High-Energy QCD and Diffraction
Part III

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Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

ANIVERSARIO PATRIMONIO MUNDIAL

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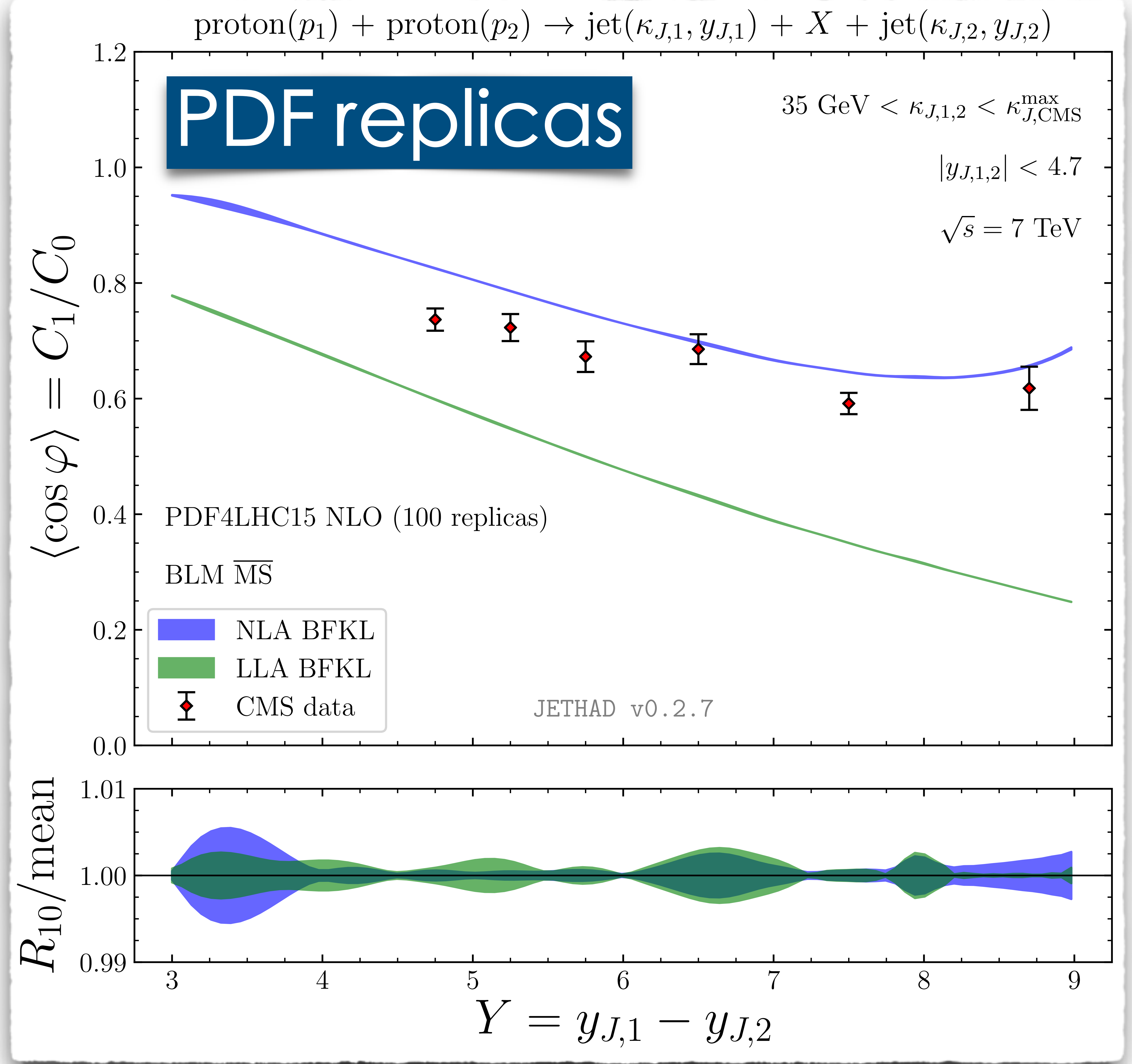
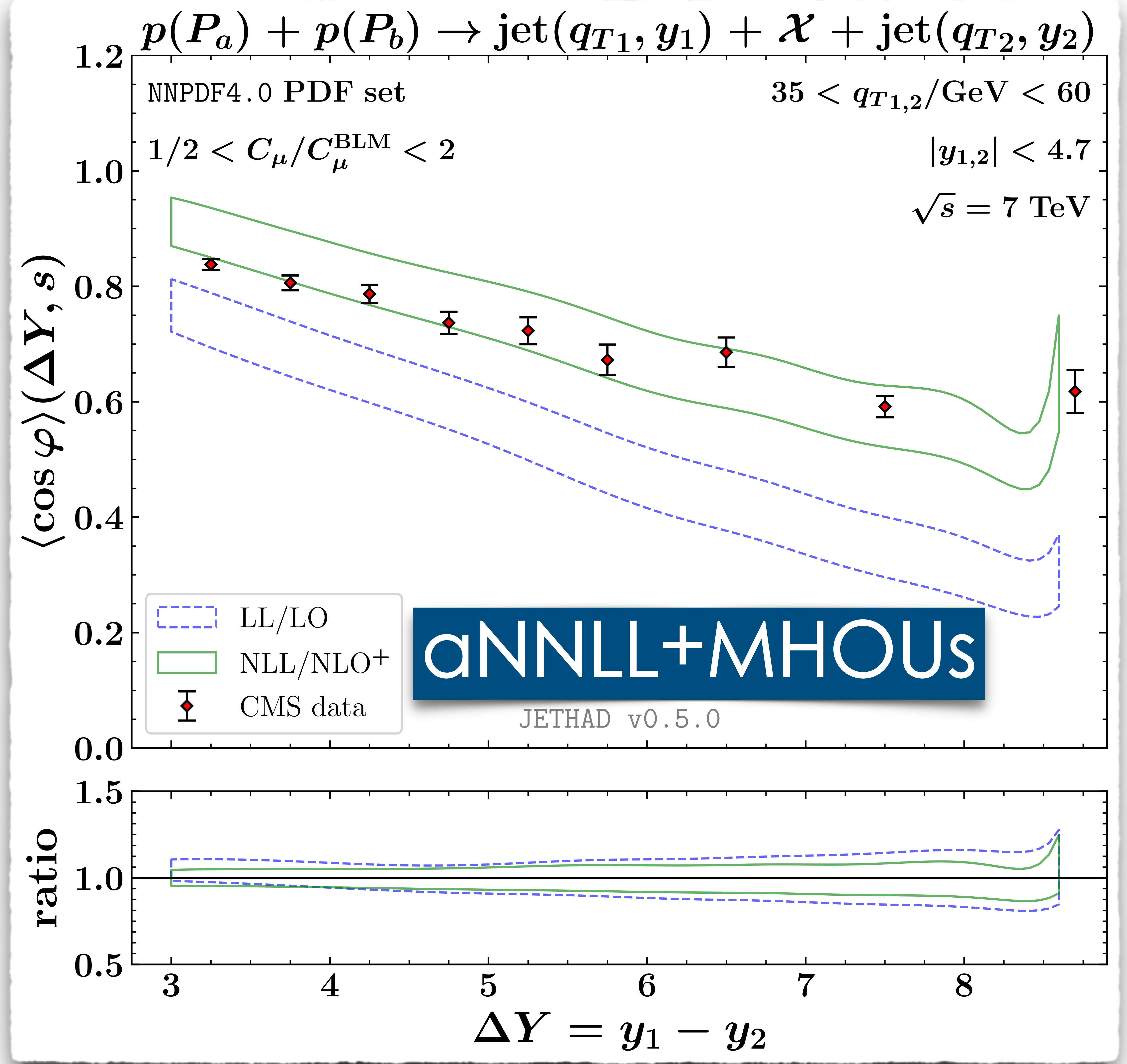
MN jets: Hunting BFKL @7TeV CMS





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

(right) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]

Mueller-Navelet jets @LHC & resummation instabilities

- BLM scales, theory vs experiment: CMS @7TeV with symmetric p_T-ranges ✓
- Strong manifestation of higher-order instabilities via scale variation (¡!)
- ¡ At natural scales: NLL/LL ratio large, no agreement with data, unphysical values !

[CMS Collaboration, JHEP 08 (2016) 139]
[B. Ducloué et al., Phys. Rev. Lett. 112 (2014) 082003]
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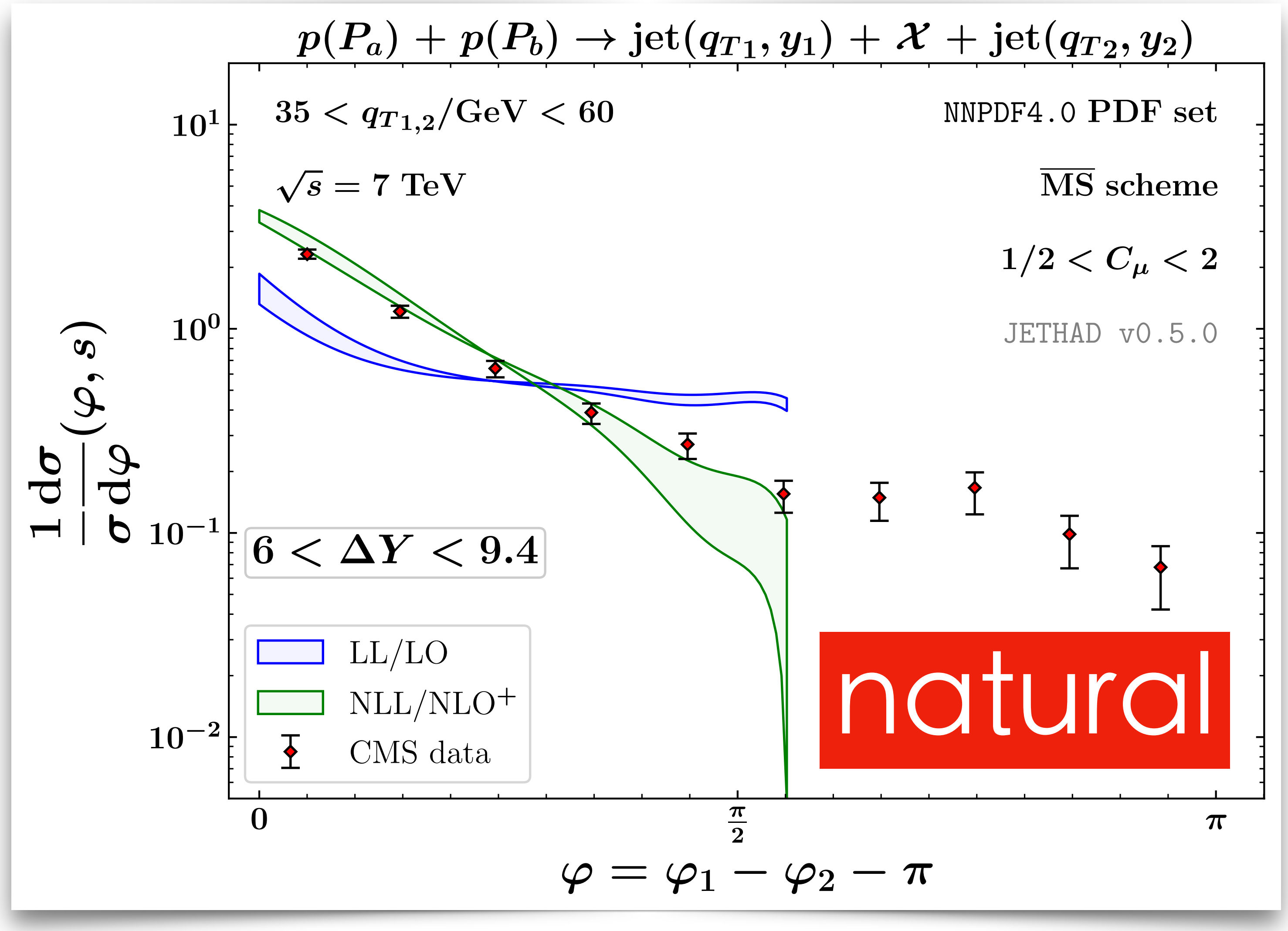

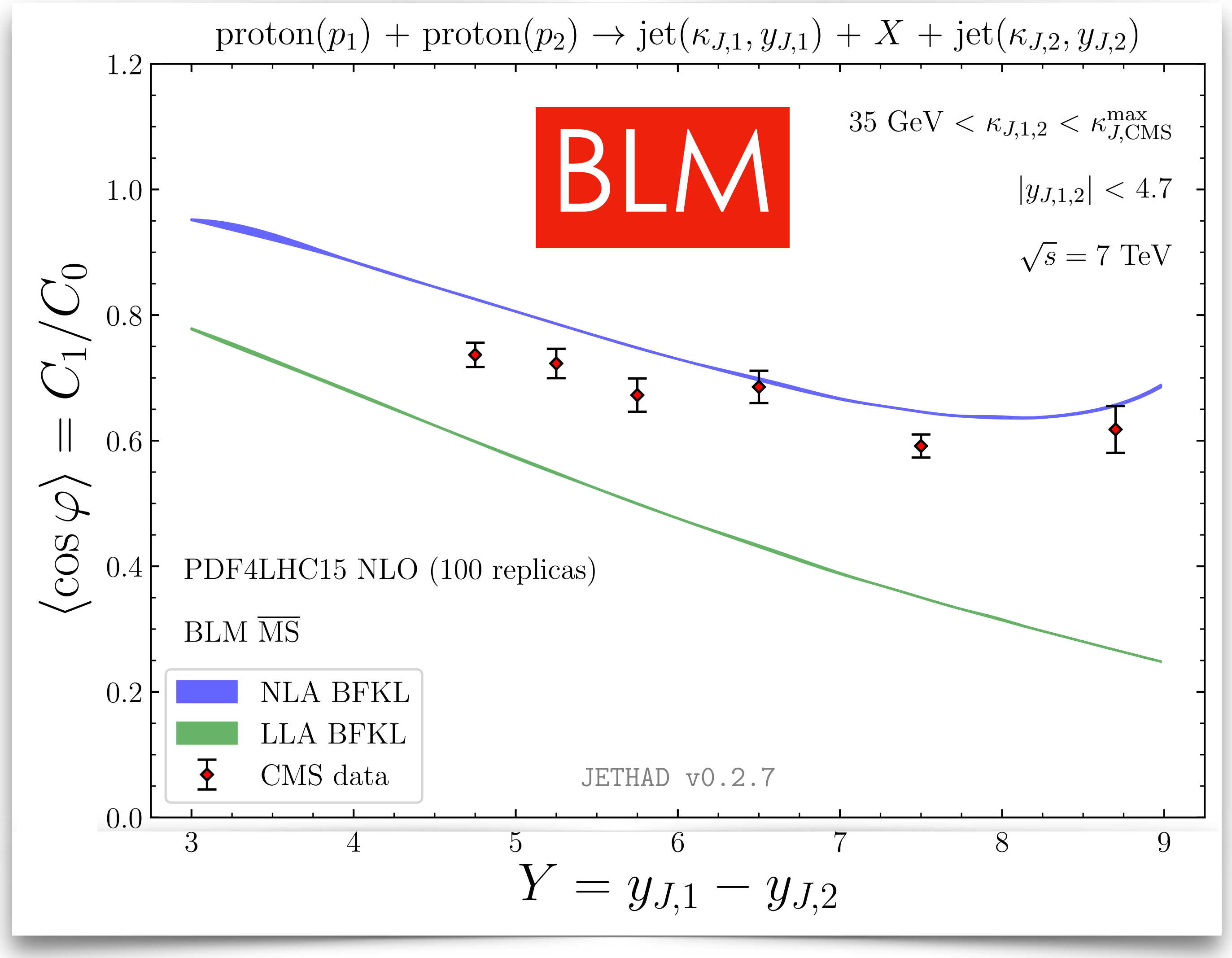

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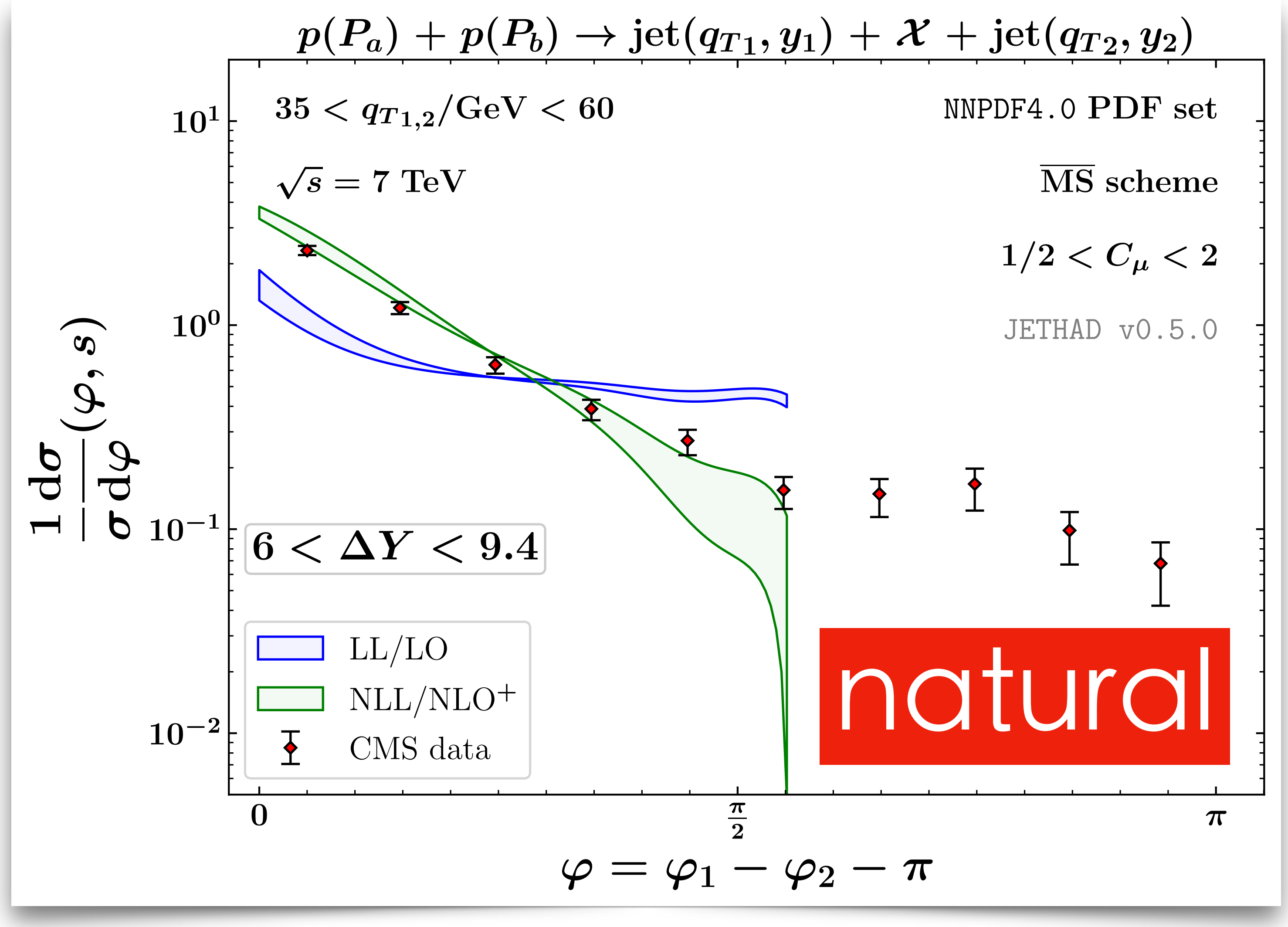

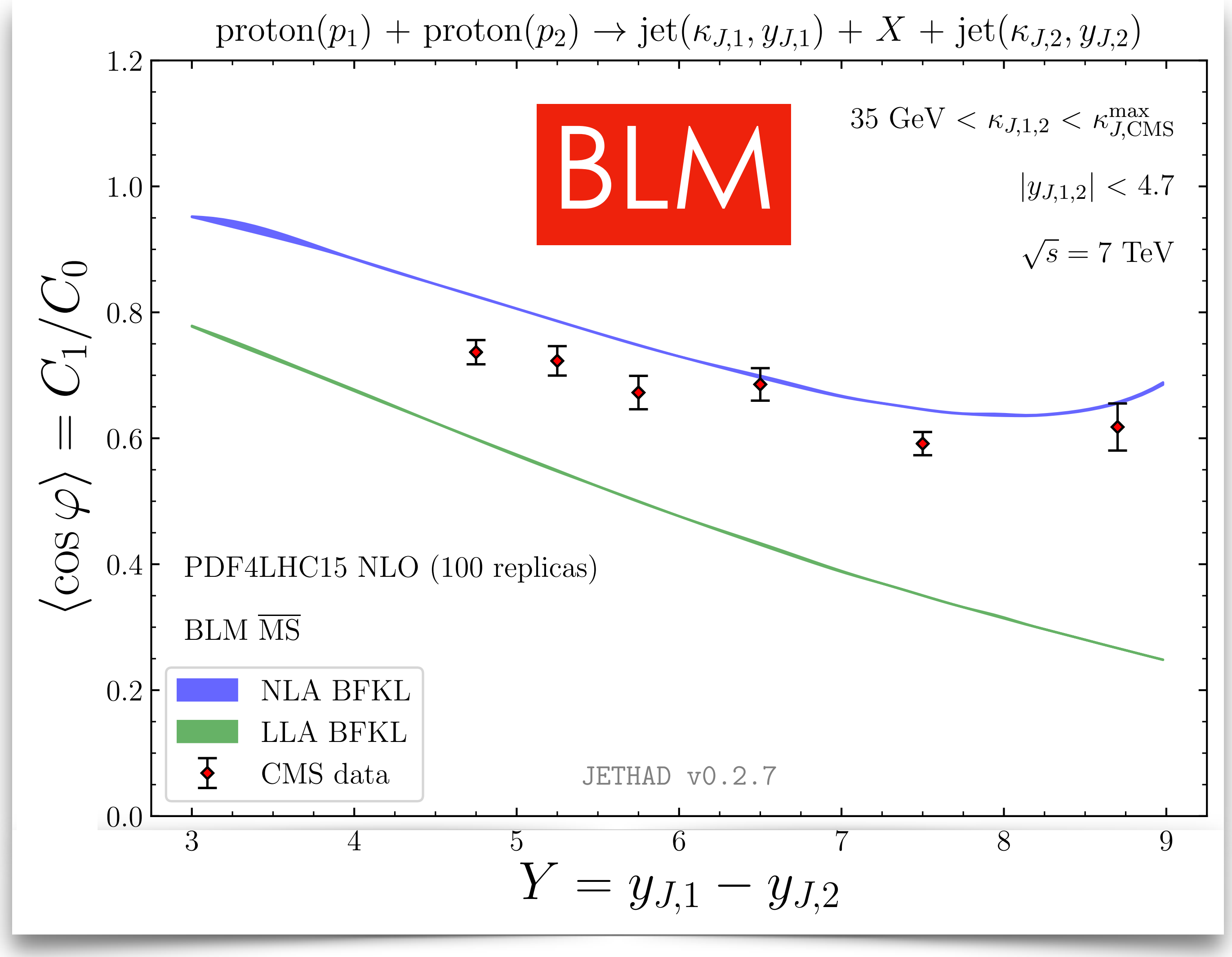

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- $\mu_R^{\text{BLM}} \gg \mu_R^{\text{nat.}} \;\Rightarrow\; d\sigma^{\text{BLM}}/d\sigma^{\text{nat.}} \sim 10^{-(1\div 2)}$ ⇒ precision studies hampered ✗
- Unsuccessful scale optimization → processes featuring natural stability (¿?)

Highlights of Lecture II

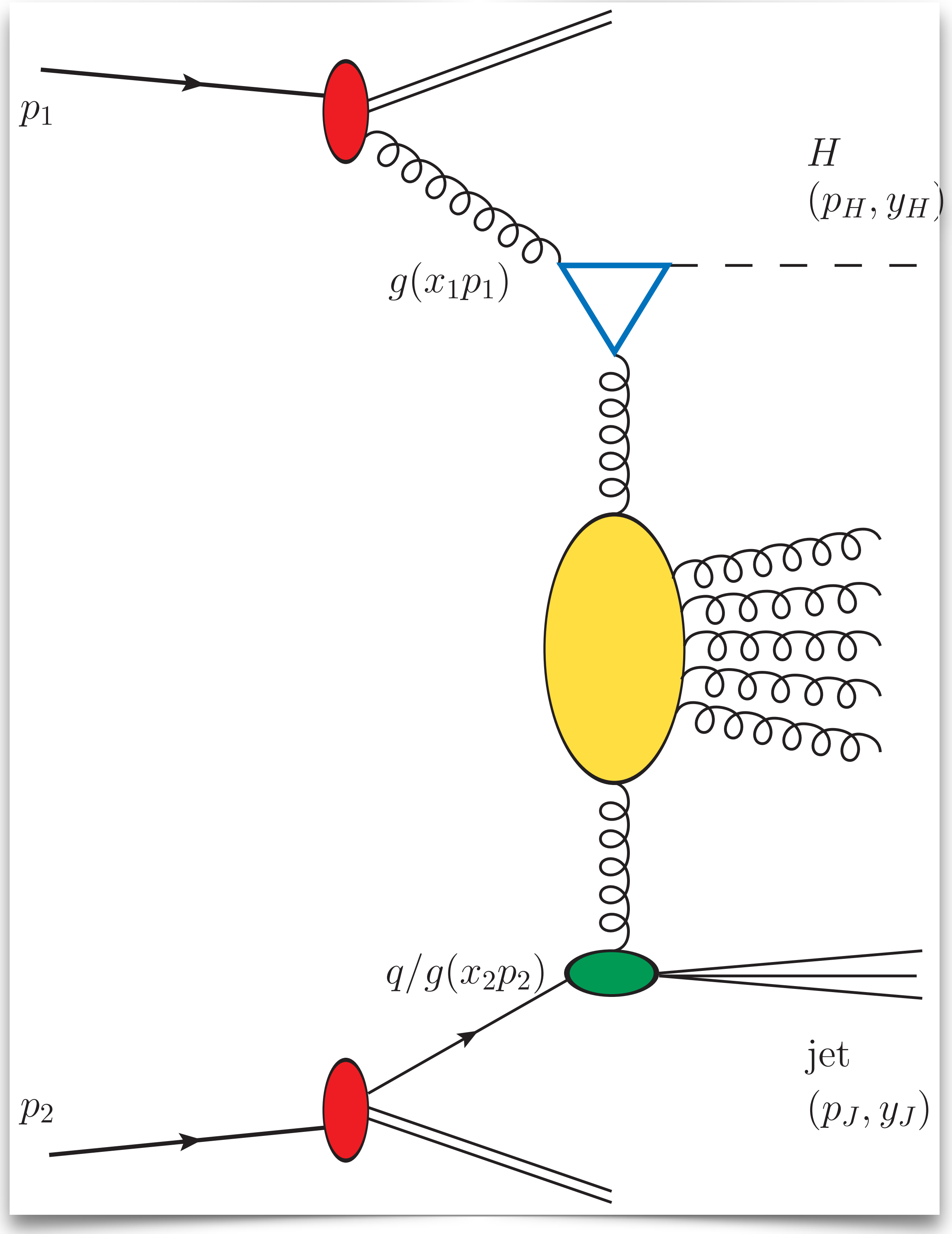
1

Higgs + jet

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

HIGGS BOSON

Stabilizers ⇔ large Higgs transverse masses



(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

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From Mueller-Navelet to Higgs and heavy flavor

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Higgs boson

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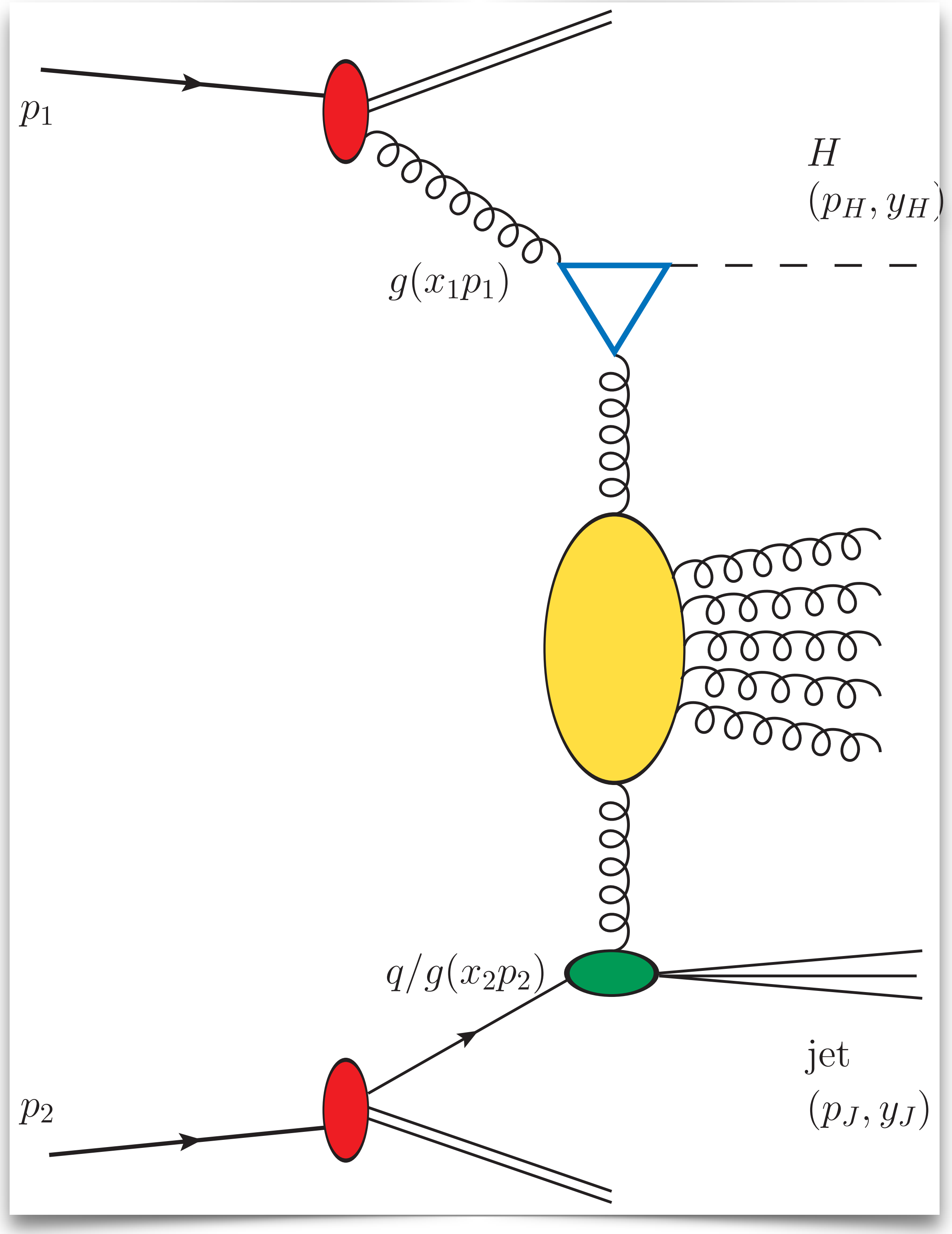

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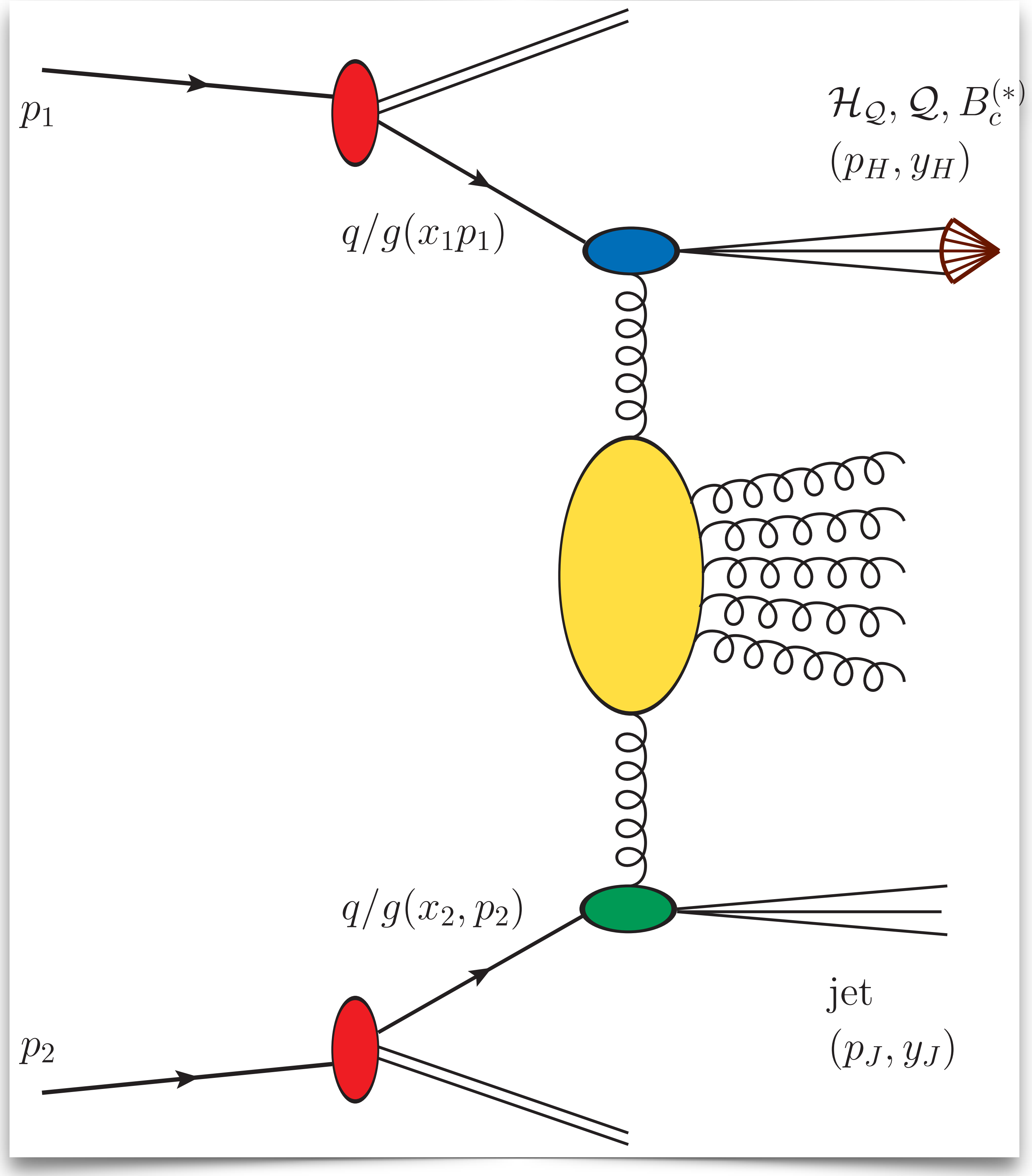
Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels



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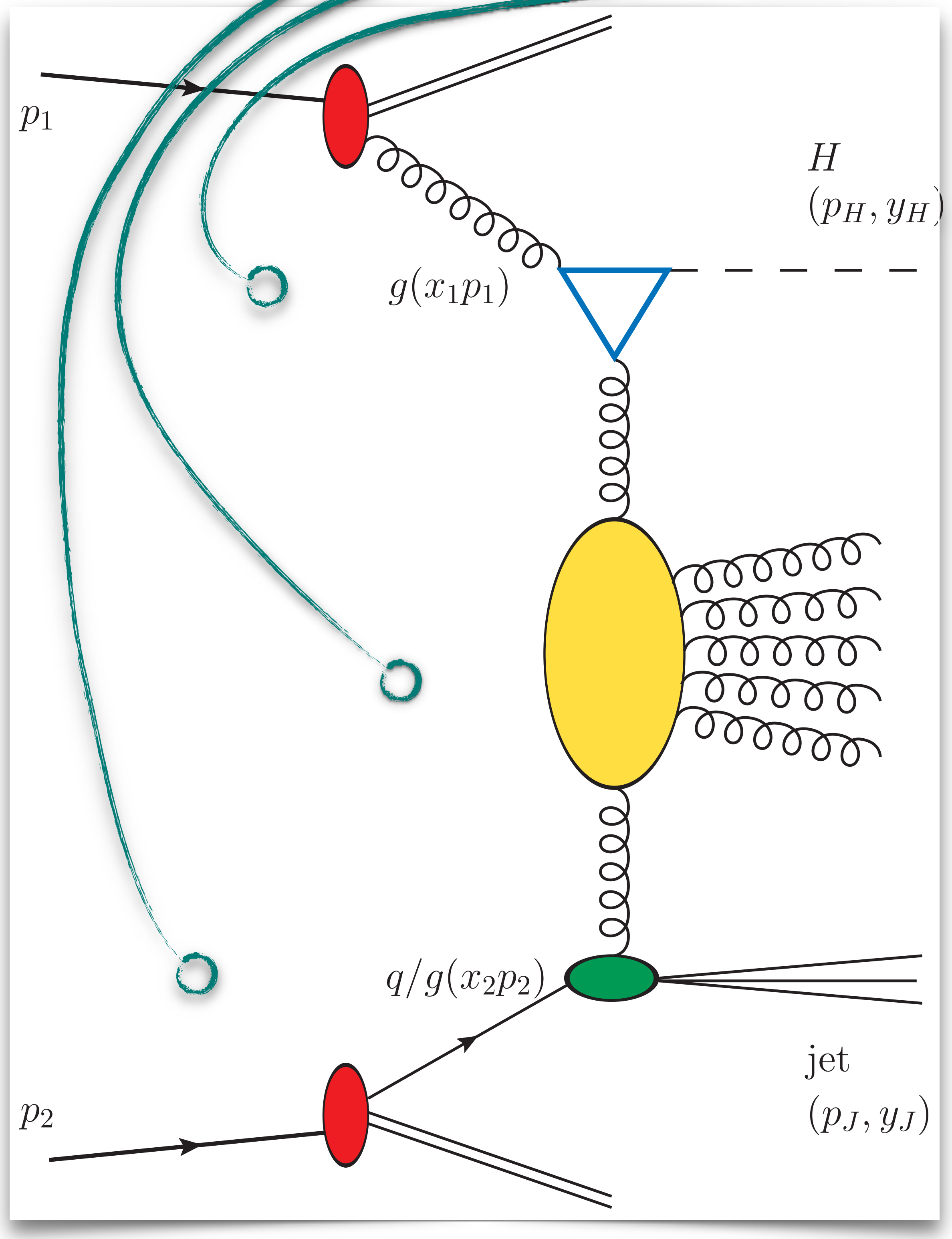
$\mu_{F,R} \sim M_{H,\perp}$



NLO*

= LO + NLO^{RGE}

NLL

NLO

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HEAVY FLAVOR AT LARGE p_T

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NLL

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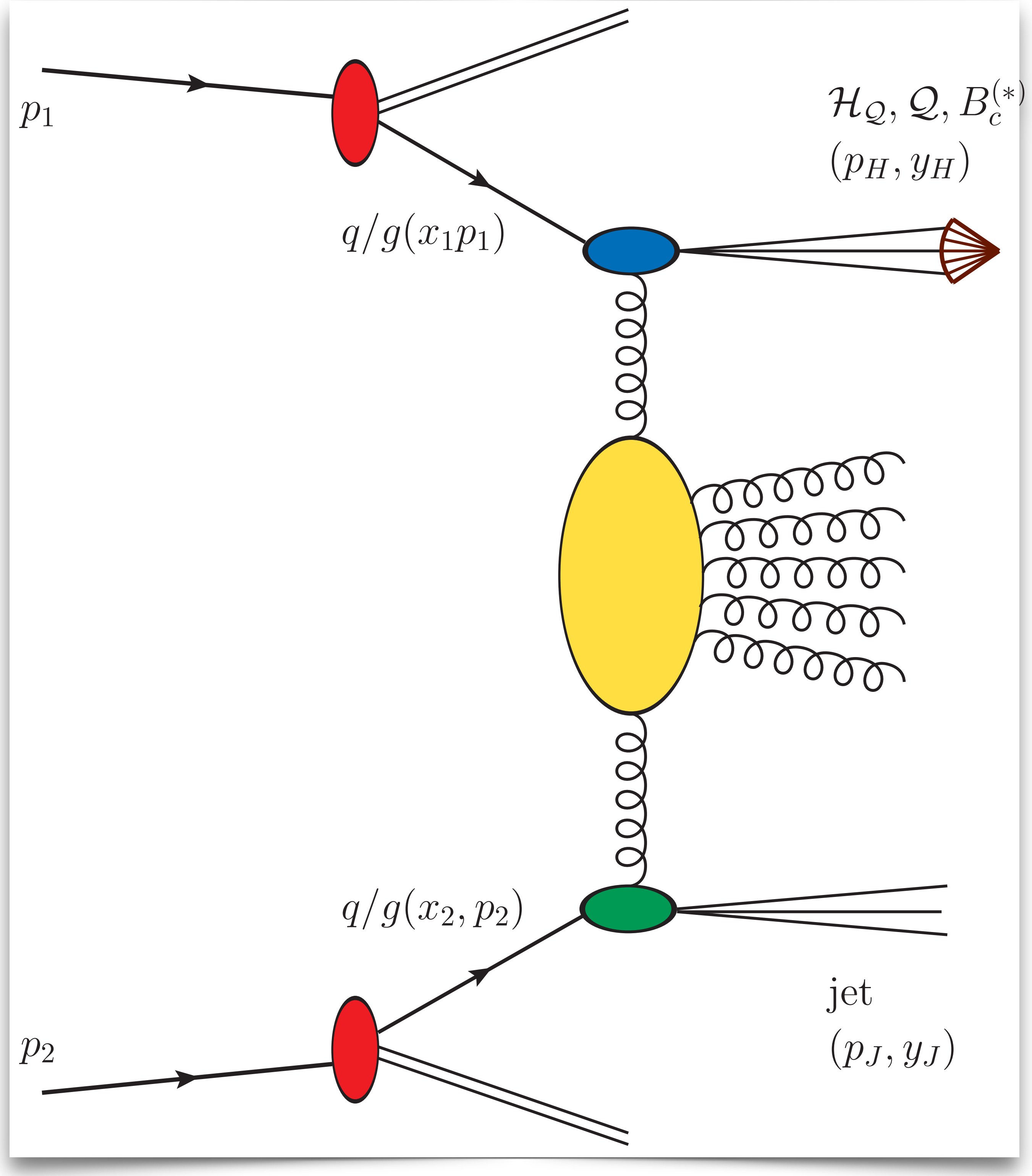

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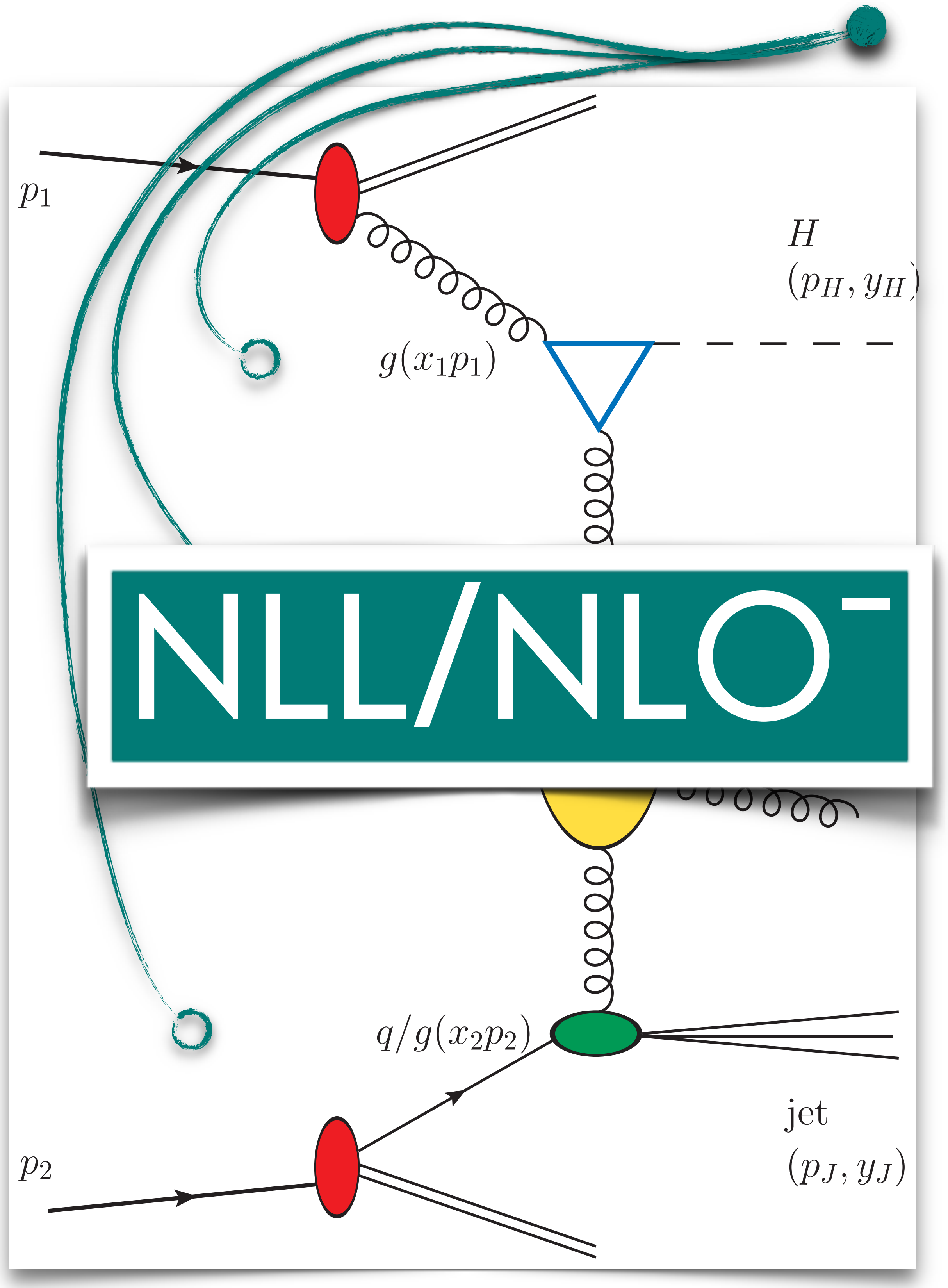

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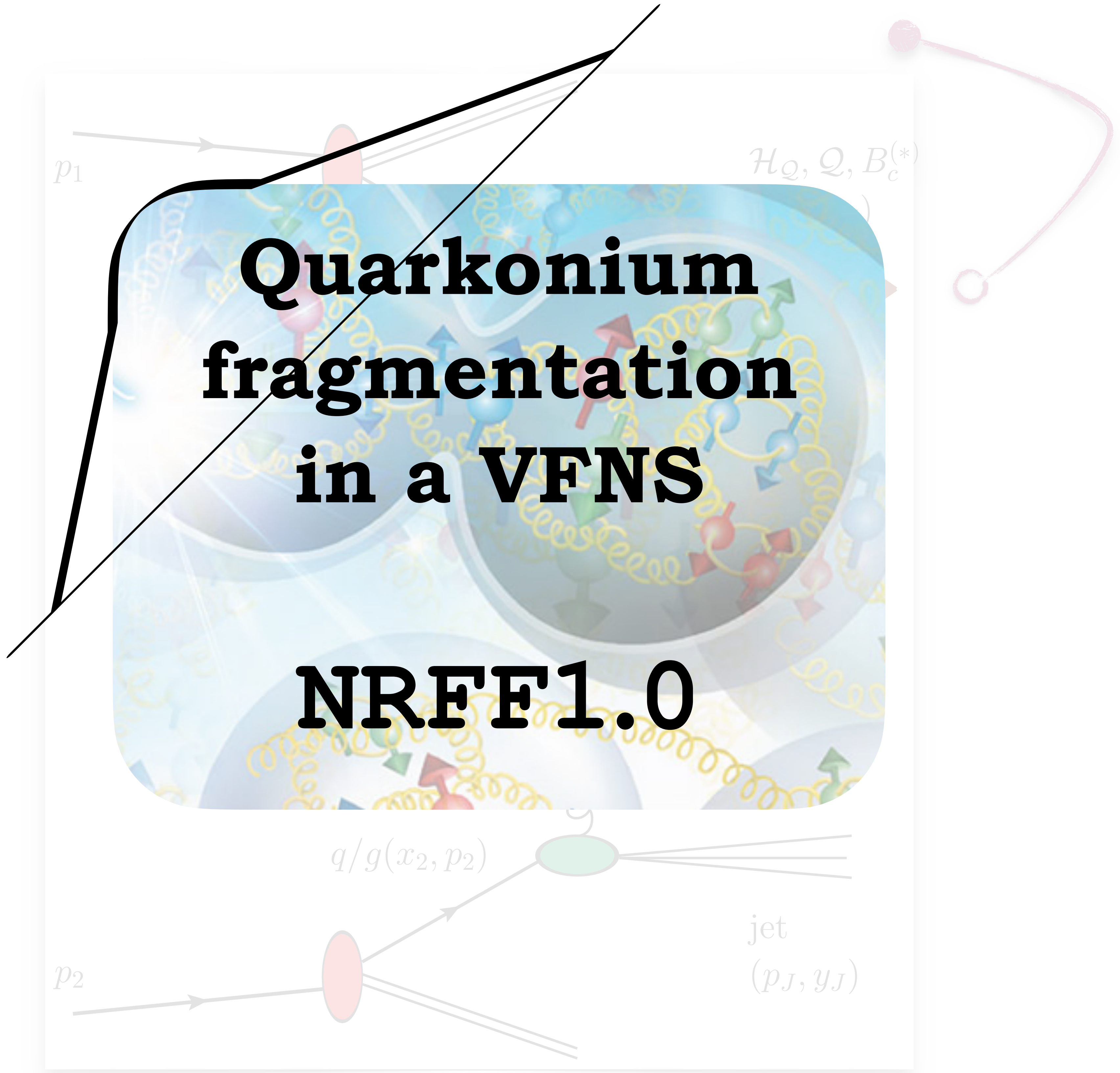

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Higgs production from LHC to FCC

PHYSICAL REVIEW LETTERS **120,** 202003 (2018)

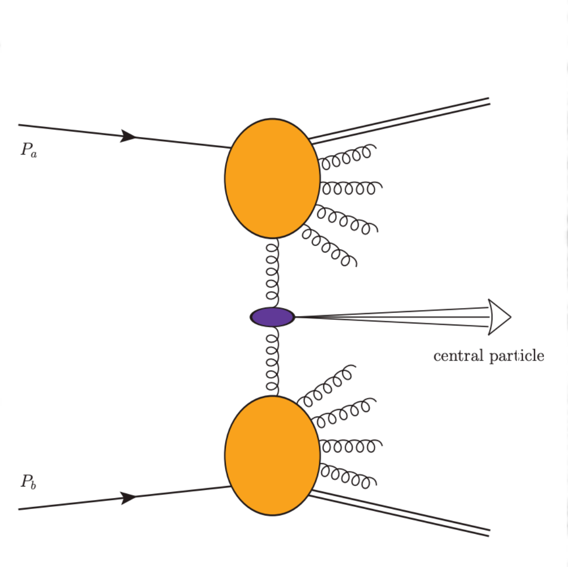
Double Resummation for Higgs Production

Marco Bonvini[1,*] and Simone Marzani[2,†]
[1]*INFN, Sezione di Roma 1, Piazzale Aldo Moro 5, 00185 Roma, Italy*
[2]*Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy*

(Received 26 February 2018; published 16 May 2018)

We present the first double-resummed prediction of the inclusive cross section for the main Higgs production channel in proton-proton collisions, namely, gluon fusion. Our calculation incorporates to all orders in perturbation theory two distinct towers of logarithmic corrections which are enhanced, respectively, at threshold, i.e., large x, and in the high-energy limit, i.e., small x. Large-x logarithms are resummed to next-to-next-to-next-to-leading logarithmic accuracy, while small-x ones to leading logarithmic accuracy. The double-resummed cross section is furthermore matched to the state-of-the-art fixed-order prediction at next-to-next-to-next-to-leading accuracy. We find that double resummation corrects the Higgs production rate by 2% at the currently explored center-of-mass energy of 13 TeV and its impact reaches 10% at future circular colliders at 100 TeV.

DOI: 10.1103/PhysRevLett.120.202003



(*b*) Single central

High-energy resummation (BFKL) ⇒ PDFs at small-x

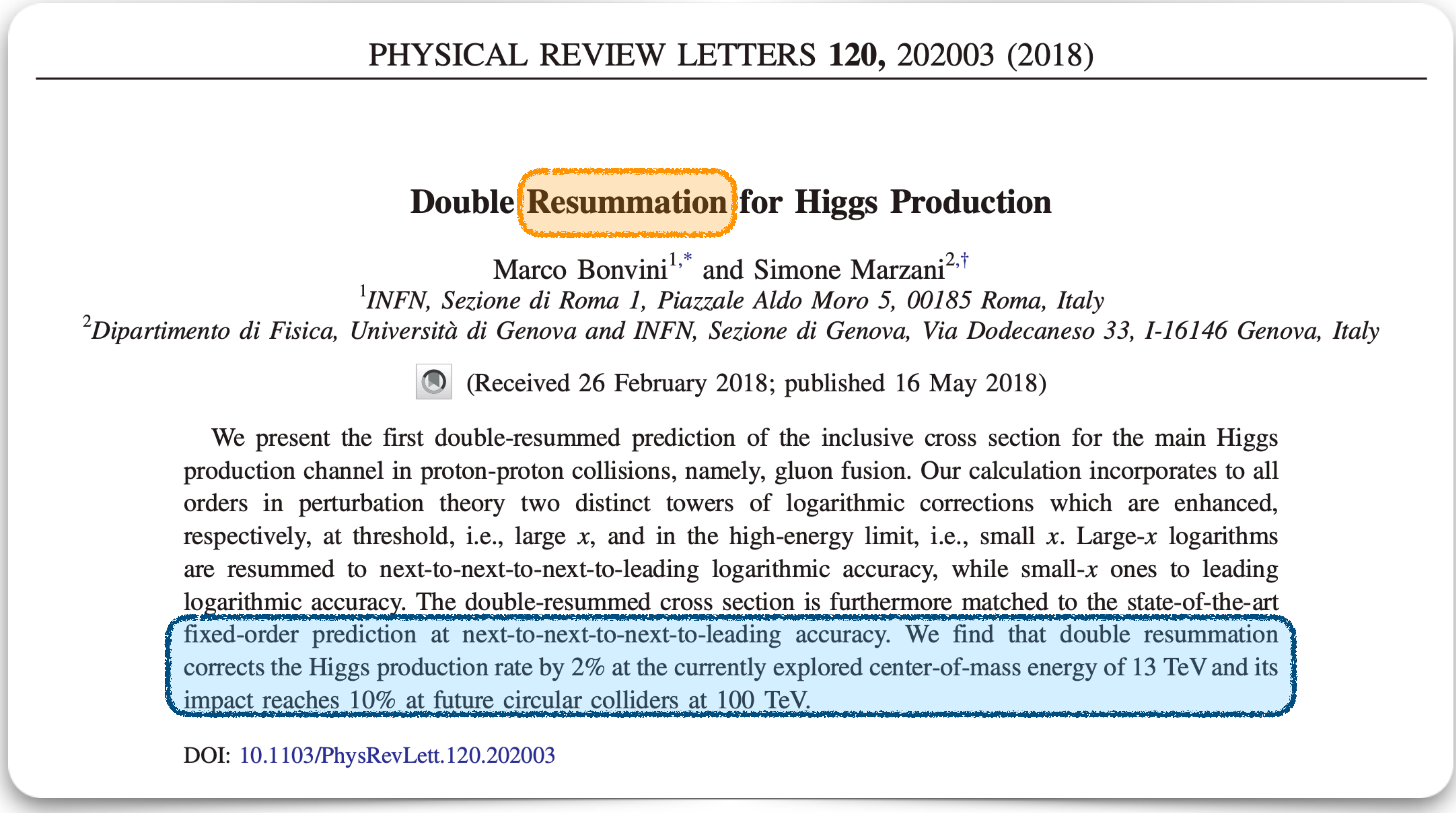
Altarelli-Ball-Forte to stabilize the $\mathrm{NLL_{sx}}$ BFKL kernel

$\mathrm{N^3LL_{lx}}$/$\mathrm{LL_{sx}}$/$\mathrm{N^3LO}$ rapidity-inclusive coefficient functions

$$C_{ij}(x,\alpha_s) = C^{\mathrm{fo}}_{ij}(x,\alpha_s) + \Delta C^{\mathrm{lx}}_{ij}(x,\alpha_s) + \Delta C^{\mathrm{sx}}_{ij}(x,\alpha_s)$$

III.1 Higgs + jet

Higgs production from LHC to FCC



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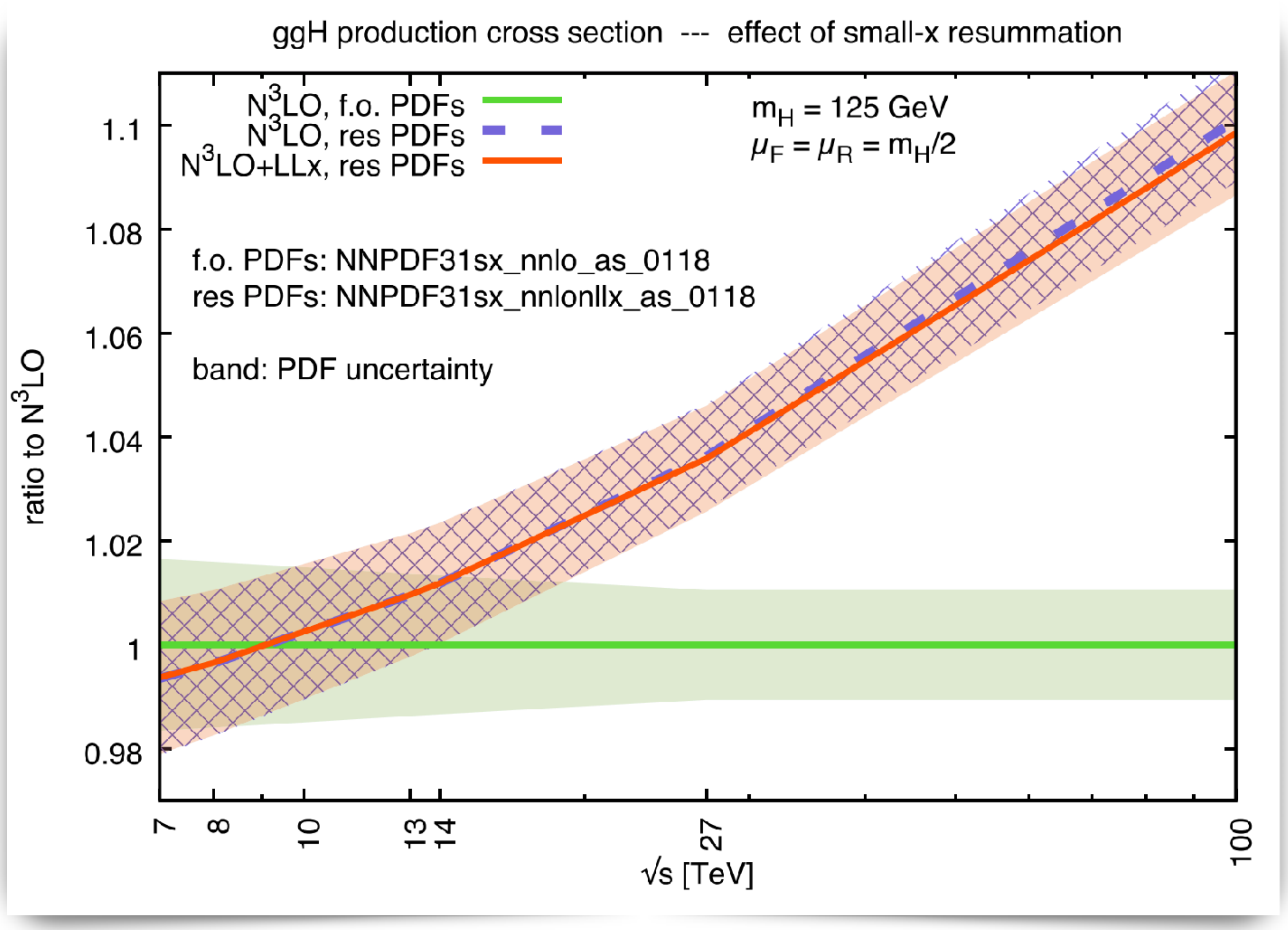

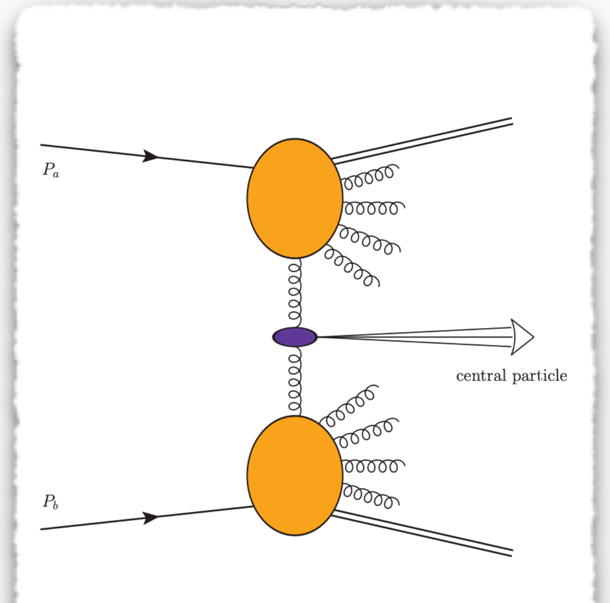

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(¡!) 100 TeV EW physics ⇔ small-x physics!

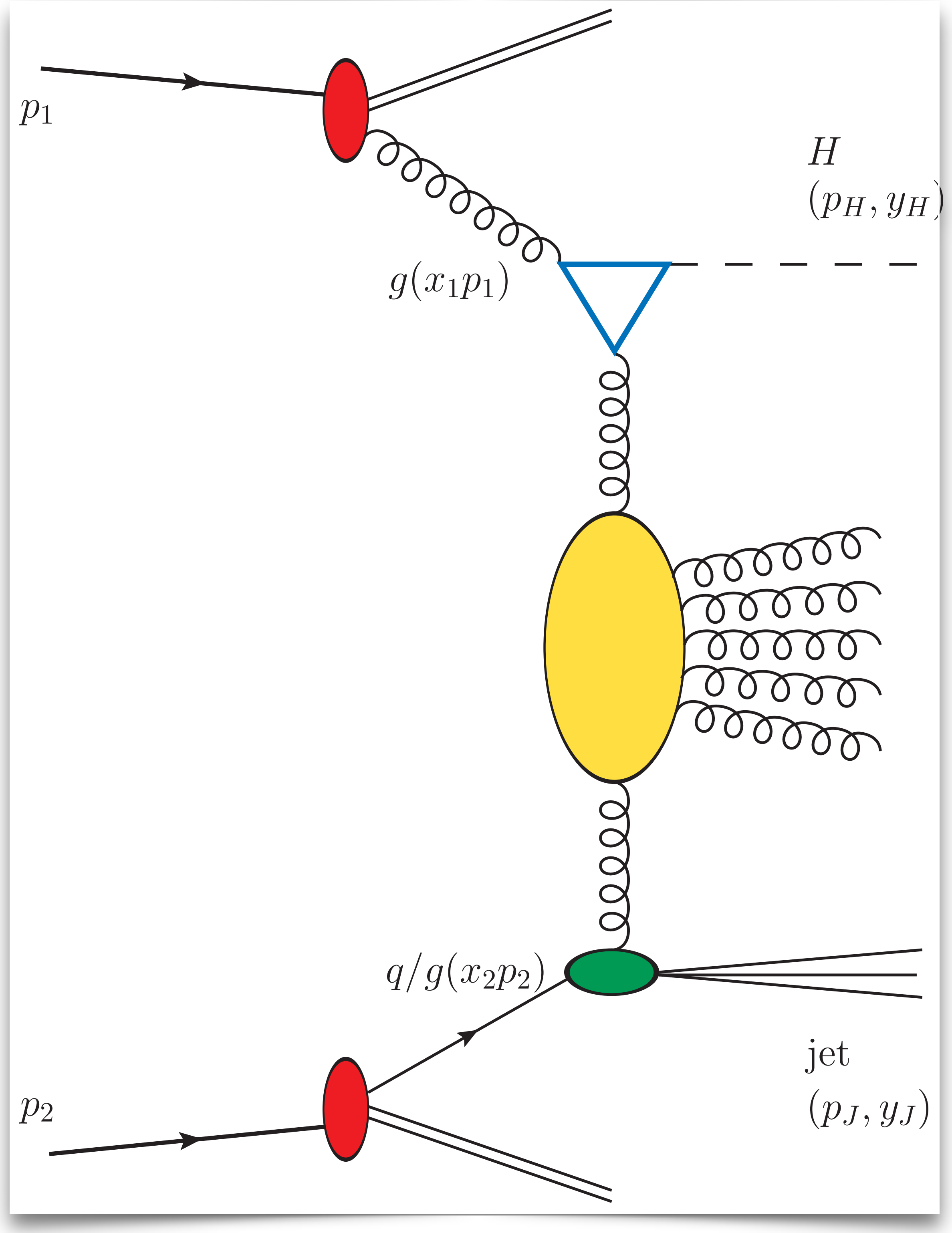
(¿?) Can LHC physics be BFKL physics?

Inclusive Higgs + jet at the LHC

- Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, ΔY
- Large energy scales expected to stabilize the high-energy resummed series

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\, \mathcal{C}_n\right]$$

$$\varphi = \varphi_H - \varphi_J - \pi$$



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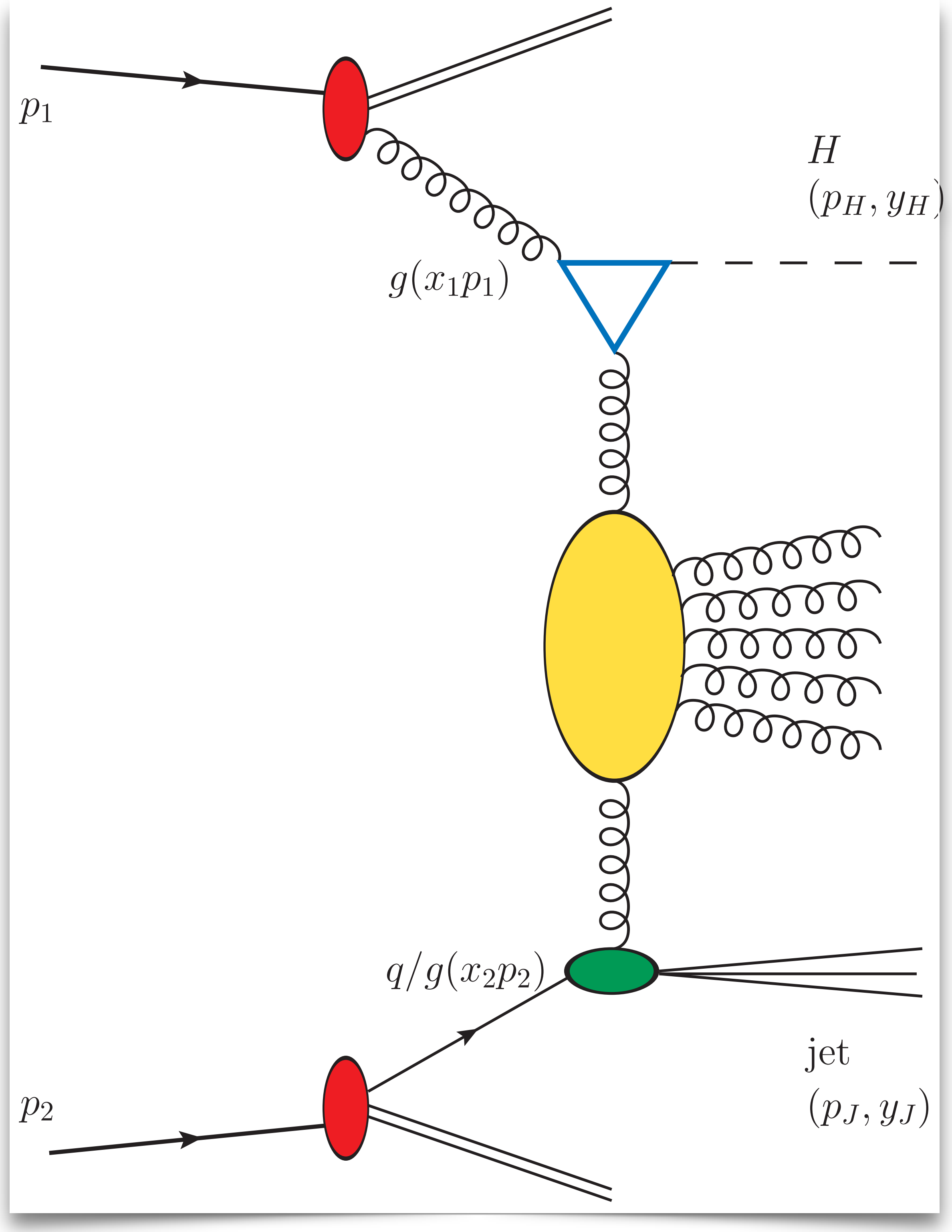

NLO* = LO + NLO[RGE]

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$

NLO* $$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H)$$

NLL $$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i}\left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$

NLO(*) $$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

BFKL Green's function

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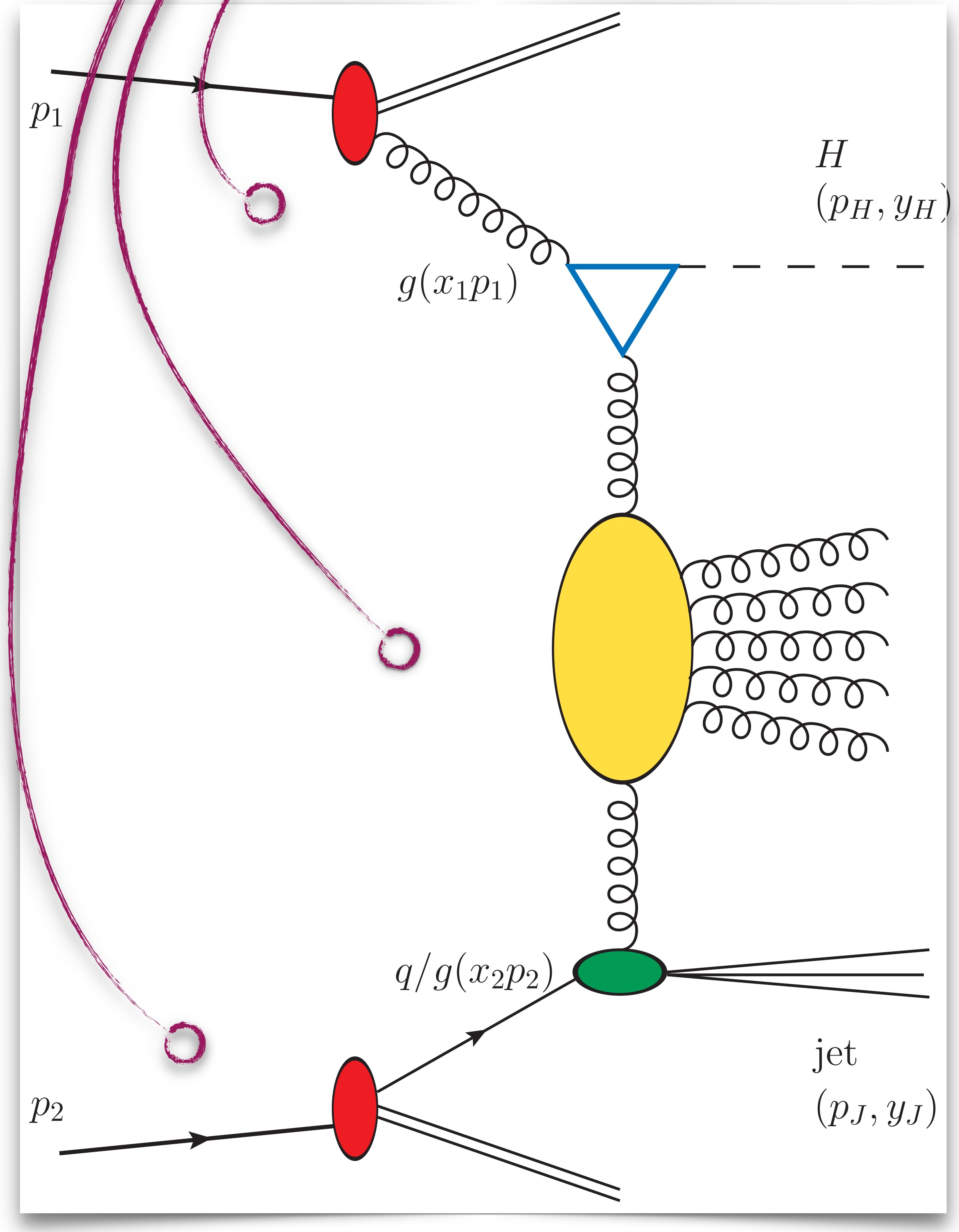

$\mu_{F,R} \sim M_{H,\perp}$

$\mu_R \sim \sqrt{M_{H,\perp}\, p_J}$

$\mu_{F,R} \sim p_J$

NLO* = LO + NLO^RGE

NLO*

NLL

NLO^(*)

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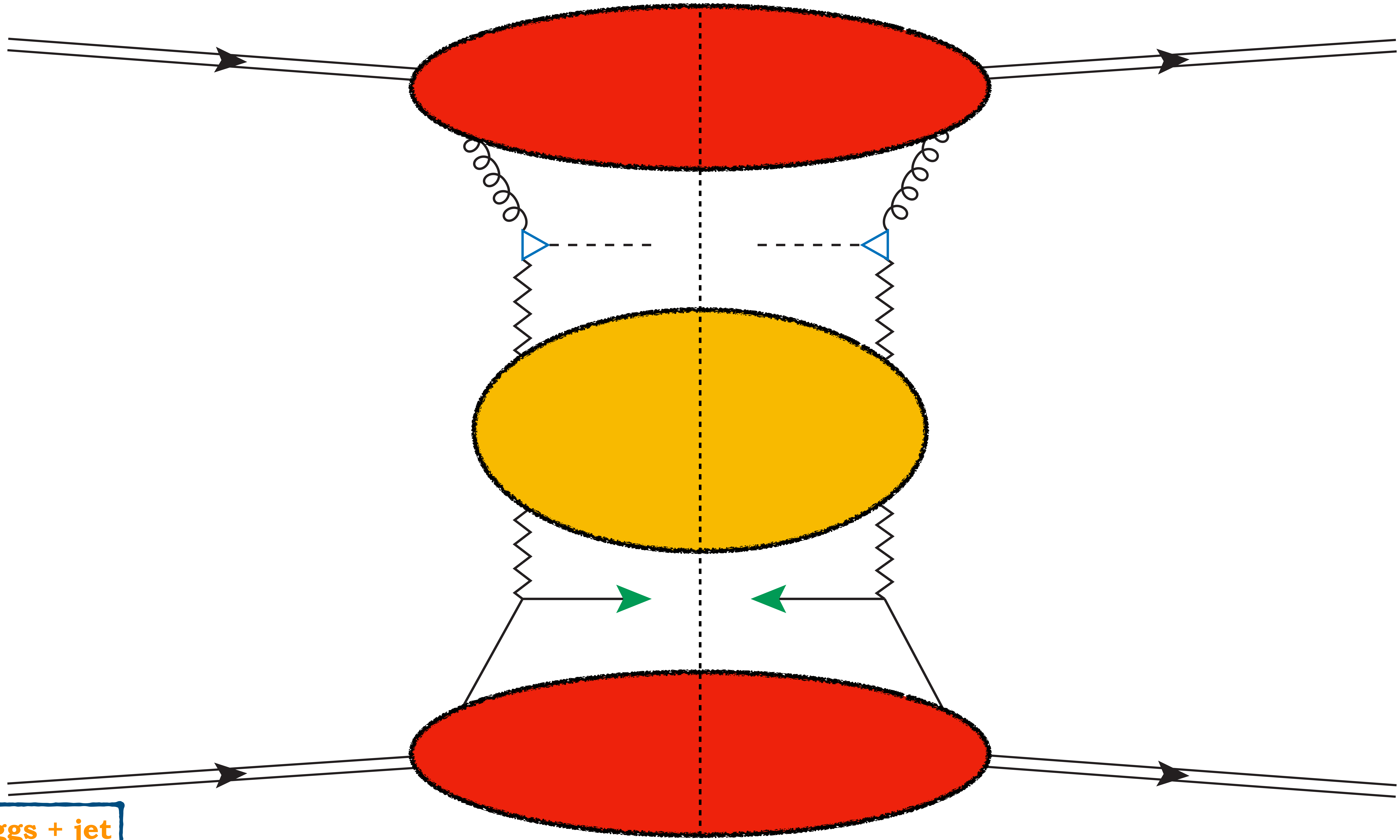
BFKL Green's function

Anatomy of Higgs + jet in hybrid factorization (HyF)



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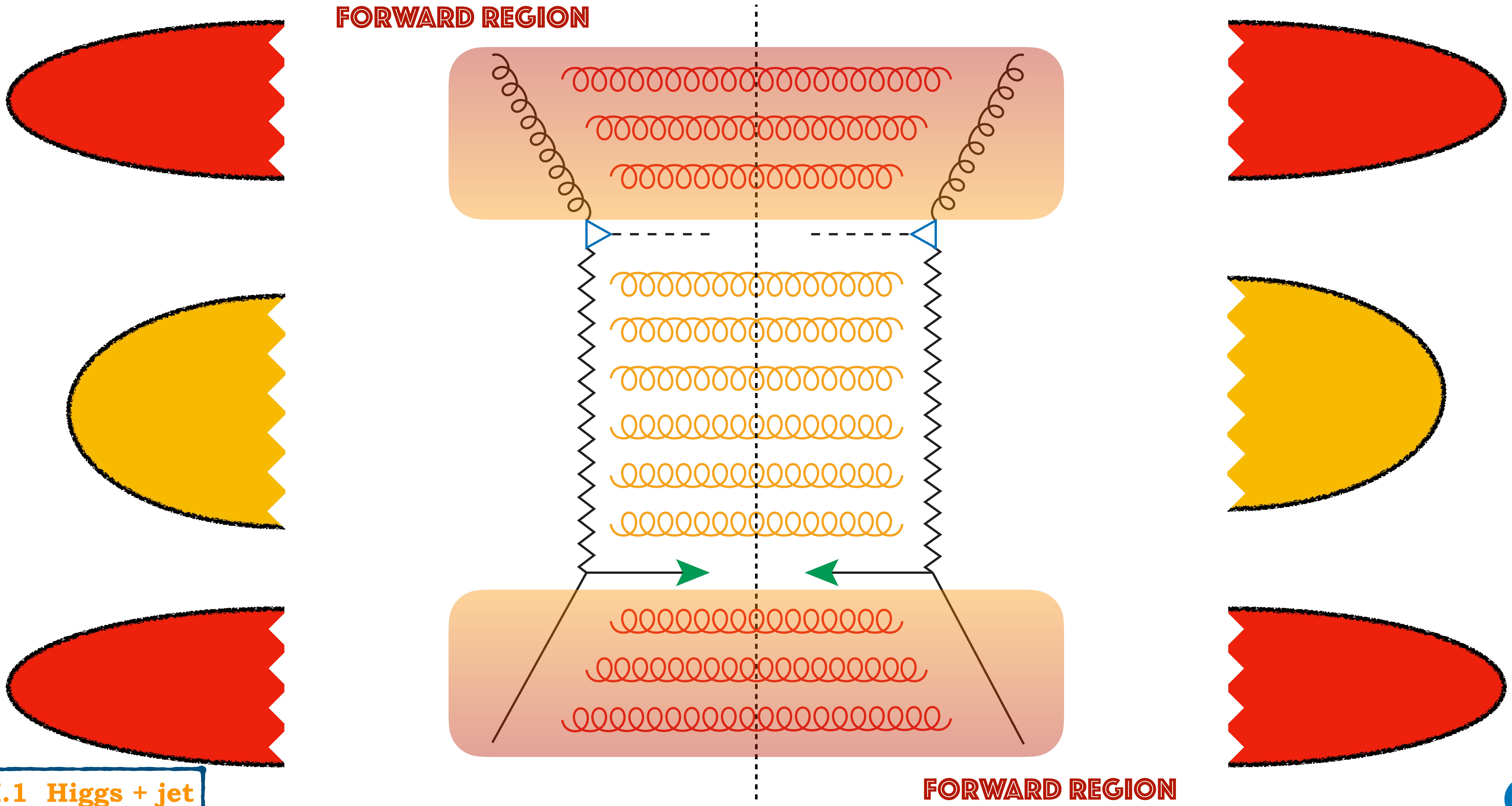

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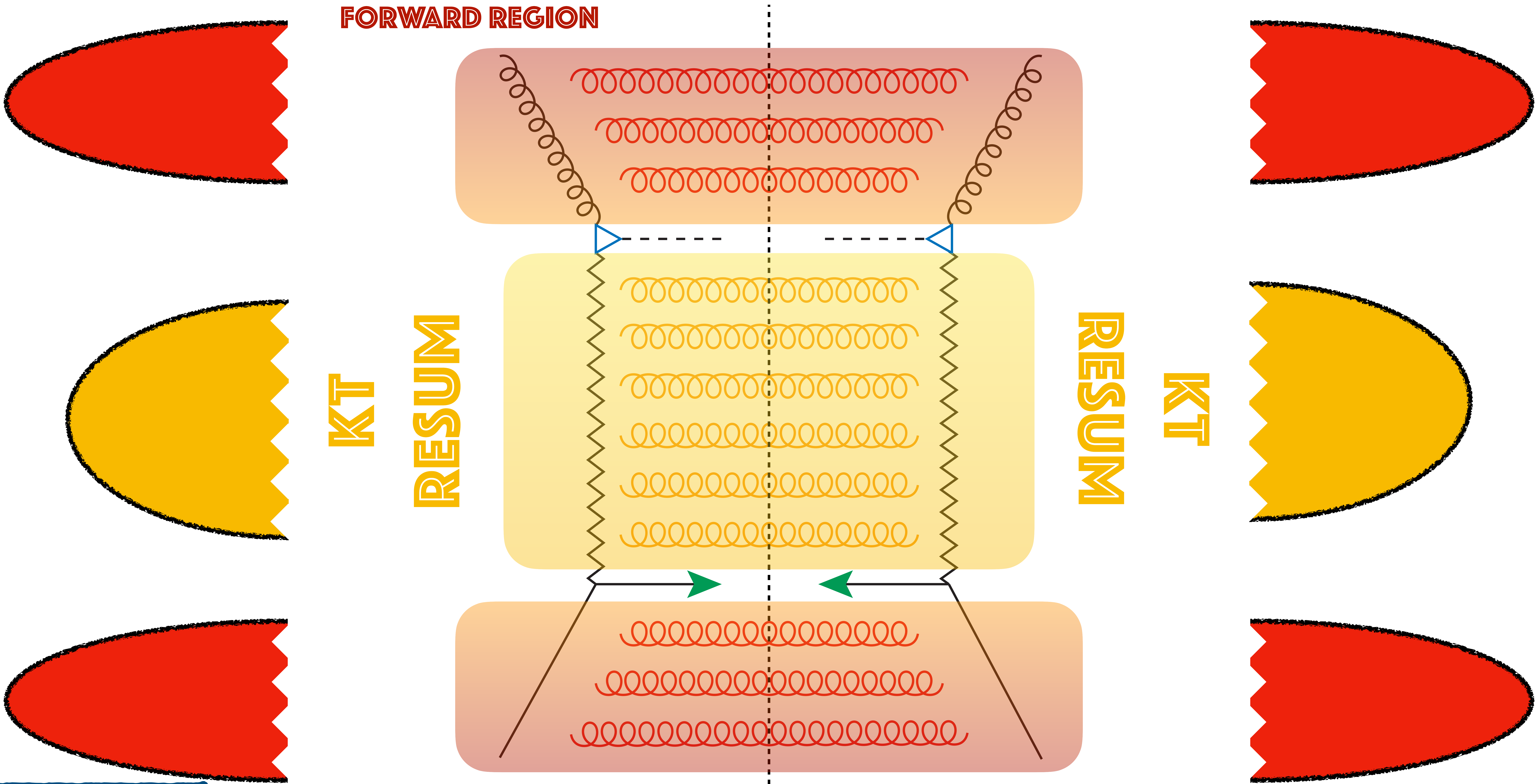
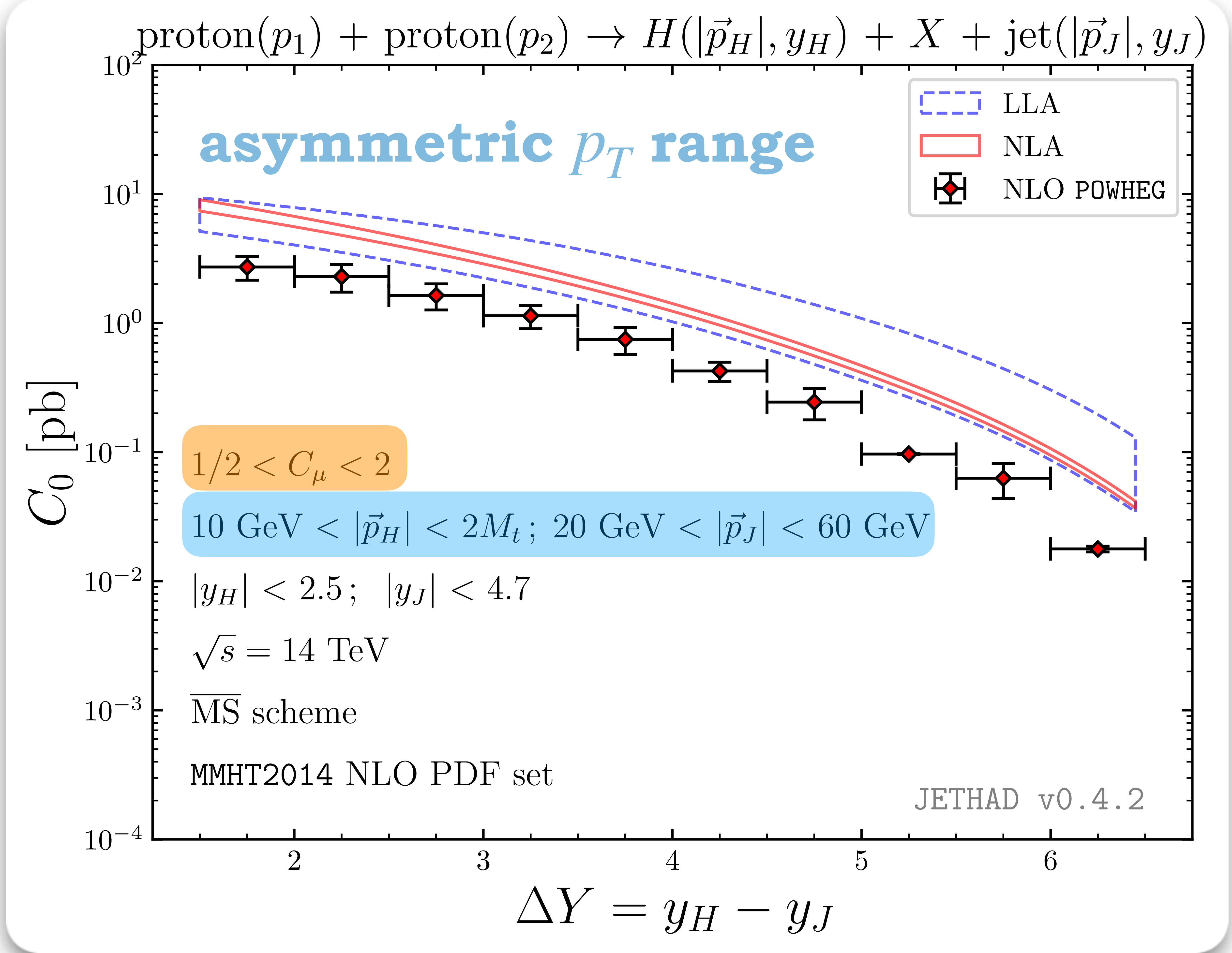


ΔY-distribution

$$\mathcal{C}_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$



[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Angular correlations

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

MUELLER-NAVELET JETS

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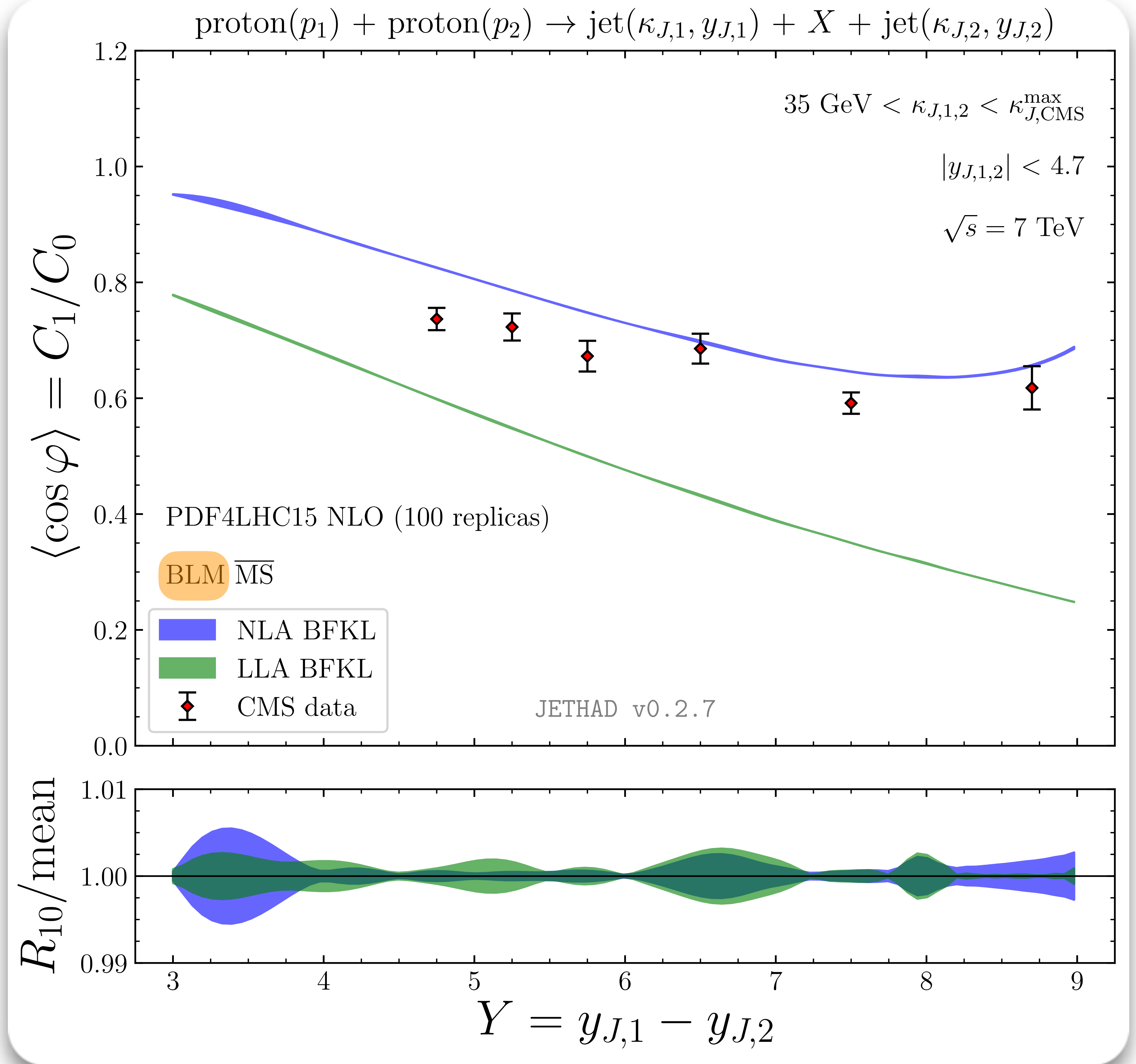

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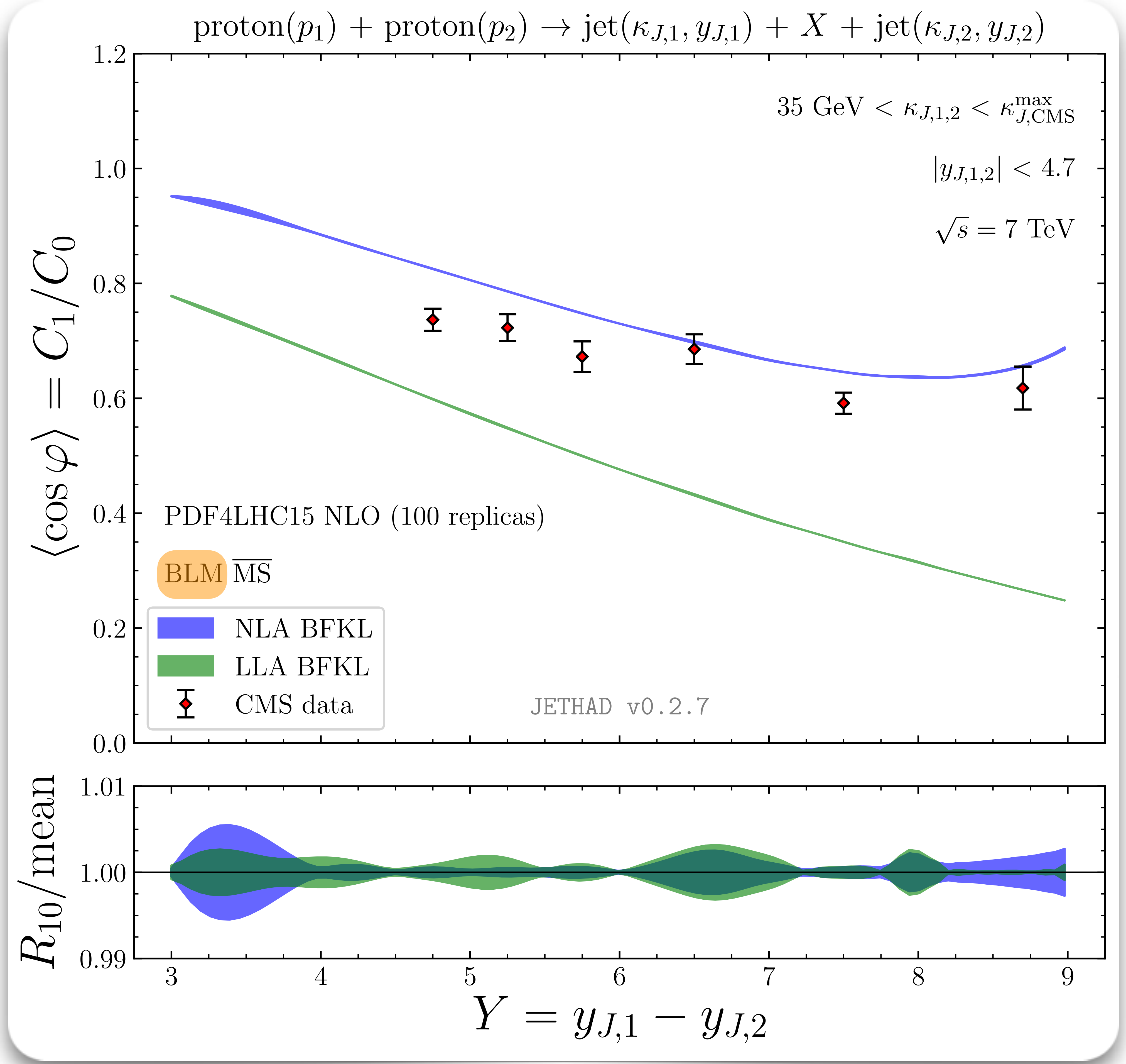

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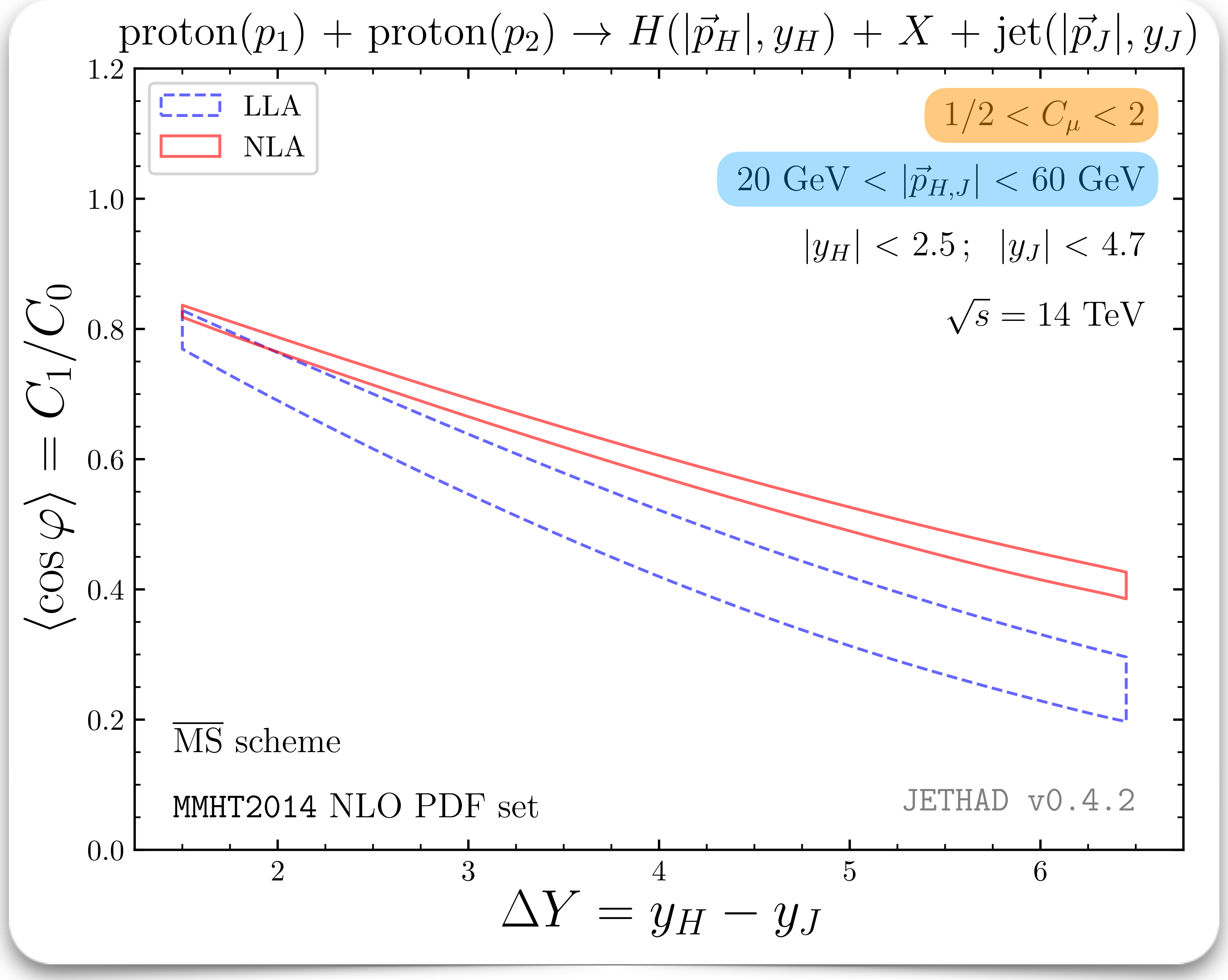

natural scales

symmetric p_T range

Azimuthal-angle multiplicity

$$\frac{1}{\sigma}\frac{d\sigma(\Delta Y, s)}{d\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}$$

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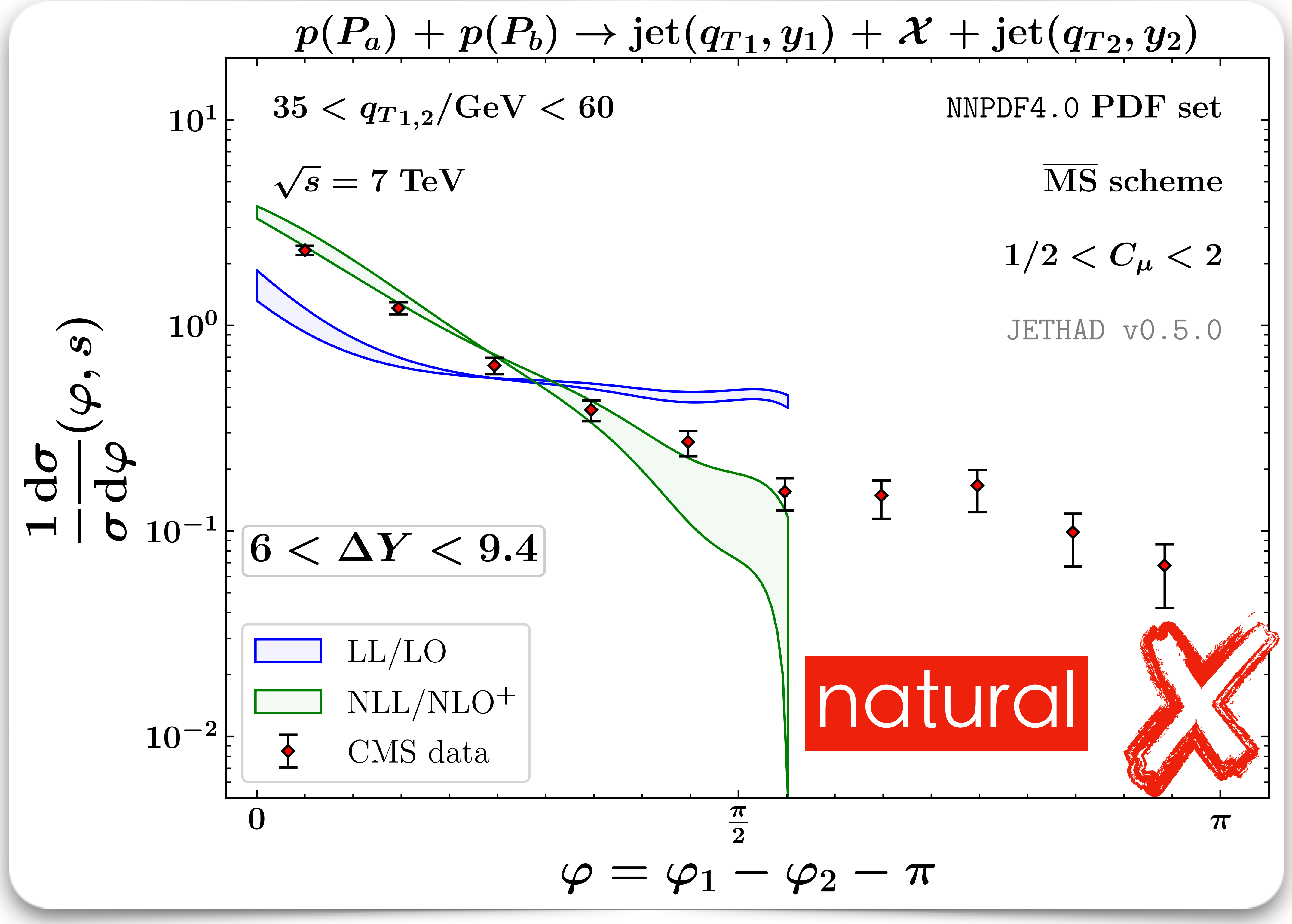

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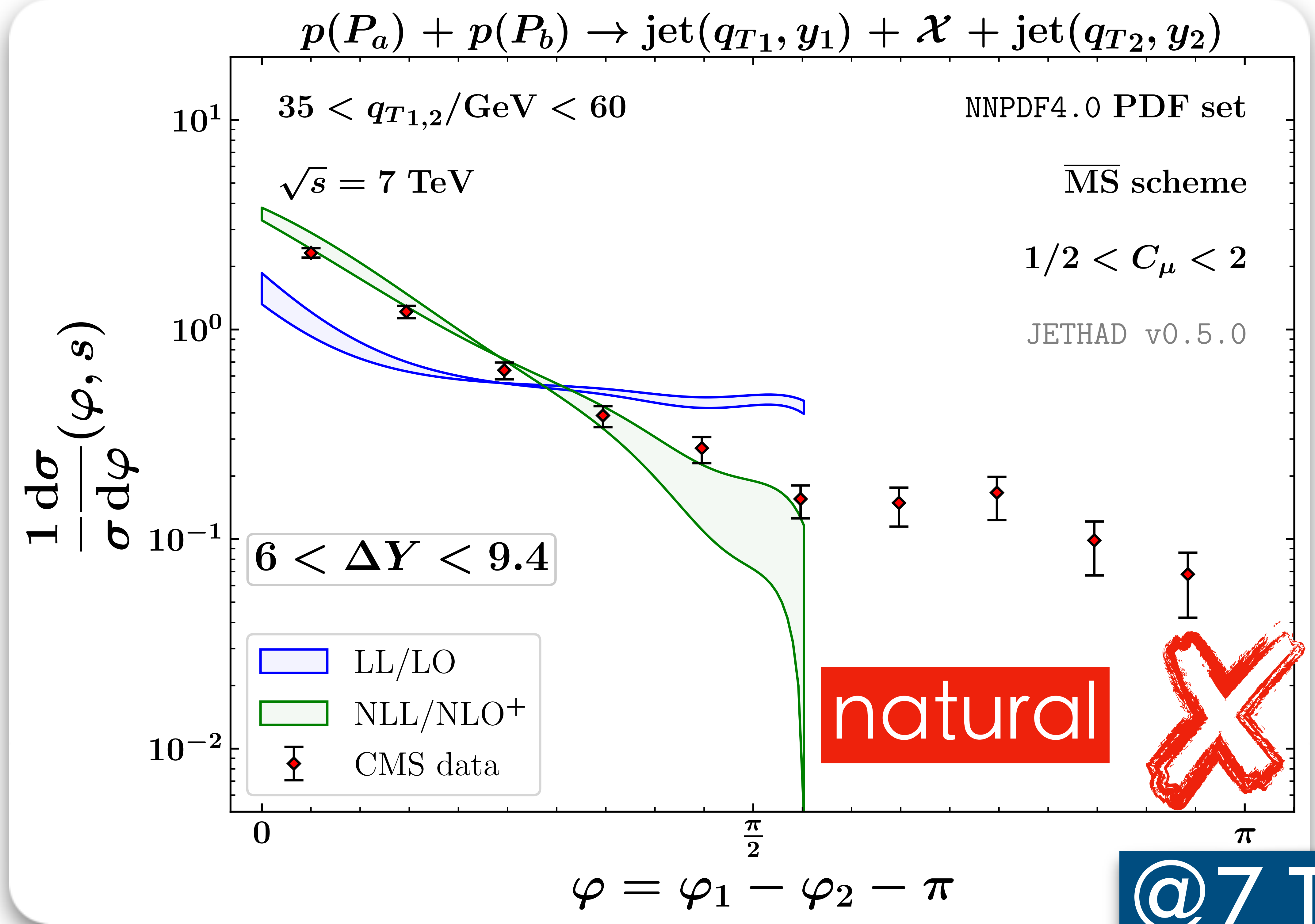

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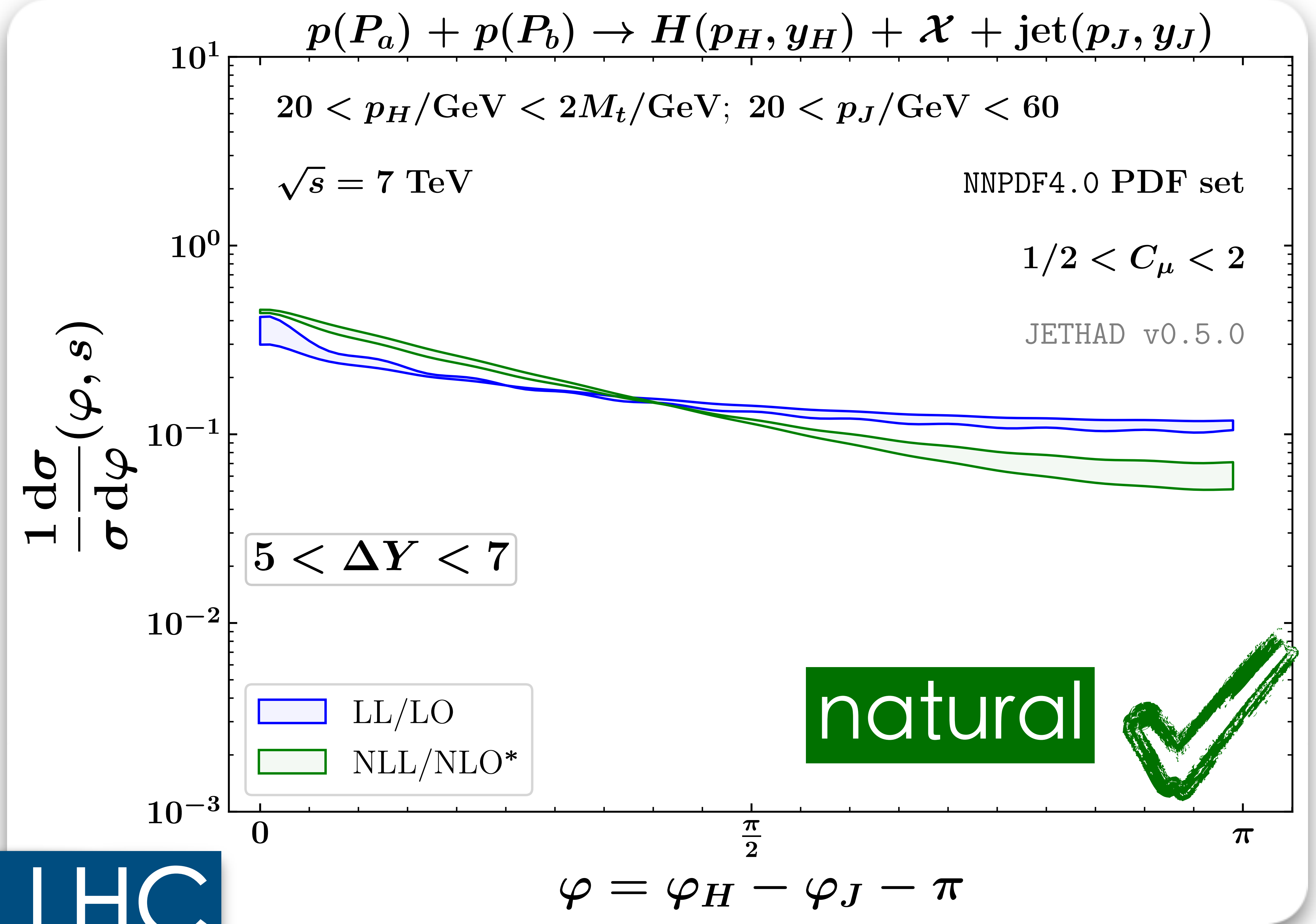
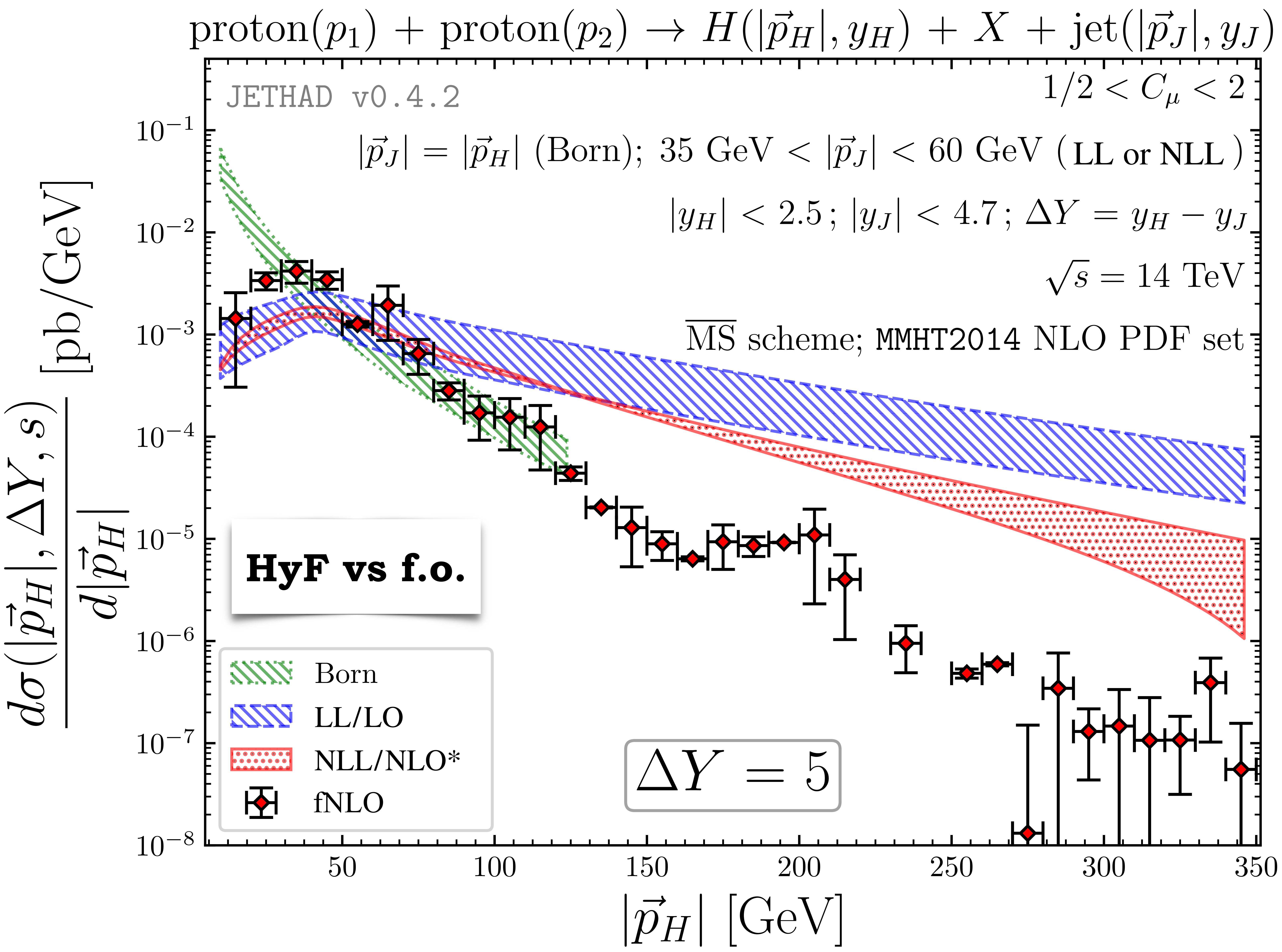


@7 TeV LHC

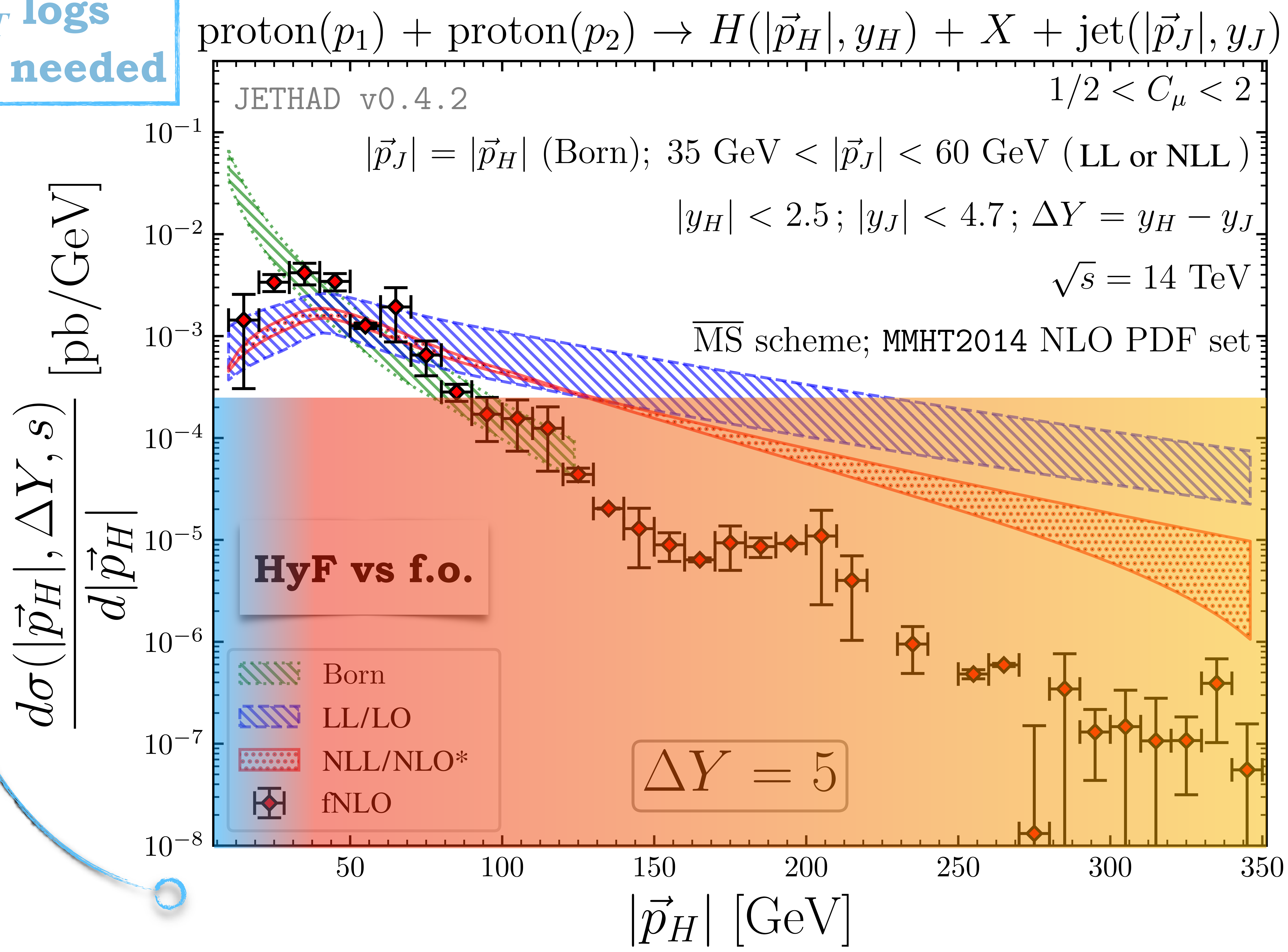
Hybrid factorization via the JETHAD code

[F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]. [F. G. C. , Phys. Rev. D 105 (2022) 11, 114008]

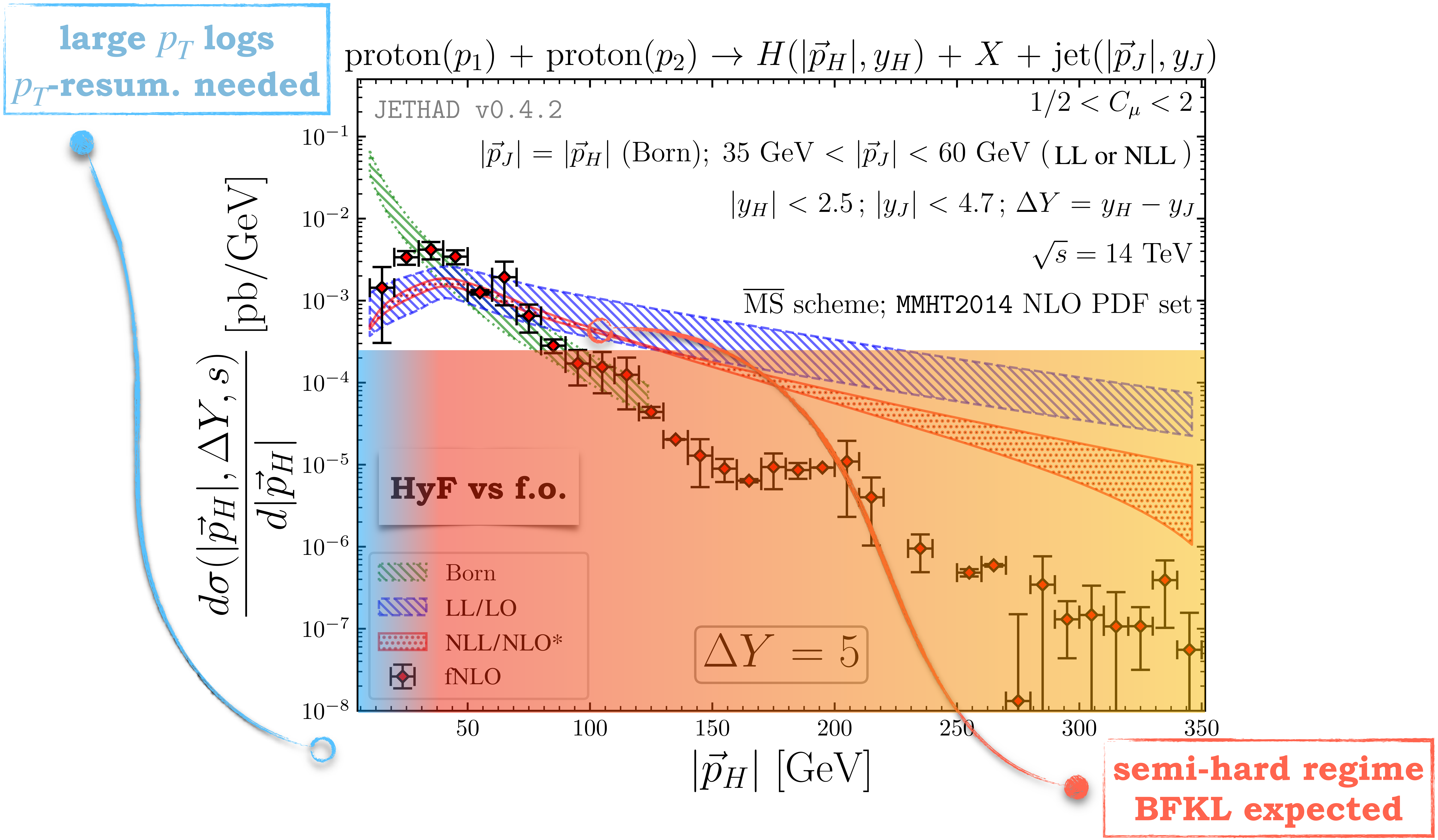


(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

large p_T logs
p_T-resum. needed



(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]



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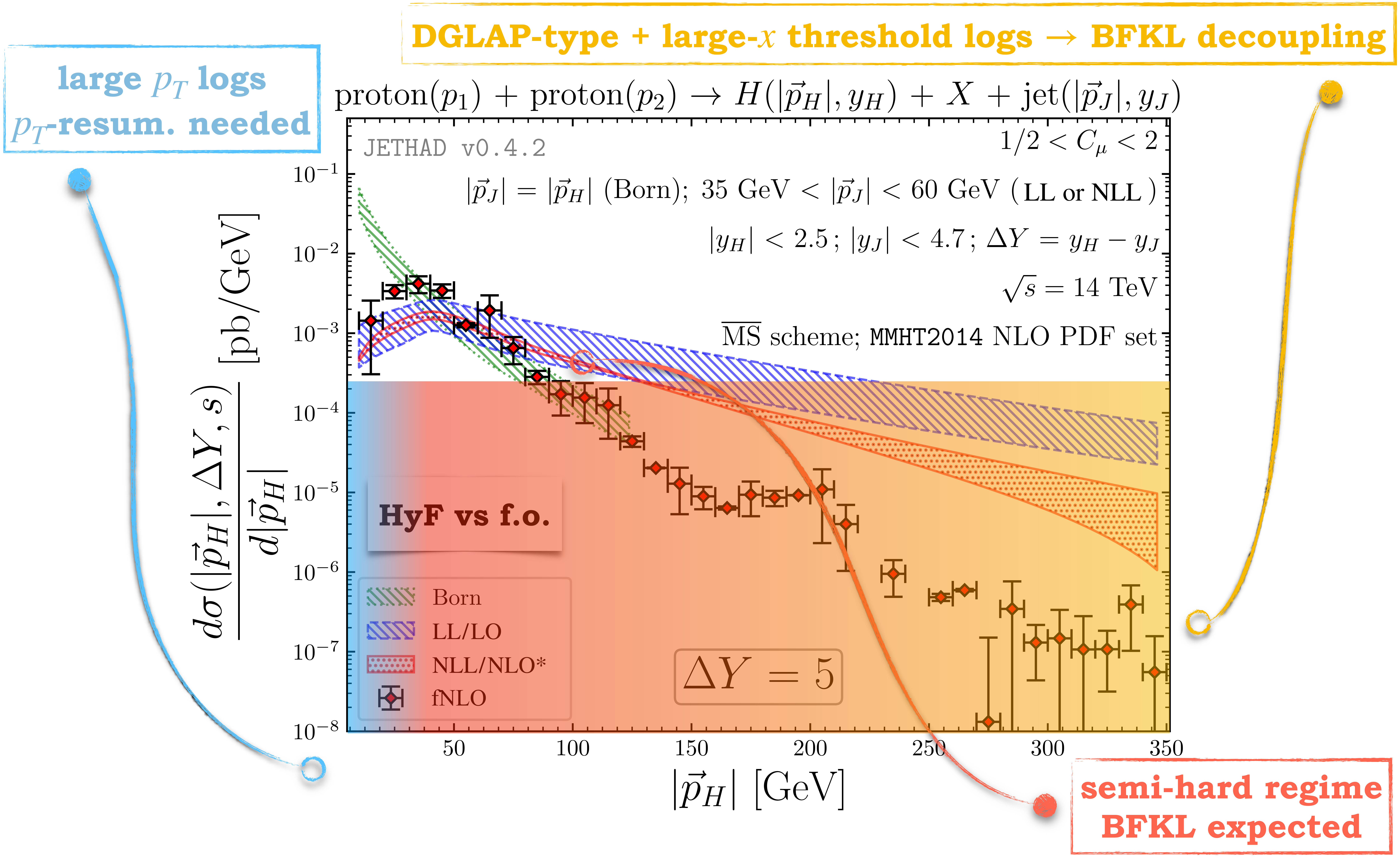

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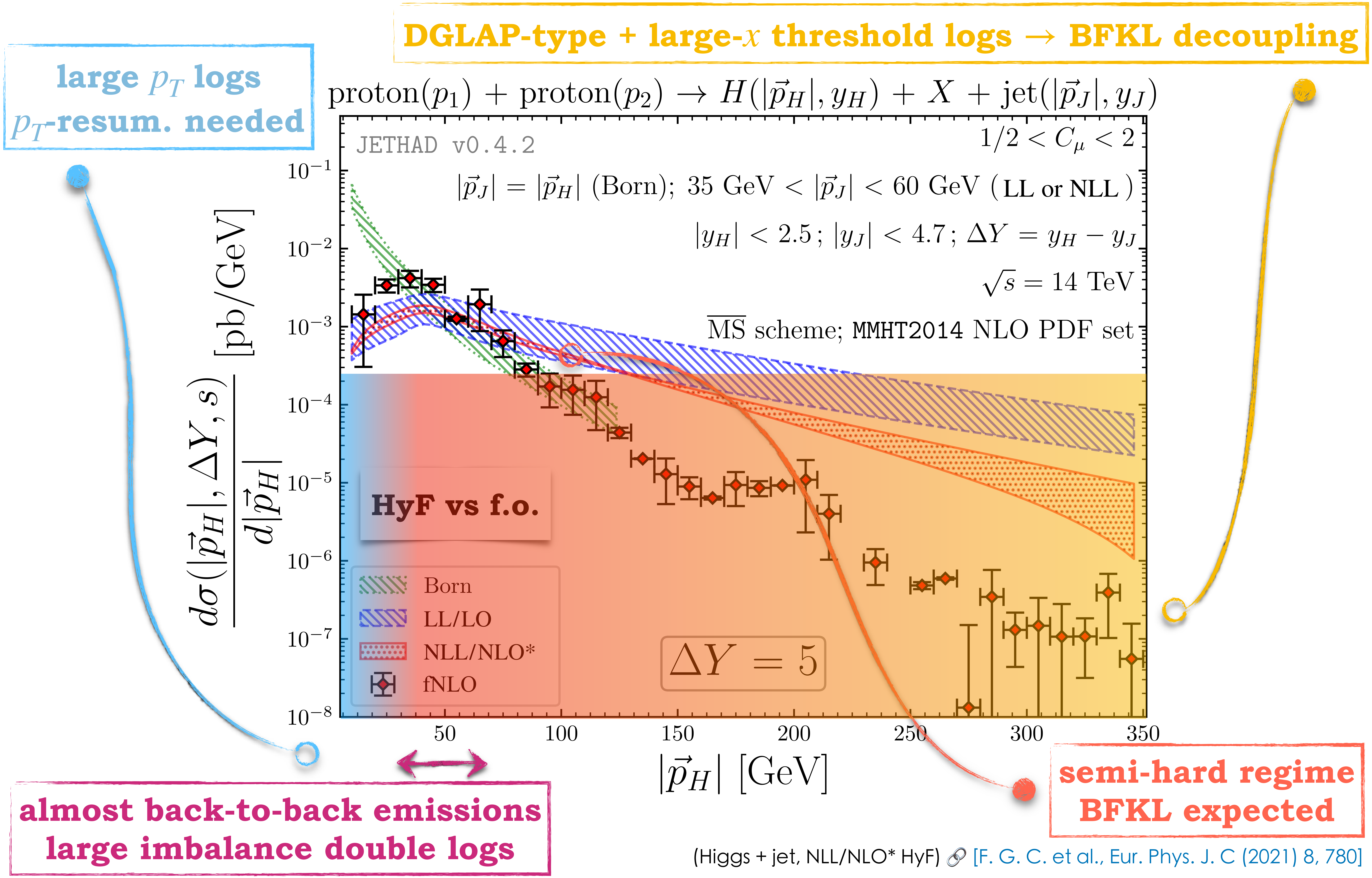
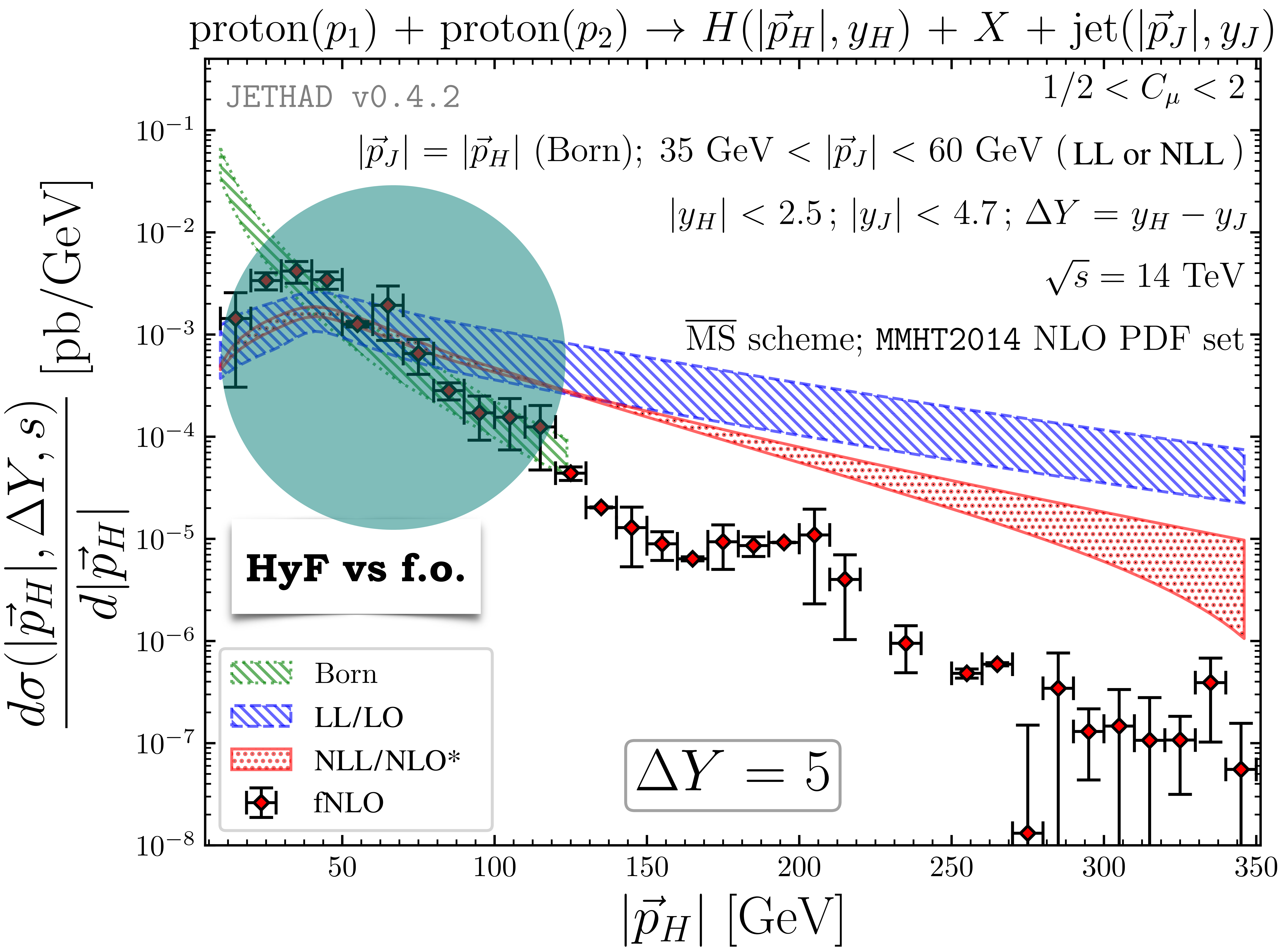


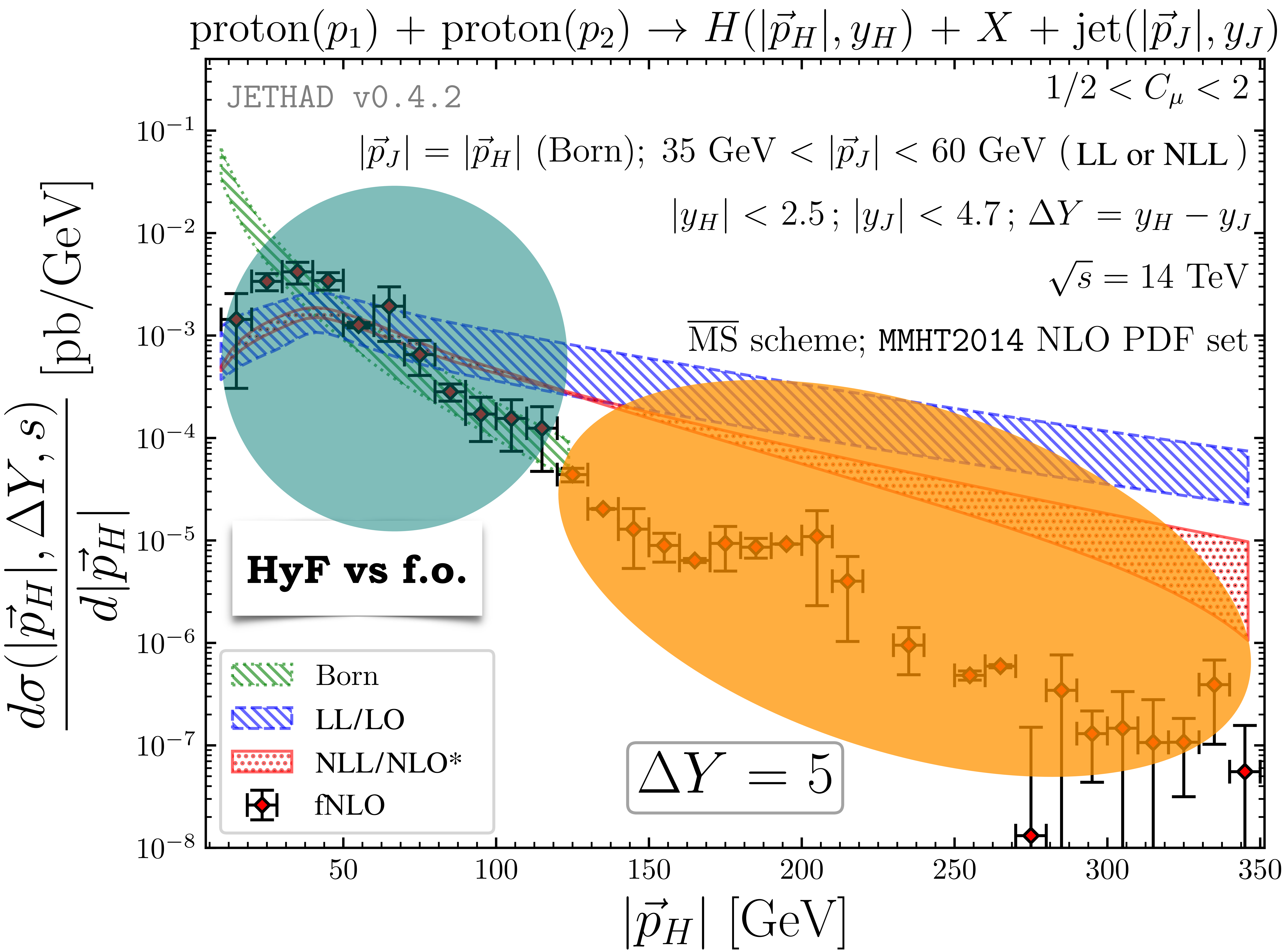
(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C., D Yu. Ivanov, M, M. A. Mohammed, A. Papa, Eur. Phys. J. C (2021) 8, 780]



¡ **Precision corrections** *expected*

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C., D Yu. Ivanov, M, M. A. Mohammed, A. Papa, Eur. Phys. J. C (2021) 8, 780]



¡ **Precision corrections** *expected*, but **HyF** *predicts* **large deviations** from **f.o.** !

¿ How to properly combine BFKL with the fixed order?

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\mathrm{d}\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)} = \underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \mathrm{d}\sigma^{\mathrm{NLL^-}}(\Delta Y, \varphi, s) - \Delta\mathrm{d}\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)$$

Matching NLL to NLO with JETHAD

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JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{{\rm d}\sigma^{\rm NLL/NLO^{-}}(\Delta Y, \varphi, s)} \;=\; \underbrace{\underbrace{{\rm d}\sigma^{\rm NLO}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \underbrace{{\rm d}\sigma^{\rm NLL^{-}}(\Delta Y, \varphi, s)}_{\textbf{NLL}^{-}\ \textbf{resum}\ \text{(HyF)}} - \Delta{\rm d}\sigma^{\rm NLL/NLO^{-}}(\Delta Y, \varphi, s)$$

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

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$$\underbrace{d\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)} = \underbrace{d\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}} + \underbrace{d\sigma^{\mathrm{NLL^-}}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{resum}\ \text{(HyF)}} - \underbrace{\Delta d\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{expanded}\ \text{at NLO}}$$

NLO fixed order → **NLO** POWHEG w/o PS

NLL⁻ resum (HyF) − **NLL⁻ expanded** at NLO → **NLL⁻** JETHAD w/o NLO⁻ double counting

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\underbrace{d\sigma^{\rm NLL/NLO^-}(\Delta Y, \varphi, s)}_{\textbf{NLL/NLO}^-\ \text{matched}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \oplus\ \textbf{NLL}^-\ \texttt{JETHAD}} = \underbrace{\underbrace{d\sigma^{\rm NLO}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \underbrace{\underbrace{d\sigma^{\rm NLL^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{resum}\ \text{(HyF)}} - \underbrace{\Delta d\sigma^{\rm NLL/NLO^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{expanded}\ \text{at NLO}}}_{\textbf{NLL}^-\ \texttt{JETHAD}\ \text{w/o NLO}^-\ \text{double counting}}$$

HELL + ggHiggs

$N^3LL_{lx}/LL_{sx}/N^3LO$

Inclusive Higgs

[M. Bonvini, S. Marzani (2018)]

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

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HELL + ggHiggs

$\mathrm{N^3LL_{lx}/LL_{sx}/N^3LO}$

Inclusive Higgs

[M. Bonvini, S. Marzani (2018)]

HEJ framework

$\mathrm{NLL_{sx}^-/NLO}$

Higgs + jet(s)

[J. R. Andersen et al. (2022)]

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\underbrace{d\sigma^{\rm NLL/NLO^-}(\Delta Y,\varphi,s)}_{\textbf{NLL/NLO}^- \text{ matched}}}_{\text{NLO POWHEG} \,\oplus\, \text{NLL}^- \text{ JETHAD}} = \underbrace{\underbrace{d\sigma^{\rm NLO}(\Delta Y,\varphi,s)}_{\textbf{NLO} \text{ fixed order}}}_{\text{NLO POWHEG w/o PS}} + \underbrace{\underbrace{d\sigma^{\rm NLL^-}(\Delta Y,\varphi,s)}_{\textbf{NLL}^- \textbf{ resum} \text{ (HyF)}} - \underbrace{\Delta d\sigma^{\rm NLL/NLO^-}(\Delta Y,\varphi,s)}_{\textbf{NLL}^- \textbf{ expanded} \text{ at NLO}}}_{\text{NLL}^- \text{ JETHAD w/o NLO}^- \text{ double counting}}$$

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[M. Bonvini, S. Marzani (2018)]

HEJ framework

NLL_{sx^-}/NLO

Higgs + jet(s)

[J. R. Andersen et al. (2022)]

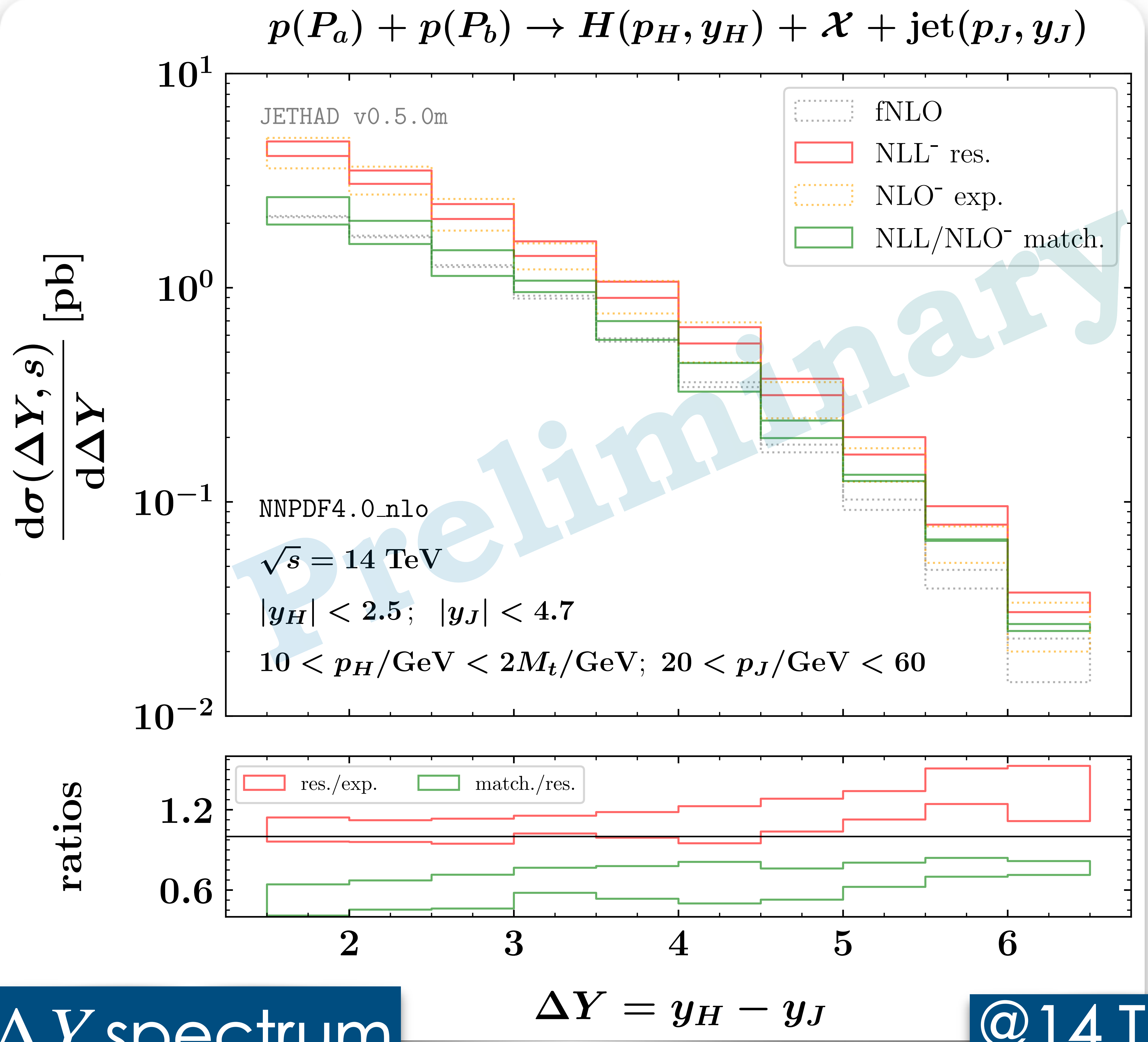
RadISH + MCFM-8.3

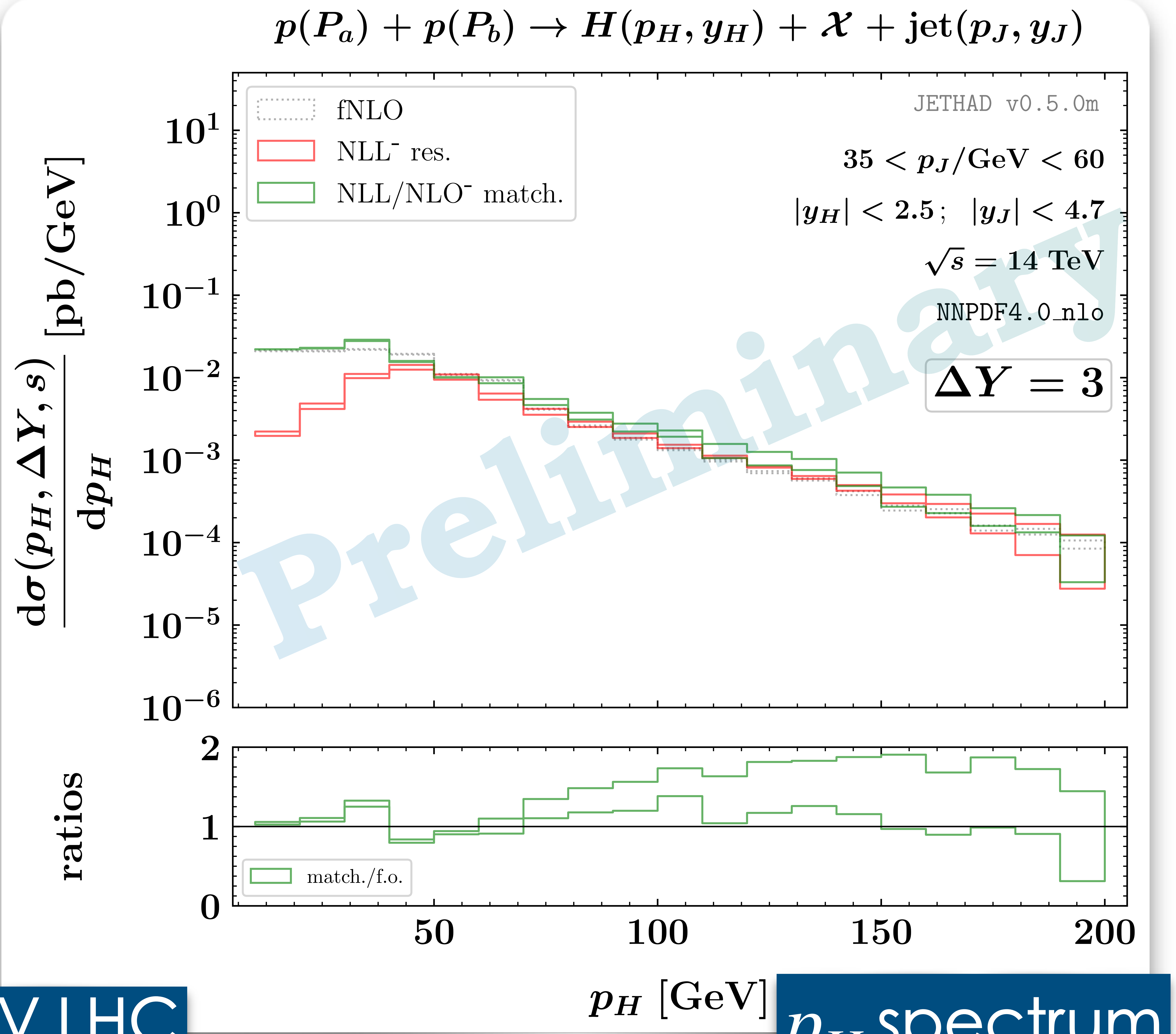
$NNLL_{TM}/NLO$

Higgs + jet

[P.F. Monni et al. (2020)]

The Higgs + jet spectrum from POWHEG + JETHAD





ΔY spectrum

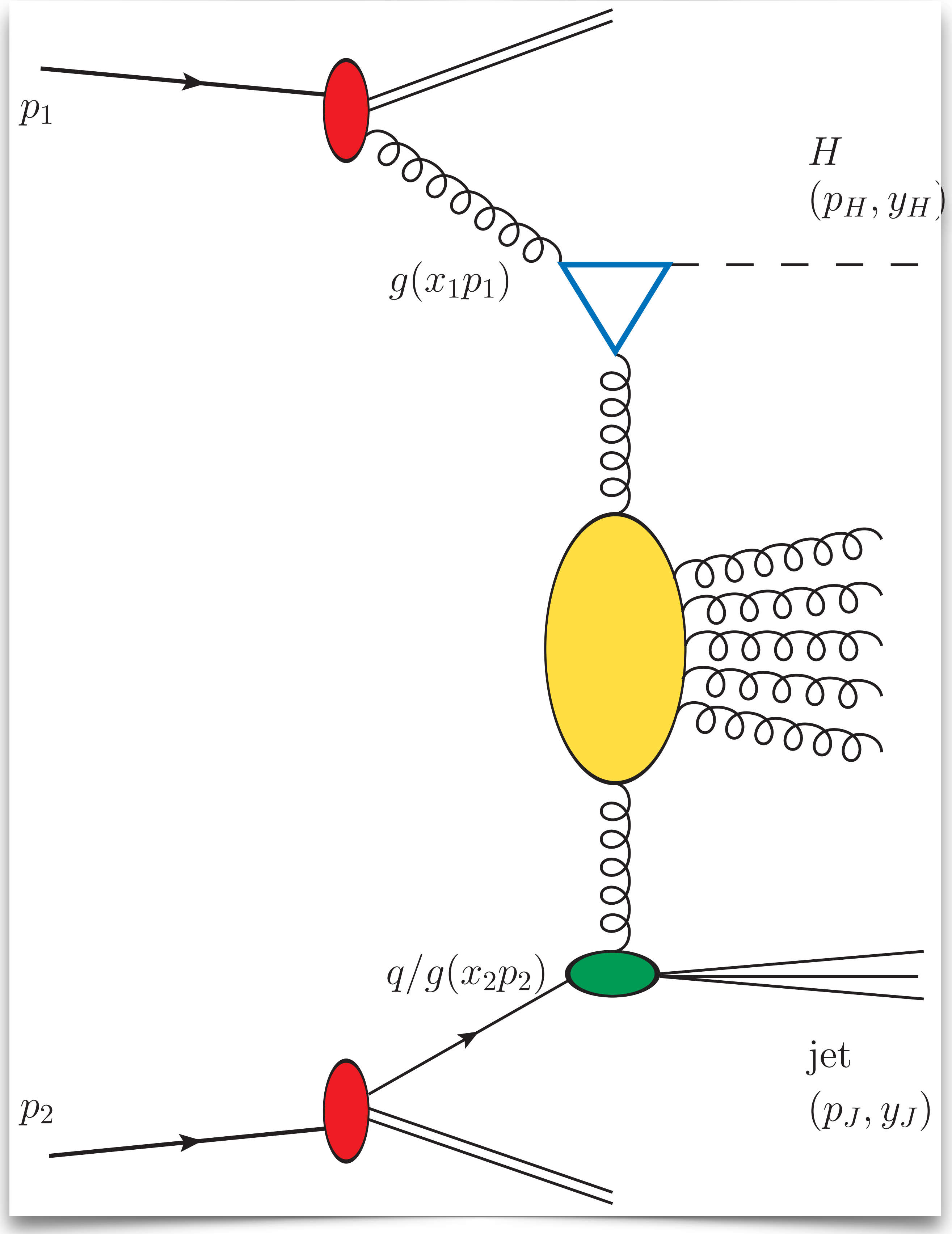
@14 TeV LHC

p_H spectrum

NLL matched to NLO fixed-order POWHEG + JETHAD (in progress)

High-energy resummation for electroweak physics

HIGGS BOSON + JET

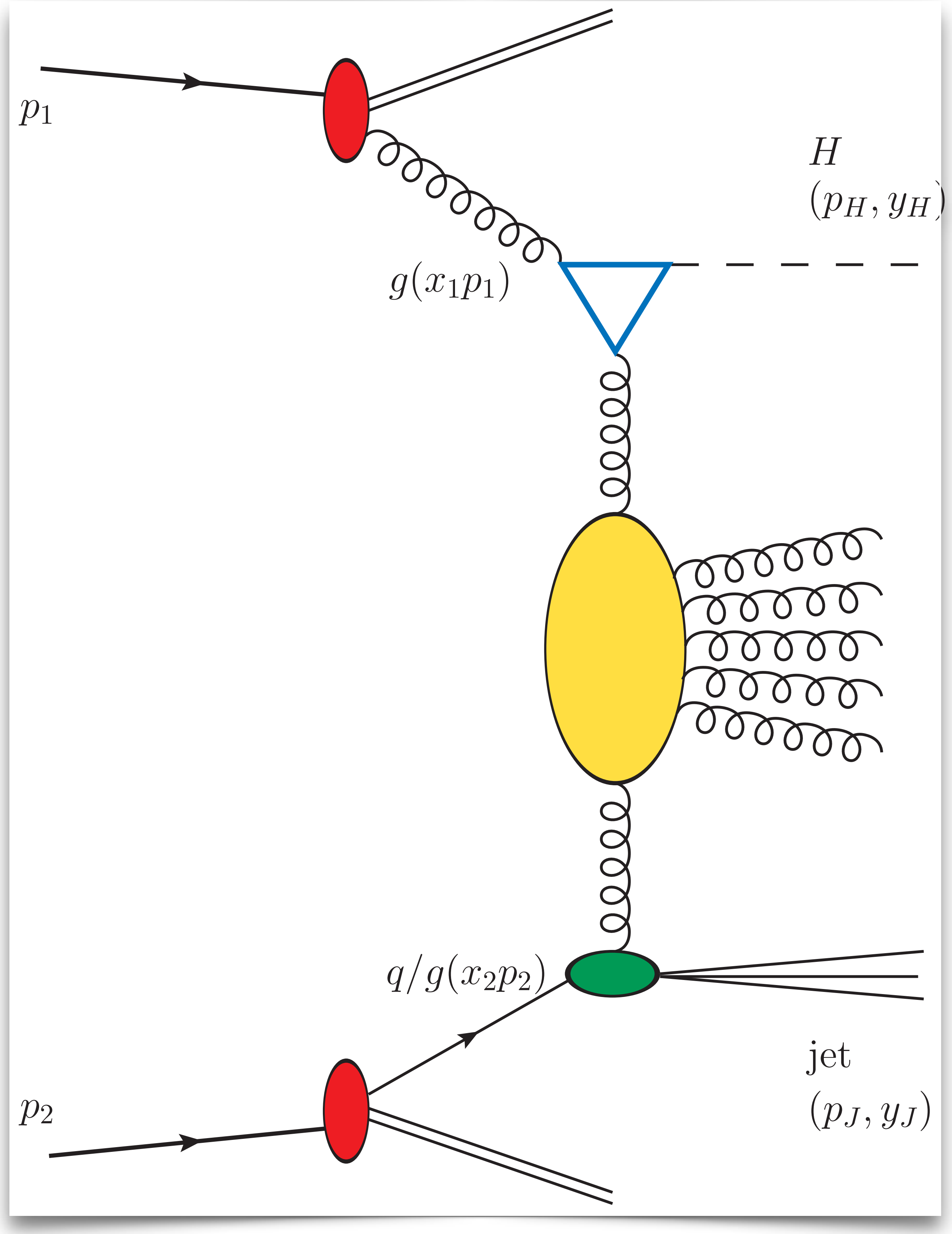


(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO emission function) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

High-energy resummation for electroweak physics

HIGGS BOSON + JET



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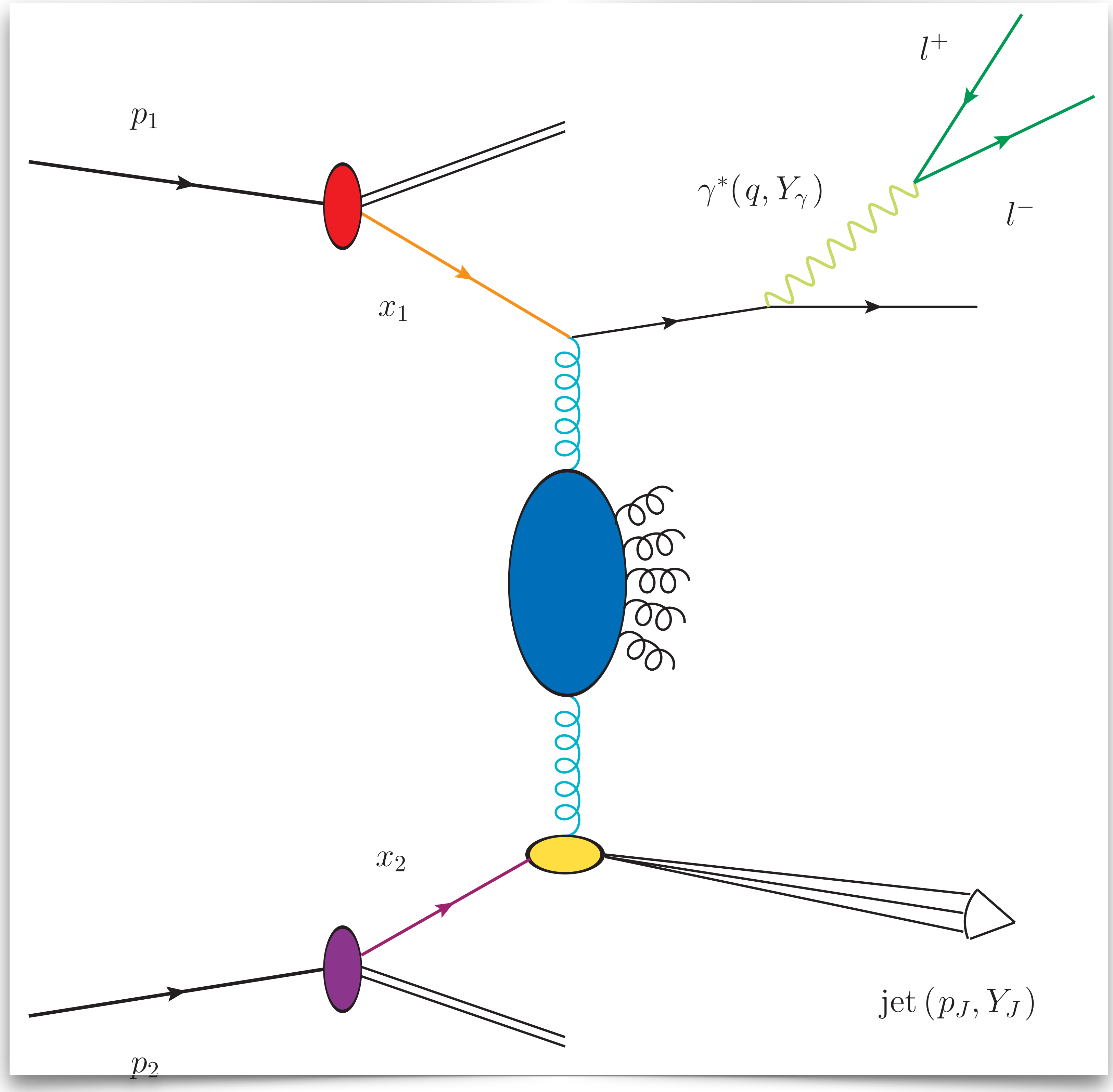
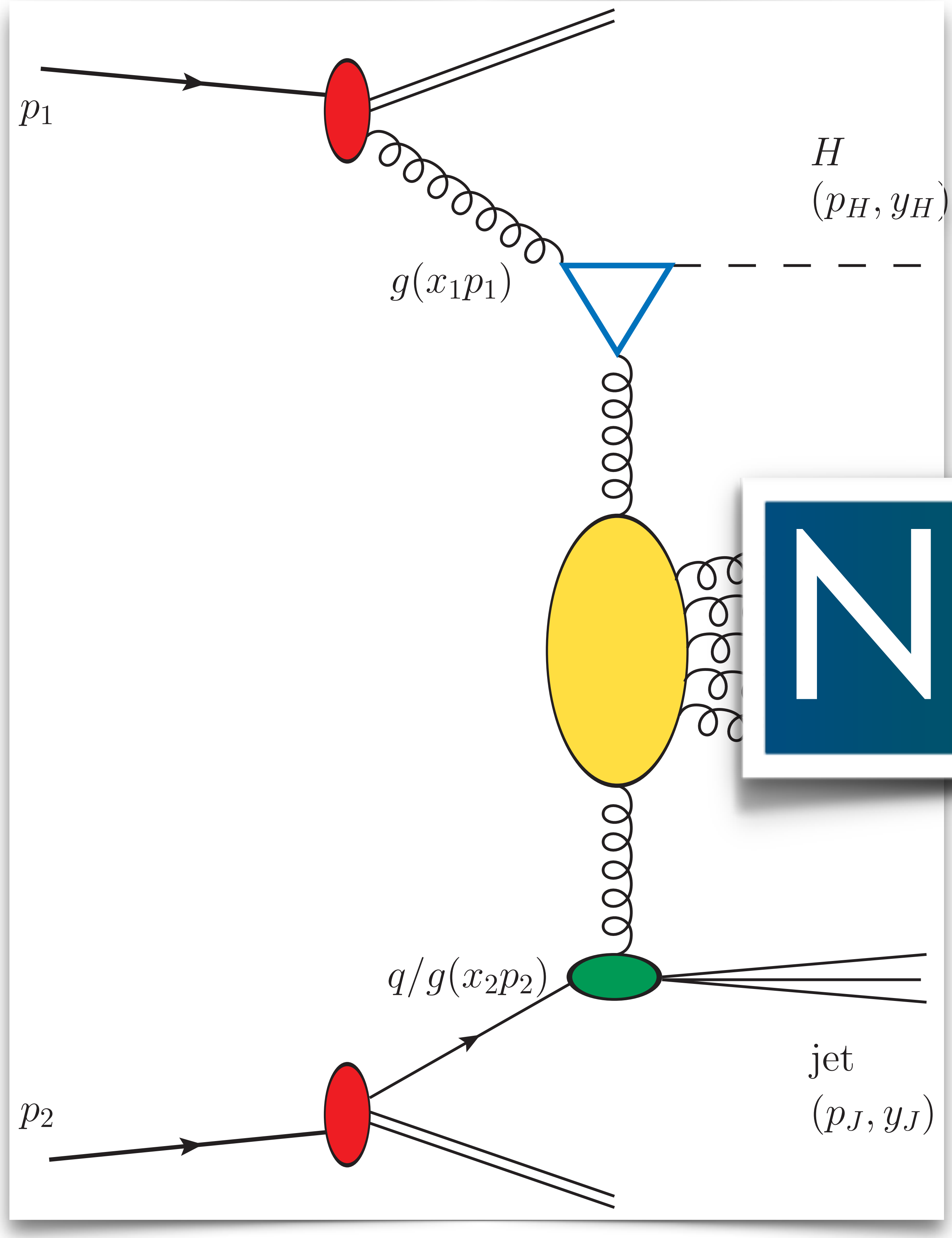
Z BOSON + JET



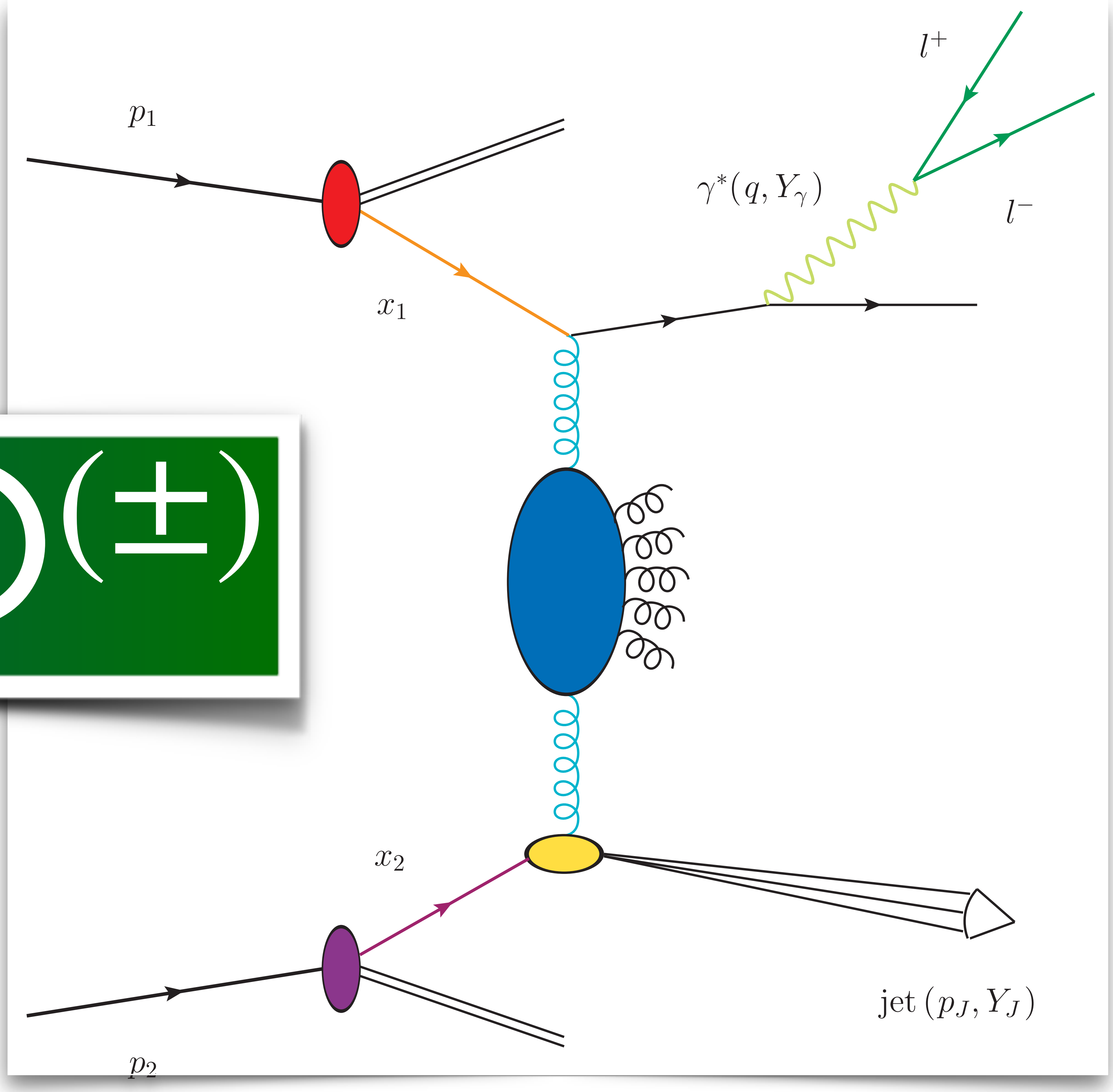
(DY + jet, LL/LO$^+$) 🔗 [L. Motyka et al., JHEP 12 (2018) 091]
(DY and Z + jet, NLL/NLO$^-$) [F. G. C. et al. (in progress)]

High-energy resummation for electroweak physics

HIGGS BOSON + JET



Z BOSON + JET



NLL/NLO$^{(\pm)}$

(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO emission function) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

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(DY and Z + jet, NLL/NLO$^-$) [F. G. C. et al. (in progress)]

2

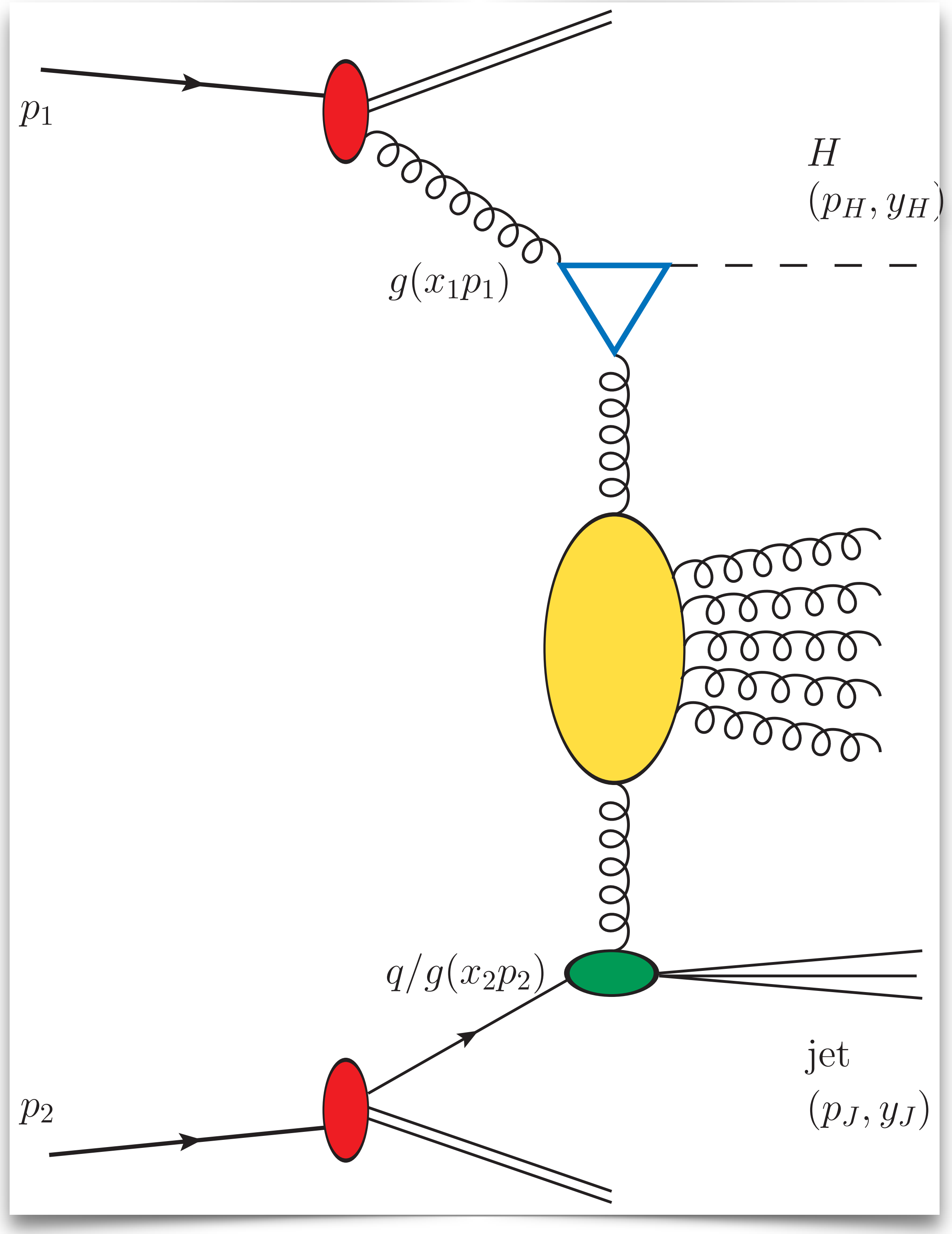
Open heavy flavor

From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

HIGGS BOSON

Stabilizers ⇔ large Higgs transverse masses



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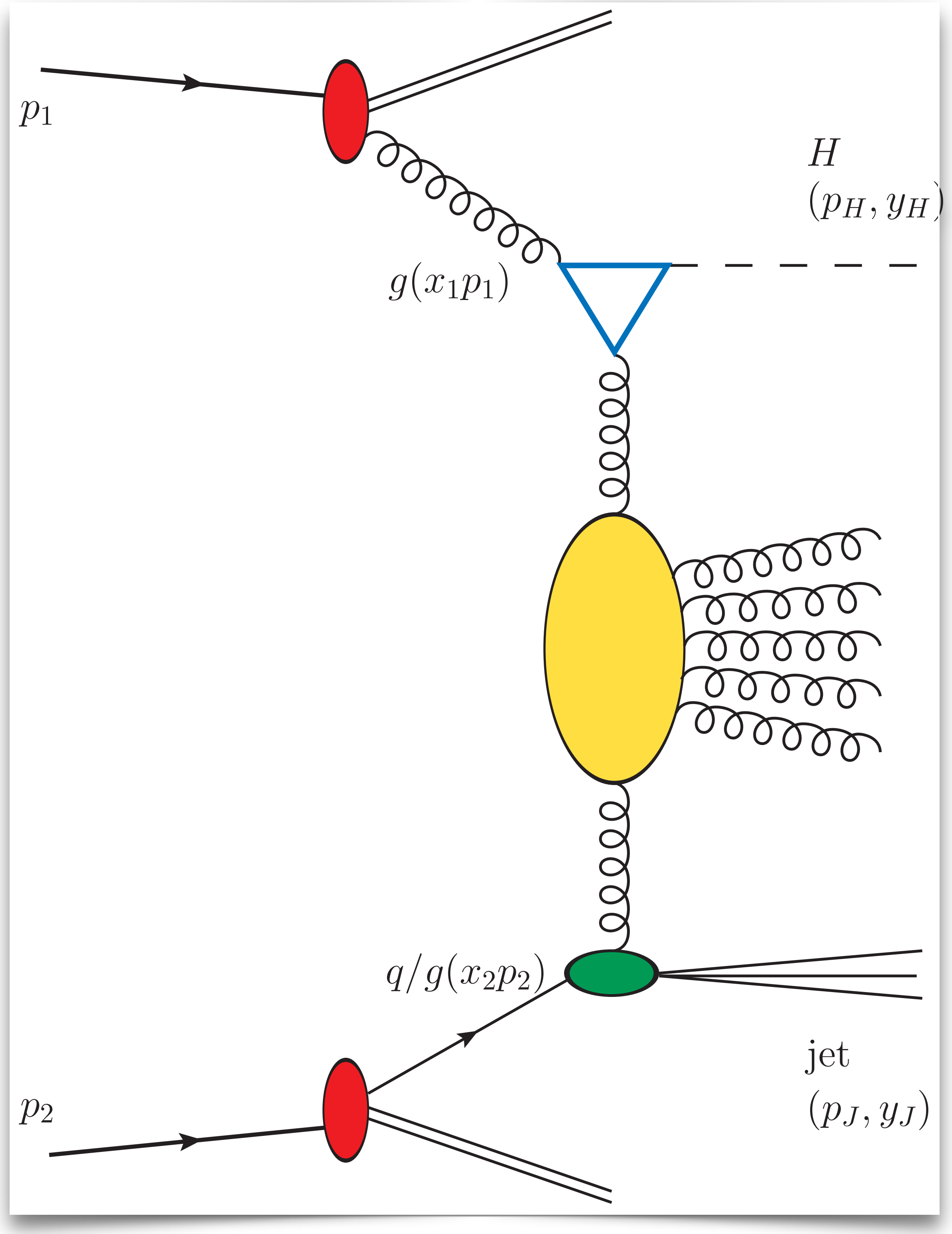
(NLO Higgs coeff. function) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses



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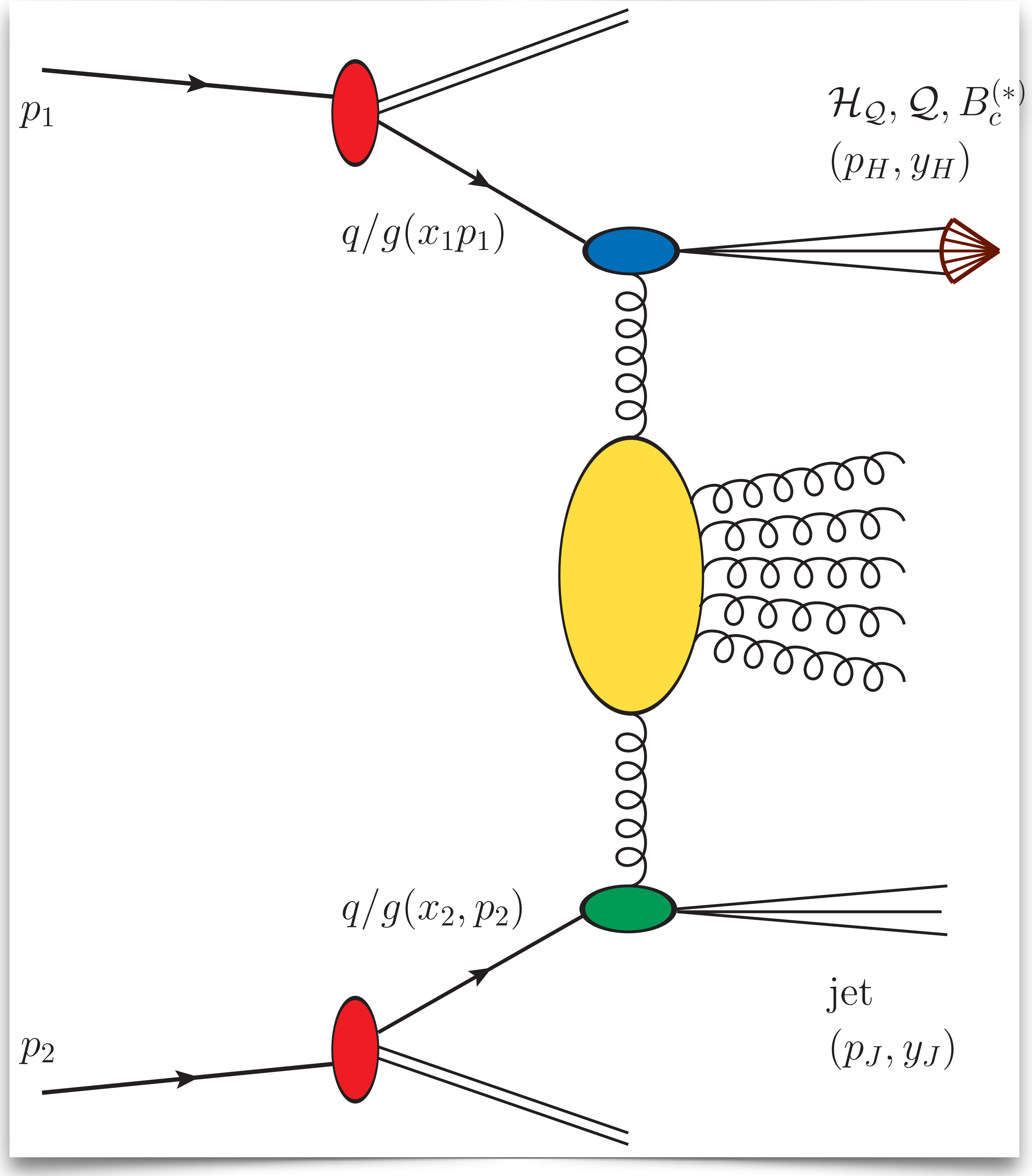
(NLO Higgs coeff. function) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels



($\Lambda_c^{\pm}$ baryons, NLL/NLO) 🔗 [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

(J/ψ or Υ, NLL/NLO) 🔗 [F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

($B_c^{\pm}(^1S_0)$ or $B_c^{*\pm}(^3S_1)$, NLL/NLO) 🔗 [F. G. C., Phys. Lett. B 835 (2022) 137554]

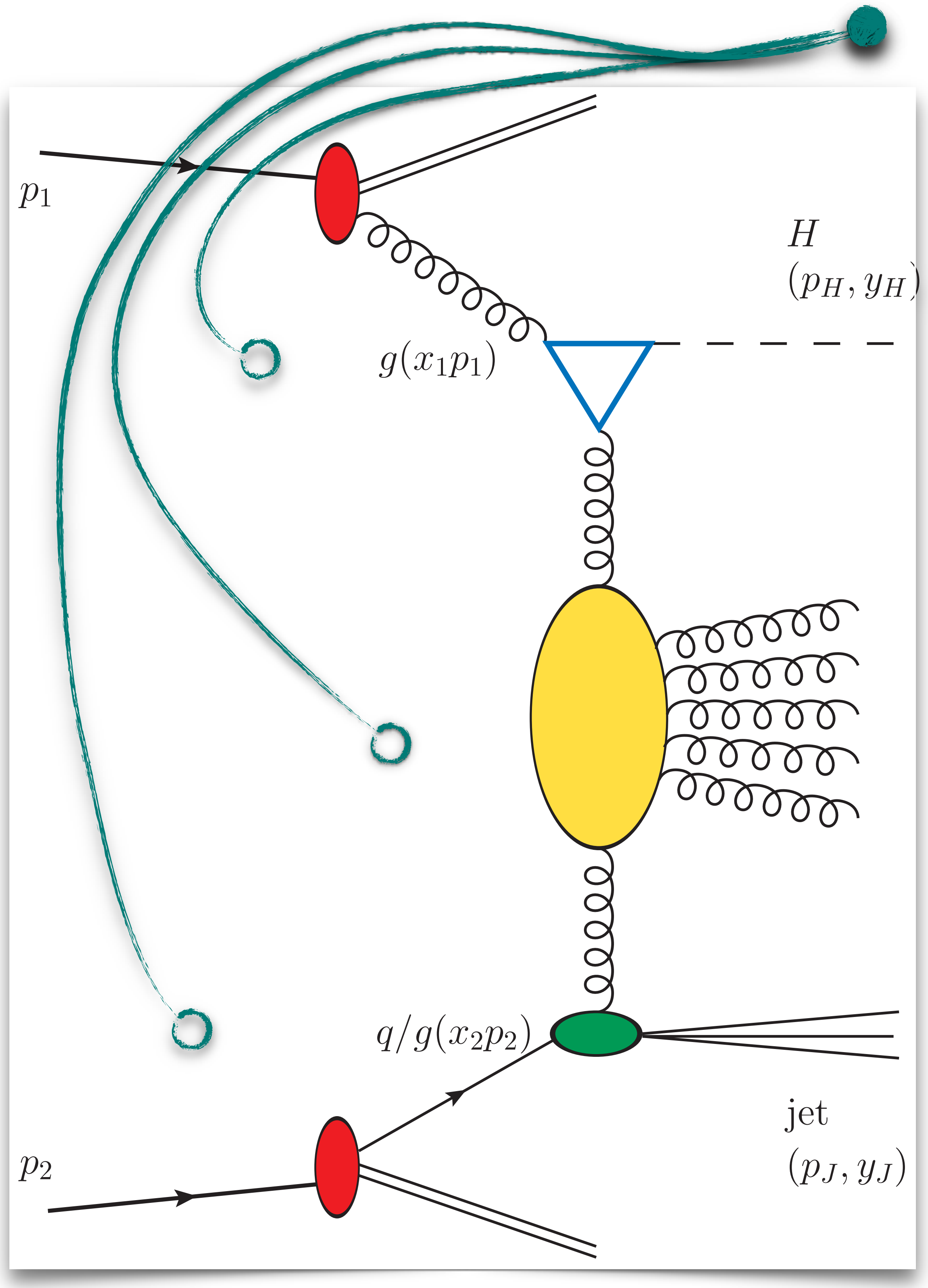
From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses

$\mu_{F,R} \sim M_{H,\perp}$



NLO*

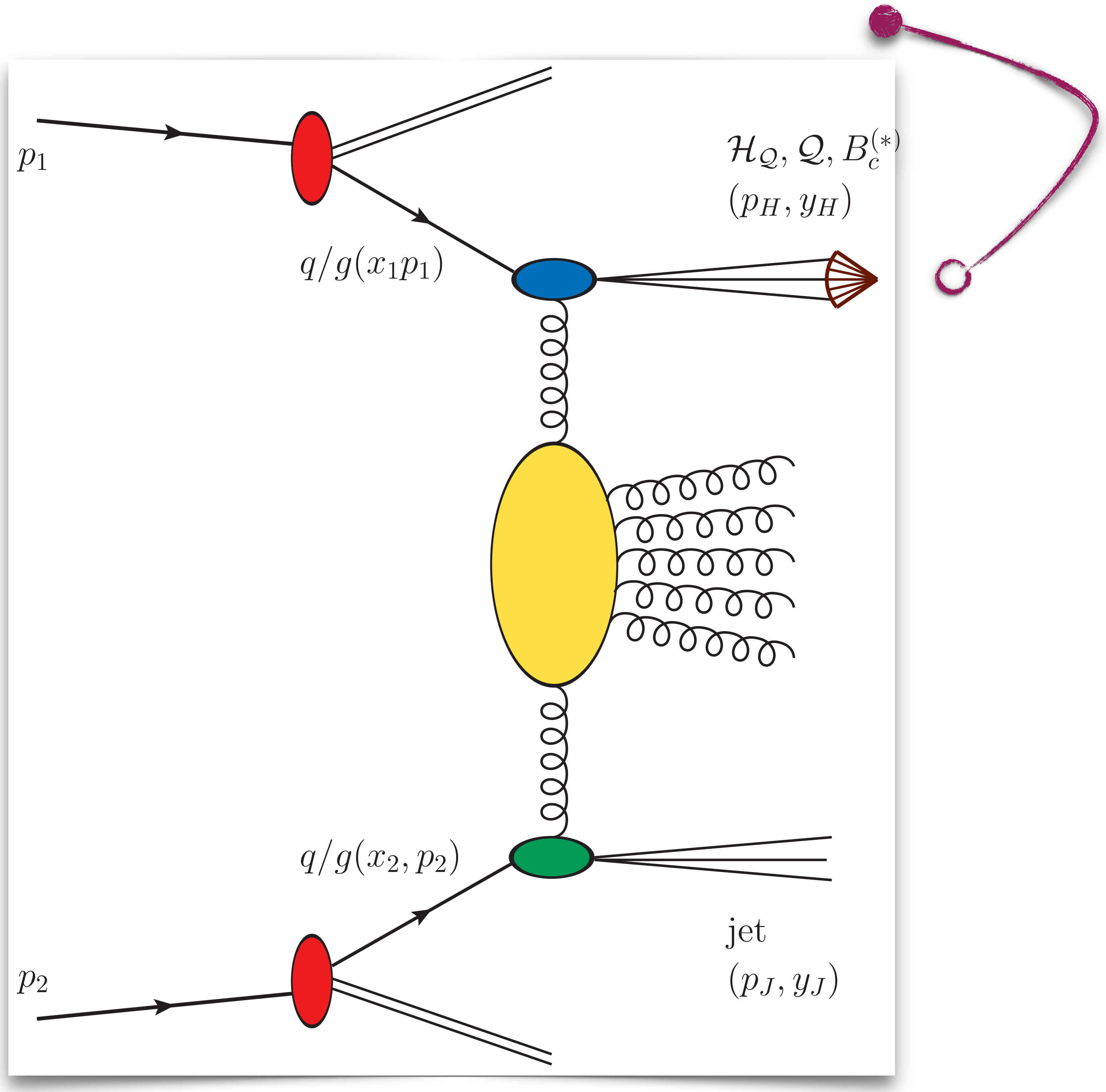
= LO + NLO$^{\mathrm{RGE}}$

NLL

NLO

Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels



NLO$^{(+)}$

NLL

NLO$^{(+)}$

(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]
(NLO Higgs coeff. function) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

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From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

HIGGS BOSON

Stabilizers ⇔ large Higgs transverse masses

$\mu_{F,R} \sim M_{H,\perp}$

NLO*

LO + NLO^{RGE}

NLL/NLO^{+}

NLL

NLO

(Higgs + jet, NLL/NLO*) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO Higgs coeff. function) [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

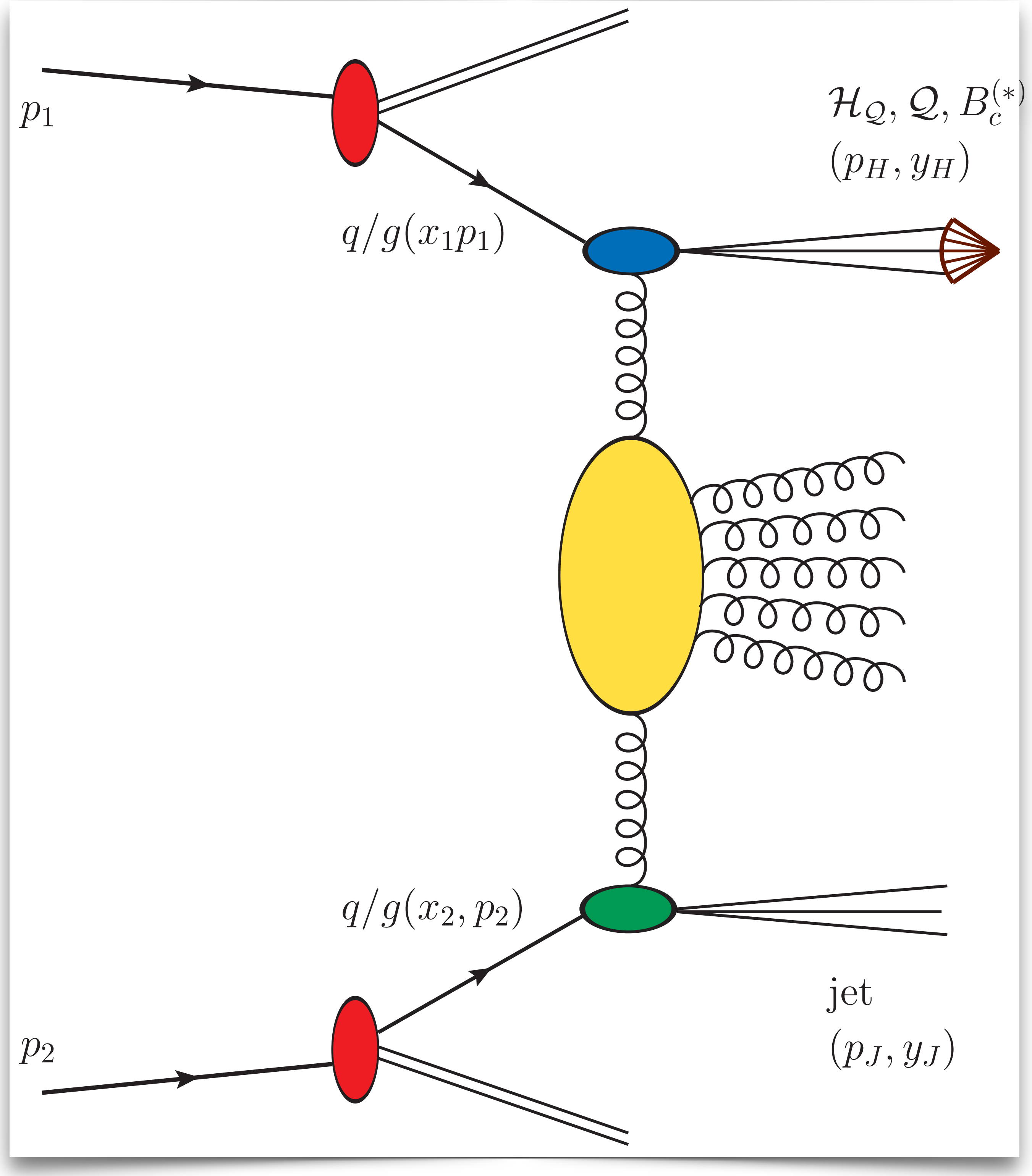
HEAVY FLAVOR AT LARGE p_T

Stabilizers ⇔ gluon fragmentation channels

NLO$^{(+)}$

NLL

NLO$^{(+)}$



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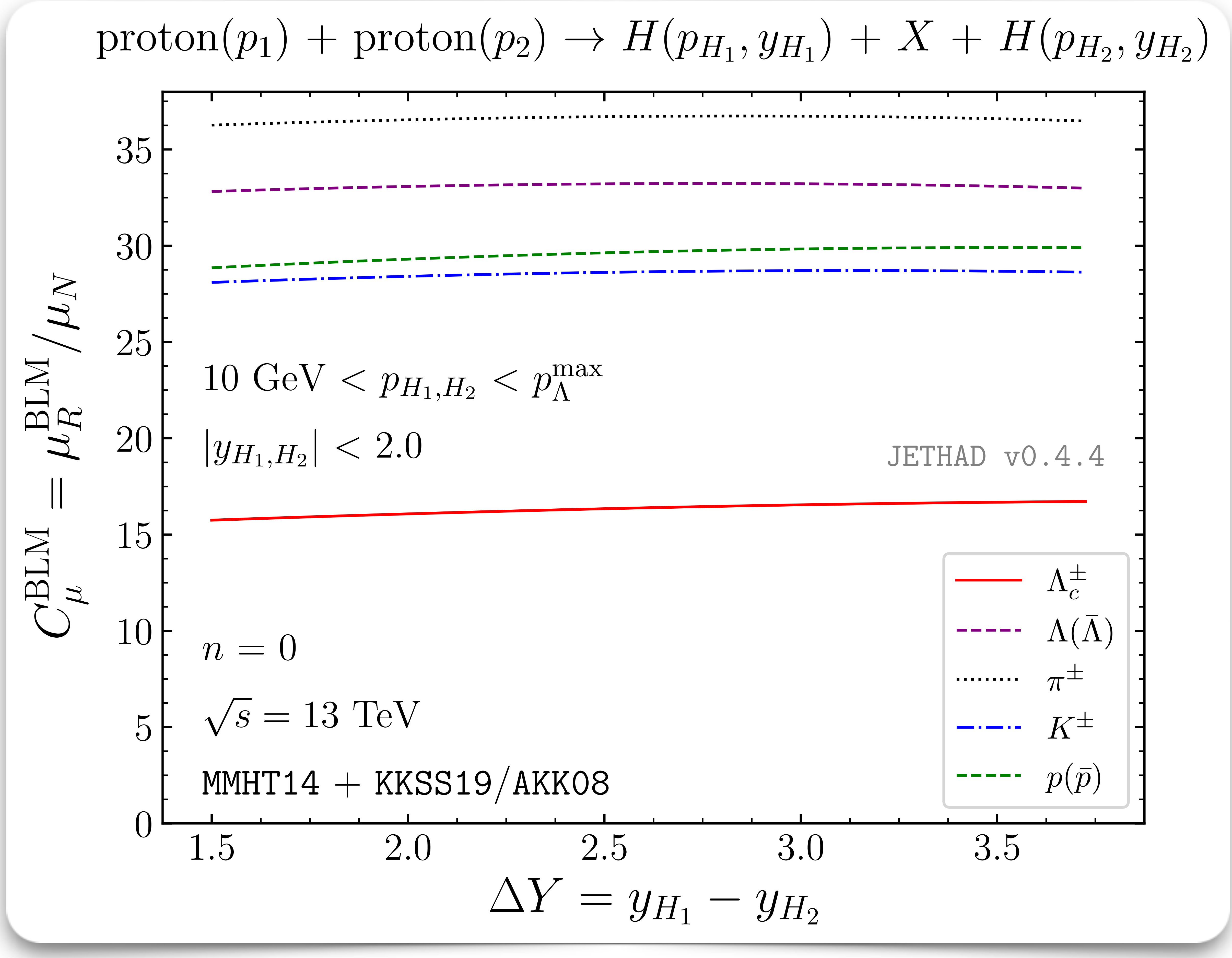
($B_c^{\pm}(^1S_0)$ or $B_c^{*\pm}(^3S_1)$, NLL/NLO) [F. G. C., Phys. Lett. B 835 (2022) 137554]

Heavy flavor at the LHC: BLM scales

Heavy-light hadrons



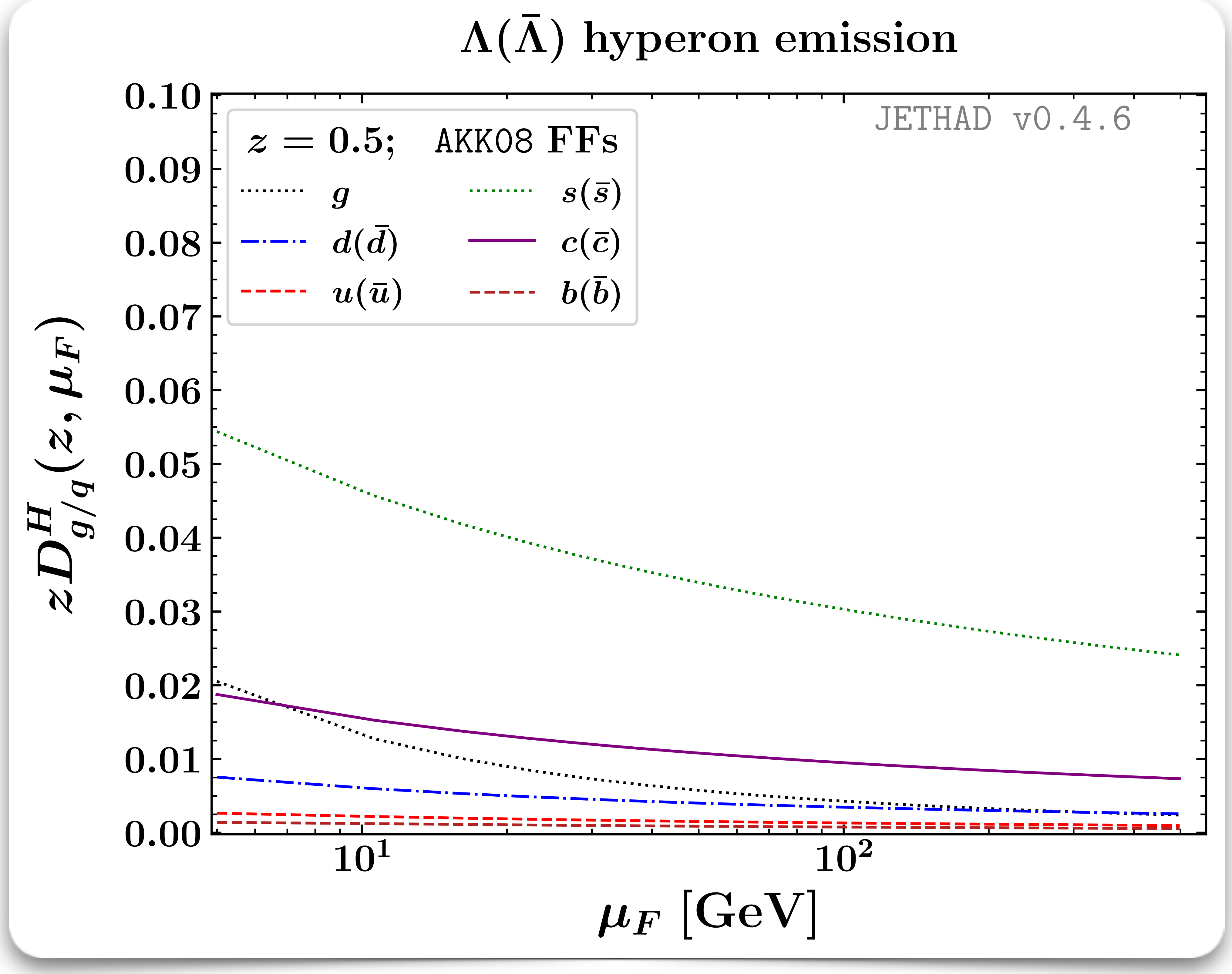
Vector quarkonia

[F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

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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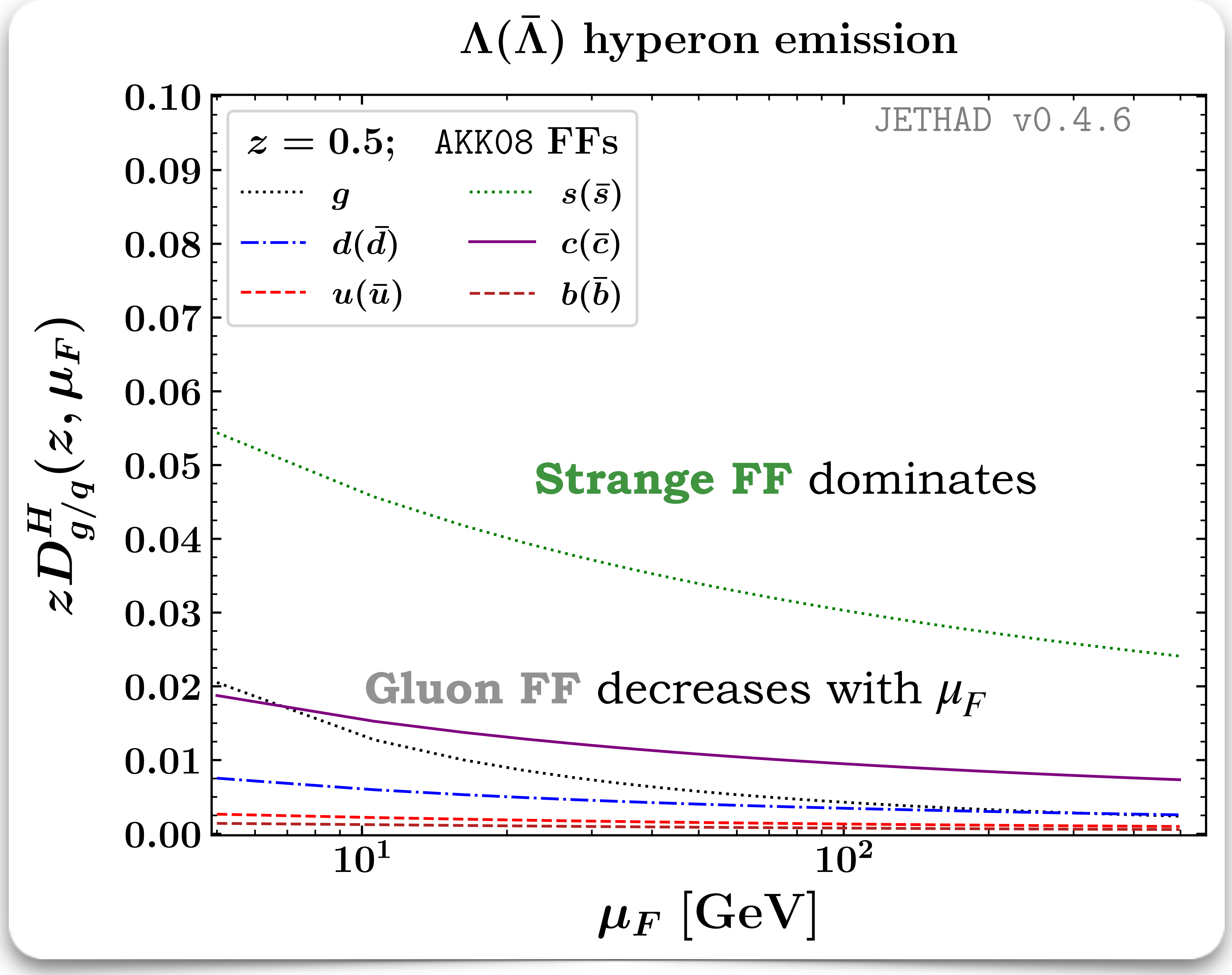

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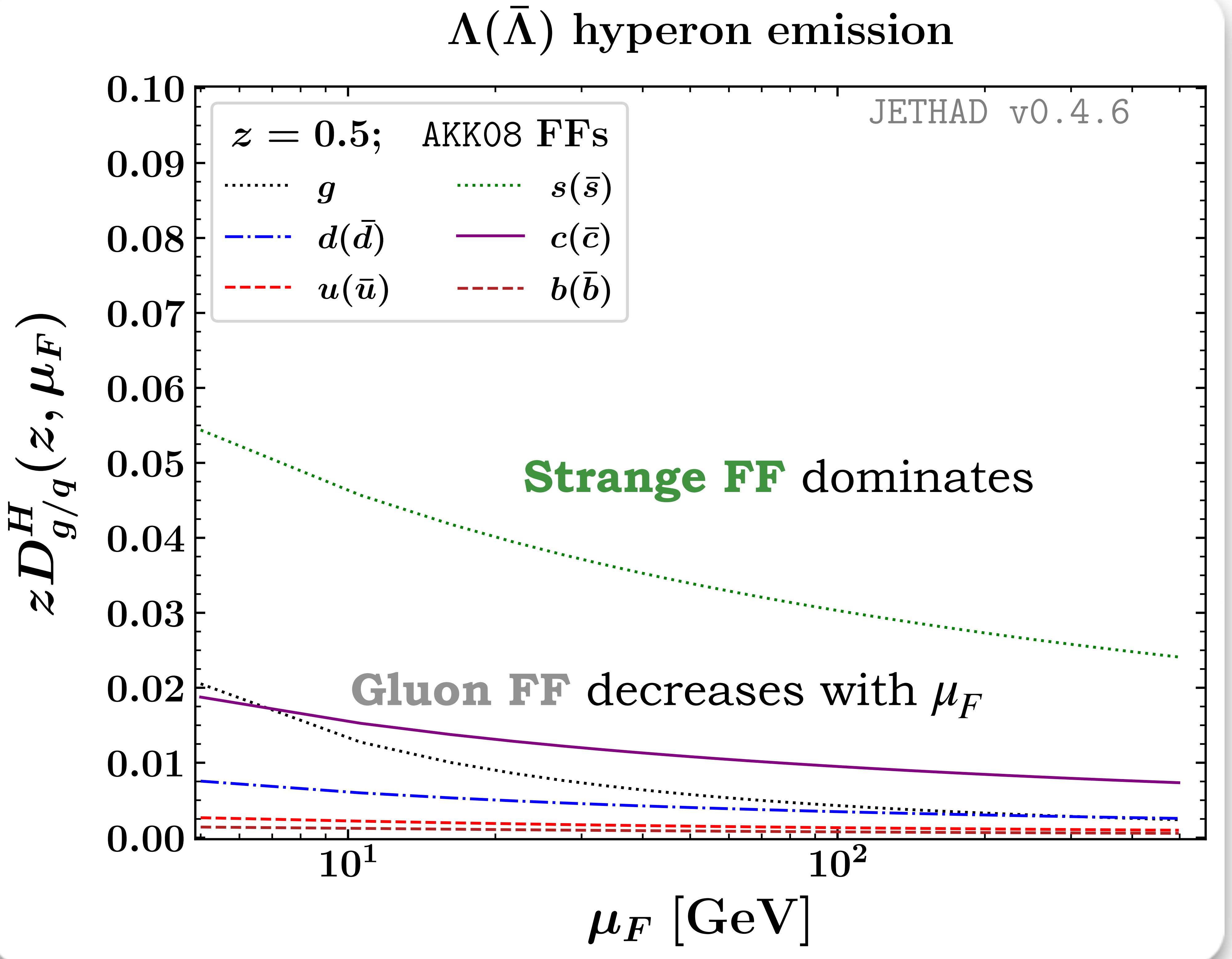
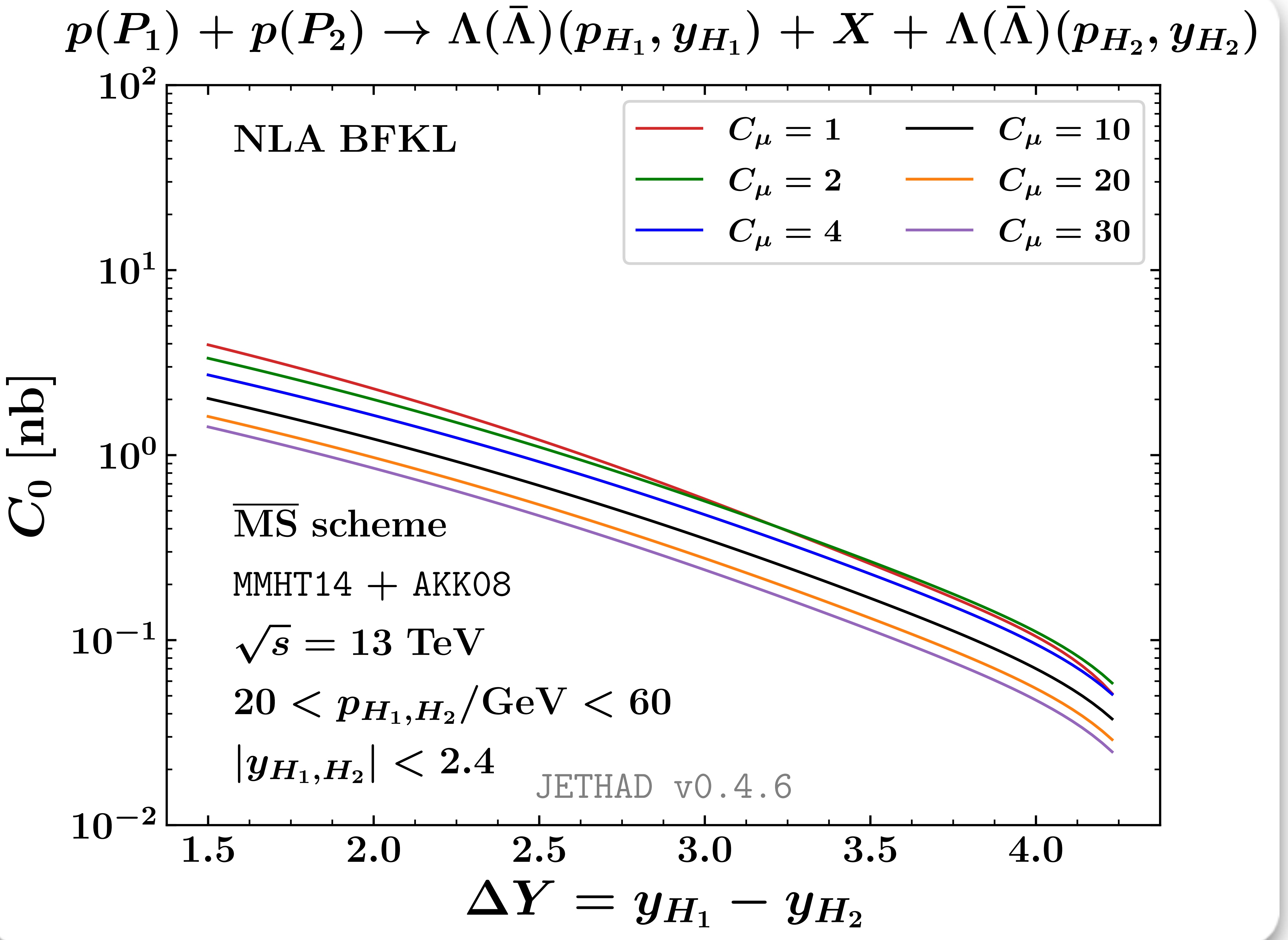




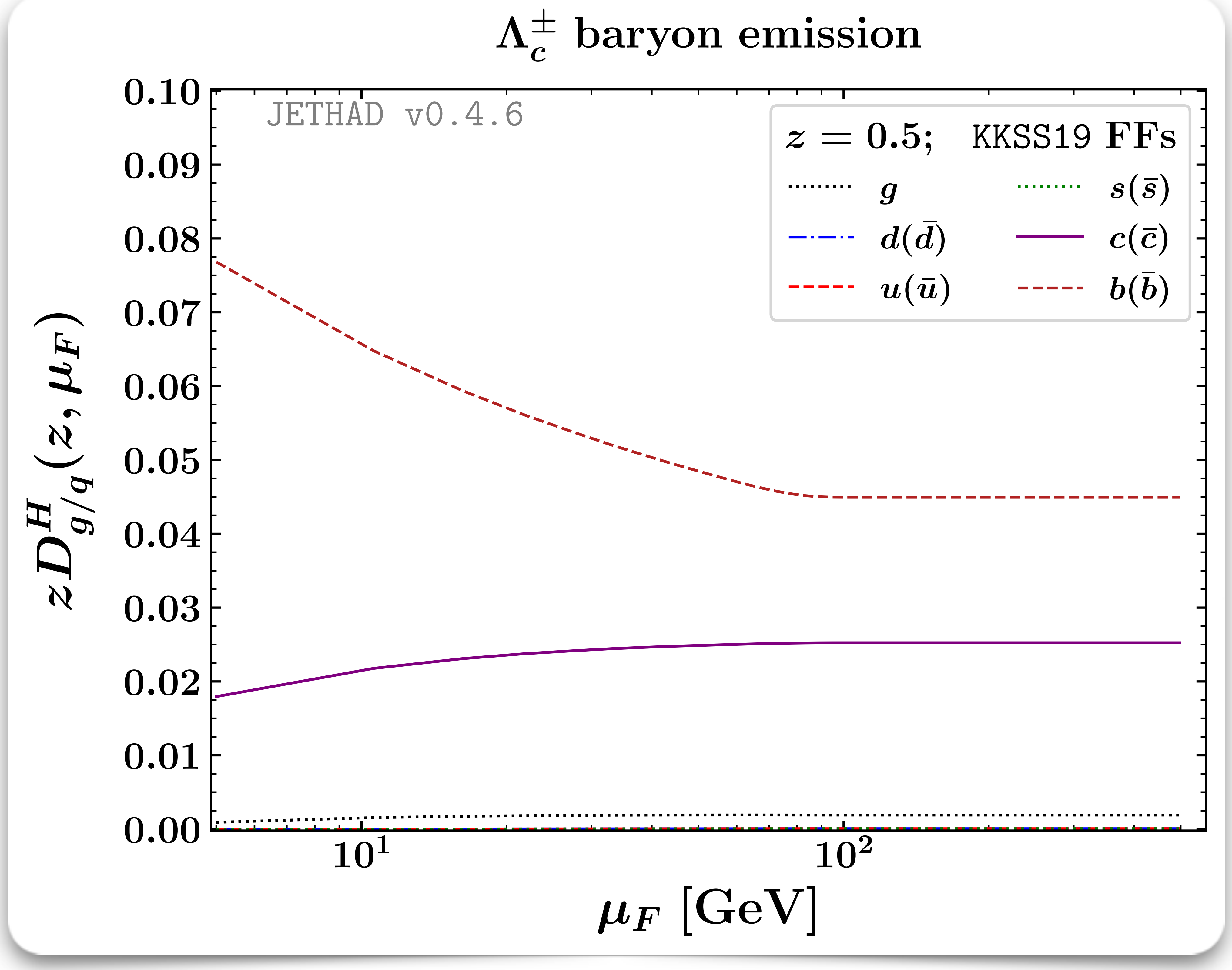
Rapidity distribution sensitive to scale variations

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

(cascade Ξ baryons) [F. G. C., Eur. Phys. J C 83 (2023) 4, 332]

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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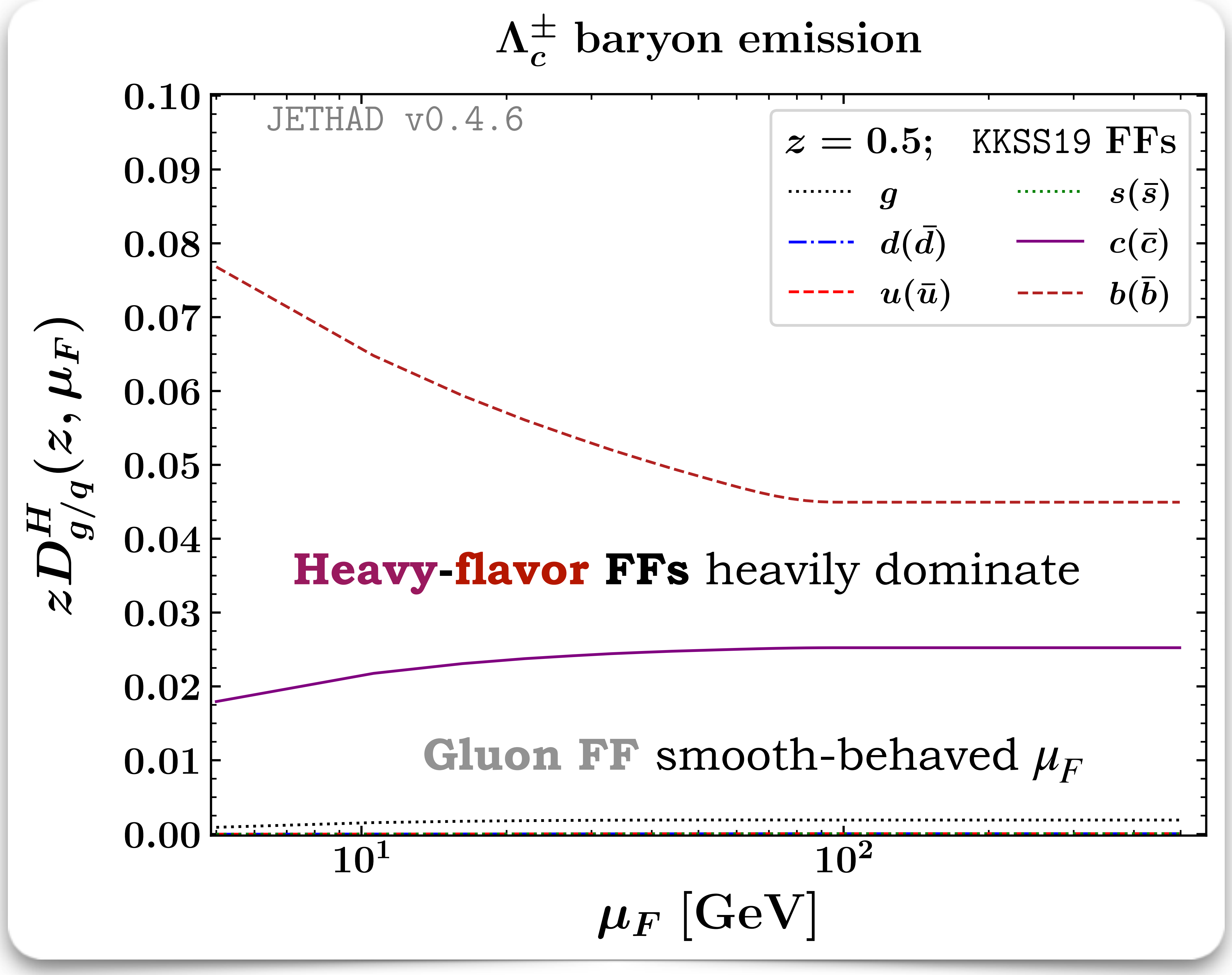

Stabilizing effects of heavy-flavor fragmentation

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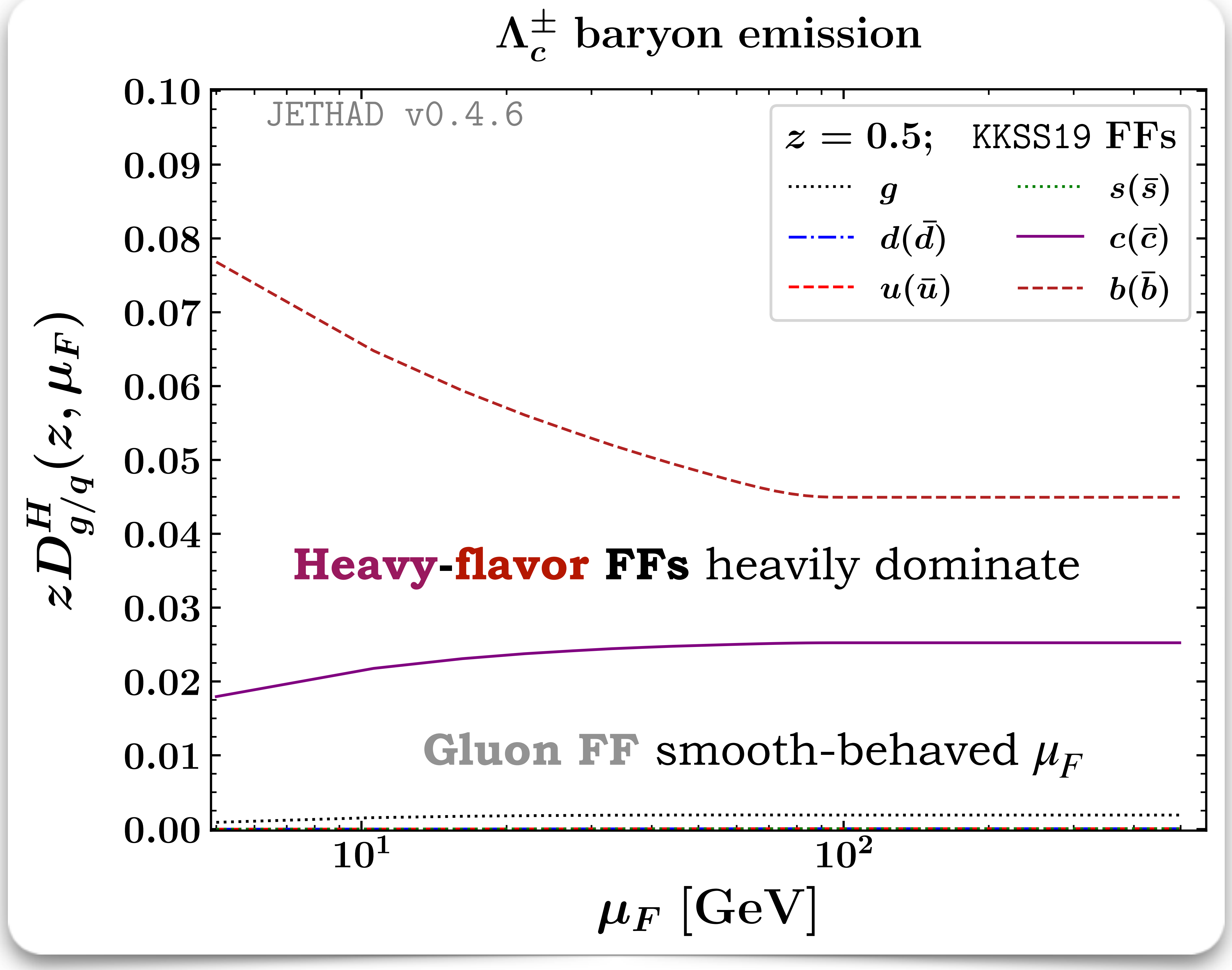
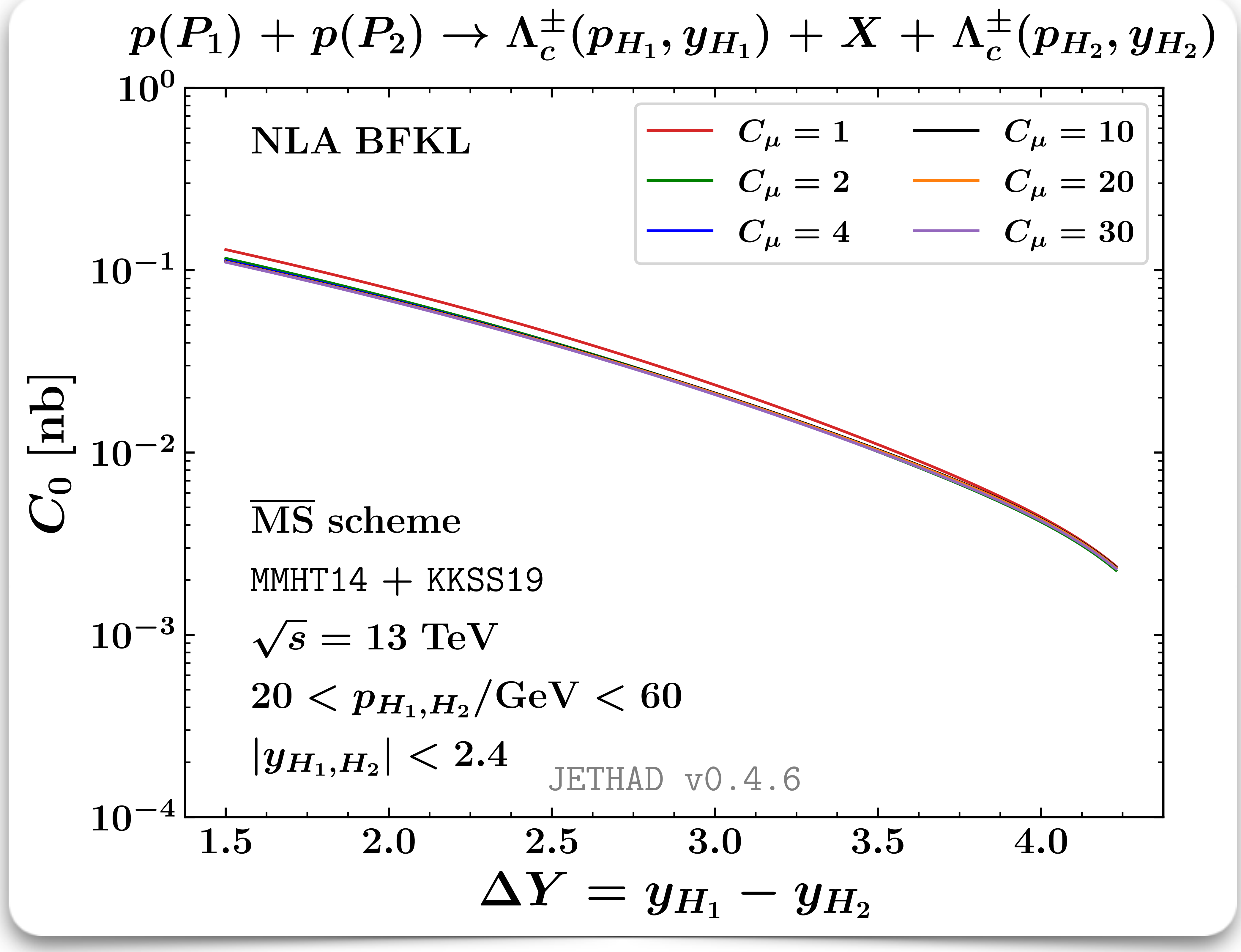




Rapidity distribution stable under scale variations

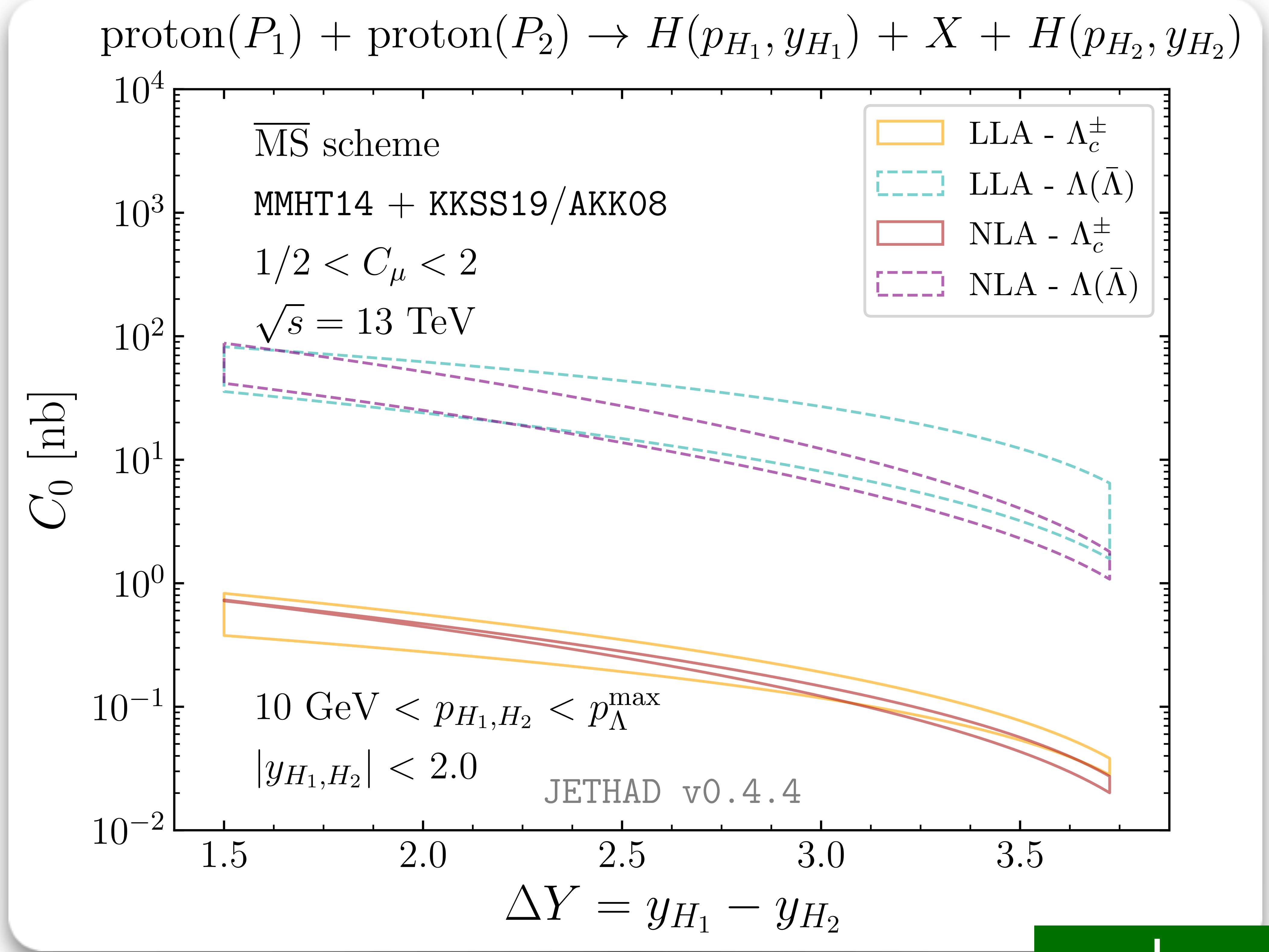
($B_c^{(*)}$ hadrons) [F. G. C., Phys. Lett. B 835 (2022) 137554]

(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

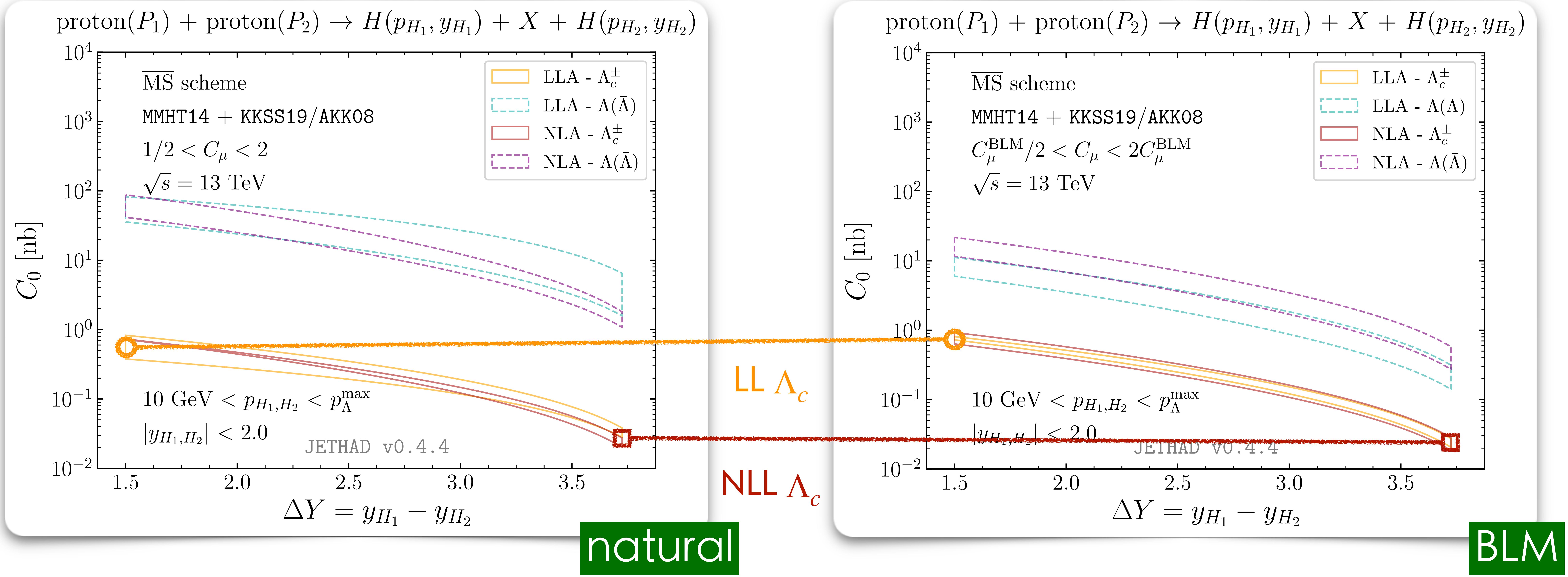
Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



natural

Stability under scale variations & NLL corrections

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



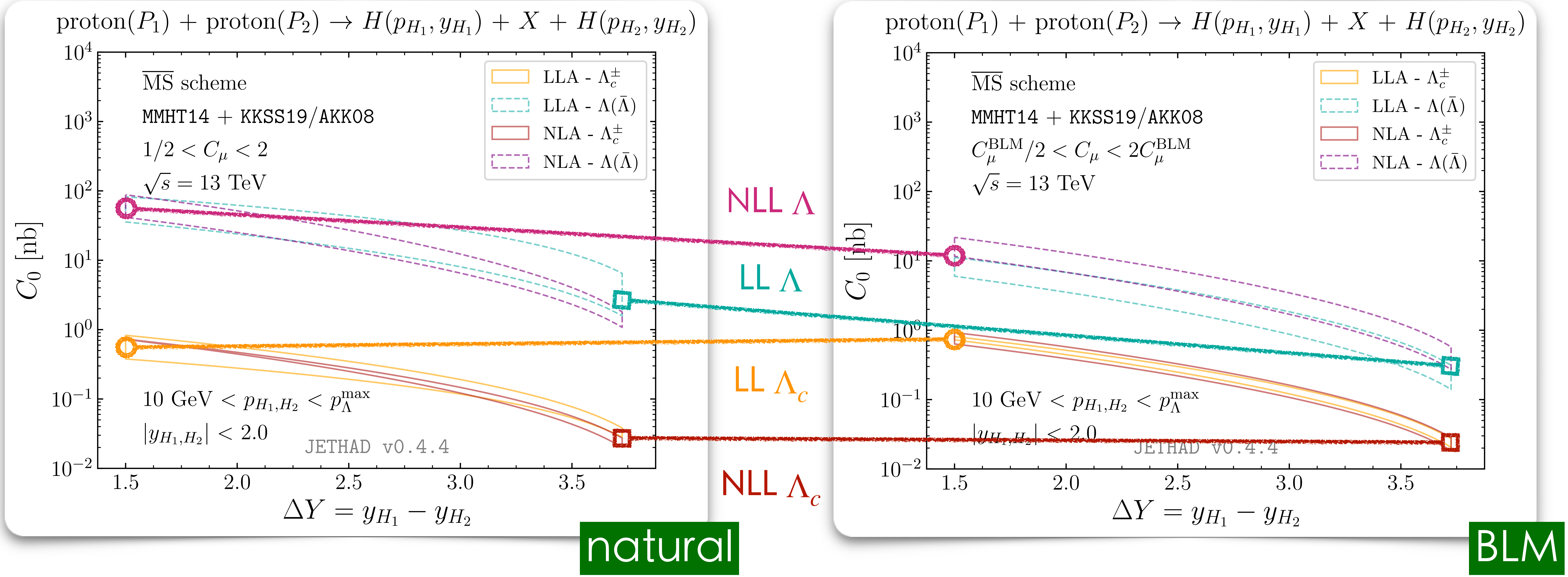
NLL corrections: rapidity distribution stable for Λ_c

(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 $|uds\rangle$



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

(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]

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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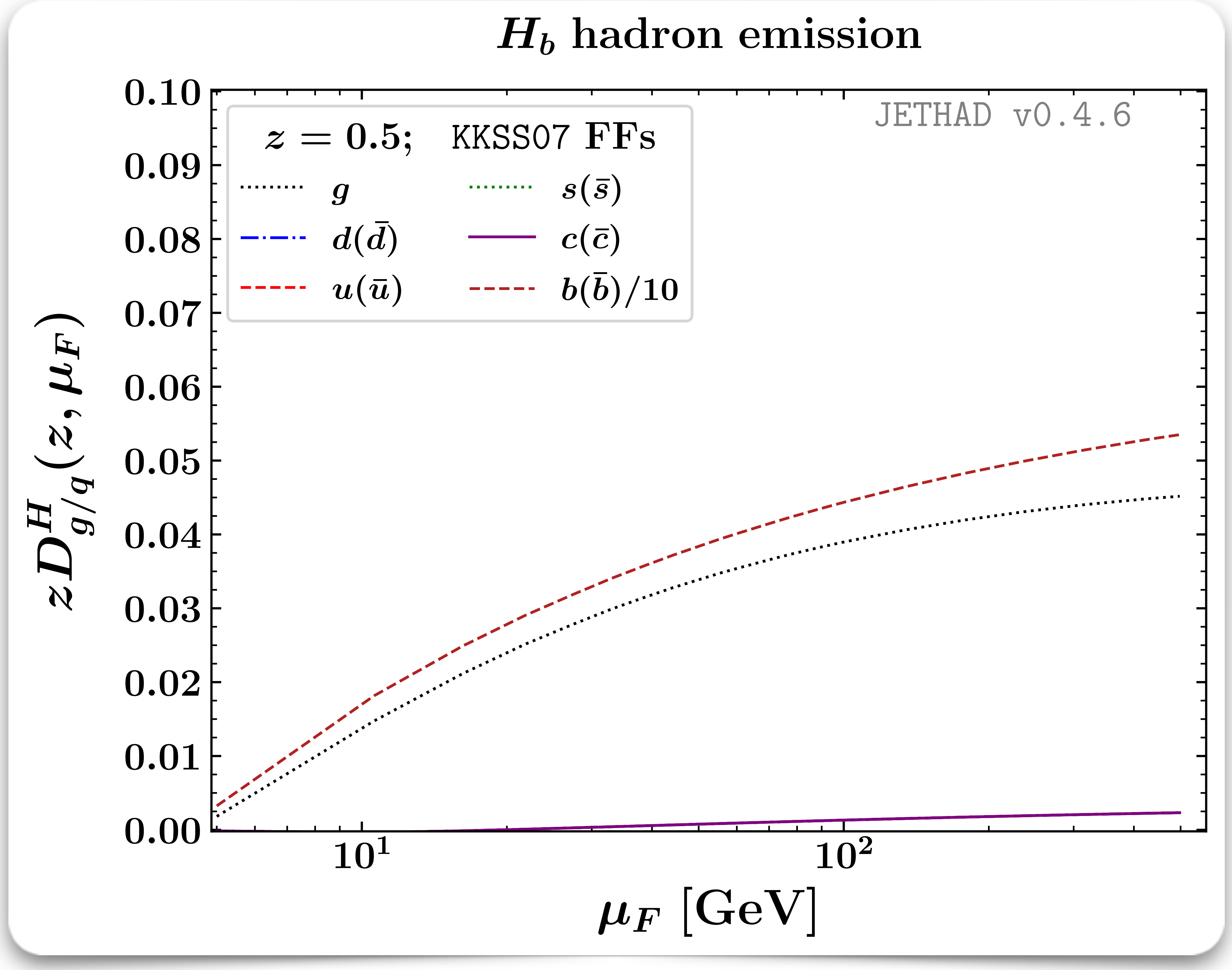

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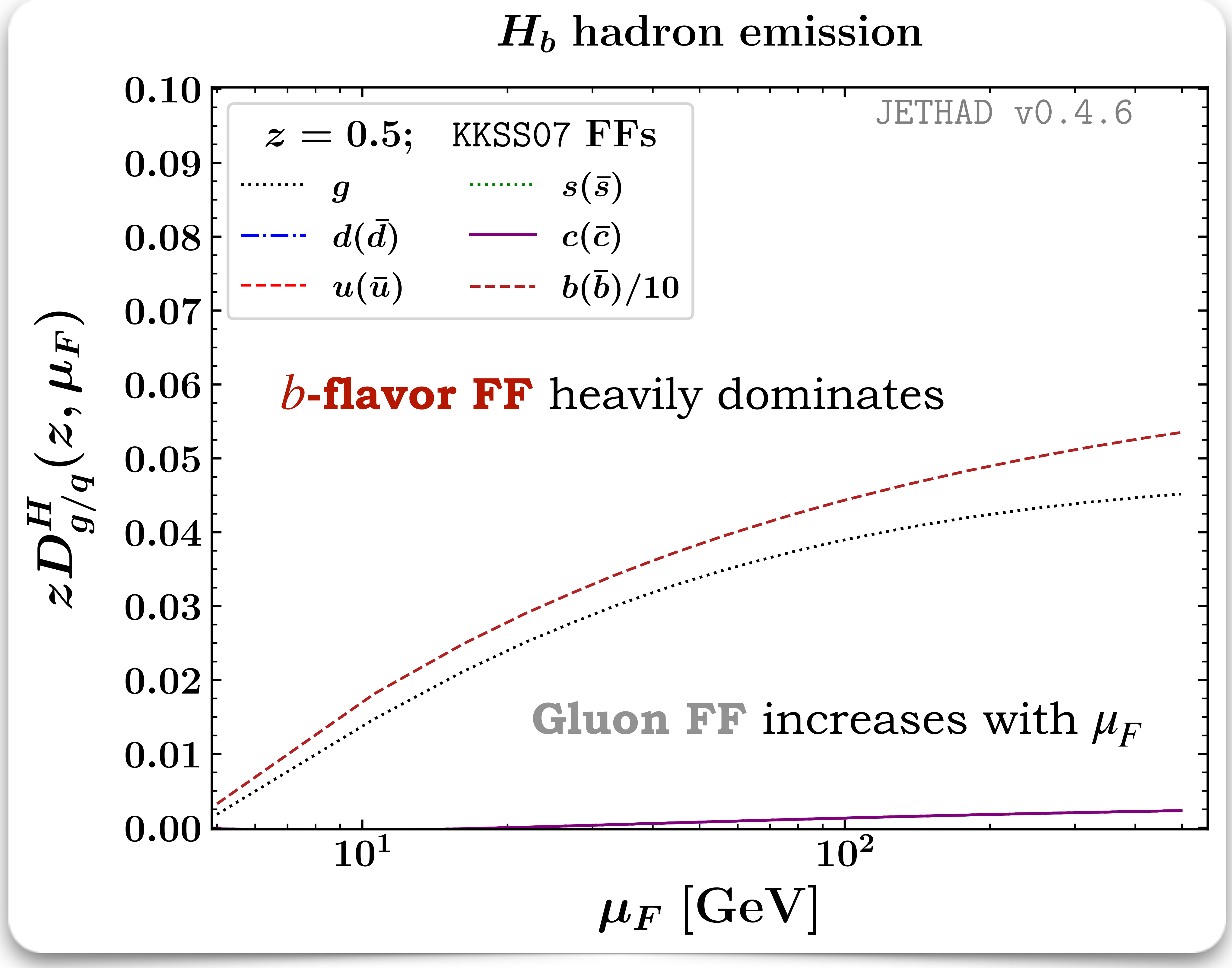

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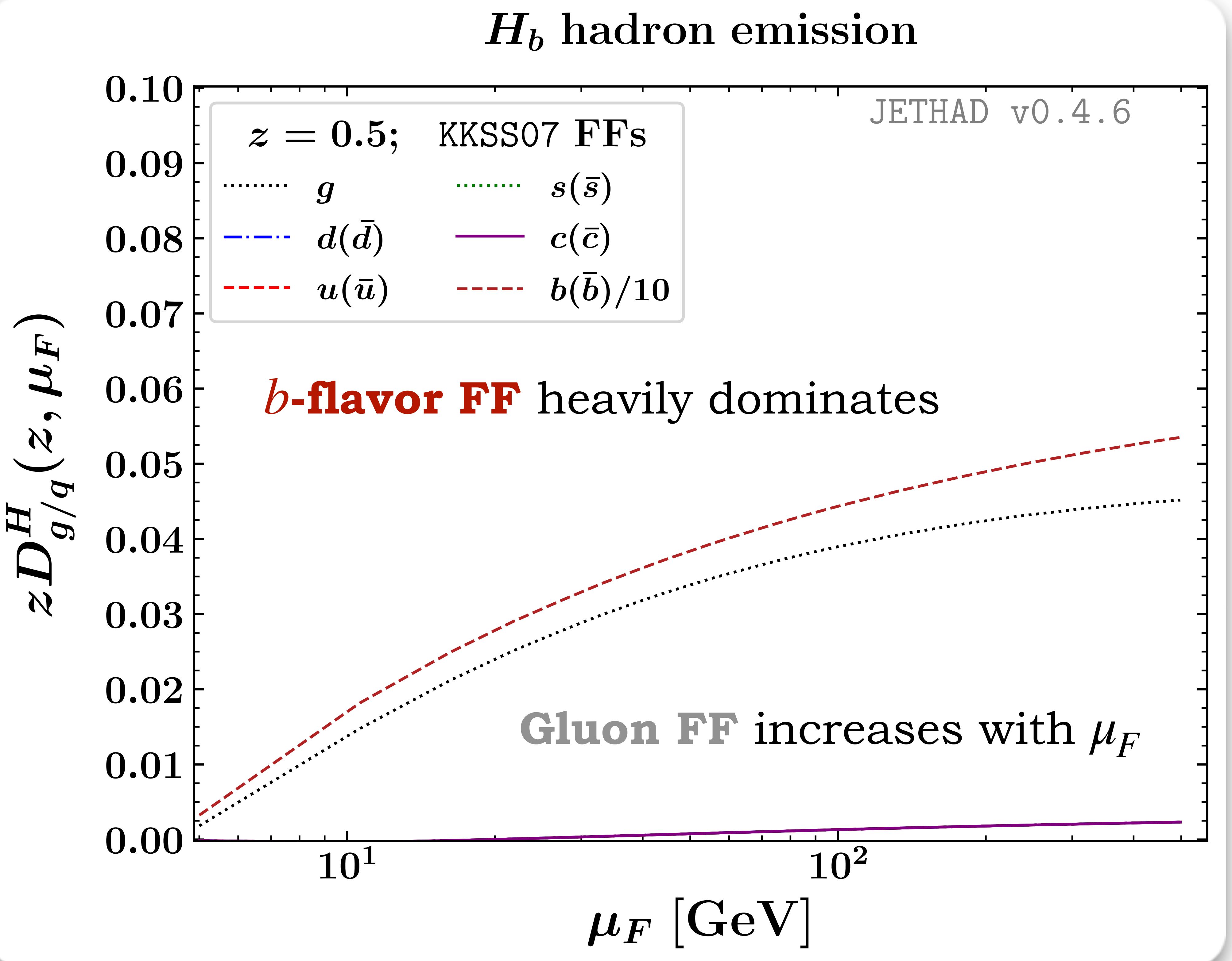

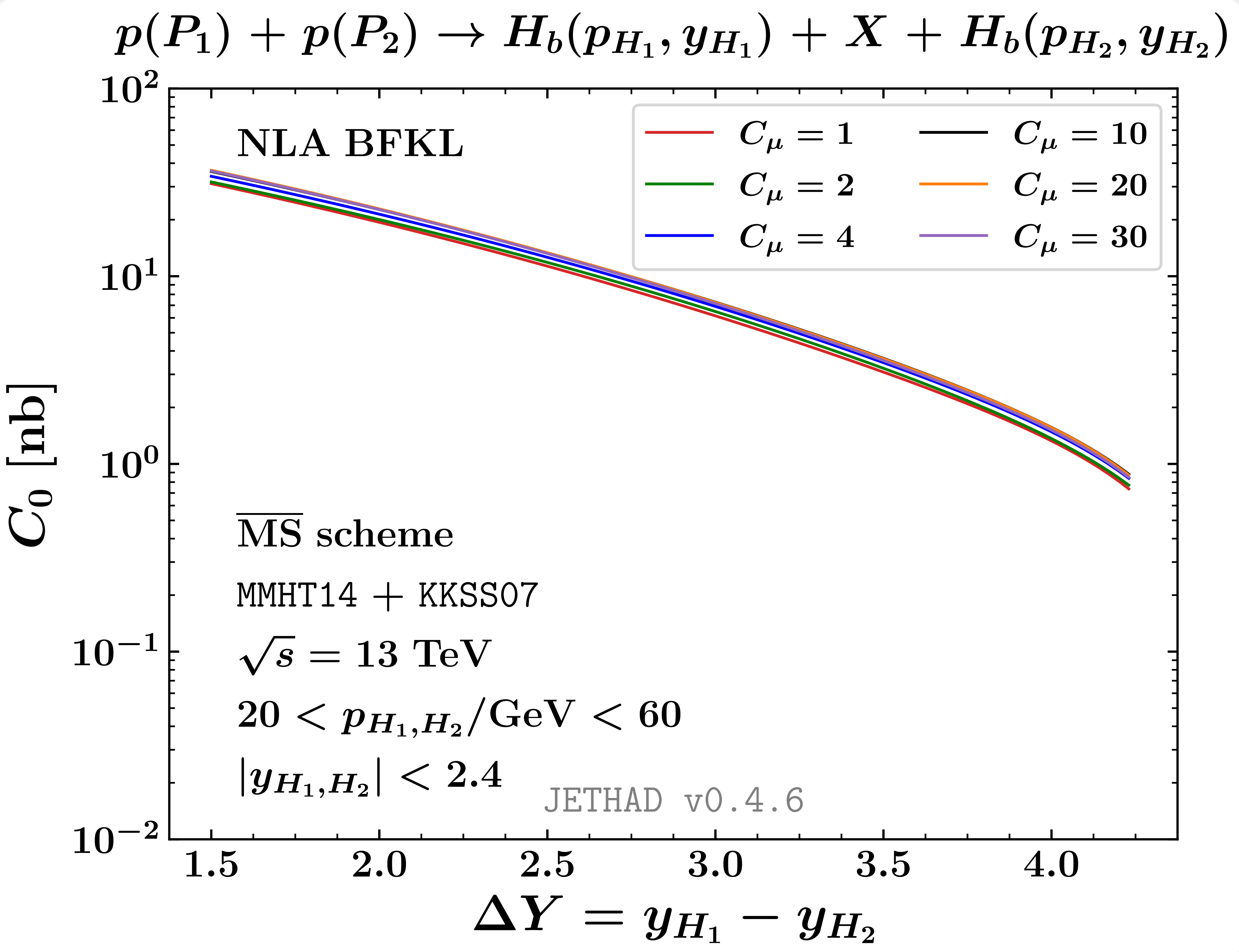

Rapidity distribution very stable under scale variations

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

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

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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- 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]

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

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¿ Is natural stability robust ?

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(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* ?

3

Quarkonia

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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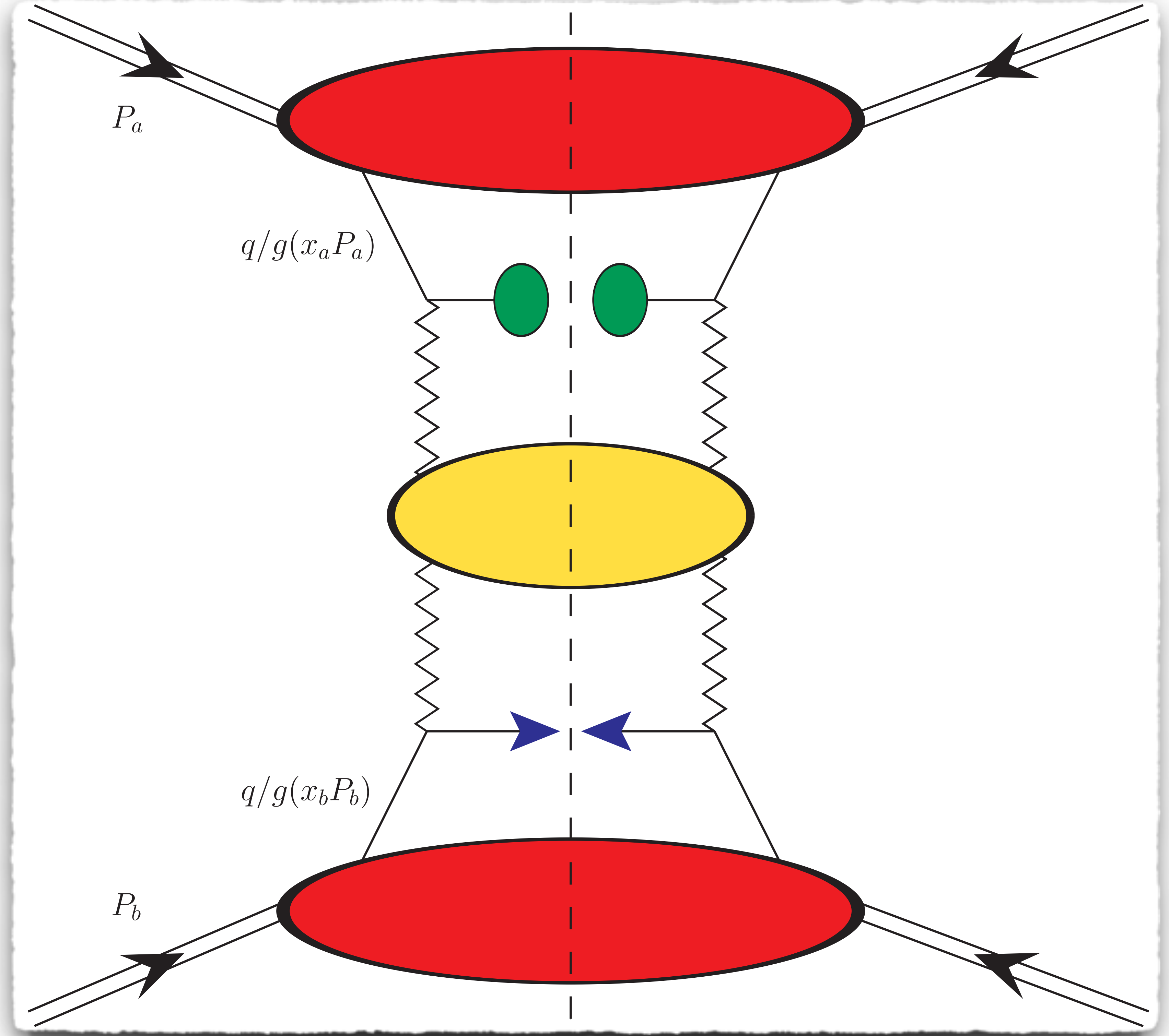


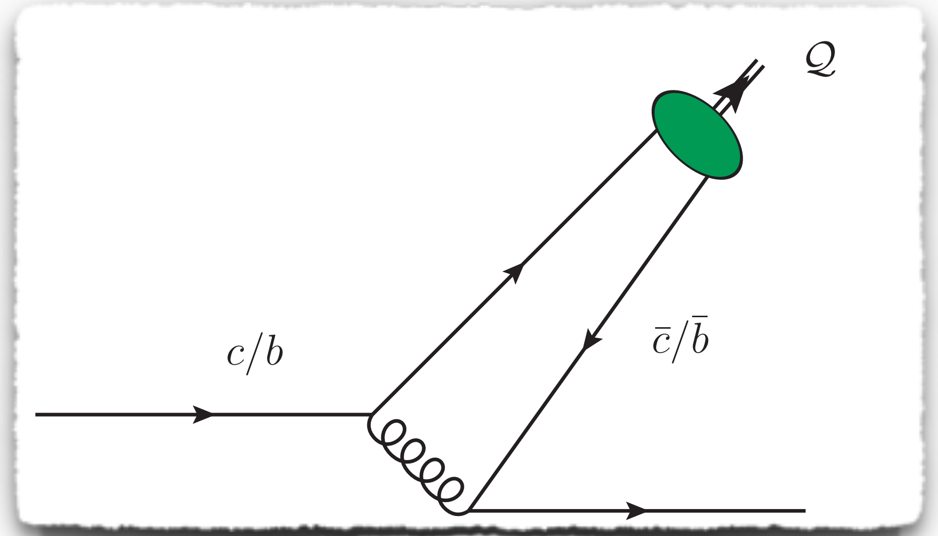
2.1 High-energy resummed cross section

The process under investigation is

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

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.

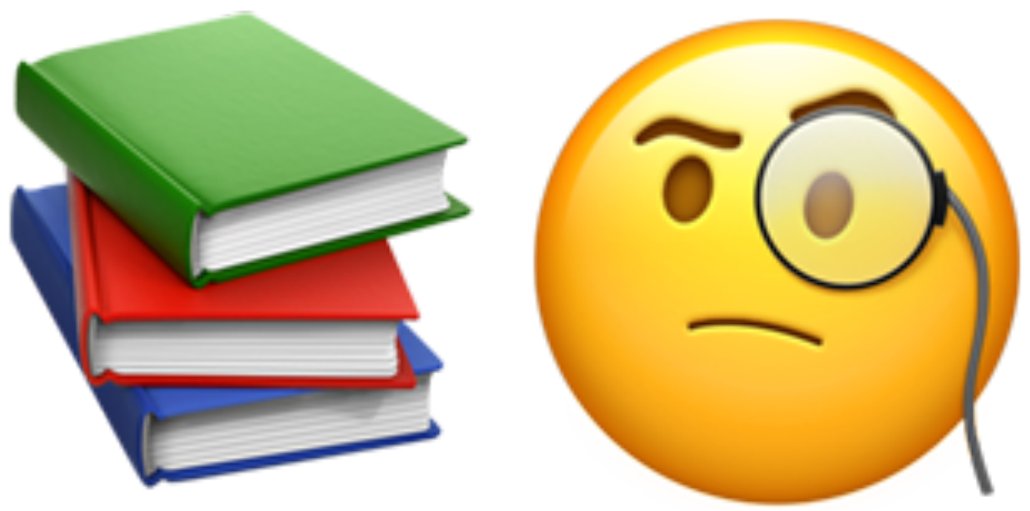
[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]



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

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

¿ What is a quarkonium ?



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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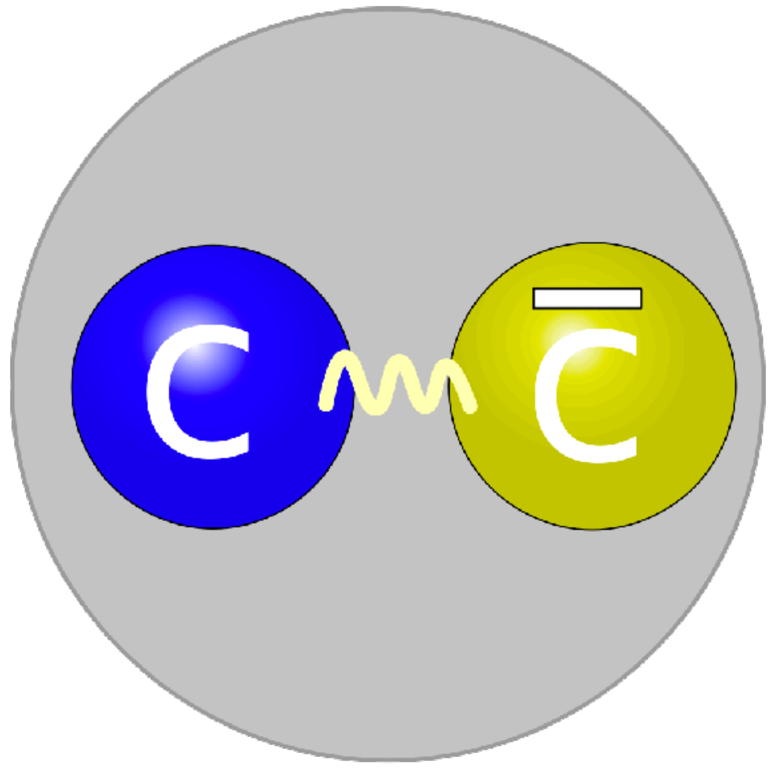
Charmonia

J/ψ

η_c



$\psi(2S)$

χ_c

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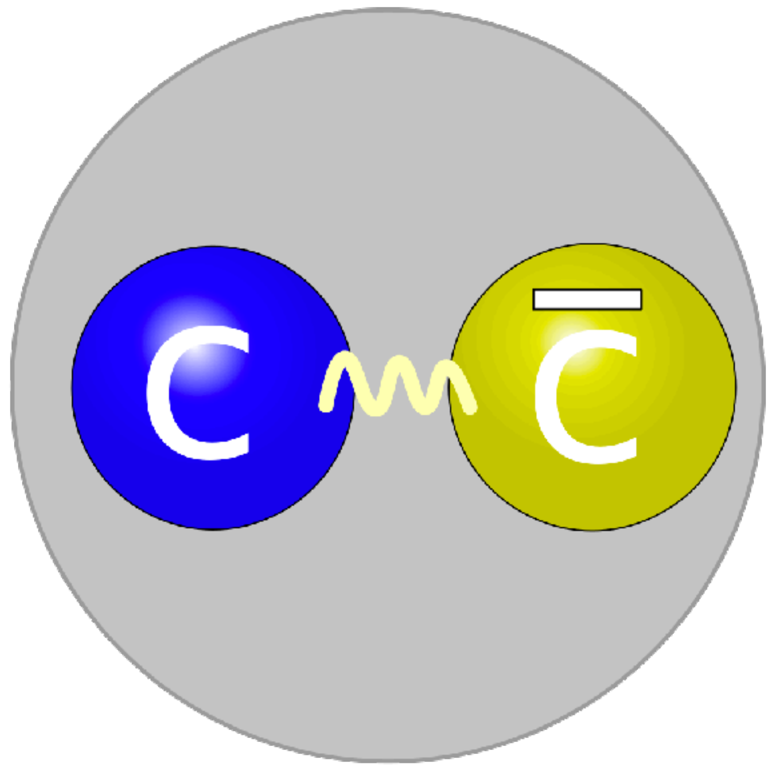
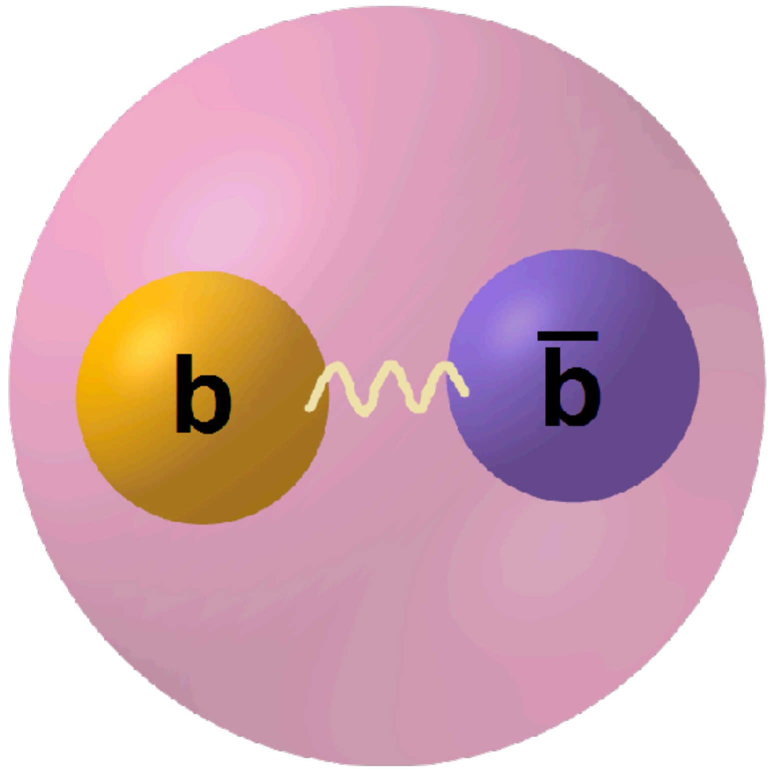


$\psi(2S)$ χ_c

Bottomonia

Υ η_b



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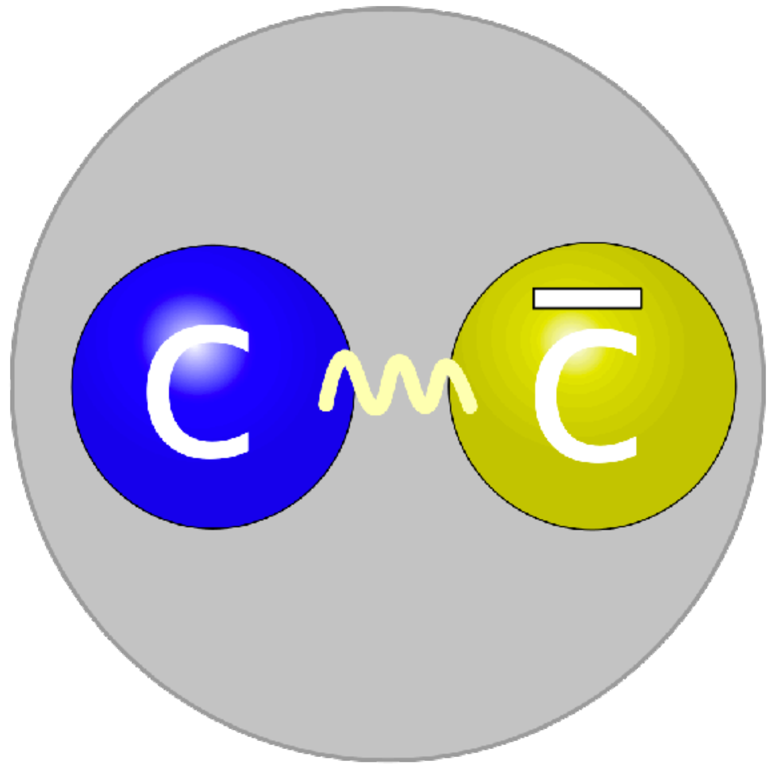
J/ψ $\quad$ η_c



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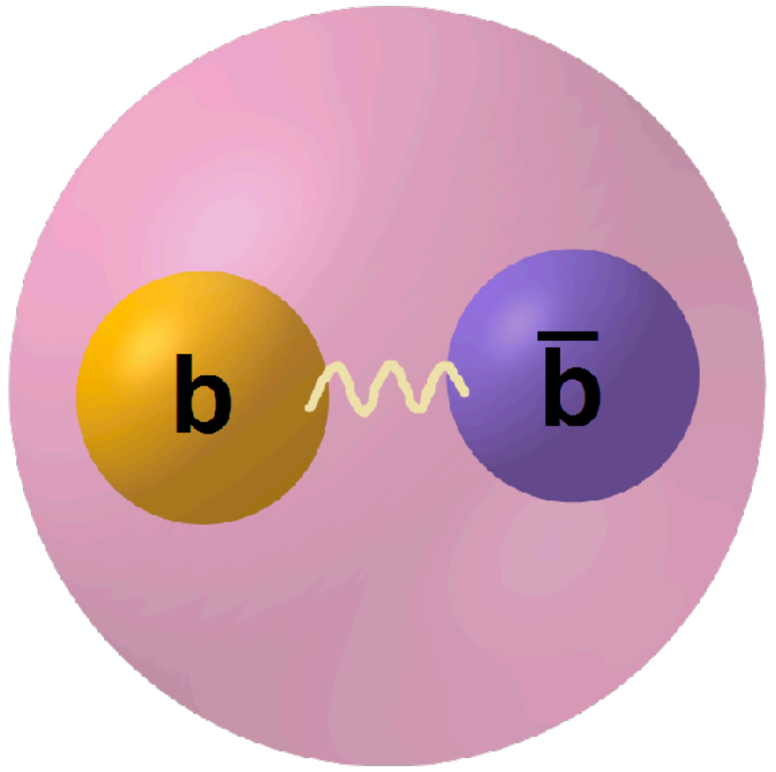
Bottomonia

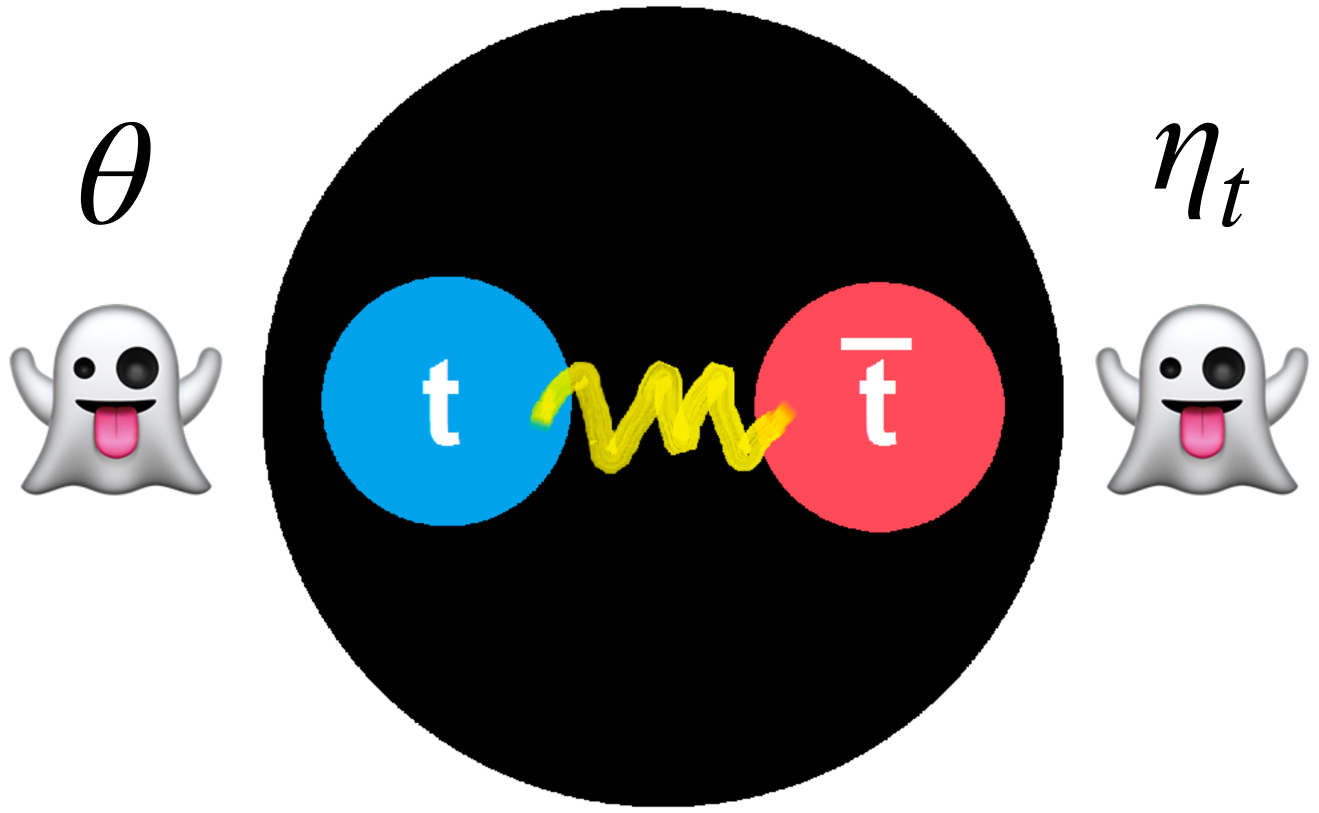
Υ $\quad$ η_b



$\Upsilon(2S)$ $\quad$ χ_b

Toponia

θ $\quad$ η_t



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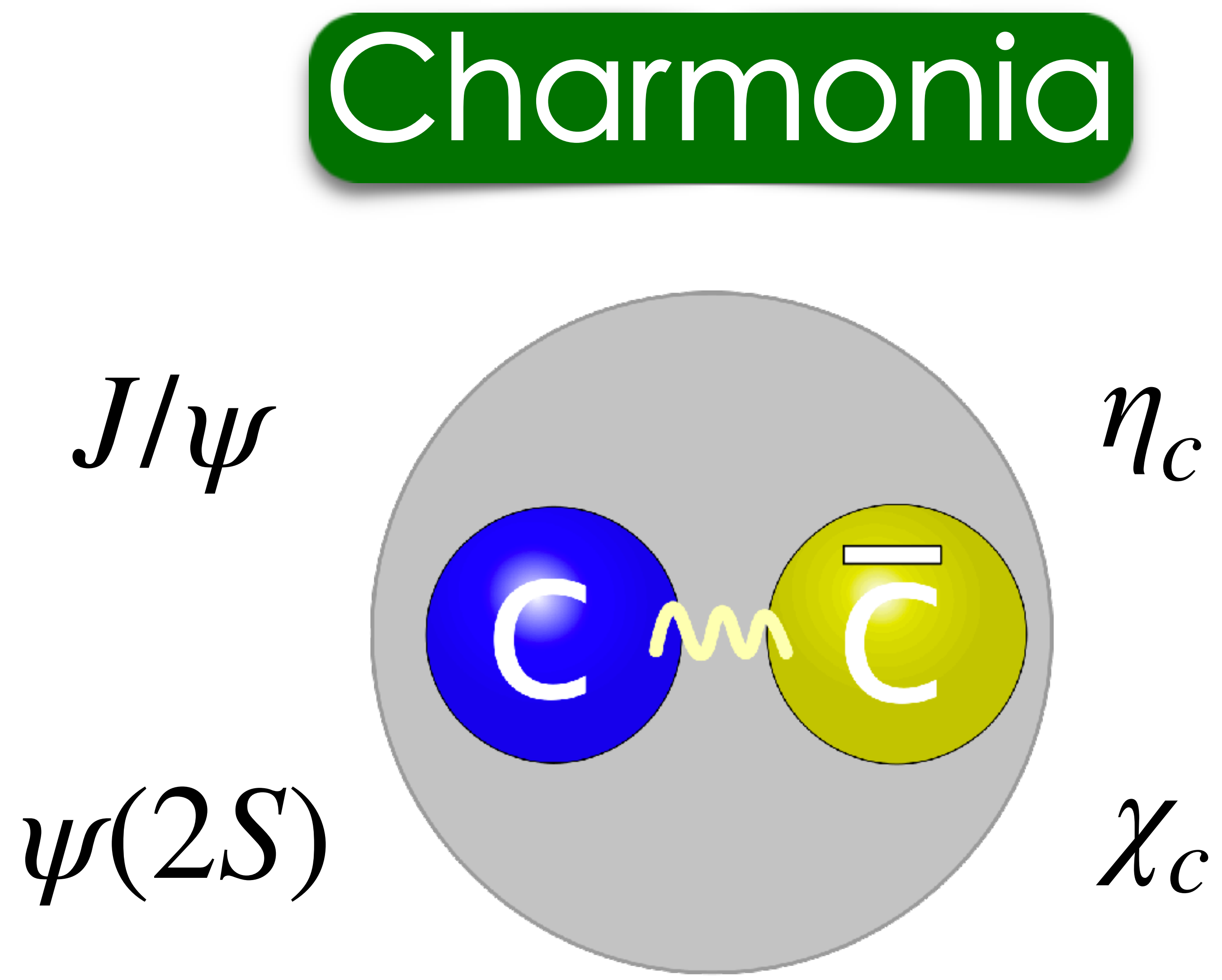

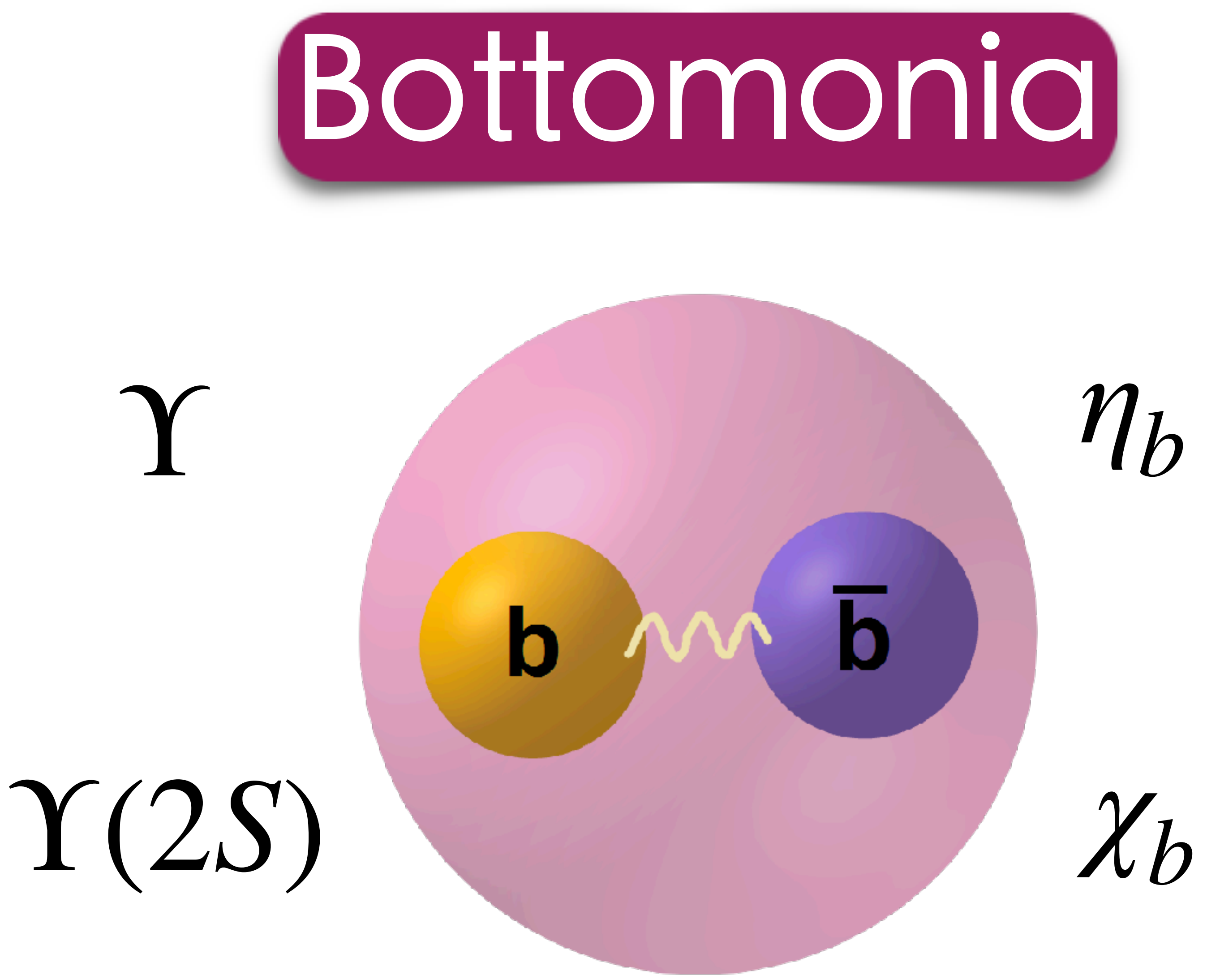

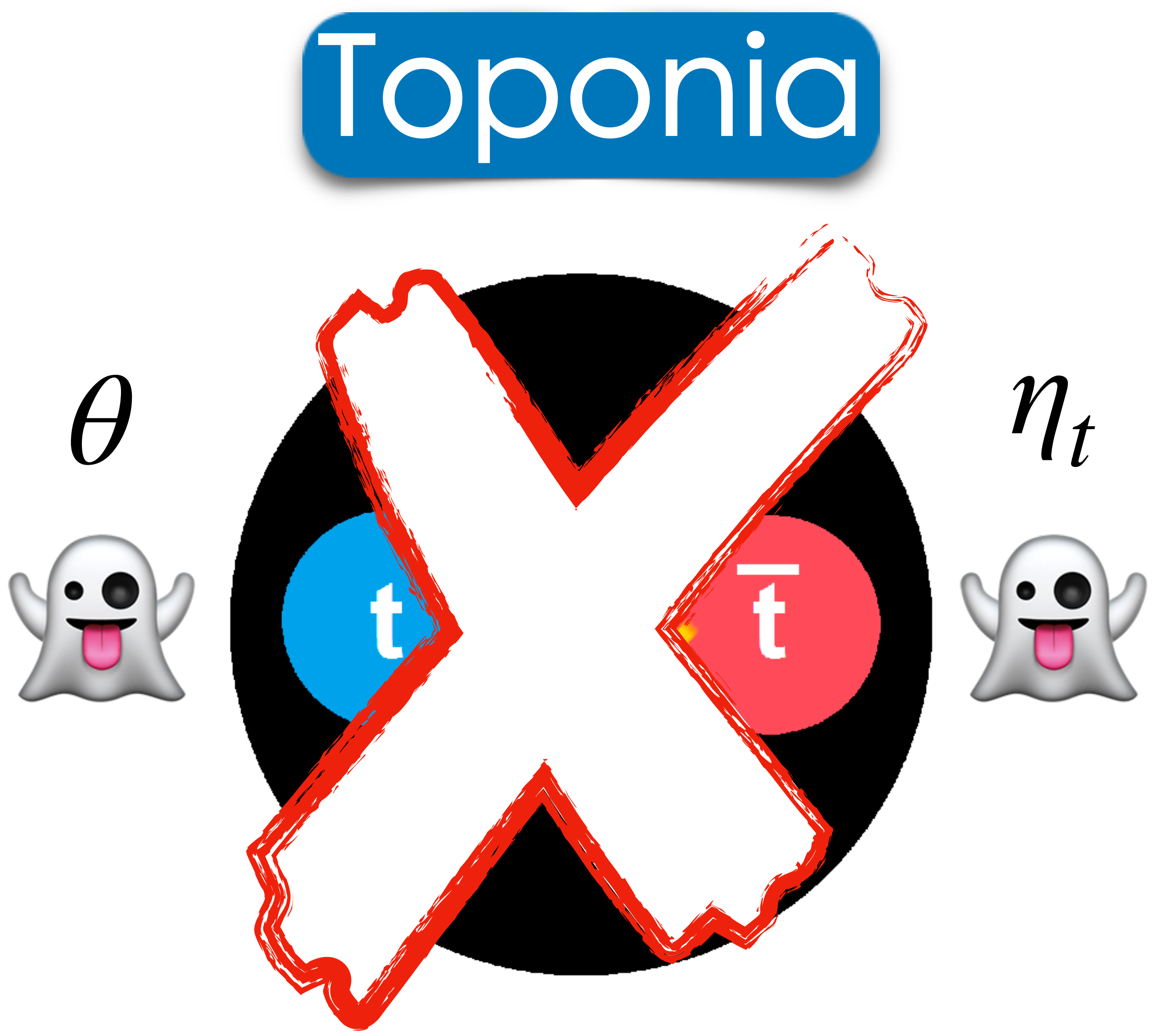

Quarkonia as Tools: Precision & Exploration

Precision determinations of QCD running coupling

$\Upsilon(1S)$ hadronic inclusive decays

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

QCD Hydrogen Atoms

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Forward inclusive reactions

Gluon PDF positivity at low x and low Q^2

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Quarkonia in nuclear matter

Confined matter to QGP transition

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Quarkonia as Tools: Precision & Exploration

Portals to exotic matter and BSM physics

Hadroquarkonium
EW boson rare decays

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

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Highlights of Non-Relativistic QCD

- **NRQCD** $\rightarrow$ effective field theory $\rightarrow$ 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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$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\overline{Q}\,[n] + X)\,\langle \mathcal{O}^H\,[n] \rangle$$

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Highlights of Non-Relativistic QCD

NRQCD:

- an effective field theory
- Idea: start from the heavy quark Lagrangian $\mathcal{L}_{heavy} = \bar{\Psi}(i\gamma^\mu D_\mu - m_q)\Psi$ and expand in velocity

$$\longrightarrow \psi^\dagger\left(iD_t + \frac{1}{2m_q}\vec{D}^2 + \dots\right)\psi \leftarrow \text{quark term}$$

$$+ \chi^\dagger\left(iD_t - \frac{1}{2m_q}\vec{D}^2 + \dots\right)\chi \leftarrow \text{antiquark term}$$

$$\Psi \sim \begin{pmatrix} \psi \\ \chi \end{pmatrix}$$

- This Lagrangian conserves heavy quarks and antiquarks

$\Rightarrow$ Add mixing terms like $\mathcal{O} = \psi^\dagger \chi \chi^\dagger \psi$ to describe production and decay

$$\delta\mathcal{L} = \sum_i \frac{f_i}{m_q^2}\mathcal{O}_i \qquad \mathcal{O} \sim$$ 

🔗 [Lectures by Jani Penttala]

- expansion in the (relative) velocity v and $\alpha_s \sim v$
- write particles in terms of different spin and color states

spectroscopic notation for the spin and orbital angular momentum of the $q\bar{q}$ pair

Example:

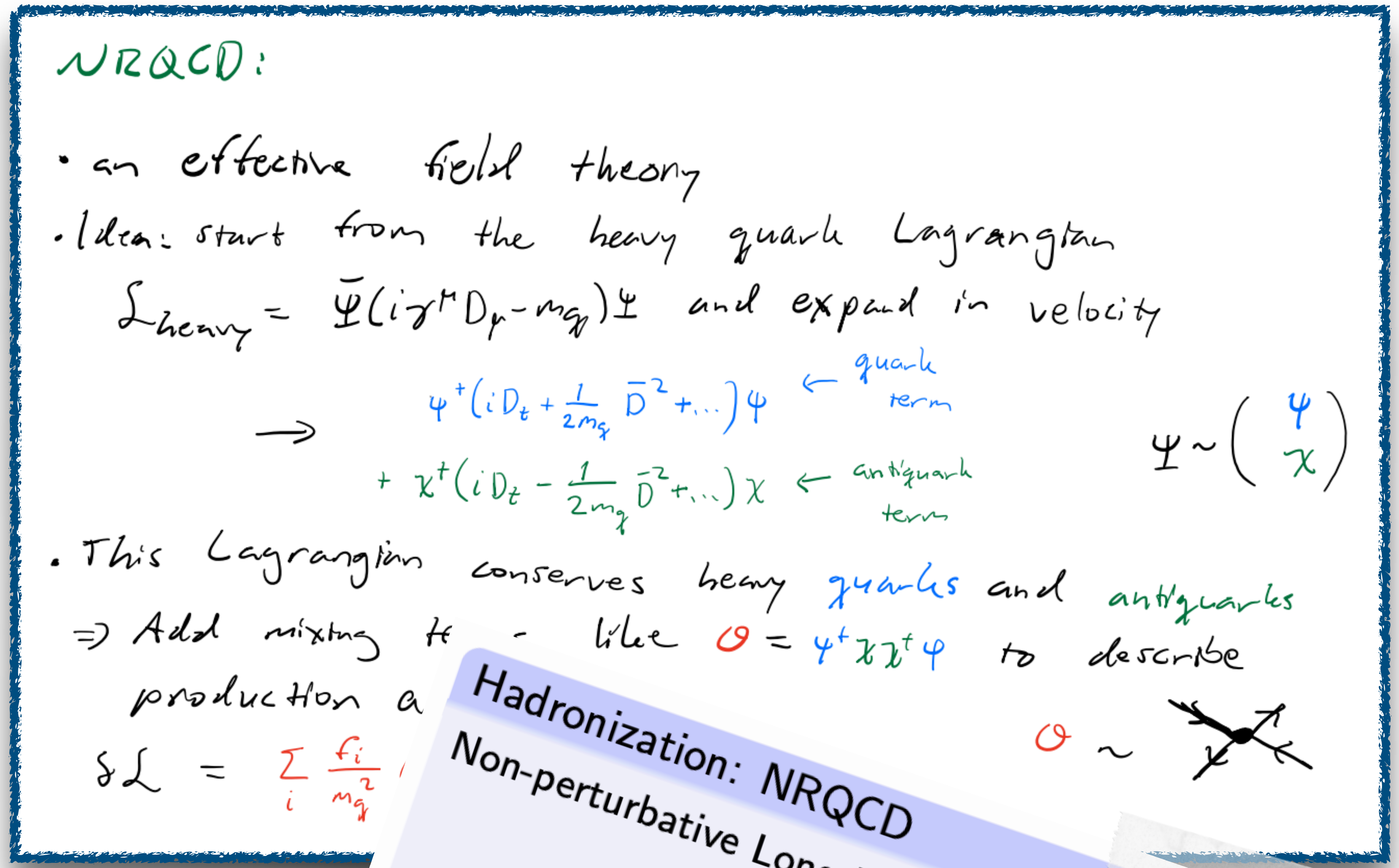
$$|J/\psi\rangle = \mathcal{O}(v^0)\,|{}^3S_1^{[1]}\rangle + \mathcal{O}(v)\,|{}^3P_J^{[8]}g\rangle + \mathcal{O}(v^{3/2})\,|{}^1S_0^{[8]}g\rangle + \mathcal{O}(v^2)\,|{}^3D_J^{[1]}\rangle + \dots$$

color state of the $q\bar{q}$ system

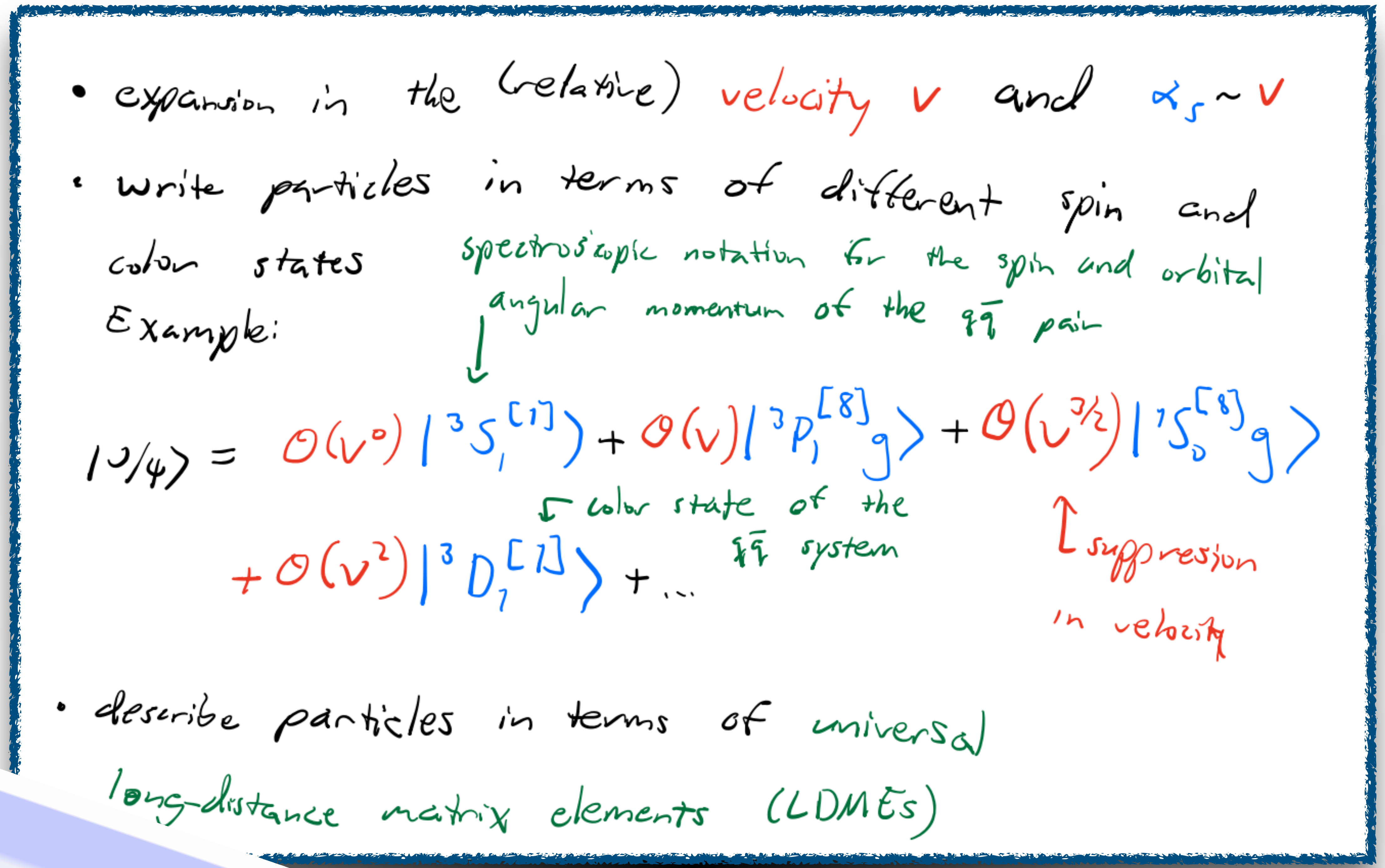
suppression in velocity

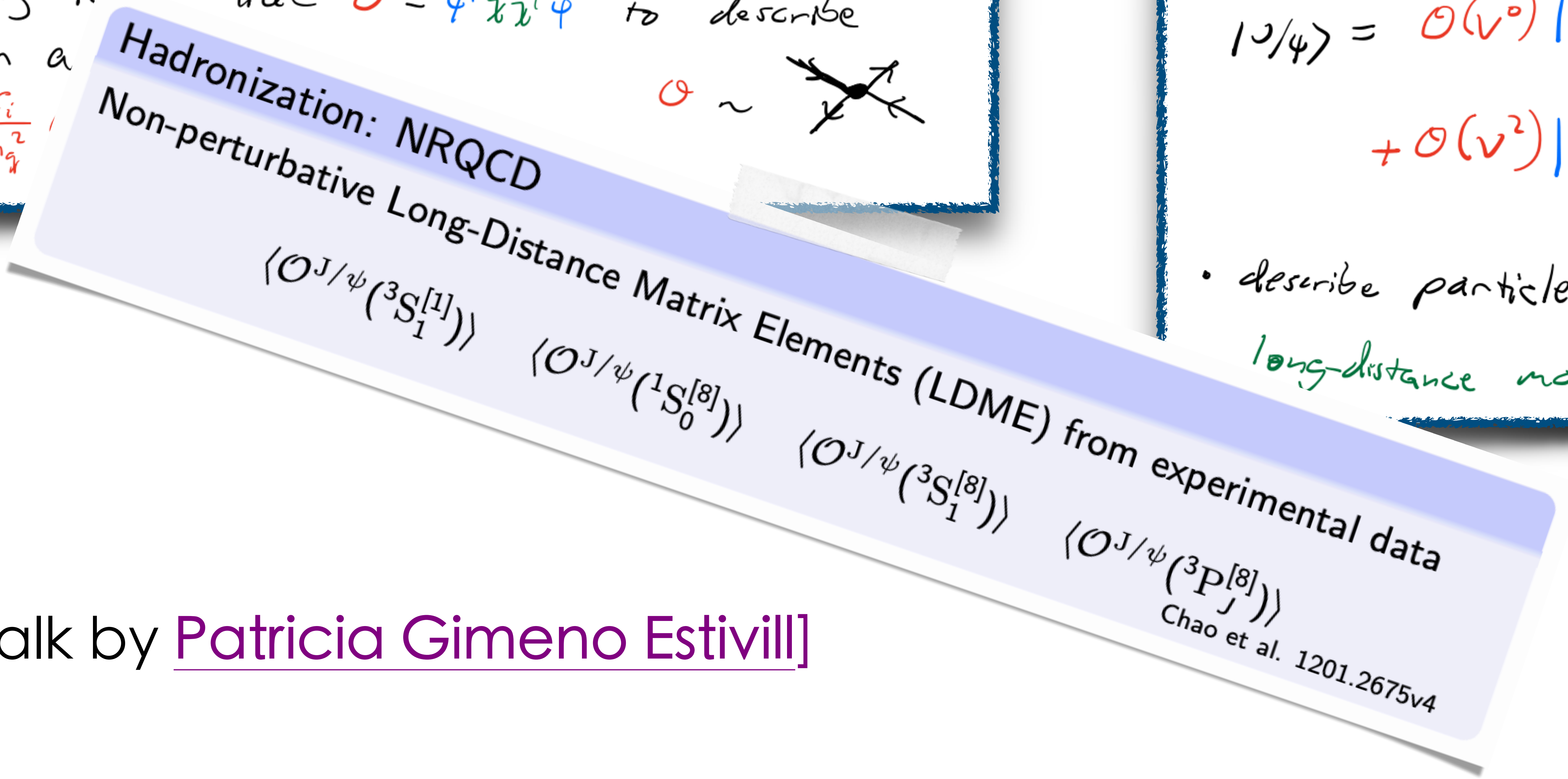
- describe particles in terms of universal long-distance matrix elements (LDMEs)

Highlights of Non-Relativistic QCD



🔗 [Lectures by Jani Penttala]



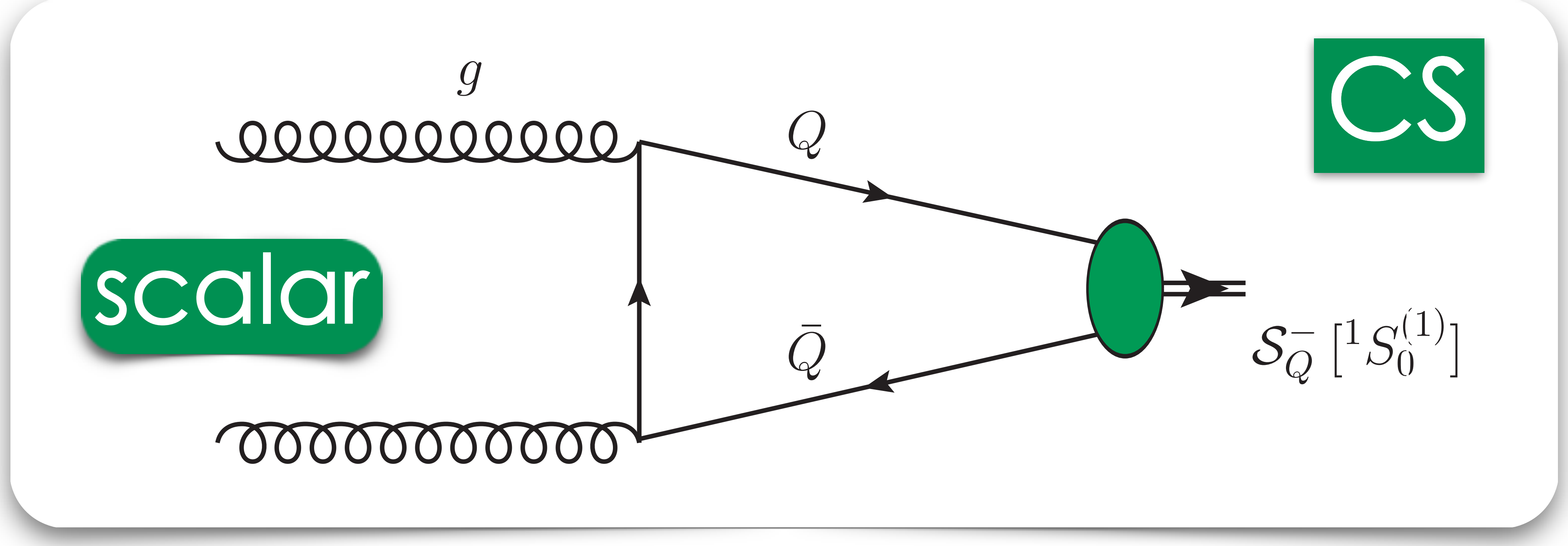


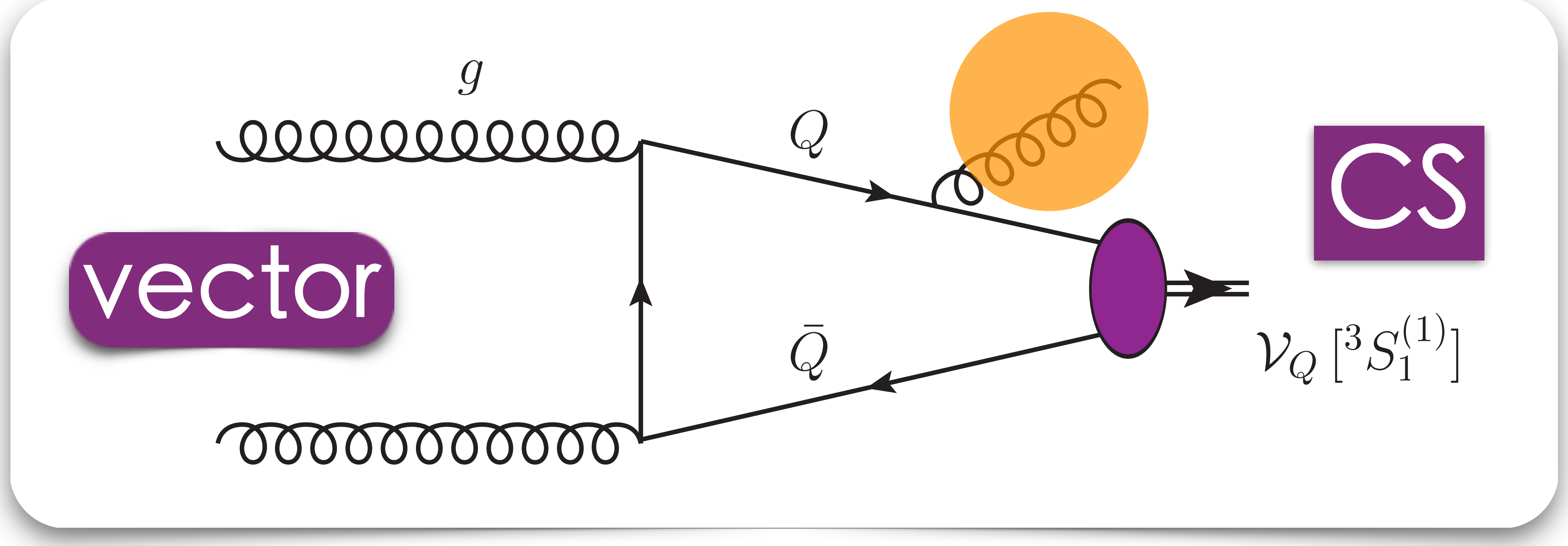
🔗 [Talk by Patricia Gimeno Estivill]

From low to high energies

Low energy, low p_T

Short-distance production





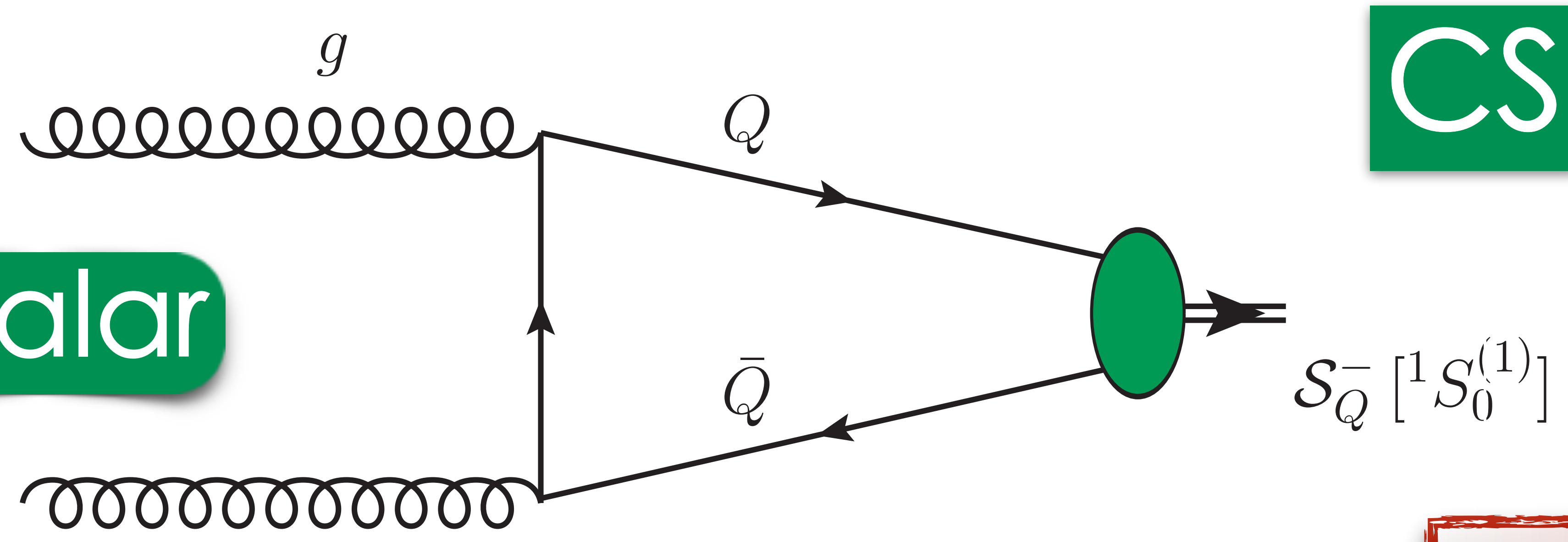
Extra gluon due to Landau-Yang selection rule

From low to high energies

Low energy, low p_T
Short-distance production

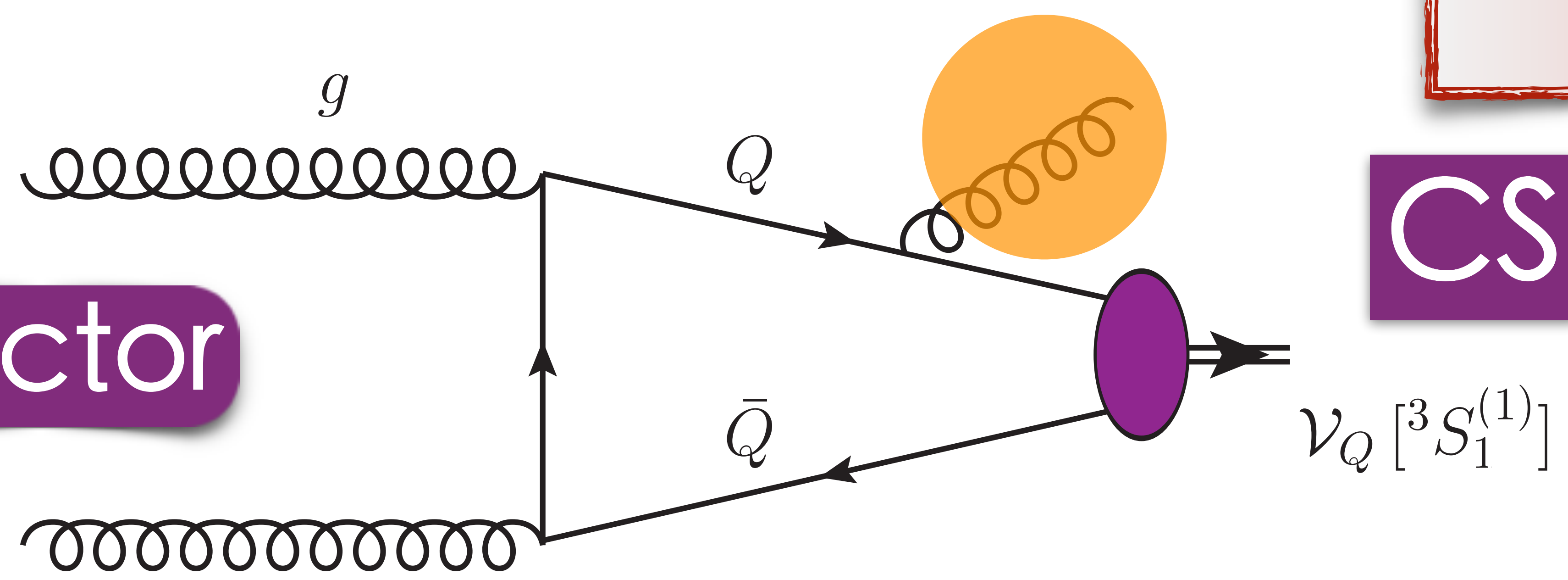
scalar

CS



vector

CS

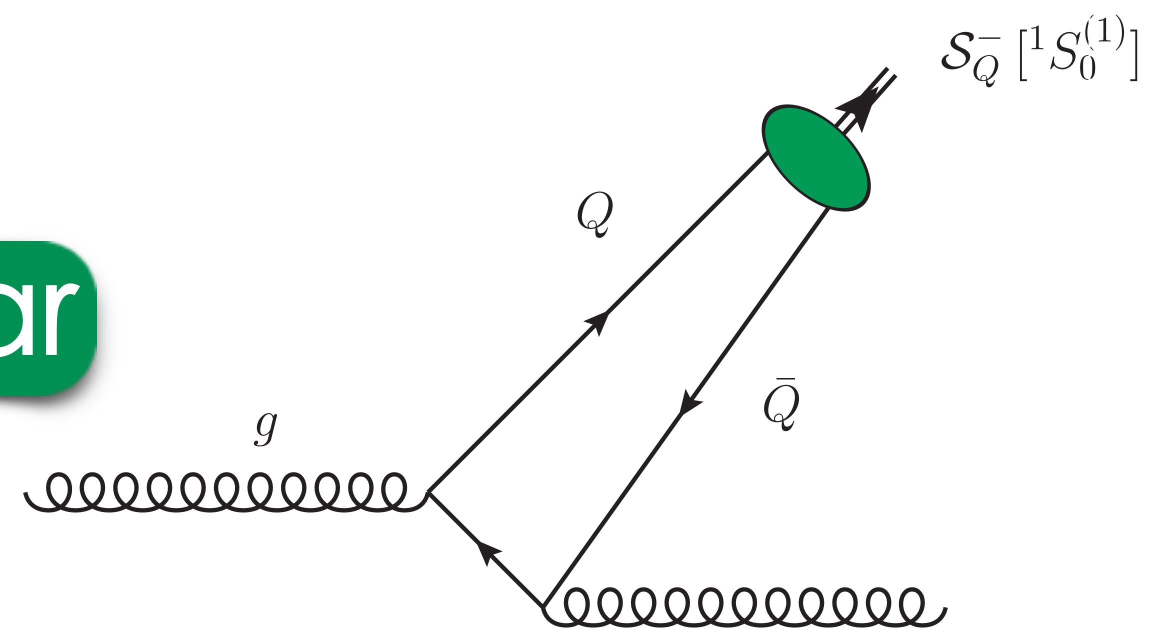


$p_T \gtrsim 10 \div 15$ GeV (charmonia)

High energy, high p_T
Single-parton fragmentation

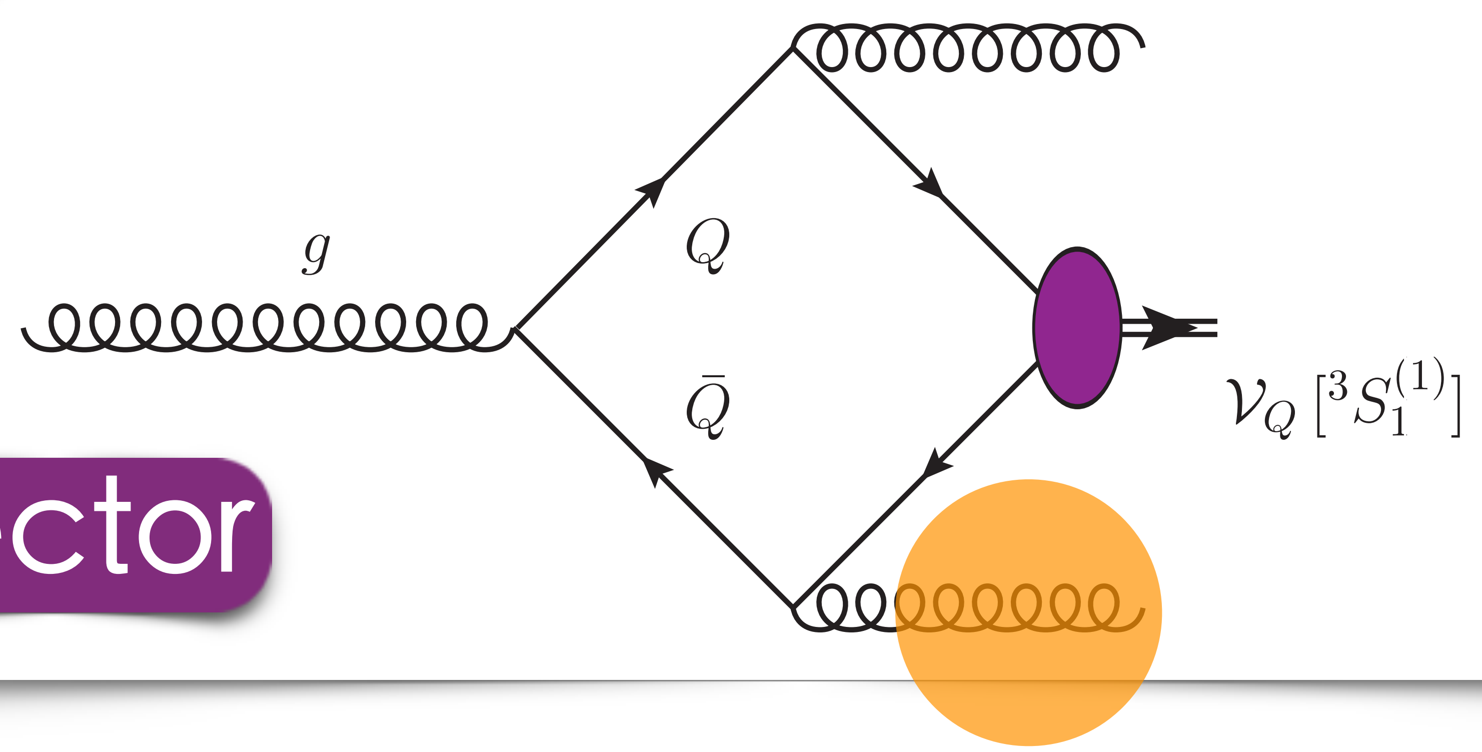
scalar

CS



vector

CS



Extra gluon due to Landau-Yang selection rule

¿ How to address onium fragmentation ?

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

Heavy-Flavor Non-Relativistic evolution

HADRONIC STRUCTURE

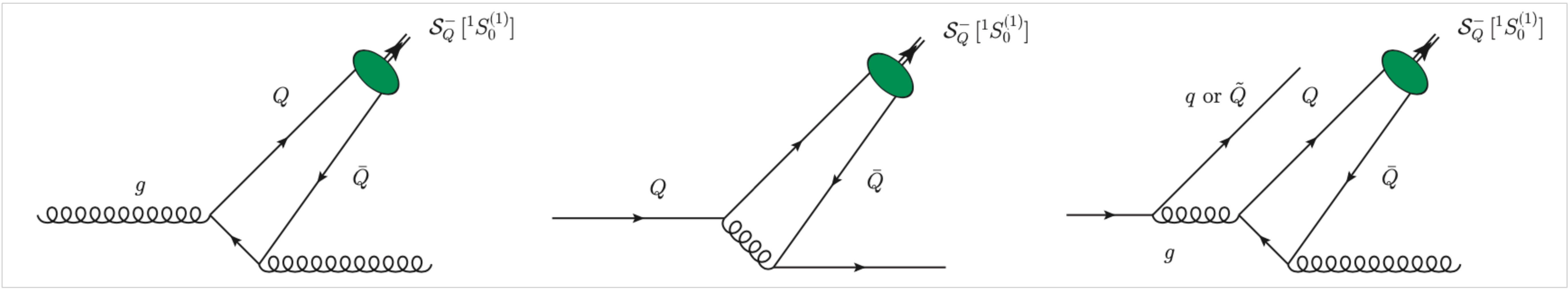
QUARKONIUM THEORY

PRECISION QCD

COLLINEAR FACTORIZATION

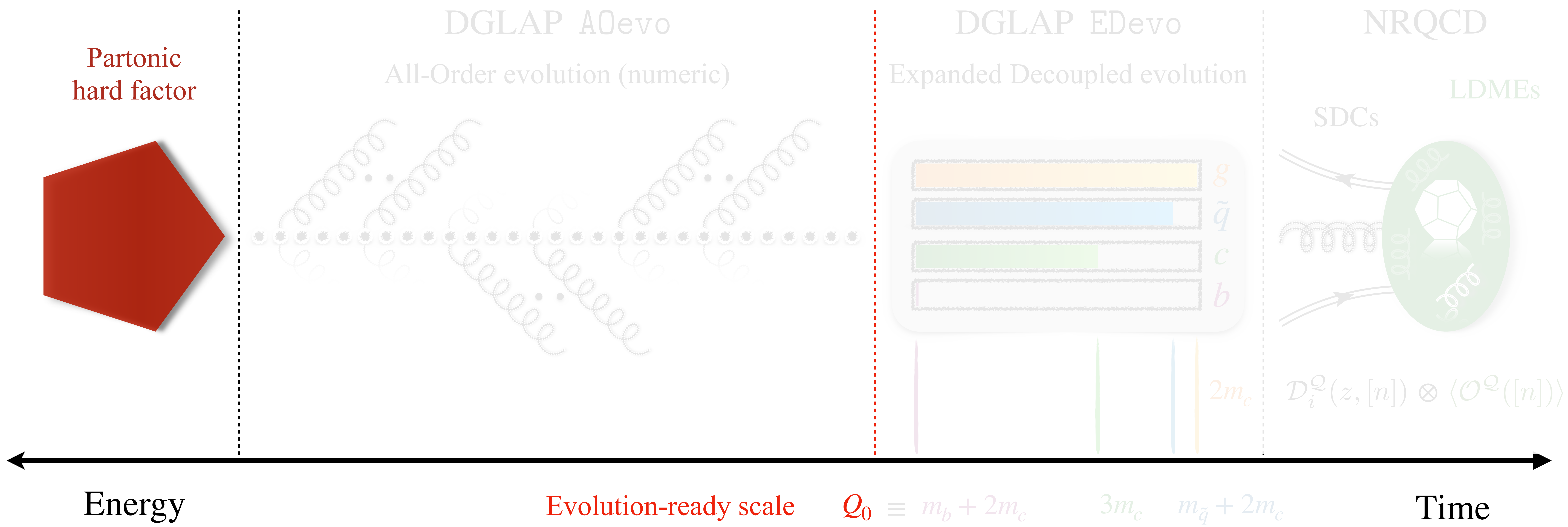
Guiding principle ⇒ ¡ Use the best of the Two Worlds as much as we can !

HF-NRevo: Initial-scale NRCQD inputs



Scalar η_c

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



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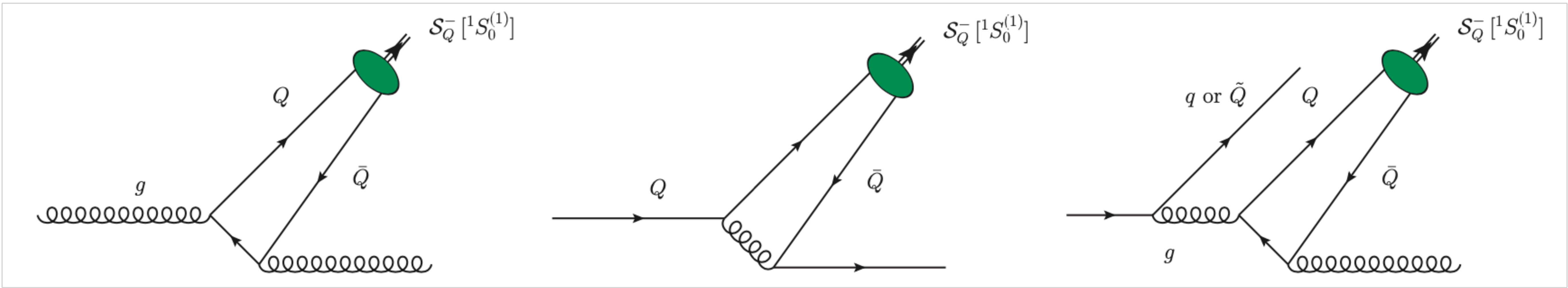

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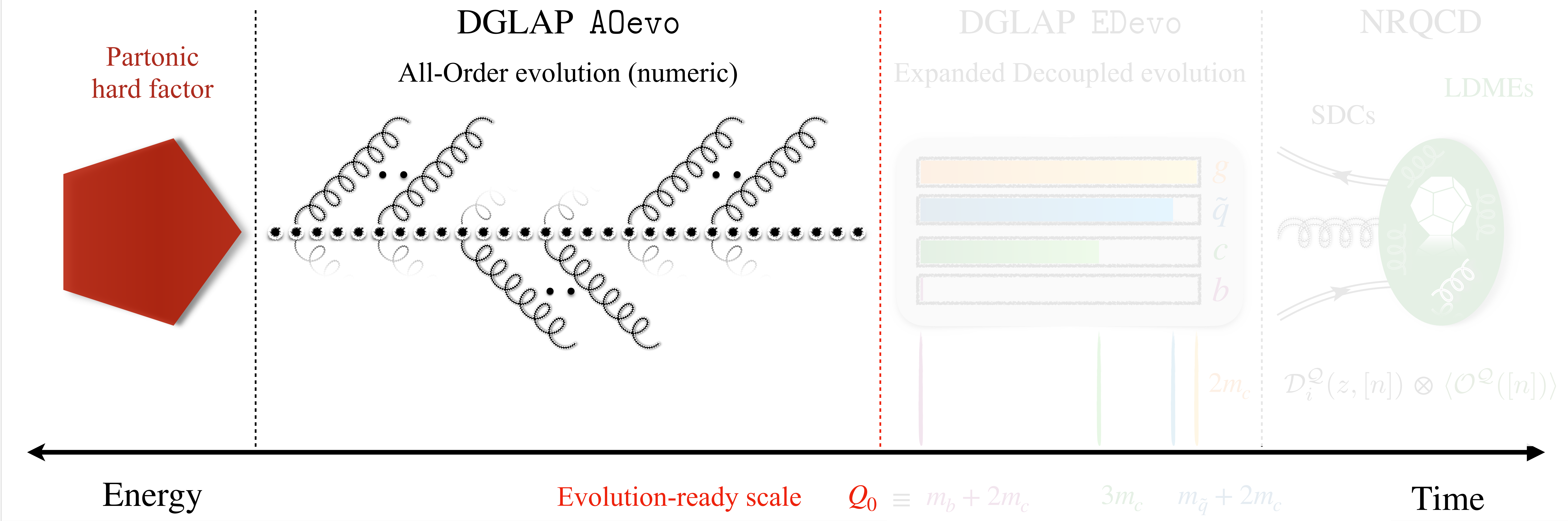

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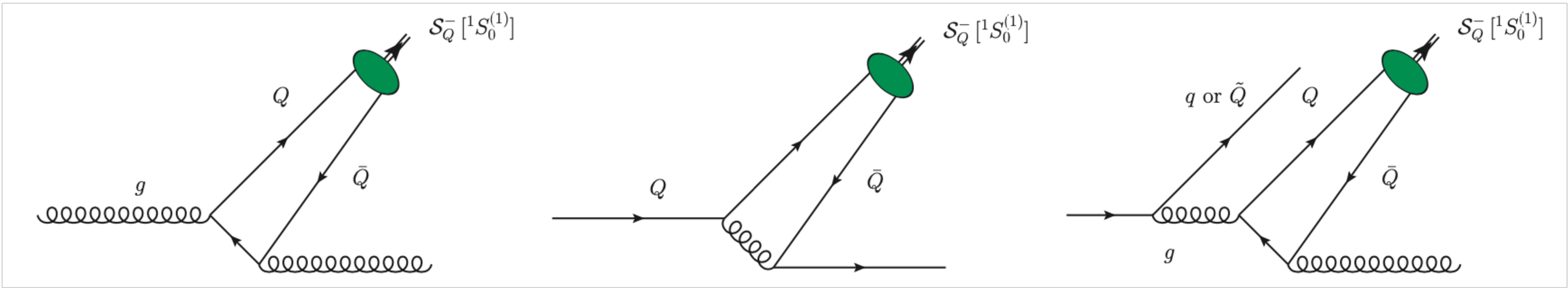

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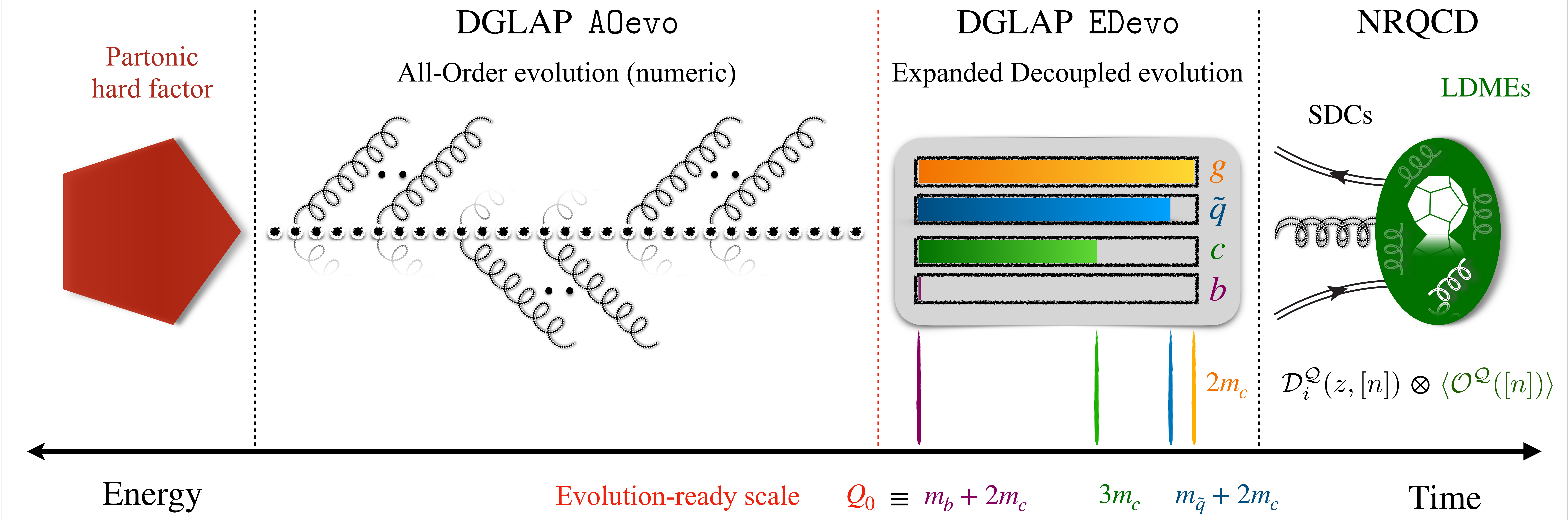

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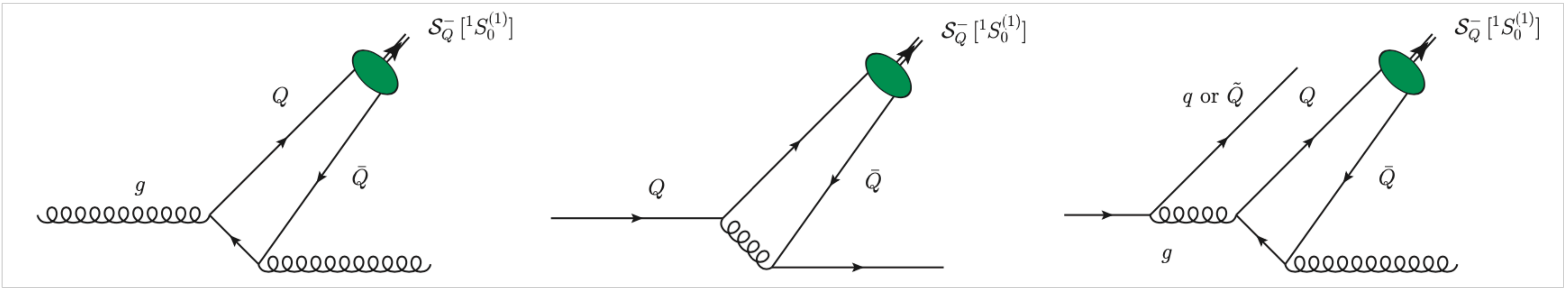
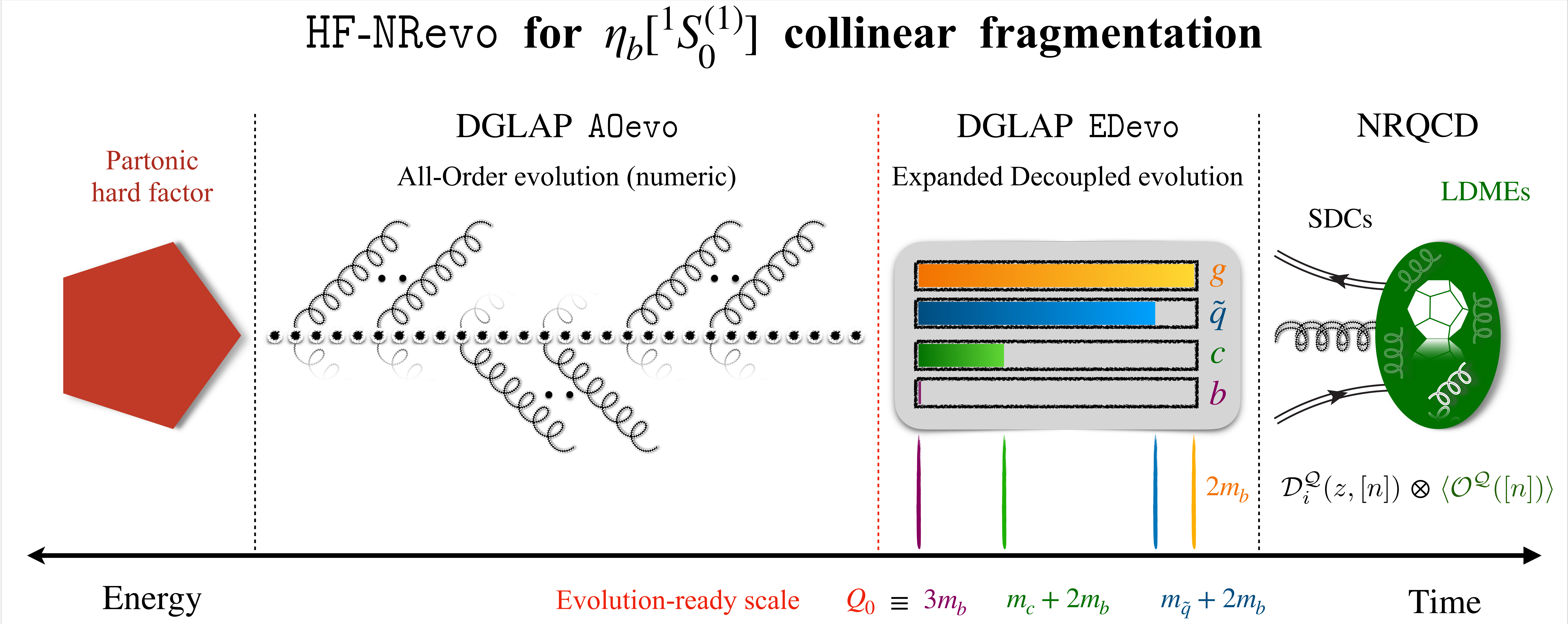
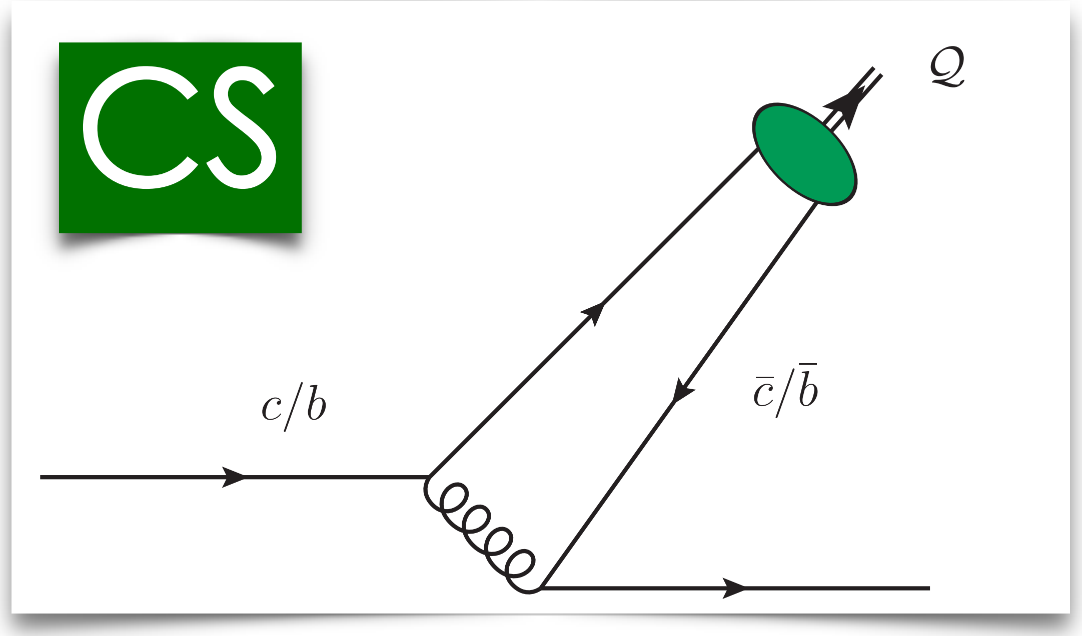


Scalar η_b



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



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

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

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

🔗 [F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]
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Vector quarkonium from single-parton fragmentation

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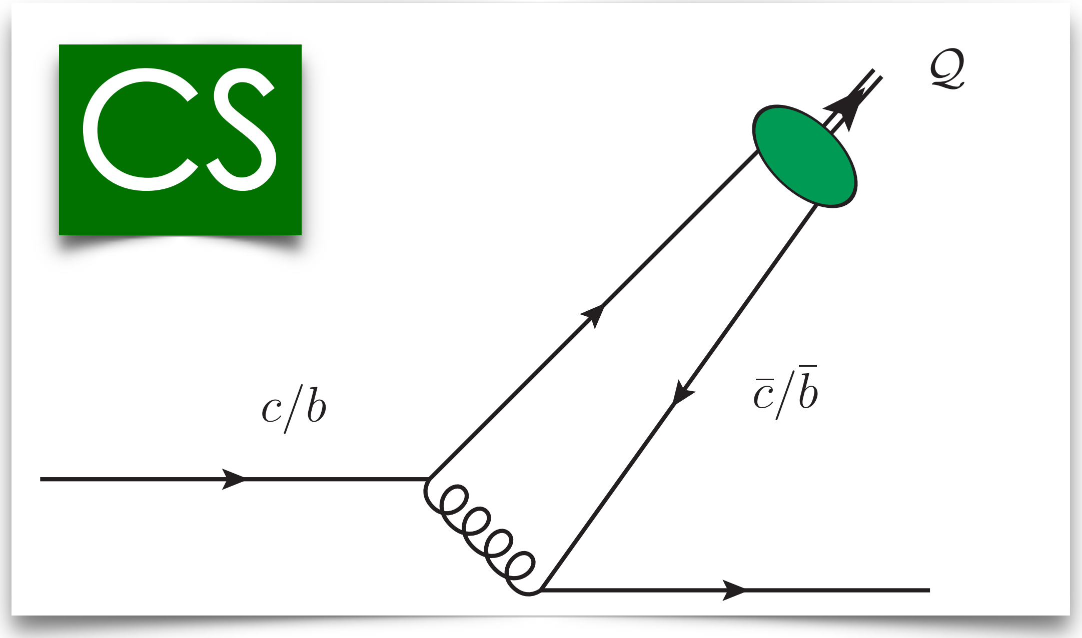

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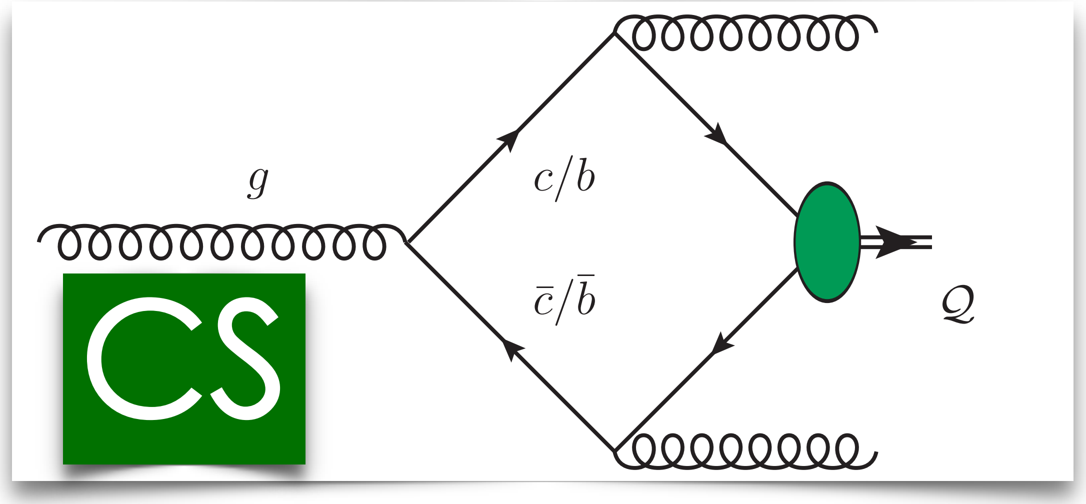

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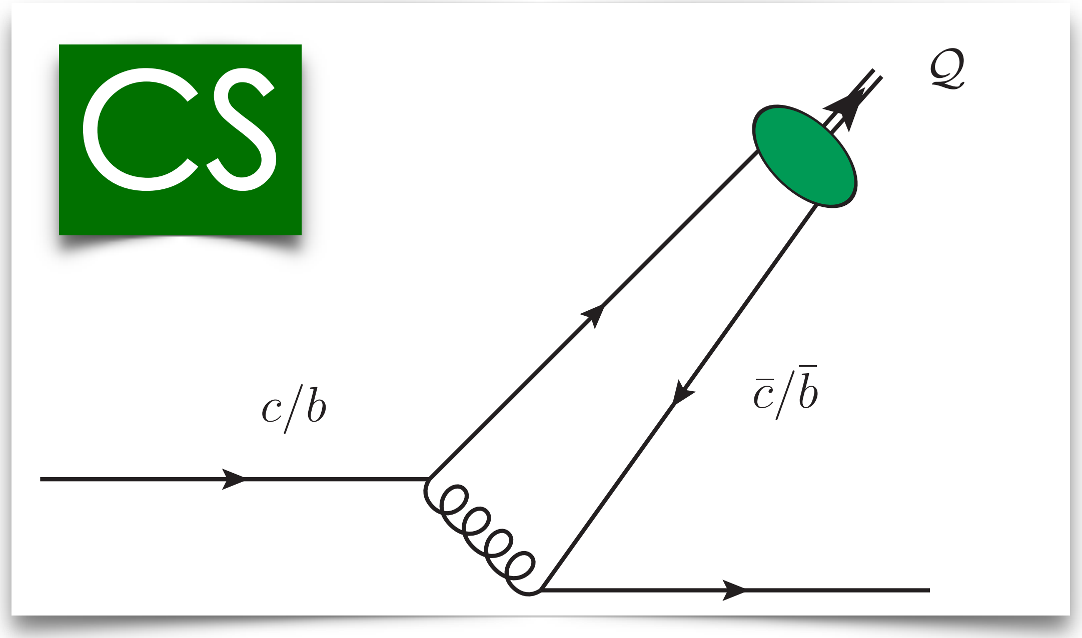

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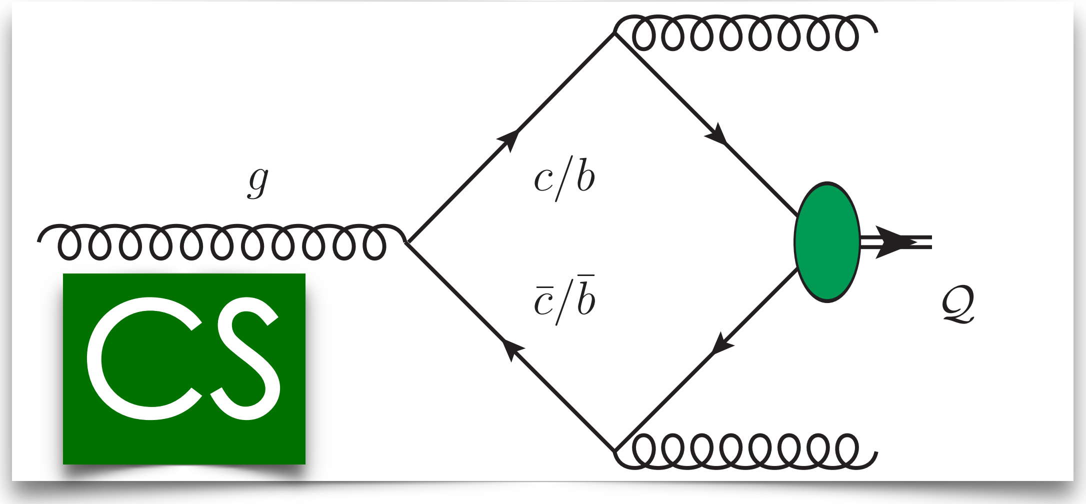

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ZCW19⁺/NRFF1.0

quarkonium FFs

$=$

APFEL++/EKO

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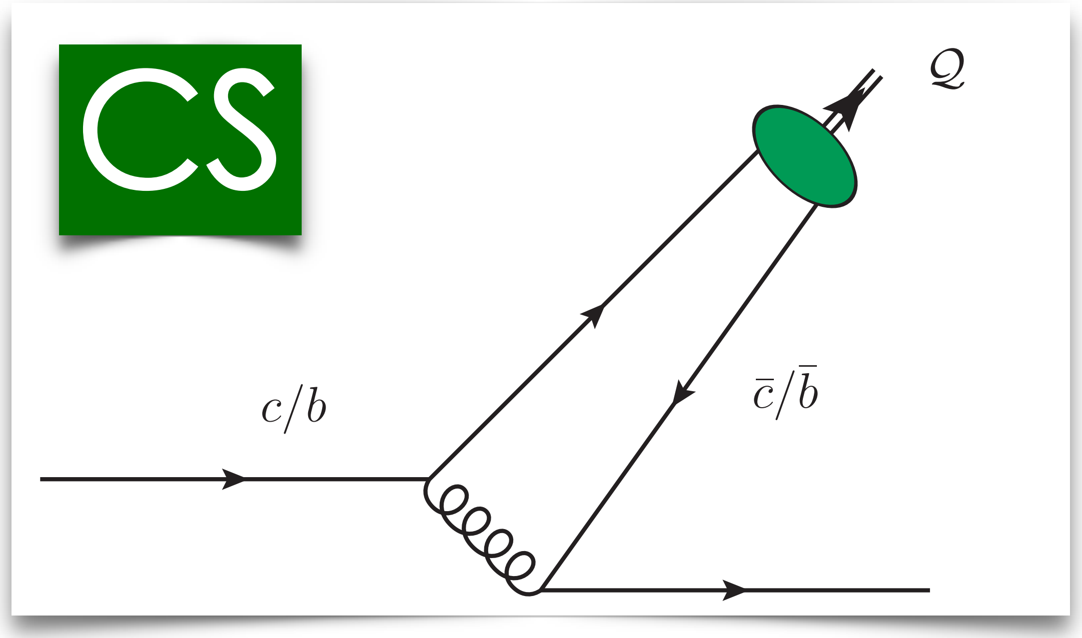

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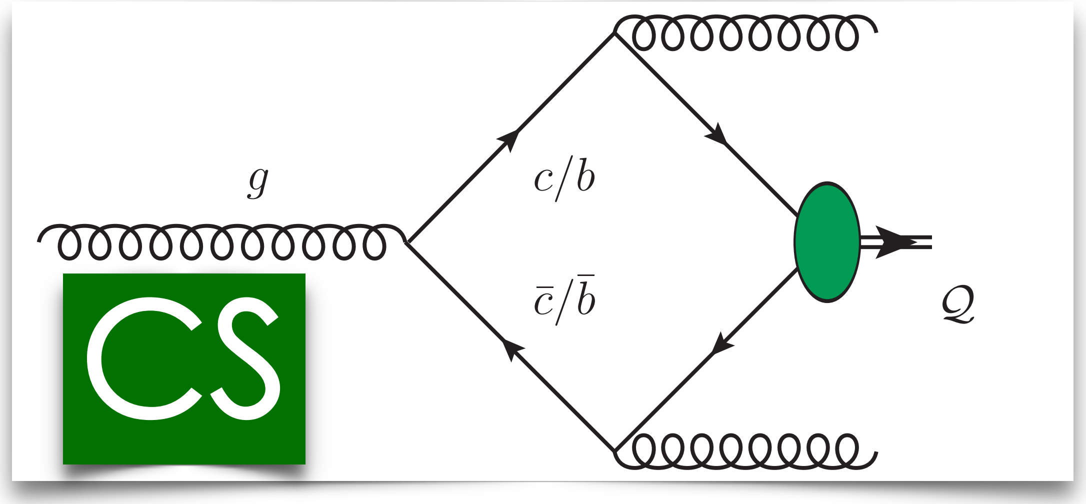

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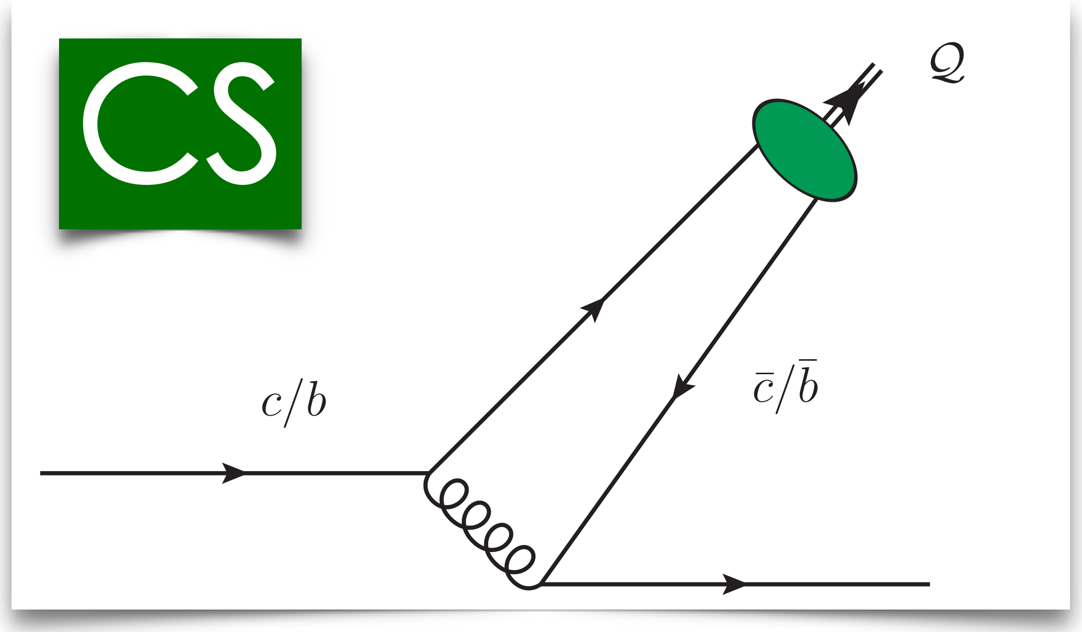

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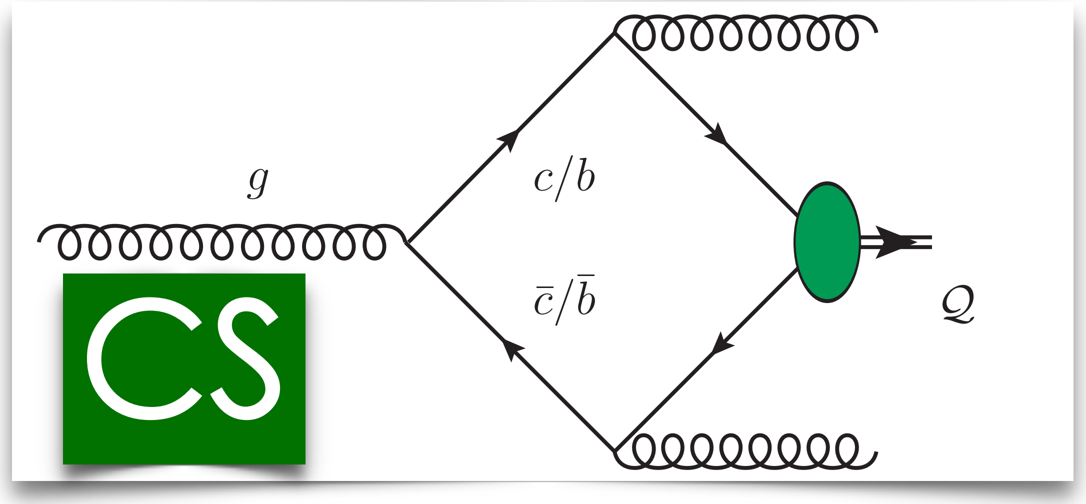

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ZCW19+/NRFF1.0

quarkonium FFs = $\otimes$ **APFEL++/EKO**

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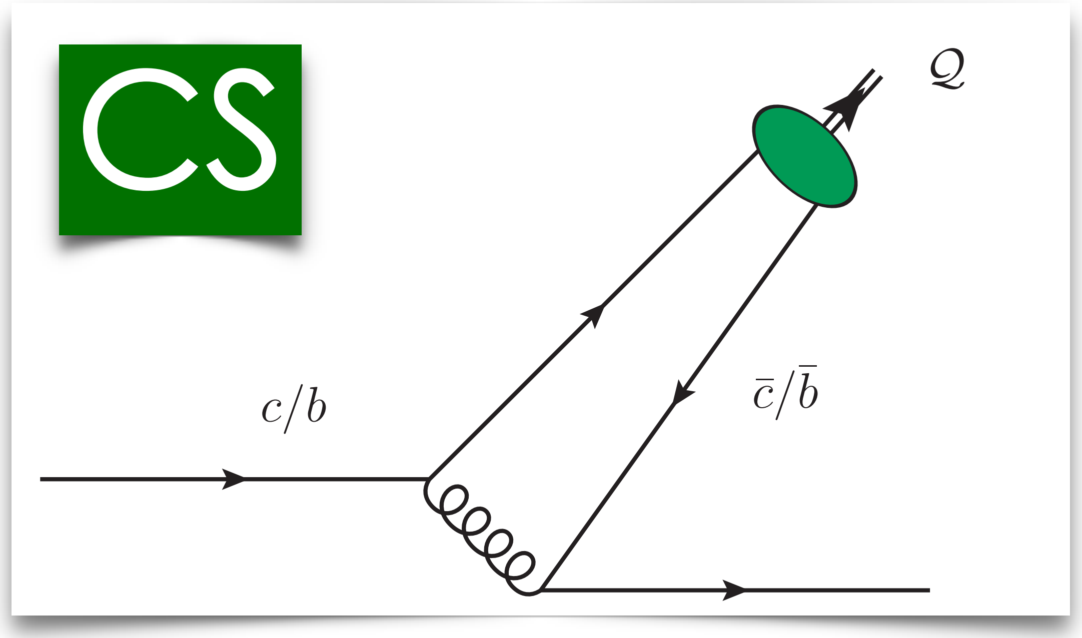

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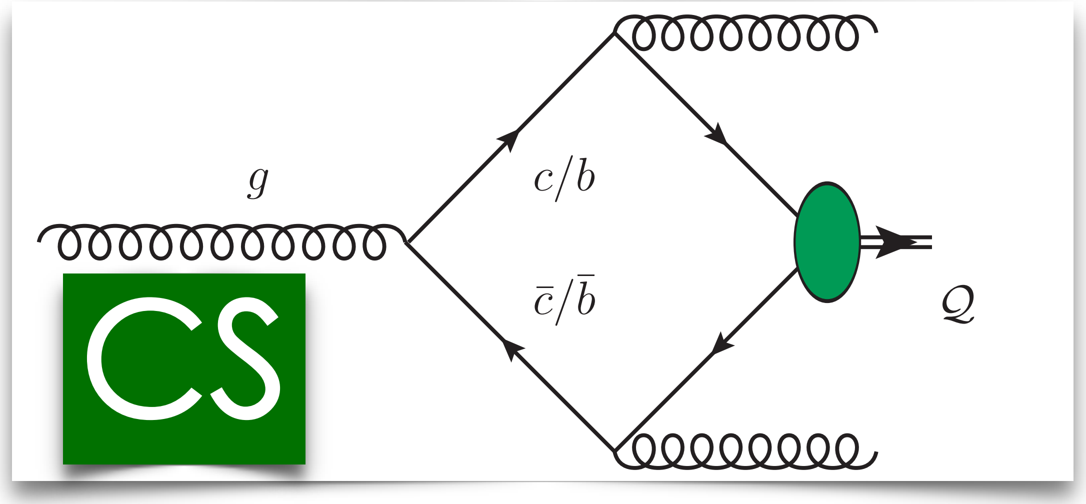

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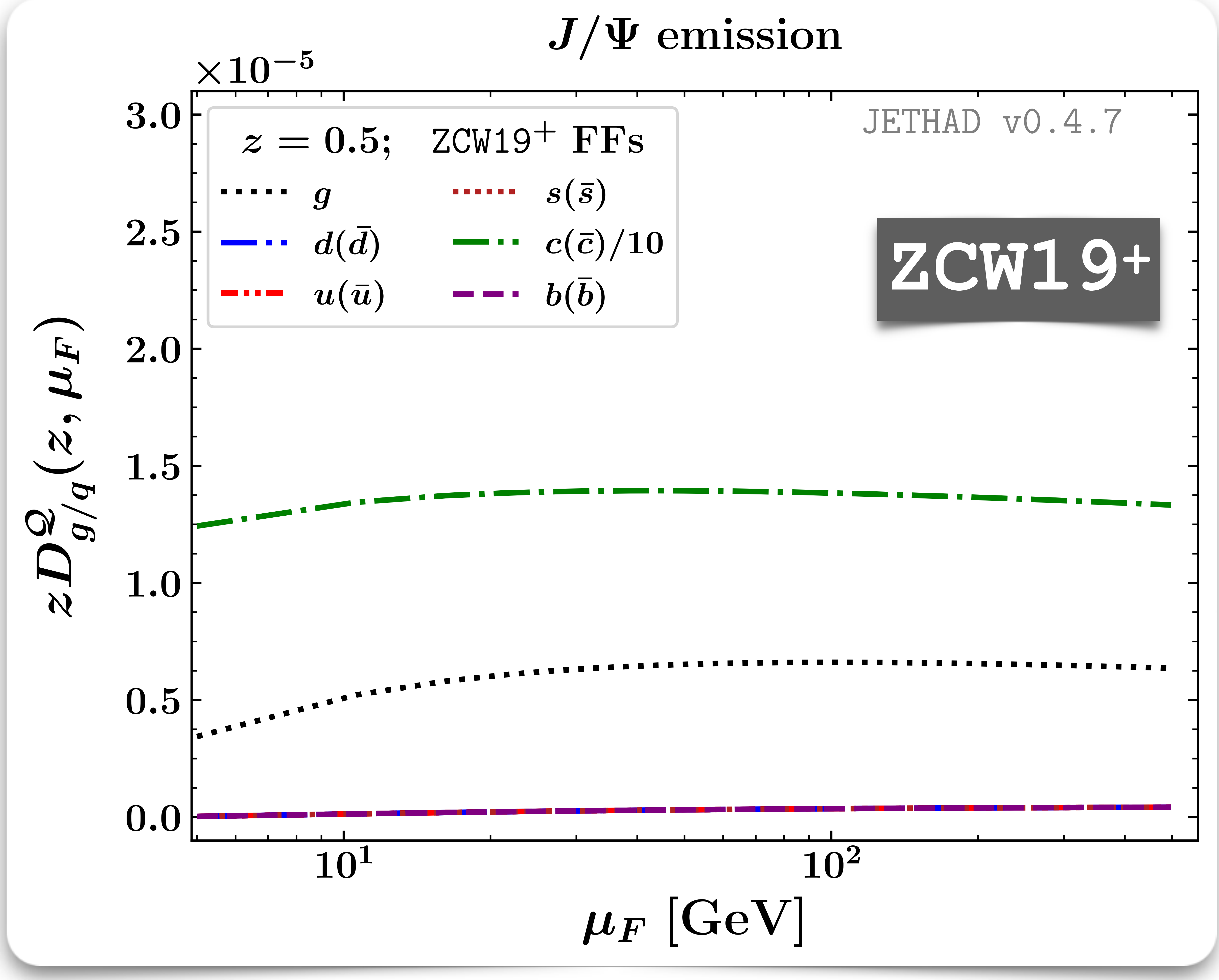
ZCW19+/NRFF1.0

quarkonium FFs

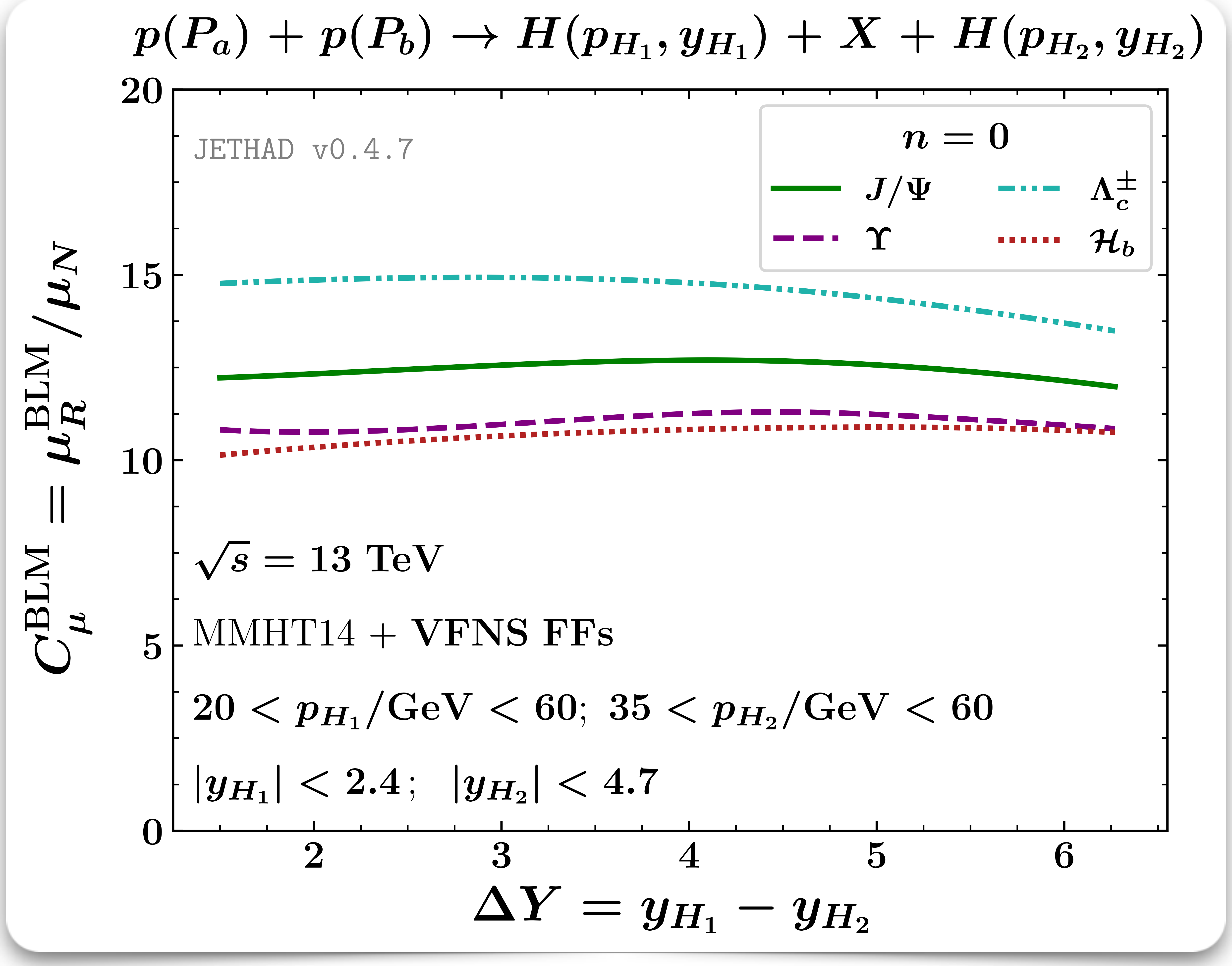
= **APFEL++/EKO**

J/ψ + jet production at the LHC

Collinear FFs

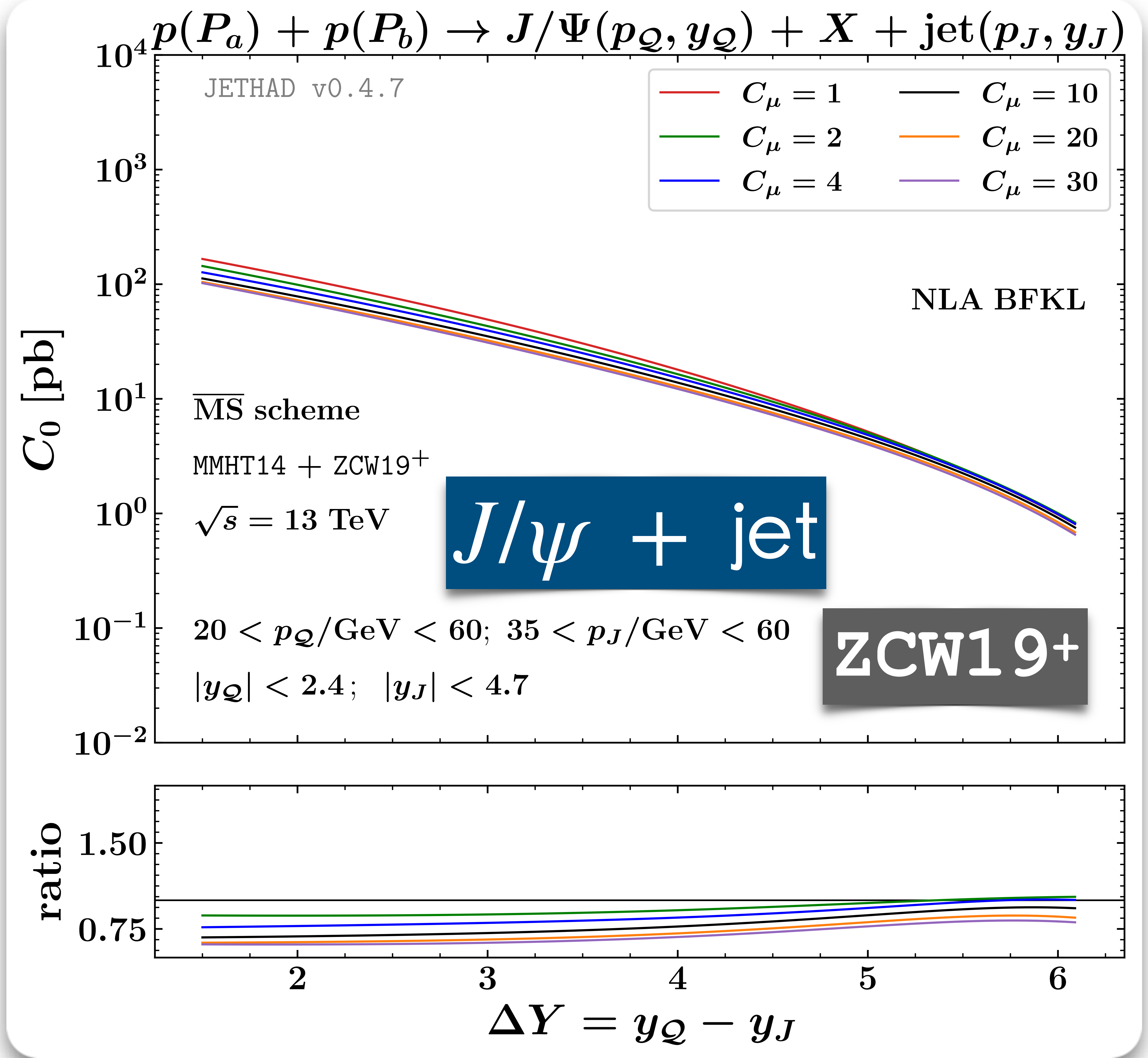


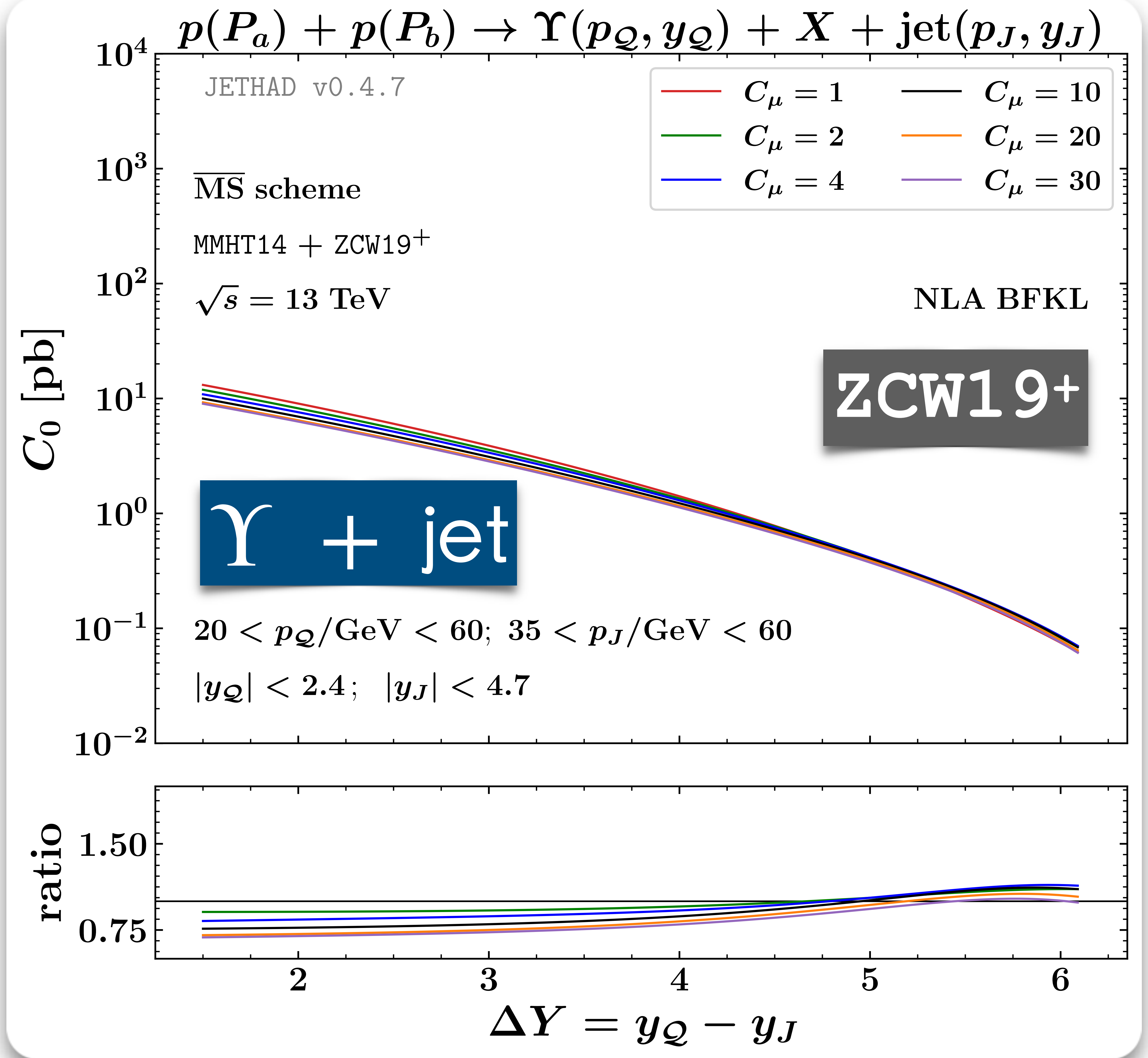
BLM scales



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

Vector quarkonium + jet at the LHC





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Lecture III Checkpoint

Lecture III: Summary & Outlook

Checkpoint of Lecture III

Natural stability of the high-energy resummation

Checkpoint of Lecture III

Lecture III: Summary & Outlook

- Natural stability of the high-energy resummation

- Higgs distributions ⇒ Tools for precision studies of high-energy QCD

Checkpoint of Lecture III

Lecture III: Summary & Outlook

- Natural stability of the high-energy resummation

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Checkpoint of Lecture III

Lecture III: Summary & Outlook

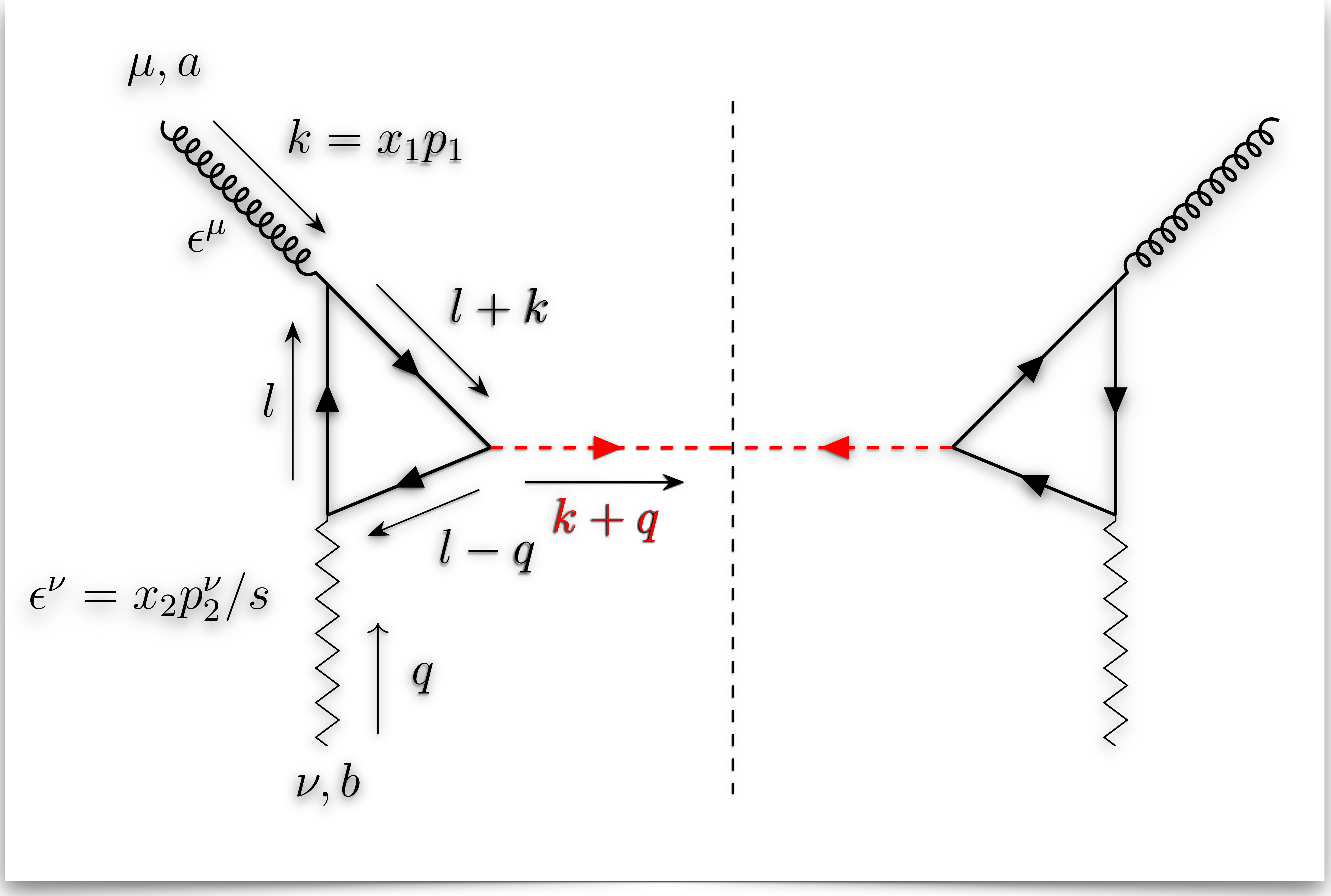
- Natural stability of the high-energy resummation
- Higgs distributions ⇒ Tools for precision studies of high-energy QCD
- Heavy flavor FFs ⇒ Basis for explorations outside high-energy QCD
- High-energy resummation ⇒ Proton structure and spin at small-x

Checkpoint of Lecture III

Extras

Higgs + Jet

Forward-Higgs LO impact factor



$$\frac{d\Phi_J^{(0)}(\nu, n)}{dx_J d^2\vec{p}_J} = 2\alpha_s \sqrt{\frac{C_F}{C_A}} (\vec{p}_J^{\,2})^{i\nu - 3/2} \left(\frac{C_A}{C_F} f_g(x_J) + \sum_{a=q\bar{q}} f_a(x_J) \right) e^{in\phi_J}$$

Forward-Higgs NLO-RG impact factor

$$\tilde{c}_H^{(1)}(n,\nu,|\vec{p}_H|,x_H) = c_H(n,\nu,|\vec{p}_H|,x_H)\left\{\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_1}}{|\vec{p}_H|}+\frac{5}{3}\right)+\frac{\chi\left(n,\nu\right)}{2}\ln\left(\frac{s_0}{M_{H,\perp}^2}\right)\right.$$

$$+\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_1}}{M_{H,\perp}}\right)$$

$$\left.-\frac{1}{2N_c f_g(x_H,\mu_{F_1})}\ln\frac{\mu_{F_1}^2}{M_{H,\perp}^2}\int_{x_H}^1\frac{dz}{z}\left[P_{gg}(z)f_g\left(\frac{x_H}{z},\mu_{F_1}\right)+\sum_{a=q,\bar{q}}P_{ga}(z)f_a\left(\frac{x_H}{z},\mu_{F_1}\right)\right]\right\}$$

Forward-jet NLO-RG impact factor

$$
\begin{aligned}
\tilde{c}_J^{(1)}(n,\nu,|\vec{p}_J|,x_J) = c_J(n,\nu,|\vec{p}_J|,x_J) \Bigg\{ & \frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_2}}{|\vec{p}_J|}+\frac{5}{3}\right) + \frac{\chi(n,\nu)}{2}\ln\left(\frac{s_0}{|\vec{p}_J|^2}\right) \\
& - \frac{1}{2N_c\left(\frac{C_A}{C_F} f_g(x_J,\mu_{F_2}) + \sum_{a=q,\bar{q}} f_a(x_J,\mu_{F_2})\right)} \ln\frac{\mu_{F_2}^2}{|\vec{p}_J|^2} \\
& \times \left(\frac{C_A}{C_F} \int_{x_J}^1 \frac{dz}{z}\left[P_{gg}(z) f_g\left(\frac{x_J}{z},\mu_{F_2}\right) + \sum_{a=q,\bar{q}} P_{ga}(z) f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right. \\
& \left. + \sum_{a=q,\bar{q}} \int_{x_J}^1 \frac{dz}{z}\left[P_{ag}(z) f_g\left(\frac{x_J}{z},\mu_{F_2}\right) + P_{aa}(z) f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right) \Bigg\} \,.
\end{aligned}
$$

Inclusive Higgs + jet: NLL/NLO* azimuthal coefficients

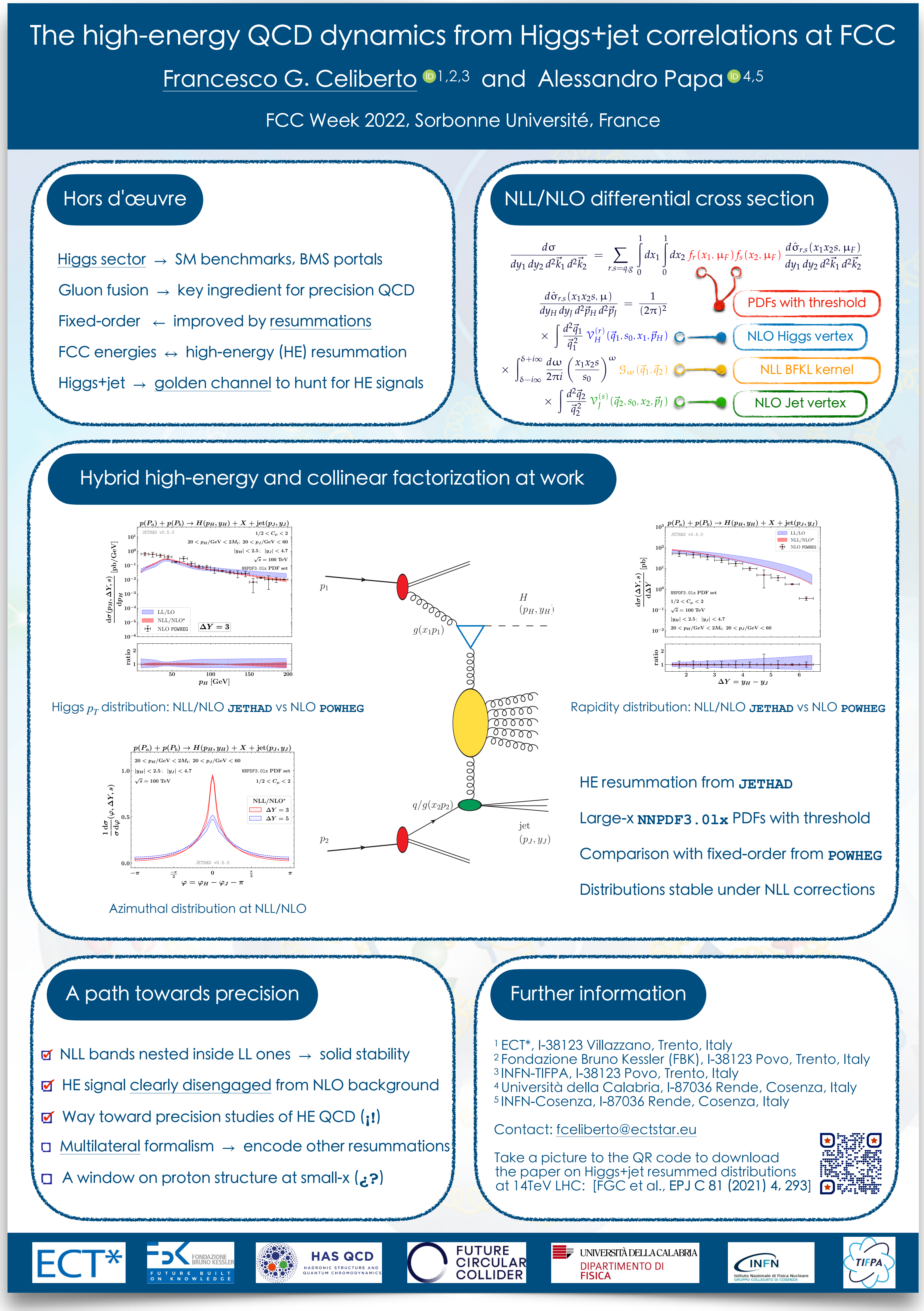
$$\mathcal{C}_n = \frac{e^{\Delta Y}}{s} \frac{M_{H,\perp}}{|\vec{p}_H|}$$

$$\times \int_{-\infty}^{+\infty} d\nu \left(\frac{x_J x_H s}{s_0} \right)^{\bar{\alpha}_s(\mu_{R_c})\left\{\chi(n,\nu)+\bar{\alpha}_s(\mu_{R_c})\left[\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left[-\chi(n,\nu)+\frac{10}{3}+4\ln\left(\frac{\mu_{R_c}}{\sqrt{\vec{p}_H \vec{p}_J}}\right)\right]\right]\right\}}$$

$$\times \left\{\alpha_s^2(\mu_{R_1}) c_H(n,\nu,|\vec{p}_H|,x_H)\right\} \left\{\alpha_s(\mu_{R_2})[c_J(n,\nu,|\vec{p}_J|,x_J)]^*\right\}$$

$$\times \left\{ 1 + \bar{\alpha}_s(\mu_{R_1}) \frac{\tilde{c}_H^{(1)}(n,\nu,|\vec{p}_H|,x_H)}{c_H(n,\nu,|\vec{p}_H|,x_H)} + \bar{\alpha}_s(\mu_{R_2}) \left[\frac{\tilde{c}_J^{(1)}(n,\nu,|\vec{p}_J|,x_J)}{c_J(n,\nu,|\vec{p}_J|,x_J)} \right]^* \right\} .$$

Higgs + jet highlights from the FCC Week 2022



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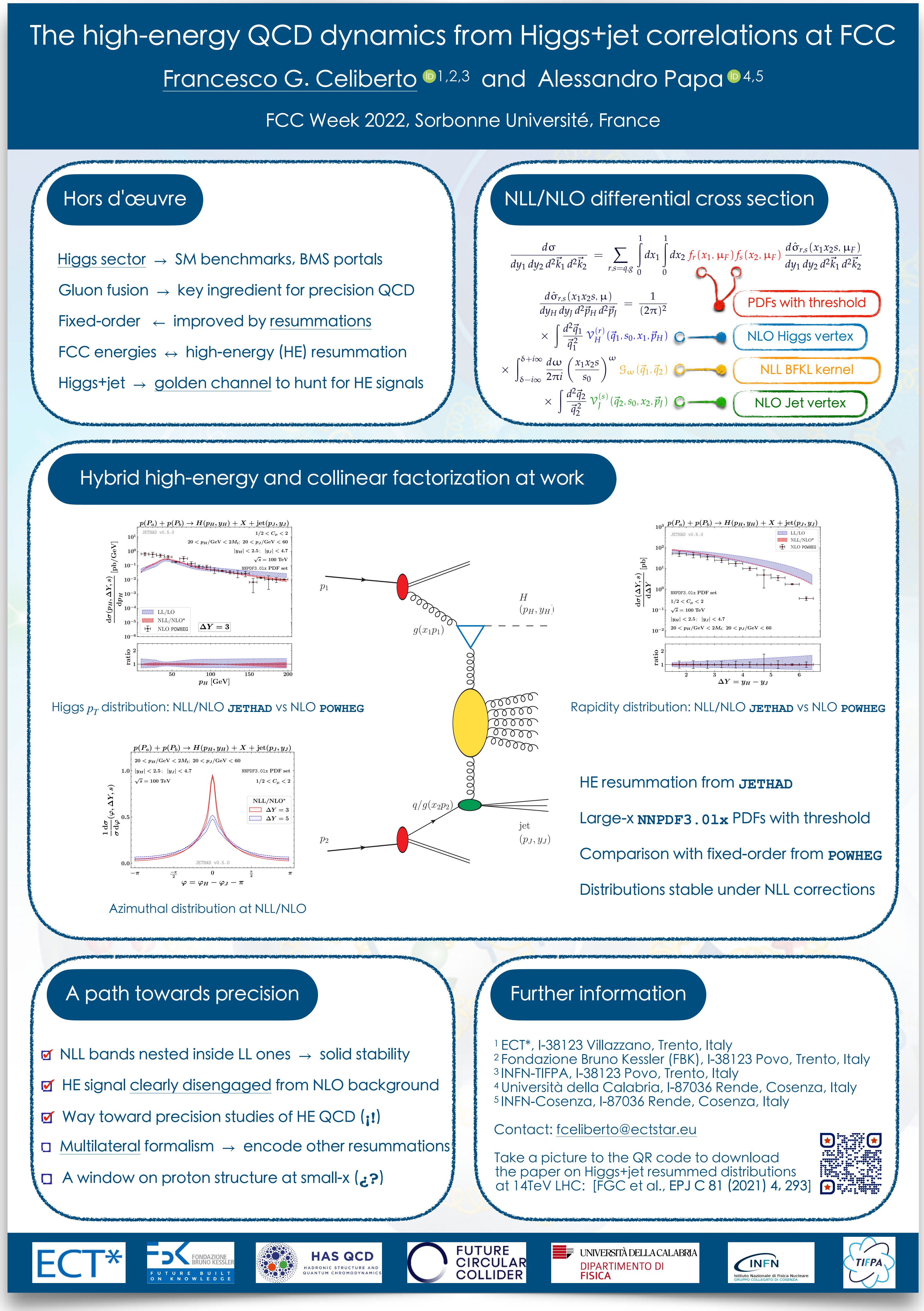
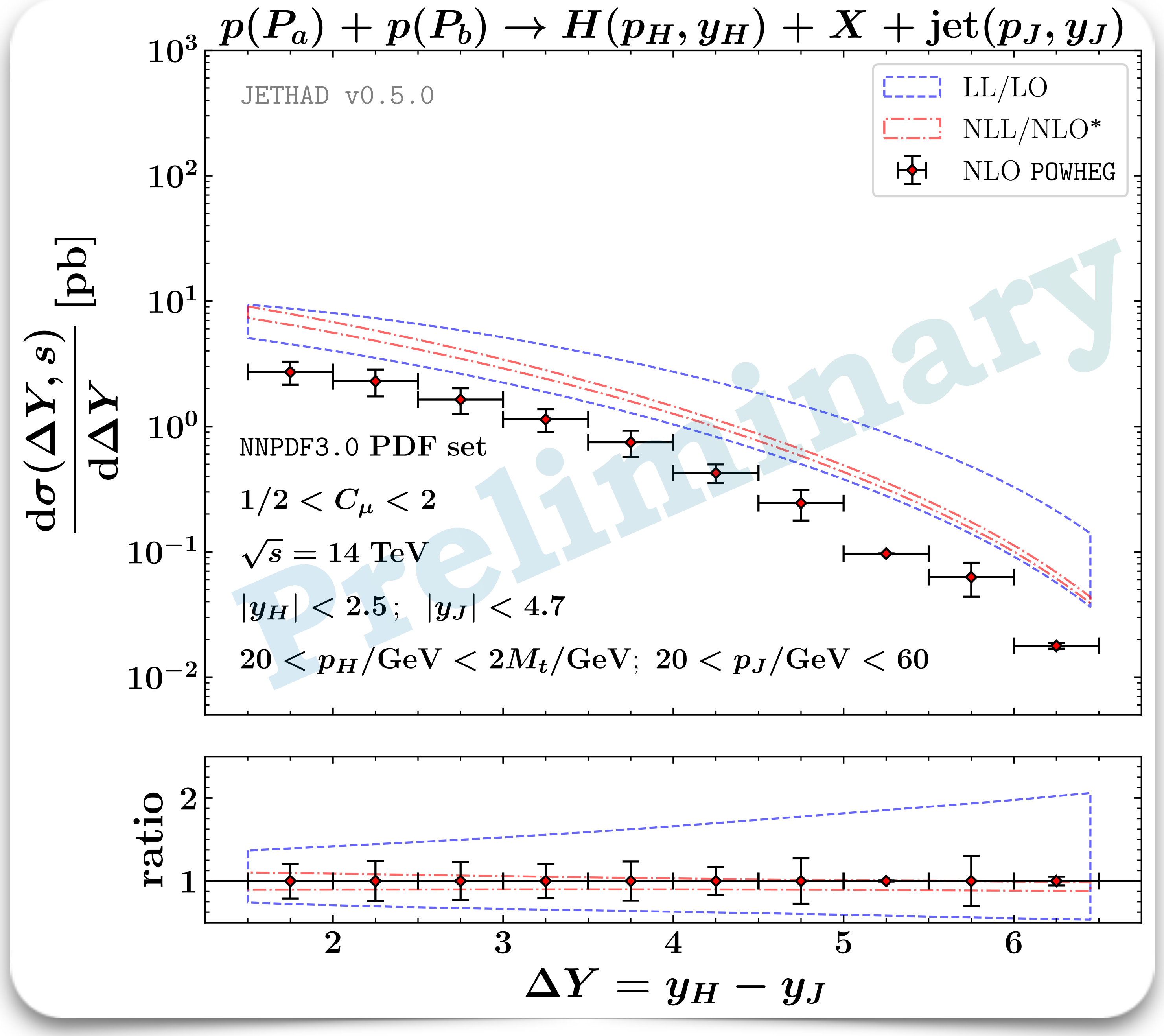
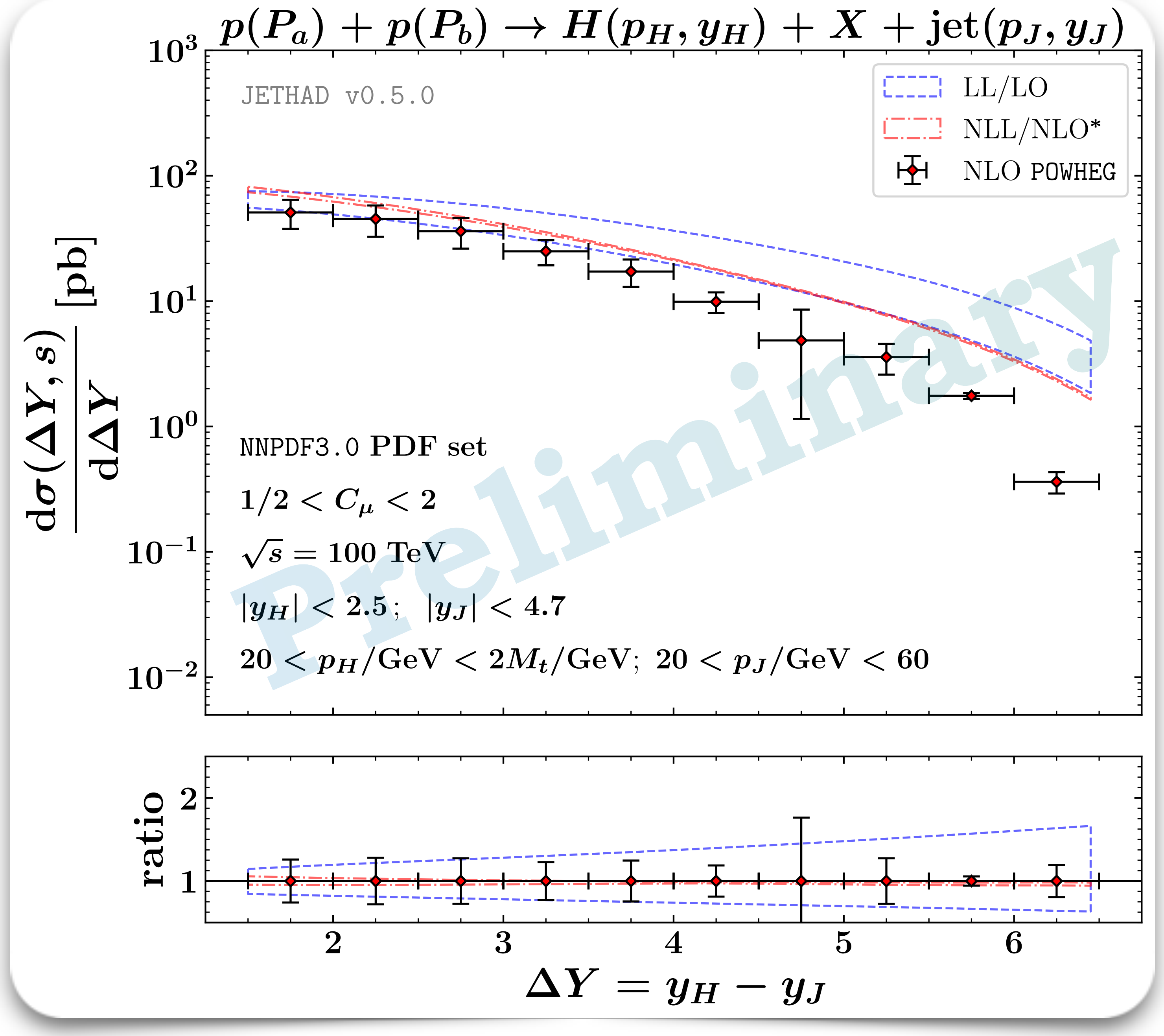


$$
C_n(\Delta Y, s) = \int_{p_H^{\rm min}}^{p_H^{\rm max}} d|\vec p_H| \int_{p_J^{\rm min}}^{p_J^{\rm max}} d|\vec p_J| \int_{y_H^{\rm min}}^{y_H^{\rm max}} dy_H \int_{y_J^{\rm min}}^{y_J^{\rm max}} dy_J\, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n
$$

Rapidity distribution: NLL/NLO* JETHAD vs NLO POWHEG



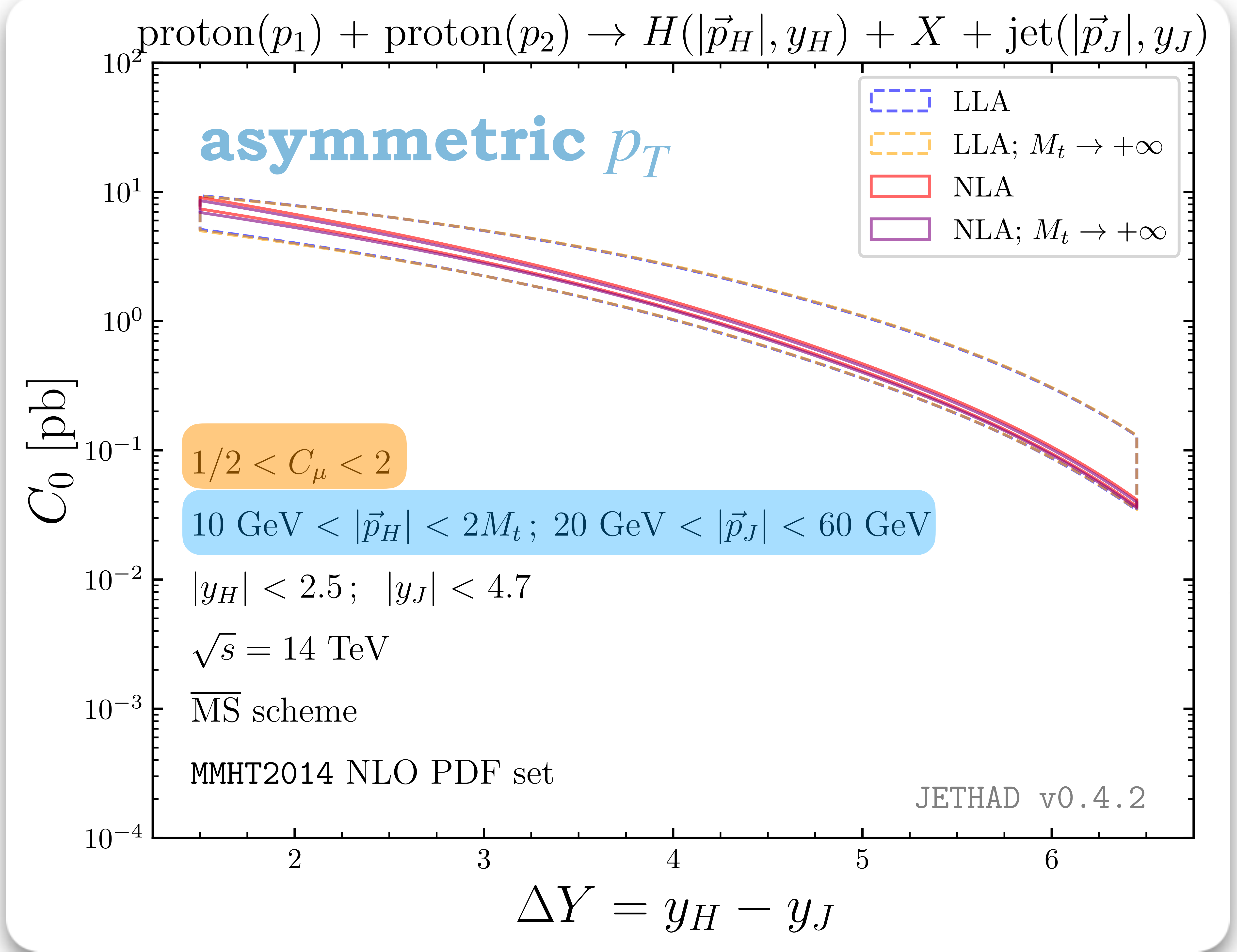
14 TeV LHC



100 TeV FCC

ΔY-distribution in the infinite top-mass limit

$$C_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$



[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

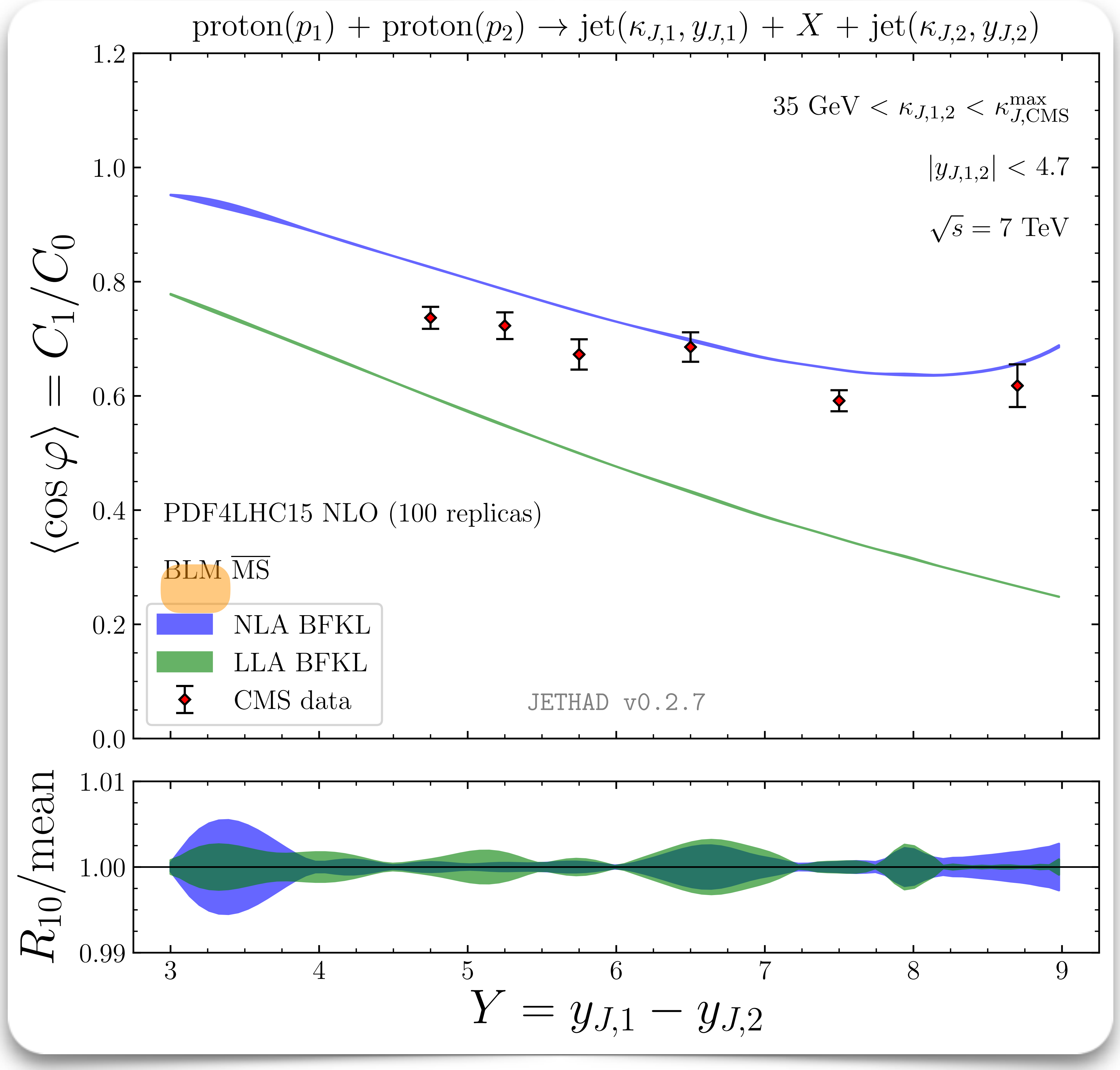
Angular correlations in the infinite top-mass limit

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

Mueller-Navelet jets

[B. Ducloué, L. Szymanowski, S. Wallon, Phys.Rev.Lett. 112 (2014) 082003]

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



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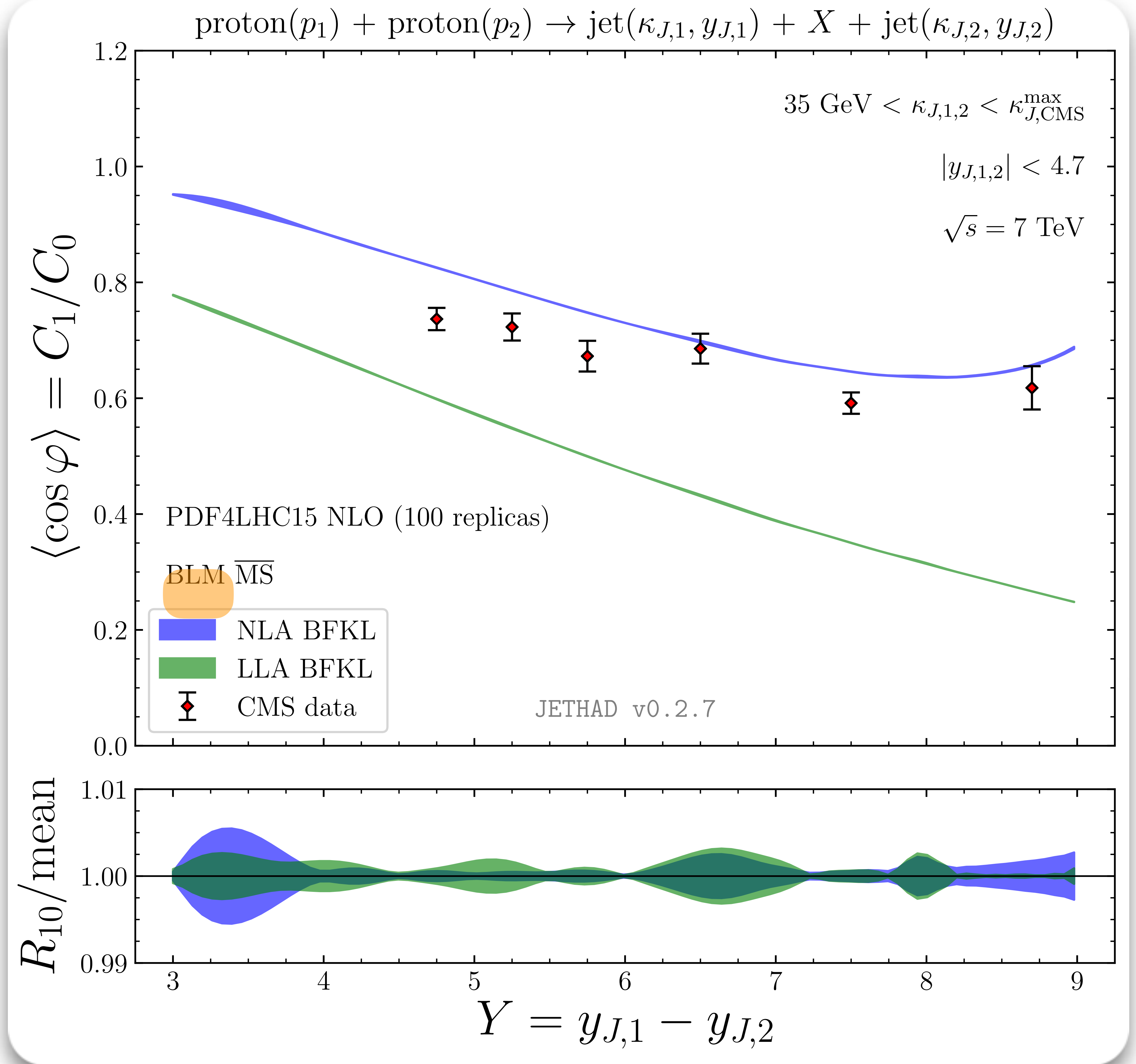
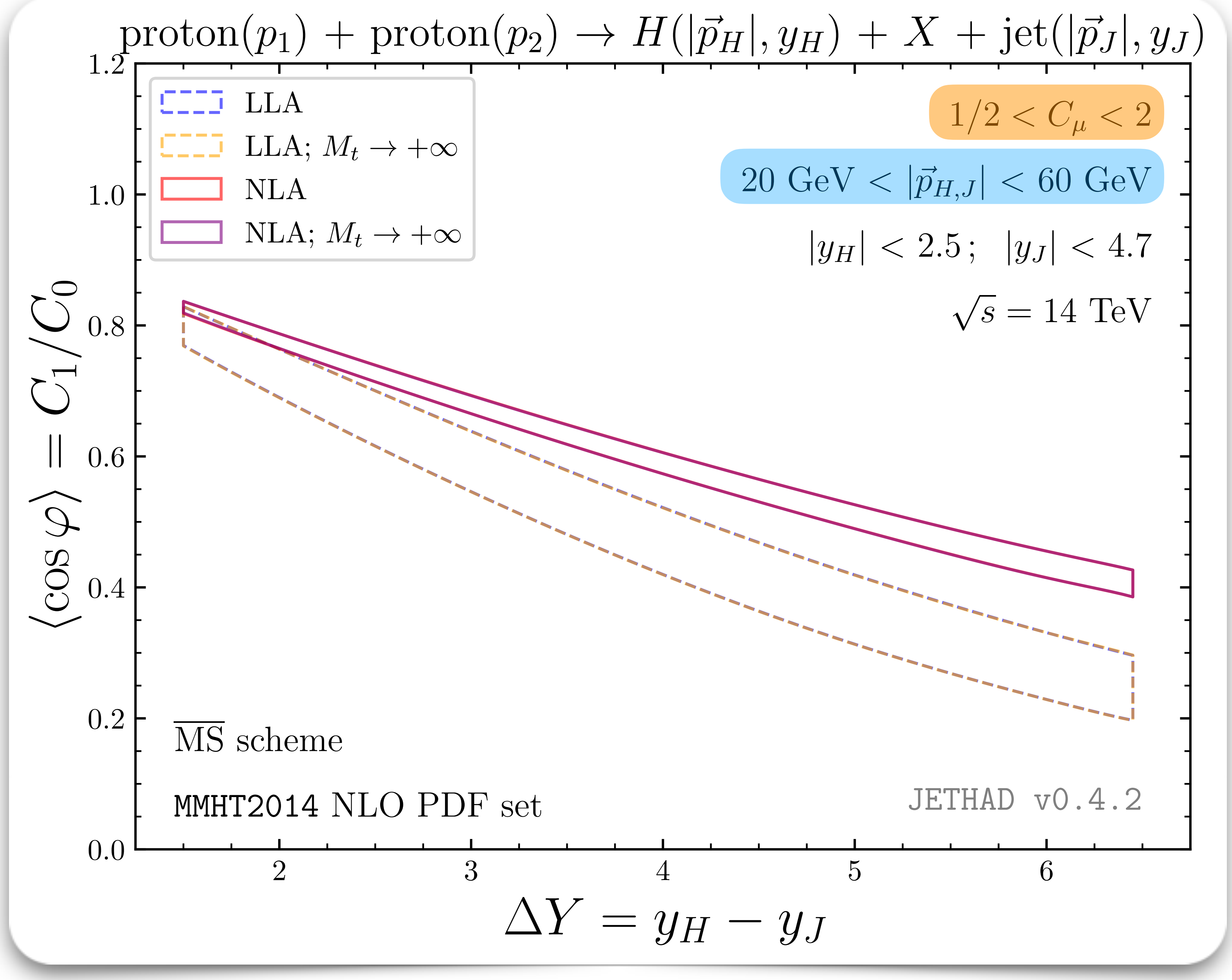


Higgs + jet

(figure below) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

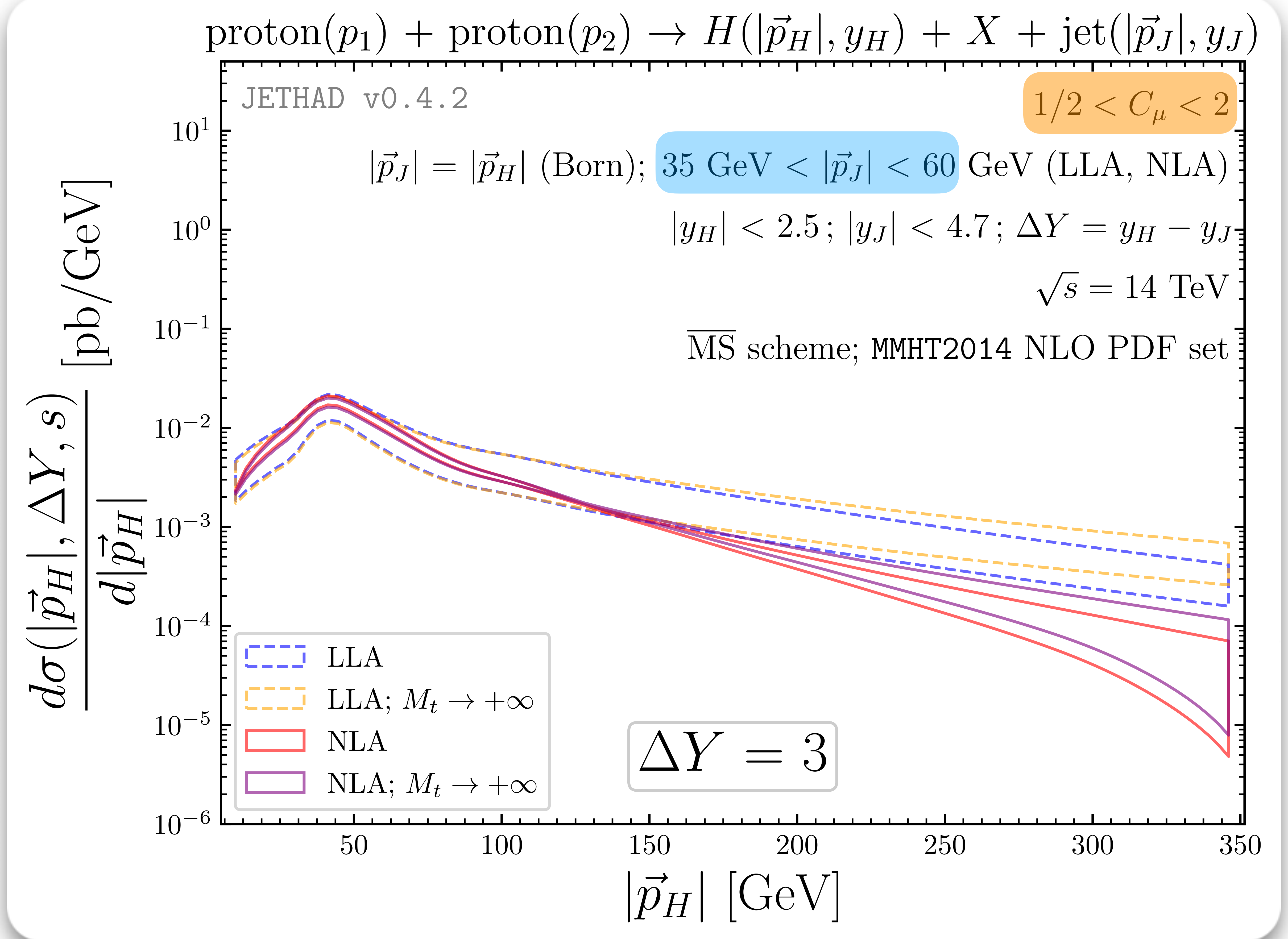
(NLO Higgs impact factor) [F. G. C. et al., under review (2022)]

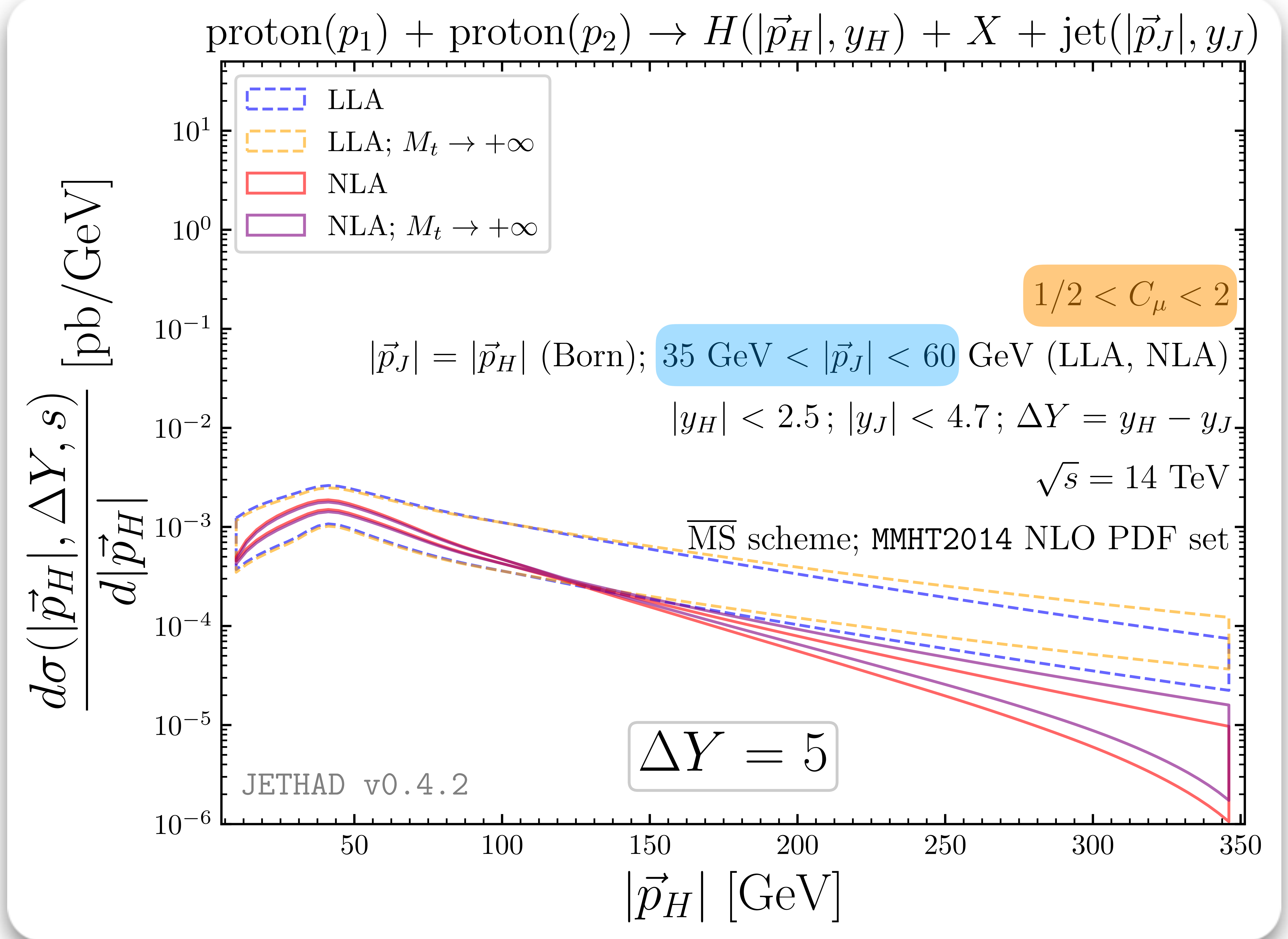


natural scales

symmetric p_T range

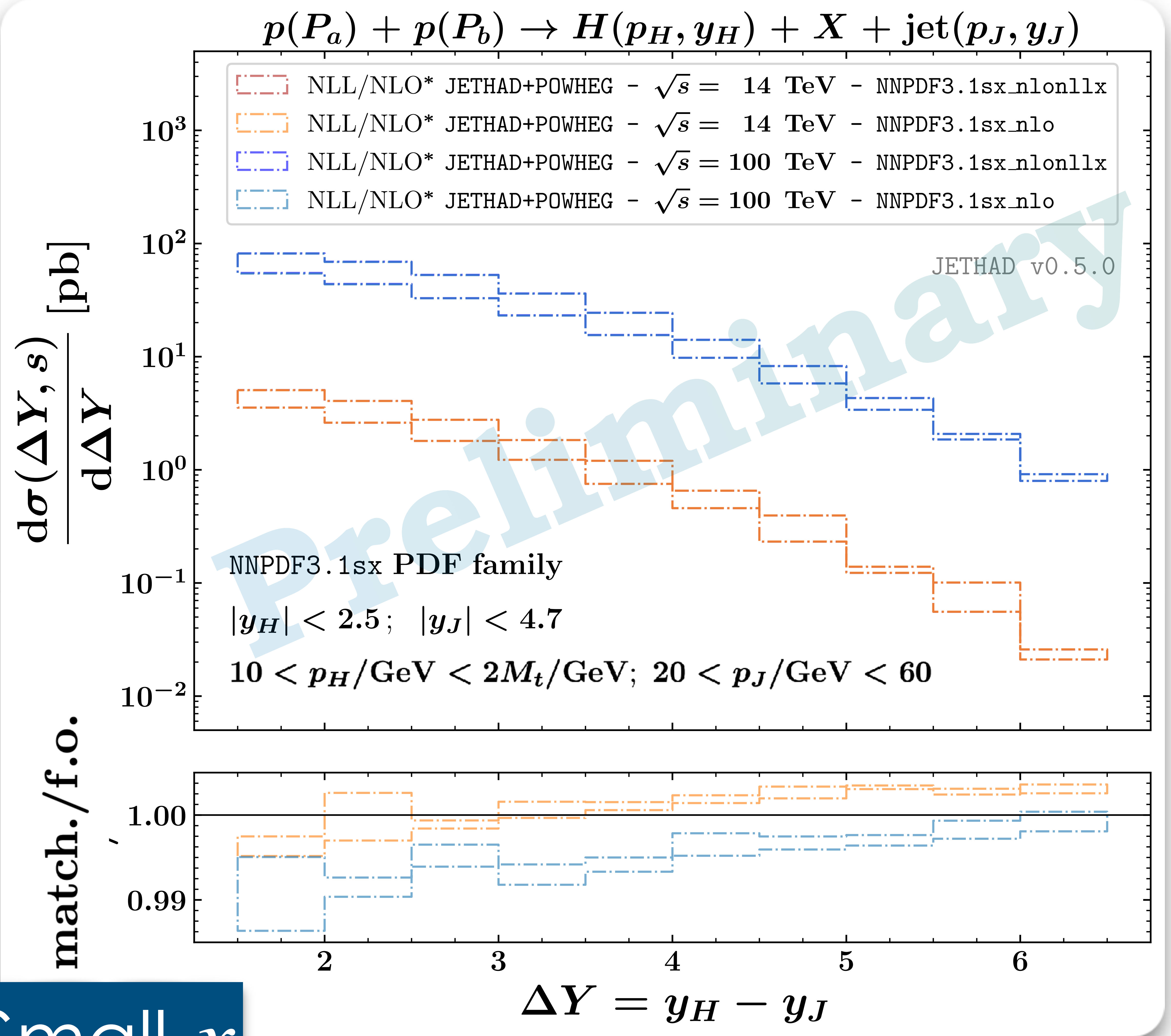
Higgs transverse-momentum distribution for $(M_t \to +\infty)$



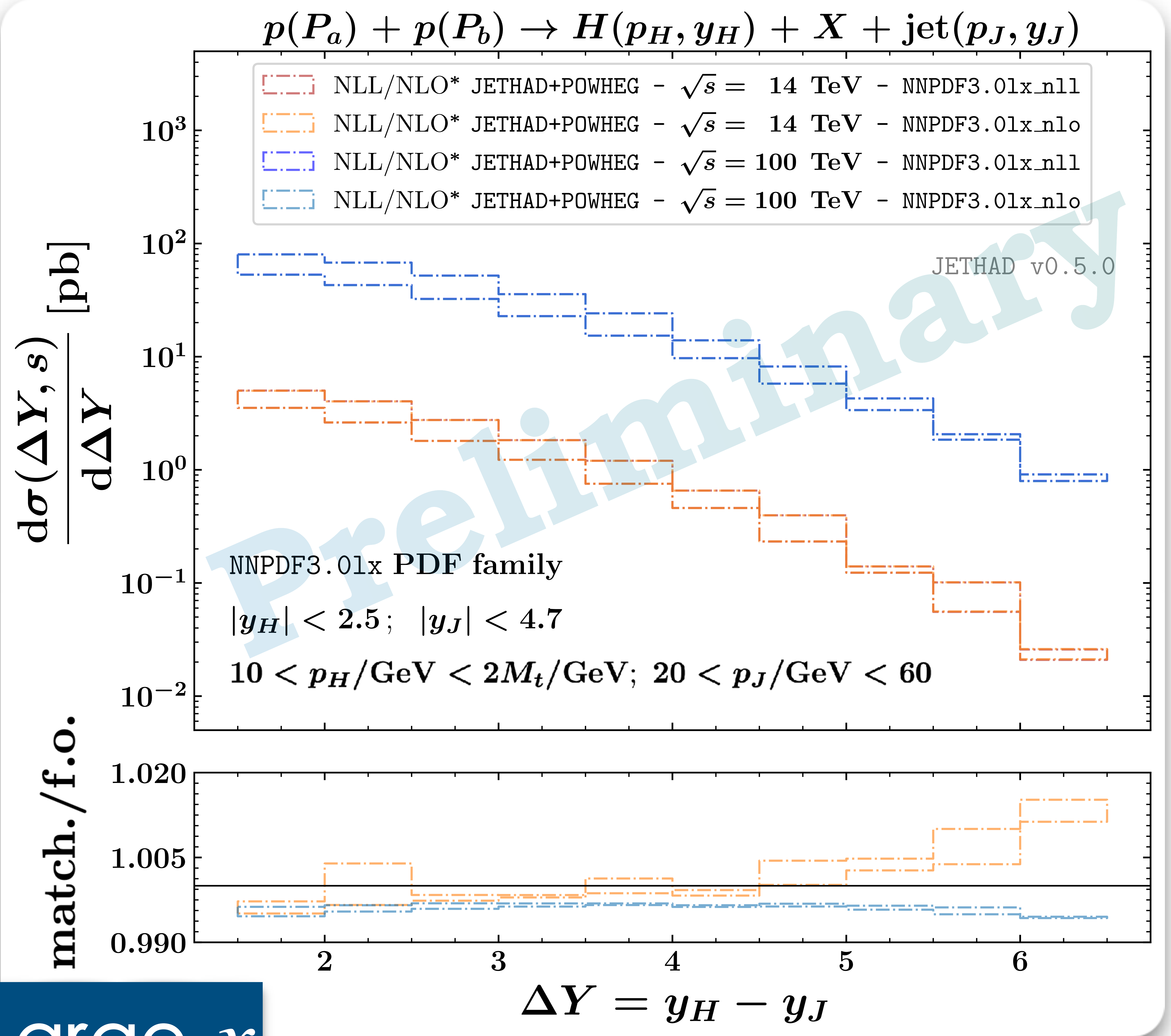


[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Small-x and large-x enhancement from PDFs



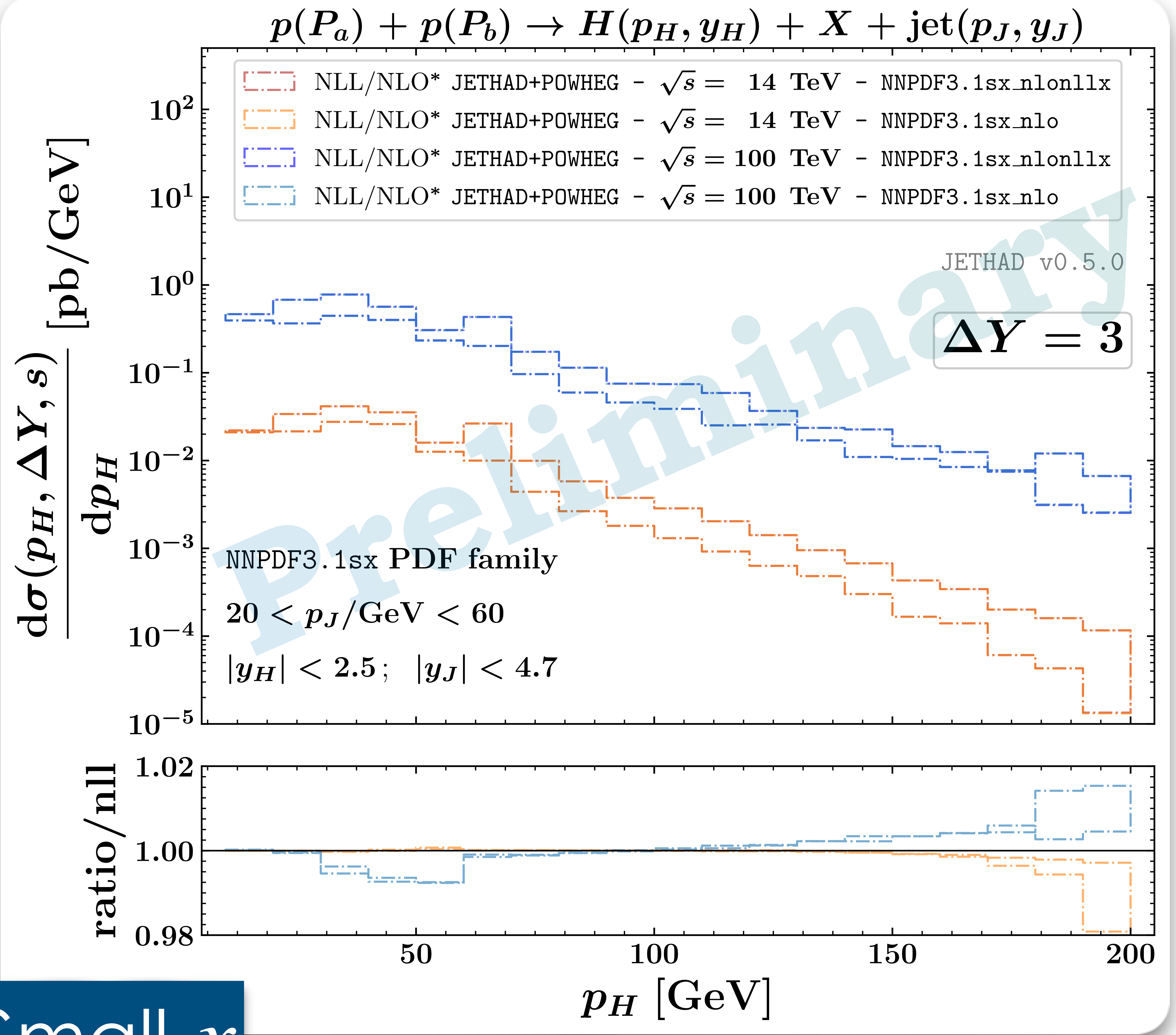
Small-x



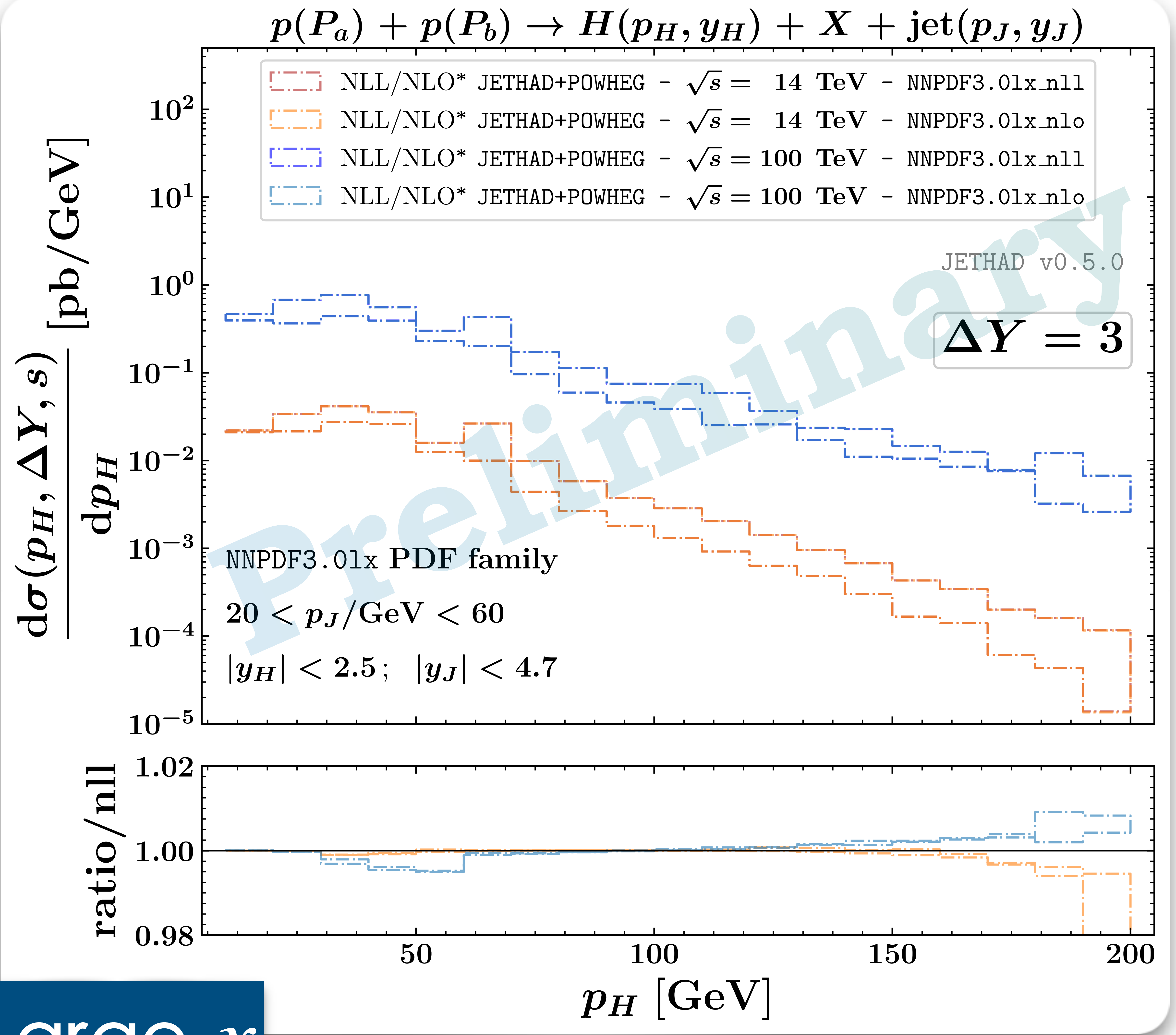
Large-x

Impact of large-x threshold logs on NLO emission functions to be gauged

Small-x and large-x enhancement from PDFs



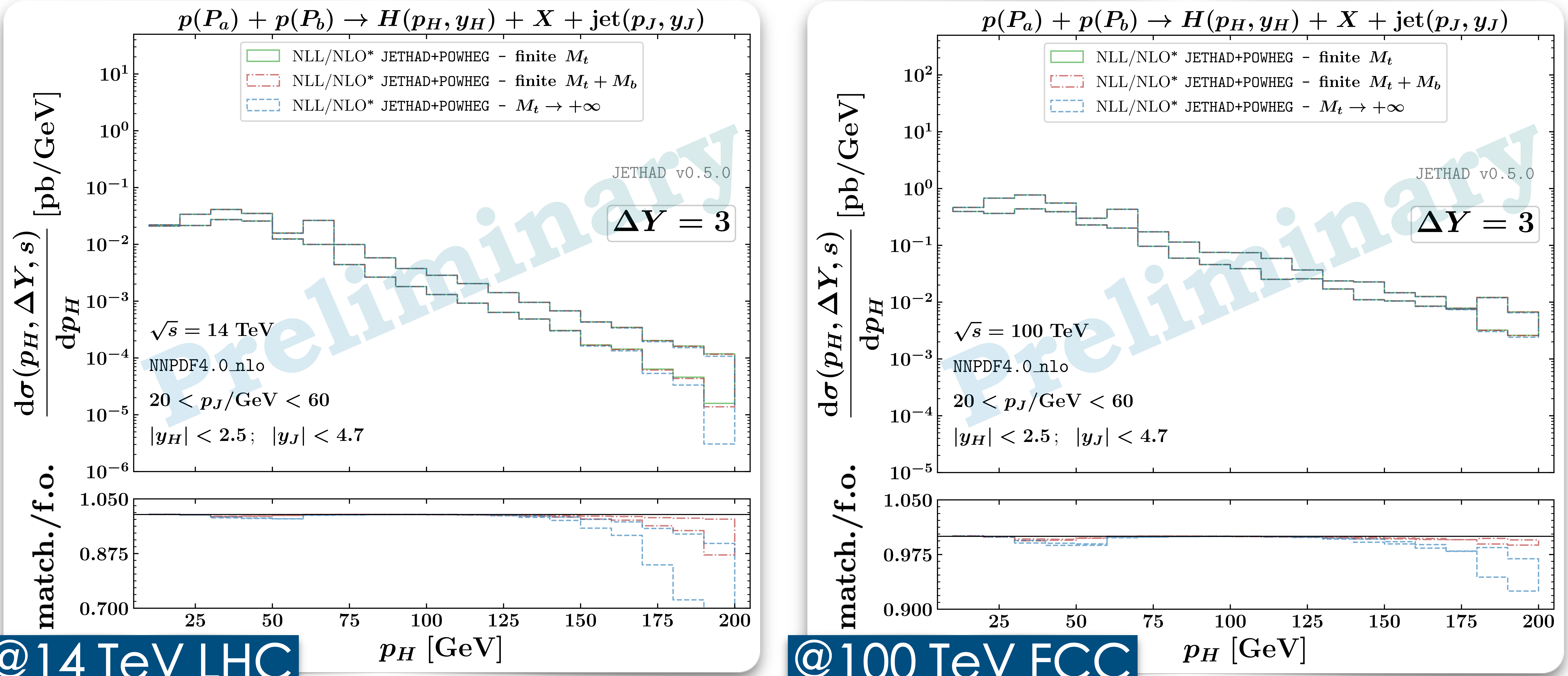
Small-x



Large-x

Impact of large-x threshold logs on NLO emission functions to be gauged

Finite top- and bottom-mass corrections

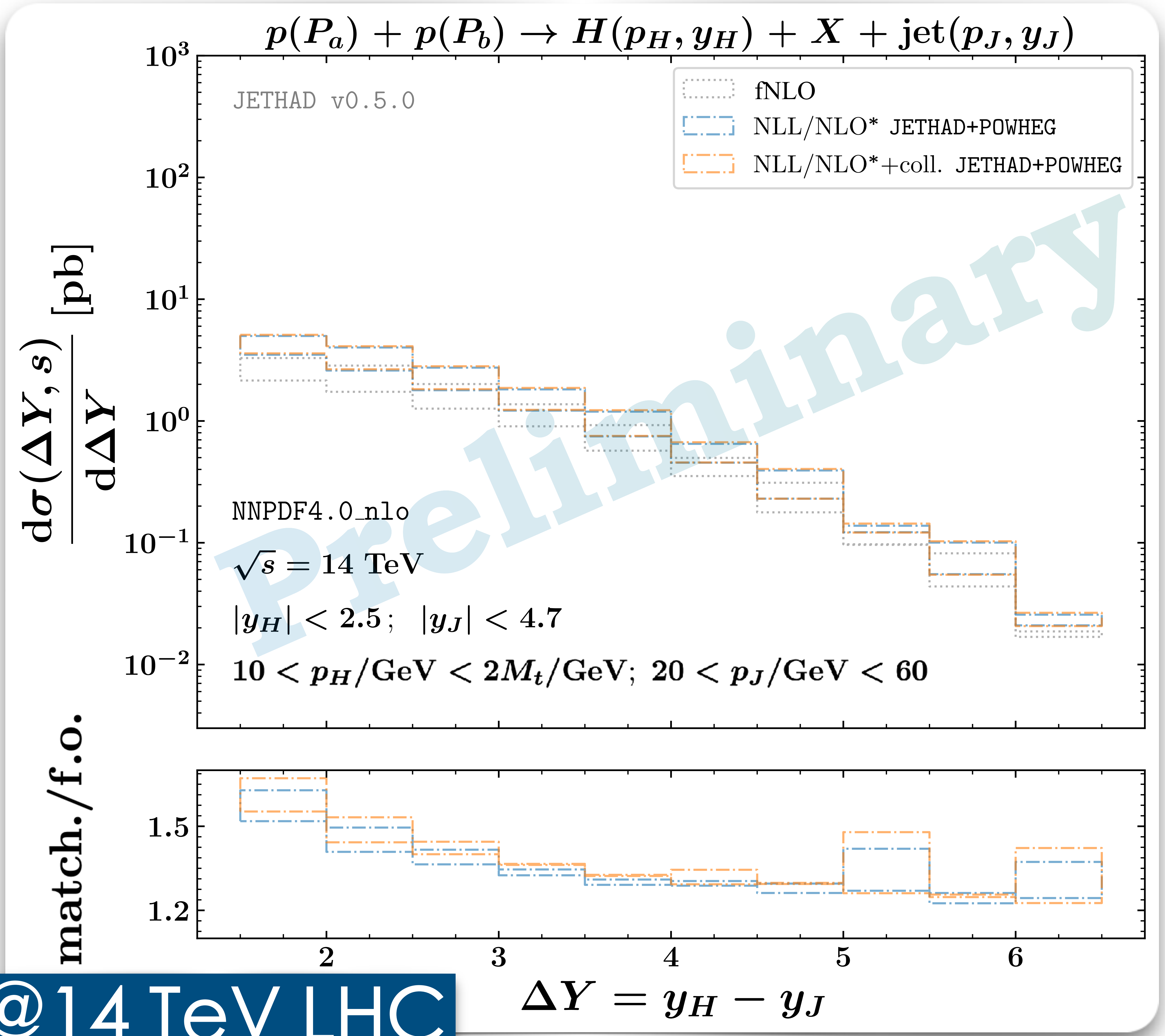


@14 TeV LHC

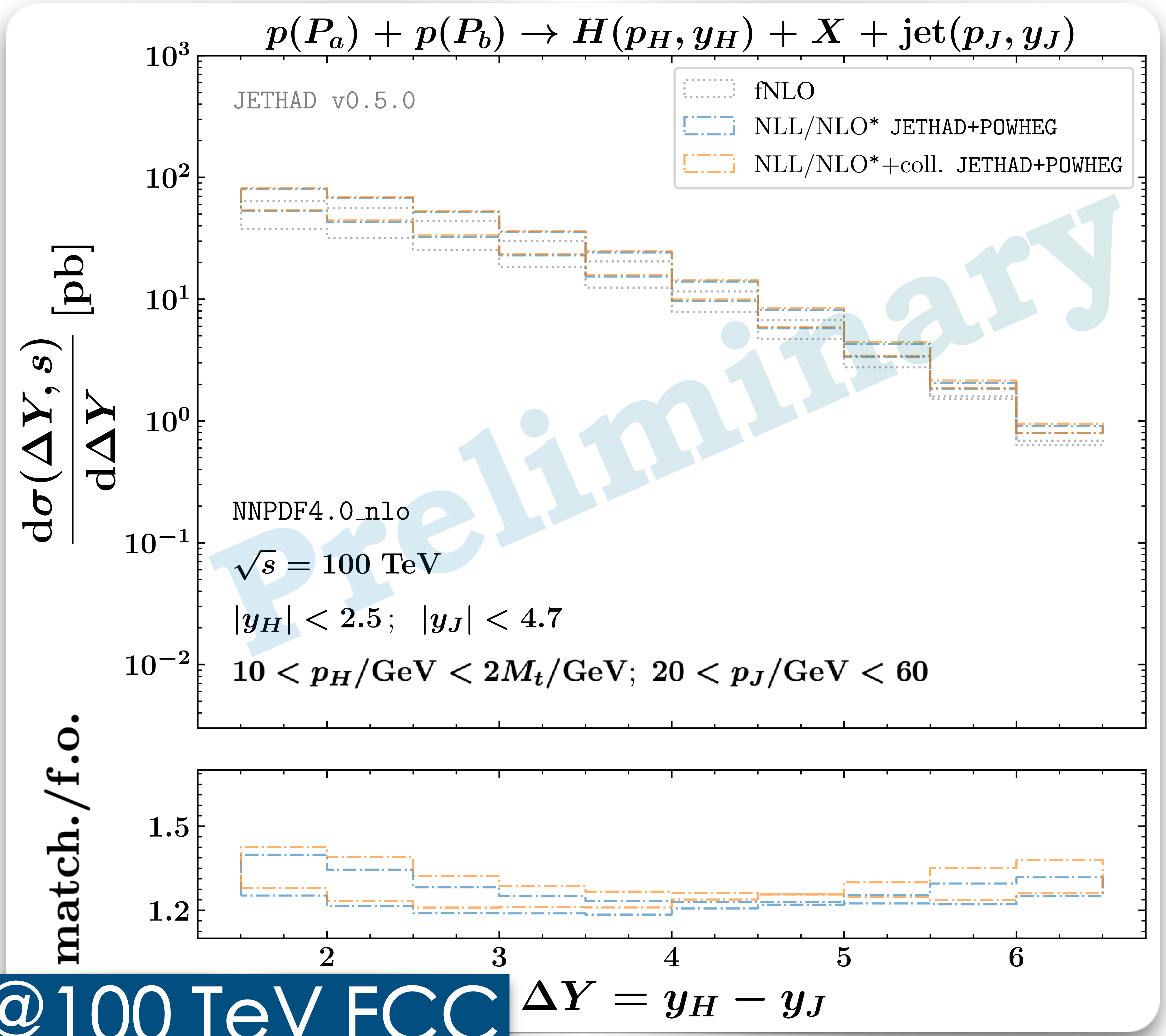
@100 TeV FCC

Effect of finite heavy-quark masses on NLO emission fns. to be gauged

Effect of collinear improvement on NLL BFKL kernel



@14 TeV LHC

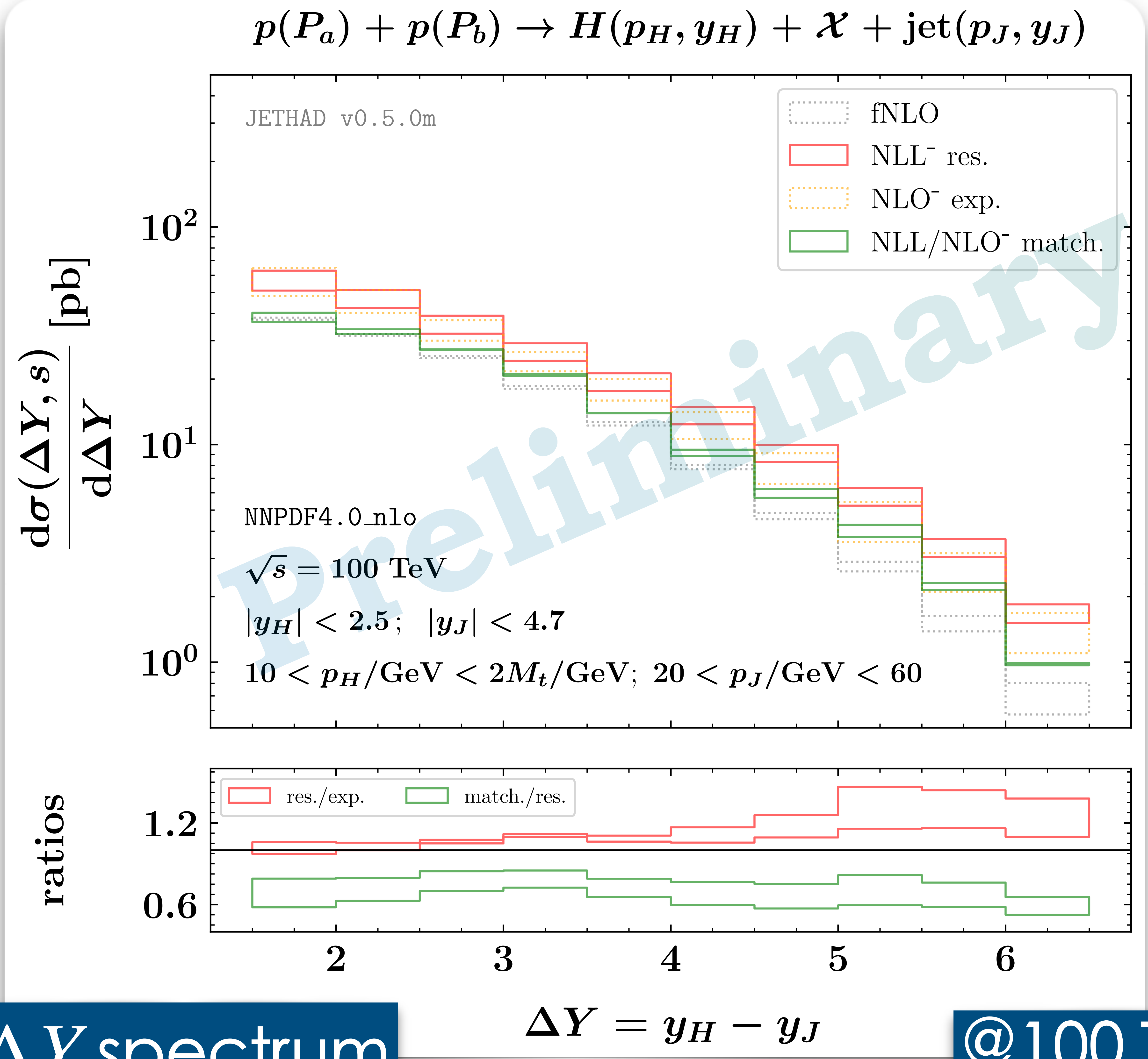


@100 TeV FCC

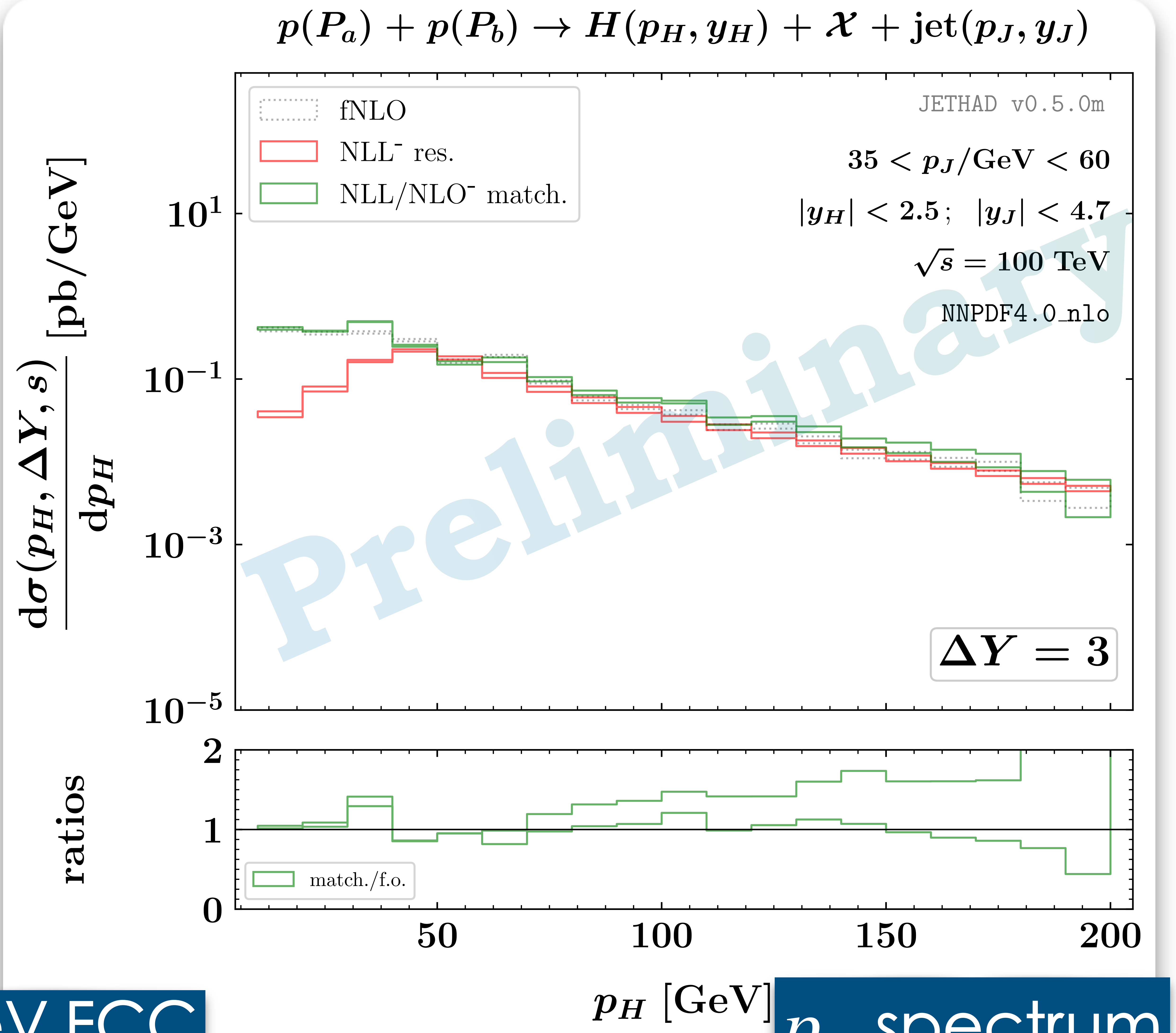
(Collinear improvement) [G.P. Salam, JHEP 07 (1998) 019]; [M. Ciafaloni et al., Phys.Lett.B 587 (2004) 87-94]; [A. Sabio Vera, Nucl.Phys.B 722 (2005) 65-80]

WORK IN PROGRESS — Effect of ABF-stabilized kernel to be gauged

The Higgs + jet spectrum from POWHEG + JETHAD



ΔY spectrum



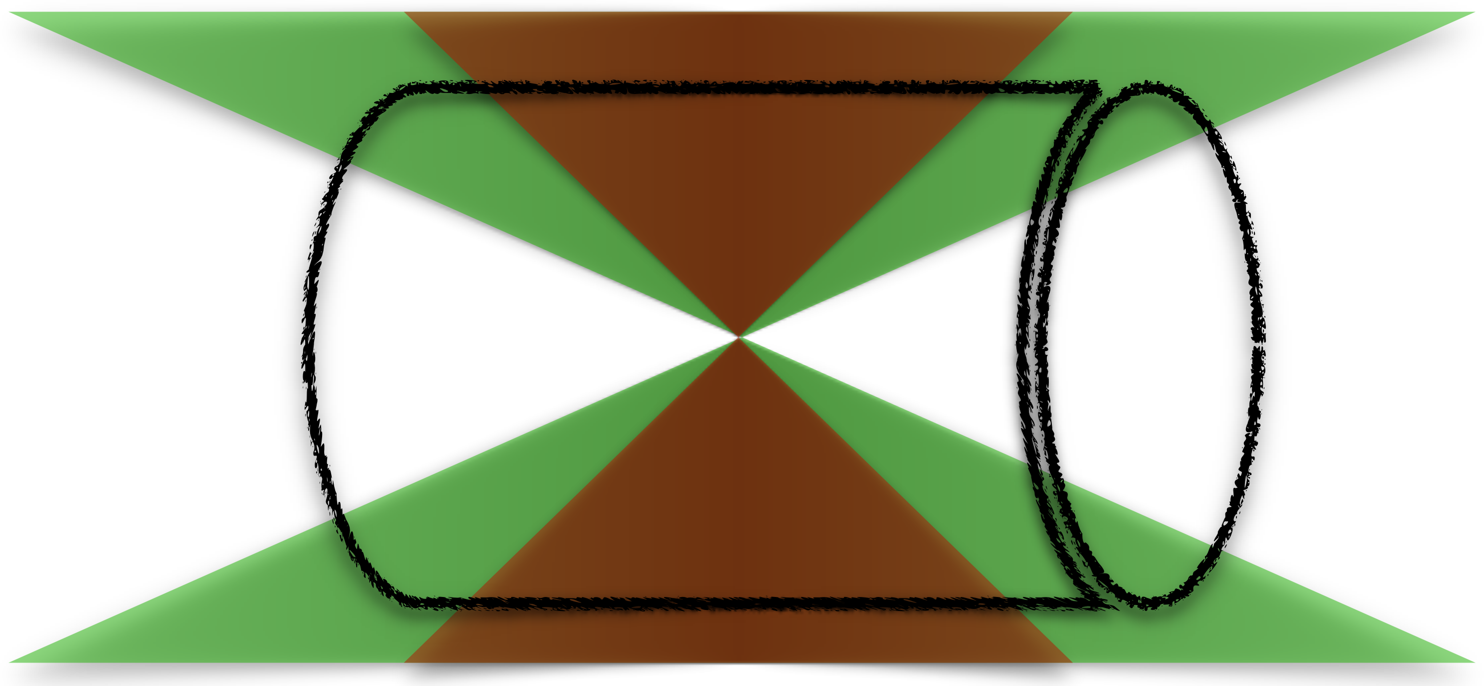
p_H spectrum

@100 TeV FCC

NLL matched to NLO fixed-order JETHAD + POWHEG (in progress)

High-energy QCD at new-gen Forward Facilities

Forward + backward CMS detections: Mueller-Navelet, hadron-jet, di-hadron



$|y_{\rm jet}| < 4.7$

barrel + endcap

$|y_{\rm hadron}| < 2.4$

barrel

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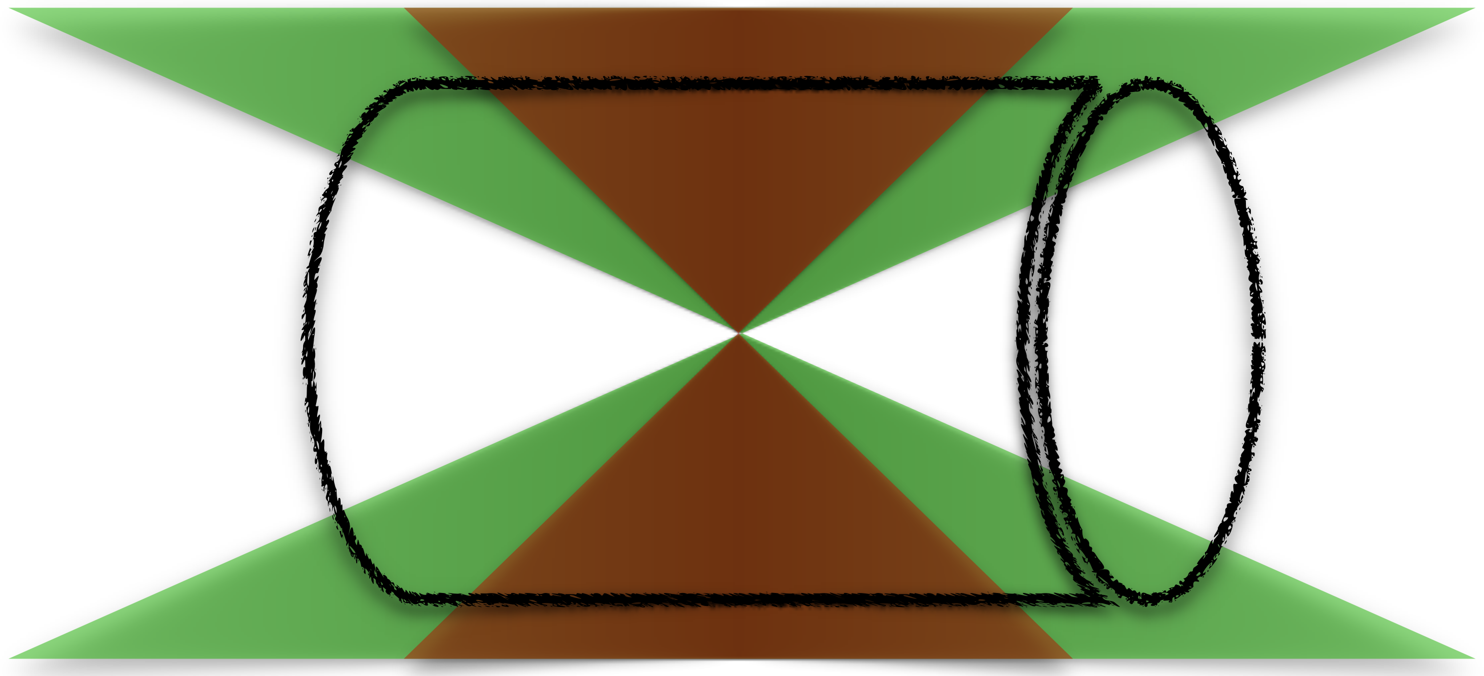

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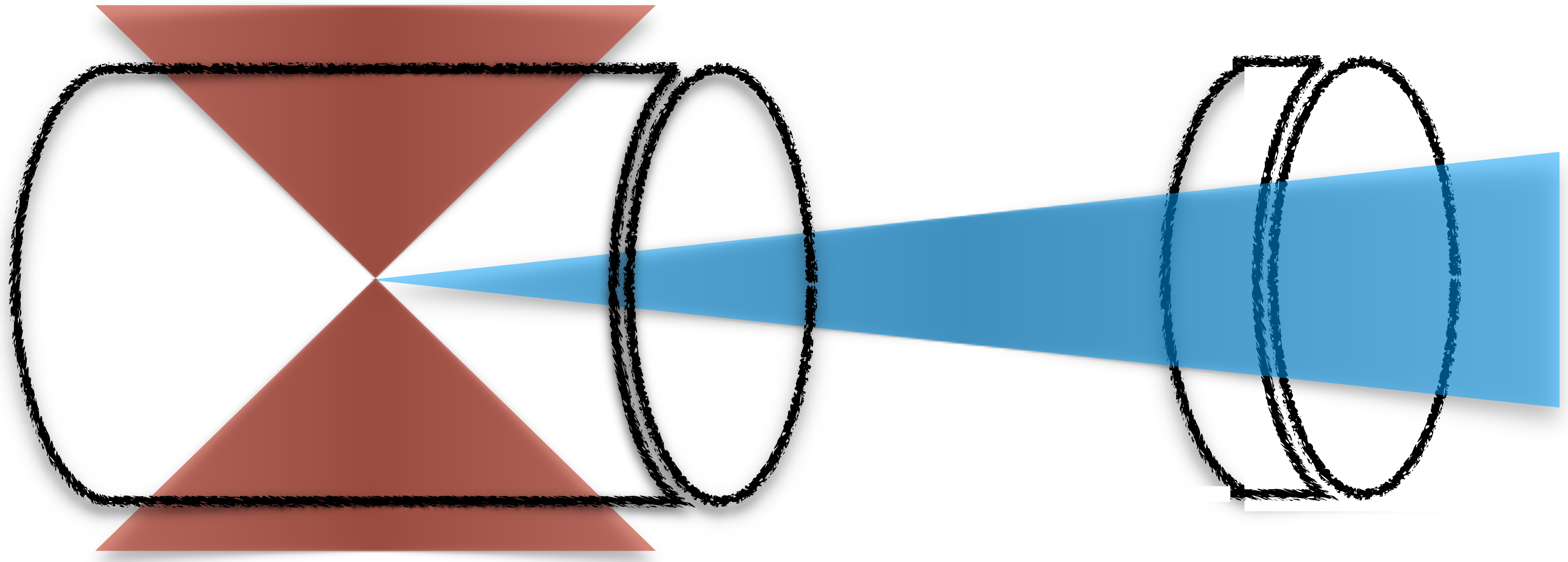
- Ultra-forward FPF + central ATLAS detections: single-charmed hadrons + Higgs



$5 < |y_{D^*, \Lambda_c}| < 7$

FPF

$|y_{\rm Higgs}| < 2.5$

ATLAS barrel

(charm + Higgs) 🔗 [F. G. C. et al., Phys. Rev. D 105 (2022) 11, 114056]

(light mesons + heavy flavor) 🔗 [F. G. C., Phys. Rev. D 105 (2022) 11, 114008]

High-energy QCD in ultraforward directions


Physics Reports 968 (2022) 1–50

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The Forward Physics Facility: Sites, experiments, and physics potential

Luis A. Anchordoqui [1], Akitaka Ariga [2,3], Tomoko Ariga [4], Weidong Bai [5], Kincso Balazs [6], Brian Batell [7], Jamie Boyd [6], Joseph Bramante [8], Mario Campanelli [9], Adrian Carmona [10], Francesco G. Celiberto [11,12,13], Grigorios Chachamis [14], Matthew Citron [15], Giovanni De Lellis [16,17], Albert De Roeck [6], Hans Dembinski [18], Peter B. Denton [19], Antonia Di Crescenzo [16,17,6], Milind V. Diwan [20], Liam Dougherty [21], Herbi K. Dreiner [22], Yong Du [23], Rikard Enberg [24], Yasaman Farzan [25], Jonathan L. Feng [26,*], Max Fieg [26], Patrick Foldenauer [27], Saeid Foroughi-Abari [28], Alexander Friedland [29], Michael Fucilla [30,31], Jonathan Gall [32], Maria Vittoria Garzelli [33,*], Francesco Giuli [34], Victor P. Goncalves [35], Marco Guzzi [36], Francis Halzen [37], Juan Carlos Helo [38,39], Christopher S. Hill [40], Ahmed Ismail [41], Ameen Ismail [42], Richard Jacobsson [6], Sudip Jana [43], Yu Seon Jeong [44], Krzysztof Jodłowski [45], Kevin J. Kelly [46], Felix Kling [29,47,**], Fnu Karan Kumar [20], Zhen Liu [48], Rafał Maciuła [49], Roshan Mammen Abraham [41], Julien Manshanden [33], Josh McFayden [50], Mohammed M.A. Mohammed [30,31], Pavel M. Nadolsky [51], Nobuchika Okada [52], John Osborne [6], Hidetoshi Otono [4], Vishvas Pandey [53,46], Alessandro Papa [30,31], Digesh Raut [54], Mary Hall Reno [55], Filippo Resnati [6], Adam Ritz [28], Juan Rojo [56], Ina Sarcevic [57], Christiane Scherb [58], Holger Schulz [59], Pedro Schwaller [60], Dipan Sengupta [61], Torbjörn Sjöstrand [62], Tyler B. Smith [26], Dennis Soldin [54], Anna Stasto [63], Antoni Szczurek [49], Zahra Tabrizi [64], Sebastian Trojanowski [65,66], Yu-Dai Tsai [26,46], Douglas Tuckler [67], Martin W. Winkler [68], Keping Xie [7], Yue Zhang [67]

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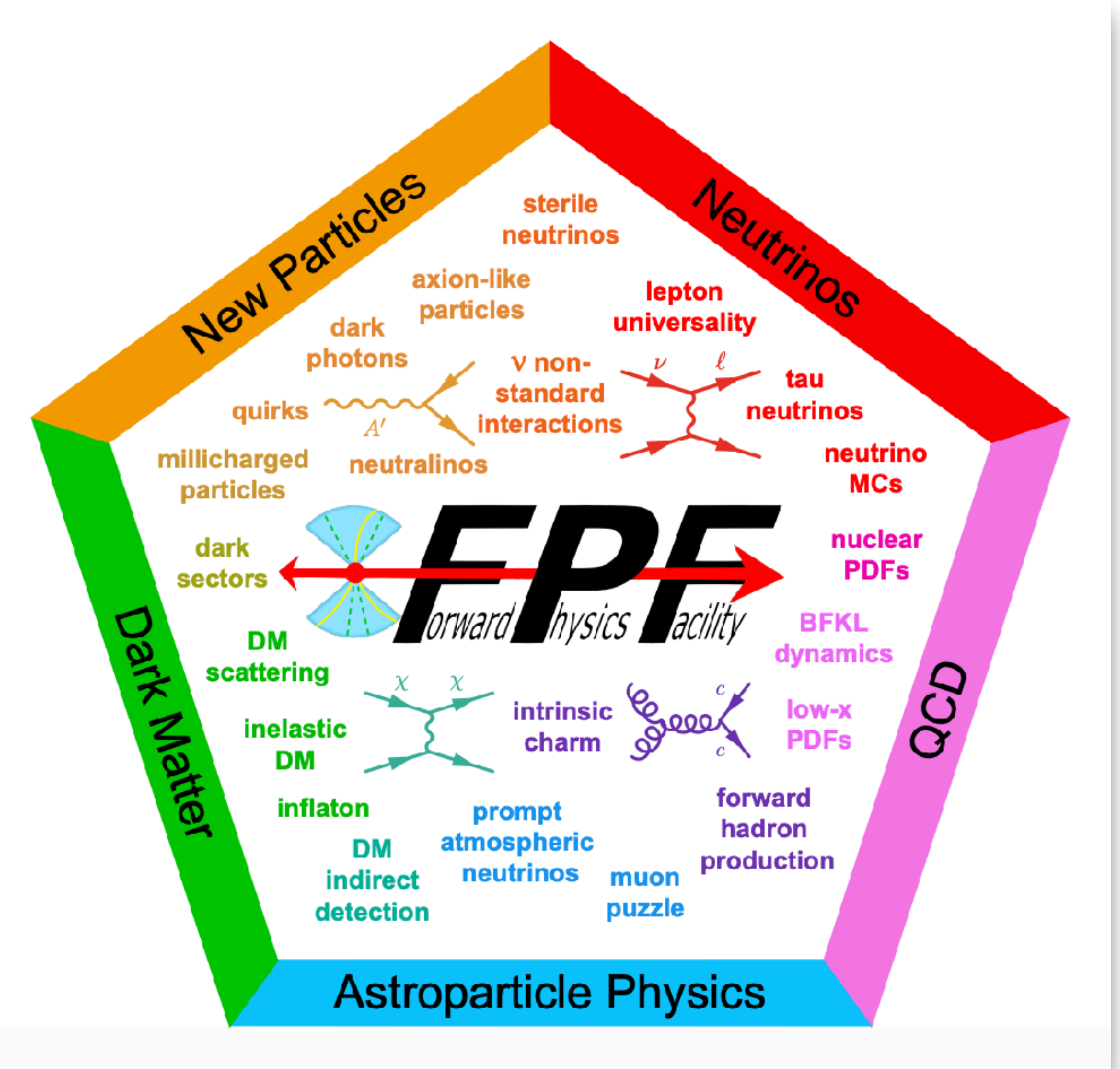
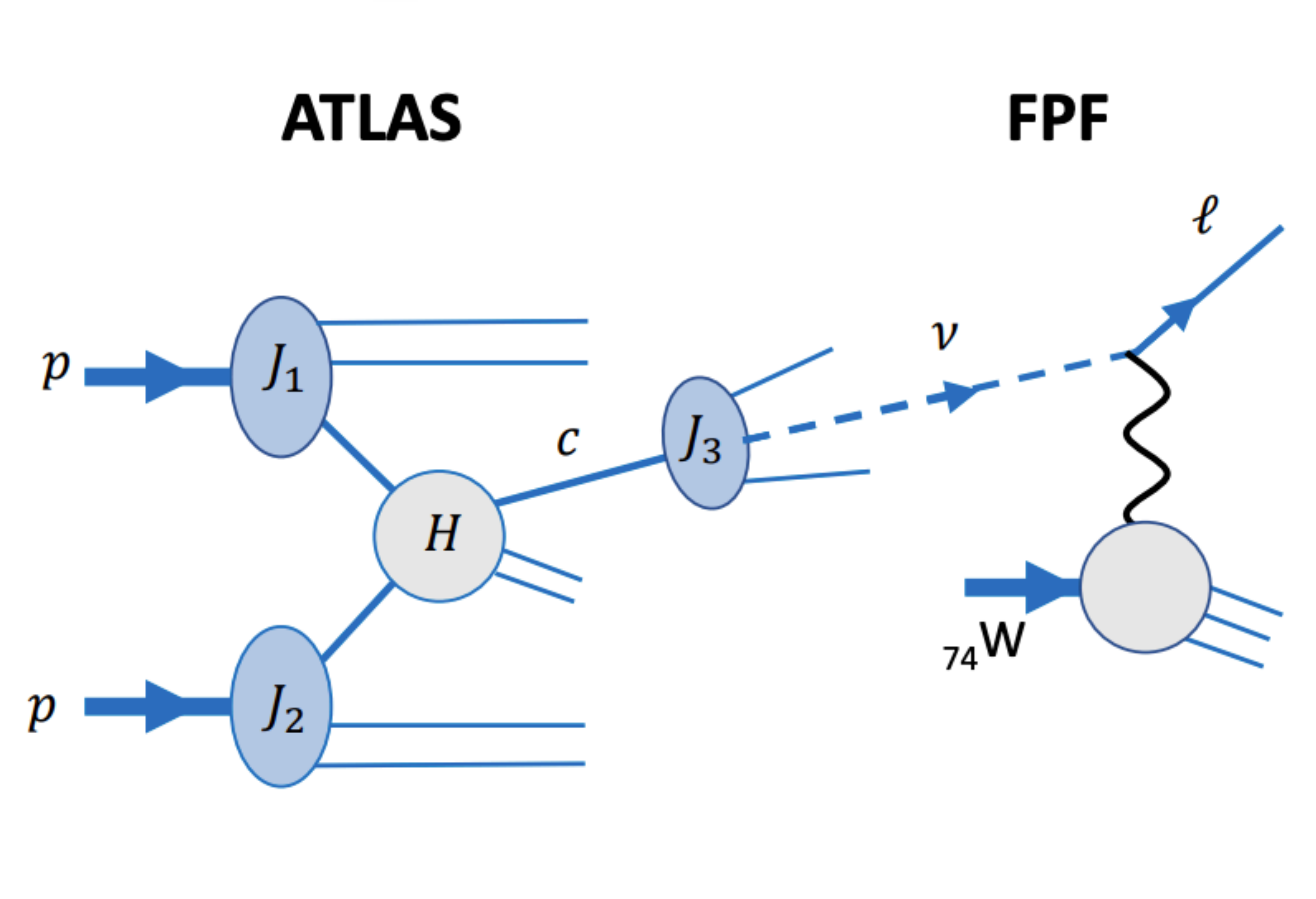
https://doi.org/10.1016/j.physrep.2022.04.004



🔗 [FPF Snowmass Whitepaper]



Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

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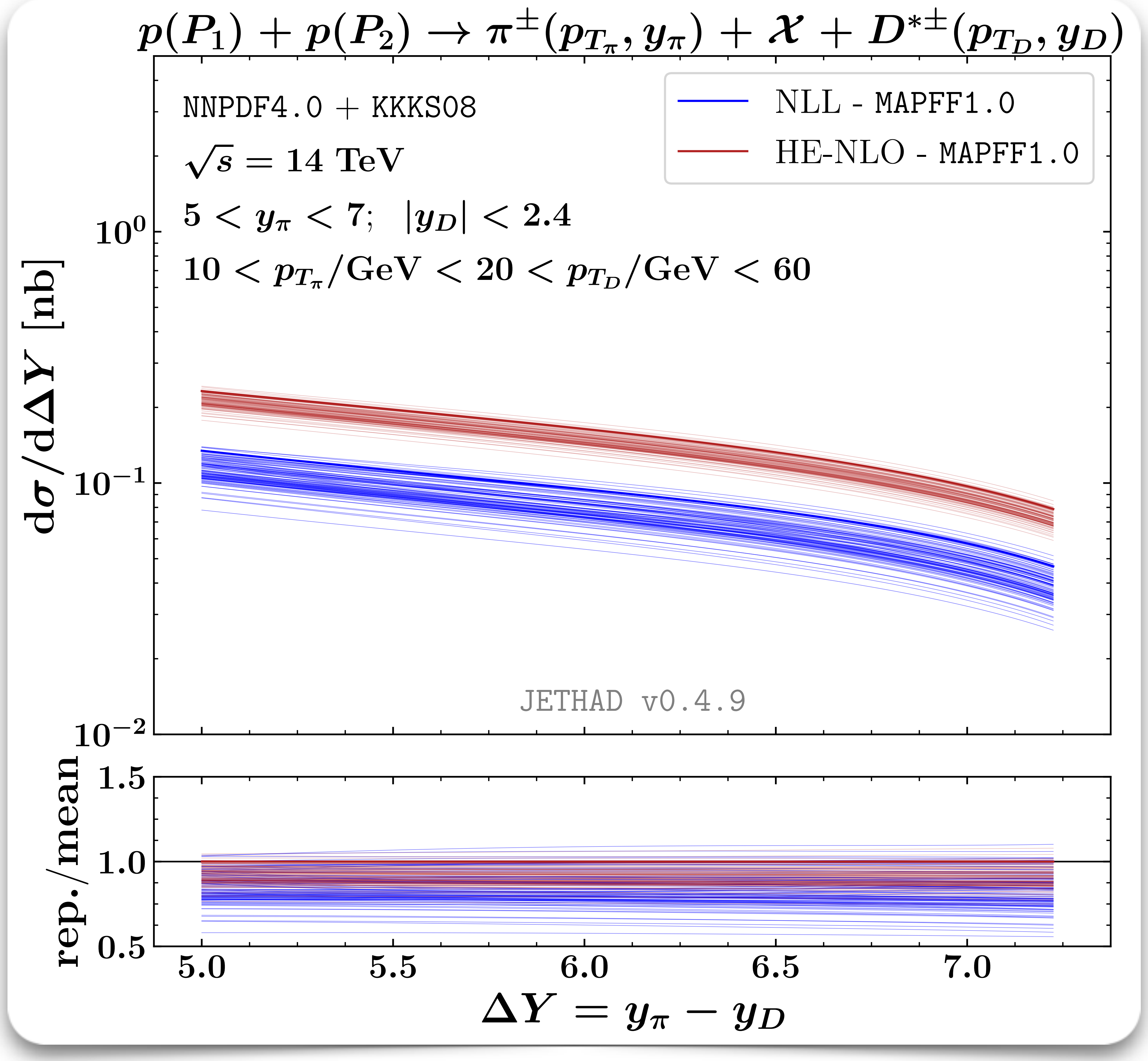

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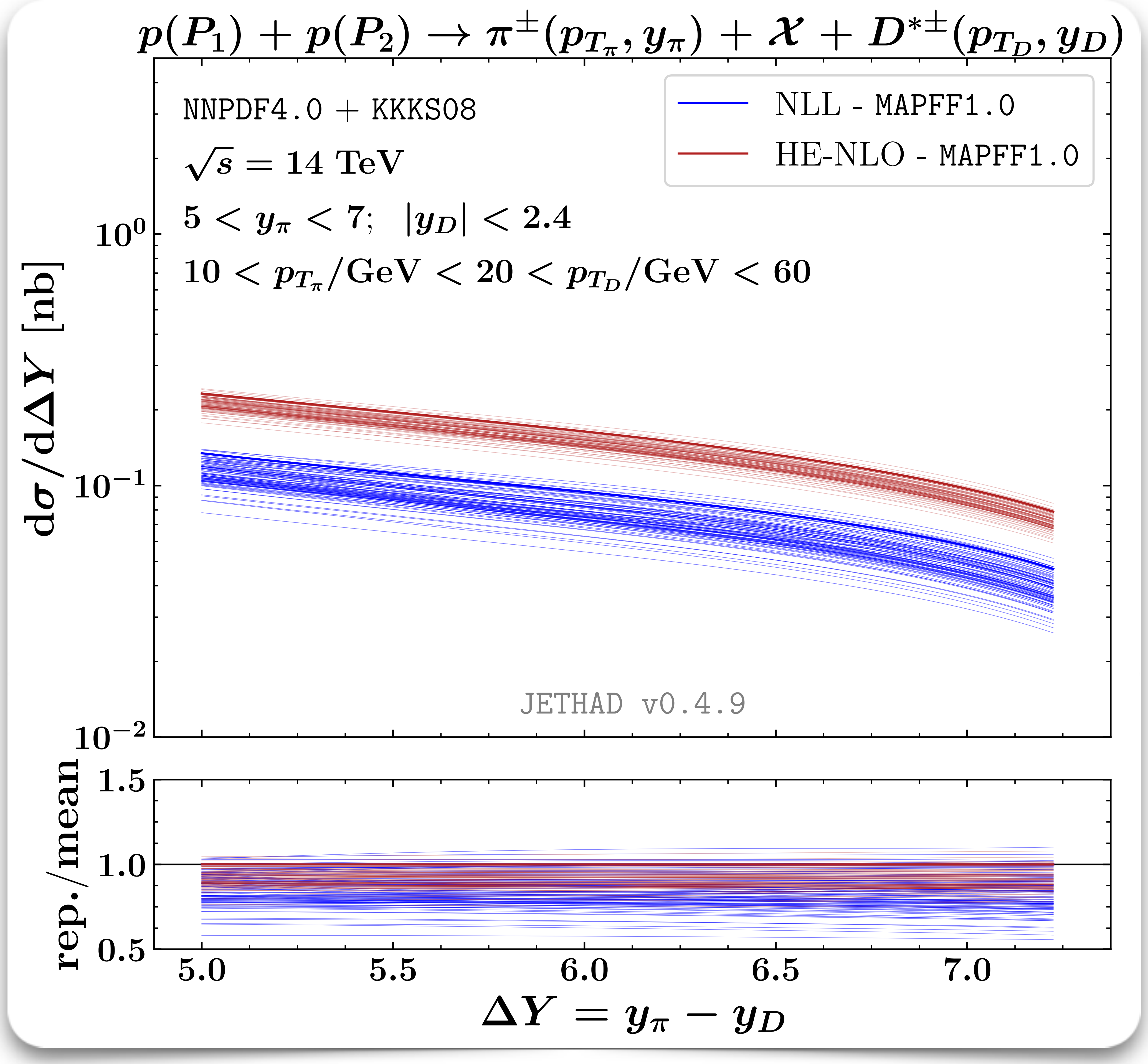

- Impact of collinear FFs on ΔY-distribution
- Replica method at work

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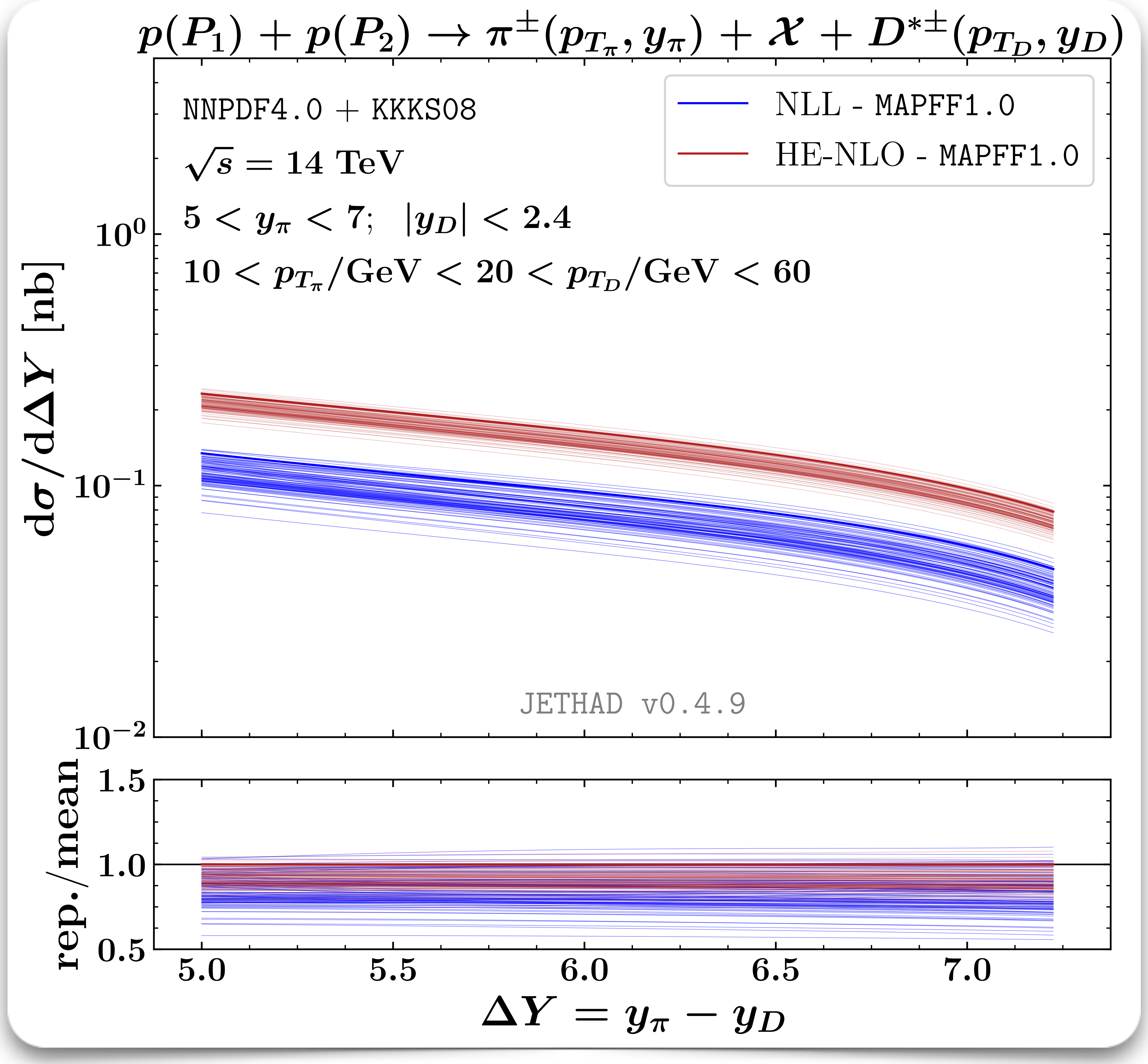

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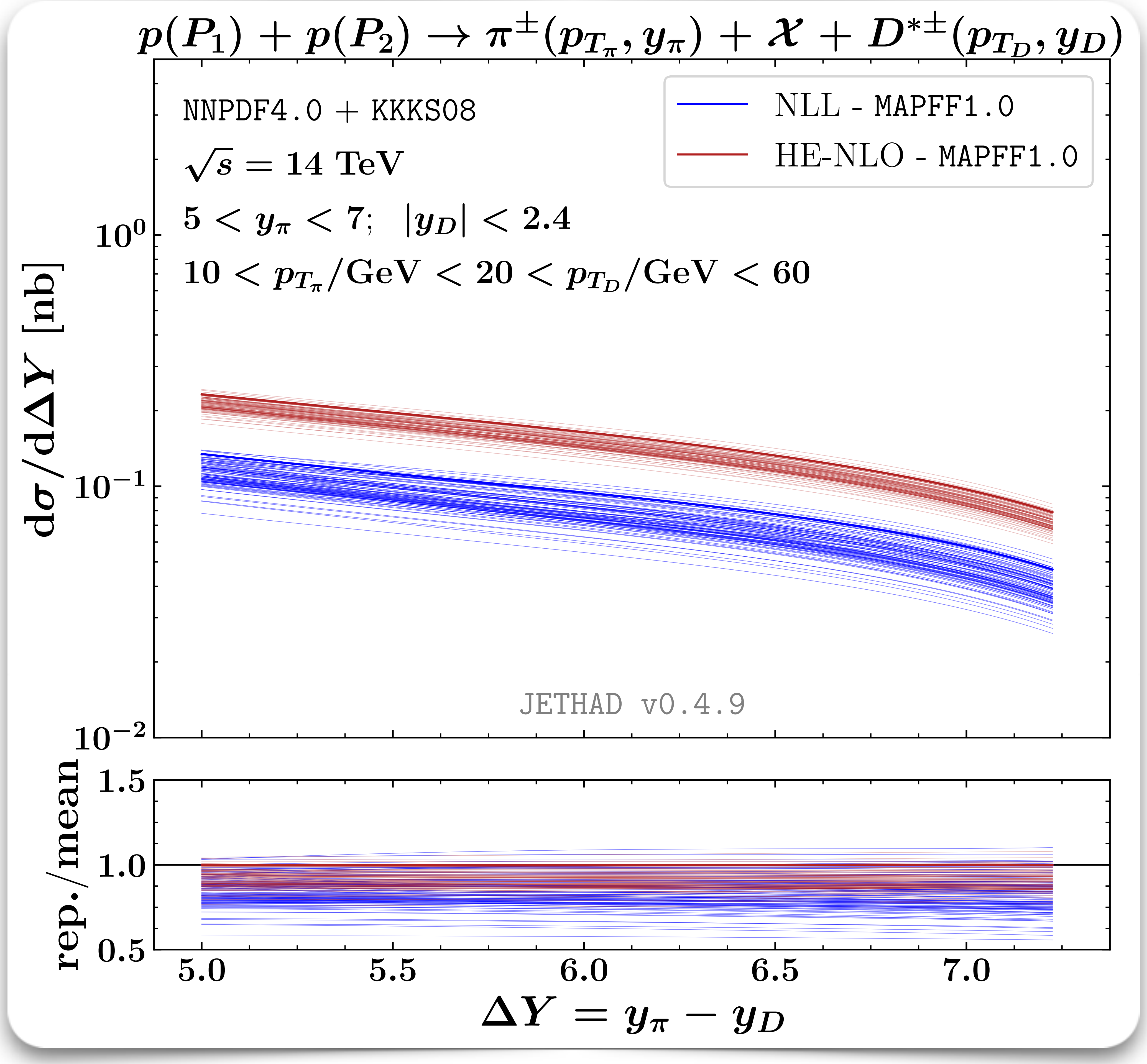
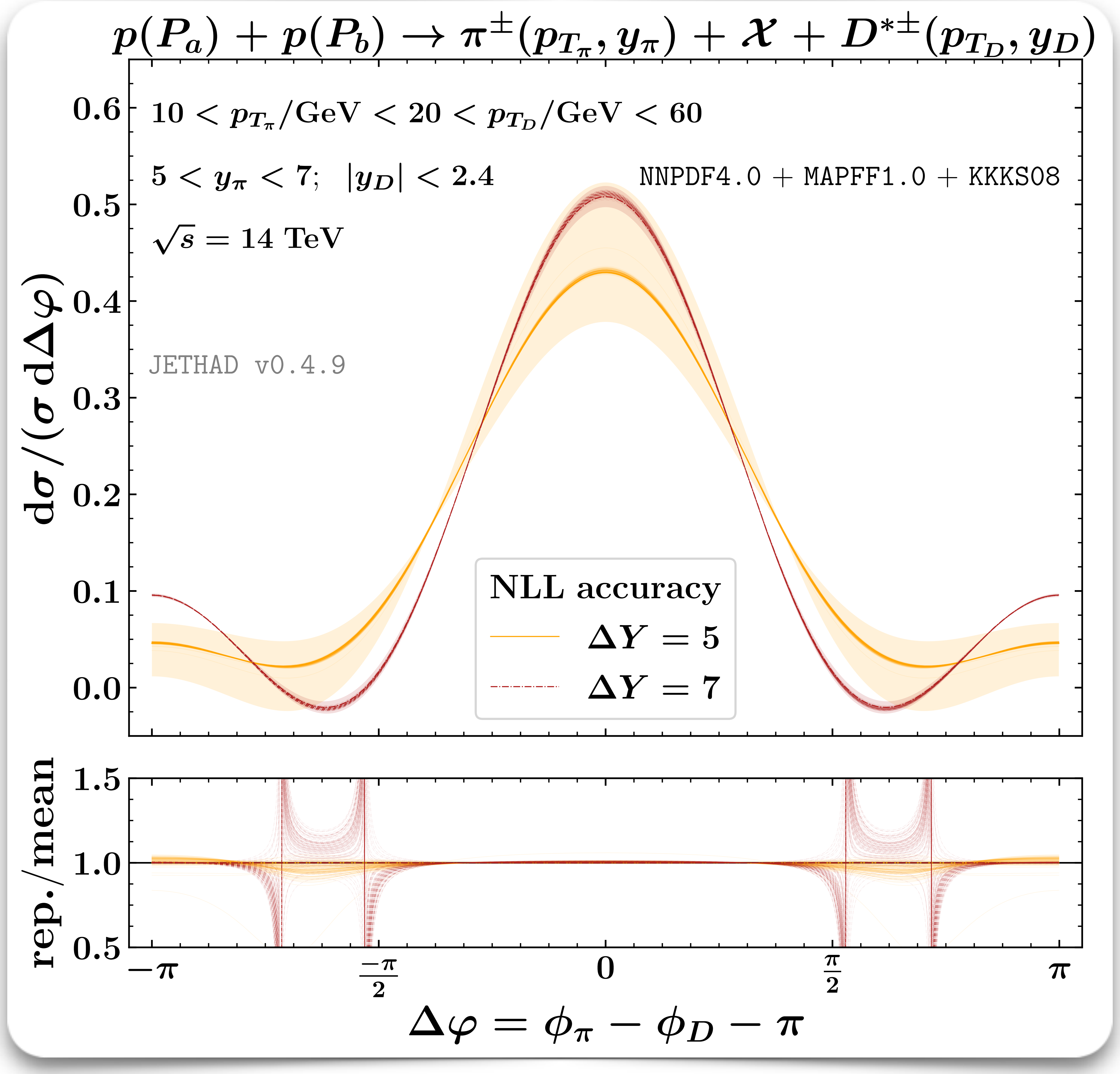
Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) ΔY-spectrum



Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) $\Delta\varphi$-spectrum



[FPF Snowmass Whitepaper]

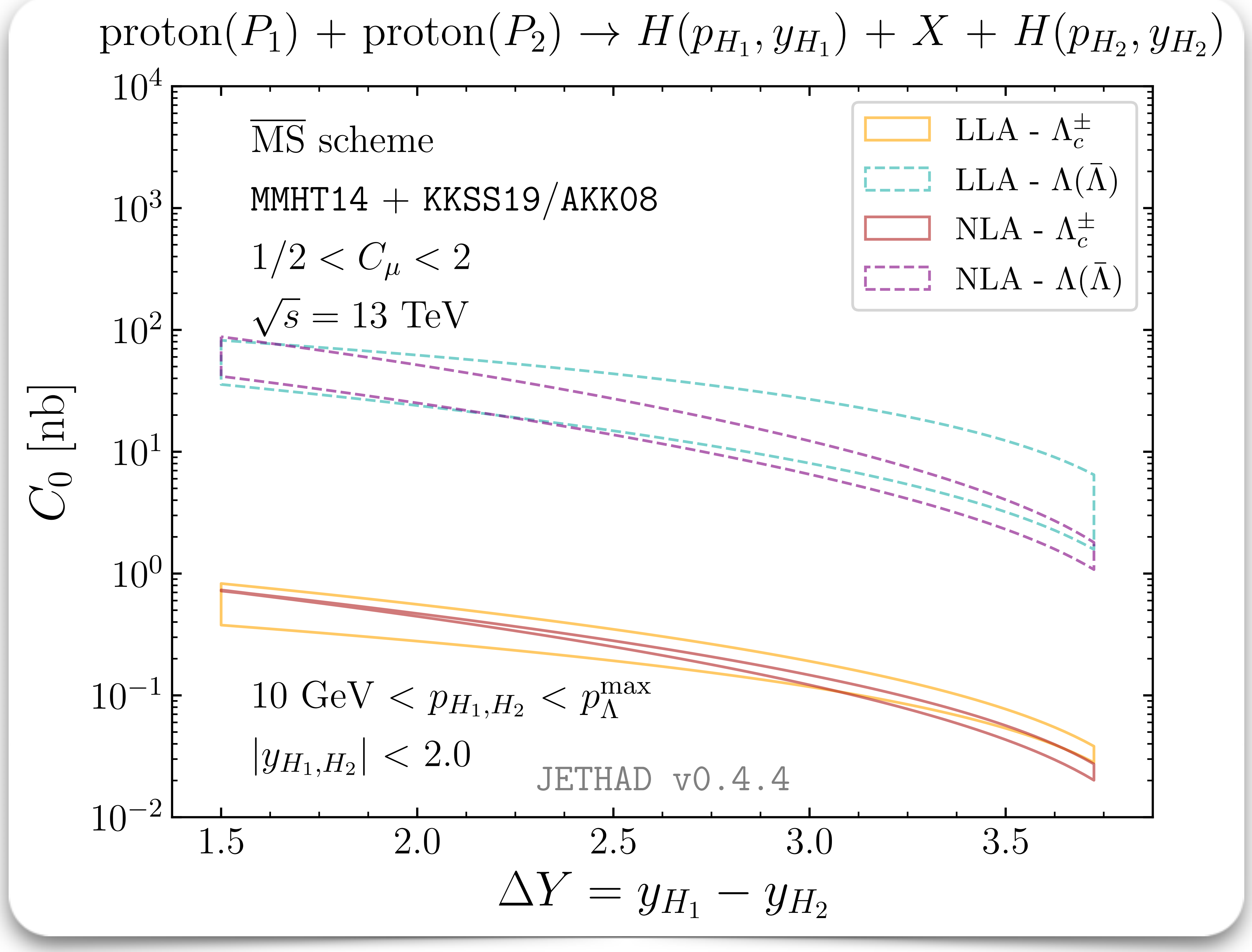
Open Heavy Flavor

From light to heavy-light bound states

Light-hadron+jet: higher-order instabilities via scale variation, as in Mueller-Navelet (¡!)

Λ_c baryons

[F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]



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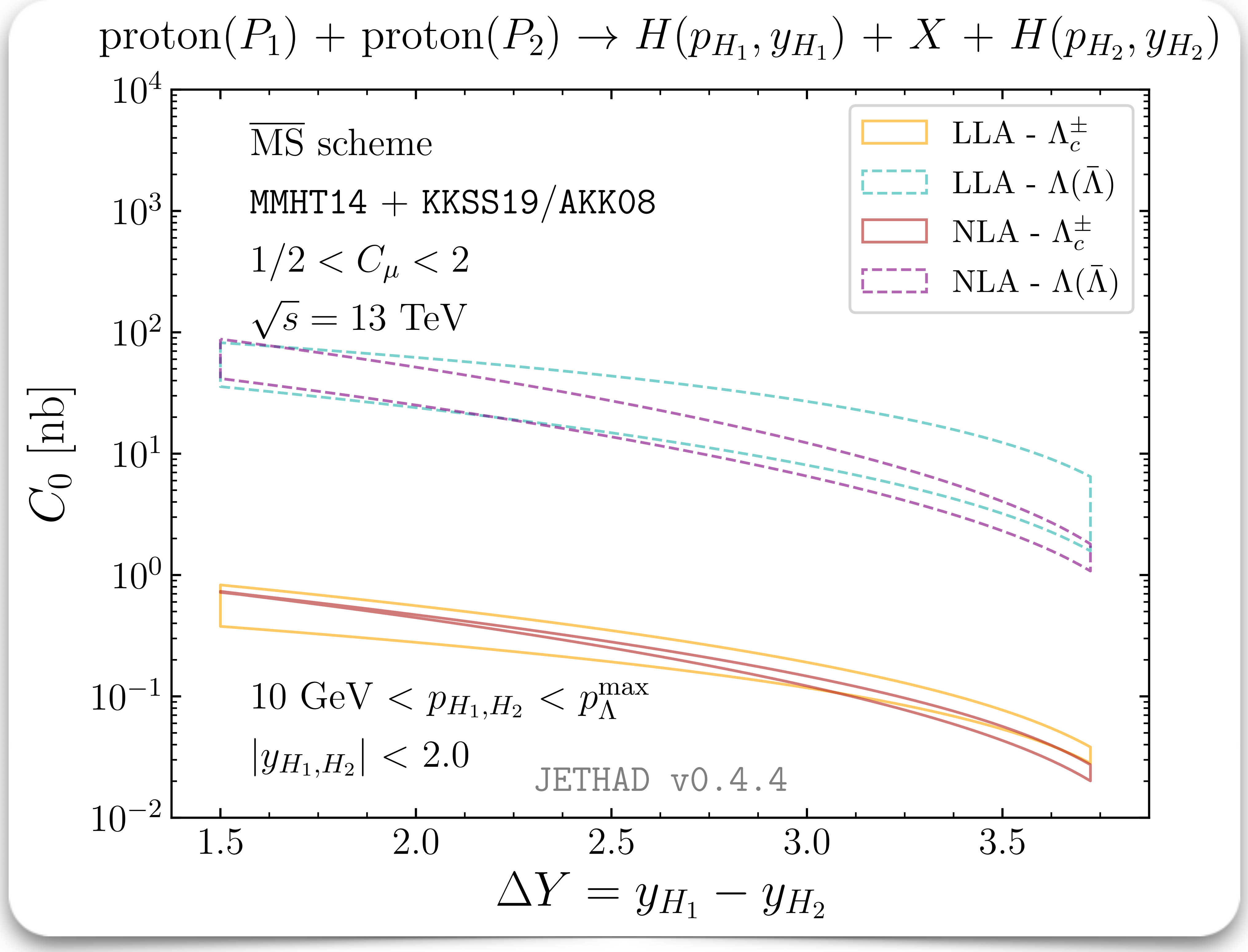
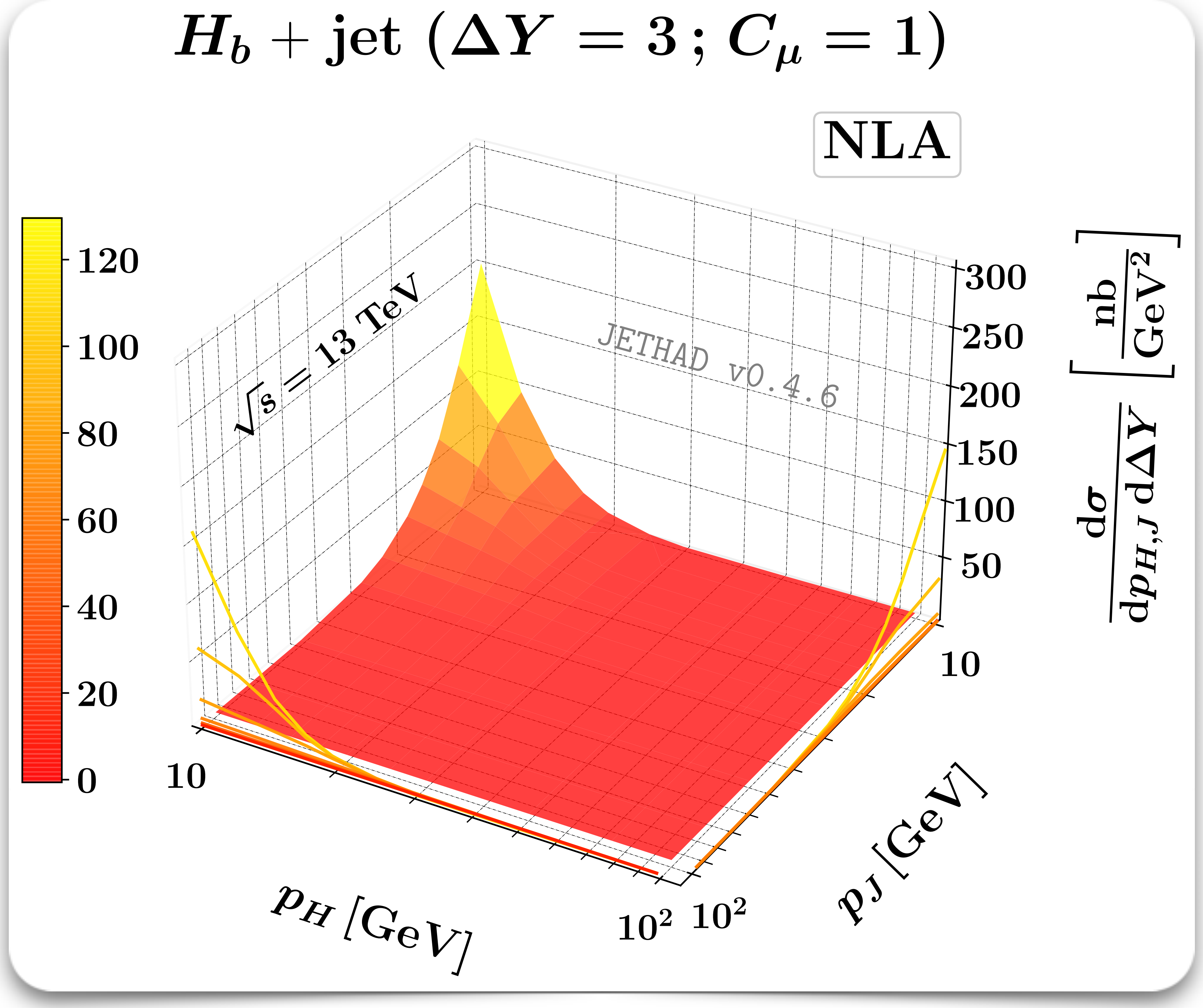


Bottom-flavored hadrons

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



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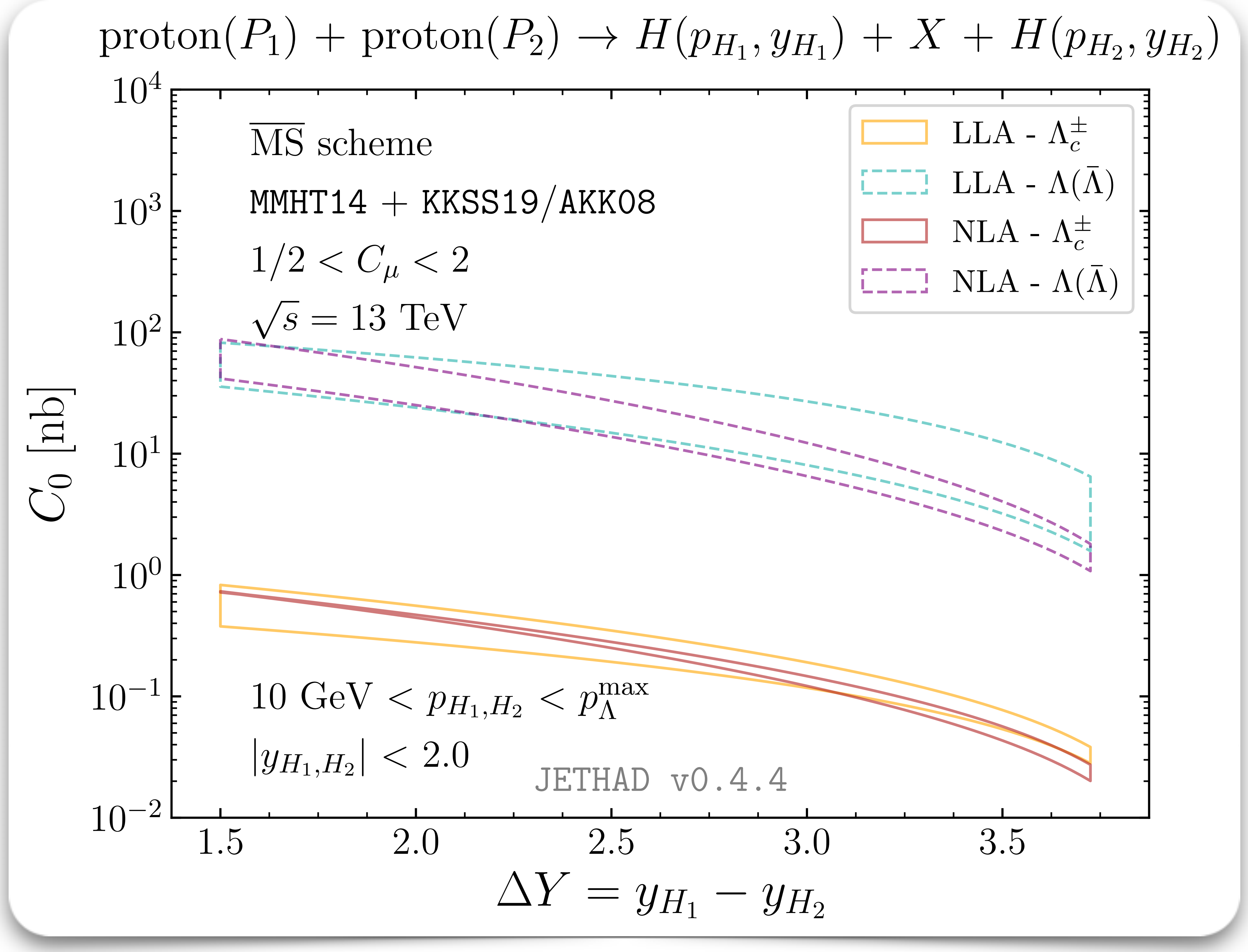

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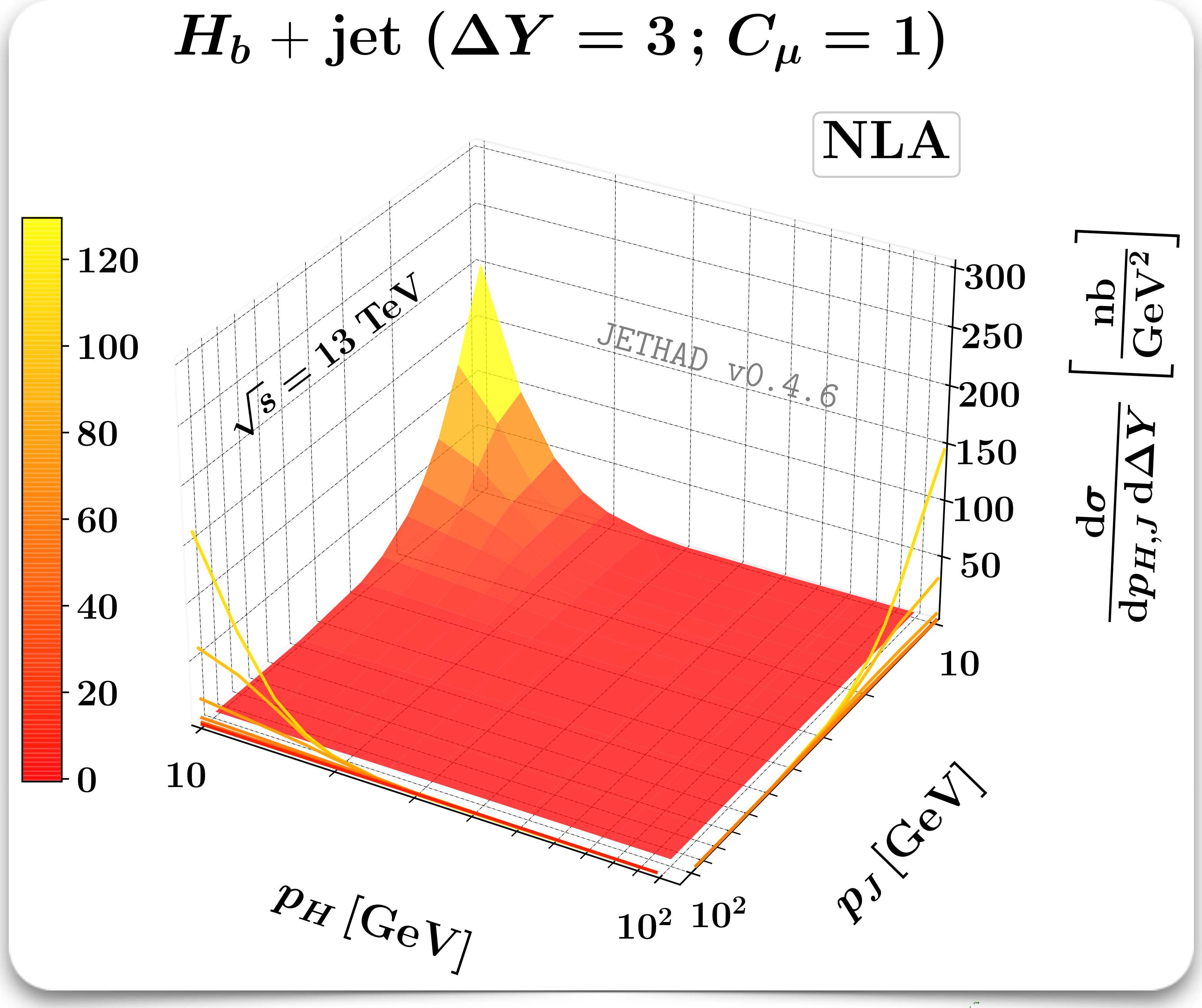

Natural stability as a tool to investigate high-energy dynamics of QCD ✓

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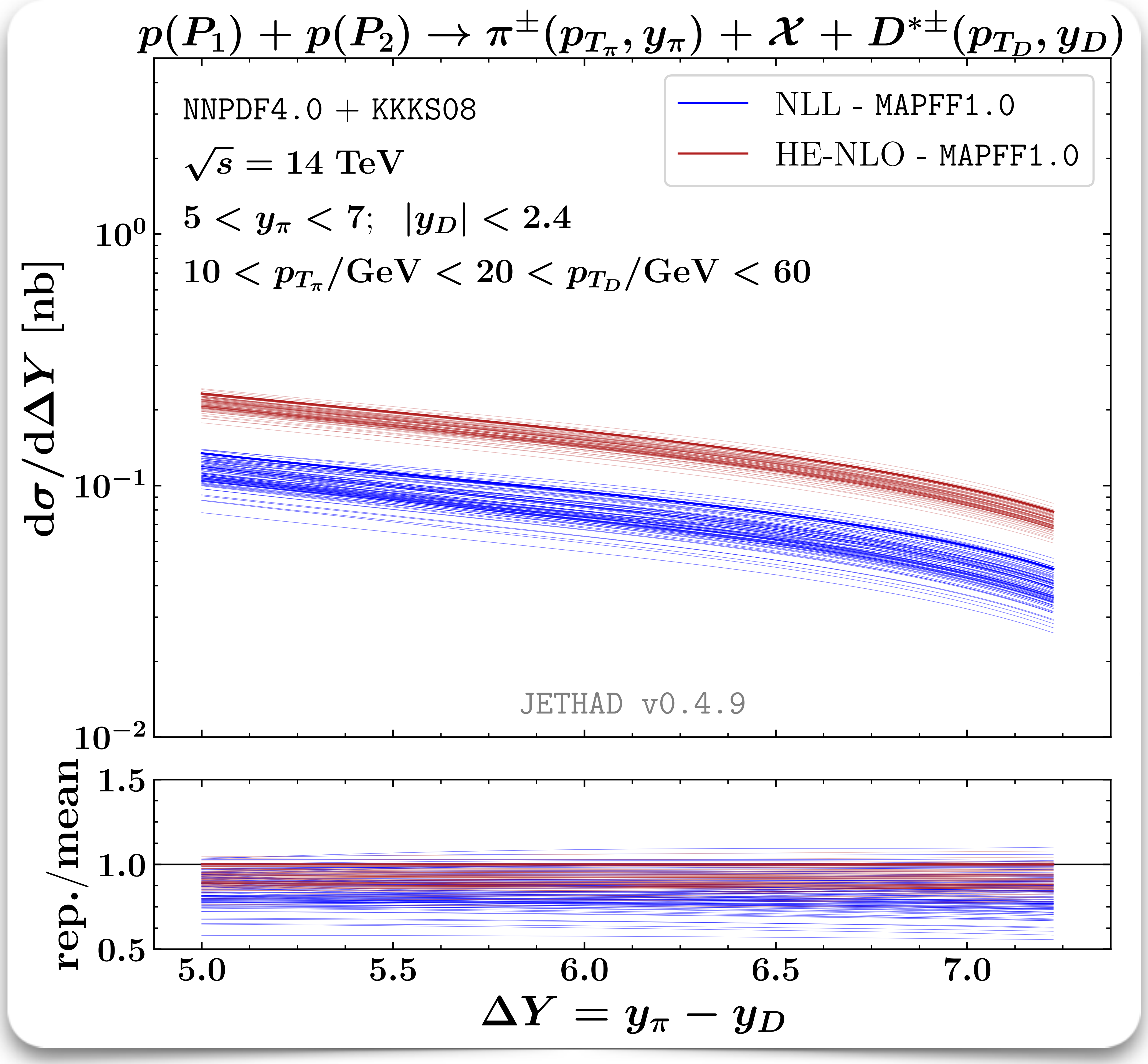

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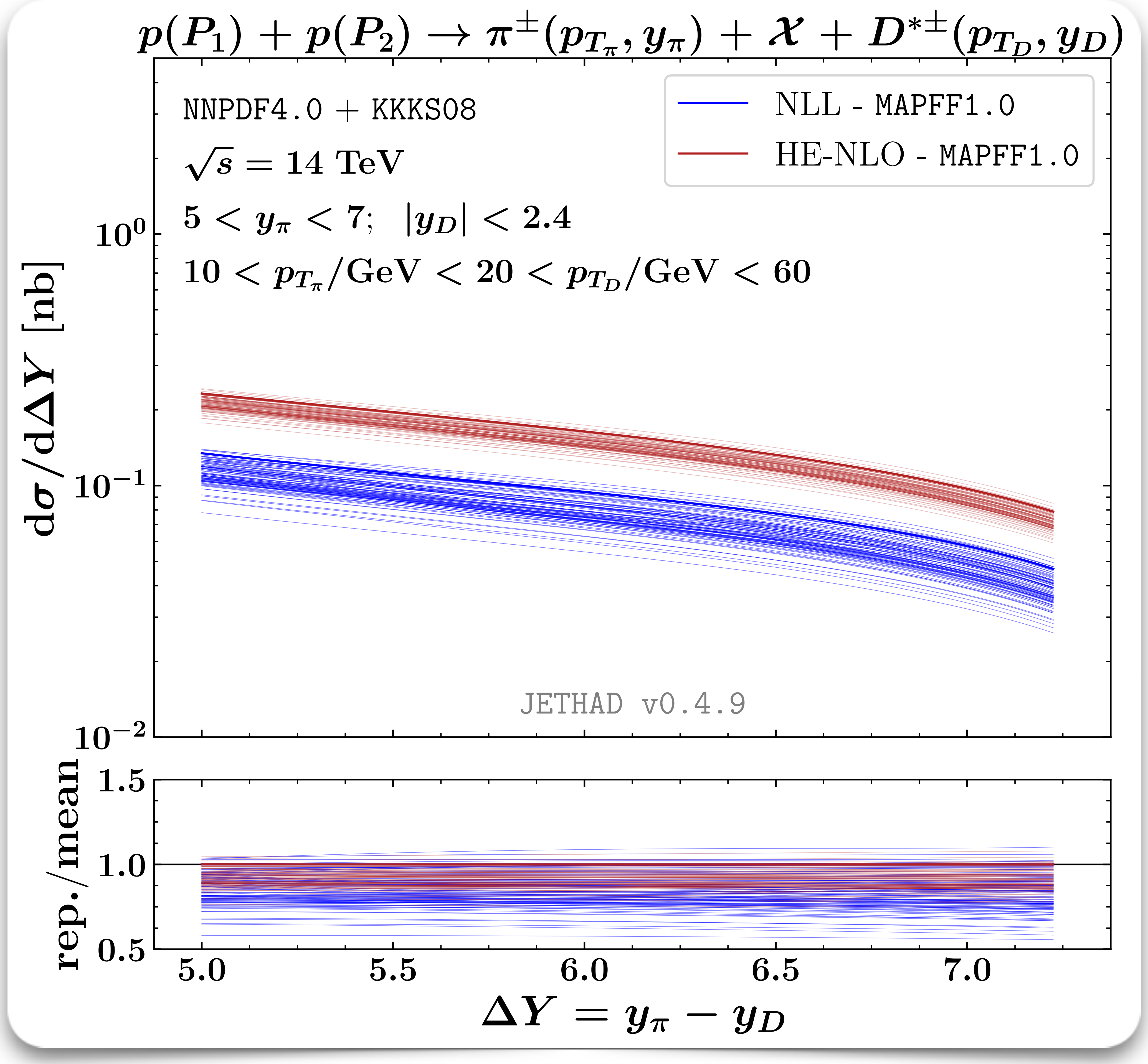

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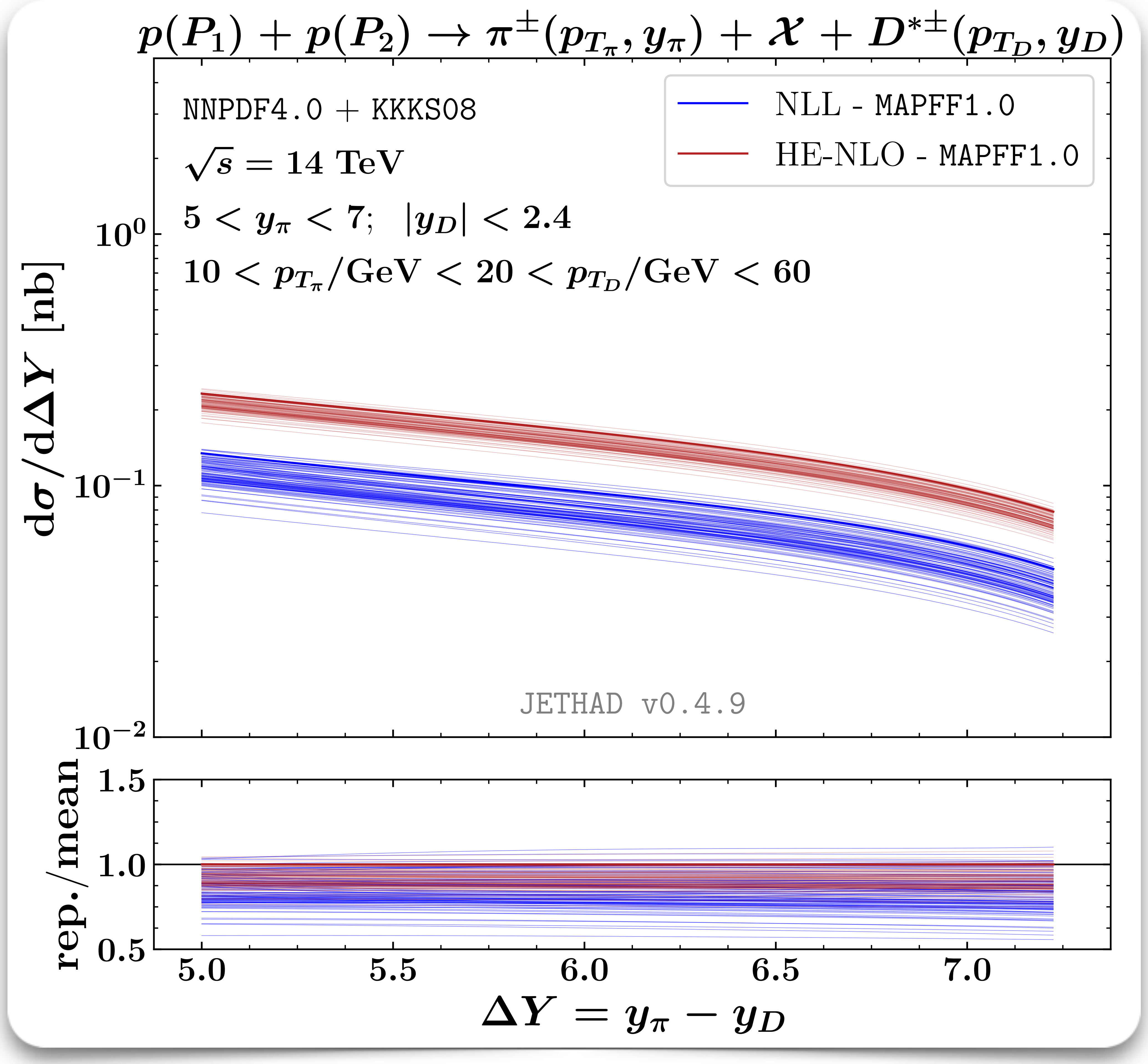

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Quarkonia

Quarkonium studies: Progresses & challenges

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

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- ✓ GIM mechanism (1970) → charm to explain electroweak flavor rotation
- ✓ Proof of asymptotic freedom & confinement ← $\psi(2S)$ resonance
- ¡! Quarkonia → easy to measure, difficult to understand

Spectroscopic notation for quarkonia

Spin

Color: Singlet (CS) or Octet (CO)

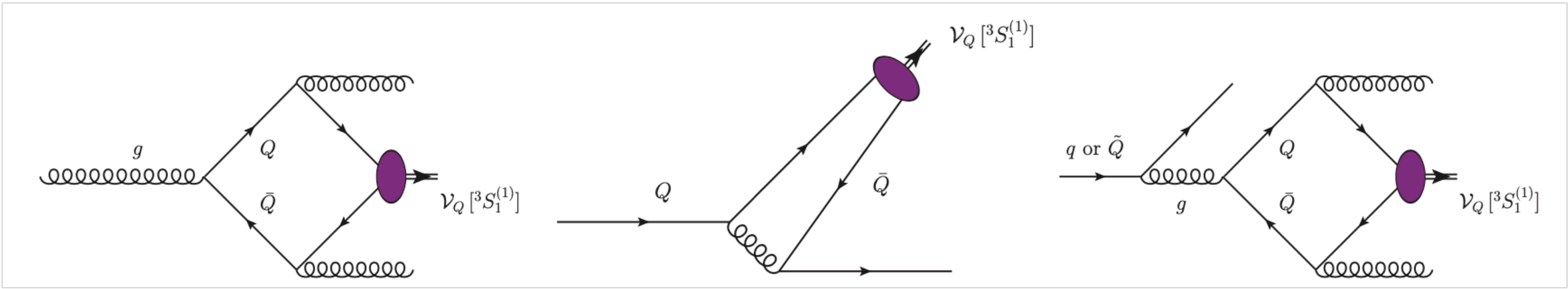
$$[n] \equiv {}^{2S+1}L_J^{(c)}$$

Orbital angular momentum

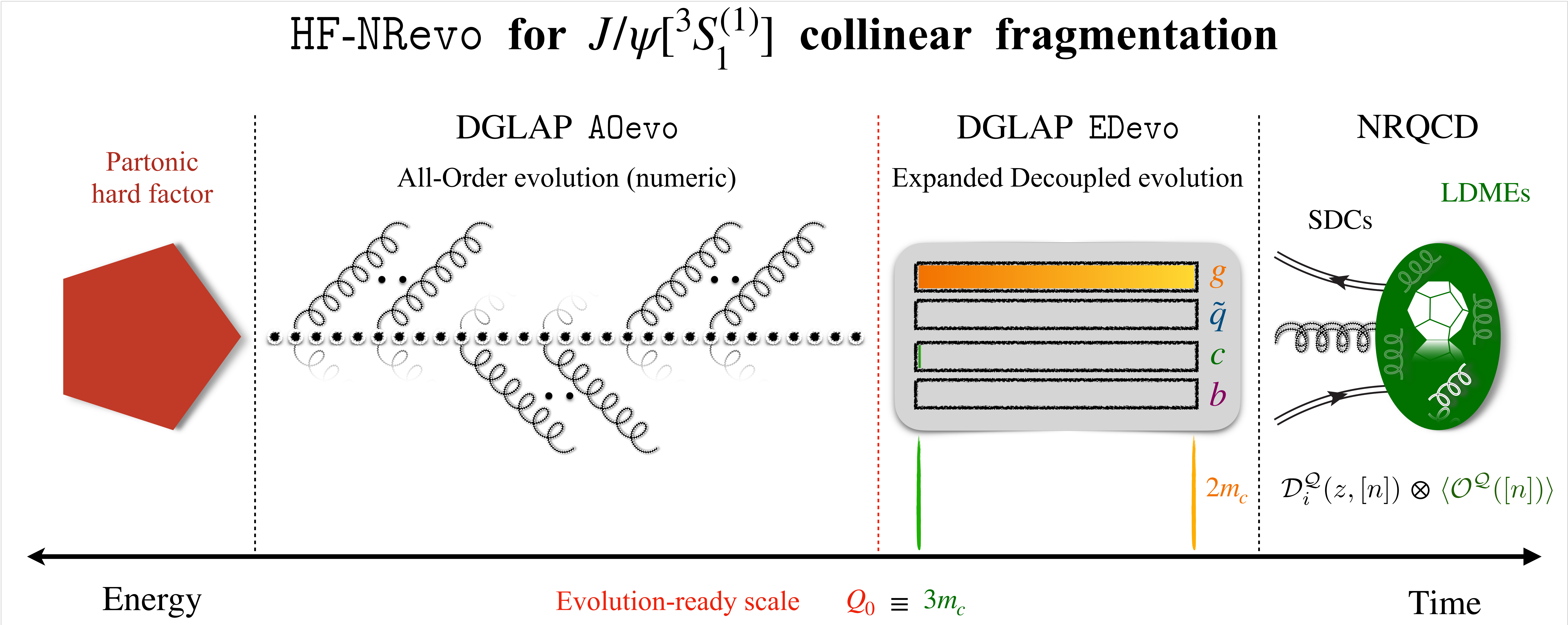
Total angular momentum

$$J = L + S$$

HF-NRevo: Initial-scale NRCQD inputs



Vector J/ψ



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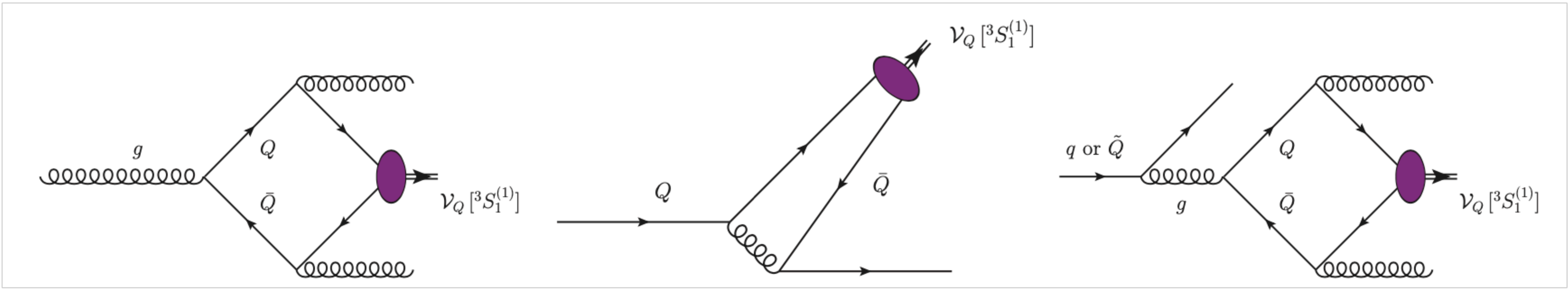
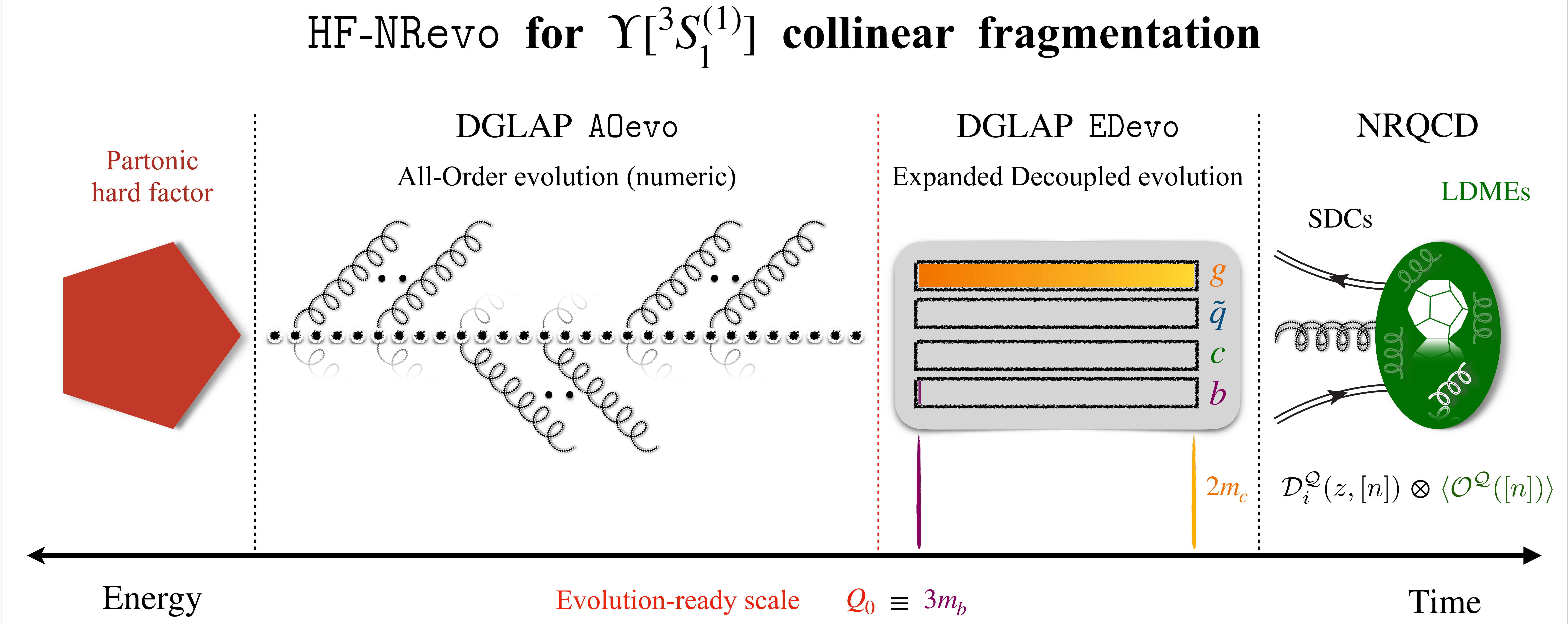
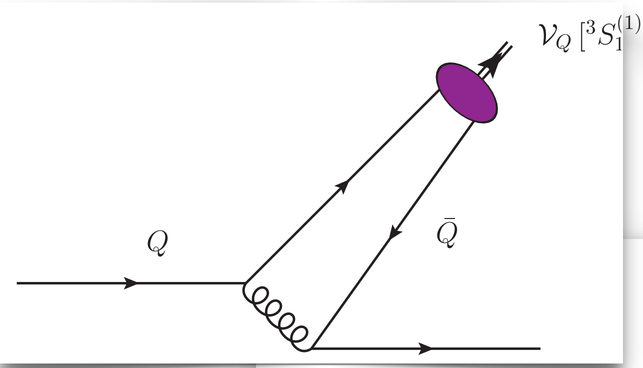


Vector Υ

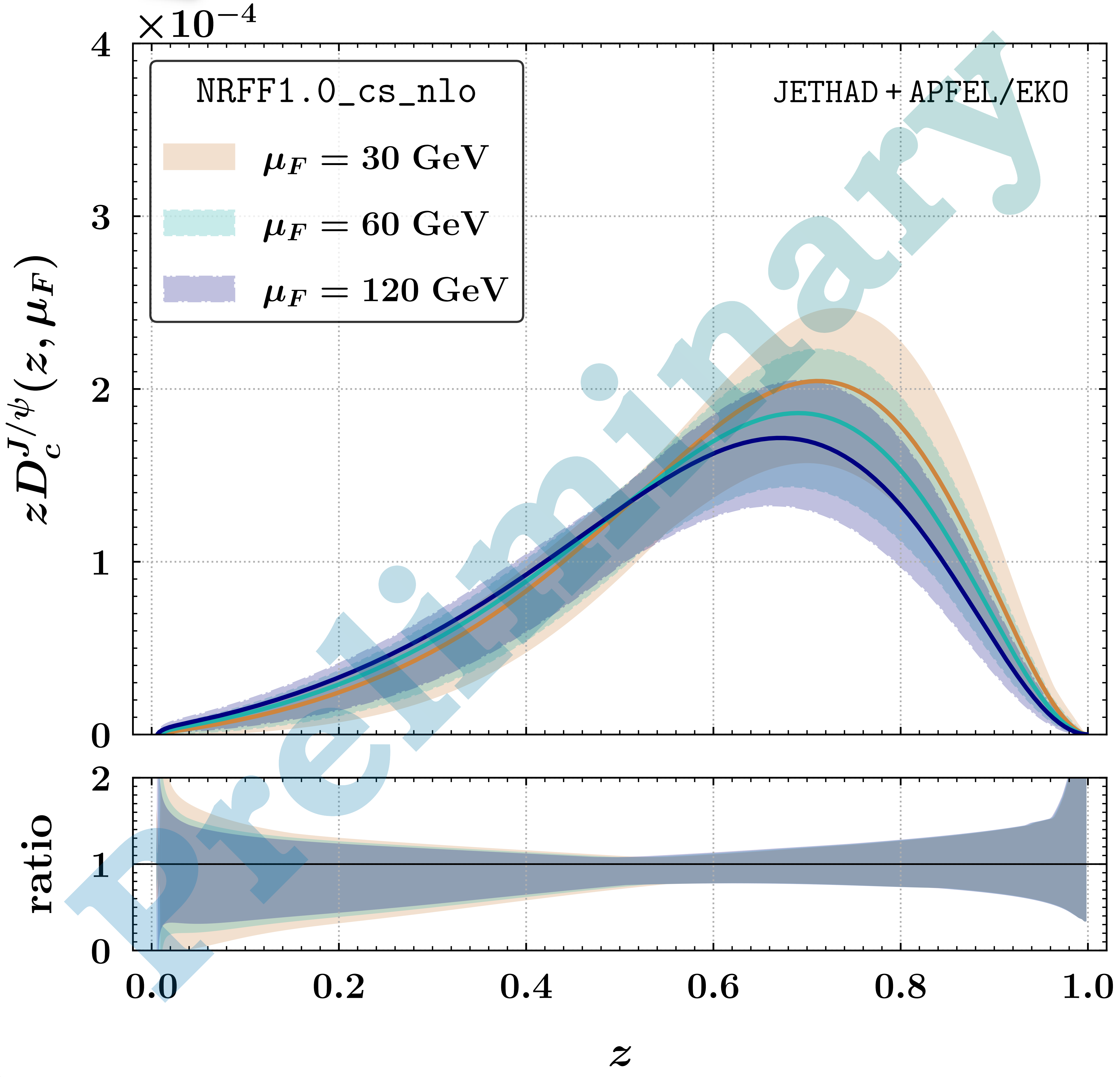


NRFF1.0: Charm fragmentation to charmonia

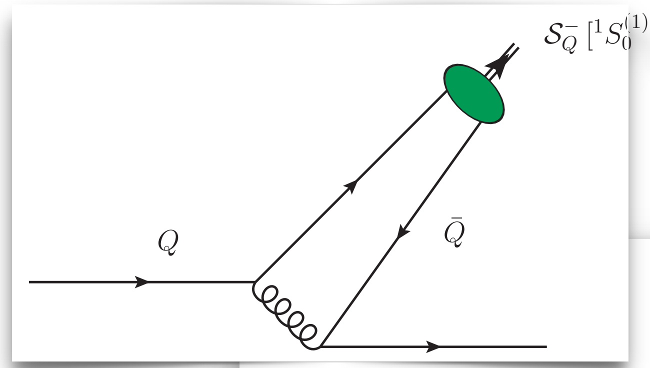
Vector J/ψ



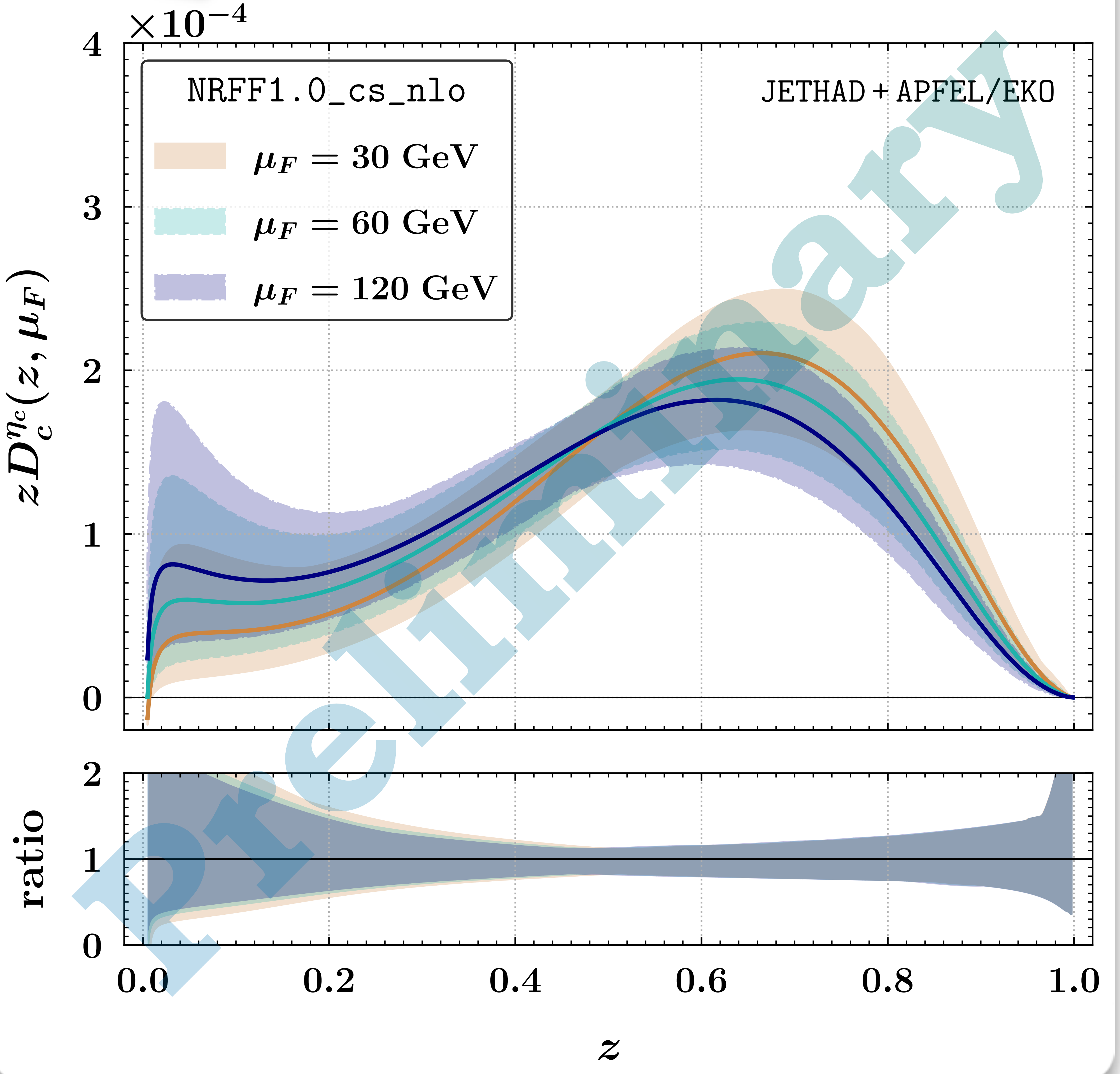
$(c \to J/\psi)$ fragmentation channel



Scalar η_c



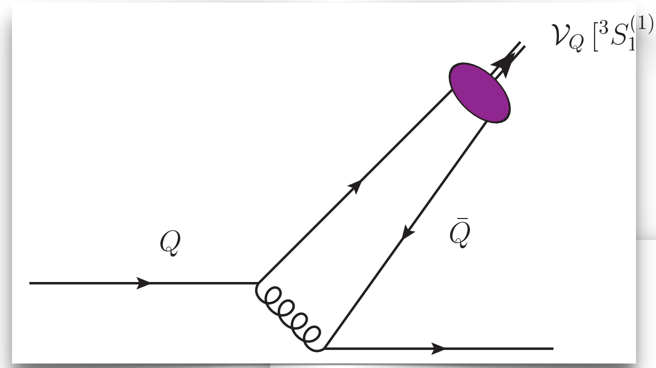
$(c \to \eta_c)$ fragmentation channel

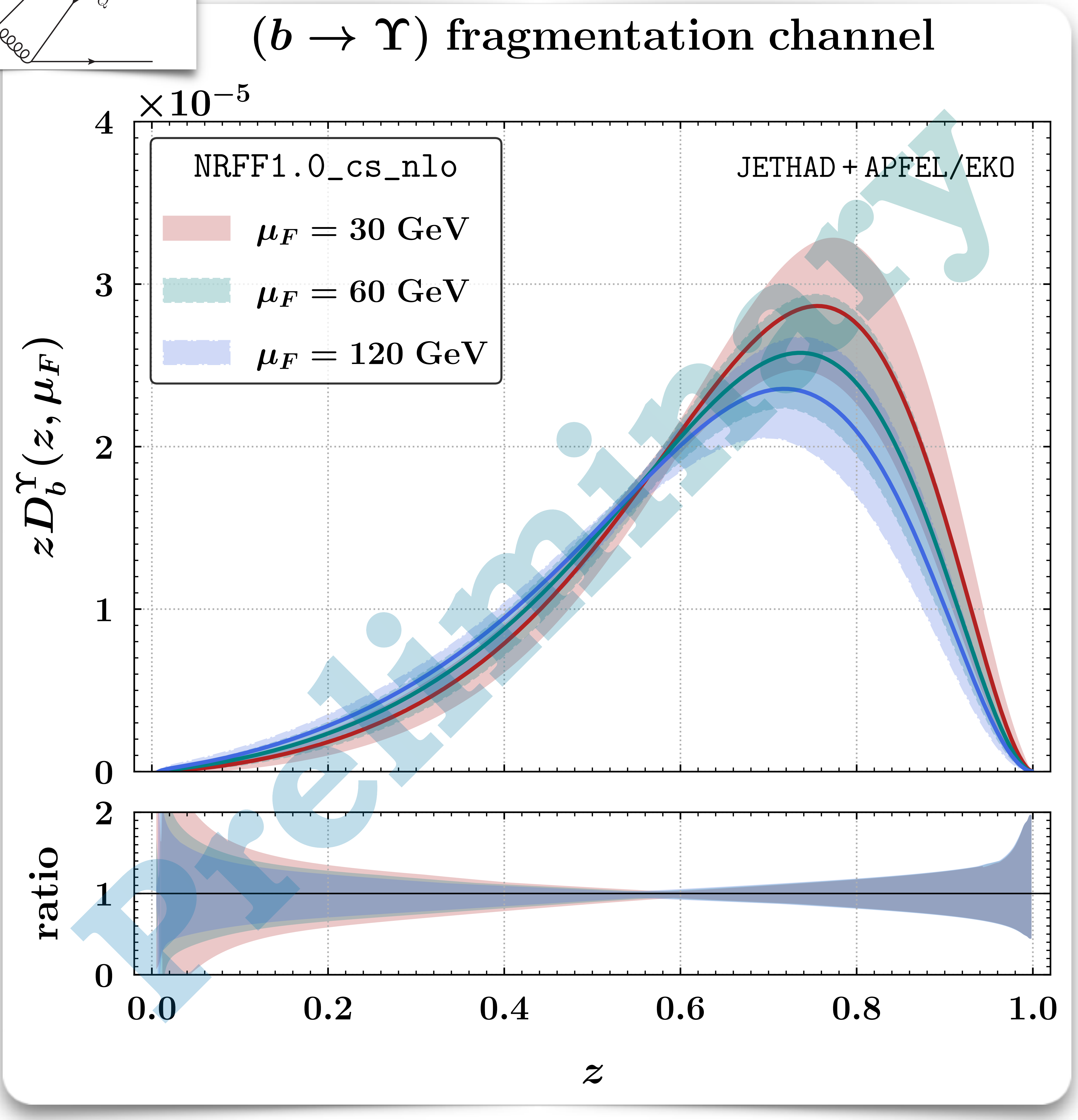


[F. G. C., in preparation]

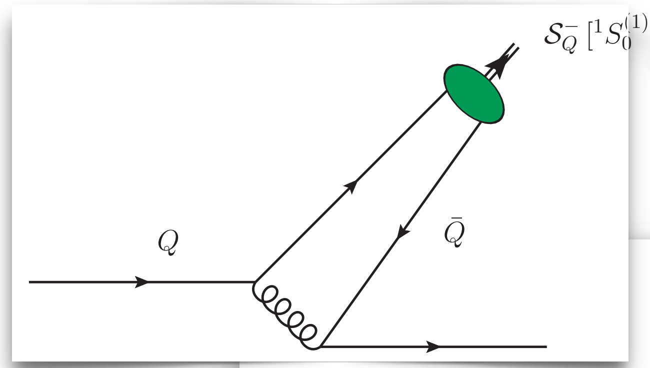
NRFF1.0: Bottom fragmentation to bottomonia

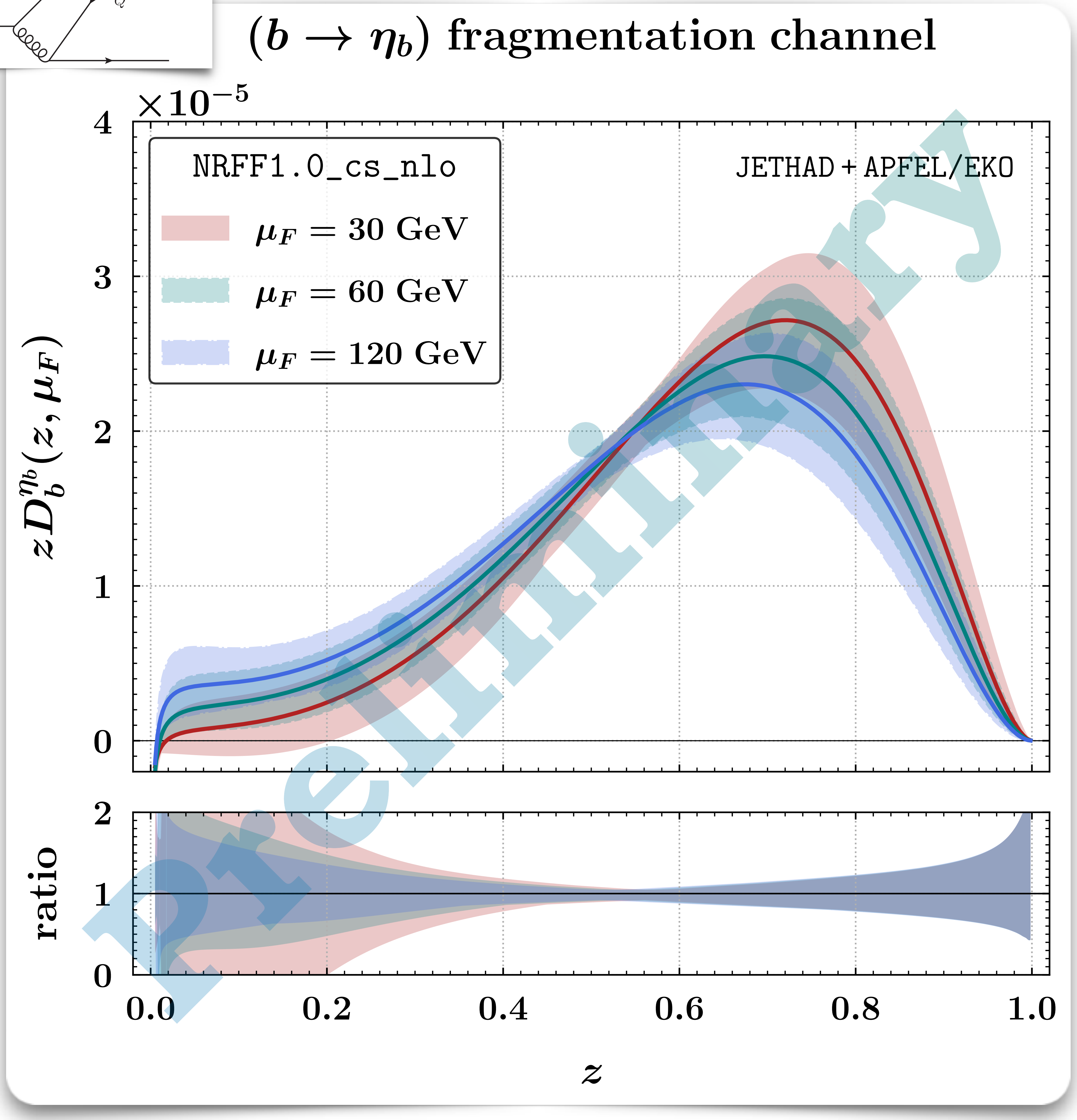
Vector Υ





Scalar η_b

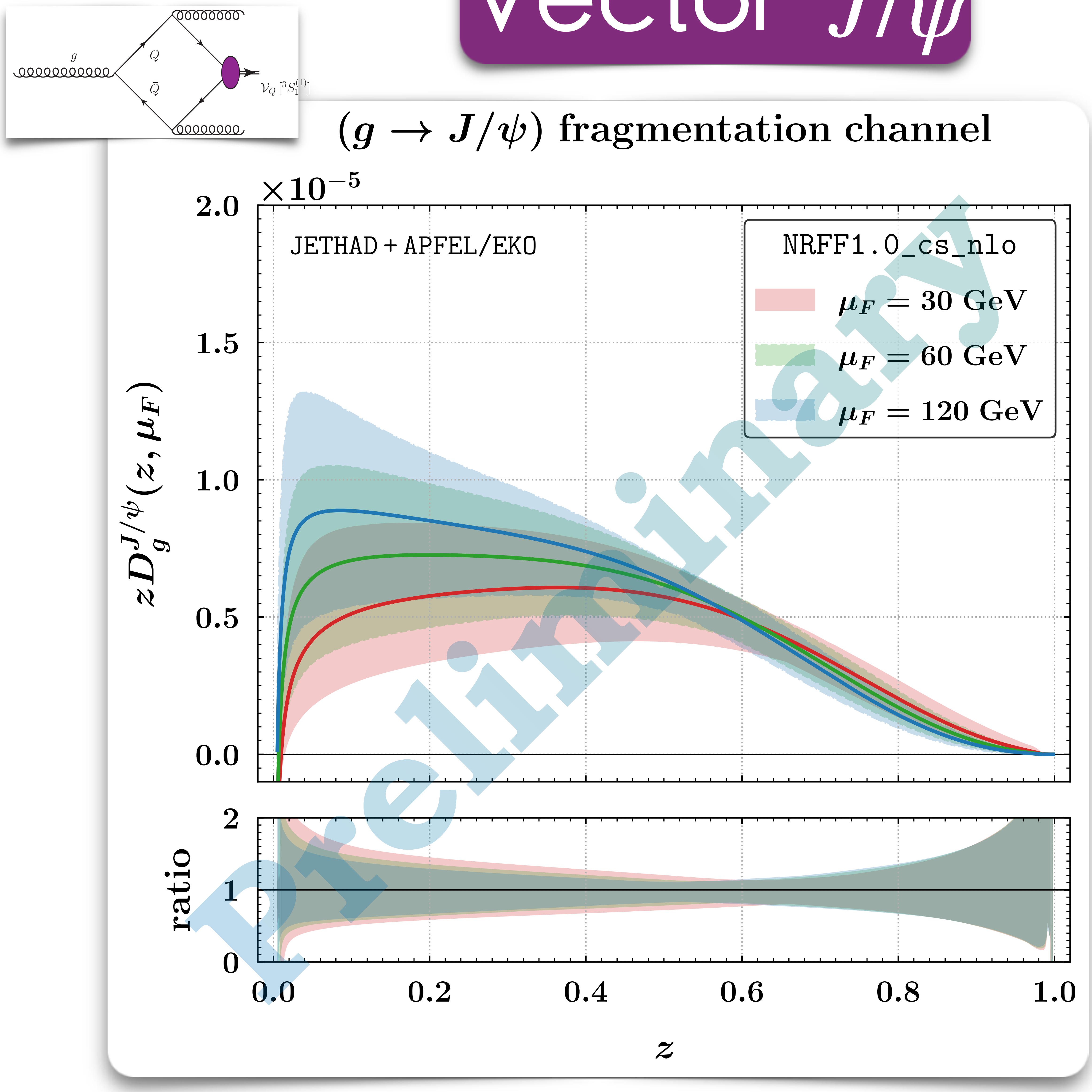




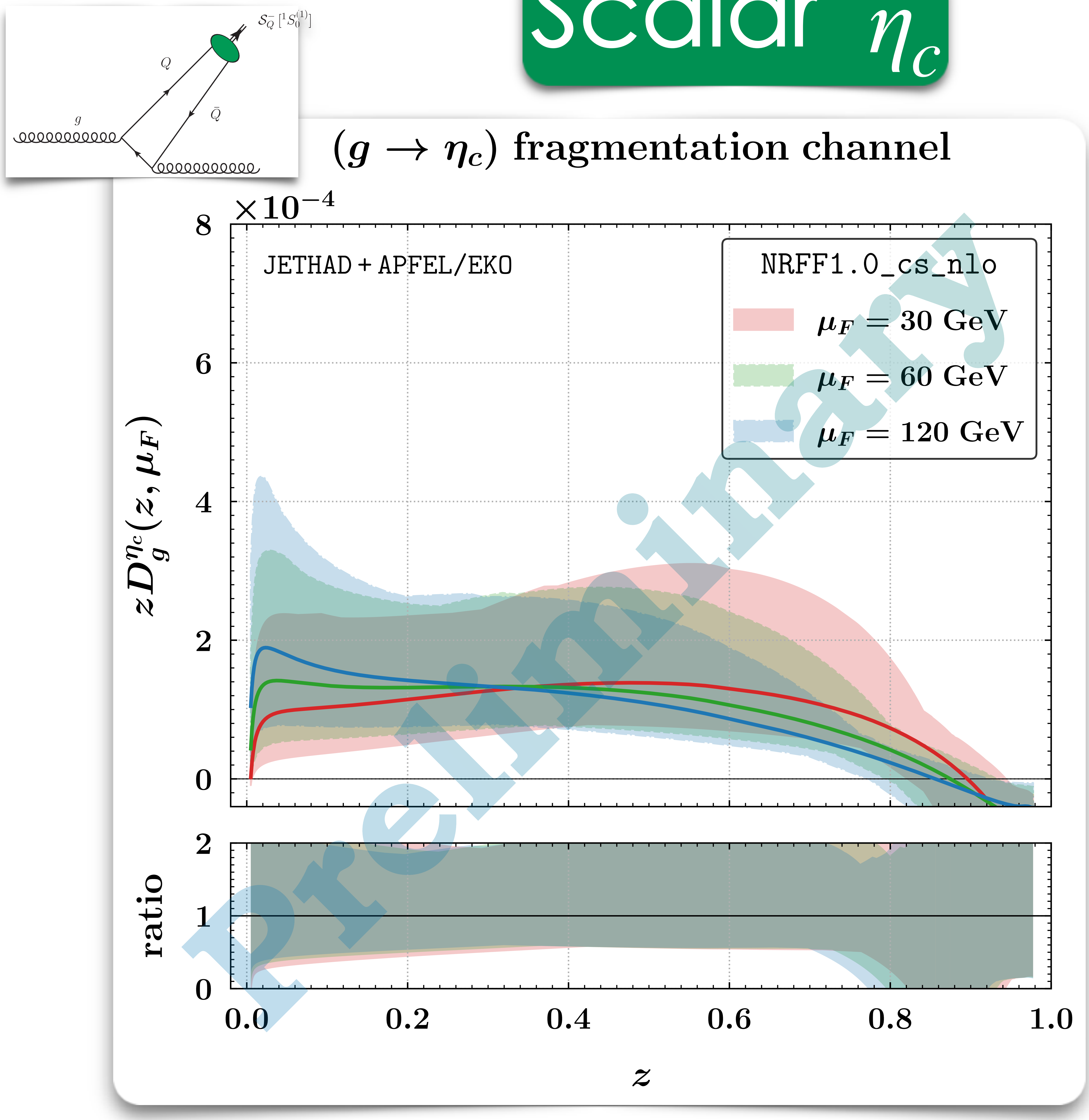
[F. G. C., in preparation]

NRFF1.0: Gluon fragmentation to charmonia

Vector J/ψ



Scalar η_c



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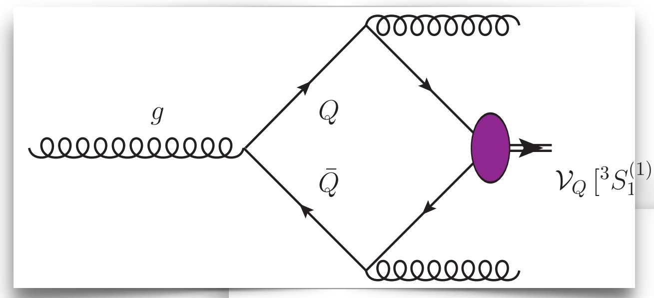
NRFF1.0: Gluon fragmentation to bottomonia



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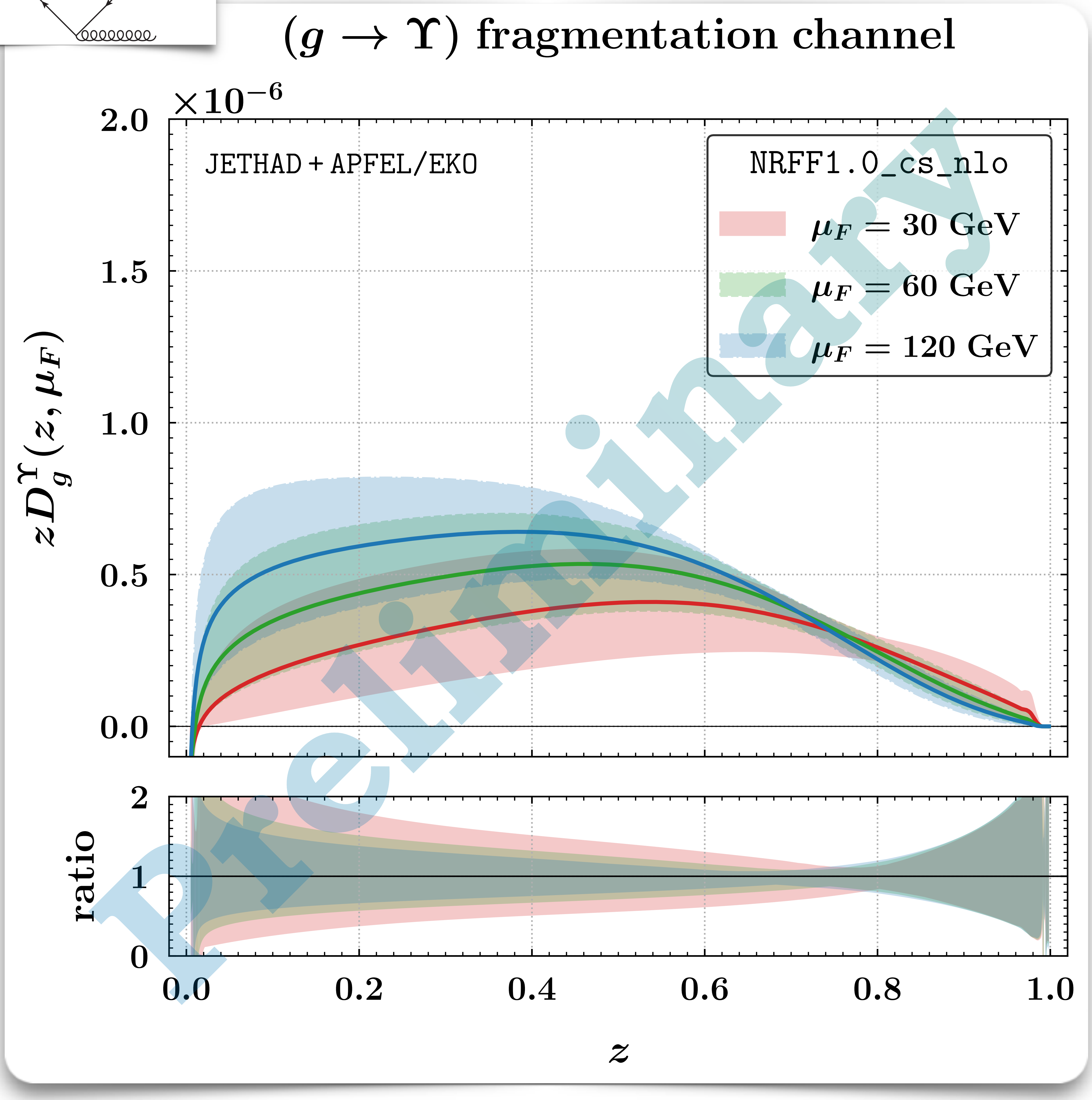

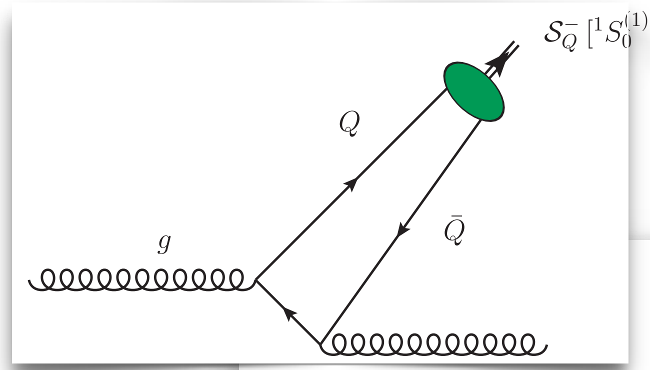

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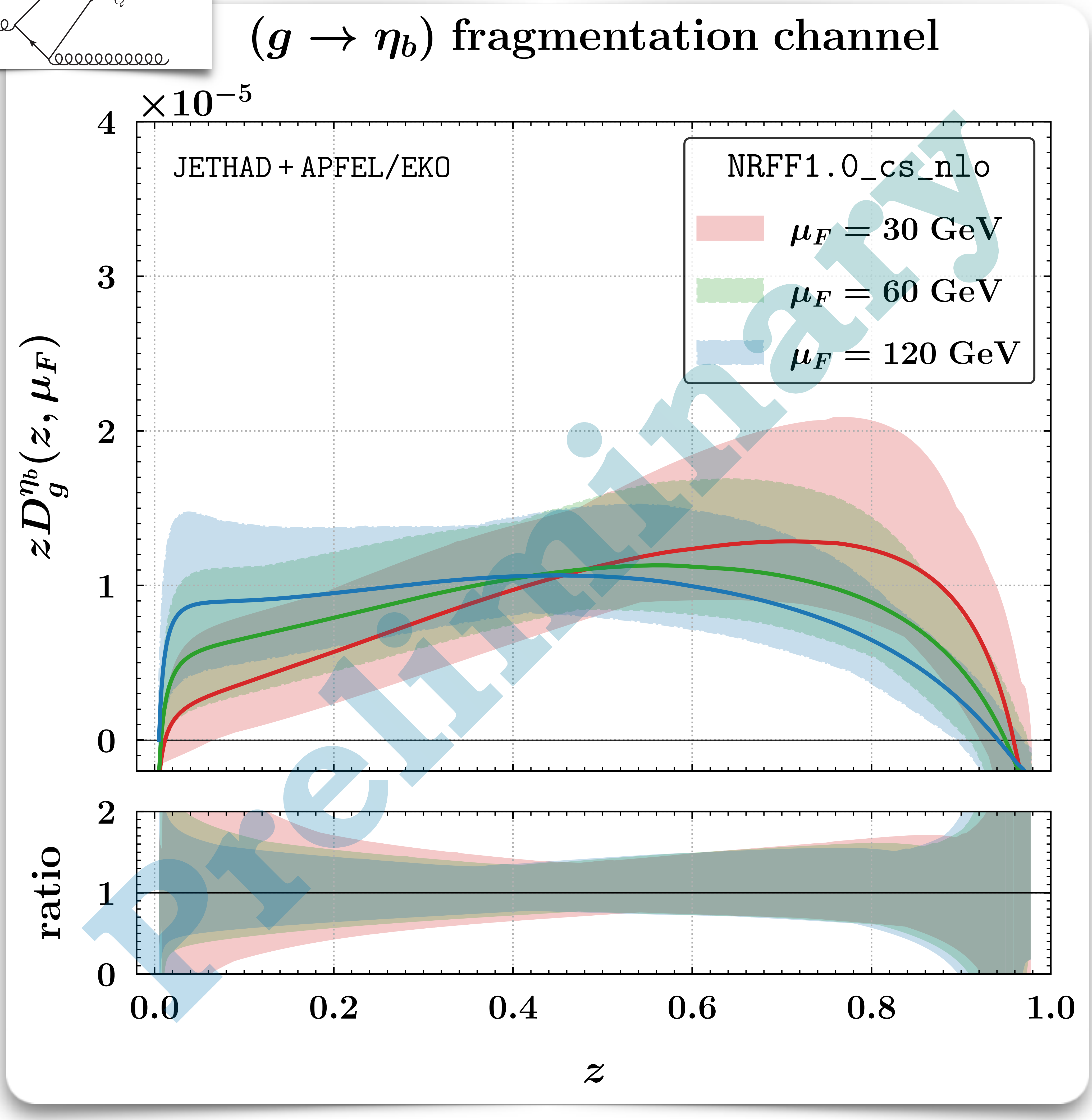
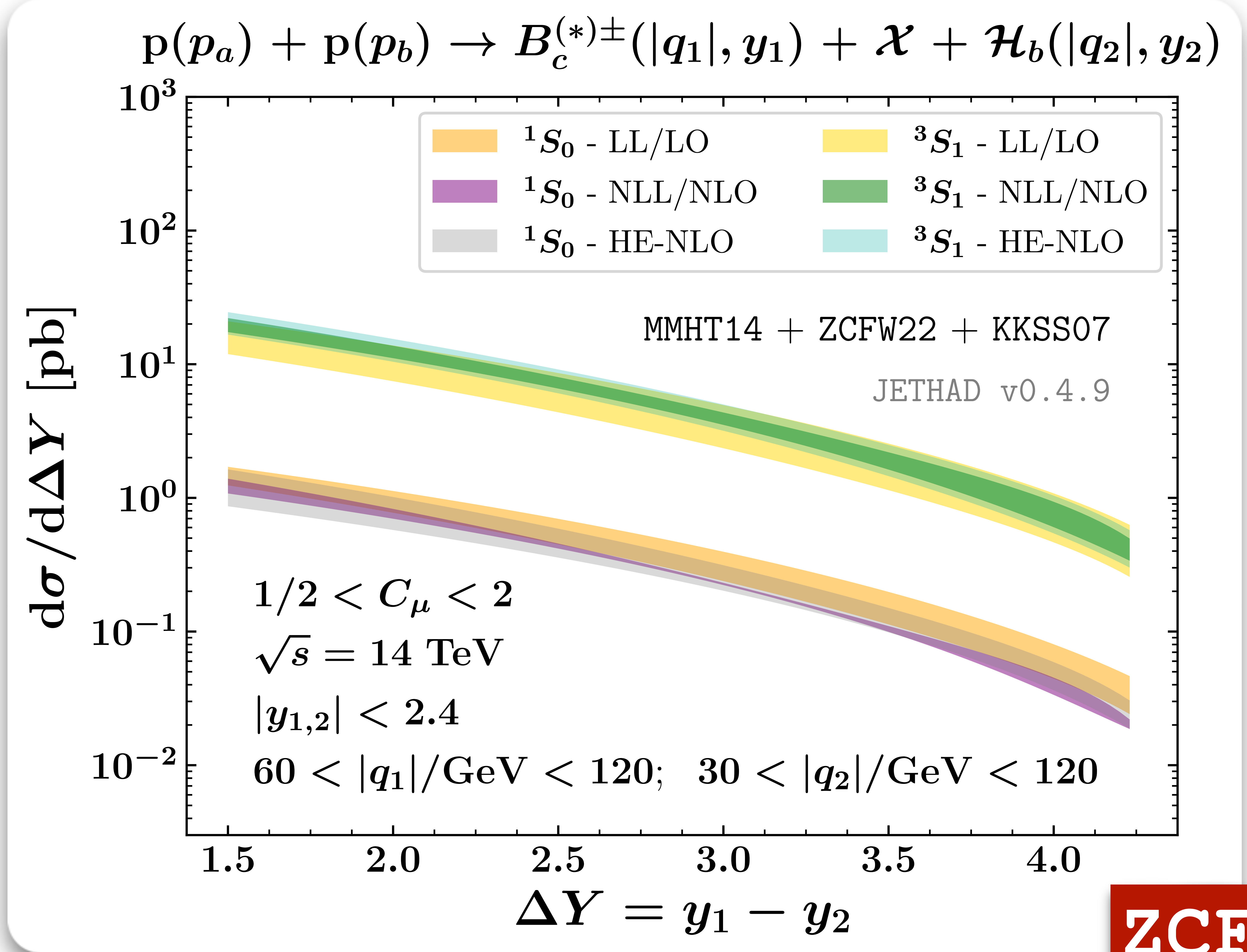


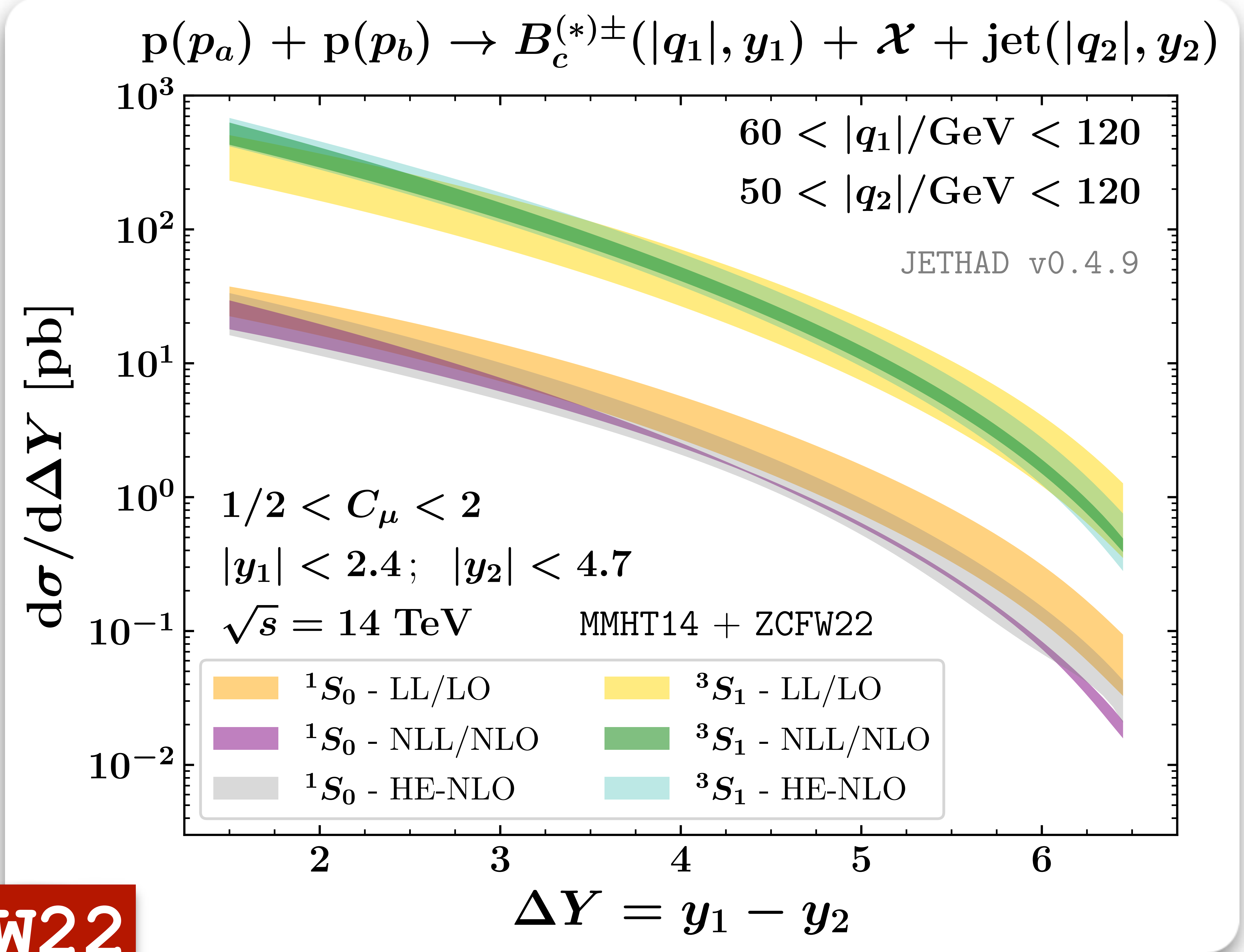
[F. G. C., in preparation]

Charmed B-mesons + jet at the HL-LHC

$B_c^{\pm}(^1S_0)$ + b-hadron



$B_c^{\pm}(^3S_1)$ + jet



ZCFW22

[F. G. C., Phys. Lett. B 835 (2022) 137554]

¿ What is the exotic matter ?

- Barions & mesons → composite states → $|q_1 q_2 q_3\rangle$ & $|q_1 \bar{q}_2\rangle$
- Ordinary hadrons ← simplest valence-quark colorless states
- QCD color neutrality → tetraquarks, pentaquarks, hybrids allowed
- Exotic hadrons ← different quantum numbers than ordinary hadrons
- First discovery of an exotic hadron at Belle (🇯🇵) in 2003 → $X(3872)$

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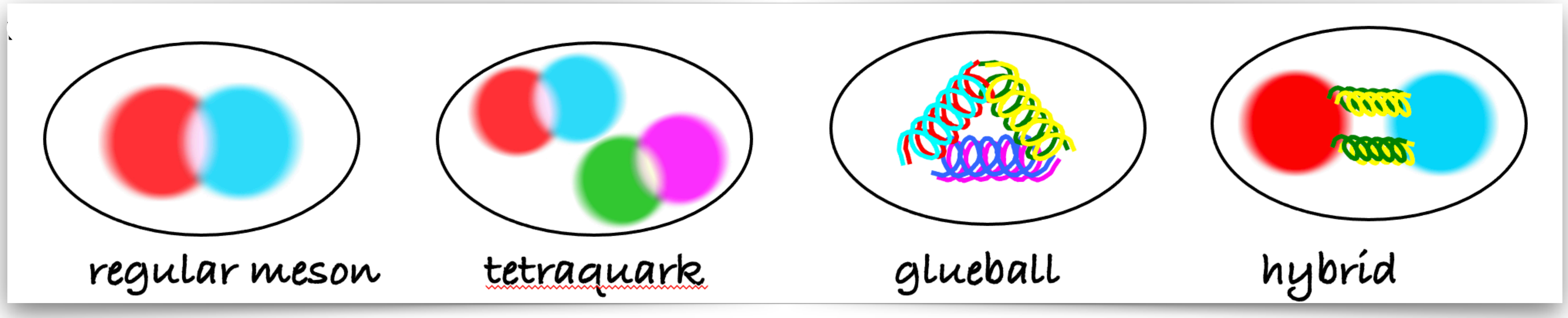
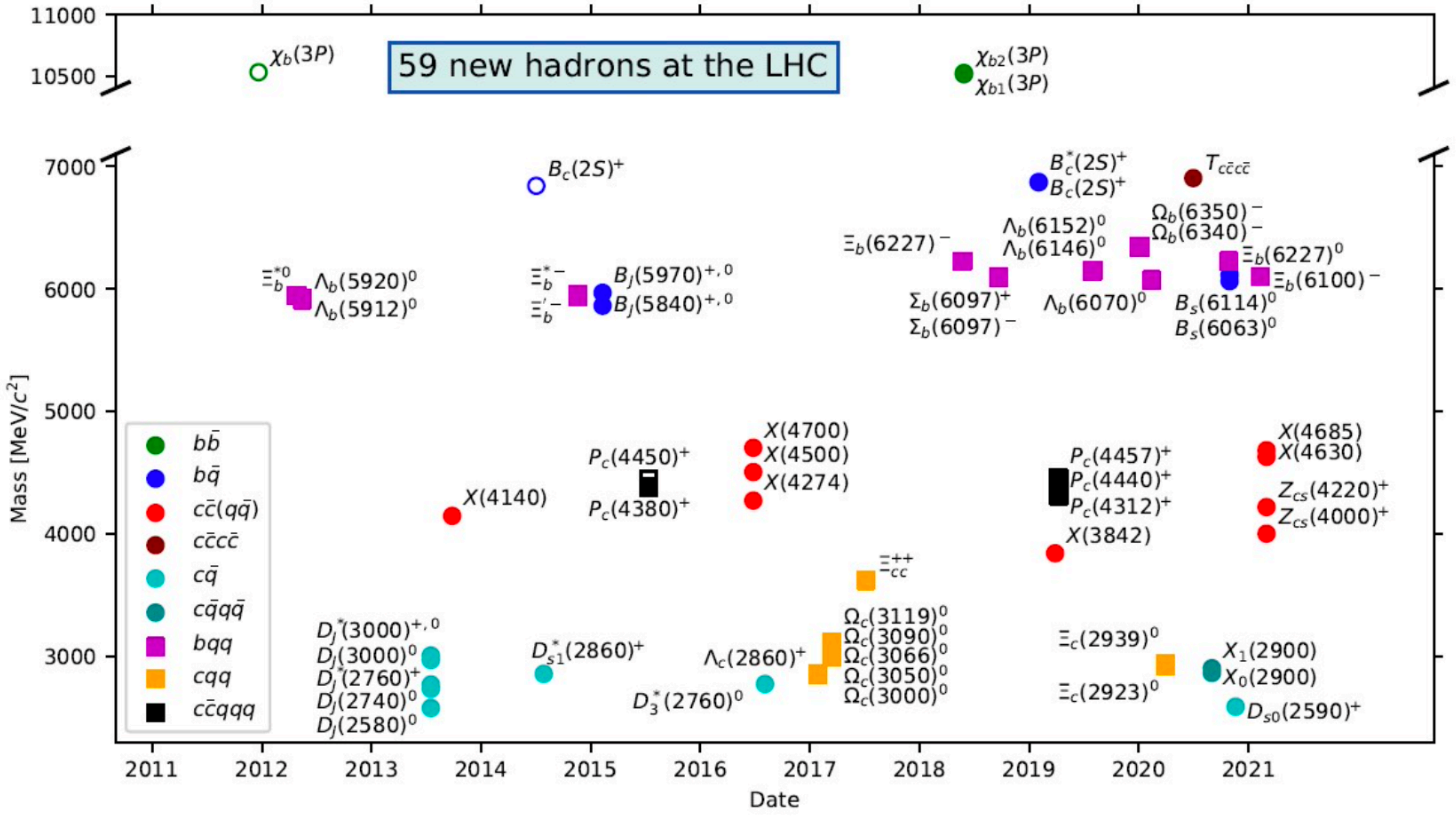
Hadron Spectroscopy



Exotic hadrons at the LHC

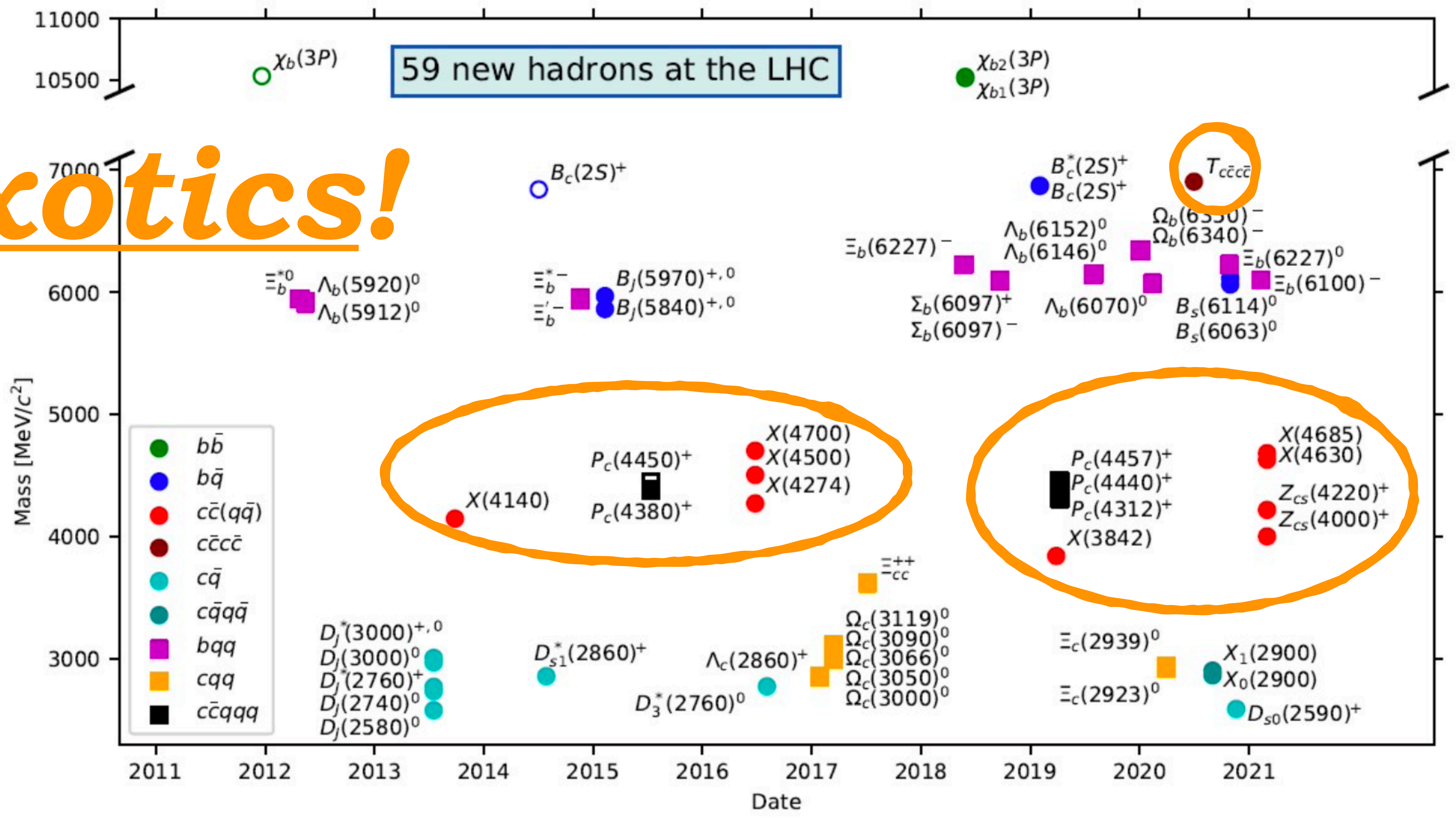


The full list of new hadrons found at the LHC, organised by year of discovery (horizontal axis) and particle mass (vertical axis). The colours and shapes denote the quark content of these states. (Image: LHCb/CERN)

https://home.cern/news/news/physics/59-new-hadrons-and-

Exotic hadrons at the LHC

¡Exotics!



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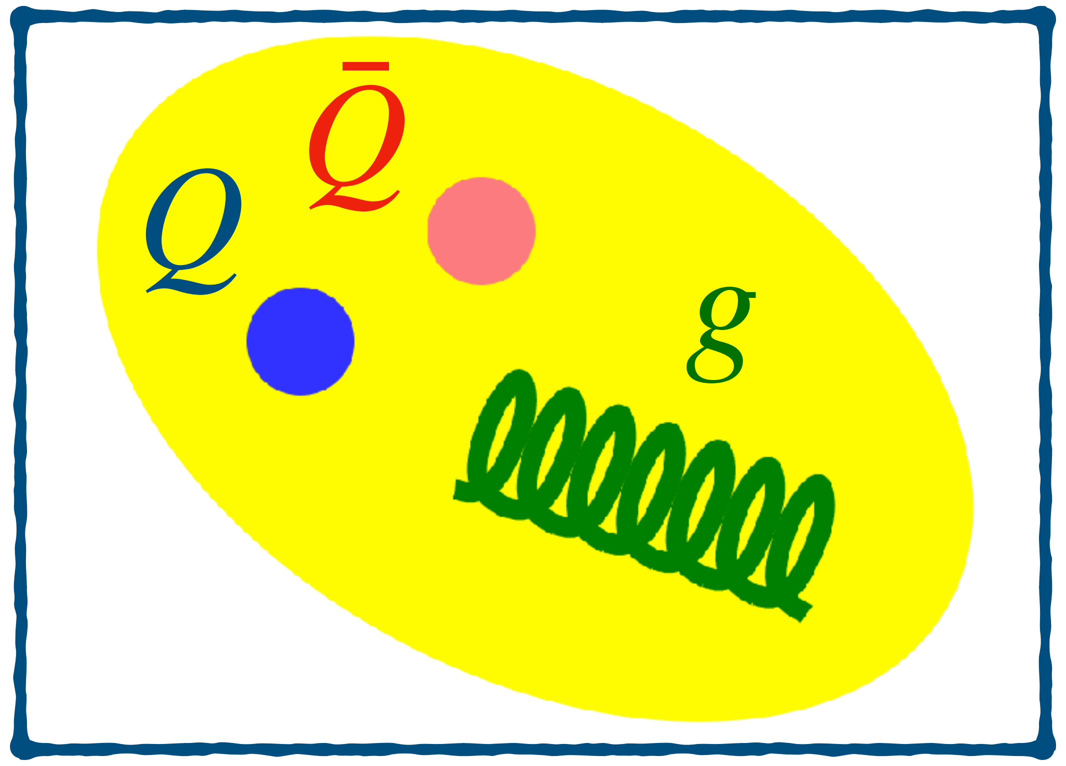
Interpretation of exotic states

Meson + continuum

Interpretation of exotic states

Meson + continuum

Hybrid



Interpretation of exotic states

Meson + continuum

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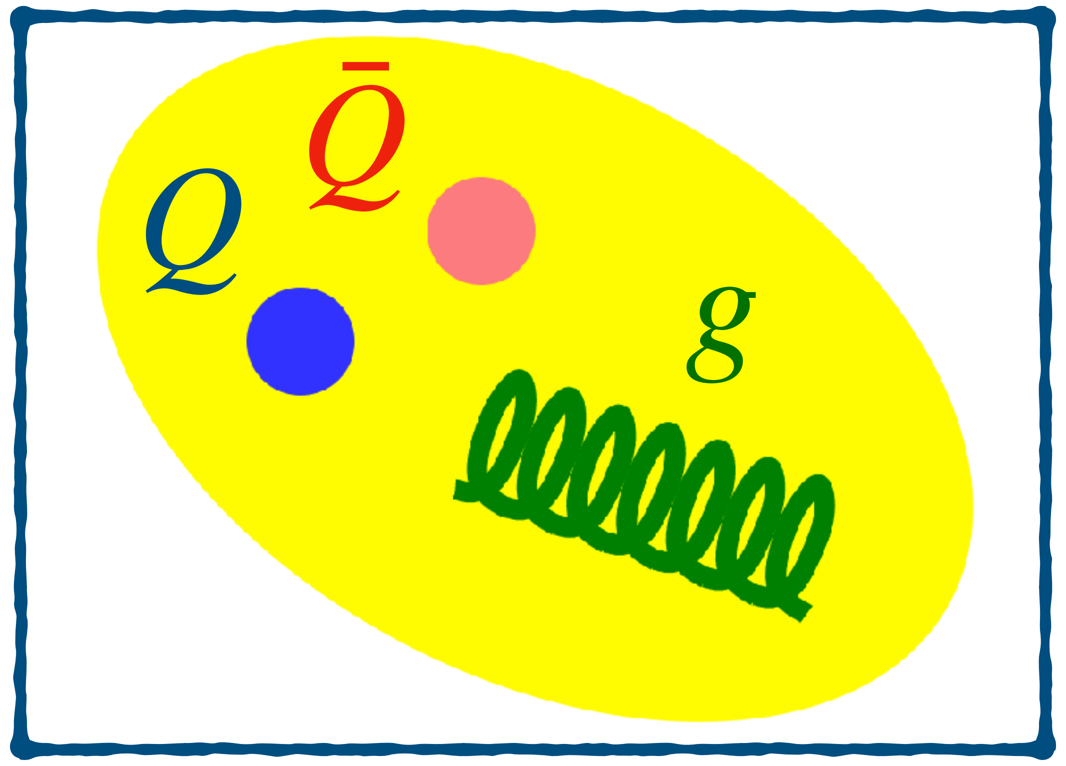
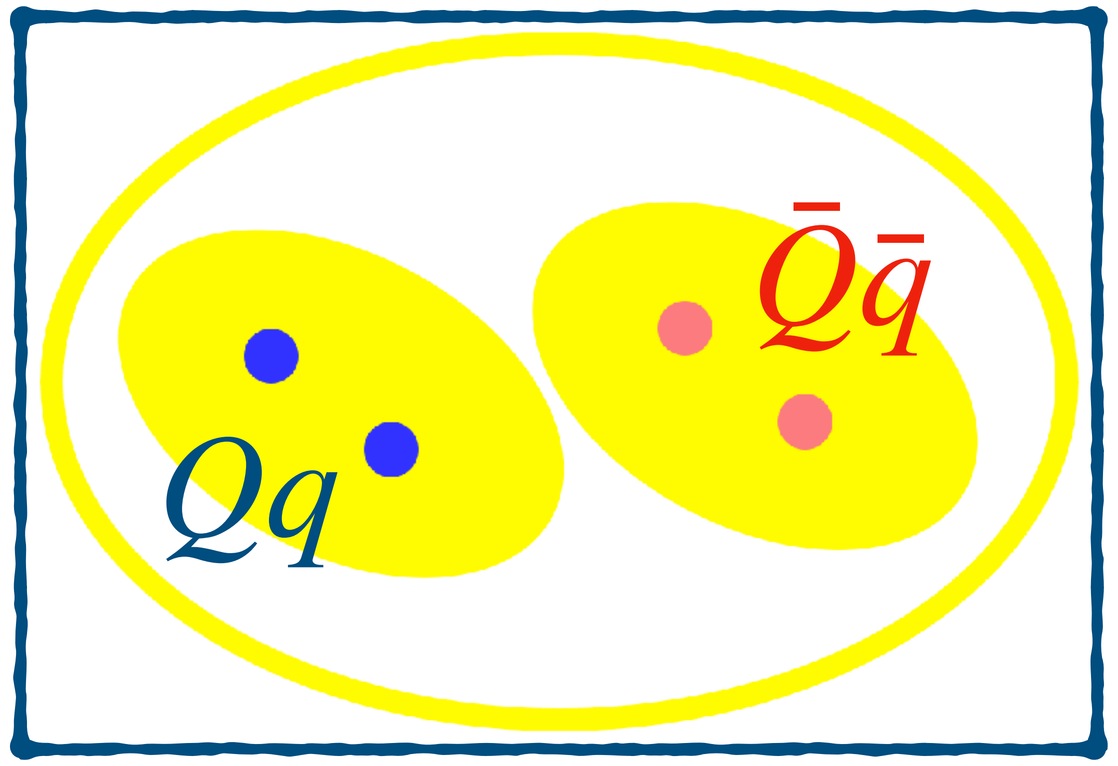


Diquark + antidiquark



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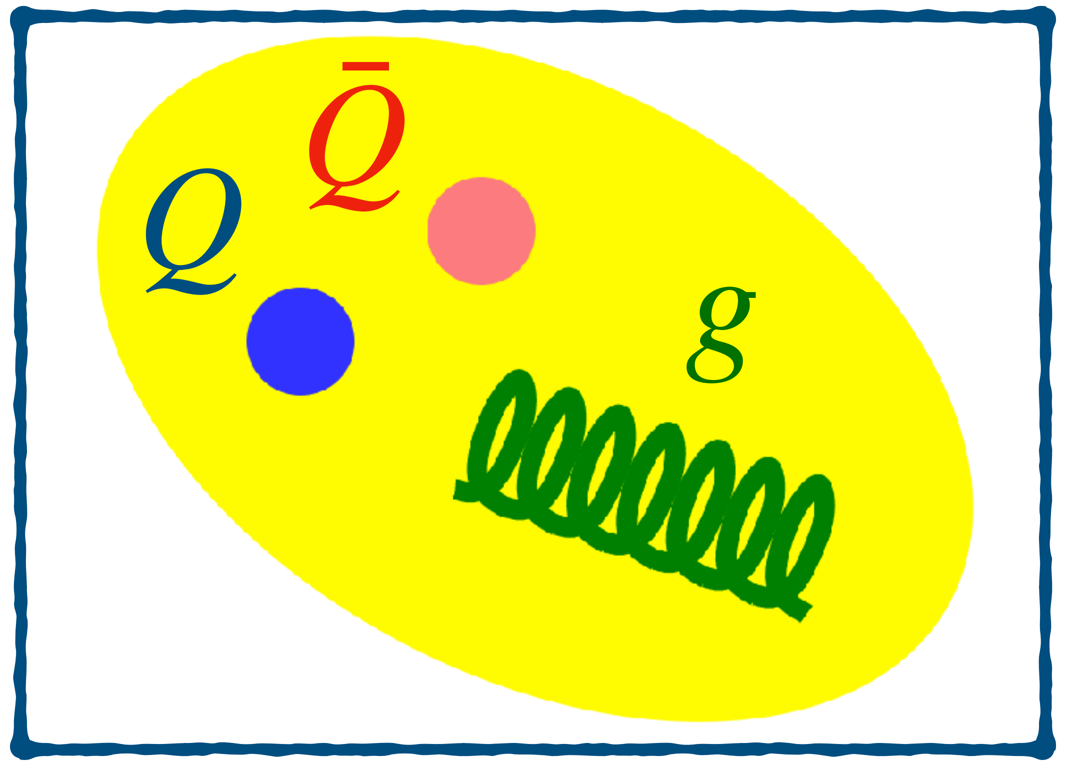

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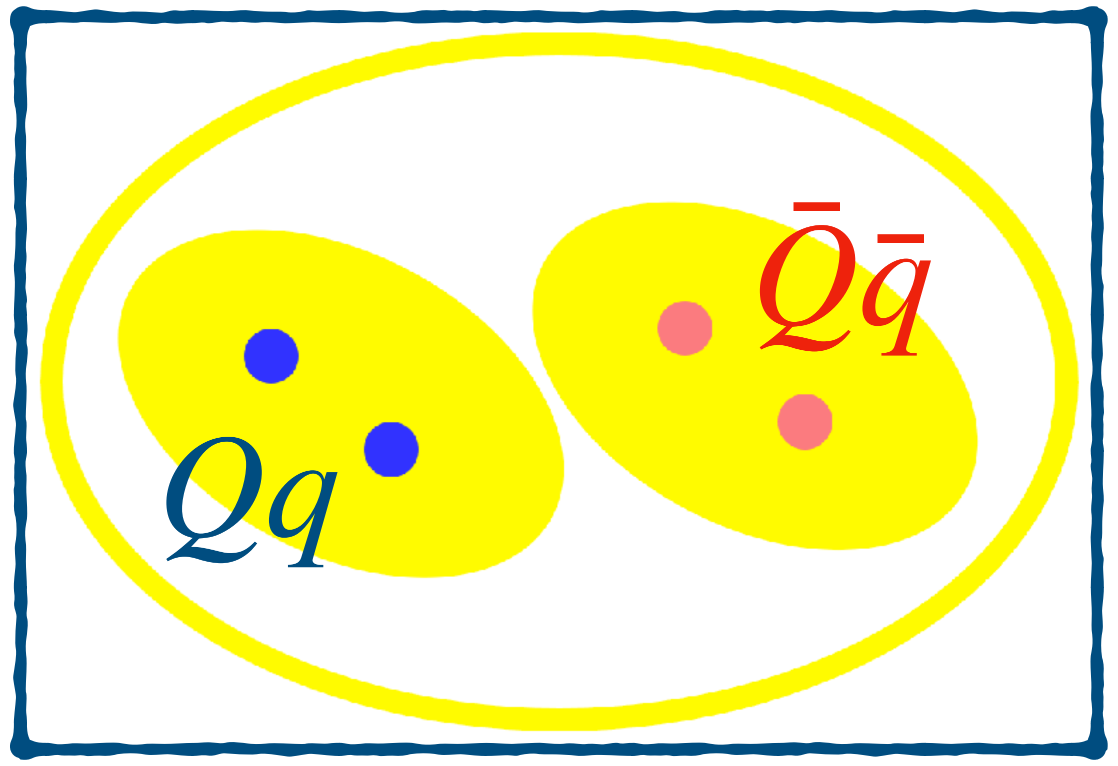
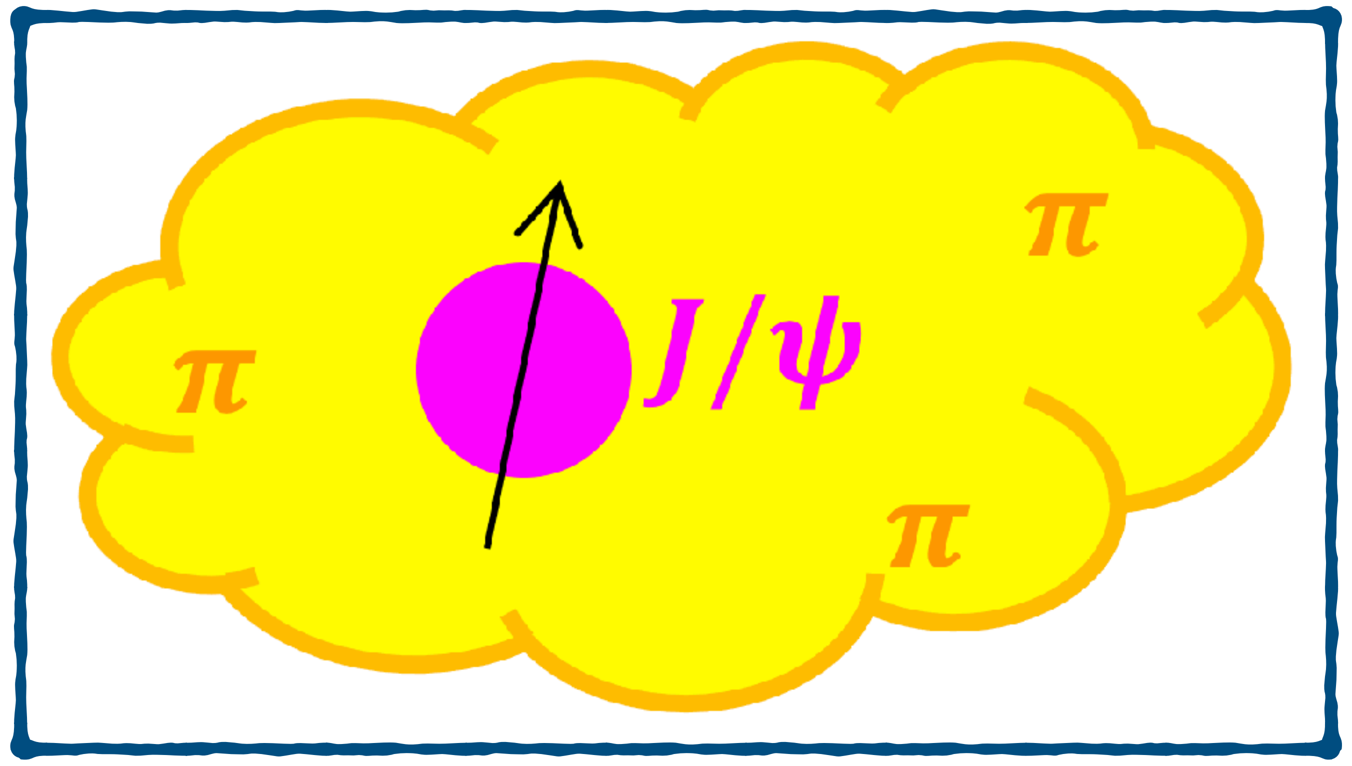


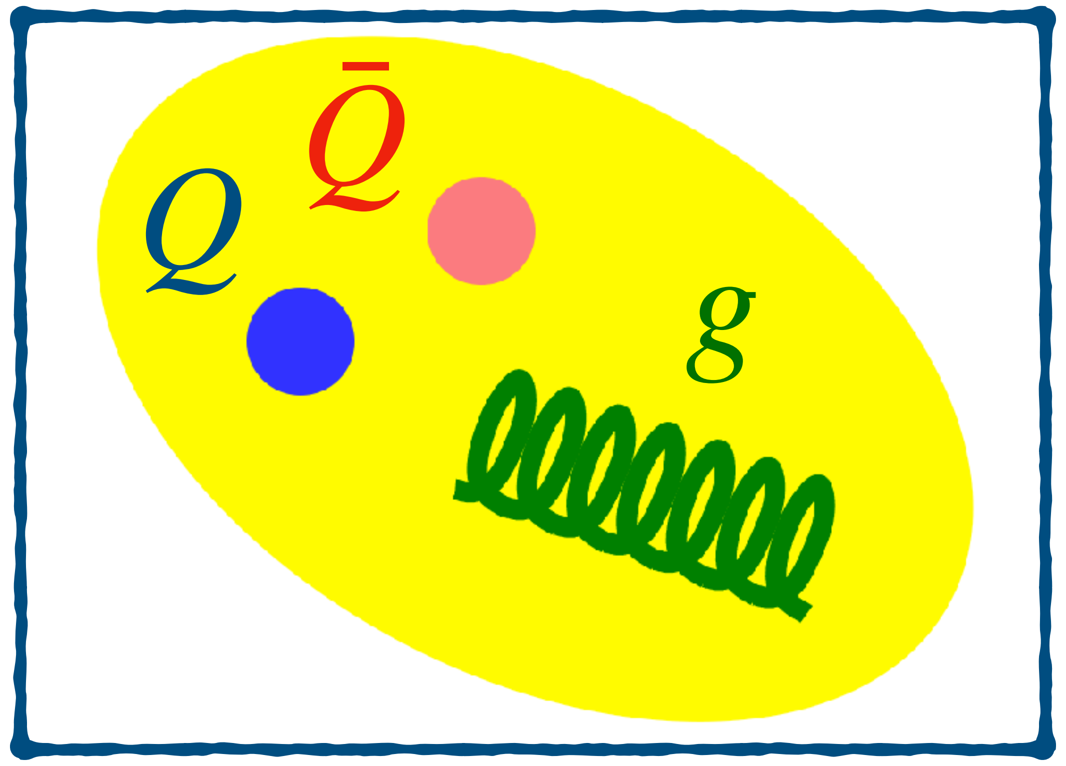


Hadroquarkonium

Interpretation of exotic states

Meson + continuum

Hybrid



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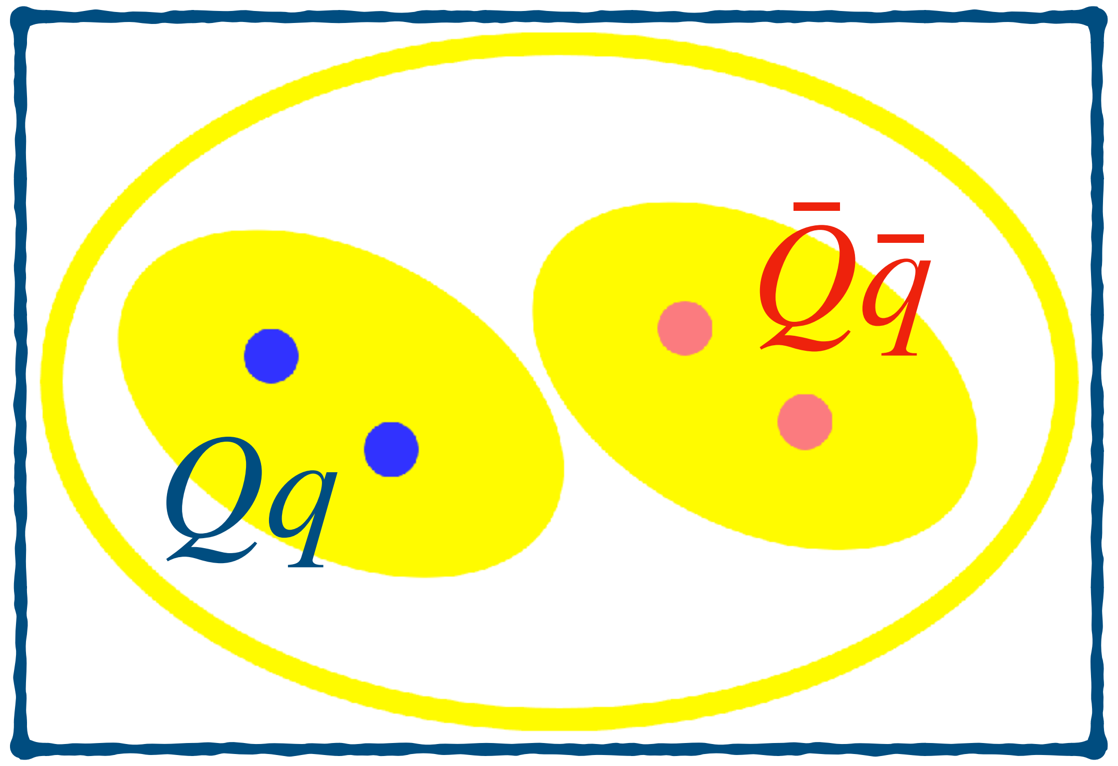

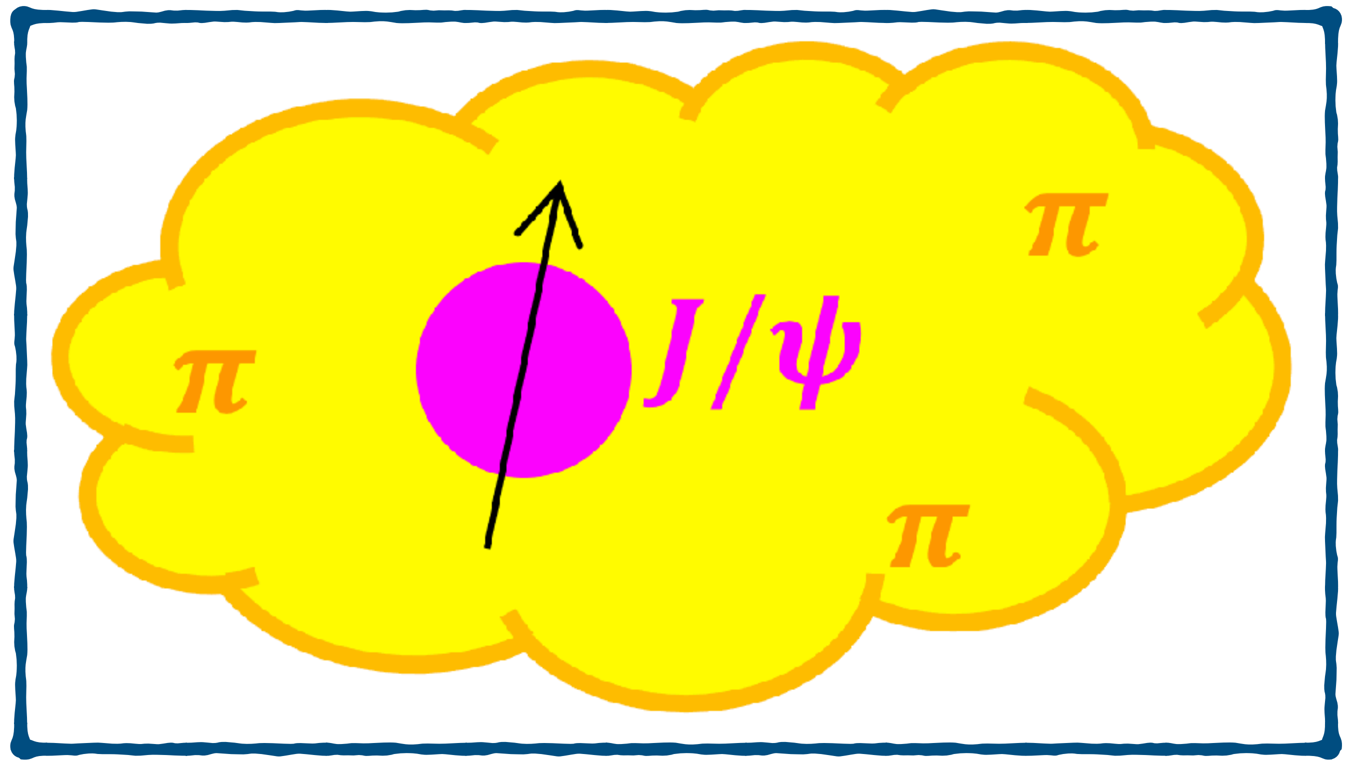

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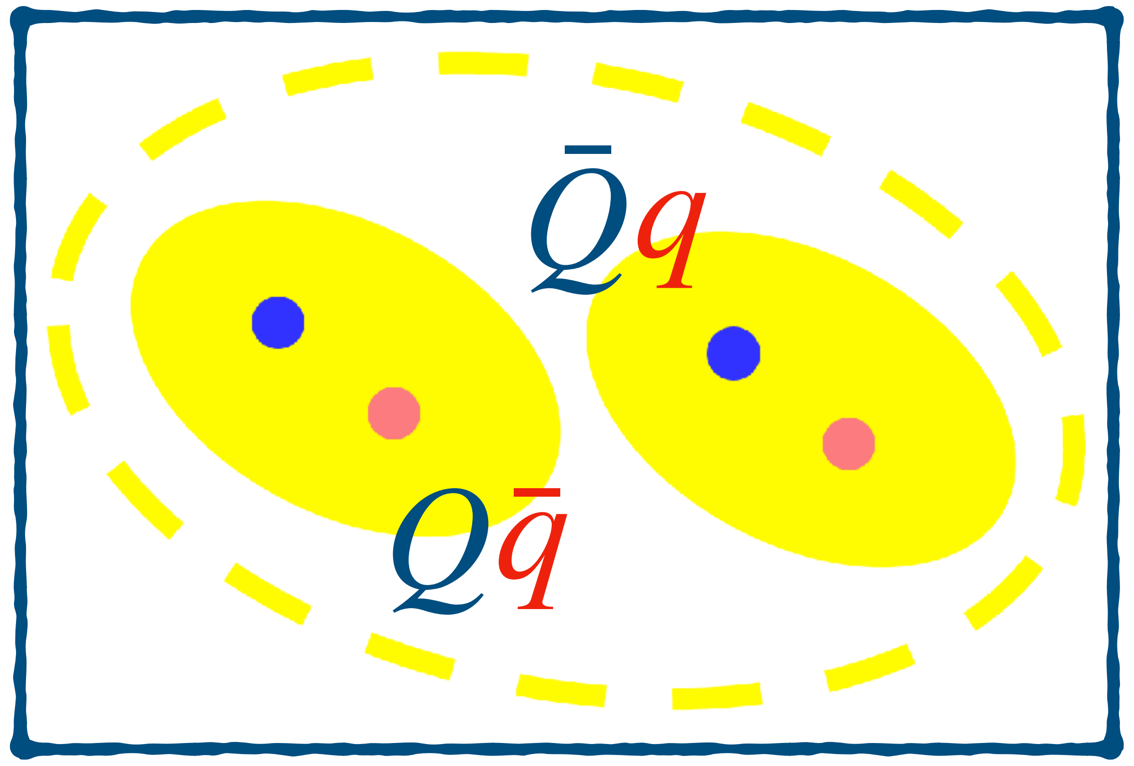
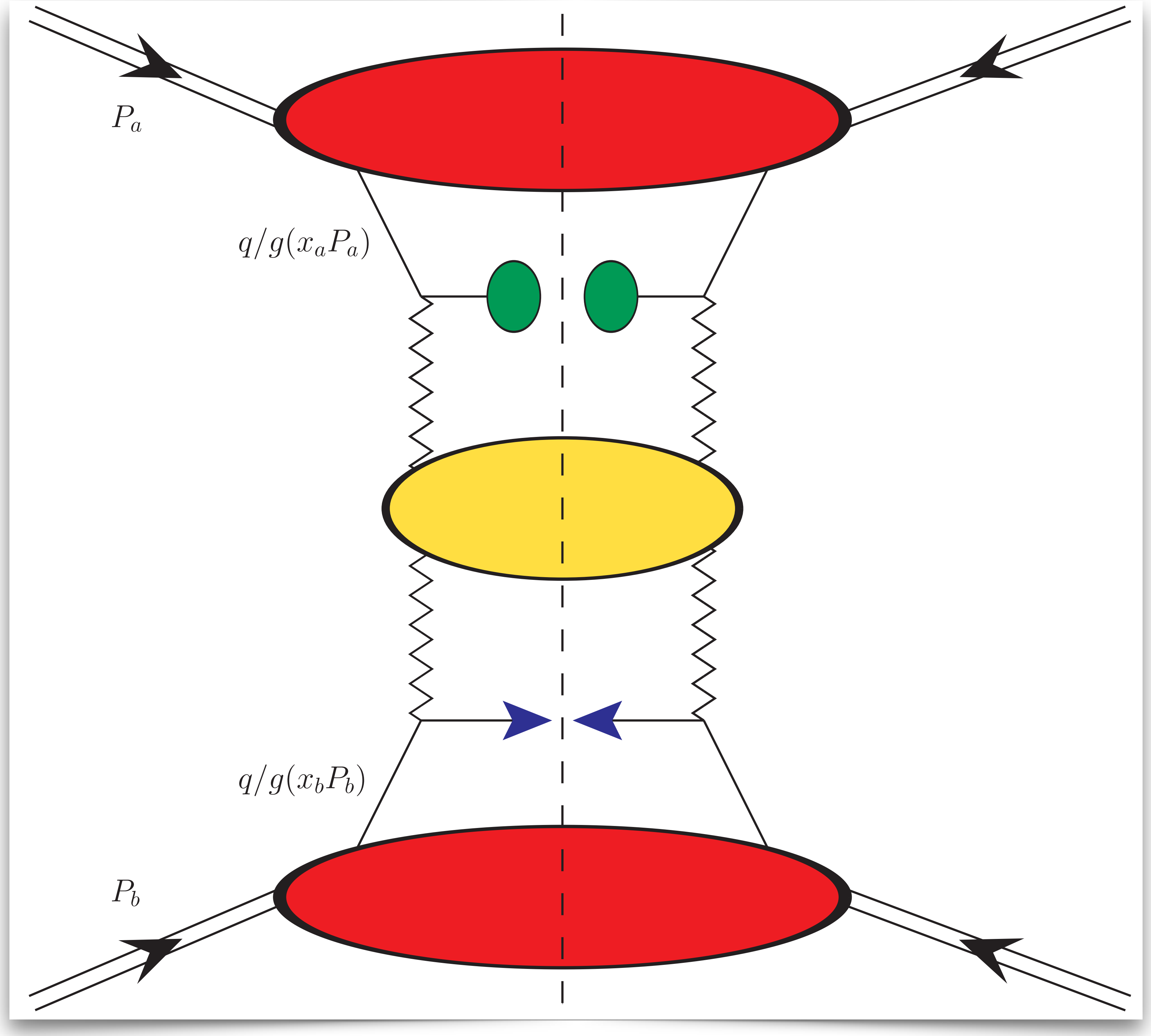
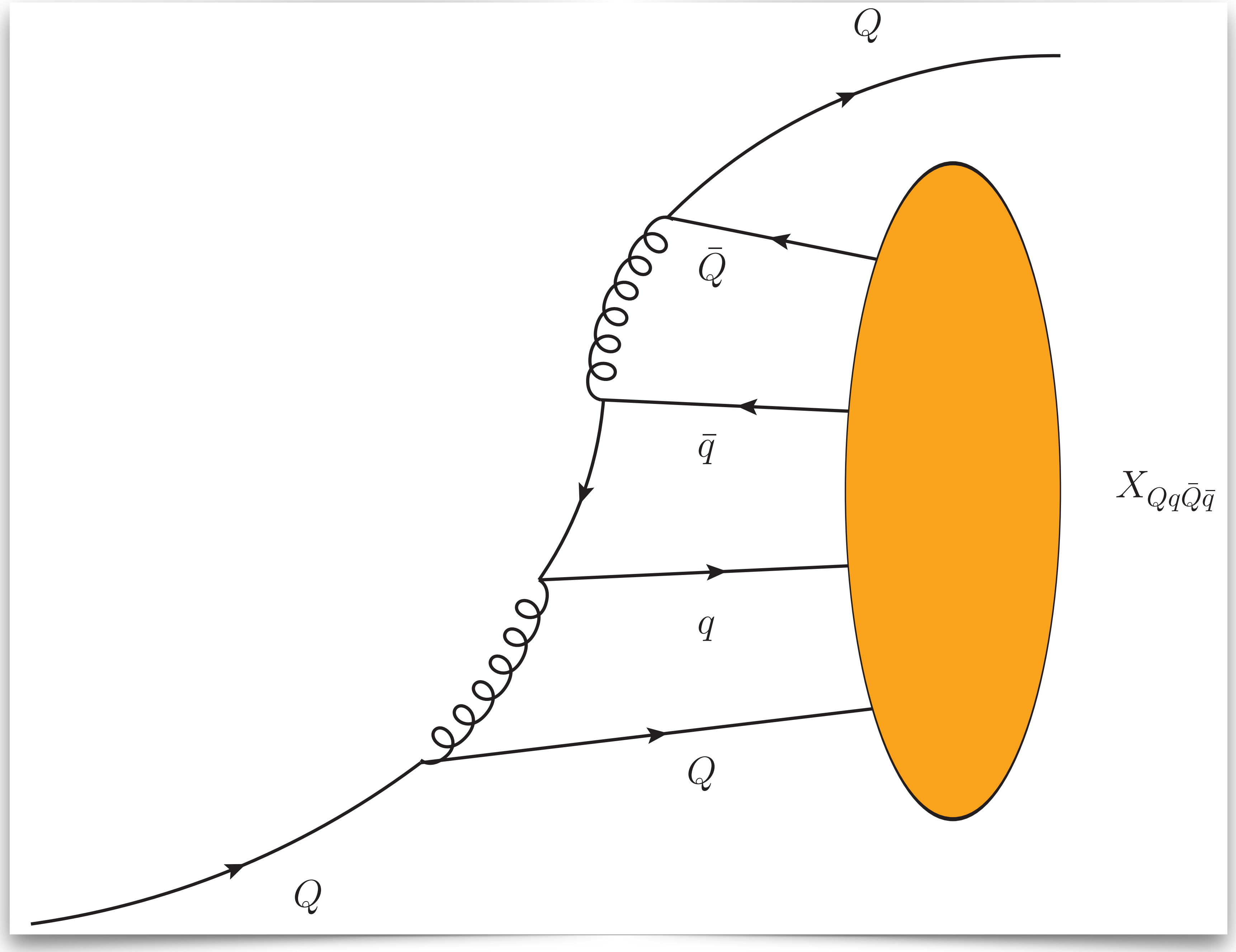


Molecule of mesons

Heavy-light tetraquark from single-parton fragmentation

¡ *Let us consider heavy-light $X_{Qq\bar{Q}\bar{q}}$ tetraquarks at large p_T* → *single-parton* ***fragmentation*** !





🔗 [F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406]

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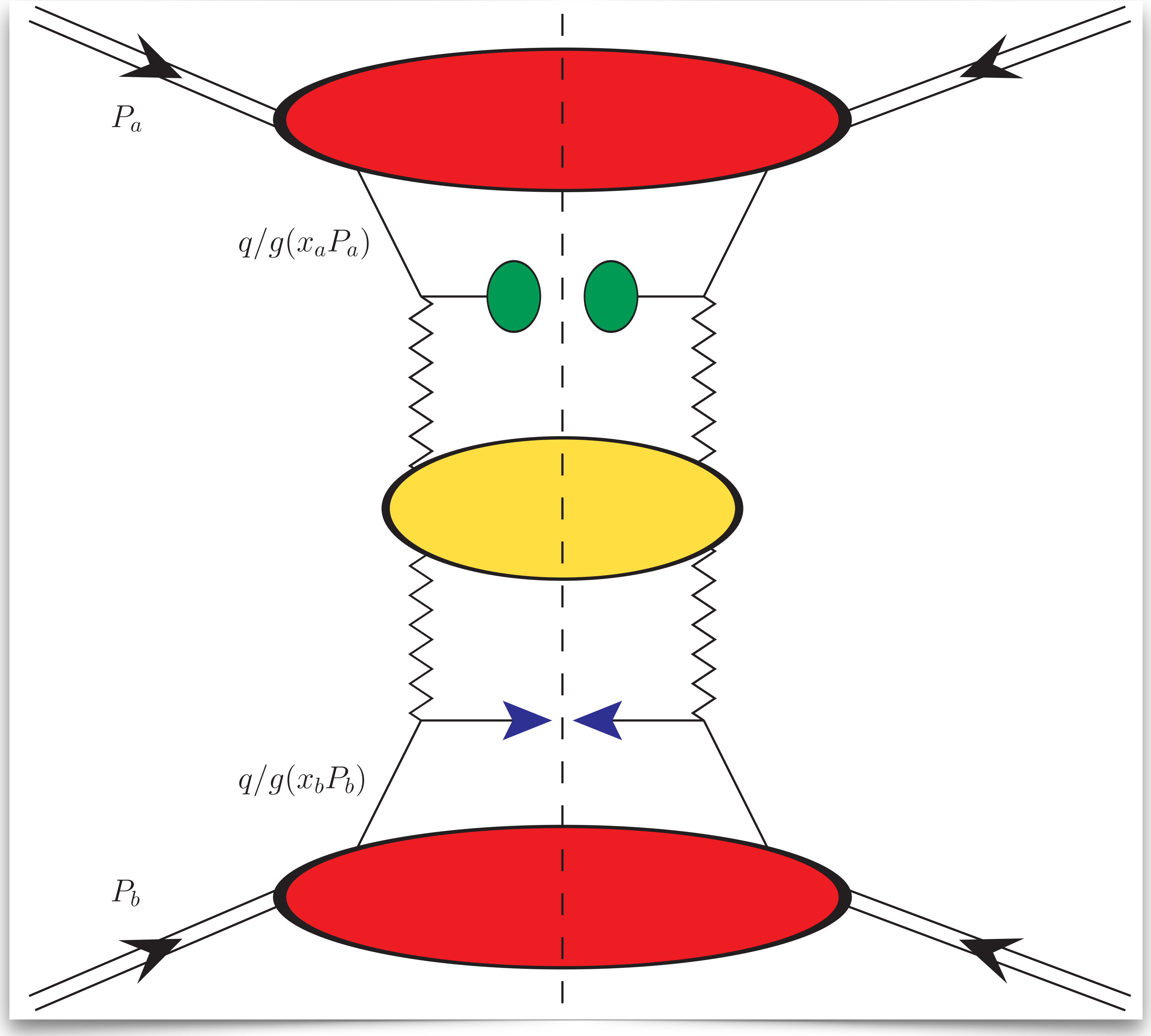
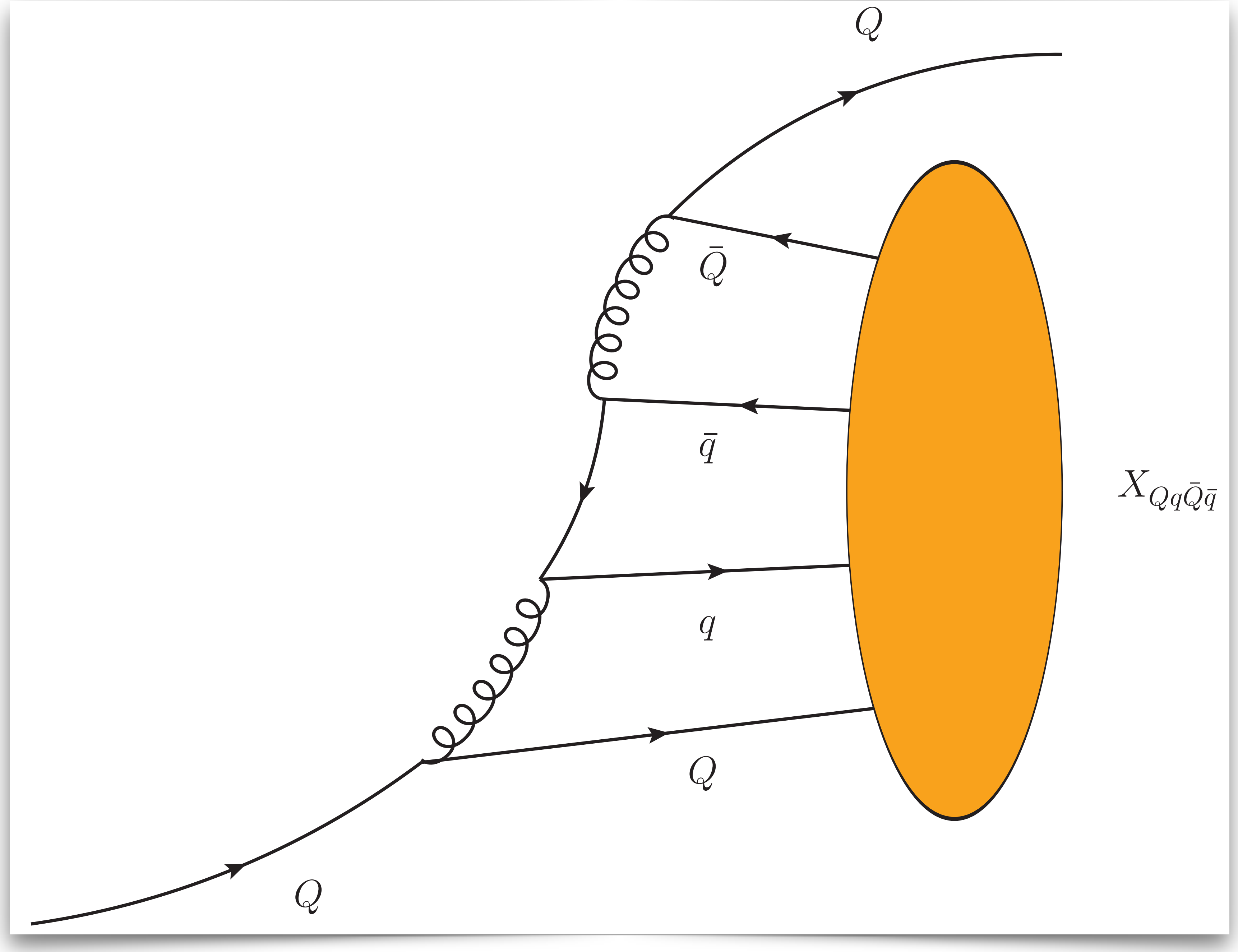




[F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406]

TQHL1.0 FFs: $(Q \rightarrow X_{Qq\bar{Q}\bar{q}}) \otimes$ **APFEL++**

$[\mu_0 = m_X + m_Q]$

S-wave

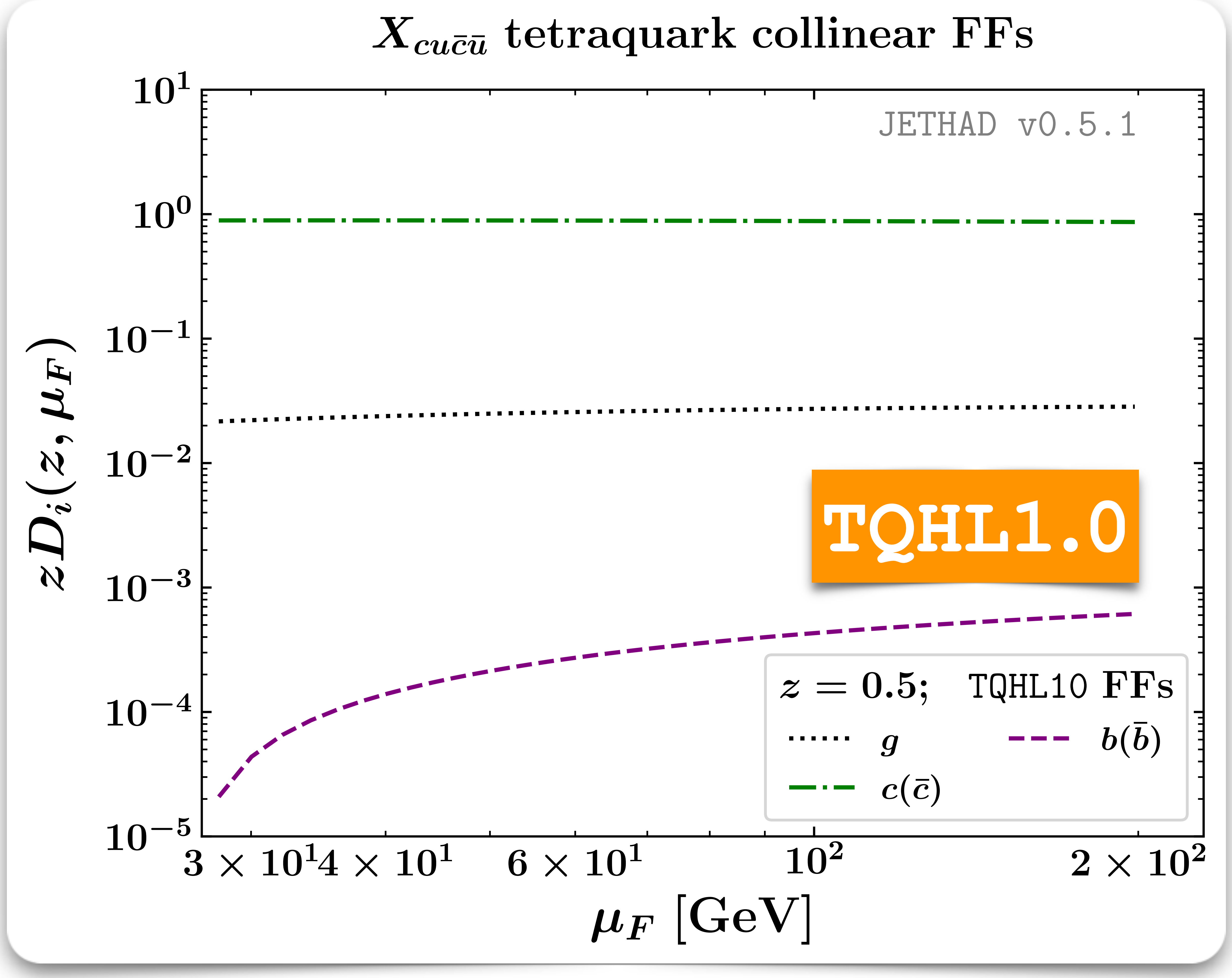
$$D_Q^X(z,\mu_0) = N \frac{z \times \Sigma_{\text{spin}} \Gamma\bar{\Gamma}}{(m_X^2 - 2m_Q^2 + 2p\cdot s')^2}$$
$$= N \frac{z \times \Sigma_{\text{spin}} \Gamma\bar{\Gamma}}{[m_X^2 - (m_Q^2 + \langle p_T^2\rangle)(1 + z - \frac{1}{1-z})]^2}$$

(LO) [S. M. Moosavi Nejad, Phys. Rev. D 05 (2022) 3, 034001]

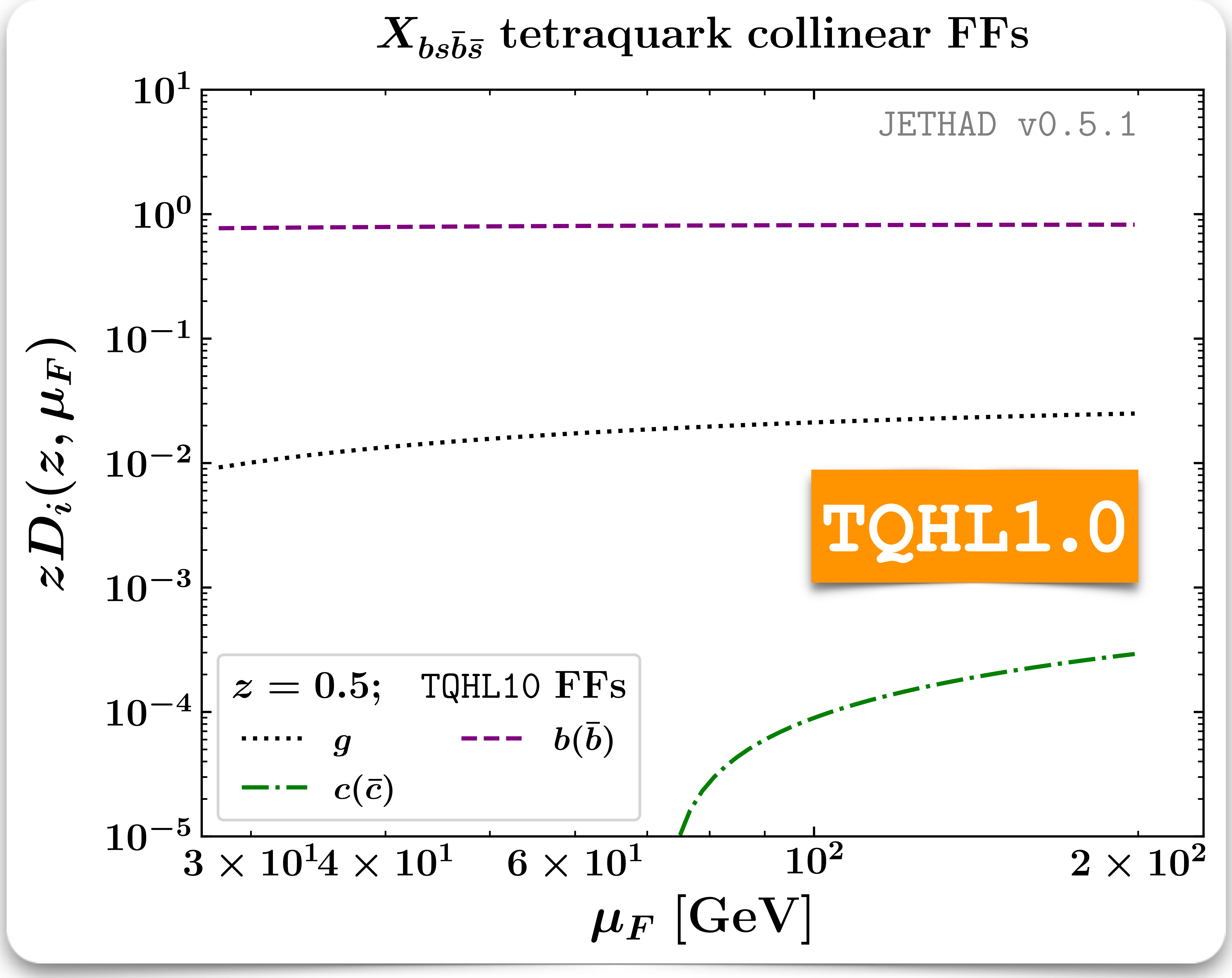
(framework) [M. Suzuki, Phys. Rev. D 33 (1986) 676]

Heavy-light tetraquarks at the HL-LHC

$X_{cu\bar{c}\bar{u}}$ collinear FFs

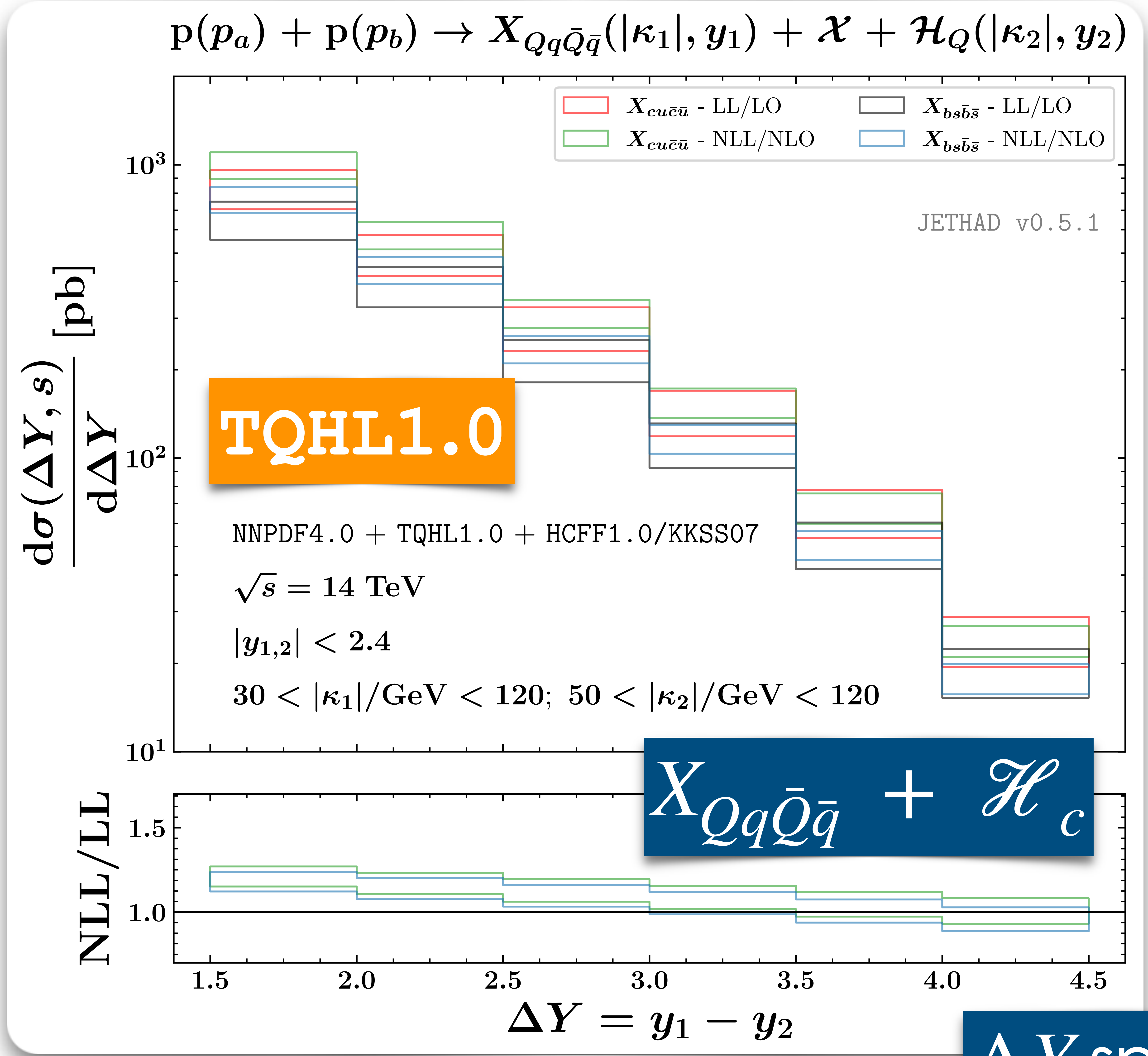


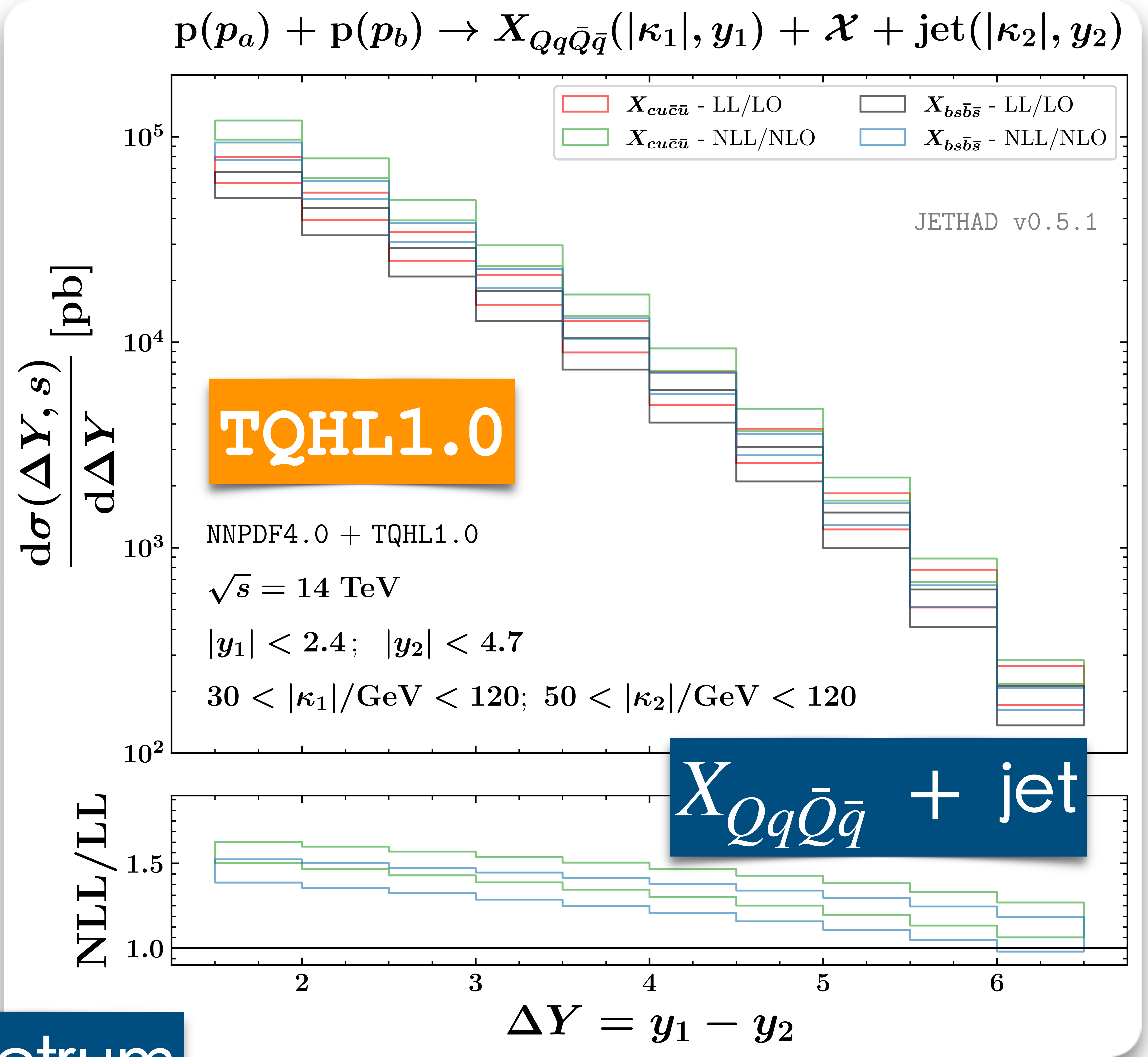
$X_{bs\bar{b}\bar{s}}$ collinear FFs



[F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406]

Heavy-light tetraquarks at the HL-LHC

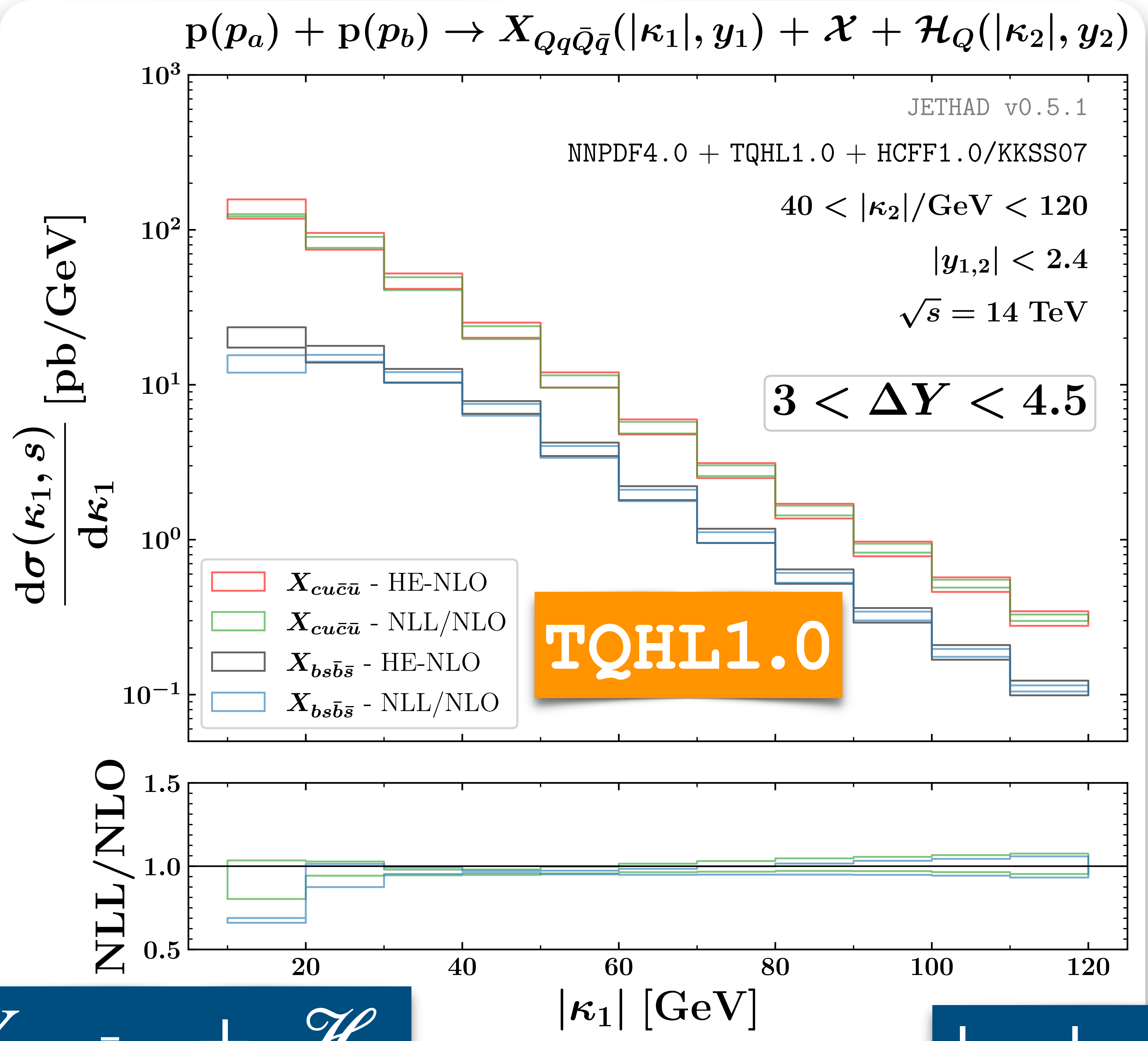


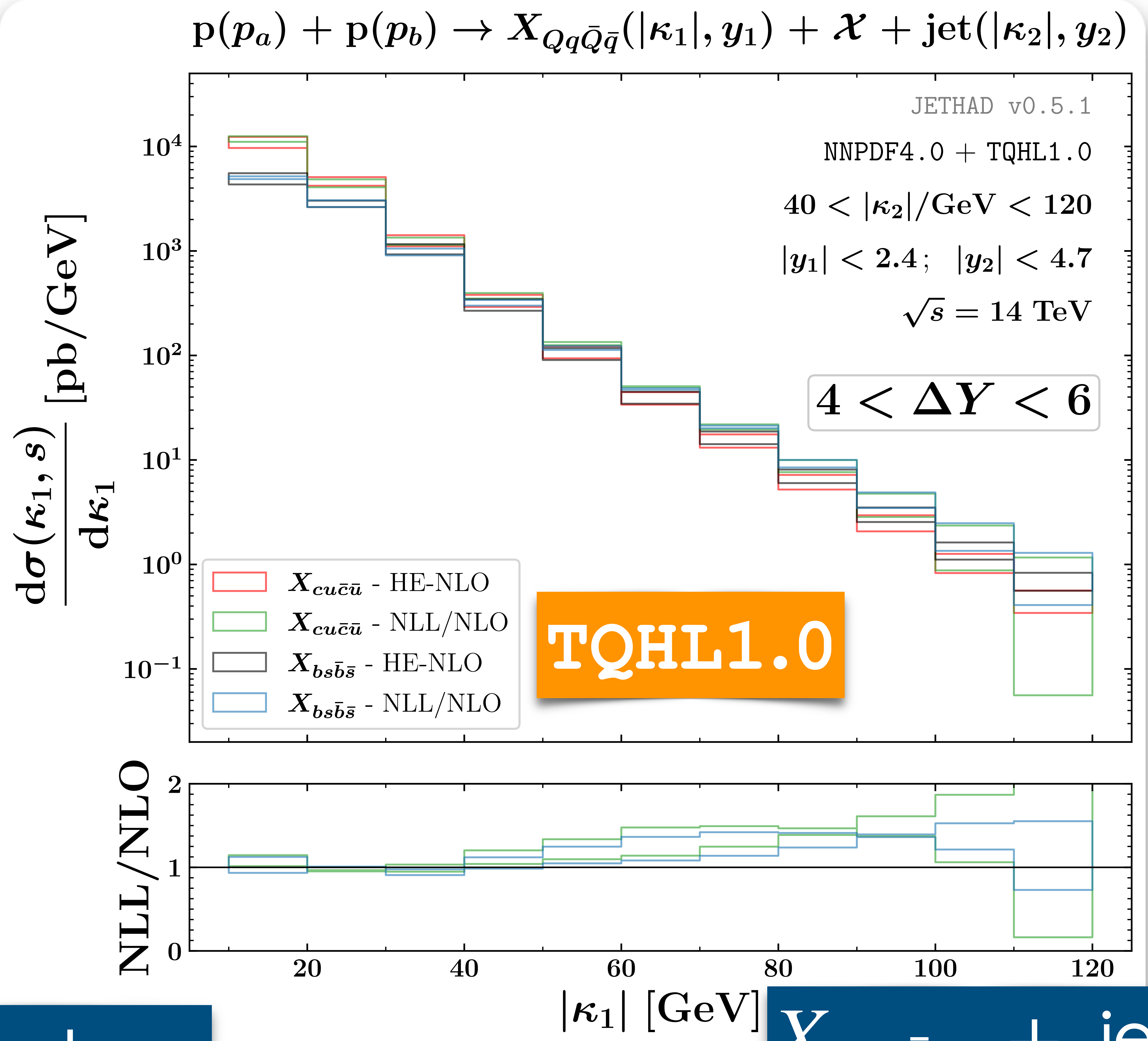


ΔY spectrum

[F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406]

Heavy-light tetraquarks at the HL-LHC





$X_{Qq\bar{Q}\bar{q}} + \mathscr{H}_c$

$|\kappa_1|$ spectrum

$X_{Qq\bar{Q}\bar{q}}$ + jet

[F. G. C., A. Papa, Phys. Lett. B 848 (2024) 138406]

Tetraquark fragmentation from a simpler HF-NRevo

Phys. Lett. B 848 (2024) 138406

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Letter

A high-energy QCD portal to exotic matter: Heavy-light tetraquarks at the HL-LHC

Francesco Giovanni Celiberto [a,*], Alessandro Papa [b,c]

[a] Universidad de Alcalá (UAH), Departamento de Física y Matemáticas, Campus Universitario, Alcalá de Henares, E-28805, Madrid, Spain
[b] Dipartimento di Fisica, Università della Calabria, Ponte Pietro Bucci, Cubo 31C, Arcavacata di Rende, I-87036, Cosenza, Italy
[c] INFN, Gruppo Collegato di Cosenza, Ponte Pietro Bucci, Cubo 31C, Arcavacata di Rende, I-87036, Cosenza, Italy

A R T I C L E I N F O

Editor: B. Grinstein

Dataset link: https://github.com/FGCeliberto/Collinear_FFs/

Keywords:
High-energy resummation
HL-LHC phenomenology
Heavy-light tetraquarks
Hidden flavor
Exotic matter

A B S T R A C T

By taking advantage of the natural stability of the high-energy resummation, recently discovered in the context of heavy-flavor studies, we investigate the inclusive hadroproduction of a neutral heavy-light, hidden-flavored tetraquark ($X_{cu\bar{c}\bar{u}}$ or $X_{bs\bar{b}\bar{s}}$ state), in association with a heavy (single *c*- or *b*-flavored) hadron or a light jet at the (HL-)LHC. We make use of the JETHAD multi-modular working package to provide predictions for rapidity, azimuthal-angle and transverse-momentum distributions calculated *via* the hybrid high-energy and collinear factorization, where the Balitsky–Fadin–Kuraev–Lipatov resummation of energy logarithms is supplemented by collinear parton densities and fragmentation functions. We rely upon the single-parton fragmentation mechanism, valid in the large transverse-momentum regime, to describe the tetraquark production. Our study represents a first attempt at bridging the gap between all-order calculations of high-energy QCD and the exotics.

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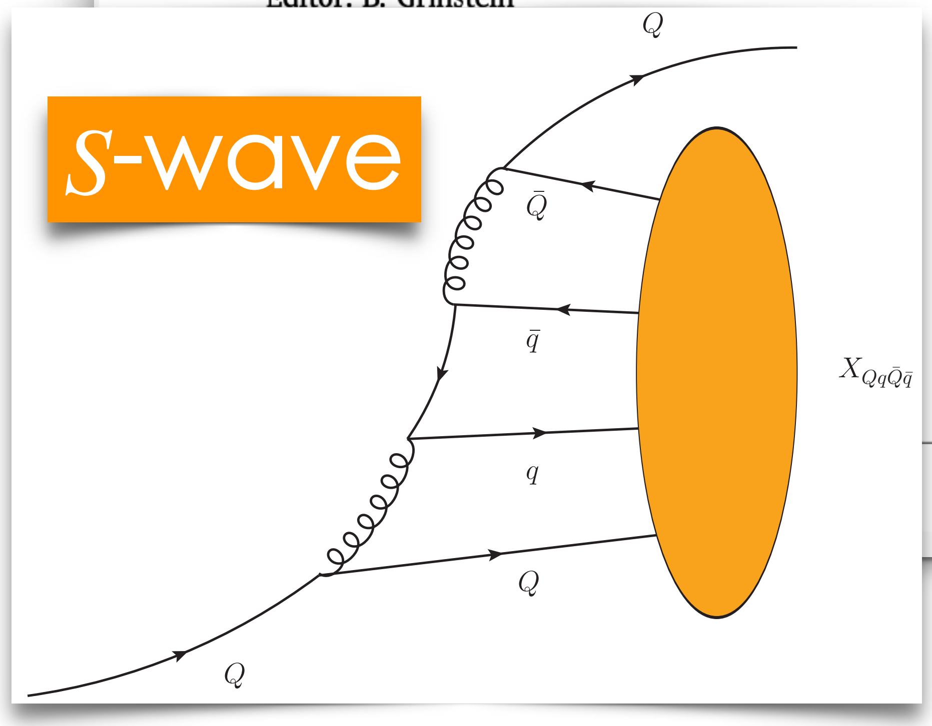

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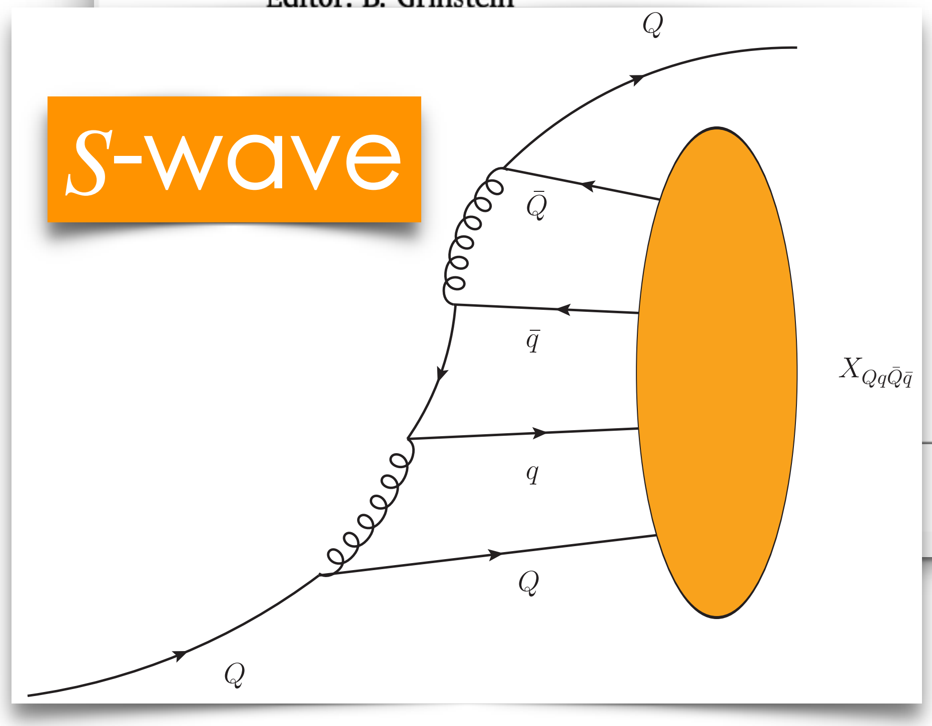

TQHL1.0 FFs: $(Q \to X_{Qq\bar{Q}\bar{q}}) \otimes$ APFEL++

Fully charmed tetraquarks from LHC to FCC: Natural stability from fragmentation

Francesco Giovanni Celiberto [1 †], Gabriele Gatto [2,3 ‡], and Alessandro Papa [2,3 §]

[2] *Universidad de Alcalá (UAH), E-28805 Alcalá de Henares, Madrid, Spain*

[2] *Dipartimento di Fisica, Università della Calabria, I-87036 Arcavacata di Rende, Cosenza, Italy*

[3] *Istituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza, I-87036 Arcavacata di Rende, Cosenza, Italy*

Abstract

We study the inclusive detection of a fully charmed tetraquark, $T_{4c}(0^{++})$ or its radial excitation $T_{4c}(2^{++})$, in association with a light jet in proton collisions. We build our study upon the collinear fragmentation of a single parton in a variable flavor number scheme, suited to describe the tetraquark formation mechanism at moderate to large transverse momenta. To this extent, we derive a novel set of DGLAP-evolving collinear FFs, named TQ4Q1.0 functions. They encode initial-scale inputs from both gluon and heavy-quark fragmentation channels, respectively defined in the context of quark potential and spin-physics inspired models. We work within the NLL/NLO$^+$ hybrid factorization and make use of the JETHAD numeric interface and the symJETHAD symbolic calculation plugin to provide predictions for observables sensitive to high-energy QCD dynamics at center-of-mass energies ranging from 14 TeV LHC to 100 TeV nominal FCC.

Tetraquark fragmentation from a simpler HF-NRevo

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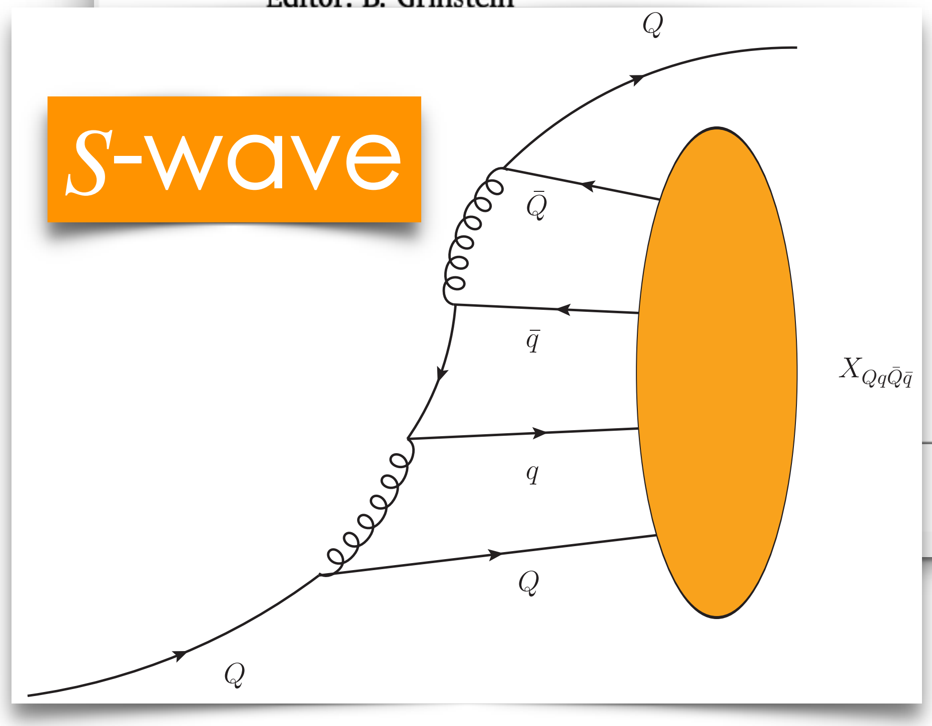
of heavy-flavor studies, we investigate the inclusive hadroproduction of a neutra
tetraquark ($X_{cu\bar{c}\bar{u}}$ or $X_{bs\bar{b}\bar{s}}$ state), in association with a heavy (single c- or b-flav
the (HL-)LHC. We make use of the JETHAD multi-modular working package to pr
azimuthal-angle and transverse-momentum distributions calculated *via* the hyb
factorization, where the Balitsky–Fadin–Kuraev–Lipatov resummation of energ
by collinear parton densities and fragmentation functions. We rely upon the
mechanism, valid in the large transverse-momentum regime, to describe the tetr
represents a first attempt at bridging the gap between all-order calculations of hig



TQHL1.0 FFs: $(Q \to X_{Qq\bar{Q}\bar{q}}) \otimes$ APFEL++

Fully charmed tetraquarks from LHC to FCC:
Natural stability from fragmentation

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Abstract

We study the inclusive detection of a fully charmed tetraquark, $T_{4c}(0^{++})$ or its radial excitation $T_{4c}(2^{++})$, in association with a light jet in proton collisions. We build our study upon the collinear fragmentation of a single parton in a variable flavor number scheme, suited to describe the tetraquark formation mechanism at moderate to large transverse momenta. To this extent, we derive a novel set of DGLAP-evolving collinear FFs, named
tial-scale inp
defined in th
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and the sym
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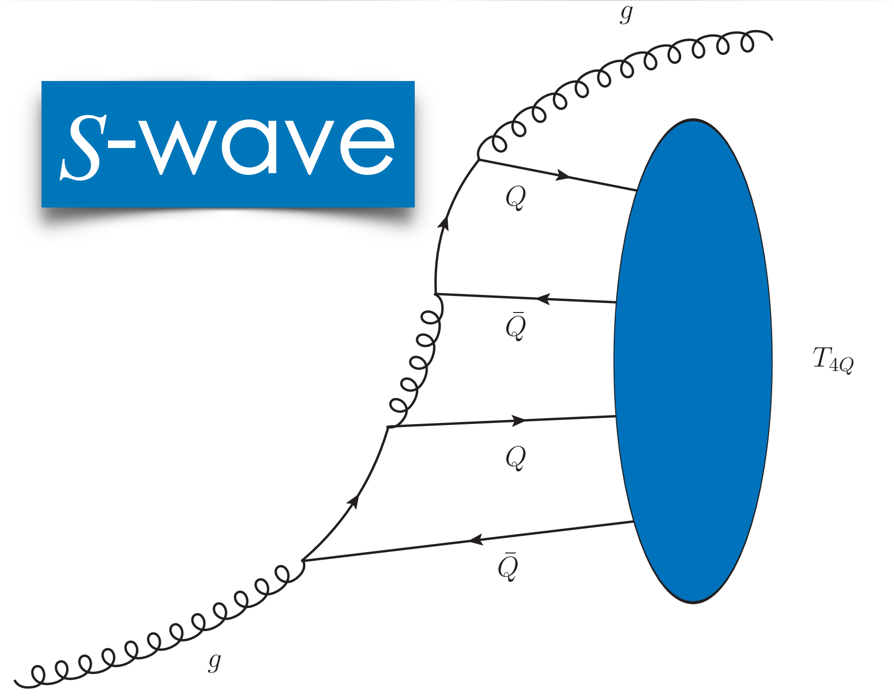
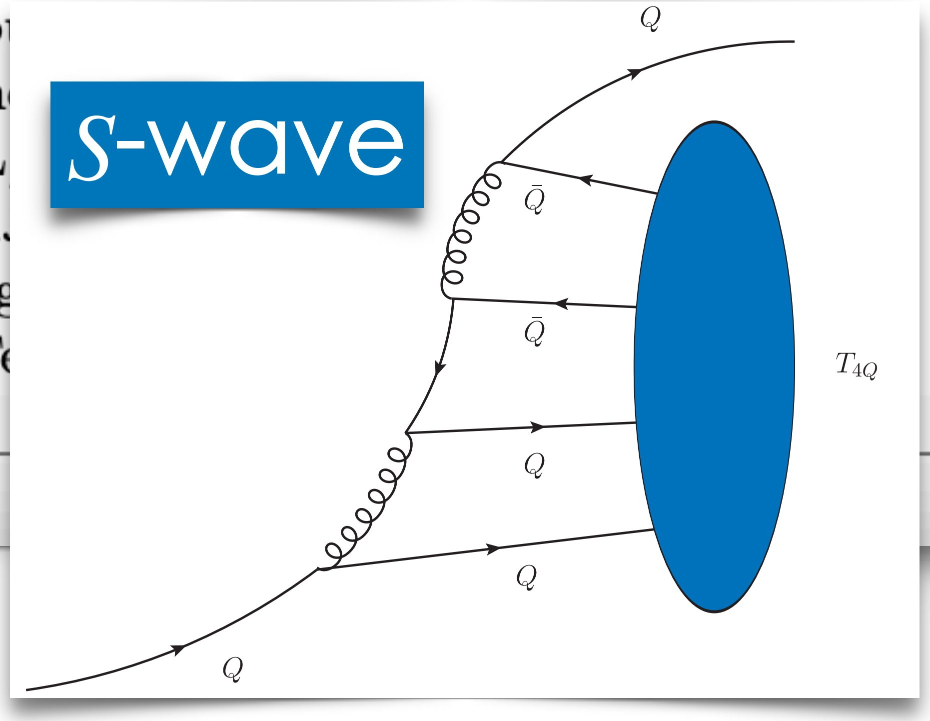
HC to 100 Te





TQ4Q1.0 FFs: $(Q + g \to X_{Qq\bar{Q}\bar{q}}) \otimes$ APFEL++

A high-energy QCD portal to exotic matter

- High-energy QCD precision era is at the energy frontier(s) of new-generation colliders

¡ ***Key ingredient***: *interplay between* ***resummation(s)*** *&* ***production mechanisms*** !

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High-energy physics

Hadronic structure

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High-energy physics

Hadronic structure

¿ *Might* ***high-energy QCD*** *give us* ***access*** *to* ***exotic matter*** ?

Need for fragmentation mechanisms depicting exotic atoms / molecules / hadrons

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