

Hadronic Footprint of (sub-) GeV Dark Matter

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BEYOND STANDARD MODEL

IRN Brussels
October 18, 2019



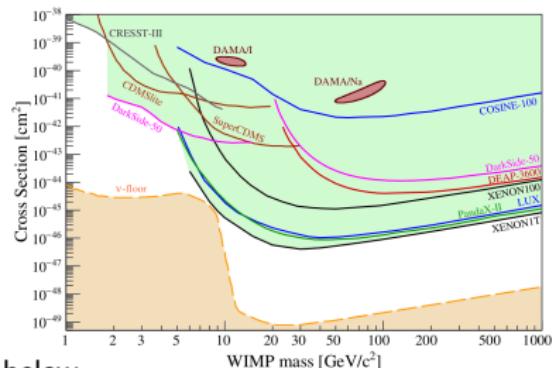
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1911.XXXXX published soon with
Tilman Plehn and Peter Richardson

Where to go in DM searches?

Many models and a wide range of energy scales

- LHC → TeV scale
- Direct Detection → weak scale (~ 100 GeV) and below
- Indirect Detection → strong constraints to GeV and subGeV DM by measurements of
 - ➊ temperature and polarization power spectra of the CMB
 - ➋ flux of gamma rays in Dwarf galaxies



Indirect Detection

Limits from CMB:

$$\frac{dE}{dt dV}(z) = 2g\rho_{\text{crit}}^2(1+z)^6 c^2 \Omega_{\text{DM}}^2 f(z) \underbrace{\frac{\langle \sigma v \rangle}{m_{\text{DM}}}}_{\text{particle physics}},$$

- last scattering of photons before decoupling
- extra free electrons and photons broadening the last scattering surface
→ constraint on DM models

neglect the redshift dependence and take f_{eff} to be constant

$$f_{\text{eff}}(m_{\text{DM}}) = \frac{1}{2m_{\text{DM}}} \int_0^{m_{\text{DM}}} E dE \left[2f_{\text{eff}}^{e^+ e^-}(E) \left(\frac{dN}{dE} \right)_{e^+} + f_{\text{eff}}^\gamma(E) \left(\frac{dN}{dE} \right)_\gamma \right].$$

In dense regions of the sky:

- Dwarf spheroidal galaxies with high DM densities
- flux of gamma ray photons observed in a solid angle $\Delta\Omega$ at the Fermi Large Area Telescope (Fermi-LAT) is given by:

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\text{DM}}^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega} \int_{l.o.s} \rho_{\text{DM}}(\mathbf{r})^2 d/d\Omega'}_{J-\text{factor}}.$$

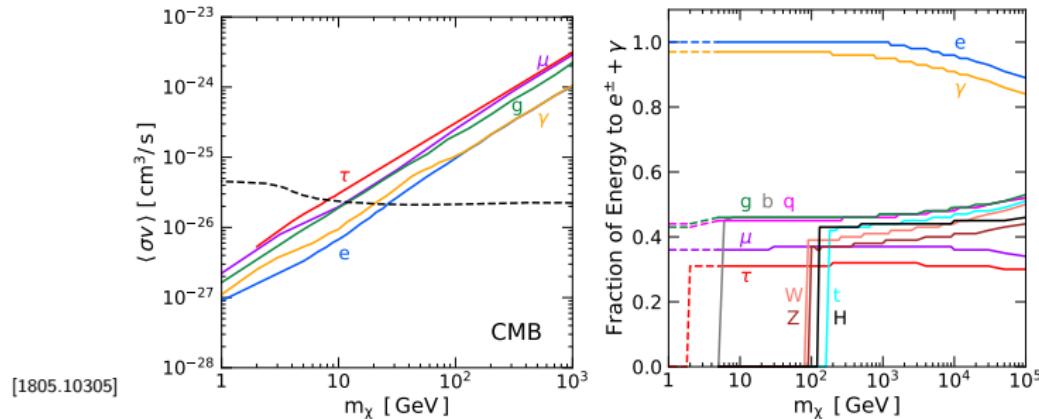
Indirect Detection

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$$f_{\text{eff}}(m_{\text{DM}}) \frac{\langle\sigma v\rangle}{m_{\text{DM}}} < 4.1 \cdot 10^{-28} \text{ cm}^3/\text{s}/\text{GeV}. \quad (\text{Planck})$$

If you now assume 100% s-wave annihilation to individual channel and match relic density
→ many channels excluded



DM in the sub-GeV range

Weaker constraints for models with:

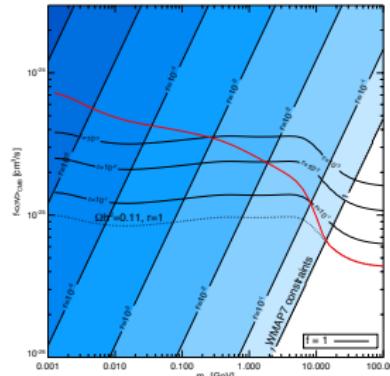
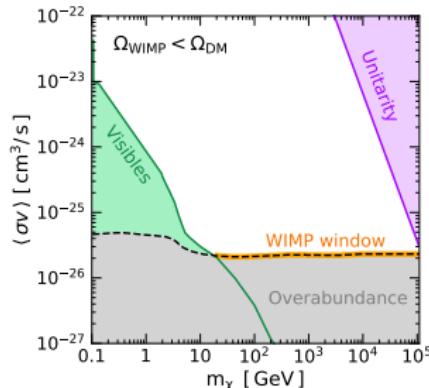
- ① mixture of s- and p-wave mediating WIMP
- ② sizable fraction of DM annihilation to invisible particles
- ③ or WIMP only describing a fraction of all DM
- ④ Asymmetric DM (ADM)

For 1-3 subdominant WIMP cross-section translates into:

$$\langle\sigma v\rangle_{\text{WIMP}} > \frac{\langle\sigma v\rangle_{\text{thermal}}^2}{\langle\sigma v\rangle_{\text{limit}}}$$

For ADM:

$$\frac{2r_\infty}{(1+r_\infty)^2} f(z) \frac{\langle\sigma v\rangle}{m_{\text{DM}}} < 4.1 \cdot 10^{-28} \text{ cm}^3/\text{s}/\text{GeV} \quad \text{with } r_\infty = \Omega_\chi / \Omega_{\bar{\chi}}$$



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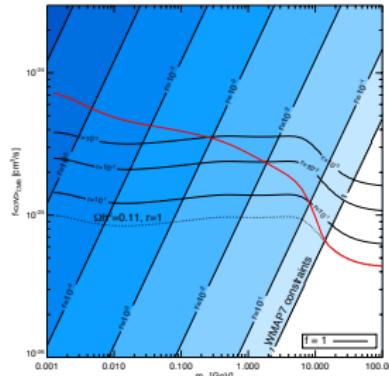
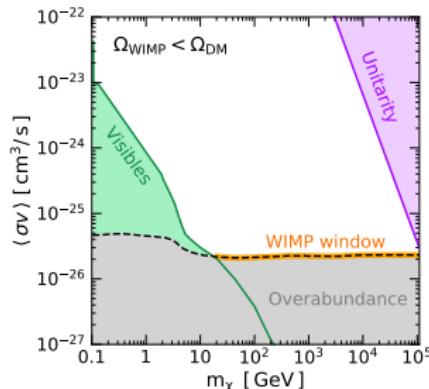
But no energy spectra below 5 GeV!

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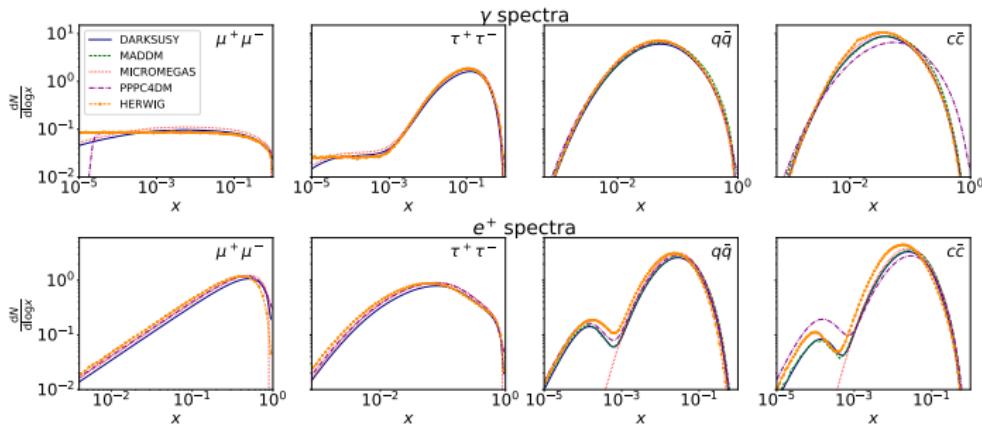
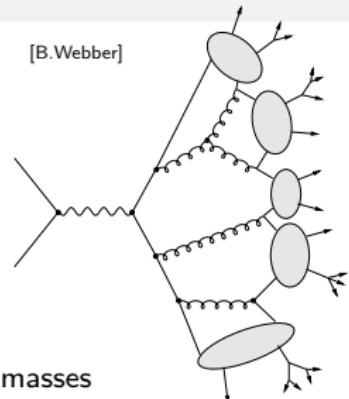


Particle Physics Part of ID

Generation of energy spectra with normal collider procedure

- ① Calculation of Hard Process
- ② Parton Shower
- ③ Hadronization
- ④ Decay to stable particles $\rightarrow \gamma, e^\pm, \nu' s, p/\bar{p}$

→ All DM tools in agreement with each other down to 5 GeV DM masses



Processes in the sub-GeV range

Mainly based on measurements of $e^+e^- \rightarrow \text{hadrons}$
and the VMD model:

$$\mathcal{M} = \frac{e}{\hat{s}} \bar{v}(p_{e^+}) \gamma_\mu u(p_{e^-}) \langle X | J_{\text{em}}^\mu | 0 \rangle$$

with

$$J_{\text{em}}^\mu = \sum_{q=u,d,s} e_q \bar{q} \gamma^\mu q = \frac{1}{\sqrt{2}} J^{l=1,3,\mu} + \frac{1}{3\sqrt{2}} J^{l=0,\mu} - \frac{1}{3} J^{s,\mu}$$

where

$$J_\mu^{l=1,3} = (\bar{u} \gamma_\mu u - \bar{d} \gamma_\mu d) / \sqrt{2},$$

$$J_\mu^{l=0} = (\bar{u} \gamma_\mu u + \bar{d} \gamma_\mu d) / \sqrt{2},$$

$$J_\mu^s = \bar{s} \gamma_\mu s .$$

→ Task: find parametrization for hadronic currents

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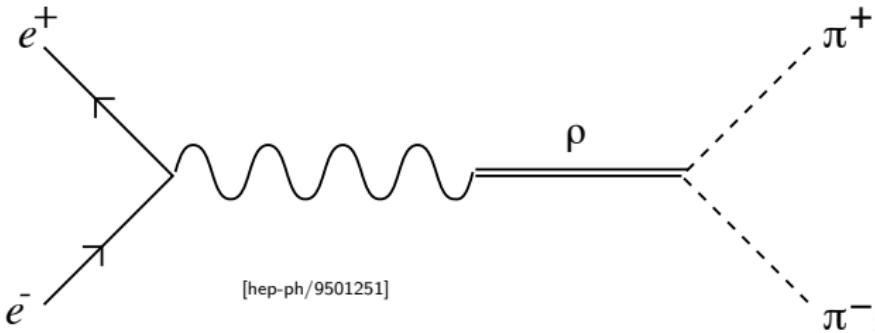
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i.e. for $\pi^+\pi^-$

$$\langle \pi^+\pi^- | e J_{\text{em}}^\mu | 0 \rangle = -e (p^+ - p^-)^\mu F_\pi(q^2)$$



[hep-ph/9501251]

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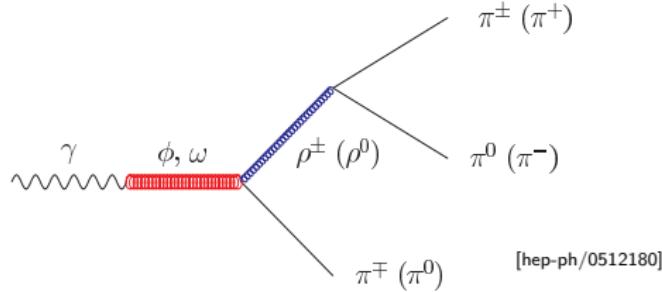
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i.e. for $\pi^+ \pi^- \pi^0$:

$$\langle \pi^+ \pi^- \pi^0 | e J_{\text{em}}^\mu | 0 \rangle = -e \epsilon_{\alpha\beta\gamma}^\mu q_+^\alpha q_-^\beta q_0^\gamma F_{3\pi}(q_+, q_-, q_0)$$

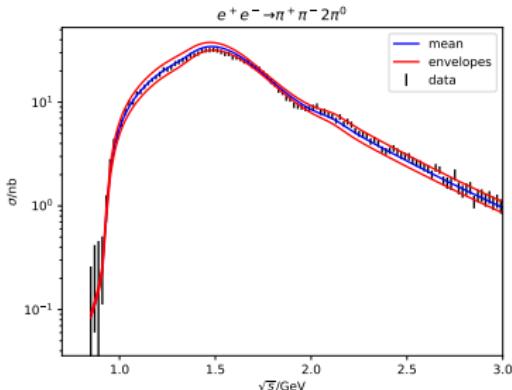
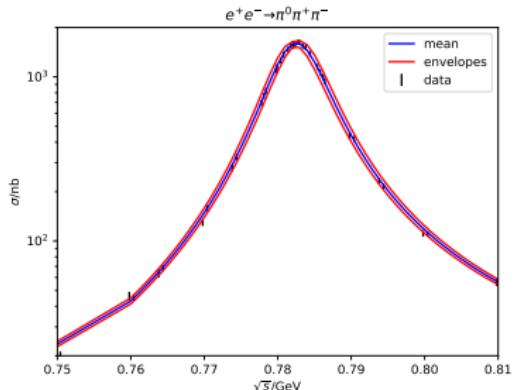
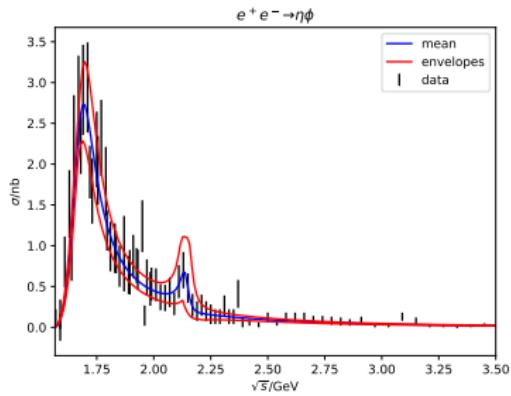
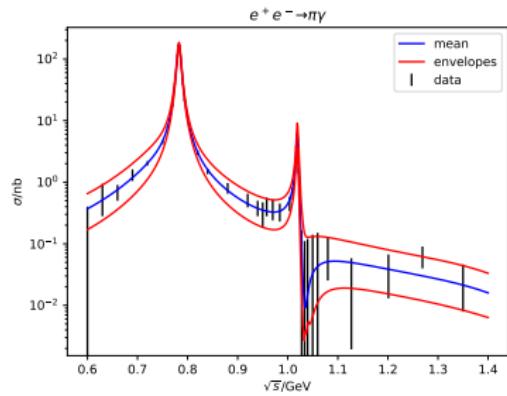


Dominant Processes

Channel	Parametrization	Fit	threshold energy [GeV]
$\pi\gamma$	SND	SND	0.140
$\pi\pi$	Phokhara	Phokhara	0.280
$\pi\pi\pi$	Phokhara	Phokhara	0.420
$\eta\gamma$	SND	SND	0.548
4π 's	Phokhara	own	0.560
$\eta\pi\pi$	Phokhara	own	0.827
$\omega\pi$	SND	SND	0.918
KK	Phokhara	own	0.996
$\omega\pi\pi$	own	own	1.062
$KK\pi$	own	own	1.135
$\phi\pi$	own	own	1.160
$\eta'\pi\pi$	Phokhara	own	1.237
$\eta\omega$	own	own	1.331
$\eta\phi$	own	own	1.568
$p\bar{p}/n\bar{n}$	Phokhara	own	1.877

Data taken from BABAR , SND, KLOE, BESIII, CLEO, FENICE, DM1/2, ADONE, MAMI, BLAST, JLAB, Fermilab E760, SLAC, CMD-2/3

Cross-section fits



DM Processes

DM current constructed in same way as e.m. current:

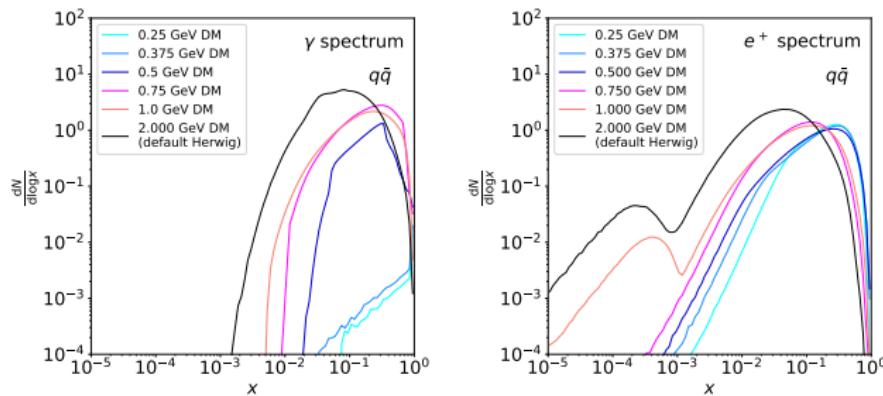
$$J_{\text{DM}}^{\mu} = \frac{1}{\sqrt{2}} \left((a_u + a_d) J^{I=1,3,\mu} + (a_u - a_d) J^{I=0,\mu} \right) + a_s J^{s,\mu}$$

The matrix element is then:

$$\mathcal{M} = a_{\text{DM}} \bar{v}(p_1) \gamma^{\nu} u(p_2) d_{\nu\mu}^{\text{DM}} \langle X | J_{\text{DM}}^{\mu} | 0 \rangle$$

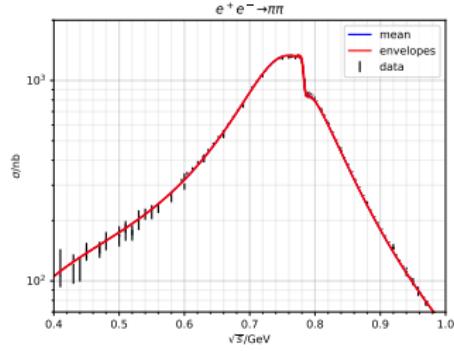
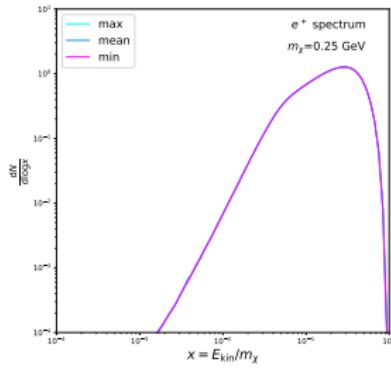
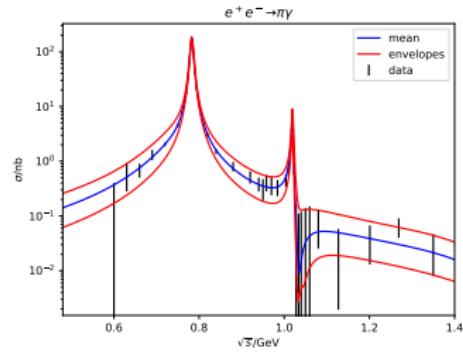
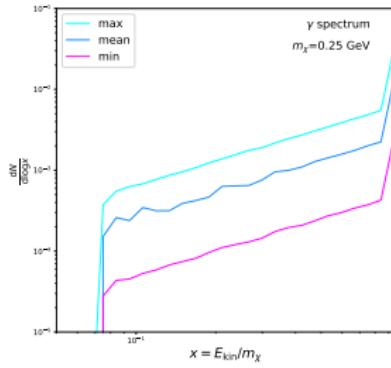
For now, take process:

$$\chi\chi \rightarrow Z' \rightarrow q\bar{q} \quad \text{with} \quad m_{Z'} \approx 2m_{\chi} .$$



Translation of envelopes

show 0.250 GeV gamma and positron case, maybe additional one if done by then



Summary & Outlook

Summary:

- updated fits for $e^+e^- \rightarrow$ hadrons
- translated e.m. processes to DM processes
- closed gap of generating energy spectra in the sub-GeV range for hadronic processes
- introducing uncertainties to Low Energy Hadronic Processes

Further work:

- spectrum uncertainties for all processes
- work on DM model part
- make code publicly available
- **comments and suggestions are welcome!**