

PADUA2023 - September 2023

Probing dark sectors at accelerators via proton bremsstrahlung

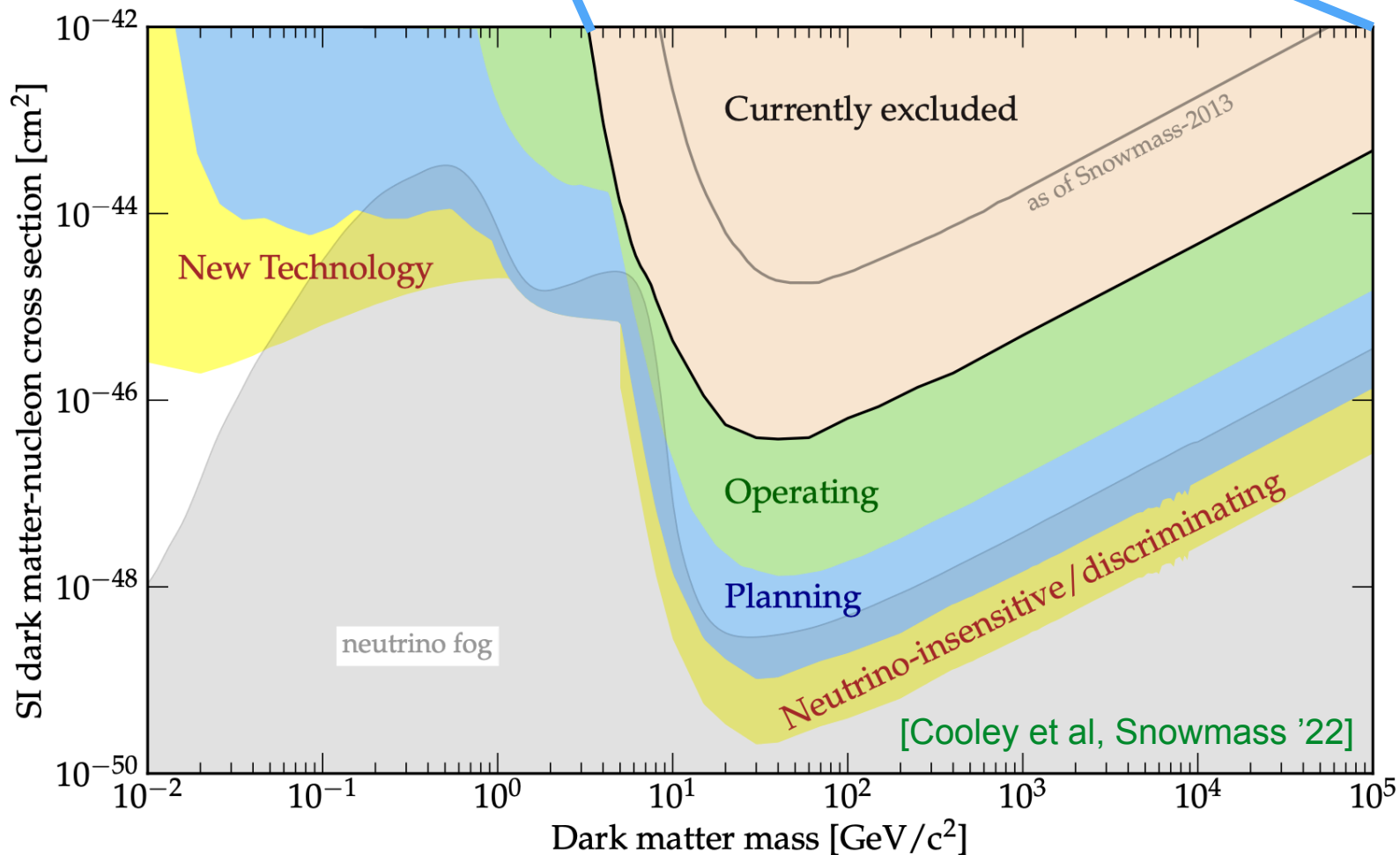
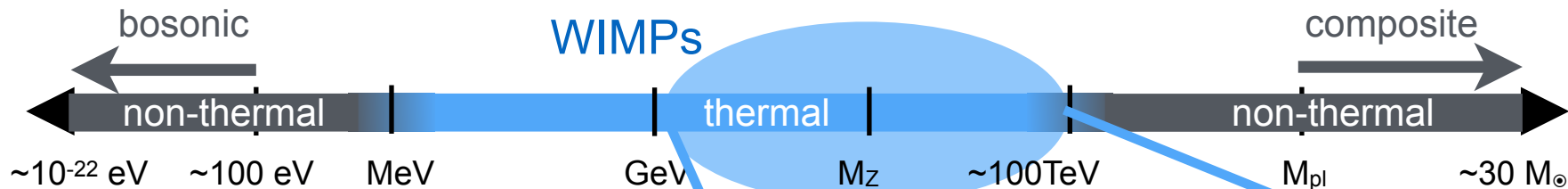
Adam Ritz

University of Victoria

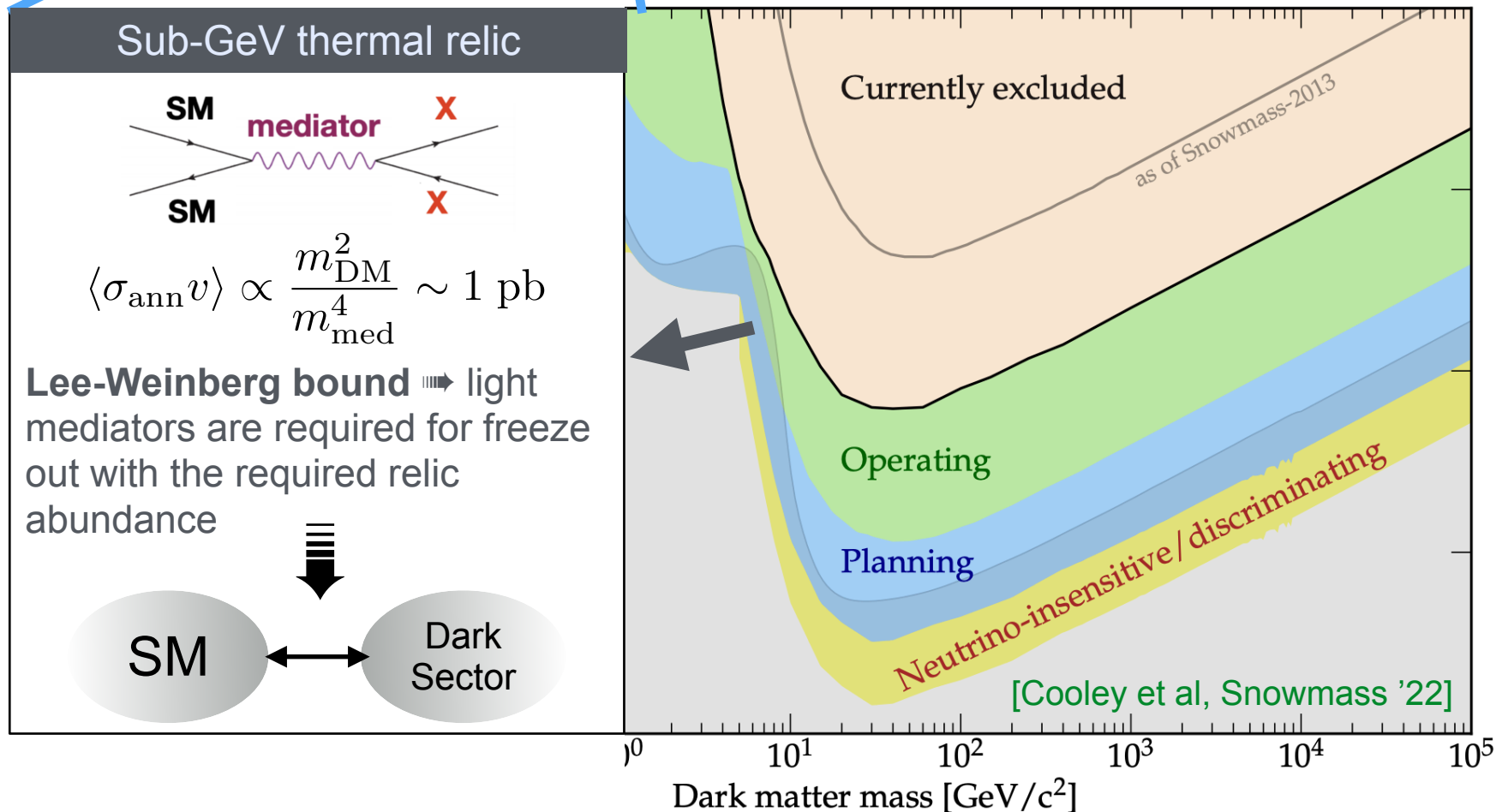
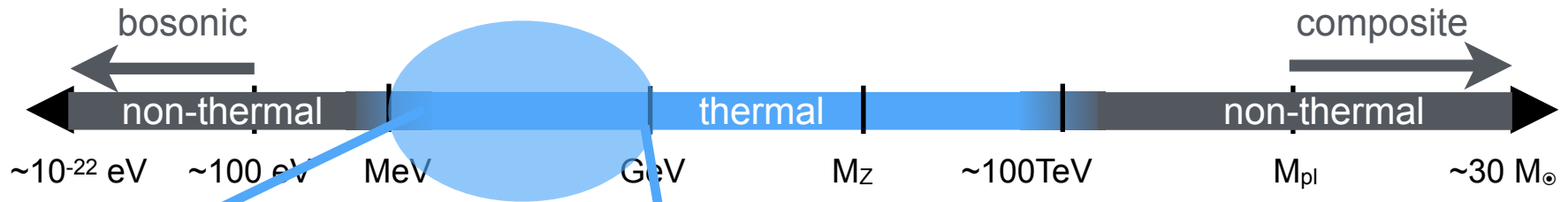


[w/- Saeid Foroughi-Abari, arXiv:2108.05900 and to appear]

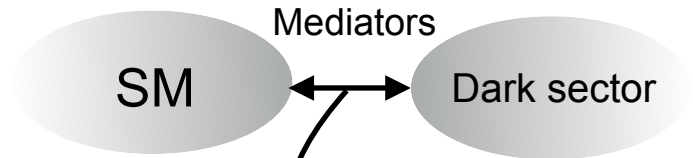
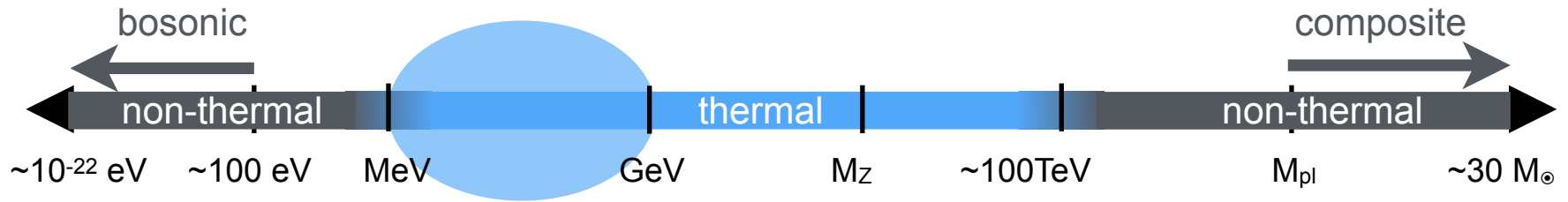
Motivations - Thermal CDM landscape



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Dark sectors & forward physics



EFT framework for (SM neutral) light dark sectors, covering all light sub-GeV mass mediators coupled through dimension ≤ 4 'portal' operators

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\text{SM})} \mathcal{O}_l^{(\text{med})} = \mathcal{L}_{\text{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal

[Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal

[Patt & Wilczek]

Neutrino portal

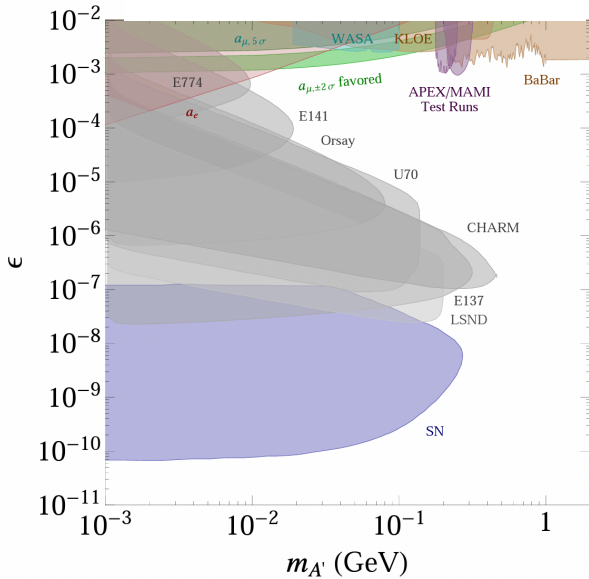
[Minkowski, Minkowski; Yanagida; Mohapatra, Senjanovic]

High-luminosity accelerator-based search strategy, with light states preferentially produced in forward region. Opportunity to probe full kinematics of DM freezeout

Vector portal - status a decade ago

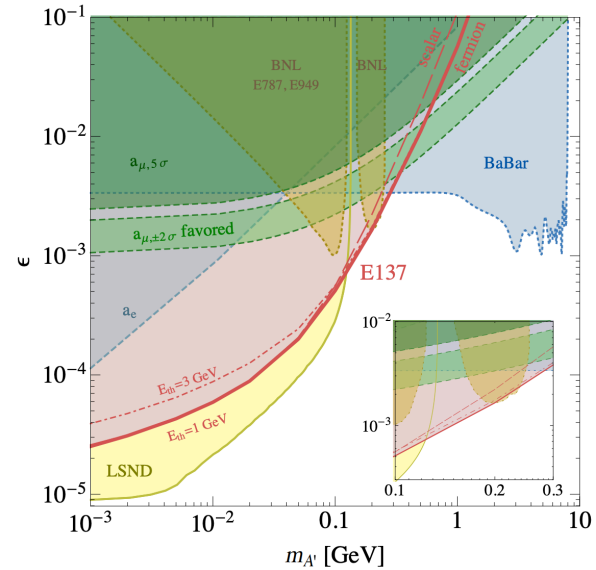
Initial constraints via recasting existing data

$A' \rightarrow \text{SM}$



[Snowmass, Essig et al 2013]

$A' \rightarrow \text{invisible}$

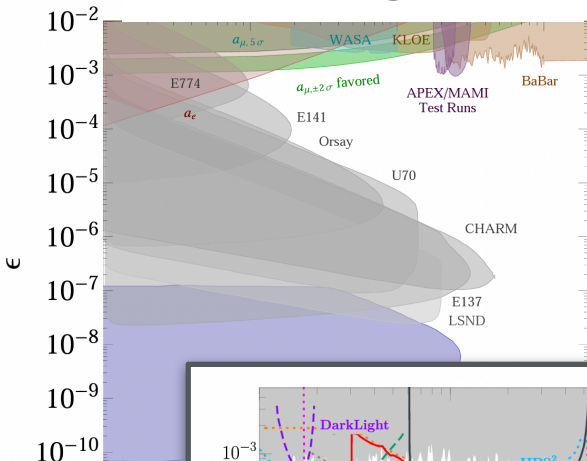


[Batell et al 2014]

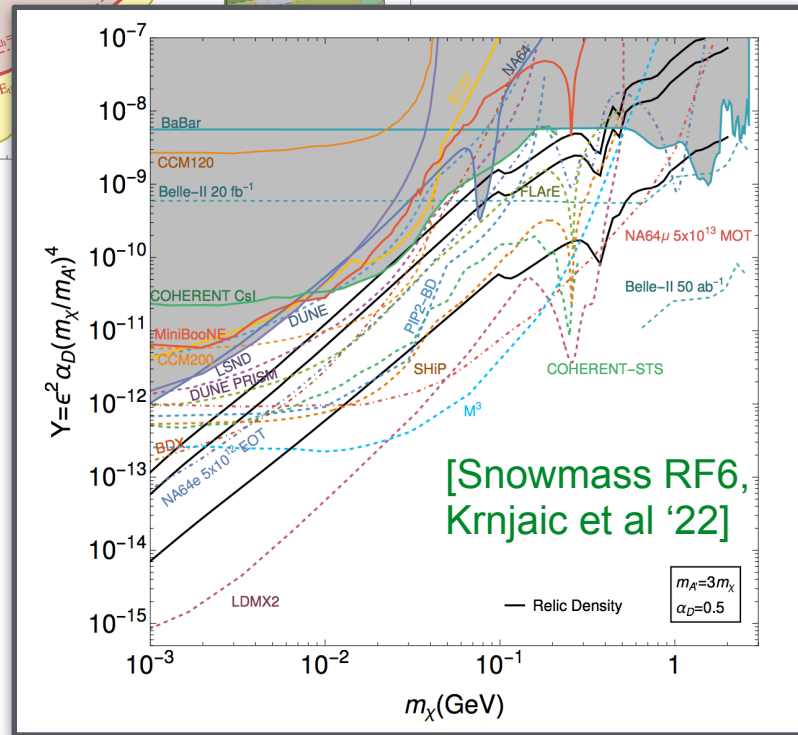
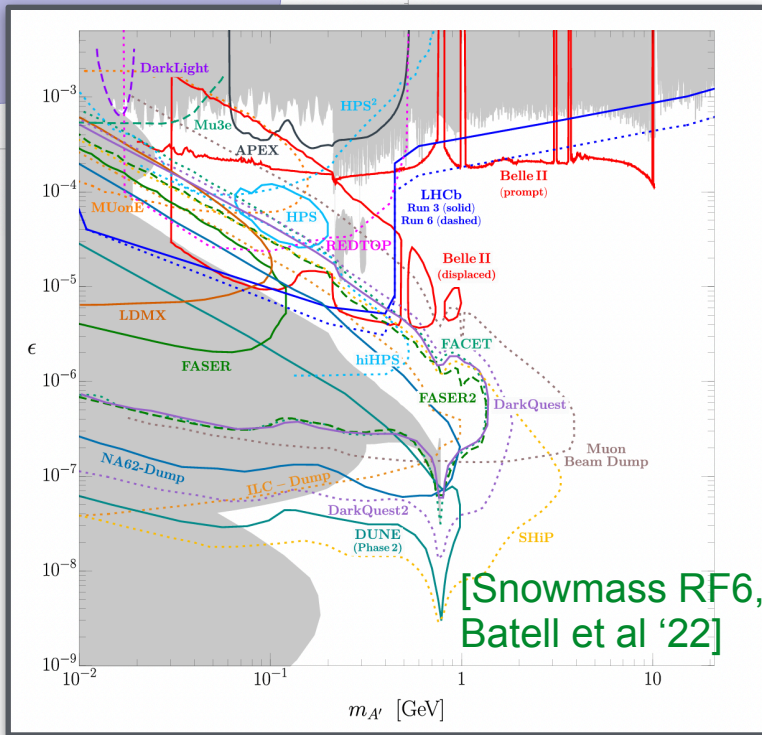
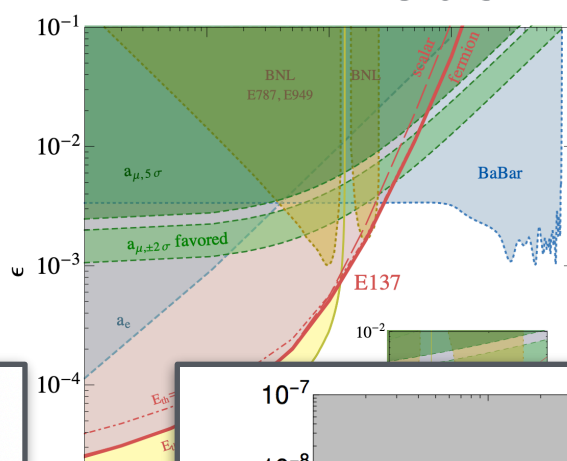
Vector portal - status today

Initial constraints via recasting existing data

$A' \rightarrow \text{SM}$



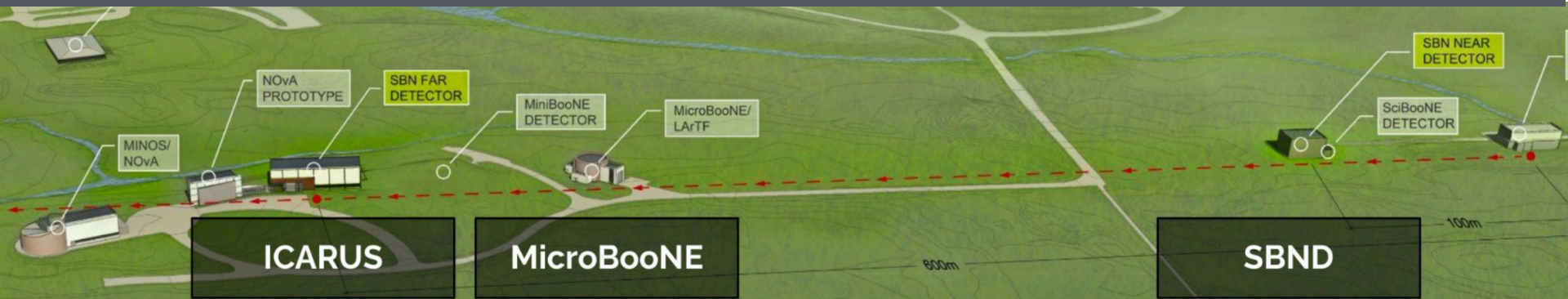
$A' \rightarrow \text{invisible}$



Full experimental searches & analyses, and multiple new proposals

New/proposed proton beam experiments - Fermilab & CERN

Synergistic with new FNAL short-baseline neutrino program + DUNE, DarkQuest



Multiple proposals to broadly probe LLPs (PBC benchmarks) at CERN

Diagram illustrating various proposed experiments at CERN, overlaid on an aerial view of the facility. Key locations and experiments are labeled:

- LHCb**: CODEX-b @ LHCb IP, MOEDAL/MAPP@LHCb IP
- ATLAS**: FASER @ ATLAS IP, ANUBIS @ ATLAS shaft, Forward Physics Facility @ ATLAS IP
- CMS**: MilliQan @ CMS IP, FACET @ CMS IP, MATHUSLA @ CMS IP
- LHC**: NA64++(e) @ EHN1, HIKE/SHADOWS @ ECN3, SHIP @ ECN3
- SPS**: SPS (Super Proton Synchrotron) beamline

Additional labels include: TT90-TCC9-ECN4 (EOI → CDS study), ECN3, LSS2, LSS3, LSS4, BA4, Point 1.8, Point 1, UA23, UJ23, UJ19, RR17, UJ17, UA1.0, UJ14, UJ14, UJ14, UJ13, UJ12, RT12, UA15, UJ15, UJ12, RT12, LSS4, PGC8, T3.8, T1.2, PM12, PM15, PM18, UJ18, UJ16, UJ15, UJ14, UJ13, UJ12, RT12, UA15, UJ15, UJ12, RT12.

Bottom right text: **FASER ready to take data** [Lanfranchi '21]

Hadronic production of dark vectors

Consideration of new experimental proton beam experiments motivates further scrutiny of signatures and (in particular) the modelling of hadronic production rates for dark sectors...

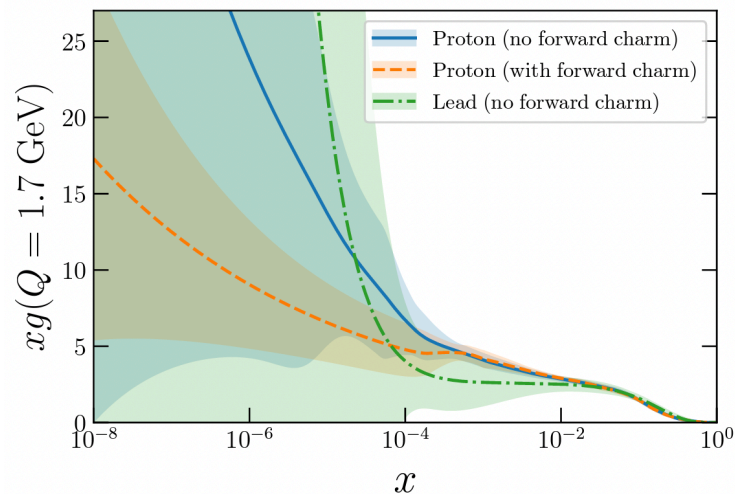
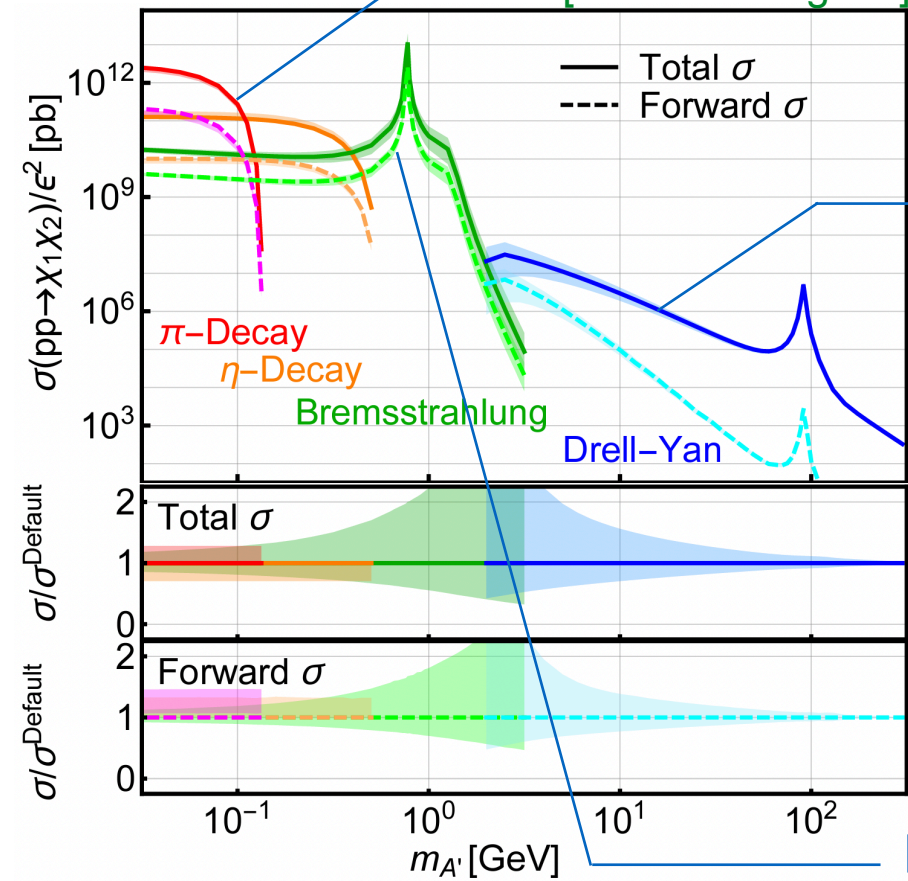
[Berlin & Kling '18]

Radiative meson decay

$$\pi/\eta \rightarrow \gamma + A'$$

Drell-Yan (very small x)

$$q + \bar{q} \rightarrow A'^* + X$$



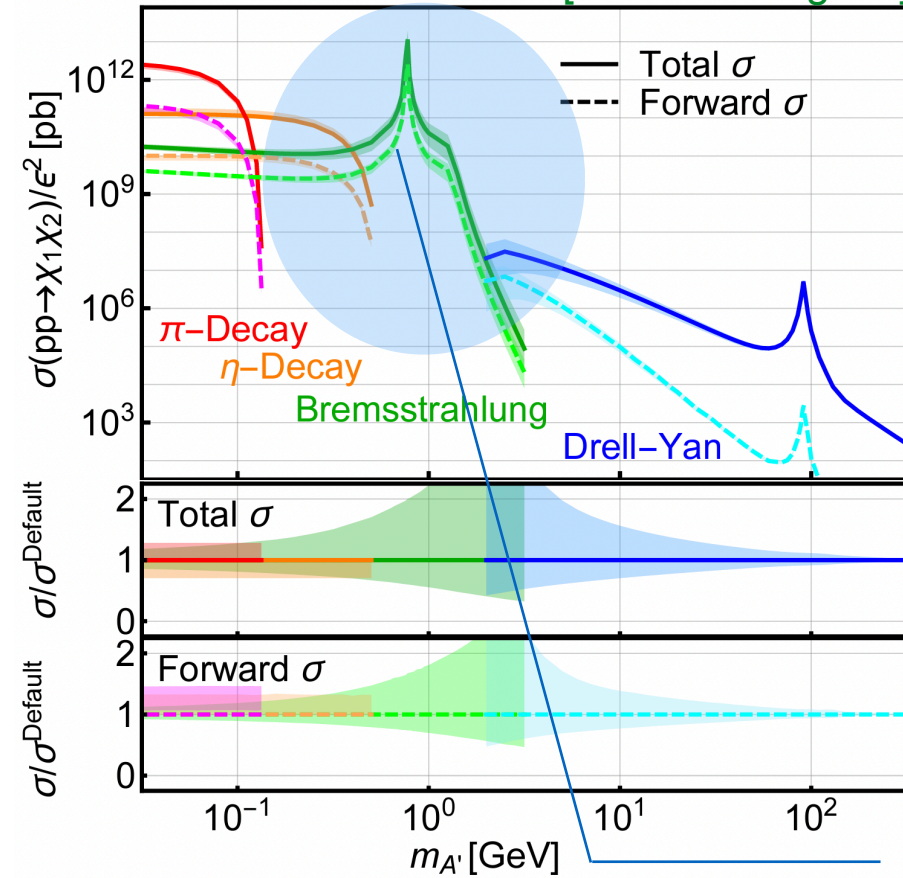
Proton bremsstrahlung

$$p + N \rightarrow X + A'$$

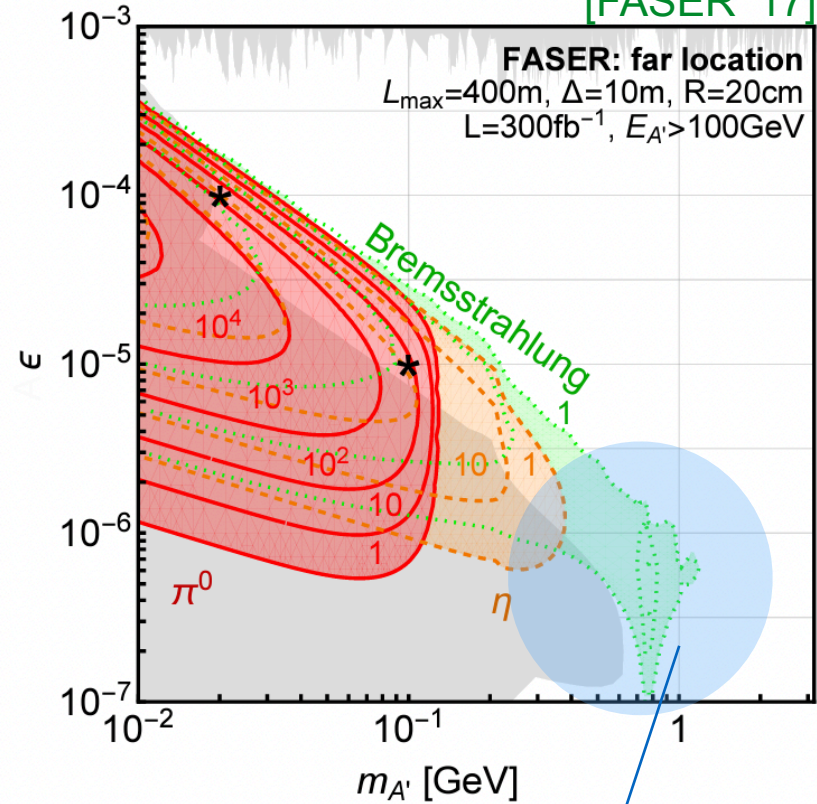
Proton Bremsstrahlung

For the intermediate (hadronic) mass range 0.5 - 1.5 GeV, forward production modelling has focussed on proton brem and mixing with vector mesons
 [Blumlein & Brunner '13, Batell et al '14, deNiverville et al '16]

[Berlin & Kling '18]



[FASER '17]

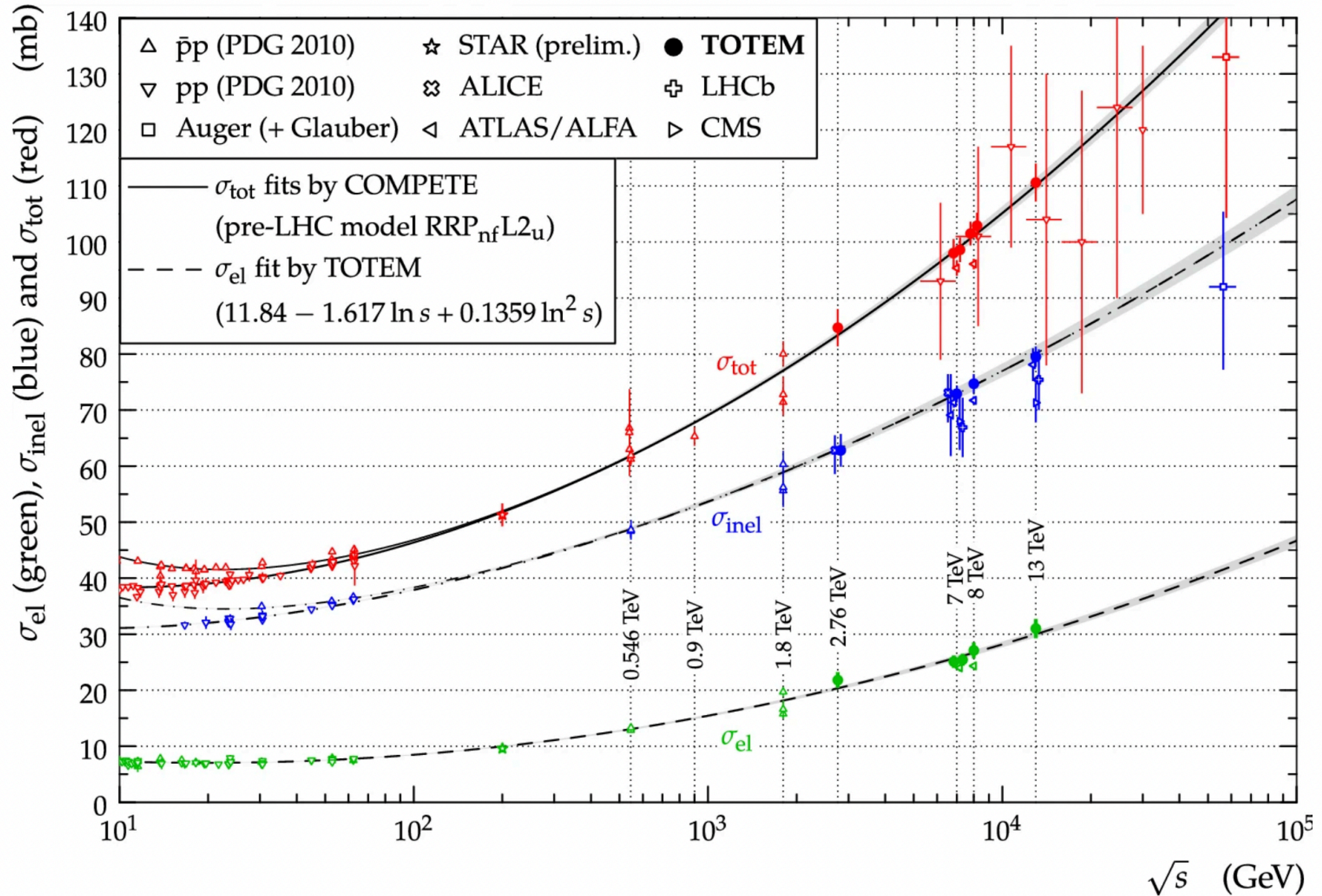


Proton bremsstrahlung

What is the precision of the proton brem calculation, e.g. for TeV beams at FASER/ FPF?

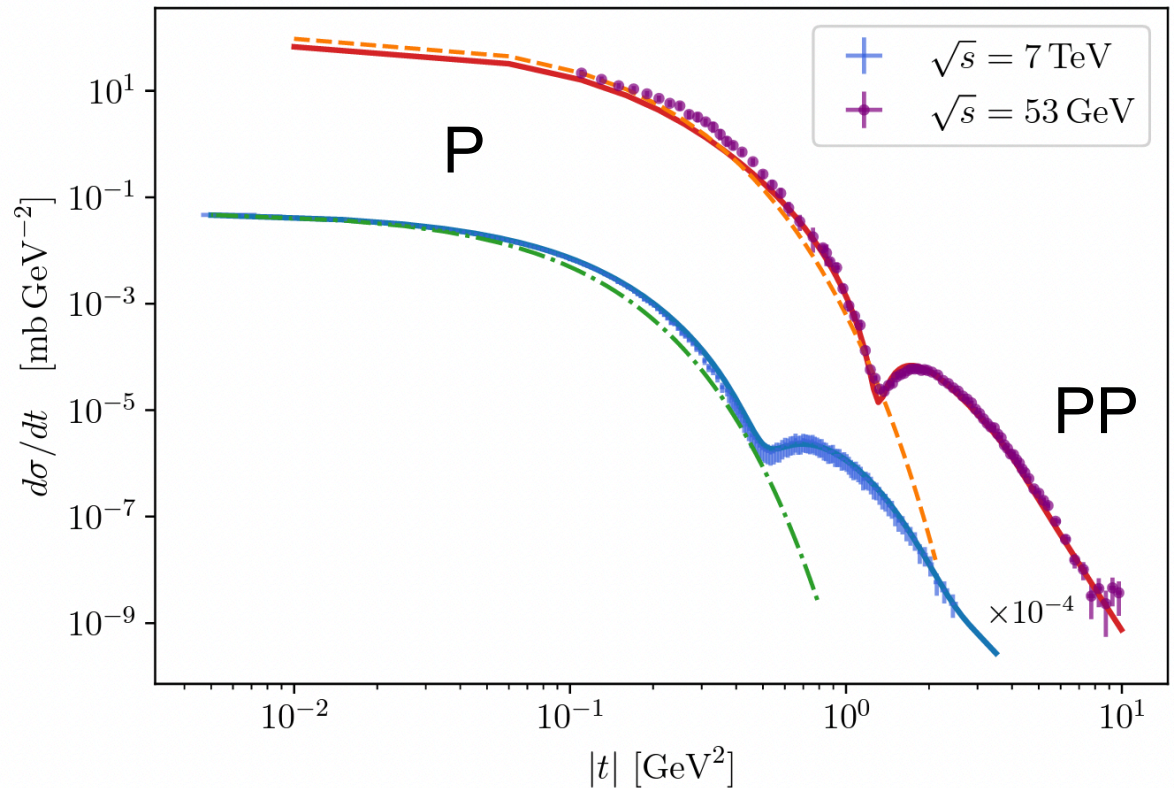
Forward pp scattering

[TOTEM '19]

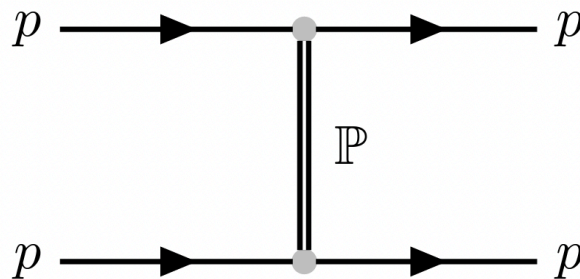


(Forward) elastic scattering

Donnachie-Landshoff
model [DL '82,84,11,13]



Single pomeron
exchange fits data
well for low t

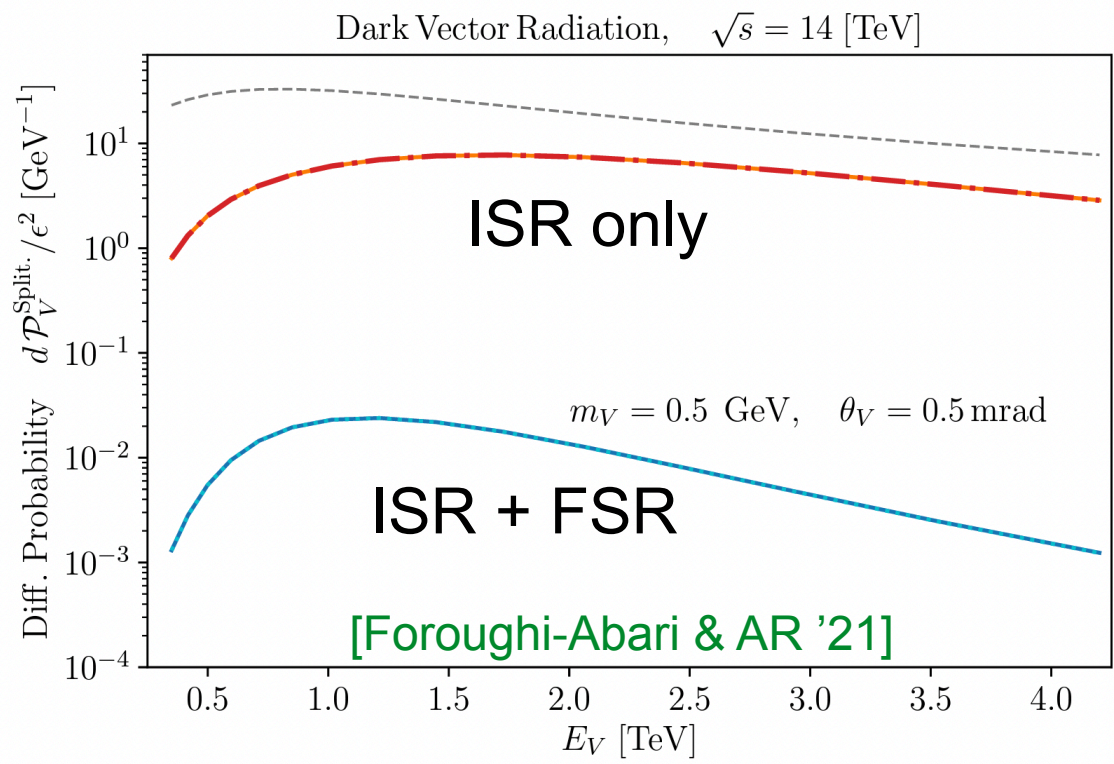
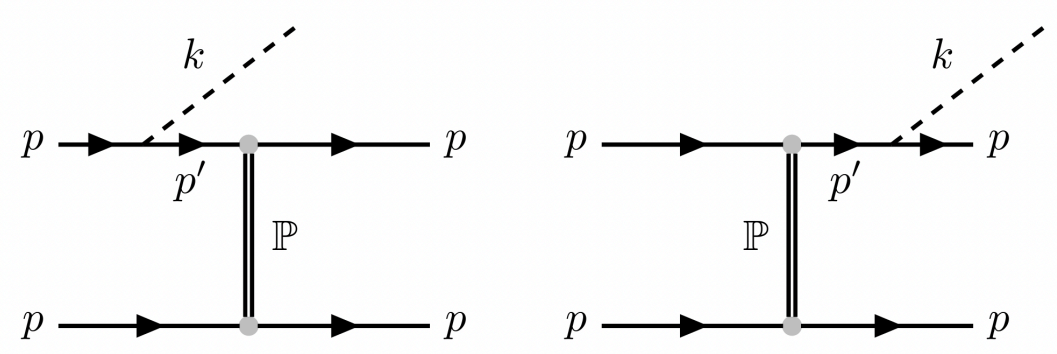


$$\frac{d\sigma^{\text{el}}}{dt} \simeq F(t)(s\alpha'_P)^{\alpha_P(t)-1}$$

$$\alpha_P(t) = \epsilon_P + \alpha'_P t \simeq 1.08 + 0.25t$$

Dark vector radiation from quasi-elastic scattering

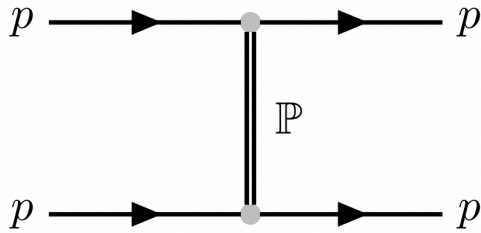
V-production using the DL model for quasi-elastic scattering



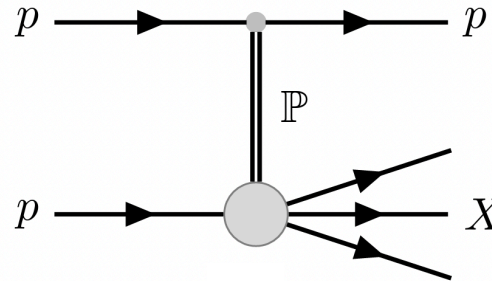
ISR + FSR interference leads to significant suppression

Production via ISR

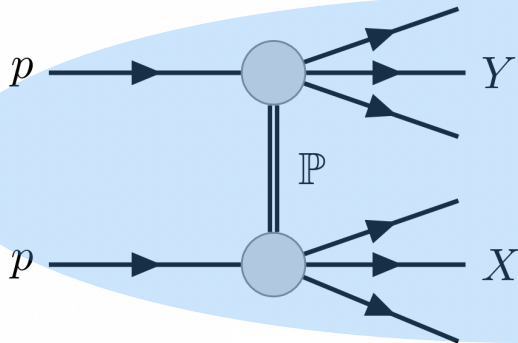
Elastic



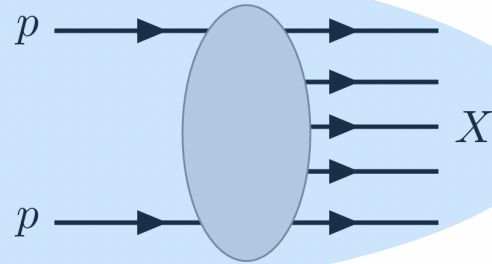
Single diffractive



Double diffractive

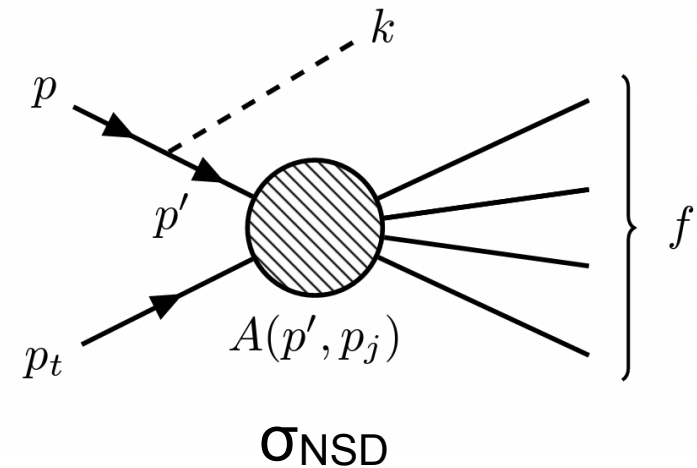


Non-diffractive



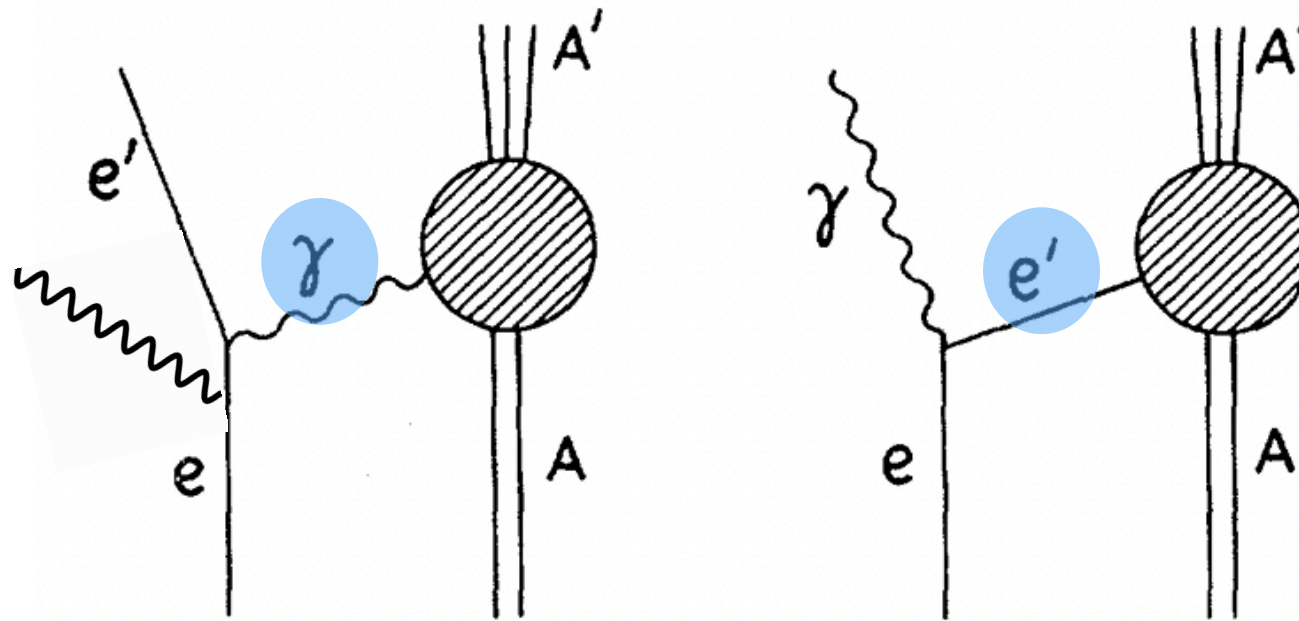
Non-diffractive processes contribute ~60% of the total cross-section

Model production via ISR only in NSD scattering



Equivalent particle approximations

Approximations for relativistic collinear scattering & radiation (QED)



[Chen & Zerwas '75]

Equivalent photon

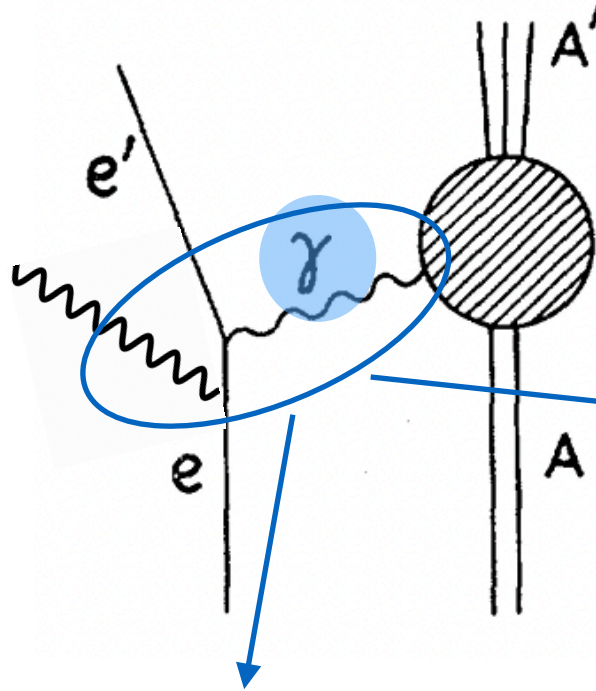
[Fermi '24; Weizsäcker '34;
Williams '35, Kim & Tsai '73;
Bjorken et al '09; Blumlein &
Brunner '13...]

Equivalent fermion

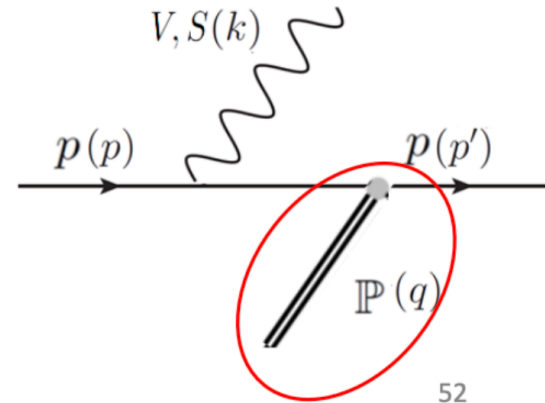
[Gribov & Lipatov '72;
Baier, Fadin & Khoze
'73; Chen & Zerwas '75;
Dokshitzer '77; Altarelli
& Parisi '77; ...]

Equivalent particle approximations

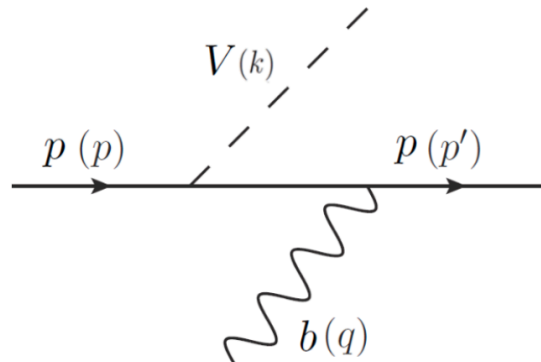
Approximations for relativistic collinear scattering & radiation (p beams)



Hadronic generalization (following Kim & Tsai '75) with an “equivalent pomeron” provides an excellent approximation to (suppressed) quasi-elastic ISR+FSR radiation



$$p + b \rightarrow p' + V$$

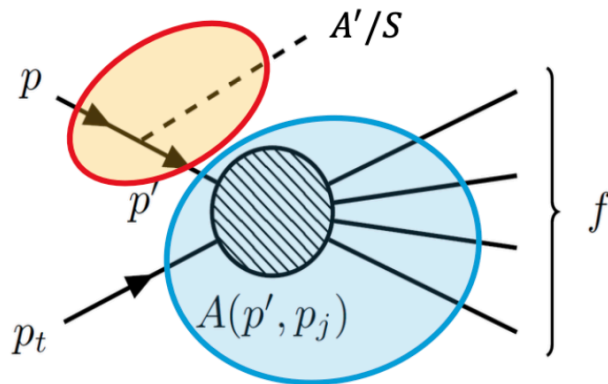
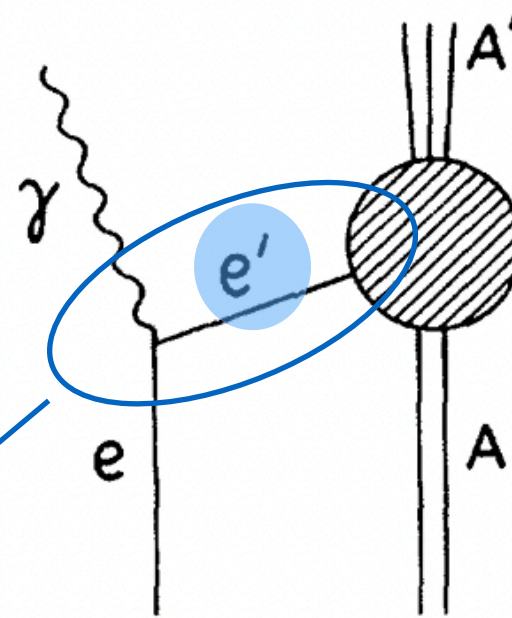


Modified application to proton brems (Blumlein & Brunner '13) used an “equivalent vector” approximation as a means to estimate an ISR splitting function, then convoluted with the total (*not elastic*) cross section

Equivalent particle approximations

Approximations for relativistic collinear scattering & radiation (p beams)

For comparison, analyze the “equivalent proton” or quasi-real approximation (QRA) to determine the splitting function for vector ISR (with small p_T)

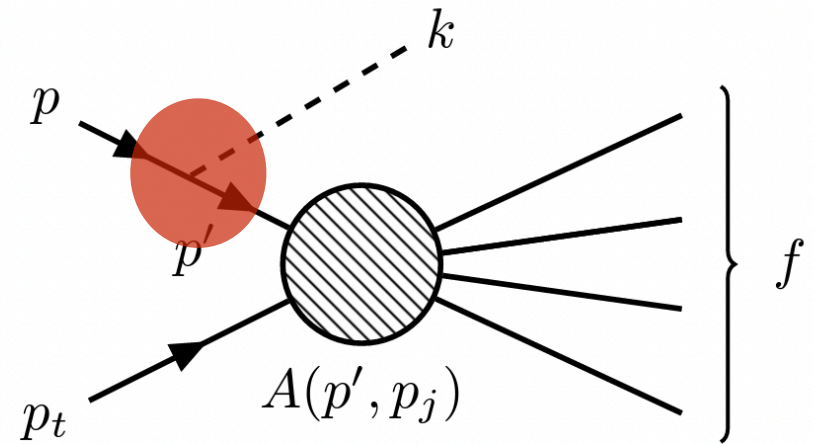


$$d\sigma^{pp_t \rightarrow Df}(s) \approx d\mathcal{P}_{p \rightarrow p'D} \times \sigma_{pp}^{\text{NSD}}(s')$$

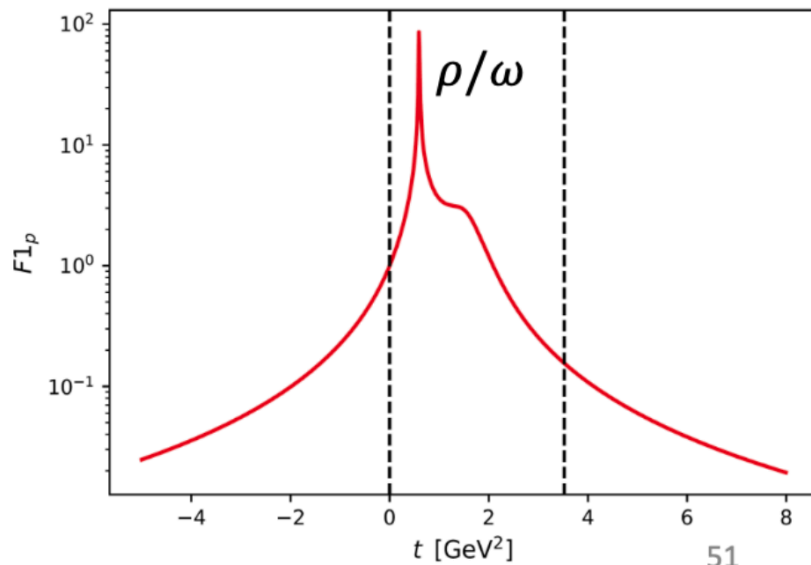
Convolute with NSD (*not total*) cross section, given observation of suppressed radiation in diffractive scattering

Form factor(s)

The dark vector is radiated with timelike momentum, thus can mix with hadronic resonances, while the intermediate proton is slightly off-shell, so the vertex is a transition form-factor



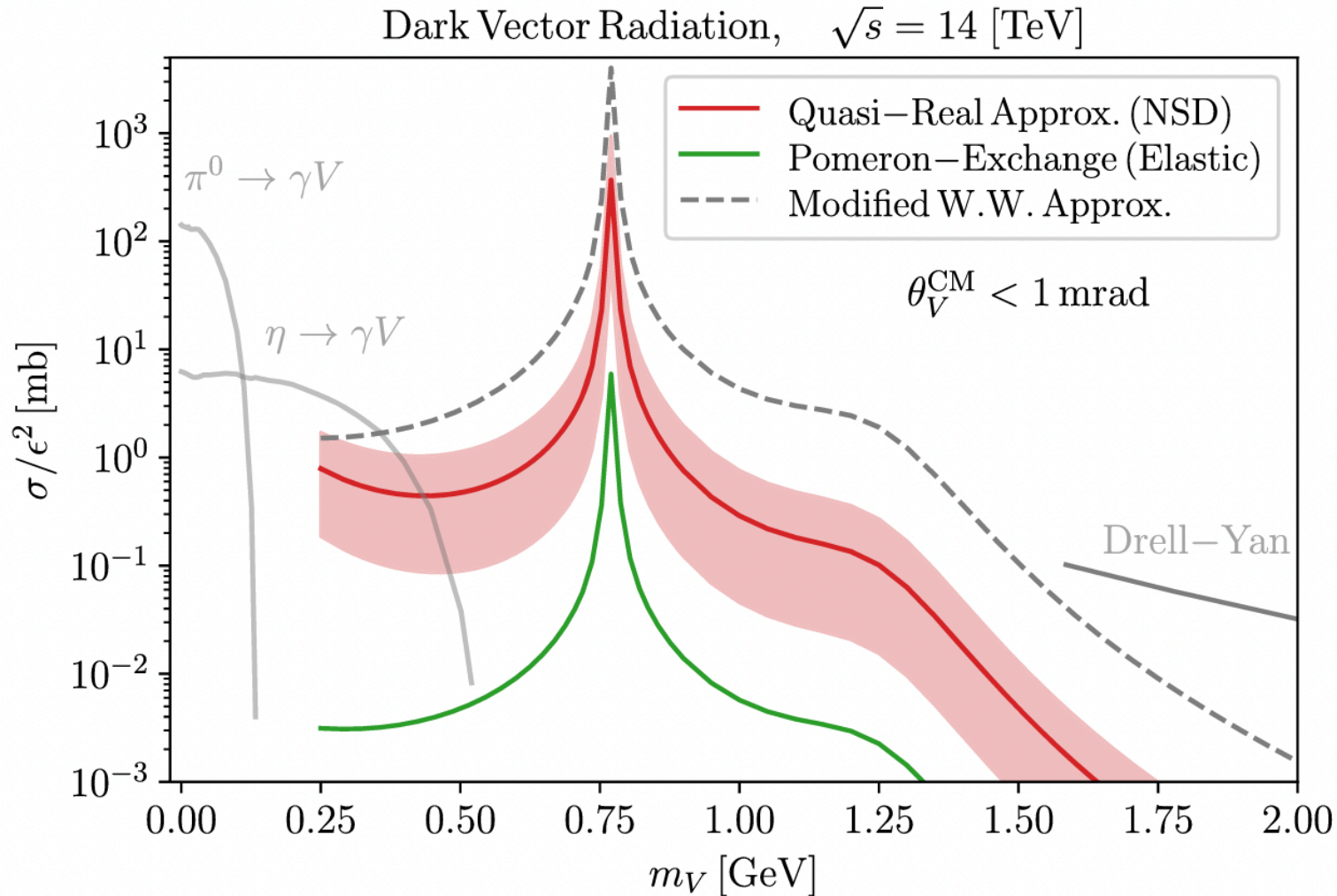
[Faessler et al '09, Adamuscin et al '16]



Also include a dipole form-factor profile with scale Λ for dependence on virtuality of intermediate proton

[Feuster & Mosel '98]

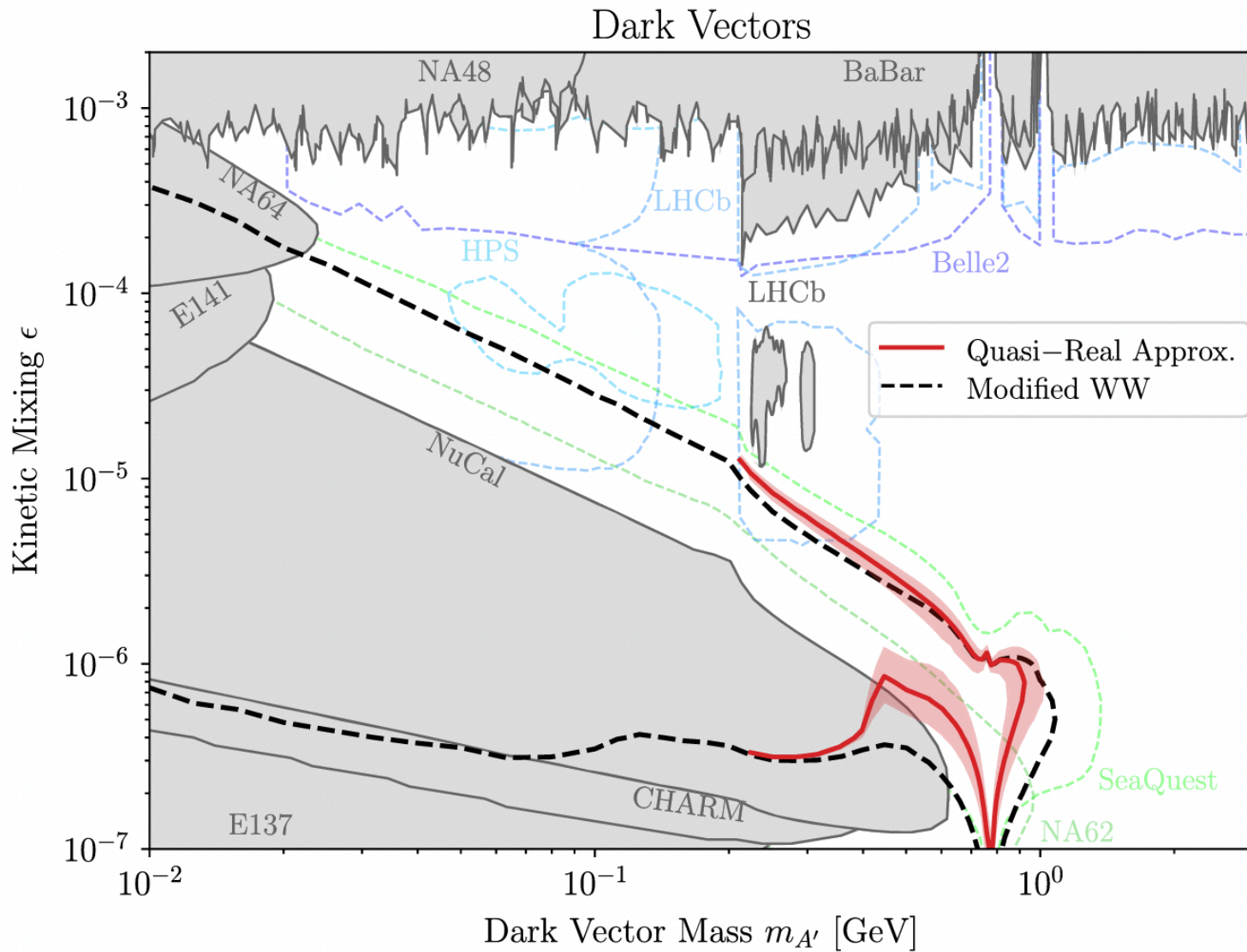
Impact on production rate - vectors



Red band from varying form-factor scale Λ from 1 to 2 GeV

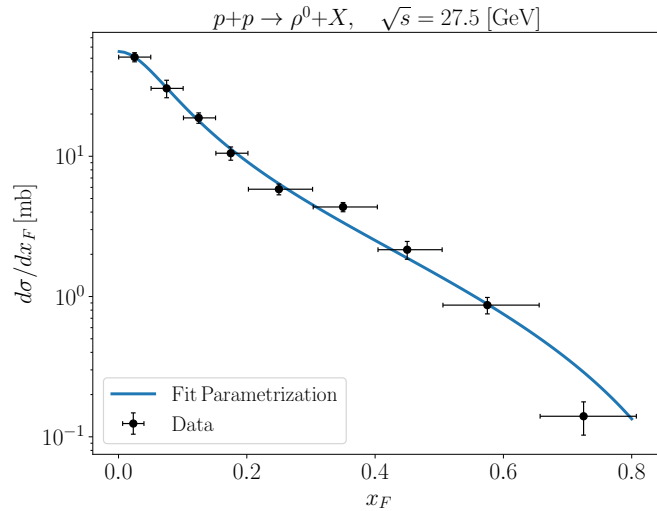
Sensitivity

Impact on sensitivity for a FASER2-like experiment at the HL-LHC

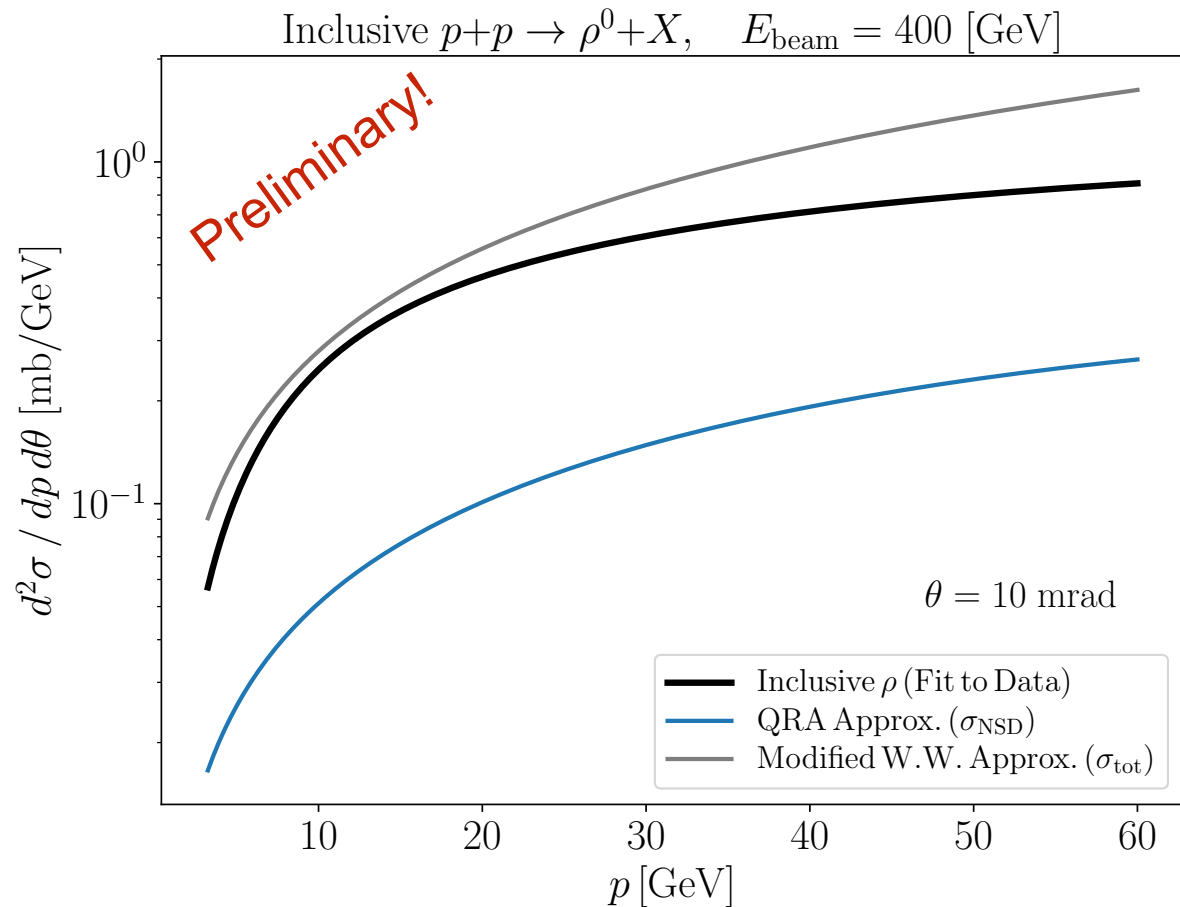


Benchmarks (rho production)

Contrast these mechanisms for inclusive rho production with data from NA27

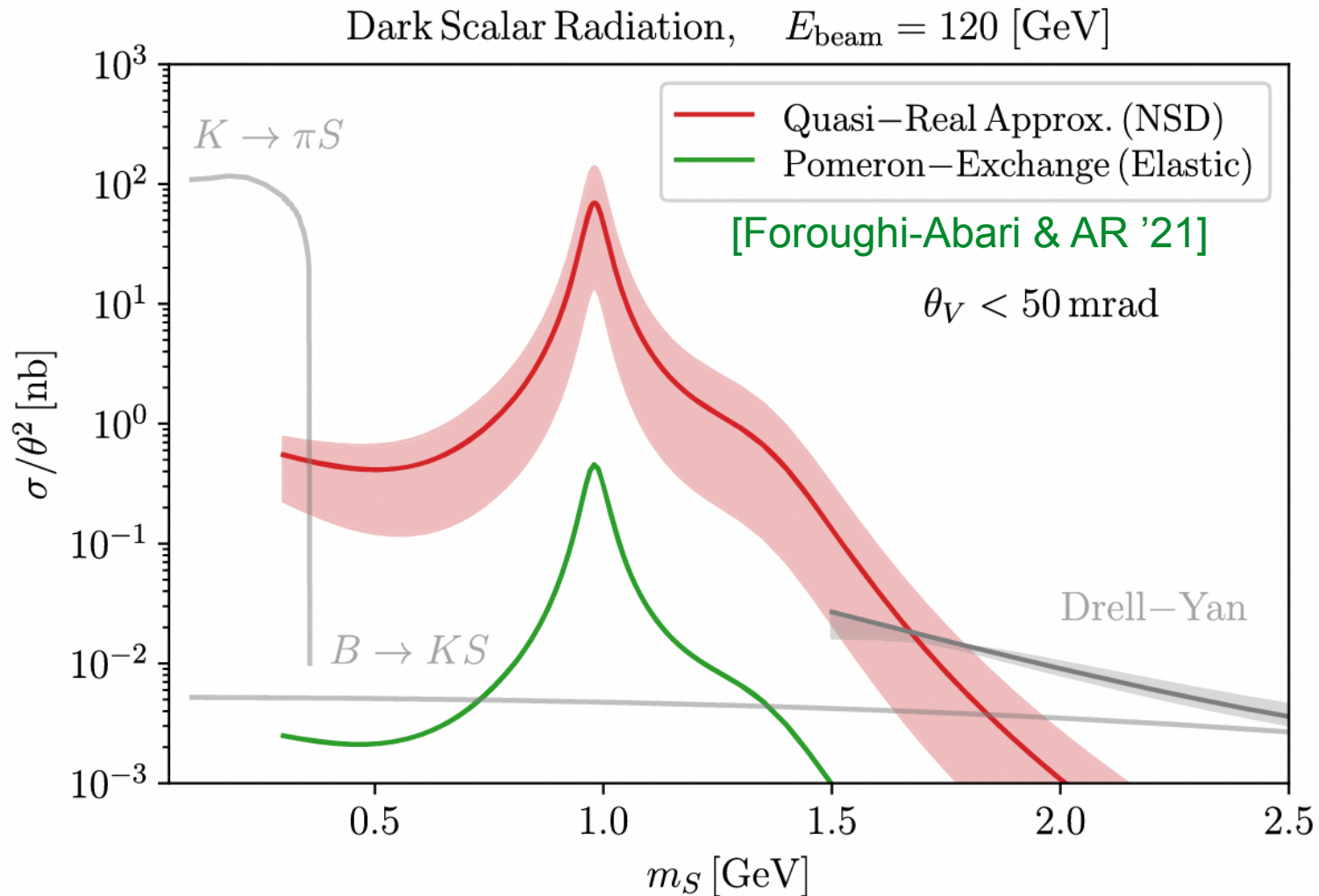


Consider regime with
 $p_L \ll p_L^{\max}$ (small x_F)
and $p_T < \text{GeV}$



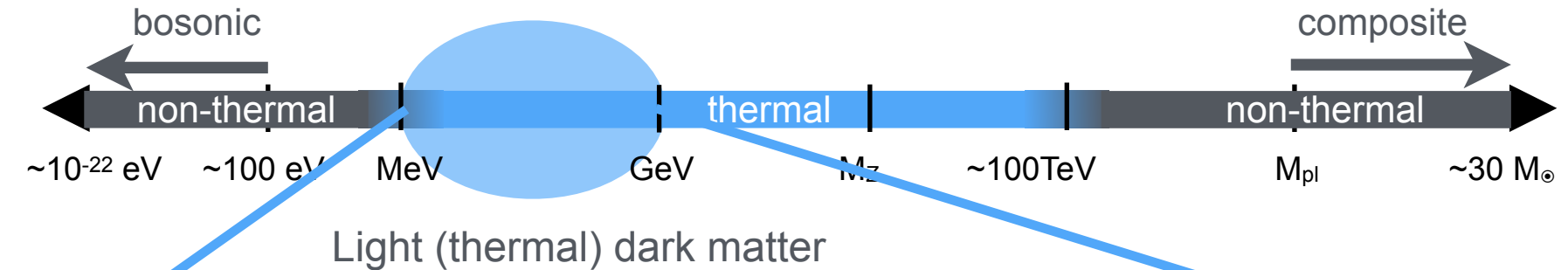
[Foroughi-Abari & AR, to appear]

Impact on production rate - scalars



- Peak at ~ 1 GeV reflects mixing with scalar f_0 meson [Batell et al '20]
- Red band from varying form-factor scale Λ from 1 to 2 GeV
- Production from B decays dominates at LHC energies

Summary



High-luminosity accelerators have the kinematics to test facets of thermal freezeout in MeV-GeV DM models, a complementary probe to direct detection (N- or e-scattering)

- Multiple new/proposed proton beam facilities at Fermilab (SBND, ICARUS, DUNE, DarkQuest) and CERN (FASER, HIKE/SHADOWS, SHiP, FPF,...) motivate efforts to quantify (and improve) precision of dark sector production and detection.
- Proton brem as an important forward production mode in the 0.5 - 1.5 GeV regime. Contrasted several approximations as one (crude) means to assess precision, along with benchmarking against SM vector meson production data.