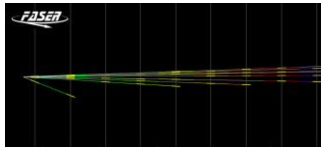
Broad Physics Opportunities and Discovery Potential in the Forward Region at the LHC

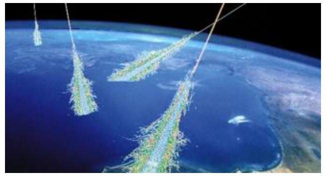
Max Fieg (UC Irvine → FNAL)

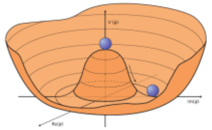
In collaboration with many great people:

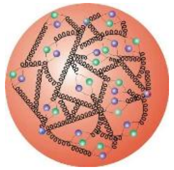
Jonathan Feng, Felix Kling, Juan Rojo, Roshan Mammen Abraham, Juan M. Cruz-Martinez, Tommaso Giani, Peter Krack, Toni Mäkelä, Tanjona Rabemananjara, Holger Schulz, Torbjorn Sjostrand, Keith Dienes, Brooks Thomas, Fei Huang, Seung Lee, FASER

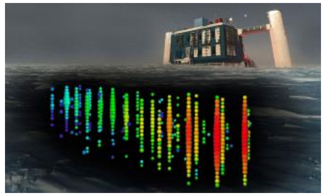
Mitchell Conference on Collider, Dark Matter, and Neutrino Physics







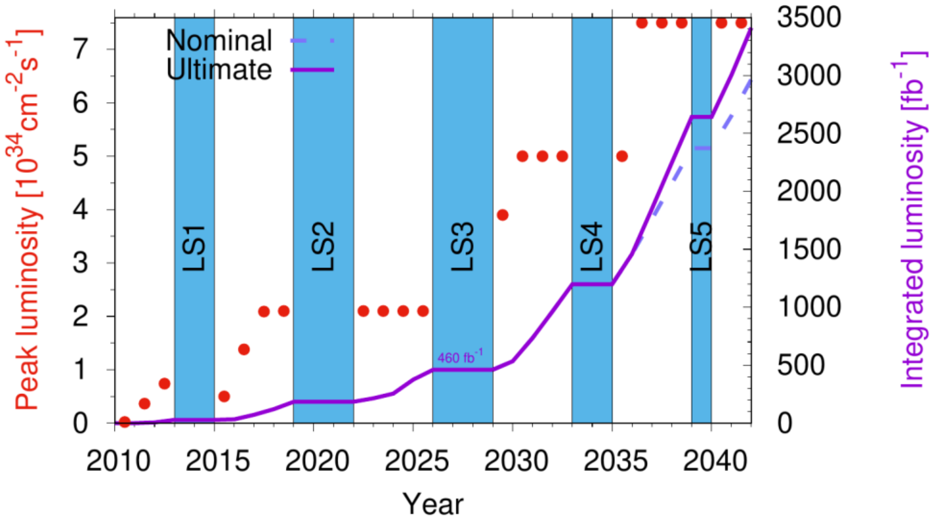




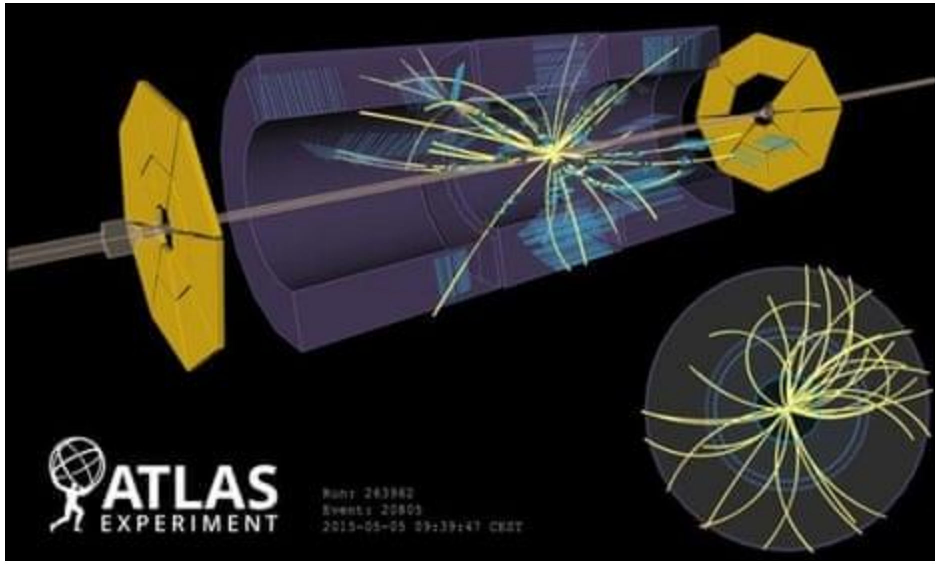
What more can we do with the LHC?

Only a small fraction of collisions, < 10% of total lumi

- LHC has collected the same fraction of data as an 8-year-old

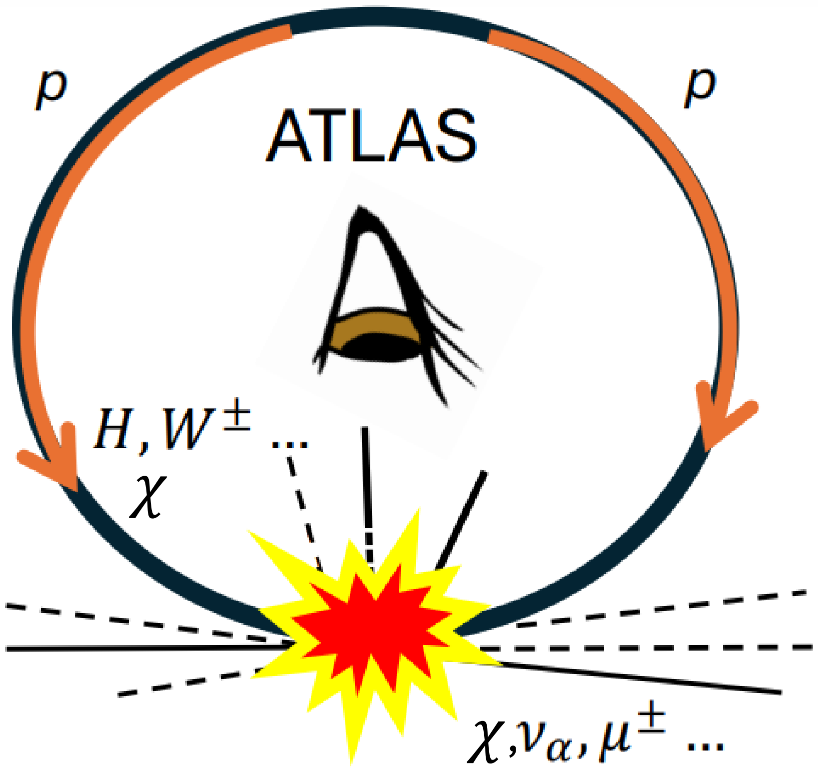


More luminosity, upgrades, new analysis strategies all lead to a higher probability of discovery. New measurements will also be important



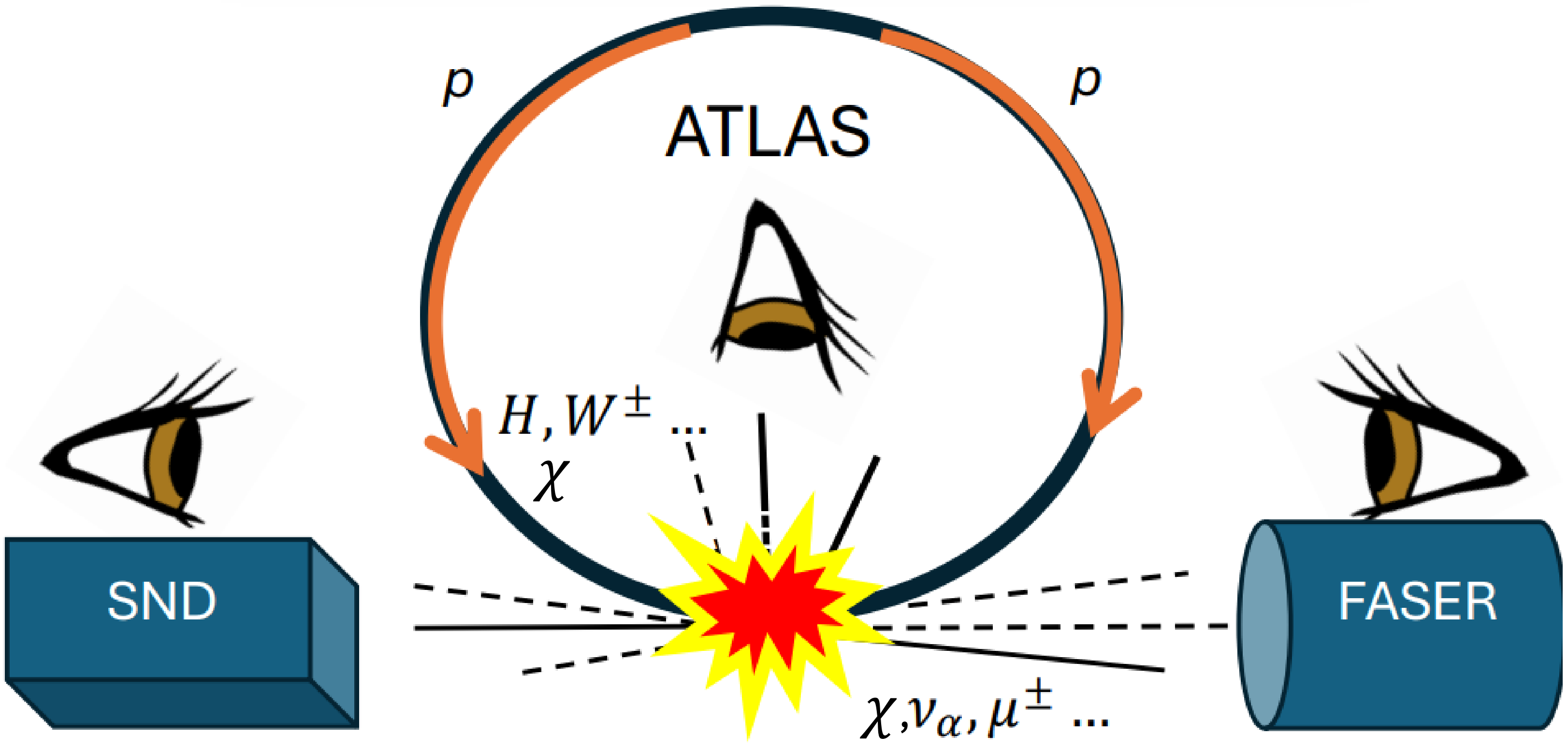
In recent years, forward physics has become a burgeoning field, why?

Forward Physics:A new way to observe collisions



Central experiments miss most of the soft collisions at the LHC

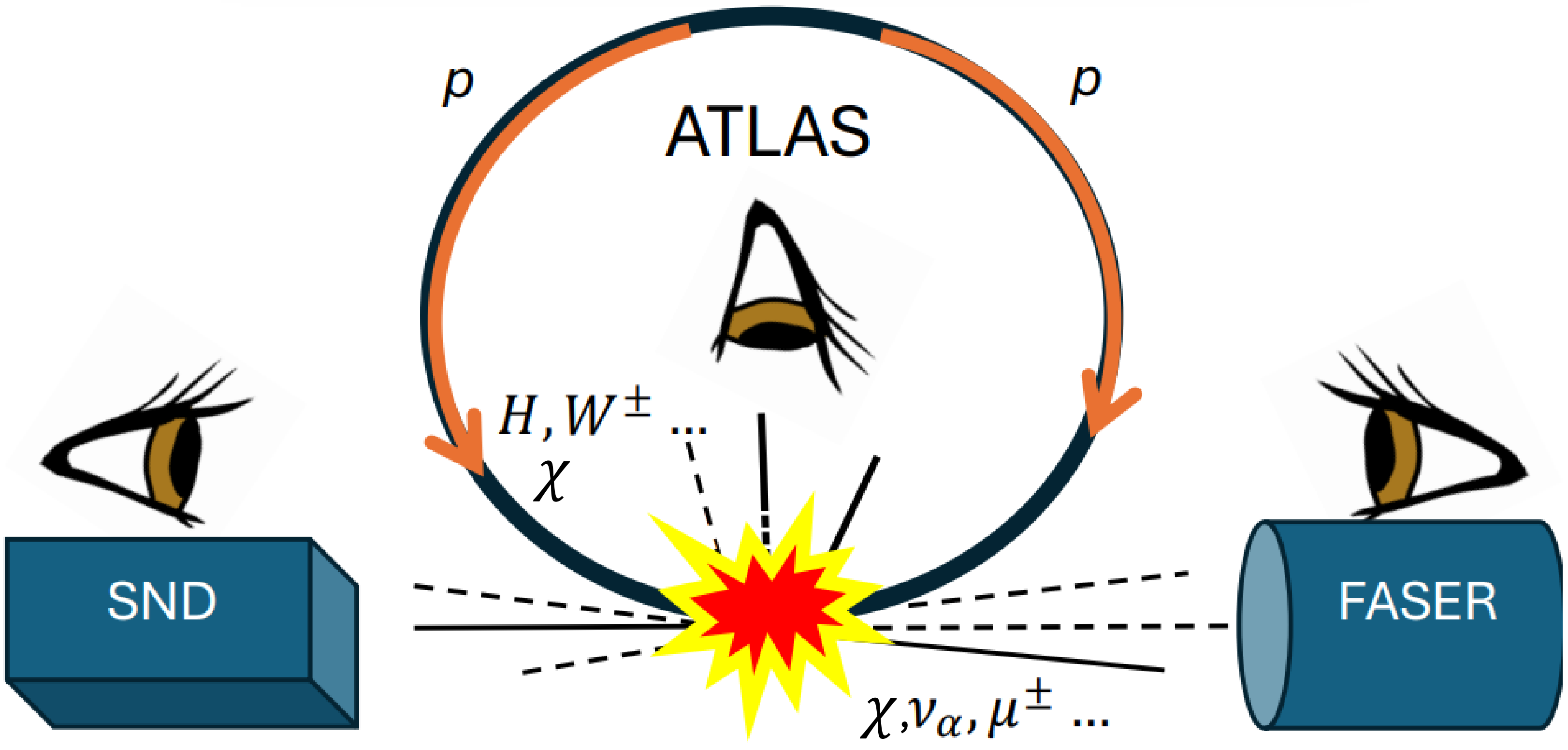
Forward Physics:A new way to observe collisions



Central experiments miss most of the soft collisions at the LHC

Today the forward direction is instrumented by the FASER and SND experiments

Forward Physics:A new way to observe collisions



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" These **sources** are complicated... Unless you have many ways to ***look*** at them, you're not going to figure them out."
-Francis Halzen on Multimessenger Astronomy, Scientific American

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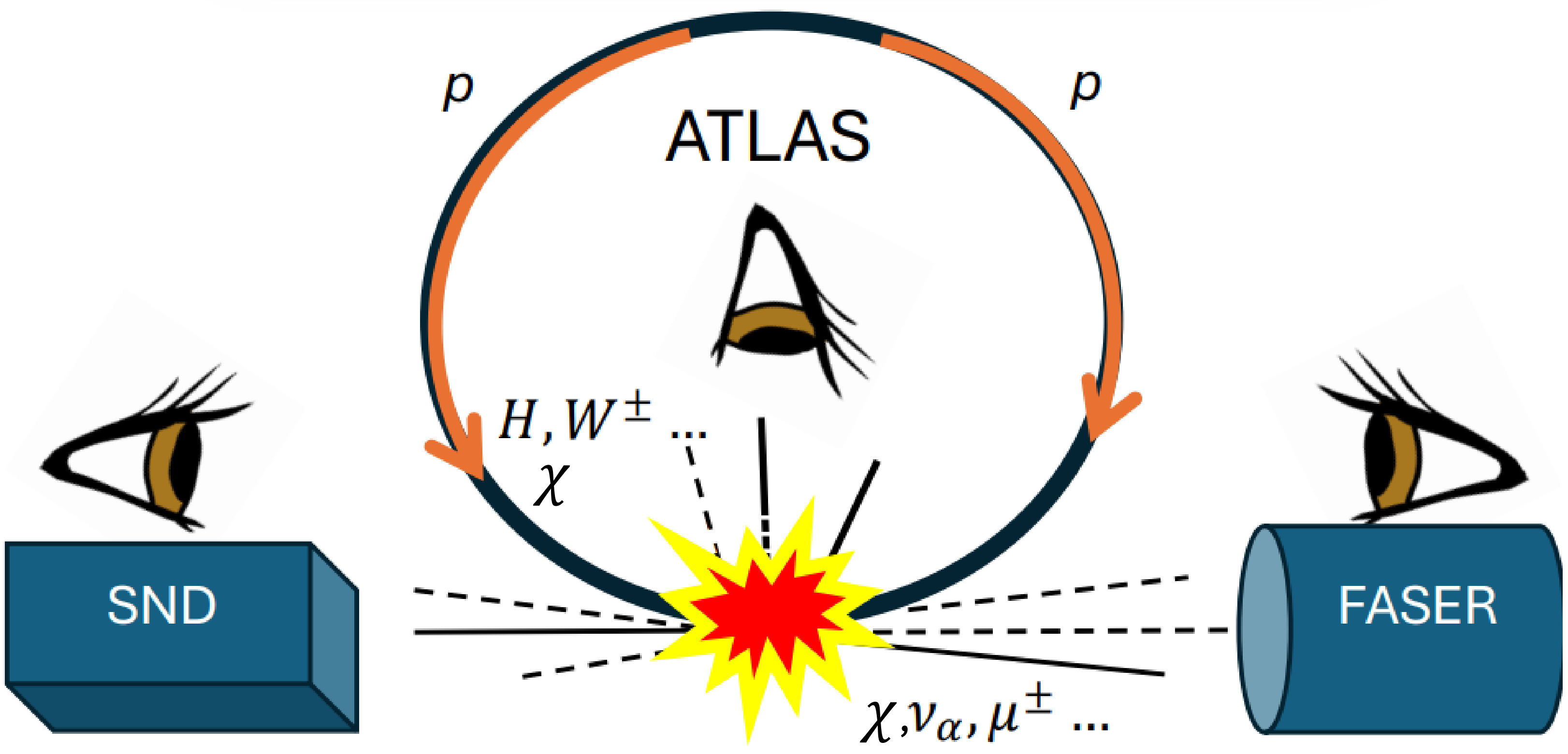
Multimessenger *Collider Physics*

Forward Physics:A new way to observe collisions



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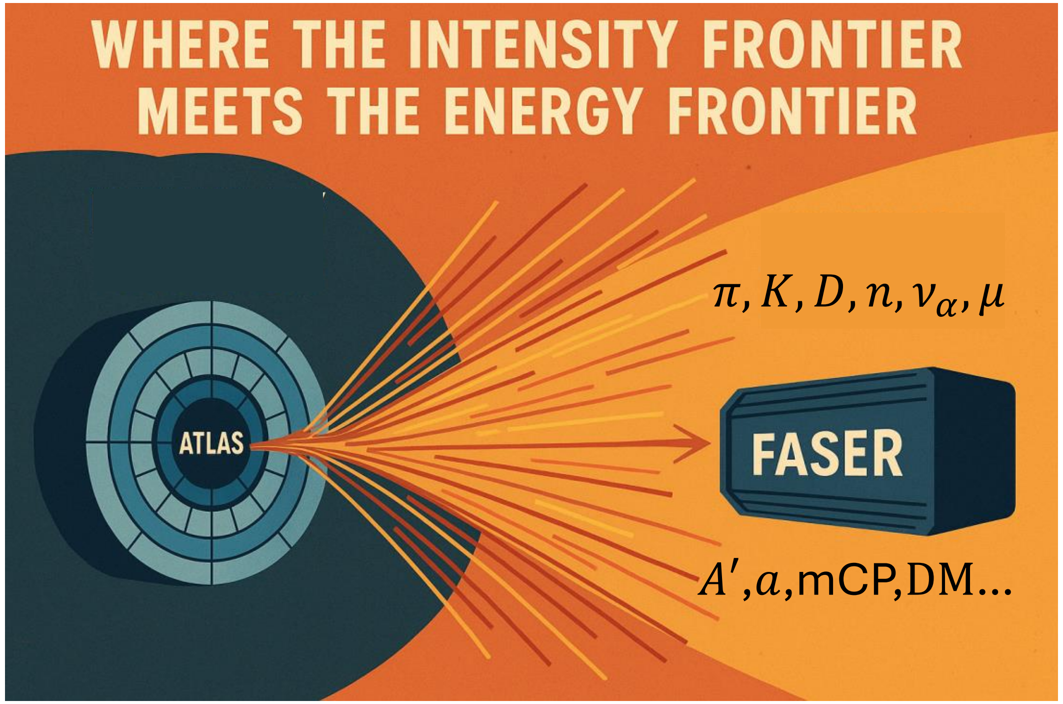
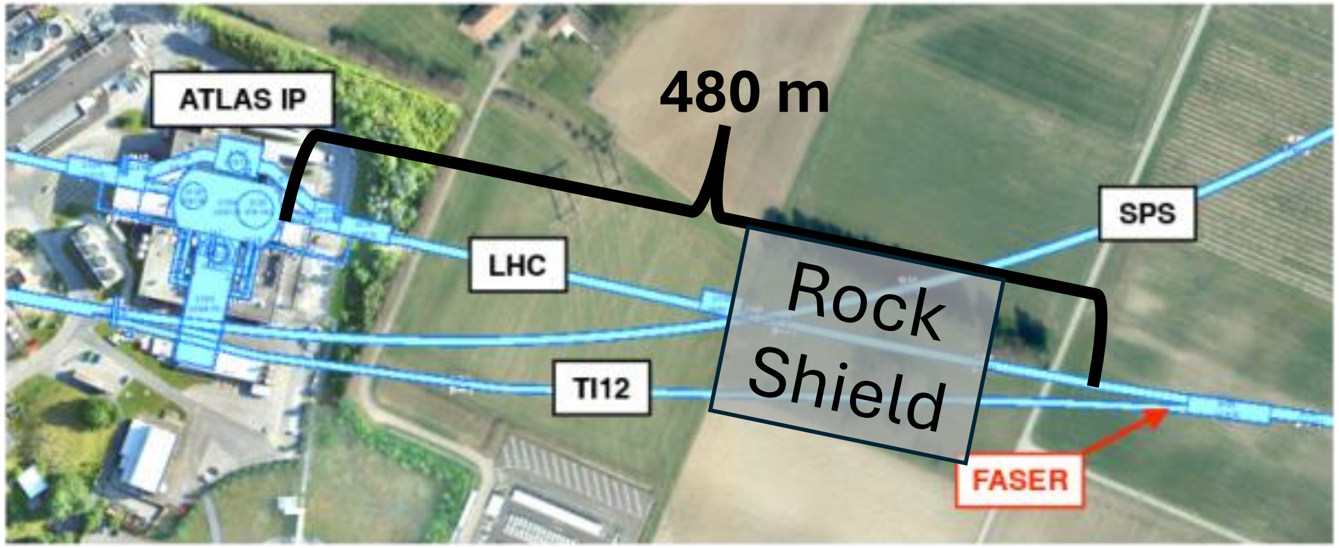
Multimessenger *Collider Physics*

What should we expect to see in the forward direction?

Intensity and Energy, why not both?

- Proton collisions are dominated by low p_T, soft events
- At large psudorapidity, an intense zoo of TeV particles
  - Hadrons $\rightarrow \nu, \mu, \mathrm{BSM}$
- Large energies and huge flux allow for unique opportunities within and beyond the SM





Guaranteed Discoveries

SM

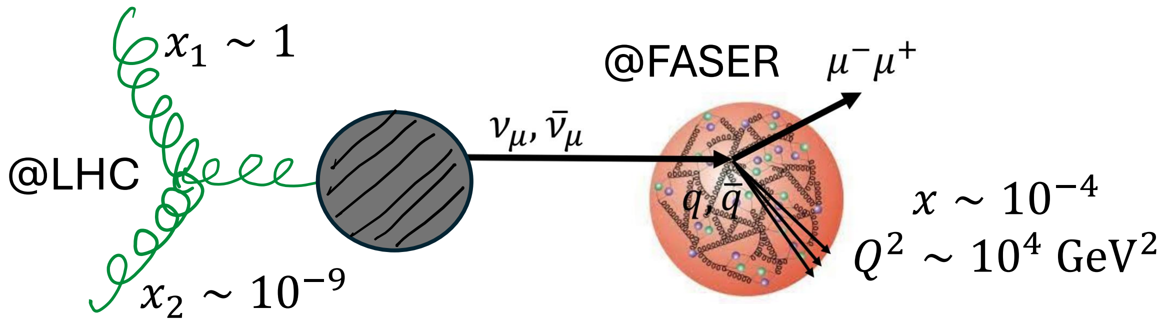
Neutrinos are a signal and a tool

- TeV neutrino xsec previously unmeasured
- Trace the forward hadron flux, relevant for astroparticle

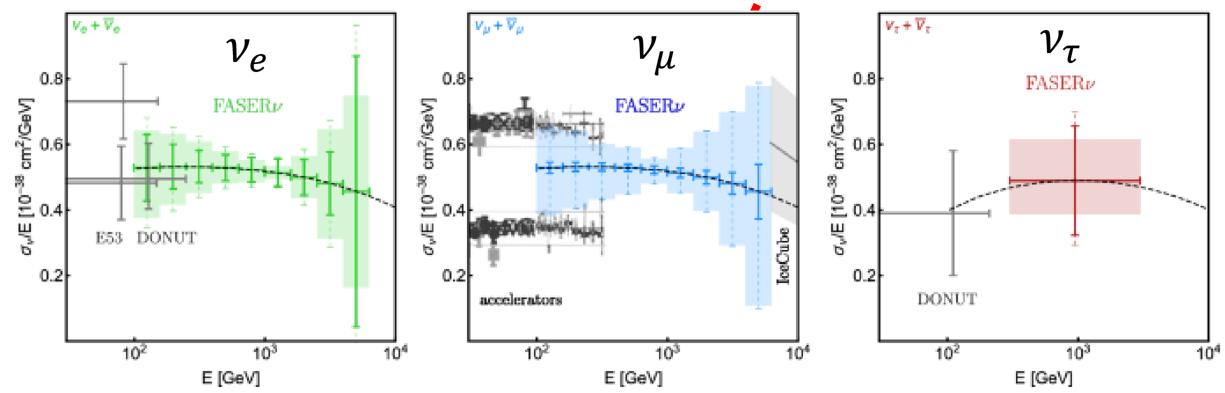
$$\sqrt{s}_{\text{Lab}} = \sqrt{s}_{\text{Fixed Target}} = \sqrt{2m_p \times E_{\text{beam}}}$$

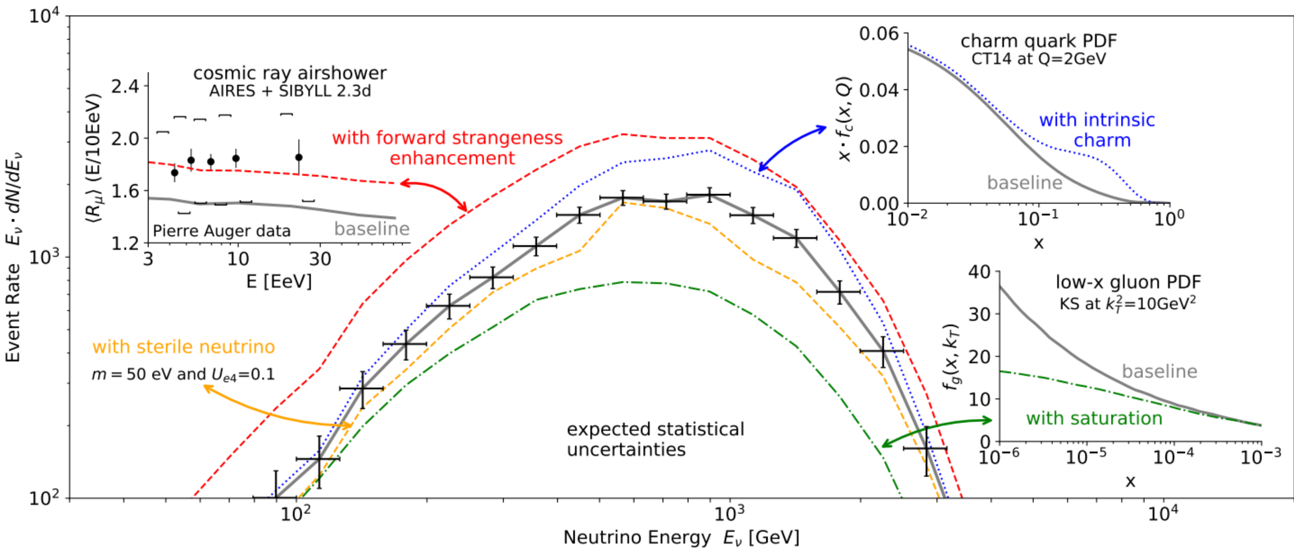
$$\sqrt{s}_{\text{Lab}} = 14\ \text{TeV} \Rightarrow E_{\text{beam}} = 100\ \text{PeV}$$

Test QCD under extreme conditions



Gap between astro and collider xsec measurements





Input to EPPSU 2503.19775

Possible Discoveries

BSM

Intense hadron beam (e.g. $\sim 10^{11}\ \pi^0/\mathrm{fb}^{-1}$) provides an efficient means of BSM production through decay, even for small couplings

$$\frac{N_{A'}}{\mathrm{fb}^{-1}} \approx 10^5 \left(\frac{\epsilon}{10^{-3}}\right)^2$$

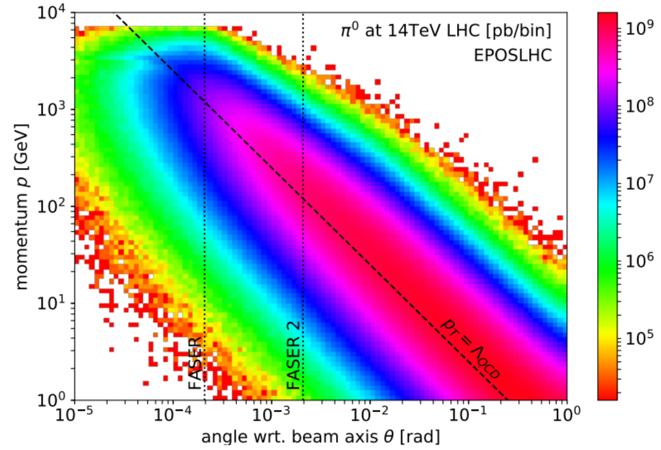
Very weakly coupled GeV-scale motivated by freezeout

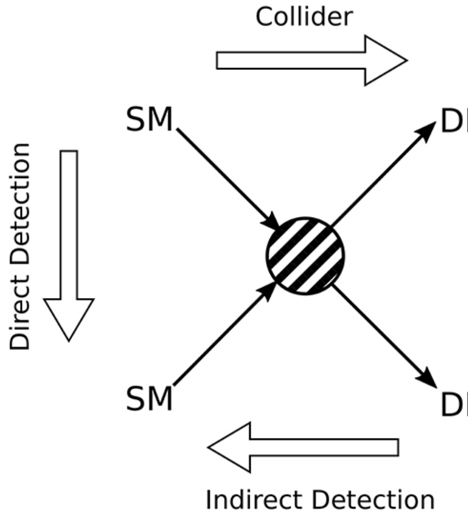
$$\langle \sigma v \rangle \approx \left(\frac{\alpha_{\mathrm{weak}}}{\mathrm{TeV}}\right)^2 \sim \left(\frac{10^{-5}}{\mathrm{GeV}}\right)^2$$

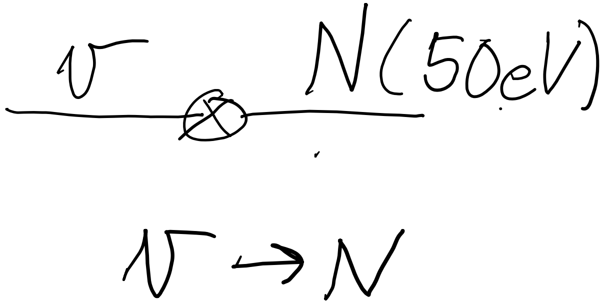
Neutrino BSM seaches

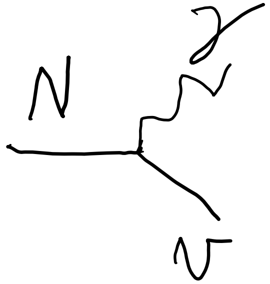
- $\mathcal{O}(100)\ \nu_\tau$ by Run 4, tests of LFUV
- 50 eV sterile neutrino oscillations
- Neutrino EM form factors, sterile dipoles $\bar{N}\sigma^{\mu\nu}\nu F_{\mu\nu}$
- Test NuTeV anomaly on $\sin(\theta_W)$

Many more models (some of which I will discuss today)



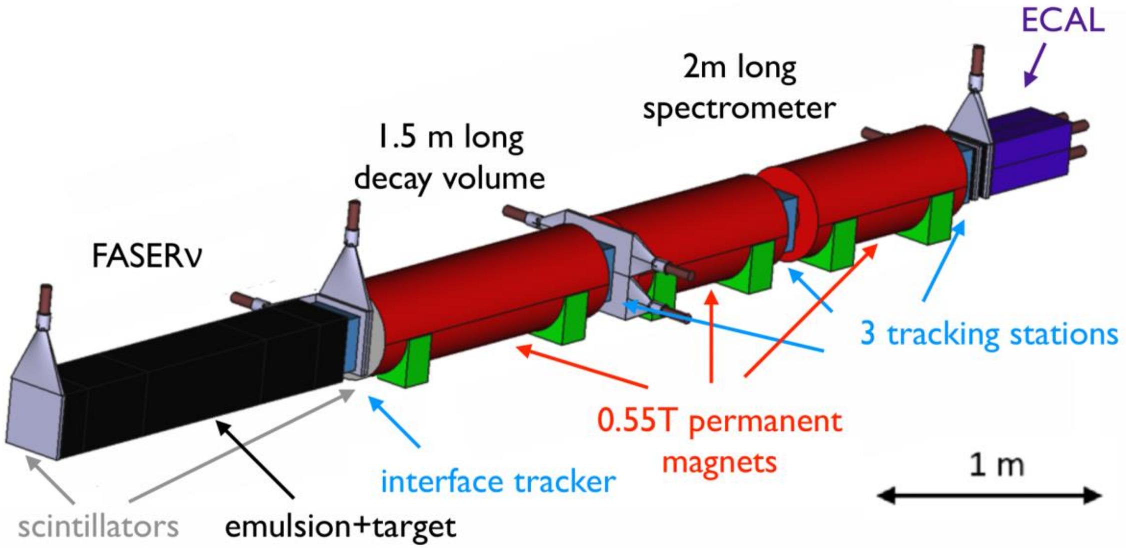




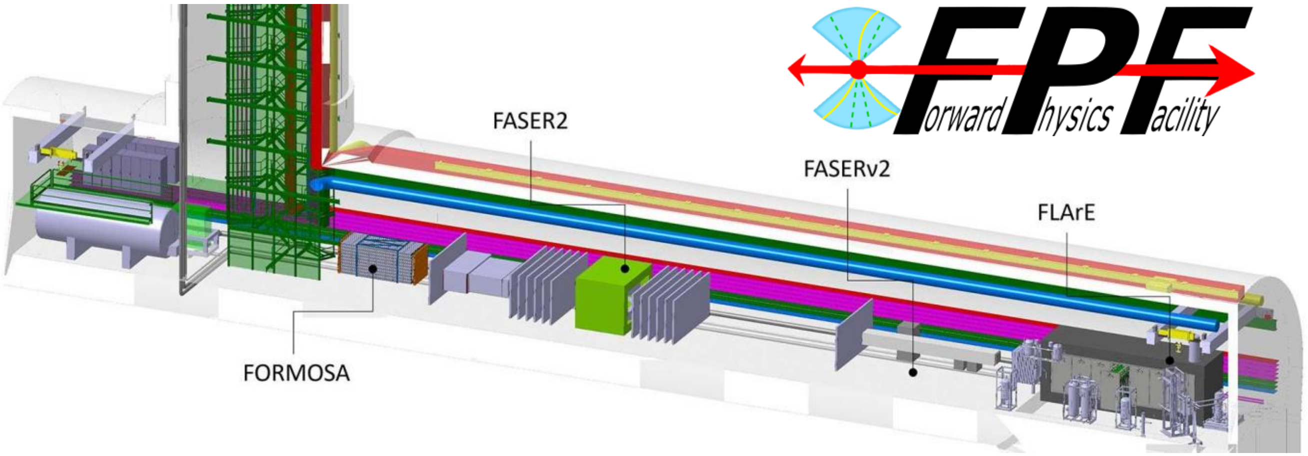


FASER Experiment

- Installed long the atlas collision axis
  - Includes FASERν emulsion experiment, decay volume, tracking system with spectrometer and calorimeter
- Upcoming Run 4 upgrades



- Proposed Forward Physics Facility includes FASER upgrades + other experiments

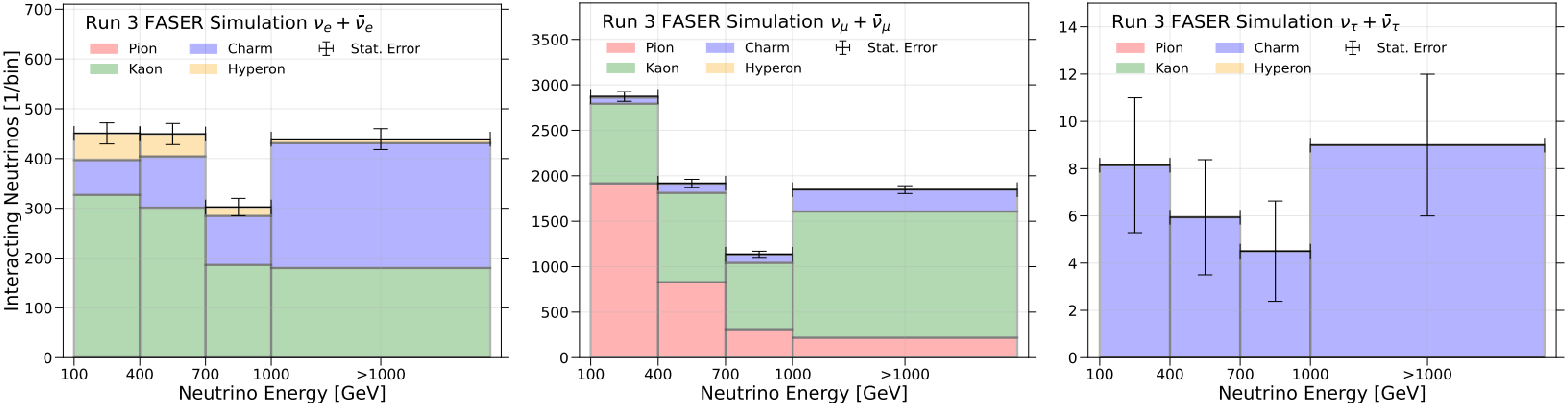


What can we do within the SM in the forward direction?

Forward hadron fluxes are messy and important

Use Neutrino fluxes at LHC to reconstruct forward hadron flux!

Simulation:

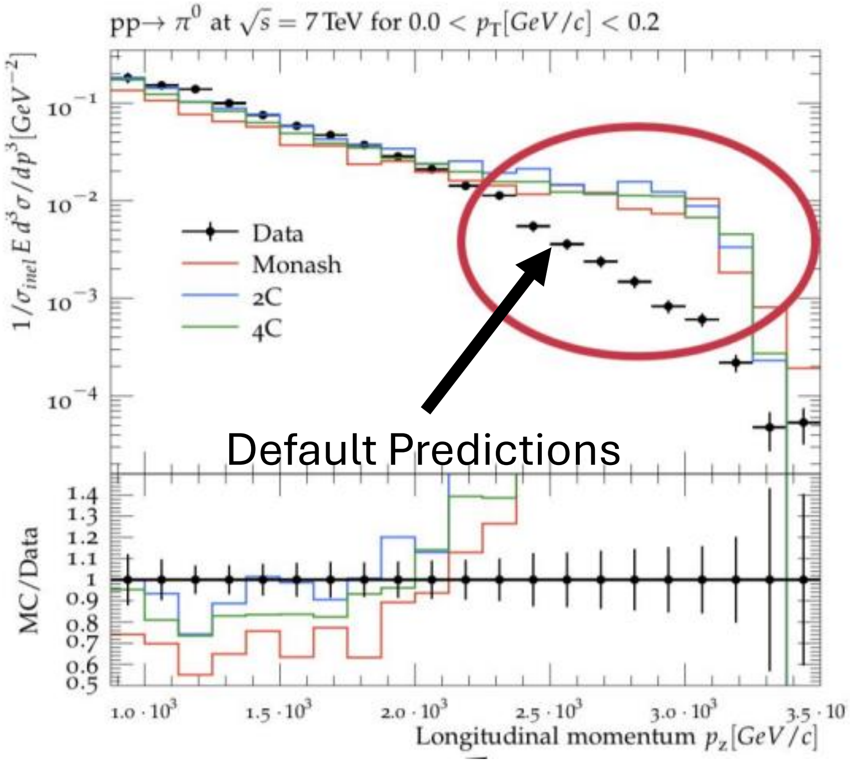


FASER (2402.13318)

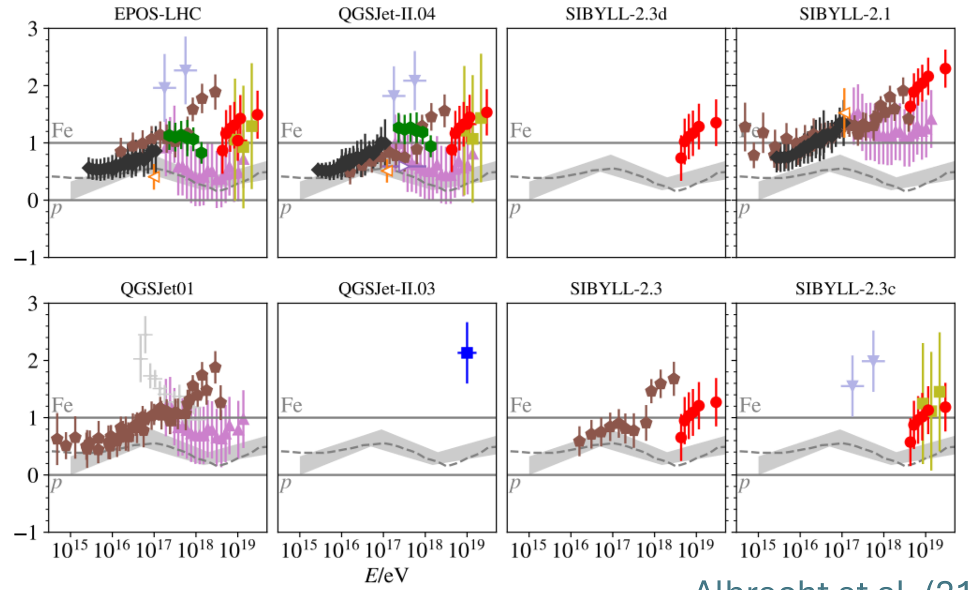
Forward hadron fluxes are messy and important!

The current forward data is not well-described by event generators

LHCf pion spectrum

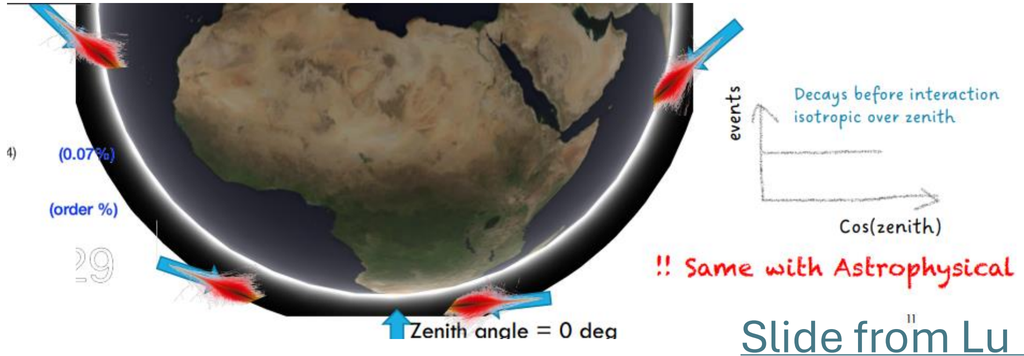


The "muon puzzle": too many CR produced muons for $E_\mu > 10$ PeV



Albrecht et al. (2105.06148)

Propmt neutrino background ($D \rightarrow \nu$) for extragalactic neutrino observations



Slide from Lu Lu

See Pedro, Vedran, Matheus and Bhupal talks from this morning

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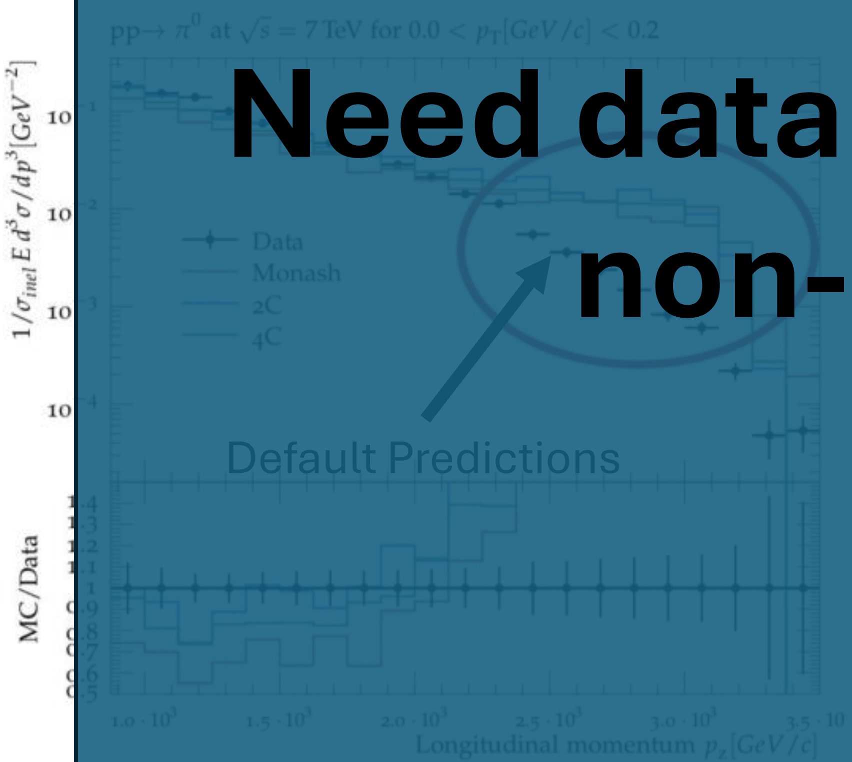
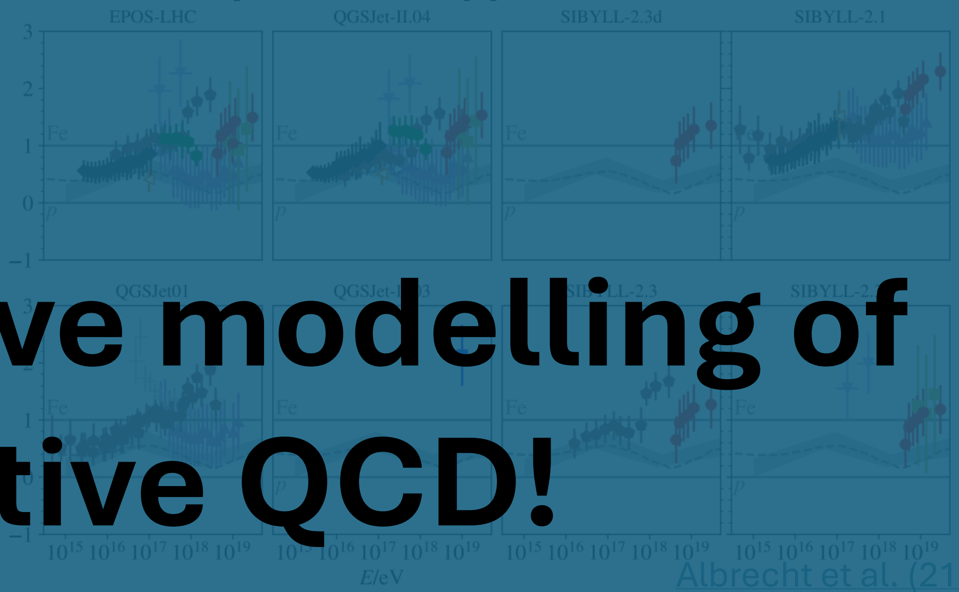
The current forward data is not well-described by event generators

LHCf pion spectrum



Default Predictions

The “muon puzzle”: too many CR produced muons for



Albrecht et al. (2105.06148)

Need data to improve modelling of non-perturbative QCD!

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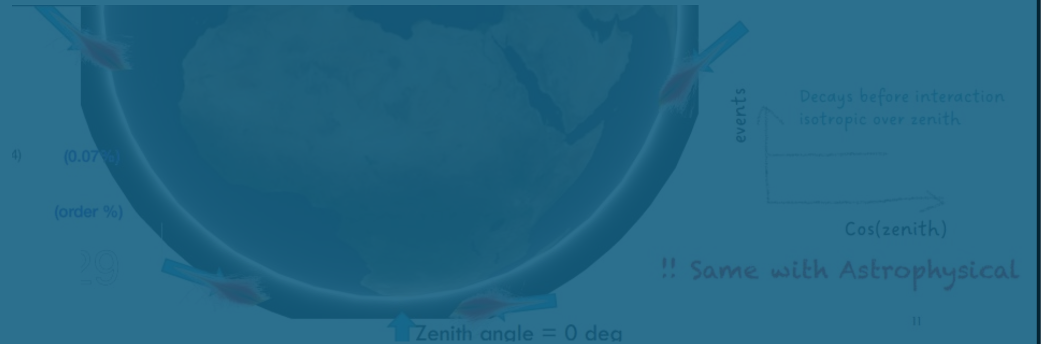
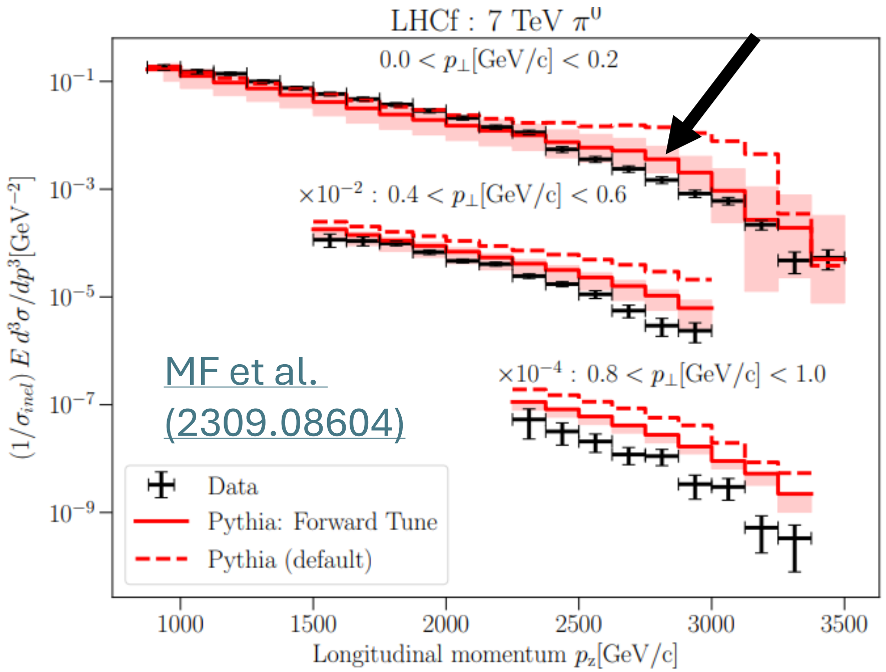


Slide from Lu Lu

Along with LHCf, FASER provides crucial data to reduce flux uncertainties!

LHCf

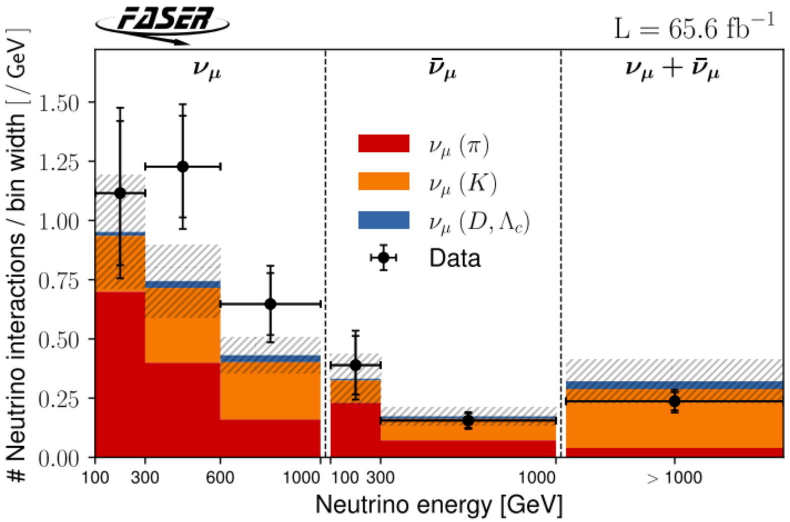
After tuning to LHCf



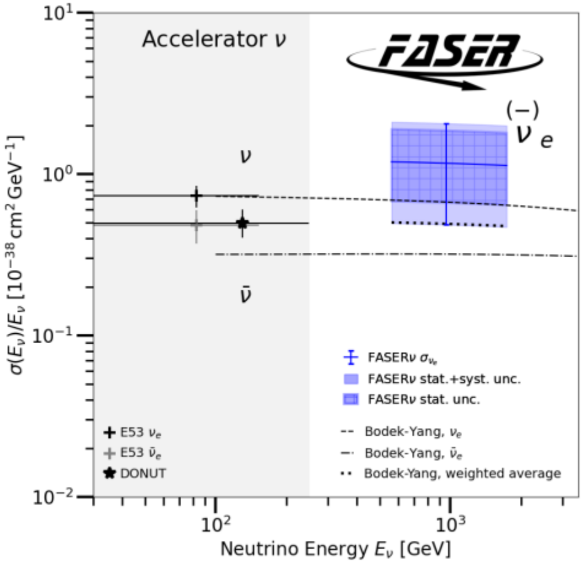
MF et al. (2309.08604)

LHCf measures neutral particle spectra (π^0, n, γ)

FASER(ν)



FASER (2412.03186)

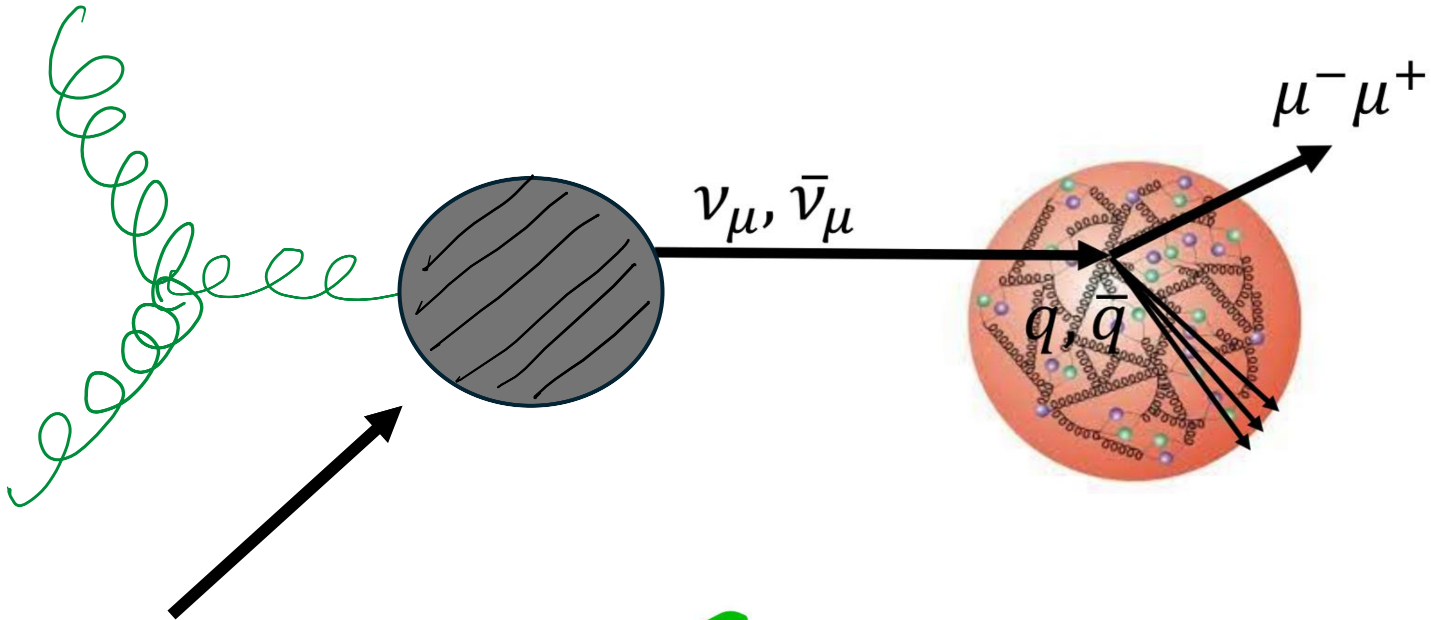


FASER (2403.12520)

FASER(ν) reconstructs the $\pi^\pm, K^\pm$, D spectra

Charm production most important for neutrino telescopes, Run 4 proposal to improve these measurements, "*FORTVNE*"

Non-perturbative QCD on both sides



Hadron production

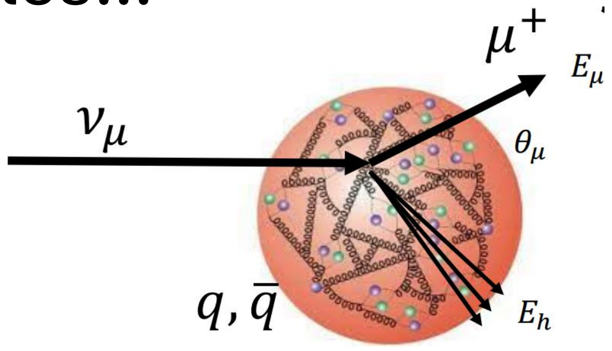
TeV DIS laboratory

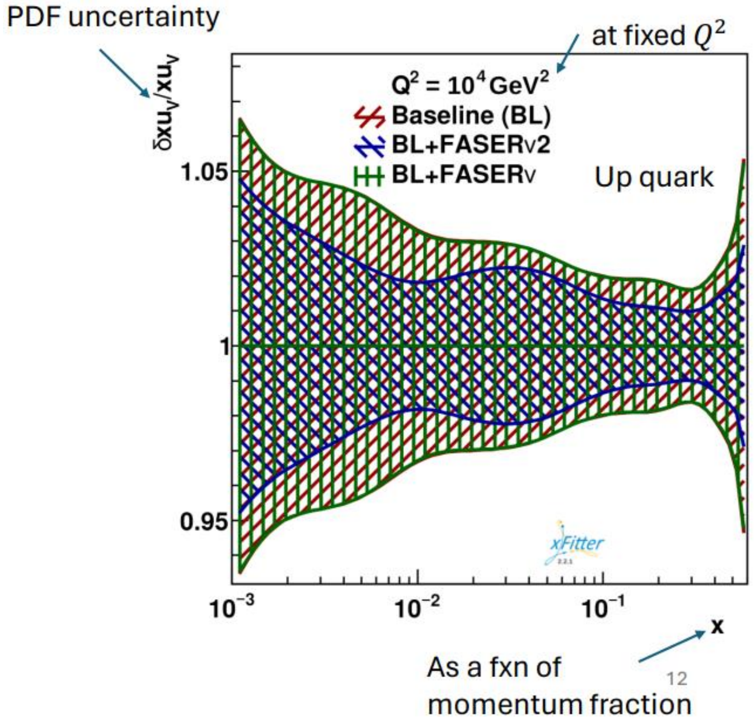
ν =signal

ν = tool

Use neutrinos to crack open the inside of the proton

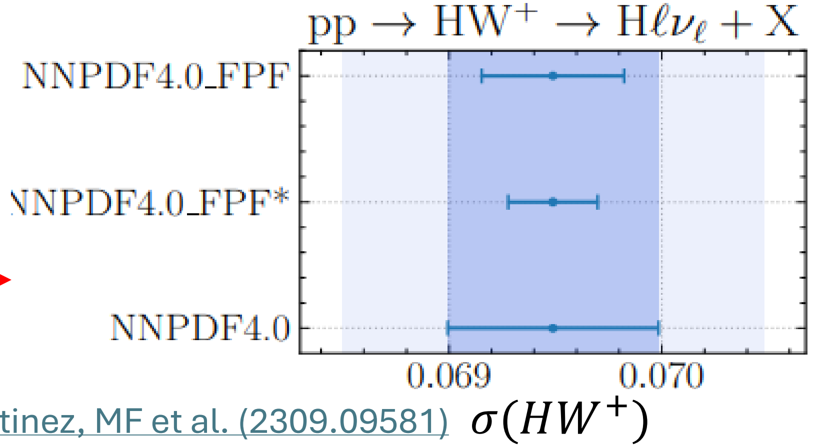
By carefully reconstructing DIS variables...





we can fit the underlying PDF!

Reduce theory uncertainties for Drell-Yan production of, e.g. heavy bosons at the LHC!



Cruz-Martinez, MF et al. (2309.09581)

Let’s look at some of the recent BSM searches, and some ideas

Courtesy of Roshan Mammen Abraham

Dark photon, and dark photon-like models

Kinetically mixed dark photon, $\epsilon F'_{\mu\nu} F^{\mu\nu}$

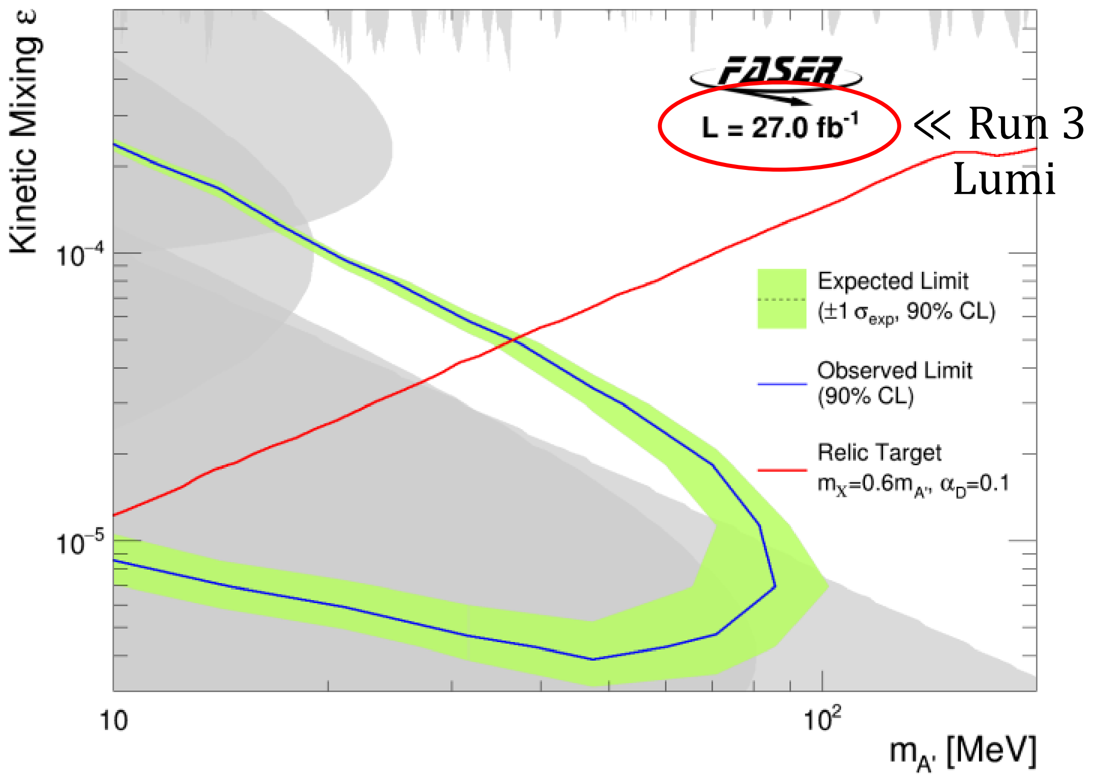
- Visible decays to e^+e^-
- In upcoming analyses, will probe larger A' masses and FASER will be sensitive to other final states, $\mu^+\mu^-, \pi^+\pi^-$

Also searched for Gauged $\mathrm{U(1)_{B-L}}$

- Motivated by conserved quantum numbers, similar final states as vanilla A'

Other vector models

- $B - 3L_i$, $L_i - L_j$
- DM from $A' \to \chi\chi$ can be probed directly through scattering in FASERν and calorimeter



Let's look at a model of inelastic DM

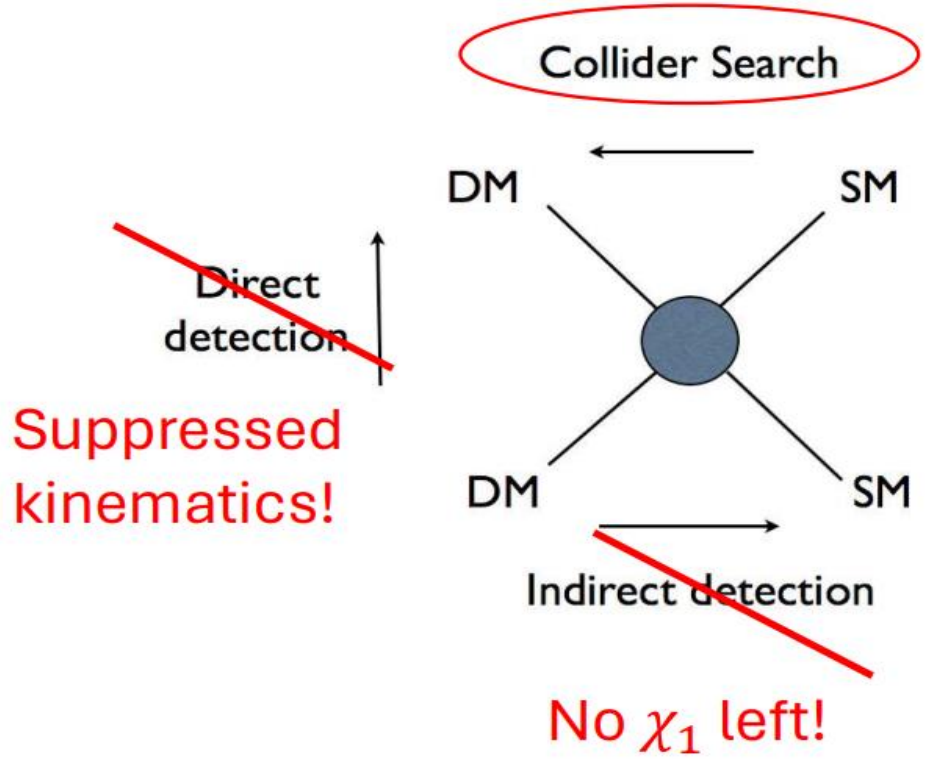
Inelastic Dark Matter

- General class of models where DM only interacts with SM via an off-diagonal interaction with an excited state

- iDM well-motivated for collider searches due to suppressed I.D., D.D.

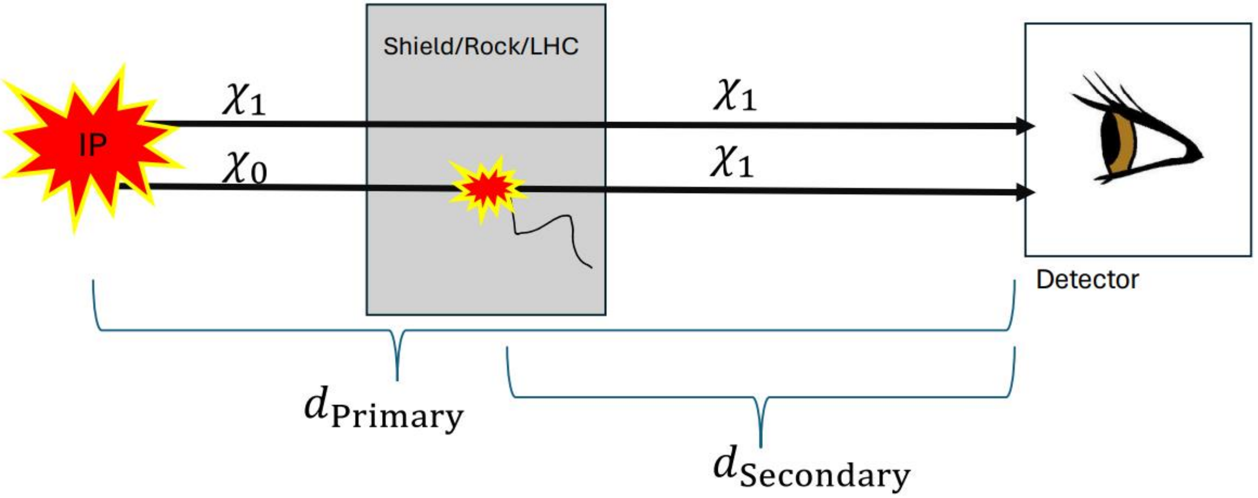
- Secondary production for FASER from shield/target, probe smaller lifetimes Kling Trojanowski (1911.11346)

Let's look at a particular realization iDM that we studied to see one of FASER's unique capabilities



*Exceptions, see e.g. upscattered DM (Menon et al. 2009, Krnjaic,McDermott 2019, Bell et. Al 2021)

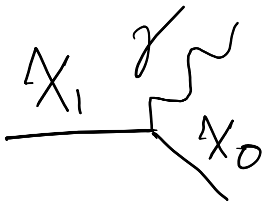
See Christopher's, Bhupal's talks on iDM



Dipole Inelastic Dark Matter

- Magnetic (electric) Dipole iDM: simple model with 3 parameters, m_0, m_1, Λ

$$\mathcal{L} \supset 1/\Lambda_{M(E)} \overline{\chi_1} \sigma^{\mu\nu} (\gamma^5) \chi_0 F_{\mu\nu}$$



Two ways to get an LLP for $\chi_1 \to \chi_0 \gamma$

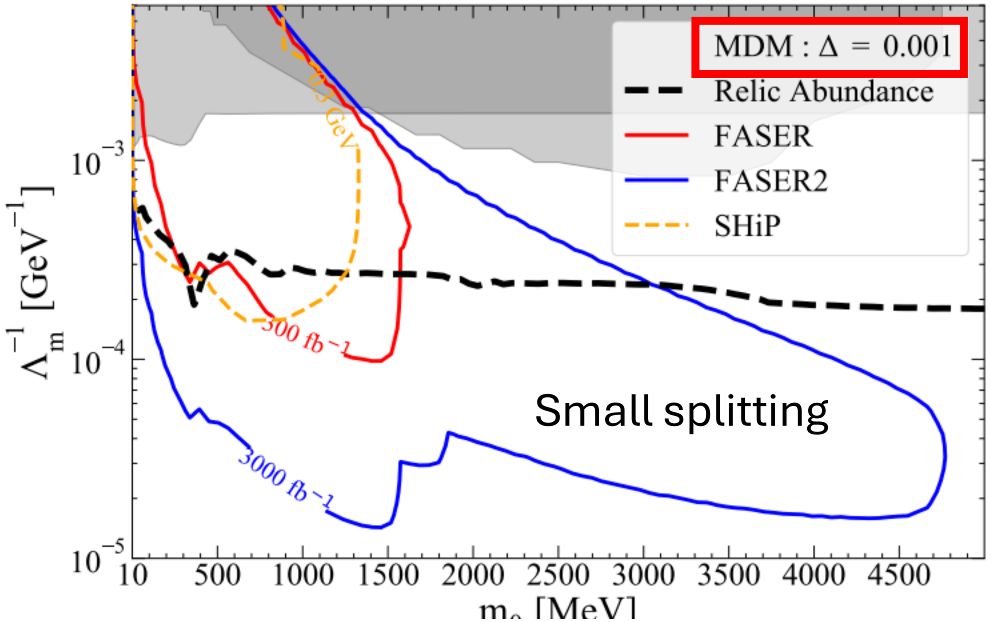
1. Small couplings (tried and true)
2. Small mass splitting, $\Delta = \frac{m_1 - m_0}{m_0}$

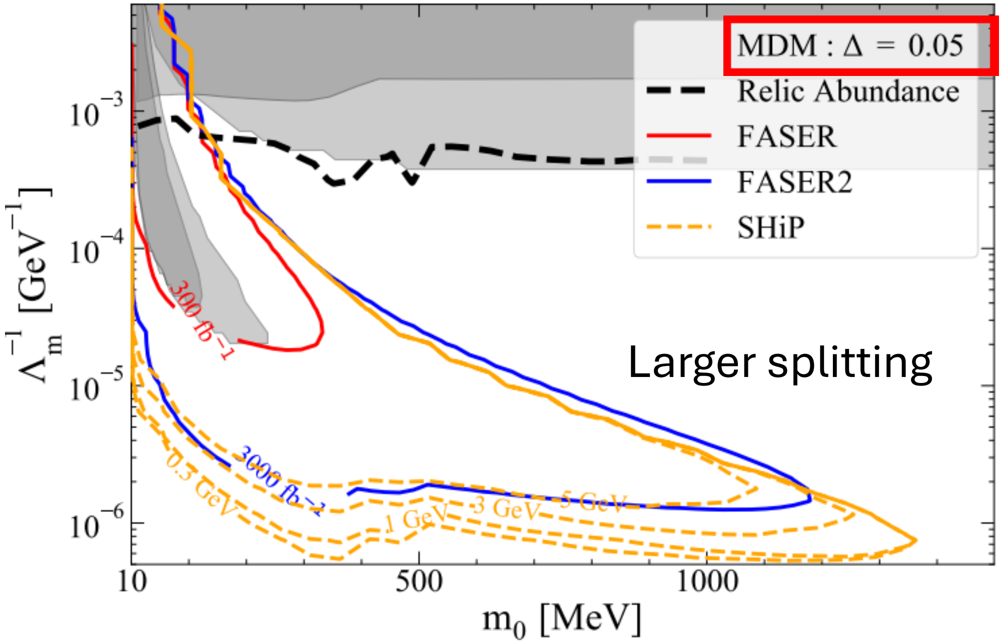
For second option, very small photon energy E_γ, except for huge boosts

$$E_\gamma \approx \Delta\, \mathrm{E}_\gamma = \mathrm{GeV} \left(\frac{\Delta}{10^{-3}}\right) \left(\frac{E_{\chi_1}}{\mathrm{TeV}}\right)$$

Falls below threshold at most high intensity experiments, unless is large

Complementarity with SHiP's more intense but less beam





What about new scalars?

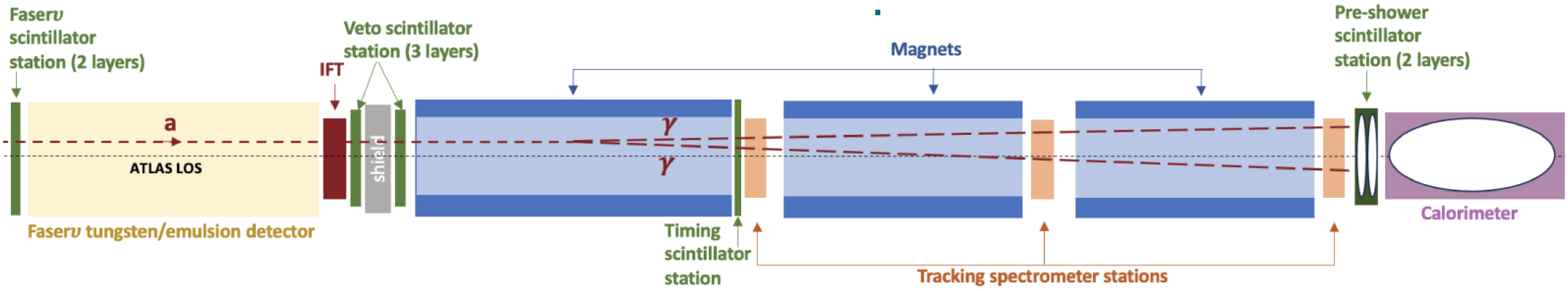
Faser search for ALPs of all shapes and sizes

First trackless FASER search, 2γ only.
Searched for a number of ALP models

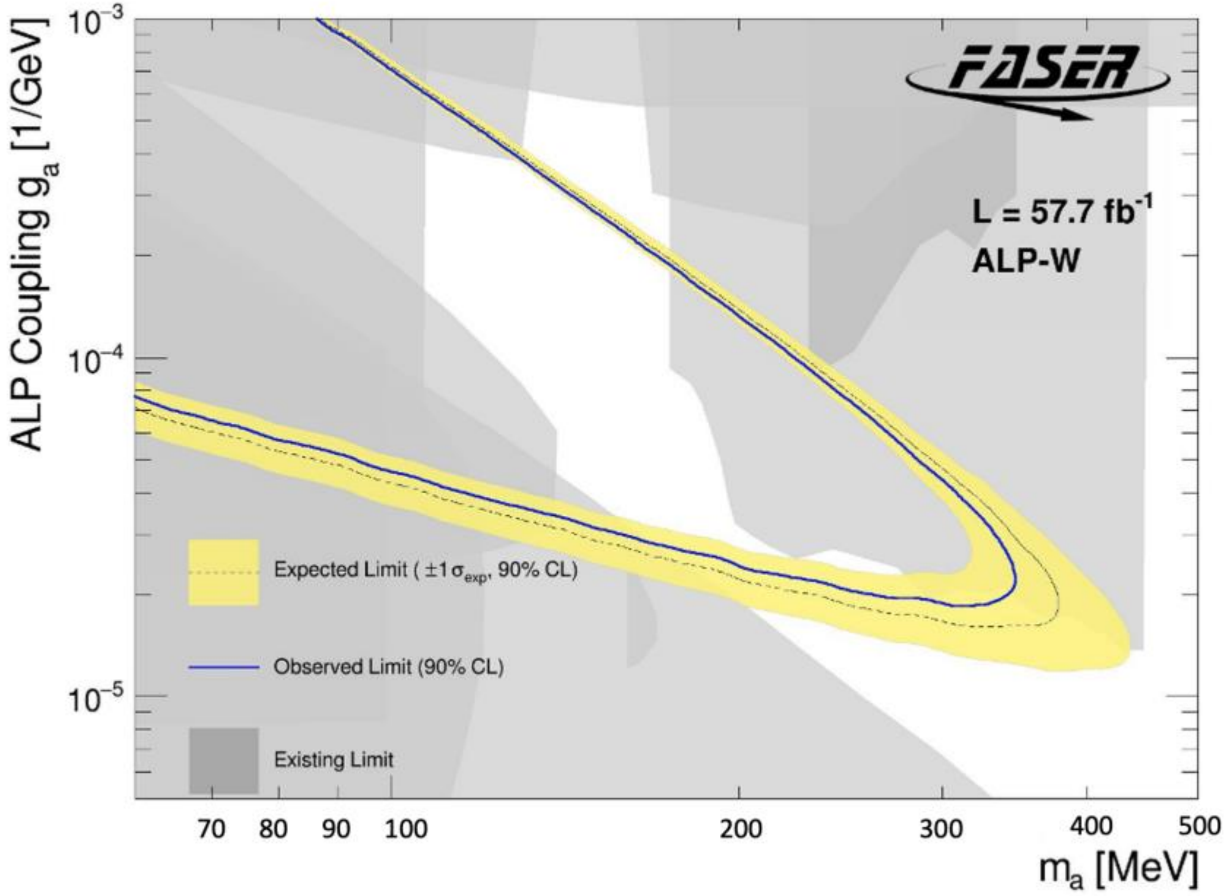
- ALP-gluon ($\frac{a}{f_a} G\tilde{G}$) motivated by strong CP
- ALP-W, best FASER sensitivity ☺
- ALP-γ

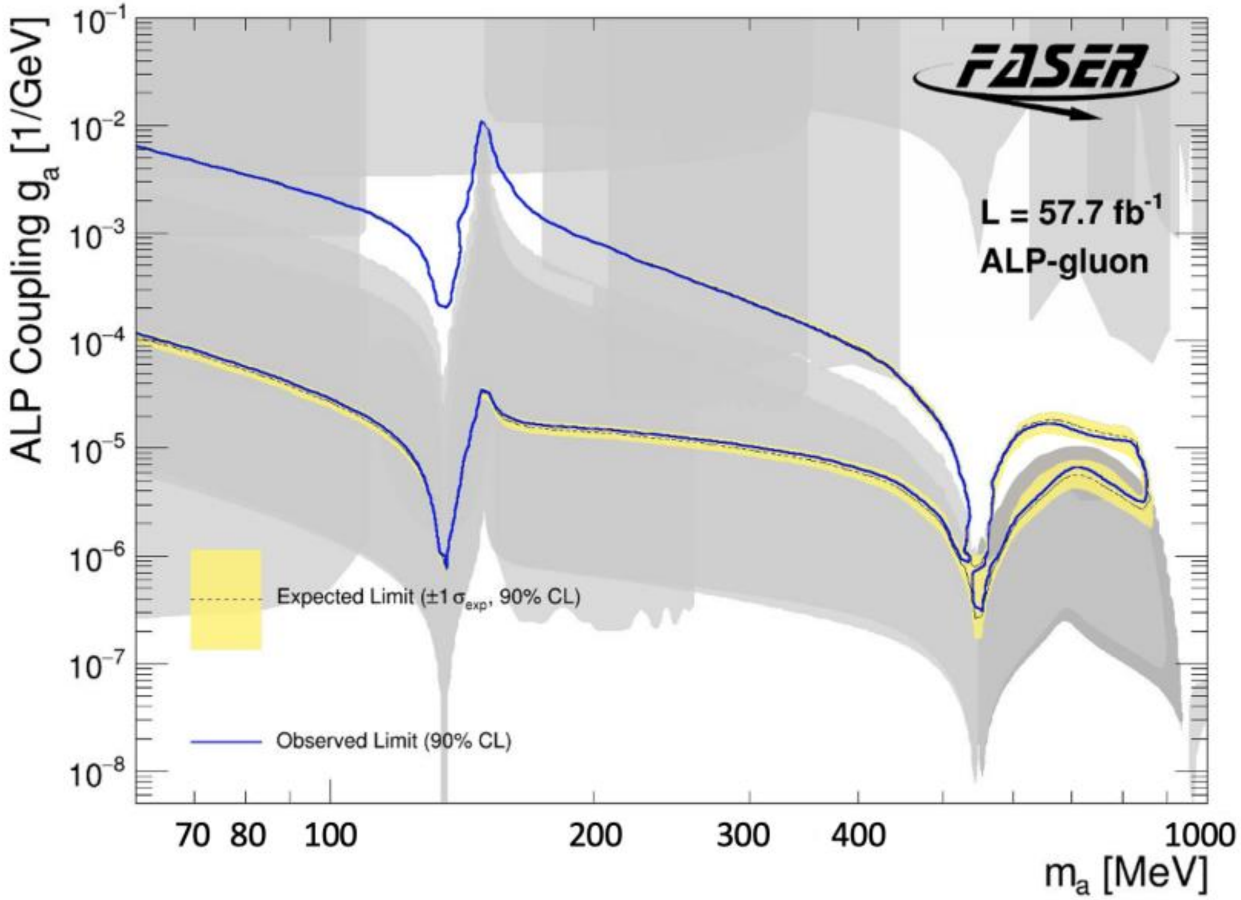
Also searched for:

- Up-philic scalars avoid flavor constraints (e.g. B decays)
- Fermiophobic 2HDM
- $\mathrm{U}(1)_{\mathrm{B}}$ *vector*, decays to $\pi^0 \to 2\gamma$ for sufficient masses



Some of the results





What else can we look for with photon signatures?

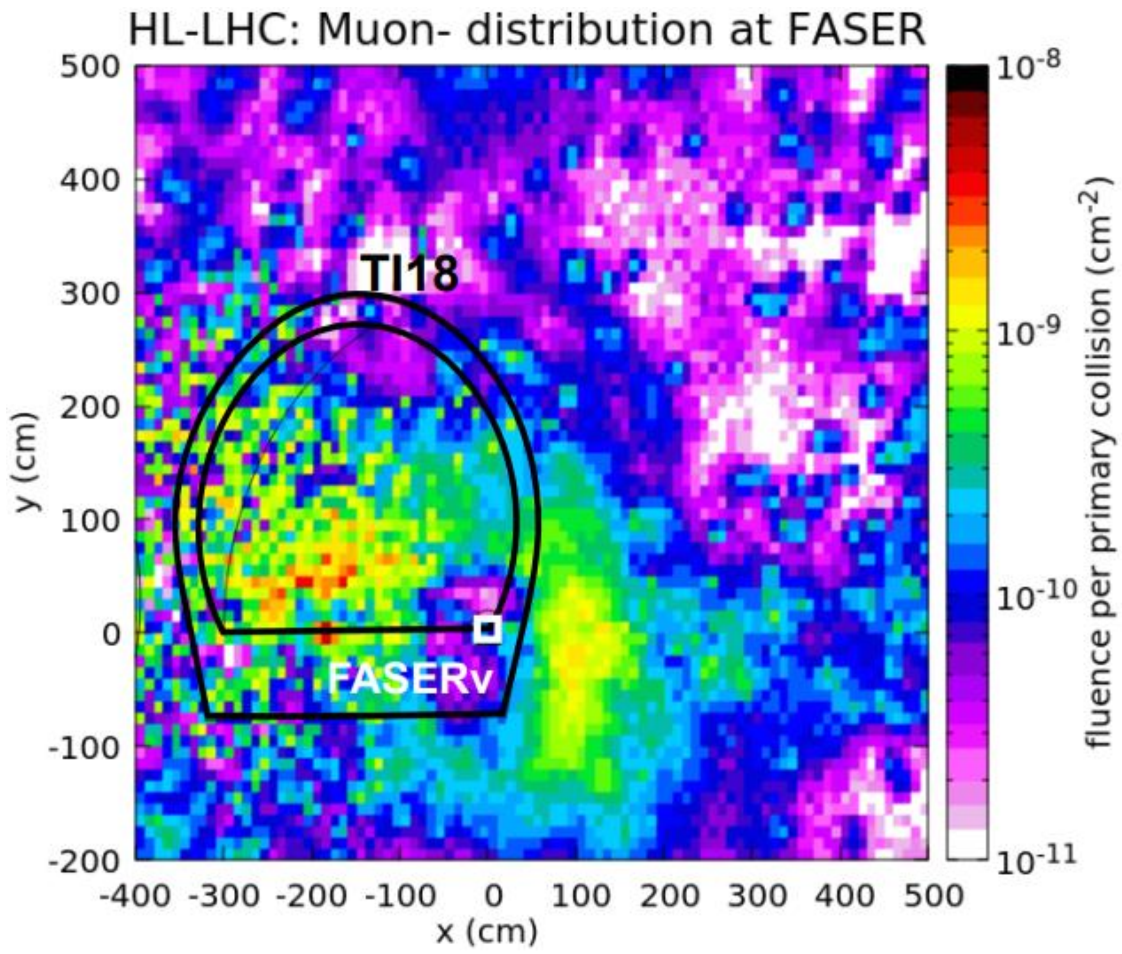
Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER

The LHC as a TeV Muon Beam Dump

The intense TeV muon beam is currently treated as background

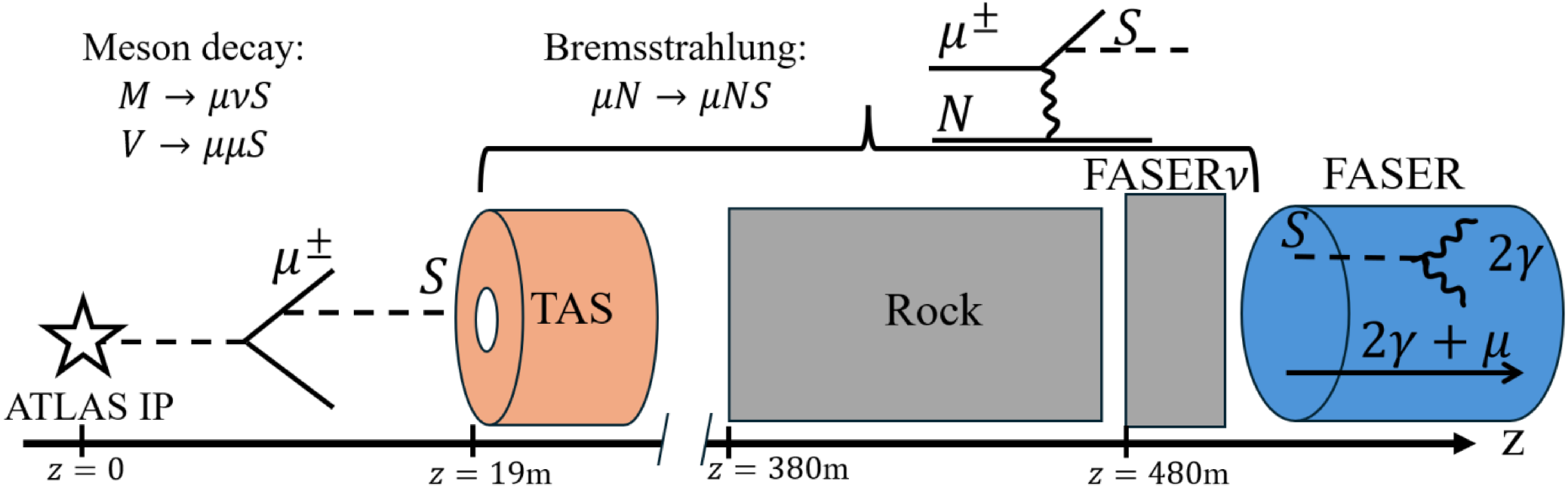
But one physicist's trash can be another's treasure

- Could there be BSM hiding in the discarded muon events?
- Could the muon beam be used as a BSM production mechanism?
- Connections to $(g-2)_\mu$?



Muonphilic Scalar Production

$$\mathcal{L} \sim g_s S \bar{\mu}\mu + m_S^2 S^2$$



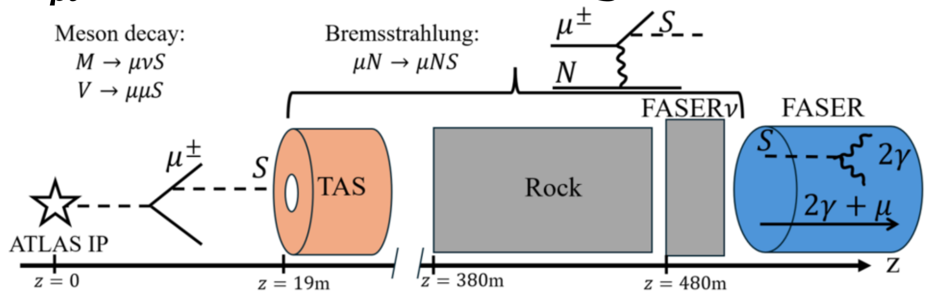
Muonphilic Scalars at FASER

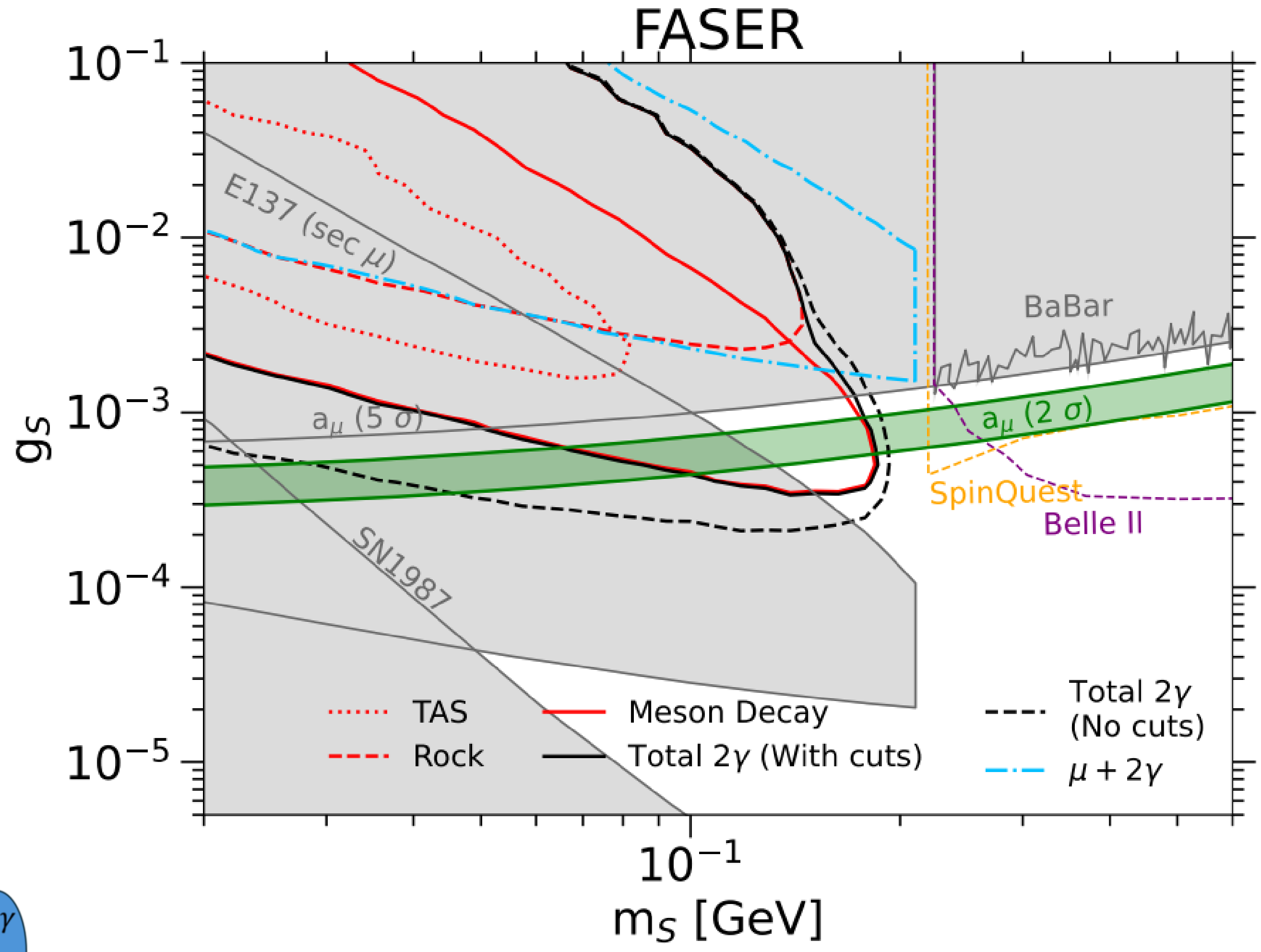
FASER sensitive to muonphlic scalars

- Including those that can explain $(g-2)_\mu$

Novel $2\gamma + \mu$ (teal) probes shorter lifetimes

FASER 2 can completely cover $(g-2)_\mu$ couplings for $m_S < 2m_\mu$





Abraham, MF (2501.09071)

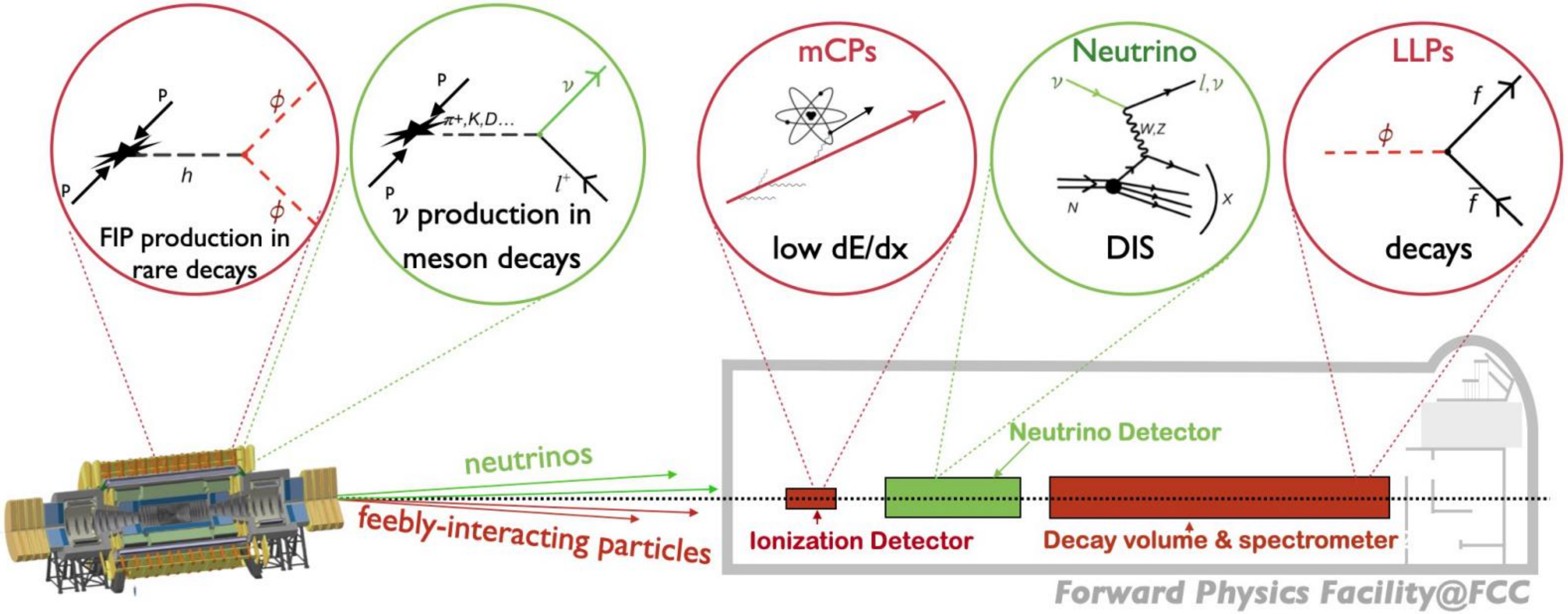
Still more to do at the LHC, but for now let’s look very far forward in time (2070s)

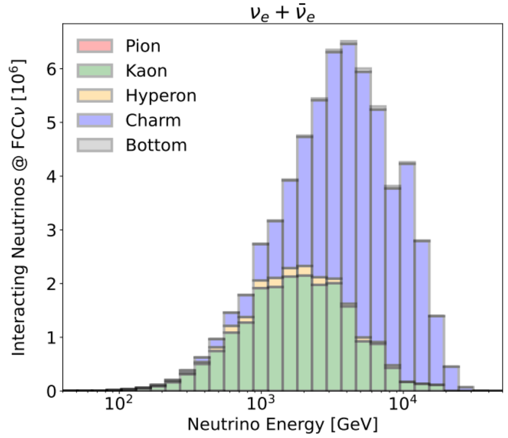
Discussions on the next collider: FCC, MuCol?


WE'VE PROPOSED ONE FPF, YES
BUT WHAT ABOUT A SECOND FPF?
imgflip.com

Forward Physics Facility at the 100 TeV FCC-pp

$\sim 10\text{M}\ \nu_e, 100\text{M}\ \nu_\mu, 1\text{M}\nu_\tau$





+ν from Pb-Pb collisions, polarized PDFs, 100 GeV dark Higgs 10 TeV-scale quirks...

Neutrinos at MuCol considered, see Zhen Liu's talk from this morning

Abraham, MF. et al. (2409.02163)

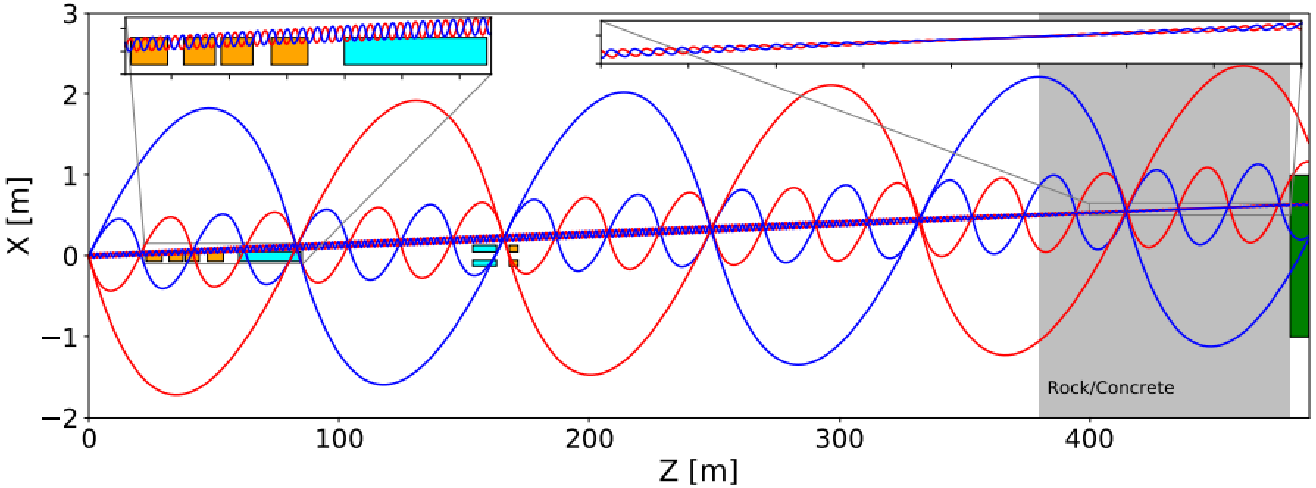
Quirks

Found in models of neutral naturalness, quirks have a flipped hierarchy from quarks, new non-abelian "infracolor" charge

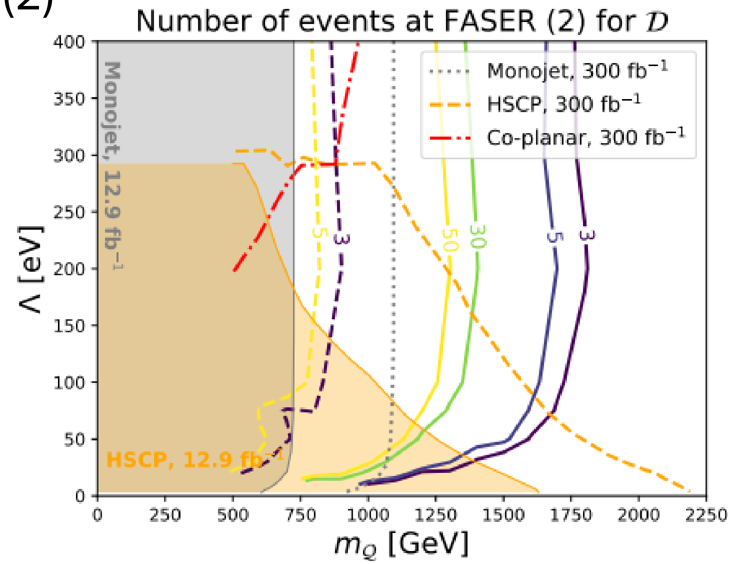
$$\Lambda_{\mathrm{IC}} \ll m_Q$$

Leads to macroscopic color string that cannot break. So when quirks are pair produced ($p_T = 0$) then prefer to go in the forward direction

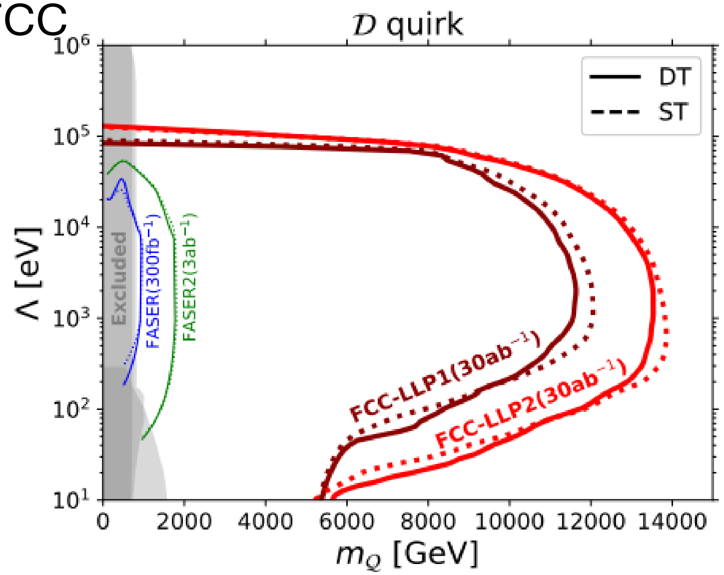
Sensitive to $\sim \mathrm{TeV}$ at FASER, 14 TeV for FPF@FCC



FASER(2)



FPF@FCC



Abraham, MF. et al. (2409.02163)

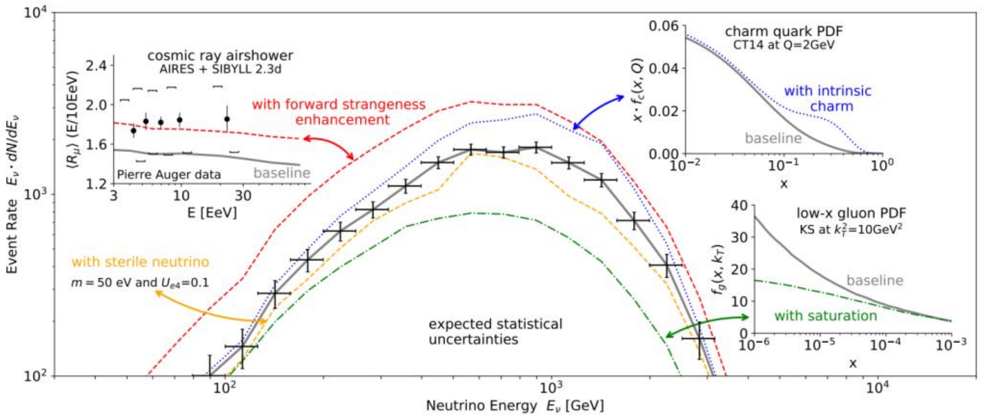
Li et al. (2108.06748)

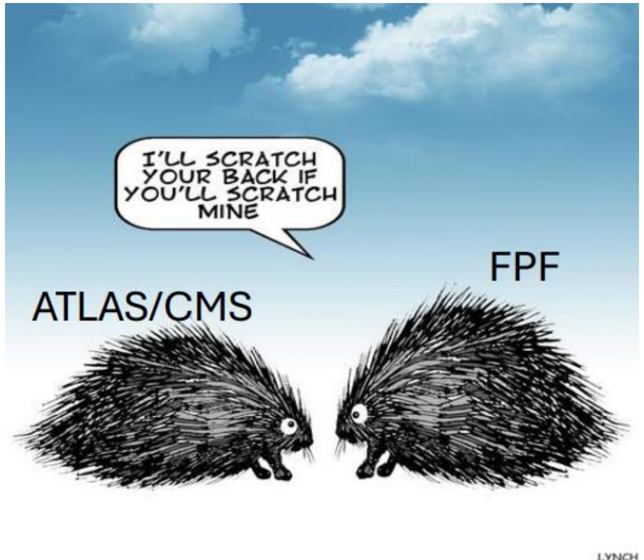
Summary

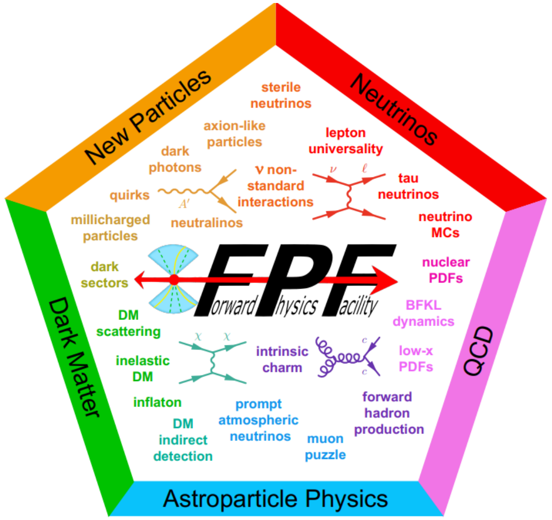
With TeV particles and large fluxes, the forward region is where the intensity frontier meets the energy frontier

FASER has directly observed neutrinos at the LHC, and searched for BSM. It has only just begun, Run 4 upgrades and FPF will greatly increase the forward program

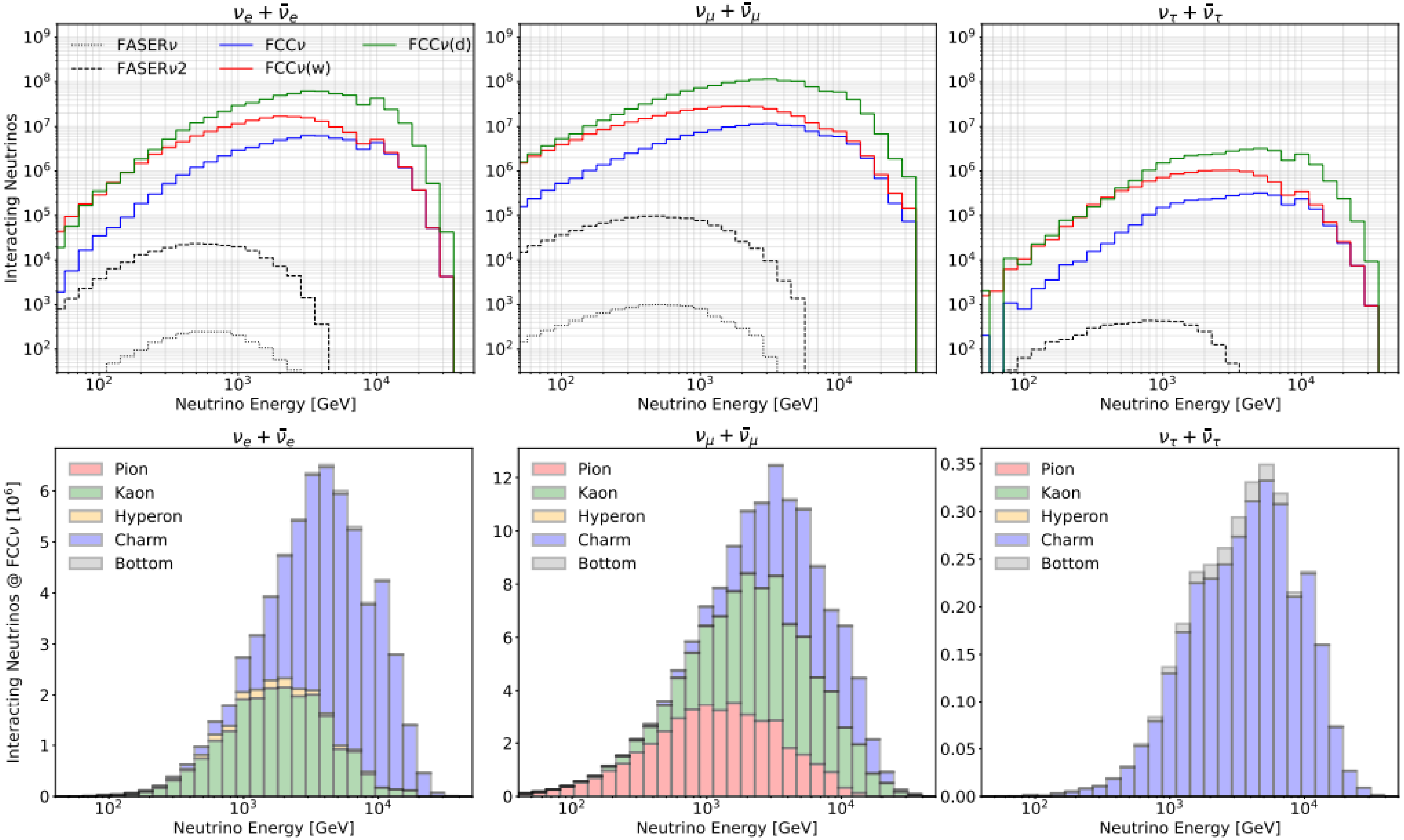
Measurements have wide reaching implications for physics, QCD, neutrino & CR telescopes, dark matter, and EW boson production at ATLAS/CMS



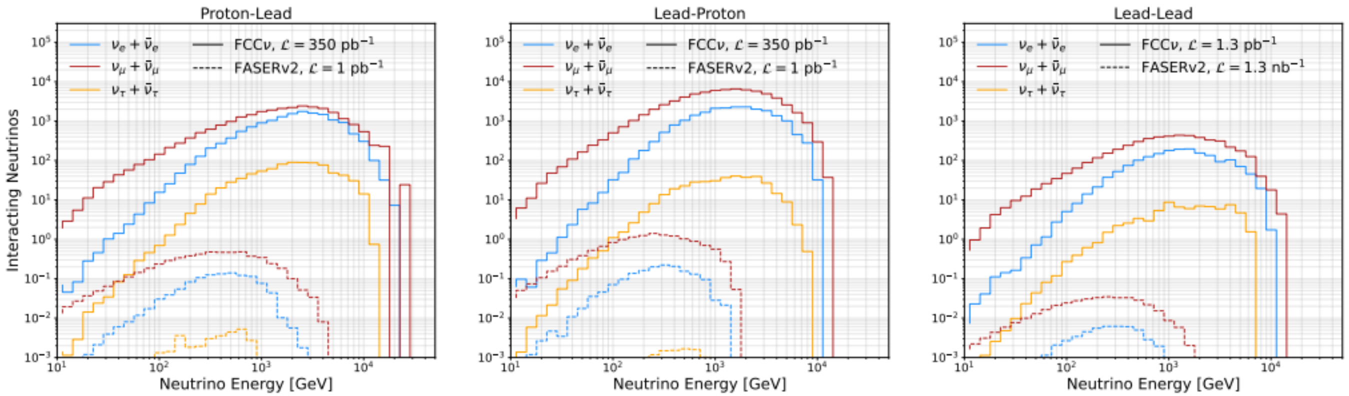




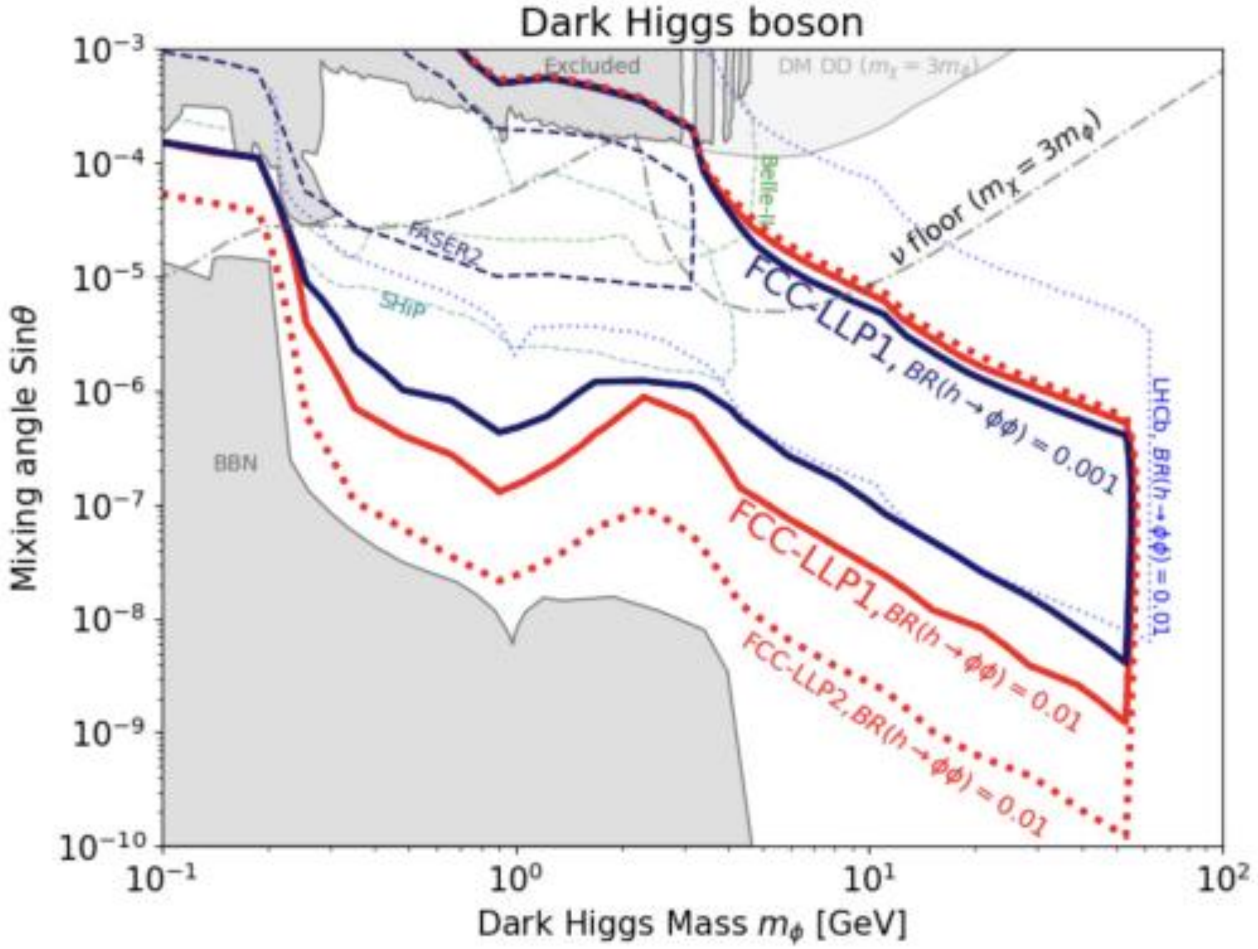
Back up



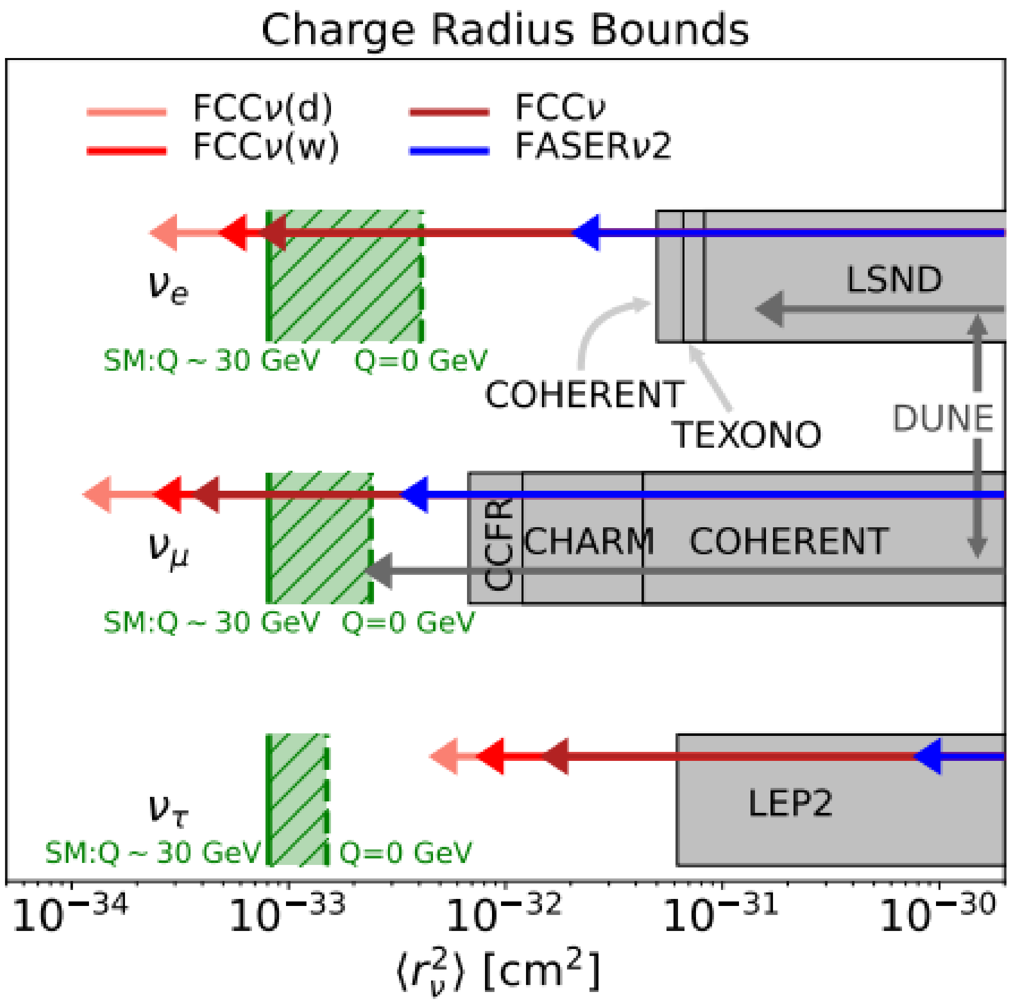
$\nu_e + \bar{\nu}_e$
$\nu_\mu + \bar{\nu}_\mu$
$\nu_\tau + \bar{\nu}_\tau$
FASERν
FASERν2
FCCν
FCCν(w)
FCCν(d)
Interacting Neutrinos
Neutrino Energy [GeV]
Pion
Kaon
Hyperon
Charm
Bottom
Interacting Neutrinos @ FCCν [10^6]



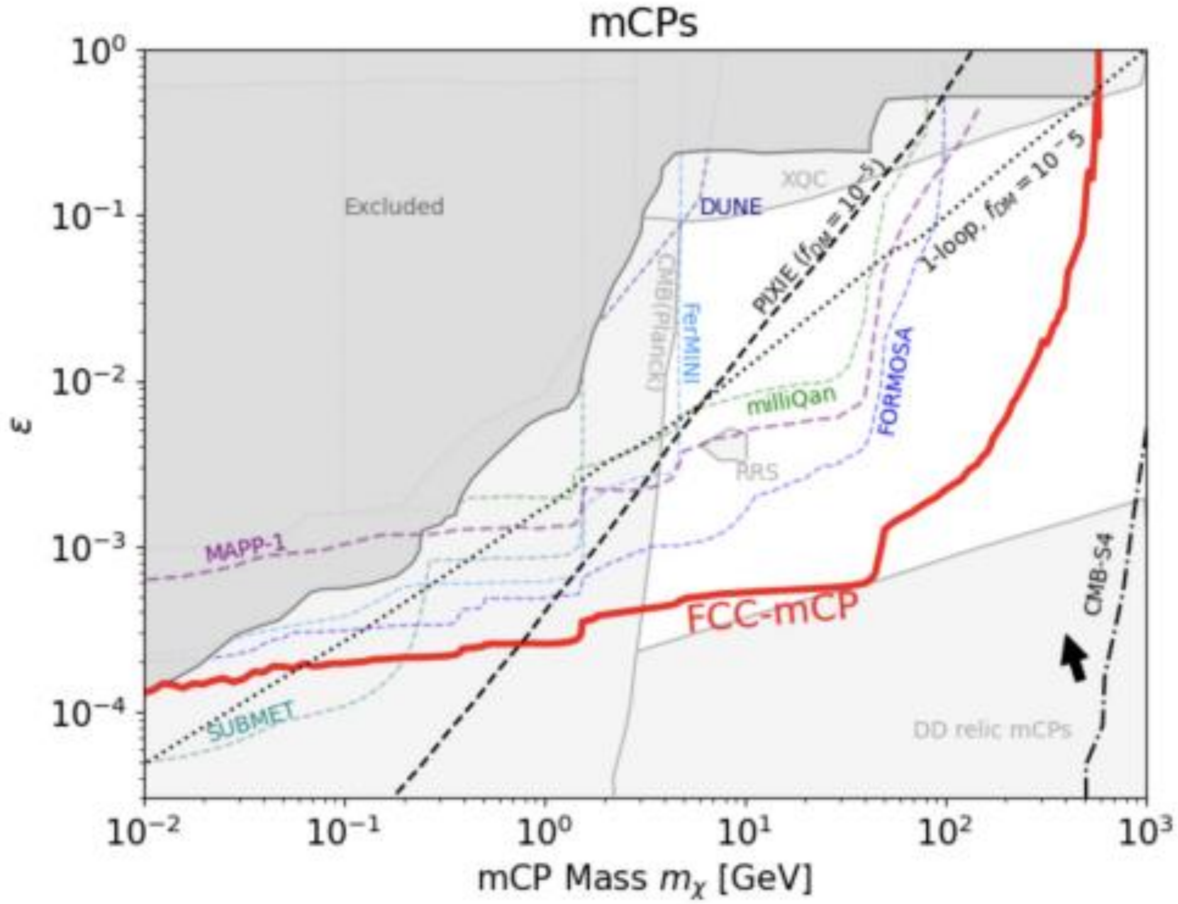
Proton-Lead
Lead-Proton
Lead-Lead
$\nu_e + \bar{\nu}_e$
$\nu_\mu + \bar{\nu}_\mu$
$\nu_\tau + \bar{\nu}_\tau$
FCCν, $\mathcal{L} = 350$ pb^{-1}
FASERv2, $\mathcal{L} = 1$ pb^{-1}
FCCν, $\mathcal{L} = 1.3$ pb^{-1}
FASERv2, $\mathcal{L} = 1.3$ nb^{-1}
Interacting Neutrinos
Neutrino Energy [GeV]

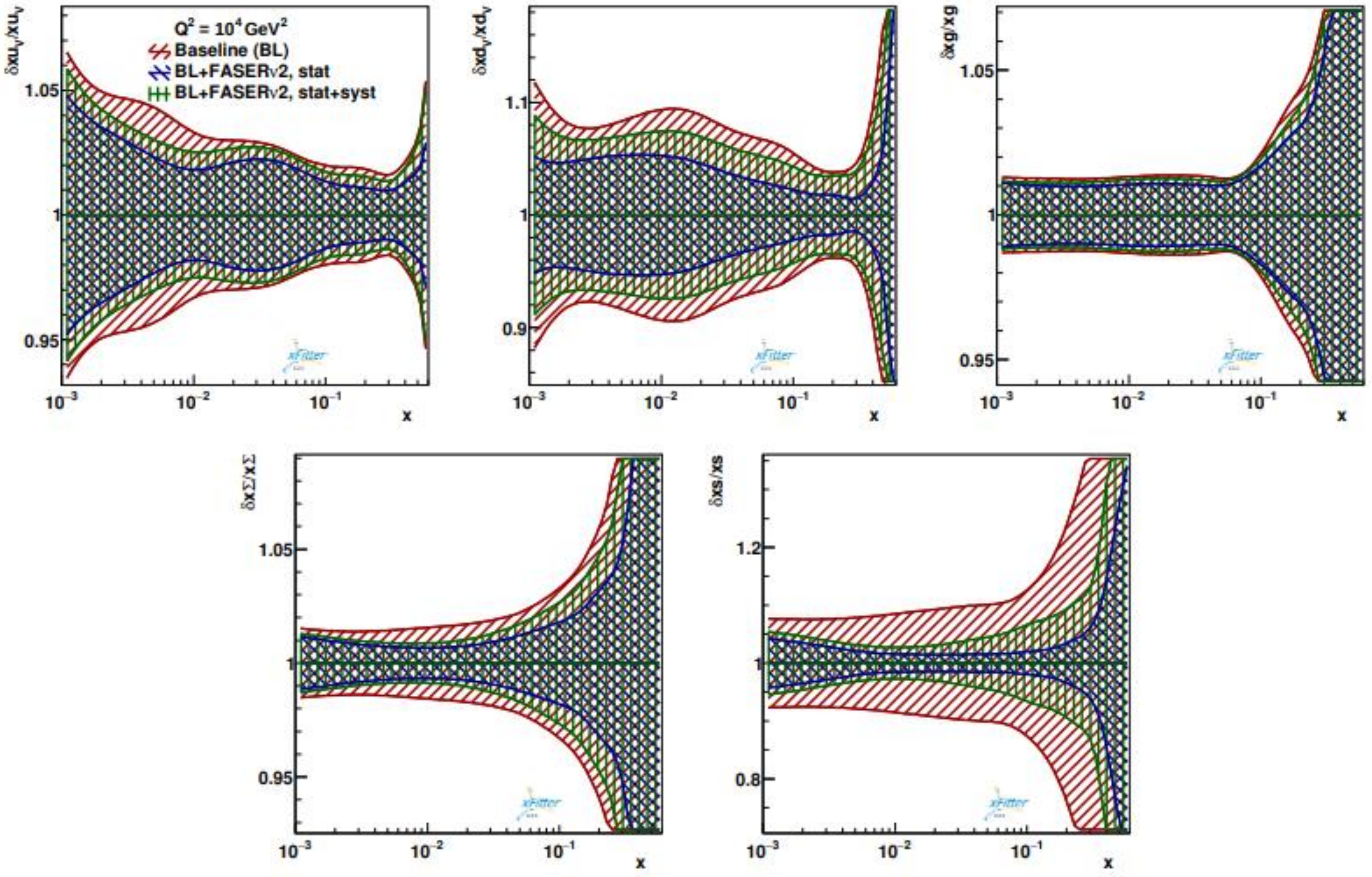


Dark Higgs boson
Excluded
DM DD ($m_\chi = 3m_\phi$)
ν floor ($m_\chi = 3m_\phi$)
Belle-II
FASER2
SHiP
BBN
LHCb, BR($h \to \phi\phi$) = 0.01
FCC-LLP1, BR($h \to \phi\phi$) = 0.001
FCC-LLP1, BR($h \to \phi\phi$) = 0.01
FCC-LLP2, BR($h \to \phi\phi$) = 0.01
Mixing angle Sinθ
Dark Higgs Mass m_ϕ [GeV]



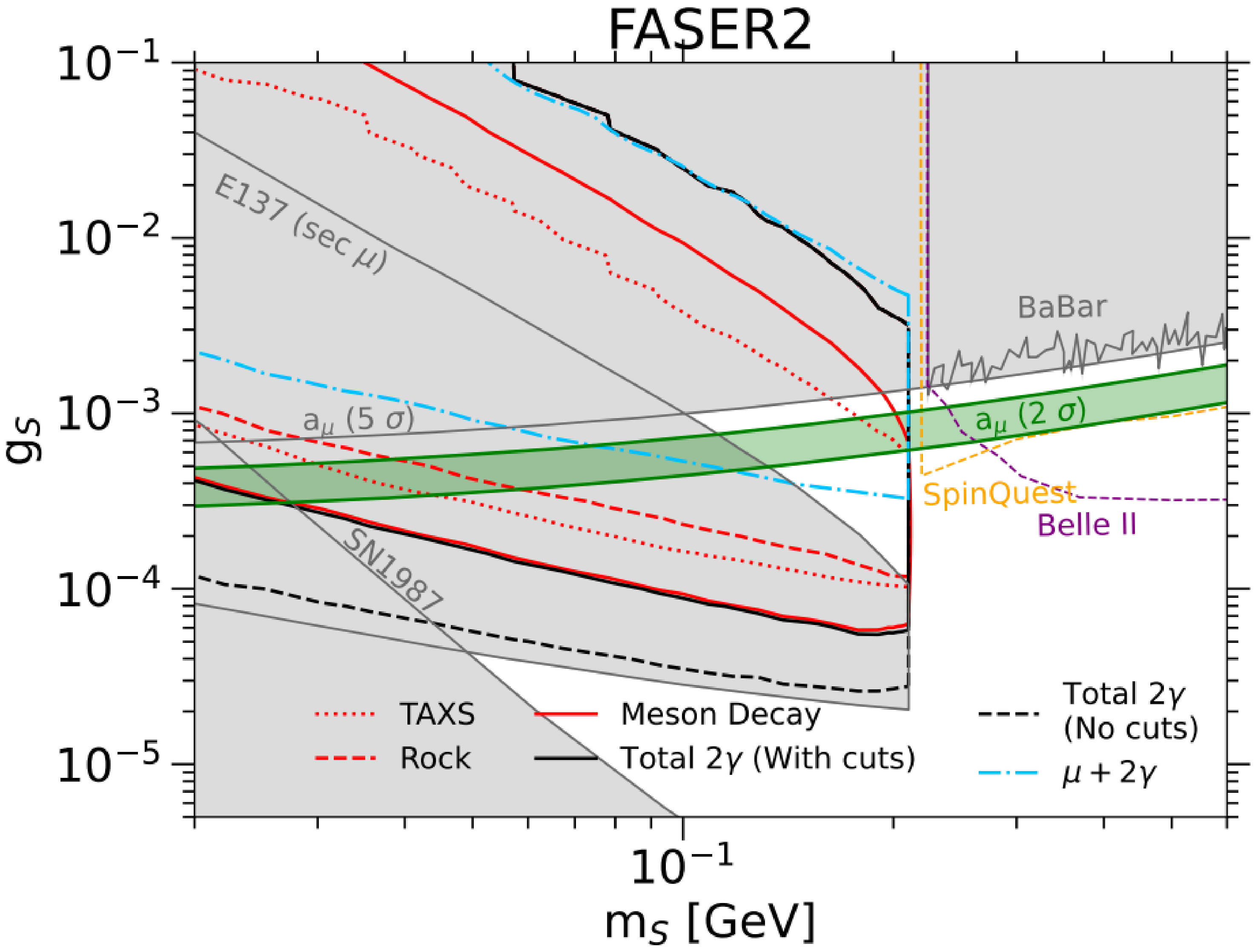
Charge Radius Bounds
FCCν(d)
FCCν(w)
FCCν
FASERν2
ν_e
ν_μ
ν_τ
SM:Q ~ 30 GeV
Q=0 GeV
LSND
COHERENT
TEXONO
DUNE
CCFR
CHARM
LEP2
$\langle r_\nu^2 \rangle$ [cm^2]


mCPs
Excluded
XQC
DUNE
PIXIE ($f_{DM} = 10^{-5}$)
1-loop, $f_{DM} = 10^{-5}$
CMB(Planck)
ferMINI
FORMOSA
milliQan
RRS
MAPP-1
FCC-mCP
SUBMET
CMB-S4
DD relic mCPs
ϵ
mCP Mass m_χ [GeV]



$Q^2 = 10^4\,GeV^2$
Baseline (BL)
BL+FASERν2, stat
BL+FASERν2, stat+syst
$\delta xu_v/xu_v$
$\delta xd_v/xd_v$
$\delta xg/xg$
$\delta x\Sigma/x\Sigma$
$\delta xs/xs$
x
xFitter

pp → Z → ℓℓ̄ + X
pp → W⁻ → ℓν̄ℓ + X
pp → W⁺ → ℓ̄νℓ + X
pp → Hjj + X
pp → HW⁺ → Hℓ̄νℓ + X
pp → HW⁻ → Hℓν̄ℓ + X
pp → W⁺W⁻ → ℓ̄νℓℓ′ν̄ℓ′ + X
pp → ZW⁺ → ℓℓ̄ℓ̄′νℓ′ + X
pp → ZW⁻ → ℓℓ̄ℓ′ν̄ℓ′ + X
NNPDF4.0_FPF
NNPDF4.0_FPF*
NNPDF4.0
PDF4LHC21_FPF
PDF4LHC21_FPF*
PDF4LHC21
σ [pb]



FASER2
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
g_S
m_S [GeV]
E137 (sec μ)
a_μ (5 σ)
a_μ (2 σ)
SN1987
BaBar
SpinQuest
Belle II
TAXS
Rock
Meson Decay
Total 2γ (With cuts)
Total 2γ (No cuts)
$\mu + 2\gamma$