MadDump: a Monte Carlo tool for BSM searches at beam dump experiments

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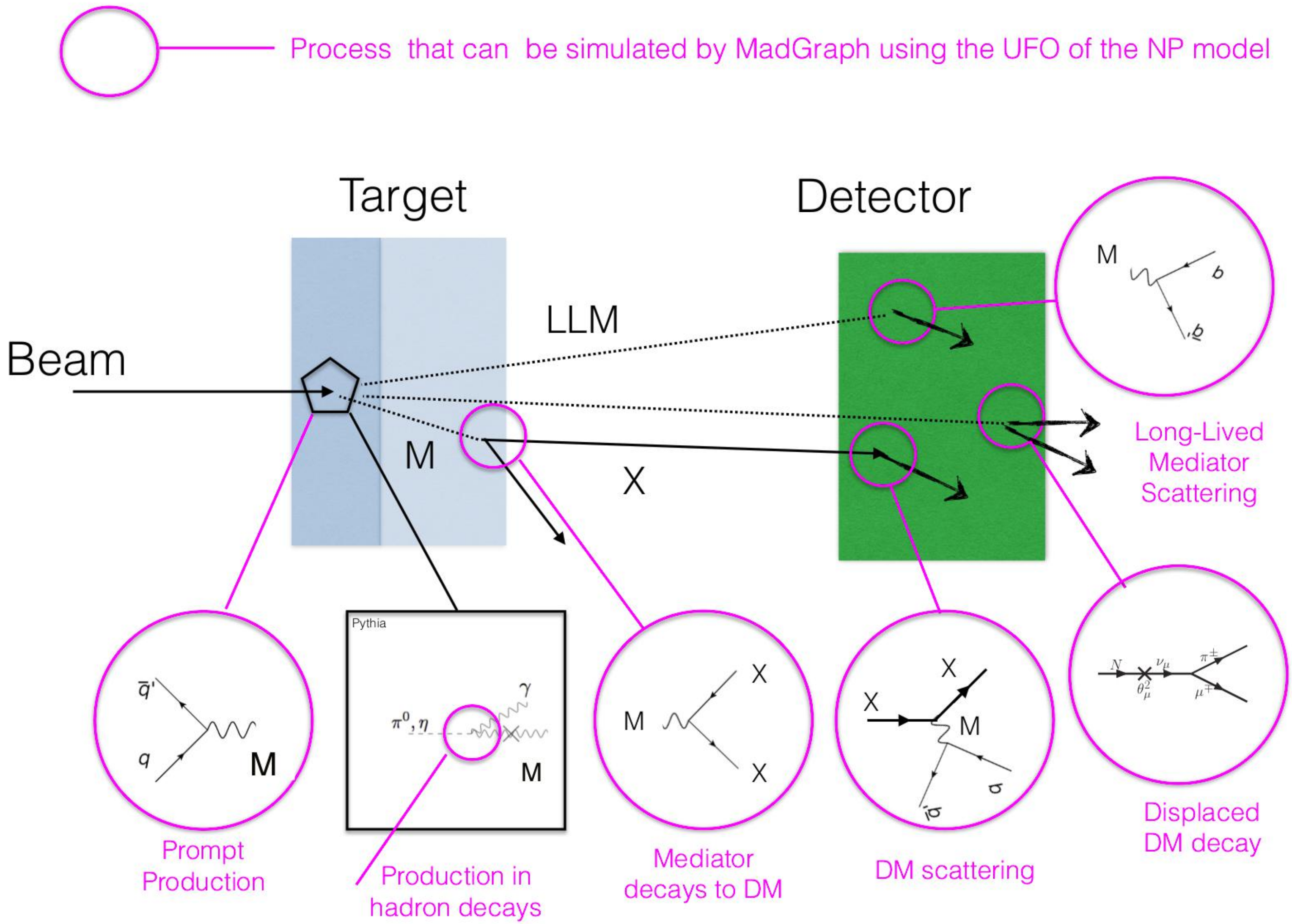
Outline

- Motivations
- How MadDump works: basic workflow and MC algorithms
- Preliminary results (SHiP physical case)
- Summary and outlook

Relevant physics scenarios: an overview



Relevant physics scenarios: our goals

Embed all BSM physics **in a single tool** which:

- Is easy to extend with new models
- Computes acceptance
- Computes event distributions
- Generates unweighted events

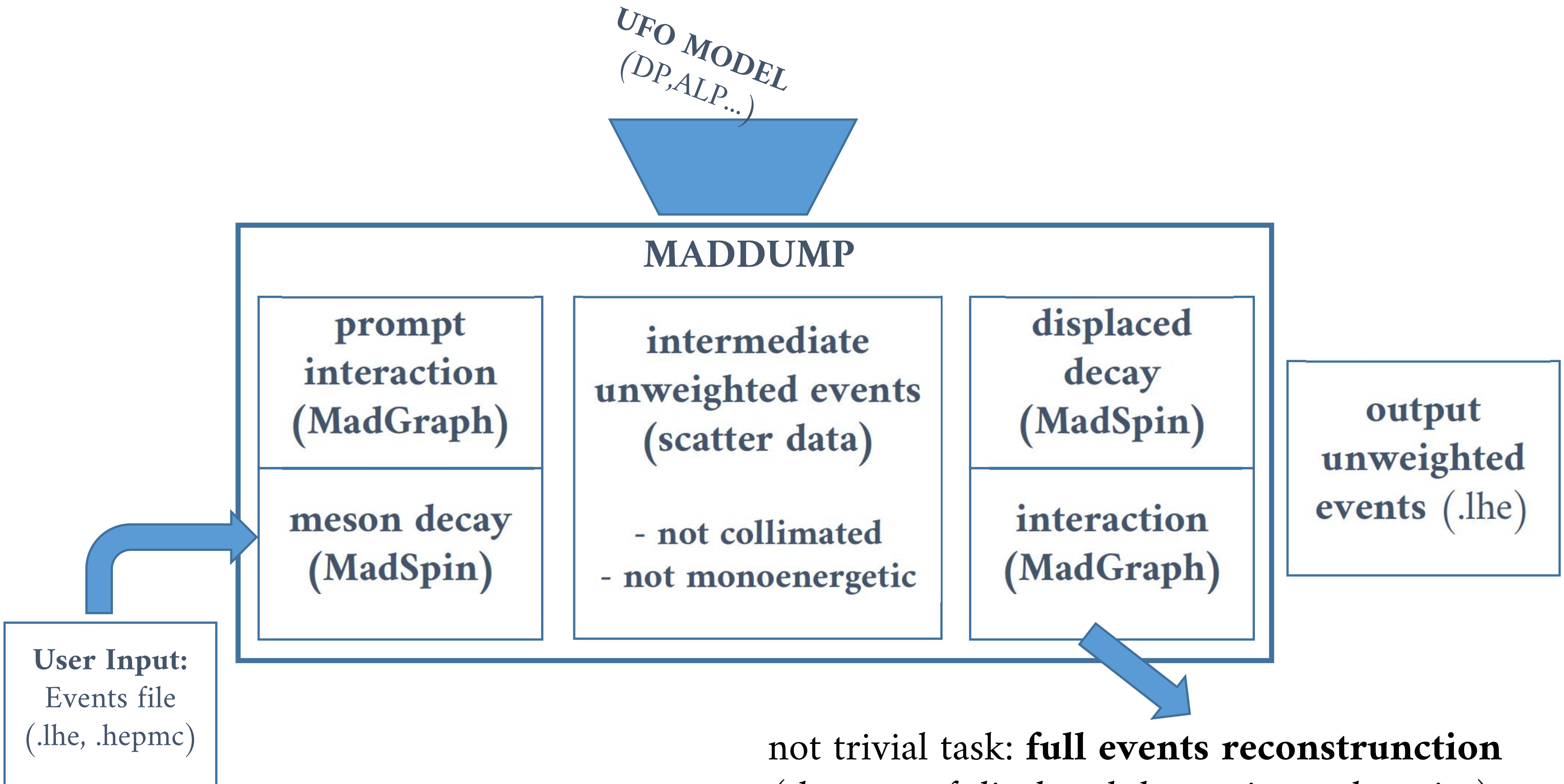
and provides automation for the following tasks:

- **widths computation**
- **scan** over relevant parameter space

Why a MadGraph plugin?

- Mature generator, **well established** (large community among CMS/ATLAS), lots of functionalities (dedicated module for **decay** (MadSpin), **auto-width, parameter scan**)
- **Constantly** developed and **improved**
- **Flexible** multipourposes generator: it works with every model defined by a **UFO** descriptor file
- **Easy to interface** to other external tools (parton showers, detector simulation programs, analysis tools, etc)
- **Easy to extend** through plugin development (in Python)
- **User-friendly** interface

MadDump: basic workflow



not trivial task: **full events reconstrunction**
(the case of displaced decays is much easier)

BSM physics emboded in a **single tool**:

- **one model** and **one parameter card** (avoid possible mistakes!)
- **one input file** (change the UFO, SM physics is the same!)

How it works in practice: main ingredients

- Incoming DM (scatter events) -> **flux in energy and other kinematical variables** (angles, positions)

- The interaction cross section is given by the **convolution integral** of the flux with the **elementary 'partonic'** cross section

- Detector properties (geometrical acceptance, energy threshold,...) are taken into account through an **efficiency function**

$$\sigma = \int \mathrm{dEd}\vec{x}\,\phi(E,\vec{x})W(E,\vec{x})\hat{\sigma}(E)$$

flux function — $\phi(E,\vec{x})$; detection efficiency function — $W(E,\vec{x})$; 'partonic' cross section — $\hat{\sigma}(E)$

The partonic cross section **depends only on energy**

$$\tilde{\phi}(E) = \int d\vec{x}\,\phi(E,\vec{x})W(E,\vec{x})$$

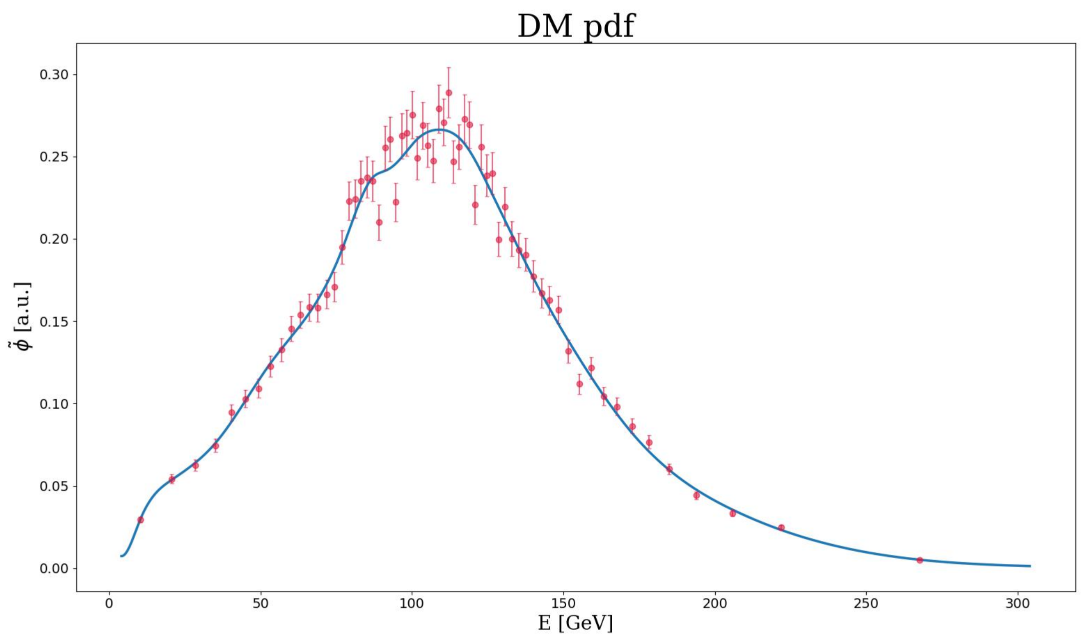
effective DM pdf
(one-dimensional)

How it works in practice: main ingredients

- It allows us to implement the process in the standard collision formalism (as in proton collisions), introducing a fake collimated beam of DM particles **along the beam axis**

- **Reweighting procedure** to take into account detector acceptance

- Estimates for **total rates only** (the information on angles and positions has been integrated over!)



Prompt production and geometrical acceptance for a SHiP-like configuration (~12% acceptance)

Red points: result of the reweighting procedure
Blue line: 1D-spline fit (to smooth the pdf behavior)

Full events reconstruction: strategy & approximations

Full reconstruction of the events a posteriori **is in priciple possible**:

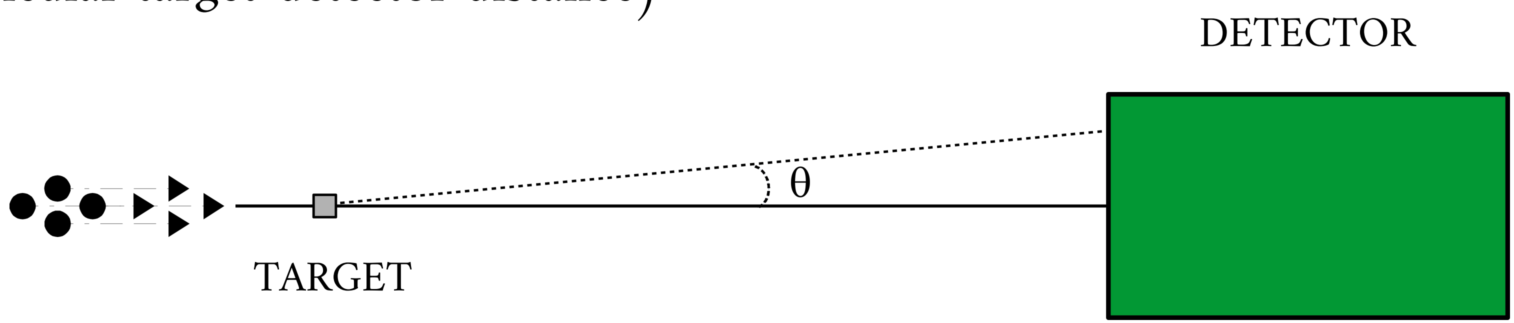
- given a fake event with energy E_0, generate (unweighted) the ***x*** vector according to

$$P(\vec{x})d\vec{x} = \tilde{\phi}(E,\vec{x})|_{E=E_0}d\vec{x}$$

- rotate/displace the original event

In practise, we are limited by the **multi-dimensional fitting issue**.

We solved fully the problem in the approximation of a **point-like target** (dimensions of the target smaller wrt the other characteristic distances, in particular target-detector distance)



2D Mesh Fitter: automation

Only **Energy-(polar)angle correlations** are relevant

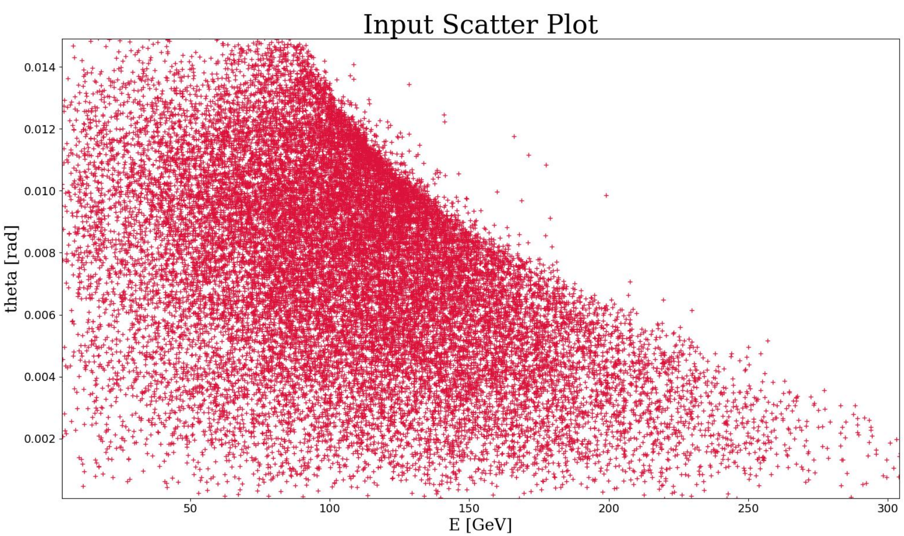
→ it's needed just a 2D fit
(not only for detector configuration with cylindrical symmetry,
in a moment!)

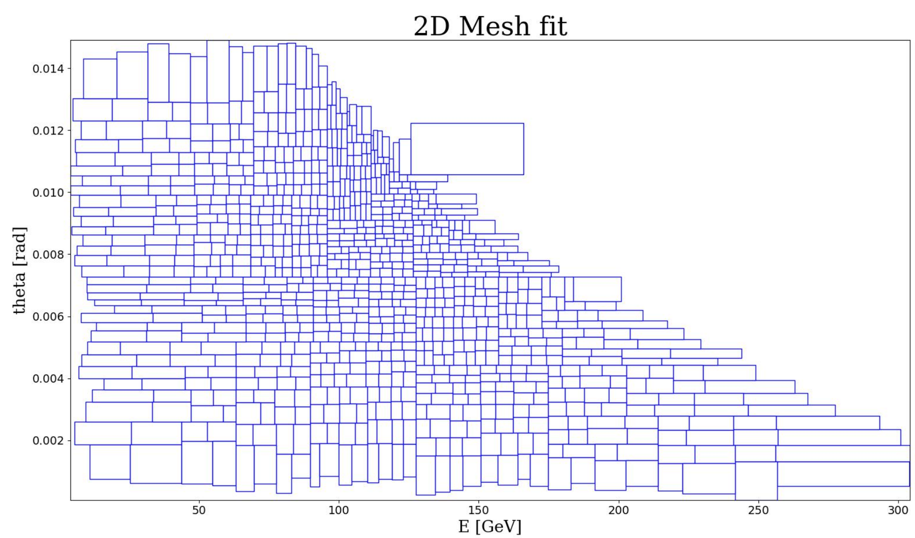
Automation issue

Fitting algorithm (fully integrated in the tool) which is

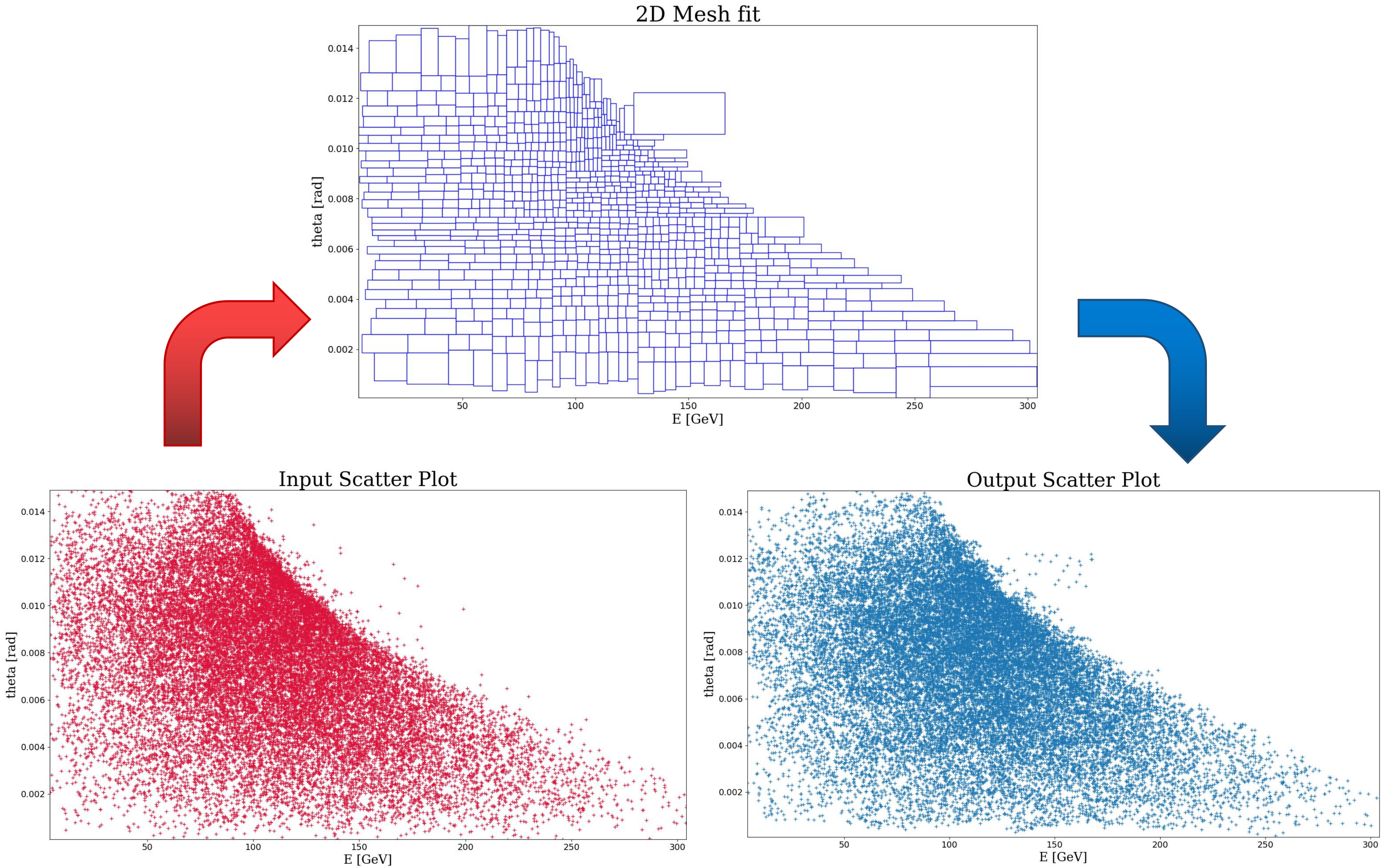
- flexible/adaptive
- fast and robust

We developed a smart 2D-histogramming procedure inspired by the adaptive MonteCarlo integrator (Vegas/Foam). It's an **iterative** process of **democratic splittings** according to the **principle of equal weight**.





2D Mesh Fitter: validation

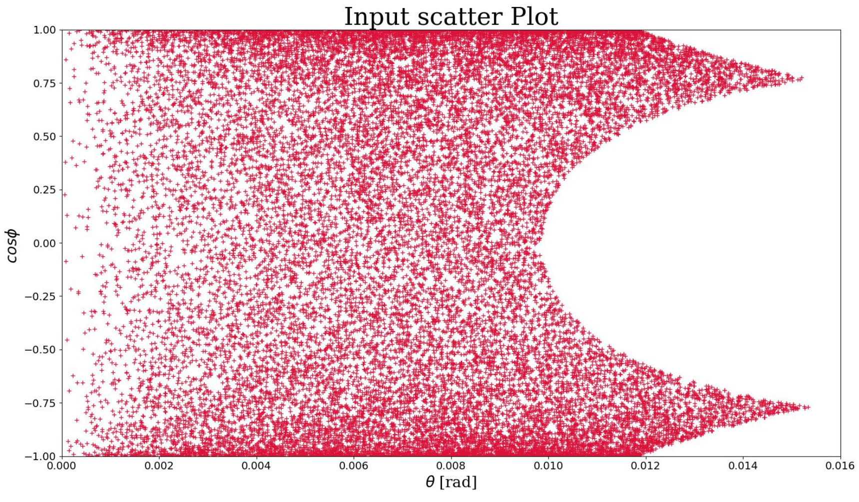


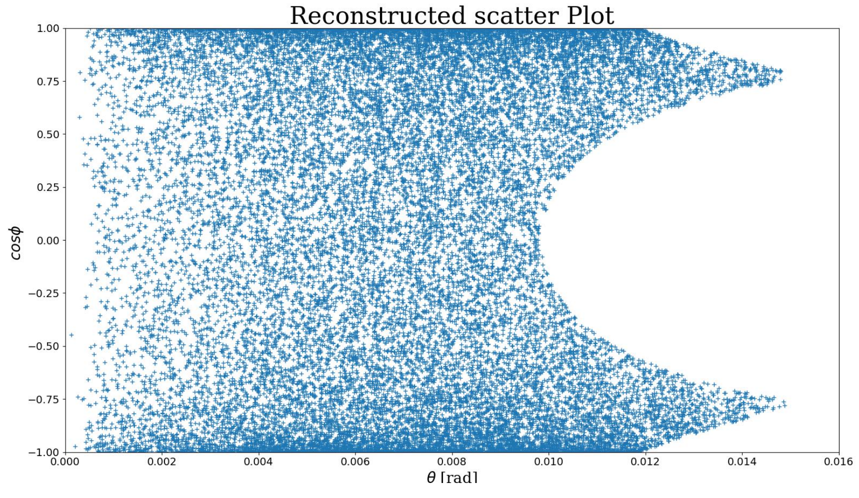
Full detector geometry

Assumption: physics at production point is cylindrical symmetric
(with respect to the beam axis)
Distributions wrt azimuthal angle (phi) is **flat**. No apriori energy-azimuthal or polar-azimuthal correlations.
The shape of the detector introduces correlations (geometrical constraints), between polar and azimuthal angles, as for a rectangular detector:

$$\theta_{\mathbf{min}} \leq \theta \leq \theta_{\mathbf{max}}, \quad \varphi_{\mathbf{min}}(\theta) \leq \varphi \leq \varphi_{\mathbf{max}}(\theta)$$

Strategy:
- DM pdf with reweighting for geometrical acceptance
- for each energy E, generate a polar angle according the 2D fit
- for each theta, generate a azimuthal angle uniformly in the constained region





Full detector geometry

Current Status:

- The same strategy has been applied also for **detector depth**
- Two basic geometric built-in in MadDump: cylindrical and rectangular ones (on-axis)
- **Displaced decays** (WIP): much easier (no reconstruction needed); the user can supply his own custom geometry as a python function.
- **Remark:** more realistic detector properties can be simulated interfacing the output of MadDump (unweighted events) with other tools (Geant,...)

Near Outlooks:

- More flexible way to add new detector configurations (quite straightforward), in particular for **off-axis** cases
- Detailed investigations on the main approximations

A selection of preliminary results

Sensitivity studies using MadDump alone

Analysed Models:

- GeV Leptophobic forces
- Sub GeV Dark Photon (presented at last PBC meeting)
- GeV scalar mediator

SHiP physical case:

- 2 $*10^{20}$ proton on target (Mo)
- distance target-detector 38.04 m
- parallelepiped on axis detector (90.3x74.9x321 cm^3)
  average density 5.0 g/cm^3

GeV leptophobic forces: the model

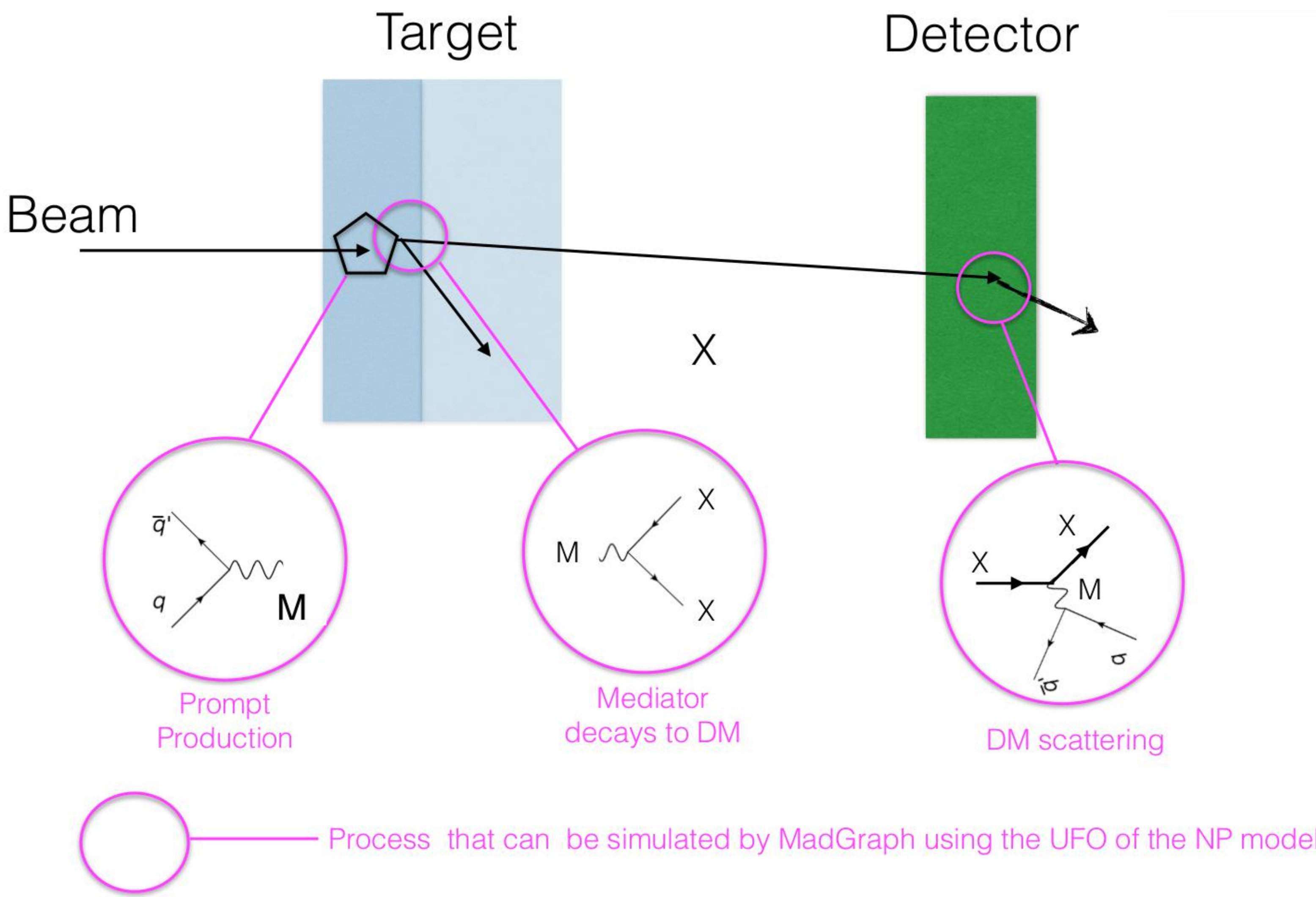
- BaBar sets stringent bounds on DM model coupled to electrons in the GeV mass range
- An interesting way to overpass them is to consider a 'leptophobic' model in which the global baryon symmetry is promoted to a local U(1) gauge charge
- We consider here the case of a spin-1 mediator (Z' mediator):

$$\mathcal{L}_q = \frac{g_z}{2} Z'_\mu \times \frac{1}{3} \sum_q \bar{q}\gamma^\mu q$$

$$\mathcal{L}_\chi = \frac{g_z}{2} Z'^\mu \times \begin{cases} z_\chi \overline{\psi}_\chi \gamma_\mu \psi_\chi, & \text{fermion} \\ i z_\chi \left[(\partial_\mu \phi^\dagger_\chi)\phi_\chi - \phi^\dagger_\chi \partial_\mu \phi_\chi \right] & \text{scalar} \end{cases}$$

- Existing bounds in the 1-10 GeV mass range come from **quarkonia invisible decays** and **monojets searches** (hadron colliders)

GeV leptophobic forces: simulation



GeV leptophobic forces: simulation

Input:

- UFO model (provided by B. Dobrescu)
- Cards:

  param_card.dat (couplings, masses, widths)
  fit2D_card.dat (detector parameters)
  run_card.dat (primary collision settings)

Command Listing (just for illustrative purposes)

```
import model DMZB
generate production p p > chidmsc chidmsc~
define darkmatter chidmsc
add process interaction @DIS
output lepto_1
launch
set ebeam1 400
set ebeam2 0.938
set ... (couplings, masses)
set mzb scan:[2,10]     #scan on the mass of the mediator
set wzb auto            #enable autowidth computation for zb
```

GeV leptophobic forces: fit2D_card.dat (illustrative)

```
#*********************************************************************
# Detector parameters
#*********************************************************************
   10000 =  nevts_interaction ! Number of events to be generated within the
interaction process
   19663072216.4         =  flux_norm ! Overall flux normalization
   True =  prod_xsec_in_norm ! whether multiply for the production cross section
   3804.75 =  d_target_detector ! Distance between the target and the detector in cm
   5.0    =  target_density ! average target density per unit cube (g/cm^-3)
#*********************************************************************
# Cuts on the detector shape
#*********************************************************************
     0.0     =  xc ! x coordinate central point wrt the beam axis
     0.0     =  yc ! y coordinate central point wrt the beam axis

     False    =  cylinder ! True = select cylindrical geometry
     0.0     =  theta_min ! >= 0
     1.57079632679     =  theta_max ! <= pi/2

     True    =  parallelepiped ! True = select parallepiped geometry
     90.3     =  x_side ! in cm
     74.9     =  y_side ! in cm

     321.0     =  depth ! both for cylinder and parallepiped

     4     =  ncores ! number of cores to be used by the fit routine. It must be a
power of two: 2,4,8,...
     True    =  testplot ! if True, store the table of the original data entering the
detector ('in_DM.dat')  and the plot of the 2D fitted mesh ('mesh2D.png') in the
corresponding /Events/XXX run directory
```

GeV leptophobic forces: results

1D-scan only on mass parameter of the mediator

(xsecs scale with the coupling)

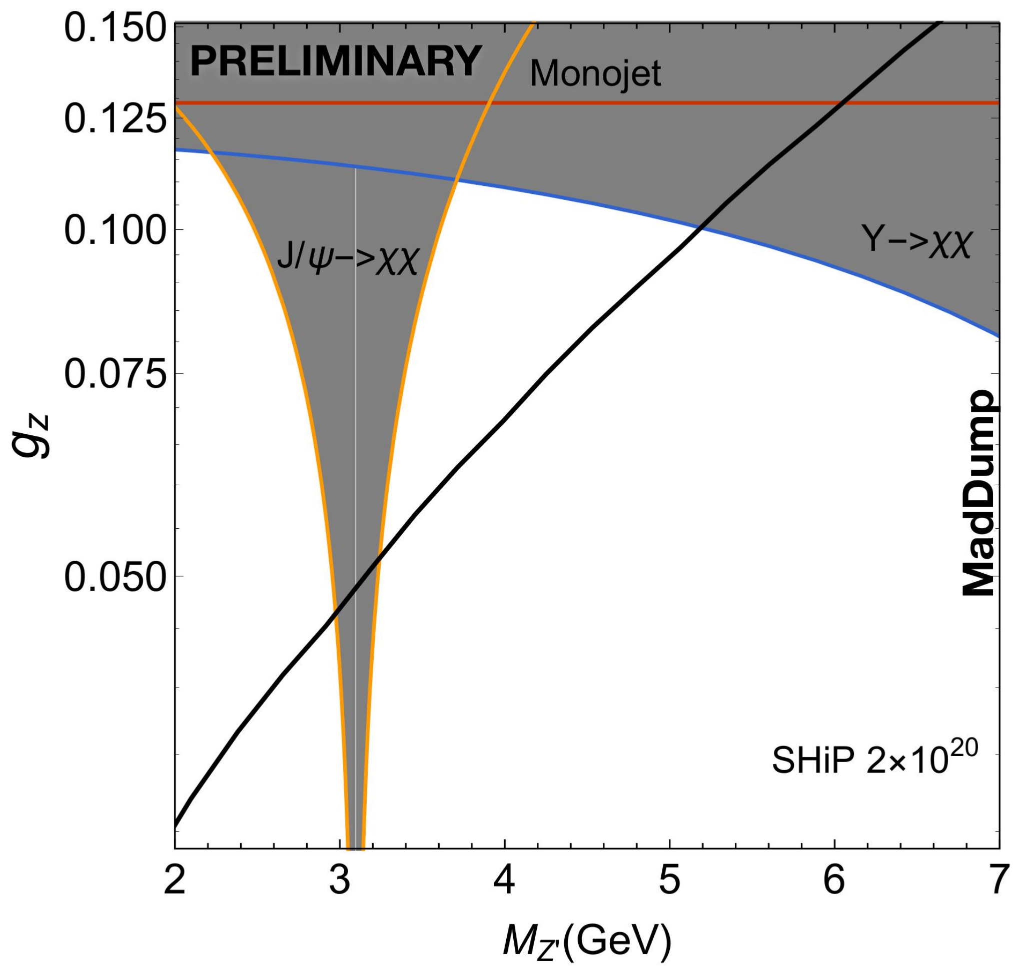
MadDump Output

- interaction events files for each run of the scan (in .lhe format)
- summary table report

#run_name	mass#10030	nevts_DIS	width#10030	xsec_prod (pb)	cross
run_04	2.000000e+00	7.487500e+05	2.631950e-04	4.207800e+03	2.106100e+04
run_05	3.000000e+00	1.525400e+05	5.560001e-04	3.233900e+03	6.188800e+03
run_06	4.000000e+00	1.683200e+04	8.291499e-04	1.088000e+03	1.896400e+03
run_07	5.000000e+00	2.527800e+03	1.089720e-03	3.964800e+02	6.674600e+02
run_08	6.000000e+00	4.394700e+02	1.343160e-03	1.549200e+02	2.562000e+02
run_09	7.000000e+00	8.816800e+01	1.592290e-03	6.352900e+01	1.038800e+02
run_10	8.000000e+00	1.933200e+01	1.838660e-03	2.677300e+01	4.350800e+01
run_11	9.000000e+00	4.616200e+00	2.083070e-03	1.145600e+01	1.852400e+01
run_12	1.000000e+01	1.262800e+00	2.434920e-03	4.677900e+00	7.889300e+00

GeV leptophobic forces: results

Z' on shell production $\sim g_Z$ + **Z' decay in DM** $O(1)$ + **DM-SM coupling** $\sim g_Z^2$ → Signal $\propto g_Z^6$



- **Benchmark scenario**:

  $g_Z = 0.1,\ z_\chi = 3$

  $m_\chi = 750\ \text{MeV}$

[Coloma, Dubresco, Friugiuele, Harnik, 1512.03852]

- Detection efficiency for signal & background assumed to be 1
- **Background**: neutrino NC ~900K events

Sub-GeV dark photon: the model

- New gauge boson A' associated to an abelian gauge symmetry U(1)', kinematically mixed with the photon:

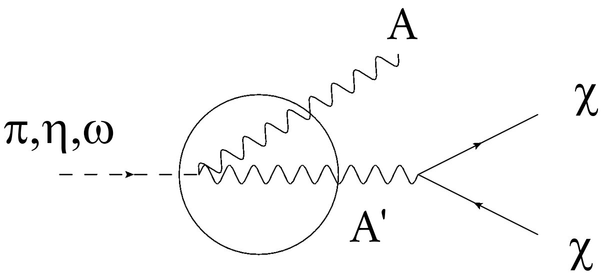
$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon\, F'_{\mu\nu}F^{\mu\nu}$$

- New particle (a scalar or a fermion) charged under U(1)'

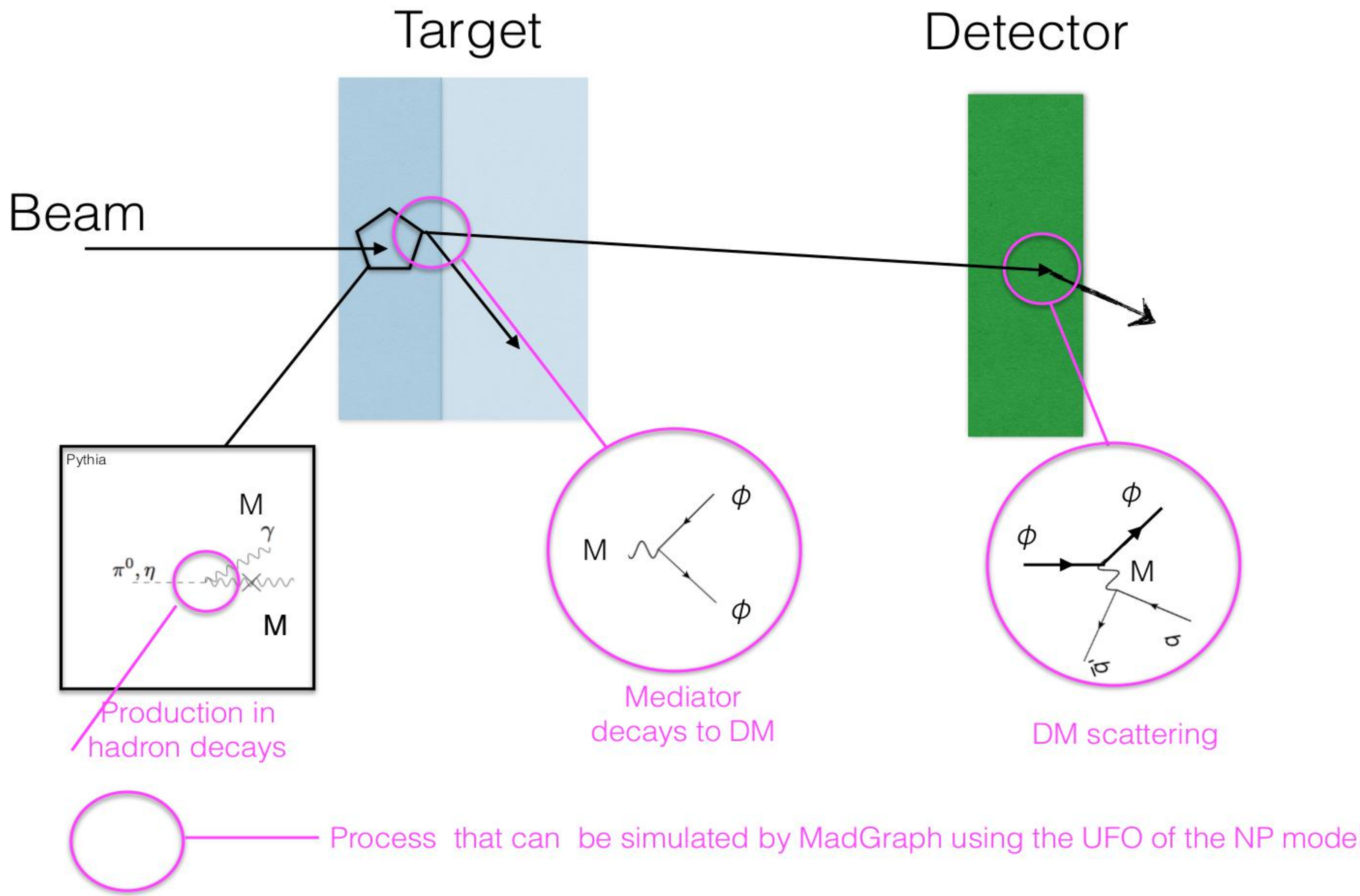
$$\mathcal{L}_{\chi} = \frac{g_D}{2}A'^{\mu} \times \begin{cases} \overline{\psi}_{\chi}\gamma_{\mu}\psi_{\chi}, & \text{fermion} \\ i\left[(\partial_{\mu}\phi_{\chi}^{\dagger})\phi_{\chi} - \phi_{\chi}^{\dagger}\partial_{\mu}\phi_{\chi}\right] & \text{scalar} \end{cases}$$

- At SHiP, in the sub-GeV region, the dominant production mechanism is given by (rare) meson decays with the A' **almost on-shell**

→ EFT approach



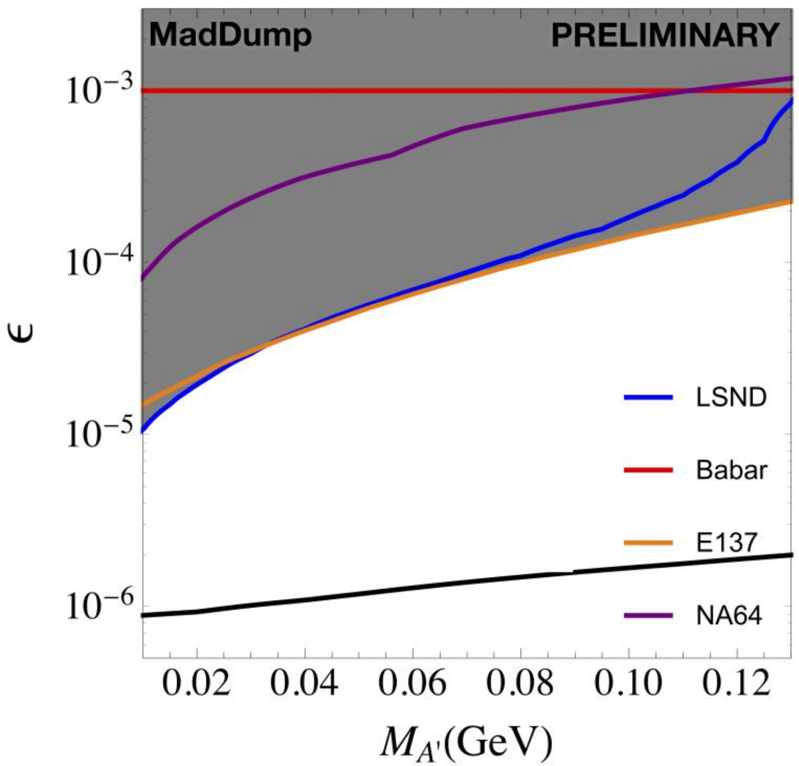
Sub-GeV dark photon: simulation



Sub-GeV dark photon: results

Remark: the user generates once (and for all the scan) the events file (in .lhe or .hepmc format) for the production of mesons in the primary collision

DP - SM fermion coupling $g_{A'ff} = \epsilon e q_f$ + **DP - DM coupling** $O(1)$ + **DP on shell production** → Signal $\propto \epsilon^4$



- **Benchmark scenario**:

  $m_\chi = m_{A'}/3$

  $\alpha_D = g_D^2/4\pi = 0.5$

  [US cosmic vision 2017, 1707.04591]

- **Selection cuts** (signal and background):

  $E_e > 100$ MeV

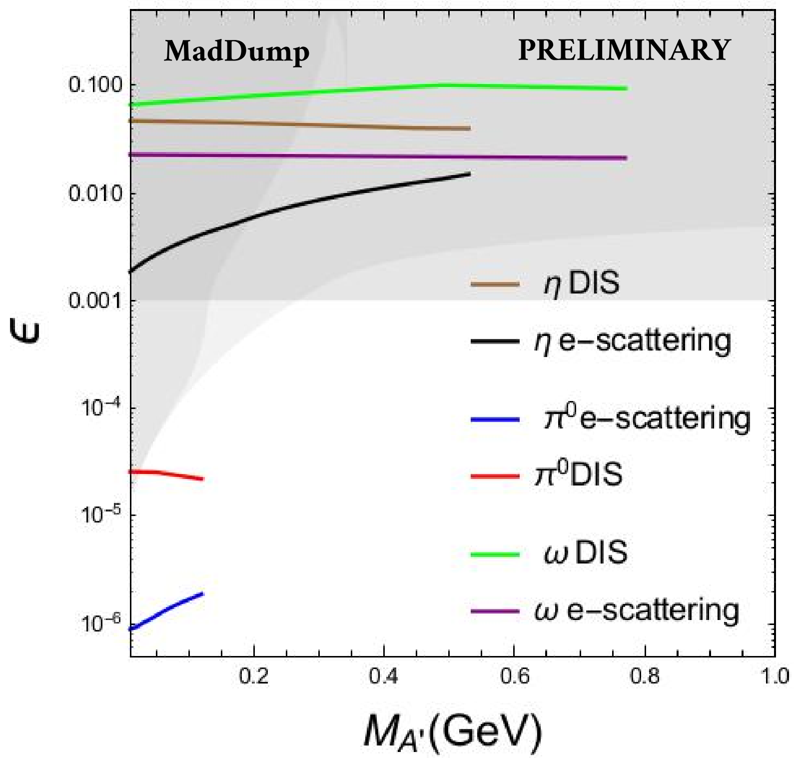
  $(10 < \theta e < 20)$ mrad

- **Background**: ~300 events

Sub-GeV dark photon: results

Remark: the user generates once (and for all the scan) the events file (in .lhe or .hepmc format) for the production of mesons in the primary collision

DP - SM fermion coupling $g_{A'ff} = \epsilon e q_f$ + **DP - DM coupling** $O(1)$ + **DP on shell production** ➡ Signal $\propto \epsilon^4$



Comparative analysis

- different meson species
- different interaction channels (DIS and electron)

GeV scalar mediator: the model

- The scalar/pseudo-scalar portal is a natural embedding for a non trivial flavour structure of the mediator-quark couplings.

- Interesting case at a proton fixed target experiments due to their sensitivity to the first quark generation (complementarity wrt to e+e- facilities)

- Simplified model:

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 + y_u S \bar{u} u + y_d S \bar{d} d - S \bar{\chi} \chi$$

stable Dirac fermion

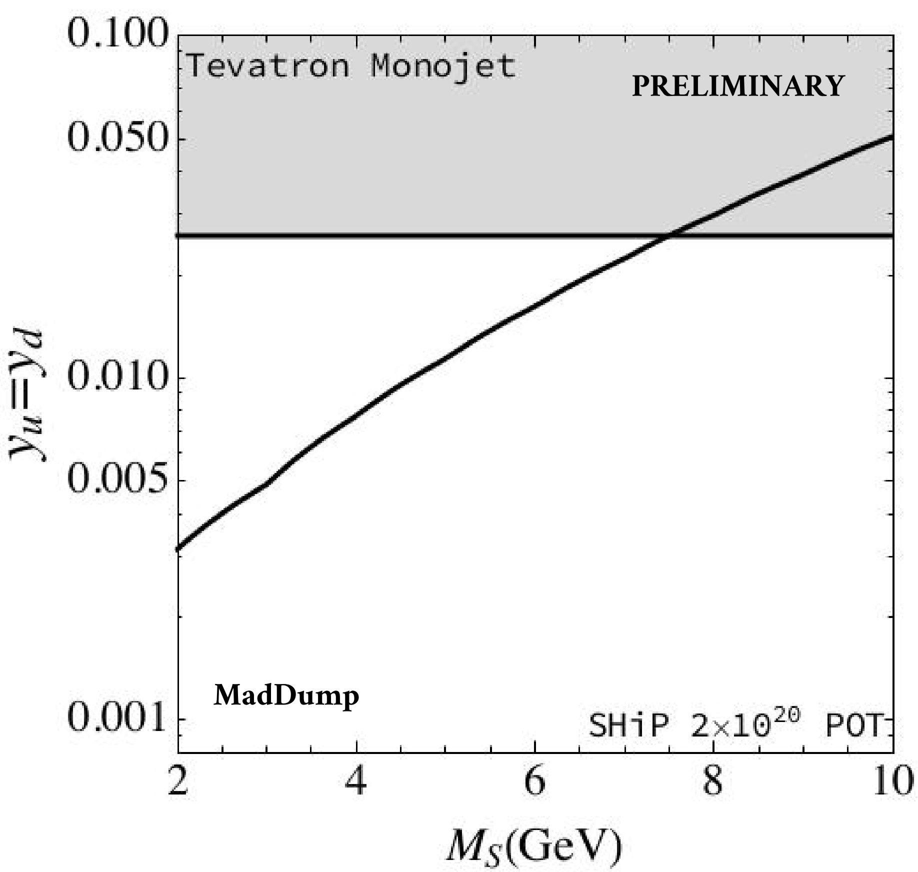
- We assume large couplings only to the first quark generation. The flavour structure is different from what dictated by MFV

- Not trivial embedding (more complicated than the renormalizable higgs portal). In ETF approach, S-quark interaction could arise from dimension 5 opeartor (in the unbroken phase)

$$\mathcal{L}_S \supset \sum_i \left(\frac{\tilde{y}_i v}{\Lambda} \bar{H}_C Q_L^i d_R^i + h.c. \right) \quad \Rightarrow \quad y_i = \frac{\tilde{y}_i v}{\Lambda}$$

GeV scalar mediator: results

DP - SM fermion coupling $y_u = y_d = y$ + **DP - DM coupling** $O(1)$ + **DP on shell production** → Signal $\propto y^4$



- mass DM = 750 MeV
- Detection efficiency for signal & background assumed to be 1
- Background: neutrino NC ~900K events

Conclusions

- We developed a MC event generator for BSM searches at beam dump facilities based on MadGraph
- The tool has been designed to be **a stand-alone module for BSM physics** easy to insert in an existing pipeline
- The main advantages of our approach are:
  - strong control on the BSM model and parameters
  - easy and flexible way to extend the analyses to new models
  - automation (auto-width, scan)
  - full differential results
- We exhibited a collection of realistic and physical motivated analyses done with our tool
- The **first stable beta version** of MadDump will be publicly available in the very near future (1-2 weeks) on the *launchpad.net* platform

Stay tuned!