Rightarrow$ fixed LLP mass gives the $\beta\gamma$ spectrum
  $\Rightarrow$ Tails can be relevant.
- LLP angular spectra.
  - Allow one to incorporate detector geometry.
  - For detectors with (approximate) spherical symmetry: θ.
  - For full geometry also ϕ necessary.
- Associated visible particles, very important (next slide).

The displaced vertex event



- Associated particles for triggering; P_t and angular thresholds.
- Reconstruct the point of origin: The primary vertex (PV).
- Displaced vertex (DV): charged tracks crossing at a distance from PV.
- In case of only one visible track: Impact parameter.
- Distance between DV and PV must be larger than experimental resolution $x_{\rm res}$.

The detector response



- Schematic view of the detector components.
- The respective sensitivities do overlap significantly.
- Particle ID strongly depends on where the decay occurs.
- Lower boundary: number of events produced.
- Left boundary: long lifetimes “escape” from the detector
- Right boundary: lifetimes below the resolution $x_{\rm res}$ are prompt.

A word on backgrounds

There are many, especially for short lifetimes, for instance...

- Proton beam halo.
- Detector noise.
- Long lived SM particles: τ, π^0, $K_s^0, \ldots$
- Pile up!

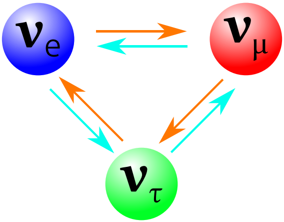
$\Rightarrow$ Loss in efficiency to deal with those.

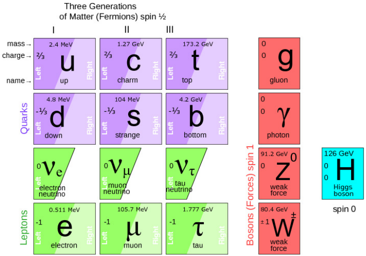
$\Rightarrow$ Difficult to recast existing analyses.

The chapter on backgrounds of the LHC-LLP white paper (in preparation) includes also scary and unexpected ones

Now for a specific example:
Dispaced vertices from Heavy Neutrinos at the LHC

Motivation



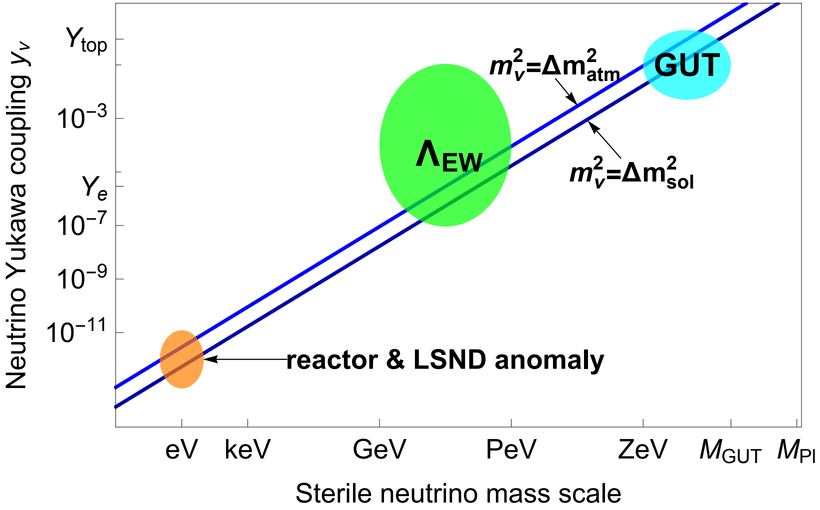


courtsy M. Shaposhnikov

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.

⇒ Neutrino oscillations are evidence of physics beyond the SM.

The Big Picture



Heavy neutrino interactions

- **Charged current** (CC):

$$j_\mu^\pm = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

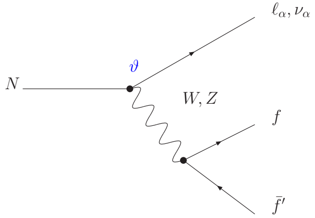
$$j_\mu^0 = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2\; + (\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2\; + \;\mathrm{H.c})\right]$$

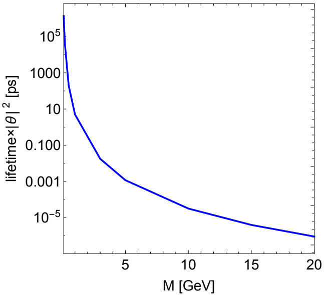
- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3}\xi_{\alpha 2}\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^*_{\alpha\beta}\frac{\theta_\beta}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

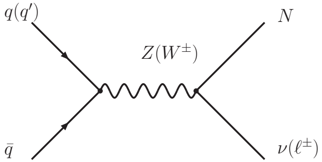
“Naturally” long lived





- For $M < m_W$ all decays are via off-shell weak gauge bosons (and the Higgs).
- Current direct searches require: total mixing squared $|\theta|^2 < 10^{-5}$.
- Total decay width $\propto |\theta|^2 \times G_f$ tiny.
  $\Rightarrow$ Macroscopic life times!

Number of displaced events at the LHC



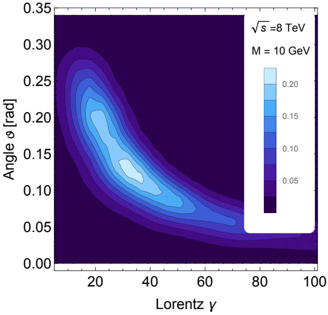
$$N_{\rm dv}(\sqrt{s}, \mathcal{L}, M, |\theta|^2) = N_{xN} \times \int D_{xN}(\vartheta, \gamma)\, P_{\rm dv}(x_{\rm min}, x_{\rm max}, \Delta x_{\rm lab})\, d\vartheta d\gamma$$

- $N_{xN} = \sum_{x=\nu,\ell^{\pm}} \sigma_{xN}(\sqrt{s}, M, |\theta|^2) \times \mathrm{Br}_{\mu jj} \times$ luminosity
  $\sigma_{xN} \sim \mathcal{O}(1000)$ pb $\times |\theta|^2 \times$efficiency
- D_{xN} distribution of events in γ, ϑ
- $P_{\rm dv}$ distribution of events in a given (lab) volume
- ϑ angle wrt. beam axis
- γ Lorentz boost of N proper frame wrt. lab frame
- $x_{\rm min}, x_{\rm max}$ are functions of ϑ

We evaluated this for the LHCb experiment$_{\text{using WHIZARD}}$

- Distributions for the process $pp \to \nu N$:

including the angular acceptance of LHCb



- Dist.s for $pp \to \ell^{\pm} N$ similar, but smaller values for ϑ
- Dist.s for $pp \to \ell^{+} N$ get closest to the beam

- Consider for decay products:
  - $2 < \eta(f) < 5$, $f = \mu, j$
  - $P_t(\mu) > 12$ GeV

CERN-EP-2016-283
LHCb-PAPER-2016-047
September 27, 2017

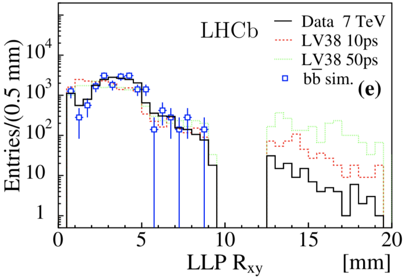
Search for massive long-lived particles decaying semileptonically in the LHCb detector

The LHCb collaboration†

Abstract

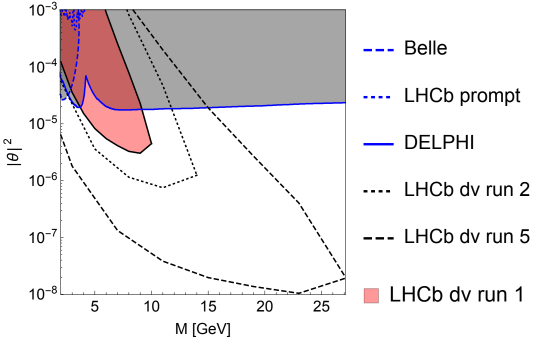
A search is presented for massive long-lived particles decaying into a muon and two quarks. The dataset consists of proton-proton interactions at centre-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 1 and 2 fb^{-1}, respectively. The analysis is performed assuming a set of production mechanisms with simple topologies, including the production of a Higgs-like particle decaying into two long-lived particles. The mass range from 20 to 80 GeV/c^2 and lifetimes from 5 to 100 ps are explored. Results are also interpreted in terms of neutralino production in different R-Parity violating supersymmetric models, with masses in the 23–198 GeV/c^2 range. No excess above the background expectation is observed and upper limits are set on the production cross-section for various points in the parameter space of theoretical models.

LHCb analysis result



- Search for one displaced vertex with invariant mass > 5 GeV and one muon.
- Before preselection no event with radial displacement > 2 cm.
- After preselection no event above 5 mm.

Our recast of the LHCb result



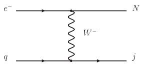
Antusch, Cazzato, OF; arXiv:1706.05990

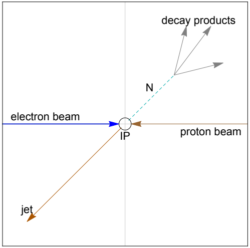
- Assuming 100% efficiency and $\Delta r > 5$ mm, $\Delta z < 2$ m.
- black dotted: sensitivities for the present amount of data of 5 fb^{-1}
- black dashed: 380 fb^{-1} for the high-luminosity run.
- All limits for $|\theta|^2 = |\theta_\mu|^2$ (i.e. $|\theta_e| = |\theta_\tau| = 0$).

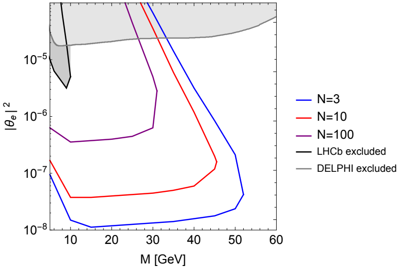
Next:
Future colliders (electron-positron, electron-proton).

No details on the colliders in the talk. Ask!

Displaced vertex searches at Electron-Proton colliders

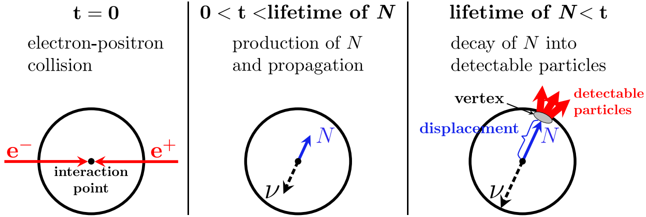




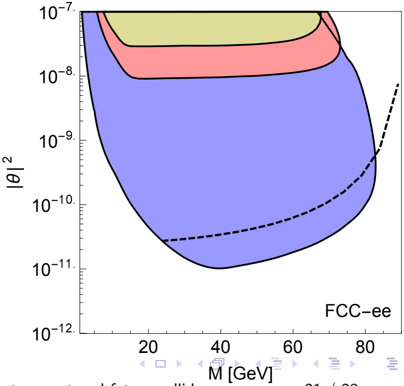


- DIS jet for excellent determination of PV.
- Advantages over LHC searches:
  - Clean environment, no pile up, no QCD backgrounds.
  - Excellent resolution for DV determination.
- Disadvantages:
  - Lower production rates.
  - Lower $\sqrt{s}$ (1.2 TeV for LHeC) - no problem here.
- Complementary with and comparable reach to LHC.

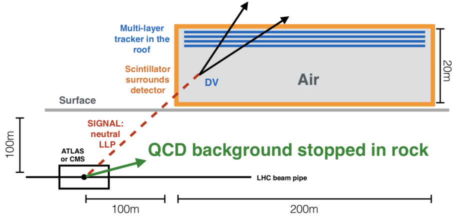
Displaced vertex searches at Future Lepton Colliders



- Substantial missing energy.
- Assumption: no SM background for displacements > 0.1 mm.
- Applies to CEPC, FCC-ee, ILC, CLIC
- Possible at different $\sqrt{s}$



External detector: MATHUSLA



- MAssive Timing Hodoscope for Ulrtastable neutraL pArticles.
- Proposal: build on surface close to ATLAS/CMS
- Goal: detect decays from long lived particles produced at the interaction points.
- Comparatively simple technology and superb background control.
- Can be used conjointly with (HL-)LHC and FCC
- Synergies with Cosmic Ray and Neutrino Physics.

Outlook

Gaps in current LHC data taking procedures:

- System optimized for prompt SUSY signatures.
- Difficulty at testing many models with "natural" LLPs.
- LHC LLP: A growing community trying to address this.

Many ways to continue from here:

- LHC detector upgrades.
- External detectors: CODEX, MILLIQAN, FASER, MATHUSLA.
- Beam dumps: NA62, SHiP, ...
- LHC 'upgrade' with electron beam: LHeC.
- Future colliders: ILC, FCC, CEPC/SppC, CLIC.
- Many models left untested.

Brian Shuve: Are we ready to discover a new (long lived) particle?