Tools for Feebly Interacting Particles at the intensity frontier

Luc Darmé

INFN – LNF

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Istituto Nazionale di Fisica Nucleare

Based on 2001.01490 with S. Ellis and T. You
and on 2006.09419 with A. Celentano, L. Marsicano and E. Nardi

Outline

Introduction: FIPs and portal operators

Simulating the SM at intensity frontier experiments

Simulation chain and tools for production and detection of FIPs

Introduction

FIPs and portals

Dark sectors, how to define them and make them interact with the SM

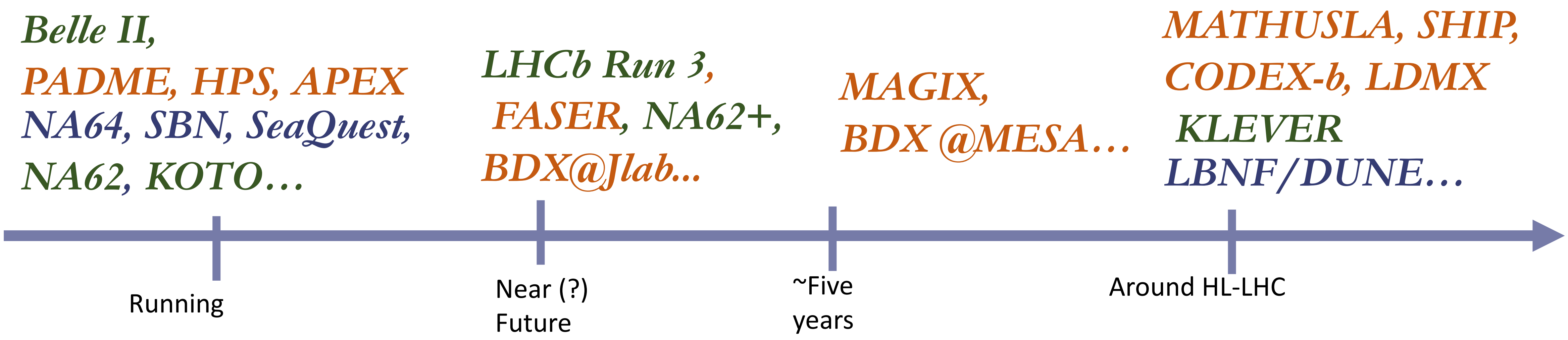
Feebly-Interaction Particles and portals

- FIPs= "new (quasi-) neutral particle which interact with the SM via suppressed new interactions" → assumed light (MeV to few GeVs) in this talk
- Appear in various NP models aiming at dark matter, neutrino masses, strong CP problem, flavour etc …

	SM operator		*FIPs / dark sector*	
Scalar portal	$\|H\|^2 \quad (d=2)\,,$	⟷	$\|S\|^2$	*Dark Higgs*
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	⟷	$F'^{\mu\nu}$	*Dark photon*
Neutrino portal	$LH \quad (d=5/2)$	⟷	N	*Sterile neutrino/HNL*
Axion portal / fermion portal	$\bar{f}_i\,\Gamma^\mu f_j \quad (d=3)$	→	$\partial_\mu a$ $\Psi\Gamma_\mu\Psi$	*Axion/ALP* *Dark fermions*

Experimental searches

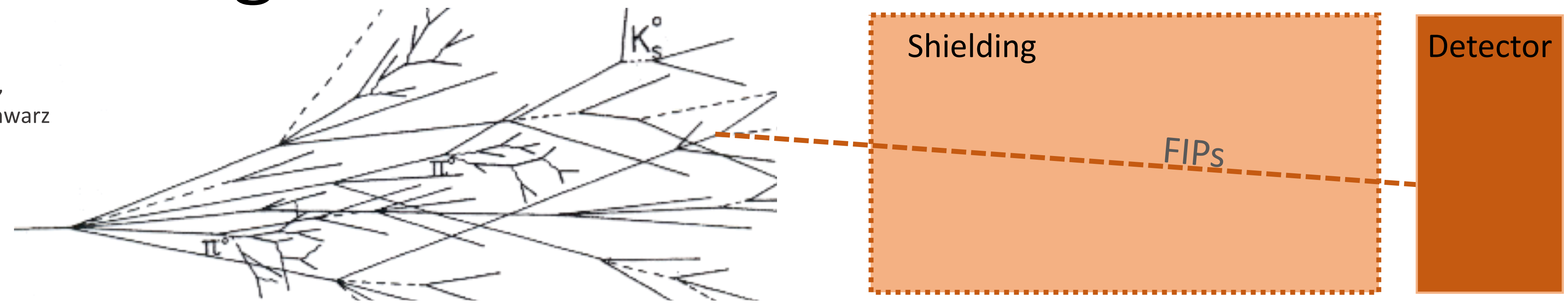
- Many upcoming relevant lab-based experiments:
  - Neutrino experiments -> the near detectors can search for FIPs
  - Dark sector-oriented -> looking for decays/ missing energy
  - Flavour/ Rare mesons decay -> Missing energy searches, invisible meson decay, etc…



- Astrophysical searches (direct/indirect DM detection, stellar/novae limits …) (not included in this talk)

FIPs hunting

Proton based shower , illustration Grupen, Shwarz 2008



e^+e^-, $e^\pm Z$

pp, pZ

→

SM by-products:
- (Flavoured) mesons
- e^+/e^-, photons, (muons)

→

FIPs production
- Mesons decay
- EM-derived processes (e.g. dark brem, etc..)

FIPs propagation →

FIPs visible signals
- Scattering
- Fully visible decay
- Partially visible decay (eg $\chi_2 \to \chi_1 \ell\ell$)

Can be roughly estimated once and for all per experiment

Typically portal dependent

→ Can be classified

Depends on the details of the FIPs model & of a possible dark sector

Recasting tools

- As the physics mostly depends on the nature of the portal operator, natural recasting path to re-interpret experimental searches → Two portals covered
- Existing tools, both python-based
  - DarkCAST, Re-interpret dark photon searches in term of a generic new vector boson: vector portal (1/5)

    Ilten et al., 1801.04847

Darme et al., 2001.01490

  - DarkEFT, re-interpret various limit in terms of fermion portal (2/5): effective four-fermions interactions

$$\sum_q \frac{g_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\chi_2)(\bar{q}\gamma^\mu q)$$

    - Included Recasts of iDM limits in beam dump
    - Possibility to extend to axion portal (3/5?)

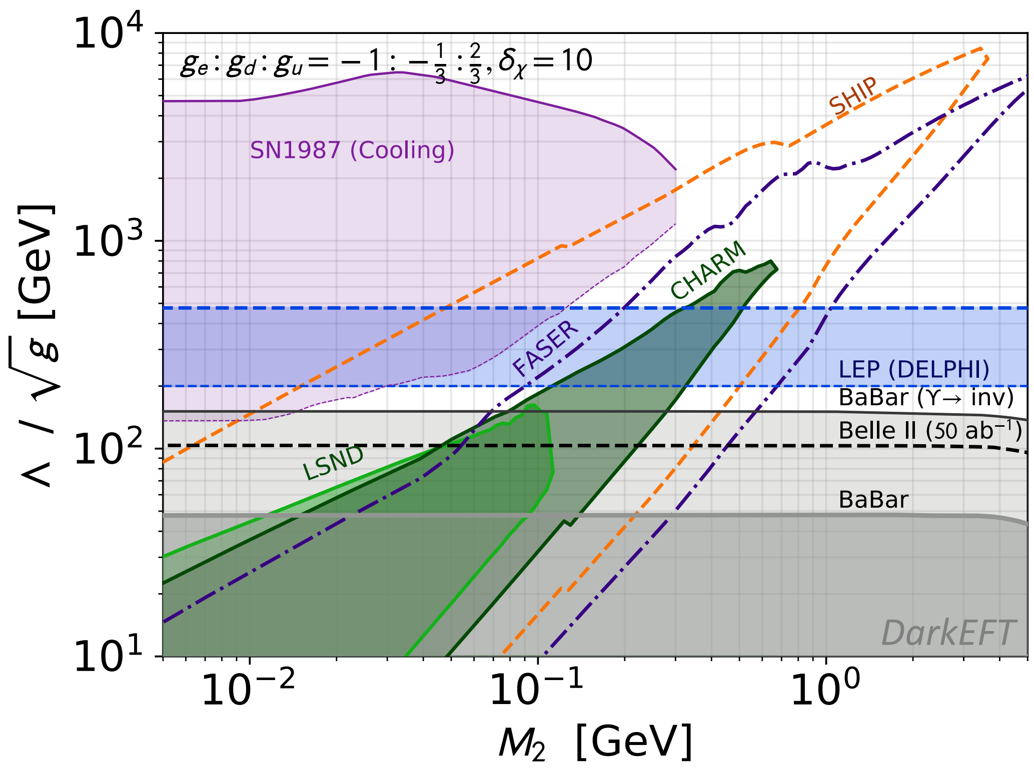
Recast vector portal searches:

Mono-photon at BaBaR/Belle-II

Beam dump searches for iDM with a dark photon

Mono-photon at LEP

Rare invisible decay of Upsilon



FIPs hunting at the intensity frontier: Standard Model simulations

Accurate SM description for FIPs

e^+e^-, pp →

- Direct production
- Parton showers to mesons

$e^\pm Z, pZ$ →

- Hadronic showers (+ sub-EM showers)
- EM showers

- For mesons, typically the distributions in energy/polar angles are needed $f_M(\theta_M, E_M)$
- For $\gamma, e^+/e^-$ descriptions of EM showers, differential track lengths $T_{\gamma,e^\pm}(\theta, E)$: ("Total travelled distance in the target by all $\gamma, e^\pm$")

$$\mathcal{N}_{\rm FIP} \sim \frac{\mathcal{N}_A \rho_{\rm tar}}{A_{\rm tar}} \times T_{e^\pm,\gamma} \times \sigma_{\rm FIP}$$

$T_{\gamma,e^\pm}(\theta, E)$, $f_M(\theta_M, E_M)$ can be be typically obtained via:

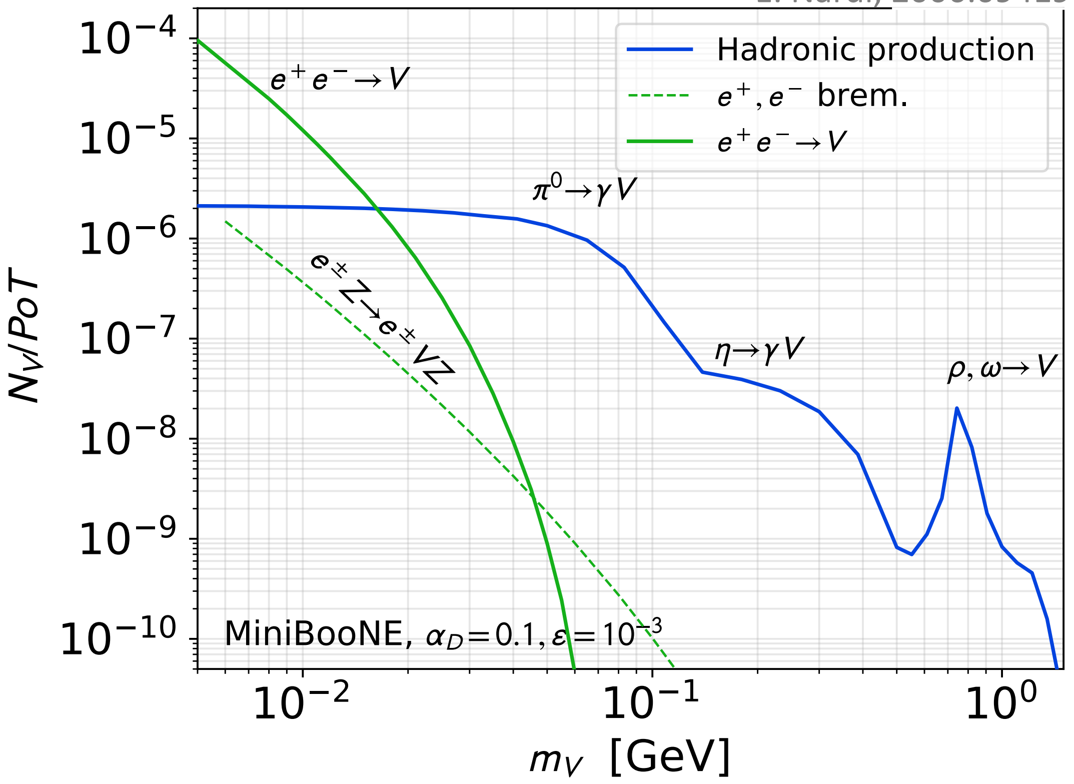
- Empirical distributions of light mesons (BMTP, Sanford-Wang, Burman-Smith)
- Analytical EM shower description, track length (Tsai, Rossi-Greisen/Lipari)
- Numerics: Pythia8, EPOS@LHC, QGS JETII, etc… or GEANT4 , FLUKA … (include secondaries)

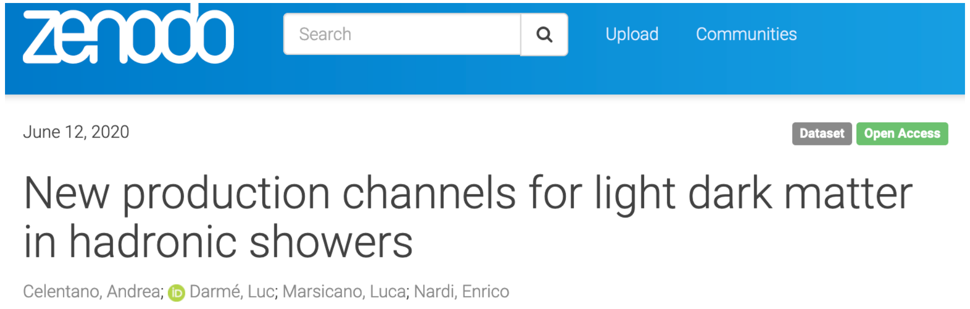
Bonesini et al., hep-ph/0101163
Sanford, Wang 1967
Burman, Smith 1989
Tsai, 1986
Rossi, Griesen 1941
Lipari, 0809.0190
Bierlich et al.
Pierog 2013
Ostapchenko 2007

Track length database: proton beam dump

- Proton beam dump are particularly challenging to simulate
  - Hadronic shower -> mesons distribution
  - EM- sub-showers
- GEANT4 simulation: secondary production dominate by almost 2 orders of magnitude for low dark photon mass
- Create and save $T_{\gamma,e^{\pm}}(\theta, E)$, $f_M(\theta_M, E_M)$ for a variety of proton beam dump experiments
  - Differential energy track lengths
  - Events dataset for $e^+/e^-/\pi^0$, for direct sampling

A. Celentano, LD, L. Marsicano, E. Nardi, 2006.09419





FIPs production and visible signatures

FIPs production in the lab

$e^{\pm}Z, pZ$ → Mesons: f_{π^0}, f_η, f_K, …

EM processes: $T_{e^\pm}, T_\gamma$ →

e^+e^-, pp →

Flavoured mesons decay
$B \to K\,X, K \to \pi X, K \to inv$ or $D, B, J/\Psi \to \ell N$ etc …

→ Flavoured FIPs, Higgs portal and neutrinos portal

Light mesons decay
$\pi^0, \eta \to \gamma\, V$; $\rho, \omega \to V$ or $\pi^0 \to a$; $\pi^0, \eta \to \chi\chi$ etc …

EM-derived processes
$e^+e^- \to V\gamma, a\,\gamma$; $e\,N \to e\,N\,V$, etc …

→ Vector portal, ALP/fermion portal

- Mesons decays estimations
  - No automatic tool available (new light states: not possible to apply standard WET-based tools)

  → Analytical calculation required. BR usually estimated by standard techniques (χPT, Vector Meson Dominance, …) For VMD, see e.g. Fujiwara et al. (1985)

→ Limit on rare BR, $B \to K, K \to \pi$, $\pi \to inv.$, etc…

- EM-derived processes
  - For collider experiments: standard MC tools can be used (MG5_aMC@NLO, CalcHEP, etc…) Alwall et al. 2014, Belyaev et al. 2012
  - For beam dump → must include the track-lengths information, nucleus form factors…

→ Limits on mono-photon search @ BaBar/NA64/LEP

FIPs propagation and decay

FIPs production rates → *Propagation* →

Scattering signatures

$\chi e \to \chi e \,;\, \chi N \to \chi N$

→ Models of light dark matter

Pure visible decay signatures

$\mathrm{V}, \mathrm{a} \to \ell\ell, had. \;;\mathrm{a} \to \ell\ell, \gamma\gamma \;\;;\;\; S \to \ell\ell, had.$

$S \to V\, e^{+}e^{-}$

→ Dark photon, ALP, dark Higgs, Higgsed dark photon

Semi-visible decay signatures

$\chi_2 \to \chi_1 e^{+}e^{-} \;\;; \mathrm{N} \to \nu\, \ell\ell, \nu\, \pi, etc..$

→ Sterile neutrinos, inelastic DM …

- Requires MC tools: two public codes available, mostly for light dark matter
  - BdNMC (neutrino experiments mainly) deNiverville et al. 1609.01770
    - C++ code, include various empirical distribution for mesons, hard-coded dark photon production processes
    - Easily modifiable to include decay signatures and various experimental cuts
  - MadDump (Madgraph plugin) Buonocore et al. 1812.06771
    - Use the full MG machinery, can be thus used in variety of NP scenarios
    - Can be interfaced with track length databases
    - Mostly scattering signature currently → plan to include full decay search capability

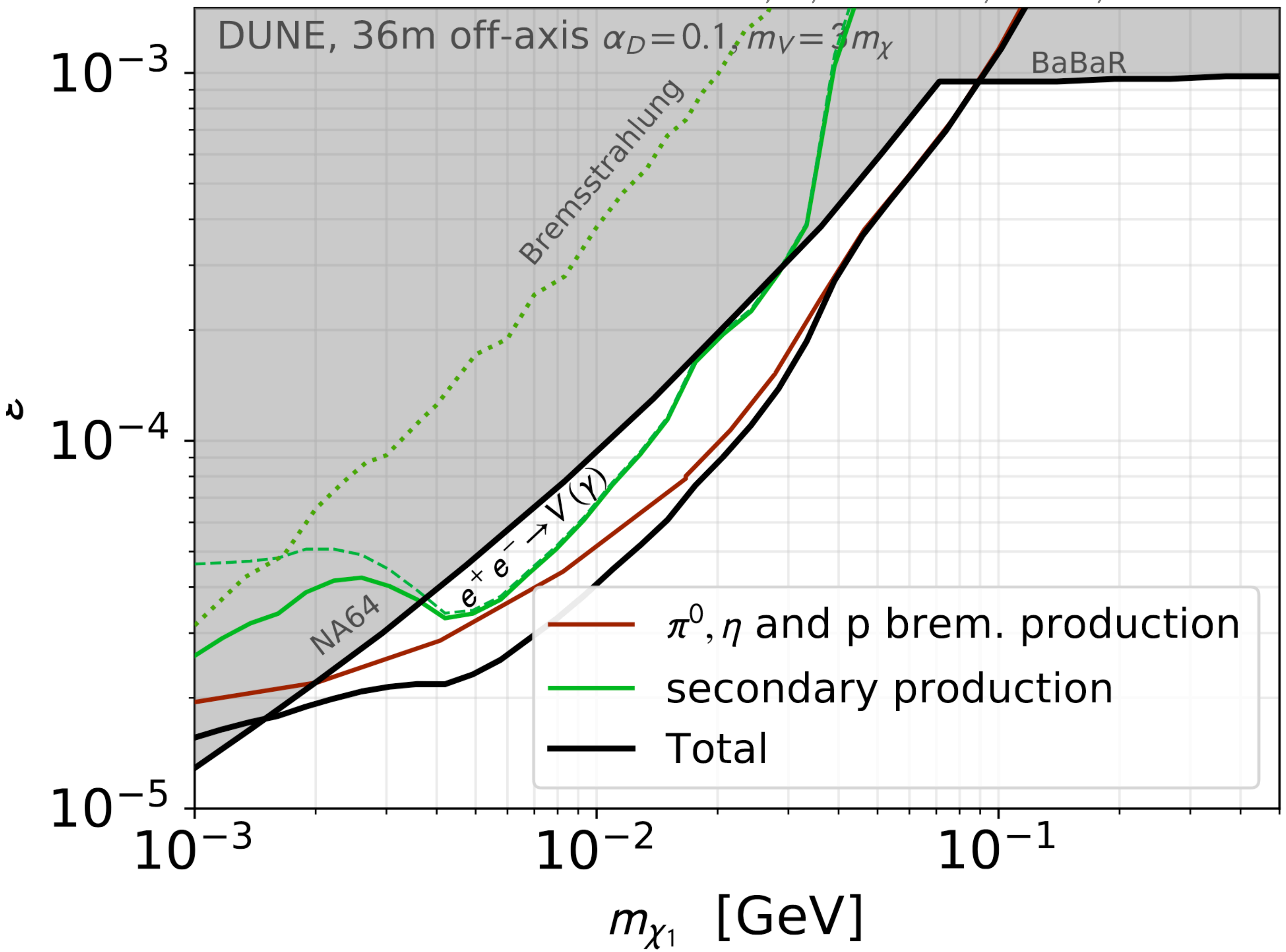
Simulation of DUNE near detector

- Use MadDump interfaced with the above datasets

→ Include secondary particles from EM showers

- Uses NUMI beam (proton beam 120 GeV)
- Cuts and signatures using BdNMC code for the FIPs propagation/detection

A. Celentano, LD, L. Marsicano, E. Nardi, 2006.09419



Conclusions

Conclusion

- Signatures of FIPs require
  - SM aspects → once-and-for-all approach could be viable with databases per experiments
  - FIPs production → depends mostly on the type of portal operators,
  - FIPs detection → requires additional developments of MC tools

→ Promising possibilities for recasting between equivalent portal operators (2/5 portals currently available)

- Much remain to be done to attain the level of precision available at the high-energy frontier

→ But also a strong need as FIPs are the target of flourishing experimental effort

If I missed/misrepresented your very own code which can be used for FIPs hunting at intensity frontier experiment, let me know so I can include those in the proceedings!

Back-up slides

MadDump status

MadDump is a plugin of MG5 designed to assist the simulation of events in a beam dump experimental setup (production + detection in microscopically separated locations)

- Integration within the MG5 environment: Feynrules + UFO to extend the available physics models,
- On the fly fit of 2d-dimensional distribution of the BSM particle fluxes in the intermediate step of the computation

Main characteristics

- Production: pQCD (madevent), meson decay (madspin)
- Detection: Scattering and simple displacement decay mode

Development version (available on request, to make public around the end of the year) with:

- Internal proton bremsstrahlung module (including effective vector mixing effect)
- Electron beam dump mode: possibility to fit/take as input an effective (2d) pdf for electron/positron/photon
- Development and testing of the off-axis geometry
- Improvements of the displaced decay module (for example possibility to handle multi-particle labels)

Future prospects:

- Direct interface to database of track-lengths and pion/eta distribution
- More efficient strategies for displaced decays

Recasting using DarkEFT

- Recast existing searches on limits for dimension 6, four-fermions operators (fermion portal)
  - Simple python-based approach

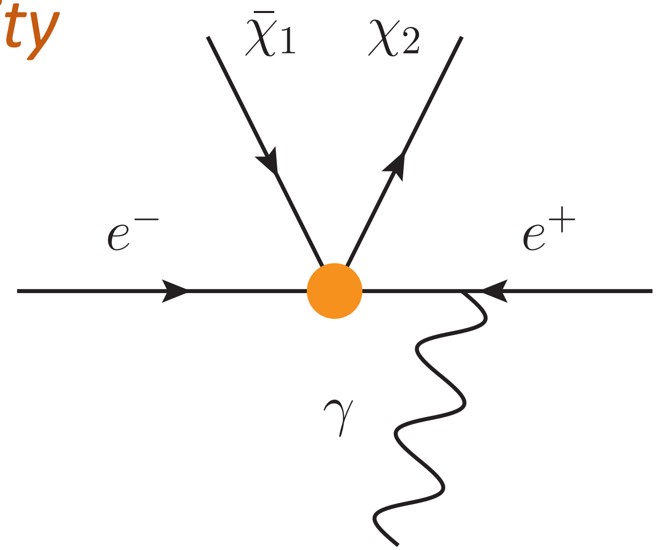
$$\frac{g_\ell^{ij}}{\Lambda^2}\bar{\chi}_2(\gamma^5)\gamma^\nu\chi_1\ \bar{\ell}_i(\gamma^5)\gamma_\nu\ell_j \qquad \frac{g_q^{ij}}{\Lambda^2}\bar{\chi}_2(\gamma^5)\gamma^\nu\chi_1\ \bar{q}_i(\gamma^5)\gamma_\nu q_j$$

→ Include vector or Axial-vector operator
→ Couplings to quarks & leptons with potential flavour-violation
→ Include signals from long-lived FIPs in 3 body $\chi_2 \to \chi_1\ell\ell$ searches

- Extension to ALP-portal scenarios under way

Dark Sector searches in the lab (1)

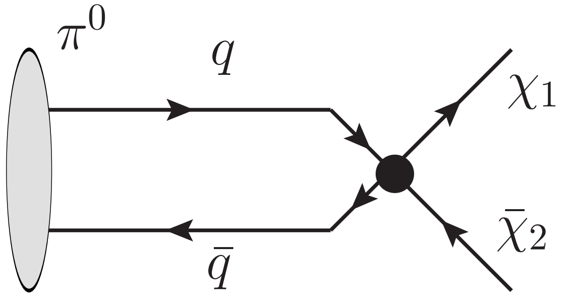
- Light dark sector particles may be accessible at *the intensity frontier* (GeV energy / large intensity / low background)



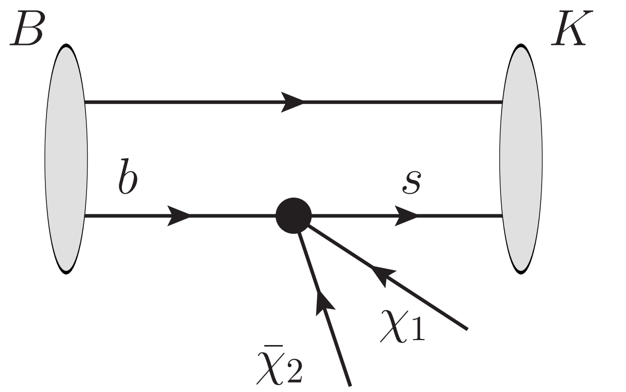
- Missing energy/ Invisible decay: Mono-photon/mono-jet searches missing energy signature @ BaBar, Belle, LEP, LHC.
- Invisible meson decay: $\pi^0 \to \bar{\chi}\chi$ (NA62), $\Upsilon \to \bar{\chi}\chi$ (BaBar)
  →Important for flavour-violating operators, e.g $\mathrm{B} \to K\bar{\chi}\chi$

$$\sum_q \frac{\tilde{g}_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\gamma^5\chi_2)(\bar{q}\gamma^\mu\gamma^5 q)$$

$$\sum_q \frac{g_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\chi_2)(\bar{q}\gamma^\mu q)$$



→Many ≠ meson decays
→ BR typically suppressed $\propto \frac{M_m^4}{\Lambda^4}$



Decay and scattering signatures

Most existing limits are obtained for vanilla cases (e.g iDM, pure dark photon …) → need to recast these searches as function of the EFT

- Different approaches for each search strategies
  → Meson decay: direct evalution of the BRs
  → Adapt results from EFT-coupled dark matter candidates
  → Full recast of existing vector portal results for searches at beam dumps
- Decay limits are particularly challenging, rescale for production rates

$$\Lambda_{\rm lim} = 410 \text{ GeV} \times \sqrt{g_{\rm eff}} \left(\frac{0.001}{\varepsilon}\right)^{1/2} \left(\frac{\mathcal{N}^{\rm eff}_{\rm prod}}{\mathcal{N}^{\rm DP}_{\rm prod}}\right)^{1/8}$$

→For different splitting, detection probability is modified (also rescale for decay rates, keeping $M_1 + M_2$ constant)

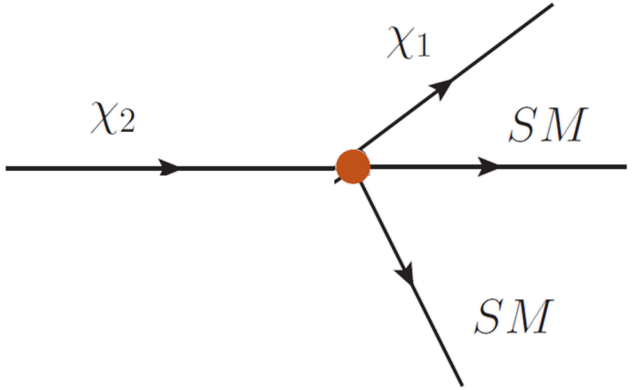
Limits in the vector case

$$\sum_q \frac{g_q}{\Lambda^2}(\bar{\chi}_1\gamma_\mu\chi_2)(\bar{q}\gamma^\mu q)$$

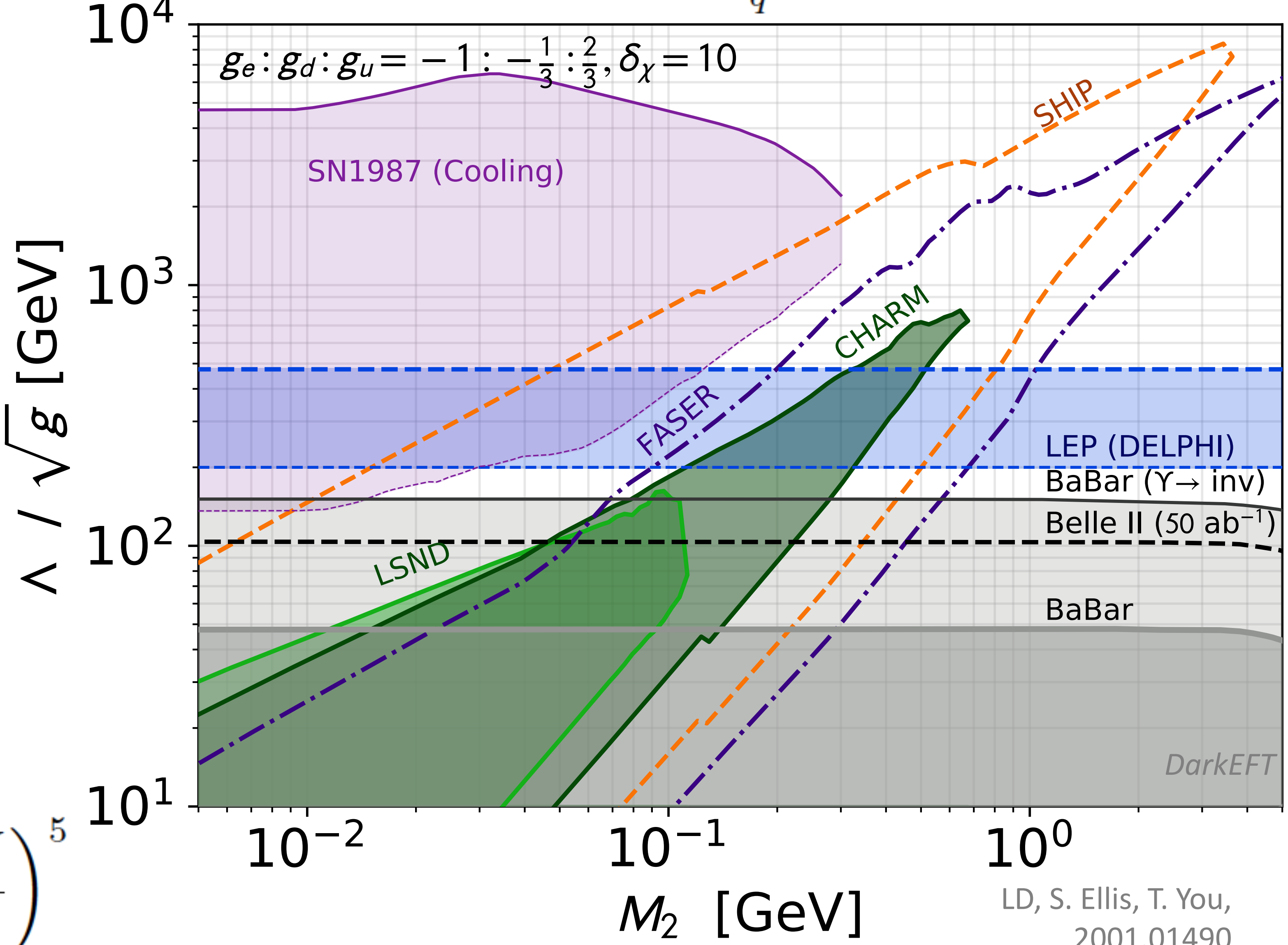
Include limits/projections:

→Mono-photon: LEP, BaBar and Belle II

→Decay searches at saturation ($M_2 \gg M_1$) at LSND, CHARM, SeaQuest (hypothetical Phase 2 with $\sim 10^{18}$ PoT) and SHIP



$$c\tau^{\rm sat} \sim 2\ {\rm m} \times \left(\frac{\Lambda/\sqrt{g}}{1\ {\rm TeV}}\right)^4 \left(\frac{1\ {\rm GeV}}{M_{\chi_2}}\right)^5$$



LD, S. Ellis, T. You, 2001.01490

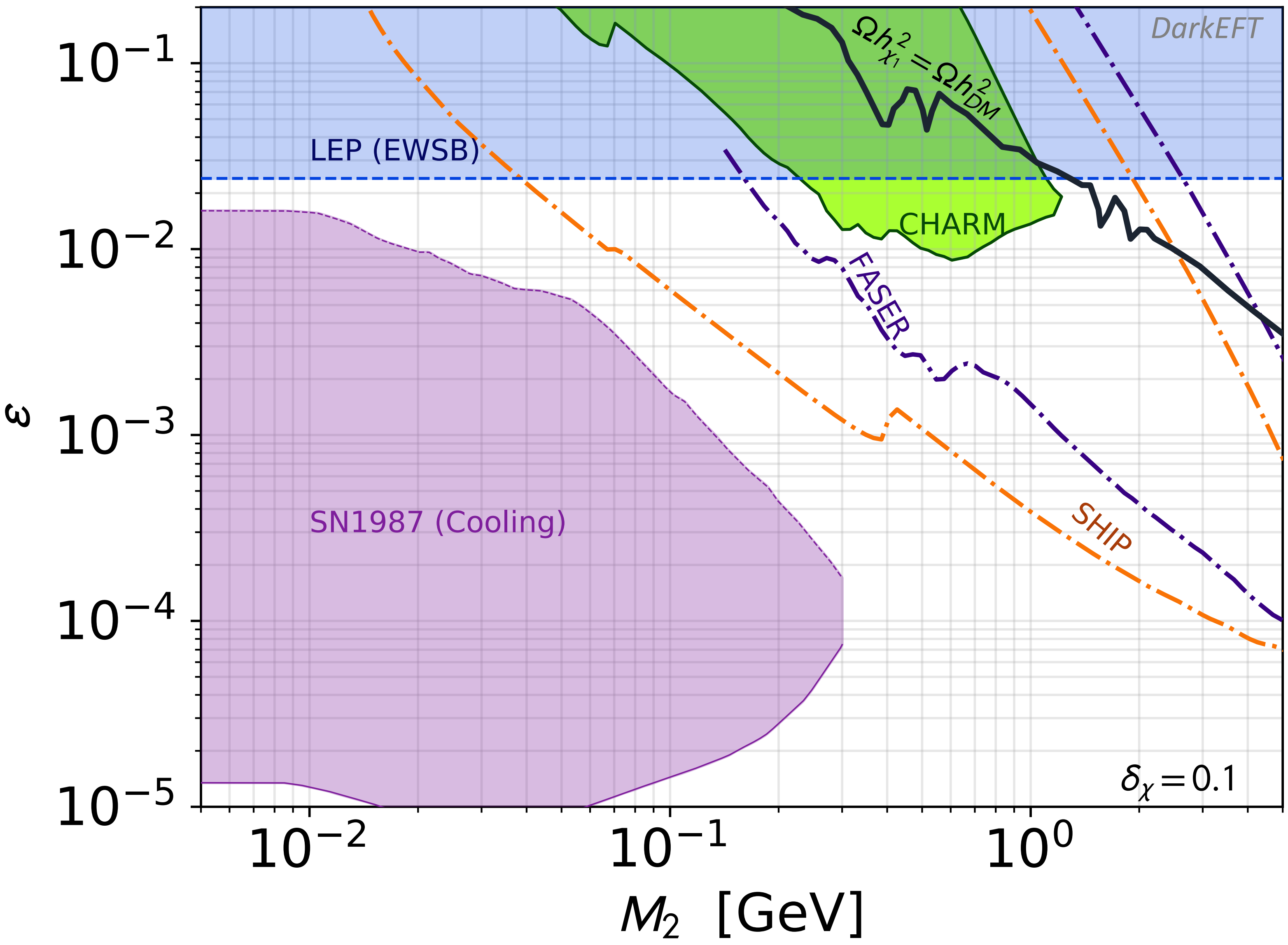
Practical example: off-shell dark photon

LD, S. Ellis, T. You, 2001.01490

- Standard iDM scenario with a heavy dark photon ($M_V \sim 15$ GeV, with $M_V \gg M_\chi$)

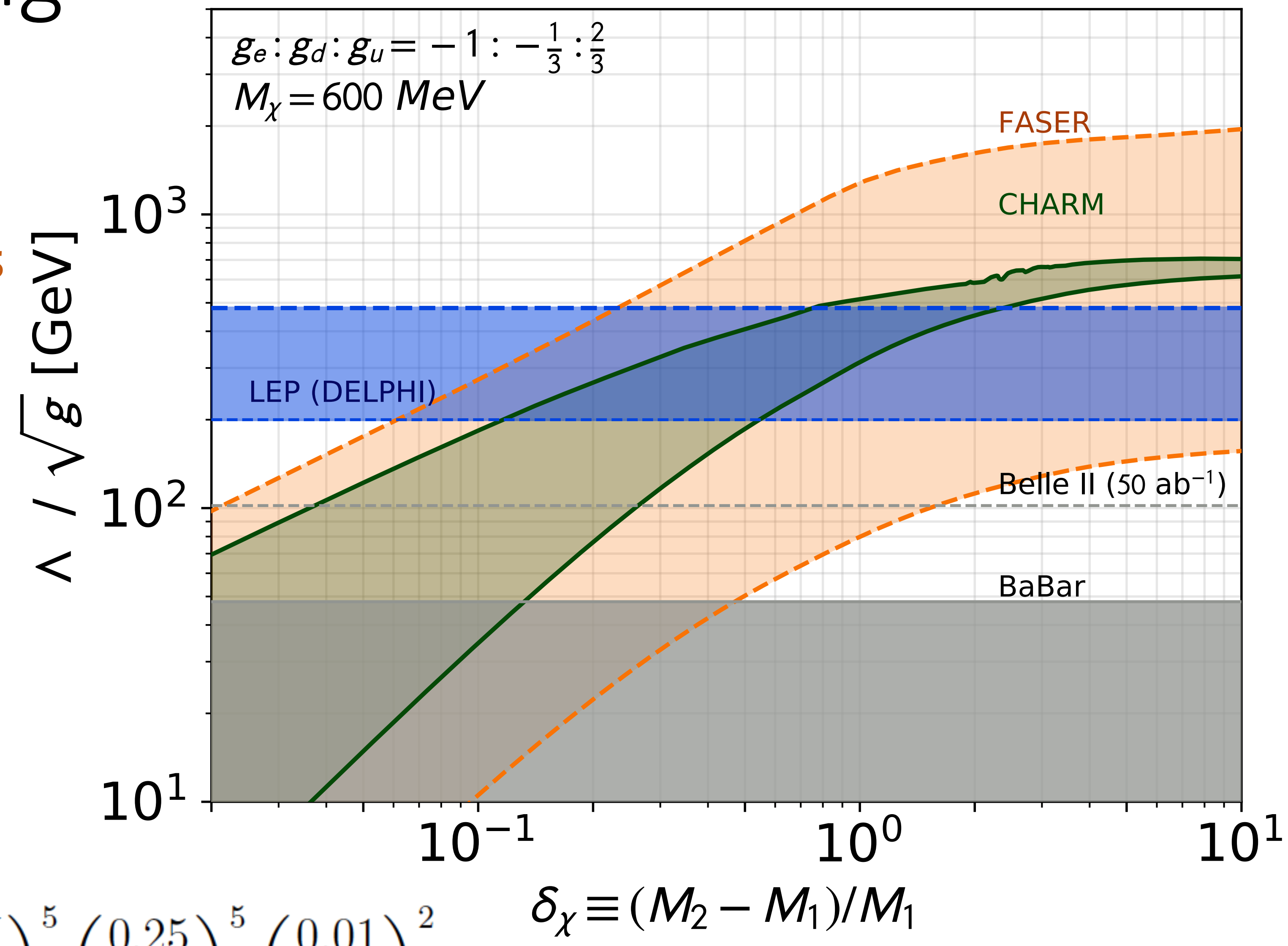
$$\frac{\varepsilon e g_D}{M_V^2} \leftrightarrow \frac{g}{\Lambda^2}$$

- Very weak limits from Babar (no resonance search available)
- Relic density in reach of next generation experiments



Varying the splitting

- Decay signatures depends strongly on splitting $M_2 - M_1$
  - Lifetime scales as $(M_2 - M_1)^{-5}$
  - Then reach saturation for $M_2 \gg M_1$
- Both upper limits and lower limits are modified
  - Long-lived limit -> linear suppression
  - Short-lived limit ->exponential dependence



$$c\tau^{\rm pD} \sim 375 \text{ m} \times \left(\frac{100 \text{ GeV}}{\Lambda}\right)^4 \left(\frac{1 \text{ GeV}}{M_{\chi 1}}\right)^5 \left(\frac{0.25}{\Delta_\chi}\right)^5 \left(\frac{0.01}{g}\right)^2$$

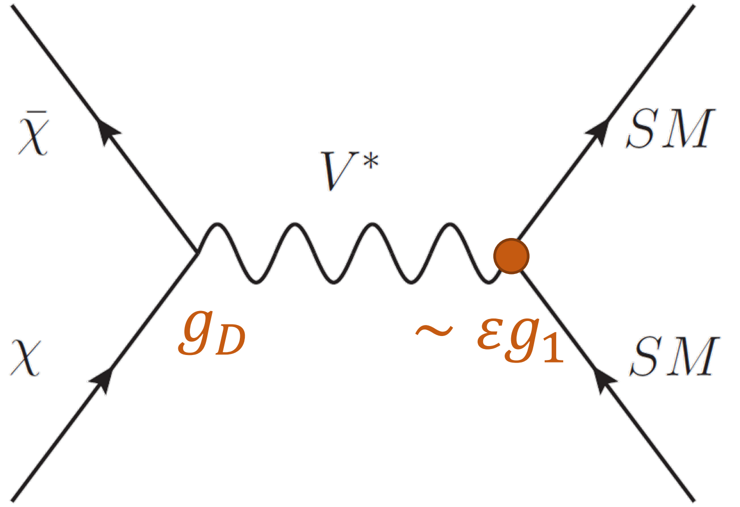
Light dark sector: dark photon and dark matter

- Light Dark sector = "new neutral particles which interact with the SM via suppressed new interactions" + below the GeV

- In this short talk: consider a simple sub-GeV DM example
  - Vector mediator -> Dark photon with kinetic mixing, large invisible width !
  - Dark matter -> Complex Scalar

$$\mathcal{J}_D^\mu = i\left(\chi^* \partial^\mu \chi - \chi \partial^\mu \chi^*\right)$$

$$\mathcal{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} \frac{\varepsilon}{\cos\theta_w} B_{\mu\nu} F'^{\mu\nu} - V'_\mu g_D \mathcal{J}_D^\mu \,,$$

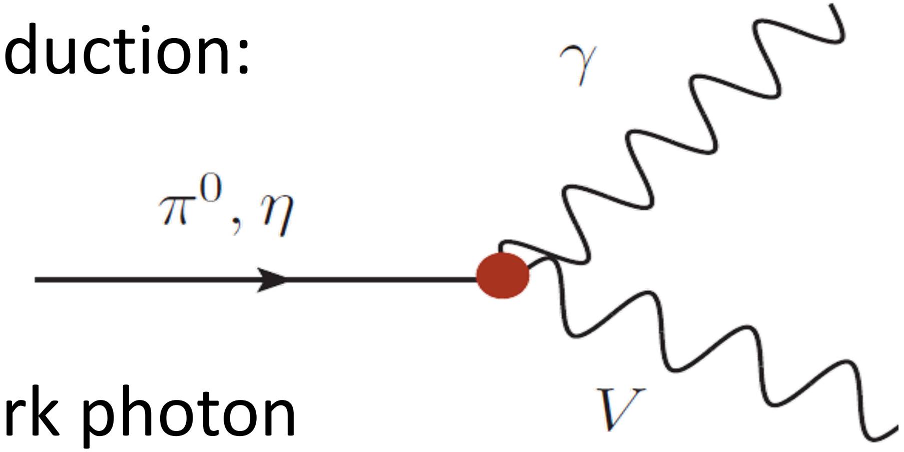


- Basic question: how many DM particles do we expect to produce in proton-based experiments ?

Light meson decays and sub-showers

- Basics of dark sector production: statistics and low background
- For light dark photon, standard meson decay production:

$p\ p$ or $p\ N$ collision → Light mesons π^0, η ... → Decay to dark photon



- Long lifetime of π^0, η helps with the suppressed coupling $\quad N_{\pi^0} \propto \varepsilon^2$

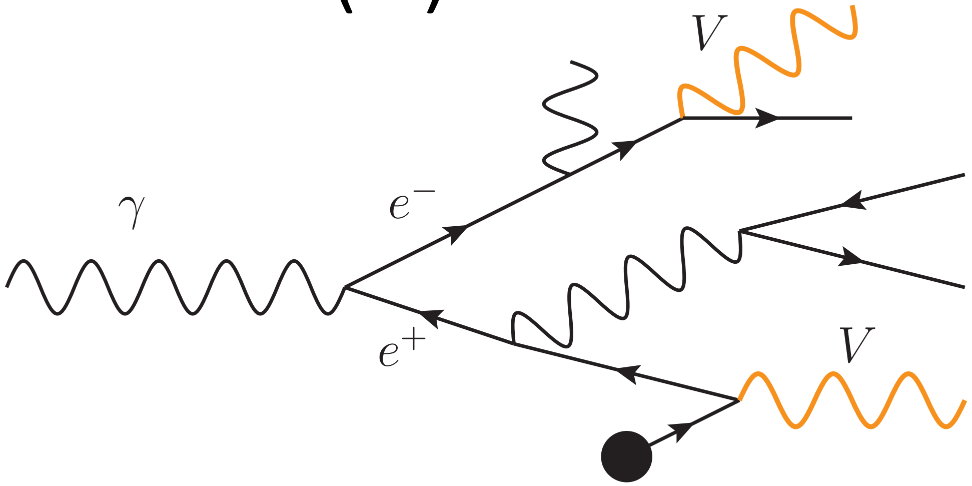
- However the main effects of $\pi^0, \eta \to \gamma\gamma$ decays is the generation of electromagnetic sub-showers!

→Typically ½ of the total hadronic shower goes into many e^+, e^-, γ

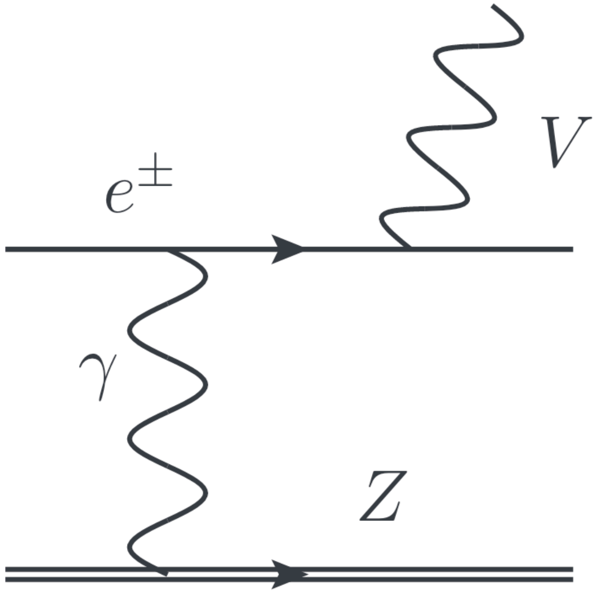
→Natural mechanism to convert energy to statistics!

Dark photon production in showers (1)

- Mimics the usual SM process, for e^+/e^-
  - Dark bremsstrahlung
  - But also resonant, Compton, …



- Let's compare the rates with meson decays
  (in material with atomic number Z)



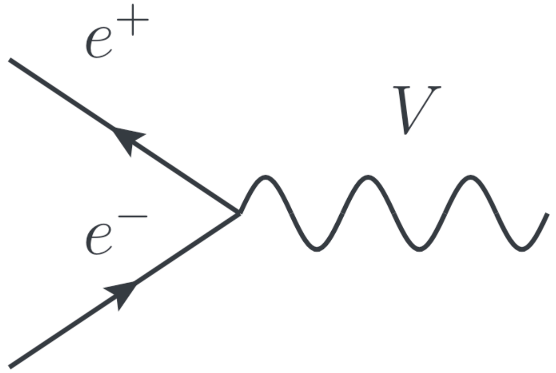
Electron bremsstrahlung: standard mechanism for electron beam dump

→ But showers have a lot of electrons …

$N_{brem} \propto \varepsilon^2\, \alpha_{em}^3 Z^2$ and $E_V^{brem} \propto E_e^{ini}$

Dark photon production in showers (2)

- Due to the numerous positrons in the showers: access to resonant production (remember large width from $V \to \chi\chi$)

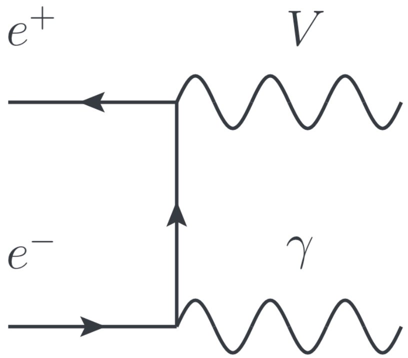


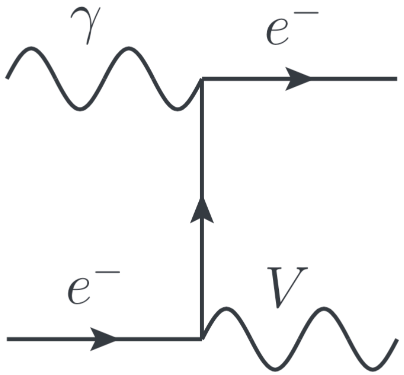
Large rate, fixed outgoing energy

$$\mathrm{N}_{res} \propto \varepsilon^2 Z\, \alpha_{em}$$

$$\mathrm{E}_V \propto M_V^2/2m_e$$

- More generally, also the sub-dominant associated and inverse Compton





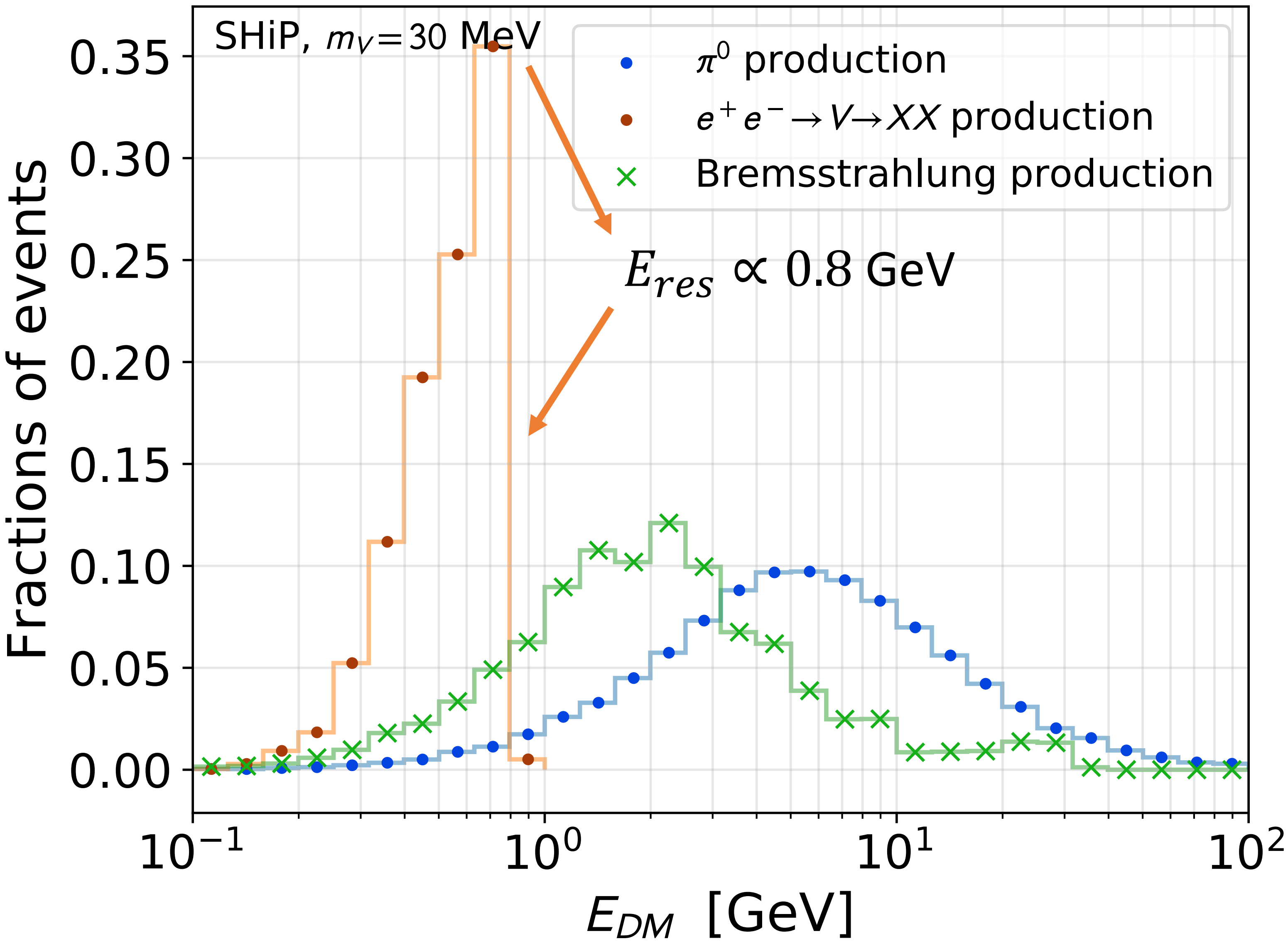
$$\mathrm{N}_{assoc} \propto \varepsilon^2\, Z\, \alpha_{em}^2$$

The flip side – Lower energy

- Shower-induced events have of course a much lower energy

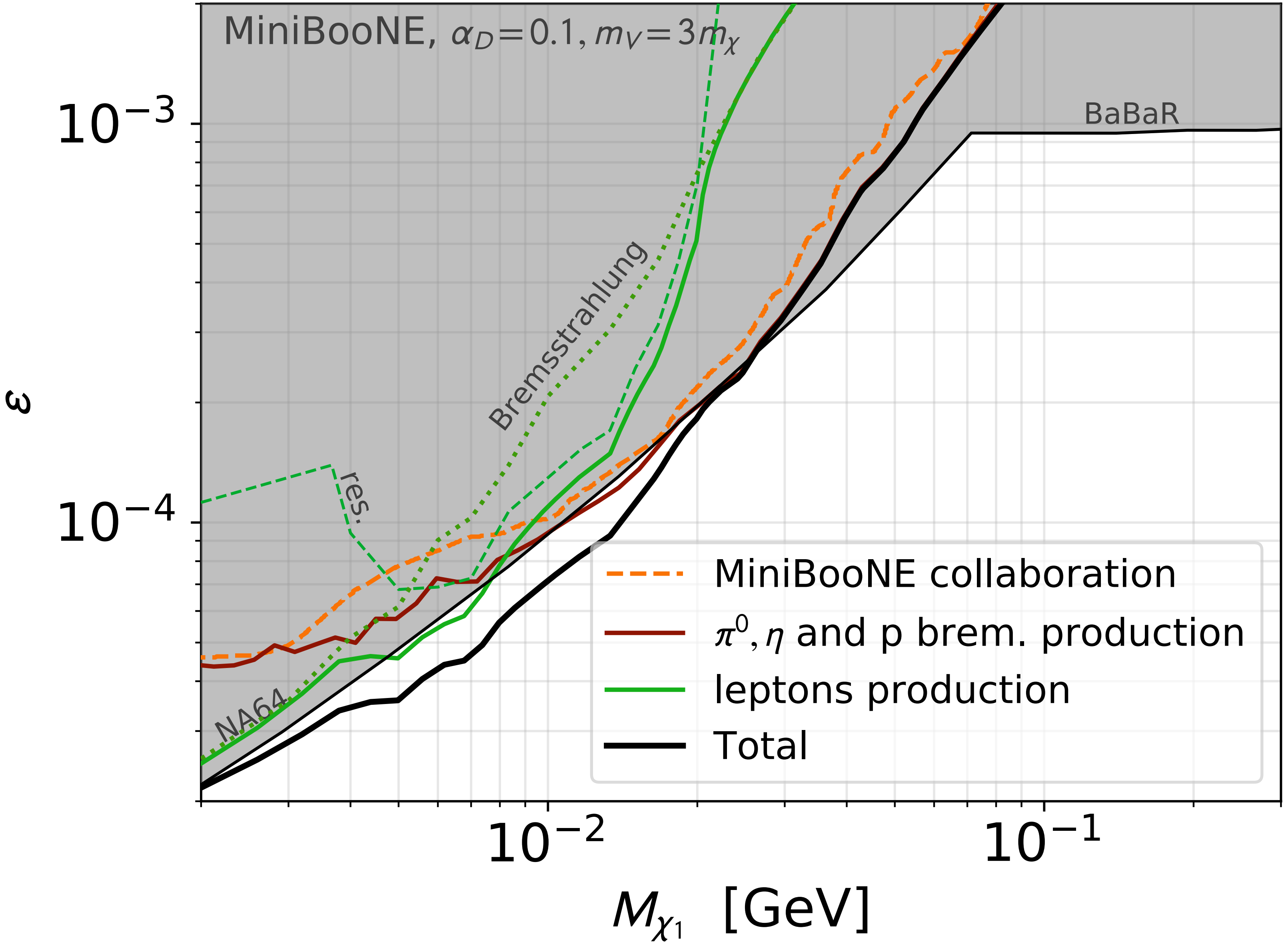
→Note the threshold from resonant production

→Shower brem. production better, but relatively low rate



Example 1: MinibooNE

- Proton-beam dump experiment, 8 GeV energy
- Low energy threshold (75 MeV)
- Limits for leptonic processes-only, and for all process
- For $M_V < 30$ MeV, total production rate 3x larger than meson decay alone



Example 2: SHiP

- Uses SPS beam at 400 GeV
- High energy threshold (1 GeV)
- Cut-off in the resonant production events
- Shower Bremsstrahlung processes nonetheless dominate at very small masses