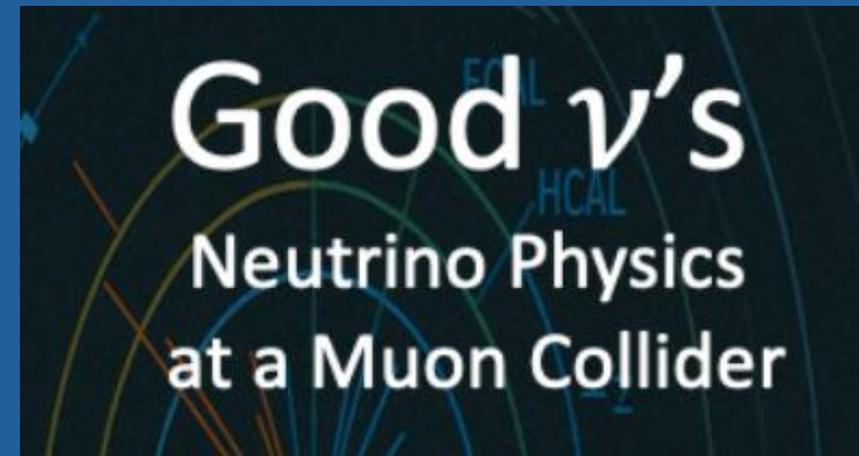# Lessons from FASER on detecting TeV neutrinos in the lab
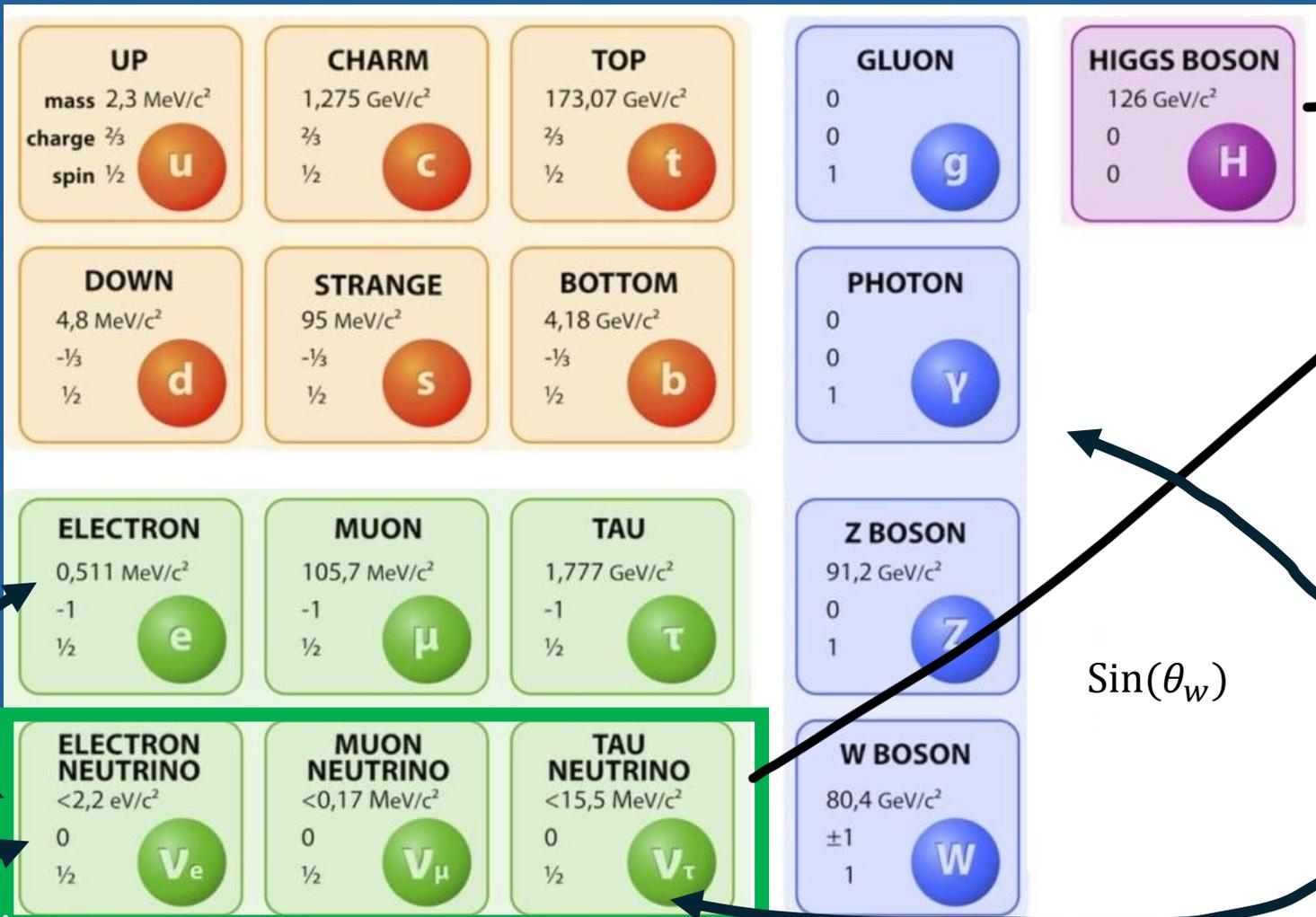
Max Fieg (Fermilab)

Good $\nu's$

Neutrinos are important for physics

Nuclear Structure/PDFs

CKM

Astroparticle

Weinberg Op.

BSM

$\nu - $ philic DM

HNLs

Dipole portal

$\text{Sin}(\theta_w)$

...

EM properties

Cosmology

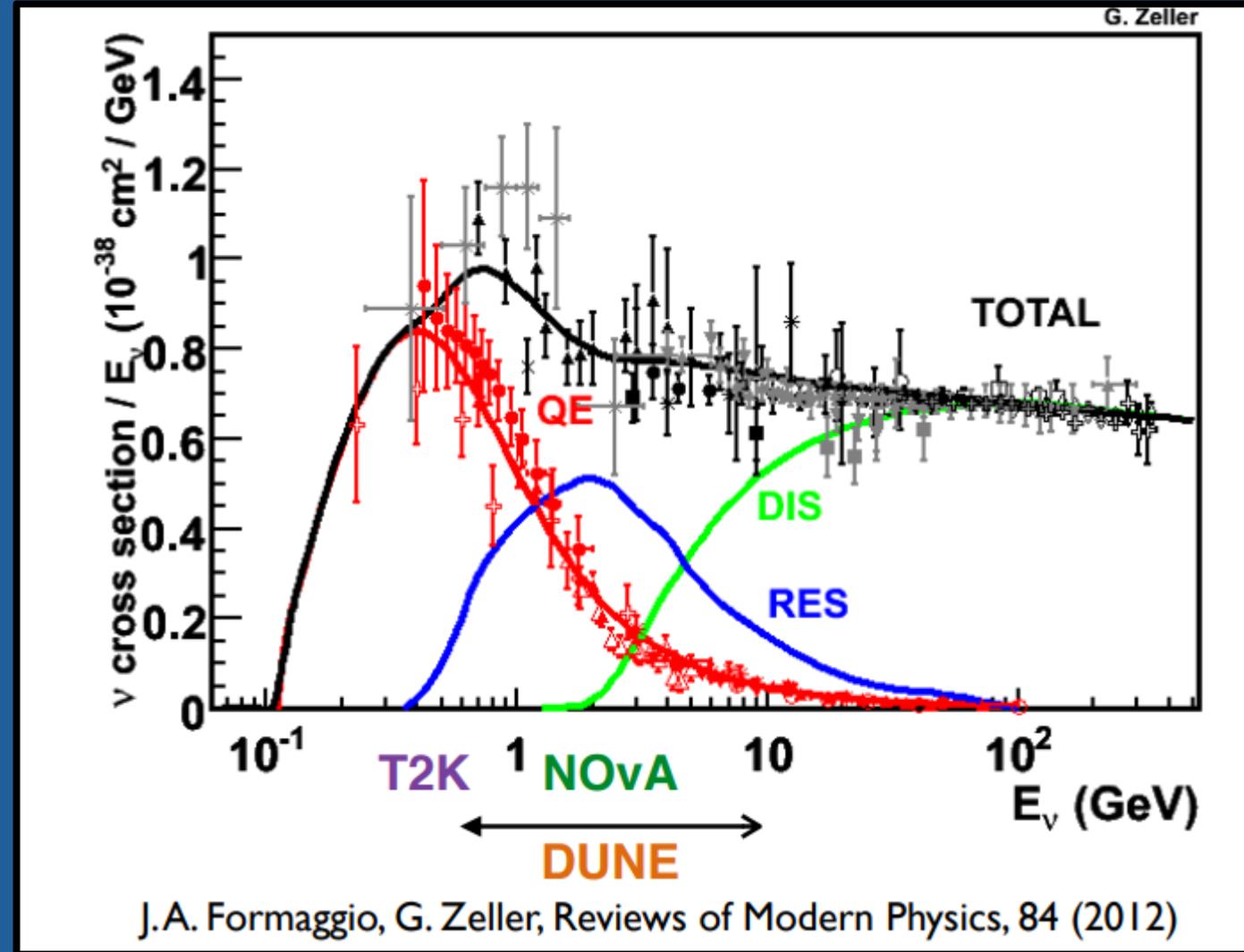Lepton-flavor universality

Non-standard interactions

Oscillations

TeV Neutrinos

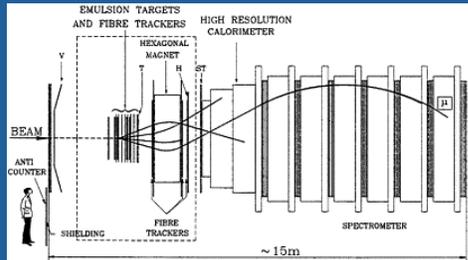Above $E_\nu \approx 10$ GeV, neutrinos interact entirely via DIS

Over the decades, experiments have made progress at this front

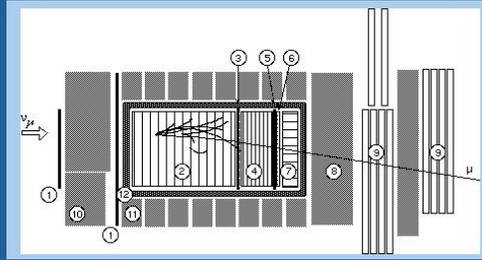- What technology is best depends on physics target, time, and money

J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Sub-TeV in the lab

Progress on the DIS front

E_ν

| $E_\nu \sim 30$ GeV | $E_\nu \sim 30$ GeV | $E_\nu \sim 120$ GeV |

CHORUS

- Emulsion based

NOMAD

- Electronic Calorimeter

CDHS

- Iron-scintillator

CCFR / NuTeV

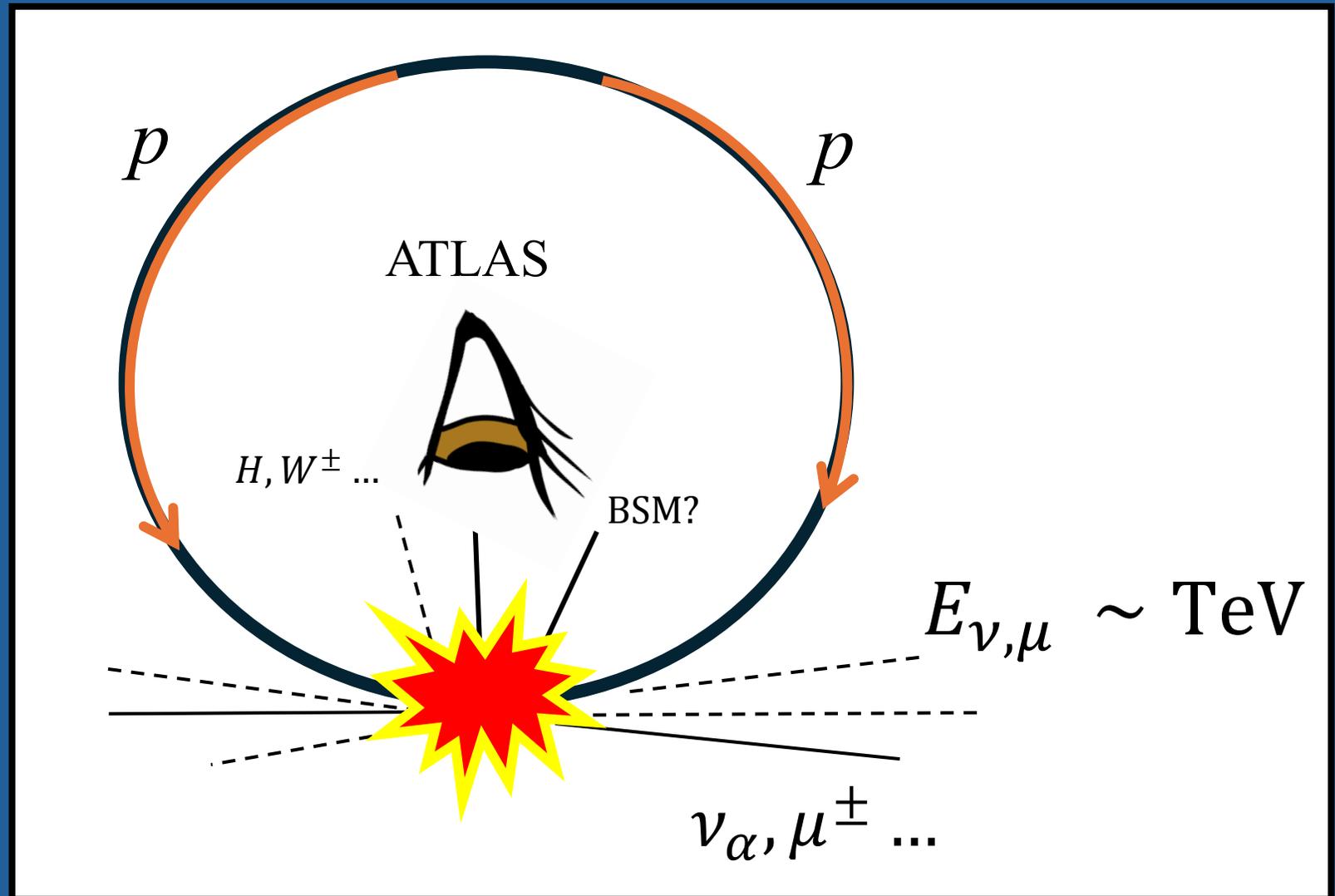- Iron-scintillator

+ many more experiments that ended in mid 90's

Fantastic program that measured neutrino cross sections, PDFs, $\sin(\theta_W)$ (+NuTeV anomaly), trident production

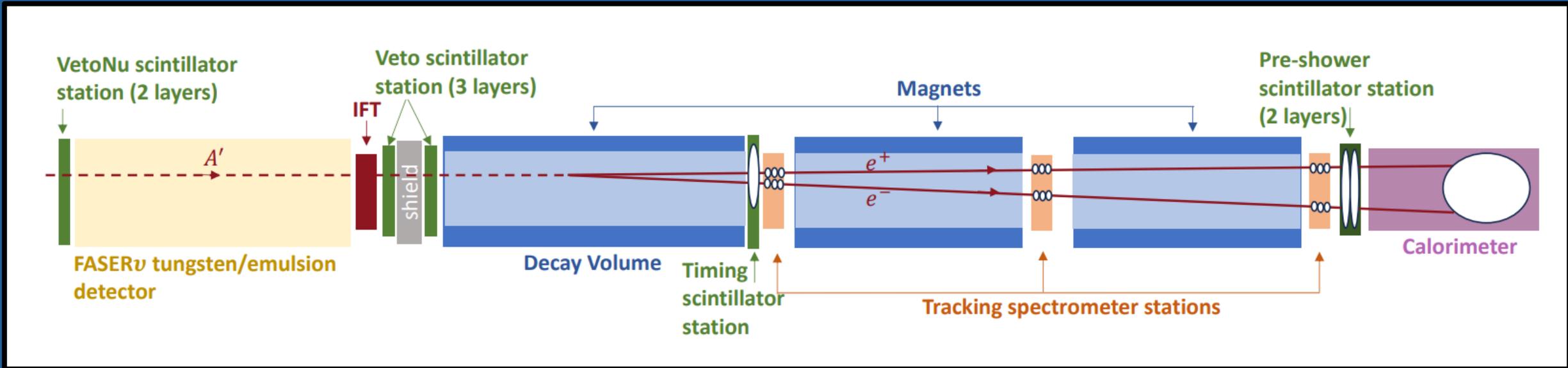# At the LHC

Lots of attention on the heavy frontier

TeV neutrinos have been produced in the lab for over a decade

p

p

ATLAS

$H, W^\pm \dots$

BSM?

$E_{\nu,\mu} \sim \text{TeV}$

$\nu_\alpha, \mu^\pm \dots$

Dawn of Collider Neutrino Physics - TeV

Collider neutrinos have been observed!

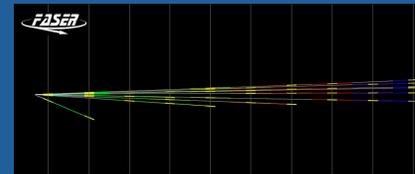- FASER and SND the first experiments to discover neutrinos at any collider
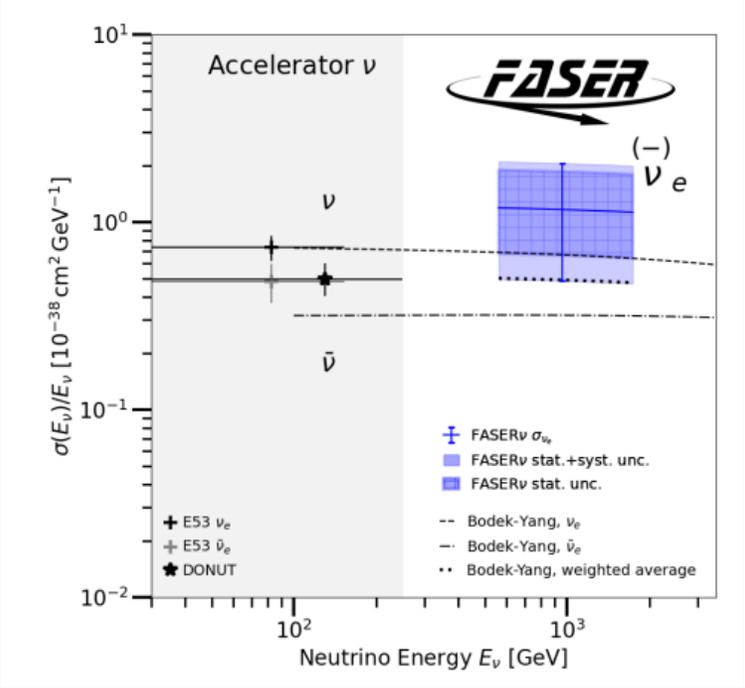
FASER(ν): LLP and ν experiment

FASER is on-axis with:

- Muon veto
- Emulsion interleaved with Tungsten
- Spectrometer + tracker with 0.5 T magnet
- Calorimeter
- Interface tracker

Max Fieg (FNAL)

FASER neutrino results so far

$\langle \nu_{\mu(e)} + \bar{\nu}_{\mu(e)} \rangle$ cross sections with emulsion

ν_μ and $\bar{\nu}_\mu$ cross sections with electronic components only

First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector

First Measurement of the Muon Neutrino Interaction Cross Section and Flux as a Function of Energy at the LHC with FASER

FASER'24

Max Fieg (FNAL)

FASER'24

Looking beyond Run 3

Forward Physics Facility (FPF)

Construct a dedicated cavern before HL-LHC to significantly expand neutrino program

• LAr + Emulsion

FPF@FCC

Forward program at the FCC-hh

$\approx$ 100M neutrinos bring novel probes into neutrino, QCD and BSM physics

Looking beyond Run 3

Forward Physics Facility (FPF)   **FPF@FCC**

energy spectrum for $\nu_\mu + \bar{\nu}_\mu$

$>1M \; \nu_\mu, \; 100k \; \nu_e, \; 10k \; \nu_\tau$ $>100M \; \nu_\mu, \; >10Mk \; \nu_e, \; 1M \; \nu_\tau$

Looking beyond Run 3

Forward Physics Facility (FPF)

> The Forward Physics Facility at the High-Luminosity LHC
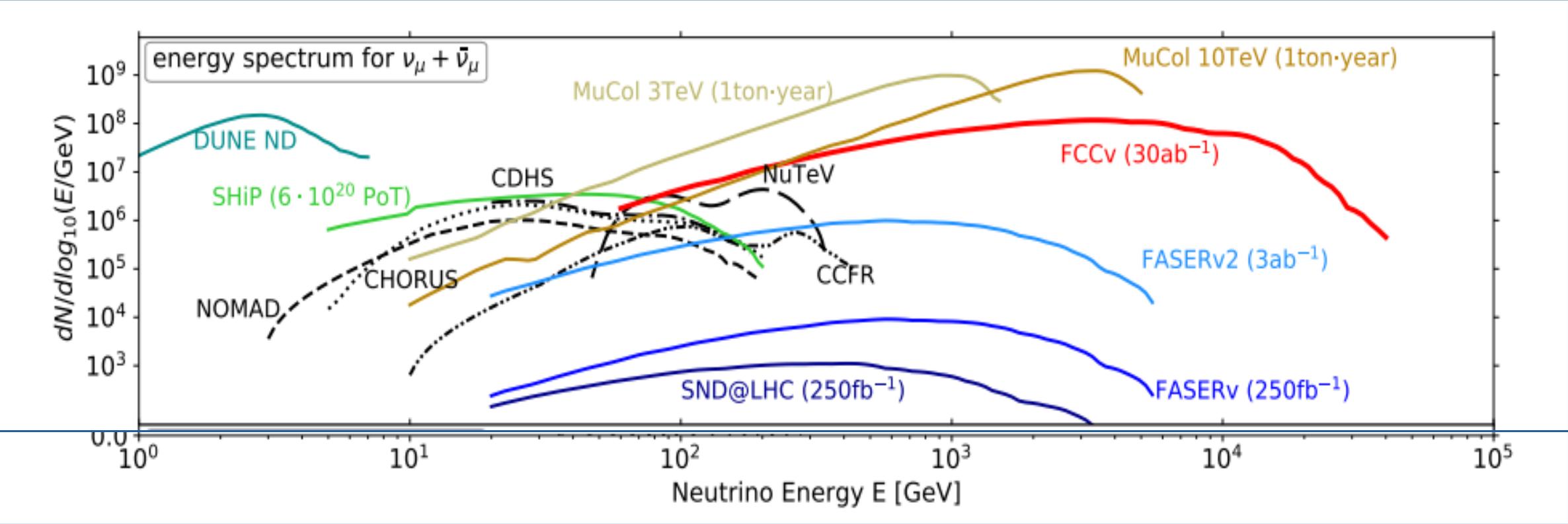
FPF Whitepaper   (2203.05090)

Many ν studies can be directly applied to MuCol

FPF@FCC

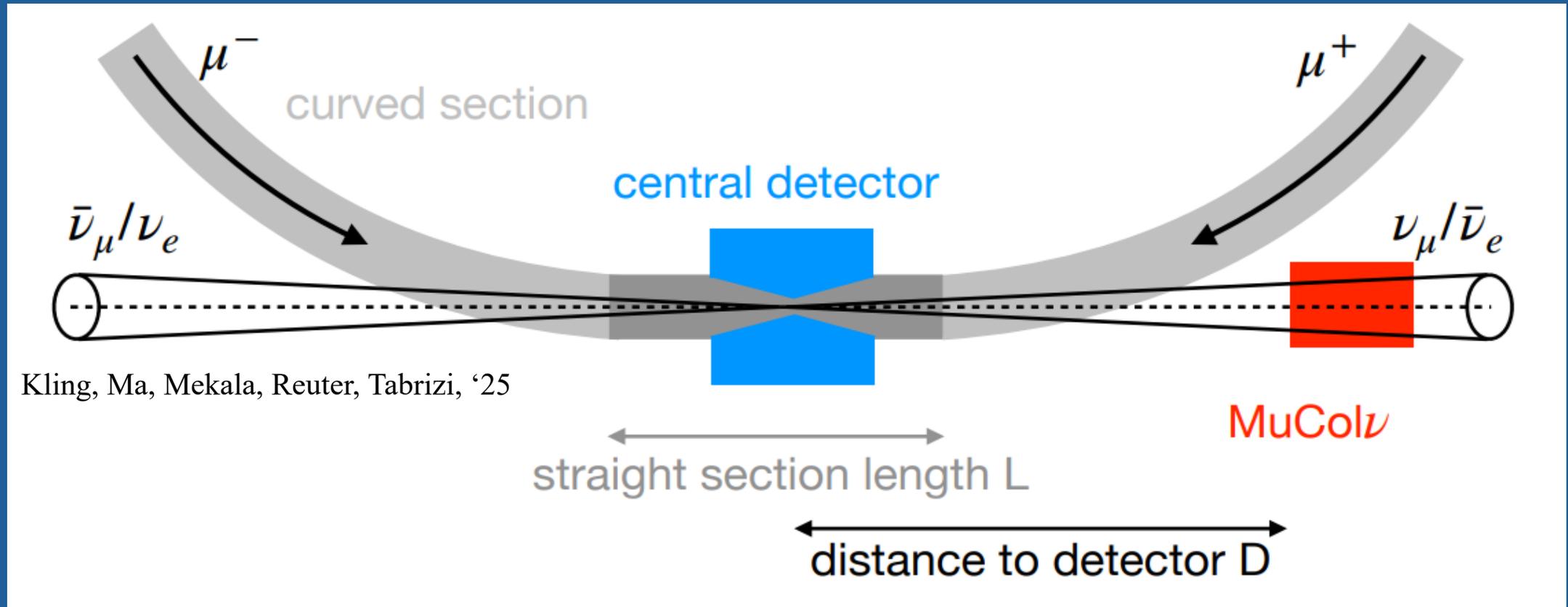> FPF@FCC: Neutrino, QCD, and BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider

FPF@FCC   (MF et al. 2409.02163)

Supercharged FPF + Unique opportunities

• e.g. Polarized PDFs

FPF@Muon Collider

Kling, Ma, Mekala, Reuter, Tabrizi, '25

I'll be thinking about forward going neutrinos, and what to do with them at the Muon Collider

Clean beam at Muon Collider

pp

Hadron Collider ν_α, μ

? ?

Bad $\nu's$: No QCD studies of colliding hadrons

Production

Detection

Muon Collider μ $\nu_e \nu_\mu$

✓ + any forward scattered muons

?

Good $\nu's$: Well-understood beam for precision studies!

"Dirty beam"

pp→ π^0 at $\sqrt{s} = 7$ TeV for $0.0 < p_T$ [GeV/c] < 0.2

LHCf π^0

Pythia

pp → nX (or $\bar{n}$X) at $\sqrt{s} = 13$ TeV in $\eta > 10.75$

LHCf n

Pythia

FASER '24

MF, Kling, Schulz, Sjostrand, 2309.08604

Hadron, Neutrino beam not well-understood at FPF, vs.

μ **MEAN LIFE** τ

$$\frac{VALUE \ (10^{-6} \ s)}{2.1969811 \pm 0.0000022}$$

Limited by precision knowledge of muon beam

Some Forward Physics targets relevant for MuCol

SM

BSM

- Cross sections, $\sigma_{\nu N}$

- **PDFs / Nuclear Structure,** f_q

- ν_τ

- Heavy flavor production, D

- EM properties of neutrinos

- Rare processes

- NSI / LFU

- Light DM scattering

- Sterile Oscillations $\mathcal{O}(10s)$ eV

What lessons learned on TeV neutrinos can we take from FASER to the Muon Collider?

#1: Build every collider with forward physics in mind

- FASER was lucky that there was a tunnel in the right place from LEP days
- Limited civil engineering → Need for FPF
- No access to tunnel during operation

FASERν will come

FASER spectrometer with 0.55-T magnets

Calorimeter

#1: Build every collider with forward physics in mind

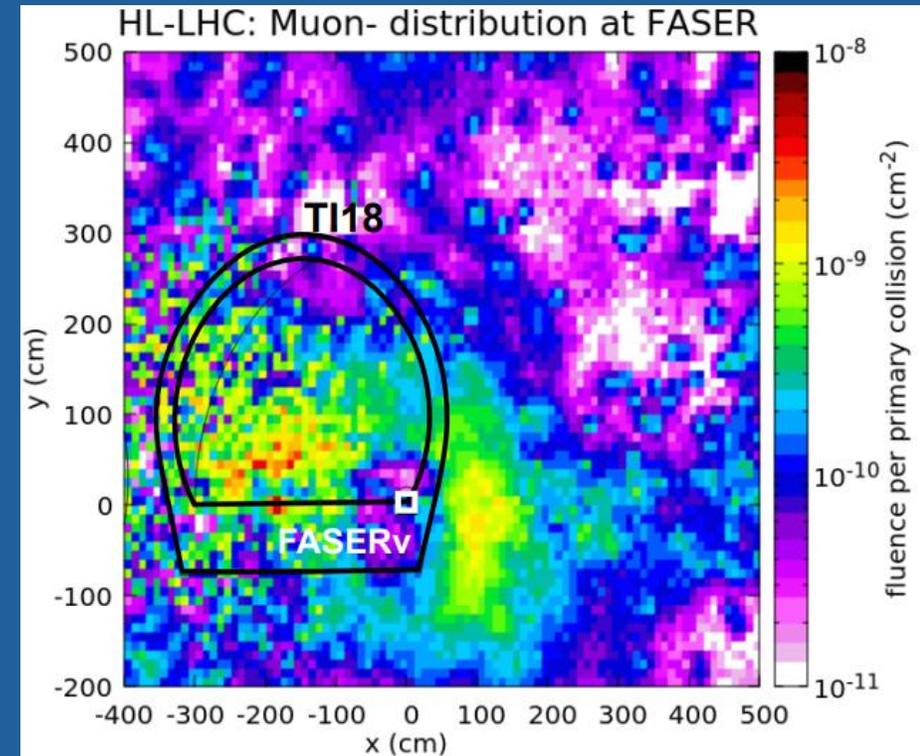No access to tunnel means we must be strategic about experimental choices

e.g. Emulsion can get blacked out from muon flux.
1 kHz muon trigger

Forward muons can also be useful at FPF and MuCol

FASER '19
1908.02310

#2: On-axis maximizes the event rate

Consider FASER (on-axis $\eta > 8.5$) vs SND (off−axis $7.2 < \eta < 8.4$)

- FASER made first observation of 153 ν_μ with 35 fb^{-1}

- SND made first observation of 9 ν_μ with 69 fb^{-1}

Off-axis detectors have some advantages at a proton collider

- Different hadron species contribute to ν rate

Cruz-Martinez, MF, Giani, Krack, Makela, Rabemananjara,Rojo, 2309.09581

Event rate: Inclusive (Semi-inclusive charm)

Detector		N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν		400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	2309.09581	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)

#2: On-axis maximizes the event rate

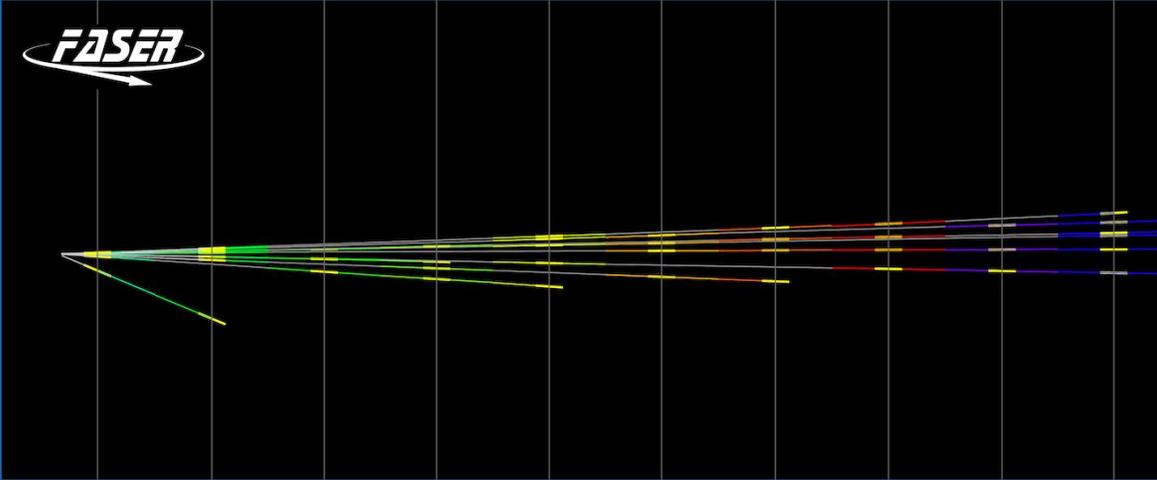Huge event rate, $\mathcal{O}$(kg) detectors are fine → opportunity to get systematics and ID well-under control

At a muon collider, enormous event rate from straight section, so long as straight section near IP is not too short

Slide from Zhen's talk

$$N_\nu \sim 10^5 \left(\frac{m}{kg}\right) \left(\frac{t}{yr}\right) \left(\frac{L}{50\text{m}}\right) \left(\frac{500\text{m}}{D}\right)^2$$

#3: Emulsion is both amazing and an enormous hassle

The good $\nu's$:

Micron spatial resolution
- Charm ID
- τ ID
- ν_e CC vs ν_μ NC

The bad $\nu's$:
- $\mathcal{O}(\text{months})$ temporal resolution

Labor intensive, after data taking:
1. Retrieve the emulsion
2. Chemically develop in dark room
3. Fly to Japan
4. Scan the emulsion
5. Reconstruct tracks
6. Analysis

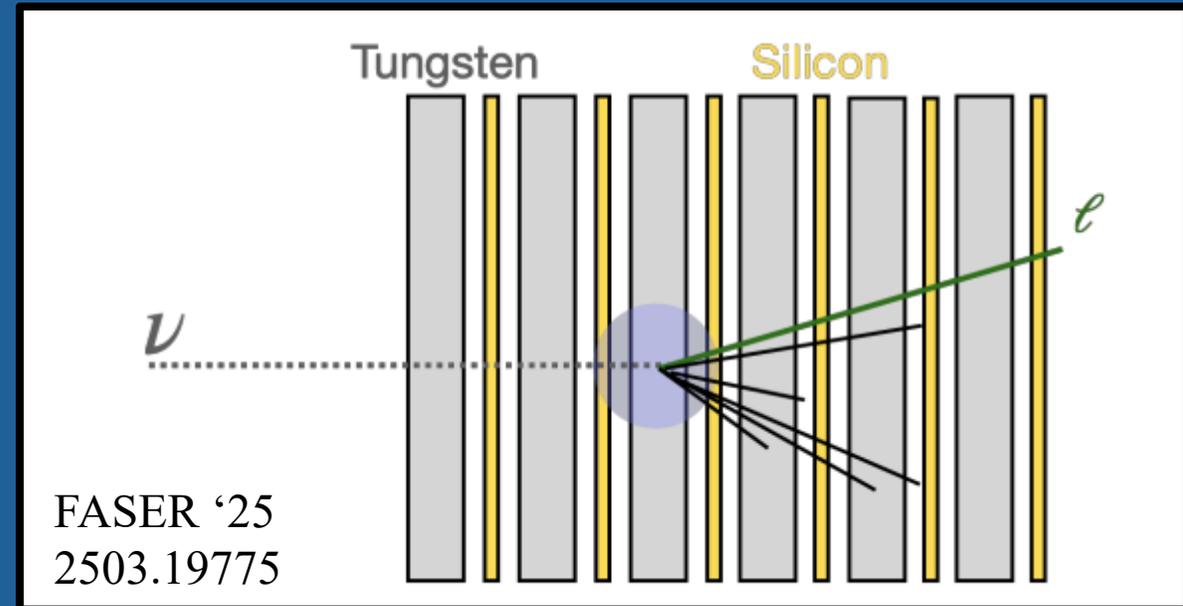So far, only 1% of collected data has been analyzed…

#3: Emulsion is both amazing and an enormous hassle

Something from this century would be preferred

- One possibility: silicon strip detectors interleaved with tungsten, electronic readout
- Tungsten can act as scattering material for hadrons, which could mimic, e.g., a τ or charm decay

At MuCol, Tungsten material may not be needed

- Huge flux, silicon can act as target + tracker

FASER '25
2503.19775

FASER, *not* FASERν, first observed neutrinos

#4: Good experiments should have magnets

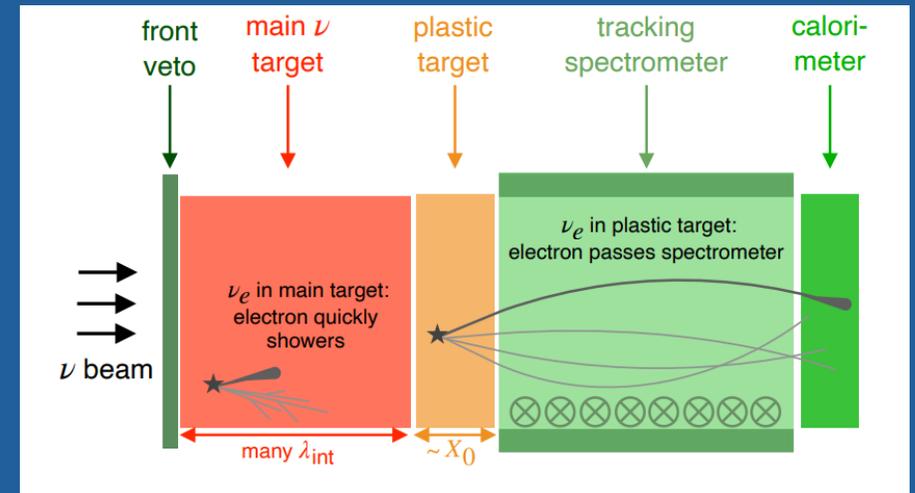First observation of collider neutrinos relied on the FASER magnet

- Muon energy measurement allowed for much faster ν_μ cross section measurement

Neutrino Detection without Neutrino Detectors:
Discovering Collider Neutrinos at FASER with Electronic Signals Only

Arakawa, Feng, Ismail, Kling, Waterbury 2206.09932

More generally, important for charge ID

- Unexpected backgrounds
- Non-standard interactions
- Trident processes
- Charm ID
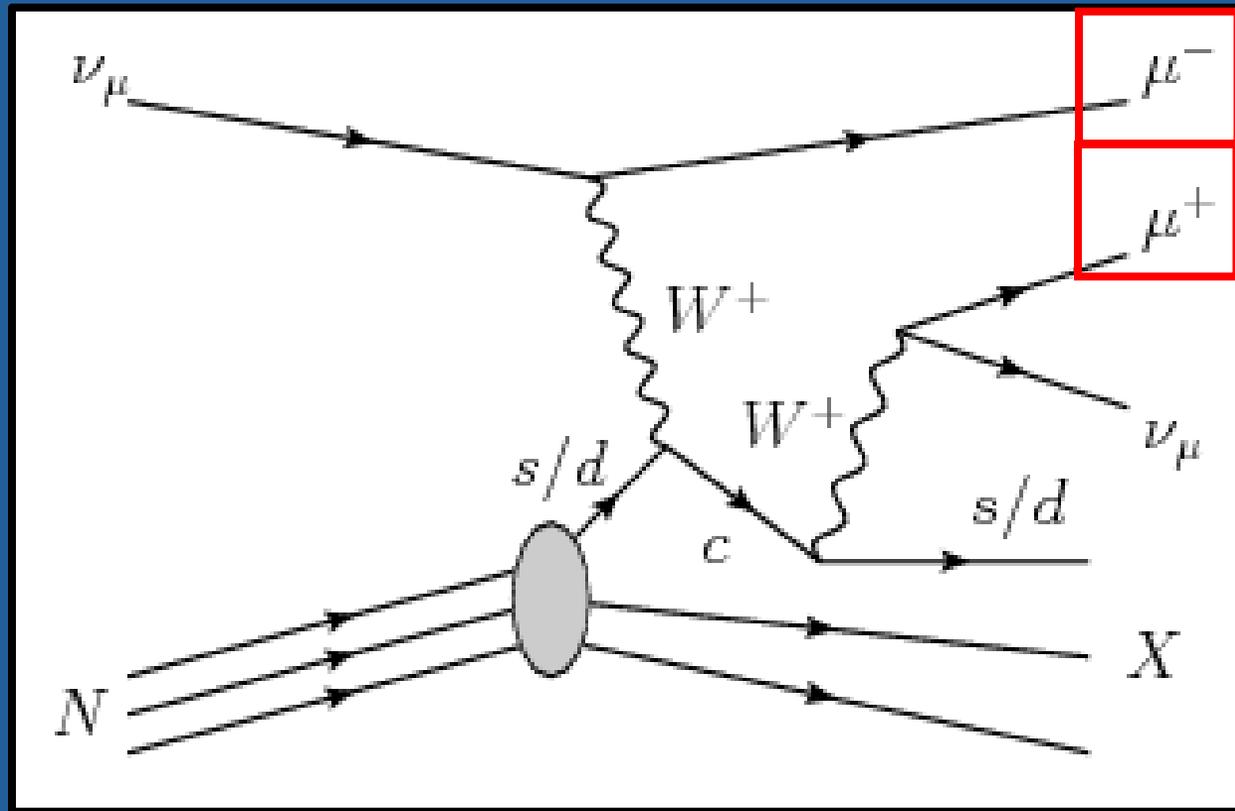- $e^\pm$ can be tagged given sufficiently thin target

Kling, Makela, McFayden, 2507.00262

#4: Good experiments should have magnets

Even for μ^- decay, charge ID is important

For example, semi-leptonic decaying charm mesons can be tagged via dimuon

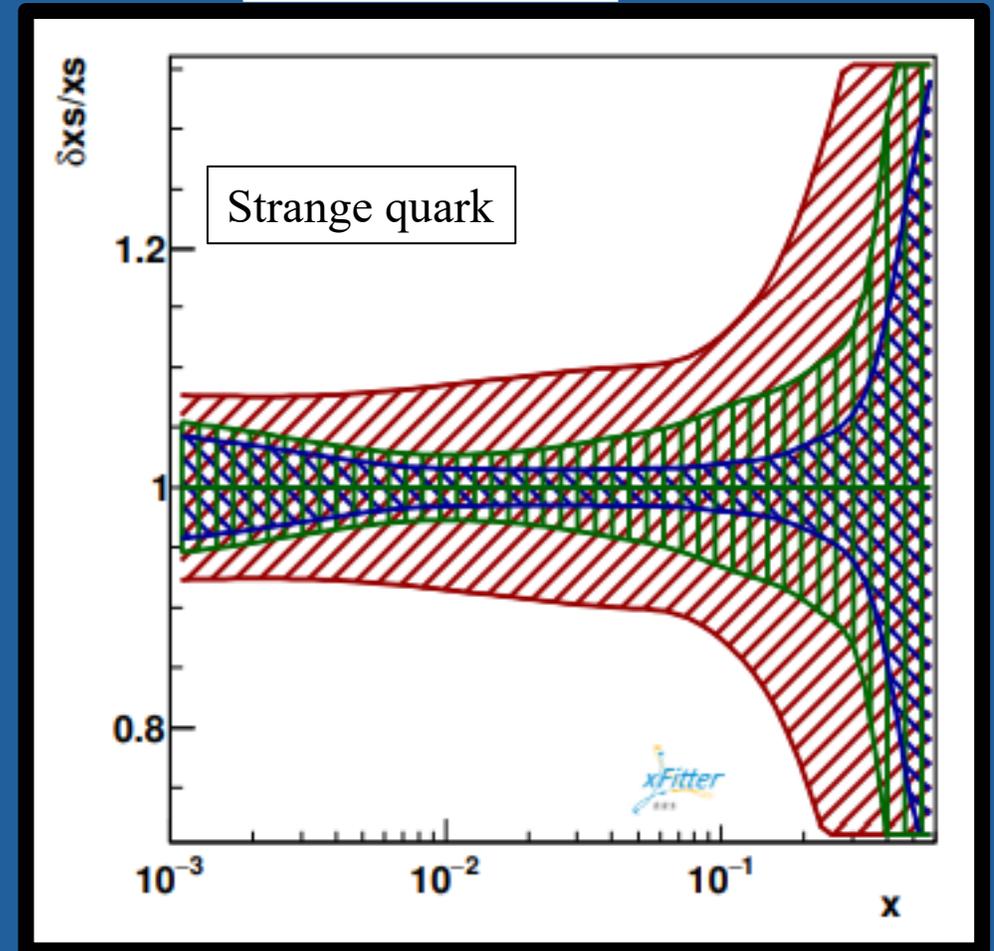Reconstructing oppositely charged muons and

#5: Tags and IDs

Projected PDF fits post-FPF

Charm production excellent for tagging a down-type quark

Charm production a background for trident processes
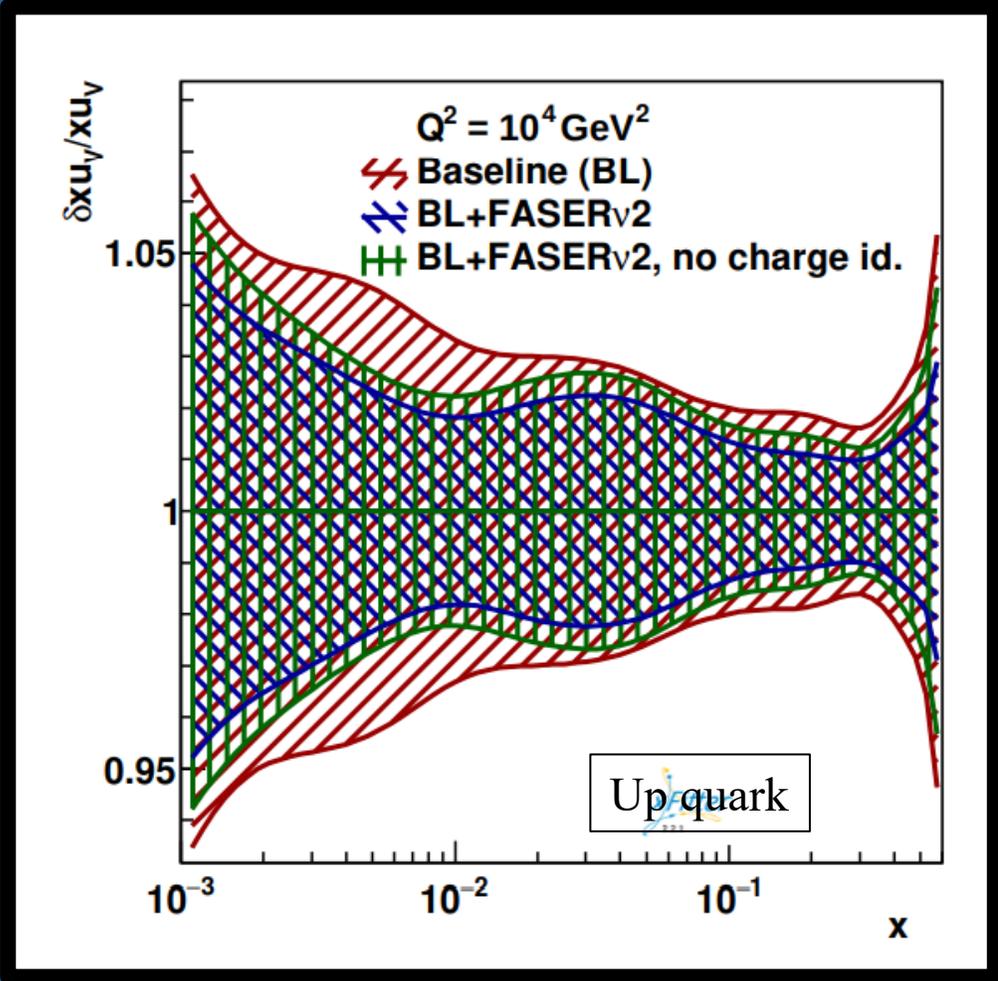
Useful for tests of LFU

Charm ID

Cruz-Martinez, MF, Giani, Krack, Makela, Rabemananjara,Rojo ,2309.09581

#5: Tags and IDs

Charge ID

Projected PDF fits post-FPF

Charge ID important for $\nu, \bar{\nu}$ discrimination

Cruz-Martinez, MF, Giani, Krack, Makela, Rabemananjara,Rojo ,2309.09581
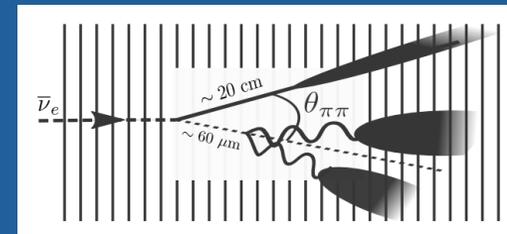
#5: Tags and IDs

ν_e CC vs ν_α NC

- $\mathcal{O}(10)$ charged tracks per DIS
- Soft-ish $e^\pm$ can be difficult to untangle from hadronic shower
- Important for ν_e studies, $\sin(\theta_w)$ measurement, neutrino EM form factors
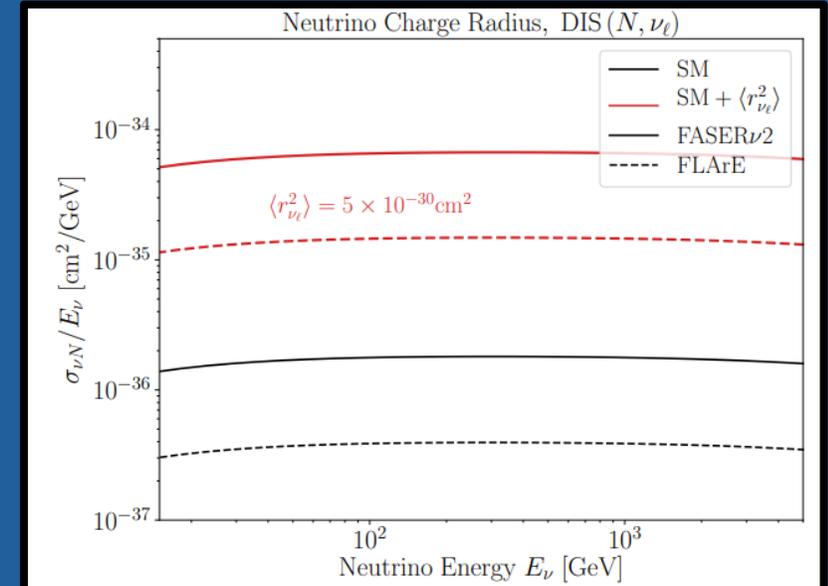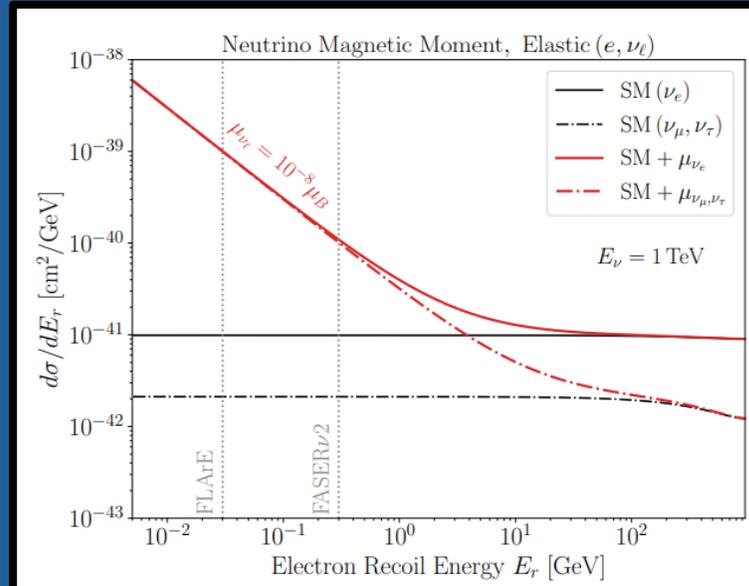
Similar challenge for ρ resonance

Brdar, De Gouvea, Machado, Plestid 2112.03283

#6: Low-energy signatures

Neutrino EM form factors

Abraham,
Foroughi-Abari,
Kling, Tsai
2301.10254

- Millicharge and magnetic moment operators exhibit an excess at low electron recoil energies

- Charge radius affects overall normalization of NC events

#6: Low-energy signatures

$$E_h \propto \frac{Q^2}{x}$$

- DIS kinematic coverage at FASERν2 vs FLArE

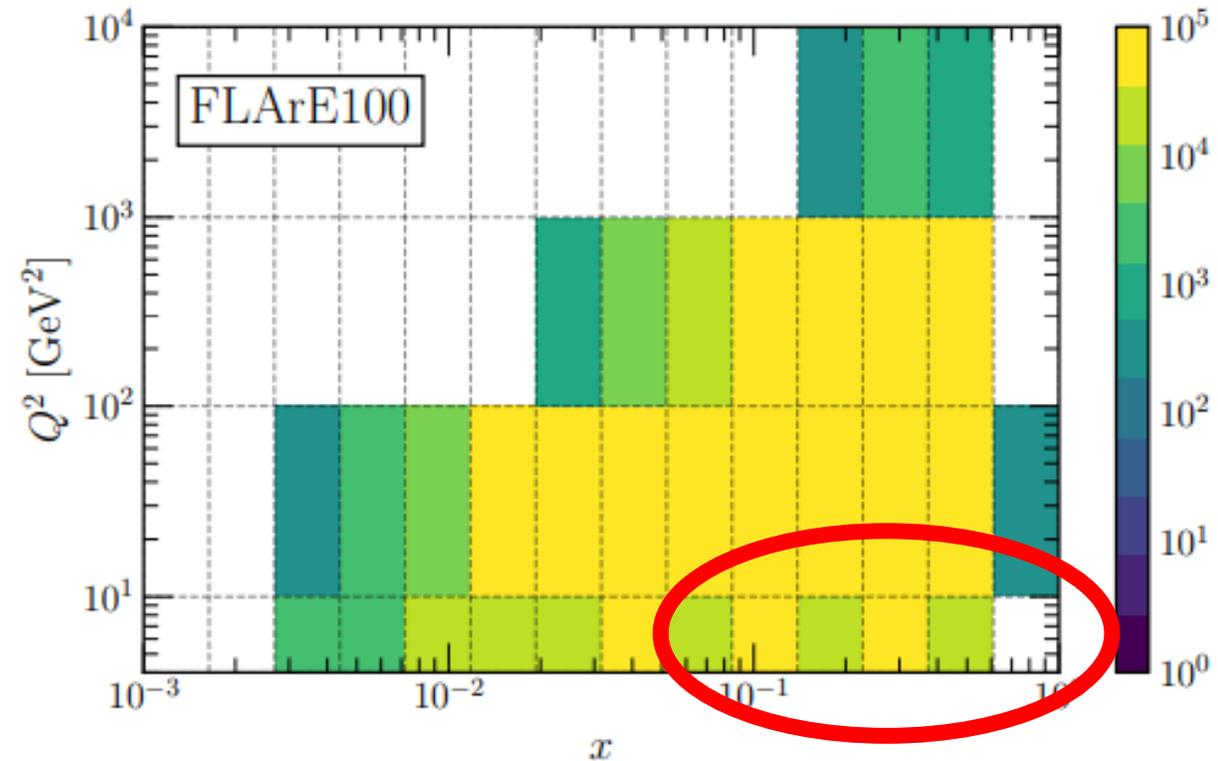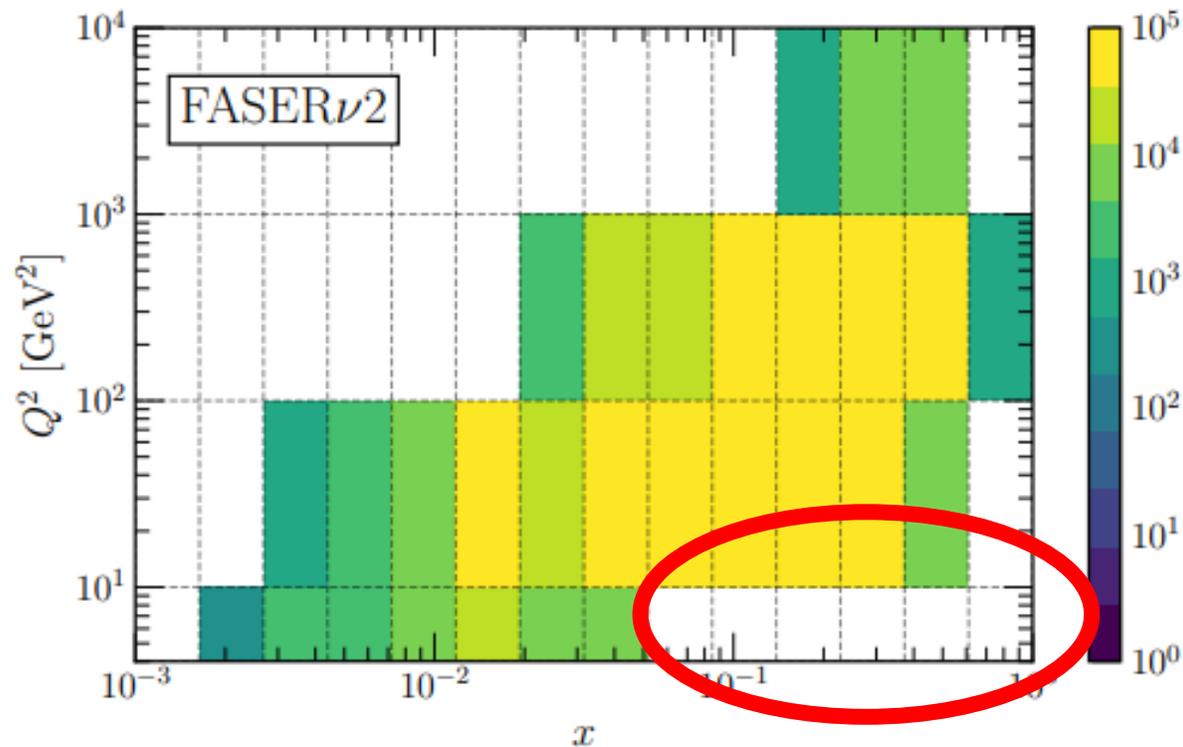- Low energy hadronic recoils give access to lower Q^2

Cruz-Martinez, MF, Giani, Krack, Makela, Rabemananjara,Rojo ,2309.09581

#6: Low-energy signatures

DM scattering peaks at low energies for light mediators, e.g. A'

$$\frac{d\sigma}{dE_e} \approx \frac{8\pi\, \epsilon^2\, \alpha\, \alpha_D\, m_e}{(m_{A'}^2 + 2m_e E_e)^2}$$

Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343

Compressed mass spectra can give low energy decay products, e.g. iDM

χ_2

γ

χ_1

Dienes, Feng, MF, Huang, Lee, Thomas 2301.05252

$$E_\gamma \approx \frac{E_{\chi_2}}{m_2}(m_2 - m_1)$$

#7: Event generators need some improvements

Good $\nu's$: The flagship MC generator, GENIE includes all processes. QES, Res. DIS

Bad ν's: Relies on obsolete PDFs, only includes up down and strange, does not include NLO corrections, primarily designed for sub-TeV

Important to include all processes

CERN-FASER-CONF-2025-002

GENIE interfaces with Pythia, which hadronizes in vacuum. Final state quark interactions generally increase track multiplicity

We should be thinking about targets and requirements

Physics	Low energy	Charm ID	Tau ID	NC vs CC	Magnet/E_μ	Spatial Res.	Energy Res. (Had, Lep)
PDFs							
Trident							
$\sin(\theta_W)$							
ν EM int							
NSI /LFU							
DM Scattering							
HNL osc.							

Summary

- TeV neutrinos at the Muon Collider benefit from a wealth of research done for FASER and the FPF

- Many mutual physics targets
  - Cross sections, PDFs, weak angle, NSI/LFU, HNLs, light DM…

- Enormous flux at MuCol means we should focus on systematics

- Let's build the Muon Collider with an FPF in mind, so our ancestors don't need to fight to build one of their own…

SM

BSM

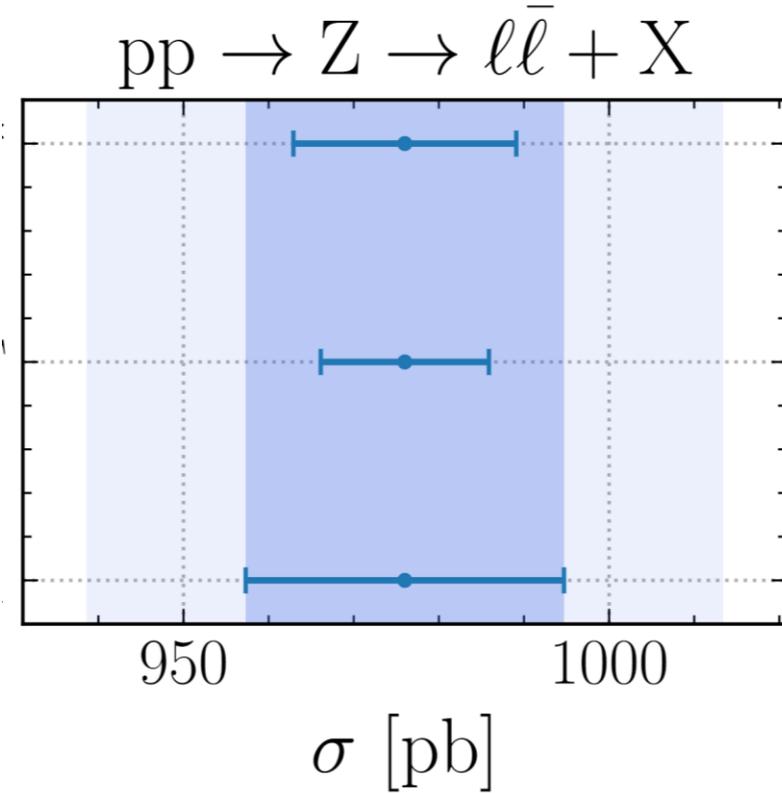- Cross sections, $\sigma_{\nu N}$
- PDFs / Nuclear Structure, f_q
- ν_τ
- Heavy flavor production, D

EM properties of neutrinos

- Rare processes

- NSI / LFU
- Light DM scattering
- Sterile Oscillations $\mathcal{O}(10s)\ eV$

Backup

Practical use
SM

With FPF

Stat + sys

Stat only

Without FPF

$pp \to Hjj + X$

$pp \to Z \to \ell\bar{\ell} + X$

σ [pb]

σ [pb]

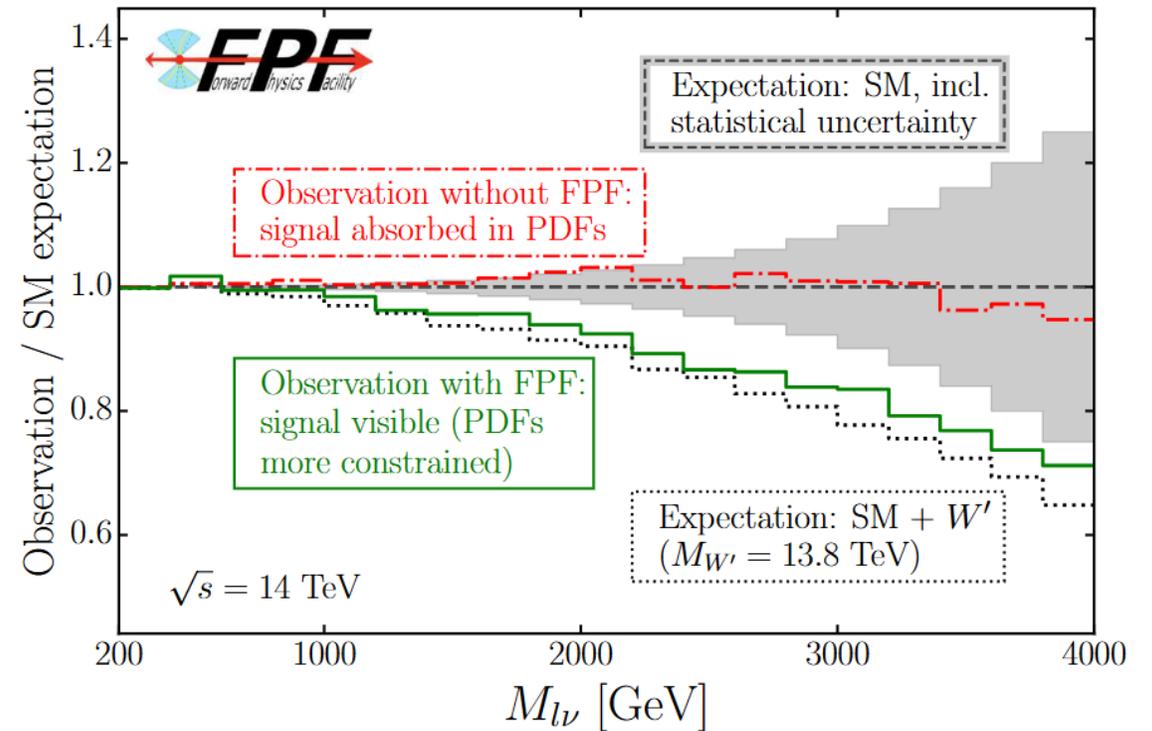Smaller uncertainties for $q\bar{q}$ initiated processes!
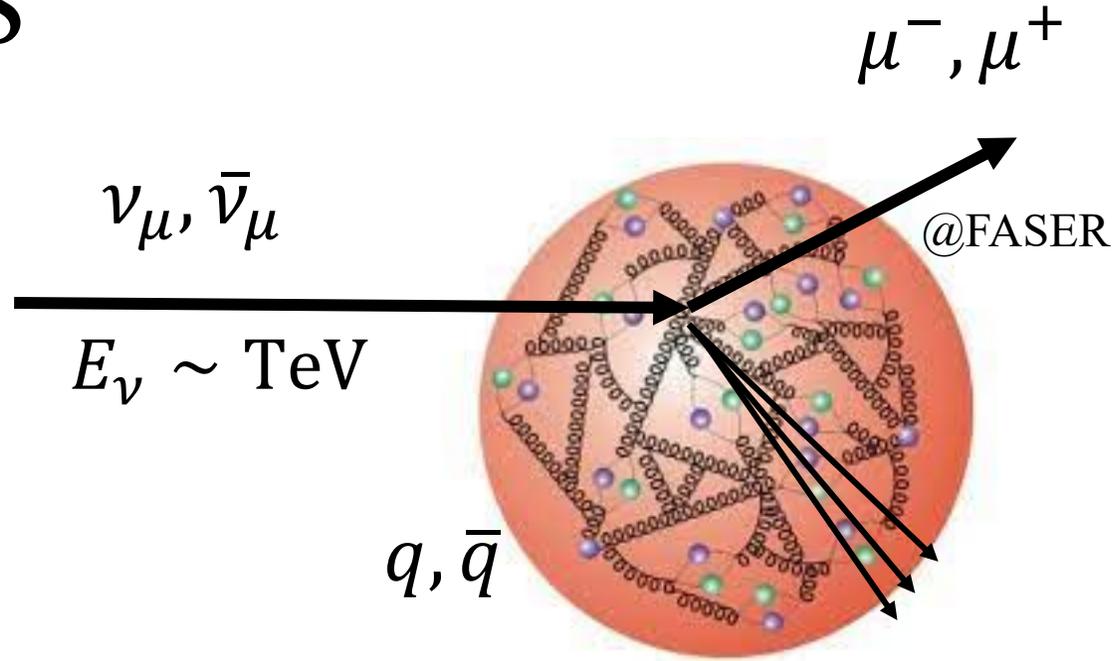
Practical use

BSM

Massive W' should lead to destructive interference

But if same dataset is used to fit the PDF, the signal can be absorbed!

FPF PDF measurements can break the degeneracy

Expectation: SM, incl. statistical uncertainty

Observation without FPF: signal absorbed in PDFs

Observation with FPF: signal visible (PDFs more constrained)

Expectation: SM + W' ($M_{W'} = 13.8$ TeV)

$\sqrt{s} = 14$ TeV

Observation / SM expectation

$M_{l\nu}$ [GeV]

Hammou, Ubiali, '24

Neutrino DIS

$\nu_\mu, \bar{\nu}_\mu$

$E_\nu \sim \text{TeV}$

μ^-, μ^+

@FASER

$q, \bar{q}$

PDF Kinematics

Neutrino energy E_ν

Momentum fraction, Bjorken-x
$$\frac{p_q}{E_N} = x$$

Momentum Transfer Q^2
$$\left(p_\mu - p_\nu\right)^2 = Q^2$$

Reconstruct w/
observables

Observables

Muon energy E_μ
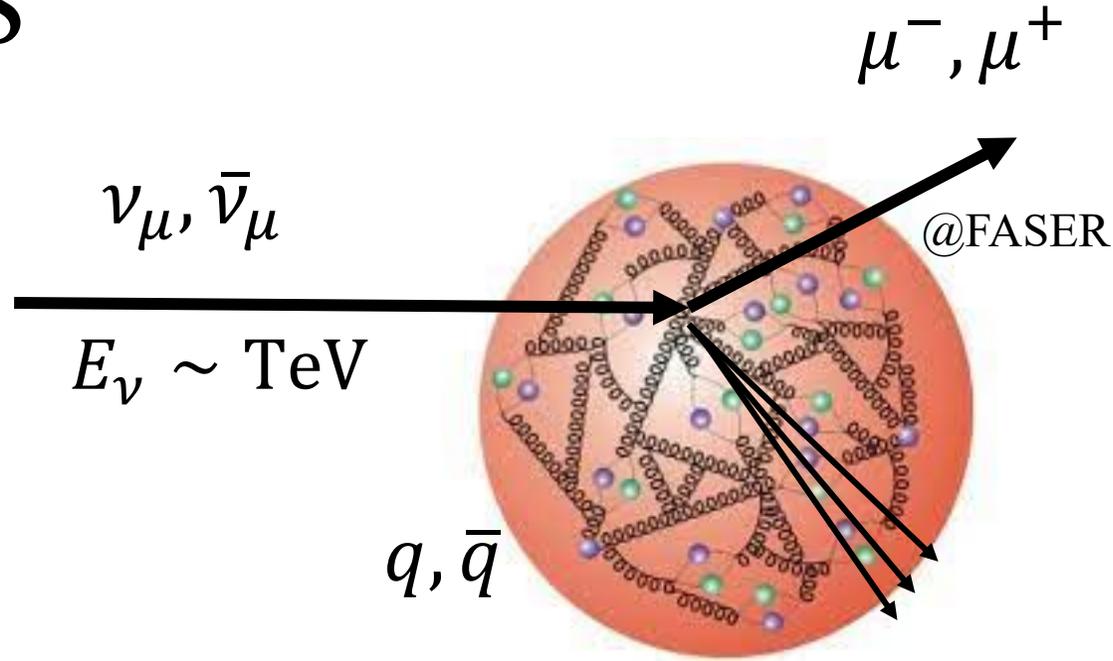
Muon scattering angle θ_μ

Hadronic Energy deposited, E_h
$$E_\nu = E_\mu + E_h$$
$$Q^2 = 4\left(E_h + E_\mu\right)E_\mu \sin^2 \frac{\theta_\mu}{2}$$
$$x = \frac{Q^2}{2m_N E_h}$$

Neutrino DIS

$$\nu_\mu, \bar{\nu}_\mu$$

$$E_\nu \sim \text{TeV}$$

$$\mu^-, \mu^+$$

@FASER

$$q, \bar{q}$$

PDF Kinematics
Neutrino energy E_ν

Momentum fraction, Bjorken-x
$$\frac{p_q}{E_N} = x$$
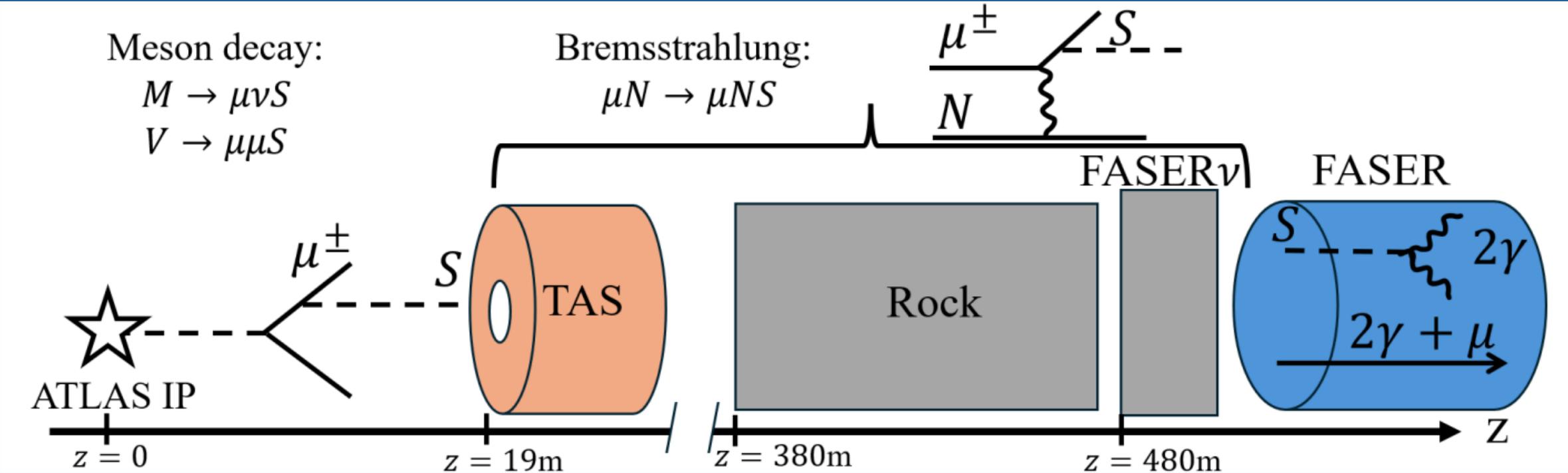
Momentum Transfer Q^2
$$(p_\mu - p_\nu)^2 = Q^2$$

Structure fxns. encode PDF. σ(PDF):

$$\frac{d^2\sigma^{\nu A}(x, Q^2, y)}{dxdy} = \frac{G_F^2 s/4\pi}{(1 + Q^2/m_W^2)^2} \left[Y_+ F_2^{\nu A}(x, Q^2) - y^2 F_L^{\nu A}(x, Q^2) + Y_- x F_3^{\nu A}(x, Q^2) \right]$$

$$F_2^{\nu p}(x, Q^2) = 2x \left(f_{\bar{u}} + f_d + f_s + f_{\bar{c}} \right)(x, Q^2)$$

Goal: measure interaction rate to reconstruct $f_q(x, Q^2)$

Backup

Backup

Backup

Backup