State-Driven Fragmentation of All-Heavy and Hidden-Heavy Tetraquarks

Francesco Giovanni Celiberto, UAH Madrid

NSTAR 2026

🇪🇸 Sevilla - 08/09/2026 🇪🇸

[Phys. Rev. D Letters 111 (2025) 11, L111501 [arXiv:2504.03949]] 🔗
[Phys. Rev. D 113 (2026) 5, 054014 [arXiv:2511.18984]] 🔗
[Phys. Rev. D 113 (2026) 11, 114037 [arXiv:2604.11646]] 🔗
+ Work in Progress [TQHL2.0]

Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

EUGLOH

QCD Hydrogen Atoms

I

¿ Why studying (Heavy) Exotics ?

JETHAD
v0.5.5

Precision & Exploration

¿ What is an Exotic Hadron ?

- Baryons & Mesons → composite states → $|q_1 q_2 q_3\rangle$ & $|q_1 \bar{q}_2\rangle$
- Ordinary Hadrons ← simplest valence-quark color-singlet states
- QCD color neutrality → TetraQuarks, PentaQuarks, Hybrids allowed

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- First discovery of a (crypto-)exotic at Belle (🇯🇵) in 2003 → $X(3872)$

[Today's overview talk by Q. Wang 🔗; talks by Y. Yamaguchi 🔗 and A. Carducci 🔗]

Interpretation of Exotic States

Compact MultiQuark

Interpretation of Exotic States

Compact MultiQuark

Hybrid

Interpretation of Exotic States

diQuark + AntidiQuark

Compact MultiQuark

Hybrid

Interpretation of Exotic States

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Compact MultiQuark

Hybrid

Molecule of Mesons

Interpretation of Exotic States

Compact MultiQuark

diQuark + AntidiQuark

HadroQuarkonium

Hybrid

Molecule of Mesons

All-Charm TetraQuarks: Experimental Highlights

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2025-118
2025/06/10

CMS-BPH-24-002

Determination of the spin and parity of all-charm tetraquarks

The CMS Collaboration*

arXiv:2506.07944v1 [hep-ex] 9 Jun 2025

Abstract

The traditional quark model accounts for the existence of baryons, such as protons and neutrons, which consist of three quarks, as well as mesons, composed of a quark-antiquark pair. Only recently has substantial evidence started to accumulate for exotic states composed of four or five quarks and antiquarks. The exact nature of their internal structure remains uncertain. This paper reports the first measurement of quantum numbers of the recently discovered family of three all-charm tetraquarks, using data collected by the CMS experiment at the Large Hadron Collider from 2016 to 2018. The angular analysis techniques developed for the discovery and characterization of the Higgs boson have been applied to the new exotic states. The quantum numbers for parity P and charge conjugation C symmetries are found to be $+1$. The spin J of these exotic states is consistent with $2\hbar$, while $0\hbar$ and $1\hbar$ are excluded at 95% and 99% confidence level, respectively. The $J^{PC} = 2^{++}$ assignment implies particular configurations of constituent spins and orbital angular momenta, which constrain the possible internal structure of these tetraquarks.

Submitted to Nature

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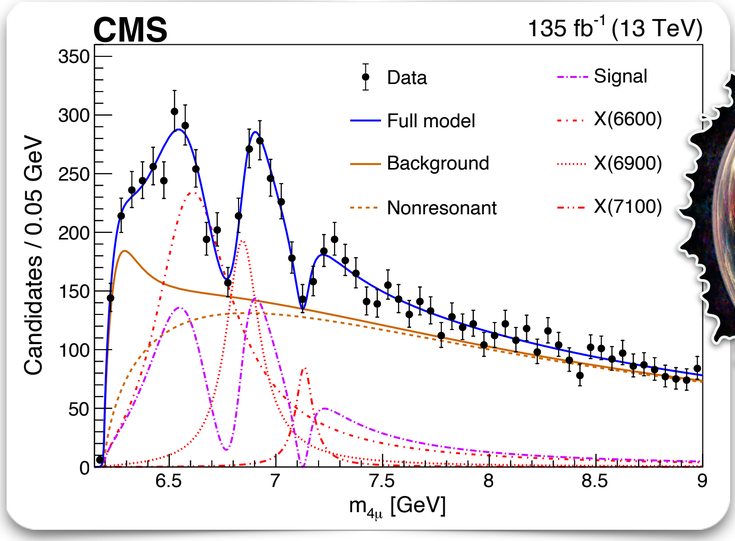

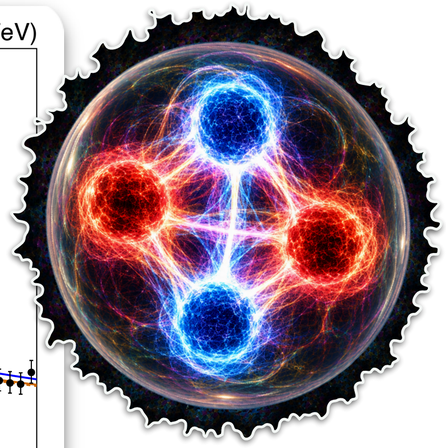

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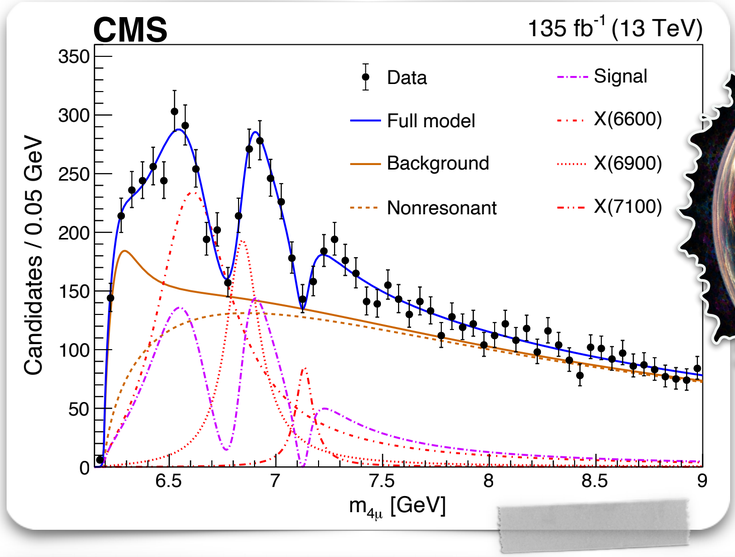

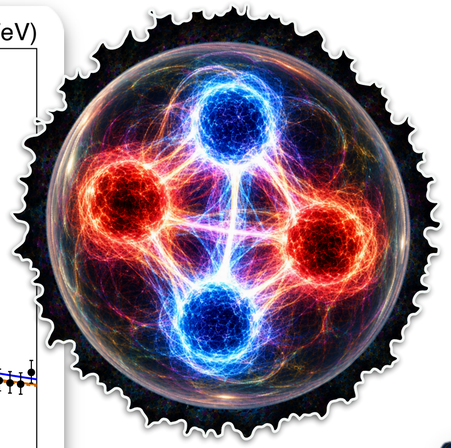

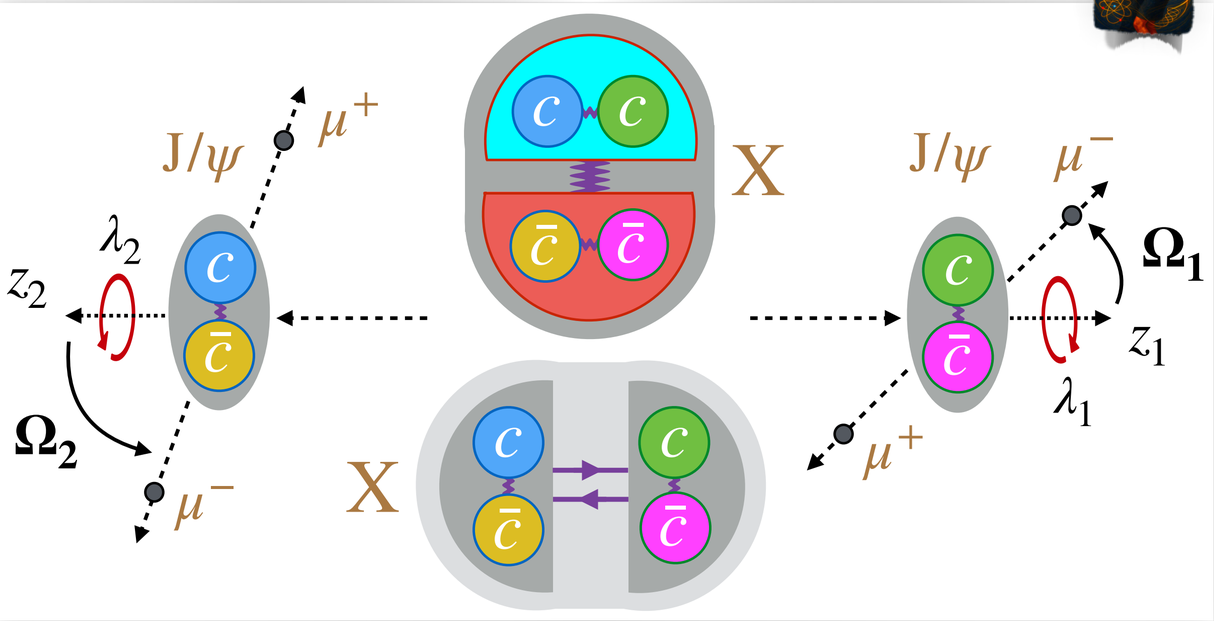

All-Charm TetraQuarks: Experimental Highlights

Article

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https://doi.org/10.1038/s41586-025-09711-7

Received: 9 June 2025

Accepted: 6 October 2025

Published online: 3 December 2025

Open access

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The traditional quark model[1,2] accounts for the existence of baryons, such as protons and neutrons, which consist of three quarks, as well as mesons, composed of a quark–antiquark pair. Only recently has substantial evidence started to accumulate for exotic states composed of four or five quarks and antiquarks[3]. The exact nature of their internal structure remains uncertain[4–29]. Here we report the first measurement of quantum numbers of the recently discovered family of three all-charm tetraquarks[30–32], using data collected by the CMS experiment at the Large Hadron Collider from 2016 to 2018 (refs. 33,34). The angular analysis techniques developed for the discovery and characterization of the Higgs boson[35–37] have been applied to the new exotic states. Here we show that the quantum numbers for parity P and charge conjugation C symmetries are found to be +1. The spin J of these exotic states is determined to be consistent with $2\hbar$, while $0\hbar$ and $1\hbar$ are excluded at 95% and 99% confidence levels, respectively. The $J^{PC} = 2^{++}$ assignment implies particular configurations of constituent spins and orbital angular momenta, which constrain the possible internal structure of these tetraquarks.

¿ Why Fragmentation is so relevant ?

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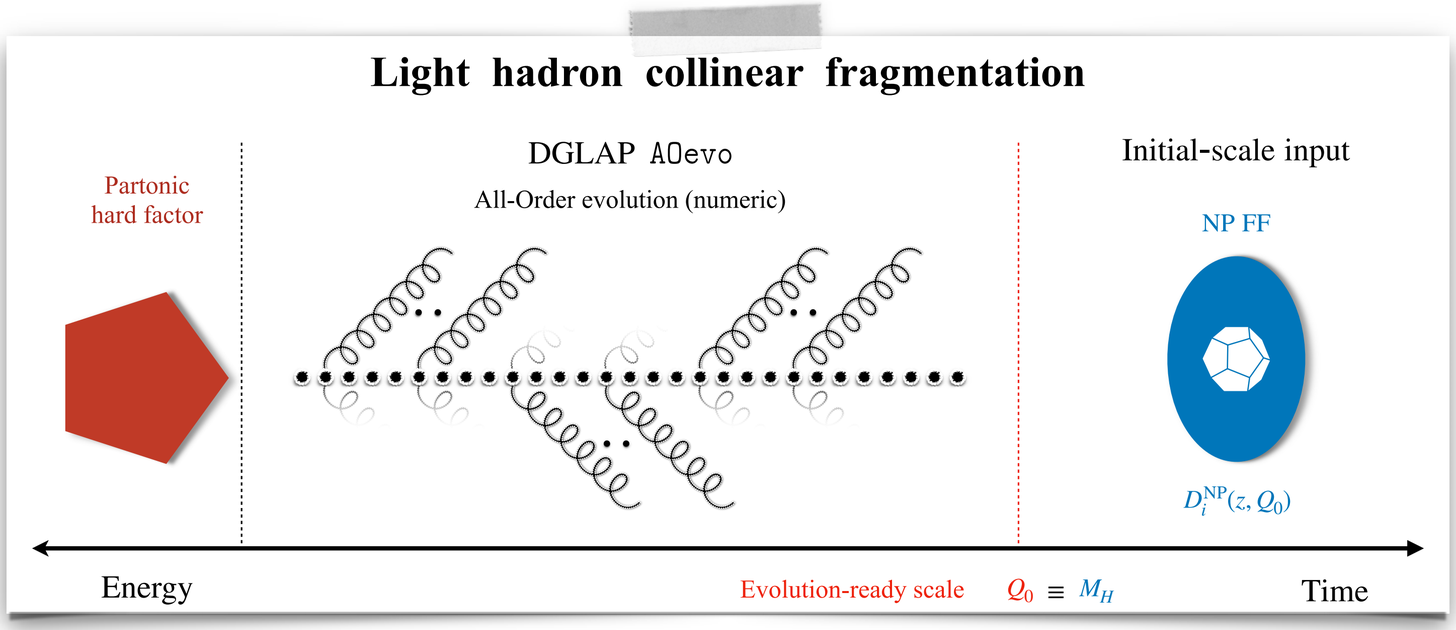
Fragmentation in QCD (with Heavy Flavors)

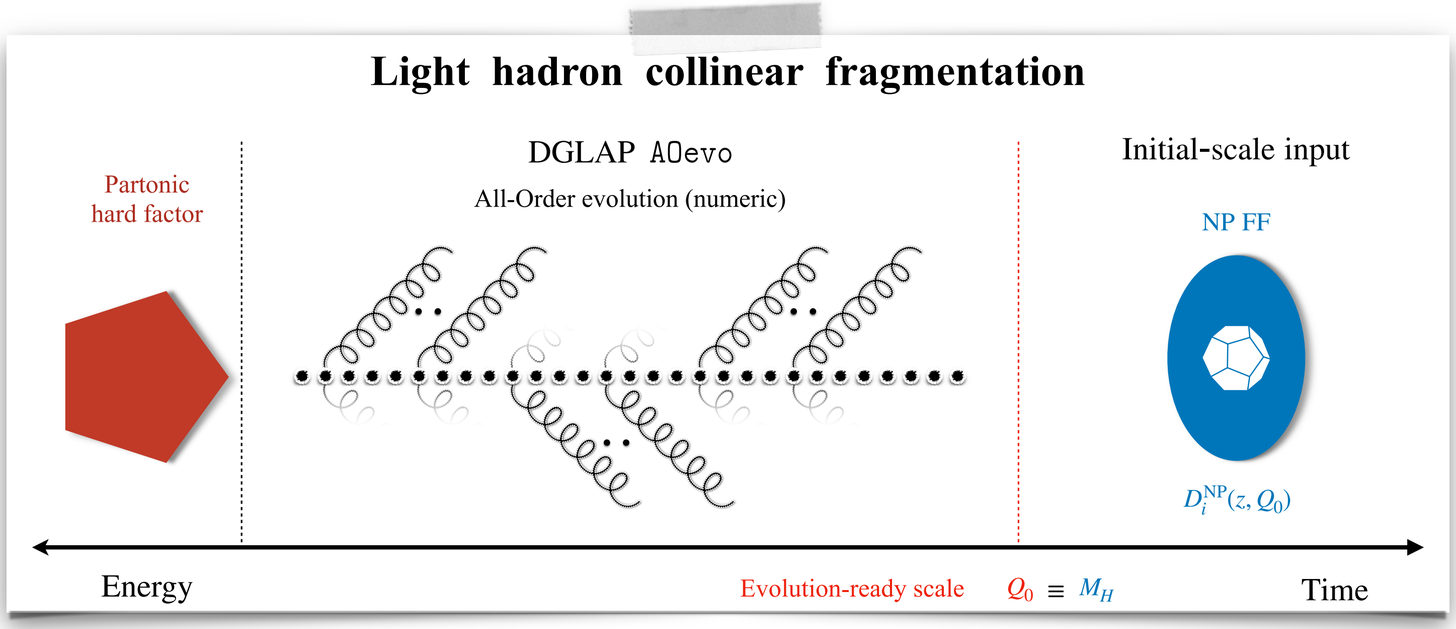
PRECISION CONTROL

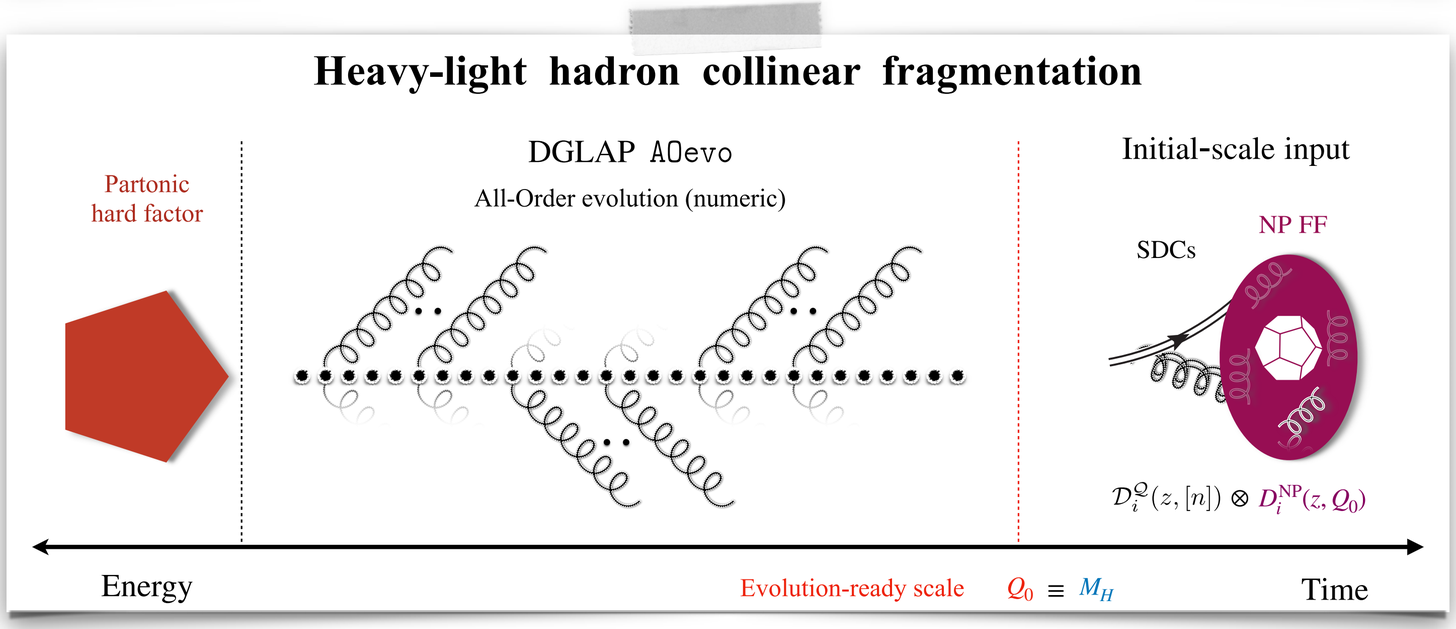


DISCOVERY POTENTIAL

Fragmentation in QCD (with Heavy Flavors)

PRECISION CONTROL





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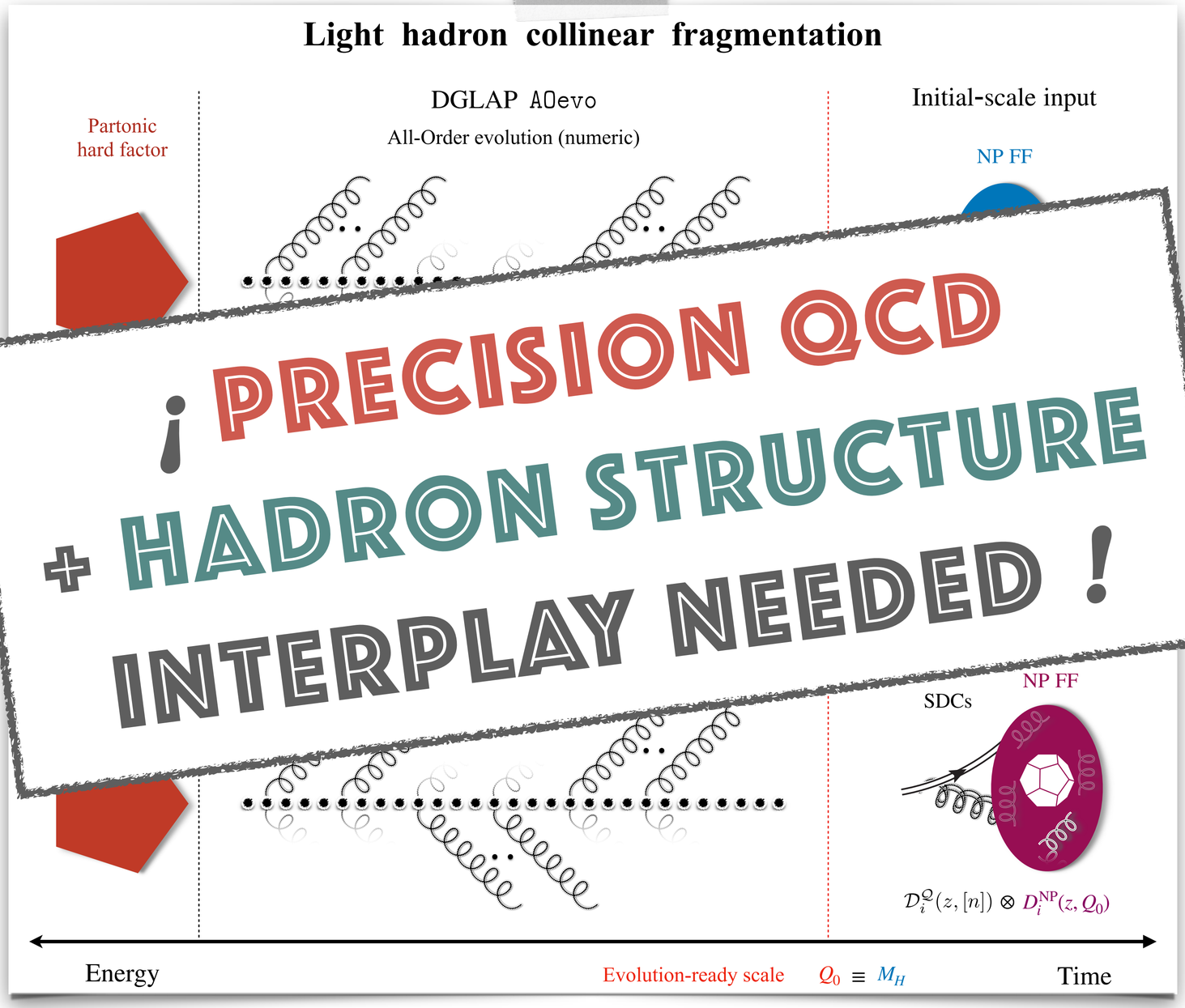

¡ PRECISION QCD
+ HADRON STRUCTURE
INTERPLAY NEEDED !

DISCOVERY POTENTIAL

1

Hidden-Heavy TetraQ MultiModal Fragmentation

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TQHL2.0: Toward a State-Driven Fragmentation

Table 1: Scalar (0^{++}) hidden-heavy-flavor tetraquark candidates considered as representative case studies within the multimodal TQHL2.0 fragmentation framework. Masses are quoted as central values with uncertainties in parentheses. Inline references indicate key experimental observations and phenomenological interpretations relevant to each state.

State	Mass [MeV]	Status	Leading Fock	Comments
$X(3860)$	3862(44)	Candidate	$\lvert c\bar{c}\, q\bar{q}\rangle$	Non-strange 0^{++} candidate close to the $D\bar{D}$ threshold [1]. Useful as a controlled test case for assessing $[u \leftrightarrow d]$ quark mixing effects in hidden-heavy tetraquarks, with $q = u, d$.
$X(3960)$	3960(40)	Observed	$\lvert c\bar{c}\, s\bar{s}\rangle$	Observed in the $D_s^+ D_s^-$ channel by LHCb [2, 3]. Its flavor structure is clean, with no $[u \leftrightarrow d]$ quark mixing. Compatible with both compact [4] and molecular [5] interpretations.
$X_b(s)$	10 700(100)	Hypothetical	$\lvert b\bar{b}\, s\bar{s}\rangle$	Bottom counterpart of $X(3960)$ with clean heavy–strange content. Predicted in several tetraquark models [6–8]. Additional constraints may arise from studies of $X_0(4140)$ [9].

[F. G. C., in preparation]

MultiModal Fragmentation to TetraQuarks

Mode 1

Direct MultiQuark

Scalar S-wave *X*

TQHL1.0 (All-charm) 🔗 [F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406, arXiv:2308.01539]

TQHL1.0 (All-bottom, Best Paper Award) 🔗 [F. G. C., Symmetry 16 (2024) 5, 550, arXiv:2403.15639]

TQHL1.1 (All-heavy) 🔗 [F. G. C., G. Gatto, Phys. Rev. D. 111 (2025) 3, 034037, arXiv:2412.10549]

TQHL2.0 (All-heavy, physical states, uncertainties) [F. G. C., in preparation]

MultiModal Fragmentation to TetraQuarks

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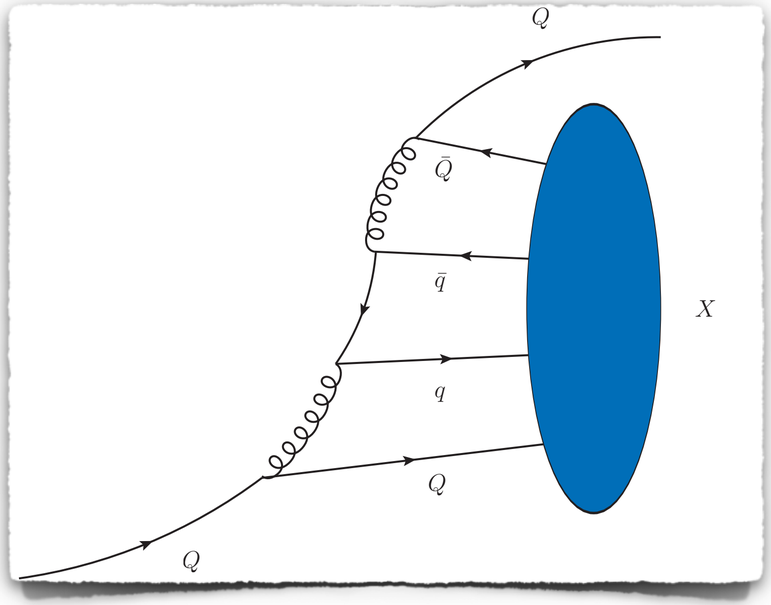

Initial-scale input: 🔗🔗 Suzuki model

TQHL2.0 FFs: $(Q \to X) \otimes$ **APFEL++**

F-MHOUs [P] + F-NPWF [NP]

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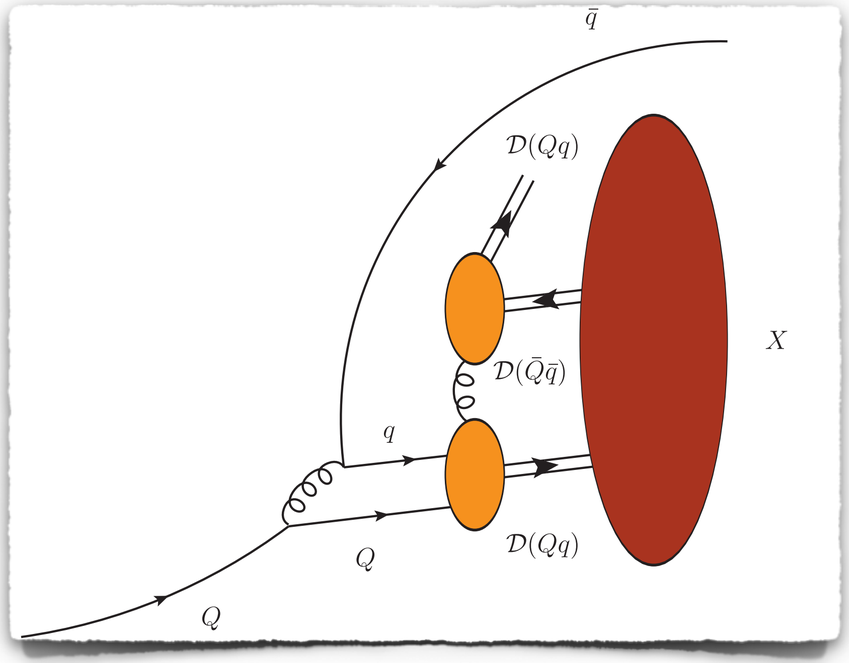
MultiModal Fragmentation to TetraQuarks

Mode 2
Scalar DiQuark
Scalar S-wave *X*



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TQHL2.0 (Hidden-heavy, physical states, uncertainties) [F. G. C., in preparation]

1

TQHL2.0_cs_nlo

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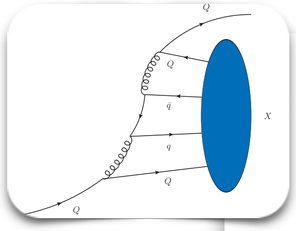
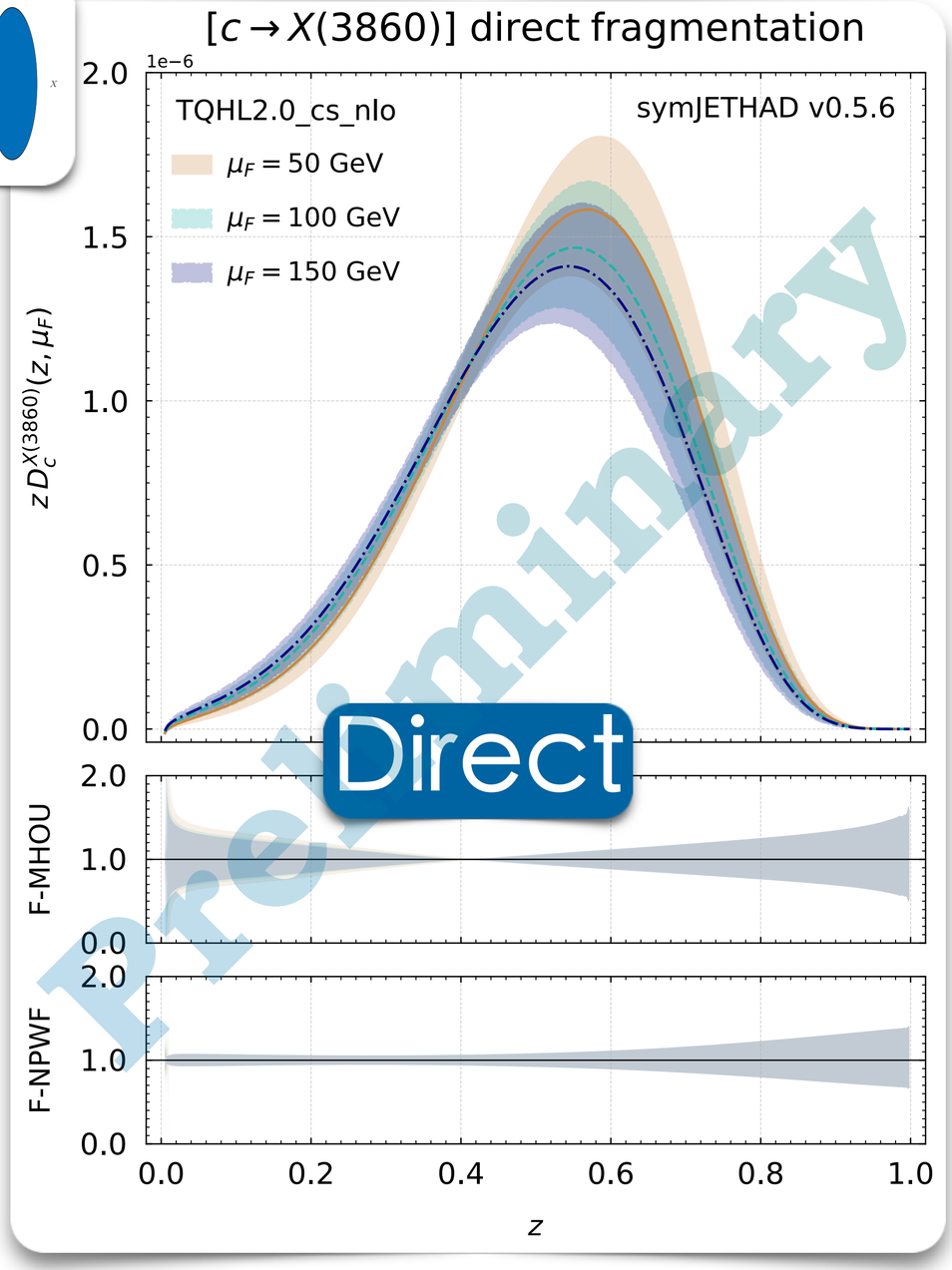
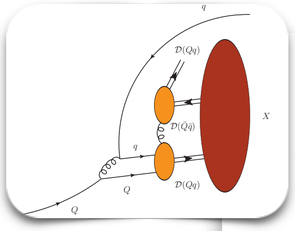
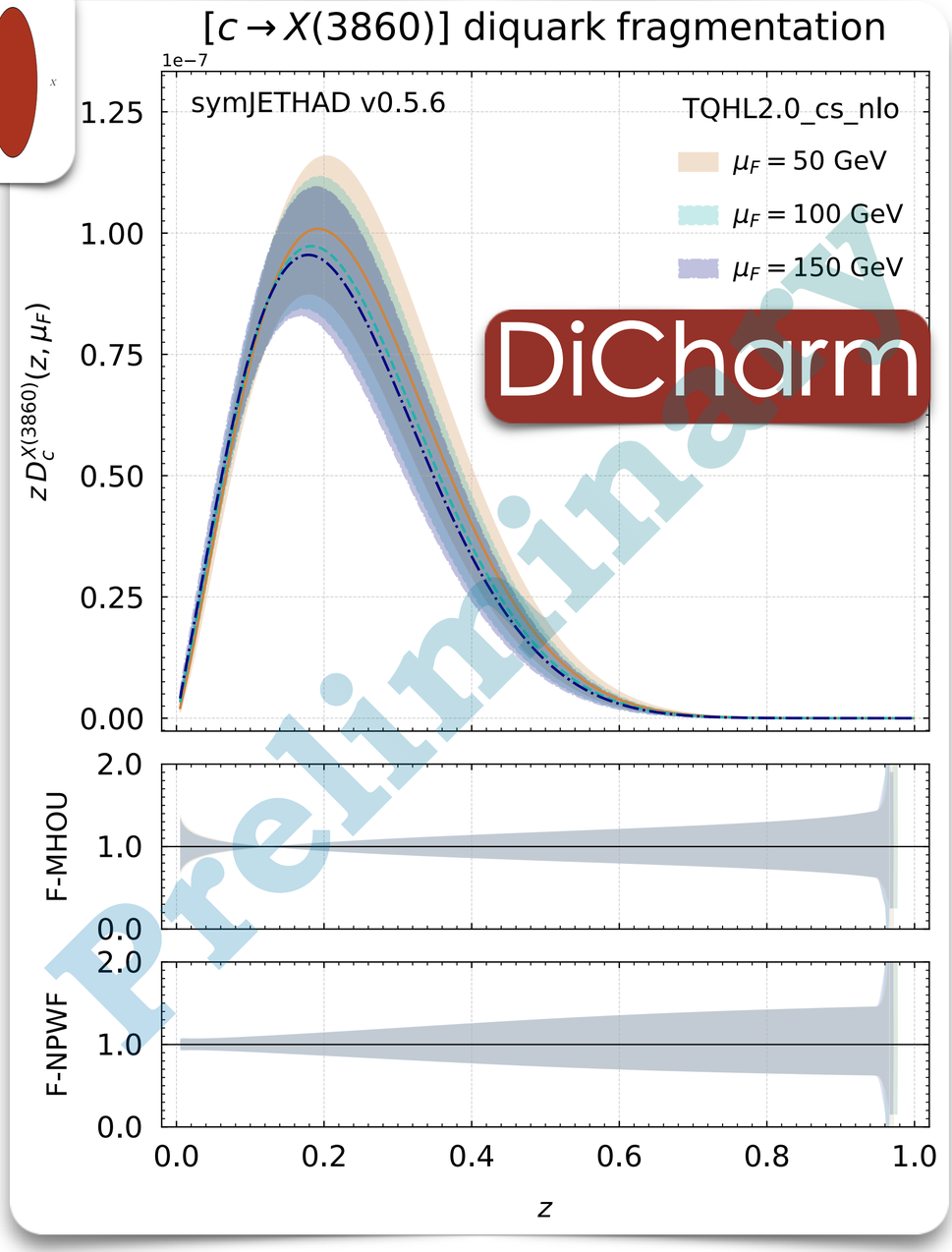
TQHL2.0: Charm Fragmentation to X(3860)

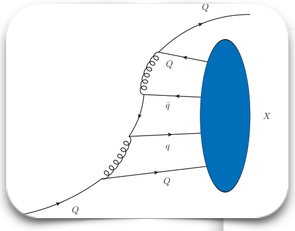


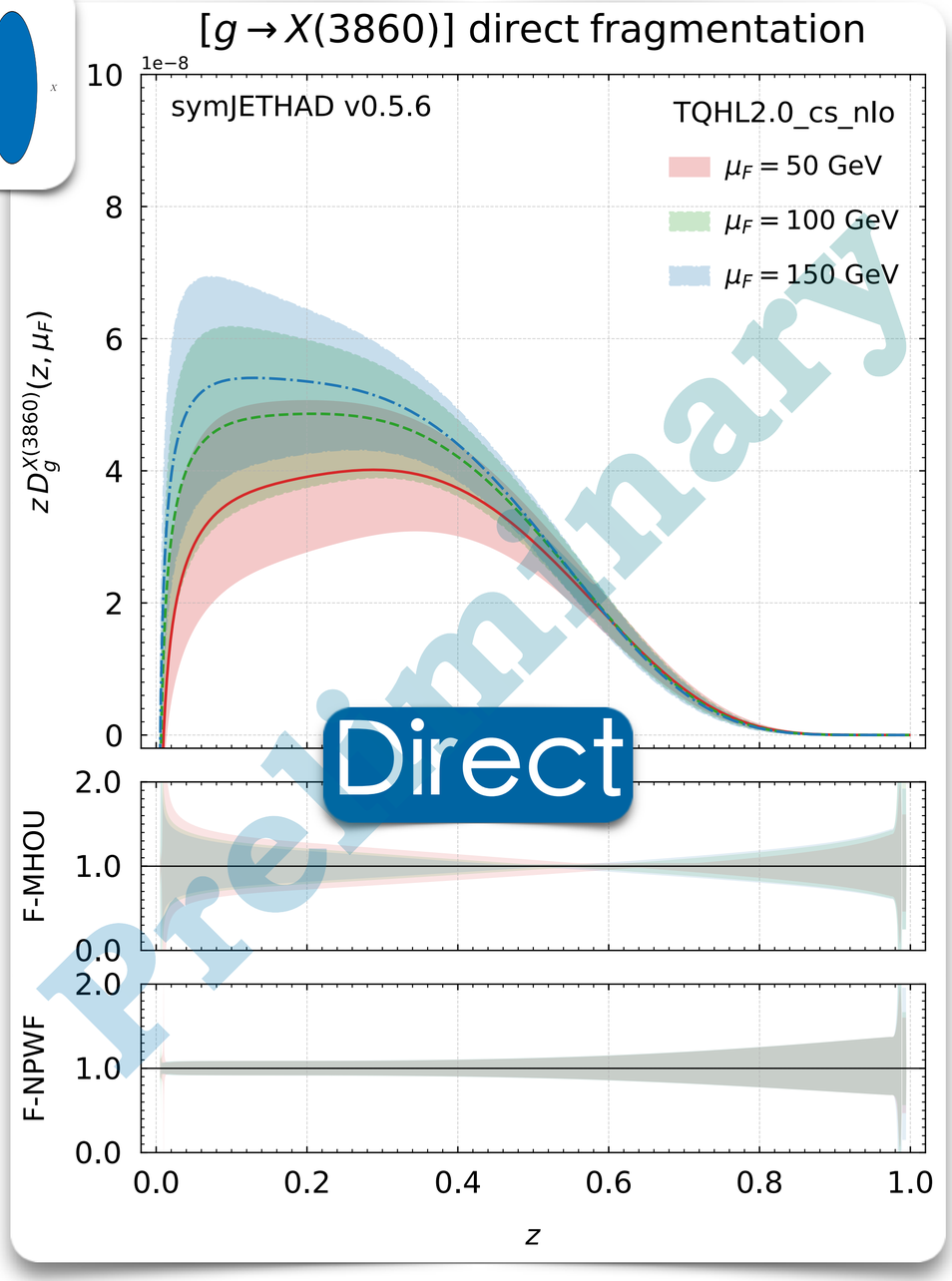


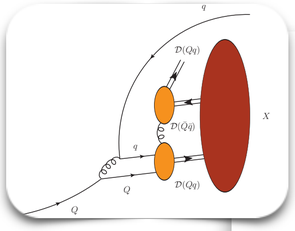


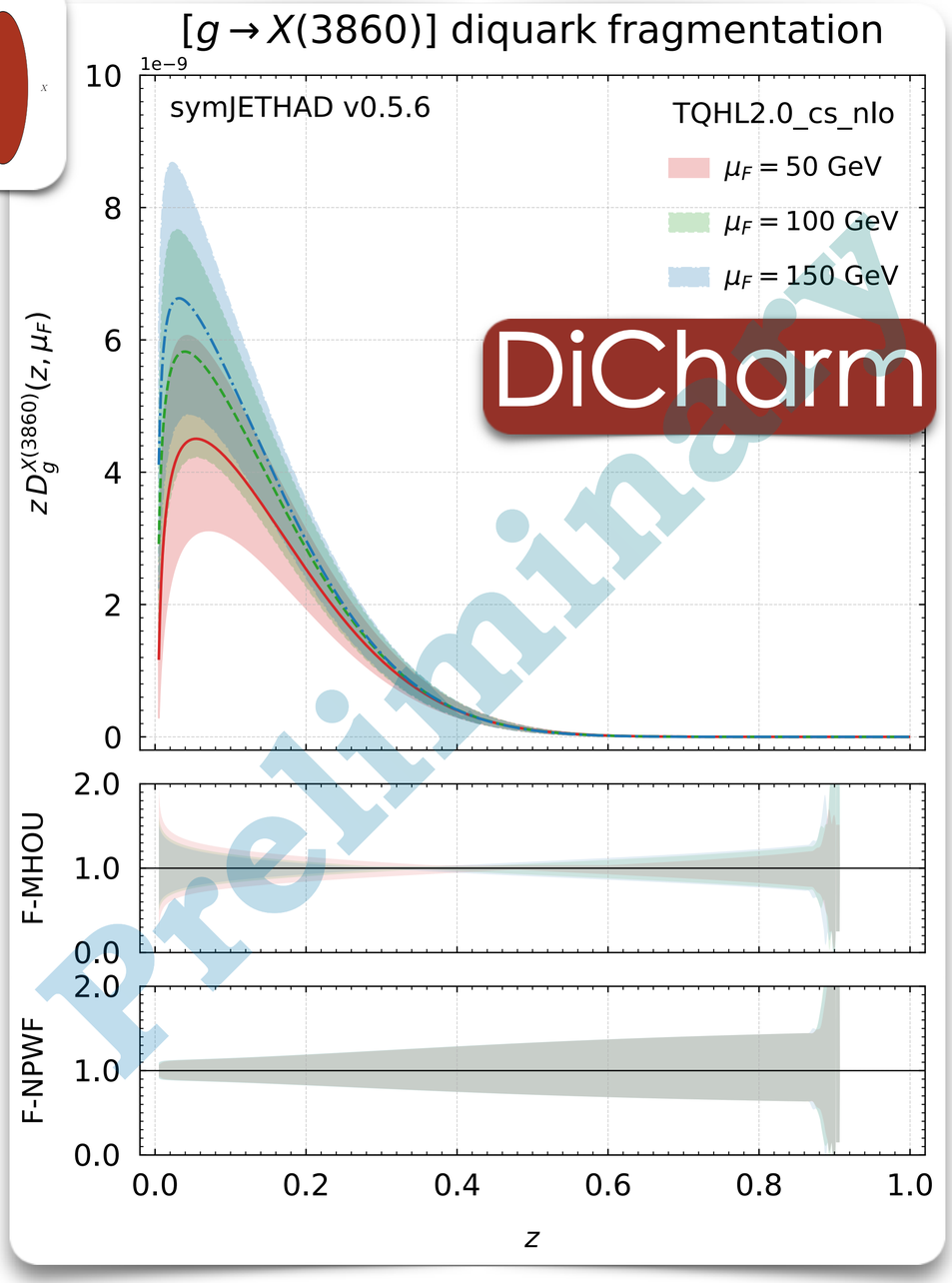


TQHL2.0: Gluon Fragmentation to X(3860)









2

All-Heavy-TetraQ NonRelativistic Fragmentation

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Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

Guiding principle ⇒ ¡ Use the Best of the Two Worlds as much as we can !

Interpretation

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

PRECISION QCD

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Guiding principle ⇒ ¡ Use the Best of the Two Worlds as much as we can !

Interpretation

Evolution

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

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COLLINEAR FACTORIZATION

Guiding principle ⇒ ¡ Use the Best of the Two Worlds as much as we can !

Interpretation

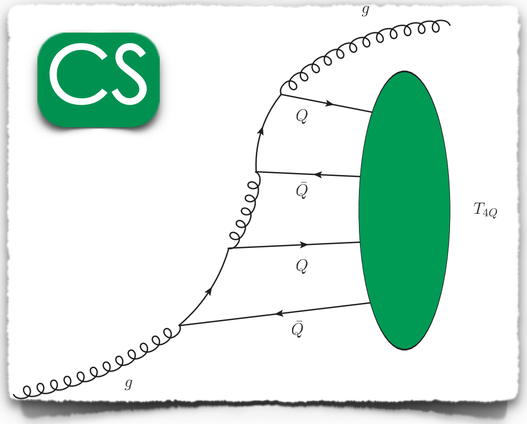
Evolution

Uncertainties

TetraQuark Fragmentation from NRQCD & symJETHAD

LO

Gluon

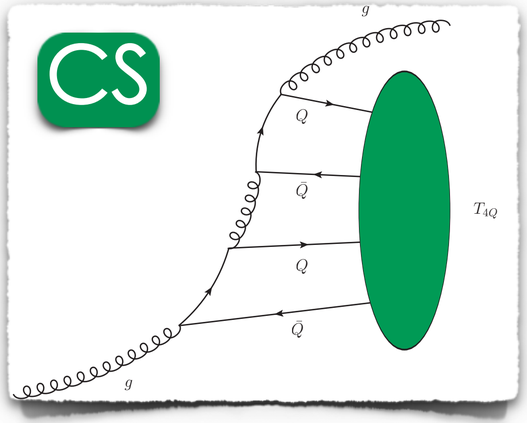


[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]

TetraQuark Fragmentation from NRQCD & symJETHAD

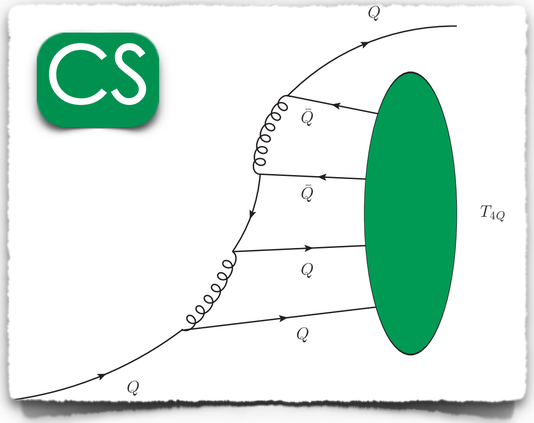
LO

Gluon



[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]

Constituent heavy quark



[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002

TetraQuark Fragmentation from NRQCD & symJETHAD

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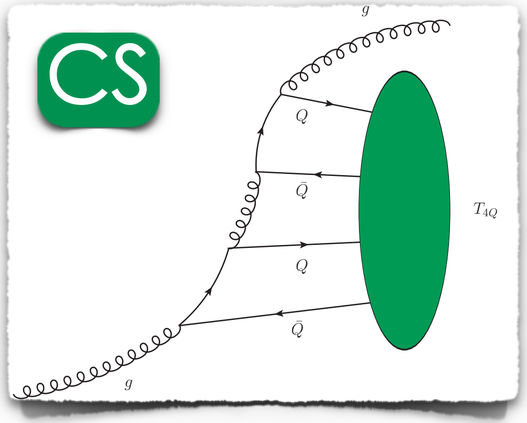
Gluon



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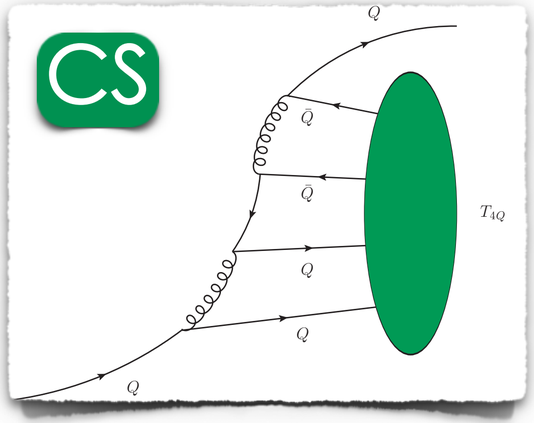
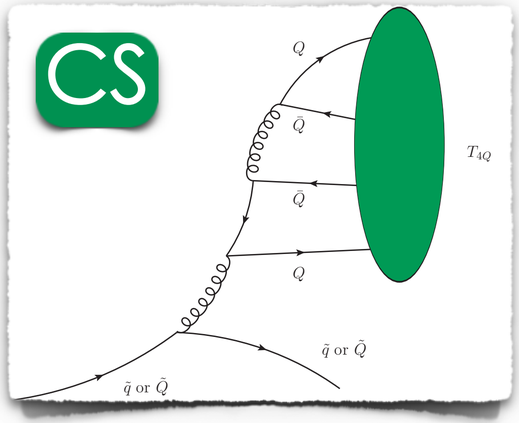


[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002

Non-constituent heavy or light quark



[X.-W. Bai, Y. Huang et al., Phys. Rev. D 111 (2025) 5, 054006]

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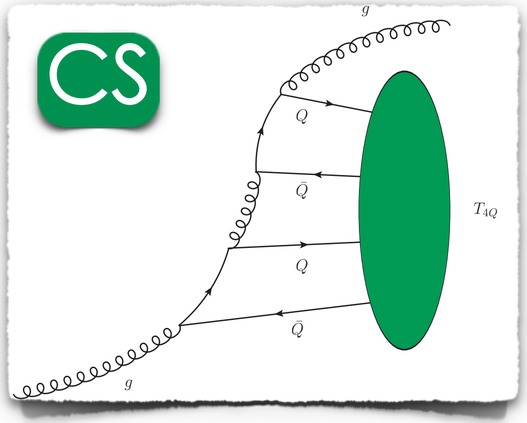
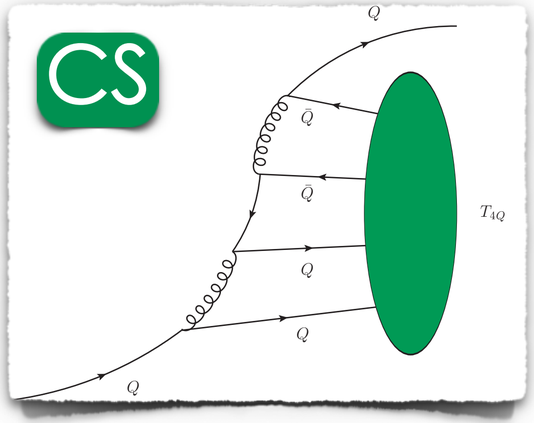


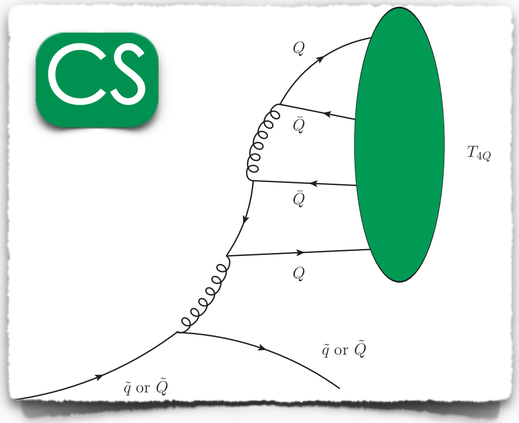
[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]

Constituent heavy quark



[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002

Non-constituent heavy or light quark



[X.-W. Bai, Y. Huang et al., Phys. Rev. D 111 (2025) 5, 054006]

$J^{PC} = 0^{++}$

$J^{PC} = 1^{+-}$

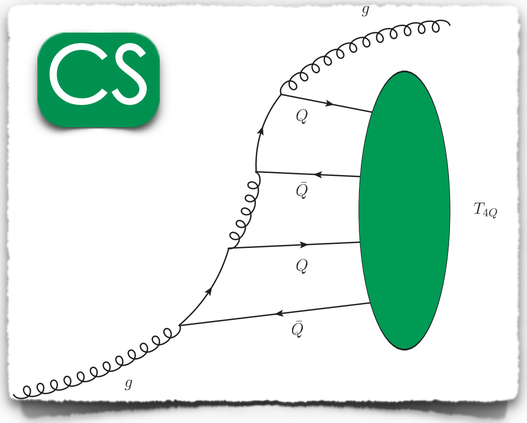
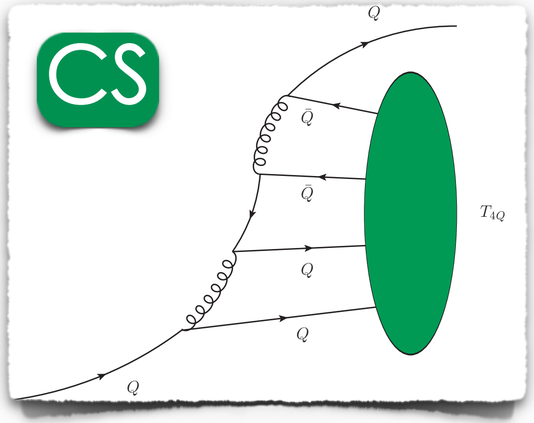
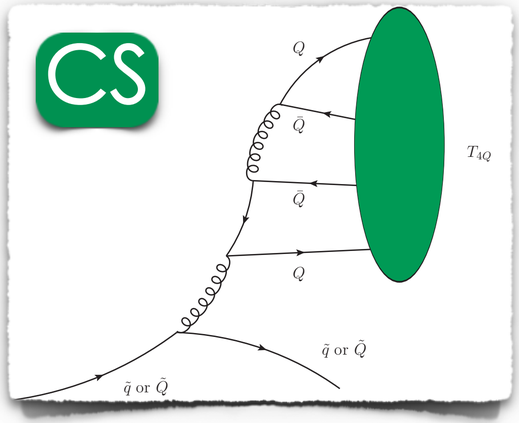
$J^{PC} = 2^{++}$

TetraQuark Fragmentation from NRQCD & symJETHAD

LO

2024

TQ4Q1.0

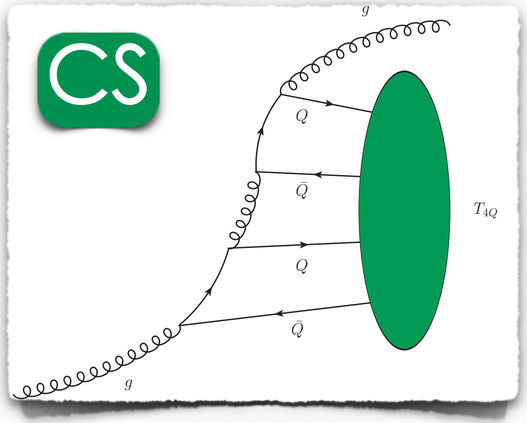
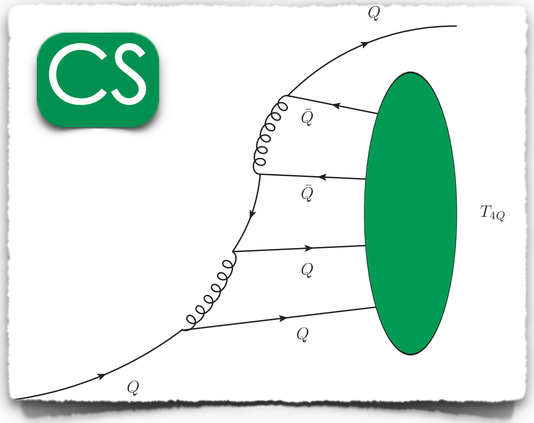
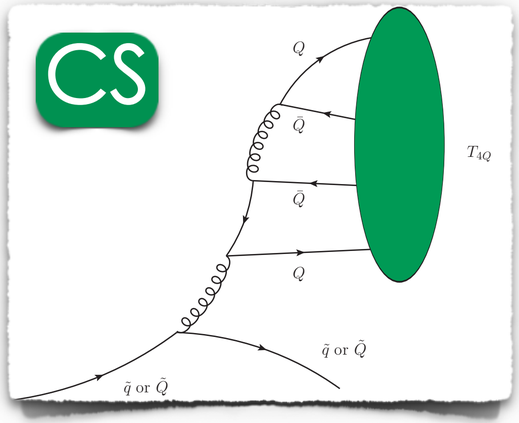
Gluon	Constituent heavy quark	Non-constituent heavy or light quark
		
[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]	[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002	[X.-W. Bai, Y. Huang et al., Phys. Rev. D 111 (2025) 5, 054006]
$J^{PC} = 0^{++}$ TQ4Q1.0+ ✓	¡! Suzuki [TQ4Q1.0]	¡! Not implemented
$J^{PC} = 1^{+-}$ Landau-Yang LO: evolution only ✗	¡! Not implemented	C-parity LO: evolution only ✗
$J^{PC} = 2^{++}$ TQ4Q1.0+ ✓	¡! Suzuki [TQ4Q1.0]	¡! Not implemented

TetraQuark Fragmentation from NRQCD & symJETHAD

LO

2024 → 2025

TQ4Q1.1

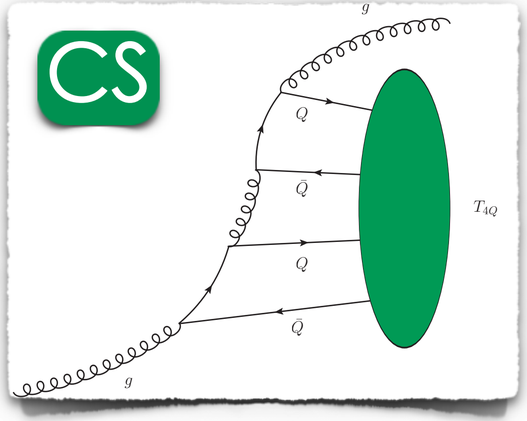
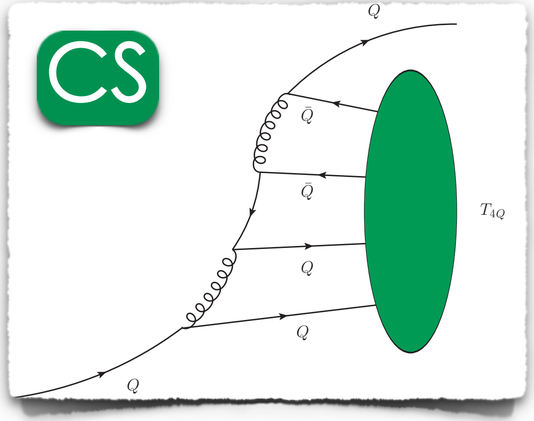
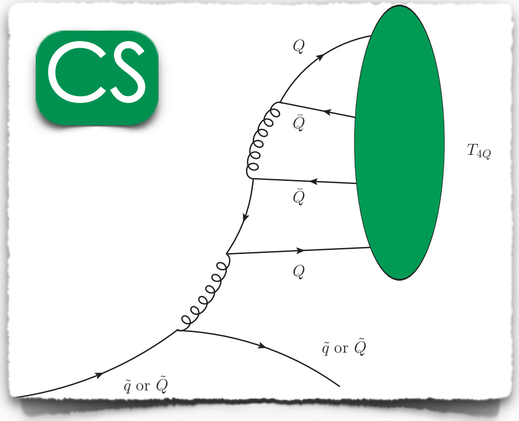
	Gluon	Constituent heavy quark	Non-constituent heavy or light quark
			
	[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]	[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002	[X.-W. Bai, Y. Huang et al., Phys. Rev. D 111 (2025) 5, 054006]
$J^{PC} = 0^{++}$	TQ4Q1.0+ ✓	TQ4Q1.1+ ✓	¡! Not implemented
$J^{PC} = 1^{+-}$	Landau-Yang LO: evolution only ✗	TQ4Q1.1+ ✓	C-parity LO: evolution only ✗
$J^{PC} = 2^{++}$	TQ4Q1.0+ ✓	TQ4Q1.1+ ✓	¡! Not implemented

TetraQuark Fragmentation from NRQCD & symJETHAD

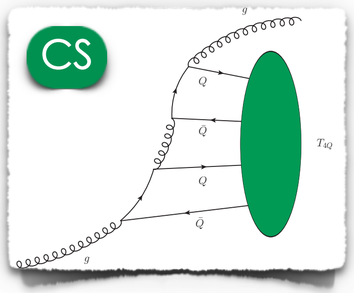
LO

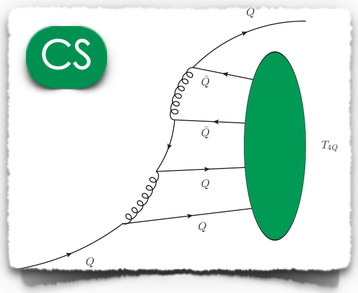
2024 → 2025 → 2026

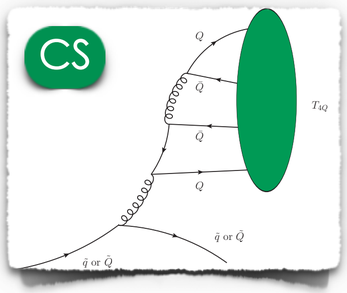
TQ4Q2.0

	Gluon	Constituent heavy quark	Non-constituent heavy or light quark
			
	[F. Feng, Y. Huang et al., Phys. Rev. D 106 (2022) 11, 114029]	[X.-W. Bai, F. Feng et al., JHEP 09 (2024) 002	[X.-W. Bai, Y. Huang et al., Phys. Rev. D 111 (2025) 5, 054006]
$J^{PC} = 0^{++}$	TQ4Q1.0+ ✓	TQ4Q1.1+ ✓	NEW TQ4Q2.0+ ✓
$J^{PC} = 1^{+-}$	Landau-Yang LO: evolution only ✗	TQ4Q1.1+ ✓	C-parity LO: evolution only ✗
$J^{PC} = 2^{++}$	TQ4Q1.0+ ✓	TQ4Q1.1+ ✓	NEW TQ4Q2.0+ ✓

HF-NRevo: Initial-Scale NRCQD Inputs







Scalar $[J^{PC} = 0^{++}]$

Tensor $[J^{PC} = 2^{++}]$

HF-NRevo for $T_{4c}(0^{++}, 2^{++})$ collinear fragmentation

Partonic hard factor

DGLAP AOevo

All-Order evolution (numeric)

DGLAP EDevo

Expanded Decoupled evolution

NRQCD

Color-composite LDMEs

SDCs

g

$\tilde{q}$

c

b

$4m_c$

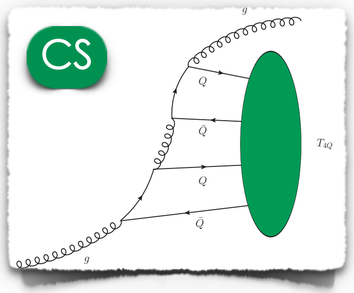
$\mathcal{D}_i^{\mathcal{Q}}(z, [n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

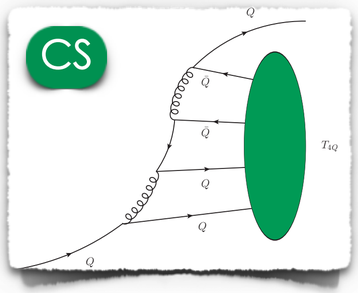
Energy

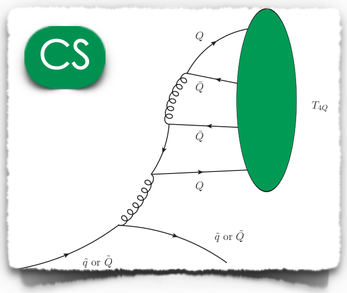
Evolution-ready scale $Q_0 \equiv m_b + 4m_c$ $5m_c$ $m_{\tilde{q}} + 4m_c$

Time

HF-NRevo: Initial-Scale NRCQD Inputs





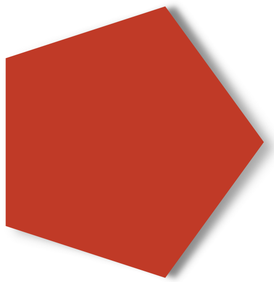


Scalar $[J^{PC} = 0^{++}]$

Tensor $[J^{PC} = 2^{++}]$

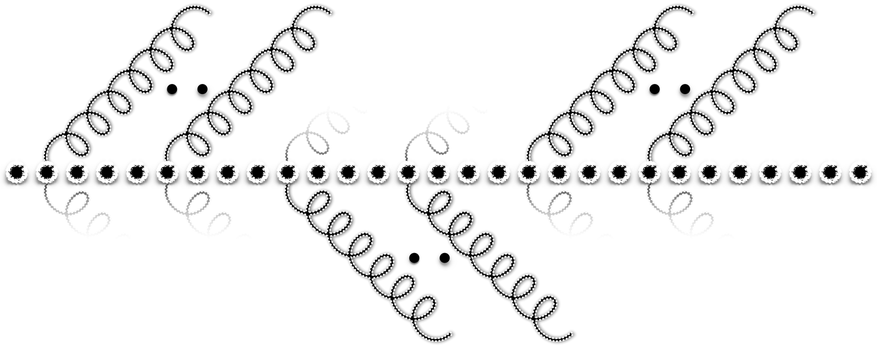
HF-NRevo for $T_{4c}(0^{++}, 2^{++})$ collinear fragmentation

Partonic hard factor



DGLAP AOevo

All-Order evolution (numeric)



DGLAP EDevo

Expanded Decoupled evolution

NRQCD

Color-composite LDMEs

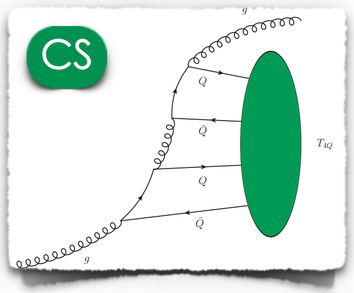
SDCs

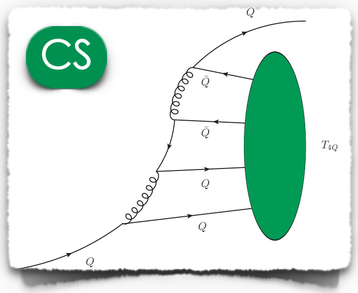
$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

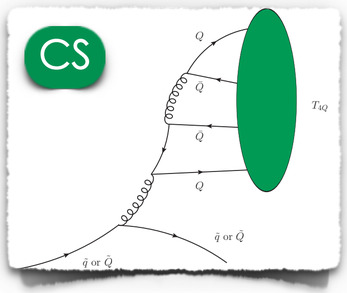
Energy ← → Time

Evolution-ready scale $Q_0 \equiv m_b + 4m_c$ $\quad 5m_c \quad m_{\tilde{q}} + 4m_c$

HF-NRevo: Initial-Scale NRCQD Inputs



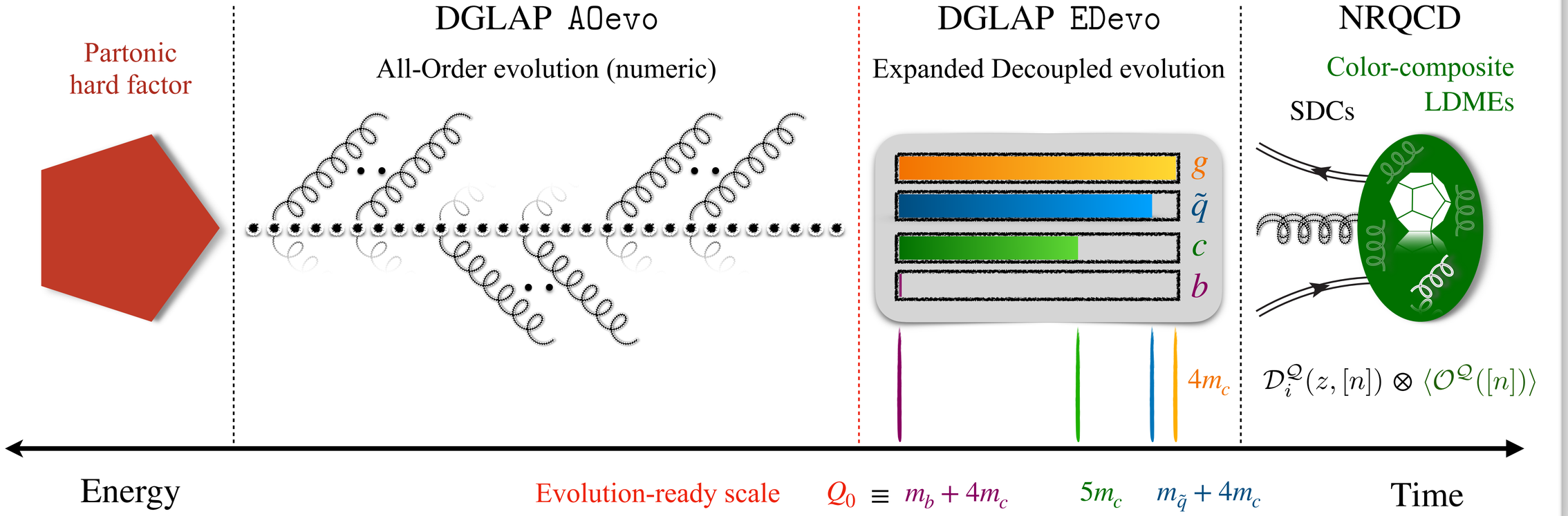




Scalar $[J^{PC} = 0^{++}]$

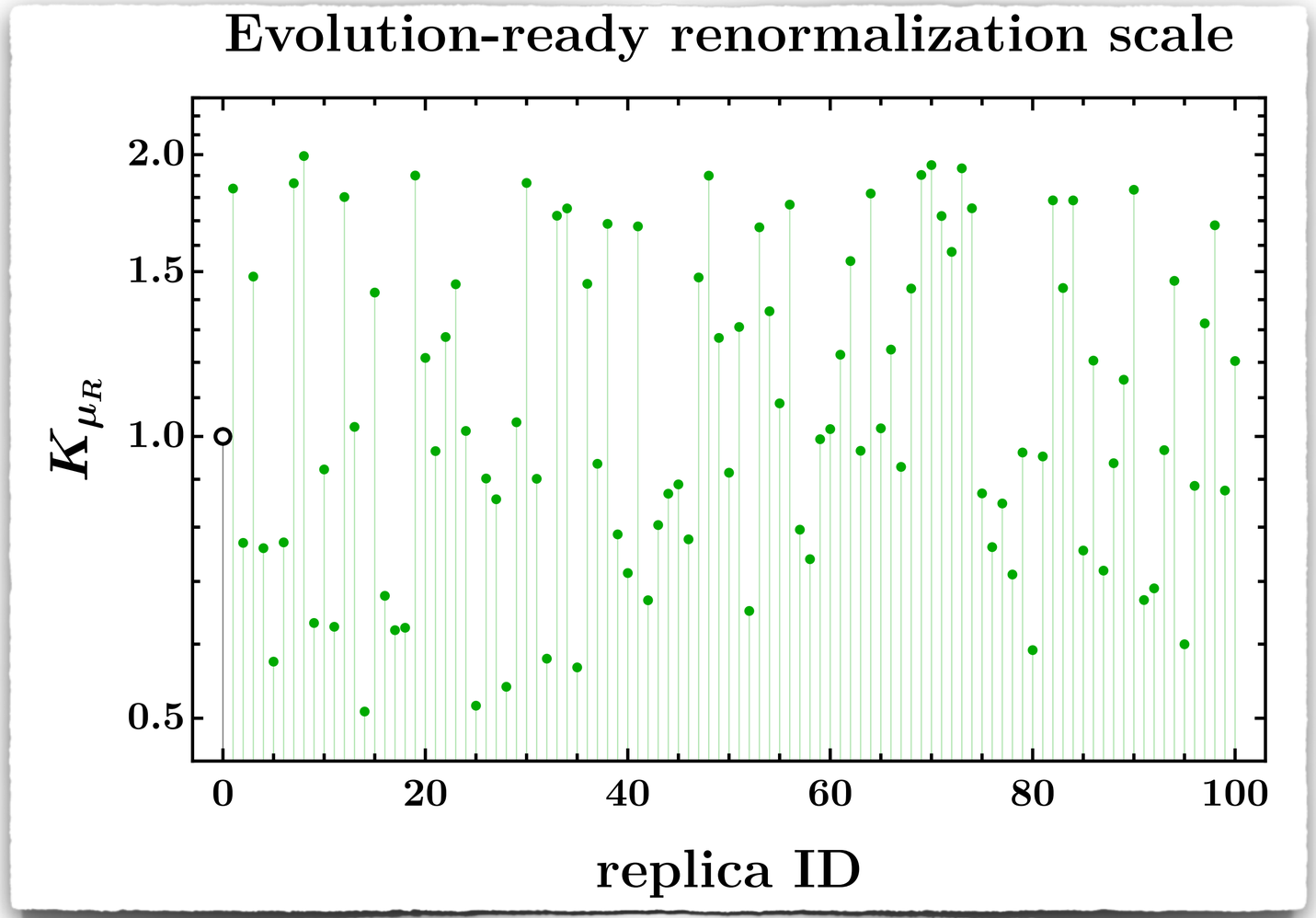
Tensor $[J^{PC} = 2^{++}]$

HF-NRevo for $T_{4c}(0^{++}, 2^{++})$ collinear fragmentation



TQ4Q2.0: F-MHOU Replica Analysis

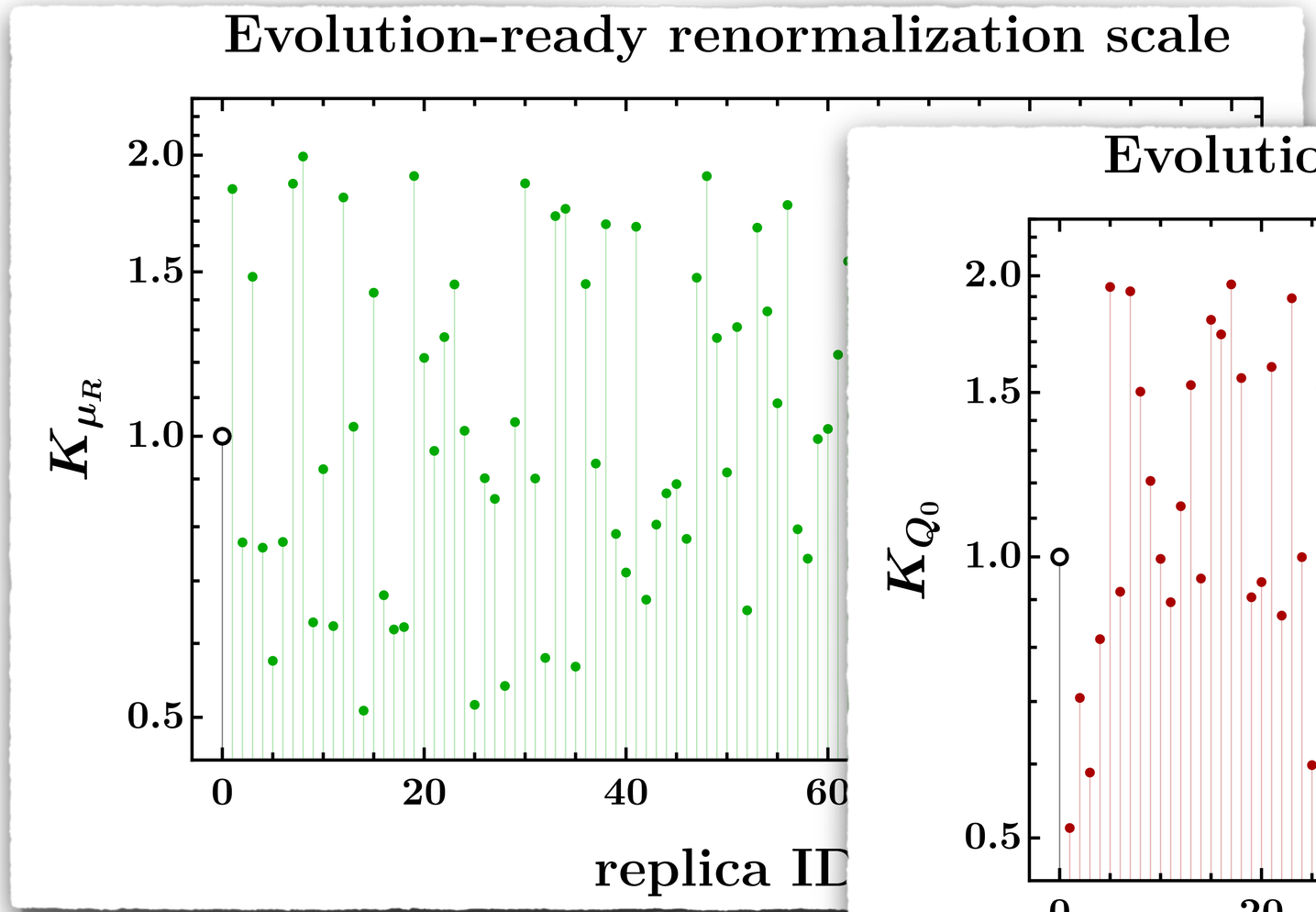
T_{4Q}

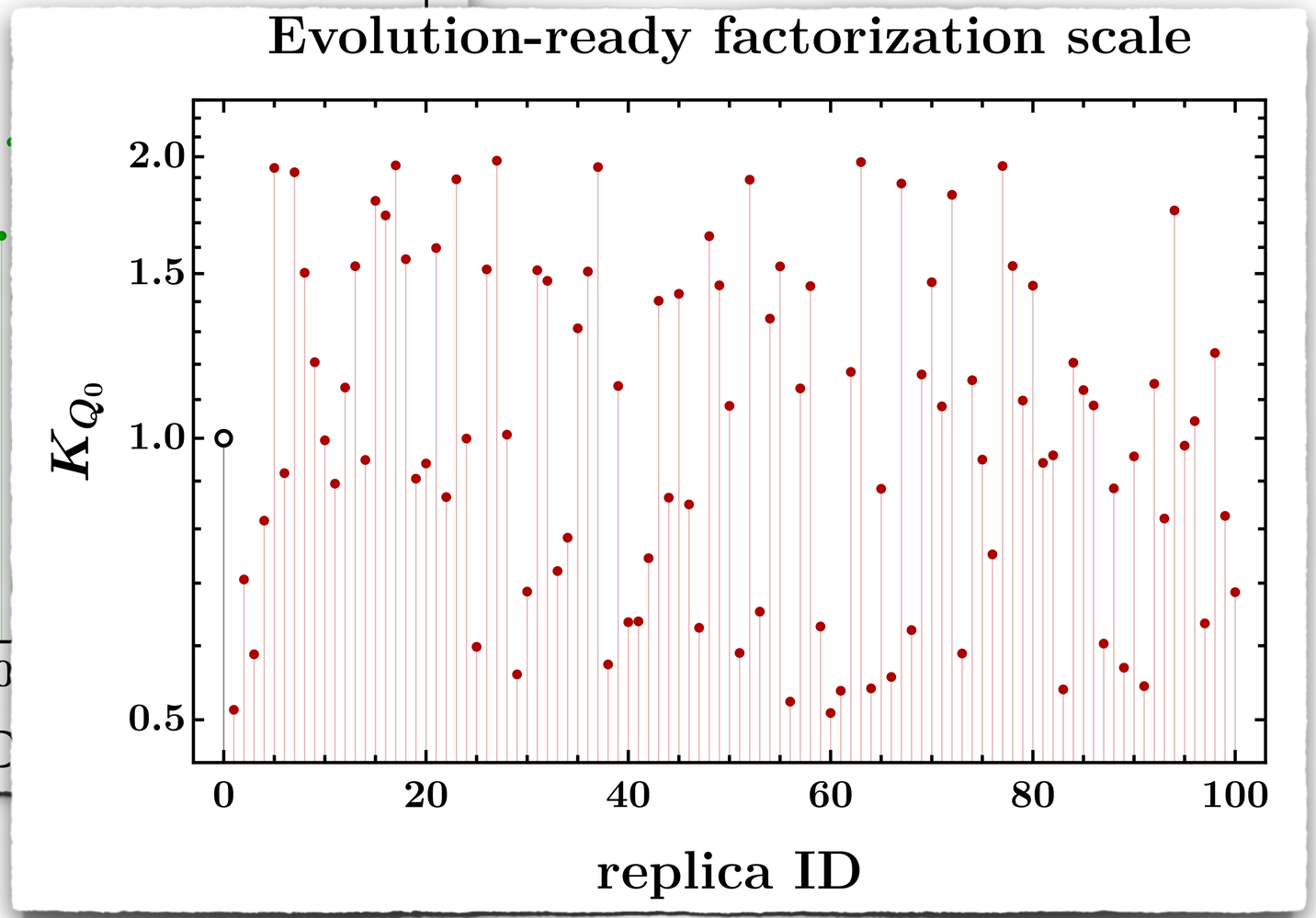


[F. G. C., Phys. Rev. D 113 (2026) 11, 114037 [arXiv:2604.11646]]

TQ4Q2.0: F-MHOU Replica Analysis

T_{4Q}





[F. G. C., Phys. Rev. D 113 (2026) 11, 114037 [arXiv:2604.11646]]

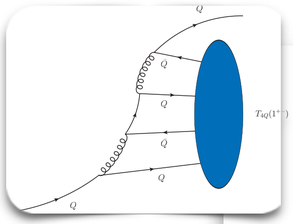
2

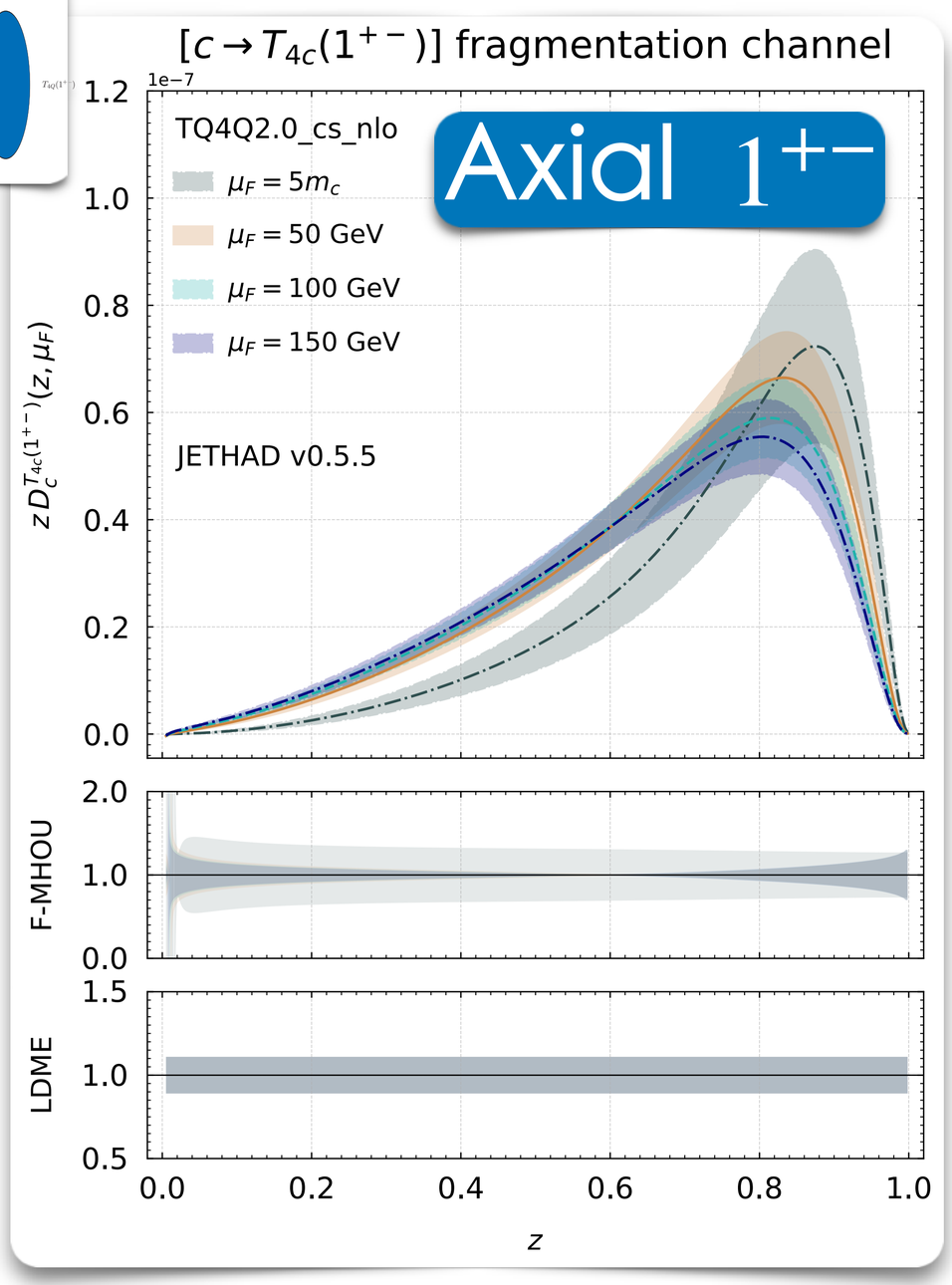
TQ4Q2.0_cs_nlo

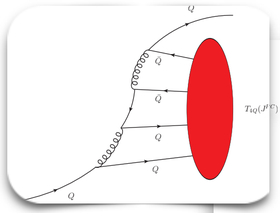
JETHAD

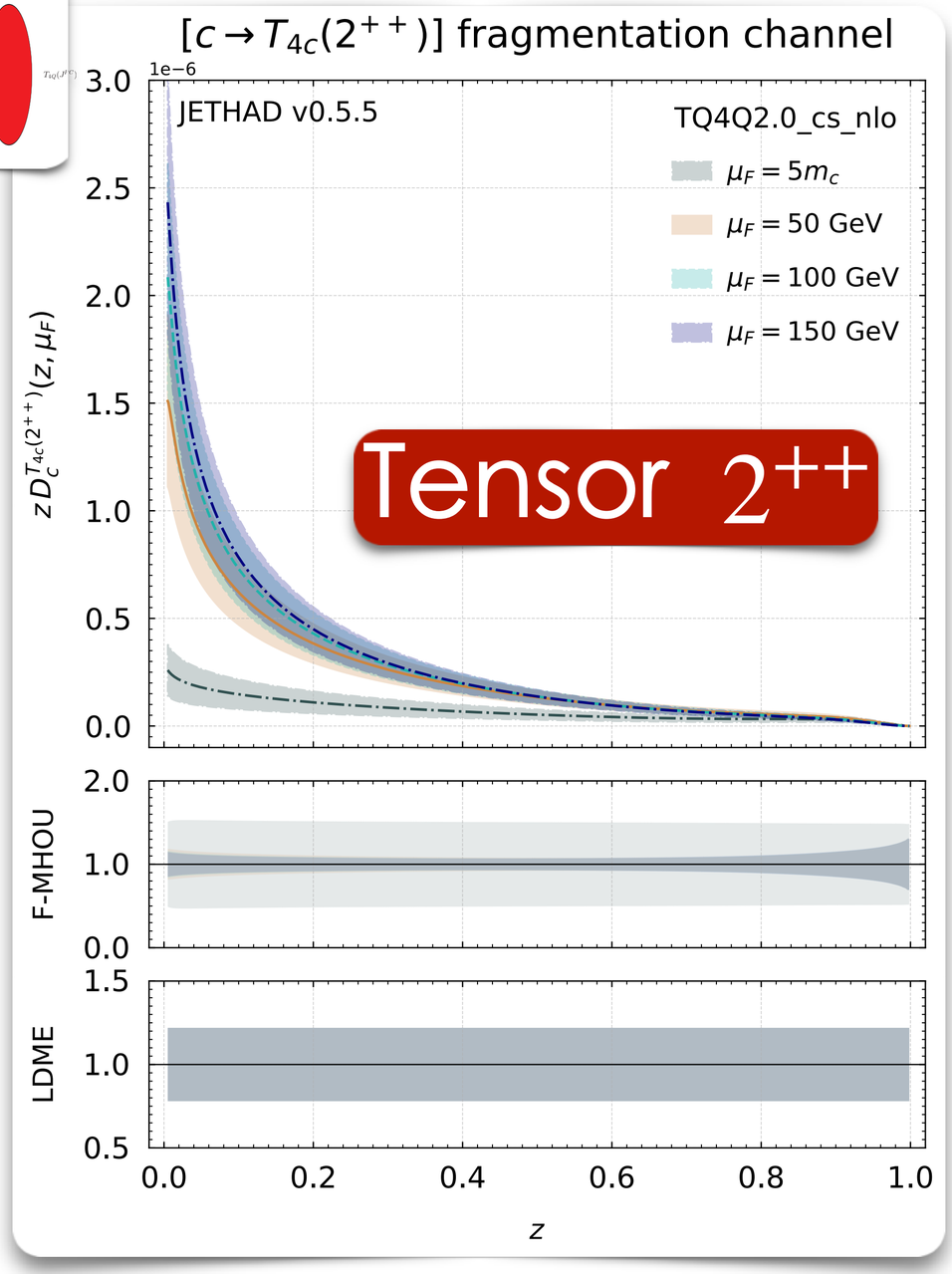
v0.5.5

TQ4Q2.0: Charm Fragmentation to Charmoniumlike

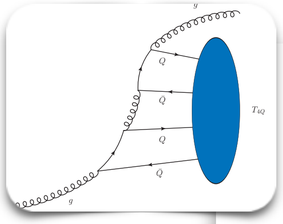


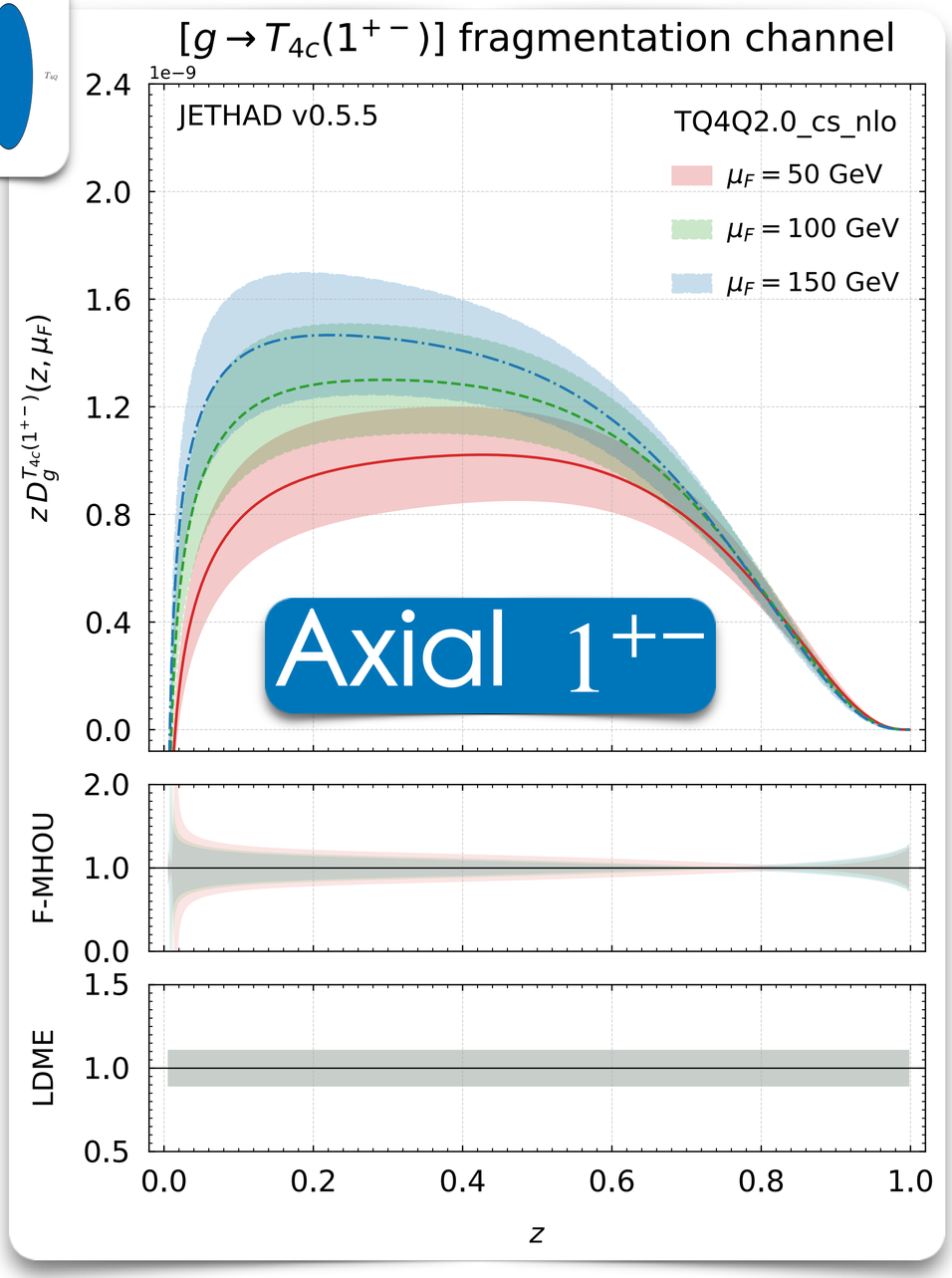


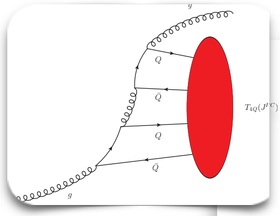


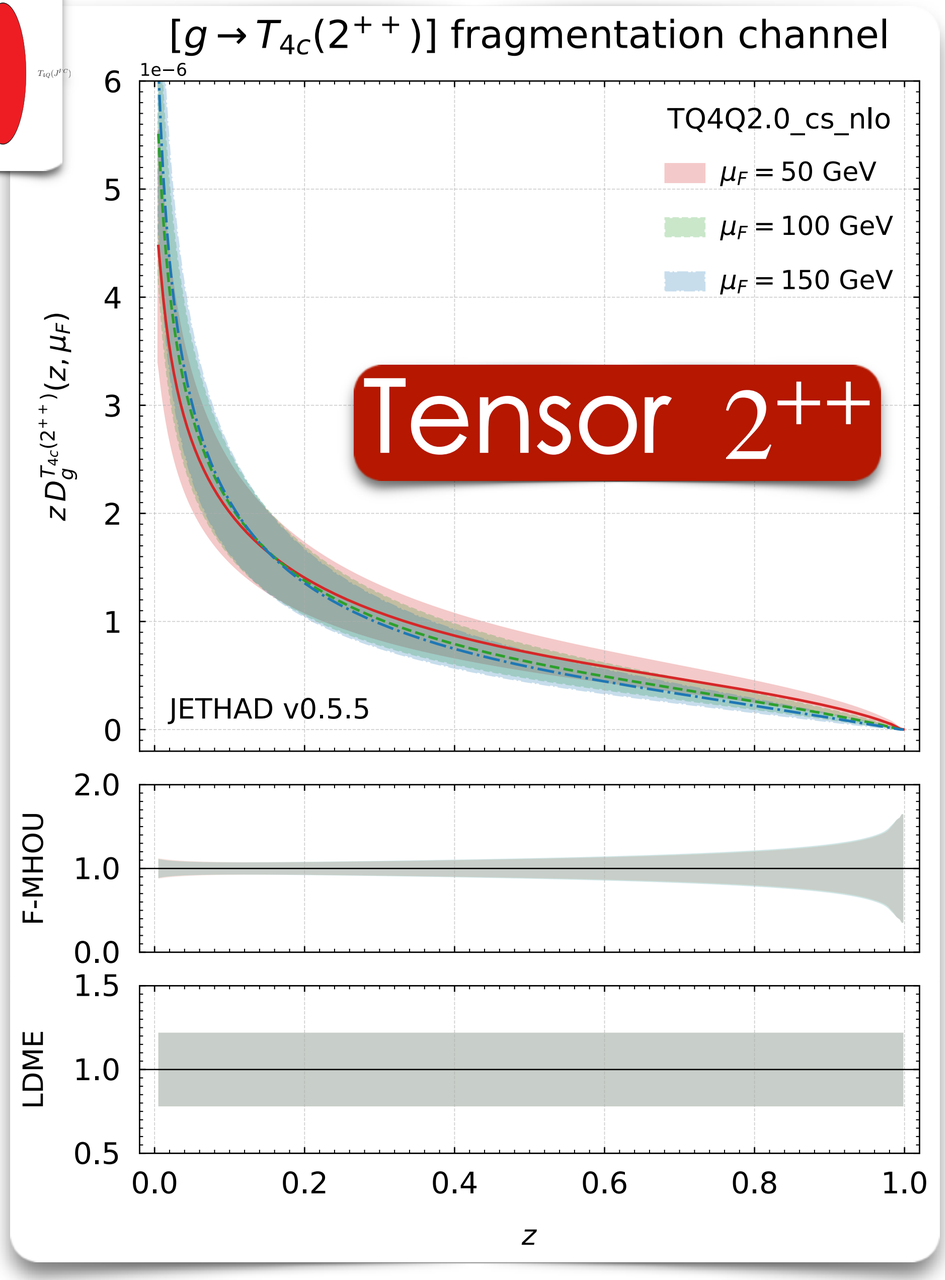


TQ4Q2.0: Gluon Fragmentation to Charmoniumlike

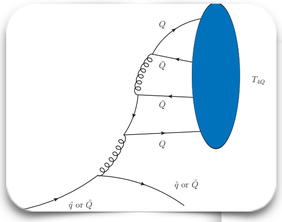


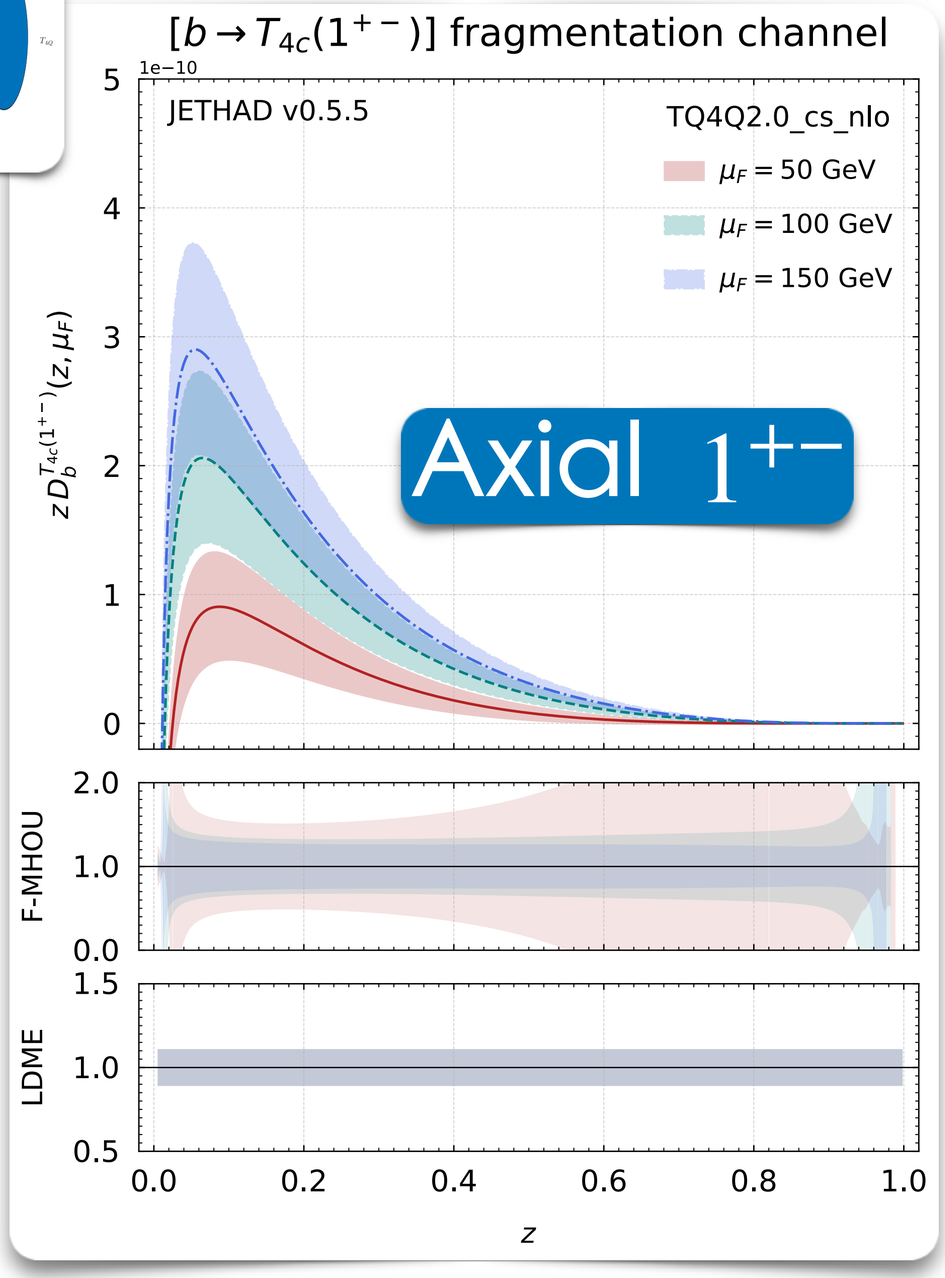


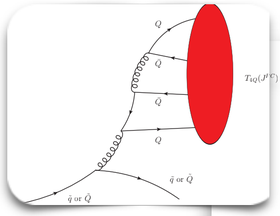


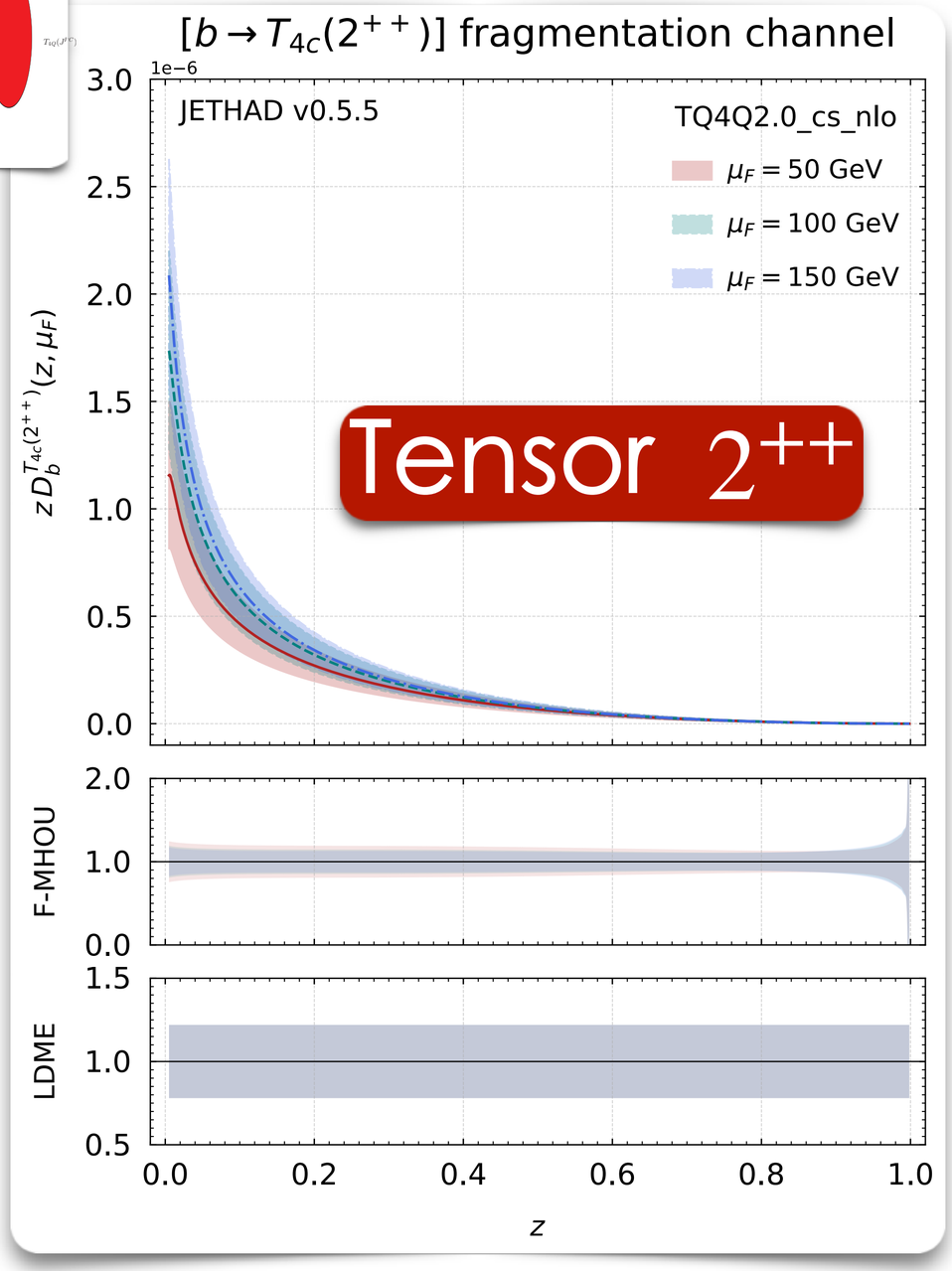


TQ4Q2.0: Bottom Fragmentation to Charmoniumlike

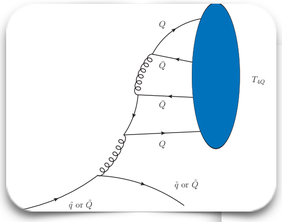


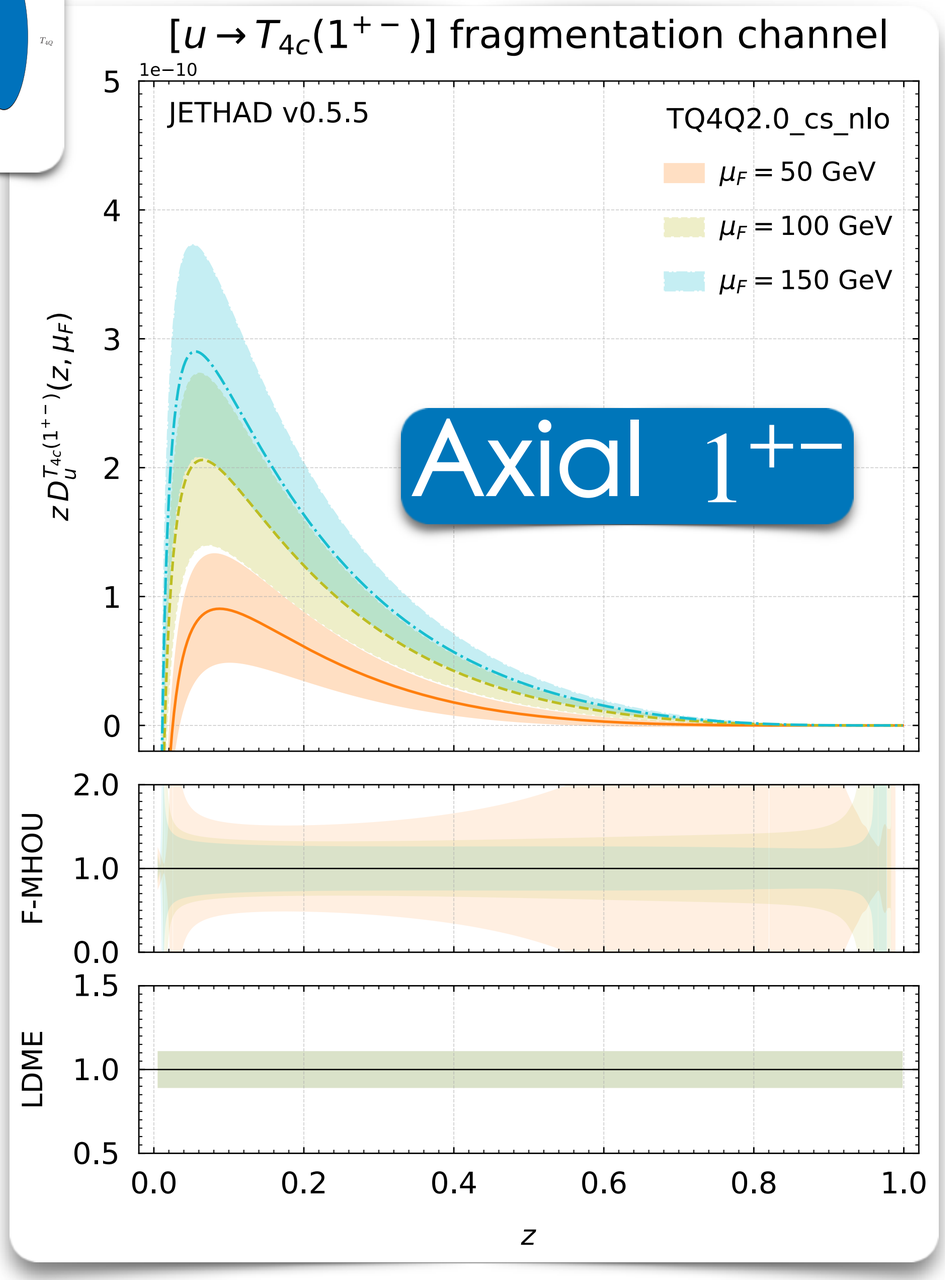


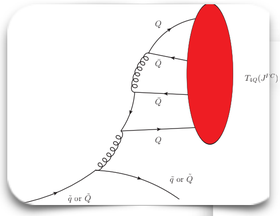


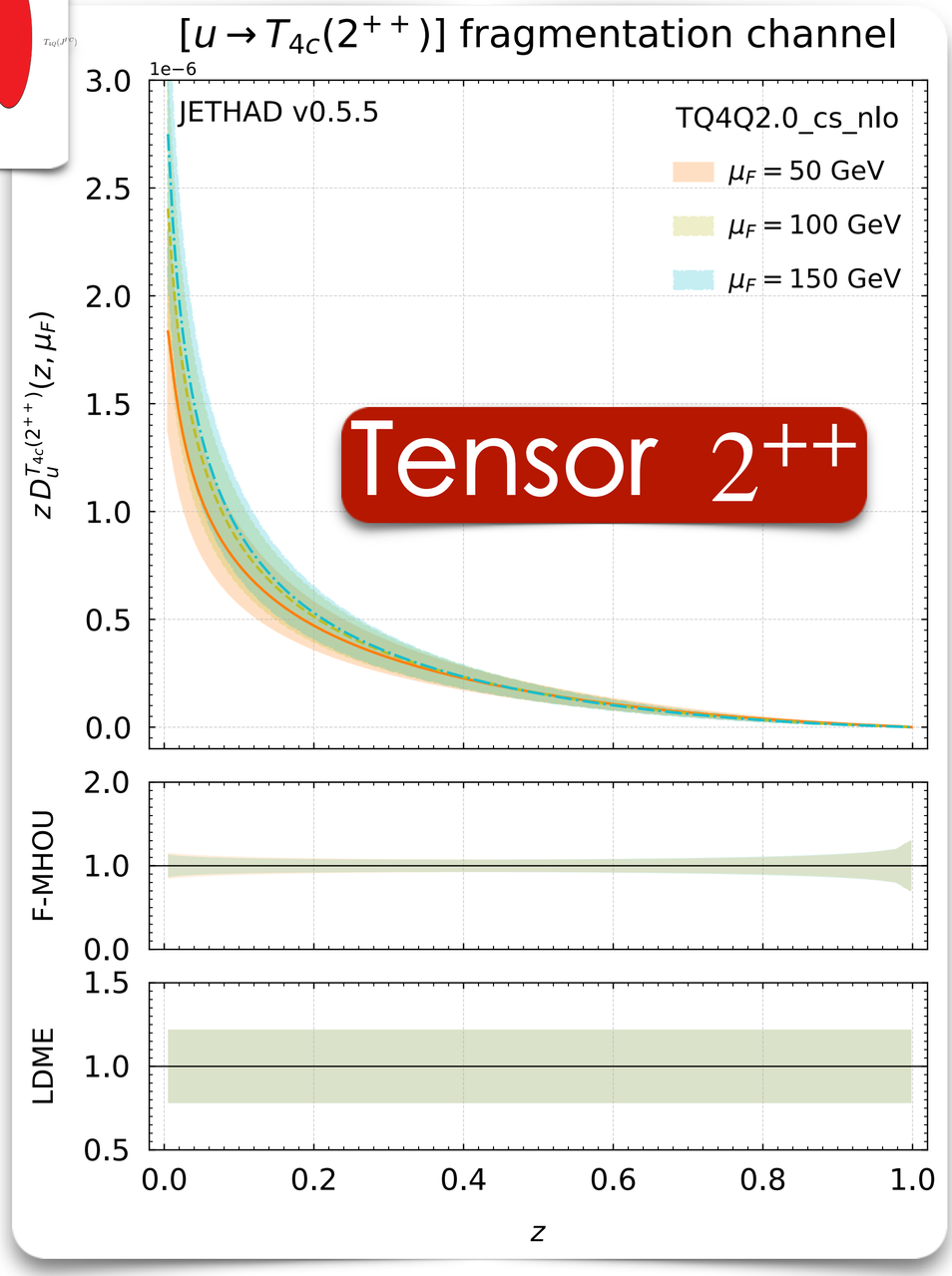


TQ4Q2.0: Light-Quark Fragmentation to Charmoniumlike









A Multimodal Perspective

Final Remarks

JETHAD
v0.5.5

A Portal to Exotic Matter

Exotic Matter State-Driven MultiModal Fragmentation

Quantum Superposition

$+ e^{-i\vartheta_1 \Delta t}$

$+ e^{-i\vartheta_2 \Delta t}$

$+ e^{-i\vartheta_3 \Delta t}$

Compact | Diquark | Molecule | Hadro-onium

Exotic Matter State-Driven MultiModal Fragmentation

Quantum Superposition

$+ e^{-i\vartheta_1 \Delta t}$

$+ e^{-i\vartheta_2 \Delta t}$

$+ e^{-i\vartheta_3 \Delta t}$

Compact | Diquark | Molecule | Hadro-onium

Δt_1

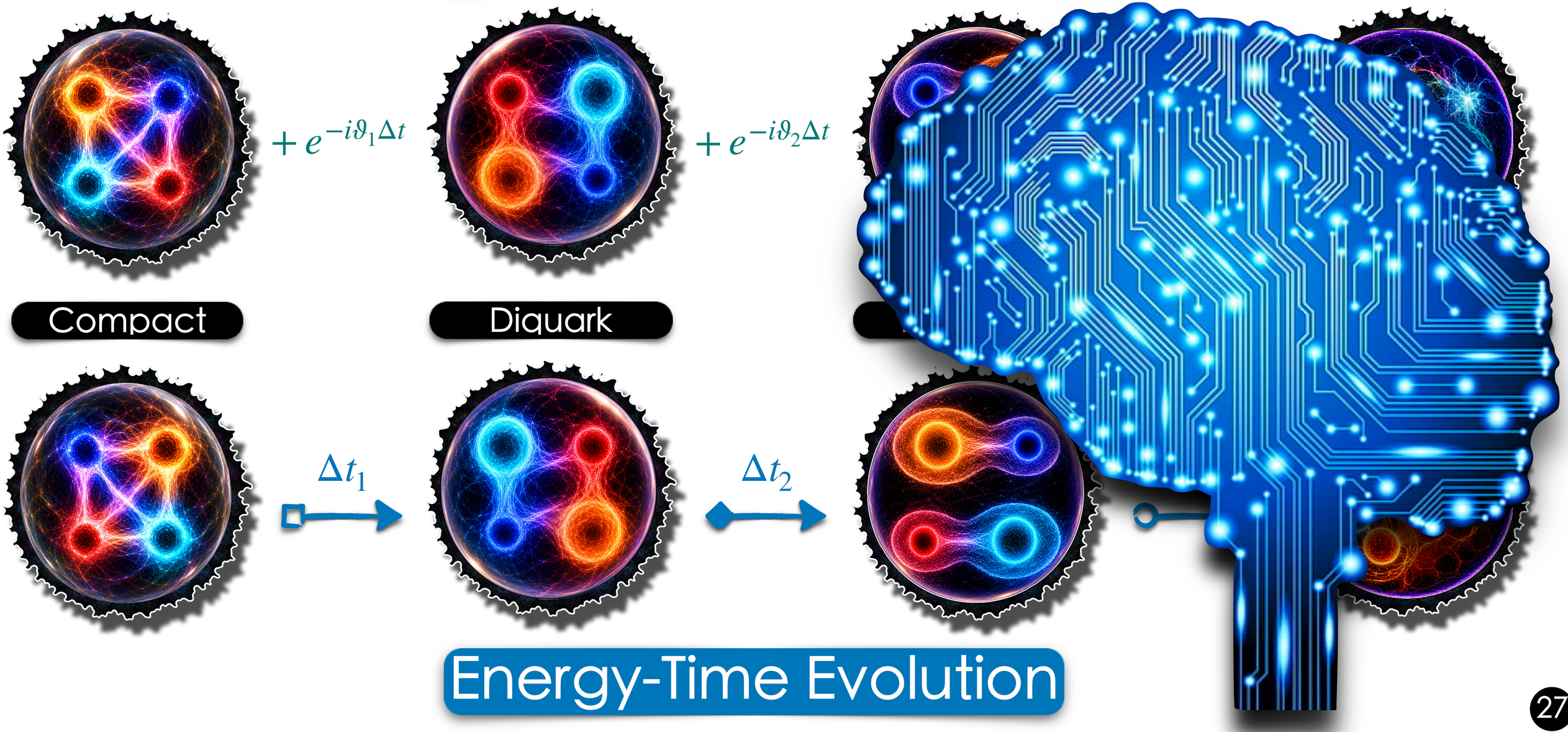
Δt_2

Δt_3

Energy-Time Evolution

Exotic Matter State-Driven MultiModal Fragmentation

Quantum Superposition



Energy-Time Evolution

Heavy-Flavor Fragmentation from **HF-NRevo**

Collinear_FFs Public

Unpin | Unwatch 1

main | 1 Branch | 0 Tags | Go to file T | Add file | Code

FGCeliberto Update Readme.md — 76bec1e · 2 weeks ago — 191 Commits

- NRFF10
- OMG3Q10
- OMG3Q11
- PQ5Q10
- PQ5Q11
- TQ4Q10
- TQ4Q11
- TQ4Q20
- TQHL10
- TQHL11
- LICENSE
- README.md

Heavy-Flavor Fragmentation from HF-NRevo

Collinear_FFs Public

main | 1 Branch | 0 Tags | Go to file

FGCeliberto Update Readme.md

- NRFF10
- OMG3Q10
- OMG3Q11
- PQ5Q10
- PQ5Q11
- TQ4Q10
- TQ4Q11
- TQ4Q20
- TQHL10
- TQHL11
- LICENSE
- README.md

README | CC0-1.0 license

Collinear_FFs

Collections of collinear fragmentation functions (FFs) given as LHPDF grids.

Available FF families to date:

1. NRFFx.y (NonRelativistic Fragmentation Functions)

   NRFF1.0 (NLO, 2 sets, central value only, LDME uncertainties)

2. OMG3Qx.y (OMeGa baryons with 3 heavy Quarks VFNS FFs)

   OMG3Q1.0 (NLO, 2 sets, central value only, diquark-like)

   OMG3Q1.1 (NLO, 2 sets, F-MHOU + F-NPWF uncertainties, replica 0->8, diquark-like)

3. TQHLx.y (TetraQuarks with Heavy and Light flavors)

   TQHL1.0 (NLO, 4 sets, central value only)

   TQHL1.1 (NLO, 4 sets, central value only)

4. TQ4Qx.y (TetraQuarks with 4 heavy Quarks)

   TQ4Q1.0 (NLO, 4 sets, central value only)

   TQ4Q1.1 (NLO, 6 main + 4 supplementary sets, replica-like MHOU uncertainties in main sets)

   TQ4Q2.0 (NLO, 6 sets, replica-like MHOU uncertainties)

5. PQ5Qx.y (PentaQuarks with 5 heavy Quarks)

   PQ5Q1.0 (NLO, 2 sets, replica 0 = direct multiquark, replica 1 = diquark-like)

   PQ5Q1.1 (NLO, 1 set, F-MHOU + F-NPWF uncertainties, replica 0->8 = direct multicharm, replica 9->17 = diquark-like)

🔗 https://github.com/ FGCeliberto/Collinear_FFs/

Heavy-Flavor Fragmentation from HF-NRevo

Collinear_FFs Public

main | 1 Branch | 0 Tags | Go to file

FGCeliberto Update Readme.md

- NRFF10
- OMG3Q10
- OMG3Q11
- PQ5Q10
- PQ5Q11
- TQ4Q10
- TQ4Q11
- TQ4Q20
- TQHL10
- TQHL11
- LICENSE
- README.md

README | CC0-1.0 license

Collinear_FFs

Collections of collinear fragmentation functions (FFs) given as LHPDF grids.

Available FF families to date:

1. NRFFx.y (NonRelativistic Fragmentation Functions)

   NRFF1.0 (NLO, 2 sets, central value only, LDME uncertainties)

2. OMG3Qx.y (OMeGa baryons with 3 heavy Quarks VFNS FFs)

   OMG3Q1.0 (NLO, 2 sets, central value only, diquark-like)

   OMG3Q1.1 (NLO, 2 sets, F-MHOU + F-NPWF uncertainties, replica 0->8, diquark-like)

3. TQHLx.y (TetraQuarks with Heavy and Light flavors)

   TQHL1.0 (NLO, 4 sets, central value only)

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   TQ4Q1.0 (NLO, 4 sets, central value only)

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NEW

TQHL2.0 ¡to be released soon!

🔗 https://github.com/ FGCeliberto/Collinear_FFs/

Toward ExoFF

Toward ExoFF

Exotic hadrons ⇒ precision QCD & production mechanisms

Toward **ExoFF**

- Exotic hadrons ⇒ precision QCD & production mechanisms

- **HF-NRevo** ⇒ consistent evolution, uncertainty-aware FFs

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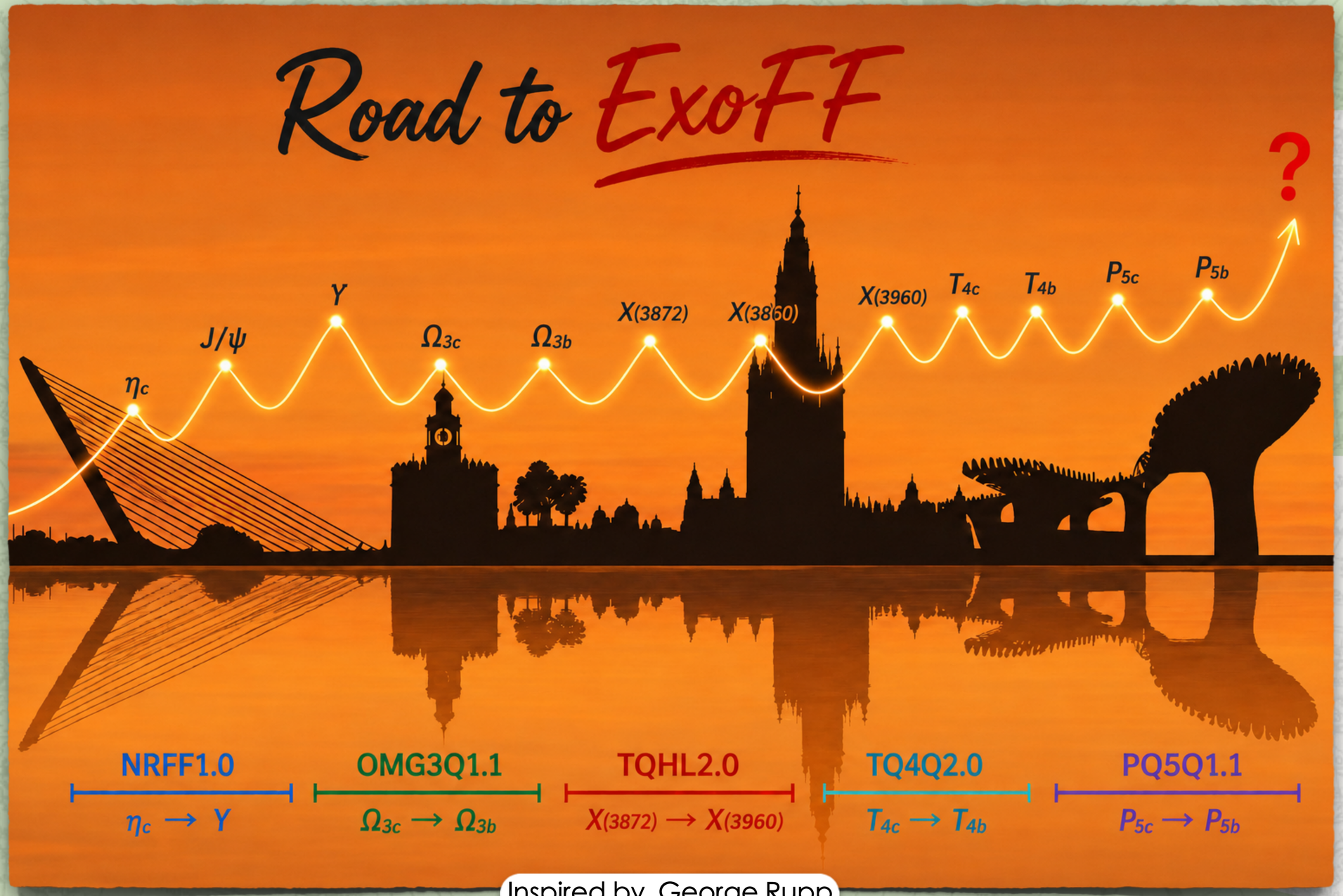
- From theory-driven benchmarks to state-oriented fragmentation
- Road to a MULTIMODAL **ExoFF** framework

A New Era of Discovery



Inspired by George Rupp

EXTRAS

TetraQuark-Jet Systems with Resummation: Event Yields

Expected events yields [13 TeV Run 2]

T_{4Q}	J^{PC}	TQ4Q2.0	TQ4Q1.1	Δ (%)
T_{4c}	0^{++}	2016031 ± 399168	1768764 ± 309078	+13.98%
T_{4c}	1^{+-}	8619 ± 1770	8619 ± 1612	+0%
T_{4c}	2^{++}	3071882 ± 602910	2721362 ± 480942	+12.88%
T_{4b}	0^{++}	6046 ± 1168	5151 ± 945	+17.38%
T_{4b}	1^{+-}	17 ± 3	17 ± 2	+0%
T_{4b}	2^{++}	8095 ± 1552	7108 ± 828	+13.88%

TABLE IV: Expected event yields for all-heavy tetraquark production at $\sqrt{s} = 13$ TeV, obtained by integrating the NLL-resummed ΔY distributions over the rapidity range $|\Delta Y| < 6.5$. The yields assume an integrated luminosity of $\mathcal{L}^{(\mathrm{CMS})} = 138.6\ \mathrm{fb}^{-1}$, corresponding to the total dataset collected by CMS during Run 2 [308, 309]. The last column shows the relative variation $\Delta = (R - 1) \times 100$, with $R =$ TQ4Q2.0/TQ4Q1.1. Uncertainties are propagated from the ΔY distributions and reflect the combined effect of scale variations, FF evolution, and LDME inputs.

Expected events yields [100 TeV FCC]

T_{4Q}	J^{PC}	TQ4Q2.0	TQ4Q1.1	Δ (%)
T_{4c}	0^{++}	22140238 ± 4433814	19465674 ± 3373524	+13.74%
T_{4c}	1^{+-}	23463 ± 1094	23463 ± 1053	+0%
T_{4c}	2^{++}	32784967 ± 6421338	29144313 ± 5467493	+12.49%
T_{4b}	0^{++}	23424 ± 1982	20237 ± 1552	+15.75%
T_{4b}	1^{+-}	50 ± 2	50 ± 3	+0%
T_{4b}	2^{++}	27894 ± 1972	24493 ± 1323	+13.89%

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Pile-up effects can degrade
Experimental discrimination

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$\Delta(\%)$

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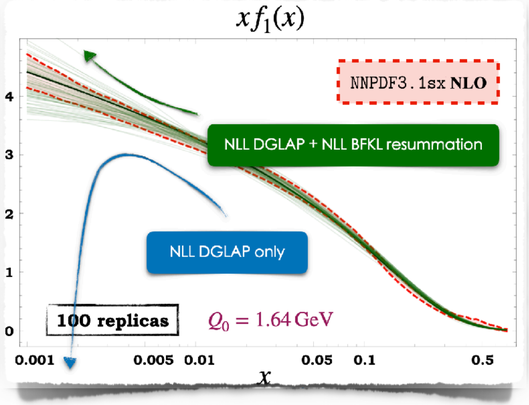
Pile-up effects can degrade Experimental discrimination

All-Charm TetraQuarks & Intrinsic Charm

Quakonium Studies: Challenges

Forward Onia ⇒ Gluon PDF & TMD Positivity



Low x and low Q^2

[G. Altarelli et al. (1998)]
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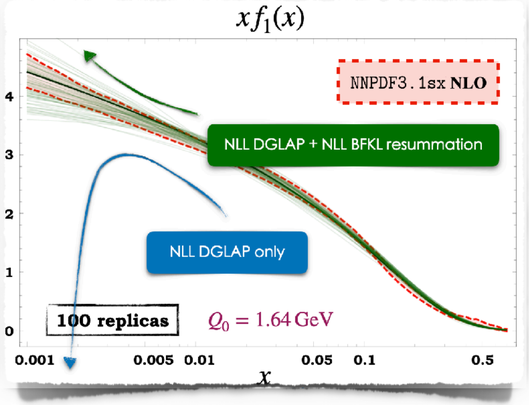

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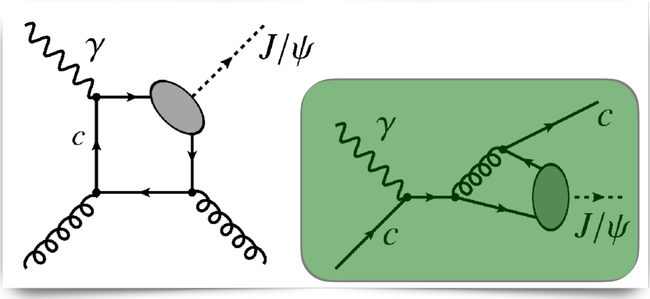
$\gamma + g \to J/\psi + c$ ⇒ Valence Intrinsic Charm @EIC

Large x
Moderate to large p_T



(J/ψ @EIC) 🔗 [C. Flore, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina (2020)]
(Intrinsic Charm + valence) studies 🔗🔗 [NNPDF Collaboration (2022, 2023)]

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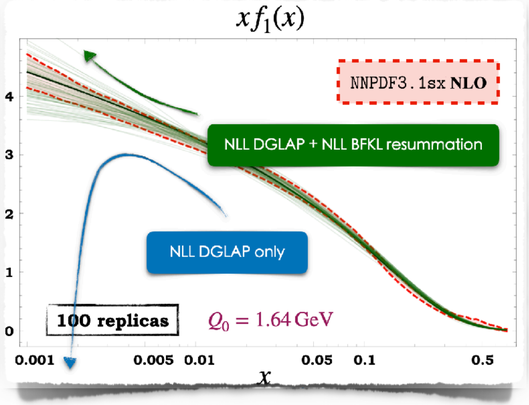

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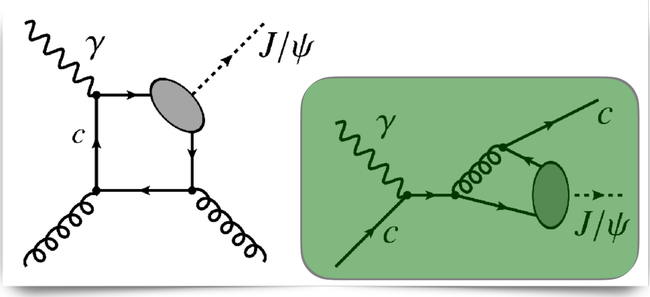

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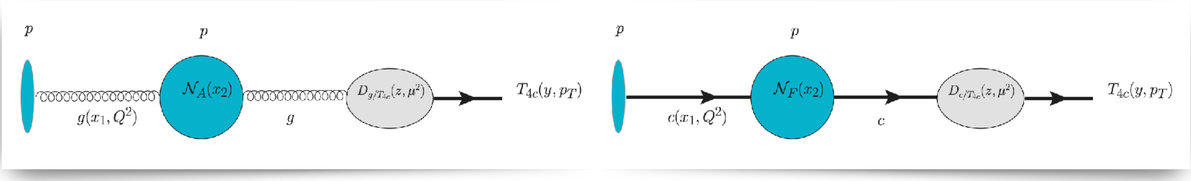
TetraQuark Explorations: Assets

$\{T_{4c}\} \ni X(6900)$ ⇒ Charm PDF @HL-LHC, FCC

Forward 0^{++}, 1^{+-}, 2^{++} within the CGC

[F.G. C, A.V. Giannini, V.P. Gonçalves, Y.N. Lima (2025)]



$$\sigma(pp \to T_{4c}X) \propto g(x_1, Q^2) \otimes \mathcal{N}_A(x_2) \otimes D_{g/T_{4c}} + c(x_1, Q^2) \otimes \mathcal{N}_F(x_2) \otimes D_{c/T_{4c}}$$

All-Charm TetraQuarks & Intrinsic Charm

Quakonium Studies: Challenges

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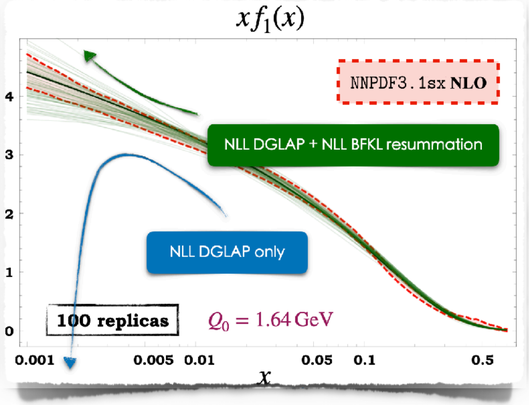

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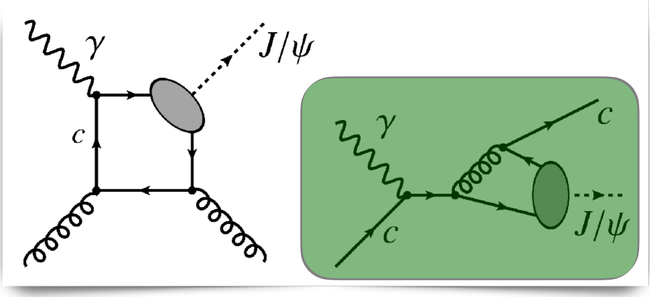

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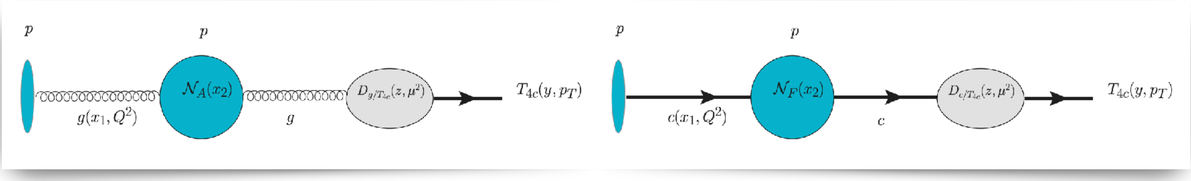

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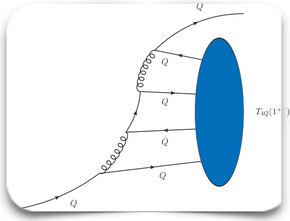
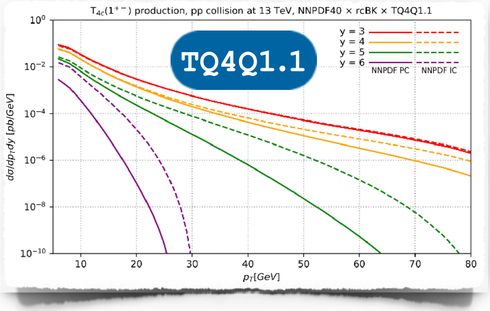
Forward $T_{4c}(1^{+-})$ ⇒ Intrinsic Charm @pp, pA



1^{+-} FFs

dilute-dense

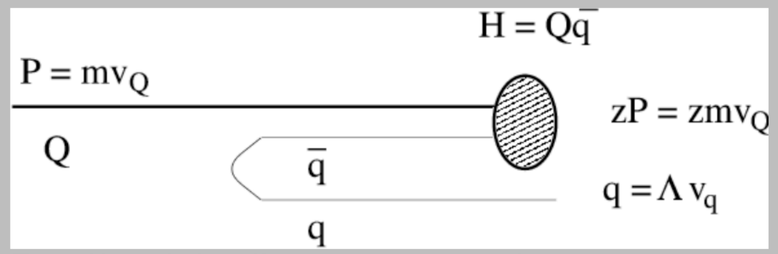


Highlights on Heavy-Flavor Fragmentation

We observe hadrons, whose momentum is different from that of the parent heavy quark. We usually write this as

FF(hadron) = FF(quark) $\otimes$ FF(quark$\rightarrow$hadron)

What are the characteristics of FF(quark$\rightarrow$hadron)?



The heavy quark has momentum $P = mv_Q$, the light quarks have momentum $q = \Lambda v_q$, with Λ a hadronic mass scale

For the binding we need $v_Q \simeq v_q = v$. We have then

$$P = zP + q \qquad\qquad mv = zmv + \Lambda v$$

and therefore

$$\langle z \rangle \simeq 1 - \frac{\Lambda}{m}$$

Hence, FF(quark$\rightarrow$hadron) is peaked near $z = 1$ and binding effects scale linearly in the heavy quark mass (Bjorken/Suzuki ($\sim$ 1977))

(NB. more rigorous derivations of this result are available)

Quarkonia as Tools: Precision & Exploration

Precision determinations of QCD running coupling

$\Upsilon(1S)$ hadronic inclusive decays

[CLEO Collaboration (2006)]
[N. Brambilla et al. (2007)]
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QUARKONIA

QCD Hydrogen Atoms

Quarkonia as Tools: Precision & Exploration

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Forward inclusive reactions

Gluon PDF positivity at low x and low Q^2

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Quarkonia in nuclear matter

Confined matter to QGP transition

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Quarkonia as Tools: Precision & Exploration

Portals to exotic matter and BSM physics

Hadroquarkonium
EW boson rare decays

[S. Dubynskiy et al. (2008)]
[F.-K. Guo et al. (2018)]
[J. Ferretti et al. (2020)]
[CMS Collaboration (2019)]

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QUARKONIA

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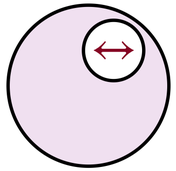
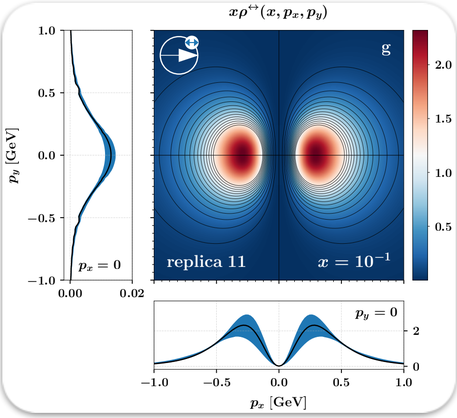
Quarkonium Studies: Assets & Challenges

Hadronic structure: Assets



EIC, LHCb, LHCspin

Boer-Mulders



[A. Bacchetta, F.G. C., M. Radici, P. Taels (EPJC 2020)]

Quarkonium Studies: Assets & Challenges

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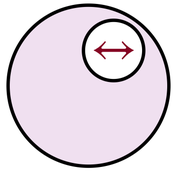

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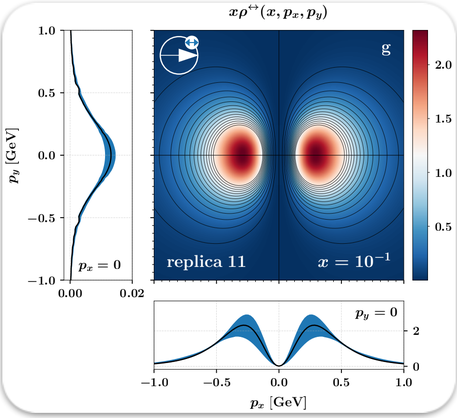

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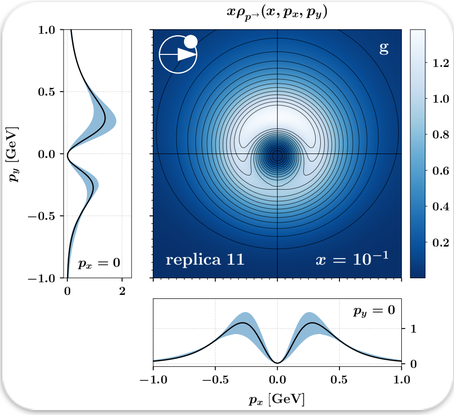
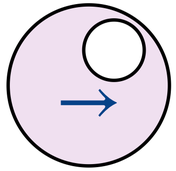


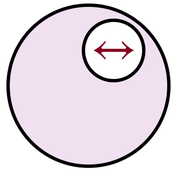


EIC, LHCspin

Sivers

Quarkonium Studies: Assets & Challenges

Hadronic structure: Assets



EIC, LHCb, LHCspin

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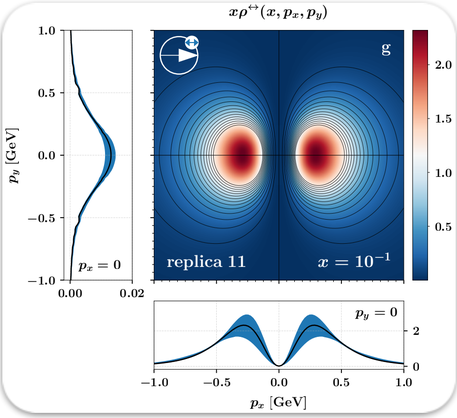

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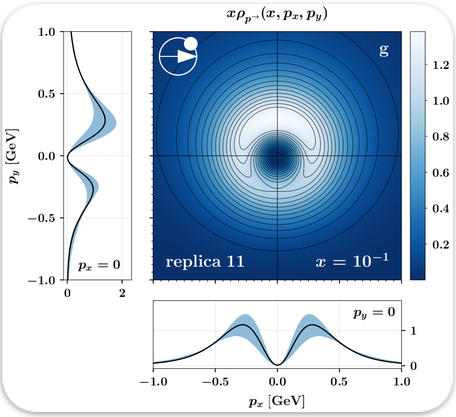
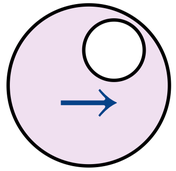


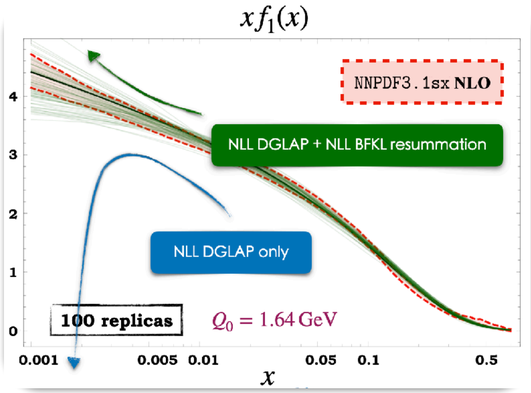


EIC, LHCspin

Sivers

Precision QCD: Challenges

Forward Onia ⇒ Gluon PDF & TMD Positivity



Low x and low Q^2

[G. Altarelli et al. (1998)]
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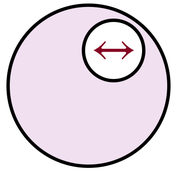
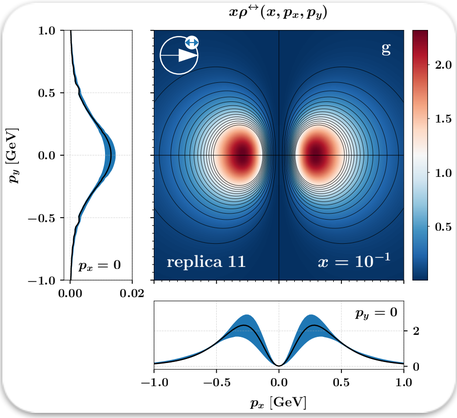
Quarkonium Studies: Assets & Challenges

Hadronic structure: Assets



EIC, LHCb, LHCspin

Boer-Mulders



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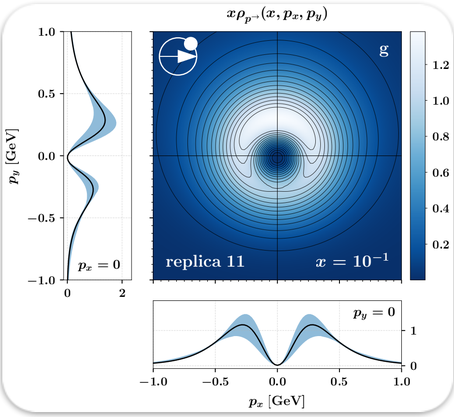

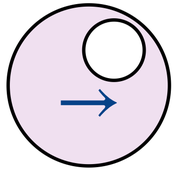

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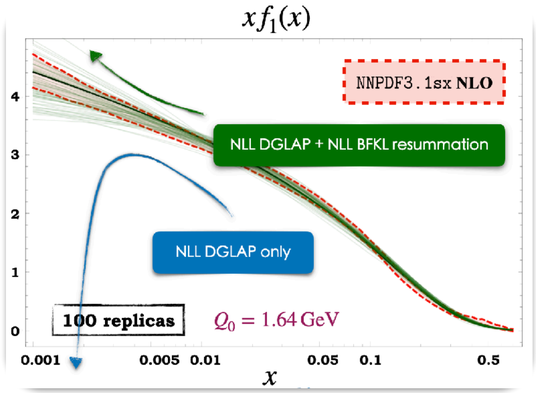

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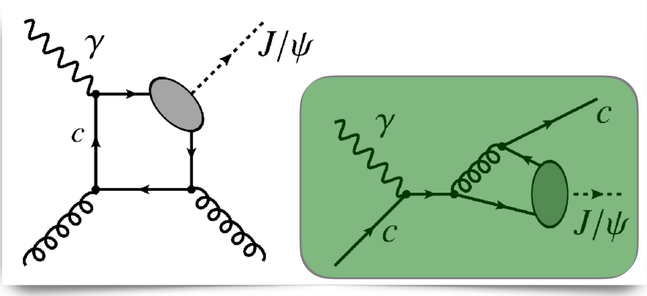
$\gamma + g \to J/\psi + c$ ⇒ Valence Intrinsic Charm @EIC

Large x
Moderate to large p_T



(J/ψ @EIC) [C. Flore, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina (2020)]
(Intrinsic Charm + valence) studies [NNPDF Collaboration (2022, 2023)]

Highlights of Non-Relativistic QCD

- **NRQCD** → effective field theory → nonrelativistic (NR) $Q\bar{Q}$ system

- Heavy-quark spinor fields as NR DOFs in the NQRCD Lagrangian

$$\mathcal{L}_{\mathrm{NRQCD}} = \psi^\dagger \left(iD_0 + \frac{\vec{D}^2}{2m_Q} \right) \psi + \chi^\dagger \left(iD_0 - \frac{\vec{D}^2}{2m_Q} \right) \chi + \mathcal{L}_{\mathrm{light}} + \delta\mathcal{L}$$

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- [cross section] = [short-distance coeffs.] $\otimes$ [long-distance matrix elements]

$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\overline{Q}\,[n] + X)\,\langle \mathcal{O}^H\,[n] \rangle$$

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$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}\,[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}\,[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}\,[^1S_0^{(8)}g]\rangle$$
$$+ \mathcal{O}(v^2)\,|Q\bar{Q}\,[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}\,[^3D_J^{(1,8)}gg]\rangle + \ldots\,.$$

HF-NREVO

FOUNDING PILLARS

HF-NRevo

Interpretation

Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Interpretation

Evolution

Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Interpretation

Evolution

Uncertainties

Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Interpretation

Evolution

Uncertainties

- NRQCD $\Rightarrow$ proxy for initial-scale FF inputs
- A heavy-flavor-scheme based vision
- Low vs large p_T $\Rightarrow$ FFNS vs VFNS fragmentation

Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Interpretation | Evolution | Uncertainties

- Proper DGLAP collinear evolution
- Thresholds at work for all partons
- Two-step strategy $\Rightarrow$ EDevo $\otimes$ AOevo

Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Interpretation Evolution **Uncertainties**

- Initial-scale MHOUs ⇒ first systematic analysis
- Idea ⇔ ThCovM 🔗🔗 & MCscales 🔗 MHOUs
- Future ⇐ extraction of NP LDMEs from data

ALL-HEAVY PENTAQUARK FRAGMENTATION

MultiModal Fragmentation to PentaQuarks

Mode 1

Direct MultiQuark

Scalar S-wave P_{5c}

🔗 [F. G. C., Eur. Phys. J. C 85 (2025) 12, 1395]; 🔗 [F. G. C., Phys. Rev. D. (to appear), arXiv:2605.01539]

MultiModal Fragmentation to PentaQuarks

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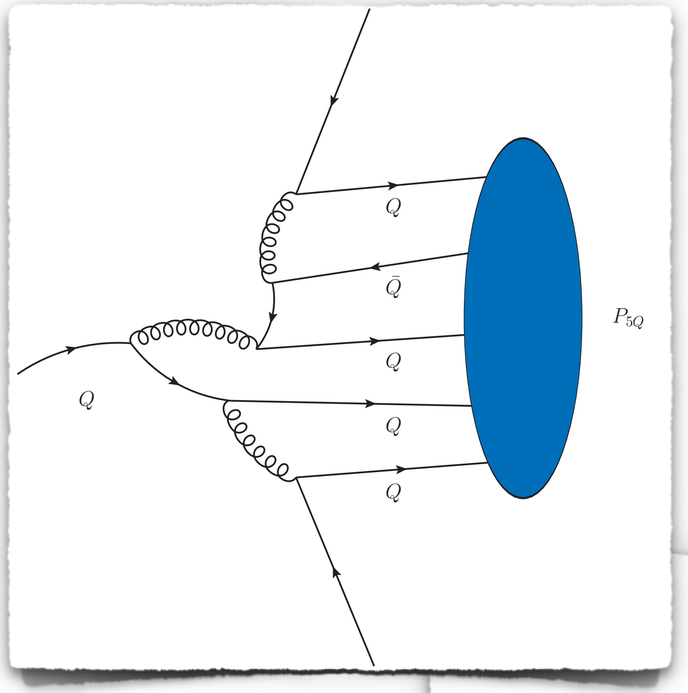
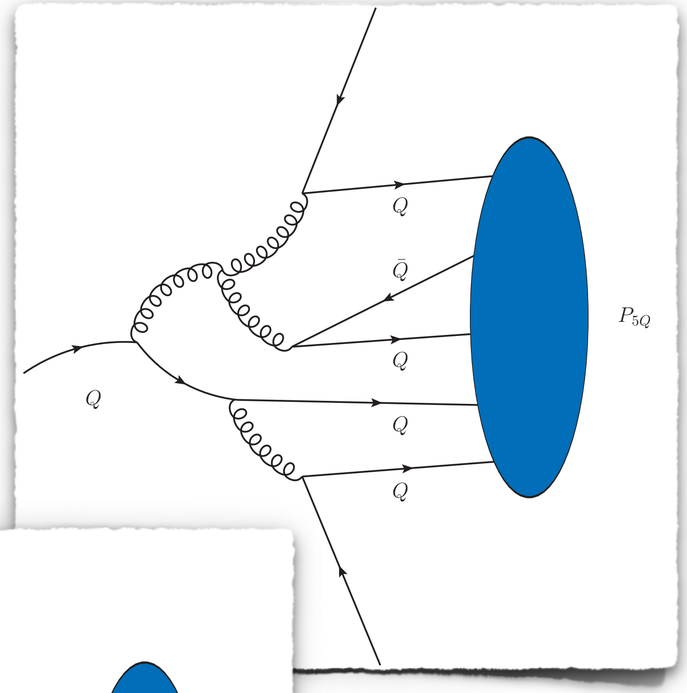
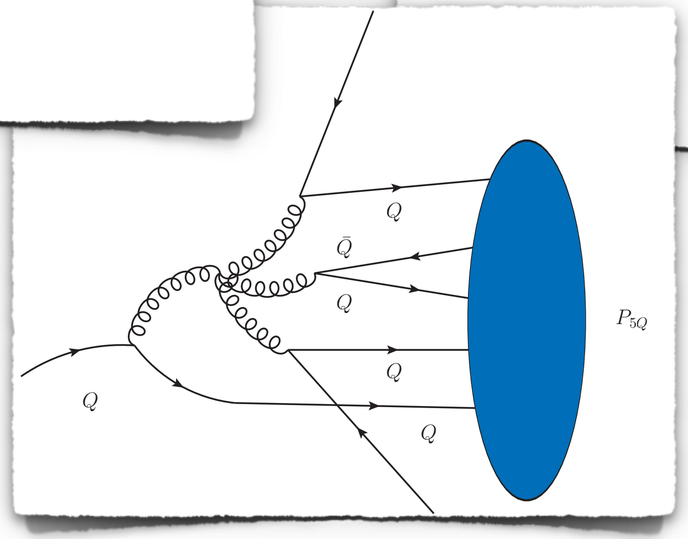






Initial-scale input: 🔗🔗 Suzuki model

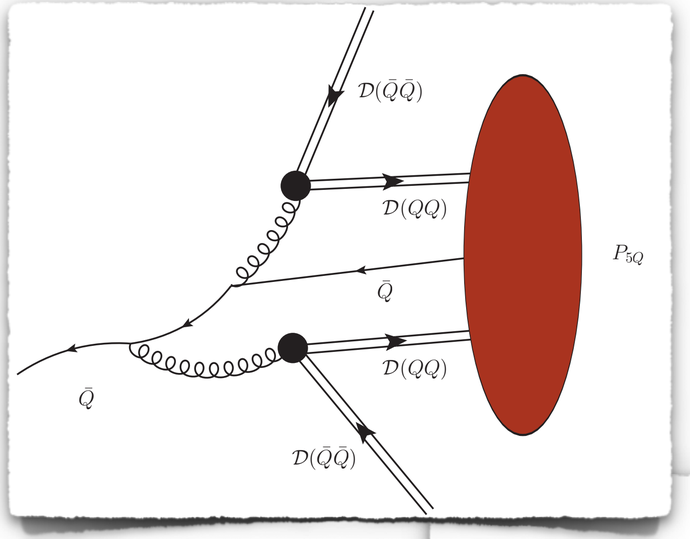
PQ5Q1.y FFs: $(Q \to P_{c\bar{c}ccc}) \otimes$ **APFEL++**

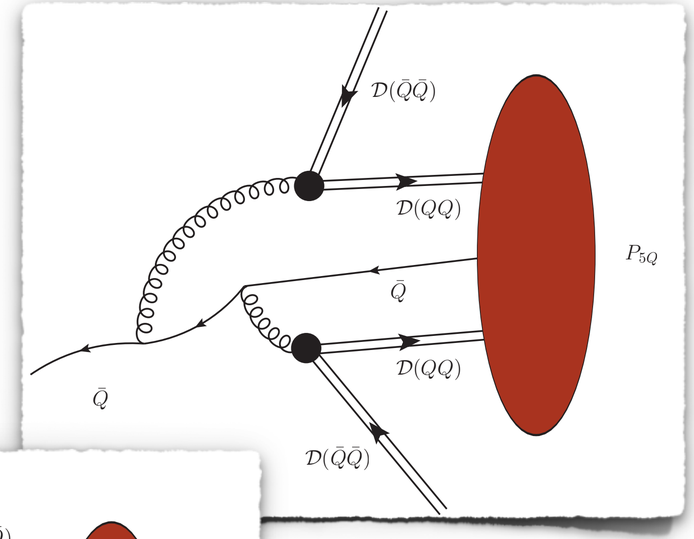
F-MHOUs [P] + F-NPWF [NP]

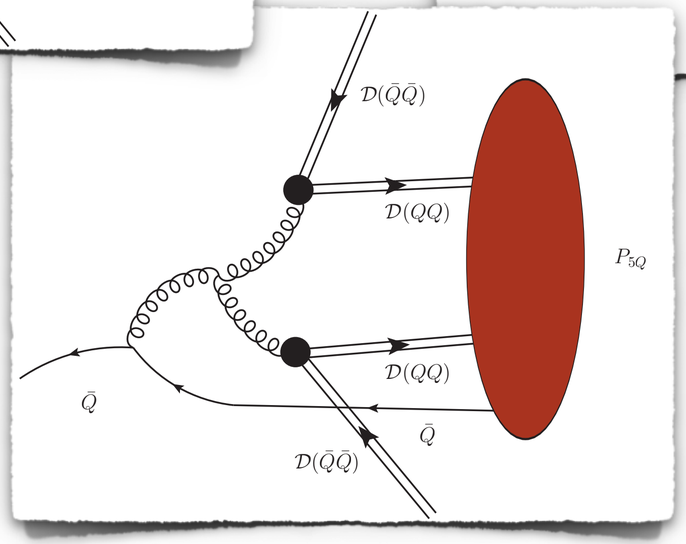
🔗 [F. G. C., Eur. Phys. J. C 85 (2025) 12, 1395]; 🔗 [F. G. C., Phys. Rev. D. (to appear), arXiv:2605.01539]

MultiModal Fragmentation to PentaQuarks

Mode 2
Scalar DiQuark
Scalar S-wave P_{5c}







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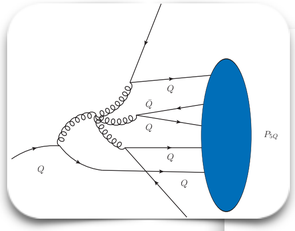
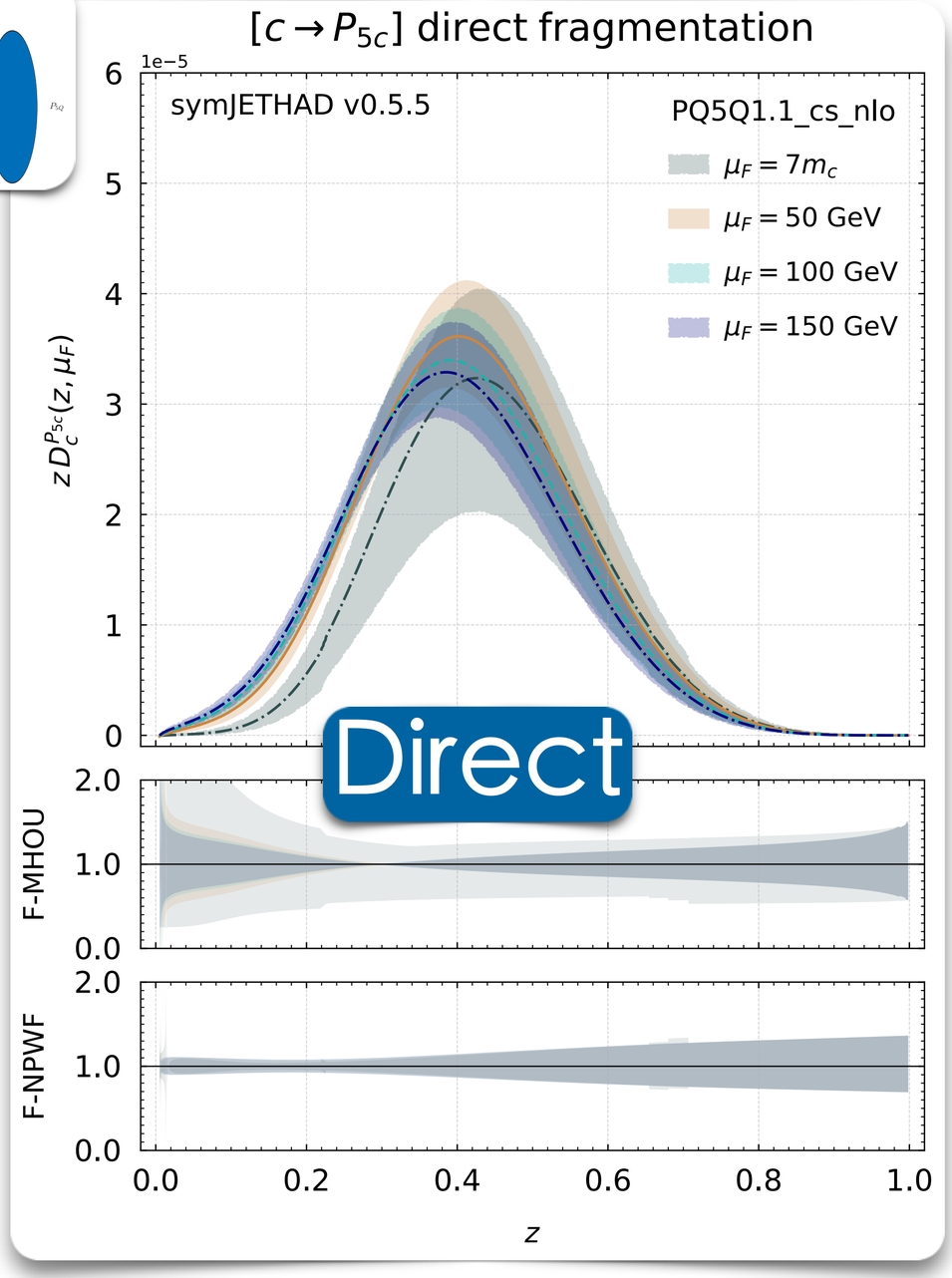
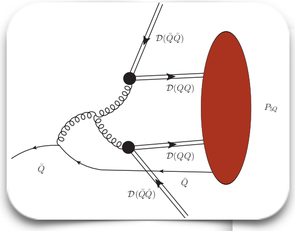
PQ5Q1.1_cs_nlo

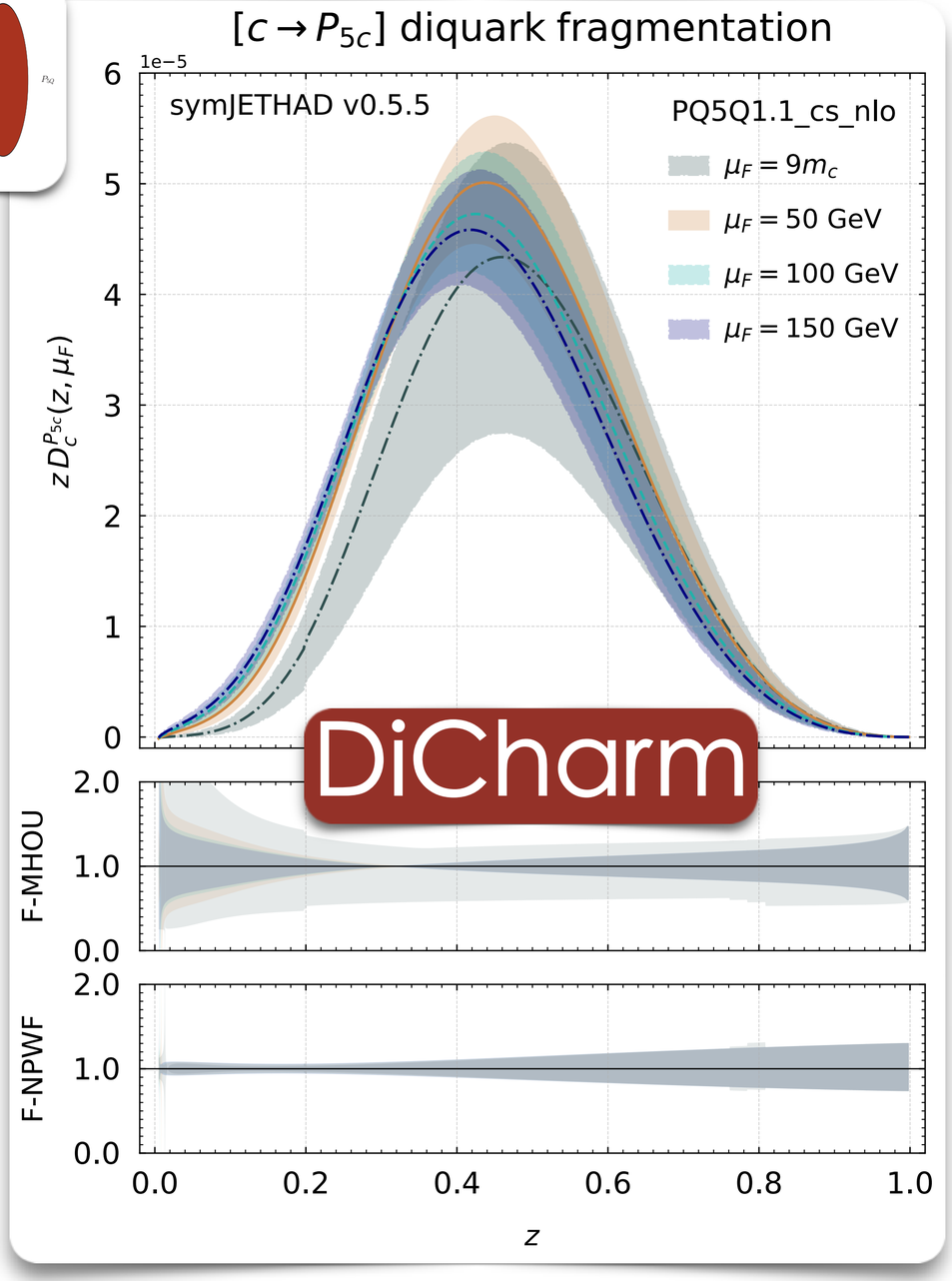
JETHAD
v0.5.5

PQ5Q1.1: Charm Fragmentation to PentaCharm

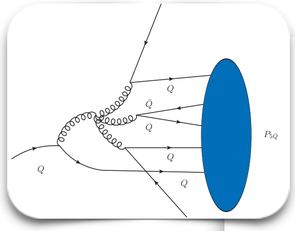


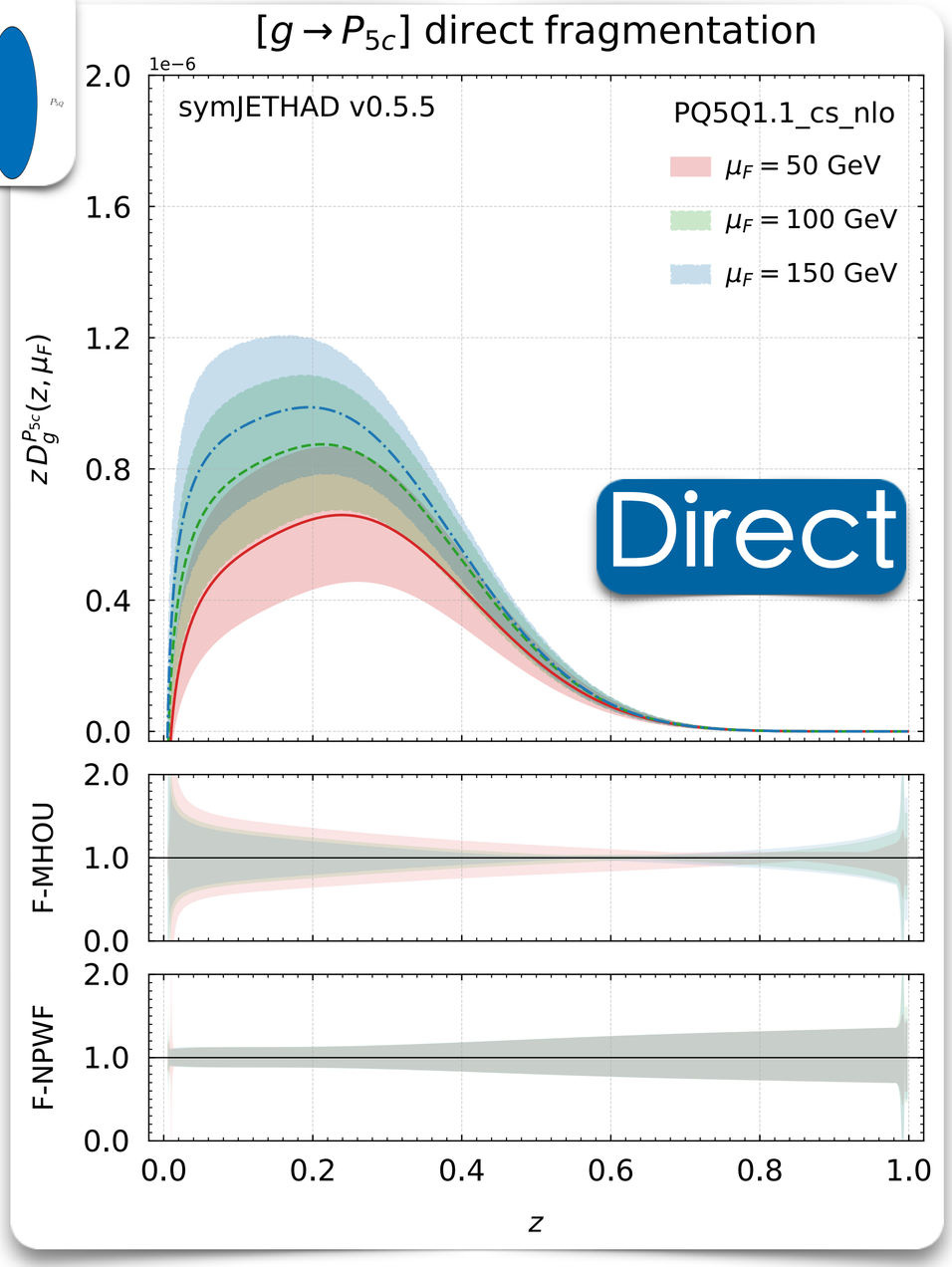


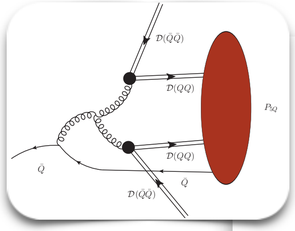


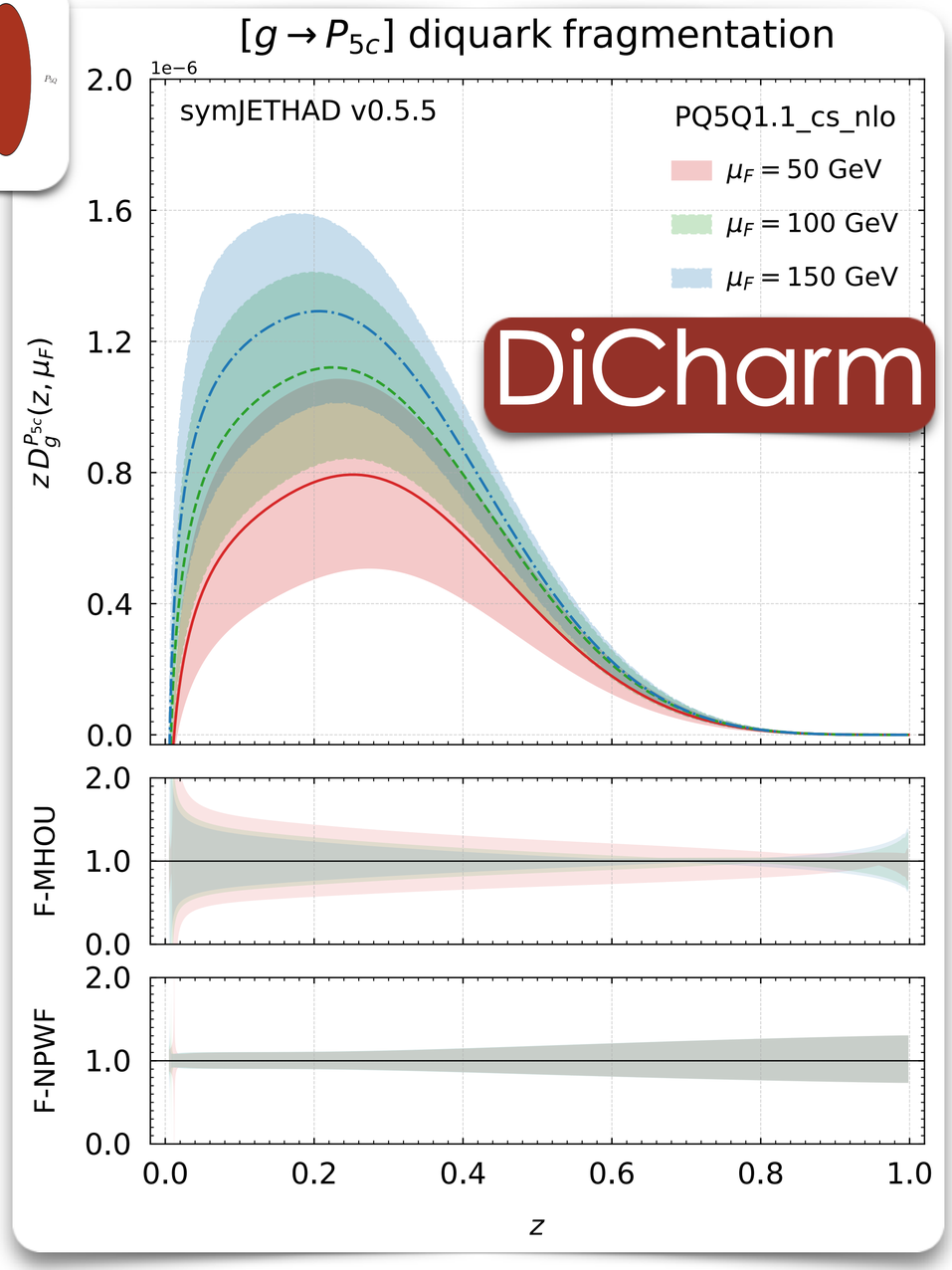


PQ5Q1.1: Gluon Fragmentation to PentaCharm

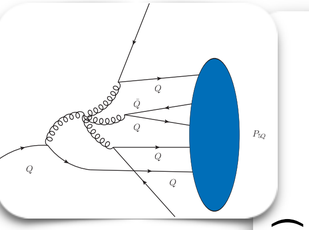


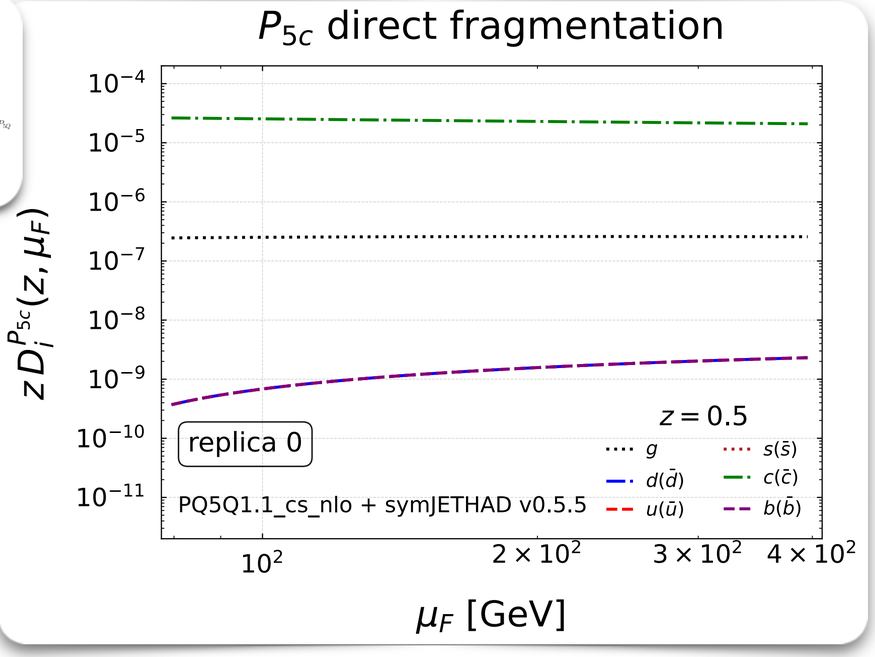


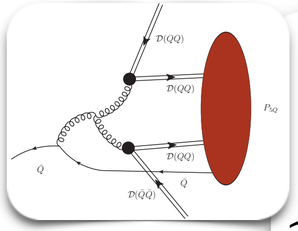


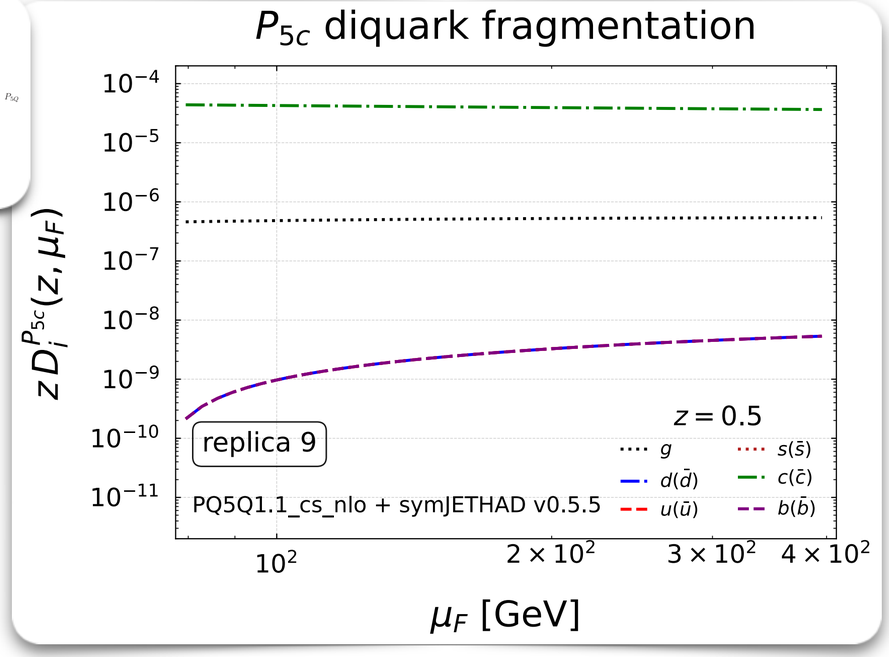


PQ5Q1.1: Energy Spectrum









DiCharm

DiRect

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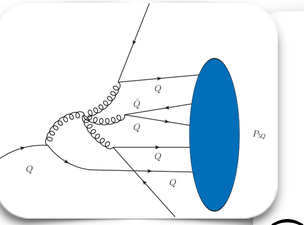
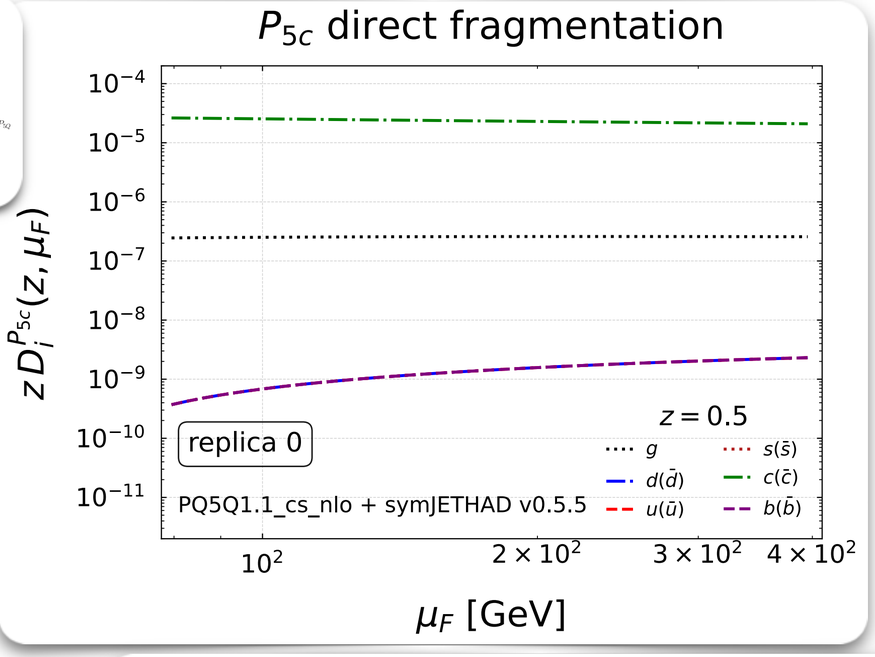
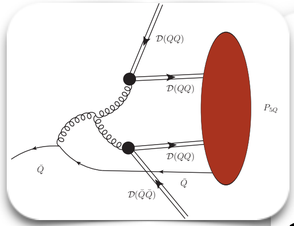
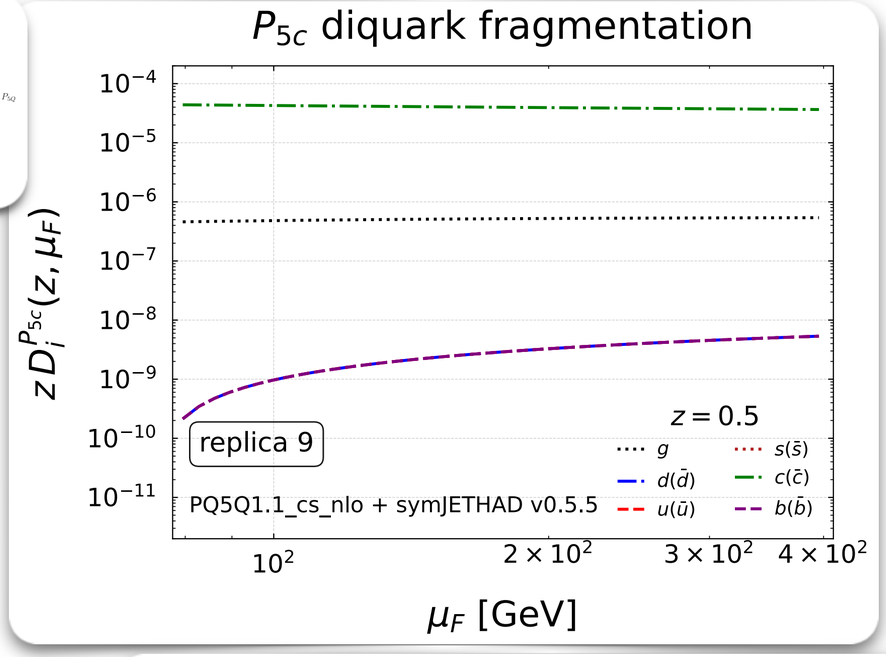
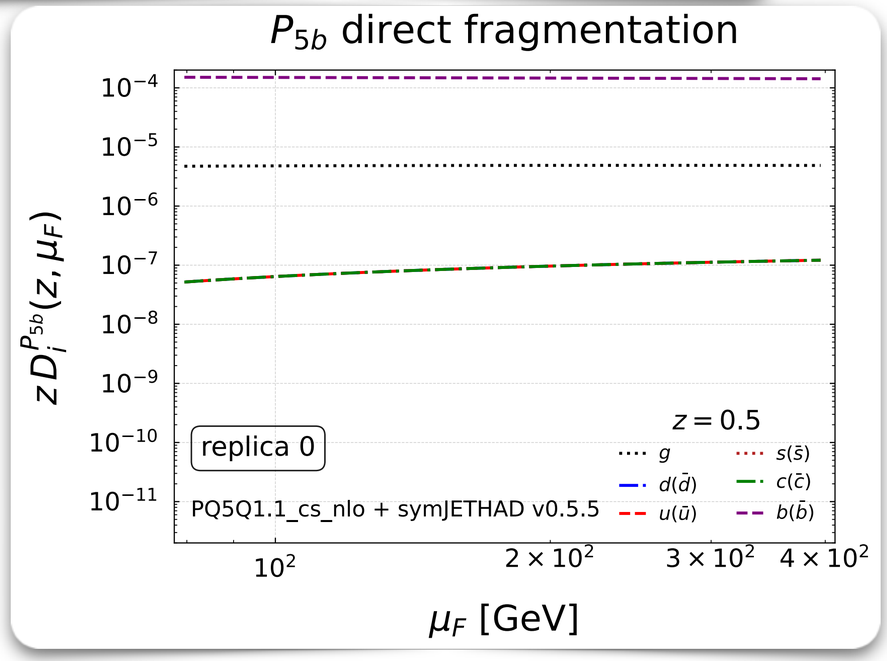




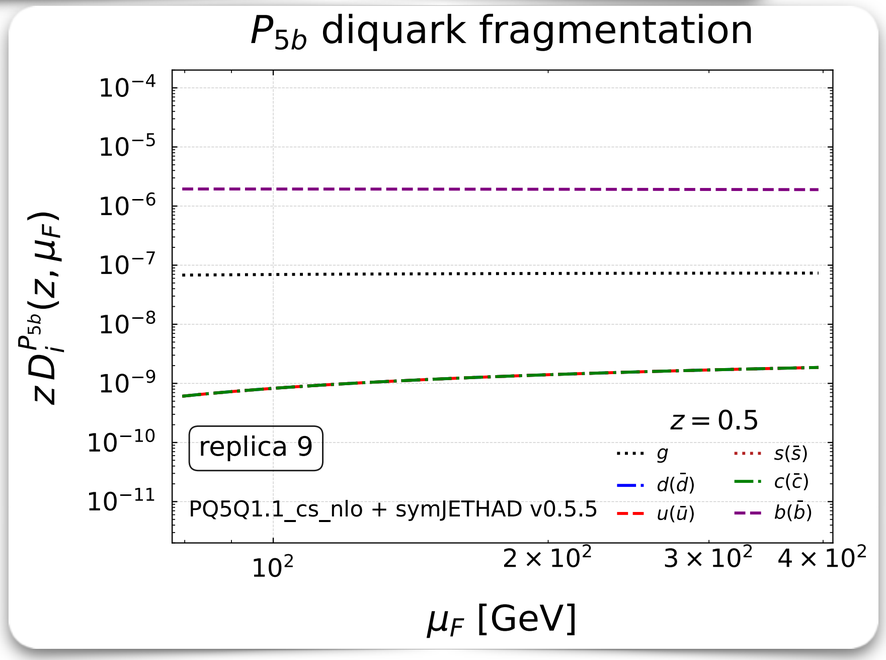




DiCharm



DiRect

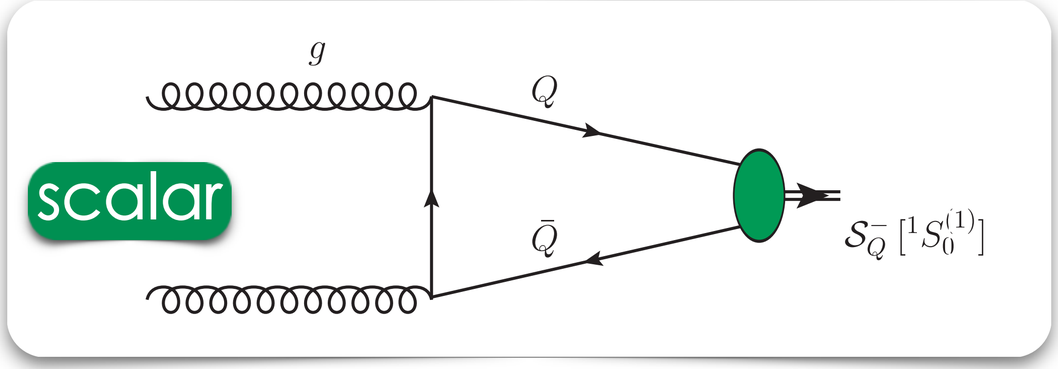


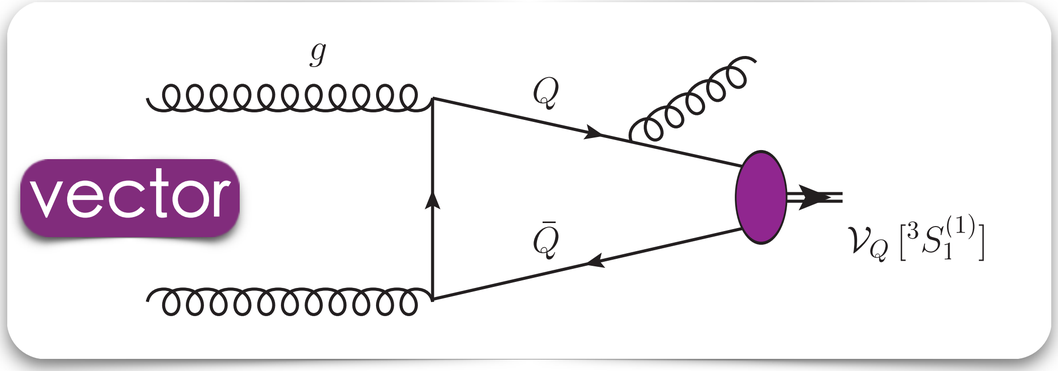
QUARKONIUM FRAGMENTATION

From low energies to high energies

Low $p_T \Rightarrow$ two-parton FFs

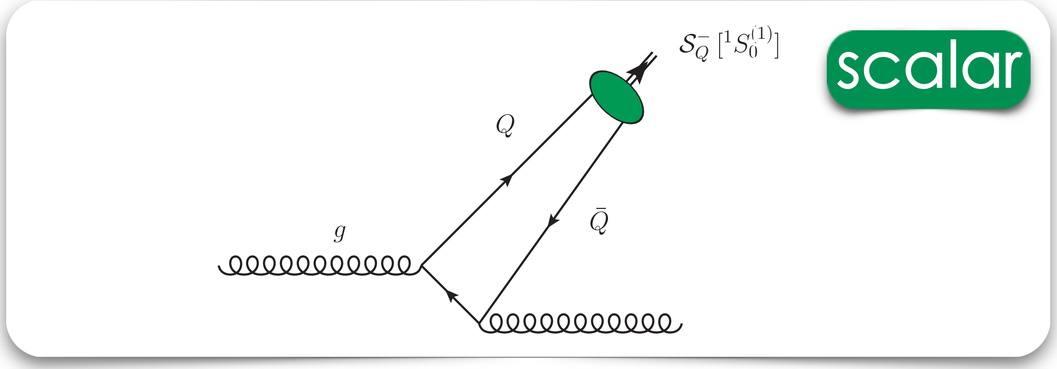
Genuine higher-twist FFNS FFs

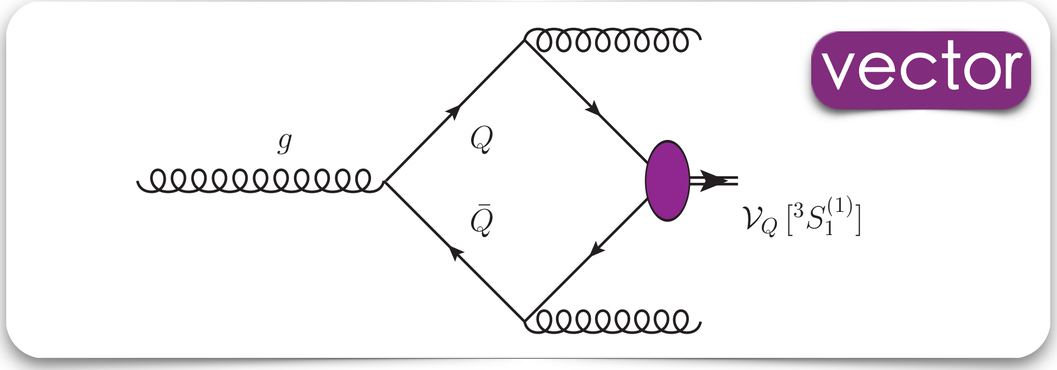




High $p_T \Rightarrow$ single-parton FFs

Twist-2 VFNS FFs + power corrections





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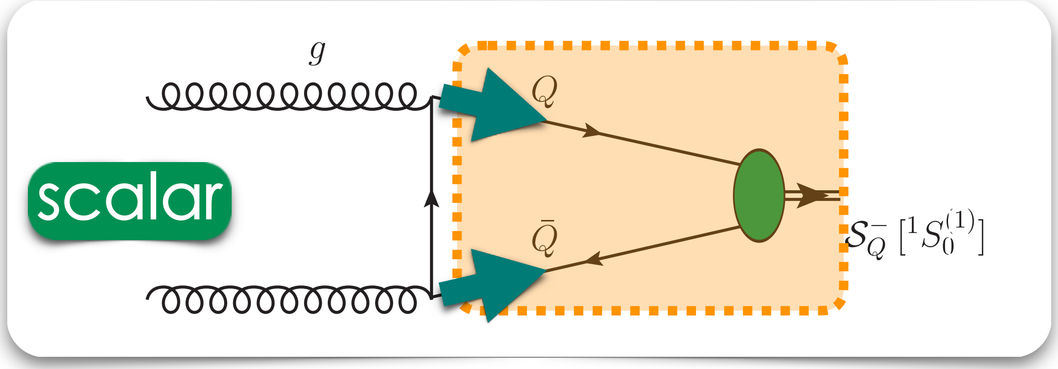

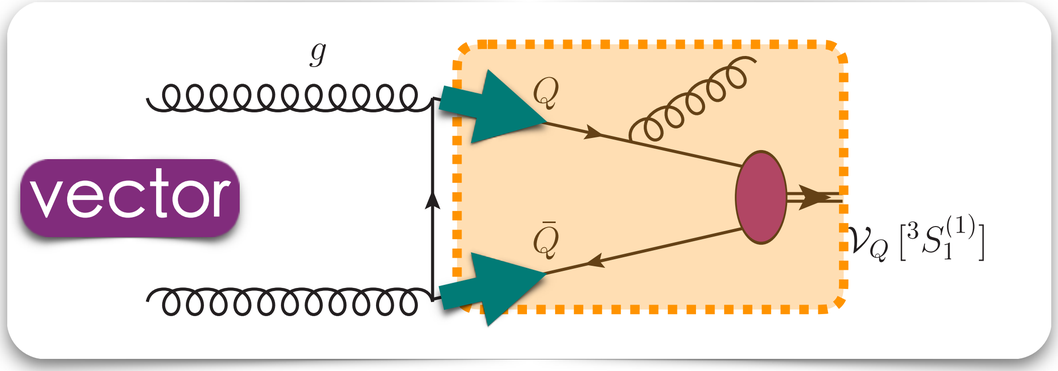

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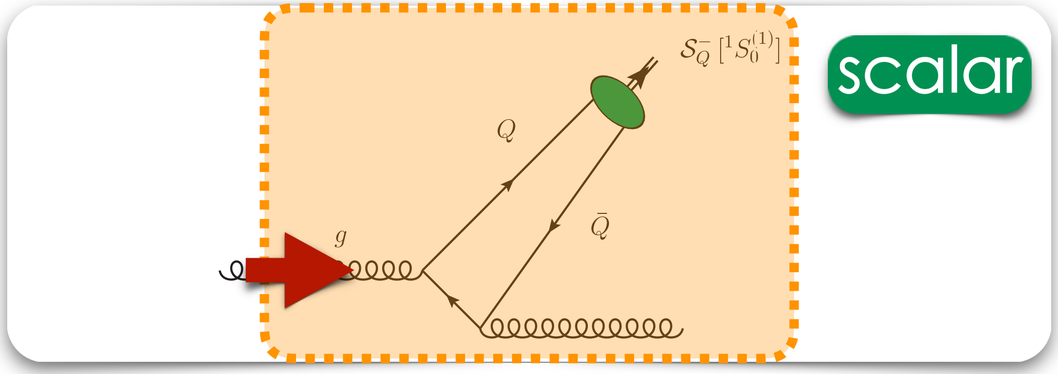
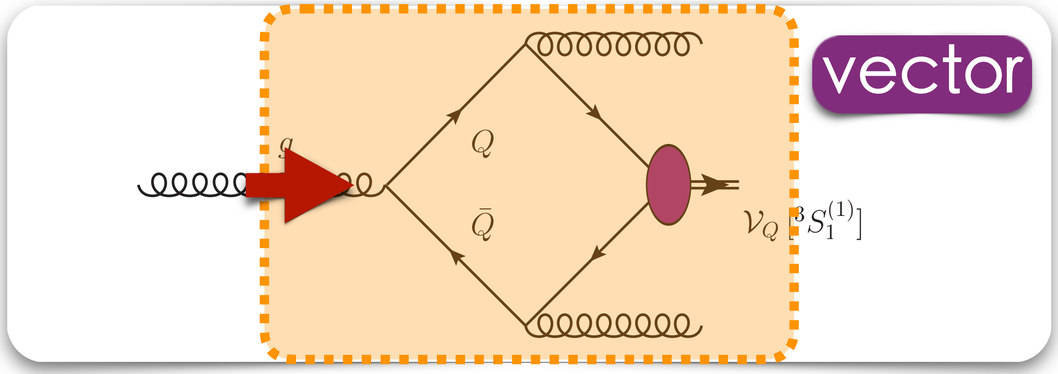




Collinear Fragmentation Correlator (CFC)

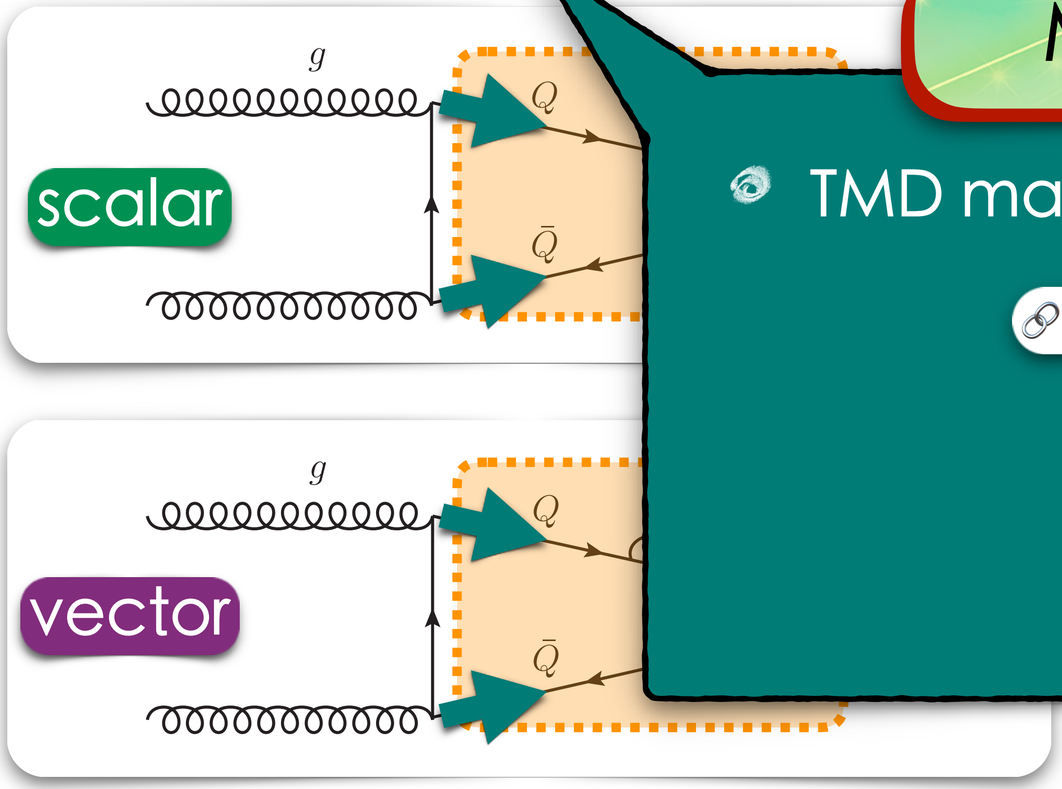
From low energies to high energies

Low p_T $\Rightarrow$ two-parton FFs

Genuine higher-twist FFNS FFs

High p_T $\Rightarrow$ single-parton FFs

Twist-2 VFNS FFs + power corrections



Matching low & high p_T

- TMD matching tails $\Rightarrow$ different singularities

[D. Boer, J. Bor, L. Maxia, C. Pisano, F. Yuan (2023)]

From low energies to high energies

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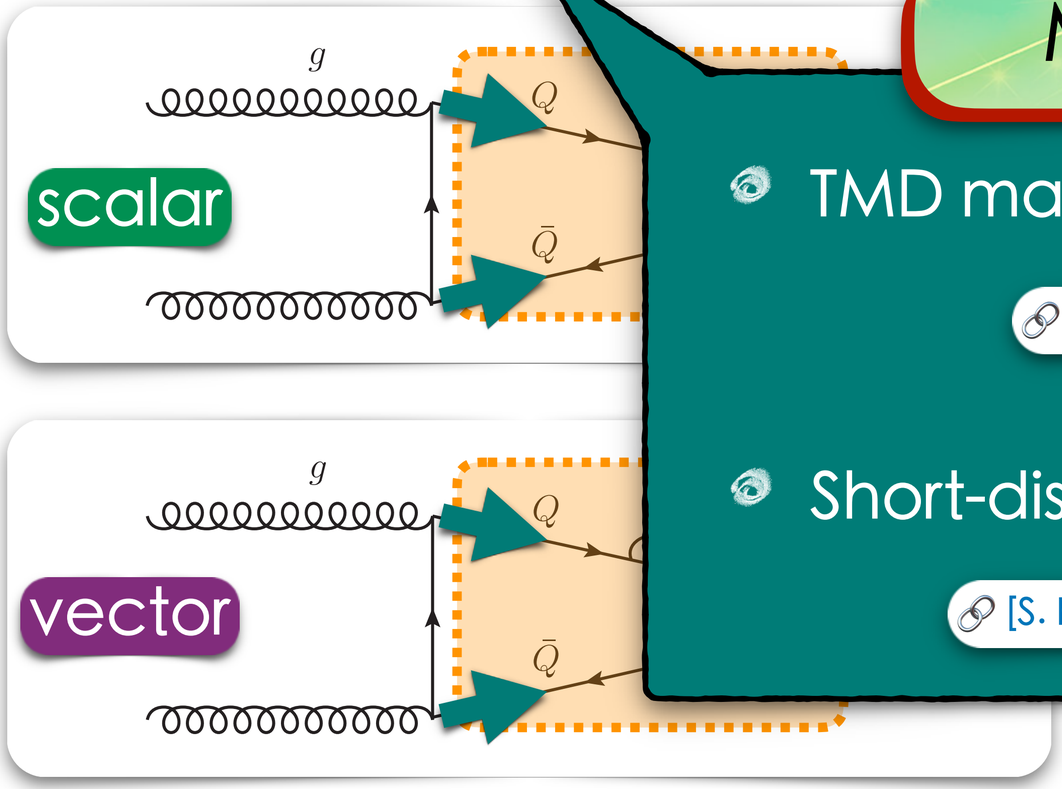


Matching low & high p_T

- TMD matching tails $\Rightarrow$ different singularities

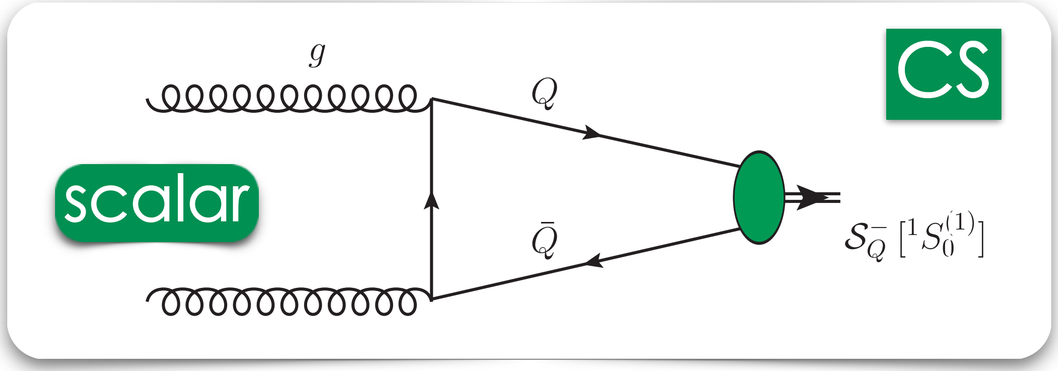
  [D. Boer, J. Bor, L. Maxia, C. Pisano, F. Yuan (2023)]

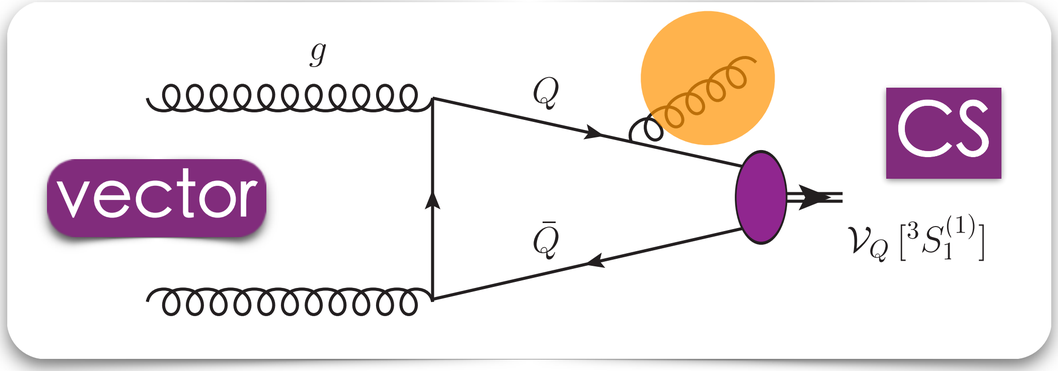
- Short-distance $\Leftrightarrow$ double-parton FFs (SCET)

  [S. Fleming, A.K. Leibovich, T. Mehen, I.Z. Rothstein (2012)]

From low energies to high energies

Low energy, low p_T
Short-distance production

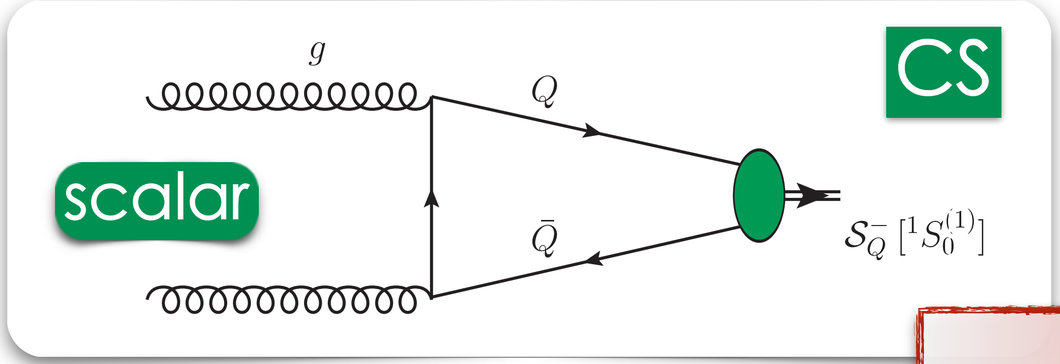


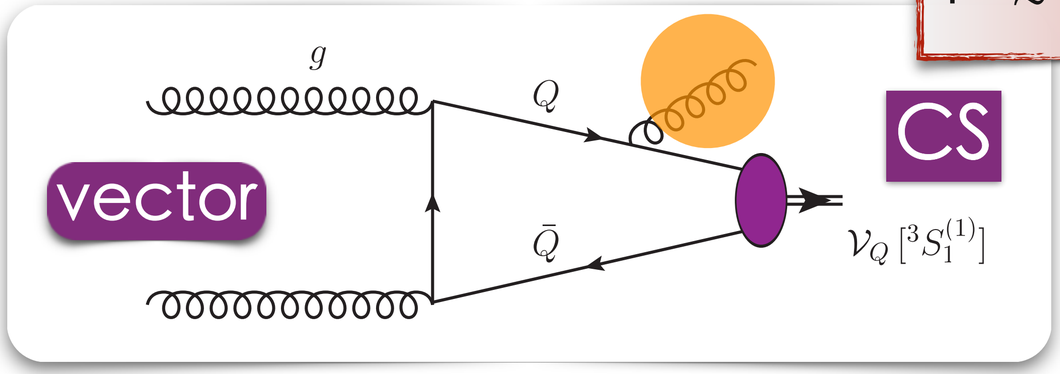


Extra gluon due to Landau-Yang selection rule

From low energies to high energies

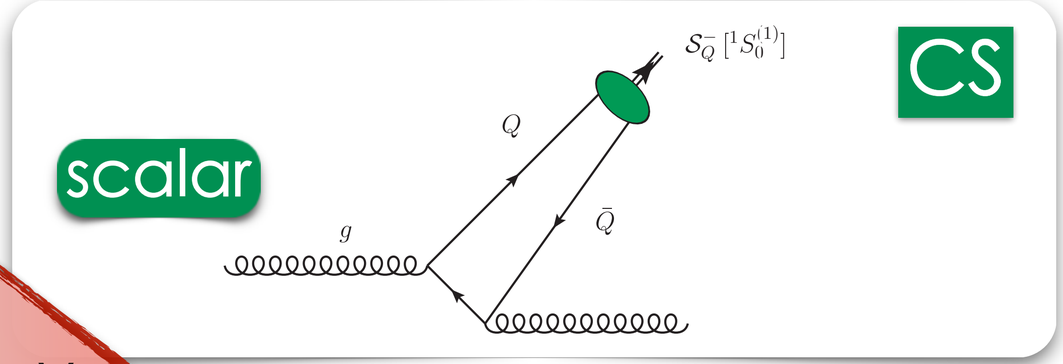
Low energy, low p_T
Short-distance production

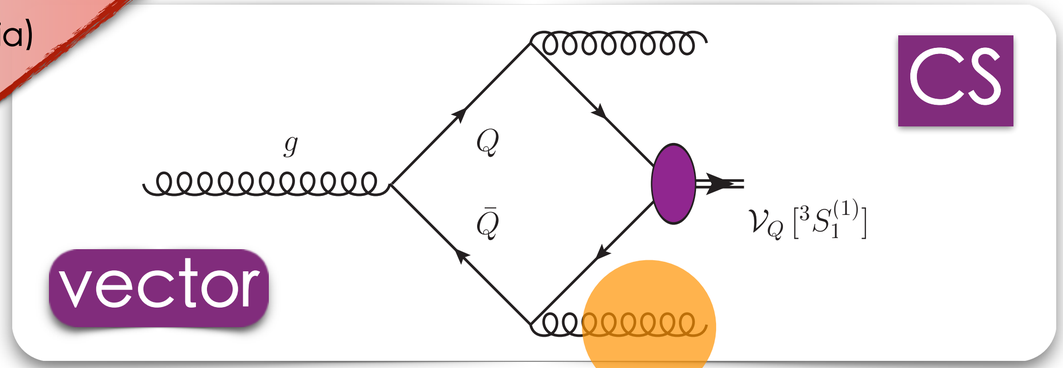




$p_T \gtrsim 10 \div 15$ GeV
(charmonia)

High energy, high p_T
Single-parton fragmentation





Extra gluon due to Landau-Yang selection rule

HF-NRevo: Initial-scale NRCQD inputs

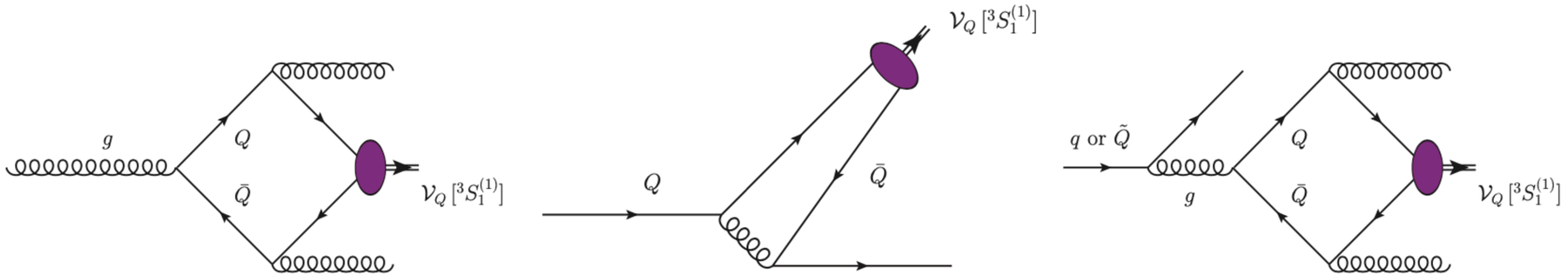


Fig. 1 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet vector quarkonium $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Right panel: a leading diagram for the fragmentation of a nonconstituent light (q) or heavy ($\tilde{Q}$) quark to $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^4)$. Violet blobs refer to the $\mathcal{V}_Q\,[^3S_1^{(1)}]$ nonperturbative NRQCD LDME.

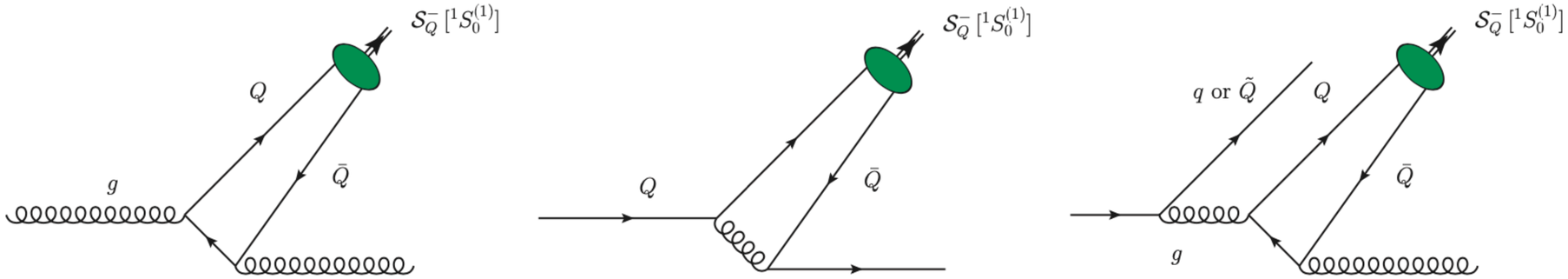
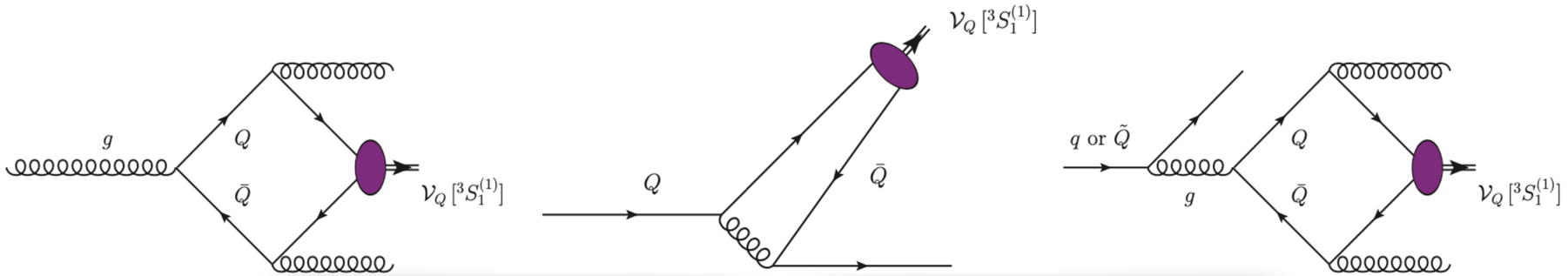


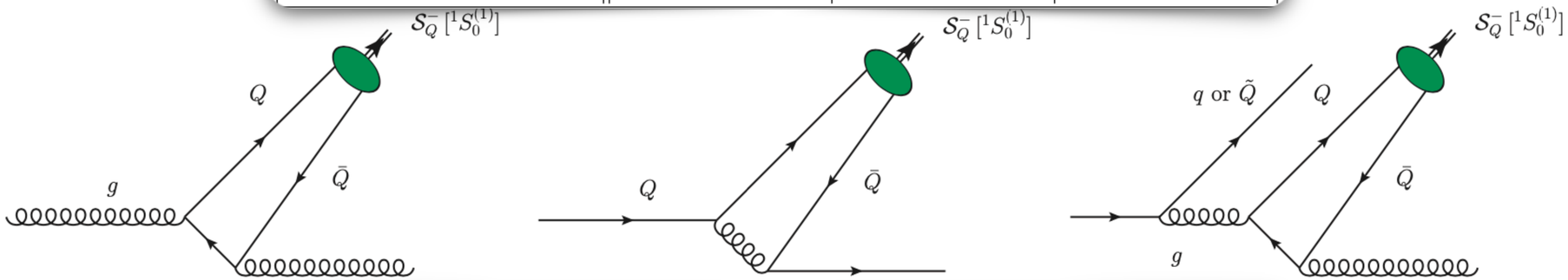
Fig. 2 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet pseudoscalar quarkonium $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Right panel: a leading diagram for the fragmentation of a nonconstituent light (q) or heavy ($\tilde{Q}$) quark to $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Green blobs refer to the $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ nonperturbative NRQCD LDME.

[F. G. C., in preparation]

HF-NRevo: Initial-scale NRCQD inputs



Quarkonium ($\mathcal{Q}$)	$g \to \mathcal{Q}$	$Q \to \mathcal{Q}$	q or $\tilde{Q} \to \mathcal{Q}$
$\mathcal{Q} \equiv \mathcal{V}_Q\,[^1S_0^{(1)}] \equiv J/\psi, \Upsilon$	–	$\mathcal{O}(\alpha_s^2) \equiv$ LO	–
	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	–
	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO
	$\vdots$	$\vdots$	$\vdots$

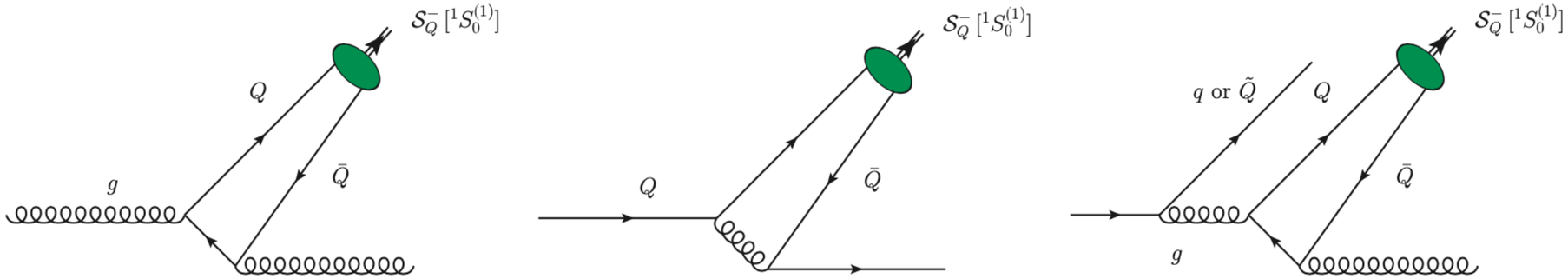


$\mathcal{Q} \equiv \mathcal{S}_Q^-\,[^3S_1^{(1)}] \equiv \eta_c, \eta_b$	$\mathcal{O}(\alpha_s^2) \equiv$ LO	$\mathcal{O}(\alpha_s^2) \equiv$ LO	–
	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	$\mathcal{O}(\alpha_s^3) \equiv$ NLO
	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO
	$\vdots$	$\vdots$	$\vdots$

[F. G. C., in preparation]

HF-NRevo: Initial-scale NRCQD inputs

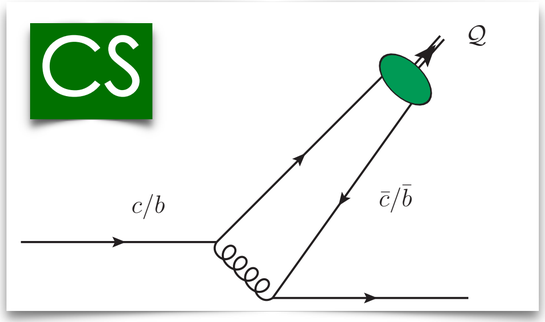
$\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ quarkonium	$\mu_{F,0}(g \to \mathcal{S}_Q^-)$	$\mu_{F,0}(d,u,s \to \mathcal{S}_Q^-)$	$\mu_{F,0}(Q \to \mathcal{S}_Q^-)$	$\mu_{F,0}(\tilde{Q} \to \mathcal{S}_Q^-)$	$Q_0 \equiv \max(\{\mu_{F,0}\})$
η_c	$2m_c$	$m_{d,u,s} + 2m_c$	$3m_c$	$m_b + 2m_c$	$m_b + 2m_c$
η_b	$2m_b$	$m_{d,u,s} + 2m_b$	$3m_b$	$m_c + 2m_b$	$3m_b$



[F. G. C., in preparation]

Vector quarkonium from single-parton fragmentation

¡ *Let us consider J/ψ and Υ at large p_T $\rightarrow$ initial-scale* ***heavy-quark*** + ***gluon*** *from* ***NRQCD*** !



$$D_{\mathcal{Q}}^{\mathcal{Q}}(z, \mu_F \equiv \mu_0) = D_{\mathcal{Q}}^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3} |\mathcal{R}_{\mathcal{Q}}(0)|^2 \, \Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

$(Q \rightarrow \mathcal{Q}\, Q)$ at $\mu_0 = 3m_Q$

(LO) [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]
(NLO) [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

[My talk at the Higgs Centre, Edinburgh (2023)]
[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

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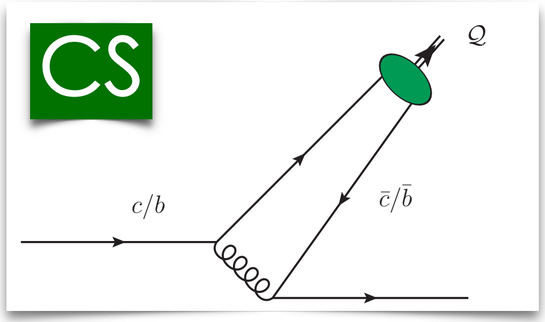

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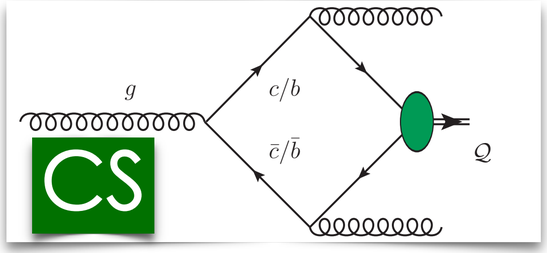

$$D_g^{\mathcal{Q}}(z,2m_Q) = \frac{5}{36(2\pi)^2}\alpha_s^3(2m_Q)\frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_{\mathcal{Q}}^3}\int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2}$$
$$\sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau)\frac{1+\xi-2\tau}{2(\tau-\xi)\sqrt{\tau^2-\xi}} \ln\left(\frac{\tau-\xi+\sqrt{\tau^2-\xi}}{\tau-\xi-\sqrt{\tau^2-\xi}}\right)\right],$$

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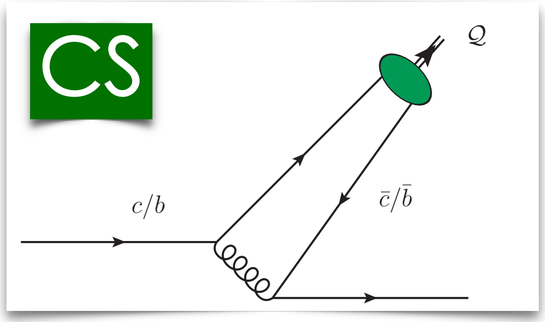

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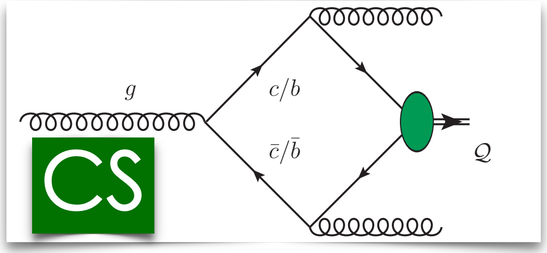

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[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

NRFF1.0
quarkonium FFs

=

APFEL++/EKO

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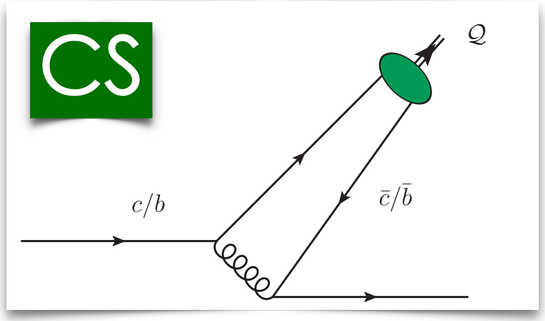

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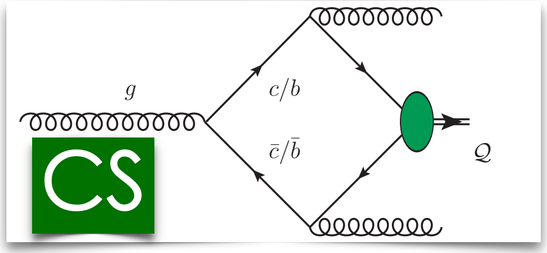
+



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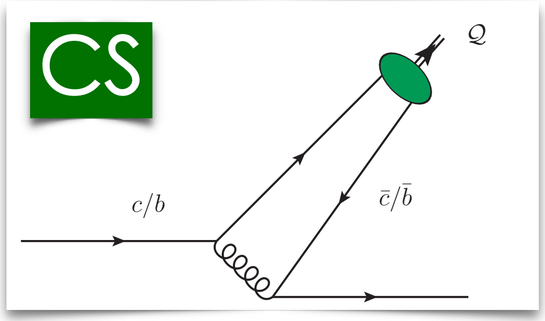

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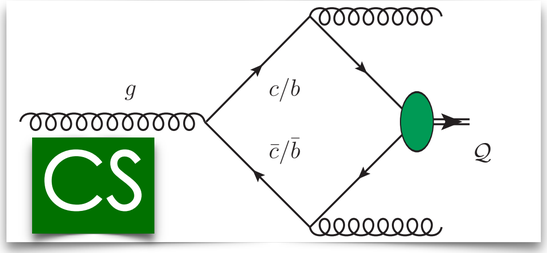

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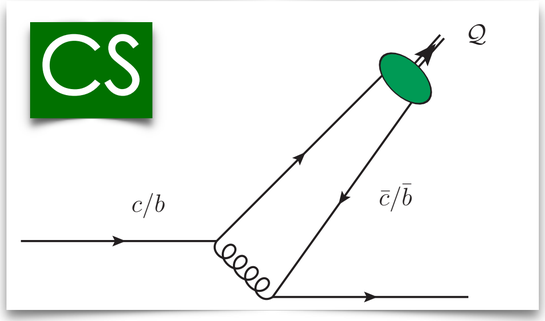

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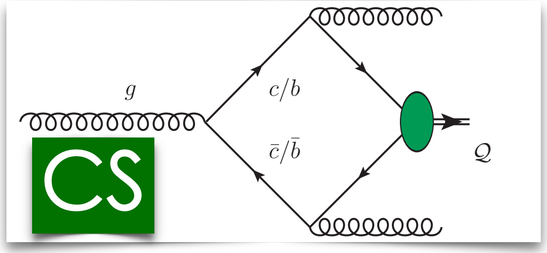

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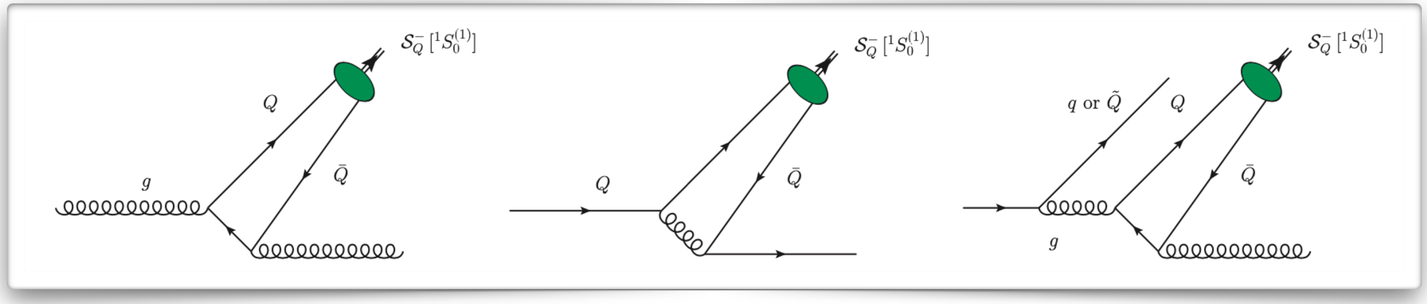


Scalar η_c

HF-NRevo for $\eta_c[^1S_0^{(1)}]$ collinear fragmentation

Partonic hard factor

DGLAP AOevo

All-Order evolution (numeric)

DGLAP EDevo

Expanded Decoupled evolution

NRQCD

SDCs

LDMEs

g
$\tilde{q}$
c
b

$2m_c$

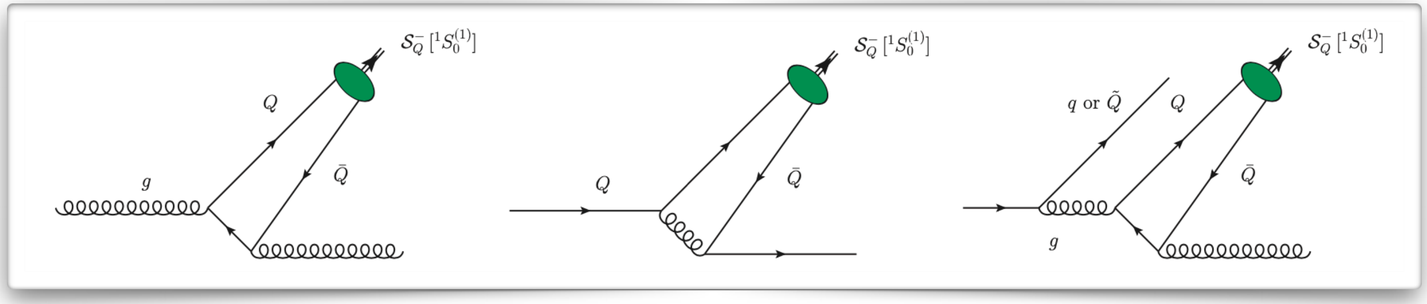
$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy

Evolution-ready scale $Q_0 \equiv m_b + 2m_c$ $3m_c$ $m_{\tilde{q}} + 2m_c$

Time

HF-NRevo: Initial-scale NRCQD inputs



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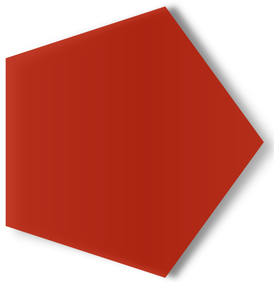
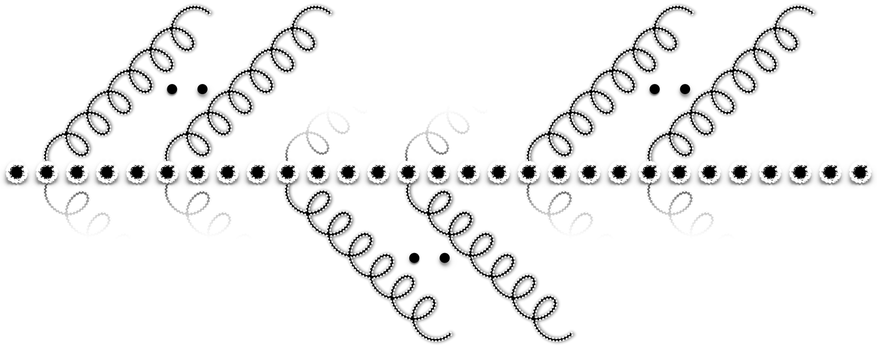


DGLAP AOevo

All-Order evolution (numeric)



DGLAP EDevo

Expanded Decoupled evolution

NRQCD

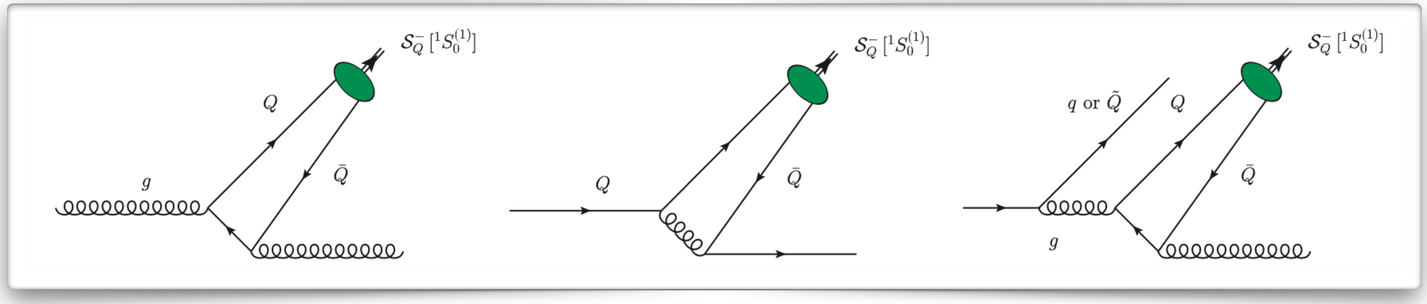
SDCs

LDMEs

$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy — Evolution-ready scale $Q_0 \equiv m_b + 2m_c$ — $3m_c$ — $m_{\tilde{q}} + 2m_c$ — Time

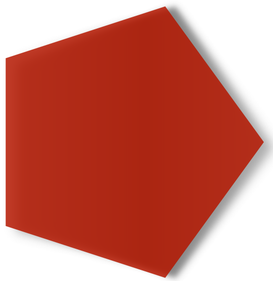
HF-NRevo: Initial-scale NRCQD inputs



Scalar η_c

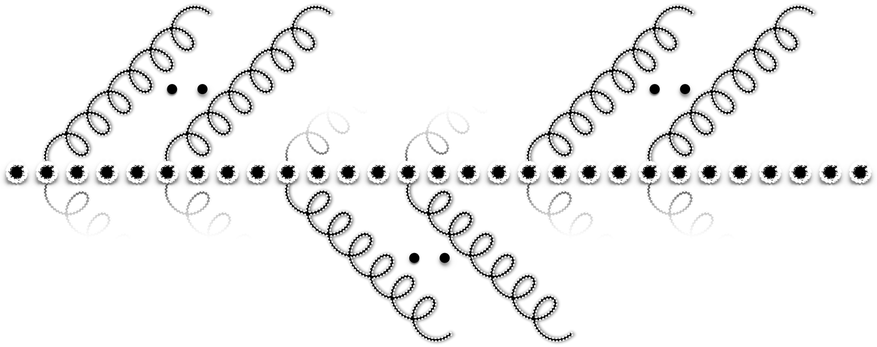
HF-NRevo for $\eta_c[^1S_0^{(1)}]$ collinear fragmentation

Partonic hard factor



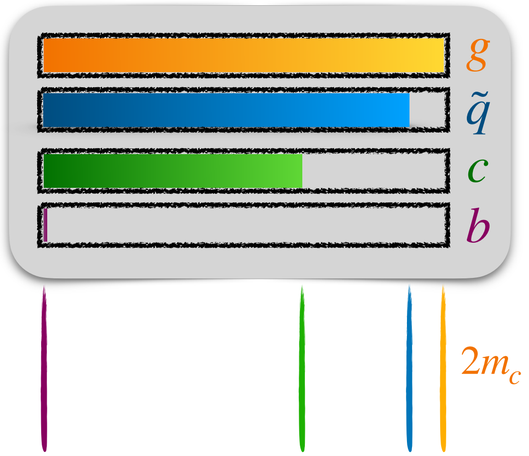
DGLAP AOevo

All-Order evolution (numeric)



DGLAP EDevo

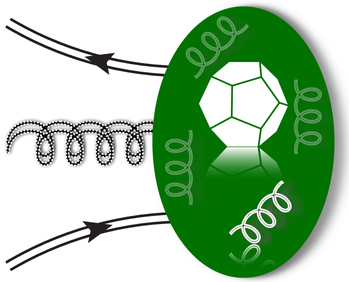
Expanded Decoupled evolution



NRQCD

SDCs

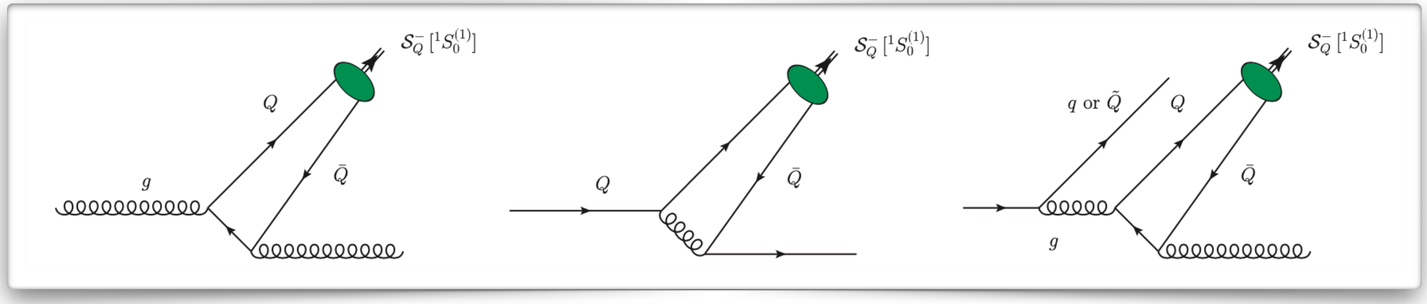
LDMEs



$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy — Evolution-ready scale $Q_0 \equiv m_b + 2m_c$ — $3m_c$ — $m_{\tilde{q}} + 2m_c$ — Time

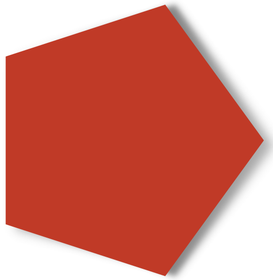
HF-NRevo: Initial-scale NRCQD inputs



Scalar η_b

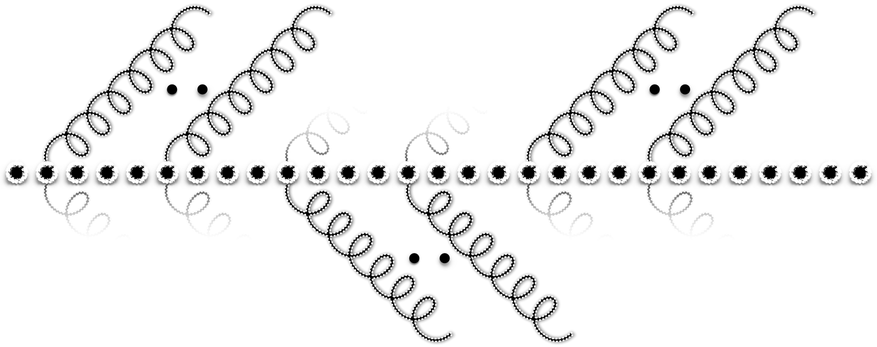
HF-NRevo for $\eta_b[^1S_0^{(1)}]$ collinear fragmentation

Partonic hard factor



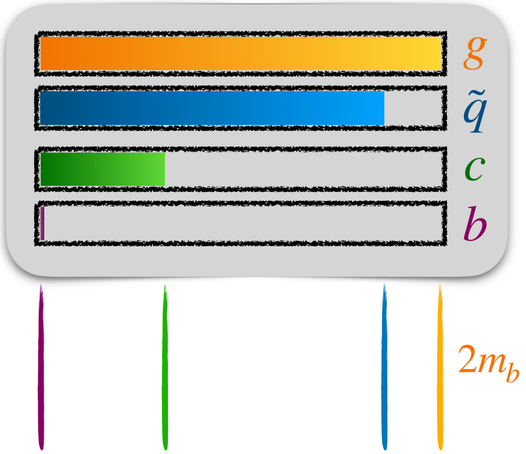
DGLAP AOevo

All-Order evolution (numeric)



DGLAP EDevo

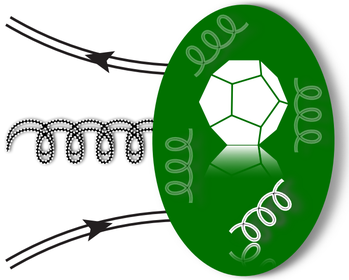
Expanded Decoupled evolution



NRQCD

SDCs

LDMEs

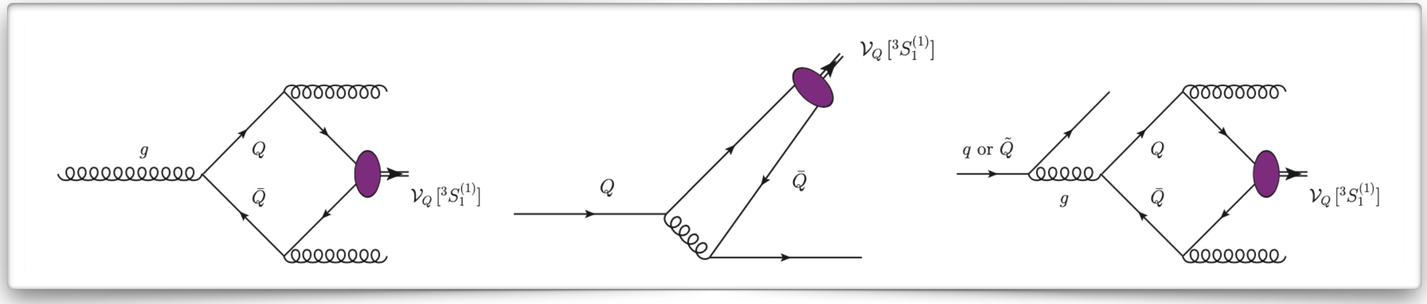


$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy ⟷ Time

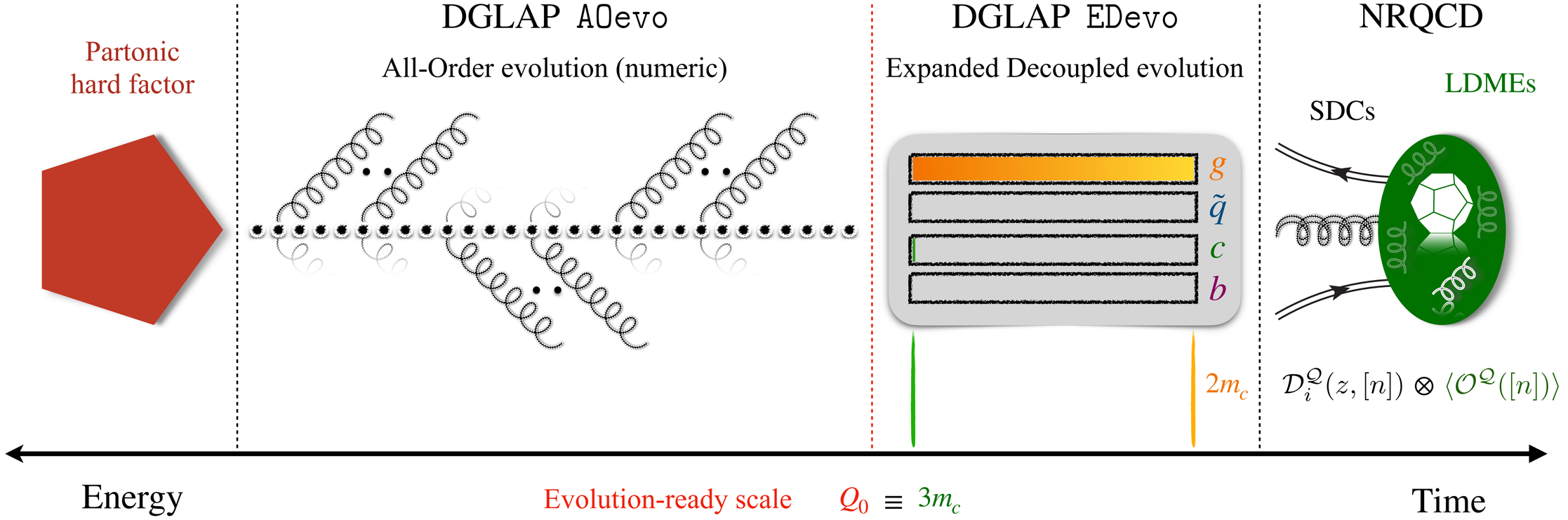
Evolution-ready scale $Q_0 \equiv 3m_b$ $\quad m_c + 2m_b$ $\quad m_{\tilde{q}} + 2m_b$

HF-NRevo: Initial-scale NRCQD inputs

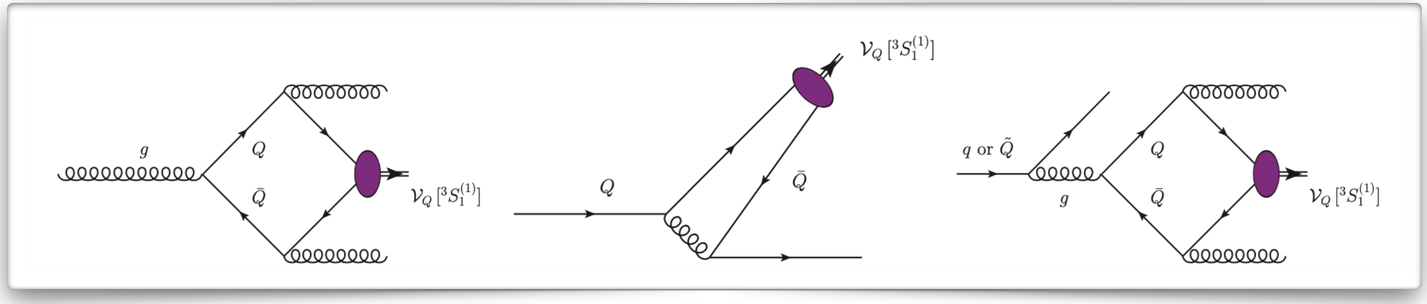


Vector J/ψ

HF-NRevo for $J/\psi[^3S_1^{(1)}]$ collinear fragmentation

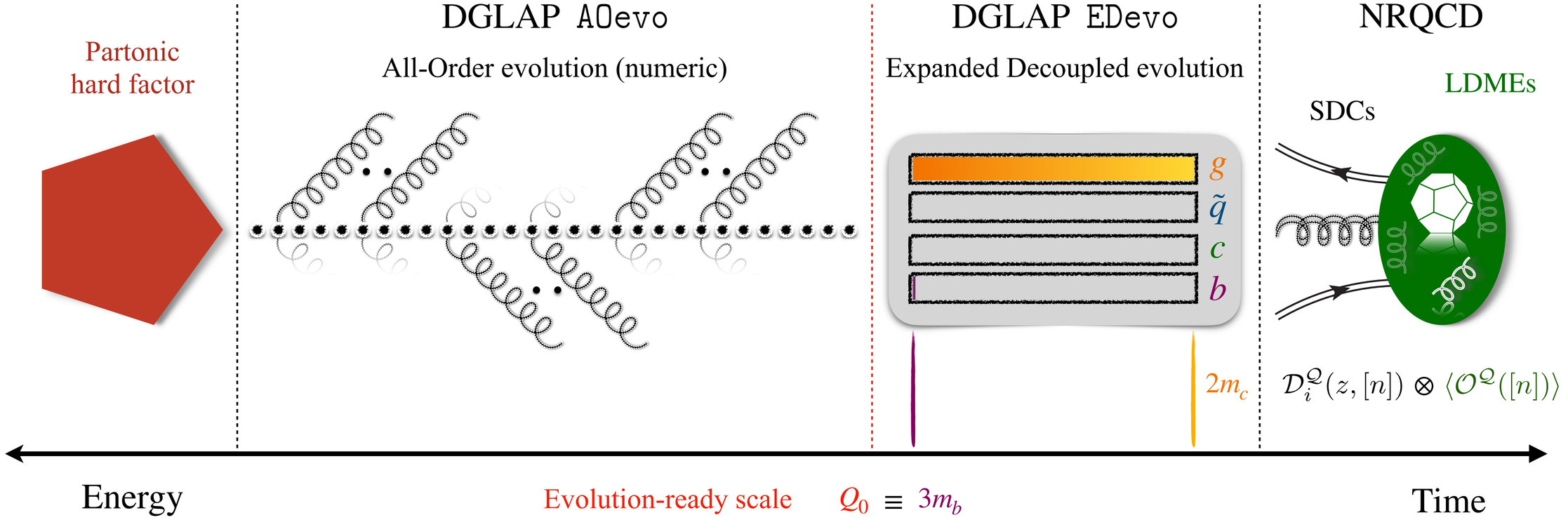


HF-NRevo: Initial-scale NRCQD inputs



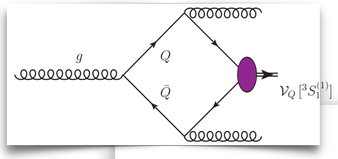
Vector Υ

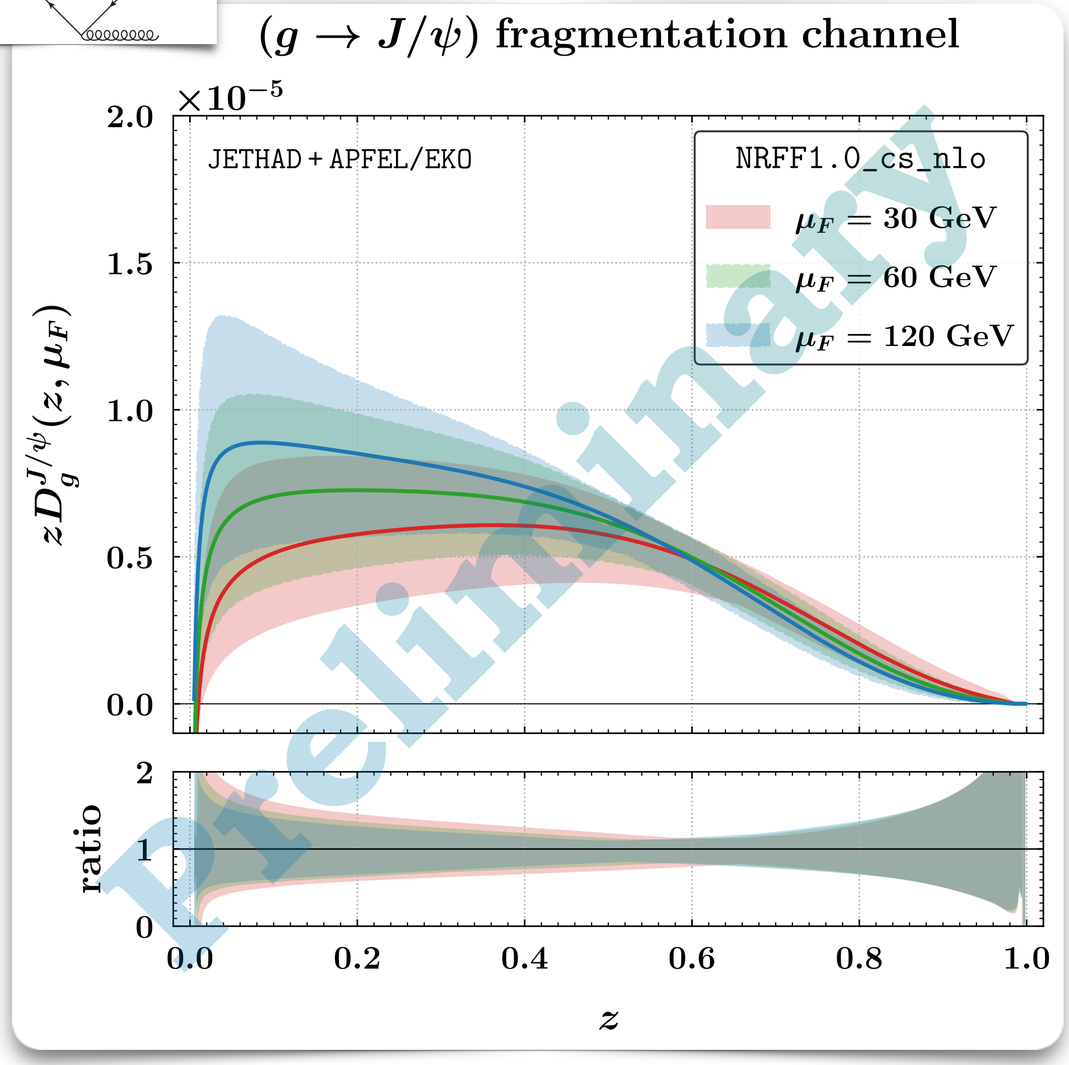
HF-NRevo for $\Upsilon[^3S_1^{(1)}]$ collinear fragmentation



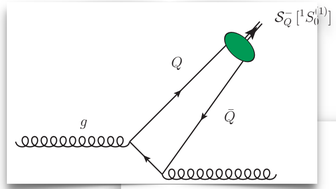
NRFF1.0: Gluon fragmentation to charmonia

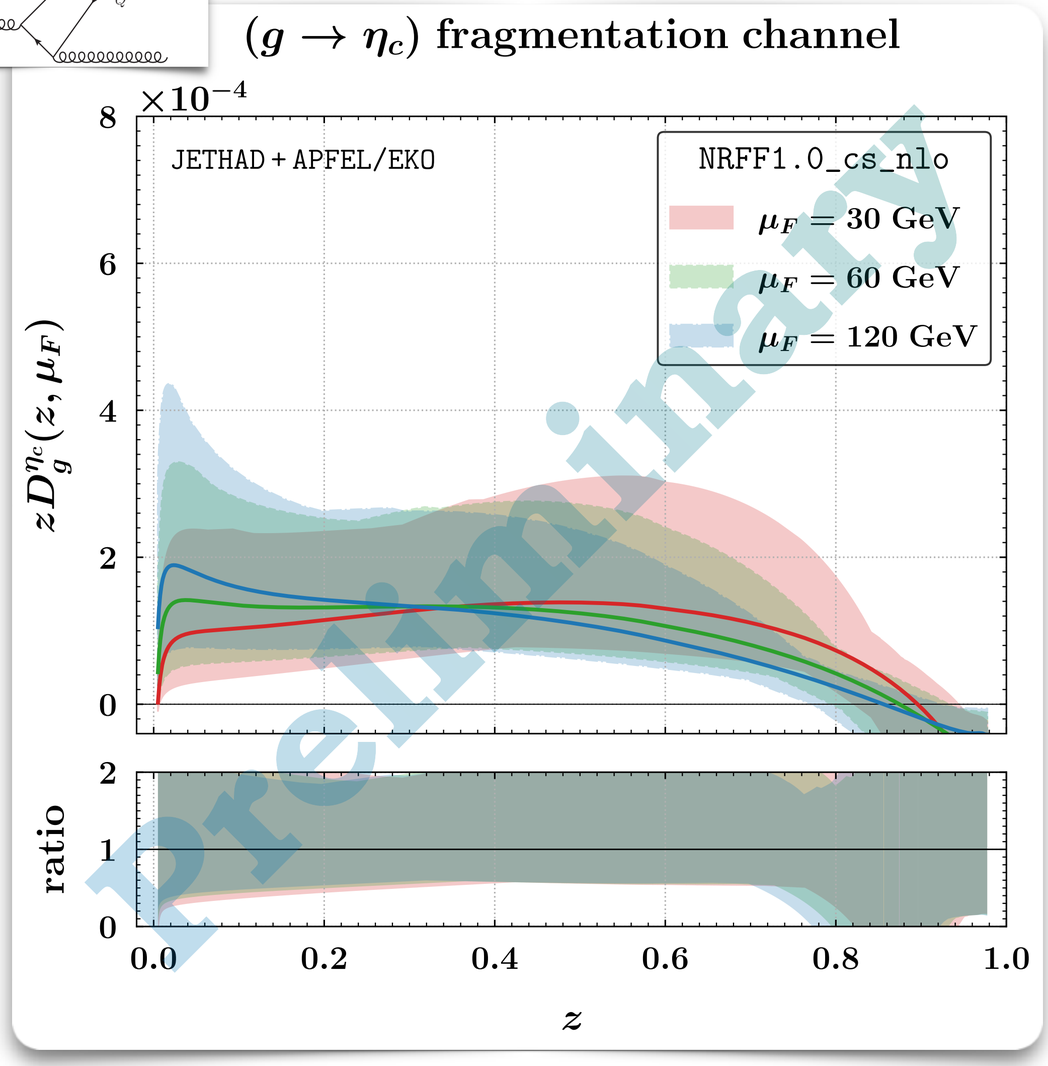
Vector J/ψ





Scalar η_c

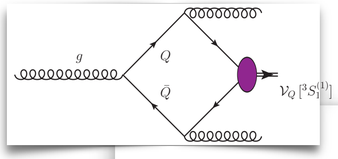


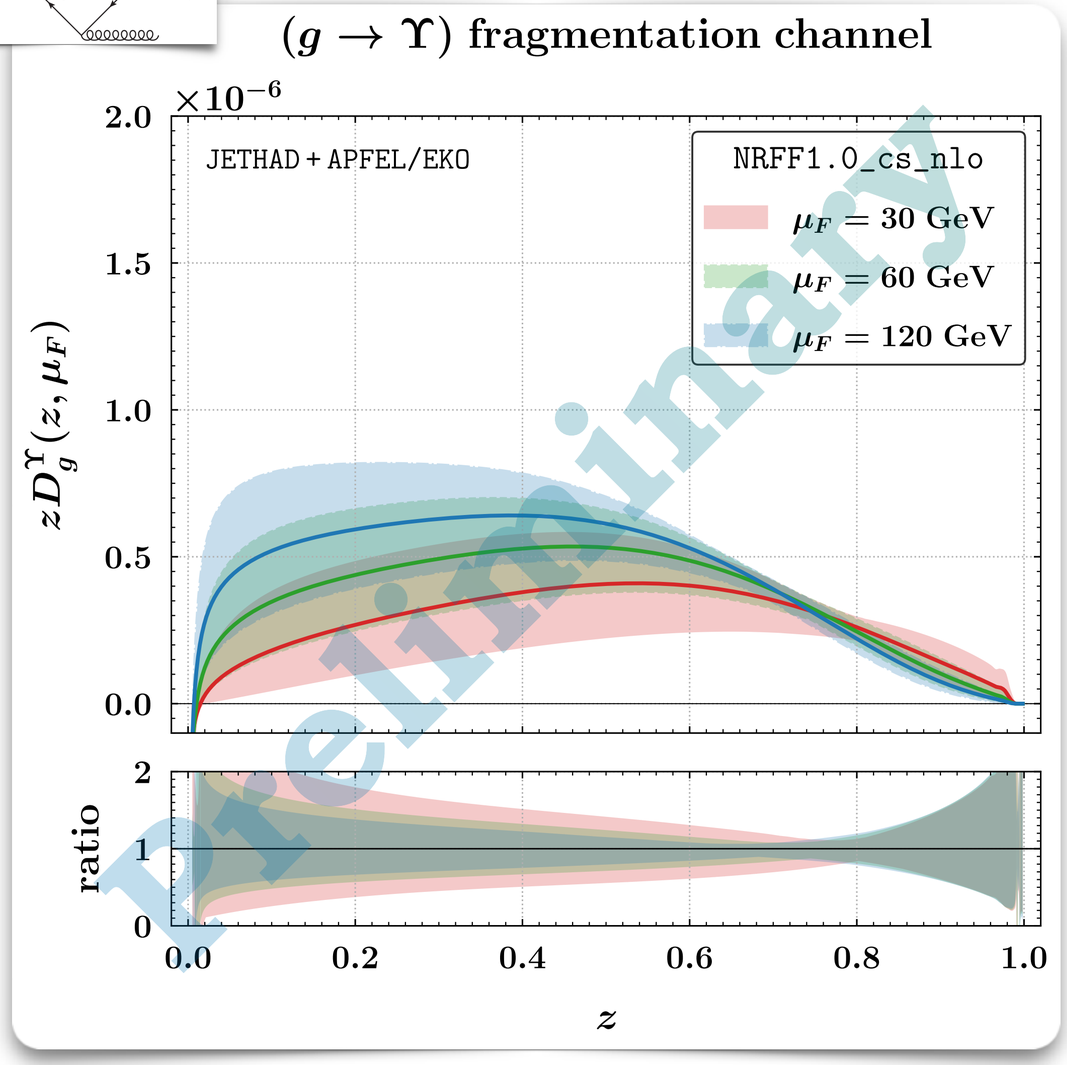


[F. G. C., in preparation]

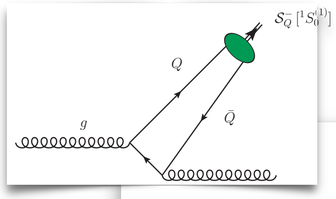
NRFF1.0: Gluon fragmentation to bottomonia

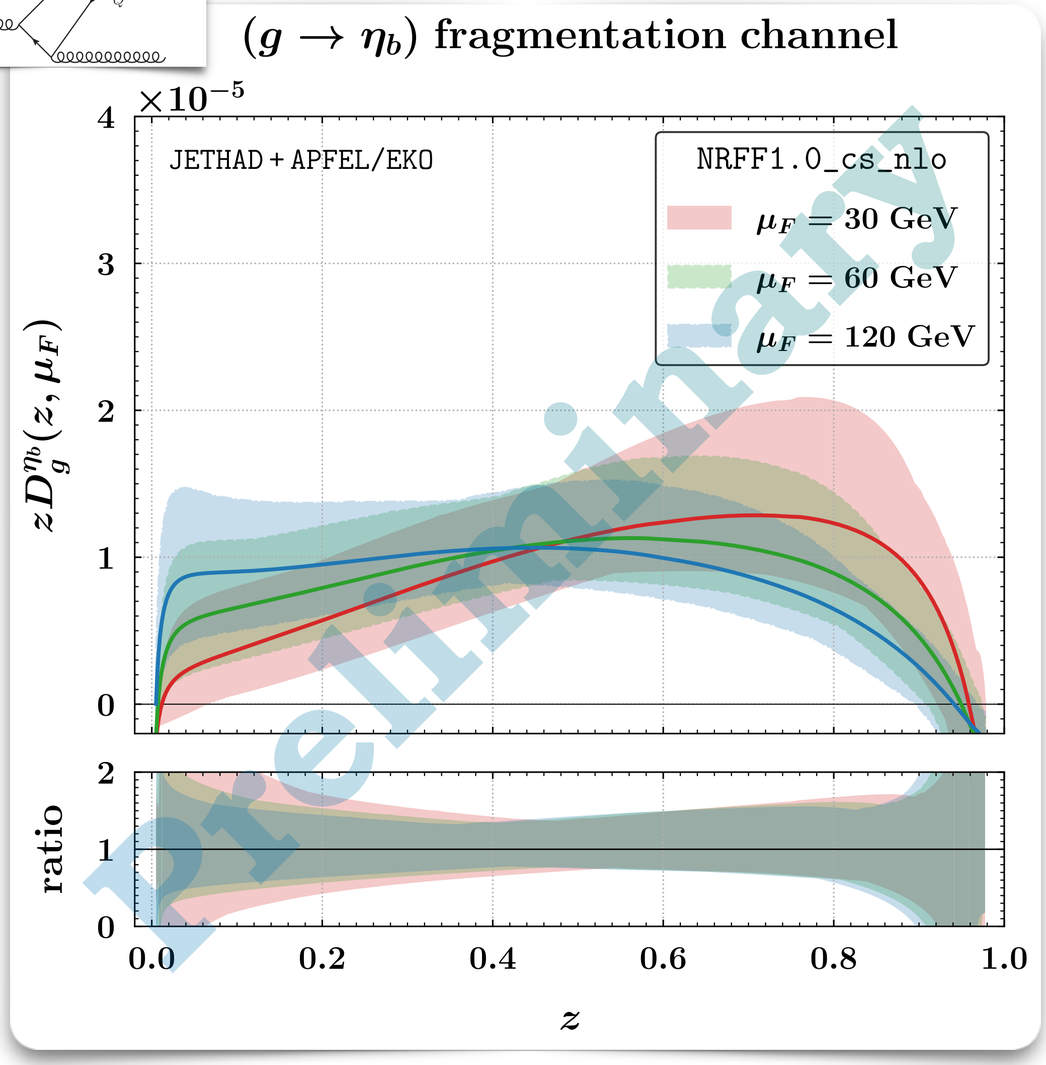
Vector Υ





Scalar η_b

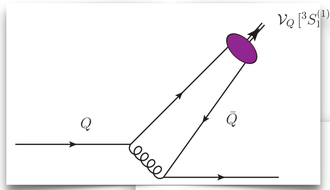


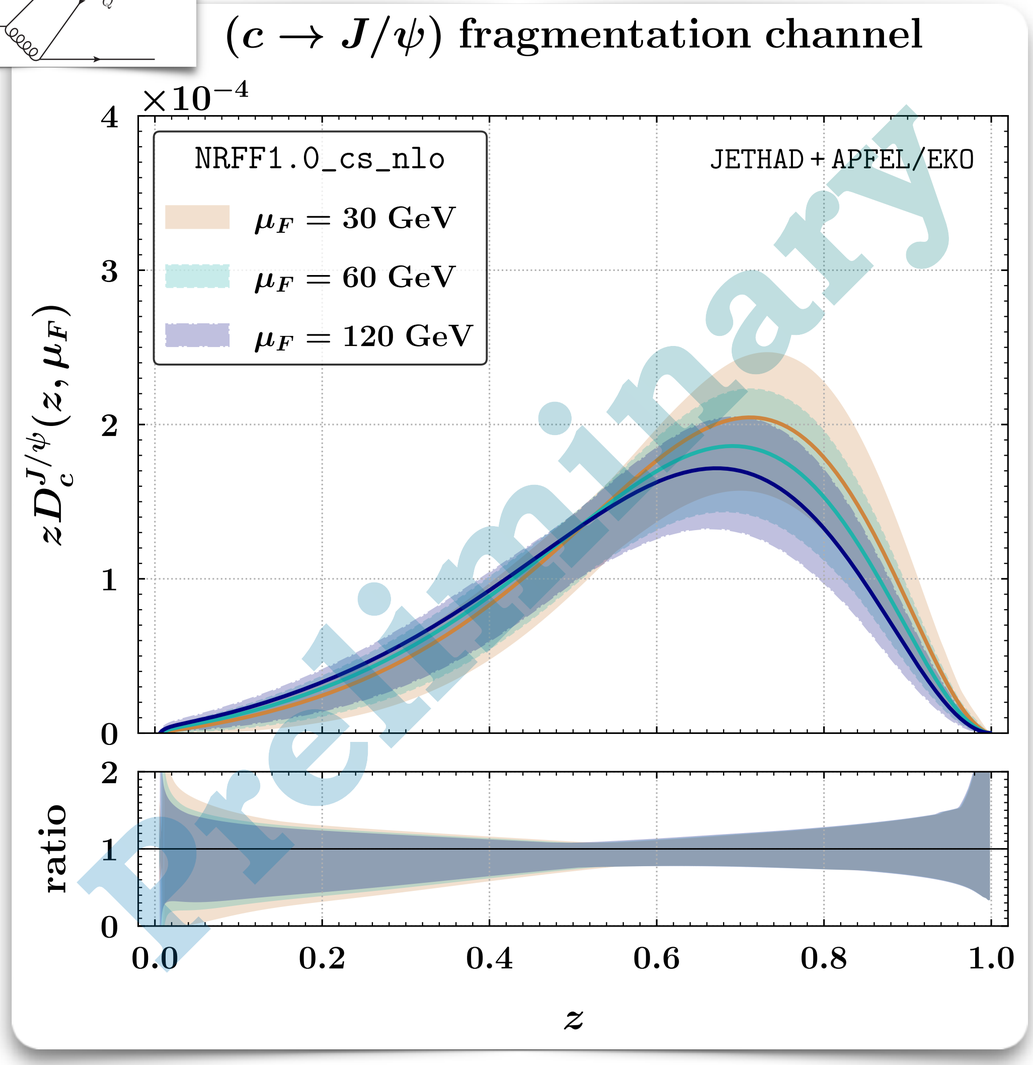


[F. G. C., in preparation]

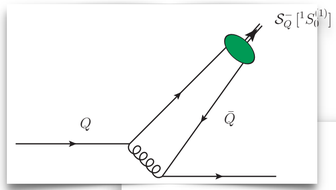
NRFF1.0: Charm fragmentation to charmonia

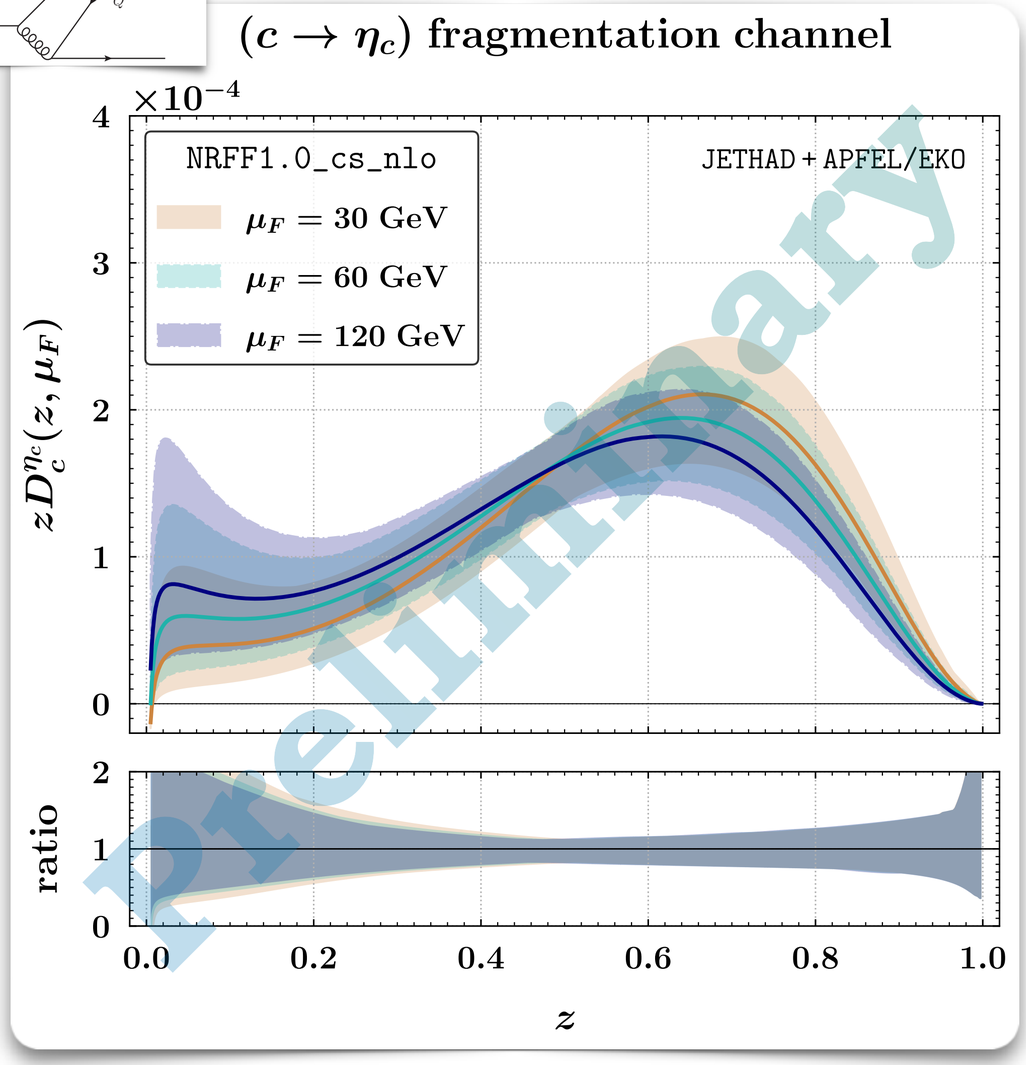
Vector J/ψ





Scalar η_c

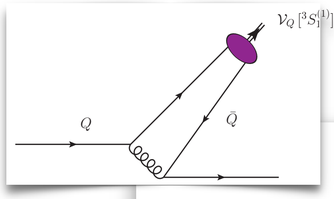


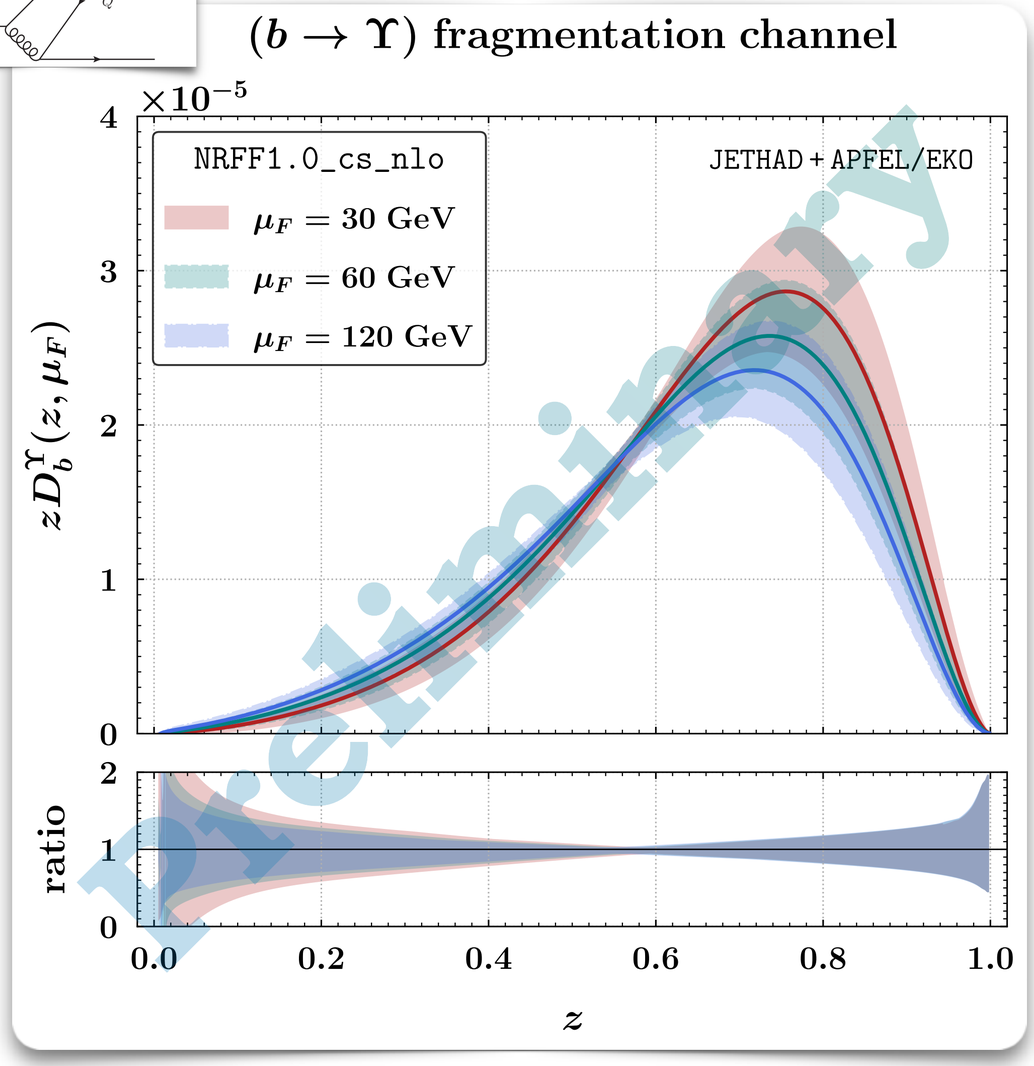


[F. G. C., in preparation]

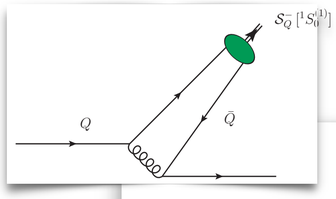
NRFF1.0: Bottom fragmentation to bottomonia

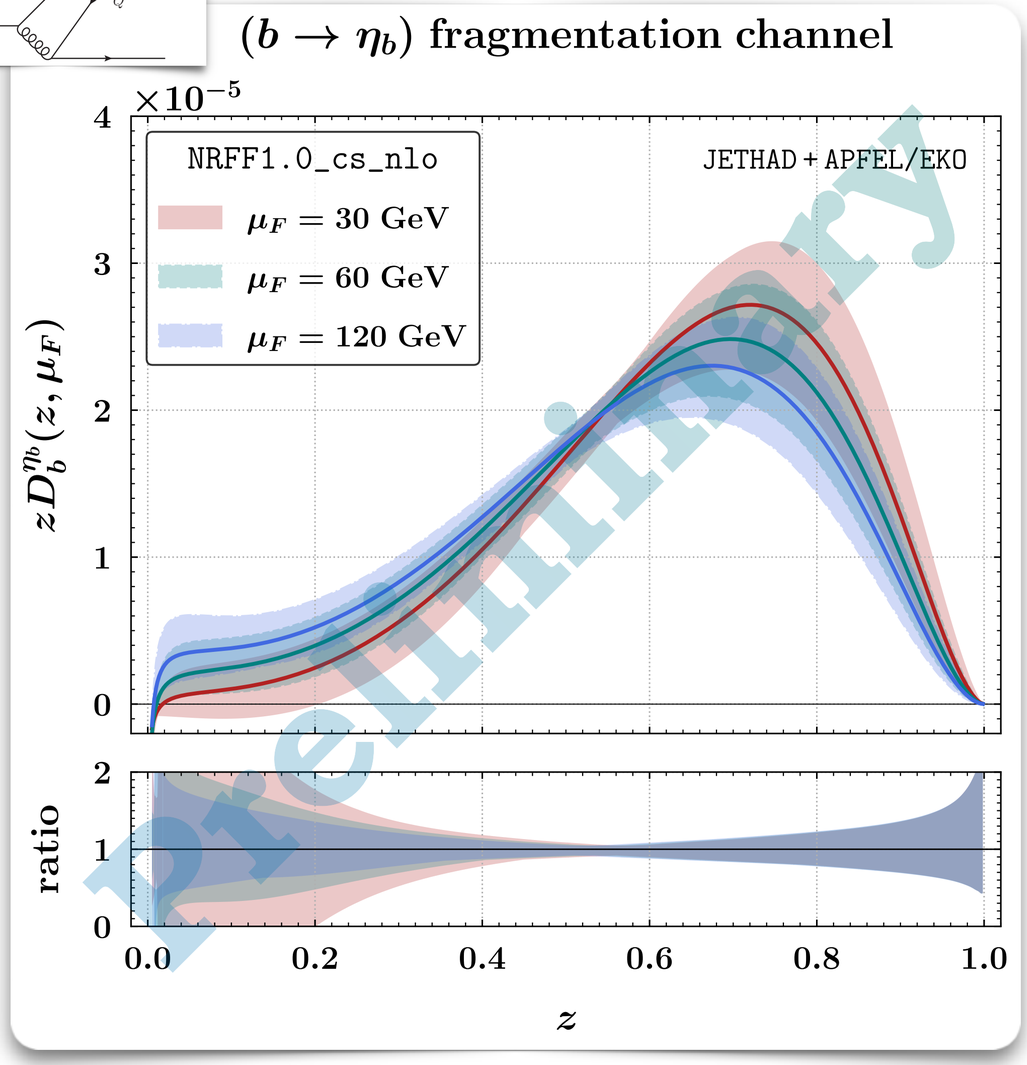
Vector Υ





Scalar η_b





[F. G. C., in preparation]