Radiative events in BABAYAGA@NLO as a tool for Dark Matter searches at flavour factories

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arXiv:1007.4984 [hep-ph]

Outlook

1. The Dark Matter: definition, features, signals and models.

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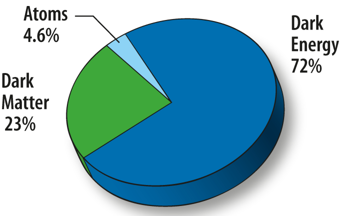
2. Searches at GeV colliders: motivations, techniques and BABAYAGA@NLO.
3. Numerical results: effects of radiative corrections and statistical significance.

The Dark Matter

Definition and features



http://map.gsfc.nasa.gov/media/080998/index.html

- ⋆ Fritz Zwicky (1933): something is missing in the description of the Universe.
- ⋆ This “something” is invisible (undetectable), but it gives rise to gravitational effects (e.g. anomalous galactic rotation curves, hierarchical large-scale structure of the Universe, . . .).
- ⋆ It is the most part of the Universe!
- ⋆ It can be divided into *Dark Matter* and *Dark Energy*.

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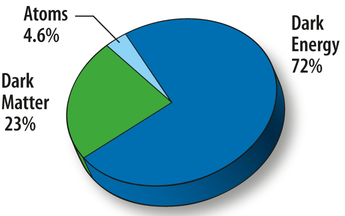

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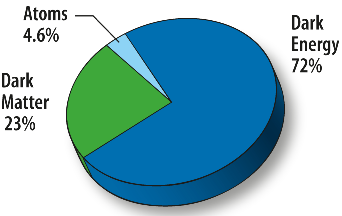

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⇓

Looking for new theory or, at least, for a suitable extension of the Standard Model.

The Dark Matter

Suspicious astrophysical observations

⋆ **Examples of hints of the exotic nature of Dark Matter, from astrophysical observations**

[N. Arkani-Hamed *et al.*, *Phys. Rev.* **D79**:015014, 2009, arXiv:0810.0713 [hep-ph], and references therein]

- INTEGRAL: 511 keV signal indicating $\sim 3 \times 1042 \frac{e^+}{s}$ annihilating in the galactic center, far more than expected from supernovæ (already observed in balloon-borne experiment in early '70s);
- PAMELA: excess in the positron fraction $\frac{e^+}{e^+ + e^-}$ in the region $10 \div 100$ GeV, counter to what is expected from high–energy cosmic rays interacting with the interstellar medium;
- ATIC–2: $4 \div 6\,\sigma$ excess (over a simple power law) in $e^+ + e^-$ data at energies of $\sim 300 \div 800$ GeV, with a sharp cutoff in the $600 \div 800$ GeV range;
- WMAP: hard component in microwave emission from the galactic center which is not spatially correlated with any known galactic emission mechanism;
- DAMA/LIBRA: indication of an annual modulation consistent with that expected from Dark Matter induced nuclear scattering.

The Dark Matter

Extension of the Standard Model: common features

- ⋆ A dark gauge boson U, leptophilic and light ($M_U \leq 2\,M_{\rm p}$), can explain astrophysical observations.

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  - $\longrightarrow$ a Dark Matter field χ,
  - $\longrightarrow$ a massive gauge boson U ("*dark photon*"),
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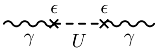
- ⋆ The dark photon couples with ordinary photon through the kinetic mixing:

$$\mathscr{L}_\mathrm{mix} = -\frac{\epsilon}{2} F^\mathrm{em}_{\mu\nu} F^{\mu\nu}_\mathrm{DM} \qquad (\epsilon \ll 1)\ .$$



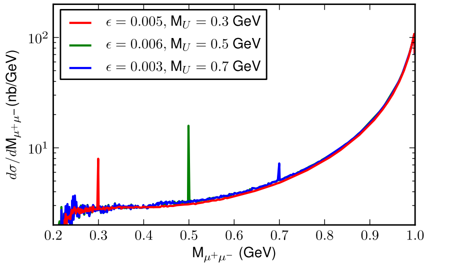
Searches at colliders

The flavour factories: an ideal environment

Looking for the dark-photon!

- ⋆ $\mathcal{O}$ (GeV) e^+e^- colliders:
  - → cross-section scaling with $\sqrt{s}$;
  - → high luminosity;
  - → clear signature in the resonant channel.
- ⋆ Signal: $\frac{d\sigma_{F(ull)}}{dM_{\ell^+\ell^-}} - \frac{d\sigma_{B(ackground)}}{dM_{\ell^+\ell^-}}$

$e^+e^- \to \gamma, U \to \mu^+\mu^-\gamma$



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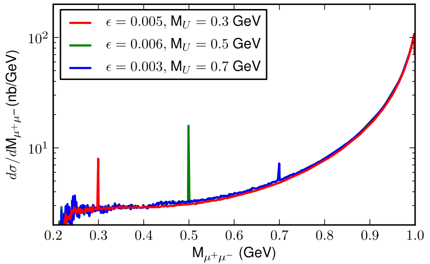


(Fairly) high number of detectable events.

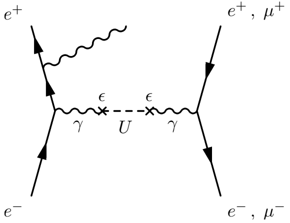
. . . but. . .

Extremely large Standard Model background!

Searches at colliders

Radiative events for discovery

⋆ Search by radiative return



- ⋆ γ/U physical coupling replaced by effective coupling to leptons.
- ⋆ 16 diagrams and all the γ/U and s/t channel interferences kept into account.
- ⋆ Complete tree-level matrix element computed via `ALPHA` [F. Caravaglios and M. Moretti, *Phys. Lett.* **B358**:332, 1995, arXiv:hep-ph/9507237].
- ⋆ Complete three-body kinematics.
- ⋆ Fully implemented in `BABAYAGA@NLO`.

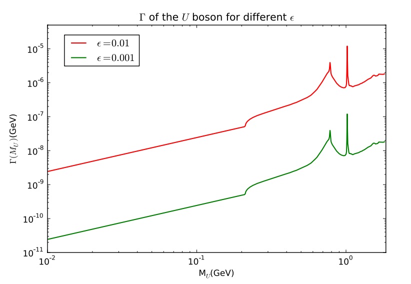
⋆ Computed Γ_U

$$\Gamma_{U\to\ell^+\ell^m} = \frac{\alpha\epsilon^2}{3} M_U \sqrt{1-\frac{4m_\ell^2}{M_U^2}}\left(1+\frac{2m_\ell^2}{M_U^2}\right)$$

$$\Gamma_{U\to\text{hadrons}} = \frac{\epsilon^2}{3}\sqrt{1-\frac{4m_\mu^2}{M_U^2}}\left(1+\frac{2m_\mu^2}{M_U^2}\right) R\left(s\equiv M_U^2\right)$$

→ $R(s)$ compiled accordingly to [T. Teubner *et al.*, 2010, arXiv:1001.5401 [hep-ph]]

Dramatically tiny resonance!



Searches at colliders

A Monte Carlo event generator for signal and background

⋆ BABAYAGA@NLO

http://www.pv.infn.it/~hepcomplex/babayaga.html

- ⋆ Yesterday...
  - $\longrightarrow$ $e^+e^- \rightarrow \gamma \rightarrow e^+e^-,\ \mu^+\mu^-,\ \gamma\gamma$.
  - $\longrightarrow$ Commonly used for luminometry at flavour factories.
  - $\longrightarrow$ Improved NLO accuracy ($\mathcal{O}(1‰)$ theoretical precision) on Standard Model processes.

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Featuring:

⋆ fully exclusive generation of the lepton pair;
⋆ multiple soft and hard collinear emission$^{(\star)}$;
⋆ $\alpha_{\rm QED}$ running contribution ($\Delta\alpha^{(5)}_{\rm hadr} \leftrightarrow$ HADR5N).

BABAYAGA@NLO "SM"

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$$d\sigma(s,\ t) = \int_0^1 dx_{i+} dx_{i-} dx_{f+} dx_{f-} d\sigma_0(\hat{s},\ \hat{t}) \quad D^{(i)}(x_{i+},\ \hat{s})\, D^{(i)}(x_{i-},\ \hat{s})\, D^{(f)}(x_{f+},\ \hat{s})\, D^{(f)}(x_{f-},\ \hat{s})$$

$$D(x,\ s) = \frac{\exp\left[\frac{\beta}{2}\left(\frac{3}{4} - \gamma_E\right)\right]}{\Gamma(1+\frac{\beta}{2})} \frac{\beta}{2}(1-x)^{\frac{\beta}{2}-1} - \frac{\beta}{4}(1+x) + \frac{\beta^2}{32}\left[(1+x)(-4\ln(1-x) + 3\ln x) - 4\frac{\ln x}{1-x} - 5 - x\right]$$

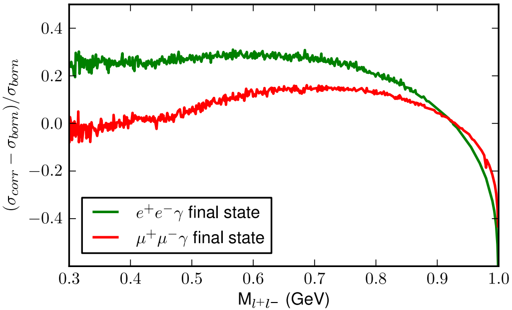
$$\beta \quad \to \quad \begin{cases} \frac{2\alpha}{\pi}\left(\log\frac{s}{m_e^2} - 1\right) & \text{(ISR)} \\ \frac{2\alpha}{\pi}\left(\log\frac{s}{m_{e,\,\mu}^2} - 1\right) & \text{(FSR)} \end{cases}$$

Numerical results

Higher-order radiative corrections

KLOE/KLOE2

- → $\sqrt{s} = 1.02$ GeV
- → $35^\circ \leq \theta_{\ell^\pm,\gamma} \leq 145^\circ$
- → $E^{min}_{\ell^\pm,\gamma} = 10$ MeV
- → $M_U = 0.98$ GeV



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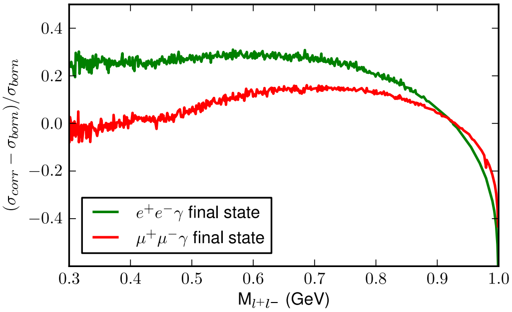

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- ⋆ $M_U \leq 2\,M_p \Rightarrow$ multiple photon radiation more relevant at Φ factories and for a "heavy" U boson.
- ⋆ Signal invariant mass distribution altered by FS radiation, above all in Bhabha scattering.

Numerical results

Experimental sensitivity

⋆ **Statistical significance:**

$$\frac{N_{\mathbf{S}}}{\sqrt{N_{\mathbf{B}}}} \equiv \frac{L\left(\sigma_{\mathbf{F}} - \sigma_{\mathbf{B}}\right)}{\sqrt{L\sigma_{\mathbf{B}}}}$$

$N_S \longrightarrow$ expected number of signal events;

$N_B \longrightarrow$ expected number of background events;

$\sigma_F \longrightarrow$ full cross section (i.e. $\gamma + U$ exchange);

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⋆ From:

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⋆ it follows:

$\Rightarrow$ 5σ bound imposes a constraint on the accessible (M_U, ϵ) pairs.

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Super B factory

- → $\sqrt{s} = 10.56$ GeV
- → $30^\circ \leq \theta_{\ell\pm,\gamma} \leq 150^\circ$
- → $E^{\rm min}_{\gamma,(\ell\pm)} = 20\ (30)$ MeV
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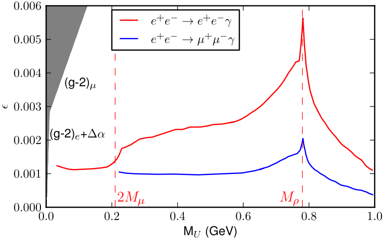
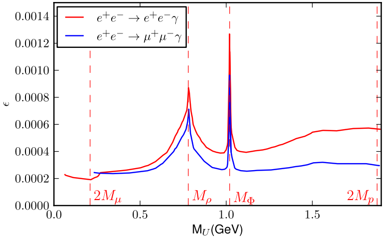
- → $|M_U - M_{\ell+\ell-}| \leq \delta_M \sim [1 \div 10]$ MeV





Minimum accessible threshold (for discovery): $\epsilon^2 \propto \frac{\sqrt{s}}{\sqrt{L}}$

$\sim 1 \times 10^{-3}$ at KLOE $\quad\Rightarrow\quad (2 \div 3) \times 10^{-4}$ at Super-B

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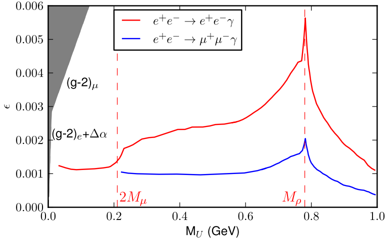

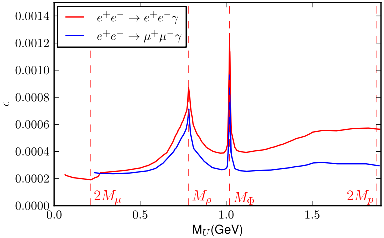

Statistical significance strongly degraded around hadronic resonance (e.g. $M_U \sim M_{\rho,\Phi}$).

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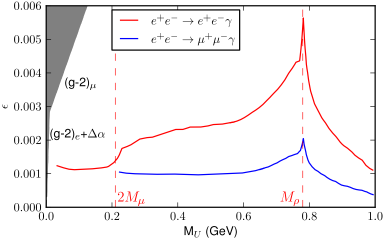

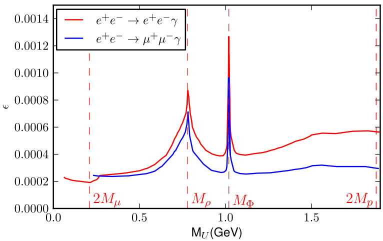

Statistical significance slightly affected by radiative corrections.

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- ⋆ U is supposed to be detectable at low energies e^+e^- colliders since it should contribute to lepton pair production processes (Bhabha, $\mu^+\mu^-$). Discovery could be reached by performing radiative return.

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- ⋆ Statistical significance studies suggest that the accessible dark coupling for discovery is $\sim 1 \times 10^{-3}$ at present flavour factories, $(2 \div 3) \times 10^{-4}$ at future Super–B.

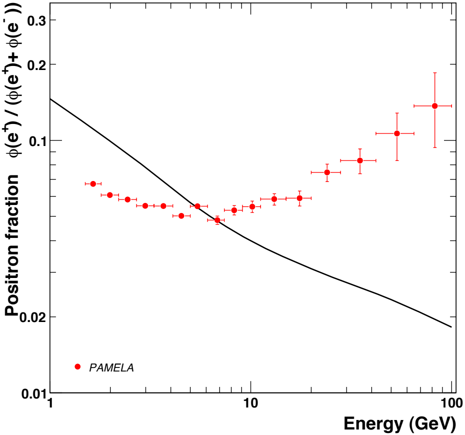
BACKUP SLIDES

⋆ The inclusion of the U–boson channel involves only a small relative correction on the background integrated cross section.

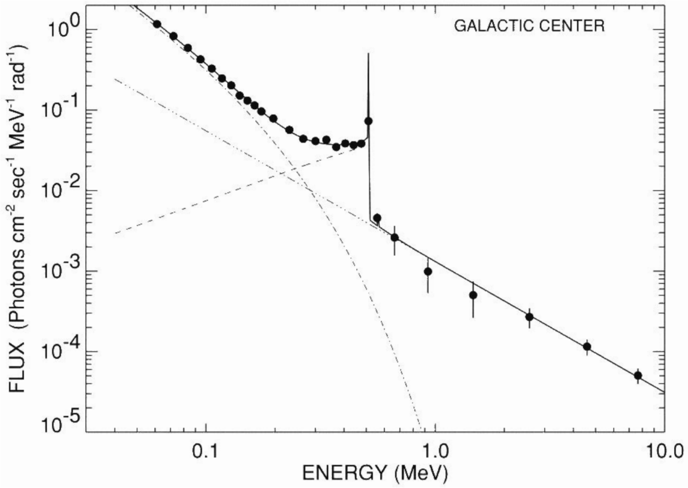
$\Downarrow$

⋆ Signal events are detected as peaks in $M_{\ell^+\ell^+}$:

$\longrightarrow$ A "zoom" on the region of interest is performed, i.e.
$\longrightarrow$ $d\sigma_S$ is integrated on $M_{\ell^+\ell^+} \in [M_U - \delta_M,\ M_U + \delta_M]$
$\longrightarrow$ δ_M should optimally coincide with the detector resolution.



Excess of positrons, PAMELA



[W. N. Johnson III and R. C. Haymes, *Astrophys. J.* **184**:103, 1973]

511 keV line, confirmed by CGRO and INTEGRAL satellites