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

EXOTICO - ECT*, Trento, 20th October 2022

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ECT*/FBK Trento & INFN-TIFPA

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

TIFPA Trento Institute for Fundamental Physics and Applications

HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

High-energy QCD and the proton structure

High-energy physics

Proton structure

High-energy QCD and the proton structure

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- Precision studies ← SM and beyond
- Fixed-order perturbative calculations…
- …enhanced by resummations (p_T, energy)
- SM measurements: H, W, Z mass

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- Inner structure $\leftarrow$ intrinsic parton motion
- Parton densities $\rightarrow$ NP nature, global fits
- Fragmentation functions $\rightarrow$ NP nature, dynamics
- Several types: 1D collinear, 3D TMD

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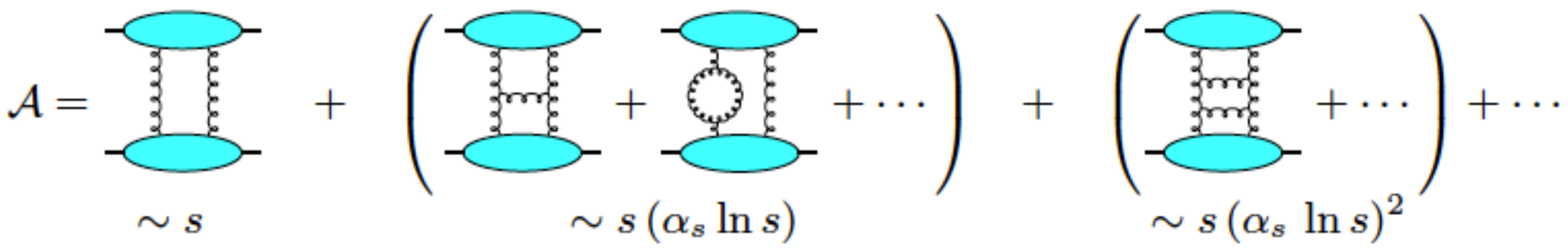
Perturbative and nonperturbative aspects ⇔ key ingredients to a joint search for **New Physics**

The high-energy resummation

- **BFKL resummation**: [V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975, 1976, 1977); Y.Y. Balitskii, L.N. Lipatov (1978)]

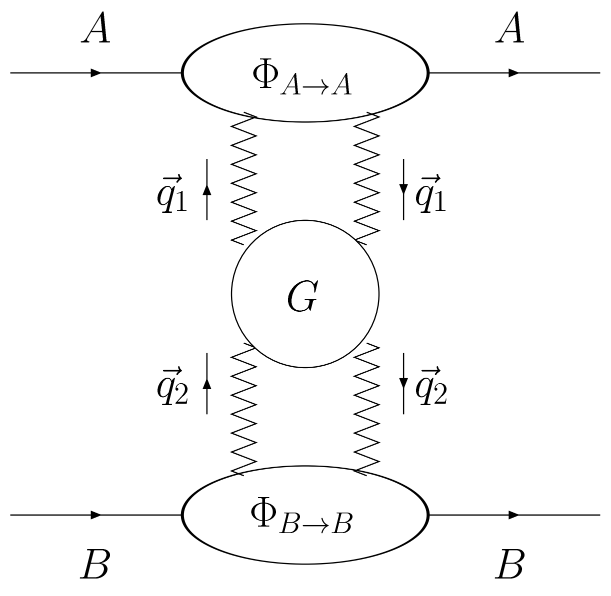
  $\xrightarrow{\text{based on}}$ **gluon Reggeization**

  leading logarithmic approximation (LL): $\alpha_s^n (\ln s)^n$



  next-to-leading logarithmic approximation (NLL): $\alpha_s^{n+1} (\ln s)^n$

Total cross section for $A + B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{I}m_s\{\mathcal{A}_{AB}^{AB}\}}{s} \Leftarrow$ ***optical theorem***



▶ $\mathcal{I}m_s\left\{\mathcal{A}_{AB}^{AB}\right\}$ factorization:

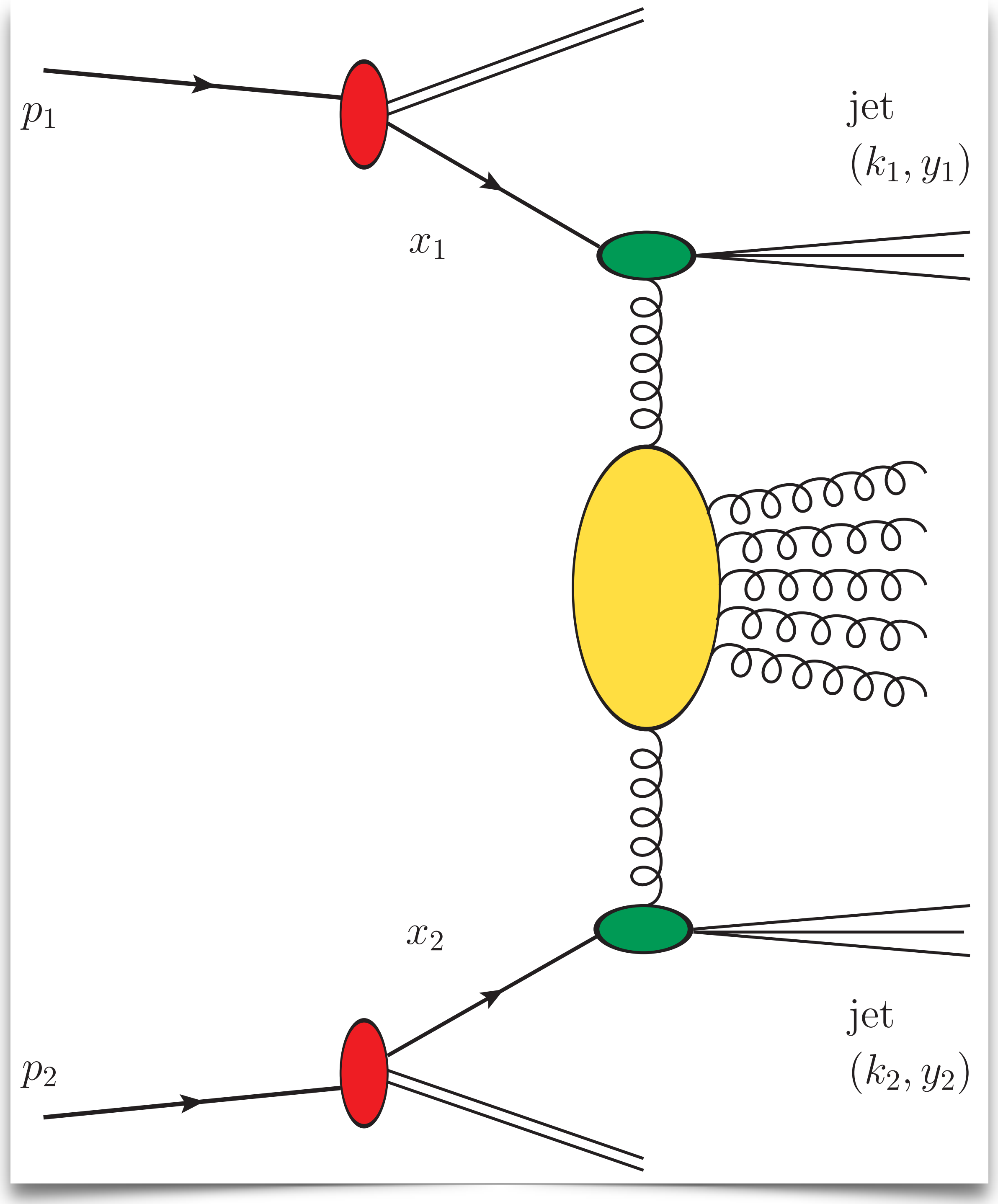
convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles

Green's function is **process-independent**, describes energy dependence and obeys BFKL equation; impact factors are known in the NLL **just for few processes**

Mueller-Navelet jets at the LHC

- Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY
- Moderate x (collinear PDFs), but t-channel p_T (BFKL resummation) → hybrid factorization

$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \sum_{r,s=q,g} \int_0^1 dx_1 \int_0^1 dx_2\, f_r(x_1,\mu_F)\, f_s(x_2,\mu_F)\, \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu_F)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2}$$



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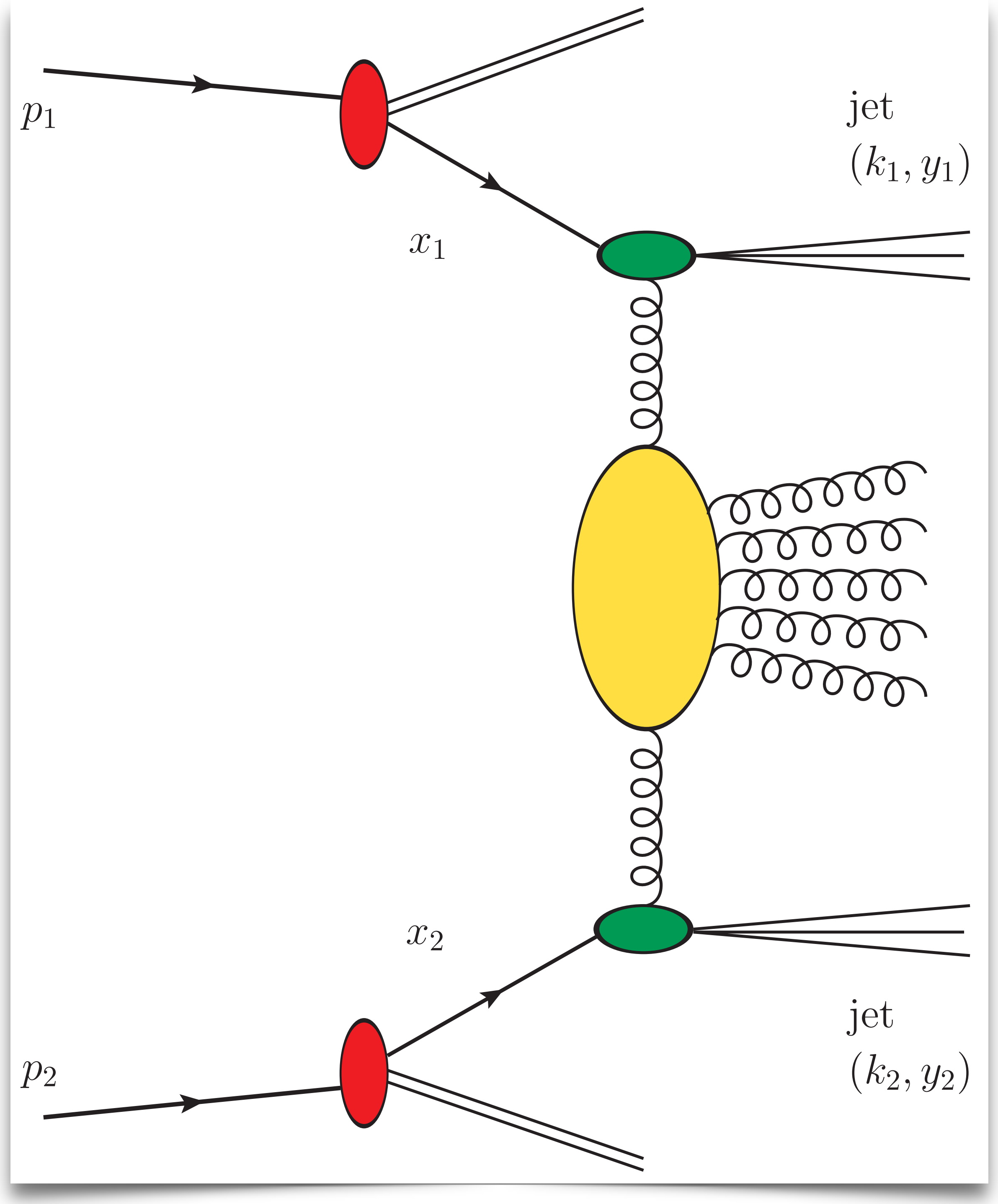

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \frac{1}{(2\pi)^2}$$

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

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

jet vertices (off-shell amplitudes)

BFKL Green's function

- Hybrid NLL/NLO factorization via the `JETHAD` Method

python + F

[F. G. C. (2021)]

From Mueller-Navelet to Higgs and heavy flavor

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

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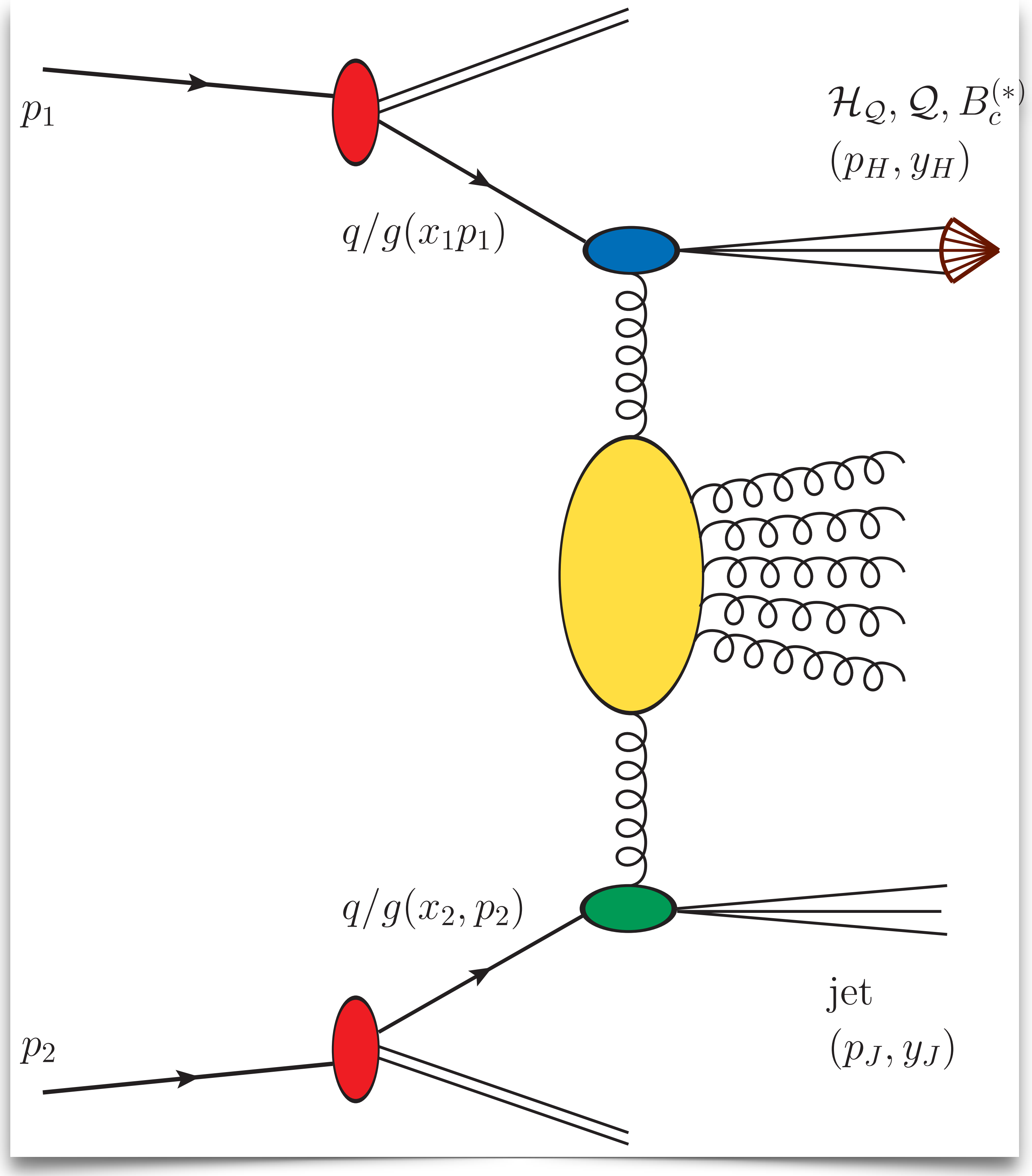
Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels



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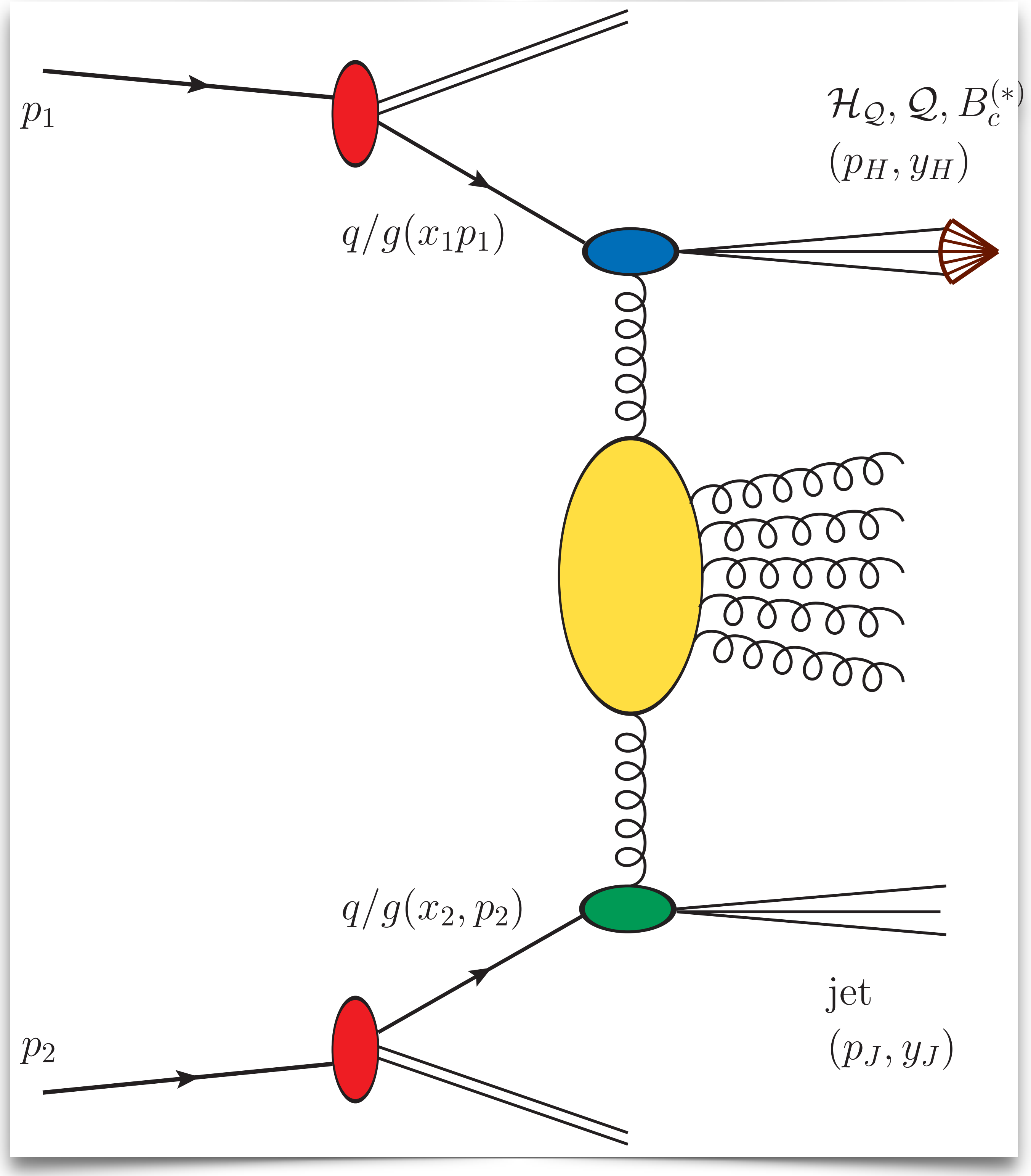
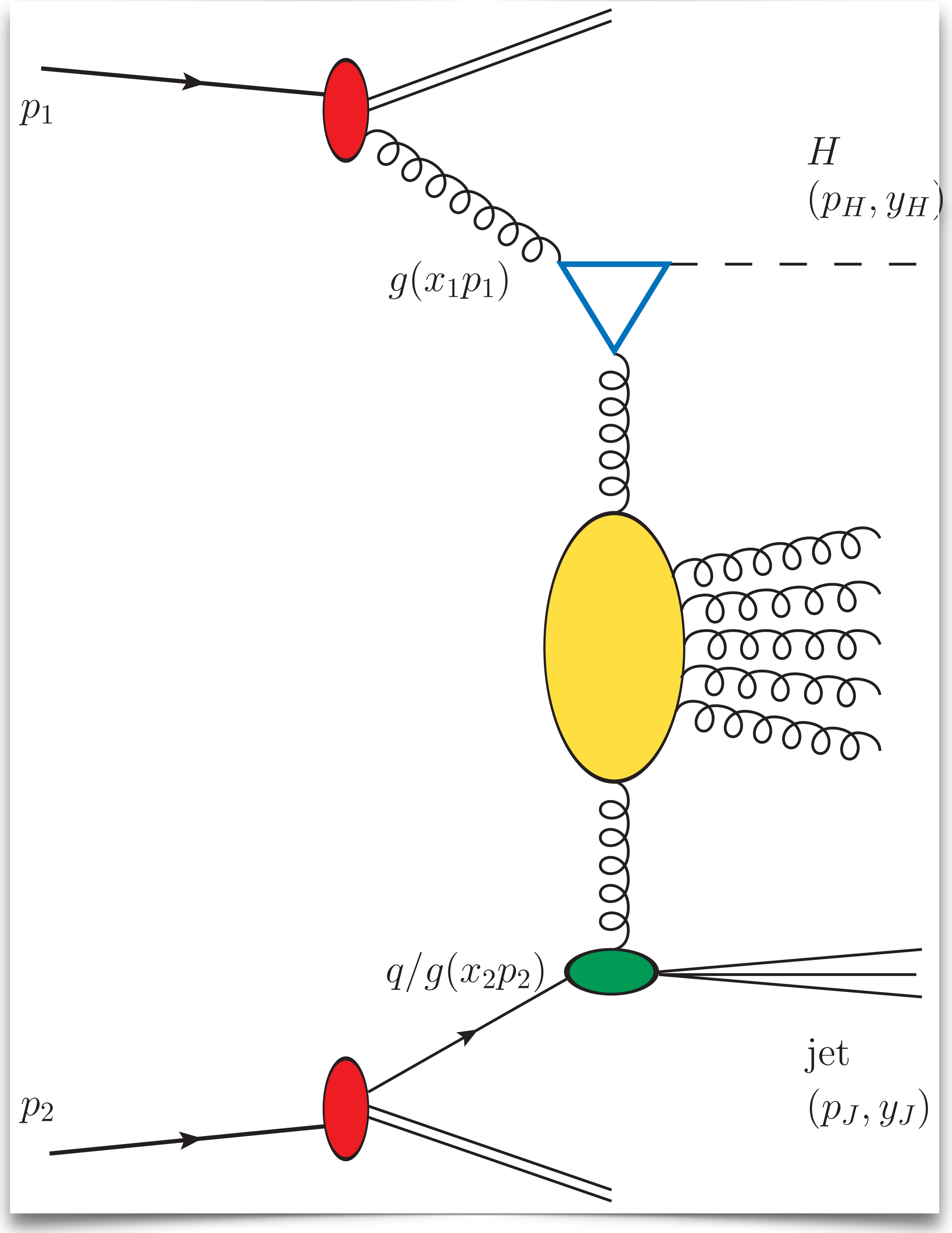


Higgs boson

Stabilizers ⇔ large Higgs transverse masses



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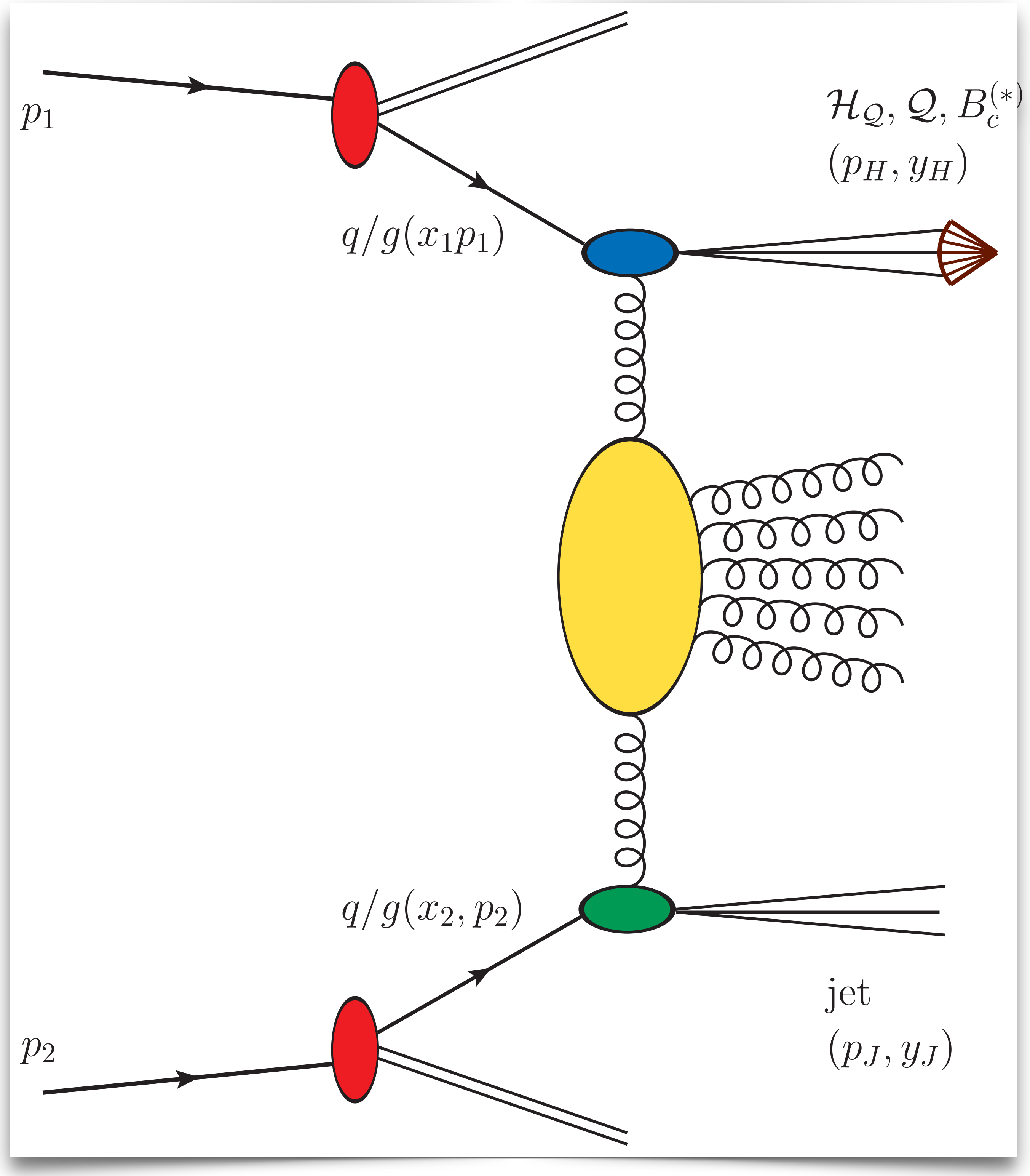

($\Lambda_c^\pm$ baryons, NLL/NLO) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

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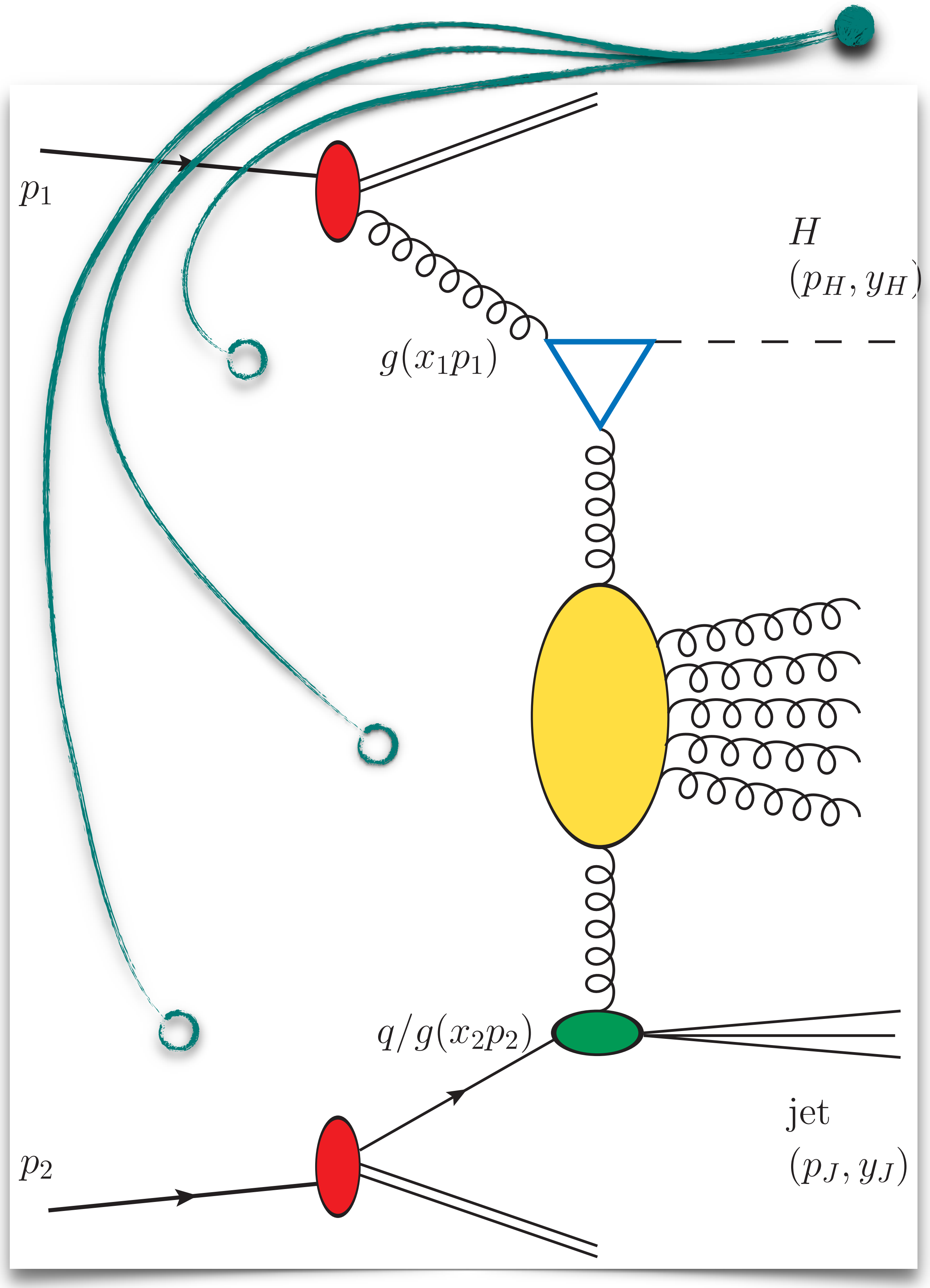

$\mu_{F,R} \sim M_{H,\perp}$

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

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

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

(NLO Higgs impact factor) [F. G. C. et al., JHEP 08 (2022) 092]

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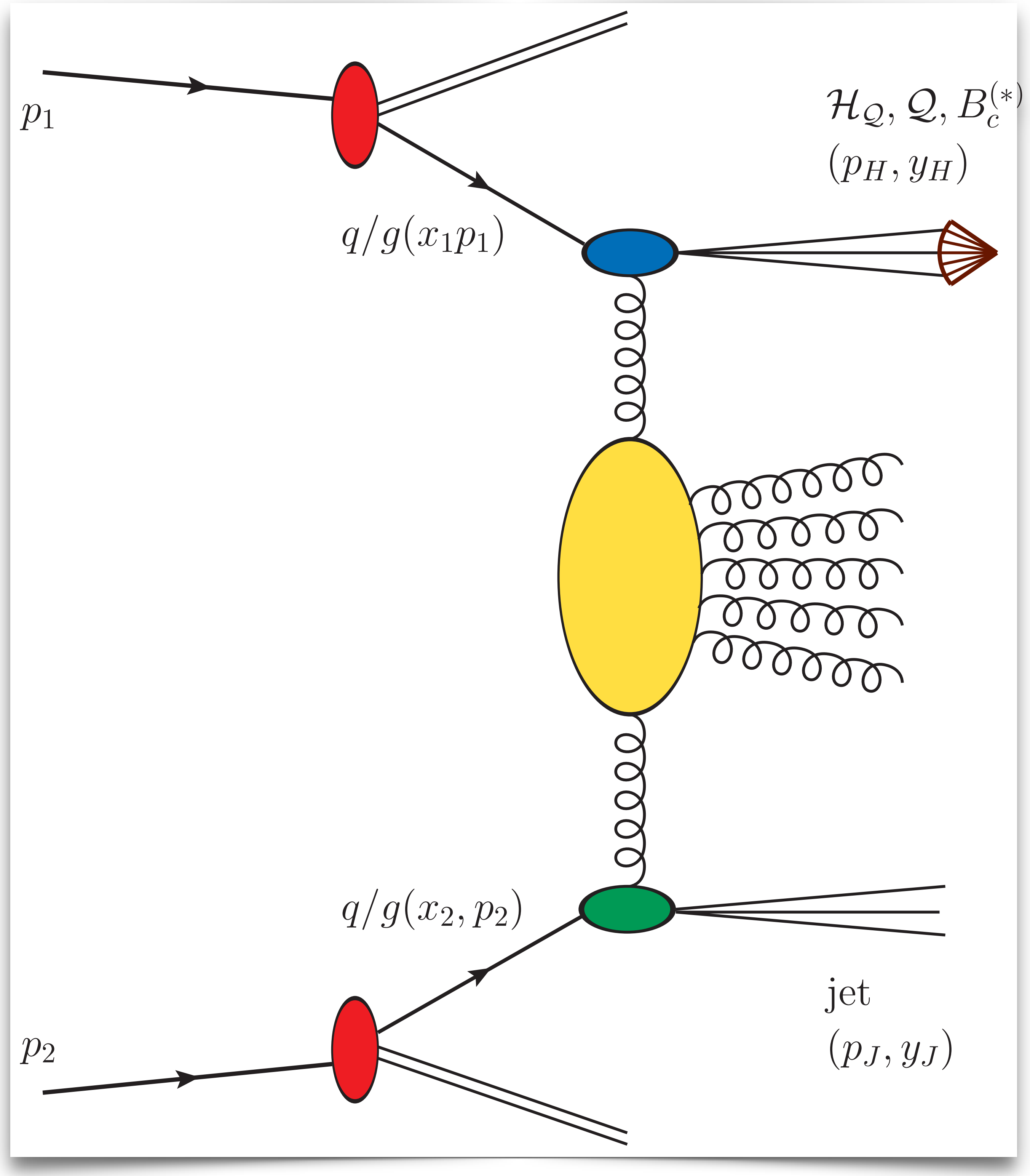

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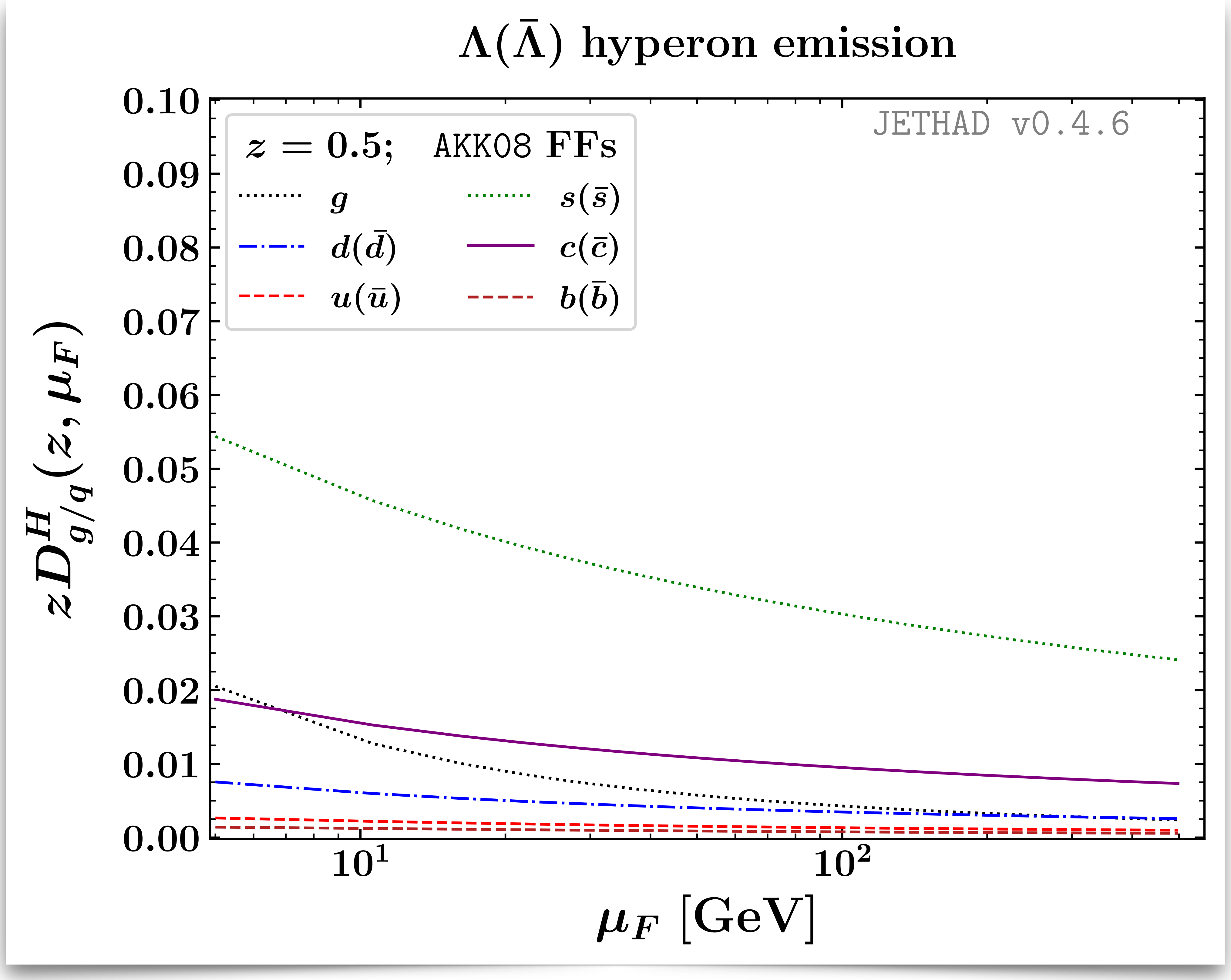
Stabilizing effects of heavy-flavor fragmentation

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

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



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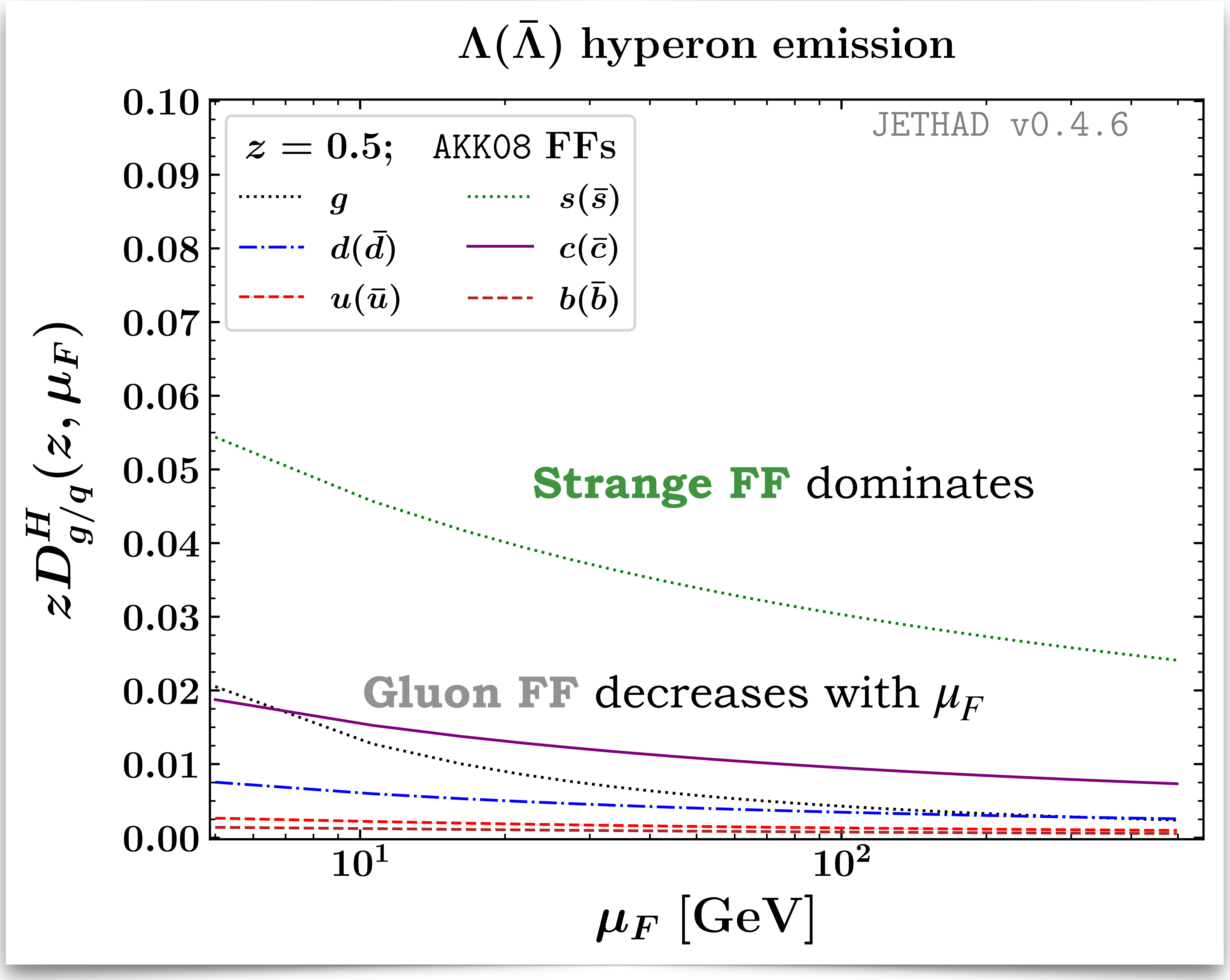

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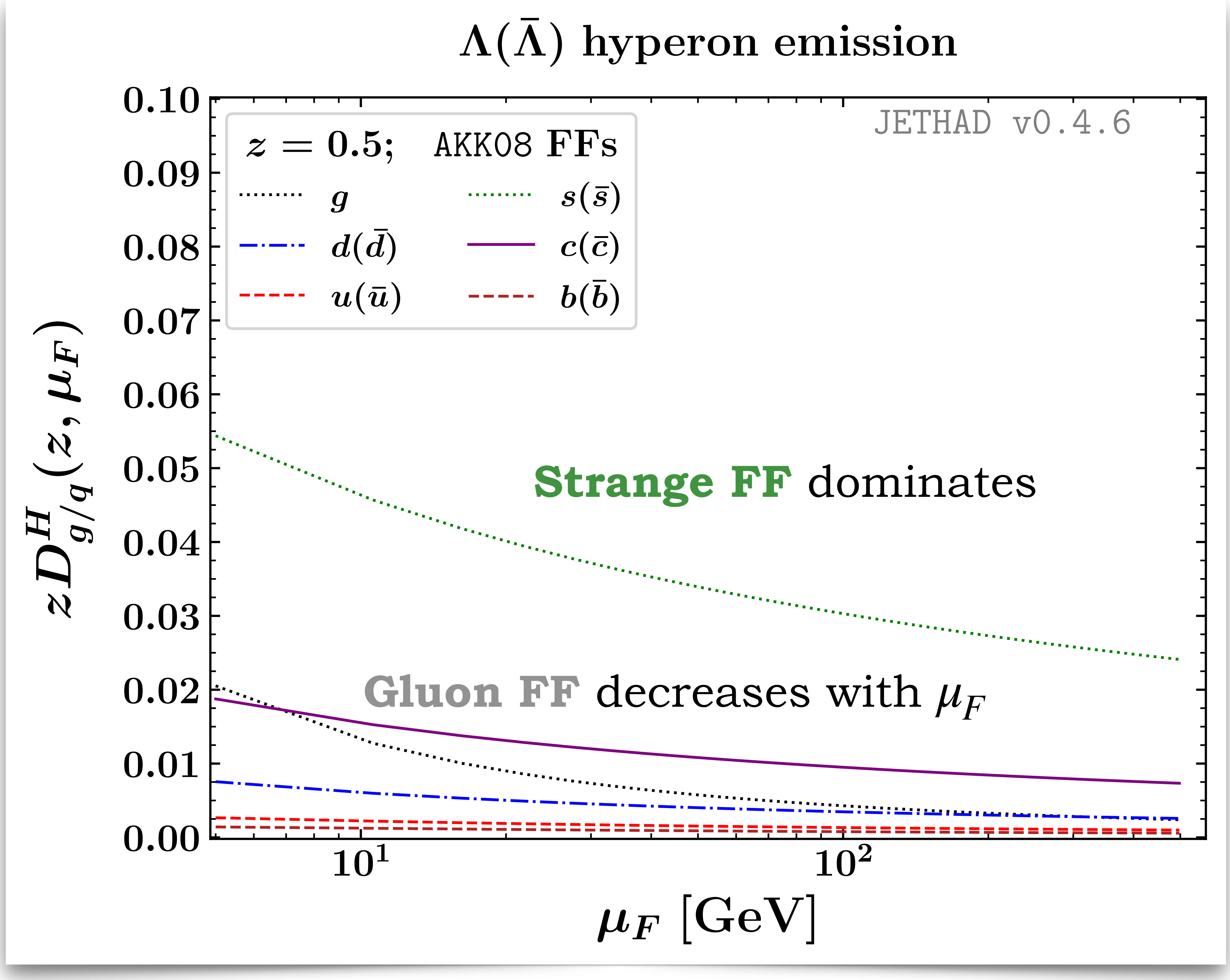

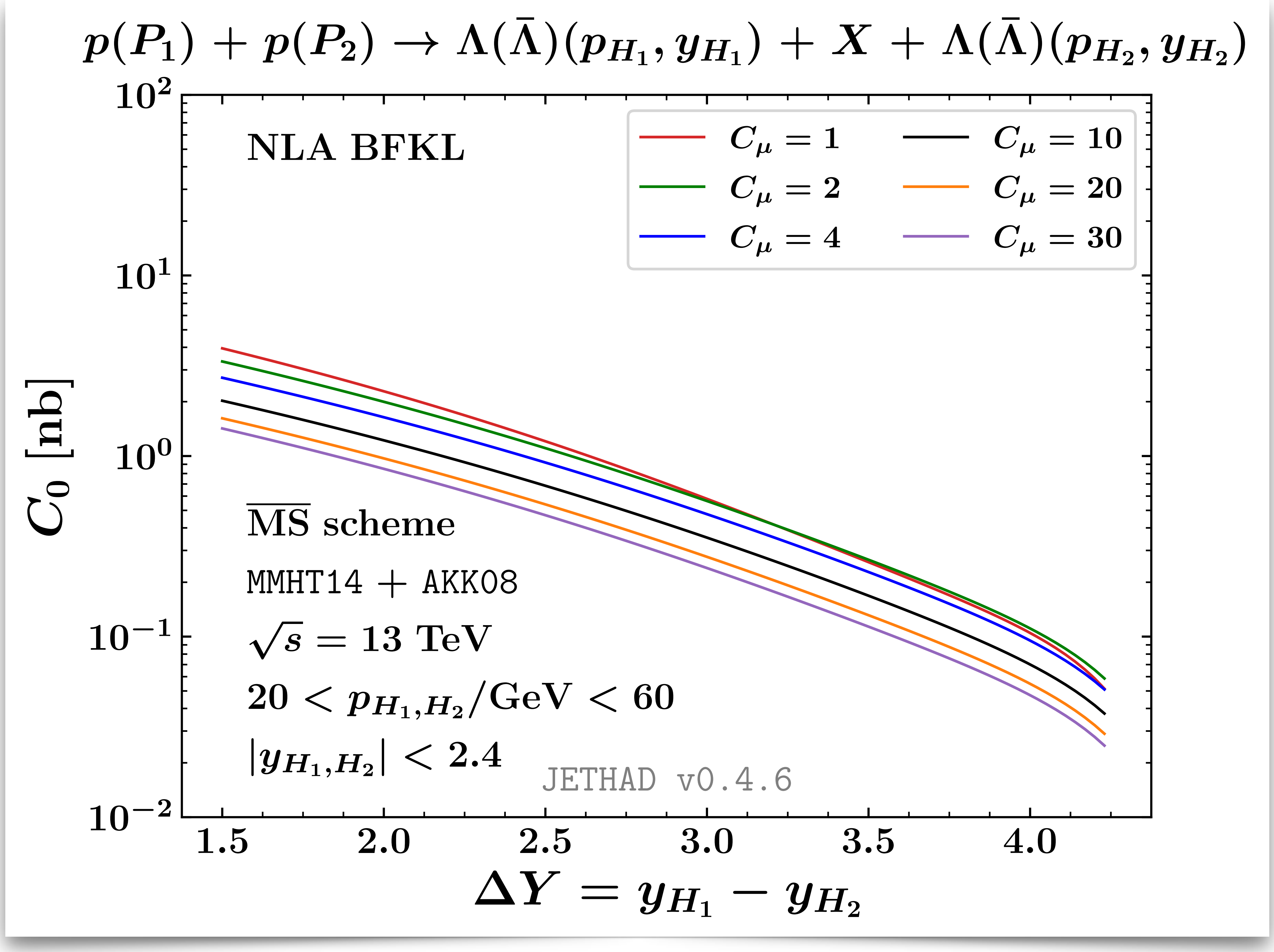

Rapidity distribution sensitive to scale variations

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

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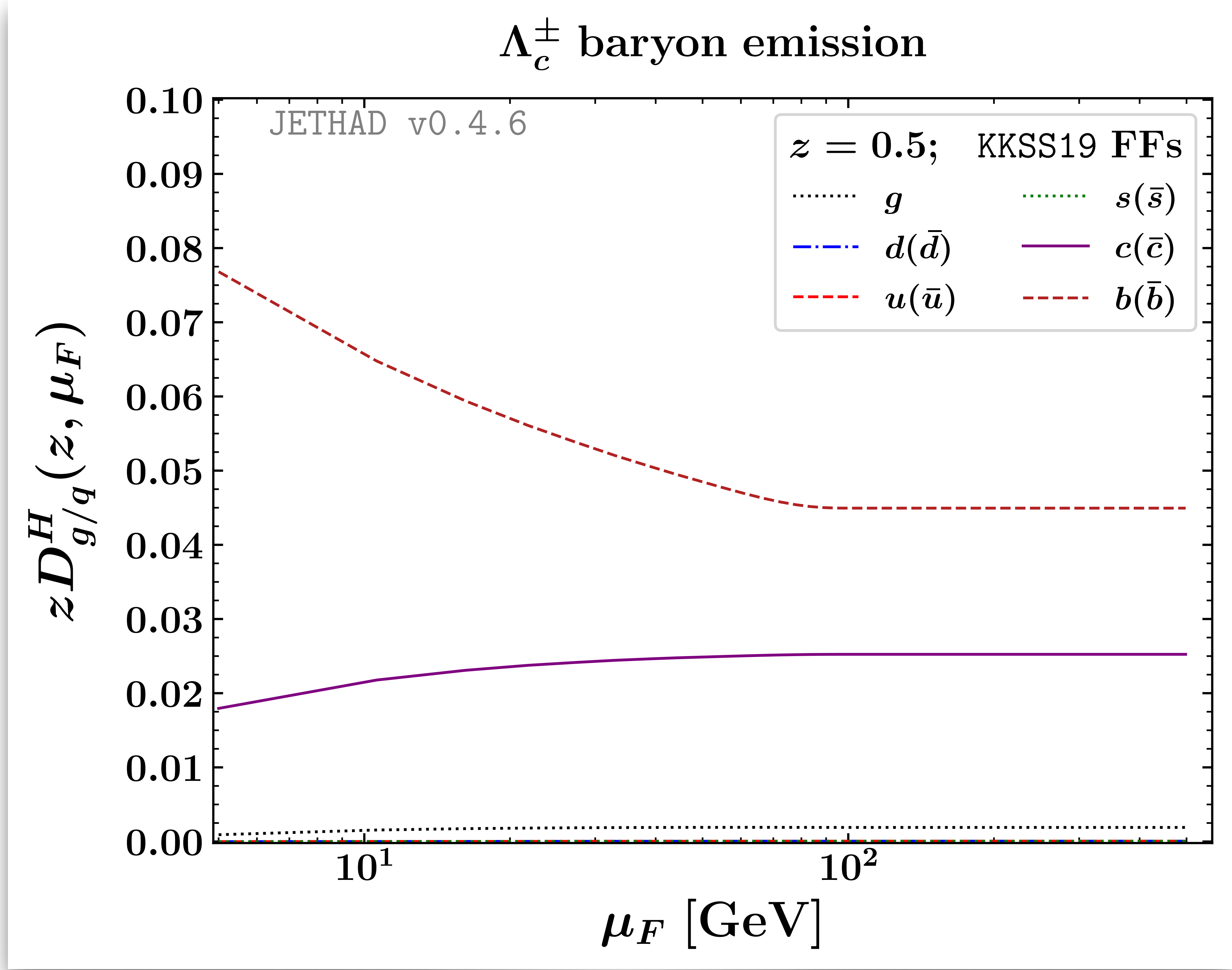

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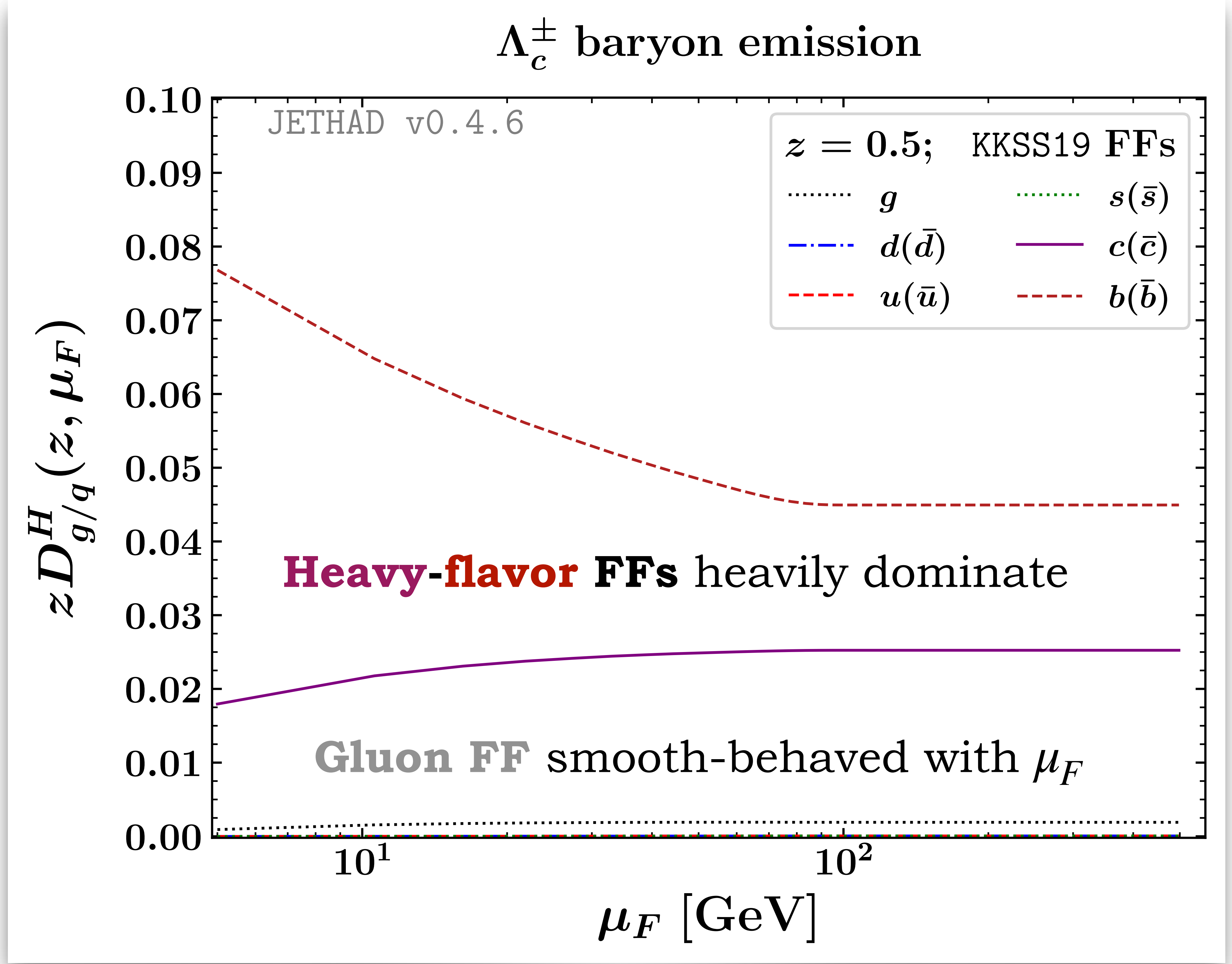

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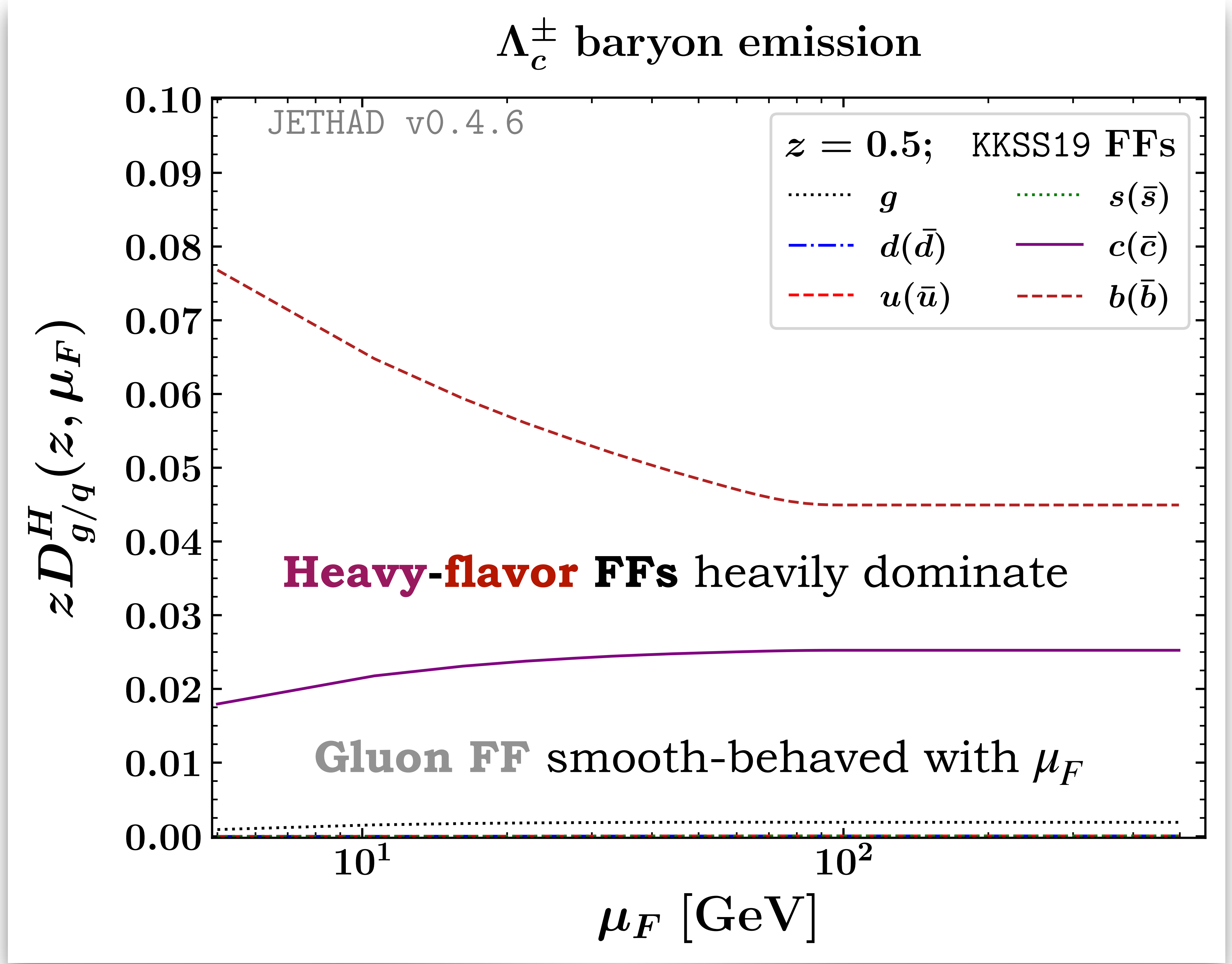

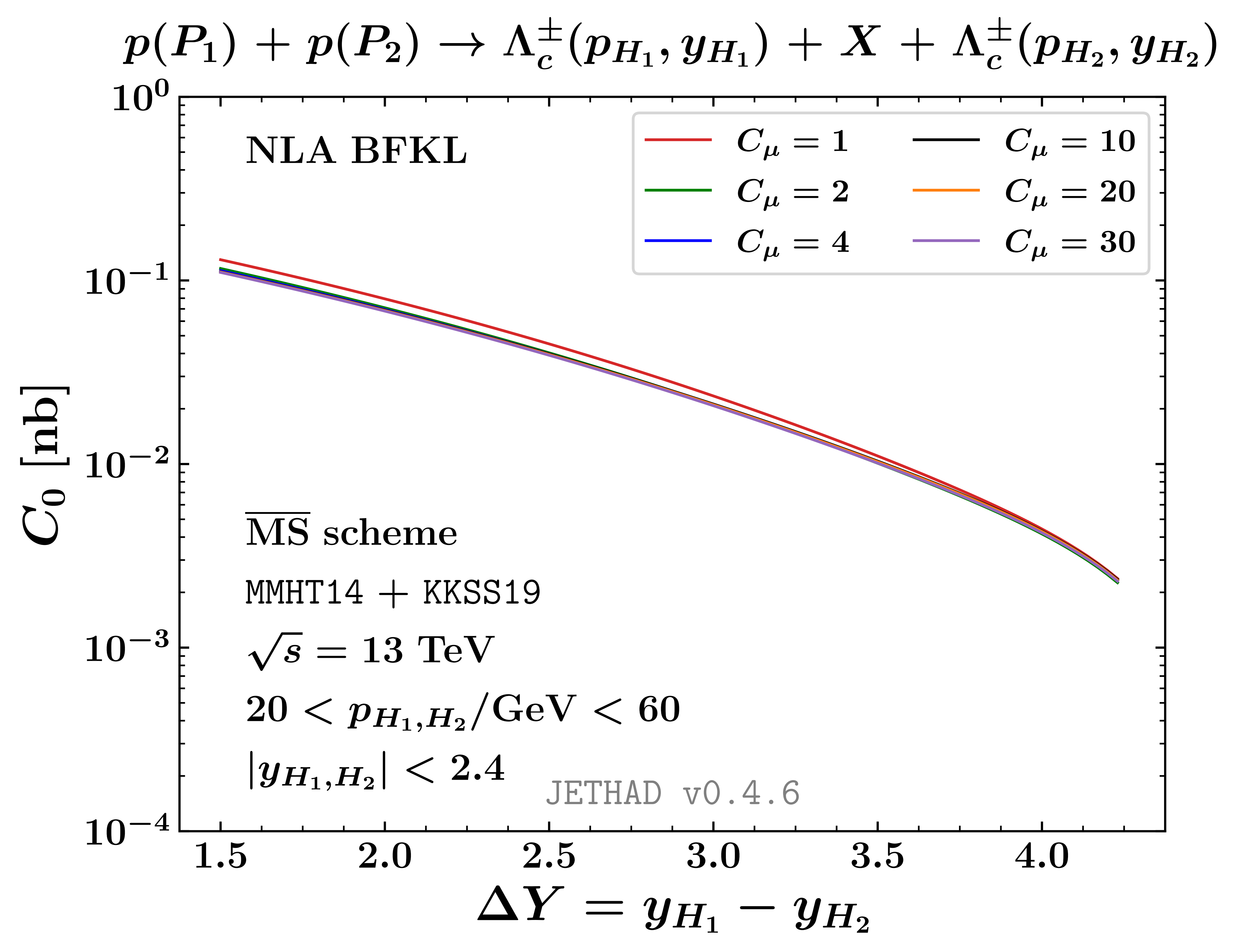

Rapidity distribution stable under scale variations

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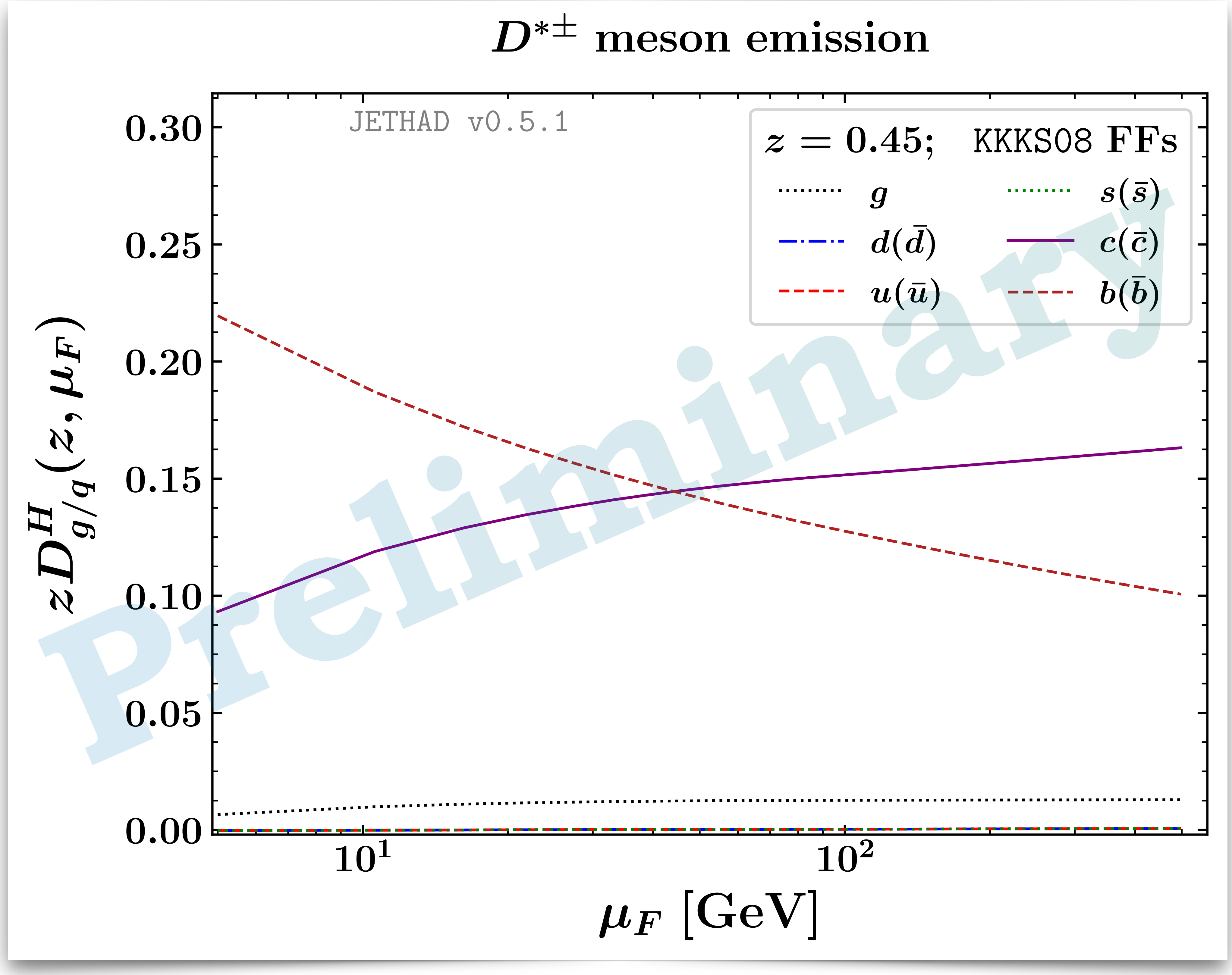

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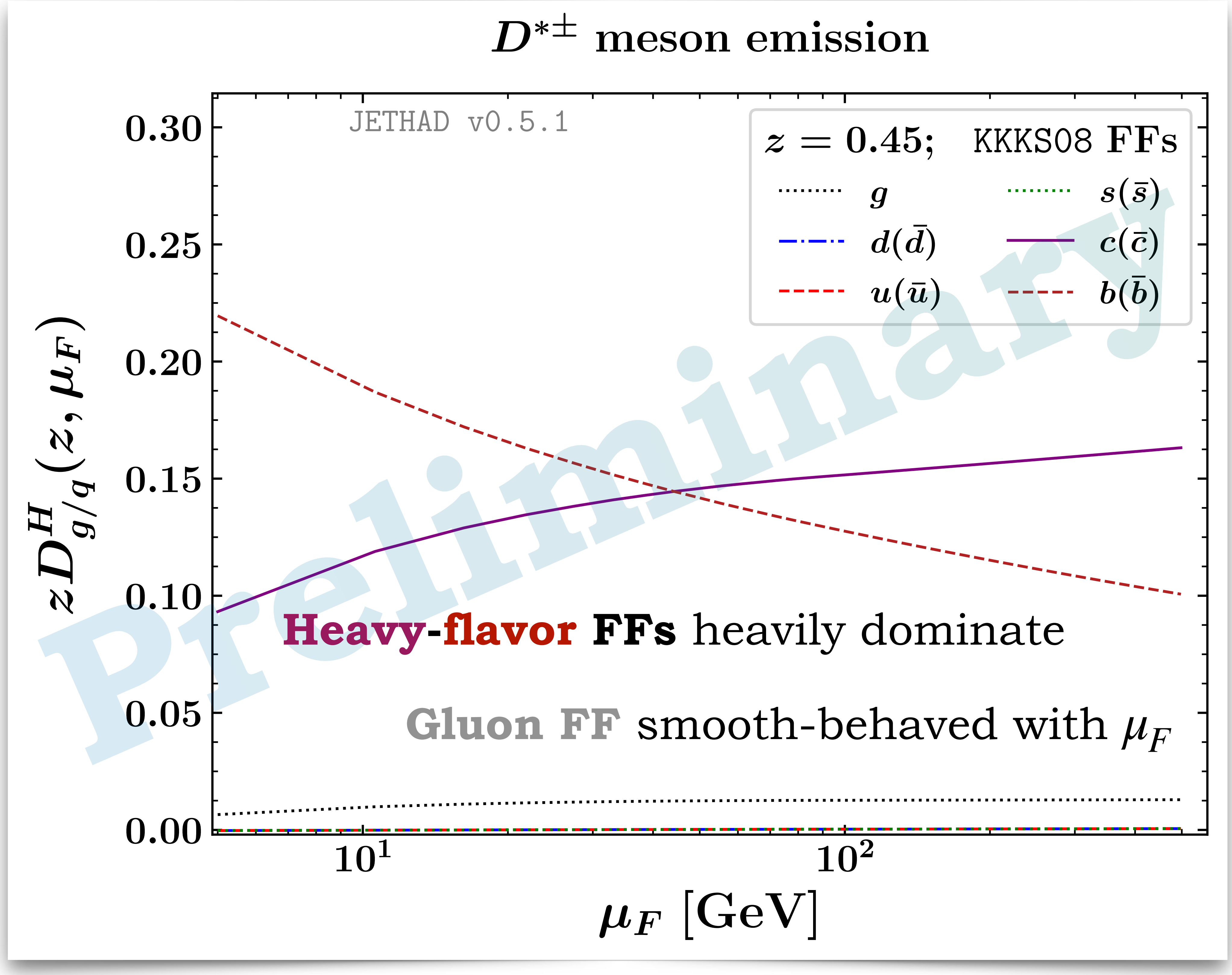

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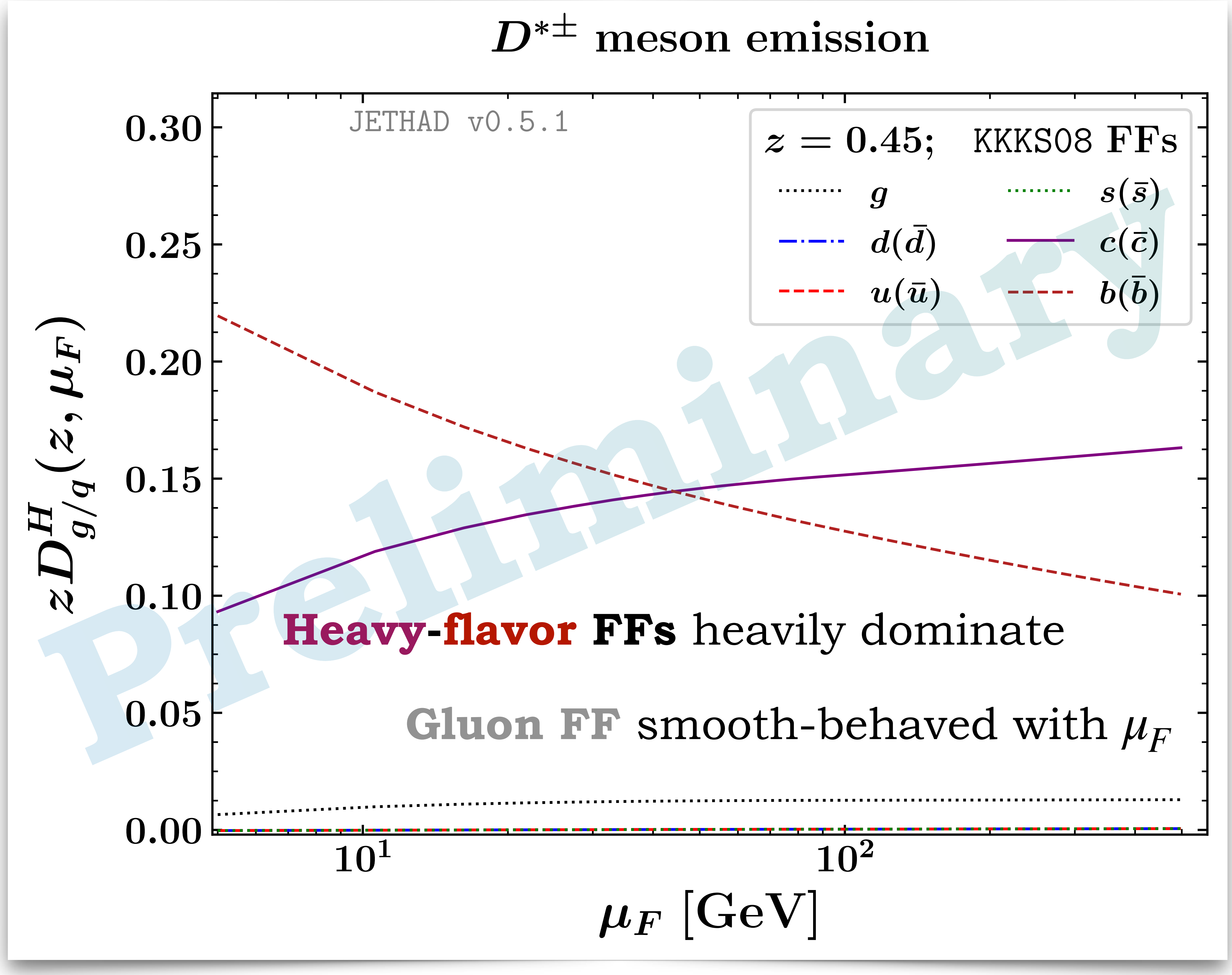

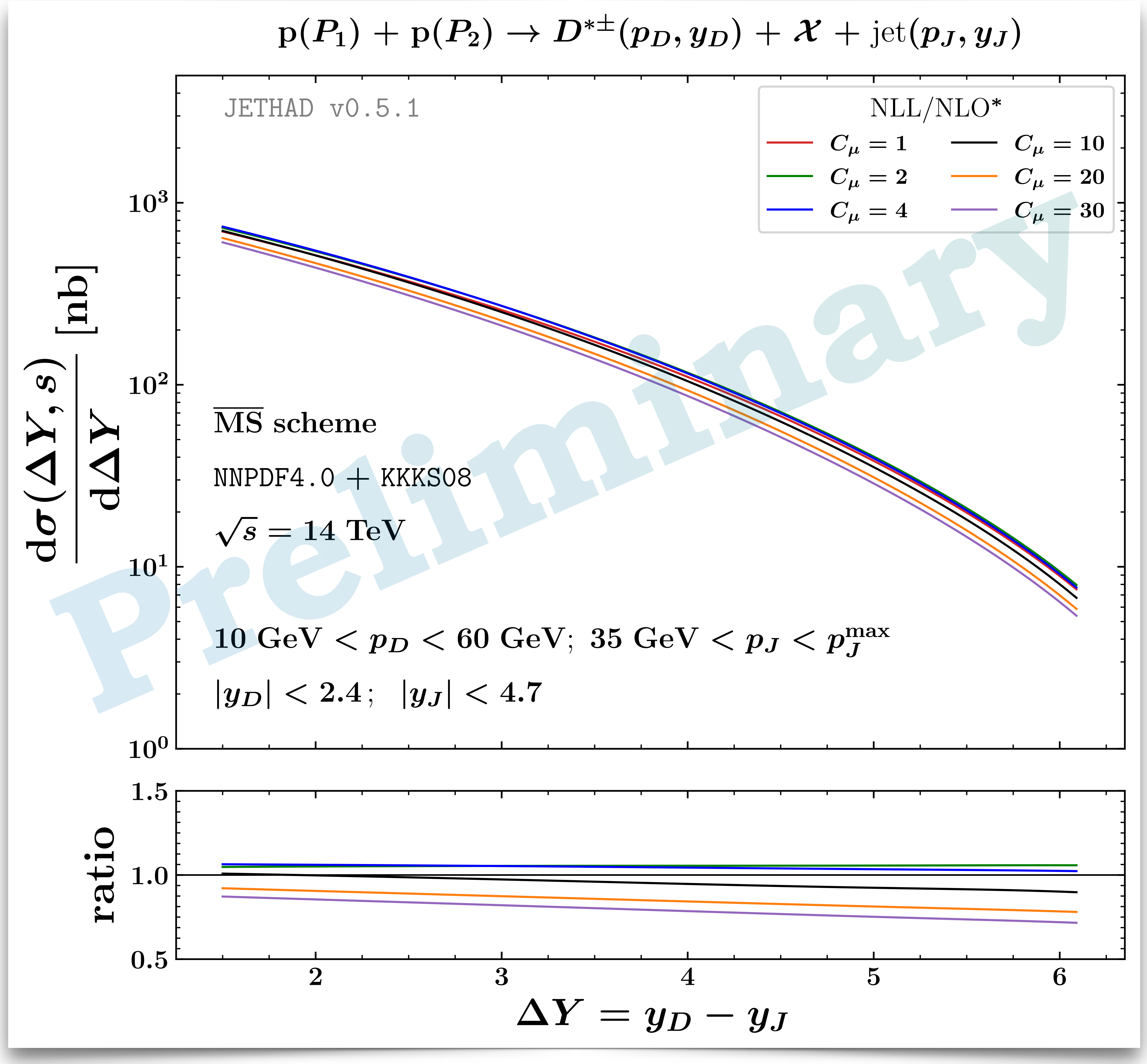

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($D^{*\pm}$ mesons, in this slide) [F. G. C. et al., in preparation]

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 ⇒ this compensates PDF and BFKL kernel decreasing behavior

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Is the natural stabilization robust?

(1) **KKKS08** and **KKSS19** VFNS collinear FFs share the same extraction technology

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

Is the natural stabilization robust?

(1) **KKKS08** and **KKSS19** VFNS collinear FFs share the same extraction technology

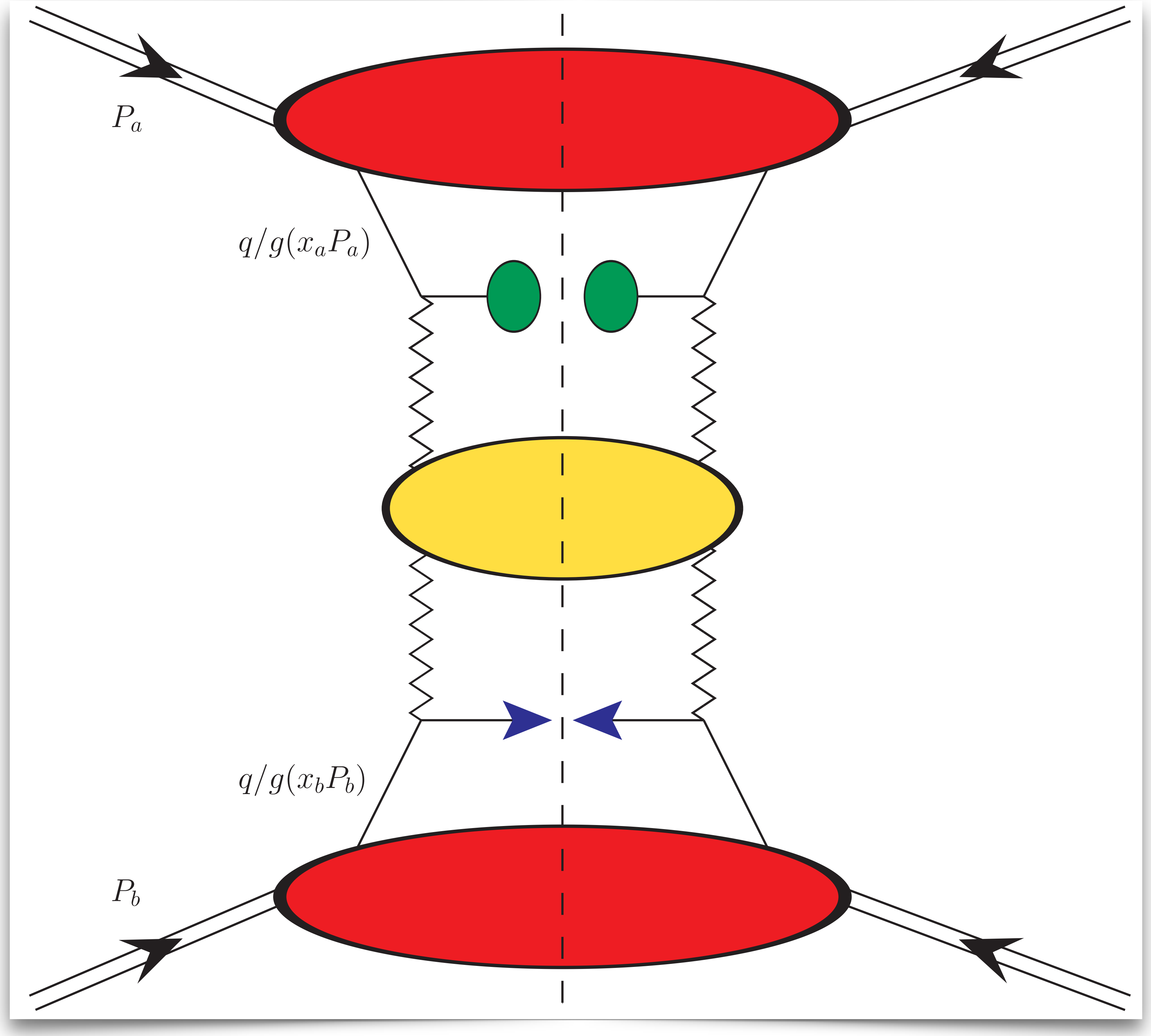
¿ *Might natural stability be related to the given FF determination(s)* ?

(2) **KKKS08** 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* → *single-parton* ***fragmentation*** *from* ***NRQCD*** !



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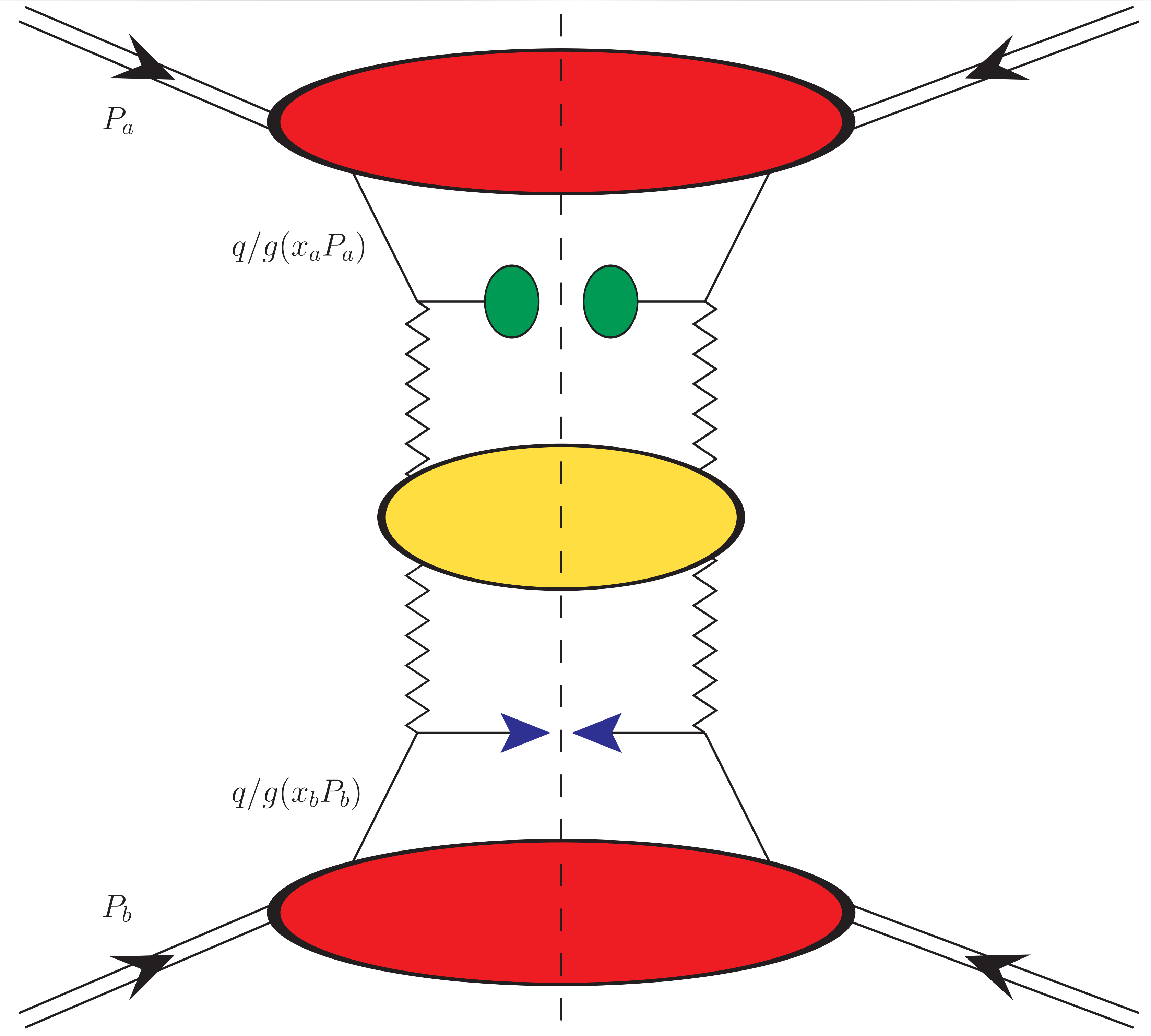

Eur. Phys. J. C (2022) 82:929
https://doi.org/10.1140/epjc/s10052-022-10818-8

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Diffractive semi-hard production of a J/ψ or a Υ from single-parton fragmentation plus a jet in hybrid factorization

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[4] Dipartimento di Fisica, Università della Calabria, 87036 Arcavacata di Rende, Cosenza, Italy
[5] Istituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza, 87036 Arcavacata di Rende, Cosenza, Italy
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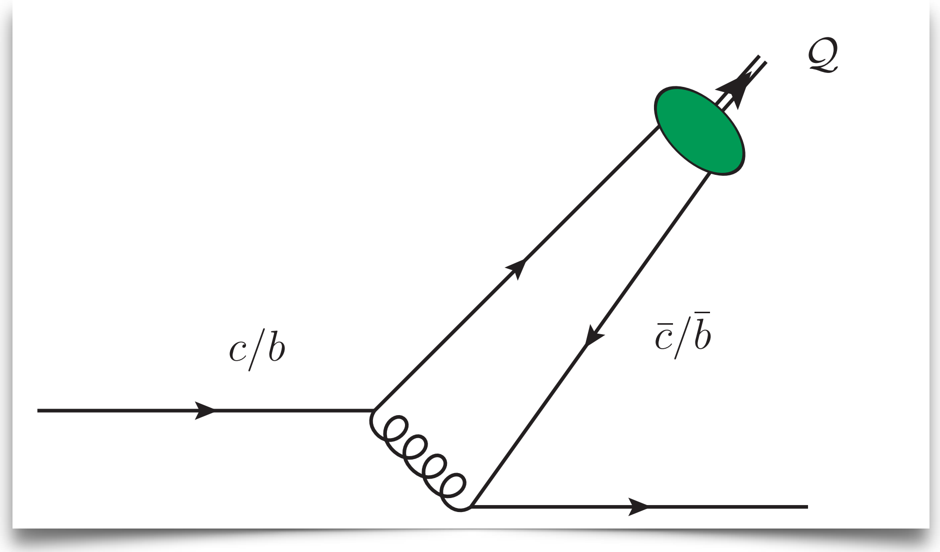
[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

ZCW19 onium FFs: $(Q \rightarrow \mathcal{Q}\, Q)$ $\otimes$ **APFEL++**

$[\mu_0 = 3 m_Q]$



Color Singlet (CS)

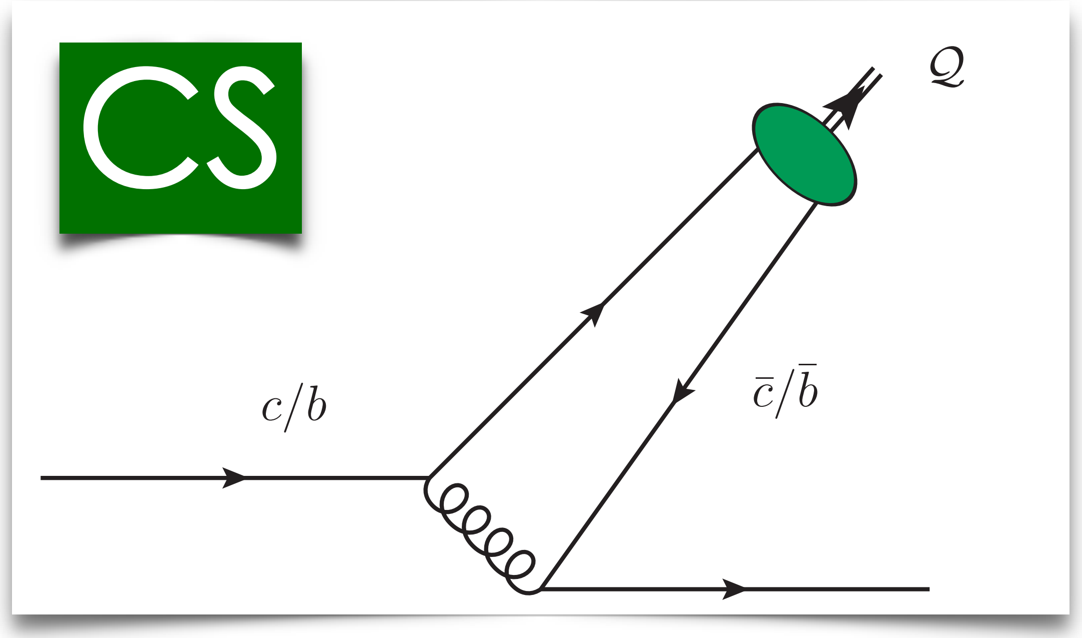
$$D_Q^{\mathcal{Q}}(z, \mu_F \equiv \mu_0) = D_Q^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3} |\mathcal{R}_{\mathcal{Q}}(0)|^2 \, \Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

(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 from single-parton fragmentation

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



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

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

(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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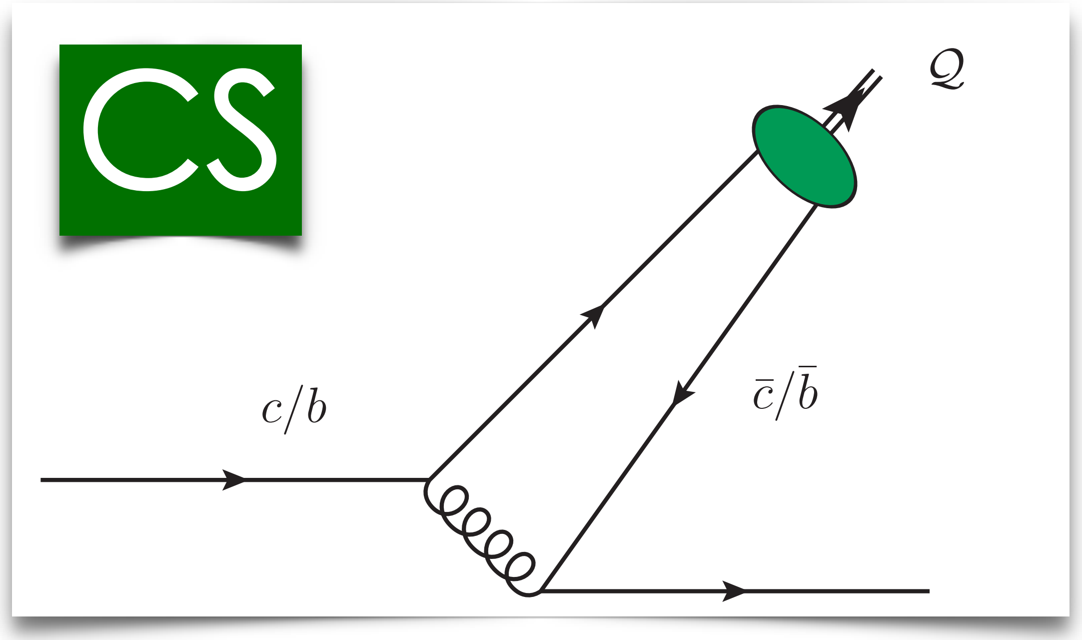

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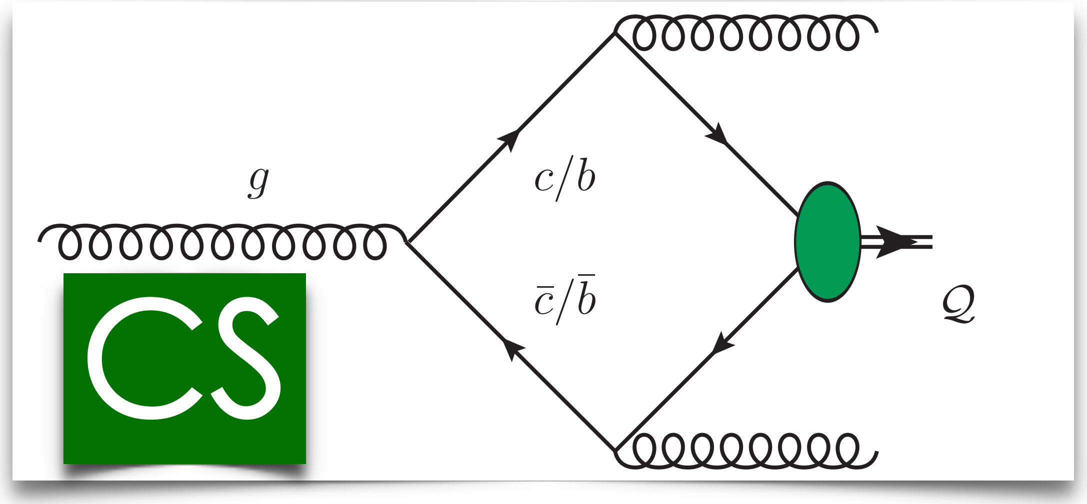

$$D_g^{\mathcal{Q}}(z, 2m_Q) = \frac{5}{36(2\pi)^2} \alpha_s^3(2m_Q) \frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_Q^3} \int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2}$$
$$\sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau)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

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

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

Vector quarkonium from single-parton fragmentation

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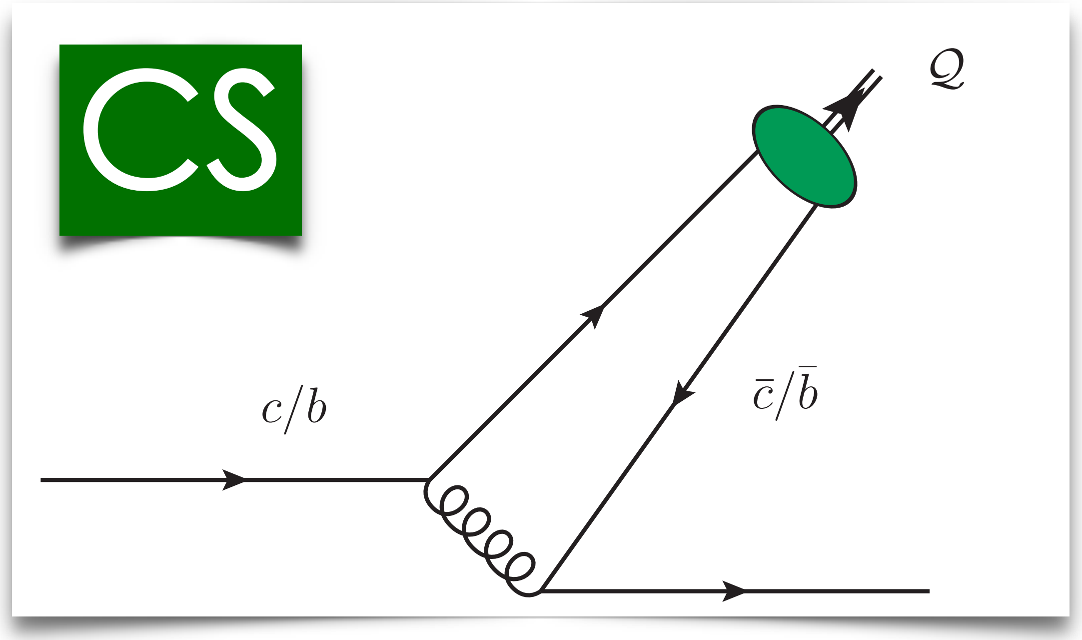

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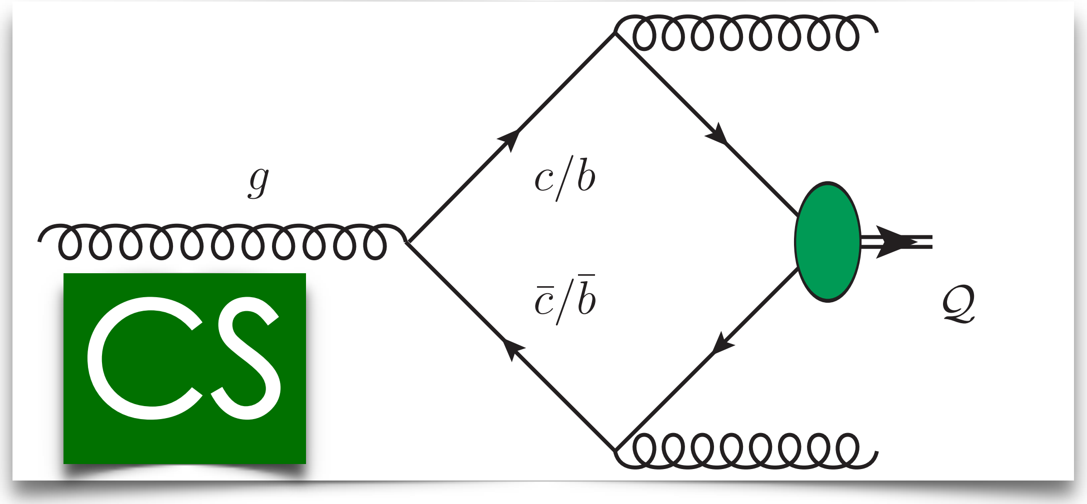

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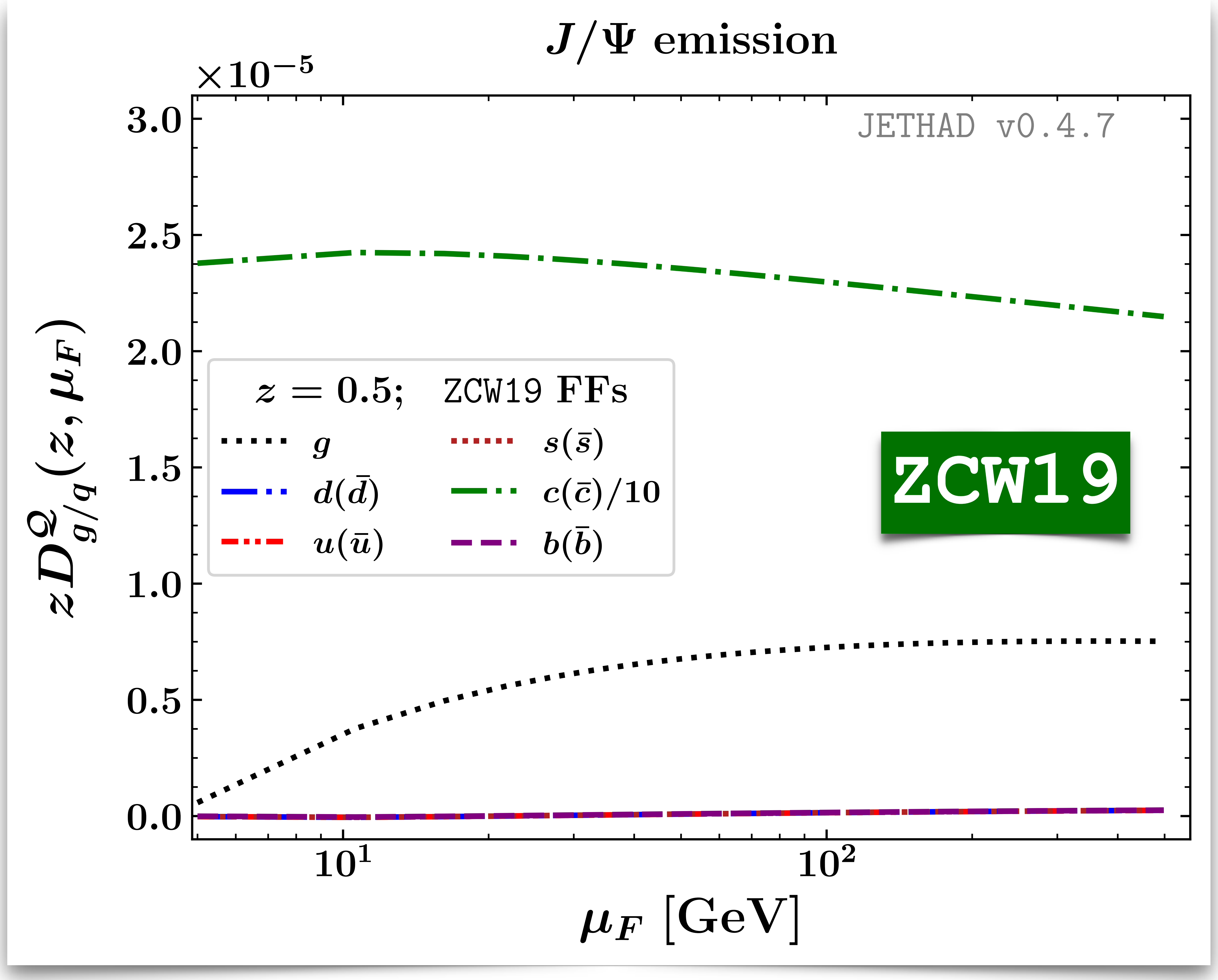
$\otimes$

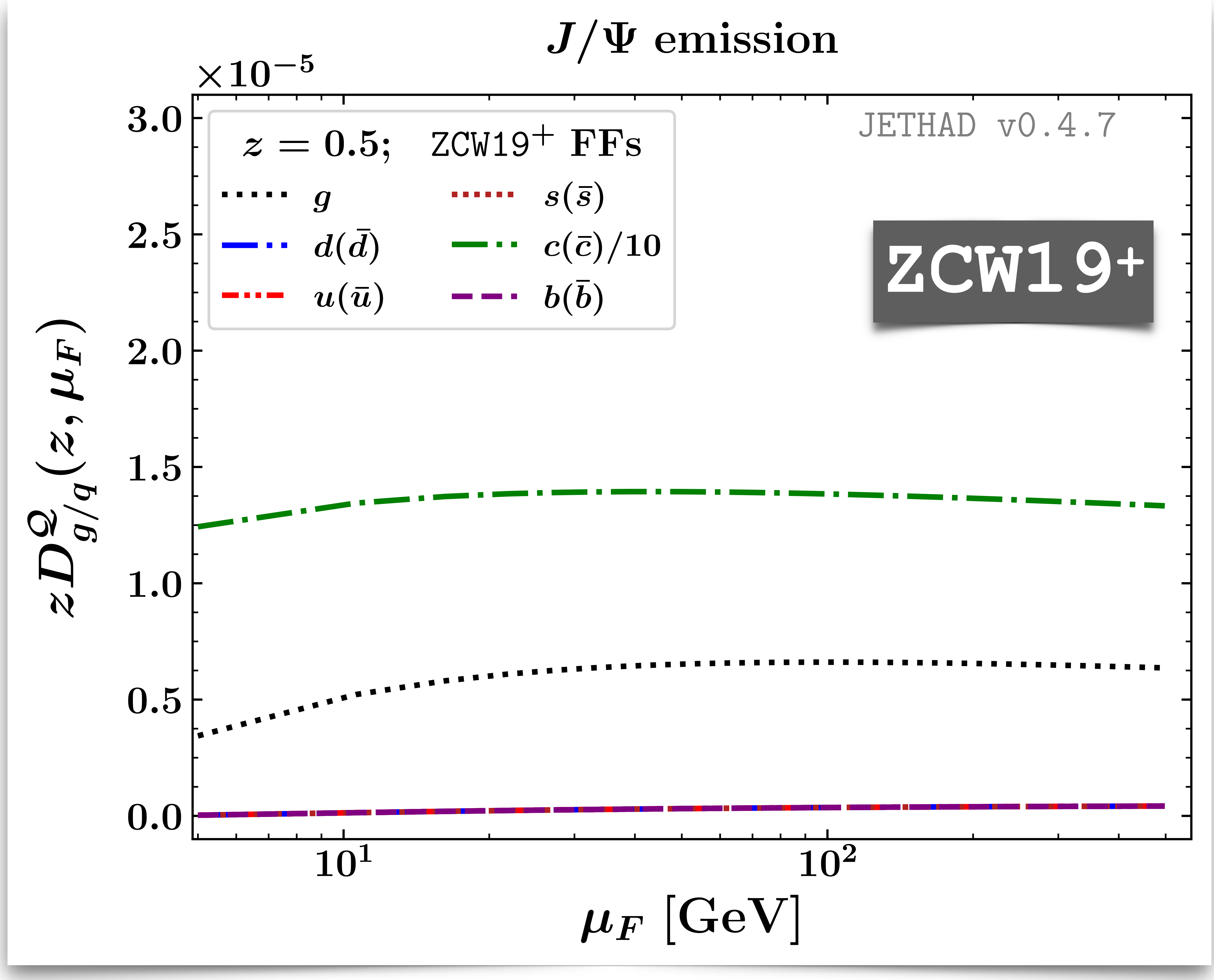
[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

ZCW19+ onium FFs = APFEL++

Vector quarkonium + jet at the LHC

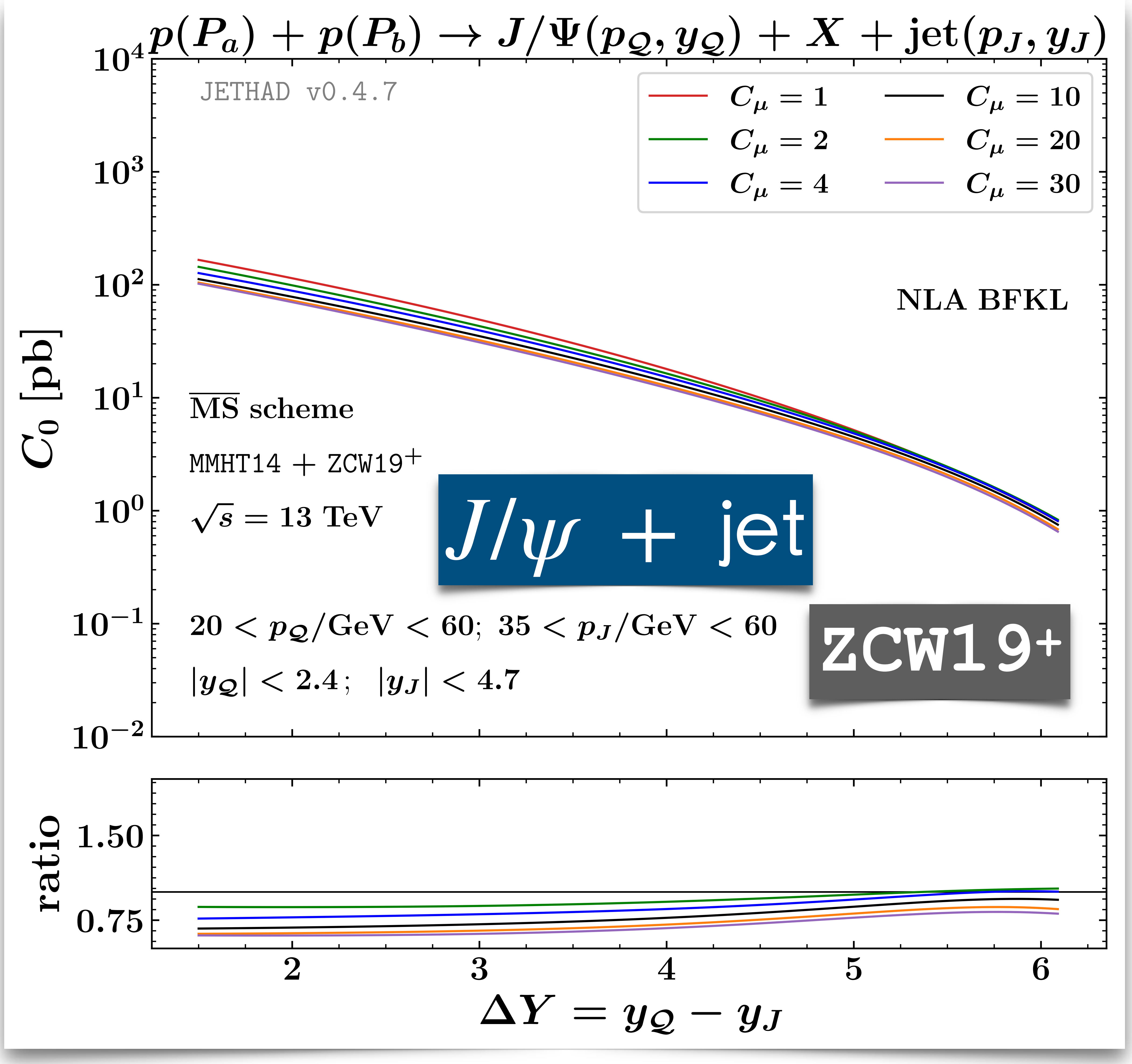
J/ψ collinear FFs

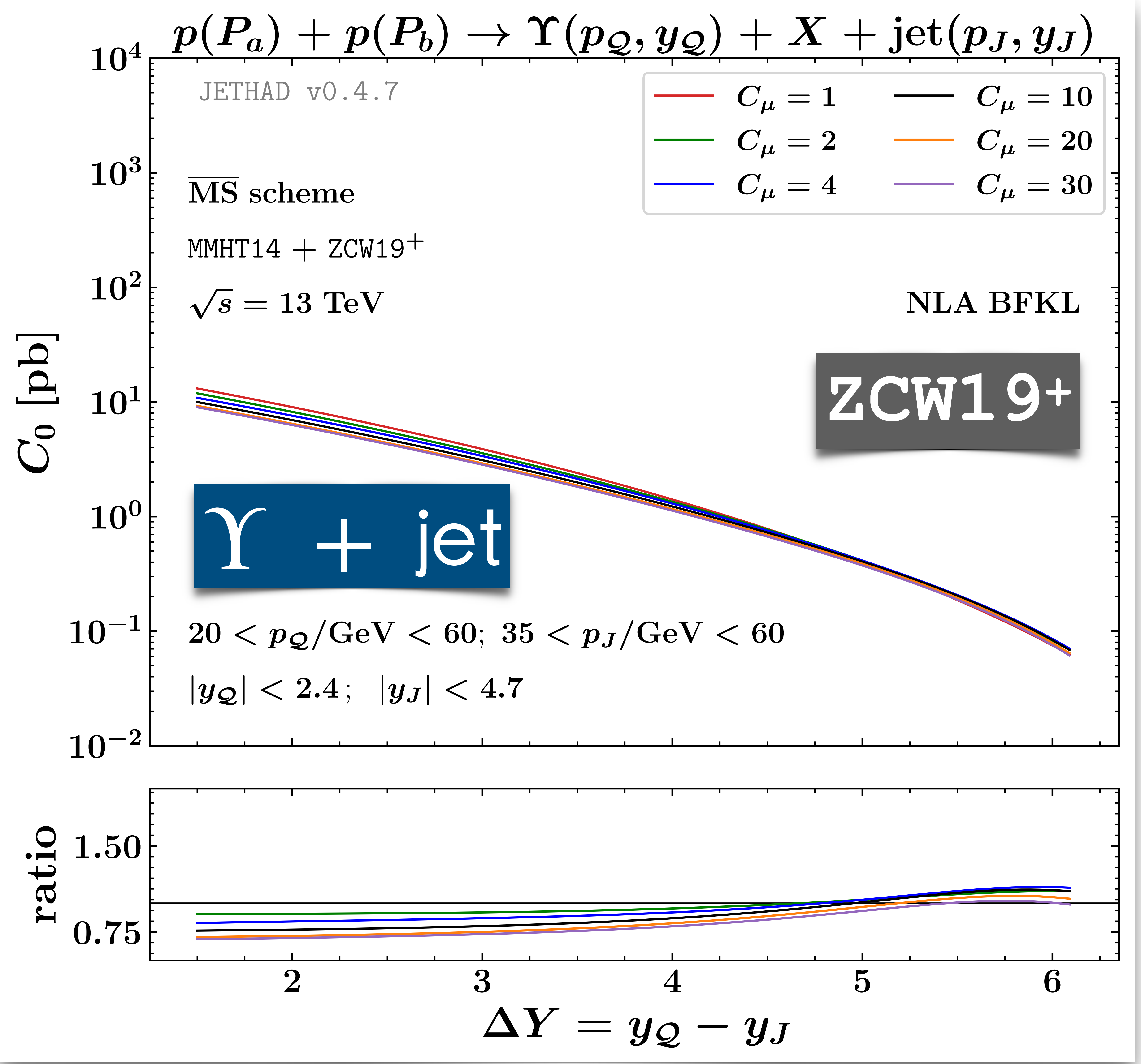




[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

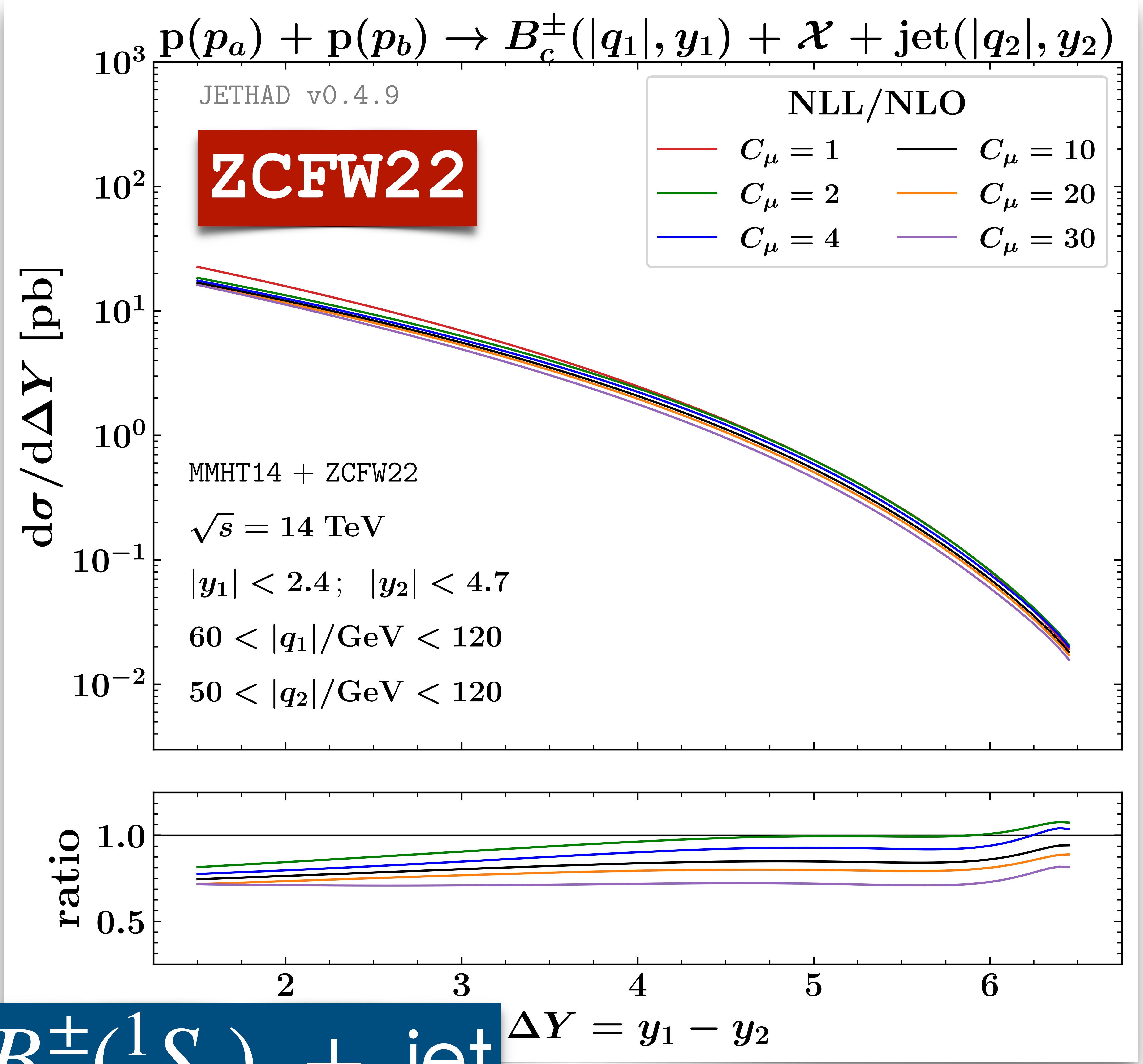
Vector quarkonium + jet at the LHC



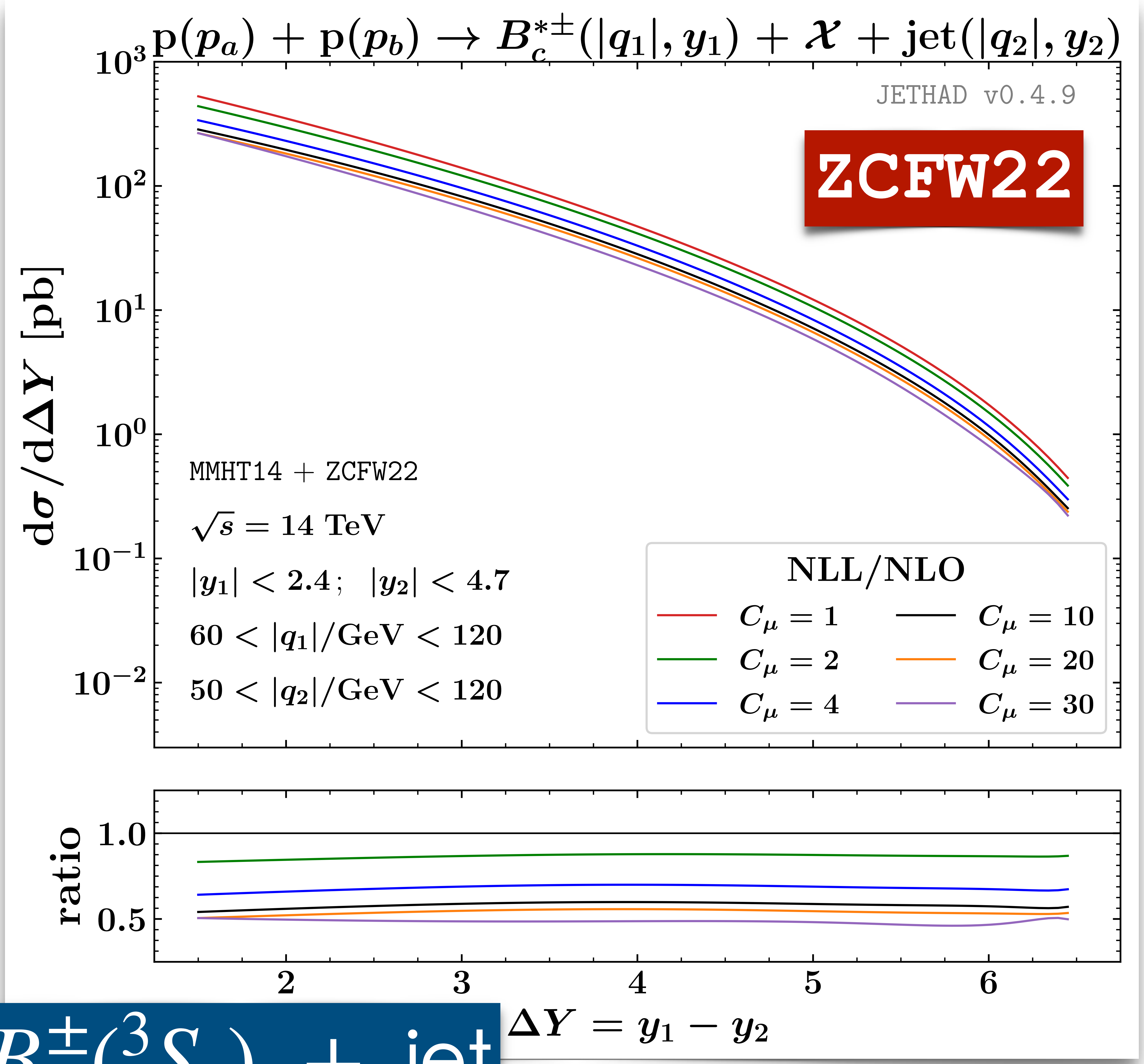


[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

Charmed B-mesons + jet at the HL-LHC



$B_c^{\pm}(^1S_0)$ + jet



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

[F. G. C., under revision (2022)]

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

High-energy physics

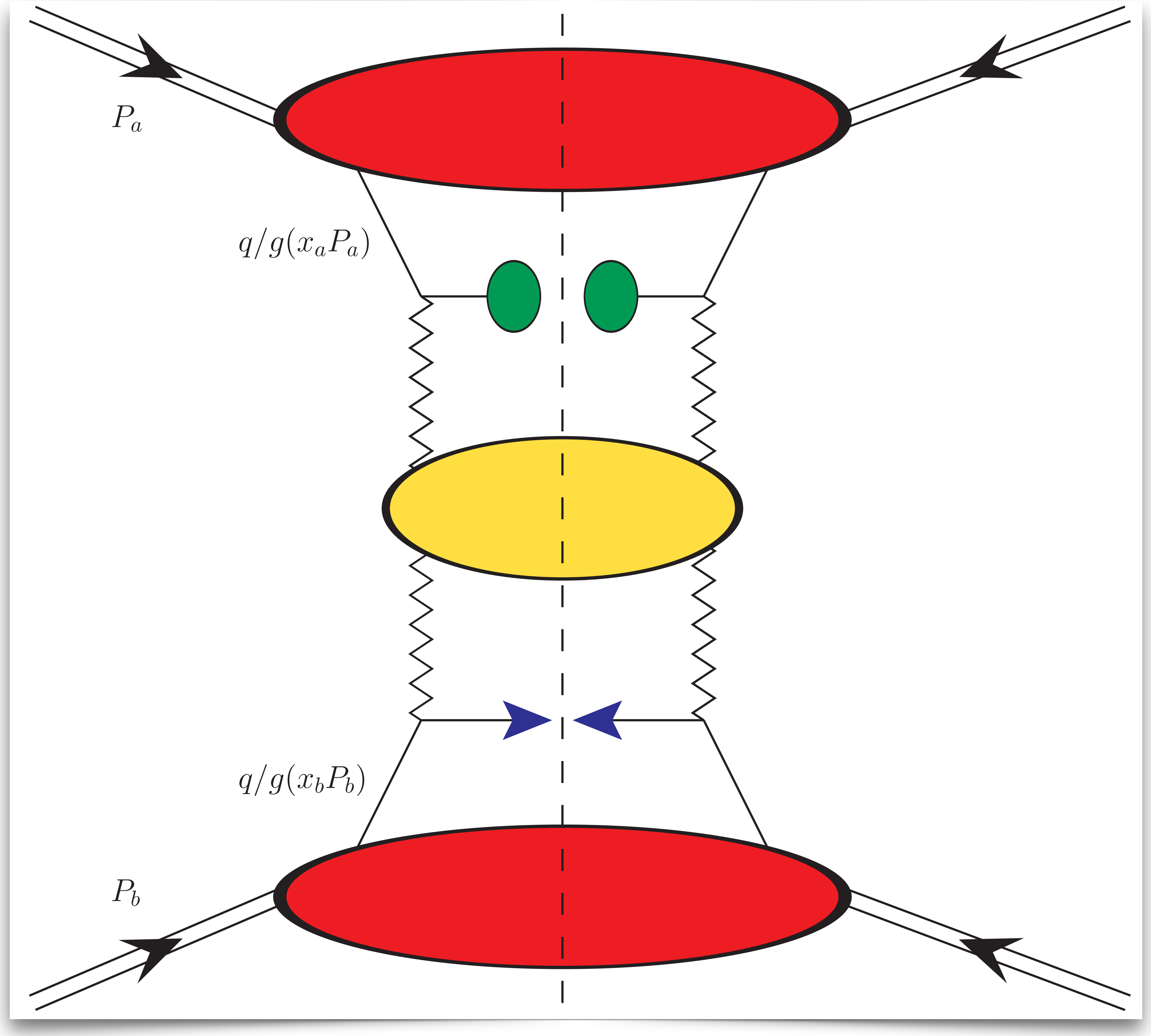
Hadronic structure

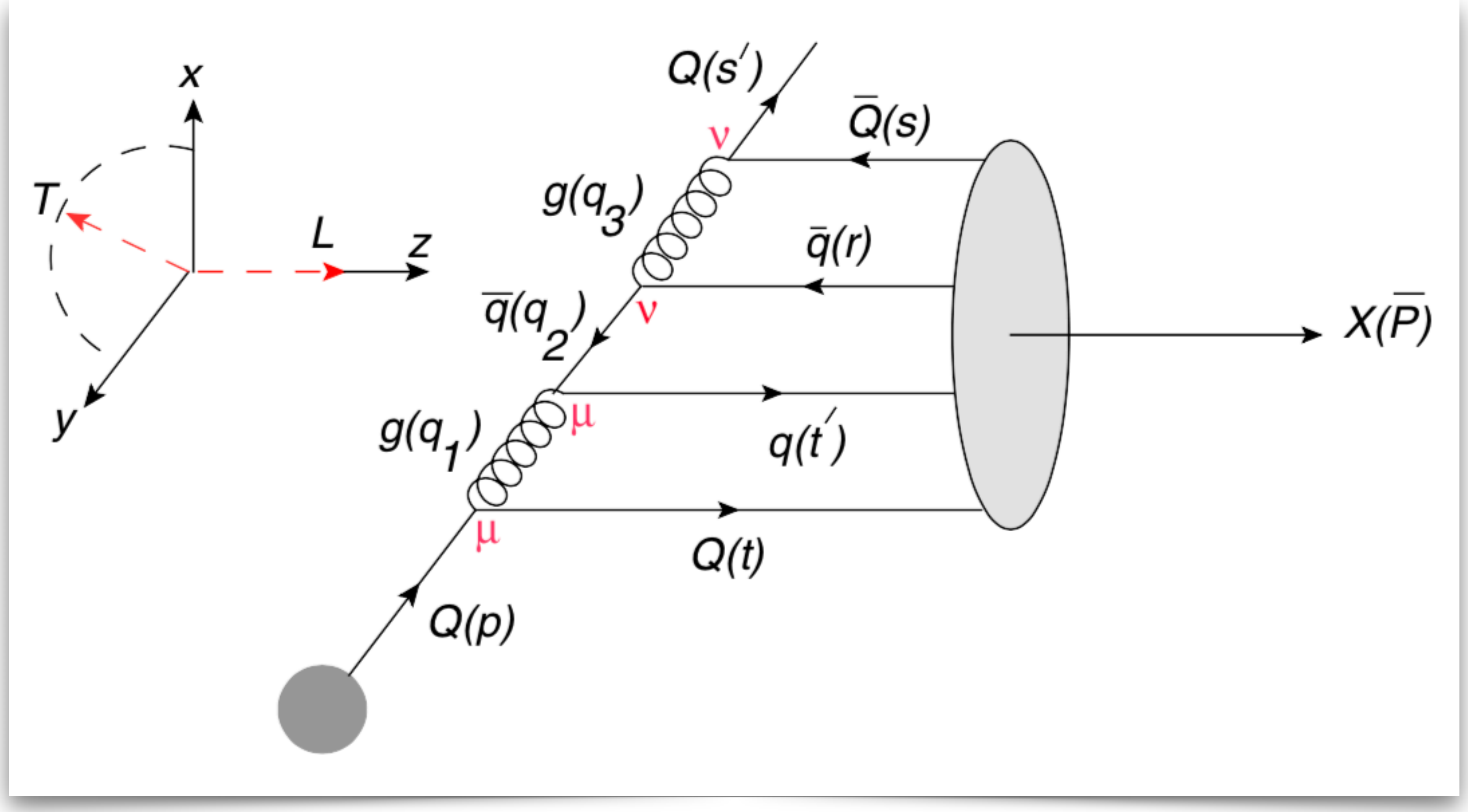
*¿ Might **high-energy QCD** give us **access** to **exotic matter** ?*

- Need for fragmentation mechanisms depicting exotic atoms/molecules/hadrons

Vector quarkonium from single-parton fragmentation

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





[F. G. C., A. Papa, in preparation]

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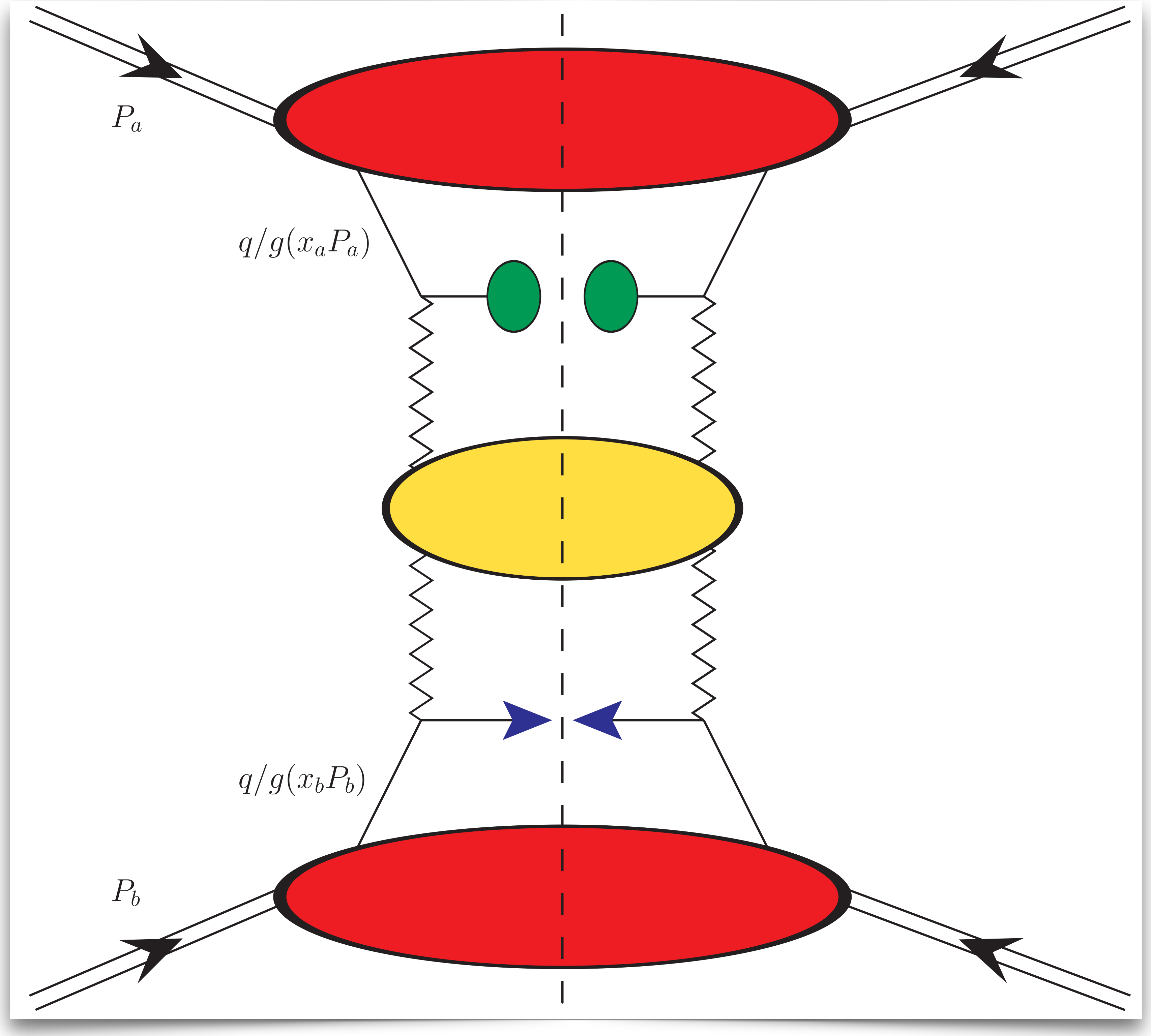
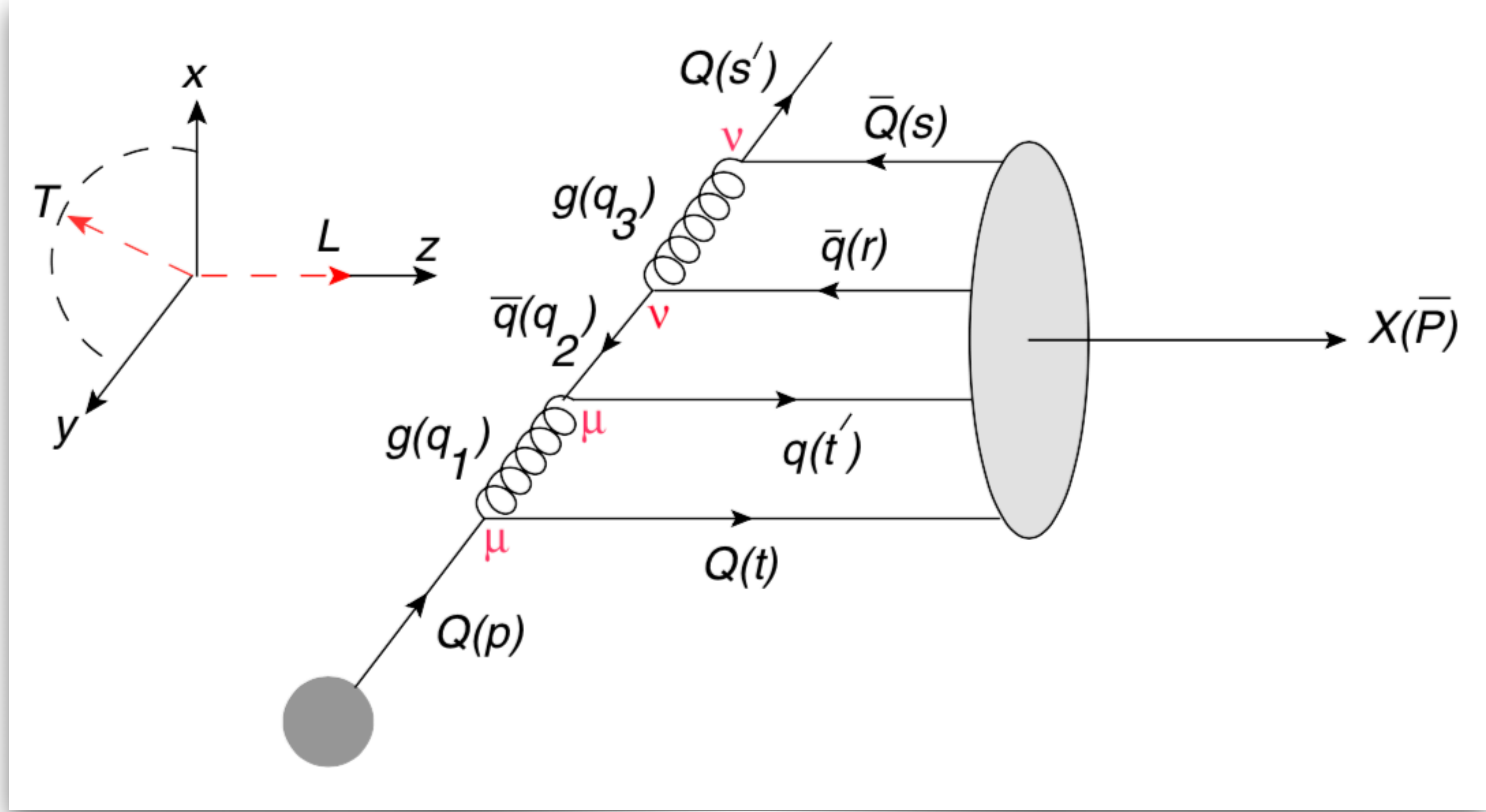


TQHL1.0 FFs: $(Q \to X_{Qq\bar{Q}\bar{q}}) \otimes$ **APFEL++**

$[\mu_0 = m_X + m_Q]$



[F. G. C., A. Papa, in preparation]

S-wave

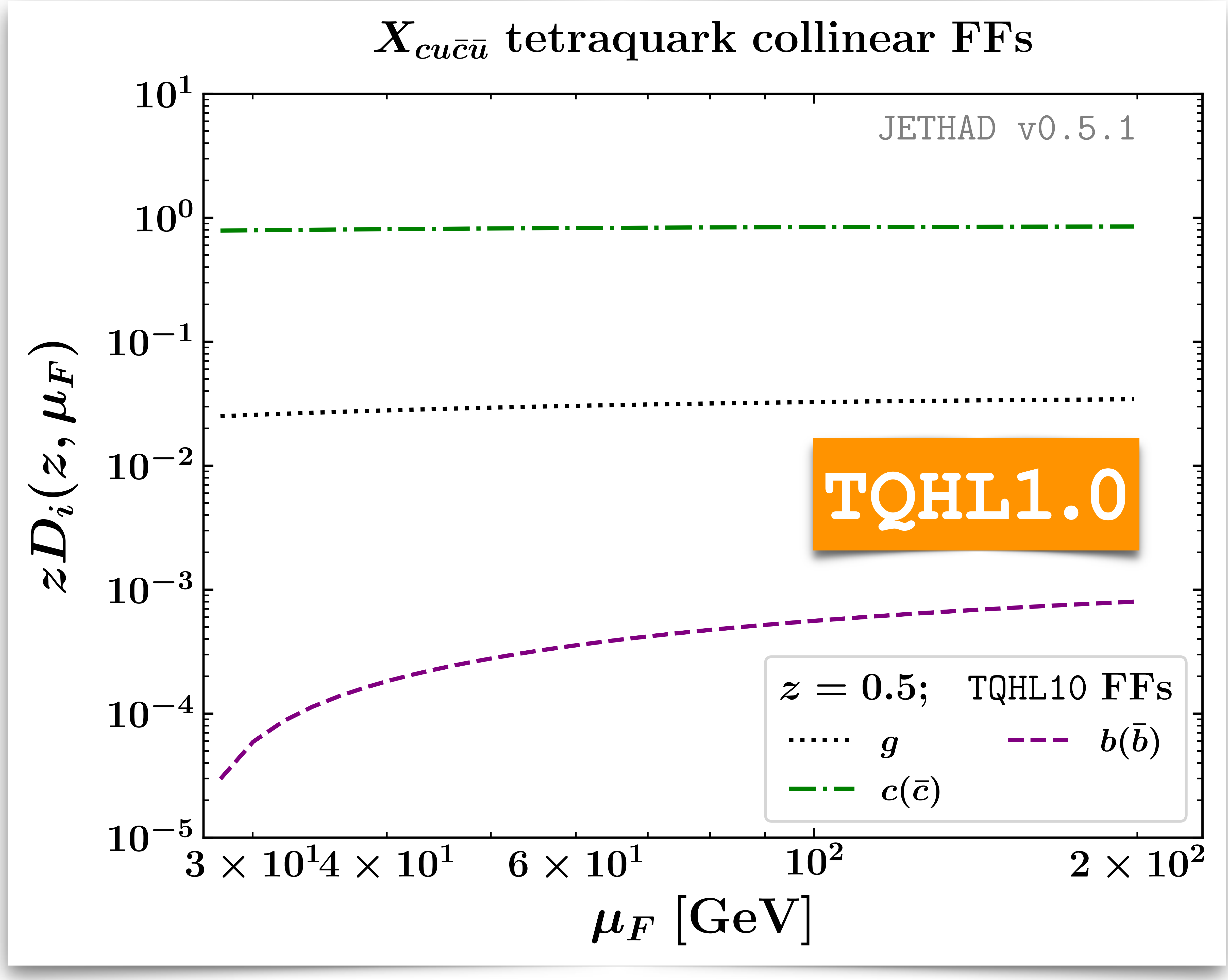
$$D_Q^X(z,\mu_0) = N \frac{z \times \Sigma_{\rm spin}\Gamma\bar{\Gamma}}{(m_X^2 - 2m_Q^2 + 2p\cdot s')^2}$$
$$= N \frac{z \times \Sigma_{\rm spin}\Gamma\bar{\Gamma}}{[m_X^2 - (m_Q^2 + \langle p_T^2\rangle)(1 + z - \frac{1}{1-z})]^2}$$

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

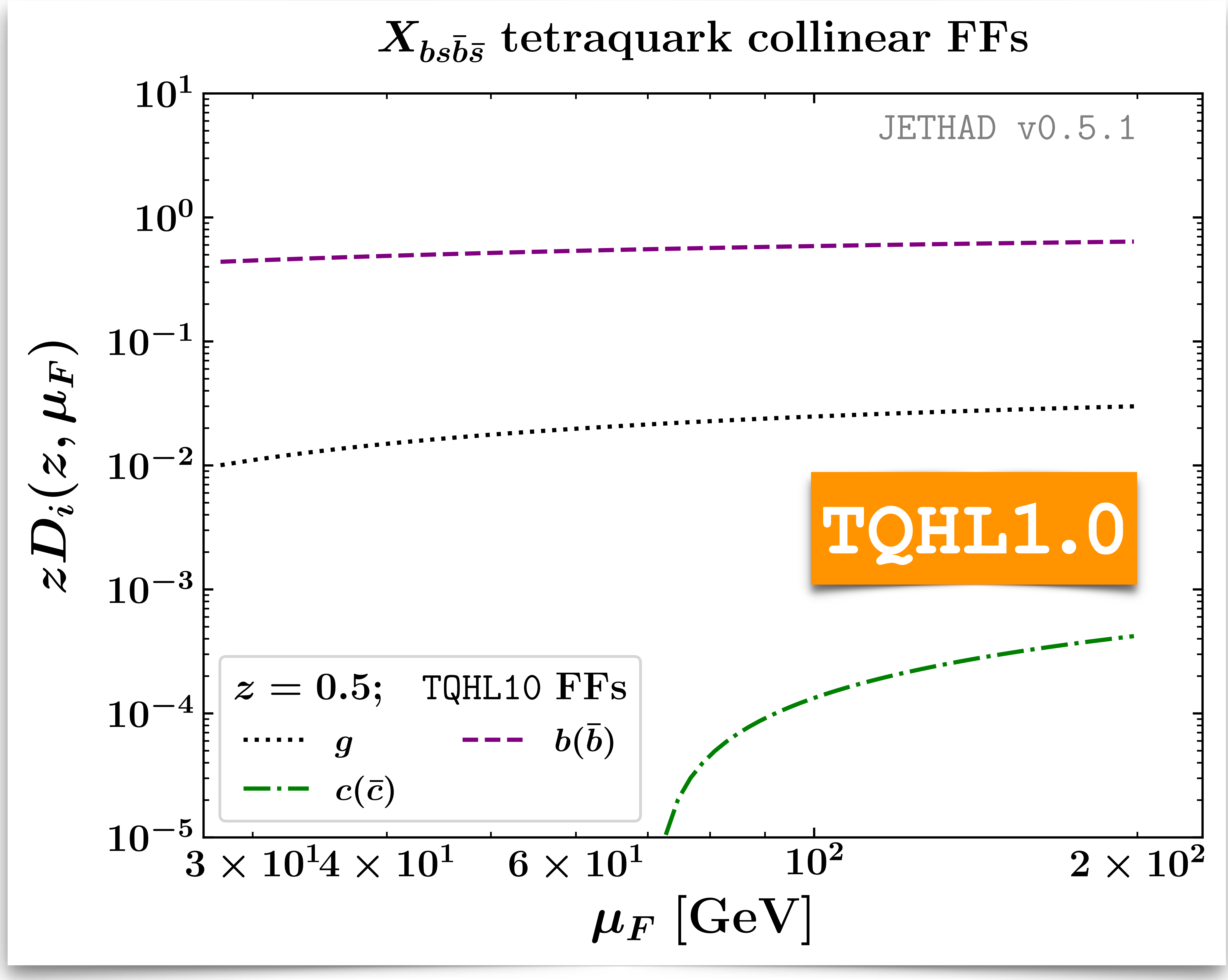
(framework) 🔗 [M. Suzuki, Phys. Rev. D 33 (1986) 676]

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, in preparation]

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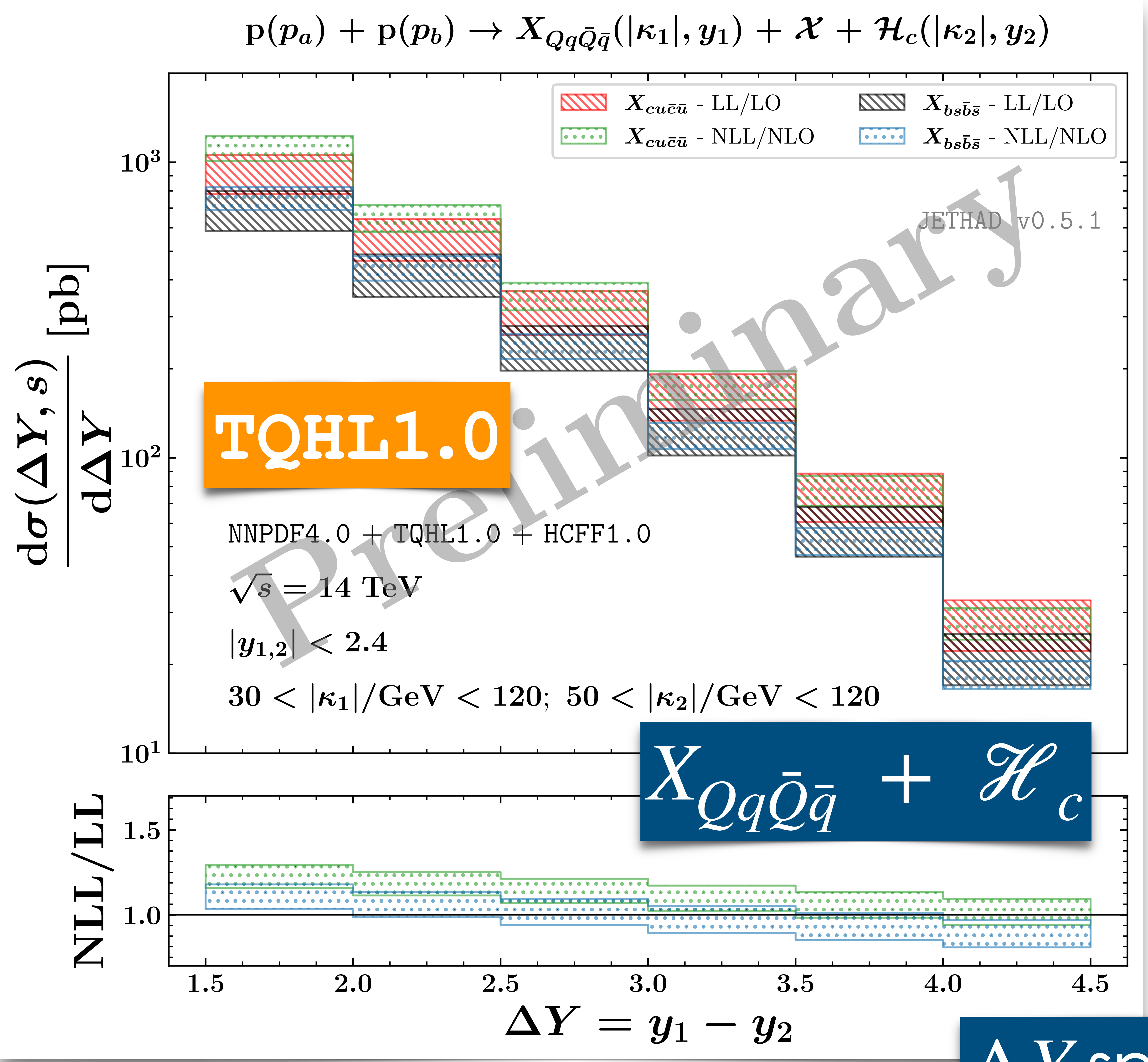

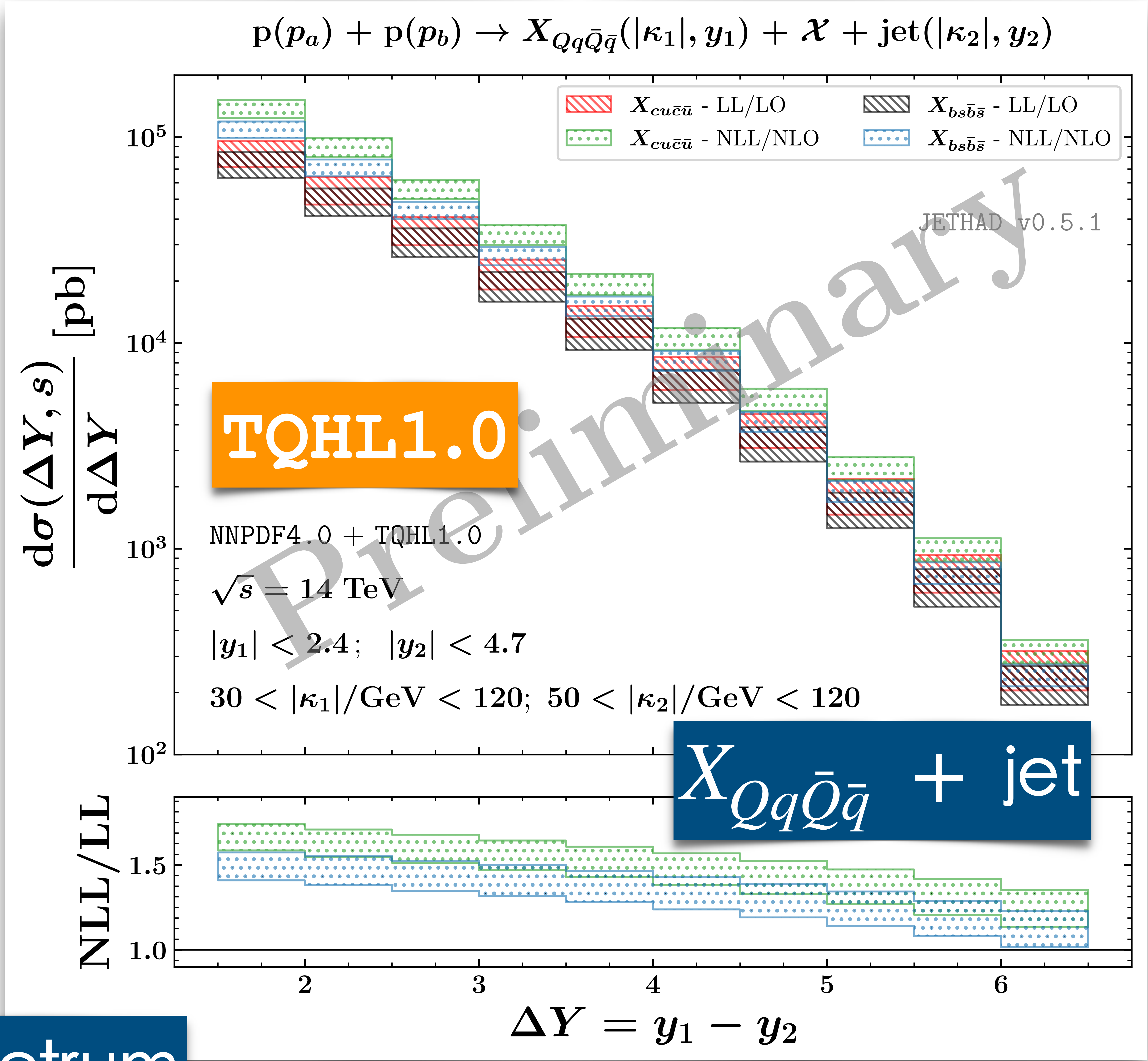

ΔY spectrum

[F. G. C., A. Papa, in preparation]

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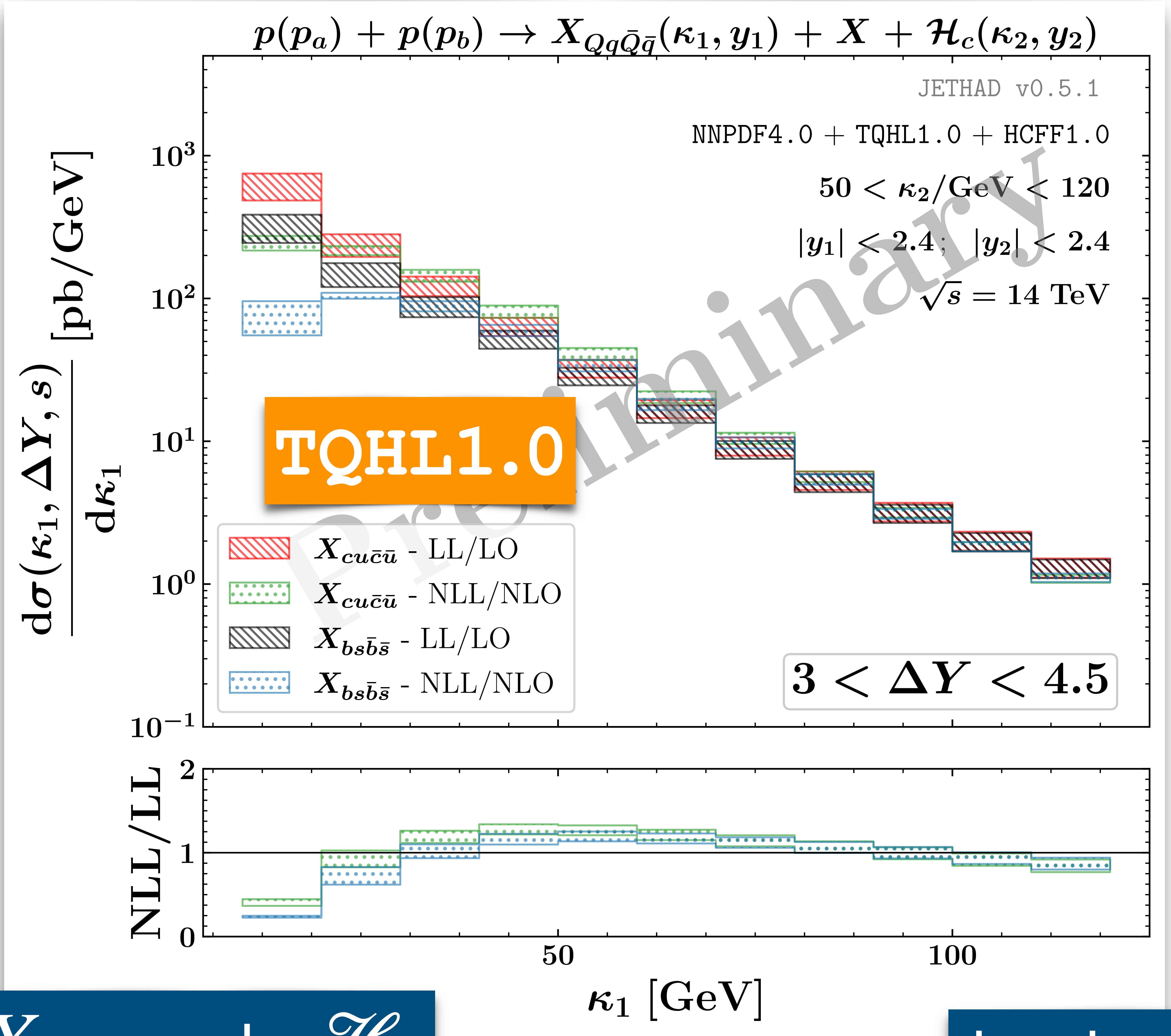
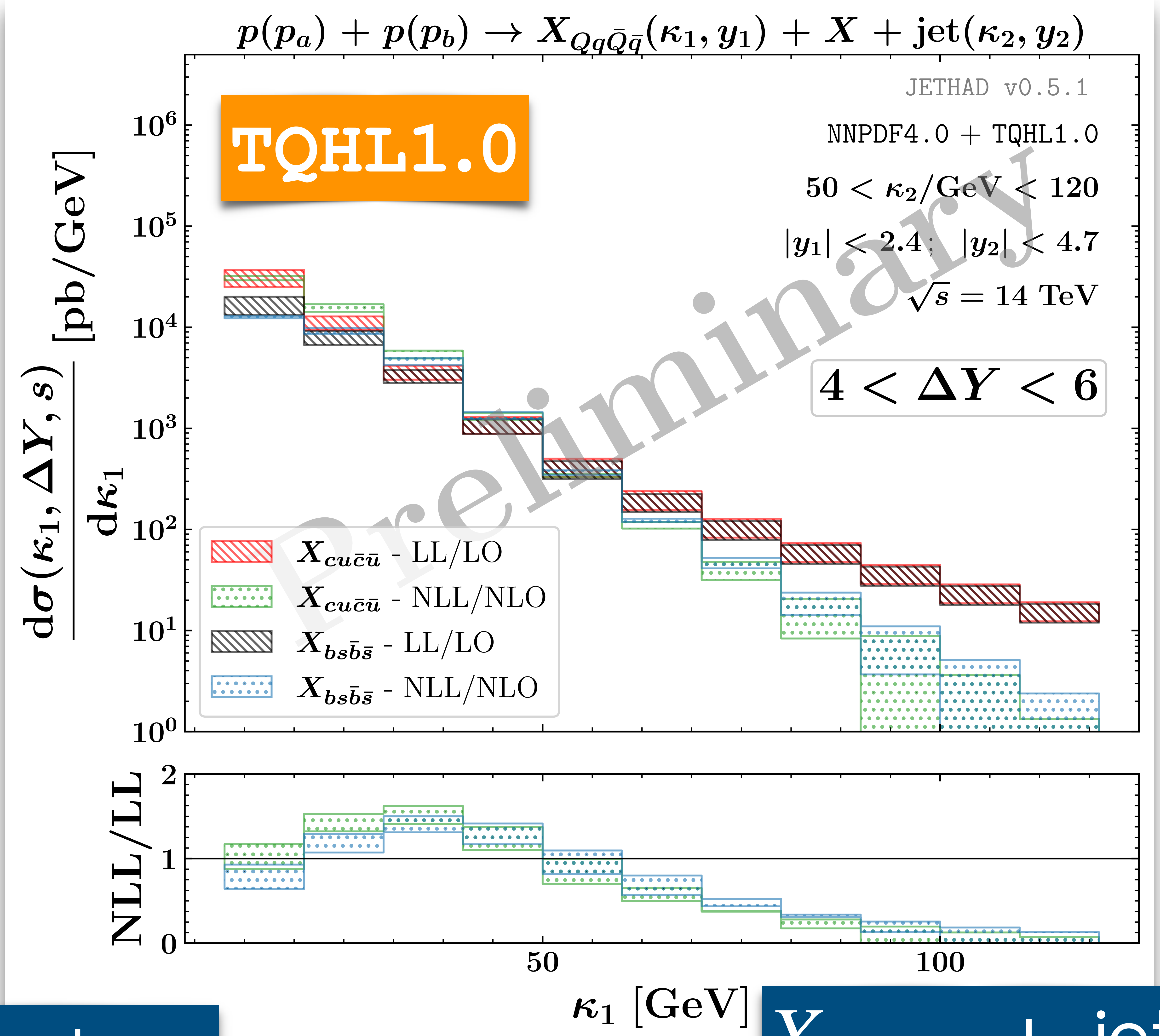




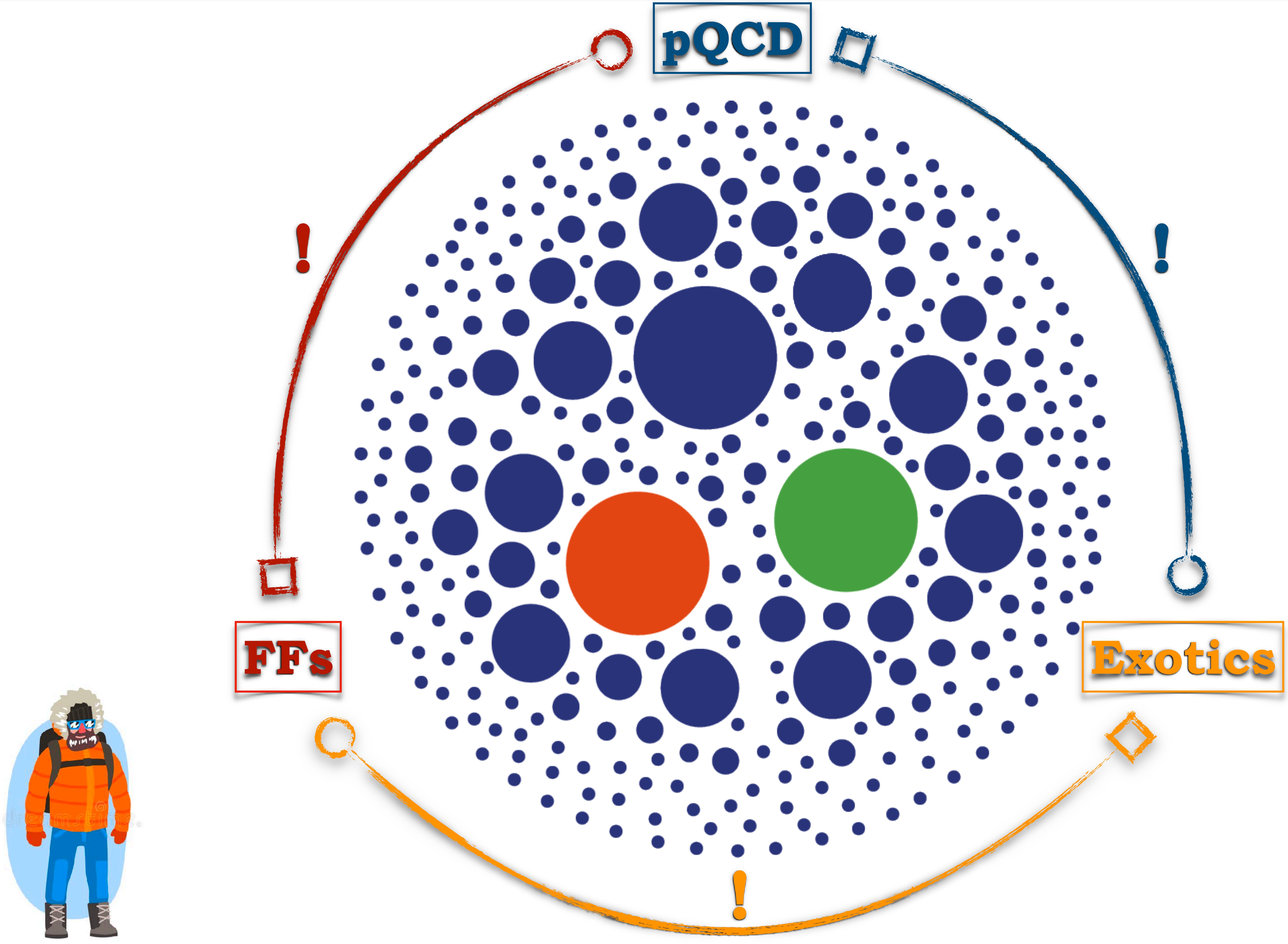
$X_{Qq\bar{Q}\bar{q}} + \mathcal{H}_c$

$|\kappa_1|$ spectrum

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

[F. G. C., A. Papa, in preparation]

Shedding light on exotic matter...



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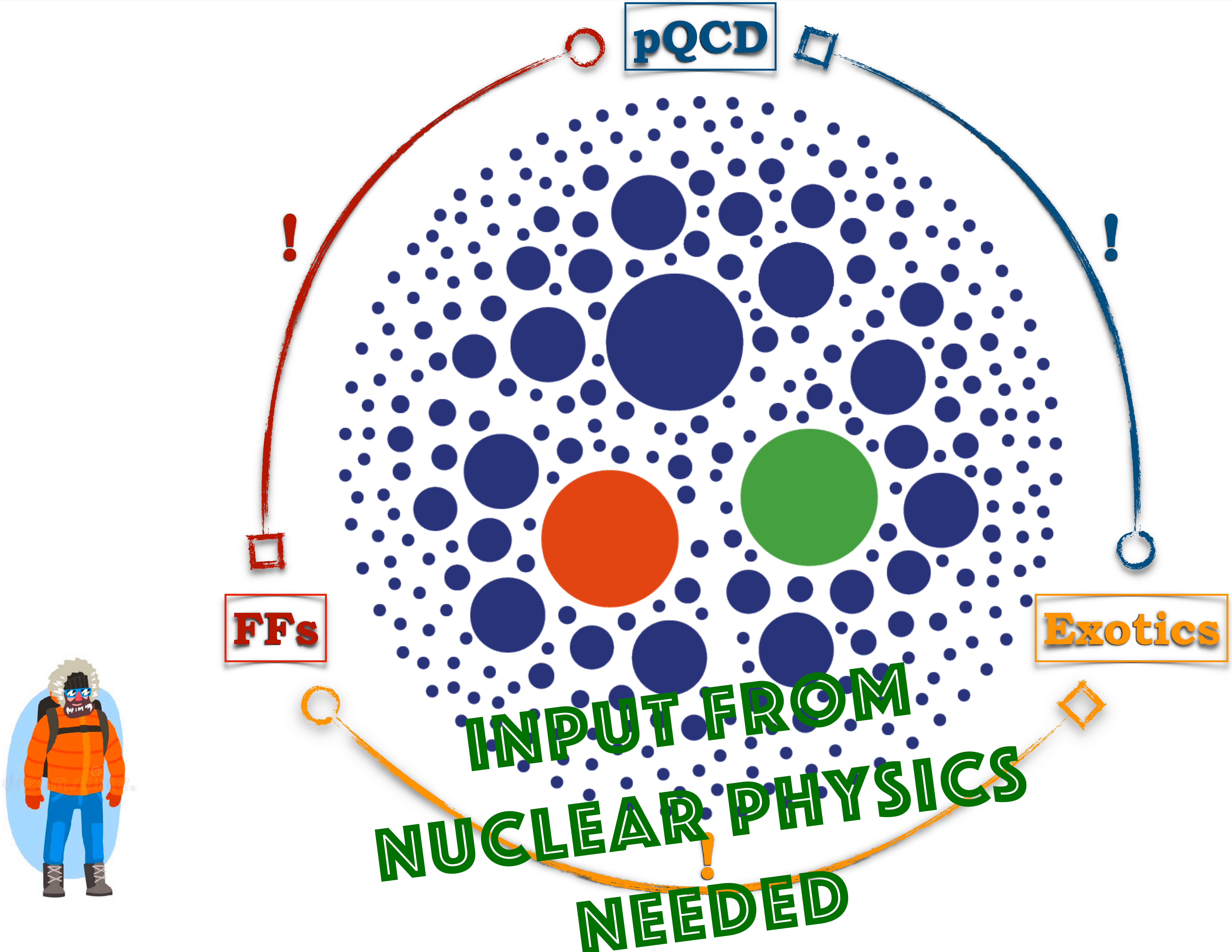

Extras

Mueller-Navelet jets & resummation instabilities

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

Backup

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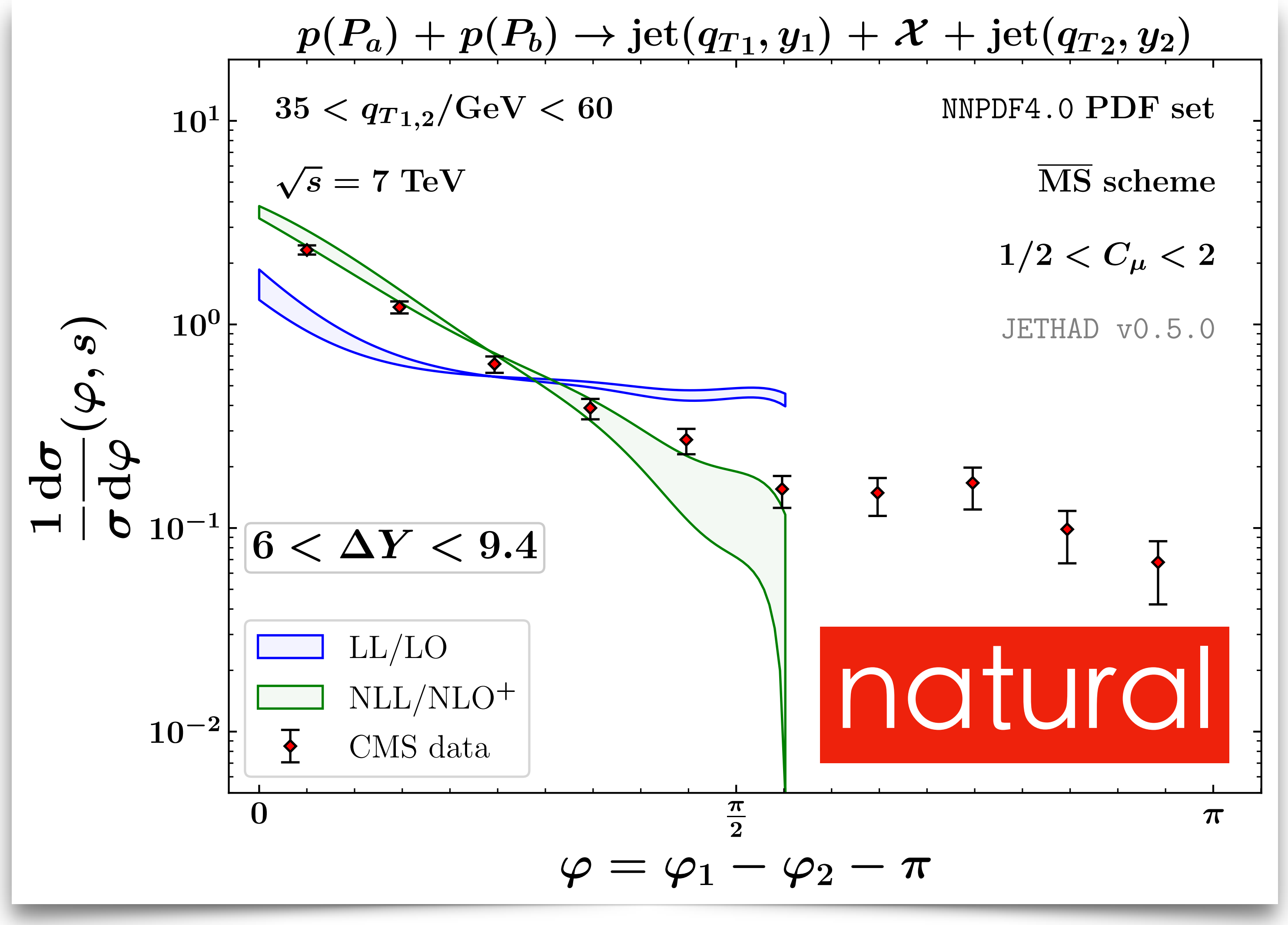
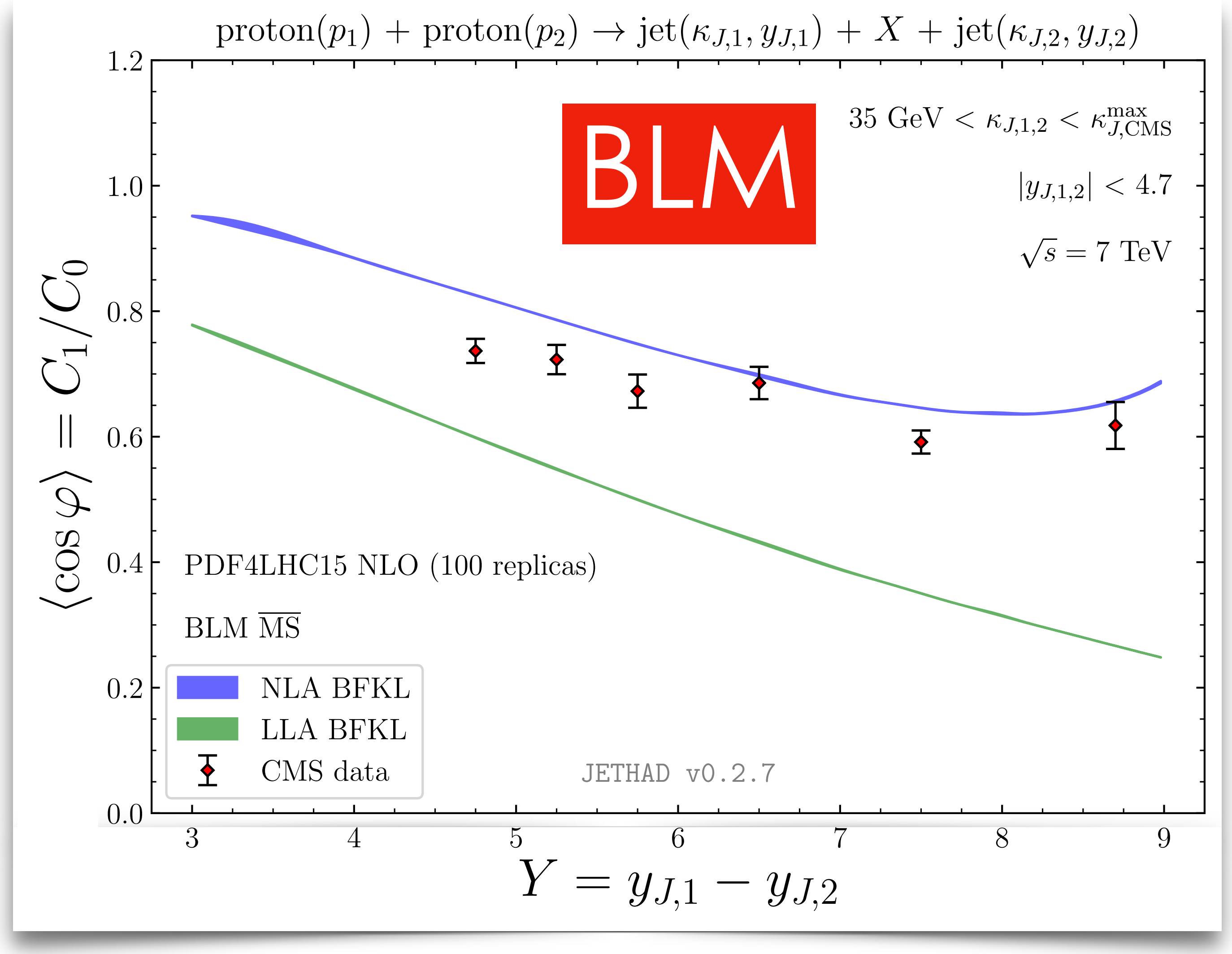
[B. Murdaca et al., Eur. Phys. J. C 74 (2014) 10, 3084]





(left figure) [F. G. C., A. Papa (2022)]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Backup

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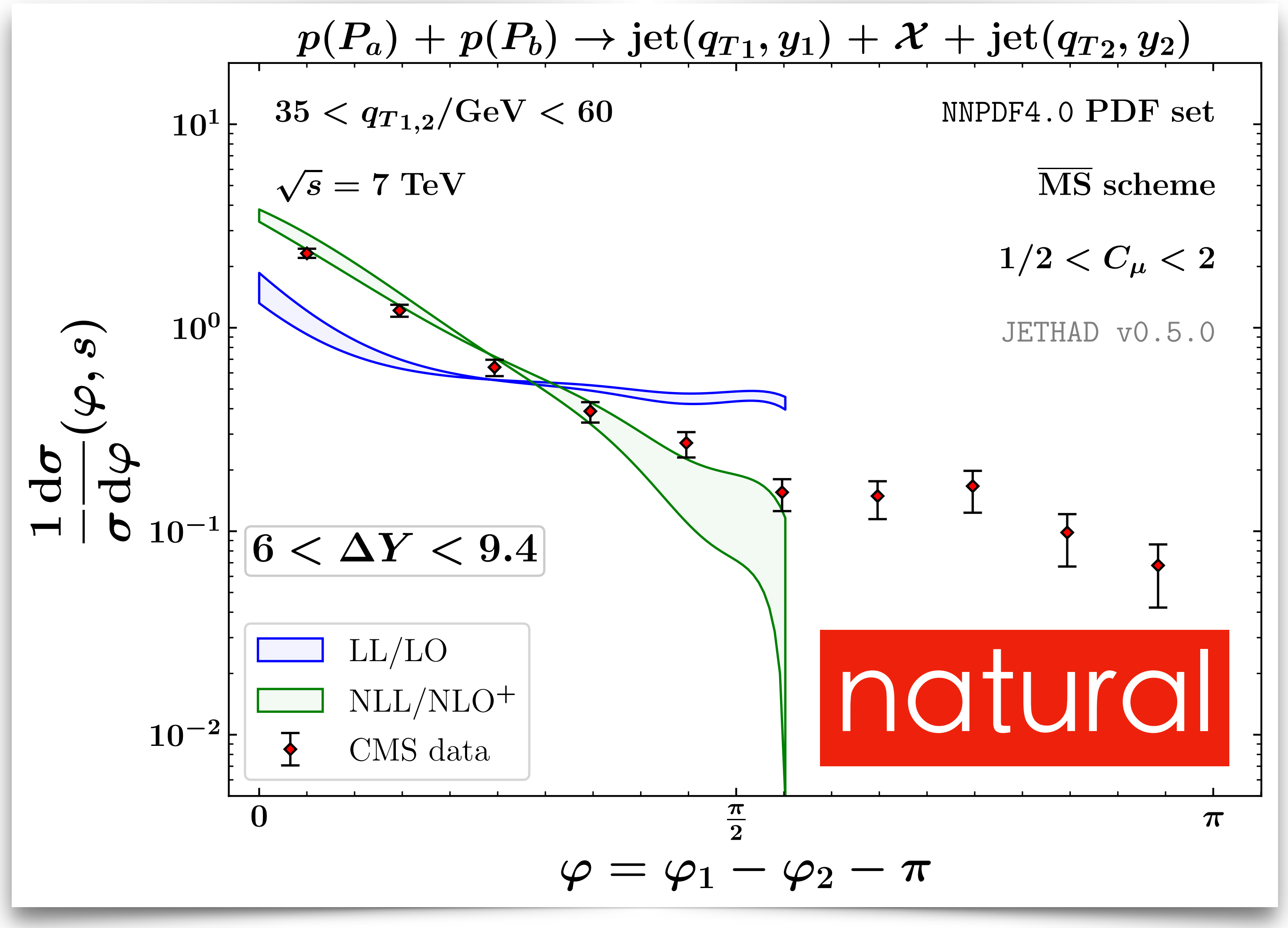
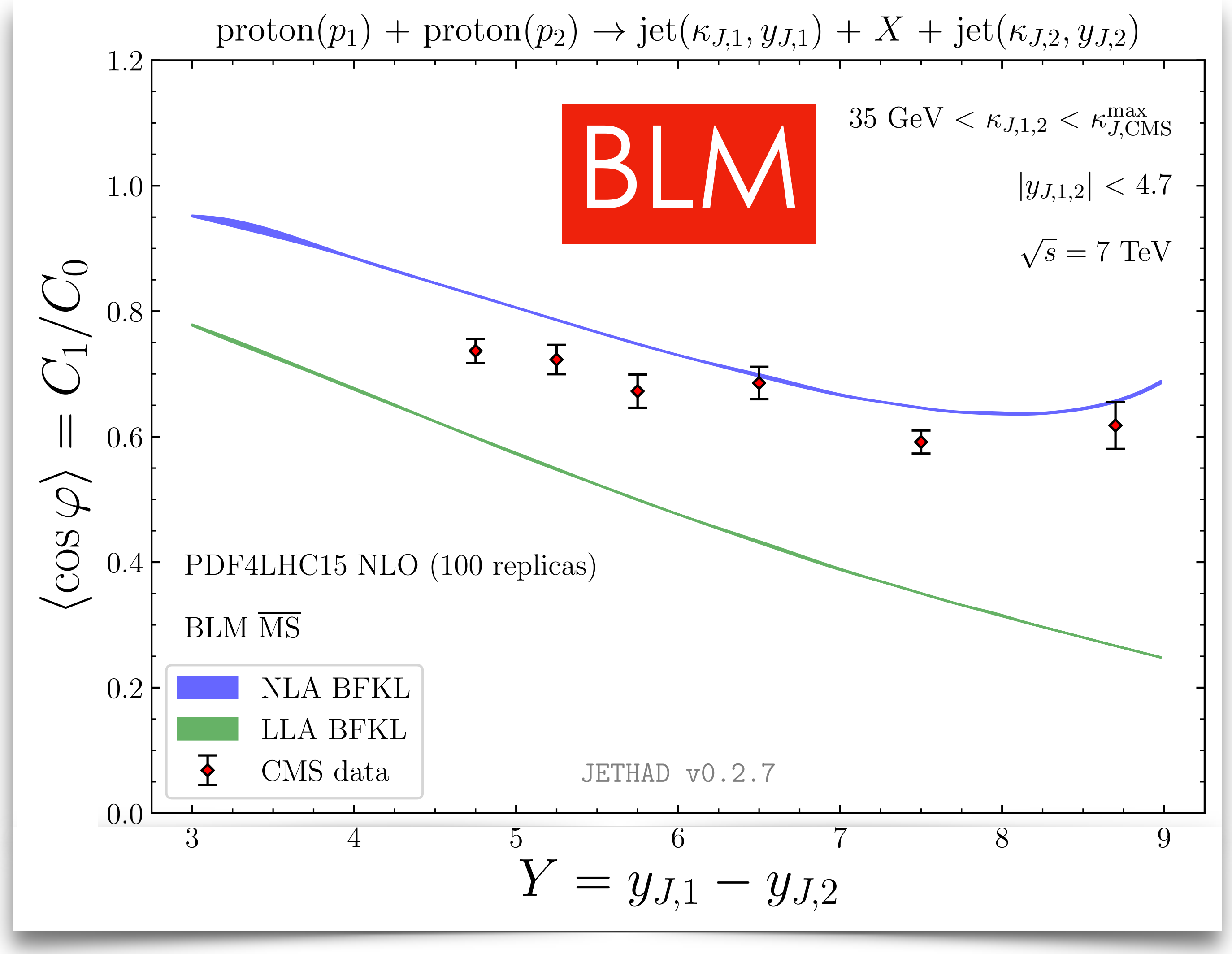




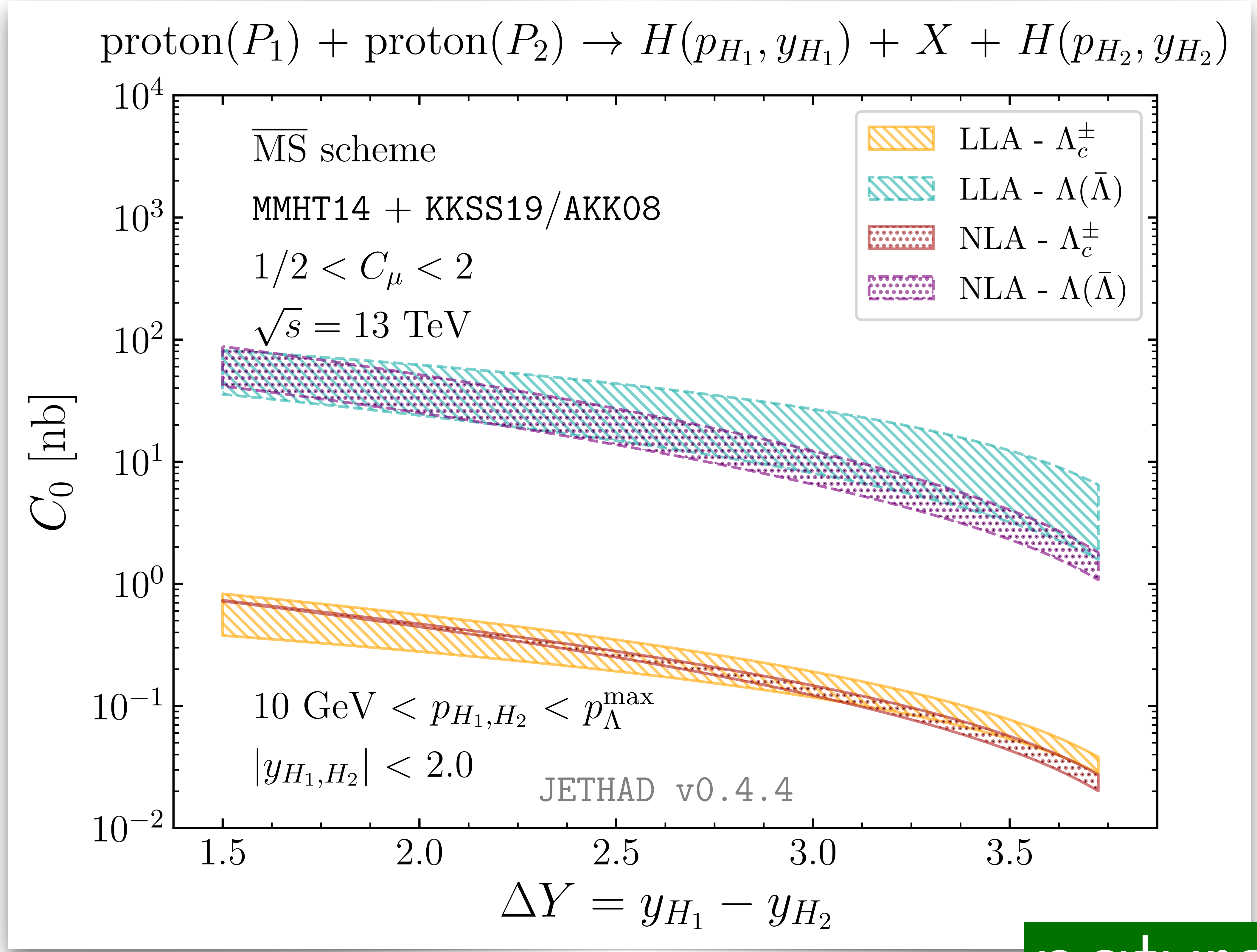
(left figure) [F. G. C., A. Papa (2022)]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

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

Backup

Stability under scale variations & NLL corrections

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



natural

Backup

Stability under scale variations & NLL corrections

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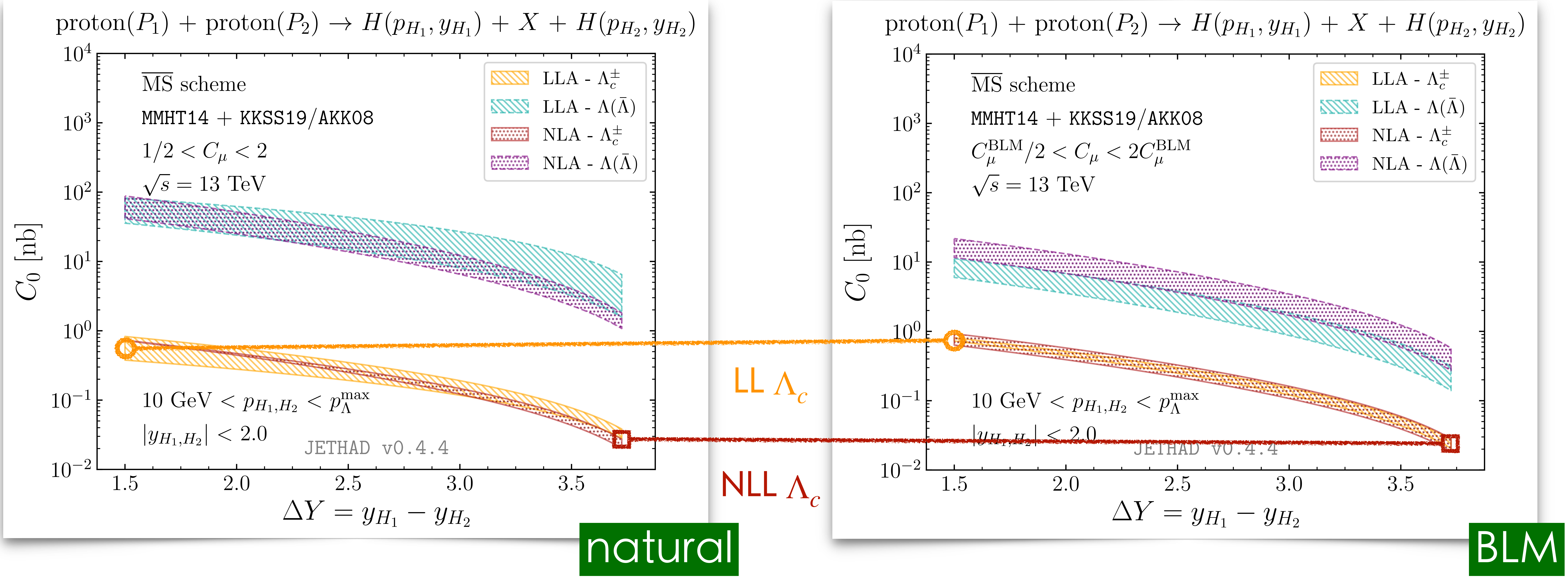

- NLL corrections: rapidity distribution stable for Λ_c

(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]

Backup

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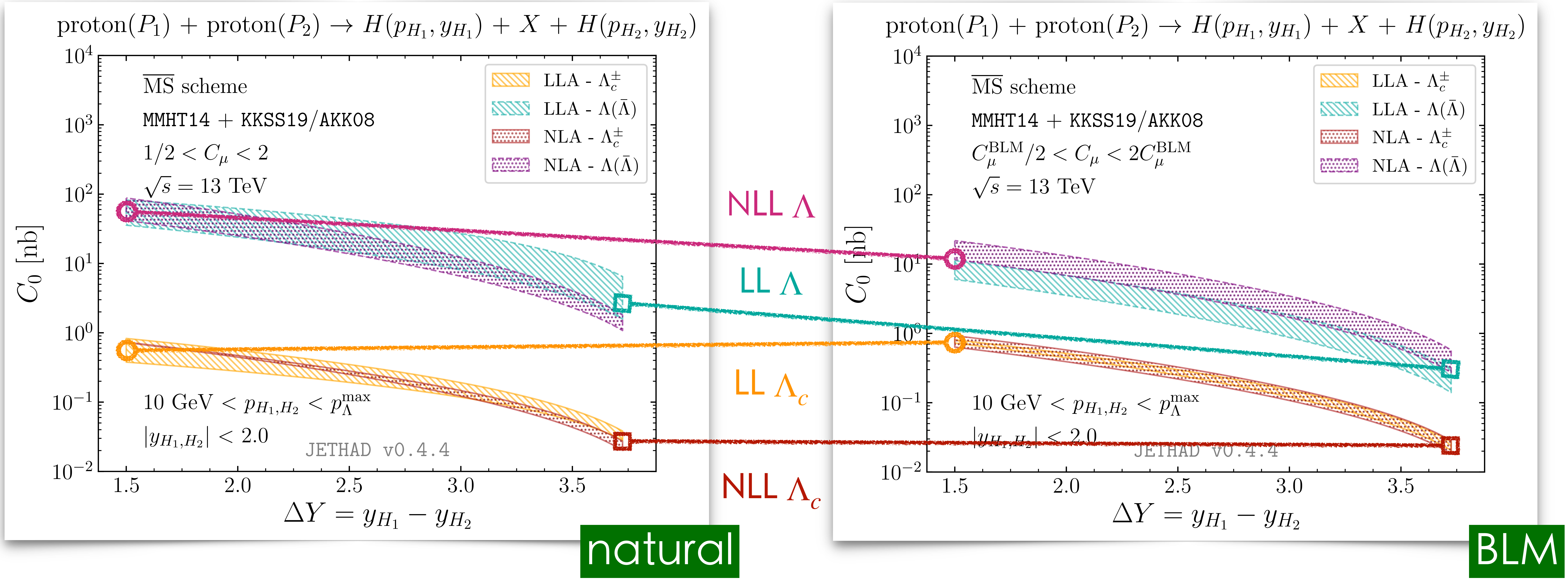

NLL corrections: rapidity distribution stable for Λ_c, loses $\sim 10^1$ magnitude for Λ

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

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Backup

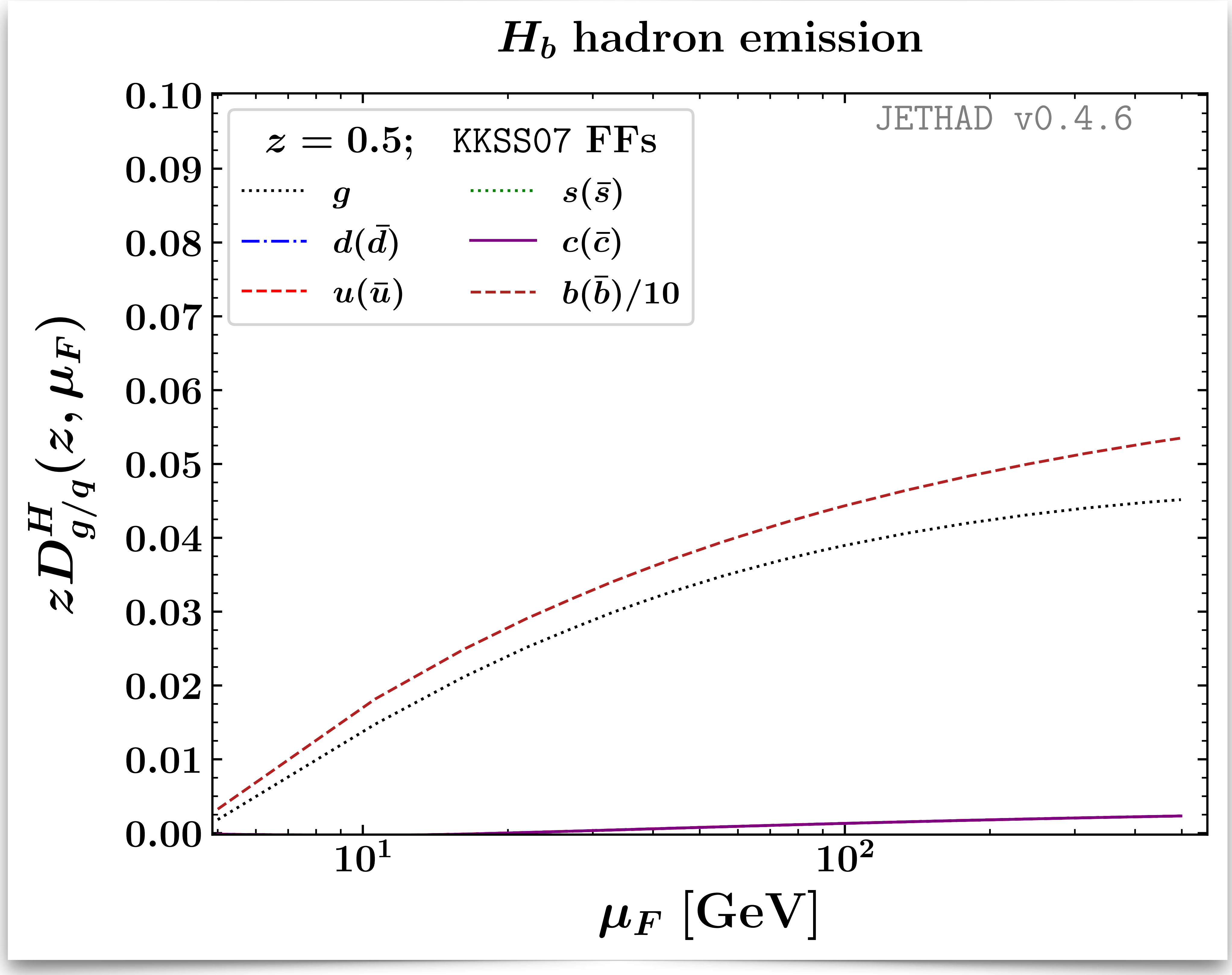
Stabilizing effects of heavy-flavor fragmentation

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]

[B. A. Kniehl et al., Phys. Rev. D 77 (2008) 11, 014011]



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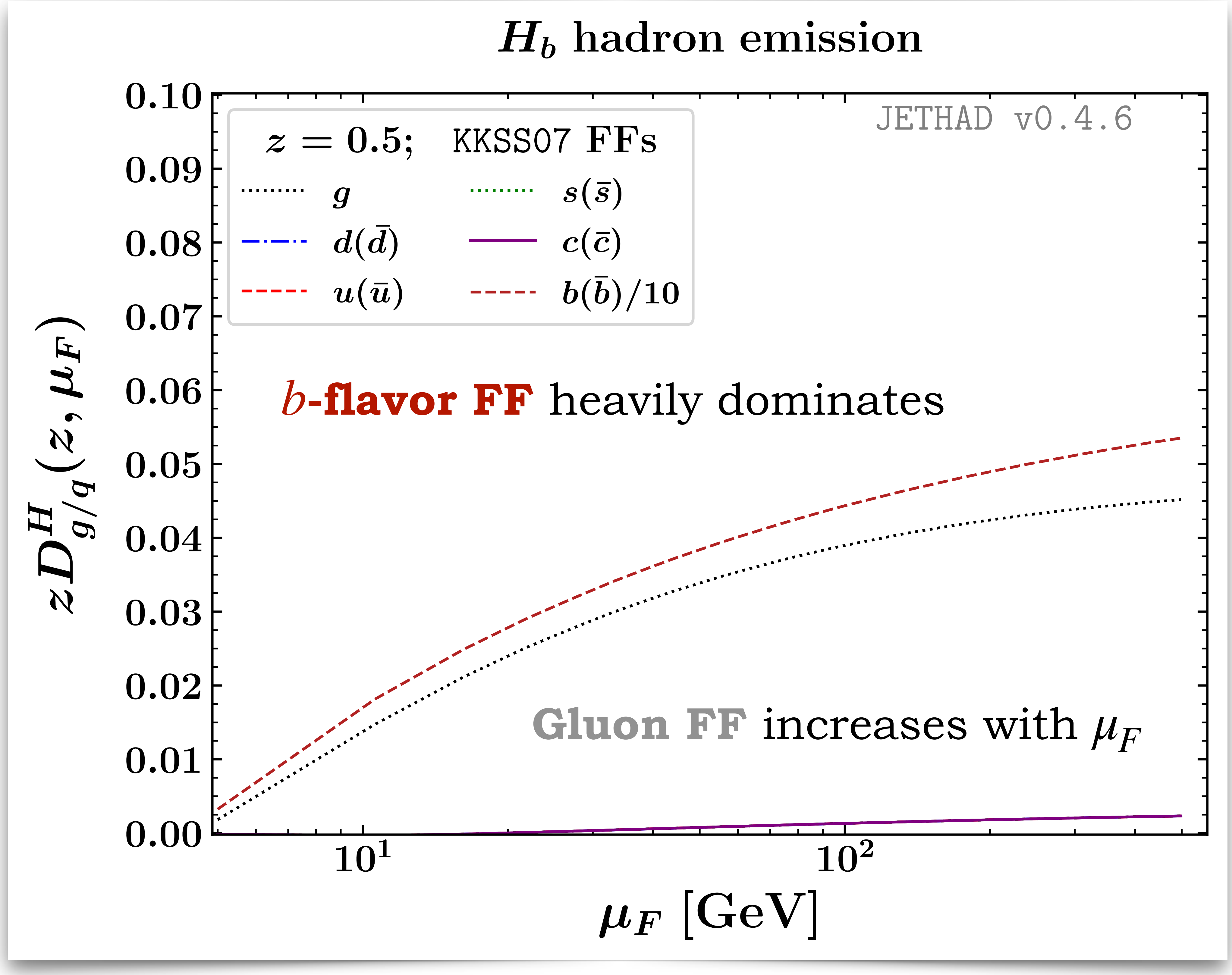

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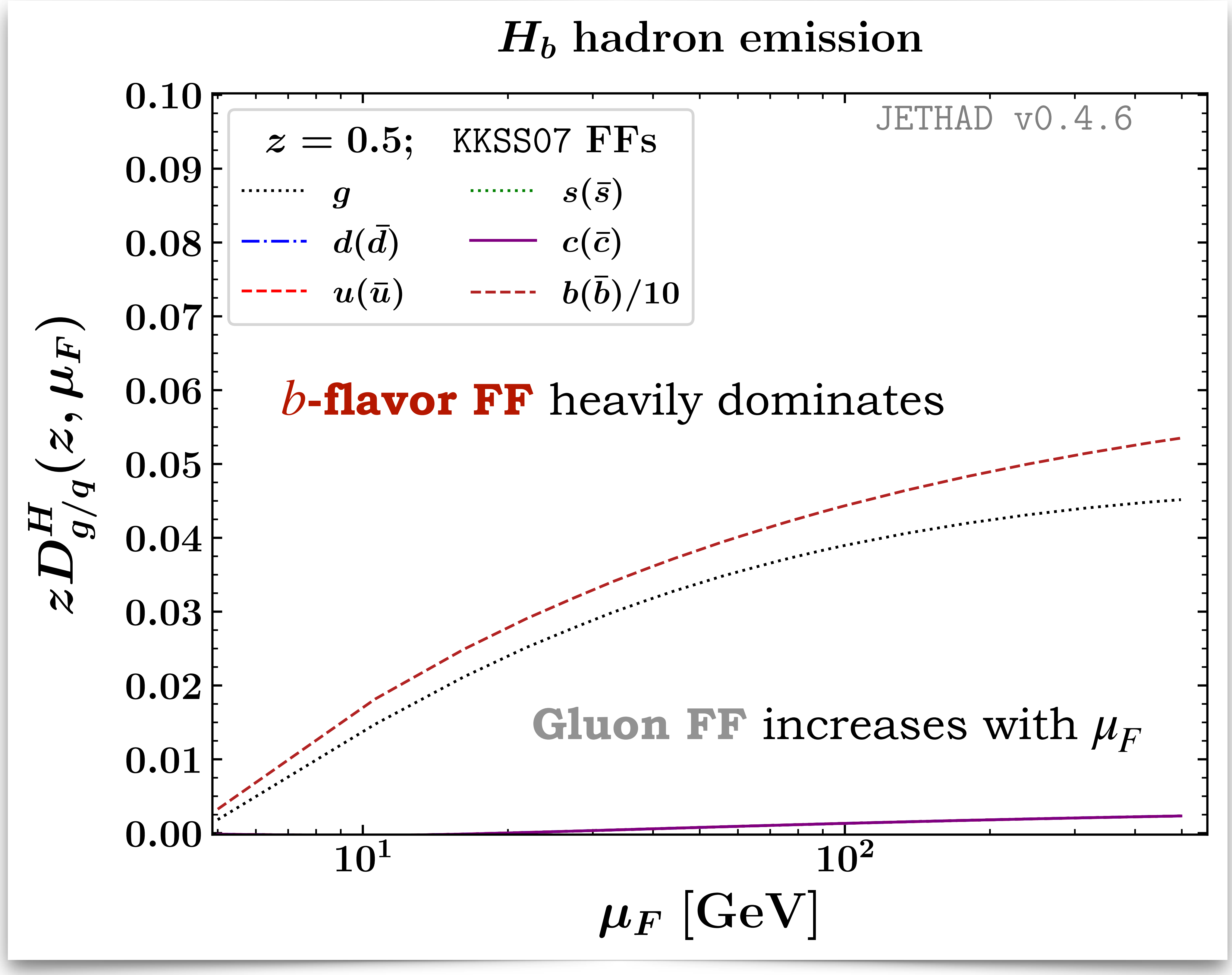
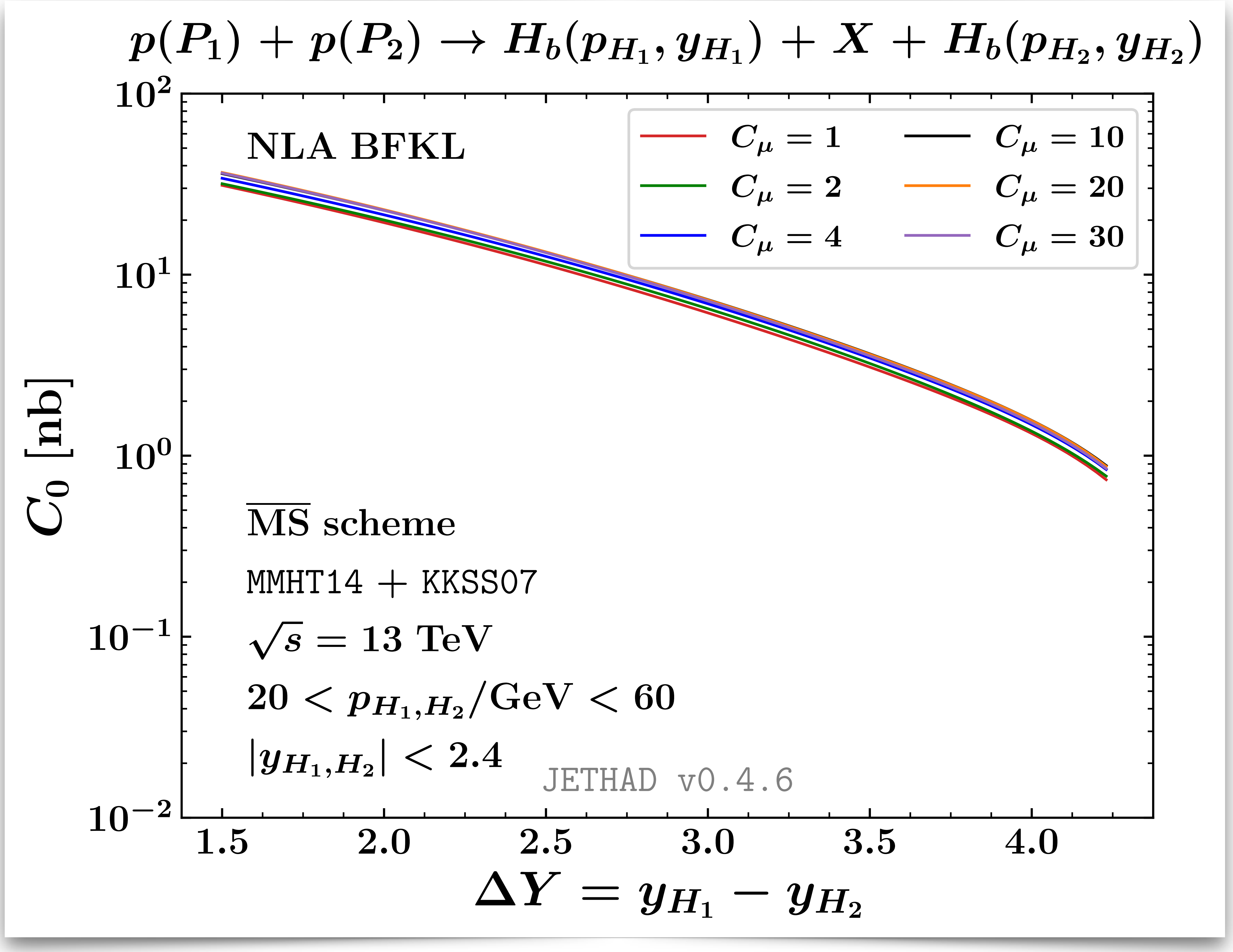




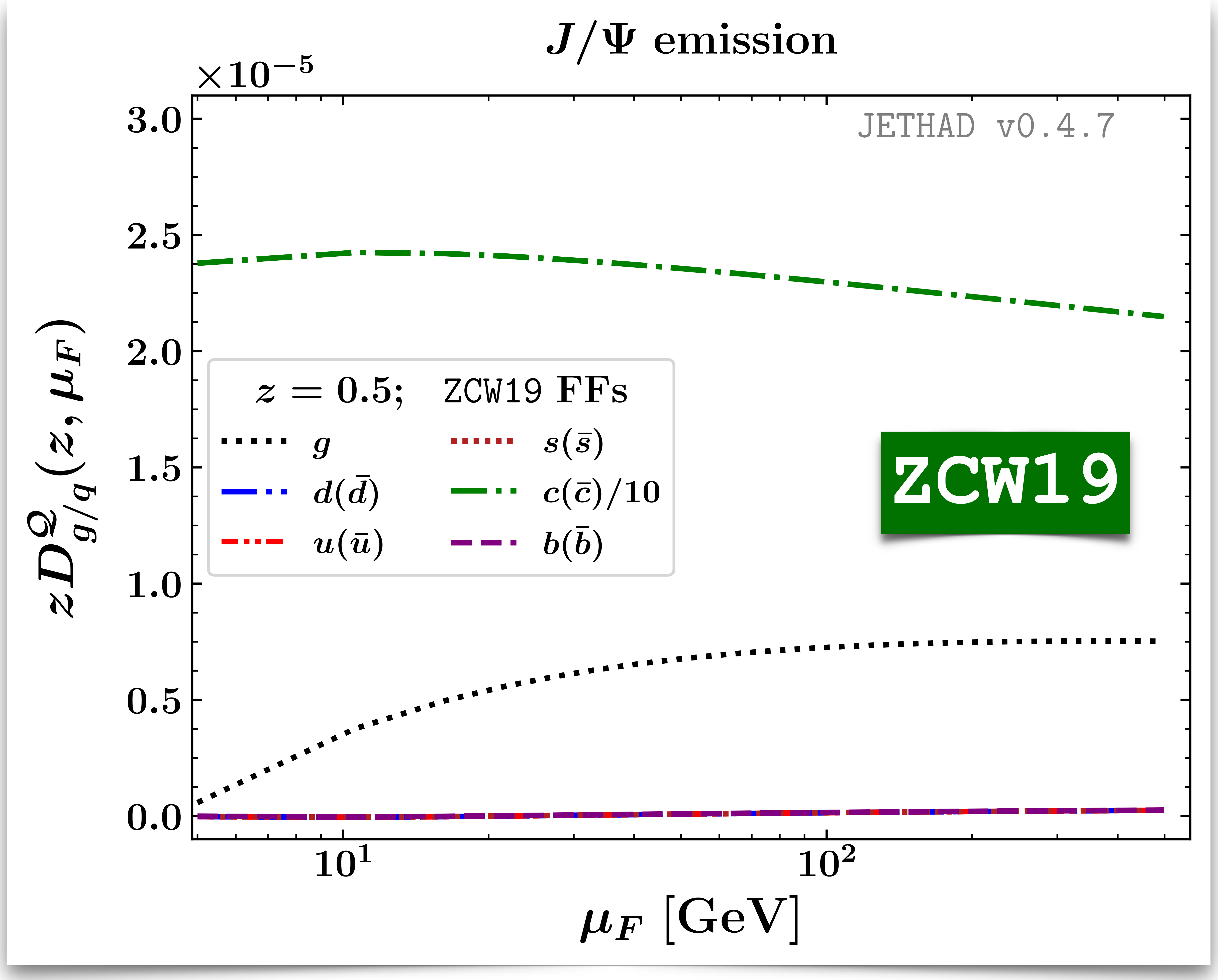
Rapidity distribution very stable under scale variations

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

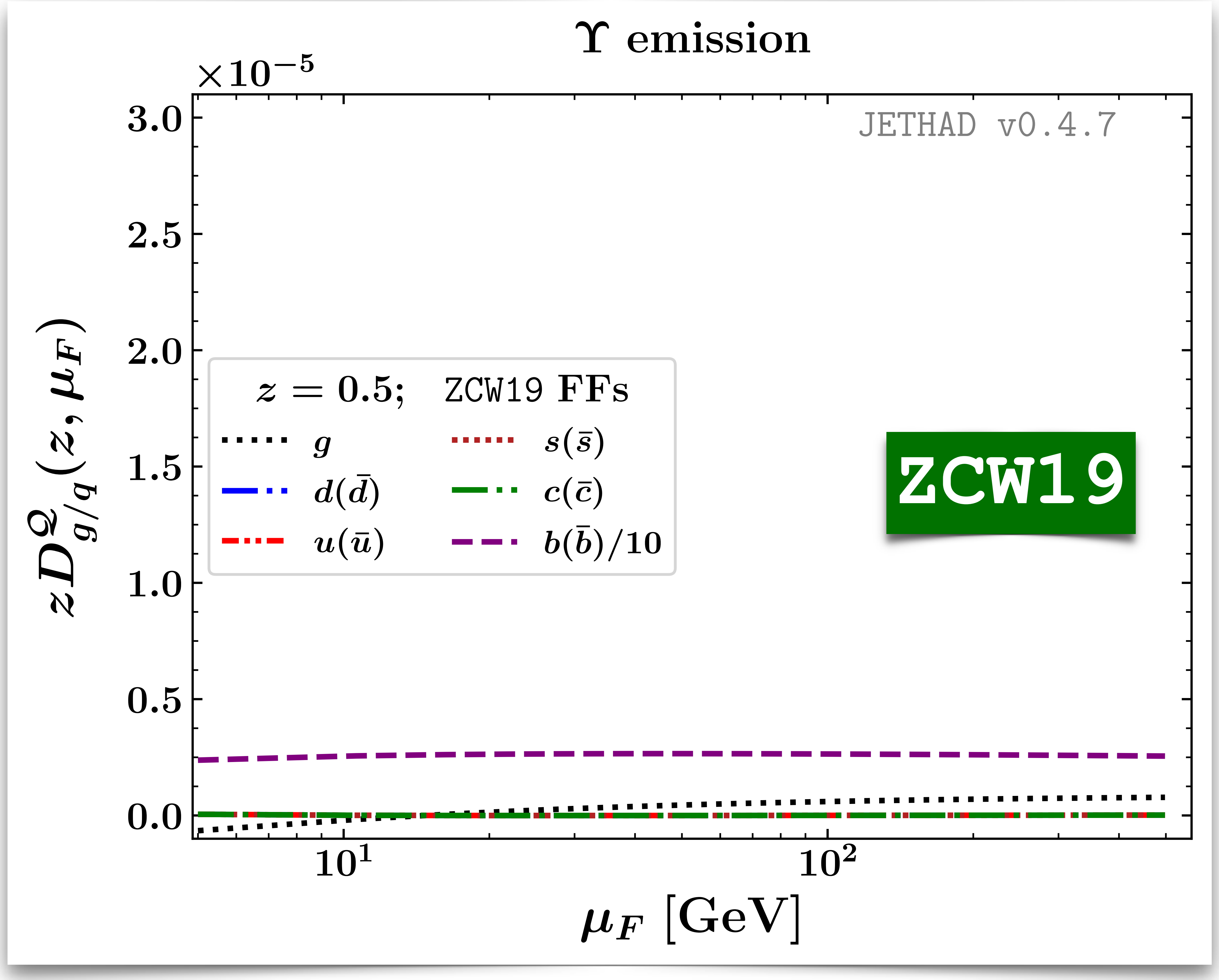
Backup

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



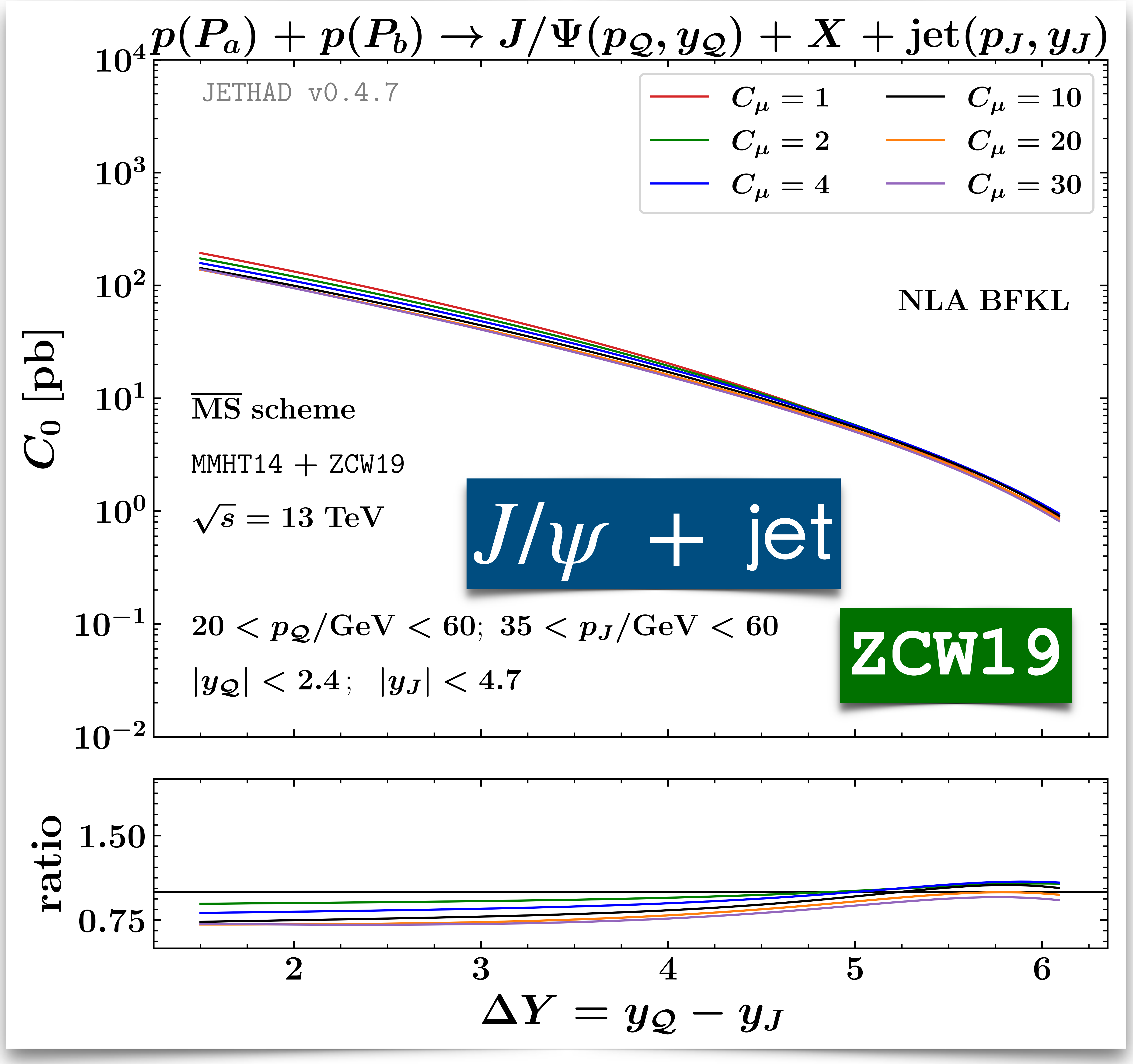
Υ collinear FFs

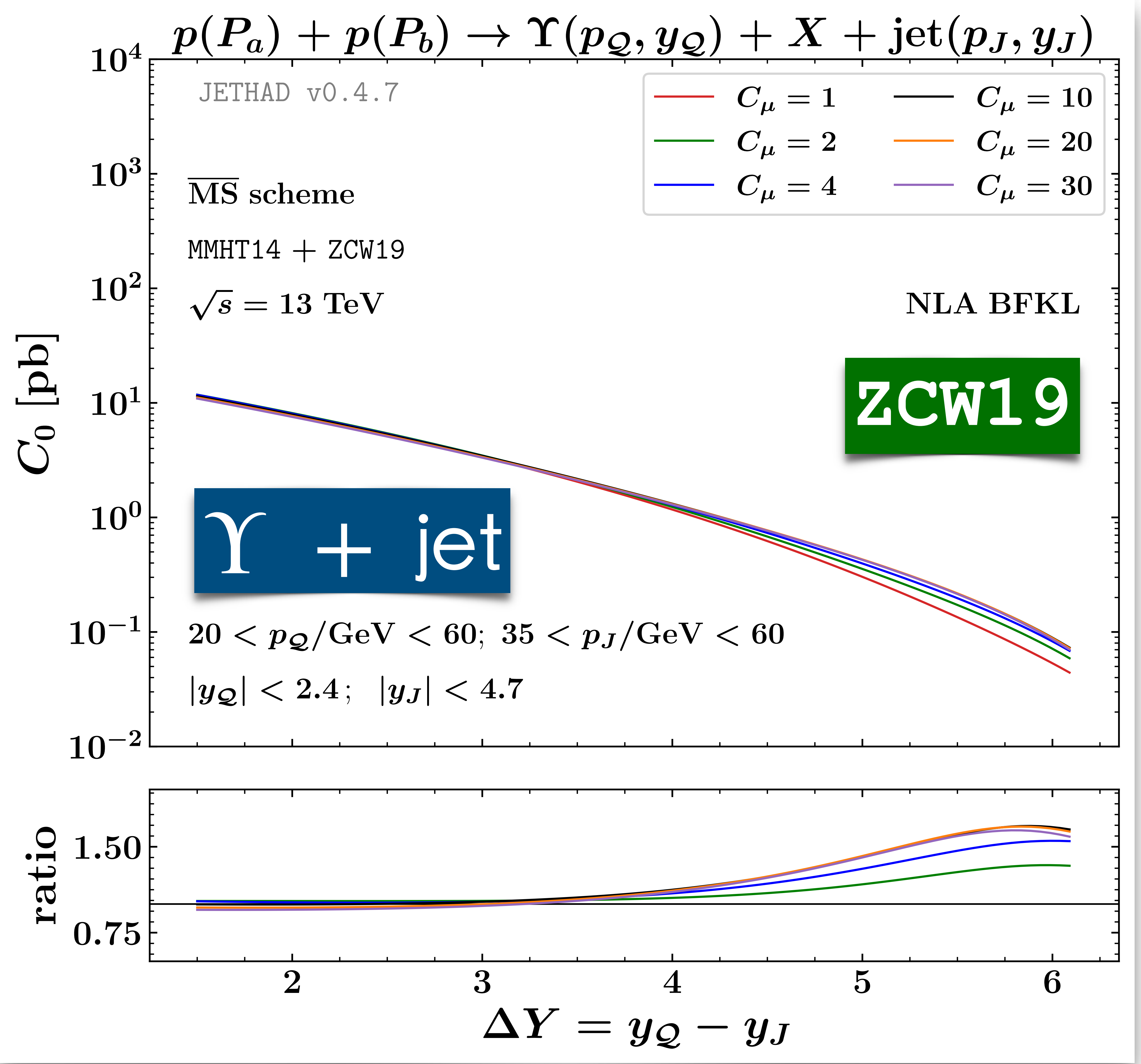


Backup

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

Vector quarkonium + jet at the LHC





Backup

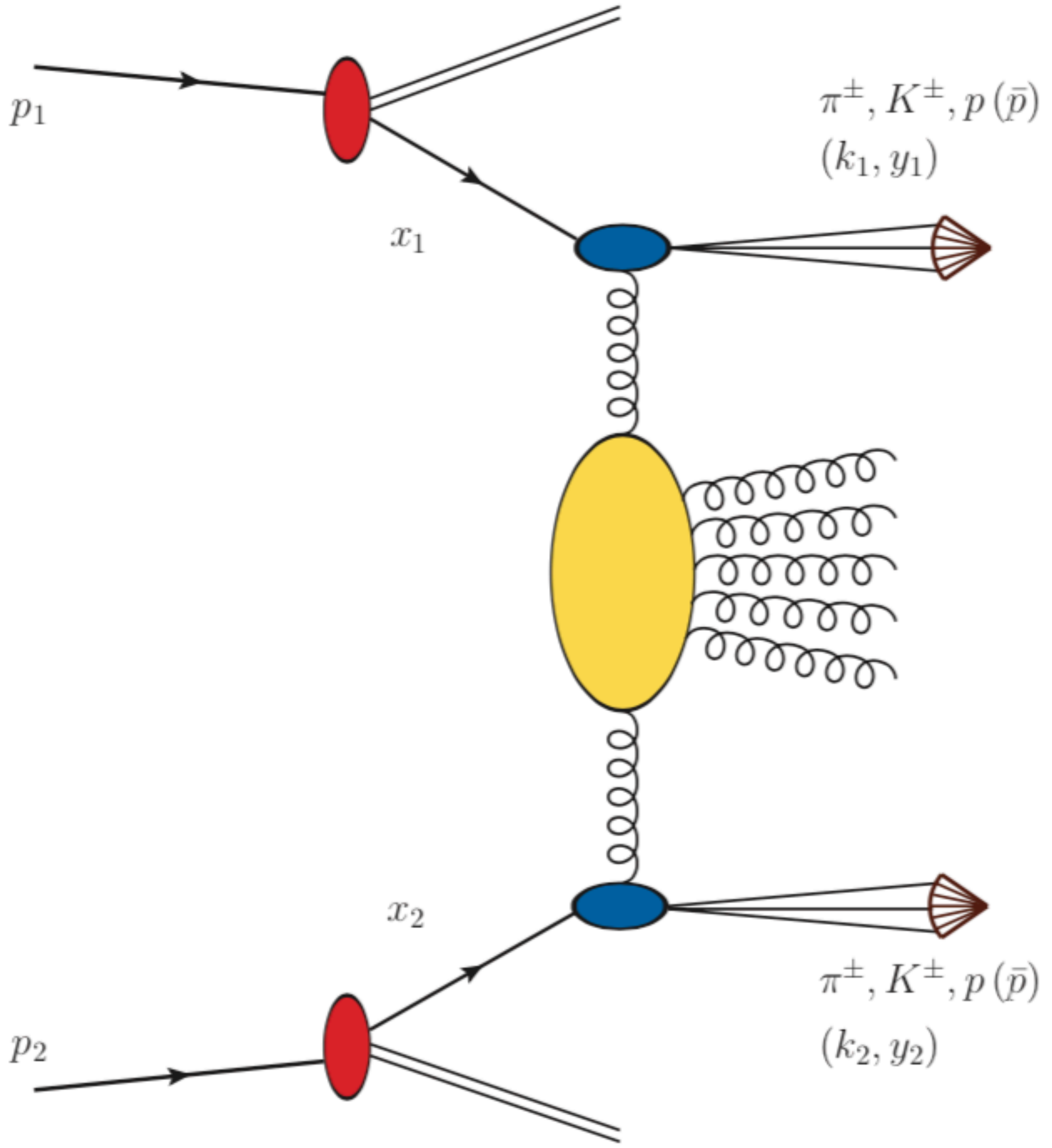
[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

Heavy-light hadrons

Di-hadron and hadron-jet correlations

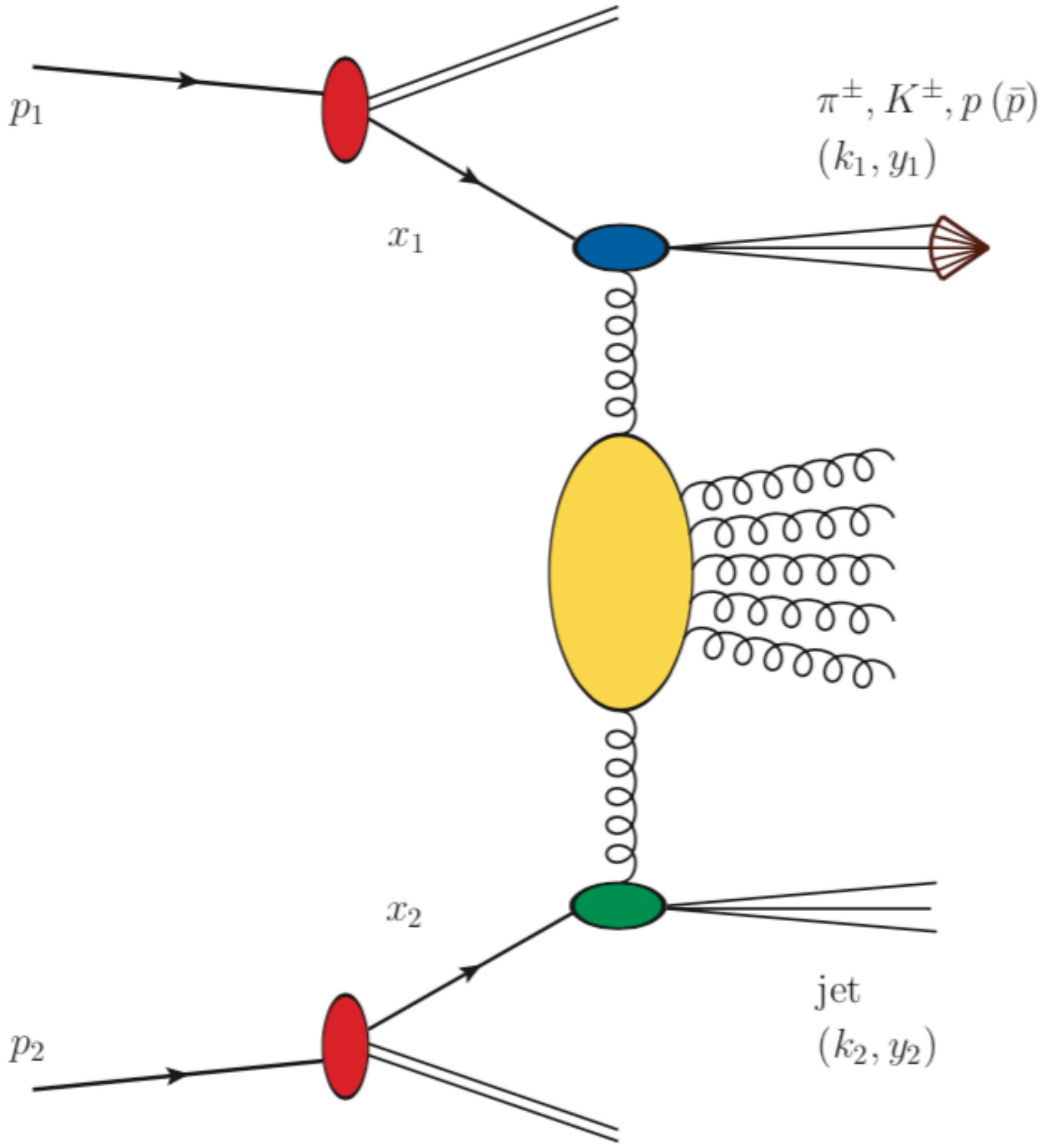
Inclusive di-hadron production

[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]

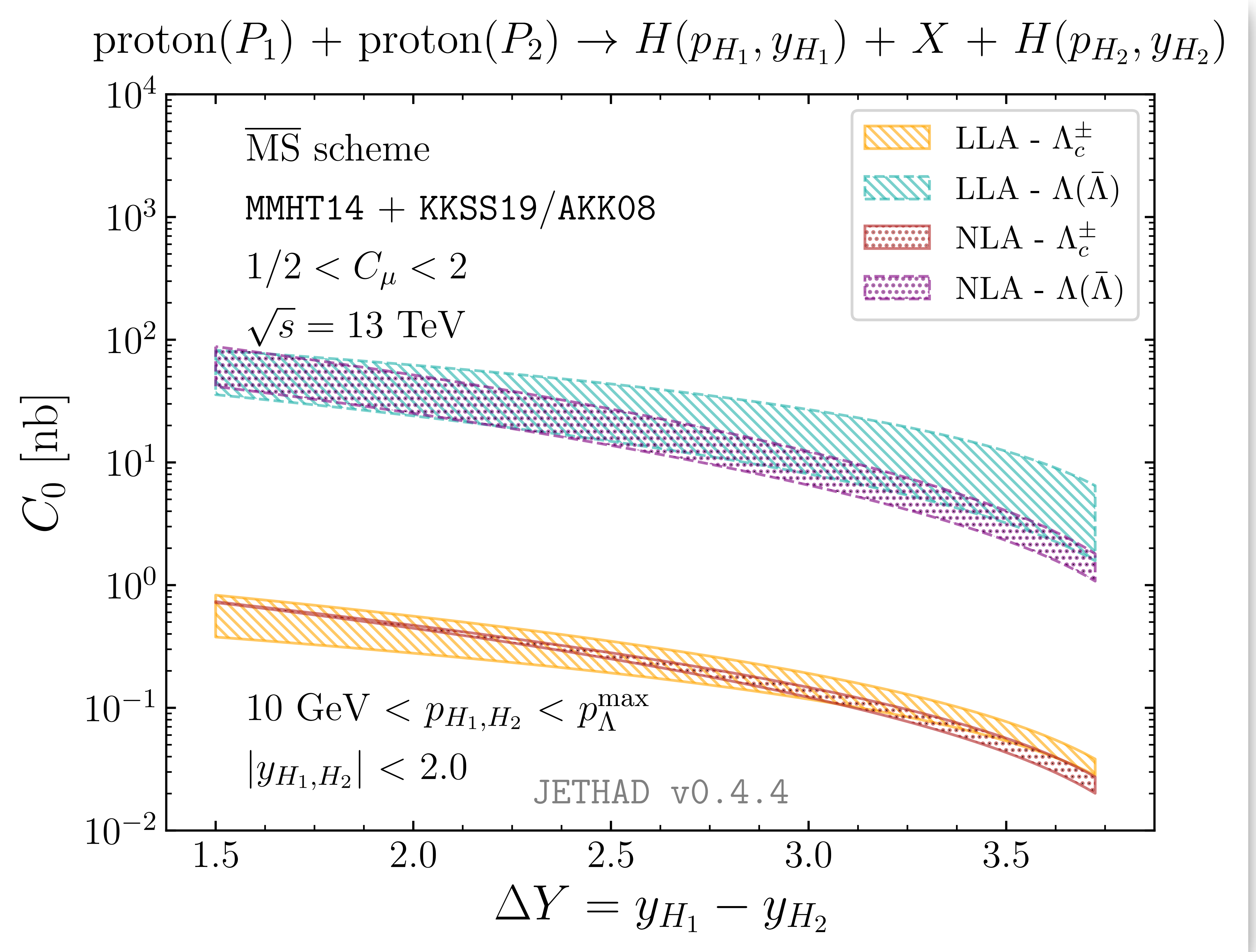
Backup

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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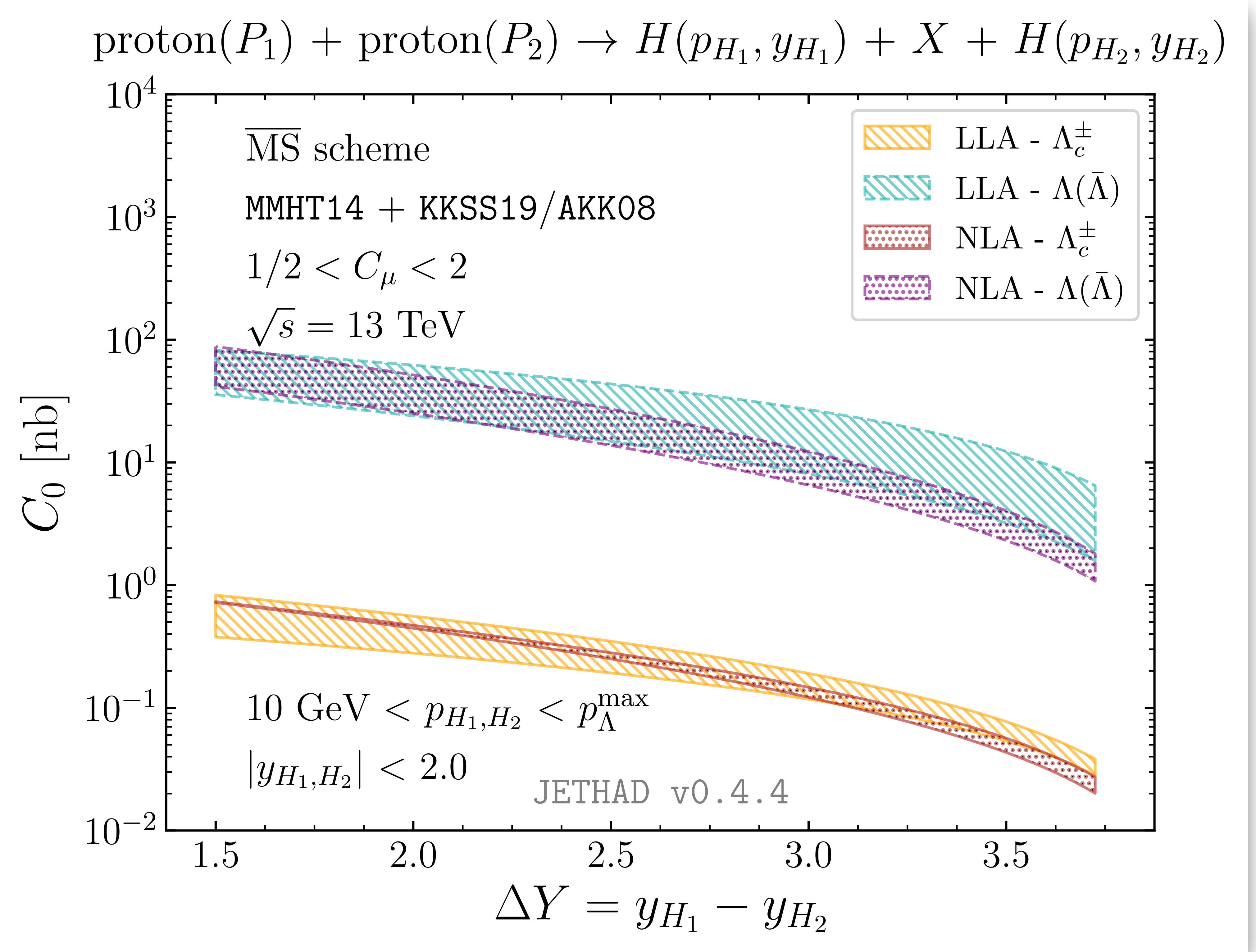
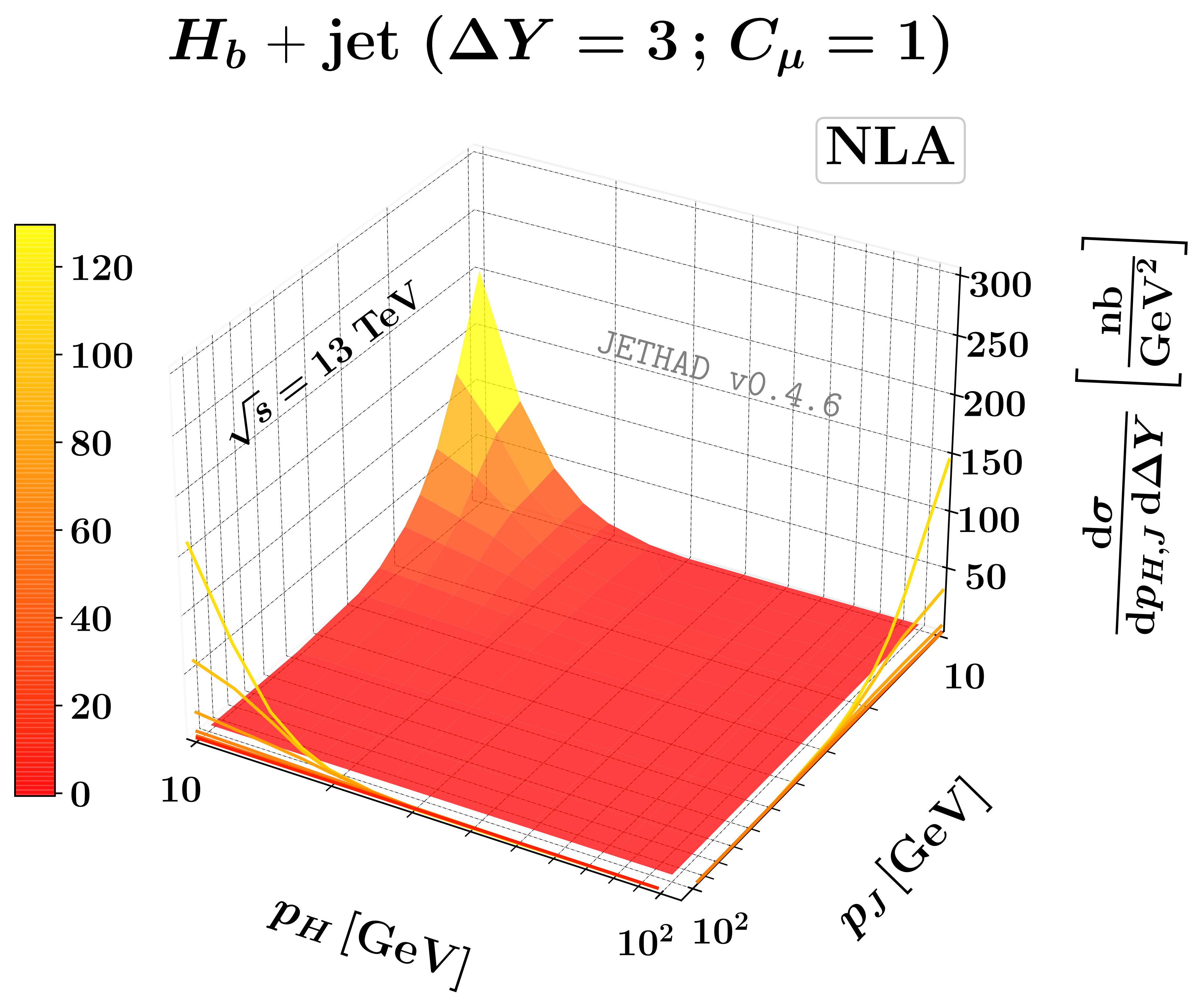


Bottom-flavored hadrons

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



Backup

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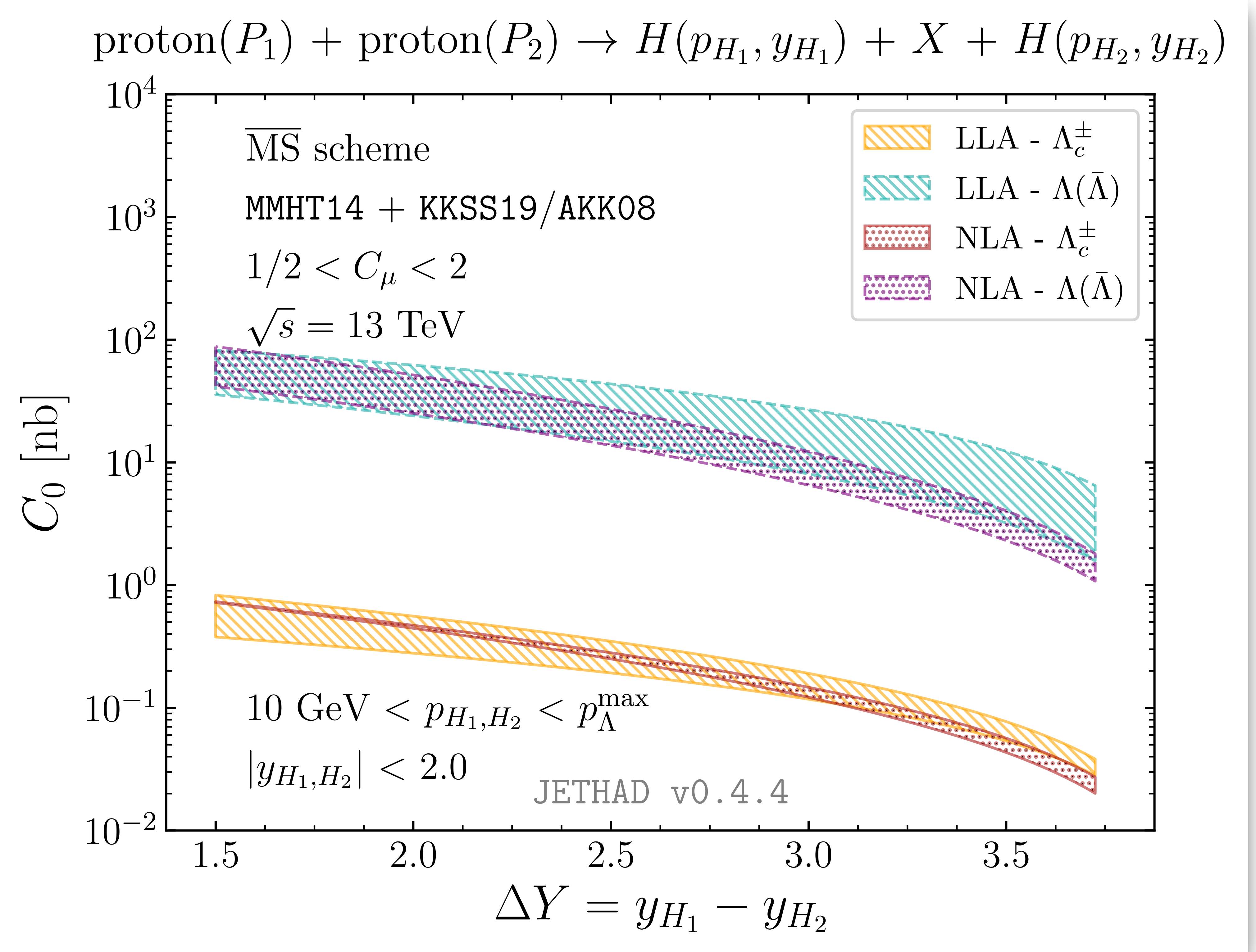

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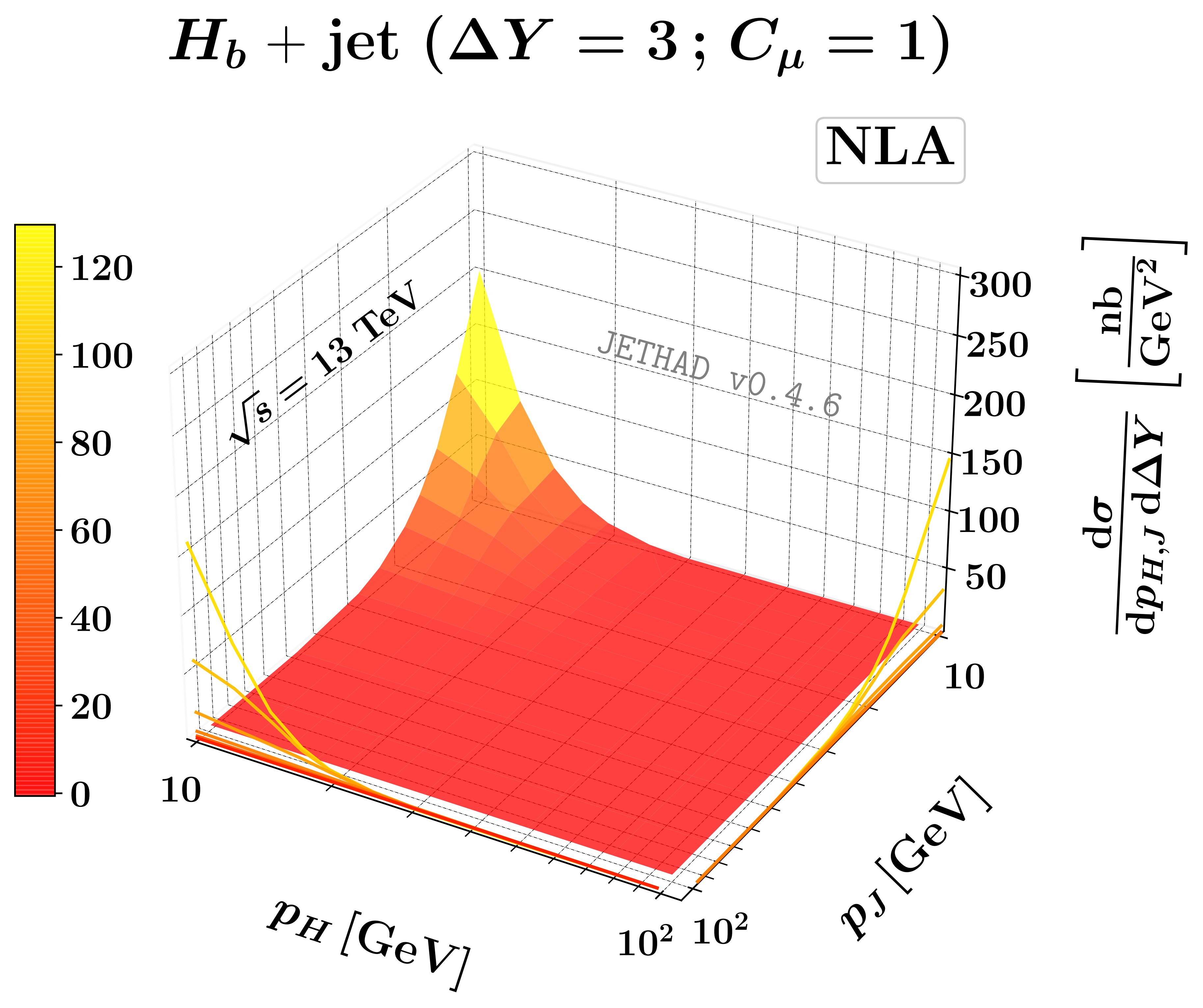


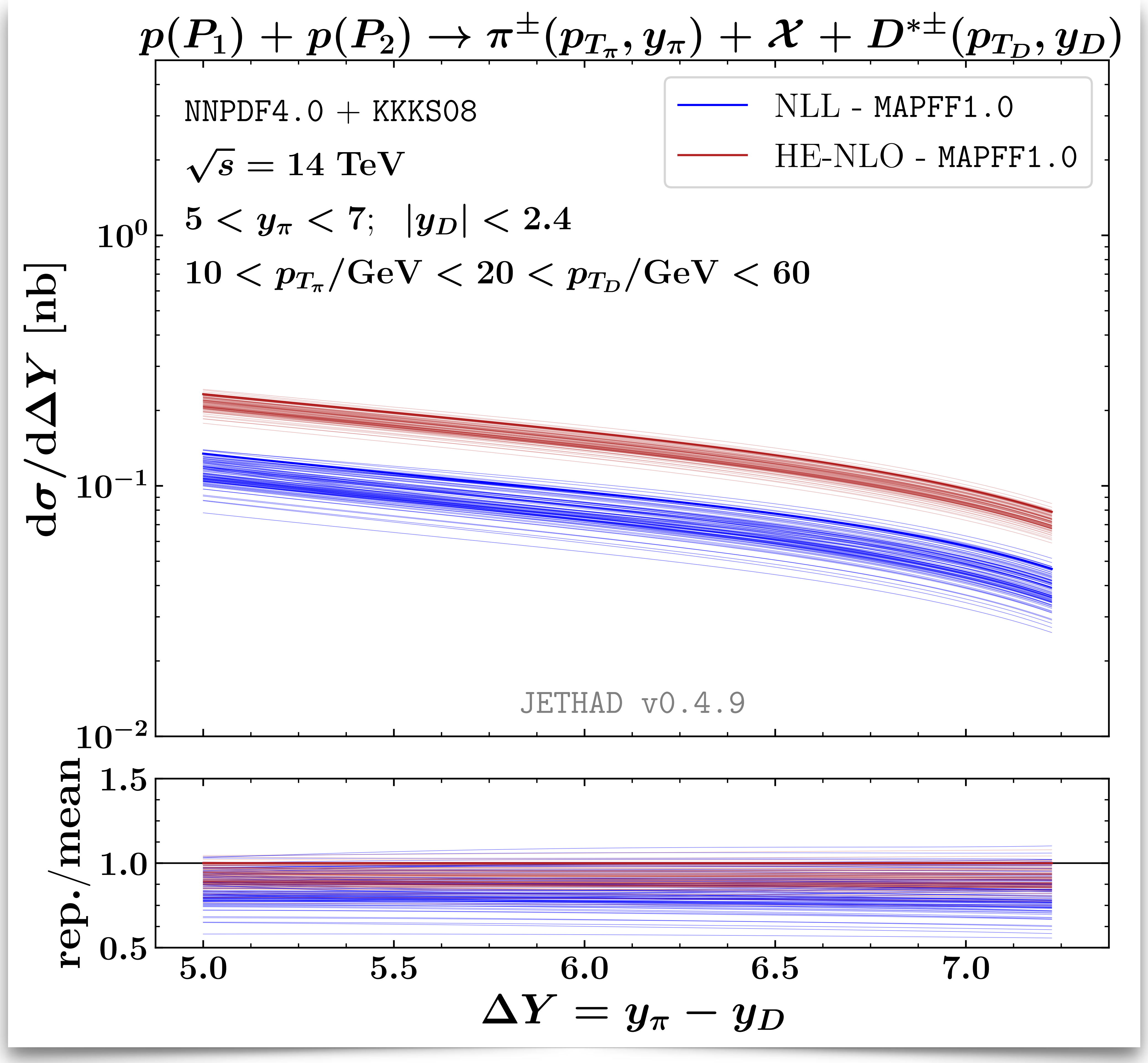
- Natural stability as a tool to investigate high-energy dynamics of QCD ✔

Backup

Rapidity distributions @FPF+ATLAS

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

[FPF Snowmass Whitepaper]



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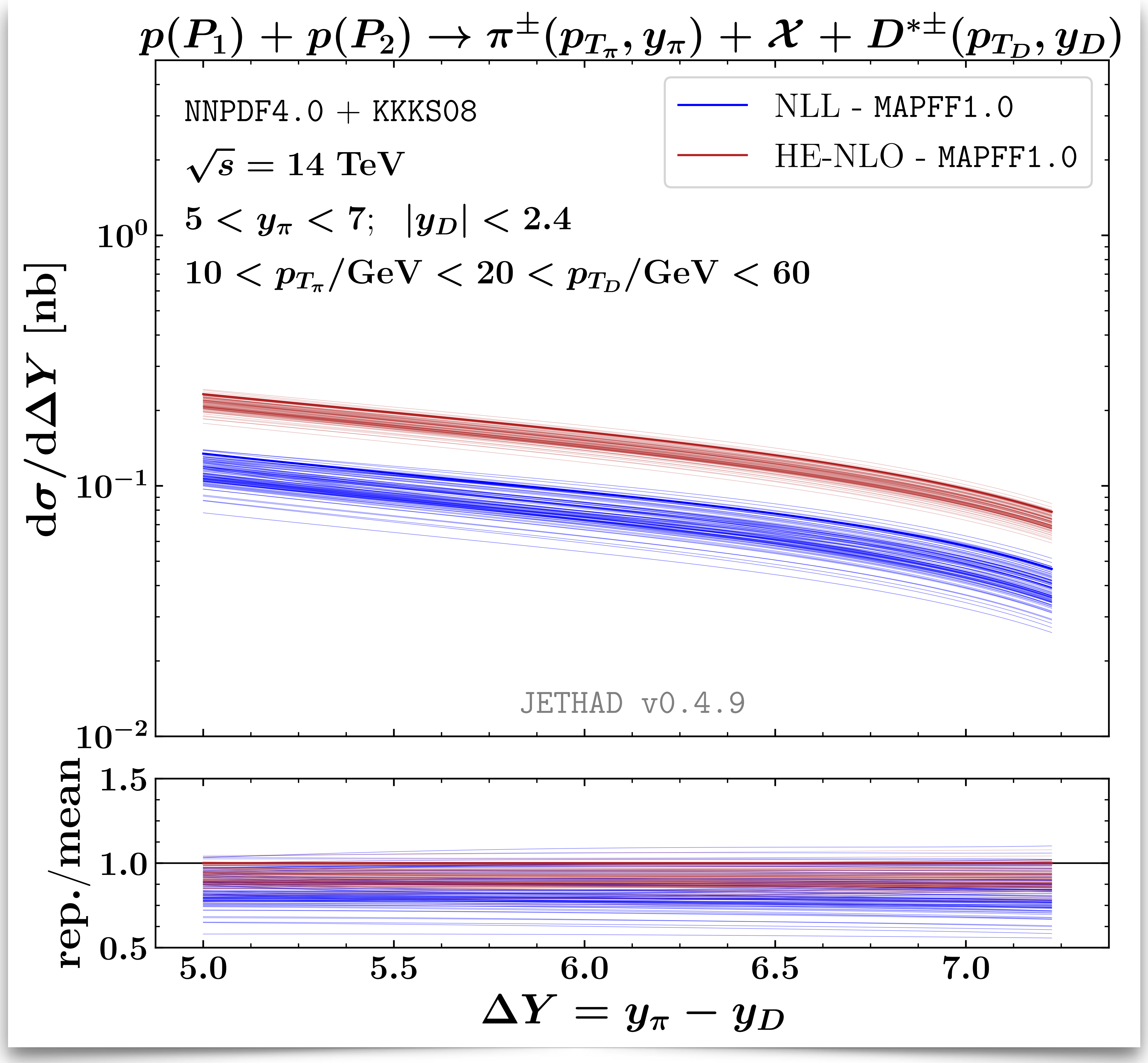

- ✱ Impact of collinear FFs on ΔY-distribution
- ✱ Replica method at work

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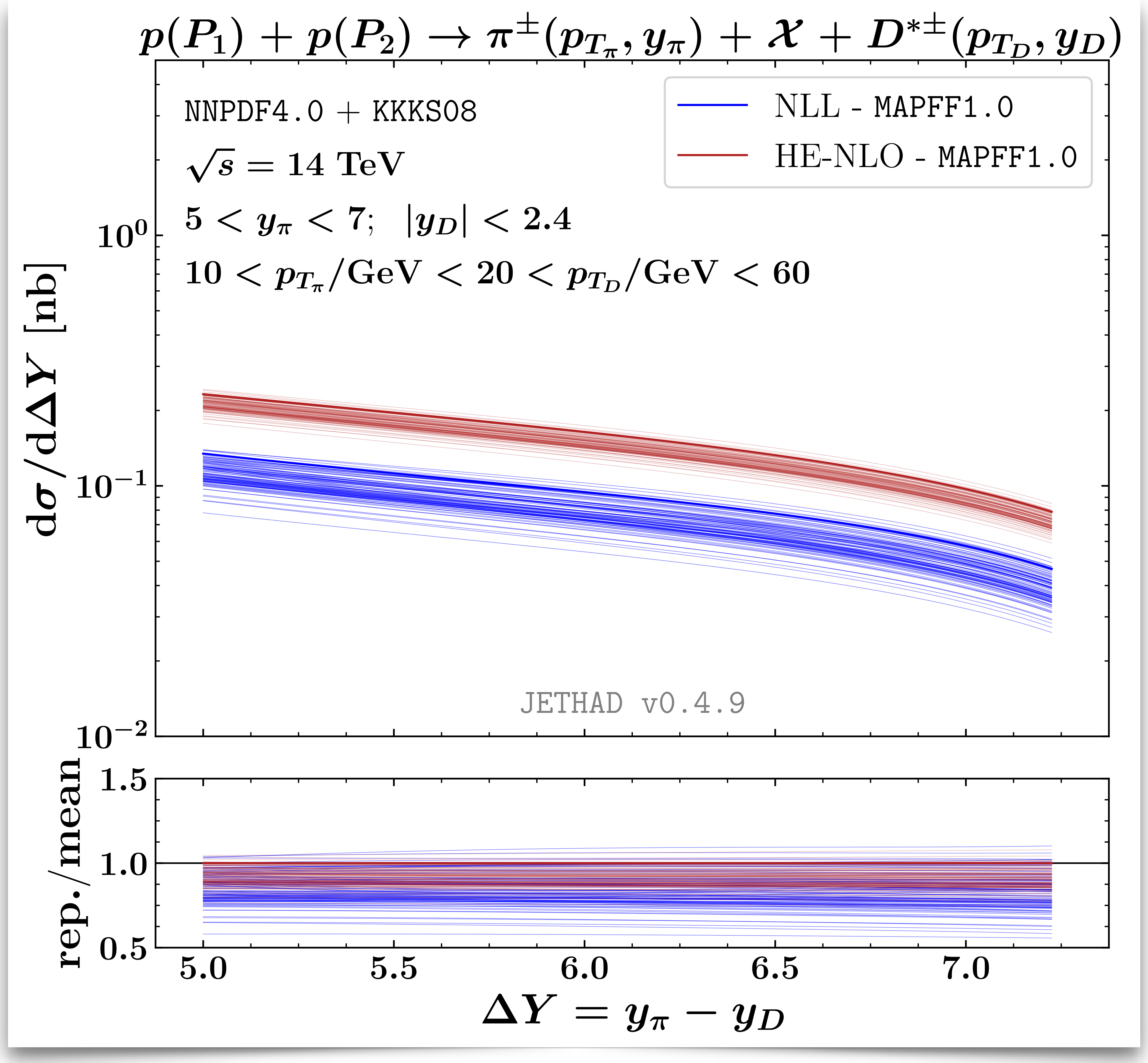


- ✱ Impact of collinear FFs on ΔY-distribution
- ✱ Replica method at work
- ✱ Larger spread of replicas at NLL
- ✱ Probe FFs in complementary ranges

  Weight of FF replicas in the same set

  Different sets via functional correlation?

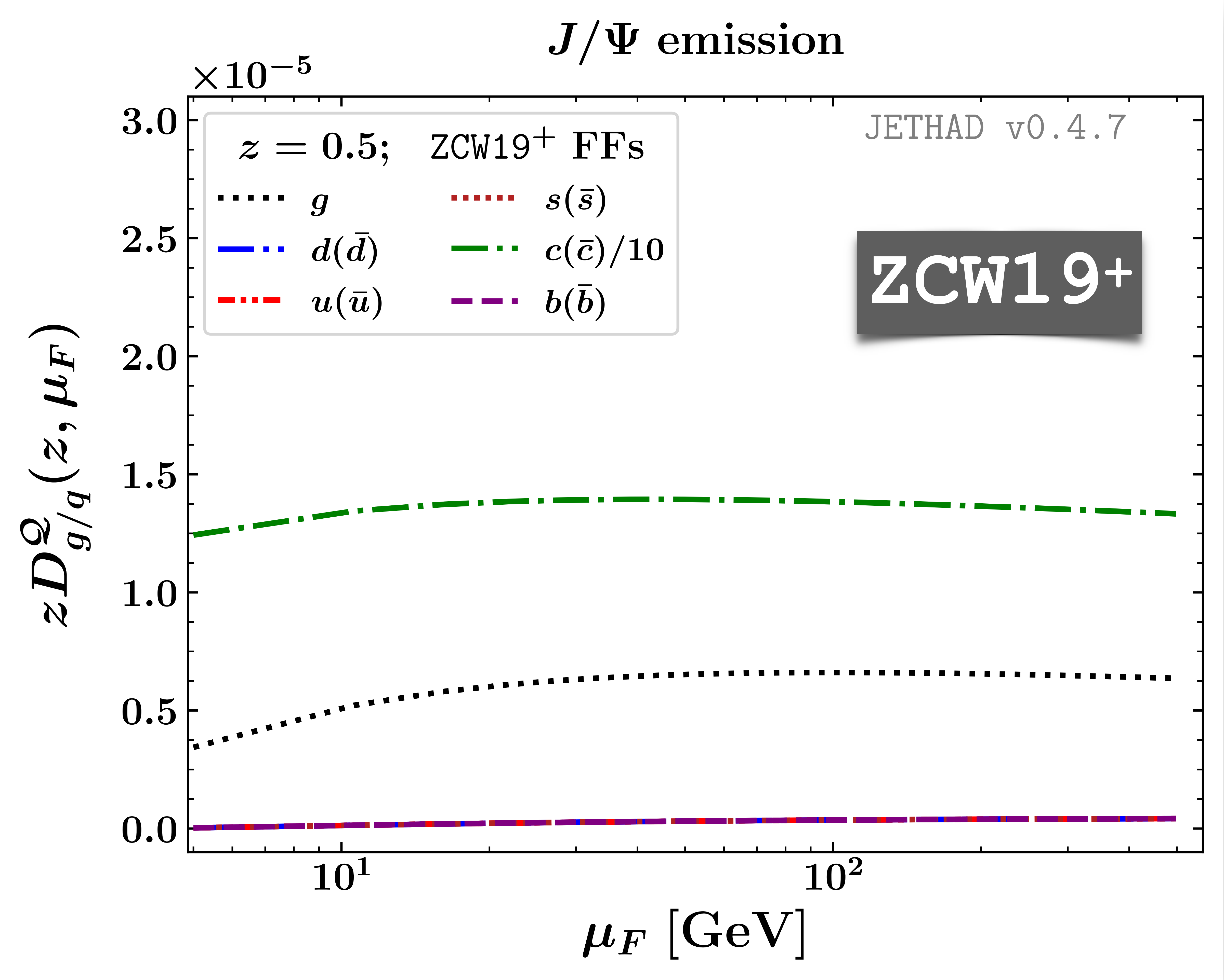
- ✱ Complementary studies on FFs

Backup

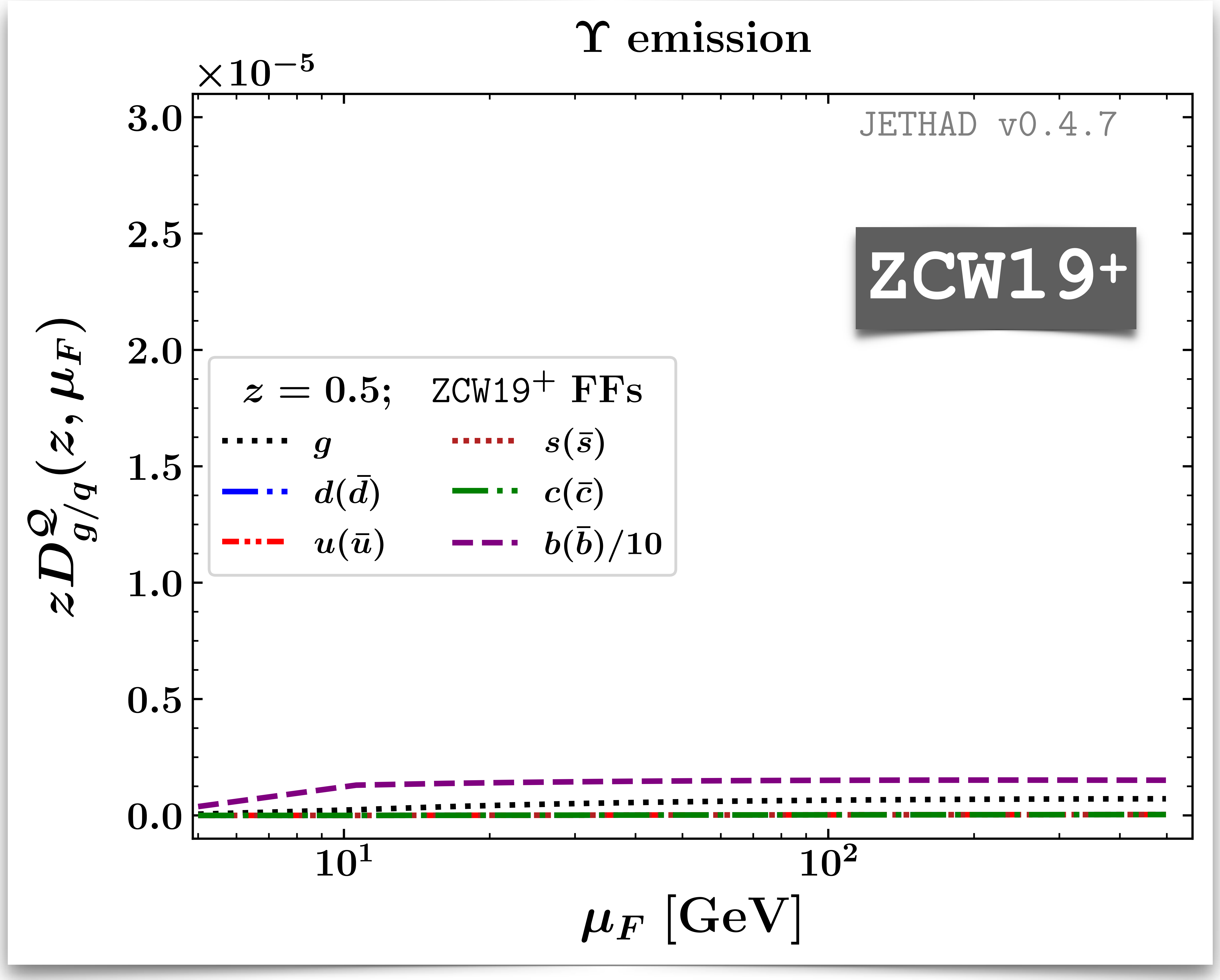
Quarkonia

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



Υ collinear FFs

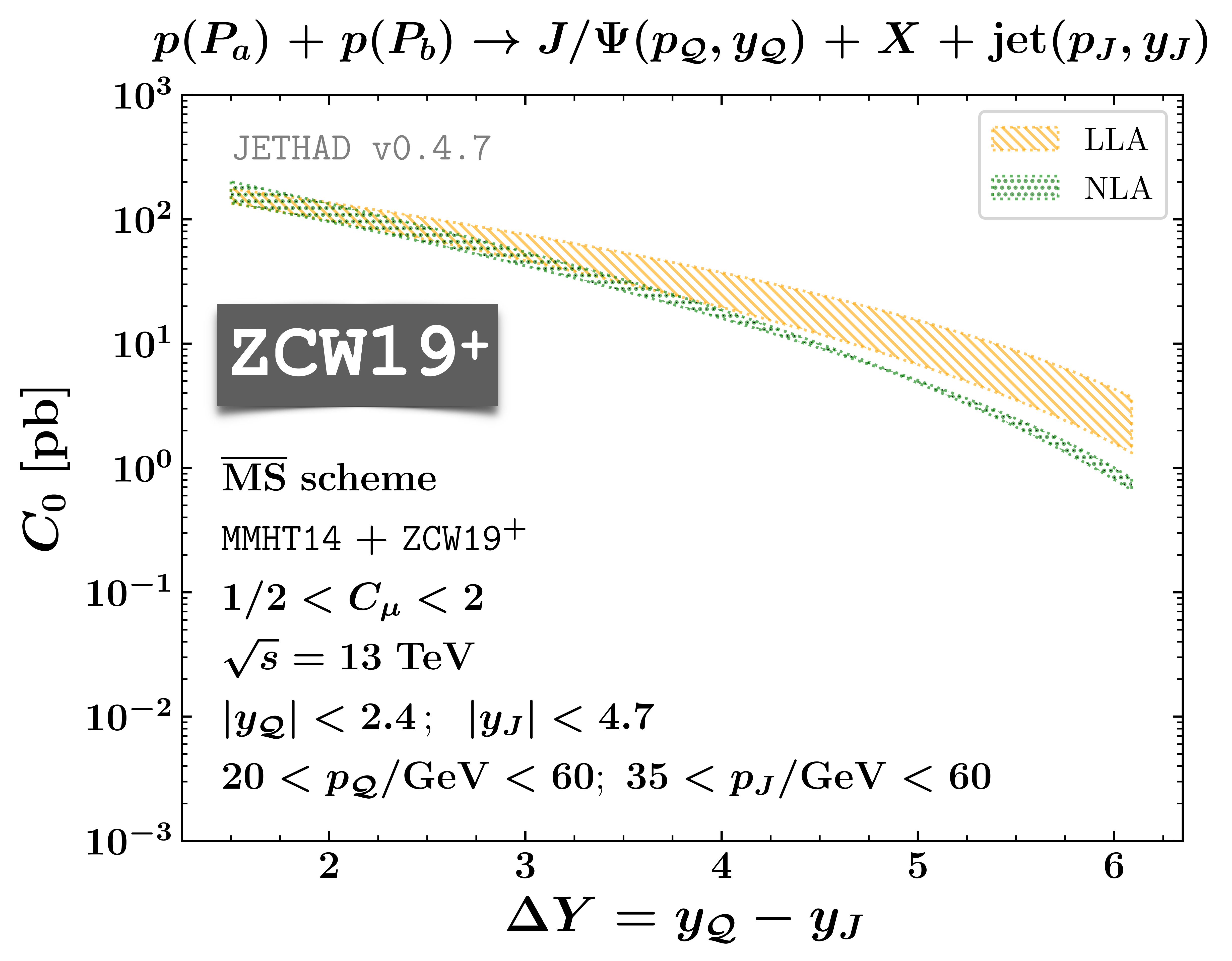


🔗 [F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

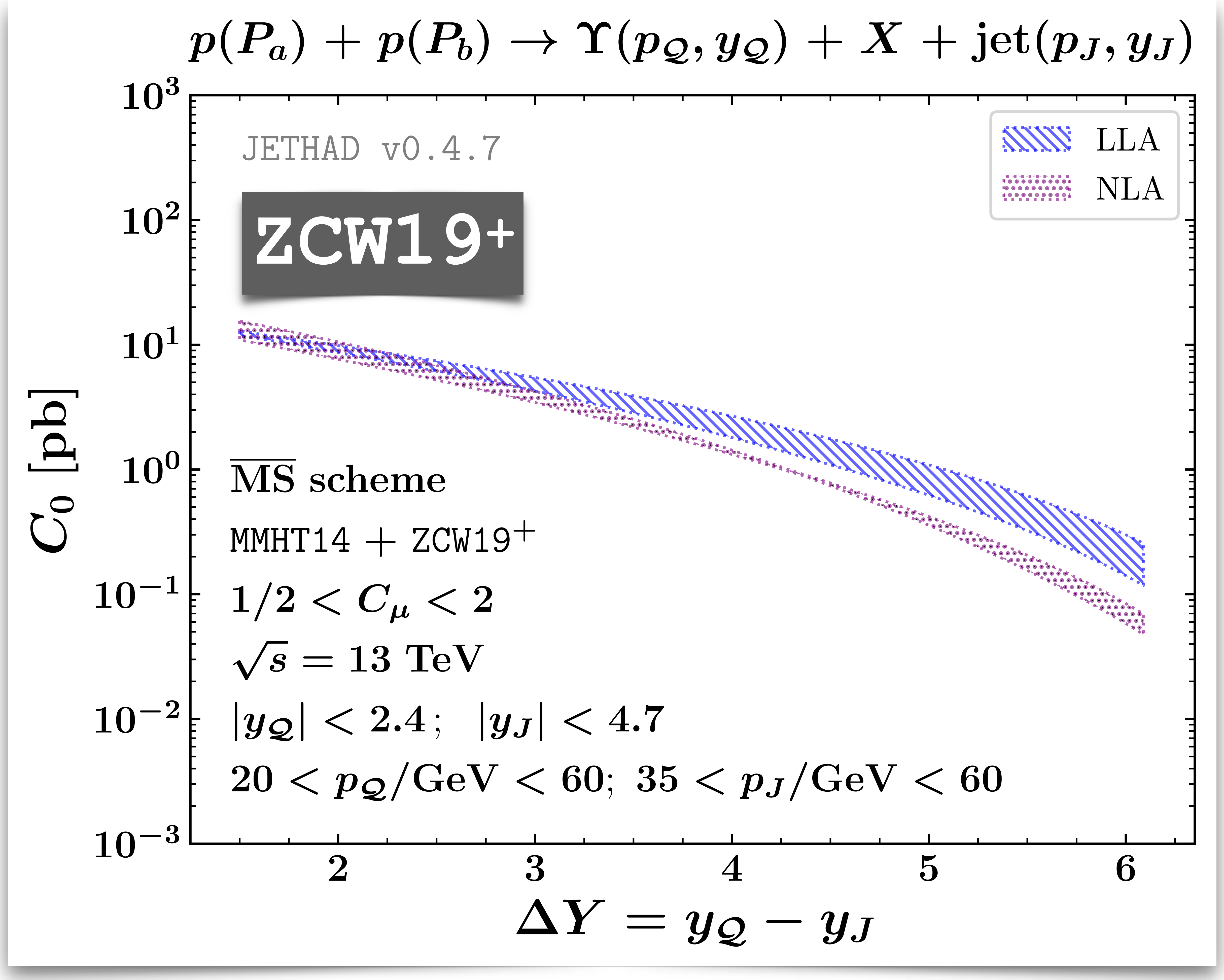
Backup

Vector quarkonium + jet at the LHC

J/ψ + jet



Υ + jet

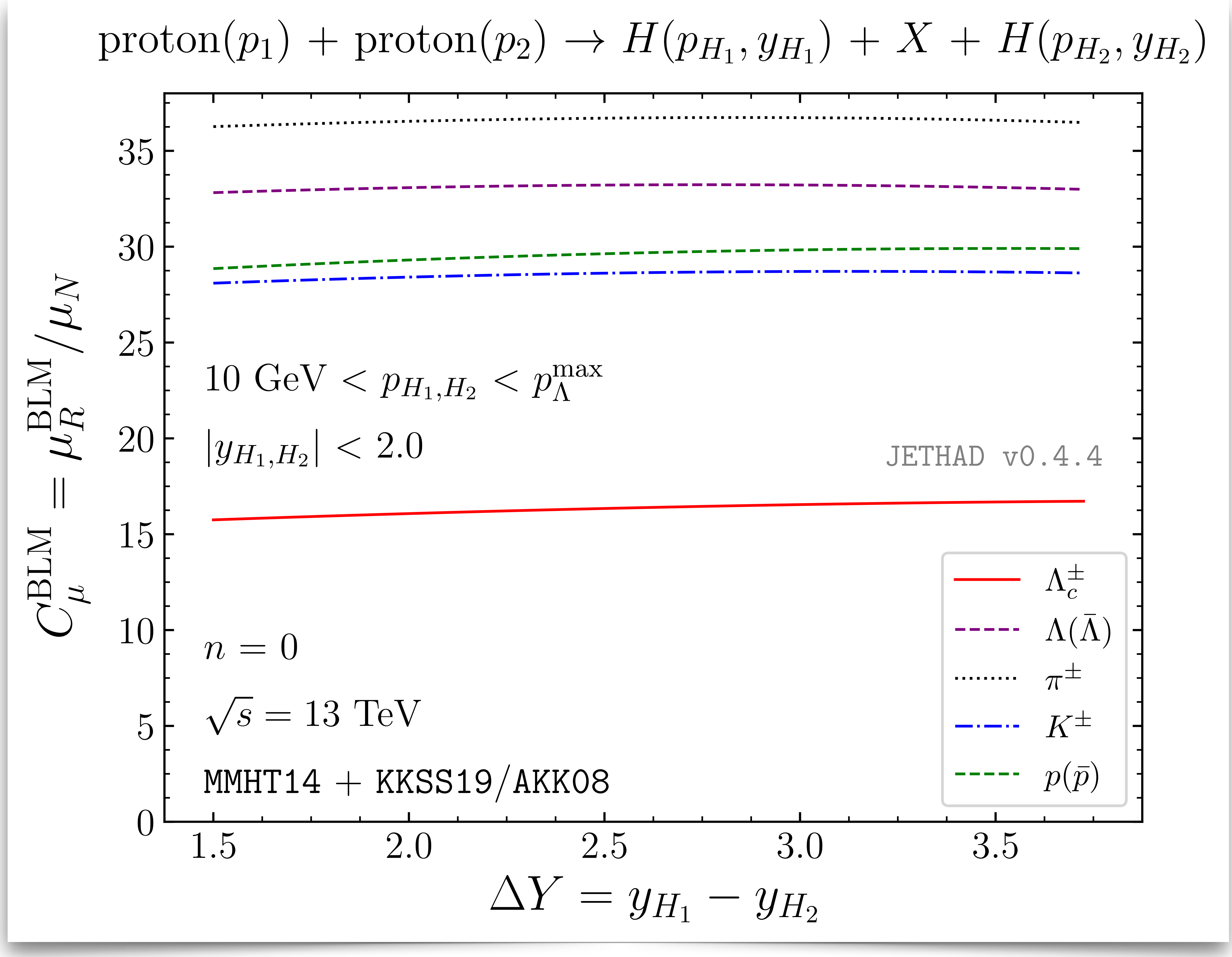


[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

Backup

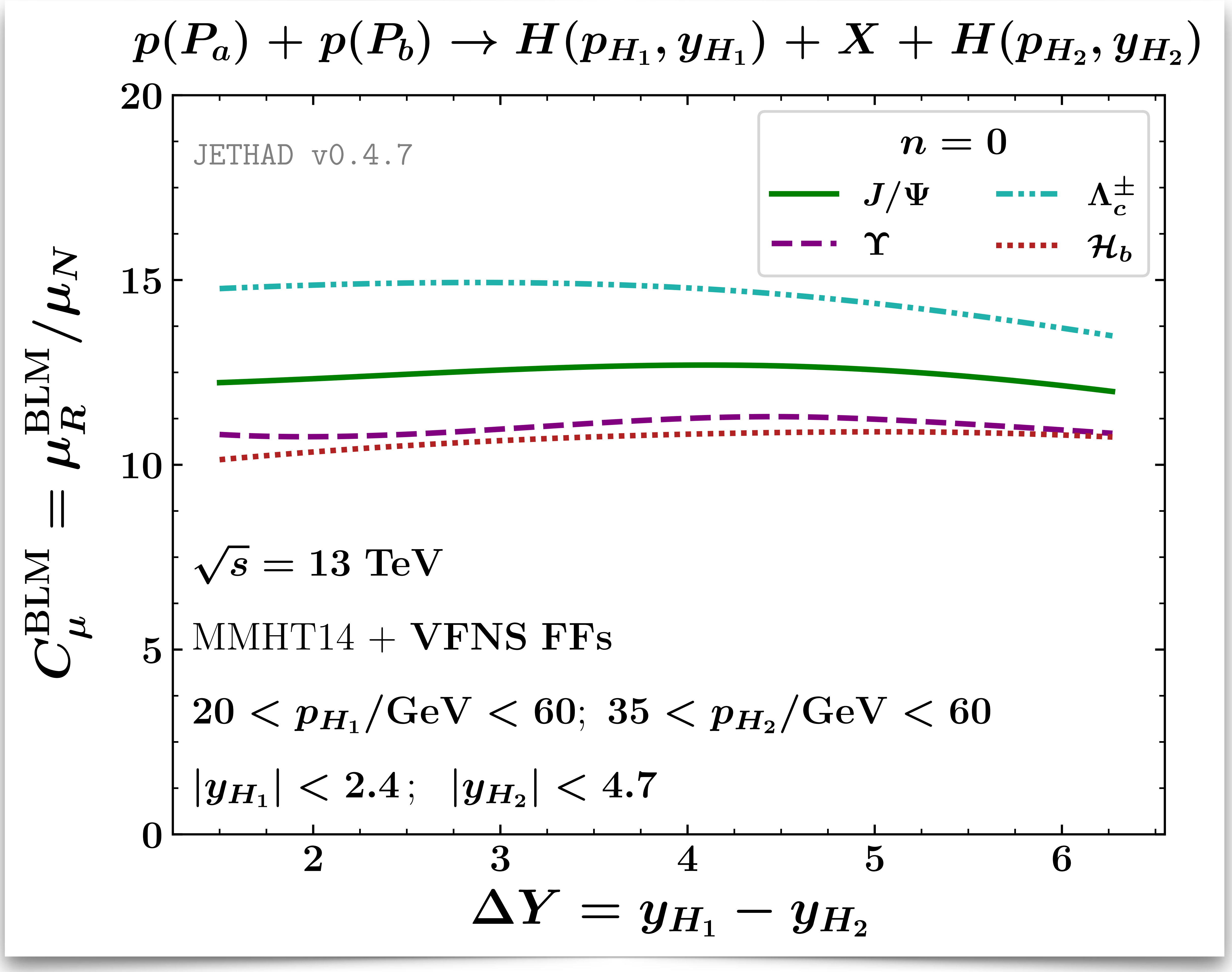
Heavy flavor at the LHC: BLM scales

Heavy-light hadrons



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

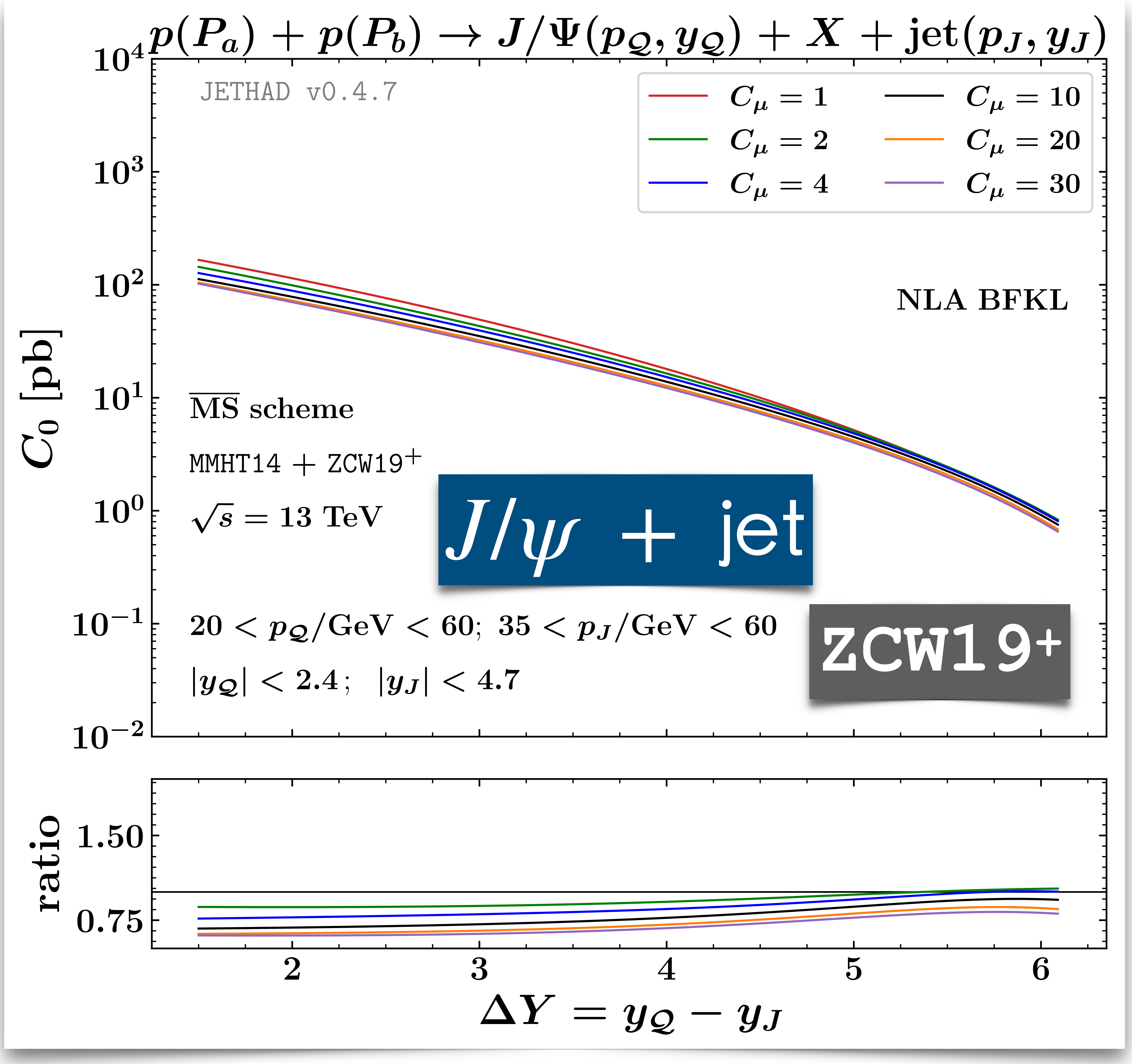
Vector quarkonia

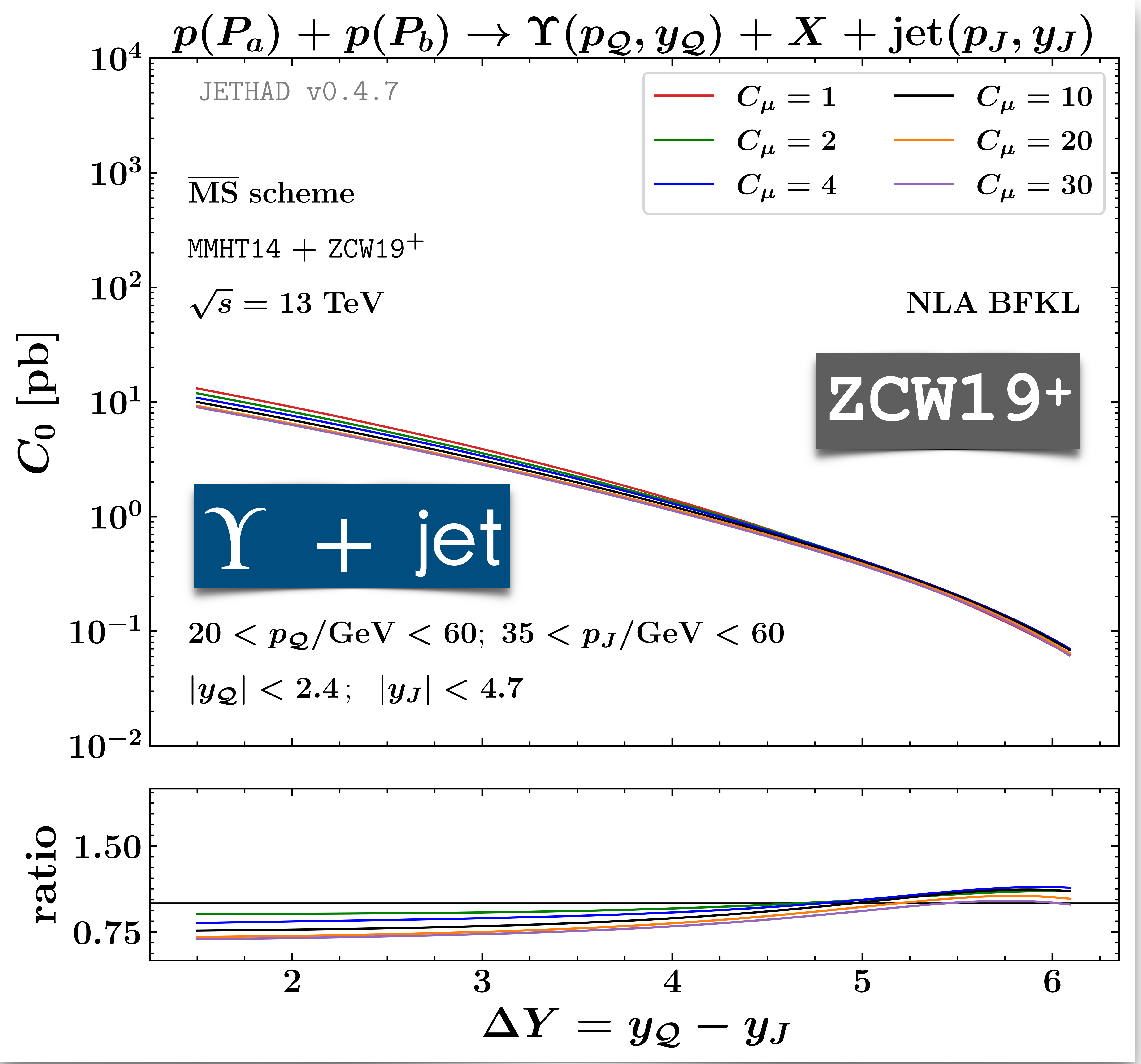


🔗 [F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

Backup

Vector quarkonium + jet at the LHC





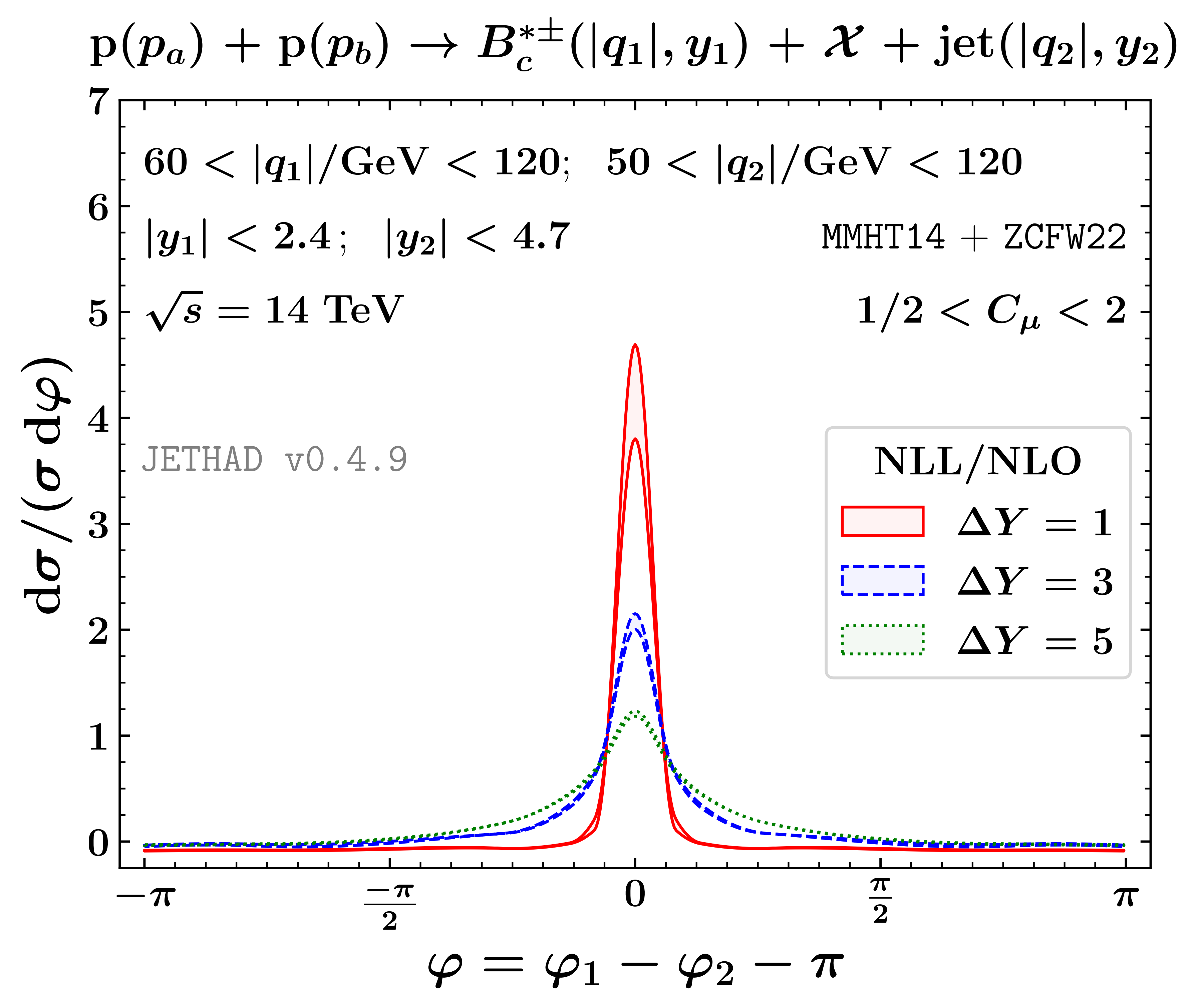
Backup

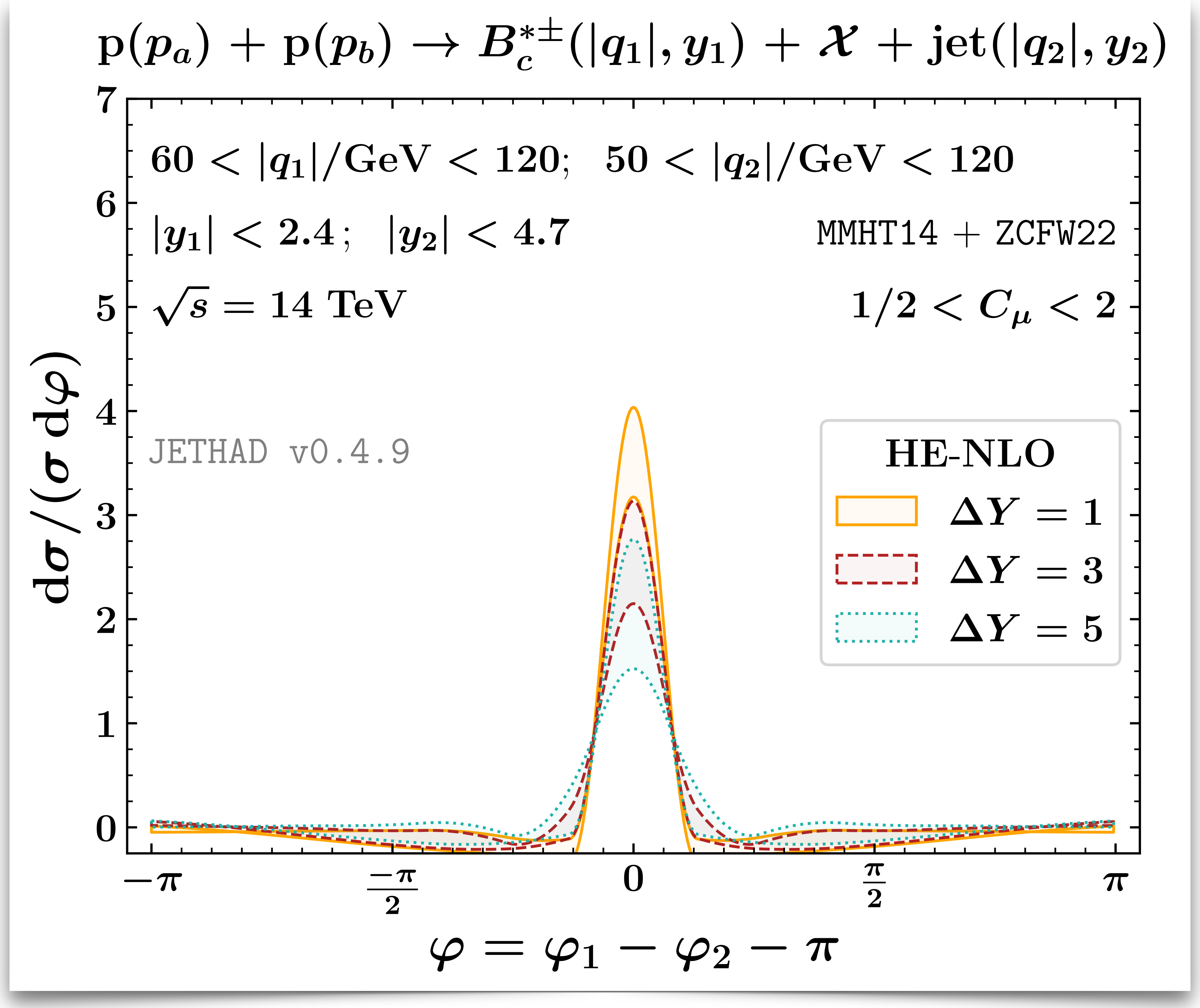
Charmed B-mesons from single-parton fragmentation

(2) ¡ *Let us consider $B_c(^1S_0)$ and $B_c(^3S_1)$ at large p_T* $\rightarrow$ *single-parton* ***fragmentation*** *from* ***NRQCD*** !

(NLO heavy quark) [X. Zheng et al., Phys. Rev. D 100 (2019) 3, 034004]

(NLO gluon) [X. Zheng et al., JHEP 05 (2022) 036]



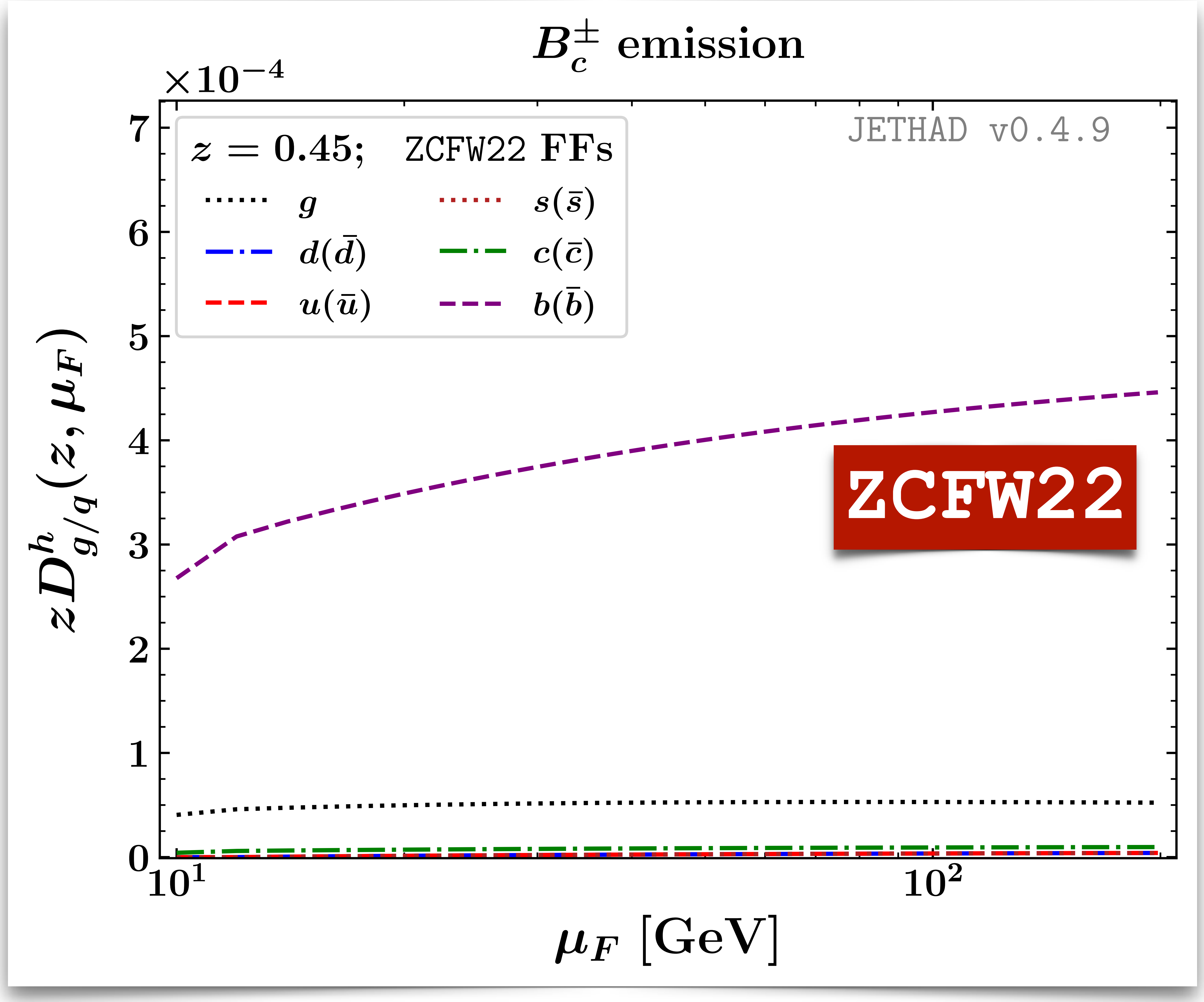


[F. G. C., under revision (2022)]

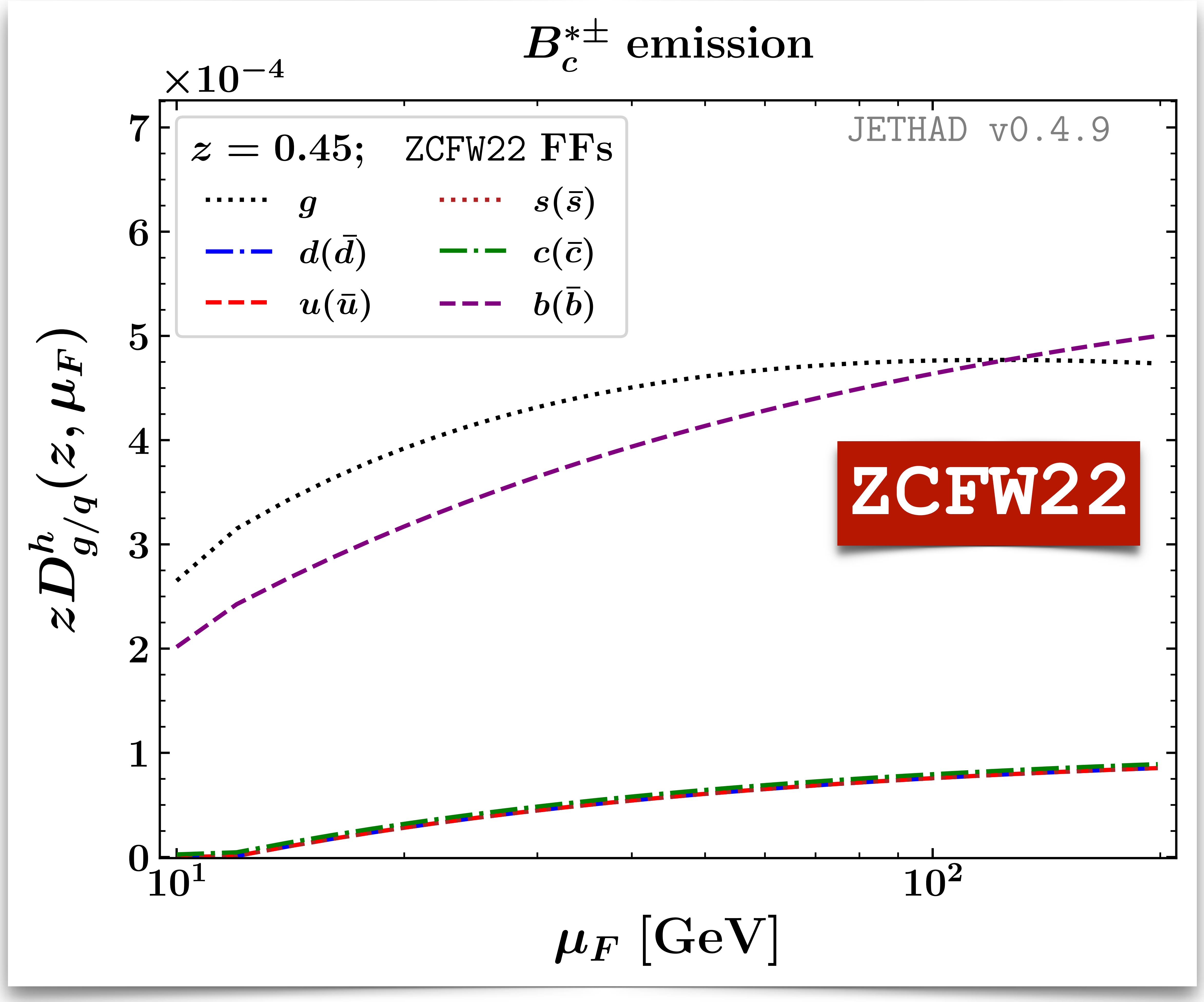
Backup

Charmed B-mesons + jet at the HL-LHC

$B_c^{\pm}(^1S_0)$ collinear FFs



$B_c^{\pm}(^3S_1)$ collinear FFs

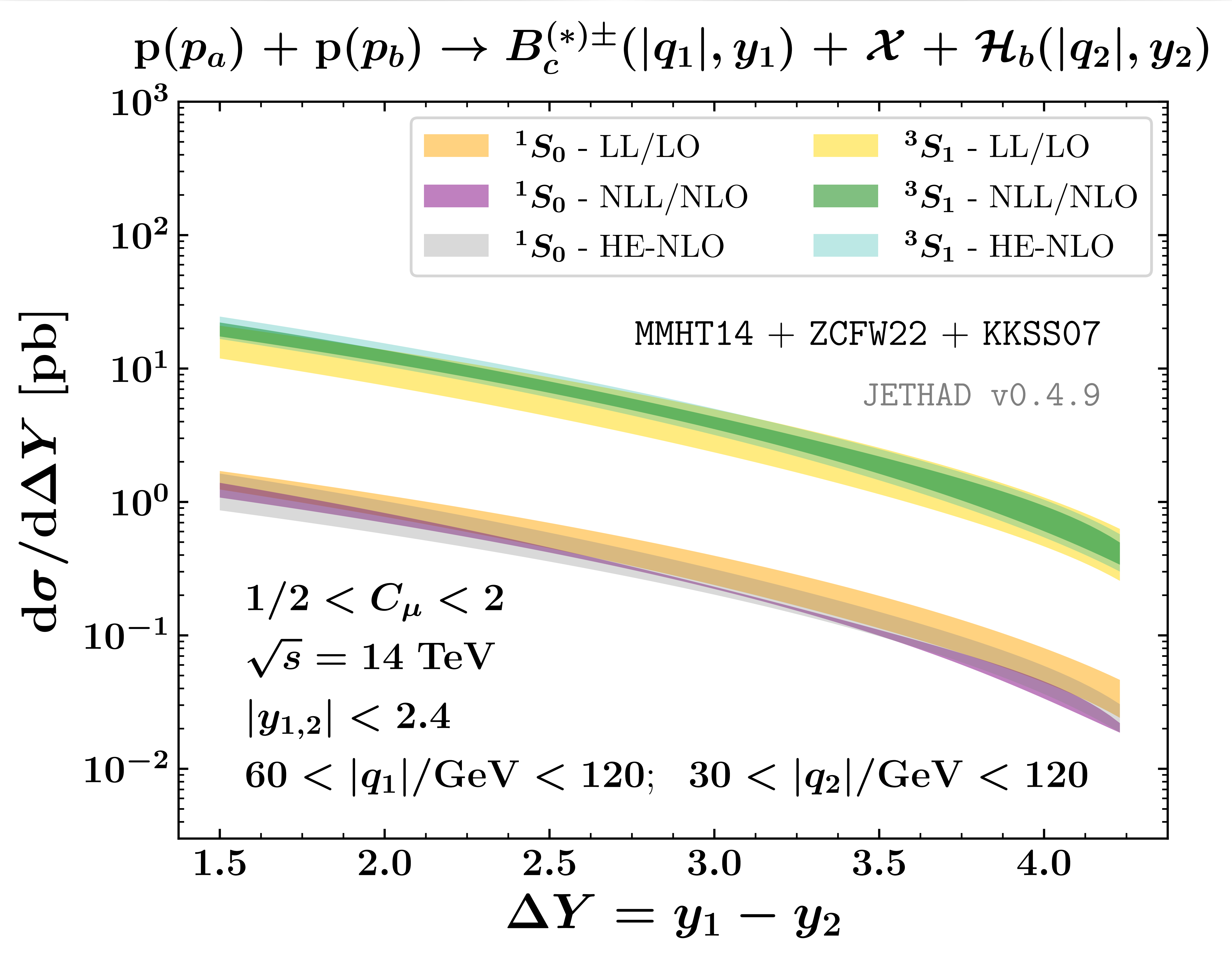


[F. G. C., under revision (2022)]

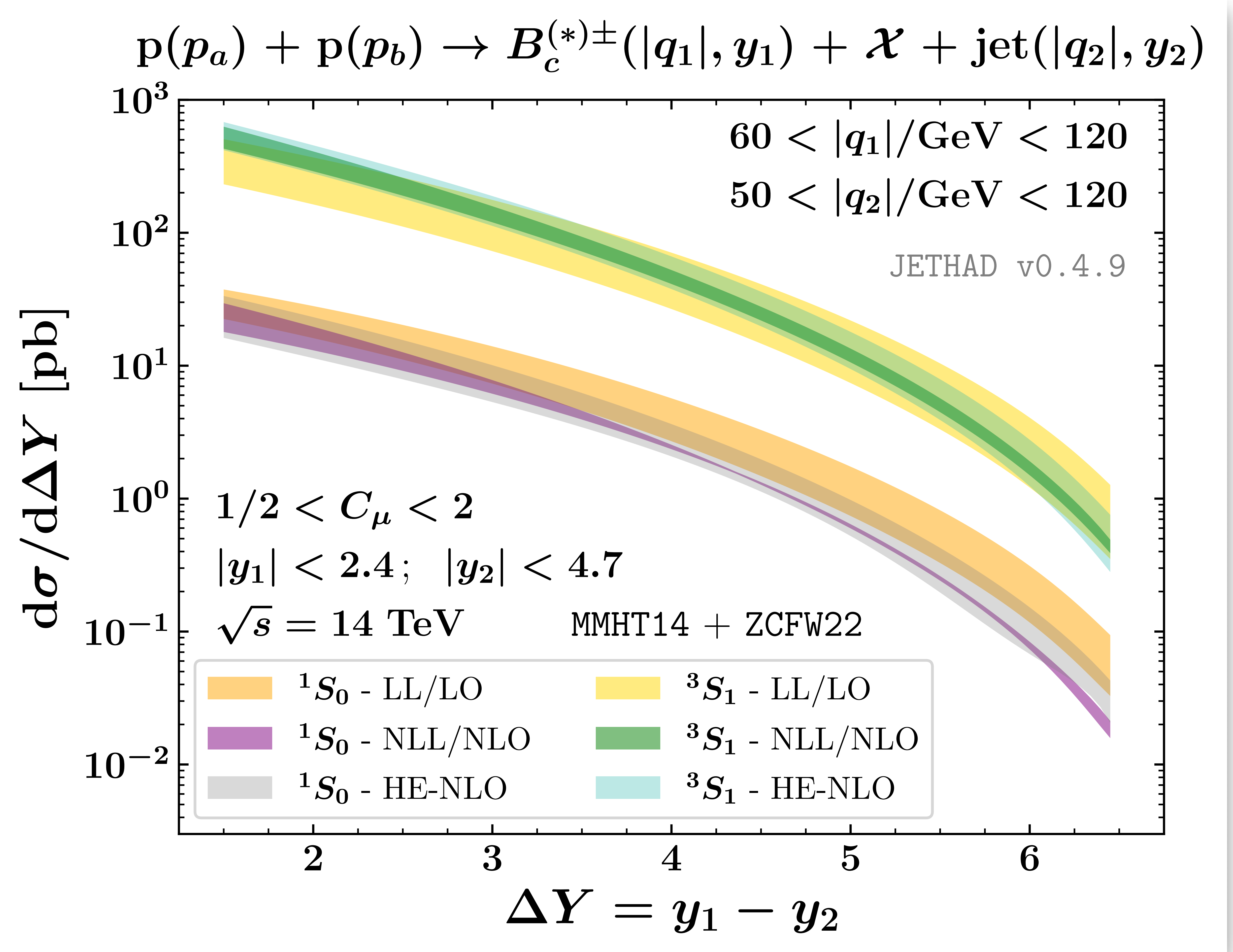
Backup

Charmed B-mesons + jet at the HL-LHC

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



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



[F. G. C., under revision (2022)]

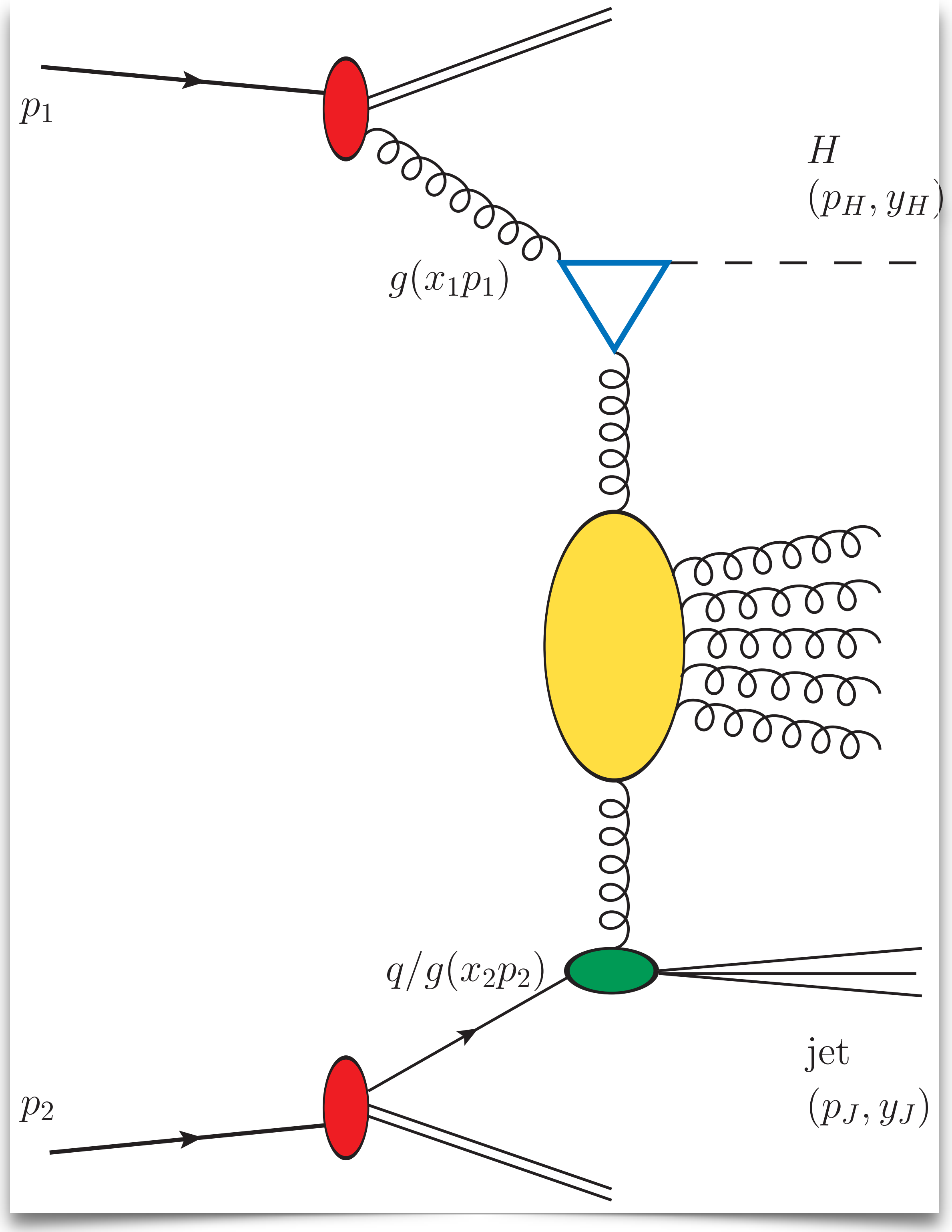
Backup

Higgs+jet distributions

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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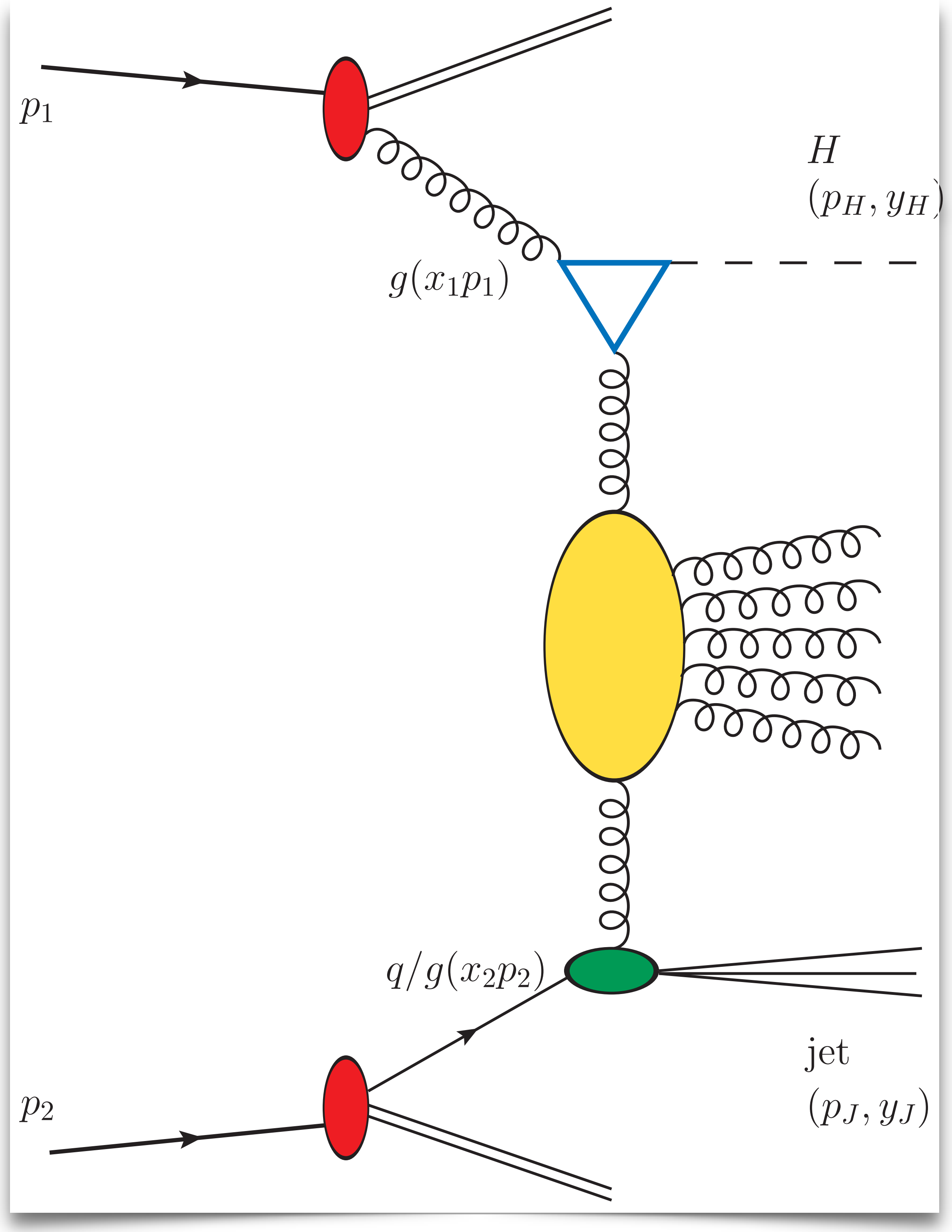

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$

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 amplitude)

jet vertex (off-shell amplitude)

BFKL Green's function

Backup

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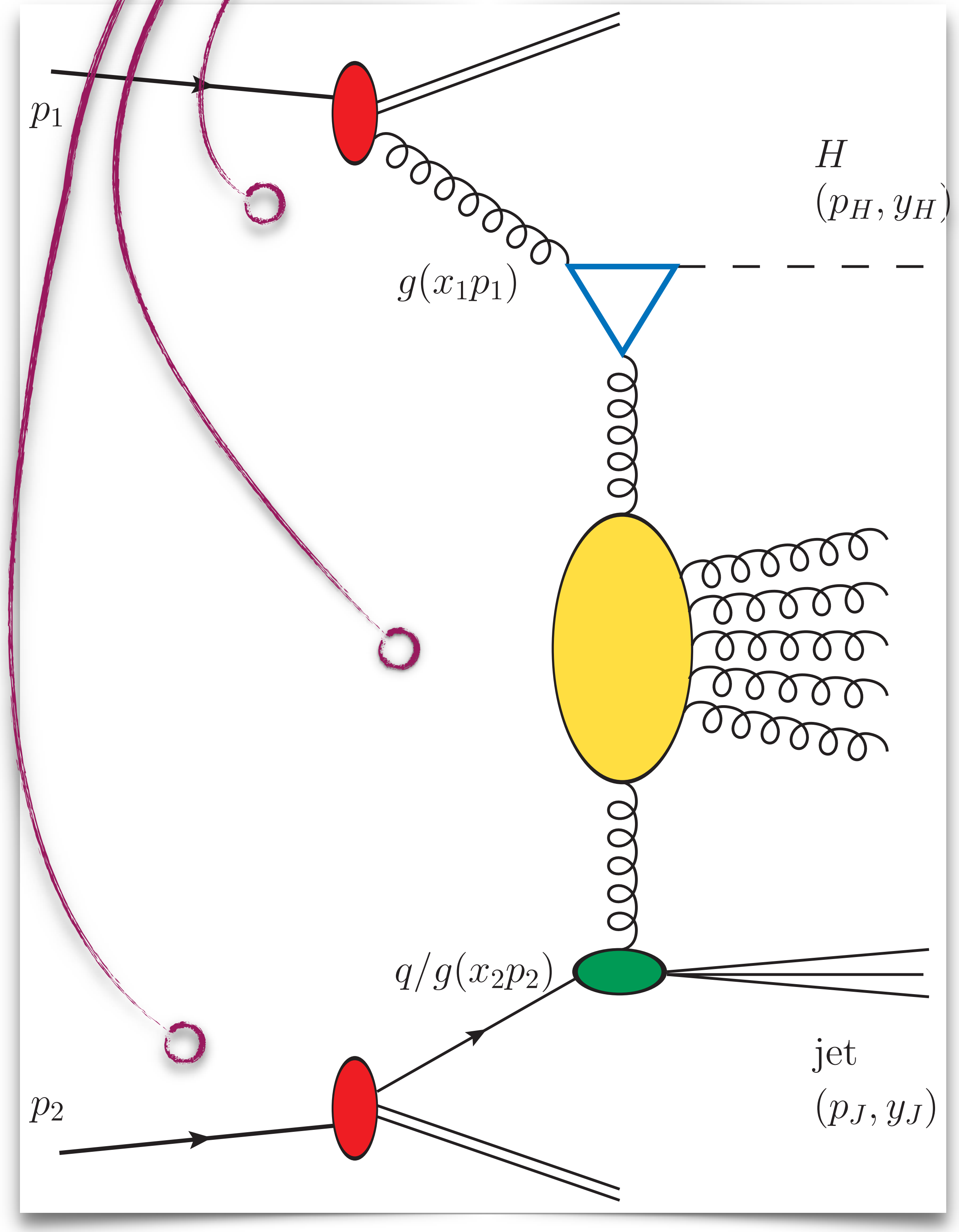

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\, \mathcal{C}_n\right]$$

Higgs vertex (off-shell amplitude)

jet vertex (off-shell amplitude)

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

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

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

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

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

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BFKL Green's function

Backup

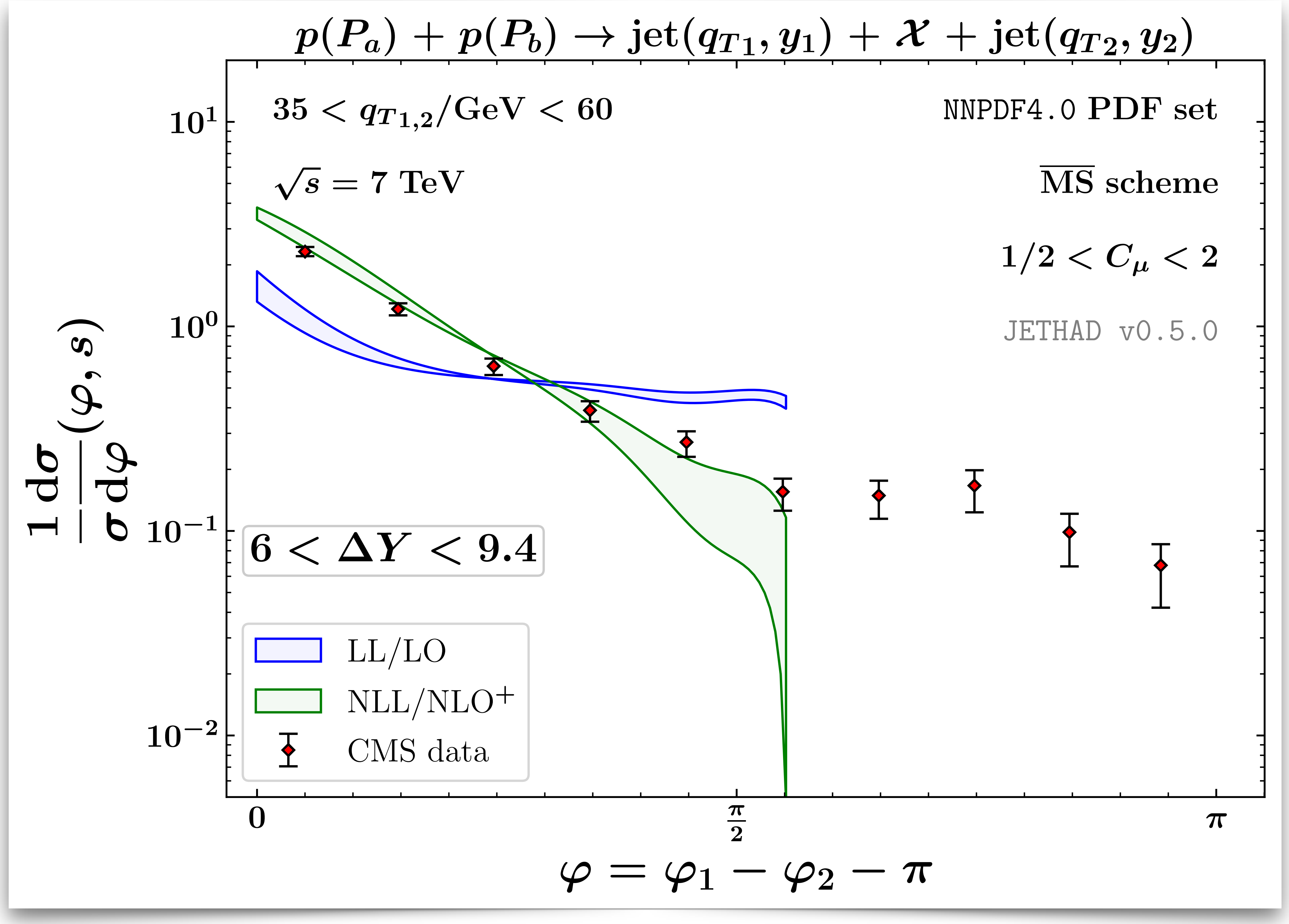
Azimuthal-angle multiplicity

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

Mueller-Navelet jets

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

(figure below) [F. G. C., A. Papa (2022)]



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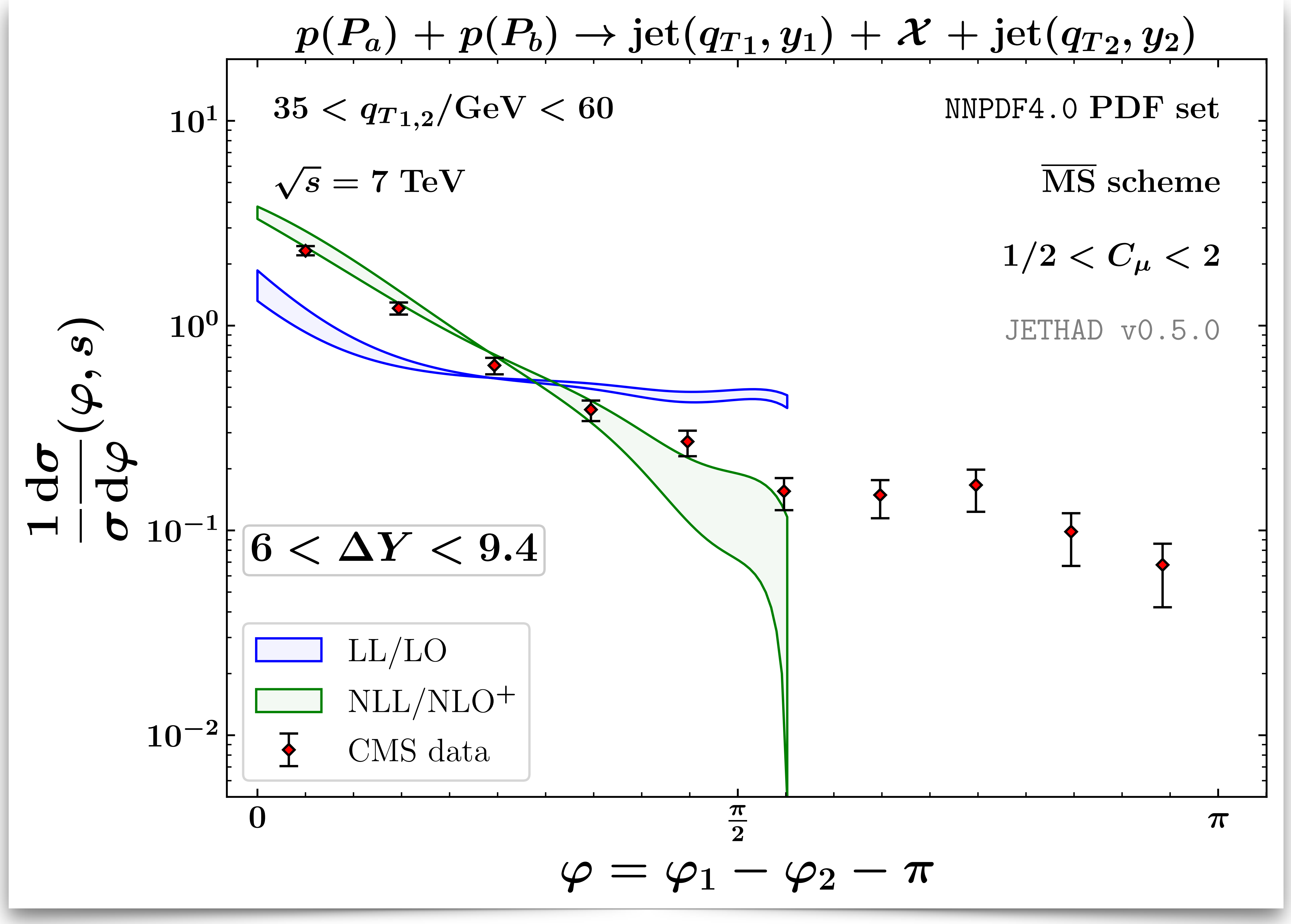
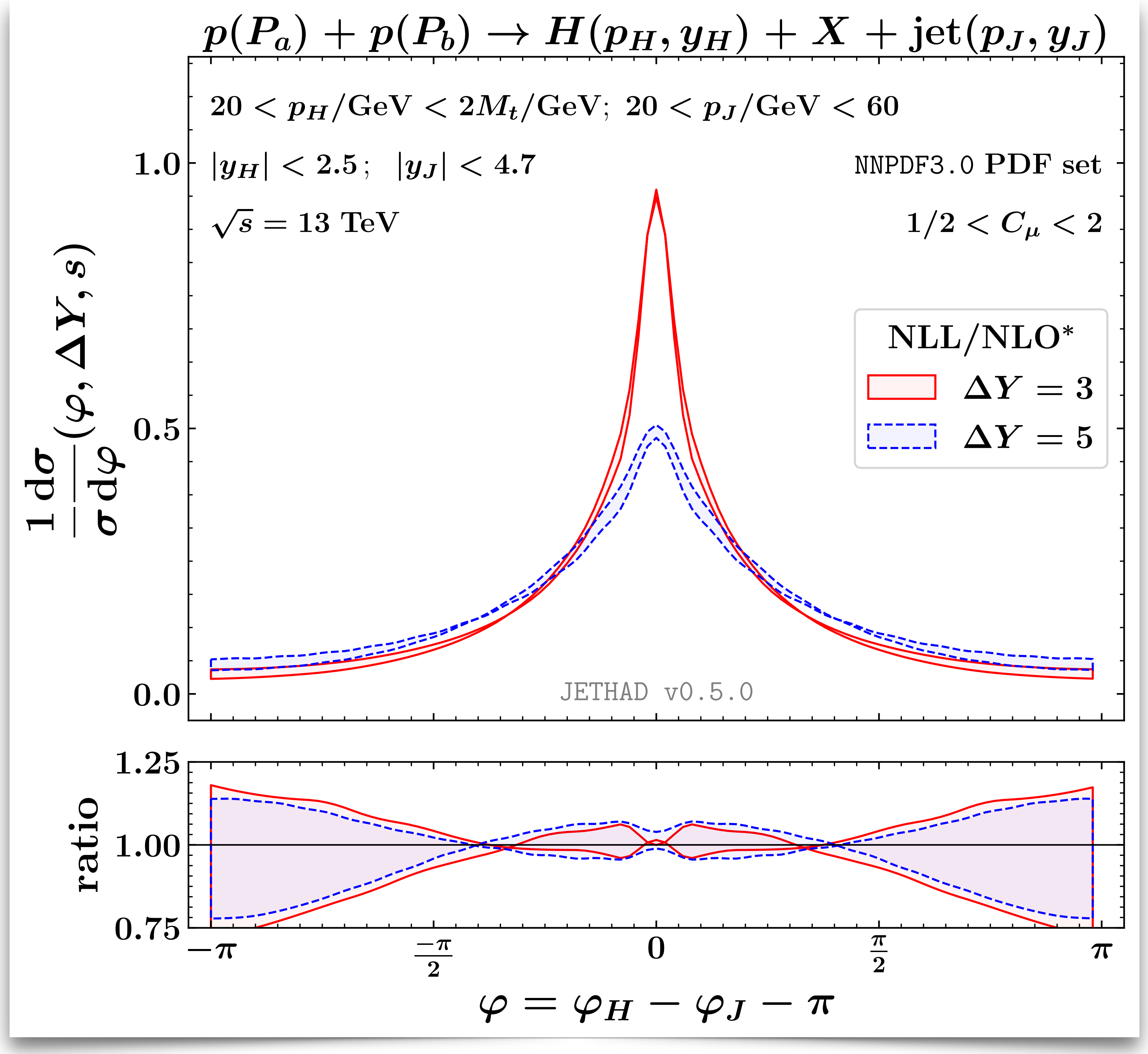


Higgs + jet

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

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

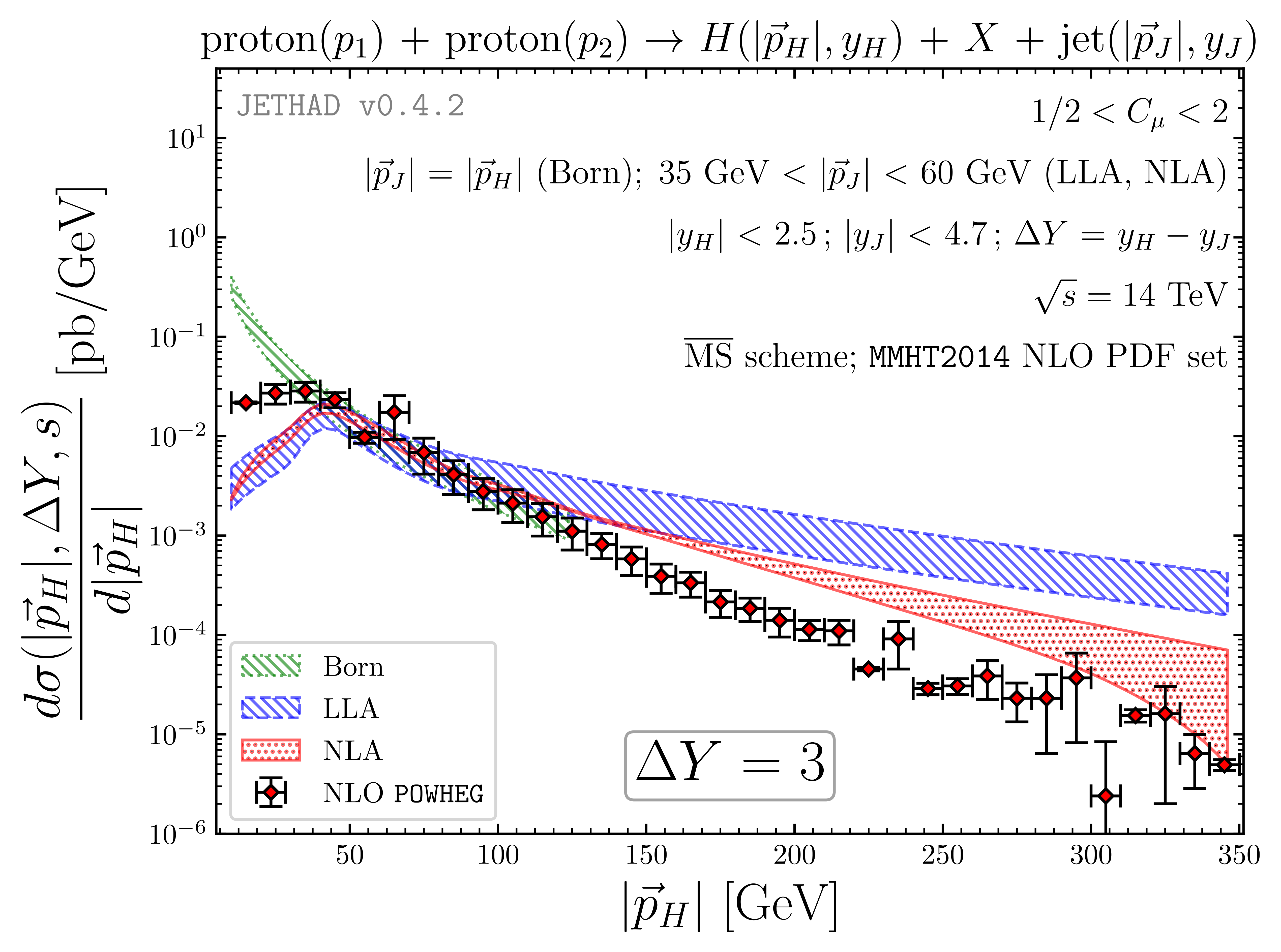


Backup

NLL resummation via the JETHAD Method python + F 🔗 [F. G. C. (2021)]

Higgs transverse-momentum distribution

$$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_0$$

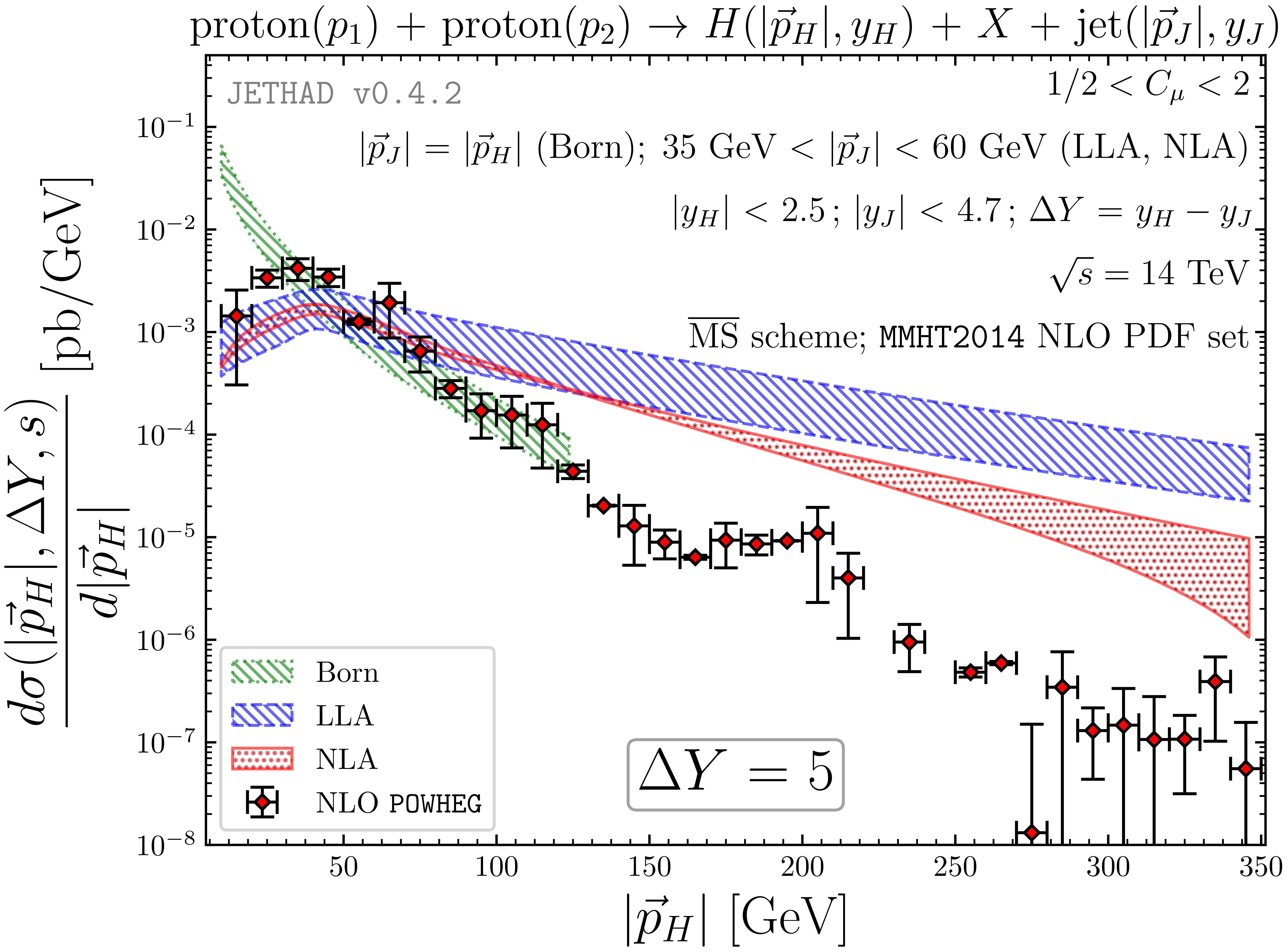


- HE resummation from JETHAD
- Comparison with fixed-order POWHEG
- Distributions stable under NLL corrections

Backup

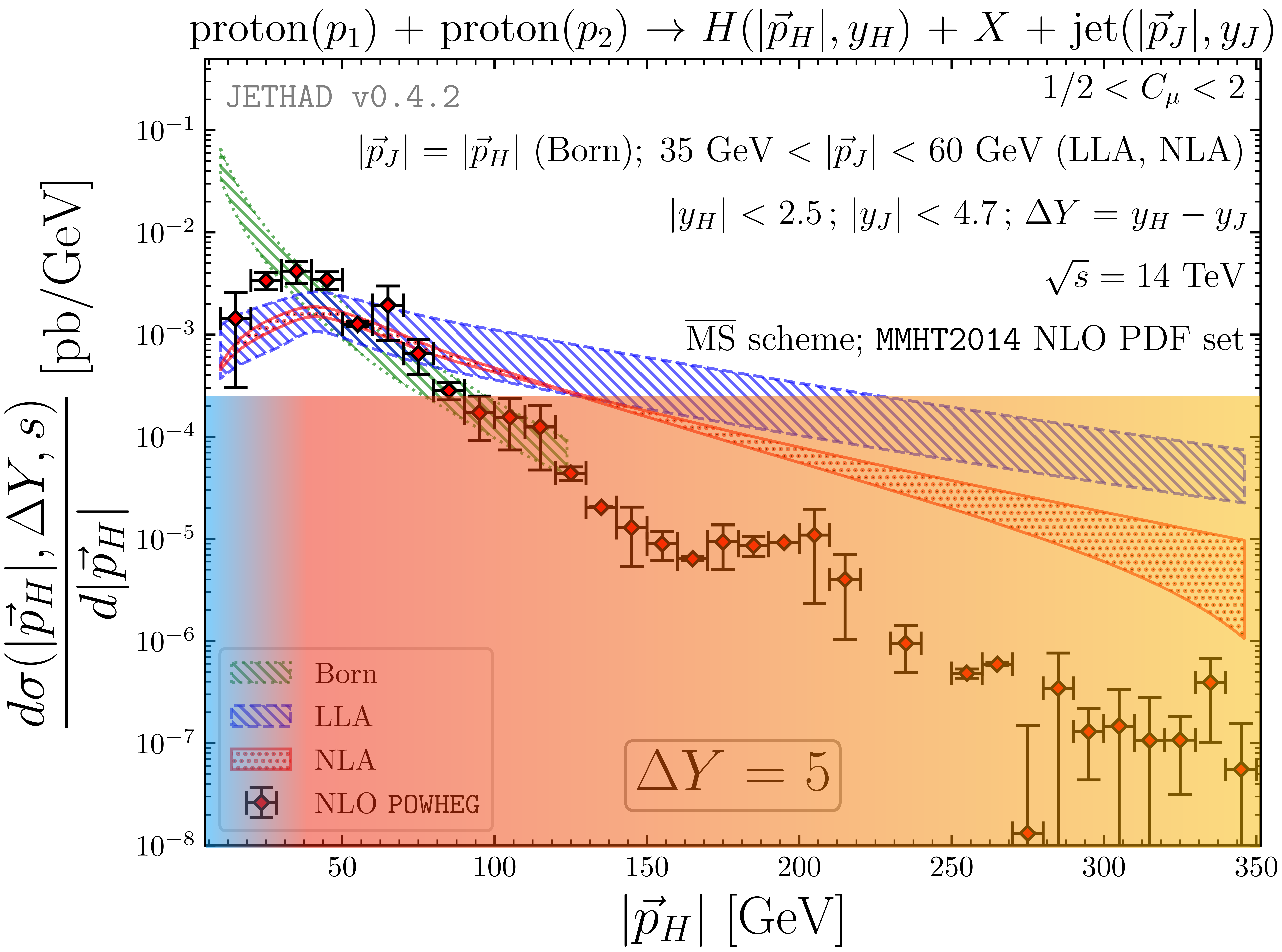
[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Backup



proton(p_1) + proton(p_2) → $H(|\vec{p}_H|, y_H)$ + X + jet($|\vec{p}_J|, y_J$)
JETHAD v0.4.2
$1/2 < C_\mu < 2$
$|\vec{p}_J| = |\vec{p}_H|$ (Born); 35 GeV $< |\vec{p}_J| <$ 60 GeV (LLA, NLA)
$|y_H| < 2.5\,;\ |y_J| < 4.7\,;\ \Delta Y = y_H - y_J$
$\sqrt{s}$ = 14 TeV
$\overline{\rm MS}$ scheme; MMHT2014 NLO PDF set
$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H|}$ [pb/GeV]
$|\vec{p}_H|$ [GeV]
$\Delta Y = 5$
Born
LLA
NLA
NLO POWHEG
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
50
100
150
200
250
300
350

Backup



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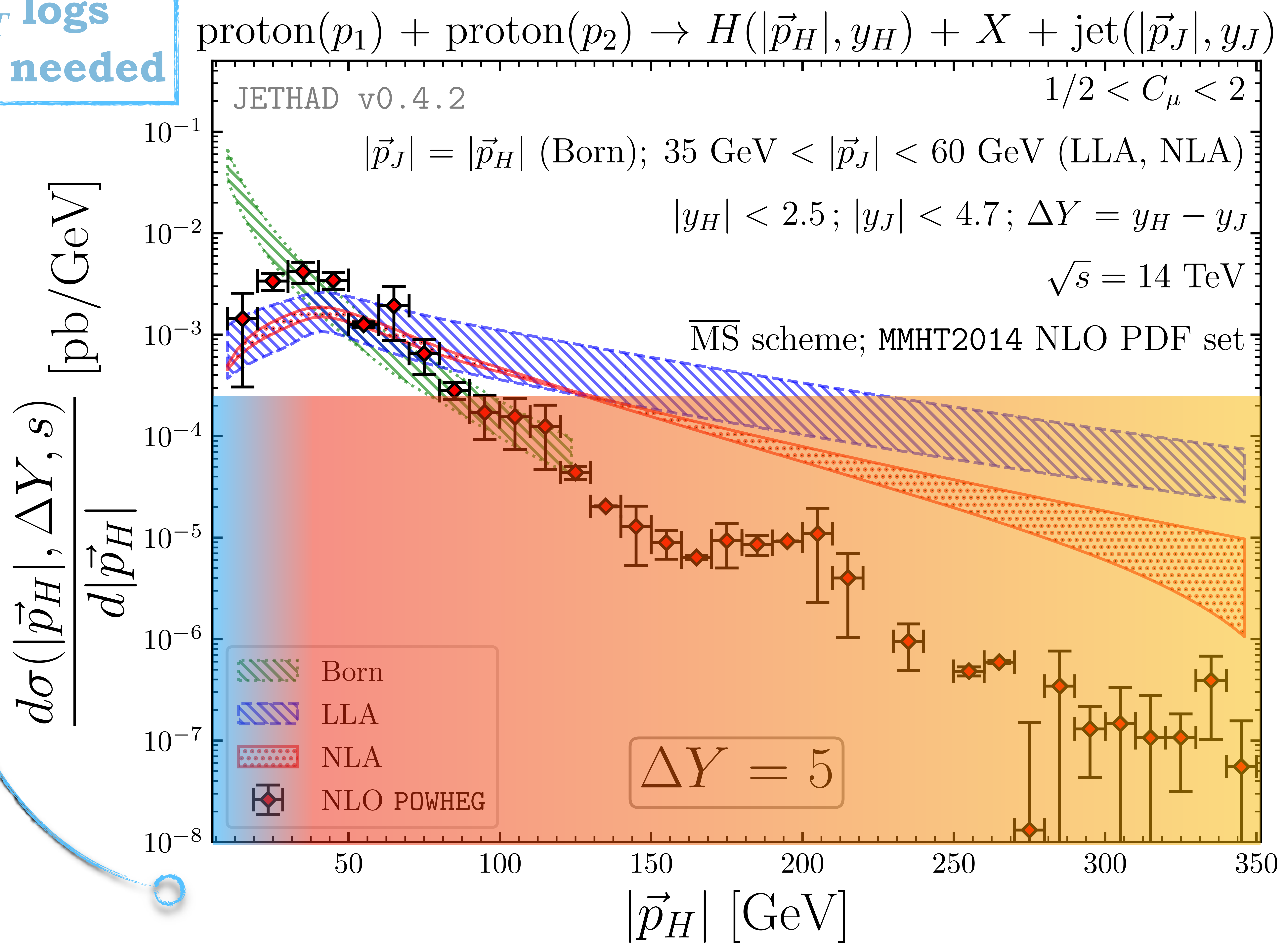
Born
LLA
NLA
NLO POWHEG
$\Delta Y = 5$
$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H|}$ [pb/GeV]
$|\vec{p}_H|$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
50
100
150
200
250
300
350

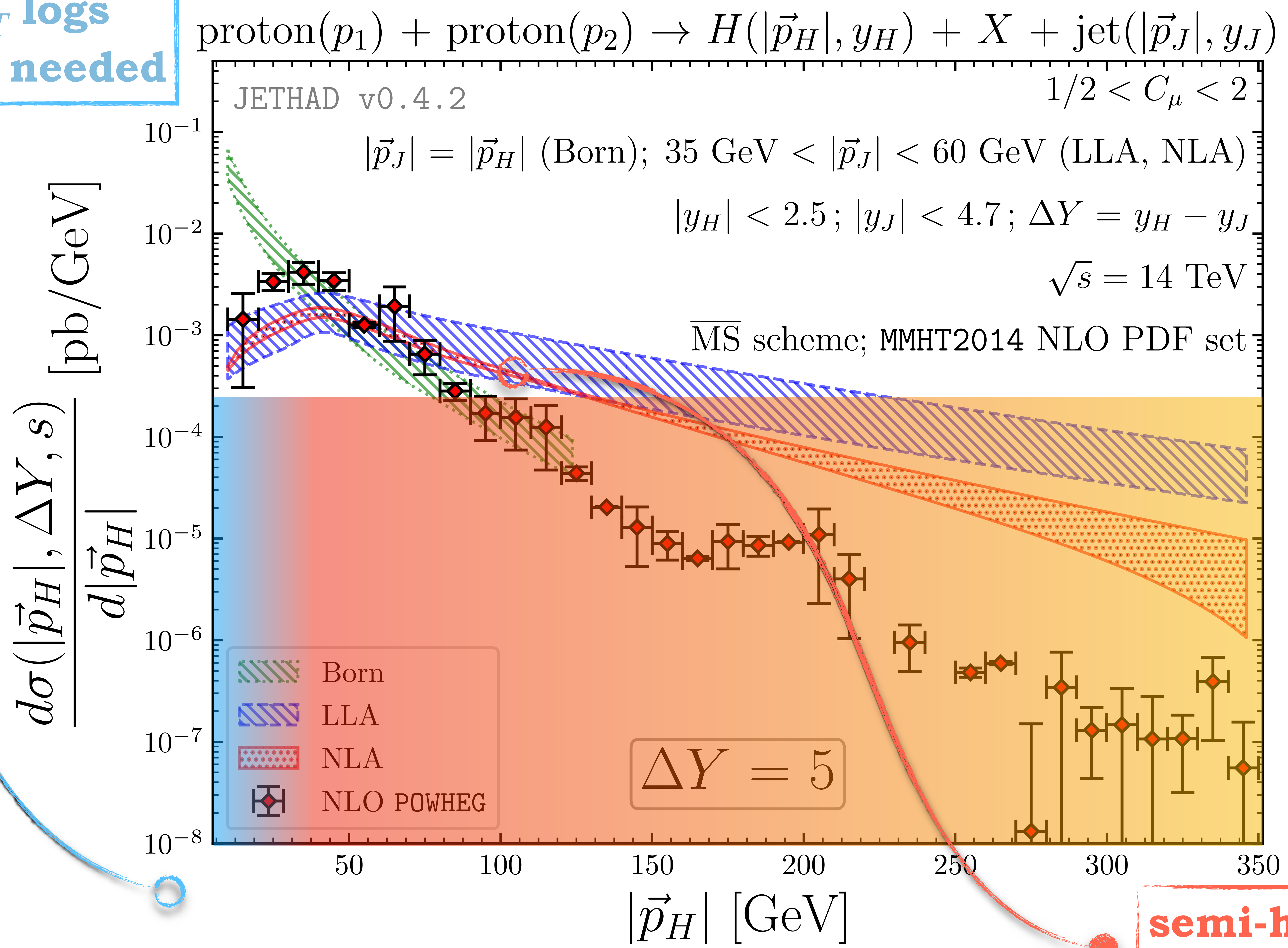
large p_T logs
p_T-resum. needed

Backup



large p_T logs
p_T-resum. needed

Backup

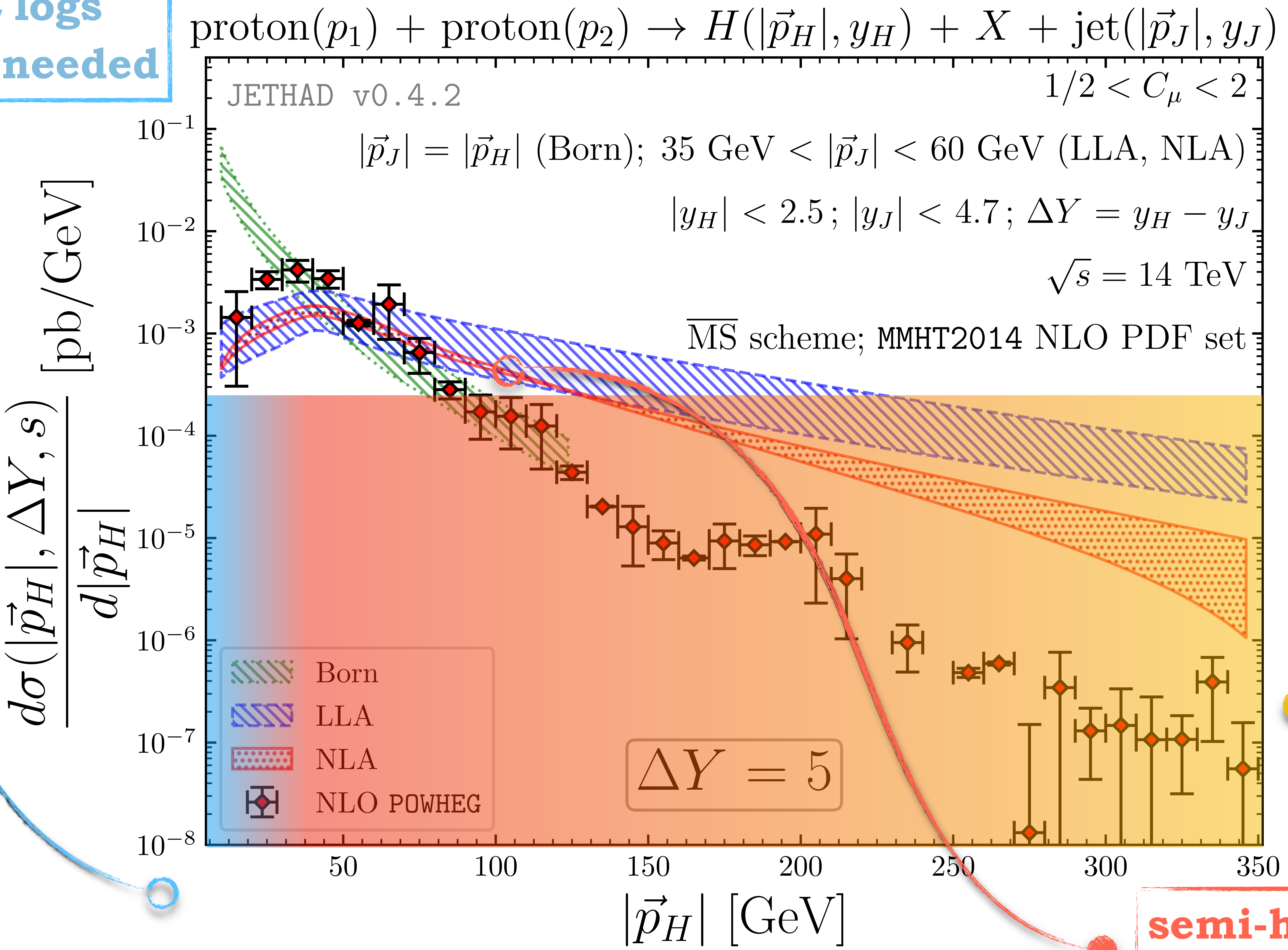


semi-hard regime
BFKL expected

DGLAP-type + large-x threshold logs → BFKL decoupling

large p_T logs
p_T-resum. needed

Backup

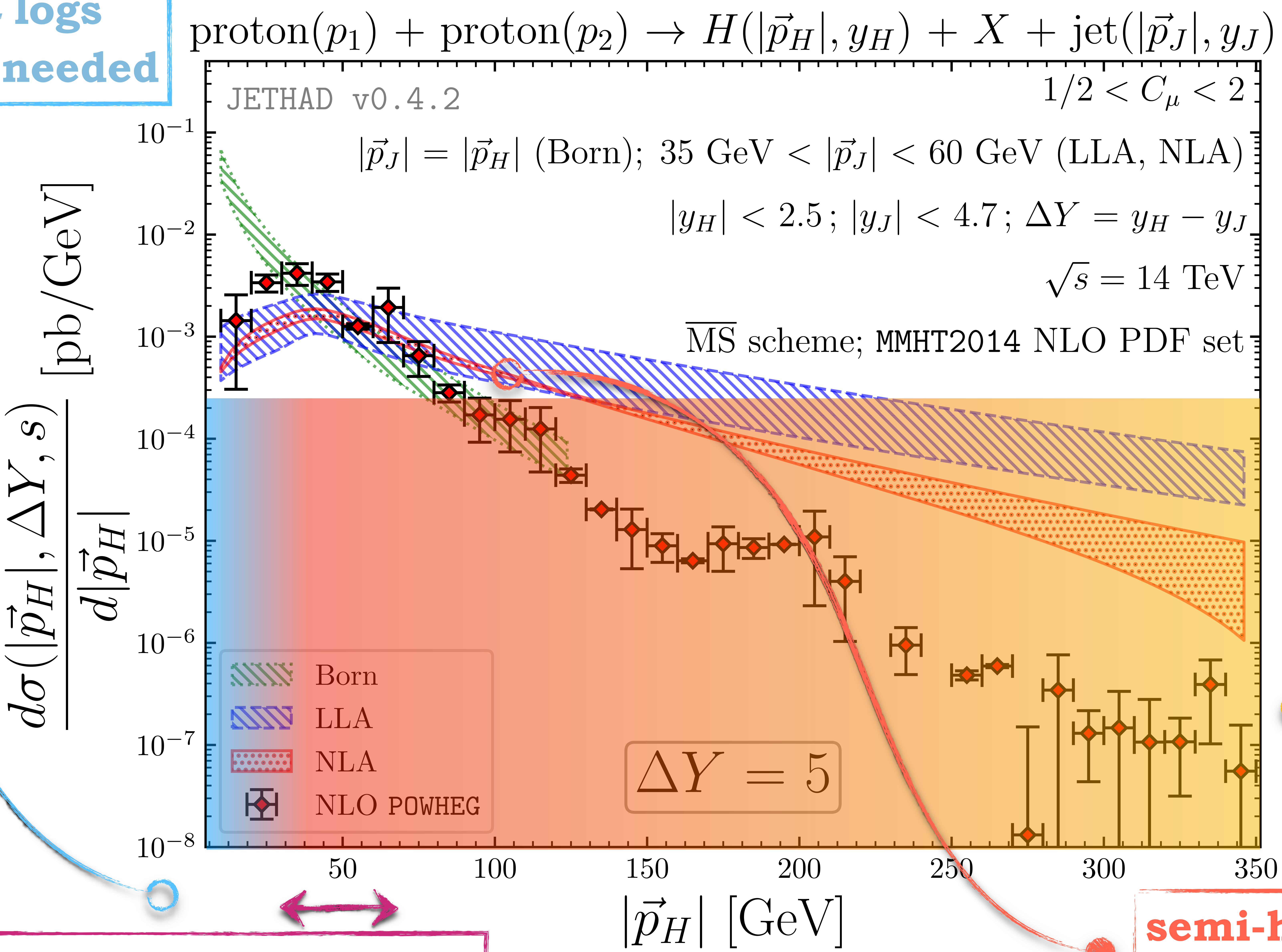


semi-hard regime
BFKL expected

Backup

DGLAP-type + large-x threshold logs → BFKL decoupling

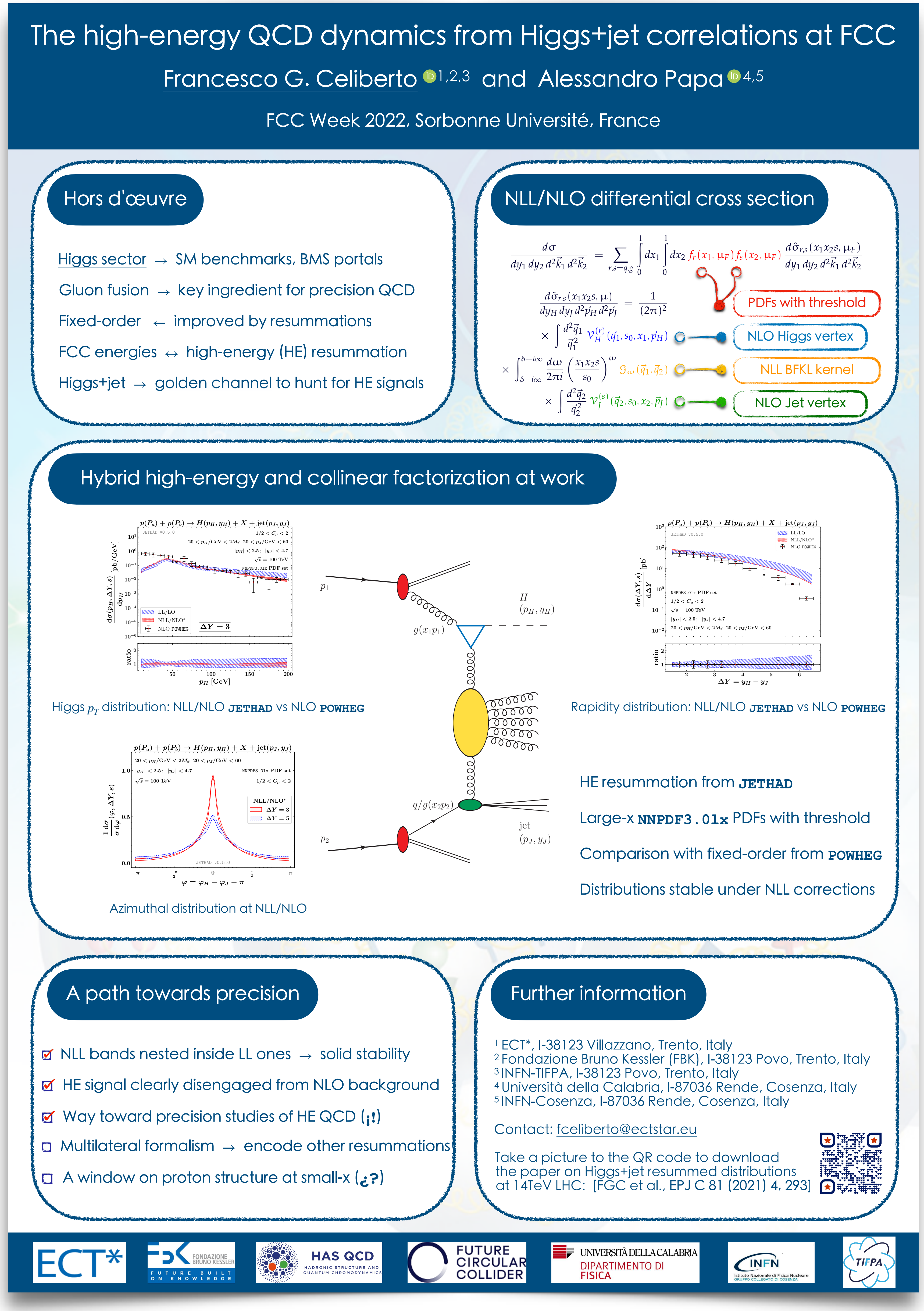
large p_T logs
p_T-resum. needed



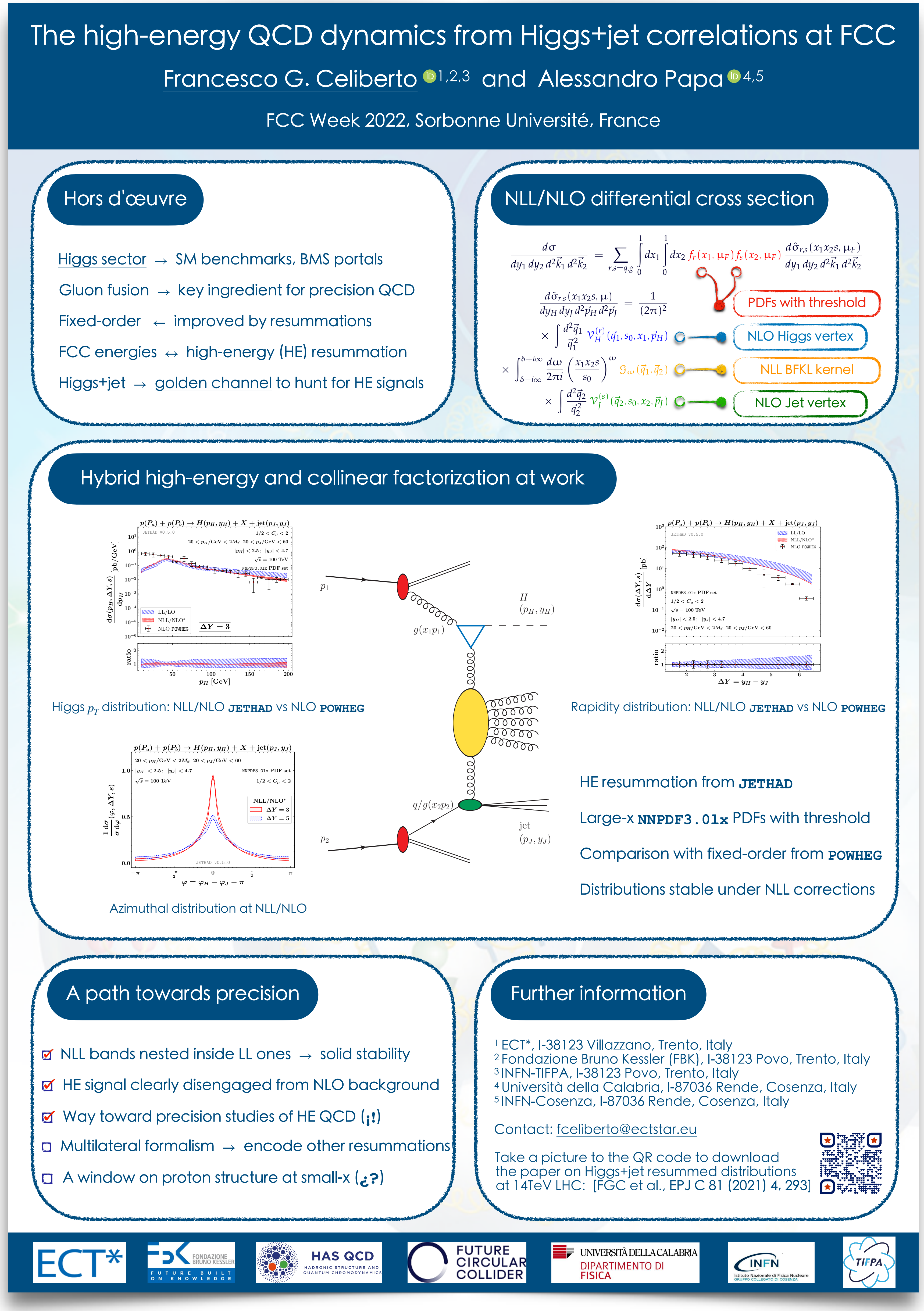
almost back-to-back emissions
Sudakov-type double logs

semi-hard regime
BFKL expected

Higgs + jet highlights from the FCC Week 2022

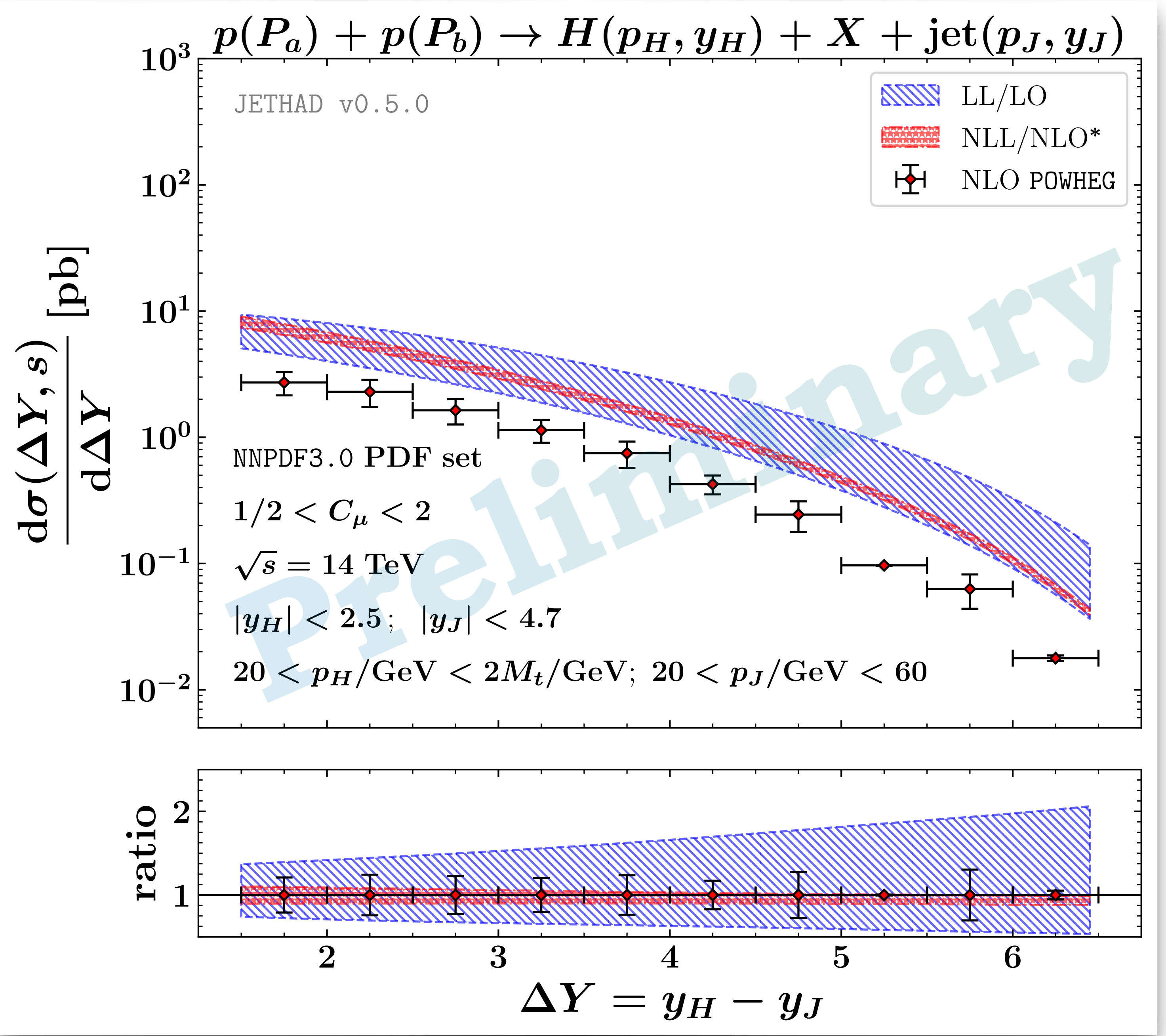


Higgs + jet highlights from the FCC Week 2022

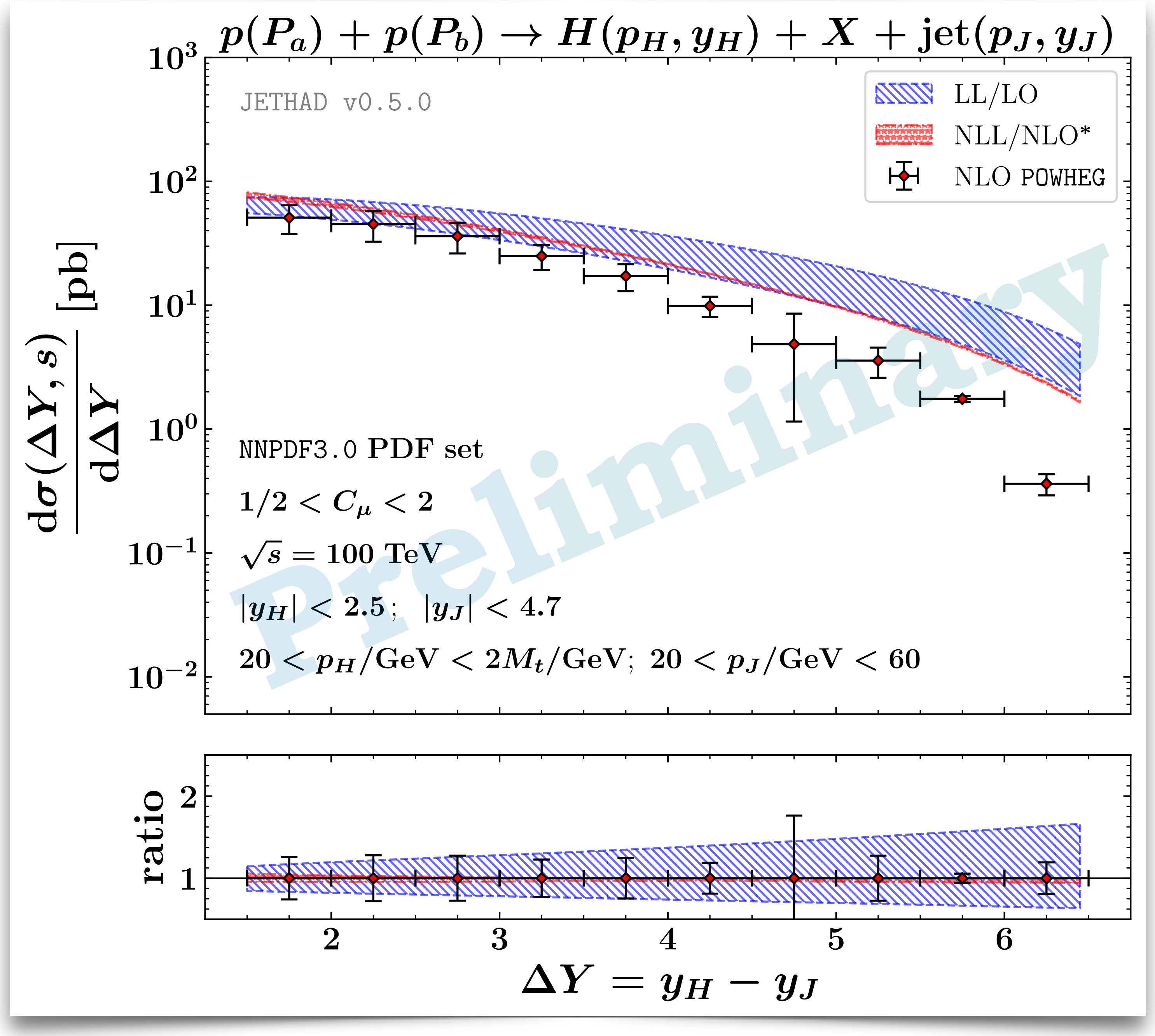


$$C_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$

Rapidity distribution: NLL/NLO* JETHAD vs NLO POWHEG



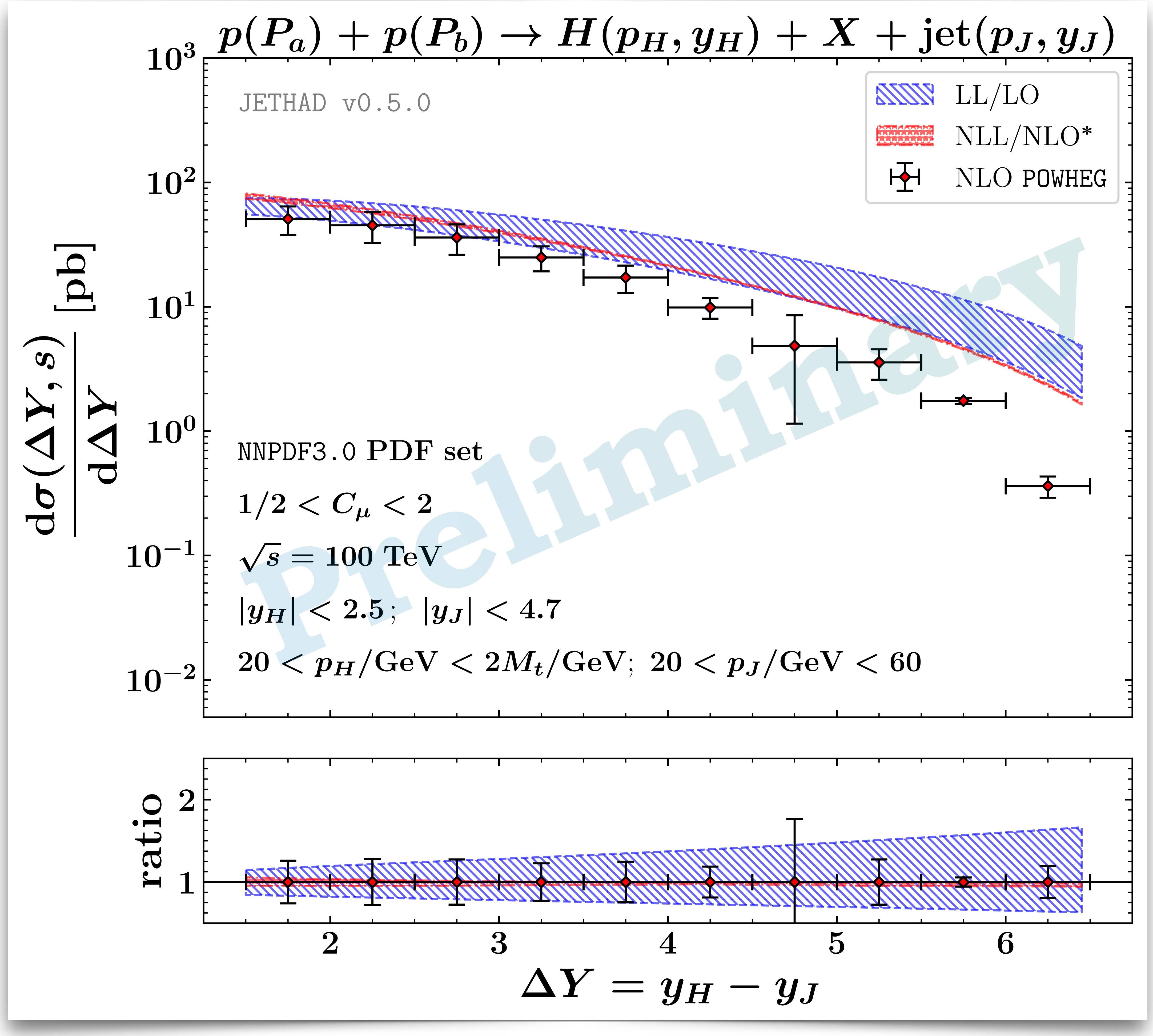
14 TeV LHC



100 TeV FCC

Higgs + jet at @FCC: small-x enhancement from PDFs

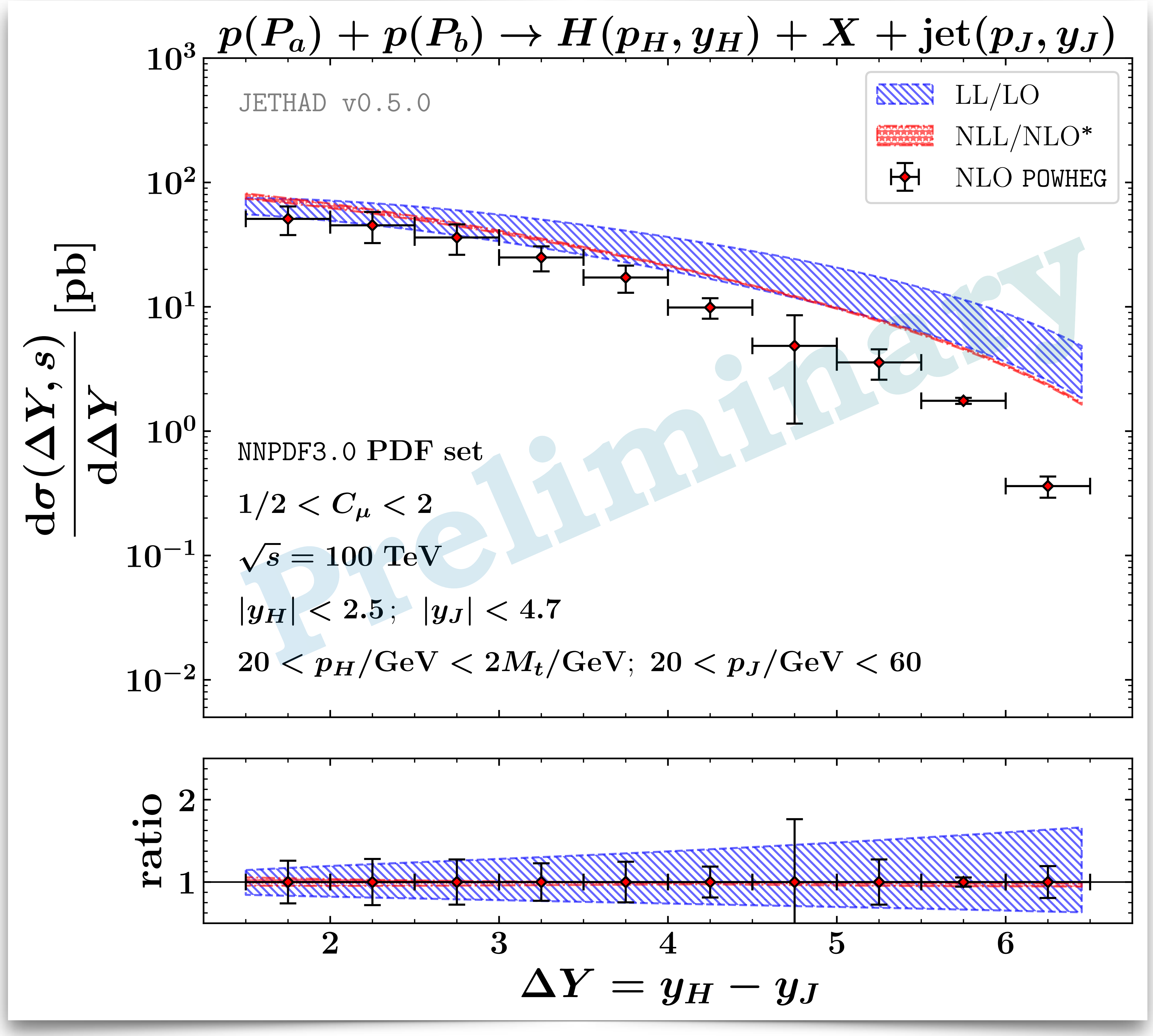
High-energy resummation + **NNPDF3.0** 🔗



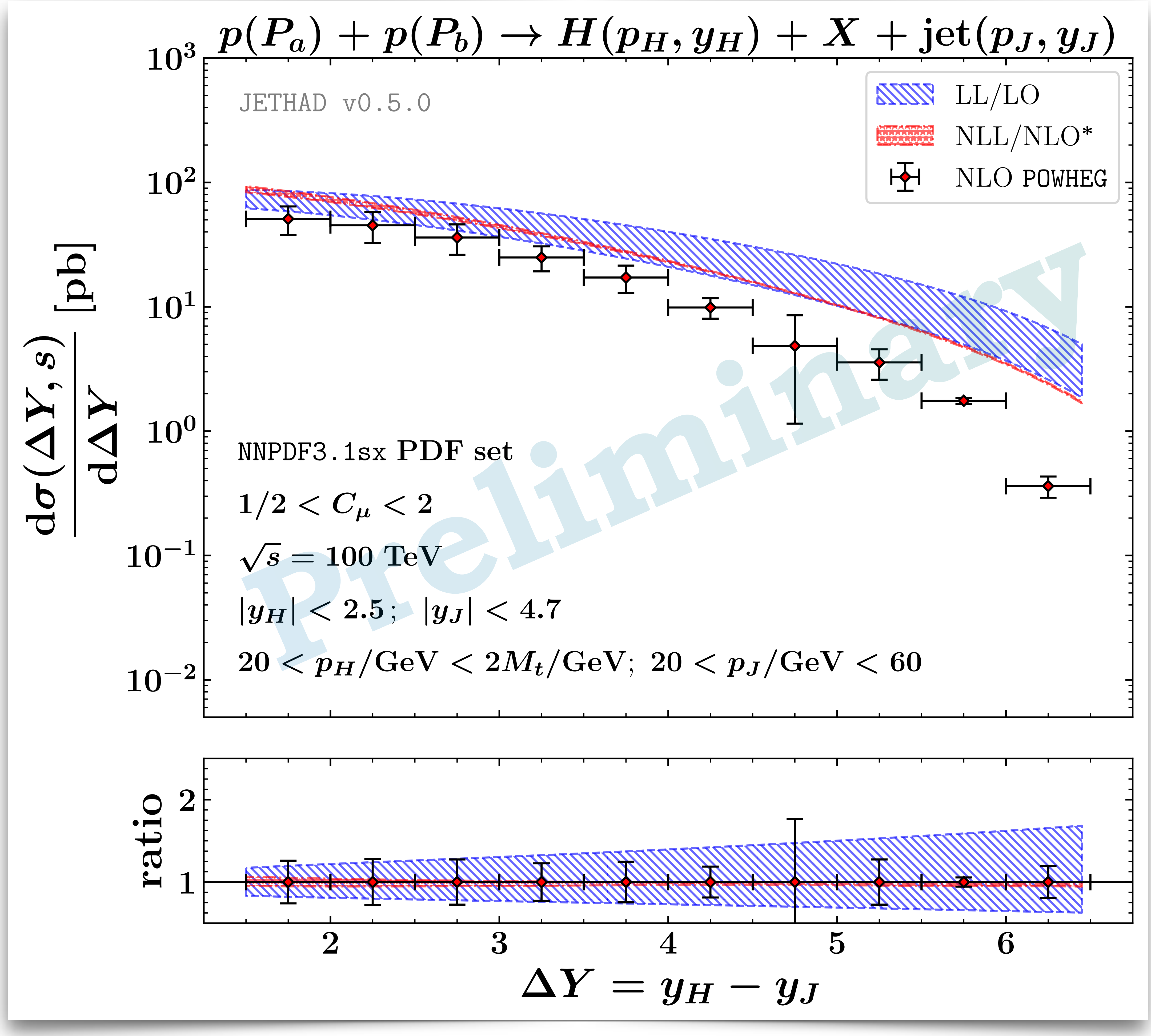
Backup

Higgs + jet at @FCC: small-x enhancement from PDFs

High-energy resummation + **NNPDF3.0** 🔗



High-energy resummation + **NNPDF3.1sx** 🔗

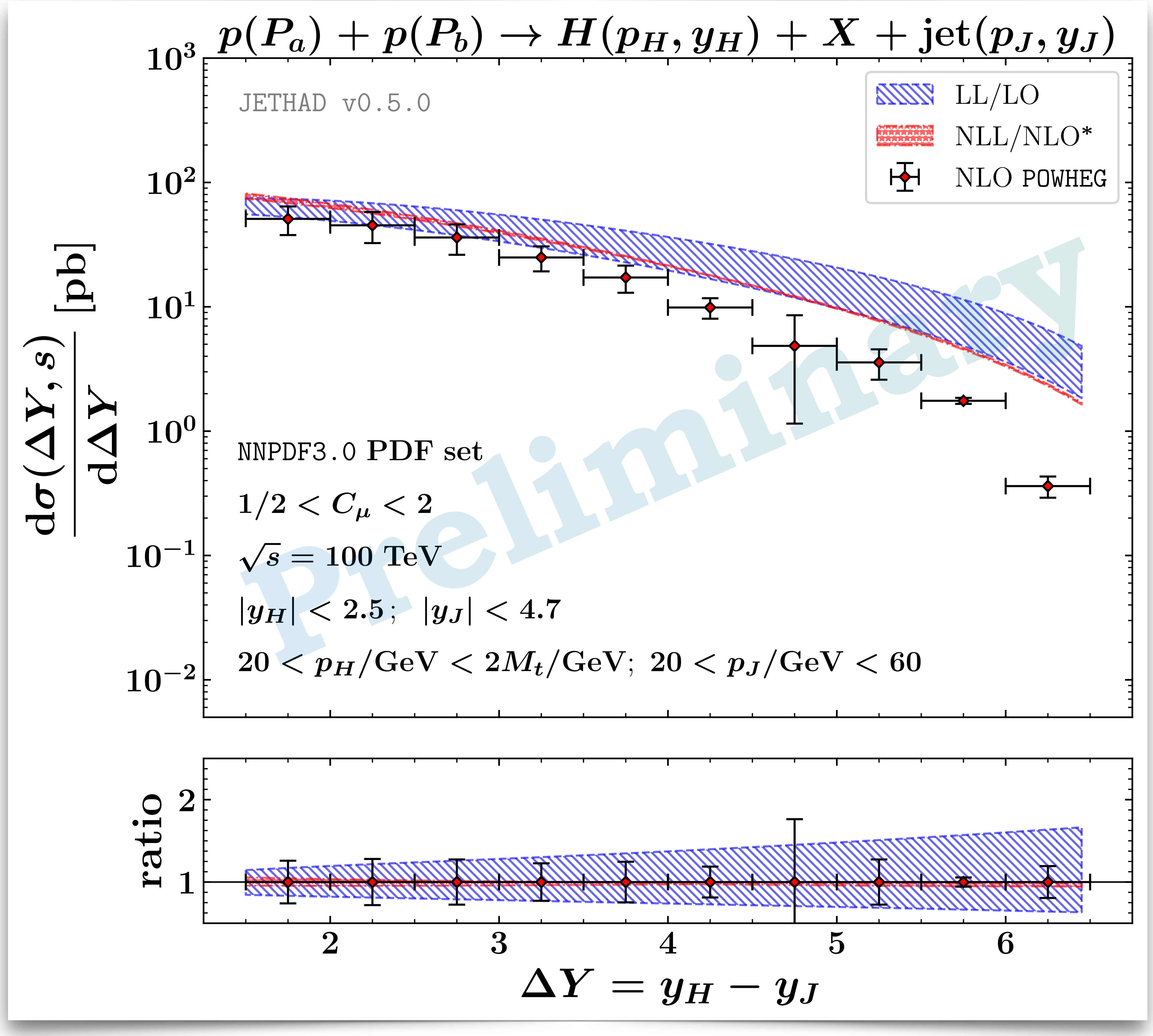


Small-x resummation on PDFs $\Rightarrow$ $+(13.5 \div 2.10)\,\%$ @NLL/NLO*

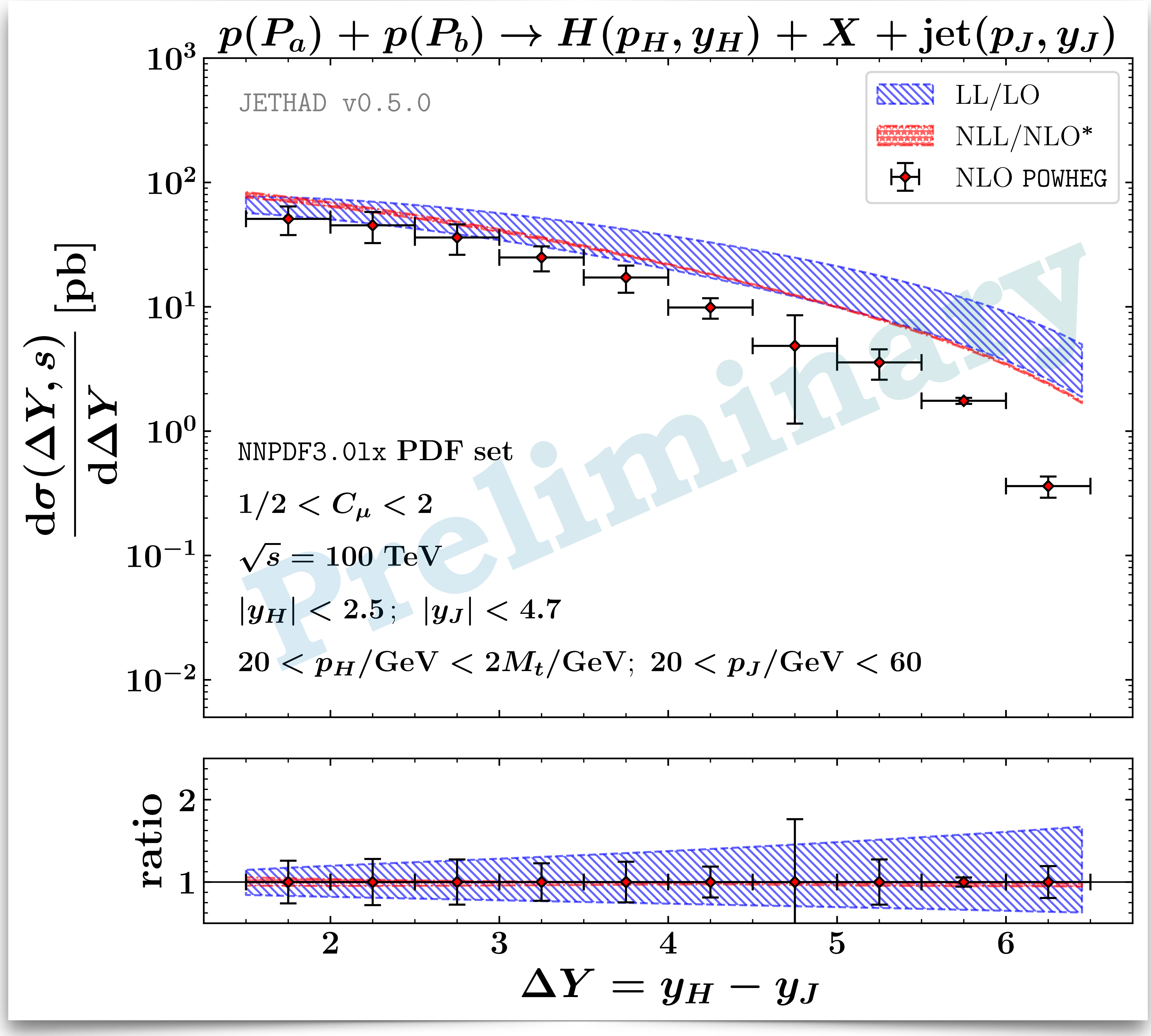
Backup

Higgs + jet at @FCC: large-x enhancement from PDFs

High-energy resummation + **NNPDF3.0**



High-energy resummation + **NNPDF3.01x**

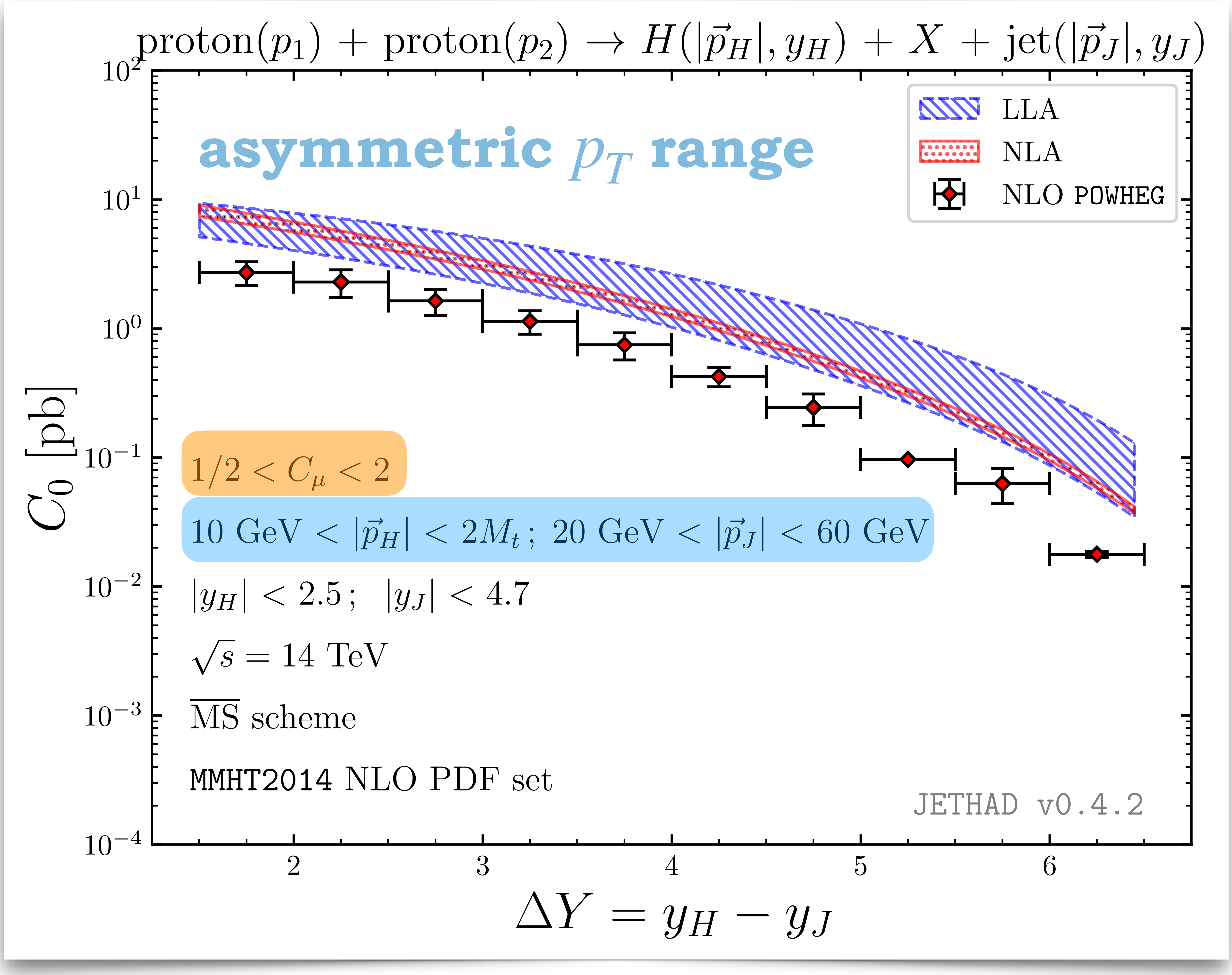


Backup

Threshold resummation on PDFs $\Rightarrow$ $+(10.7 \div 2.15)\,\%$ @NLL/NLO*

ΔY-distribution

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

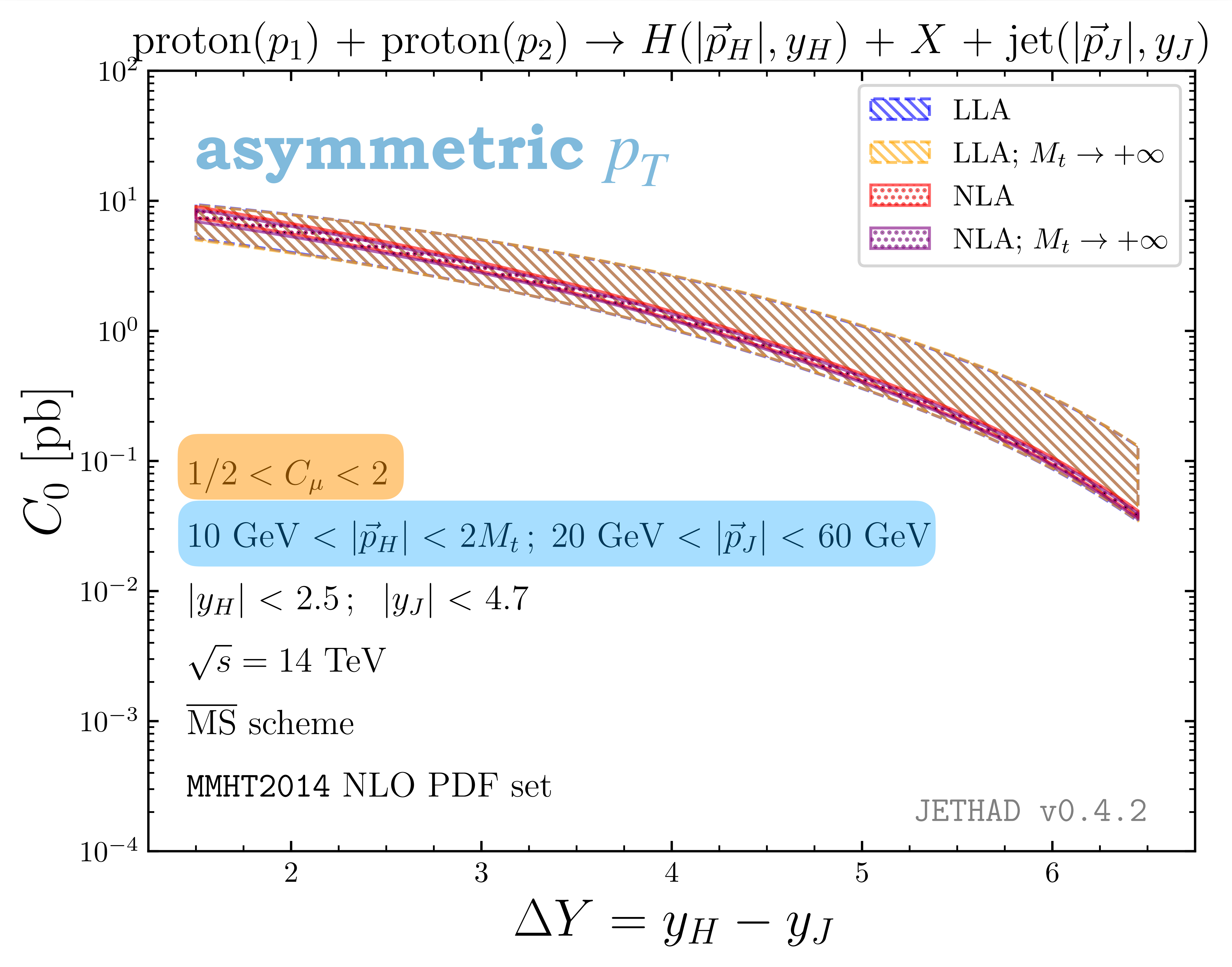


Backup

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

ΔY-distribution in the infinite top-mass limit

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



Backup

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

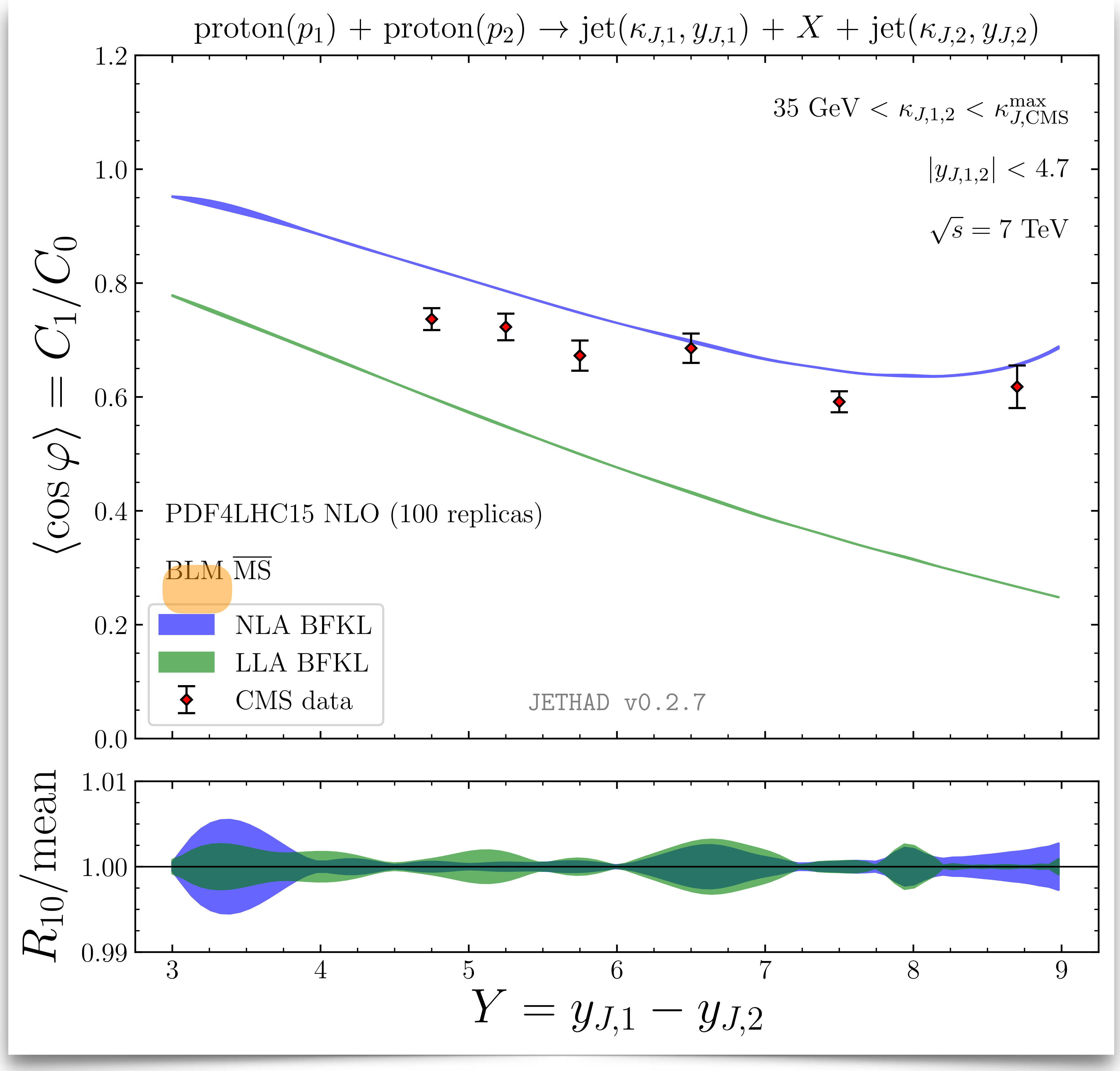
Angular correlations in the infinite top-mass limit

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

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]



Backup

Angular correlations in the infinite top-mass limit

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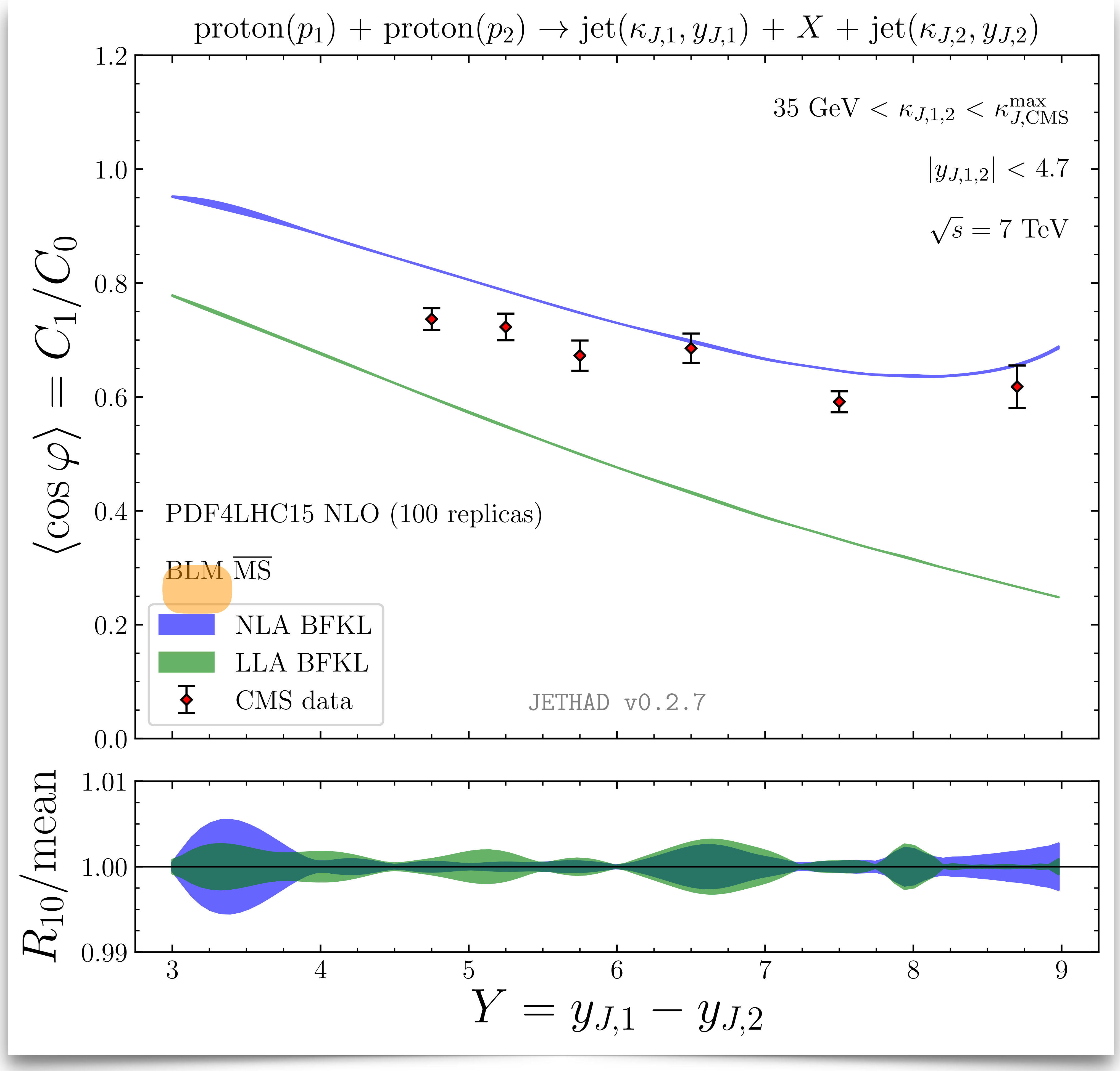
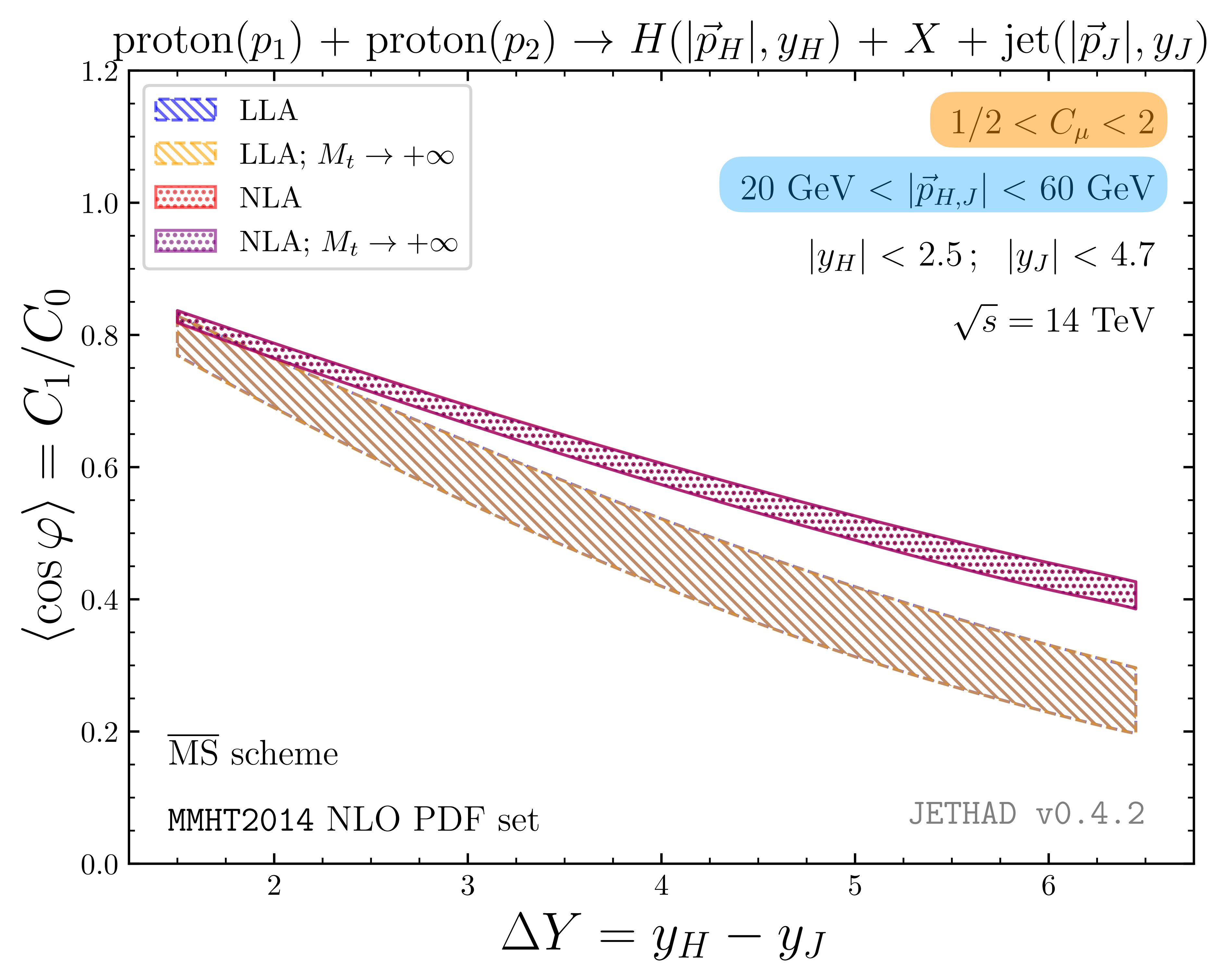


Higgs + jet

(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)]

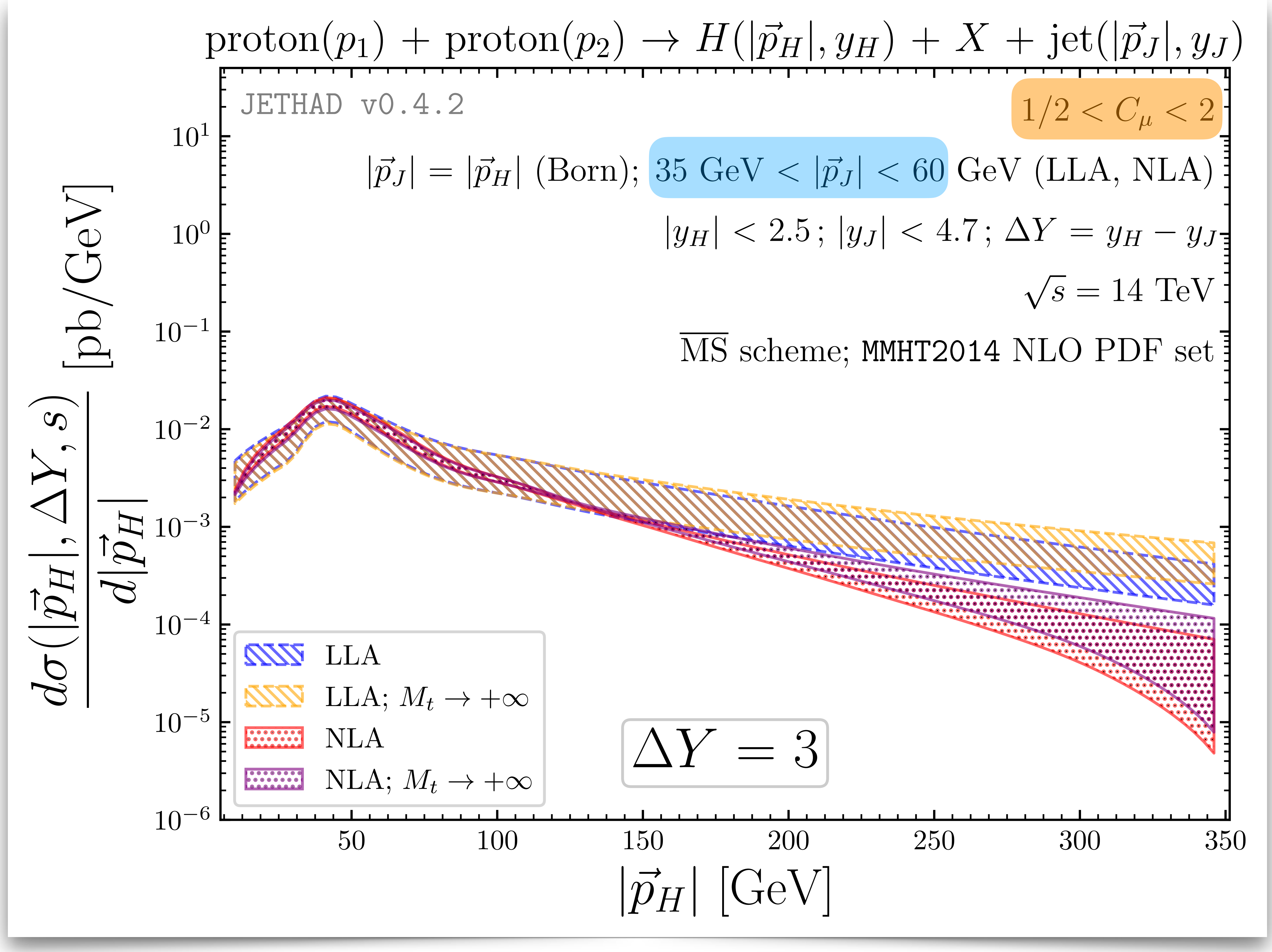


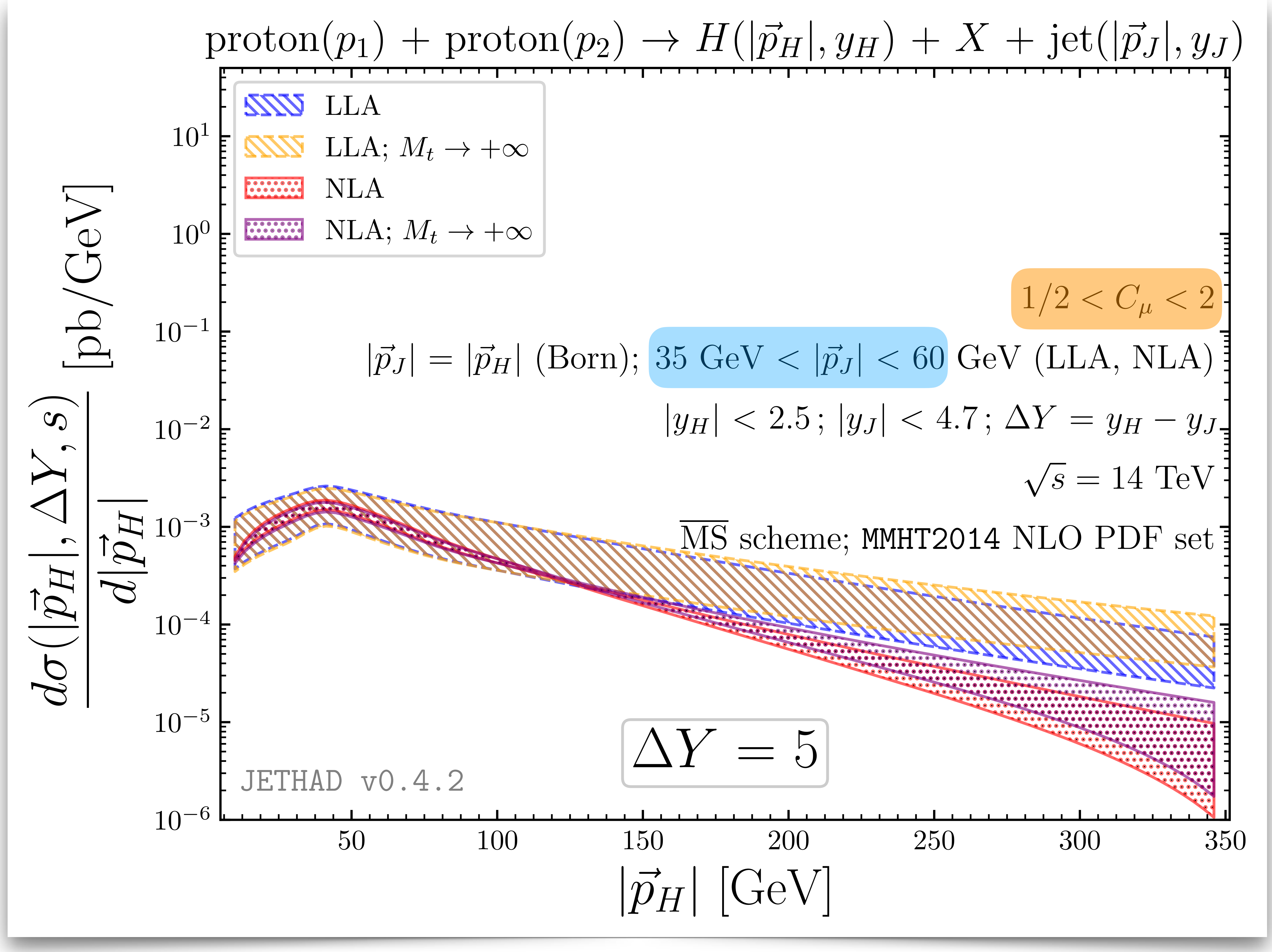
natural scales

symmetric p_T range

Backup

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]

Backup

Basics of BFKL

Gluon Reggeization in perturbative QCD

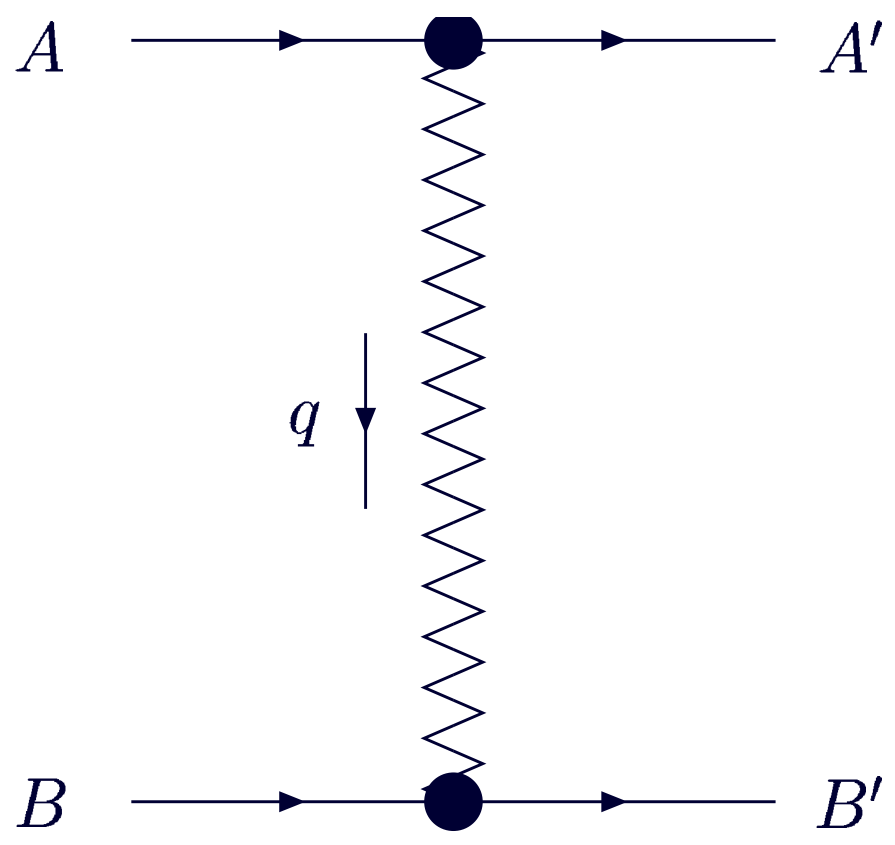
- Gluon quantum numbers in the t-channel: 8^- representation
- Regge limit: $s \simeq -u \to \infty$, t not growing with s

$\to$ amplitudes governed by **gluon Reggeization** $\to D_{\mu\nu} = -i\frac{g_{\mu\nu}}{q^2}\left(\frac{s}{s_0}\right)^{\alpha_g(q^2)-1}$

$\xrightarrow{\text{feature}}$ all-order resummation: **LLA** $[\alpha_s^n(\ln s)^n]$ + **NLA** $[\alpha_s^{n+1}(\ln s)^n]$

$\xrightarrow{\text{consequence}}$ factorization of elastic and real part of inelastic amplitudes

$\xrightarrow{\text{example}}$ Elastic scattering process: $A + B \longrightarrow A' + B'$



$$(\mathcal{A}_8^-)_{AB}^{A'B'} = \Gamma_{A'A}^c \left[\left(\frac{-s}{-t}\right)^{j(t)} - \left(\frac{s}{-t}\right)^{j(t)}\right] \Gamma_{B'B}^c$$

$$j(t) = 1 + \omega(t)\,, \qquad j(0) = 1$$

$\omega(t) \to$ Reggeized gluon trajectory

$\Gamma_{A'A}^c = g\langle A'|T^c|A\rangle \Gamma_{A'A} \to$ PPR vertex

$T^c \to$ fundamental (q) or adjoint (g)

- QCD is the unique SM theory where all elementary particles reggeize
- Possible extensions: N=4 SYM, AdS/CFT,...

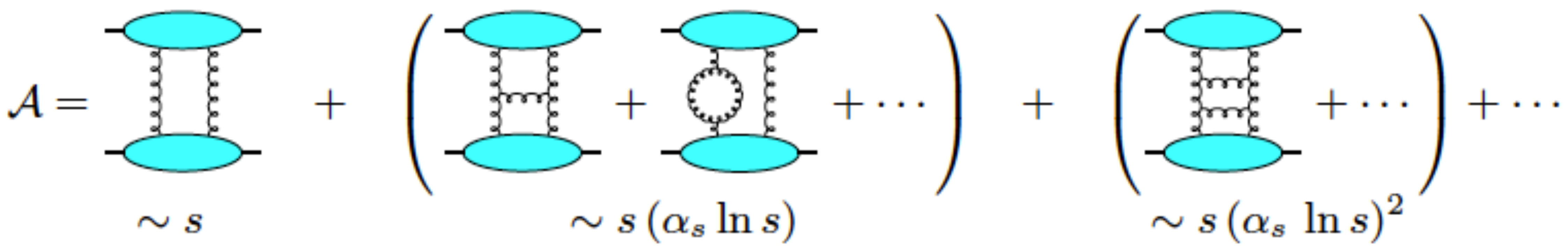
Backup

The high-energy resummation

- **BFKL resummation**: [V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975, 1976, 1977); Y.Y. Balitskii, L.N. Lipatov (1978)]

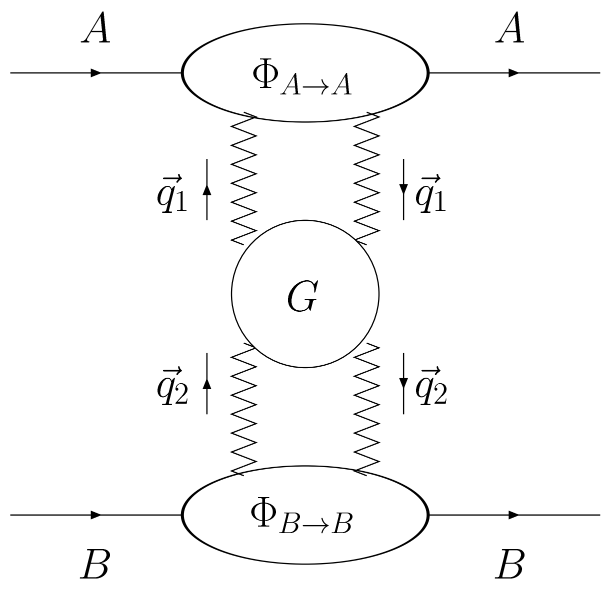
$\xrightarrow{\text{based on}}$ **gluon Reggeization**

leading logarithmic approximation (LL): $\alpha_s^n (\ln s)^n$



next-to-leading logarithmic approximation (NLL): $\alpha_s^{n+1} (\ln s)^n$

Total cross section for $A + B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{I}m_s\{\mathcal{A}_{AB}^{AB}\}}{s} \Leftarrow$ *optical theorem*



- $\mathcal{I}m_s\left\{\mathcal{A}_{AB}^{AB}\right\}$ factorization:

  convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles

Green's function is **process-independent**, describes energy dependence and obeys BFKL equation; impact factors are known in the **NLL just for few processes**

The high-energy resummation

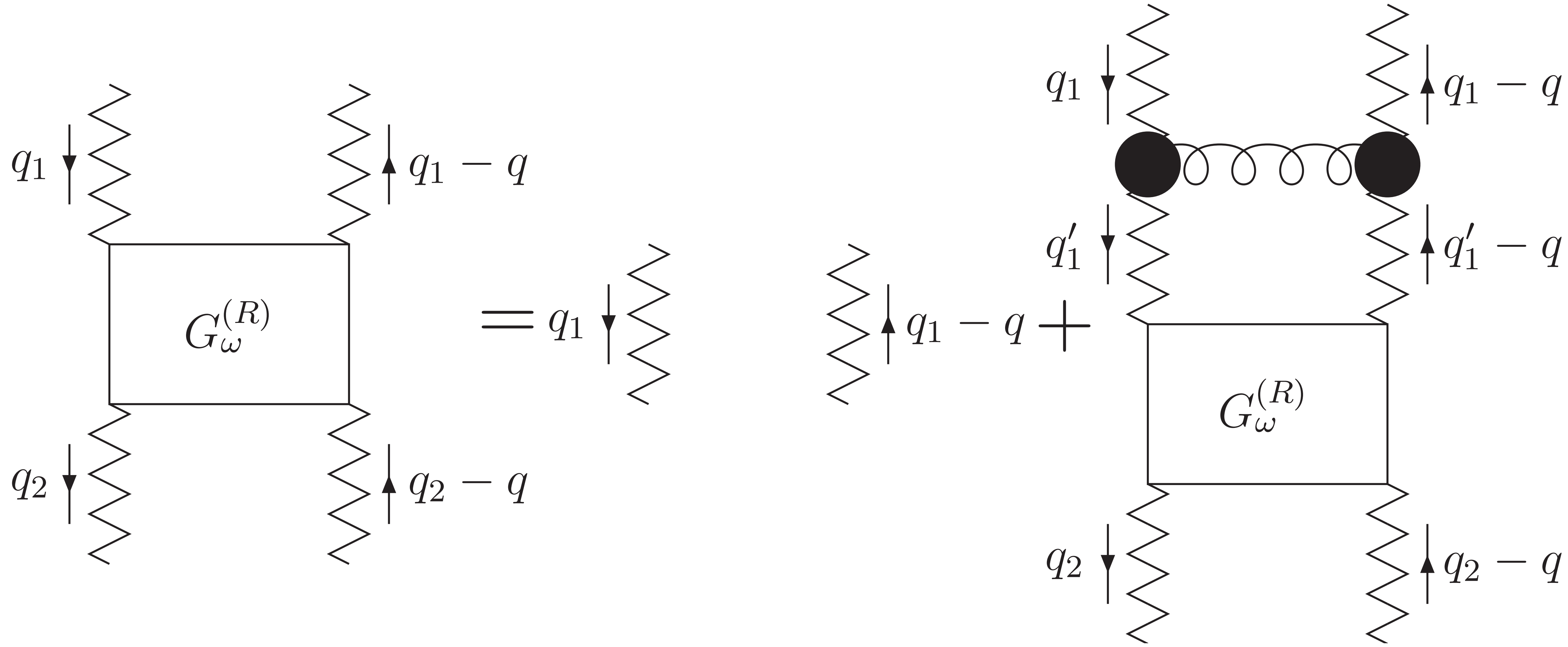
$$\mathcal{I}m_s\{\mathcal{A}\} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1, \vec{q}_2)$$

- **Green's function** is **process-independent** and takes care of the **energy dependence**

$\longrightarrow$ determined through the **BFKL equation**

[Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

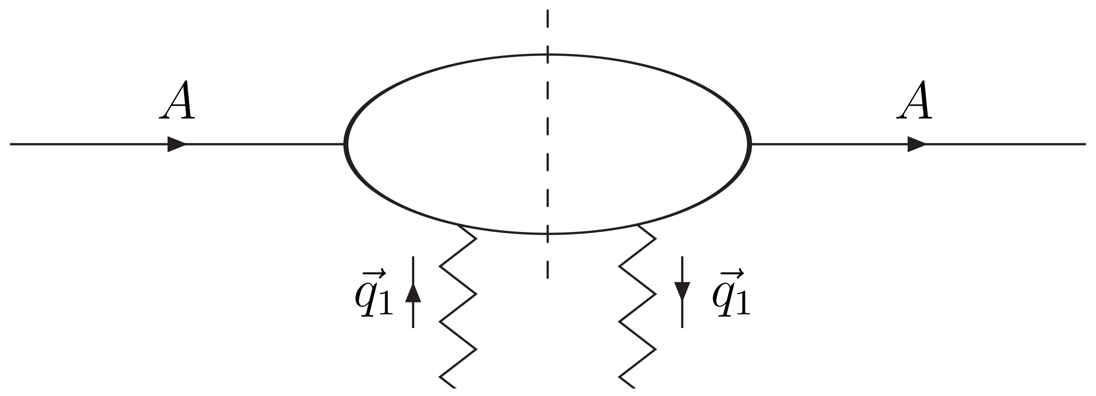
$$\omega\, G_\omega(\vec{q}_1, \vec{q}_2) = \delta^{D-2}(\vec{q}_1 - \vec{q}_2) + \int d^{D-2}q\, K(\vec{q}_1, \vec{q})\, G_\omega(\vec{q}, \vec{q}_1)\,.$$



Backup

The high-energy resummation

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy $\longrightarrow$ known in the NLA just for few processes



- **colliding partons**

[V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
[M. Ciafaloni, G. Rodrigo (2000)]

- $\gamma^* \longrightarrow V$, with $V = \rho^0,\ \omega,\ \phi$, forward case

[D.Yu. Ivanov, M.I. Kotsky, A. Papa (2004)]

- forward jet production

[J. Bartels, D. Colferai, G.P. Vacca (2003)]
(exact IF) [F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, A. Perri (2012)]
(small-cone IF) [D.Yu. Ivanov, A. Papa (2012)]
(several jet algorithms discussed) [D. Colferai, A. Niccoli (2015)]

- forward identified hadron production

[D.Yu. Ivanov, A. Papa (2012)]

- $\gamma^* \longrightarrow \gamma^*$

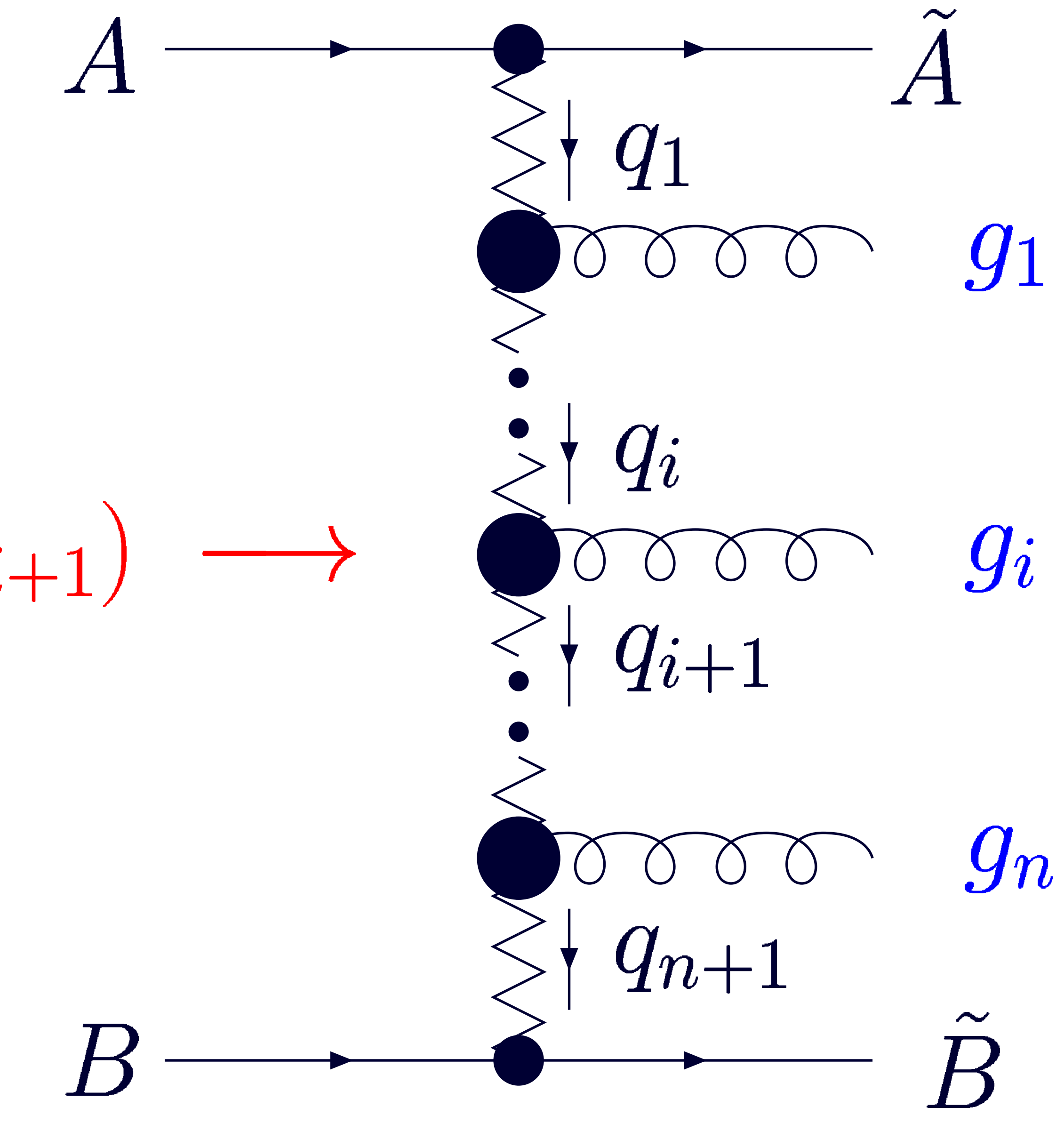
[J. Bartels *et al.* (2001), I. Balitsky, G.A. Chirilli (2011, 2013)]

Backup

BFKL in the LLA (I)

Inelastic scattering process $A + B \rightarrow \tilde{A} + \tilde{B} + n$ in the LLA

$\gamma^{G_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \longrightarrow$



multi-Regge kinematics

$$\mathrm{Re}\mathcal{A}^{\tilde{A}\tilde{B}+n}_{AB} = 2s\, \Gamma^{c_1}_{\tilde{A}A} \left(\prod_{i=1}^{n} \gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \left(\frac{s_i}{s_R}\right)^{\omega(t_i)} \frac{1}{t_i} \right) \frac{1}{t_{n+1}} \left(\frac{s_{n+1}}{s_R}\right)^{\omega(t_{n+1})} \Gamma^{c_{n+1}}_{\tilde{B}B}$$

$\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \rightarrow$ RRG vertex

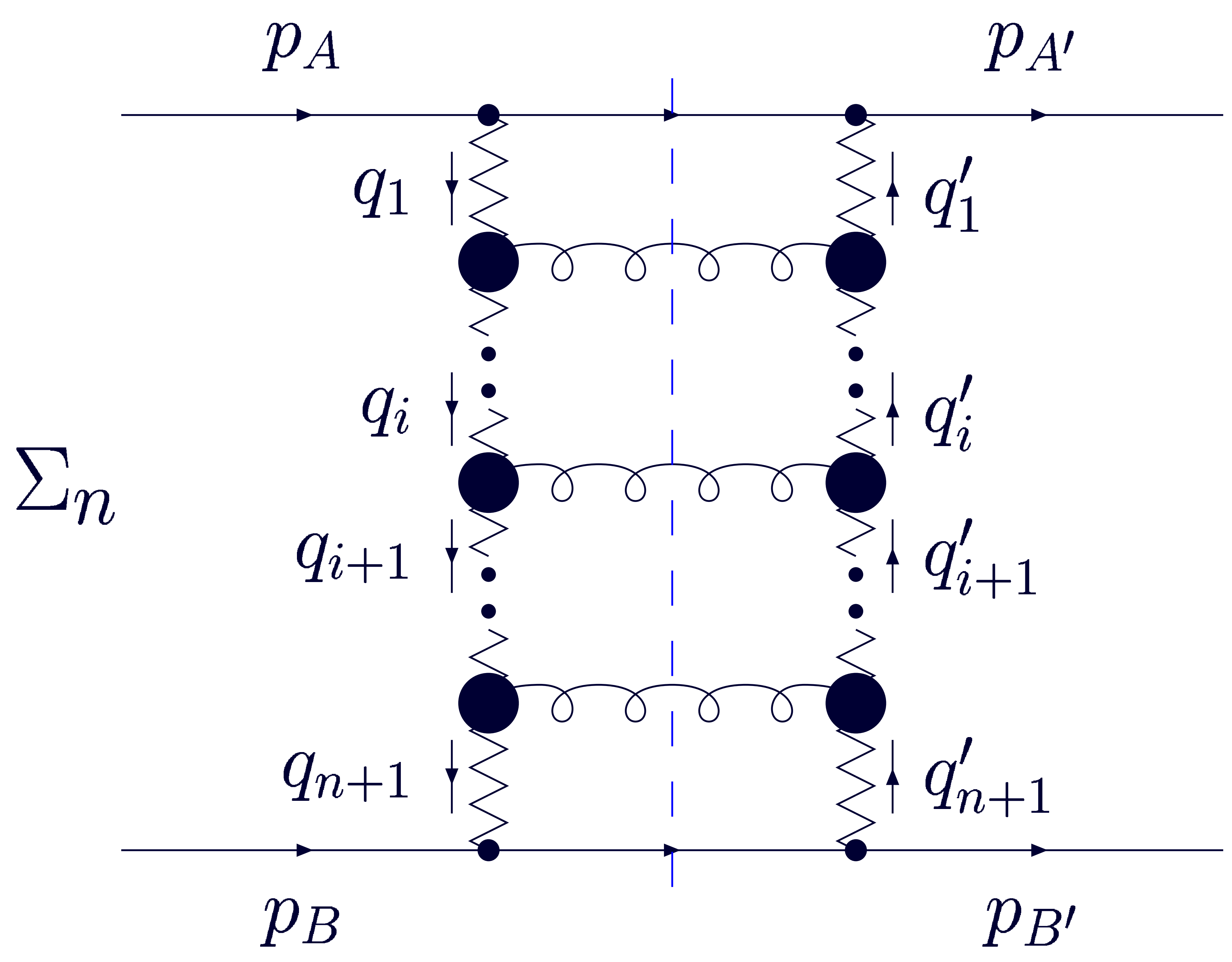
$s_R \rightarrow$ energy scale, irrelevant in the LLA

Backup

The high-energy resummation

BFKL in the LLA (II)

Elastic amplitude $A + B \longrightarrow A' + B'$ in the LLA via s-channel unitarity



$$\mathcal{A}_{AB}^{A'B'} = \sum_{\mathcal{R}} (\mathcal{A}_{\mathcal{R}})_{AB}^{A'B'} \,, \qquad \mathcal{R} = 1 \text{ (singlet)},\ 8^- \text{ (octet)}, \ldots$$

The 8^- color representation is important for the bootstrap, i.e. the consistency between the above amplitude and that with one Reggeized gluon exchange

Backup

The high-energy resummation

$$\mathrm{Im}_s\left(\mathcal{A}\right) = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A\left(\vec{q}_1, s_0\right) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B\left(-\vec{q}_2, s_0\right) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega\left(\vec{q}_1, \vec{q}_2\right)$$

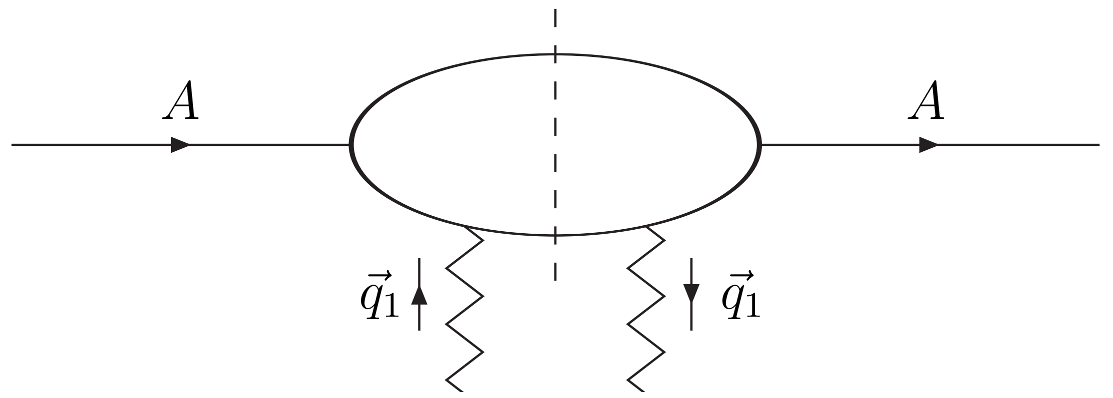
- **Green's function** is **process-independent** and takes care of the **energy dependence**

  $\longrightarrow$ determined through the **BFKL equation**

  [Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy

  $\longrightarrow$ known in the NLA just for few processes



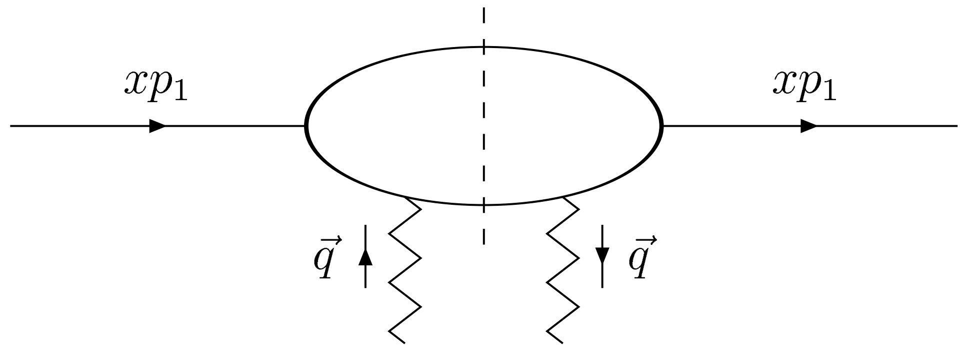
- Successful tests of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

(**MN jets**) [B. Ducloué, L. Szymanowski, S. Wallon (2014); F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2015, 2016)]
(**di-hadron**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]
(**four-jet**) [F. Caporale, F.G.C., G. Chachamis, A. Sabio Vera (2016)]
(**multi-jet**) F. Caporale, F.G.C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016, 2017, 2017)]
(**heavy-quark pair**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M. Fucilla, A. Papa (2018)]
(**hadron-jet**) [M.M.A. Mohammed, MD thesis (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]

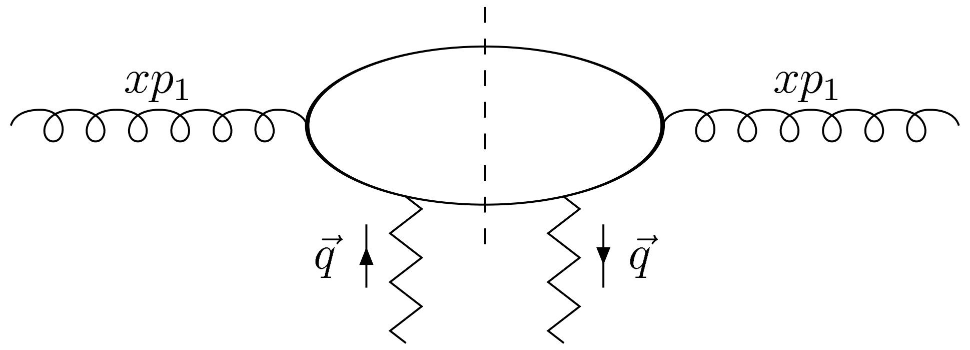
Backup

Forward-jet impact factor

- take the impact factors for **colliding partons**
  [V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
  [M. Ciafaloni and G. Rodrigo (2000)]

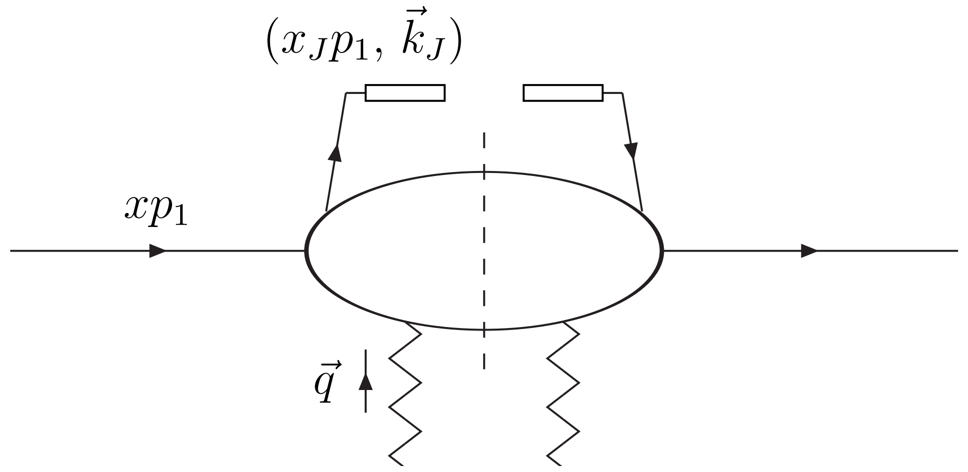


quark vertex

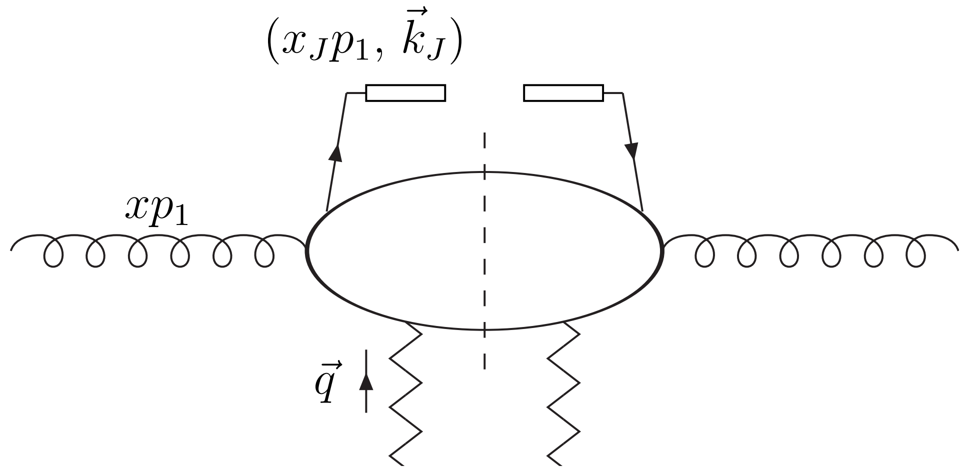


gluon vertex

- "open" one of the integrations over the phase space of the intermediate state to allow one parton to generate the jet



quark jet vertex

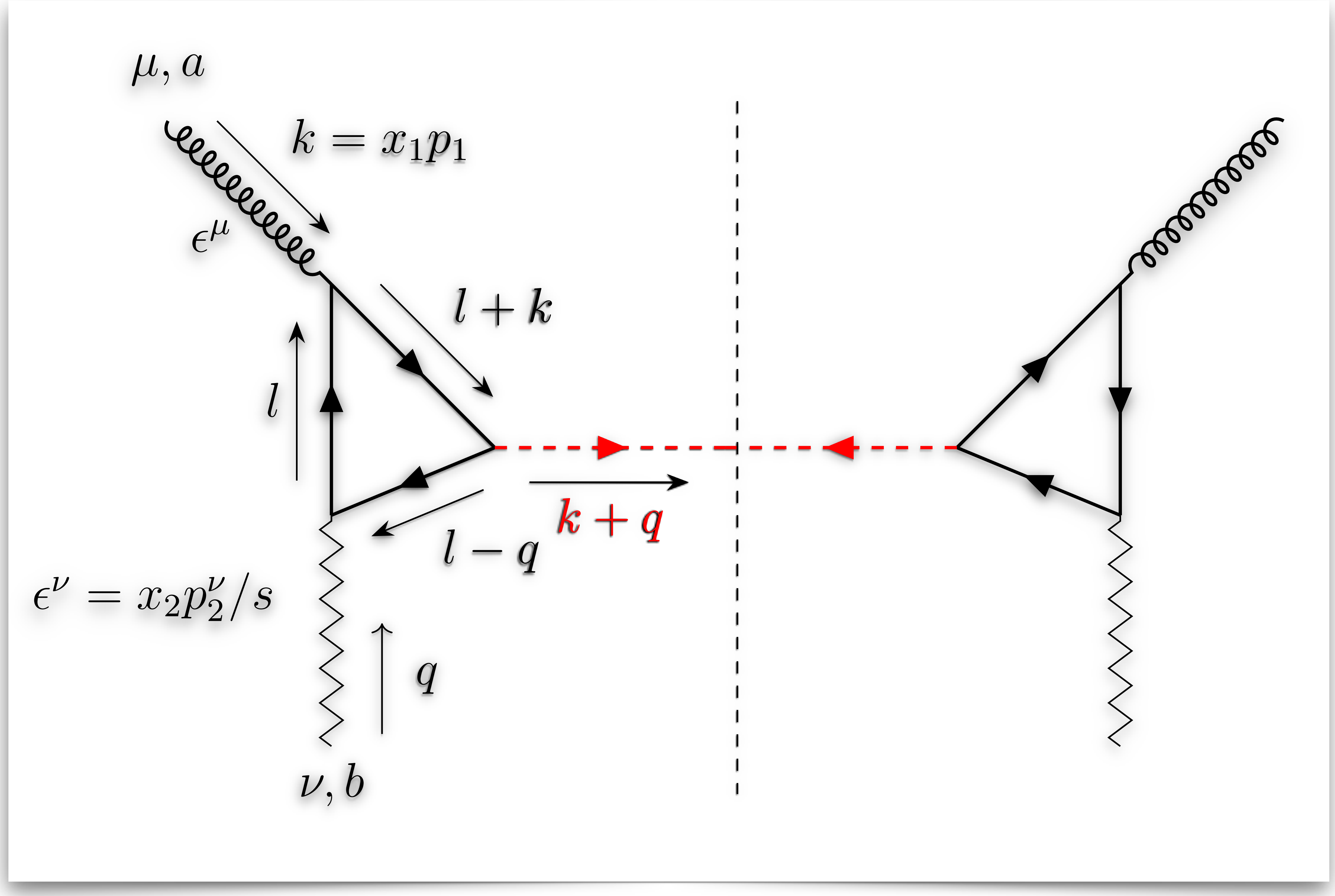


gluon jet vertex

- use QCD collinear factoriz.: $\sum_{s=q,\bar{q}} f_s \otimes$ [quark vertex] $+ f_g \otimes$ [gluon vertex]

Backup

Forward-Higgs LO impact factor



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

Backup

Forward-Higgs NLO-RG impact factor

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

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

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

Backup

Forward-jet NLO-RG impact factor

$$\tilde{c}_J^{(1)}(n,\nu,|\vec{p}_J|,x_J) = c_J(n,\nu,|\vec{p}_J|,x_J)\left\{\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_2}}{|\vec{p}_J|}+\frac{5}{3}\right)+\frac{\chi(n,\nu)}{2}\ln\left(\frac{s_0}{|\vec{p}_J|^2}\right)\right.$$

$$-\frac{1}{2N_c\left(\frac{C_A}{C_F}f_g(x_J,\mu_{F_2})+\sum_{a=q,\bar{q}}f_a(x_J,\mu_{F_2})\right)}\ln\frac{\mu_{F_2}^2}{|\vec{p}_J|^2}$$

$$\times\left(\frac{C_A}{C_F}\int_{x_J}^1\frac{dz}{z}\left[P_{gg}(z)f_g\left(\frac{x_J}{z},\mu_{F_2}\right)+\sum_{a=q,\bar{q}}P_{ga}(z)f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right.$$

$$\left.\left.+\sum_{a=q,\bar{q}}\int_{x_J}^1\frac{dz}{z}\left[P_{ag}(z)f_g\left(\frac{x_J}{z},\mu_{F_2}\right)+P_{aa}(z)f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right)\right\}.$$

Backup

Inclusive Higgs+jet: NLL/NLO* azimuthal coefficients

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

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

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

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

Backup