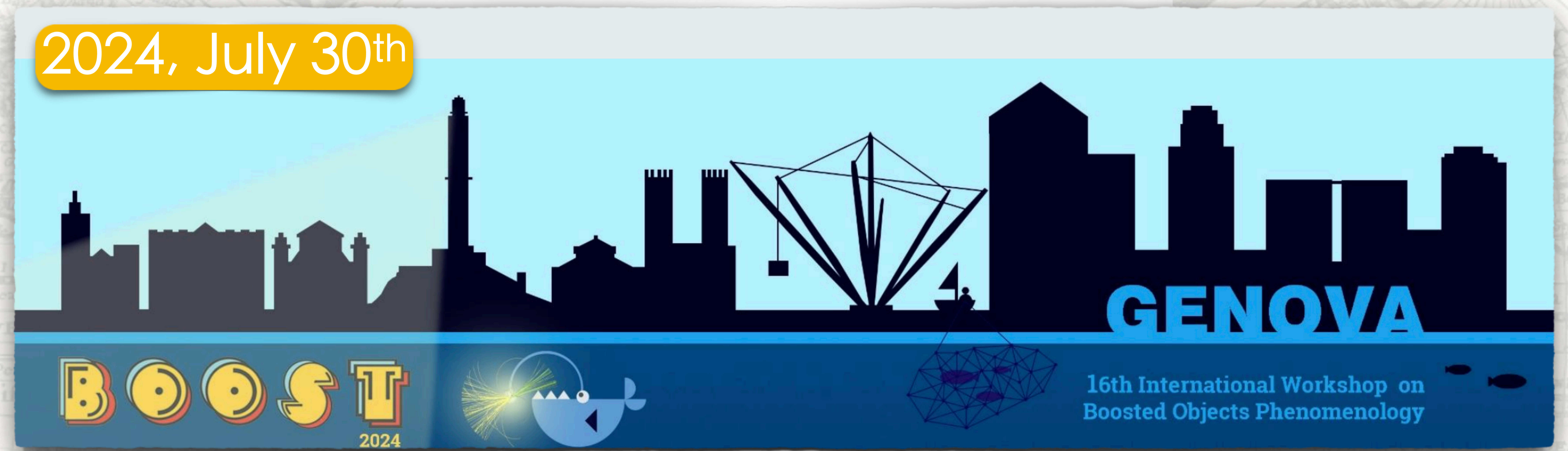
Towards Quarkonium Fragmentation from Heavy-Flavor Non-Relativistic Evolution

Francesco Giovanni Celiberto, UAH Madrid



Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

ANIVERSARIO PATRIMONIO MUNDIAL

1

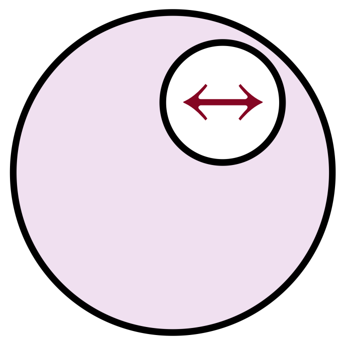
QCD Hydrogen Atoms

¿ Why studying Quarkonia ?

Precision & exploration

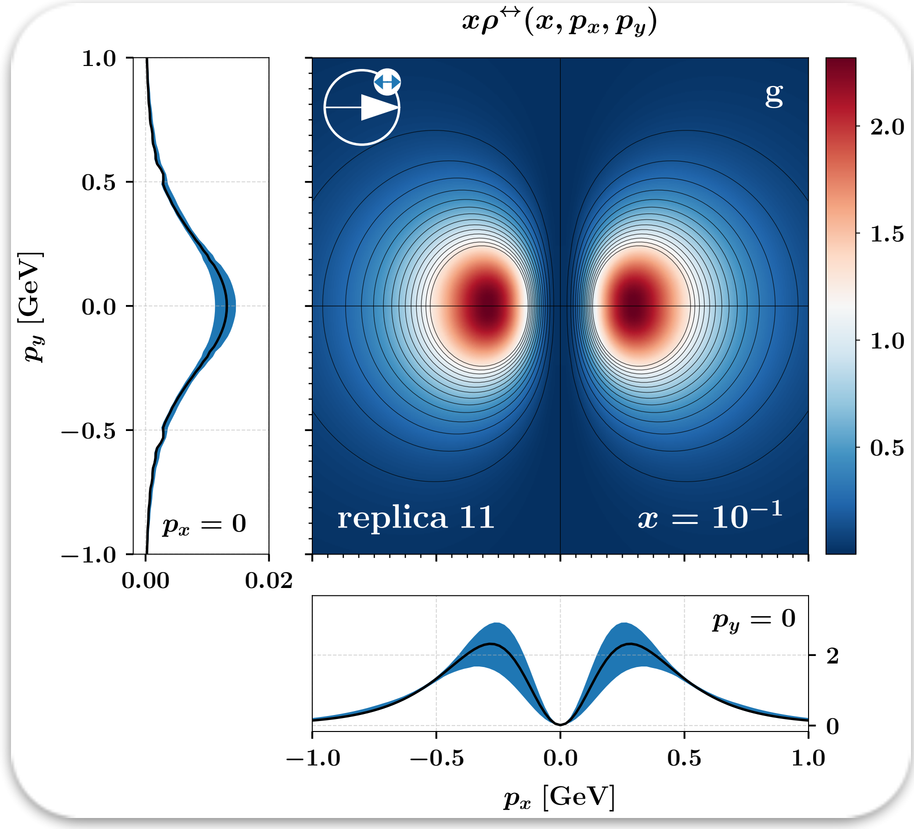
Quarkonia: Precision & Exploration

Hadronic structure: Assets



EIC, LHCb, LHCspin

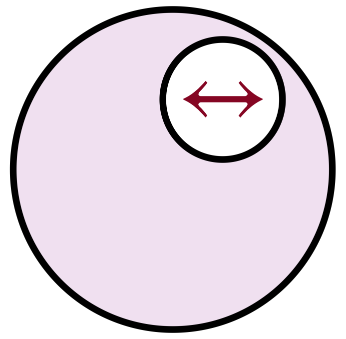
Boer-Mulders



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

Quarkonia: Precision & Exploration

Hadronic structure: Assets



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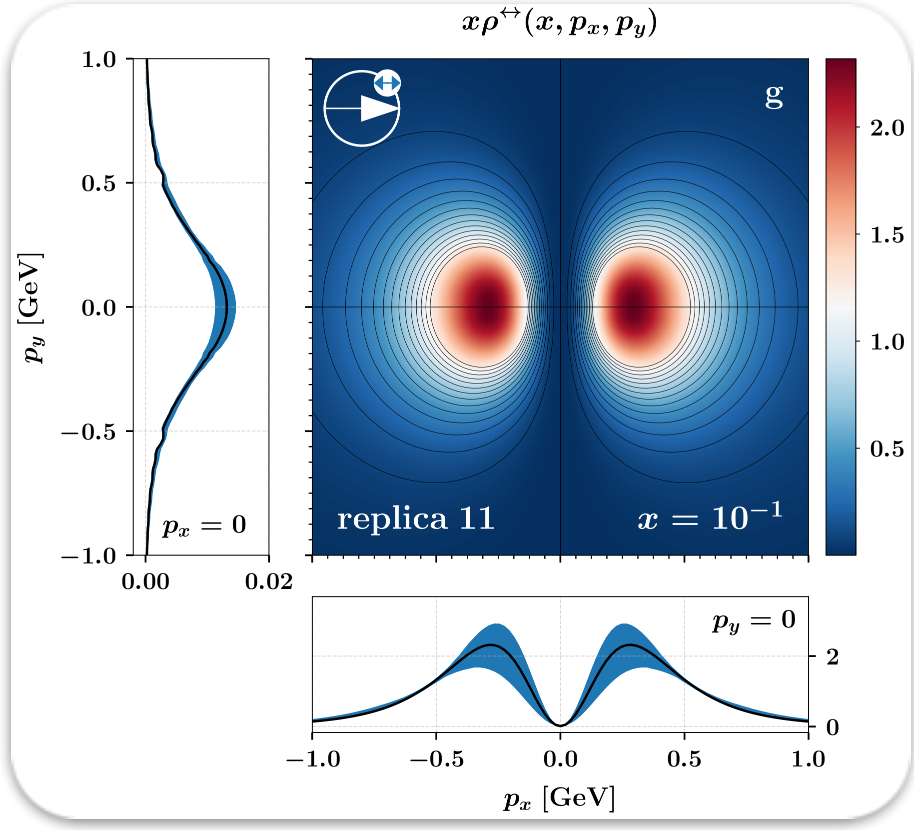

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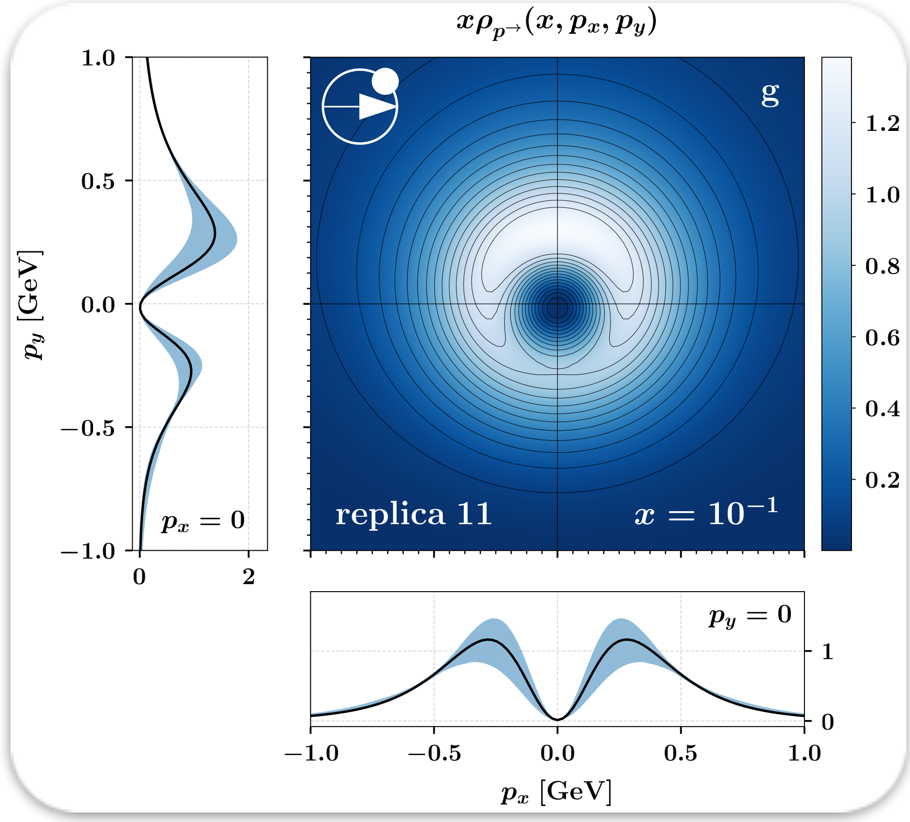
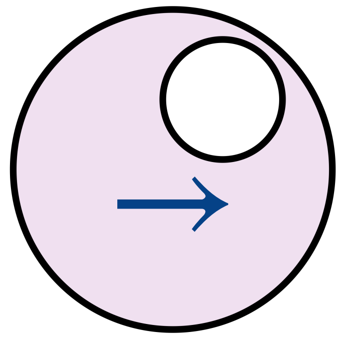




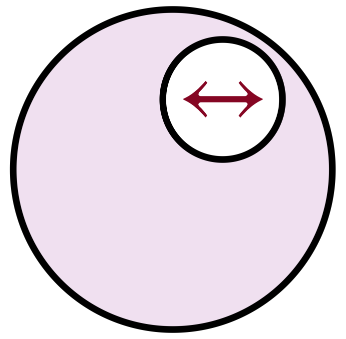
EIC, LHCspin

Sivers

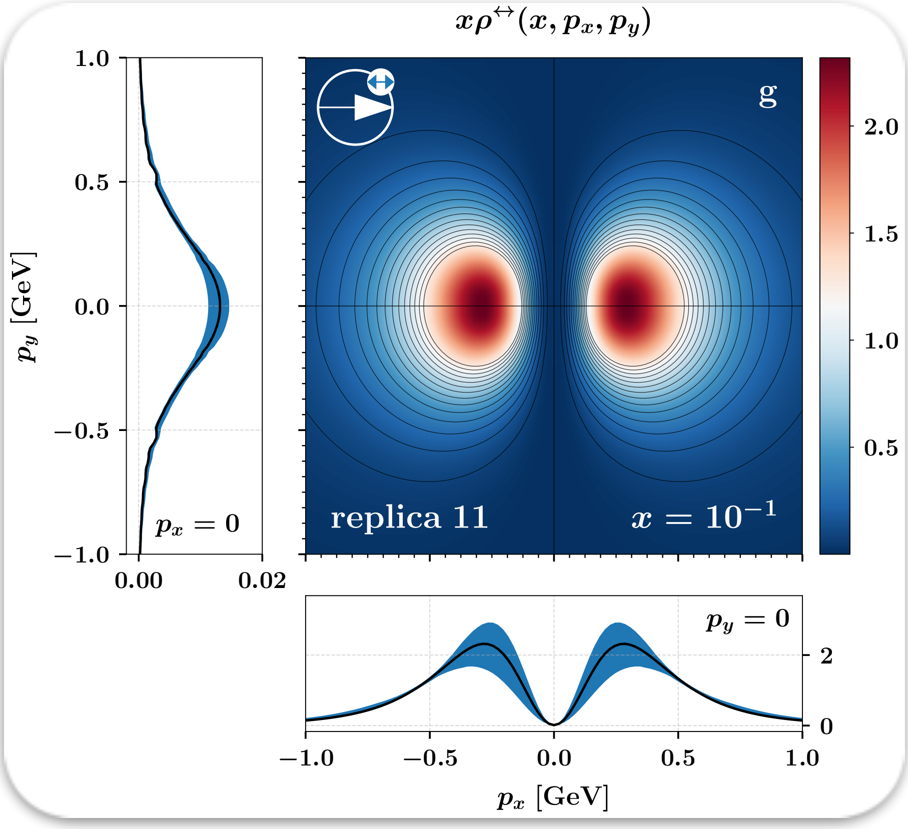
Hors d'œuvre

Quarkonia: Precision & Exploration

Hadronic structure: Assets



EIC, LHCb, LHCspin



Boer-Mulders

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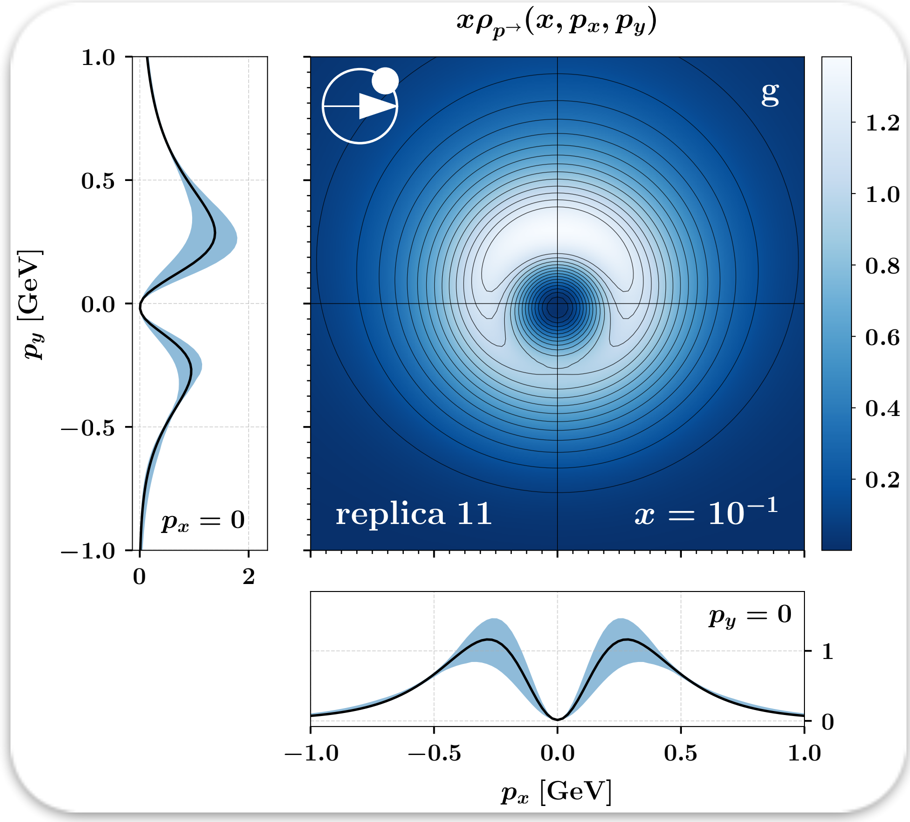
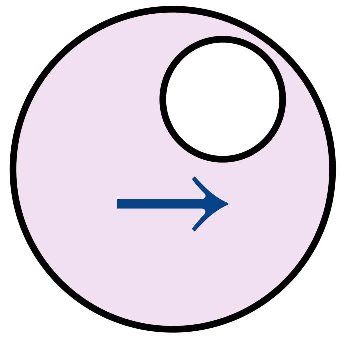


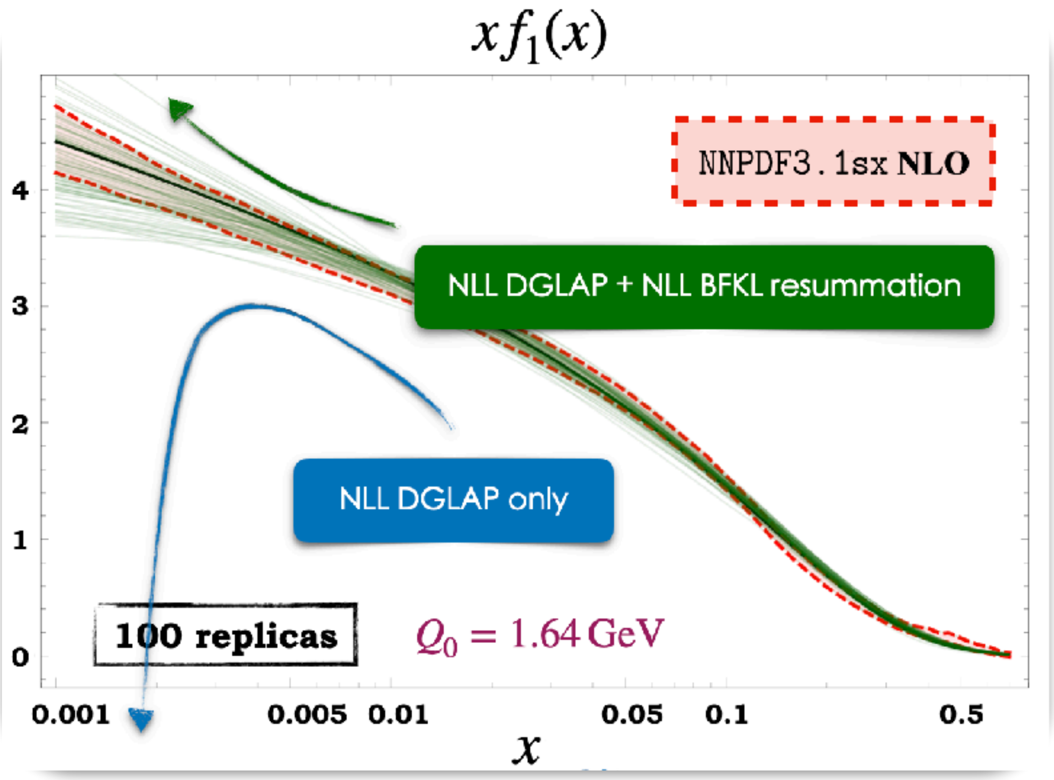


EIC, LHCspin

Sivers

Precision QCD: Challenges

Forward Onia ⇒ Gluon PDF & TMD Positivity



Low x and low Q²

[G. Altarelli et al. (1998)]
[A. Candido et al. (2020)]
[J. Collins et al. (2022)]
[A. Candido et al. (2023)]

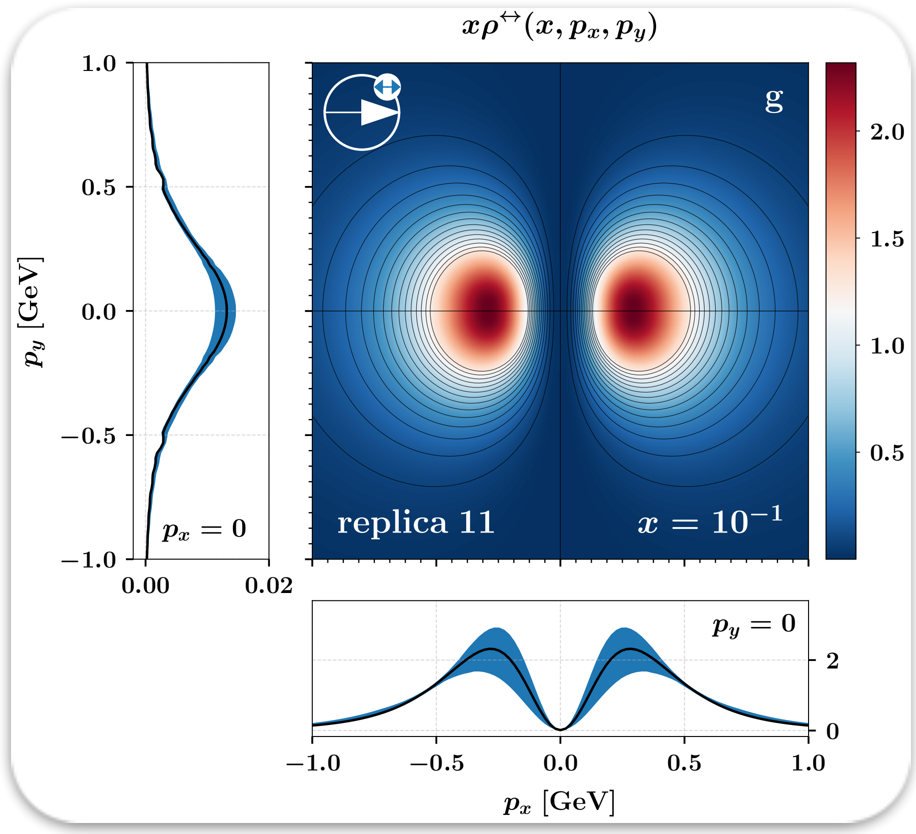
Hors d'œuvre

Quarkonia: Precision & Exploration

Hadronic structure: Assets

EIC, LHCb, LHCspin

Boer-Mulders



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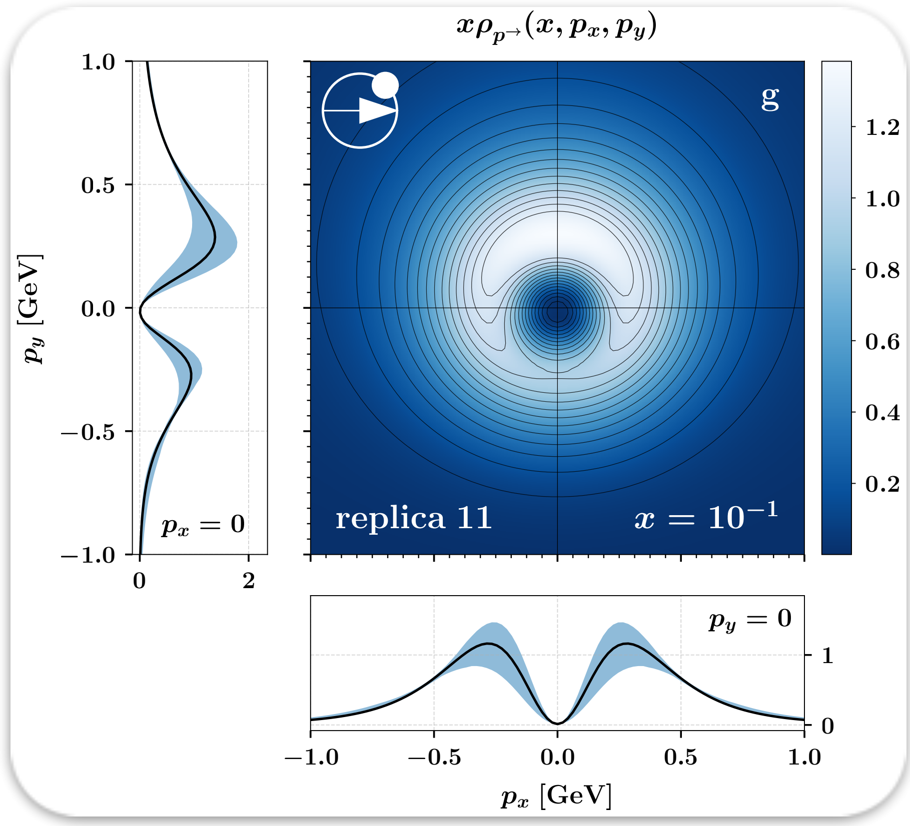

EIC, LHCspin

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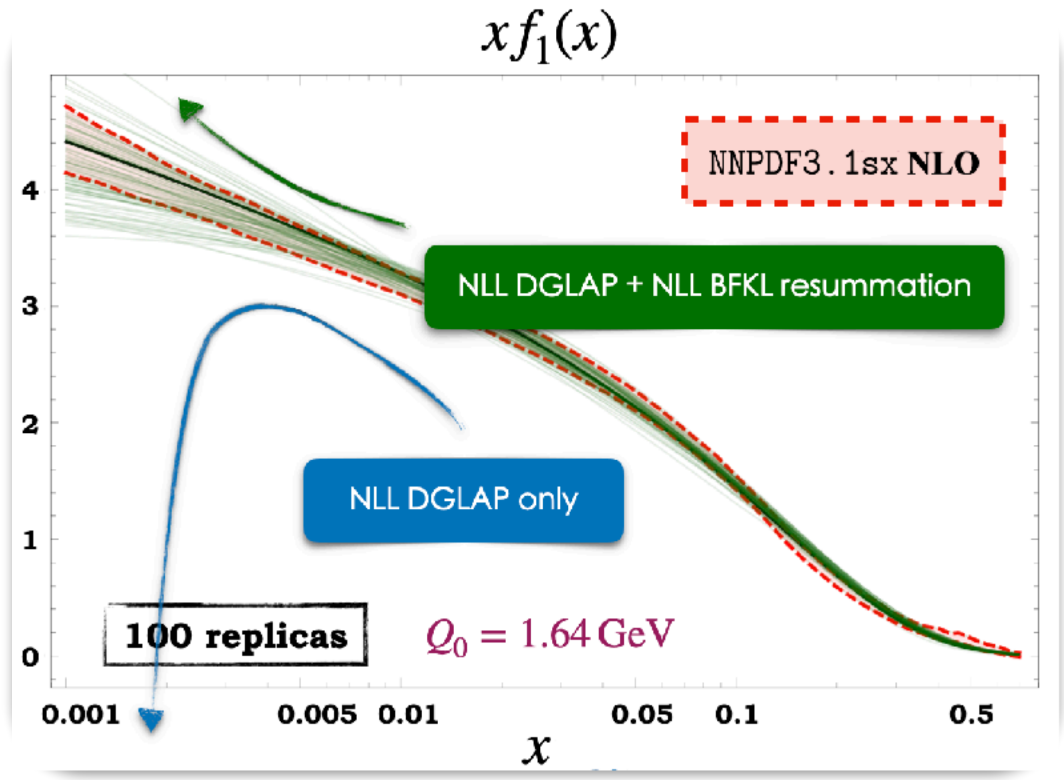

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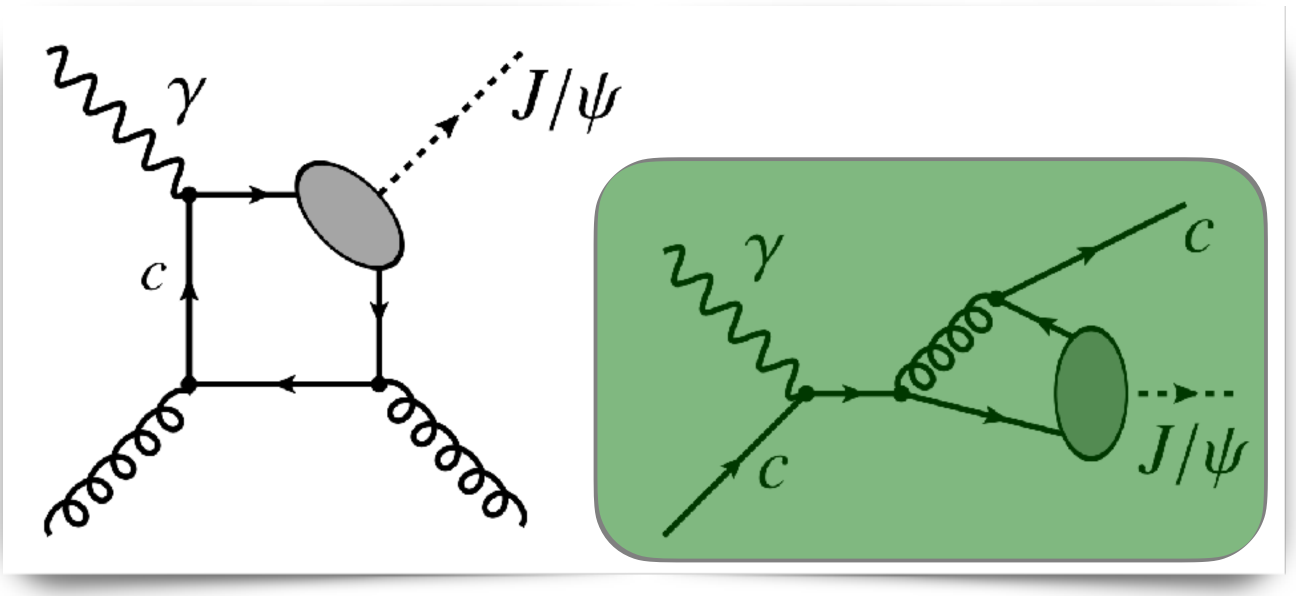
$\gamma + g \rightarrow J/\psi + c$ ⇒ Valence Intrinsic Charm @EIC

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)]

Hors d'œuvre

2

Quarkonium formation from NRQCD

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

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

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- [cross section] = [short-distance coeffs.] ⊗ [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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$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\overline{Q}\,[n] + X)\,\langle \mathcal{O}^H\,[n] \rangle$$

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

③

Quarkonium fragmentation from HF-NRevo

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

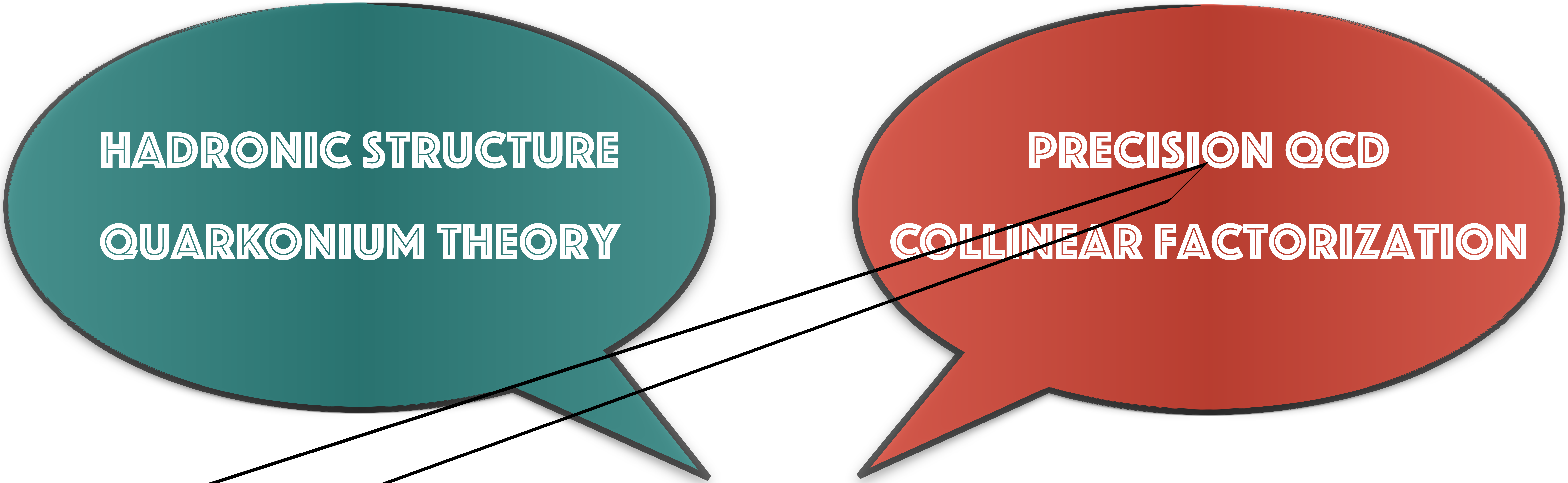
QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

3.1 The best of the Two Worlds

Heavy-Flavor Non-Relativistic evolution



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

3.1 The best of the Two Worlds

HF-NRevo

Interpretation

HF-NRevo

Interpretation

Evolution

HF-NRevo

Interpretation

Evolution

Uncertainties

HF-NRevo

Interpretation

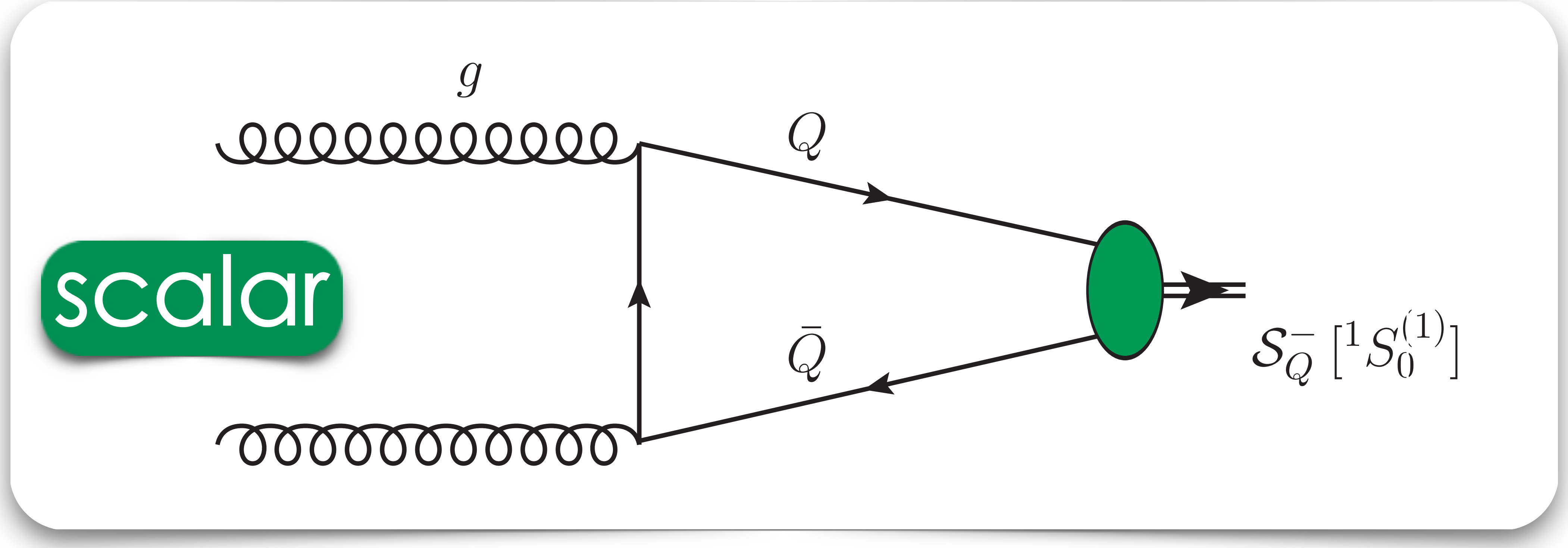
Evolution

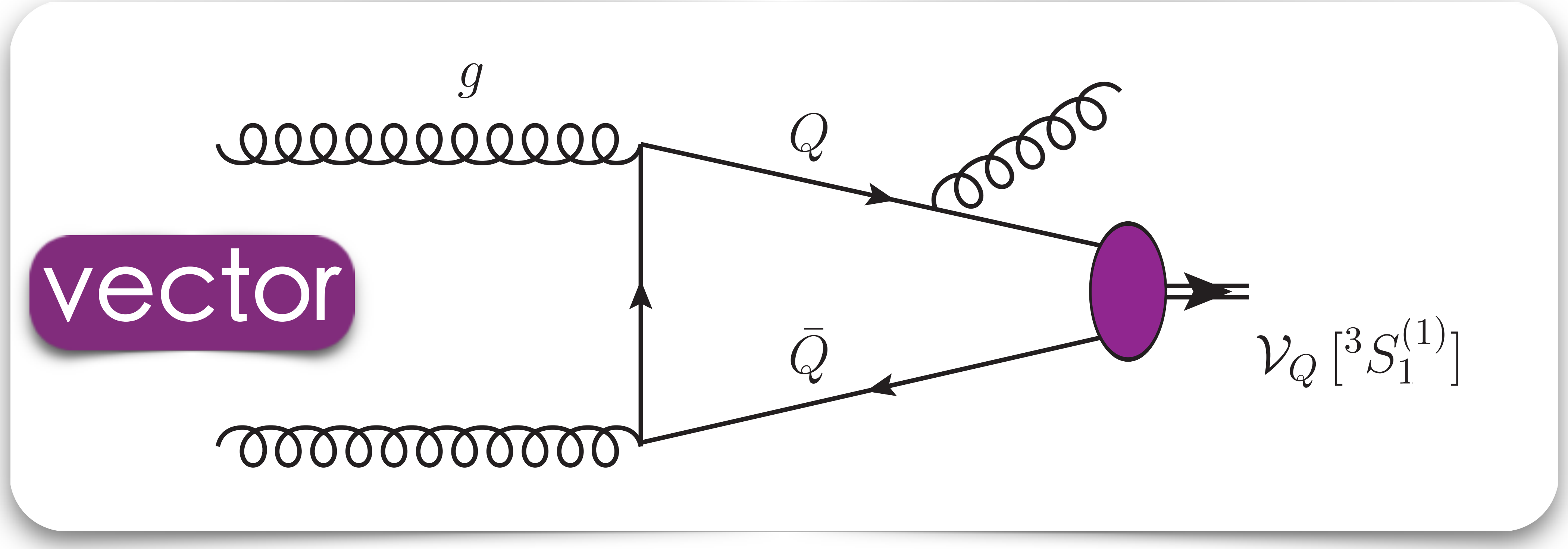
Uncertainties

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

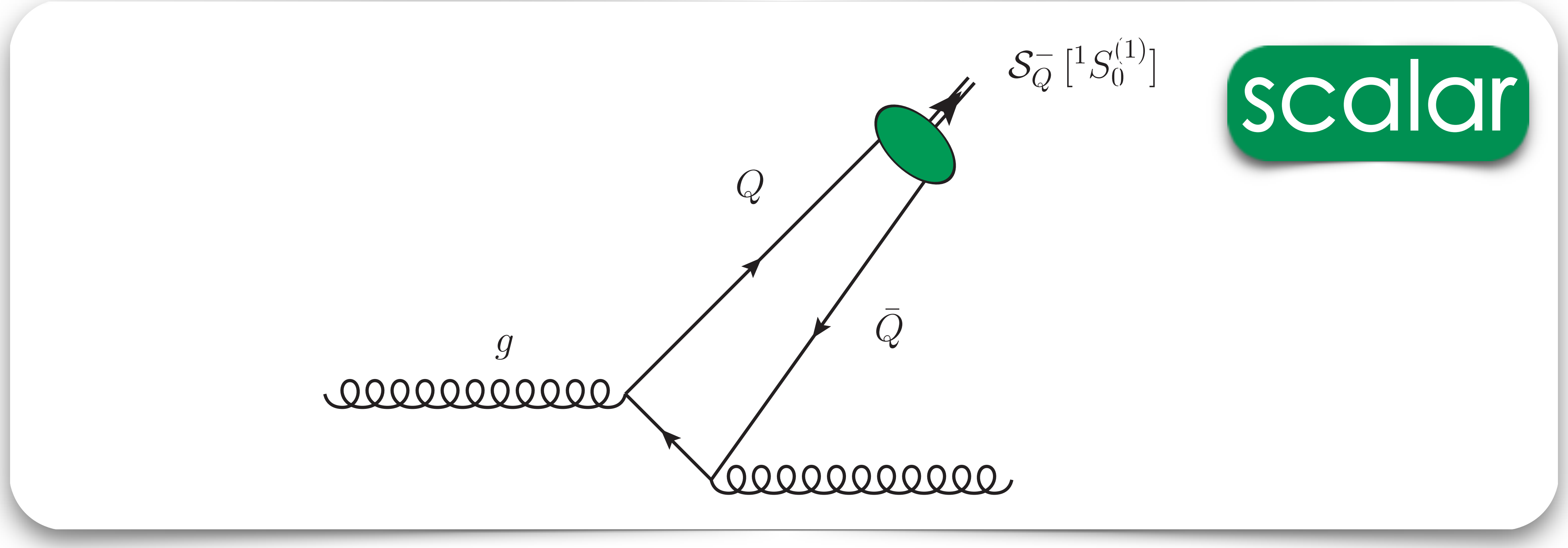
From low energies to high energies

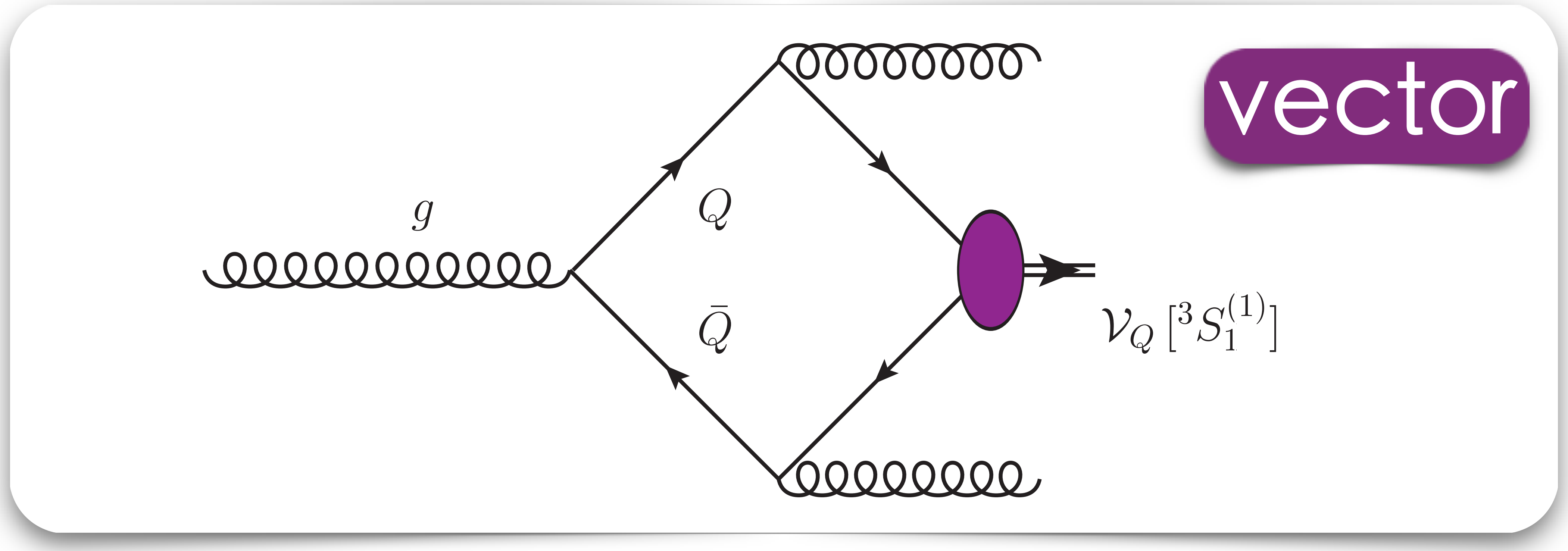
Low $p_T \Rightarrow$ two-parton FFs
Genuine higher-twist FFNS FFs





High $p_T \Rightarrow$ single-parton FFs
Twist-2 VFNS FFs + power corrections

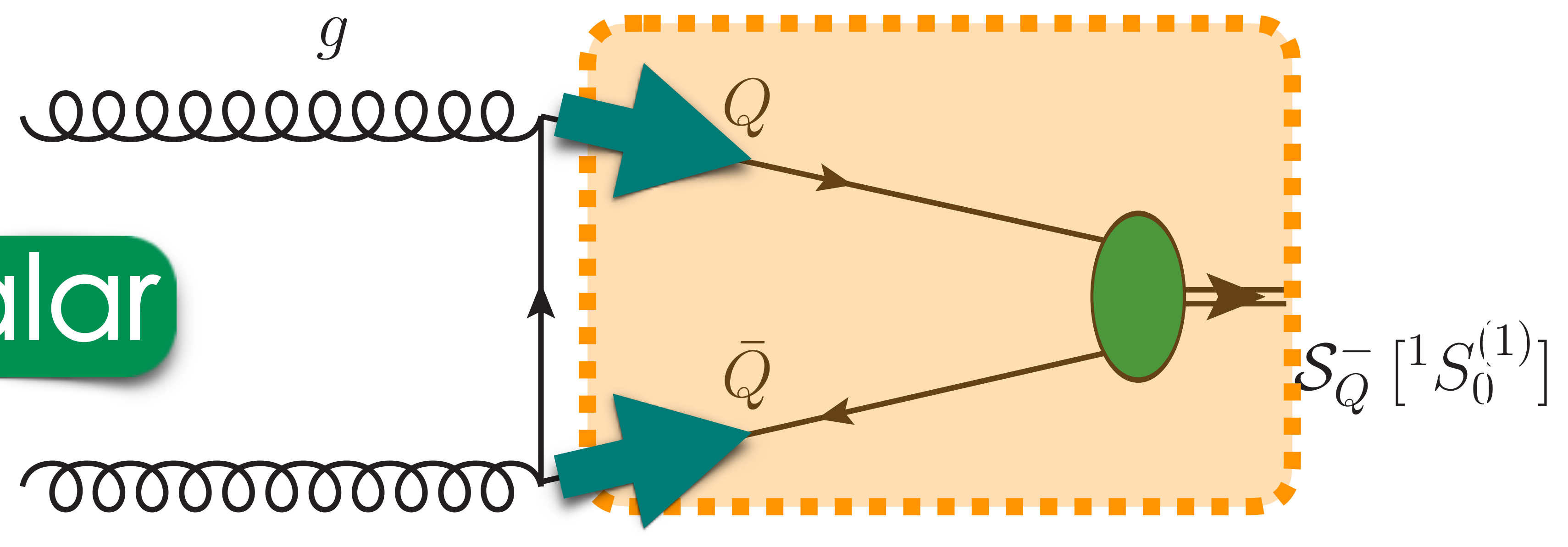




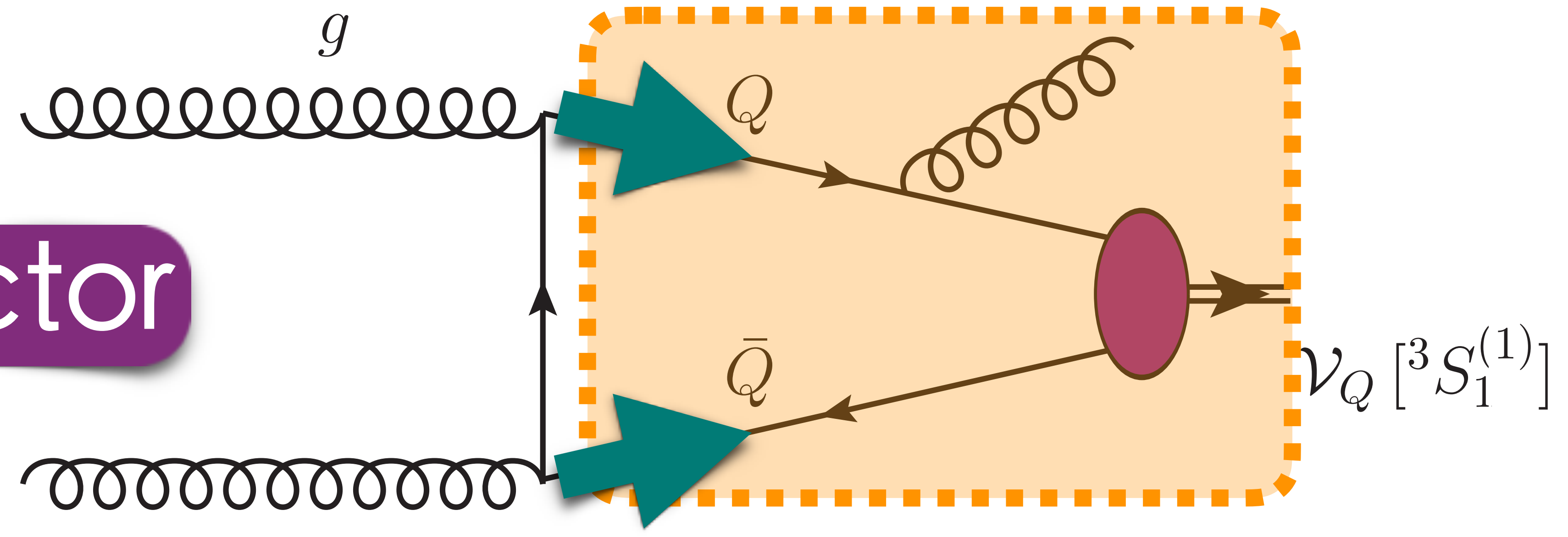
From low energies to high energies

Low $p_T \Rightarrow$ two-parton FFs
Genuine higher-twist FFNS FFs

scalar



vector



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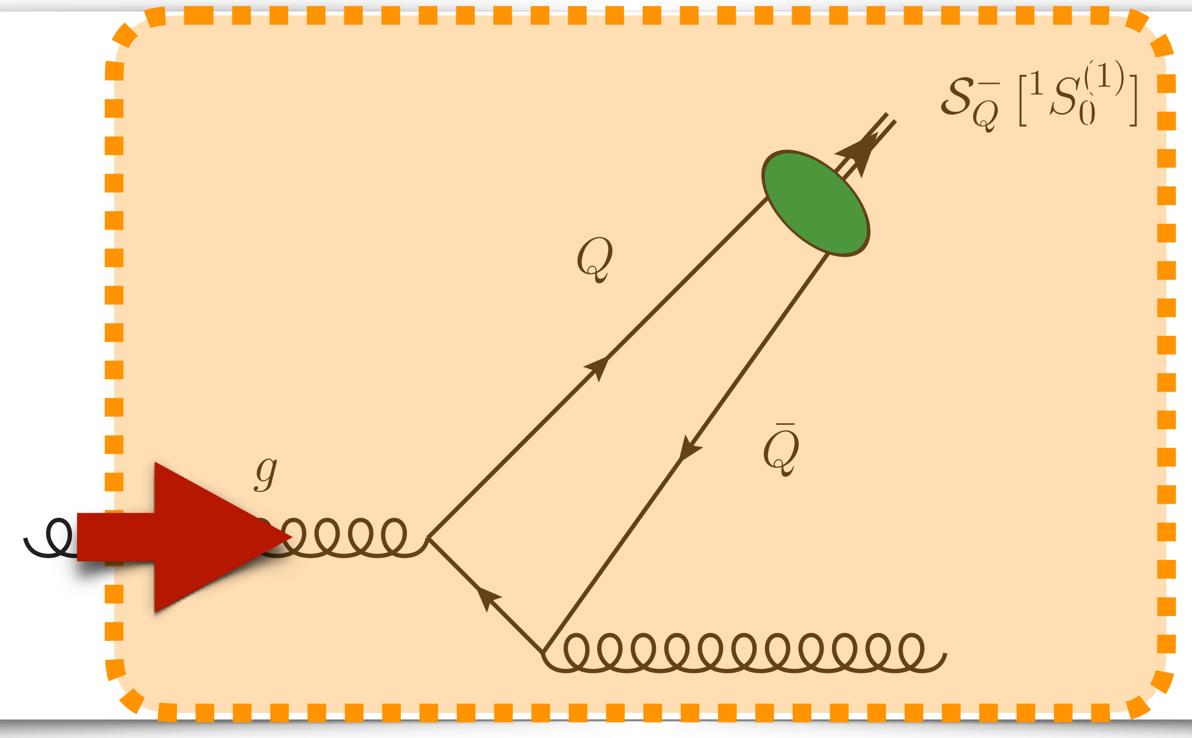
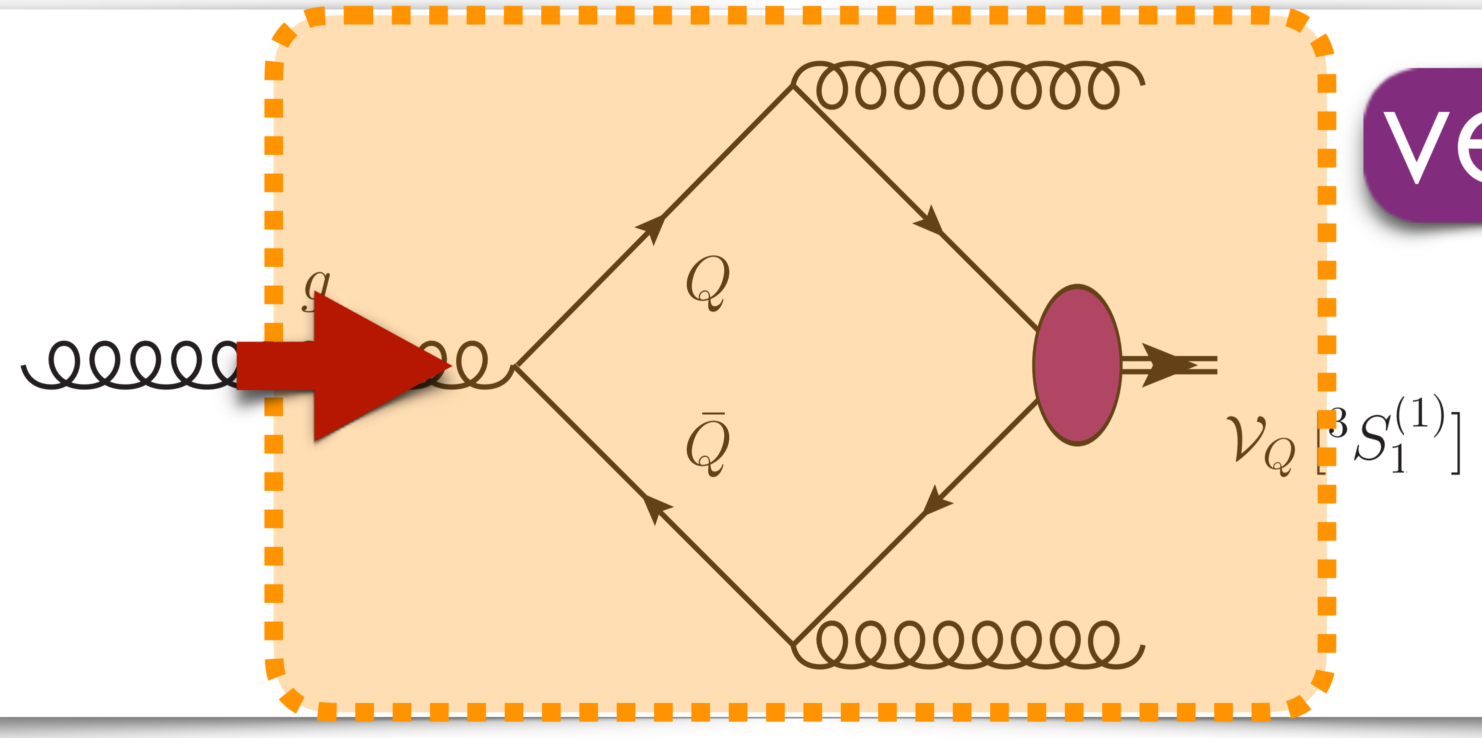


vector



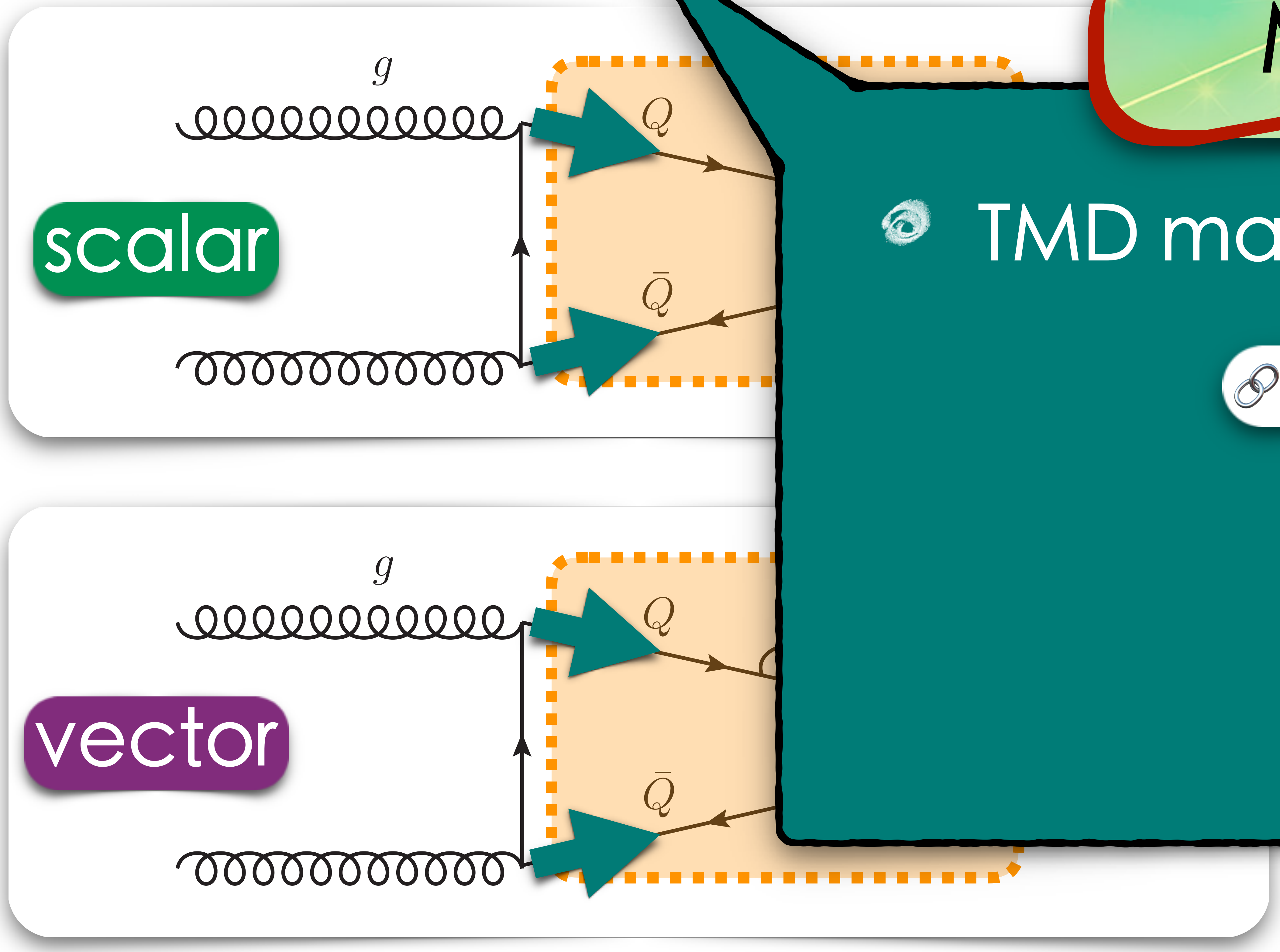
Collinear Fragmentation Correlator (CFC)

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

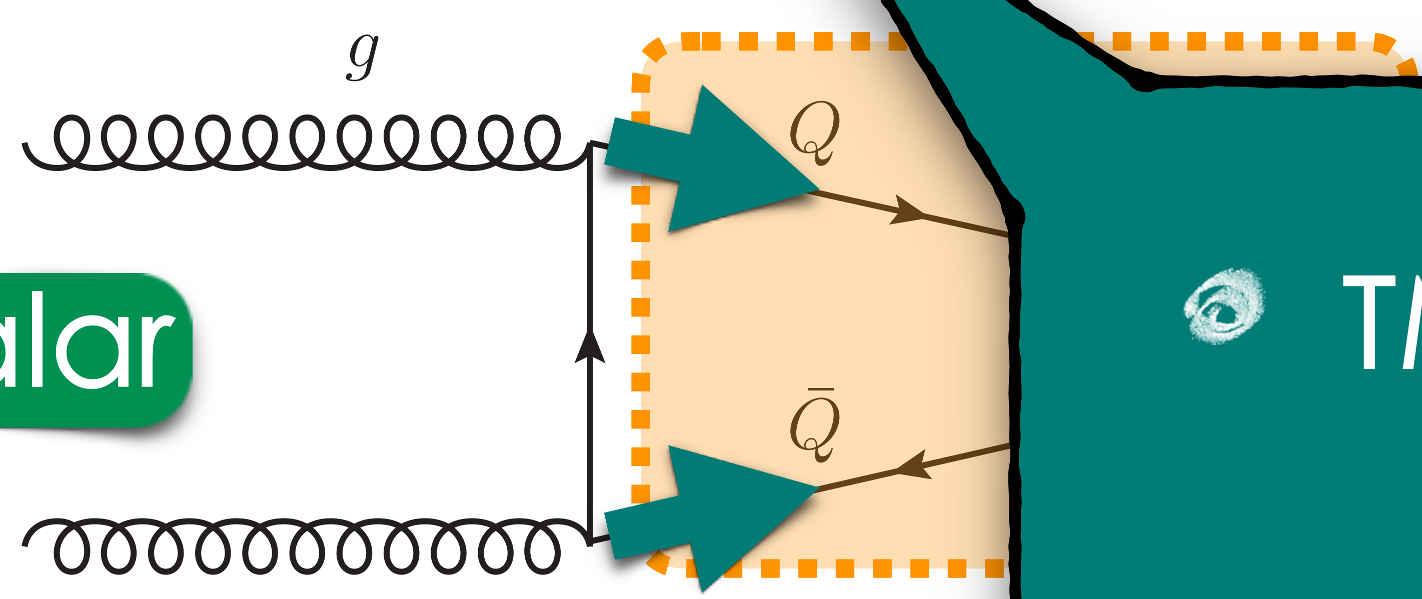
- TMD matching tails $\Rightarrow$ different singularities

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

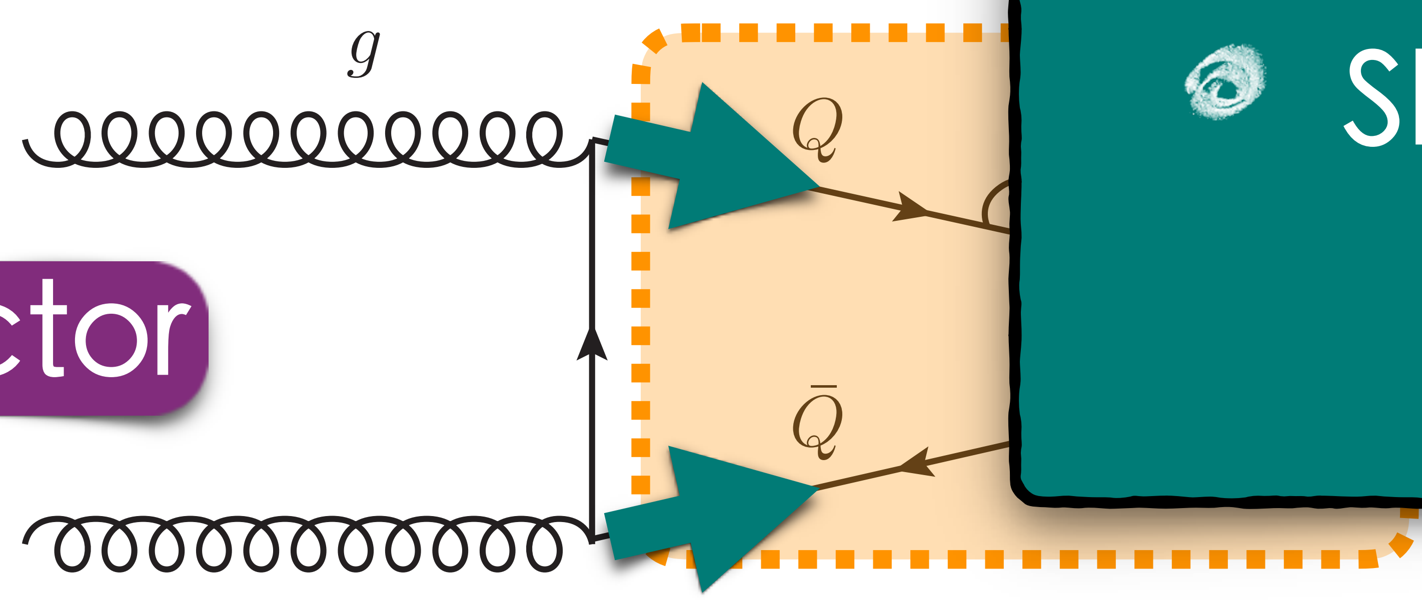
From low energies to high energies

Low p_T $\Rightarrow$ two-parton FFs
Genuine higher-twist FFNS FFs

scalar



vector



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)]

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

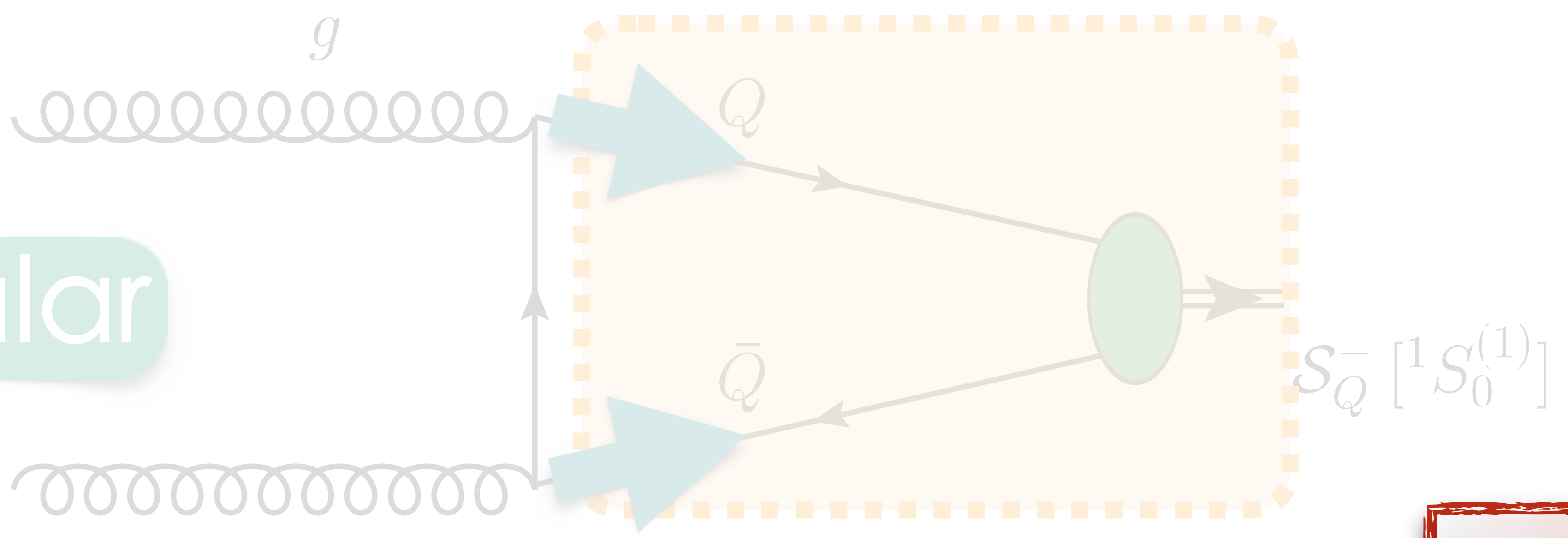
  [S. Fleming, A.K. Leibovich, T. Mehen, I.Z. Rothstein (2012)]

From low energies to high energies

Low p_T $\Rightarrow$ two-parton FFs

Genuine higher-twist FFNS FFs

scalar



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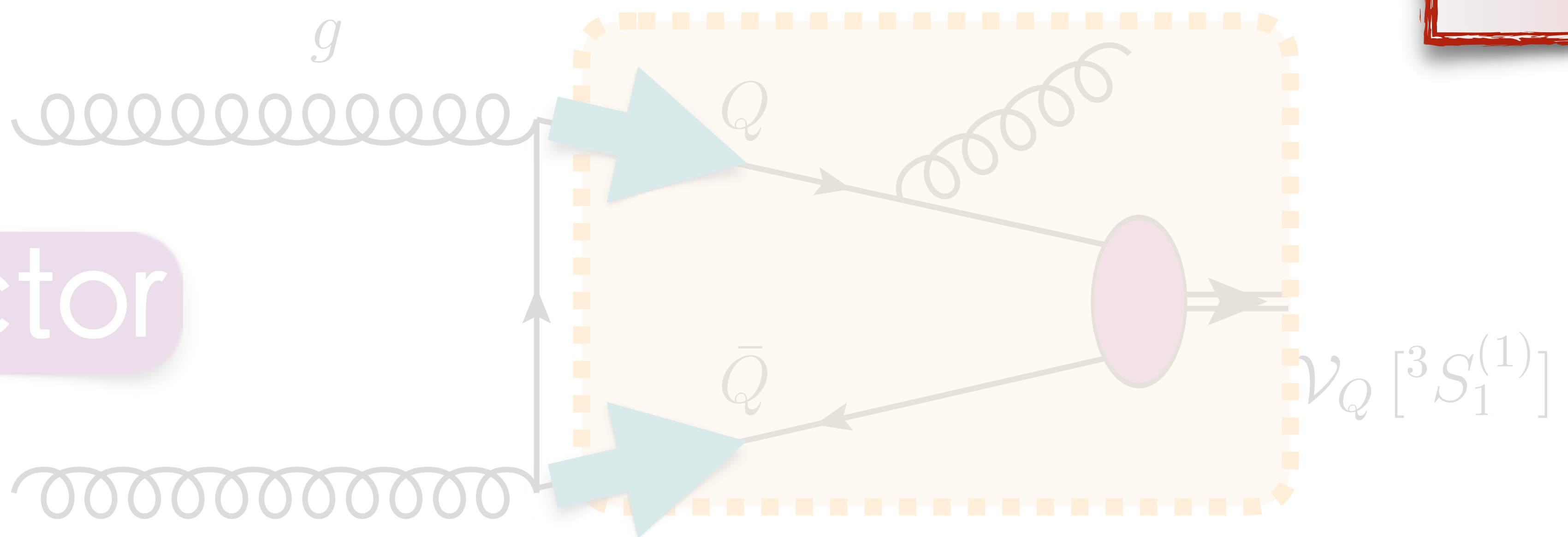
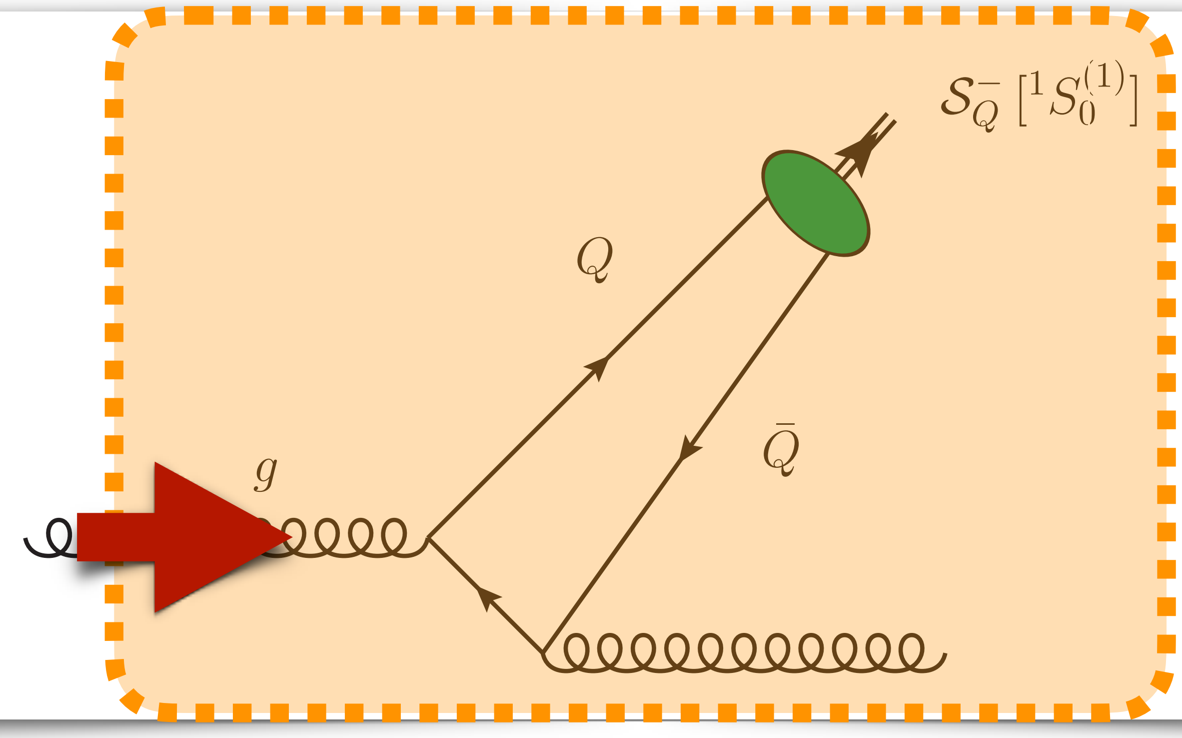


Our study & goal

High p_T $\Rightarrow$ single-parton FFs

Twist-2 VFNS FFs + power corrections



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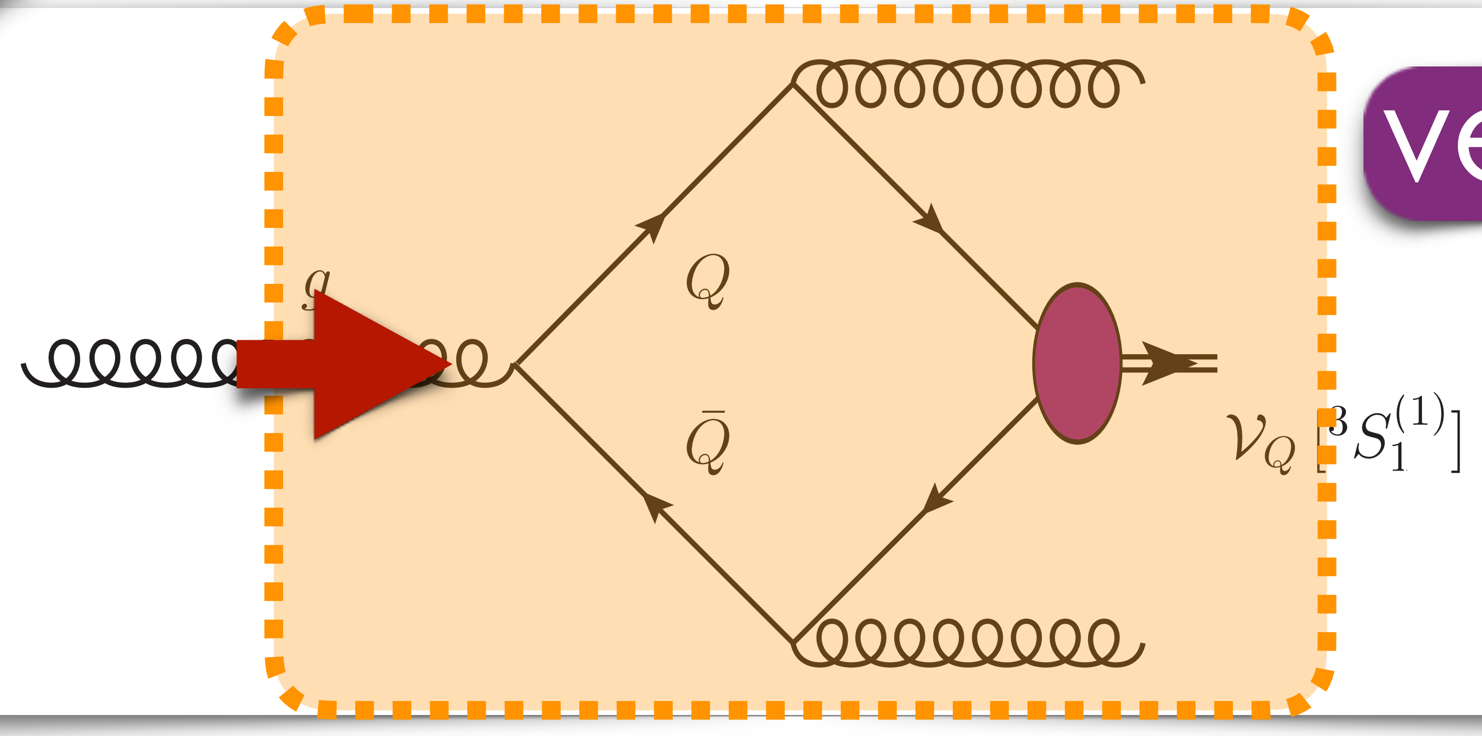


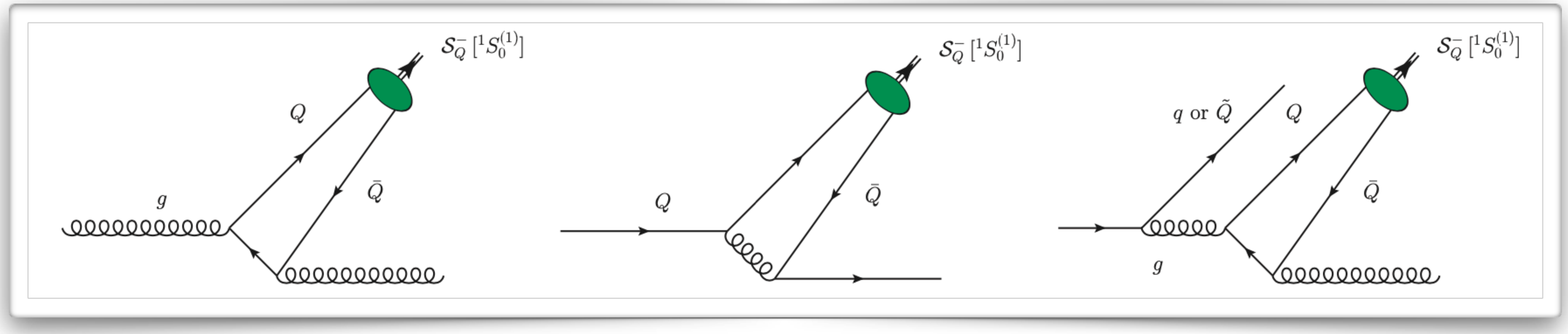
vector

HF-NRevo

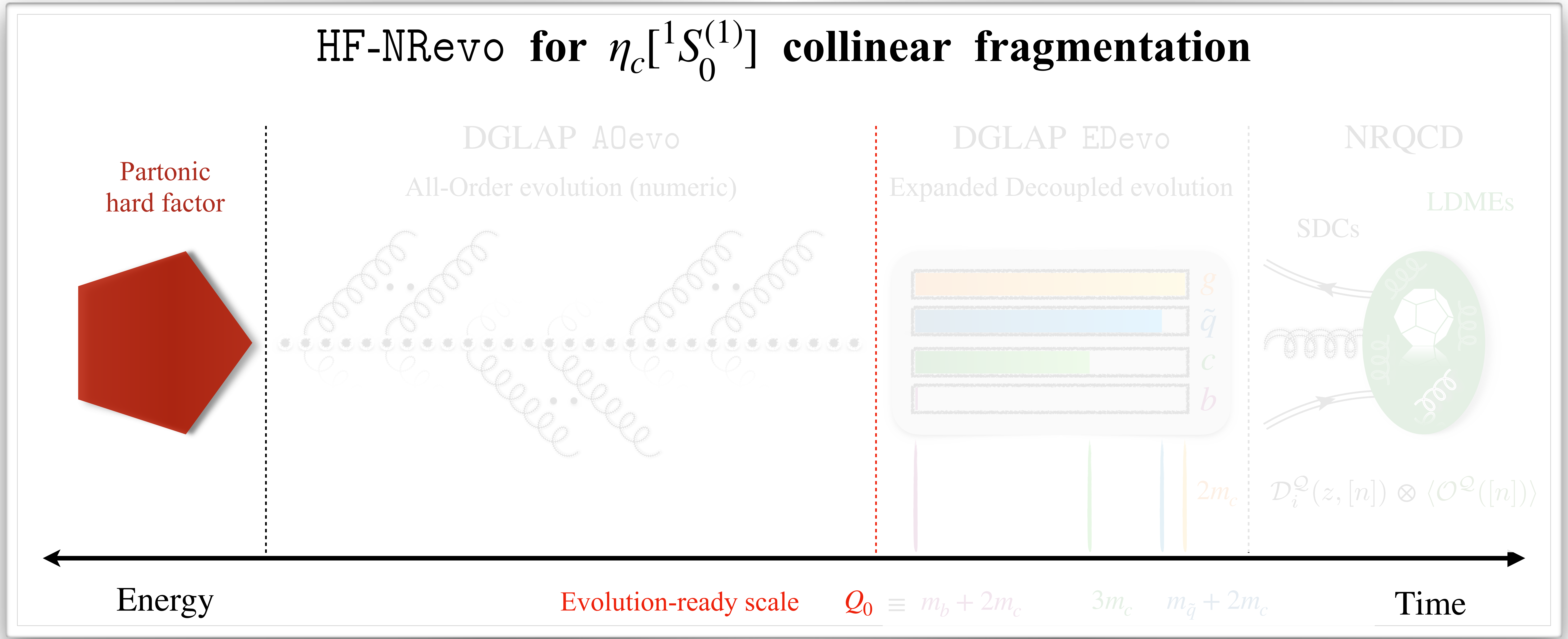
Interpretation | **Evolution** | Uncertainties

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

HF-NRevo: Initial-scale NRCQD inputs



Scalar η_c



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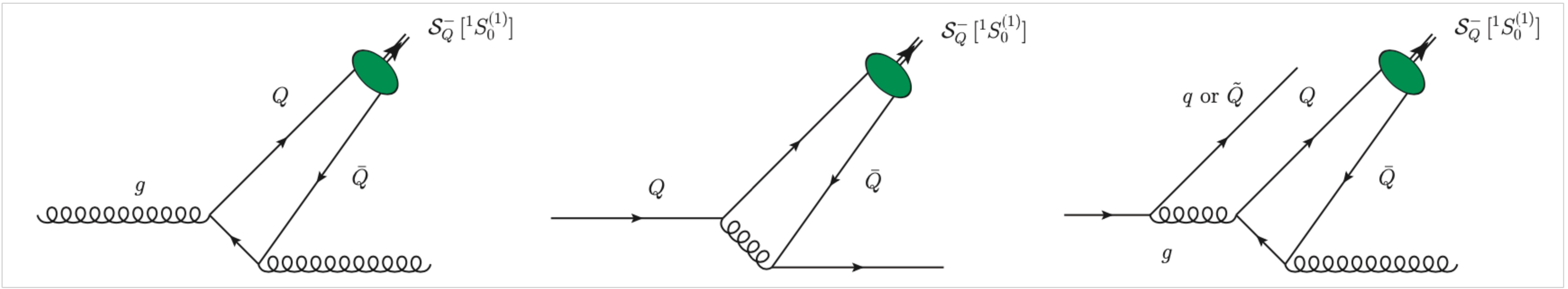
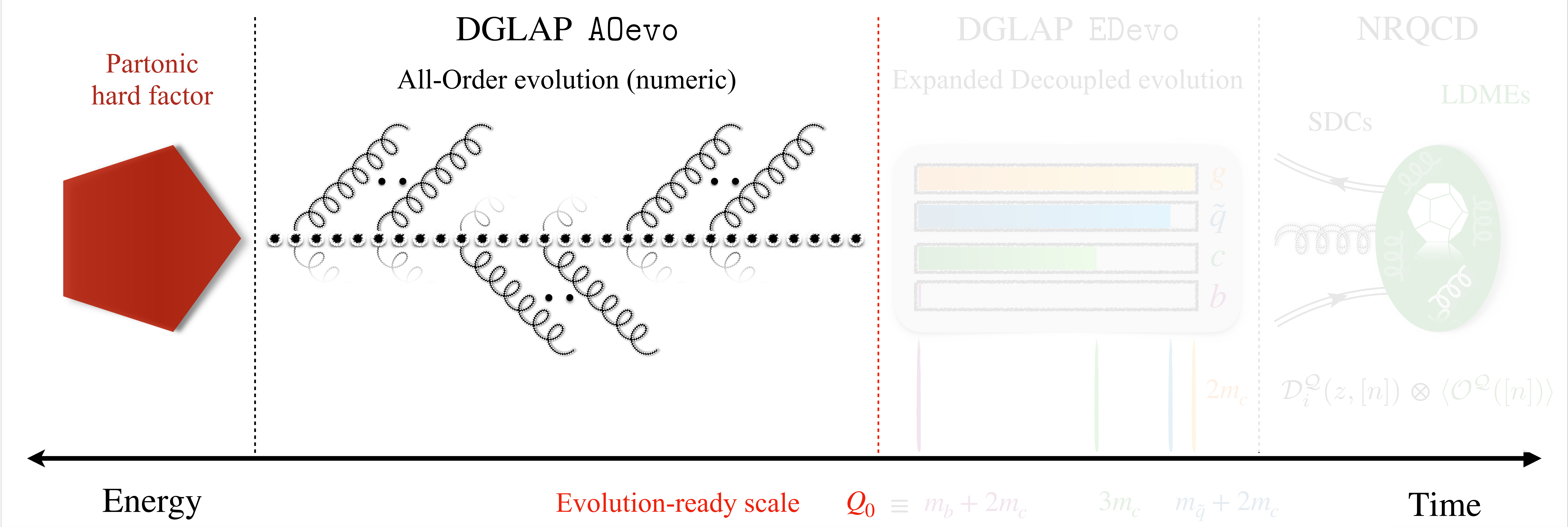


Scalar η_c

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



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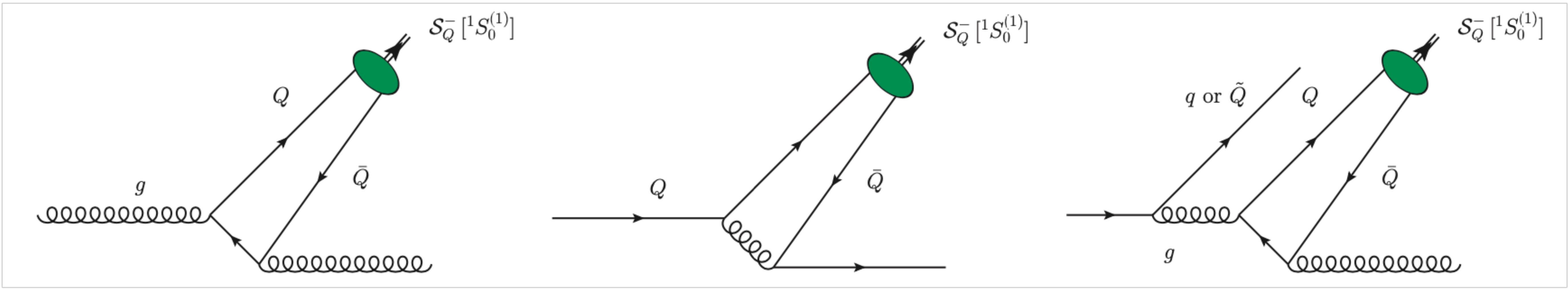

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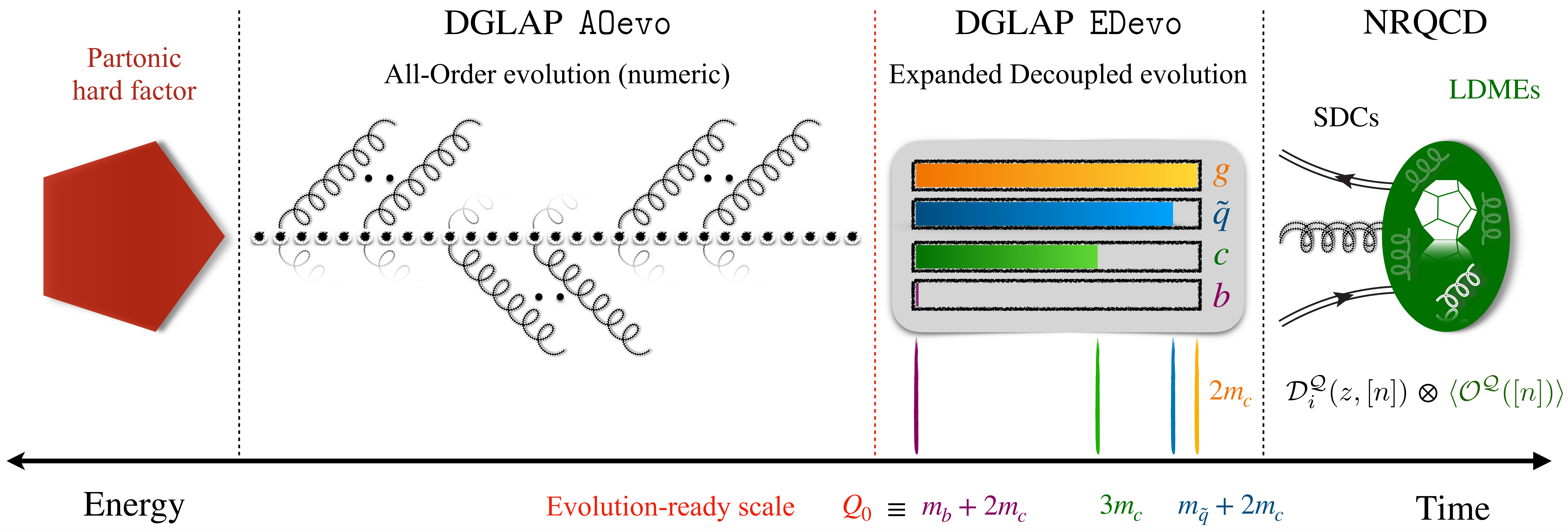

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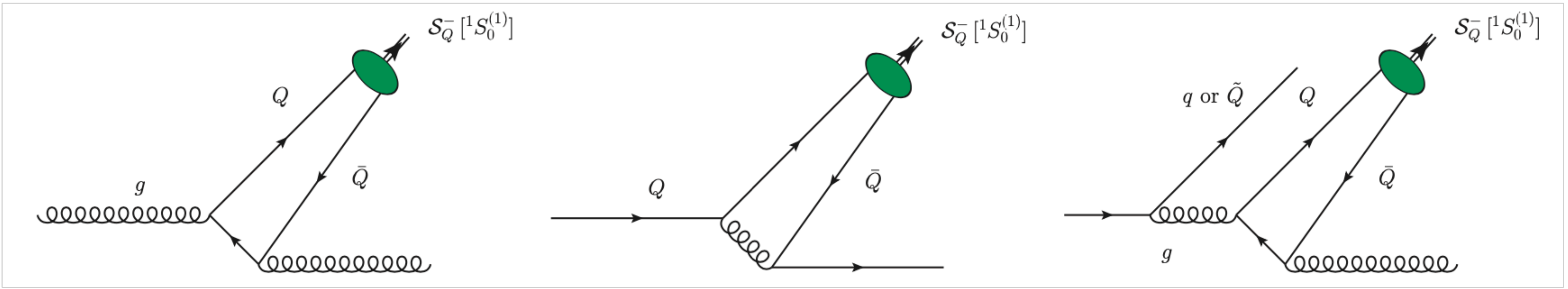
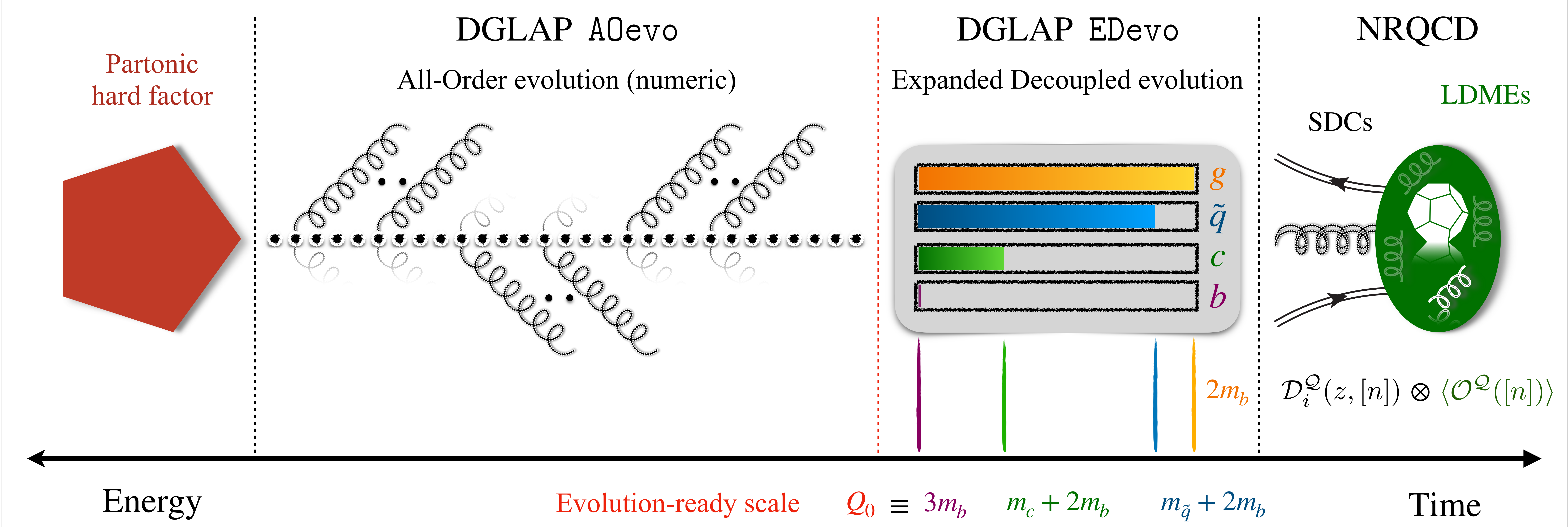
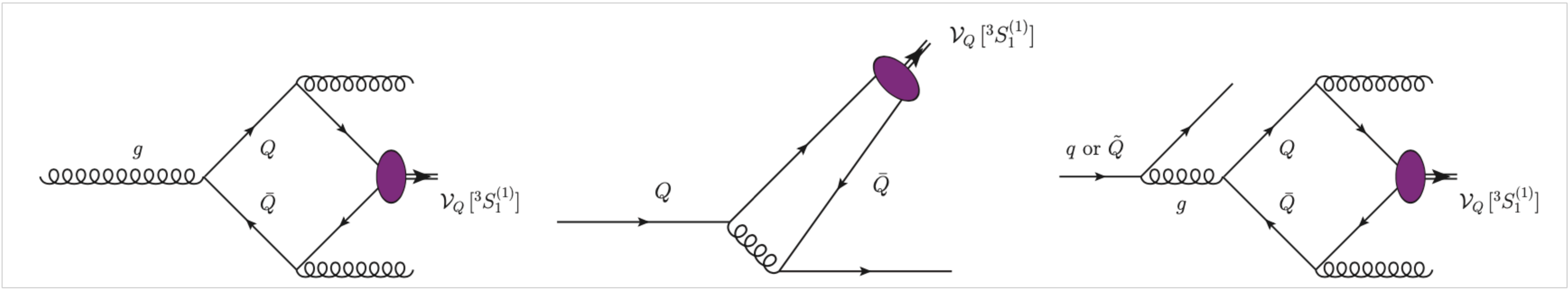


Scalar η_b

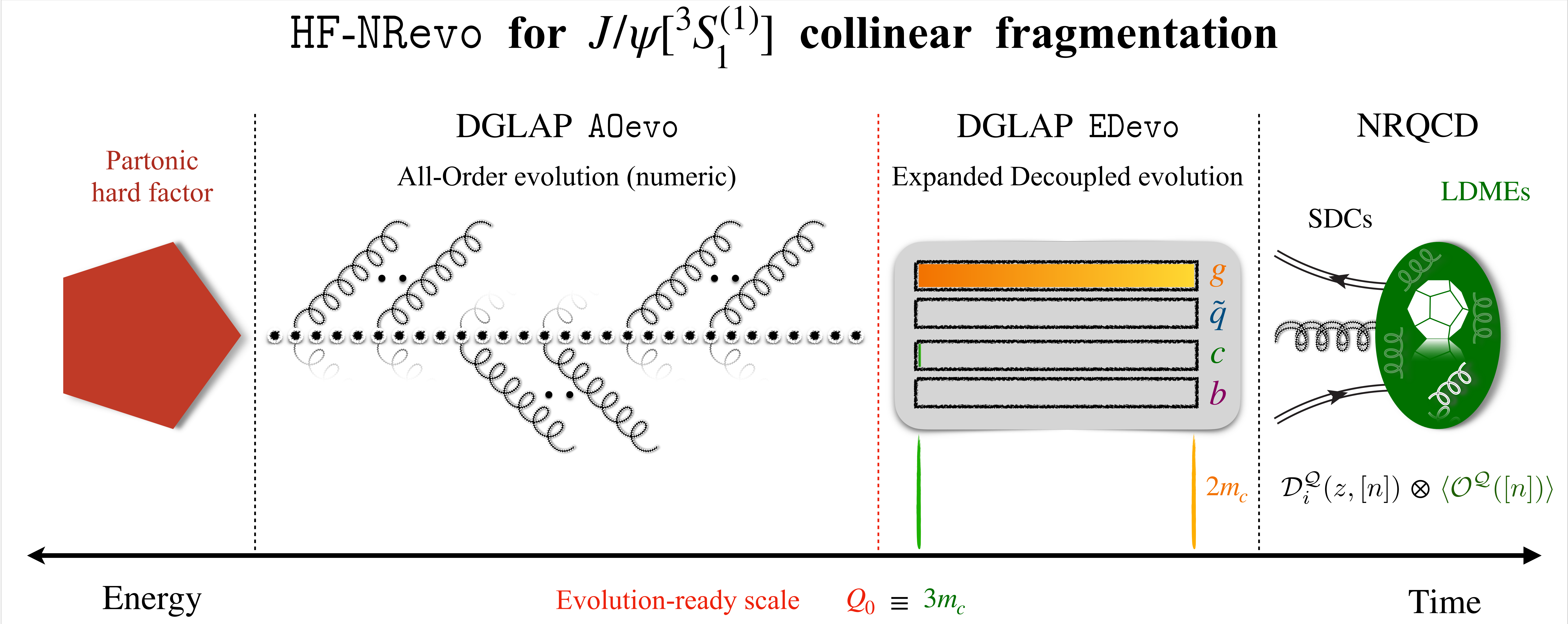
HF-NRevo for $\eta_b[^1S_0^{(1)}]$ collinear fragmentation



HF-NRevo: Initial-scale NRCQD inputs



Vector J/ψ



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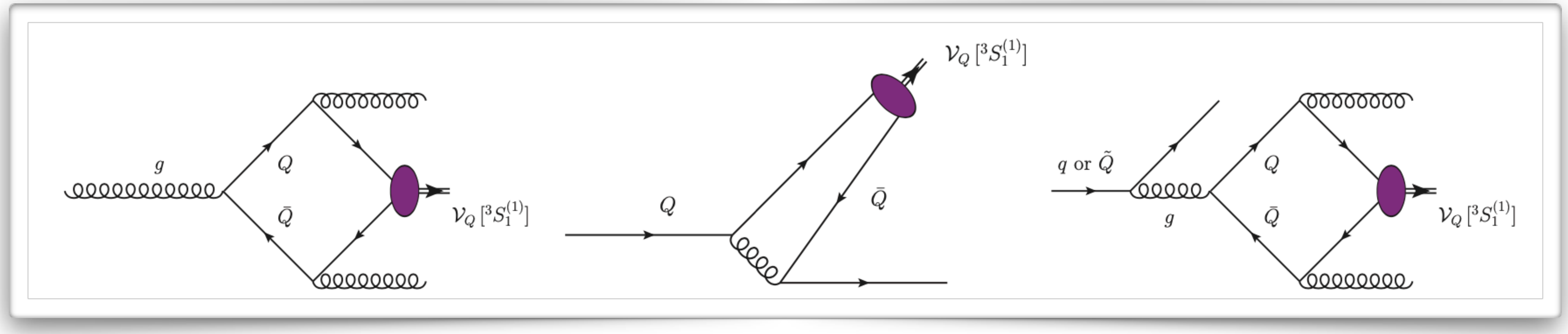
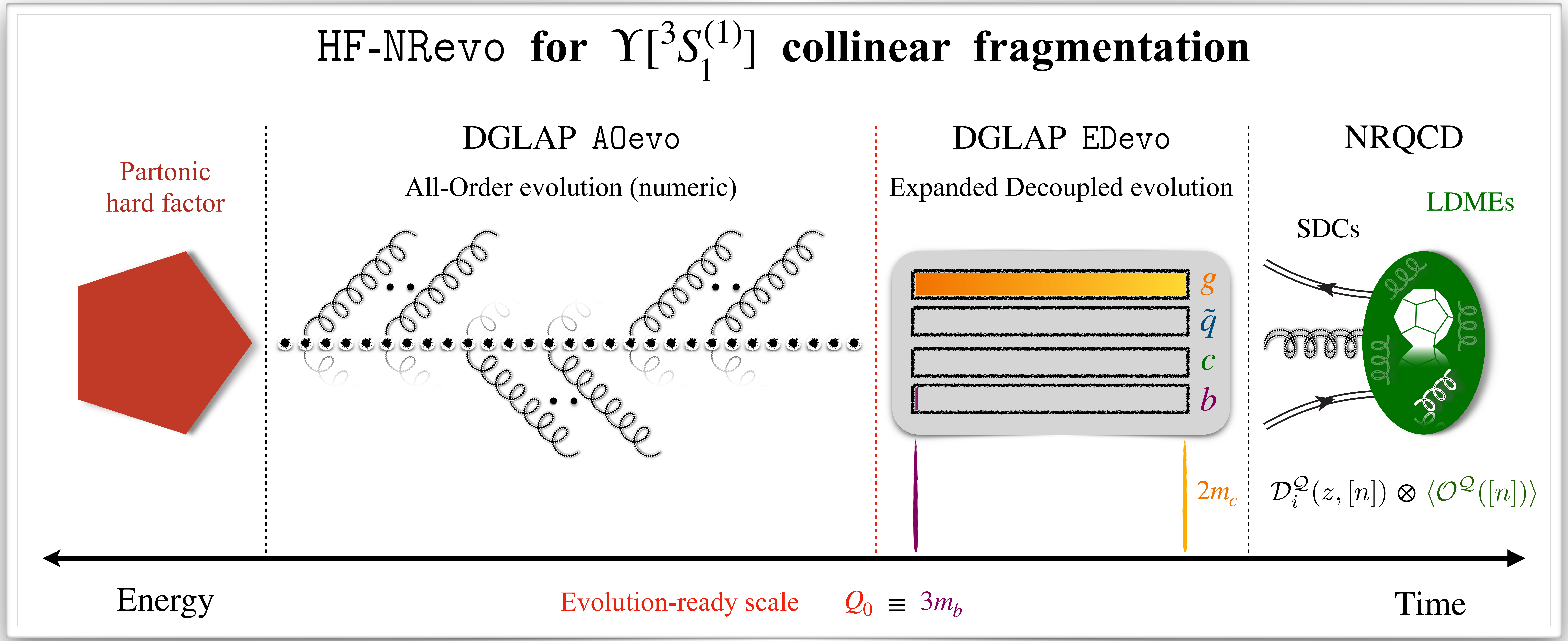


Vector Υ



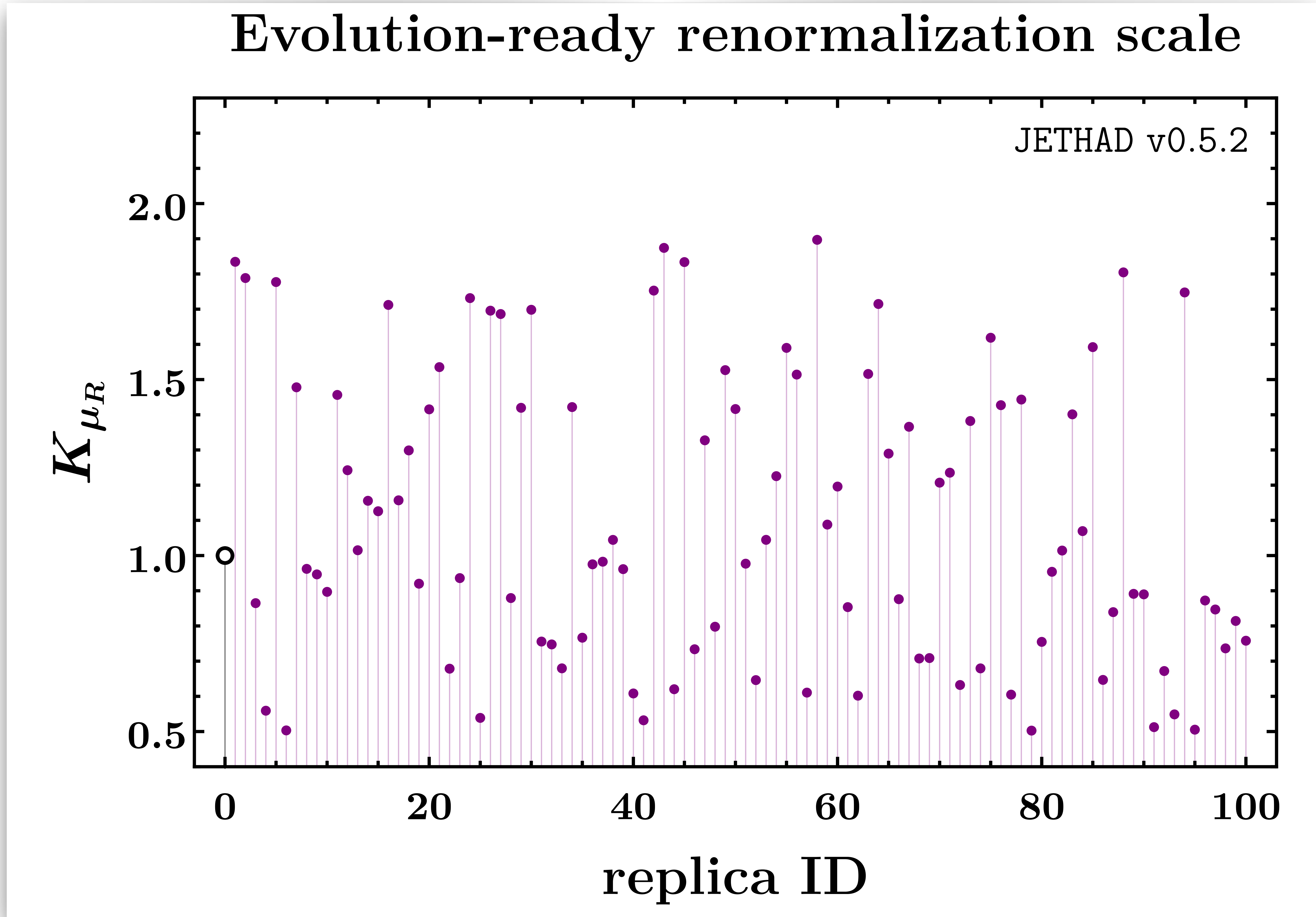
HF-NRevo

Interpretation   Evolution   Uncertainties

- Initial-scale MHOUs $\Rightarrow$ first systematic analysis
- Idea $\Leftrightarrow$ ThCovM 🔗 🔗 & MCscales 🔗 MHOUs
- Future $\Leftarrow$ extraction of NP LDMEs from data

Towards NRFF1.0: MHOU-replica analysis

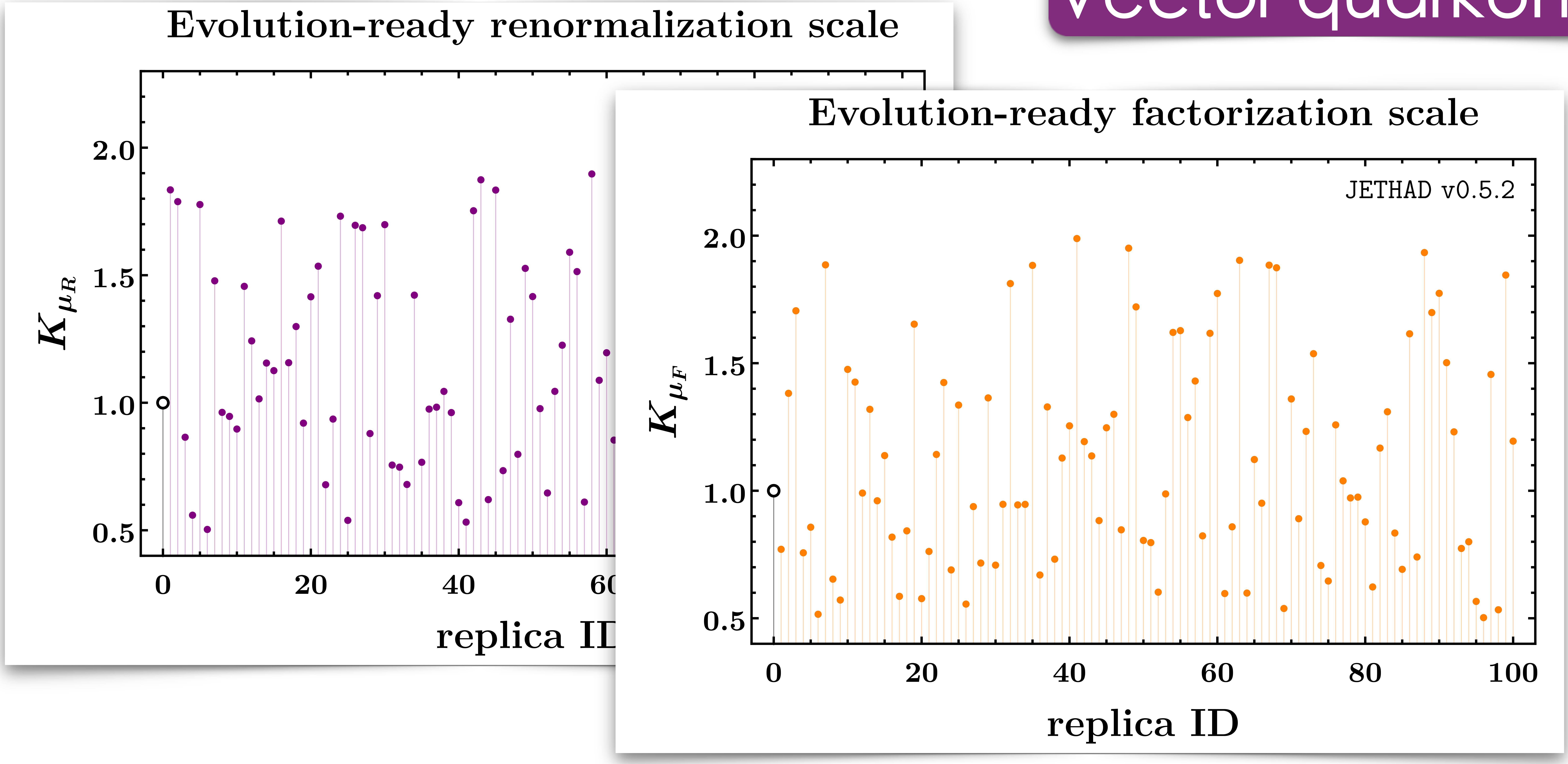
Vector quarkonia



[F. G. C., in preparation]

Towards NRFF1.0: MHOU-replica analysis

Vector quarkonia



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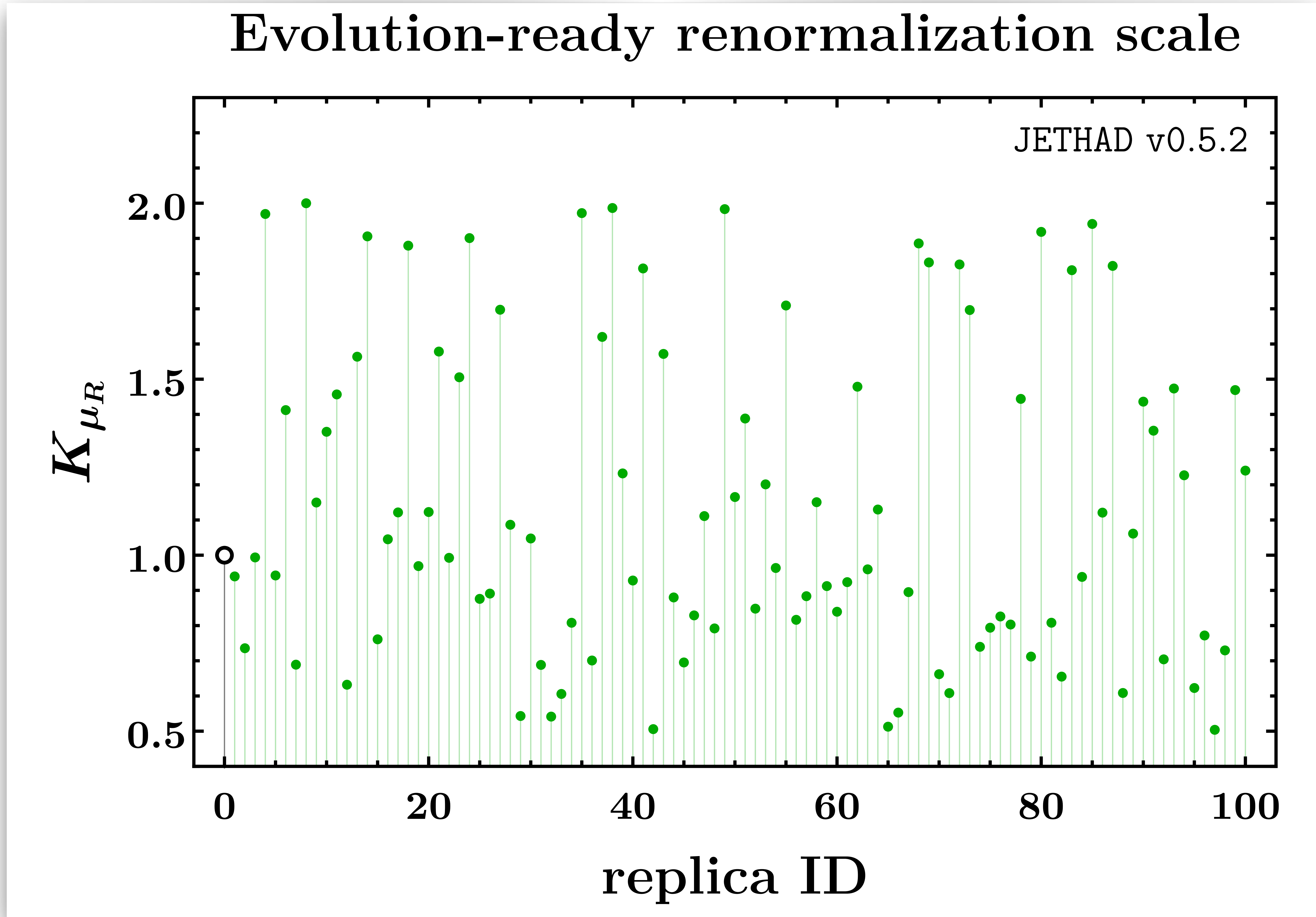
Towards NRFF1.0: MHOU-replica analysis

Scalar quarkonia



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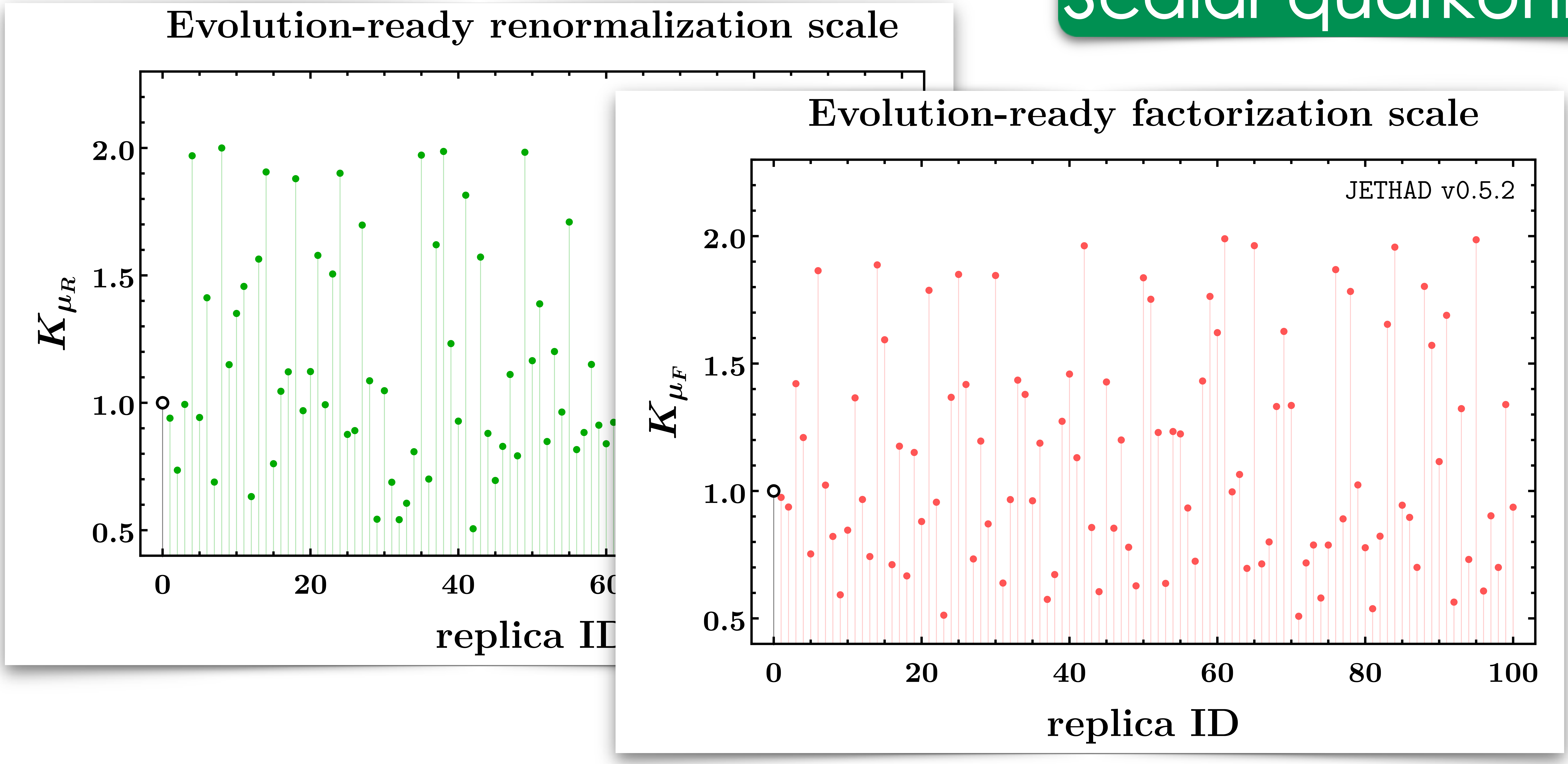
Towards NRFF1.0: MHOU-replica analysis

Scalar quarkonia



[F. G. C., in preparation]

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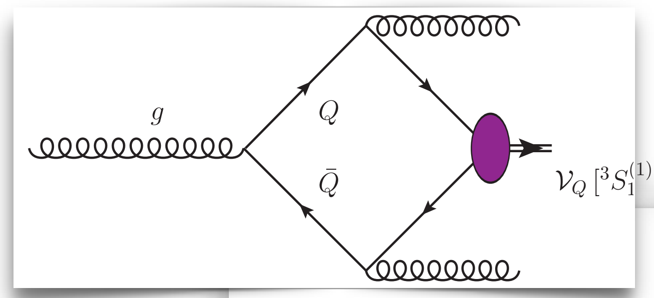
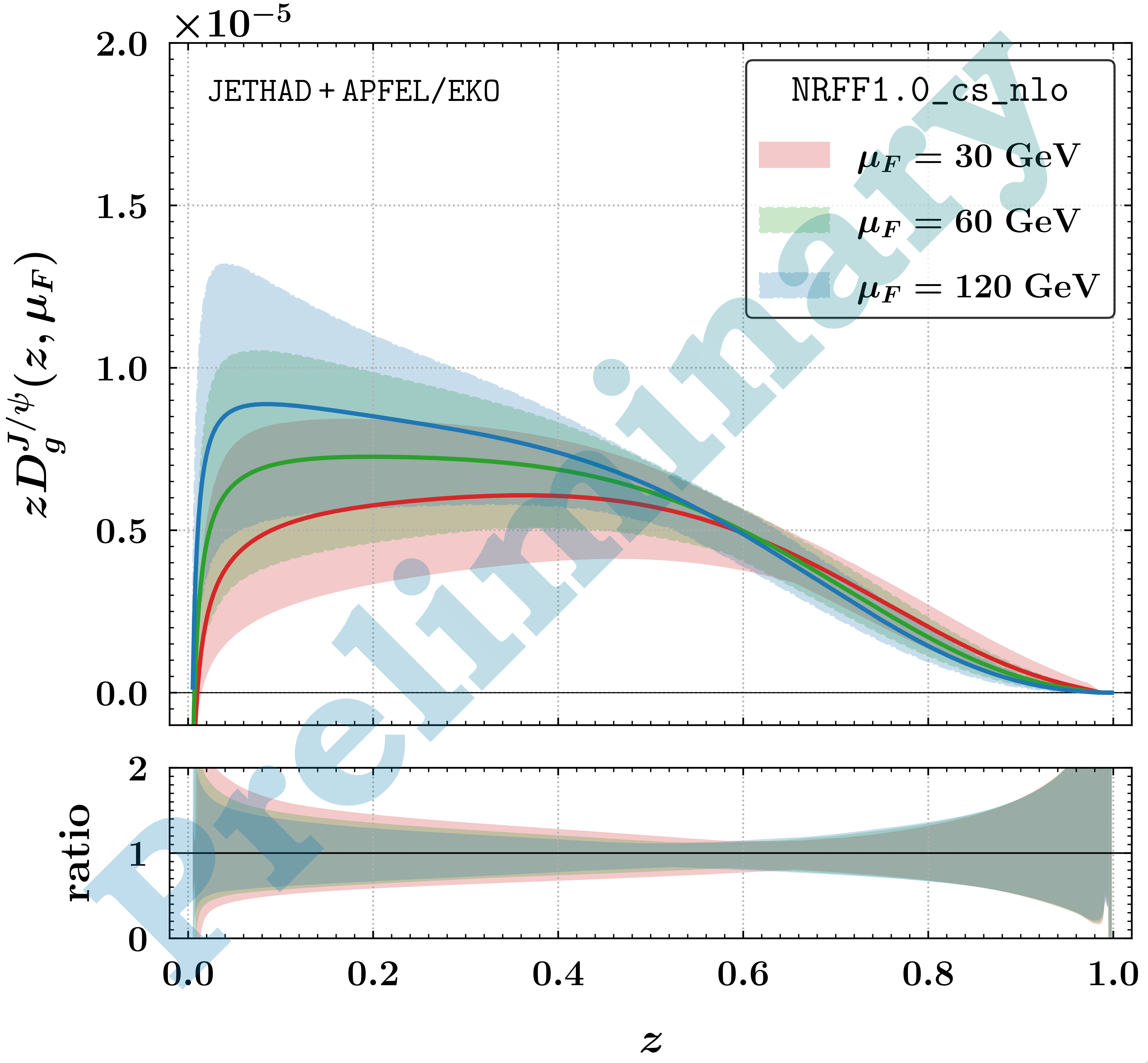
NRFF1.0_cs_nlo

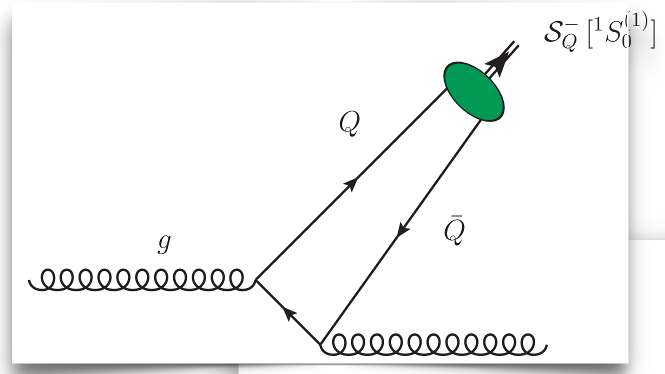
NRFF1.0: Gluon fragmentation to charmonia

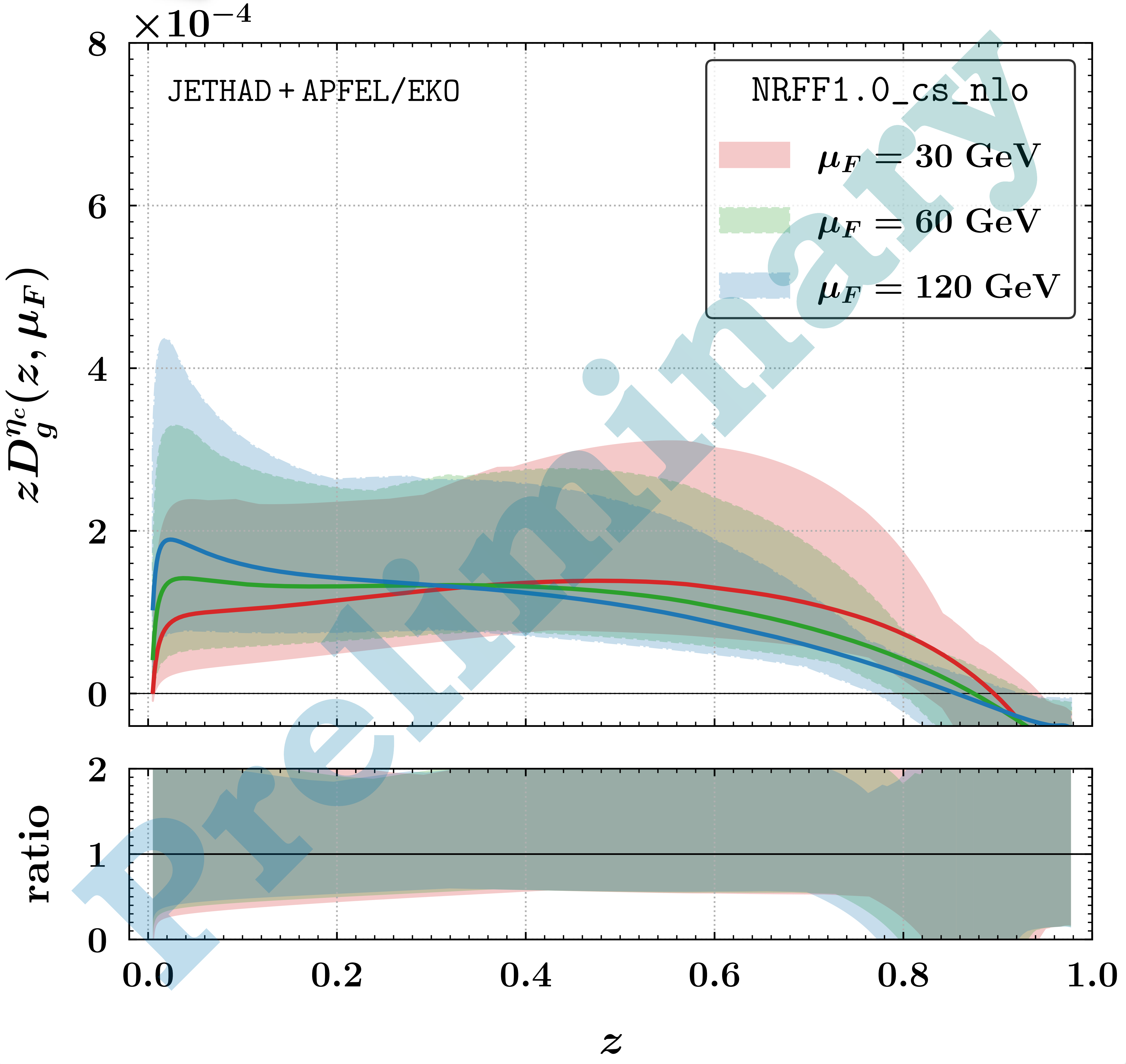
Vector J/ψ





Scalar η_c



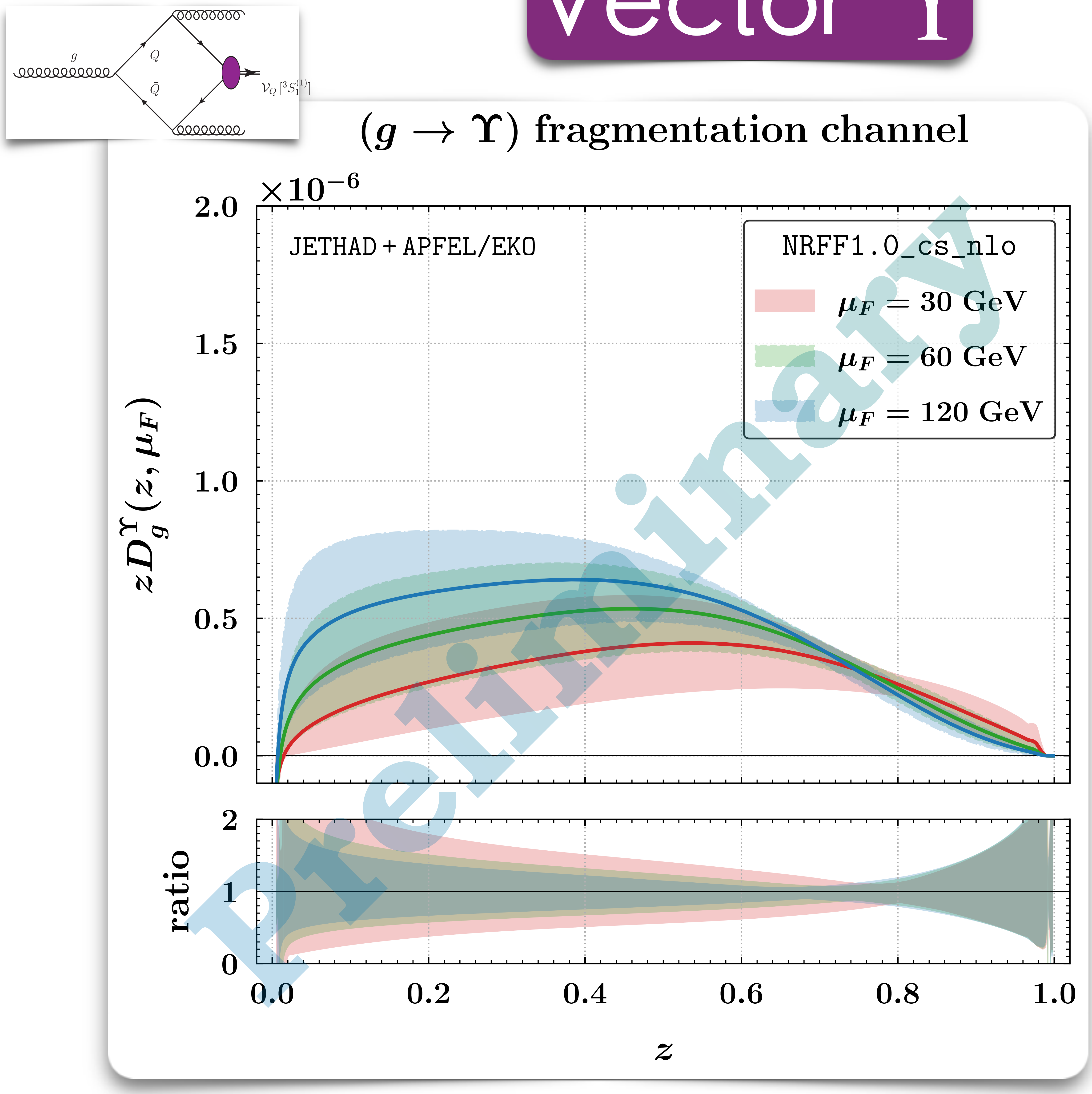


4.1 NRFF1.0 functions

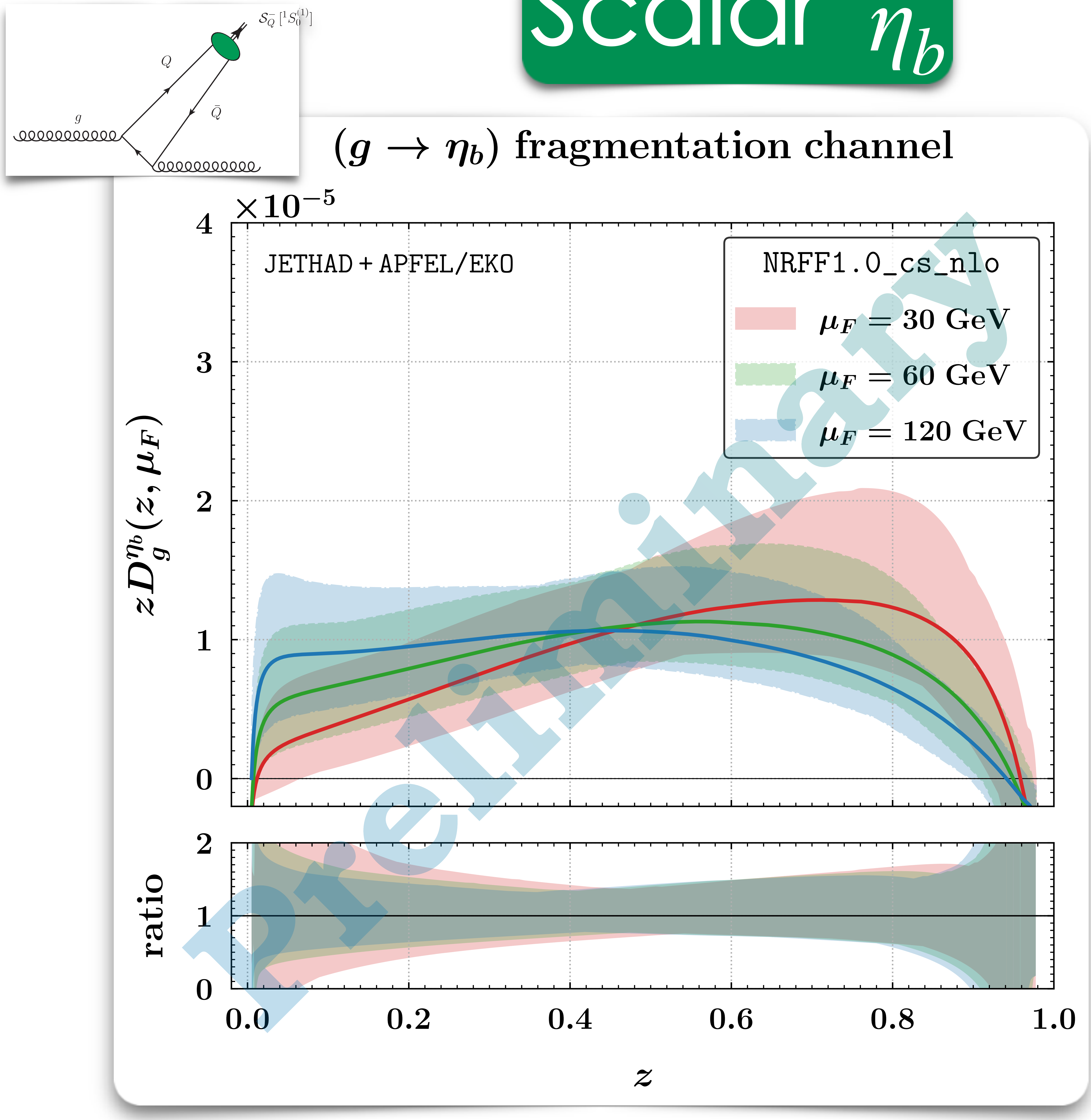
[F. G. C., in preparation]

NRFF1.0: Gluon fragmentation to bottomonia

Vector Υ



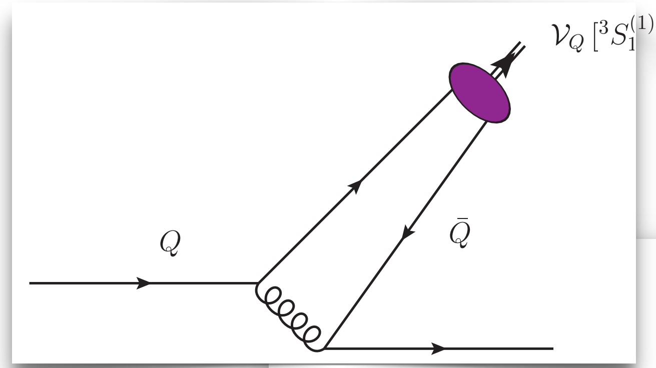
Scalar η_b

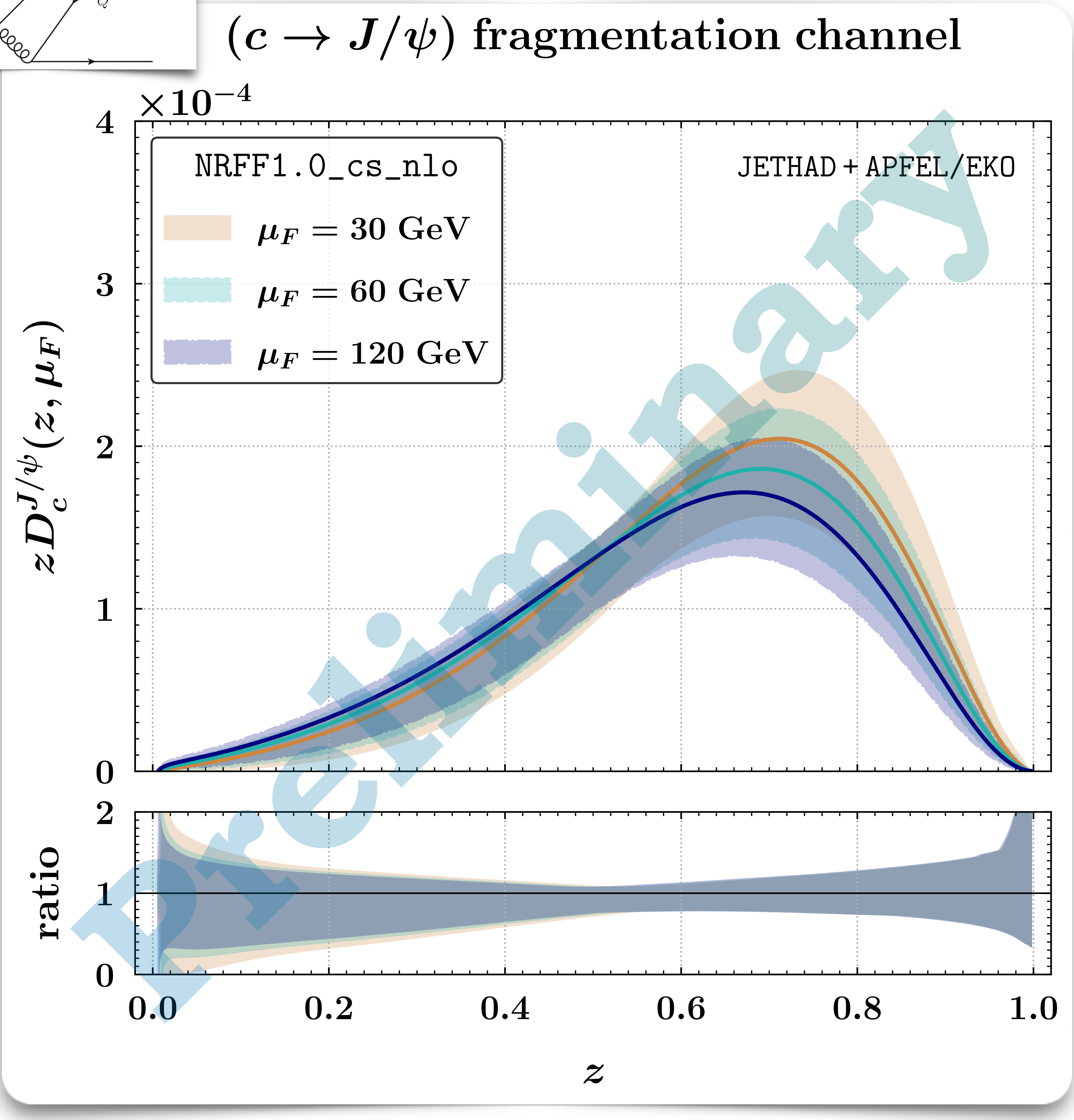


[F. G. C., in preparation]

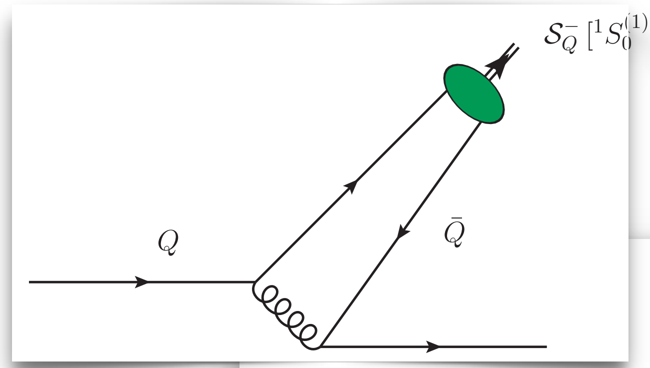
NRFF1.0: Charm fragmentation to charmonia

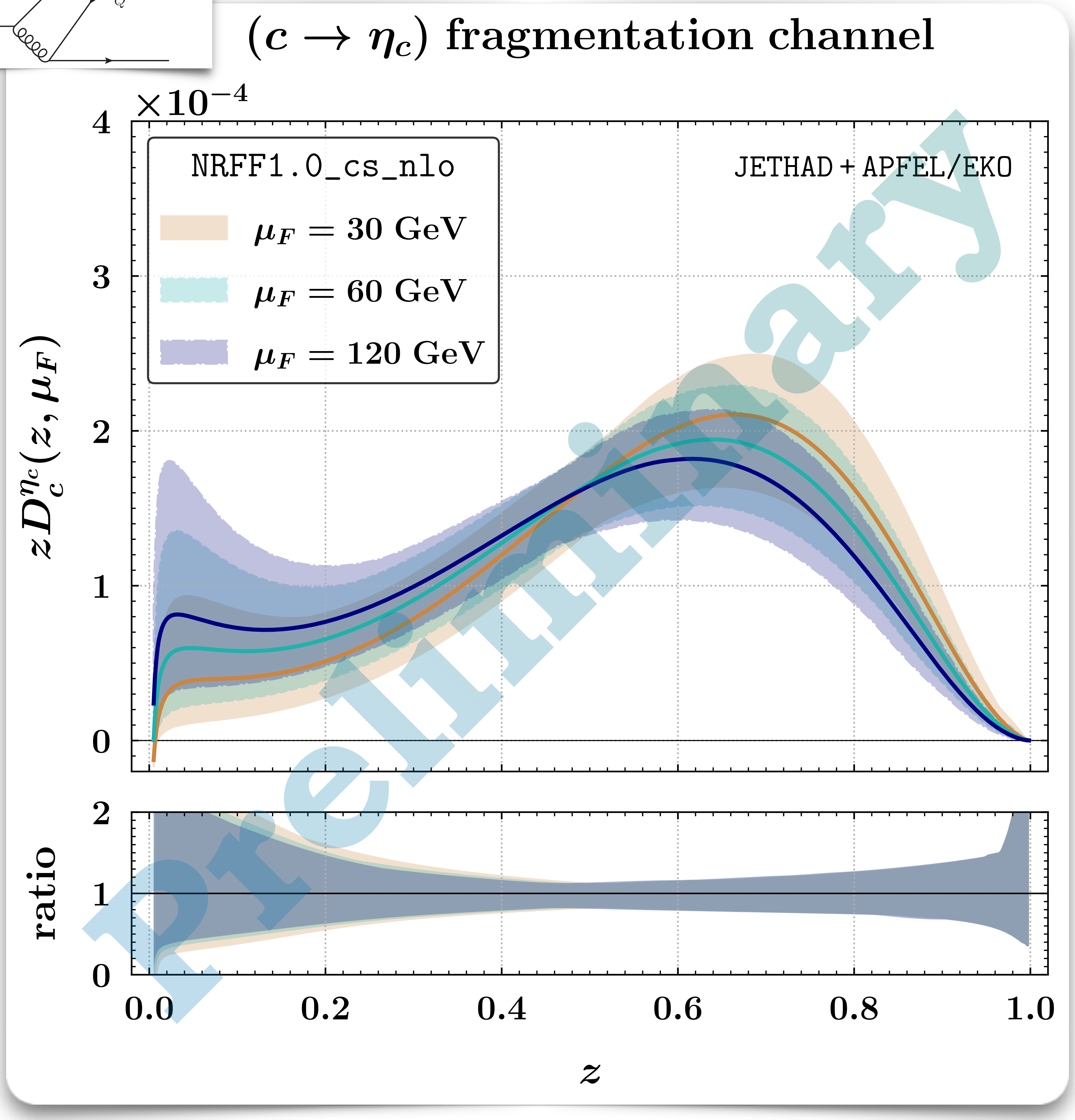
Vector J/ψ





Scalar η_c



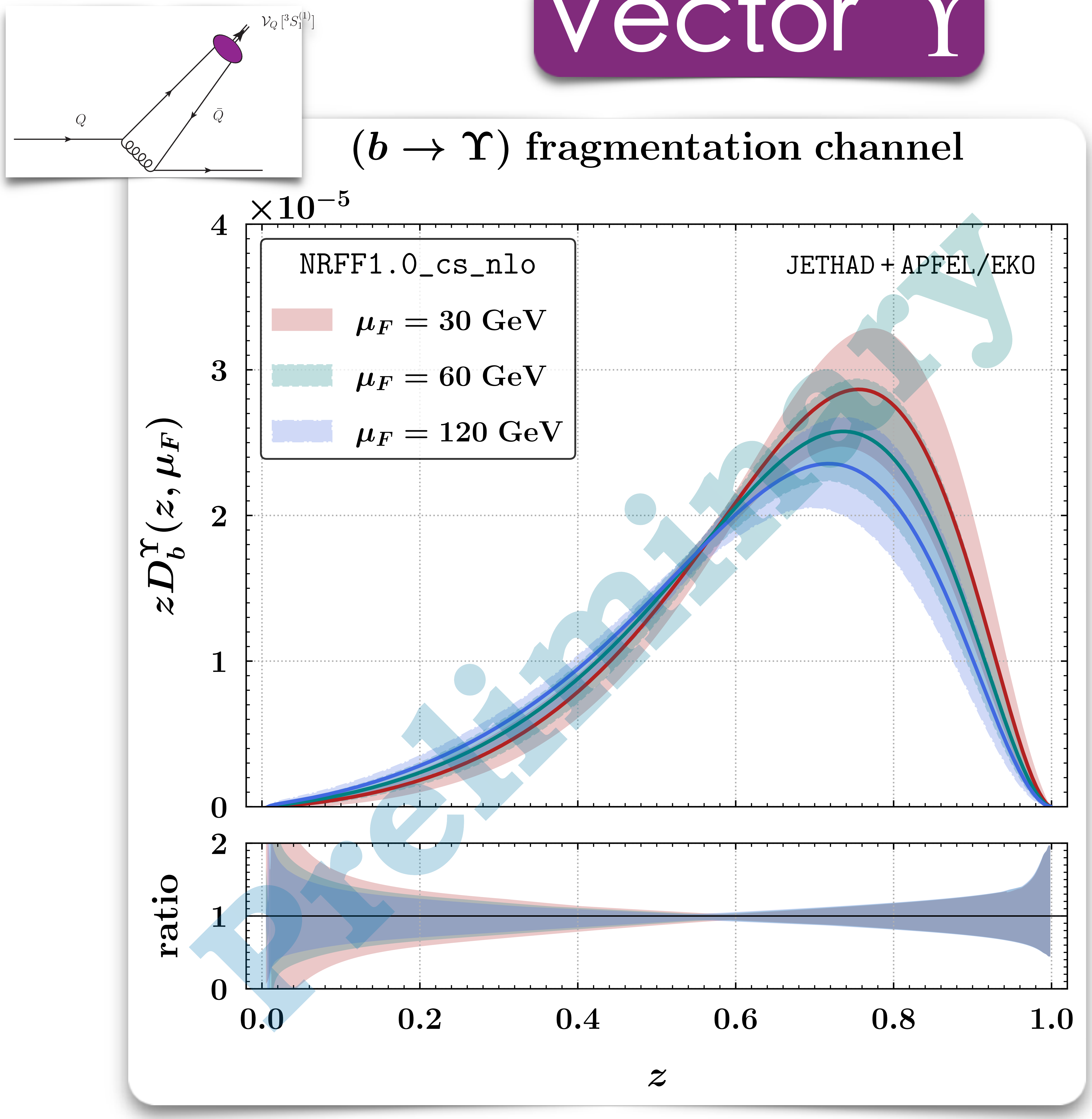


4.1 NRFF1.0 functions

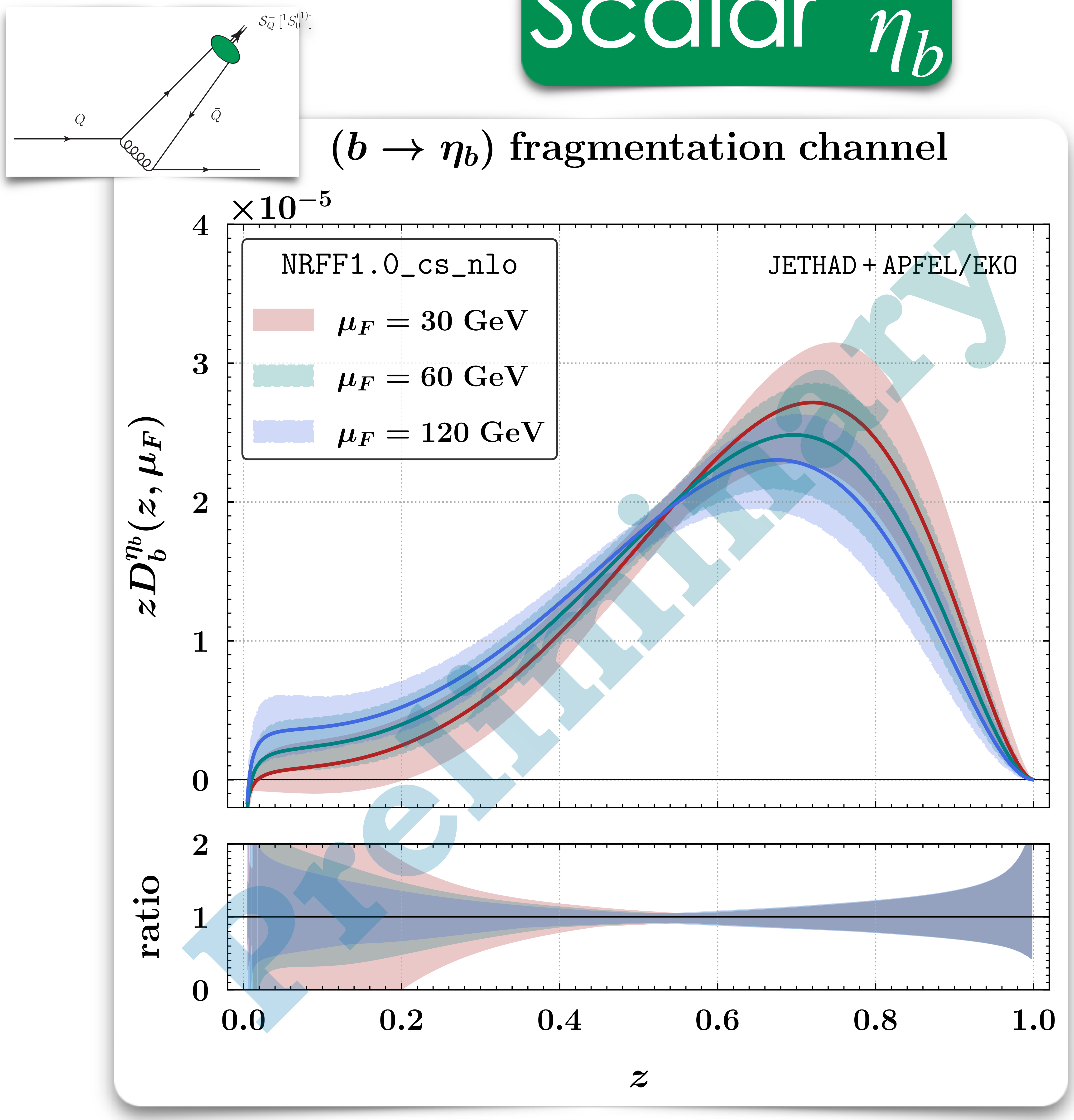
[F. G. C., in preparation]

NRFF1.0: Bottom fragmentation to bottomonia

Vector Υ



Scalar η_b



4.1 NRFF1.0 functions

[F. G. C., in preparation]

5

Towards onium-in-jet

NRFF1.0jet

From **NRQCD** FFs to semi-inclusive fragmenting jet functions (**siFJFs**)

$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^+ R, \mu) \; D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^+ R)^2)$$

[F. G. C., in preparation]

From **NRQCD** FFs to semi-inclusive fragmenting jet functions (**siFJFs**)

$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^{+}R, \mu) = \sum_j \int_{z_h}^{1} \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^{+}R, \mu)\, D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^{+}R)^2)$$

$$z = \frac{\omega_J}{\omega}, \qquad z_h = \frac{\omega_h}{\omega_J}$$

[F. G. C., in preparation]

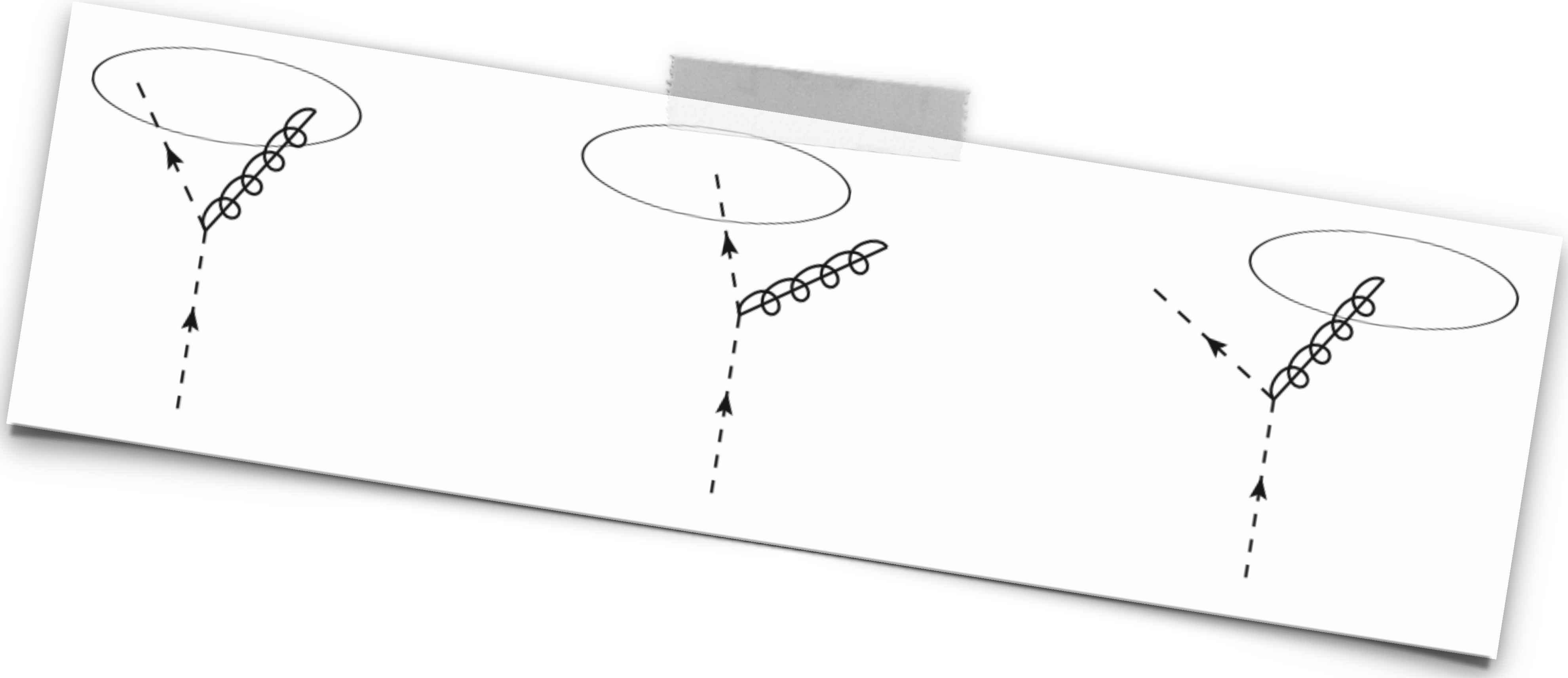
From **NRQCD** FFs to semi-inclusive fragmenting jet functions (**siFJFs**)

$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\text{jet}}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\text{jet}}^+ R, \mu) \, D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\text{jet}}^+ R)^2)$$

$$z = \frac{\omega_J}{\omega}, \qquad z_h = \frac{\omega_h}{\omega_J}$$

FJ coefficients $\Rightarrow$ known at NLO

- [M. Baumgart, A.K. Leibovich, T. Mehen, I.Z. Rothstein (2014)] (J/ψ in jet)
- [Z.-B. Kang, F. Ringer, I. Vitet (2016)] (hadron in jet, SCET, anti-k_T & cone)
- [Z.-B. Kang, J.-W. Chiu, F. Ringer, H. Xing, H. Zhang (2017)] (J/ψ in jet)



[F. G. C., in preparation]

RG evolution for **siFJFs** ⇔ two-step timelike DGLAP

$$D_j^{[\mathrm{onium}]}(z_h', \mu_0)$$

[F. G. C., in preparation]

Towards NRFF1.0jet

RG evolution for **siFJFs** ⇔ two-step timelike DGLAP

$$D_j^{[\text{onium}]}(z'_h, \mu_{\mathcal{G}} \approx p_T R)$$

$$D_j^{[\text{onium}]}(z'_h, \mu_0)$$

[F. G. C., in preparation]

RG evolution for **siFJFs** ⇔ two-step timelike DGLAP

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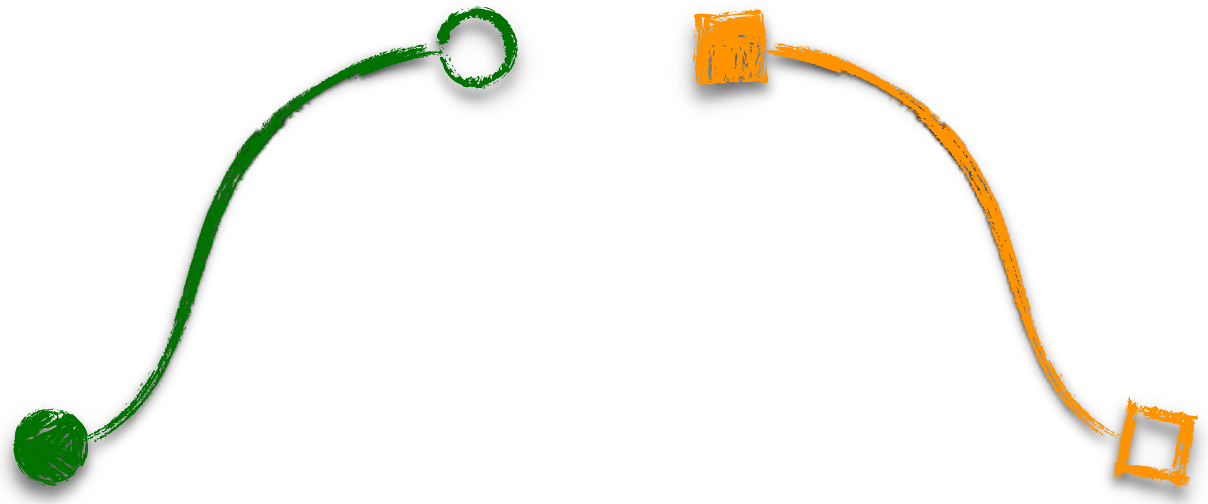


$$\mathcal{G}_i^{[\mathrm{onium}]}(z, z_h, R, \mu_F)$$

[F. G. C., in preparation]

Towards NRFF1.0jet

RG evolution for **siFJFs** ⇔ two-step timelike DGLAP

$$D_j^{[\mathrm{onium}]}(z_h', \mu_{\mathcal{G}} \approx p_T R)$$

$$D_j^{[\mathrm{onium}]}(z_h', \mu_0) \qquad \qquad \mathcal{G}_i^{[\mathrm{onium}]}(z, z_h, R, \mu_F)$$

Phenomenology opportunities with quarkonium-in-jet FFs

- Jet Substructure, Mass and Fragmentation
- Jet Radius Resummation and Angularities

[F. G. C., in preparation]

Towards `NRFF1.0(jet)` and beyond

Towards NRFF1.0(jet) and beyond

NRFF1.0 ⇒ basis for explorations at new-gen colliders

Towards NRFF1.0 (jet) and beyond

- **NRFF1.0** ⇒ basis for explorations at new-gen colliders

- **NRFF1.0jet** ⇒ mapping heavy-jet substructure

Towards `NRFF1.0(jet)` and beyond

- **`NRFF1.0`** ⇒ basis for explorations at new-gen colliders
- **`NRFF1.0jet`** ⇒ mapping heavy-jet substructure
- Phenomenology at **`(aN)NLO`** ⇒ Color Octet, GM-VFNS matching

Towards NRFF1.0(jet) and beyond

- **NRFF1.0** ⇒ basis for explorations at new-gen colliders

- **NRFF1.0jet** ⇒ mapping heavy-jet substructure

- Phenomenology at **(aN)NLO** ⇒ Color Octet, GM-VFNS matching

- AI-based extraction of onium FFs

Towards **NRFF1.0(jet)** and beyond

- **NRFF1.0** ⇒ basis for explorations at new-gen colliders
- **NRFF1.0jet** ⇒ mapping heavy-jet substructure
- Phenomenology at **(aN)NLO** ⇒ Color Octet, GM-VFNS matching
- AI-based extraction of onium FFs

¡ Thanks for the attention !

EXTRAS

Towards NRFF1.0jet: Fragmenting Jet Coefficients

$$\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \sum_j \int_{z_h}^1 \frac{dz'_h}{z'_h} \mathcal{J}_{ij}\left(z, z'_h, \omega_J, \mu\right) D_j^h\left(\frac{z_h}{z'_h}, \mu\right)$$

$$L = \ln\left(\frac{\mu^2}{\omega_J^2 \tan^2(\mathcal{R}/2)}\right)$$

$$\begin{aligned}
\mathcal{J}_{qq}(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Bigg\{ & L\left[P_{qq}(z)\delta(1-z_h) - P_{qq}(z_h)\delta(1-z)\right] \\
& + \delta(1-z)\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \mathcal{I}_{qq}^{\mathrm{alg}}(z_h)\right] \\
& - \delta(1-z_h)\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right]\Bigg\}, \\
\mathcal{J}_{gg}(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Bigg\{ & L\left[P_{gg}(z)\delta(1-z_h) - P_{gg}(z_h)\delta(1-z)\right] \\
& + \delta(1-z)\left[4C_A\frac{(1-z_h+z_h^2)^2}{z_h}\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + \mathcal{I}_{gg}^{\mathrm{alg}}(z_h)\right] \\
& - \delta(1-z_h)\left[4C_A\frac{(1-z+z^2)^2}{z}\left(\frac{\ln(1-z)}{1-z}\right)_+\right]\Bigg\},
\end{aligned}$$

🔗 [Z.-B. Kang, F. Ringer, I. Vitet (2016)] (hadron, in jet, SCET, anti-k_T & cone)

Towards NRFF1.0jet: Fragmenting Jet Coefficients

$$\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}\left(z, z_h', \omega_J, \mu\right) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

$$L = \ln\left(\frac{\mu^2}{\omega_J^2 \tan^2(\mathcal{R}/2)}\right)$$

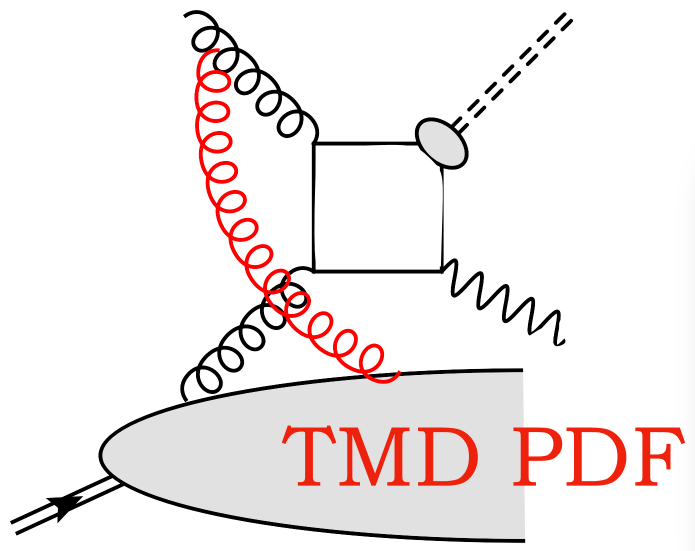
$$\begin{aligned}
\mathcal{J}_{qg}(z, z_h, \omega_J, \mu) = \frac{\alpha_s}{2\pi}\Big\{ & L\left[P_{gq}(z)\delta(1-z_h) - P_{gq}(z_h)\delta(1-z)\right] \\
& + \delta(1-z)\left[2P_{gq}(z_h)\ln(1-z_h) + C_F z_h + \mathcal{I}_{qg}^{\text{alg}}(z_h)\right] \\
& - \delta(1-z_h)\left[2P_{gq}(z)\ln(1-z) + C_F z\right]\Big\}, \\
\mathcal{J}_{gq}(z, z_h, \omega_J, \mu) = \frac{\alpha_s}{2\pi}\Big\{ & L\left[P_{qg}(z)\delta(1-z_h) - P_{qg}(z_h)\delta(1-z)\right] \\
& + \delta(1-z)\left[2P_{qg}(z_h)\ln(1-z_h) + 2T_F z_h(1-z_h) + \mathcal{I}_{gq}^{\text{alg}}(z_h)\right] \\
& - \delta(1-z_h)\left[2P_{qg}(z)\ln(1-z) + 2T_F z(1-z)\right]\Big\},
\end{aligned}$$

[Z.-B. Kang, F. Ringer, I. Vitet (2016)] (hadron, in jet, SCET, anti-k_T & cone)

Quarkonium physics: Assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

$$\frac{d\sigma}{dq_T} \sim$$

at low transverse momentum
for (pseudo)scalar state

$$\sim \mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]$$

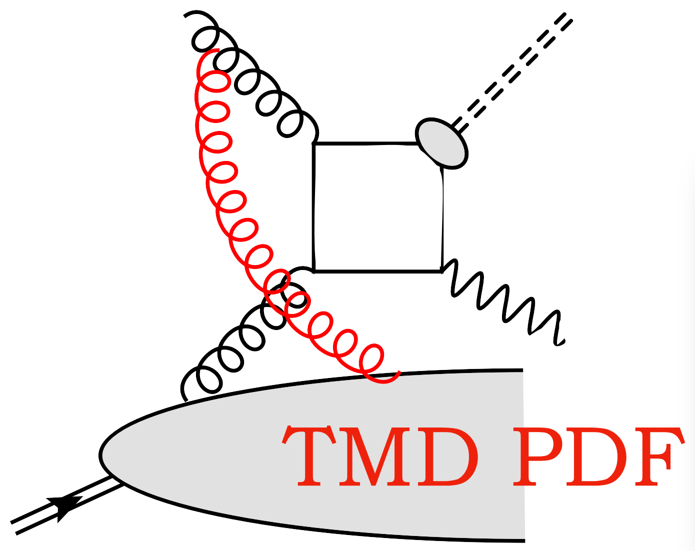
unpolarized gluons | **lin. polarized** gluons

Quarkonium physics: Assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs

Initial-state color flow ⇒ [− , −] gauge link



$$\frac{d\sigma}{dq_T} \sim$$

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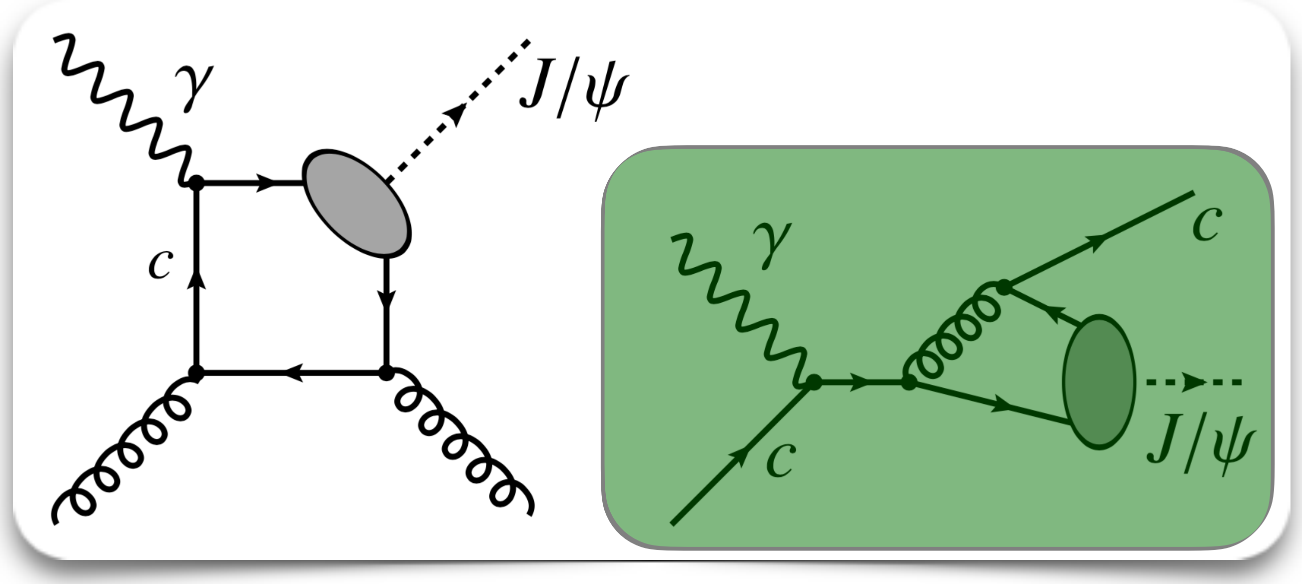
$$\sim \mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]$$

unpolarized gluons — **lin. polarized** gluons

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

EIC studies:
large x
moderate to large p_T



(polarized gluon TMDs) 🔗 [A. Bacchetta, F. G. C., M. Radici (2024)]
(J/ψ @EIC) 🔗 [C. Flore, J.-P. Lansberg, H.-S. Shao, Y, Yedelkina (2020)]
(Intrinsic Charm + valence) studies 🔗🔗 [NNPDF Collaboration (2022, 2023)]

Challenges

Precision level ⇔ production mechanism(s)

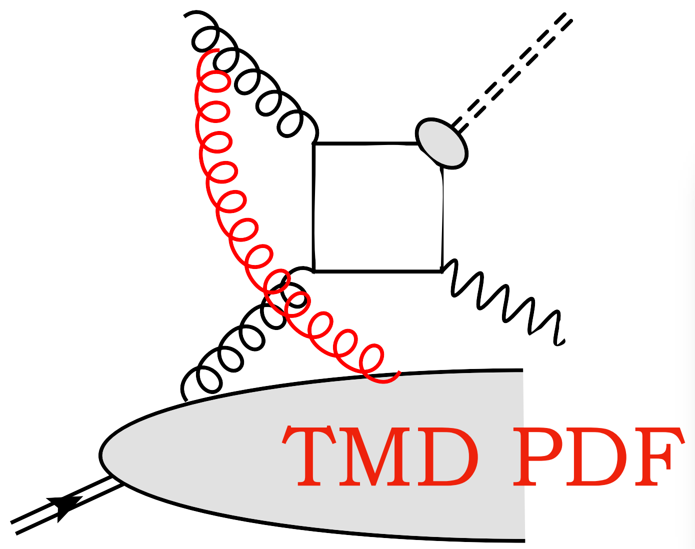
(production mechanisms, (HL-)LHC pheno) 🔗 [Quarkonia As Tools (2022)]

Quarkonium physics: Assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs

Initial-state color flow ⇒ [– , –] gauge link



$$\frac{d\sigma}{dq_T} \sim \mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons ; **lin. polarized** gluons

$\gamma + g \rightarrow J/\psi + c$ ⇒ valence Intrinsic Charm @EIC

EIC studies:

large x

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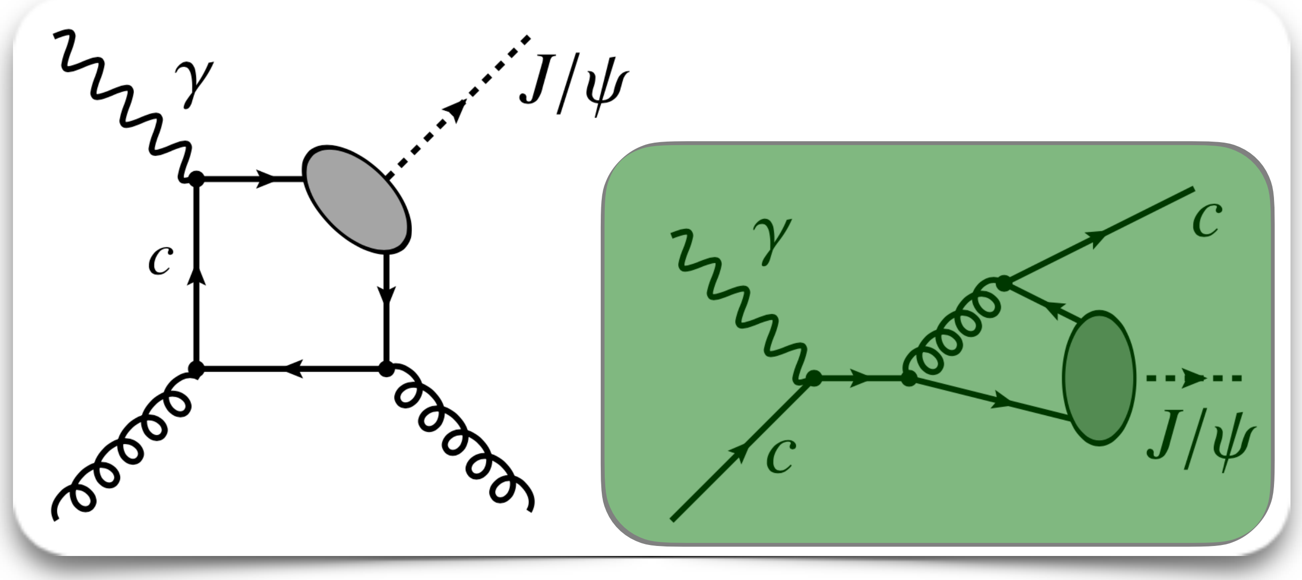

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(Intrinsic Charm + valence) studies 🔗🔗 [NNPDF Collaboration (2022, 2023)]

Challenges

Precision level ⇔ production mechanism(s)

(production mechanisms, (HL-)LHC pheno) 🔗 [Quarkonia As Tools (2022)]

- Color Evaporation Model 🔗 🔗

  $(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions

- Color Singlet Model 🔗 🔗

  $(Q\bar{Q})$ to onium, no gluon emissions

- NRQCD and Color Octet 🔗 🔗 🔗 🔗 🔗

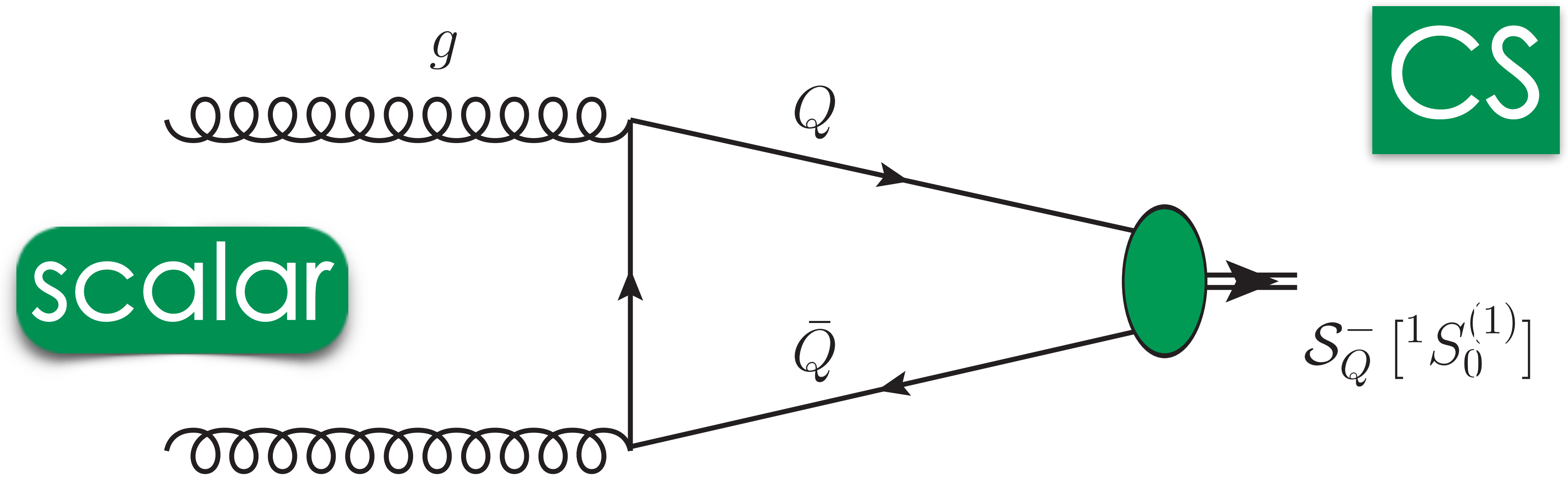
  Most complete formalism, cures P-wave divergences

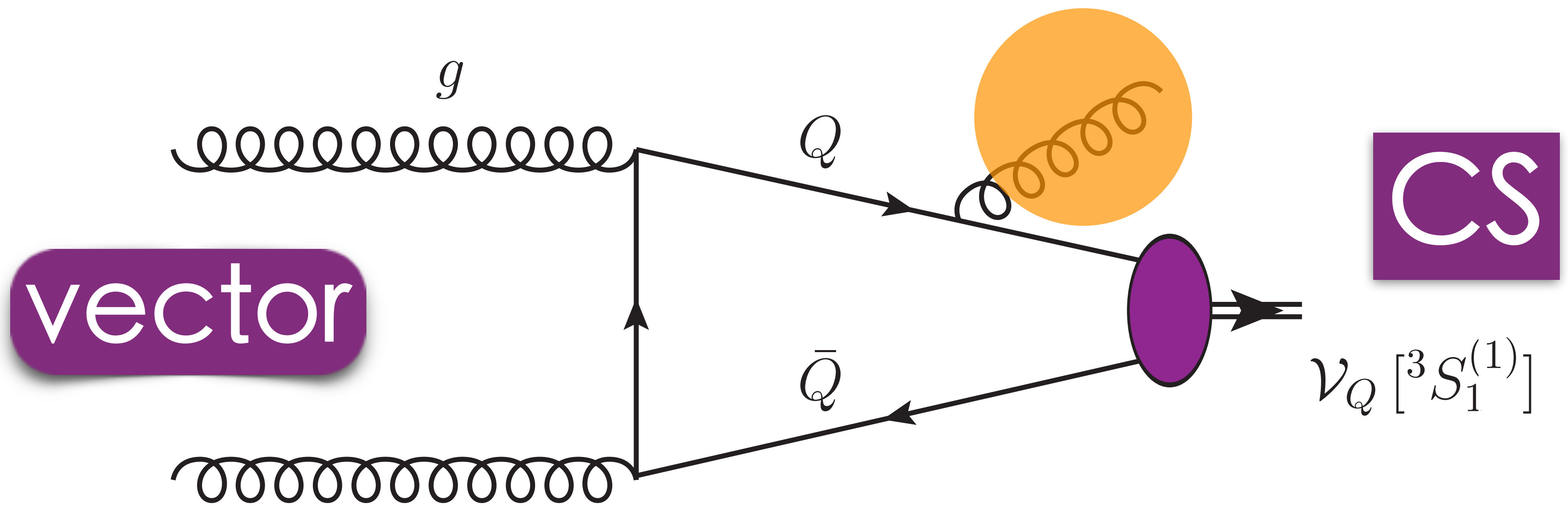
  Higher Fock states, soft gluon emissions

  Fragmentation & polarization studies needed

From low energies to high energies

Low energy, low p_T
Short-distance production





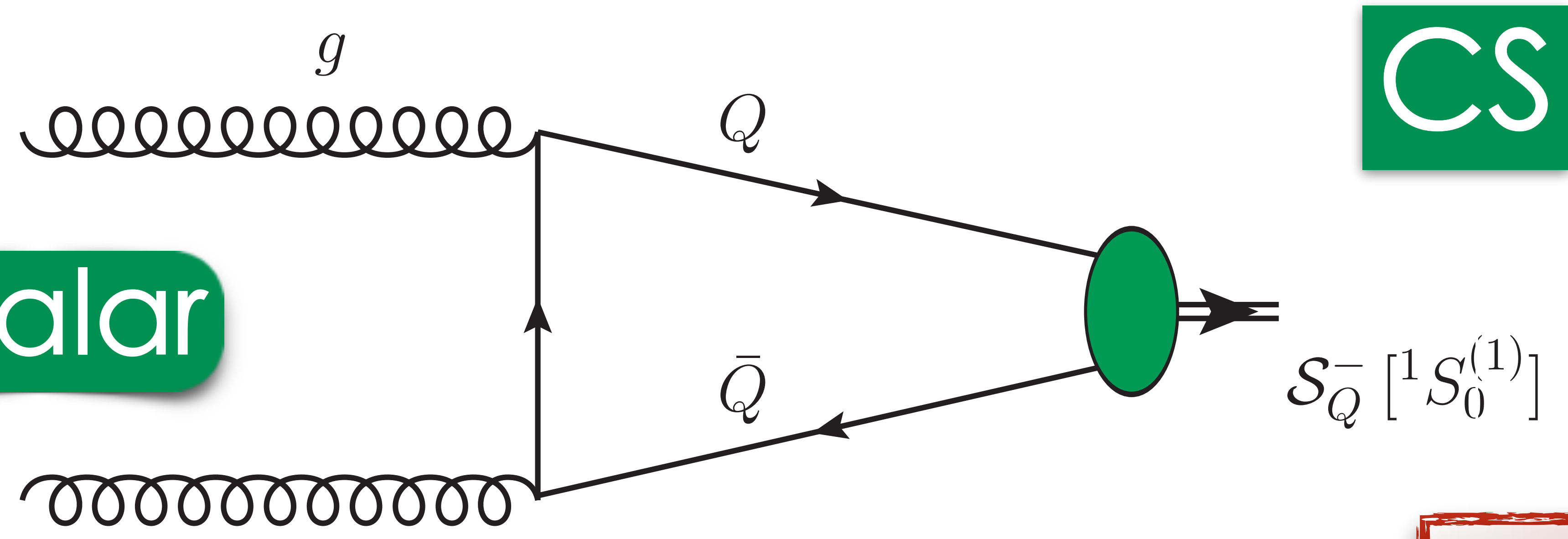
Extra gluon due to Landau-Yang selection rule

From low energies to high energies

Low energy, low p_T
Short-distance production

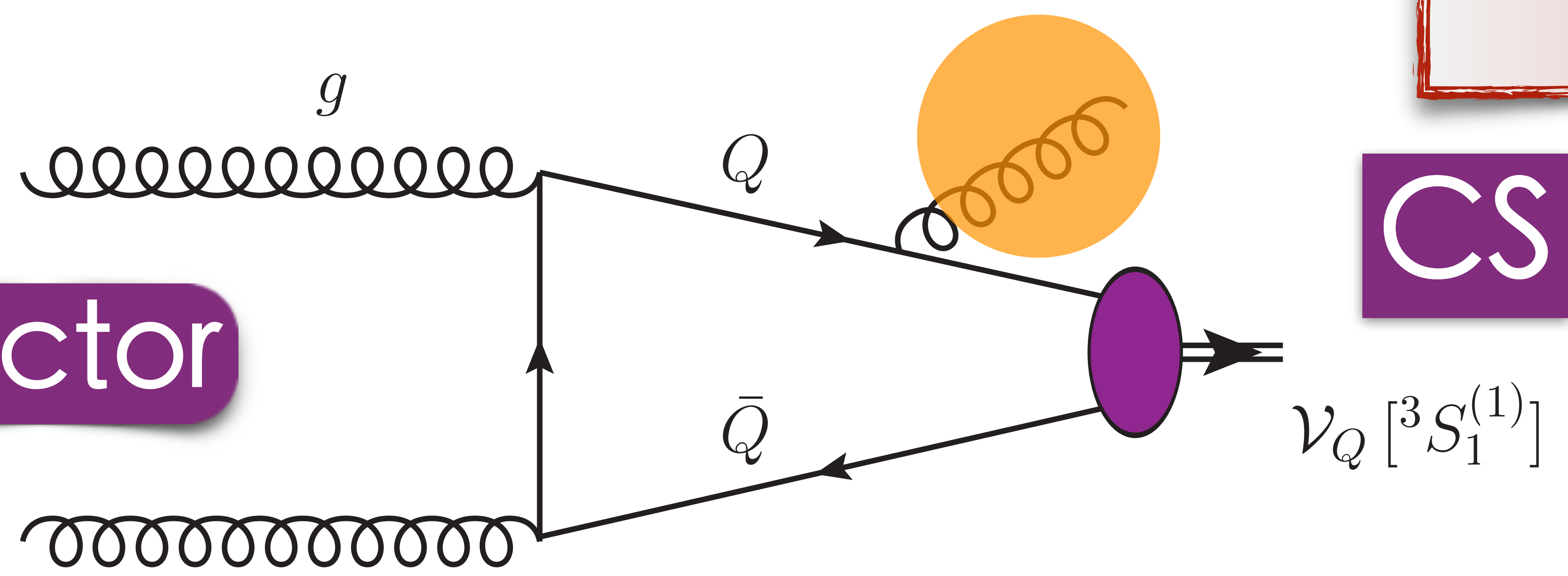
scalar

CS



vector

CS

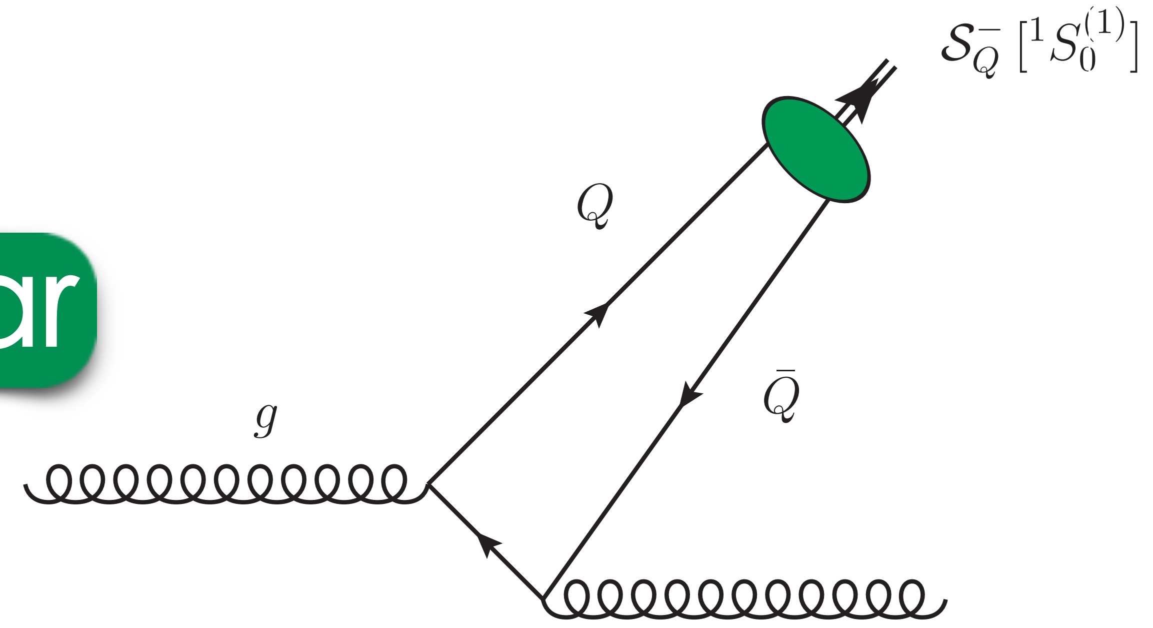


$p_T \gtrsim 10 \div 15$ GeV
(charmonia)

High energy, high p_T
Single-parton fragmentation

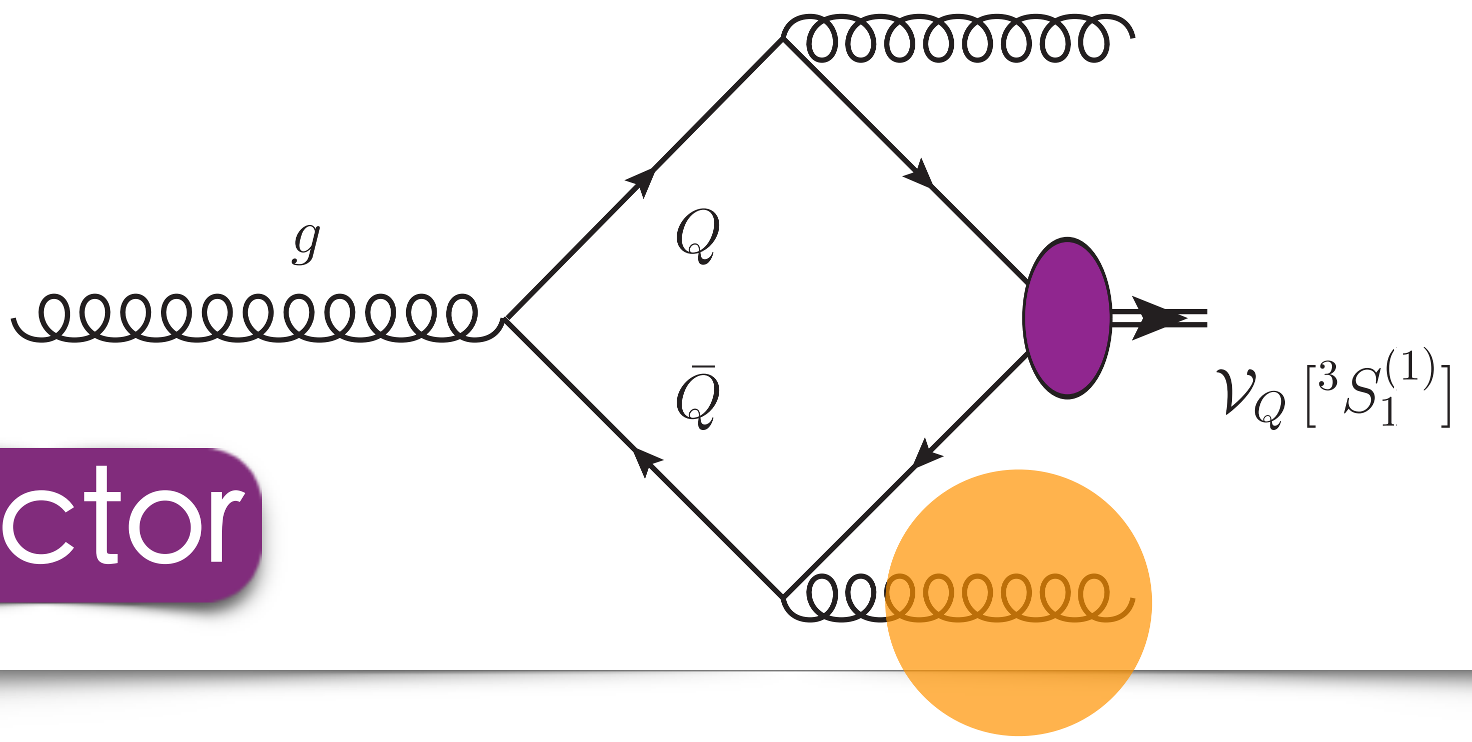
scalar

CS



vector

CS



Extra gluon due to Landau-Yang selection rule

HF-NRevo: Initial-scale NRCQD inputs

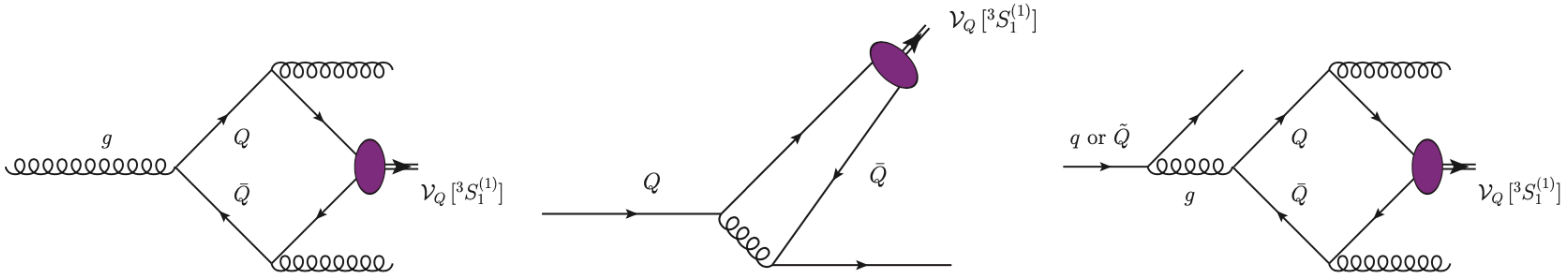


Fig. 1 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet vector quarkonium $\mathcal{V}_Q\,[^3S_1^{(1)}]$ 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.

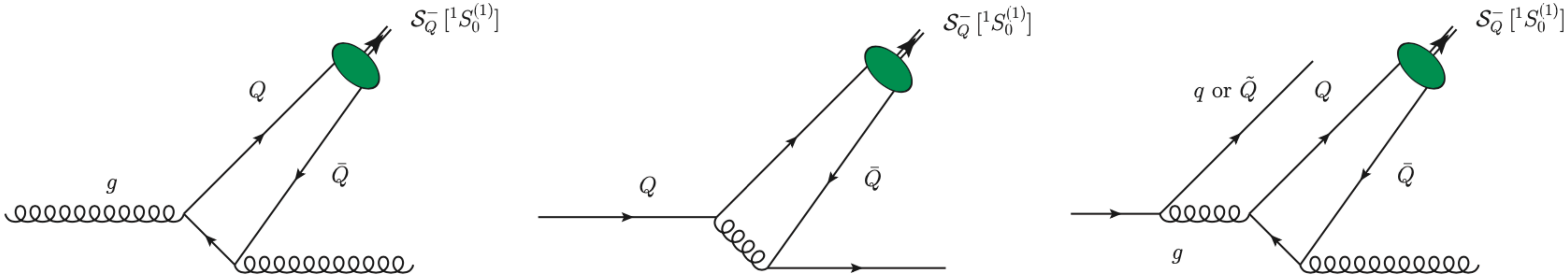
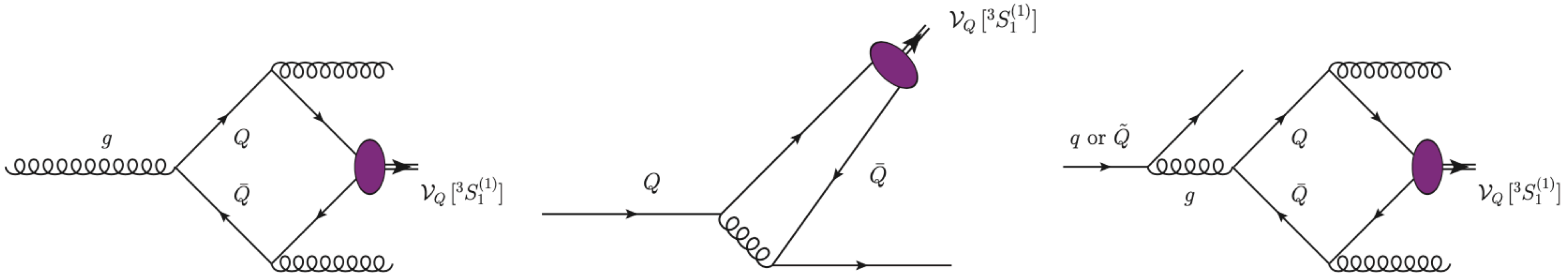


Fig. 2 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet pseudoscalar quarkonium $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ 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



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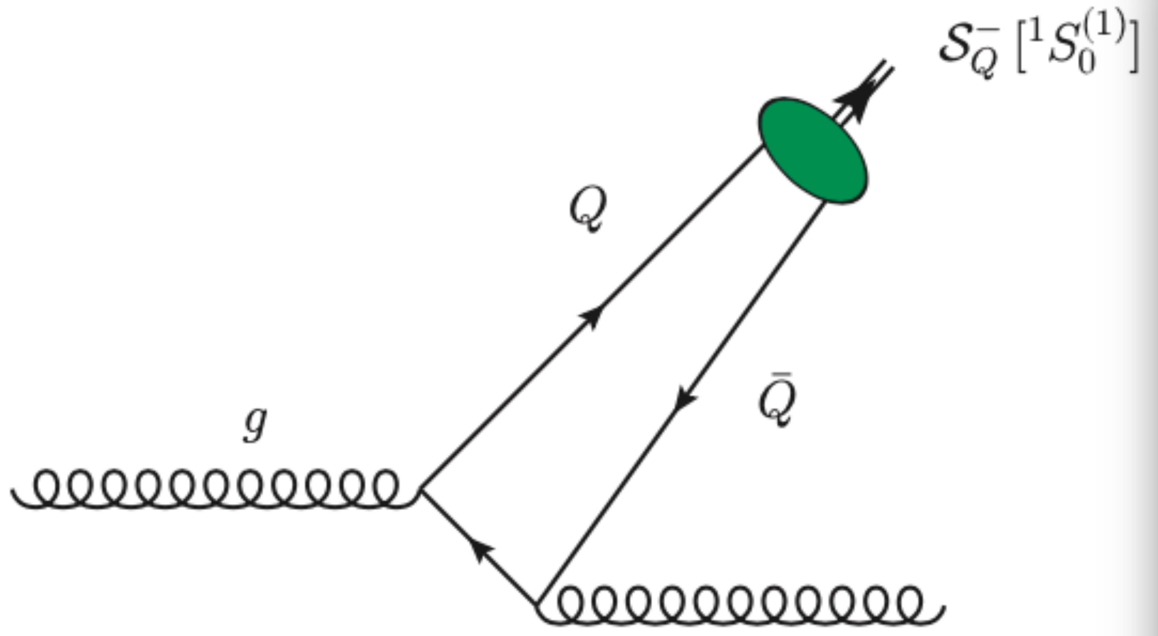


Fig. 2 Left panel: a leading diagram fo
leading diagrams for the fragmentation o
$\mathcal{S}_Q^-\,[{}^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Right panel: a leadi
to $\mathcal{S}_Q^-\,[{}^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Green blobs refe

Quarkonium ($\mathcal{Q}$)	$g \to \mathcal{Q}$	$Q \to \mathcal{Q}$	q or $\tilde{Q} \to \mathcal{Q}$
$\mathcal{Q} \equiv \mathcal{V}_Q\,[{}^1S_0^{(1)}] \equiv J/\psi, \Upsilon$	– $\mathcal{O}(\alpha_s^3) \equiv$ NLO $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮	$\mathcal{O}(\alpha_s^2) \equiv$ LO $\mathcal{O}(\alpha_s^3) \equiv$ NLO $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮	– – $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮
$\mathcal{Q} \equiv \mathcal{S}_Q^-\,[{}^3S_1^{(1)}] \equiv \eta_c, \eta_b$	$\mathcal{O}(\alpha_s^2) \equiv$ LO $\mathcal{O}(\alpha_s^3) \equiv$ NLO $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮	$\mathcal{O}(\alpha_s^2) \equiv$ LO $\mathcal{O}(\alpha_s^3) \equiv$ NLO $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮	– $\mathcal{O}(\alpha_s^3) \equiv$ NLO $\mathcal{O}(\alpha_s^4) \equiv$ NNLO ⋮

[F. G. C., in preparation]

$\texttt{HF-NRevo}$: Initial-scale NRCQD inputs

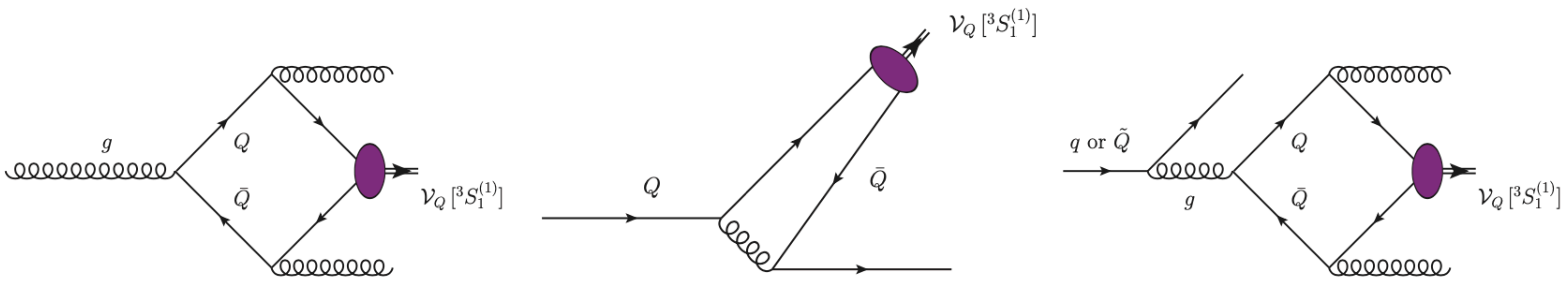
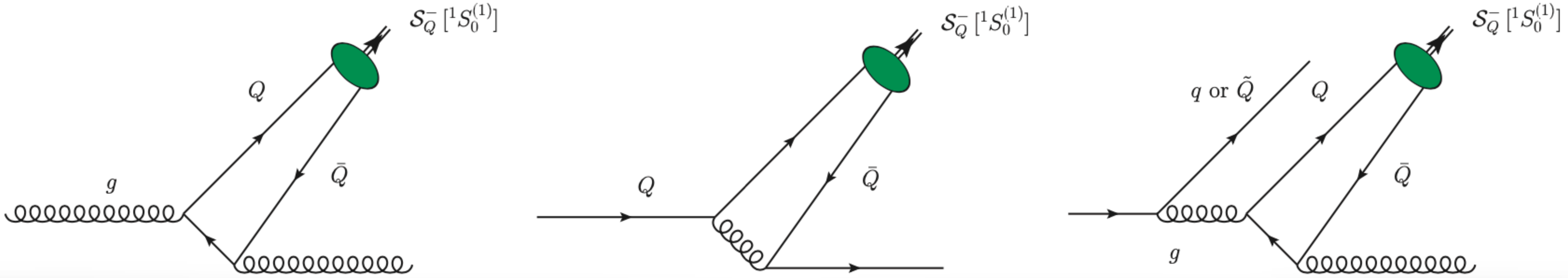


Fig. 1 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet vector quarkonium $\mathcal{V}_Q\,[^3S_1^{(1)}]$ 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.

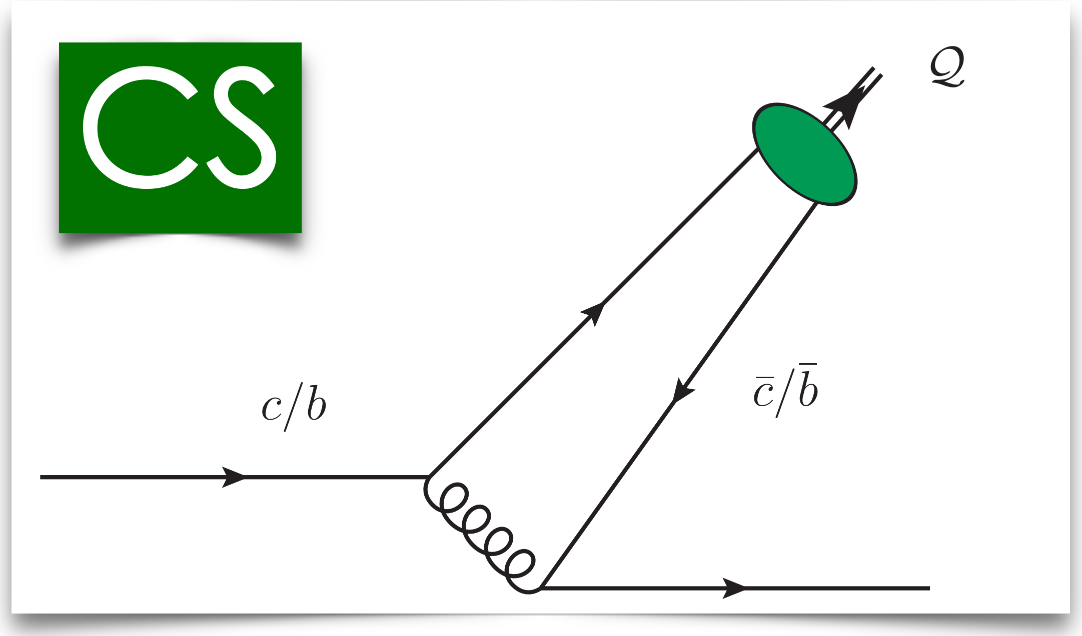


$\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ quarkonium	$\mu_{F,0}(g \to \mathcal{S}_Q^-)$	$\mu_{F,0}(d,u,s \to \mathcal{S}_Q^-)$	$\mu_{F,0}(Q \to \mathcal{S}_Q^-)$	$\mu_{F,0}(\tilde{Q} \to \mathcal{S}_Q^-)$	$Q_0 \equiv \max(\{\mu_{F,0}\})$
η_c	$2m_c$	$m_{d,u,s} + 2m_c$	$3m_c$	$m_b + 2m_c$	$m_b + 2m_c$
η_b	$2m_b$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

[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*** !



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

$(Q \rightarrow \mathcal{Q}\, Q)$ 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)]

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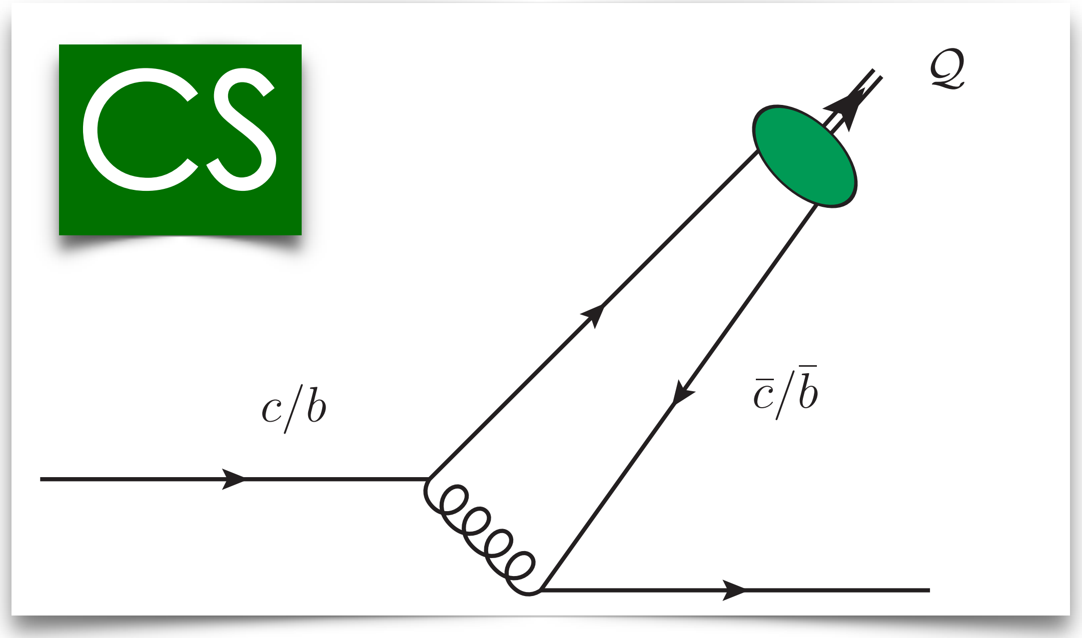

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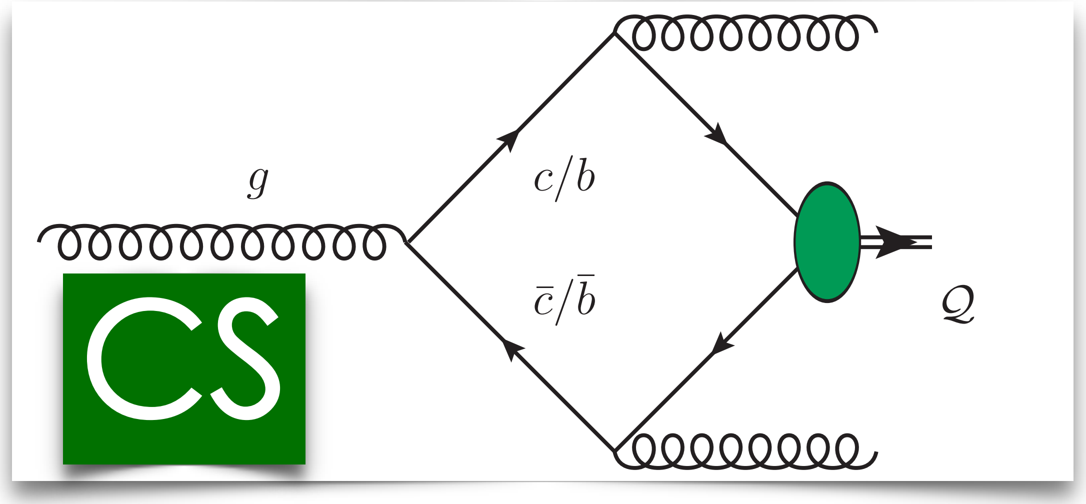

$$D_g^{\mathcal{Q}}(z,2m_Q) = \frac{5}{36(2\pi)^2}\alpha_s^3(2m_Q)\frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_Q^3}\int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2}$$
$$\sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau)\frac{1+\xi-2\tau}{2(\tau-\xi)\sqrt{\tau^2-\xi}}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

$(g \to \mathcal{Q}\,gg)$ at $\mu_0 = 2m_Q$

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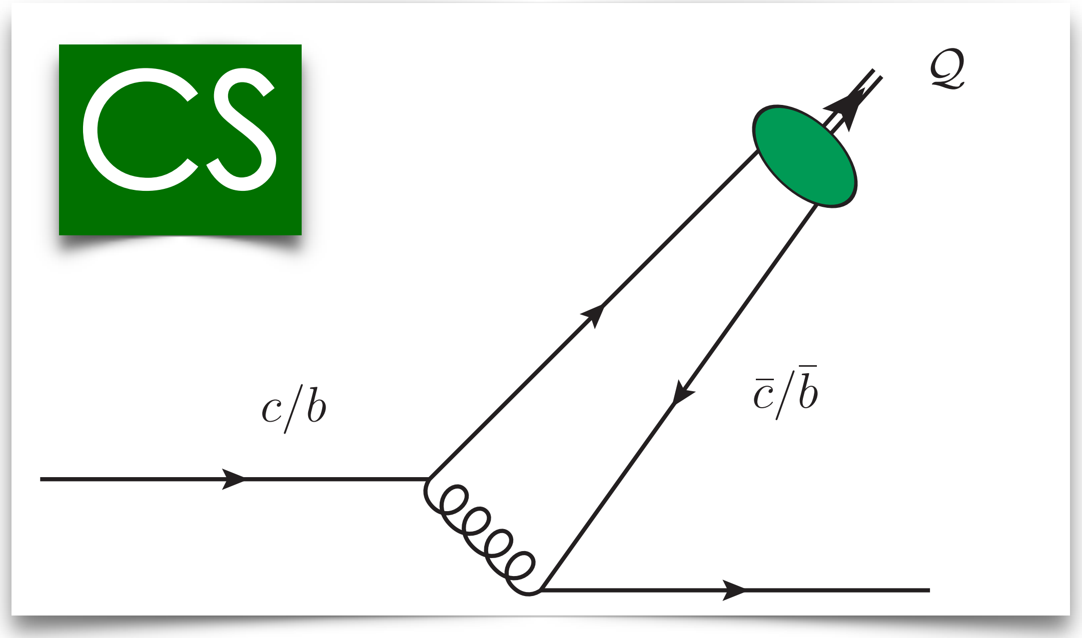

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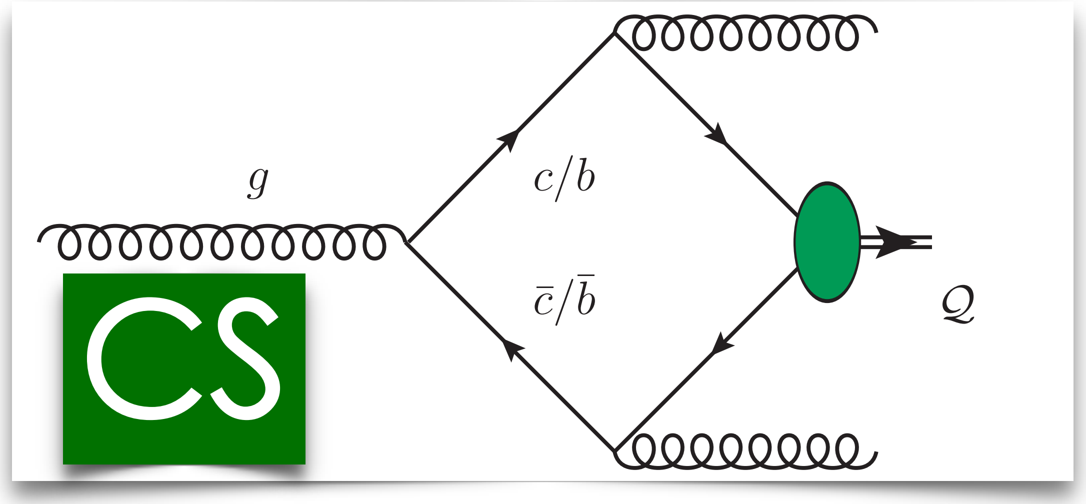

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NRFF1.0
quarkonium FFs = **APFEL++/EKO**

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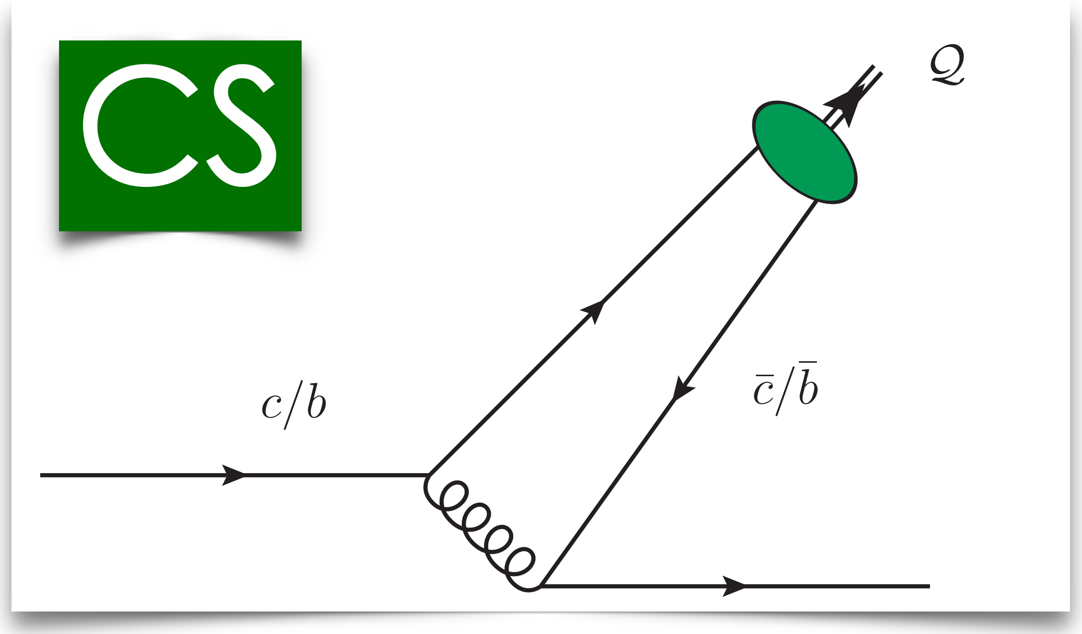

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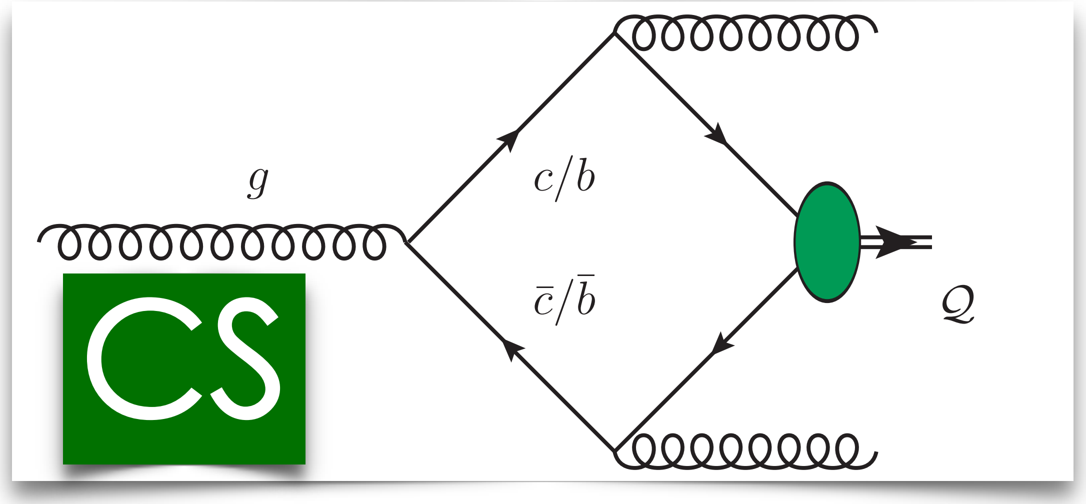

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⊗

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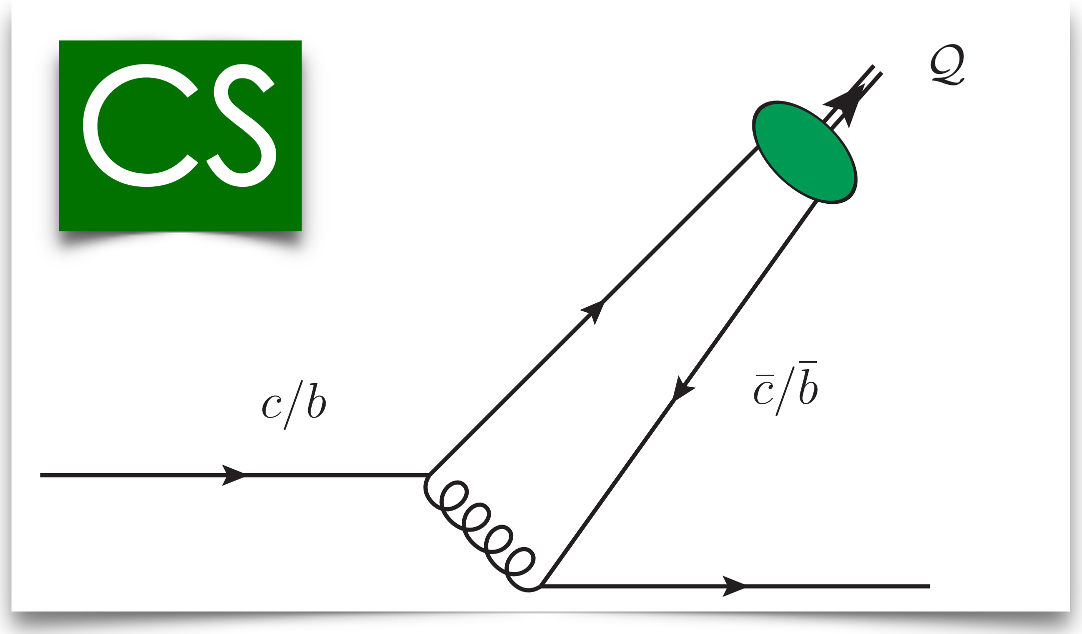
CS



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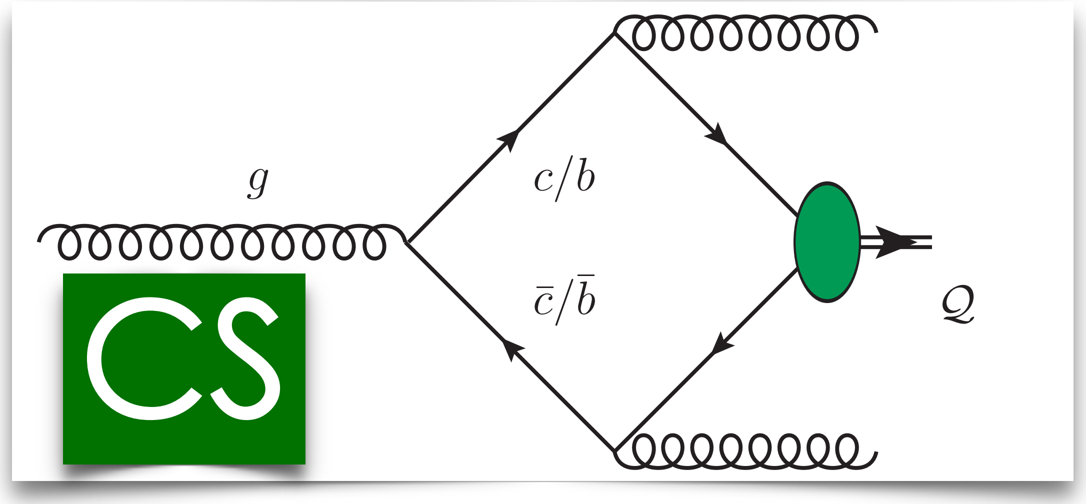

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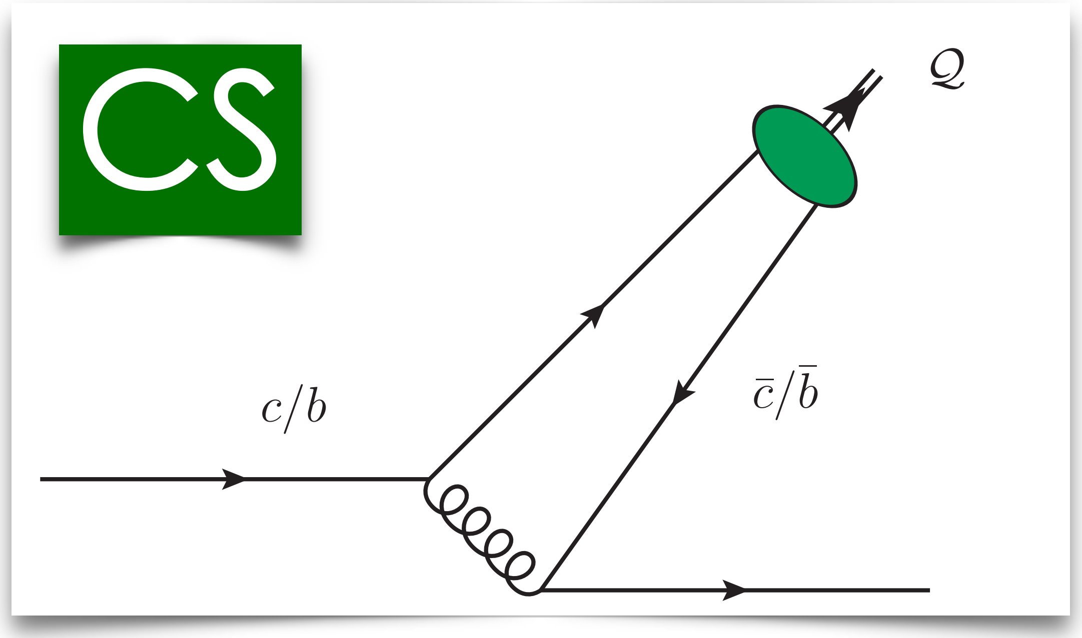

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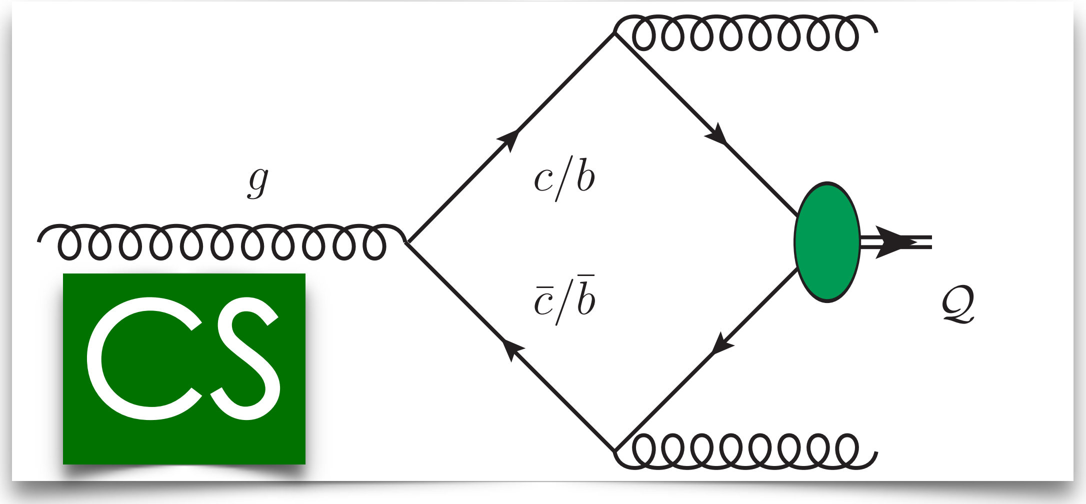

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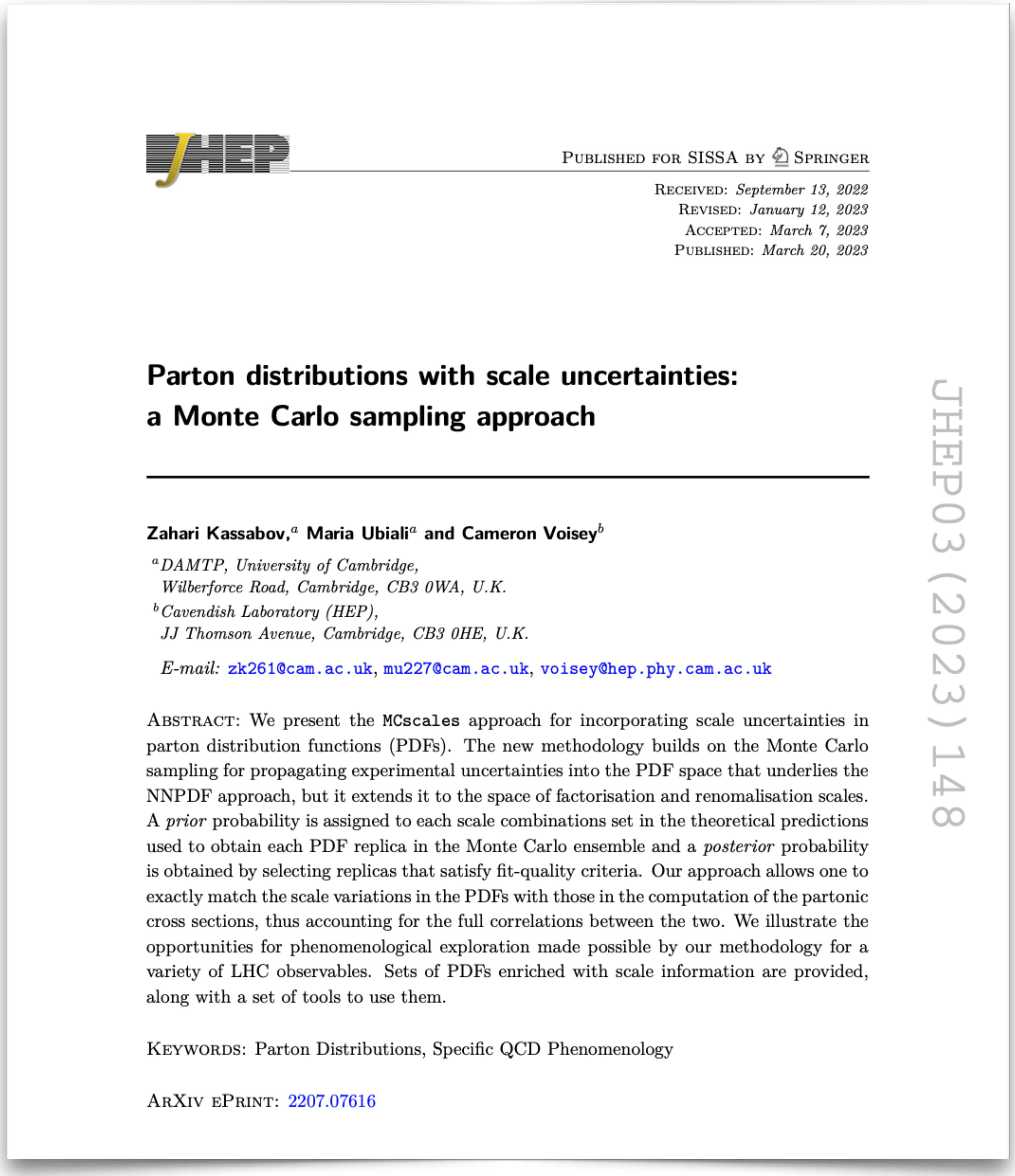
Towards NRFF1.0: ¿A connection with MCscales ?



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RECEIVED: *September 13, 2022*
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ACCEPTED: *March 7, 2023*
PUBLISHED: *March 20, 2023*

Parton distributions with scale uncertainties: a Monte Carlo sampling approach

Zahari Kassabov,[a] **Maria Ubiali**[a] **and Cameron Voisey**[b]

[a] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, U.K.*
[b] *Cavendish Laboratory (HEP), JJ Thomson Avenue, Cambridge, CB3 0HE, U.K.*

E-mail: zk261@cam.ac.uk, mu227@cam.ac.uk, voisey@hep.phy.cam.ac.uk

ABSTRACT: We present the MCscales approach for incorporating scale uncertainties in parton distribution functions (PDFs). The new methodology builds on the Monte Carlo sampling for propagating experimental uncertainties into the PDF space that underlies the NNPDF approach, but it extends it to the space of factorisation and renomalisation scales. A *prior* probability is assigned to each scale combinations set in the theoretical predictions used to obtain each PDF replica in the Monte Carlo ensemble and a *posterior* probability is obtained by selecting replicas that satisfy fit-quality criteria. Our approach allows one to exactly match the scale variations in the PDFs with those in the computation of the partonic cross sections, thus accounting for the full correlations between the two. We illustrate the opportunities for phenomenological exploration made possible by our methodology for a variety of LHC observables. Sets of PDFs enriched with scale information are provided, along with a set of tools to use them.

KEYWORDS: Parton Distributions, Specific QCD Phenomenology

ARXIV EPRINT: 2207.07616

JHEP03(2023)148

[Z. Kassabov, M. Ubiali, C. Voisey, JHEP 03 (2023) 148]

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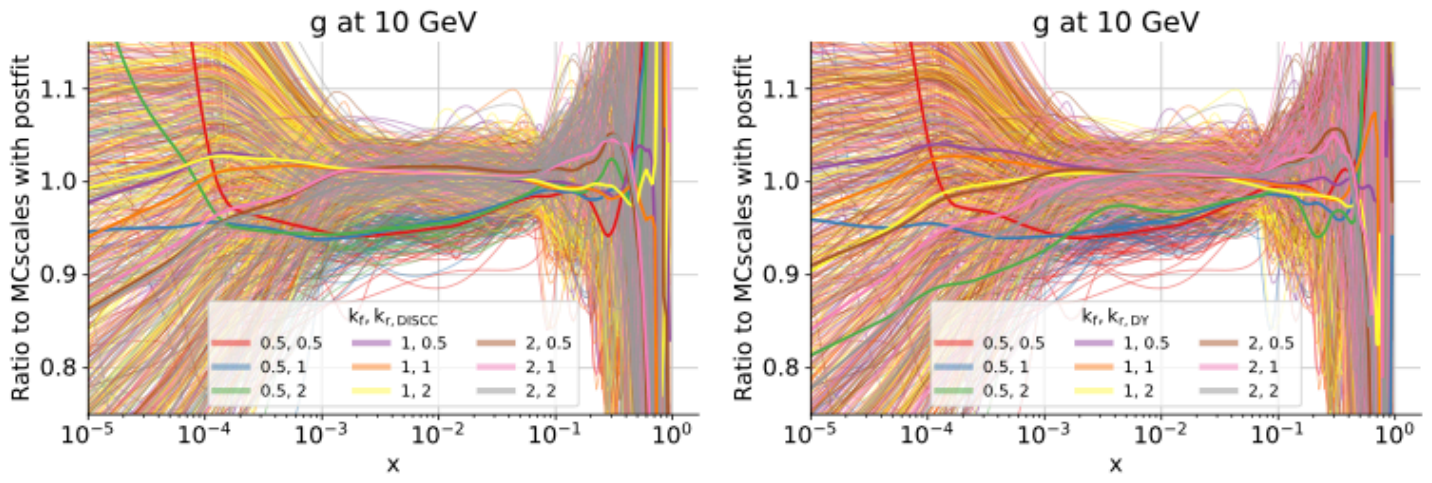


Figure 4. PDF replicas of the `MCscales with postfit` set, for the gluon at $Q = 10\,\text{GeV}$. Each replica is coloured according to its scale choice, where the numbers in the legend correspond to (k_f, k_r), where k_r corresponds to the renormalisation scale for the DIS CC predictions (left panel) or to the one for the DY predictions (right panel). The colouring of the scales is done according to the scales of two different processes included in the fit: the left-hand plot shows the values of the scales for DIS CC and the right-hand plot shows them for DY. The bold lines indicate the average over all replicas for the corresponding scale choice. The plot is normalised to the central replica so that deviations from the central value are shown.

We now study the effect of the scale uncertainties at the level of the PDFs. Figure 5 compares the `NNPDF3.1` baseline with the `MCscales uniform prior` set and the `MCscales with postfit` set. The gluon and the singlet PDFs are displayed along with their 68% C.L. error bands at $Q = 10\,\text{GeV}$. The plots are normalised to the `NNPDF3.1` baseline so its central values sit along the x-axes. We see that including scale variations in the PDF sets, as is done in the `MCscales` PDF sets, leads to increased PDF uncertainties, as we would expect. In the $x \in [10^{-4} - 10^{-2}]$ region the uncertainty broadening is much stronger for the singlet PDFs than for the gluon PDF. At very small x, $x \lesssim 10^{-4}$ this effect seems to generally be most pronounced, especially for the `MCscales uniform prior`. We see further that the uniform prior set leads to a general enhancement of the singlet PDFs, while for the gluon PDF the effect is much less marked. However in both cases, after postfit has been applied to the `MCscales` set based on an uniform prior, the general enhancement is no longer present and the increase in PDF uncertainties tends to become more symmetric.

Comparing the `NNPDF3.1` baseline and the `MCscales with postfit` set, we see the effect of scale variations once outliers have been sensibly removed. For each flavour the PDFs are compatible within uncertainties, with any shift in the central value induced by scale variations within the uncertainties of the `NNPDF3.1` baseline. The shift in the central value appears to be most prominent in the data region for the gluon, where part of the reduction in the gluon PDF observed for the `MCscales` PDFs without postfit remains after their application.

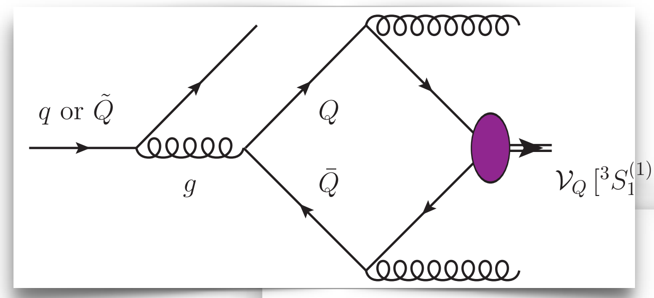
A discussion concerning the comparison with the PDFs obtained in refs. [21, 22] using

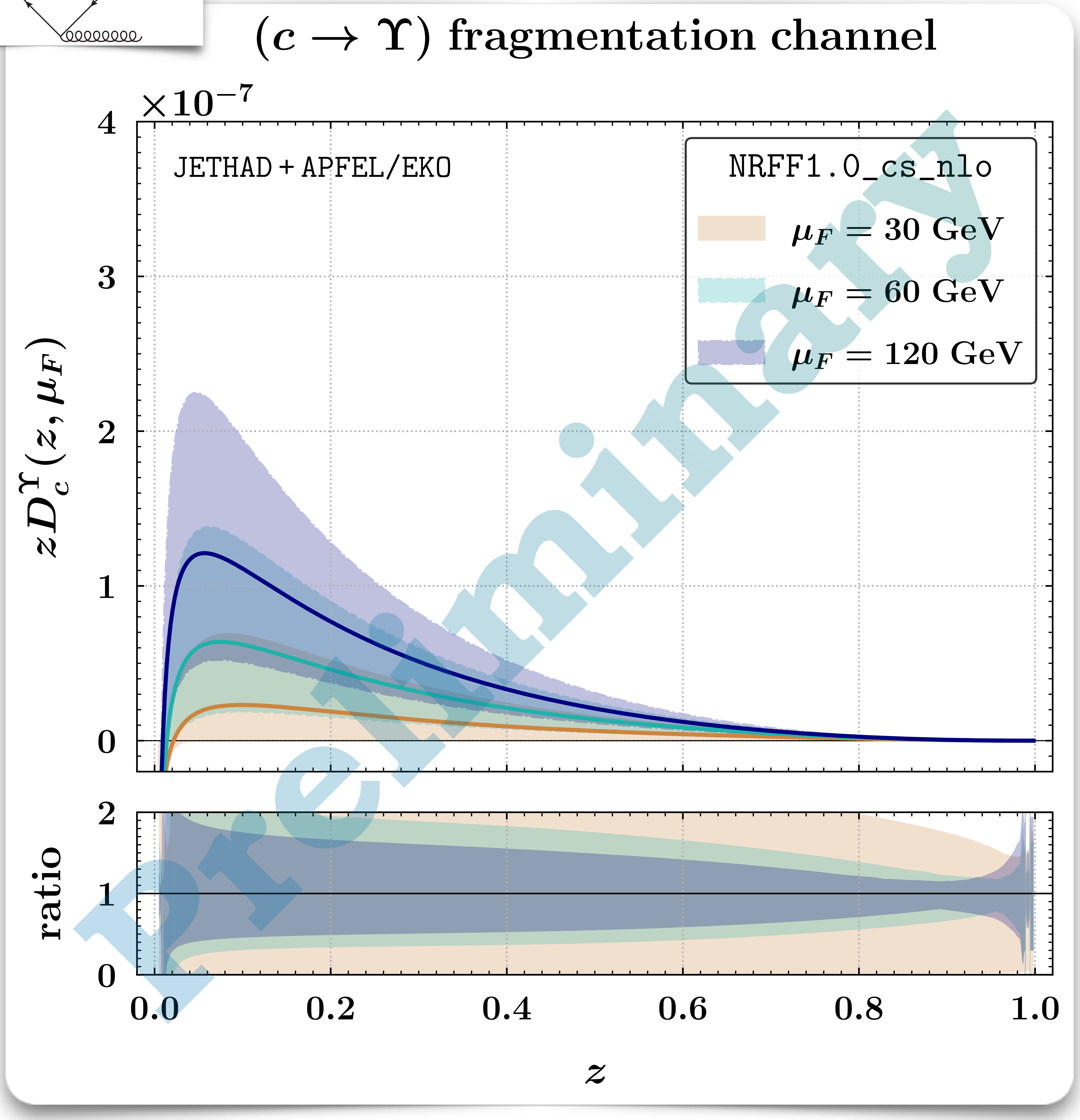
JHEP03(2023)148

[Z. Kassabov, M. Ubiali, C. Voisey, JHEP 03 (2023) 148]

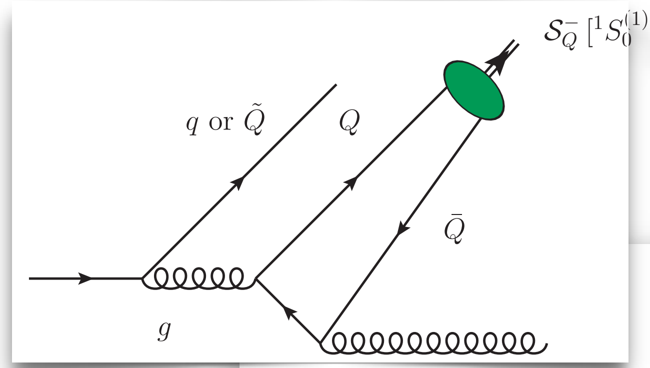
NRFF1.0: Charm fragmentation to bottomonia

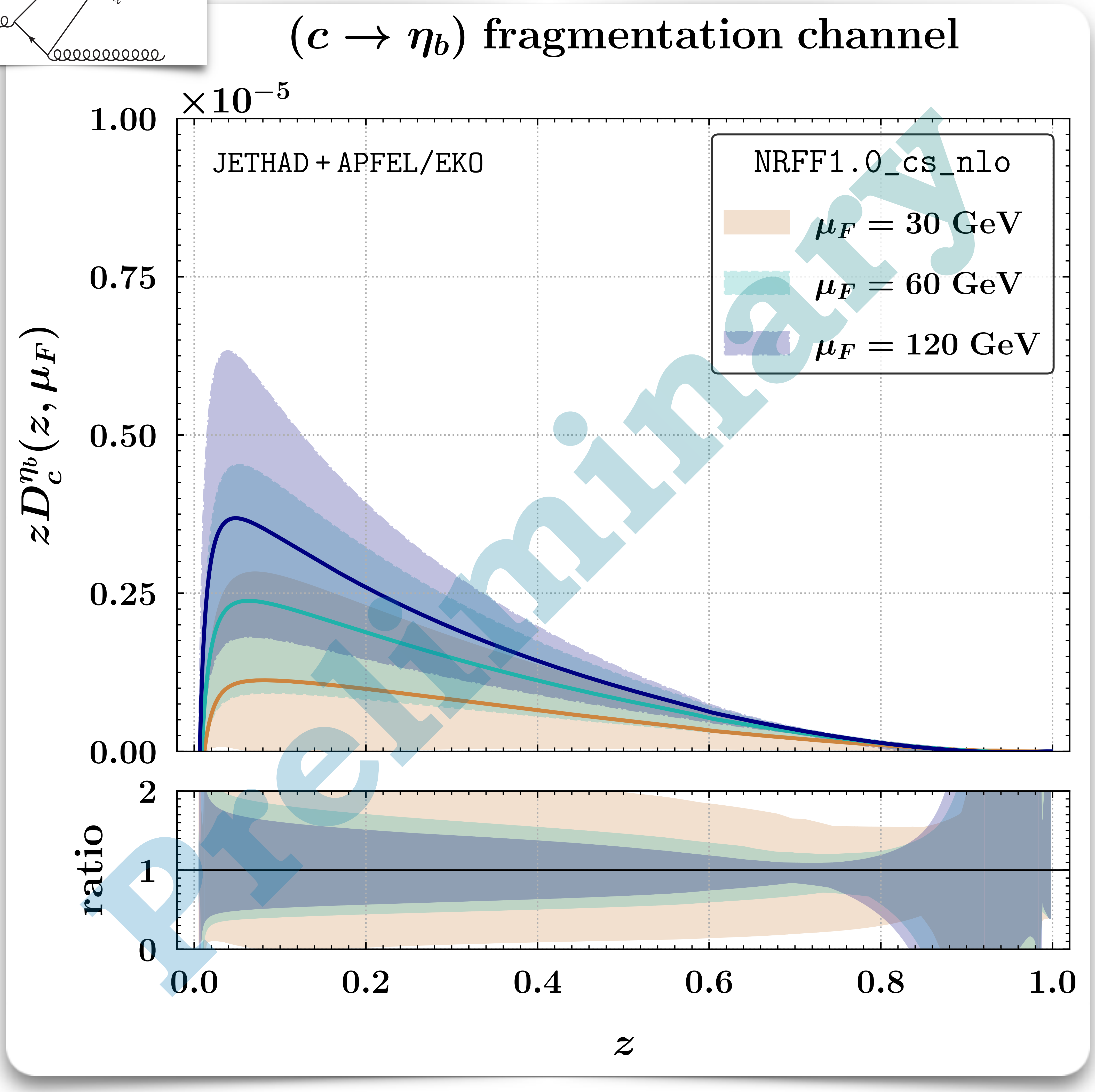
Vector Υ





Scalar η_b

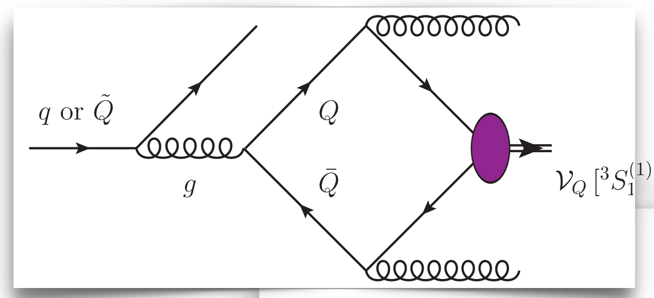


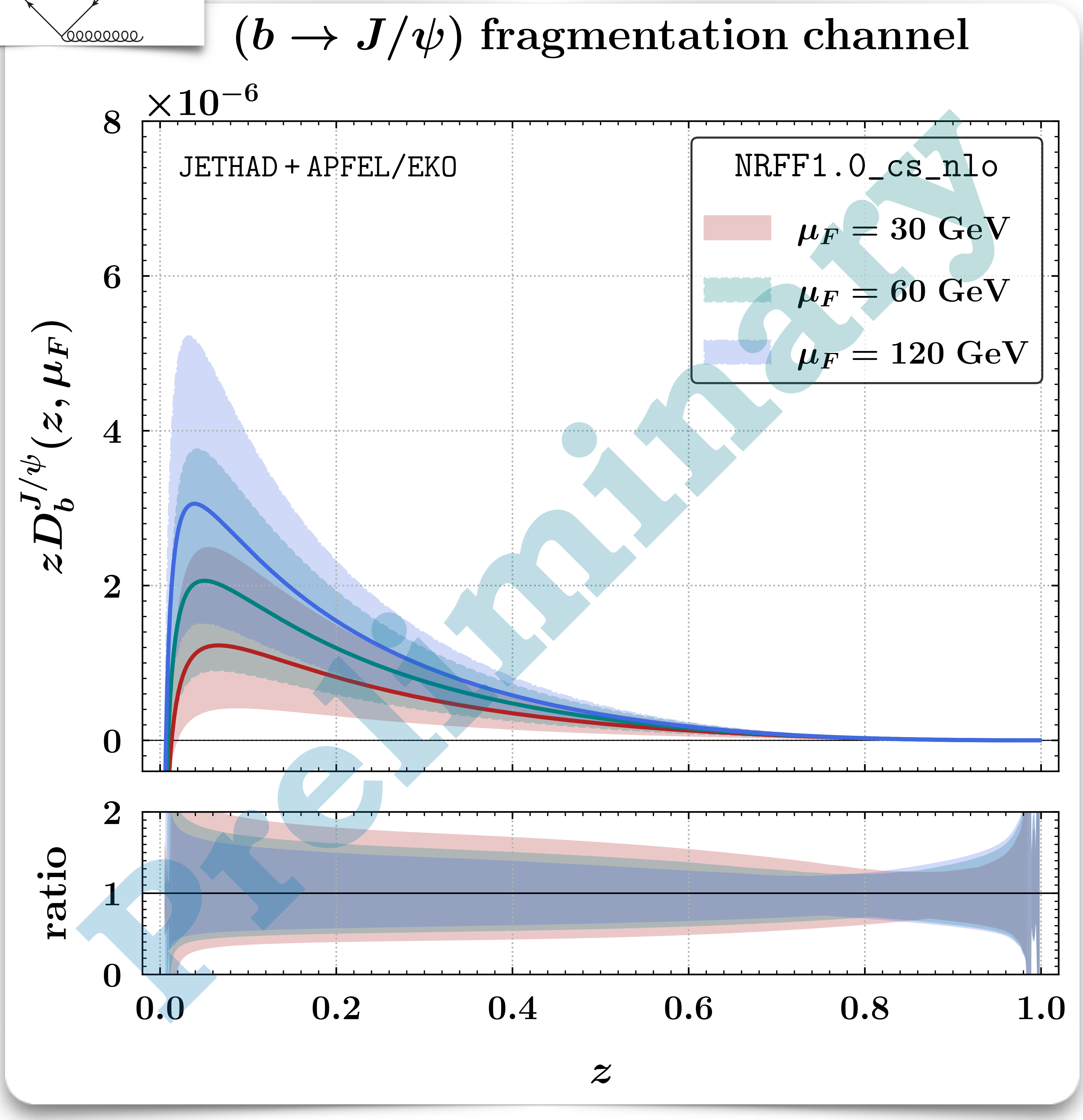


[F. G. C., in preparation]

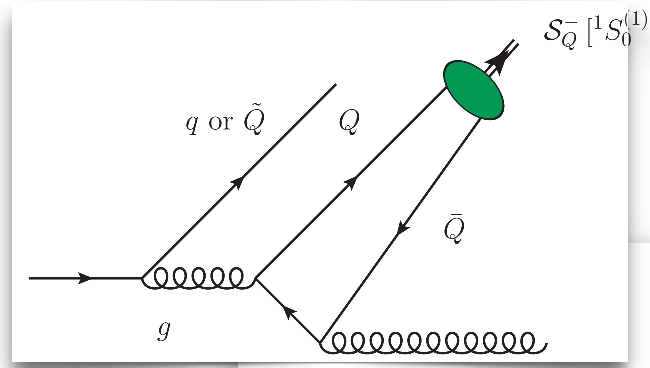
NRFF1.0: Bottom fragmentation to charmonia

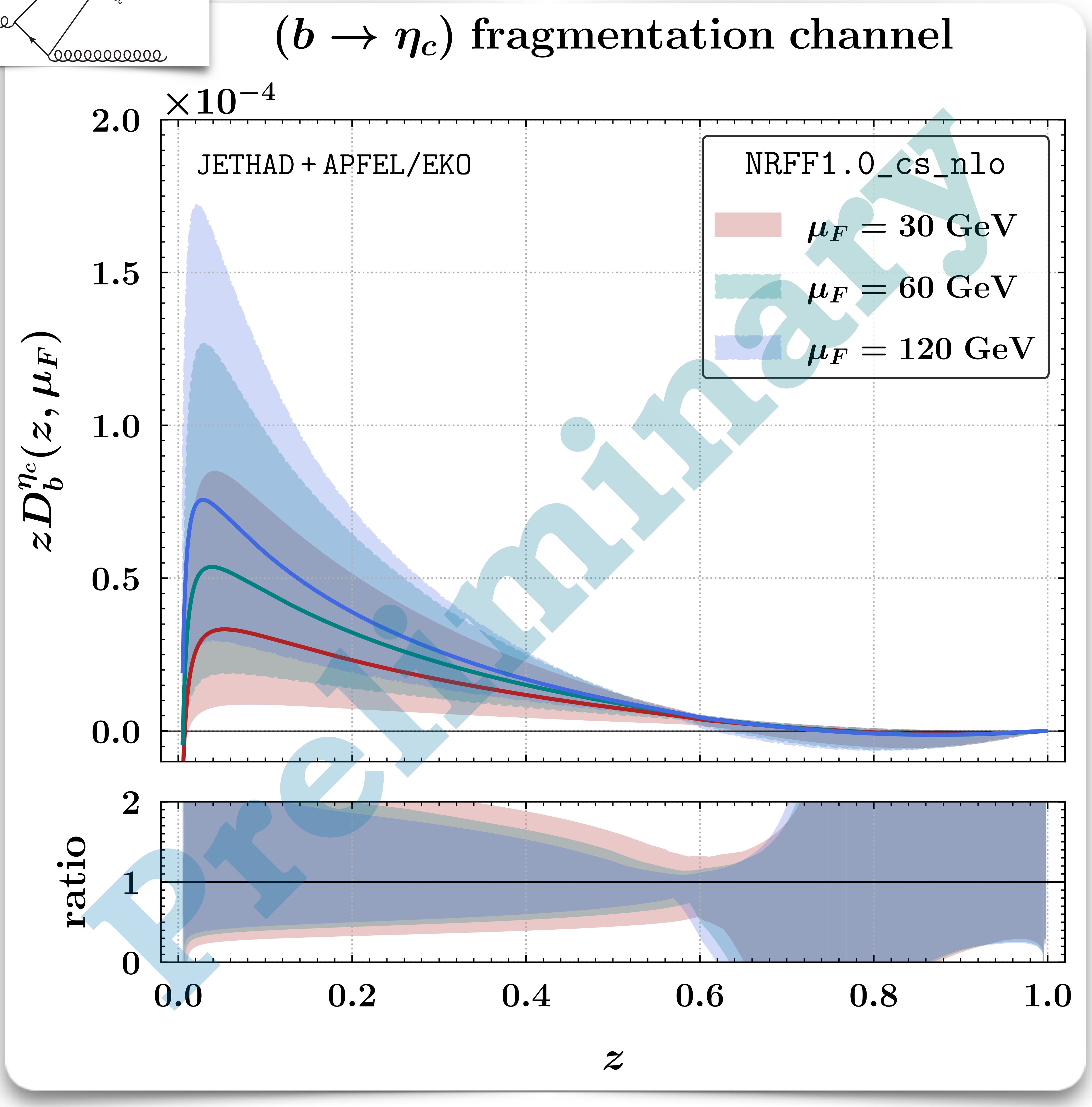
Vector J/ψ





Scalar η_c

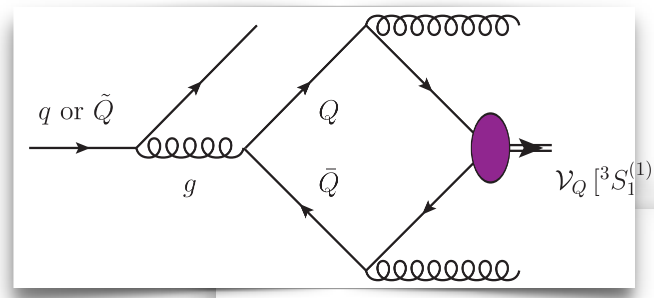


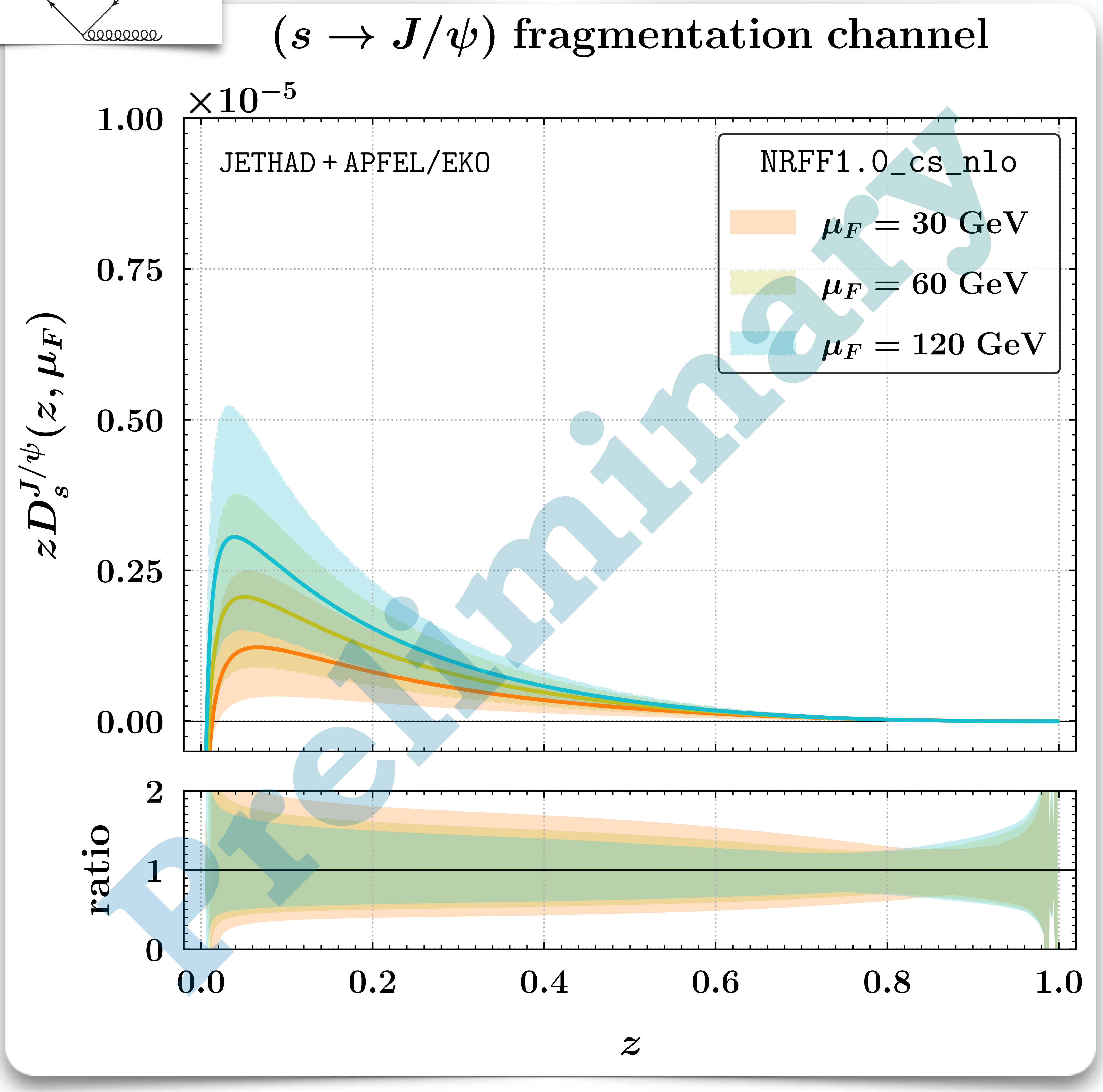


[F. G. C., in preparation]

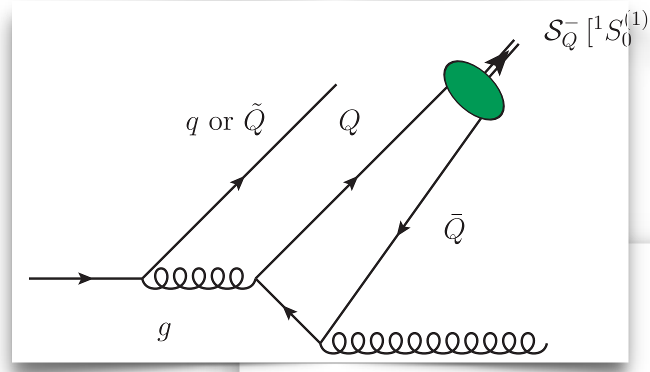
NRFF1.0: Strange fragmentation to charmonia

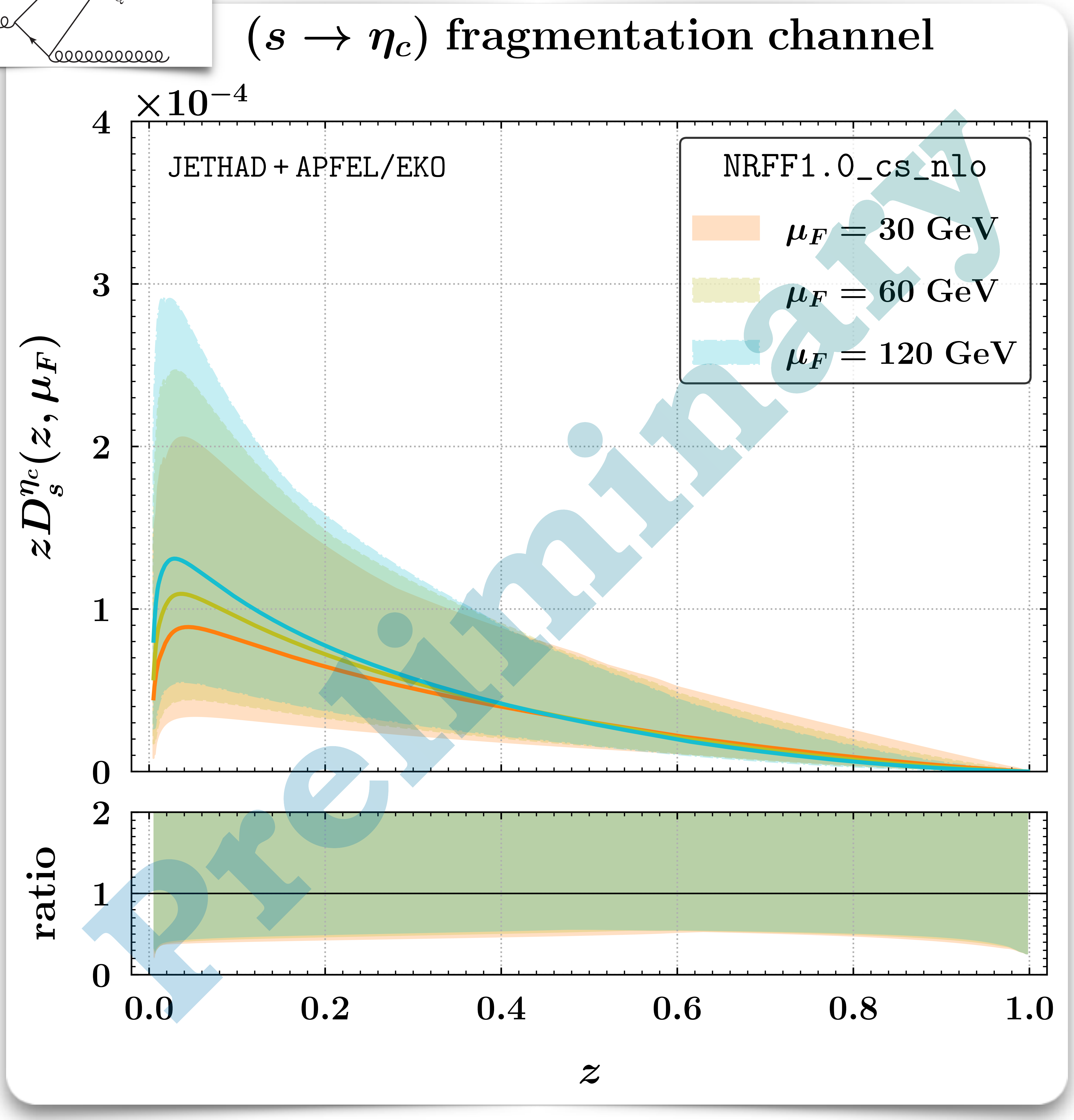
Vector J/ψ





Scalar η_c





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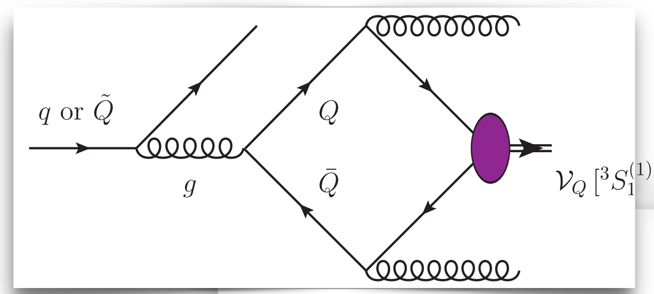
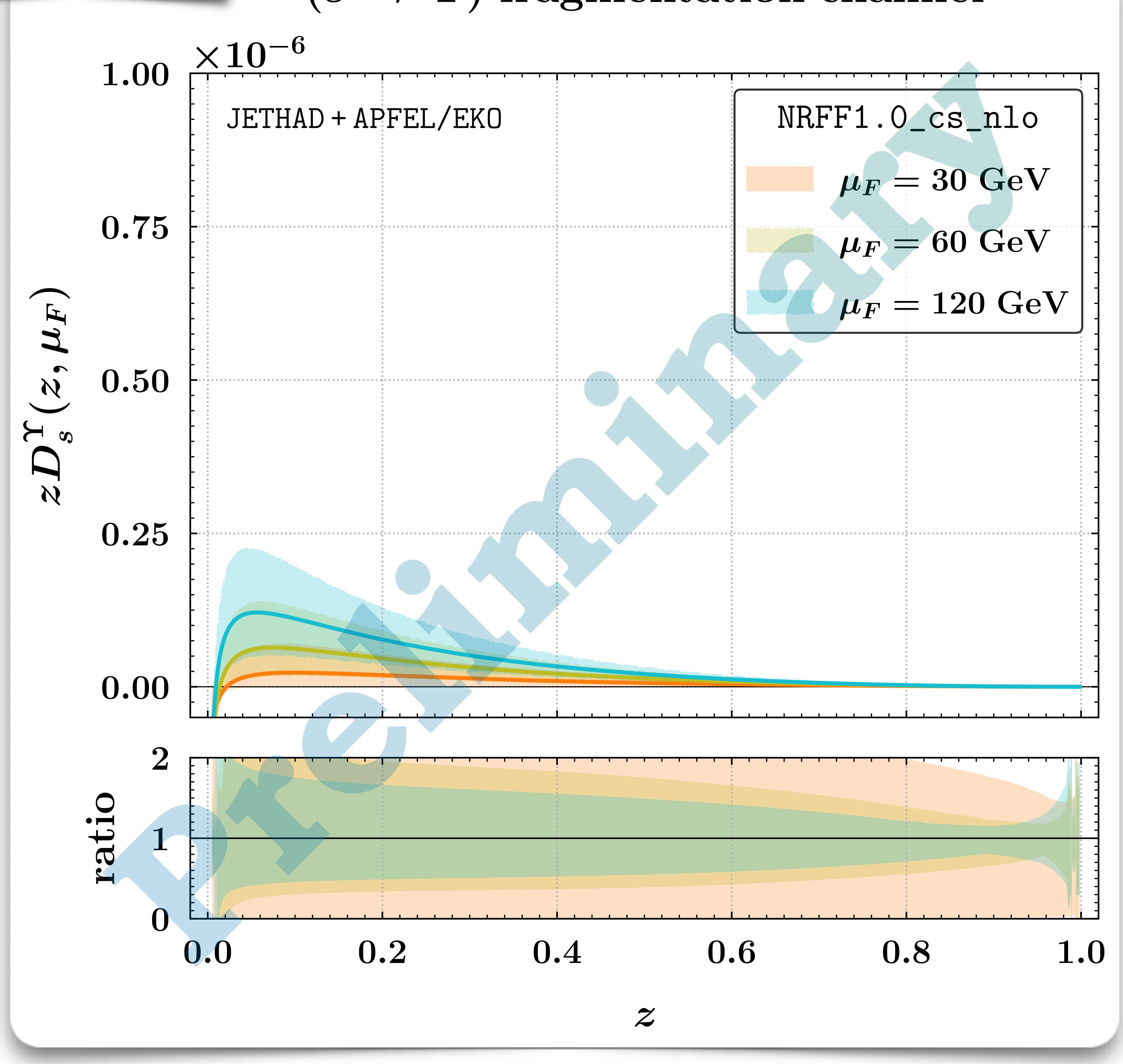
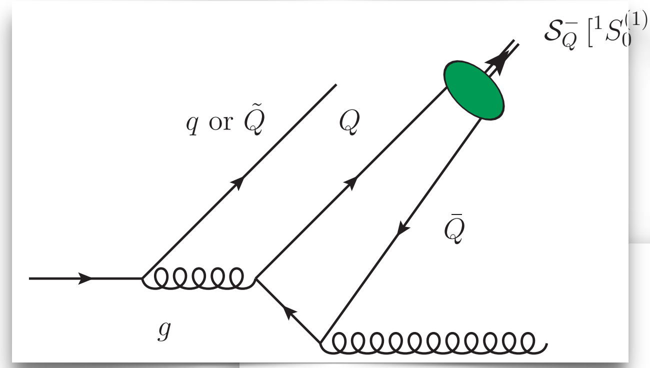
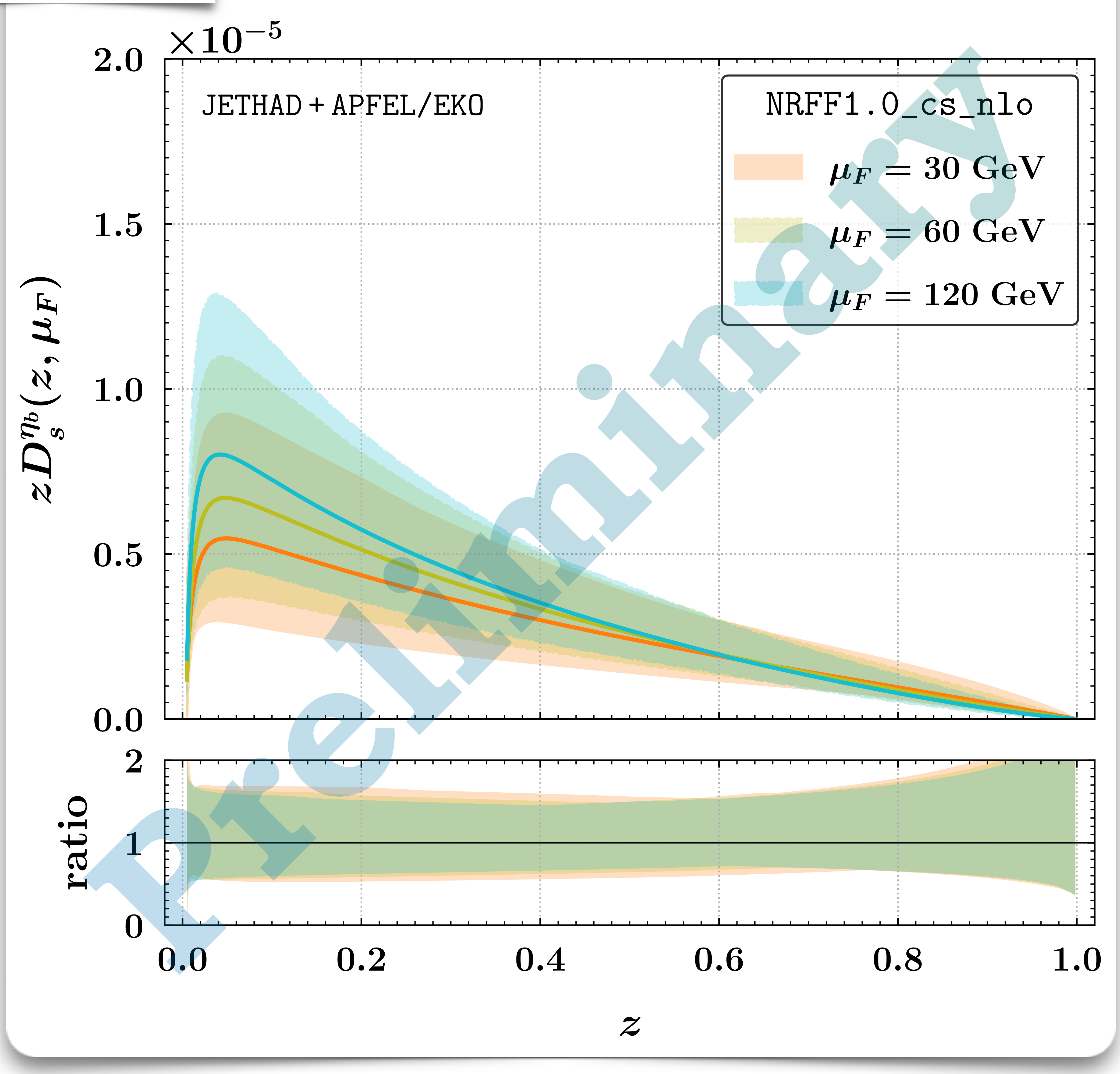
Vector Υ





Scalar η_b

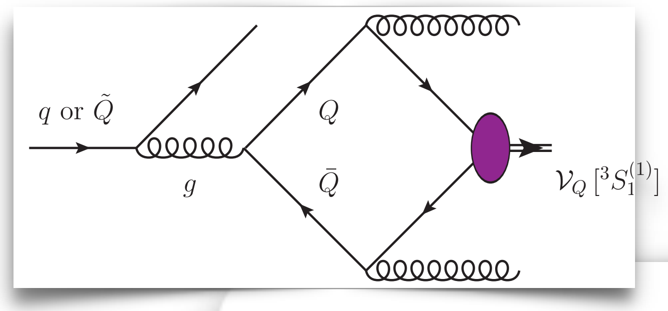


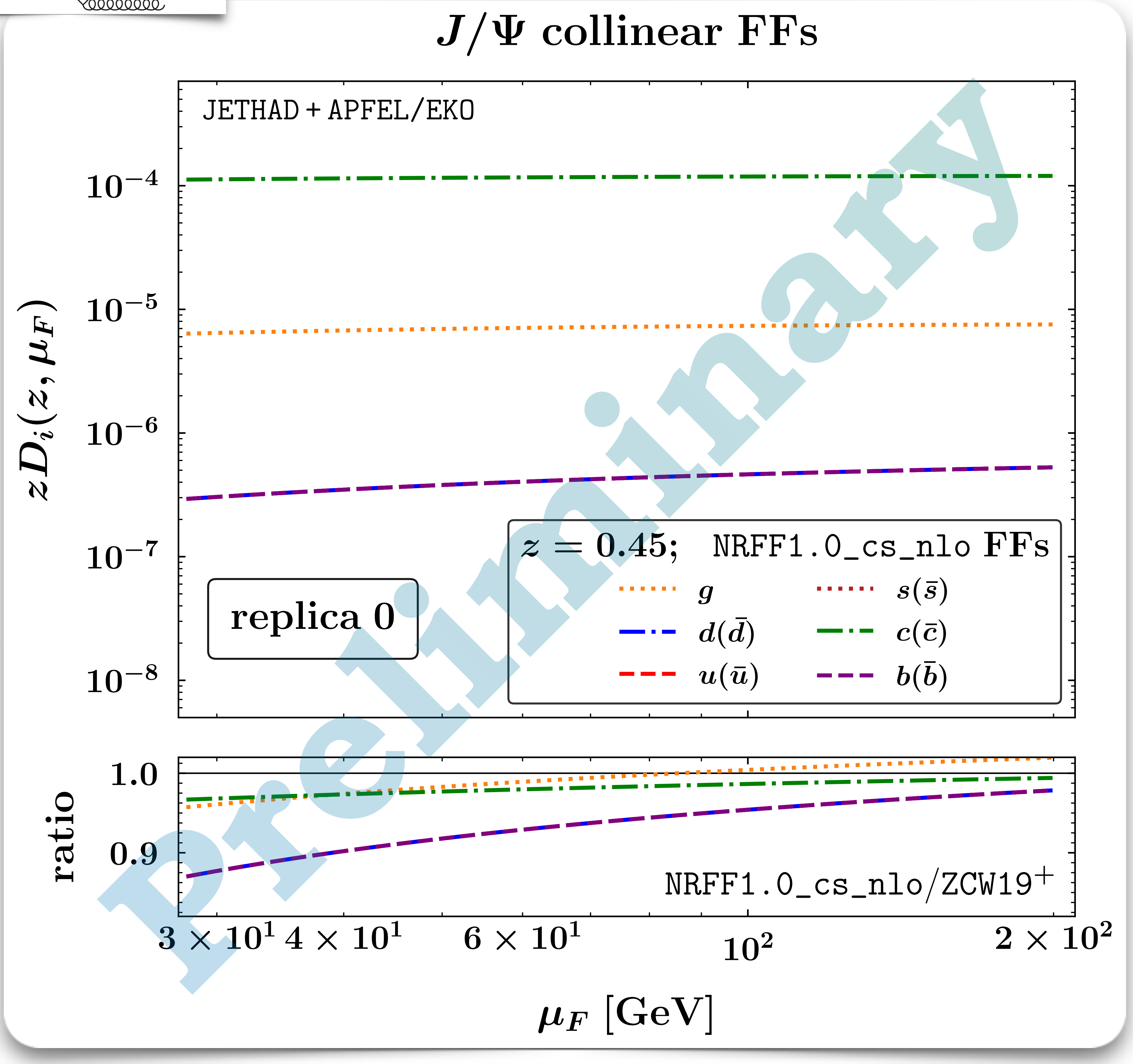


[F. G. C., in preparation]

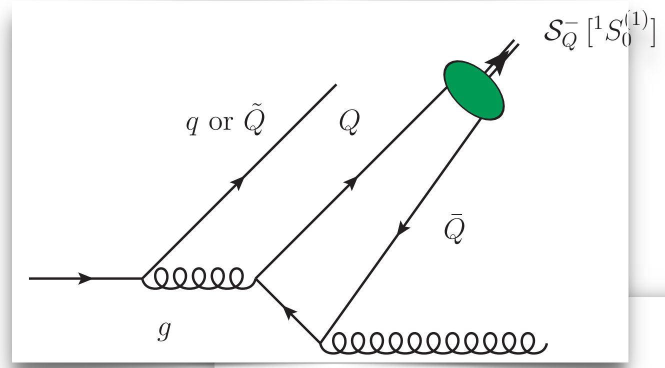
NRFF1.0: Energy dependence

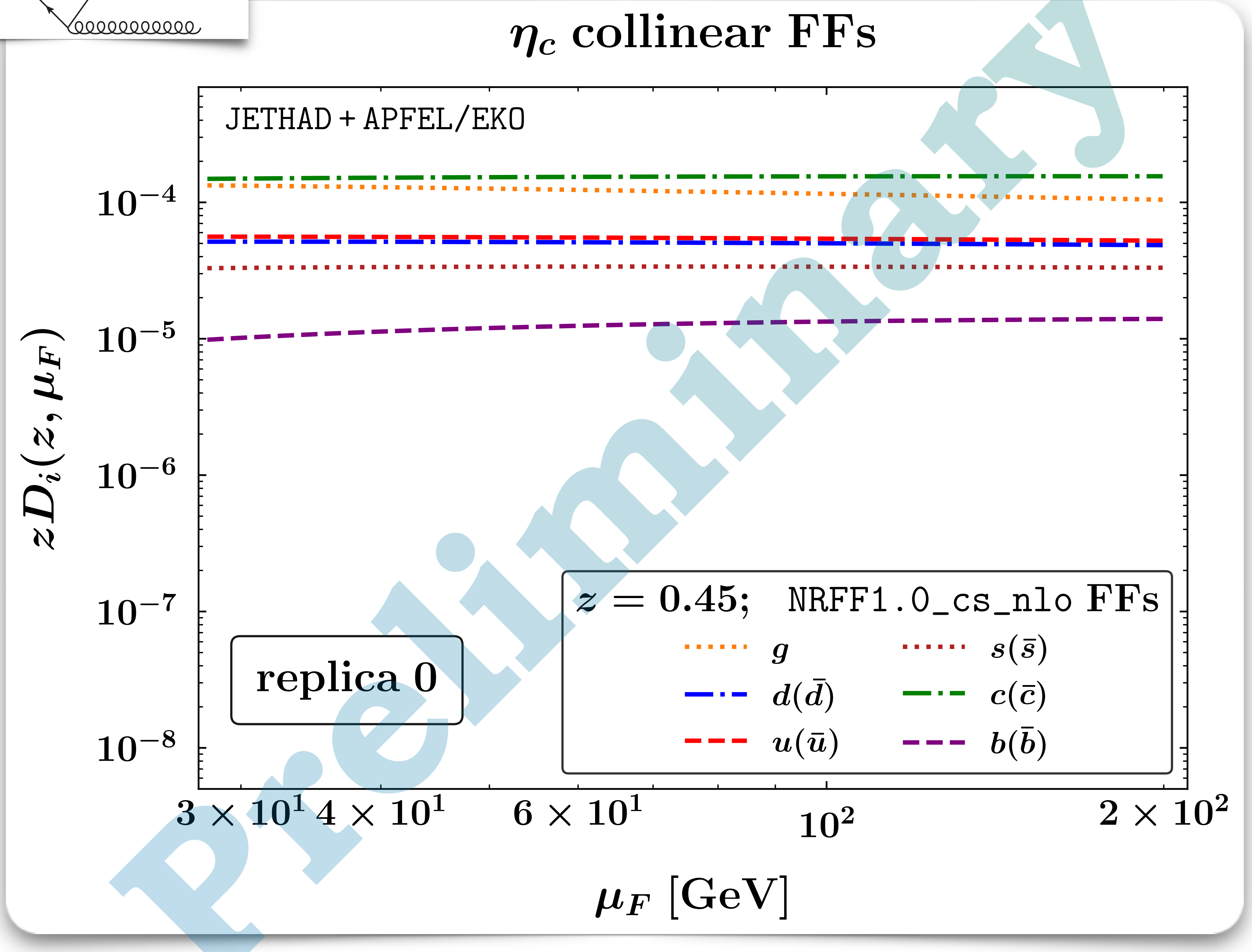
Vector J/ψ





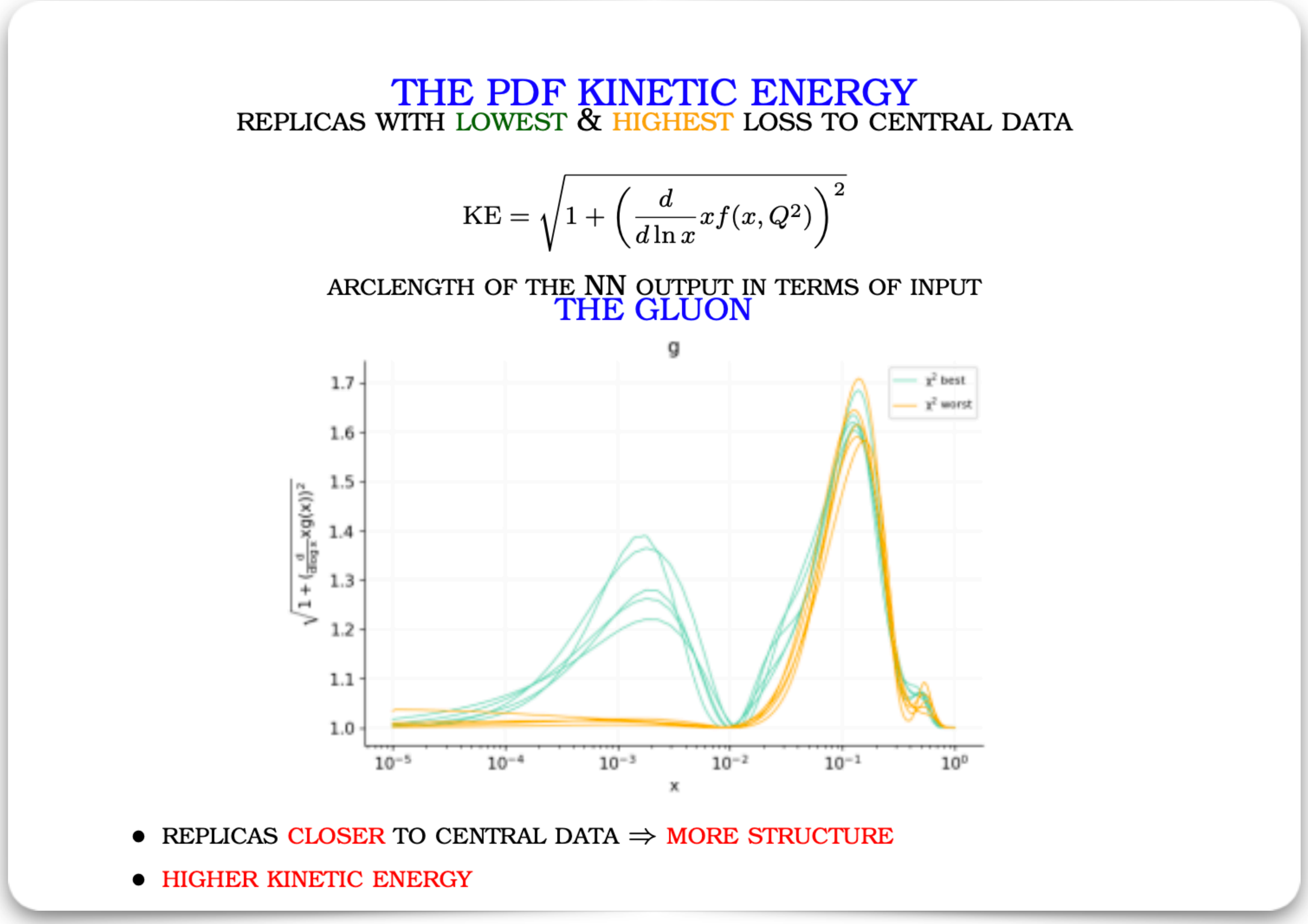
Scalar η_c





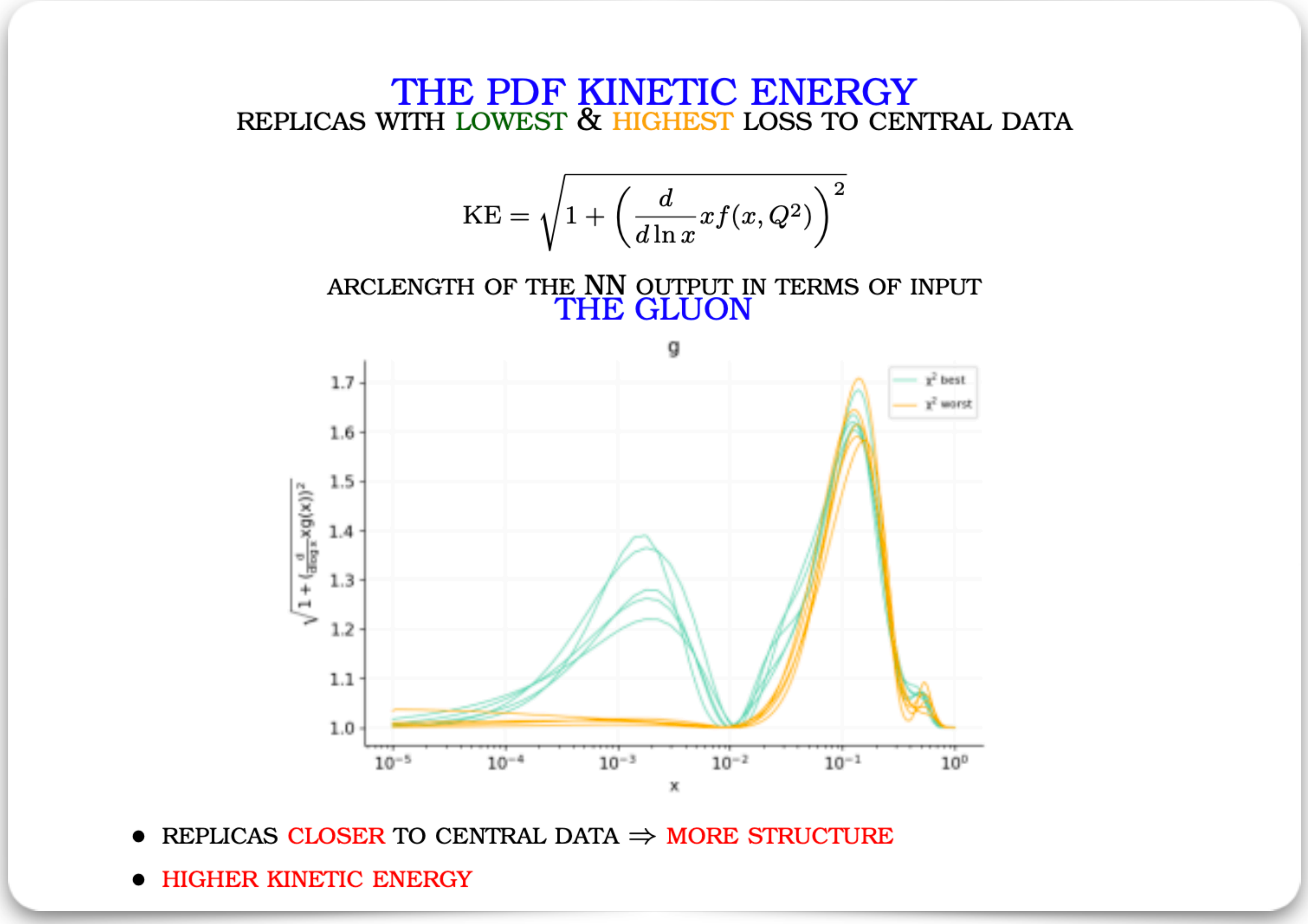
[F. G. C., in preparation]

Towards NRFF1.0: ¿ Quarkonium FF Kinetic Energy ?



🔗 [Talk by Stefano Forte at the EIC Early Career Workshop 2023]

¿ WHAT ABOUT QUARKONIUM FRAGMENTATION KINETIC ENERGY (QF-KE) ?



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What is a quarkonium?

- Quarkonia → mesons with a heavy quark & its antiquark → $|\mathcal{Q}\rangle \equiv |Q\overline{Q}\rangle$
- They owe the name to the analogy with the positronium → $|\mathscr{P}\rangle \equiv |e^+e^-\rangle$
- A quarkonium is an electrically neutral particle & is also its own antiparticle

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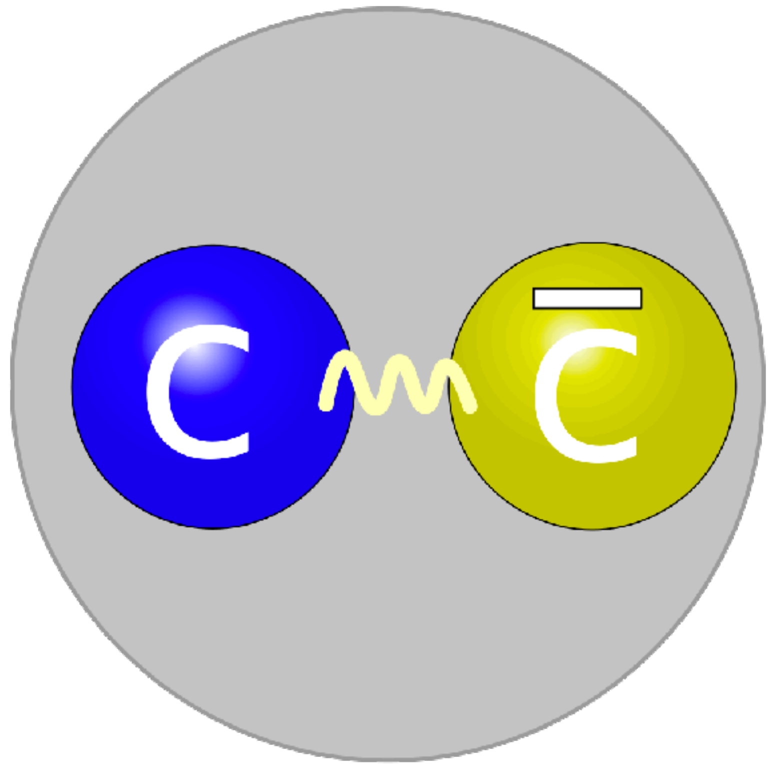
Charmonia

J/ψ η_c



$\psi(2S)$ χ_c

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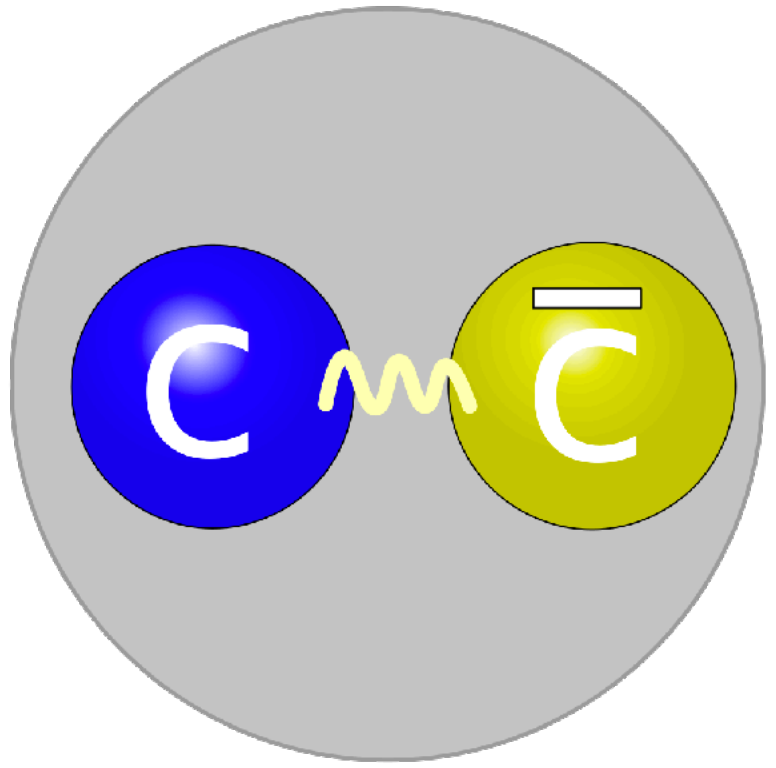

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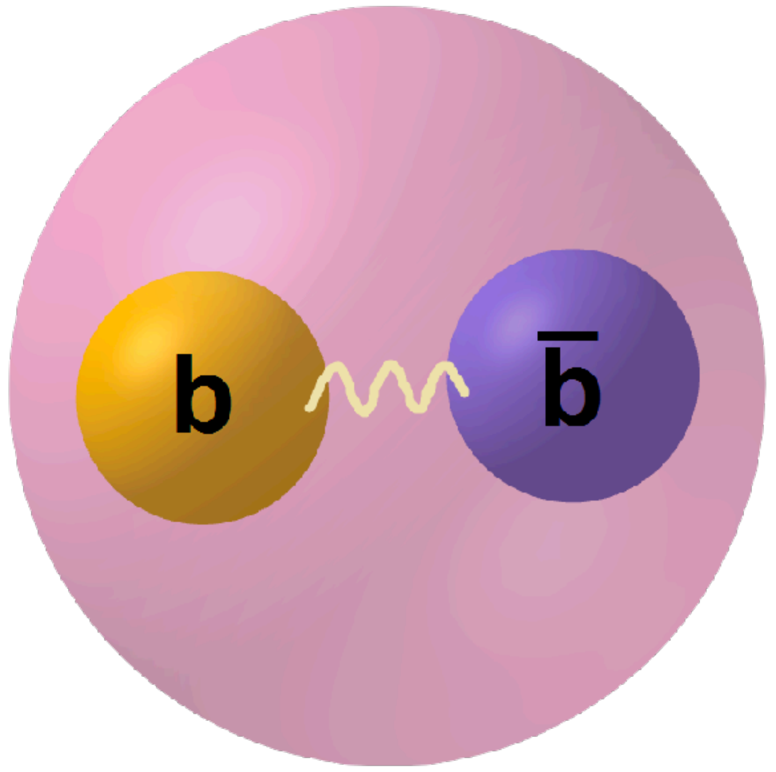
Bottomonia

Υ η_b



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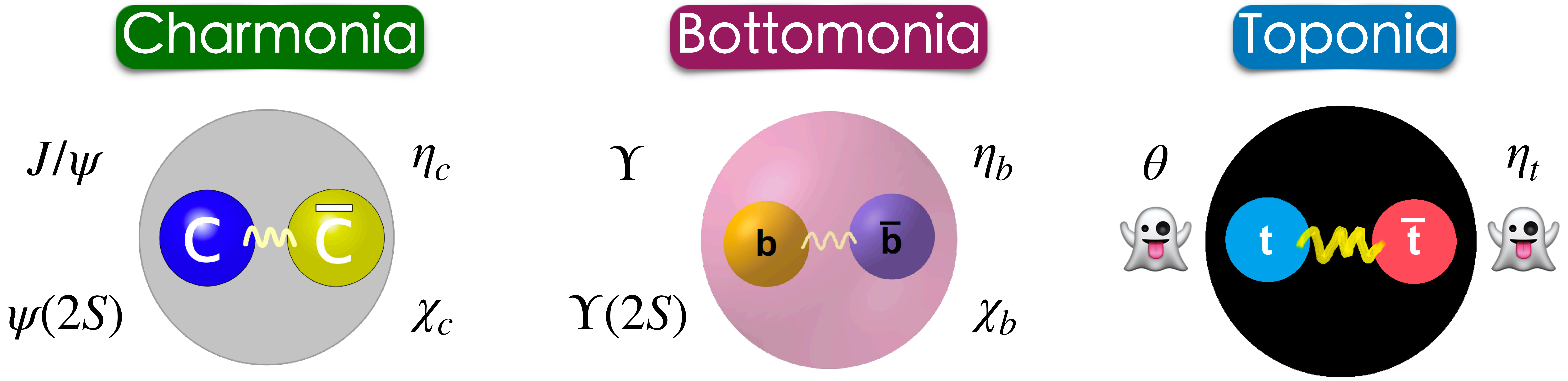

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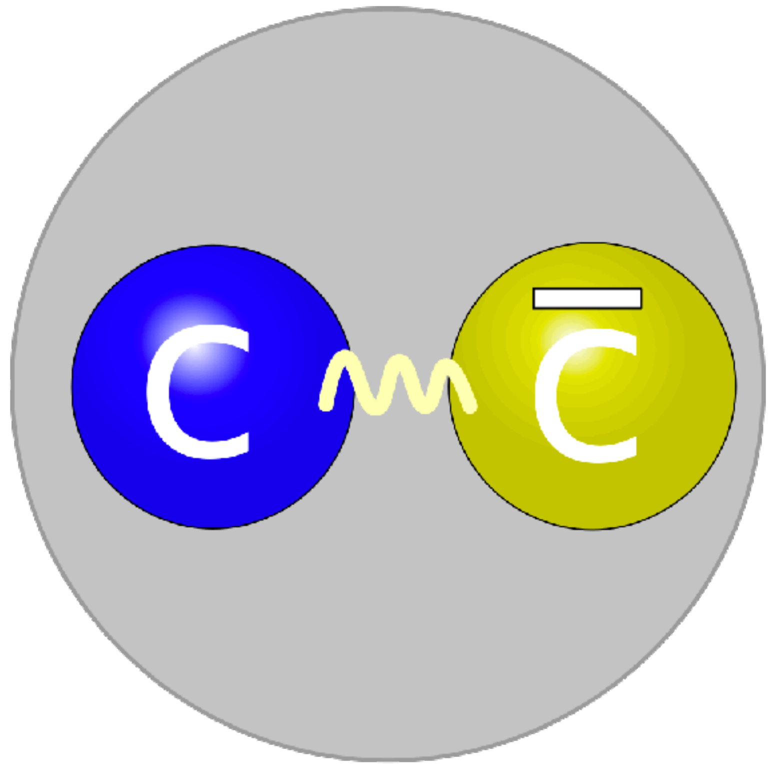

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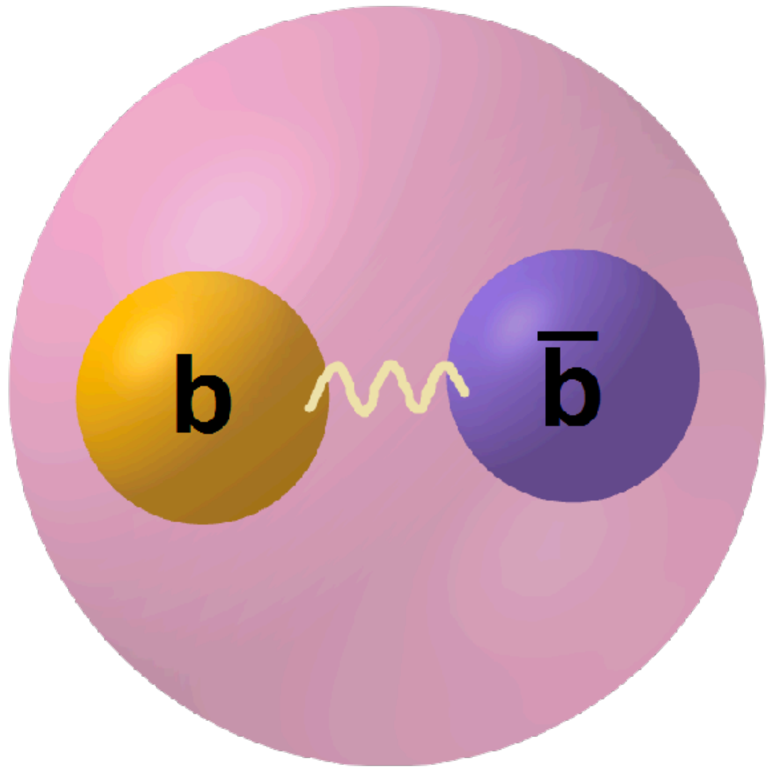
Bottomonia

Υ $\quad\eta_b$



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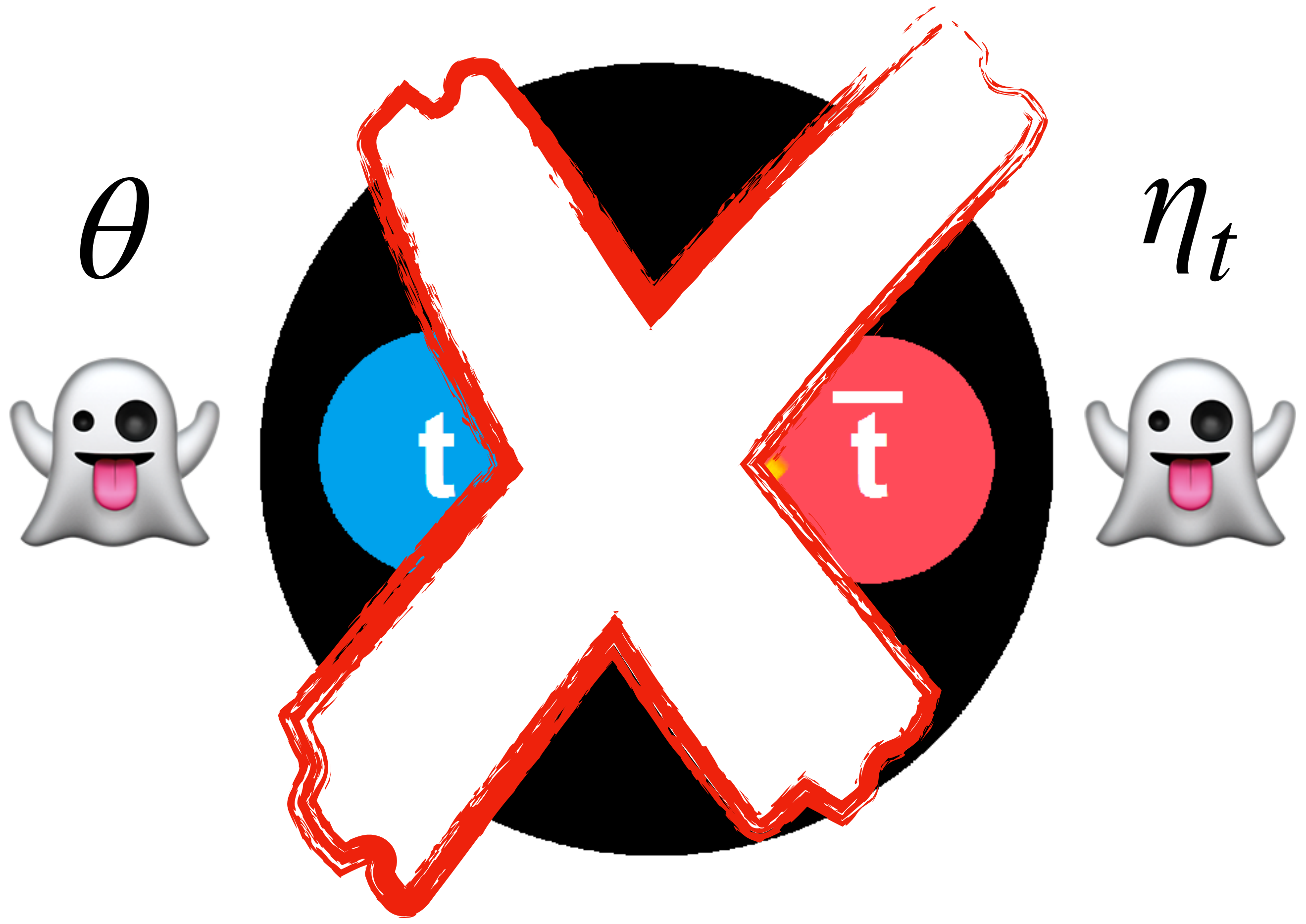
Toponia

θ $\quad\eta_t$



Quarkonium studies: Progresses & challenges

✔ Quarkonium discovery (1974): SLAC & BNL (🇺🇸), then Frascati (🇮🇹) → J/ψ

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- ¡! Quarkonia → easy to measure, difficult to understand

Spectroscopic notation for quarkonia

Spin

Color: Singlet (CS) or Octet (CO)

$$[n] \equiv {}^{2S+1}L_J^{(c)}$$

Orbital angular momentum

Total angular momentum

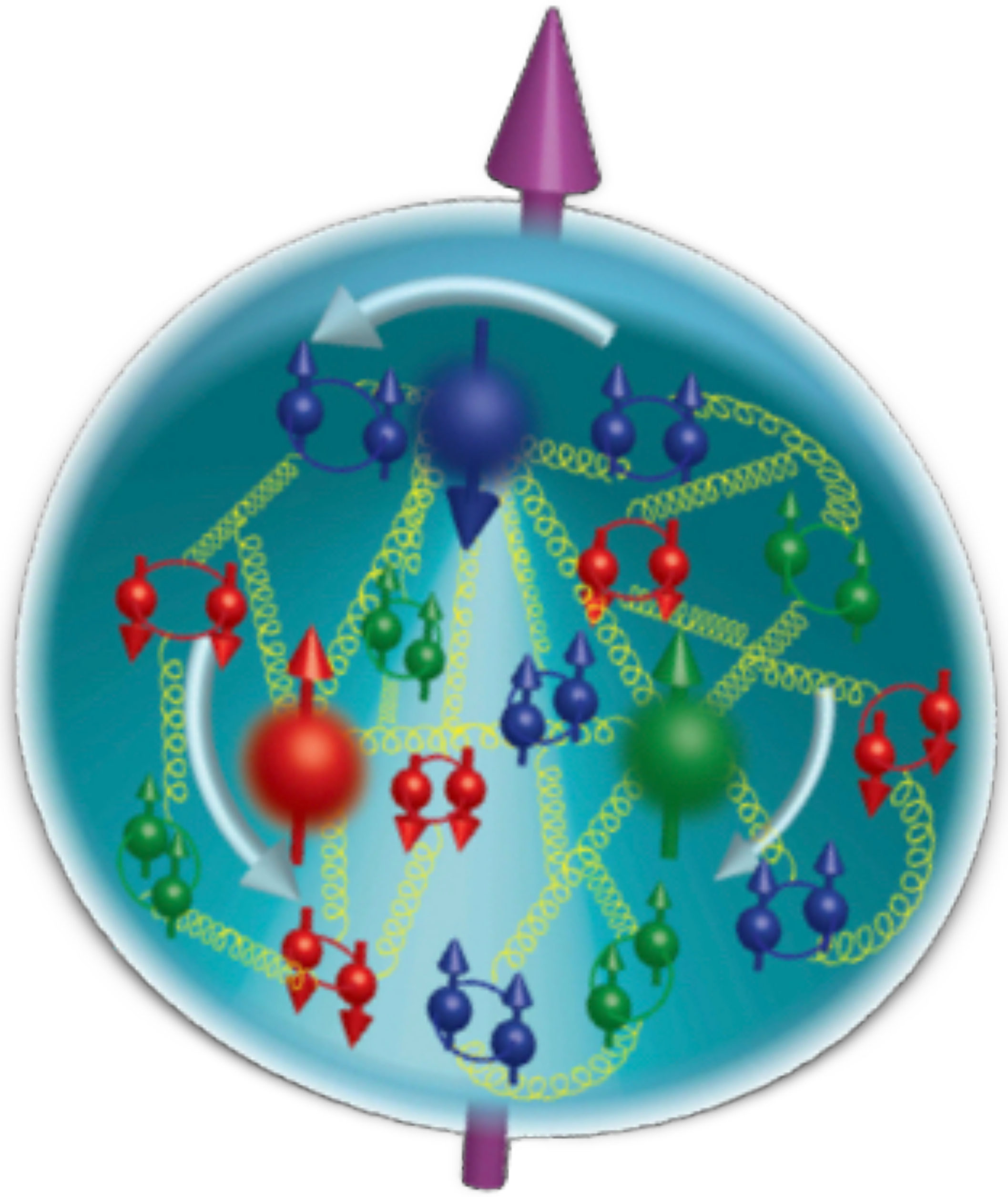
$$J = L + S$$

Parton Distribution Functions & Fragmentation Functions

PDFs & FFs → relevant for the search of **New Physics** from a **precision background**

→ …crucial role in the understanding and **exploration** of **QCD**

- Describe the internal structure of the nucleon (PDFs) and the dynamic formation of hadrons (FFs)
- **Nonperturbative** objects that enter the expression of cross sections
- Can be *extracted* from experiments via *global fits*



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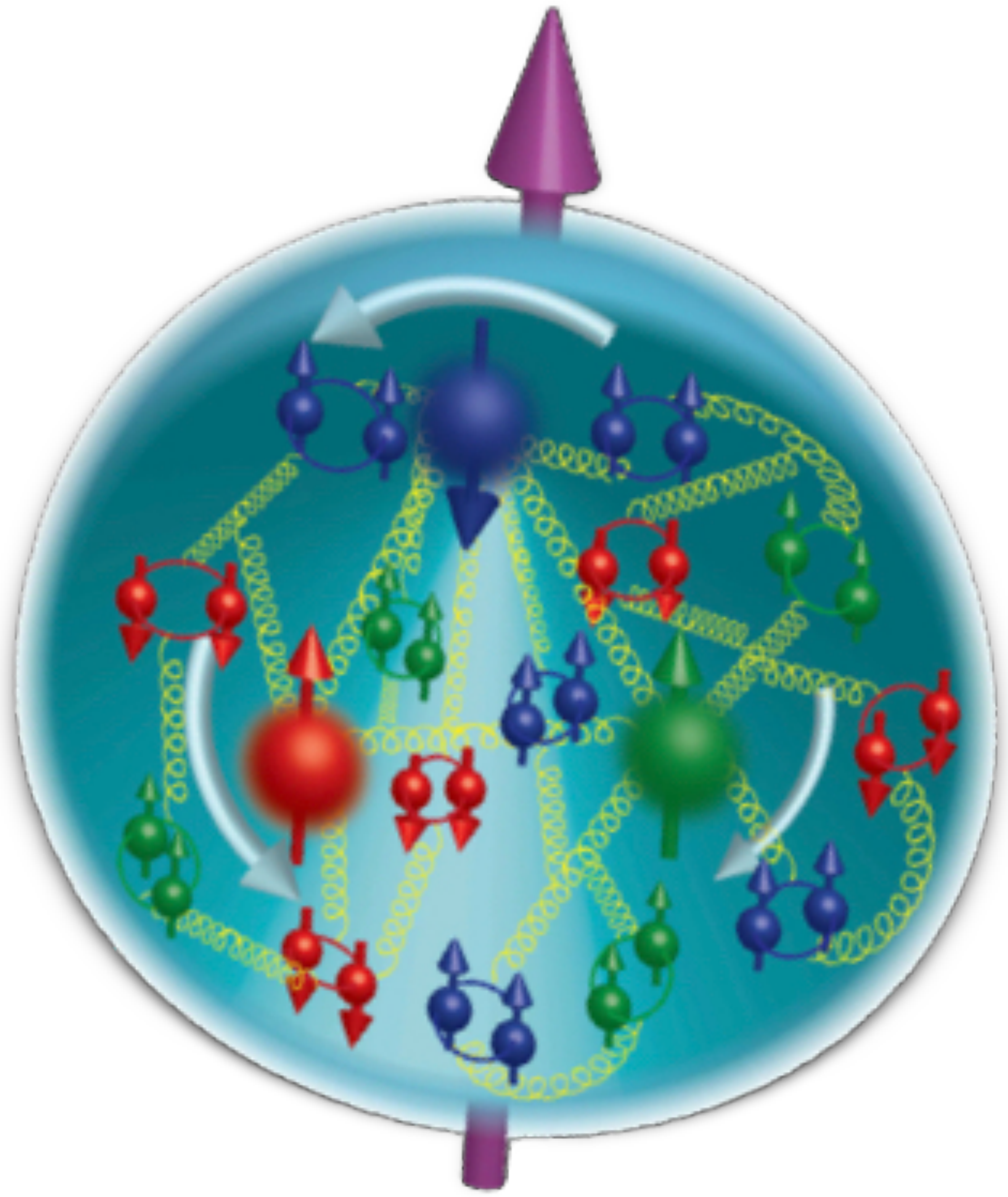
- Several types of functions (**1D collinear**, 3D TMD, 3D GPD, ...)

  - Follow from different **factorization theorems**
  - Exhibit peculiar **universality properties**
  - Obey distinct **evolution equations**



The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

ERIS super-module

$$\alpha_s \ln(s) \lesssim 1$$

JETHAD

v0.5.0m

python + F

🔗 [Eur. Phys. J. C 81 (2021) 8, 691]

🔗 [Phys. Rev. D 105 (2022) 11, 114008]

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Forward Drell-Yan, onium, Higgs

LExA, HATHOR super-modules

Proton structure

Small-x UGD

Gluon TMD PDFs

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from low to high p_T

NRFF1.0 onium FFs

Vectors & pseudoscalars

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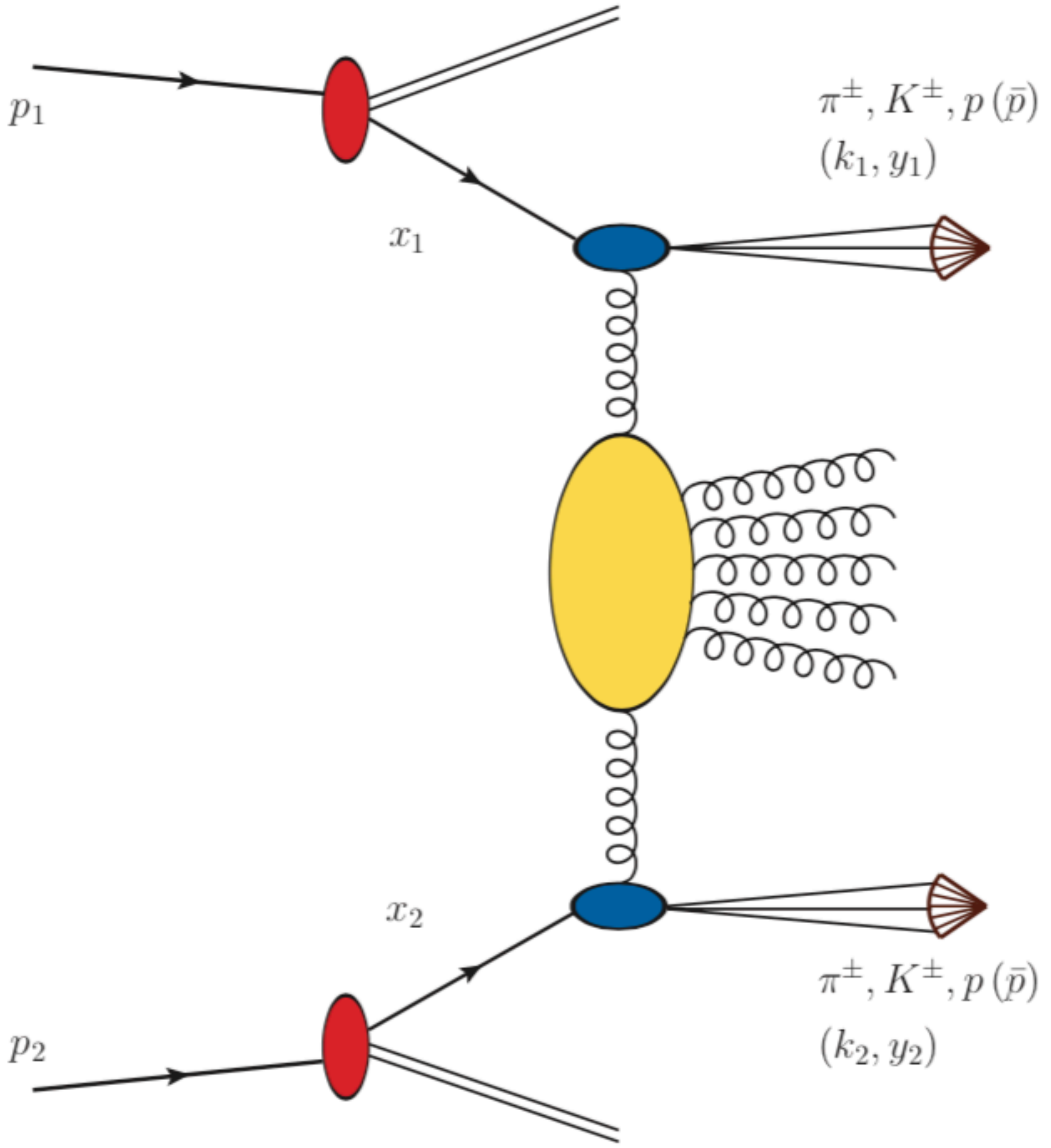
HEAVY-LIGHT HADRONS

From Higgs + jet to bound states

Di-hadron and hadron-jet correlations

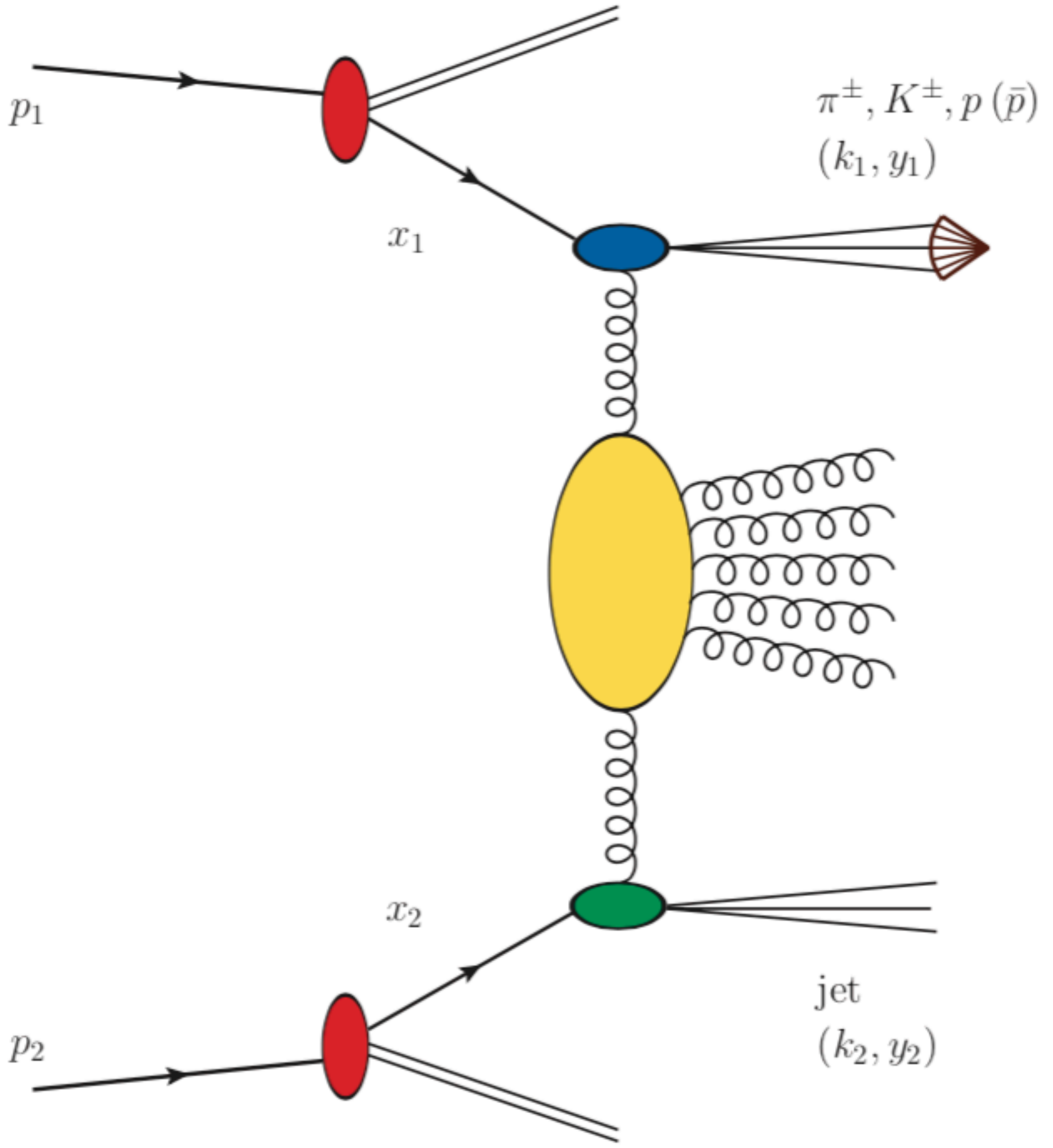
Inclusive di-hadron production

[D.Yu. Ivanov, A. Papa (2012)] (NLO forward-hadron impact factor)
[F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]



Inclusive hadron-jet production

[A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]
[F.G.C. (in preparation)]



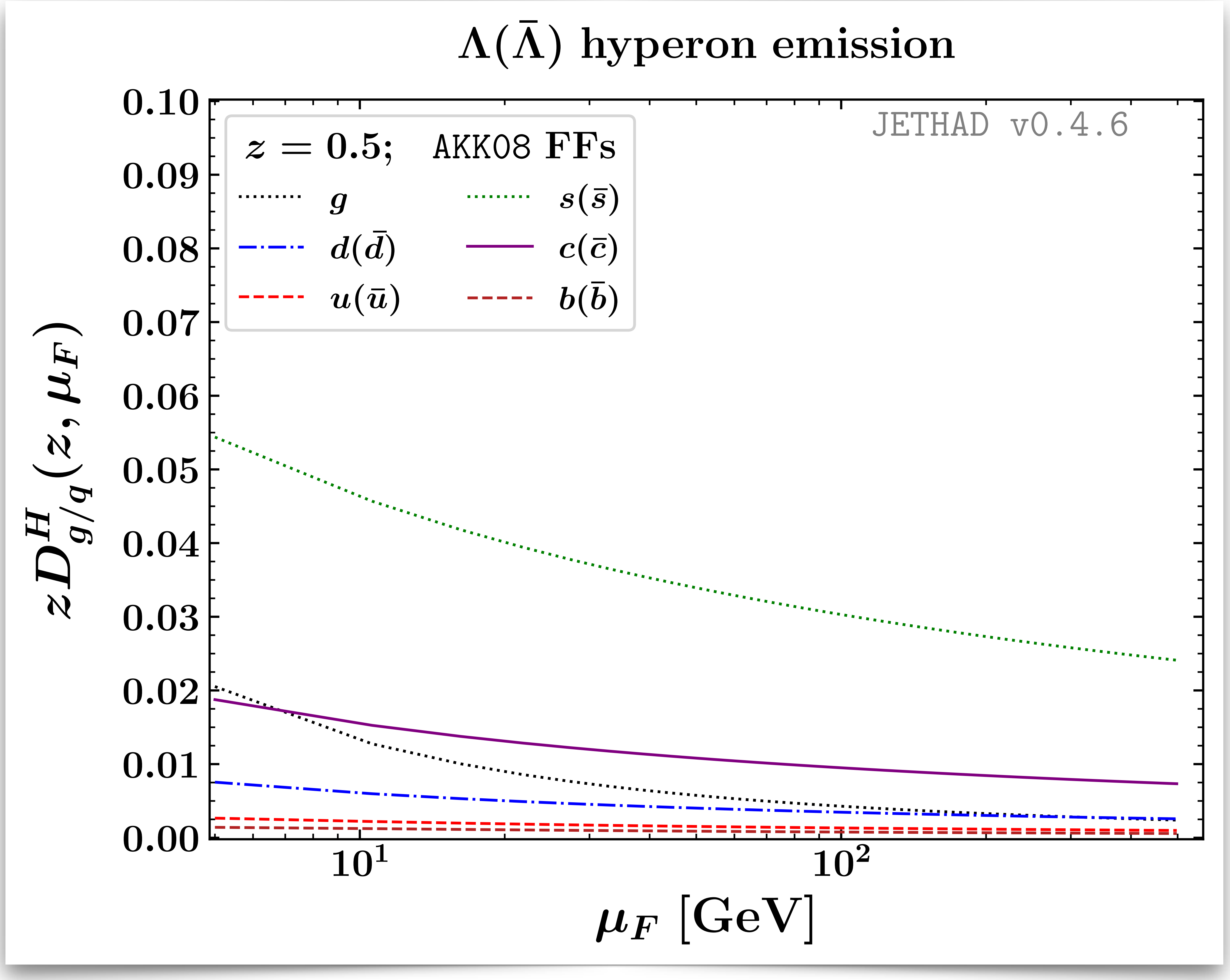
- ◇ NLO impact factors known $\Rightarrow$ full NLA BFKL analysis feasible
- ◇ PDFs + FFs at work (both), hadrons at smaller rapidities than jets (di-hadron)
- ◇ genuine *asymmetric* cuts in transverse momenta (hadron-jet)

[F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Stabilizing effects of heavy-flavor fragmentation

AKK08 VFNS collinear FFs for Λ hyperon: $|uds\rangle$

[S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]



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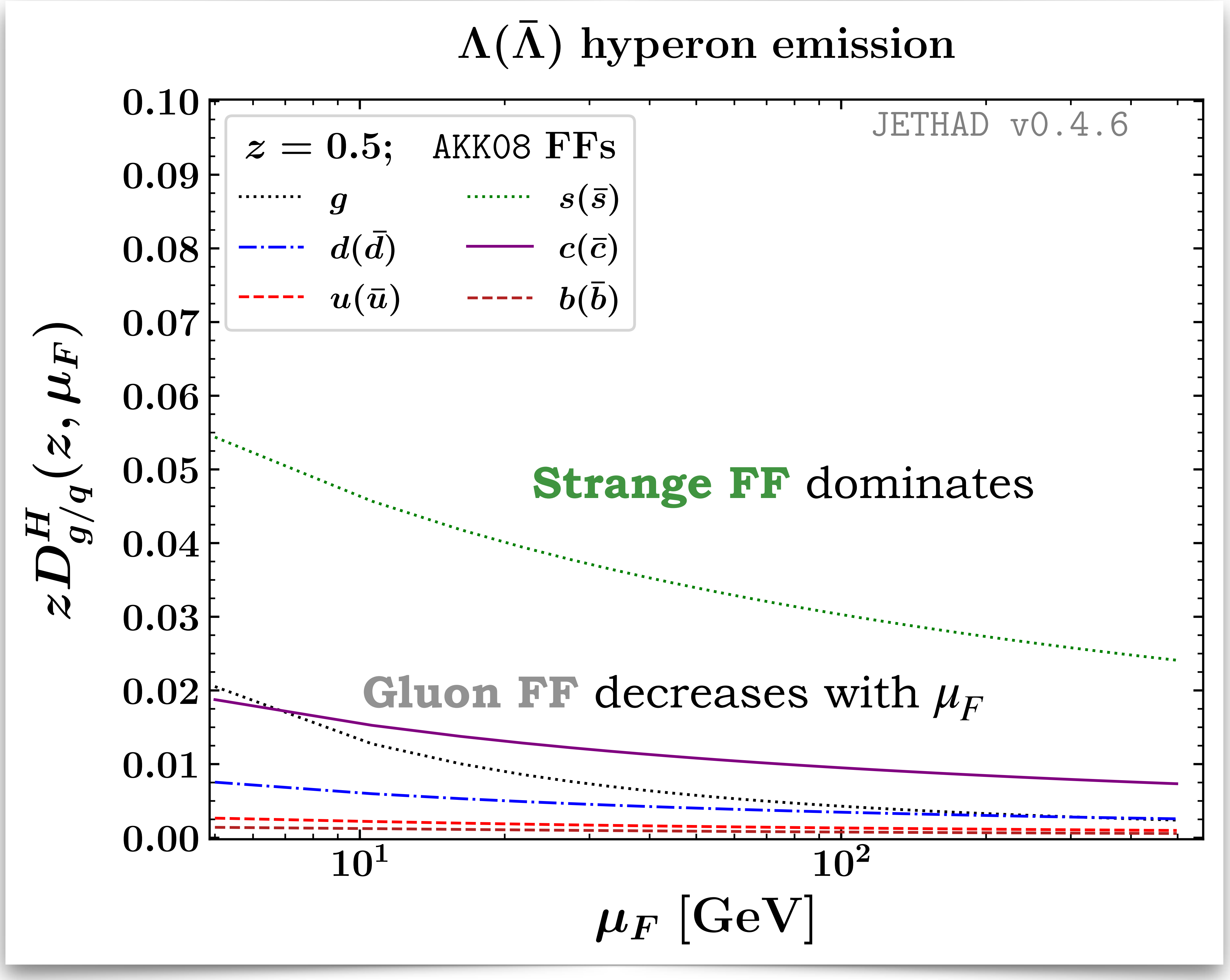

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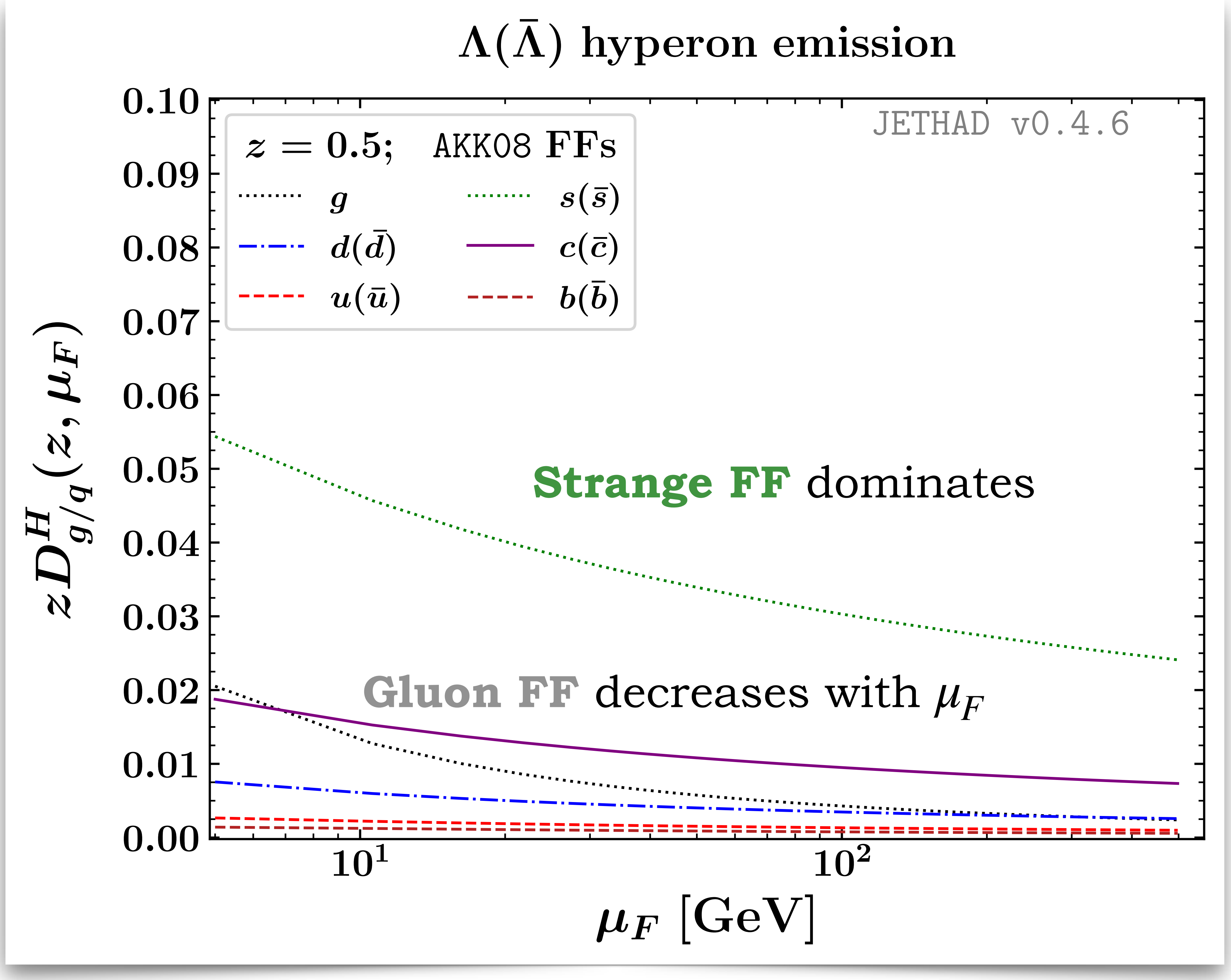

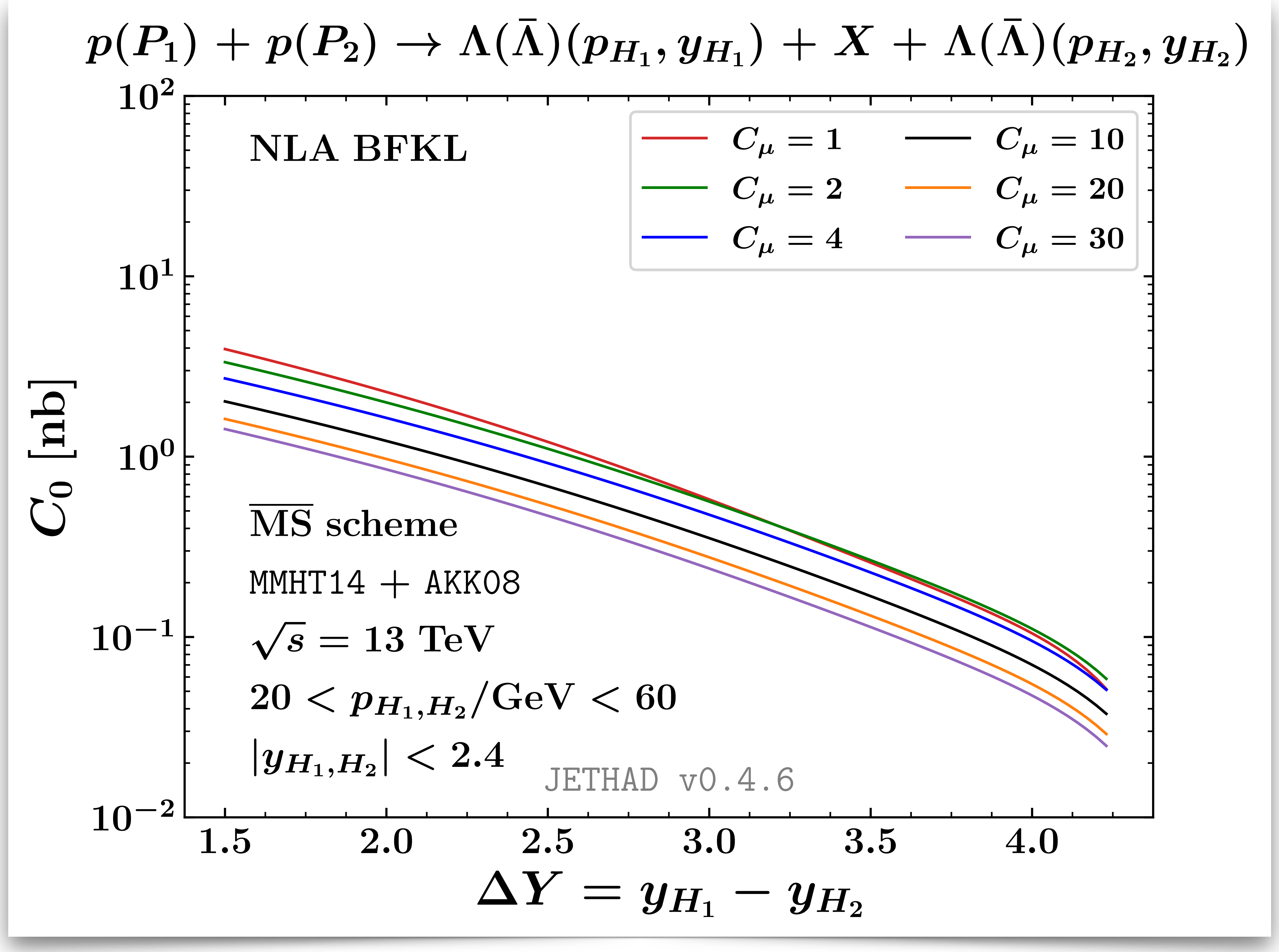

Rapidity distribution sensitive to scale variations

(Λ hyperons) [F. G. C. et al., Phys. Rev. D 102 (2020) 9, 094019]

(cascade Ξ baryons) [F. G. C., Eur. Phys. J. C (in press)]

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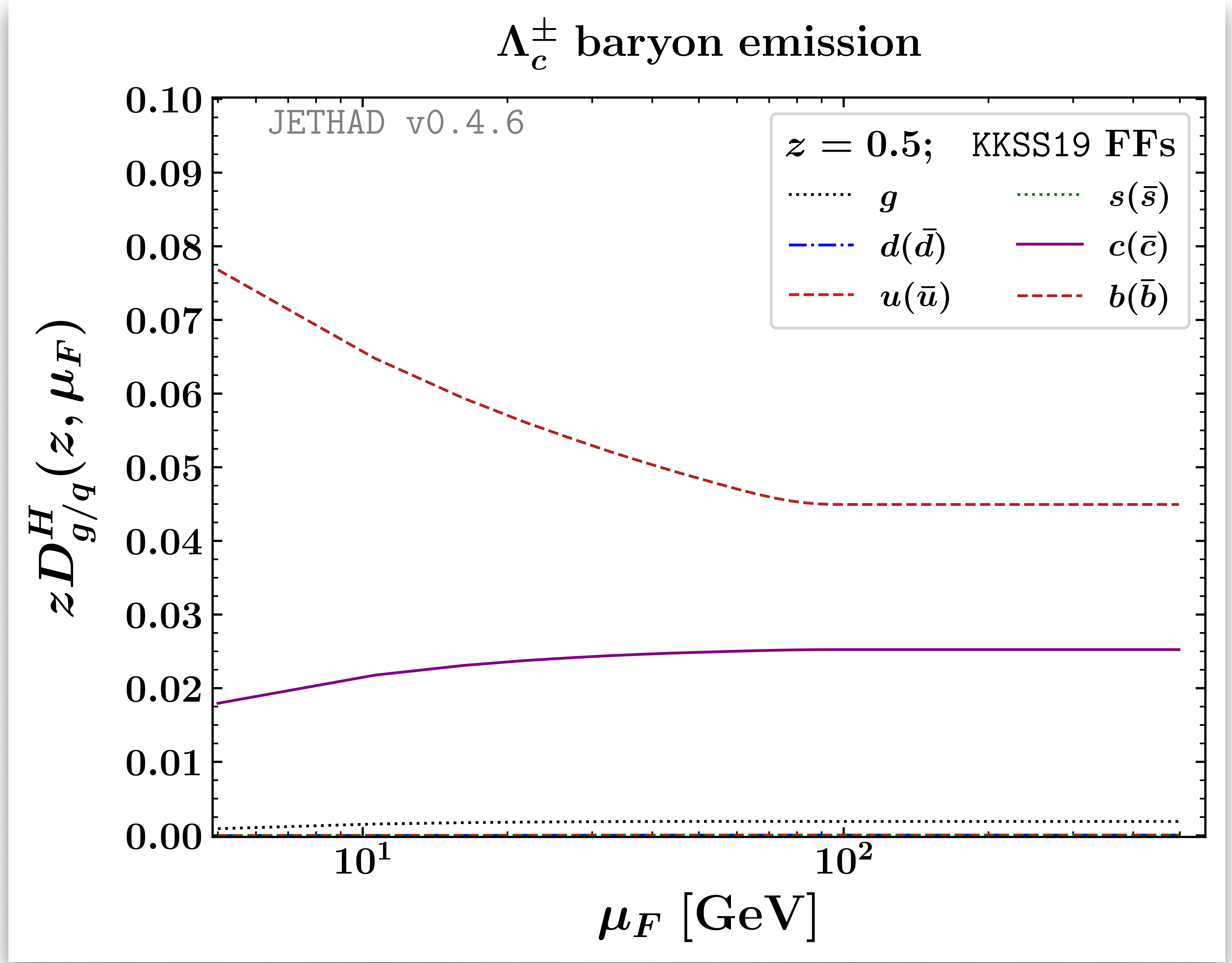
KKSS19 VFNS collinear FFs for Λ_c baryons: $|udc\rangle$ [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]



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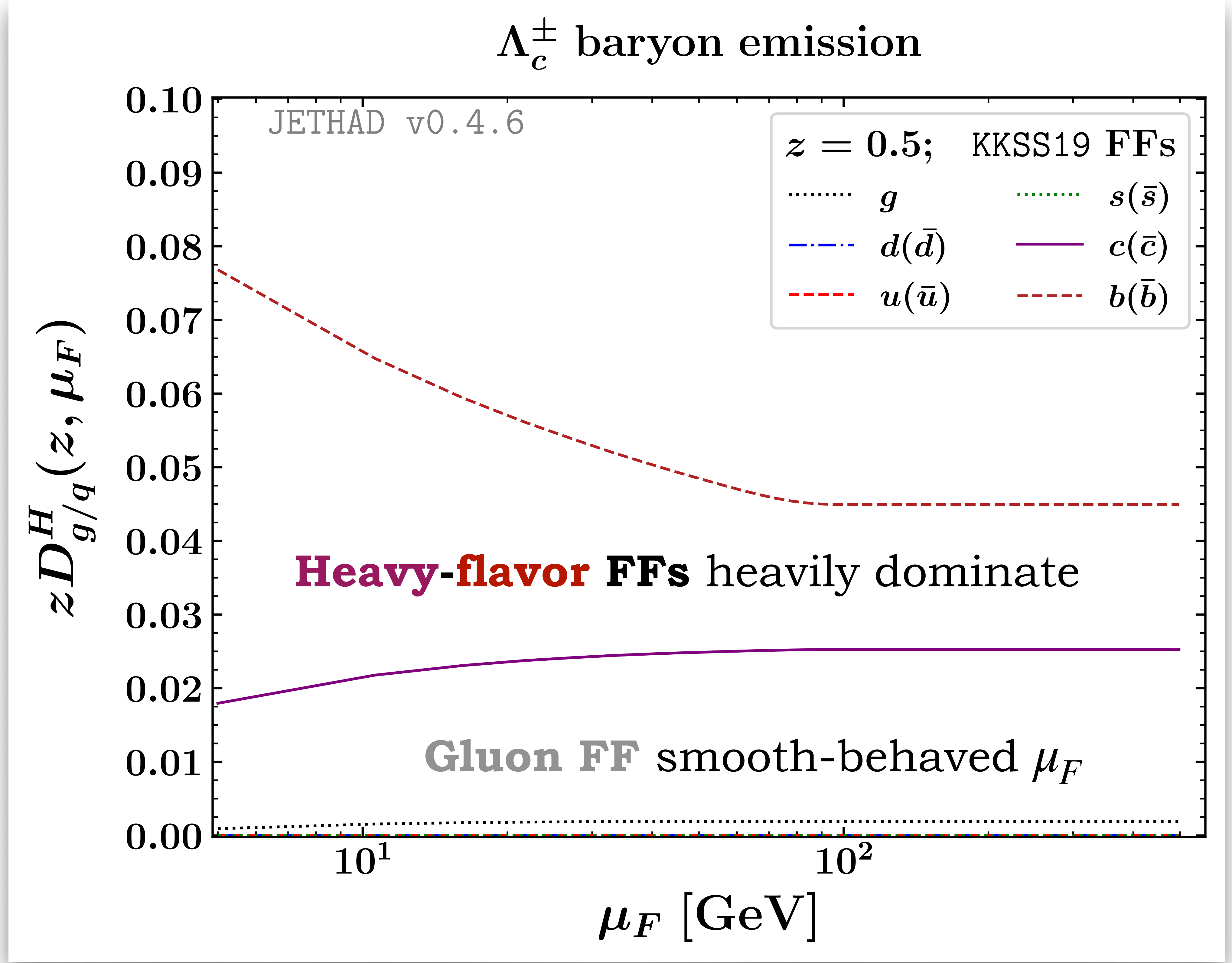

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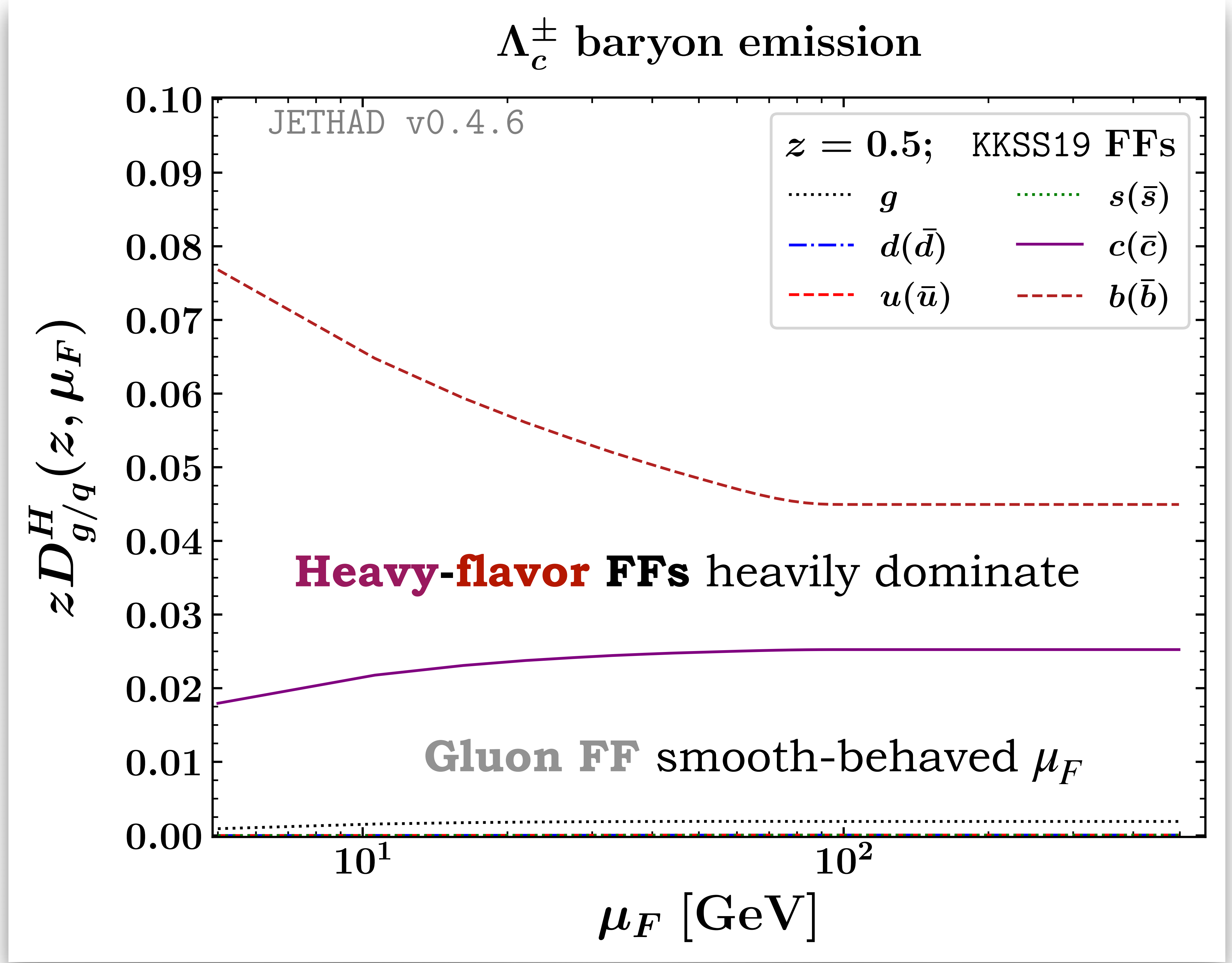
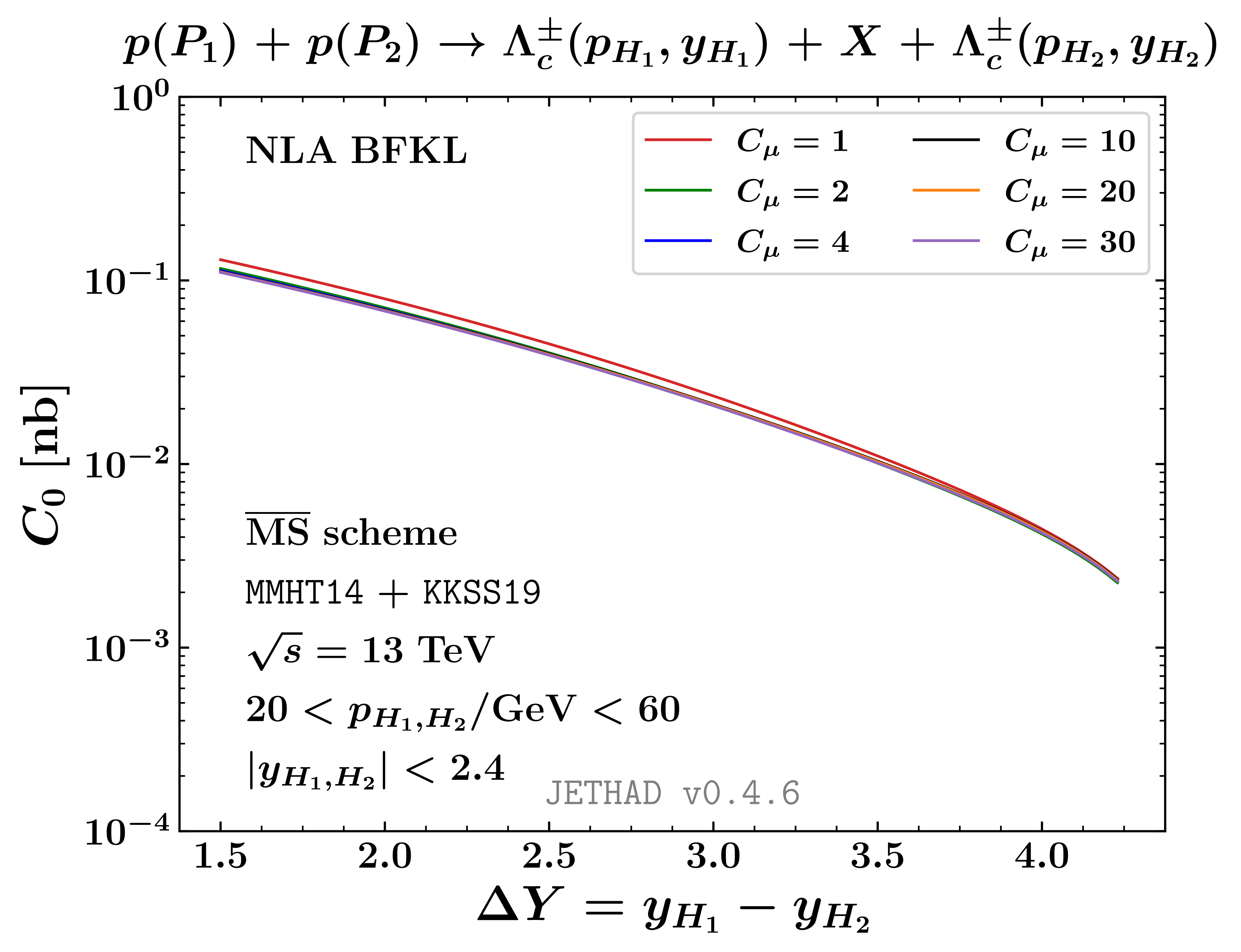




Rapidity distribution stable under scale variations

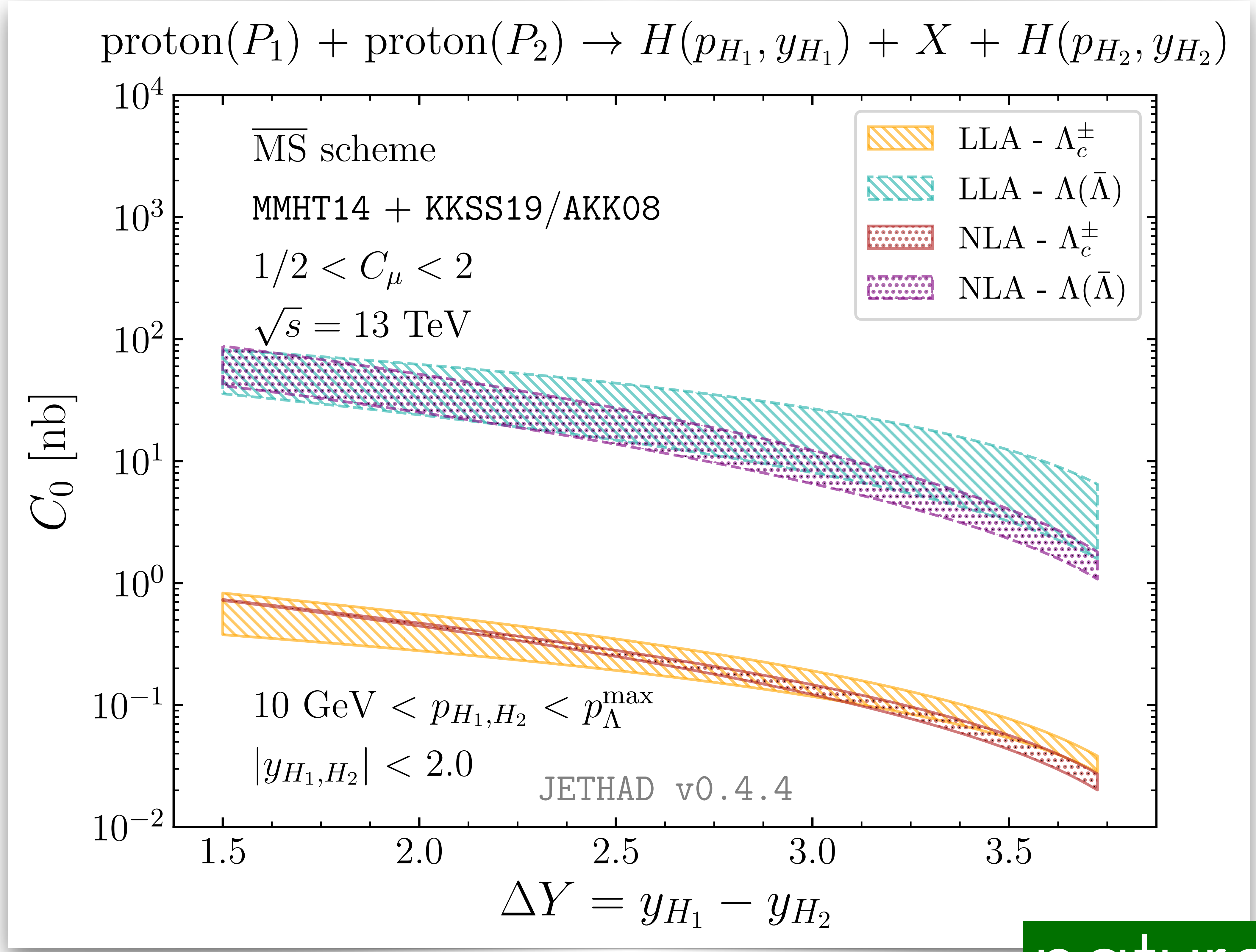
($B_c^{(*)}$ hadrons) [F. G. C., Phys. Lett. B 835 (2022) 137554]

(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

(H_b hadrons) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

Stability under scale variations & NLL corrections

Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



natural

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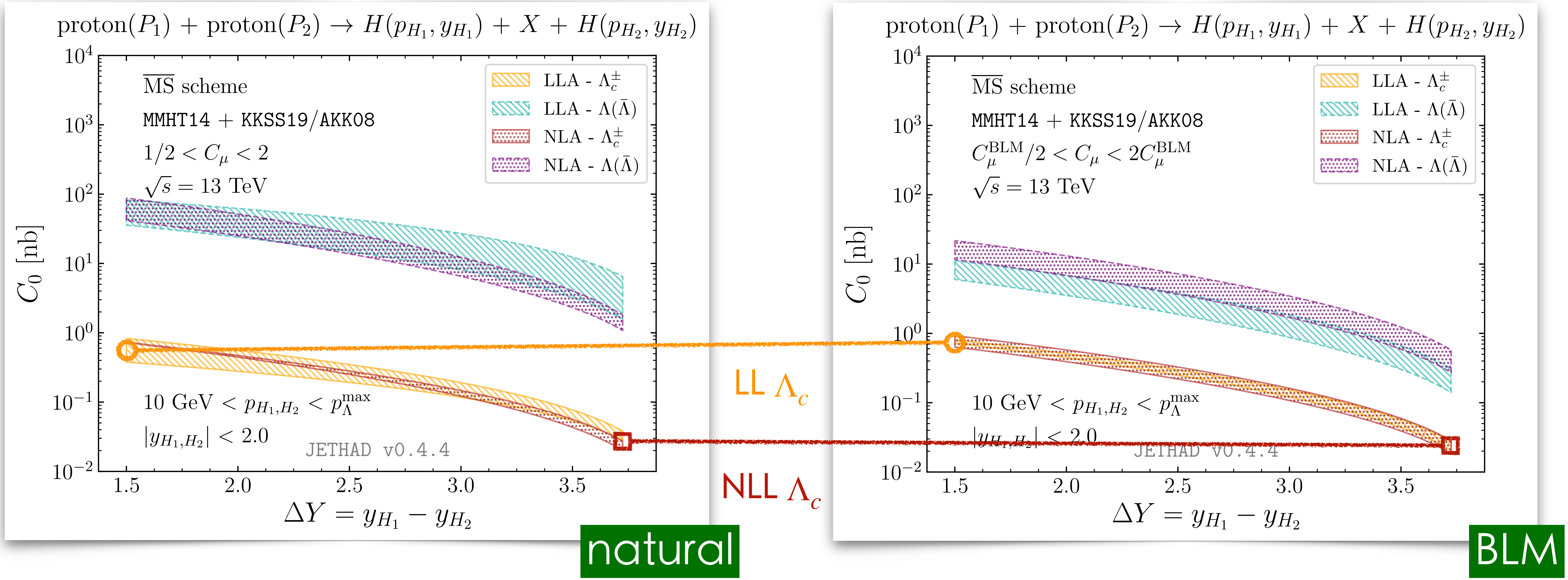

NLL corrections: rapidity distribution stable for Λ_c

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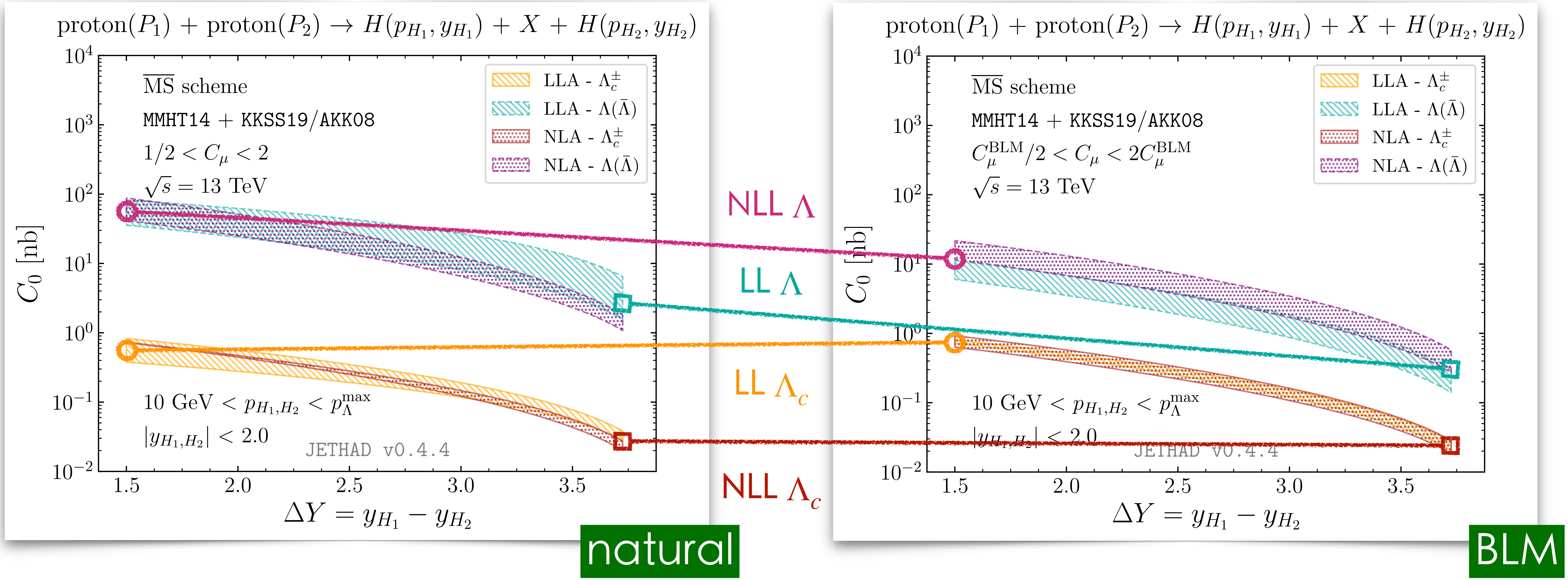

NLL corrections: rapidity distribution stable for Λ_c, loses $\sim 10^1$ magnitude for Λ

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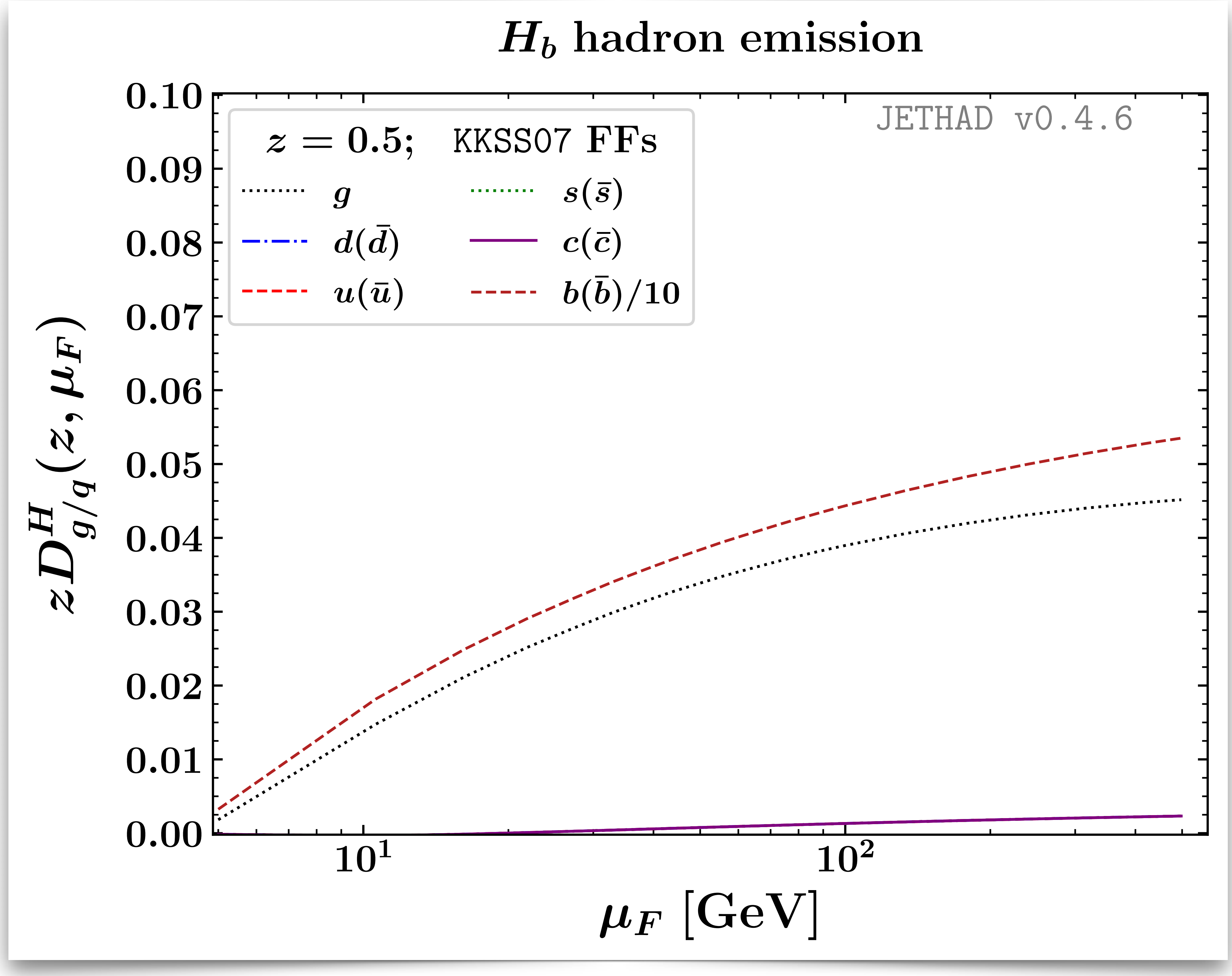

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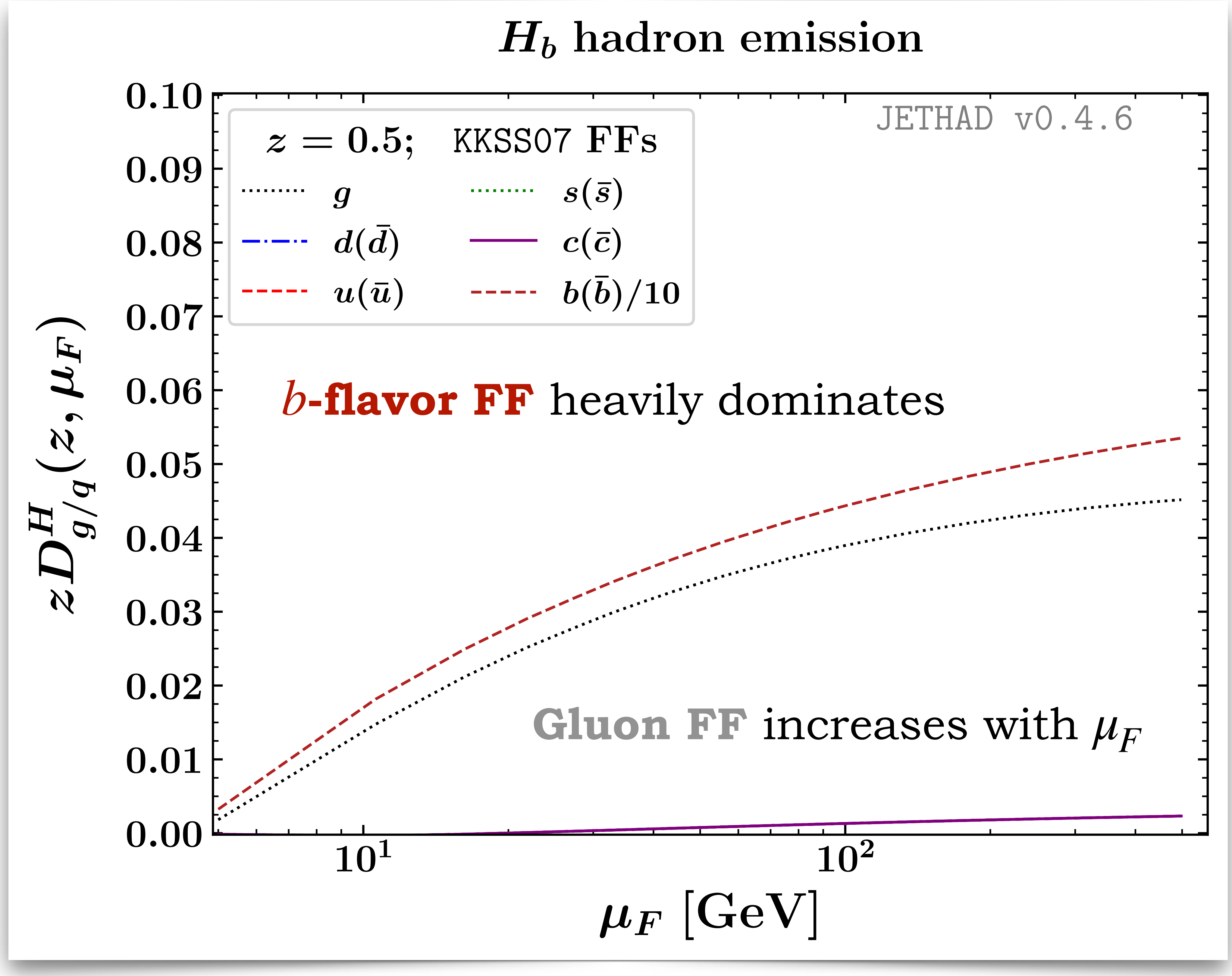

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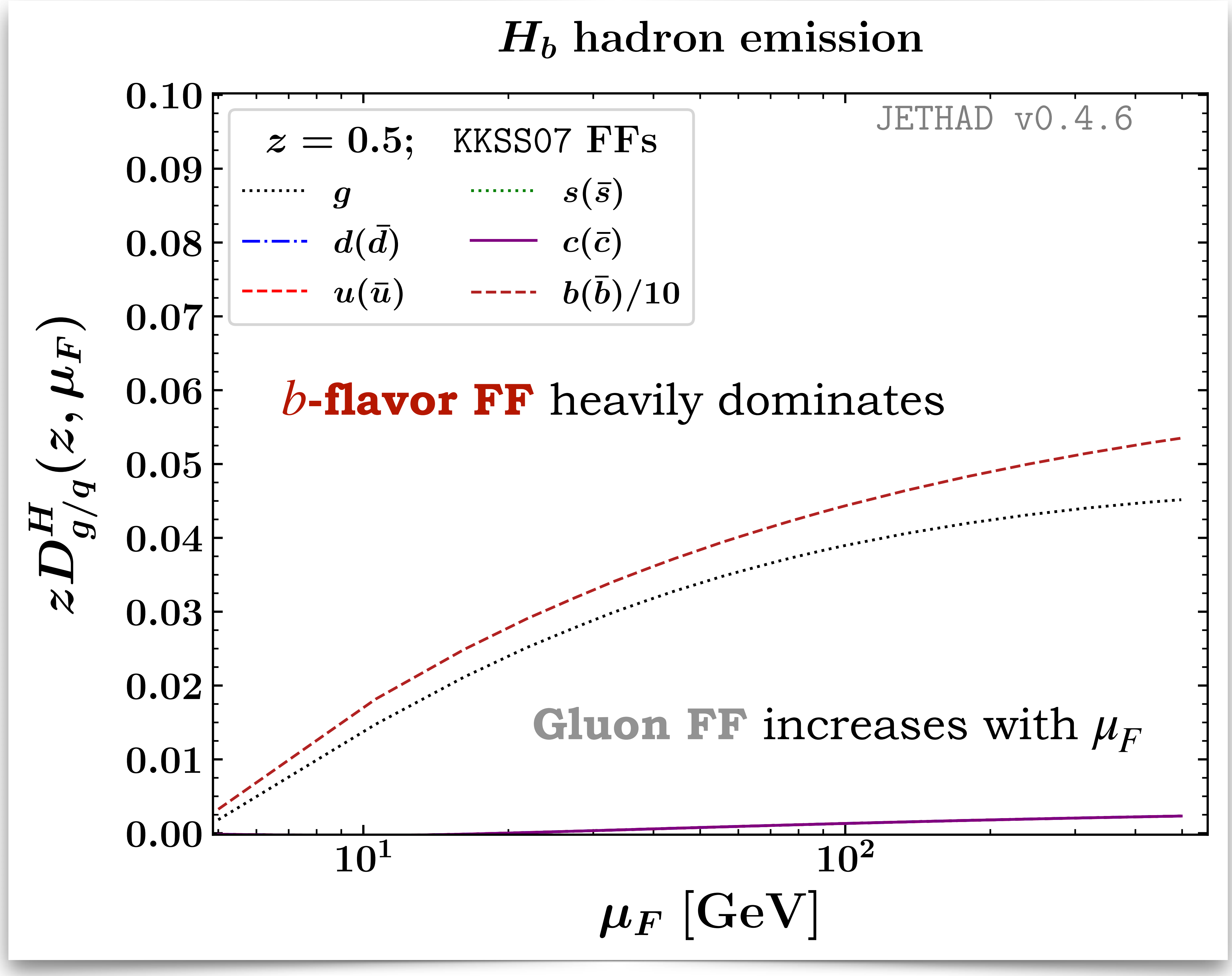

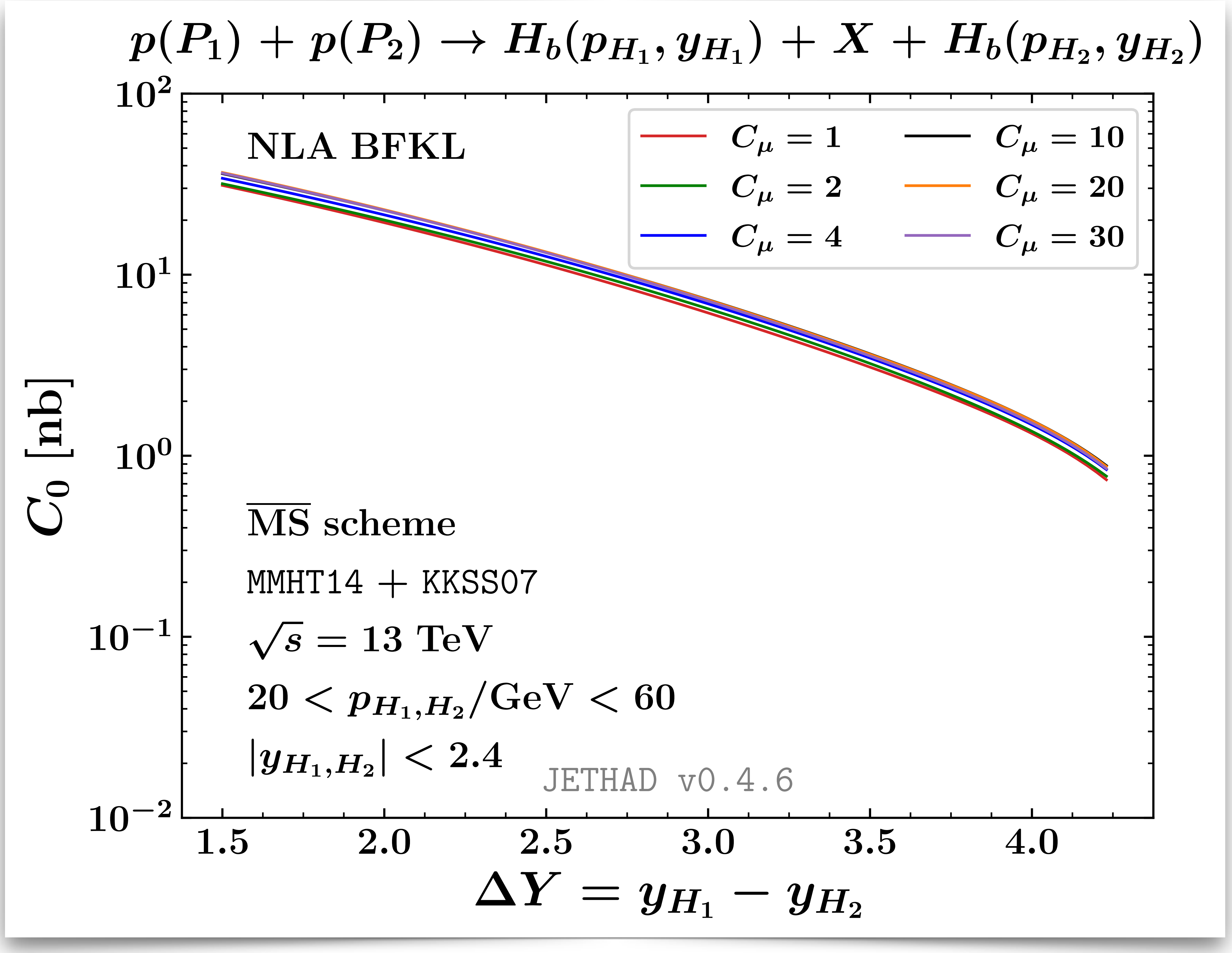

Rapidity distribution very stable under scale variations

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Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

- Forward-hadron LO impact factor $\Rightarrow$ gluon FF enhanced by gluon PDF in collinear convolution

$$c_\Lambda(n,\nu,|\vec{p}|,x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec{p}|^2)^{i\nu-1/2}\int_x^1 \frac{\mathrm{d}z}{z}\left(\frac{z}{x}\right)^{2i\nu-1}\left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar{q}} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right)\right]$$

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$$c_\Lambda(n,\nu,|\vec{p}|,x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec{p}|^2)^{i\nu-1/2}\int_x^1 \frac{\mathrm{d}z}{z}\left(\frac{z}{x}\right)^{2i\nu-1}\left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar{q}} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right)\right]$$

- Forward-hadron NLO impact factor ⇒ a non-diagonal heavy-flavor channel open...

$$c_1^{(1)}(n,\nu,|\vec{k}_1|,\alpha_1) = 2\sqrt{\frac{C_F}{C_A}}\left(\vec{k}_1^2\right)^{i\nu-\frac{1}{2}}\frac{1}{2\pi}\int_{\alpha_1}^1\frac{dx}{x}\int_{\frac{\alpha_1}{x}}^1\frac{d\zeta}{\zeta}\left(\frac{x\zeta}{\alpha_1}\right)^{2i\nu-1}$$
$$\times\left[\frac{C_A}{C_F}f_g(x)D_g^h\left(\frac{\alpha_1}{x\zeta}\right)C_{gg}(x,\zeta) + \sum_{a=q,\bar{q}}f_a(x)D_a^h\left(\frac{\alpha_1}{x\zeta}\right)C_{qq}(x,\zeta)\right.$$
$$\left. + D_g^h\left(\frac{\alpha_1}{x\zeta}\right)\sum_{a=q,\bar{q}}f_a(x)C_{qg}(x,\zeta) + \frac{C_A}{C_F}f_g(x)\sum_{a=q,\bar{q}}D_a^h\left(\frac{\alpha_1}{x\zeta}\right)C_{gq}(x,\zeta)\right]$$

...but $|C_{gg}| \sim 50 \div 10^4 |C_{gq}|$

(NLO impact factor) 🔗 [D. Yu. Ivanov, A. Papa JHEP 07 (2012) 045]

Stabilizing effects of heavy-flavor fragmentation

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- Gluon FF rises with energy $\Rightarrow$ this compensates PDF and BFKL kernel decreasing behavior

(NLO impact factor) 🔗 [D. Yu. Ivanov, A. Papa JHEP 07 (2012) 045]

VECTOR QUARKONIA

Is the natural stability robust?

(1) **KKSS07** and **KKSS19** VFNS collinear FFs share the same extraction technology

¿ *Might natural stability be related to the given FF determination(s)* ?

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¿ *Might natural stability be related to the given FF determination(s)* ?

(2) **KKSS07** and **KKSS19** VFNS collinear FFs assume no initial-scale gluon, but evolution-driven

¿ *Might natural stability be artificially generated by this Ansatz* ?

Vector quarkonium from single-parton fragmentation

(1) ¡ *Let us consider J/ψ and Υ at large p_T* $\rightarrow$ *single-parton* ***fragmentation*** *from* ***NRQCD*** !

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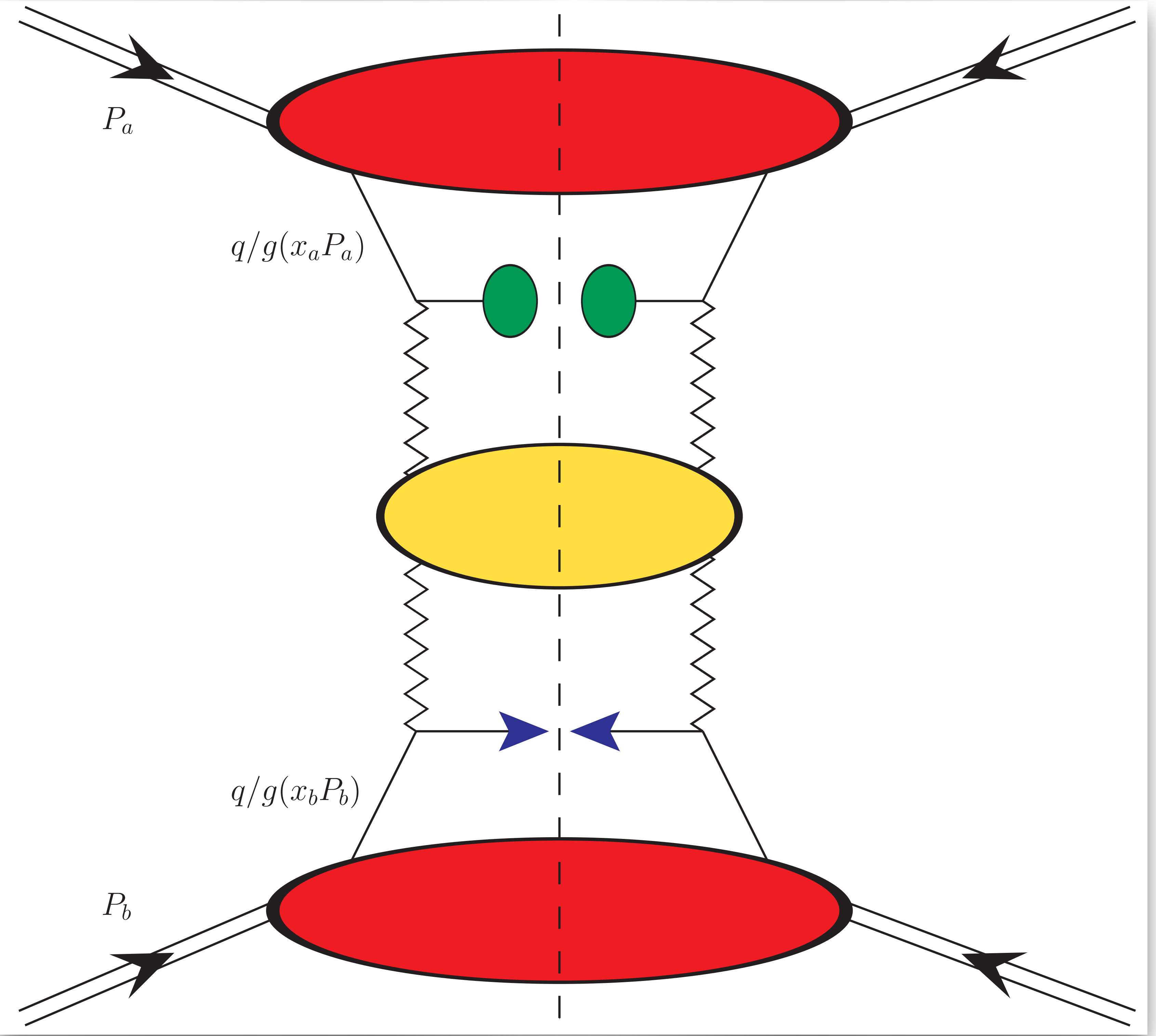

2.1 High-energy resummed cross section

The process under investigation is

$$p(P_a) + p(P_b) \to \mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q}) + X + \text{jet}(p_J, y_J) \; , \tag{1}$$

where $p(P_{a,b})$ stands for an initial proton with momentum $P_{a,b}$, $\mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q})$ is a J/ψ or a Υ emitted with momentum $p_\mathcal{Q}$ and rapidity $y_\mathcal{Q}$, the light jet is tagged with momentum p_J and rapidity y_J, and X denotes all the undetected products of the reaction. High observed transverse momenta, $|\vec{p}_{\mathcal{Q},J}|$, together with a large rapidity separation, $\Delta Y = y_\mathcal{Q} - y_J$, are required conditions to get a diffractive semi-hard configuration in the final state. Furthermore the transverse-momentum ranges need to be enough large to ensure the validity of description of the quarkonium production mechanism in terms of single-parton VFNS collinear fragmentation.

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

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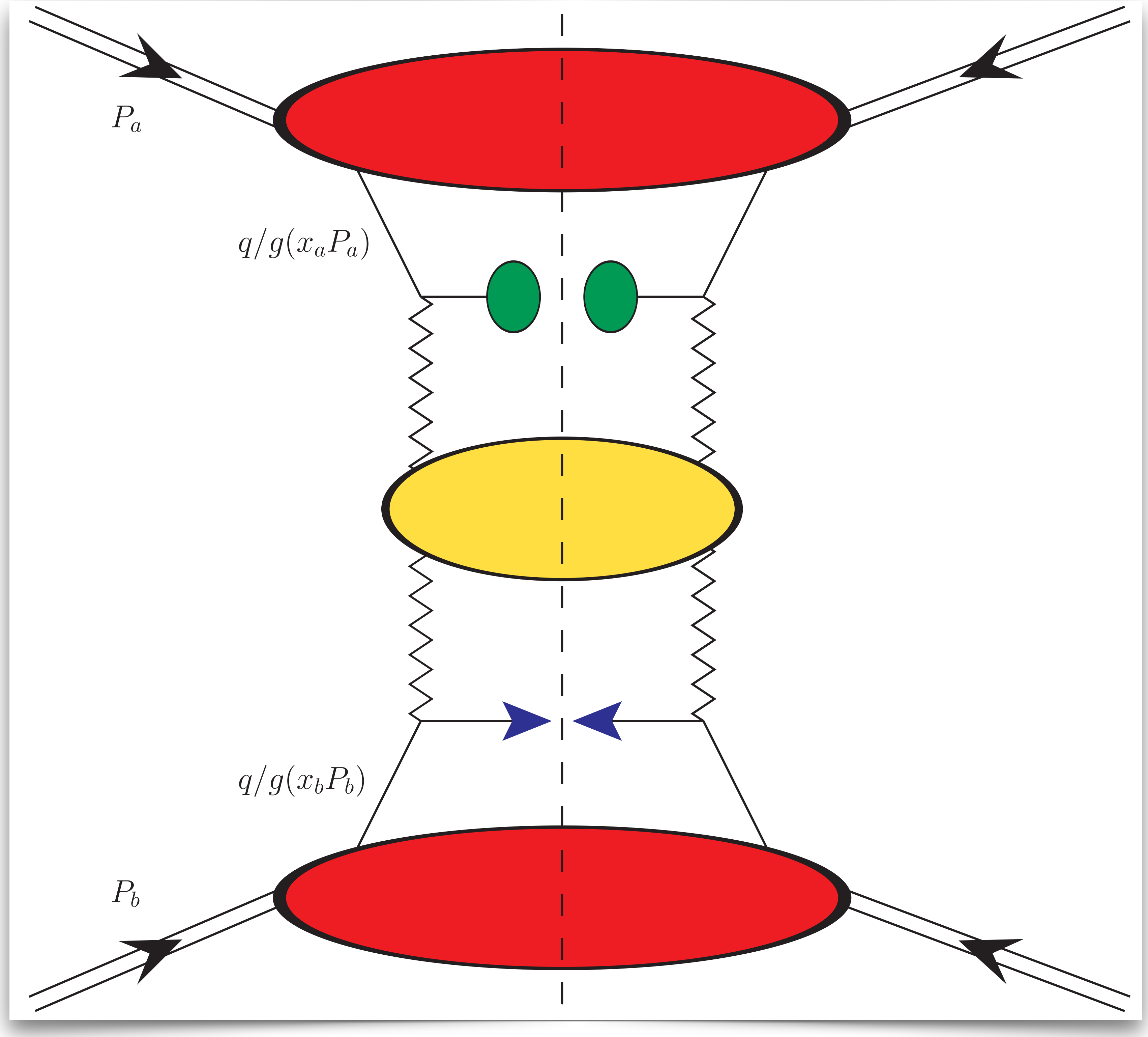

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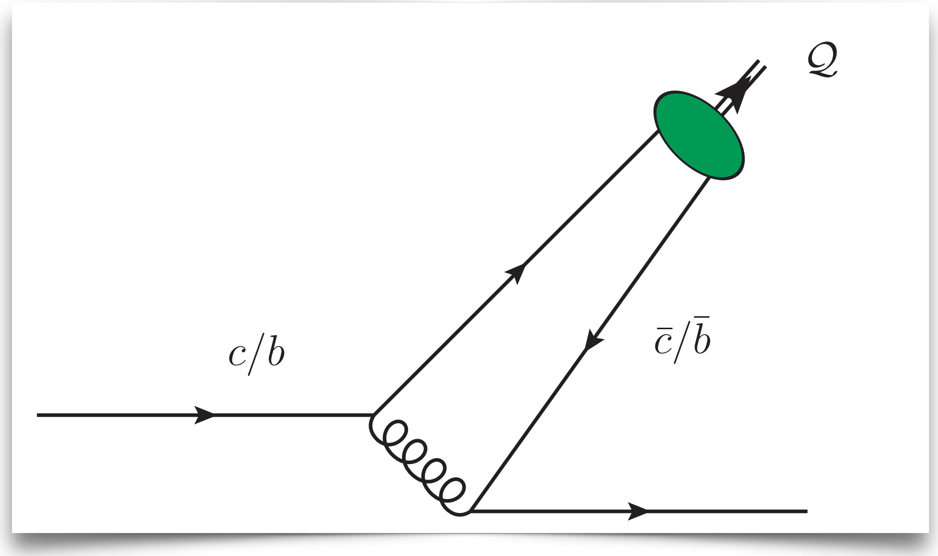
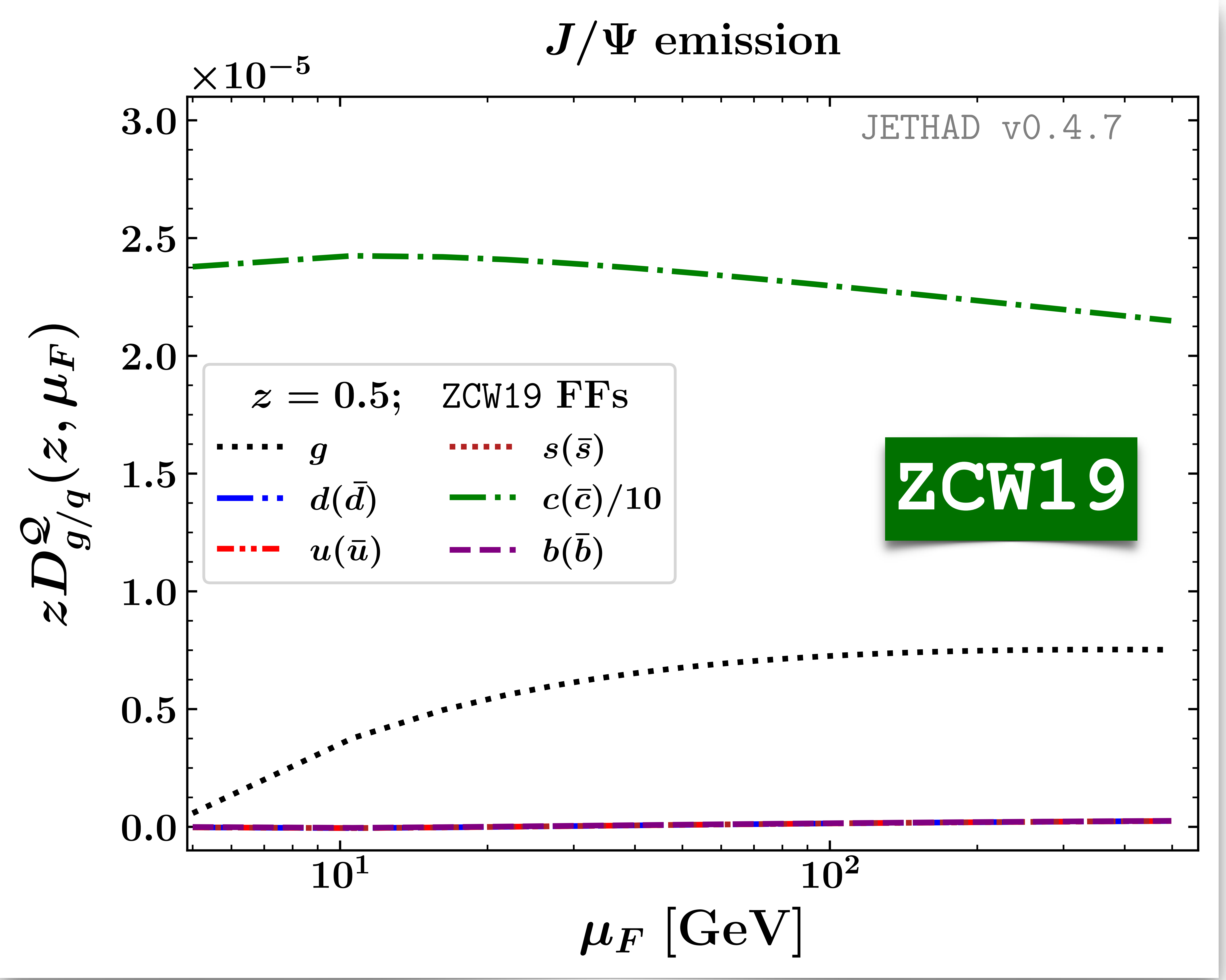


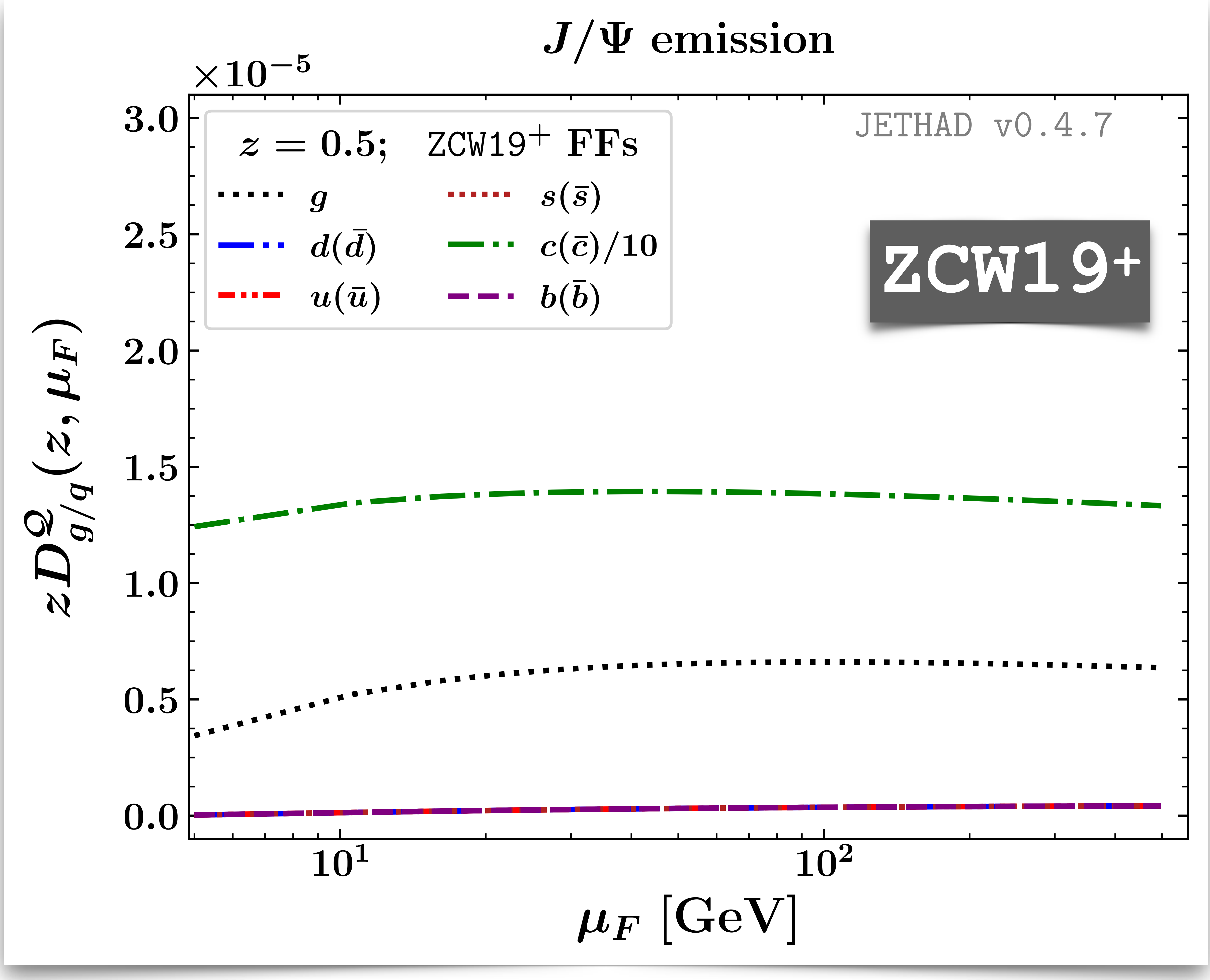
(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

(NLO) 🔗 [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

Vector quarkonium + jet at the LHC

J/ψ collinear FFs





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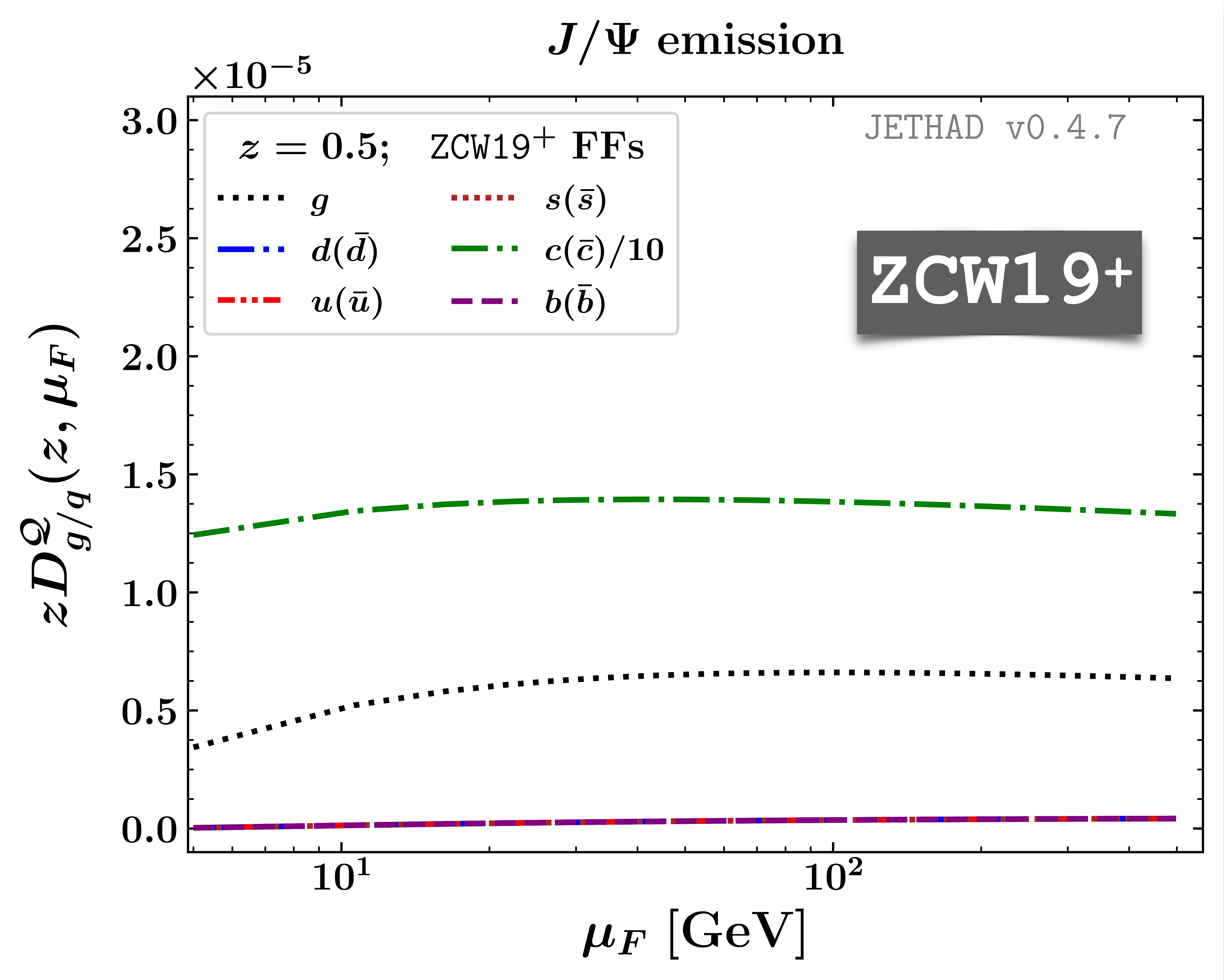
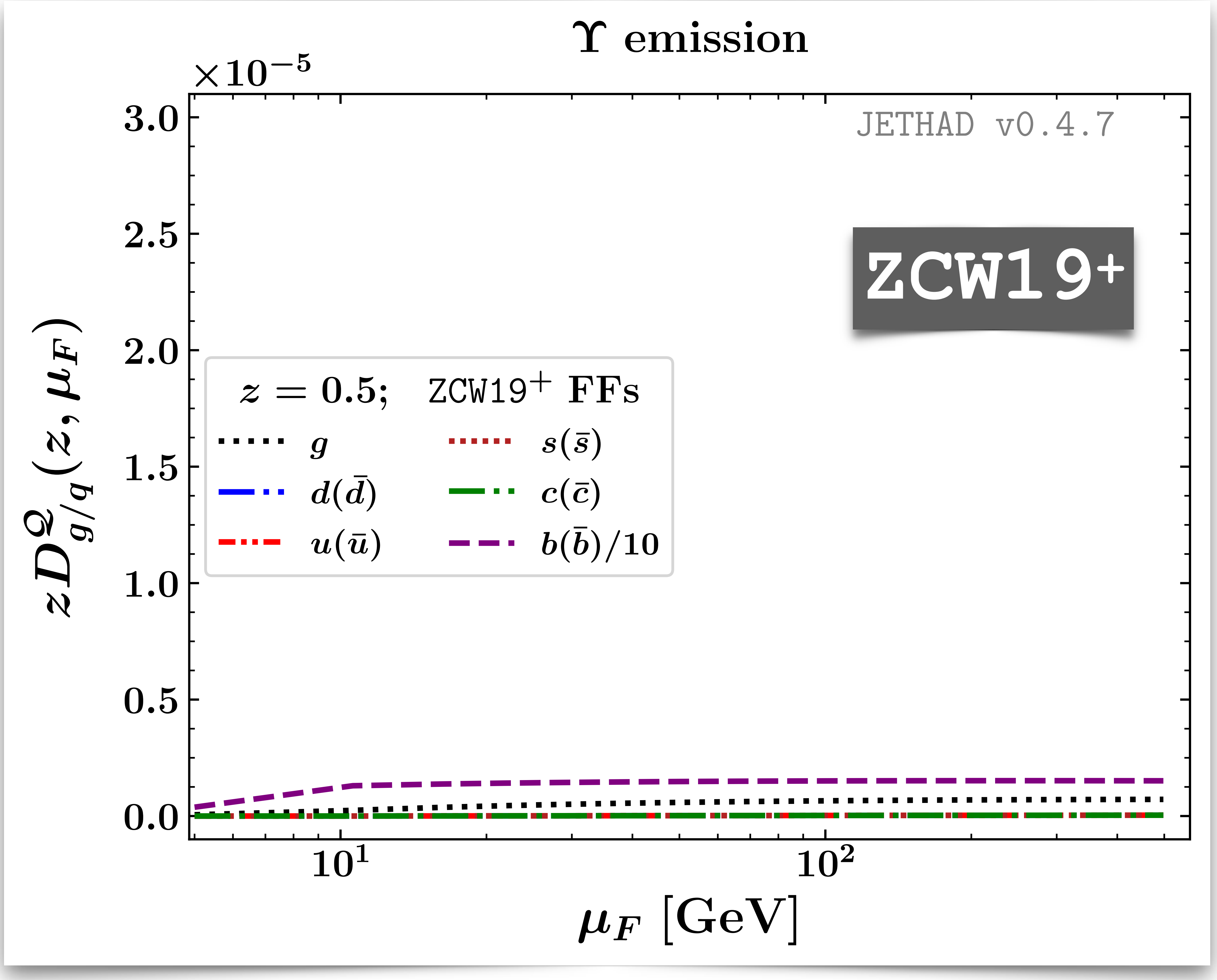


Υ collinear FFs



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