Heavy-Flavor (in Jet) Fragmentation from HF-NRevo: Towards NRFF1.0(jet)

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In collaboration with: Francesca Lonigro

Marseille
- T04 -
Ultra-relativistic
Nuclear
Collisions



2025, July 7th

Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

EUGLOH

QCD Hydrogen Atoms

1

¿ Why studying Quarkonia ?

Precision & exploration

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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[$\alpha_s(2019)$ ECT* Trento WG (2019)] 🔗

QUARKONIA

QCD Hydrogen Atoms

Hors d'œuvre

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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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Hors d'œuvre

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)]

Precision determinations of QCD running coupling

$\Upsilon(1S)$ hadronic inclusive decays

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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

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

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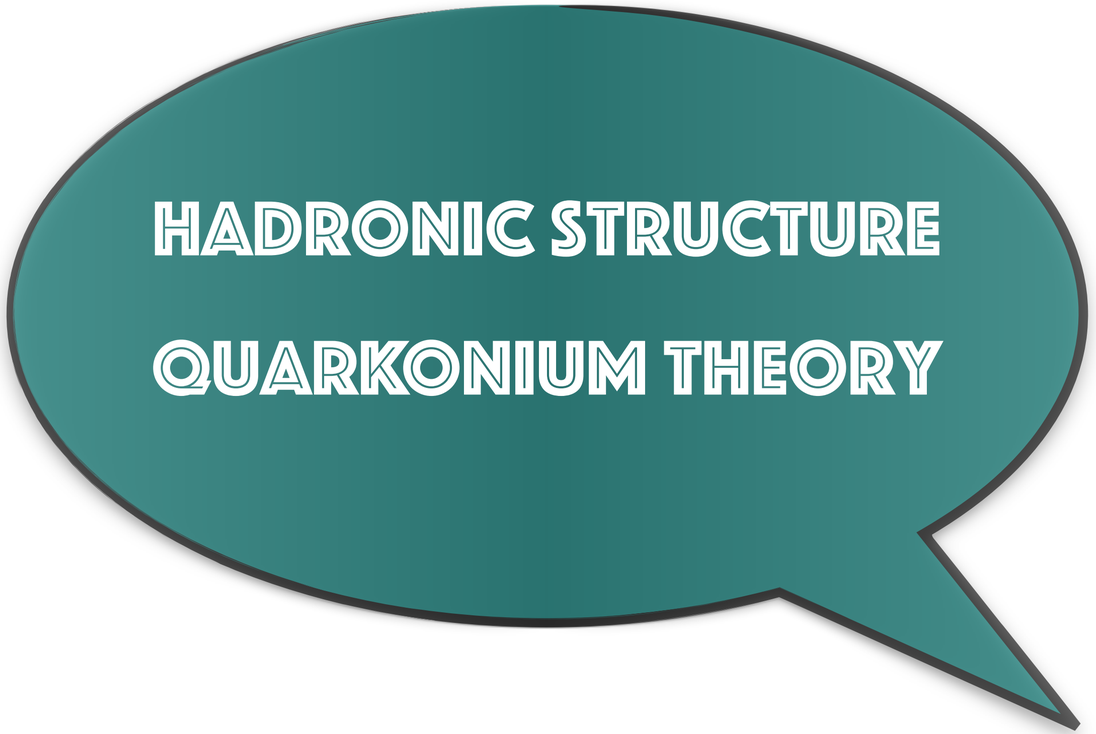
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$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\overline{Q}\,[n] + X)\,\langle \mathcal{O}^H\,[n] \rangle$$

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

③ Quarkonium fragmentation from HF-NRevo

Heavy-Flavor Non-Relativistic evolution



Heavy-Flavor Non-Relativistic evolution

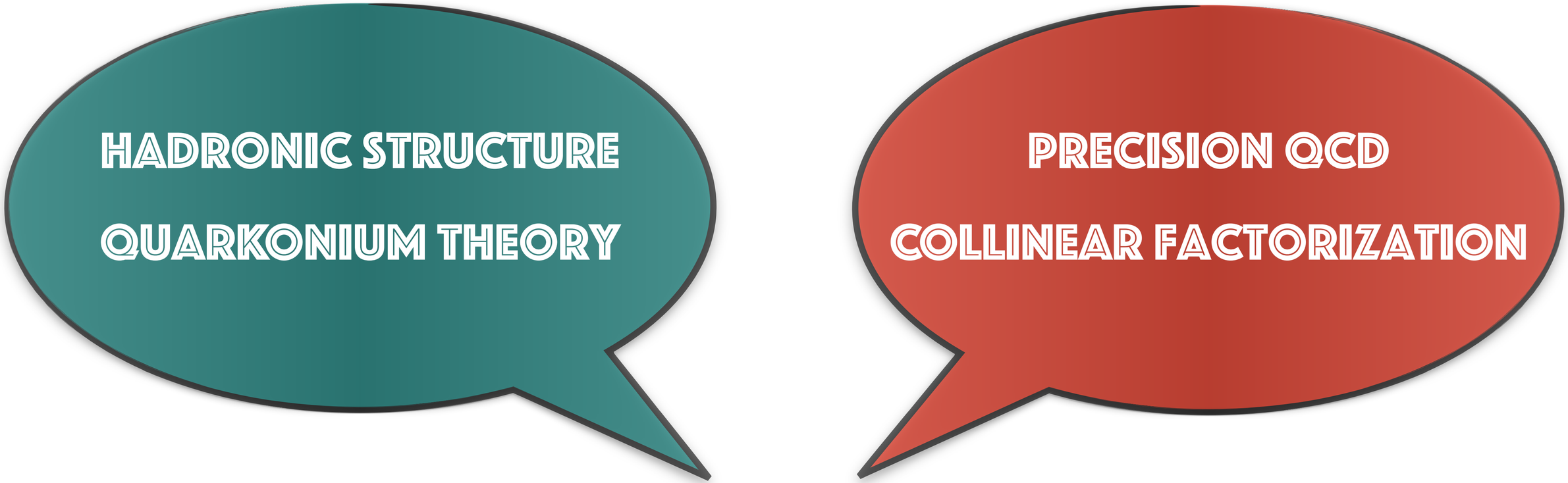
HADRONIC STRUCTURE

QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

Heavy-Flavor Non-Relativistic evolution



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

Heavy-Flavor Non-Relativistic evolution

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

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

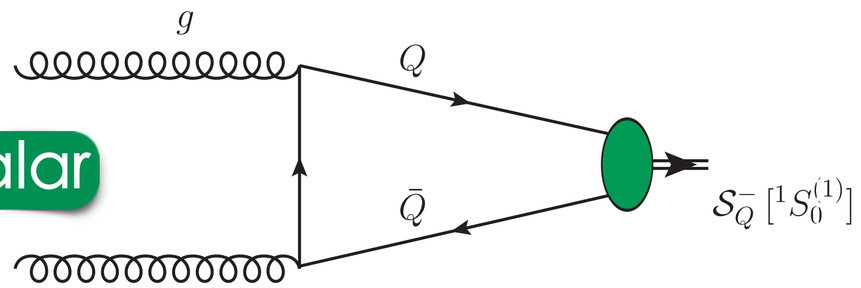
3.2 HF-NRevo: Interpretation

From low energies to high energies

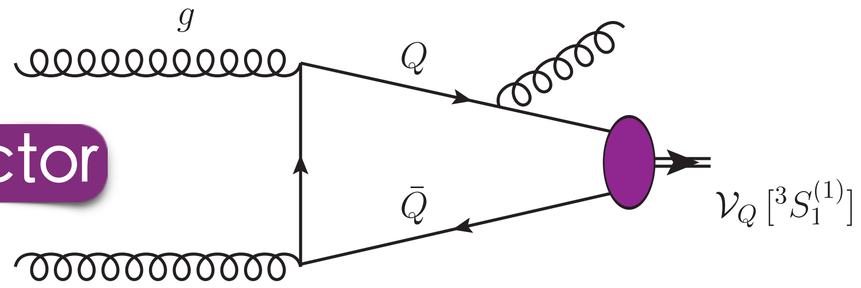
Low p_T $\Rightarrow$ two-parton FFs

Genuine higher-twist FFNS FFs

scalar



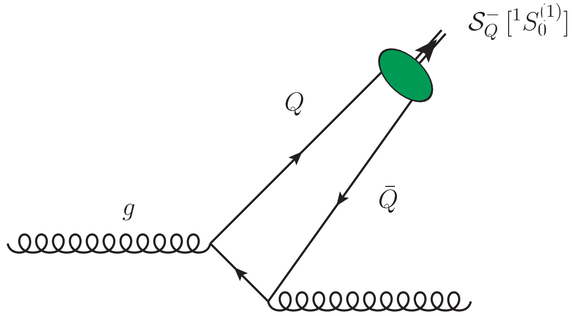
vector



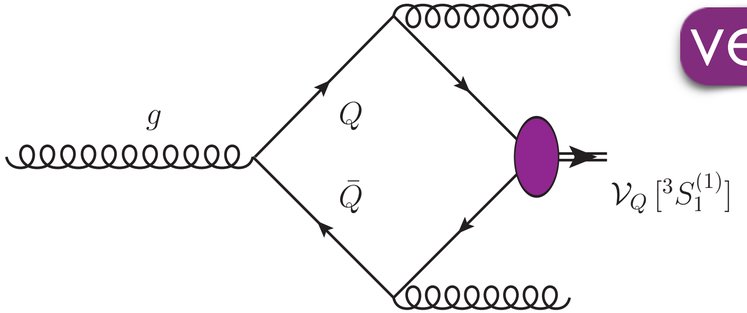
High p_T $\Rightarrow$ single-parton FFs

Twist-2 VFNS FFs + power corrections

scalar

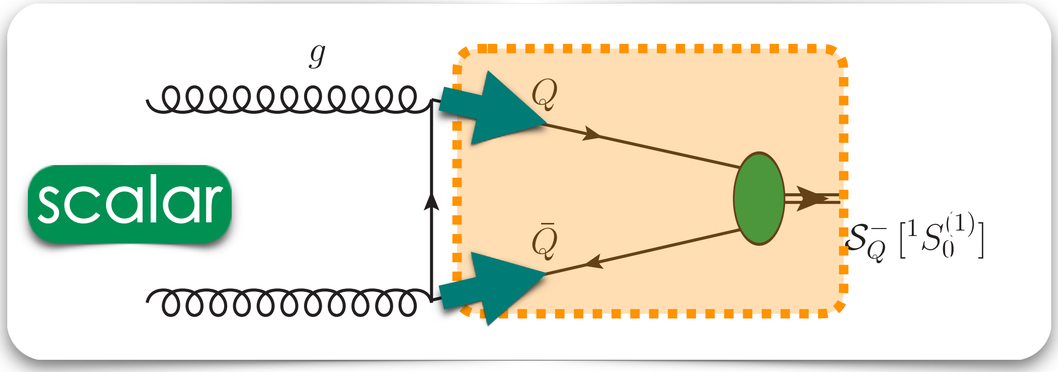


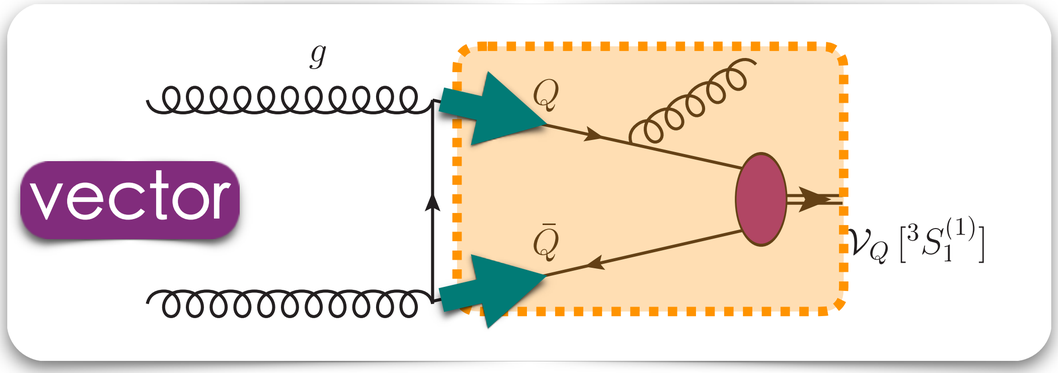
vector



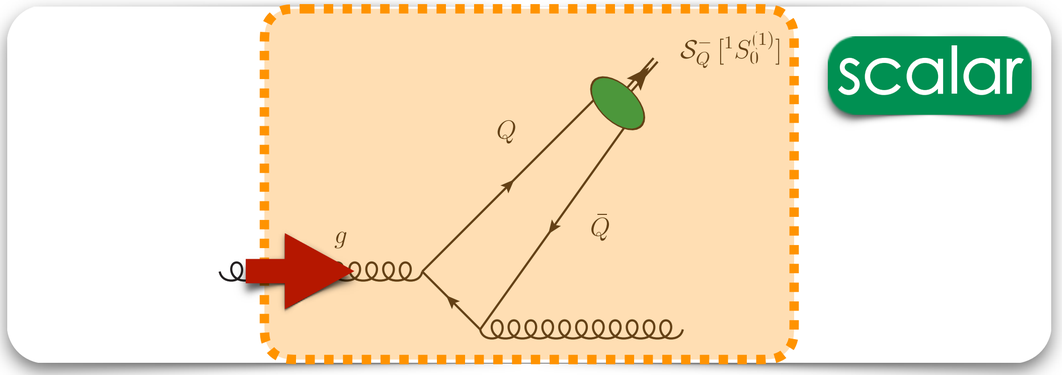
From low energies to high energies

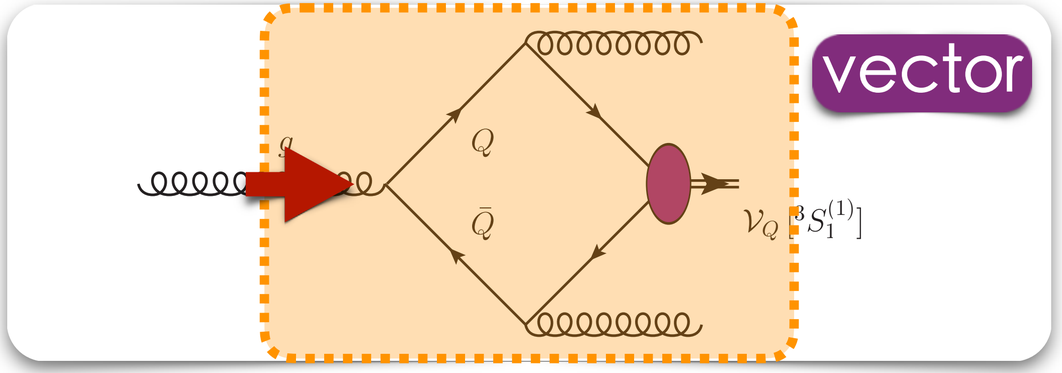
Low p_T ⇒ two-parton FFs
Genuine higher-twist FFNS FFs





High p_T ⇒ single-parton FFs
Twist-2 VFNS FFs + power corrections





Collinear Fragmentation Correlator (CFC)

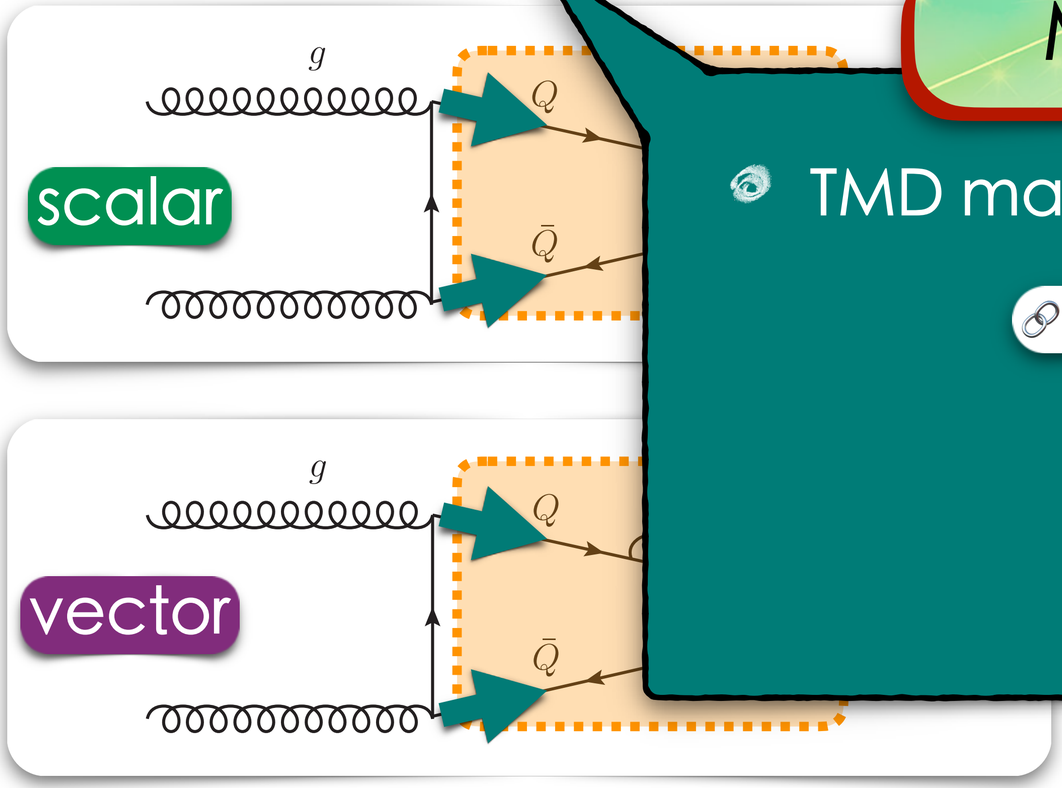
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Genuine higher-twist FFNS FFs

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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)]

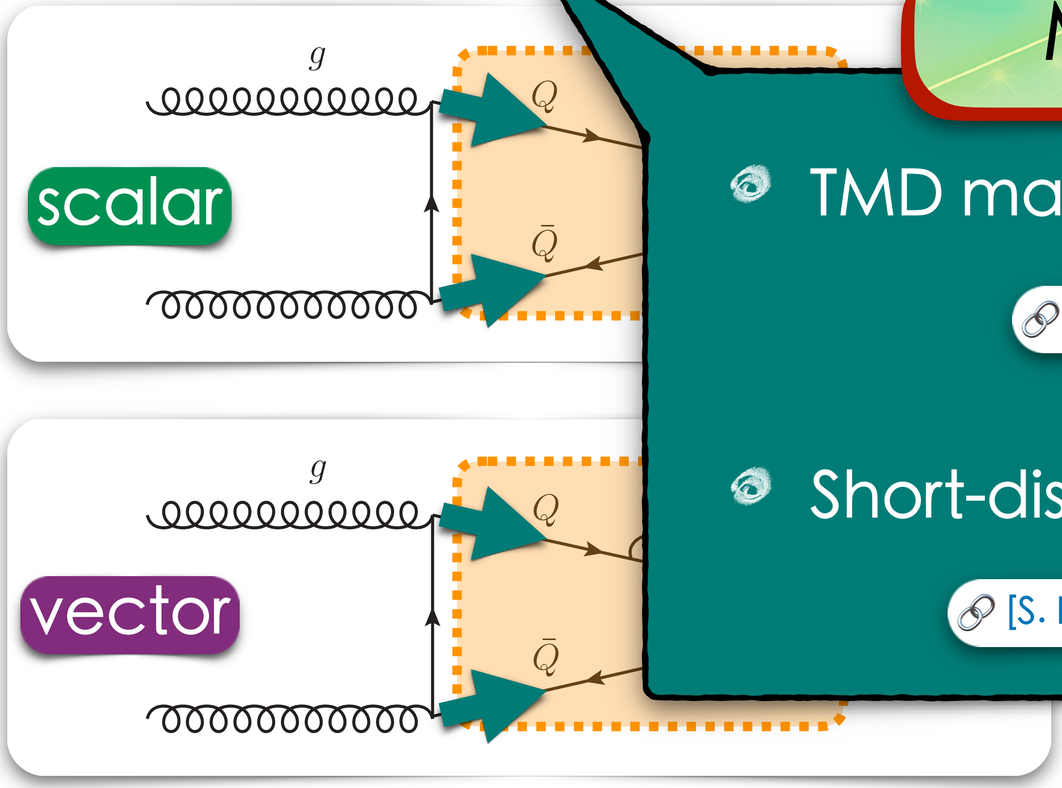
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- Short-distance $\Leftrightarrow$ double-parton FFs (SCET)

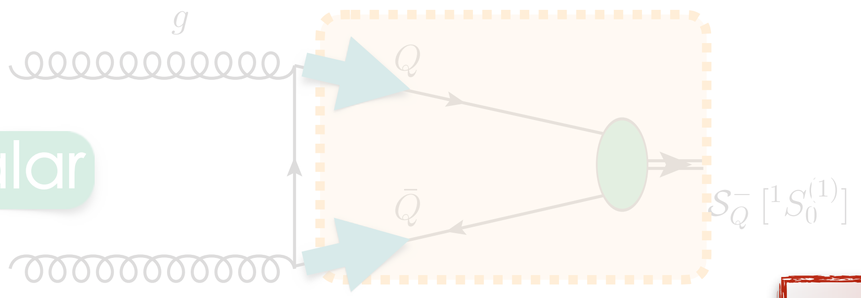
[S. Fleming, A.K. Leibovich, T. Mehen, I.Z. Rothstein (2012)]

From low energies to high energies

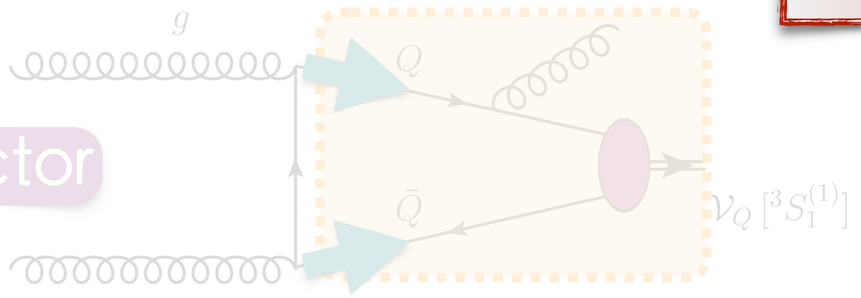
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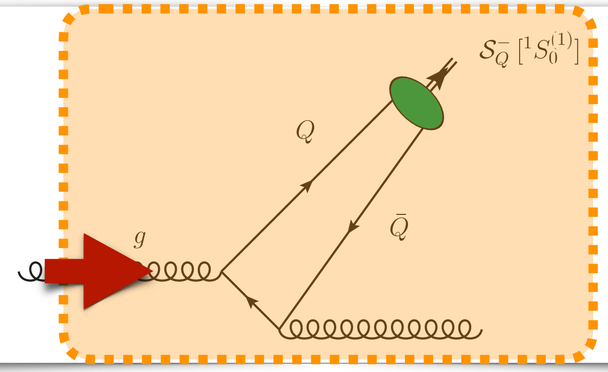
vector



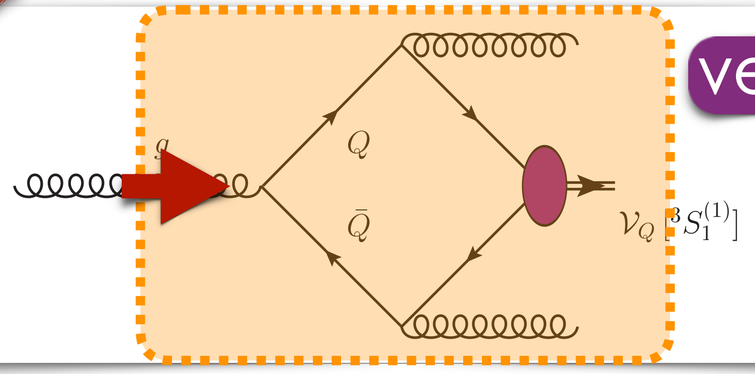
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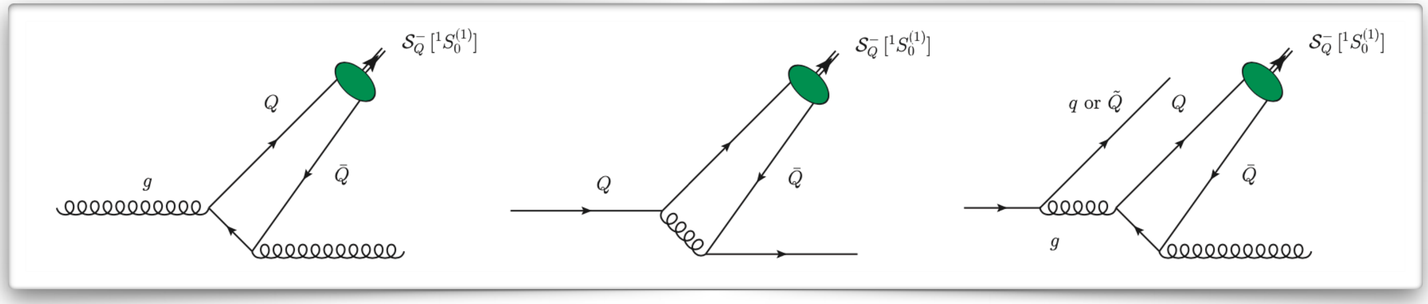
Heavy-Flavor Non-Relativistic evolution

HF-NRevo

Evolution

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

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

LDMEs

SDCs

g
$\tilde{q}$
c
b
$2m_c$

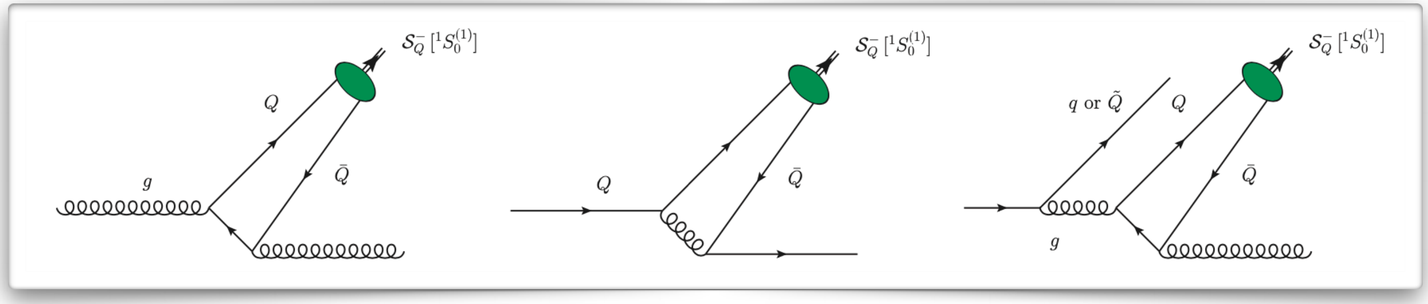
$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy

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

Time

HF-NRevo: Initial-scale NRCQD inputs



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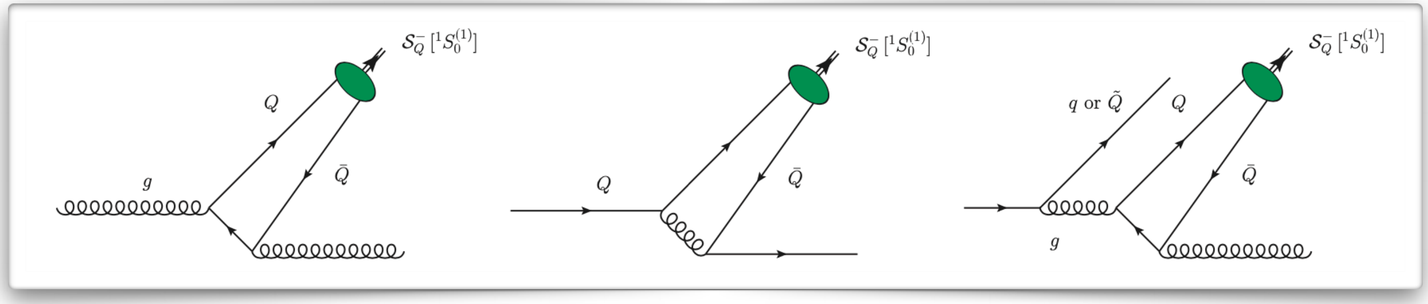
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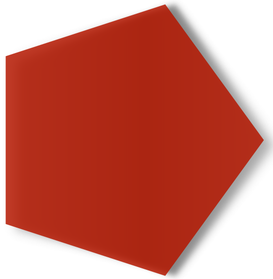
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Scalar η_c

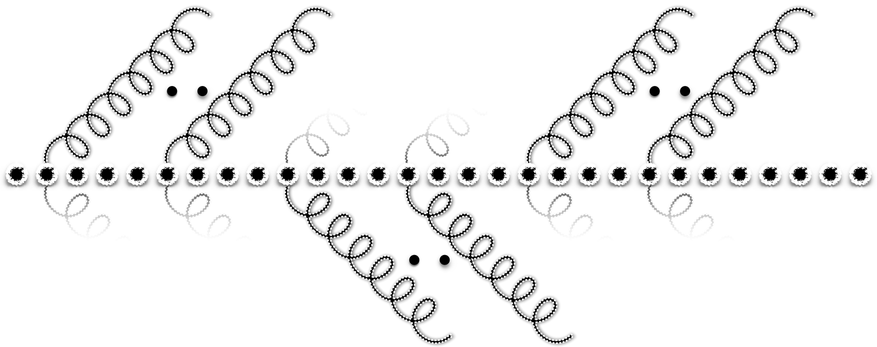
HF-NRevo for $\eta_c[^1S_0^{(1)}]$ collinear fragmentation

Partonic hard factor



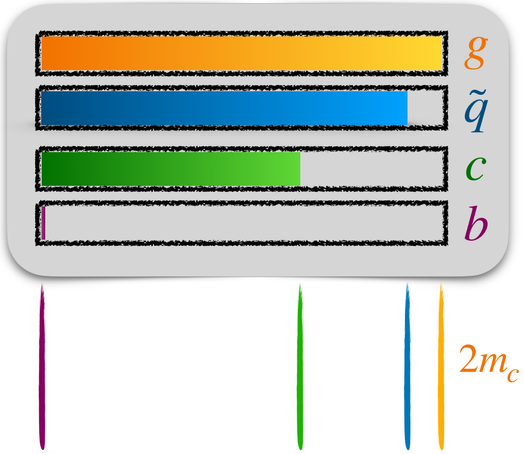
DGLAP AOevo

All-Order evolution (numeric)



DGLAP EDevo

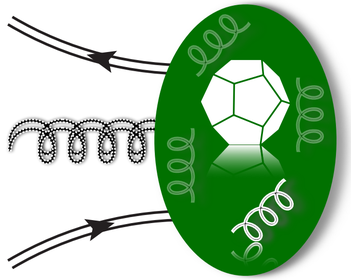
Expanded Decoupled evolution



NRQCD

LDMEs

SDCs



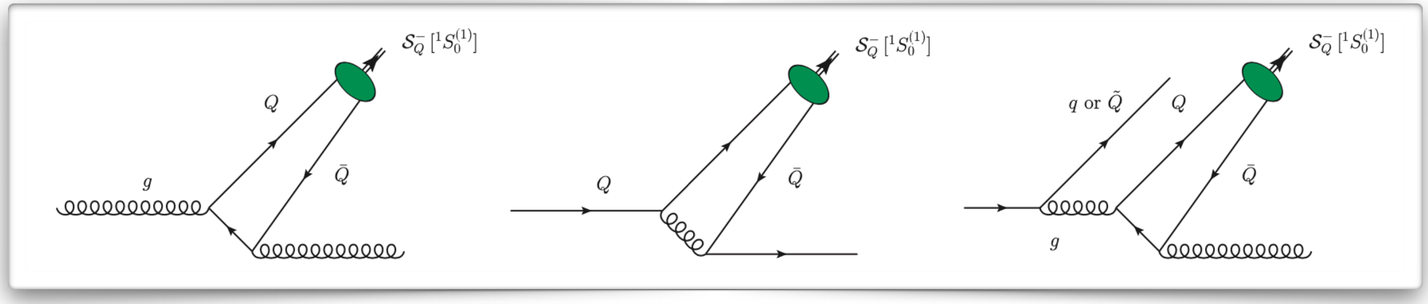
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Energy

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Time

HF-NRevo: Initial-scale NRCQD inputs



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Partonic hard factor

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All-Order evolution (numeric)

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Expanded Decoupled evolution

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SDCs

LDMEs

g
$\tilde{q}$
c
b
$2m_b$

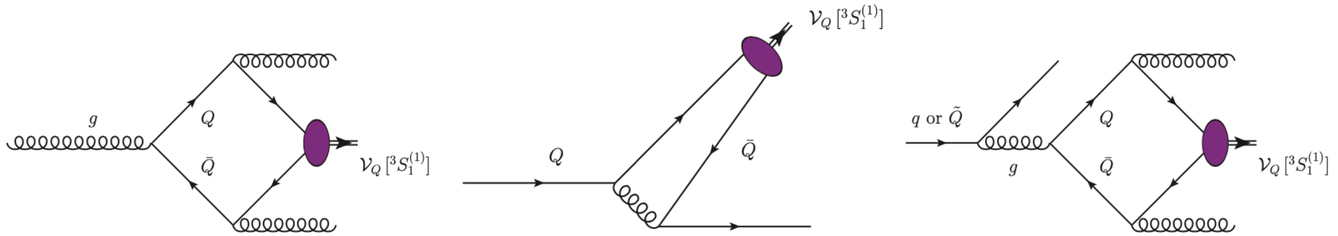
$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy

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

Time

HF-NRevo: Initial-scale NRCQD inputs



Vector J/ψ

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

Partonic hard factor

DGLAP AOevo

All-Order evolution (numeric)

DGLAP EDevo

Expanded Decoupled evolution

g
$\tilde{q}$
c
b
$2m_c$

NRQCD

SDCs

LDMEs

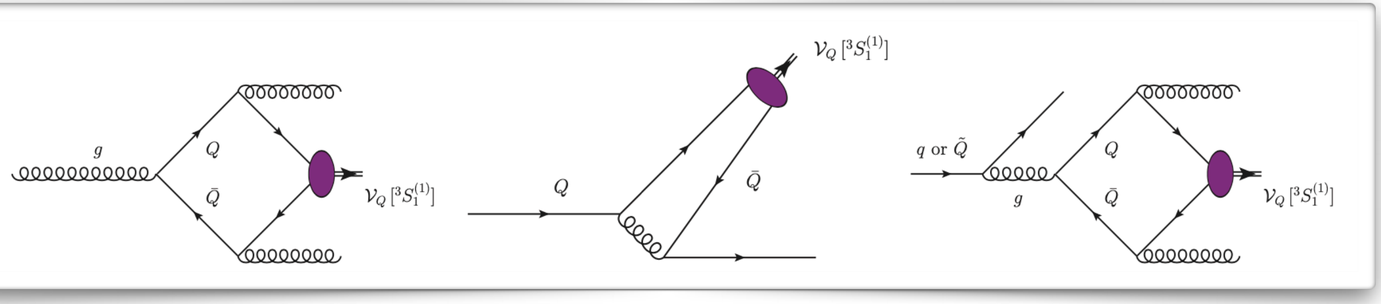
$\mathcal{D}_i^{\mathcal{Q}}(z,[n]) \otimes \langle \mathcal{O}^{\mathcal{Q}}([n]) \rangle$

Energy

Evolution-ready scale $Q_0 \equiv 3m_c$

Time

HF-NRevo: Initial-scale NRCQD inputs



Vector Υ

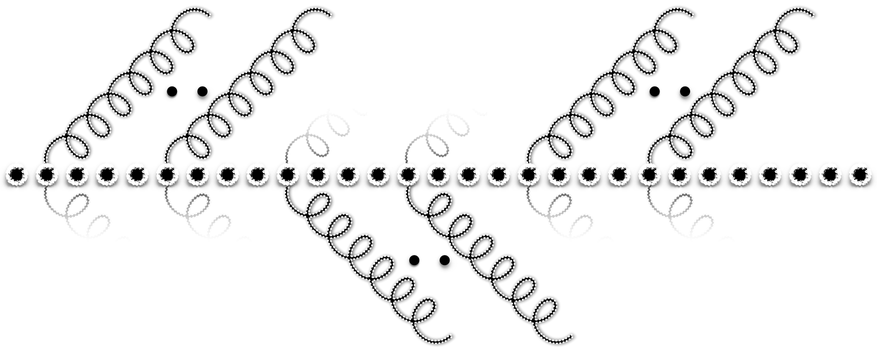
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Partonic hard factor



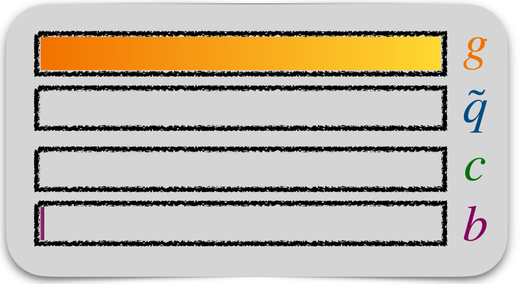
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DGLAP EDevo

Expanded Decoupled evolution

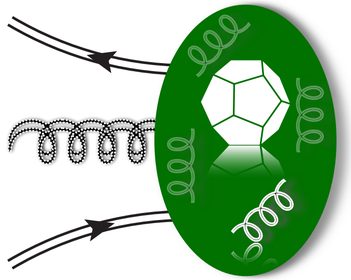


$2m_c$

NRQCD

LDMEs

SDCs



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

Energy

Evolution-ready scale $Q_0 \equiv 3m_b$

Time

Heavy-Flavor Non-Relativistic evolution

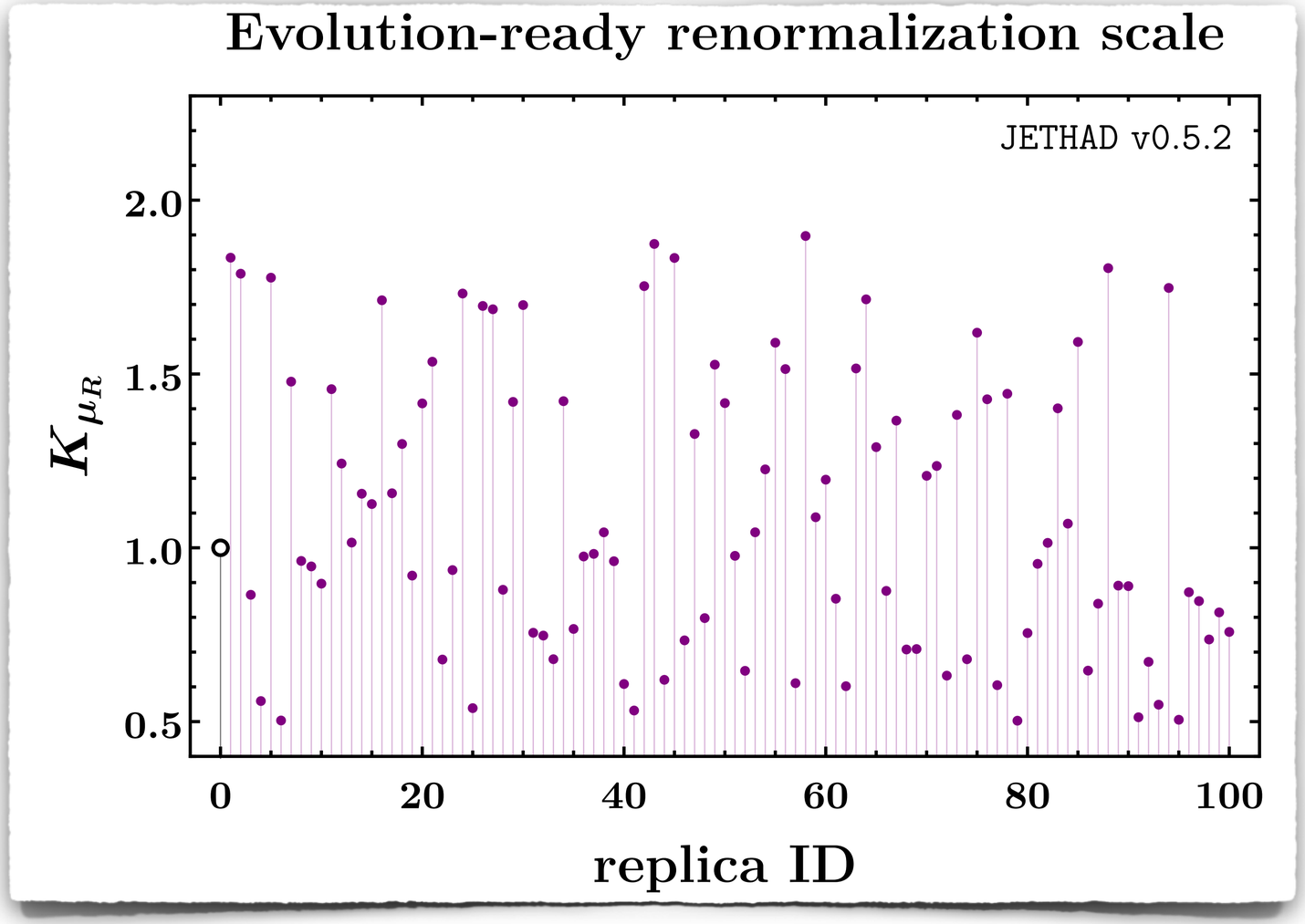
HF-NRevo

Uncertainties

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

Towards **NRFF1.0**: MHOU-replica analysis

Vector quarkonia

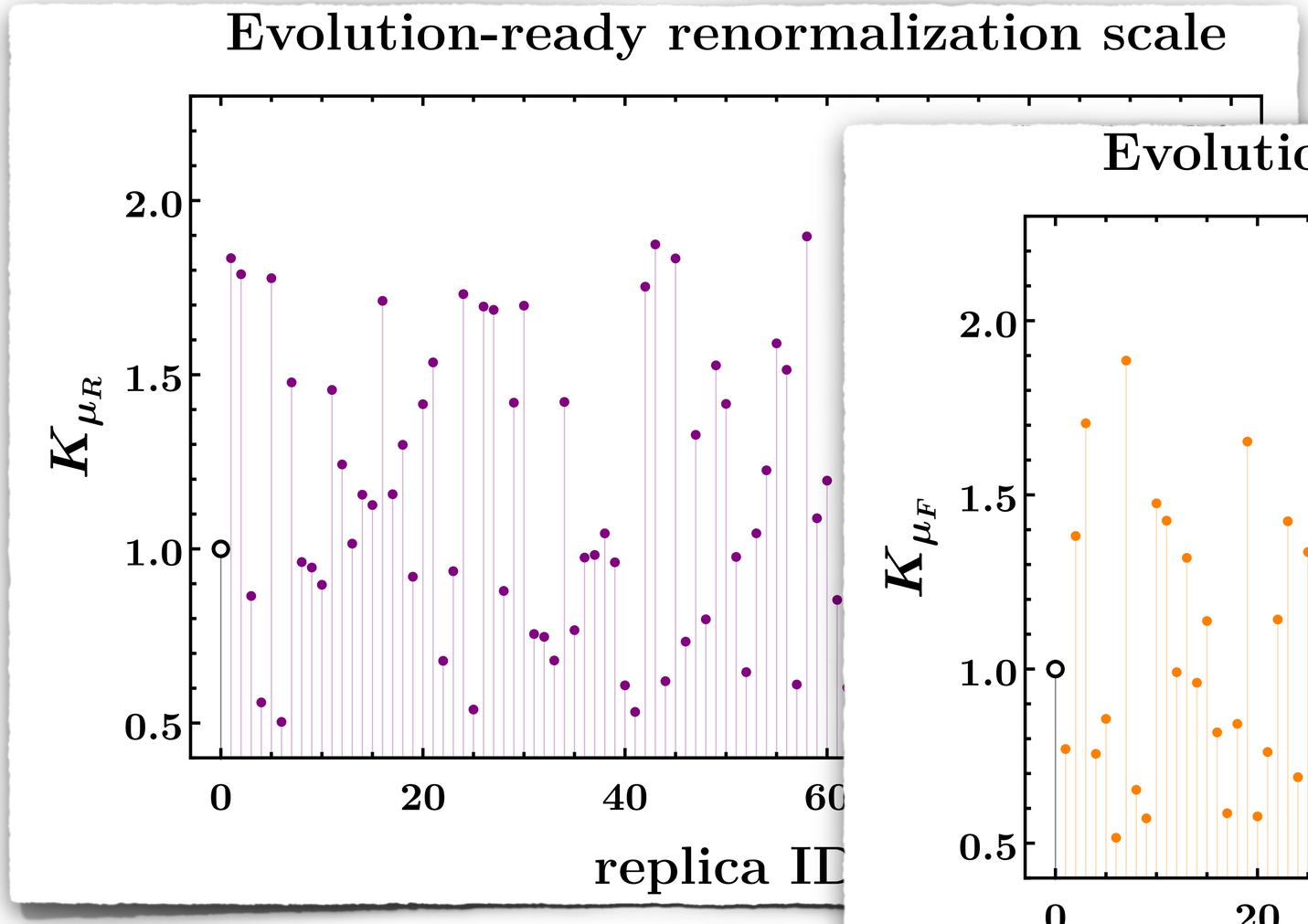


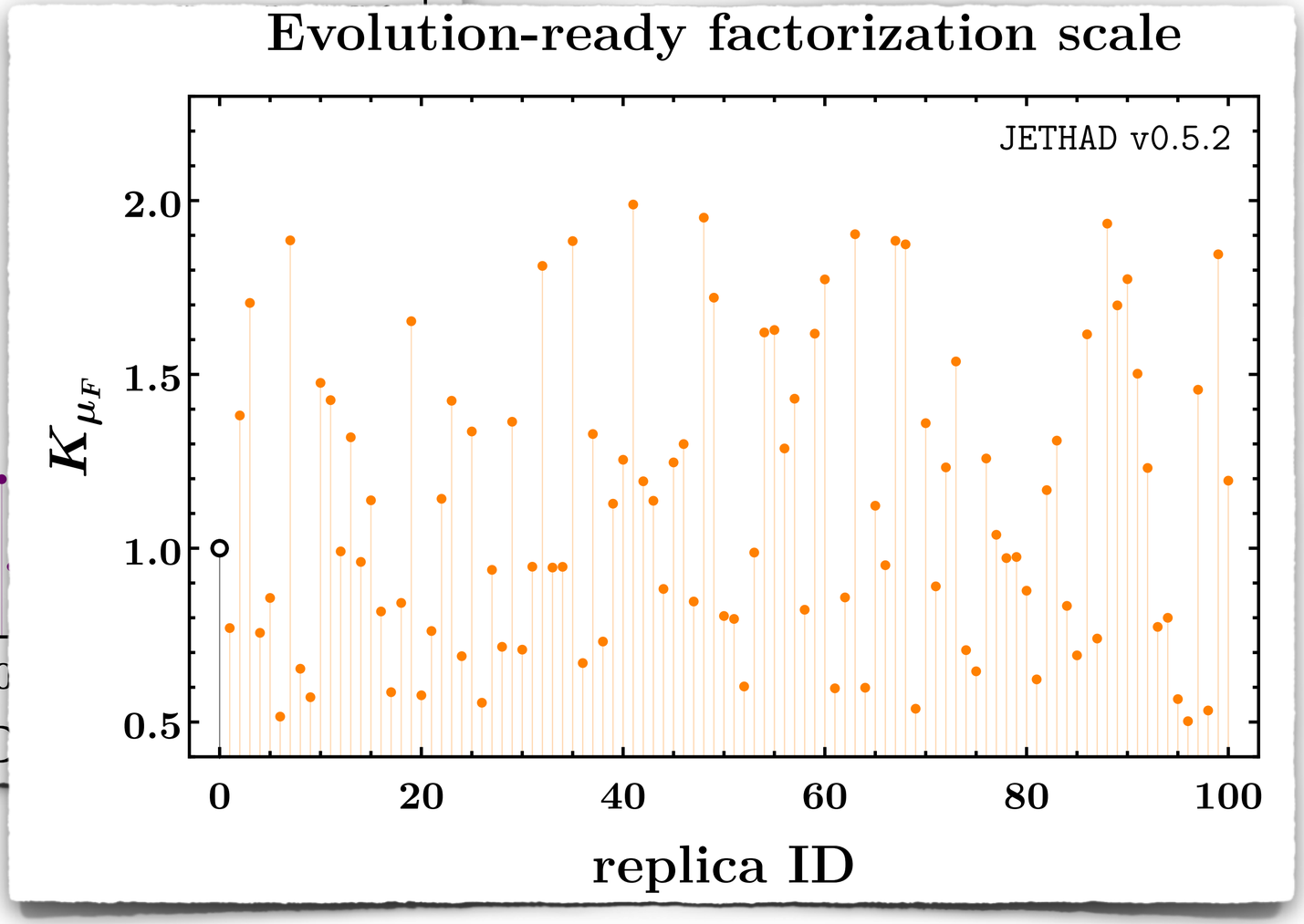
3.4 HF-NRevo: Uncertainties

[F. G. C., in preparation]

Towards **NRFF1.0**: MHOU-replica analysis

Vector quarkonia



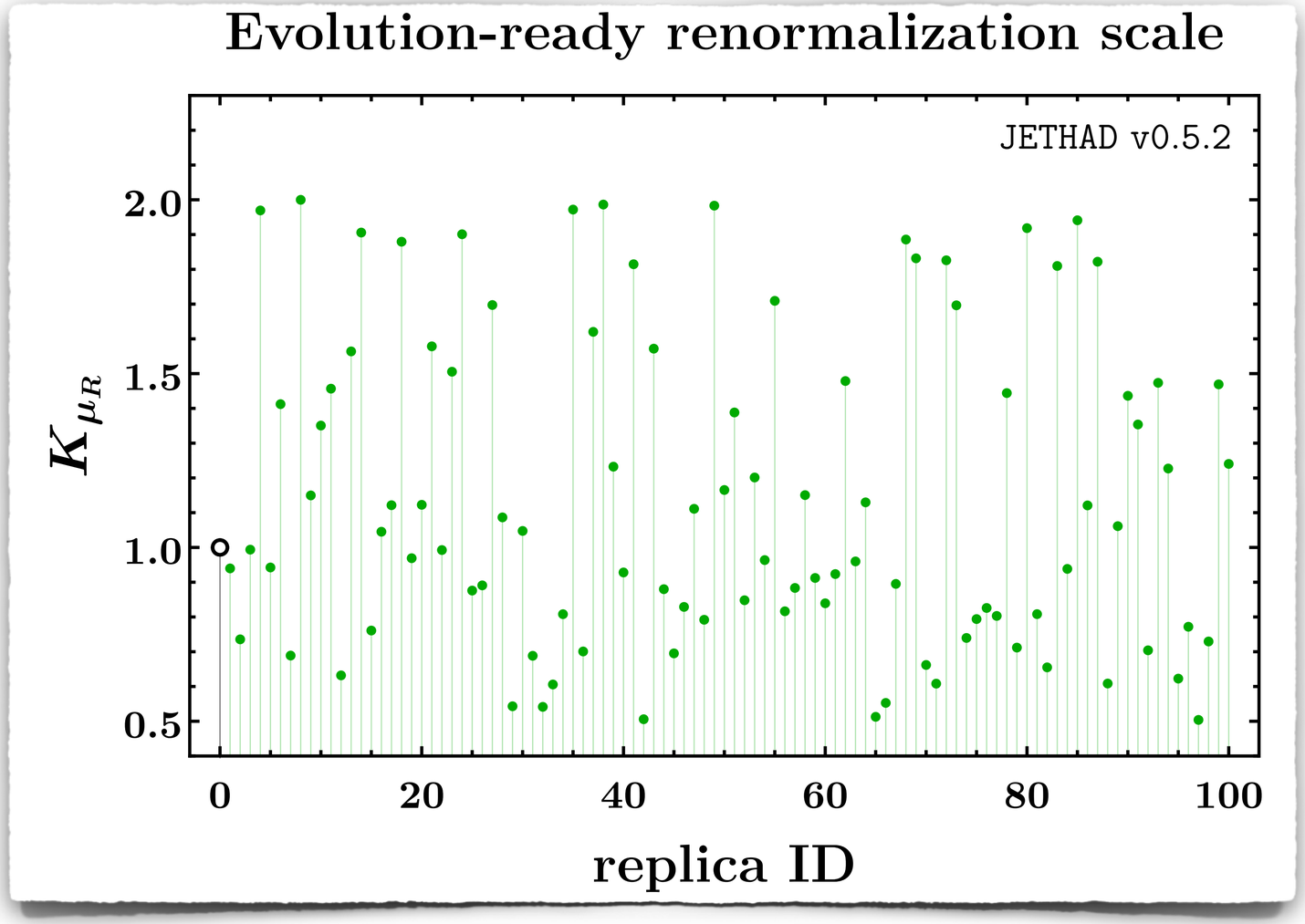


3.4 HF-NRevo: Uncertainties

[F. G. C., in preparation]

Towards **NRFF1.0**: MHOU-replica analysis

Scalar quarkonia

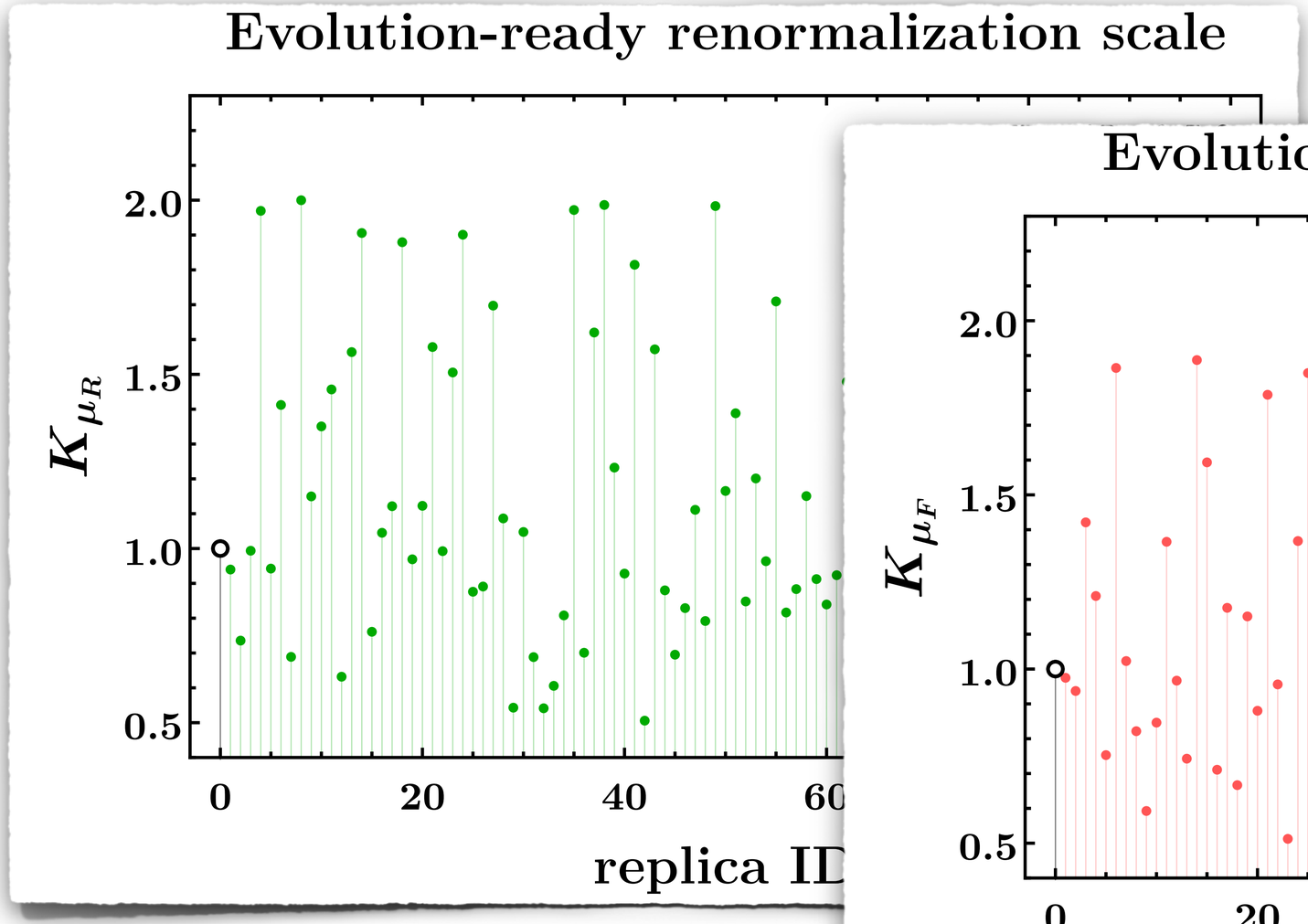


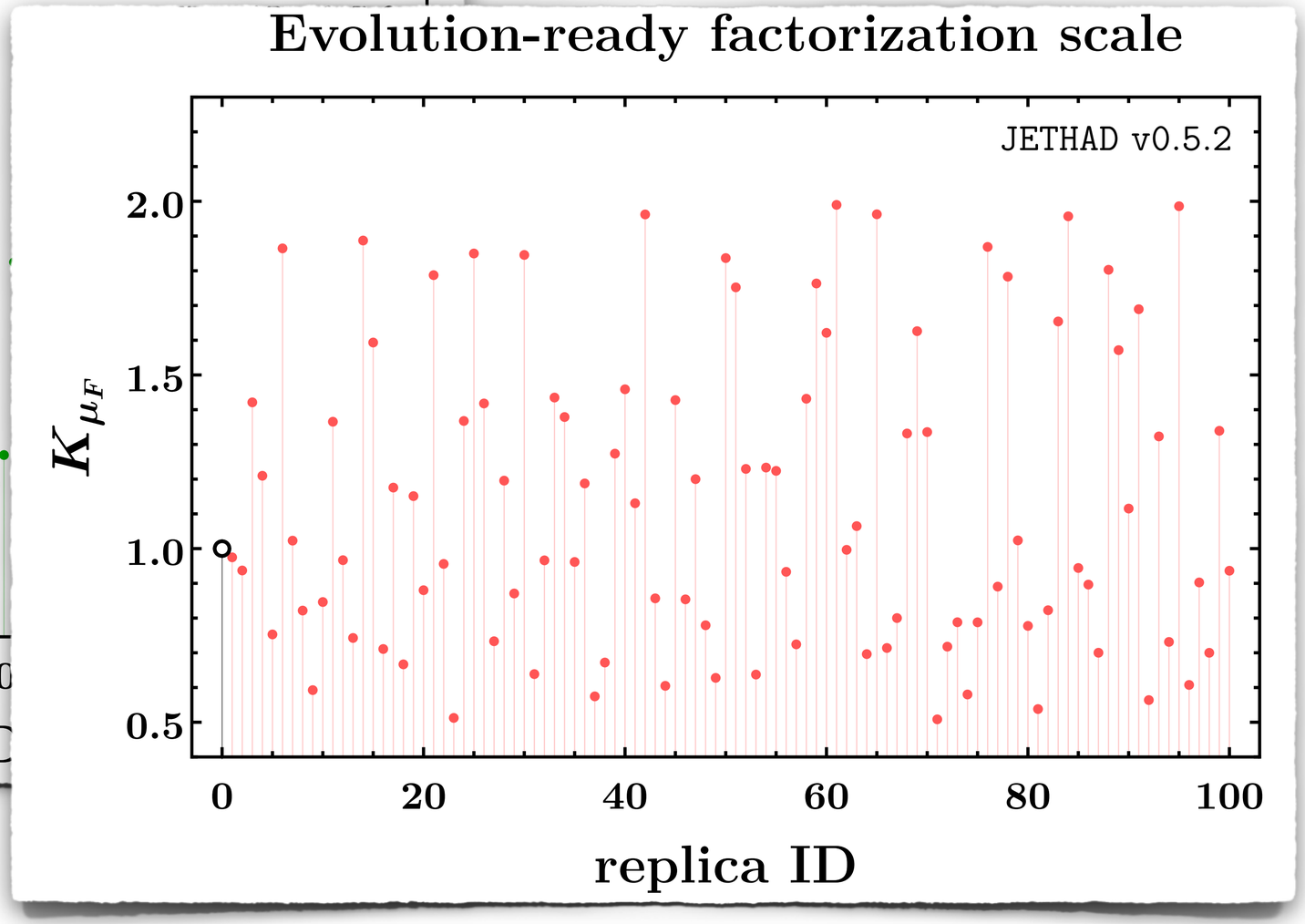
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Towards **NRFF1.0**: MHOU-replica analysis

Scalar quarkonia





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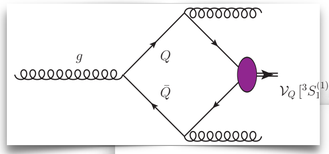
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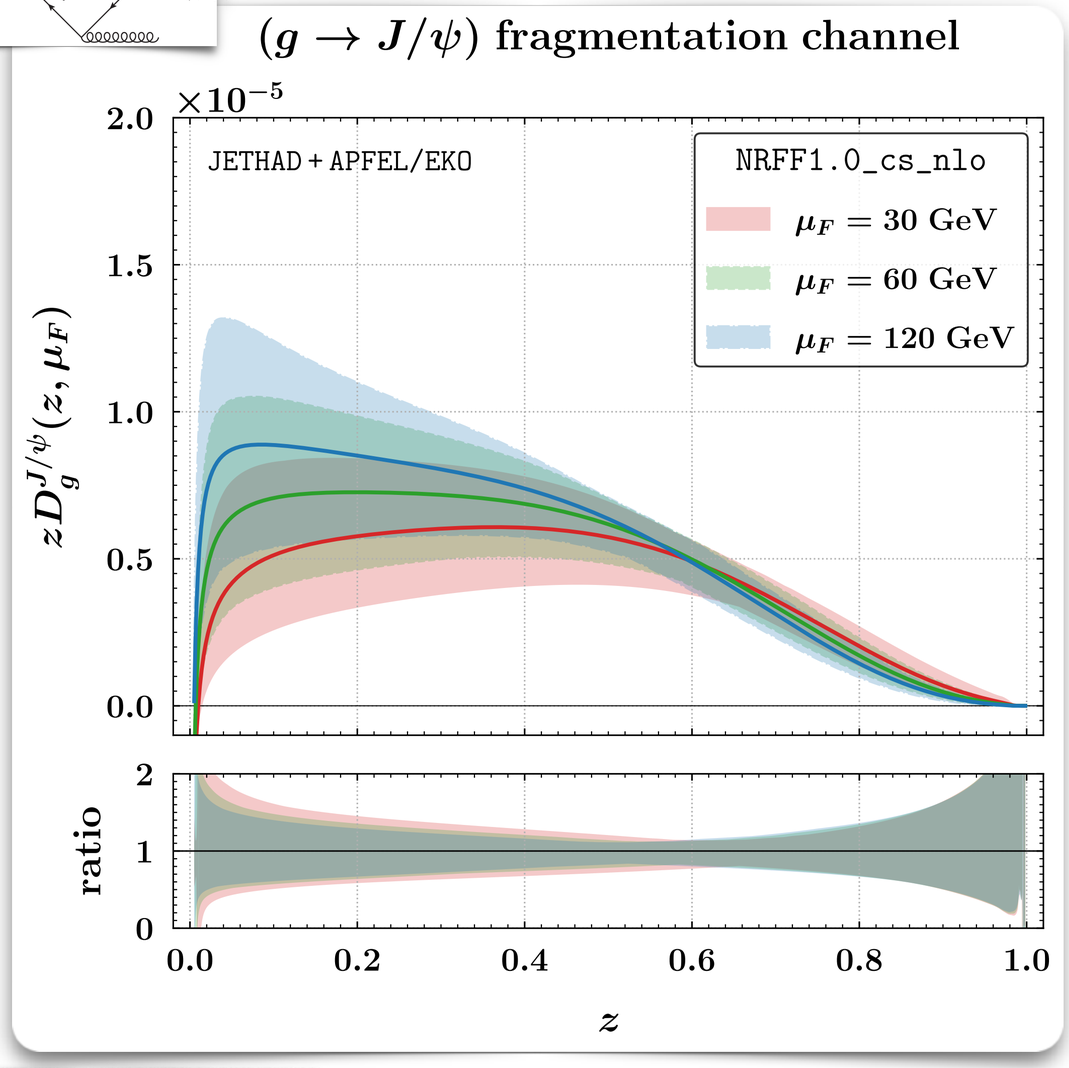
4

NRFF1.0_cs_nlo

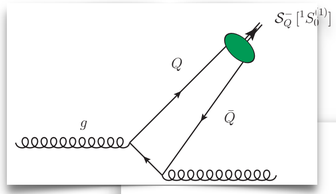
NRFF1.0: Gluon fragmentation to charmonia

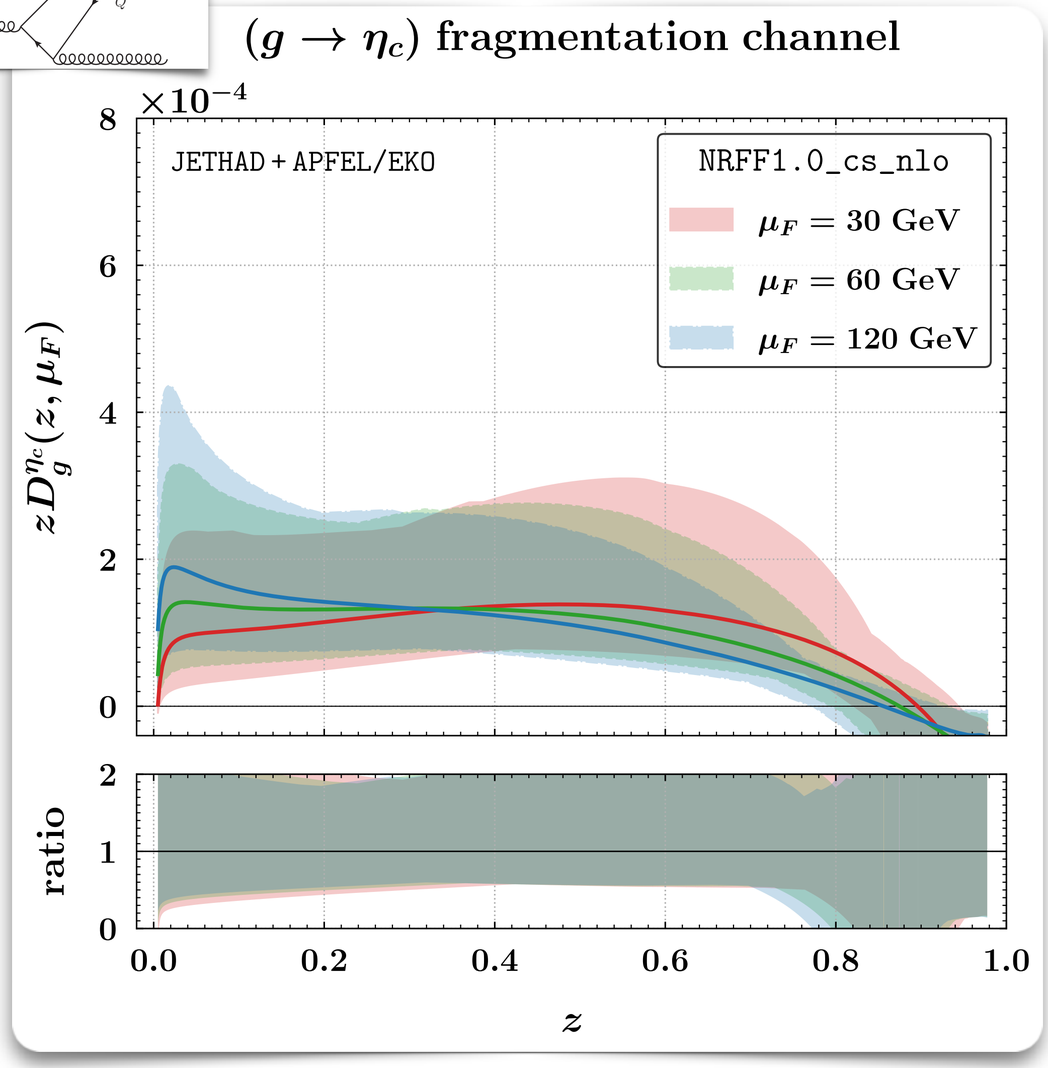
Vector J/ψ





Scalar η_c



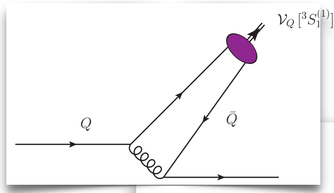


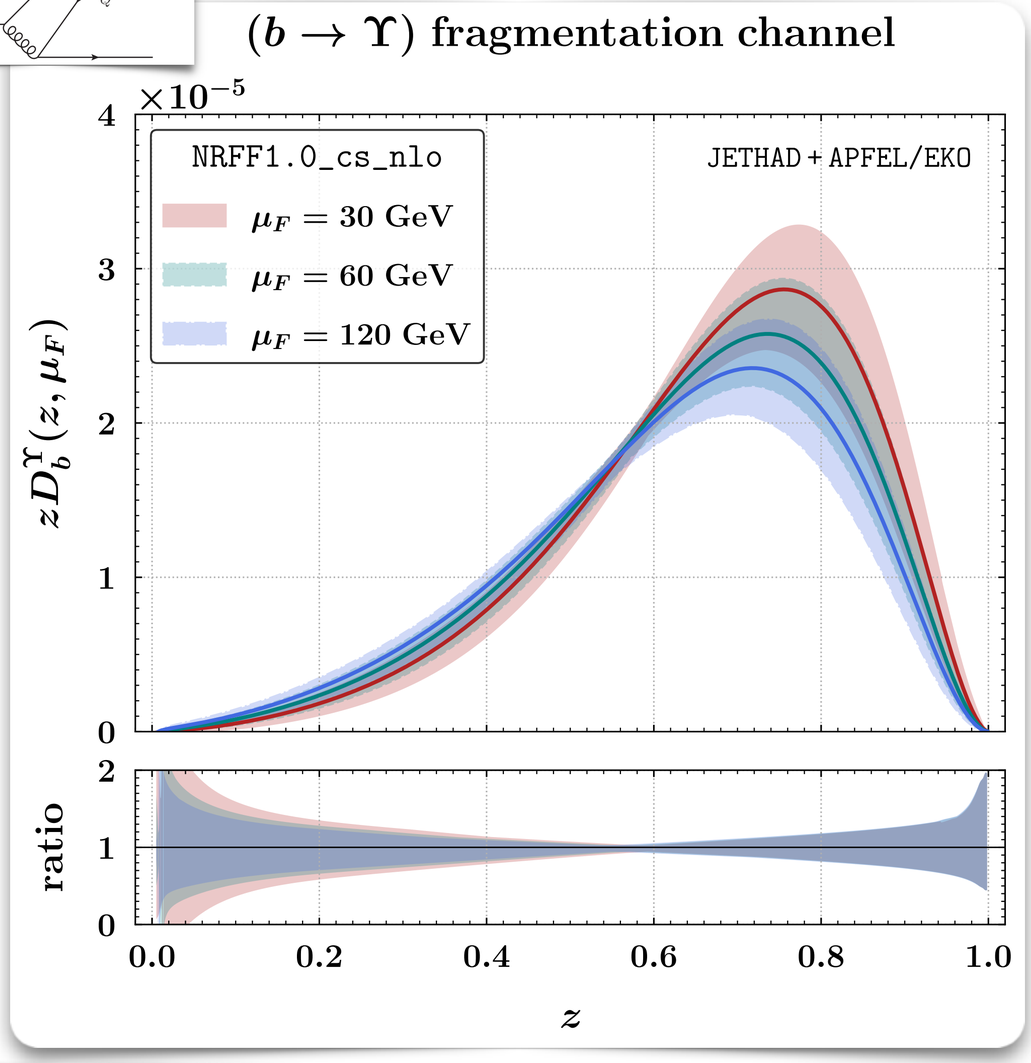
4.1 NRFF1.0 functions

[F. G. C., in preparation]

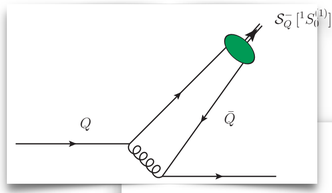
NRFF1.0: Bottom fragmentation to bottomonia

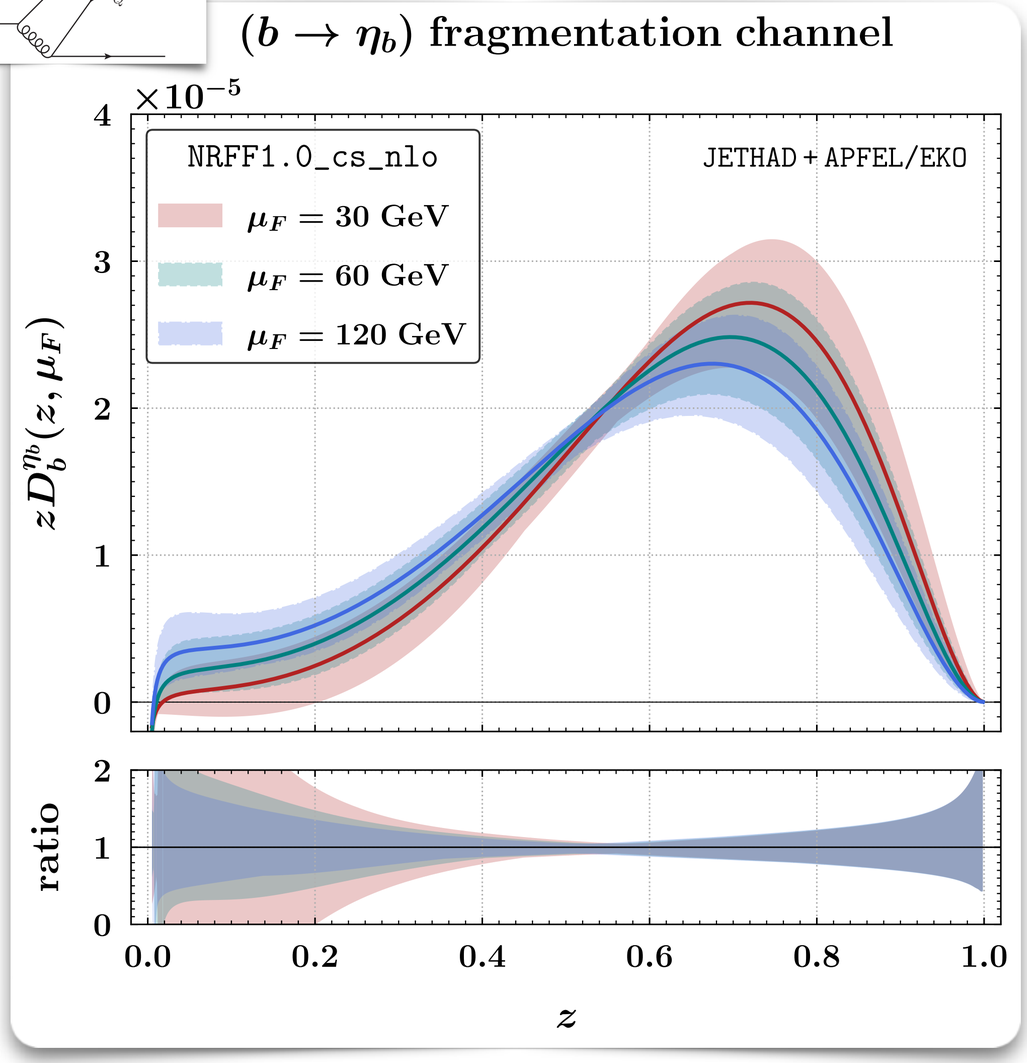
Vector Υ





Scalar η_b





4.1 NRFF1.0 functions

[F. G. C., in preparation]

From quarkonia to quarkonia in jets

TOWARDS QUARKONIUM COLLINEAR FRAGMENTATION FROM NRQCD IN A VFNS

Francesco Giovanni Celiberto, UAH Madrid

Rencontres de Moriond

2024, April 4th



24/03 to 31/03 :
- Electroweak Interactions & Unified Theories
- Very High Energy Phenomena in the Universe

31/03 - 07/04 :
- Cosmology
- QCD and High Energy Interactions

Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

ANIVERSARIO PATRIMONIO MUNDIAL

From quarkonia to quarkonia in jets

TOWARDS QUARKONIUM COLLINEAR FRAGMENTATION FROM NRQCD IN A VFNS

Francesco Giovanni



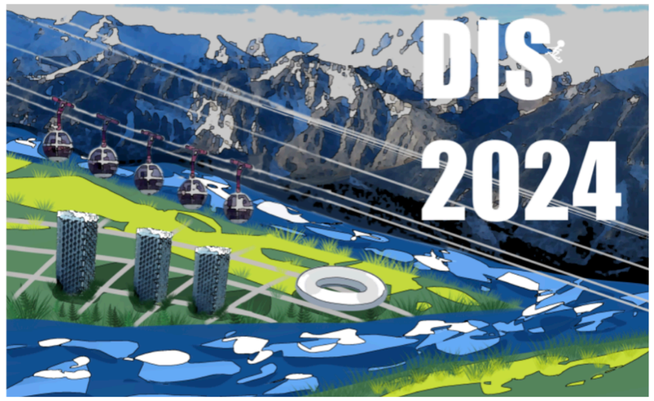


Madrid UAH

QUARKONIUM FRAGMENTATION IN A VFNS TOWARDS NRFF1.0

Francesco Giovanni Celiberto, UAH Madrid

Grenoble



2024, April 9th

Madrid UAH

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ANIVERSARIO PATRIMONIO MUNDIAL

4.2 From NRFF1.0 to NRFF1.0jet

5

Towards onium-in-jet

NRFF1.0jet

Towards **NRFF1.0jet**

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

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

5.1 Hadron-in-jet fragmentation

[F. G. C., in preparation]

Towards **NRFF1.0jet**

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

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

5.1 Hadron-in-jet fragmentation

[F. G. C., in preparation]

Towards **NRFF1.0jet**

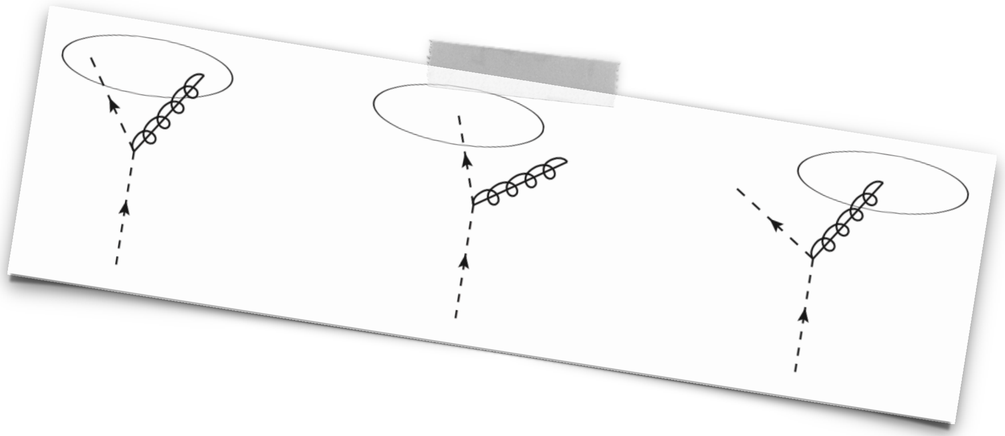
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$$z = \frac{\omega_J}{\omega}, \quad z_h = \frac{\omega_h}{\omega_J}$$

FJ coefficients ⇒ 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)



5.1 Hadron-in-jet fragmentation

[F. G. C., in preparation]

Towards **NRFF1.0jet**



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** $\Leftrightarrow$ two-step timelike DGLAP

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

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



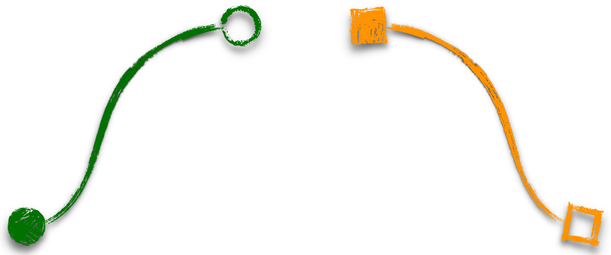
[F. G. C., in preparation]

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



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

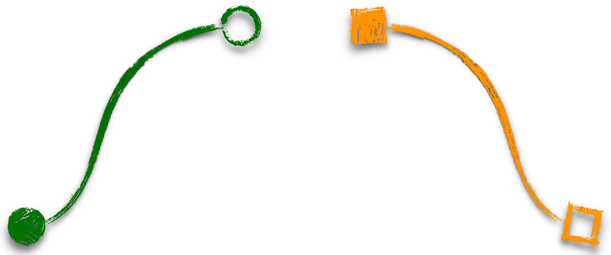
[F. G. C., in preparation]

Towards **NRFF1.0jet**

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

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

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



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

Phenomenology opportunities with quarkonium-in-jet FFs

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

5.2 Towards NRFF1.0jet

[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

Quarkonium FFs & nuclear collisions

Quarkonium FFs & nuclear collisions



Heavy-ion collisions $\Rightarrow$ medium-modified onium FFs in QGP

Quarkonium FFs & nuclear collisions



Heavy-ion collisions ⇒ medium-modified onium FFs in QGP



Jet-quenching sensitivity ⇒ parton hierarchy & energy-loss effects

Quarkonium FFs & nuclear collisions



Heavy-ion collisions ⇒ medium-modified onium FFs in QGP



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HF-NRevo ⇒ baseline for modeling in-medium hadronization

Quarkonium FFs & nuclear collisions

- Heavy-ion collisions ⇒ medium-modified onium FFs in QGP
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- **HF-NRevo** ⇒ baseline for modeling in-medium hadronization
- Onium regeneration ⇒ FF apparent-shape distortion (FF-ASD)

Quarkonium FFs & nuclear collisions

- Heavy-ion collisions ⇒ medium-modified onium FFs in QGP
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- **HF-NRevo** ⇒ baseline for modeling in-medium hadronization
- Onium regeneration ⇒ FF apparent-shape distortion (FF-ASD)

¡ Thanks for the attention !

EXTRAS

Towards **NRFF1.0jet**: Fragmenting Jet Coefficients

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

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

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

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

Towards **NRFF1.0jet**: Fragmenting Jet Coefficients

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

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

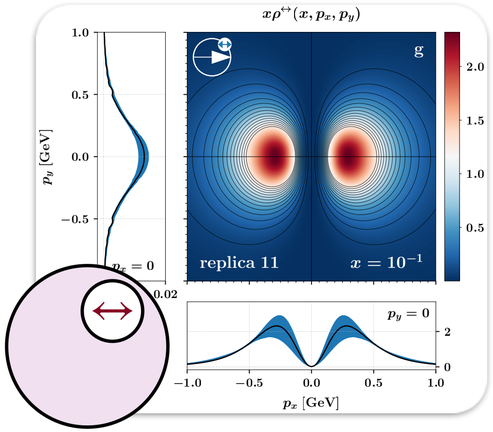
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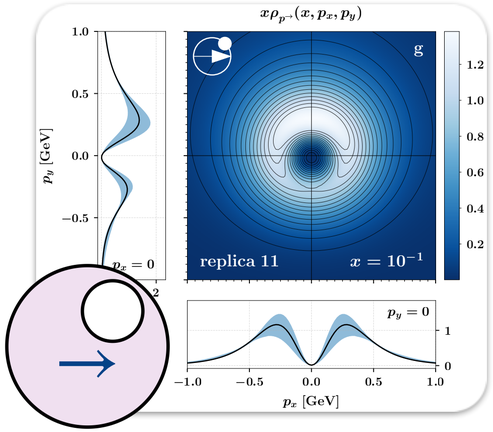
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Quarkonium studies: Assets & Challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs

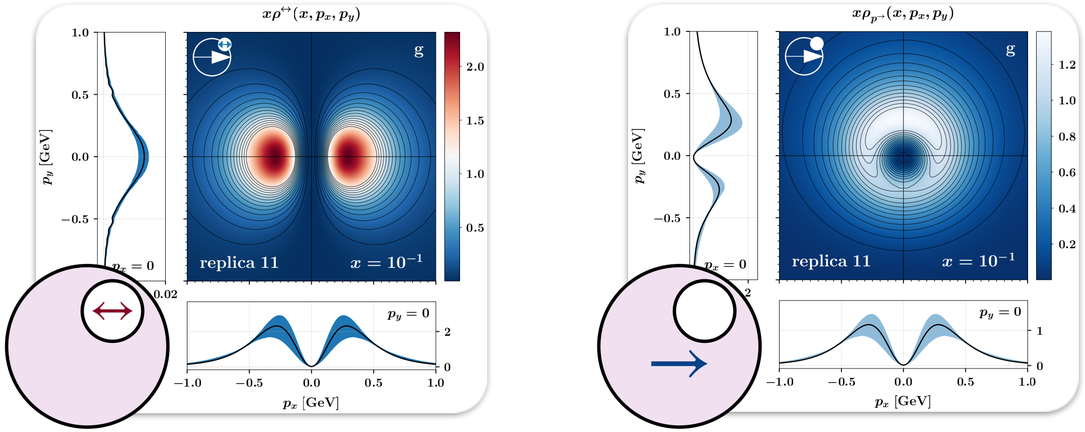




Quarkonium studies: Assets & Challenges

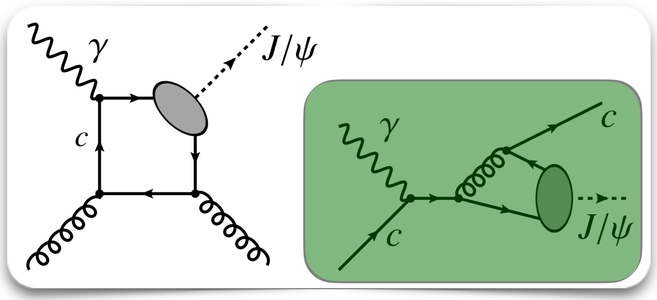
Assets

Onia ⇒ clean channels of f-type gluon TMDs



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

EIC studies:
large x
moderate to large p_T

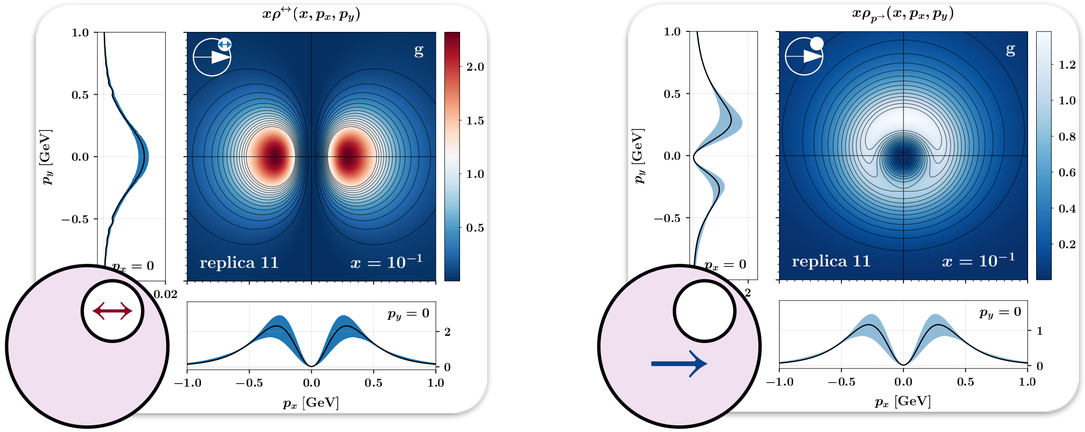


(polarized gluon TMDs) 🔗 [A. Bacchetta, F. G. C., M. Radici (2024)]
(J/ψ @EIC) 🔗 [C. Flore, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina (2020)]
(Intrinsic Charm + valence) studies 🔗🔗 [NNPDF Collaboration (2022, 2023)]

Quarkonium studies: Assets & Challenges

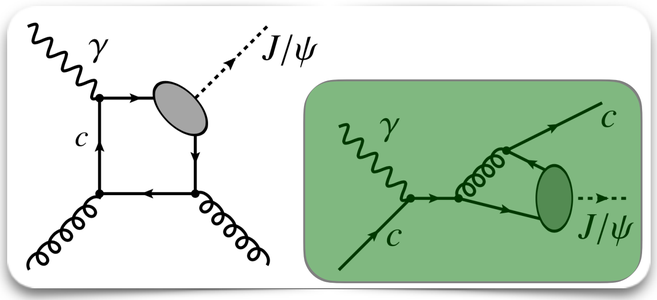
Assets

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Challenges

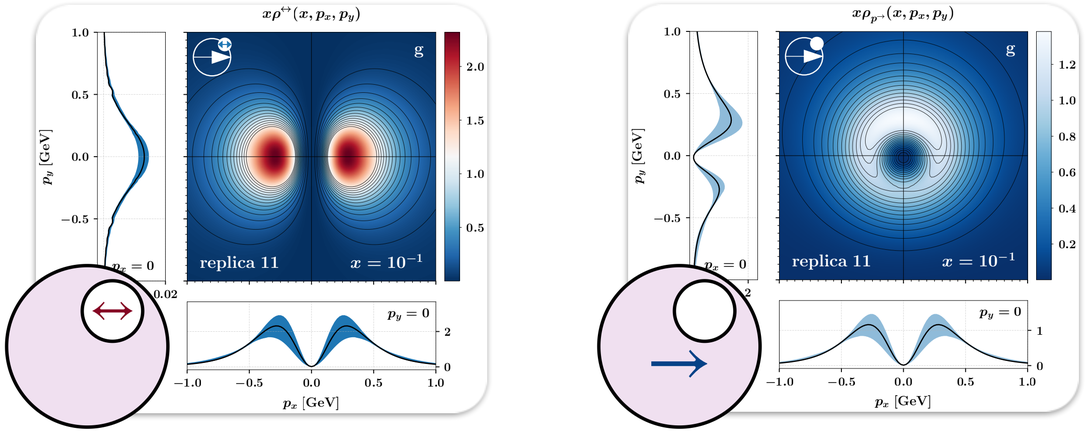
Precision level ⇔ production mechanism(s)

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

Quarkonium studies: Assets & Challenges

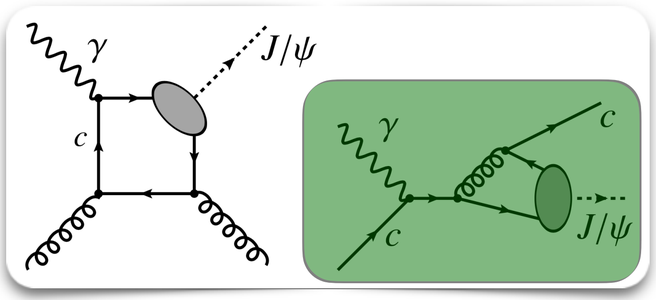
Assets

Onia ⇒ clean channels of f-type gluon TMDs



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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
Polarization effects genuinely missed
Wrong photo- vs hadroproduction universality

Color Singlet Model

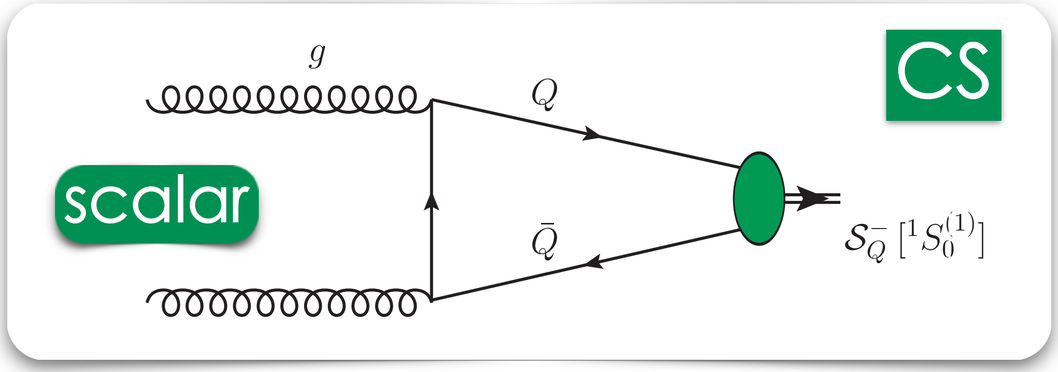
$(Q\bar{Q})$ to onium, no gluon emissions
Infrared divergences at NLO in P-wave decays
Fails at large p_T, improves at NLO

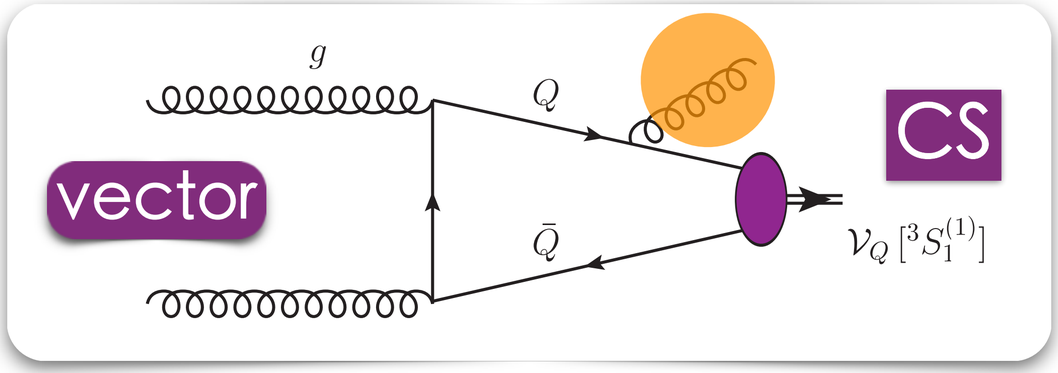
NRQCD and Color Octet

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



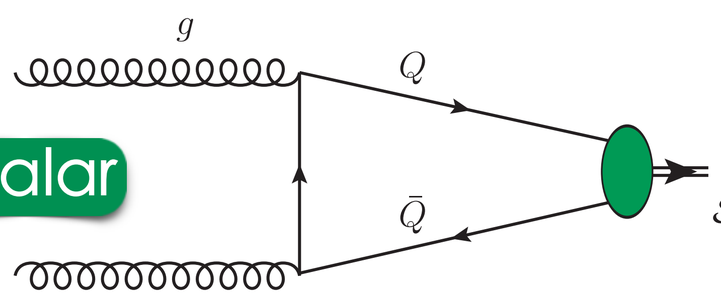


Extra gluon due to Landau-Yang selection rule

From low energies to high energies

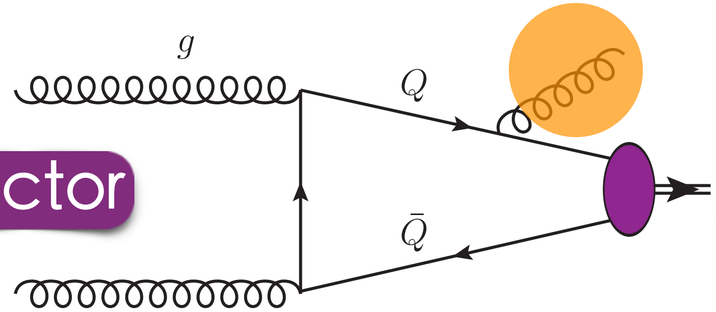
Low energy, low p_T
Short-distance production

scalar



CS

vector

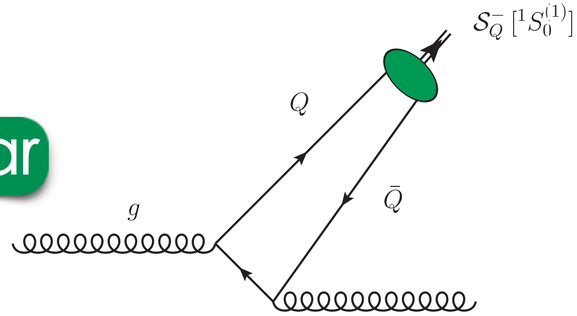


CS

(charmonia)

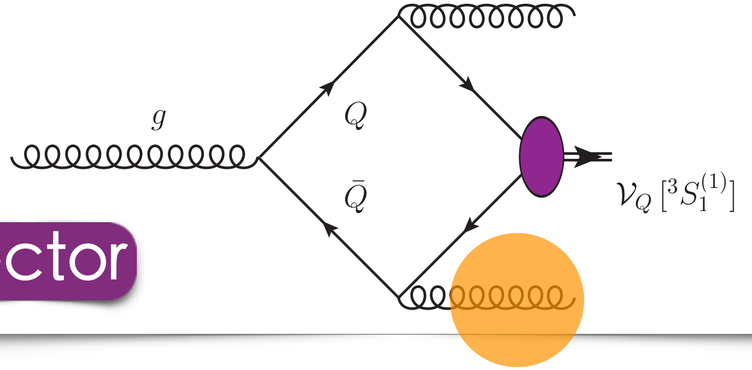
High energy, high p_T
Single-parton fragmentation

scalar



CS

vector



CS

Extra gluon due to Landau-Yang selection rule

HF-NRevo: Initial-scale NRCQD inputs

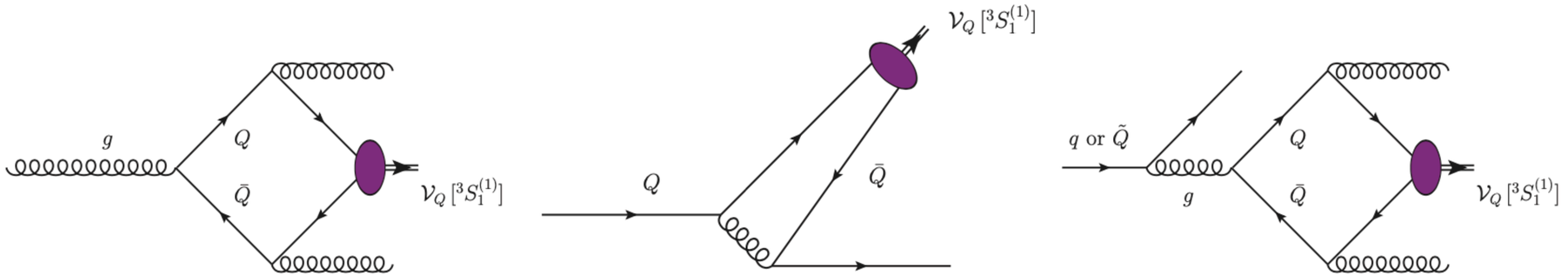


Fig. 1 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{V}_Q\,[^3S_1^{(1)}]$ at $\mathcal{O}(\alpha_s^3)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet vector quarkonium $\mathcal{V}_Q\,[^3S_1^{(1)}]$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

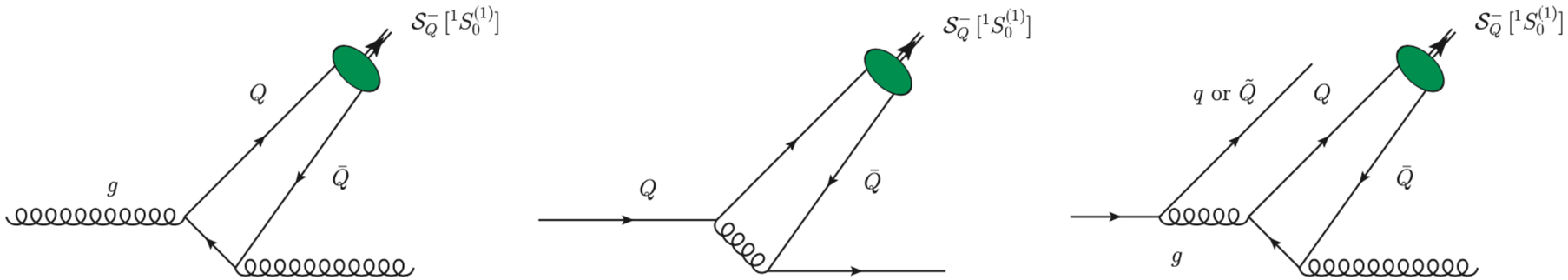
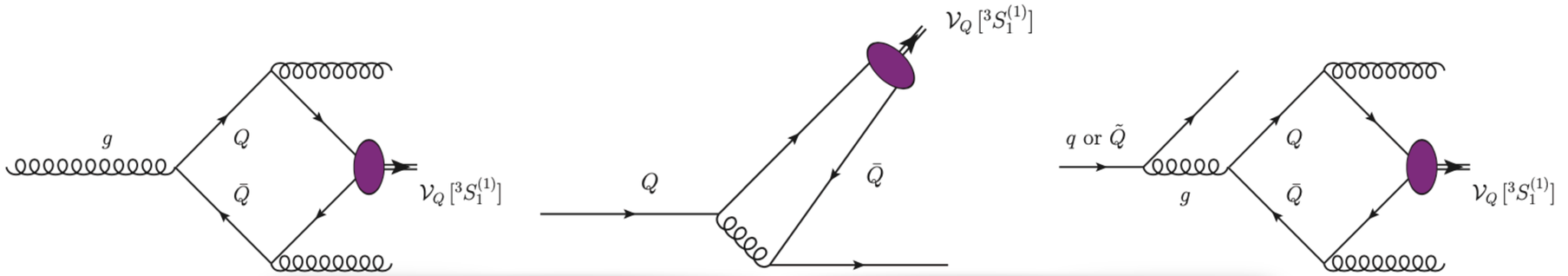


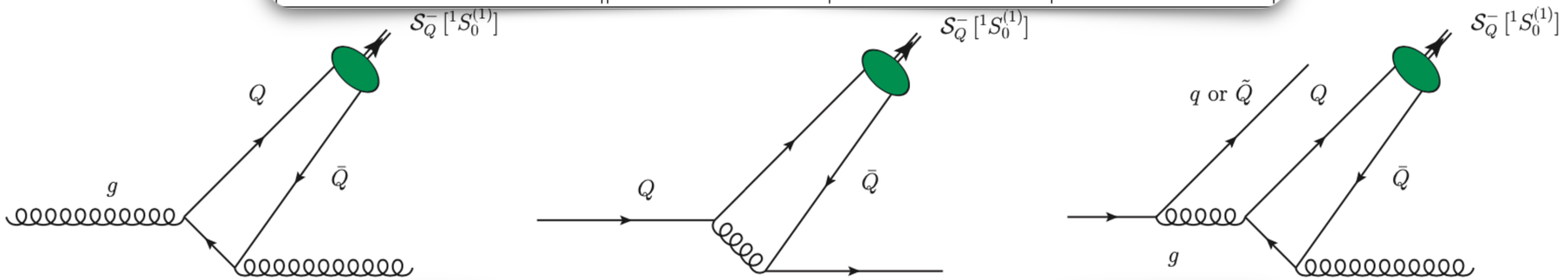
Fig. 2 Left panel: a leading diagram for the fragmentation of a gluon to $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ at $\mathcal{O}(\alpha_s^2)$. Central panel: one of the leading diagrams for the fragmentation of a constituent heavy quark (Q) to a S-wave color singlet pseudoscalar quarkonium $\mathcal{S}_Q^-\,[^1S_0^{(1)}]$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



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
	⋮	⋮	⋮

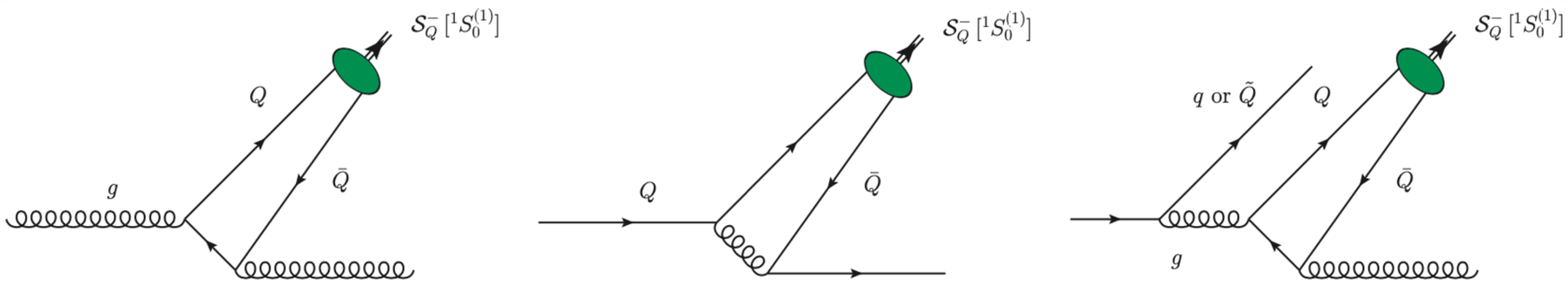


$\mathcal{Q} \equiv \mathcal{S}_Q^-\,[^3S_1^{(1)}] \equiv \eta_c, \eta_b$	$\mathcal{O}(\alpha_s^2) \equiv$ LO	$\mathcal{O}(\alpha_s^2) \equiv$ LO	–
	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	$\mathcal{O}(\alpha_s^3) \equiv$ NLO	$\mathcal{O}(\alpha_s^3) \equiv$ NLO
	$\mathcal{O}(\alpha_s^4) \equiv$ NNLO	$\mathcal{O}(\alpha_s^4)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

[F. G. C., in preparation]

HF-NRevo: Initial-scale NRCQD inputs

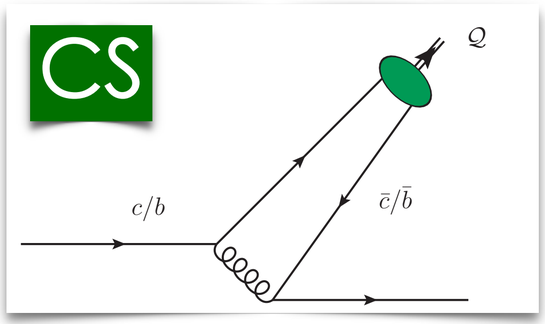
$\mathcal{S}_Q^-\,[^1S_0^{(1)}]$ quarkonium	$\mu_{F,0}(g \to \mathcal{S}_Q^-)$	$\mu_{F,0}(d,u,s \to \mathcal{S}_Q^-)$	$\mu_{F,0}(Q \to \mathcal{S}_Q^-)$	$\mu_{F,0}(\tilde{Q} \to \mathcal{S}_Q^-)$	$Q_0 \equiv \max(\{\mu_{F,0}\})$
η_c	$2m_c$	$m_{d,u,s} + 2m_c$	$3m_c$	$m_b + 2m_c$	$m_b + 2m_c$
η_b	$2m_b$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



[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*** !



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

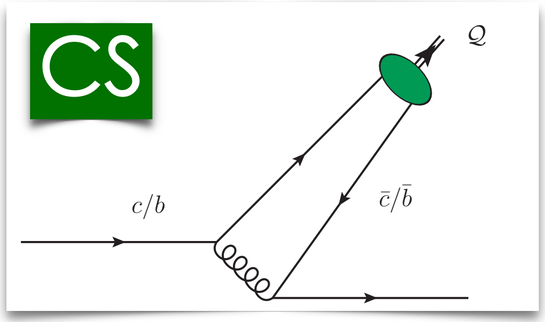
$(\mathcal{Q} \to \bar{\mathcal{Q}}\,\mathcal{Q})$ at $\mu_0 = 3m_{\mathcal{Q}}$

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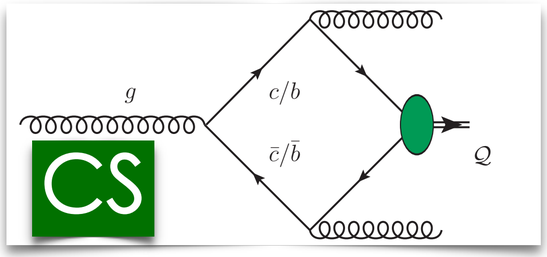
$$D_{\mathcal{Q}}^{\mathcal{Q}}(z,\mu_F \equiv \mu_0) = D_{\mathcal{Q}}^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3}\,|\mathcal{R}_{\mathcal{Q}}(0)|^2\,\Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

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

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

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$$D_g^{\mathcal{Q}}(z,2m_Q) = \frac{5}{36(2\pi)^2}\alpha_s^3(2m_Q)\frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_{\mathcal{Q}}^3}\int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2}$$

$$\sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau)\frac{1+\xi-2\tau}{2(\tau-\xi)\sqrt{\tau^2-\xi}} \ln\left(\frac{\tau-\xi+\sqrt{\tau^2-\xi}}{\tau-\xi-\sqrt{\tau^2-\xi}}\right)\right],$$

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

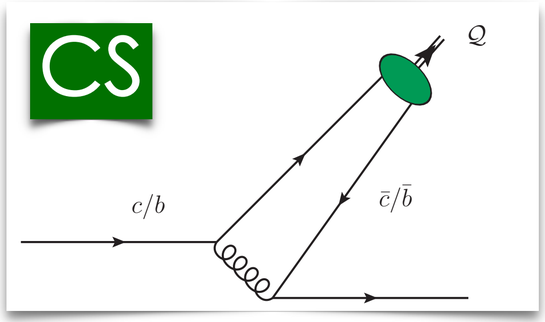
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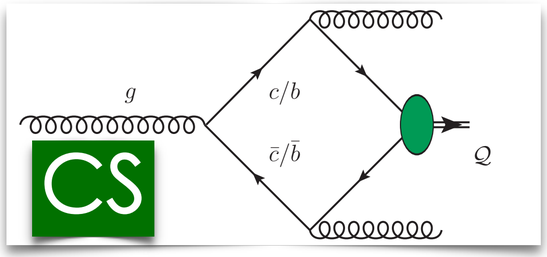


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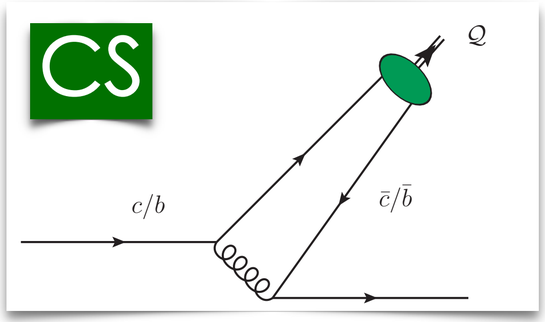
NRFF1.0
quarkonium FFs

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APFEL++/EKO

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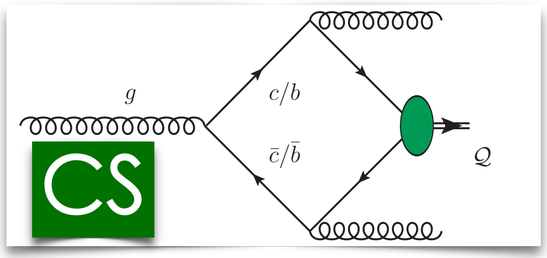


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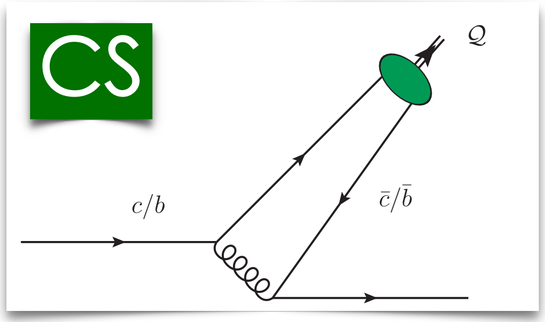
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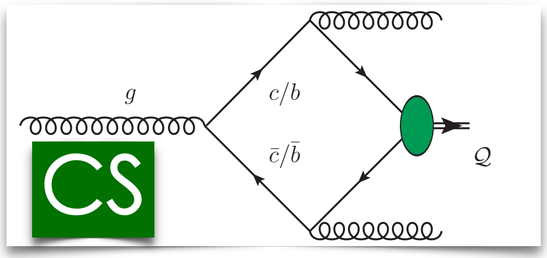


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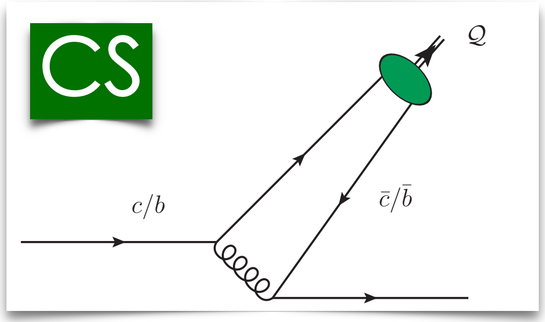
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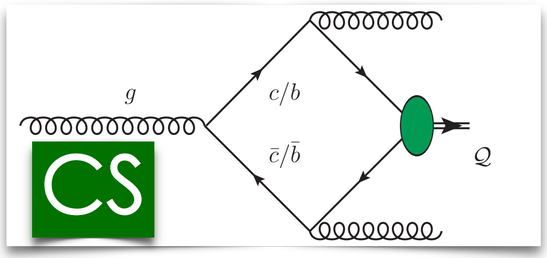
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quarkonium FFs

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Towards NRFF1.0: ¿ A connection with MCscales ?

JHEP

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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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ArXiv ePrint: 2207.07616

JHEP03(2023)148

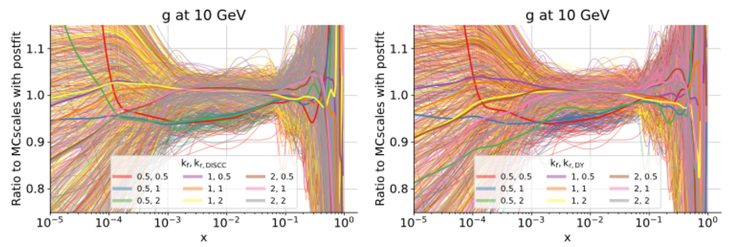


Figure 4. PDF replicas of the **MCscales with postfit** set, for the gluon at $Q = 10\,\mathrm{GeV}$. Each replica is coloured according to its scale choice, where the numbers in the legend correspond to (k_f, k_r), where k_r corresponds to the renormalisation scale for the DIS CC predictions (left panel) 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 $Q = 10\,\mathrm{GeV}$. 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, $x \lessapprox 10^{-4}$ 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.

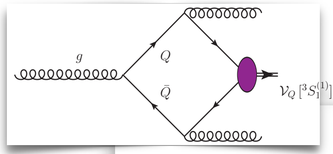
A discussion concerning the comparison with the PDFs obtained in refs. [21, 22] using

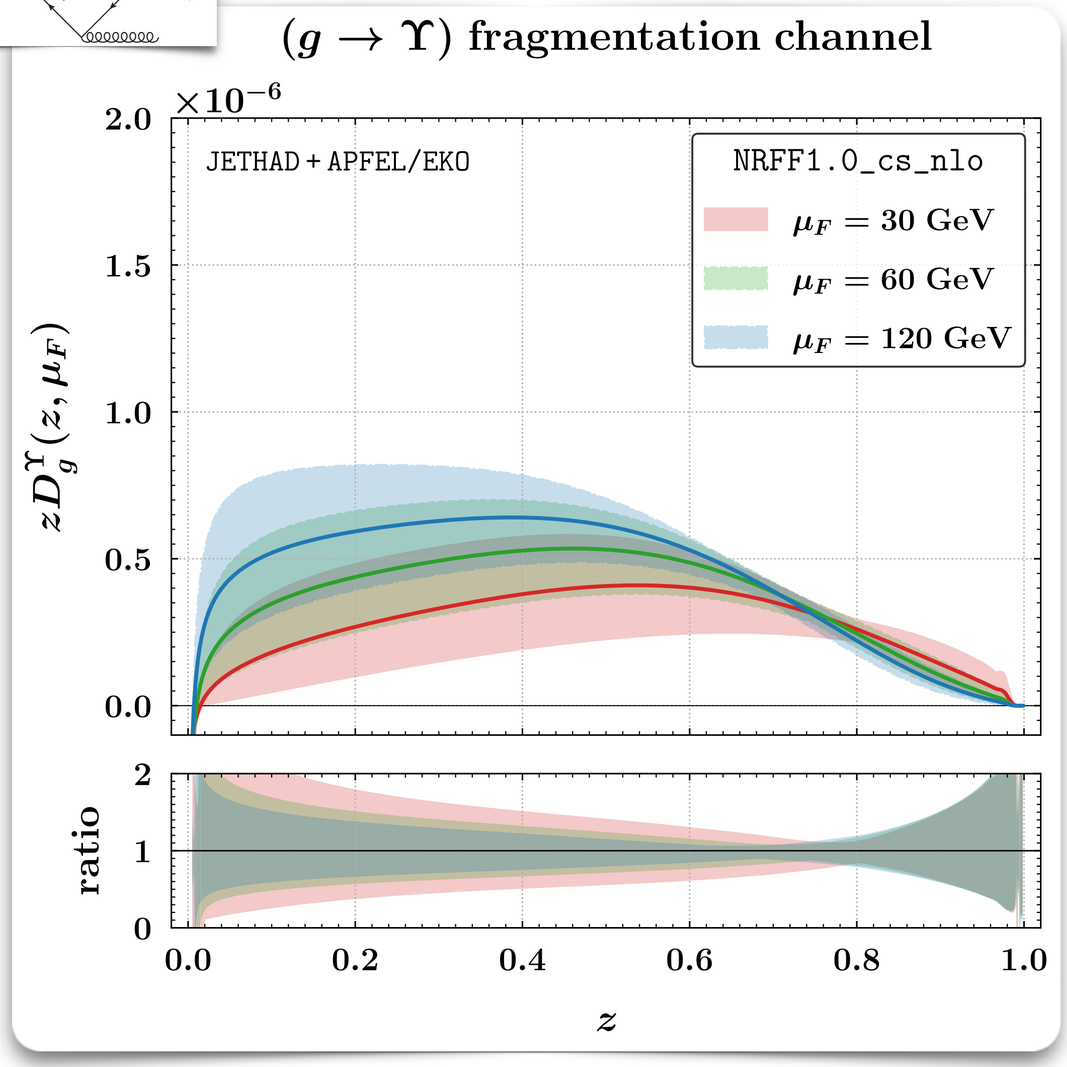
JHEP03(2023)148

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

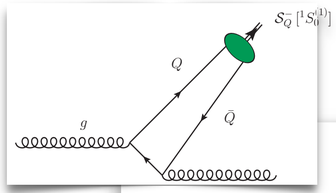
NRFF1.0: Gluon fragmentation to bottomonia

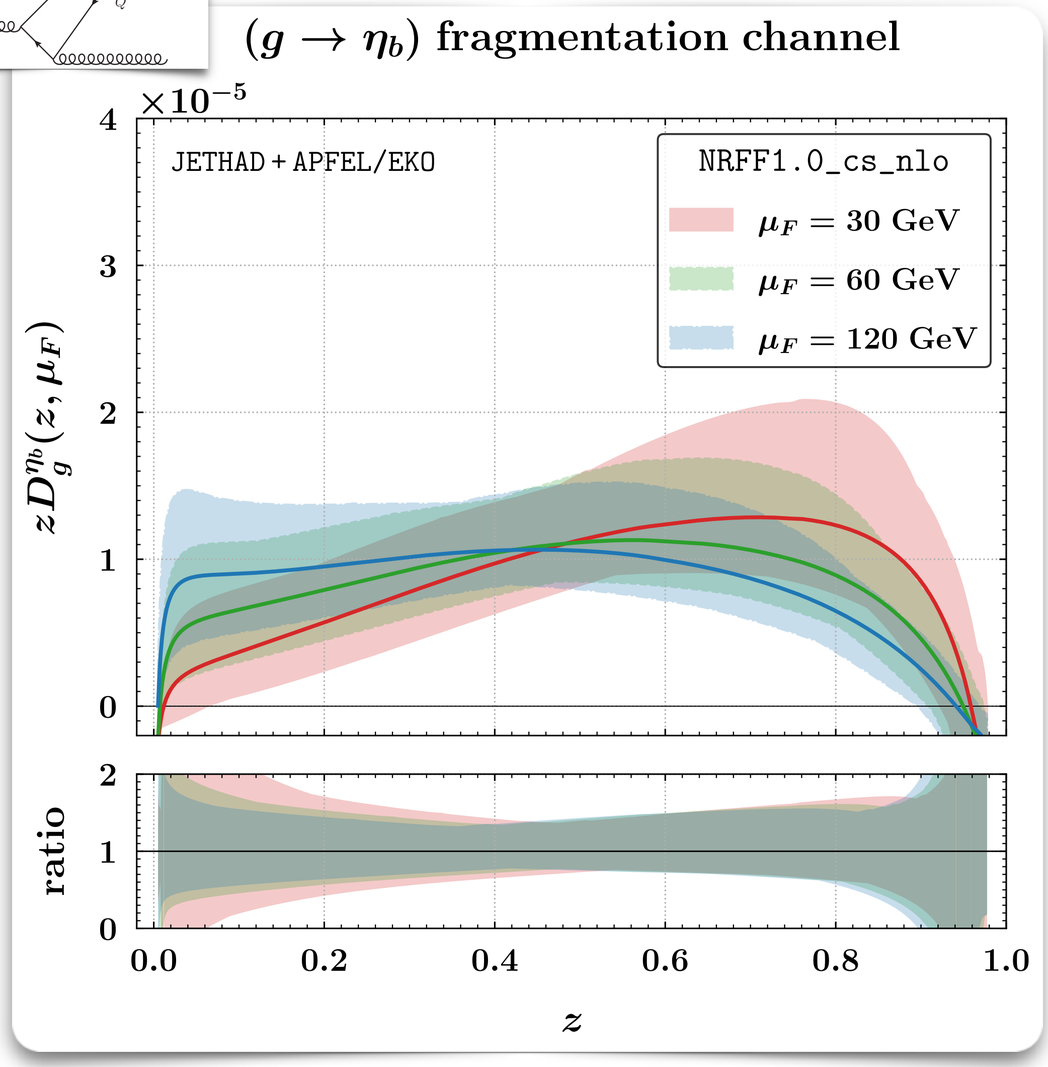
Vector Υ





Scalar η_b

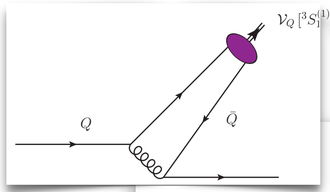


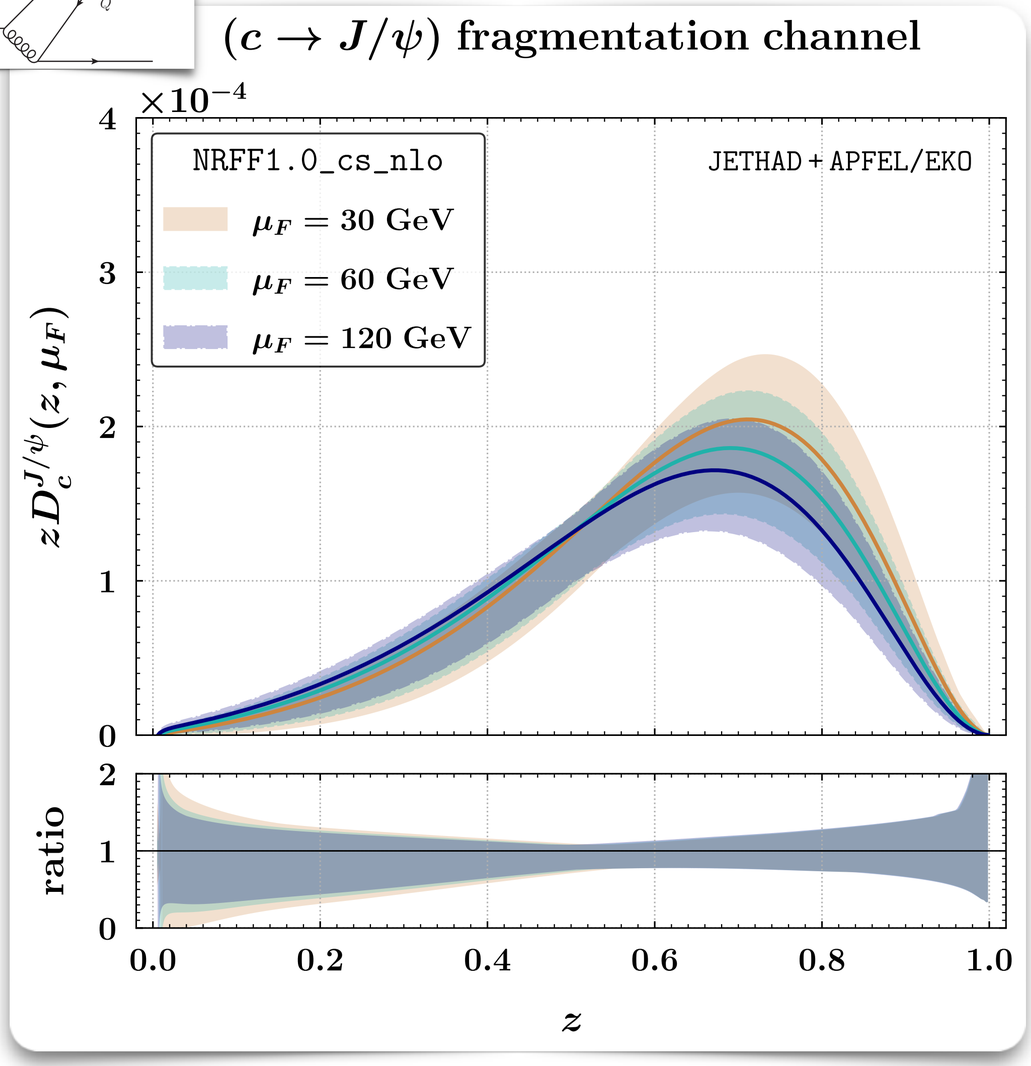


[F. G. C., in preparation]

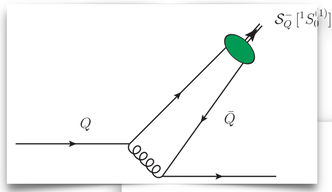
NRFF1.0: Charm fragmentation to charmonia

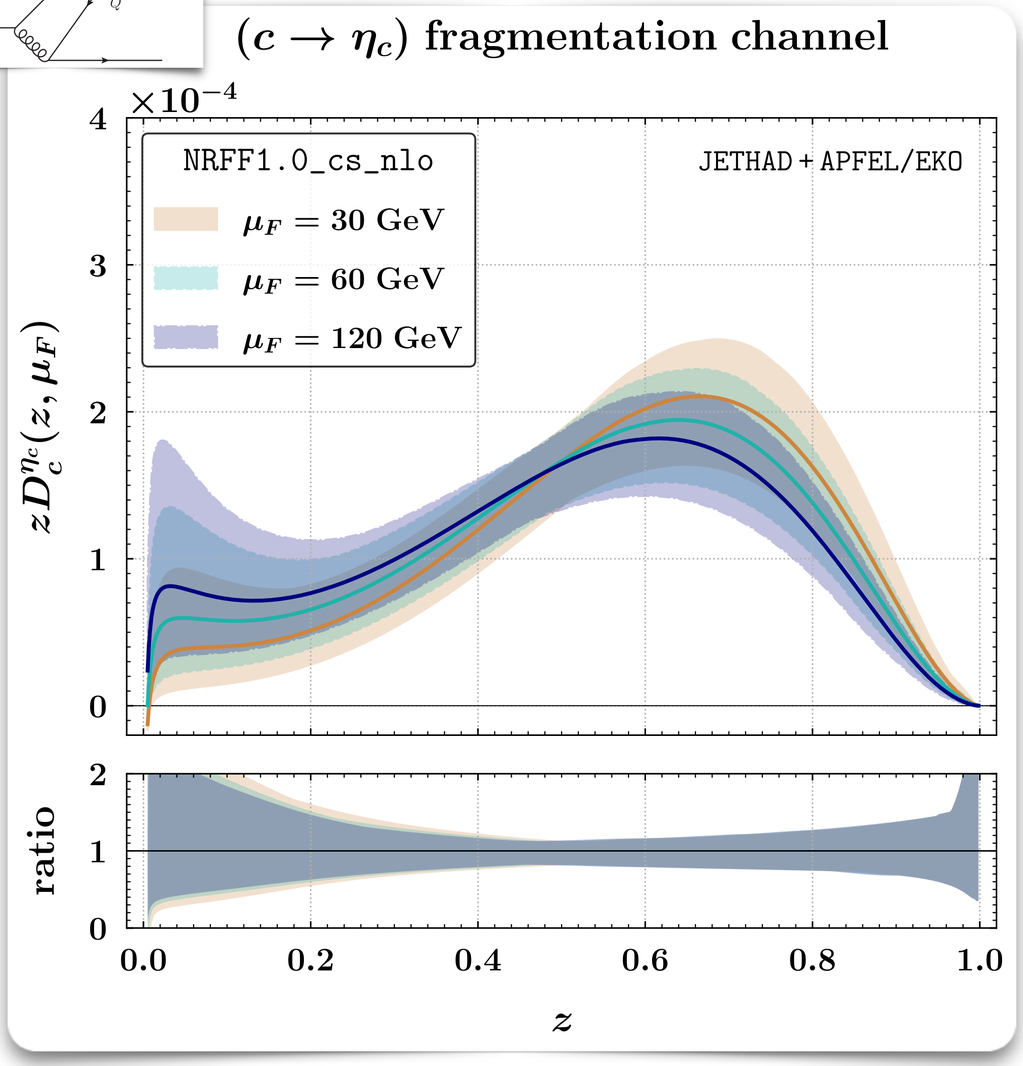
Vector J/ψ





Scalar η_c

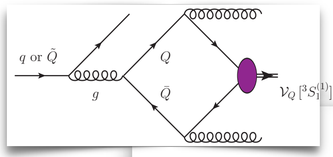


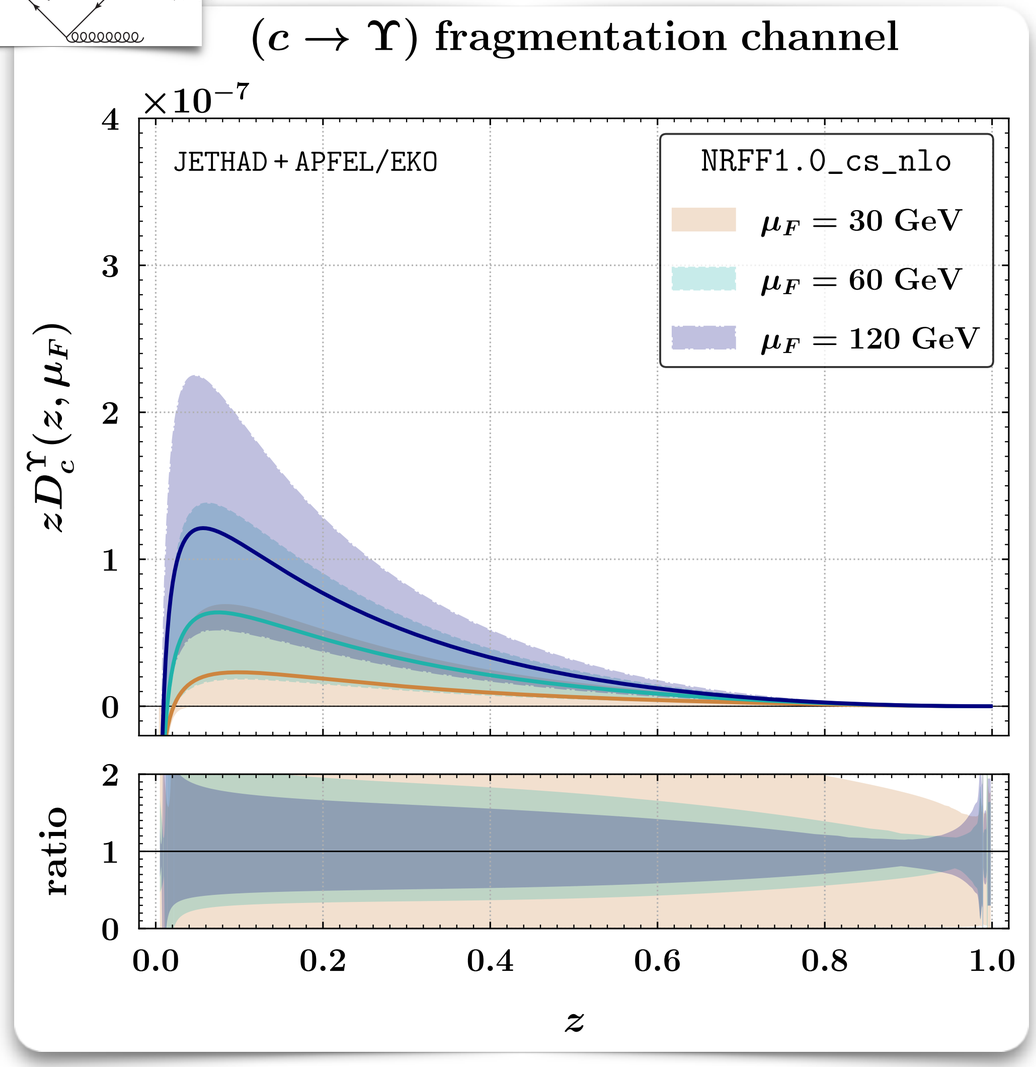


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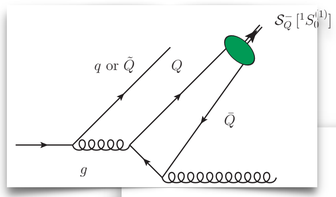
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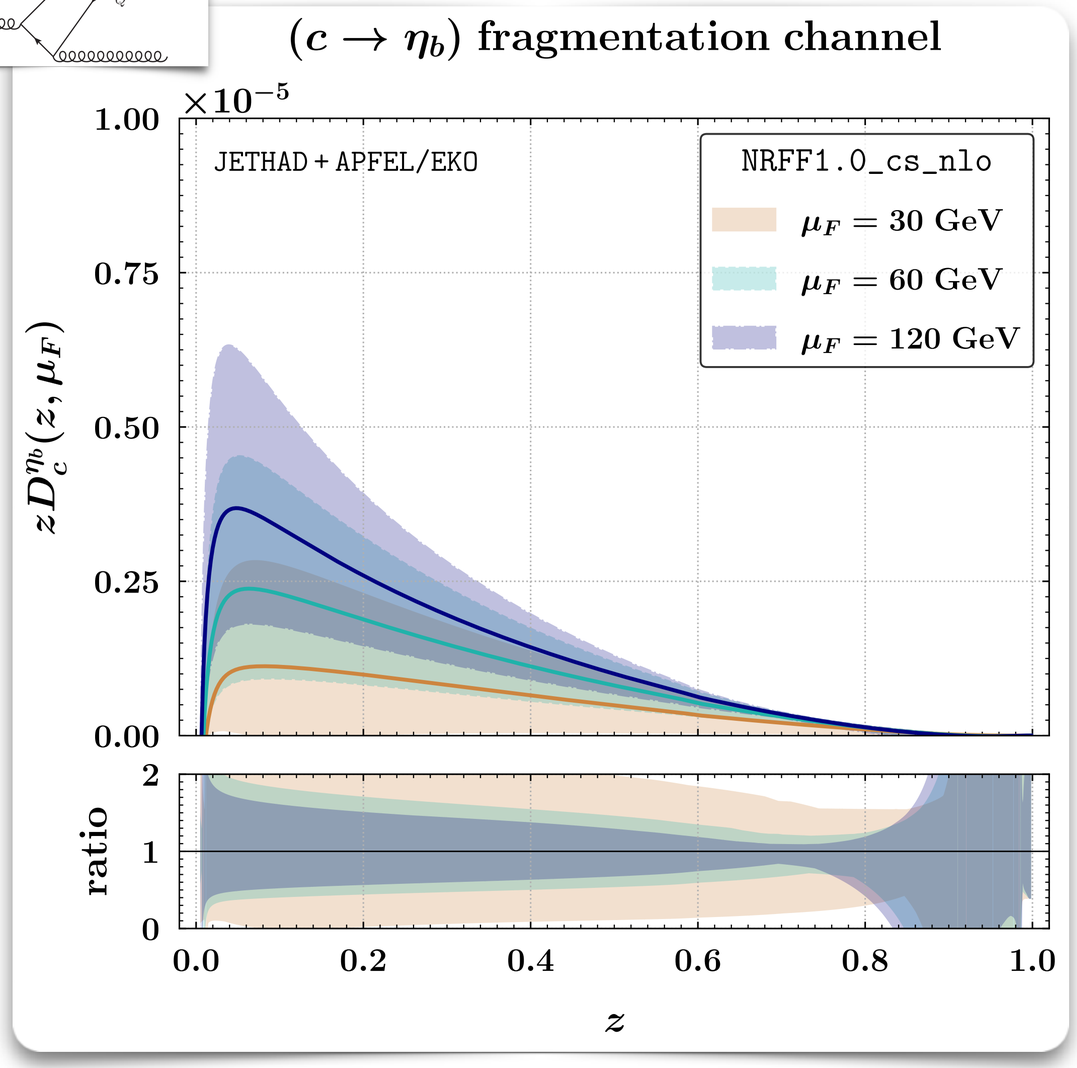
Vector Υ





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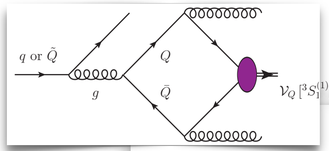


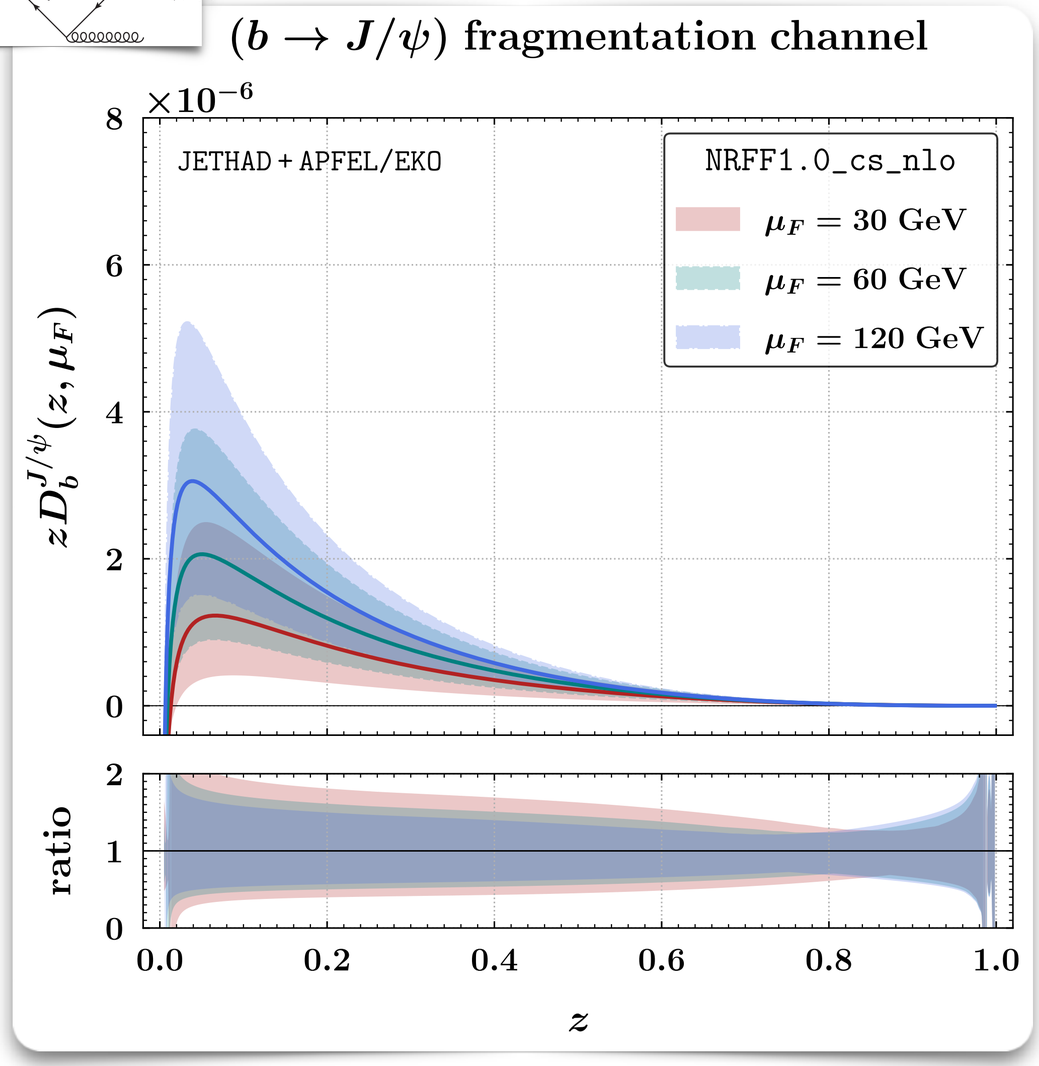


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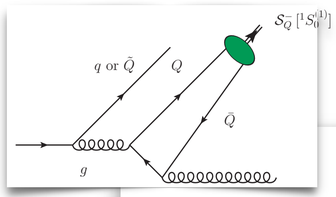
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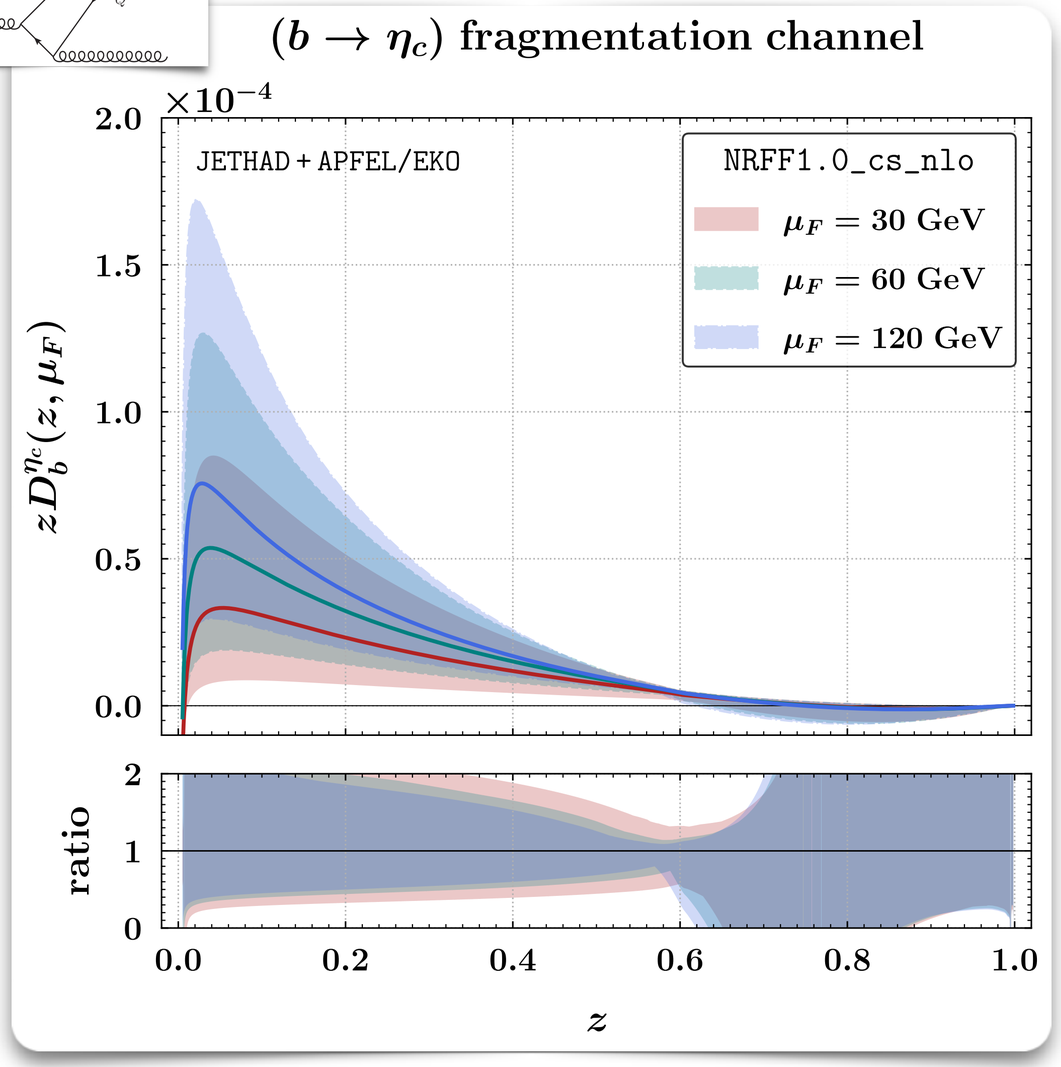
Vector J/ψ





Scalar η_c

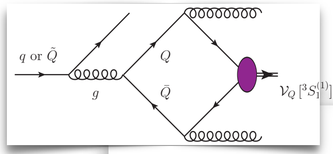


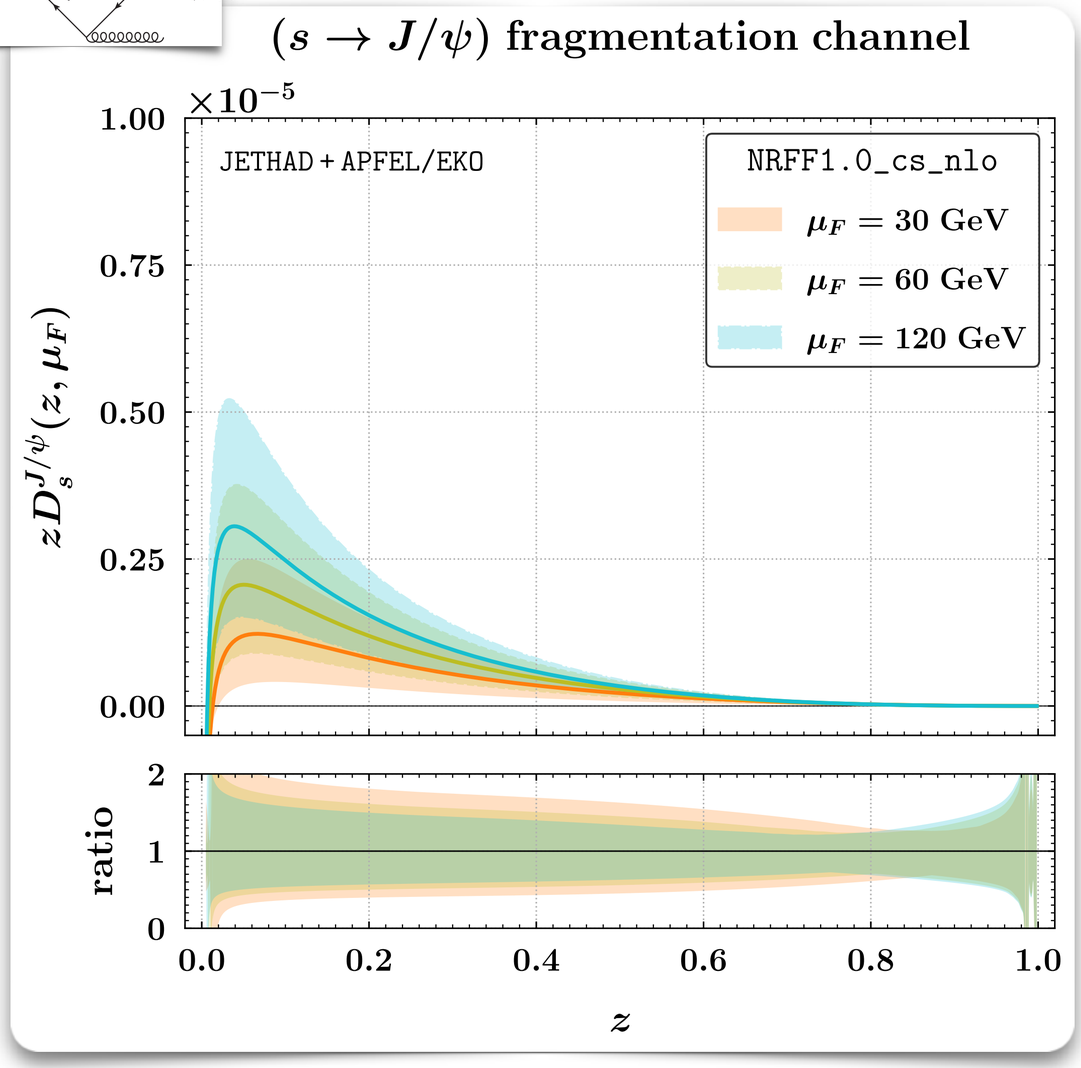


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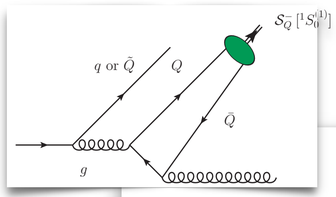
NRFF1.0: Strange fragmentation to charmonia

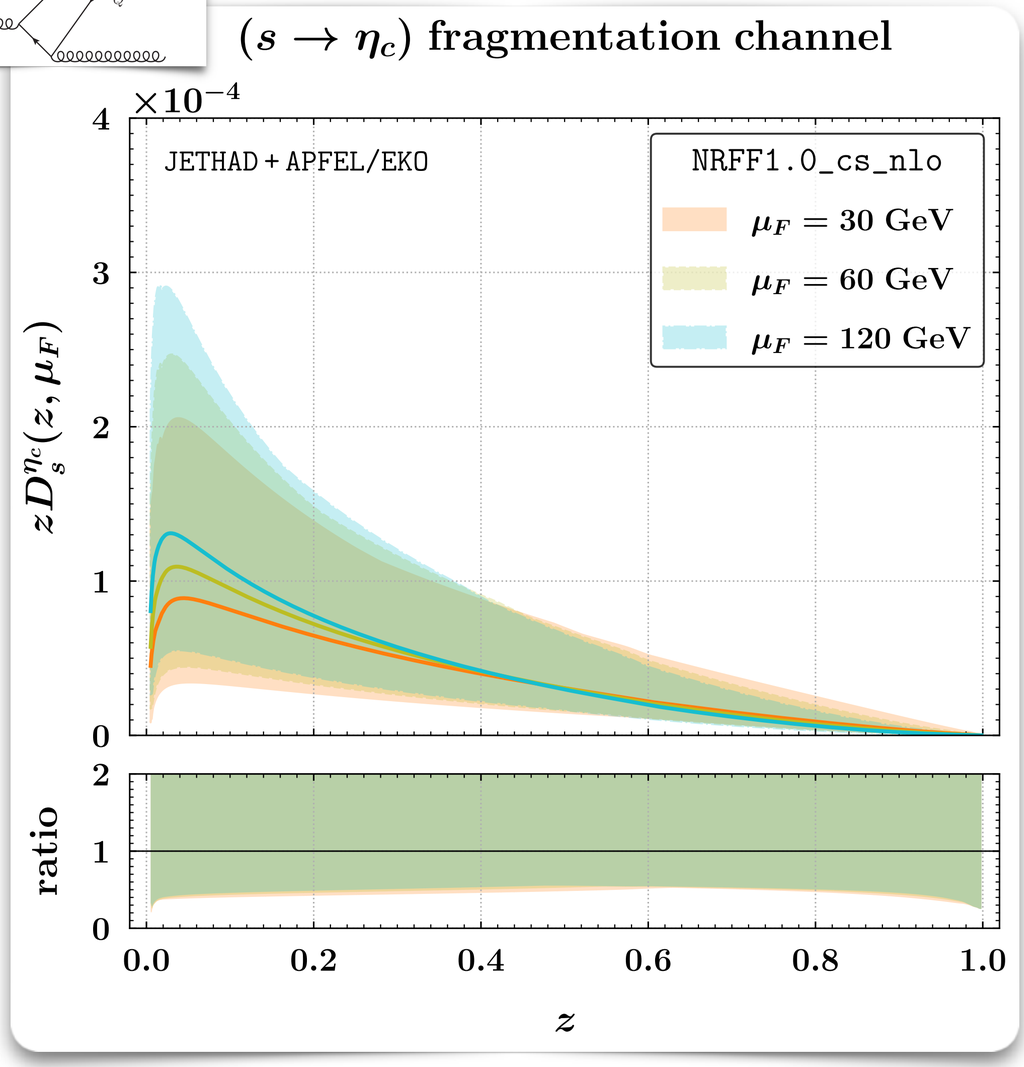
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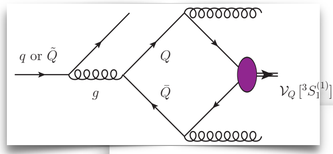


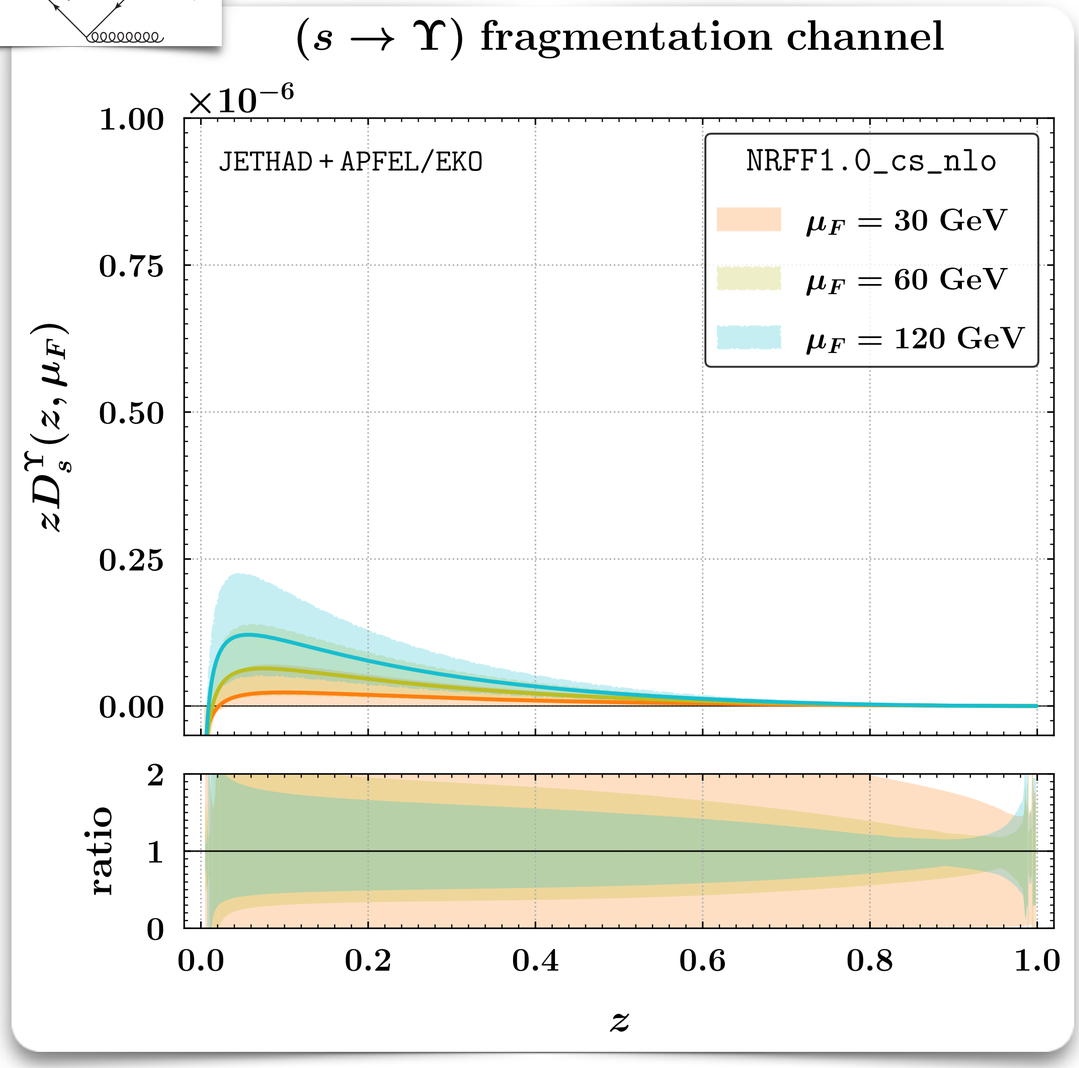


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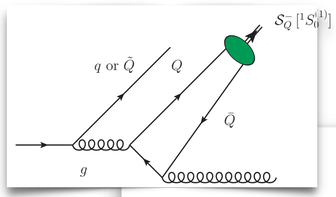
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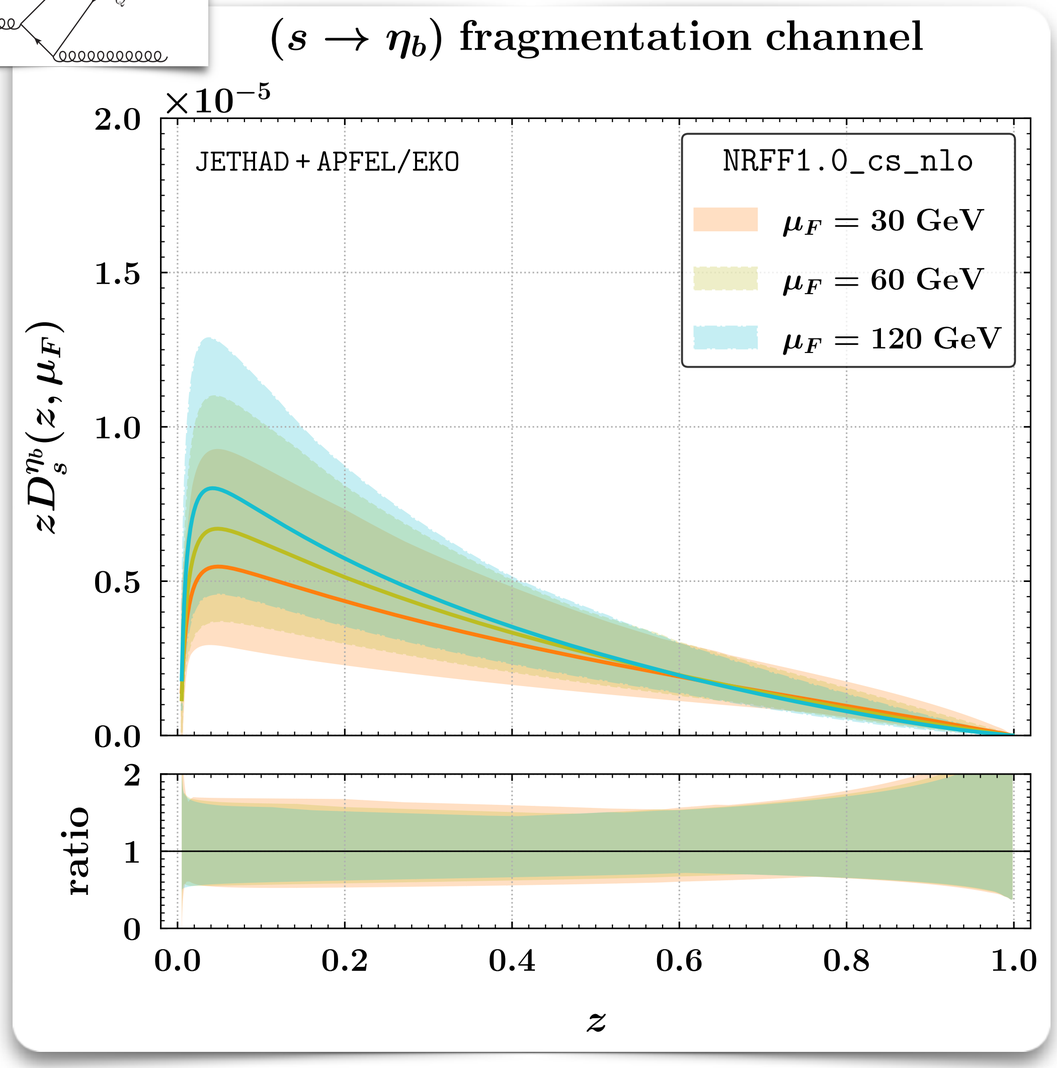
Vector Υ





Scalar η_b

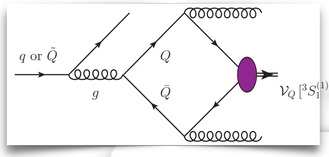


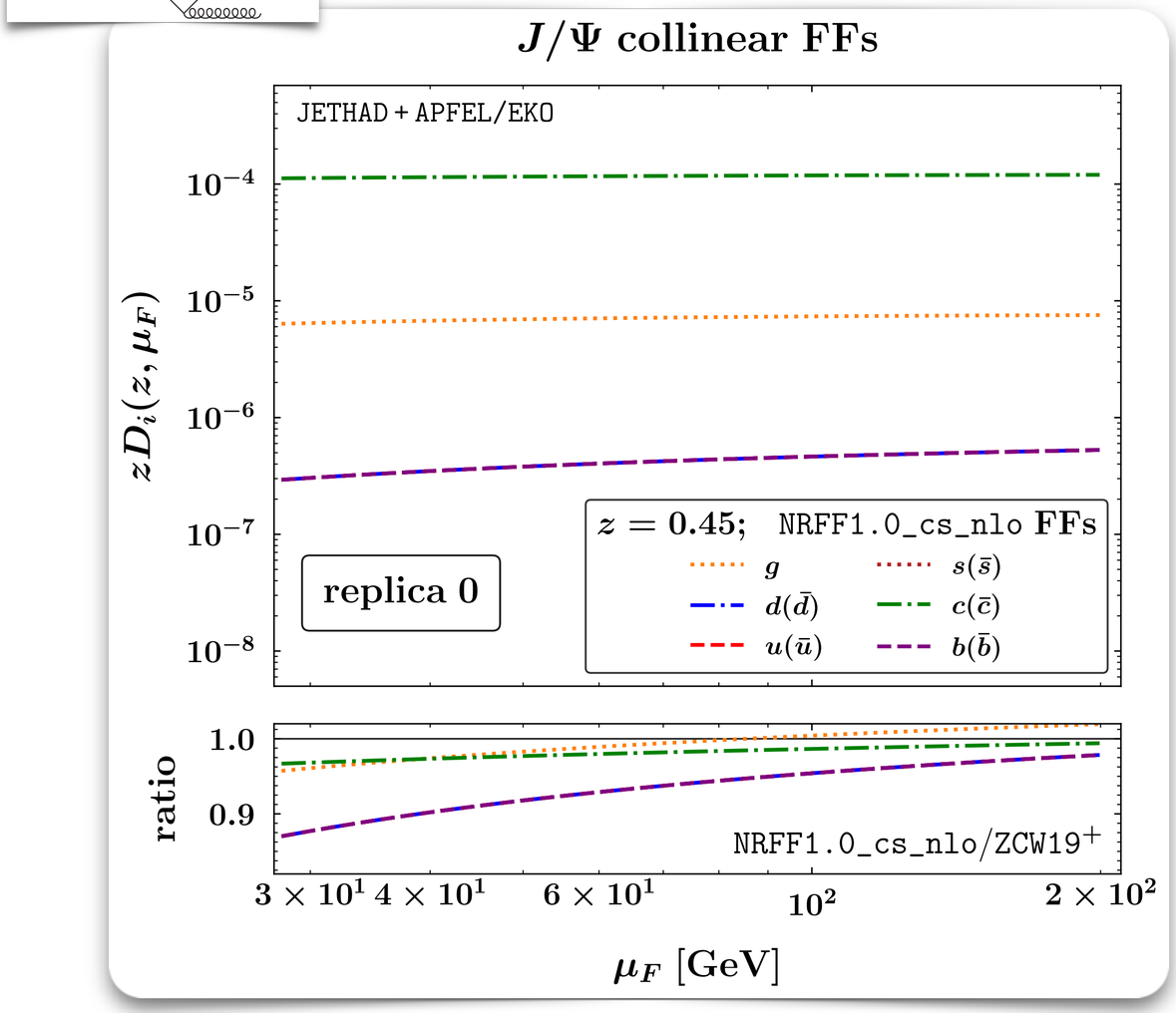


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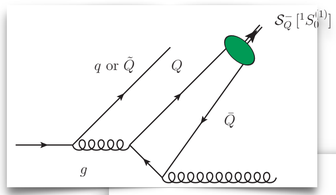
NRFF1.0: Energy dependence

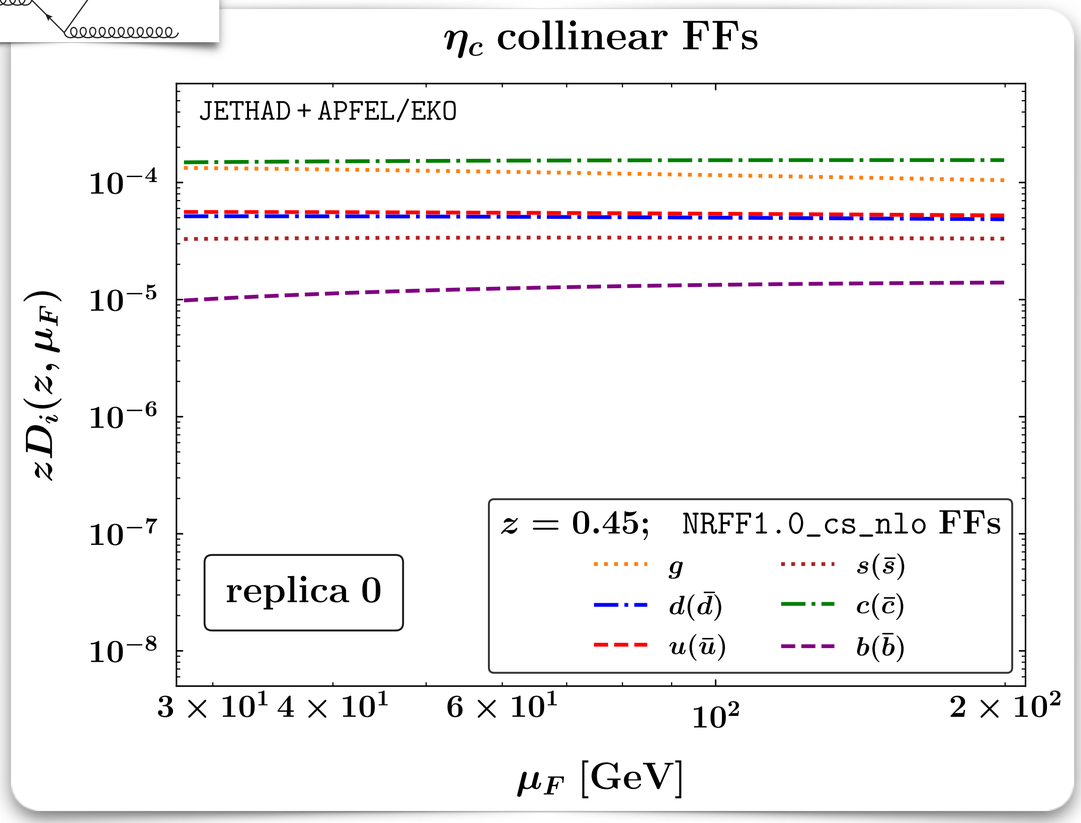
Vector J/ψ





Scalar η_c





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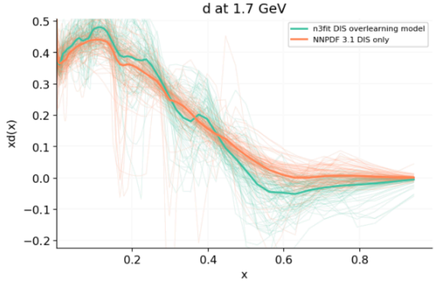
Towards NRFF1.0: ¿ Quarkonium FF Kinetic Energy ?

TEST SET RESULS

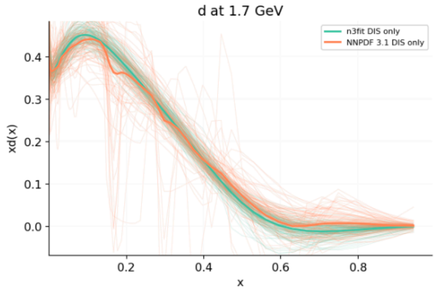
- COMPLETELY UNCORRELATED TEST SET
- OPTIMIZE ON WEIGHTED AVERAGE OF VALIDATION AND TEST
  $\Rightarrow$ NO OVERLEARNING

HYPEROPTIMIZED PDFs
DOWN QUARK

OVERFIT VS HAND-PICKED



TEST-SET VS HAND-PICKED



BUT WHO PICKS THE TEST SET?

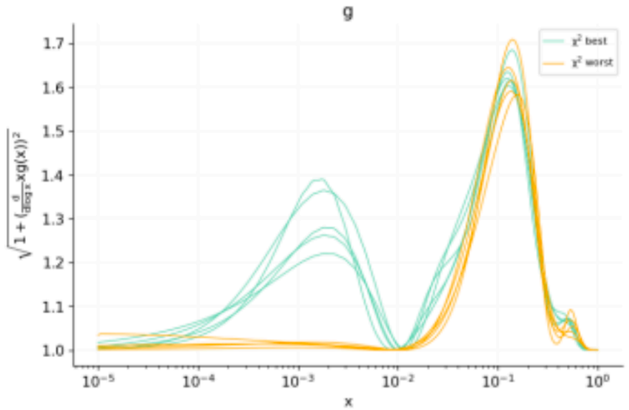
THE PDF KINETIC ENERGY

REPLICAS WITH LOWEST & HIGHEST LOSS TO CENTRAL DATA

$$\mathrm{KE} = \sqrt{1 + \left(\frac{d}{d\ln x} x f(x, Q^2)\right)^2}$$

ARCLENGTH OF THE NN OUTPUT IN TERMS OF INPUT

THE GLUON

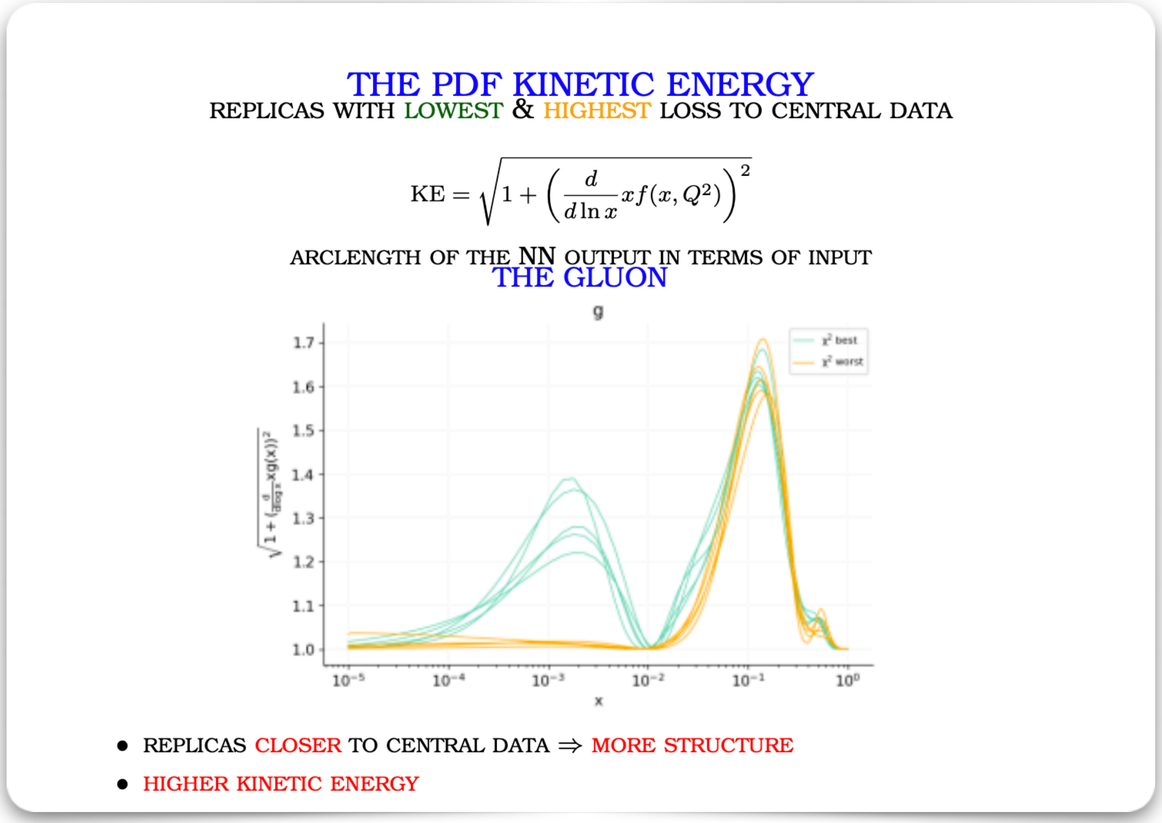


- REPLICAS CLOSER TO CENTRAL DATA $\Rightarrow$ MORE STRUCTURE
- HIGHER KINETIC ENERGY

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

Towards NRFF1.0: ¿ Quarkonium FF Kinetic Energy ?

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



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

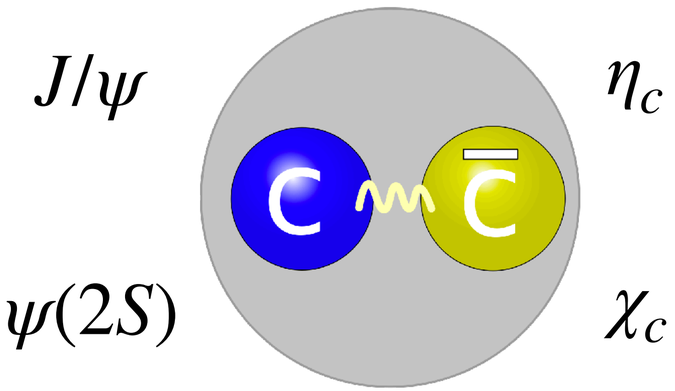
What is a quarkonium?

- Quarkonia → mesons with a heavy quark & its antiquark → $|\mathscr{Q}\rangle \equiv |Q\overline{Q}\rangle$
- 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

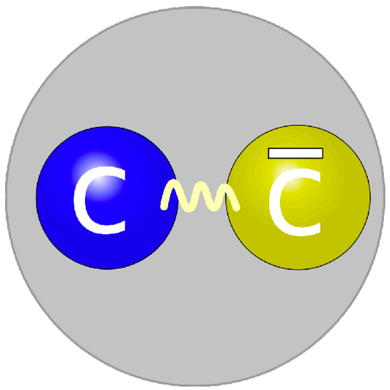


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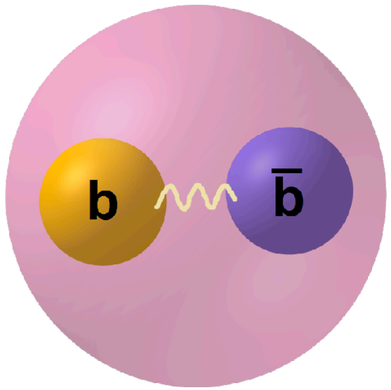
Charmonia

J/ψ η_c $\psi(2S)$ χ_c



Bottomonia

Υ η_b $\Upsilon(2S)$ χ_b

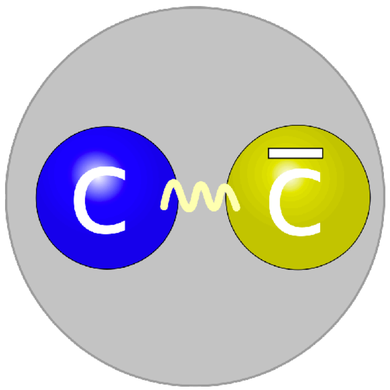


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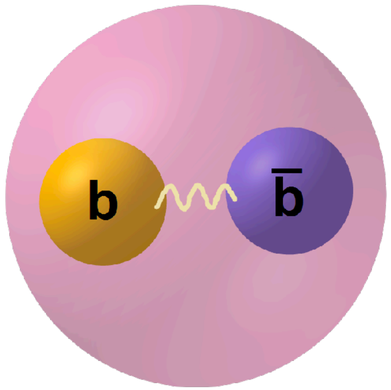
J/ψ η_c



$\psi(2S)$ χ_c

Bottomonia

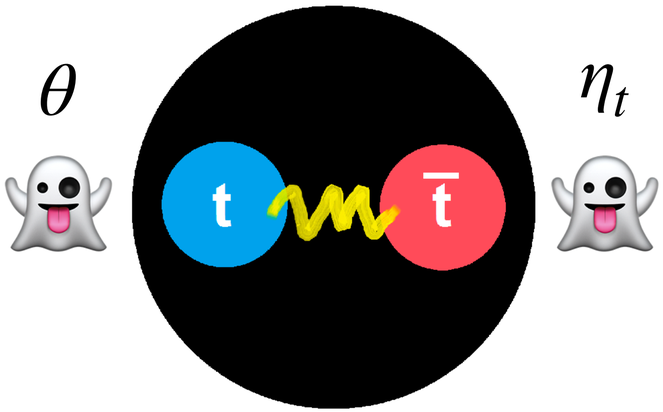
Υ η_b



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Toponia

θ η_t



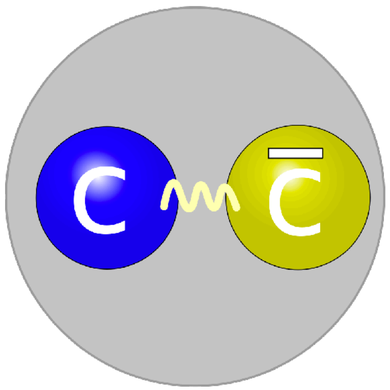
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Charmonia

J/ψ η_c

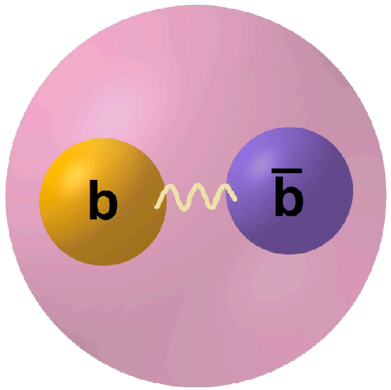
$\psi(2S)$ χ_c



Bottomonia

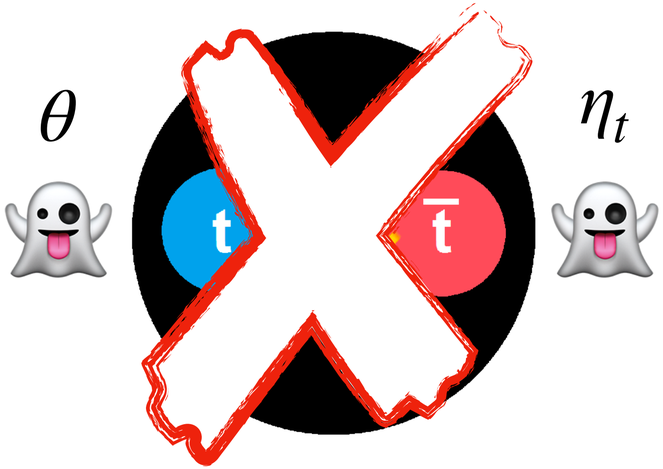
Υ η_b

$\Upsilon(2S)$ χ_b



Toponia

θ η_t



Quarkonium studies: Progresses & challenges

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

Quarkonium studies: Progresses & challenges

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- ✓ …and of quarks as real particles and not as mathematical artifacts

Quarkonium studies: Progresses & challenges

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- ✓ Proof of asymptotic freedom & confinement ← $\psi(2S)$ resonance

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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

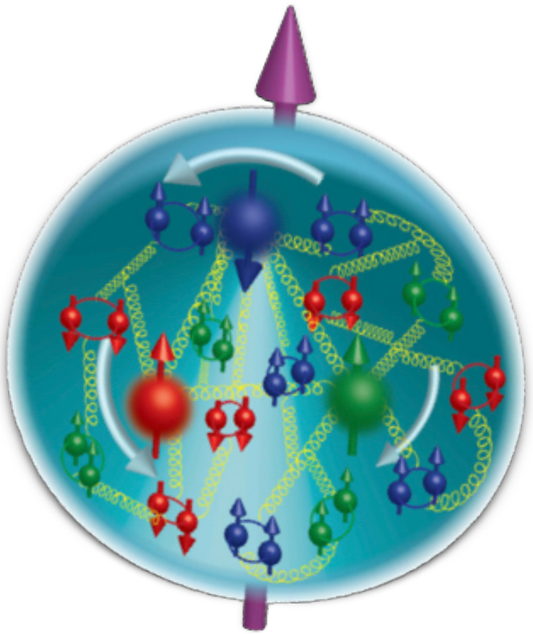
$$J = L + S$$

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*



Parton Distribution Functions & Fragmentation Functions

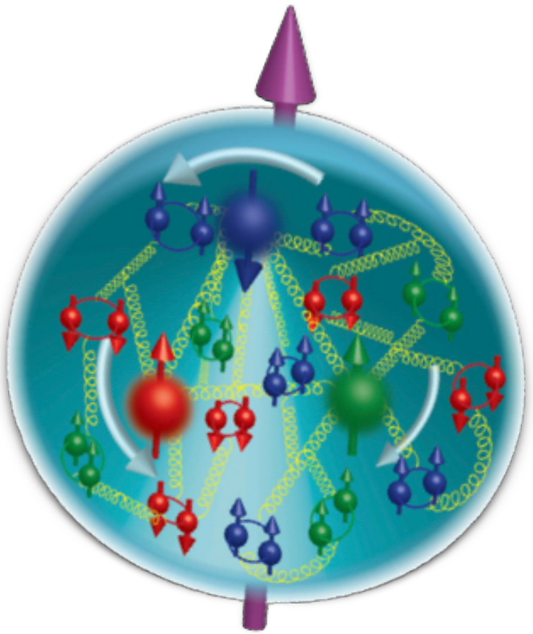
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Several types of functions (**1D collinear**, 3D TMD, 3D GPD, …)

- 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

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



🔗 [Eur. Phys. J. C 81 (2021) 8, 691]

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

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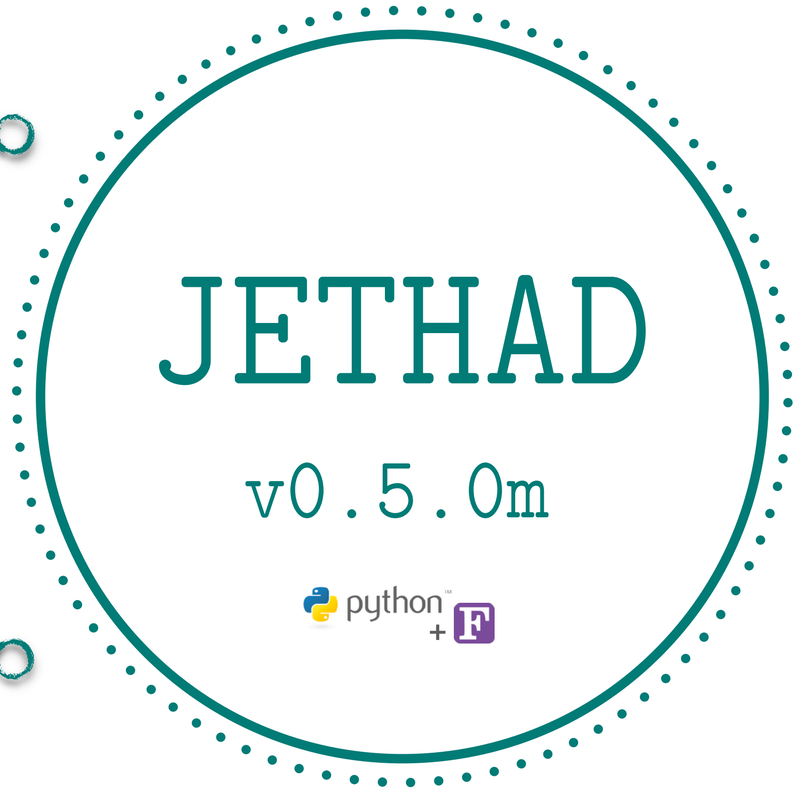
ERIS, Δναμις super-modules

Higgs + jet, weak bosons

High-energy resummation

Matching NLL/NLO

In Higgs + jet at the LHC



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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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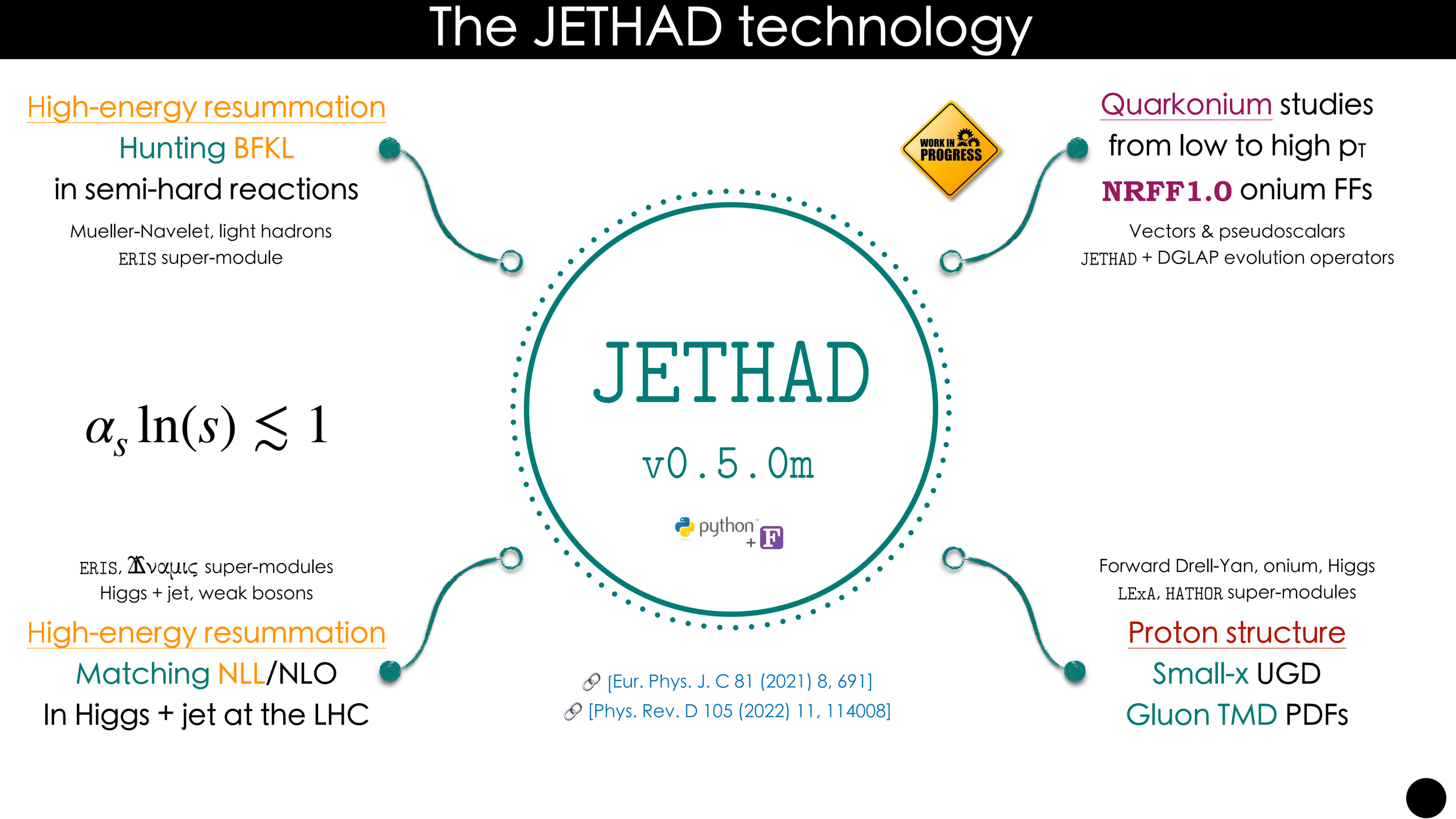
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WORK IN PROGRESS

Quarkonium studies

from low to high p_T

NRFF1.0 onium FFs

Vectors & pseudoscalars

`JETHAD` + DGLAP evolution operators

Forward Drell-Yan, onium, Higgs

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JETHAD

v0.5.0m

python + F

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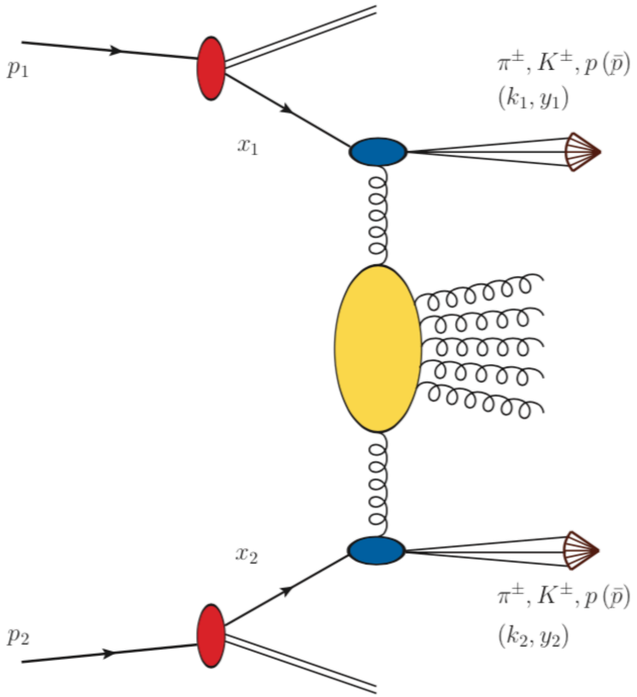
HEAVY-LIGHT HADRONS

From Higgs + jet to bound states

Di-hadron and hadron-jet correlations

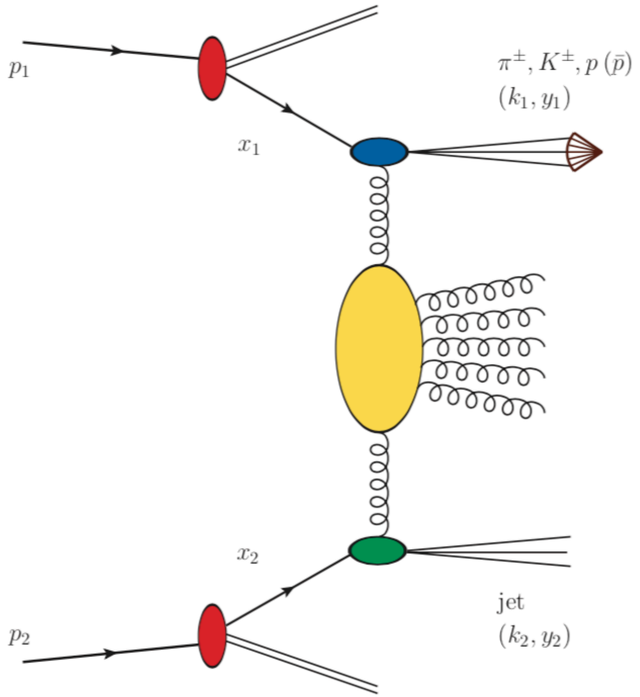
Inclusive di-hadron production

[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)]



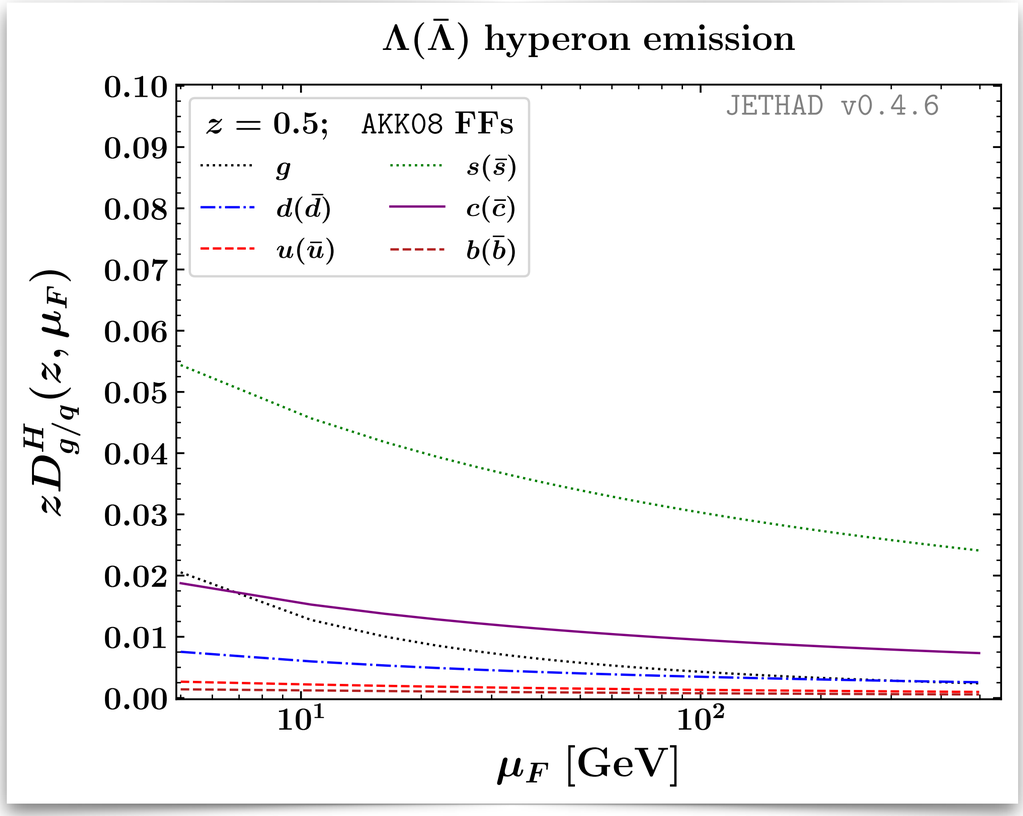
- NLO impact factors known $\Rightarrow$ full NLA BFKL analysis feasible
- PDFs + FFs at work (both), hadrons at smaller rapidities than jets (di-hadron)
- genuine *asymmetric* cuts in transverse momenta (hadron-jet)

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

Stabilizing effects of heavy-flavor fragmentation

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

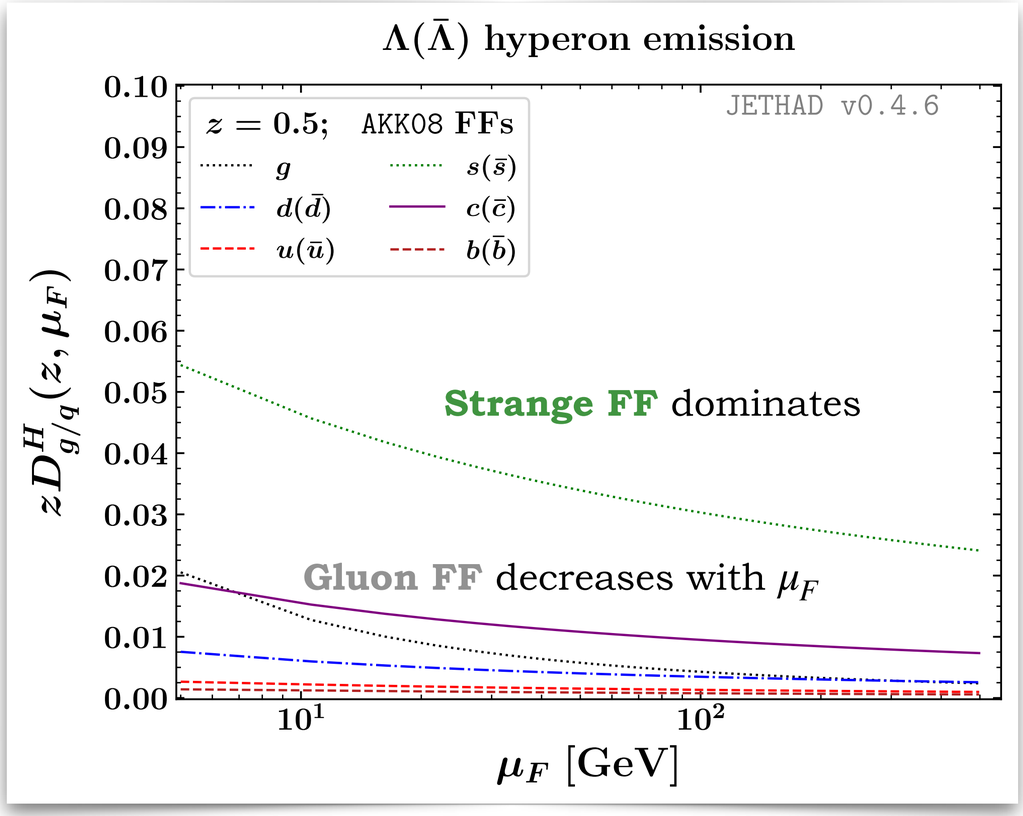
[S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]



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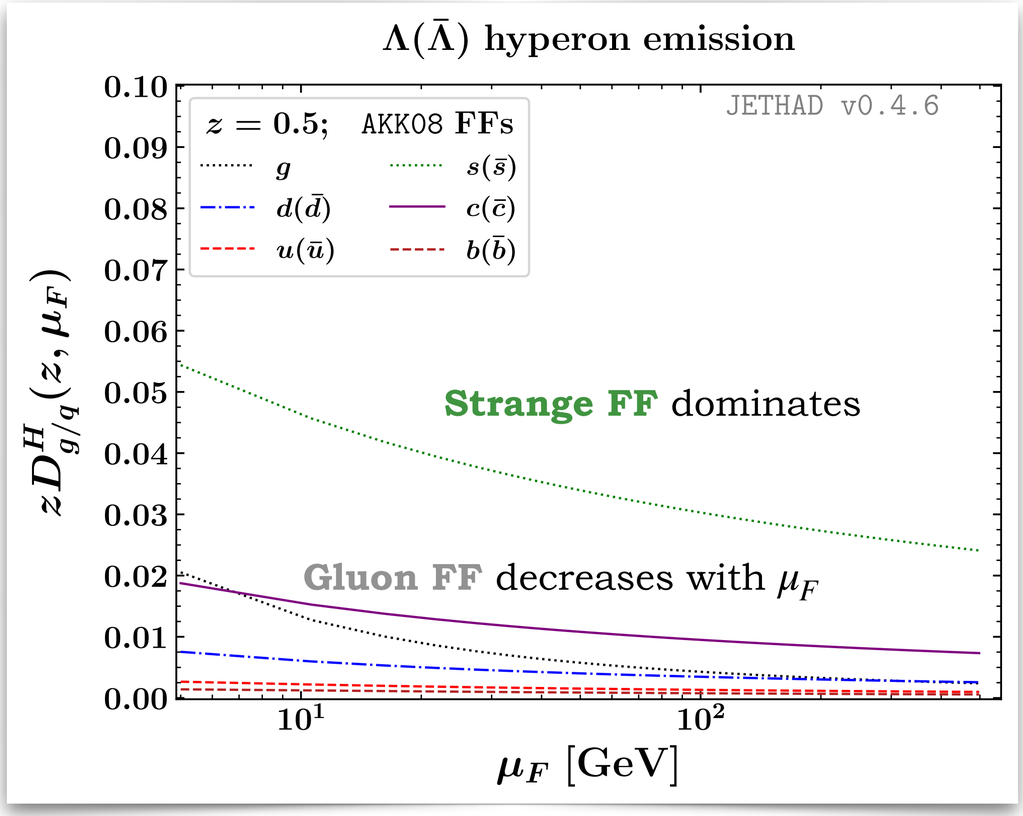
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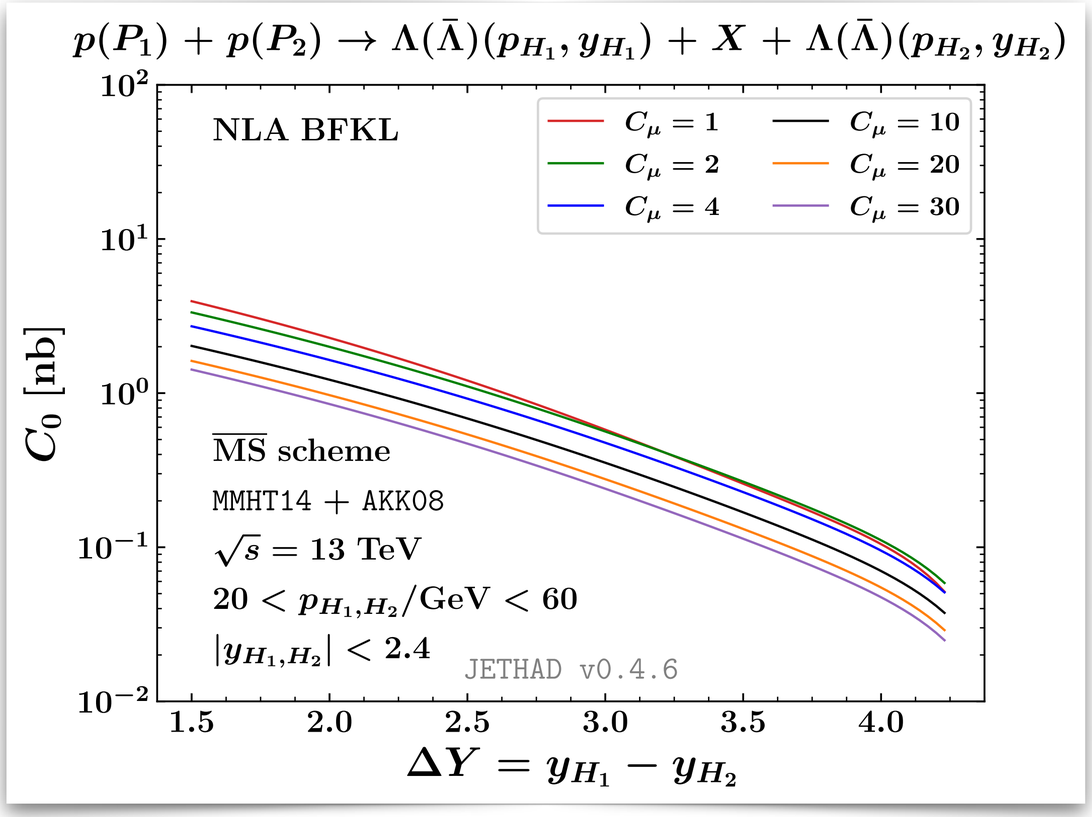


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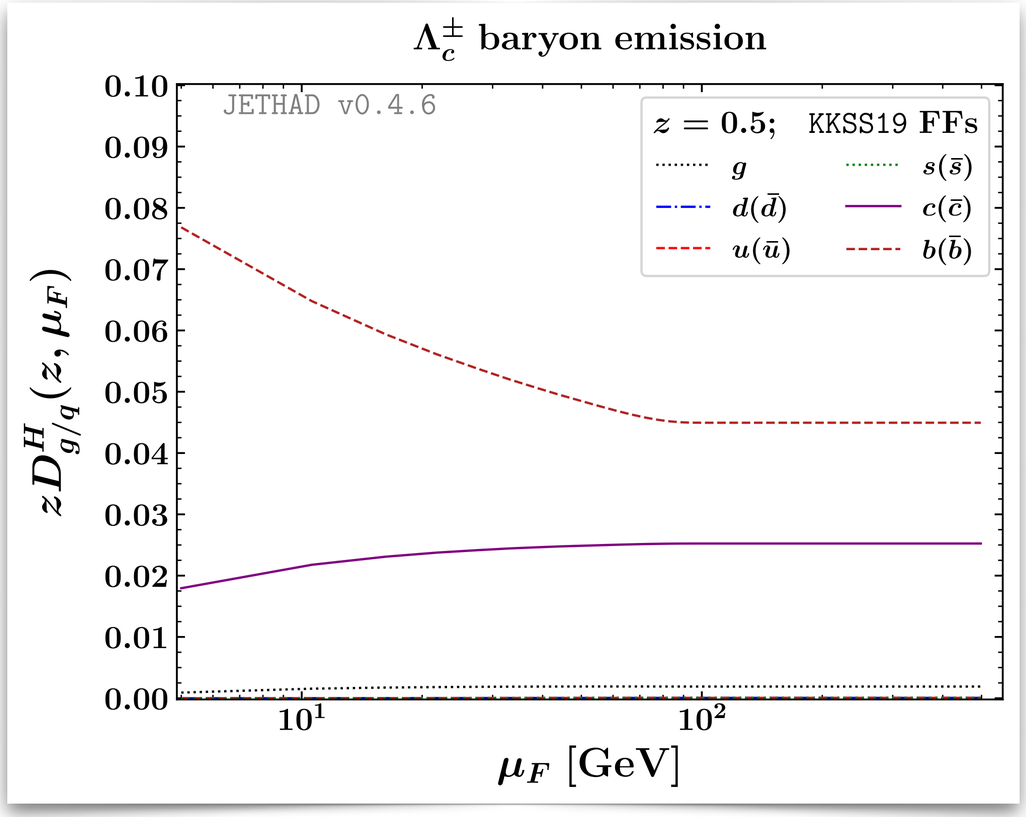
Rapidity distribution sensitive to scale variations

(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)]

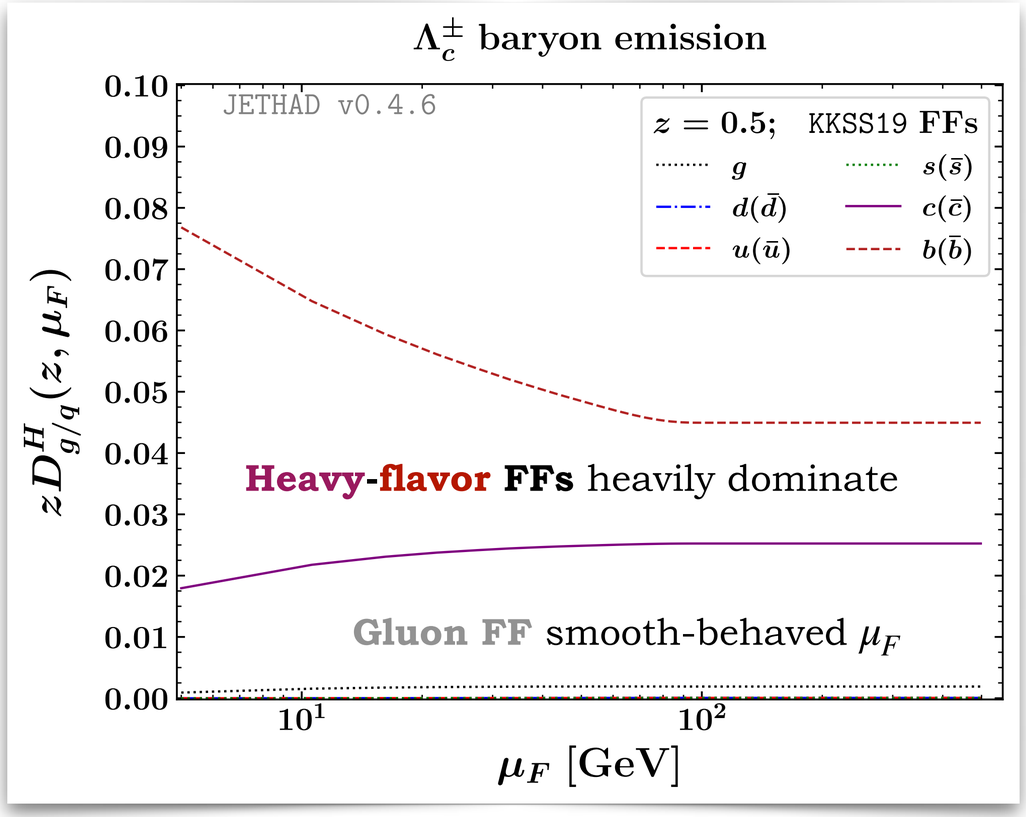
Stabilizing effects of heavy-flavor fragmentation

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



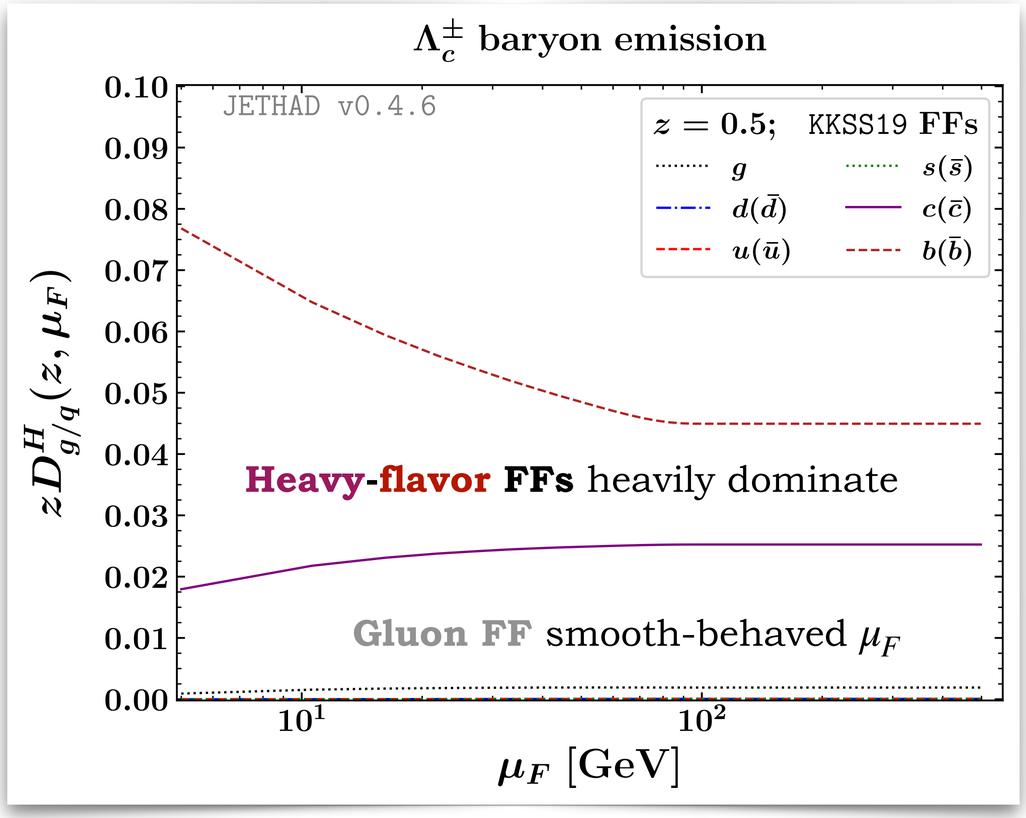
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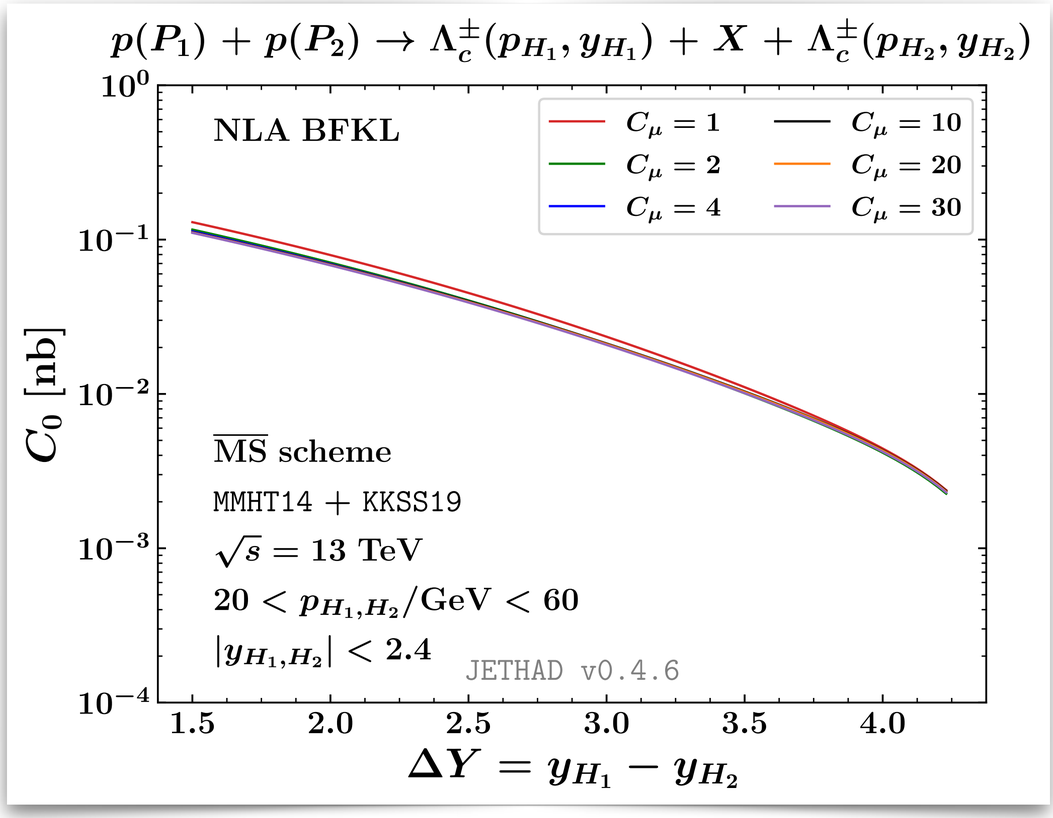
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Rapidity distribution stable under scale variations

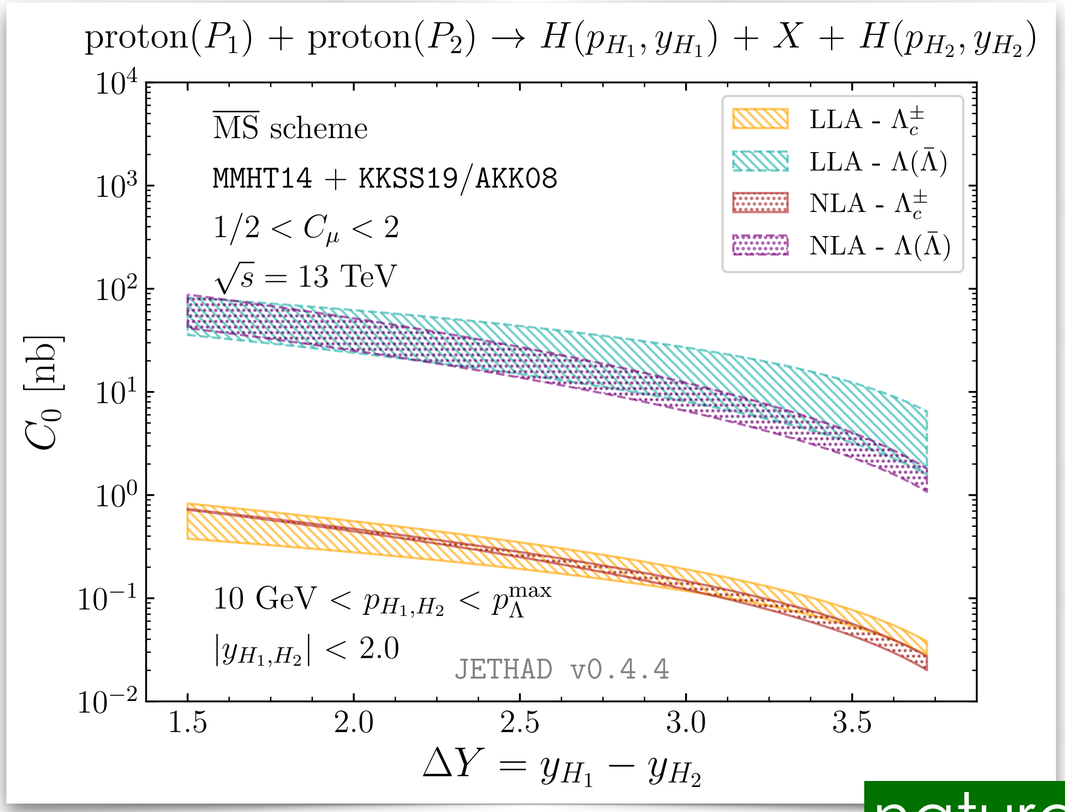
($B_c^{(*)}$ hadrons) [F. G. C., Phys. Lett. B 835 (2022) 137554]

(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

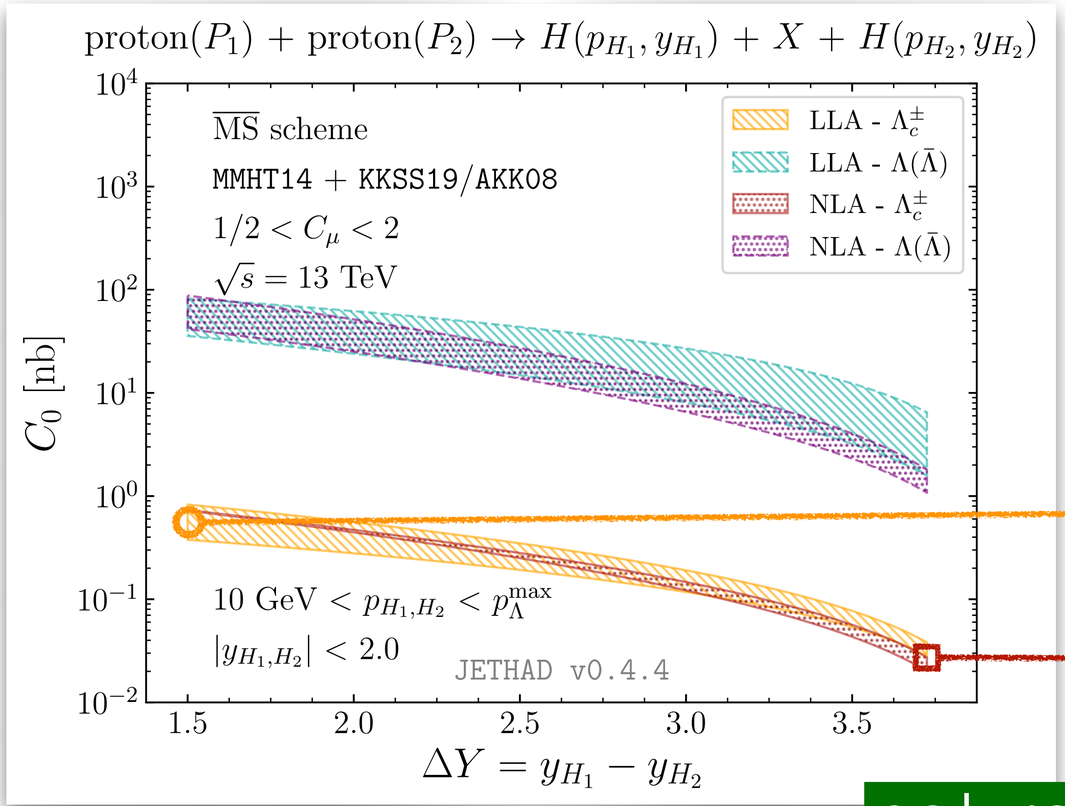
Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$

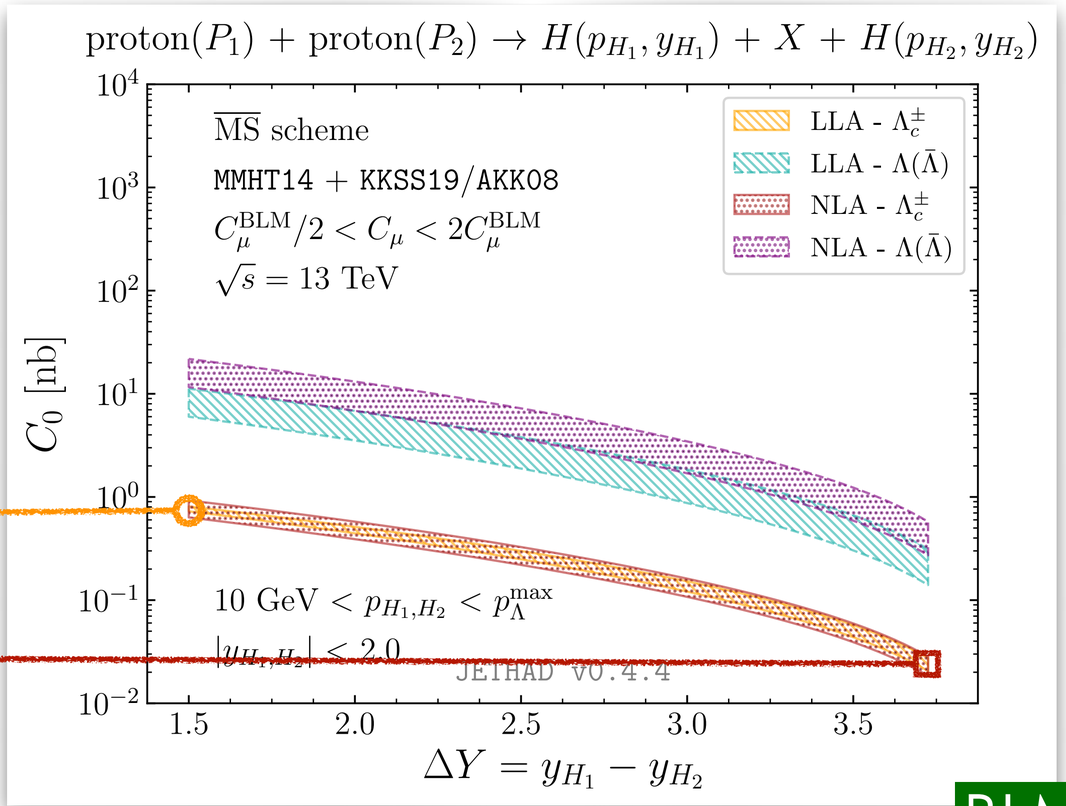


natural

Stability under scale variations & NLL corrections

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





LL Λ_c

NLL Λ_c

natural

BLM

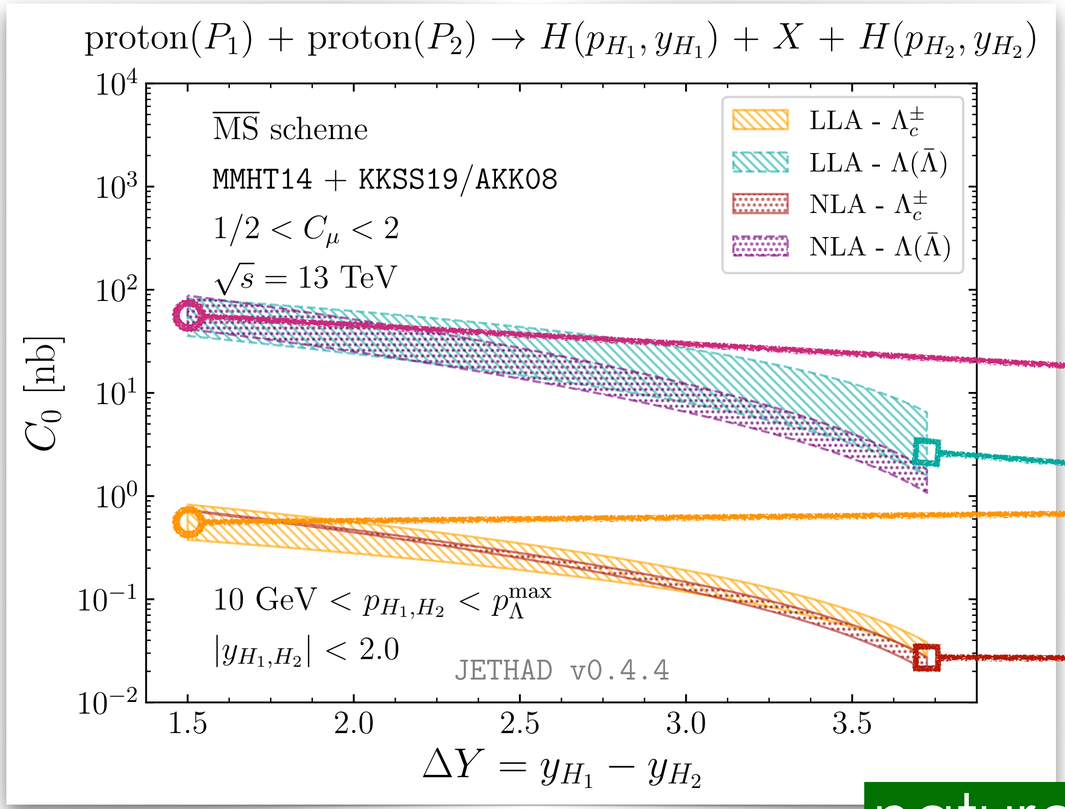
NLL corrections: rapidity distribution stable for Λ_c

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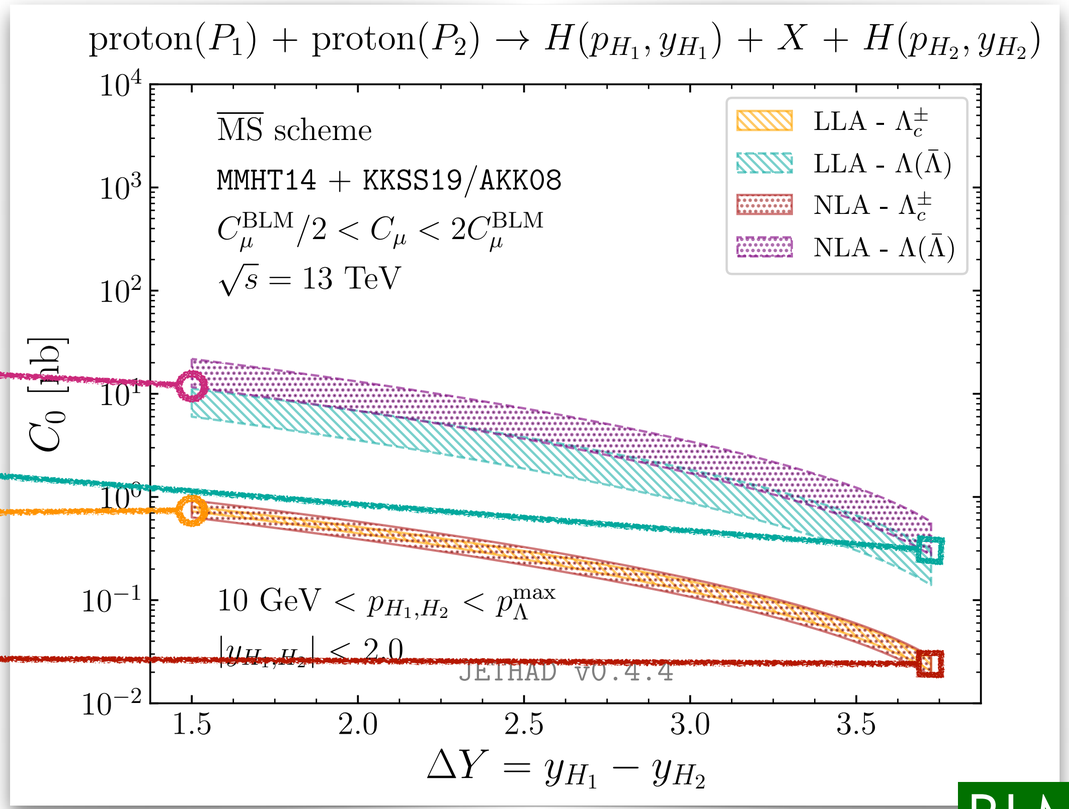


NLL Λ

LL Λ

LL Λ_c

NLL Λ_c



natural

BLM

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

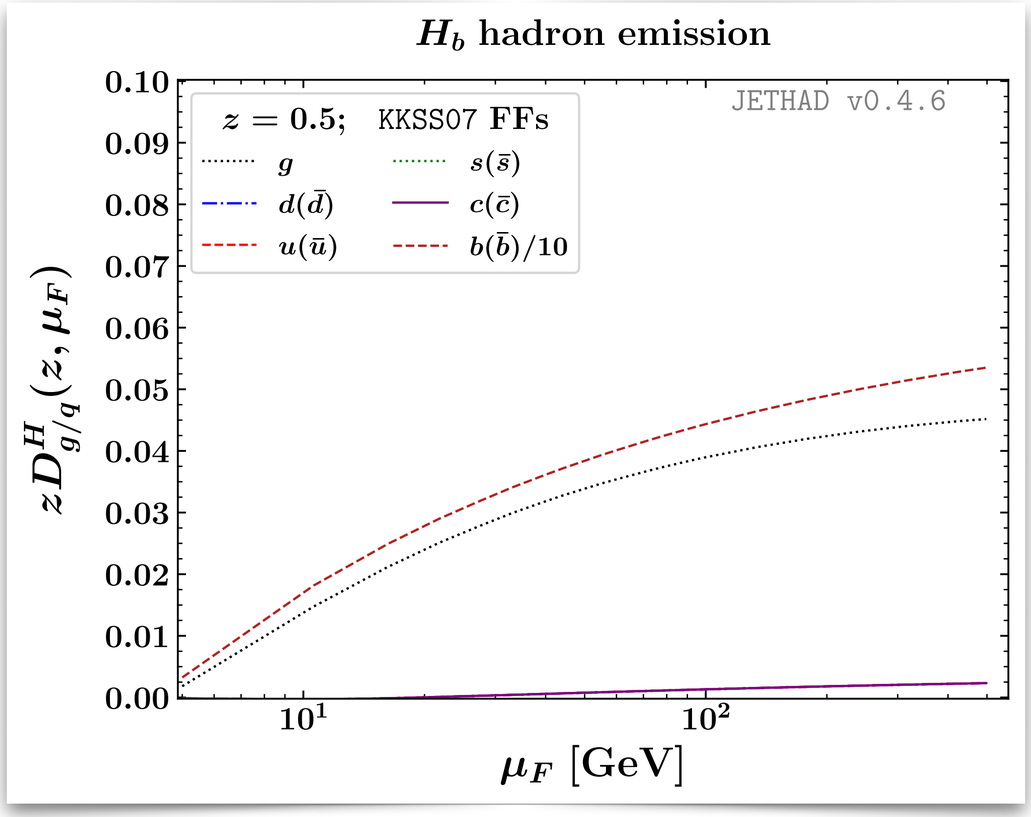
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Stabilizing effects of heavy-flavor fragmentation

KKSS07 VFNS collinear FFs for:

$$H_b = B^{\pm}, B^0, B_s^0, \Lambda_b$$



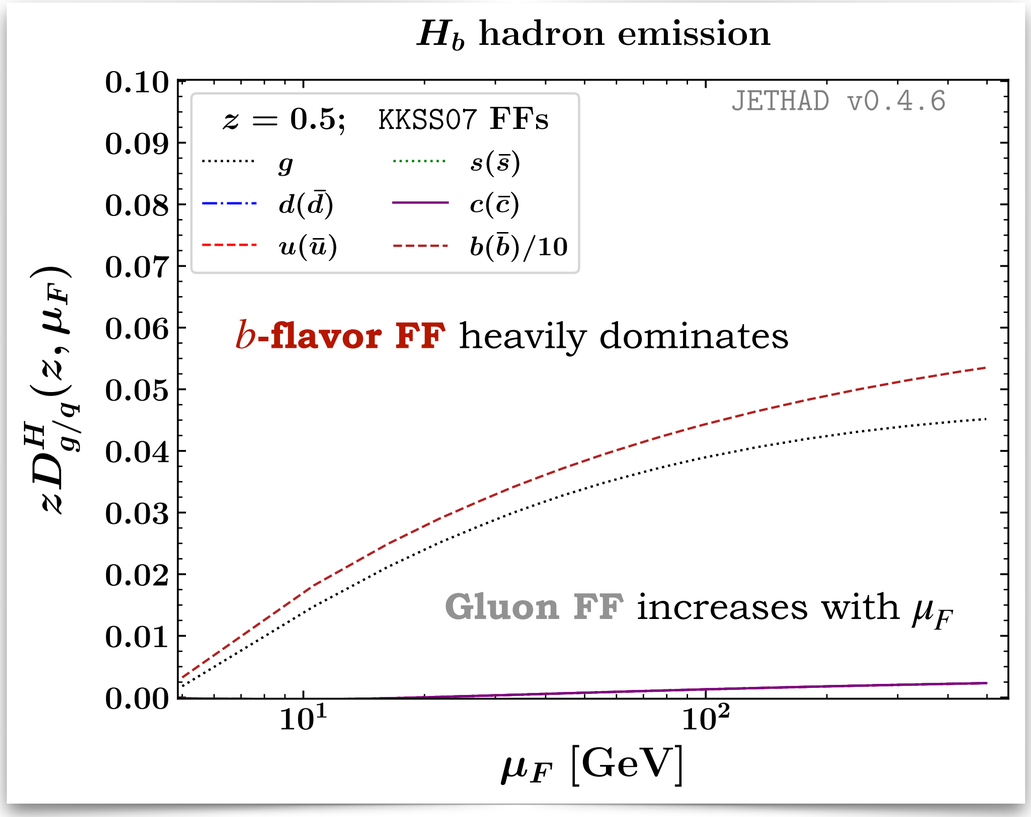
[B. A. Kniehl, H. Spiesberger, Phys. Rev. D 98 (2018) 11, 114010]

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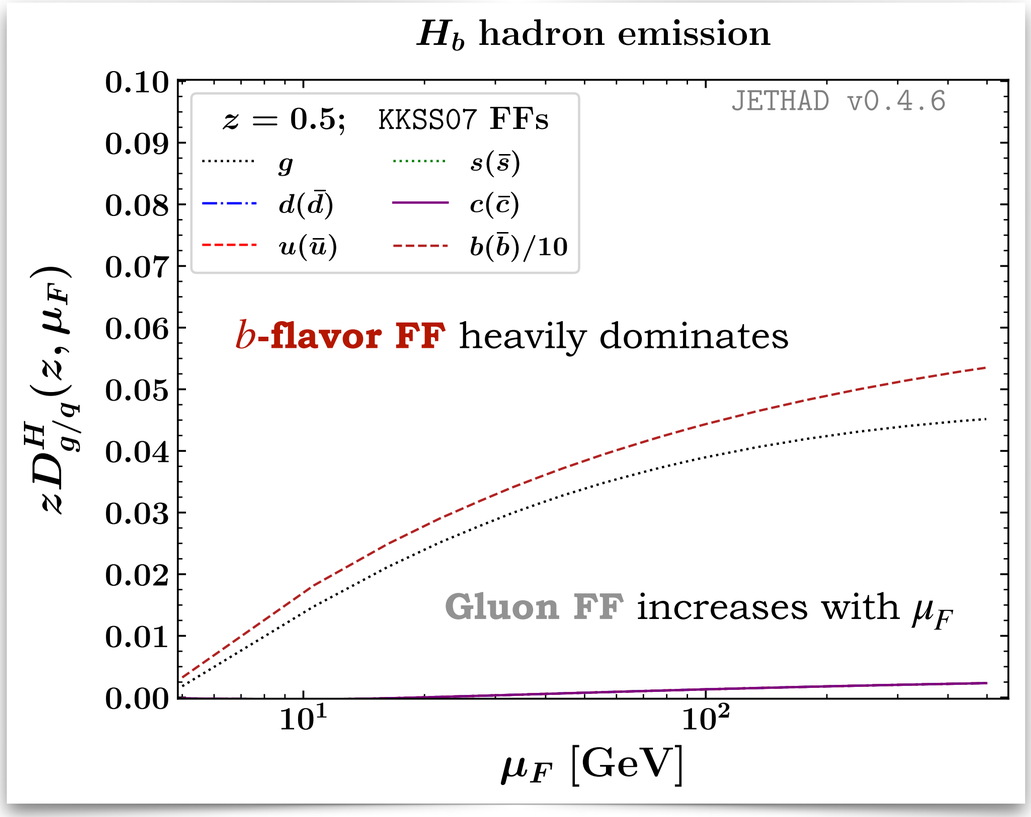
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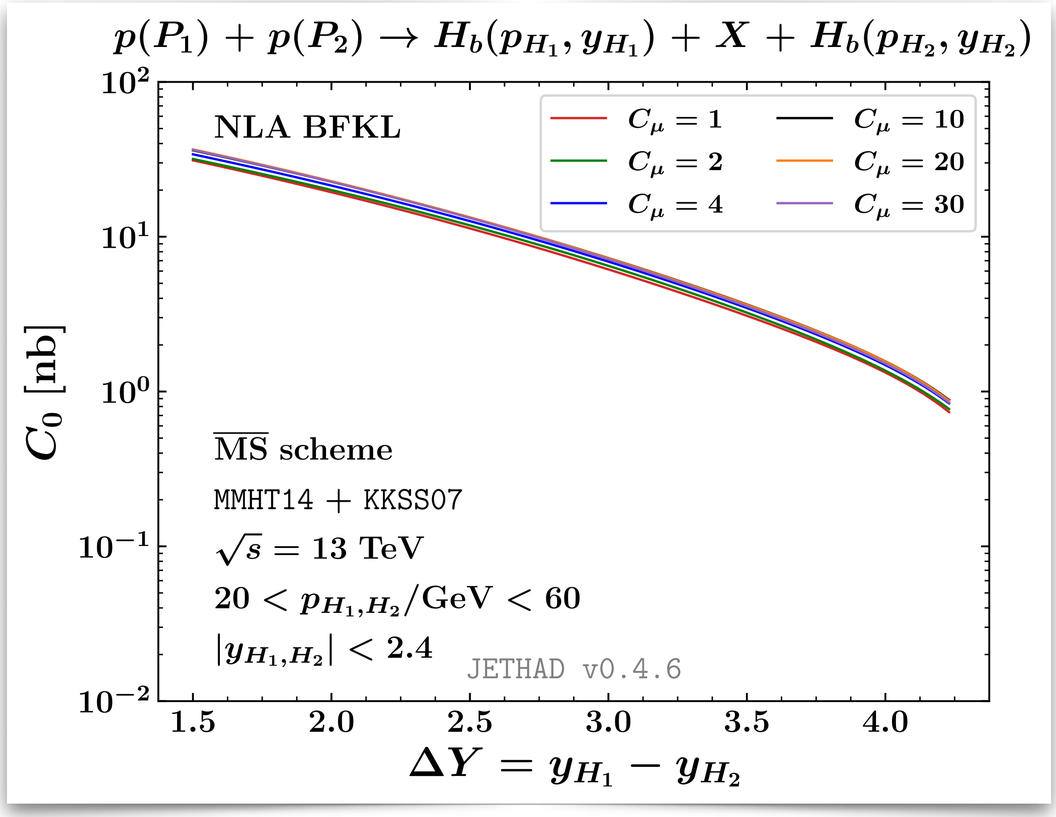
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Rapidity distribution very stable under scale variations

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Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

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

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

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

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

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Gluon FF rises with energy ⇒ 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)* ?

Is the natural stability robust?

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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

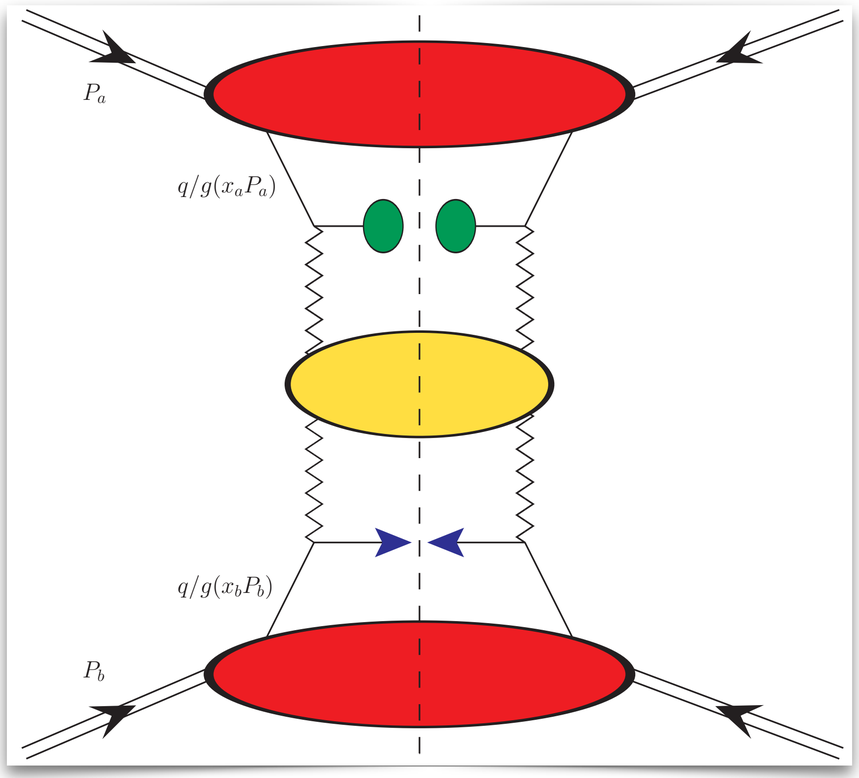
¿ *Might natural stability be artificially generated by this Ansatz* ?

Vector quarkonium from single-parton fragmentation

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

Vector quarkonium from single-parton fragmentation

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



2.1 High-energy resummed cross section

The process under investigation is

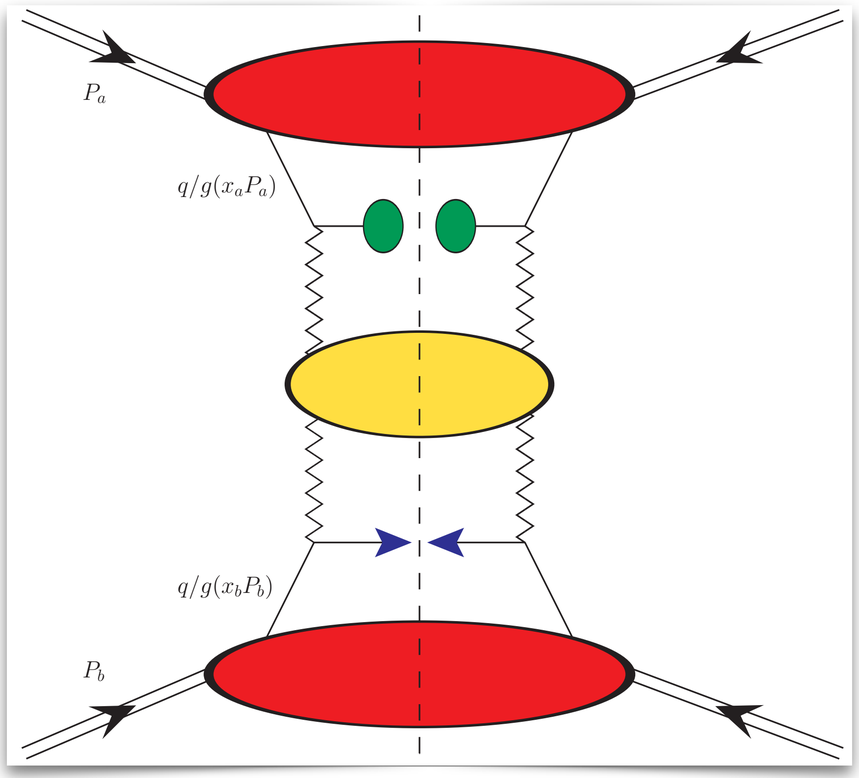
$$p(P_a) + p(P_b) \to \mathcal{Q}(p_{\mathcal{Q}}, y_{\mathcal{Q}}) + X + \text{jet}(p_J, y_J) \ , \tag{1}$$

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]

Vector quarkonium from single-parton fragmentation

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



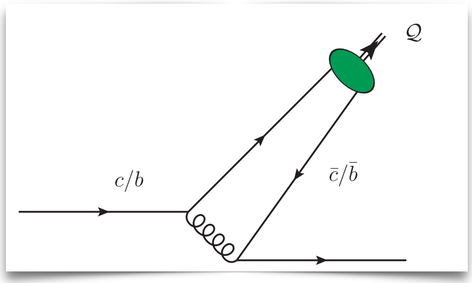
2.1 High-energy resummed cross section

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.

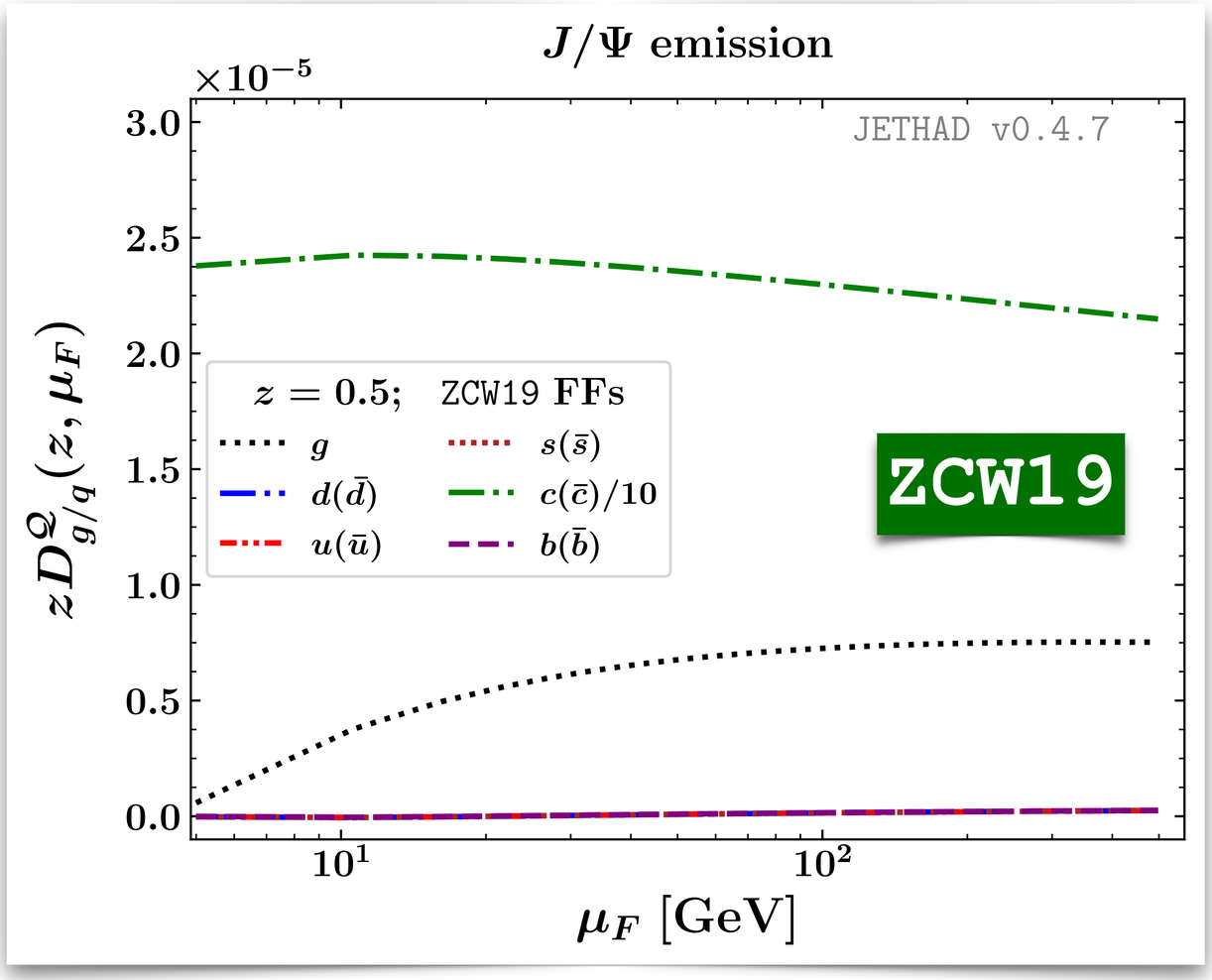
🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

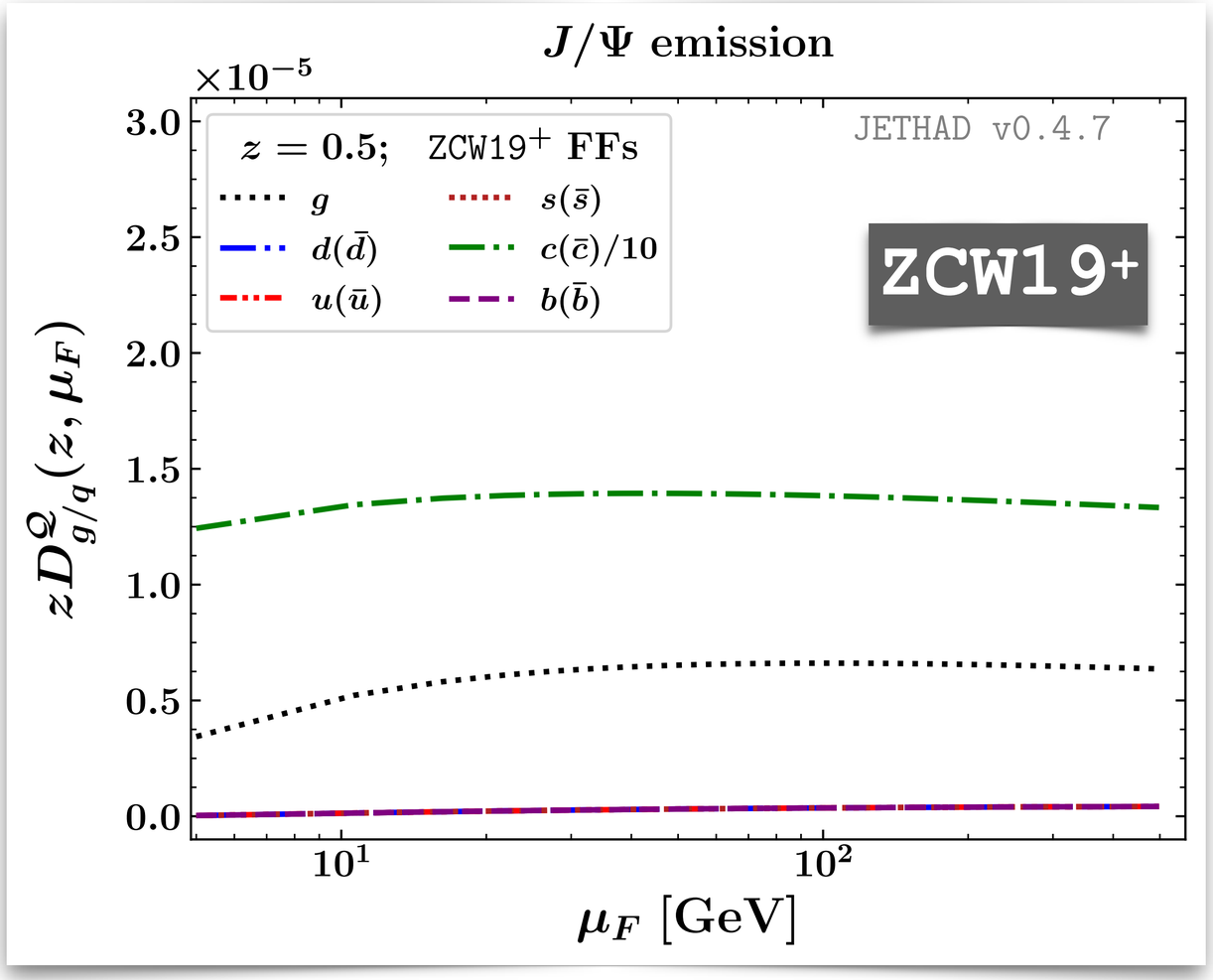


(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]
(NLO) 🔗 [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

Vector quarkonium + jet at the LHC

J/ψ collinear FFs

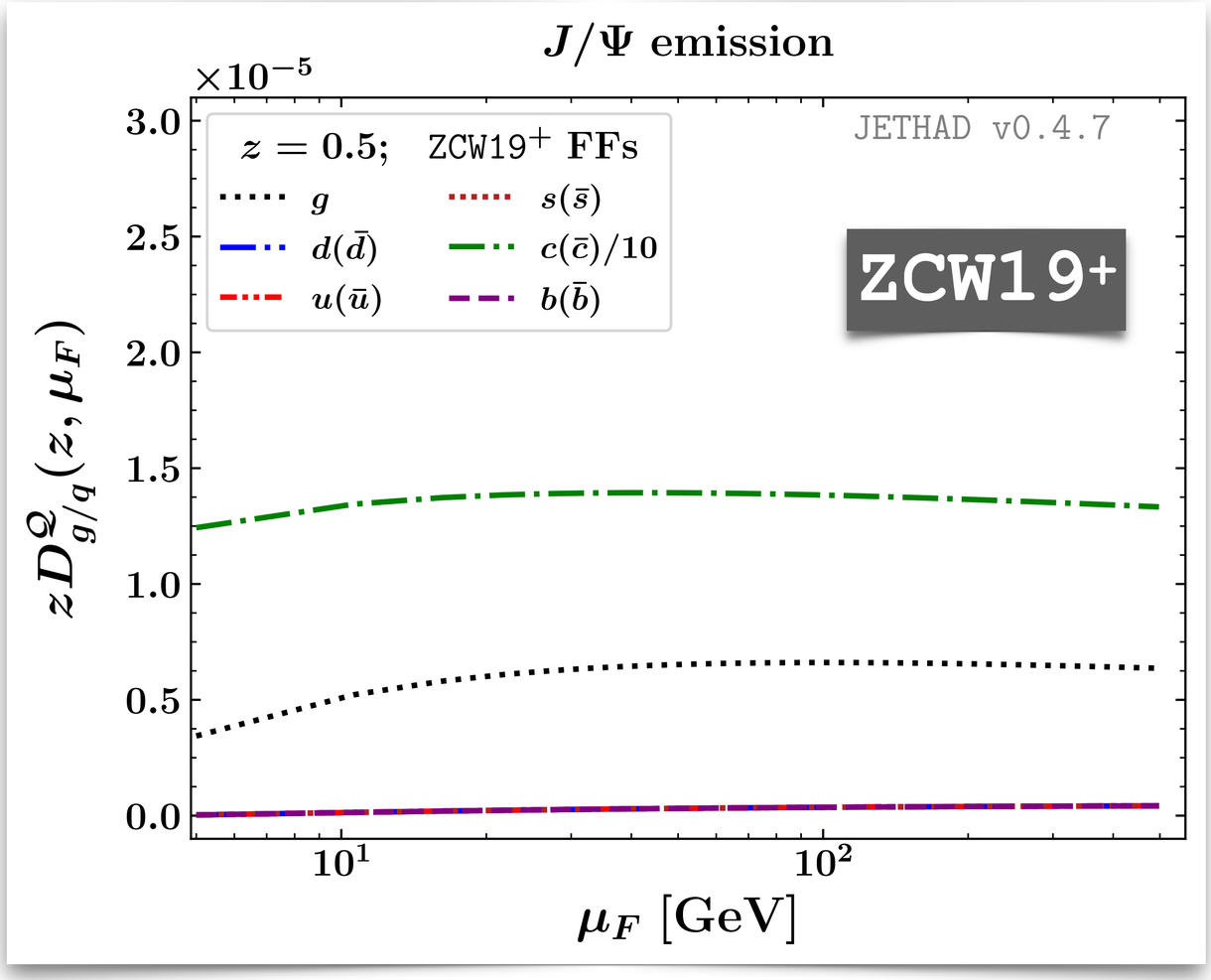




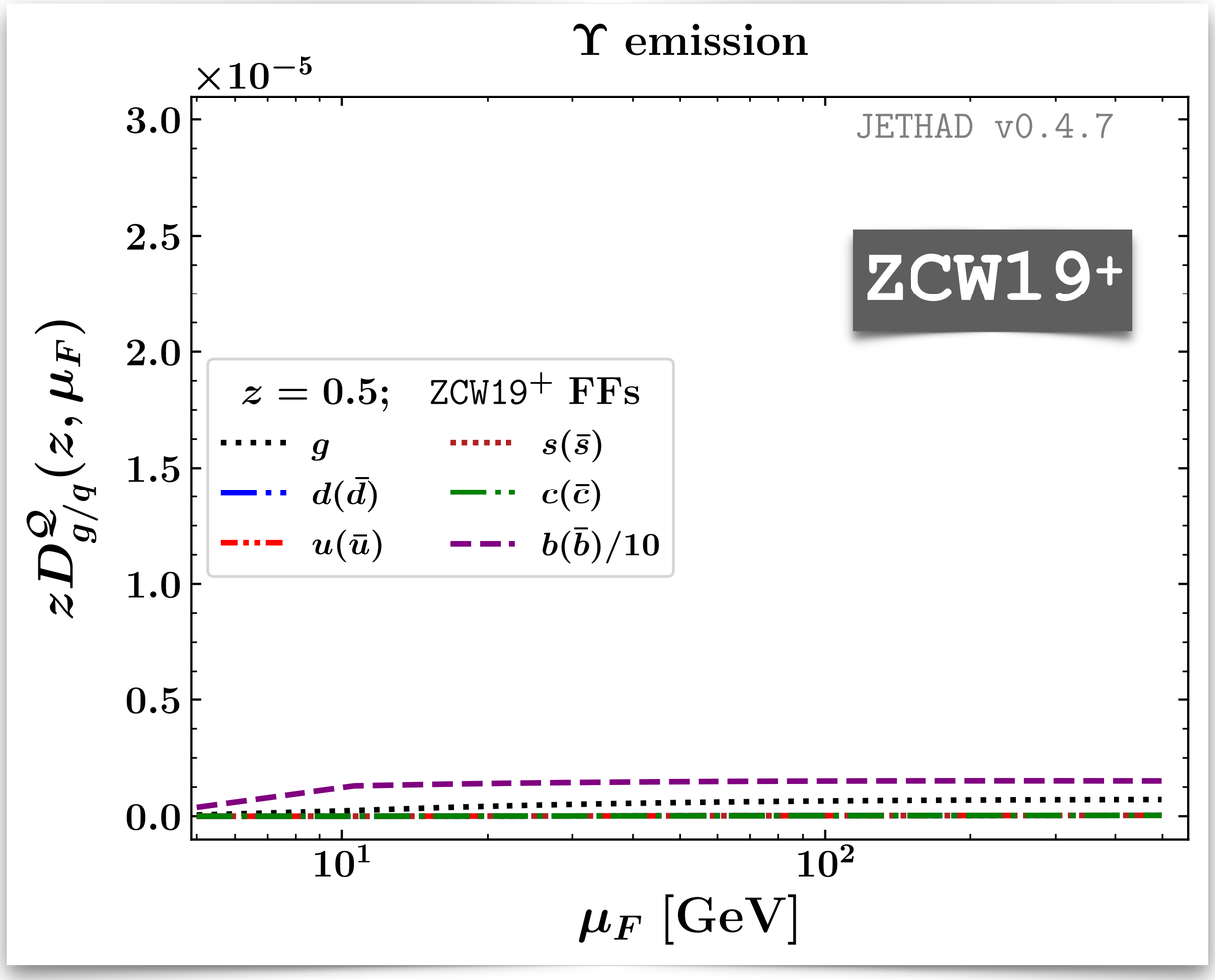
[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



Υ collinear FFs



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