Connections to the Electron-Ion Collider

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U.S. DEPARTMENT OF ENERGY

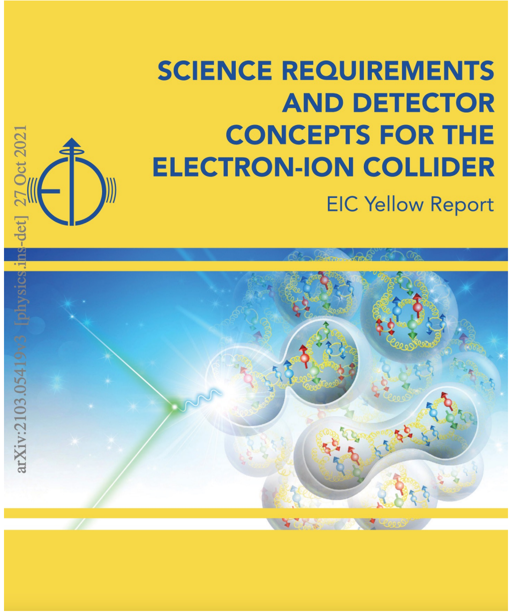
Los Alamos NATIONAL LABORATORY

Outline of the lecture

- Introduction and motivation, and the Electron-Ion Collider
- Effective field theory for charged lepton interactions in nuclear matter
- Inclusive neutrino-nucleus scattering (DIS regime) and dynamical shadowing effects
- Semi-inclusive lepton-nucleus scattering, hadronic and jet final states
- Conclusions

i) Thanks to the organizers for the invitation to give this lecture
ii) Credit for the work presented goes to my collaborators

For more information on the Electron-Ion Collider (EIC)

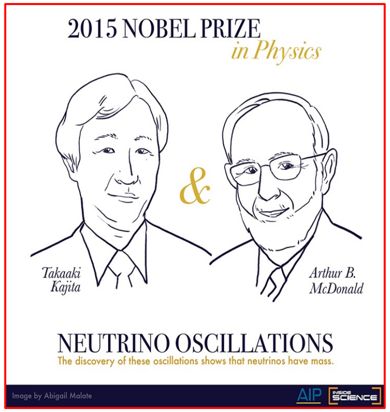


R. Abdul-Khalek et al. (2021)

Excellent sets of lectures have covered the fundamentals, including nuclear structure effects

Neutrinos as portals to new physics

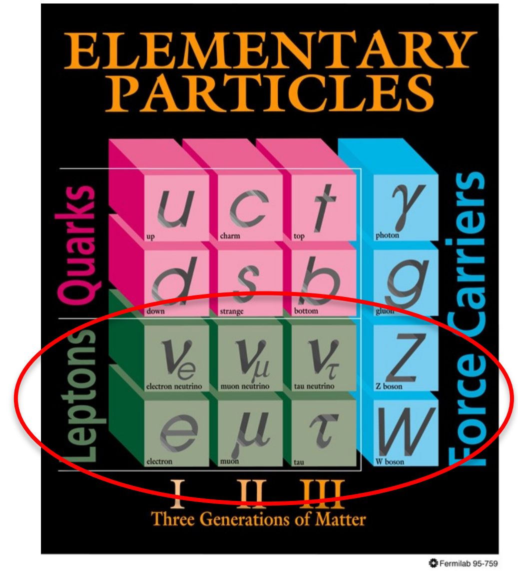
Massless neutrinos are part of the SM

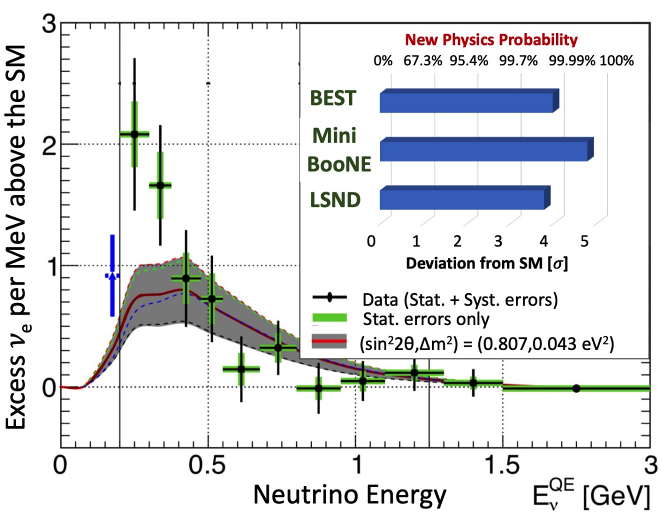


- In 1998 the Super-Kamiokande experiment discovered neutrino flavor oscillations in atmospheric neutrinos
- Oscillations confirmed by measuring the flux of solar neutrinos at the Sudbury Neutrino Observatory (SNO) in 2001

Y. Fukuda et al. (1998)

Q. Ahmad et al. (2001)



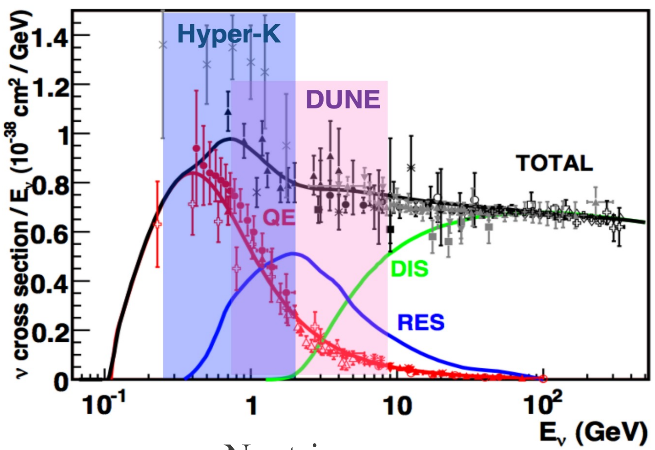


– **The nature of neutrinos, existence of sterile neutrinos, mass hierarchy and mixing angles. Are neutrinos Dirac or Majorana?**

– **Charge-Parity (CP) violation in the lepton sector. Matter – antimatter asymmetry in the universe**

A number of short-baseline neutrino anomalies point to new physics

Neutrino-nucleus scattering regimes



Neutrino energy

J. Fromaggio et al. (2012)

To determine neutrino properties, percent-level control over the muon ν disappearance and electron ν appearance signals in neutrino experiments is required

$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu(E_\nu) \times \sigma(E_\nu) \times R(E_\nu, E_\nu^{\mathrm{rec}})$$

The same % level control is required over lepton scattering cross sections

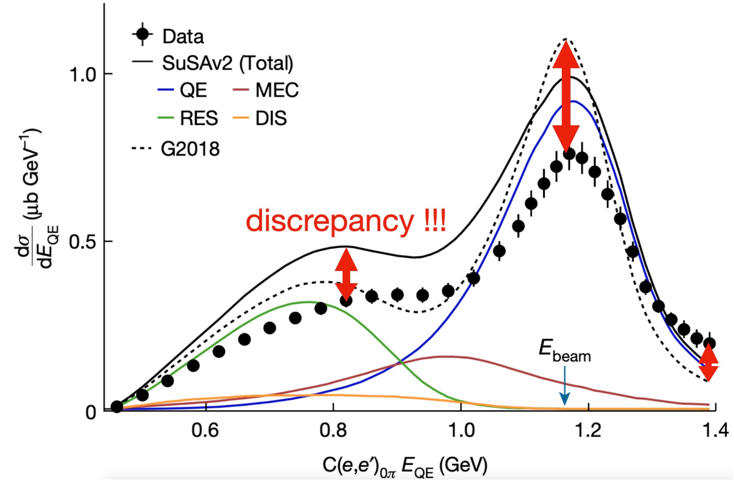
Neutrino scattering regimes important to DUNE : quasi-elastic (QE), resonance (RES), deep inelastic scattering (DIS); Hyper-K the first two

- Tree level cross sections known

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \sim \frac{M^2}{E_\nu^2}\left(\left(\tau + r^2\right) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau} C(Q^2)\right)$$

Neutrino-nucleon/nucleus elastic scattering

- Nuclear corrections and radiative effects not under control
- Recent JLab measurements of lepton-nucleus scattering find 10-50% discrepancies between theory and experiment

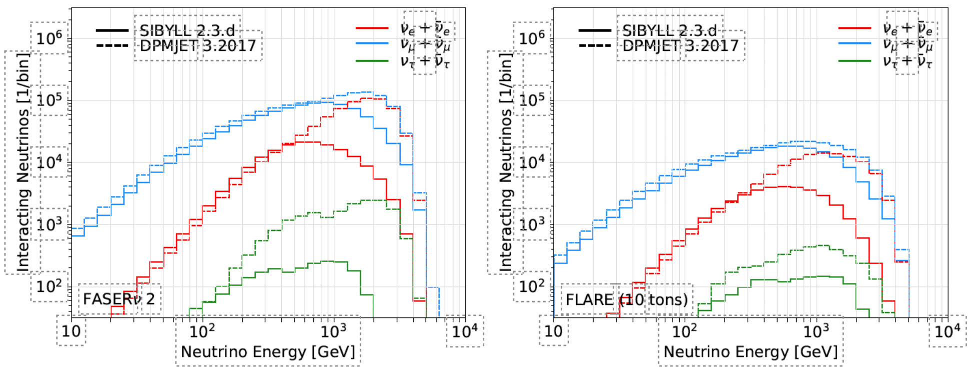


Electron energy

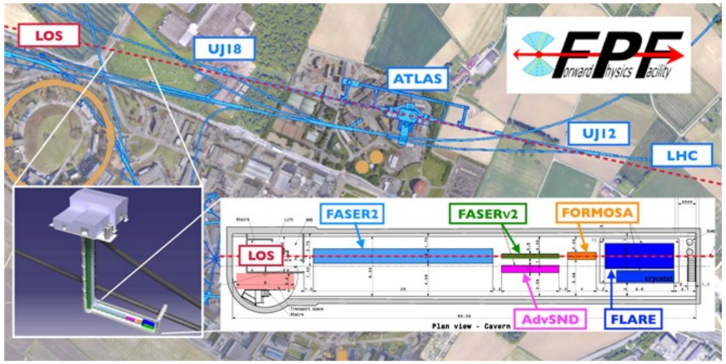
M. Khachatryan et al. (2021)

The FPF and connections to the EIC

A new proposed facility forward of ATLAS



Number of charged current neutrino interactions with the FASERv2 (left) and FLARE (right). Depends on detector assumptions, etc.



For more information on the FPF

J. Feng et al. (2022)

Depending on the approach (collinear NLO vs k_T factorization, neutrino flavor) energy normalized cross sections peak at ~ 1 TeV. Assume that broad distribution (x1/4, x4). CM energy ~ 45 GeV (x1/2, x2)

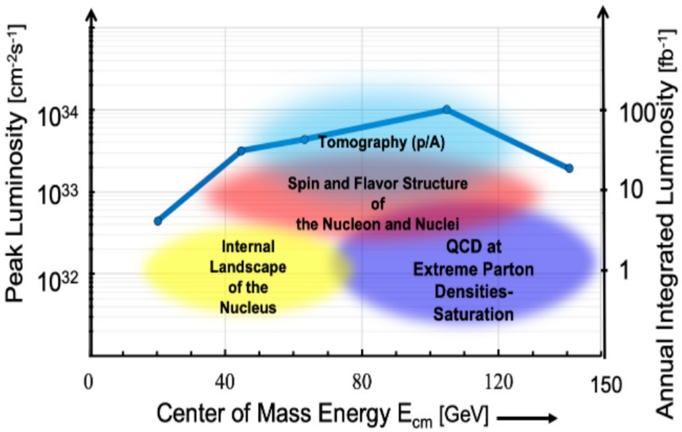
Ideal complementarity to the EIC (and in some cases even better)

$s=2m_N E_\nu$

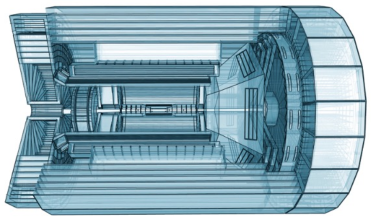
Will focus on the neutrinos and QCD/QED sector

The Electron-Ion Collider

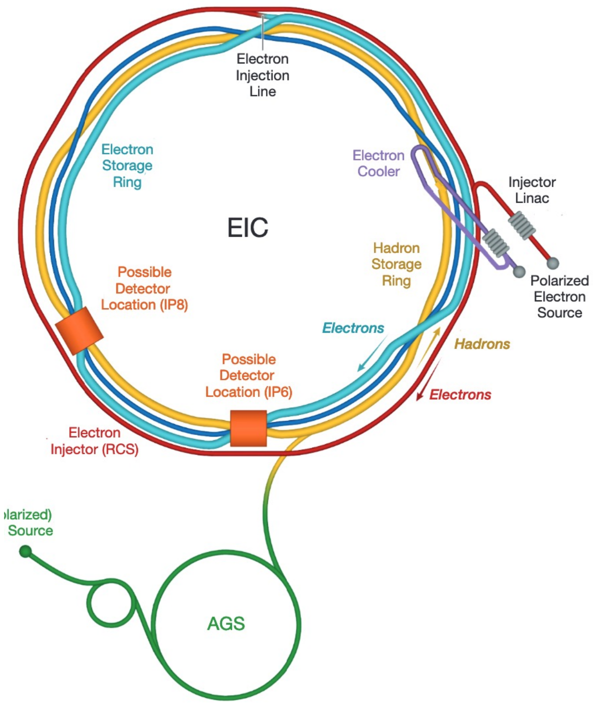
A premier nuclear physics facility for the community



Physics reach



Project detector (ePIC), community working toward 2nd one



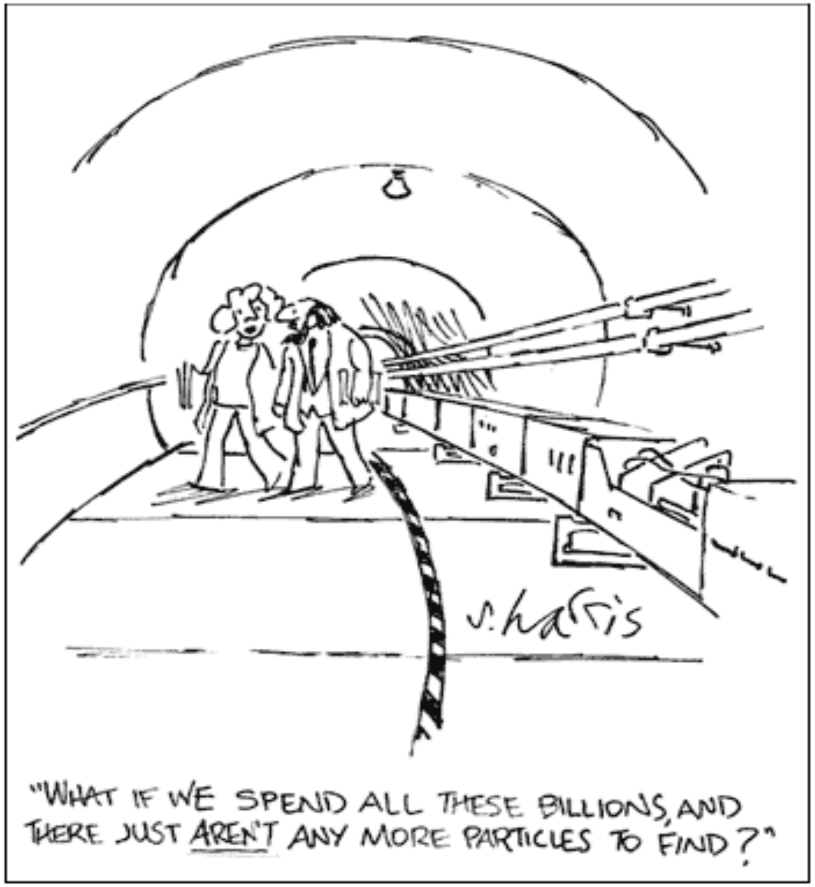
The future EIC

Important milestones

- CD-0 and site selection announced Jan. 2020
- CD-1 approval in Jul. 2021
- CD-3A approval in Apr. 2024
- CD-2 review in 2025

Variable e+p center-of-mass energies from 20−100 GeV, upgradable to 140 GeV

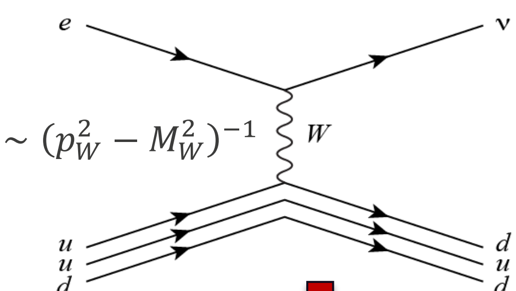
Effective field theories extended to particle propagation in matter



Effective field theories for particle interactions in matter

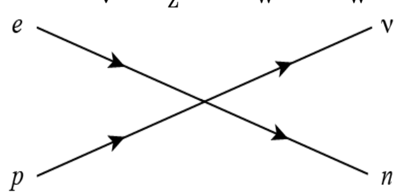
The underlying idea behind many modern calculations in matter

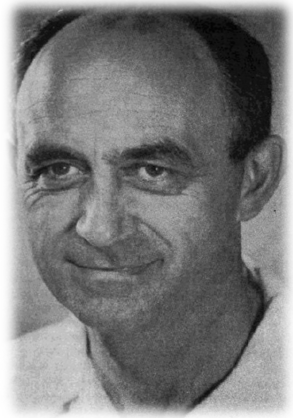
A new direction



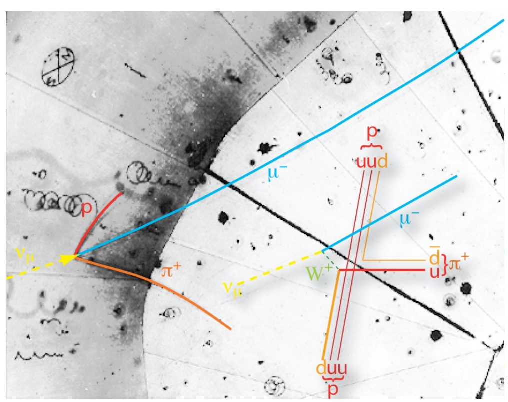
$p \ll M$

$$G_F^0 \simeq \frac{\pi\alpha}{\sqrt{2}\, M_Z^2 \cos^2\theta_W \sin^2\theta_W}$$





E. Fermi (Nobel Prize)



A direct observation of the neutrino, Nov. 1970

- Powerful framework based on exploiting symmetries and controlled expansions for problems with a natural separation of energy/momentum or distance scales.

S. Weinberg (1979)

- The first, probably best known, effective theory is the Fermi interaction

EFTs of QCD in matter

Production of particles and jets in matter remains a multi-scale problem. A major contribution of the LANL group is the development of those EFTs

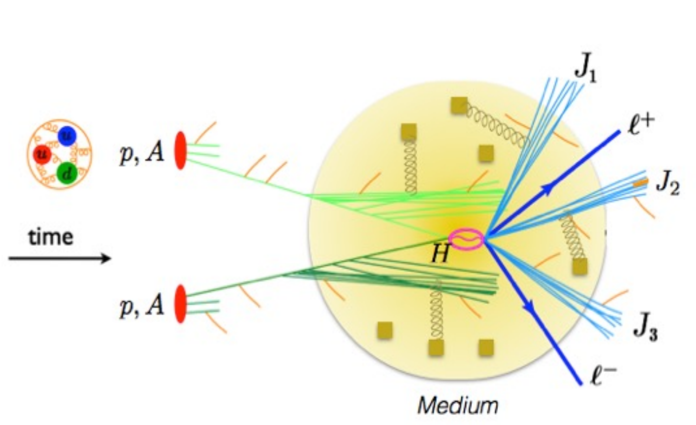
$SCET_G$ – soft collinear effective theory with Glauber gluons

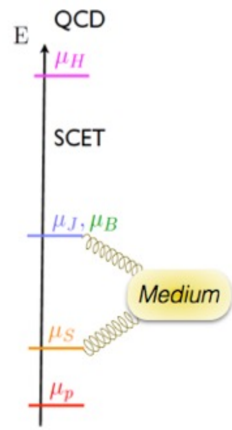
$$\mathcal{L}_G(\xi_n, A_n, \eta) = \sum_{p,p',q} e^{-i(p-p'+q)x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{qqA_G} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{ggA_G} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu \right) \bar{\eta}\, \Gamma^{\delta,a}_s\, \eta\, \Delta_{\mu\delta}(q)$$

$NRQCD_G$ – non-relativistic QCD with Glauber gluons

Examples of successful effective field theories

	Q	power counting	DOF in FT	DOF in EFT
Chiral Perturbation Theory (ChPT)	Λ_{QCD}	p/Λ_{QCD}	q, g	K,π
Heavy Quark Effective Theory (HQET)	m_b	Λ_{QCD}/m_b	ψ,A	h_v, A_s
Soft Collinear Effective Theory (SCET)	Q	$p_\perp/Q$	ψ,A	ξ_n, A_n, A_s
Non-Relativistic QCD (NRQCD)	m_Q	p/m_Q	ψ,A	ψ_Q, A_s, A_{us}





G. Ovanesyan et al. (2011)

Z. Kang et al. (2016)

Y. Makris et al. (2020)

EFT of QED for radiative corrections and in matter

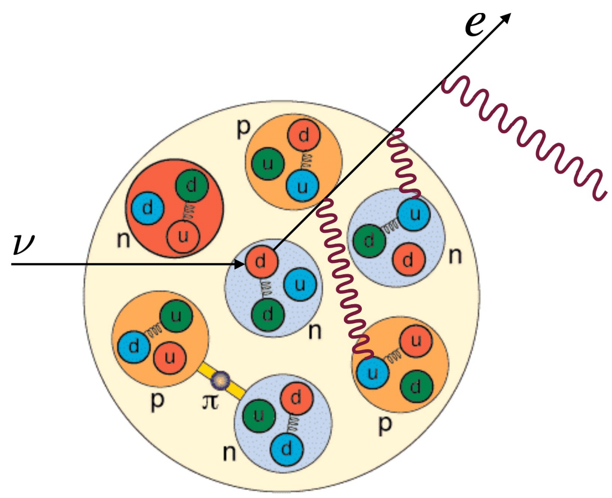
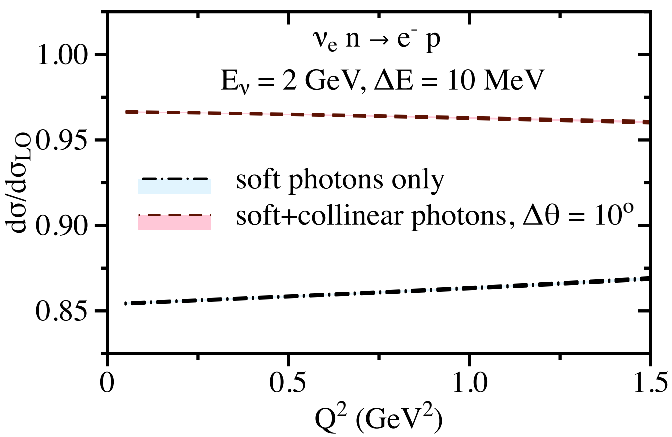


Illustration of neutrino-nucleus scattering

- Radiative corrections to neutrino interaction with neutrons and protons inside the nucleus
- First-principles quantitative description of nuclear medium effects



O. Tomalak et al. (2021)

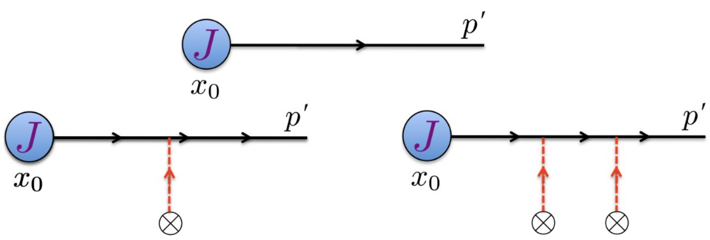
$$\mathcal{L}_{\rm G} = \mathcal{L}_{\rm F,QCD} + \sum_{p',p''} e^{-i(p'-p'')\cdot x}\overline{\chi}_{n',p''} i\left(n'\cdot\partial + ieA^{\rm G}\right)\frac{\bar{n}\!\!\!/'}{2}\chi_{n',p'} + \mathcal{L}'_{\rm SCET},$$

Soft collinear effective theory with Glauber photons

- Cross-section distortions due to elastic scattering are small – percent to permille level
- Radiative corrections from the medium are power suppressed

O. Tomalak et al. (2022)

Tree level cross section corrections



Single Born diagrams

Double Born diagrams

- Two type of interactions contribute – "direct" or single Born and "virtual" or double Born
- Required by cross section unitarity

$$v\left(\vec{q}_{\perp}\right) = \frac{e^2}{\vec{q}_{\perp}^{\,2} + \zeta^2}, \qquad \zeta R \ll 1.$$

Potential that combines the sources and the Glauber photons

Typical atomic scale $\zeta = \frac{m_e Z^{1/3}}{192}$

- Neutrino and lepton scattering corrections

$$\delta\sigma_\nu = \int \mathrm{d}z'\rho\left(z'\right) \int \frac{\mathrm{d}^2\vec{q}_{\perp}}{(2\pi)^2} |v\left(\vec{q}_{\perp}\right)|^2 \left(\sigma_\nu\left(\vec{p}^{\,\prime} - \vec{q}_{\perp}\right) - \sigma_\nu\left(\vec{p}^{\,\prime}\right)\right)$$

$$\delta\sigma_\ell = \int \frac{\mathrm{d}^2\vec{q}_{\perp}}{(2\pi)^2} |v\left(\vec{q}_{\perp}\right)|^2 \left[\int \mathrm{d}z'\rho\left(z'\right)\left(\sigma_\ell\left(\vec{p}^{\,\prime} - \vec{q}_{\perp}, \vec{p}\right) - \sigma_\ell\left(\vec{p}^{\,\prime}, \vec{p}\right)\right) + \int \mathrm{d}z\rho\left(z\right)\left(\sigma_\ell\left(\vec{p}^{\,\prime}, \vec{p} + \vec{q}_{\perp}\right) - \sigma_\ell\left(\vec{p}^{\,\prime}, \vec{p}\right)\right)\right]$$

Typical nuclei in electron and neutrino scattering experiments

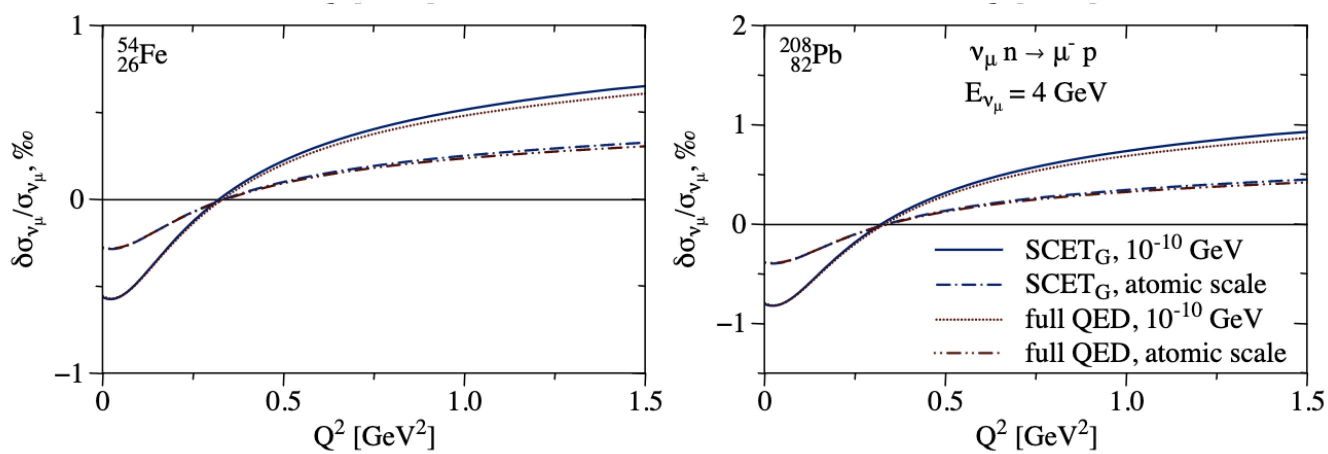
	${}^{2}_{1}\mathrm{H}$	${}^{12}_{6}\mathrm{C}$	${}^{16}_{8}\mathrm{O}$	${}^{40}_{18}\mathrm{Ar}$	${}^{56}_{26}\mathrm{Fe}$	${}^{208}_{82}\mathrm{Pb}$
R_{rms} (fm)	2.1421	2.4702	2.6991	3.4274	3.7377	5.5012

Illustrative results

$$\frac{d\sigma_\nu}{dQ^2}(Q^2,E_\nu) = \frac{c_{ud}^2}{16\pi}\frac{M^2}{E_\nu^2}\left[\left(\tau + r^2\right)A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau}C(Q^2)\right]$$

Neutrino nucleus scattering

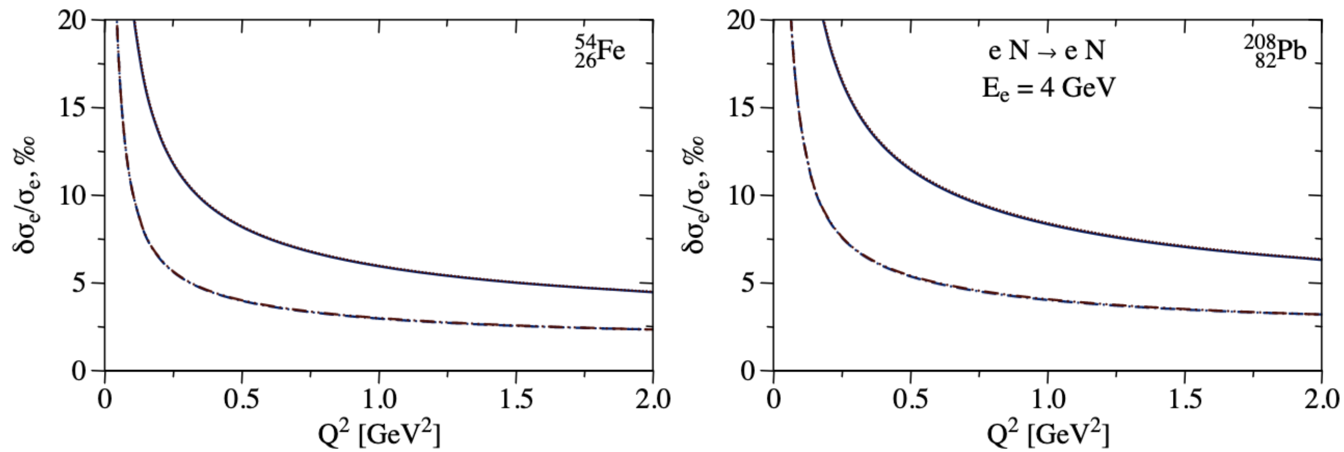
- The way cross section corrections work is they change the initial-state and final-state ($E \to E'$, $p_T \to p_T'$, $x_B \to x_B'$… kinematics required produce an observable



Electron nucleus scattering

$$\frac{d\sigma_\ell}{dQ^2}(Q^2,E_\ell) = \frac{\pi\alpha^2}{2M^2\vec{p}^2}\frac{G_M^2 + \frac{\varepsilon}{\tau}G_E^2}{1-\varepsilon_T}$$

Cross section corrections are small - permille to percent level



Resumming multiple interactions

- Let us recall the QED scales that can arise in the medium. From these we can calculate “cross sections” for very soft Glauber gluon exchanges and “opacity” parameters

$$\sigma_v \approx \frac{4\pi\alpha^2}{\left(\frac{m_e Z^{1/3}}{192}\right)^2} \frac{1}{\beta_\ell^2},$$

$$\beta_\ell = \sqrt{1 - m_\ell^2/(E_\ell')^2},$$

“Cross section”

$$\lambda_{\text{mfp}} = \frac{1}{n\sigma_v} = \frac{R_{\text{rms}}}{3Z^{1/3}} \left(\frac{\beta_\ell m_e R_{\text{rms}}}{192\alpha}\right)^2$$

“Mean free path”

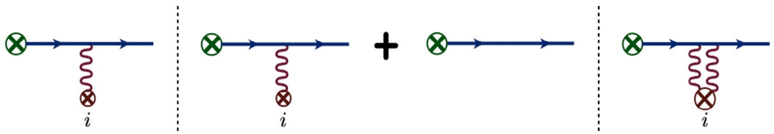
$$\chi \sim \frac{R_{\text{rms}}}{\lambda_{\text{mfp}}} \sim \frac{Z^{1/3}}{(\beta_\ell m_e R_{\text{rms}})^2}$$

“Opacity parameter”

Because the atomic scale is tiny, the mfp, opacity, … shouldn’t be over-interpreted. Only the total momentum transfer ~ $\chi\zeta^2$ matters

- The remaining diagrams have a specific structure and can be resumed most easily in impact parameter space

M. Gyulassy et al (2000)



$$\hat{R}_n = \hat{D}_n^\dagger \hat{D}_n + \hat{V}_n + \hat{V}_n^\dagger$$

Master equation

$$\frac{dN}{dp_\perp'} = \int_0^\infty b p_\perp' J_0(0, b p_\perp') e^{-\chi(1-\zeta b K_1(\zeta b))} db$$

G. Moliere (1947)

Gaussian approximation

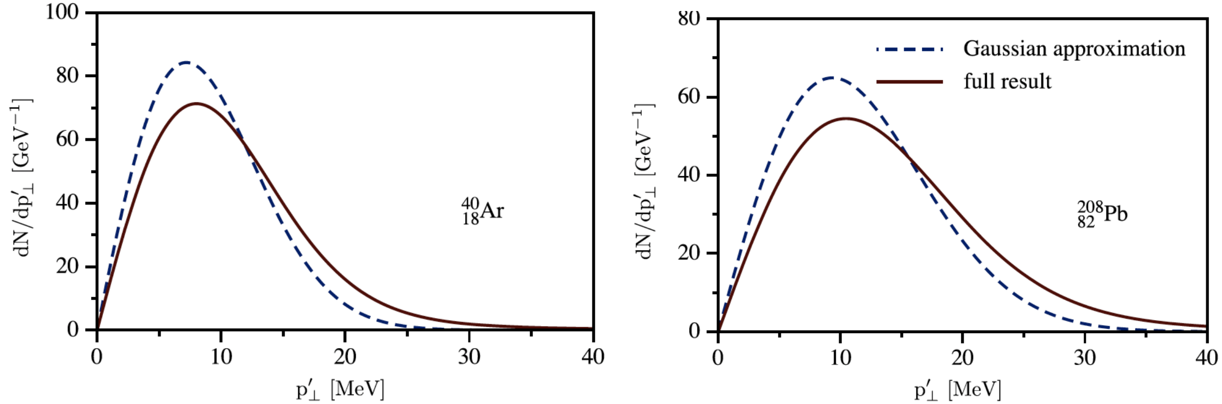
$$\frac{dN^G}{dp_\perp'} = \frac{p_\perp'}{\chi\zeta^2\xi} e^{-\frac{(p_\perp')^2}{2\chi\zeta^2\xi}}$$

$$\xi = \frac{1-2[\gamma_E - \ln 2 + \ln(\zeta R_0)]}{4}$$

O. Tomalak et al. (2023)

Phenomenological results

- In neutrino and charged lepton scattering the outgoing particle acquires transverse momentum relative the original unperturbed direction



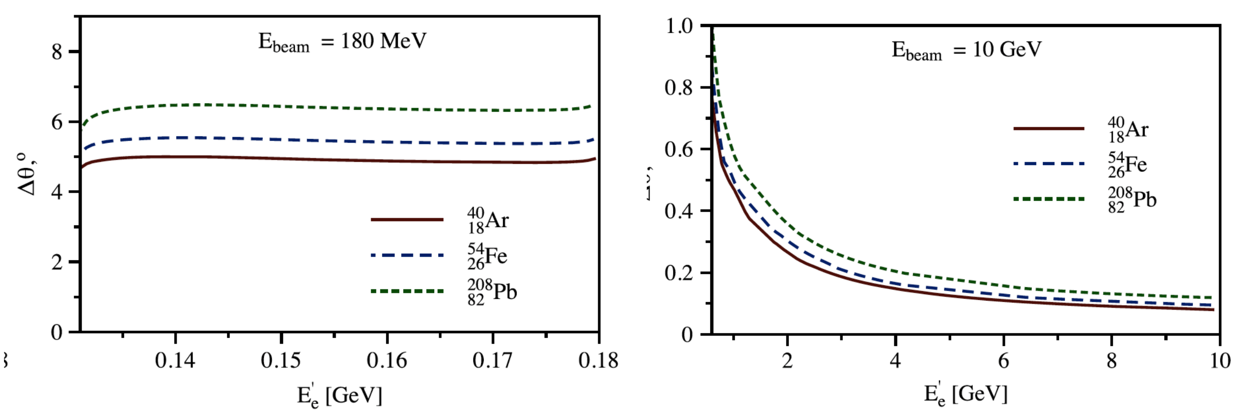
Broadening of order 10-20 MeV. The full result and Gaussian approximation differ

- The broadening affects important observables, e.g. the angular distribution of neutrinos from which the energy is determined

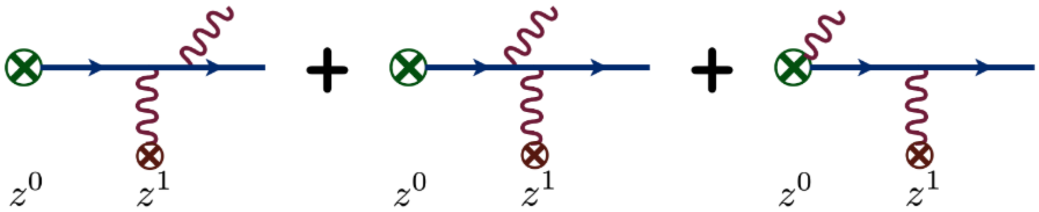
RMS angular deflection

$$\sqrt{\langle(\Delta\theta)^2\rangle} = \sqrt{\int (\theta_\ell - \theta_\ell^0)^2 \frac{dN}{dp'_\perp} dp'_\perp \frac{d\phi}{2\pi}}.$$

of order few degrees at low energies (goes away as 1/E). Important to take into account in neutrino event generators



Medium-induced radiative corrections



In addition to tree level scattering we have medium induced radiative corrections

Soft radiation amplitude without in-medium interactions

$$\mathrm{T}^{\mathrm{LO}}_{1\gamma} = e\left(\frac{p'\cdot\varepsilon^\star}{p'\cdot k_\gamma} - \frac{v\cdot\varepsilon^\star}{v\cdot k_\gamma}\right)\mathrm{T}^{\mathrm{LO}} e^{ik_\gamma\cdot x^0}.$$

O. Tomalak et al. (2024)

Soft radiation amplitude with one correlated Glauber photon exchange

$$\mathrm{T}^{1\mathrm{G}}_{1\gamma} = -ie\left(\frac{p'\cdot\varepsilon^\star}{p'\cdot k_\gamma} - \frac{v\cdot\varepsilon^\star}{v\cdot k_\gamma}\right)\sum_{z^1>z^0}\int\frac{\mathrm{d}^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{x}^1_\perp} v\left(q_\perp\right)\Gamma^{(1)}\left(\vec{q}_\perp, z^1\right)\mathrm{T}^{\mathrm{LO}}\left(p'+k_\gamma-q\right)e^{i(p'+k_\gamma)\cdot x^0},$$

$$\Gamma^{(1)} = e^{i\Omega(p'+k_\gamma,\vec{q}_\perp)\left(z^1-z^0\right)} - \frac{2p'\cdot k_\gamma}{\left(p'+k_\gamma\right)_+}\frac{e^{i\Omega(p',\vec{q}_\perp)\left(z^1-z^0\right)} - e^{i\Omega(p'+k_\gamma,\vec{q}_\perp)\left(z^1-z^0\right)}}{\Omega\left(p',\vec{q}_\perp\right) - \Omega\left(p'+k_\gamma,\vec{q}_\perp\right)}, \qquad \Omega\left(p,\vec{q}_\perp\right) = p^- - \frac{\left(\vec{p}_\perp-\vec{q}_\perp\right)^2}{p^+}.$$

- Corrections to the cross section. This can be obtained to all orders in opacity. $|\Gamma|^2$ and the cross section differences collect nuclear effects

$$\delta\mathrm{d}\sigma^{(1)}_{1\gamma} = e^2\left|\frac{p'\cdot\varepsilon^\star}{p'\cdot k_\gamma} - \frac{v\cdot\varepsilon^\star}{v\cdot k_\gamma}\right|^2\frac{\mathrm{d}^3\vec{k}_\gamma}{(2\pi)^3\,2E_\gamma}\sum_{z^1>0}\frac{N_{z^1}}{S^{z^1}_\perp}\int\frac{\mathrm{d}^2\vec{q}_\perp}{(2\pi)^2}v\left(q_\perp\right)^2$$
$$\times\left[\mathrm{d}\sigma^{\mathrm{LO}}\left(\vec{p}'+\vec{k}_\gamma-\vec{q}_\perp\right)\left|\Gamma^{(1)}\left(\vec{q}_\perp,z^1\right)\right|^2 - \mathrm{d}\sigma^{\mathrm{LO}}\left(\vec{p}'+\vec{k}_\gamma\right)\right],$$

Soft radiation and resummation

- In the soft photon emission limit we can neglect the kinematic corrections and vacuum-like radiation factorizes form the scattering series

$$|\Gamma^{(1)}\left(\vec{q}_{\perp}, z^{1}\right)|^{2} = |\Gamma^{(2)}\left(\vec{q}_{1,\perp}, \vec{q}_{2,\perp}, z^{1}, z^{2}\right)|^{2} = \ldots = |\Gamma^{(n)}\left(\vec{q}_{1,\perp}\ldots\vec{q}_{n,\perp}, z^{1}\ldots z^{n}\right)|^{2} = 1.$$

We can calculate the soft function from one emission

$$S_{1\gamma}^{\ell} = 1 + \frac{\alpha}{\pi}\left(\ln\frac{(\Delta E)^{2}}{E_{\ell}E_{\ell}'}\left[\ln\frac{Q^{2}}{m_{\ell}^{2}} - 1\right] - \frac{1}{2}\ln^{2}\frac{E_{\ell}}{E_{\ell}'} + \frac{13}{6}\ln\frac{Q^{2}}{m_{\ell}^{2}} + \mathrm{Li}_{2}\left[\cos^{2}\frac{\theta_{\ell}}{2}\right] - \frac{\pi^{2}}{6} - \frac{28}{9}\right)$$

And exponentiate for multiple emissions into a Sudakov factor

$$S_{1\gamma}(\Delta E) \rightarrow S(\Delta E) = e^{S_{1\gamma}(\Delta E)-1}$$

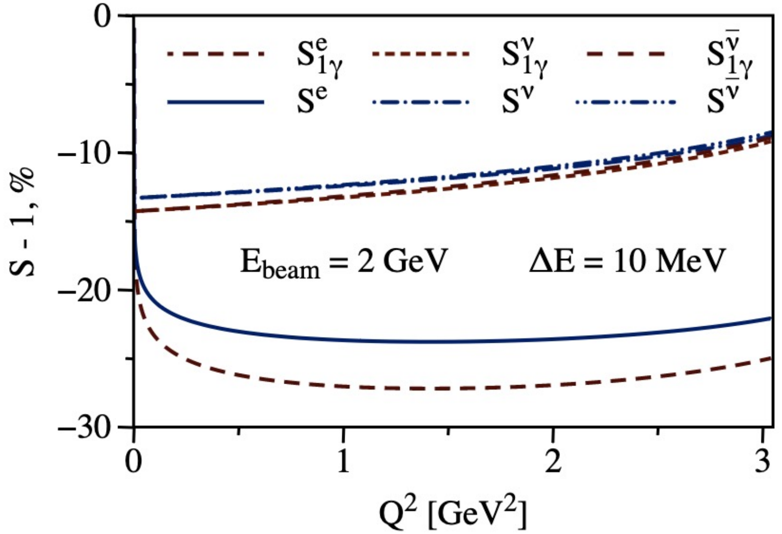
The soft radiation spectrum then is

$$\frac{\mathrm{d}N_{S}^{\gamma}}{\mathrm{d}x} = \frac{\alpha}{\pi}\frac{S(E_{\gamma})}{x}\left(\delta_{\ell}\ln\frac{Q^{2}}{m_{\ell}^{2}} + \frac{\delta_{\nu_{\ell}}}{2}\ln\frac{4\tilde{E}_{\ell}^{2}}{m_{\ell}^{2}} - 1\right)$$

$\delta_{\ell} = 0,\ \delta_{\nu_{\ell}} = 1$ for the (anti)neutrino scattering,

$\delta_{\ell} = 1, \delta_{\nu_{\ell}} = 0$ for the charged lepton scattering,

O. Tomalak et al. (2024)



- The magnitude of cross section corrections due to soft radiation is significant - 20% for charged leptons scattering and 10% for neutrino scattering. These corrections are nucleon-like. They "commute" with the multiple scattering

Collinear photon radiation

- For collinear radiation one one needs the full spinor structure of the matrix elements to account for spin flip when the energy fraction taken by the photon is large

The lepton photon splitting function

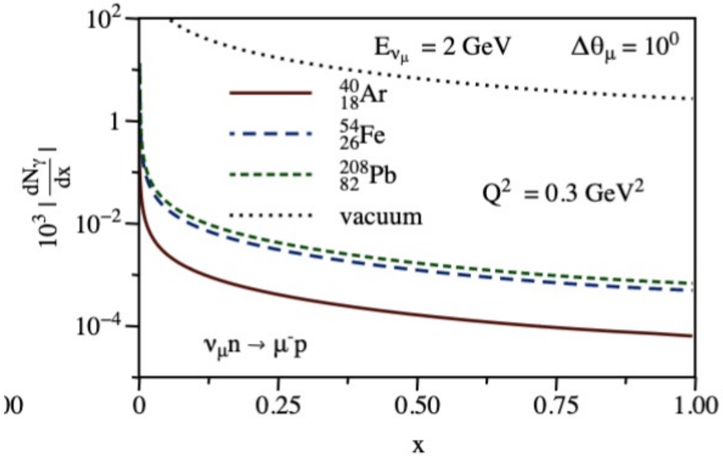
$$\frac{d\sigma^{LO}_{1\gamma}}{d\sigma^{LO}\left(\vec{p}+\vec{k}_\gamma\right)} \frac{2\pi \vec{k}^2_{\gamma,\perp}}{dx d^2\vec{k}_{\gamma,\perp}} = \frac{\alpha}{\pi} P_{e\to e}(x) = \frac{\alpha}{\pi}\frac{1+(1-x)^2}{x},$$

Note $x \to 1-x,$

Integrating within a cone, the spectrum of the radiation is

$$\frac{dN^\gamma_c}{dx} \approx \frac{\alpha}{\pi}\frac{1+(1-x)^2}{x} \ln \frac{\left(E'_\ell + E_\gamma\right)\Delta\theta}{m_\ell},$$

- The medium-induced collinear radiation has the same multiple scattering series structure. The soft pre-factor is replaced by the collinear.



Collinear radiation spectrum

$$|\Gamma^{(1)}|^2 = 1 + 2\frac{A^2_{\perp,1}}{A^2_{\perp,2}}\left(1-\cos\frac{A^2_{\perp,2}\left(z^1-z^0\right)}{x\,(p')^+}\right) - 2\frac{\vec{A}_{\perp,1}\cdot\vec{A}_{\perp,2}}{A^2_{\perp,2}}\left(1-\cos\frac{A^2_{\perp,2}\left(z^1-z^0\right)}{x\,(p')^+}\right)$$

- The magnitude of cross section corrections due to collinear radiation- 5% for charged leptons scattering and 2-3% for neutrino scattering. Nuclear corrections so not change the radiation spectrum. They are strongly suppressed.

Problem 1

Let the opacity of the medium (mean number of scatterings) in which a lepton propagates be $\chi = \int \sigma(z)\rho(z)dz = L/\lambda,$

Relating the final momentum of the lepton to the one before the multiple scattering and summing over all orders in opacity we obtain [dN(…) same as dN(…)/d^2**p**]

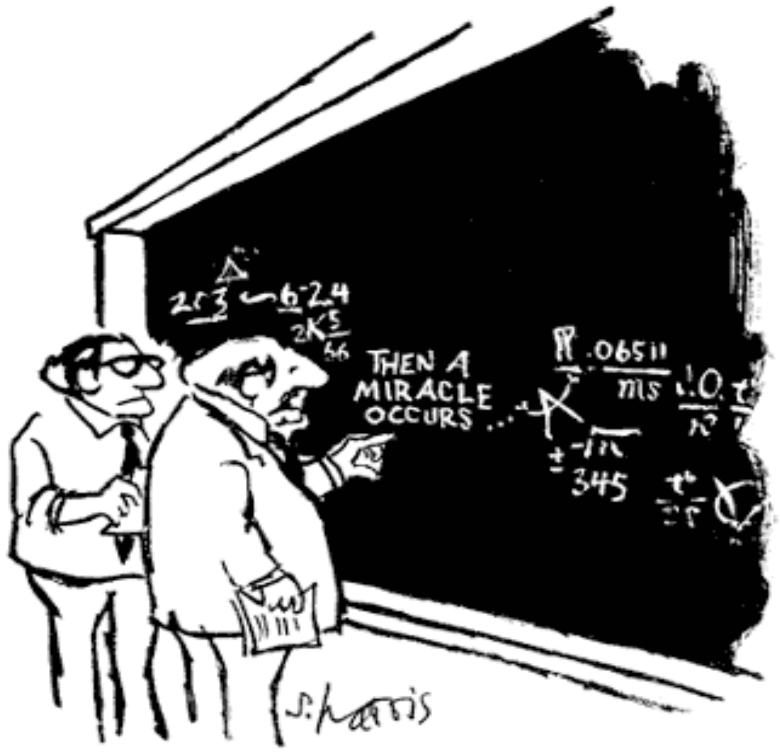
$$dN(\mathbf{p}) = \sum_{n=0}^{\infty} e^{-\chi} \frac{\chi^n}{n!} \int \prod_{i=1}^{n} d^2\mathbf{q}_i \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2\mathbf{q}_i} \, dN^{(0)}(\mathbf{p} - \mathbf{q}_1 - \cdots - \mathbf{q}_n)$$

Let is start with a normalized to unity lepton flux with no transverse momentum component $dN^{(0)}/d^2\mathbf{p} = \delta^2(\mathbf{p})$. and the normalized scattering cross section to be of Yukawa form

$$\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2\mathbf{q}_i} = \frac{1}{\pi} \frac{\mu^2}{(\mathbf{q}^2 + \mu^2)^2}$$

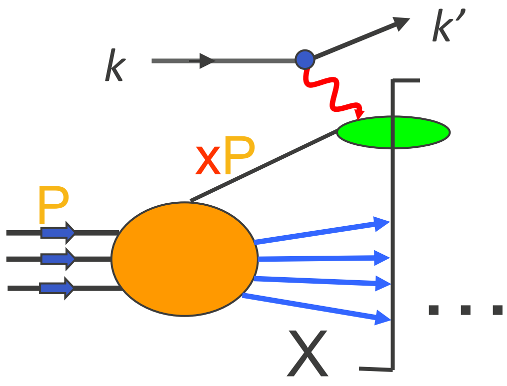
a) By representing the initial flux on the RHS in impact parameter space, demonstrate that the series can be resumed.
b) Expand the Bessel function $\mu b \cdot K_1(\mu b)$ to order b^2 (neglecting any log(b) dependence and collecting numerical factors such as Euler gamma, etc in a constant ξ)
c) Show that the b integral can be taken and leads to a Gaussian distribution of the outgoing flux of leptons. Calculate the $\langle \mathbf{p}^2 \rangle$ of the final distribution.

Inclusive DIS



"I think you should be more explicit here in step two."

DIS Preliminaries



Variables: $q = k - k', \ \nu = E - E',$

$y = (E - E')/E, \ Q^2 = -q^2, \ x = Q^2/(2p\cdot q)$

$$\frac{d\sigma_{lh}}{dx dy} = \frac{4\pi\alpha_{\rm em}}{Q^2}\frac{1}{xy}\left[\frac{y^2}{2}2xF_1(x,Q^2) + \left(1 - y - \frac{m_N xy}{2E}\right)F_2(x,Q^2)\right]$$

$F_1(x,Q^2), \ F_2(x,Q^2)$ - the DIS structure functions

Used to determine the parton distribution functions (PDFs)

Convenient to calculate in a basis of polarization states of

$$F_T(x,Q^2) = F_1(x,Q^2),$$

$$F_L(x,Q^2) = \frac{F_2(x,Q^2)}{2x} - F_1(x,Q^2),$$

if $\frac{4x^2 m_N^2}{Q^2} \ll 1$

R. Brock et al., (1995)

Where QCD kicks in: In the perturbative regime

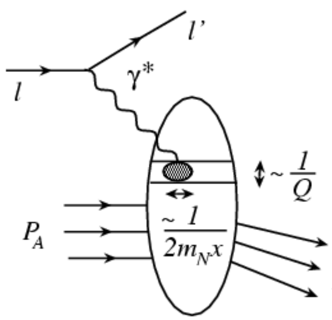
$$F_T(x,Q^2) = \frac{1}{2}\sum_f Q_f^2 \int d\lambda_0 e^{ix\lambda}\left\langle p\left|\bar{\Psi}(0)\frac{\gamma^+}{2p^+}\Psi(\lambda_0)\right|p\right\rangle$$

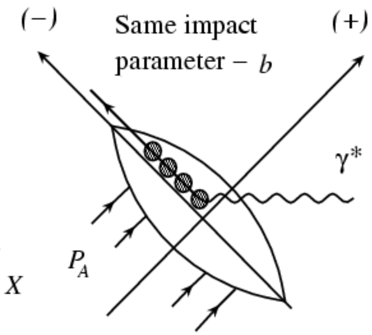
Leading Twist PDF

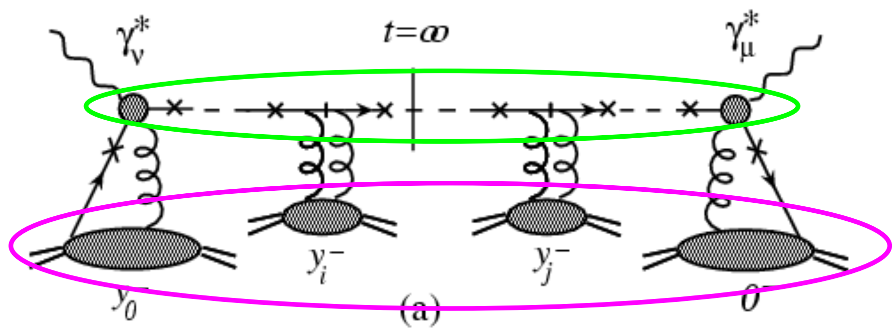
$$= \frac{1}{2}\sum_f Q_f^2\, \phi_f(x,Q^2) + \mathcal{O}(\alpha_s)$$

$$F_L(x,Q^2) = 0 + \mathcal{O}(\alpha_s)$$

New contributions to DIS with nuclei







- Focus on the coherent small x regime

Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ then $\Delta z > r_0$

Transverse size: $\sim 1/Q$

If $Q < m_N$ then exceed the parton size

- Lightcone gauge: $A \cdot n = A^+ = 0$
- Breit frame: $\bar{n} = [1,0,0_\perp]$, $n = [0,1,0_\perp]$

$$q = -xp^+\bar{n} + \frac{Q^2}{2xp^+}n, \quad p = \bar{n}p^+, \quad xp + q = \frac{Q^2}{2xp^+}n$$

The idea behind the calculation: propagator decomposition

$$i(xp^+/Q^2)\gamma^- \qquad \text{(contact term } \longrightarrow \text{)}$$

$$i(\gamma^+/2p^+)/(x_i - x \pm i\epsilon) \quad \text{(pole term } \times\!\!\longrightarrow \text{)}$$

- Emergence of a non-perturbative parameter and length enhancement

$$\xi^2 = \left(\frac{3\pi\alpha_s(Q^2)}{8r_{0\perp}^2}\right)\underbrace{\left\langle p\left|\hat{F}^2(\lambda_i)\right|p\right\rangle}_{\frac{1}{2}\lim_{x\to 0} xG(x,Q^2)}$$

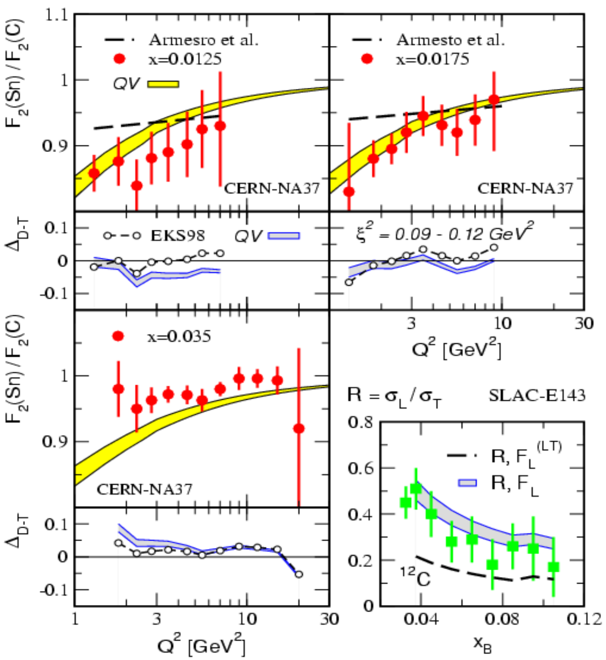
Dynamically generated parton mass per scattering

Comparison to data

- Coherent scattering in nuclei gives a new contribution to the longitudinal structure function and a suppression in the transverse structure function – a microscopic picture for shadowing

$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right)$$

$$F_L^A(x,Q^2) \approx A\, F_L^{(LT)}(x,Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x,Q^2)$$

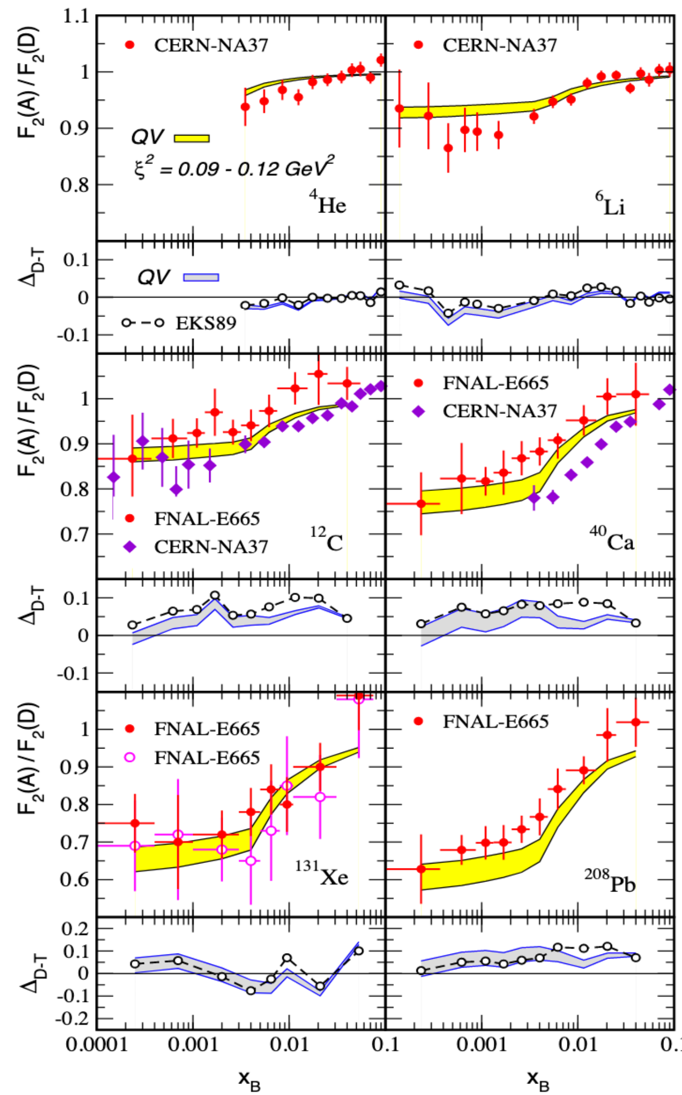


NMC data shows evidence for a power law in $1/Q^2$ behavior in

$$F_2(Sn)/F_2(C)$$

$$R(x,Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_L(x,Q^2)}{F_1(x,Q^2)}$$

J. Qiu et al. (2003)



Neutrino (ν) DIS

Mediated by the electroweak bosons (CC, NC) (exchange $W^{\pm}, Z^{0}$)

- 3σ deviation from the Standard Model (Now $1.8\ \sigma$)

$$\sin^2\theta_W(SM) = 0.2227 \pm 0.0004$$

$$\sin^2\theta_W(NuTeV) = 0.2277 \pm 0.0013 \pm 0.0009 \pm \ldots$$

NuTeV experiment

G.P.Zeller et al., (2002)

$$\frac{d\sigma^{\nu,\bar\nu}_{cc}}{dx\,dy} \propto \frac{1}{\left(\sin^2\theta_W\right)^2}\left[\frac{y^2}{2}2xF_1^{W^\pm}(x,Q^2) + \left(1 - y - \frac{m_N xy}{2E}\right)F_2^{W^\pm}(x,Q^2) \pm \left(y - \frac{y^2}{2}\right)xF_3^{W^\pm}(x,Q^2)\right]$$

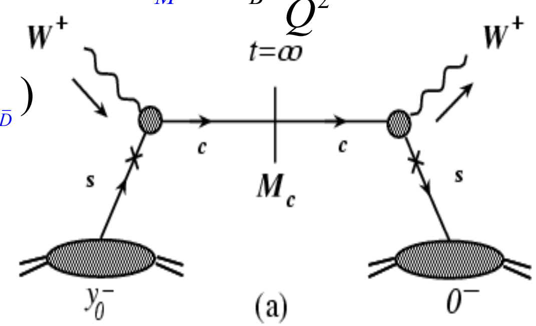
Axial and vector part (weak current)

Similarly for the neutral current

- First glimpse at production of heavy quarks

$$x_M = x_B \frac{M^2}{Q^2}$$

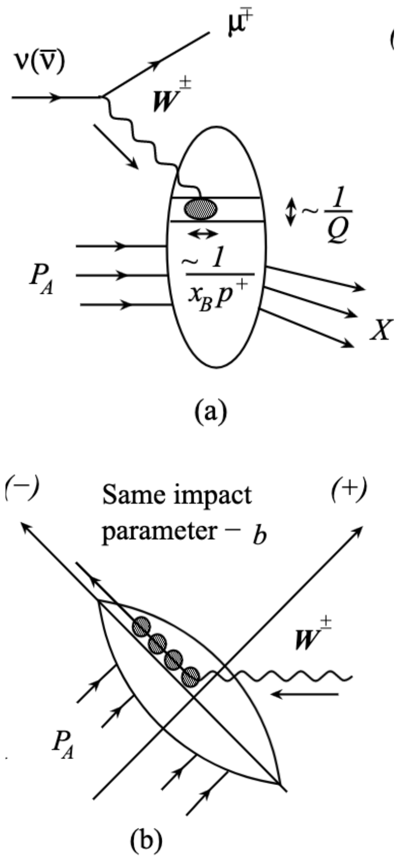
$$F_L^{(\nu W^+)}(x_B,Q^2) = \sum_{D,U} |V_{DU}|^2 \frac{M_U^2}{Q^2}\phi_D(x_B + x_{M_U}) + \sum_{\bar U,\bar D}|V_{\bar U\bar D}|^2 \frac{M_{\bar D}^2}{Q^2}\phi_{\bar U}(x_B + x_{M_{\bar D}})$$



Energy conservation $x_B \to x_B\left(1 + \frac{M^2}{Q^2}\right)$

- There was no theory for the shadowing in $\nu + A$

Summary of results for inclusive νA



- **Physics interpretation – generation of dynamical parton mass in the background gluon field of the nucleon/nucleus**

$$x_M = \frac{M^2}{2p\cdot q} = x_B \frac{M^2}{Q^2} \qquad x_{\rm HT} = x_B \frac{\xi^2}{Q^2}(A^{1/3}-1)$$

$$\frac{1}{A}F_{1,3}^{\nu A}(x_B,Q^2) \approx \{2\}\left(\sum_{D,U}|V_{DU}|^2\phi_D^A\left(x_B+x_{\rm HT}+x_{M_U},Q^2\right) \pm \sum_{\bar U,\bar D}|V_{\bar U\bar D}|^2\phi_{\bar U}^A\left(x_B+x_{\rm HT}+x_{M_{\bar D}},Q^2\right)\right)$$

$$\frac{1}{A}F_{1,3}^{\bar\nu A}(x_B,Q^2) \approx \{2\}\left(\sum_{U,D}|V_{UD}|^2\phi_U^A\left(x_B+x_{\rm HT}+x_{M_D},Q^2\right) \pm \sum_{\bar D,\bar U}|V_{\bar D\bar U}|^2\phi_{\bar D}^A\left(x_B+x_{\rm HT}+x_{M_{\bar U}},Q^2\right)\right)$$

$$\frac{1}{A}F_L^{\nu A}(x_B,Q^2) \approx F_L^{\rm (LT)}(x_B,Q^2) + \sum_{D,U}|V_{DU}|^2\left[\frac{M_U^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_U^2}{Q^2+M_U^2}\right)^2\right]\phi_D^A\left(x_B+x_{\rm HT}+x_{M_U},Q^2\right)$$
$$+\sum_{\bar U,\bar D}|V_{\bar U\bar D}|^2\left[\frac{M_{\bar D}^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_{\bar D}^2}{Q^2+M_{\bar D}^2}\right)^2\right]\phi_{\bar U}^A\left(x_B+x_{\rm HT}+x_{M_{\bar D}},Q^2\right),$$

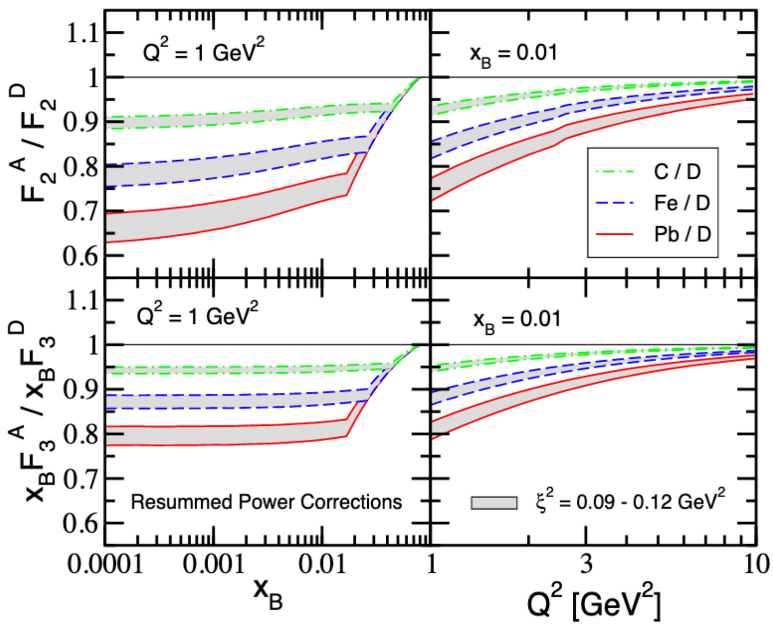
$$\frac{1}{A}F_L^{\bar\nu A}(x_B,Q^2) \approx F_L^{\rm (LT)}(x,Q^2) + \sum_{U,D}|V_{UD}|^2\left[\frac{M_D^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_D^2}{Q^2+M_D^2}\right)^2\right]\phi_U^A\left(x_B+x_{\rm HT}+x_{M_D},Q^2\right)$$
$$+\sum_{\bar D,\bar U}|V_{\bar D\bar U}|^2\left[\frac{M_{\bar U}^2}{Q^2}+\frac{\xi^2}{Q^2}\left(2-\frac{M_{\bar U}^2}{Q^2+M_{\bar U}^2}\right)^2\right]\phi_{\bar D}^A\left(x_B+x_{\rm HT}+x_{M_{\bar U}},Q^2\right).$$

Similar but a bit more challenging because of the mass in the propagator

- **We have now also calculated and resummed higher twist corrections in the structure functions for small-x in νA**

Areas of interest in νA at the FPF

- **Hierarchy in F_2 and F_3 dynamical shadowing**



$$R^{A/A'}_{sea/val.}(x_B, Q^2) = \frac{F_2^A(x_B,Q^2)}{F_2^{A'}(x_B,Q^2)} \Big/ \frac{F_3^A(x_B,Q^2)}{F_3^{A'}(x_B,Q^2)}$$

$$= 1 - (\alpha_{sea} - \alpha_{val.})(A^{1/3} - A'^{1/3})\xi^2/Q^2 + \cdots$$

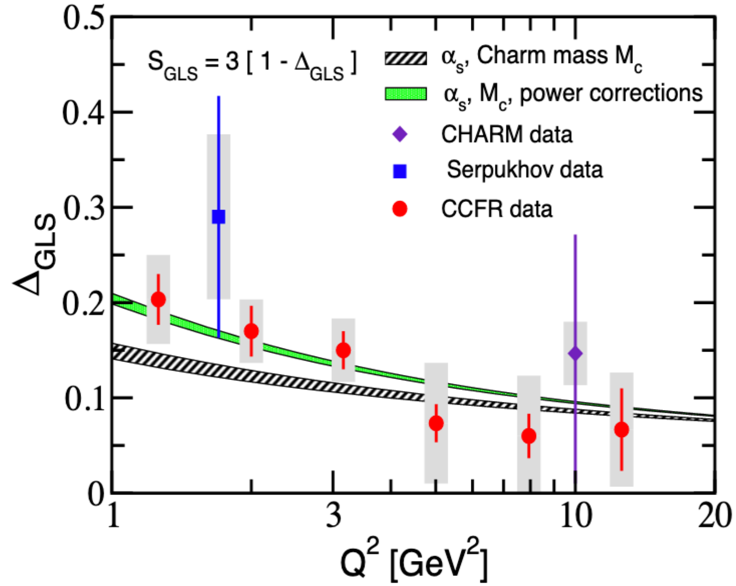
J. Qiu et al. (2004)

- **Gross-Llewellyn Smith (GLS) sum rule**

$$S_{\rm GLS} = \int_0^1 dx_B \, \frac{1}{2x_B} \left(x_B F_3^{\nu A} + x_B F_3^{\bar{\nu} A} \right)$$

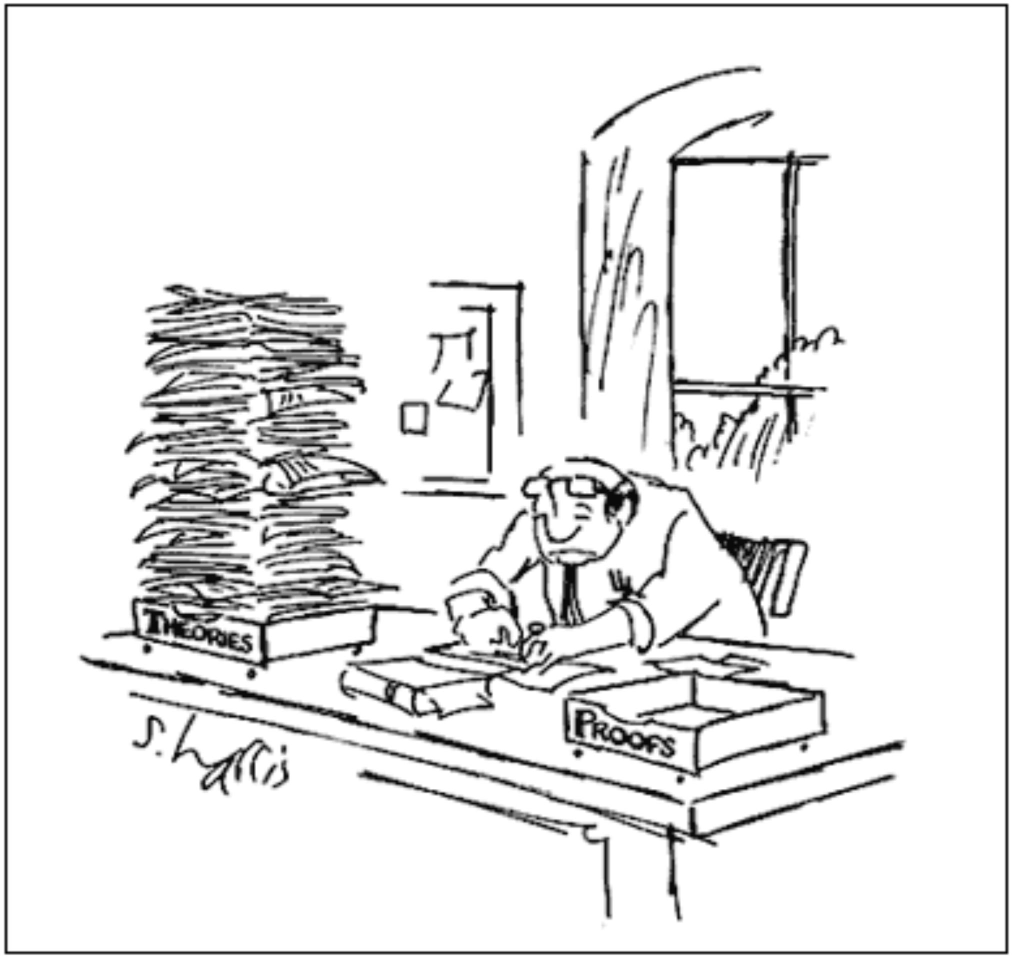
At tree level counts the number of valance quarks

$$\Delta_{\rm GLS} \equiv \frac{1}{3}(3 - S_{\rm GLS}) = \frac{\alpha_s(Q^2)}{\pi} + \frac{\mathcal{G}}{Q^2} + \mathcal{O}(Q^{-4})$$



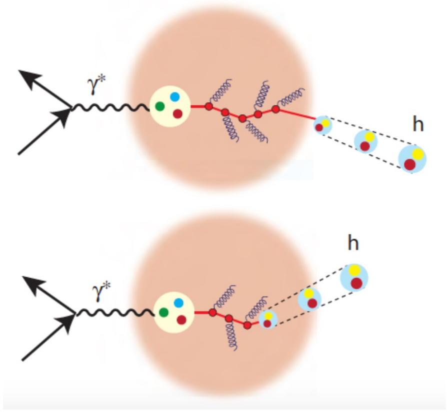
- **Inclusion of high twist effects as boundary conditions for evolution**

Final-state interactions in DIS



Open questions about hadronization

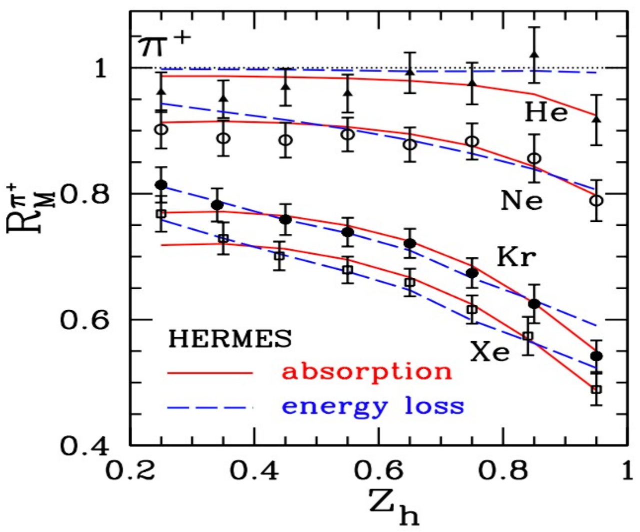
- Open questions about the nature of hadronization – independent fragmentation, string fragmentation, cluster hadronization
- The space-time picture of hadronization is unknown, but critical for e+A
- Competing physics explanations of HERMES hadron suppression data based on energy loss and absorption



W. Wang et al. (2002) *B. Kopeliovich et al. (2003)*

Light hadron measurements cannot differentiate between competing mechanisms

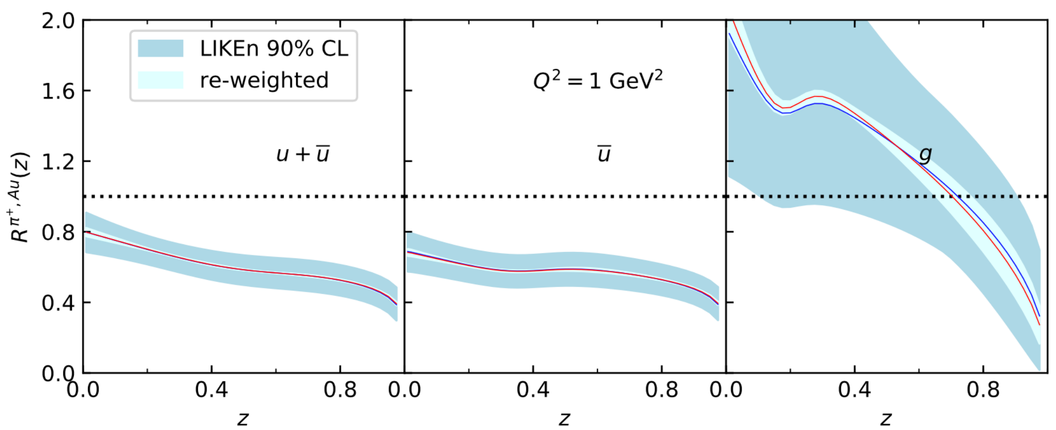
A. Accardi et al. (2009)



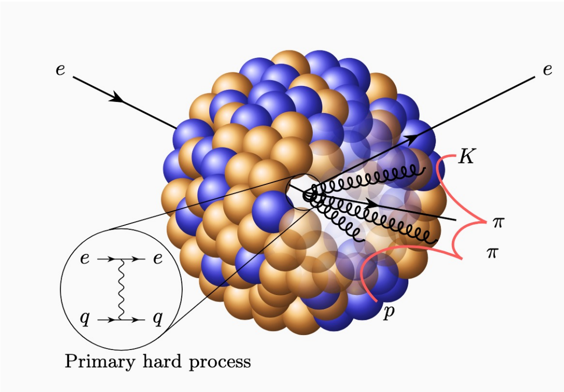
Ideas to parametrize nFFs assuming universality

Effect of 10 fb-1 EIC data

P. Zurita et al. (2021)



EFTs for parton showers in matter



- Evaluated using EFT approaches - SCET$_G$, SCET$_{M,G}$
- Cross checked using light cone wavefunction approach
- Factorize from the hard part
- Gauge invariant
- Contain non-local quantum coherence effects (LPM)
- Depend on the properties of the nuclear medium

G. Ovanesyan et al. (2011)

- Compute analogues of the Altarelli-Parisi splitting functions
- Enter higher order and resumed calculations

Quark to quark splitting function example

$$\left(\frac{dN^{\rm med}}{dx\, d^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\mathbf{q}_\perp}\left\{\left(\frac{1+(1-x)^2}{x}\right)\left[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\times\left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}-\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z]) + \frac{1}{N_c^2}\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right] + x^3m^2\left[\frac{1}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\mathbf{B}_\perp^2+\nu^2}-\frac{1}{\mathbf{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\} \quad (2.51)$$

Z. Kang et al. (2016) *M. Sievert et al. (2019)*

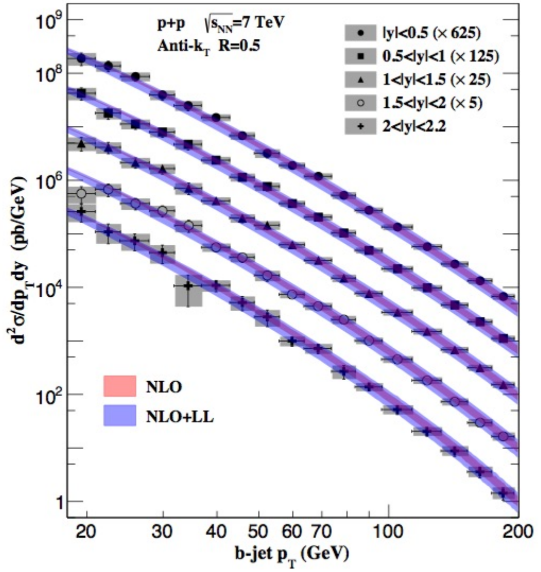
- **In-medium parton showers are softer and broader than the ones in the vacuum**
- **New contributions to factorization theorems and evolution**

Hadronic physics in lepton-nucleon/nucleus scattering

- **The goal is to understand QCD in the nuclear environment**

$$\frac{d\sigma^{\ell N\to hX}}{dy_h d^2\mathbf{p}_{T,h}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times\left[\hat\sigma^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat\sigma^{\gamma i\to f}\right] \times D^{h/f}(z,\mu)\,,$$

$$\frac{d\sigma^{\ell N\to JX}}{dy_J d^2\mathbf{p}_{T,J}} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times\left[\hat\sigma^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat\sigma^{\gamma i\to f}\right] \times J_f(z,p_T R,\mu)\,.$$



Z. Kang et al. (2016)

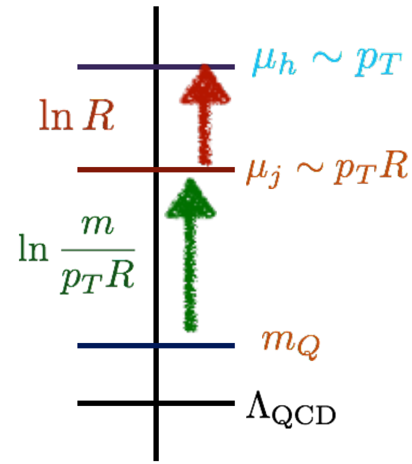
- **New theoretical approach using semi-inclusive jet function**

The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu)\end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} P_{qq}(z) & 2P_{gq}(z) \\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu)\end{pmatrix}$$

$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar Q}(p_T R, m) = 2\sum_{l=g,Q}\bar K_{l/g}(p_T R, m, \mu_F)\bar D_{Q/l}(m,\mu_F)$$

scales



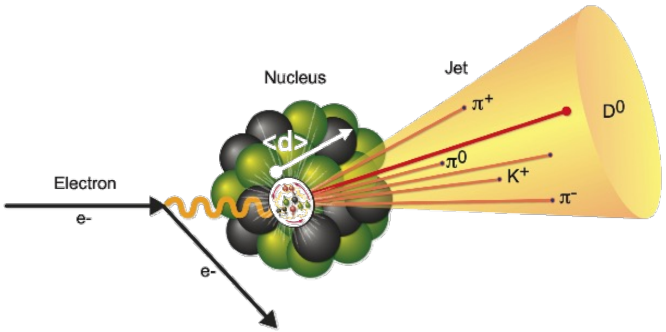
L. Dai et al. (2018)

In-medium evolution of fragmentation functions

- **Medium-induced splitting functions provide correction to vacuum showers and correspondingly modification to DGLAP evolution for FFs**

N. Chang et al. (2014)

Z. Kang et al. (2014)



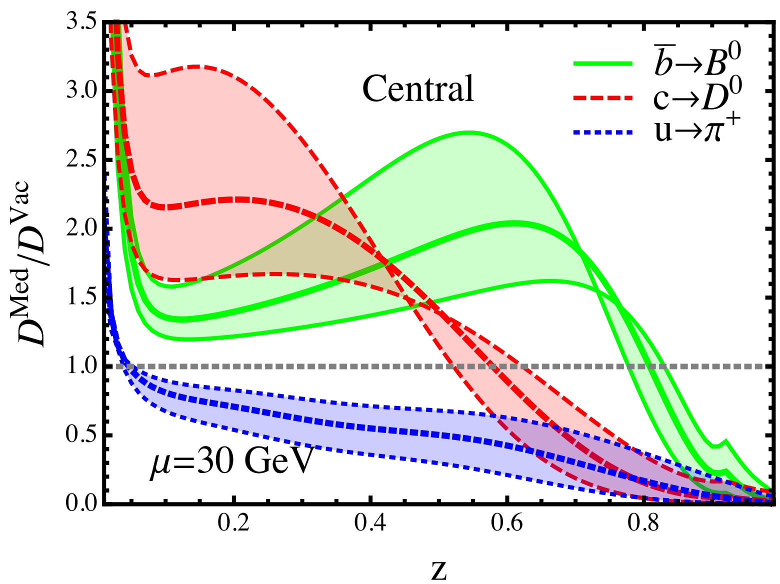
$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right)+P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_{\bar q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar q}\left(\frac{z}{z'},Q\right)+P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right.$$

$$\left.+P_{g\to q\bar q}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right)+f_{\bar q}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

- **Enhancement at small z but for pions (light hadrons) at very small values – mostly suppression**
- **Very pronounced differences between light and heavy flavor fragmentation.**
- **Related to the shape of fragmentation functions**



H. Li et al. (2020)

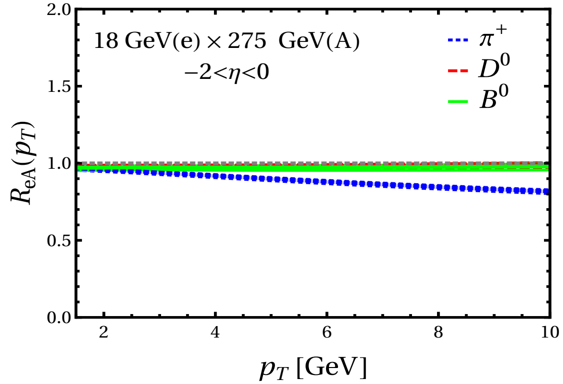
Phenomenological results - hadrons

- **Differential hadronization cross sections normalized by the cross section for R=1 jet**

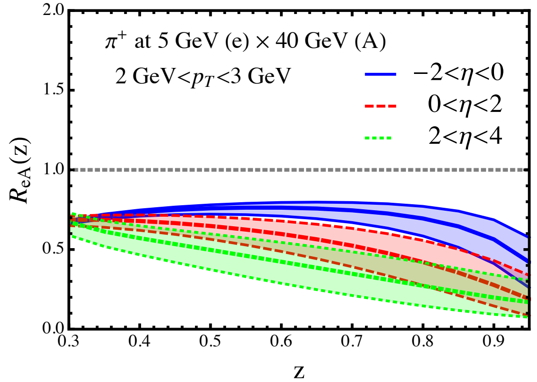
$$R^h_{eA}(z) = \frac{\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\Big|_{eA}}{\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\Big|_{ep}}$$

- **Modifications to hadronization grow form backward to forward rapidity**
- **Transition from enhancement to suppression for heavy flavor**

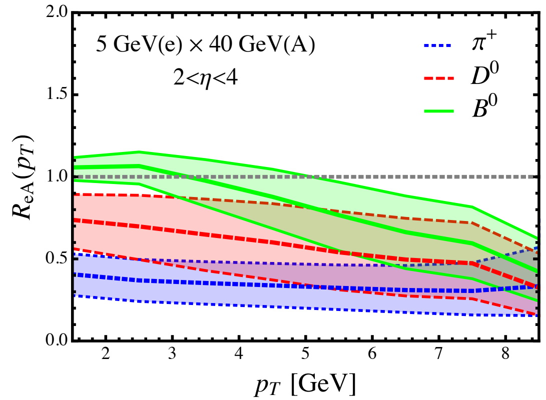
Backward rapidity, large C.M. energy



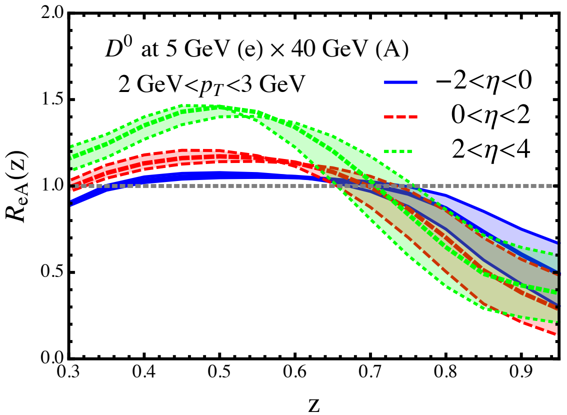
Light pions



Forward rapidity, small C.M. energy



Heavy flavor

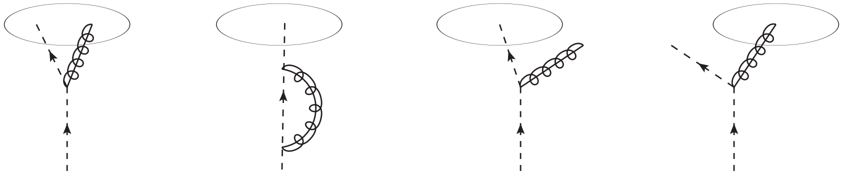


Differential in p_T

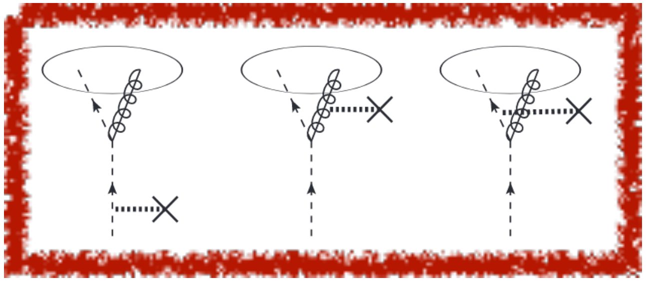
Differential in p_T and z

Final-state in-medium jet cross section modification

Diagrams that contribute to the SiJF at NLO



Medium contributions to the first diagram



- The medium contribution to the jet functions can be expressed in terms of the in-medium splitting functions
- Included at fixed order - NLO level
- Suitable for numerical implementation

The medium NLO contributions to SiJF

$$J_q^{\rm med}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{q\to qg}^{\rm med}(z, \mathbf{k}_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{q\to gq}^{\rm med}(z, \mathbf{k}_\perp)\ ,$$

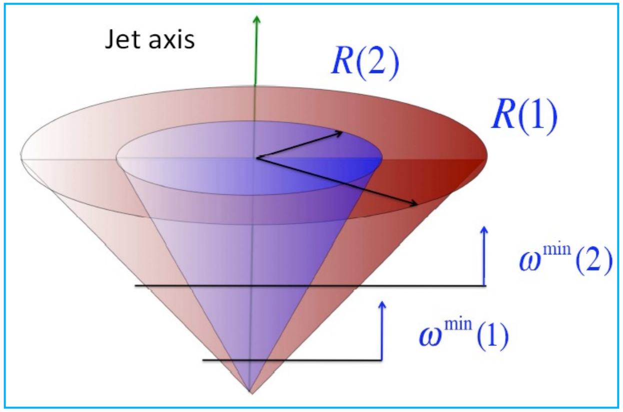
$$J_g^{\rm med}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(z, \mathbf{k}_\perp)\left(\frac{z}{1-z} + z(1-z)\right)\right)\right]_+ + n_f\left[\int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp f_{g\to q\bar{q}}(z, \mathbf{k}_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} d^2\mathbf{k}_\perp \left(h_{gg}(x, \mathbf{k}_\perp)\left(\frac{1-z}{z} + \frac{z(1-z)}{2}\right) + n_f f_{g\to q\bar{q}}(z, \mathbf{k}_\perp)\right)\ ,$$

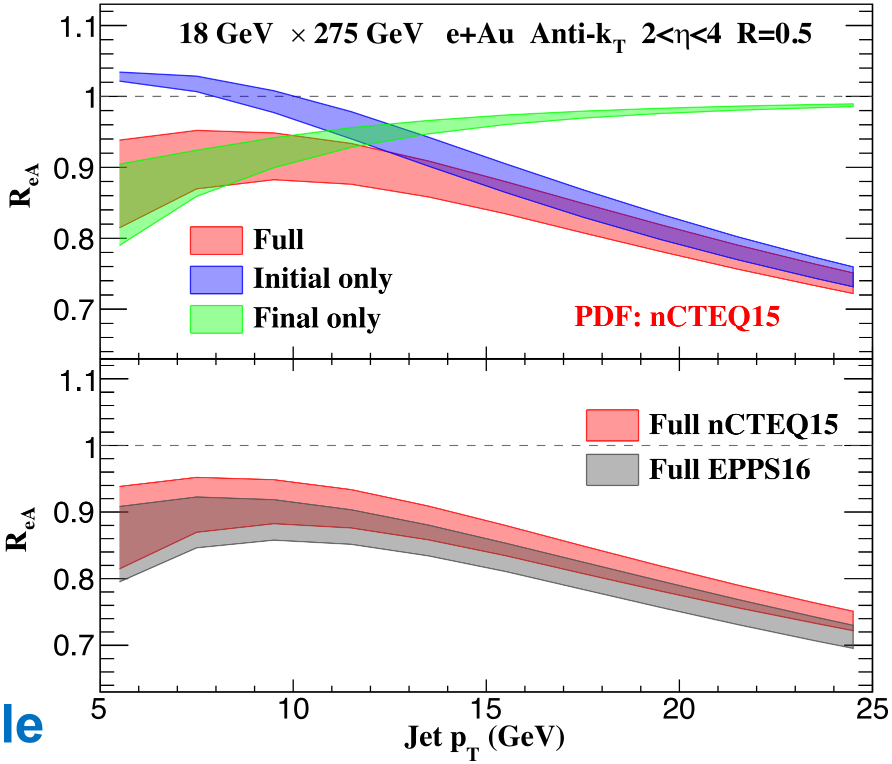
Z. Kang et al. (2017) *H. Li et al. (2021)*

Jet results at the EIC

- The physics of reconstructed jet modification

$$R_{eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+p}}$$





Two types of nuclear effect play a role

- **Initial-state effects parametrized in nuclear parton distribution functions or nPDFs**
- **Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers and jet energy loss**

- Net modification 20-30% even at the highest CM energy
- E-loss has larger role at lower p_T. The EMC effect at larger p_T

H. Li et al., (2020)

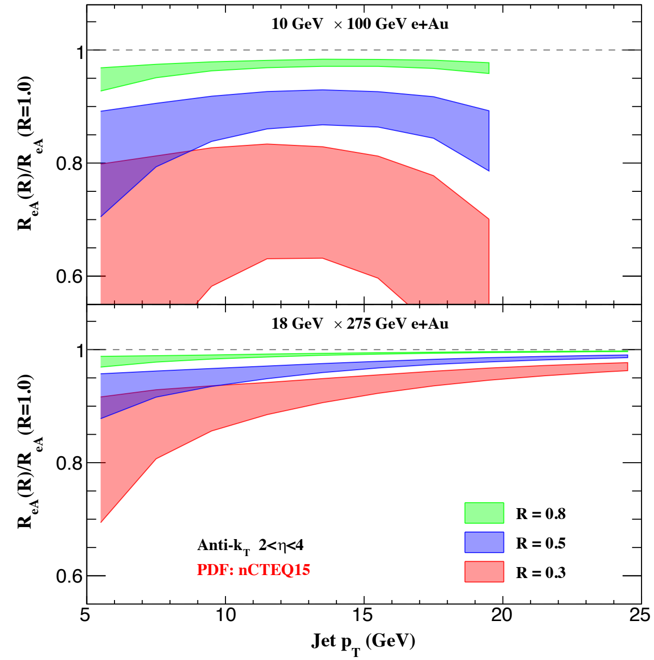
Separating initial-state and final-state effects with jets in DIS

A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?

Define the ratio of modifications for 2 radii (it is a double ratio)

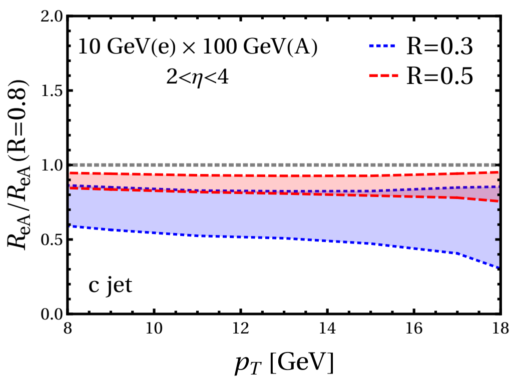
$$R_R = R_{eA}(R)/\ R_{eA}(R=1)$$

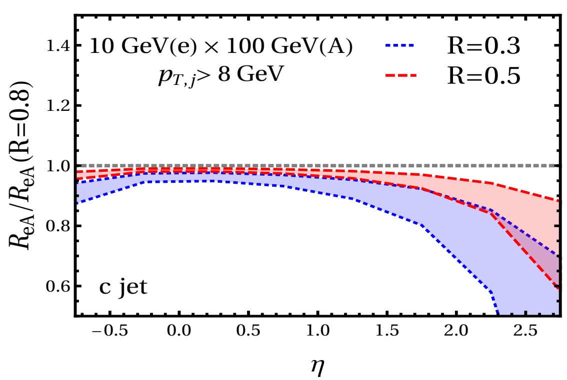
- Jet energy loss effects are larger at smaller center of mass energies (electron-nuclear beam combinations)
- Effects can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)



Initial-state effects are successfully eliminated

H. Li et al., (2020)





The suppression is similarly large for heavy flavor jets

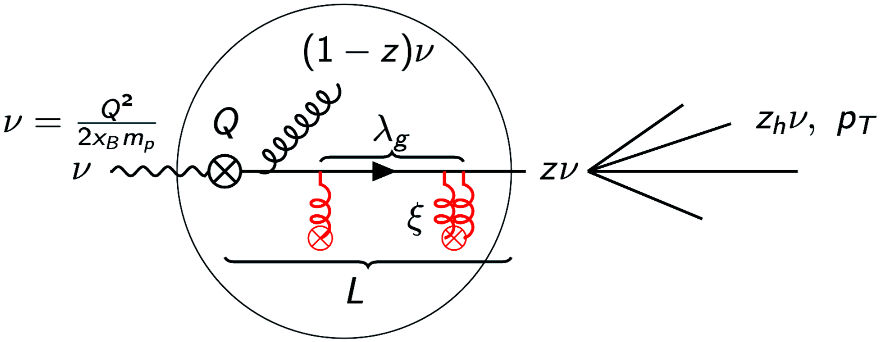
H. Li et al., (2021)

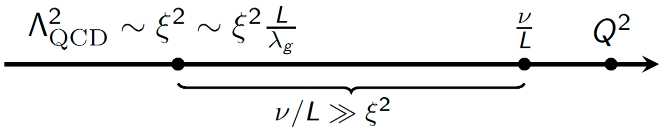
Reading assignment

There are new approaches to understanding parton evolution in matter based on renormalization group analysis. You can take a look and see the latest developments in this direction

Advanced topic: scales in the in-medium parton shower problem

In-medium DGLAP does not tell us what kind of large logs are being resumed





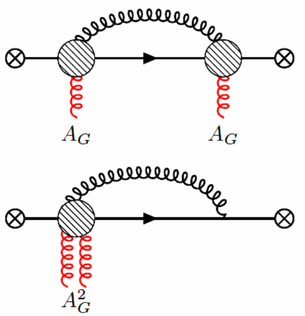
- **We encounter many ratios of scales in DIS on nuclei**
- **Will resume large logarithms of Q/Qo and E/ξ²L**

- **Consider differential hadron production in ep and eA**

W. Ke et al. (2023)

$$\frac{d\sigma_{ep\to h}}{dx_B\, dQ^2 dz_h} = \frac{2\pi\alpha_e^2}{Q^4}\sum_{i,j} \underbrace{e_q^2 f_{i/A}(x_B)\otimes C_{ij}^h(x,z)}_{F_{ij}(z)} \otimes d_{h/j}(z_h)$$

$$\frac{d\sigma_{eA\to h}}{dx_B\, dQ^2 dz_h} = \sum_{i,j}\frac{2\pi\alpha_e^2}{Q^4}\left[F_{ij}(z) + \Delta F_{ij}^{\rm med}(z)\right]\otimes d_{h/j}(z_h)$$



- **The distribution of partons in the shower receives contributions proportional to the in-medium splitting functions**

$$\Delta F_{ij}^{\rm med}(z) = F_{ik}^{(0)} \otimes P_{kj}^{\rm med(1)}$$

Advanced topic: analytic understanding of the in-medium shower

- **We were able to identify a simple analytic limit of the splitting functions integrate the transverse degrees of freedom using dim. reg. and isolate the endpoint divergences**

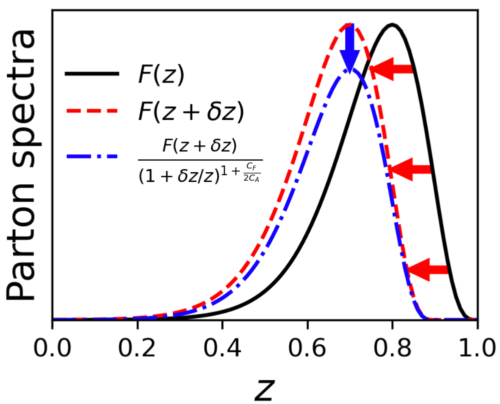
Color non-singlet distribution as an example

$$\Delta F_{\rm NS}^{\rm med}(z) = \int_z^1 \frac{dx}{x} F_{\rm NS}\left(\frac{z}{x}\right) P_{qq}^{\rm med(1)}(x) \quad + \quad \text{virtual term.}$$

$$P_{qq}^{\rm med(1)}(x) = A(\alpha_s, \cdots) \cdot \frac{P_{qq}^{vac(0)}(x)}{[x(1-x)]^{1+2\epsilon}} \cdot \left[\frac{\mu^2 L}{\chi z \nu}\right]^{2\epsilon} \cdot C_n \Delta_n(x)$$

- **Divergences are cancelled by the soft-collinear sector**

$$\Delta F_{\rm NS}(z) = A(\alpha_s, \cdots)\left(\frac{1}{2\epsilon} + \ln\frac{\mu^2 L}{\chi z \nu}\right) 2C_F[\underbrace{2C_A\left(-\frac{d}{dz} + \frac{1}{z}\right)}_{\text{from } x\to 1} + \underbrace{\frac{C_F}{z}}_{x\to 0}]F_{\rm NS}(z) + \text{F.O.}$$



- **Derived a full set of RG evolution equations. The NS distribution has a very elegant traveling wave solution**

$$\frac{\partial F_{\rm NS}(\tau, z)}{\partial \tau} = \left(4C_F C_A \frac{\partial}{\partial z} - \frac{4C_F C_A + 2C_F^2}{z}\right) F_{\rm NS}$$

$$\frac{\partial F_f}{\partial \tau} = \left(4C_F C_A \frac{\partial}{\partial z} - \frac{4C_F C_A + 2C_F^2}{z}\right) F_f + 2C_F T_F \frac{F_g}{z},$$

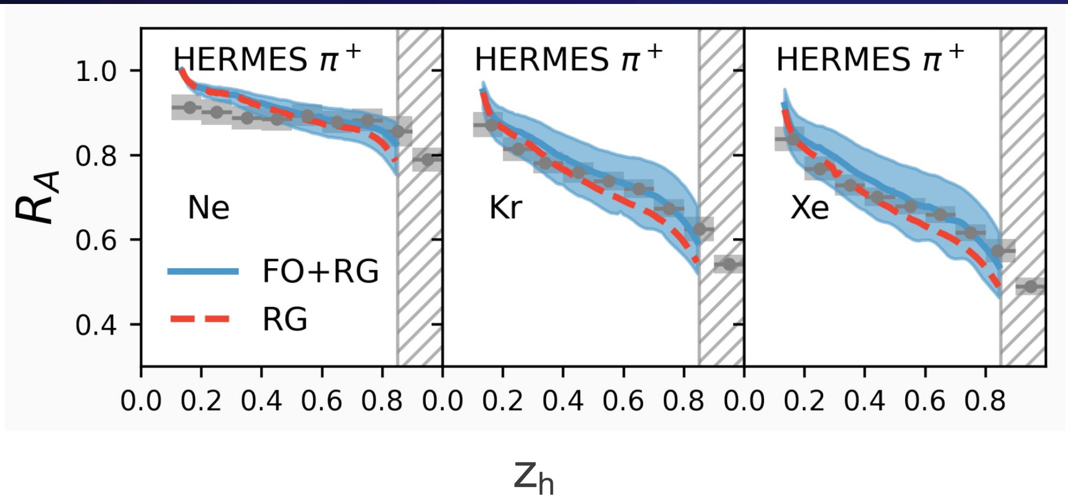
$$\frac{\partial F_g}{\partial \tau} = \left(4C_A^2 \frac{\partial}{\partial z} - \frac{2N_f C_F}{z}\right) F_g + 2C_F^2 \sum_f \frac{F_f}{z}.$$

$$\tau(\mu^2) = \frac{\rho_G L^2}{\nu}\frac{\pi B}{2\beta_0}\left[\alpha_s(\mu^2) - \alpha_s\left(\chi\frac{z\nu}{L}\right)\right]$$

$$F_{\rm NS}(\tau, z) = \frac{F_{\rm NS}\left(0, z + 4C_F C_A \tau\right)}{(1 + 4C_F C_A \tau / z)^{1 + C_F/(2C_A)}}$$

Can directly identify parton energy loss, the nuclear size dependence of the modification, etc

Phenomenological applications of the new RG analysis



Observable chosen to eliminate initial-state effects

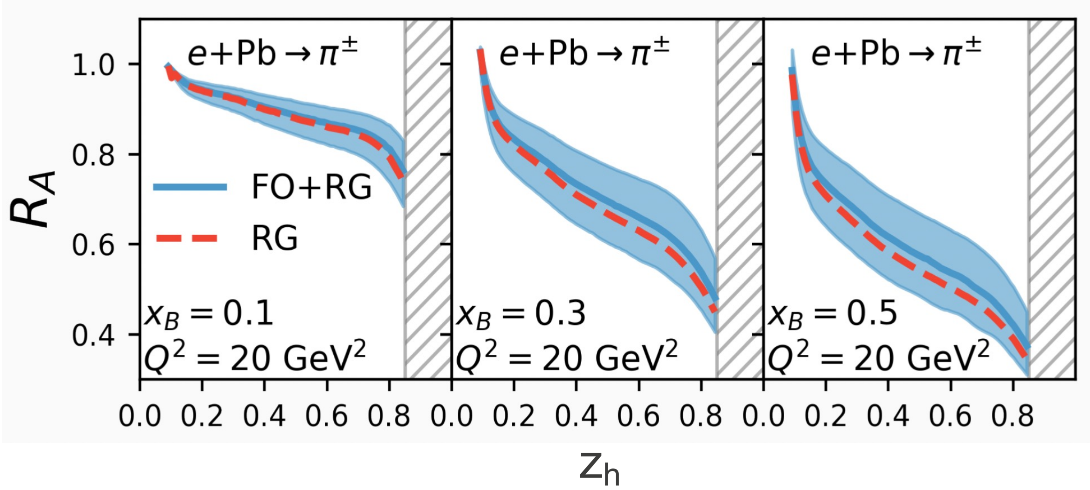
$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_D}$$

- **RG evolution gives a good description of the data at small to intermediate z_h .**
- **Fixed order corrections improve the agreement at large z_h**

W. Ke et al. (2023)

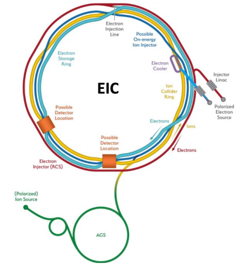
Results for EIC

- **The modifications to hadronization at EIC depends on kinematics x_B,Q^2 (which affects the)**
- **At large x_B and (forward rapidities) the modification can be very significant**

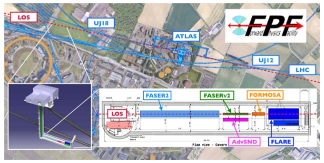


Conclusions

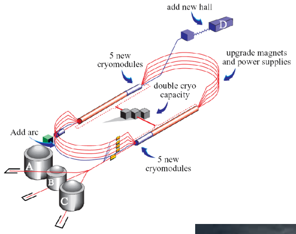
- **There is great complementarity between FPF and EIC, oscillation experiments and Jlab electron scattering**
- **QED medium effects on lepton scattering are now understood. They are at the percent to per-mille level and most important in angular distributions**
- **In neutrino-nucleus DIS there is opportunity to better understand the microscopic physics behind shadowing, sum rules, and structure functions**
- **FPF and EIC, especially with the ν(e)A program can answer fundamental questions about hadronization, many-body QCD, transport properties of matter, the effects of heavy quark mass on parton showers**



EIC



FPF

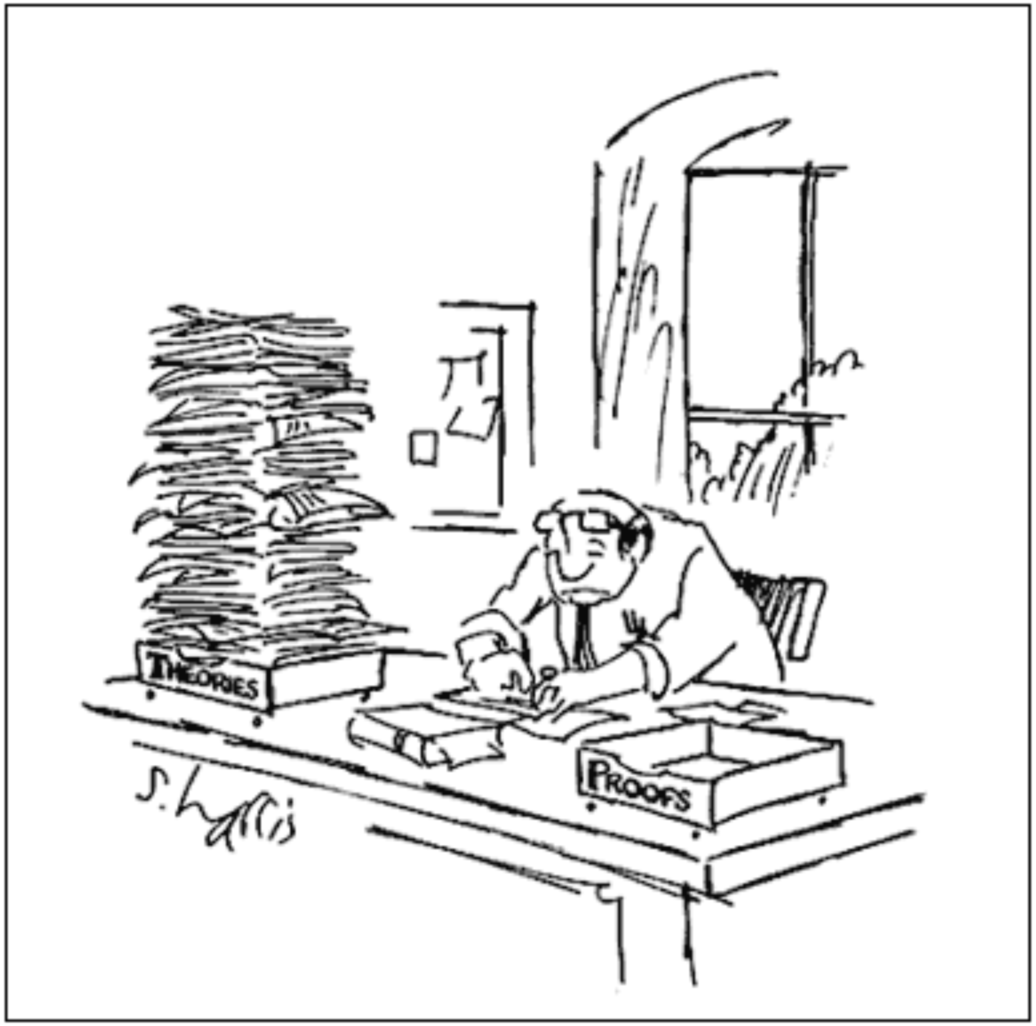


JLab

HyperK

Thank you

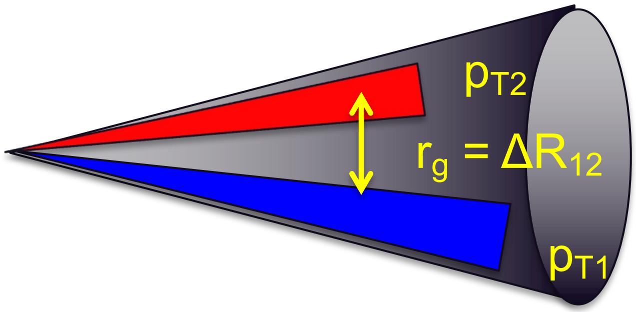
Backup



Jet momentum sharing distributions

Soft dropped momentum sharing distributions

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



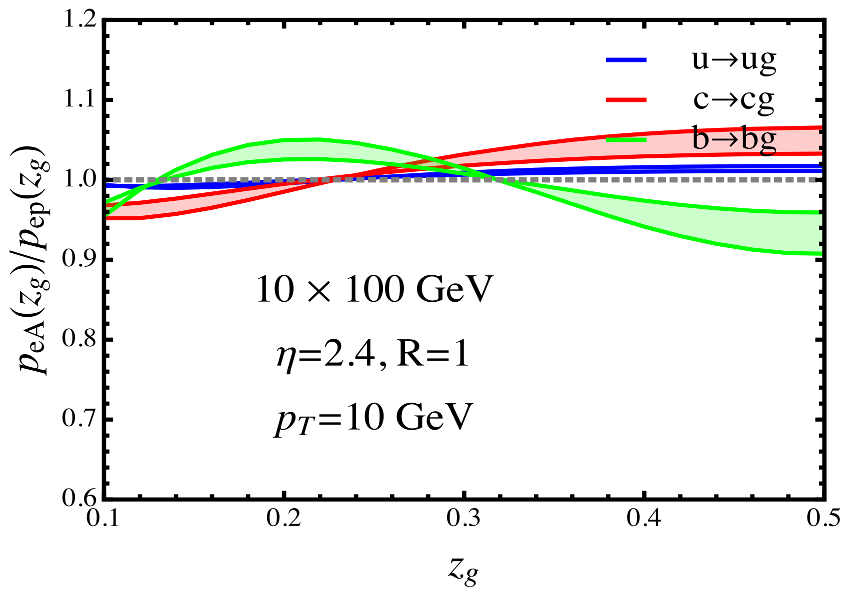
There is a contribution from the medium. The softer in-medium branching was observed in HIC!

- The most significant manifestation of the "dead cone" effect – role of heavy quark mass in parton showers

$$\frac{p_{med}^{Q\to Qg}(z_g)}{p_{\rm pp}^{Q\to Qg}(z_g)} \sim \frac{1}{z_g^2}, \quad \frac{p_{med}^{j\to i\bar{i}}(z_g)}{p_{\rm pp}^{j\to i\bar{i}}(z_g)} \sim \frac{1}{z_g}, \quad \frac{p_{med}^{g\to Q\bar{Q}}(z_g)}{p_{\rm pp}^{g\to Q\bar{Q}}(z_g)} \sim \text{const.}$$

H. Li et al., (2018)

$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$



- **Modification of both c-jets and b-jets substructure in eA is relatively small**
- **It is dominated by limited phase space**