Forward Collider Neutrinos and Implications for Hadronic Physics

Nuclear Physics Seminar
Faculty of Physics, University of Warsaw
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Outline

- **Forward Physics Program @ LHC and beyond**
- **Forward neutrinos**
- **Implications for hadronic physics**

1

Forward Physics Program

@ LHC and beyond

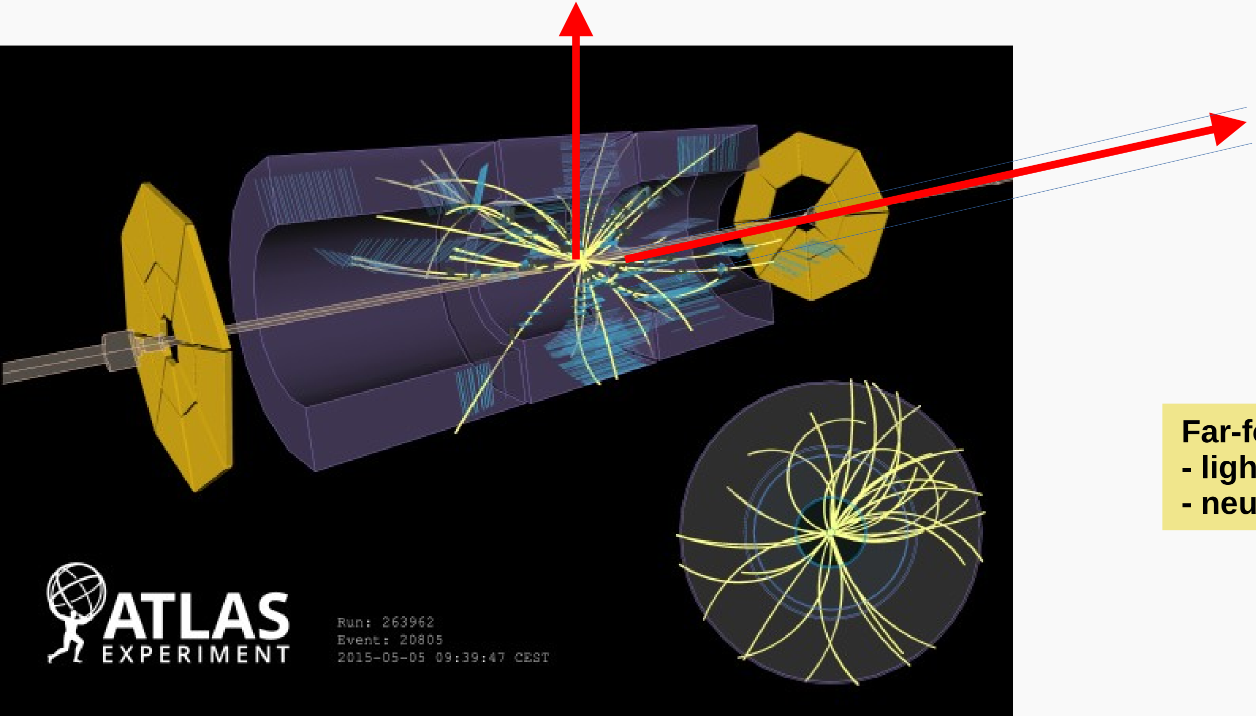
Large Hadron Collider (LHC)

- Underground tunnel @ Swiss-French border
- High-energy proton-proton (pp) collisions with $\sqrt{s}$ = 14 TeV
- Several Interaction Points (IP) – where protons collide
- Of our primary interest: **ATLAS IP** (close to CERN) [driven by available infrastructure]
- Close to ATLAS IP – proton injector from Super Proton Synchrotron (SPS) (e.g., NA61/SHINE)

High-energy collisions @ ATLAS IP

Transverse physics

- high transverse momentum (p_T)
- Higgs boson (expected ~10^8 H to be produced at 3 ab^{-1} (HL-LHC)
- search for heavy new physics (SUSY, etc.)



Forward physics

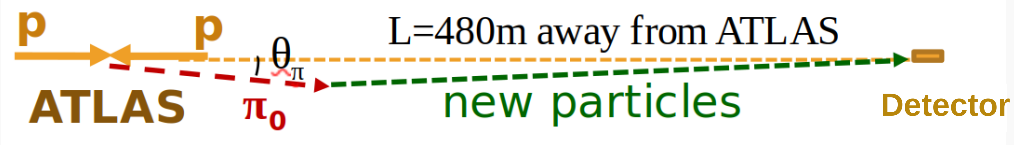
- low p_T
- mesons (expected ~10^{18} π at 3 ab^{-1})
- diffractive physics

& other forward phenomena

LHC Forward WG, arXiv: 1611.05079

Far-forward physics program
- light new physics (up to a few tens of GeV)
- neutrinos

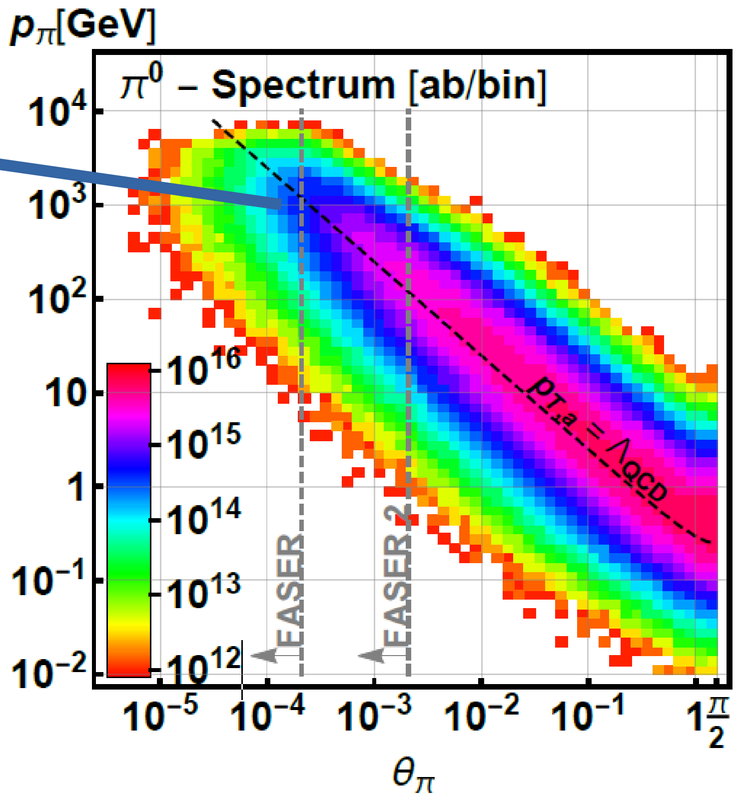
Forward pions



Hard pions highly collimated along the beam axis since their $p_T \sim \Lambda_{QCD}$ e.g. for $E_{\pi 0} \geq 10$ GeV

~ 1.7% of π_0s go towards FASER (10cm radius)

~ 24% of π_0s go towards FASER 2 (1m radius)

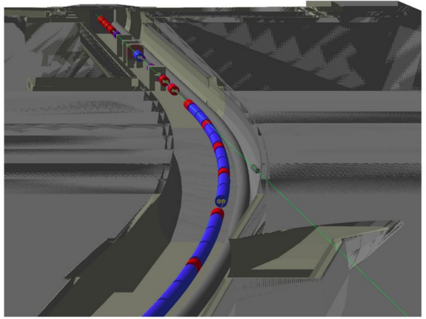


This can be compared to the angular size of both detectors with respect to the total solid angle of the forward hemisphere (2 π):

~ (2×10^{-6})% for FASER

~ (2×10^{-4})% for FASER 2

Far Forward Physics at colliders



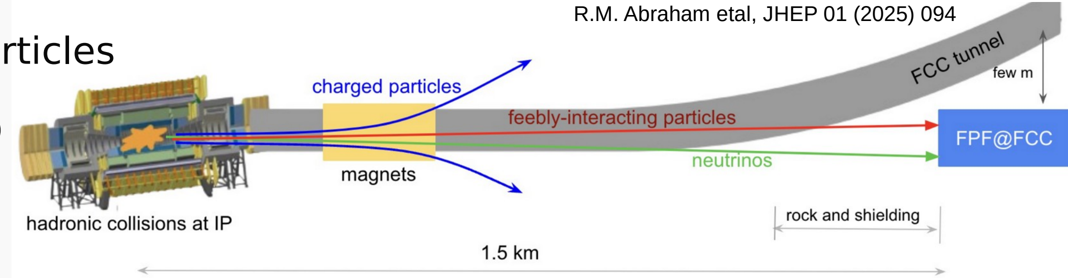
- Detectors positioned away from the pp IP (~480m during LHC Run 3)
- Along the beam collision axis (after the main tunnel turns)
- Idea: enormous intensity of forward meson production

  --> possible forward flux of light new particles

  produced in meson decays (& more)

  J.L. Feng, I. Galon, F. Kling, ST, 1708.09389

R.M. Abraham etal, JHEP 01 (2025) 094



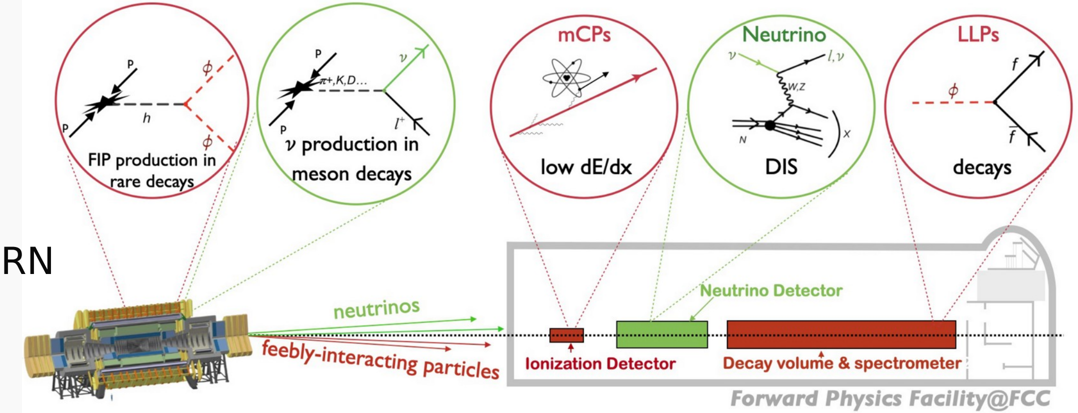
- **FASER experiment**

  FASER Collaboration, 1812.09139
- Forward neutrinos @ FASERν

  FASER Collaboration, 1908.02310

  (soon followed by the SND@LHC proposal)

  SND@LHC Collaboration, 2210.02784



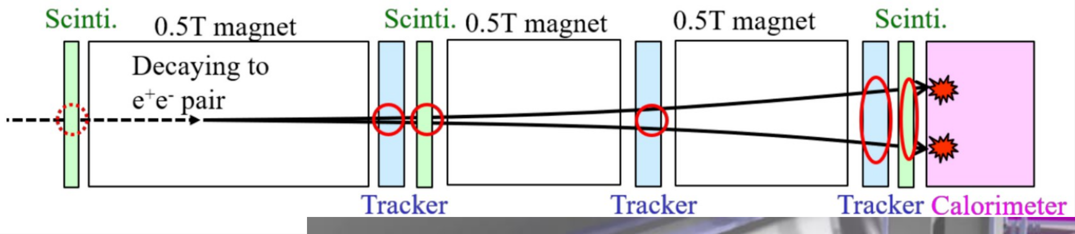
- Proposed extension (HL-LHC):

  Forward Physics Facility (FPF) at CERN

  J.L. Feng etal, J.Phys.G 50 (2023) 3, 030501
- Could continue @ future colliders

FASER experiment (currently running)

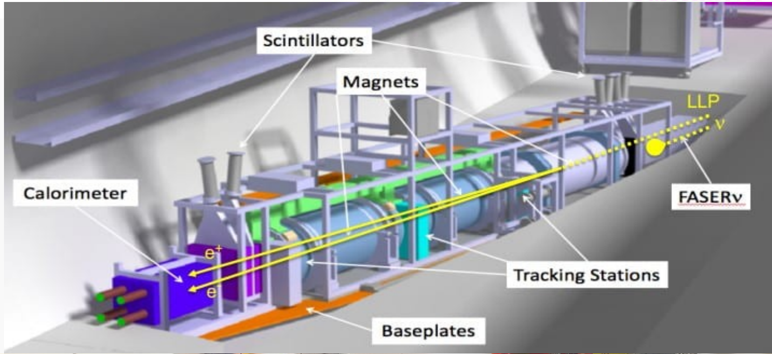
https://faser.web.cern.ch/



- Main physics goals:

  - search for rare decays of new particles

  - study high-energy neutrino scatterings



- New physics search:

  - can be made essentially BG free

  - search for e^+e^- pairs or γγ produced in the decay vessel

  - magnetized spectrometer, calorimeter

- Neutrino measurements

  - dedicated emulsion subdetector FASERν

  - final-state muons from νμ CC scatterings can be tracked in the main FASER detector

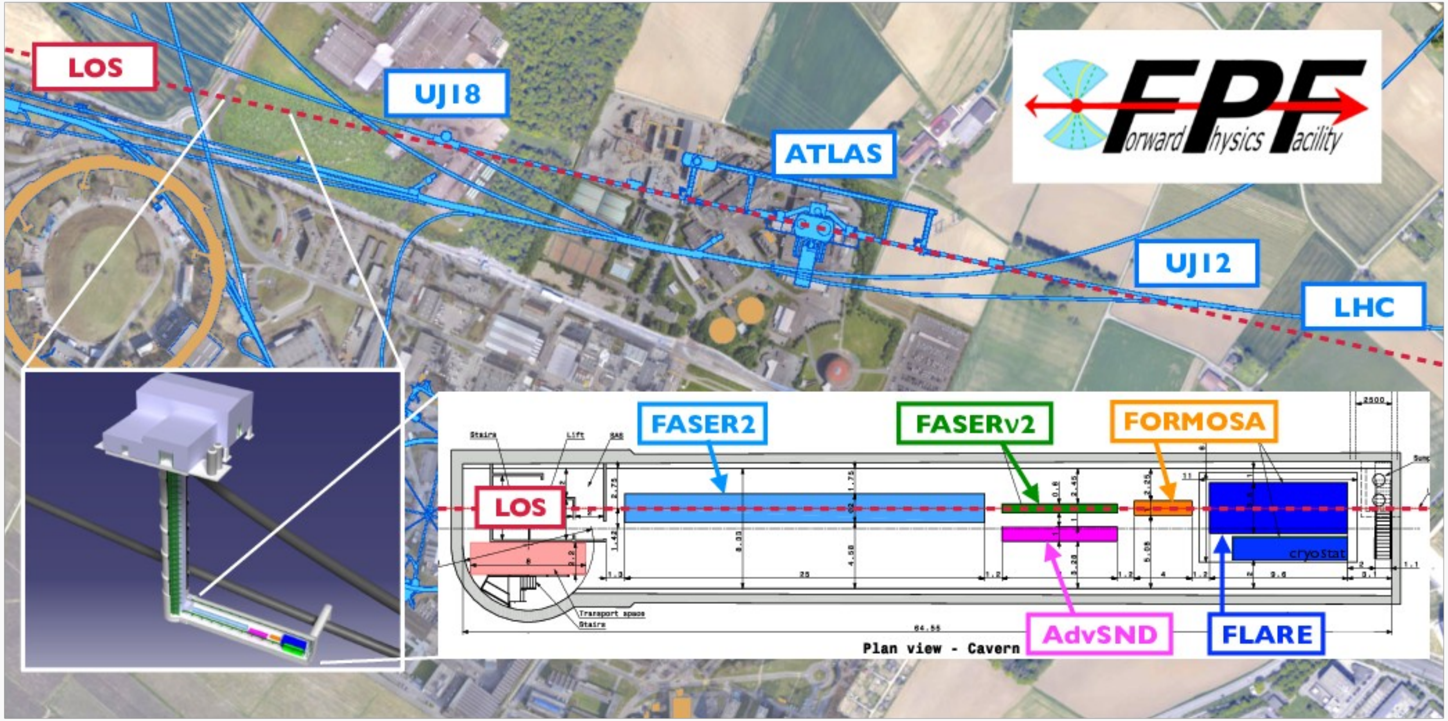
  - muon-induced backgrounds need to be rejected

Far Forward Facility (FPF) @ CERN (proposed)

J.L. Feng etal, J.Phys.G 50 (2023) 3, 030501

- New underground tunnel proposed to host a suite of far-forward experiments (HL-LHC)
- Includes larger FASER2 and FASERν2 experiments...
- ... but also FLArE detector proposed to search for light dark matter scatterings (currently BNL developed at BNL, UC Irvine, ...)

B. Batell, J.L. Feng, ST, 2101.10338



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Forward Neutrinos

Forward neutrinos @ LHC

First collider neutrinos: FASER, 2303.14185

- Two essential aspects of this program:

  - neutrino production

  window to study parent mesons & hadronic physics

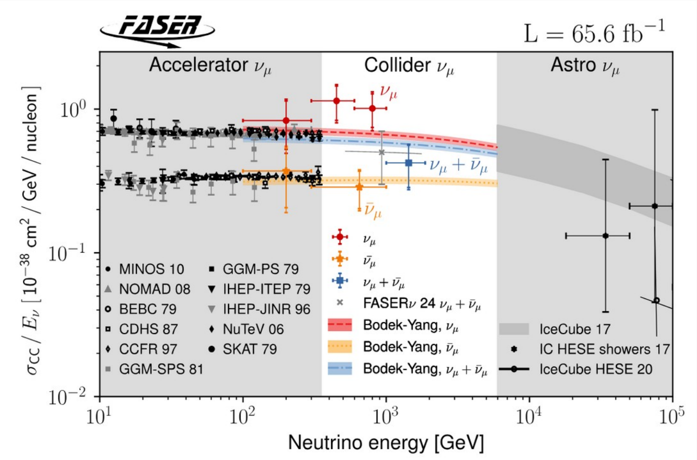
  - neutrino interaction

  sensitive to PDFs, charm production, ...

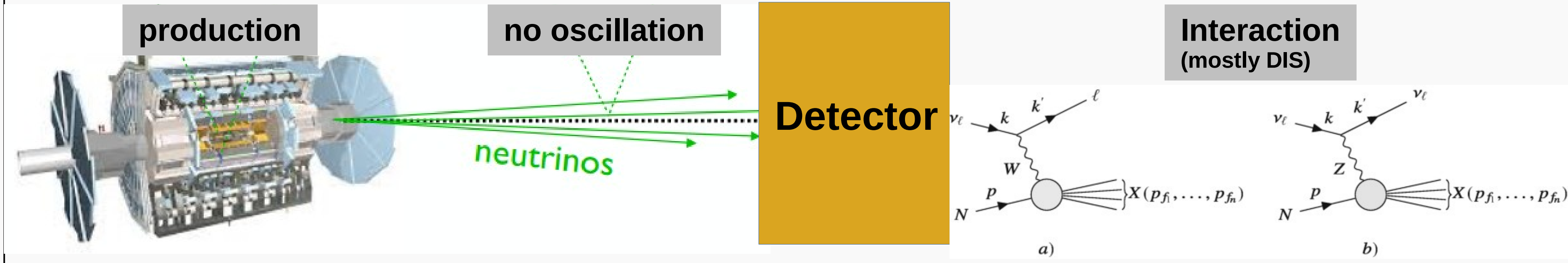
  - no oscillations expected at this L/E (in the SM)

- Flux uncertainties dominate (hadronic physics at high η)
- Could be window to new physics & rare neutrino scattering processes

FASER, 2412.03186



Neutrino Trident Production @ LHC: W. Altmannshofer etal, 2406.16803



Forward neutrinos @ LHC

FASER, 2402.13318

- Expected event rates @ LHC Run 3 (ongoing) in FASERν

  $\nu_e \sim 1$k, $\nu_\mu \sim 7$-8k, $\nu_\tau \sim$up to a few tens

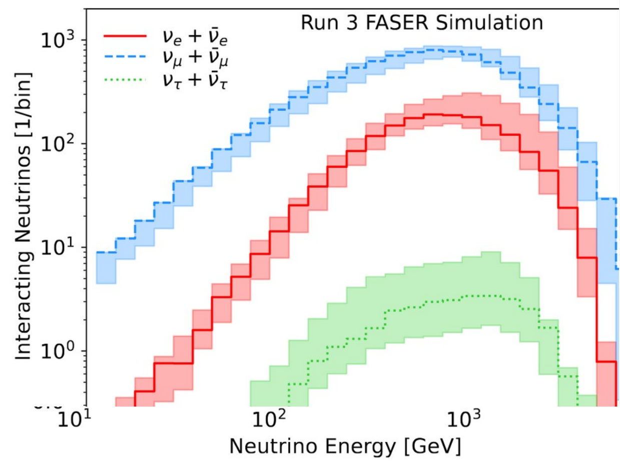
- Peak energy E_ν at a few hundred GeV

- Different mesons contribute to different neutrino flavor prod.

  & this is energy dependent

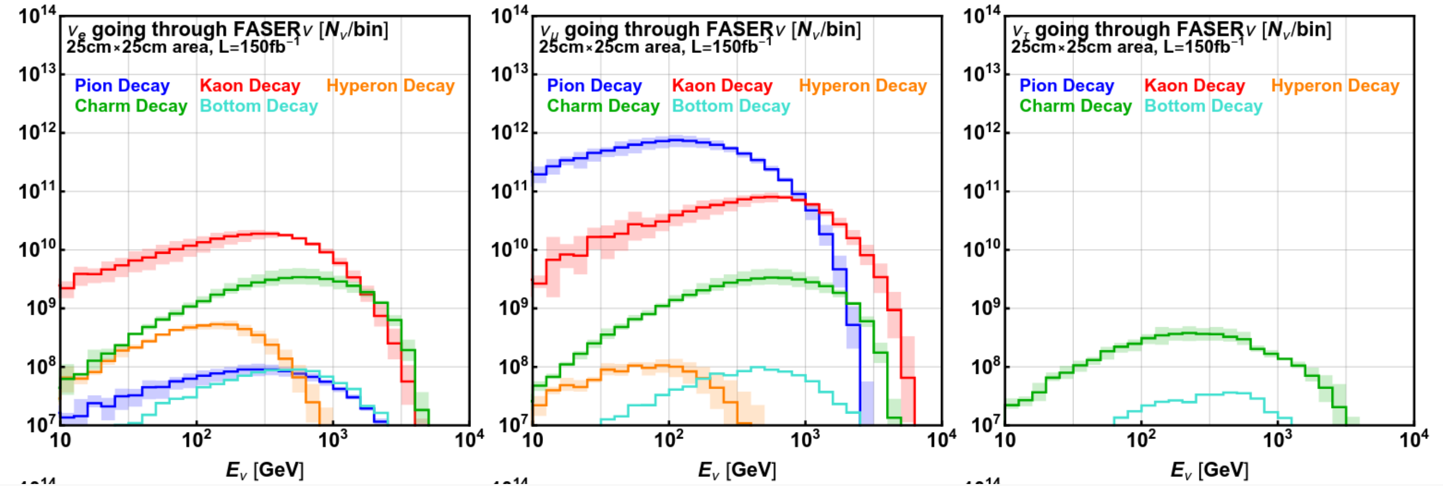
- Suppress neutrino flux uncertainties with future data

  with multivariate analysis (energy, flavor, pseudorapidity)



FASER, 1908.02310

F. Kling, T. Makela, ST, 2309.10417

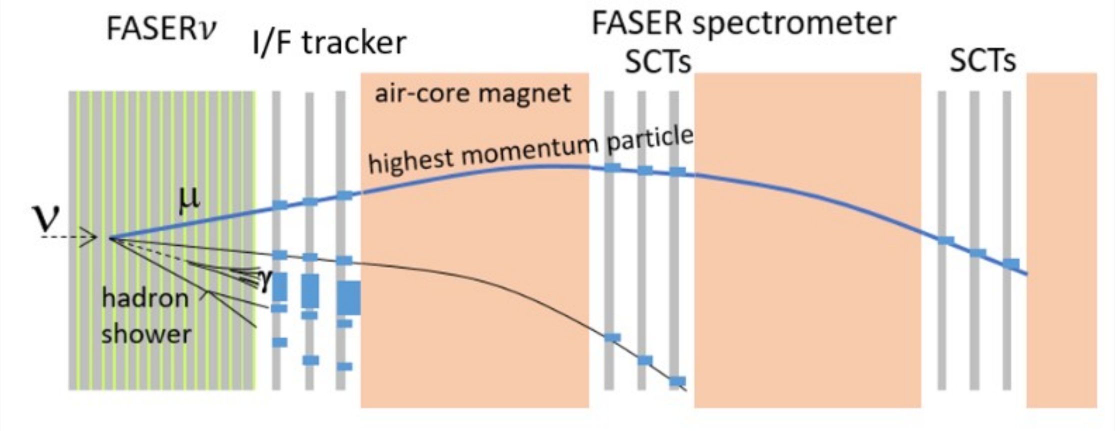


Forward neutrino detection @ FASERν

FASER, 1908.02310, 2001.03073

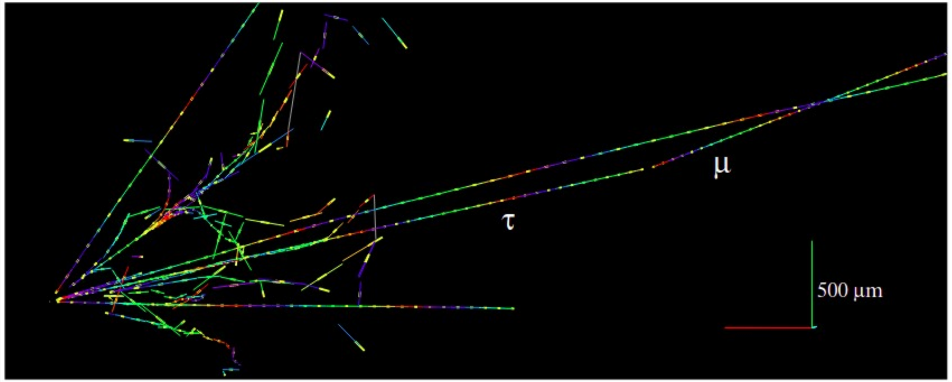
- Emulsion detector
- Good spatial & angular resolution
- No dynamic time info

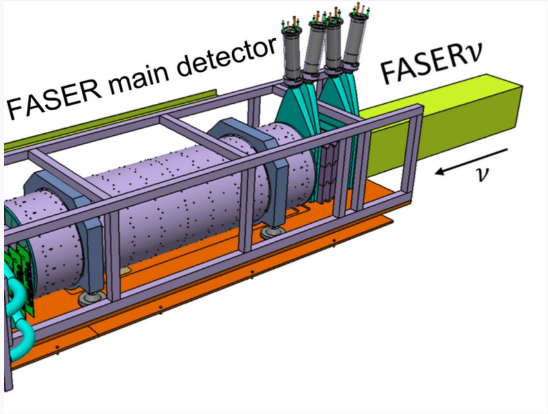
  --> muon-induced backgrounds
- Combination of emulsion + tracker:



Expected first separate observation of ν_τ and $\bar{\nu}_\tau$

ν_τ CC scattering event display in emulsion (simulation)





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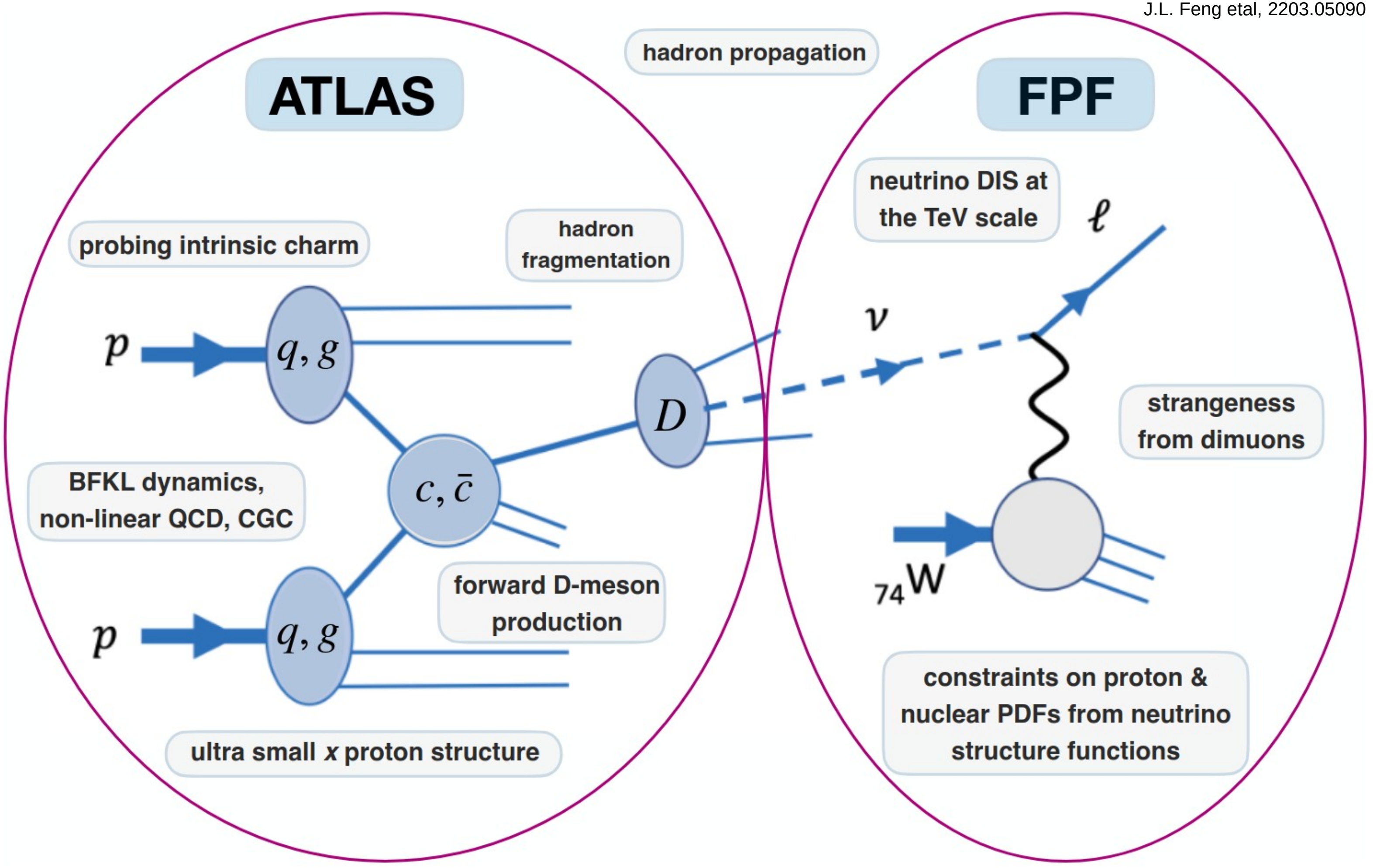
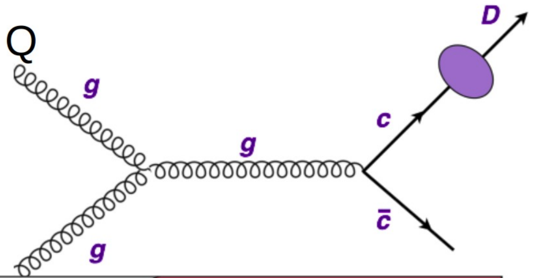
Implications for hadronic physics

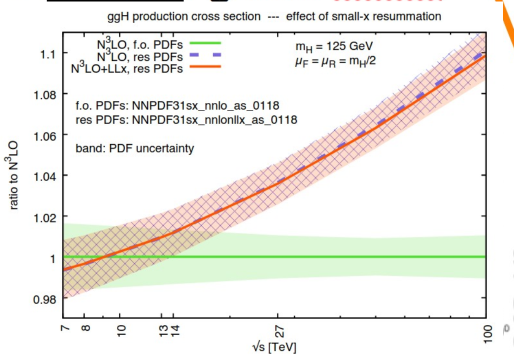
J.L. Feng etal, 2203.05090



- probes of low-x ($\sim 10^{-7}$) and high-x (~0.1-1) regimes at low Q



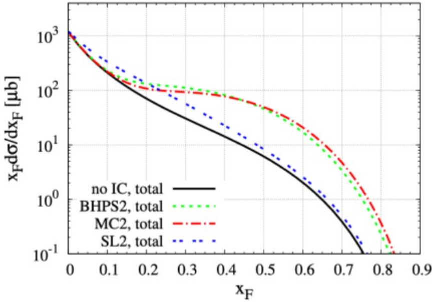
- <u>Small x</u>: **gluon PDFs**

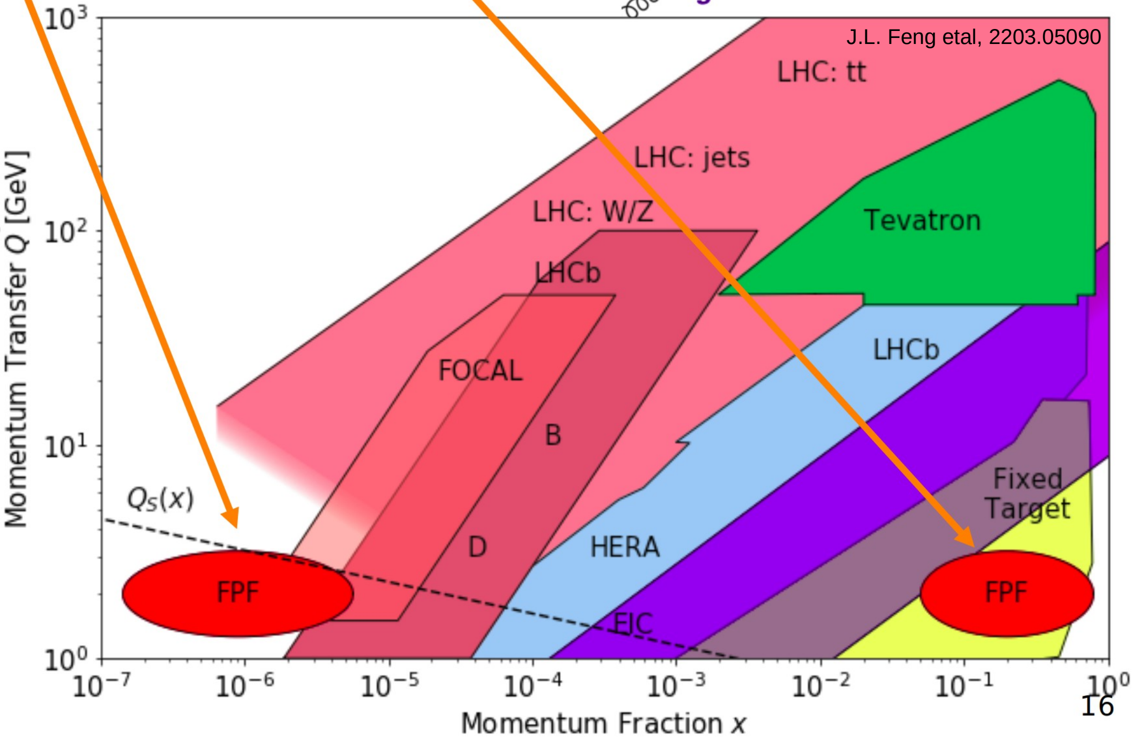


- <u>Large x</u>:

charm sea &

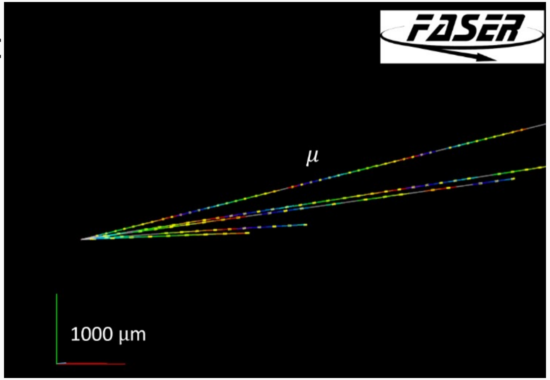
potentially **intrinsic charm**





Detailed neutrino scattering event characteristics

FASER, 2403.12520

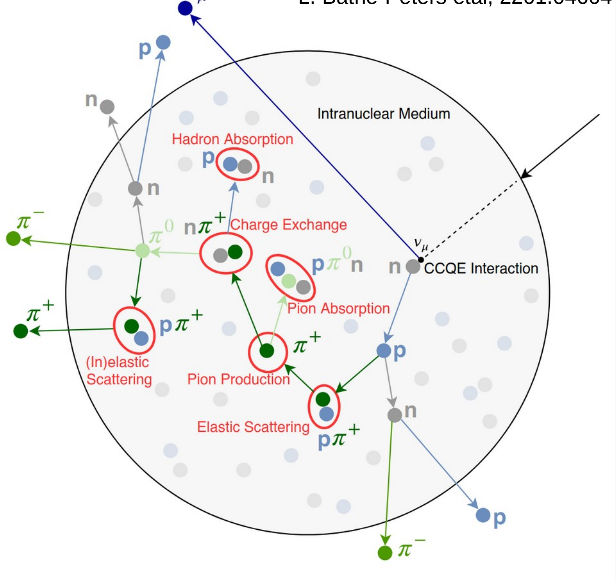


FASER, 1908.02310

- Emulsion detectors give access to detalied νN event characteristic
- Among variables considered in reconstruction are

  charged track multiplicity for p > 0.3 GeV & angles
- At such energies, in-medium effects become important

L. Bathe-Peters etal, 2201.04664



Topological Variables		related to
n_{tr}	Multiplicity of charged tracks at the neutrino interaction vertex with momentum $p_{\mathrm{tr}} > 0.3$ GeV and angle $\tan\theta_{\mathrm{tr}} > 0.3$	E_{had}
n_γ	Photon multiplicity	E_{had}
$\lvert 1/\theta_\ell \rvert$	Inverse of lepton angle with respect to neutrino direction	E_ℓ
$\sum \lvert 1/\theta_{\mathrm{had}} \rvert$	Sum of inverse of hadron track angles	E_{had}
$1/\theta_{\mathrm{median}}$	Inverse of the median of the track angles of all charged particles	E_{had}, E_ℓ
Track Momentum via MCS		
p_ℓ^{MCS}	Estimated lepton momentum from MCS	E_ℓ
$\sum p_{\mathrm{had}}^{\mathrm{MCS}}$	Sum of estimated charged hadron momenta from MCS	E_{had}
Energy in Showers		
$\sum E_\gamma$	Sum of energy in photon showers	E_{had}

In-medium effects in high-energy neutrino scatterings

- Study in-medium effects in a new energy regime
- In DIS scatterings, expected impact of color transparency – predicted in QCD…

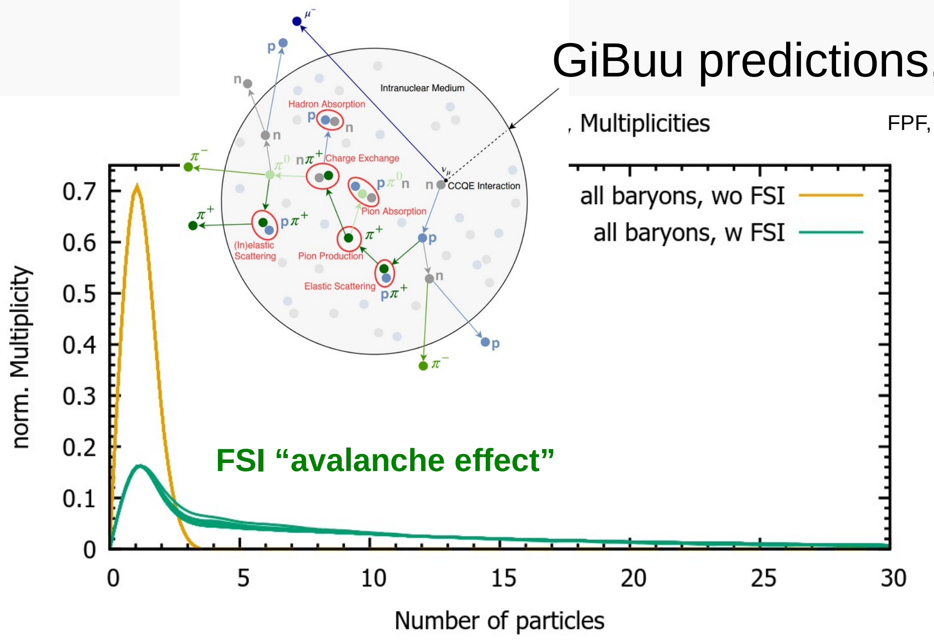
Mueller, Brodsky, 1982

… but not observed (for baryons) up to $Q^2 \sim 14\ GeV^2$

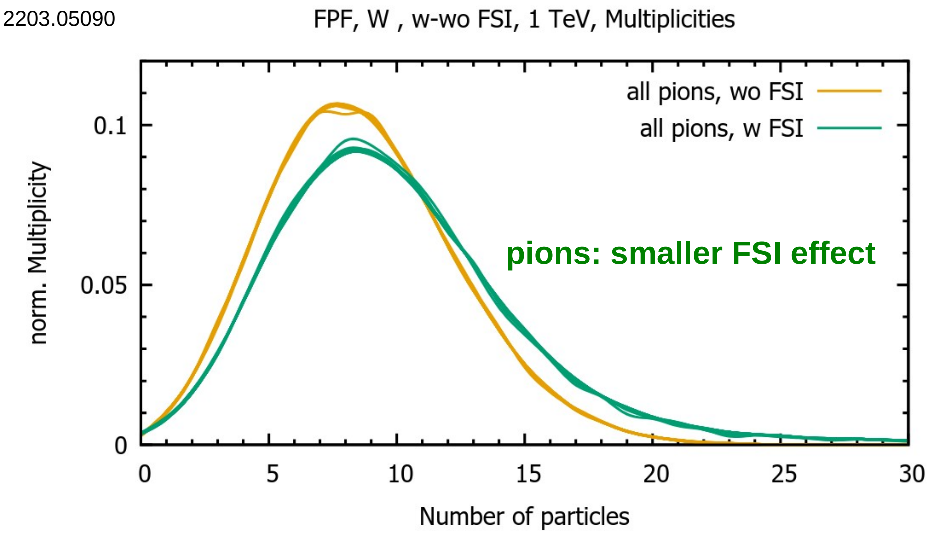
D. Bhetuwal etal, 2011.00703

- Forward neutrinos @ LHC might help resolving the problem

GiBuu predictions, 1 TeV, tungsten target

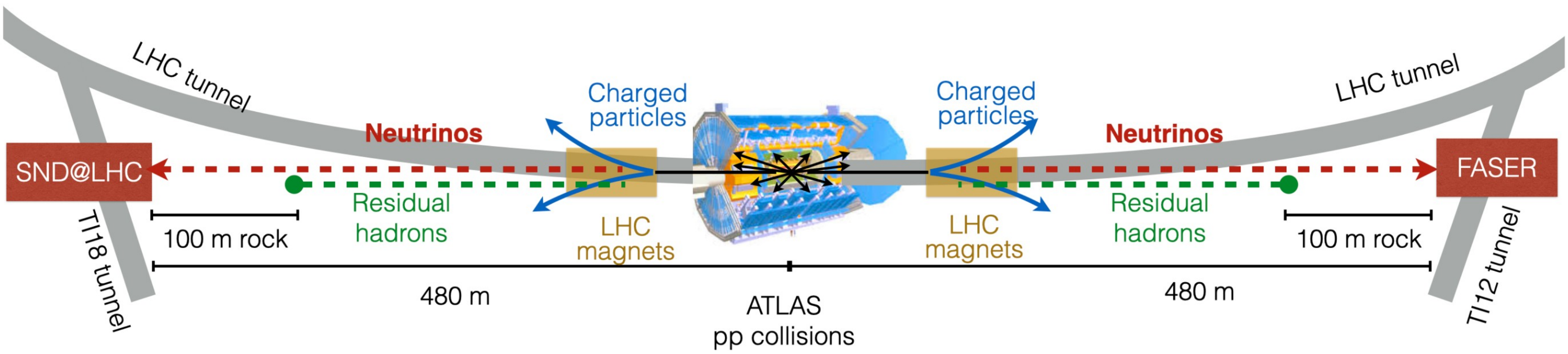


FPF, 2203.05090



Take home

- New far-forward physics program @ LHC initiated during the ongoing Run 3 data-taking period (FASER & SND@LHC experiments)
- Aims: new physics searches & high-energy neutrino measurements
- First collider neutrinos observed recently
- Window to study hadronic physics via neutrino production and in neutrino scatterings



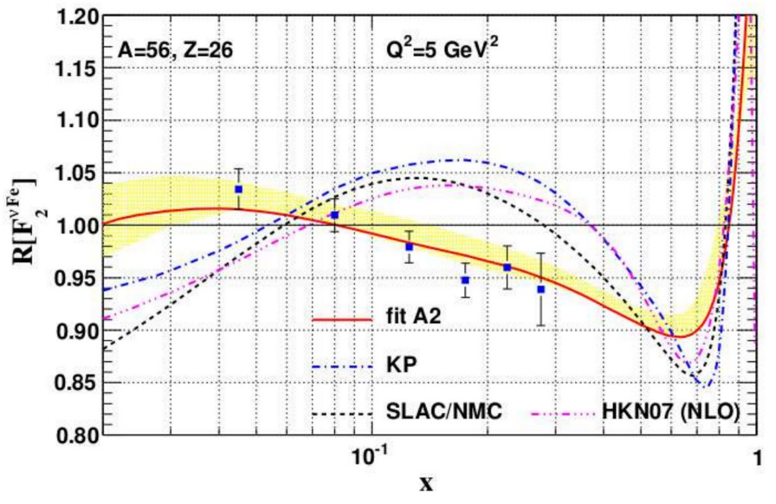
BACKUP

(Anti)shadowing

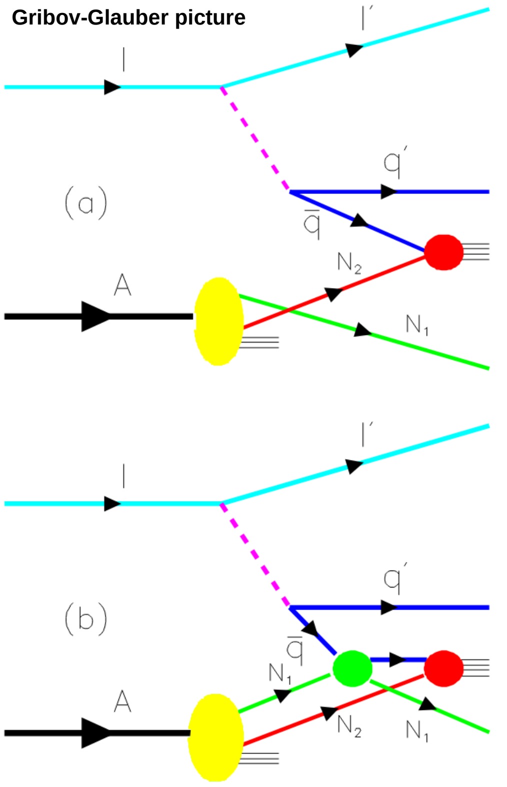
S.J. Brodsky etal, 0409279

- Expected suppression or enhancement in nuclear PDF due to coherent multile scattering off consecutive nucleons
- Neutrino behavior differs from electrons
- Nuclear correction factor $F^A_{2,3}(x,Q) = R_i(x,Q,A) F^N_{2,3}(x,Q)$
- Possibility to change target materials (nuclei) in the future

M. Sajjad Athar etal, 2206.13792



Gribov-Glauber picture



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