Dark Sector Production via Proton Bremsstrahlung

Saeid Foroughi-Abari

University of Victoria

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Based on 2108.05900 with A. Ritz, and work in progress

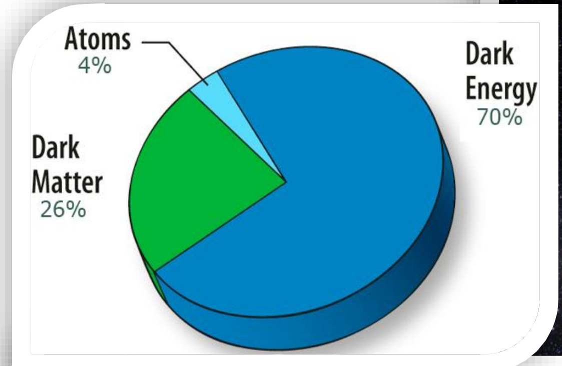
2010.07941; Collaborators: F. Kling, Y. D. Tsai, and R. M. Abraham

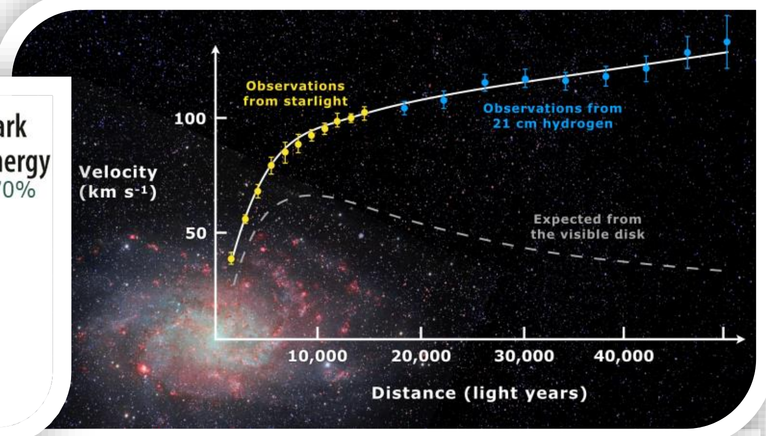
Outline

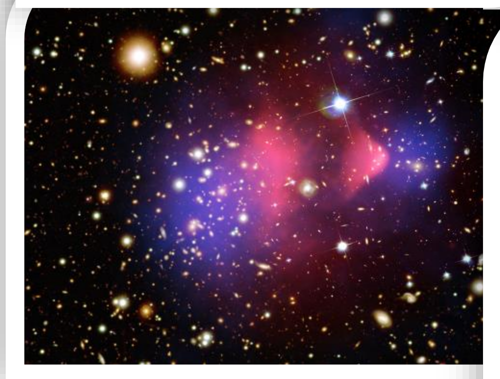
- Motivation to new physics BSM and dark sectors
- Dark Sectors Production via Proton Bremsstrahlung
- Gluon-coupled ALP production at proton beam facilities
- Hunting for millicharged particles at the LHC
- Probing Neutrino EM properties at the LHC

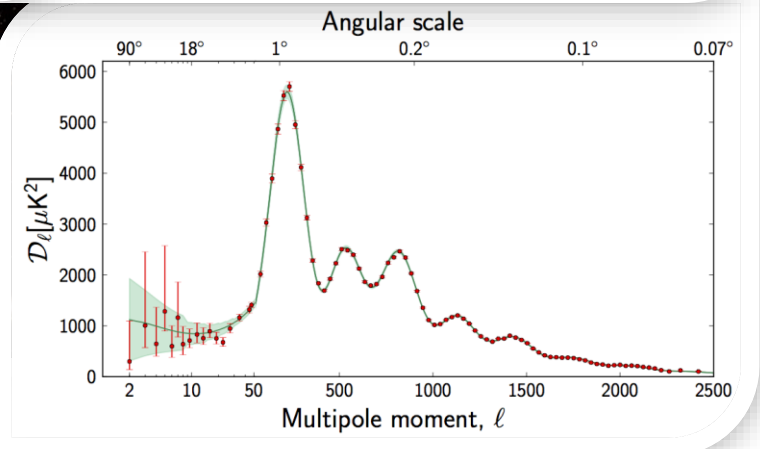
Motivation for BSM

- Dark mater evidence
  - Electrically neutral (dark!)
  - Cold (structure formation)
  - Non-baryonic (BBN)









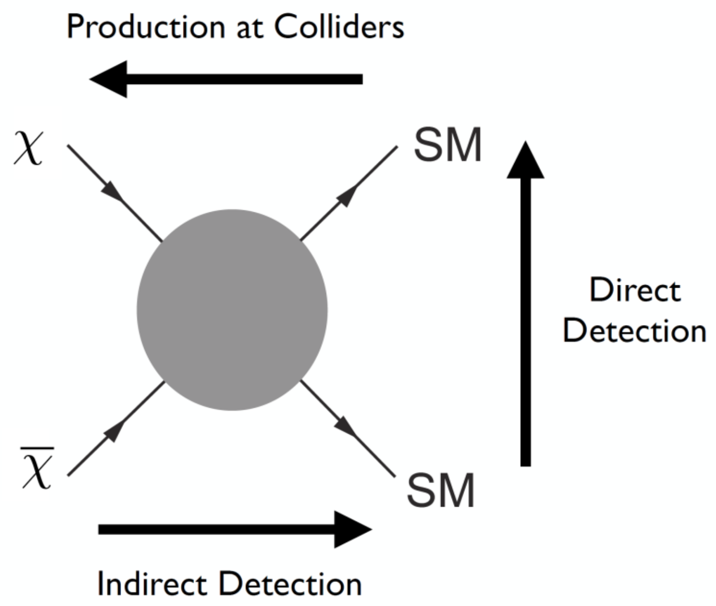
- Neutrino mass and mixing

- Particle physics puzzles
  - anomalies in data e.g., $(g-2)_\mu$

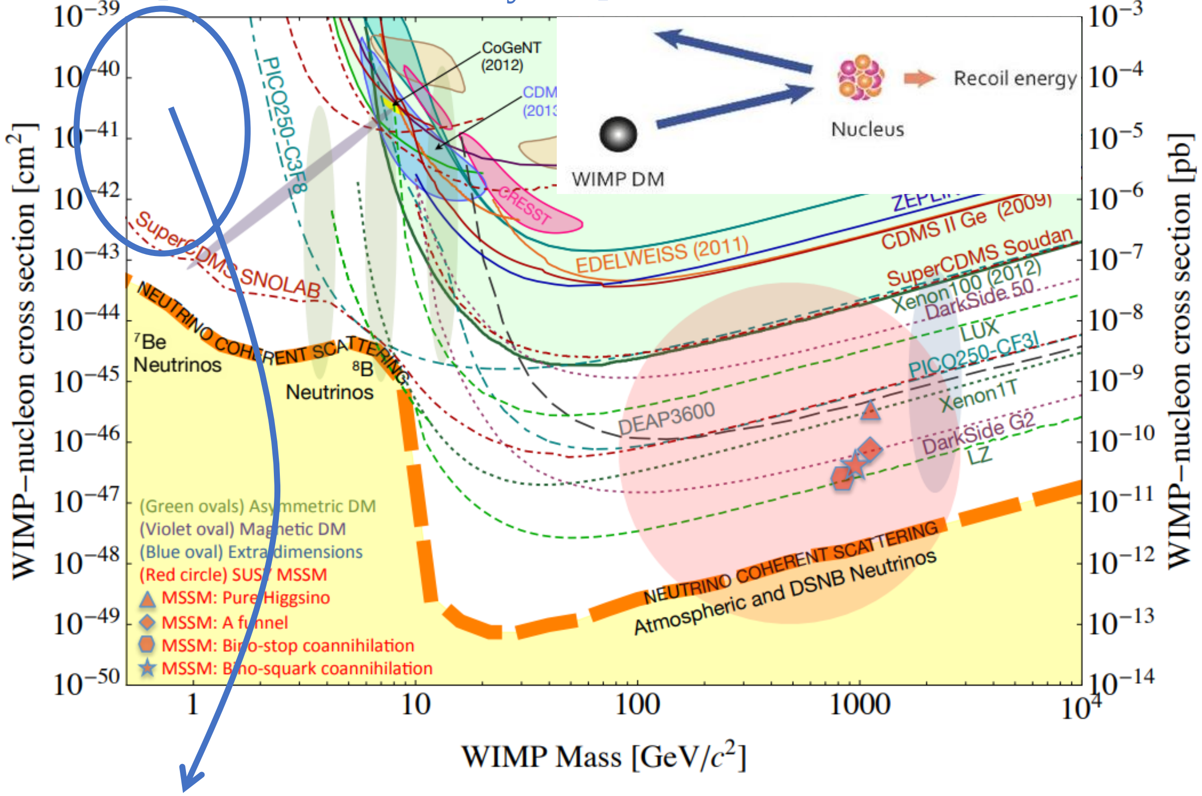
WIMP Searches

- **W**eakly **I**nteracting **M**assive **P**articles:
  - Minimal & linked to EWSB
  - Cosmological abundance generated via thermal freeze-out

- Different Strategies to search for DM non-gravitational interactions



[Snowmass Summary ’13]



Sub-GeV DM: $m_e < m_{DM} < m_{had}$

Direct detection sensitivity drops due to recoil thresholds

A high intensity relativistic beam is advantageous!

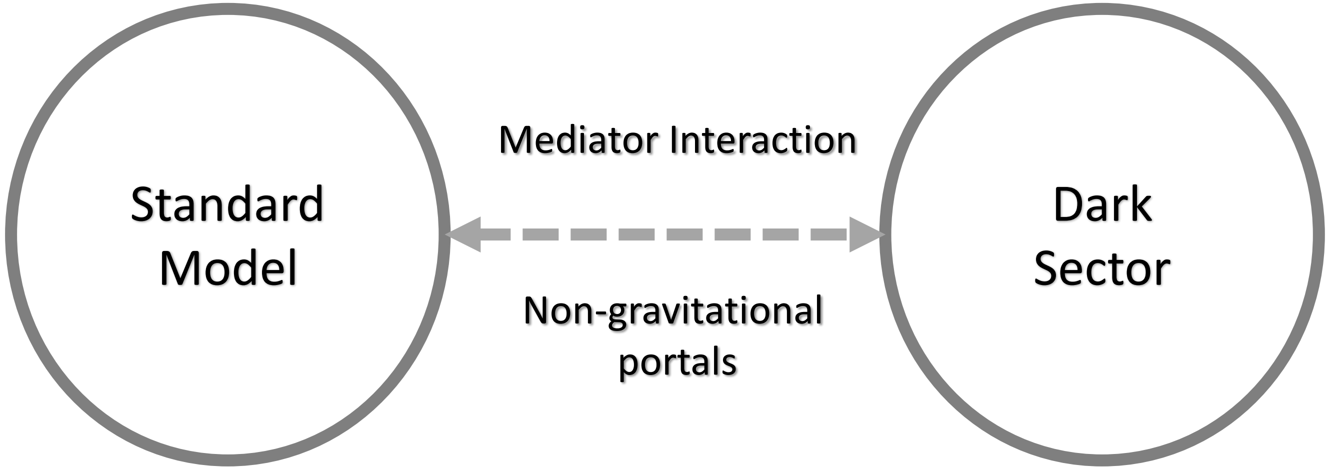
Dark Sectors Paradigm

- Viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states as part of a hidden sector

[Boehm & Silk et al.]
[Pospelov, Ritz, Voloshin '07]

$$\Omega_\chi h^2 \propto \frac{1}{<\sigma v>} \;,\; \sigma_{\text{ann}} \propto \frac{m_{\text{DM}}^2}{M_{\text{mediator}}^4}$$

- Dark Sector: a collection of particles that are neutral under the SM forces



Portals to Dark Sectors

- EFT for a DS: $$\mathcal{L}_{mediation} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})}}{\Lambda^n} \sim \mathcal{O}_{\mathrm{portals}} + \mathcal{O}(\frac{1}{\Lambda})$$

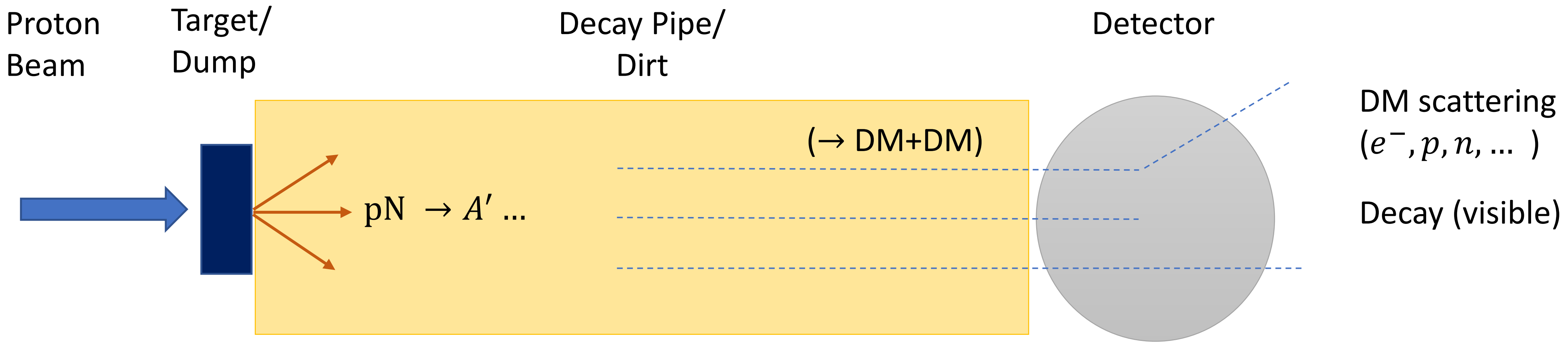
Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal "*portals*" to a neutral hidden sector

- Vector portal [Okun; Holdom; Foot et al.] — $\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu}$ — Dark Photon A'
- Higgs portal [Patt, Wilczek] — $H^\dagger H (AS + \lambda S^2)$ — Dark Higgs S
- Neutrino portal — $y\bar{L}HN$ — Sterile neutrino?

- Axion portal (dim-5) — $\frac{1}{f_a} \mathrm{tr}(G^{\mu\nu} \tilde{G}_{\mu\nu}) a$ — Axions & ALPs

Proton-Beam Fixed Target Probes

- Production of a high intensity “new weakly coupled light mediator beam” followed by the decay or recoil in the detector
- Production channels: **proton bremsstrahlung**, and secondary meson decays



- Past, existing and near Future neutrino experiments:

  LSND, CHARM, MiniBooNE, MicroBooNE,
  MINOS, NOvA, SBND, SeaQuest, SHIP, …

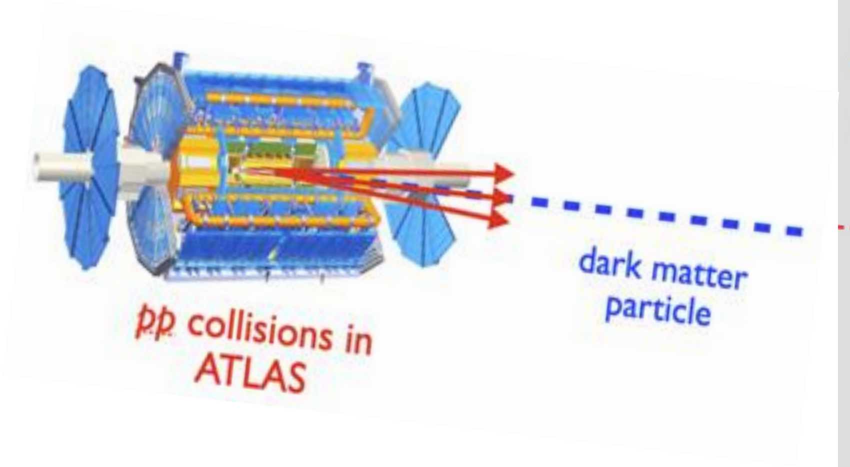
[Batell, Pospelov, Ritz ‘09]
[McKeen, deNiverville, Ritz ‘14]
[Krnjaic, Kahn et al ’17]

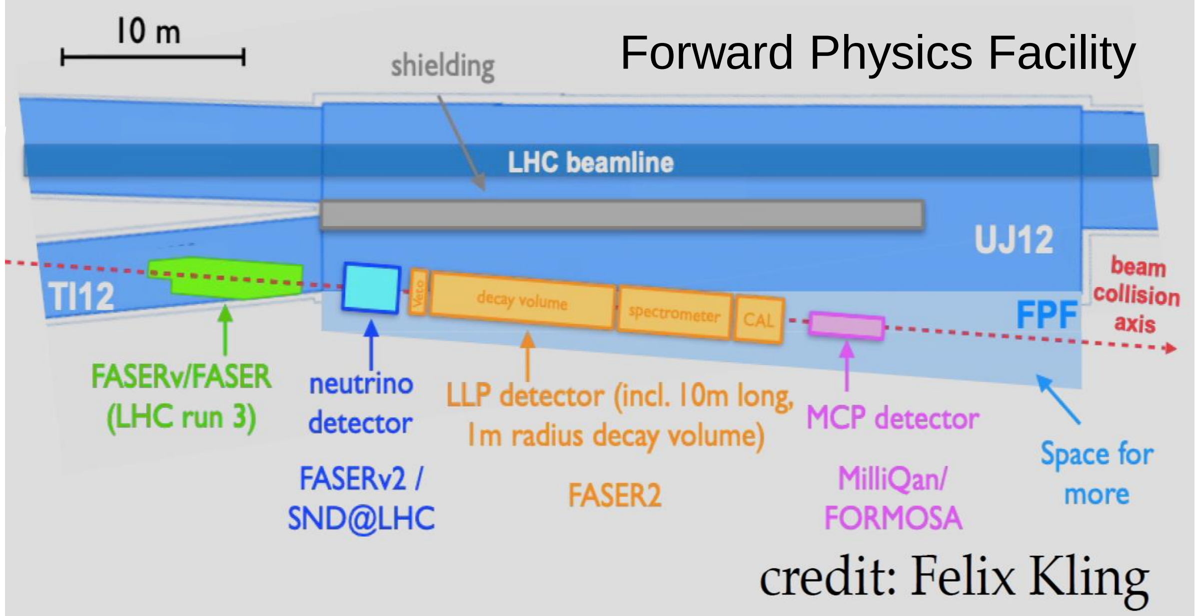
Dark Sector in the far-forward region @ LHC

- LHC Higgs factory: new physics searches focus on the central region. (high-p_T)
- But light particles mainly directed in the **forward region**! (Energetic, low p_T)

- **F**orward **P**hysics **F**acility for the HL-LHC

[Feng, Batell, Kling, Trojanowski, et al.]





FPF experiments provide sensitive and complementary probes of models of light DS:

long-lived particles, dark matter, millicharged particles + neutrinos (~TeV)

Dark Sectors

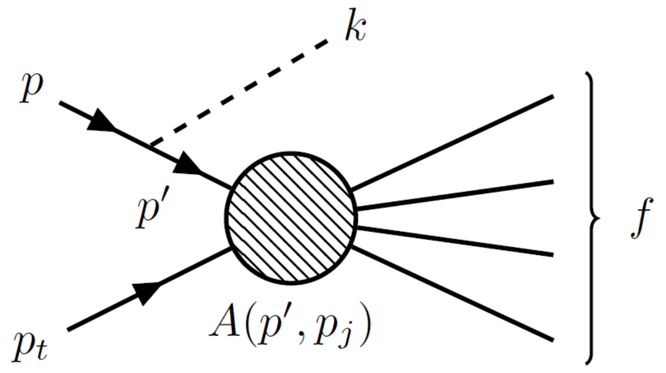
DS production via proton bremsstrahlung

Search for gluon-coupled ALP

Millicharged particle hunt @ FPF

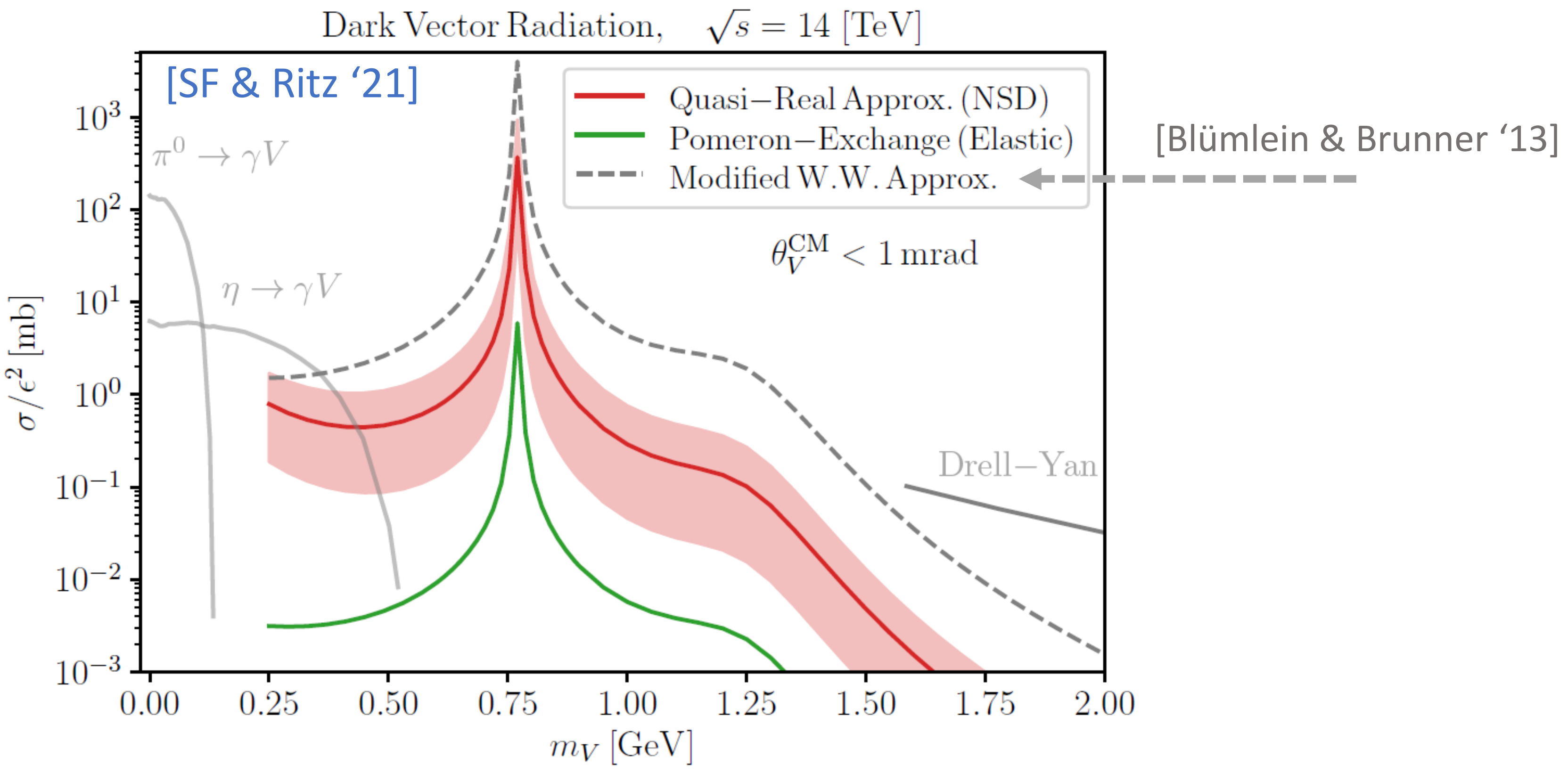
Neutrino EM properties @ FPF

Higgs portal @ LSND



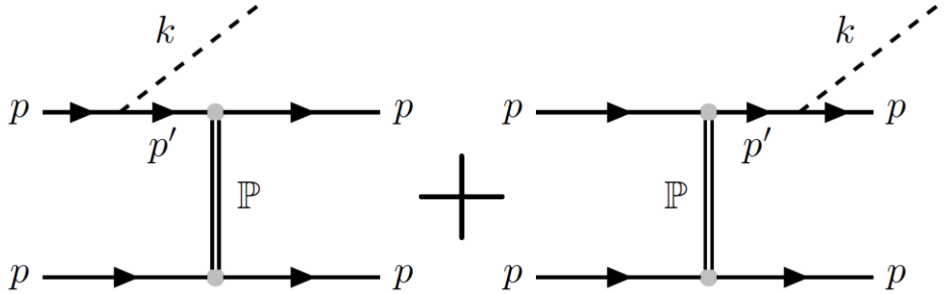
Proton Bremsstrahlung

- Primary production channel for dark sector mediators with mass ~ [0.5,1.5] GeV at proton beam facilities
- Important regime near vectors (ρ,ω,…), and scalar (f_0,…) meson resonances

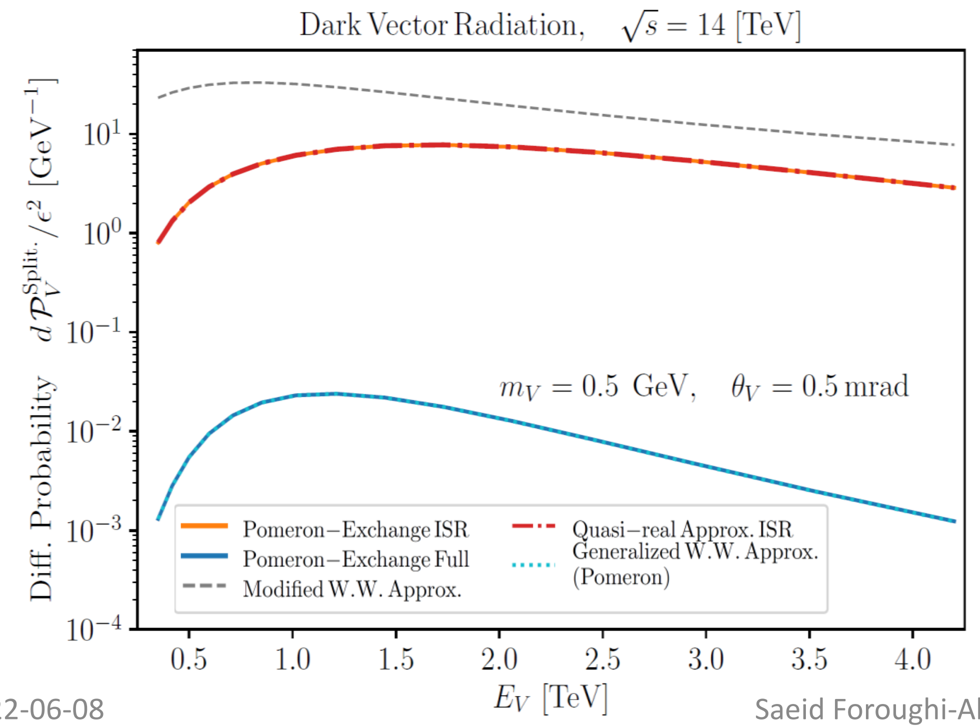


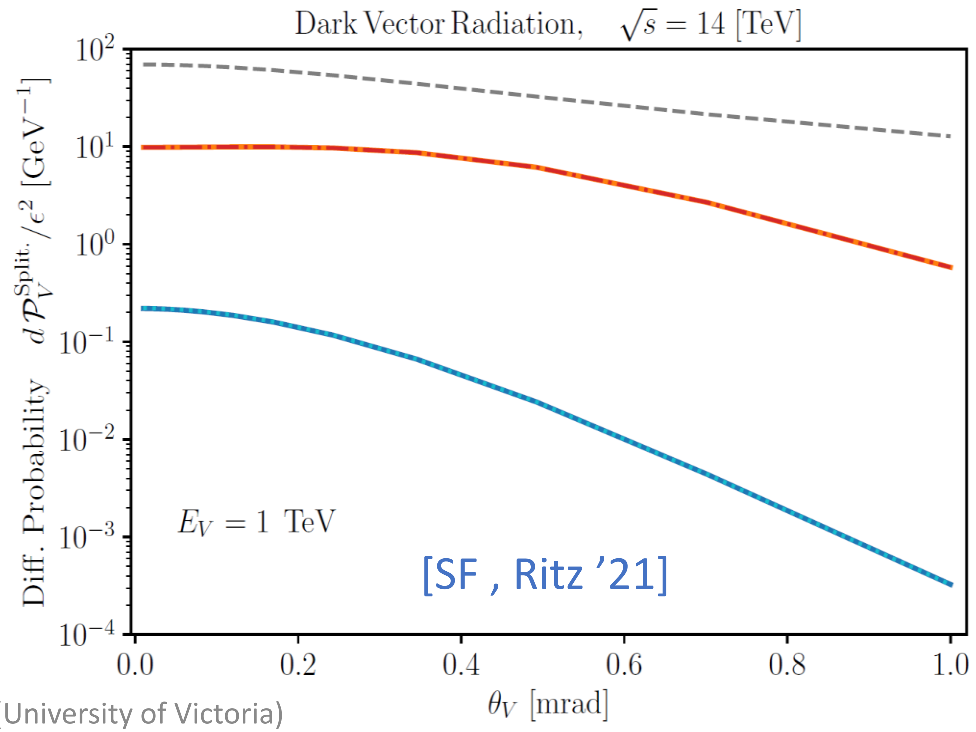
ISR and FSR in Quasi-Elastic scattering

- Modeling forward pp scattering with Pomeron
  Donnachie & Landshoff model [D&L '82, '84, '11, '13]



- Observe the large **cancellation** between ISR & FSR in quasi-elastic scattering

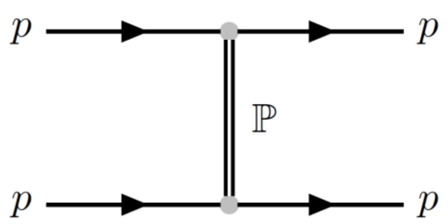




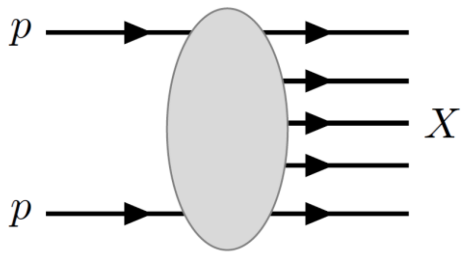
Topologies of events in σ_{pp}

- Diffractive processes constitute up to 40% of σ_{tot}

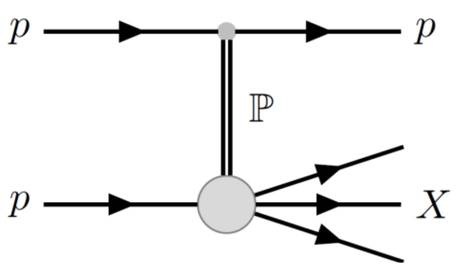
Elastic



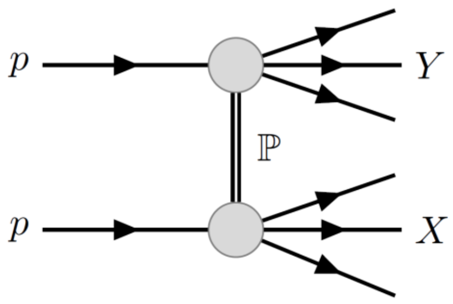
Non-Diffractive



Single Diffractive



Double Diffractive

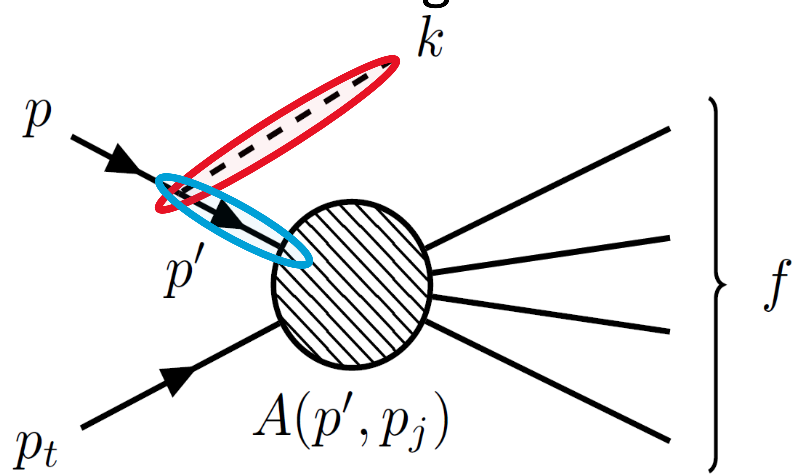


Event	*PP* collision at √s = 14 TeV
σ_{tot}	~ 110 mb
σ_{el}	~ 30 mb
σ_{SD}	~ 10 mb
σ_{DD}	~ 7 mb

Radiation in Non-Single Diffractive Processes

- The dominant contribution comes from ISR in non-single diffractive scattering.
- Quasi-Real Approx.: Intermediate p' near on-shell

$$d\sigma^{pp_t \to Df}(s) \approx d\mathcal{P}_{p\to p'D} \times \sigma_{pp}^{\mathrm{NSD}}(s')$$



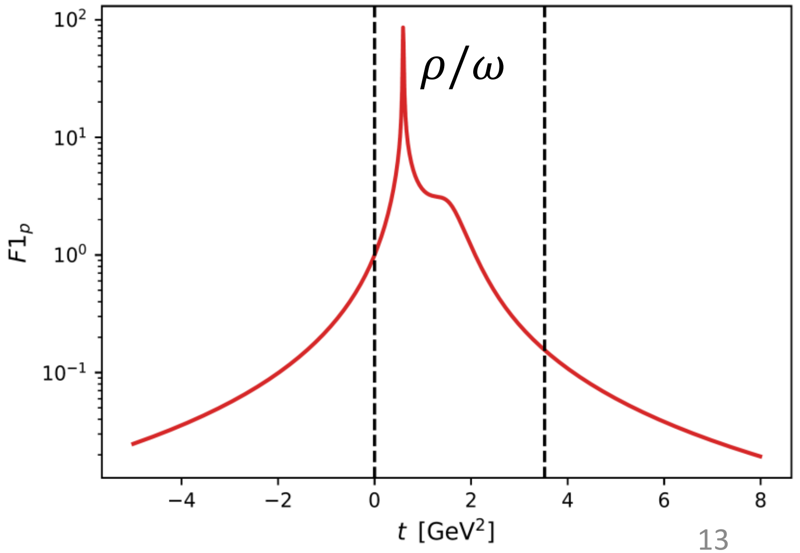
- Transition (Off-Shell) form factor: [Feuster & Mosel '98]

❖ Accounts for the suppression when the intermediate p' goes far off-shell

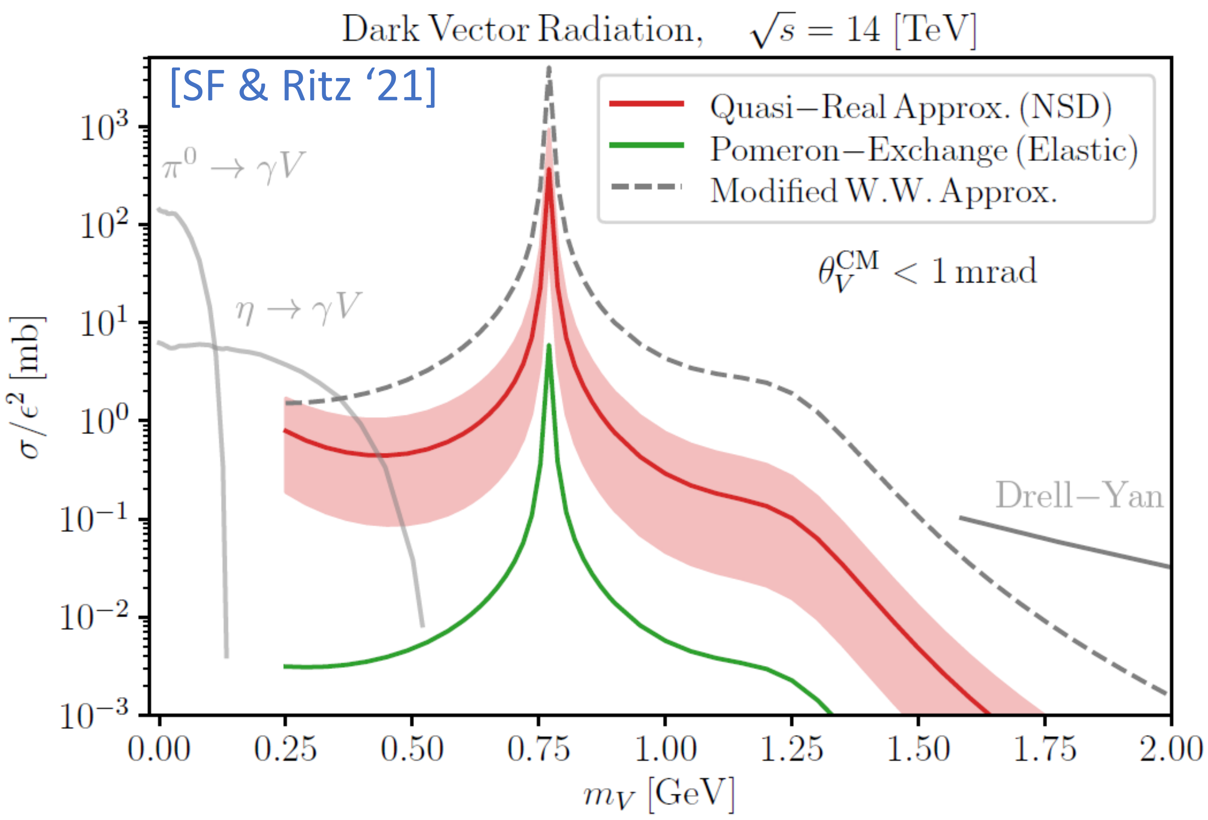
$$F_{pp^\star D}(p'^2) = \frac{\Lambda_p^4}{\Lambda_p^4 + (p'^2 - m_p^2)^2}$$

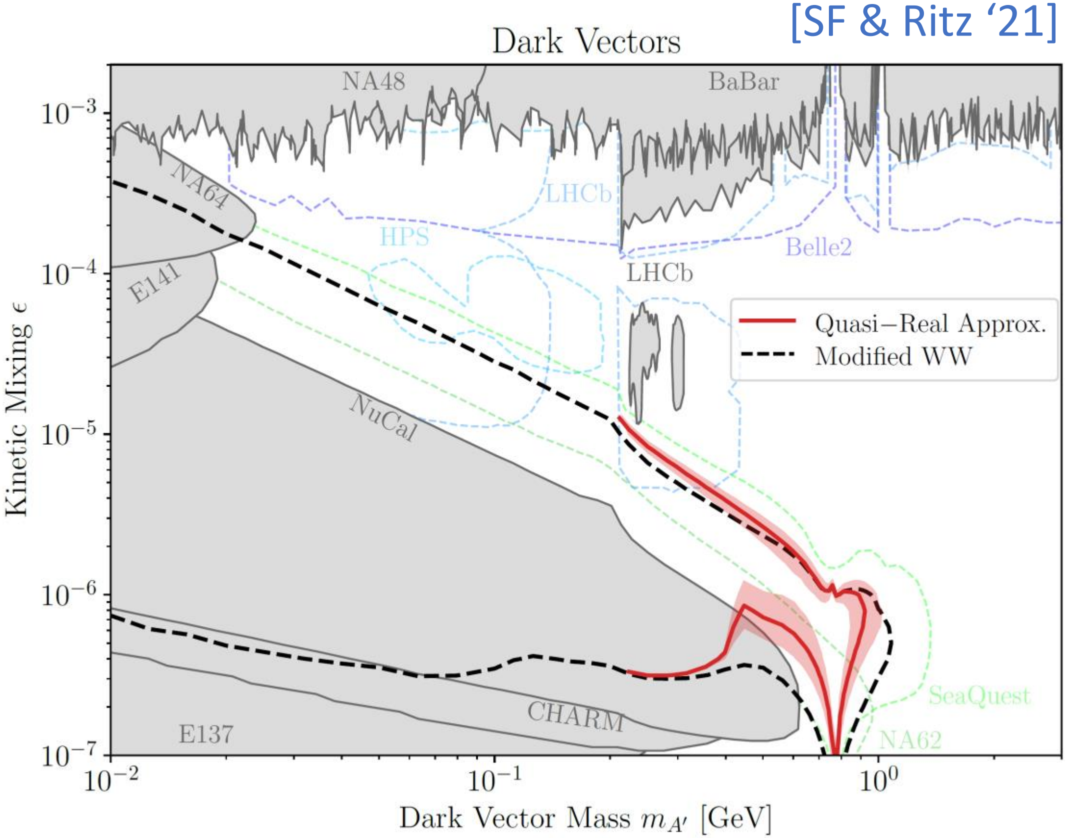
- Time-like nucleon form factor: [Faessler et al '09]

❖Mixing with meson resonances



Revisiting Proton Bremsstrahlung





Dark Sectors

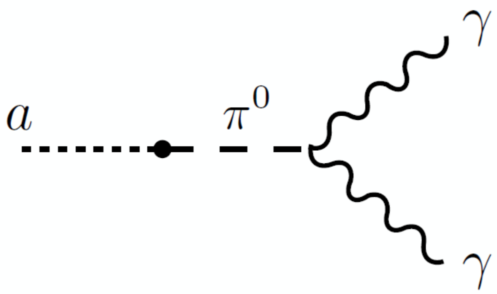
DS production via proton bremsstrahlung

Gluon-coupled ALP

Millicharged particle hunt @ FPF

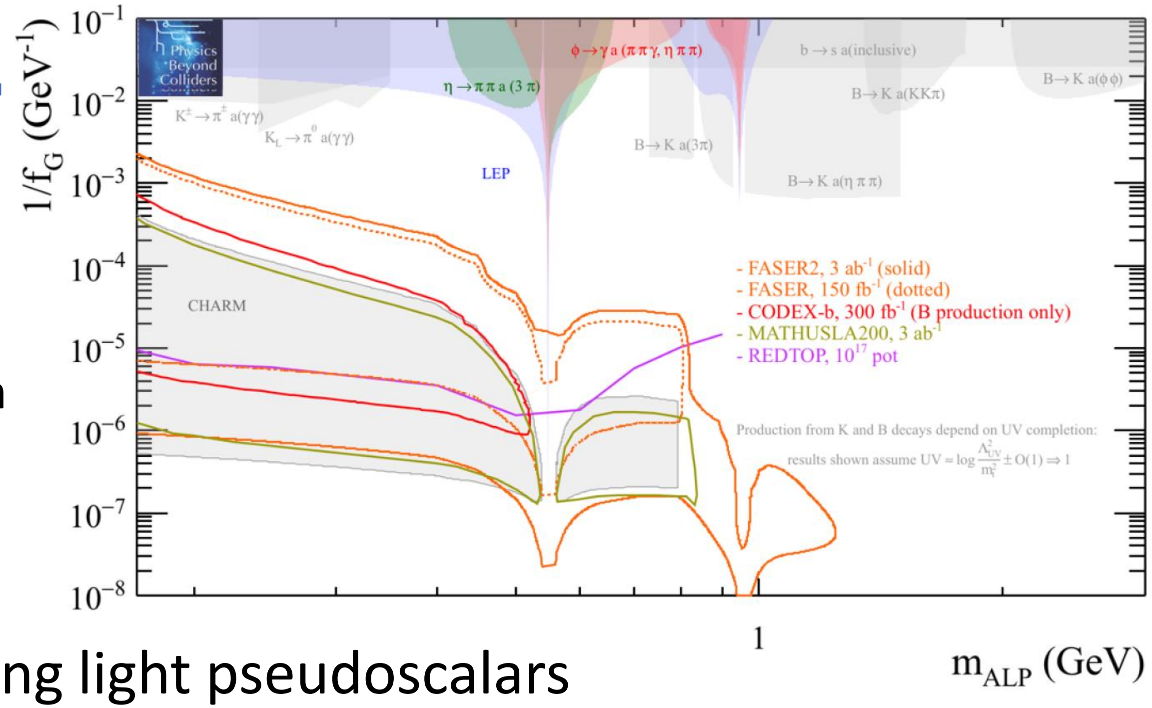
Neutrino EM properties @ FPF

Higgs portal @ LSND



Axion Portal

[PBC ’19]



- Axion are theoretically well-motivated:

  - solution to the Strong CP problem; $\theta \sim a/f_a$
  - viable candidate for dark matter
  - Axion acquires a small mass from mixing with the pion

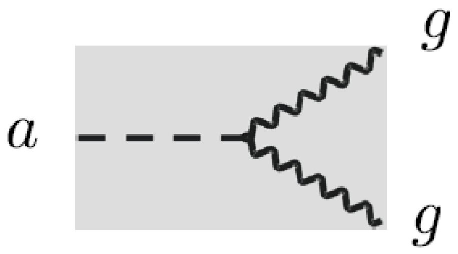
  [Peccei,Quinn 77; Weinberg 78]

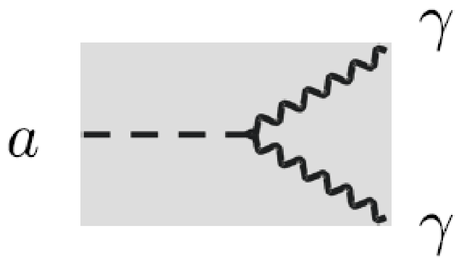
- Axion-Like Particles (ALPs) are weakly interacting light pseudoscalars
  mass & coupling are independent! [Wilczek 82; Berezhiani,Khlopov 90]

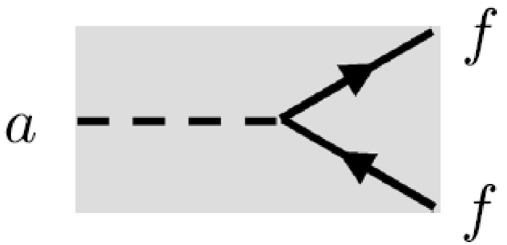
[Bauer, Neuber, Thamm et al. ’17 ’21]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

Focus of this talk







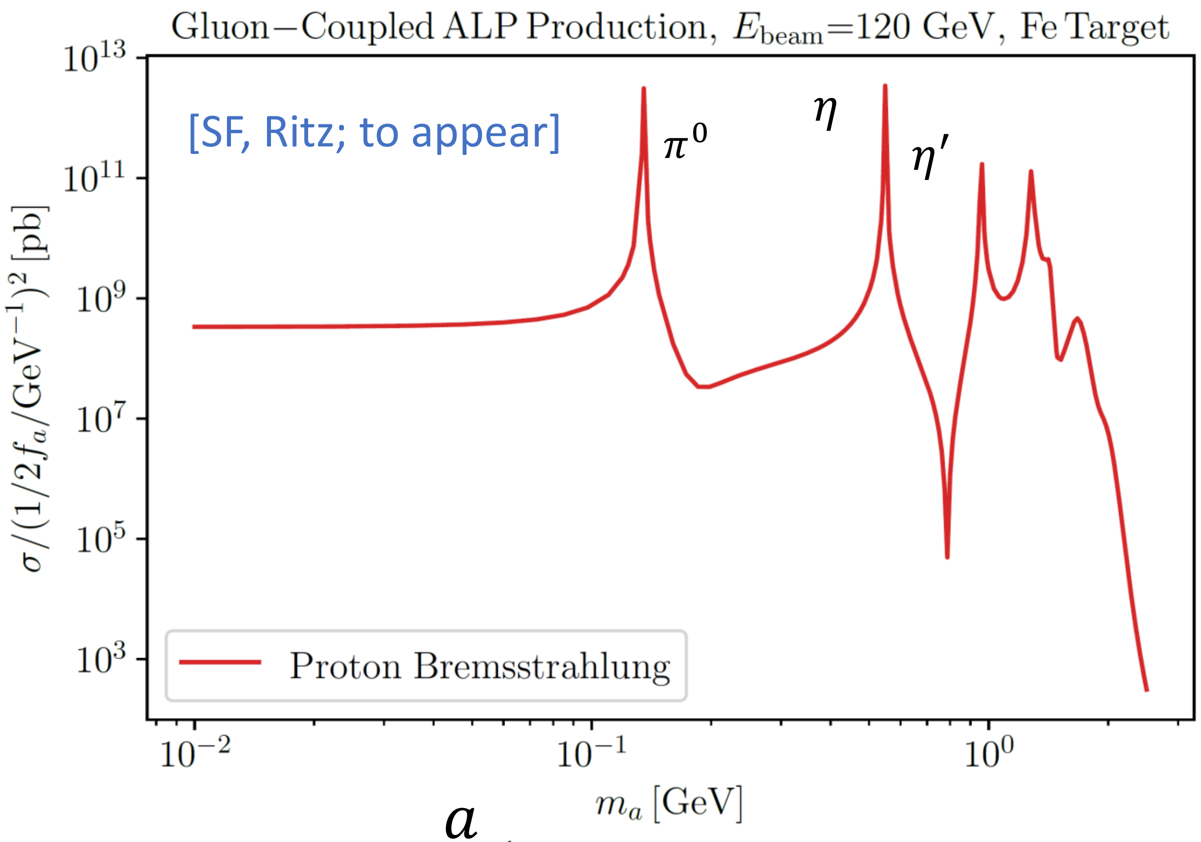
Axion Portal (gluon coupling)

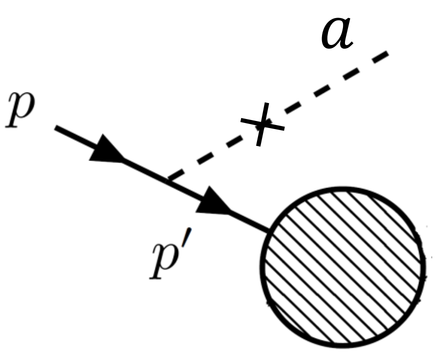
- Perform Chiral rotation: eliminate the $aG\tilde{G}$ term in favor of ALP coupling to quarks
- Axial-vector currents and coupling to nucleons:

$$J_{\mu 5} = \frac{1}{2}\delta_I J^3_{\mu 5} + \frac{1}{2\sqrt{3}} J^8_{\mu 5} + \frac{1}{\sqrt{6}} J^0_{\mu 5}$$

$$\langle N(p')|J^i_{\mu 5}|N(p)\rangle$$

- ALP mixing with pseudoscalar mesons π^0, η, η'
- Axial Form Factors probe the axial structure of the nucleon: axial vector mesons a_1, f_1, f_1' resonances





Also look at N. Blinov et al. 2112.09814

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DS production via proton bremsstrahlung

Search for gluon-coupled ALP

Millicharged particle hunt @ FPF

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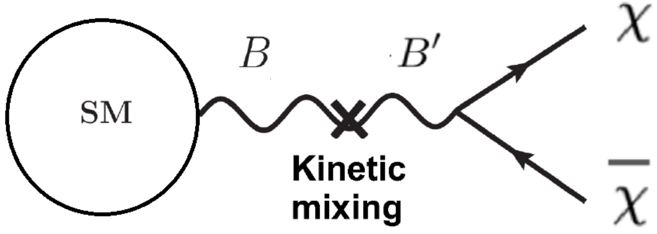
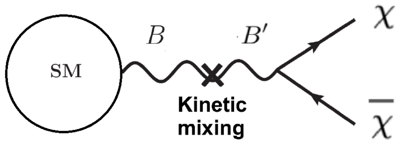


Millicharged Particles

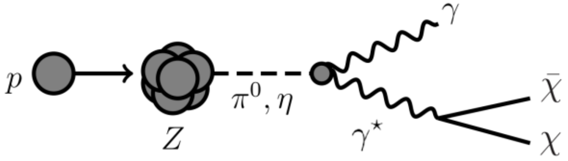
- mCPs could arise from vector portal **Kinetic Mixing** in a massless phase: [Holdom, '85]

$$\mathcal{L}_{\mathrm{MCP}} = \bar{\chi}(i\partial\!\!\!/ - \epsilon' e B\!\!\!/ - m_\chi)\chi$$

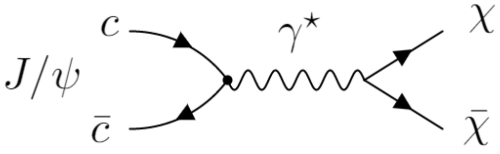


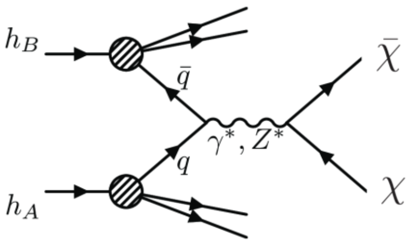
- Production Channels

❖Meson decays

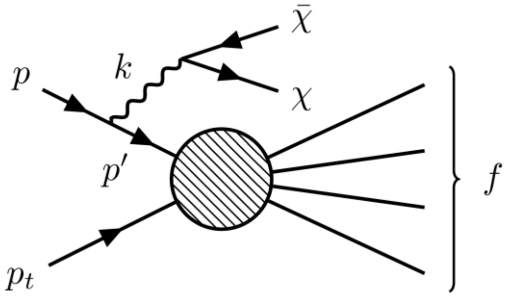


❖Drell-Yan

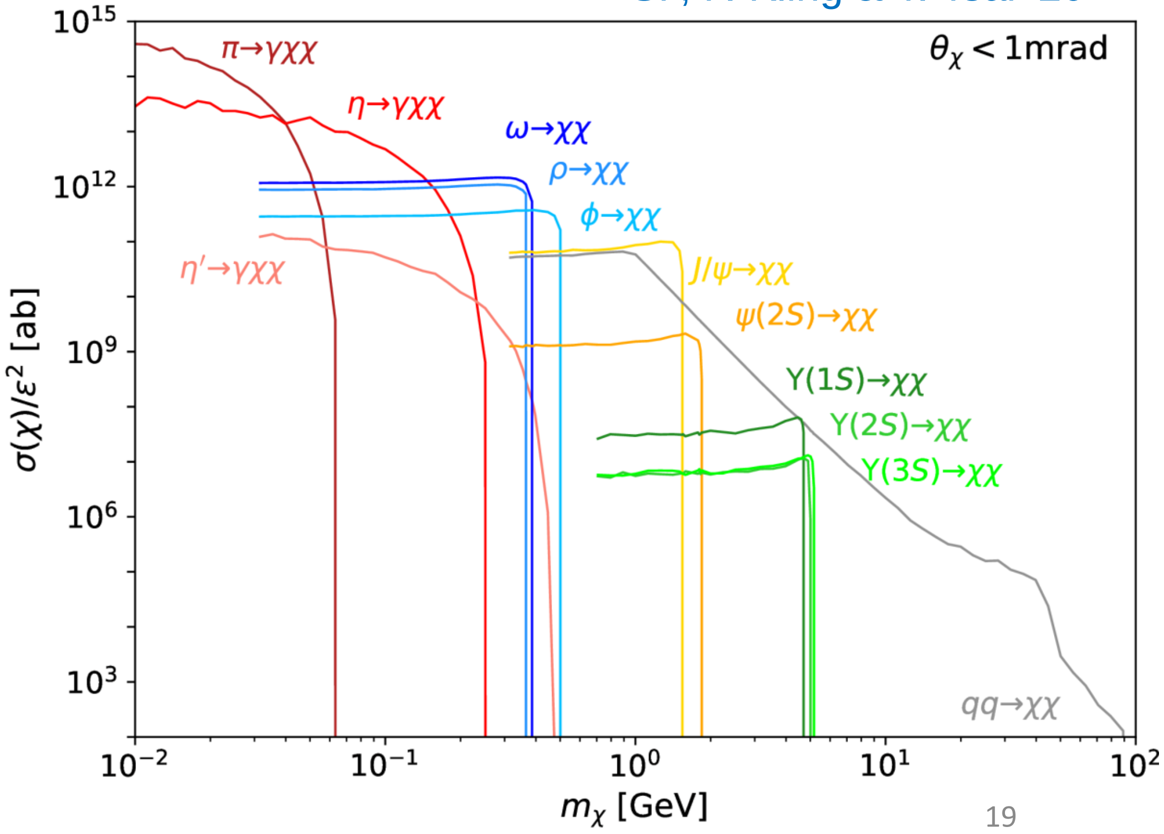




❖P-Brem?



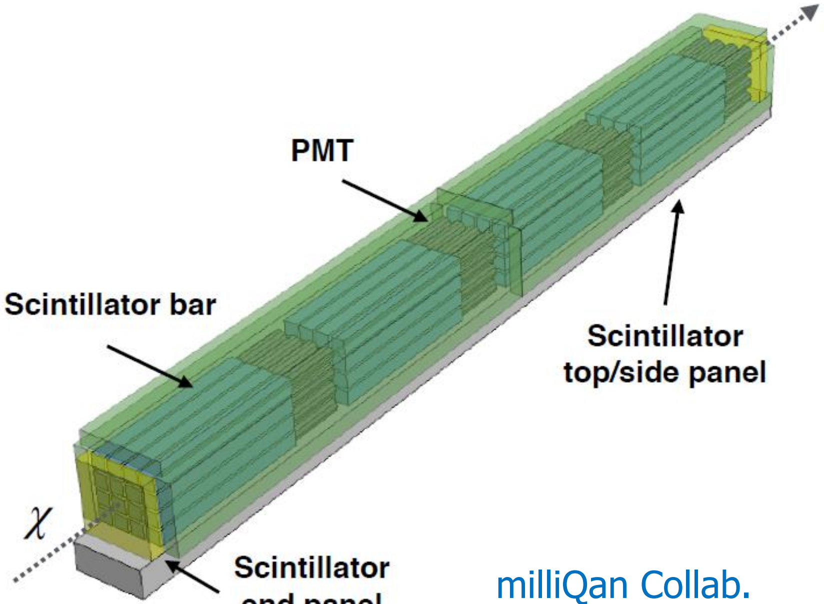
SF, F. Kling & Y. Tsai '20

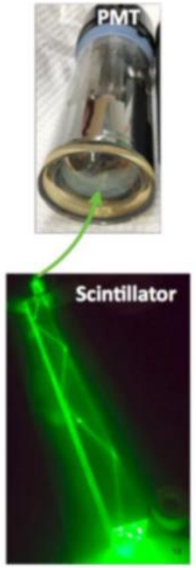


Millicharged Particle Hunting at the LHC

Scintillator detector at Forward Physics Facility

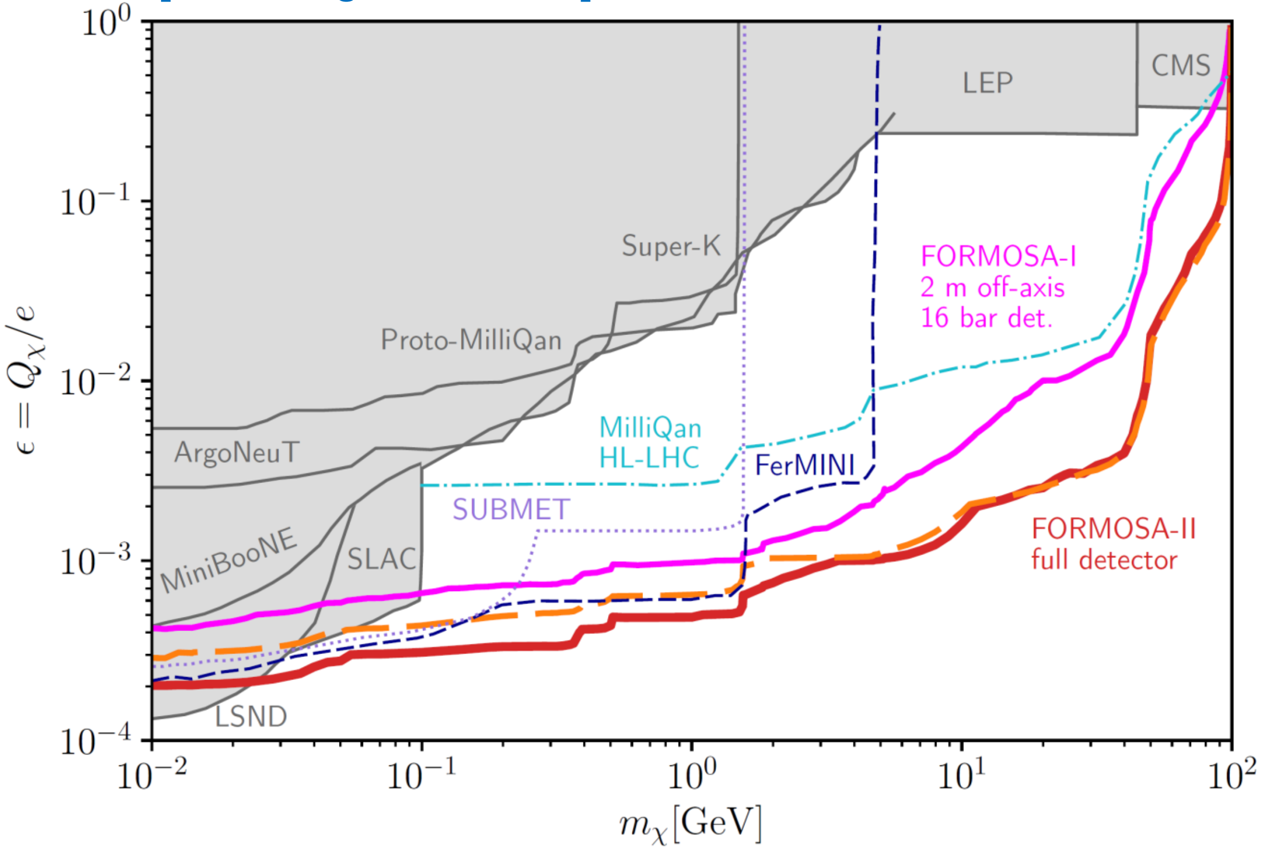
FORMOSA





milliQan Collab. 1607.04669

[SF, Kling & Tsai '20]

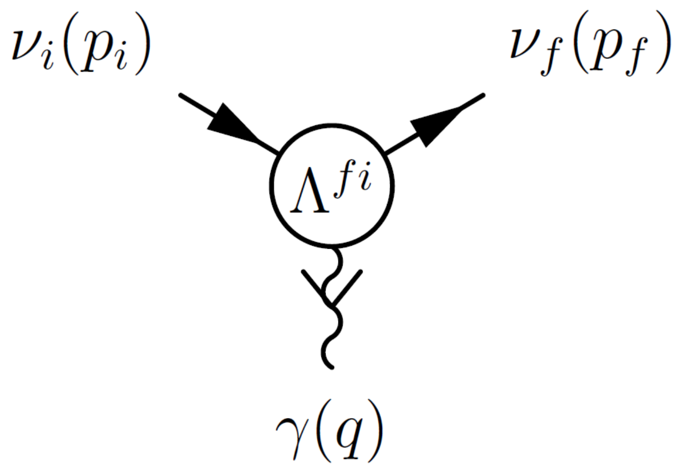


Deposition of energy due to ionization

mCP flux enhancement in the forward direction

Dark Sectors

- DS production via proton bremsstrahlung
- Search for gluon-coupled ALP
- Millicharged particle hunt @ FPF
- **Neutrino EM properties @ FPF**
- Higgs portal @ LSND

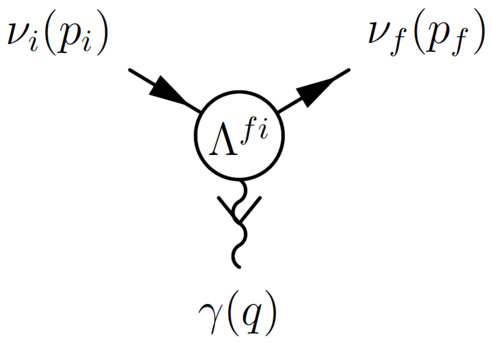


Neutrino EM properties at the FPF

- Non-zero neutrino electromagnetic properties through loops

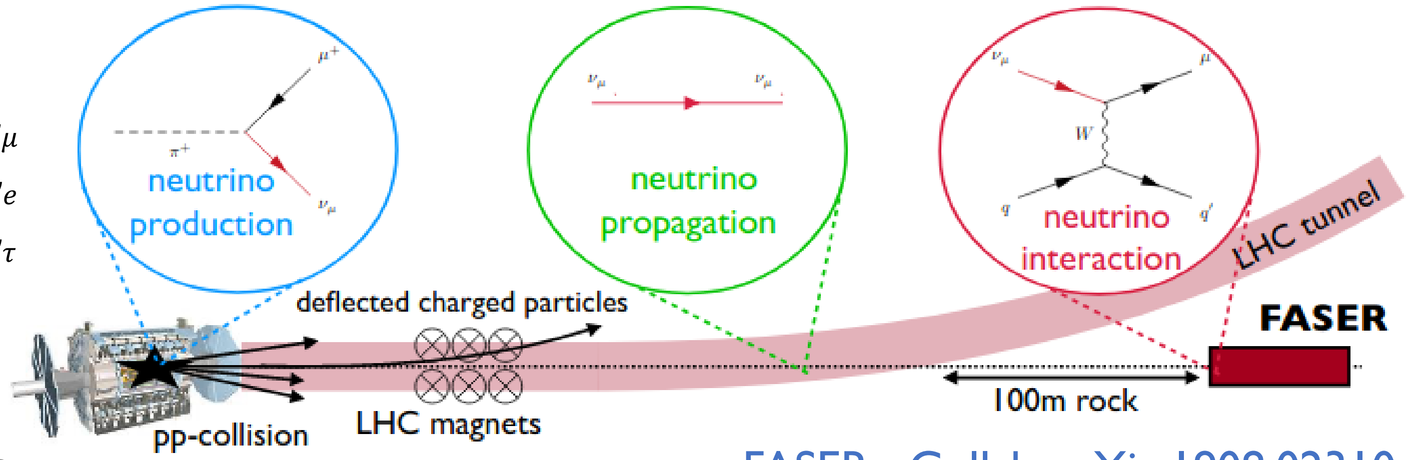
[Giunti, Studenikiny '15]

$$\Lambda^{\alpha}_{kj}(q) = \gamma^{\alpha}\left(Q_{\nu_{kj}} + \frac{q^2}{6}\langle r^2\rangle_{\nu_{kj}}\right) - i\sigma^{\alpha\beta}q_{\beta}\,\mu_{\nu_{kj}}$$



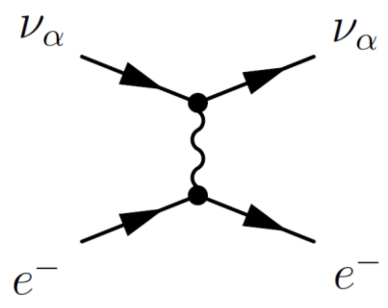
- Large flux of neutrinos in the far forward region
  $E_\nu \sim$ [100GeV – few TeV]

$10^{18}\,\pi \rightarrow \nu_\mu$
$10^{17}\,K \rightarrow \nu_e$
$10^{16}\,D \rightarrow \nu_\tau$



FASERν Collab. arXiv:1908.02310

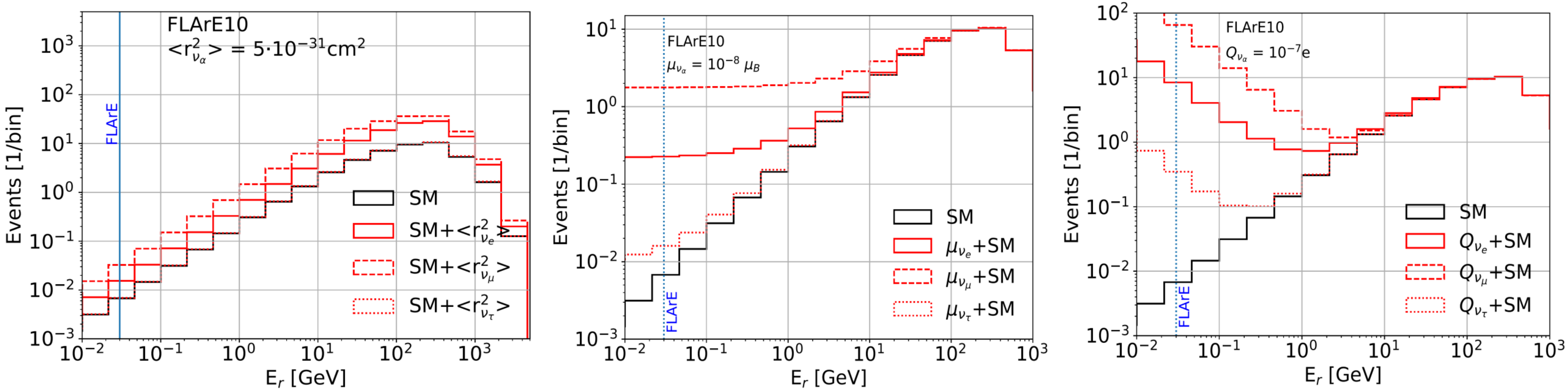
- Experimental signature: electron **recoiling**



Neutrino EM properties at the FPF

- SM predictions: $\mu_{\nu_{kk}}^{\text{Dirac}} \simeq 3 \times 10^{-19} \left(\frac{m_{\nu_k}}{\text{eV}}\right) \mu_{\text{B}}$ $\langle r^2 \rangle_{\nu_\alpha}^{\text{SM}} \sim 10^{-32}\,\text{cm}^2$

[Abraham, SF, Kling, Tsai, to appear]



- Bounds: $< r^2 >_\nu < \sim 10^{-31}\text{cm}^2$, $\mu_{\nu_\tau} < 4 \times 10^{-8} \mu_B$, $|Q_\nu| < \sim 10^{-8}\text{e}$,
- FLArE-10 can do order of magnitude better than DONUT hep-ex/0102026

Outlook

- The dark sector paradigm is well-motivated and could have connections to other fundamental puzzles in nature.

- Dark Sector Production via Proton Bremsstrahlung as an important production channel is nontrivial to estimate in the forward region as it involves nonperturbative QCD.

- ALP coupling to nucleons in the three-flavour theory is used to estimated the ALP emission rate in proton-nucleus bremsstrahlung

- millicharged Dark sectors could be probed using scintillator-based detector in the LHC forward region providing leading sensitivity in the 100 MeV to 100 GeV mass window.

- Probing Neutrino EM properties like milli-charge, and charge radius at FPF

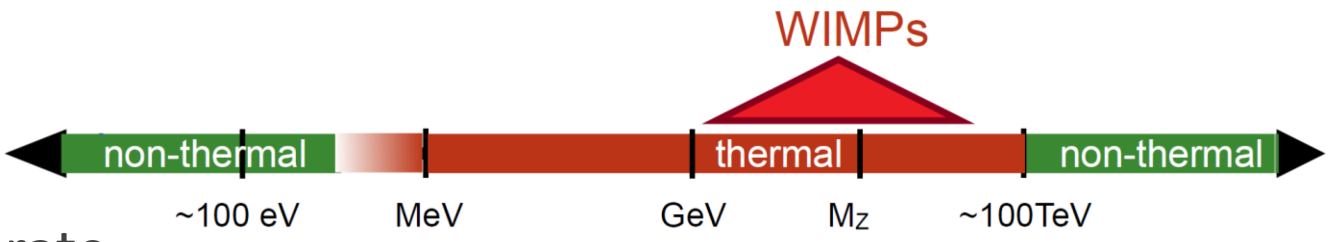
Image courtesy of KIPAC/SLAC

“Thank you for your attention”

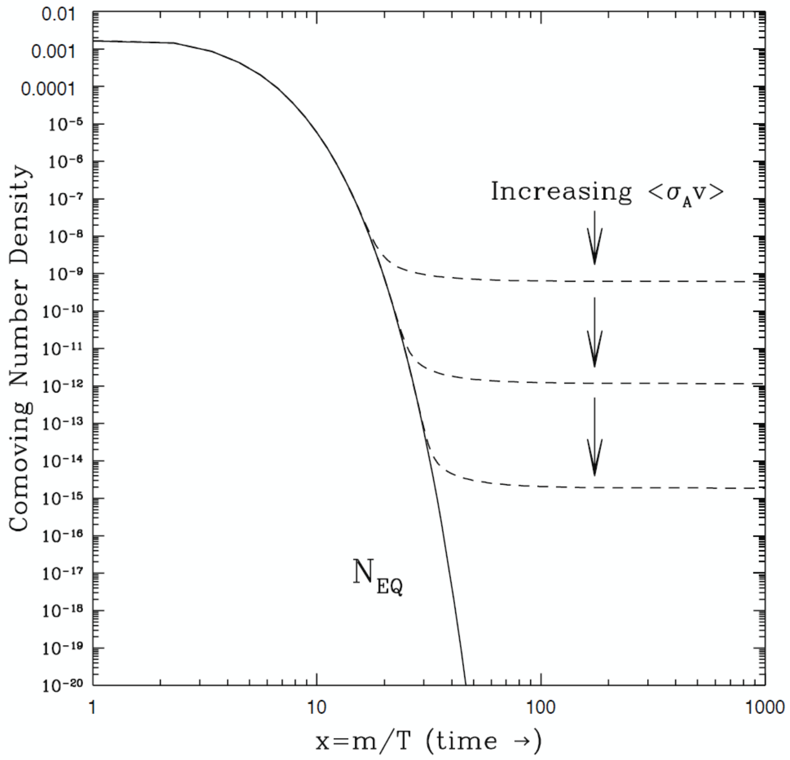
Back-up Slides

DM Candidates – Thermal WIMP

- Thermal candidates



DM freeze-out occurs when annihilation rate becomes smaller than the Hubble rate



- Correct relic density requires

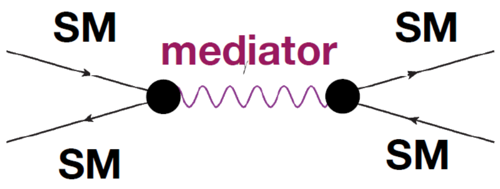
  Lee-Weinberg mass limit > ~ GeV

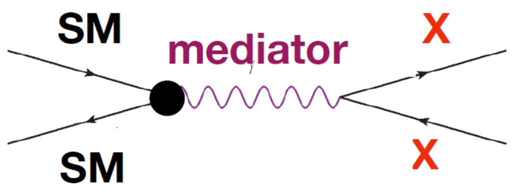
$$\langle \sigma v \rangle \sim \frac{G_F^2 m_\chi^2}{\pi} \approx 1\,\mathrm{pb} \times \left(\frac{m_\chi}{5\,\mathrm{GeV}}\right)^2$$

- Light thermal DM interacting via weak interactions generically overproduced

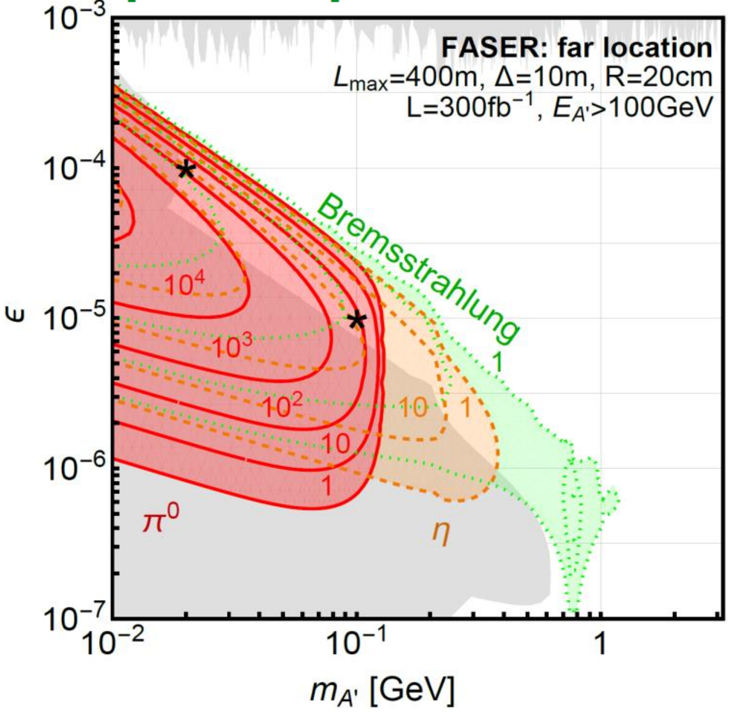
Decays of Portal Mediators

- Visible and invisible decays of dark mediators

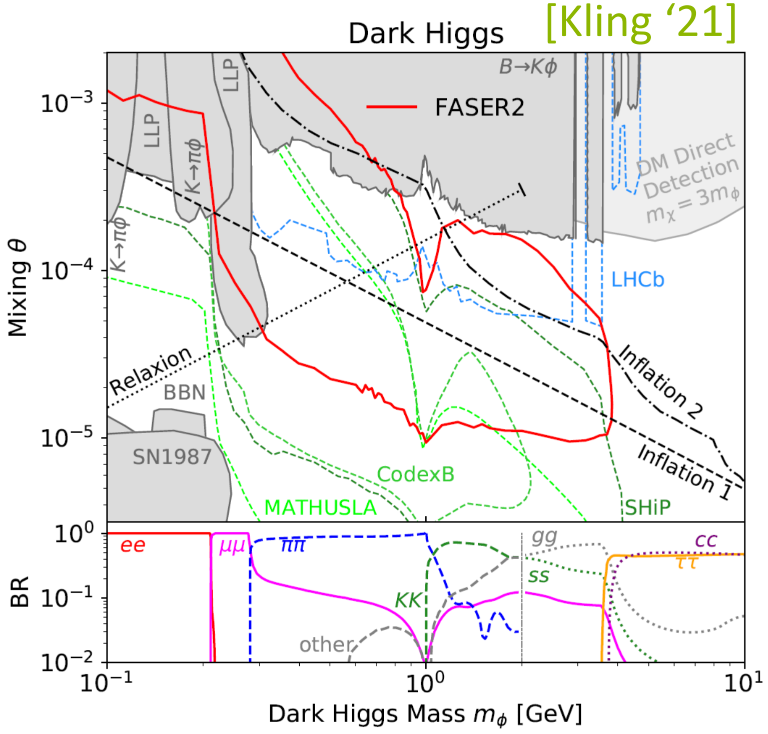




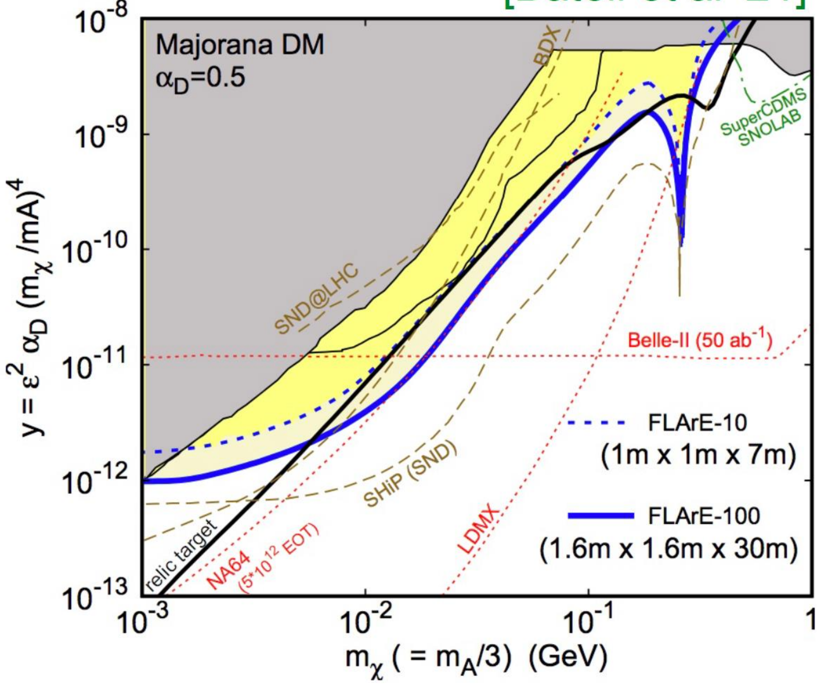
[FASER '17]



[Kling '21]



[Batell et al '21]

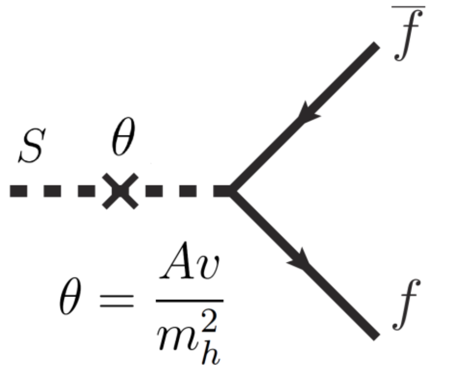


(Minimal) Higgs Portal to the Dark Sector

- Higgs-mediated DM scenario:
  - $m_S < 2m_{DM}$ to avoid strong constrains [Krnjaic '15]
  - dark scalar decay to visible particles

- Induced couplings after EWSB: S mixes with physical Higgs

$$\mathcal{L} \supset -ASH^\dagger H \qquad \Rightarrow \theta \frac{m_f}{v} S\bar{f}f + \ldots$$



- $\theta \ll 1$ production and decay rates are suppressed relative to SM!

- Light scalars are hugely constraint by rare K and B decays @ E949, NA62 LHCb, Belle,…

Dark Scalar at LSND

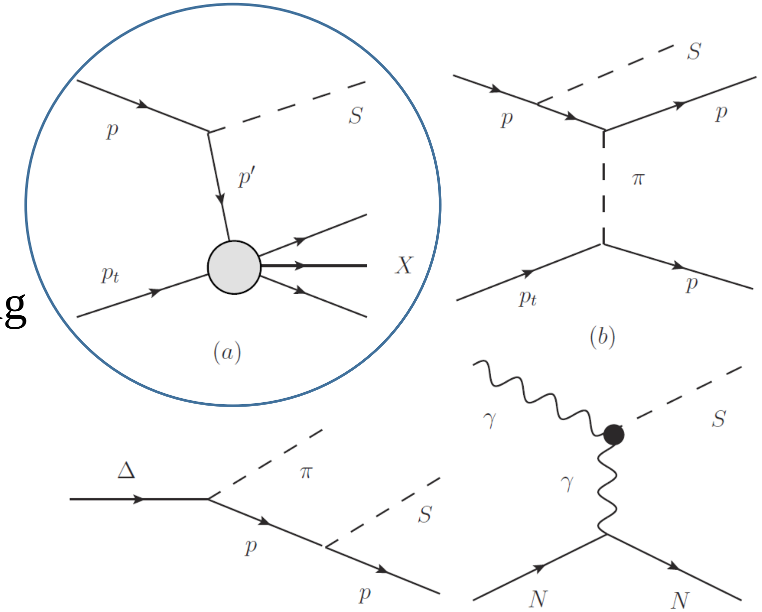
- The LSND experiment:
  800 MeV proton beam impacting a thick target with $\sim 10^{23}$ POT

- Production modes at LSND:
  - π and Δ are the relevant hadronic dof.
  - K and B mesons are not kinematically accessible!

Proton Bremsstrahlung

Δ decay

Primakov process



[SF, Ritz '20]