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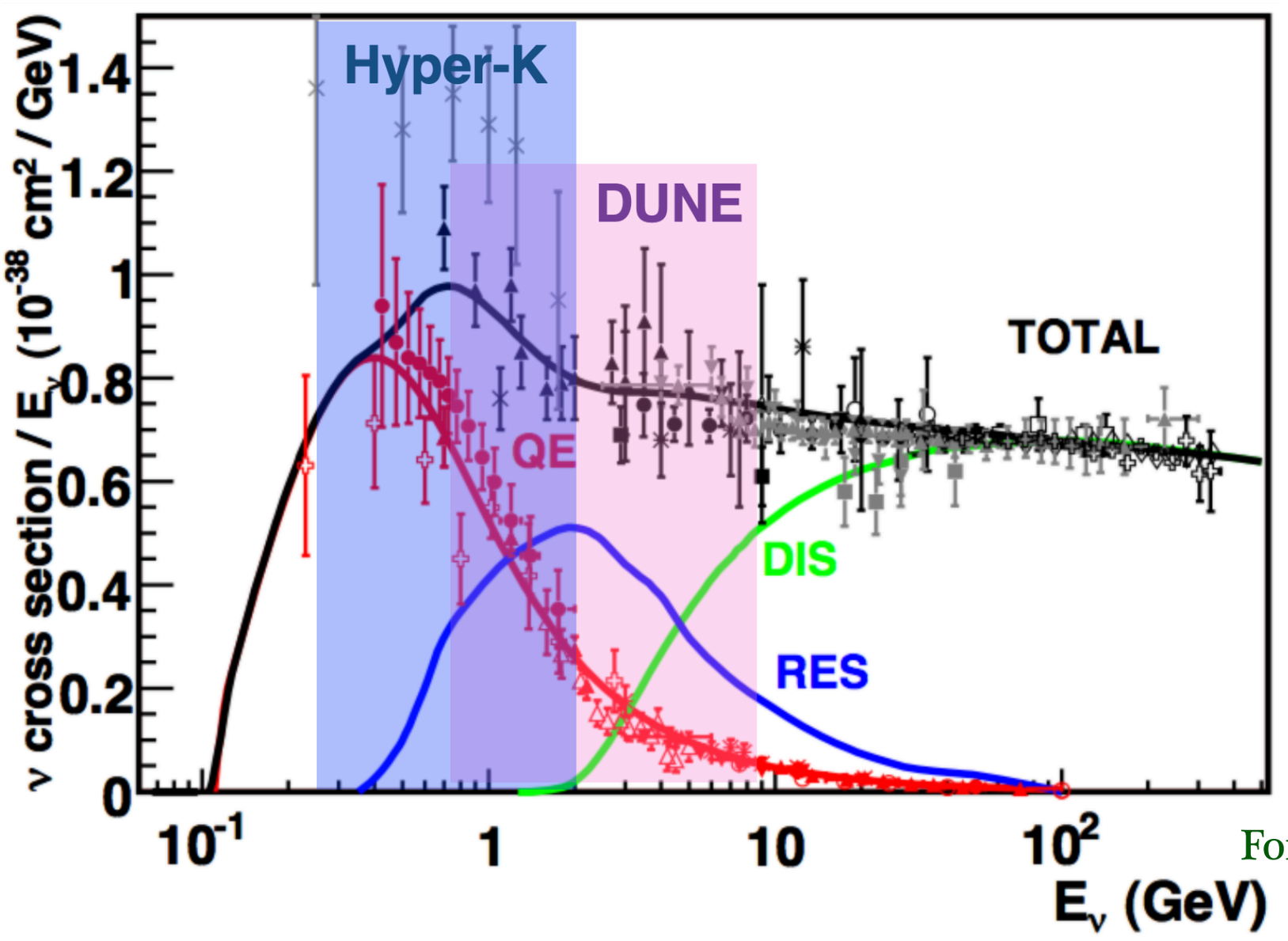
Radiative corrections to CCQE neutrino-nucleon scattering in effective field theory

Oleksandr Tomalak

Kaushik Borah, Richard J. Hill, Gabriel Lee and O. T. (arXiv: 2003.13640)
O. T. (arXiv: 2008.03527)
Qing Chen, Richard J. Hill, Kevin S. McFarland and O. T. (arXiv: to appear)

CCQE. Why should we care?

- neutrino-nucleus cross sections and future accelerator-based fluxes

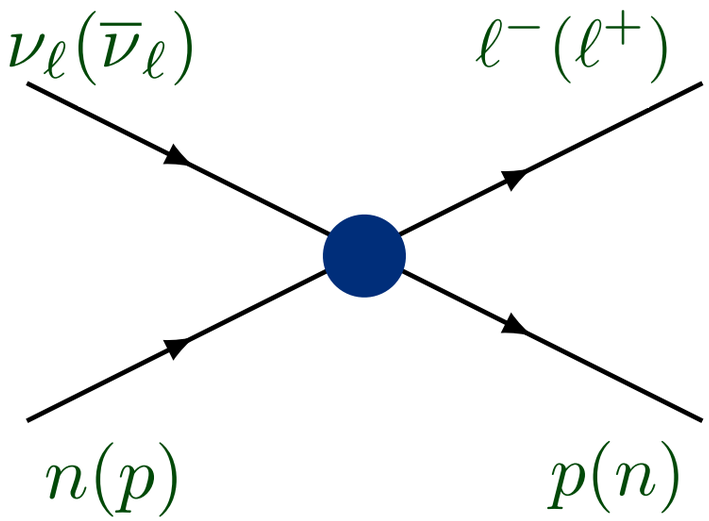


Noemi Rocco
Neutrino 2020

Formagio and Zeller (2013)

- basic process: bulk of events at Hyper-K and DUNE
- best channel for reconstruction of neutrino energy

CCQE scattering on free nucleon



$$s - u = 4ME_\nu - Q^2 - m_\ell^2$$

$$\tau = \frac{Q^2}{4M^2}$$

unpolarised observables are measured

cross section expression:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \sim \frac{M^2}{E_\nu^2}\left(A(Q^2)\frac{m_\ell^2 + Q^2}{M^2} - B(Q^2)\frac{s-u}{M^2} + C(Q^2)\left(\frac{s-u}{M^2}\right)^2\right)$$

Llewellyn Smith

- structure-dependent functions:

$$A = 2\tau(F_D^V + F_P^V)^2 - (1+\tau)\left[(F_D^V)^2 + \tau(F_P^V)^2 - (F_A)^2\right]$$
$$- \frac{m_\ell^2}{4M^2}\left[(F_D^V + F_P^V)^2 + (F_A + 2F_P)^2 - 4(1+\tau){F_P}^2\right]$$

$$B = \pm 4\tau F_A(F_D^V + F_P^V) \quad C = \frac{1}{4}\left[(F_D^V)^2 + \tau(F_P^V)^2 + (F_A)^2\right]$$

- cross section measurements give us axial form factor

CCQE scattering on free nucleon

- only 3 experiments performed with deuterium bubble chamber

direct access to form-factor shape

ANL 1982: 1737 events

BNL 1981: 1138 events

FNAL 1983: 362 events

world data: ~3200 events

Fermilab bubble chamber, Richard Drew

- cross section measurements give us axial form factor

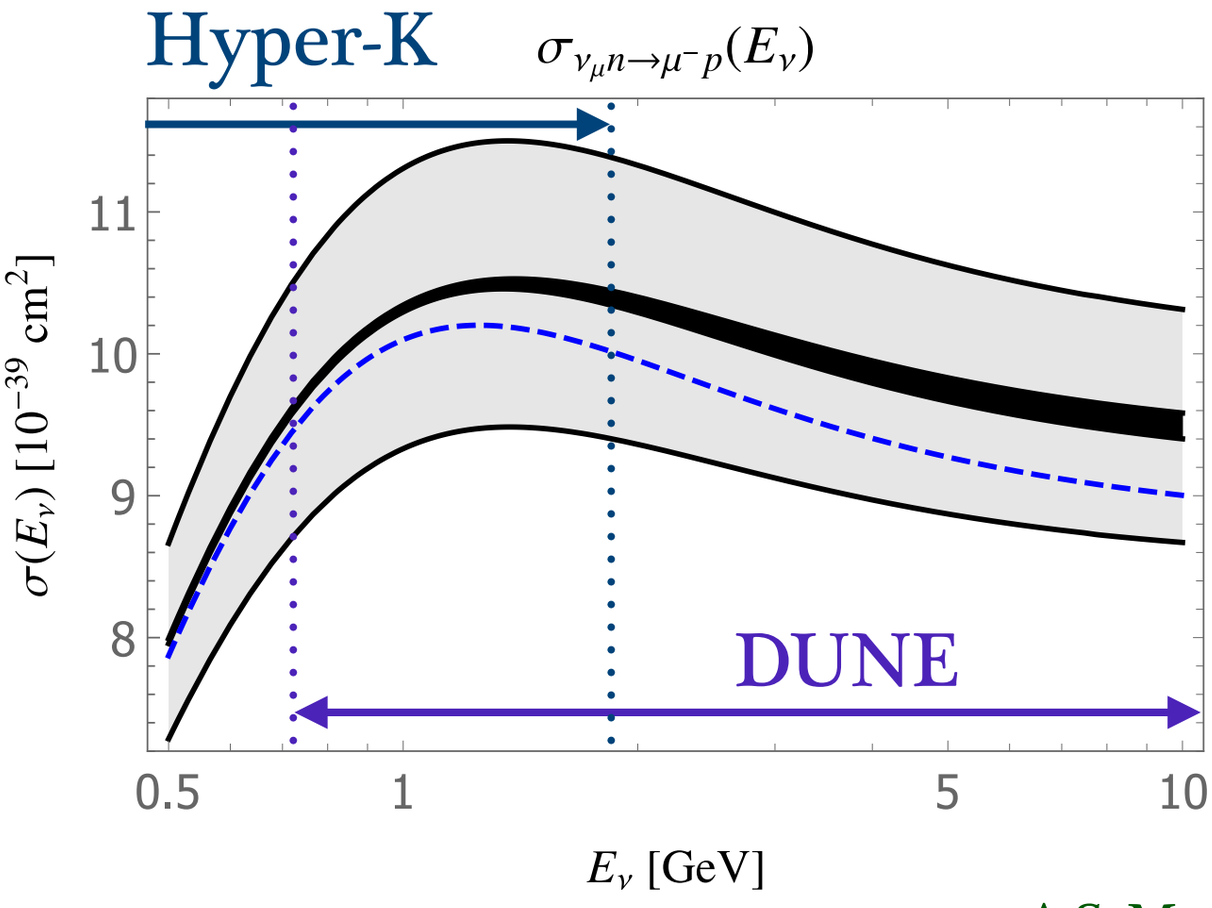
A.S. Meyer, M. Betancourt, R. Gran and R.J. Hill (2016)

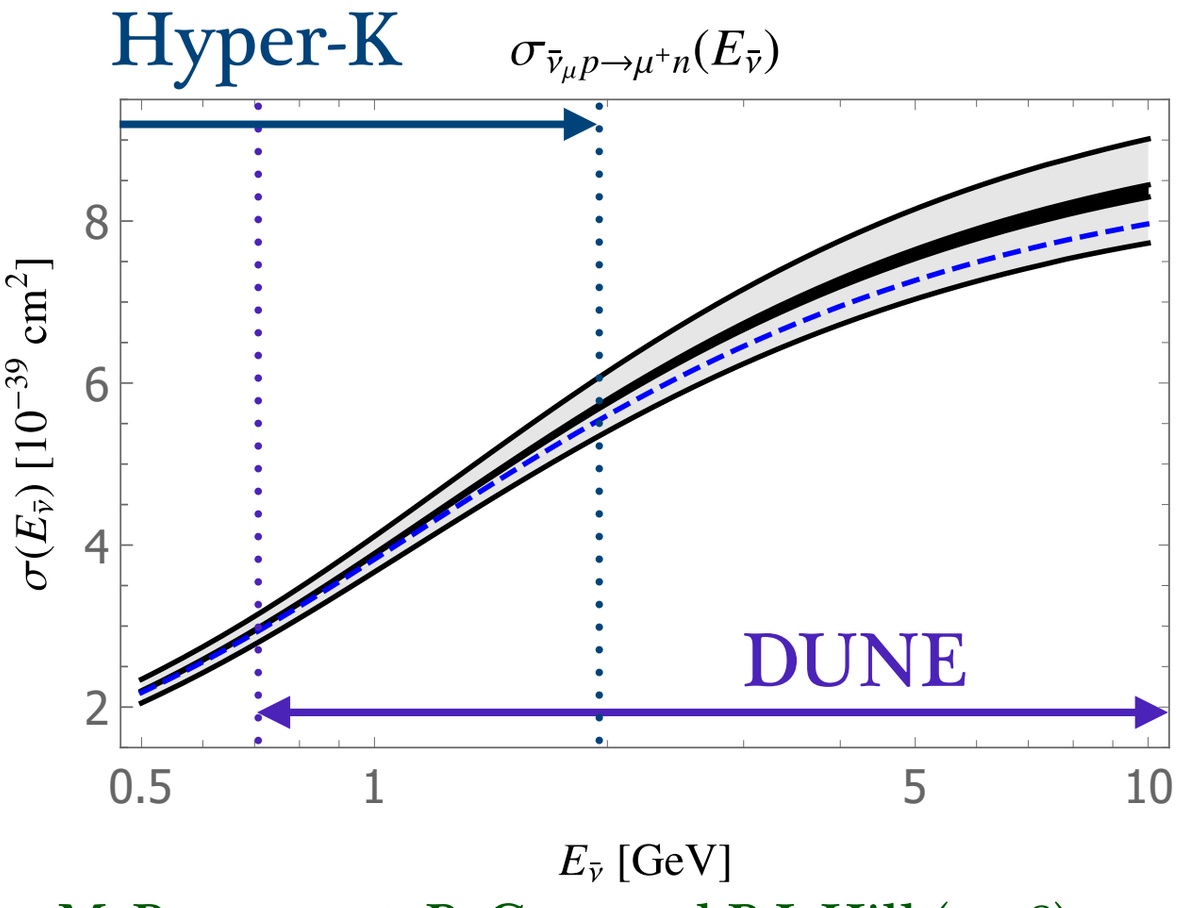
CCQE scattering cross section

- dark band: uncertainty of iso 1 fit

- light band: uncertainty of axial form factor

- blue line: BBBA2005 fit of electromagnetic form factors



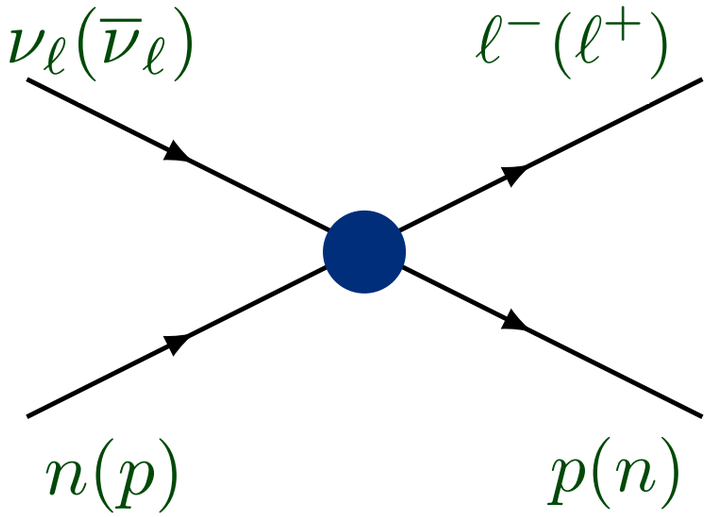


A.S. Meyer, M. Betancourt, R. Gran and R.J. Hill (2016)

Kaushik Borah, Richard J. Hill, Gabriel Lee and O. T. (arXiv: 2003.13640)

- strong motivation to reduce 10-20% axial form factor error

Form factors and polarization observables



polarized target and/or recoil

$$A = \frac{\mathrm{d}\sigma\left(S\right) - \mathrm{d}\sigma\left(-S\right)}{\mathrm{d}\sigma\left(S\right) + \mathrm{d}\sigma\left(-S\right)}$$

- spin asymmetries are not suppressed by m_ℓ or coupling constant: comparable to unpolarized cross section rates

- sensitivity to axial form factor at GeV muon antineutrino energies

recent studies: Samoil M. Bilenky and Ekaterina Christova (2013)
Krzystof M. Graczyk and Beata E. Kowal (2019)

- sensitivity to pseudoscalar form factor with tau (anti)neutrino and muon (anti)neutrino of hundreds MeV energies O. T. (arXiv: 2008.03527)

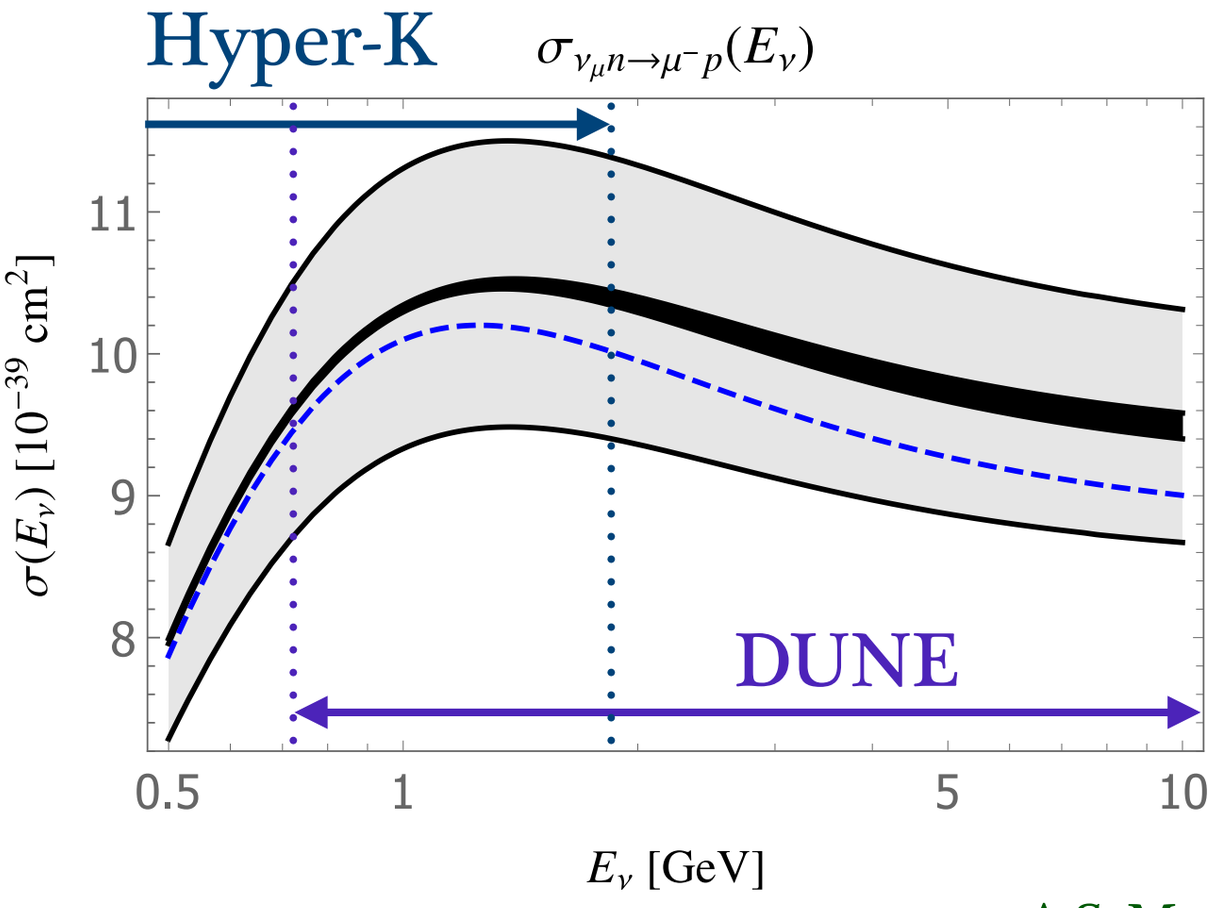
- pseudoscalar form factor can be accessed independently
- sizable contribution of axial form factor at GeV energies

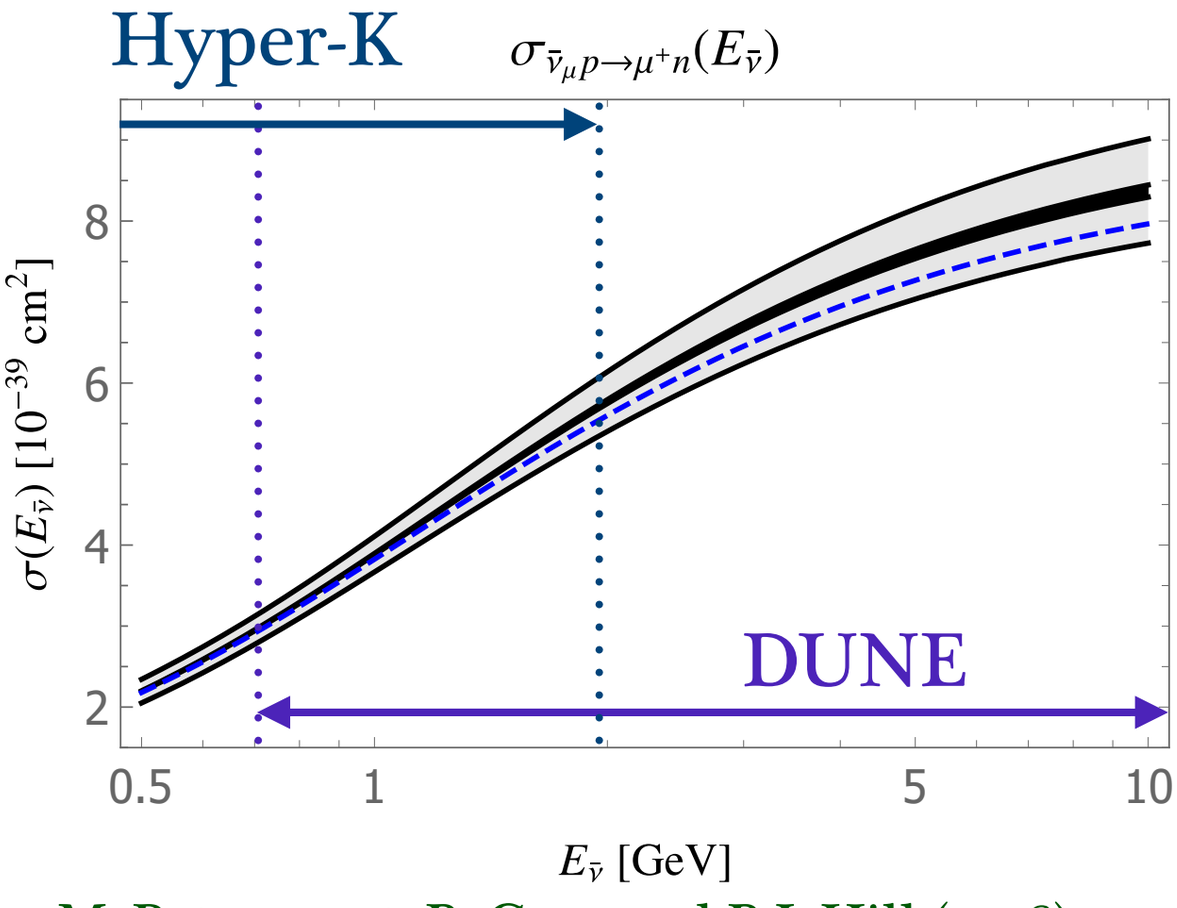
CCQE scattering cross section

- dark band: uncertainty of iso 1 fit

- light band: uncertainty of axial form factor

- blue line: BBBA2005 fit of electromagnetic form factors





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- strong motivation to reduce 10-20% error of axial form factor

Radiative corrections in CCQE

- large kinematical logarithms enhance radiative corrections

$\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by $\ln \frac{E_\nu}{m_\ell} \sim 6 - 10$

A. De Rujula, R. Petronzio and A. Savoy-Navarro (1979)
Melanie Day and Kevin S. McFarland (2012)
O. Tomalak and R.J. Hill (2020)

- CCQE with electron flavor is subject to large corrections

- phase-space restrictions enhance radiative corrections

$\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by $\ln^2 \frac{E_\nu}{m_\ell} \sim 36 - 100$

$E_\gamma < \Delta E$ soft photons $4 \ln \frac{E_\nu}{m_\ell} \ln \frac{\Delta E}{m_\ell} \sim 70 - 120$

smaller collinear logarithms

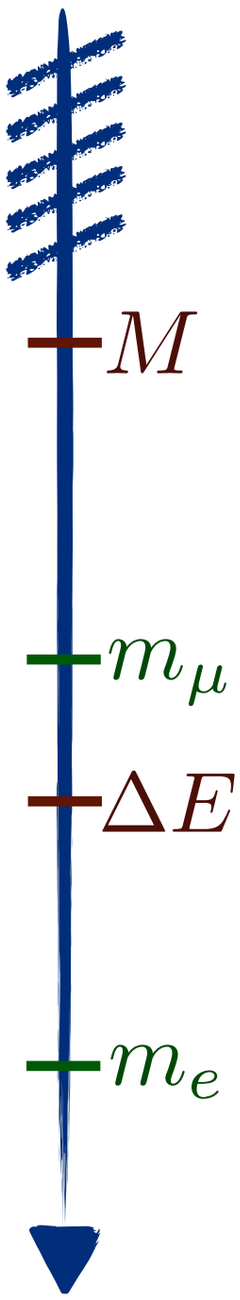
- crucial dependence on detector details

- radiative corrections crucial for %-level oscillation expts

Factorization approach

- cross section with soft photons is given by factorization formula

$$\mathrm{d}\sigma \sim S\left(\beta_\ell, \frac{\Delta E}{\mu}\right) J\left(\frac{m_\ell}{\mu}\right) H\left(\frac{M}{\mu}, \ldots\right) + \mathrm{O}\left(\frac{m_\ell^2}{M^2}, \frac{m_\ell^2}{M E_\nu}\right)$$

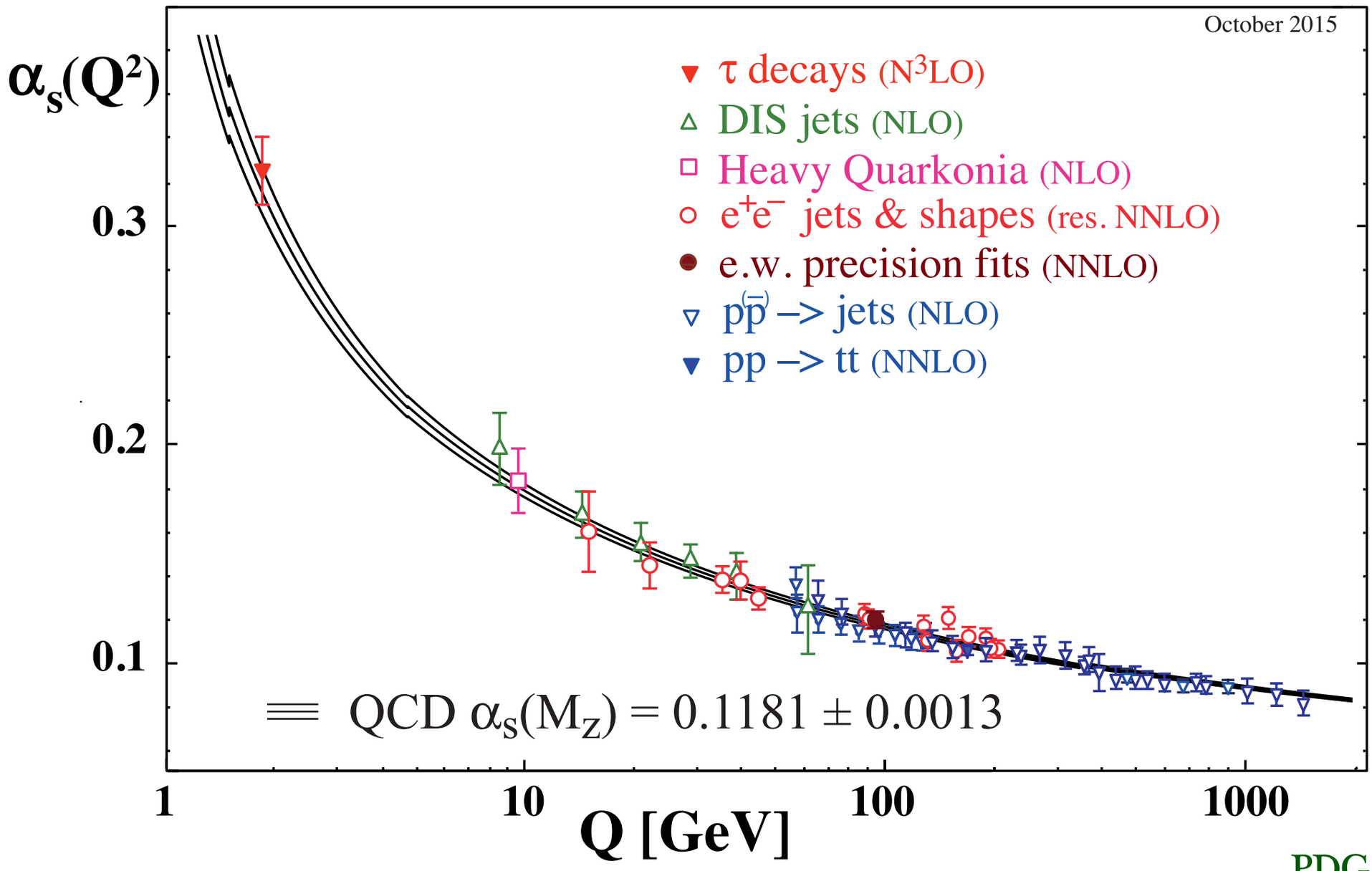


- determine hard function at hard scale matching

  experiment or model to the theory with heavy nucleon

Interaction with nucleons

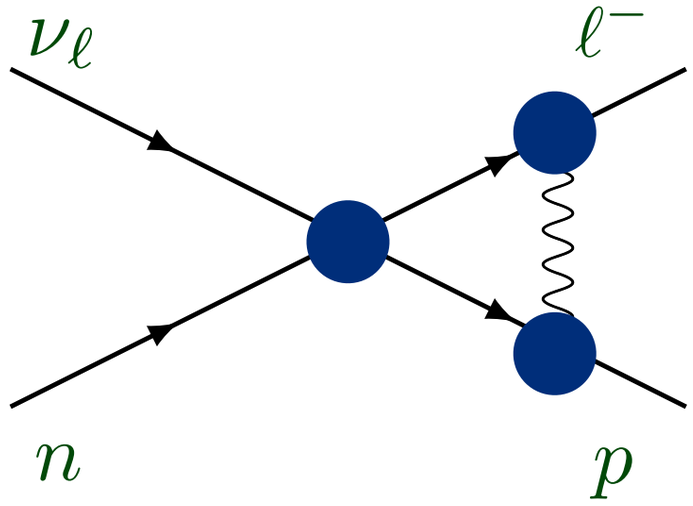
- QCD running coupling



PDG 2015

- hadrons are correct degrees of freedom at GeV energy

Hadronic model at GeV scale



- exchange of photon between the charged lepton and proton

- assume onshell form for each interaction vertex

discussed for CCQE: Krzystof M. Graczyk (2013)

- add self energy for charged particles

- the best determination of hard function

- add real soft and collinear radiation on top

- correct kinematical and infrared logarithms

Factorization approach

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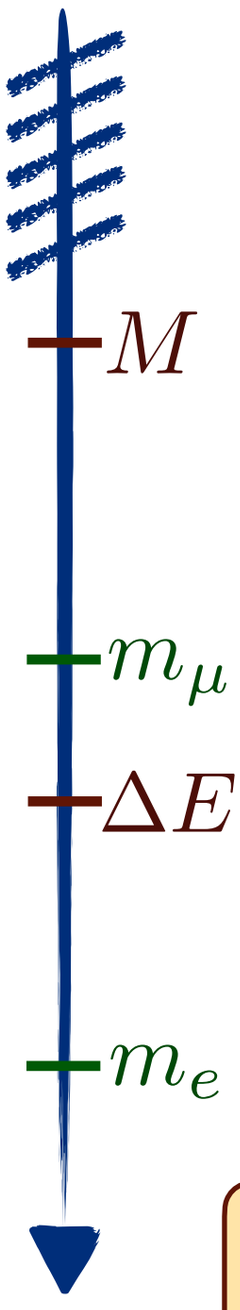
$$\mathrm{d}\sigma \sim S\left(\beta_\ell, \frac{\Delta E}{\mu}\right) J\left(\frac{m_\ell}{\mu}\right) H\left(\frac{M}{\mu}, \ldots\right) + \mathrm{O}\left(\frac{m_\ell^2}{M^2}, \frac{m_\ell^2}{M E_\nu}\right)$$



- determine hard function at hard scale matching
  experiment or model to the theory with heavy nucleon

- RGE evolution of the hard function to scales $\Delta E, m_\ell$

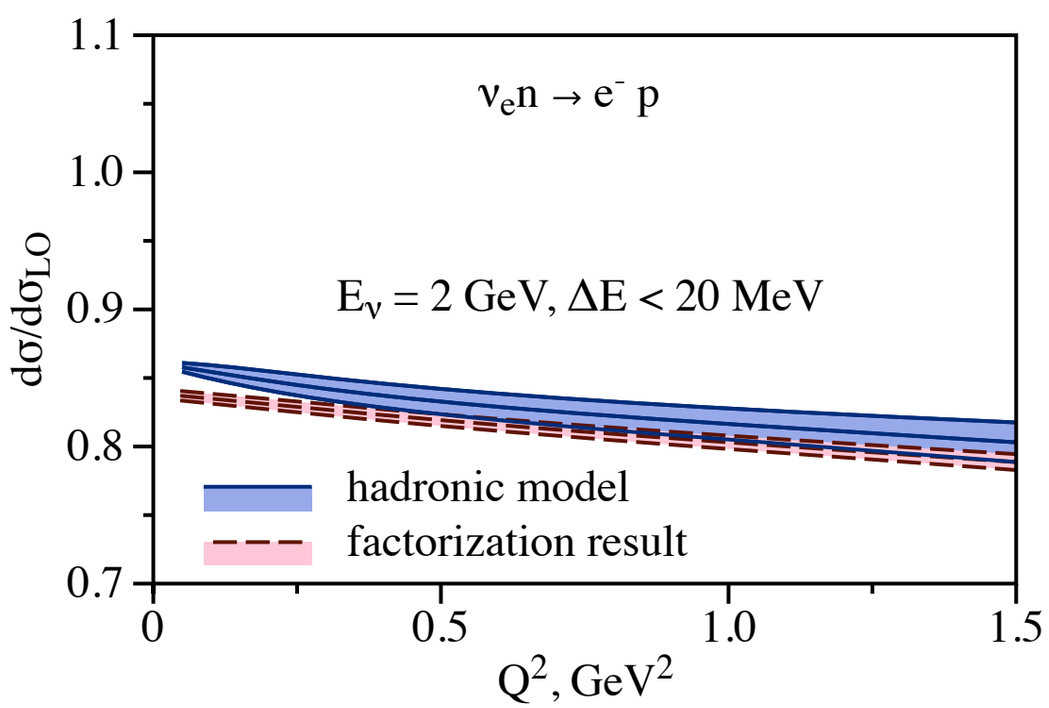
- soft and collinear functions are evaluated perturbatively

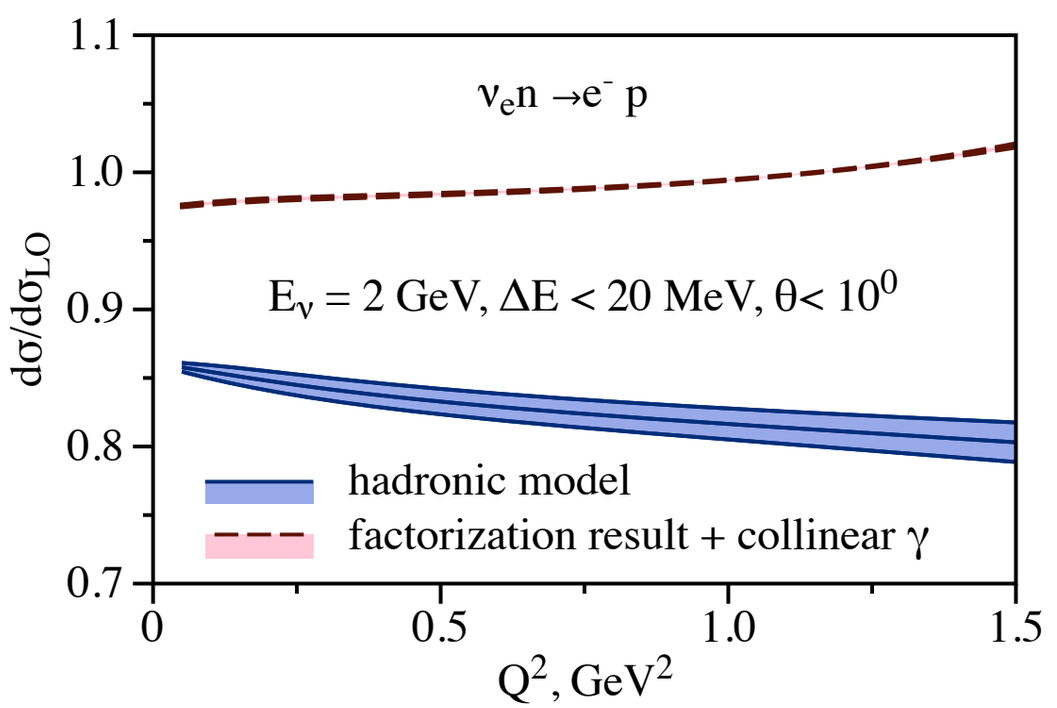
- calculate cross section at low energies accounting for all large logs

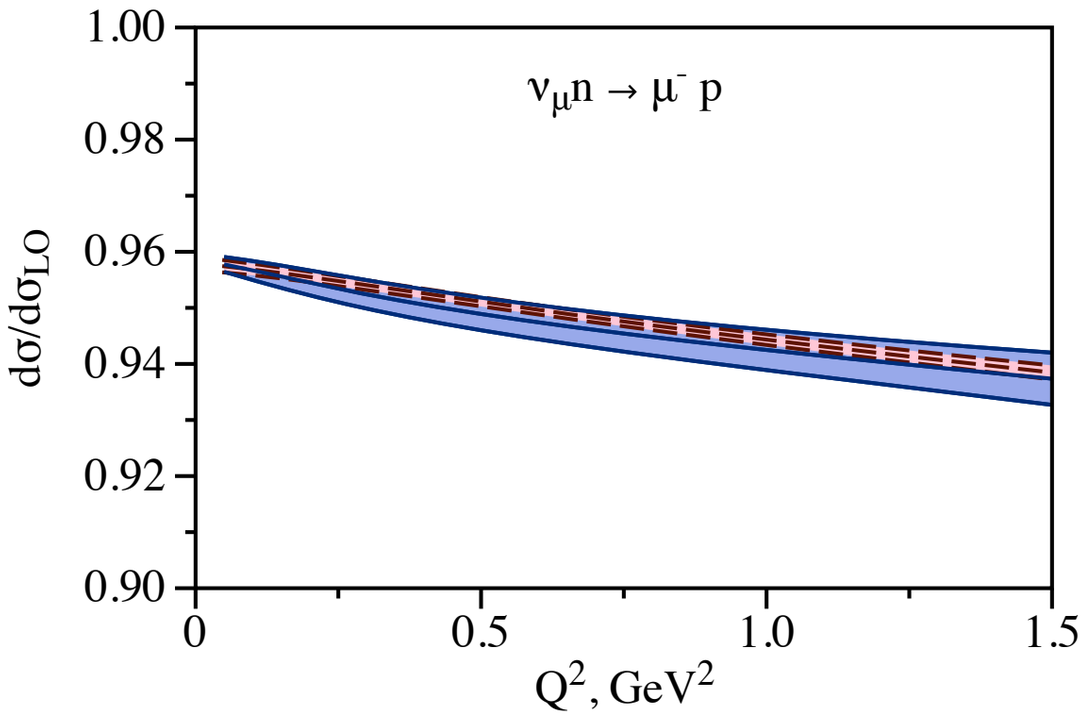
ep scattering: R.J. Hill (2016)

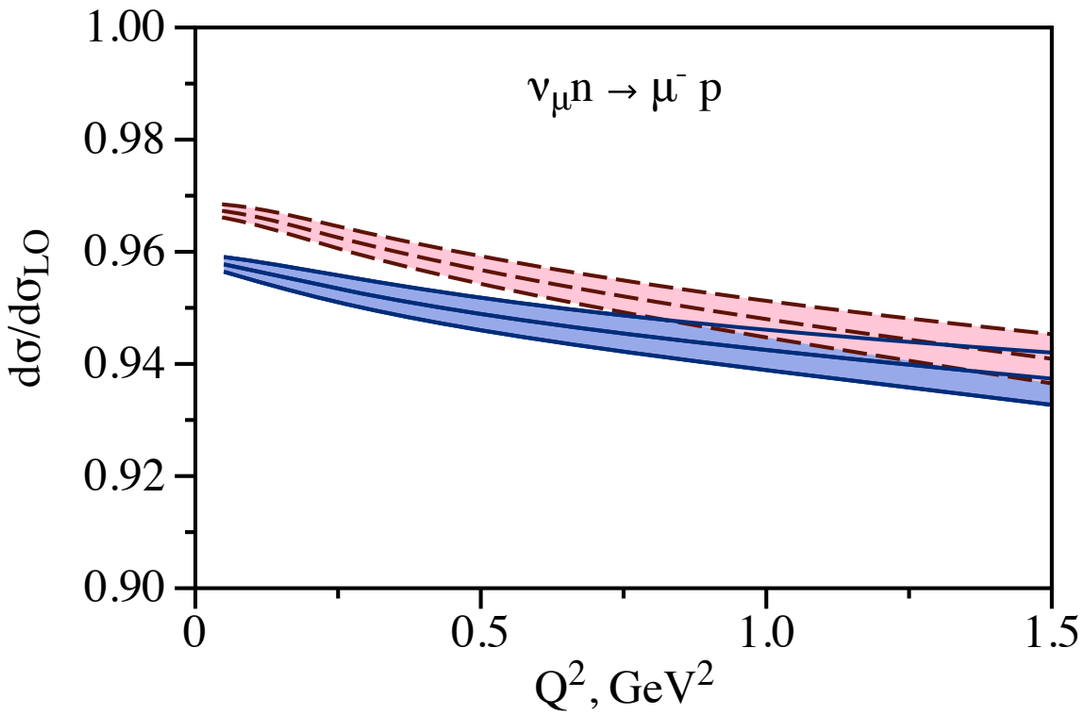
- soft and collinear functions obtained analytically
- hard function describes physics at GeV energies

Cross section. Preliminary results



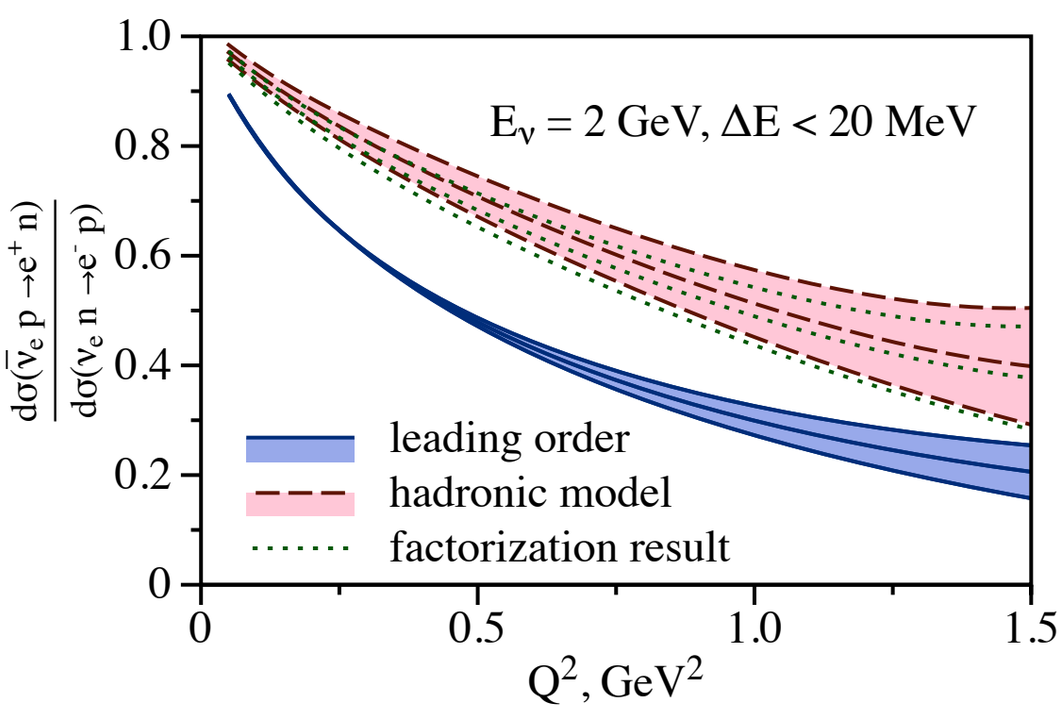


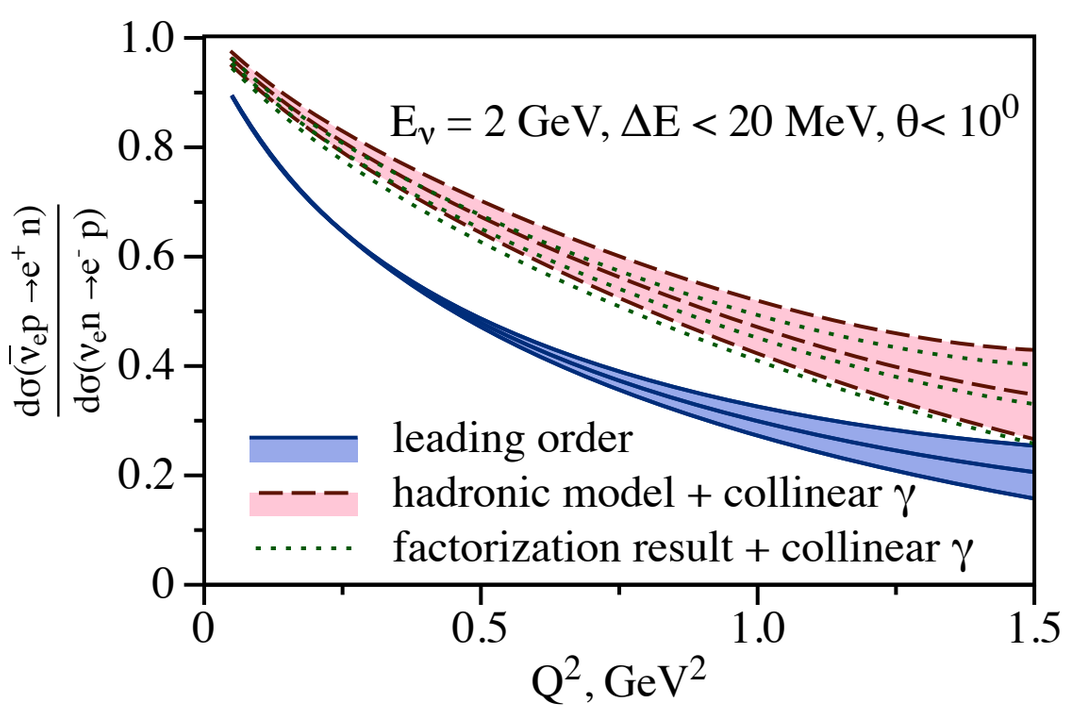


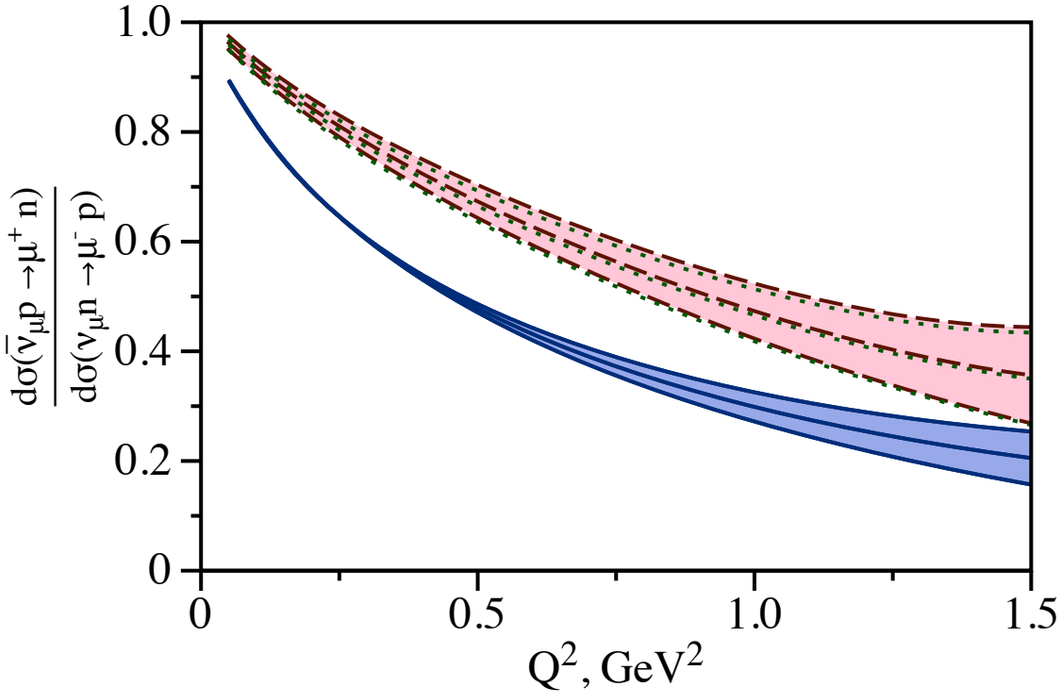


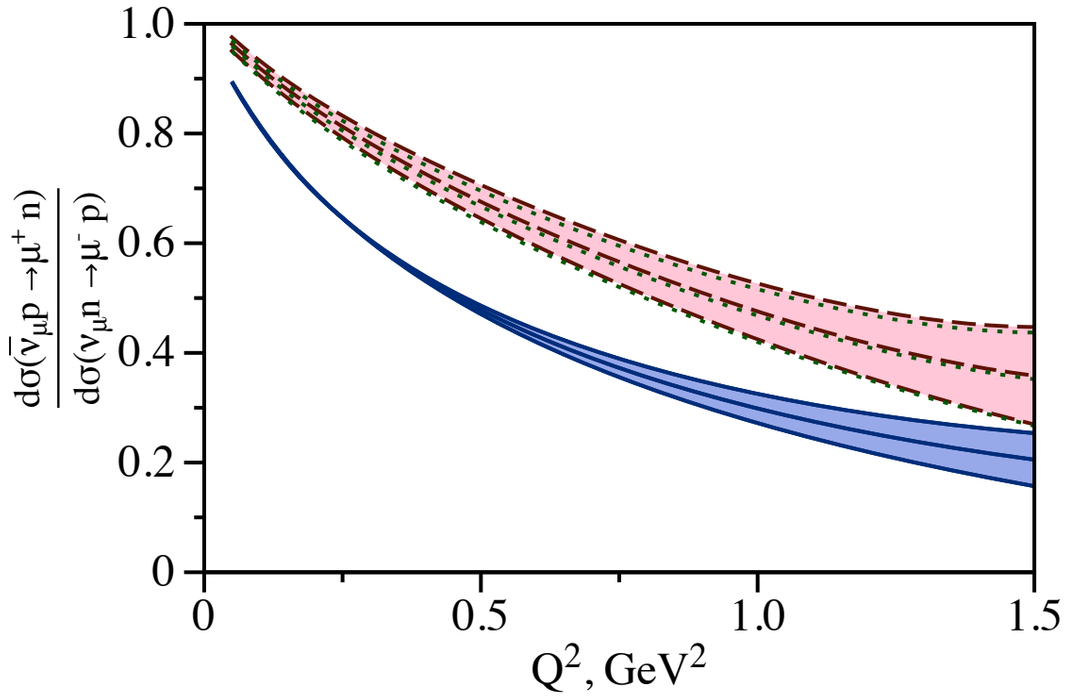
- corrections with e larger; cancellation virtual vs real

Cross section. Preliminary results



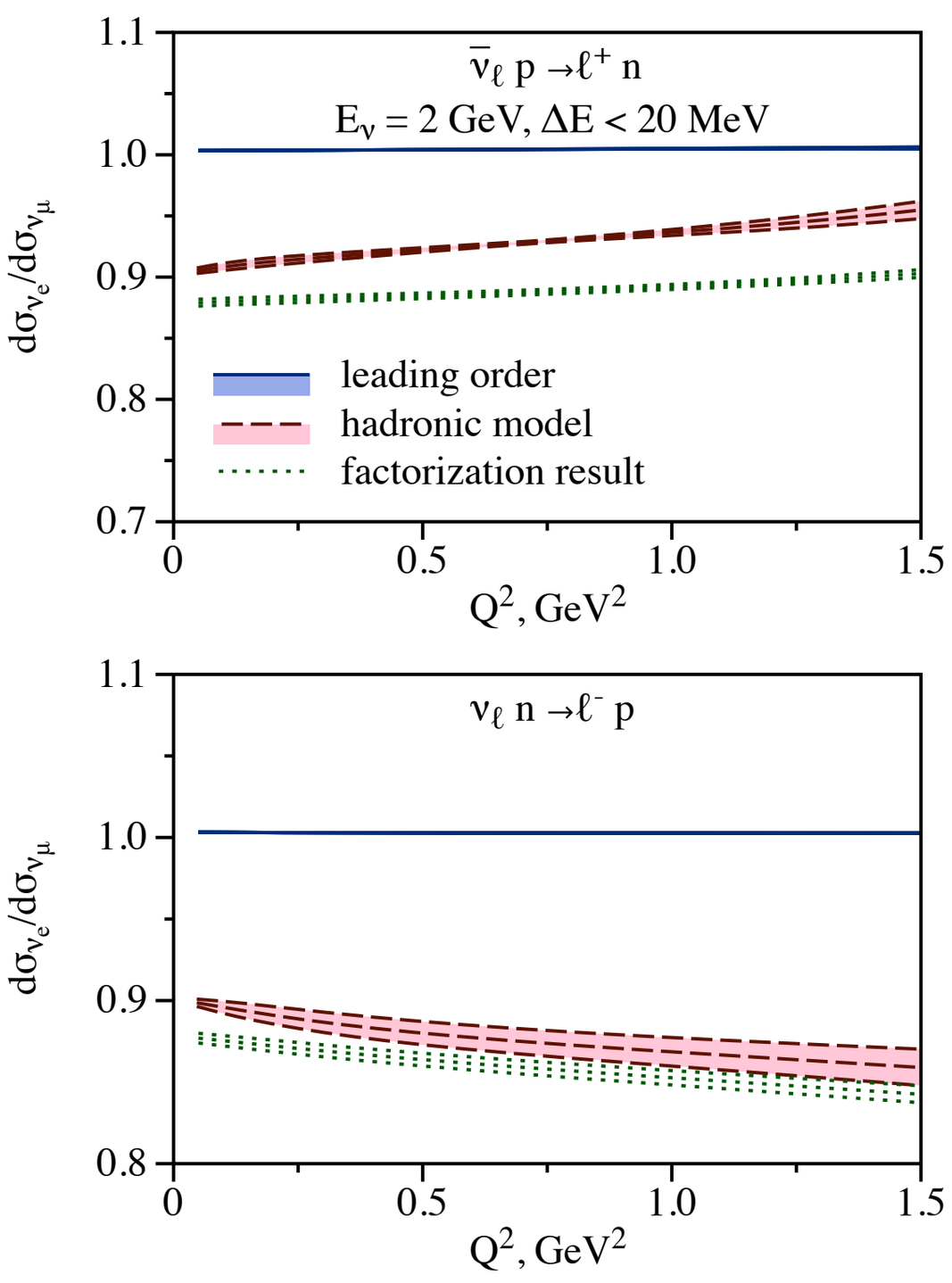


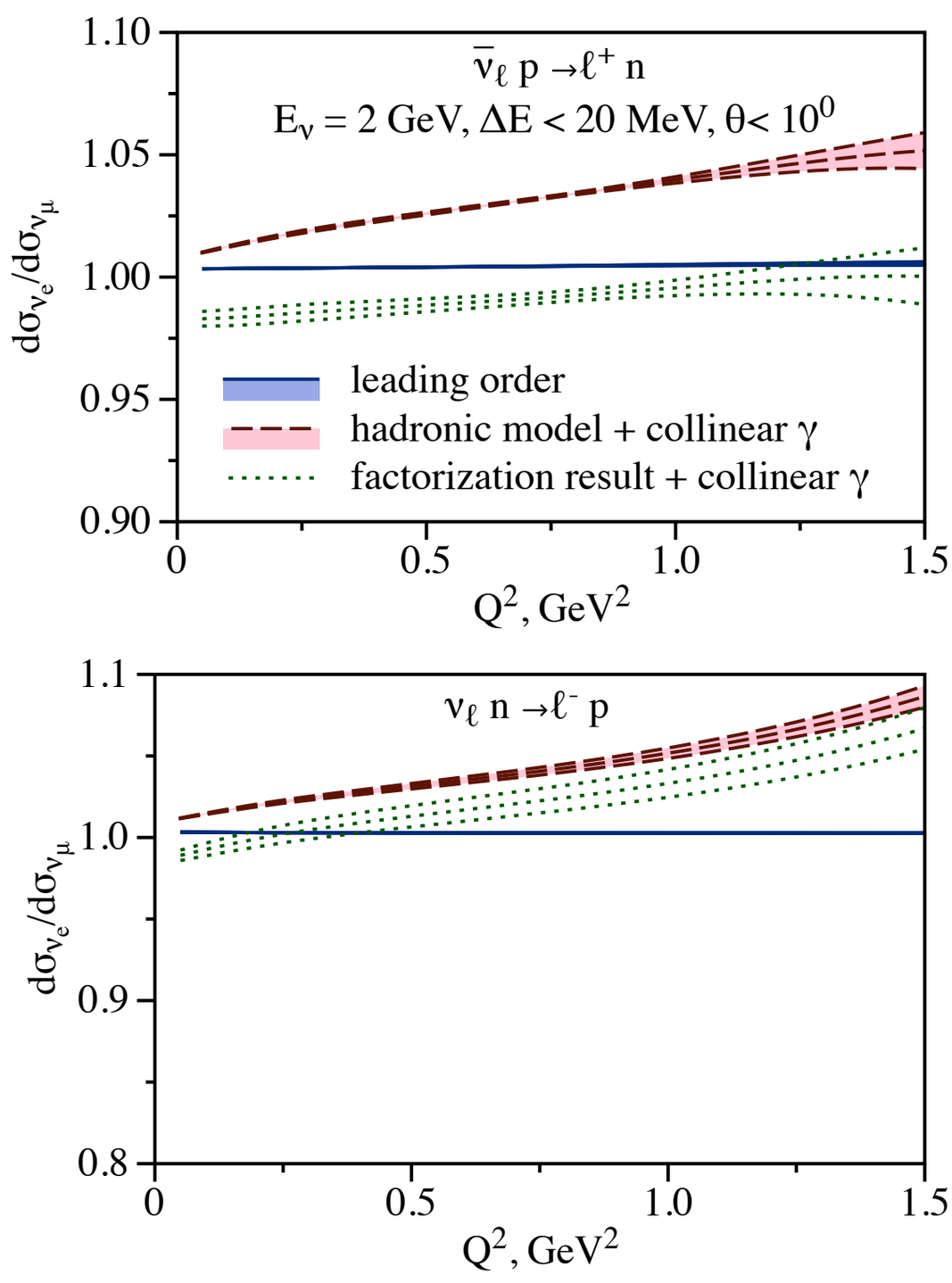




- similar muon and electron anti- over neutrino ratios

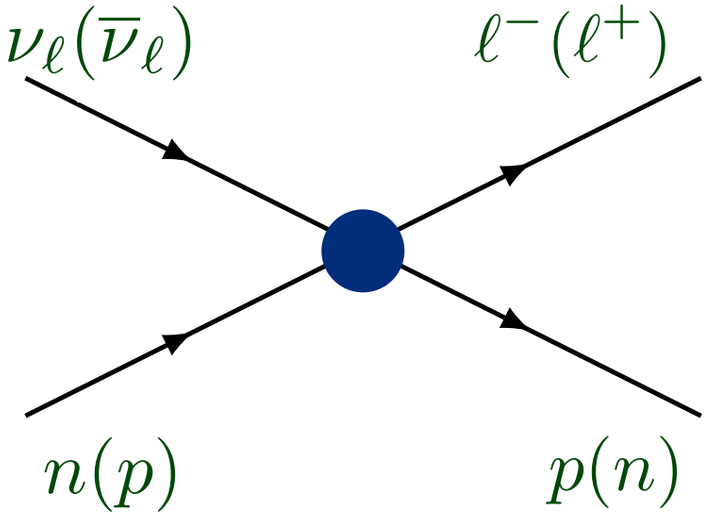
Cross section. Preliminary results





- similar muon and electron cross sections with collinear ɣ

Conclusions



signal channel

energy reconstruction

axial form factor

neutrino flux

- radiative corrections are formulated in factorization framework
- model for hard function: hadronic model with nucleon state
- kinematical, phase-space and perturbative logarithms included
- radiative corrections are calculated with % level of accuracy

Ongoing

- improve error estimate
- quantify details of real radiation

Thanks for your attention !!!