Tools: A Theory Overview

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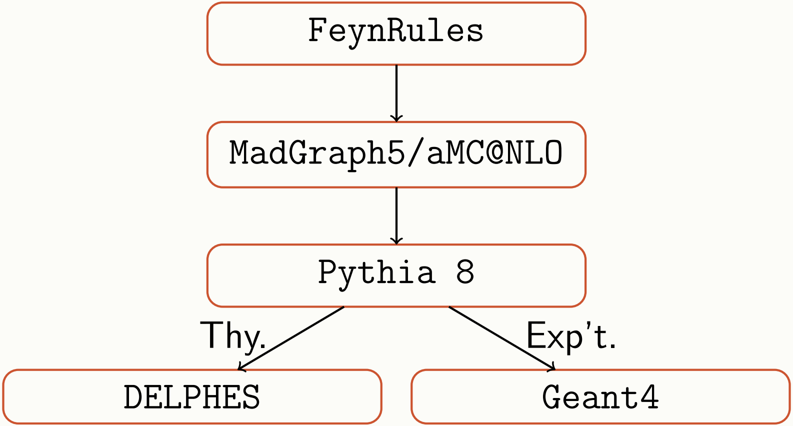
PITT PACC Nu Tools Workshop

Lessons from the LHC

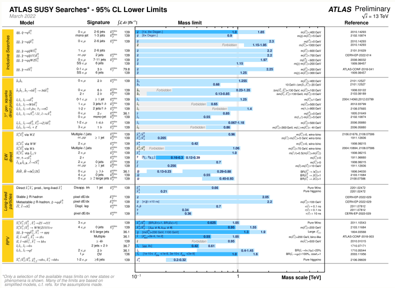
At colliders, we have a pipeline:

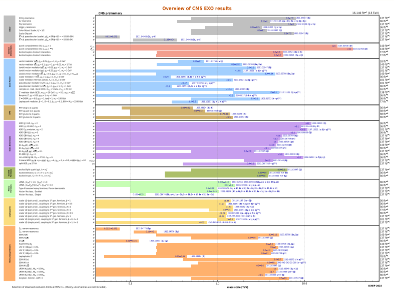


What It Means for Theory

- Thousands of theory models
  SUSY to long-lived particles to dark showers
- Theorists can easily generate model for pheno study or to hand to experimentalists
- "Basic" models are fairly hands-off
- Flexible enough for complex topologies
- Can swap out tools at any stage

What It Means for Experiment





ATLAS: ATL-PHYS-PUB-2022-013

CMS: ICHEP 2022

Neutrino Experiments

Accelerator ν exp'ts are a flagship program in US & Japan

SB/ND (100s m)	
SBND	MicroBooNE
ICARUS	DUNE ND
NOvA ND	T2K ND280
JSNS^2	

LB/FD (100s-1000s km)	
DUNE	NoVA
Super-K	Hyper-K

Intense proton beam on target

$\Downarrow$

Look for BSM in beam!

10s of kton detectors

$\Downarrow$

Look for astrophysical BSM!

What Kinds of Models?

Unstable Dark Sector States

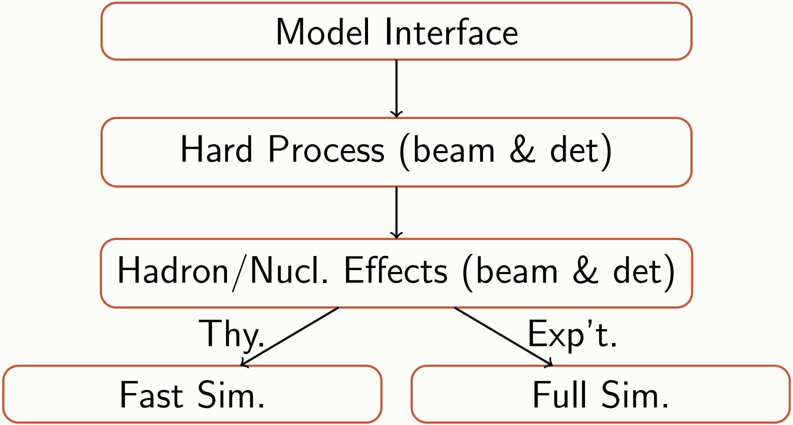
- Portal to the SM: $\mathcal{L} \propto \theta \, \phi_{\mathsf{DS}} \, \phi_{\mathsf{SM}}$
- New interactions, e.g. axions, new force
- Produce in beam: 100s of MeV mass range

Dark Matter

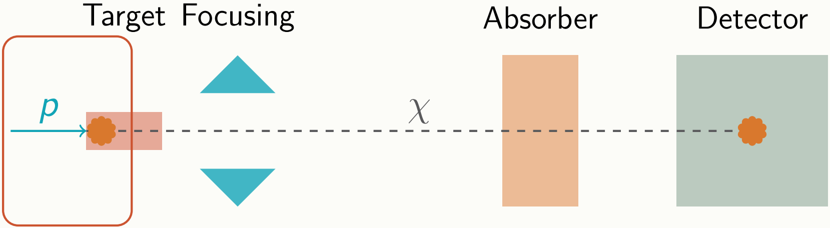
- Canonical example: vector portal mediated
- More "exotic": inelastic DM, induced nucleon decay
- Produce in beam *or* astrophysically

A Pipeline ν Experiments

Is this necessary/possible?

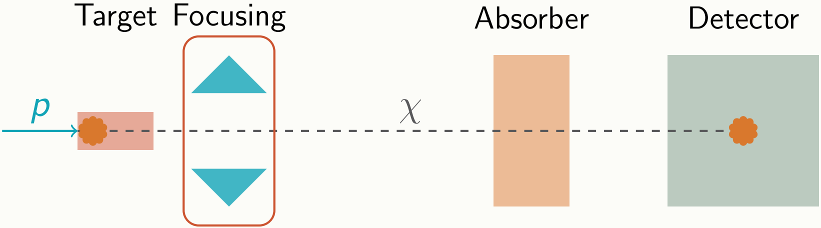


Simulations for ND



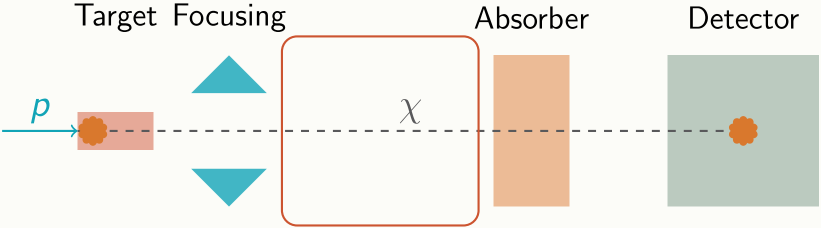
- Simulate p-^AZ collisions w/ DS production
- Direct production: Dark brem., DIS, etc.
- Also: production in meson decay
- Long-lived mesons possible (e.g. $\pi^\pm$, $K^\pm$, K_L^0)
- Secondary interactions possible

Simulations for ND



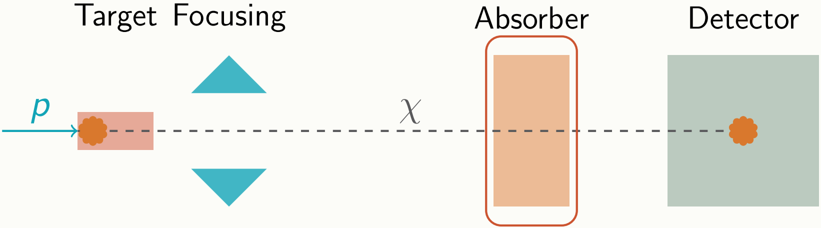
- Magnetic focusing horn steers π^+, K^+

Simulations for ND



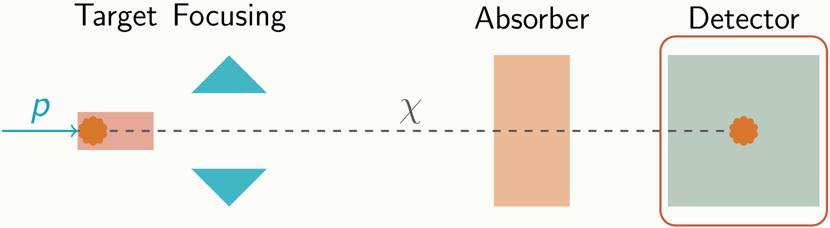
- Include propagation of particles to get flux
- Account for unstable DS state decay

Simulations for ND



- Catch protons that didn't interact in target
- Signals from meson decay at rest (DAR)

Simulations for ND



- DS decay, scatter off e^-, scatter off ^AZ
- Secondary signals possible (e.g. iDM decay)
- Keep position/time as well as momentum
- Also: simulate detector response & reco

Survey of Existing Tools

	Production					Dark → Standard					
Process	Brem.	Direct	Prompt	LL	Flux	Decay	e	N El.	N Inel.	Det.	Reco.
MadDump		✓	✓		✓		✓		✓		
BdNMC	✓	✓	✓		✓	✓	✓	✓	✓		
GENIE							✓	✓	✓		
Geant4			✓	✓	✓	✓				✓	
ACHILLES						✓	✓	✓	✓		
FORESEE	✓	✓	✓	✓	✓	✓	✓	✓			

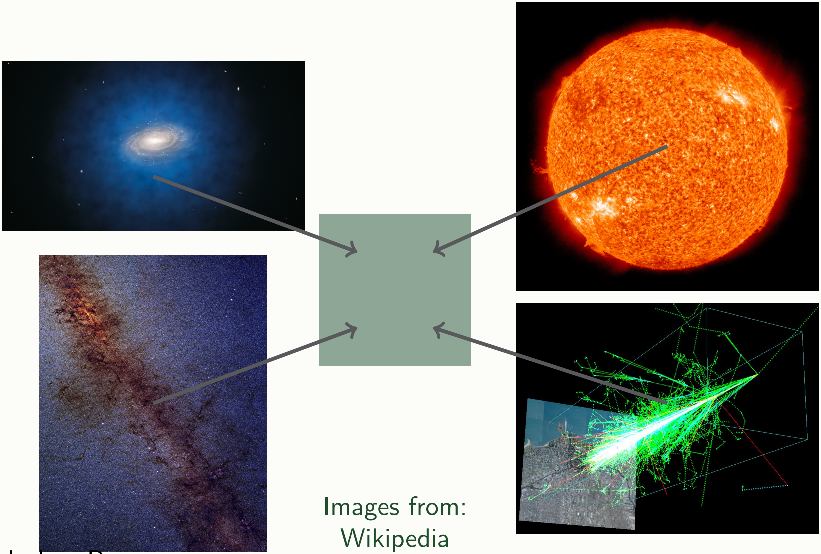
Batell, JB, et. al. (Snowmass): 2207.06898

Some Generator Details

Generator	Model(s)	Features
`MadDump`	General UFO	Flexible model, some missing processes
`BdNMC`	Vector Med.	Many processes, no FSI
`GENIE`	Vector Med.	Focused on detection side, integrates with exp't
`Geant4`	HP, HNL	Used for mesons & det. sim., basis for `MeVPrtl`
`ACHILLES`	General	Rapidly developing detection-side alternative
`FORESEE`	Vector, Scalar	Collider-focused, full-featured flux

See several talks throughout workshop!

Simulations for FD



Images from:
Wikipedia

Challenges: Diversity of Production

- Beam production:

Dark brem	Vector portal	`BdNMC`
DIS	Heavier mediators	`MadDump`
Prompt meson decay	Heavy axions	Multiple tools
Long-lived mesons	Higgs Portal	`MeVPrtl`

See talk by G. Putnam

- Astrophysical production:

Halo DM	Hylogenesis	"By hand?"
Sun	Nuclear BDM	`GenSolFlux`
Galactic Center	Leptonic BDM	"By hand?"
Cosmic Ray Accel.	Light BDM	"By hand?"

deNiverville et. al.: Phys.Rev.D 95 (2017) 3, 035006, Buonocore et. al.: JHEP 05 (2019) 028, JB: 1812.05616

Challenges: Diversity of Detection

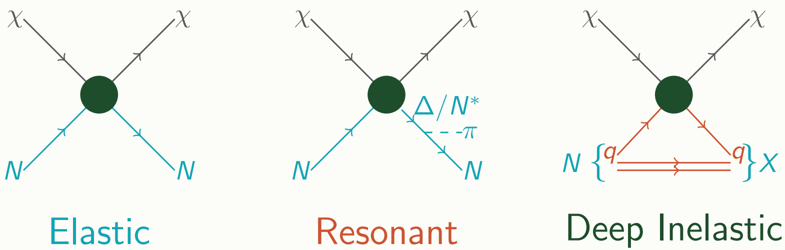
- Decay vs. Scattering vs. Scattering + Decay
- Decay: carefully sample beam geom.
- Scattering off e^-: usually $2 \to 2$
- Scattering off nuclei: challenging GeV regime

Elastic:	$\chi + N \to \chi + N$	Form factors, FSI
Resonant:	$\chi + N \to \chi + N^*$	Model
Deep Inelastic:	$\chi + q \to \chi + q$	FSI

- Scattering + Decay: Need to combine w/ detailed spatial info

See talks by S. Dytman and J. Isaacson

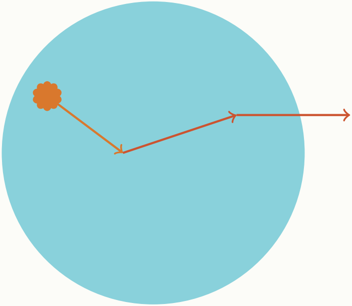
Challenges: Nuclear Modeling



- Three challenging processes (w/ uncertainties)
- Include nucleon motion: $p \lesssim p_F \approx 240$ MeV
- Include Pauli blocking

See talk by S. Li

Challenges: Final State Interactions



- Rescattering as nucleons/mesons escape nuclear remnant
- Multiple (semi-empirical) models

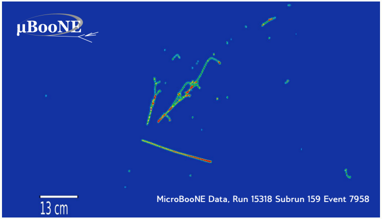
Challenges: Complex Beam Structure

- Thin target: Both target and absorber possible
- Secondary interactions: $p + {}^{A}Z$ can give energetic protons/pions that can rescatter
- Magnetic horns: Primarily a worry for long-lived mesons
- Timing: Complex beam bunch structure, but interesting targets for background reduction
- Flux systematics: Can we propagate uncertainties (also from nuclear)?

See talk by W. Jang

Challenges: Complex Topologies

Even "simple" topologies can be complicated:
$\nu_\mu + \mathrm{Ar} \to \mu + \pi^0 + X$



MicroBooNE: 2205.07943

- Studies of efficiency/resolution in progress
- Need to store detailed positional info as well as momentum
- How do we do a parameterized or fast sim.?

Challenges: Standards

- In collider world, some standard formats
  - Model format: LHA, UFO
  - Event format: LHE, HepMC
- In neutrino world, a bit of a free-for-all
  - Model implementation by hand
  - GENIE: ROOT tree w/ GENIE libraries
  - Plug into LArSoft at some stage

See talk by G. Petrillo

Challenges: Accessibility

Q: I just came up with a cool new model. How do I simulate it?

A: Best case scenario: hack it into `Pythia`

Worst case scenario: code by hand

Q: My friend generated some events for me. How do I look at them?

A: First, install `ROOT`, `GENIE`, `Geant4`, and `dk2nu`...

What We Want To See

- Possible simulation of production, flux, and interaction models
- Propagation of nuclear/flux uncertainties
- Multiple models for nuclear effects
- Integration of beam geom. when necessary
- Detailed event info, including positions
- Seamless flow from theorist brain through BSM simulation through detector simulation

Computational Challenges

- Neutrino events are really big

Detector	Event Size
ATLAS	Few MB
DUNE FD	Few GB

- How do we generate and store signal samples across many DS models *and* nuclear models?

Connecting to LArSoft

- LArSoft: Framework for connecting sim. and reco. tools at LArTPC experiments
- If you want you want experimentalists to look for your model: must connect to LArSoft
- Two options:
  (1) Build gen. into LArSoft (see MeVPrtl)
  (2) Generate format readable by LArSoft
- 1: Hard for theorists
- Track metadata like uncertainties?

Beyond Background Free

- ✓: finite number of bkg. sources
  Atmo. ν, Beam ν, Cosmics, Radioactivity?
- ×: complex bkg. topologies possible
- ×: samples are not readily available and accessible to theorists
- ×: large systematics in some bkgs.

Outlook

- Current and future neutrino experiments are sensitive to many dark sector models (see B. Dutta's talk)
- Need a flexible & accessible framework for BSM event generation to achieve a broad-based program
- Tools are being developed rapidly, but many challenges remain, particularly across simulation stages
- More discussion/collaboration needed between members of this community to tackle them: this workshop!