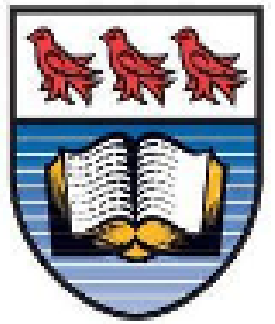
Using Proton Bremsstrahlung to Explore Light New Physics

Saeid Foroughi-Abari

University of Victoria



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

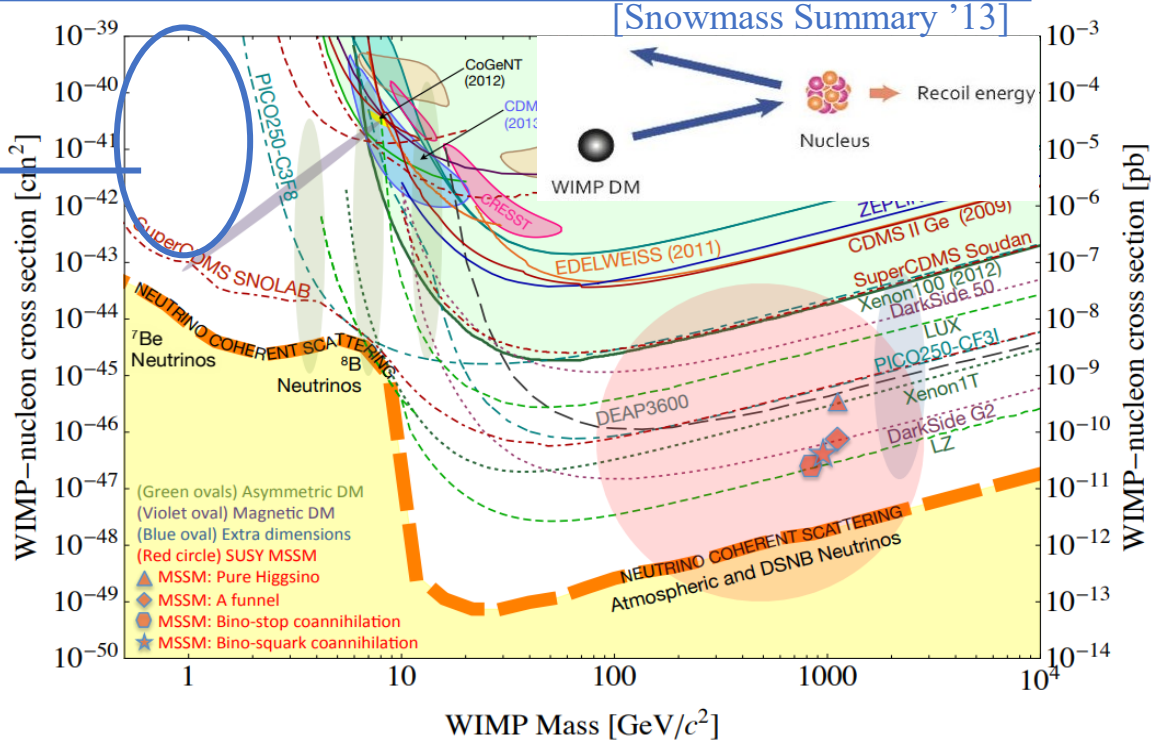
Outline

- Motivation to dark sectors
- Probing dark sectors at proton beam facilities
- Production via proton Bremsstrahlung
- Search for gluon-coupled ALP
- Hunting for millicharged particles

Dark Sectors Paradigm

- WIMP Direct detection sensitivity drops due to the recoil thresholds

[Snowmass Summary '13]



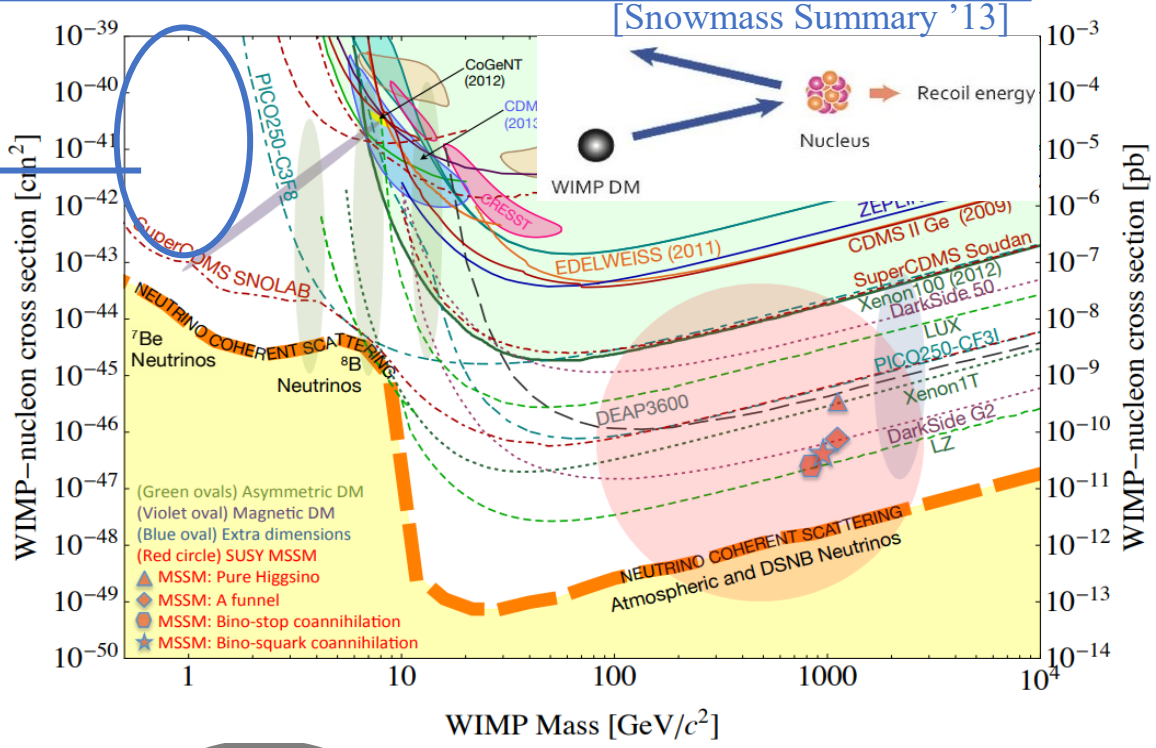
Dark Sectors Paradigm

- WIMP Direct detection sensitivity drops due to the recoil thresholds

- **Sub-GeV** WIMP requires new annihilation channel through **light** states as part of a hidden/dark sector

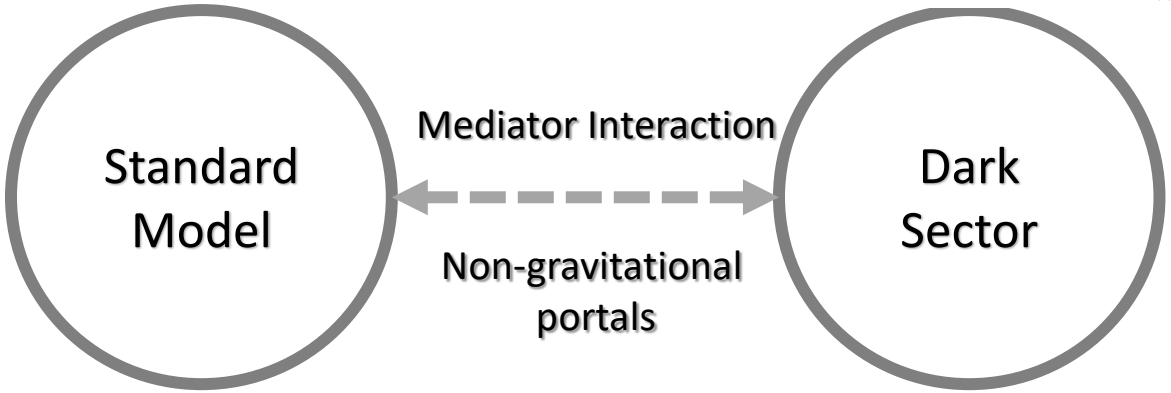
$$\Omega_\chi h^2 \propto \frac{1}{<\sigma v>} \ , \ \sigma_{\rm ann} \propto \frac{m_{\rm DM}^2}{M_{\rm mediator}^4}$$

[Snowmass Summary '13]



[Boehm & Silk et al.]

[Pospelov, Ritz, Voloshin '07]



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

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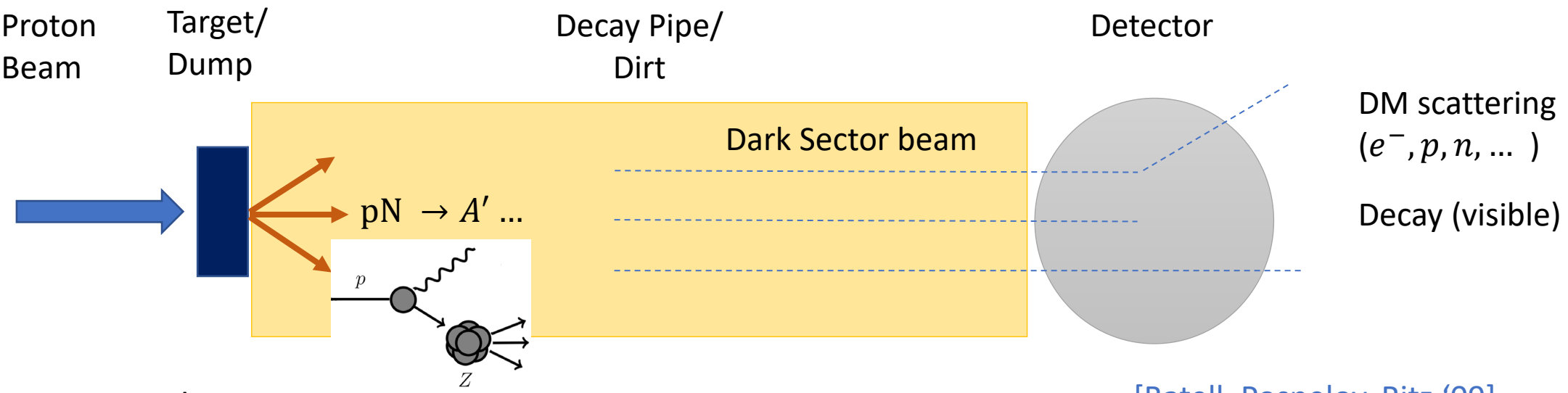
- Axion portal (dim-5) $\frac{1}{f_a}\mathrm{tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})a$ Axions & ALPs

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 mesons decay



- Past, existing and near Future neutrino experiments:

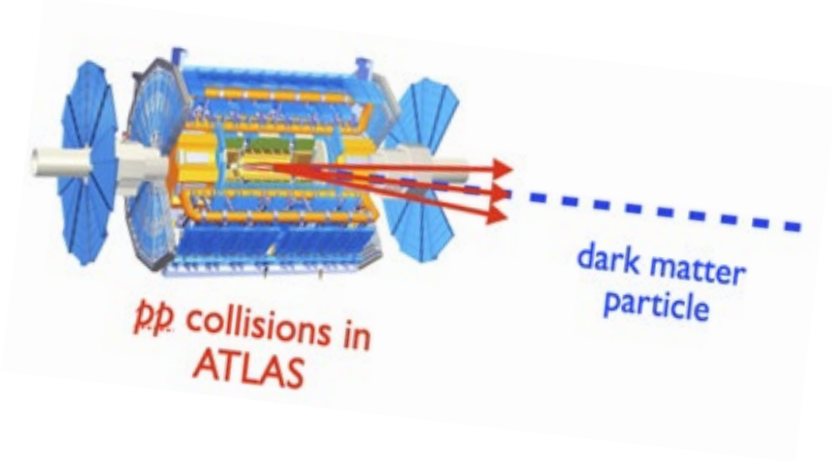
  LSND, CHARM, MiniBooNE, MicroBooNE, MINOS, NOvA, SBND, SeaQuest, SHIP, …

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

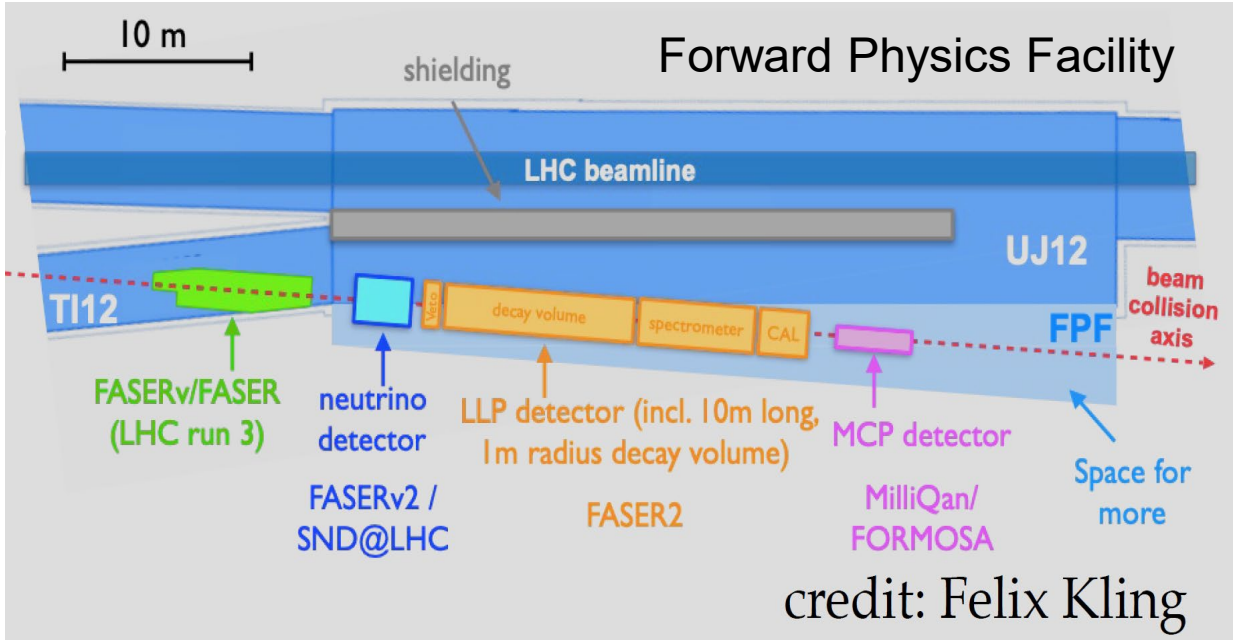
Forward Physics Facility @ LHC

- 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)

- Forward Physics Facility 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

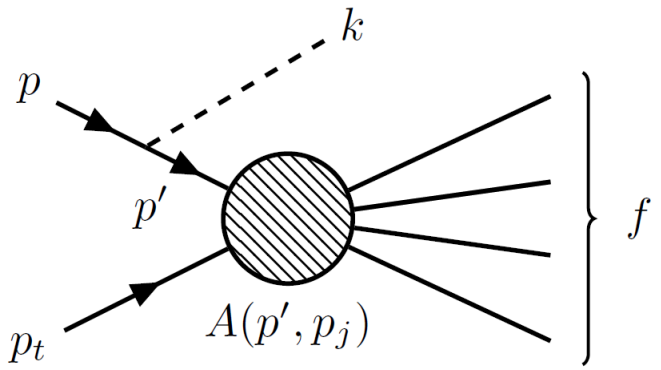
DS production via proton bremsstrahlung

Search for gluon-coupled ALP

Millicharged particle hunt @ FPF

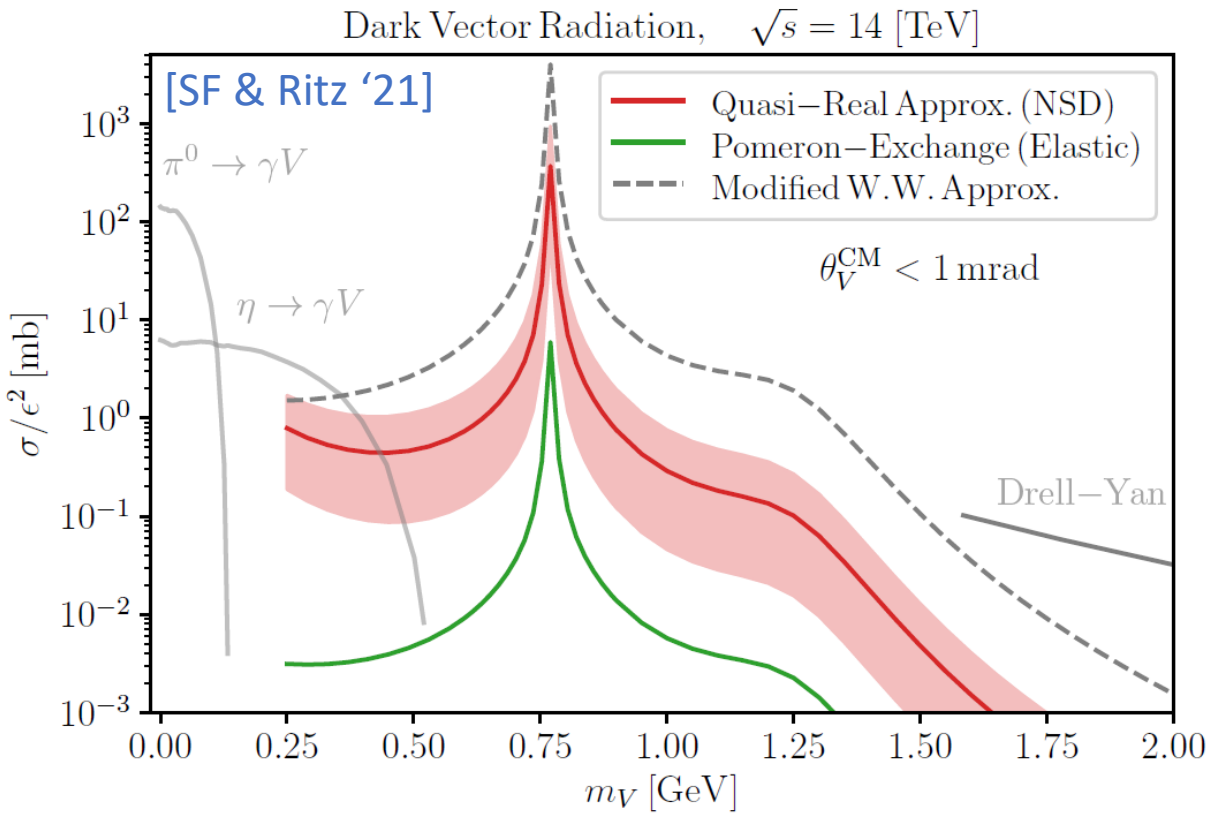
Neutrino EM properties @ FPF

Higgs portal @ LSND



Proton Bremsstrahlung

- Primary production channel in the forward direction for the dark sector mediators with mass ~ [0.5,1.5] GeV at the proton beam facilities [deNiverville, Pospelov, Ritz '16]
- Important regime near vectors (ρ,ω,…), and scalar (f_0,…) meson resonances



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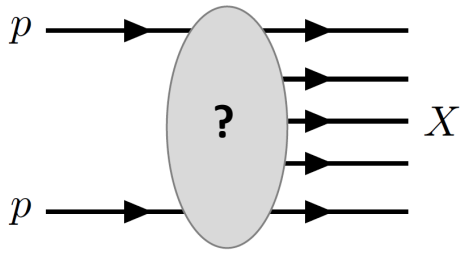
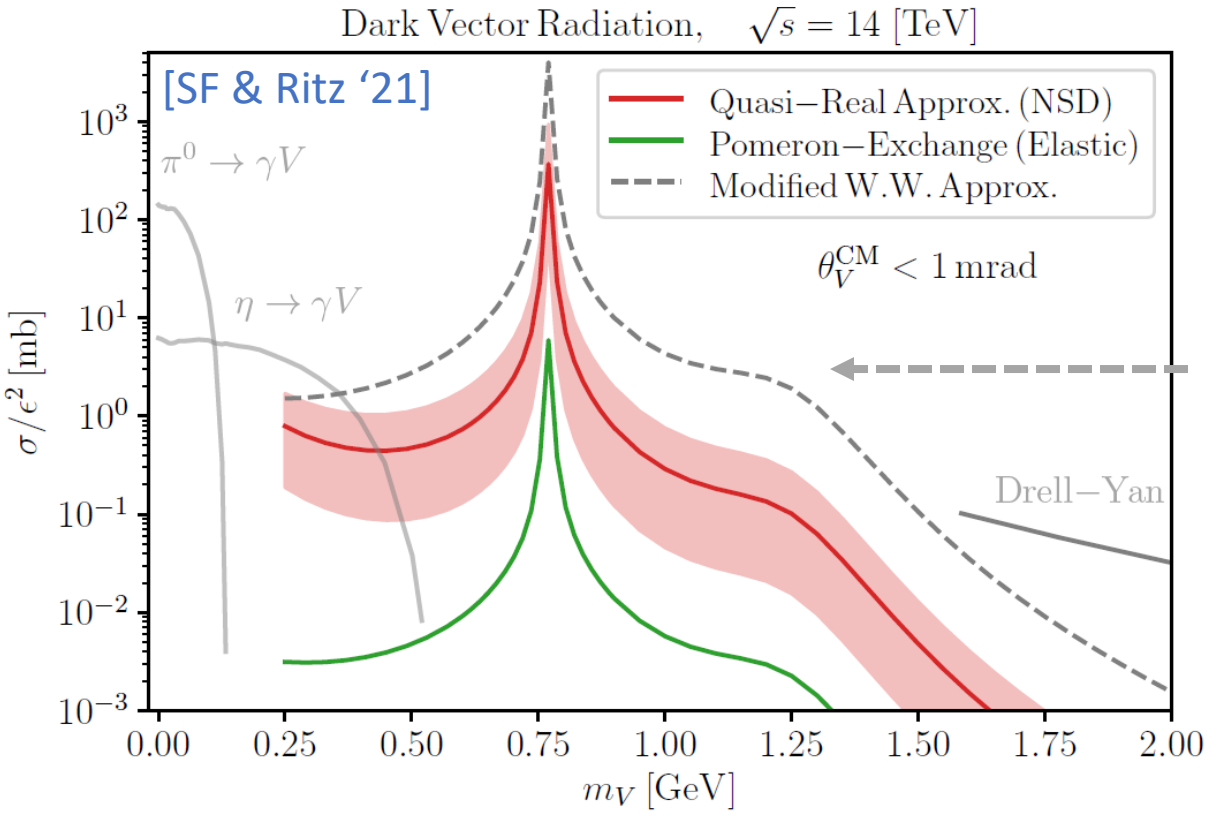
- Equivalent Photon Approx. (F. W. W.): a well-known approach in QED

- p-brem is difficult to compute: due to the **non-perturbative** QCD





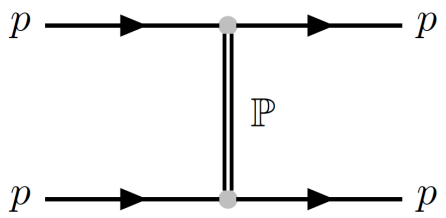
[Blümlein & Brunner '13]

Topologies of events in σ_{pp}

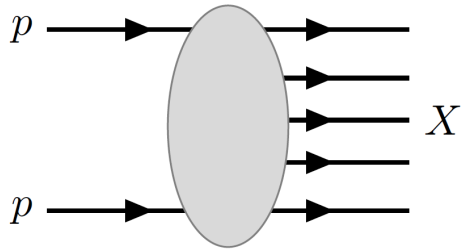
- Non-Diffractive processes constitute up to 60% of σ_{tot}

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

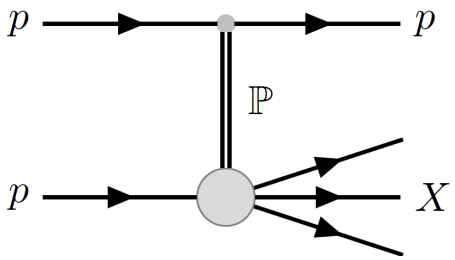
Elastic



Non-Diffractive



Single Diffractive



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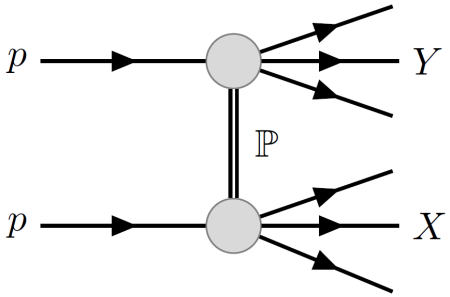
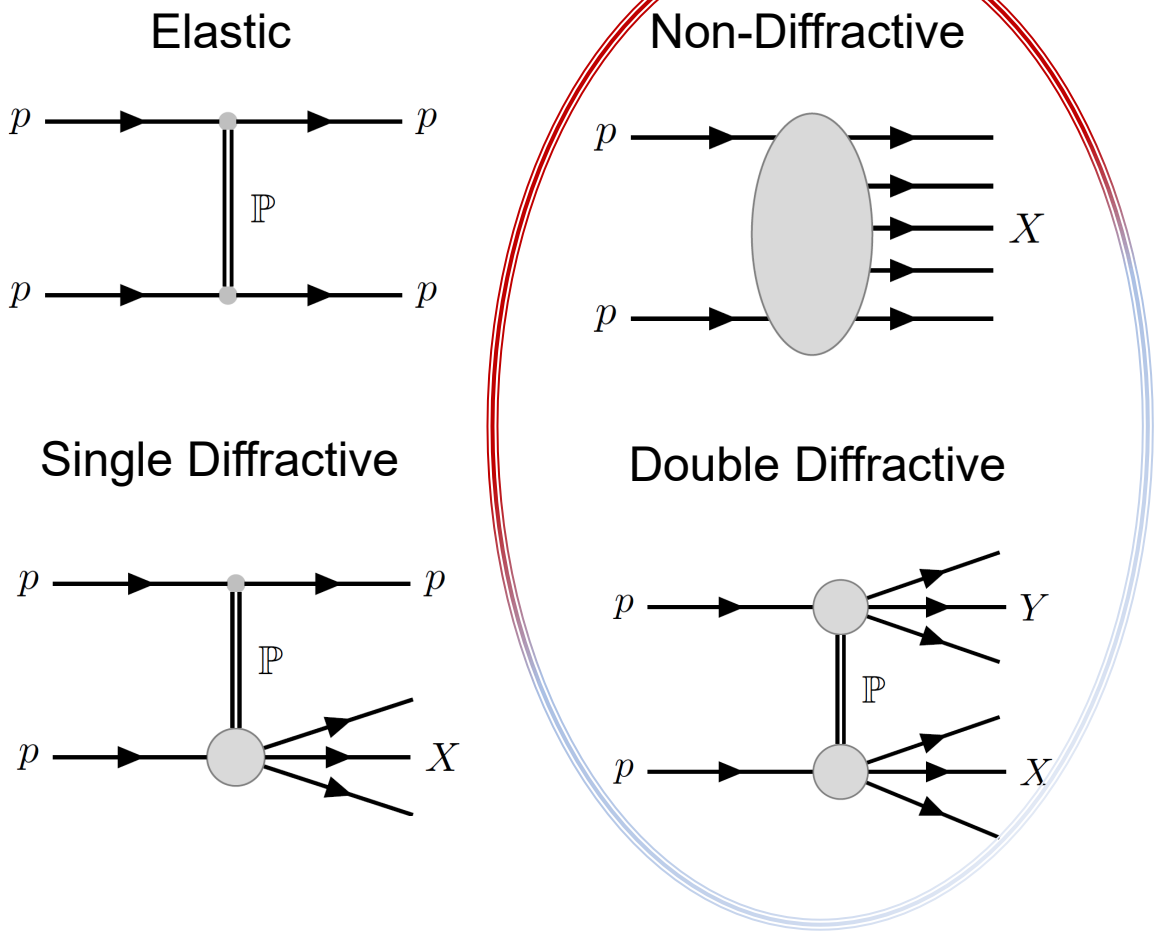


Topologies of events in σ_{pp}

- Non-Diffractive processes constitute up to 60% of σ_{tot}

- In our approximation we consider the NSD events with no intact proton in the final states:

  the leading contribution to the p-brem.

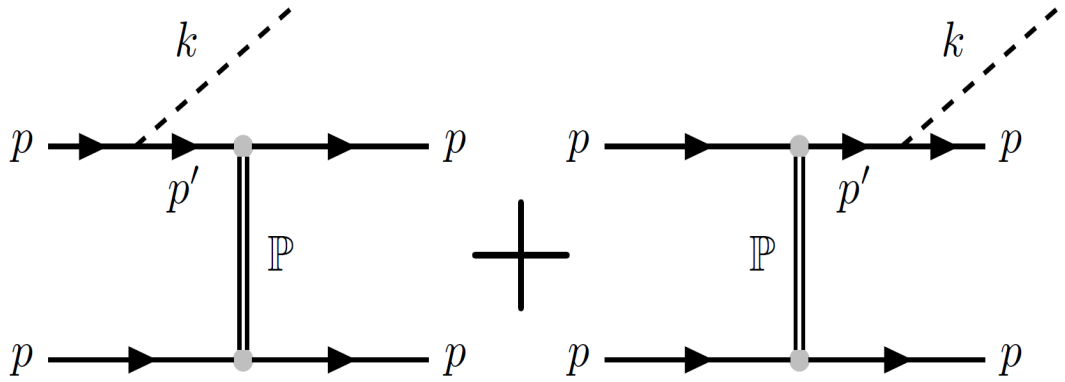


ISR and FSR in Quasi-Elastic scattering

- Modeling forward pp scattering with **Pomeron**

  Donnachie & Landshoff model [D&L ’82, ’84, ‘11, ‘13]

- Pomeron is a color singlet gluonic object relevant for the diffractive phenomena



- The pomeron vertex is like photon
  calculate the brem rate of the 2 to 3 process.

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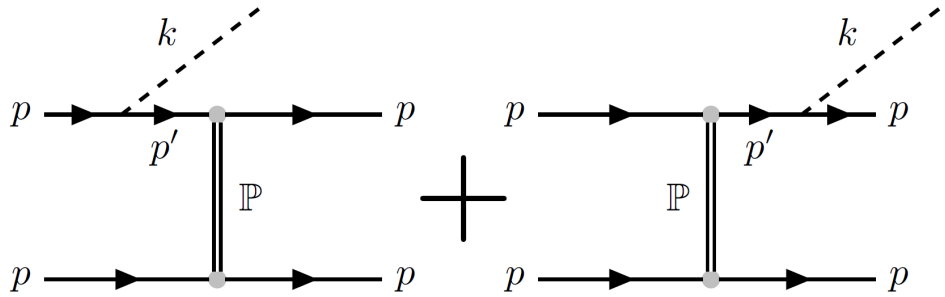
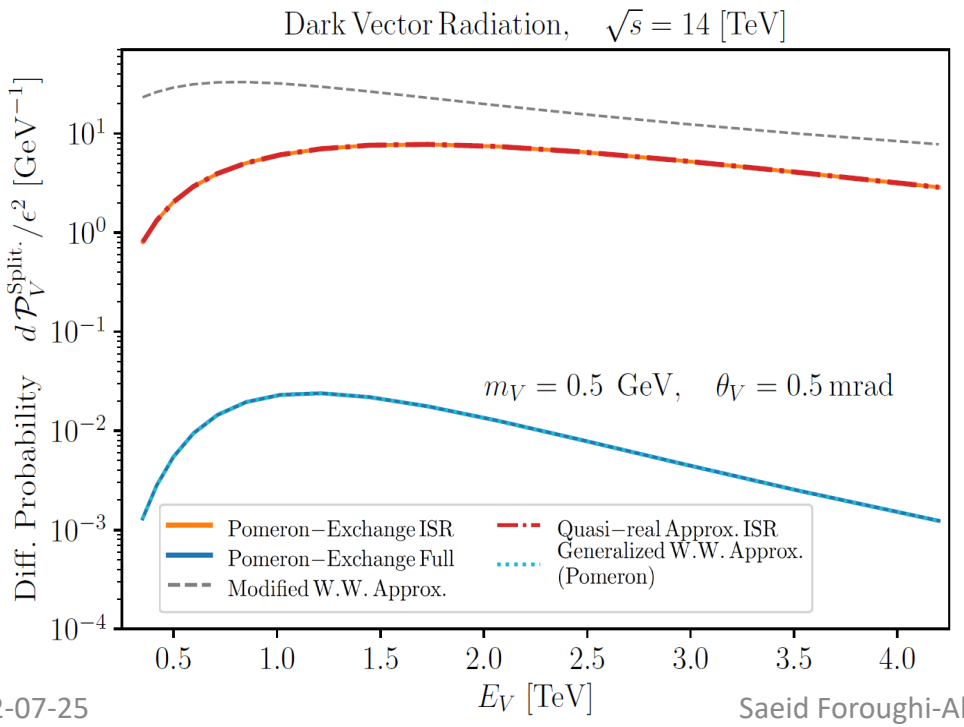
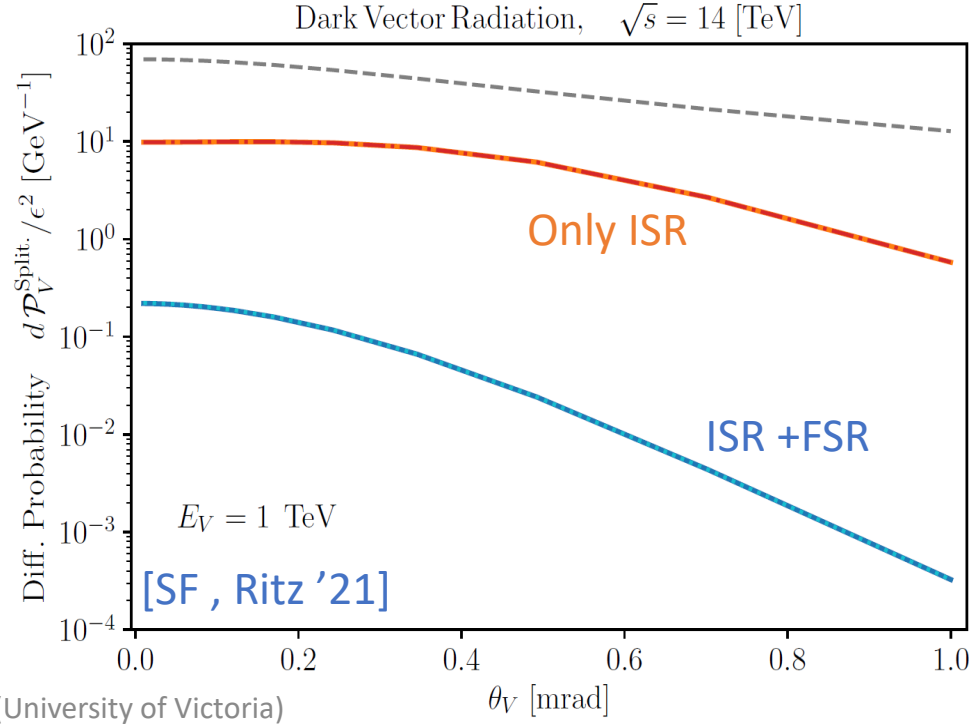


- Observe the large **cancellation** between ISR & FSR in quasi-elastic scattering



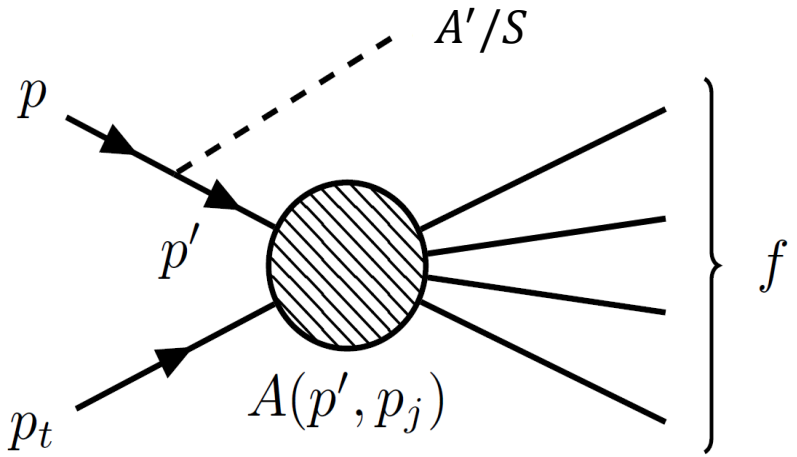


Radiation in Non-Single Diffractive Processes

- The dominant contribution comes from ISR in non-single diffractive scattering.
- **Quasi-Real Approx.**:

Collinear radiation with low p_T
Intermediate p' near on-shell

$$\frac{p_T^2}{4z(1-z)^2 p_p^2} \ll 1$$



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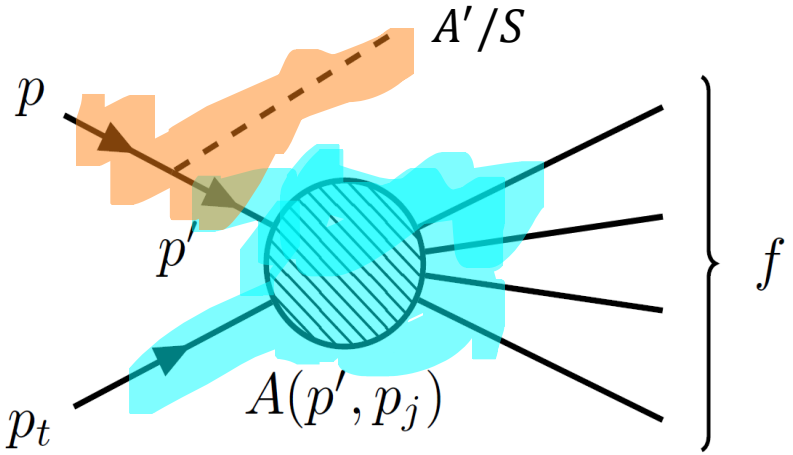

- The cross section divides into a splitting probability and the cross section of the subprocess involving the p' with the reduced energy.

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

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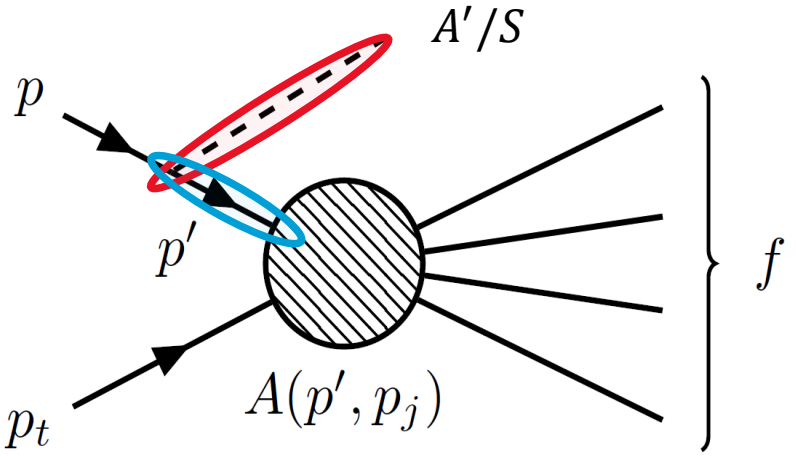
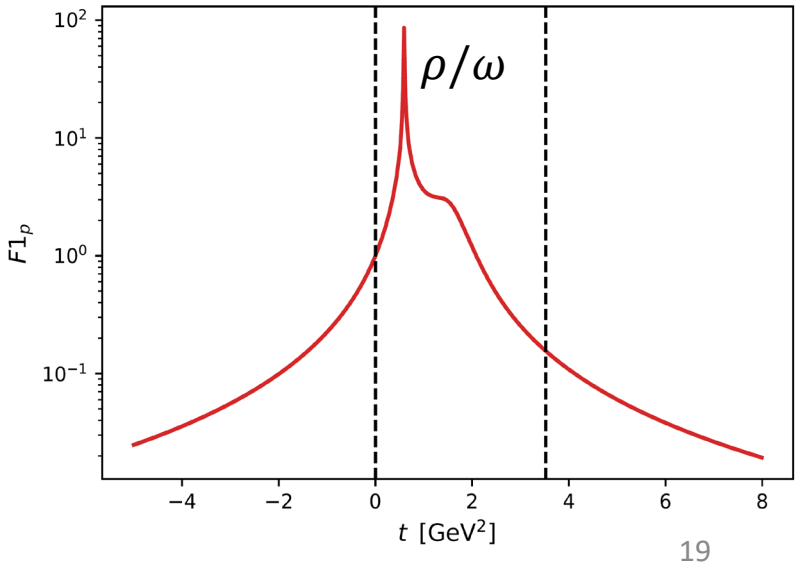


- **Time-like** nucleon form factor: [Faessler et al '09]

❖ Mixing with meson resonances

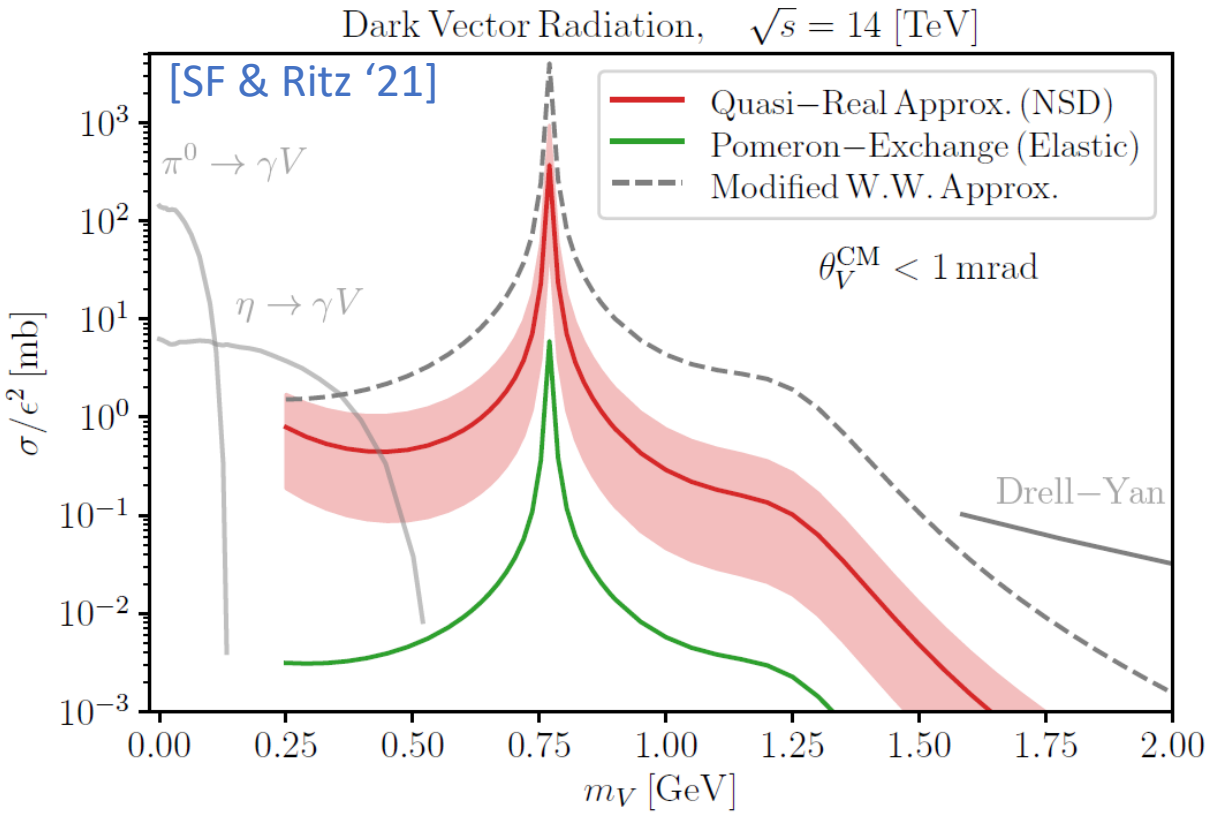


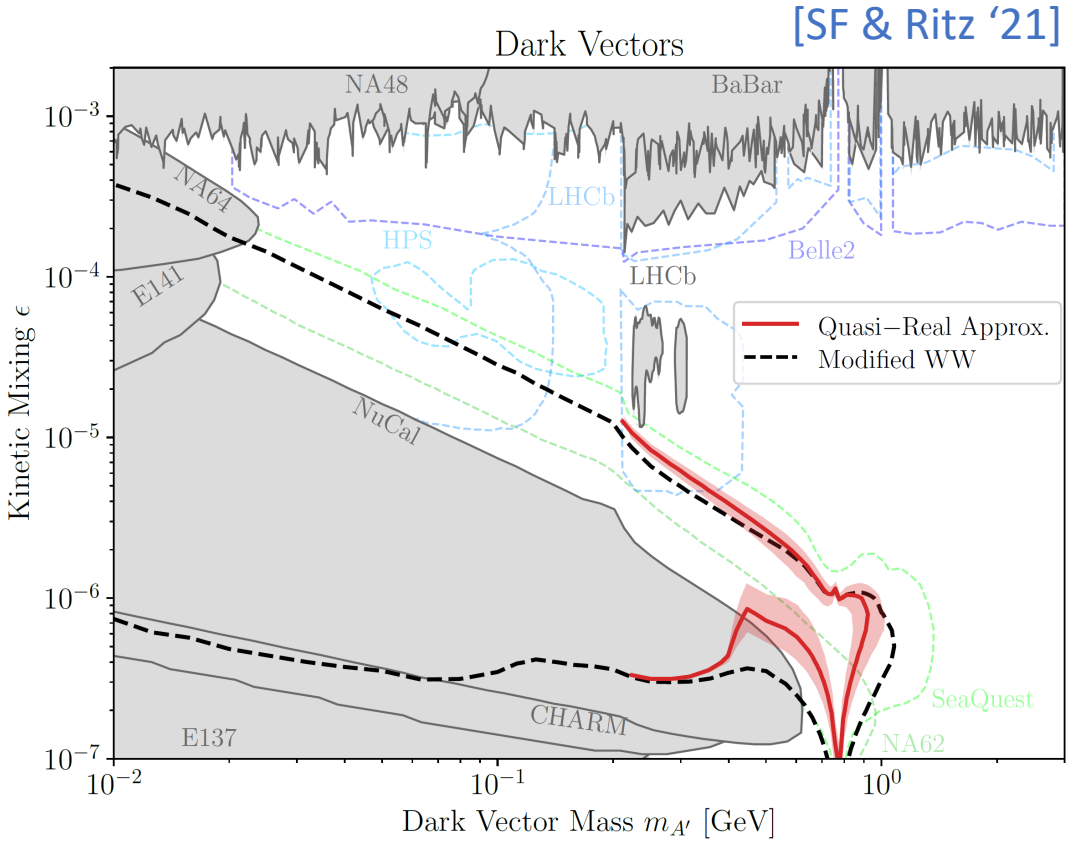
- **Transition (Off-Shell)** form factor: [Feuster & Mosel '98]

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

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

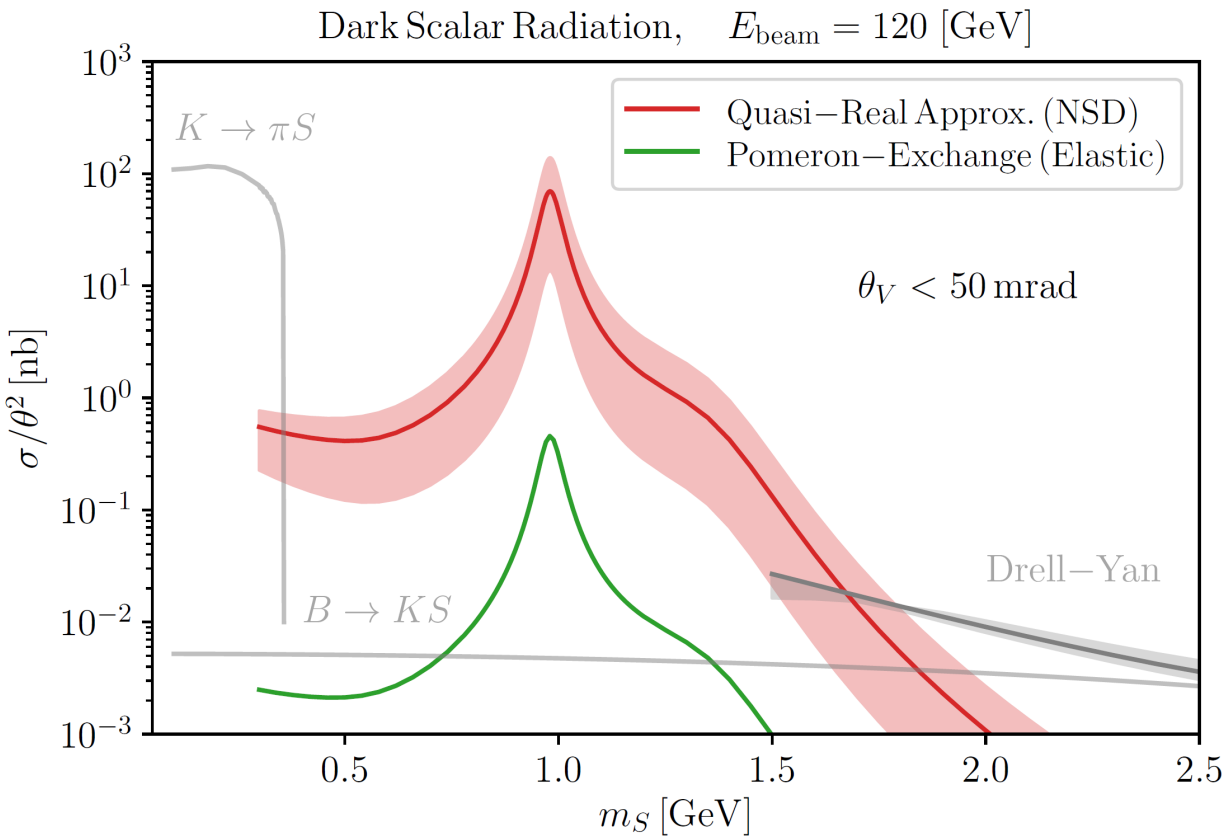
Revisiting Proton Bremsstrahlung

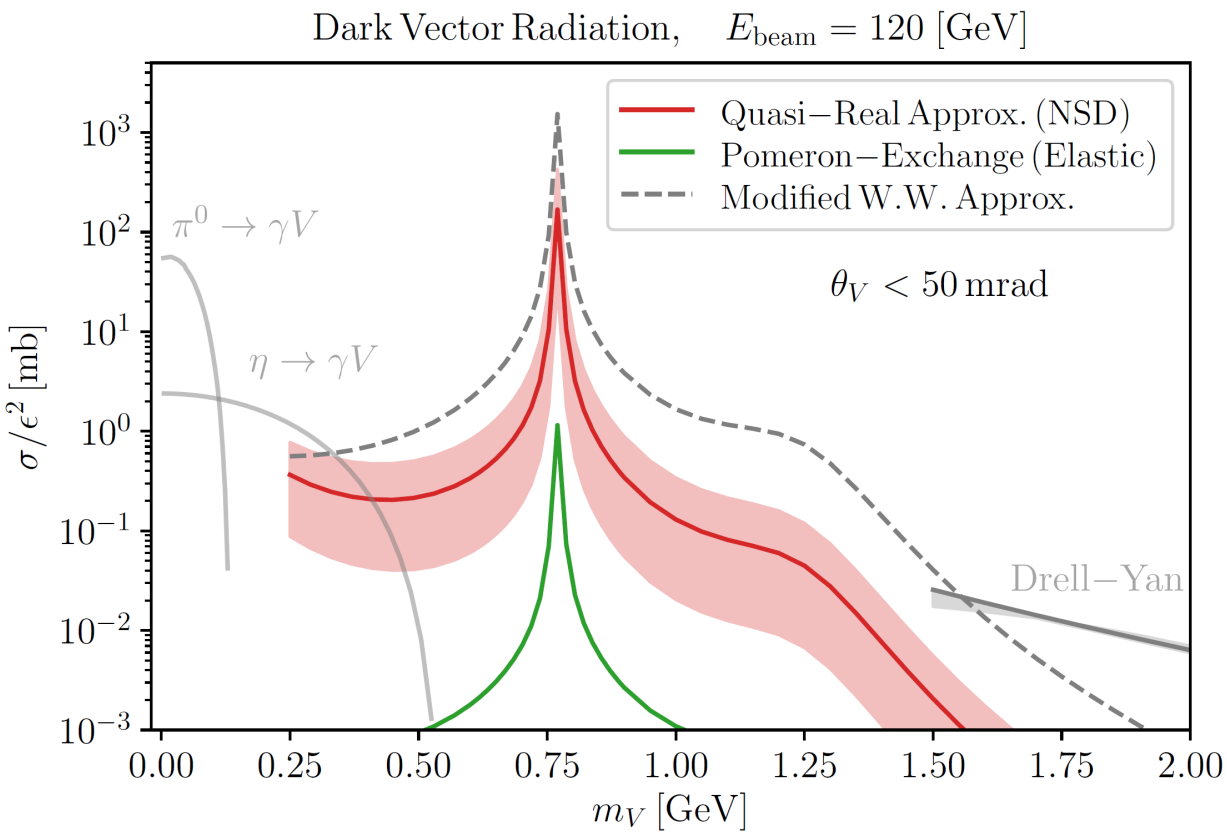




Revisiting Proton Bremsstrahlung

- At fixed targets, the cross section σ_{pA} scales with $\sim A^{0.77}$





Dark Sectors

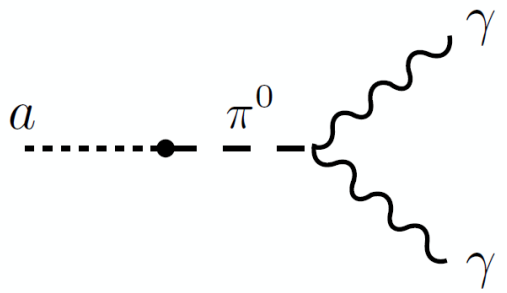
DS production via proton bremsstrahlung

Gluon-coupled ALP

Millicharged particle hunt @ FPF

Neutrino EM properties @ FPF

Higgs portal @ LSND



Axion Portal

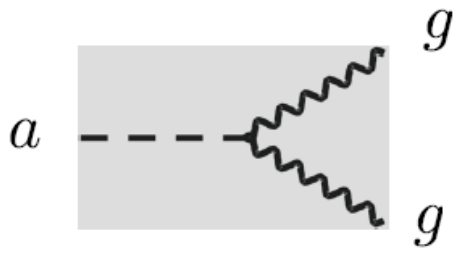
- Axions are theoretically well-motivated:

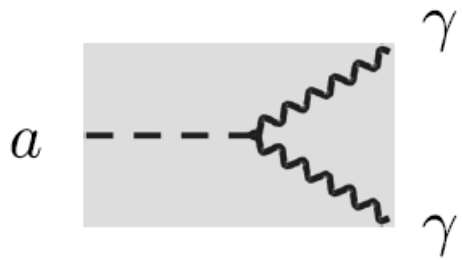
  - solution to the Strong CP problem; $\theta \sim a/f_a$
  - viable candidate for dark matter
  - Axion acquires a small mass from mixing with the pion

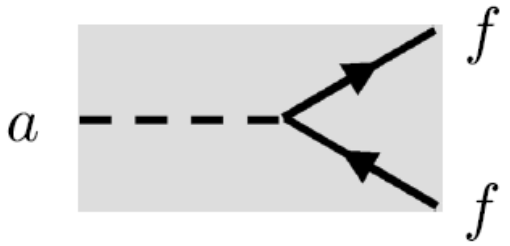
  [Peccei,Quinn 77; Weinberg 78]

- 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]

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







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[PBC '19]

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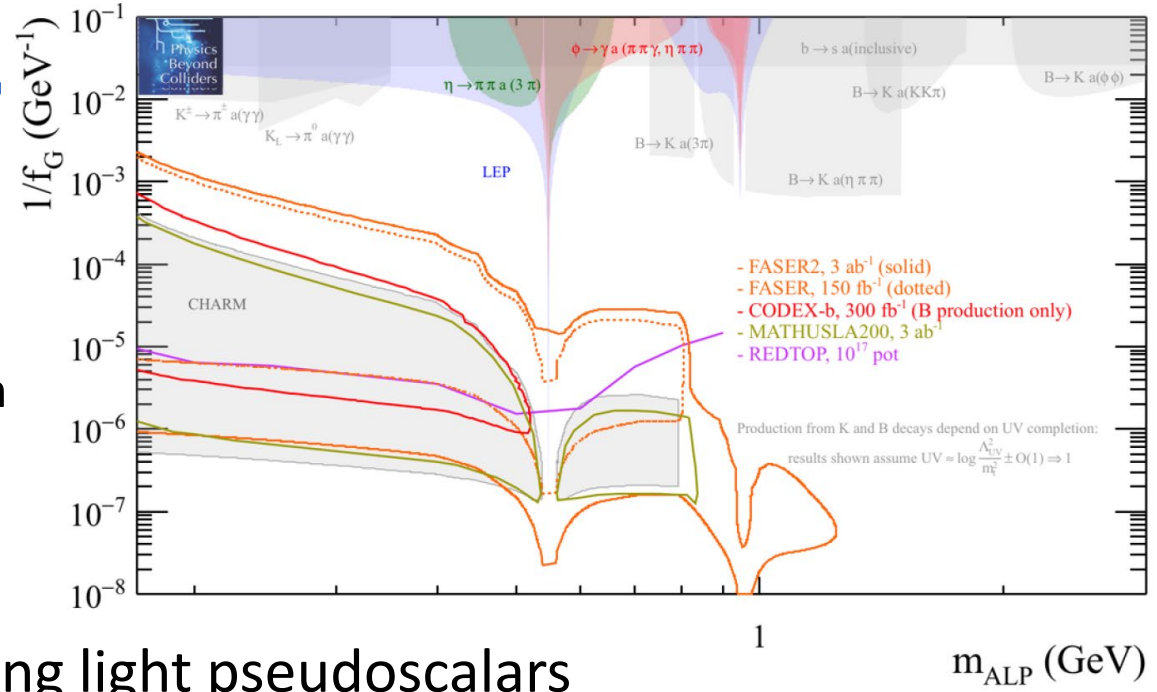

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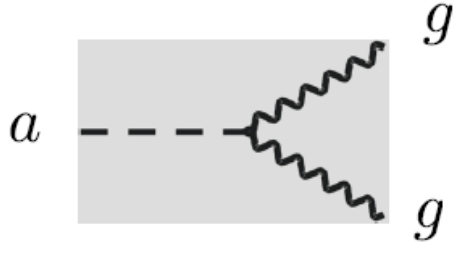
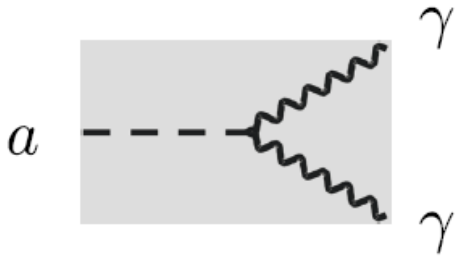
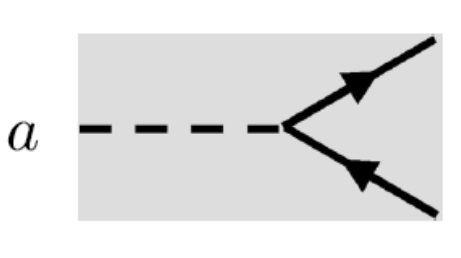
Focus of this talk

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







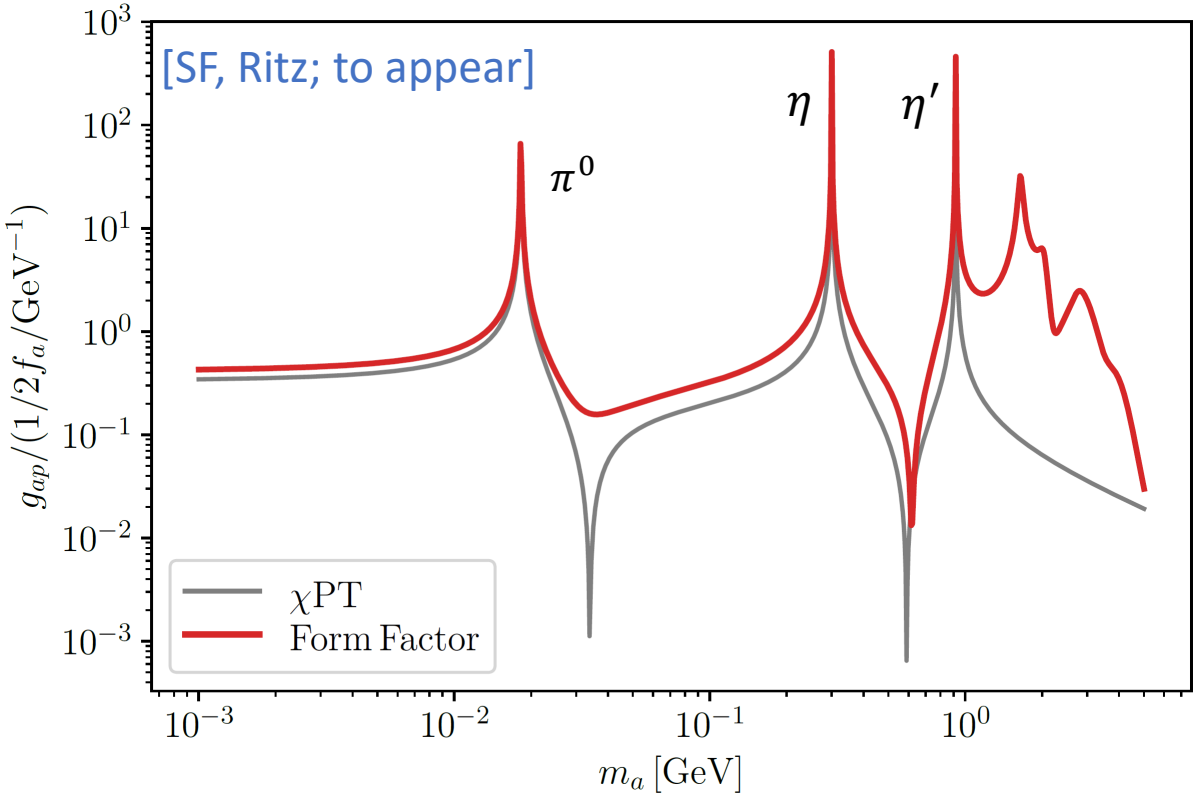
Axion Portal (gluon coupling)

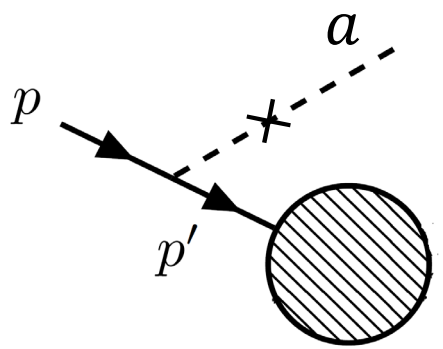
- Perform Chiral rotation: eliminate the $aG\tilde{G}$ term in favor of ALP coupling to quarks
- Axial-vector currents and coupling to nucleons:

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

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

- 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



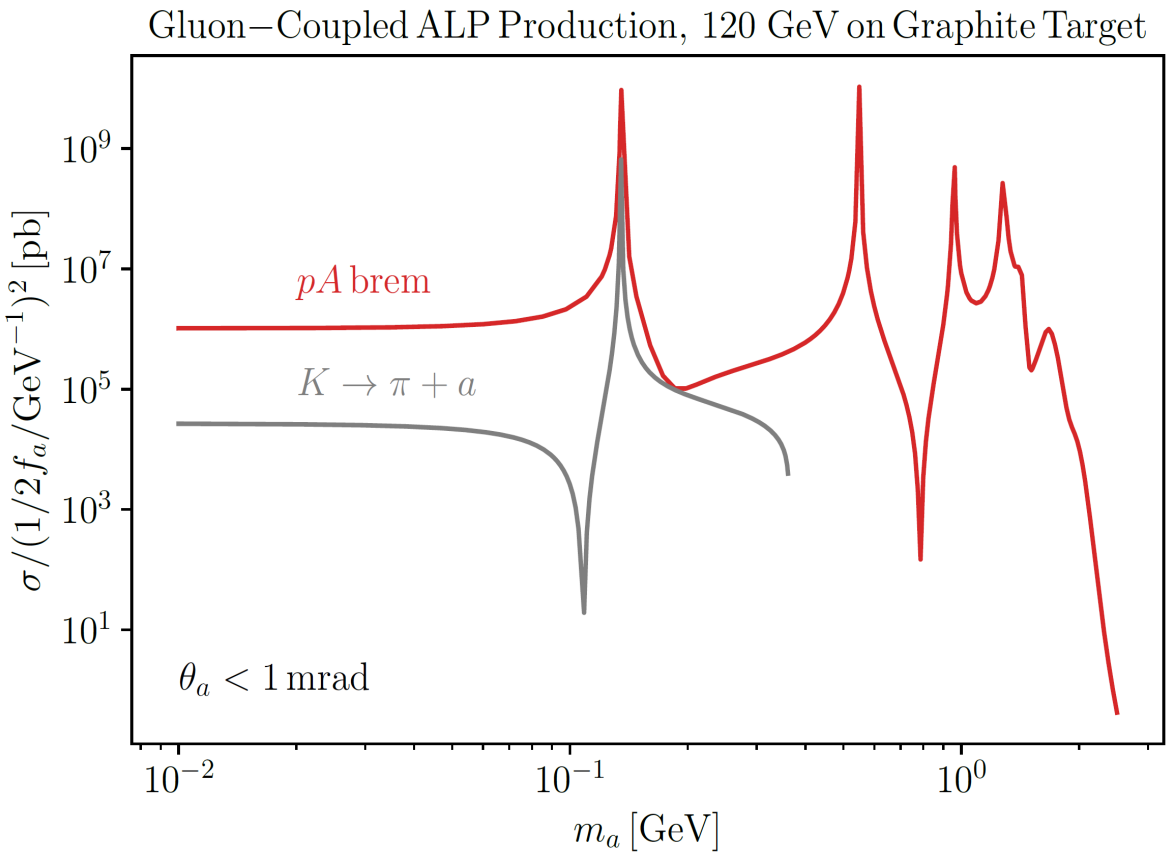


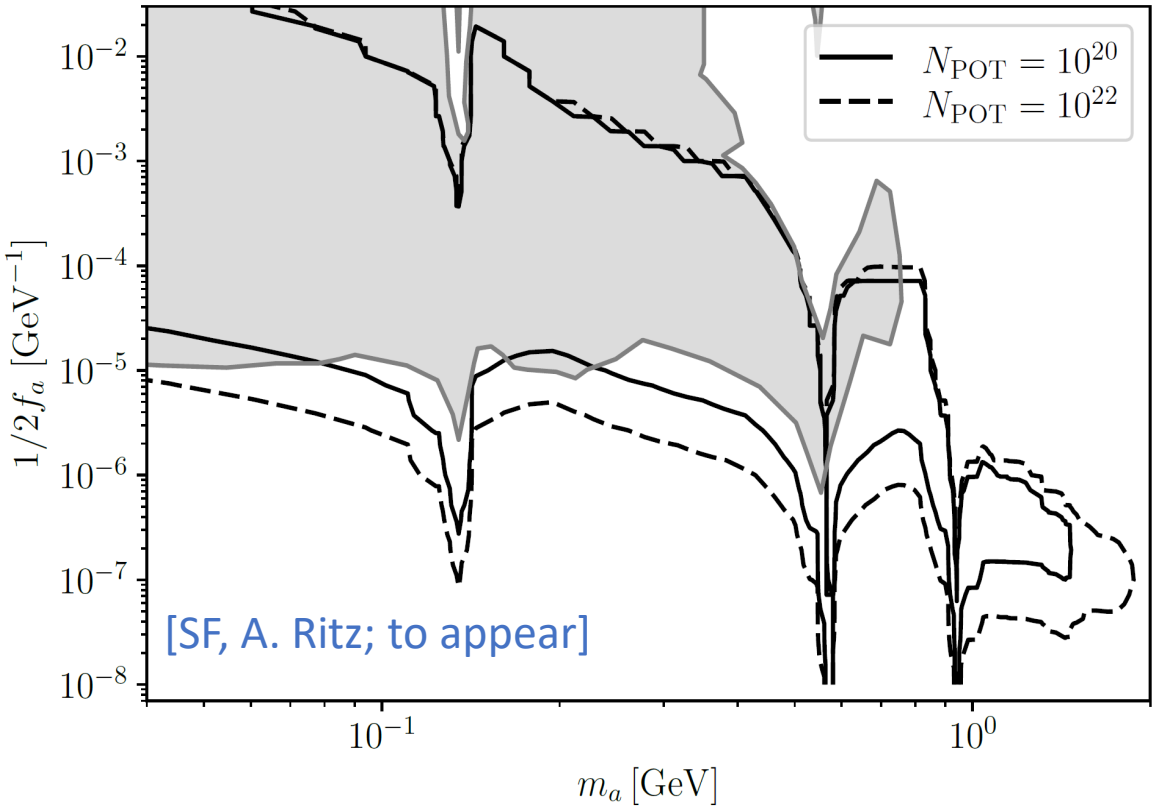
For coupling from χPT look at:
N. Blinov et al.
2112.09814

ALP Sensitivity Projection

- Dune Near Detector complex ($\theta < 1$ mrad)

Existing constraints from:
N. Blinov et al. '22
K. Kelly et al. '21





Dark Sectors

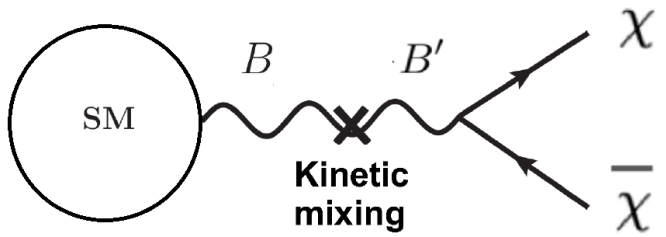
DS production via proton bremsstrahlung

Search for gluon-coupled ALP

millicharged particles hunt @ FPF

Neutrino EM properties @ FPF

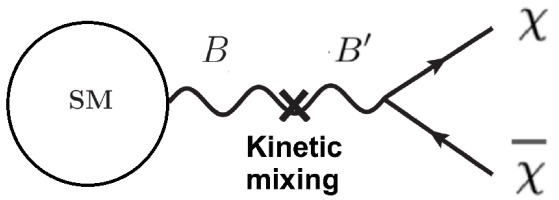
Higgs portal @ LSND



Millicharged Particles

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

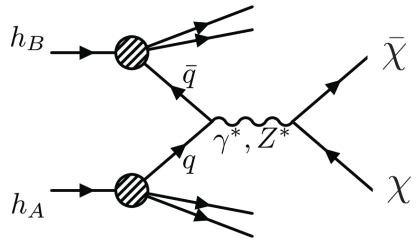
$$\mathcal{L}_{\rm MCP} = \bar{\chi}(i\partial\!\!\!/ - \epsilon' e B\!\!\!/ - m_\chi)\chi$$

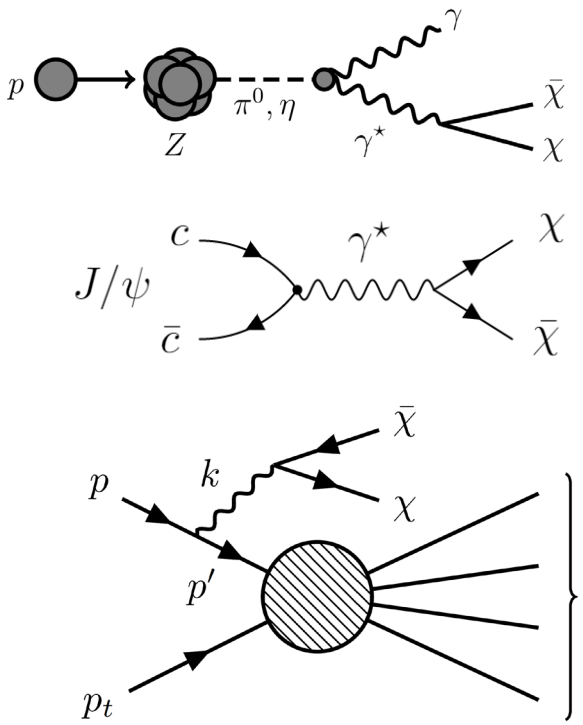


- Production Channels

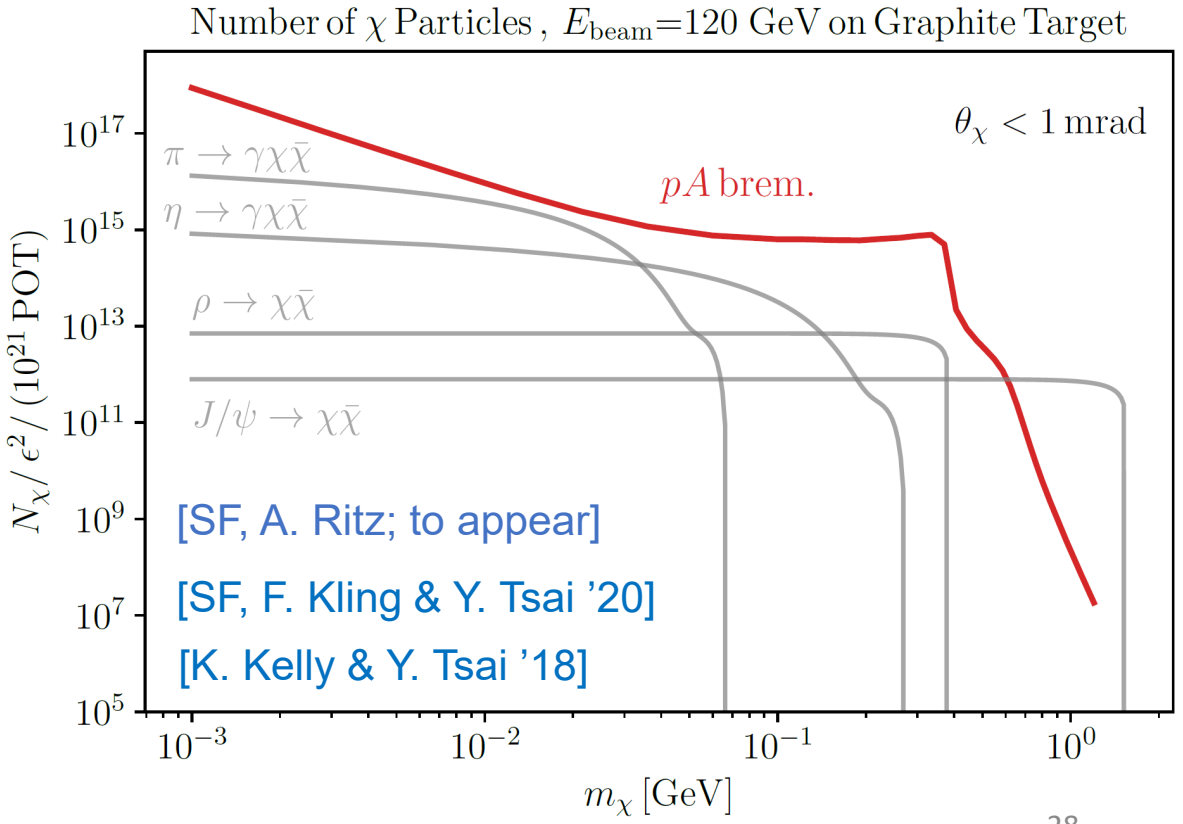
❖Meson decays

❖Drell-Yan





❖**P-Brem.**

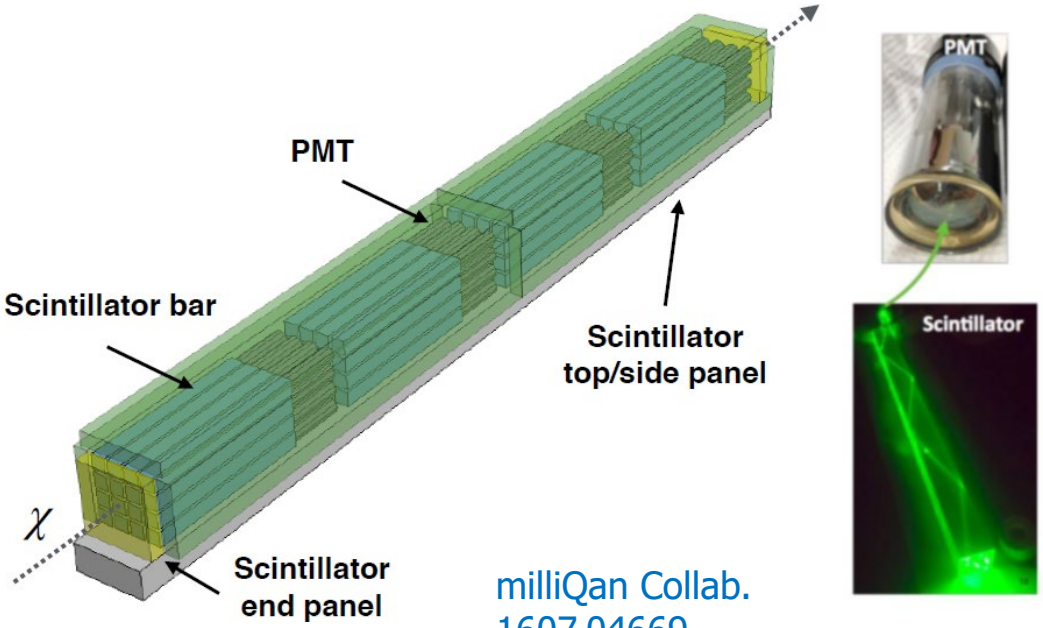


Millicharged Particles Hunting

Scintillator detector placed at:

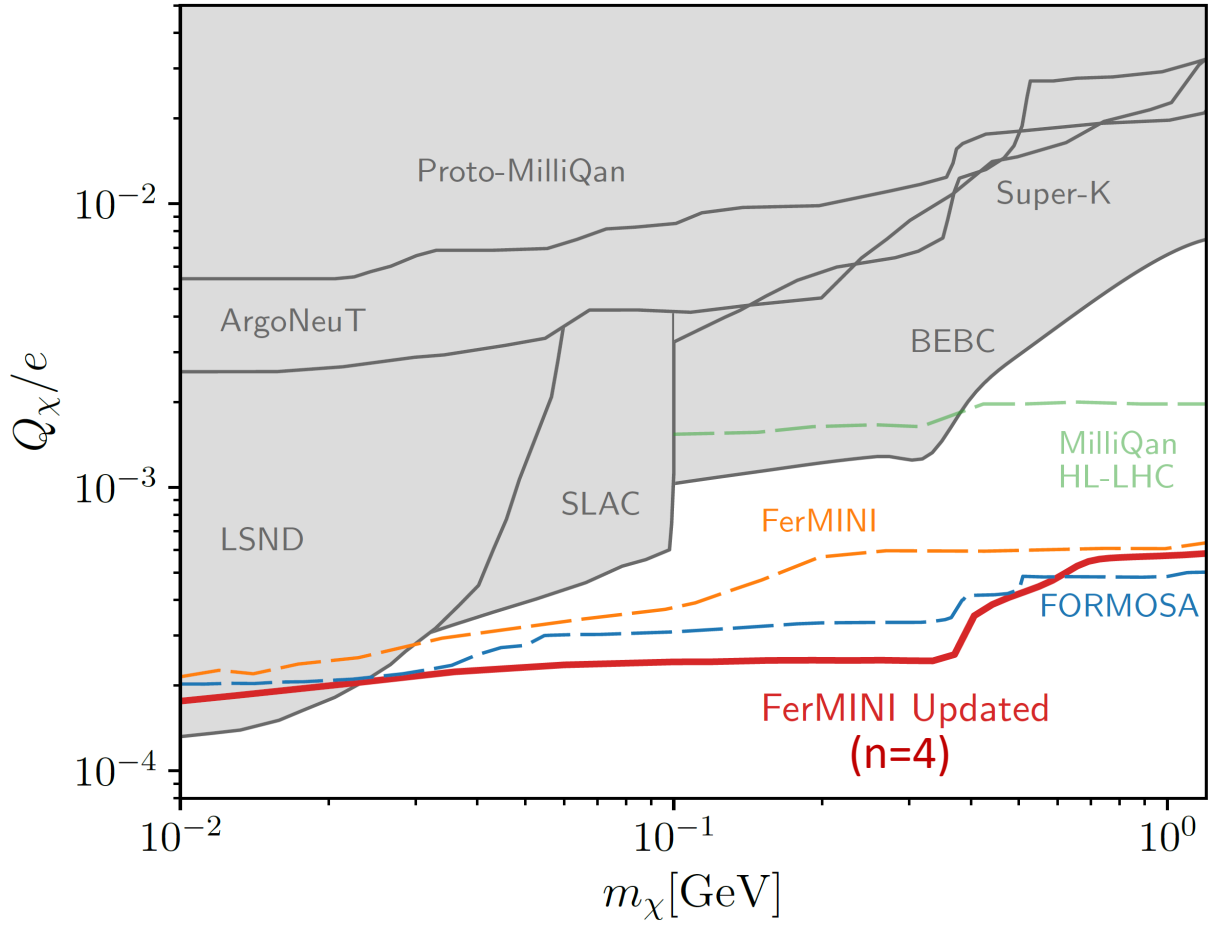
Forward Physics Facility -> **FORMOSA**

DUNE Near Detector -> **FerMINI**



milliQan Collab. 1607.04669

[SF, A. Ritz; to appear]



Deposition of energy due to ionization

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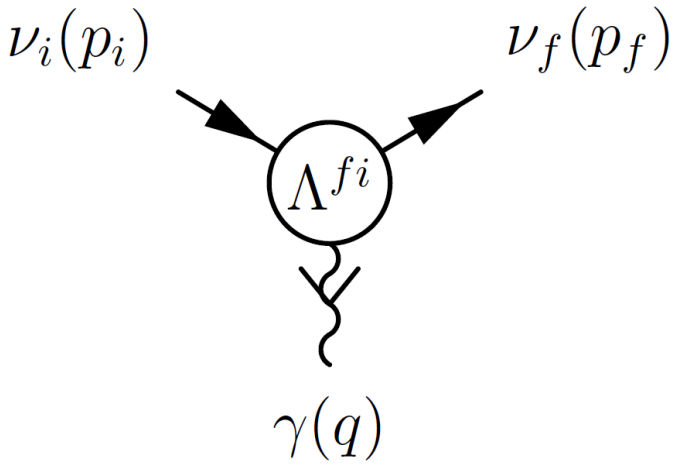
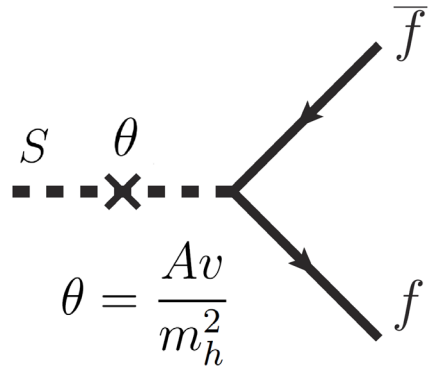
Neutrino EM properties @ FPF

Higgs portal @ LSND





Summary

- The dark sector paradigm is well-motivated and portals provide a systematic framework to explore the interaction of a variety of dark sector models for both dark matter and neutrino mass with the SM.
- Dark sector production via Proton Bremsstrahlung is an important production channel in the forward direction and can be estimated using quasi-real approximation.
- ALP coupling to nucleon in the three-flavour theory is used to estimated the ALP emission rate in the proton-nucleus bremsstrahlung
- millicharged particles could be probed using the scintillator-based detector in the forward region of neutrino detector and/or LHC providing leading sensitivity in the 100 MeV to 100 GeV mass window.

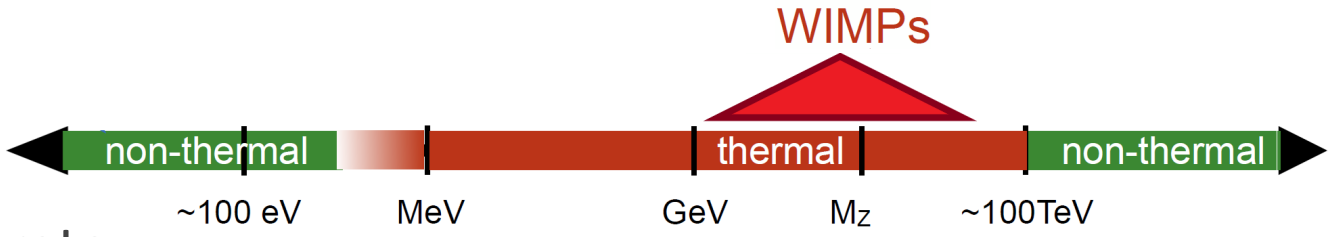
Image courtesy of KIPAC/SLAC

“Thank you for your attention”

Back-up Slides

DM Candidates – Thermal WIMP

- Thermal candidates



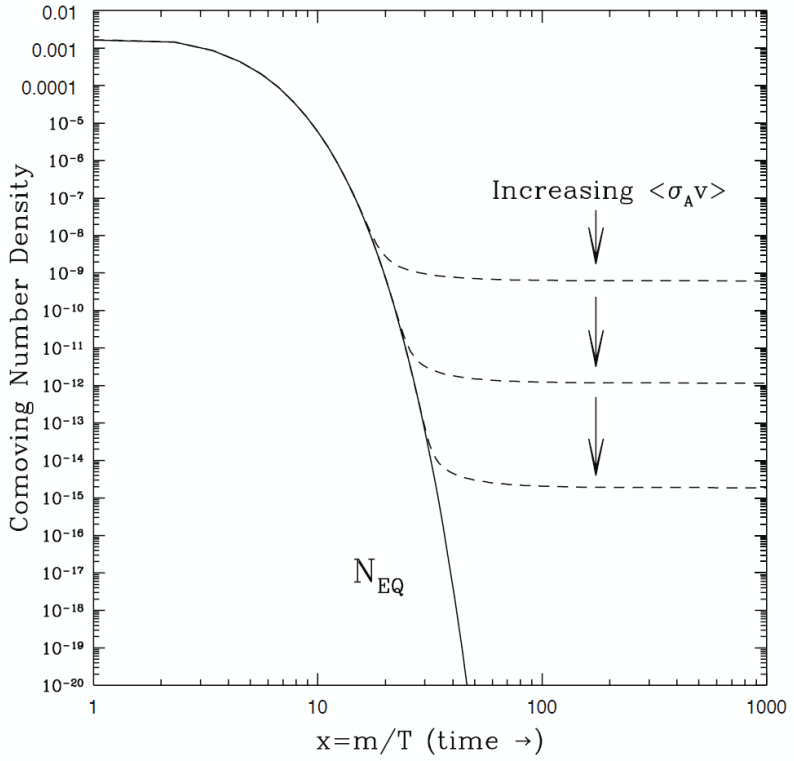
DM freeze-out occurs when annihilation rate becomes smaller than the Hubble rate

- Correct relic density requires

  Lee-Weinberg mass limit > ~ GeV

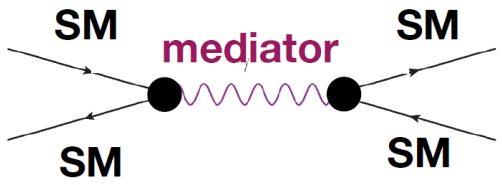
$$\langle \sigma v \rangle \sim \frac{G_F^2 m_\chi^2}{\pi} \approx 1\,\mathrm{pb} \times \left(\frac{m_\chi}{5\,\mathrm{GeV}} \right)^2$$

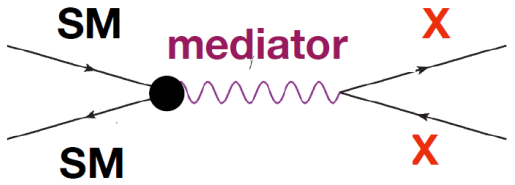
- Light thermal DM interacting via weak interactions generically overproduced



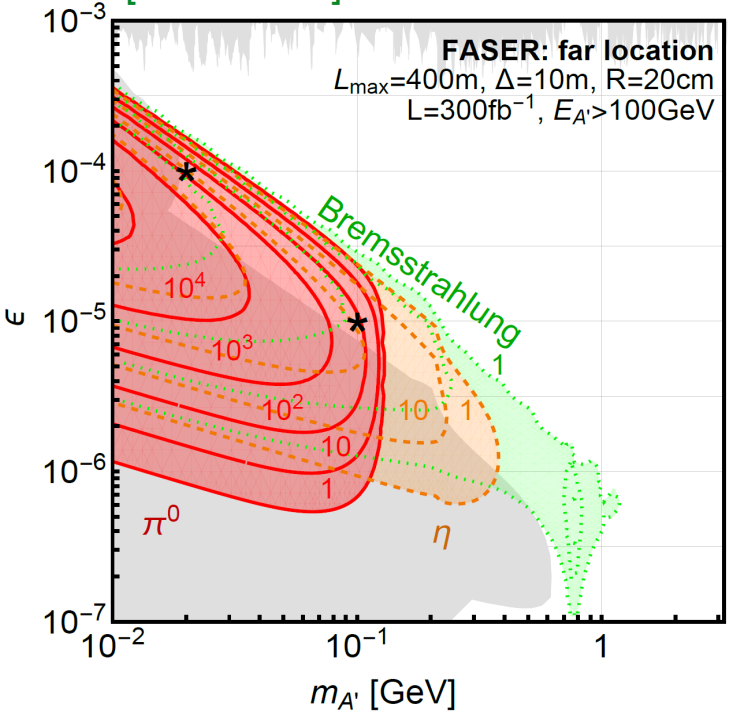
Decays of Portal Mediators

- Visible and invisible decays of dark mediators

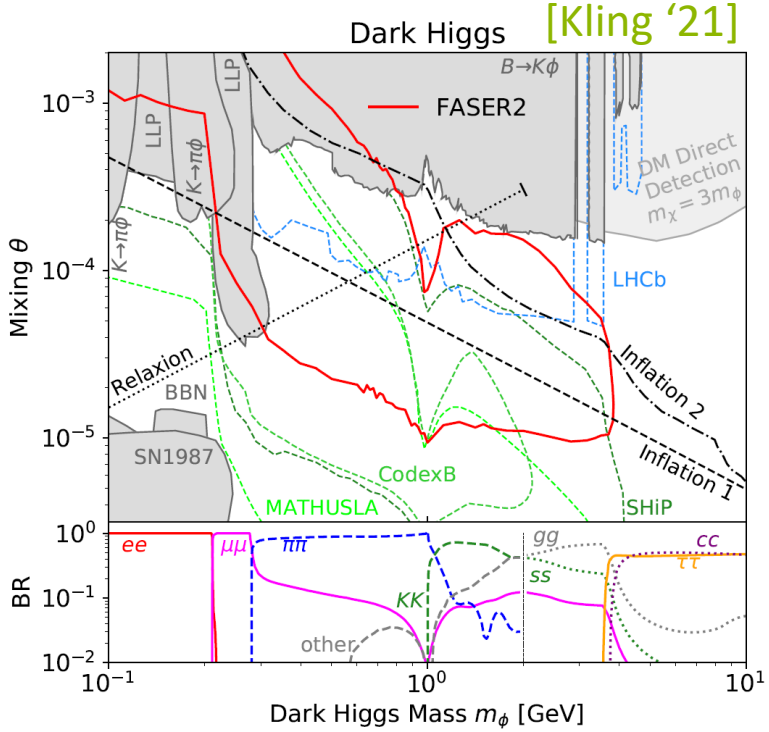




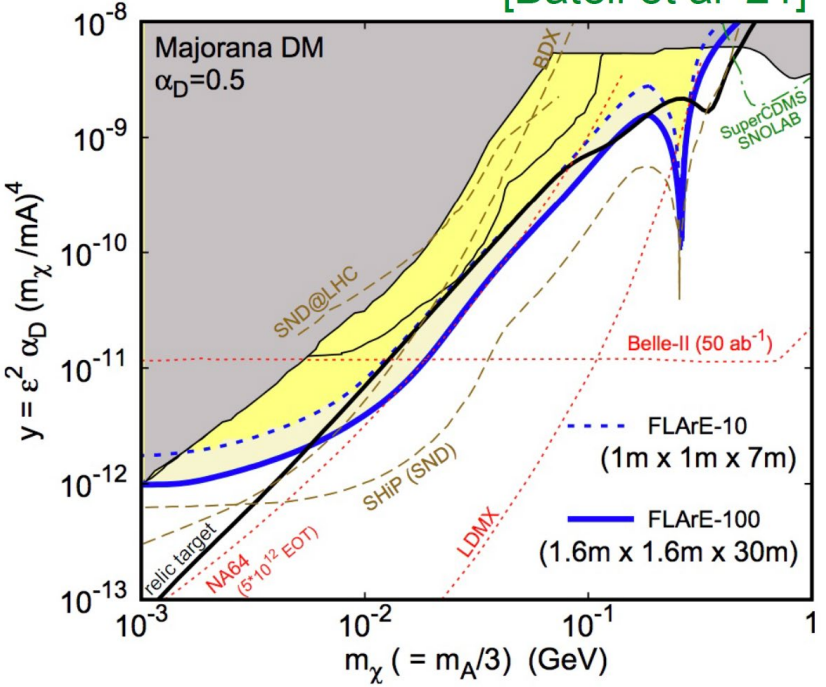
[FASER '17]



[Kling '21]

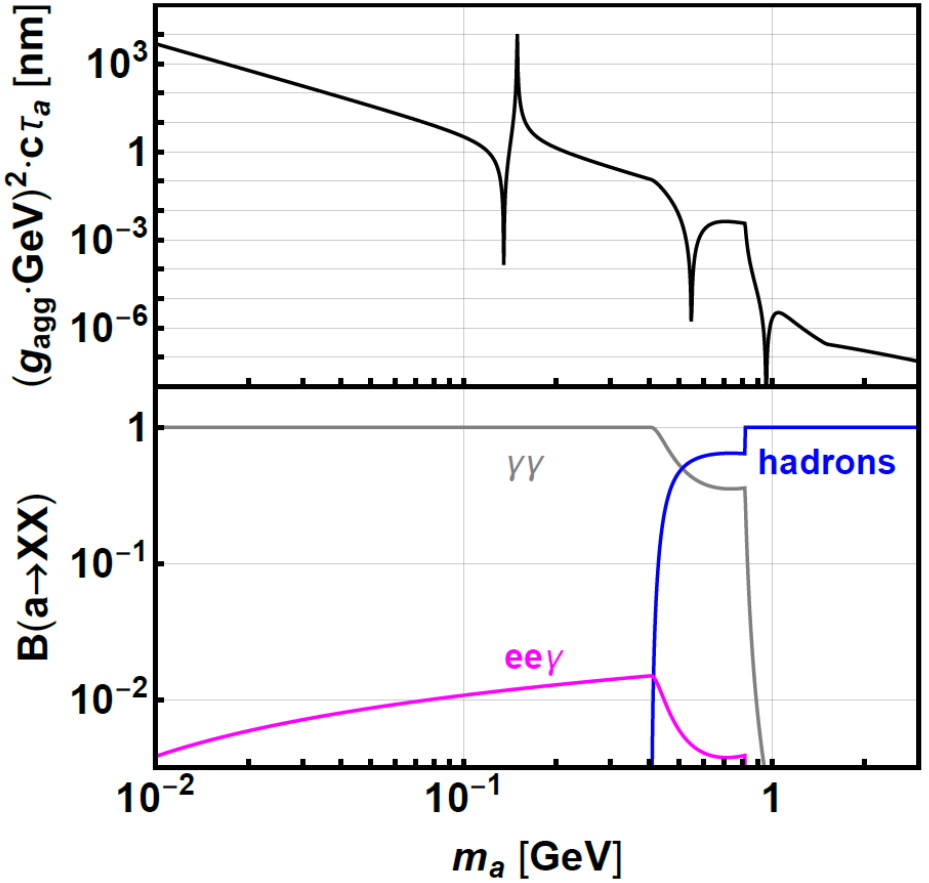


[Batell et al '21]



ALP Decay and Lifetime

- ALP mainly decays into photon pairs for $m_a < 3m_\pi$
- At large masses, $m_a > 1.5\ \mathrm{GeV}$: decay to gluons
- In the intermediate regime for ALP masses:
  - many hadronic resonances; hard to calculate

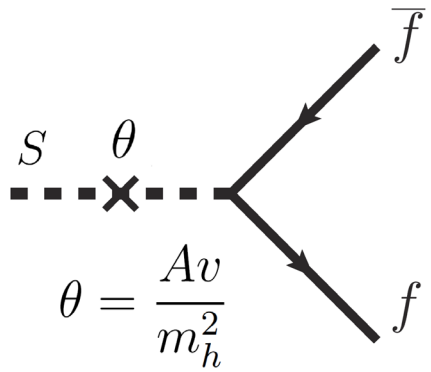


(Minimal) Higgs Portal to the Dark Sector

- 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!

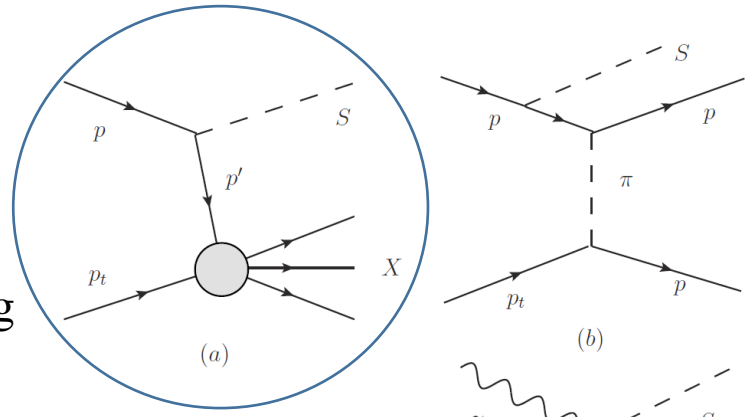
- Light scalars are hugely constraint by rare K and B decays @ E949, NA62 LHCb, Belle,…

Dark Scalar at LSND

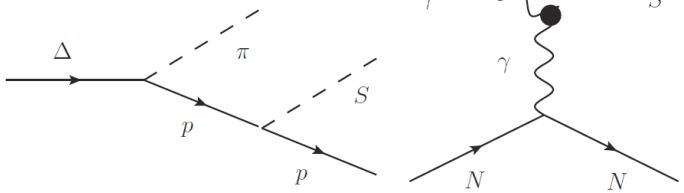
- The LSND experiment:
  800 MeV proton beam impacting a thick target with $\sim 10^{23}$ POT

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

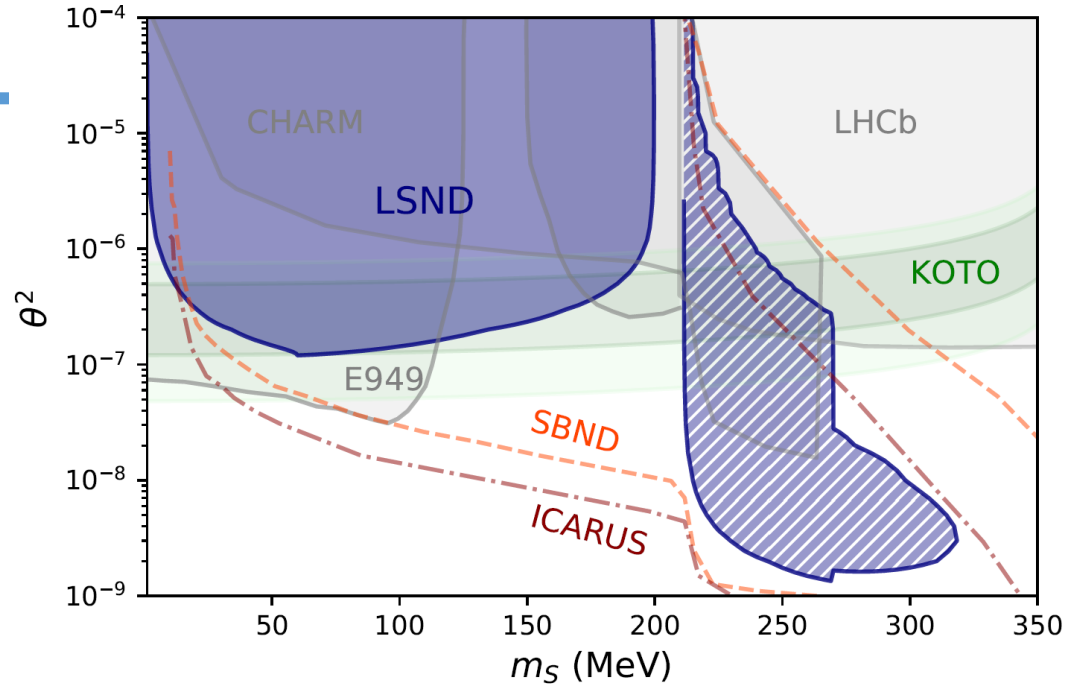
Proton Bremsstrahlung

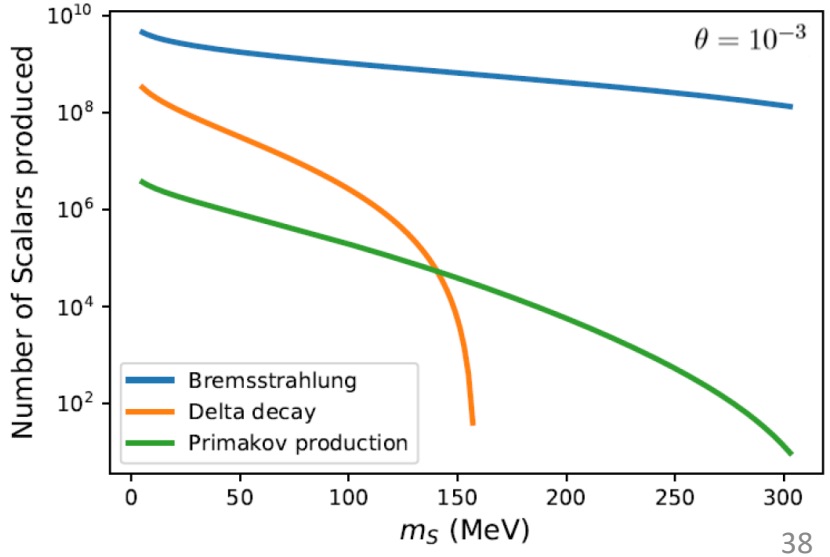


Δ decay



Primakov process

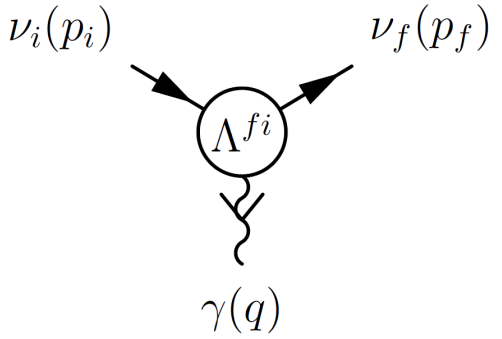




Neutrino EM properties at the FPF

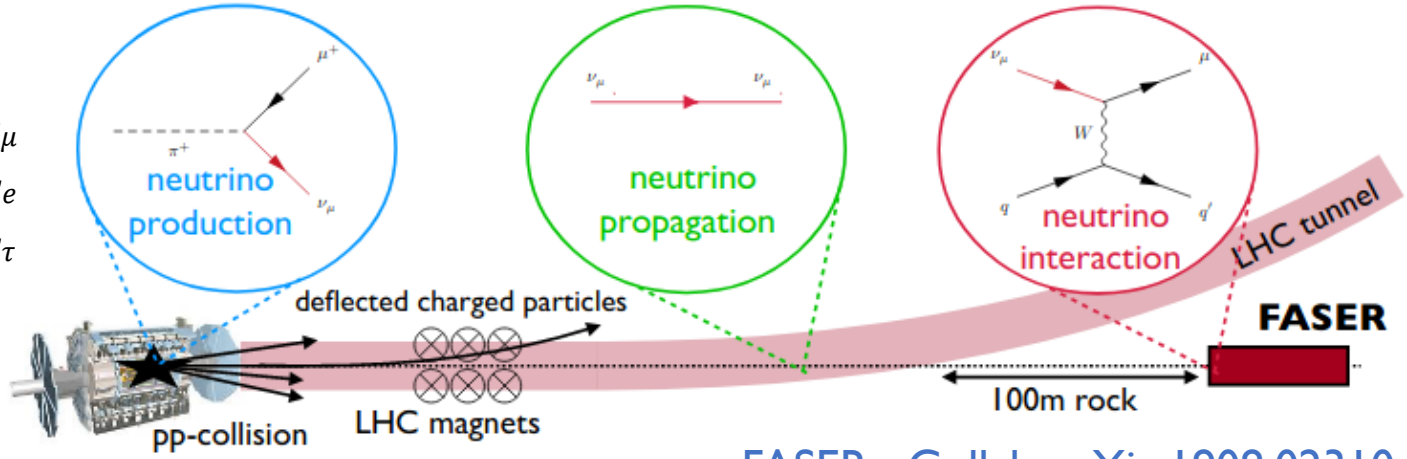
- Non-zero neutrino electromagnetic properties through loops [Giunti, Studenikiny '15]

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

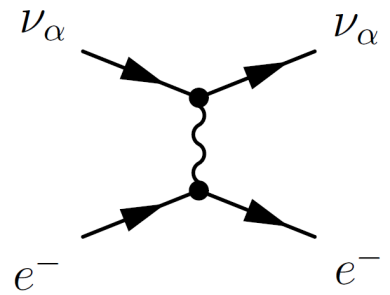


- Large flux of neutrinos in the far forward region
  $E_\nu \sim$ [100GeV – few TeV]

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



- Experimental signature: electron **recoiling**

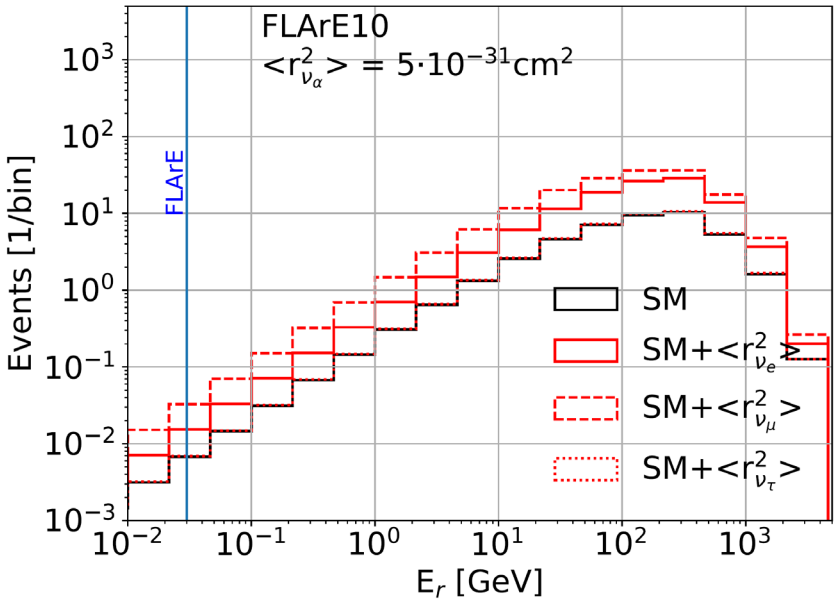


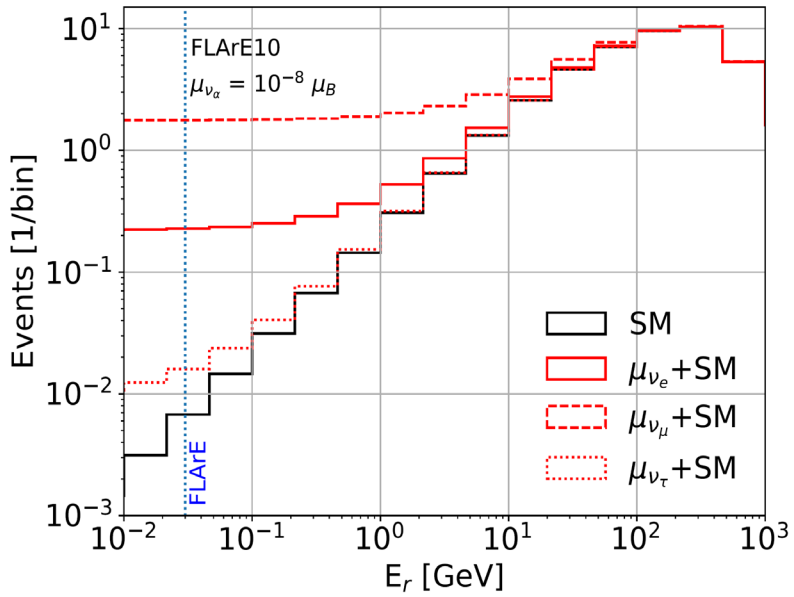
FASERν Collab. arXiv:1908.02310

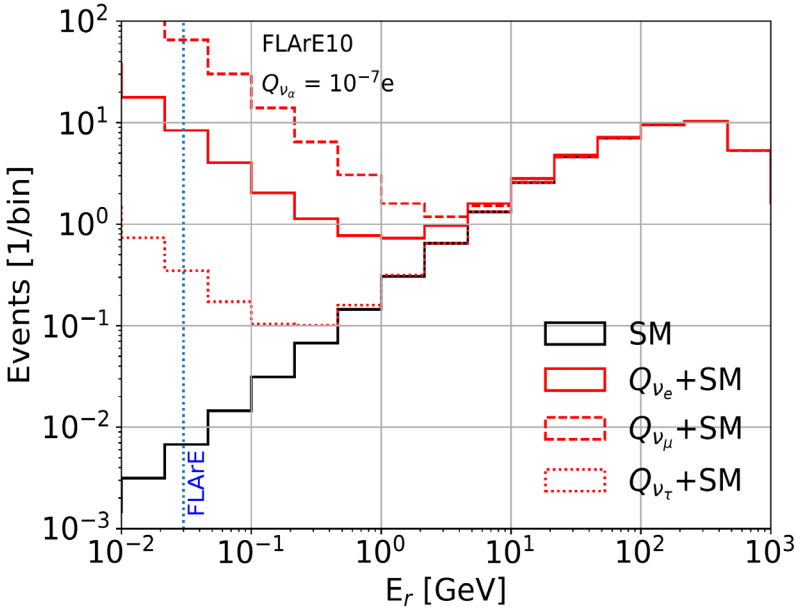
Neutrino EM properties at the FPF

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

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







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