QCD and Nuclear effects on Drell-Yan Angular Coefficients in pp and p-Fe at 120 GeV proton beam energy

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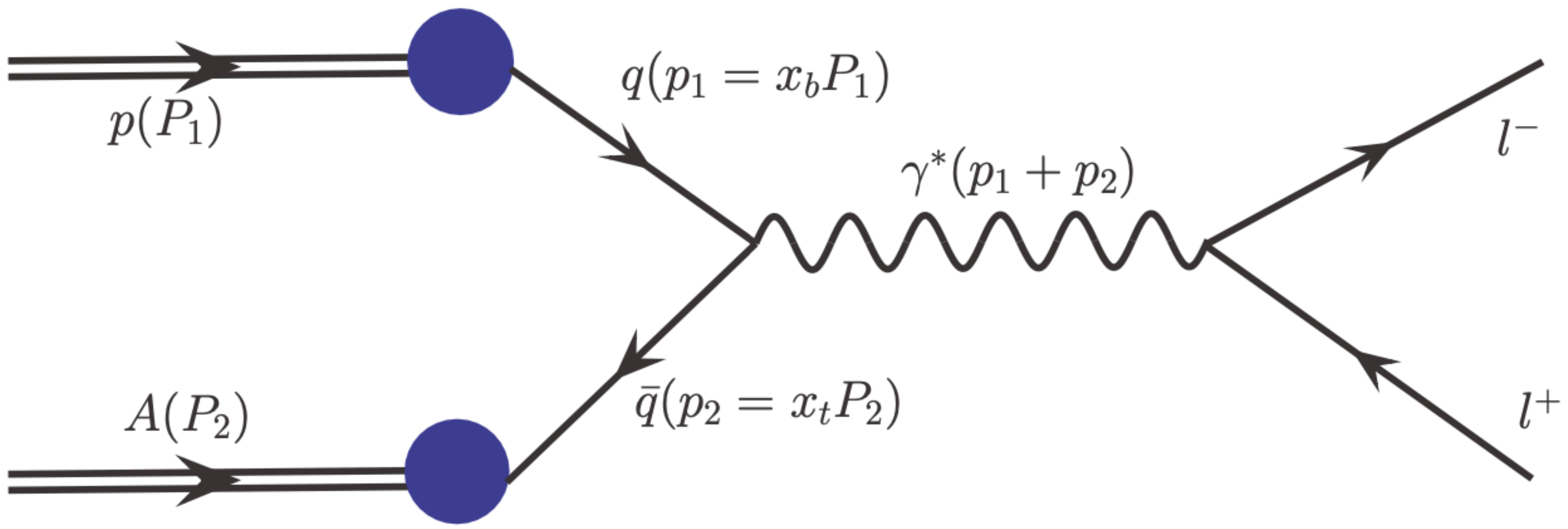
Outline

- Drell-Yan Process.
- Drell-Yan Angular Distribution.
- Perturbative-QCD Corrections
- Nuclear Effects on Drell-Yan Angular Coefficients.
- Summary

- **The Drell-Yan process is the production of lepton pairs in hadron collisions.**
- **The process is induced by the annihilation of a quark-antiquark pair into a virtual photon which subsequently decays into a lepton pair.**
- **The Drell-Yan process in hadron collisions therefore provides a direct probe of the antiquark densities in nucleons and nuclei as well as the quark distributions of pions, kaons, and antiprotons.**



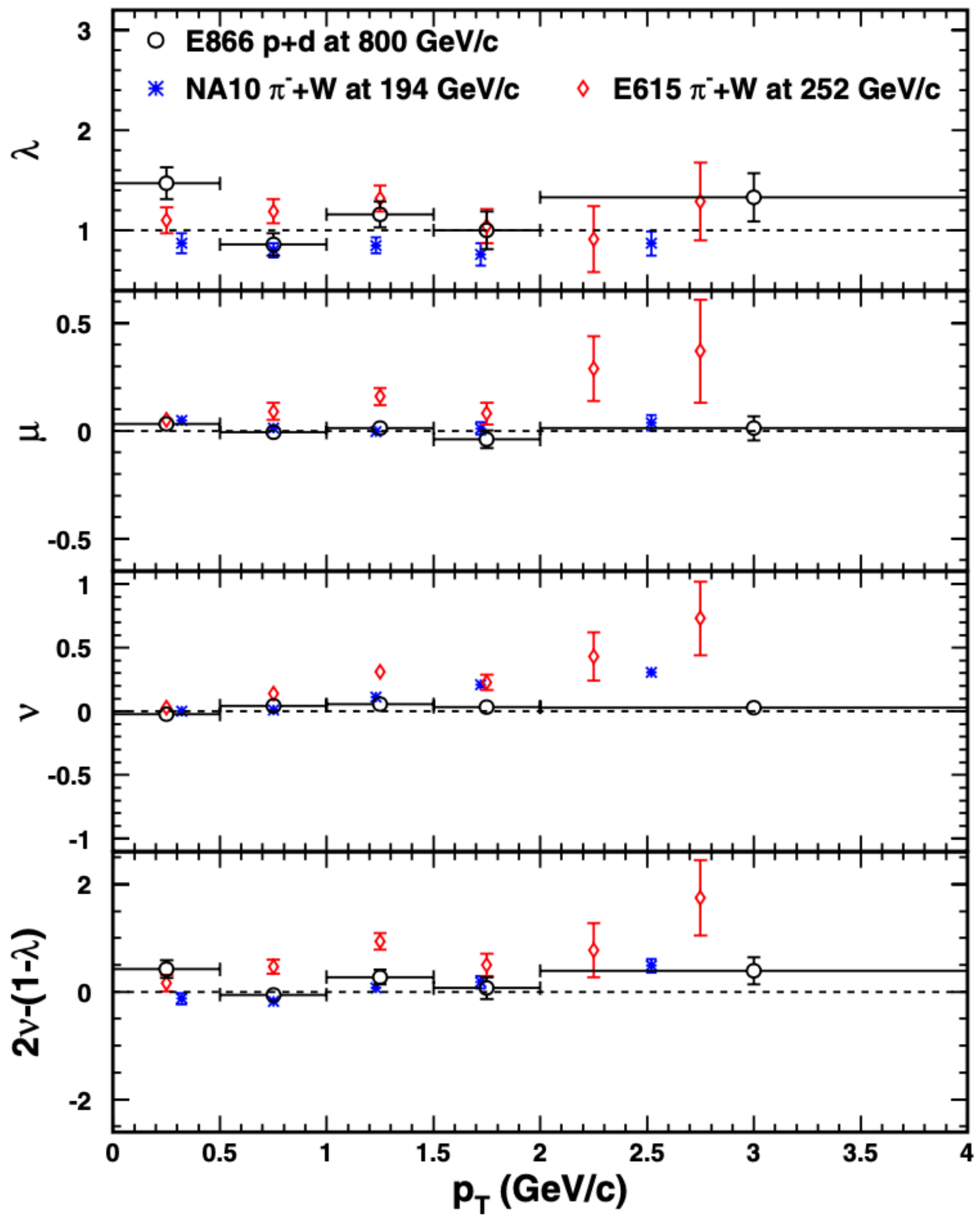


FIG. 1 (color online). Parameters λ, μ, ν, and $2\nu-(1-\lambda)$ vs p_T in the Collins-Soper frame. Open circles are for E866 $p+d$ at 800 GeV/c, crosses are for NA10 $\pi^- + W$ at 194 GeV/c, and diamonds are E615 $\pi^- + W$ at 252 GeV/c. The error bars include the statistical uncertainties only.

PRL **99**, 082301 (2007)

The angular differential cross section for the unpolarized Drell-Yan process is usually parametrized as

$$\frac{1}{\sigma^{\rm DY}}\frac{d\sigma^{\rm DY}}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right).$$

λ, μ, and ν are parameters which completely describe the angular distribution, and depend on the choice of photon rest frame

where θ and ϕ are, respectively, the polar angle and the azimuthal angle of dileptons in a dilepton center of mass frame.

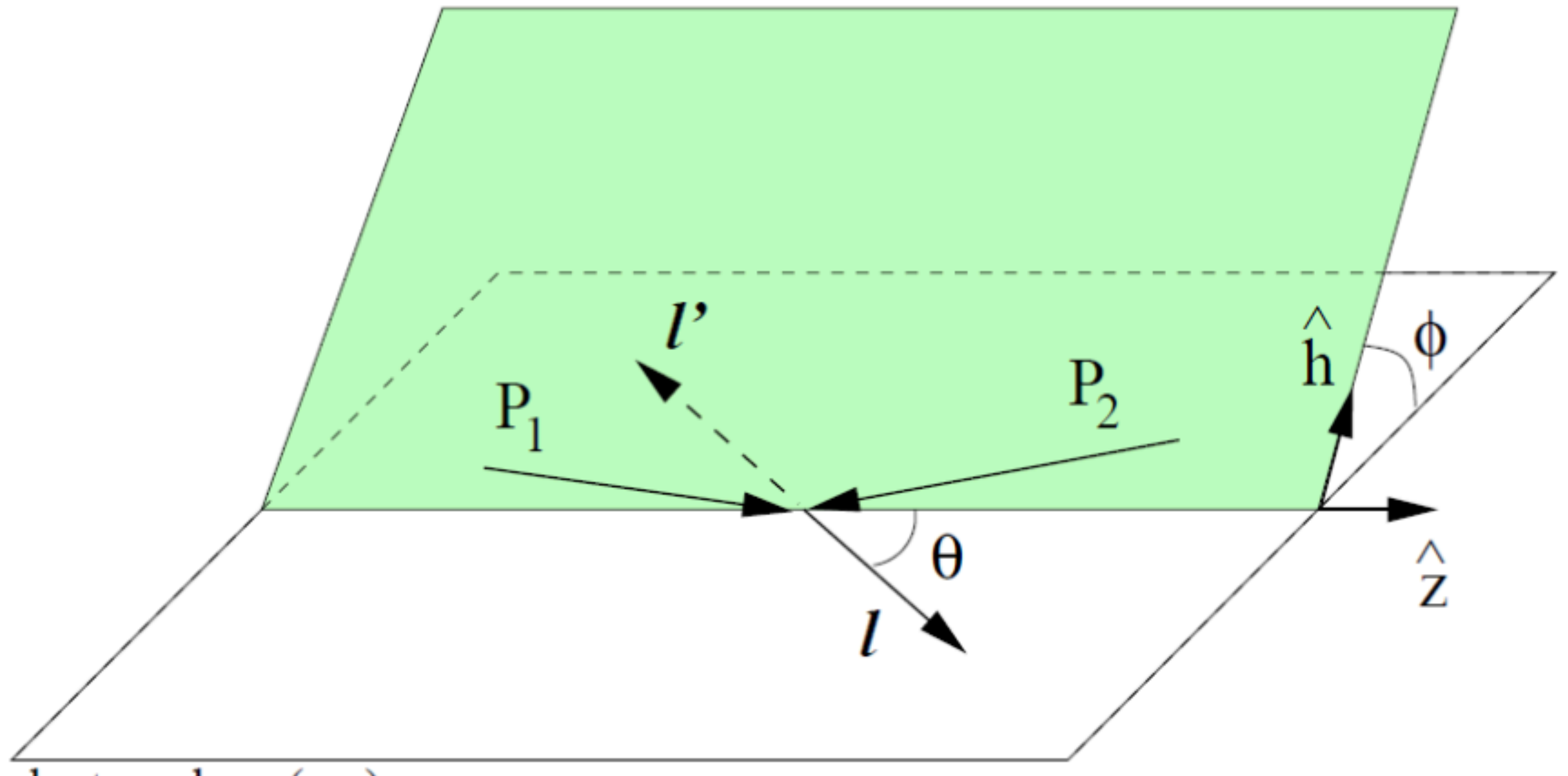
In the “naive” Drell-Yan model, where the transverse momentum of the quark is ignored and no gluon emission is considered, $\lambda = 1$ and $\mu = \nu = 0$ are obtained.

$$\lambda = 1 - 2\nu$$ Lam-Tung relation

P_T:Transverse momentum of the virtual photon

Angular Distributions of Lepton Pairs

Collins-Soper Frame



$$\lambda = \frac{2-3A_0}{2+A_0}$$

$$\mu = \frac{2A_1}{2+A_0}$$

$$\nu = \frac{2A_2}{2+A_0}$$

$$\frac{d\sigma}{d\Omega} \propto (1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

$$\propto [(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi]$$

$q\bar{q}$ annilation parton model: $O(\alpha_s^0)$ $\lambda=1,\ \mu=\nu=0;\ A_0 = A_2 = 0$

pQCD: $O(\alpha_s^1)$, ; $1-\lambda-2\nu = \frac{4(A_2-A_0)}{2+A_0} = 0$; $A_0 = A_2$

Lam-Tung Relation [PRD 18 (1978) 2447]

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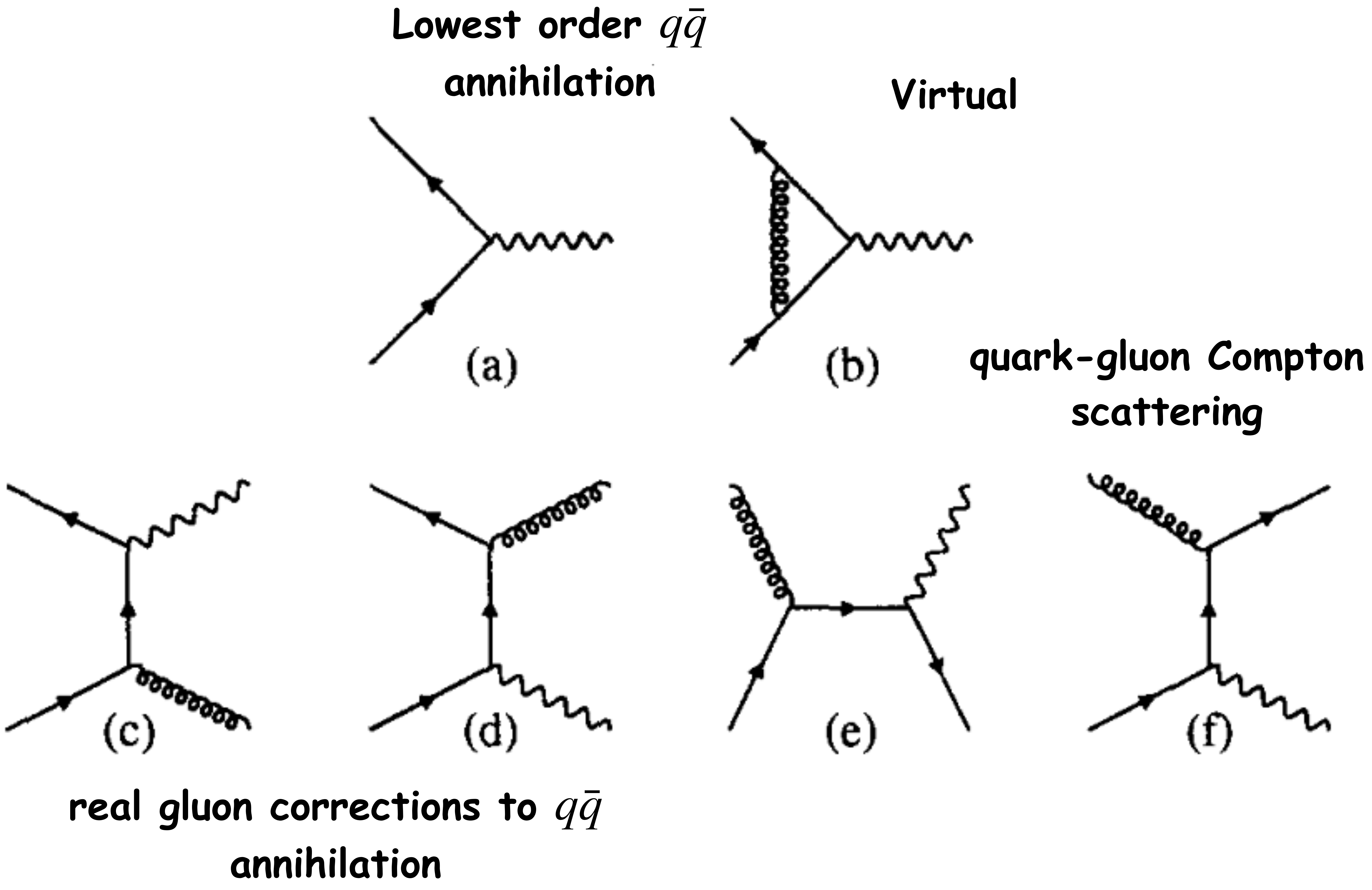
Slide courtesy of Wen-Chen Chang

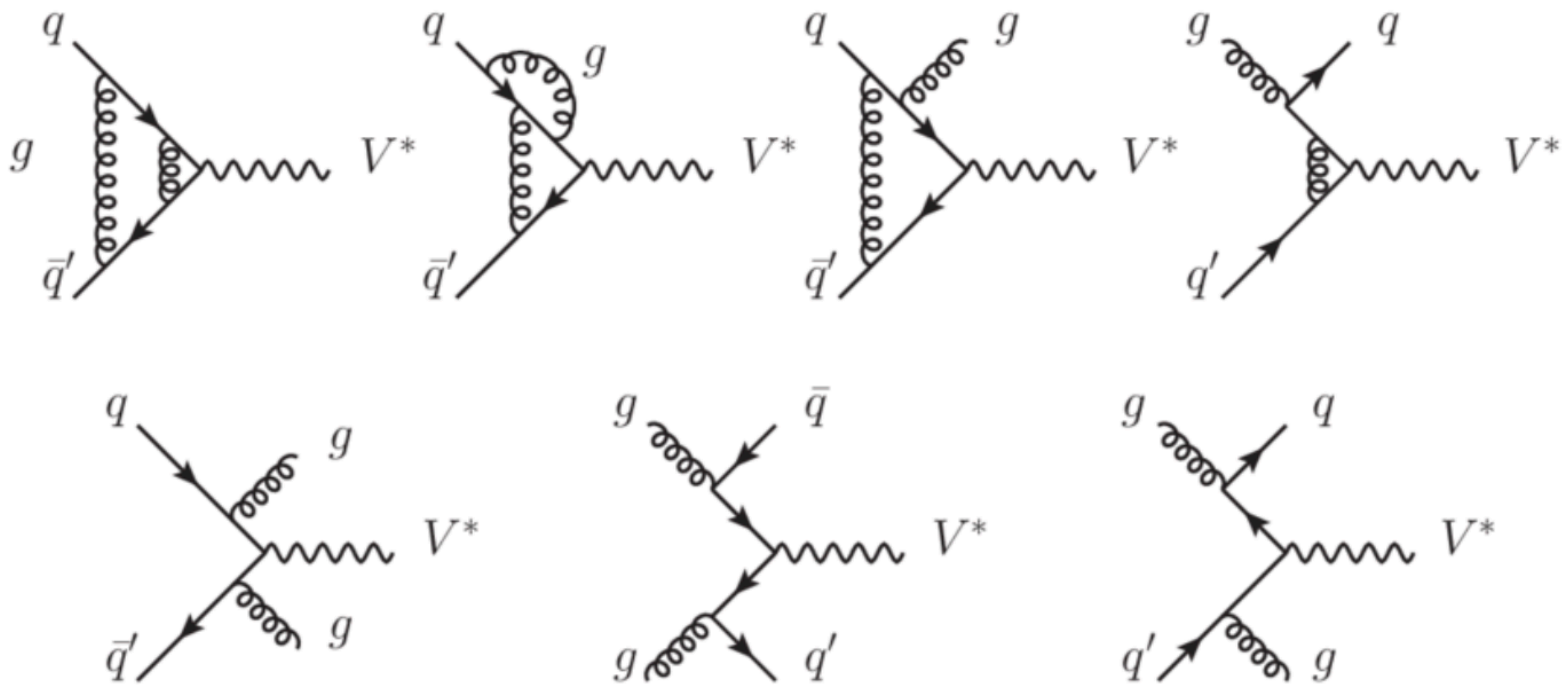
QCD corrections to the Drell-Yan process

Parton-level subprocesses contributing to the Drell-Yan process up to $O(\alpha_s)$



DYNNLO: is a parton level Monte Carlo program that computes the cross section for vector-boson production in pp and $p\bar{p}$ collisions. The calculation is performed up to NNLO in QCD perturbation theory(http://theory.fi.infn.it/grazzini).

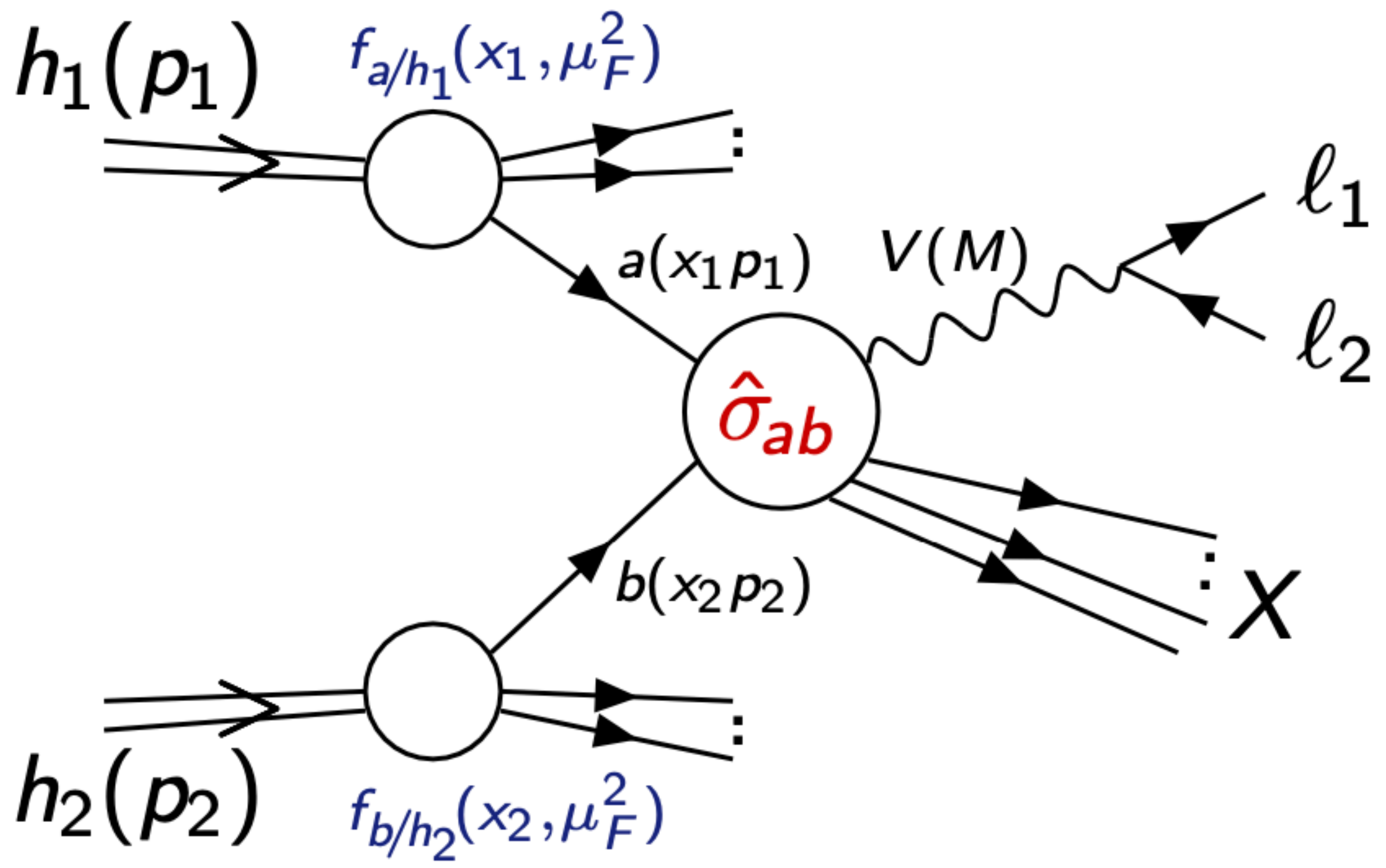
DYTurbo: Fast predictions for Drell-Yan processes(https://arxiv.org/abs/1910.07049)



Some Feynman diagrams contributing at NNLO QCD to Drell-Yan production.

JHEP 1304 (2013) 151

The Drell-Yan process



$$h_1(p_1) + h_2(p_2) \;\rightarrow\; V(M) + X \;\rightarrow\; \ell_1 + \ell_2 + X$$

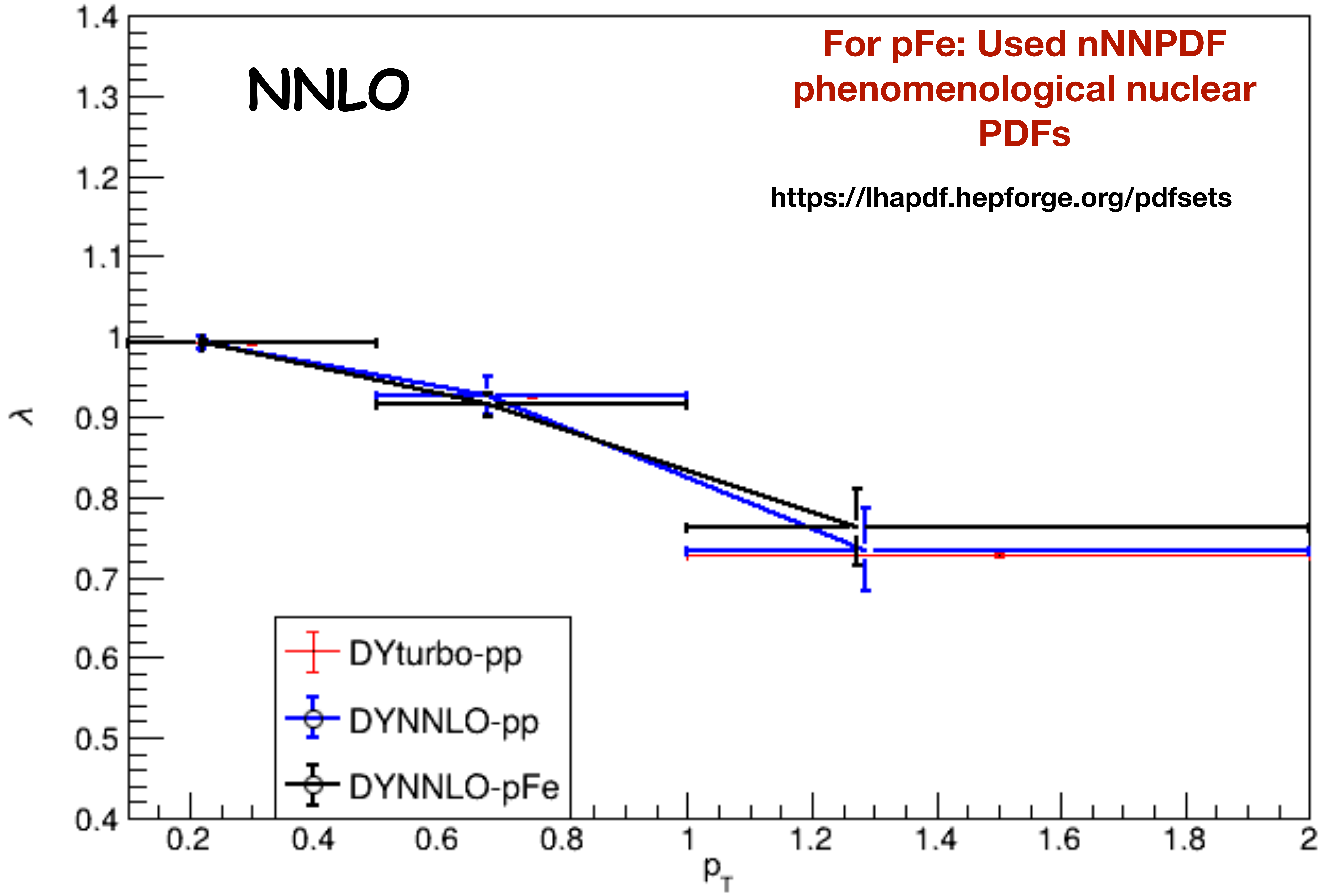
where $V = \gamma^*, Z^0, W^\pm$ and $\ell_1 \ell_2 = \ell^+\ell^-, \ell\nu_\ell$

According to the QCD factorization theorem:

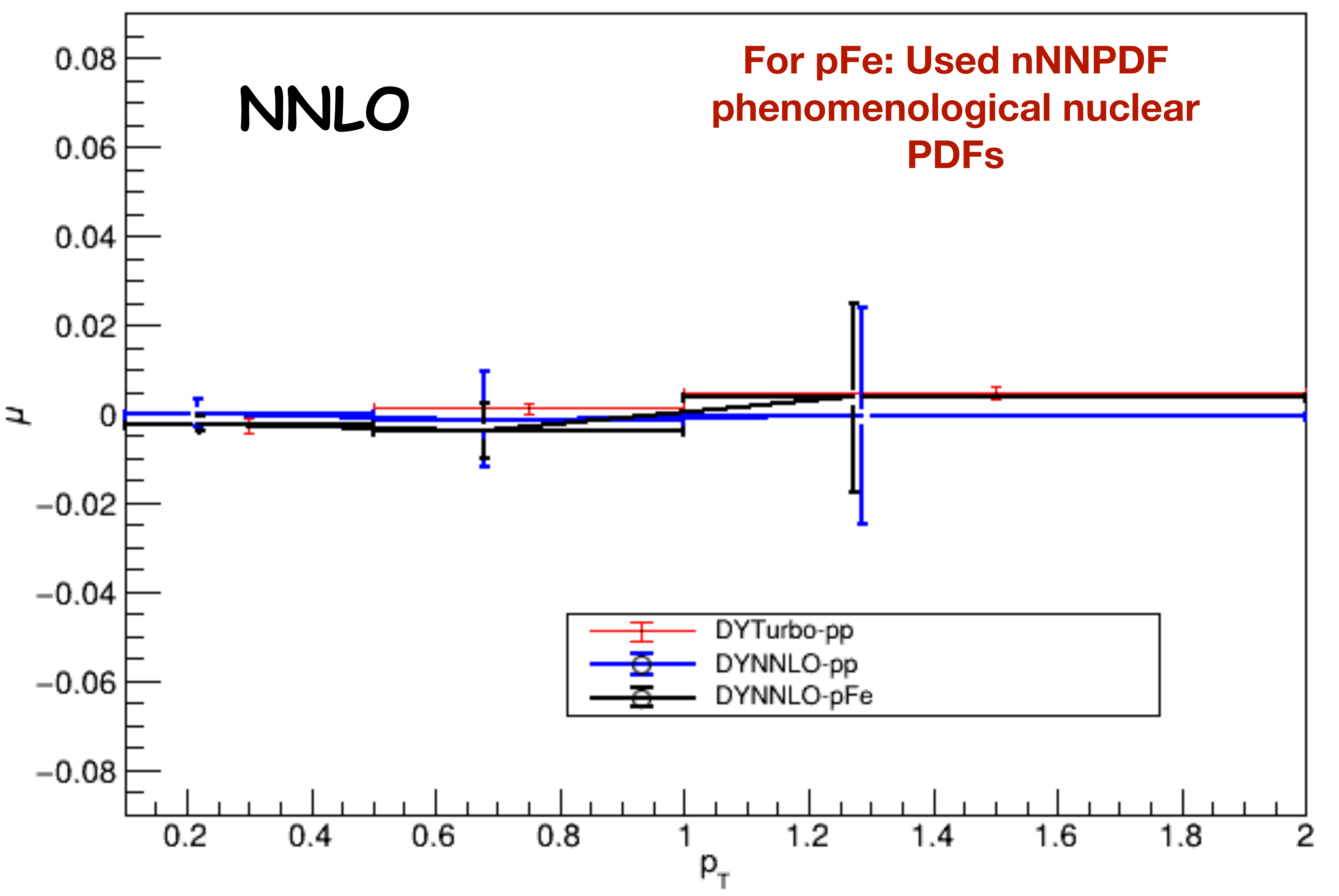
$$d\sigma(p_1,p_2,\{y\}) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2)\, d\hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \{y\}; \mu_F^2) + \mathcal{O}\left(\frac{\Lambda^2}{M^2}\right).$$

$$d\hat{\sigma}_{ab}(\hat{p}_1,\hat{p}_2,\{y\};\mu_F^2) = d\hat{\sigma}^{(0)}_{ab}(\hat{p}_1,\hat{p}_2,\{y\};\mu_F^2) + \alpha_S(\mu_R^2)\, d\hat{\sigma}^{(1)}_{ab}(\hat{p}_1,\hat{p}_2,\{y\};\mu_F^2) + \alpha_S^2(\mu_R^2)\, d\hat{\sigma}^{(2)}_{ab}(\hat{p}_1,\hat{p}_2,\{y\};\mu_F^2,\mu_R^2) + \mathcal{O}(\alpha_S^3).$$

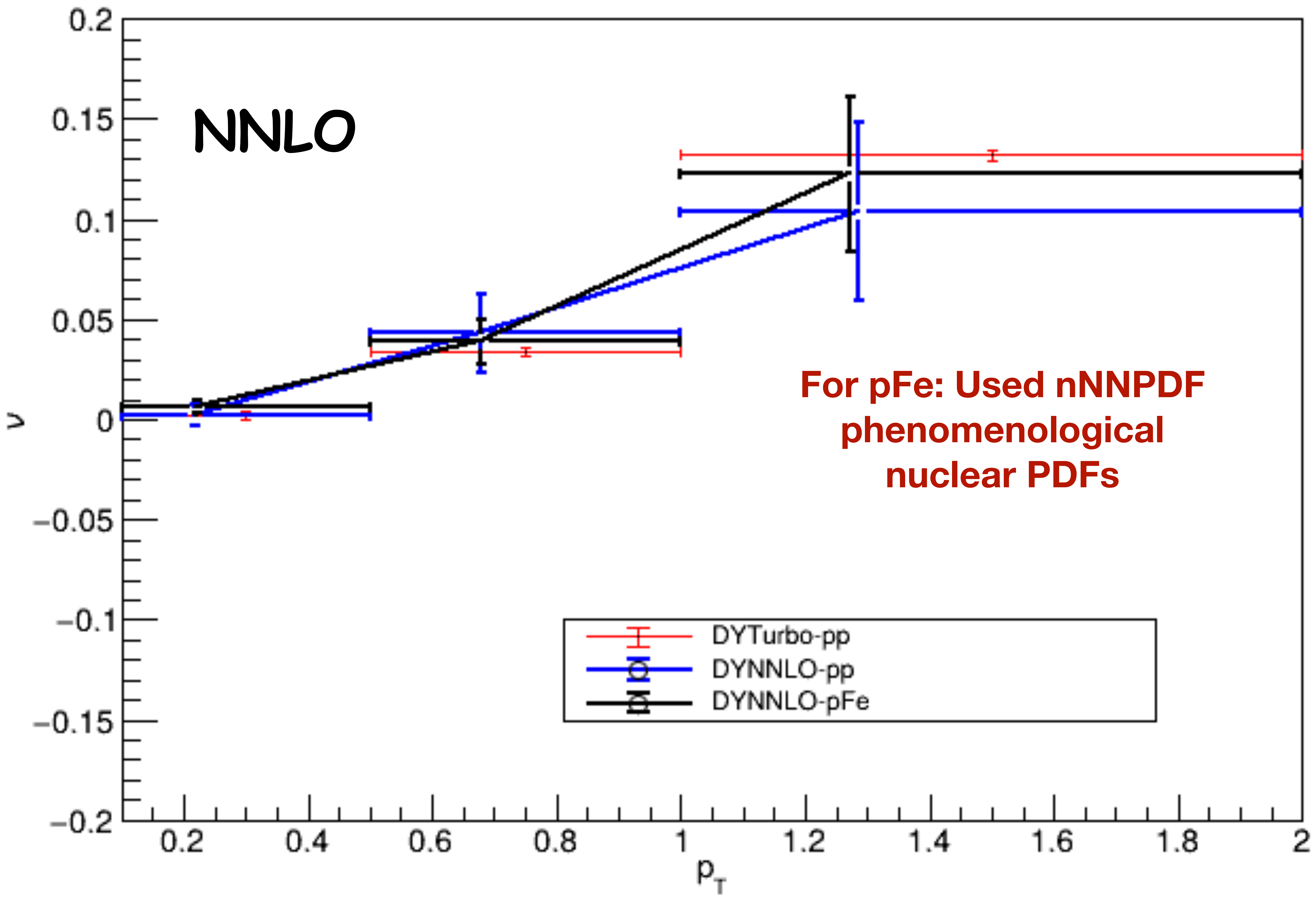
$\{y\} \equiv$ Infrared safe constraints on final states.



NNLO
For pFe: Used nNNPDF phenomenological nuclear PDFs
https://lhapdf.hepforge.org/pdfsets
λ
p_T
DYturbo-pp
DYNNLO-pp
DYNNLO-pFe
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



NNLO
For pFe: Used nNNPDF
phenomenological nuclear
PDFs
DYTurbo-pp
DYNNLO-pp
DYNNLO-pFe
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
μ
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
p_T


NNLO
For pFe: Used nNNPDF
phenomenological
nuclear PDFs
DYTurbo-pp
DYNNLO-pp
DYNNLO-pFe
v
p_T
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

In a nucleus, the nucleons are neither at rest nor non-interacting, leading to various types of nuclear effects.

- Fermi motion, binding energy and nucleon correlations through spectral function and is calculated using Lehmann's representation for the relativistic nucleon propagator.
- Nuclear many body theory is used to calculate it for an interacting Fermi sea in nuclear matter. A local density approximation is then applied to translate these results to finite nuclei.
- There are virtual mesons associated with the nucleon bound inside the nucleus. These meson clouds get strengthened by the strong attractive nature of nucleon-nucleon interactions.
- This leads to an increase in the interaction probability of virtual mediating quanta with the meson cloud. The effect of meson cloud is more pronounced in heavier nuclear targets and dominate in the intermediate region of x $(0.2<x<0.6)$.
- The shadowing suppression at small x occurs due to coherent multiple scattering of quark-anti quark pair coming from the virtual boson with destructive interference of the amplitudes and is incorporated following the works of Kulagin and Petti. Phys. Rev. D **76**, 094033(2007).

Nucleon binding

- The nucleons in the nucleus are bound and the binding energy of the nuclei is well studied and known.
- Consequently, the nucleons in the nuclei are off-mass shell and do not satisfy the energy momentum relation, that is, $p^2 = M^2$.
- There are many theoretical models suggesting that the effective mass of nucleons is reduced in the nuclear medium and the reduction is related to the strength of the potential responsible for the nuclear binding; it is therefore model dependent.
- In any case, this affects the free particle kinematics and the peak of the energy distribution is shifted in the energy distribution of the nucleus

Local Fermi gas model

- In the local Fermi gas (LFG) model, the Fermi momenta of the initial and final nucleons are not constant, but depend upon the interaction point $\vec{r}$ and are bounded by their respective Fermi momentum at r, that is, $p_{F_n}(r)$ and $p_{F_p}(r)$ for neutron and proton, respectively, where
- $p_{F_n}(r) = 3\pi^2\rho_n(r)^{1/3}$ and $p_{F_p}(r) = 3\pi^2\rho_p(r)^{1/3}$
- $\rho_n(r)$ and $\rho_p(r)$ being the local neutron and proton nuclear densities, respectively.

- The proton density is expressed in terms of the nuclear charge
- density $\rho(r)$ as $\rho_p(r) = Z\rho(r)$and the neutron density is given by $\rho_n(r) = (Z - A)\rho(r)$

- where $\rho(r)$ is the nuclear density, determined experimentally by the electron–nucleus scattering experiments for the proton and neutron matter density is obtained using the Hartree– Fock calculation.

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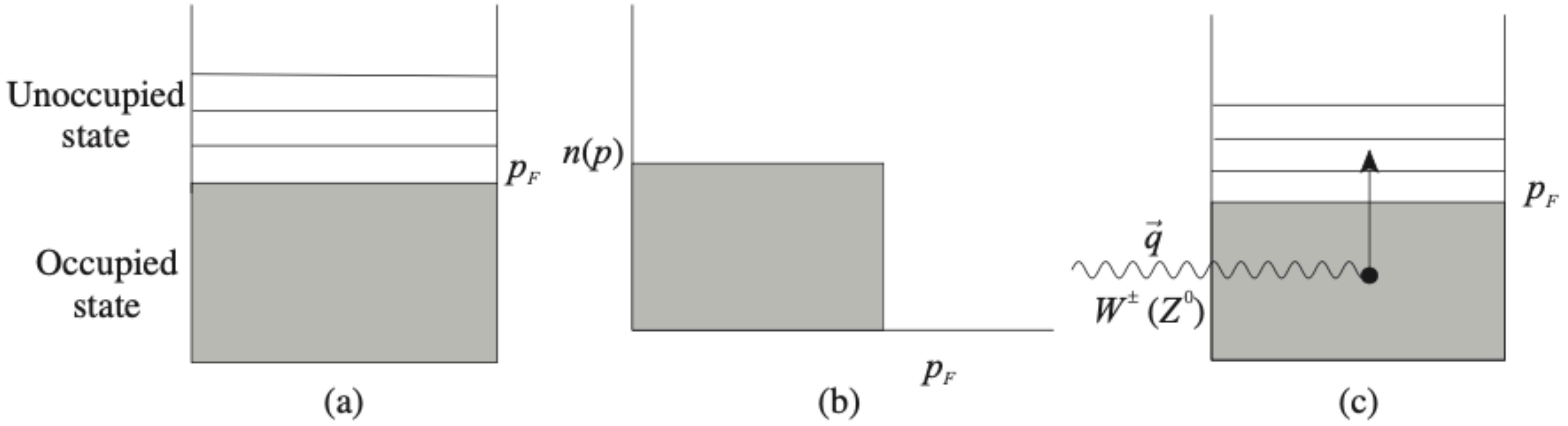
Pauli blocking

In the conventional shell model picture of nuclei, various nuclear states are filled by neutrons and protons starting from the lowest possible state up to a certain nuclear state depending upon the number of nucleons.

Similarly, in a Fermi gas picture of the nuclei, all the nuclear states in the Fermi sea are filled up to the momentum pF (Figure), (a) and (b). This defines the ground state.

In any nuclear reaction, the nucleons from a certain filled state are excited to a higher unoccupied state depending upon the energy transfer, creating a hole in the previously occupied state (Figure) (c). This is called the creation of a particle–hole ($1p - 1h$) state in the Hilbert space of nuclei or in the Fermi sea.



- *Since the nucleons are fermions and follow Pauli's exclusion principle, the excited particles are not allowed to occupy the already filled states.*

we can incorporate the nuclear medium effects like Fermi motion, binding energyand nucleon correlations in the parton distribution functions by writing them in terms of the nucleon spectral function

$$q^t_{f,SF}(x_t, q^2) = 2\sum_{i=p,n}\int d^3r \int \frac{d^3p}{(2\pi)^3}\frac{M_N}{E(\mathbf{p})}\int_{-\infty}^{\mu_i} dp^0\; S_h^i(p^0, \mathbf{p}, \rho_i(r))q^i_f(x'_t(p^0, \vec{p}), q^2)$$

$$\bar{q}^t_{f,SF}(x_t, q^2) = 2\sum_{i=p,n}\int d^3r \int \frac{d^3p}{(2\pi)^3}\frac{M_N}{E(\mathbf{p})}\int_{-\infty}^{\mu_i} dp^0\; S_h^i(p^0, \mathbf{p}, \rho_i(r))\bar{q}^i_f(x'_t(p^0, \vec{p}), q^2),$$

where $S_h(\omega, p)$ hole spectral functions

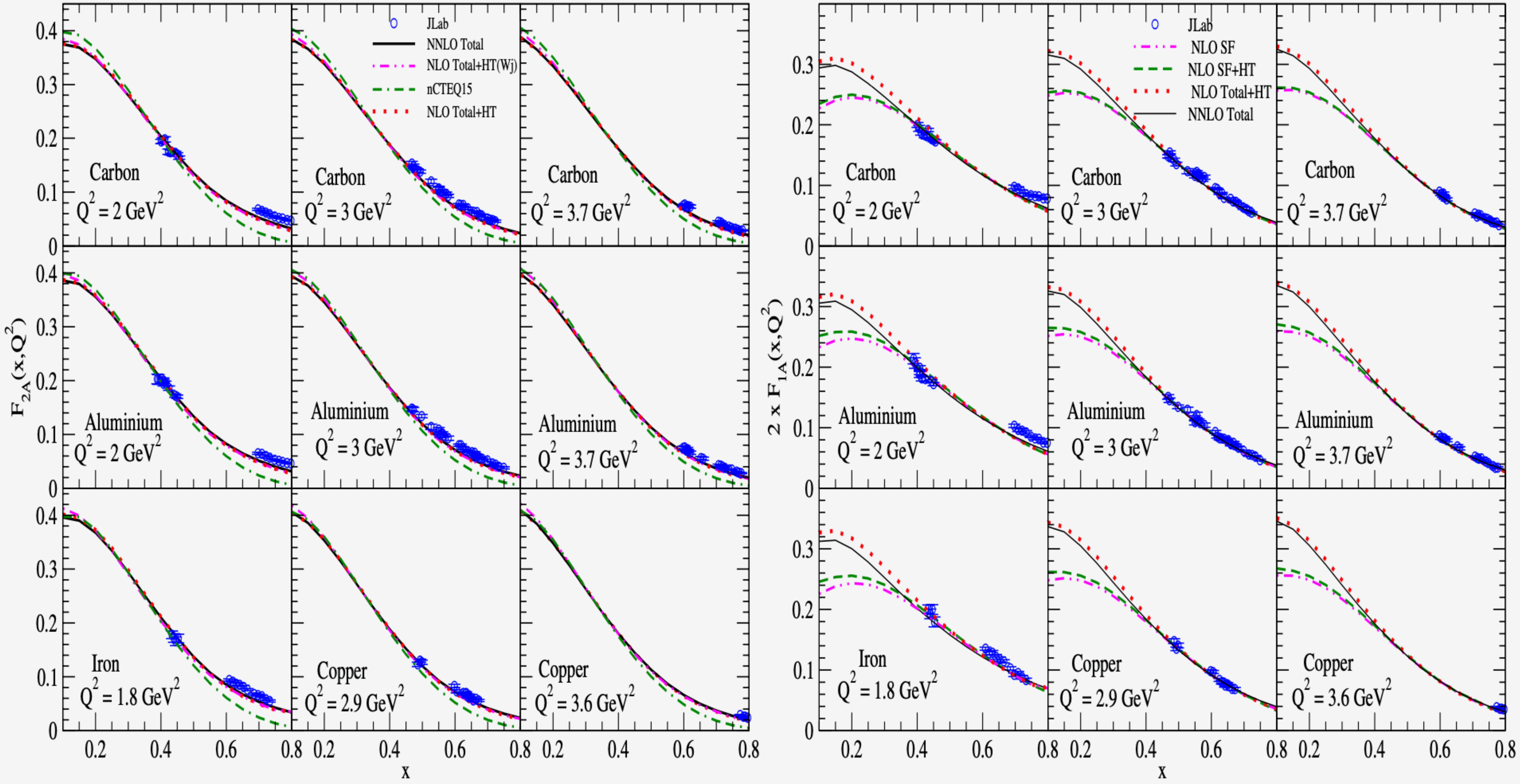
μ is the chemical potential

$$S_h(p^0, \mathbf{p}) = \frac{1}{\pi}\frac{\frac{M_N}{E(\mathbf{p})}Im\Sigma(p^0, \mathbf{p})}{(p^0 - E(\mathbf{p}) - \frac{M_N}{E(\mathbf{p})}Re\Sigma(p^0, \mathbf{p}))^2 + (\frac{M_N}{E(\mathbf{p})}Im\Sigma(p^0, \mathbf{p}))^2} \quad \text{when } p^0 \le \mu,$$

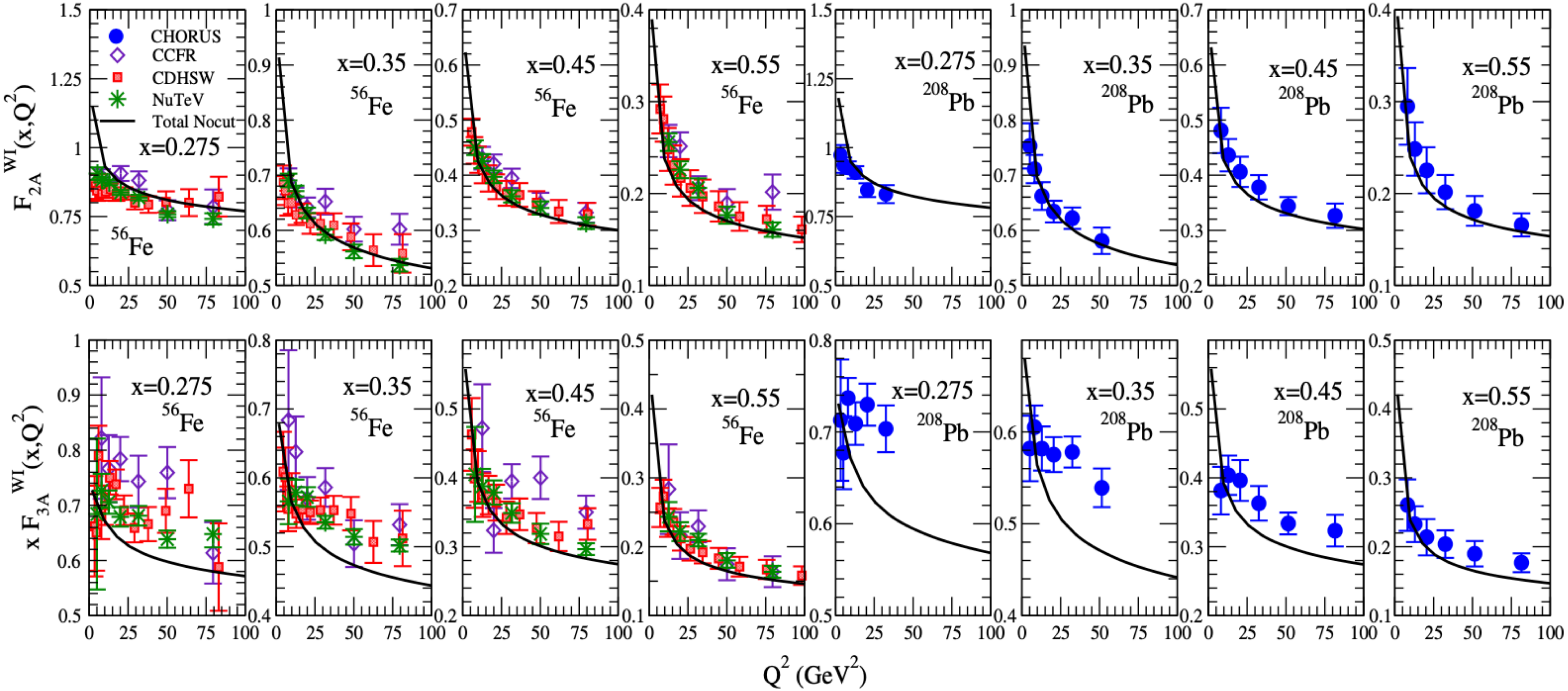
- *P. Fernandez de Cordoba and E. Oset, Phys. Rev. C 46, 1697 (1992).*

where $q^i_f(\bar{q}^i_f(x_t, q^2))$ is the quark(antiquark) PDFs for flavor f inside a nucleon of kind i and the factor of 2 is because of quark(antiquark) spin degrees of freedom. $x_t' = \frac{M_N}{p^0 - p_z}x_t$ which is obtained from the covariant expression of $x'_t = \frac{q\cdot p_1}{s_N}$ with $\mathbf{q}||z$ direction.

EM Nuclear Structure Functions



Zaidi *et al.*, Phys. Rev. D **99**, 093011 (2019).


CHORUS
CCFR
CDHSW
NuTeV
Total Nocut
x=0.275
x=0.35
x=0.45
x=0.55
56Fe
208Pb
F2A WI(x,Q2)
x F3A WI(x,Q2)
Q2 (GeV2)

Drell-Yan

J.Phys. G44 (2017) no.4, 045111

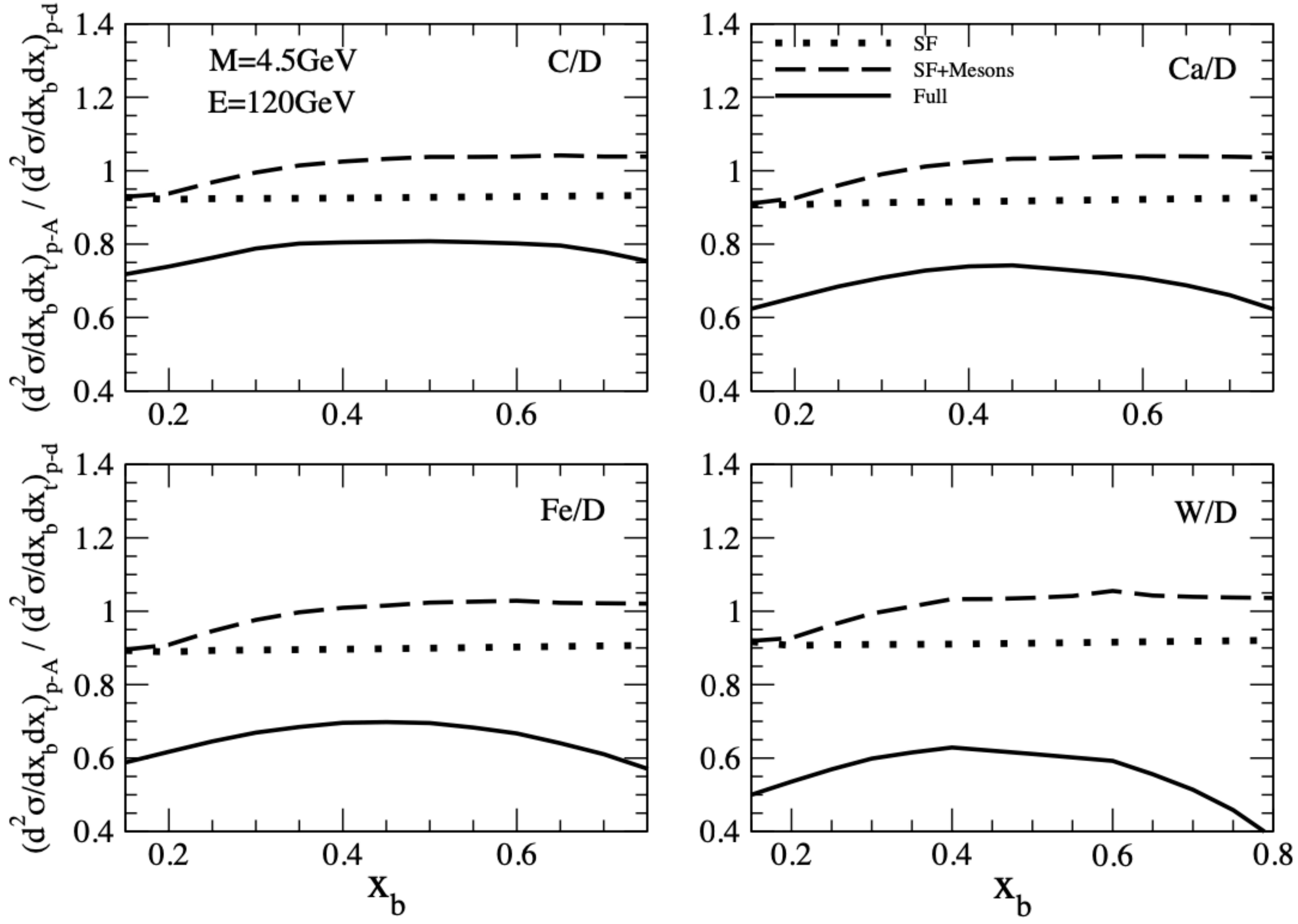


FIG. 7: $\frac{\left(\frac{d\sigma}{dx_b\ dx_t}\right)_{p-A}}{\left(\frac{d\sigma}{dx_b\ dx_t}\right)_{p-{}^2D}}$ vs x_b at $M = 4.5GeV$ for $A =^{12} C$, ^{40}Ca, ^{56}Fe and ^{184}W. For the beam energy E=120GeV($\sqrt{s_N}$=15GeV) the results are obtained with Spectral function: dotted line, including the mesonic contribution: dashed line, and for the full calculation: solid line.

$$\frac{d^2\sigma^{(A)}}{dx_b dx_t} = \frac{d^2\sigma^{(SF)}}{dx_b dx_t} + \frac{d^2\sigma^{(\pi)}}{dx_b dx_t} + \frac{d^2\sigma^{(\rho)}}{dx_b dx_t},$$

Energy loss of beam partons

The incident proton beam traverses the nuclear medium before the beam parton undergoes a hard collision with the target parton. The incident proton may lose energy due to soft inelastic collisions as it might scatter on its way within the nucleus before producing a lepton pair.

- A. Accardi, F. Arleo, W. K. Brooks, D. D'Enterria and V. Muccifora, Riv. Nuovo Cim. 32, 439 (2010).
- C. G. Duan, N. Liu and G. L. Li, Phys. Rev. C 79, 048201 (2009).

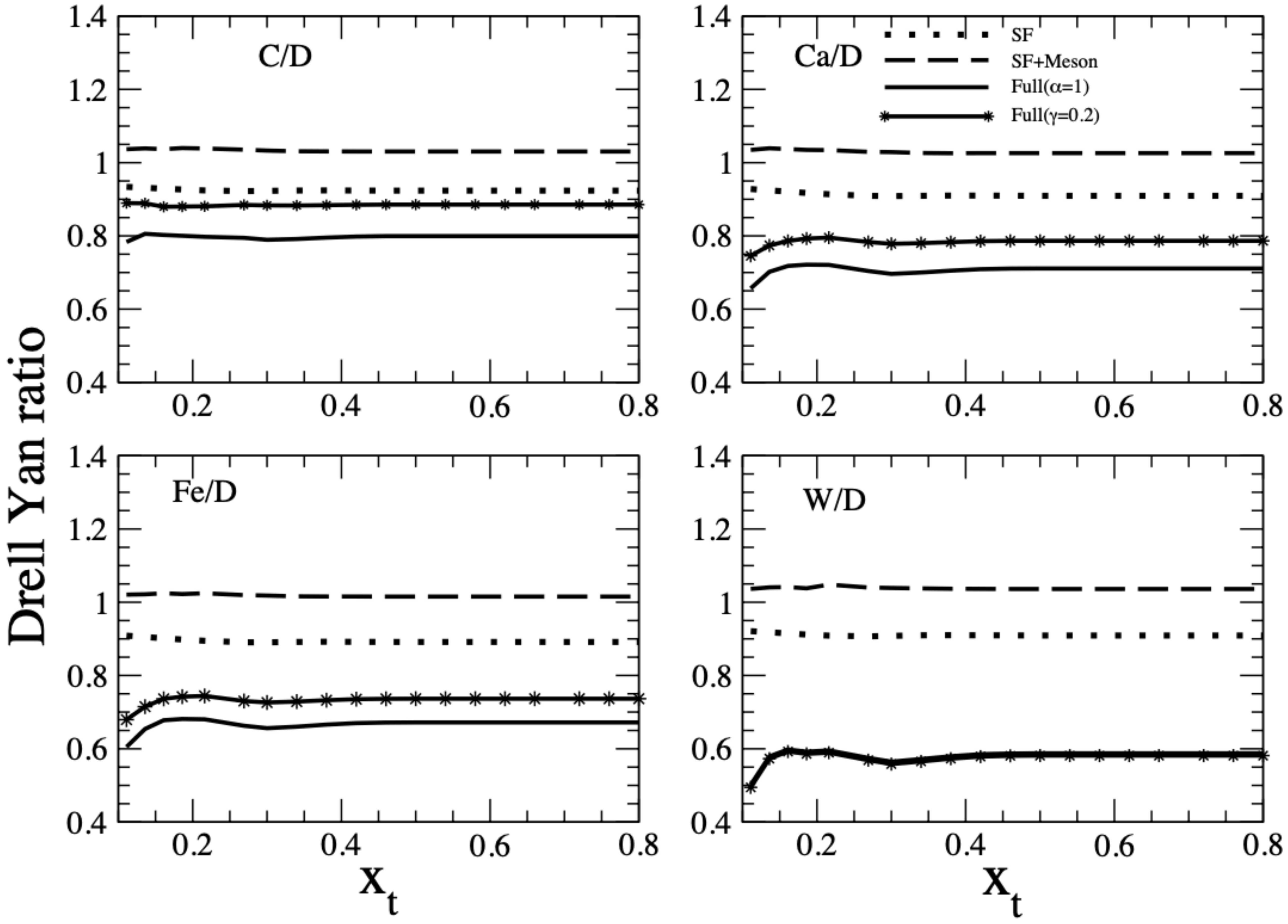


FIG. 9: Left panel: $\frac{\frac{d\sigma}{dx_t}(C,Fe)}{\frac{d\sigma}{dx_t}(D)}$ vs x_t at E=120GeV($\sqrt{s_N}$=15GeV), $x_b = x_t + 0.26$, $Q^2 > 16GeV^2$. The results are obtained with Spectral function: dotted line, Spectral function+Mesonic contribution: dashed line. The results of our full calculations are obtained with energy loss using Eq.(27) with $\alpha = 1$ (solid line) and $\gamma = 0.2$ in Eq.(28) (solid line with stars). Right panel: $\frac{\frac{d\sigma}{dx_t}(Ca,W)}{\frac{d\sigma}{dx_t}(D)}$ vs x_t, lines have same meaning as in the left panel.

Summary

- QCD effects to the angular coefficients are included using DYNNLO and DYTurbo packages available in literature.
- To take into account the nuclear effects phenomenological we have used nNNPDF nuclear parton distribution functions.
- Theoretical approach to add nuclear effect is under preparation.
- We will use AMUValencia DIS model which is also used for the Drell-Yan process and find in fair agreement with the available DIS/DY data.

Thank You