UNIVERSITÀ
DI PAVIA

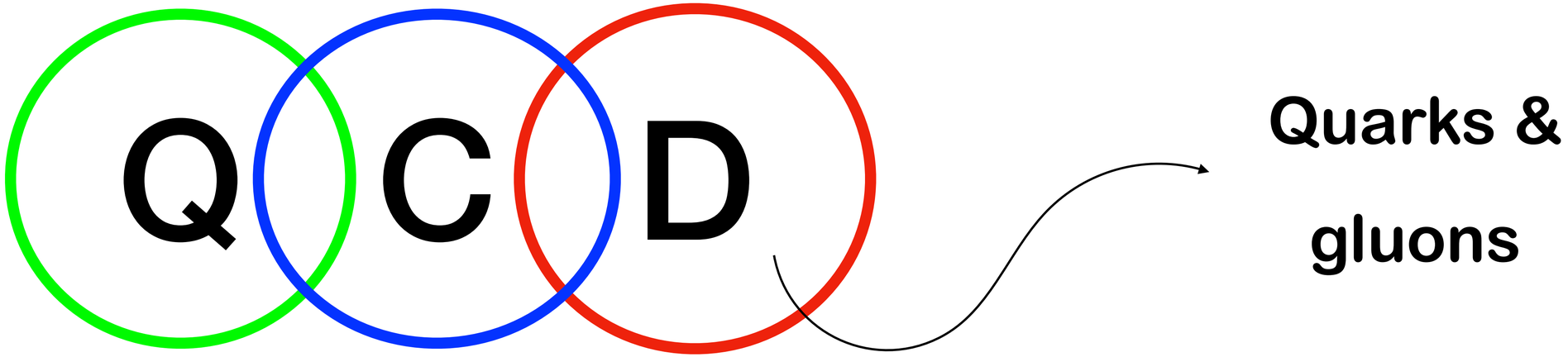
Istituto Nazionale di Fisica Nucleare

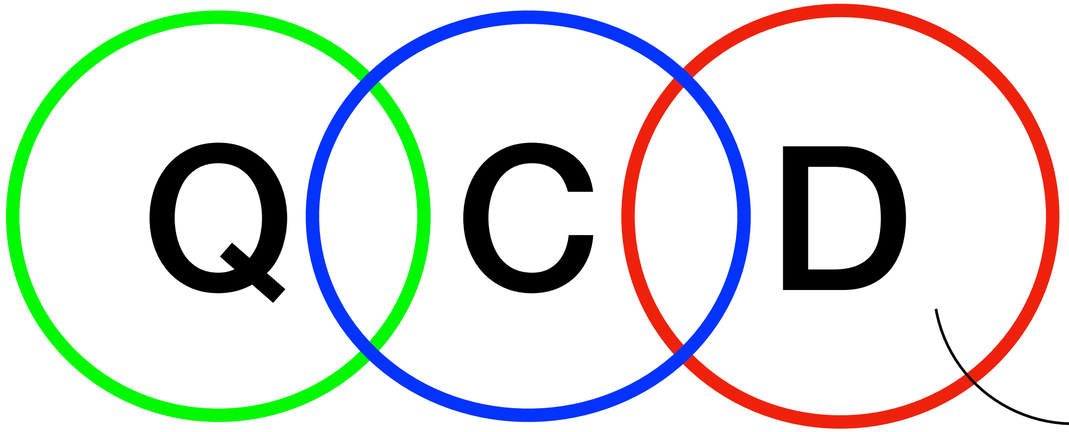
On the way to transversity: A PhD triathlon

PhD candidate:
Luca Polano

Supervisor:
Marco Radici
Alessandro Bacchetta

End of year seminars 2025

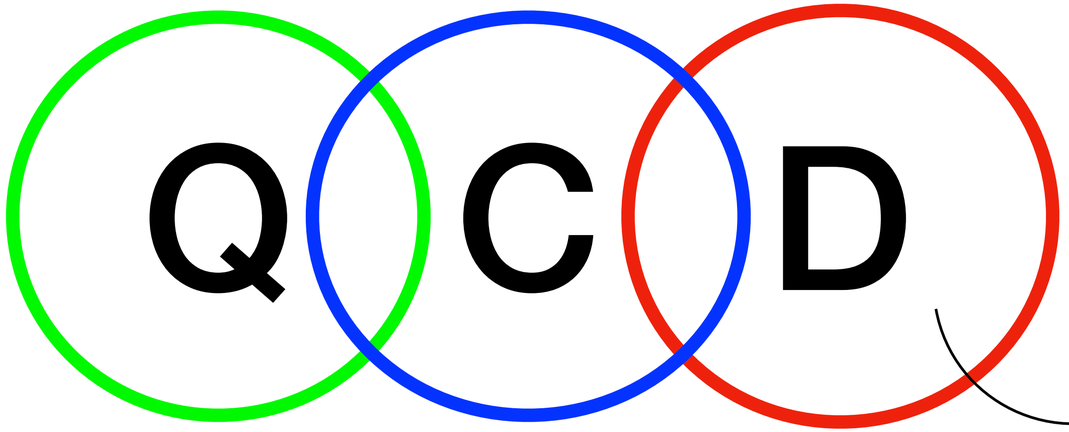

Q C D
Quarks &
gluons



Quarks &

gluons

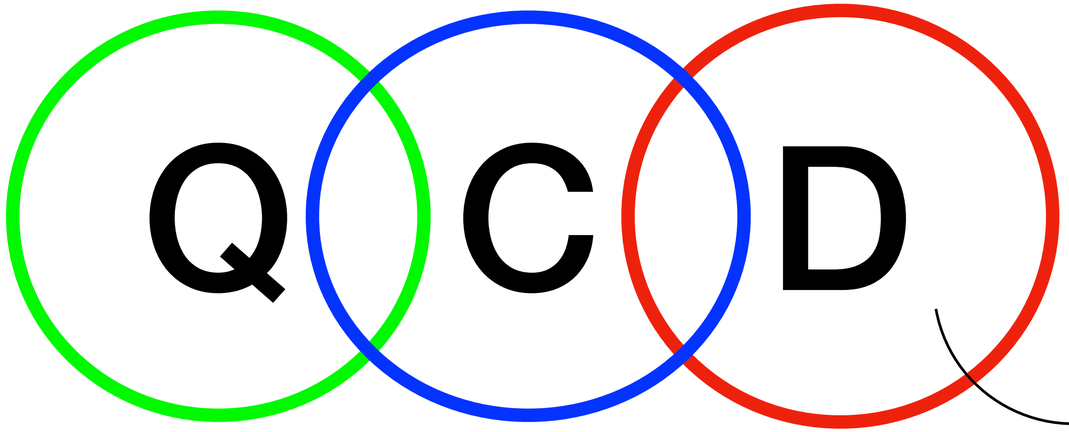
Depends on the energy scale



Quarks &

gluons

High energies



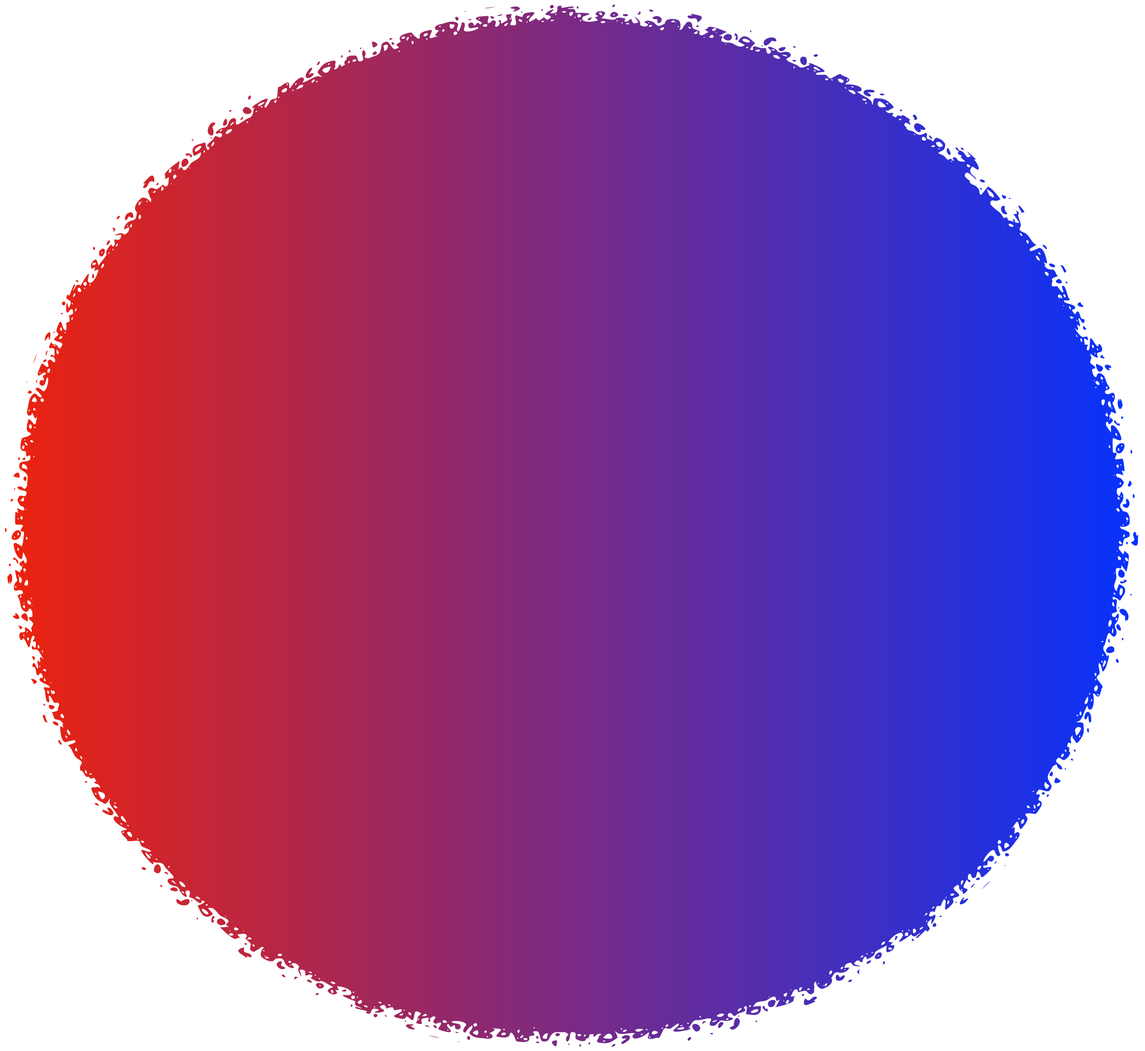
Quarks &

gluons

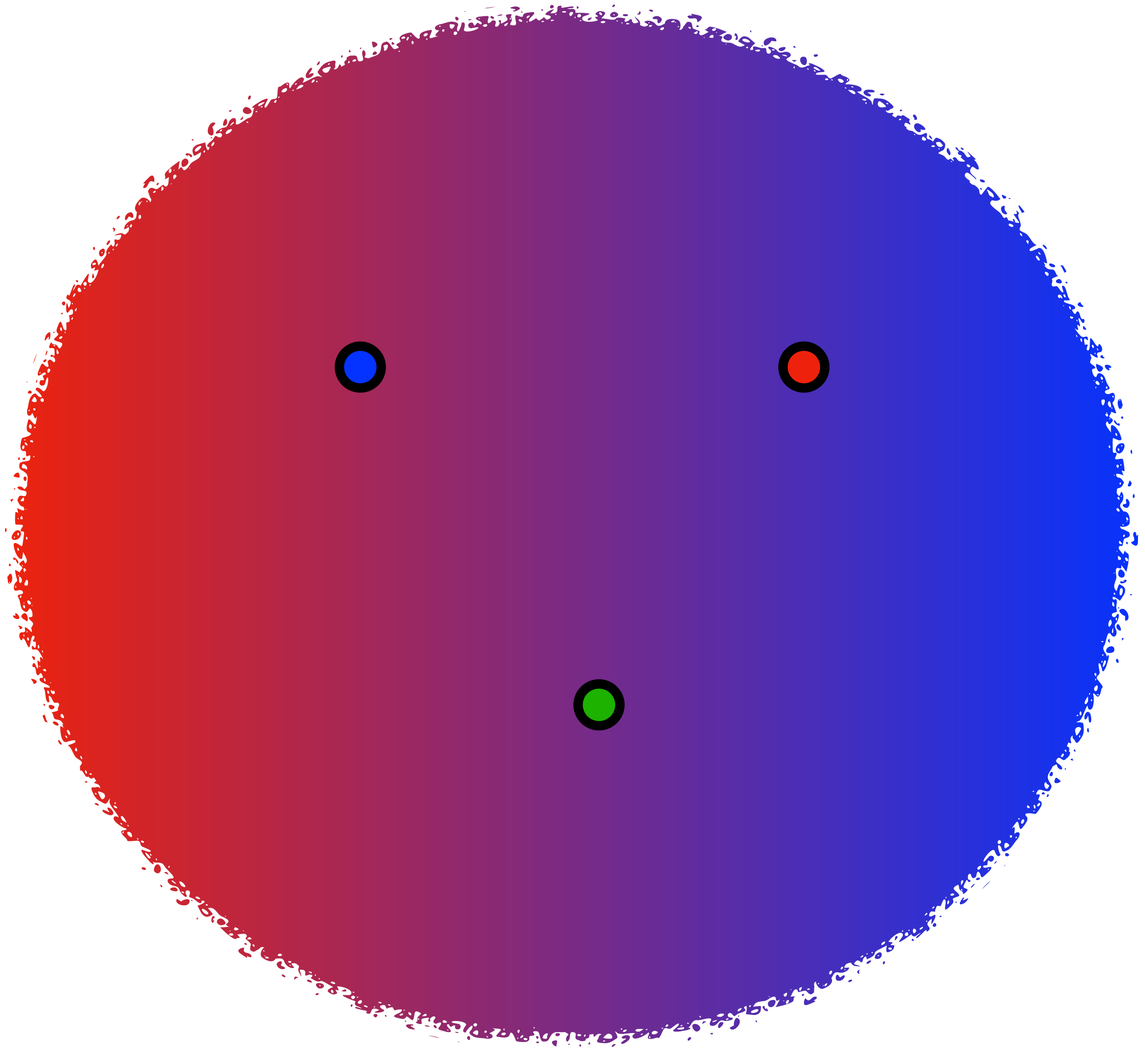
High energies

Low, $\Lambda_{QCD} \sim 200$ MeV

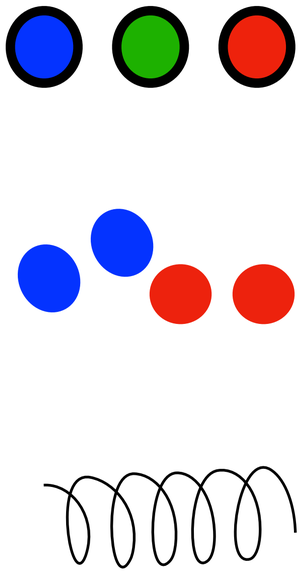
At $\sim \Lambda_{QCD} \sim 200$ **MeV**

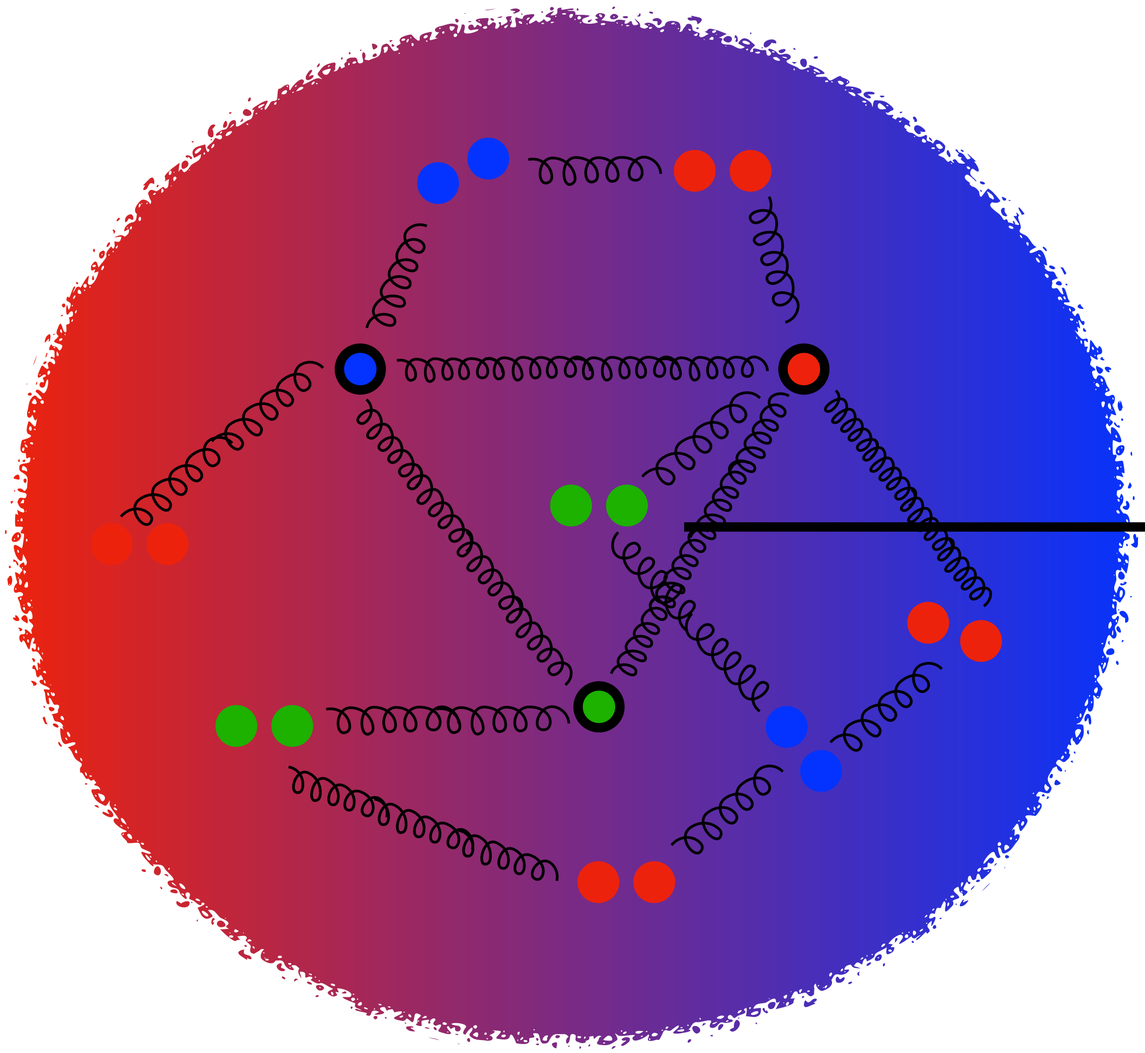


At $\sim \Lambda_{QCD} \sim 200$ **MeV**



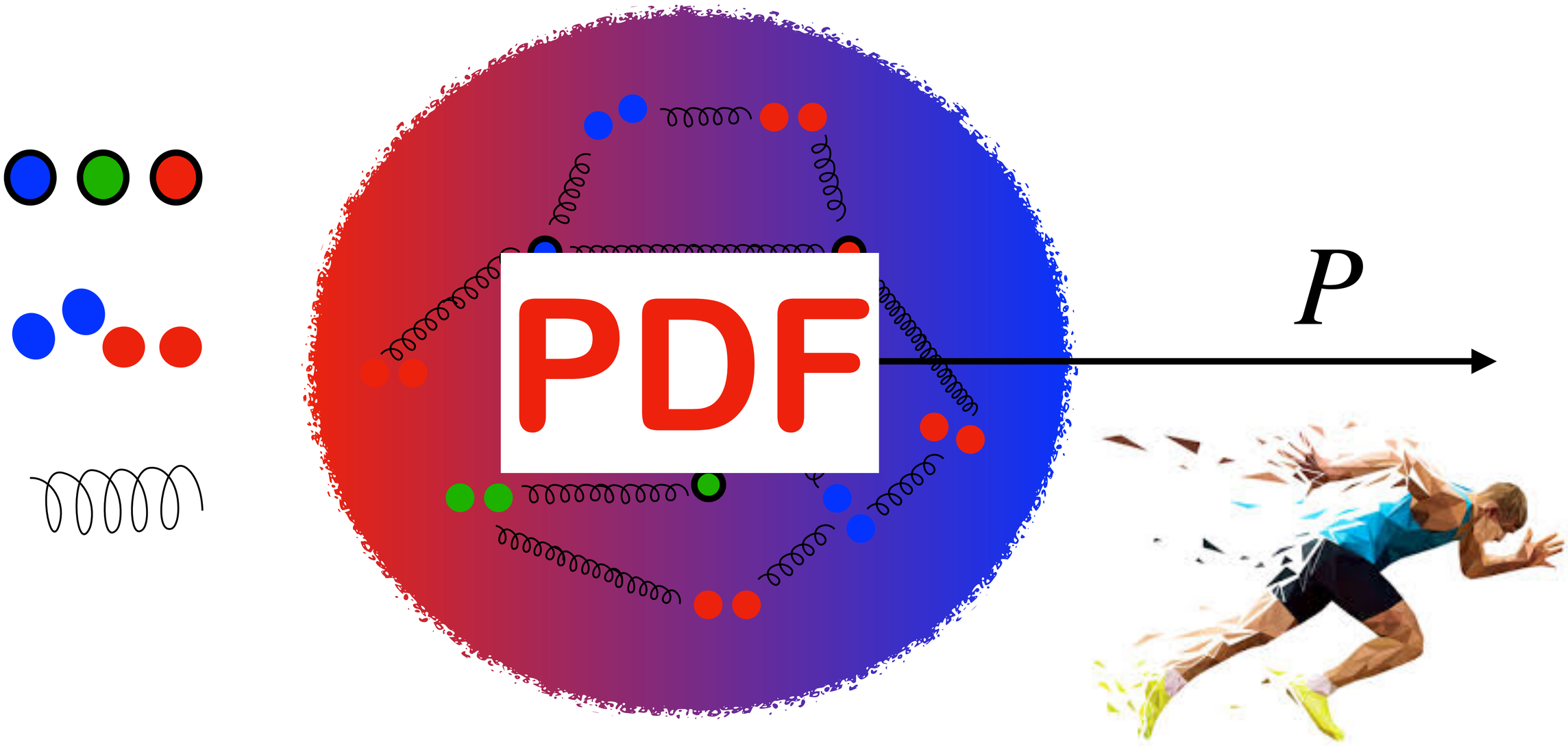
At $\sim \Lambda_{QCD} \sim 200$ **MeV**





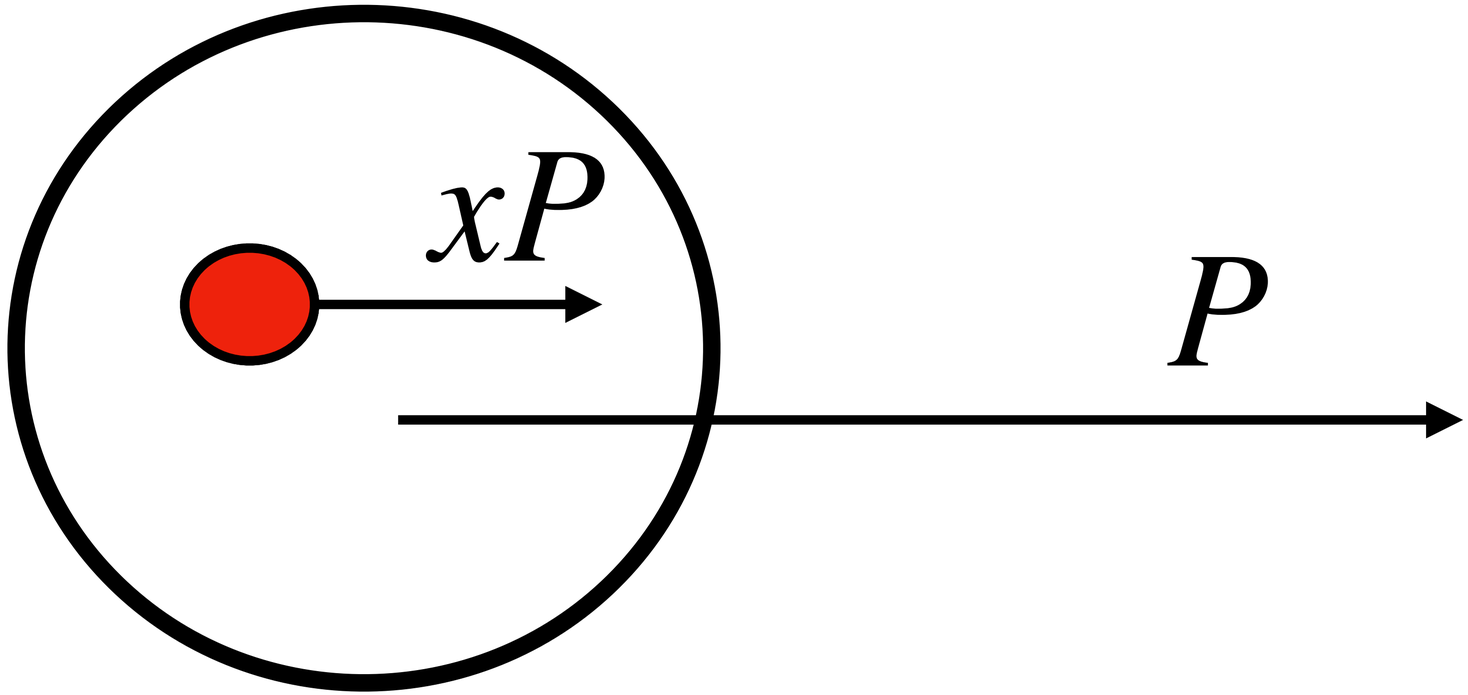
P

At $\sim \Lambda_{QCD} \sim 200$ **MeV**



At $\sim \Lambda_{QCD} \sim 200$ **MeV**

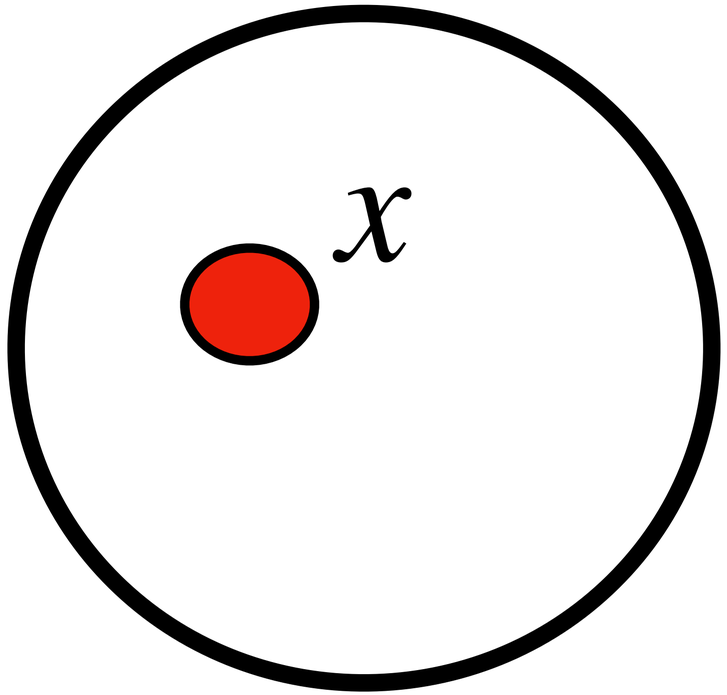
PDF



At $\sim \Lambda_{QCD} \sim 200$ MeV

PDF

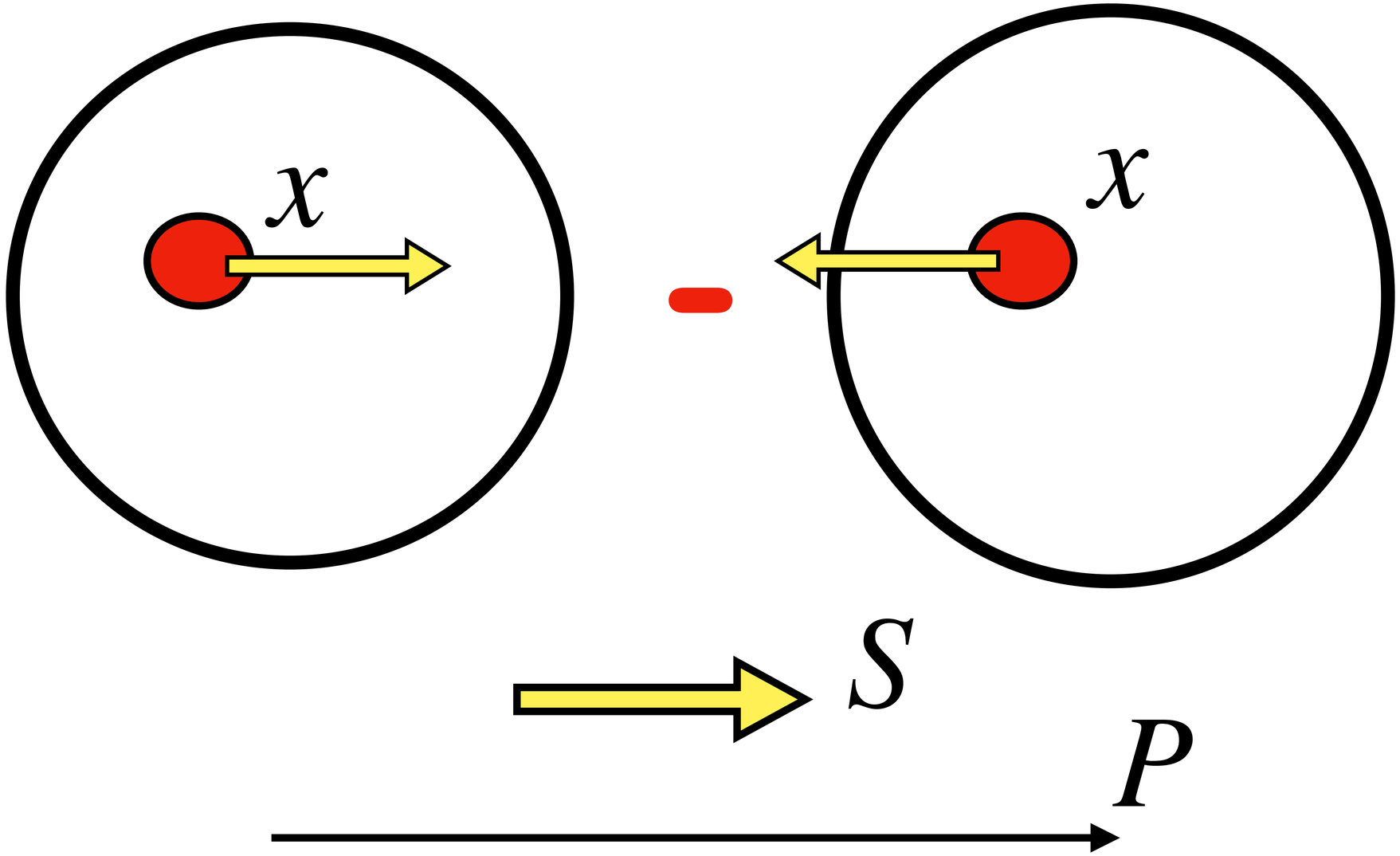
f_1



At $\sim \Lambda_{QCD} \sim 200$ MeV

PDF

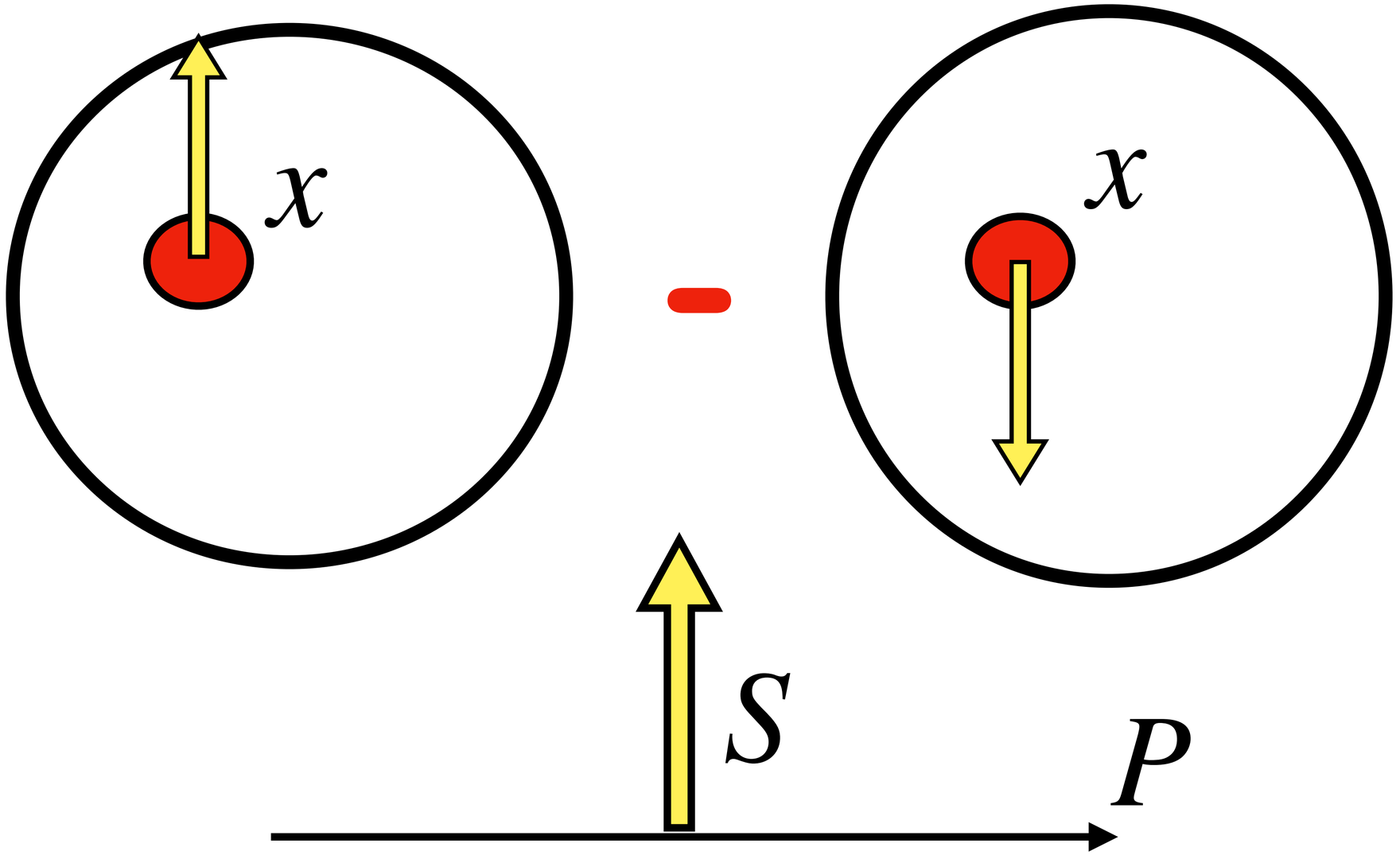
g_1



At $\sim \Lambda_{QCD} \sim 200$ MeV

PDF

h_1






X




Fragmentation Functions

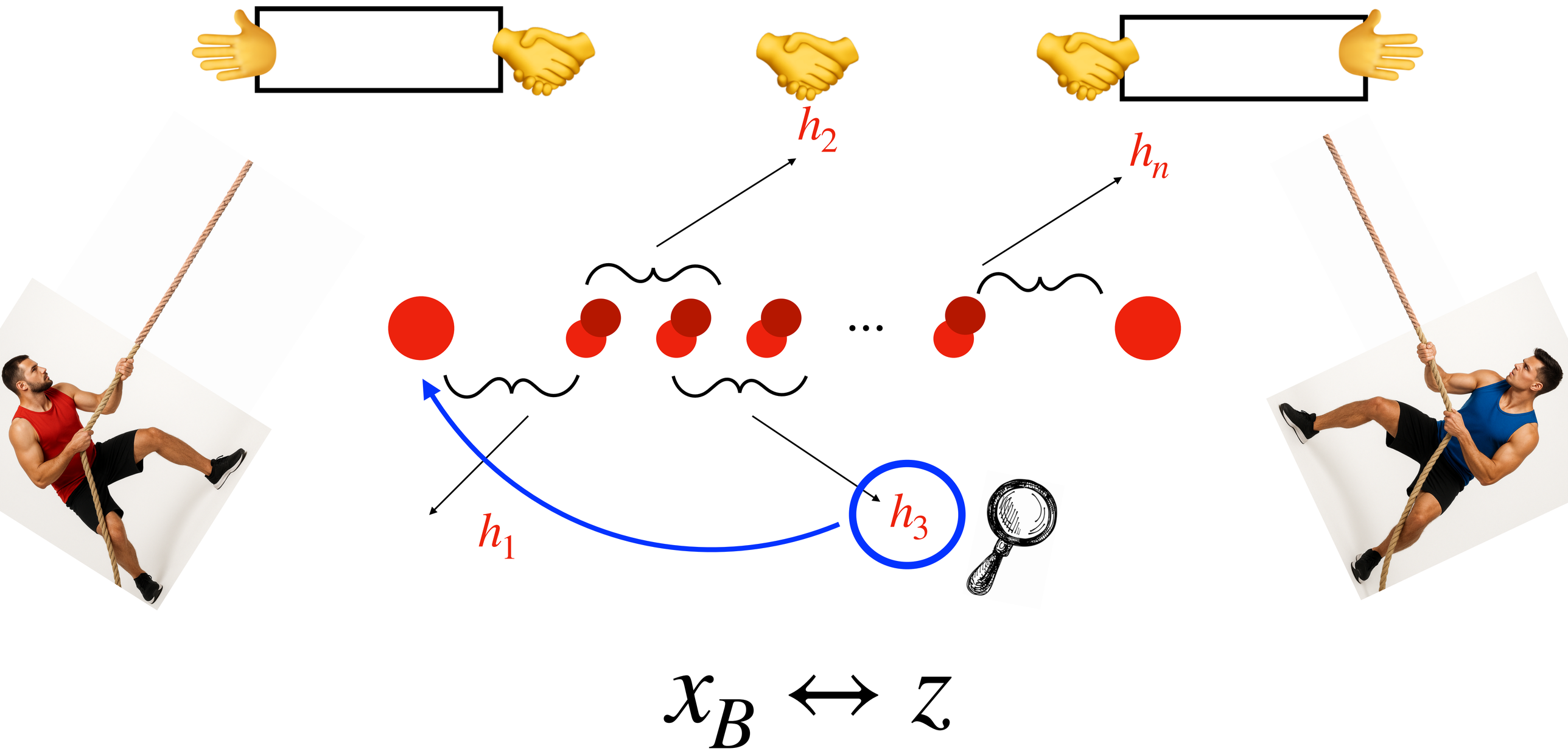




Fragmentation Functions

Fragmentation Functions

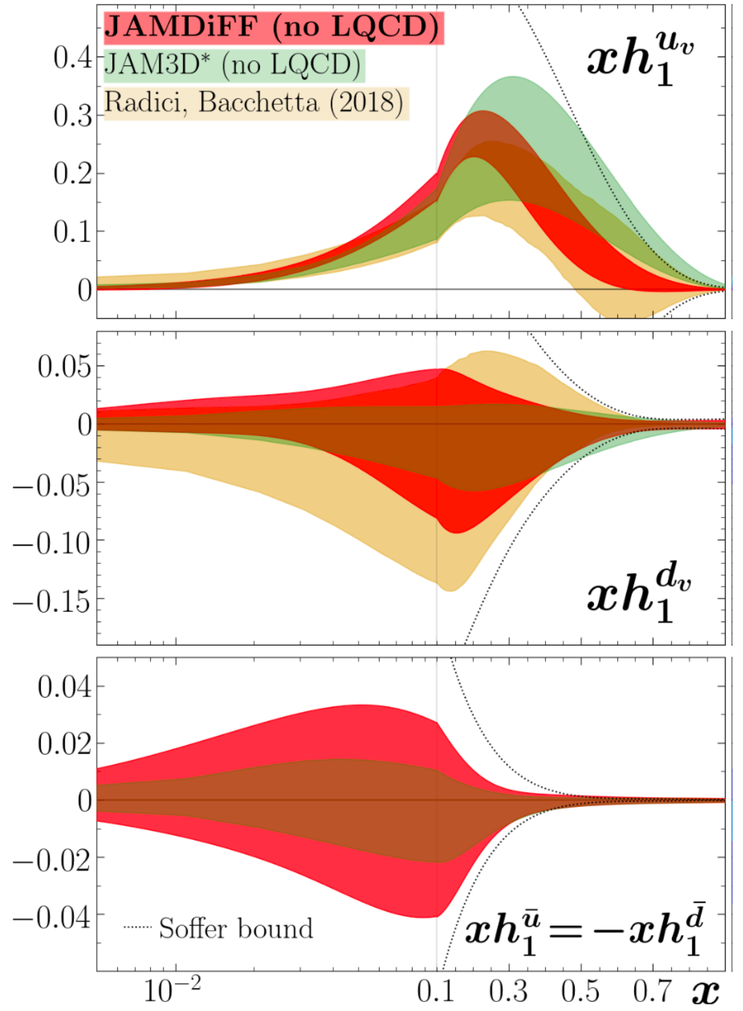
Fragmentation Functions



$$x_B \leftrightarrow z$$

Why care about transversity?

- **Have a better knowledge of the proton structure**



Why care about transversity?

- Have a better knowledge of the proton structure

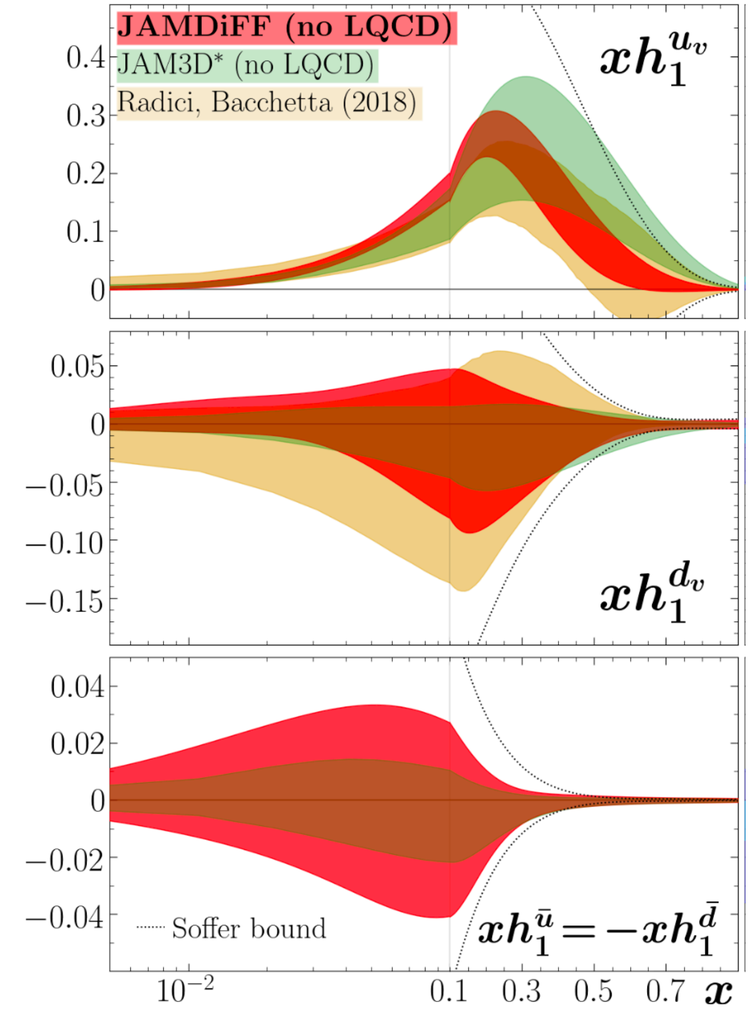
- Can be potential for Beyond SM discovery

Chiral-odd structures do not appear in the SM Tree level Lagrangian

Neutrino β-decay $\quad g_T = \delta u - \delta d$

$$\delta q = \int_0^1 dx\, h_1^q(x)$$

constraints on CP violation



Why care about transversity?

- Have a better knowledge of the proton structure

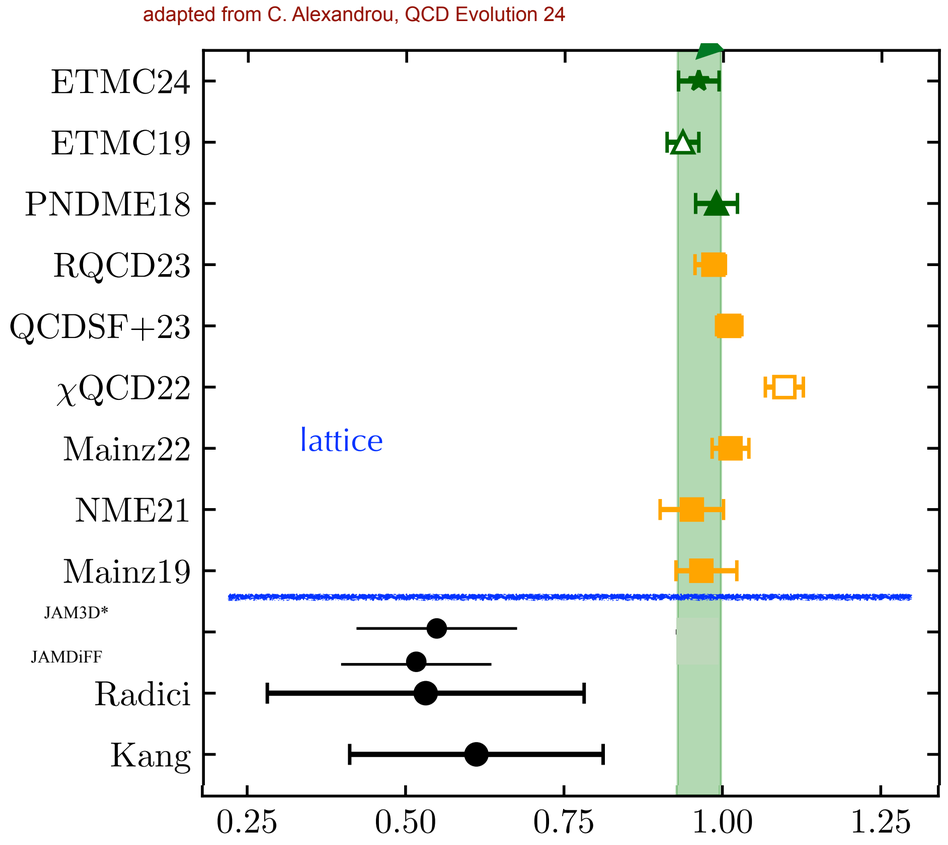
- Can be potential for Beyond SM discovery

Chiral-odd structures do not appear in the SM Tree level Lagrangian

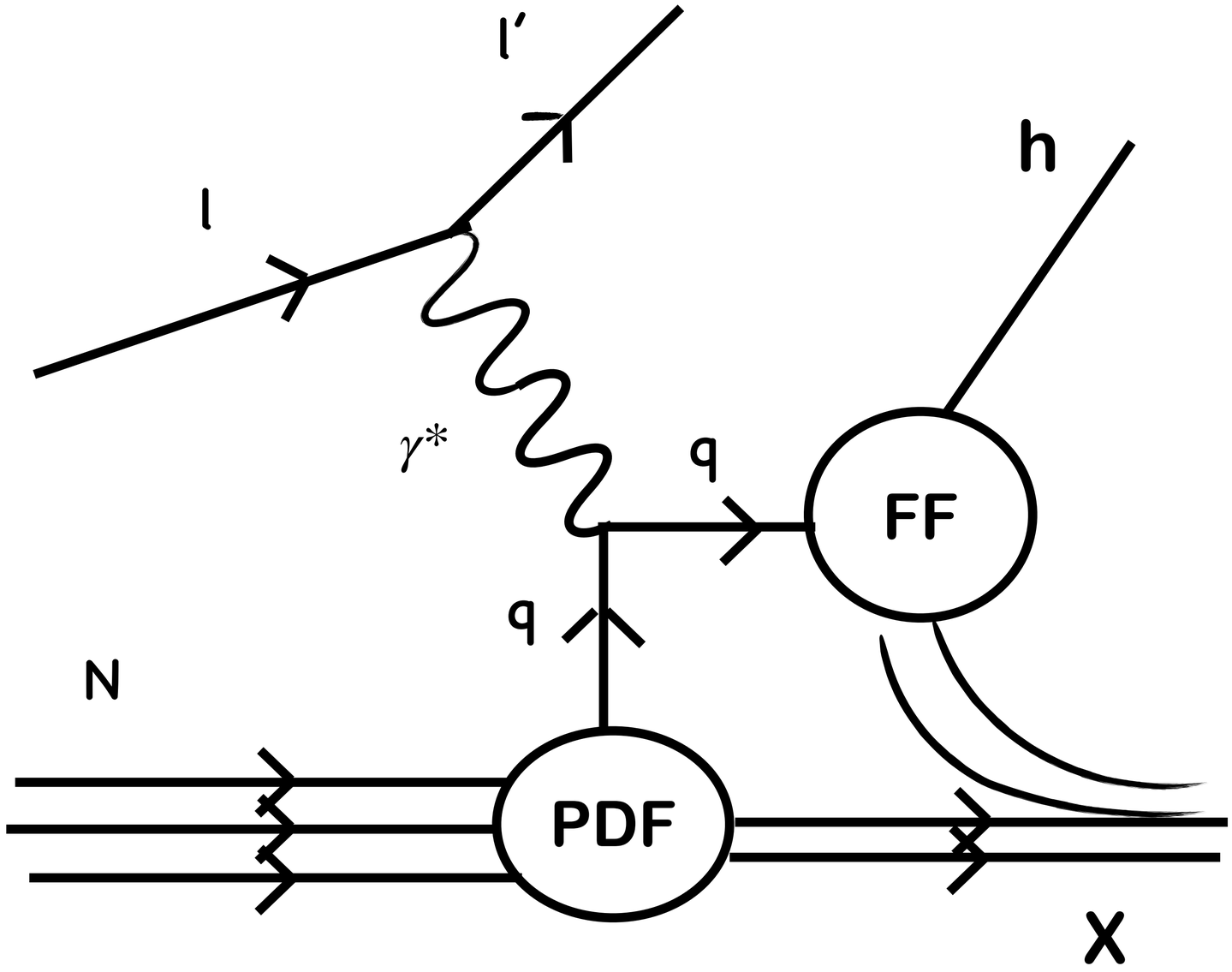
Neutrino β-decay $g_T = \delta u - \delta d$

$$\delta q = \int_0^1 dx\, h_1^q(x)$$

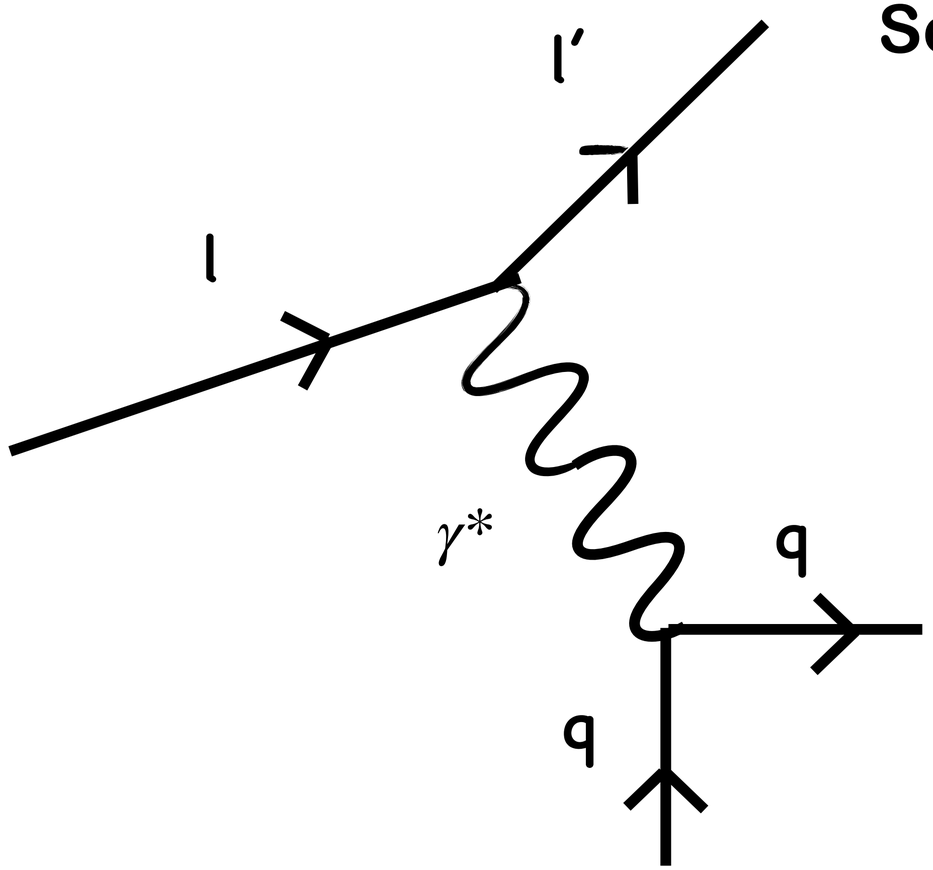
constraints on CP violation

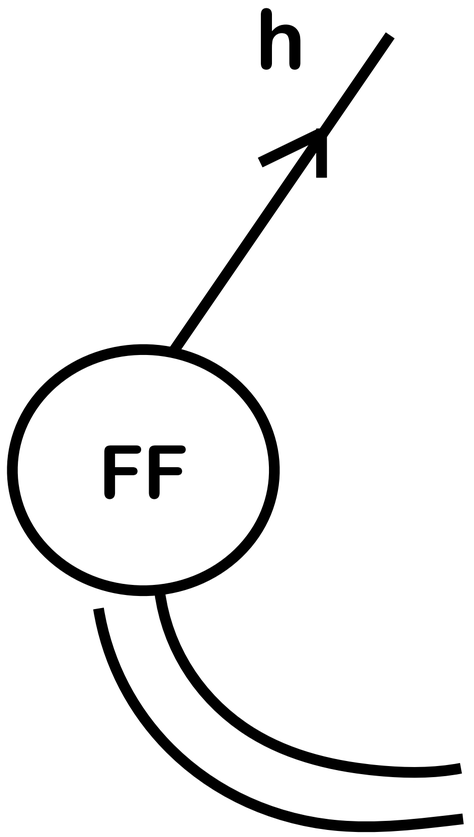


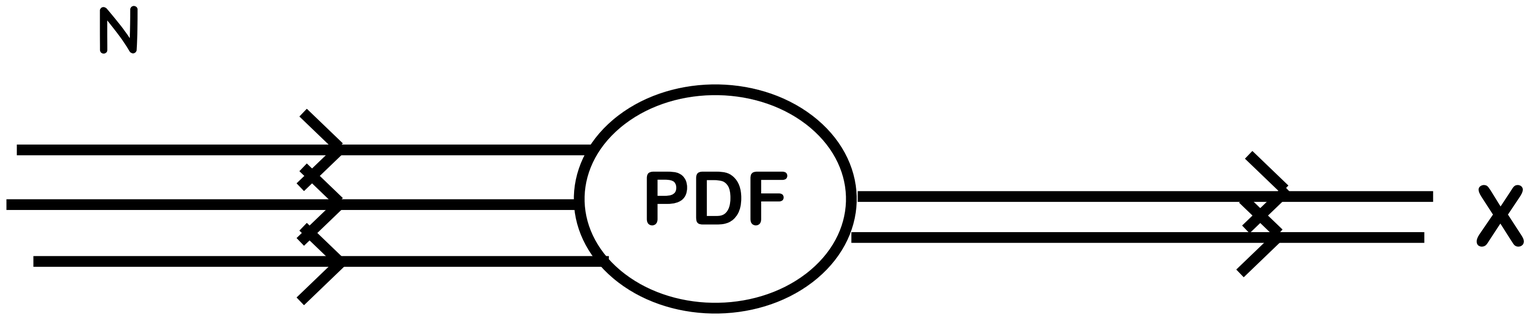
Semi-inclusive Deep Inelastic Scattering



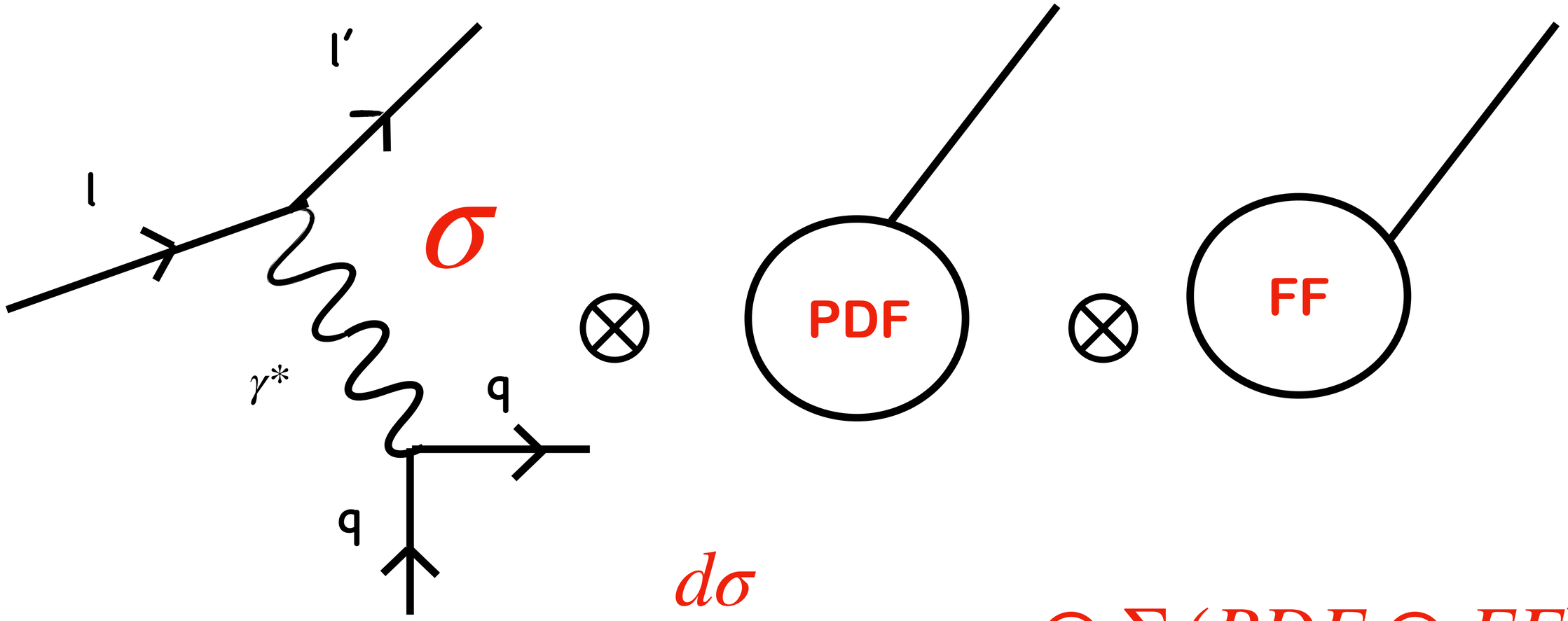
Semi-inclusive Deep Inelastic Scattering





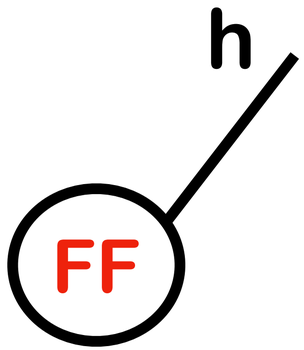


Semi-inclusive Deep Inelastic Scattering



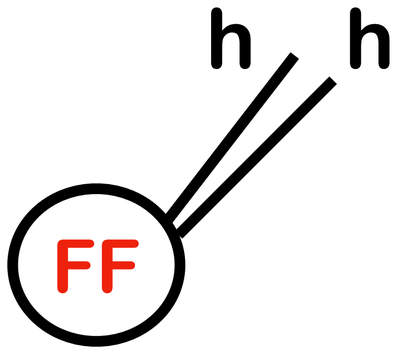
$$\frac{d\sigma}{dx dQ^2 \ldots} = \sigma \otimes \Sigma (PDF \otimes FF)$$

1 measured hadron+ X



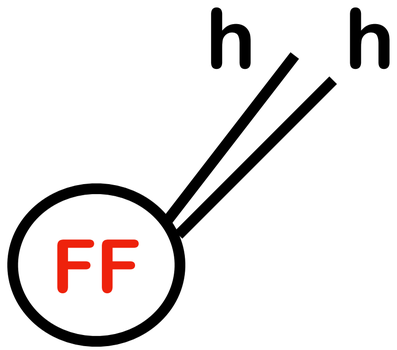
$$A_{UT}^{h} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B, k_T) \otimes H_1^{\perp,q}(z, p_\perp)}{\sum_q e_q^2 f_1^q(x_B, k_T) \otimes D_1^q(z, p_\perp)}$$

2 measured hadron+ X



$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

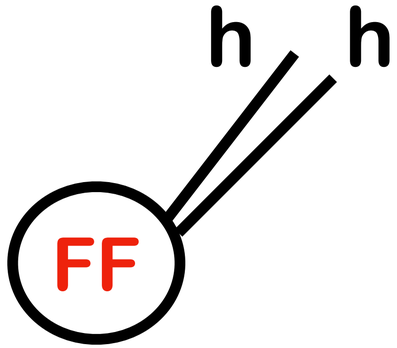
2 measured hadron+ X



$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

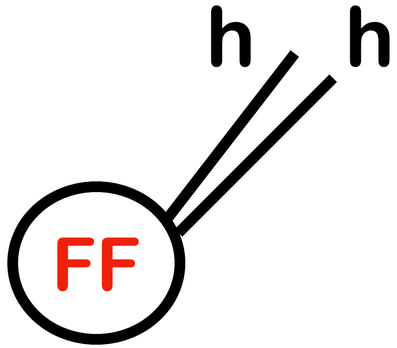
How to acces them?

2 measured hadron+ X



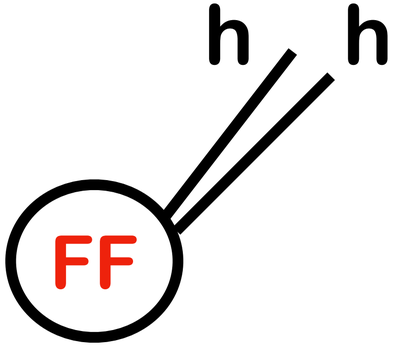
$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

2 measured hadron+ X



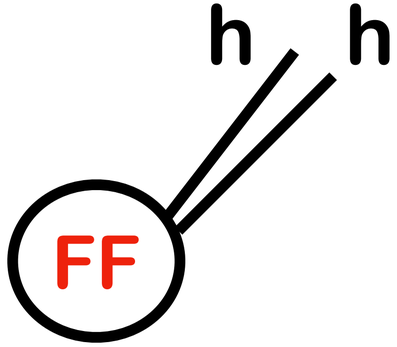
$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

2 measured hadron+ X



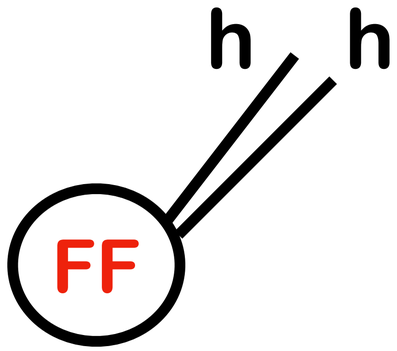
$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot \; h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

2 measured hadron+ X



$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

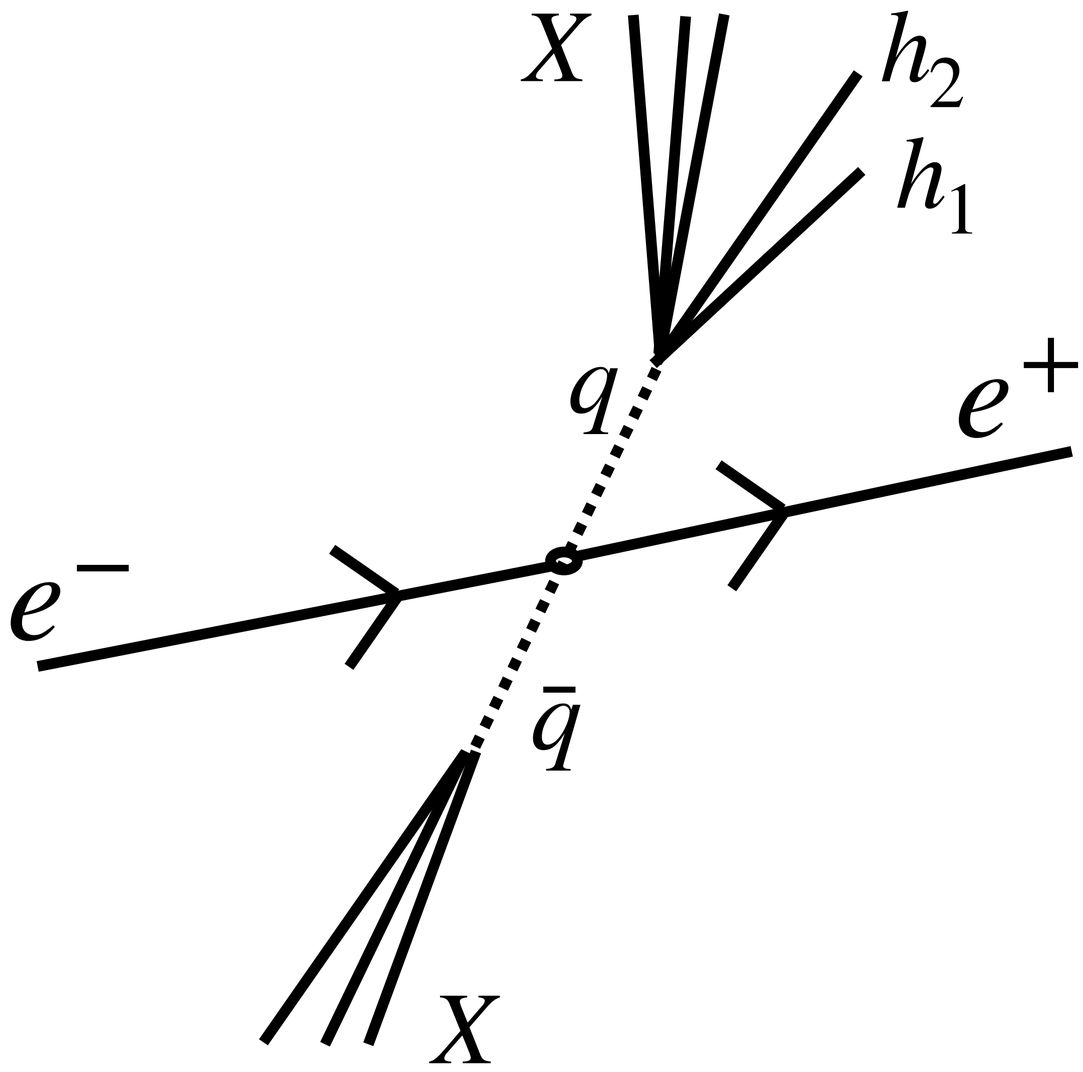
2 measured hadron+ X



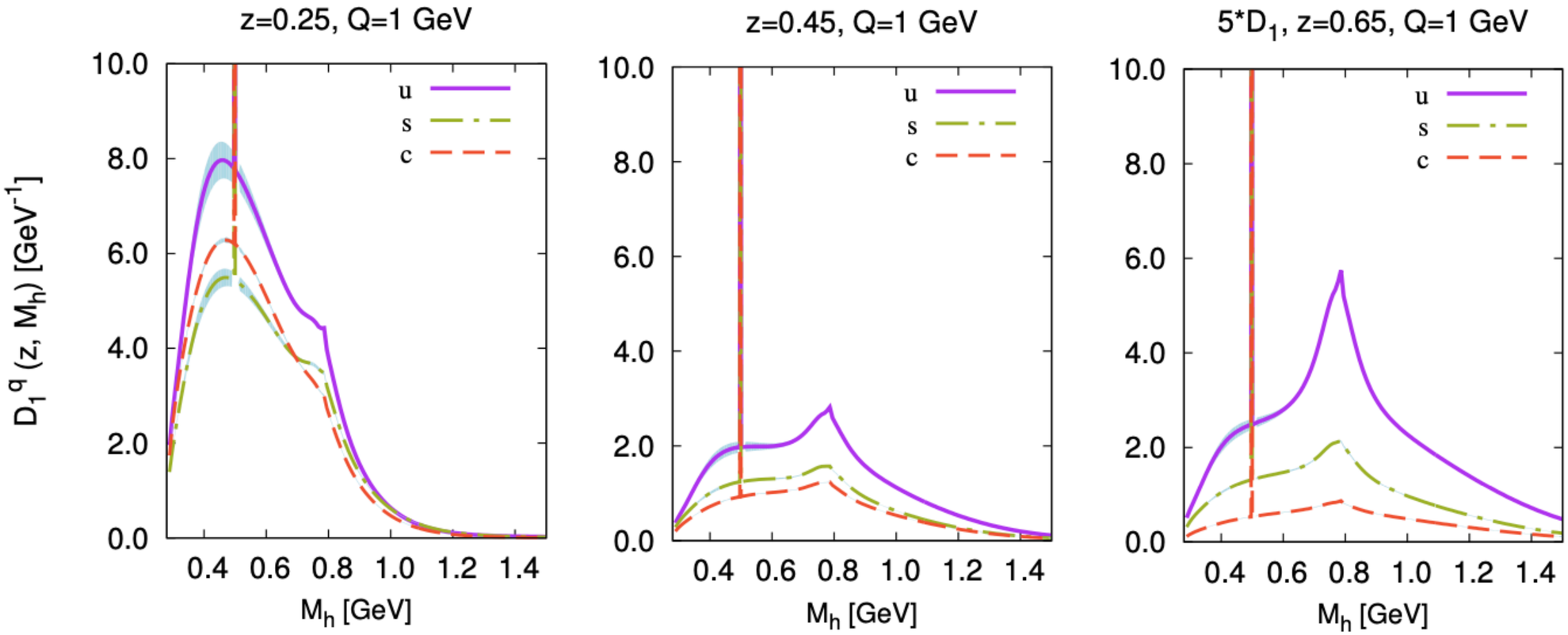
$$A_{UT}^{hh} \sim \frac{\sum_q e_q^2 \cdot h_1^q(x_B) \cdot H_1^{<,q}(z, M_h)}{\sum_q e_q^2 f_1^q(x_B) \cdot D_1^q(z, M_h)}$$

$$D_1^{hh}$$

$$e^+e^- \to h_1 h_2 X$$



2012 extraction by Pavia group



A.Bacchetta, M.Radici, A.Bianconi, A.Courtoy, Phys. Rev. D 85, (2012) 114023

Fit of MonteCarlo simulation

79 free parameters

LO

2017 BELLE data of $e^+e^- \to \pi^+\pi^- X$ at $\sqrt{S} = 10.58$ GeV

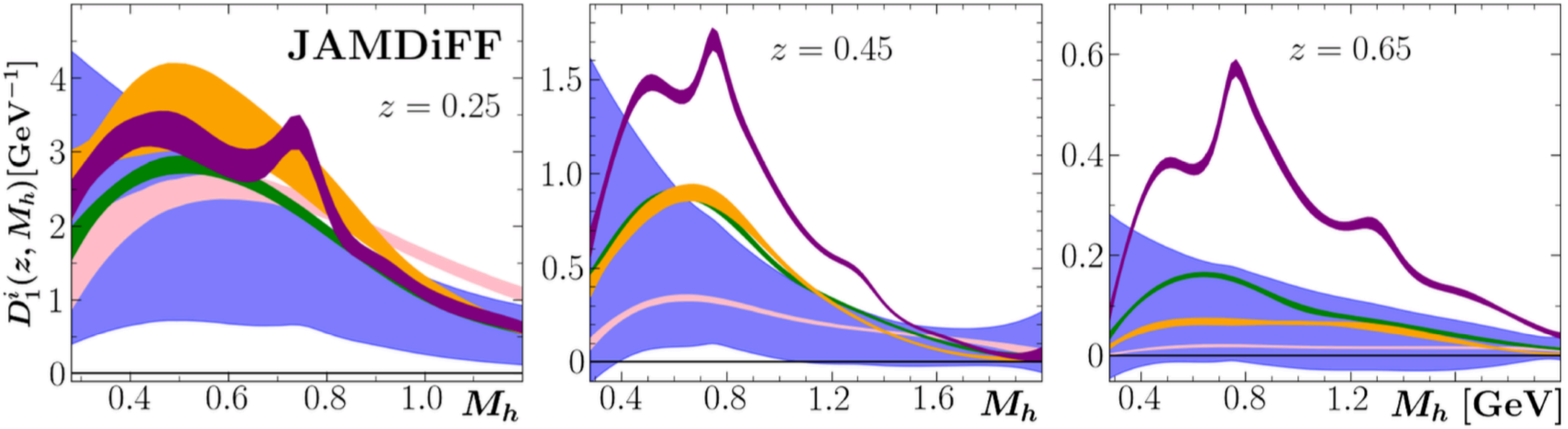
2017 BELLE data of $e^+e^- \to \pi^+\pi^- X$ at $\sqrt{S} = 10.58$ GeV

Latest extraction:

+ MonteCarlo simulation LO

u
s
c
b
g

N.Sato et al, Phys. Rev. D 109, (2024) 034024



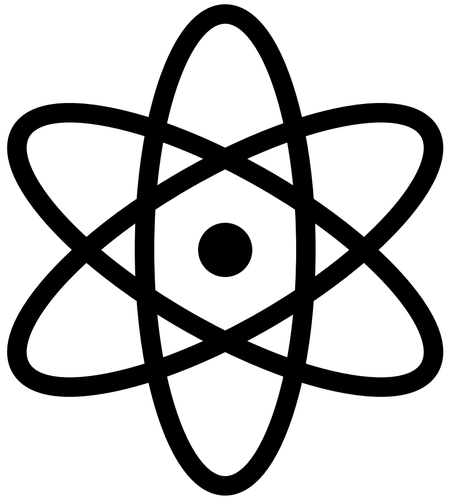
GOALS of the D_1 extraction

- 2017 BELLE data of $e^+e^- \to \pi^+\pi^- X$ at $\sqrt{S} = 10.58$ GeV
  + MonteCarlo simulation

- Extend the analysis up to NNLO

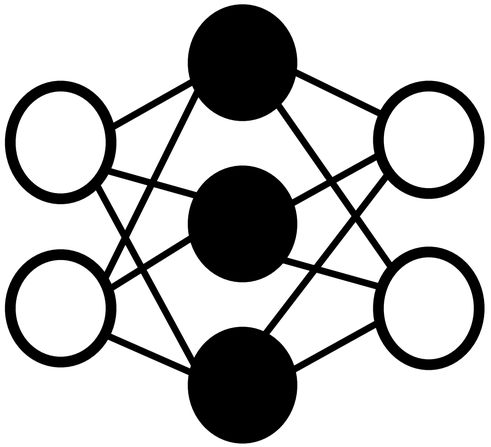
- Explore a Neural Network parameterisation

PHYSICS INFORMED



71 par

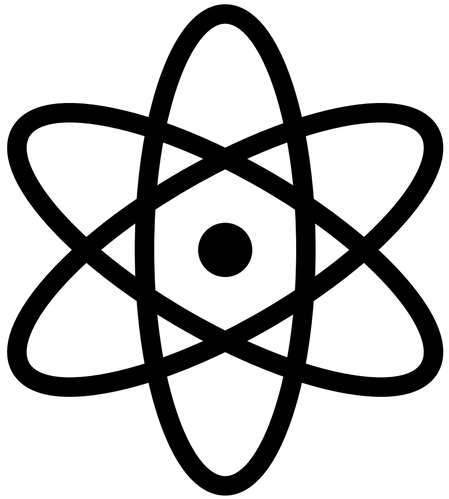
NEURAL NETWORK



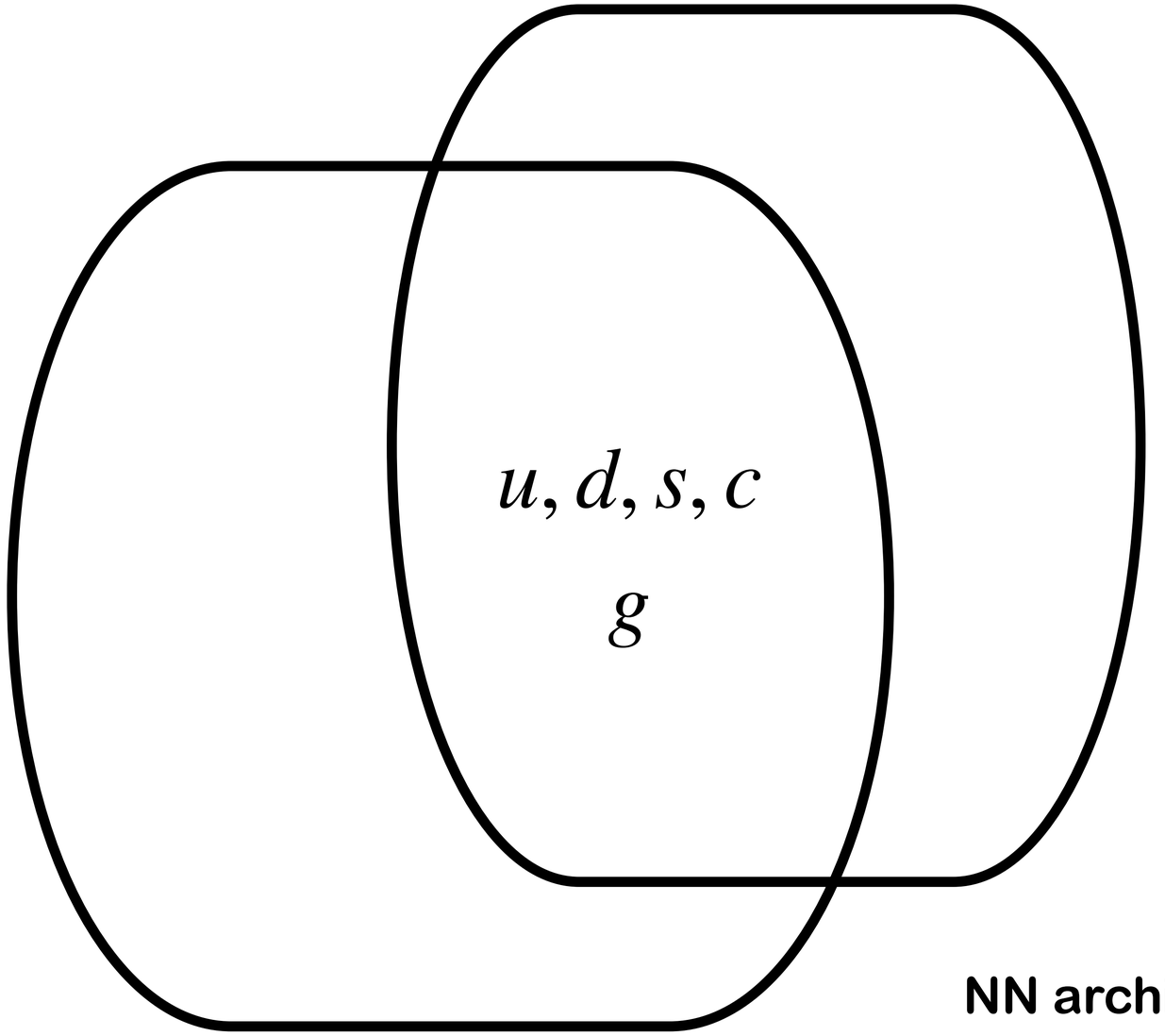
NN architecture

[2,25,5] ⇝ 205 par

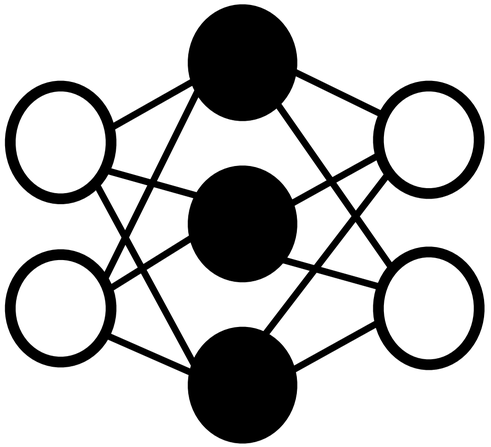
PHYSICS INFORMED



71 par



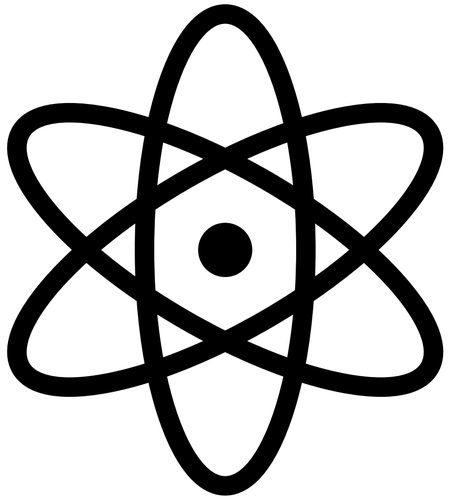
NEURAL NETWORK



NN architecture

[2,25,5] ⇝ 205 par

PHYSICS INFORMED



71 par

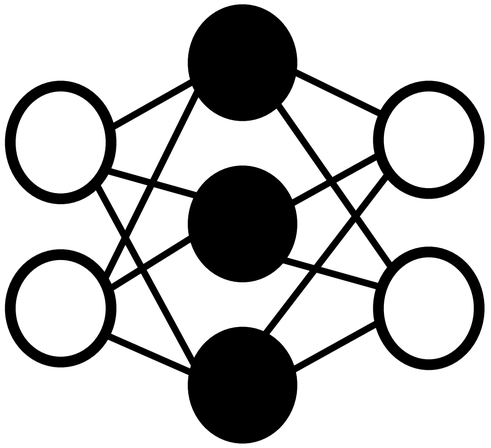
$Q_0 = 1$ GeV

u, d, s, c

g

$D_1^q = D_1^{\bar{q}}$

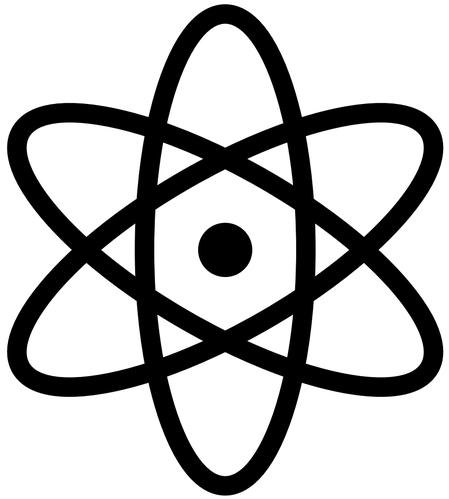
NEURAL NETWORK



NN architecture

[2,25,5] ⇝ 205 par

PHYSICS INFORMED



71 par

$D_1^u = D_1^d$

ansatz

D_1^g

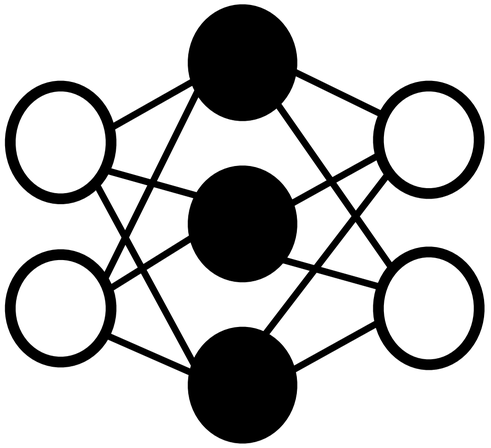
$Q_0 = 1$ GeV

u, d, s, c

g

$D_1^q = D_1^{\bar{q}}$

NEURAL NETWORK



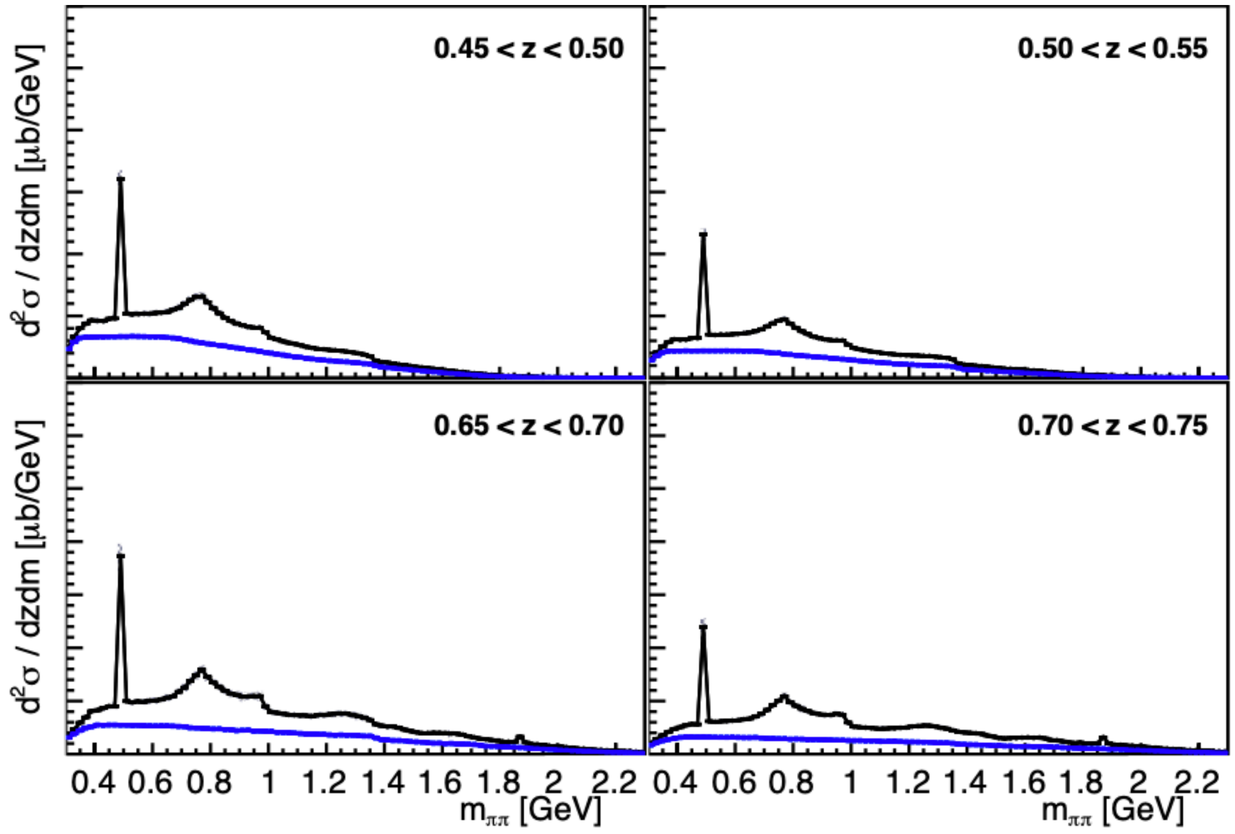
NN architecture

[2,25,5] ⇝ 205 par

Flavour analysis

Physical review D 96 (2017)
R.Siedl et al

$$\frac{d\sigma}{dzdM_h dQ^2} = \frac{4\pi\alpha^2}{Q^2} \sum_q e_q^2 D_1^q(z, Mh, Q) =$$



Flavour analysis

$$\frac{d\sigma}{dz dM_h dQ^2} = \frac{4\pi\alpha^2}{Q^2} \sum_q e_q^2 D_1^q(z, Mh, Q) = \frac{4\pi\alpha^2}{Q^2} \mathbf{D(z, Mh, Q)}$$

Need of extra information → **Monte Carlo**

$$\mathbf{R_u^{MC}} = \frac{\mathbf{D_{MC}^u(z, M_h, Q)}}{\mathbf{D_{MC}(z, M_h, Q)}}$$

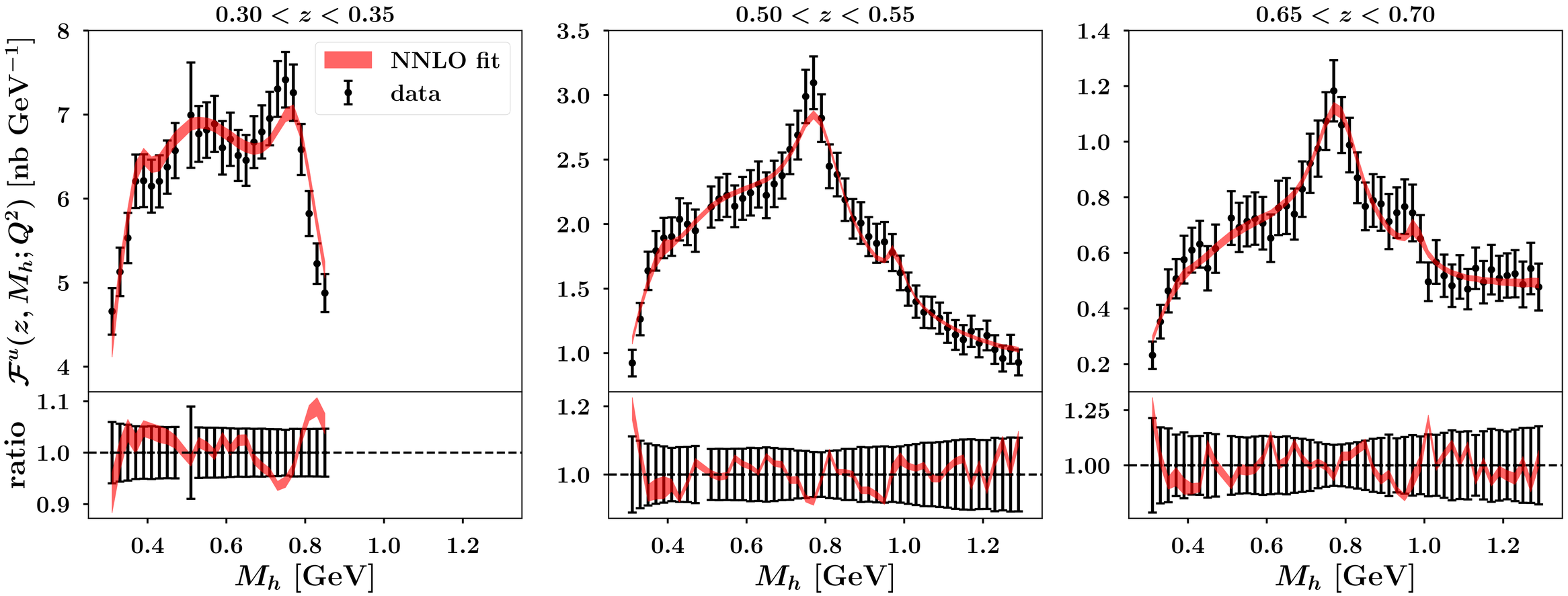
→ **Build 4 pseudo-dataset**

$$\mathscr{F}^u(z, M_h; Q^2) = \frac{4\pi\alpha^2}{Q^2} \mathbf{D(z, M_h, Q)} \times \frac{\mathbf{D_{MC}^u(z, M_h, Q)}}{\mathbf{D_{MC}(z, M_h, Q)}}$$

$\mathscr{F}q$

$q = u, d, s, c$

Predictions: Physics informed



NNLO

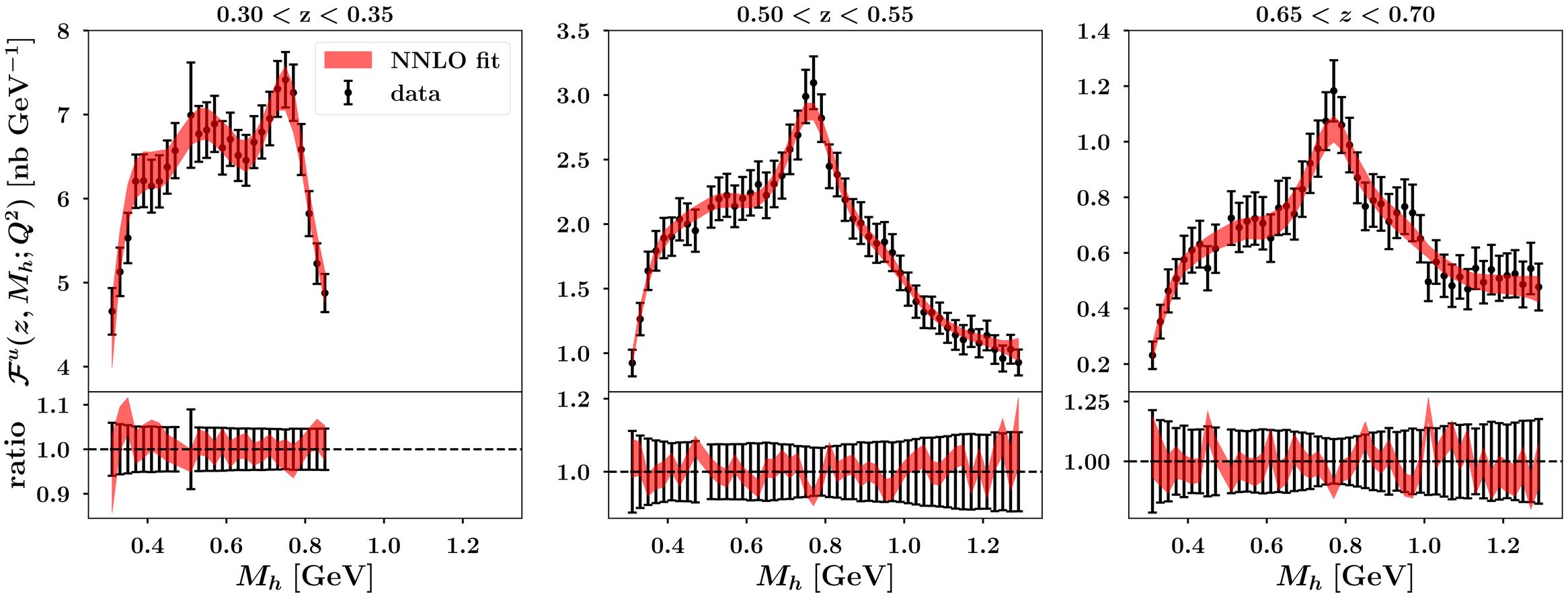
100 replicas

$$\chi^2_u = 0.380 \qquad \chi^2_s = 0.876$$

$$\chi^2_d = 0.613 \qquad \chi^2_c = 0.879$$

$$\chi^2_{tot} = 0.687$$

Predictions: Neural Network



NNLO

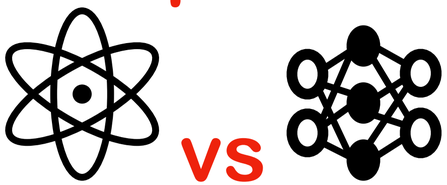
100 replicas

$$\chi^2_u = 0.209 \qquad \chi^2_s = 0.793$$

$$\chi^2_d = 0.530 \qquad \chi^2_c = 0.606$$

$$\chi^2_{tot} = 0.535$$

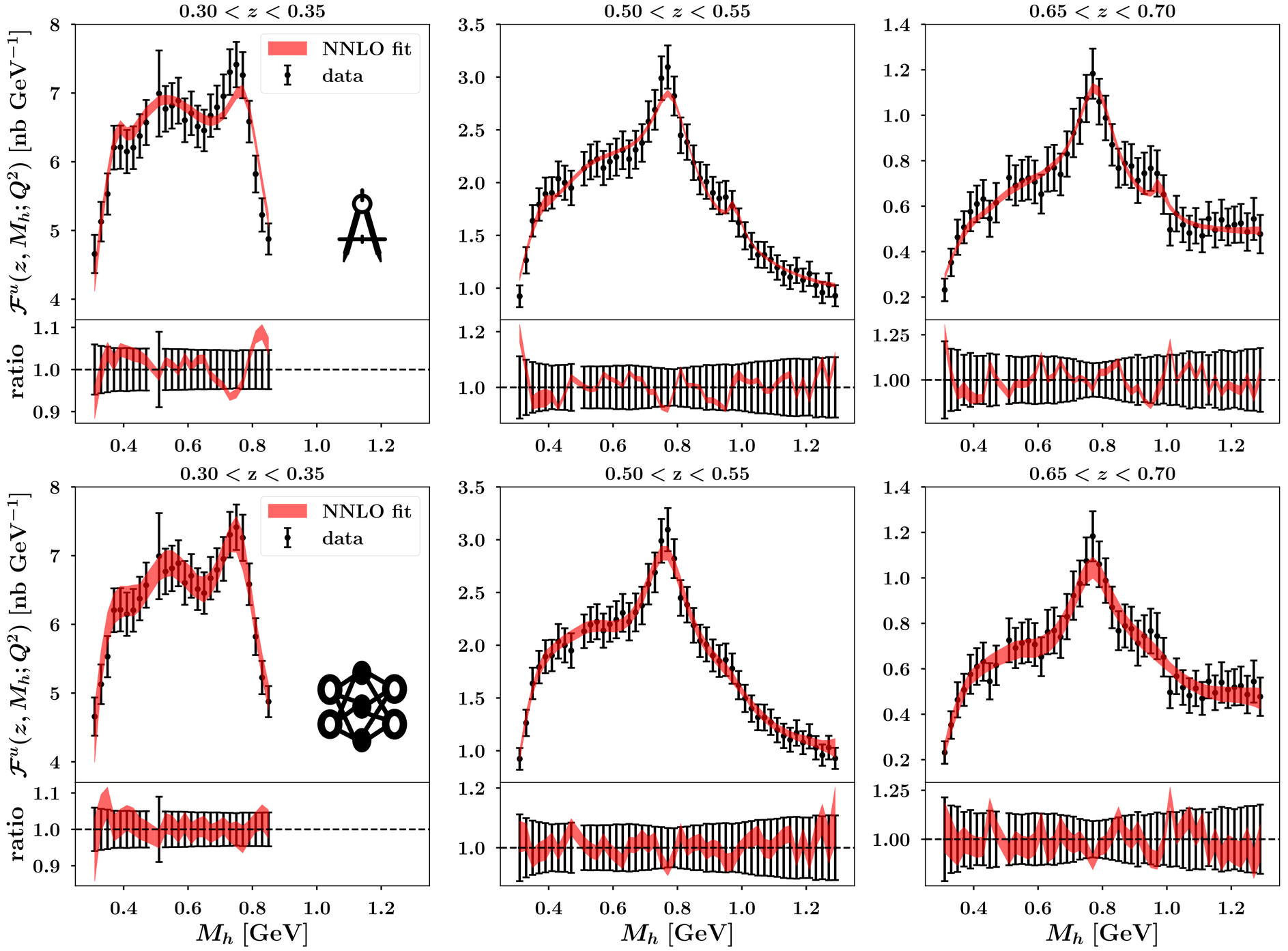
Comparison



vs

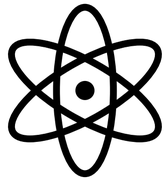
NN seems to describe better data

NN has less sensitivity on resonances



DI-HADRON FF

Physics informed



u=d

gluon assumptions

$$D_1^g(z, M_h; Q^2) = N\, z^{\alpha_1} (1-z)^{1+\alpha_2} \cdot D_1^u(z, M_h; Q^2)$$

N random unif. in (0,2)

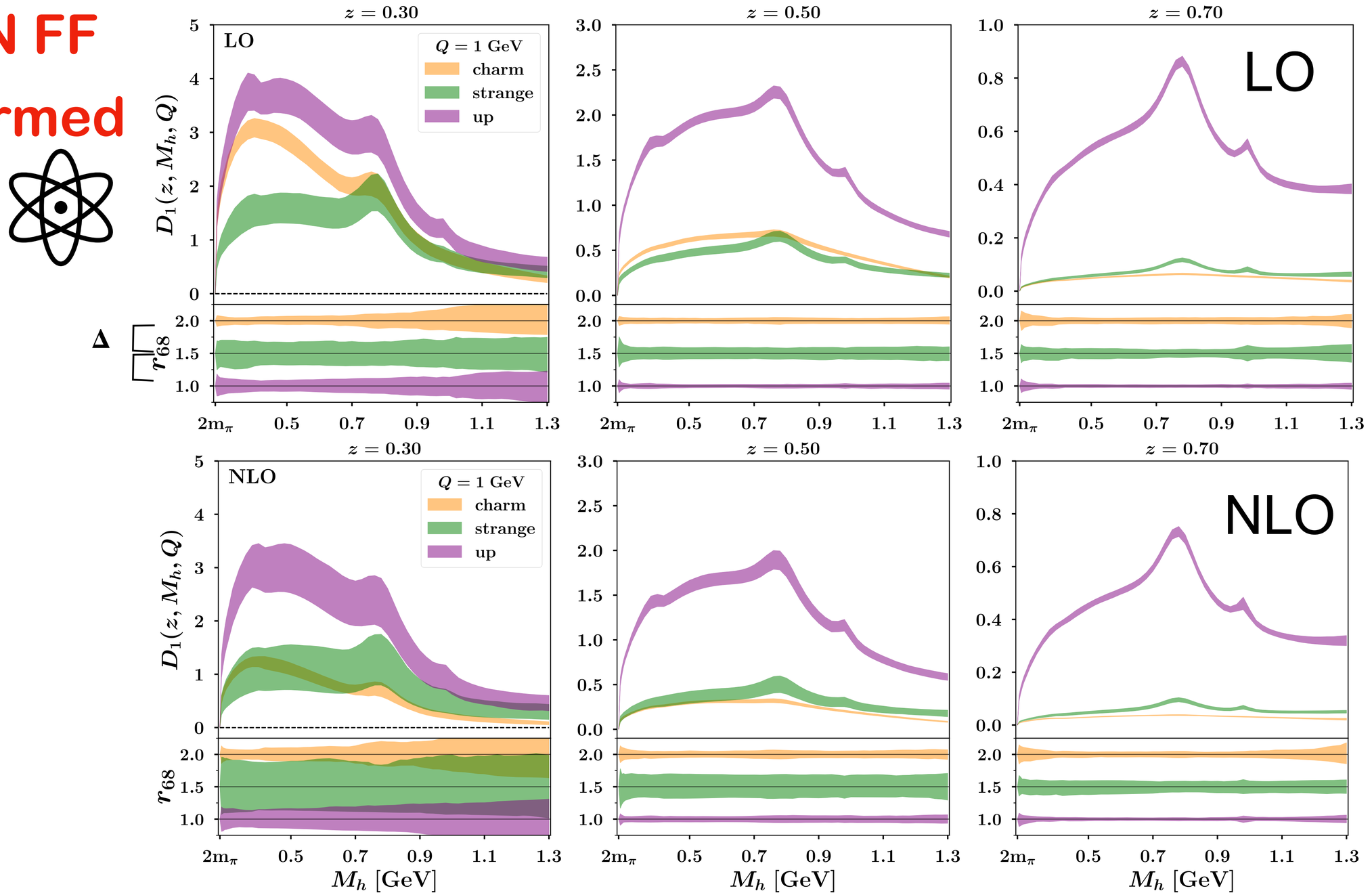
α_1, α_2 random unif. in (0,1)

DI-HADRON FF

Physics informed

u=d

ratio offset Δ = 0.5

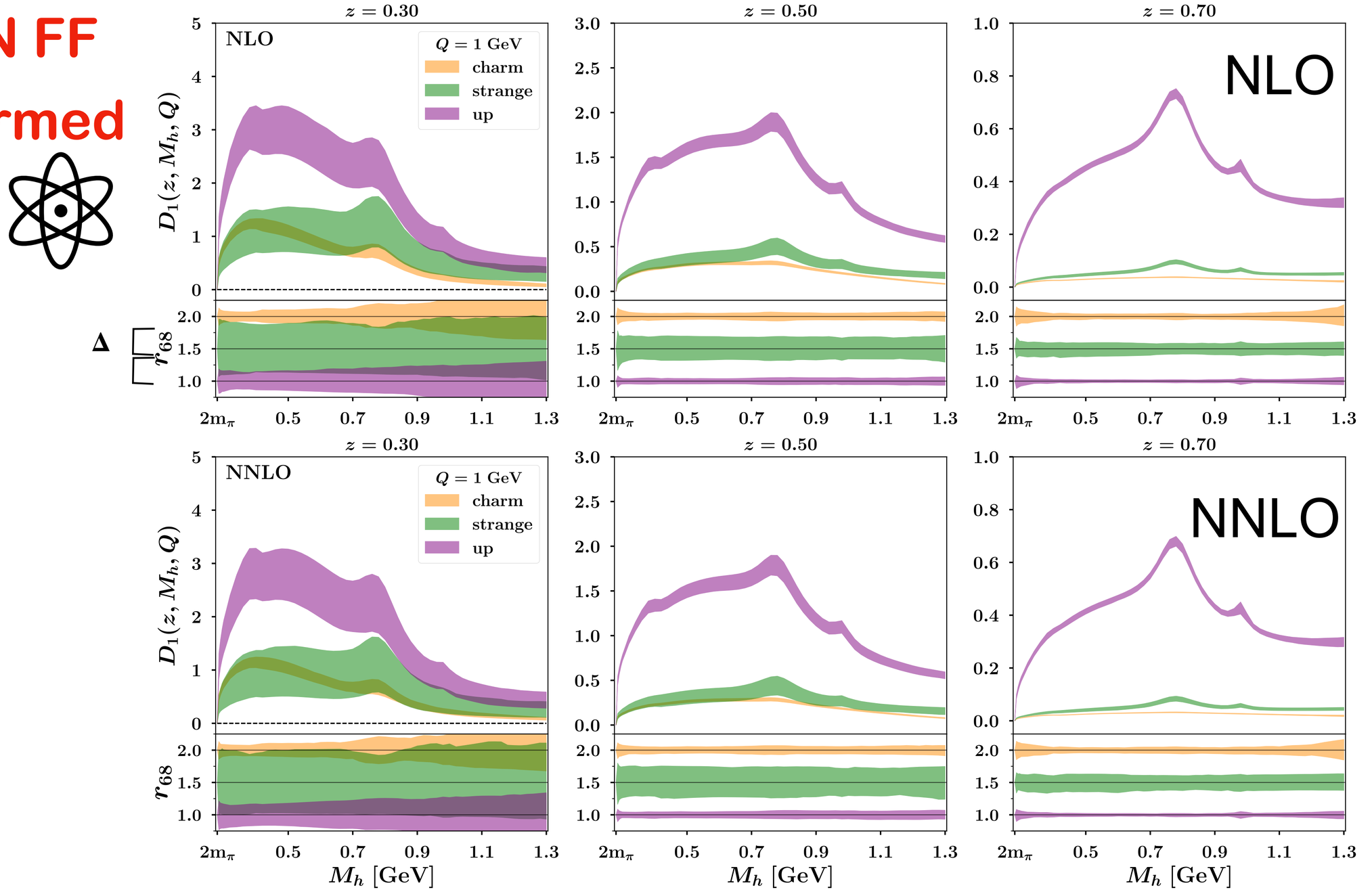


DI-HADRON FF

Physics informed

u=d

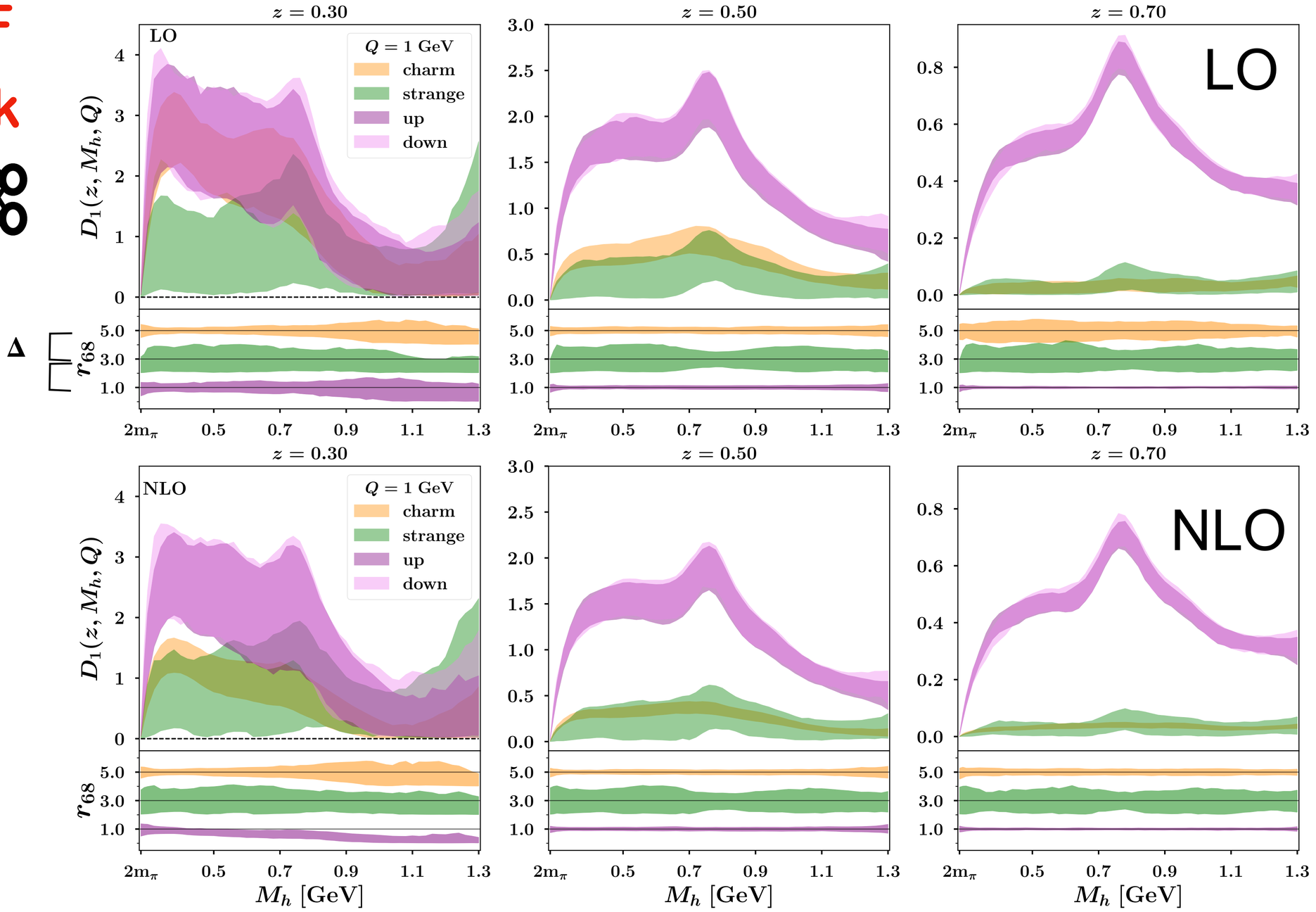
ratio offset Δ = 0.5



DI-HADRON FF
Neural Network

$\mathbf{u \neq d}$

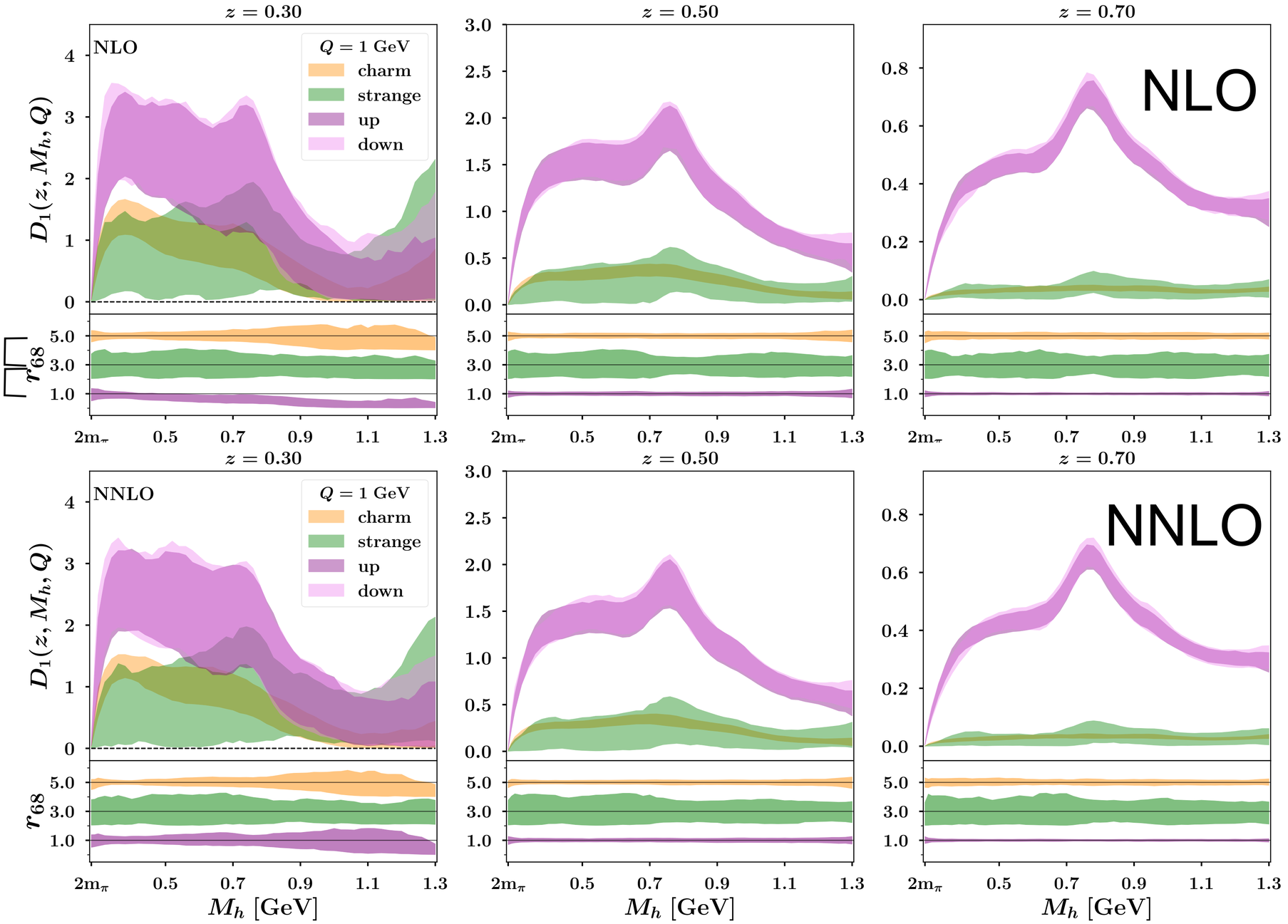
ratio offset Δ = 2.5



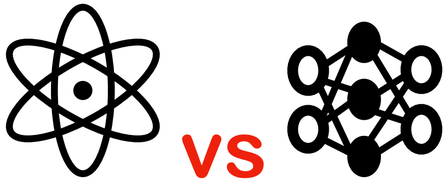
DI-HADRON FF
Neural Network

$\mathbf{u \neq d}$

ratio offset Δ = 2.5



Comparison at NNLO:



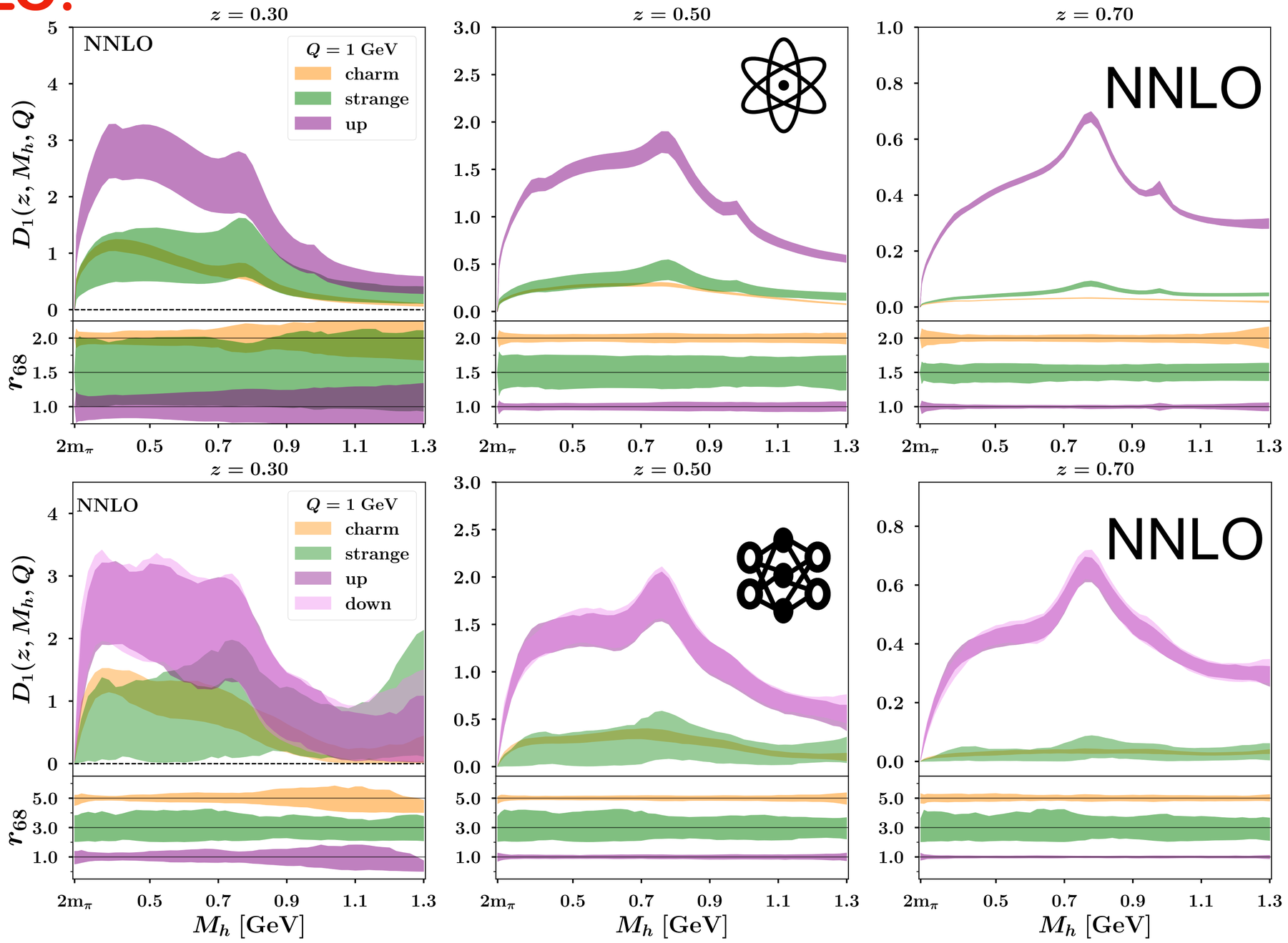
vs

Similar features and compatible results

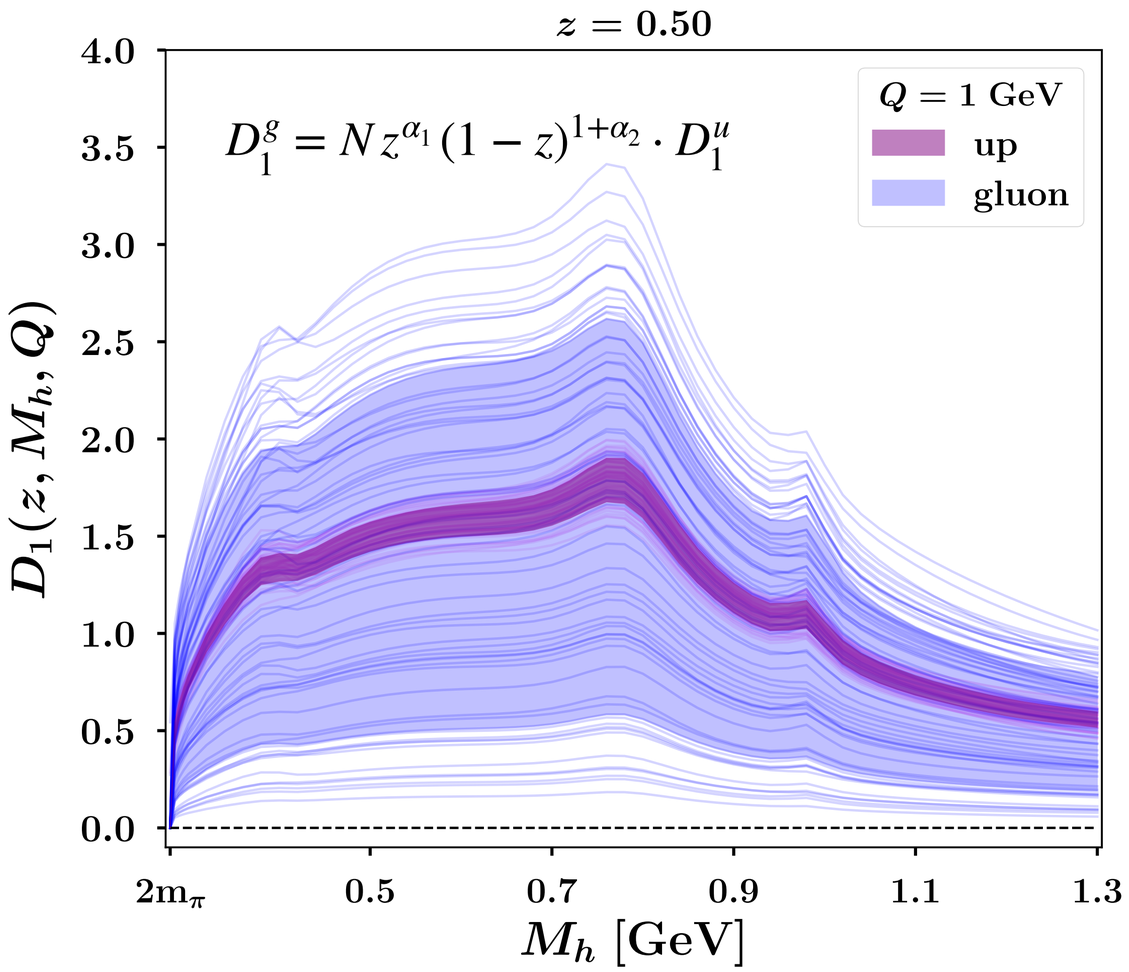
NN has wider uncertainty bands

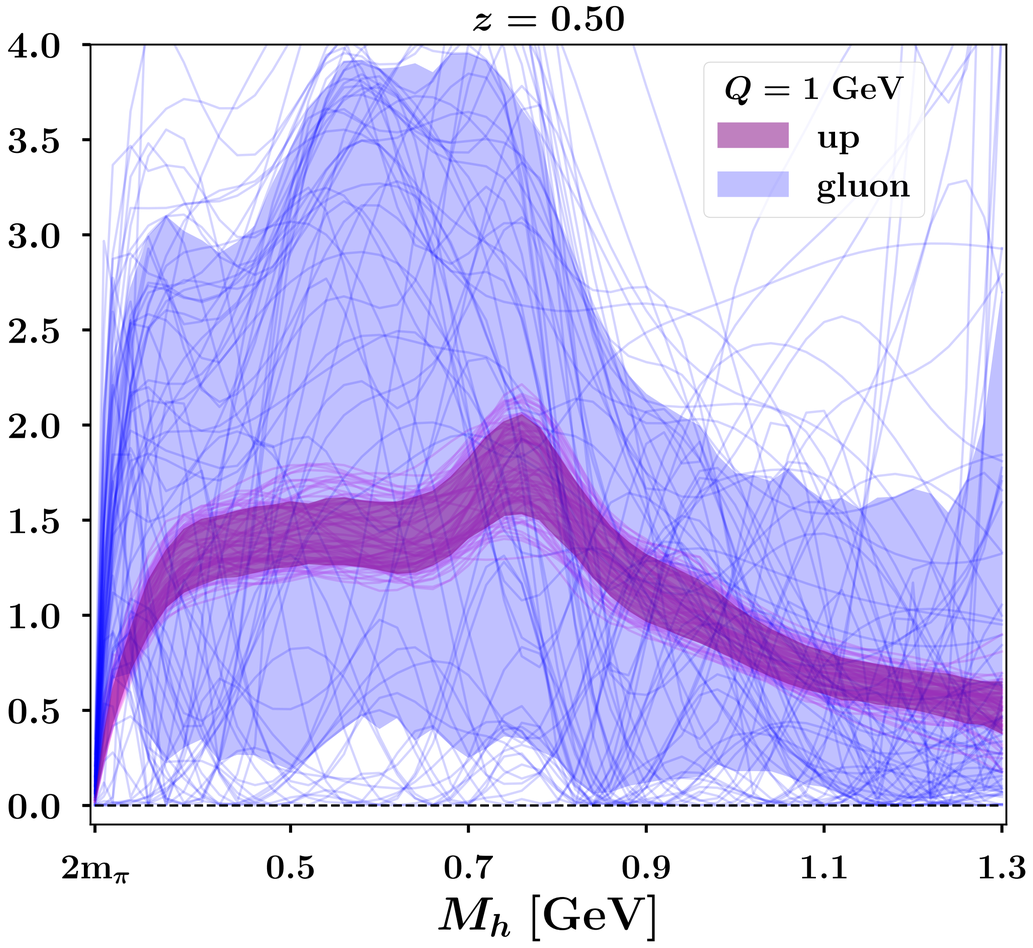
Resonances are better captured by the P.I. one

Gluon?



Gluon and up bands at NNLO





CONCLUSIONS AND OUTLOOKS

- Good agreement between both fits and data, small χ^2

CONCLUSIONS AND OUTLOOKS

- Good agreement between both fits and data, small χ^2

- The different parameterisations allow to grasp aspects of the Di-Hadron not accessible with the single ones

CONCLUSIONS AND OUTLOOKS

- Good agreement between both fits and data, small χ^2

- The different parameterisations allow to grasp aspects of the Di-Hadron not accessible with the single ones

- A hierarchy among quark flavors is clear and stable across different z values and perturbative orders (charm?)

CONCLUSIONS AND OUTLOOKS

◉ Good agreement between both fits and data, small χ^2

◉ The different parameterisations allow to grasp aspects of the Di-Hadron not accessible with the single ones

◉ A hierarchy among quark flavors is clear and stable across different z values and perturbative orders (charm?)

- Gluon component uncostrained with e^+e^- data

CONCLUSIONS AND OUTLOOKS

- Good agreement between both fits and data, small χ^2

- The different parameterisations allow to grasp aspects of the Di-Hadron not accessible with the single ones

- A hierarchy among quark flavors is clear and stable across different z values and perturbative orders (charm?)
  - Gluon component uncostrained with e^+e^- data

- Use D_1 to extract the $H_1^\sphericalangle$, and the transversity distribution h_1

CONCLUSIONS AND OUTLOOKS

- Good agreement between both fits and data, small χ^2

- s allow to grasp aspects
  e with the single ones

- s is clear and stable across
  ative orders (charm?)

- ned with e^+e^- data

- Use D_1 to extract the $H_1^\perp$, and the transversity distribution h_1

CONCLUSIONS AND OUTLOOKS

- Good agreement between both

- Use D_1 to extract the $H_1^{\perp}$, and the transversity distribution h_1