Simulation of a gas-target directional time projection chamber to detect light dark matter in a beam-dump experiment

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- **Introduction**
- **Models**
- **Preliminary simulation**
- **Conclusion**

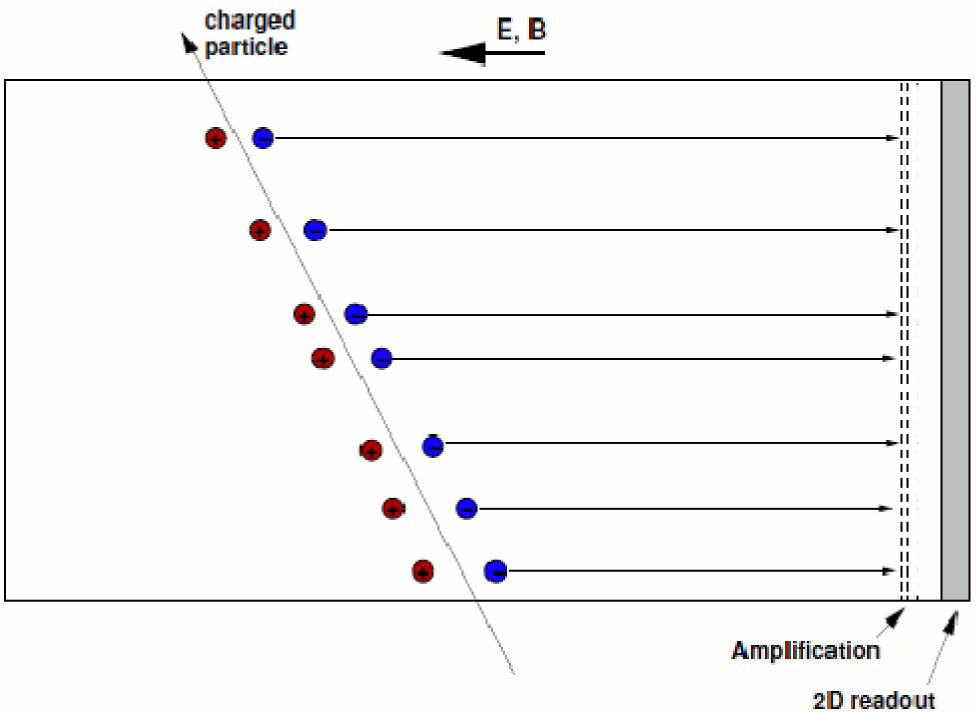
What do we want to detect ?

- **Neutron**
- **~ 1 GeV mass, keV to MeV in kinetic energy with a flux of several neutron s^{-1}**
- **Interact through strong force**

- **Light Dark Matter produced in a W beam dump by an 12 GeV electron beam**
- **Existence hypothetical**
- **Mass unknown, keV to MeV in kinetic energy**
- **Interact through weak force**
- **Hypothesis: behaves as a fast moving neutron**

Detection principle

- Detect the ionization produced when a particle scatters off nucleus of the gas material
- Neutron: C_4H_{10} (iso-butane) gas – $m_{neutron} \sim m_H$
- Light Dark Matter (LDM): ^1H, ^4He, CF_4, ^{40}Ar and ^{131}Xe gas – m_{LDM} ?



- Identifiable if elastic scattering occurs

  e.g. $n + H \rightarrow n + H$

- Amplification with Gas Electron Multipliers enables detection of electrons produced by the nuclear recoil with nearly 100 % efficiency estimated
- Readout: measure 2D + time (ie relative z) + charge (ie absolute z)

Simulation steps

- **Signal and background sources**
- **Geometry and materials**
- **Neutron/Light Dark Matter interaction with the detector**
- **Creation of the ionization in the gas target**
- **Electron transport from the primary ionization to the readout**
- **Electronic readout**

Signal and background sources

Neutron

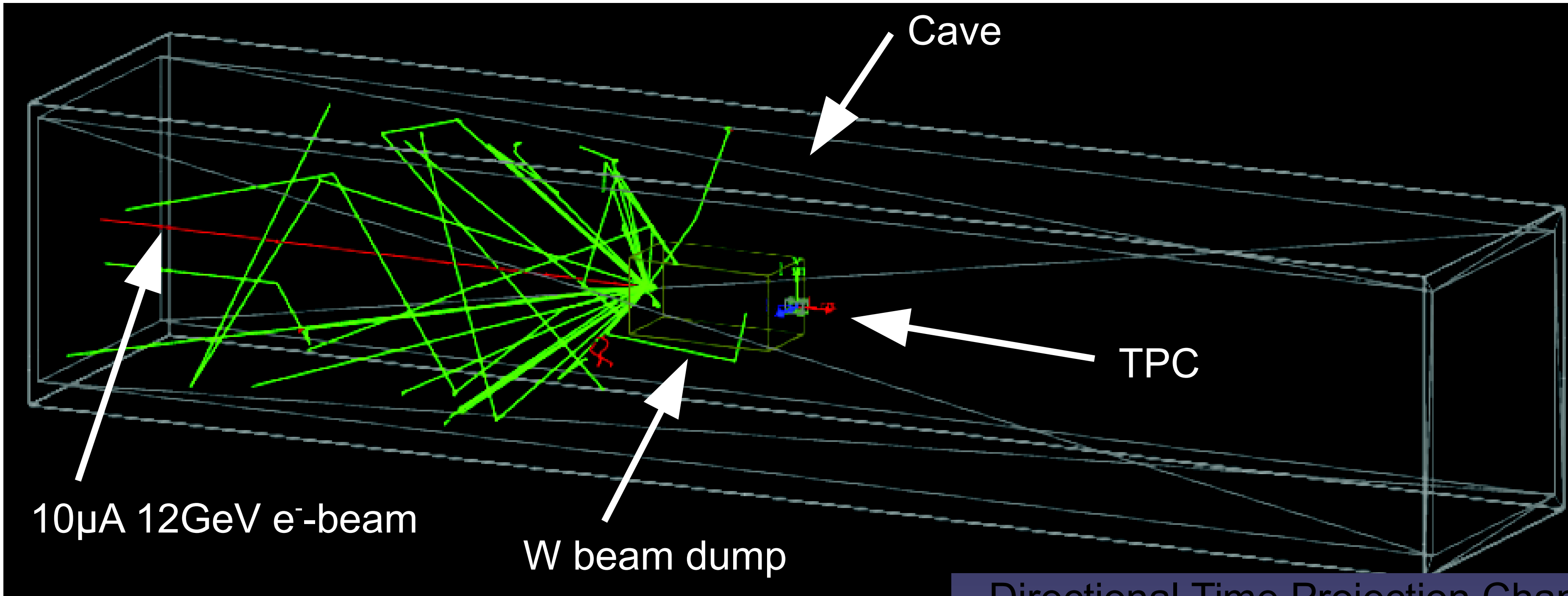
- **Neutron sources (e-beam, natural radiation)**
- **Internal background sources (alpha, beta etc ...)**

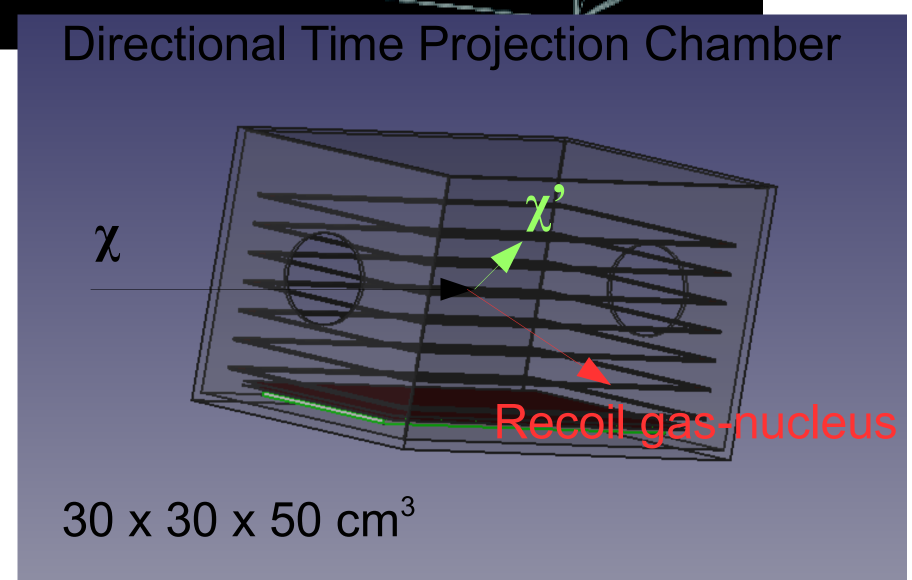
Light Dark matter

- **Light Dark Matter sources:** $e^- N \rightarrow e^- N A'[\rightarrow \chi\chi]$ or $e^- N \chi\chi$
- **Light Dark Matter detection:** $\chi + N \rightarrow \chi + N$
- **Background sources (neutron, ^{222}Rn)**

Geometry and materials

- Directional TPC placed after a Tungsten (W) beam dump in a concrete cave





Probability of interaction

- $P = \sigma . l . \rho$
  - σ cross section [b] (barn = $1e^{-24}$ cm^2)
  - l target length [cm]
  - ρ density [cm^{-3}] = ρ_0 [g/cm^3] . $\mathcal{N}_A$[mol^{-1}] / $\mathcal{M}_A$[g/mol]
- Between a neutron and a H belonging to C_4H_{10}

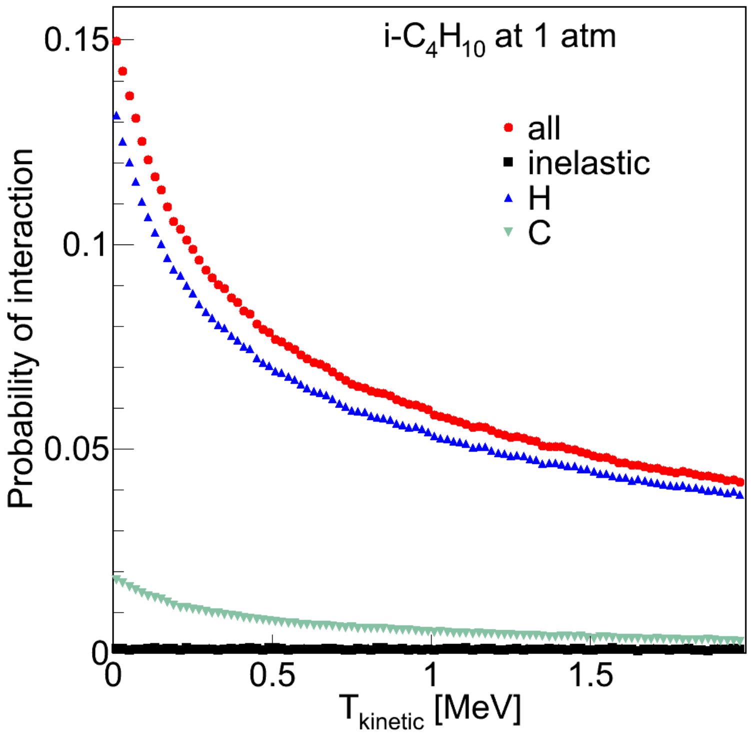
=> 0.11 % for 1 cm

- Between a neutron and a F belonging to CF_4

=> 0.003 % for 1 cm

- GEANT4 results for 50 cm^3, C_4H_{10} (1 atm)

=> ~ 5 % efficiency at 1 MeV



=> Good agreement between geant4 and analytical calculation

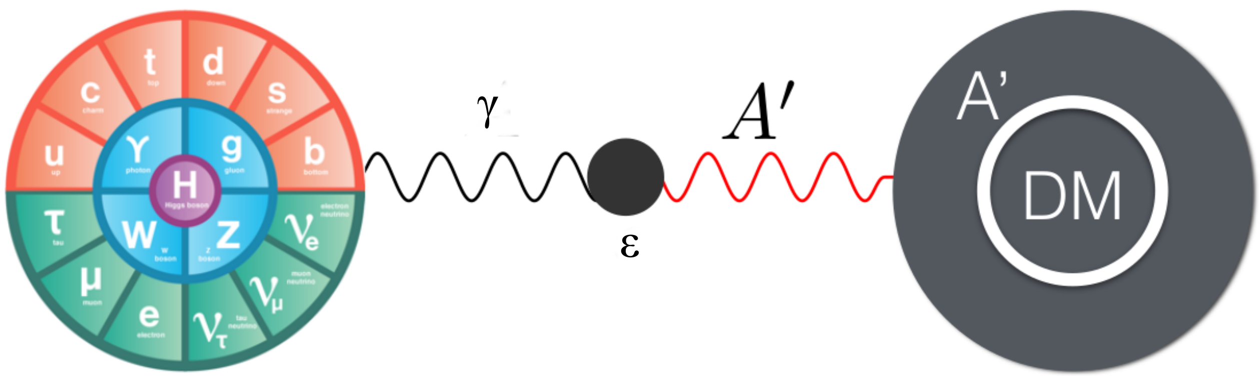
=> Efficiency can be adjusted by varying size and pressure

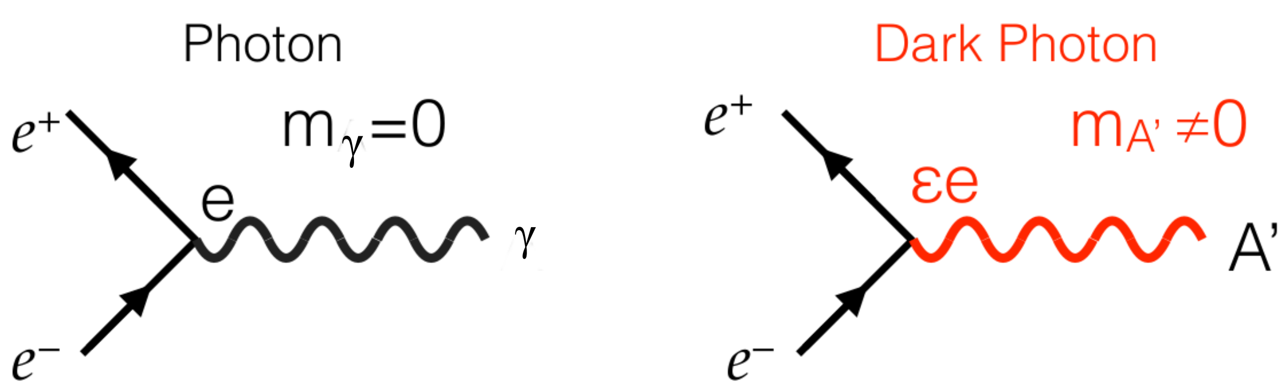
P. Fayet, Phys. Lett. B **95**, 285 (1980).
P. Fayet, Nucl. Phys. B **187**, 184 (1981).
P. Fayet and J. Kaplan, Phys. Lett. B **269**, 213 (1991).
C. Boehm and P. Fayet, Nucl. Phys. B **683**, 219 (2004).
P. Fayet, Phys. Rev. D **70**, 023514 (2004).
N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer and N. Weiner, Phys. Rev. D **79**, 015014 (2009).
M. Pospelov, A. Ritz and M. Voloshin, Phys. Lett. B **662**, 53 61b (2008).

Dark Sector Models

R. Essig, P. Schuster, and N. Toro, Phys. Rev. D **80**, 015003 (2009).

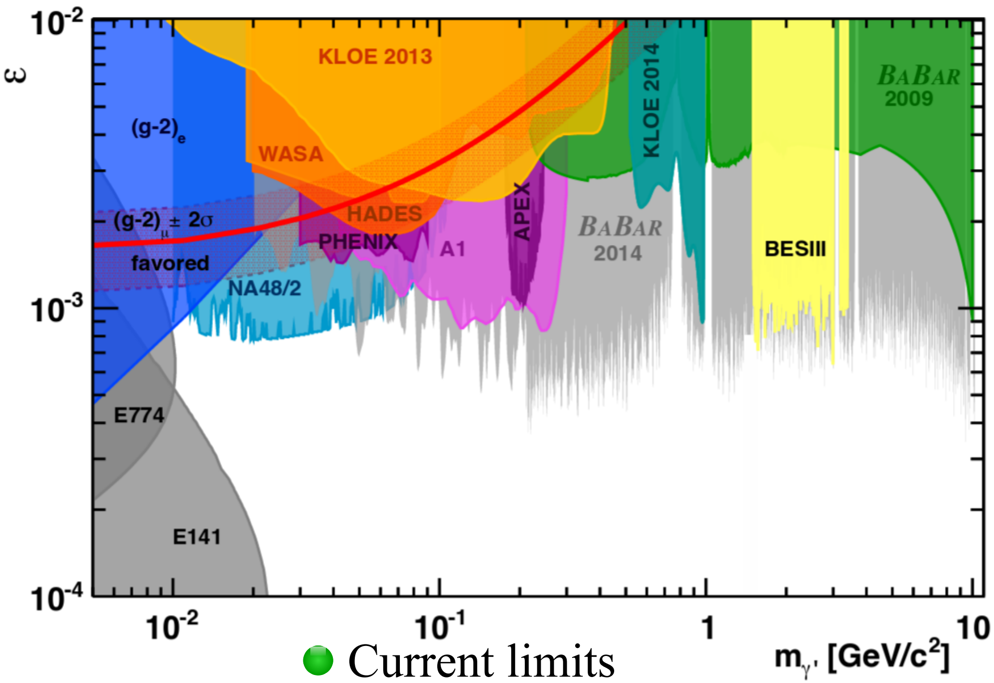
- Attempt to simultaneously explain all recent results of direct and indirect dark matter detection experiments
- Models include WIMP dark matter candidates, and a new force, mediated by "Dark Gauge Boson"
- Dark photon A' mixes with SM photon with kinetic mixing ε





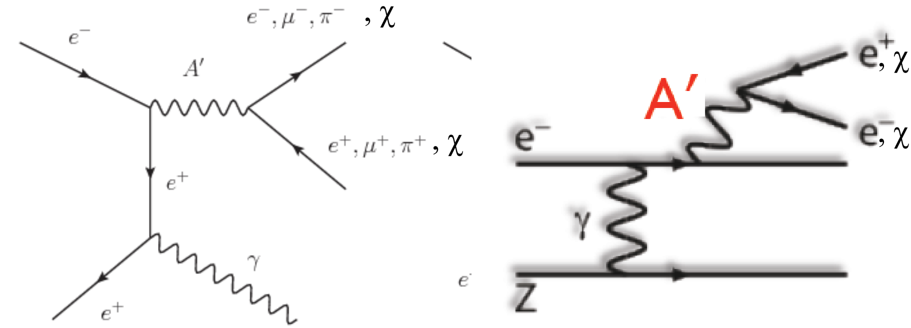
The dark gauge boson A'

- Dark gauge bosons, or dark photons, $A' = \gamma' = A = U$, have been searched since the late 80s
- Very small couplings to Standard Model particles
- Low mass: of order MeV to GeV
- LDM can be produced off-shell or on-shell



- Current limits

- Collider
- Fixed target

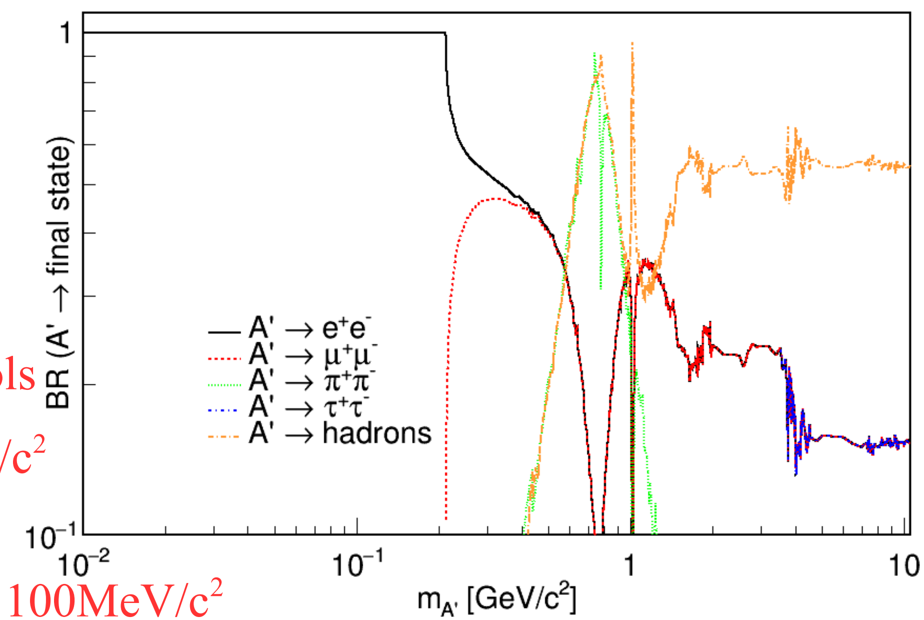


- Feynman diagrams

=> Low-energy and high-intensity beams or beam+target ideal tools

=> Collider: $\sigma \propto \alpha^2\varepsilon^2 / E_{cm}$ = 2ab for $\varepsilon=10^{-4}$ and E_{cm}=10 GeV/c^2

=> Fixed target: $\sigma \propto Z^2\alpha^3\varepsilon^2 / m_{A'}^2$= 151ab for Z=1 and $m_{A'}^2$= 100MeV/c^2



- Branching ratio

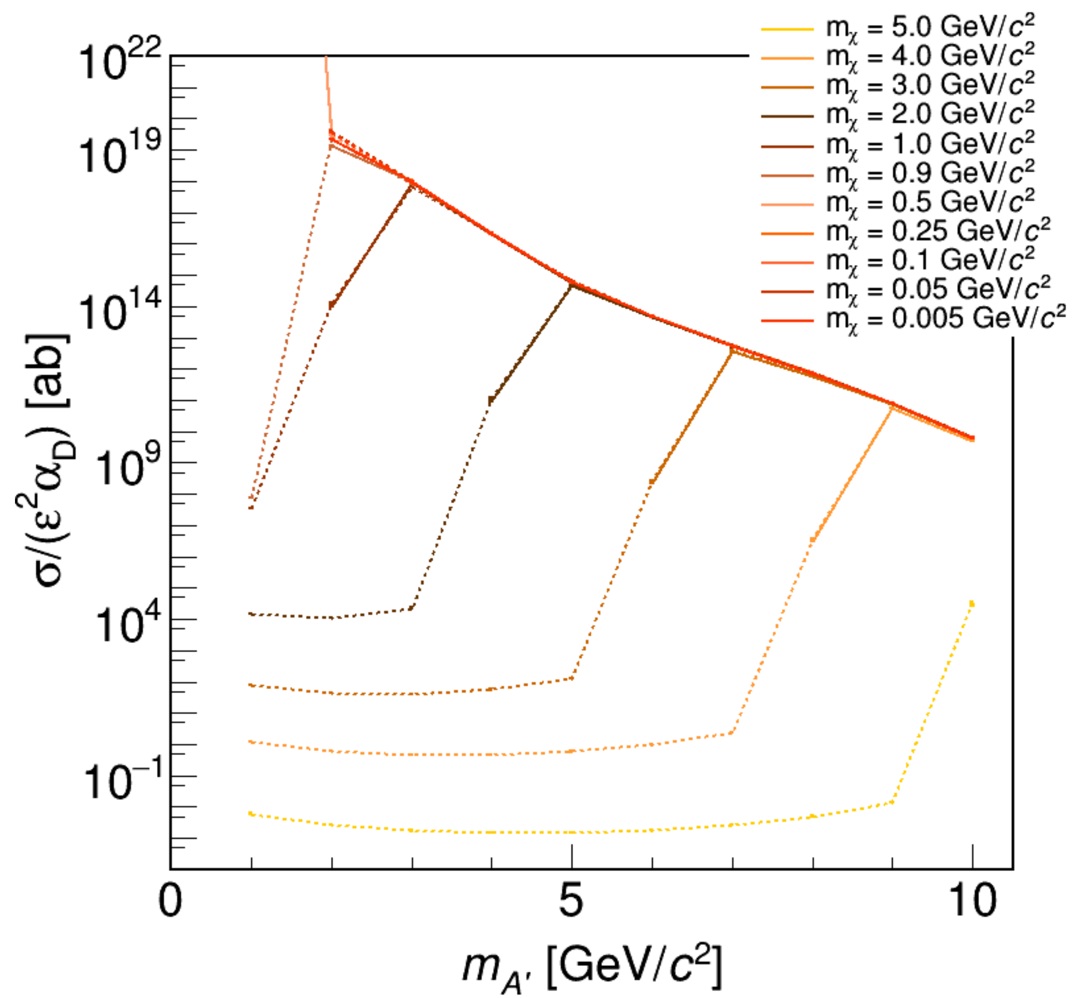
$e^- N \to e^- N A'[\to \chi\chi]$ or $e^- N \chi\chi$

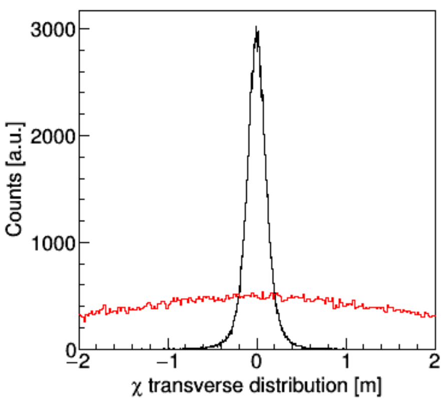
- Simulation with MadGraph and model computed by Yi-Ming Zhong
- Model based on 10.1007/JHEP11(2013)167 (R. Essig, J. Mardon, M. Papucci, T. Volansky, Y. Zhong) & arXiv:1705.01633v1 (Y. Liu & G. Miller)
- Two production modes: on-shell (full line) and off-shell (dashed line)
- 1 MeV/c^2 < $m_{A'}$ < 10 GeV/c^2
- 1 MeV/c^2 < m_χ < 5 GeV/c^2

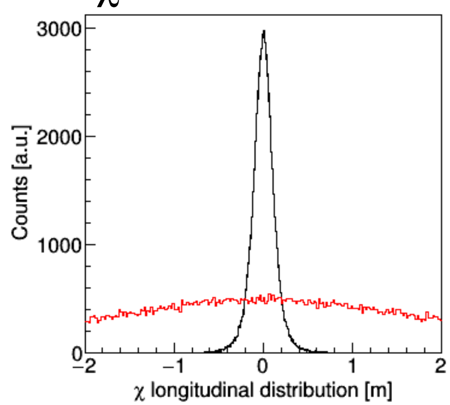
- $\varepsilon^2 = \alpha' / \alpha$ is the kinetic mixing between A' and γ
  - α' electromagnetic coupling of A' to γ
  - $\alpha = 1 / 137$ (SM electromagnetic coupling)

- $\alpha_D = g_D^2 / 4\pi$ is the dark sector constant
  - g_D is the dark sector gauge coupling of A' to Dirac fermion dark matter (ie LDM)

- χ beam profile at the TPC entrance depends of mass difference between A' and χ







$m_{A'}$ = 4 GeVc^2 - m_χ = 2 GeV/c^2

$m_{A'}$ = 10 GeVc^2 - m_χ = 2 GeV/c^2

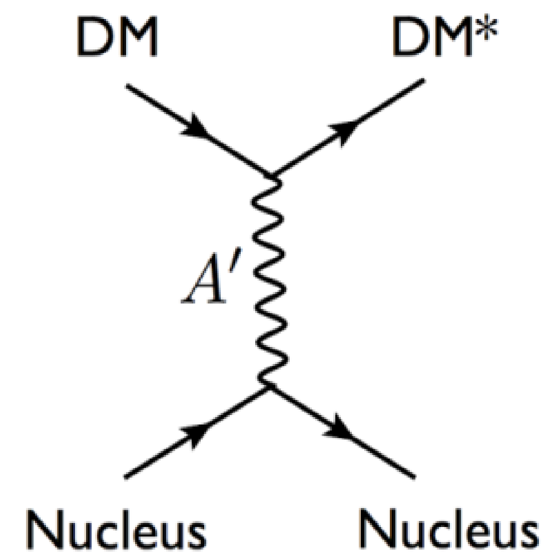
$$\Gamma_V(\phi \to e^+e^-) = \epsilon_V^2 \frac{\alpha}{3} m_\phi \left(1 + \frac{2m_e^2}{m_\phi^2}\right)\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{1/2}$$

Reach plot - general formula

J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

- **differential energy spectrum of nuclear recoils**

$$\frac{dR}{dT_R} = R_0 S(T_R) F^2(T_R) I$$



- **R is the event rate per unit mass**
- **T_R is the recoil energy**
- **R_0 is the total event rate**
- **S is the modified spectral function**
- **F is the form factor**
- **I is an interaction function**

Total cross section off nucleus and off nucleon

$$\frac{d\sigma^A(M_X)}{dT_R} = \frac{1}{V\,\rho\,\phi(M_X)\,\Delta t\,\epsilon(M_X)}\frac{dN(M_X)}{dT_R} \quad \text{and} \quad \frac{d\sigma^N(M_X)}{dT_R} = \frac{\mu_N^2(M_X)}{\mu_A^2(M_X)}\Gamma^N \frac{d}{dT_R}\frac{\sigma^A(M_X)}{\Gamma^A(T_R)}$$

- **N event number if N = 2.3 CL = 90 %, in this work N = 1**
- **V detector volume [cm^3]**
- **ρ target density [cm^{-3}] = ρ_0 [g/cm^3] . $\mathcal{N}_A$[mol^{-1}] / $\mathcal{M}_A$[g/mol]**
- **φ WIMP/LDM flux [$cm^{-2}s^{-1}$] – model dependent**
- **Δt exposure time [s]**
- **ε detection efficiency**

$M_X + A \rightarrow M_X + A$

- **μ_N nucleon reduced mass**
- **μ_A nucleus reduced mass**

- **$\Gamma^{N,A}$ "interaction" between the WIMP/LDM and the nucleon/nucleus: $\Gamma^A = F^2\, I$**

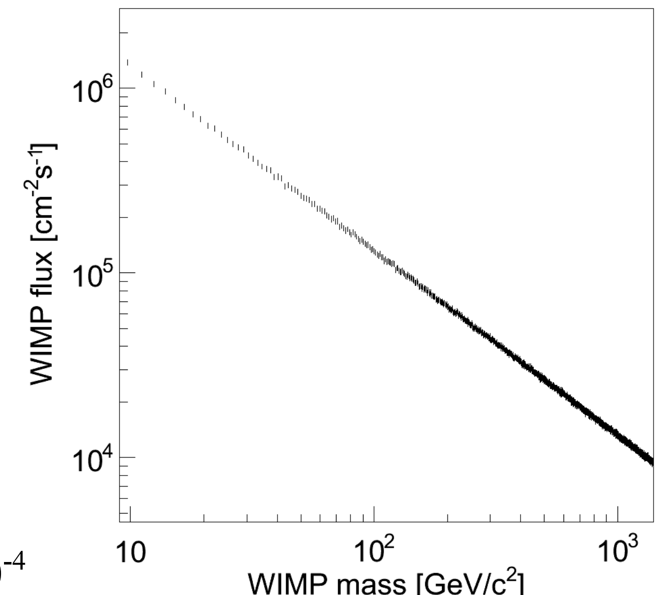
model dependent

- **$I = A^2$ for SI or $I = C^2\lambda^2 J(J+1)$ for SD**
- **$F^2\,(qr_n)$ is the form factor**

WIMP flux vs beam-induced LDM flux

J.D. Lewin, P.F. Smith Astr. Phys. 6 (1996) 87-112
Particle Dark Matter (Cambridge ed.)

- $\Phi = \rho_D v_D / M_D$ [cm^{-2}s^{-1}]
  - $\rho_D = 0.3$ [GeV/c^2/cm^3]
  - v_D depends on WIMP velocity distribution choice

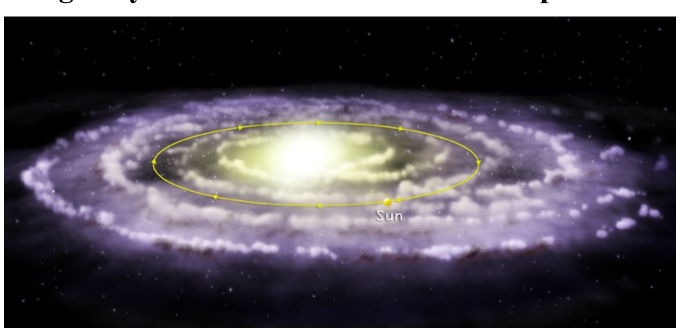


- **Gaussian velocity distribution**

$$f(v) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{|v|^2}{2\sigma^2}\right)$$

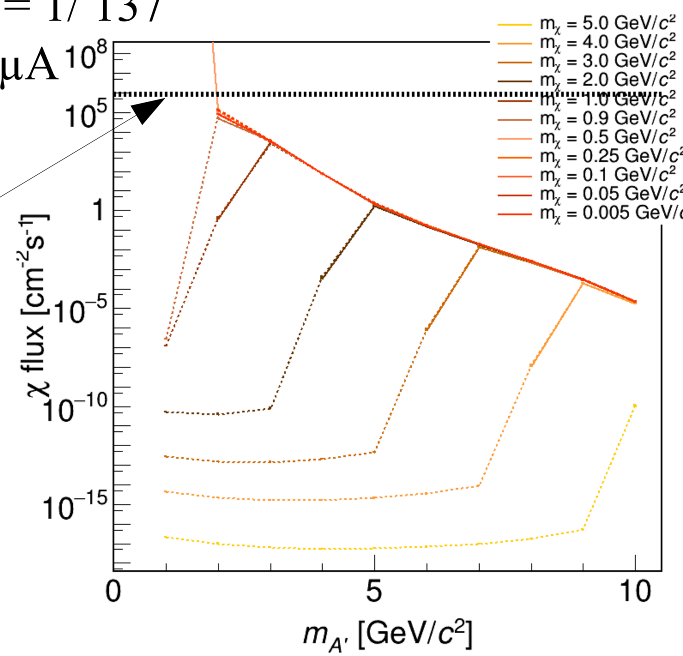
- σ is the speed dispersion = $(3/2)^{1/2} v_c$, v_c local circular speed (= 220 km/s)

- $v_{detector} = v_{galaxy} + v_{sun} + v_{earth}$, v_{escape} = 530 km/s



- $\varepsilon = 10^{-4}$
- $\alpha_D = \alpha = 1/137$
- $I = 10\mu A$

Hit rate due to beam-induced background

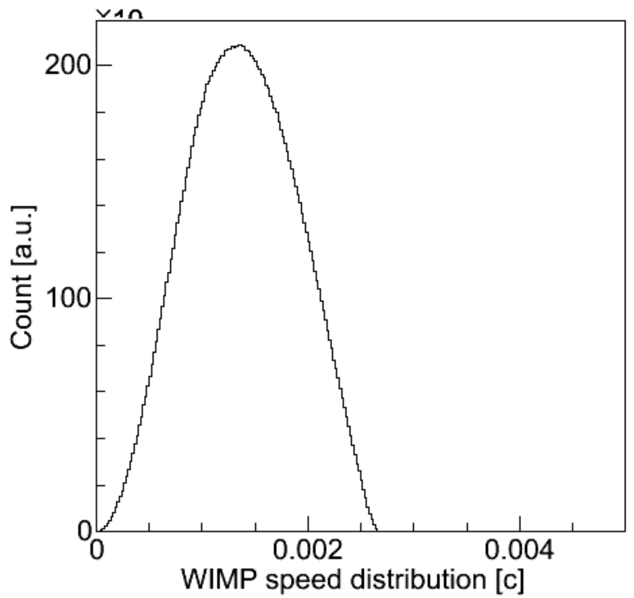


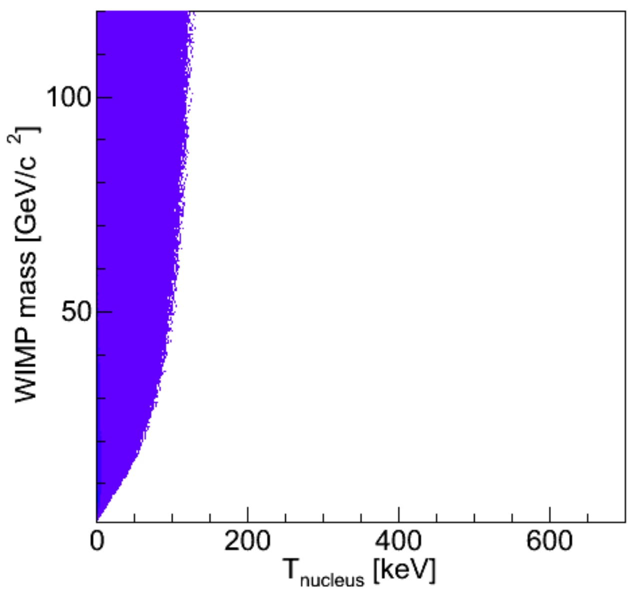
Elastic scattering

$$T^{cm}_{nucleus} = \frac{M_D^2}{(M_T+M_D)^2}\frac{M_T}{2}v^2$$

- T nucleus kinetic energy in CMS
- M_D and M_T respectively WIMP/LDM and nucleus masses
- v WIMP velocity in CMS

in LAB.





Interaction function

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- **SI : σ α $|A|^2$**
- **SD : σ α J^2**
- **I = $C^2\lambda^2 J(J+1)$**
- **C related to the quark spin**
- **$\lambda^2 J(J+1)$ related to nuclear magnetic moment and the unpaired nucleon spin**

Isotope	J	$\lambda^2 J(J+1)$	
		single particle	odd group
^{1}H	1/2	0.75	0.75
^{19}F	1/2	0.75	0.647
^{23}Na	3/2	0.15	0.041
^{27}Al	5/2	0.35	0.087
^{43}Ca	7/2	0.321	0.152
^{73}Ge	9/2	0.306	0.065
^{93}Nb	9/2	0.306	0.162
^{127}I	5/2	0.35	0.007
^{129}Xe	1/2	0.75	0.124
^{131}Xe	3/2	0.15	0.055

Table 3: Values of $\lambda^2 J(J+1)$ for various isotopes

WN	C^2_{WN}			$\frac{\sigma_{WN}\vert_{spin}}{\mu^2 I_s}$	$\frac{\sigma_{WN}\vert_{spin}}{\sigma_{\nu_M N}}$
	NQM	EMC [36]	EMC [4]		
$\tilde{\gamma}p$	0.14 ± 0.01	0.096 ± 0.009	0.06 ± 0.02	$\frac{4}{\pi}\left(\frac{\epsilon}{m_{\tilde{q}}c}\right)^4$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4$
$\tilde{\gamma}n$	0.002 ± 0.001	0.012 ± 0.003	0.03 ± 0.01		
$\tilde{H}p$	0.40 ± 0.02	0.46 ± 0.04	0.55 ± 0.10	$\frac{8G_F^2}{\pi\hbar^4}\cos^2 2\beta$	$4\cos^2 2\beta$
$\tilde{H}n$	0.40 ± 0.02	0.34 ± 0.03	0.26 ± 0.07		
$\tilde{B}p$	0.16 ± 0.01	0.10 ± 0.01	0.06 ± 0.02	$\frac{1}{\pi}\left(\frac{\epsilon}{m_{\tilde{q}}c}\right)^4 \frac{1}{\cos^2\theta_W}$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4 \frac{1}{4\cos^2\theta_W}$
$\tilde{B}n$	$(7 \pm 5) \times 10^{-4}$	0.010 ± 0.003	0.03 ± 0.01		
$\tilde{Z}p$	1.9 ± 0.1	0.9 ± 0.1	0.3 ± 0.2	$\frac{4}{\pi}\left(\frac{\epsilon}{m_{\tilde{q}}c}\right)^4 \tan^4\theta_W$	$\left(\frac{M_F}{m_{\tilde{q}}}\right)^4 \tan^4\theta_W$
$\tilde{Z}n$	0.21 ± 0.04	0.002 ± 0.006	0.1 ± 0.1		

Table 4: Values of WIMP-nucleon spin factors; $M_F = \sqrt{8}\, M_W \sin\theta_W \simeq 109\ \mathrm{GeV c^{-2}}$

Nuclear Form Factor

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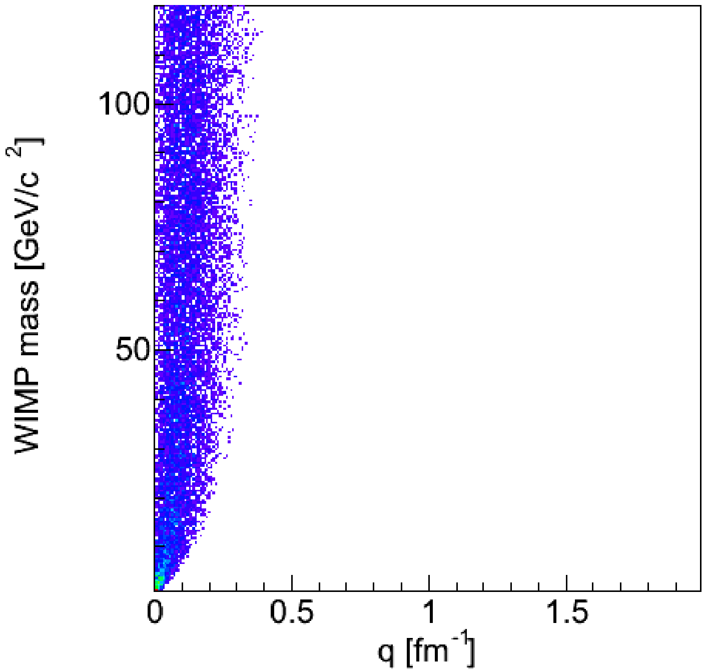
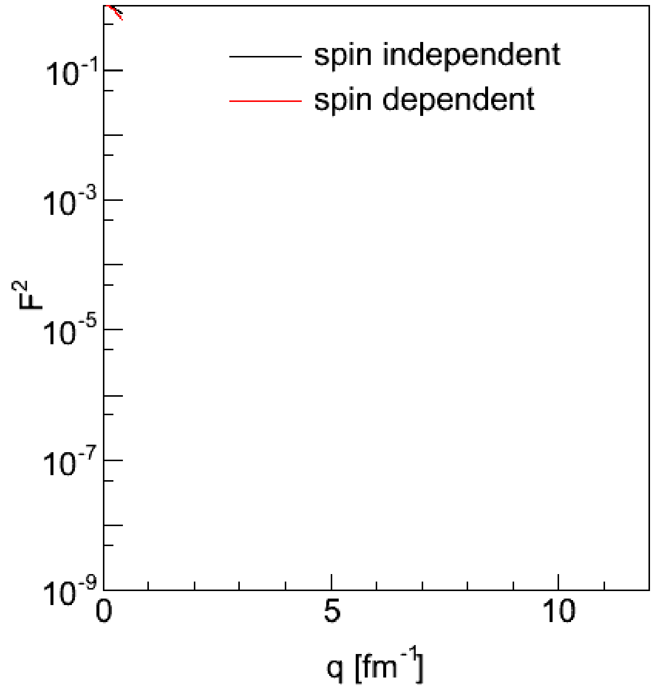
Particle Dark Matter (Cambridge ed.)

- **One nuclear form factor per nucleus**
- **Momentum transfer $q = | p_{\text{nucleus at rest}} - p_{\text{nucleus after elastic scattering}} |$**
- **Spin dependent**
- **Spin independent**





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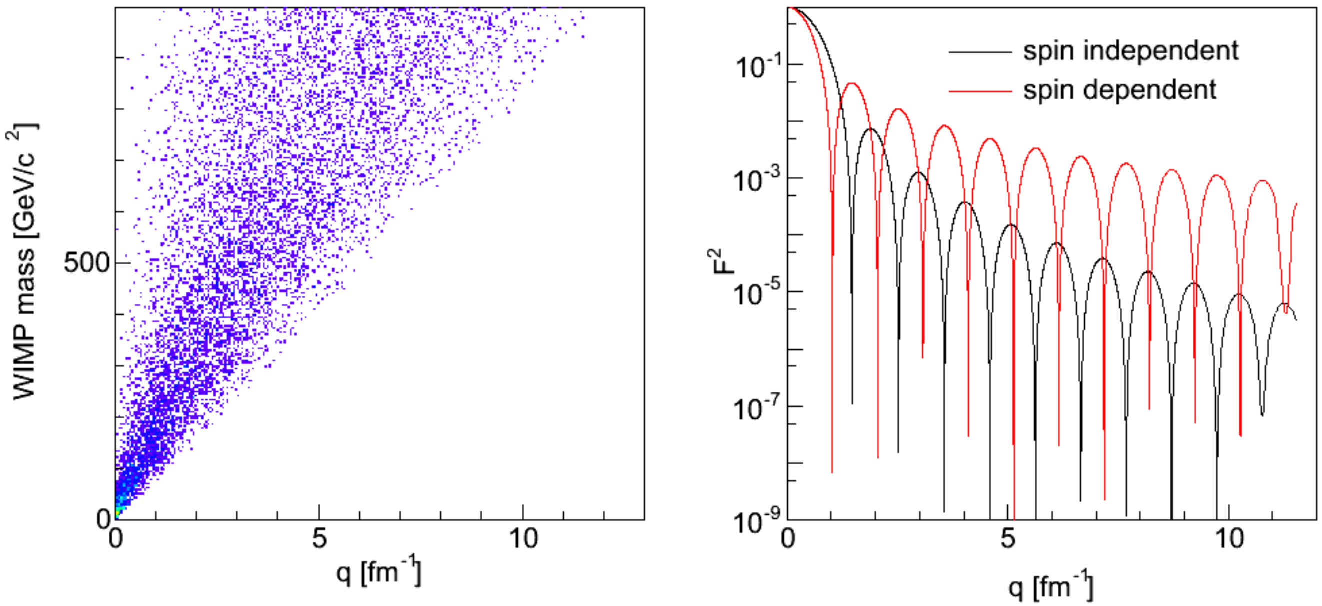
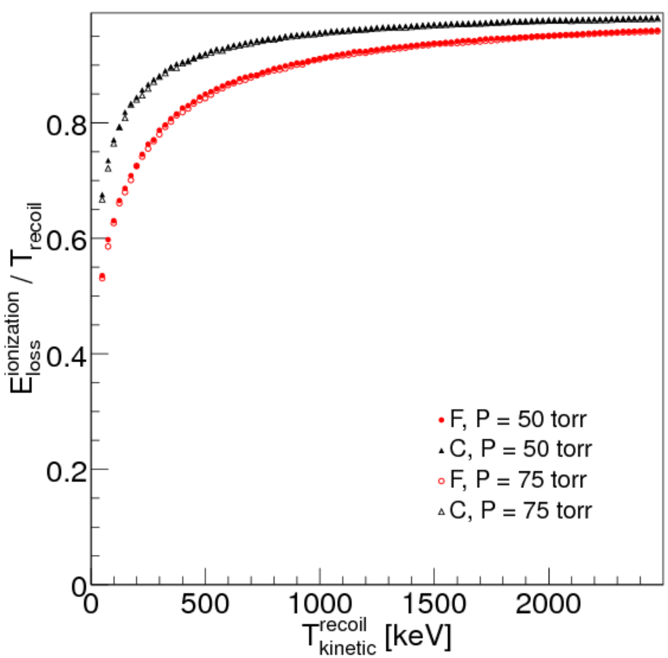


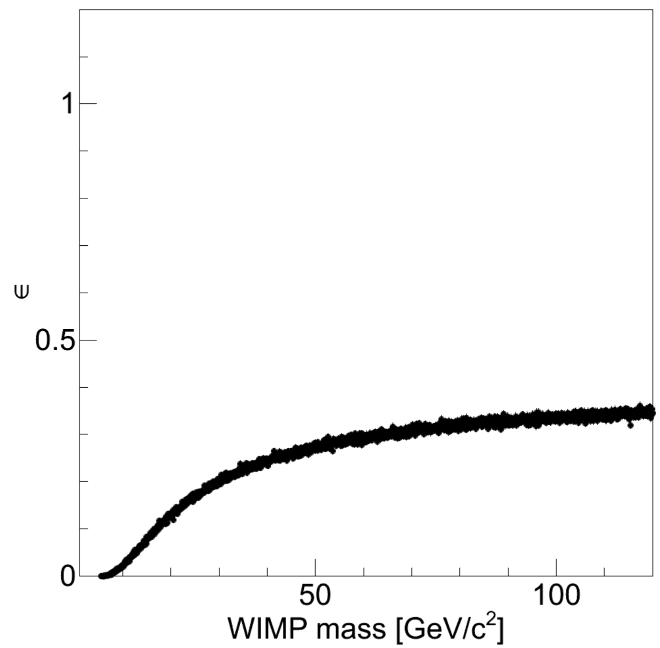
- **Remark: if enough energy is transferred one can deduce from the position of the minima what kind of interaction did occur**

Detection efficiency

- Depends on the thresholds and WIMP/LDM velocity/kinetic energy distribution
- Energy deposited eg through ionization

$$X + p \rightarrow X^{+} + p + e^{-}$$





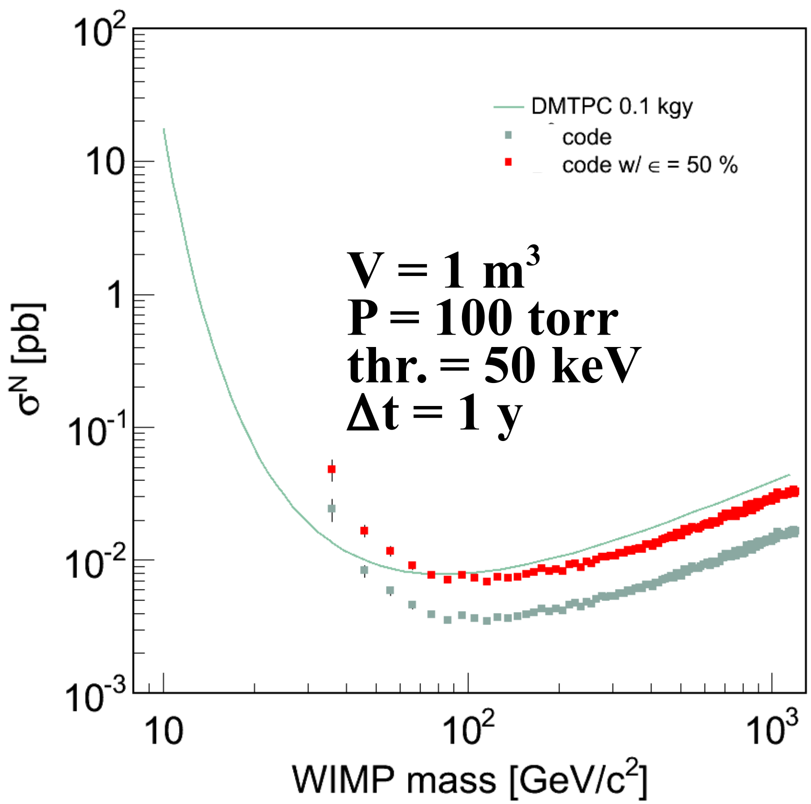
thresholds:

- Energy threshold
- Minimum track length measurable
  - GEM: at least 3 holes covered
- Directionality
  - $L / \sigma > 3$

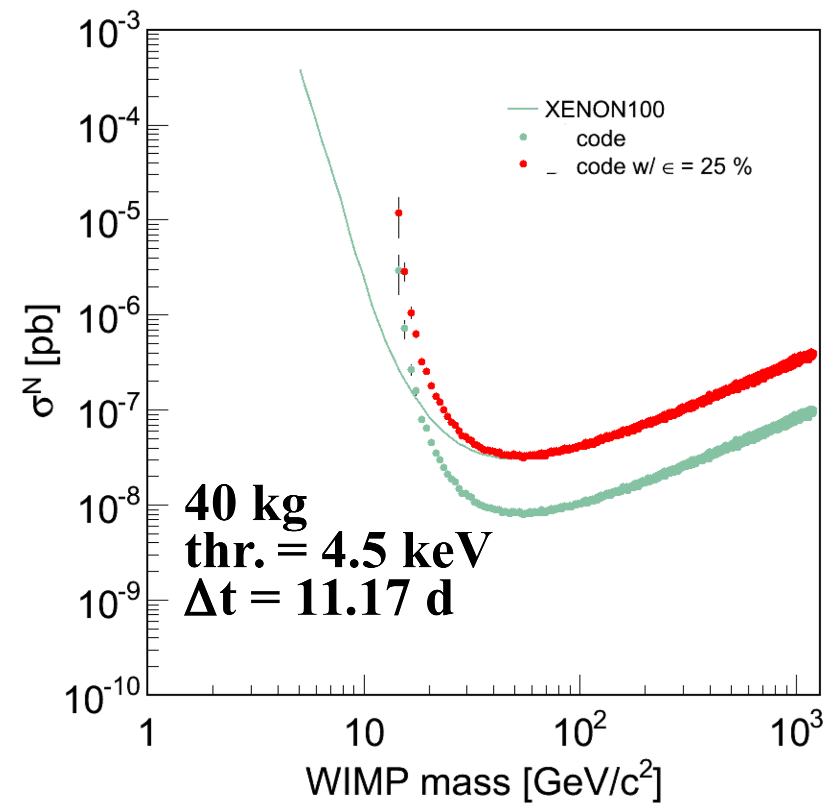
- SRIM simulation and quenching factor

Code validation

- Code tested by putting the input parameters corresponding to DMTPC and XENON100
- Detection efficiency approximated by a constant value



Quenching factor determined from SRIM

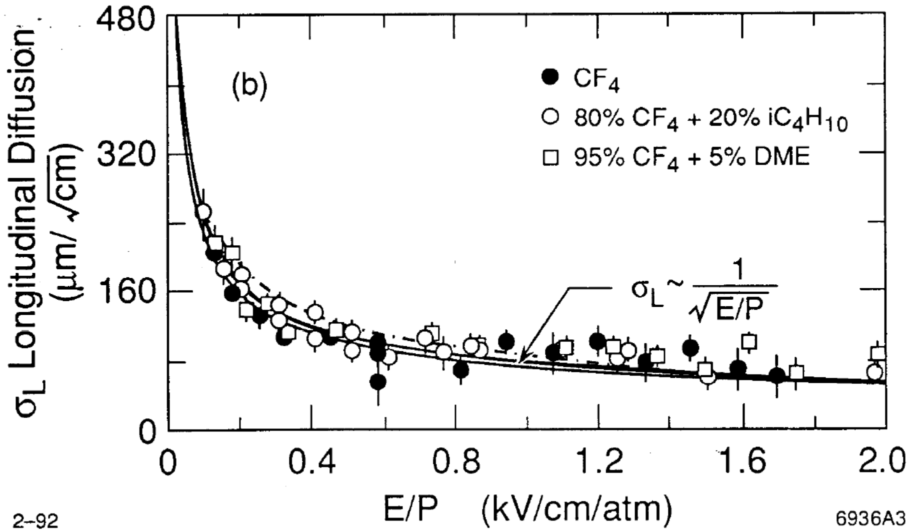


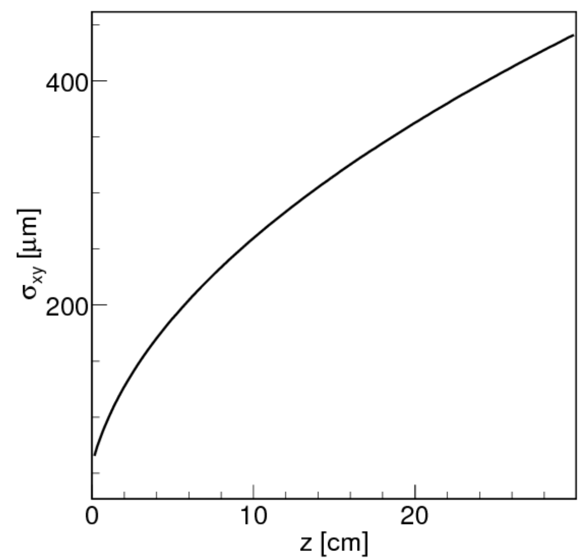
Constant quenching factor 25 %

Design optimization

- 1 m^3 divided into 3 detectors of drift length of 33.33 cm
- other key ingredients
  - energy threshold 1 keV
  - spacing between GEM holes 0.140 mm
  - pad size 0.2 mm
  - transverse diffusion

$$\frac{C_D}{\sqrt{N_{eff}}} = 80\ \mu m/\sqrt{cm}$$





$$\sigma_{xy} = \sqrt{\left(\frac{pad}{\sqrt{12}}\right)^2 + \frac{C_D^2}{N_{eff}} z}$$

- pad: pad size
- C_D transversal diffusion constant
- N_{eff} effective number of primary electrons

S. Biagi, Nucl. Instr. & Meth. A283 (1989) 716.
S. Biagi, Nucl. Instr. & Meth. A310 (1991) 133.
J. Va'vra, P. Coyle, J. Kadyk, and J. Wise, SLAC-PUB-5728 (1992).

Design optimization

- 1 m^3 divided into 3 detectors of drift length of 33.33 cm
- other key ingredients
  - energy threshold 1 keV
  - spacing between GEM holes 0.140 mm
  - pad size 0.2 mm
- transverse diffusion

$$\sigma_{xy} = \frac{1}{\sqrt{P}} f\left(\frac{E}{P}\right)$$

- by changing only the pressure

S. Biagi, Nucl. Instr. & Meth. A283 (1989) 716.
S. Biagi, Nucl. Instr. & Meth. A310 (1991) 133.
J. Va'vra, P. Coyle, J. Kadyk, and J. Wise, SLAC-PUB-5728 (1992).

Pressure optimization

- **1 m^3 of CF_4 divided into 3 detectors of drift length of 33.33 cm**

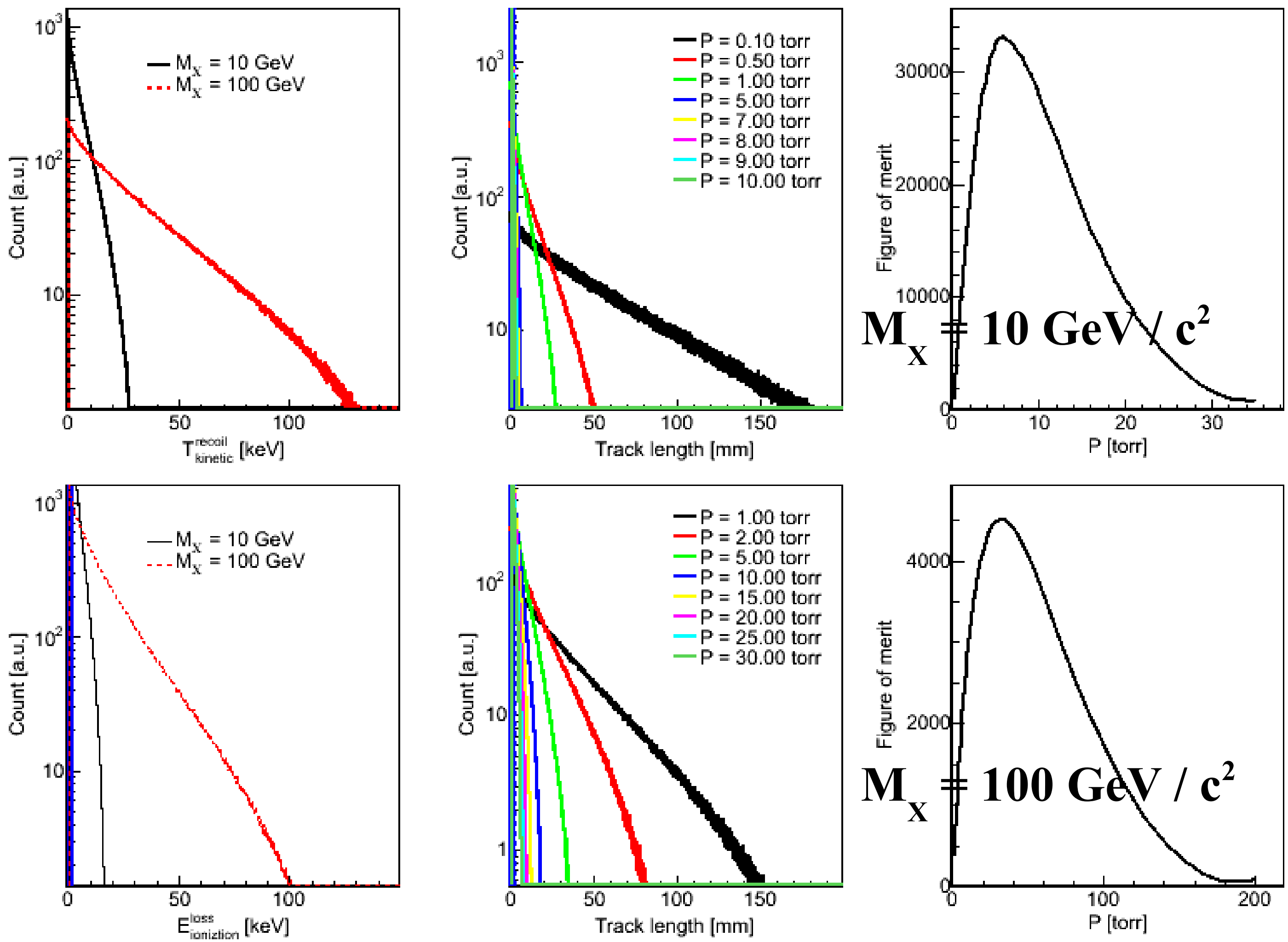
- **other key ingredients**
  - **energy threshold 1 keV**
  - **3 GEM holes covered L > 0.7 mm**
  - **L / σ > 3**

- **figure of merit calculated for two WIMP masses 10 GeV / c^2 and 100 GeV / c^2**

Pressure optimization

- **figure of merit for SI**

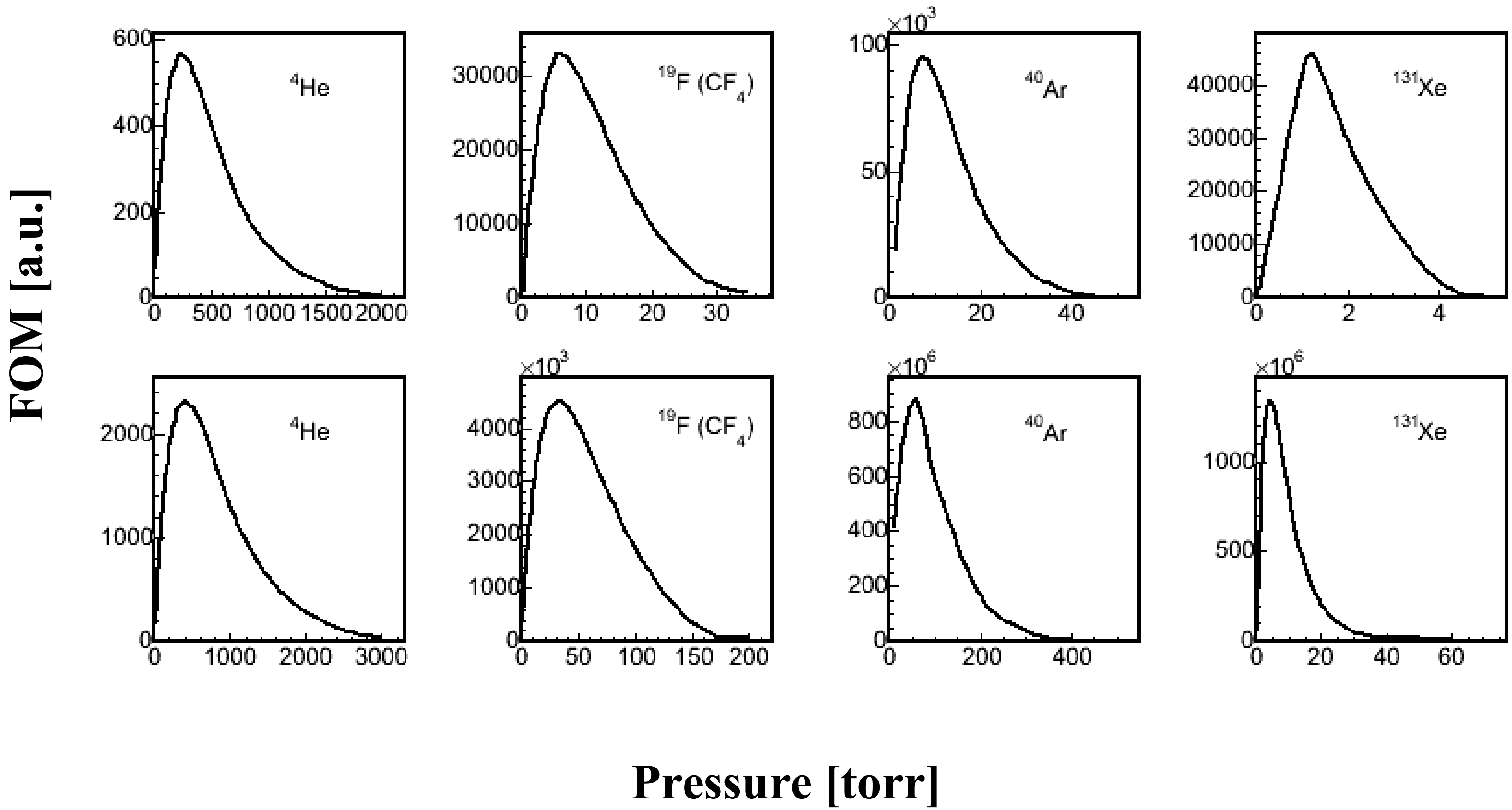
$$\frac{d\,FOM(P)}{dT_R} = \frac{\mu_A^2}{\mu_N^2}\cdot\rho(P)\,V\cdot A^2\cdot\frac{d}{dT_R}F^2(qr_n)\cdot\int_0^z \frac{L(T_R,P)\text{ above thres}}{L(T_R,P)}\,dz$$



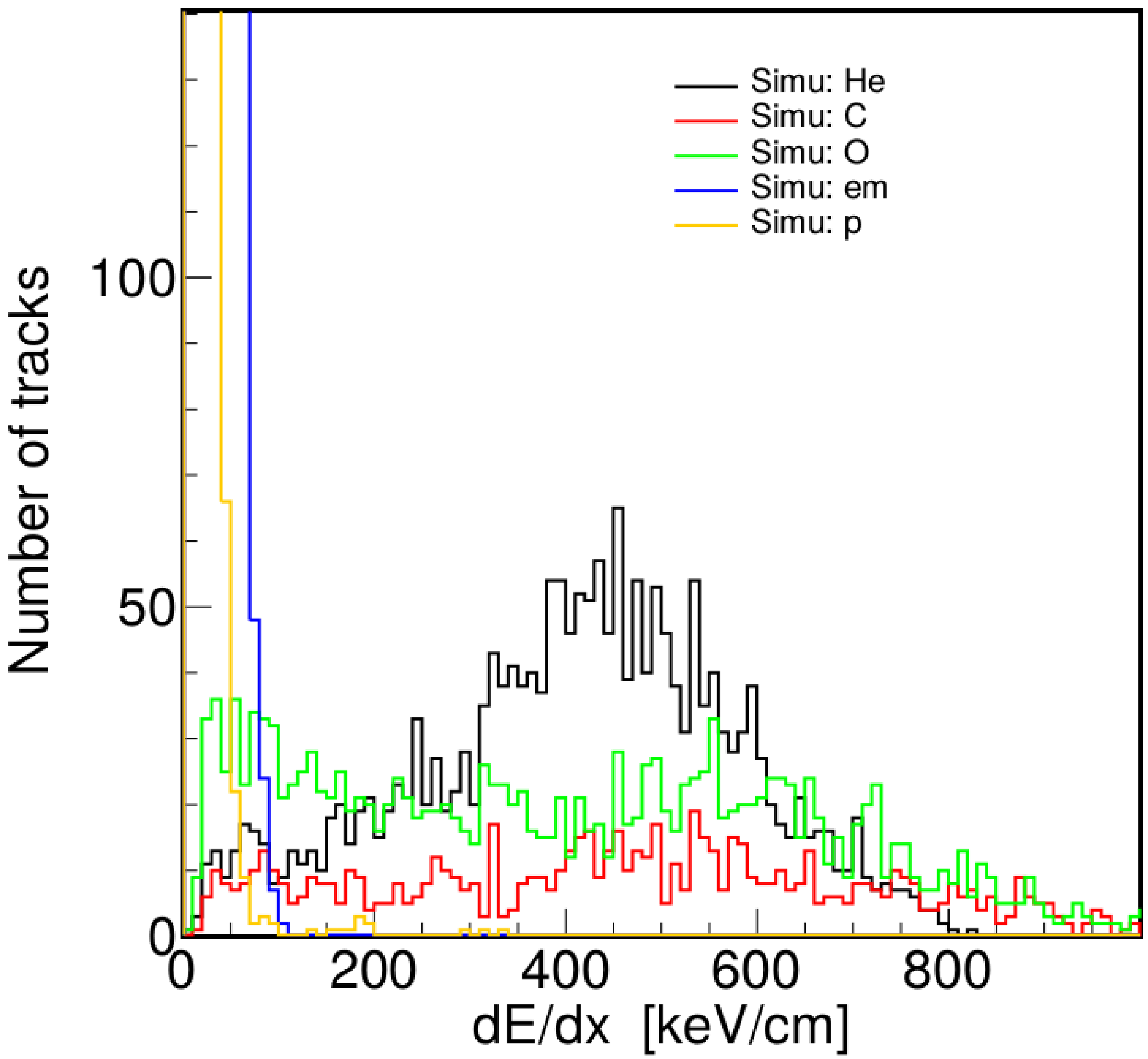
Pressure optimization

- **figure of merit for SI**

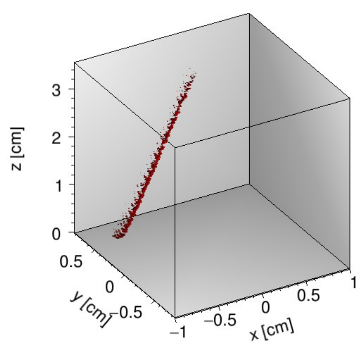
$$\frac{d\,FOM(P)}{dT_R} = \frac{\mu_A^2}{\mu_N^2}\cdot \rho(P)\,V\cdot A^2\cdot\frac{d}{dT_R}F^2(qr_n)\cdot\int_0^z \frac{L(T_R,P)\text{ above thres}}{L(T_R,P)}\,dz$$

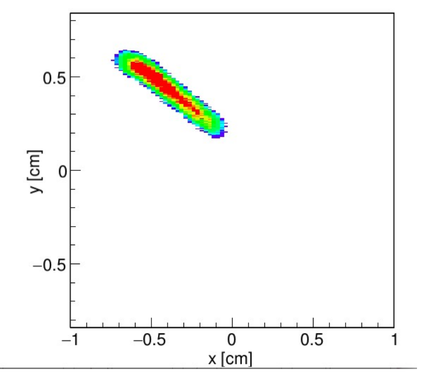


Beam-induced background



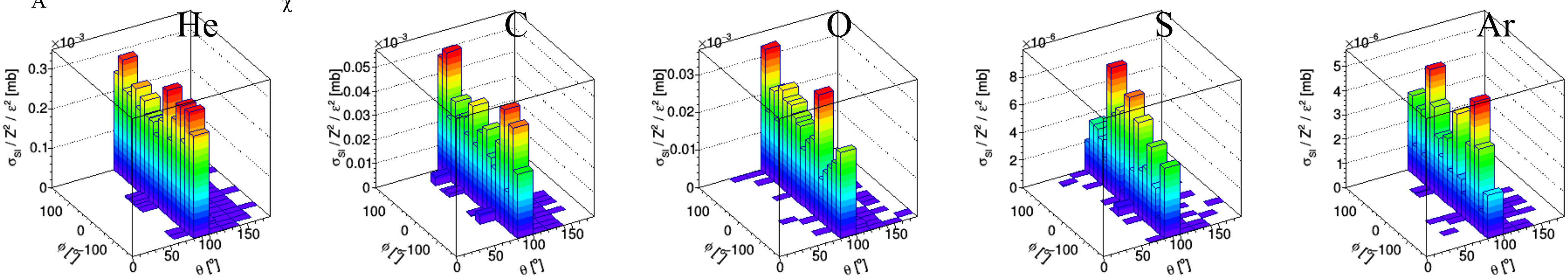
- dE/dx selection criteria can remove all non recoil gas-nucleus hit
- Most hit detected in the TPC are back-scattering ie not pointing to the beam direction but to the cave
- Only neutron can produce recoil gas-nucleus
- Neutron background should be produced mostly by natural radiation according to Geant4



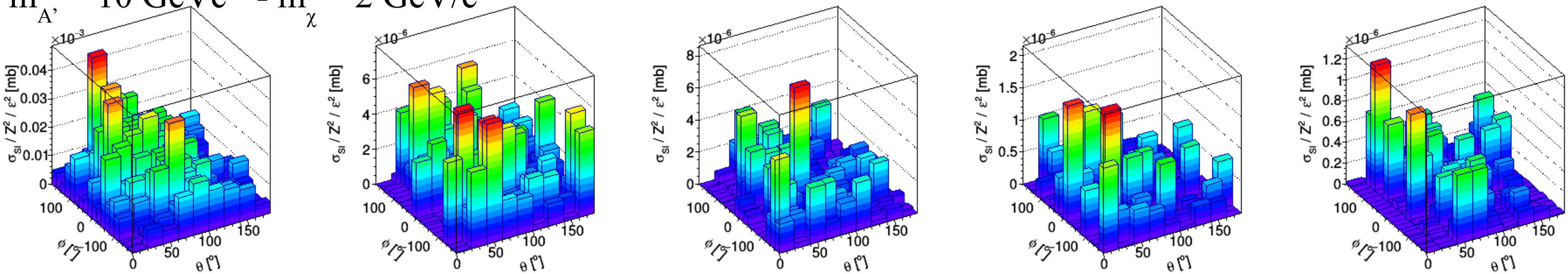


Beam-induced light dark matter scattering distributions

$m_{A'} = 4$ GeVc^2 - $m_\chi = 2$ GeV/c^2



$m_{A'} = 10$ GeVc^2 - $m_\chi = 2$ GeV/c^2



When 2 x LDM mass ~ dark photon mass, there is a clear scattering pattern

Beam-induced light dark matter scattering distributions

$m_{A'} = 4$ GeVc^2 - $m_{\chi} = 2$ GeV/c^2

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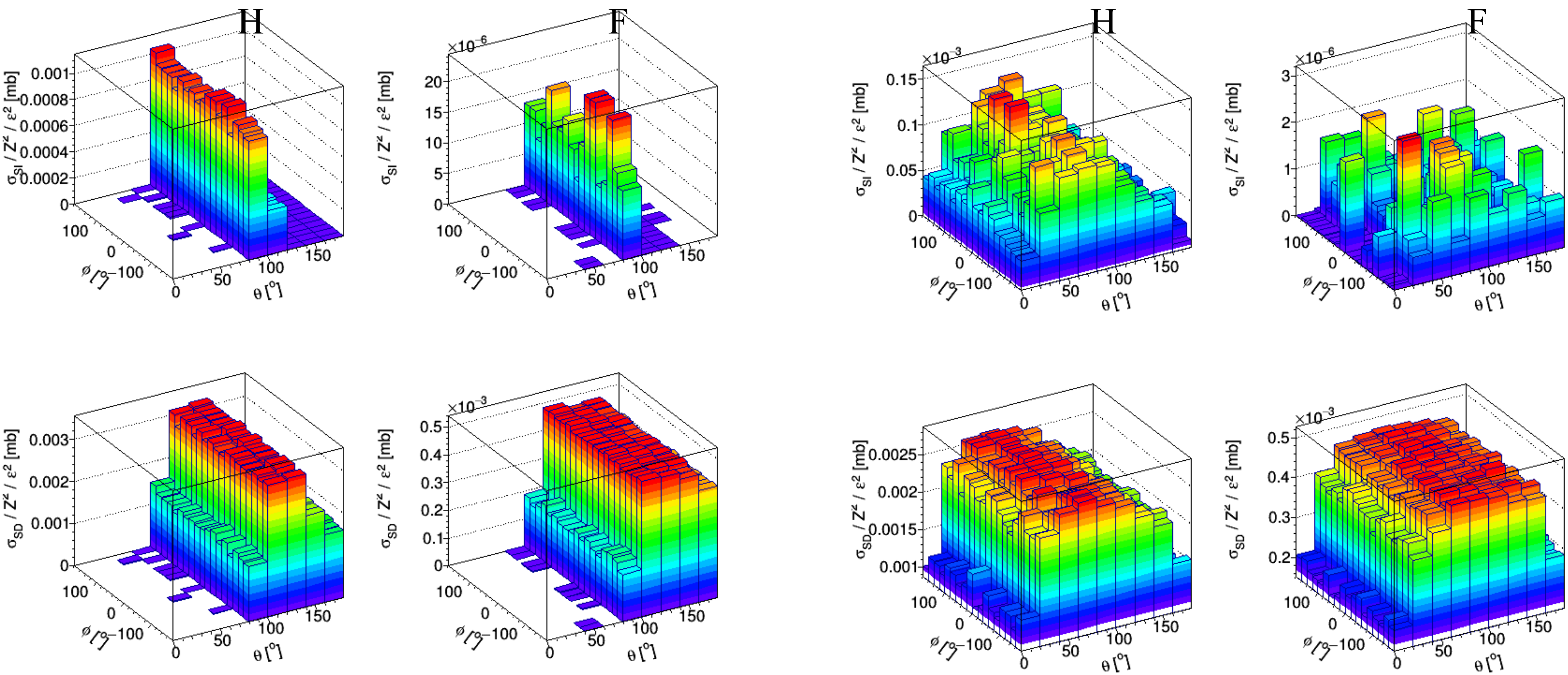
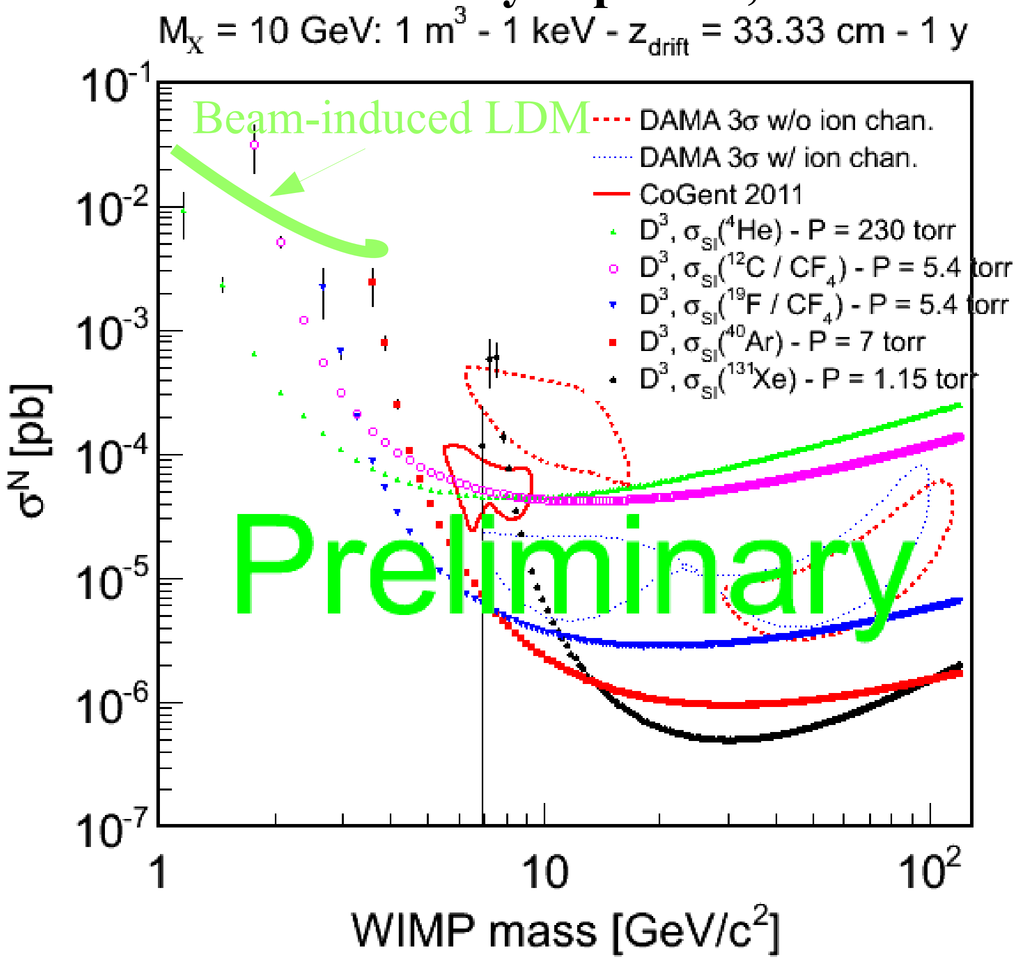
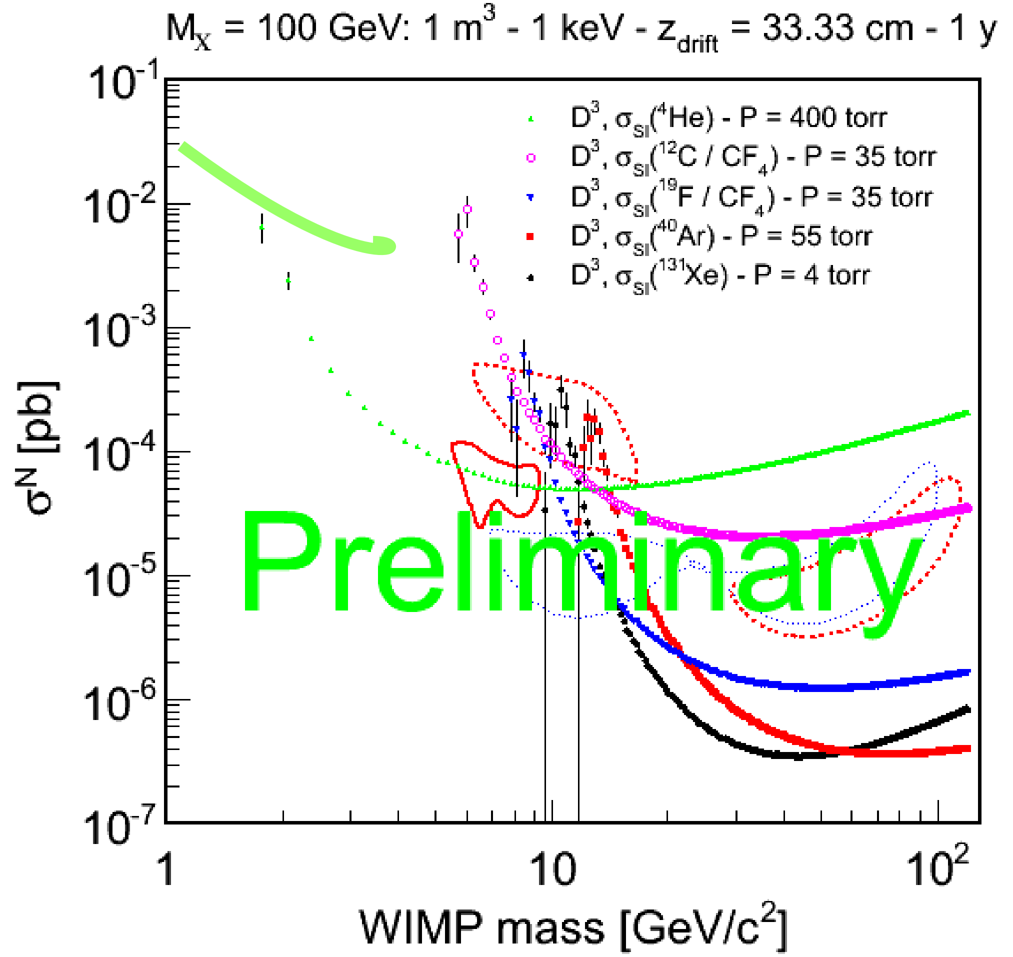


With Hydrogen scattering pattern is more pronouced

Reach plot

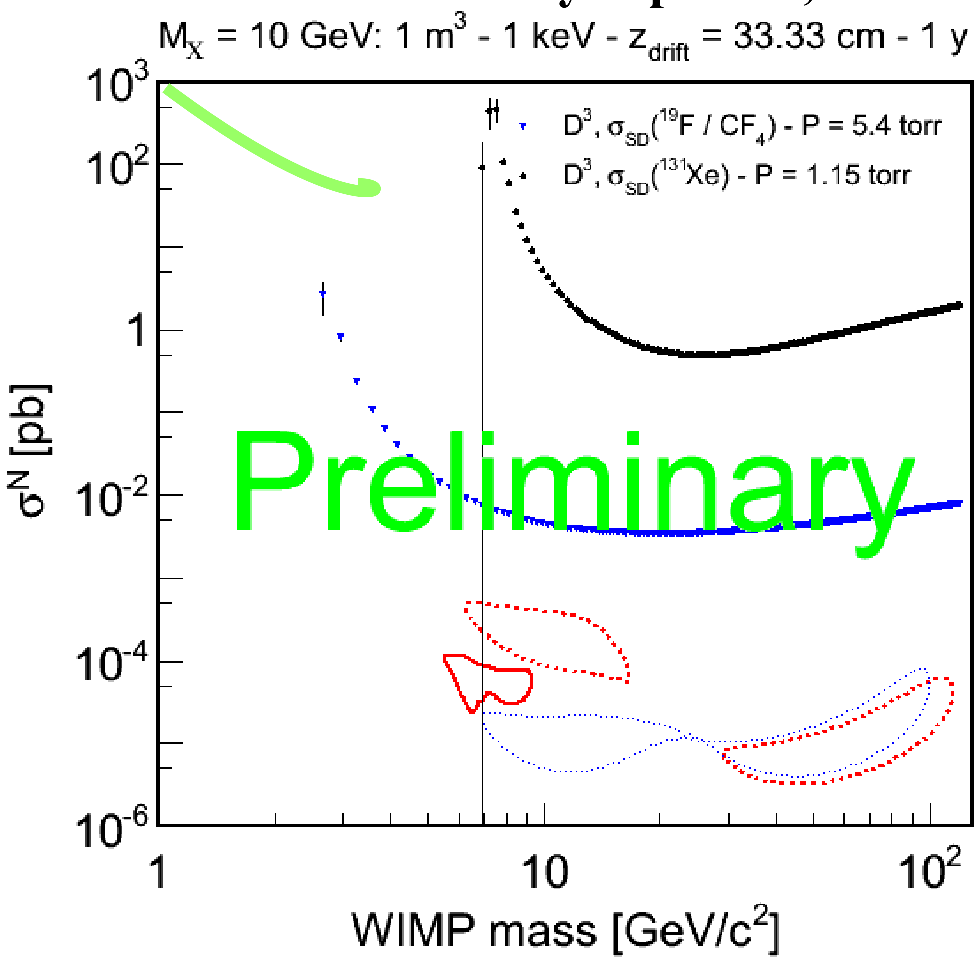
- **SI case**
- **By lowering the pressure the directional sensitivity increases for low mass WIMP/LDM beam-induced LDM 1y exposure, 150keV thres.**

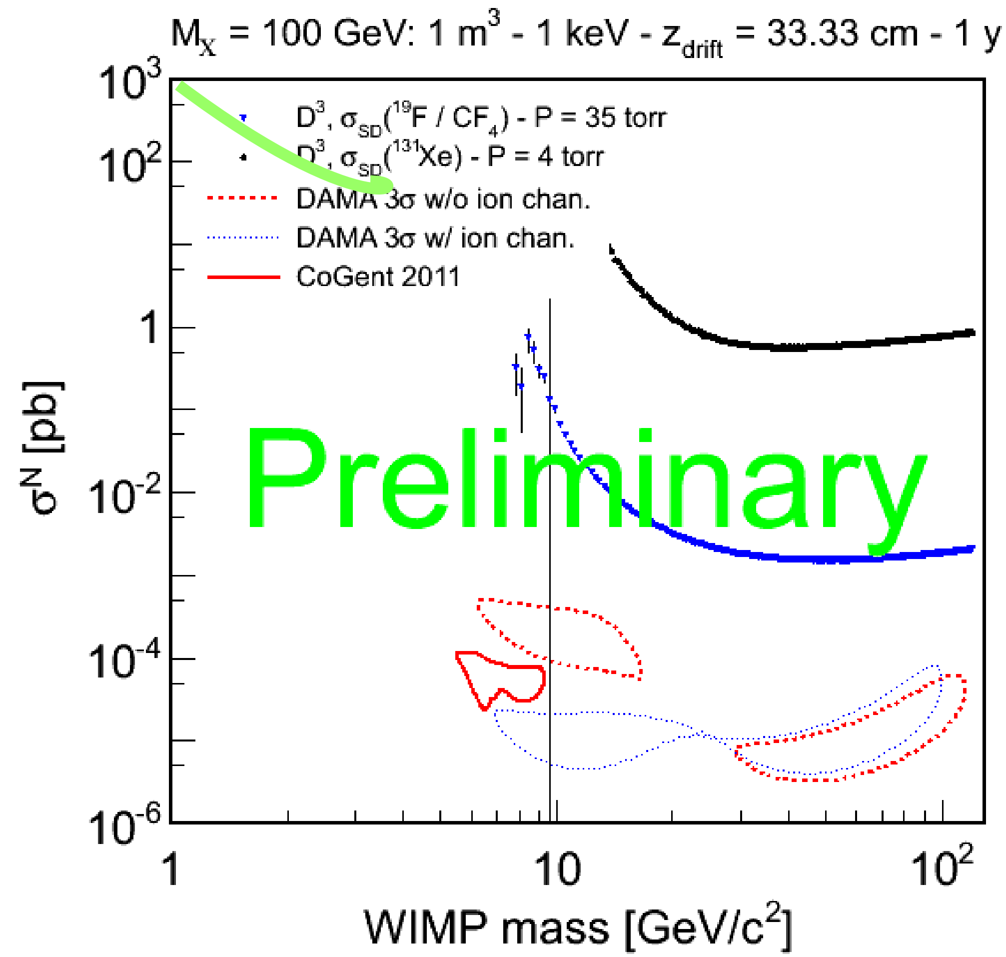




Reach plot

- **SD case**
- **By lowering the pressure the directional sensitivity increases for low mass WIMP/LDM beam-induced LDM 1y exposure, 150keV thres.**





Conclusion

- Beam-induced light dark matter flux much smaller than WIMP flux

- Beam-induced light dark matter much faster than WIMP

- A directional detector (TPC) might have a high separation power between signal and background

- If LDM mass is around 50% of the dark photon mass, there is a clear scattering pattern, pattern more pronounce if target is Hydrogen

- Preliminary design optimization of directional TPC
  - By lowering the pressure the directional sensitivity increases for low mass WIMP/LDM
  - Room for improvements

Thanks for your attention

Neutron interaction with matter depend on the neutron kinetic energy

- elastic scattering from nuclei: n+A->n+A => dominant in the MeV region
- inelastic scattering: n+A->n'+A*, A* excited state of the nucleus A*-> A + γ

=> > 1 MeV neutron enough to excite the nucleus

=> hydrogen has no excited state

- radiative neutron capture: n+(Z,A) $\rightarrow$ γ+(Z,A+1)

=> since $\sigma \sim 1 / v$, the neutron is most likely absorbed when it is slow

- other nuclear reactions: (n,p),(n,d),(n,α) etc …

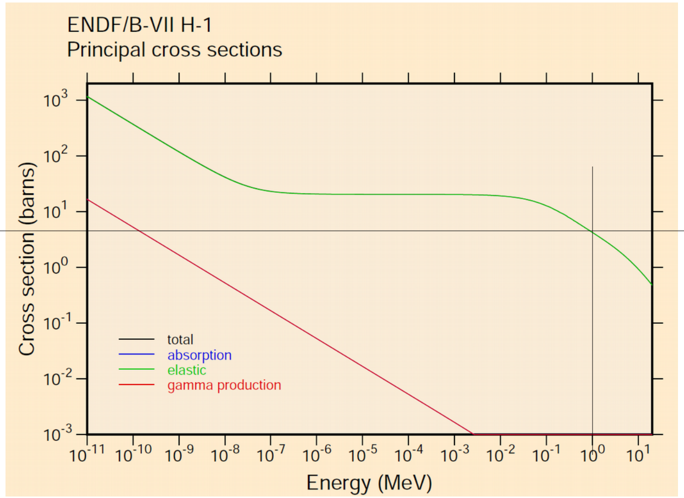
=> the neutron is captured and charged particles are emitted

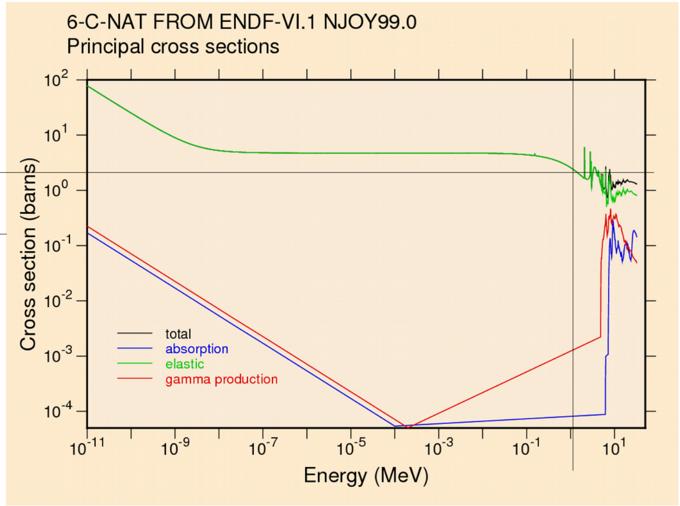
=> $\sigma \sim 1 / v$ i.e. eV to keV

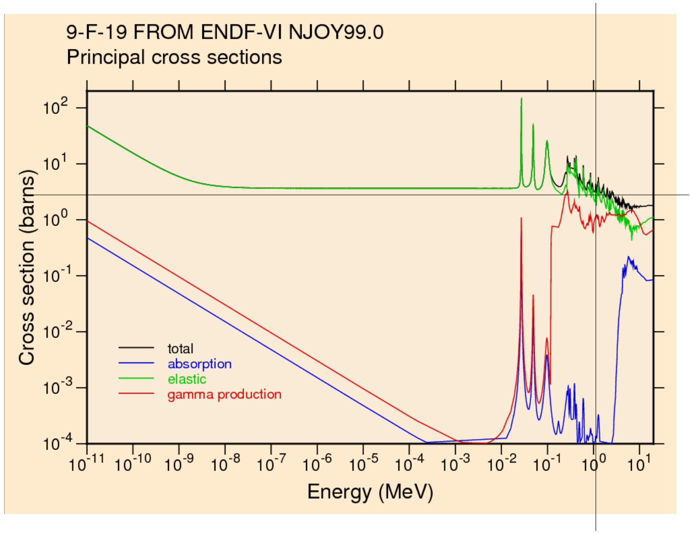
- fission => thermal energies below eV
- high energy hadron shower > 100 MeV

H, C and F cross sections

- generated by ACE-MCNP using ENDF/B-VI Cross Section Library 2006







ENDF/B-VI Cross Section Library 2006 combined

- measured cross section (by Time-of-Flight technique)
- calculation from N-body physics

- elastic scattering is the dominant process (> 95 %) in all 3 cross sections

- σ(H at 1 MeV) ~ 4.5 b
- σ(C at 1 MeV) ~ 2 b
- σ(F at 1 MeV) ~ 3.2 b