MonteCarlo simulations for dark-matter search experiments at accelerators: the Beam Dump Experiment - BDX - case

A. Celentano

INFN - Genova

Outline

- **Introduction: light dark matter search at beam-dump experiments**
  - **Physics case**
  - **MC tools: scope and requirements**

- Event generator for the signal
  - Computation strategy
  - Software implementation
    - DM production: MadGraph/MadEvent
    - DM interaction
    - Detector response: GEMC

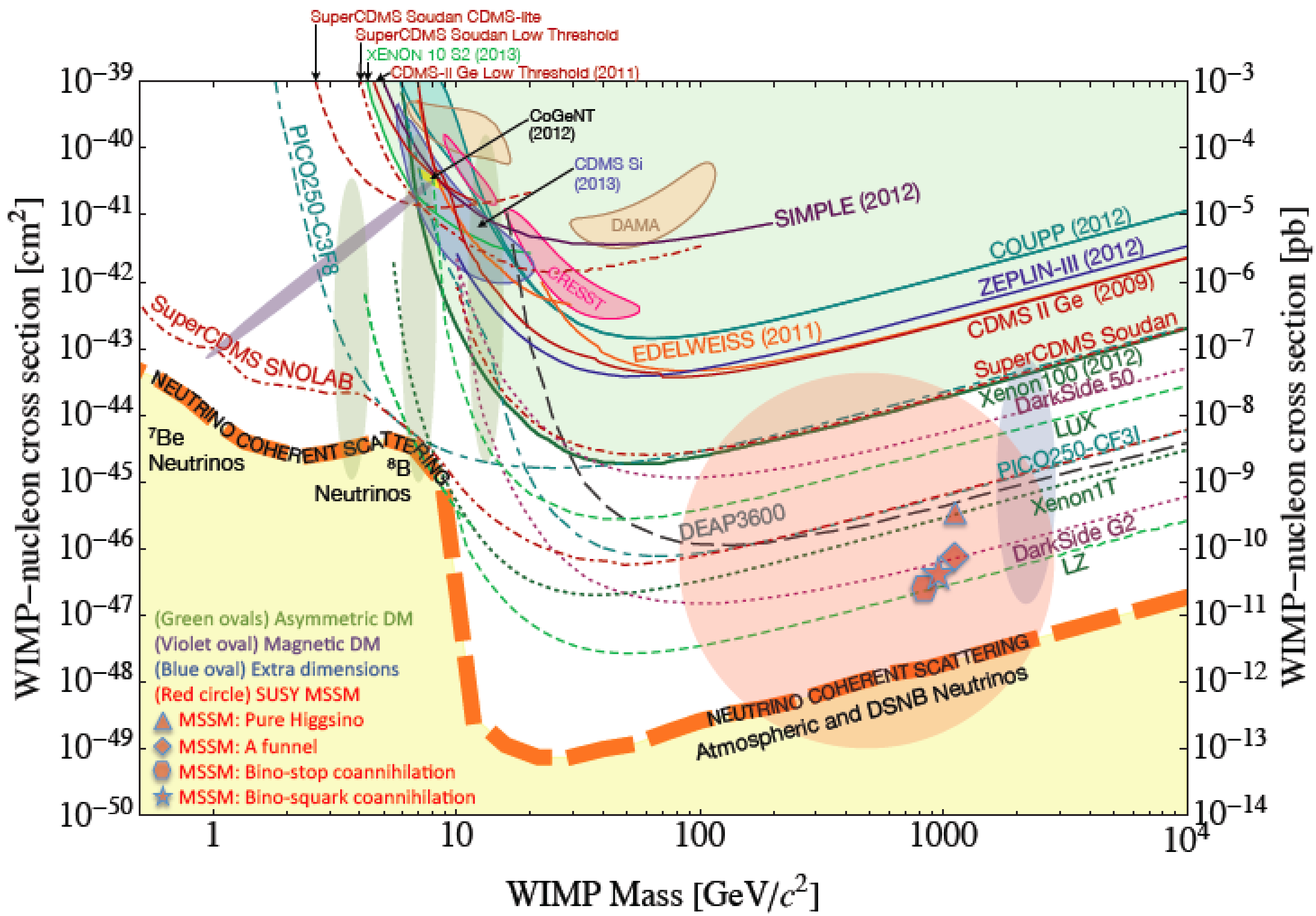
- Event generator for the beam-related background
  - Requirements-computational issues
  - Brute-force approach
  - MCNP approach

How to search for new physics beyond the SM

Dark matter (DM) direct search mainly focused in the mass region 10 GeV -10 TeV

- **WIMP:** weakly interacting massive particles with weak scale mass provides the correct DM relic abundance

- No signals seen yet



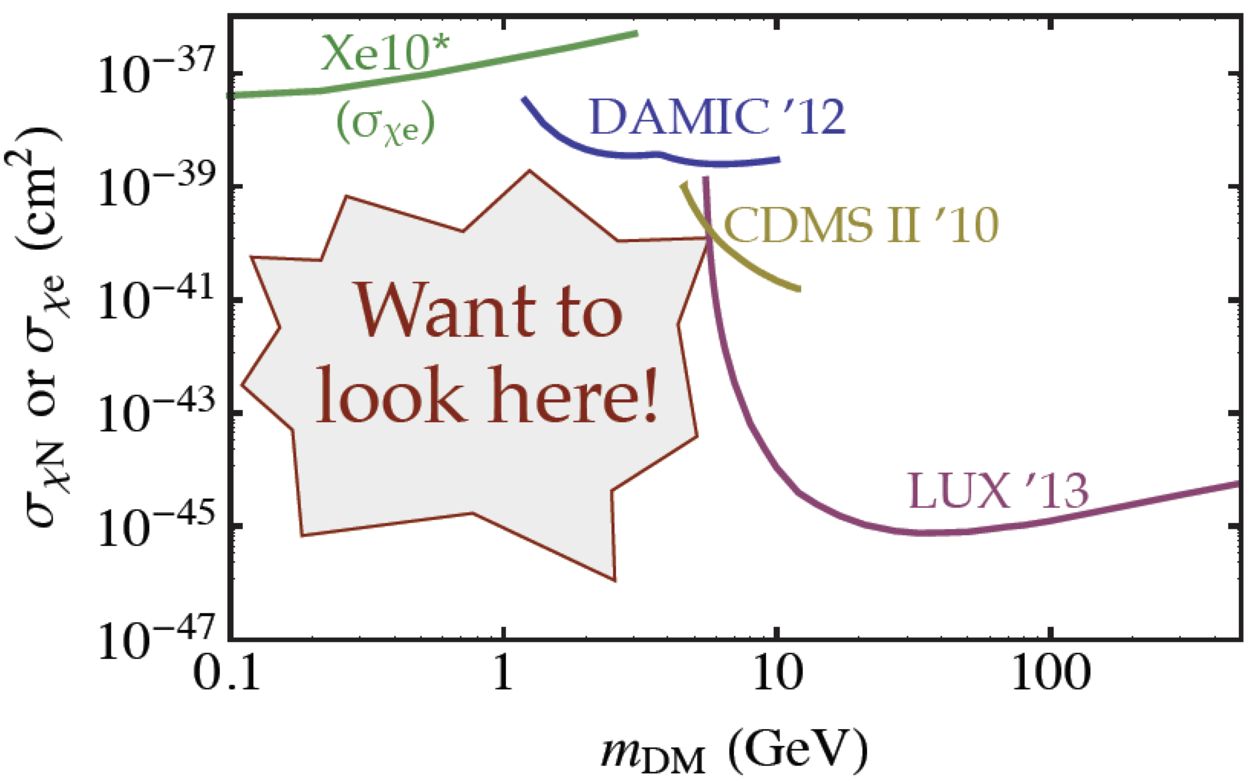
DM detection by measuring the (heavy) nucleus recoil of slow moving cosmological DM
→ no experimental sensitivity to light DM (<1 GeV)

How to search for new physics beyond the SM

Accelerators-based DM search is covering a similar mass region but can extend the reach outside the classical DM hunting territory

Many theoretical suggestions and experimental attempts to extend the search region to:

• **Higher mass (> 10 TeV):** LHC, Rare decays, …



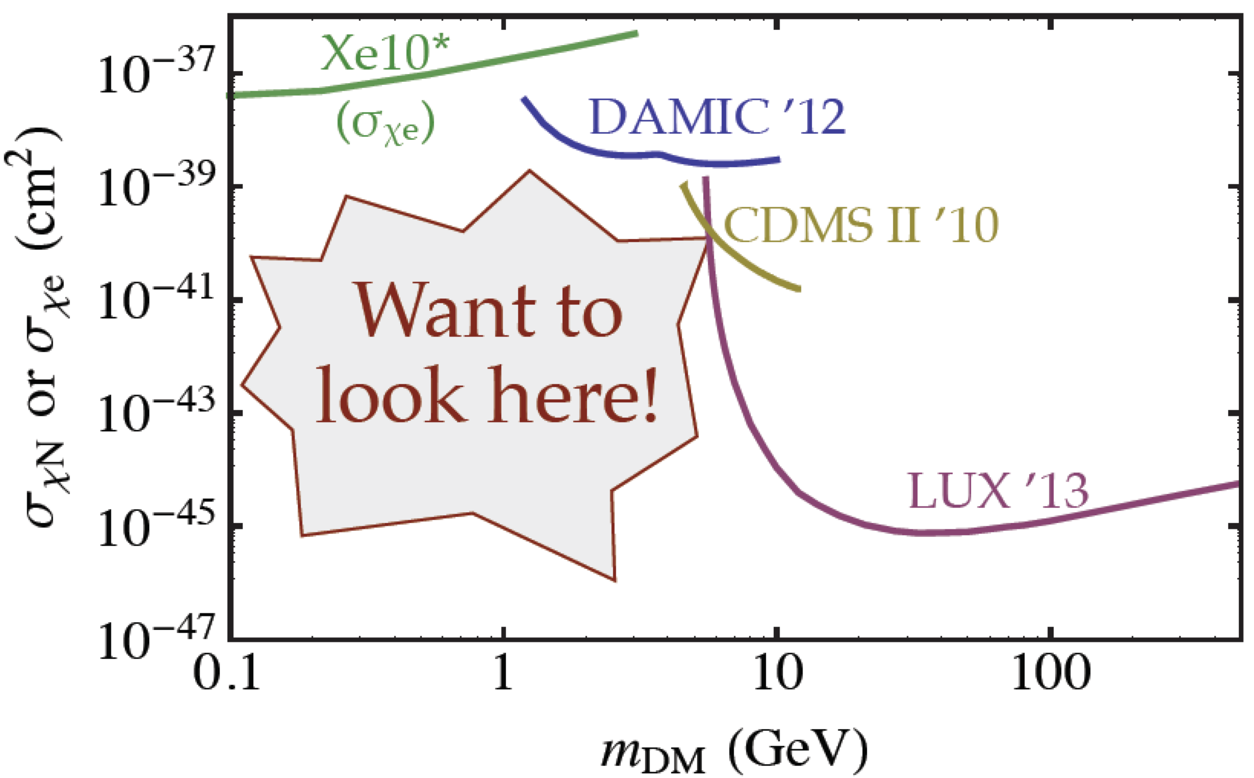
How to search for new physics beyond the SM

Accelerators-based DM search is covering a similar mass region but can extend the reach outside the classical DM hunting territory

Many theoretical suggestions and experimental attempts to extend the search region to:

• **Higher mass (> 10 TeV):**
LHC, Rare decays, …

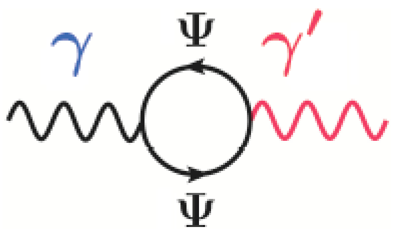
• **Lower Mass (<10 GeV)**
MiniBoone@FNAL, SPS@CERN, PADME@LNF, **BDX@JLab**



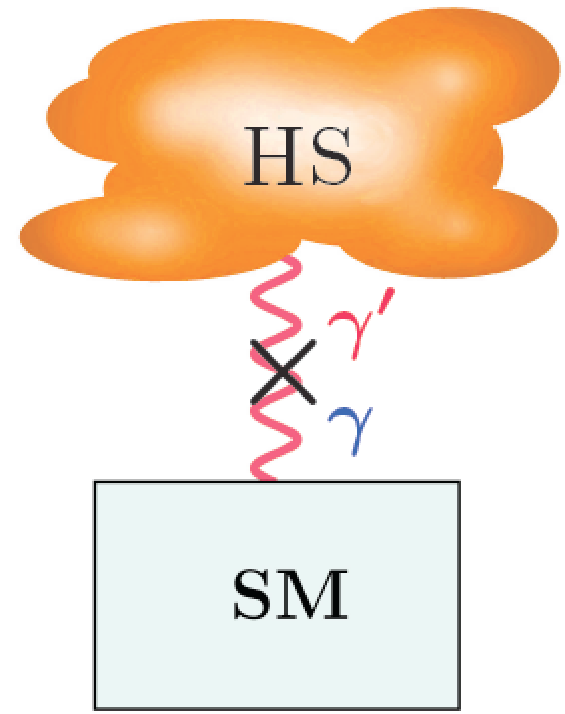
Main topic of this talk

Light dark matter model: dark photon portal

- Consider an additional U(1) hidden symmetry in nature: this leads to a kinetic mixing between the photon and the new gauge boson A'



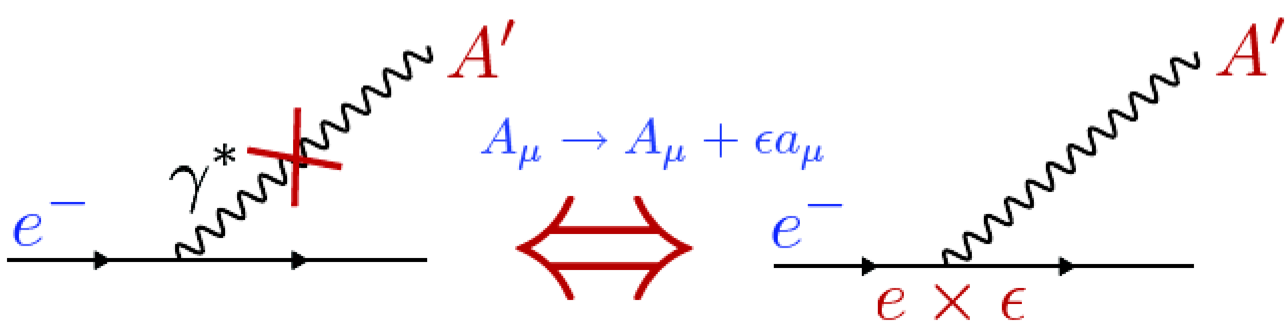
Ψ is a huge mass scale particle (M~1EeV) coupling to both SM and HS



- General hypothesis to incorporate new physics in the SM: the A' acts as a “portal” between the SM and the new sector

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m_A^2 A'^{\mu} A'_{\mu}$$

- Under A' interaction, ordinary charged matter acquires a new charge **εe:**



New interaction term:

$$\varepsilon A'_{\mu} J^{\mu}_{EM}$$

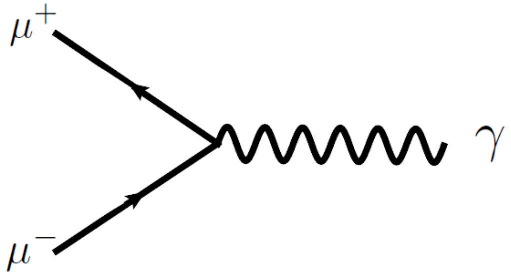
[Holdom, Phys. Lett. B166, 1986]

Hints for A' existence: muon anomalous magnetic moment

- Magnetic dipole moment of charged particle: $\vec{\mu} = g_s \left(\frac{q}{2m}\right) \vec{s}$

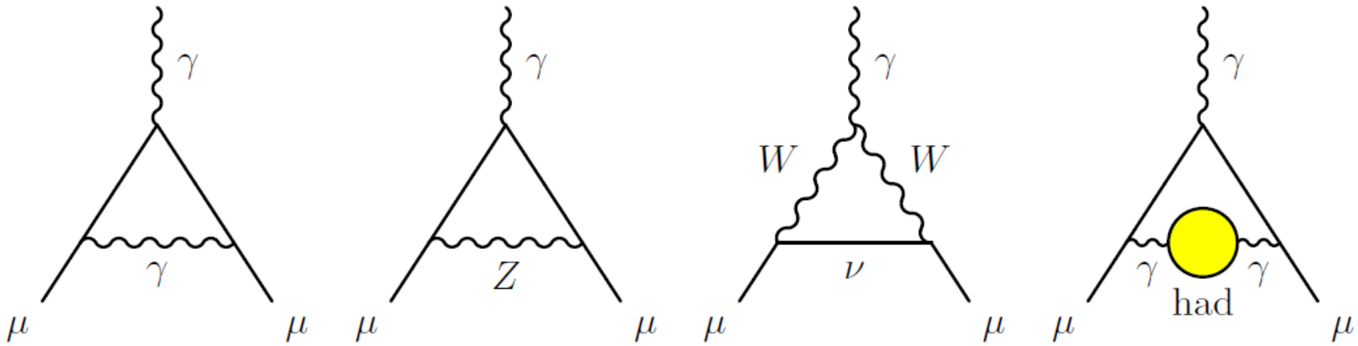
Can be measured very accurately

- SM tree-level prediction for a Dirac particle:



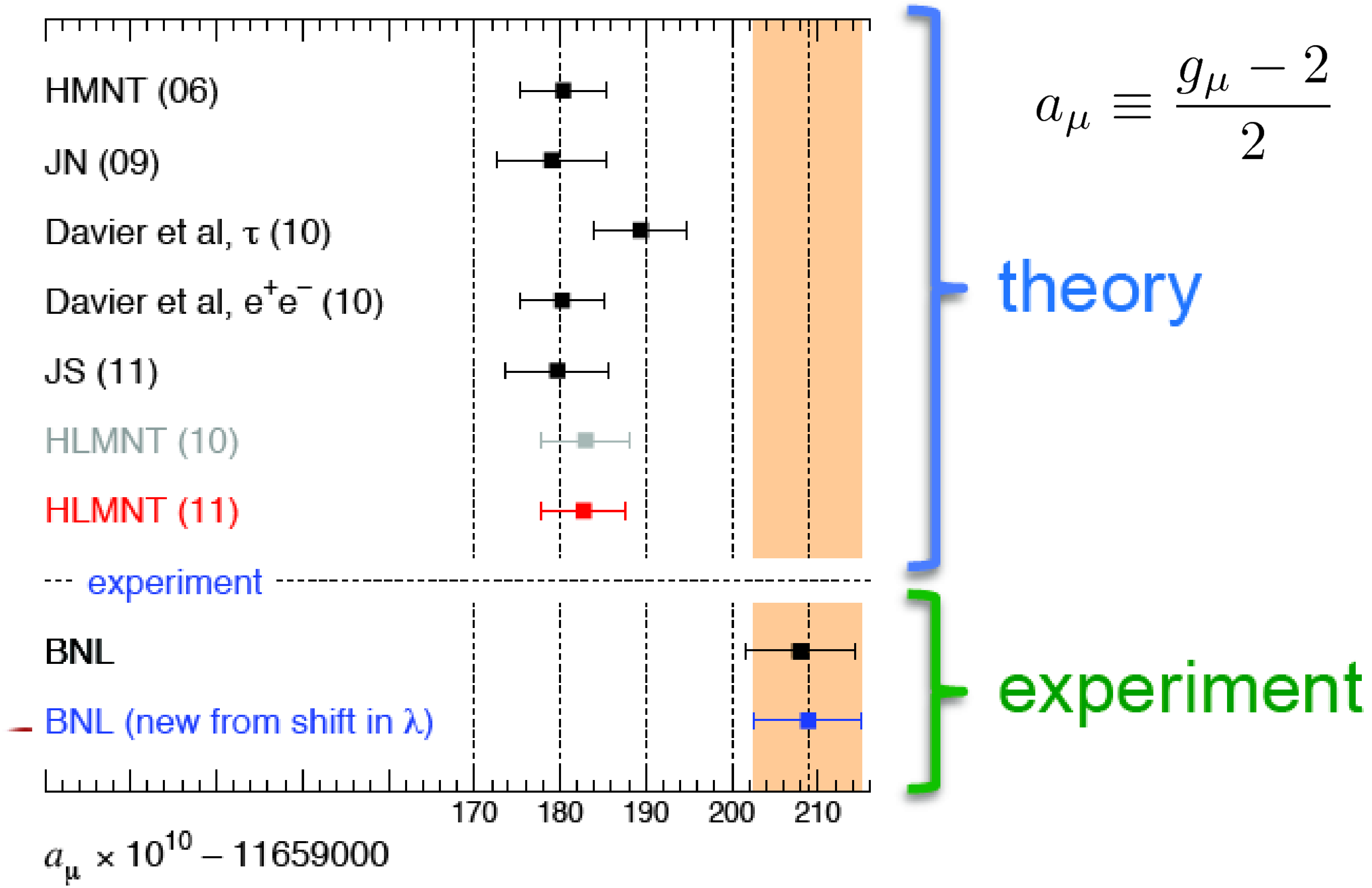
$$g_s = 2$$

- Higher-order contributions:



QED Weak Hadronic

Hints for A' existence: muon anomalous magnetic moment



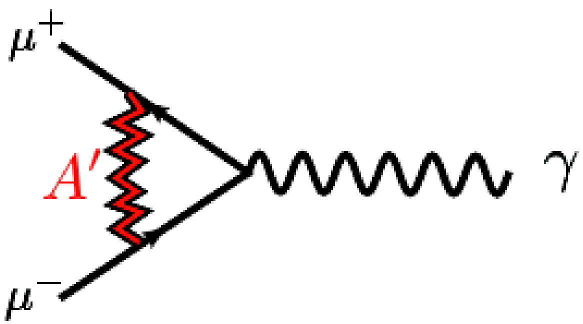
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

→ **~ 3 σ deviation experiment – SM prediction**

[Hagiwara et al; Bennet hep-ex/0602035]

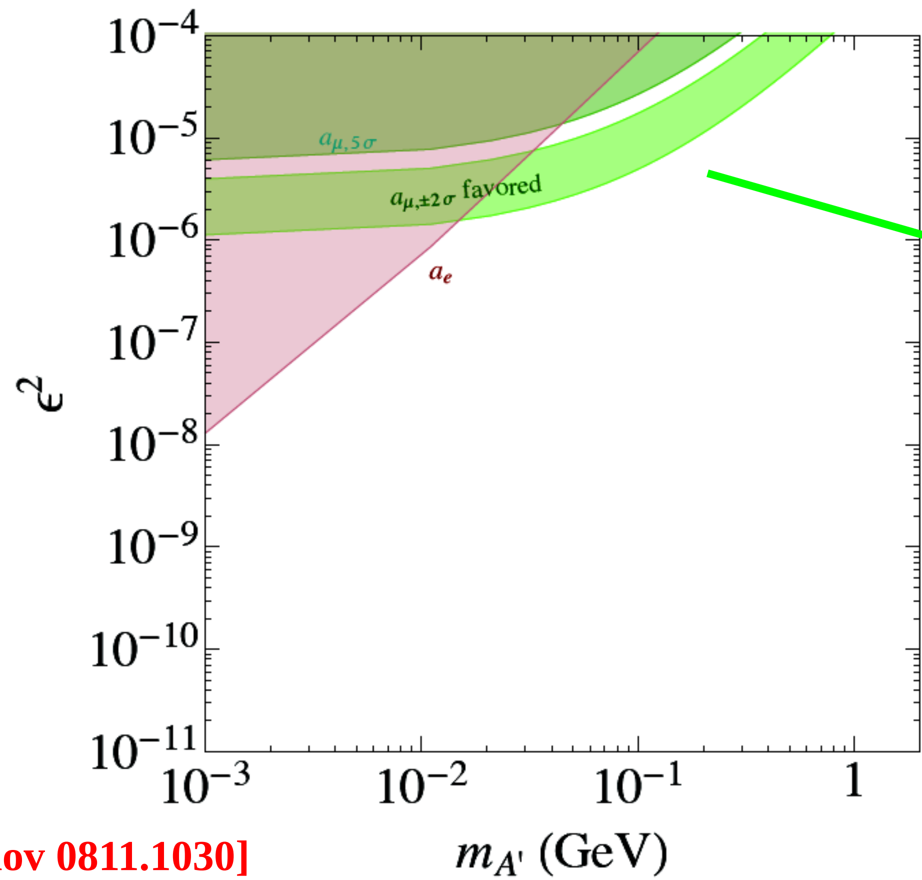
Hints for A' existence: muon anomalous magnetic moment

A dark photon with mass in the 10-100 MeV range could explain the anomaly



$$a_\mu = \frac{\alpha}{2\pi}\varepsilon^2 F(m_A/m_\mu)$$

$$F(x) = \int_0^1 dz\, 2z\,(1-z)^2/[(1-z)^2 + x^2 z]$$



A dark photon in this region may explain the observed discrepancy.

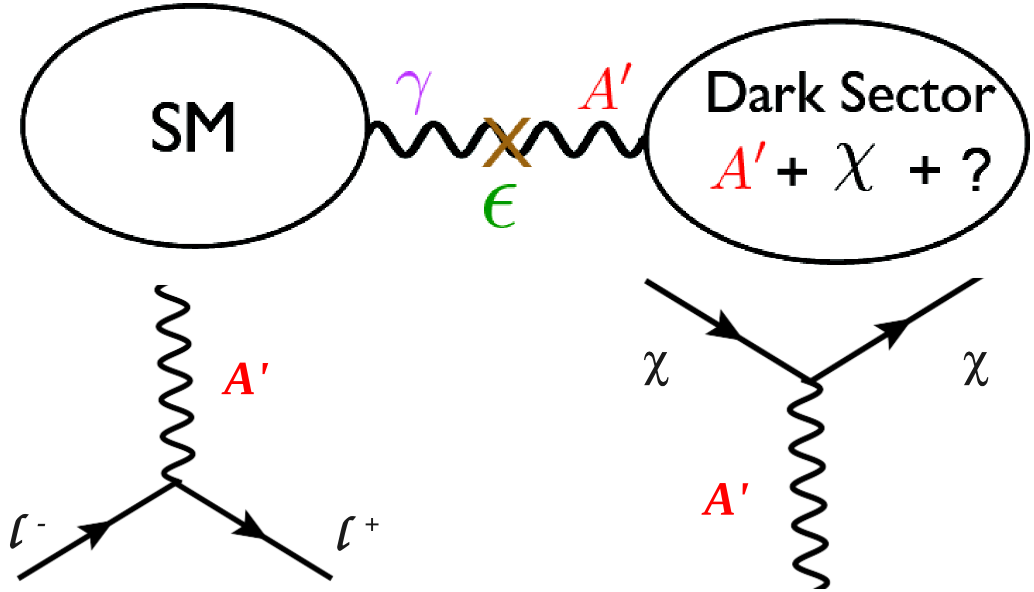
[Pospelov 0811.1030]

Dark photons and dark sector

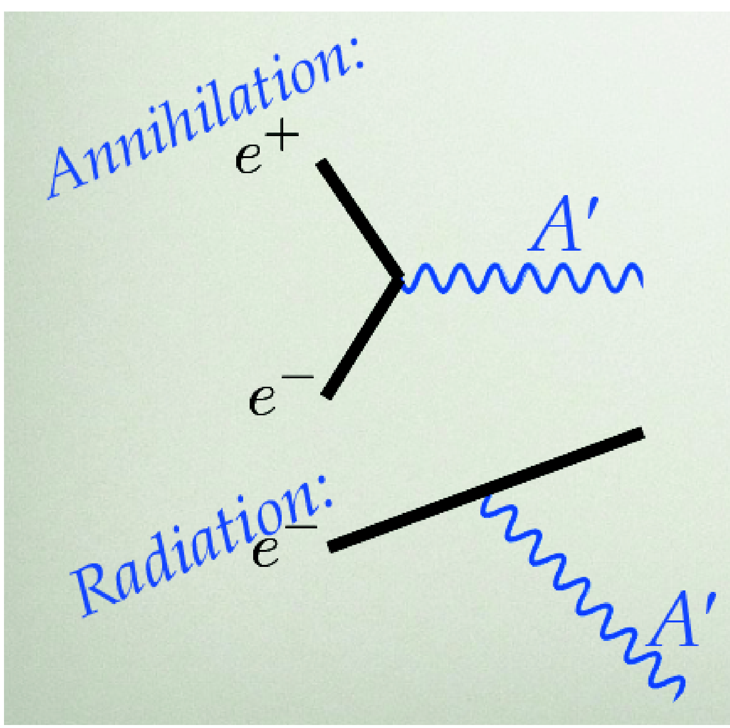
Minimal model:

- A' interacts with γ trough kinetic mixing
- Dark sector particle χ interacts with A'

4 parameters: $M_{A'},\ M_{\chi},\ \varepsilon,\ g_d$

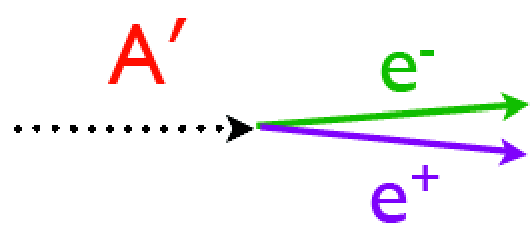


A' production: $\sigma \propto \varepsilon^2$



A' decay:

First scenario: only SM decays



- Minimal scenario
- $BR(A' \to SM) = 1$
- $\Gamma_{Tot} \propto \varepsilon^2$

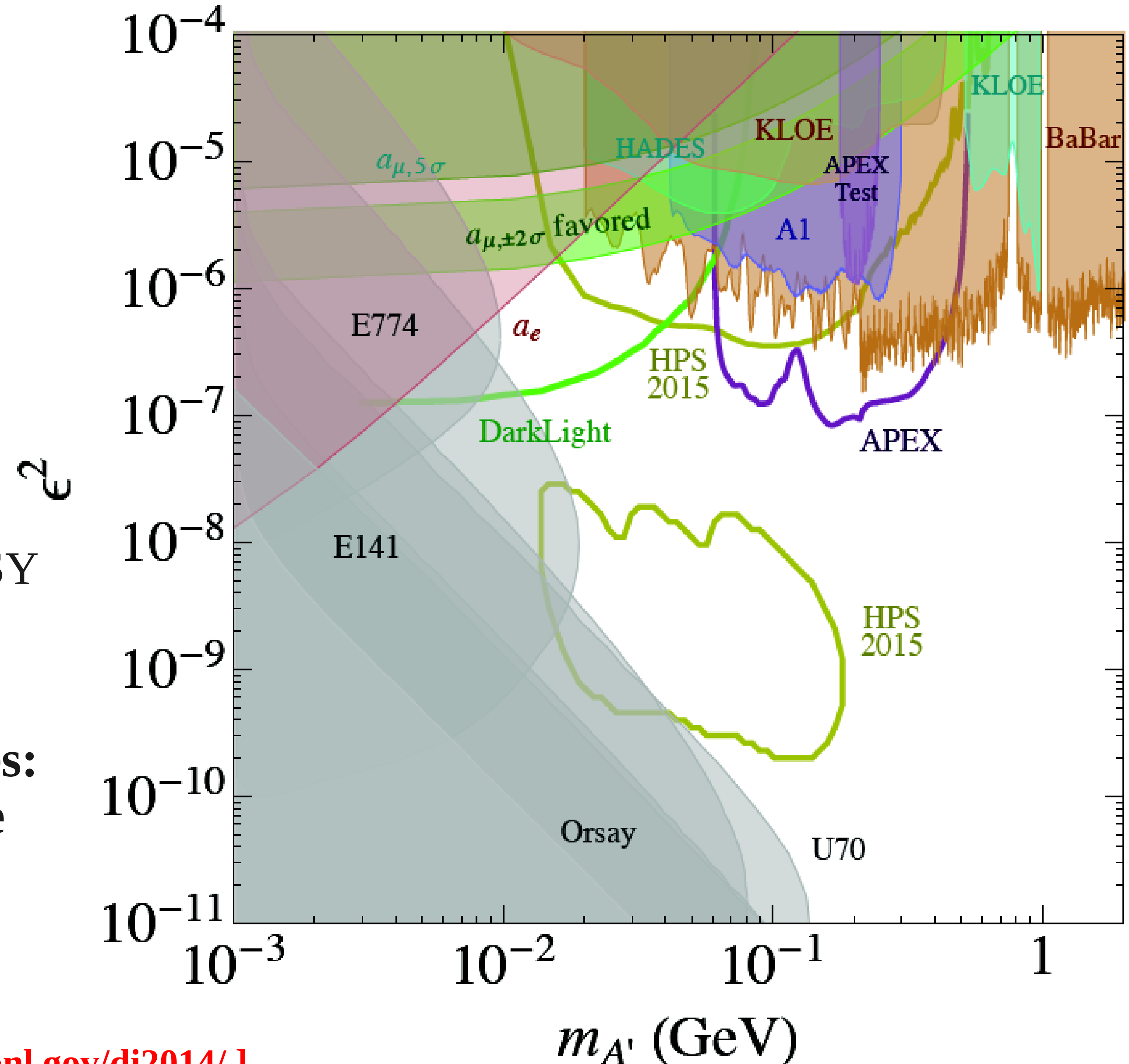
An extensive experimental effort is currently ongoing to search for visible dark-photon decays

Visible A′ decay: current searches and constrains

Any γ-rich environment is suitable for A' searches.

- Fixed target with e⁻ beam
  - JLab, Mainz
- Fixed target with p beam
  - Fermilab
- Annihilation
  - BABAR, BELLE, KLOE
- Meson decay
  - KLOE, BES-3, WASA-COSY

So far, no positive A' evidences: limits in the parameters space



[For a complete review, see: http://www.bnl.gov/di2014/]

Dark photons and dark matter

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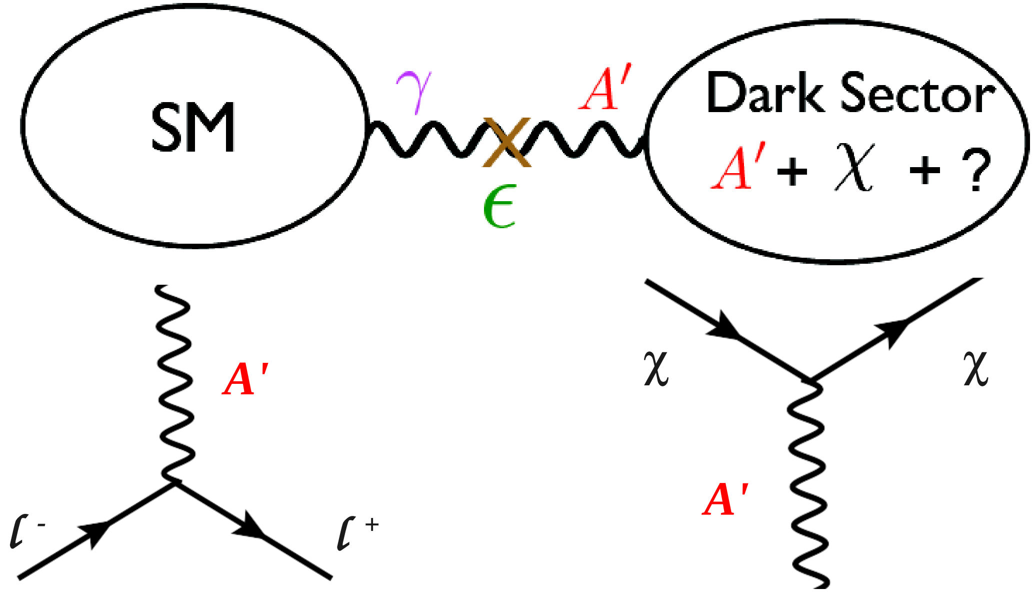

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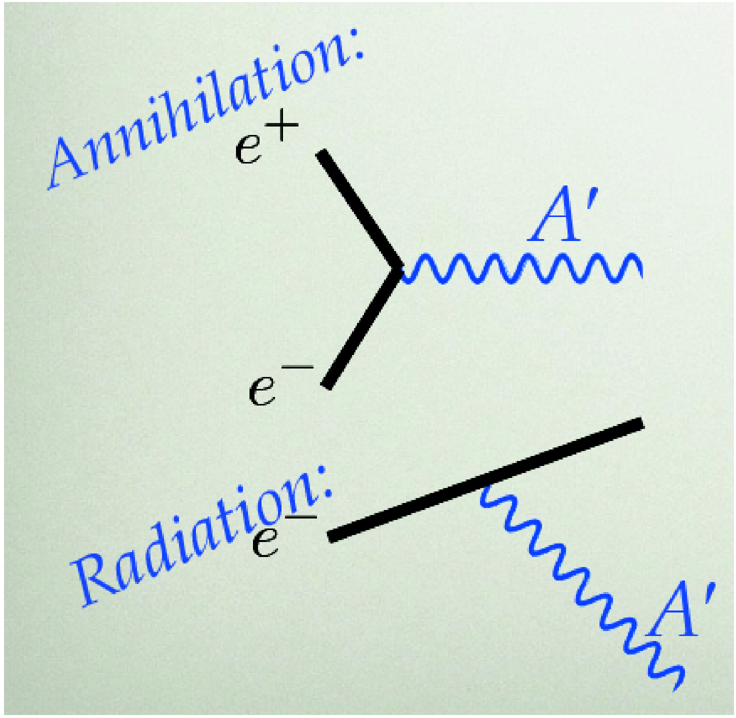
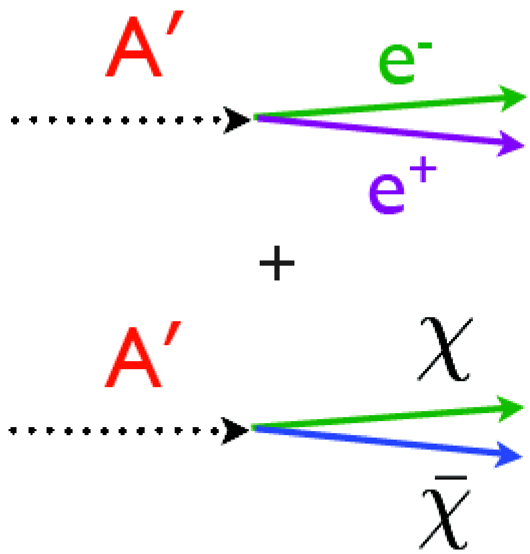


A' decay:

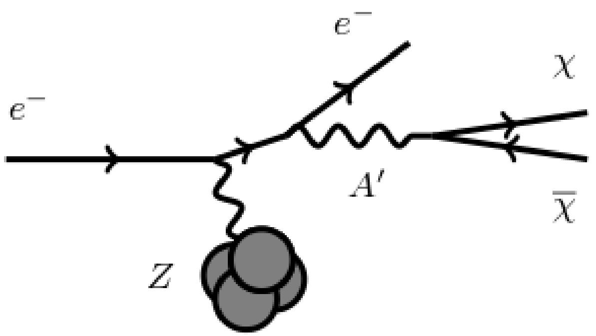
Second scenario: SM + hidden coupling



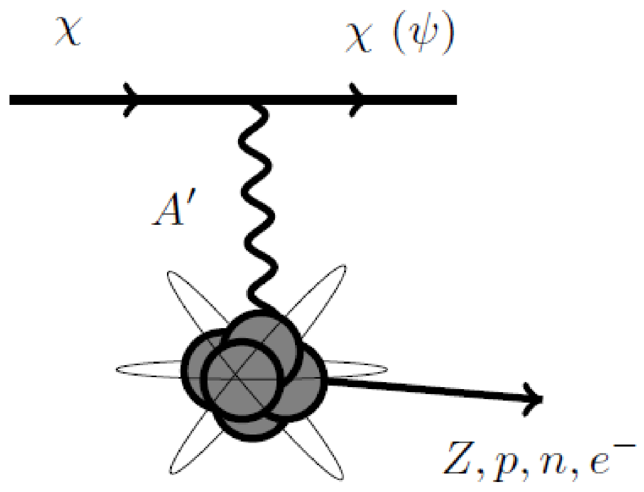
- $BR(A' \rightarrow SM) \propto \varepsilon^2$
- $\Gamma_{SM} \propto \varepsilon^2$
- $\Gamma_{\chi\chi} \simeq 1$

Beam dump experiments with e⁻ beam

How to access the A' invisible decay: direct detection in a two-step process.



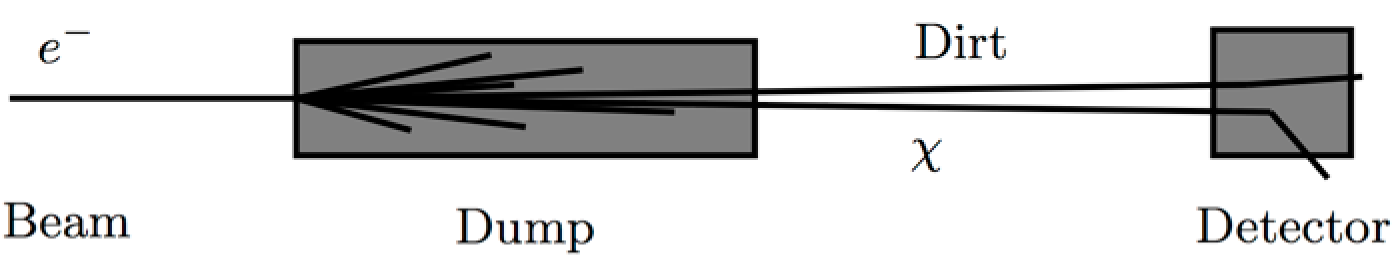
- **Fixed-target:** A' produced in the dump, decays promptly to invisible χ
- **Detector:** Neutral-current scattering of χ trough A' exchange, detect recoil. Different signals depending on the interaction (e⁻ scattering, coherent nuclear, quasi-elastic,..)



A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$



[arXiv:1307.6554]

Accelerator requirements

- **Beam current: critical.** The experimental sensitivity scales linearly with this parameter.

- **Beam energy:**

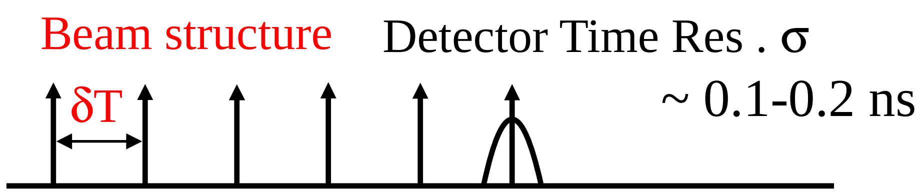
  - A' production and χ – matter interaction cross-sections increase smoothly with the beam energy.
  - At low energy ($E_0 \sim m_A$), there is a further signal enhancement with E_0 due to increased detector acceptance (χ beam more focused forward).

- **Beam structure:**

  - A pulsed beam permits to reject uncorrelated backgrounds by making a time coincidence between the beam RF signal and an hit in the detector

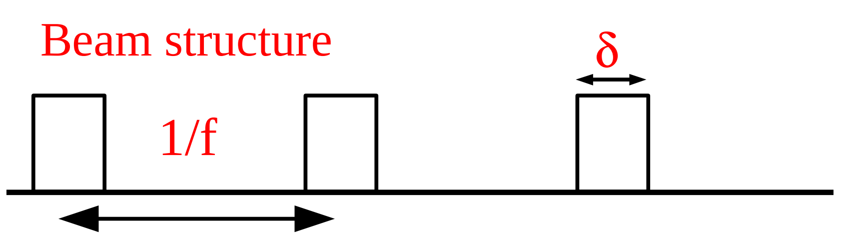
Continuous beam: detector time resolution is a mandatory requirement.

$$R \simeq \frac{\delta T}{3\sigma} <\simeq 100$$



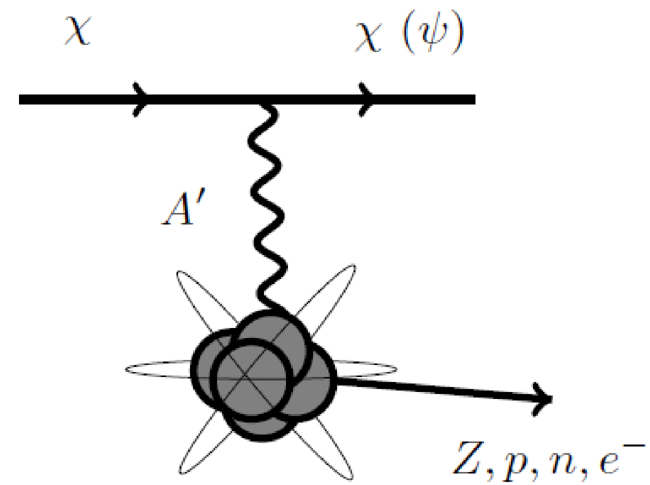
Pulsed beam: detector time resolution is not critical, if smaller than the bunch length.

$$R = \frac{1}{f \cdot \delta} = 2 \cdot 10^5 \ @ \ 50\,Hz, 100\,ns$$



χ - SM (detector) interaction

1) Quasi-elastic scattering on nucleons

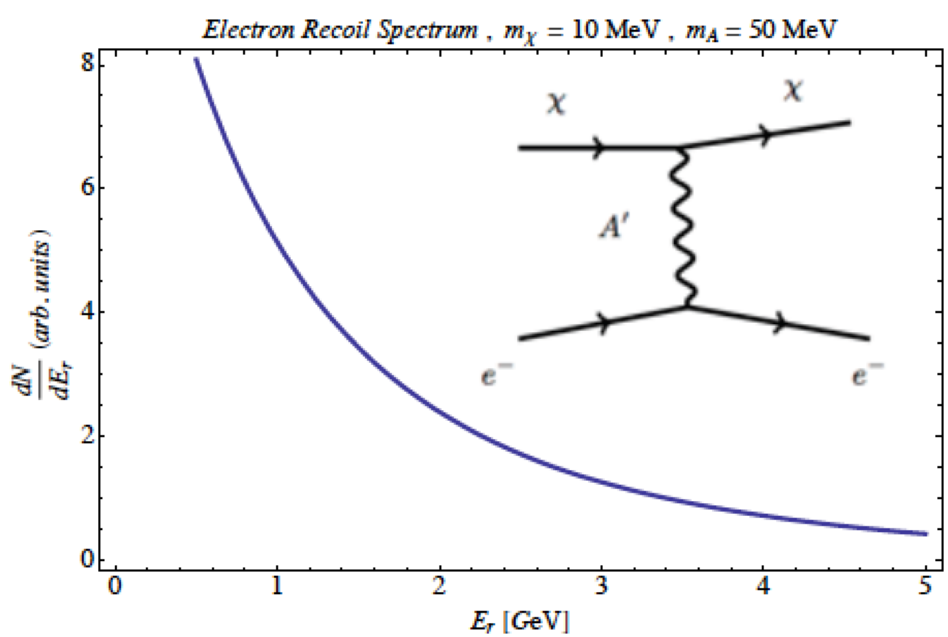


The χ scatters quasi-elastically on a bounded nucleon in the detector producing a visible recoil (~ MeV)

Experimental requirements:

- Sensitivity to ~ MeV nucleon recoil (low detection thresholds)
- Low energy backgrounds rejection capability

2) Elastic scattering on electrons



The χ scatters elastically on an electron in the detector producing a well visible recoil (~ GeV)

Experimental requirements:

- Sensitivity to ~GeV electrons (EM showers)

Detector design and requirements

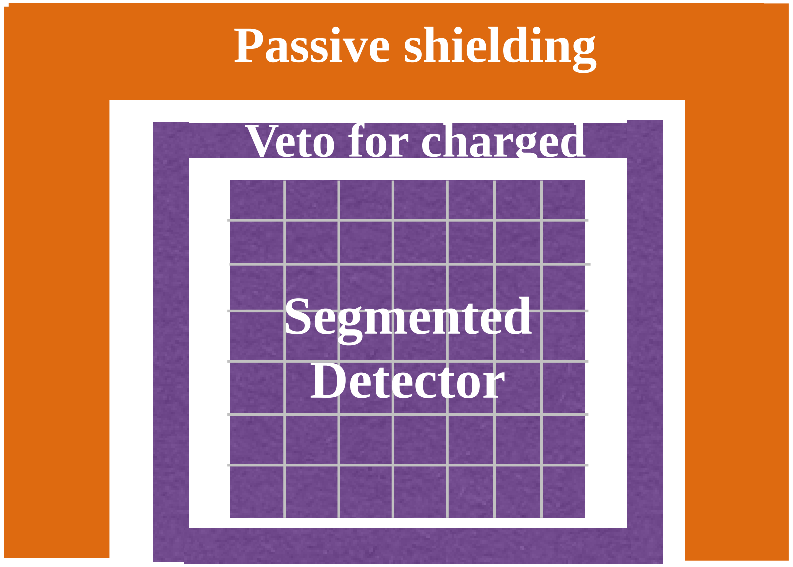
Signal detection:

- High density
- Low threshold for nucleon recoil detection (~ MeV)
- EM showers detection capability

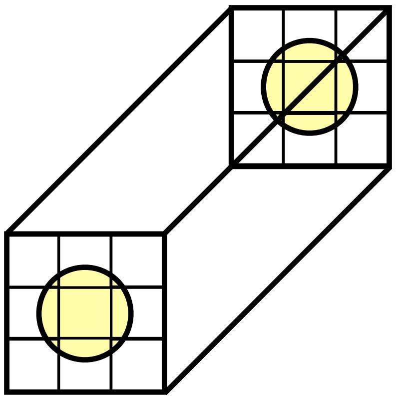
→ **Scintillation-based detector**

Background rejection / suppression:

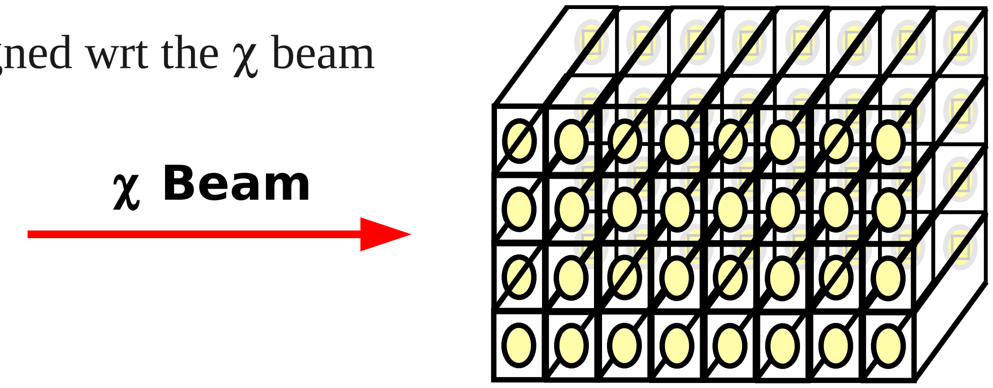
- Segmentation
- Active veto
- Passive shielding
- Good time resolution



Inner detector:



- Single optical module (possibly made of multiple opt. channels with single readout)
- Matrix of modules aligned wrt the χ beam



Backgrounds

Beam-related backgrounds:

1) Prompt backgrounds (γ/fast n):

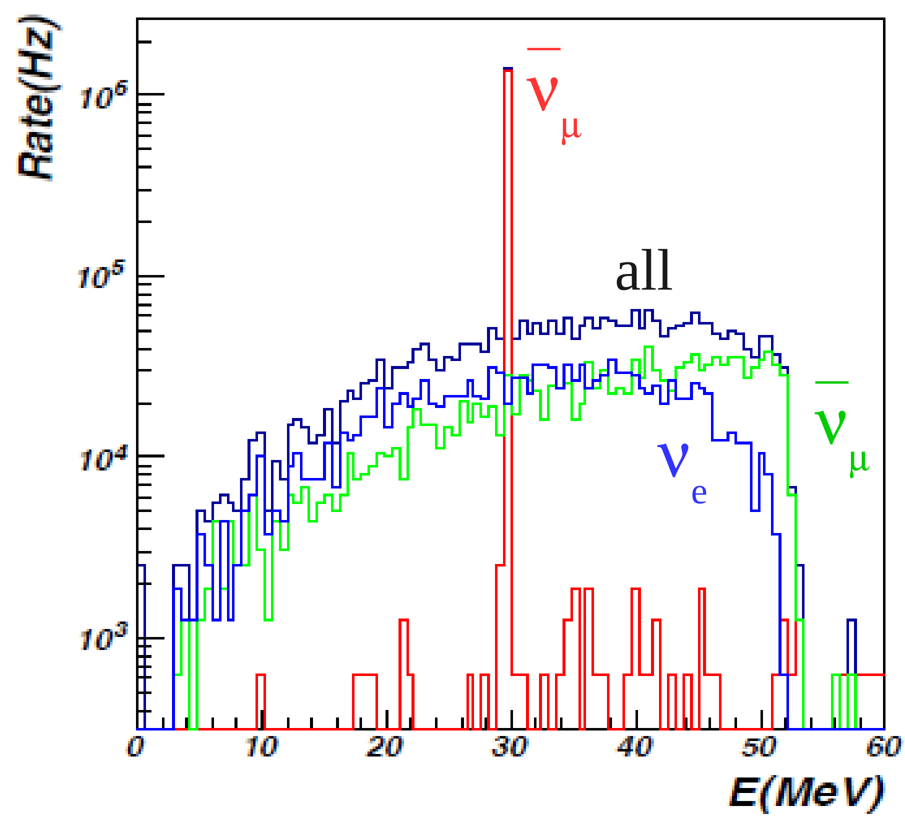
- Can't be reject with the detector-beam RF time coincidence
- Shielding is required to reduce γ/fast n rate on the detector

2) Low energy / thermal n:

- Can apply detector-beam RF time coincidence
- Very low energy hits in the detector: cut with threshold.

3) Neutrinos:

- Neutrinos are emitted from at-rest processes:
  - $\pi^+ \rightarrow \mu^+ \bar{\nu}$
  - $\mu^+ \rightarrow e^+ \nu \bar{\nu}$
- Isotropic flux
- Can't be reduced trough shielding
- Further suppression:
  - Energy threshold
  - Beam RF-detector signal coincidence (not all processes are prompt)
  - Off-axis measurement



Backgrounds

Beam-unrelated backgrounds: all reduced by the beam RF – detector time coincidence

1) Cosmic neutrinos

- Considering flux, interaction cross-sections, and thresholds the contribution is negligible.

2) Cosmic muons

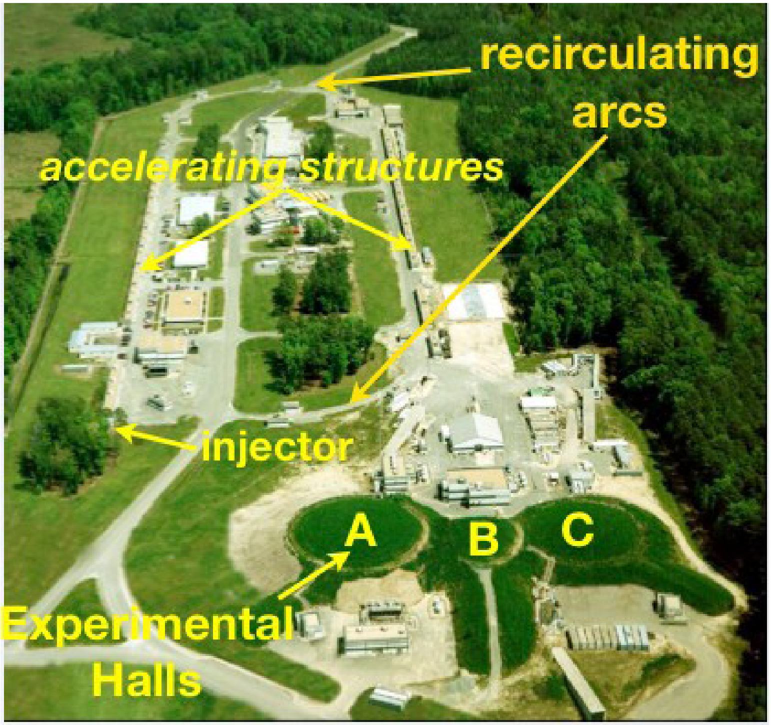
- Different background contributions (crossing/stopping/decaying/..).
- Reduced trough shielding + VETO around the detector + threshold + signal topology (different from χ-p and χ-e interactions).

3) Cosmic neutrons

- High-energy neutrons can penetrate the shielding and interact inside the detector, mimicking a χ-N interaction.
- Reduced trough shielding + VETO around the detector + threshold.

The BDX experiment at Jefferson Laboratory

The ``BeamDump Experiment'' (BDX) is a recently proposed program at Jefferson Laboratory to search for low-mass dark-matter.



Jefferson Lab accelerator:

- Electron beam with tunable energy, up to 12 GeV
- Continuous beam, 2ns bunches
- I_{beam} < 800 nA @ Hall B
- **I_{beam} < 100 μA @ Hall A, C**

BDX detector design is currently being optimized

- Modular design, overall volume ~ 2 m^3
- Each module:
  - Matrix of CsI crystals
  - Equipped with 2 veto layers, plastic-scintillator based
- Compact detector front face (~ 50x50 cm^2)
- Detector placed ~ 20 m after the beam-dump

[BDX LOI: arXiv:1406.3028]

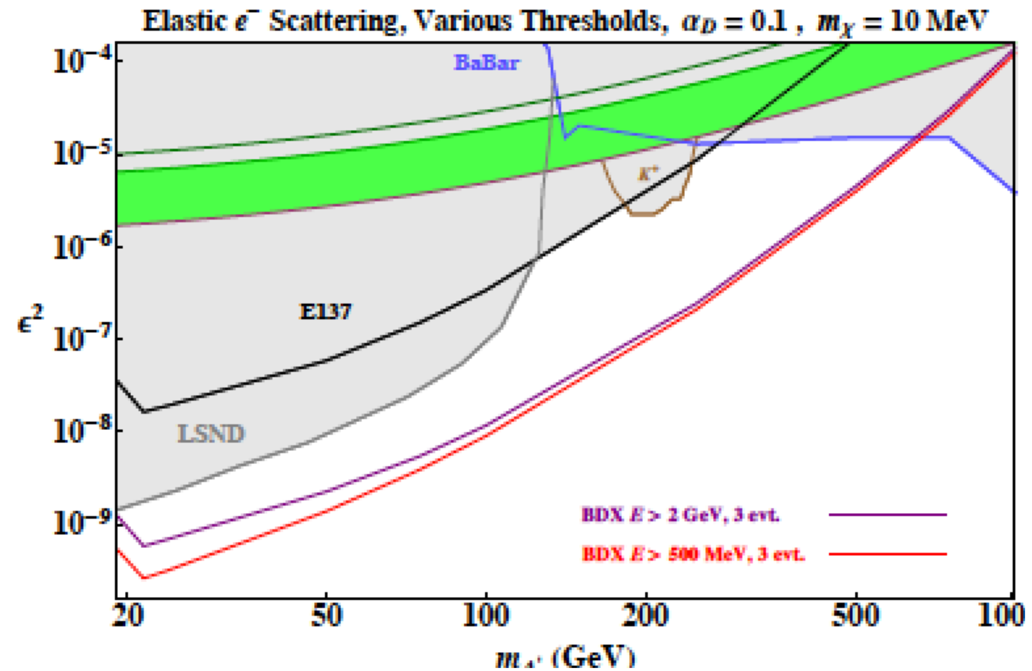
BDX experiment: reach

BDX accumulated charge: 10^{22} EOT

- Beam current: 100 μA (Hall-A / Hall – C option)
- Accelerator availability: 50%
- Run time: 1 calendar year

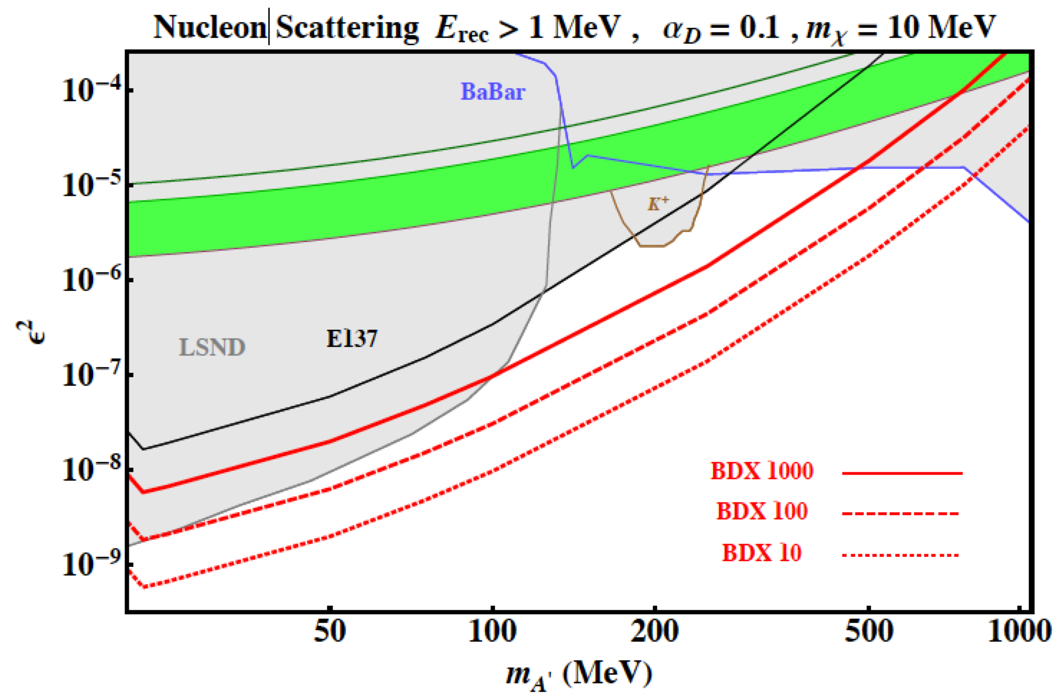
Elastic χ - e^- scattering:

- Almost background-free search.



Elastic χ - p scattering:

- Cosmogenic background is the main limiting factor.
- Beam-related background is negligible



MonteCarlo simulations: objectives

To calculate the expected number of background events

Comparisons between data and simulation: does the detector work like we think it does?

To know how many events to expect for a given signal strength

To design a new detector

To develop background suppression techniques

To develop and test reconstructions

To evaluate systematic uncertainties

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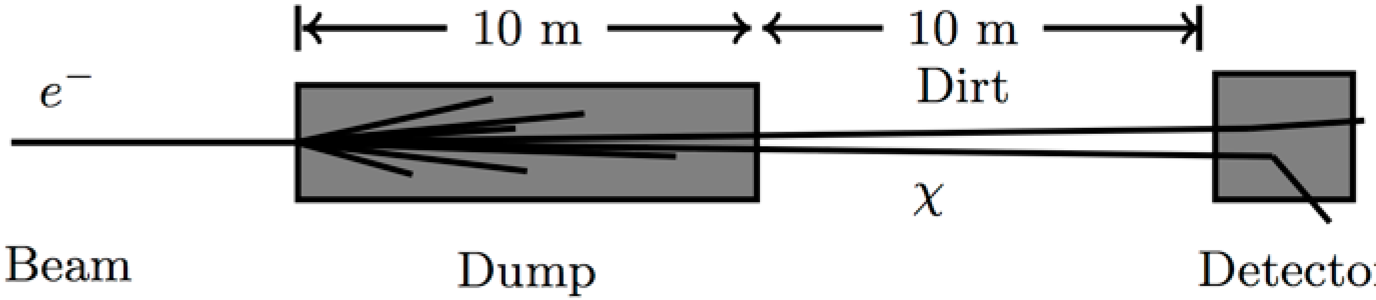
Event generator for the signal

Strategy: factorize the event generation, as in the real physical process

- **χ-beam generator:** simulate the interaction of the primary e^- beam in the dump and produce the secondary χ beam, with absolute normalization per EOT.

- **Recoils generator:** given the secondary χ-beam, produce the scattered particles in the detector: e^- and nucleons.

- **Detector simulation**: given the scattered e^- and nucleons, simulate the detector response.



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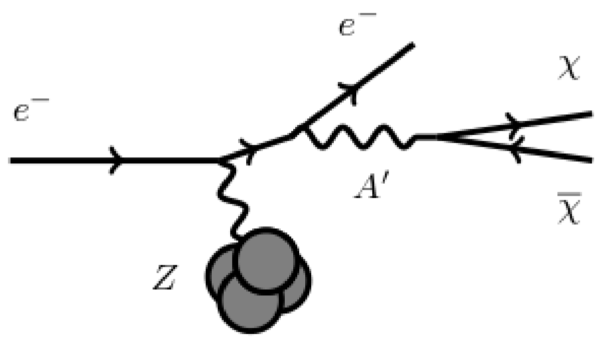
Event generator for the signal: χ - beam

Process: $e^- + Z \rightarrow e^- + Z + \chi + \bar{\chi}$

Goal:

- Compute the total χ flux per electron on target
- Generate final state 4-momenta according to dσ



Code: modified version of MadGraph/MadEvent

MadGraph/MadEvent: very popular tool in HEP, to compute tree-level cross-sections and generate events of a user-specified process. Models: SM + MSSM + HEFT + user-defined.

Written in Fortran77 + sch + Perl.

MadGraph/MadEvent provides:

- List all contributing sub processes
- Feynman diagrams for each sub process
- Cross section
- Unweighted events, Les-Houches ready (ROOT format is available trough ExRootAnalysis)
- Interfaces for PYTHIA / PGS available

[MadGraph: arXiv:1405.0301, http://madgraph.hep.uiuc.edu]

MadGraph/MadEvent : how it works

Goal: use MC methods to compute $I = \int_a^b f(s)ds$

Method: MC-average

- Extract N random numbers s_i uniformly in [a,b]
- Compute $f(s_i)$
- Take the average

$$\longrightarrow \quad I_N = \frac{(b-a)}{N} \sum_{i=1}^{N} f(s_i)$$

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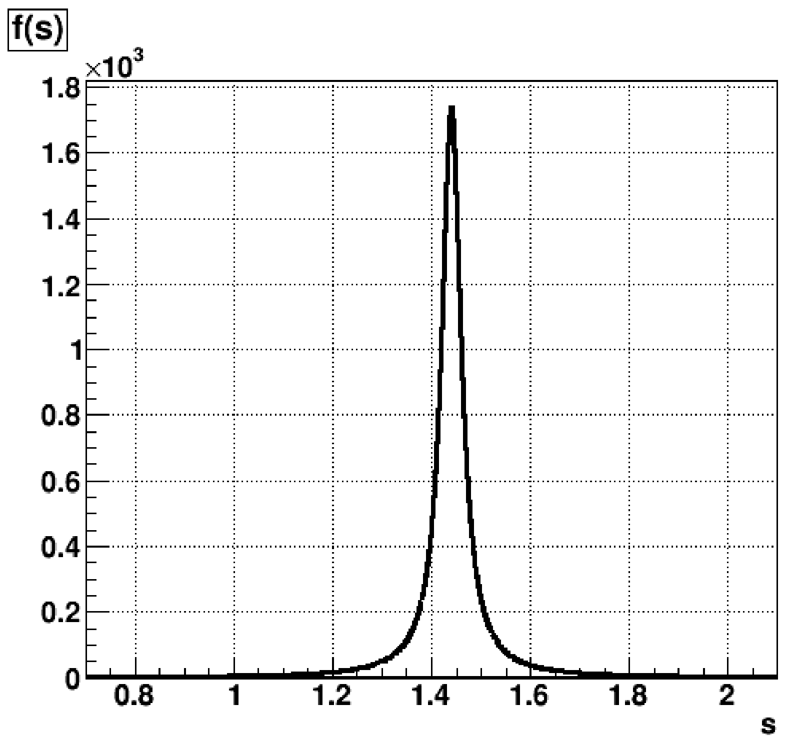
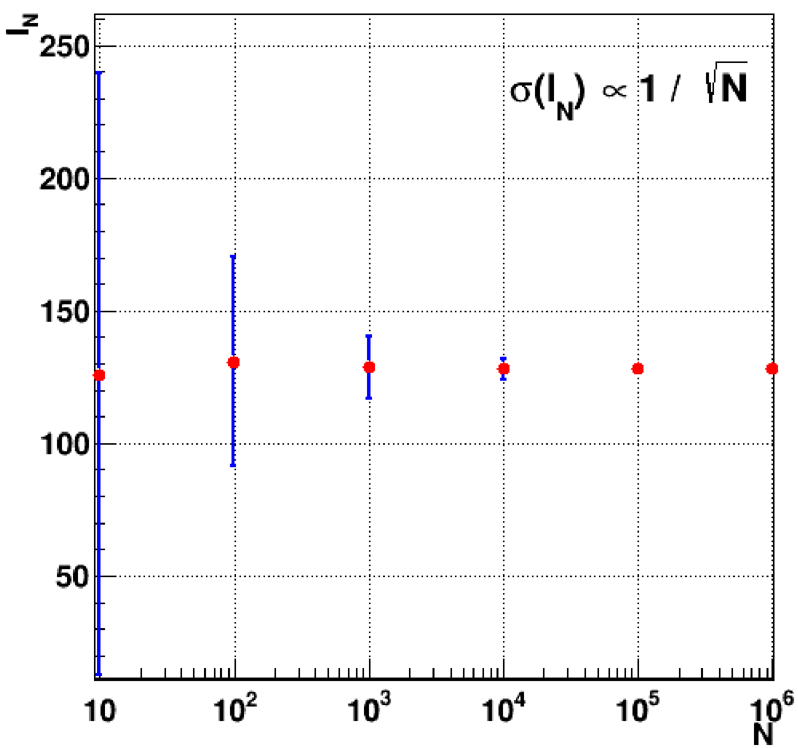
Example: $$I = \int_{0.7}^{2.1} \frac{1}{((s-1.2^2)^2 + (1.2 \cdot 0.02)^2} ds$$



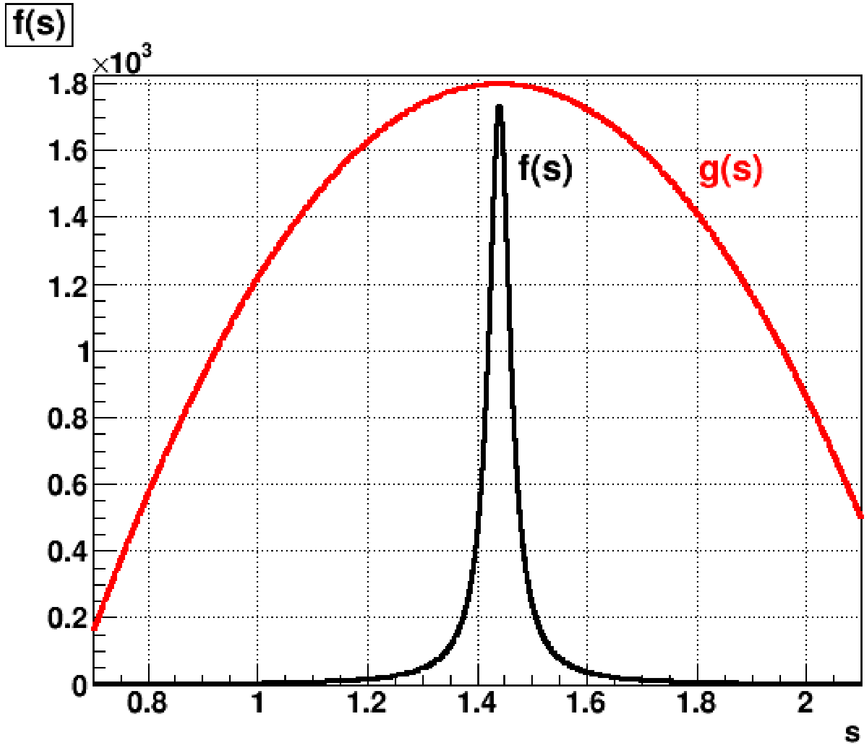


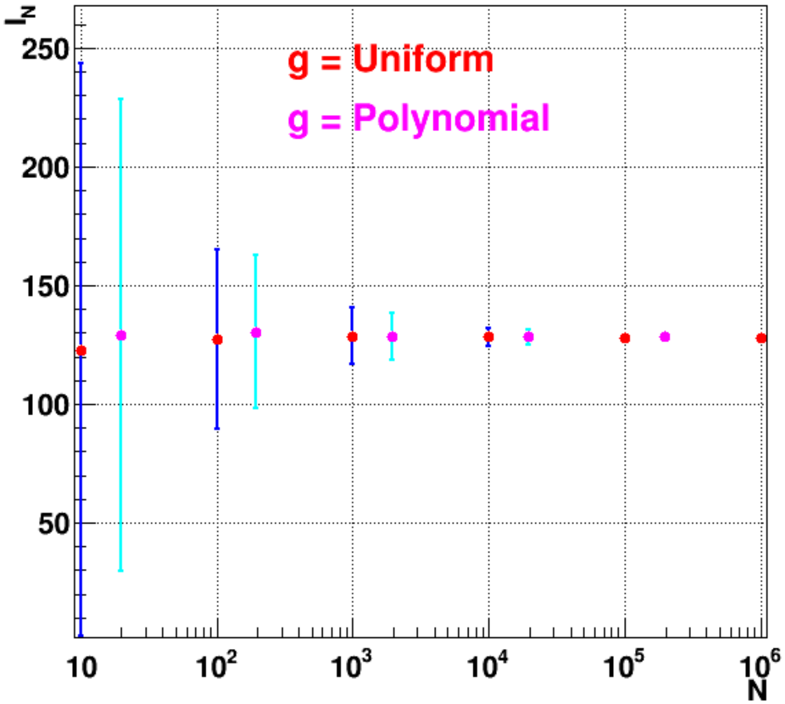
MadGraph/MadEvent : how it works

Can we do better? Yes!

$$I_N = \frac{(b-a)}{N}\sum_{i=1}^{N} f(s_i) \longrightarrow I_N = \frac{1}{N}\sum_{i=1}^{N} f(s_i)/g(s_i) \equiv \frac{1}{N}\sum_{i=1}^{N} w_i$$

Use a different *g(s)* to extract random numbers s_i, to reduce variance: select *g(s)* as similar as possible to *f(s)*, in term of “peaks”. Can't use *f* itself, since *I* is required to extract random numbers (*g* must be normalized to 1)





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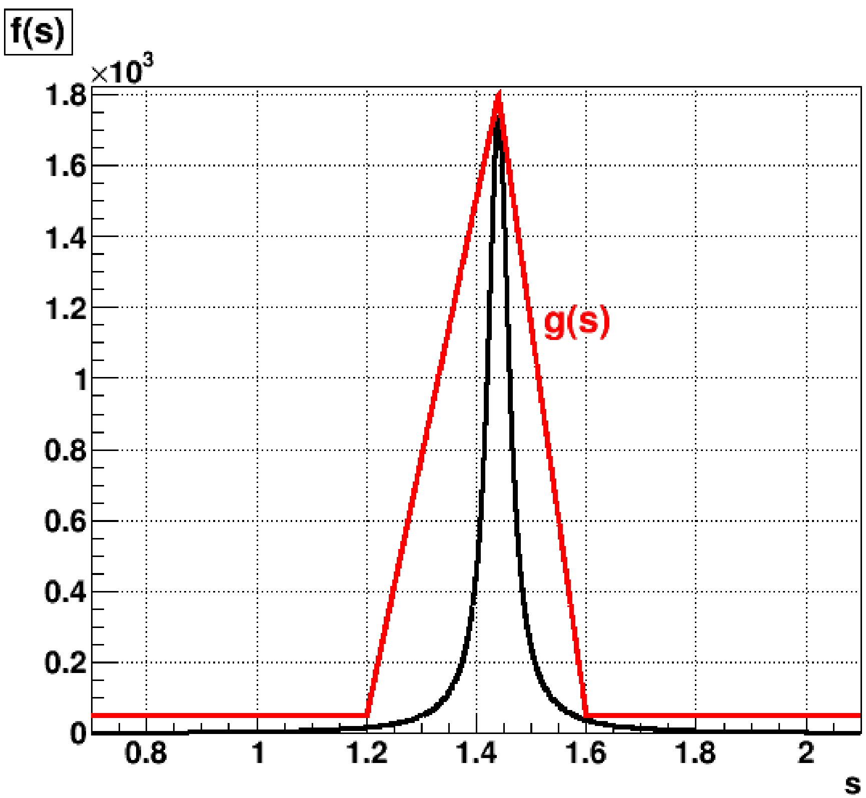
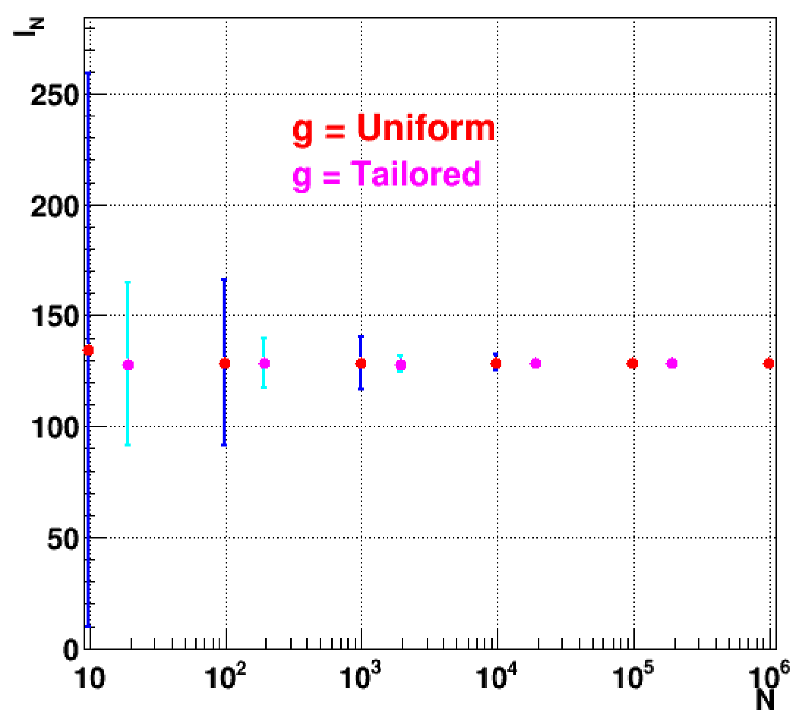




MadGraph/MadEvent : how it works

Carefully select *g* to minimize *Var*

$$I_N = \frac{1}{N}\sum_{i=1}^{N} w_i \longrightarrow \begin{aligned} <w> &= \int_a^b w(s)g(s)ds \\ Var &= \int_a^b w^2(s)g(s)ds = \int_a^b \frac{f^2}{g}ds \end{aligned}$$

Multi-channel approach:

$$g = \sum_j \alpha_j g_j$$

- Each g_j (“channel”) is normalized to 1.
- α_j are “weights” (sum normalized to 1)
- g is a PDF for s, and can be used to extract random numbers
- $<w>$ does not depend on the choice of α_j, but *Var* does

$\longrightarrow$ Use optimization techniques for α_j during MC calculation.

Caveats:

- The computation of g(s) always requires the same time, also if one of the α is small, and the corresponding contribution negligible
- Weights may be correlated, and the optimization is not trivial

MadGraph/MadEvent : how it works

Special scenario:

- Assume that *f(s)* can be written as: $f(s) = \sum f_j(s)$, with $f_j(s) > 0$
- Assume that each $f_j(s)$ can be efficiently and easily integrated with a **single pdf** $g_j(s)$

$$I = \sum_j \int f_j(s)ds = \sum_j \int g_j(s)w_j(s)ds$$

Application to physics: cross-section calculation

$$\sigma = \int d\vec{\phi}\,|A_{Tot}(\vec{\phi})|^2 = \int d\vec{\phi}\,|\sum_j A_j(\vec{\phi})|^2$$

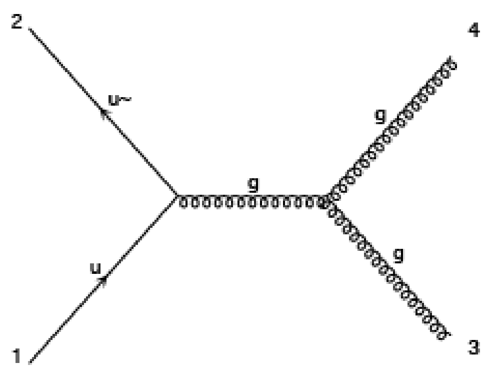
In this case, a natural decomposition arises from the physical content of the process

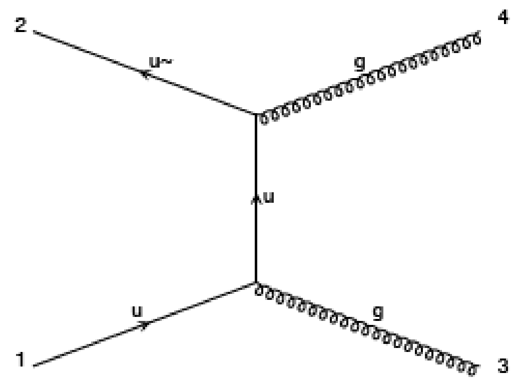
$$f_j = |A_j|^2 \frac{|A_{Tot}|^2}{\sum_i |A_i|^2}$$

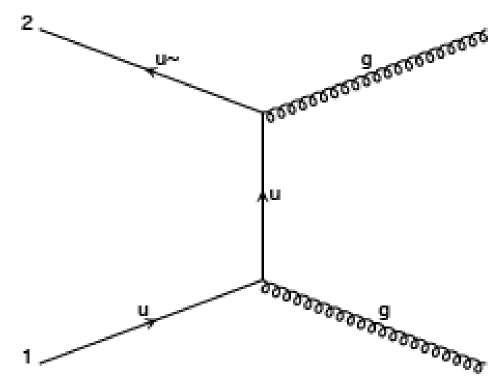
- The peak structure of each f_j is the same as of the single squared amplitude $|A_j|^2$
- Finding the suitable channel g_j is straightforward, since it can be derived from the propagator structure of the corresponding Feynman diagram.

MadGraph/MadEvent : how it works

Example: QCD 2 → 2 production







$$\propto \frac{1}{\hat{s}} = \frac{1}{(p_1 + p_2)^2} \qquad \propto \frac{1}{\hat{t}} = \frac{1}{(p_1 - p_3)^2} \qquad \propto \frac{1}{\hat{u}} = \frac{1}{(p_1 - p_4)^2}$$

Each diagram contributes to the total amplitude with a very different analytic structure (poles)

But:

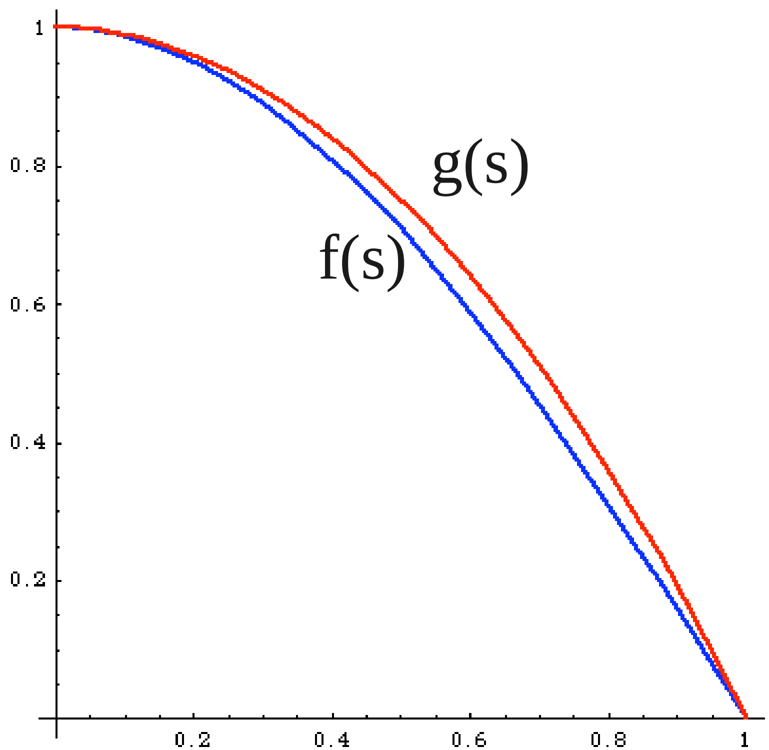
Each diagram individually is “easy” to integrate trough a MC average and a single channel approach

MadGraph/MadEvent : how it works

Application to physics: events generation

Up to here, only considered Monte Carlo as a numerical integration method.
If function being integrated is a probability density (positive definite), trivial to convert it to a simulation of physical process, i.e. an event generator.

"Hit or miss" method:



- Generate s randomly, according to g
  - → g is "simple", use inversion technique
- Compute f(s) and g(s)
- Generate y randomly, uniformly in $[0,f_{MAX}/g_{MAX}]$
- If f(s)>y g(s) accept event, else reject it.

MadGraph/MadEvent : how it works

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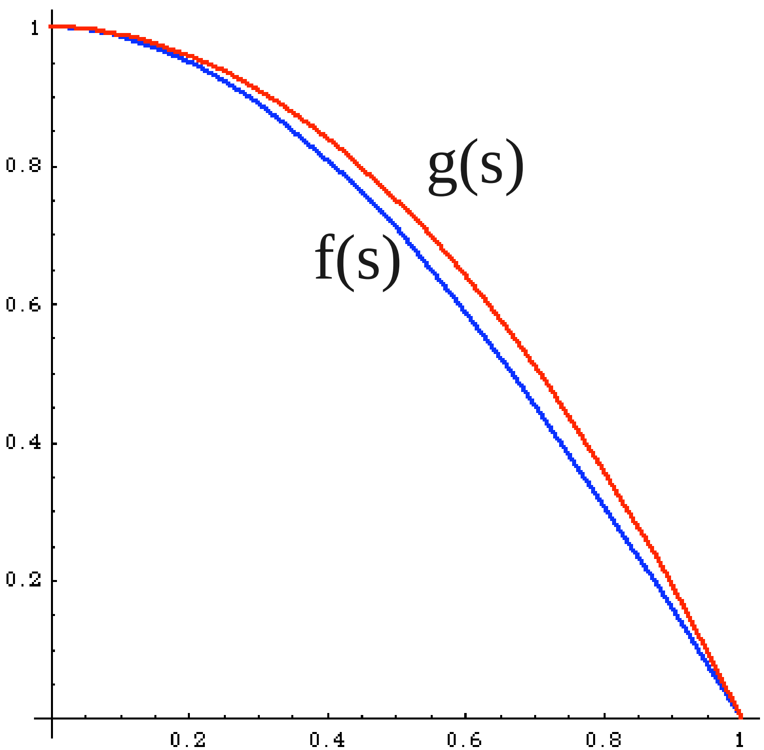

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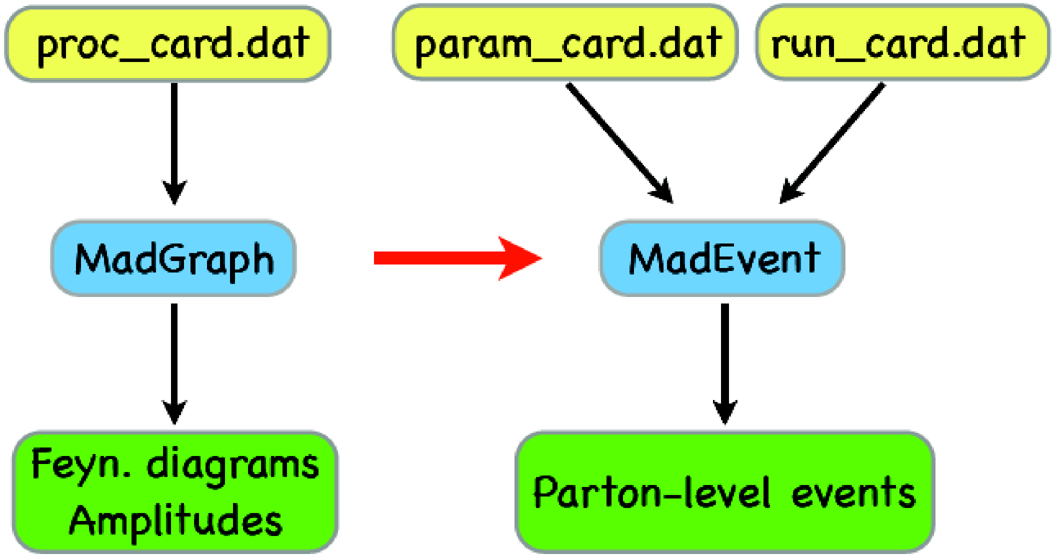
    - → g is “simple”, use inversion technique
- Compute f(s) and g(s)
- Generate y randomly, uniformly in $[0, f_{MAX}/g_{MAX}]$
- If f(s)>y g(s) accept event, else reject it.

These operations are already performed during MC integration!

MadGraph/MadEvent: use

Example: $e^+ e^- \rightarrow \mu^+ \mu^-$ @ 20+20 GeV



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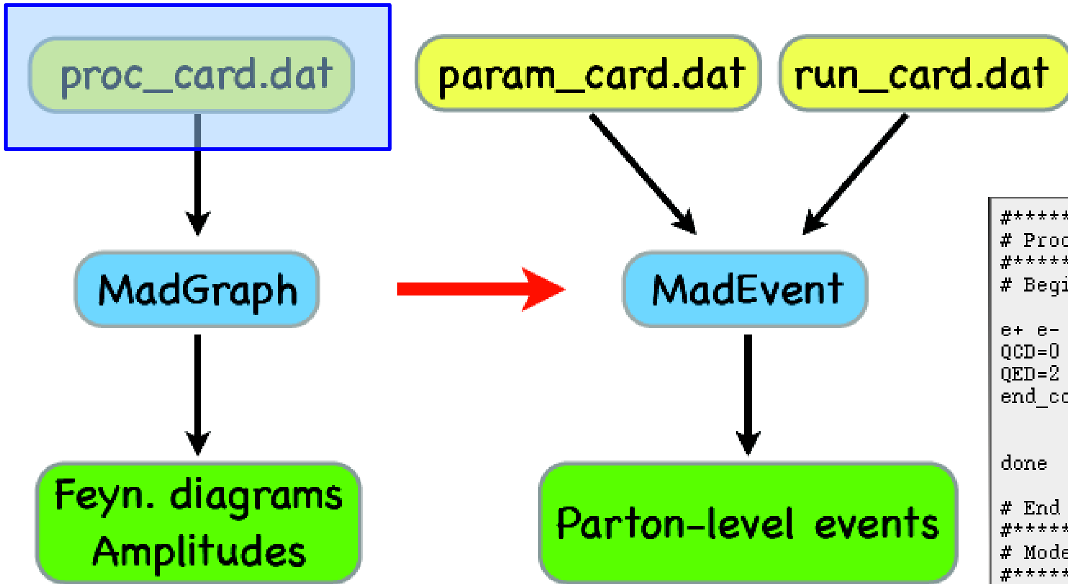
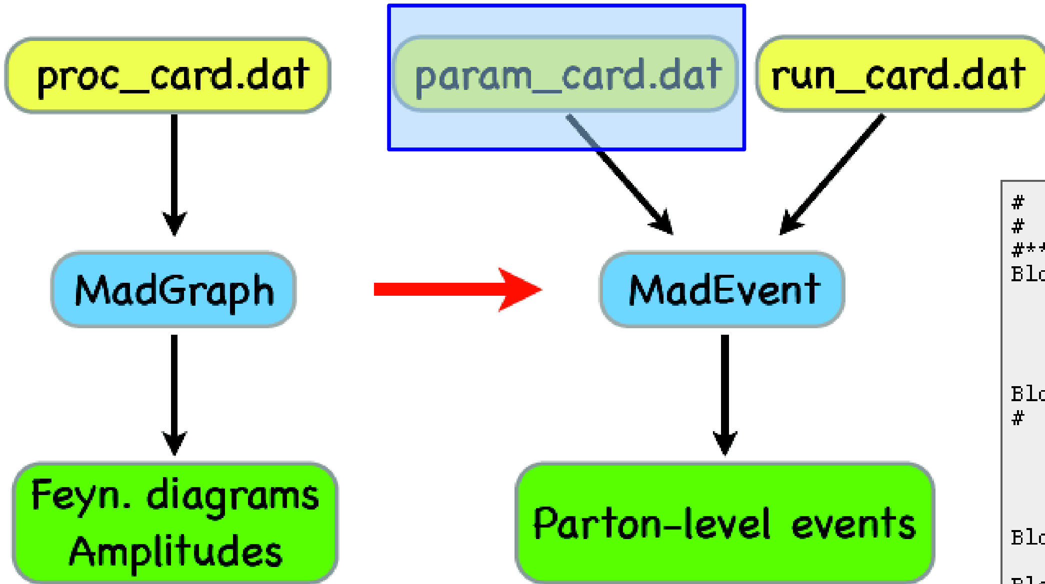


proc_card.dat : specify the process (external particles + maximum number of couplings)

```
#*********************************************************************
# Process(es) requested : mg2 input                                  *
#*********************************************************************
# Begin PROCESS # This is TAG. Do not modify this line

e+ e- >mu+ mu-  @1       # First Process
QCD=0                  # Max QCD couplings
QED=2                  # Max QED couplings
end_coup               # End the couplings input


done                   # this tells MG there are no more procs

# End PROCESS  # This is TAG. Do not modify this line
#*********************************************************************
# Model information                                                  *
#*********************************************************************
# Begin MODEL  # This is TAG. Do not modify this line
sm
# End   MODEL  # This is TAG. Do not modify this line
#*********************************************************************
# Start multiparticle definitions                                    *
#*********************************************************************
# Begin MULTIPARTICLES # This is TAG. Do not modify this line
P uu~cc~dd~ss~g
J uu~cc~dd~ss~g
L+ e+mu+
L- e-mu-
vl vevm
vl~ ve~vm~
# End  MULTIPARTICLES # This is TAG. Do not modify this line
```

MadGraph/MadEvent: use

Example: $e^+ e^- \rightarrow \mu^+ \mu^-$ @ 20+20 GeV

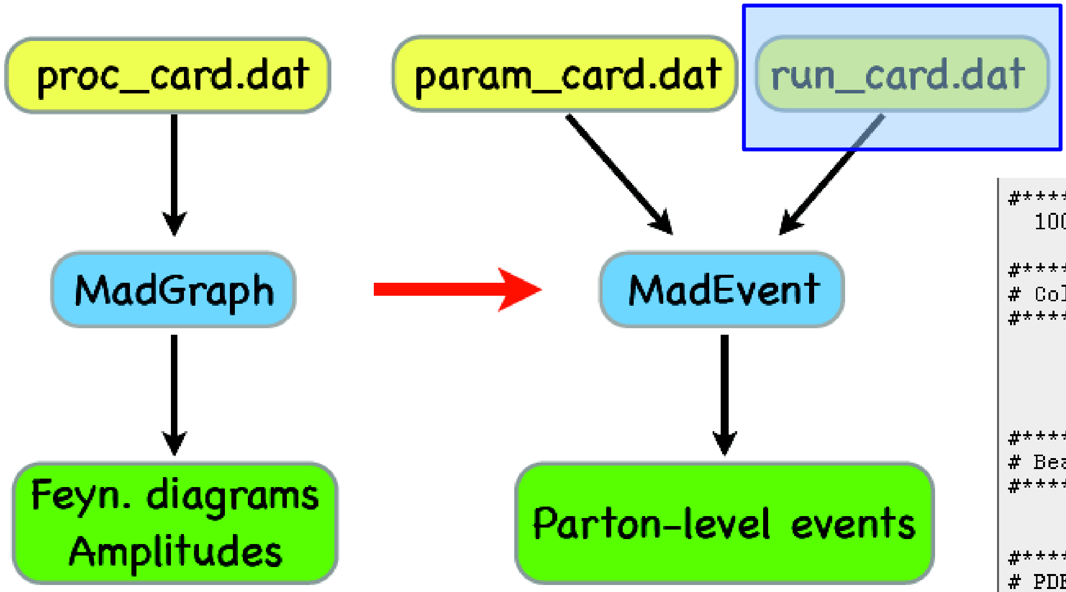


param_card.dat : specify model parameters (particle masses and widths / couplings)

```
#   and a zero mass might be hardwired in the model definition.      *
#                                                                    *
#*********************************************************************
Block SMINPUTS      # Standard Model inputs
     1         1.32506980E+02   # alpha_em(MZ)(-1) SM MSbar
     2         1.16639000E-05   # G_Fermi
     3         1.18000000E-01   # alpha_s(MZ) SM MSbar
     4         9.11880000E+01   # Z mass (as input parameter)
Block MGYUKAWA     # Yukawa masses m/v=y/sqrt(2)
#    PDG          YMASS
     5         4.20000000E+00   # mbottom for the Yukawa  y_b
     4         1.42000000E+00   # mcharm  for the Yukawa  y_c
     6         1.64500000E+02   # mtop    for the Yukawa  y_t
    15         1.77700000E+00   # mtau    for the Yukawa  y_ta
Block MGCKM     # CKM elements for MadGraph
     1   1     9.75000000E-01   # Vud for Cabibbo matrix
Block MASS      #  Mass spectrum (kinematic masses)
#       PDG       Mass
         5     4.70000000E+00   # bottom   pole mass
         6     1.74300000E+02   # top      pole mass
        15     1.77700000E+00   # tau      mass
        23     9.11880000E+01   # Z        mass
        24     8.04190000E+01   # W        mass
        25     1.20000000E+02   # H        mass
```

MadGraph/MadEvent: use

Example: $e^+ e^- \rightarrow \mu^+ \mu^-$ @ 20+20 GeV

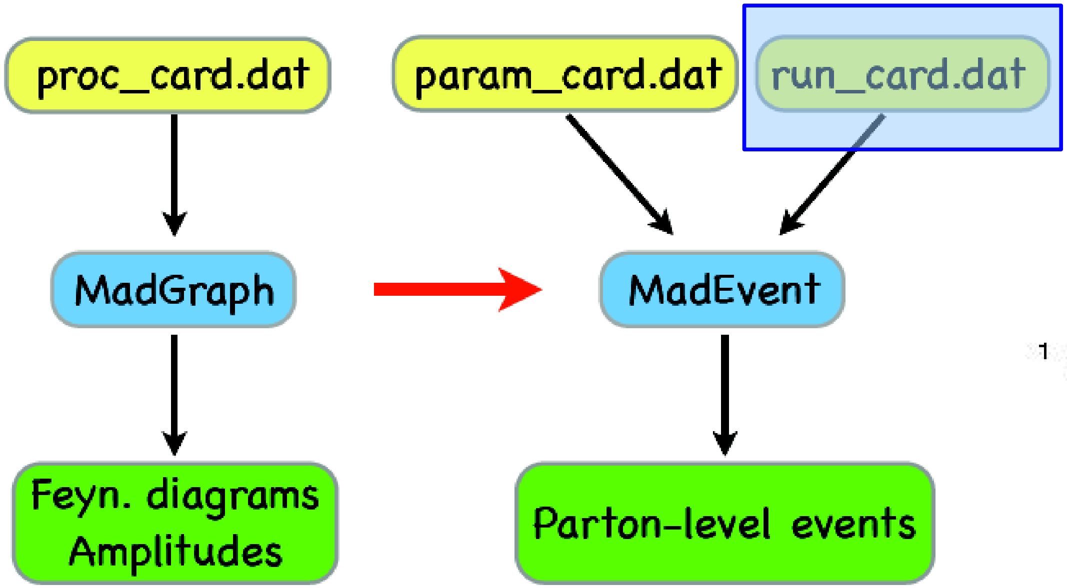


run_card.dat : specify run parameters
(beam energy / polarization / PDFs / cuts)

```
#*********************************************************************
  10000      = nevents ! Number of unweighted events requested
      0      = iseed   ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                          *
#*********************************************************************
        0     = lpp1    ! beam 1 type (0=NO PDF)
        0     = lpp2    ! beam 2 type (0=NO PDF)
       20     = ebeam1  ! beam 1 energy in GeV
       20     = ebeam2  ! beam 2 energy in GeV
#*********************************************************************
# Beam polarization from -100 (left-handed) to 100 (right-handed)   *
#*********************************************************************
        0     = polbeam1 ! beam polarization for beam 1
        0     = polbeam2 ! beam polarization for beam 2
#*********************************************************************
# PDF CHOICE: this automatically fixes also alpha_s and its evol.    *
#*********************************************************************
 'cteq6l1'    = pdlabel     ! PDF set
#*********************************************************************
# Renormalization and factorization scales                          *
#*********************************************************************
 F         = fixed_ren_scale  ! if .true. use fixed ren scale
 F         = fixed_fac_scale  ! if .true. use fixed fac scale
 91.1880   = scale            ! fixed ren scale
 91.1880   = dsqrt_q2fact1    ! fixed fact scale for pdf1
 91.1880   = dsqrt_q2fact2    ! fixed fact scale for pdf2
 1         = scalefact        ! scale factor for event-by-event scales
```

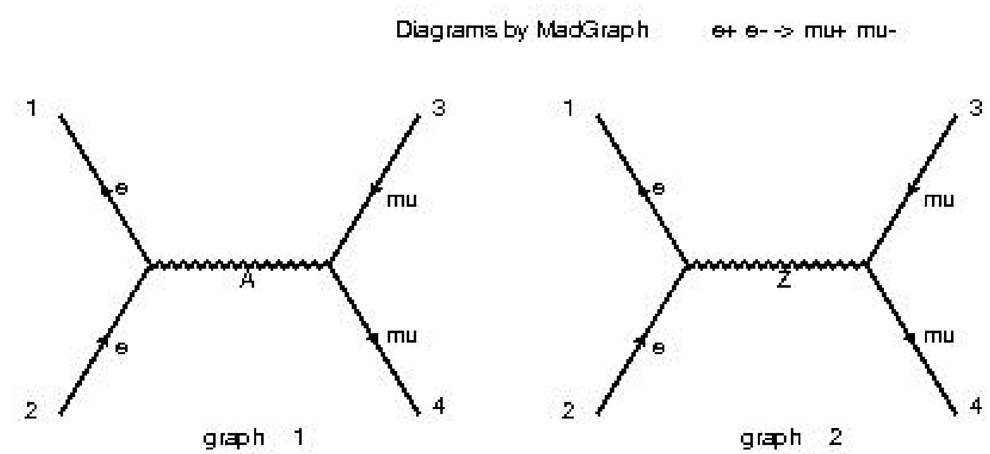
MadGraph/MadEvent: use

Example: $e^+ e^- \to \mu^+ \mu^-$ @ 20+20 GeV



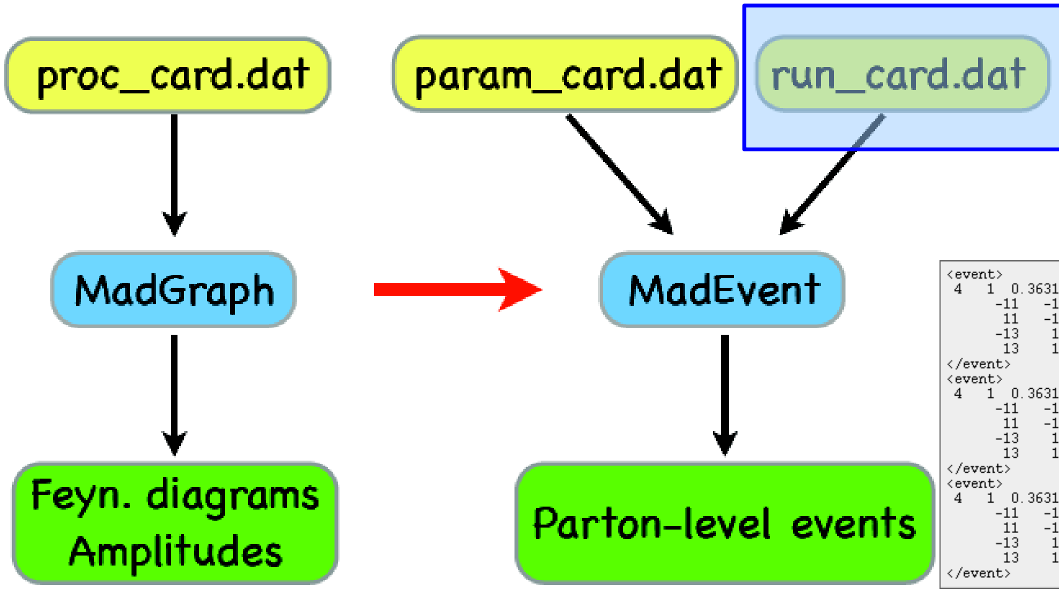
MadGraph output:

- Feynman diagrams
- Corresponding amplitudes



MadGraph/MadEvent: use

Example: $e^+ e^- \rightarrow \mu^+ \mu^-$ @ 20+20 GeV



MadEvent output:

- Total cross-section $\sigma = (58.3 \pm 0.1)$ pb
- Events (Les-Houches/ROOT format)


```
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
       -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
        11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
       -13    1    1    2    0    0  0.72097051125E+01 -0.10136838652E+02 -0.15660927633E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
        13    1    1    2    0    0 -0.72097051125E+01  0.10136838652E+02  0.15660927633E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
</event>
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
       -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
        11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
       -13    1    1    2    0    0  0.43605553096E+01 -0.14320507090E+02 -0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
        13    1    1    2    0    0 -0.43605553096E+01  0.14320507090E+02  0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
</event>
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
       -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
        11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
       -13    1    1    2    0    0  0.41366999487E+01  0.93103309042E+01  0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0.   1.
        13    1    1    2    0    0 -0.41366999487E+01 -0.93103309042E+01 -0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0.  -1.
</event>
```


```
  <LesHouchesEvents version="1.0">
    <!--
      # optional information in completely free format,
      # except for the reserved endtag (see next line)
    -->

  <header>
    <!-- individually designed XML tags, in fancy XML style -->
  </header>
  <init>
    compulsory initialization information
    # optional initialization information
  </init>
  <event>
    compulsory event information
    # optional event information
  </event>
  (further <event> ... </event> blocks, one for each event)
</LesHouchesEvents>
```

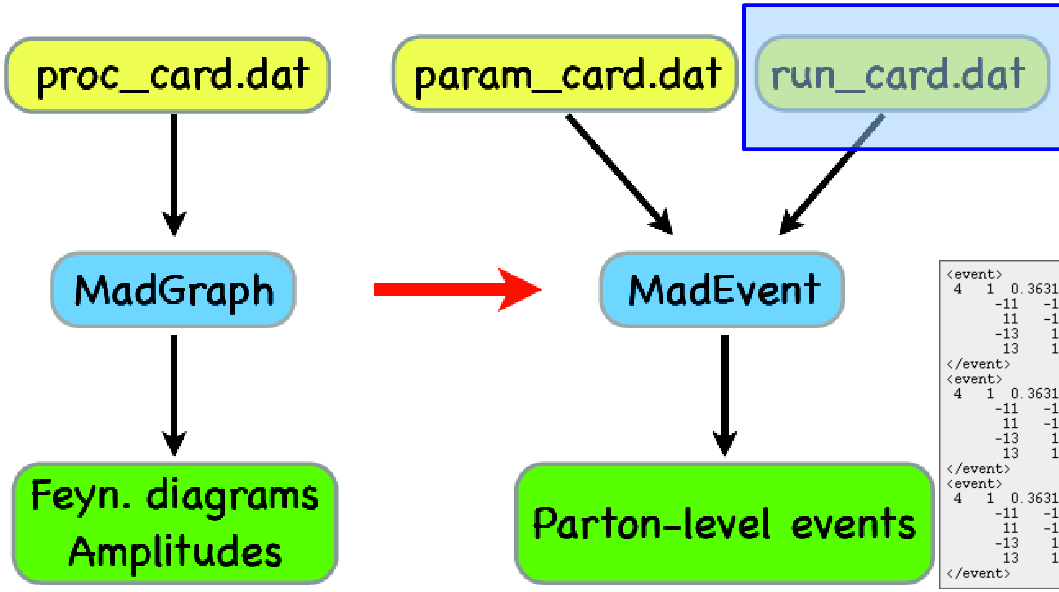
Les-Houches format:

→ XML-based data format, common in HEP, derived from Fortran common-blocks standards defined in Les Houches accords

ROOT format:
TTree with 4 momenta of external particles (1 entry per event)

MadGraph/MadEvent: use

Example: $e^+ e^- \rightarrow \mu^+ \mu^-$ @ 20+20 GeV



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```
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 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
      -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
       11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
      -13    1    1    2    0    0  0.72097051125E+01 -0.10136838652E+02 -0.15660927633E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
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 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
      -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
       11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
      -13    1    1    2    0    0  0.43605553096E+01 -0.14320507090E+02 -0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
       13    1    1    2    0    0 -0.43605553096E+01  0.14320507090E+02  0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
</event>
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
      -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
       11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
      -13    1    1    2    0    0  0.41366999487E+01  0.93103309042E+01  0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
       13    1    1    2    0    0 -0.41366999487E+01 -0.93103309042E+01 -0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
</event>
```


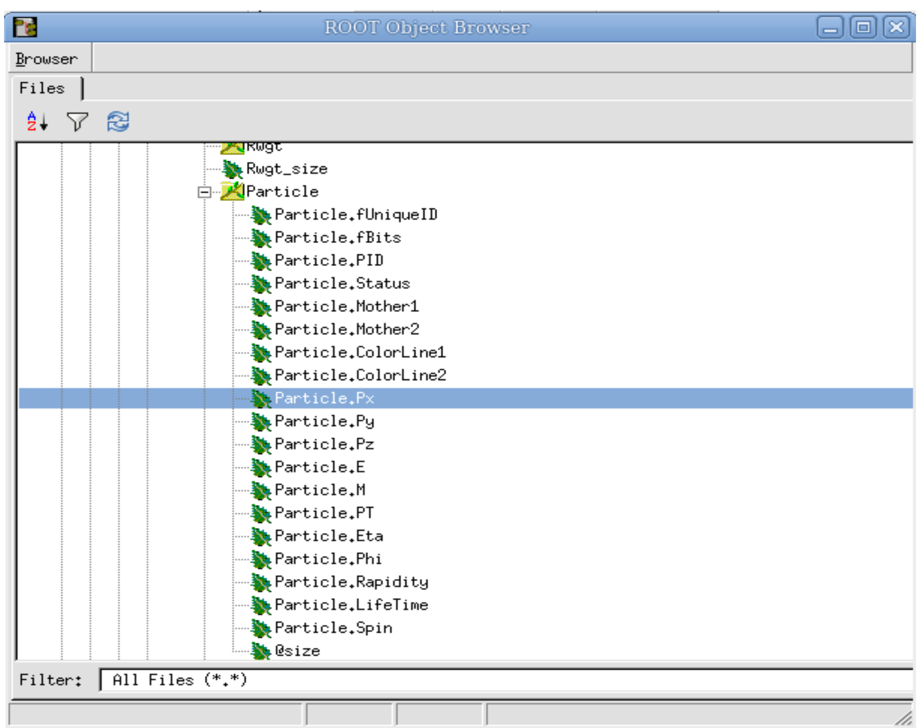

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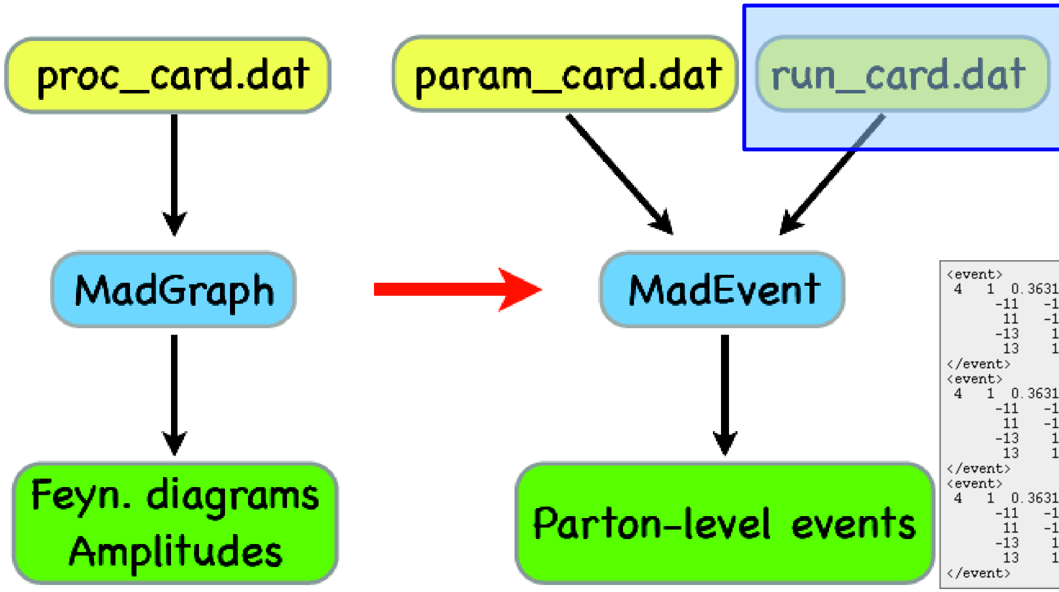

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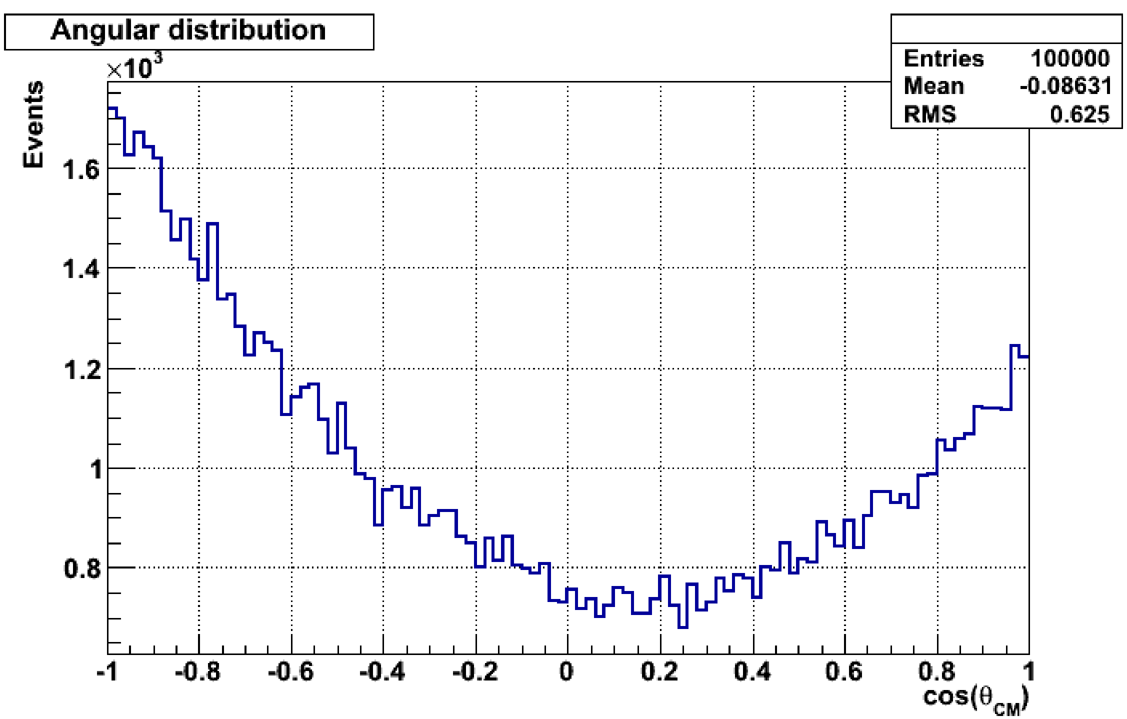
       -13    1    1    2    0    0  0.72097051125E+01 -0.10136838652E+02 -0.15660927633E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
        13    1    1    2    0    0 -0.72097051125E+01  0.10136838652E+02  0.15660927633E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
</event>
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
       -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
        11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
       -13    1    1    2    0    0  0.43605553096E+01 -0.14320507090E+02 -0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
        13    1    1    2    0    0 -0.43605553096E+01  0.14320507090E+02  0.13263055232E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
</event>
<event>
 4   1  0.3631120E-02  0.6324555E+01  0.7546772E-02  0.1991748E+00
       -11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00  0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
        11   -1    0    0    0    0  0.00000000000E+00  0.00000000000E+00 -0.20000000000E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
       -13    1    1    2    0    0  0.41366999487E+01  0.93103309042E+01  0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0.  1.
        13    1    1    2    0    0 -0.41366999487E+01 -0.93103309042E+01 -0.17210620326E+02  0.20000000000E+02  0.00000000000E+00 0. -1.
</event>
```

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Outline

- Introduction: light dark matter search at beam-dump experiments
  - Physics case
  - MC tools: scope and requirements

- **Event generator for the signal**
  - Computation strategy
  - **Software implementation**
    - DM production: MadGraph/MadEvent
    - **DM interaction**
    - Detector response: GEMC

- Event generator for the beam-related background
  - Requirements-computational issues
  - Brute-force approach
  - MCNP approach

Event generator for the signal: recoil

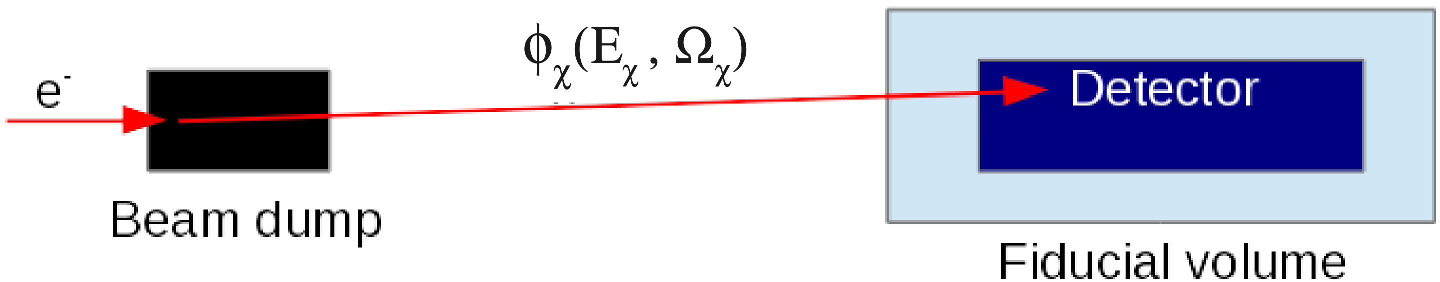
Process: $\chi + e \rightarrow \chi + e \,/\, \chi + N \rightarrow \chi + N$

Goal:

- Compute the total number of events within the detector
- Generate final state 4-momenta according to dσ

Code: standalone C++ code (using ROOT libraries)

Input from χ-beam generator: χ flux as a function of energy and angle per EOT



Output: must compute $N = \int_{V_F} \frac{d\phi_\chi}{dE_\chi d\Omega_\chi} \frac{d\sigma_I(E_\chi)}{dE_r} n_p dE_\chi d\Omega_\chi dE_r$

Event generator for the signal: recoil

Process: $\chi + e \rightarrow \chi + e$ / $\chi + N \rightarrow \chi + N$

Goal:

- Compute the total number of events within the detector
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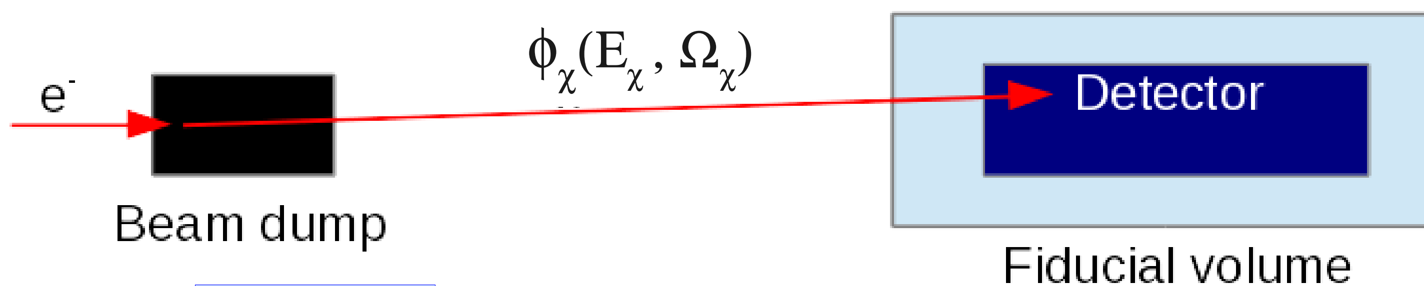
Code: standalone C++ code (using ROOT libraries)

Input from χ-beam generator: χ flux as a function of energy and angle per EOT



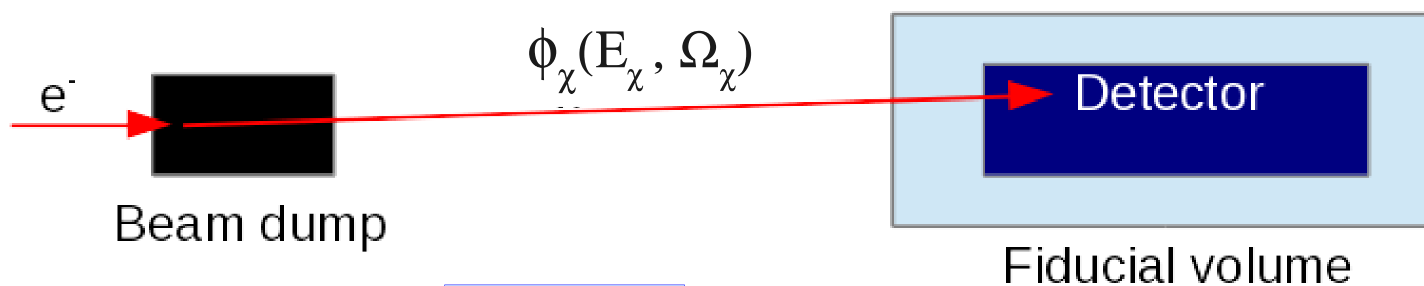
Output: must compute $N = \int_{V_F} \underbrace{\frac{d\phi_\chi}{dE_\chi d\Omega_\chi}}_{\chi\ \text{flux}} \frac{d\sigma_I(E_\chi)}{dE_r} n_p dE_\chi d\Omega_\chi dE_r$

Event generator for the signal: recoil

Process: $\chi + e \rightarrow \chi + e$ / $\chi + N \rightarrow \chi + N$
Goal:
- Compute the total number of events within the detector
- Generate final state 4-momenta according to $d\sigma$

Code: standalone C++ code (using ROOT libraries)

Input from χ-beam generator: χ flux as a function of energy and angle per EOT



Output: must compute $N = \int_{V_F} \frac{d\phi_\chi}{dE_\chi d\Omega_\chi} \boxed{\frac{d\sigma_I(E_\chi)}{dE_r}} n_p dE_\chi d\Omega_\chi dE_r$

χ interaction

Event generator for the signal: recoil

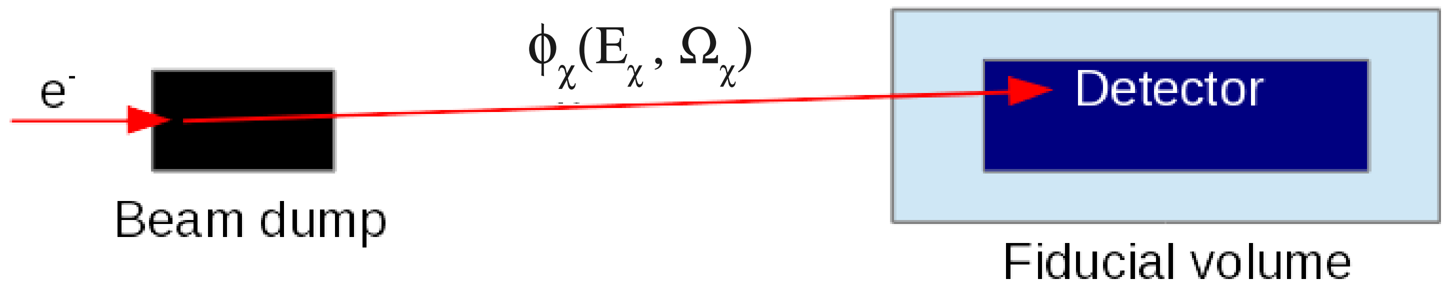
Process: $\chi + e \rightarrow \chi + e \;/\; \chi + N \rightarrow \chi + N$

Goal:

- Compute the total number of events within the detector
- Generate final state 4-momenta according to $d\sigma$

Code: standalone C++ code (using ROOT libraries)

Input from χ-beam generator: χ flux as a function of energy and angle per EOT



Output: must compute $N = \int_{V_D} \frac{d\phi_\chi}{dE_\chi d\Omega_\chi} \frac{d\sigma_I(E_\chi)}{dE_r} n_p \, dE_\chi d\Omega_\chi dE_r$

Scatter centers density

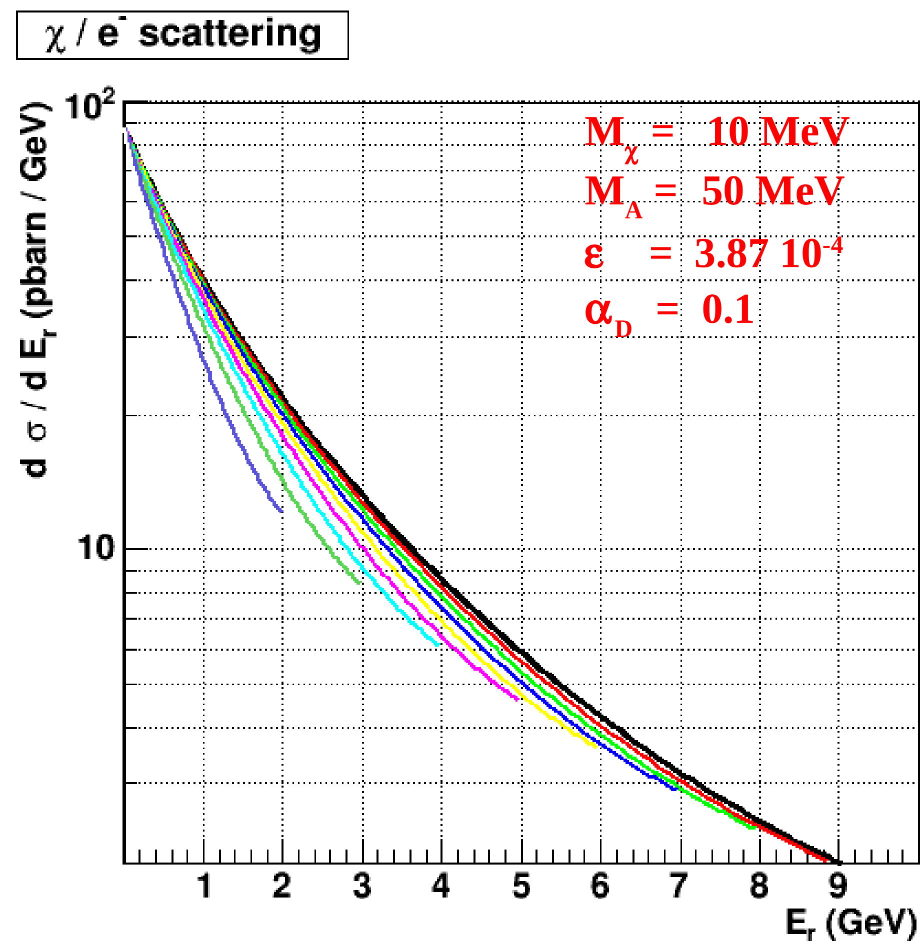
Event generator for the signal: recoil

Process: $\chi + e \rightarrow \chi + e$ / $\chi + N \rightarrow \chi + N$

Cross-section (electron scattering case):

$$\frac{d\sigma}{dE_e} = 4\pi\varepsilon^2\alpha\alpha' m_e \frac{4m_e m_\chi^2 E_e + [m_\chi^2 + m_e E_\chi]^2}{(m_A^2 + 2m_e E_e)^2 (m_\chi^2 + 2m_e E_0)^2}$$

- Smooth 1-dimensional function, easy to integrate and to sample. We use standard ROOT methods for this (TF1)
- Function depends on **incoming** χ energy E_0
  - To avoid function integration event by event, bin in E_0 before generating events (from 0 to E_{beam})
  - For each event, use the cross-section computed at the bin center

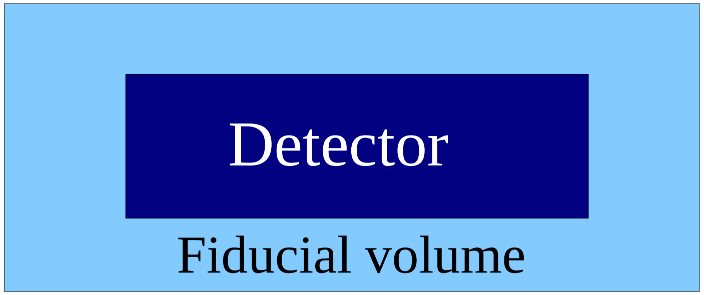


Event generator for the signal: recoil

Decouple the χ interaction simulation from the detector response simulation and use Geant4 for the latter.

$$N = \int_{V_F} \frac{d\phi_\chi}{dE_\chi d\Omega_\chi} \frac{d\sigma_I(E_\chi)}{dE_r} n_p dE_\chi d\Omega_\chi dE_r$$

- Define a simple fiducial volume in the $E_\chi - \Omega_\chi$ space, with $V_F > V_D$
- Use V_F to calculate N_F and to generate events
  - Since $L_\chi \gg L_D$, generate events uniformly: for each χ generate the interaction vertex uniformly along the part of the trajectory that lies within V_F
  - The MonteCarlo simulation is designed to handle the cases with a proton generated in V_F but not in V_D
- Compute the "real" detector response as: $N_D = N_F \cdot \varepsilon$
  - ε calculated trough Geant4 detector simulation



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  - Physics case
  - MC tools: scope and requirements
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  - Computation strategy
  - **Software implementation**
    - DM production: MadGraph/MadEvent
    - DM interaction
    - **Detector response: GEMC**
- Event generator for the beam-related background
  - Requirements-computational issues
  - Brute-force approach
  - MCNP approach

Event generator for the signal: detector response simulation

Process: e^- / protons interaction with detector material

Goal:

- Compute the overall detector efficiency
- Simulate the detector response, in terms of measured observables (deposited energy / hit multiplicity / ...)

Input from recoil generator: scattered protons / electrons four-momenta and production vertexes

Code: **GE**ant4 **M**onte-**C**arlo (GEMC) software, developed by M. Ungaro @ Jefferson Lab

[GEMC: http://gemc.jlab.org]

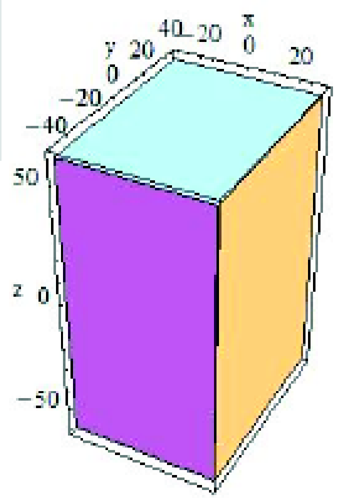
GEMC

GEMC is an application based on Geant4 libraries to simulate the passage of particles through matters

Why? GEANT4 is a C++ Library →

- Does require some programming language experience
- Does require some C++ knowledge
- OO Programming skills much preferable

```
G4Box(const G4String& pName,
            G4double  pX,
            G4double  pY,
            G4double  pZ)
```



[Rotate the Picture]
In the picture:

```
pX = 30, pY = 40, pZ = 60
```

- Write geometry in the code
- Write response function in the code
- Implement Magnetic fields in the code
- Incorporate Digitization
- Implement Input and Output

by giving the box a name and its half-lengths along the X, Y and Z axis:

pX	half length in X	pY	half length in Y	pZ	half length in Z

Do this for hundreds (thousands) of detector elements

GEMC

Users (physicists) aren't necessarily the best programmers (not applicable to this audience!): build a framework that decouples the content (geometry / fields / digitization) from the code.

GEMC wants to solve these problems:

- Users should have to deal ONLY with geometry, fields, response function parameters - NOT how they interface with Geant4 core code.
- All parameters should be in a database (with reconstruction, calibration, visualization).

The **same** GEMC executable is used for all simulations: only input configuration changes.

How it works (geometry/materials):

- User specify materials and geometry (volumes / surfaces) in a perl script, using GEANT4 C++ classes methods (default G4 materials are available).
- Materials and geometry are uploaded to a database (or to a local txt file)
- GEMC executable loads the geometry from the selected data-source and automatically constructs the detector.

GEMC basic example

Basic experimental setup: build a target (thin cylinder) and detector (parallelepiped)

Target:

```
sub build_target
{
	my %detector = init_det();
	$detector{"name"}        = "target";
	$detector{"mother"}      = "root";
	$detector{"description"} = "Example of target";
	$detector{"pos"}         = "0*cm 0*cm 0*cm";
	$detector{"rotation"}    = "0*deg 0*deg 0*deg";
	$detector{"color"}       = "880000";
	$detector{"type"}        = "Tube";
	$detector{"dimensions"}  = "0*cm 2*cm 2*mm 0*deg 360*deg";
	$detector{"material"}    = "G4_lH2";
	$detector{"visible"}     = 1;
	$detector{"style"}       = 1;
	print_det(\%configuration, \%detector);
}
```

Volume name, mother volume, and description

GEMC basic example

Basic experimental setup: build a target (thin cylinder) and detector (parallelepiped)

Target:

```
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        my %detector = init_det();
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        $detector{"visible"}     = 1;
        $detector{"style"}       = 1;
        print_det(\%configuration, \%detector);
}
```

Volume position wrt mother volume frame

GEMC basic example

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Target:

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        $detector{"visible"}     = 1;
        $detector{"style"}       = 1;
        print_det(\%configuration, \%detector);
}
```

Volume definition: G4solid name and default constructor parameters

GEMC basic example

Basic experimental setup: build a target (thin cylinder) and detector (parallelepiped)

Target:

```
sub build_target
{
        my %detector = init_det();
        $detector{"name"}        = "target";
        $detector{"mother"}      = "root";
        $detector{"description"} = "Example of target";
        $detector{"pos"}         = "0*cm 0*cm 0*cm";
        $detector{"rotation"}    = "0*deg 0*deg 0*deg";
        $detector{"color"}       = "880000";
        $detector{"type"}        = "Tube";
        $detector{"dimensions"}  = "0*cm 2*cm 2*mm 0*deg 360*deg";
        $detector{"material"}    = "G4_lH2";
        $detector{"visible"}     = 1;
        $detector{"style"}       = 1;
        print_det(\%configuration, \%detector);
}
```

Material definition: can be an embedded material or a user-defined one.

GEMC basic example

Basic experimental setup: build a target (thin cylinder) and detector (parallelepiped)

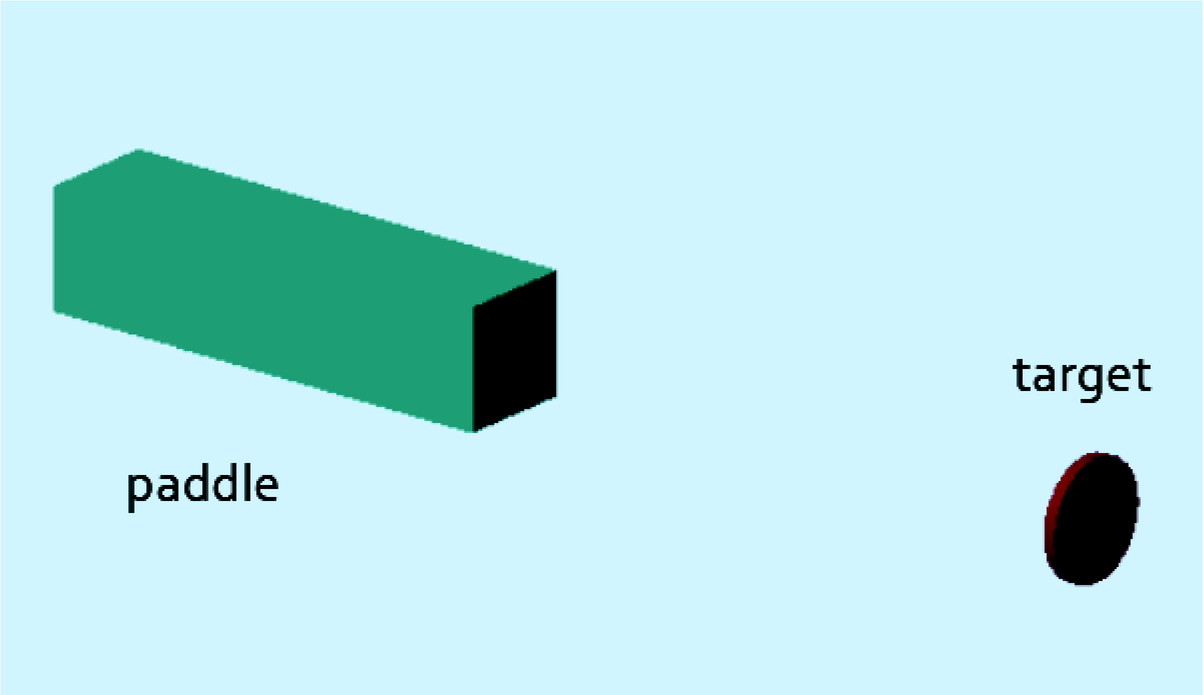
Detector:

```
sub build_simple_paddle
{
        my %detector = init_det();
        $detector{"name"}        = "paddle_1";
        $detector{"mother"}      = "root";
        $detector{"description"} = "Example of paddle";
        $detector{"pos"}         = "0*cm 0*cm 30*cm";
        $detector{"rotation"}    = "0*deg 0*deg 0*deg";
        $detector{"color"}       = "339999";
        $detector{"type"}        = "Box";
        $detector{"dimensions"}  = "2*cm 2*cm 8*cm";
        $detector{"material"}    = "G4_GLASS_LEAD";
        $detector{"visible"}     = 1;
        $detector{"style"}       = 1;
        print_det(\%configuration, \%detector);
}
```

GEMC basic example

Basic experimental setup: build a target (thin cylinder) and detector (parallelepiped)

Result:

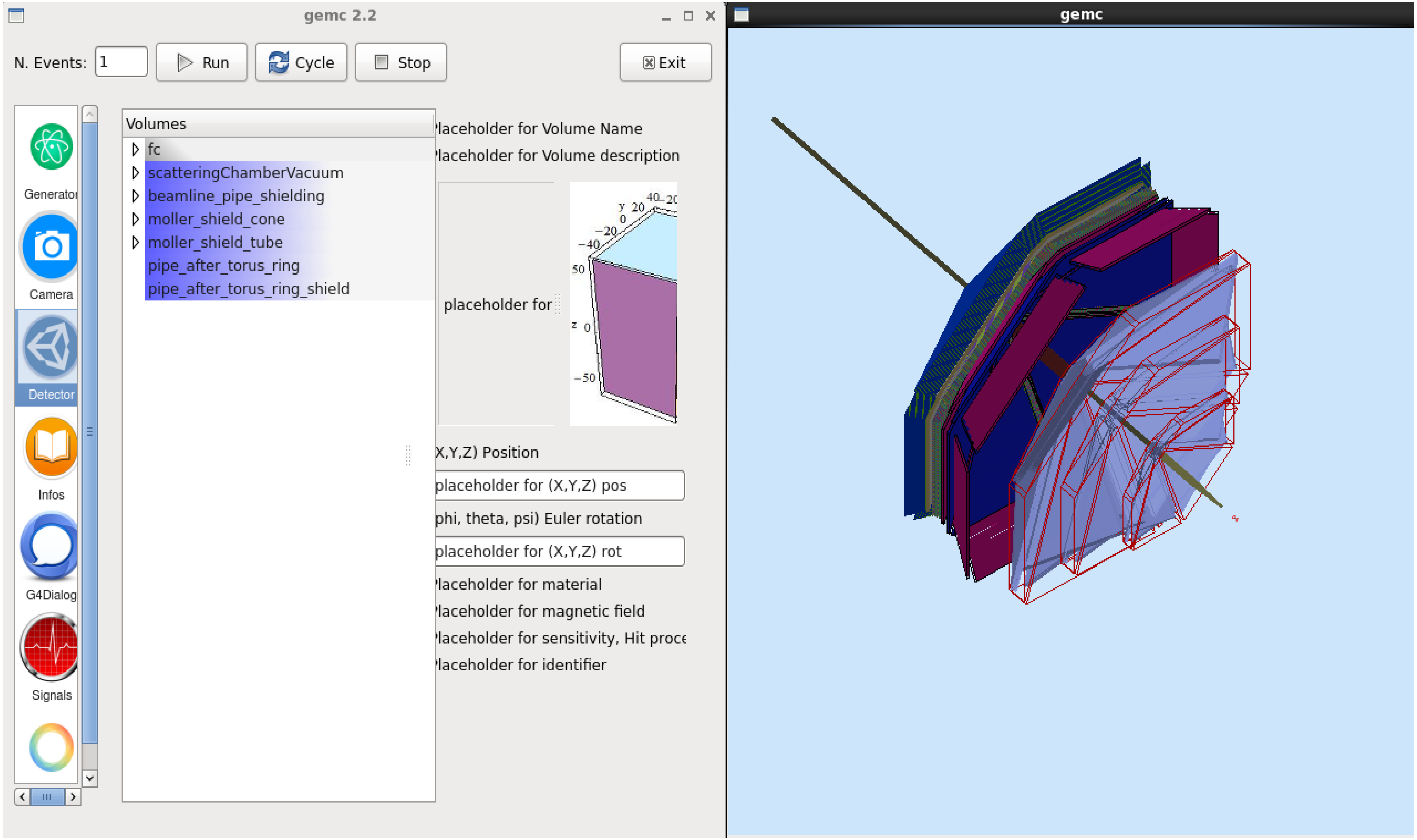


A simple geometry was defined without necessity to compile any code: user can just focus on the simulation problem → **GEMC handles the coding.**

GEMC interface

GEMC comes with a full GUI (based on Qt libraries), useful to debug MonteCarlo setup before a full MC run is started in batch mode.

Detector browser



GEMC interface

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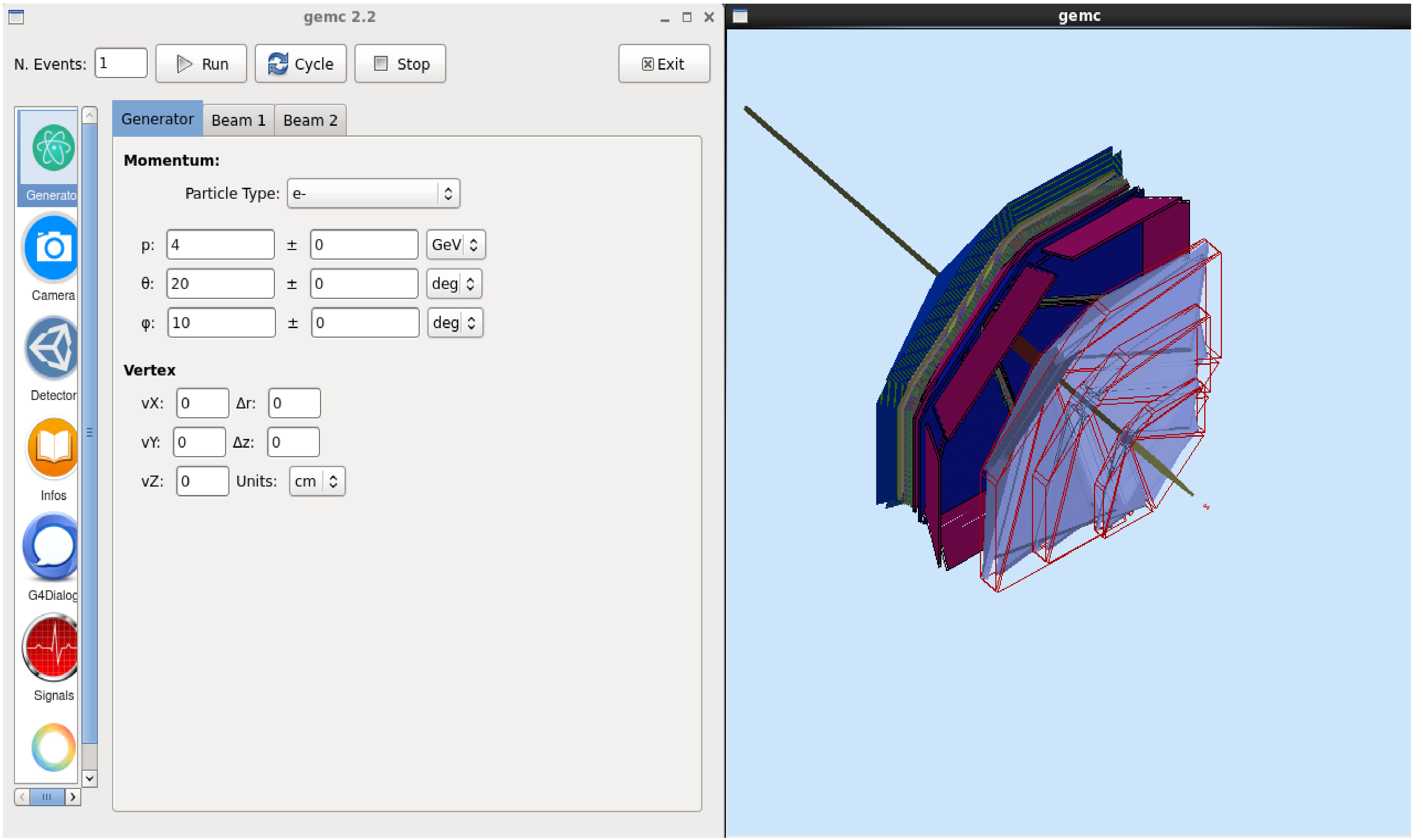
Built-in event generator



GEMC interface

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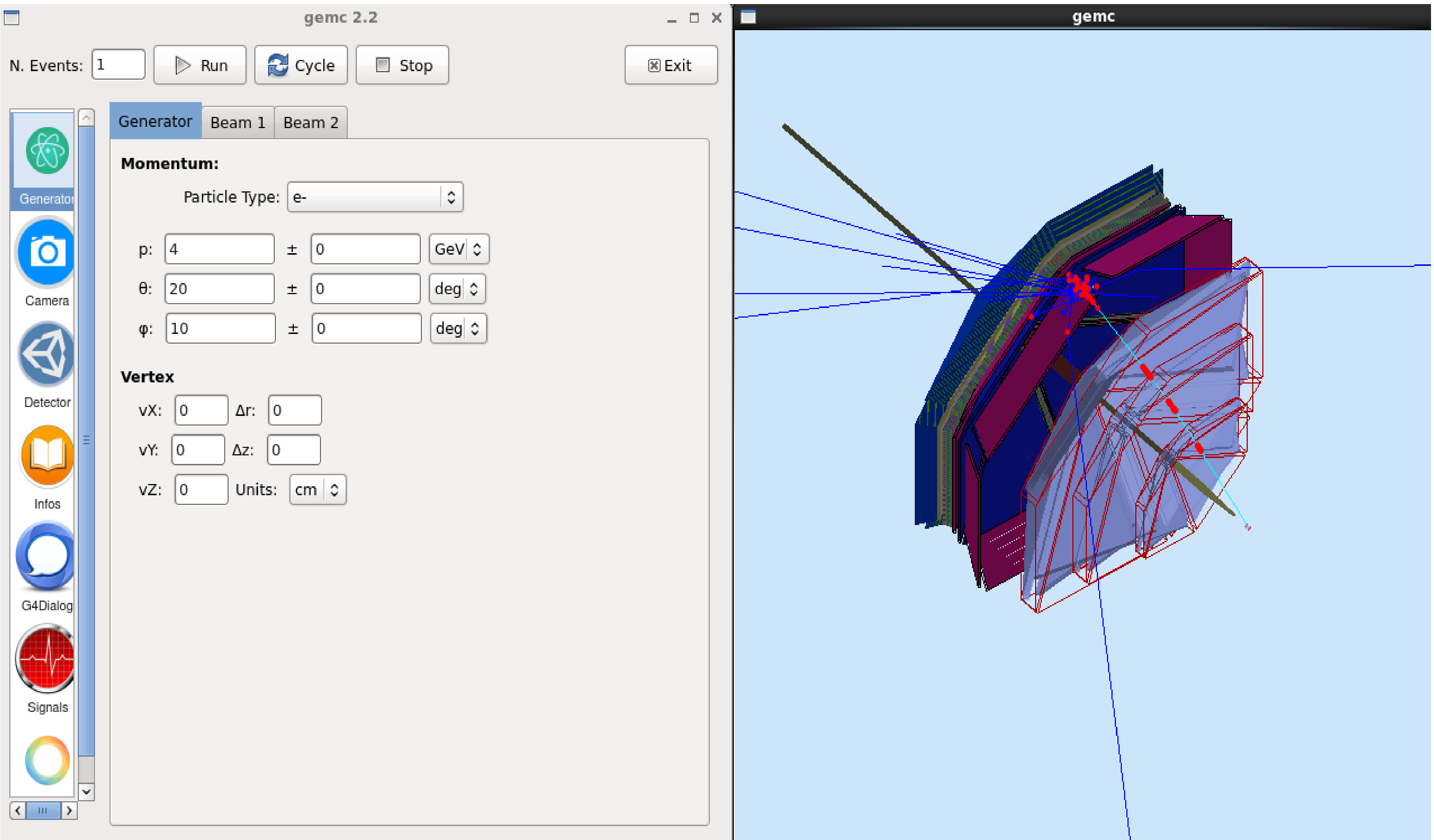
Hit-display



GEMC interface

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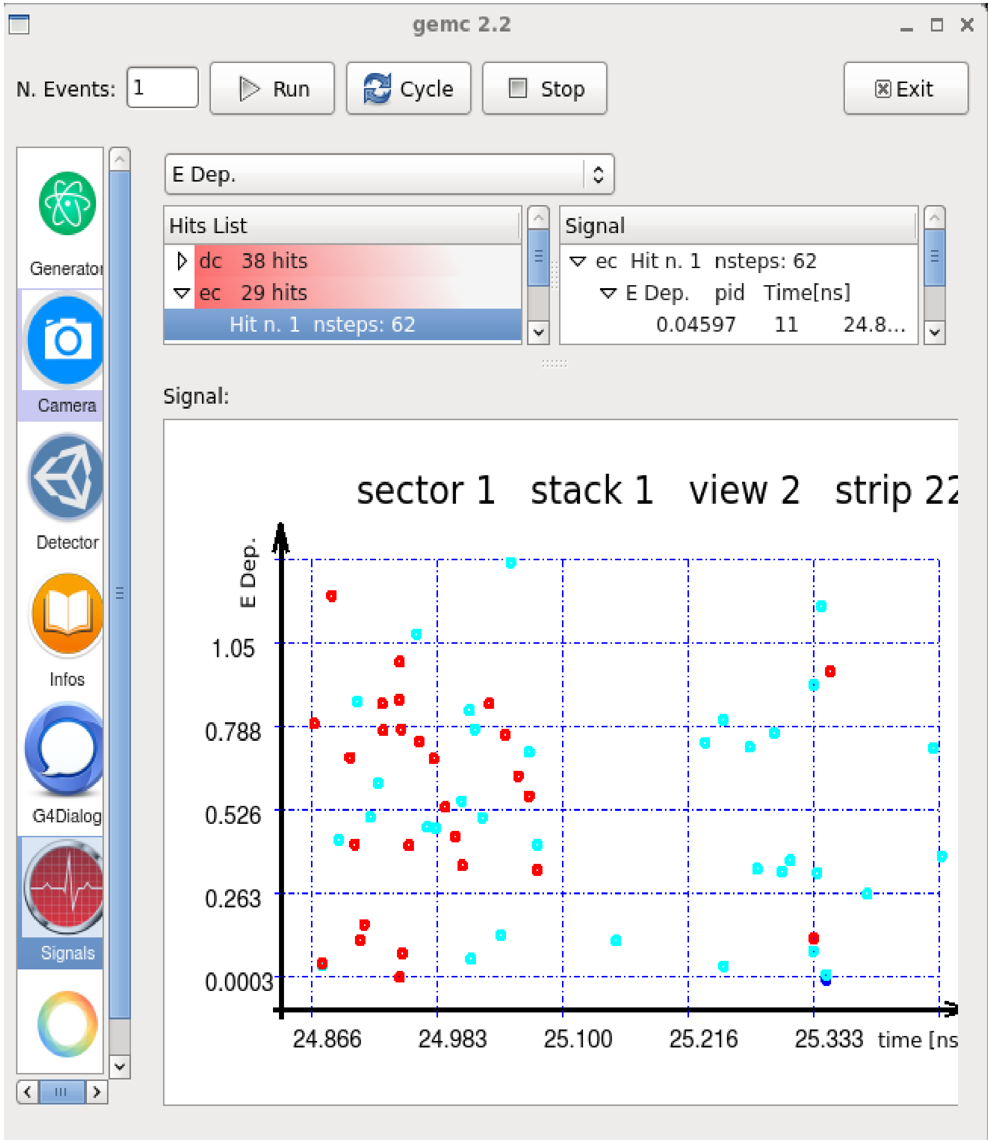
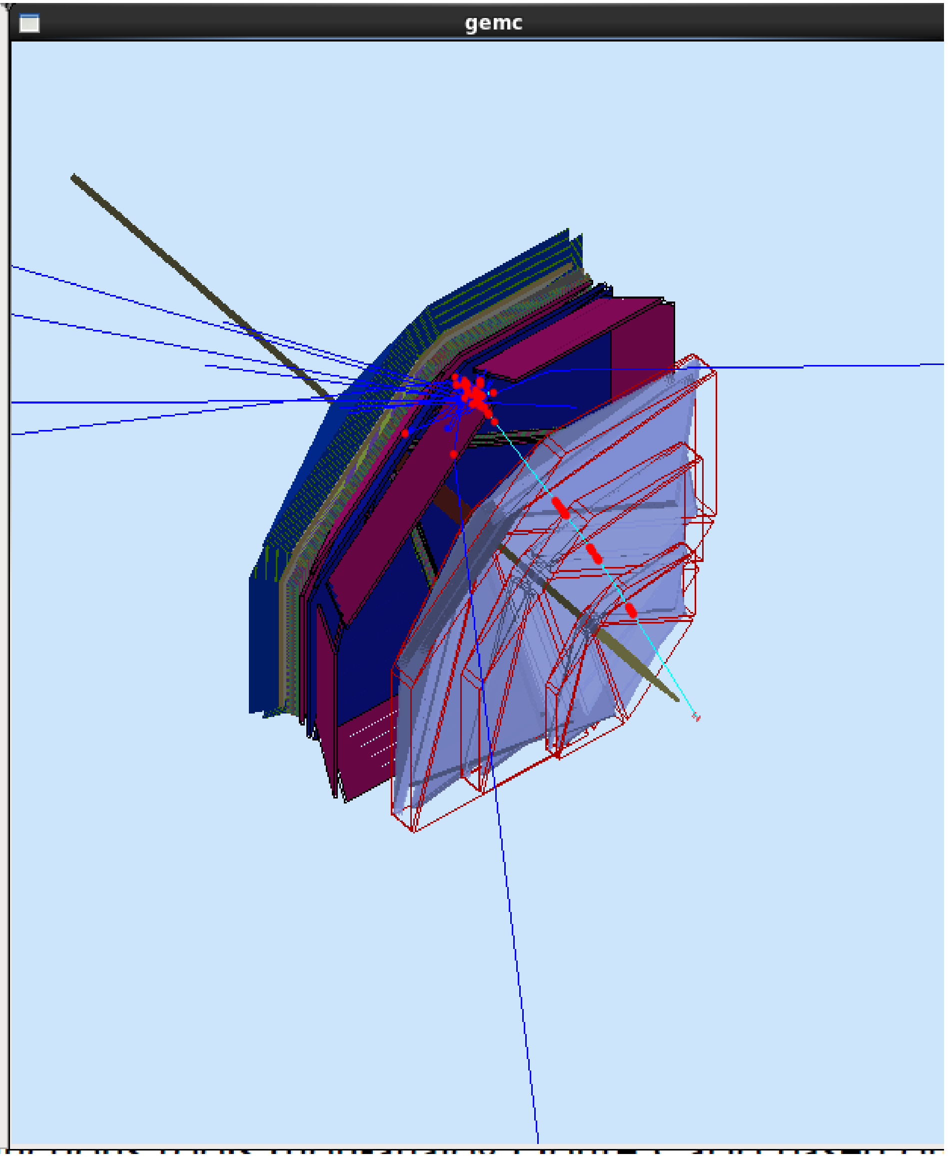
Hit history: time chart





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- **Event generator for the beam-related background**
  - **Requirements-computational issues**
  - **Brute-force approach**
  - MCNP approach

Beam-related backgrounds simulation

Goal: estimate backgrounds created by beam interaction with the dump via MC simulations.

- Determine the expected number of background events per EOT
- Study the different contributions

BDX run conditions:

- 11 GeV electrons impinging on the beam dump
- 10^{22} EOT
- 100 μA electron beam on dump for 6 months running

Computational challenges and issues:

- Computing limitations:
  - Combination of very large number of incoming particles and very massive absorbers makes full-luminosity simulations prohibitive
  - Extrapolation over several order of magnitudes needed

- Physics issues:
  - Accurate modeling of physics interaction from GeV to eV, including low energy nuclear reactions and neutron transport

Beam-related backgrounds simulation

Brute-force approach:

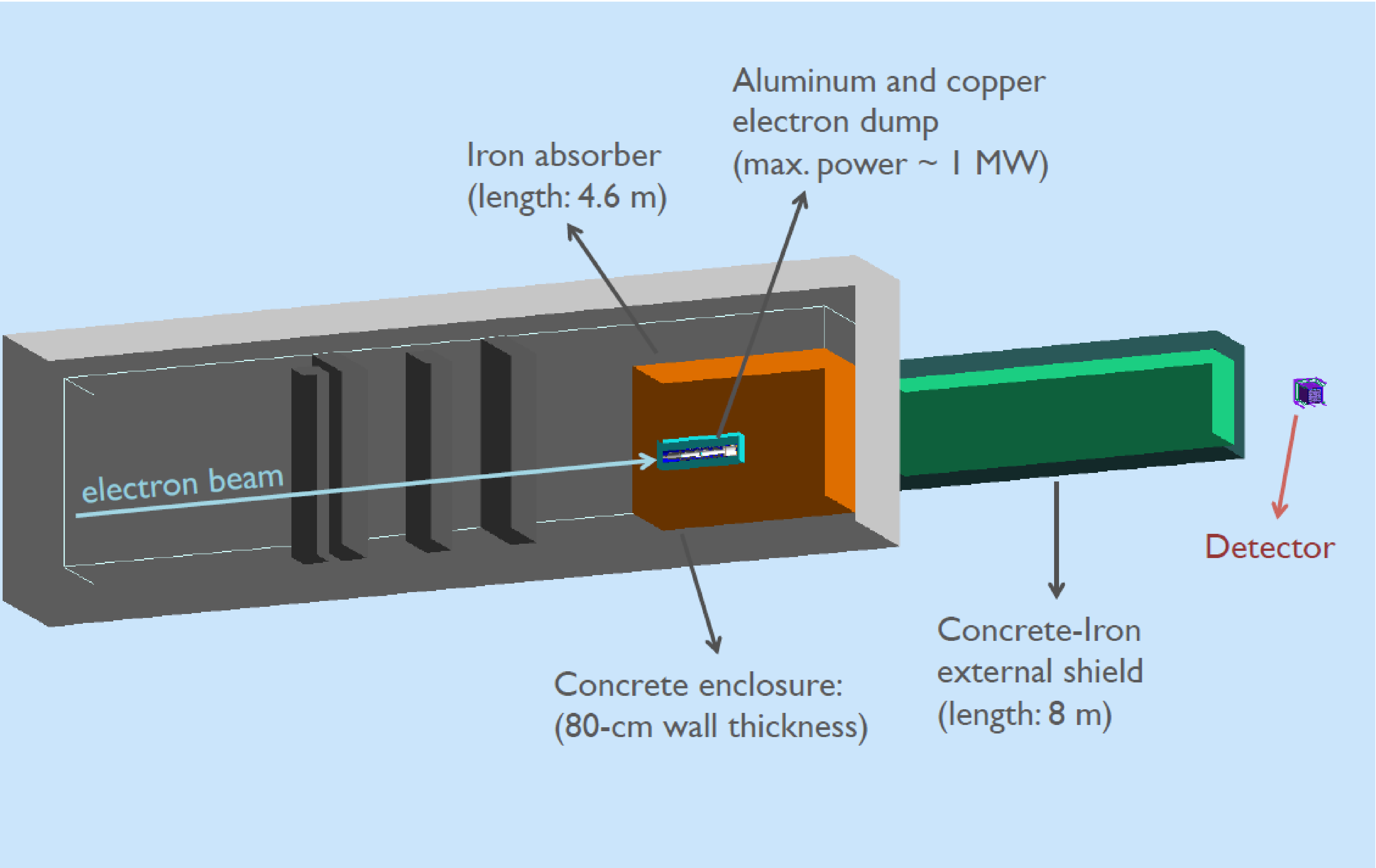
- Model beam dump geometry and materials
- Use Geant4 to simulate the interaction of the electrons in the dump
- Determine fluxes of particles exiting from the dump and reaching the detector location

GEANT4 setup: simulation based on GEMC (GEant4 Monte Carlo):

- Simulates passage of particles through matter based on Geant4 libraries
- Simulation parameters (geometry, materials fields, etc.) defined in databases (MYSQL, TXT, GDML, ...)
- Same GEMC executable is used for different detectors and experiments
- Can simulate beam structure (beam bunches, repetition rate, …)

Use high precision physics lists (QGSP_BERT_HP + EM_HP)

Beam-related backgrounds simulation: geometry

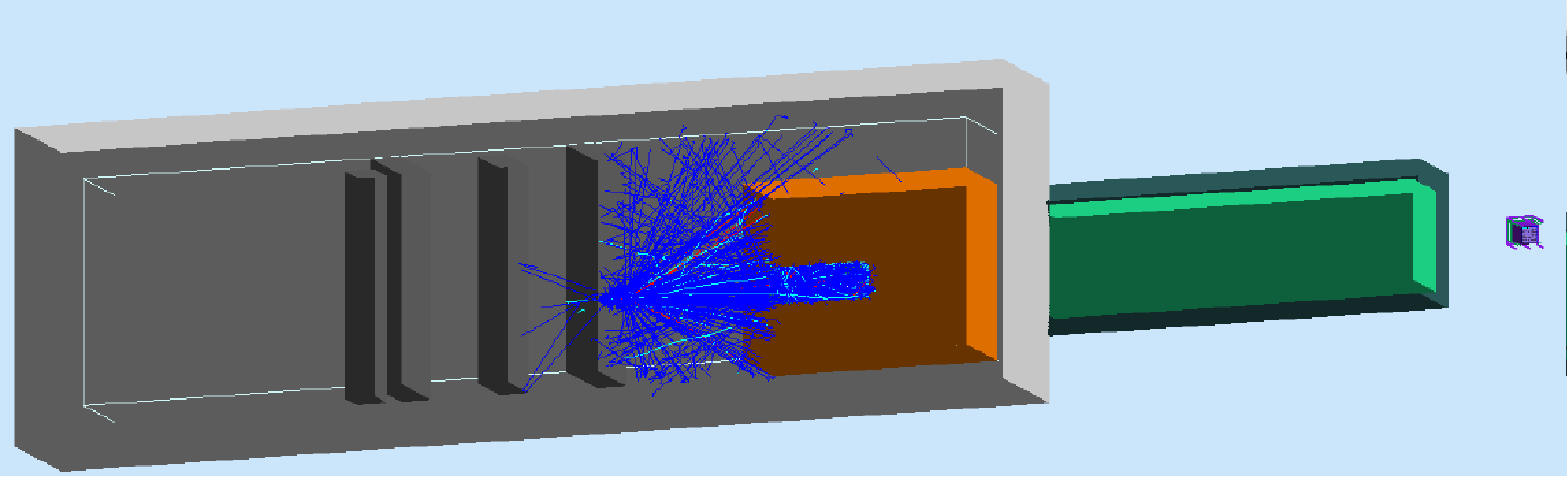


Beam-related backgrounds simulation: computing

Computing resources usage:

- 10000 EOT @ 11 GeV → 16 ps of beam on target at 100 μA
- ~ 3000 s computing time on an Intel Xeon (E5530), 2.4 GHz
- 1 month of simulations on a 200 cores farm (~3600 HepSpec2006), equivalent to $2\cdot10^9$ EOT (3.2 μs beam on target at 100 μA)
- Results would need to be extrapolated by more than 12-13 orders of magnitude to reach the desired experiment luminosity

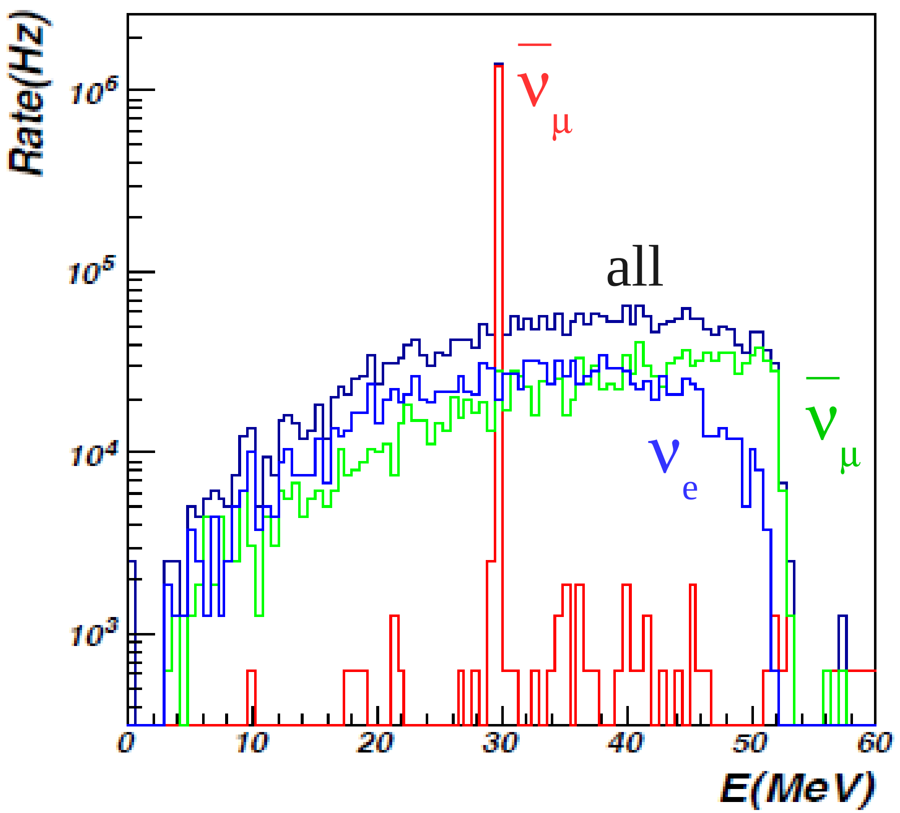
HepSpec2006: new HEP-wide benchmark for measuring CPU performance. Developed by the HEPiX Benchmarking Working Group: http://w3.hepix.org/benchmarks/doku.php/



Beam-related backgrounds simulation: brute force approach

Particle fluxes estimated at the detector location:

- Only particles observed are neutrinos and very low energy gammas (E<eV)
- Neutrinos originates from pion and muons decay at rest within the main iron absorber: isotropic process
  - Energy range: 0-60 MeV
  - Flux scales with primary beam energy and square of dump-detector distance.
- **No other particles are observed**



Beam-related backgrounds simulation: full luminosity

How to obtain full-luminosity background estimates:

- Estimated non-zero neutrino rate can be extrapolated "safely" to full luminosity
- Zero rates observed for neutrons and gammas...
  - This only allows to set an upper limit
- Increase of computing power or efficiency can gain 2-3 orders of magnitude, but cannot reach 10^{22} EOT

A different approach is required:

- Rely on GEANT4 for treatment of high energy (GeV to MeV) interactions
- Sample particle fluxes at different depths within the dump absorbers to study the flux profile and find non-zero values
- Extrapolate non-zero fluxes to full luminosity based on flux profile
- Validate results for low energy neutrons/gamma with different simulation tools (MCNP) and using variance reduction techniques

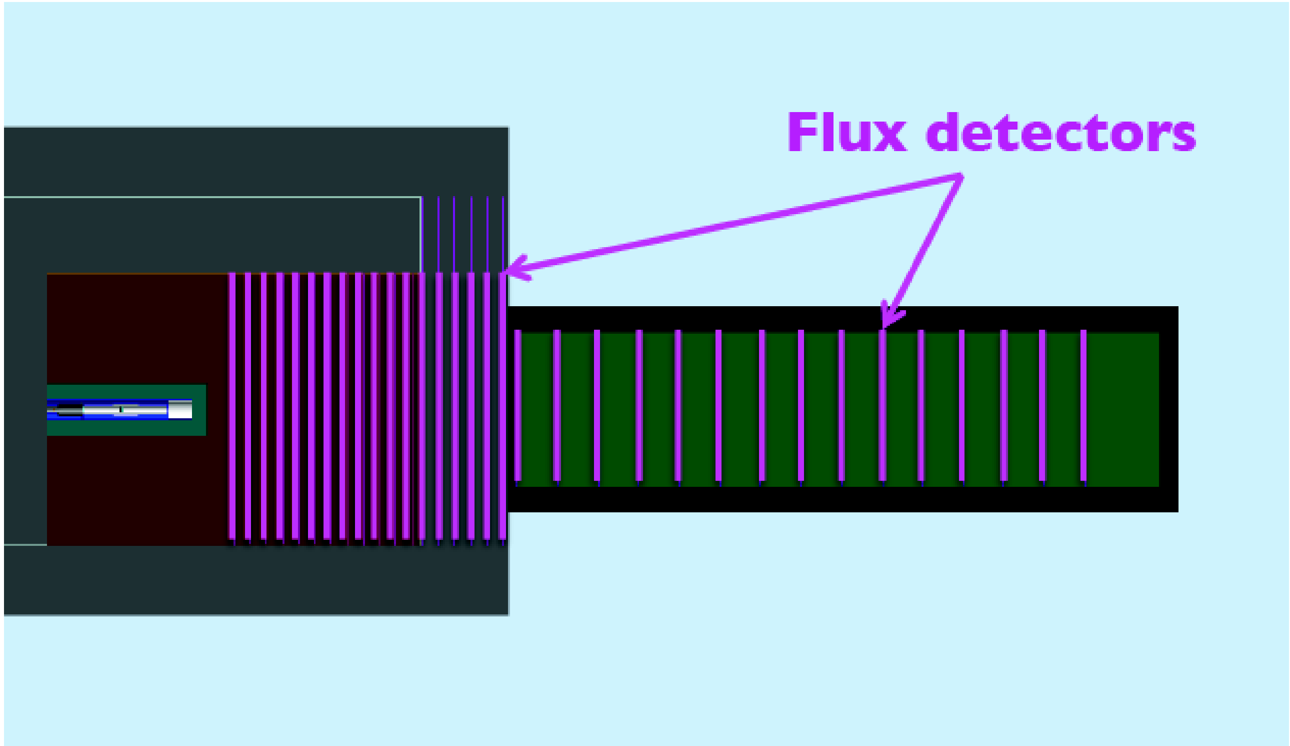
Flux detector:

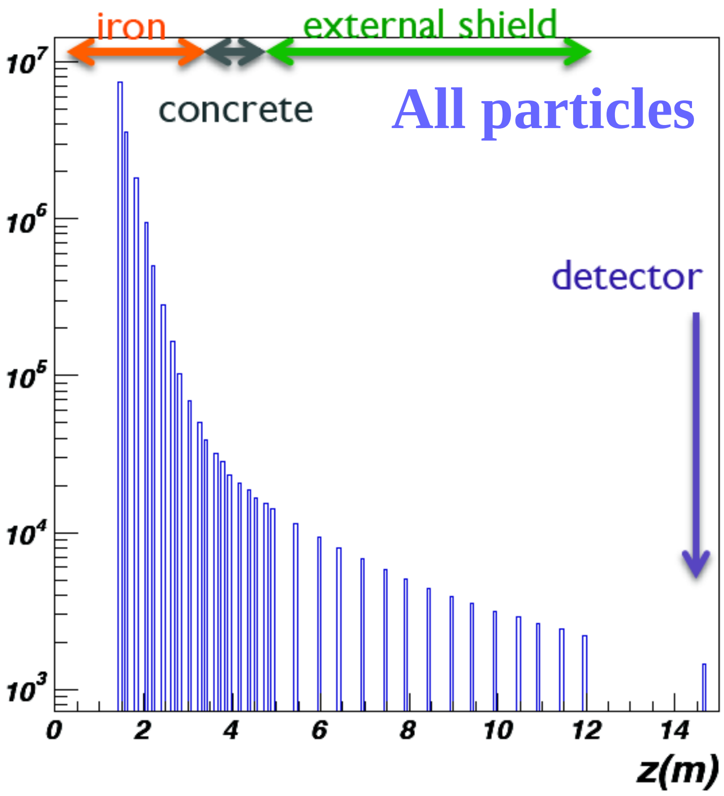
- "Ideal" 2D-detector
- For **all** passing particles it forces an hit, recording exactly:
  - Hit position
  - Particle id
  - Particle 4- momentum

Beam-related backgrounds simulation: full luminosity

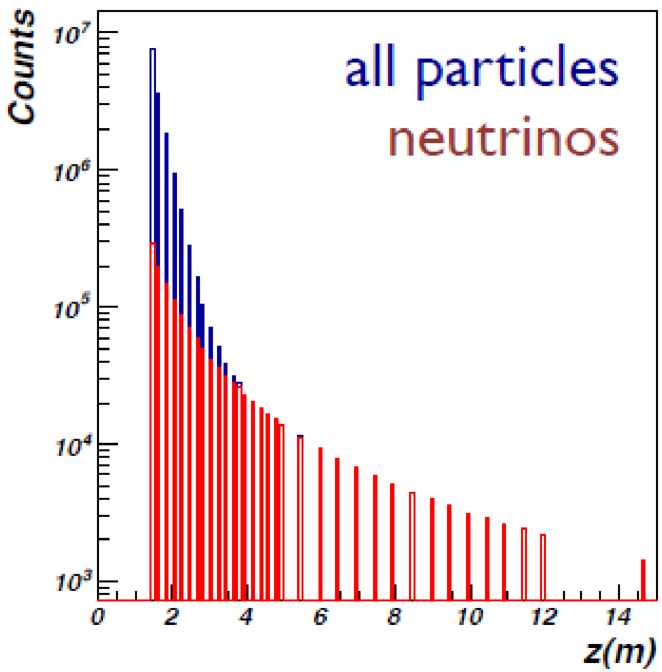
Flux-profile sampling:

- Sampled particles crossing XY planes at different position along the beam direction with “flux” detectors.
- Checked particle types and energy spectra as a function of depth within the dump absorbers.

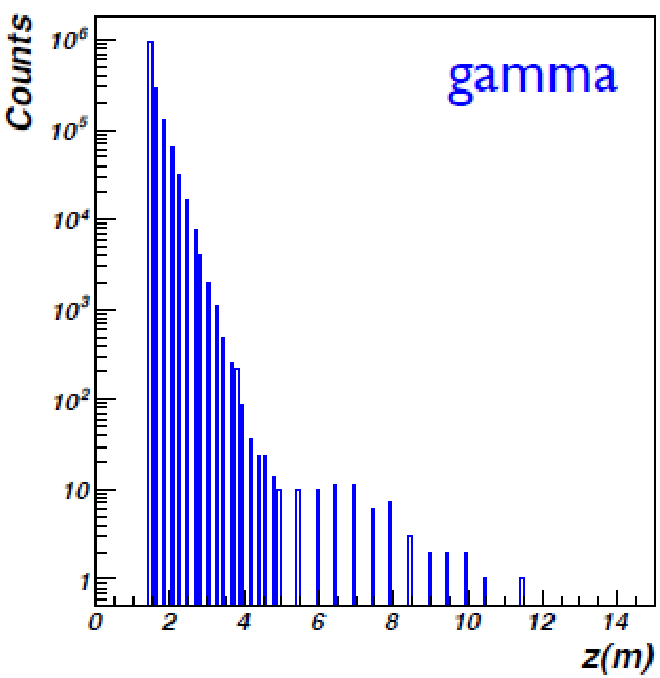


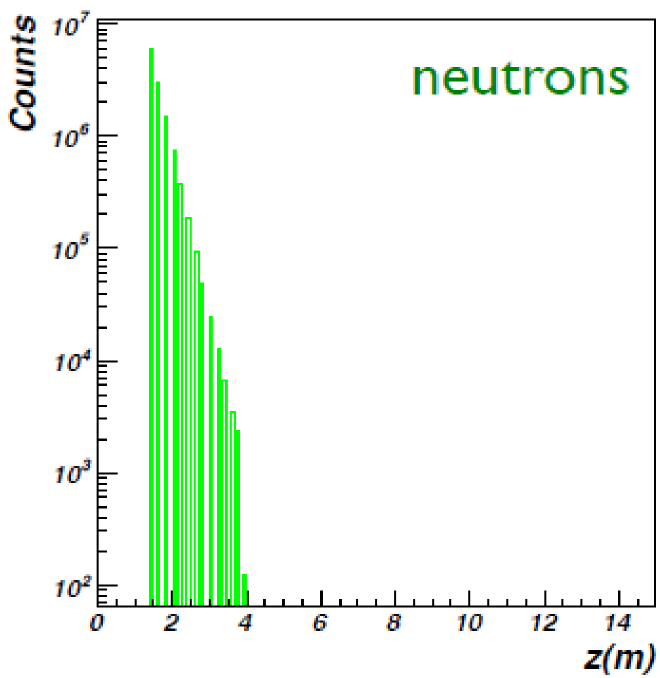


Beam-related backgrounds simulation: full luminosity



- Overall particle flux is dominated by gamma and neutrons for the first 2 m and by neutrinos at larger depths.
- Gamma:
  - Flux reduction of factor 3600 in 2.2 m of iron
  - Gamma detected after the iron absorber < keV energies
- Neutrons:
  - Attenuation of factor ~1700 in 2.2 m iron
  - Attenuation of factor ~4.3 in 10 cm of concrete
  - < 1 neutron @ 10^{22} EOT after ~3.5 m of concrete





Residual flux dominated by thermal neutrons: validation with specific tools is required

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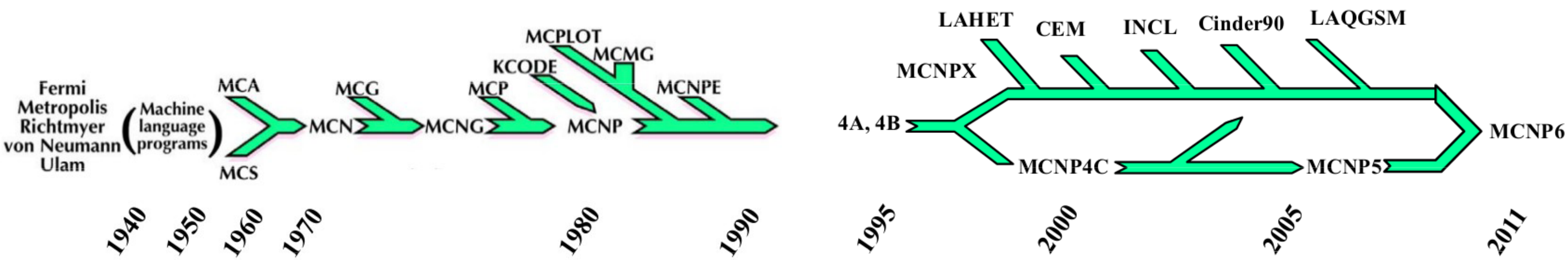
Monte Carlo N-Particle (MCNP)

General Transport Code developed at Los Alamos: more than 70 years of history!



Monte Carlo transport of particles

- MCNP5: neutrons, photons, electrons
- MCNPX: focus on high-energy physics
- MCNP6: merged code.

Features:

- 3D general geometry
- PC, Mac, Linux, Unix, Sun
- Parallel (MPI + threads)
- 350k+ lines of Fortran code
- Extensive verification/validation

- 400+ person/years development
- 10k+ users
- 15k+ citations
- Distributed by RSICC code center
- Export controlled

[MCNP: https://mcnp.lanl.gov/]

Monte Carlo N-Particle (MCNP): applications

MCNP is traditionally used (not exclusively!) in nuclear-physics fields

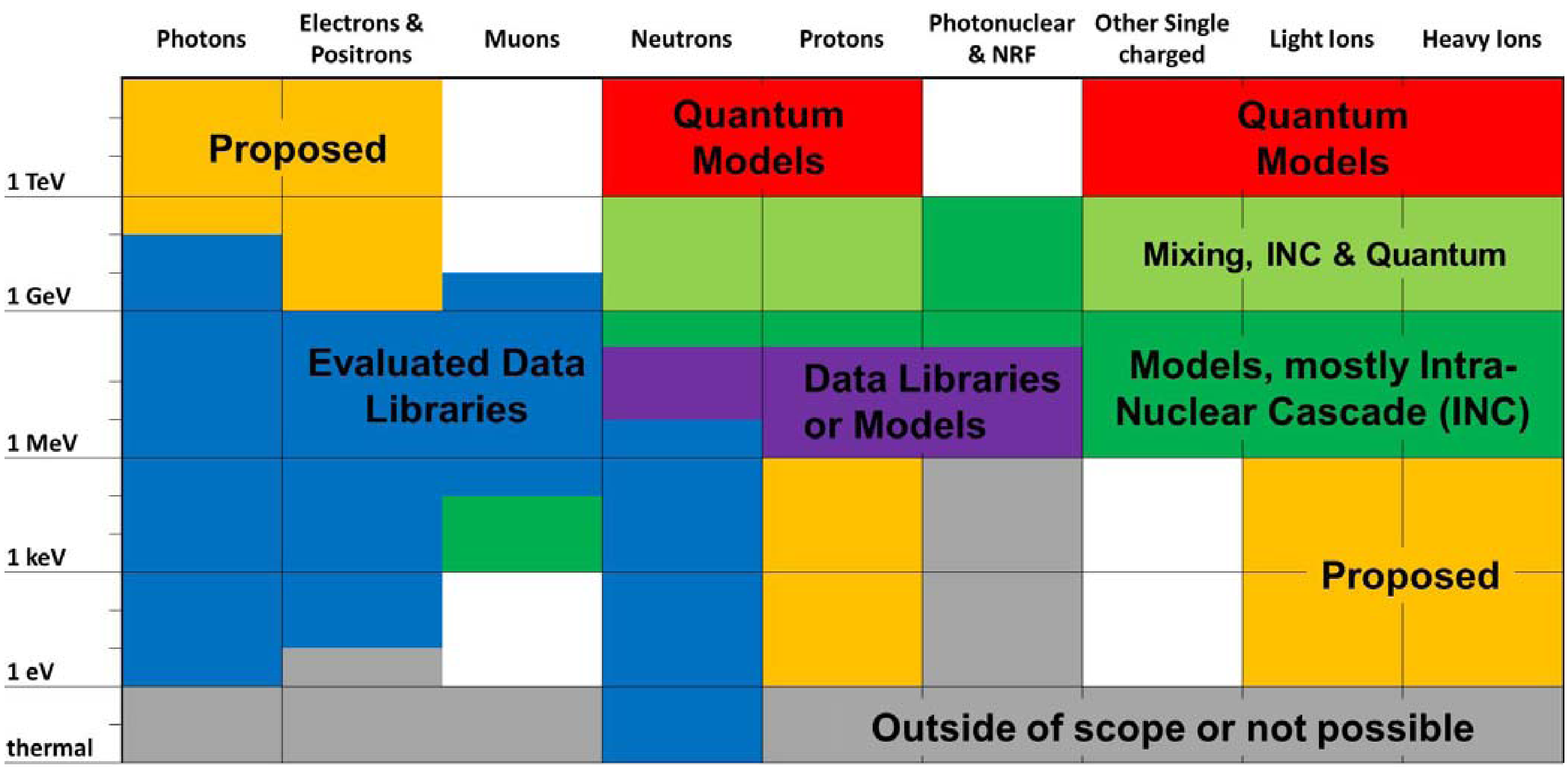
- Nuclear critical safety
- Radiation shielding
- Detector design and analysis
- Nuclear Well logging
- Personnel dosimetry
- Health physics
- Medical physics and radiotherapy
- Accelerator target design
- Fission and fusion reactor design
- Waste storage/disposal
- Radiography
- Aerospace applications
- Decontamination and decommissioning
- Nuclear Safeguards

[MCNP: https://mcnp.lanl.gov/]

Monte Carlo N-Particle (MCNP): physics

MCNP is able to transport 37 different particle types.

- MCNP is physics rich – try to use best data, models, and theory
- Neutron, proton, electron and photon transport below a certain energy are based on data libraries by default



MCNP6 particle types, energy ranges and interaction physics.

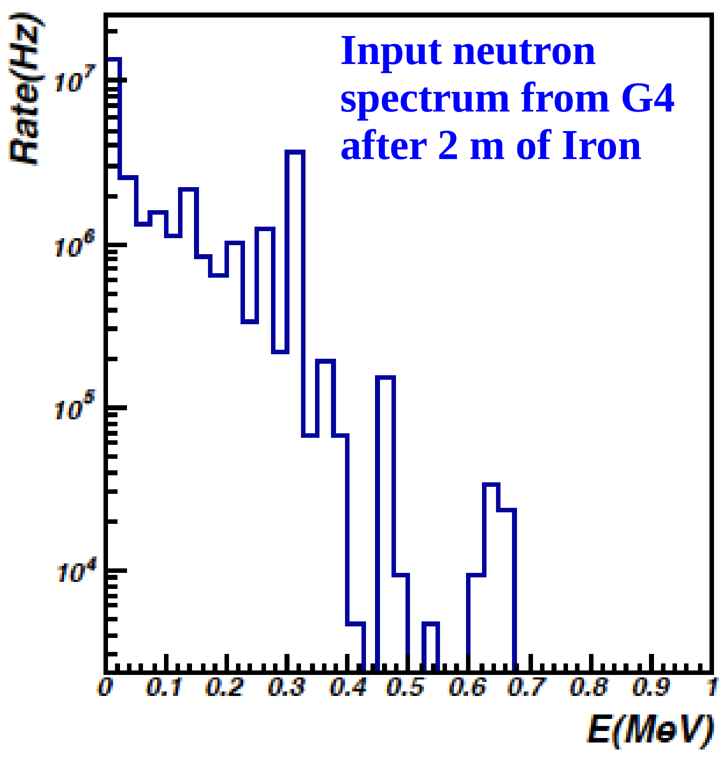
[J.T. Goorley et al., "Initial MCNP6 Release Overview"]

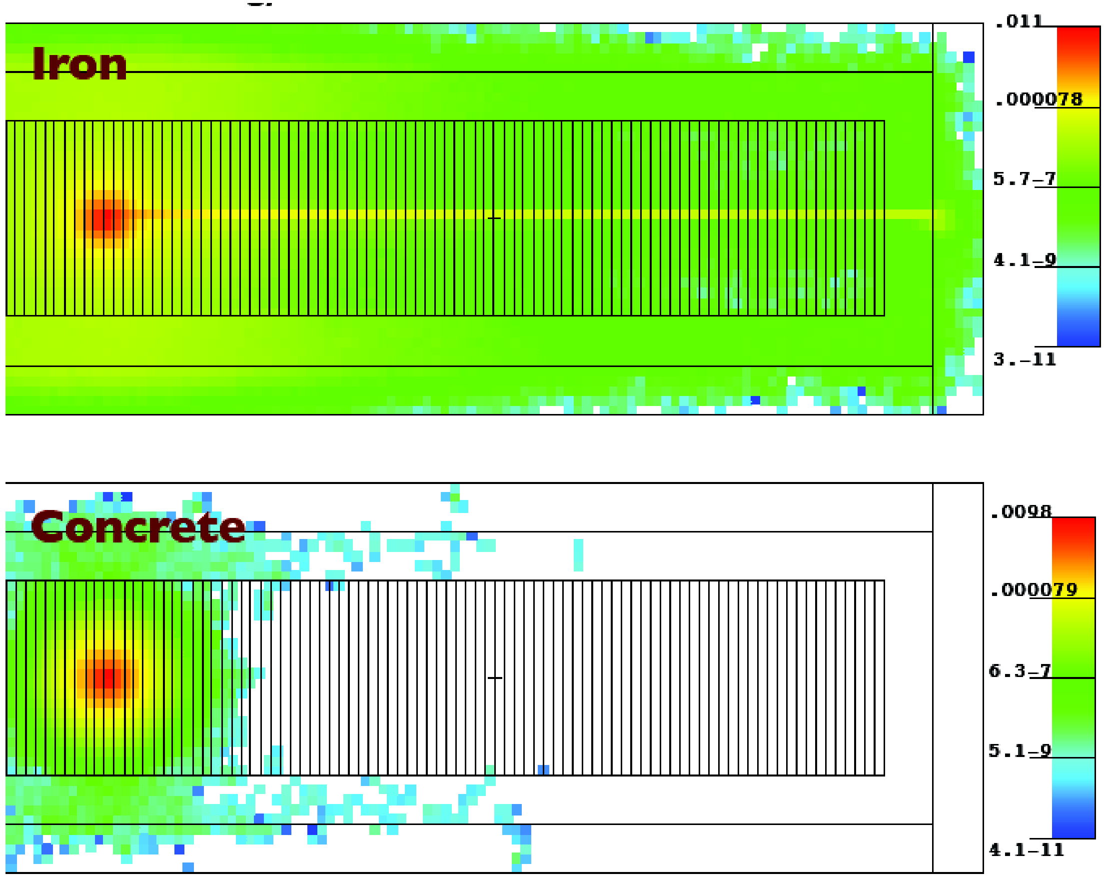
Beam-related backgrounds simulation: MCNP

Neutron flux in iron or concrete absorbers: computation strategy

- Use as initial (high-energy) neutron spectrum that from GEANT4 simulations
- Use MCNP to transport neutrons and photons down to thermal regime

Results:
- Large attenuation of neutron flux in concrete is confirmed
- Actual value strongly depends on neutron energy and dump structure

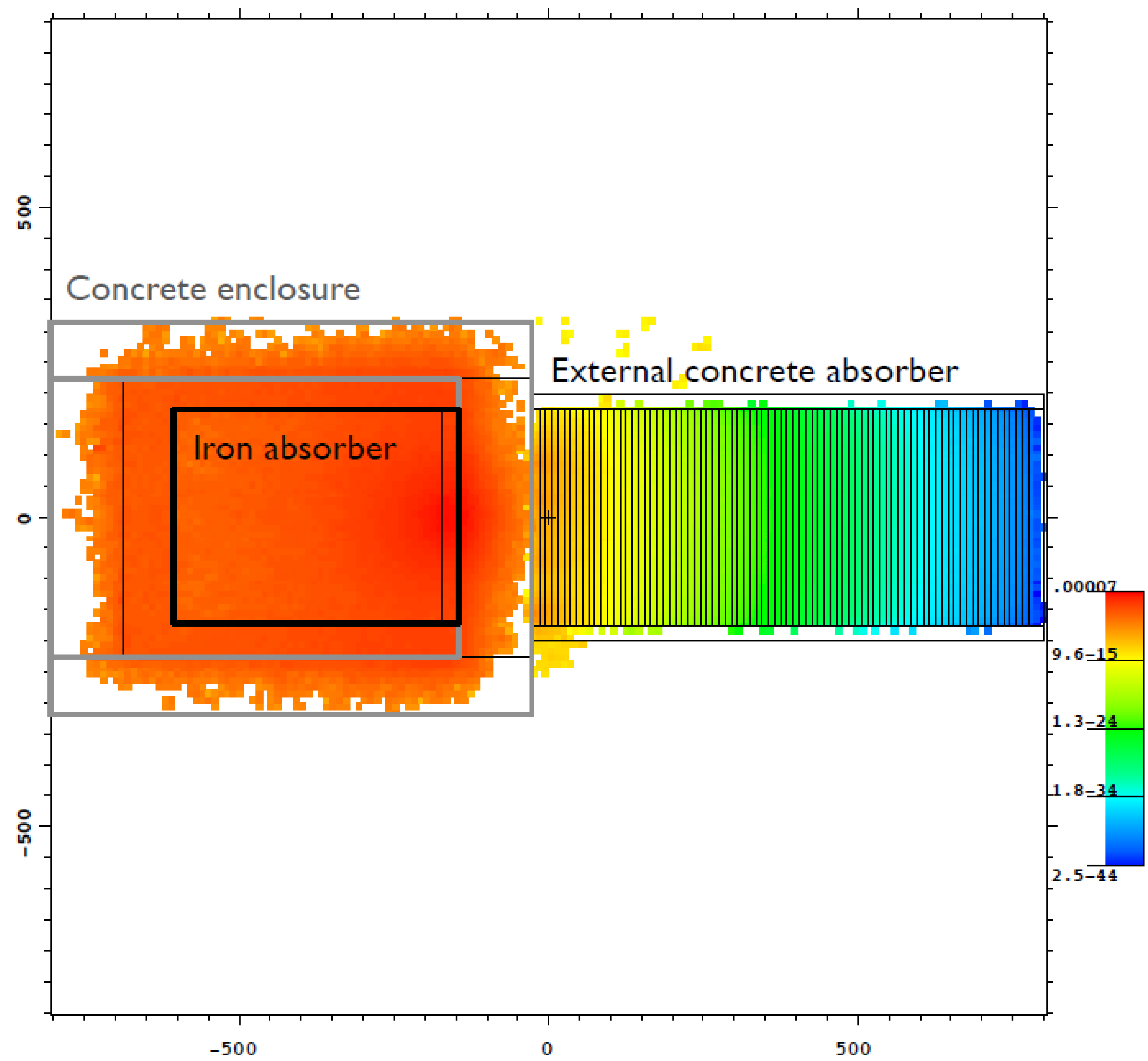




Beam-related backgrounds simulation: MCNP

First results for neutron rates with full dump geometry

- Initial neutron spectrum in iron absorber from G4 simulations
- Only thermal neutrons are exiting from the concrete enclosure
- Neutron flux attenuated by factor ~2.5 every 10 cm
- **< 1 neutron @ 10^{22} EOT after 3 m of concrete**



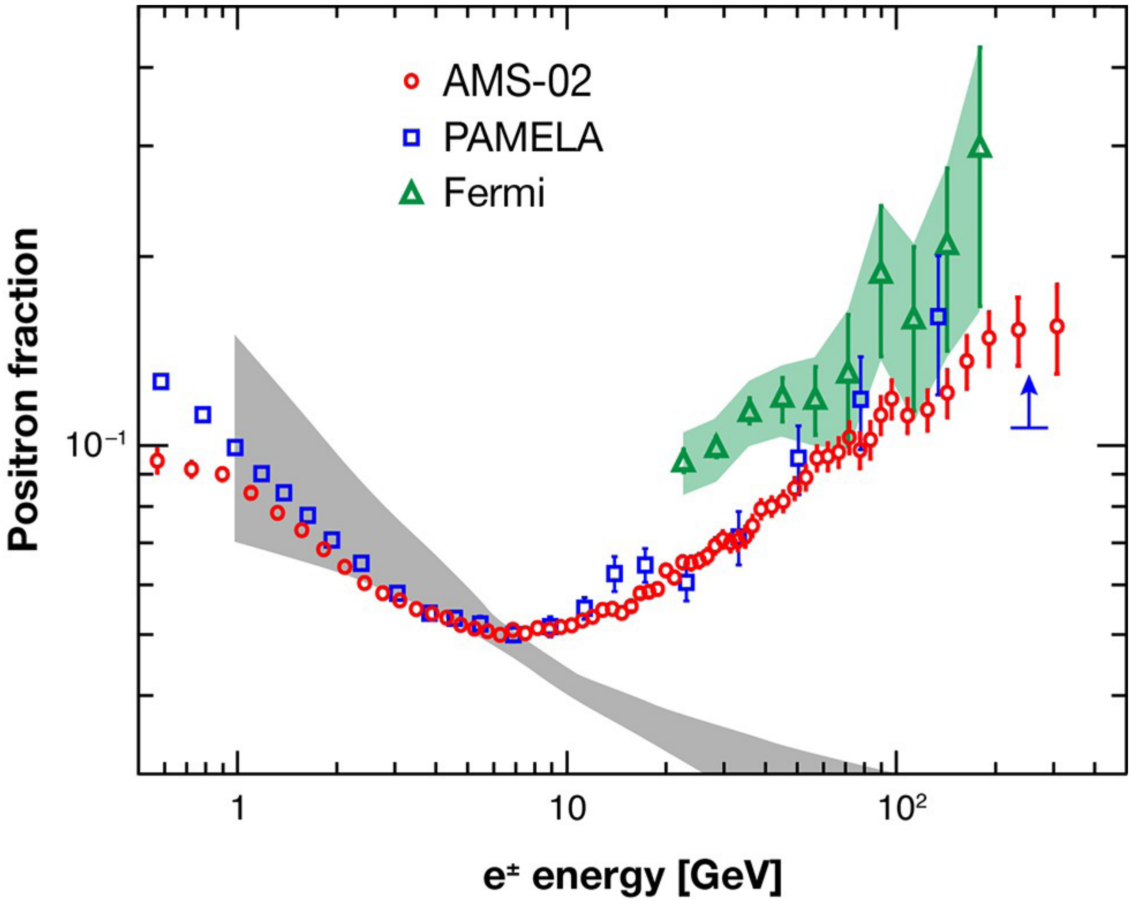
Thanks for your attention!

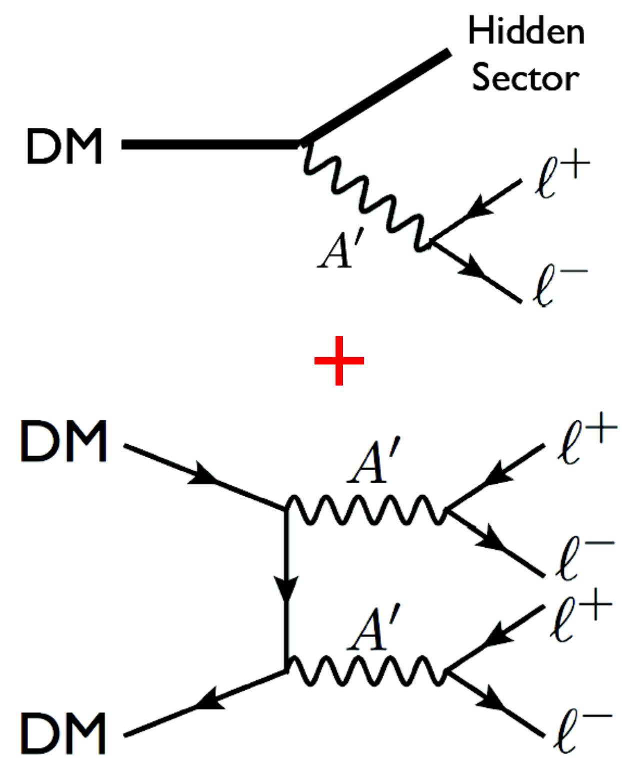
Back up

Hints for A' existence: astrophysics

Cosmic positron fraction excess (AMS, FERMI, PAMELA)

- This anomaly could be explained by dark matter decaying or annihilating in A', which then decays to $e^+ e^-$
- No excess measured in anti-proton fraction: light A' ($M_{A'}$ < ~ 2 GeV)





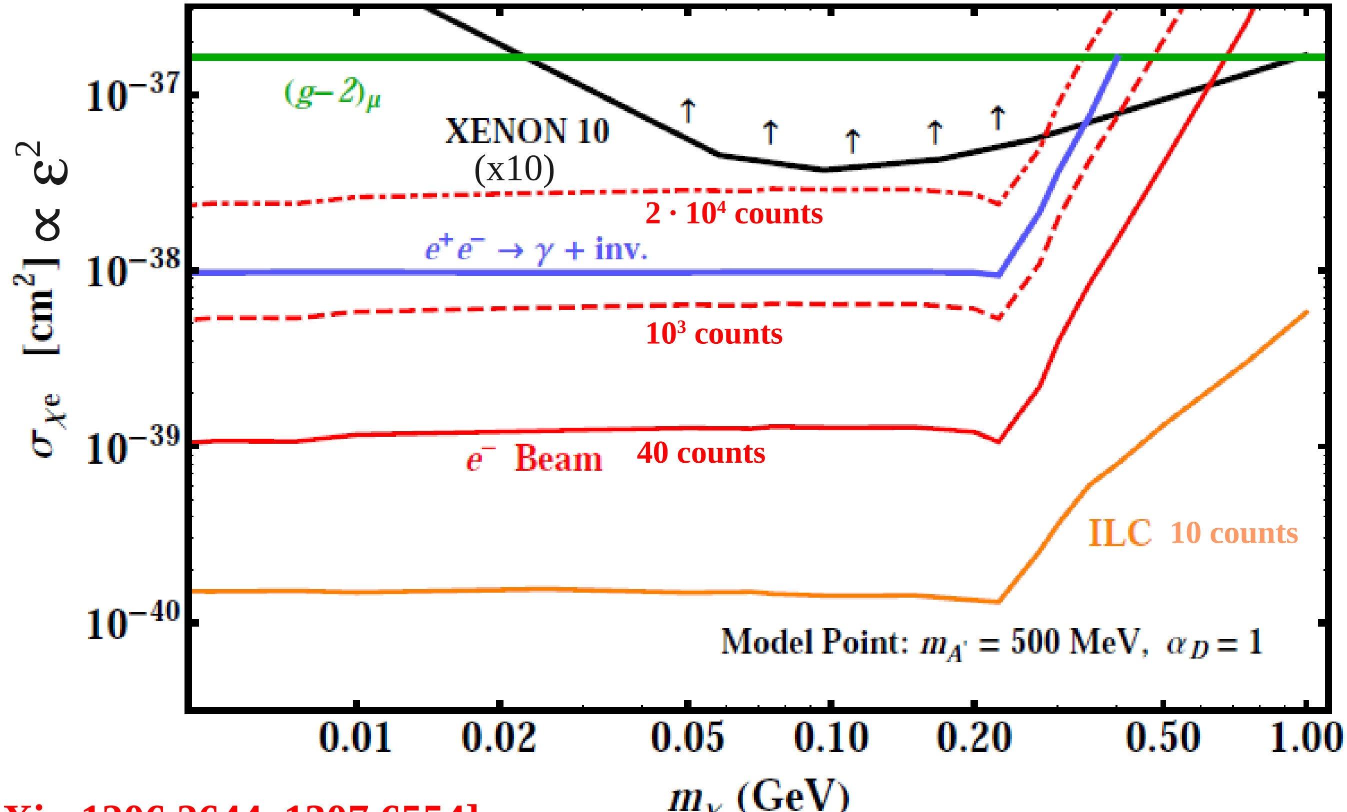
[M. Aguilar et al. PRL 110 141102]

Possible reach

Reach for a "benchmark" beam-dump experiment at an electron machine:

- 10^{22} EOT, 12 GeV / 125 GeV (ILC)
- 1 year of run
- 1 m^3 detector, ρ=1 g/cm^3, placed 20 m from the beam dump

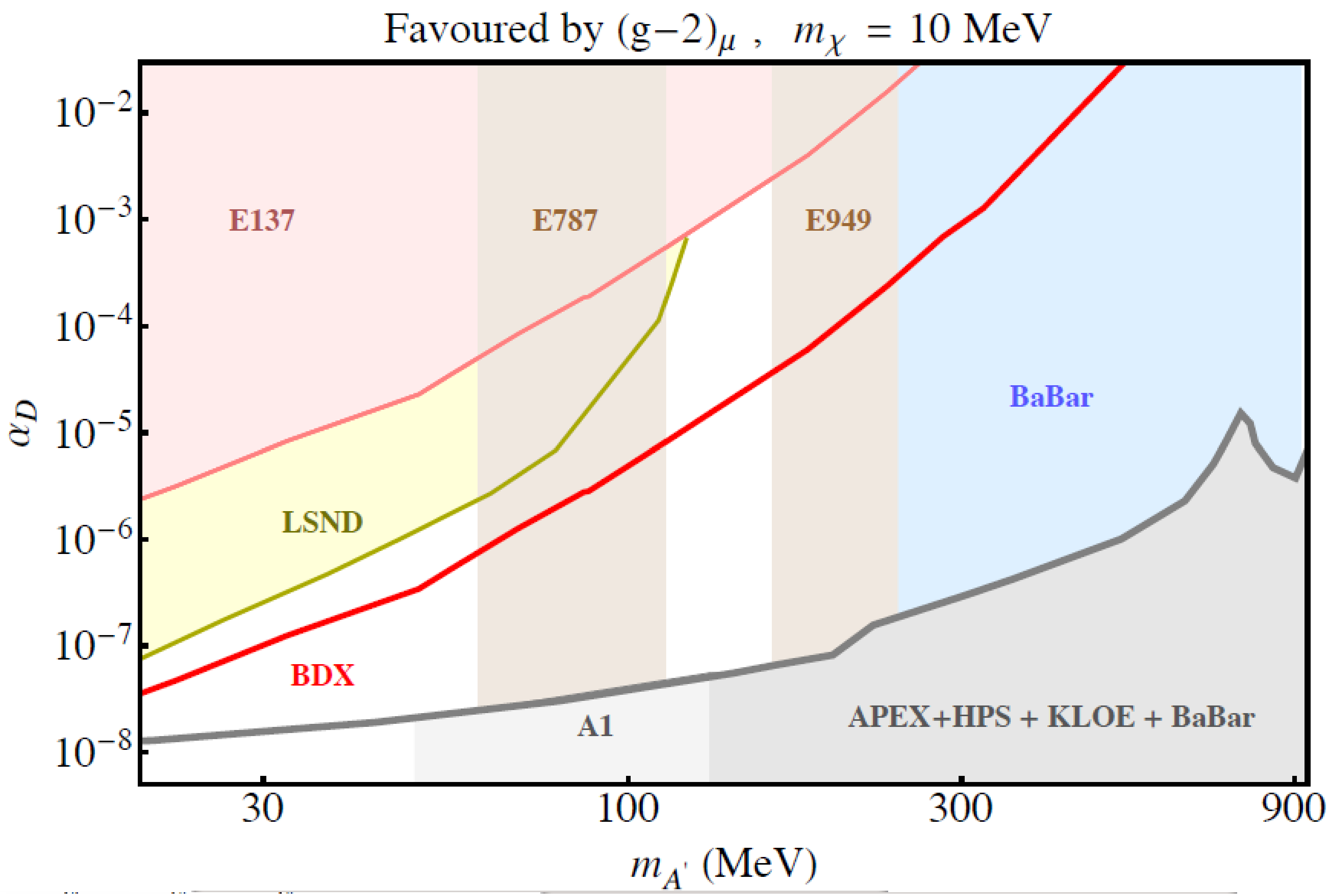
In the low-mass region (m_χ < 1 GeV), the reach of a beam-dump like experiment is O(100-1000) better than a traditional direct-search experiment.



For XENON10,
$\rho_{DM} = \rho_\chi =$ 0.4 GeV/cm^3

[arXiv:1206.2644, 1307.6554]

BDX contribution to the g-2 "puzzle"



MiniBooNE

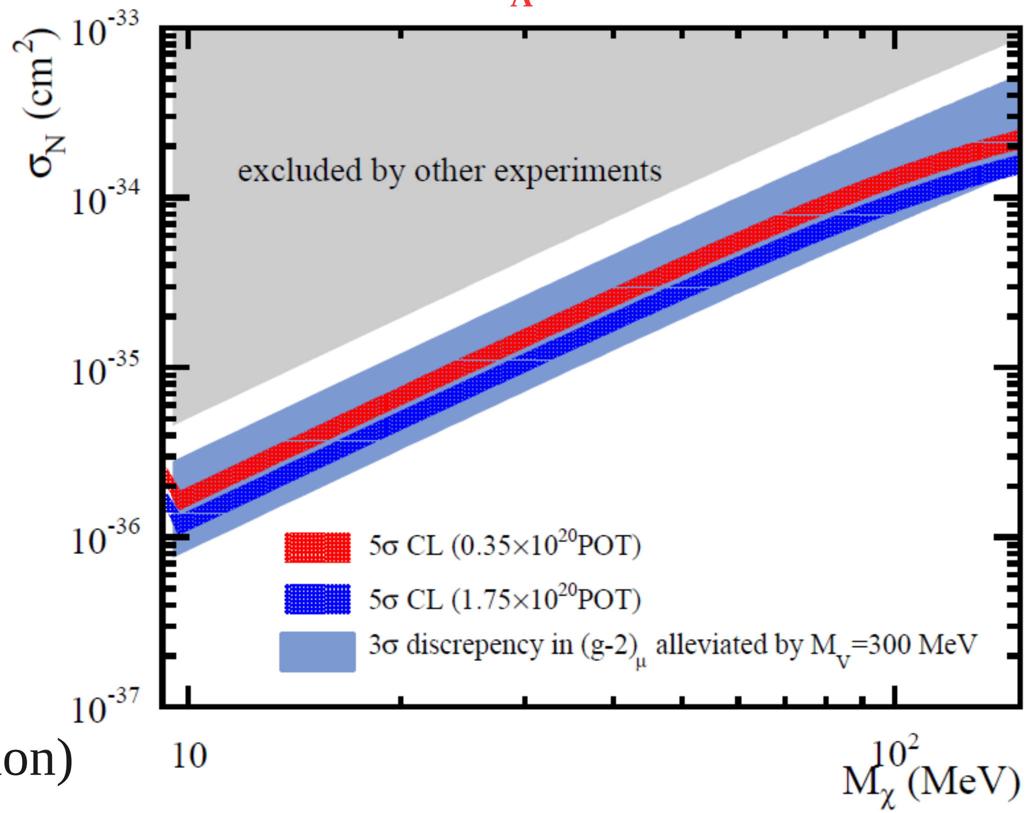
MiniBooNE DM search:

- 8 GeV protons on a 50m beam dump
- Detector ~ 500 m after the beam dump
  - 800 t mineral oil, 1280 PMTs

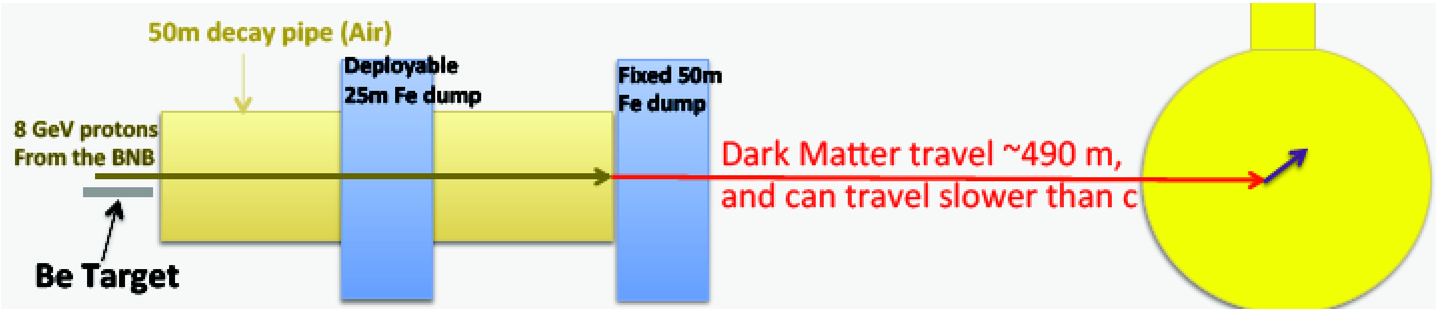
MiniBooNE test run (2013):

- 0.4 10^{20} protons on target
- "Off-axis" configuration to reduce ν background (reduction factor ~ 42)
- Selection cuts for DM events:
  - Timing (χ can travel slower than c)
  - Energy (different χ–ν energy deposition)

Preliminary, $M_{A'}$=300 MeV, α'=0.1

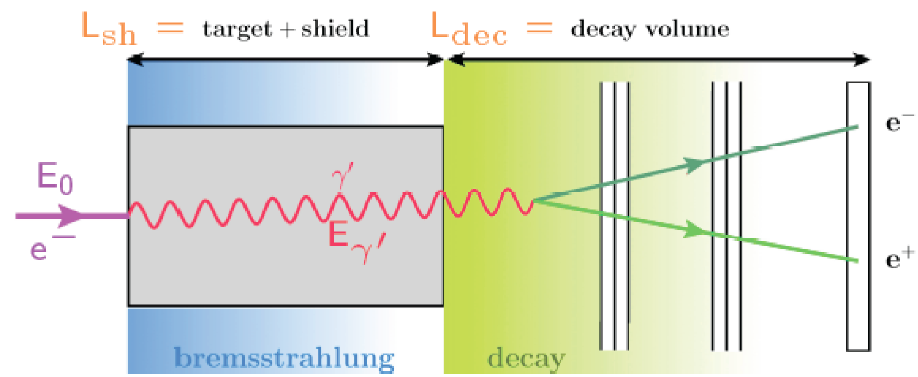


MiniBooNE 2014 proposal: 2 10^{20} PoT



First generation fixed target experiments: beam dump

Beam dump experiments for A' search:



- e^- beam incident on thick target
- A' is produce in a process similar to ordinary Bremsstrahlung
- A', emitted forward at small angle, carries most of the beam energy and decays before the detector
- Decay products are measured in the detector

$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,\left(10^{-8}\alpha/\alpha'\right)$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$