NEW INSIGHTS INTO LAMBDA FRAGMENTATION FUNCTIONS

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QCD Evolution 2025

In collaboration with
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QCD EVOLUTION

eman ta zabal zazu

Universidad del País Vasco — Euskal Herriko Unibertsitatea

INTRODUCTION

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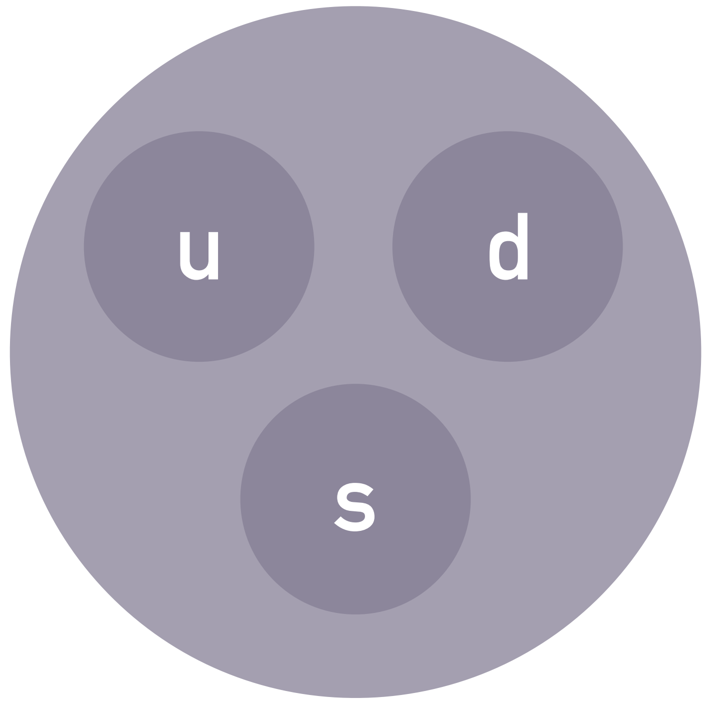
Big amount of information collected in the last decades regarding hadron production through **fragmentation functions**.
We still need to improve our knowledge on fragmentation functions focusing on specific hadrons.

The Λ^0 **baryon** has a **simple structure:**

- u and d quarks form a spin-0 isospin singlet state
- the Λ^0 spin is carried almost entirely by the strange quark



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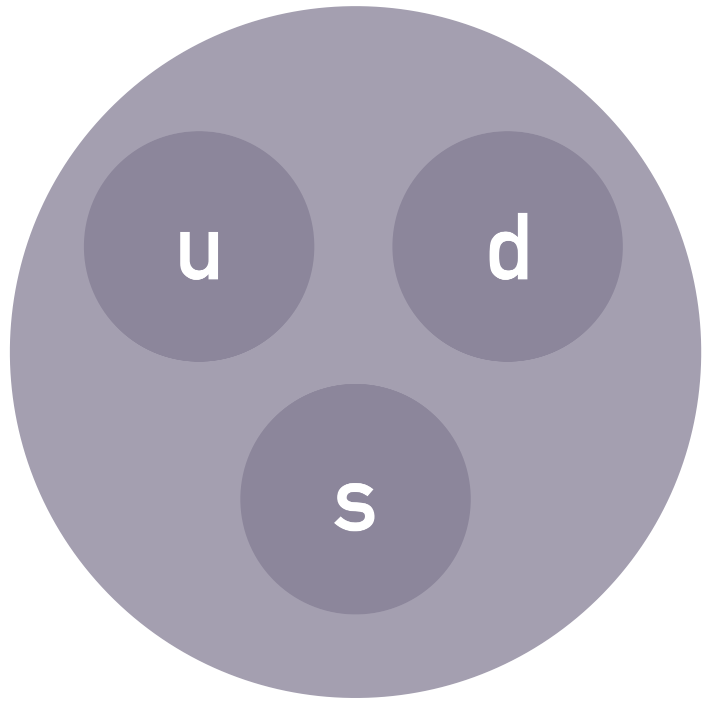

State of the art of fits (for unpolarized Λ FF)

- D. De Florian, M. Stratmann, W. Vogelsang (1998) , SIA data from LEP (ALEPH, OPAL, DELPHI), TASSO, CELLO, HRS, SLD
- S. Albino, B. A. Kniehl, G. Kramer (2006) SIA data with $\sqrt{s} = M_Z$
  (2008) SIA data with $\sqrt{s} \leq M_Z$, $pp(\bar{p})$ collisions (BRAHMS, PHENIX, STAR)
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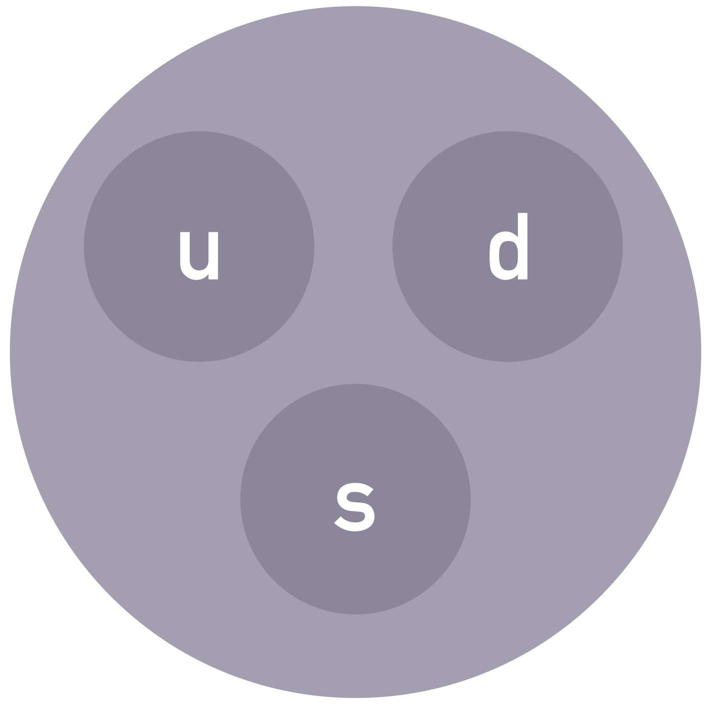

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$2025 \longrightarrow$ new global fit including SIA, SIDIS, pp collisions

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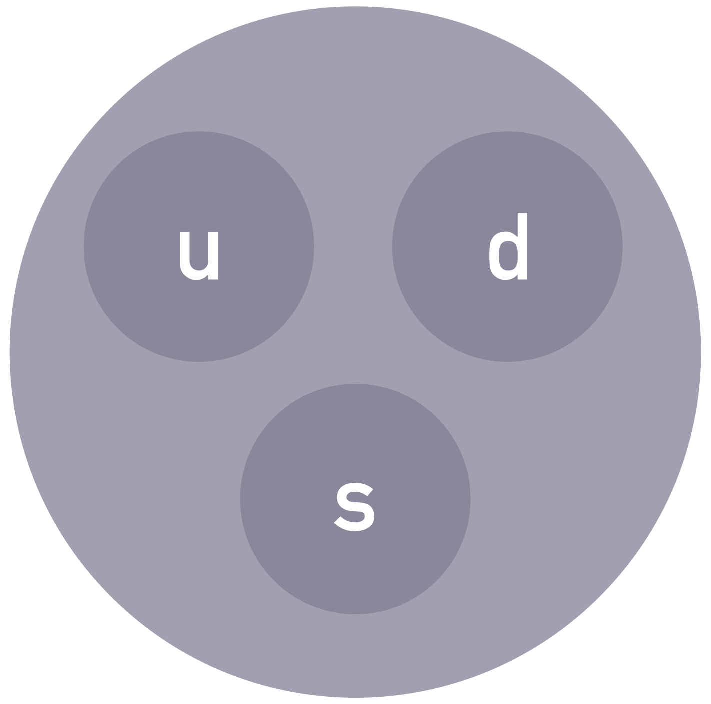

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Work in progress

EXPERIMENTS

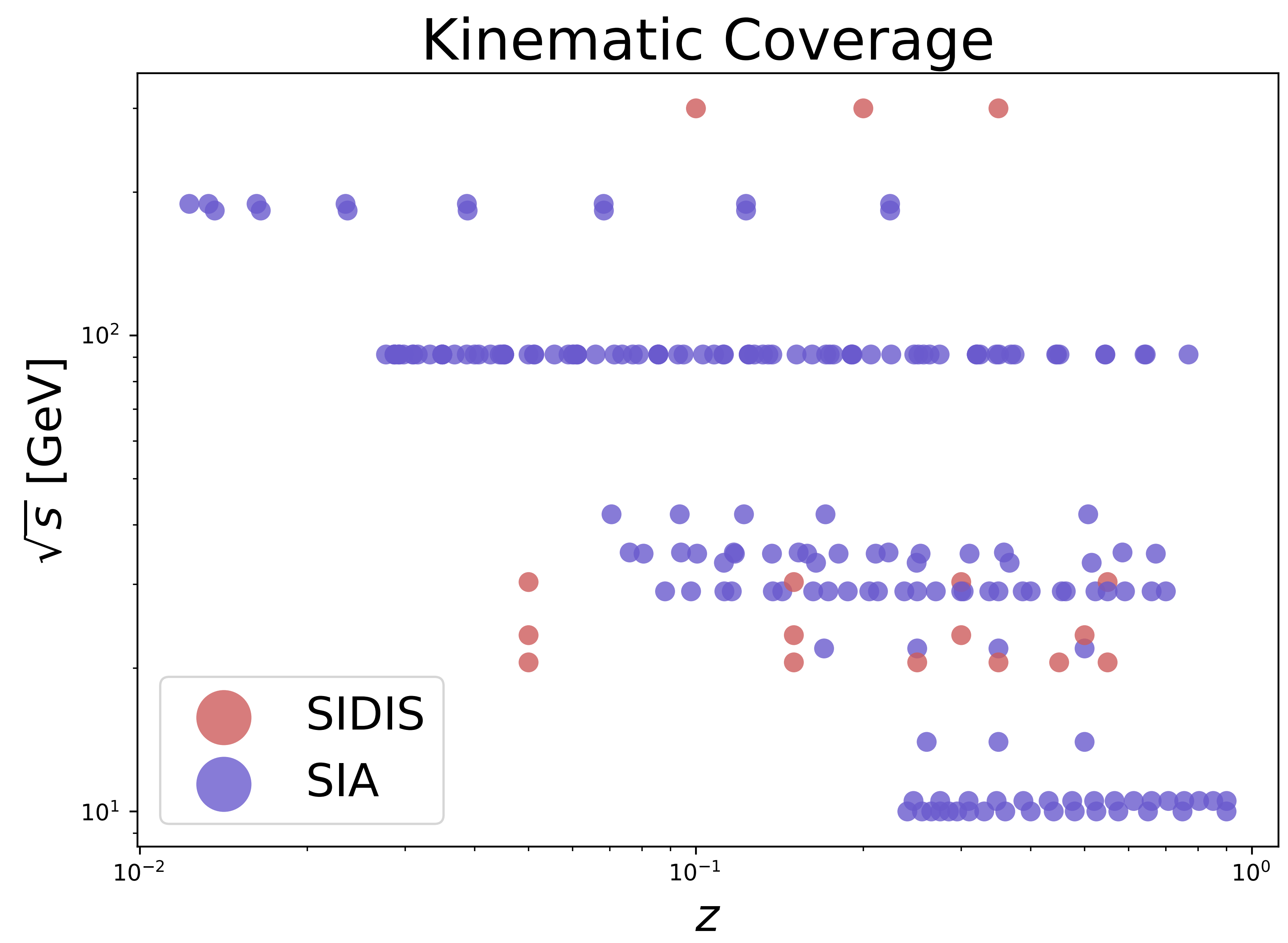
SIA

Experiment	Observable	$\sqrt{s}$ (GeV)
ARGUS	Multiplicity	10
BELLE	Cross section	10.52
TASSO @ 14,22,34	Cross section	14,22,34
TASSO @ 33.3	Cross section	33.3
TASSO @ 34.8,42.1	Cross section	34.8, 42.1
CELLO	Multiplicity	35
HRS	Cross section	29
MARK II	Cross section	29
ALEPH	Multiplicity	91.2
DELPHI @ 91 GeV	Multiplicity	91.2
OPAL	Multiplicity	91.2
SLD unt, uds-tag, c-tag, b-tag	Multiplicity	91.2
DELPHI @ 183,189	Multiplicity	183,189

SIDIS

Experiment	Observable	$\sqrt{s}$ (GeV)
Chicago-Harvard-Illinois-Oxford @ Fermilab	Multiplicity	20
EMC	Multiplicity	23.5
E665	Multiplicity	30
H1	Multiplicity	300

NC



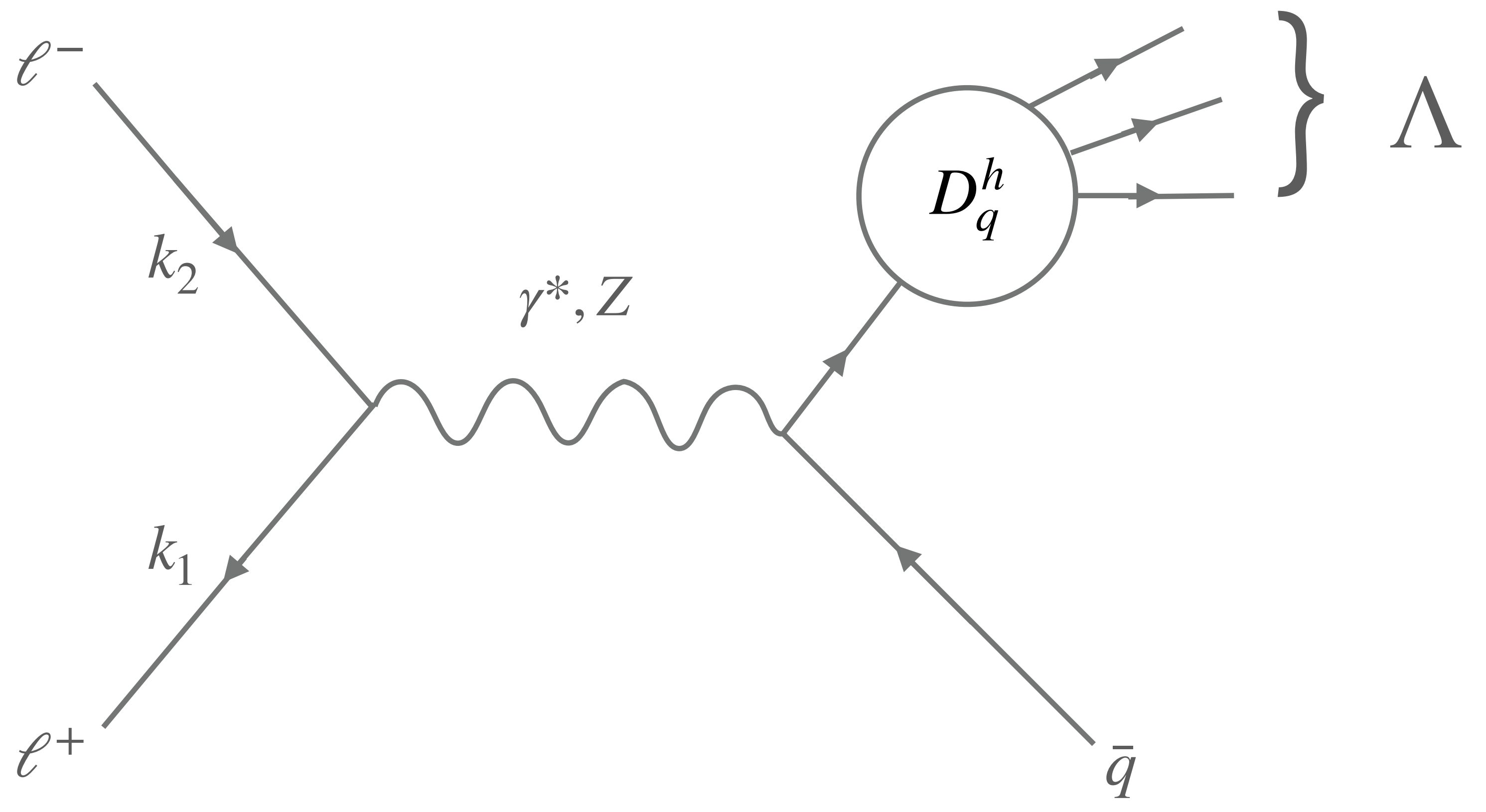
THEORETICAL BASIS

SIA kinematics

$$Q^2 = q^2$$

$$z = \frac{2P_h \cdot q}{Q^2}$$

$$\sqrt{s} = Q$$



SINGLE INCLUSIVE ANNIHILATION

$$l^+(k_1) + l^-(k_2) \to \Lambda(P_\Lambda) + X$$

- **Differential cross section**

$$\frac{d\sigma^h}{dz}(z,Q) = \frac{4\pi\alpha^2}{Q^2} F_2^h(z,Q)$$

NNPDF Collaboration, V. Bertone et al., Eur.Phys.J.C 77 (2017) 8, 516

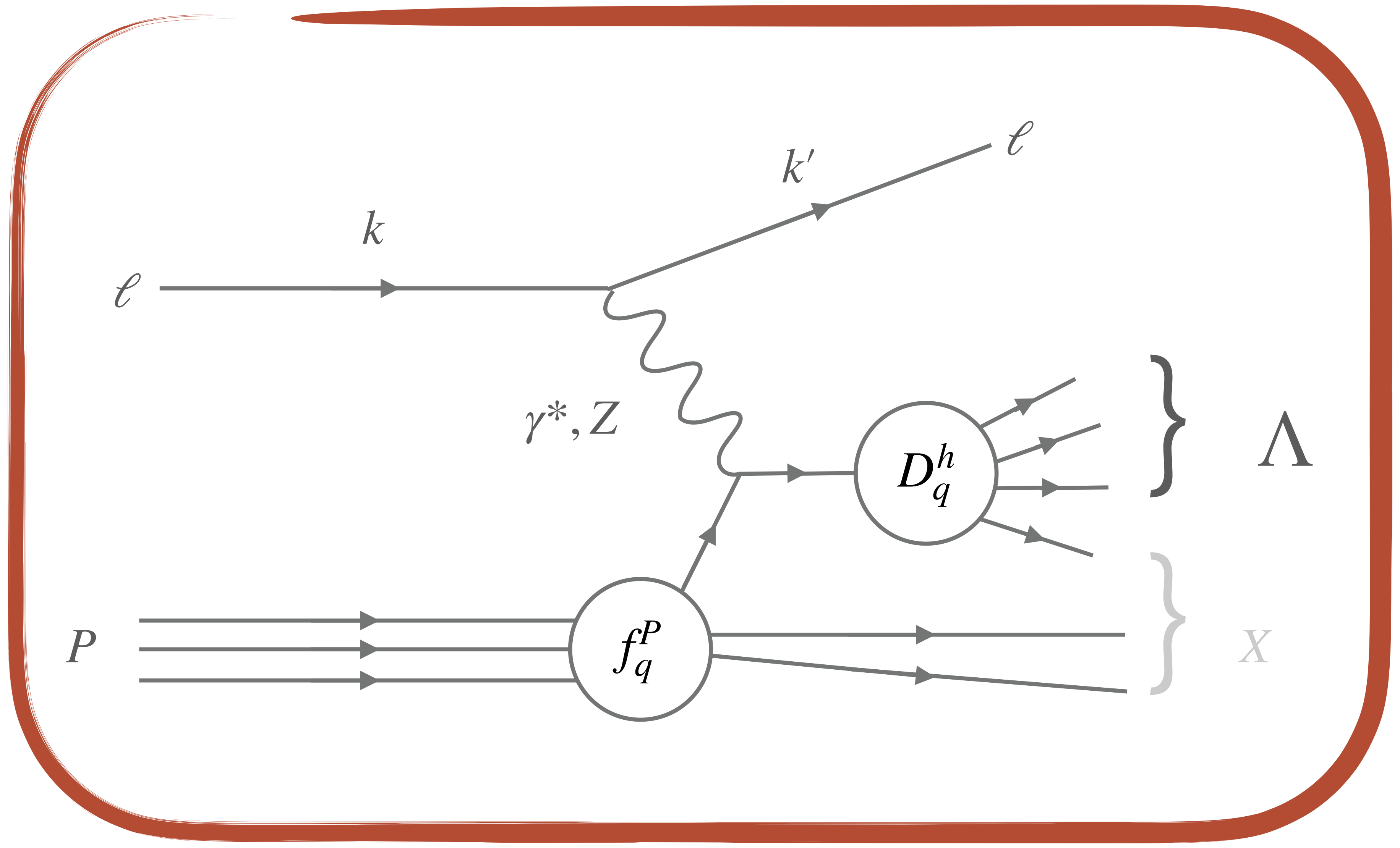
- **Fragmentation structure function**

$$F_2^h(z,Q) = \frac{1}{n_f}\sum_q^{n_f} e_q^2(Q)\Big[C_{2,q}^S\left(z,\alpha_s(Q)\right) \otimes D_\Sigma^h\left(z,Q\right) + C_{2,q}^{NS}\left(z,\alpha_s(Q)\right) \otimes D_{NS}^h\left(z,Q\right) + C_{2,g}^S\left(z,\alpha_s(Q)\right) \otimes D_g^h\left(z,Q\right)\Big]$$

THEORETICAL BASIS

SIDIS Kinematics

$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2p \cdot q}$$
$$z = \frac{P \cdot P_h}{P \cdot q}$$
$$y = \frac{Q^2}{xs}$$



SEMI INCLUSIVE DIS

$$\ell(k) + N(P) \rightarrow \ell(k') + \Lambda(P_\Lambda) + X$$

- **Differential cross section** $(Q \ll M_Z)$

$$\frac{d^3\sigma}{dxdQdz} = \frac{4\pi\alpha^2}{xQ^3}[(1 + (1-y)^2 F_2(x,z,Q) - y^2 F_L(x,z,Q)]$$

MAPFF1.0

R. A. Khalek et al.,
Phys.Rev.D 104 (2021) 3, 034007

- **Fragmentation structure function** within collinear factorisation $(Q \gg \Lambda_{QCD})$

$$F_i(x,z,Q) = x \sum_{q\bar{q}} e_q^2 \Big[(C_{i,qq}(x,z,Q) \otimes f_q(x,Q) \ + \ C_{i,qg}(x,z,Q) \otimes f_g(x,Q)) \otimes D_q^\Lambda(z,Q) + \ (C_{i,gq}(x,z,Q) \otimes f_q(x,Q)) \otimes D_g^\Lambda(z,Q) \Big] \qquad i = 2, L$$

THEORETICAL BASIS

All datasets provide $\frac{1}{\sigma_T} \frac{d\sigma^h}{dx_F} \longrightarrow$

$x_F < 0$ target fragmentation region

$x_F > 0$ current fragmentation region

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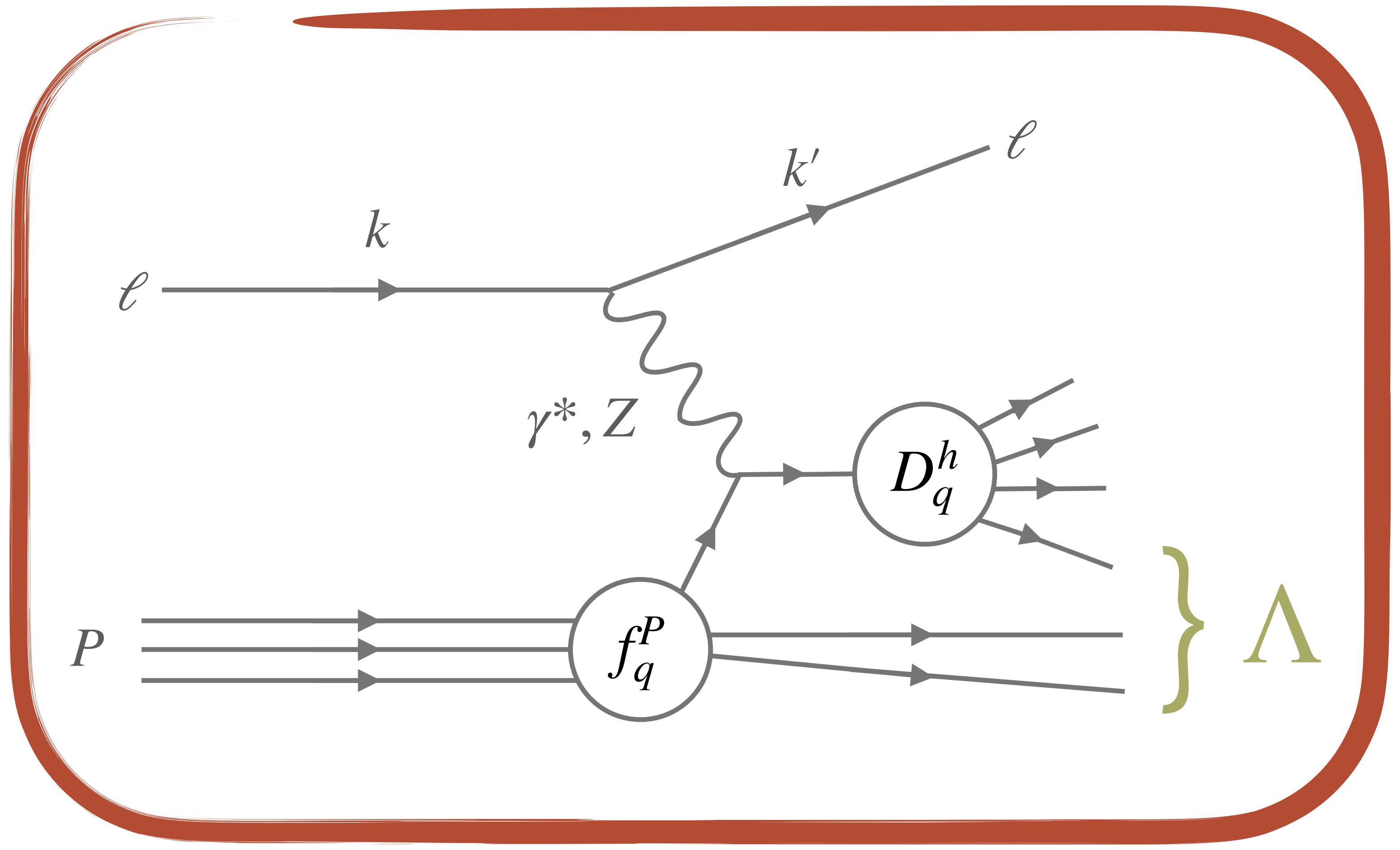

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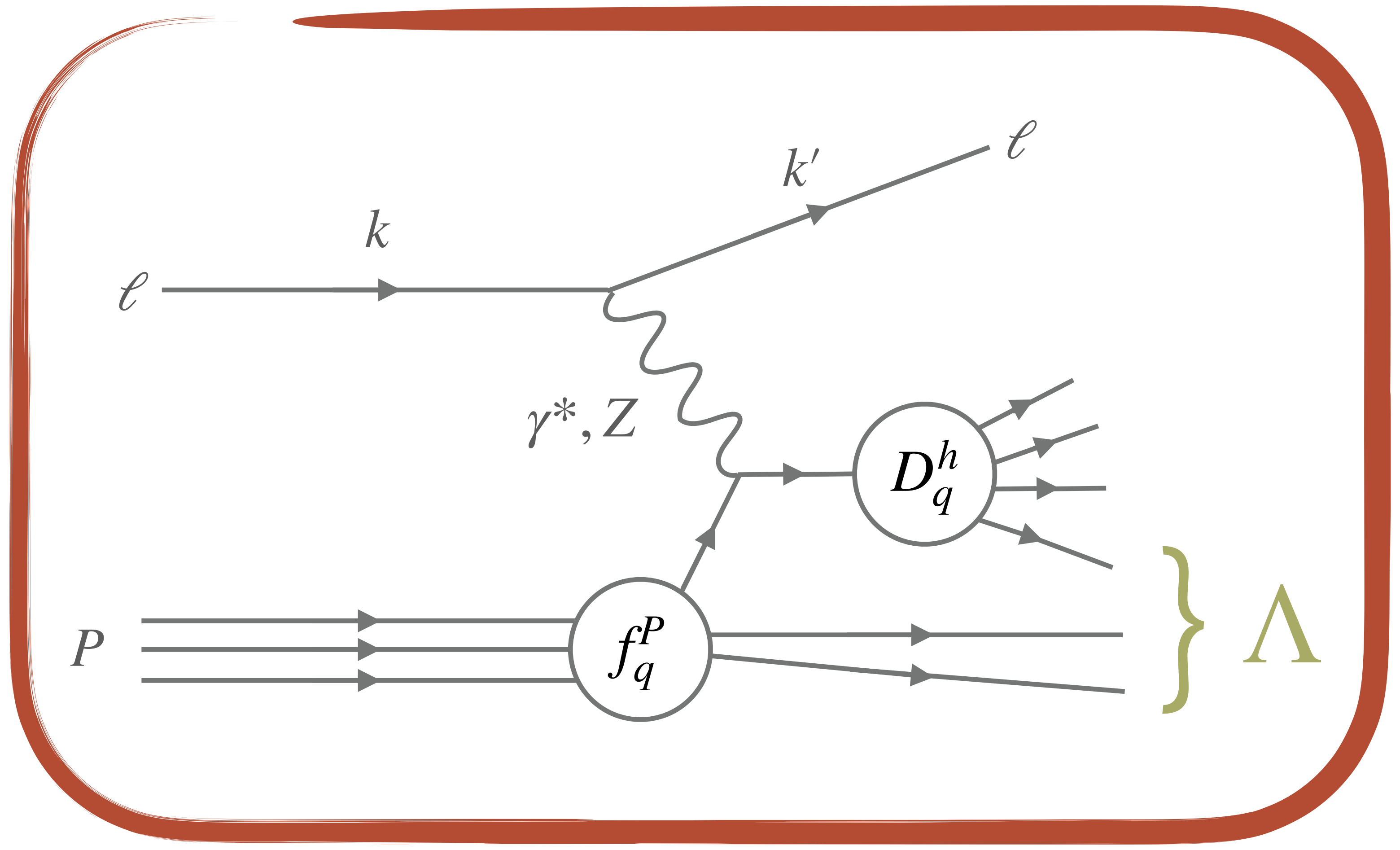

Handled with **fracture functions**
F. A. Ceccopieri, D. Mancusi (2013)

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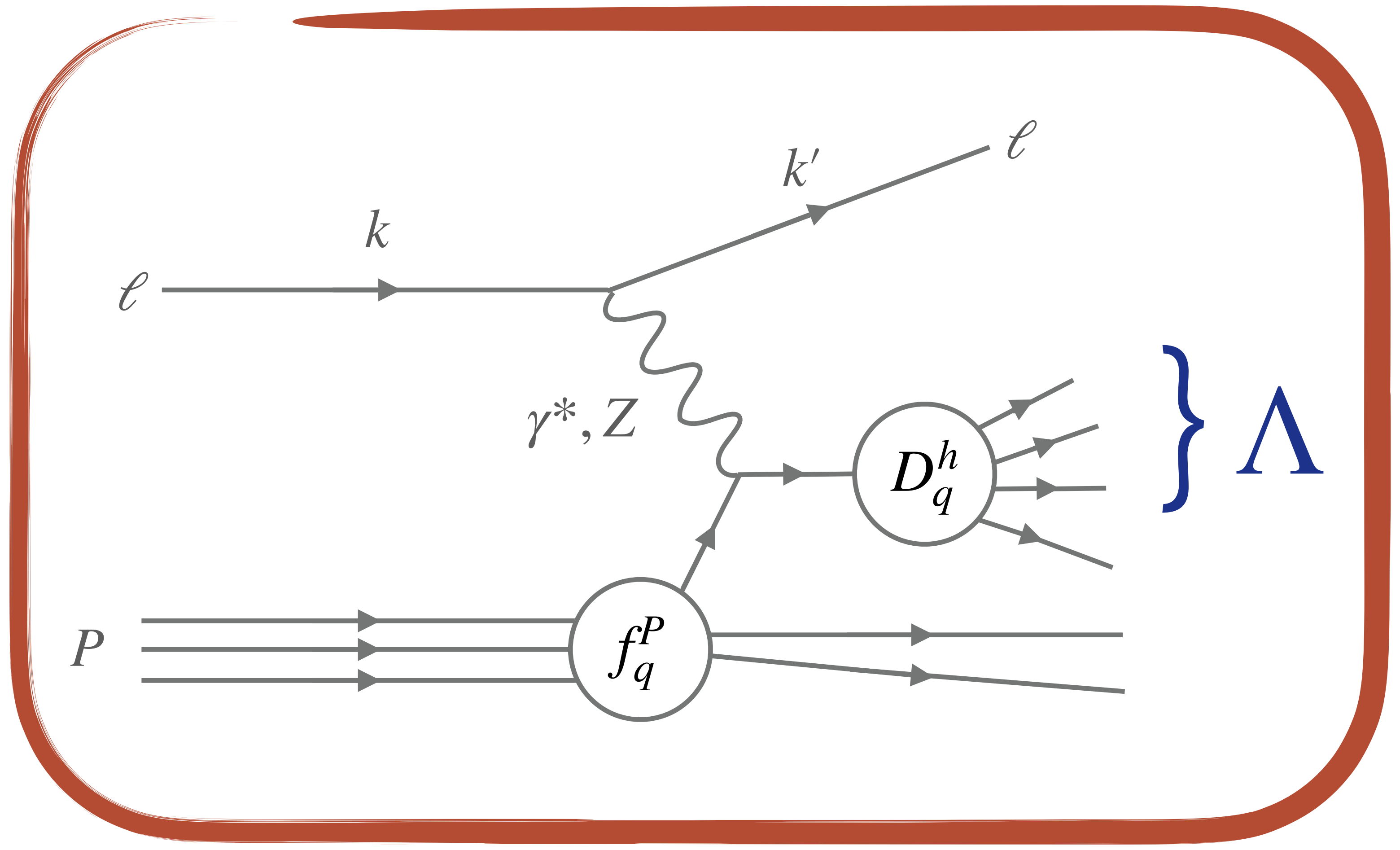

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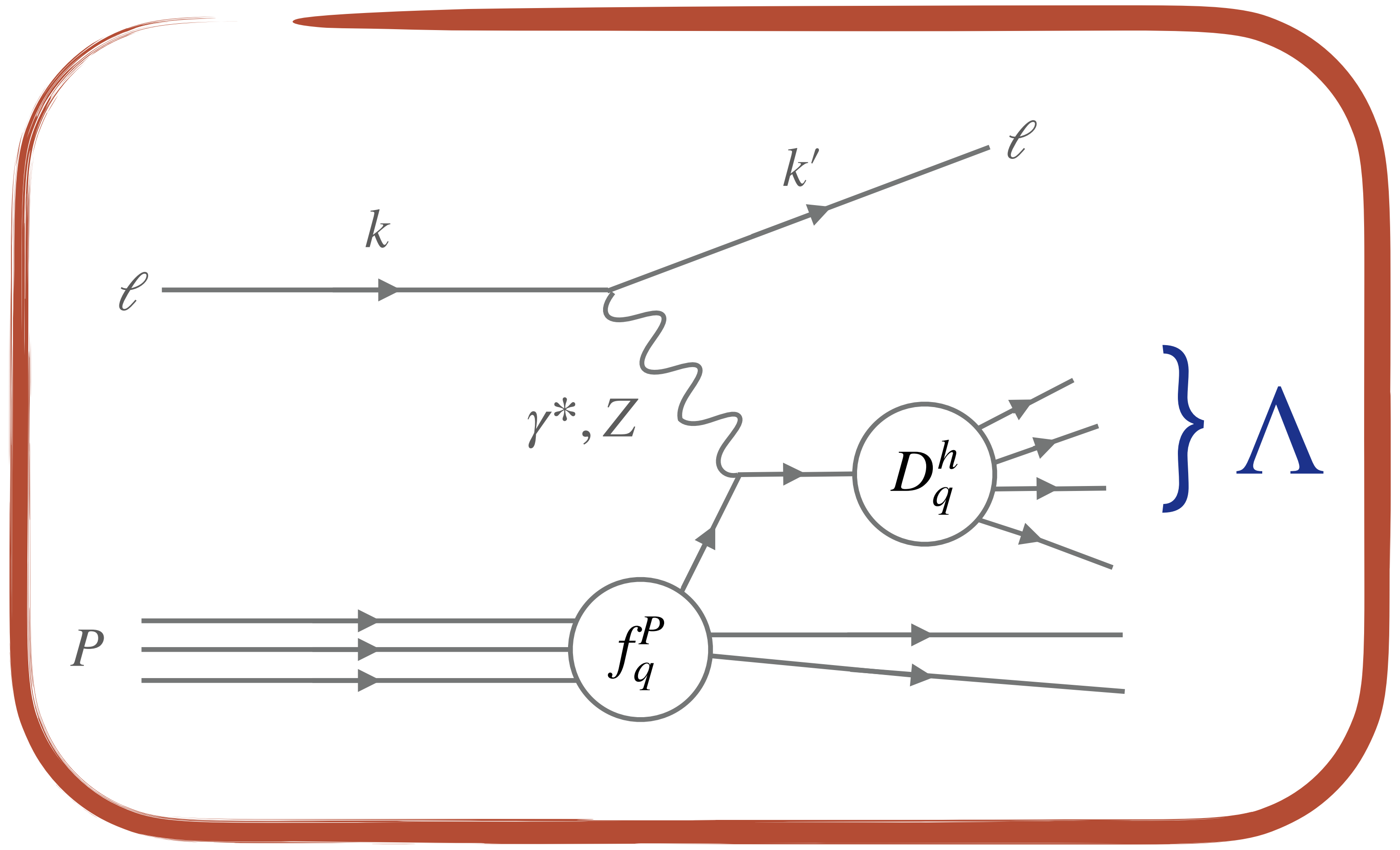

We restrict to $x_F > 0$ for proper SIDIS analysis, with $x_F = z$

$$\frac{dM}{dz} = \left[\int_{Q_{min}}^{Q_{max}} dQ \int_{x_{min}}^{x_{max}} dx \int_{z_{min}}^{z_{max}} dz \frac{d^3\sigma}{dxdQdz}\right] \Big/ \left[\Delta z \int_{Q_{min}}^{Q_{max}} dQ \int_{x_{min}}^{x_{max}} dx \frac{d^2\sigma}{dxdQ}\right]$$

MAPFF1.0

R. A. Khalek et al., Phys.Rev.D 104 (2021) 3, 034007

Bin by bin integration

THEORETICAL BASIS

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- $x_F < 0$ target fragmentation region
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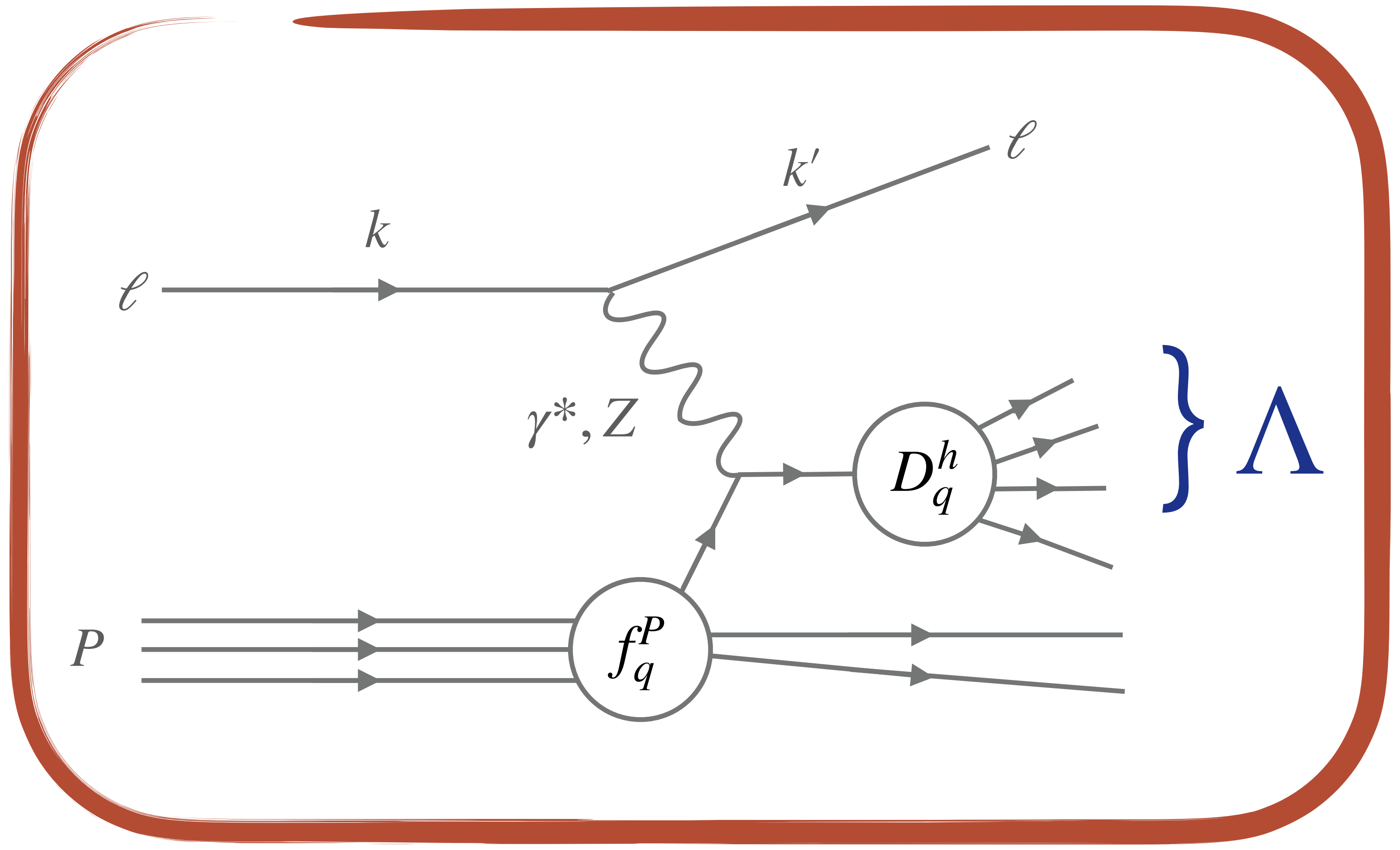

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MAPFF1.0

R. A. Khalek et al.,
Phys.Rev.D 104 (2021) 3, 034007

Bin by bin integration

Experiment	Q^2 range	x range
CHIO @ Fermilab	4 < Q^2 < 50	0.001 < x < 1
EMC	Q^2 > 4	0.02 < x < 1
E665	Q^2 > 1	0.003 < x < 1
H1	10 < Q^2 < 70	0.0001 < x< 0.01

Whole range of integration in x and Q
(as specified by the collaboration)

Phase space reduction

$$Q_{max} < \sqrt{s}$$

$$x_{min} = \max\left[x_{min}^{collab}, \frac{Q^2}{s y_{max}}\right]$$

$$x_{max} = \min\left[x_{max}^{collab}, \frac{Q^2}{s y_{min}}, \frac{Q^2}{Q^2 + W^2}\right]$$

METHODOLOGY

- Nanga Parbat
- APFEL++
- NNAD & ceres-solver

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

PASSED | codefactor A | CodeQL passing | DOI 10.5281/zenodo.10522420

APFEL++

A PDF evolution library in C++

NNAD

`NNAD` stands for Neural Network Analytic Derivatives and is a C++ implementation of the analytic derivatives of a feed-forward neural network with arbitrary architecture with respect to its free parameters. We implemented the back-propagation method using three strategies: analytic, automatic (when interfaced with `ceres-solver`) and numeric differentiation.

METHODOLOGY

- Nanga Parbat

Chi square,
Replica generation

Statistical framework relies on Monte Carlo sampling method

Data is assumed to be sampled from a multivariate Gaussian distribution:

$$\mathcal{G}\left(\mathbf{x}^{(k)}\right) \propto \exp\left[\left(\mathbf{x}^{(k)}-\mu\right)^T C^{-1}\left(\mathbf{x}^{(k)}-\mu\right)\right]$$

With $\mathbf{x}^{(k)} = \{x_1^{(k)}, x_2^{(k)}, \ldots, x_{N_{dat}}^{(k)}\}$, $k = 1,\ldots,N_{rep}$ replicas of a set of N_{dat} values

$\mu = \{\mu_1, \mu_2, \ldots, \mu_{N_{dat}}\}$ expectation values = measured data

$$C_{ij} = \delta_{ij}\sigma^2_{i,\mathrm{unc}} + \sum_\beta \sigma^{(\beta)}_{i,\mathrm{corr}}\sigma^{(\beta)}_{j,\mathrm{corr}}$$ Elements of the covariance matrix

Generation of replicas using the Cholesky decomposition $\mathbf{L}, (\mathbf{C} = \mathbf{L}\cdot\mathbf{L}^T)$

$$\mathbf{x}^{(k)} = \mu + L\cdot\mathbf{r}^{(k)}$$

With $\mathbf{r}^{(k)}$ such that

$$\frac{1}{N_{\mathrm{rep}}}\sum_k^{N_{\mathrm{rep}}} x_i^{(k)} \simeq \mu_i, \quad \frac{1}{N_{\mathrm{rep}}}\sum_k^{N_{\mathrm{rep}}} x_i^{(k)}x_j^{(k)} \simeq \mu_i\mu_j + C_{ij}$$

METHODOLOGY

- APFEL++

- Computation of SIA and SIDIS cross sections

$$\frac{d\sigma^h}{dz}(z,Q) = \frac{4\pi\alpha^2}{Q^2}F_2^h(z,Q)$$

$$\frac{d^3\sigma}{dxdQdz} = \frac{4\pi\alpha^2}{xQ^3}[(1+(1-y)^2F_2(x,z,Q^2) - y^2F_L(x,z,Q^2)]$$

- Perturbative expansion of the coefficient functions (NLO and NNLO)

$$C(x,z,Q) = \sum_n \left(\frac{\alpha_s(Q)}{4\pi}\right)^n C^{(n)}(x,z)$$

- DGLAP Evolution of FFs
- PDF for SIDIS

METHODOLOGY

- NNAD & ceres-solver

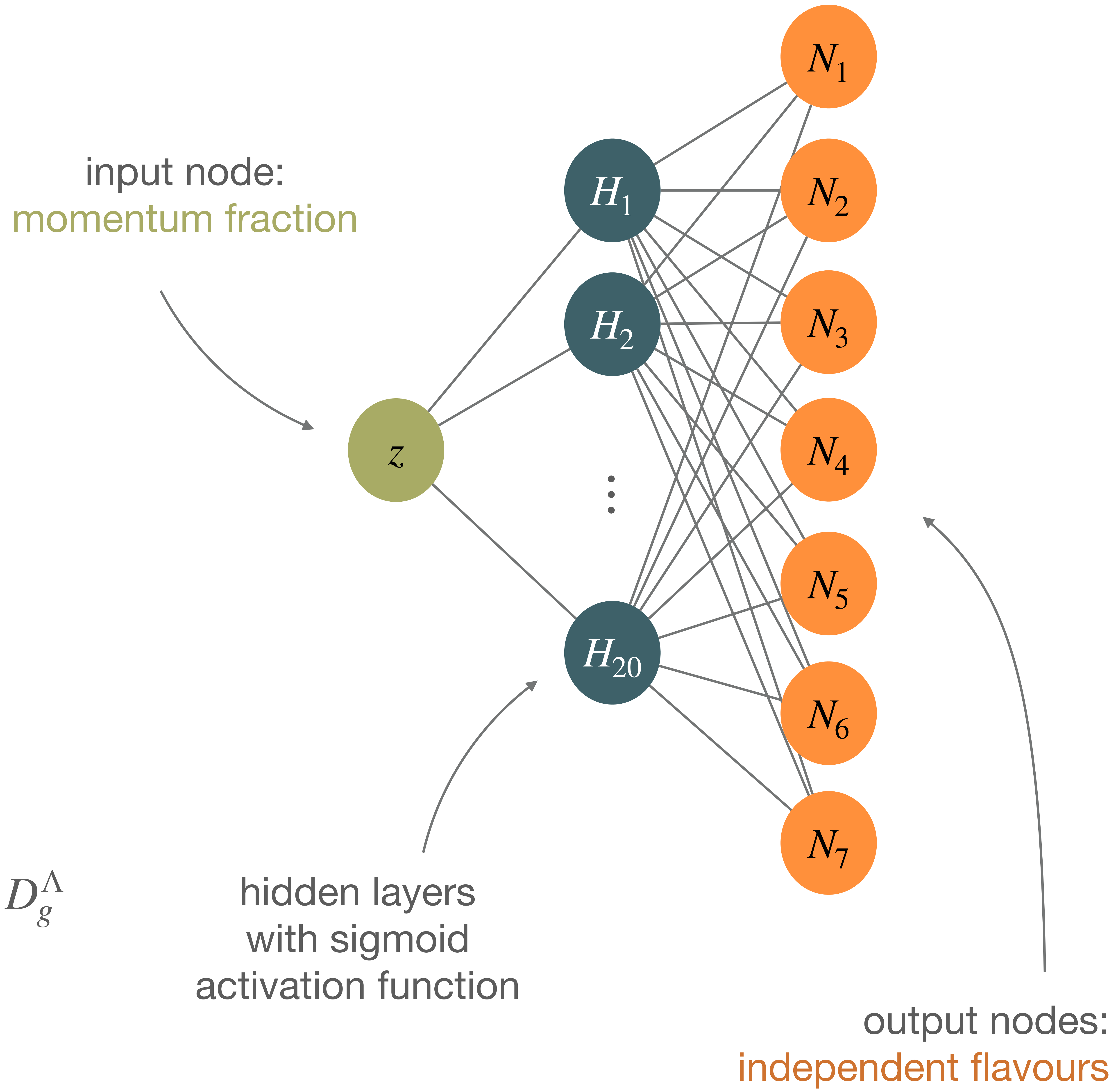
Parameterisation choice:
single one-layered feed-forward Neural Network

$$\mathcal{N}_i(z, \theta)$$

$$z\, D_i^{\Lambda}(z, \mu_0 = 5\text{ GeV}) = \left(\mathcal{N}_i(z, \theta) - \mathcal{N}_i(1, \theta)\right)^2$$

7 independent flavours

$$D_u^{\Lambda}, \quad D_d^{\Lambda}, \quad D_s^{\Lambda}, \quad D_{\bar{u}}^{\Lambda} = D_{\bar{d}}^{\Lambda} = D_{\bar{s}}^{\Lambda}, \quad D_{c^+}^{\Lambda}, \quad D_{b^+}^{\Lambda}, \quad D_g^{\Lambda}$$



METHODOLOGY

Parameterisation

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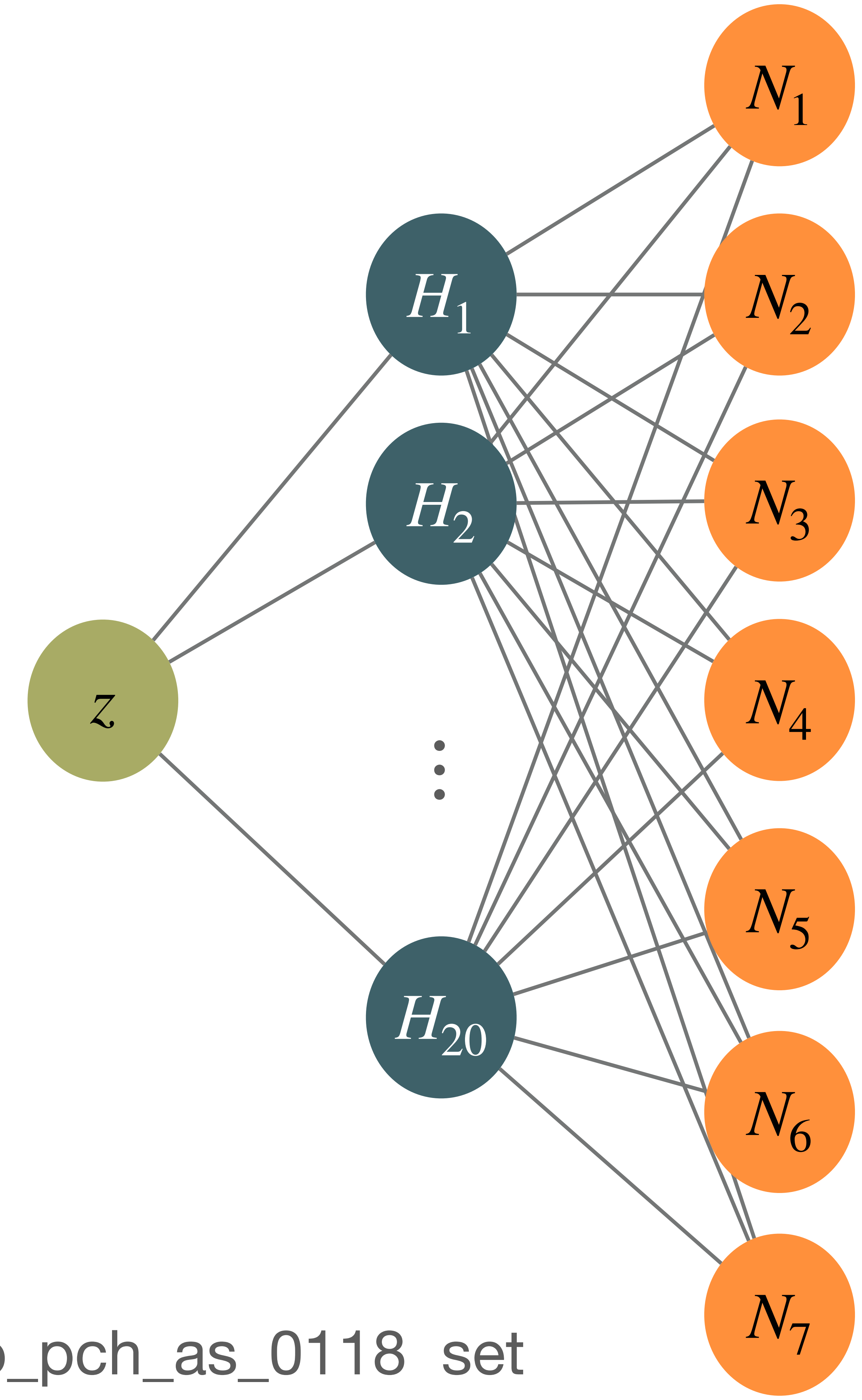


$$\chi^{2(k)} \equiv \left(T(\theta^{(k)}) - x^{(k)}\right)^T C^{-1} \left(T(\theta^{(k)}) - x^{(k)}\right)$$

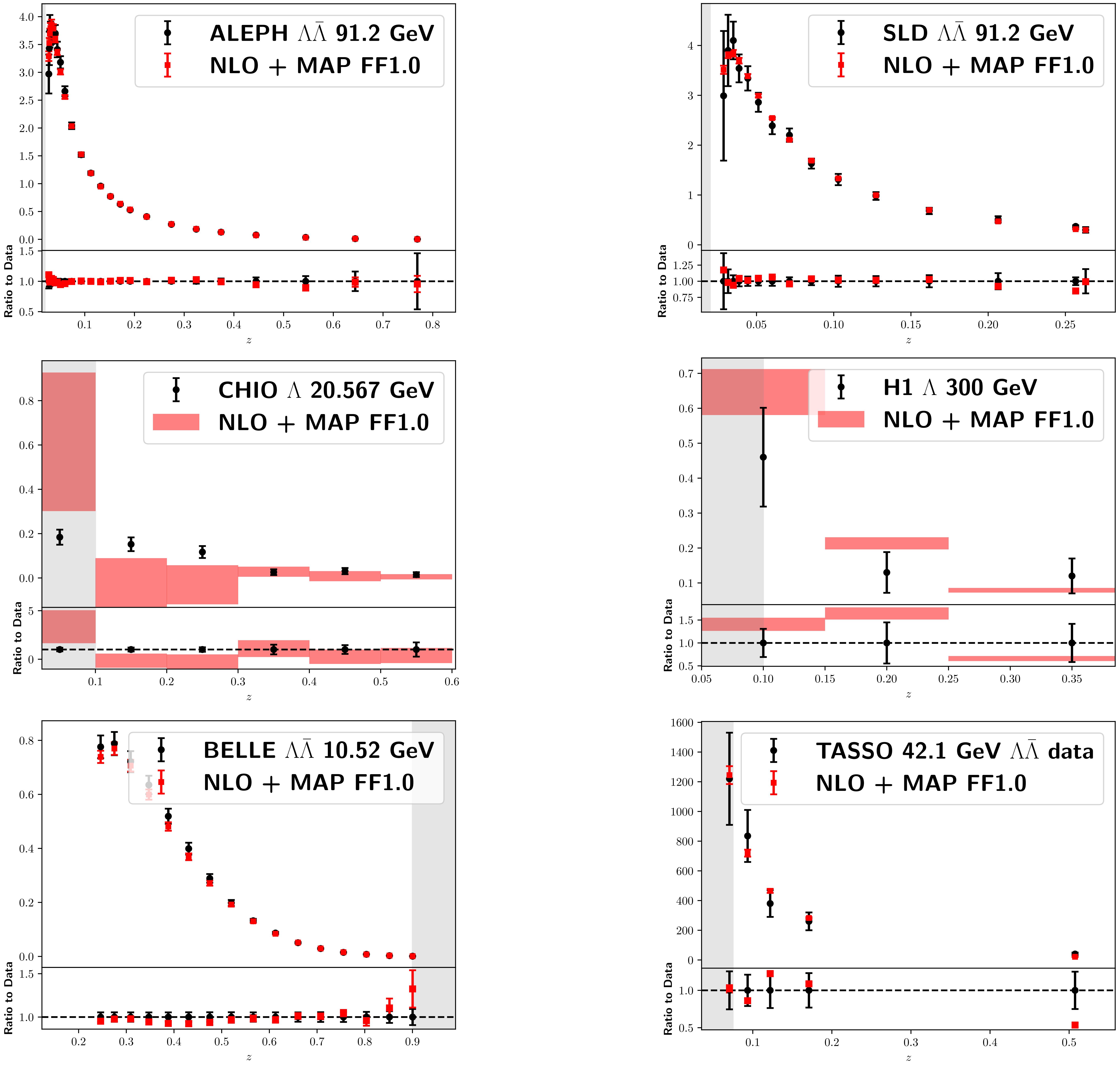
Propagation of PDF correlated uncertainties for SIDIS using the NNPDF31_nlo_pch_as_0118 set

Minimisation algorithm: **Levenberg-Marquardt** implemented in **Ceres-solver**

NN and analytical derivatives provided by **NNAD**

RESULTS

Experiment	χ^2 per point	N_{dat} after cuts
SIDIS		
E665 Λ	1.65	2
E665 $\bar{\Lambda}$	1.87	2
EMC Λ	3.55	3
H1 $\Lambda + \bar{\Lambda}$	0.91	2
CHIO Fermilab Λ	1.17	4
CHIO Fermilab $\bar{\Lambda}$	1.56	4
SIA $\Lambda + \bar{\Lambda}$		
ALEPH	0.45	25
ARGUS	1.43	16
BELLE	0.70	15
CELLO	0.60	7
DELPHI 91.2 GeV	4.75	11
DELPHI 183 GeV	3.37	5
DELPHI 189 GeV	2.58	5
HRS	0.96	12
MARK II	3.09	15
OPAL	0.88	15
SLD B	0.52	8
SLD C	1.61	8
SLD UDS	1.99	8
SLD	0.65	16
TASSO 14 GeV	0.25	3
TASSO 22 GeV	0.51	4
TASSO 33 GeV	0.77	5
TASSO 34.8 GeV	2.77	10
TASSO 42.1 GeV	1.04	4
Total	1.54	209



RESULTS

Experiment	χ^2/N_{dat} NLO	NNLO
SIDIS		
E665 Λ	1.65	1.66
E665 $\bar{\Lambda}$	1.87	1.83
EMC Λ	3.55	3.79
H1 $\Lambda + \bar{\Lambda}$	0.91	0.95
CHIO Fermilab Λ	1.17	1.06
CHIO Fermilab $\bar{\Lambda}$	1.56	1.43
SIA $\Lambda + \bar{\Lambda}$		
ALEPH	0.45	0.45
ARGUS	1.43	1.39
BELLE	0.70	0.61
CELLO	0.60	0.59
DELPHI 91.2 GeV	4.75	4.71
DELPHI 183 GeV	3.37	3.30
DELPHI 189 GeV	2.58	2.50
HRS	0.96	0.95
MARK II	3.09	3.01
OPAL	0.88	0.86
SLD B	0.52	0.49
SLD C	1.61	1.63
SLD UDS	1.99	2.08
SLD	0.65	0.66
TASSO 14 GeV	0.25	0.25
TASSO 22 GeV	0.51	0.51
TASSO 33 GeV	0.77	0.78
TASSO 34.8 GeV	2.77	2.75
TASSO 42.1 GeV	1.04	1.06
Total	1.54	1.51

- Extension of calculation at N2LO $\rightarrow \chi^2 = 1.51$

RESULTS

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E665 Λ	1.65	1.66
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ALEPH	0.45	0.45
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TASSO 33 GeV	0.77	0.78
TASSO 34.8 GeV	2.77	2.75
TASSO 42.1 GeV	1.04	1.06
Total	1.54	1.51

- Extension of calculation at N2LO $\rightarrow \chi^2 = 1.51$

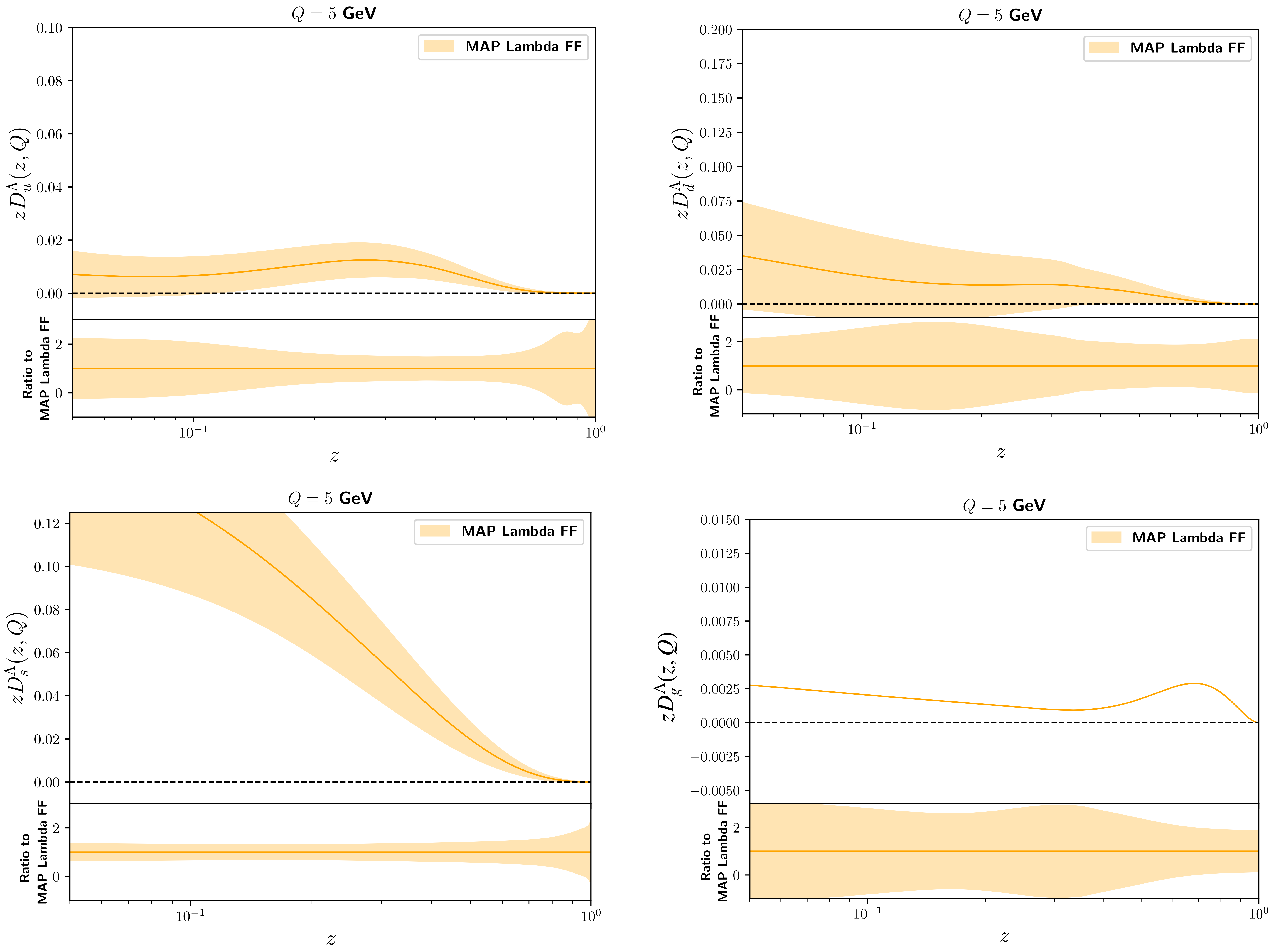
- SIA only, symmetric parameterisation $\rightarrow \chi^2 = 1.42$

$$D^{\Lambda}_{u^+}, \quad D^{\Lambda}_{d^+}, \quad D^{\Lambda}_{s^+}, \quad D^{\Lambda}_{c^+}, \quad D^{\Lambda}_{b^+}, \quad D^{\Lambda}_{g}$$

RESULTS

FFS

N2LO

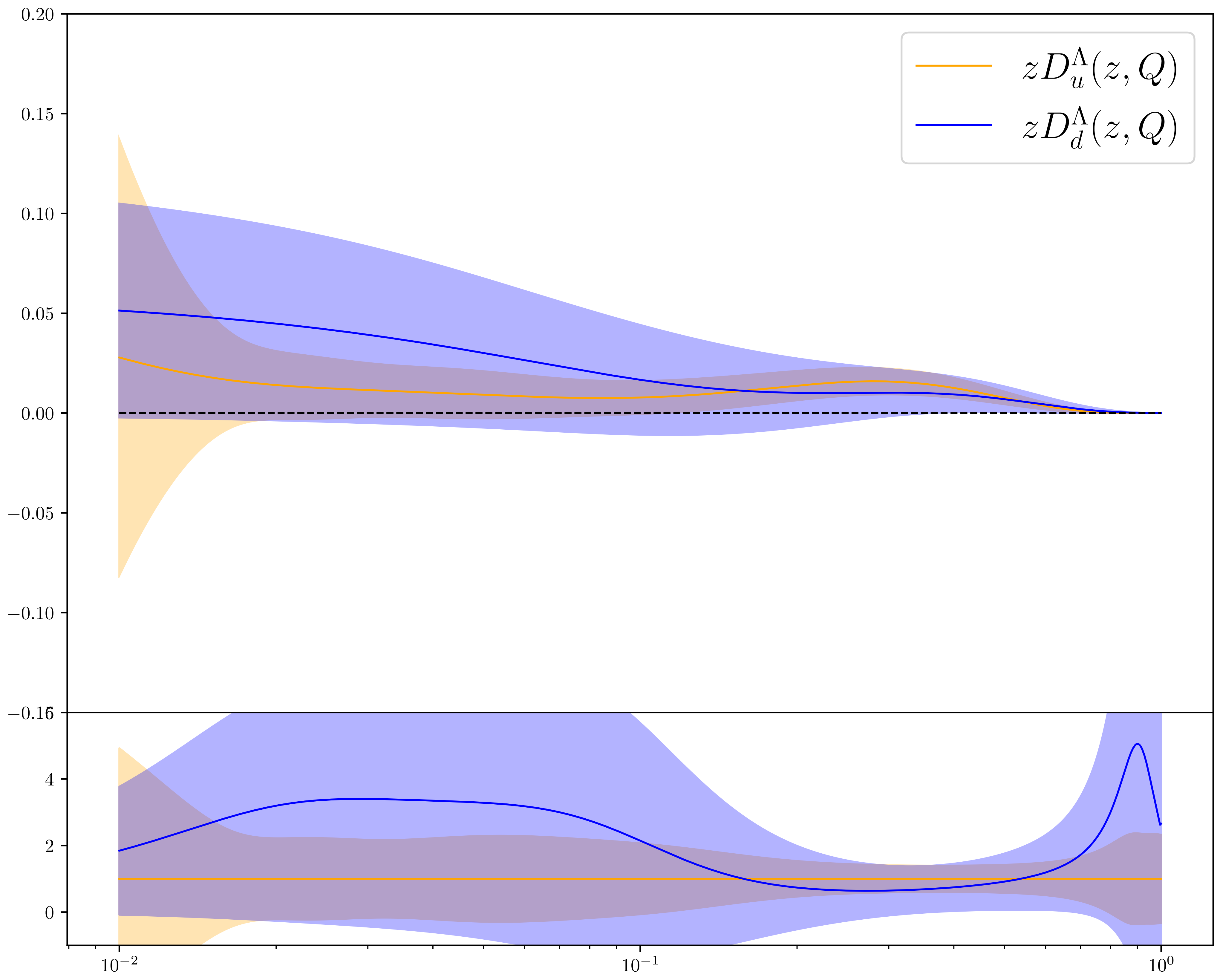


D_s^Λ dominates!

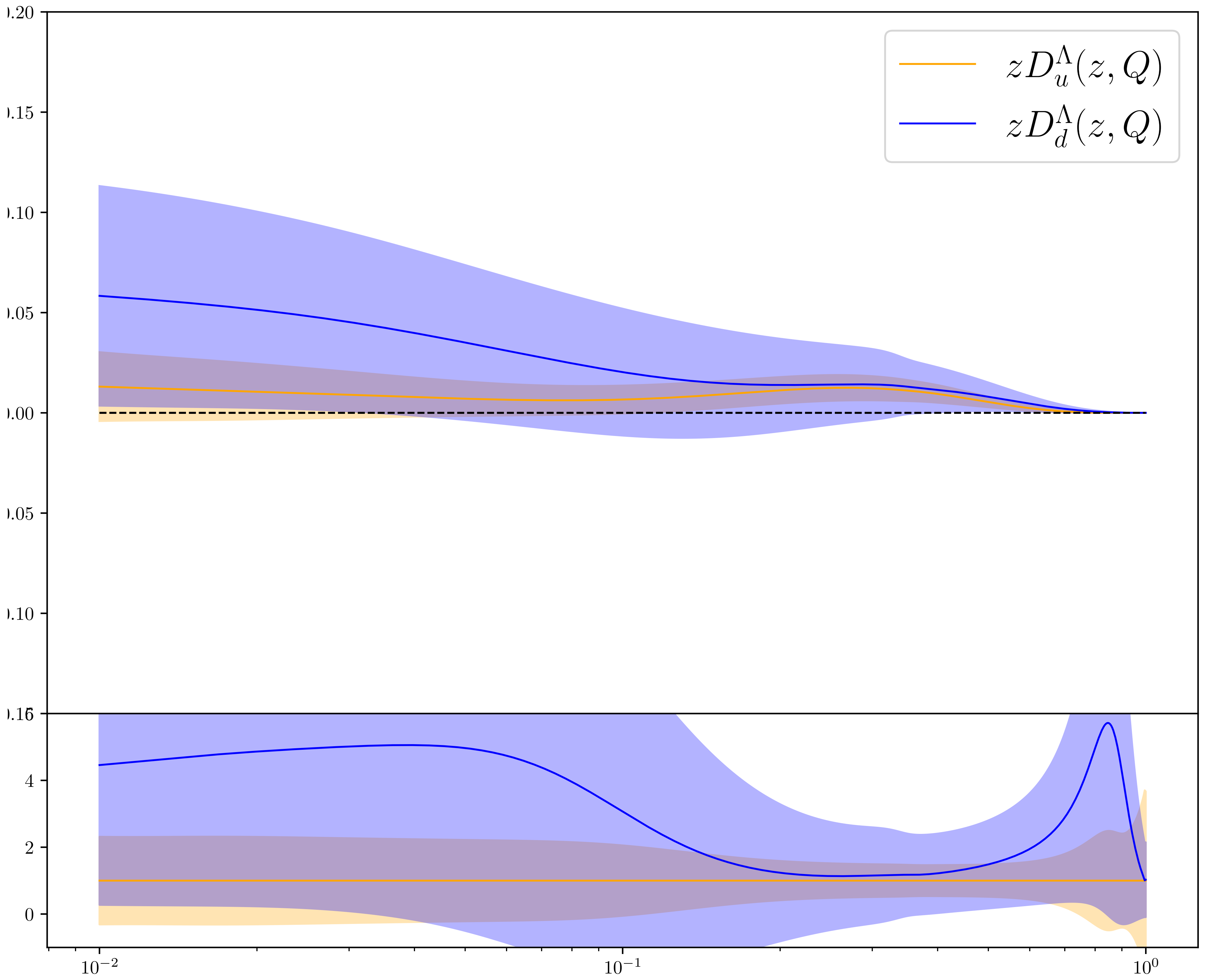
RESULTS

D_u^Λ vs D_d^Λ

NLO



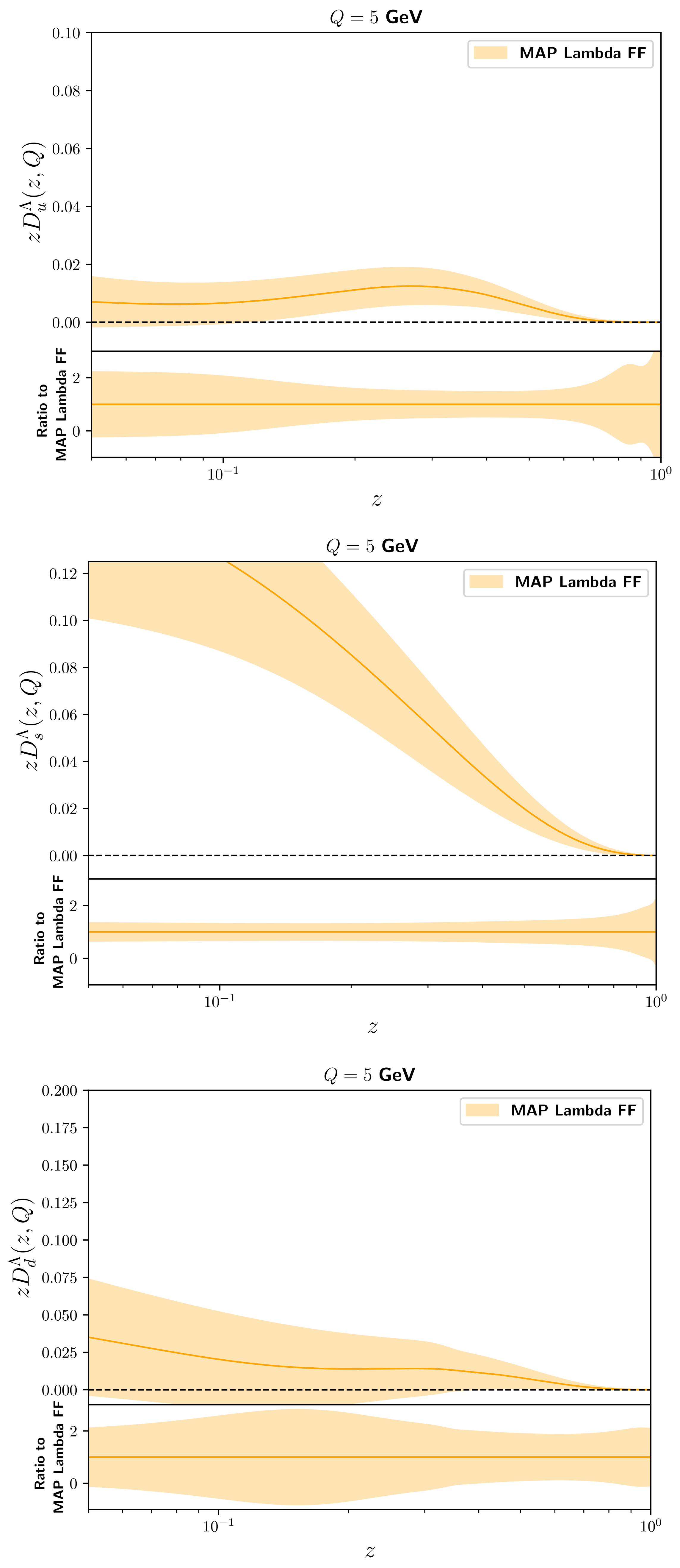
N2LO

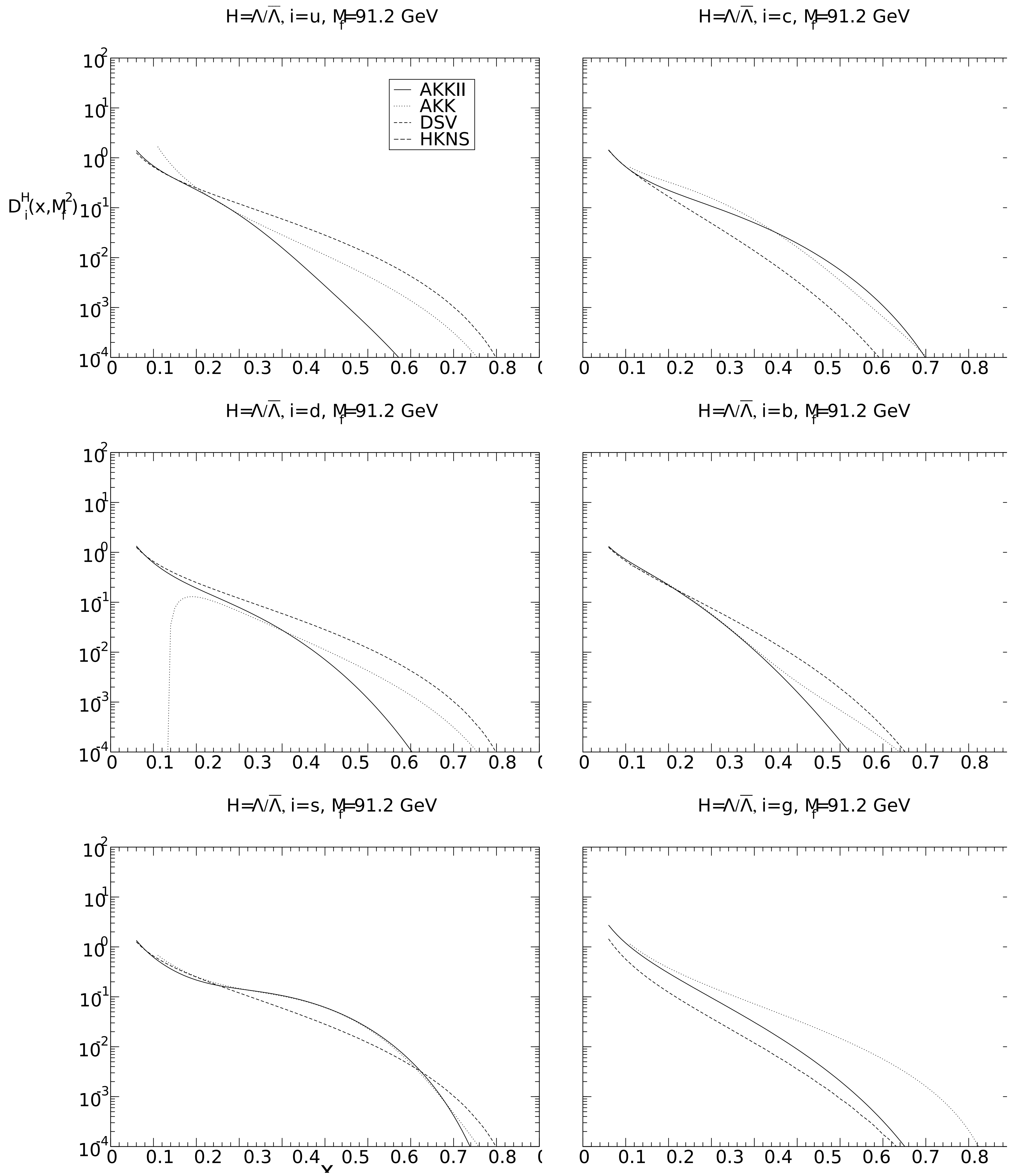


Compatible!

RESULTS

Comparison with DSV & AKK





AKK2008

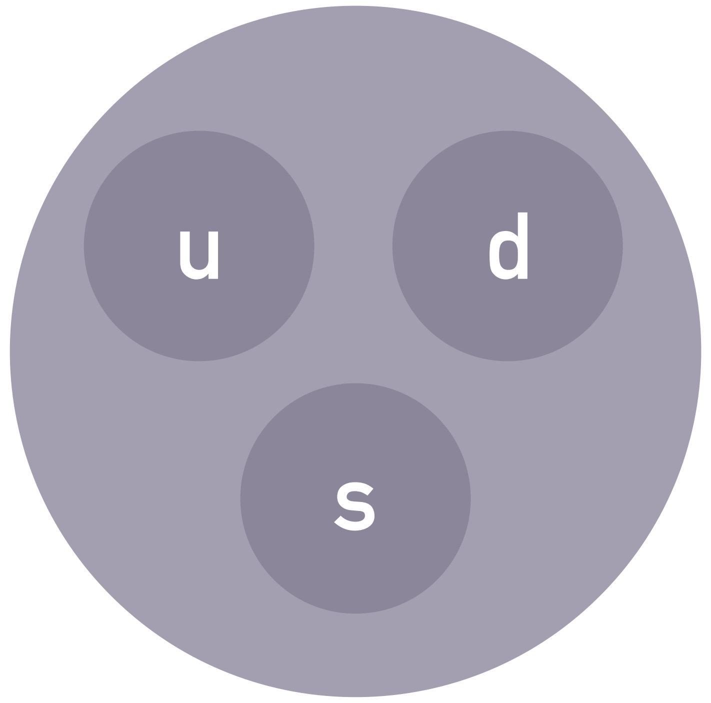
CONCLUSIONS

RECAP: New steps towards a better comprehension of the Λ baryon production in fragmentation

- Determination of Λ unpolarized collinear fragmentation function from SIA and SIDIS NC data by means of Neural Network and Monte Carlo sampling method as statistical framework at NLO and N2LO
- χ^2=1.51 at N2LO obtained requiring 7 independent flavours

Next steps:

- Extend dataset to CC SIDIS and pp collisions
- Include target and hadron mass corrections for SIDIS
- Try new flavour combinations (such as requiring isospin symmetry)
- Improve kinematic constraints in the analysis



IWHSS & QCD-N 2025

01-05th Sep, 2025
San Sebastián, Spain

Joint International Workshop on Hadron Structure and Spectroscopy (IWHSS 2025) and the QCD Structure of the Nucleon (QCD-N'25)

01–05 set 2025
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Inserisci il termine di r

- Sintesi
- Call for abstract
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- Committees

Contact
iwhss-qcdn-202…

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Inizio 1 set 2025, 08:30
Finisce 5 set 2025, 17:00
Europe/Zurich

Centro Carlos Santamaría

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Vai alla mappa

The five day long joint "*21st International Workshop on Hadron Structure and Spectroscopy*" and 6th workshop on the "*QCD Structure of the Nucleon*" (IWHSS-QCD-N'25) will be held in San Sebastián, Spain, from September 1 to 5, 2025.

The joint workshop is a collaborative effort between the IWHSS and QCD-N workshop series, with the organizational oversight being handled by the HERMES, COMPASS, and JLab communities.
The IWHSS series comprises 21 editions of annual workshops organized by COMPASS Collaboration on Hadron Structure and Spectroscopy, with most recent editions being the IWHSS-CPHI-2024 (Yerevan, Armenia), IWHSS-2023 (Prague, Czechia) and IWHSS-2022 (CERN, Switzerland).
The prior editions of the QCD-N meetings, organized by HERMES Collaboration, were convened in the following locations: Alcalá de Henares (2021), Getxo (2016), Bilbao(2012), Frascati (2006) and Ferrara (2002).

A designated session of the workshop will be allocated for the celebration of the **30th anniversary of HERMES data taking**.

The joint workshop will be preceded by the COMPASS Collaboration meeting on September 1 (morning).

https://indico.cern.ch/event/1527657/