NLL/NLO* STUDIES ON HIGGS + JET PRODUCTION WITH POWHEG + JETHAD

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In collaboration with: **Luigi Delle Rose**, **Michael Fucilla**, **Gabriele Gatto**, **Alessandro Papa**

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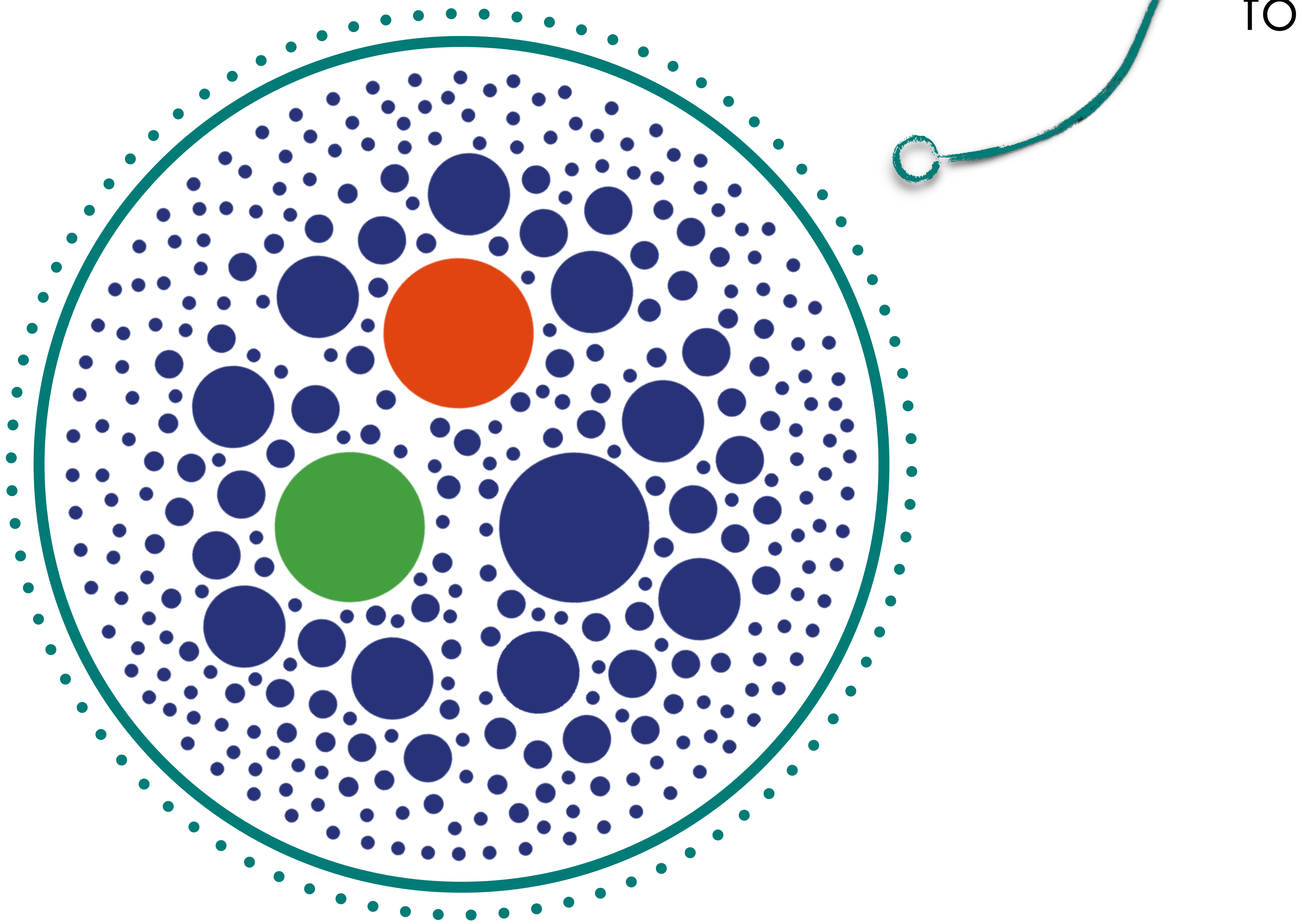
Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

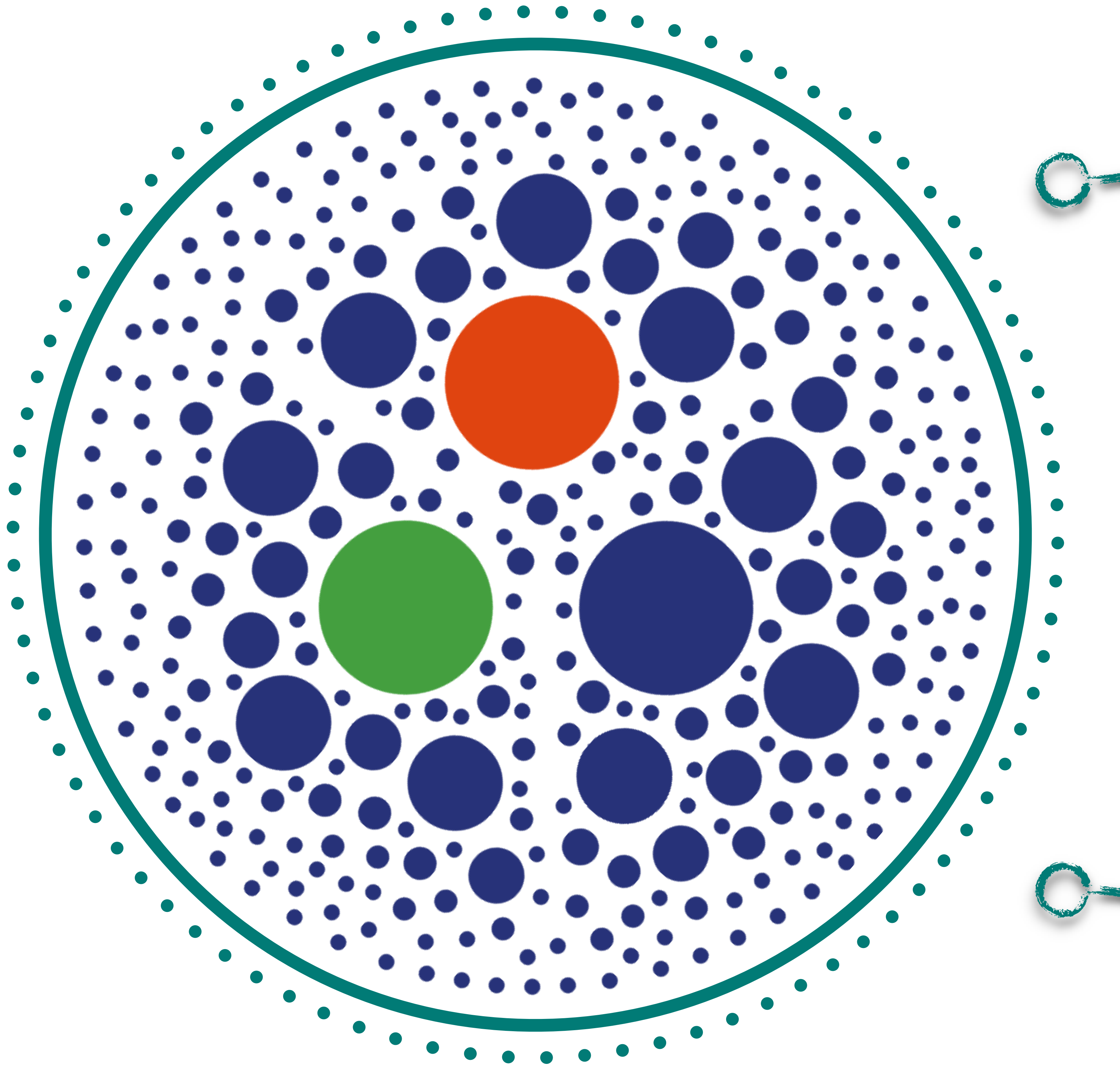
ANIVERSARIO PATRIMONIO MUNDIAL

QCD & Resummations



LHC & new-gen. colliders:
A new era
for particle physics

QCD & Resummations



LHC & new-gen. colliders:
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Fixed-order pQCD:
Accurate
calculations
of parton scatterings

QCD & Resummations

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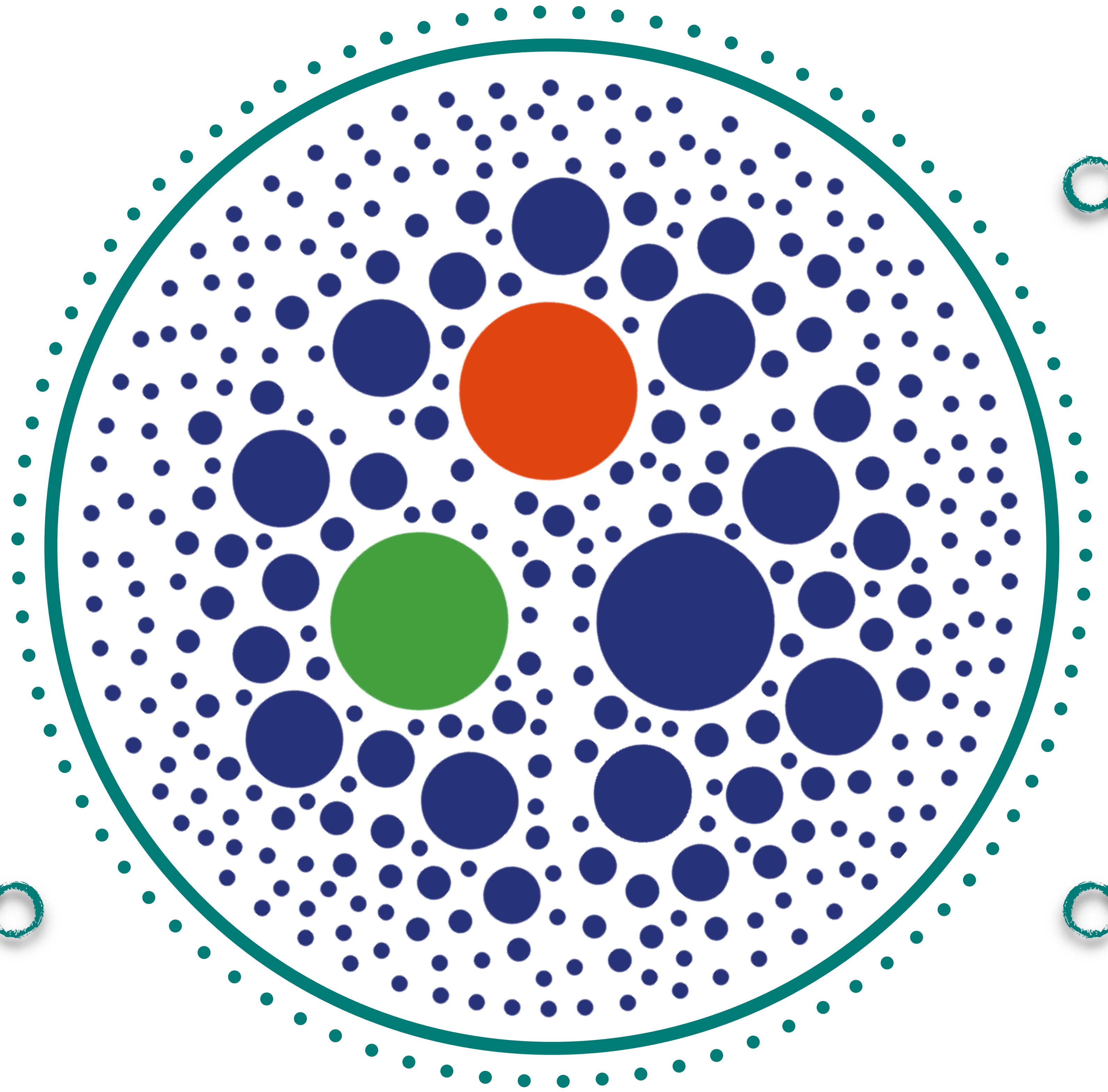

Fixed-order pQCD:
Misses
logarithmic
enhancements

Fixed-order pQCD:
Accurate
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QCD & Resummations

Restoring convergence:
All-order studies
High-energy resummation

LHC & new-gen. colliders:
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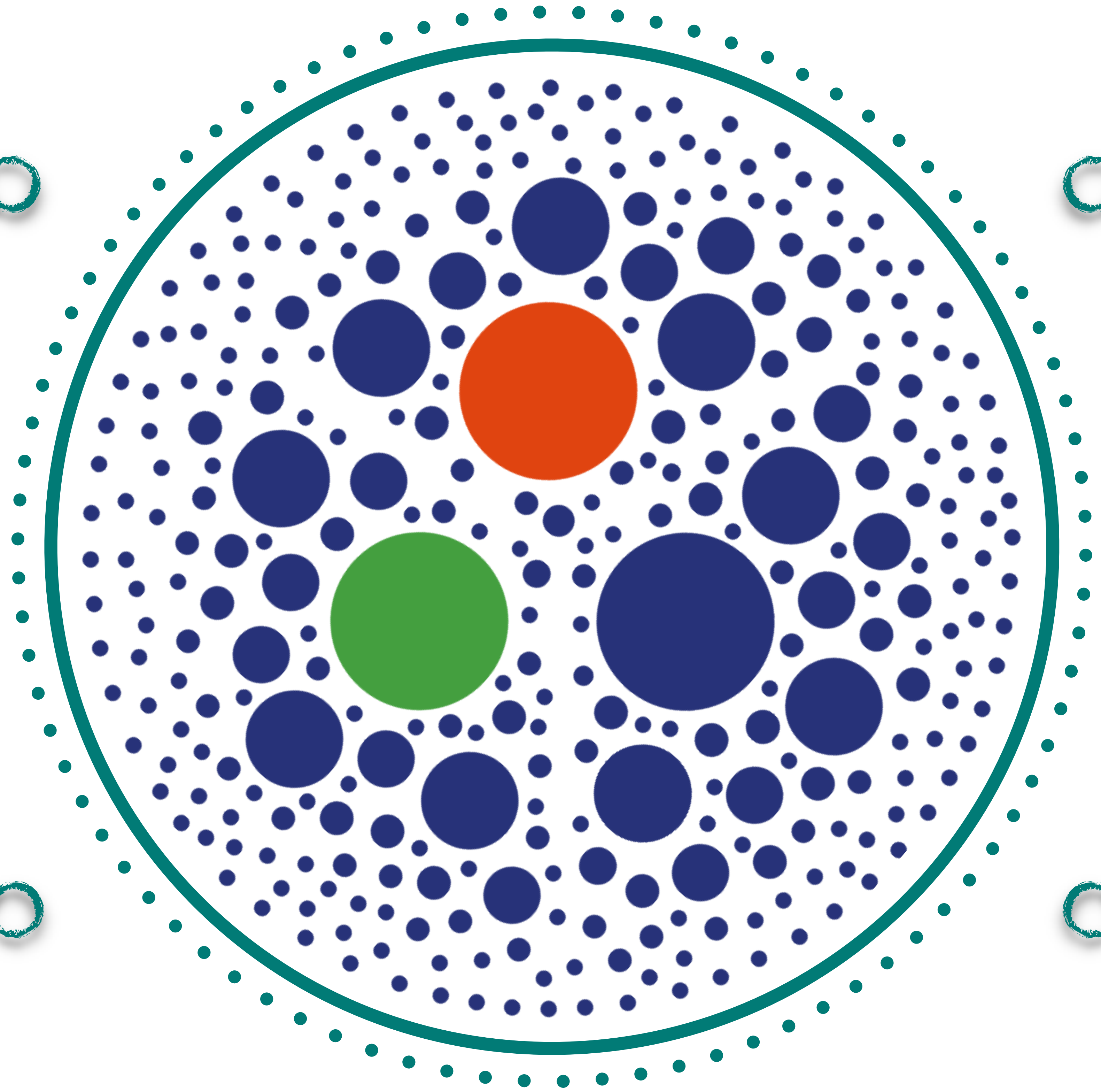

Fixed-order pQCD:
Misses
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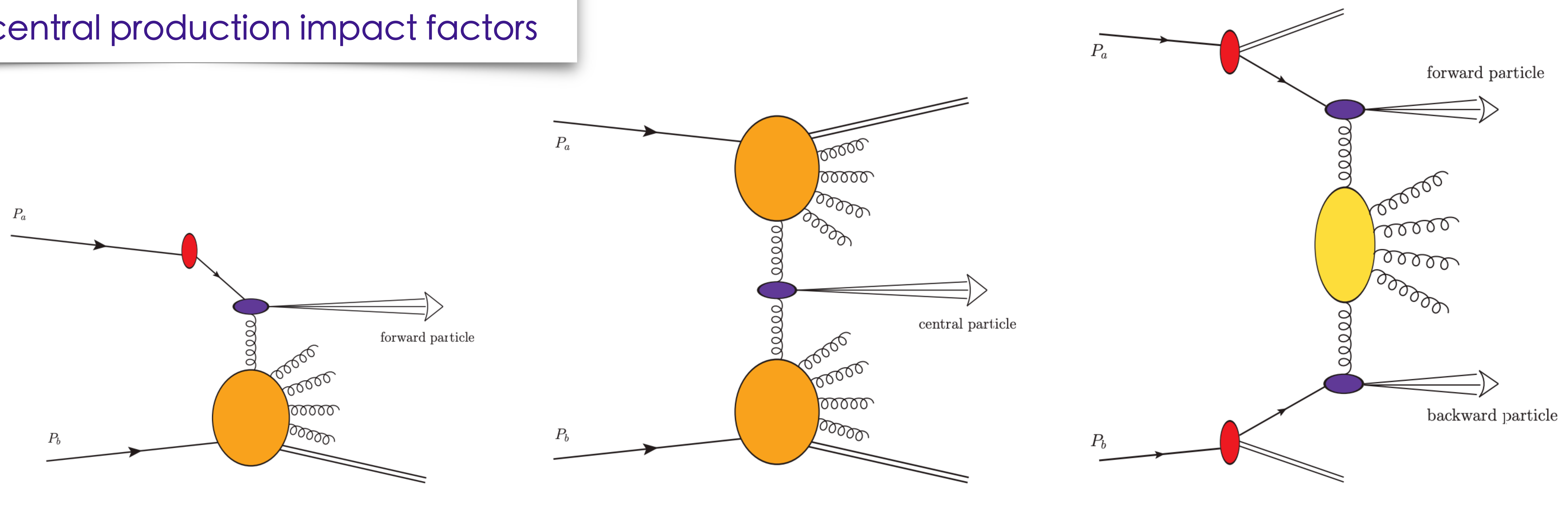
High-energy factorization at a glance

Singly/double off-shell coefficient functions
Forward/central production impact factors



(a) Single forward (b) Single central (c) Forward-backward

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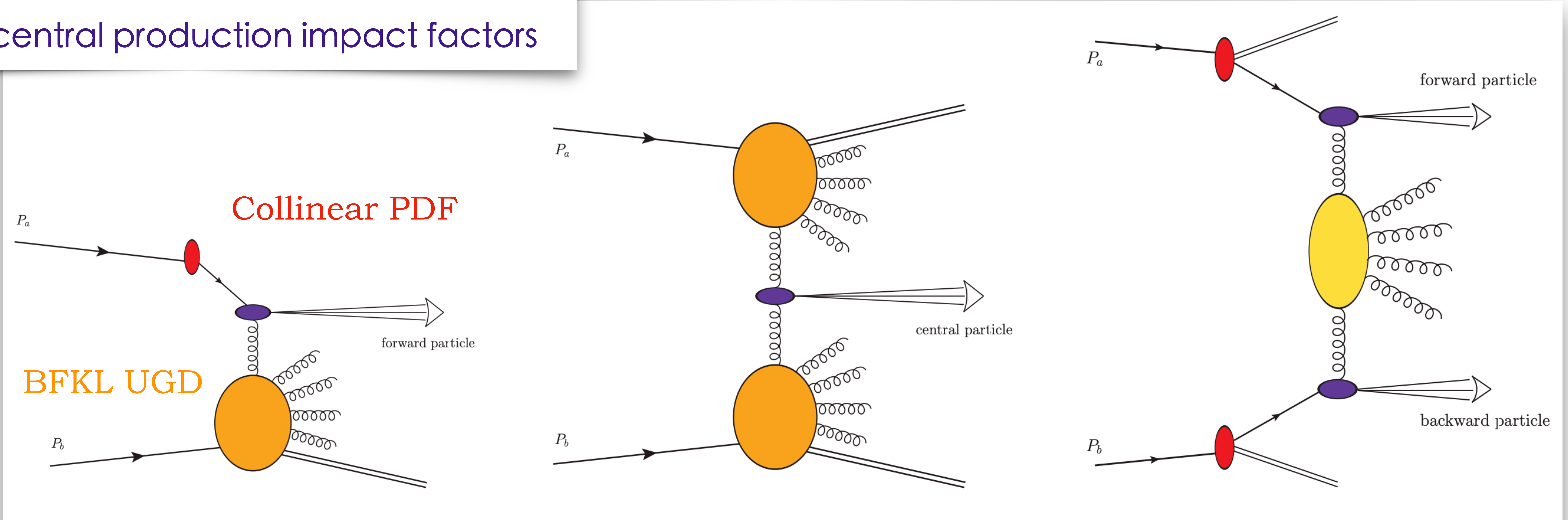

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Fast q/ g + small-x g

Hybrid factorization

BFKL + Threshold

High-energy factorization at a glance

Singly/double off-shell coefficient functions
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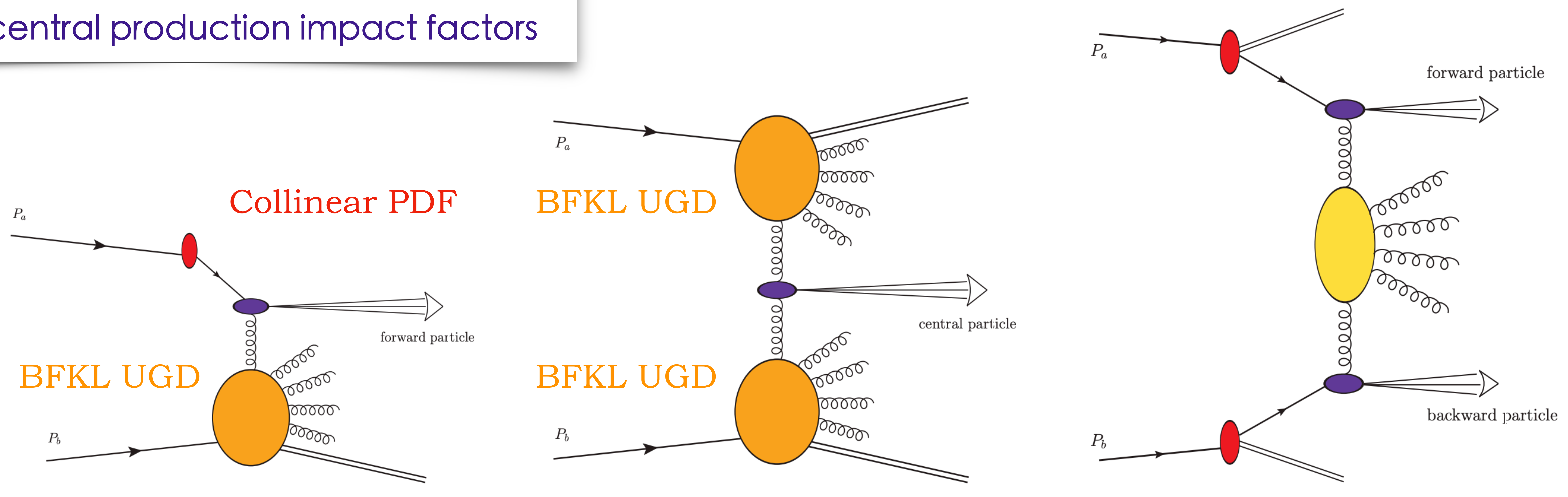

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Fast q/g + small-x g	gg induced
Hybrid factorization	High-energy factorization
BFKL + Threshold	BFKL or small-x improved PDFs

High-energy factorization at a glance

Singly/double off-shell coefficient functions
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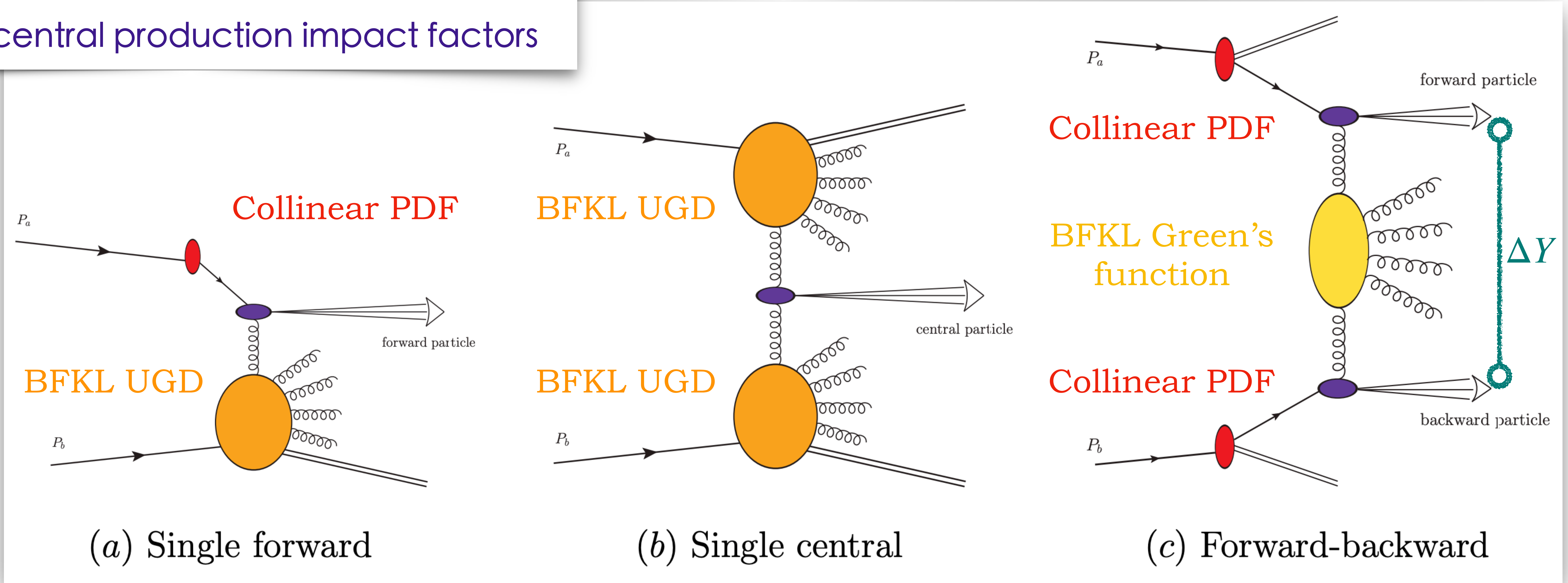


Fast q/g + small-x g

Hybrid factorization

BFKL + Threshold

gg induced

High-energy factorization

BFKL or small-x improved PDFs

🔗 [Tuesday's talk by Andreas]

Large rapidity distances, $\Delta Y \gg 1$

High energies, moderate x

PDFs + t-channel BFKL (NLL/NLO HyF)

Imbalance logs ← back-to-back

Higgs production from LHC to FCC

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

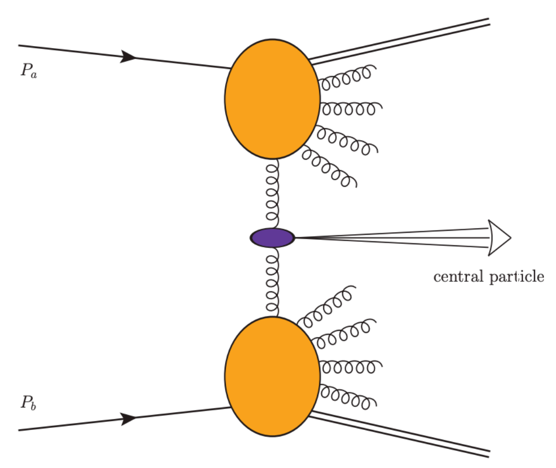
Double Resummation for Higgs Production

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

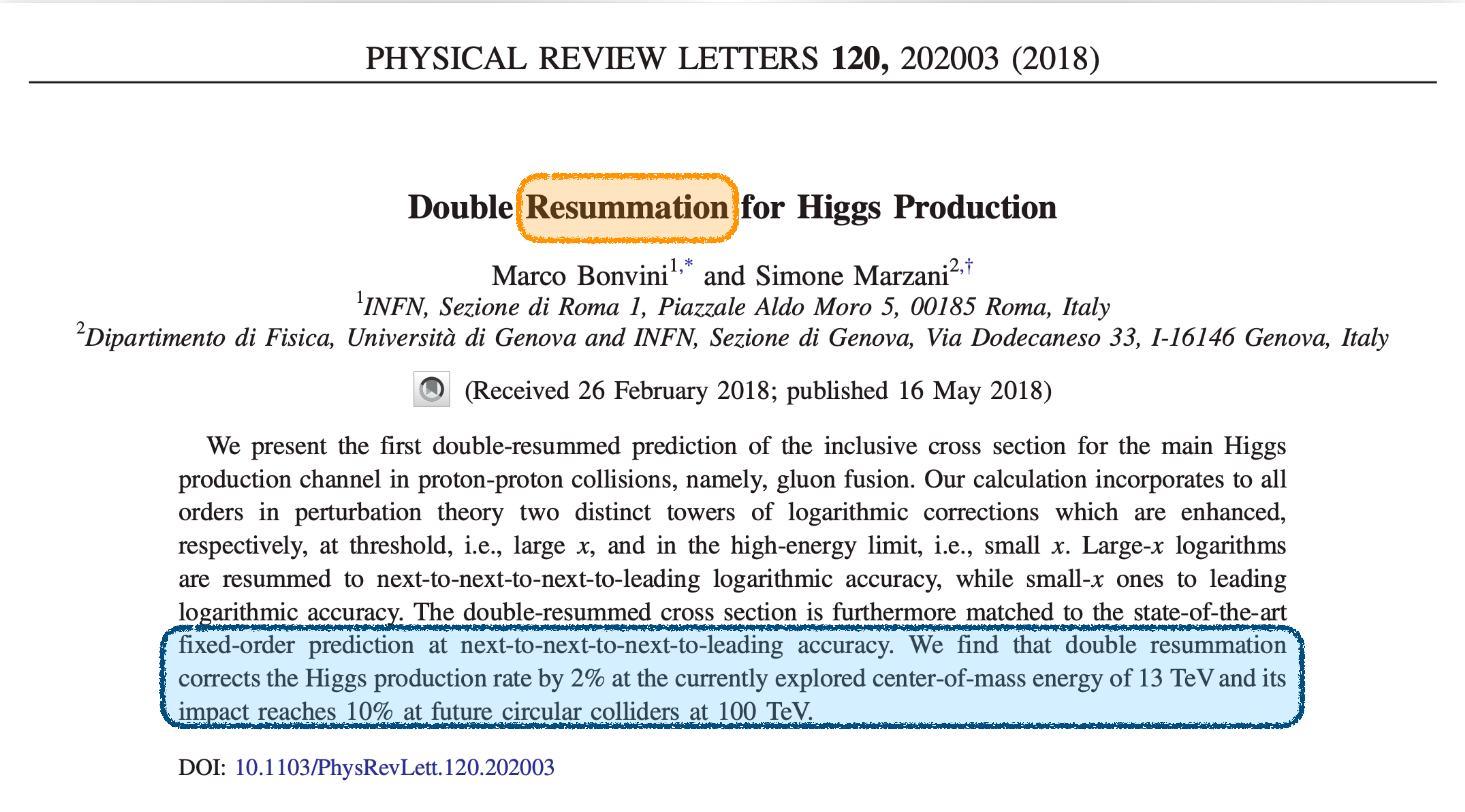
High-energy resummation (BFKL) ⇒ PDFs at small-x

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

$\text{N}^3\text{LL}_{\text{lx}}/\text{LL}_{\text{sx}}/\text{N}^3\text{LO}$ rapidity-inclusive coefficient functions

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

Higgs production from LHC to FCC



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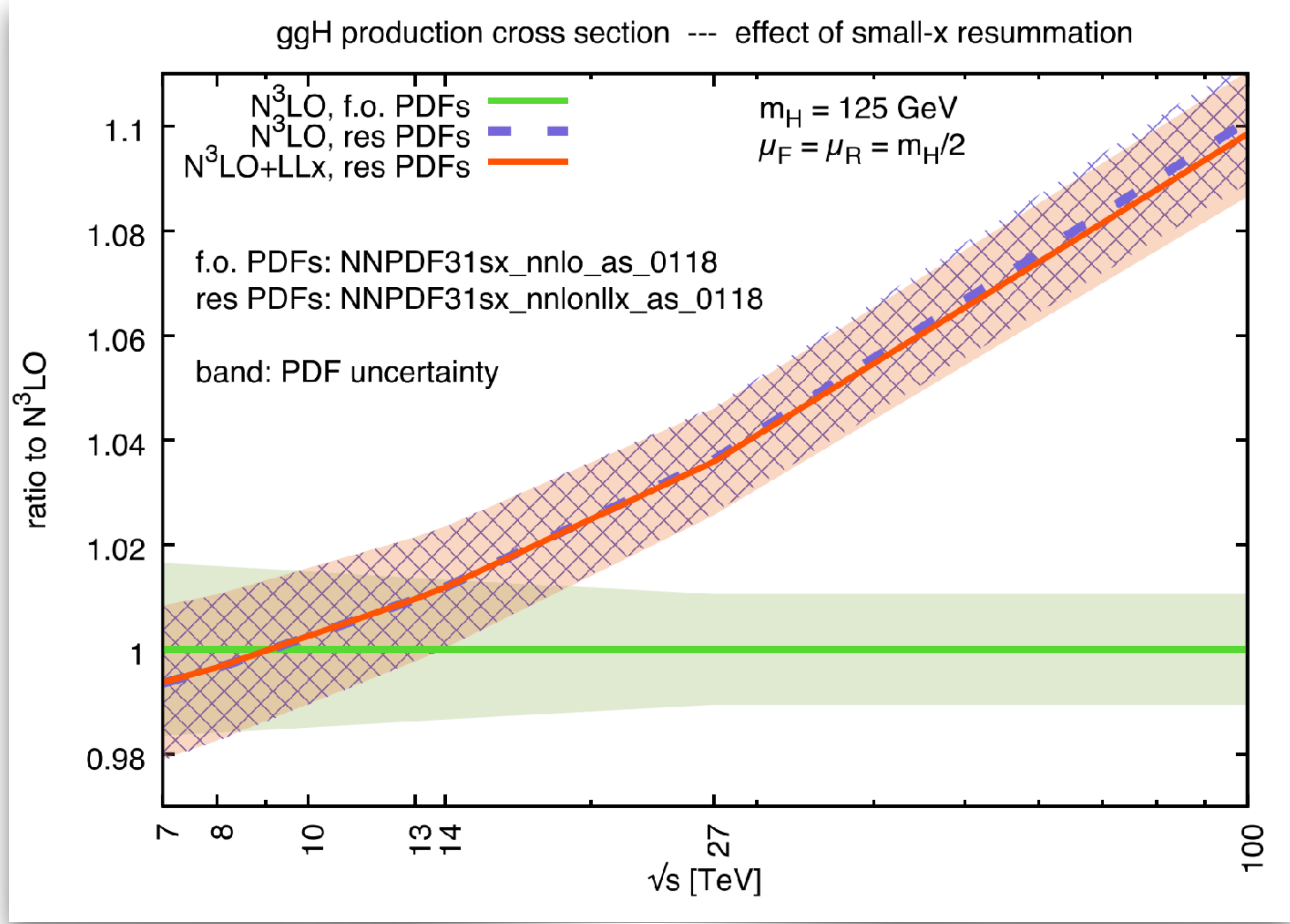

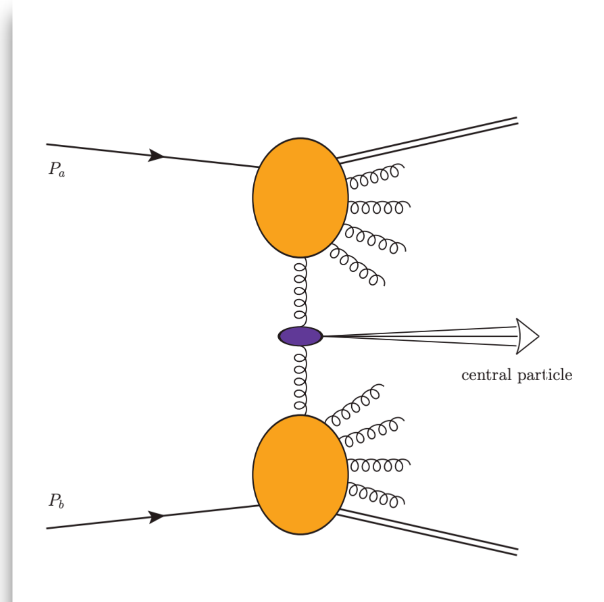

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$\mathrm{N^3LL_{lx}}$/$\mathrm{LL_{sx}}$/$\mathrm{N^3LO}$ rapidity-inclusive coefficient functions

(¡!) 100 TeV electroweak physics is small-x physics!

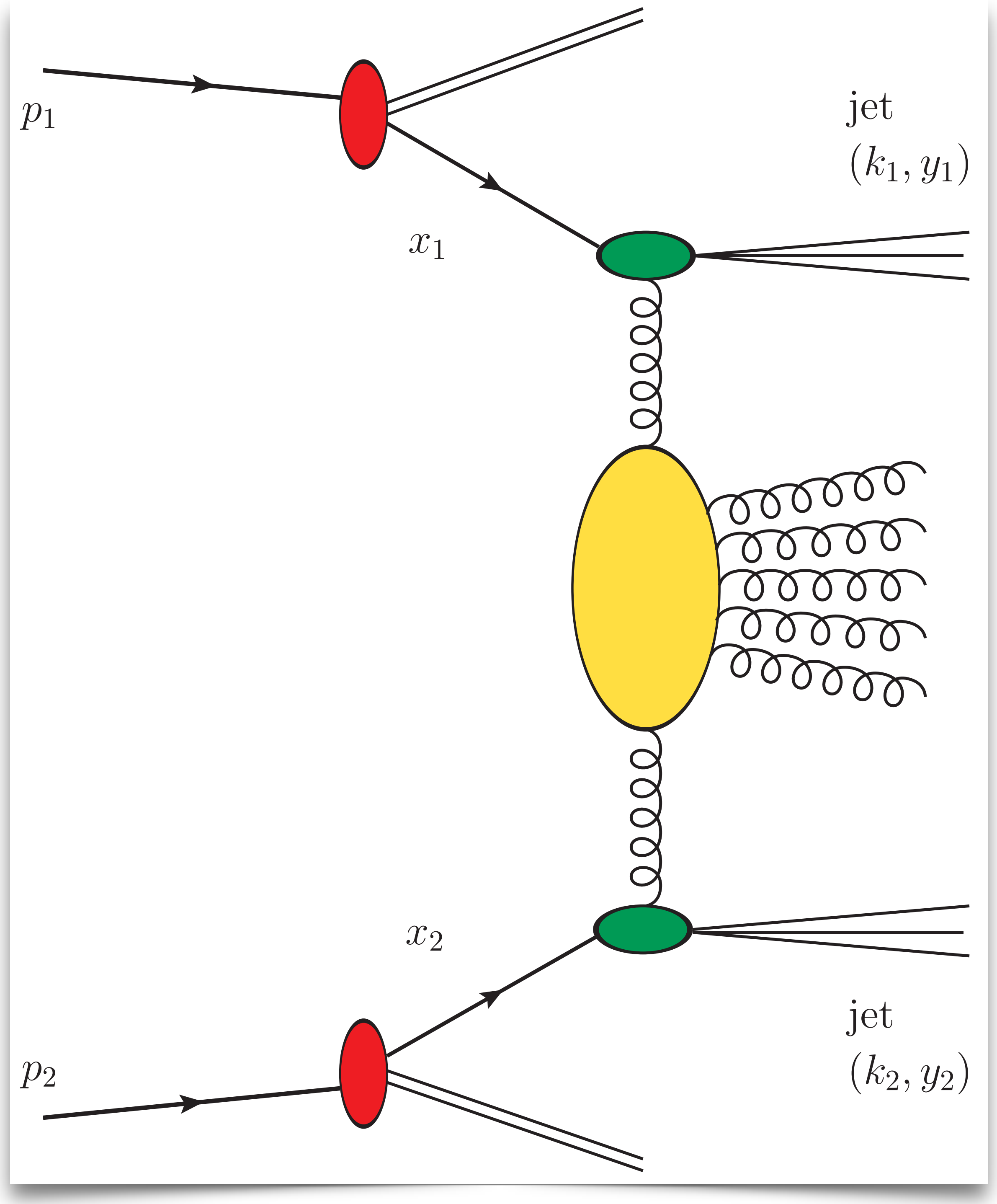
(¿?) Can LHC physics be BFKL physics?

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

Mueller-Navelet jets @LHC & resummation instabilities

- 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) $\Rightarrow$ hybrid factorization (HyF)

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



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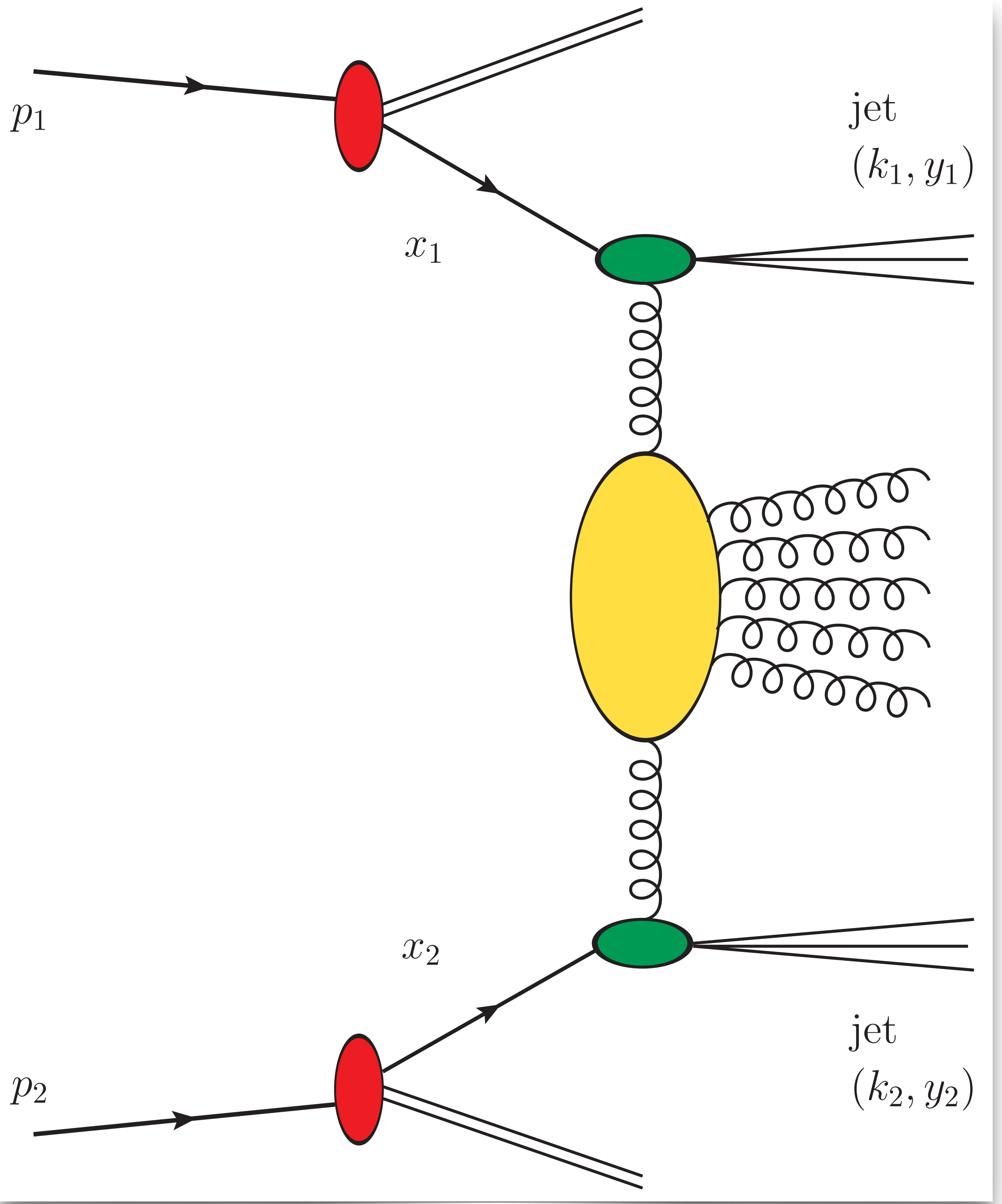
jet vertices (off-shell coefficient functions)



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

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

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

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

BFKL Green's function

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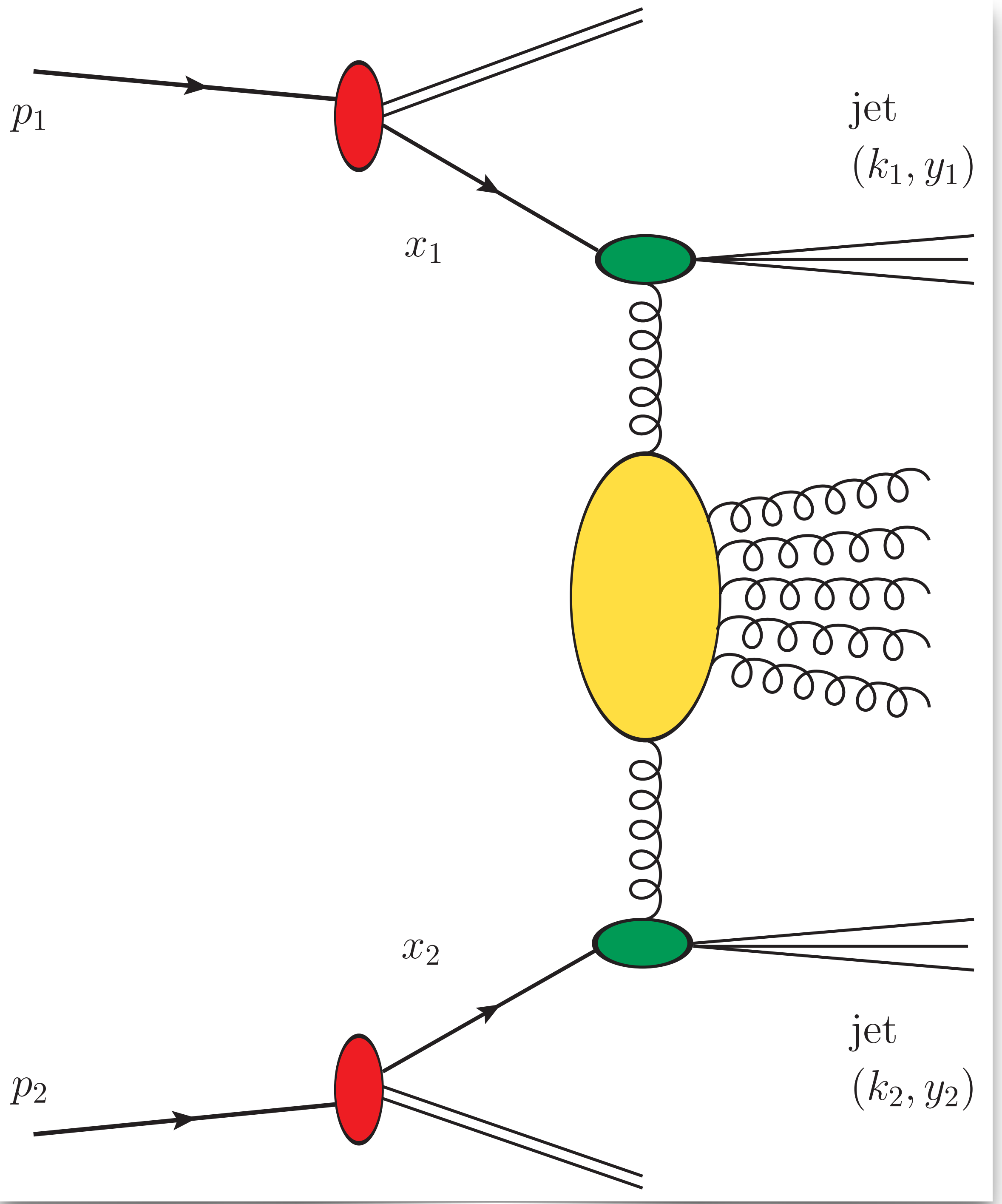

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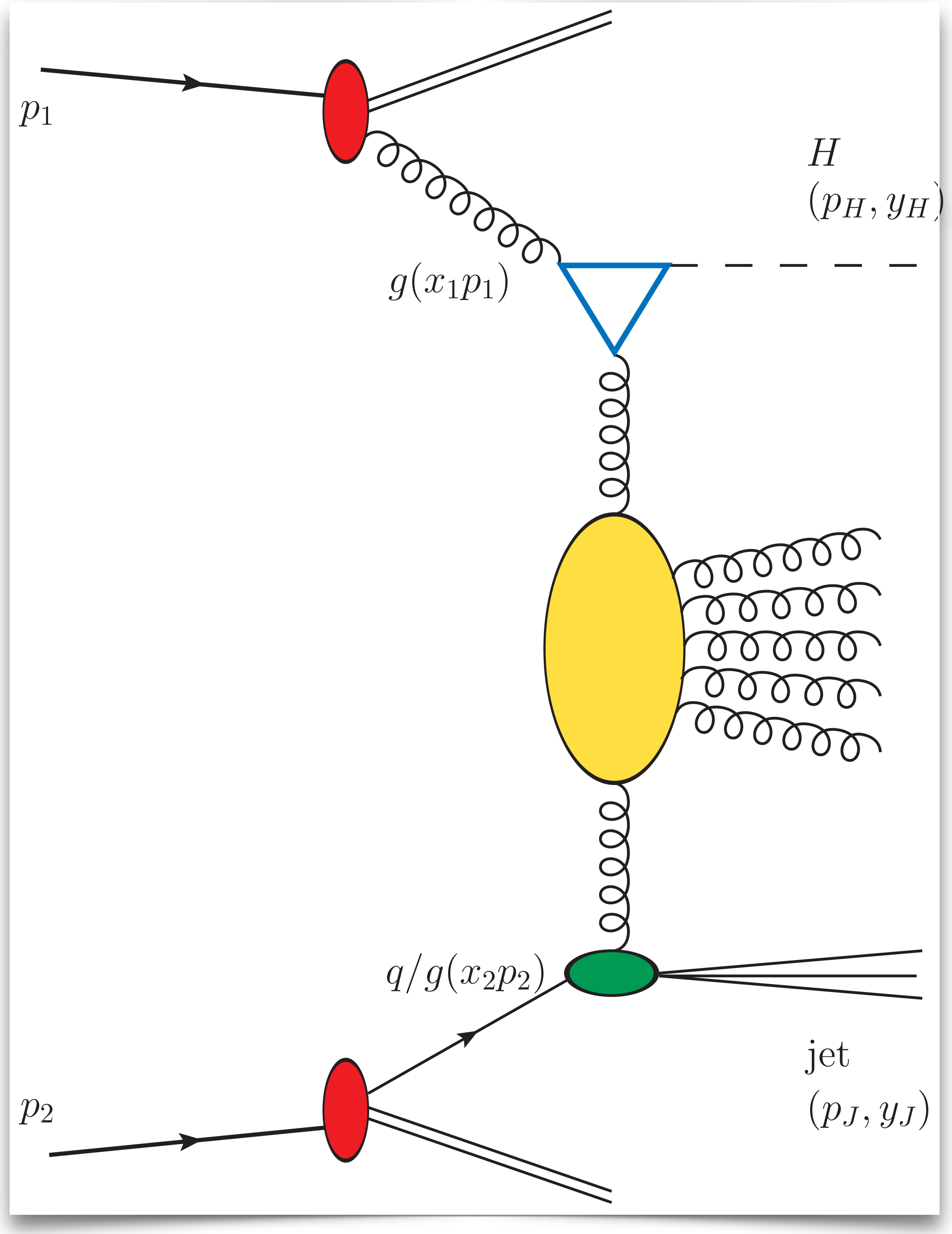
BFKL Green's function

- NLL/LL instabilities + NLO missing threshold $\Rightarrow$ precision studies hampered

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]

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

[Today's talk by Michael]

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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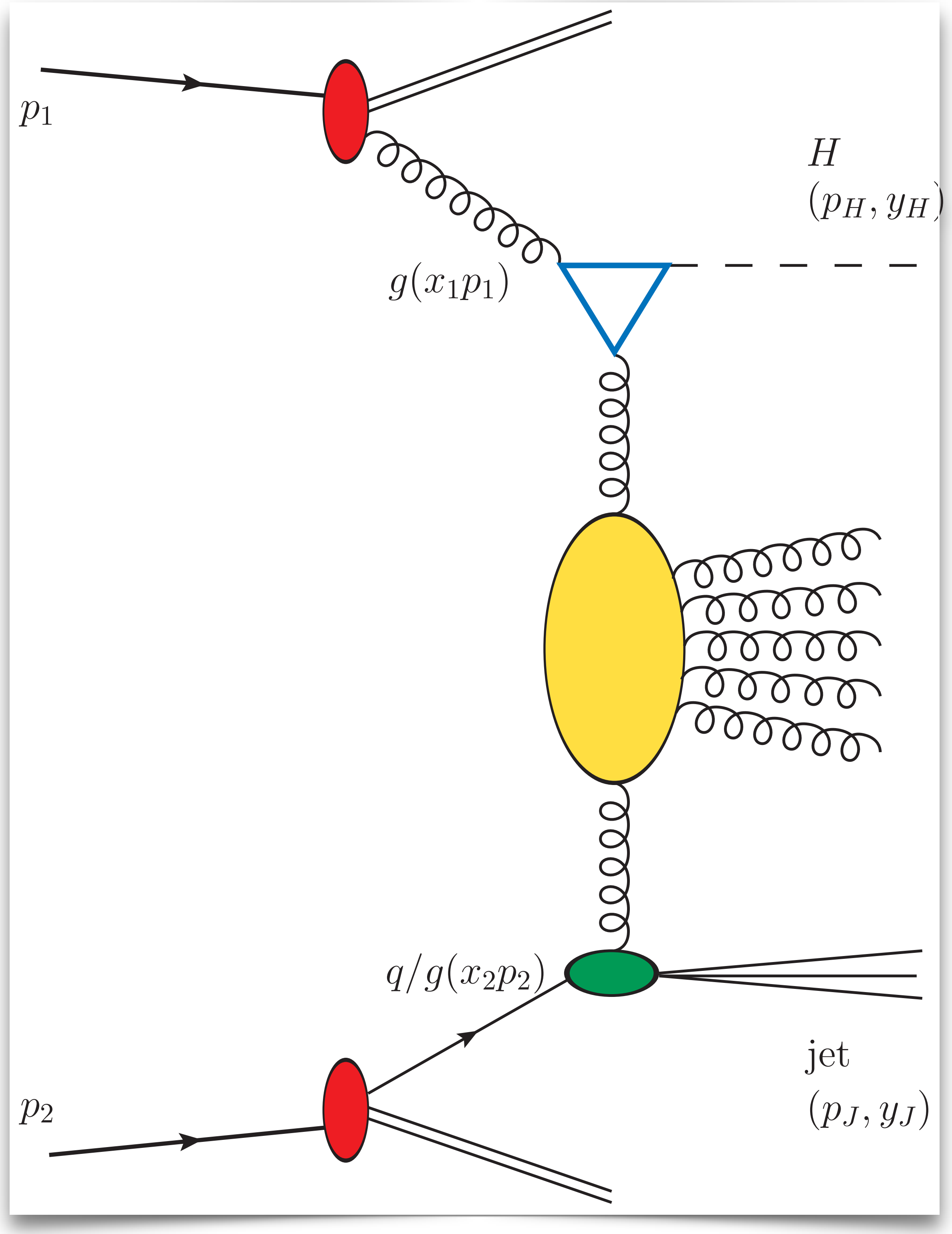

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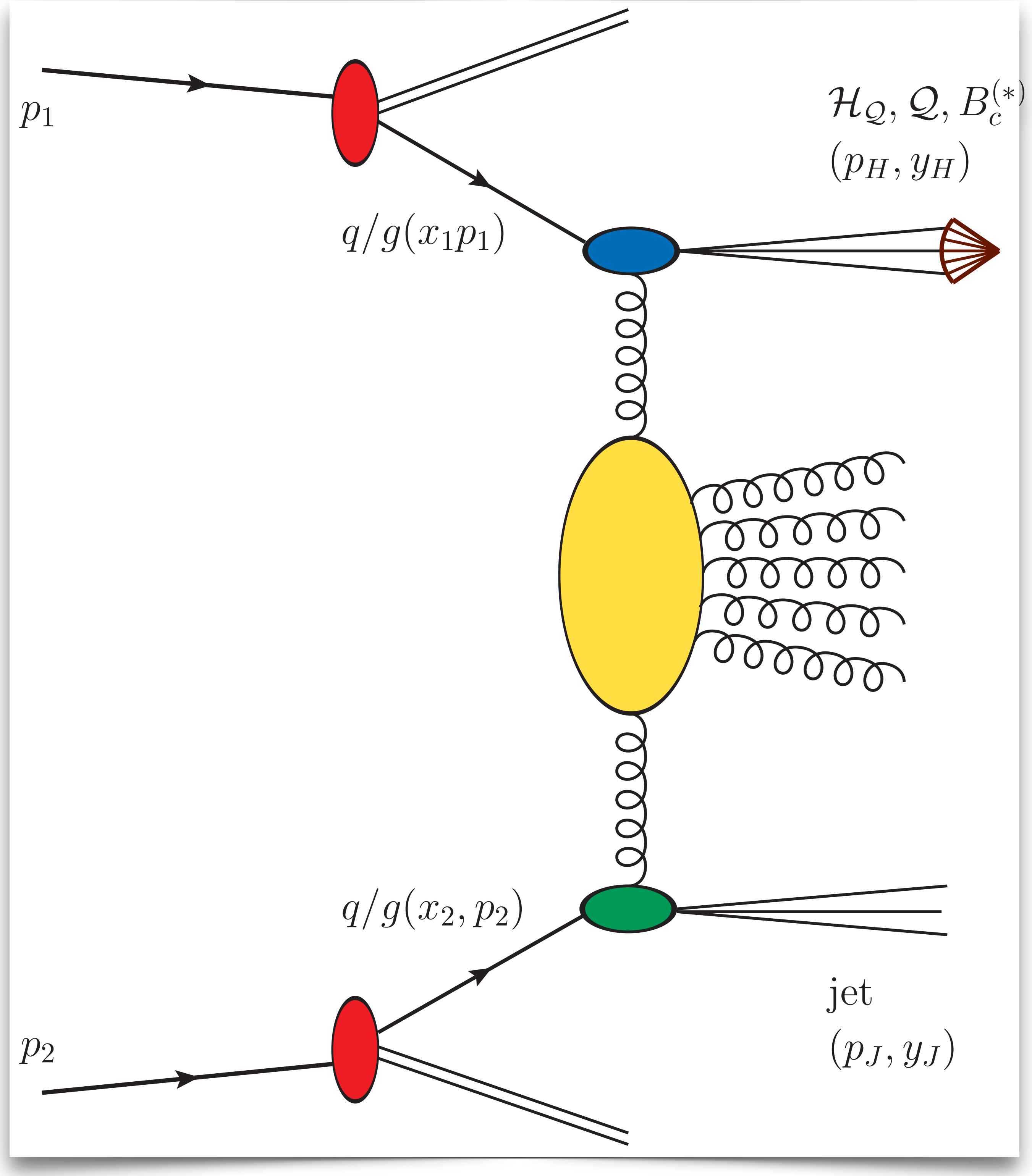
🔗 [Today's talk by Michael]

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]

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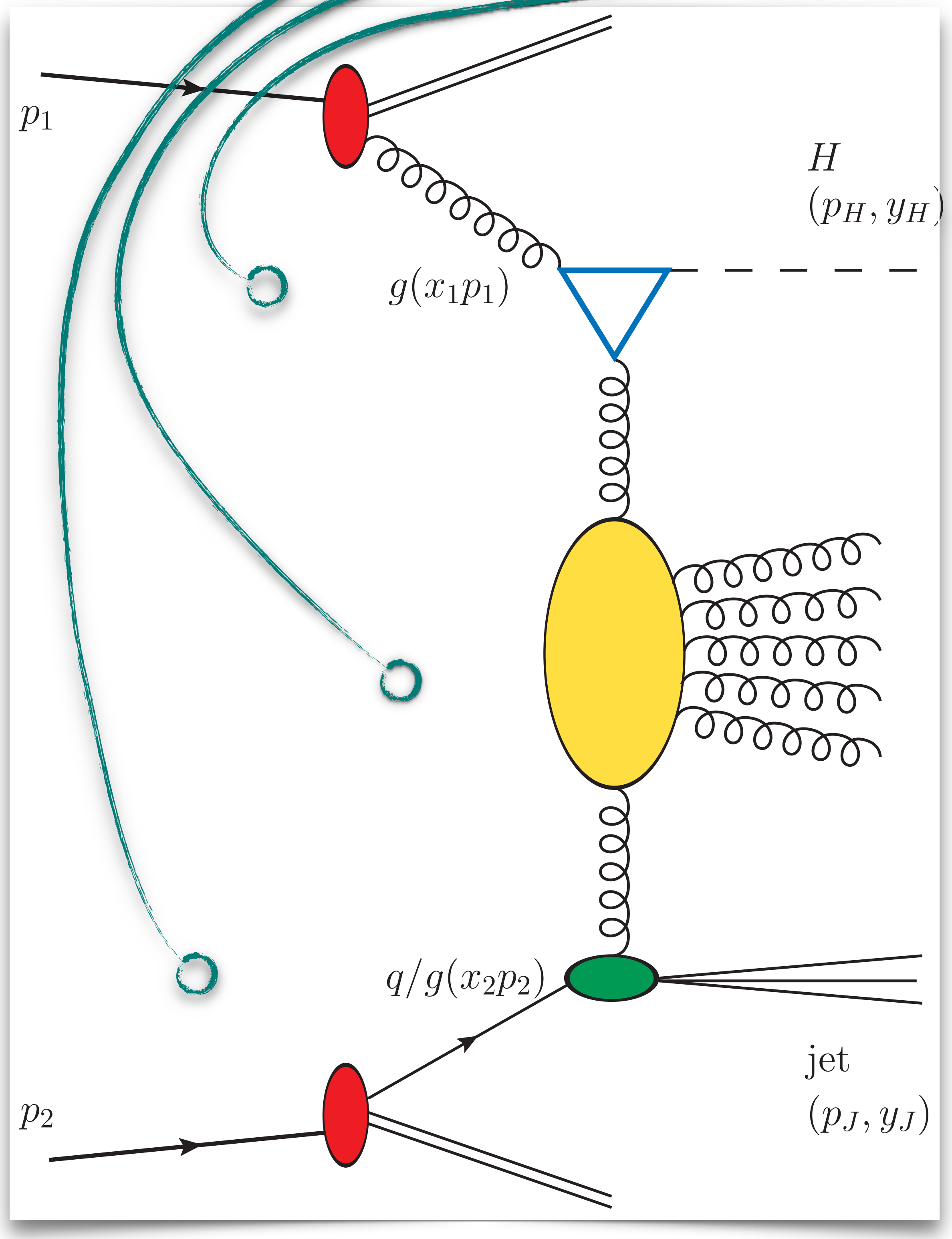
Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses

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



NLO*

NLL

NLO*

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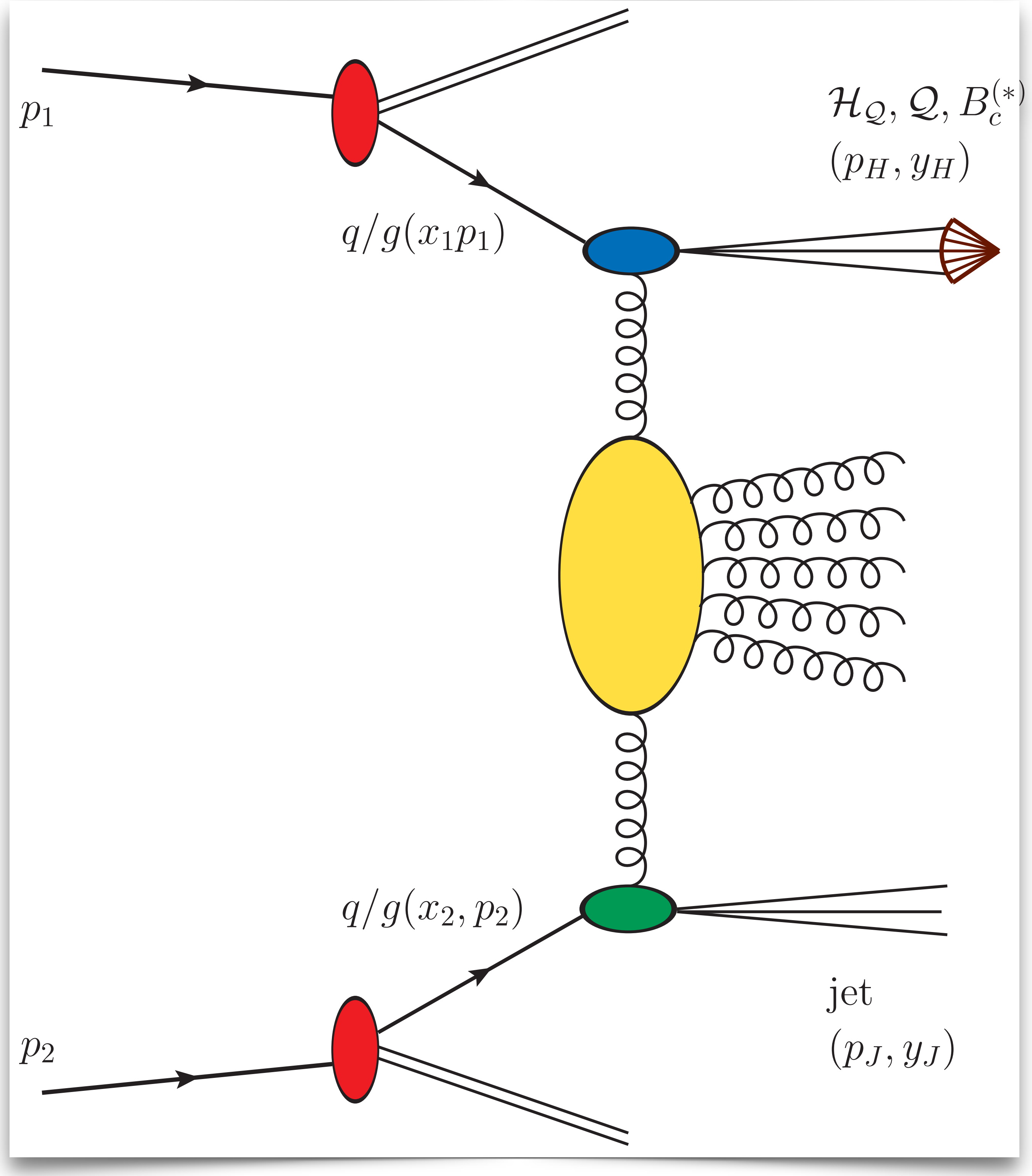
Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels

NLO(+)

NLL

NLO(+)



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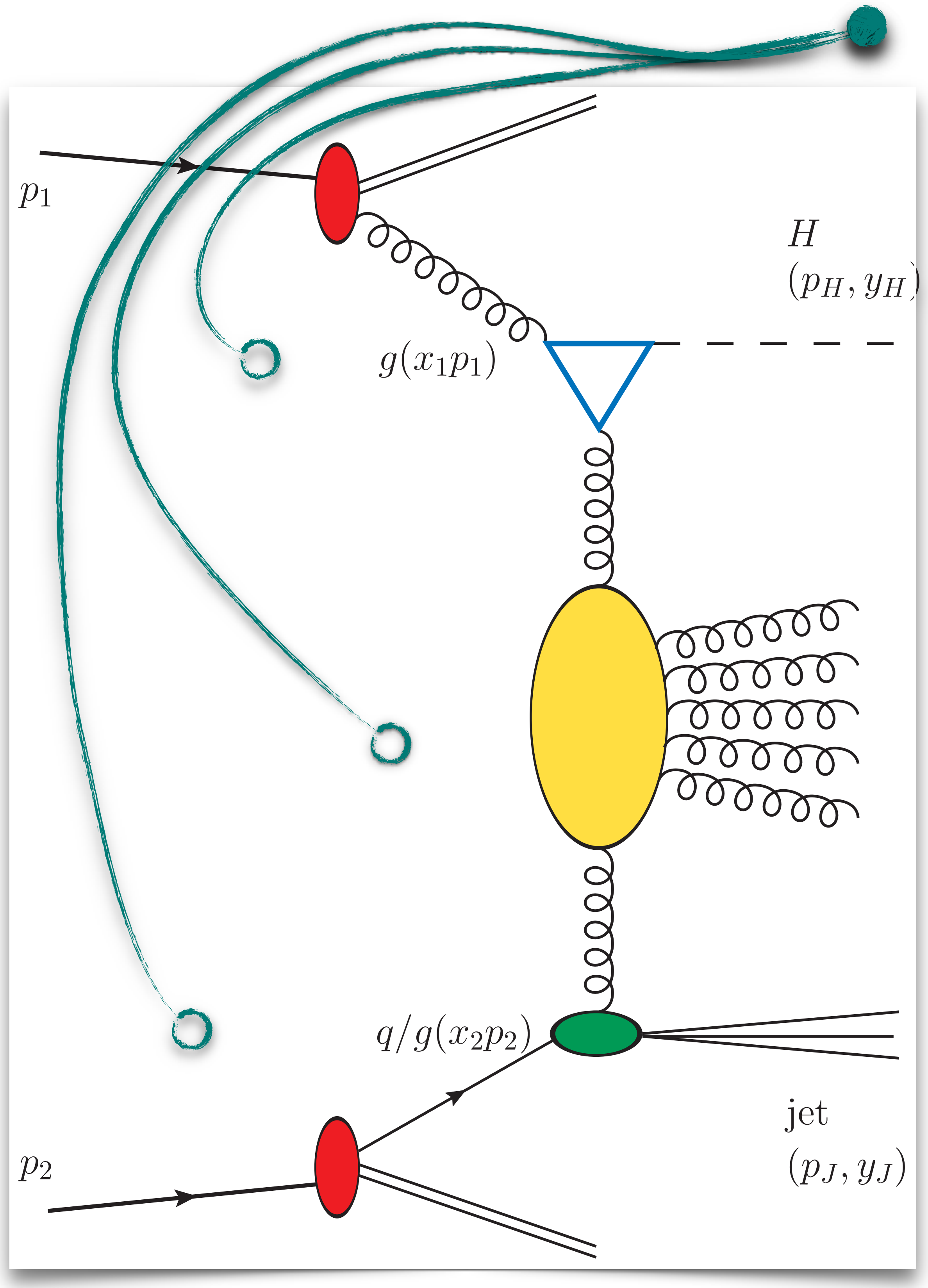

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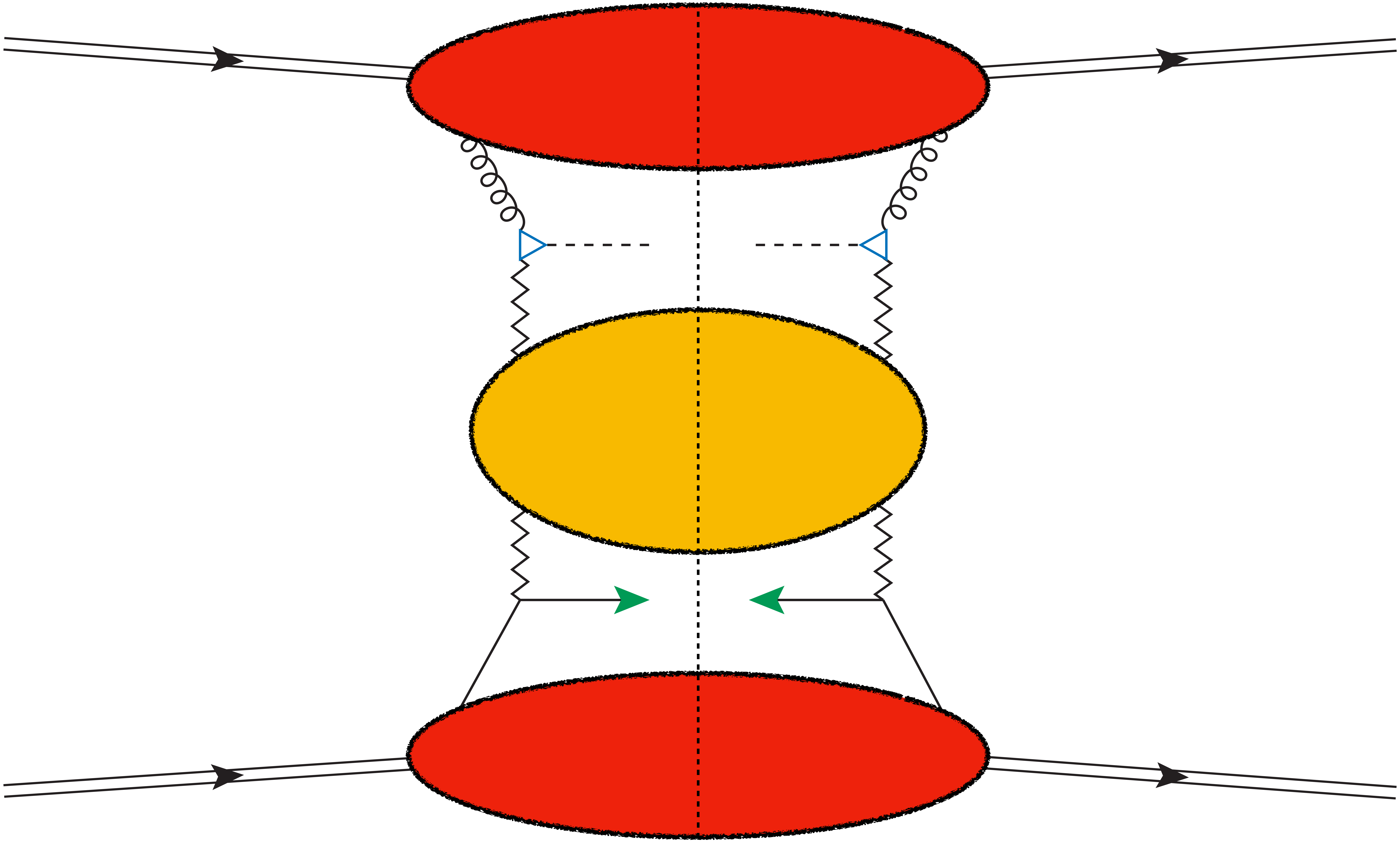
Anatomy of Higgs + jet in hybrid factorization (HyF)



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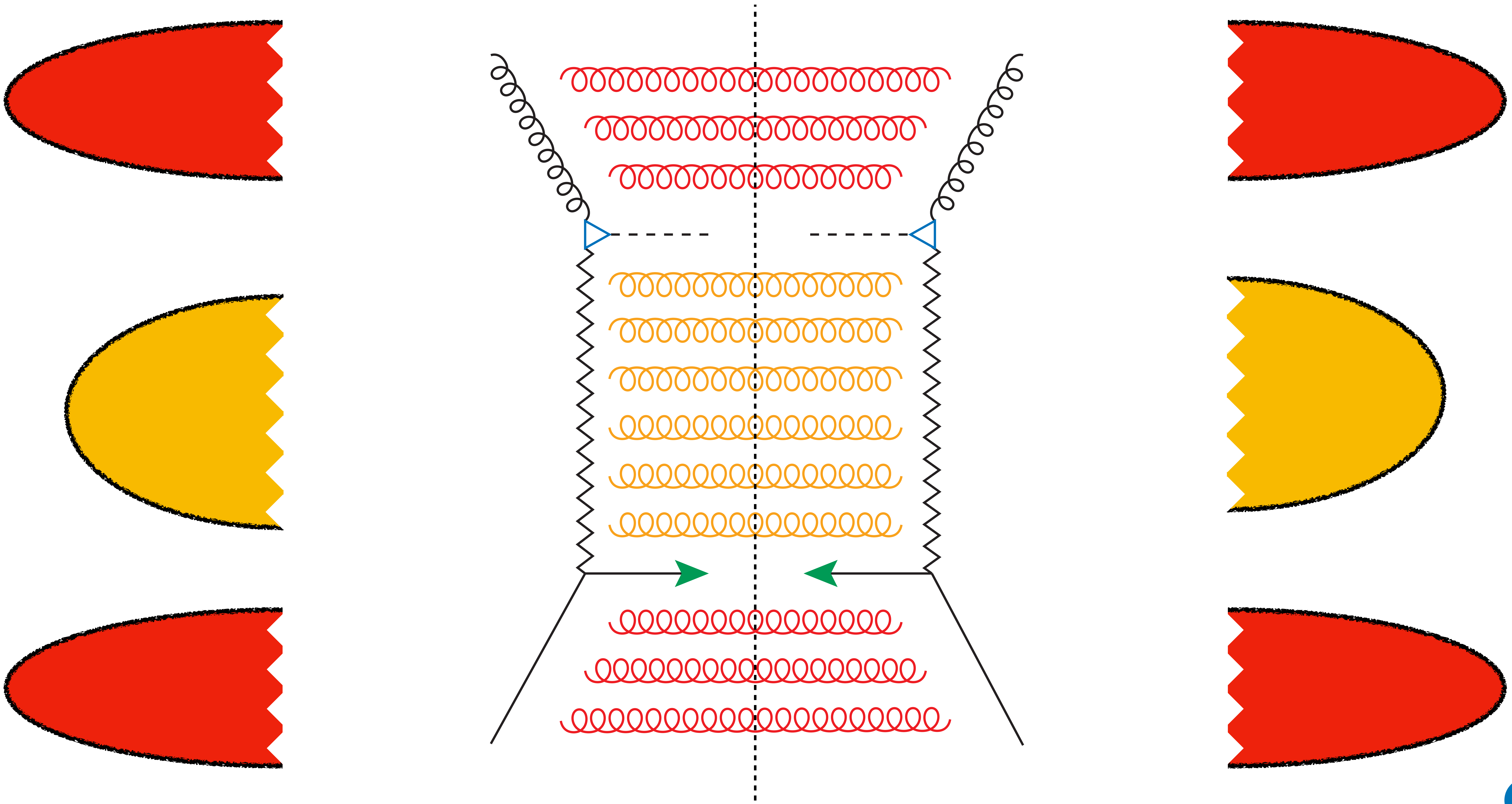

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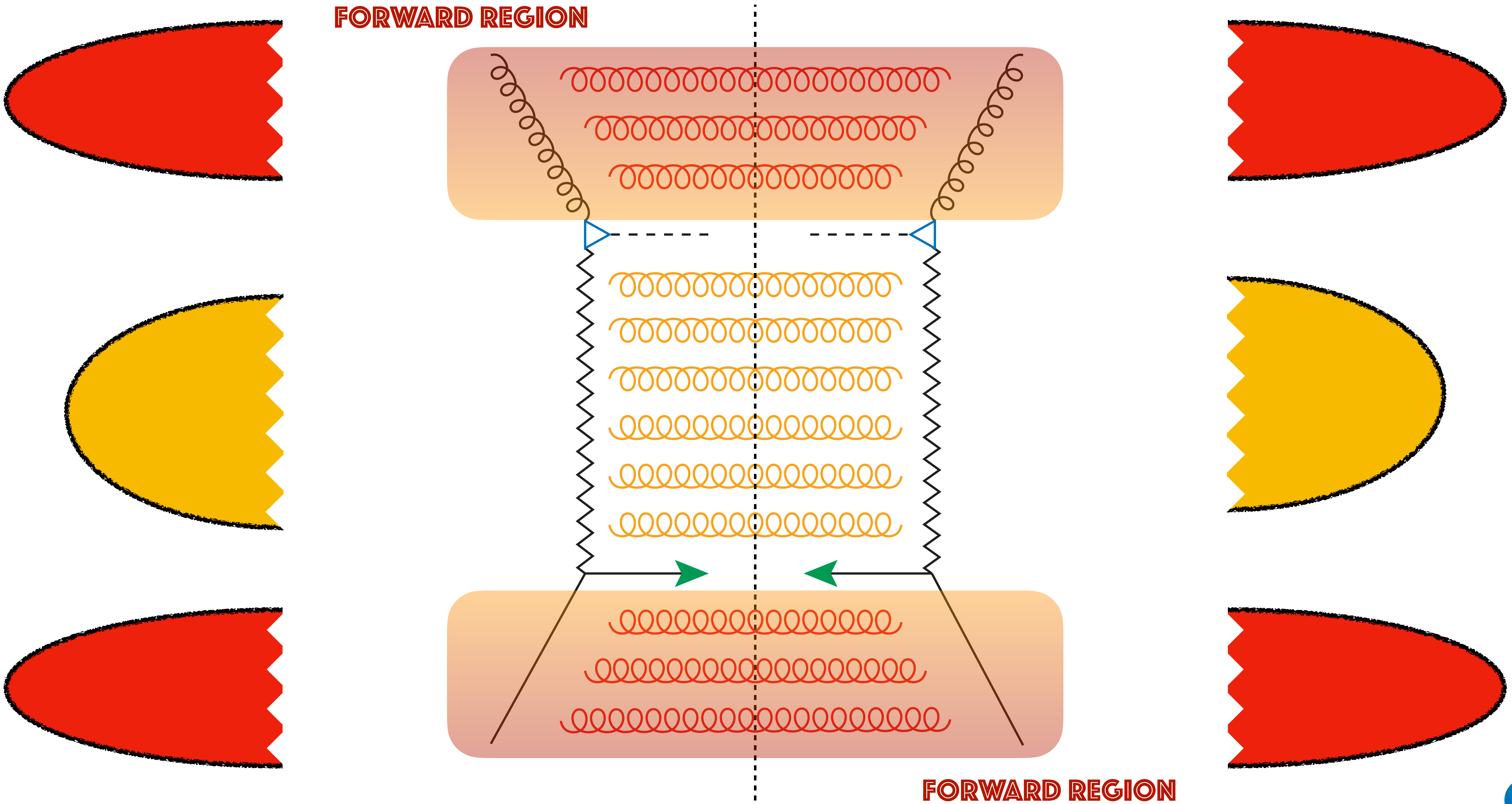

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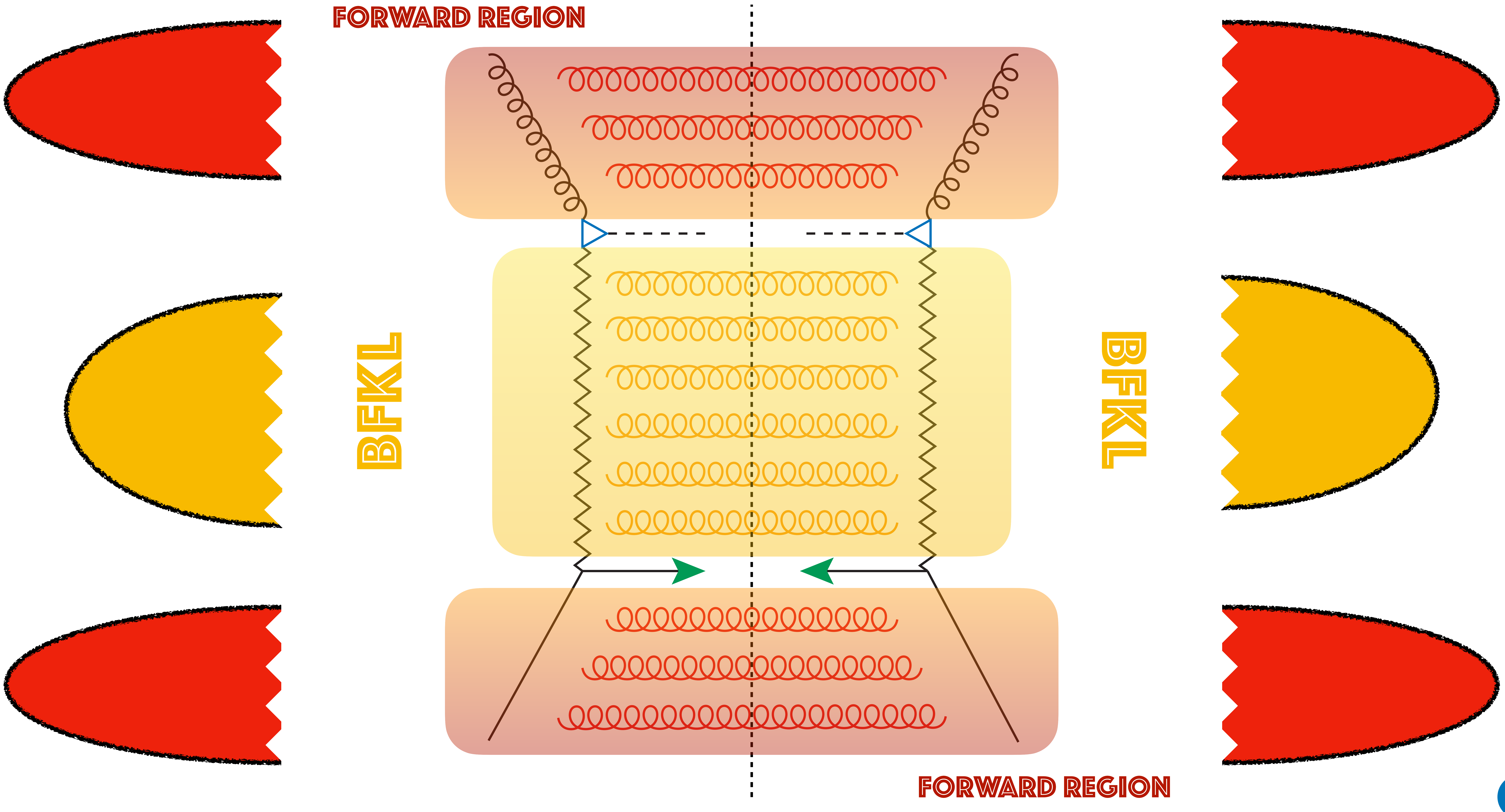
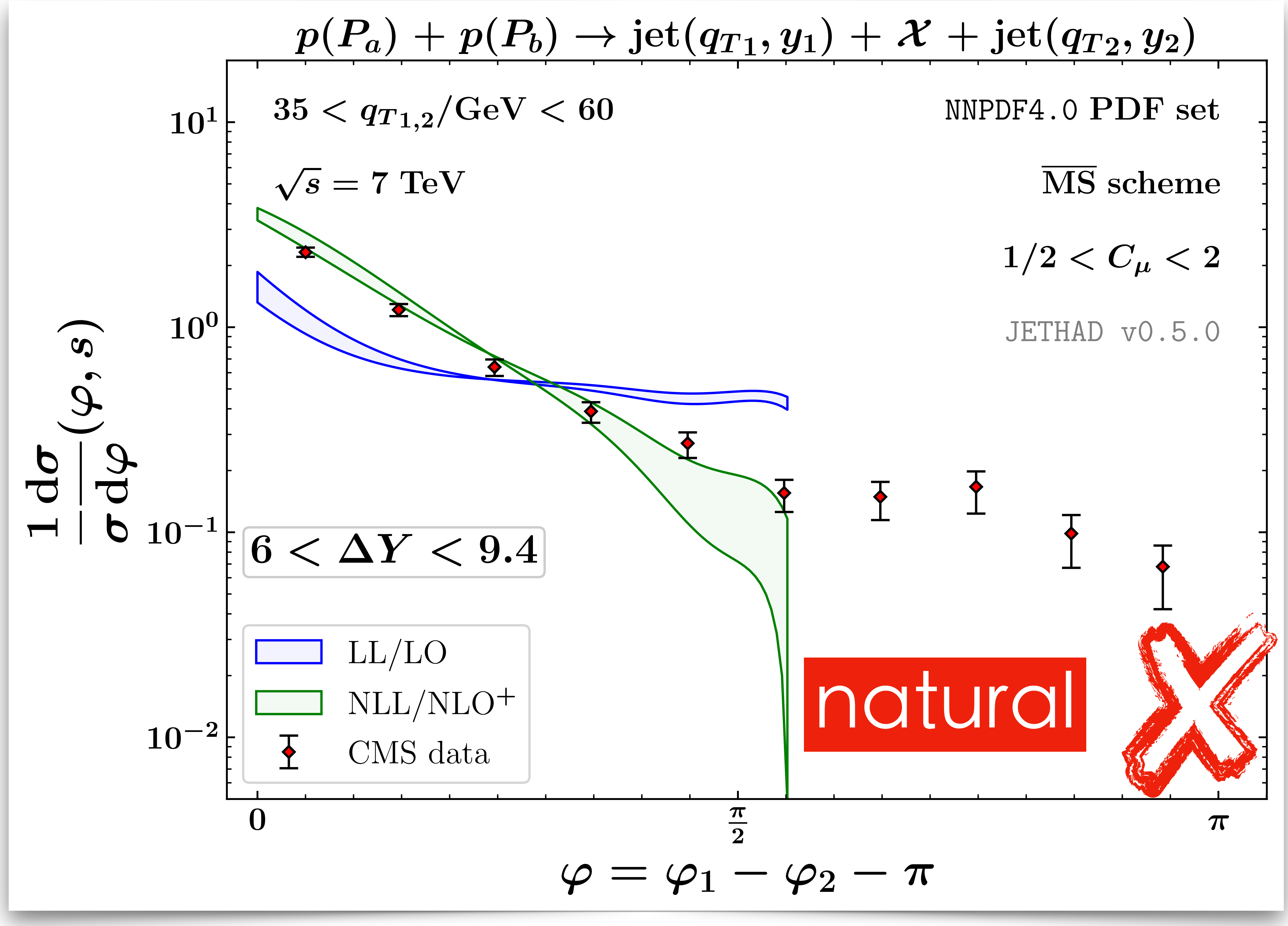


$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma(\Delta Y,s)}{\mathrm{d}\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}$$

MUELLER-NAVELET JETS

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

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



Azimuthal-angle multiplicity

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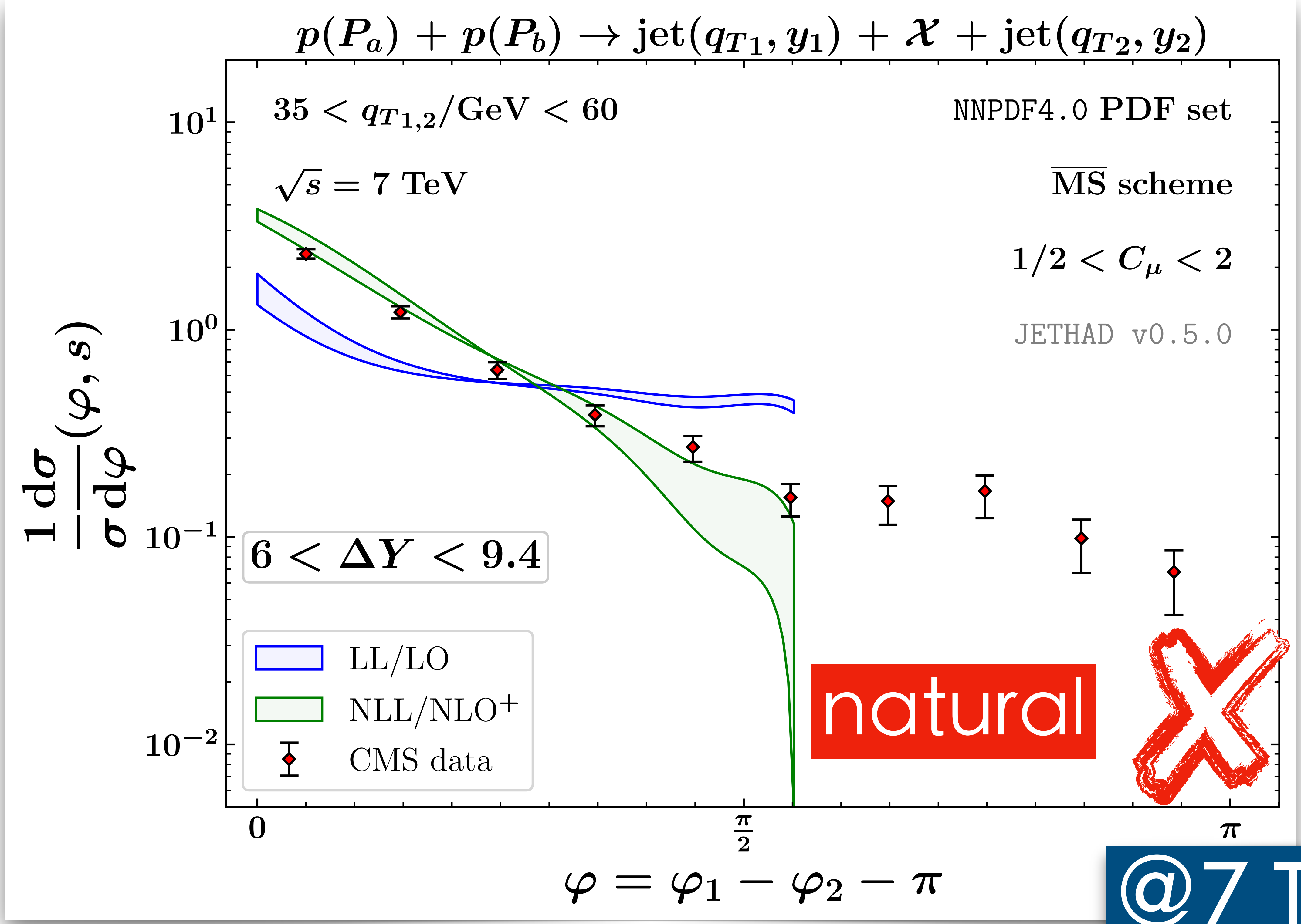
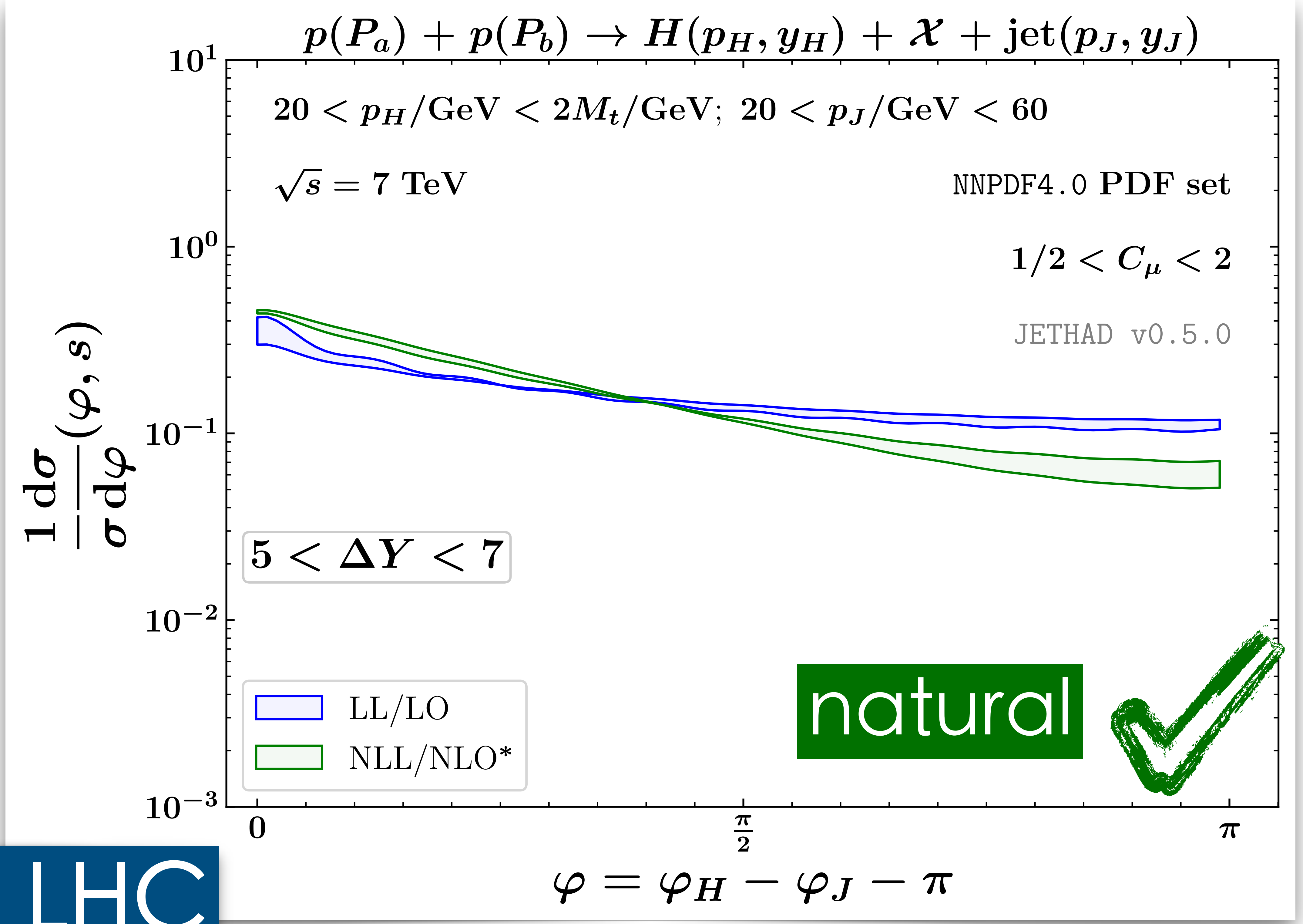
HIGGS + JET

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

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



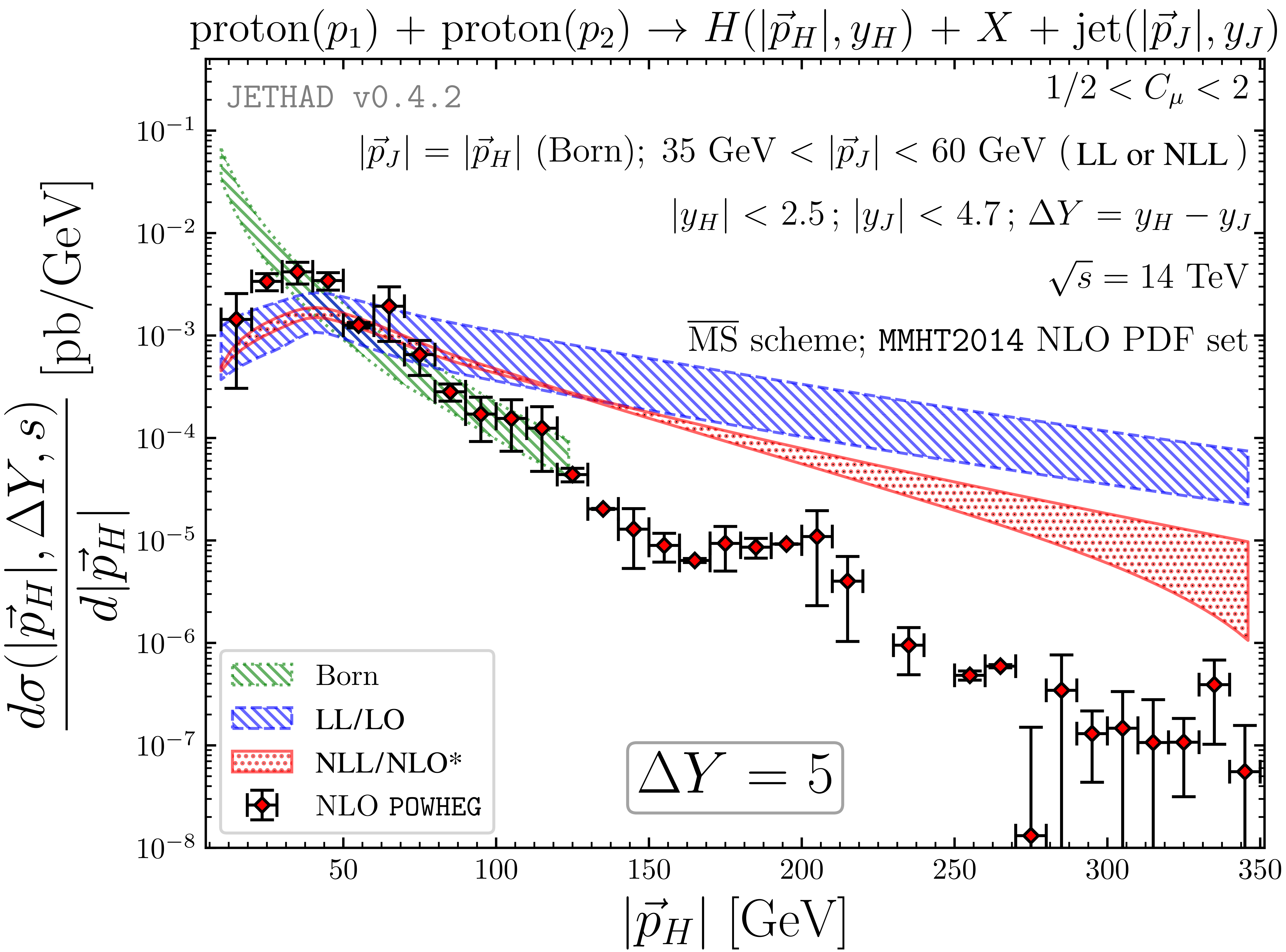


@7 TeV LHC

Hybrid factorization via the JETHAD code python + F

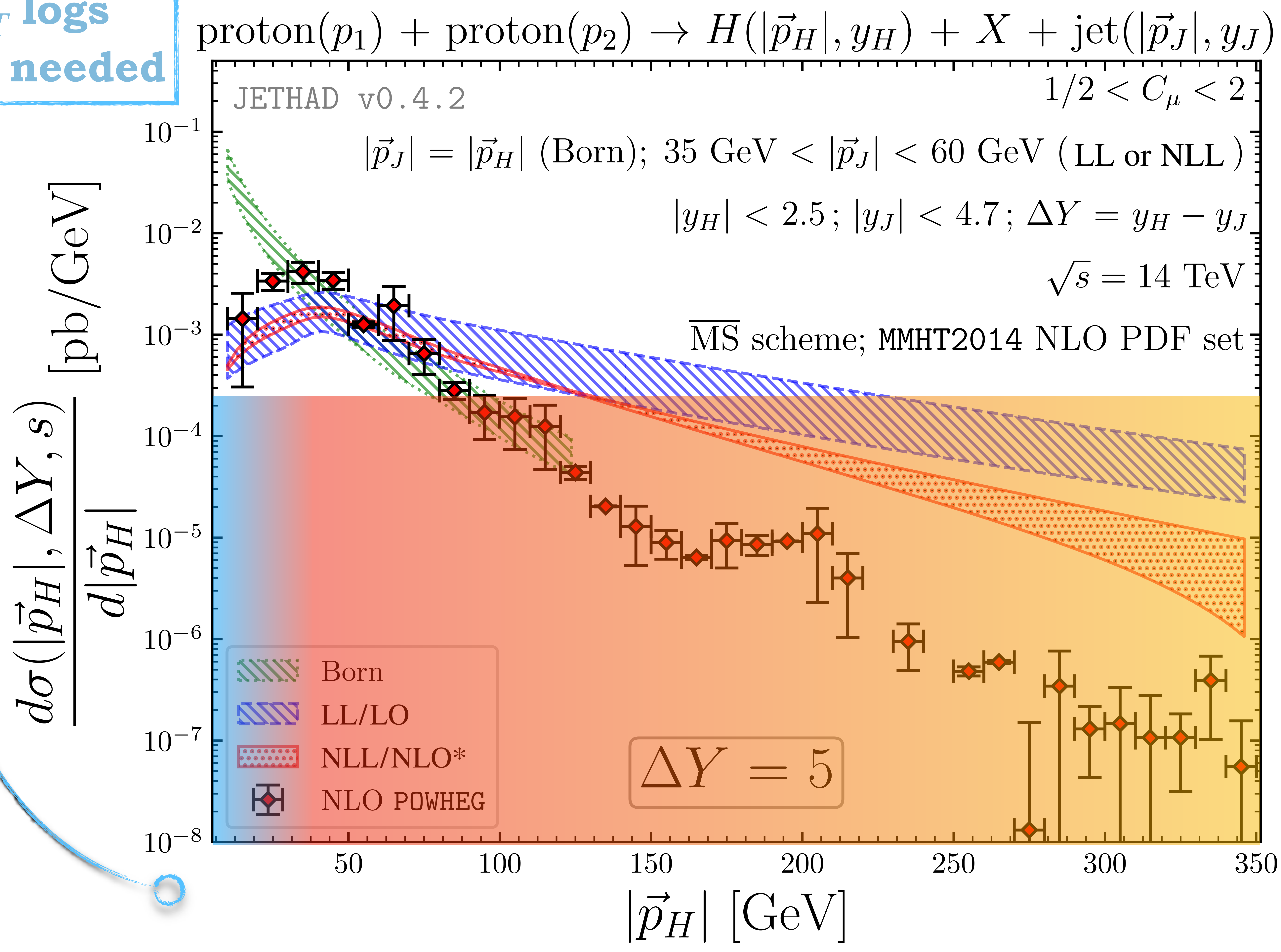
[F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]. [F. G. C. , Phys. Rev. D 105 (2022) 11, 114008]

NLL accurate predictions matched to NLO via the JETHAD Method



(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



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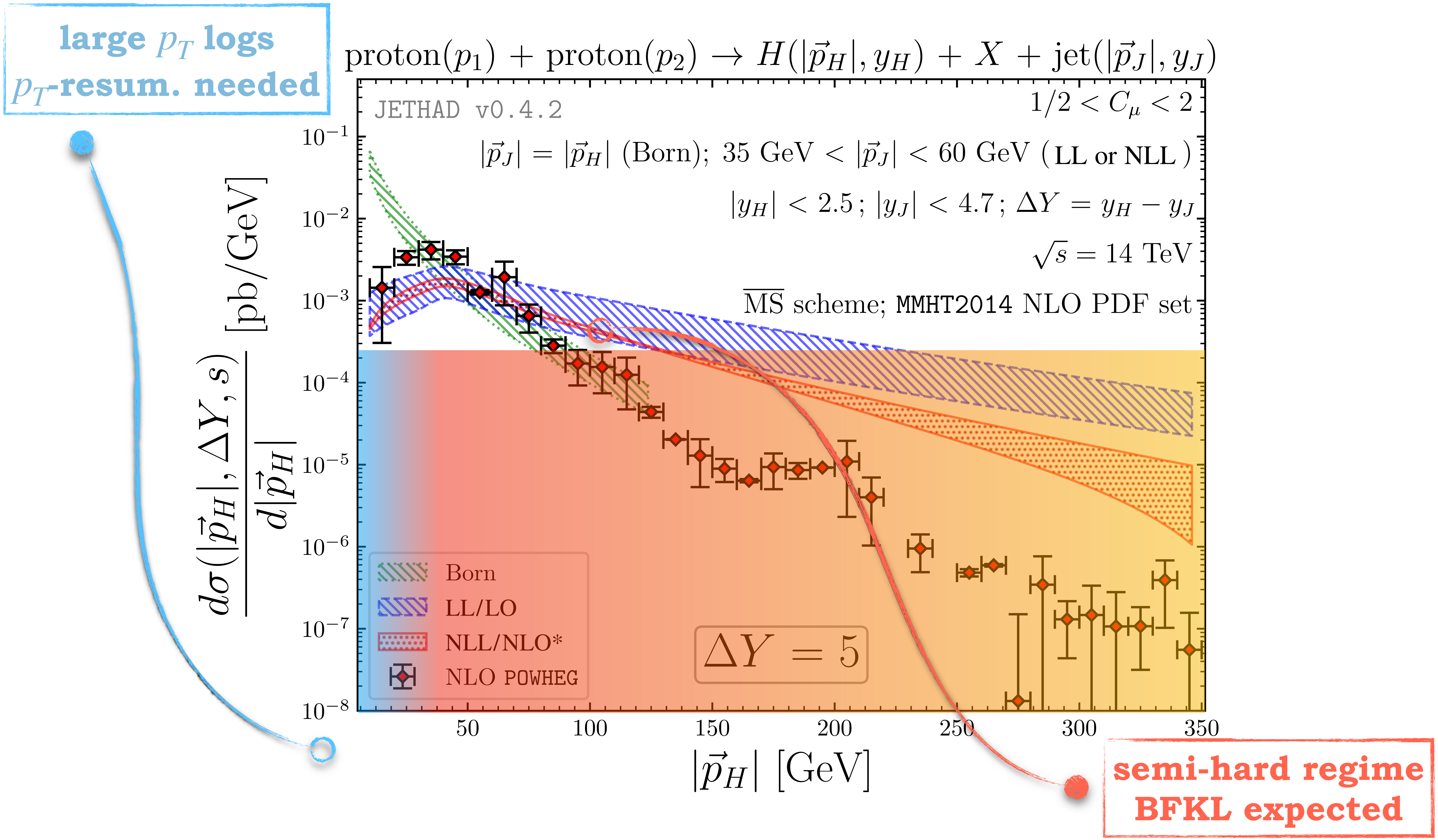

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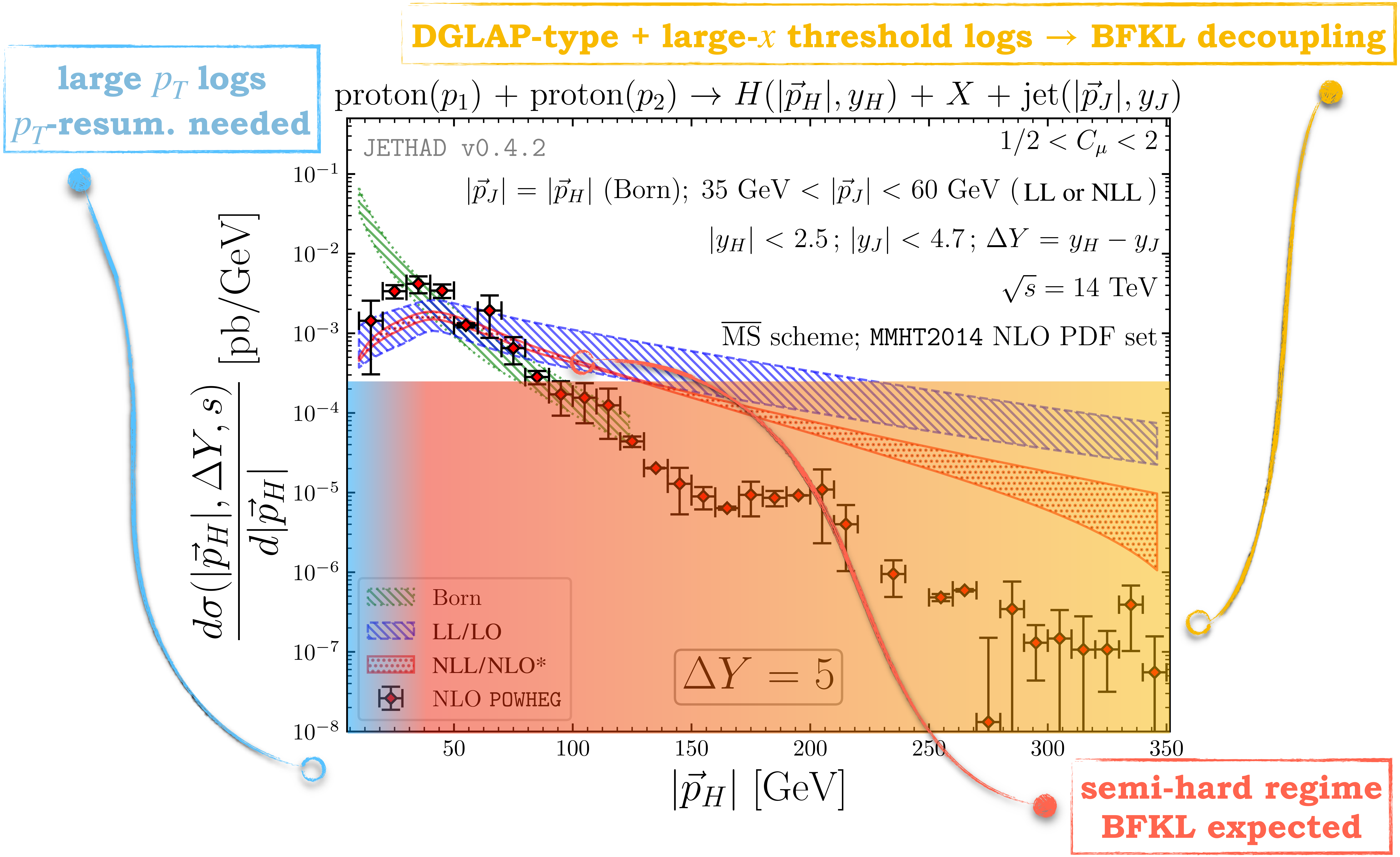
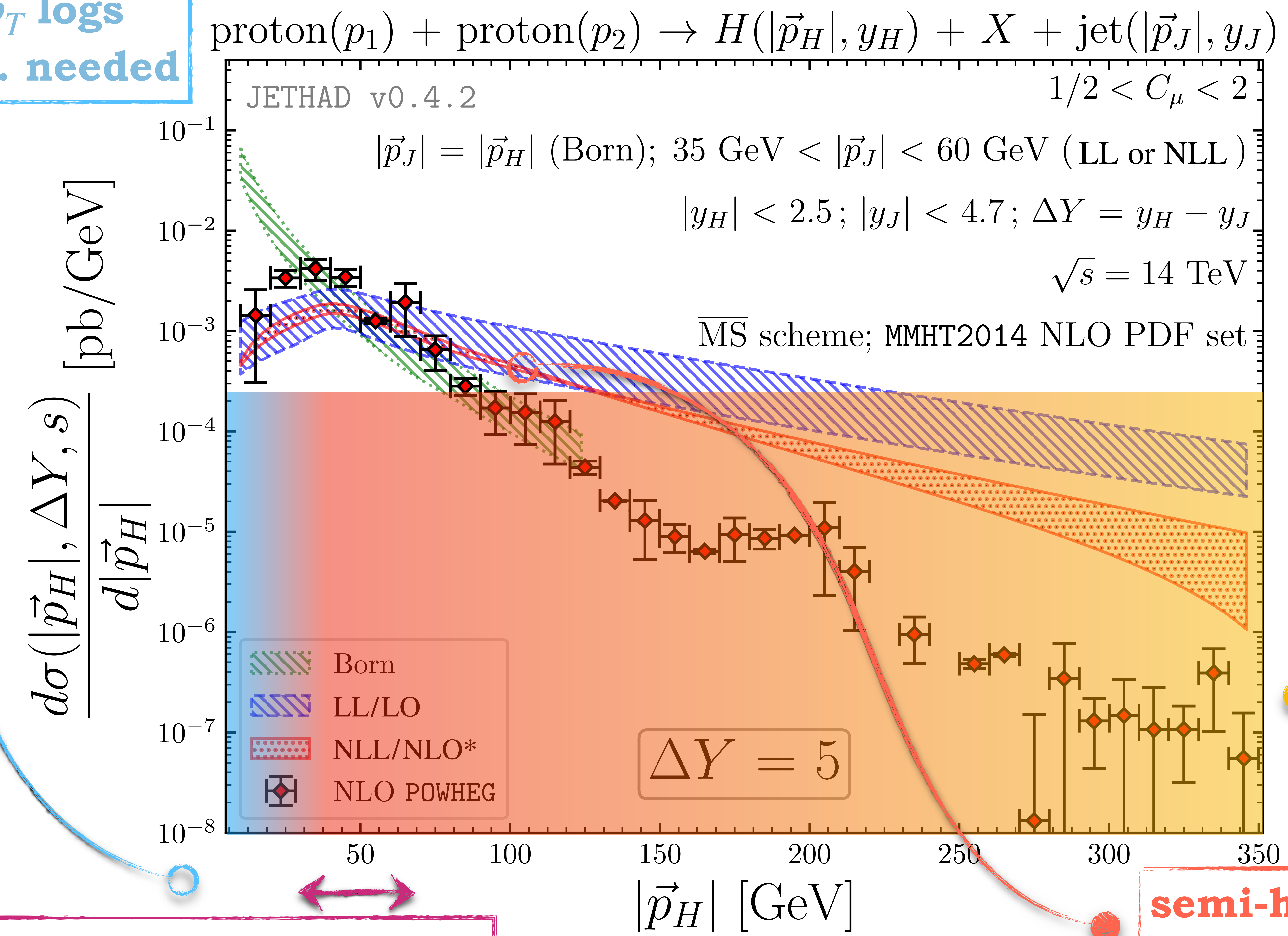


(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

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

large p_T logs
p_T-resum. needed

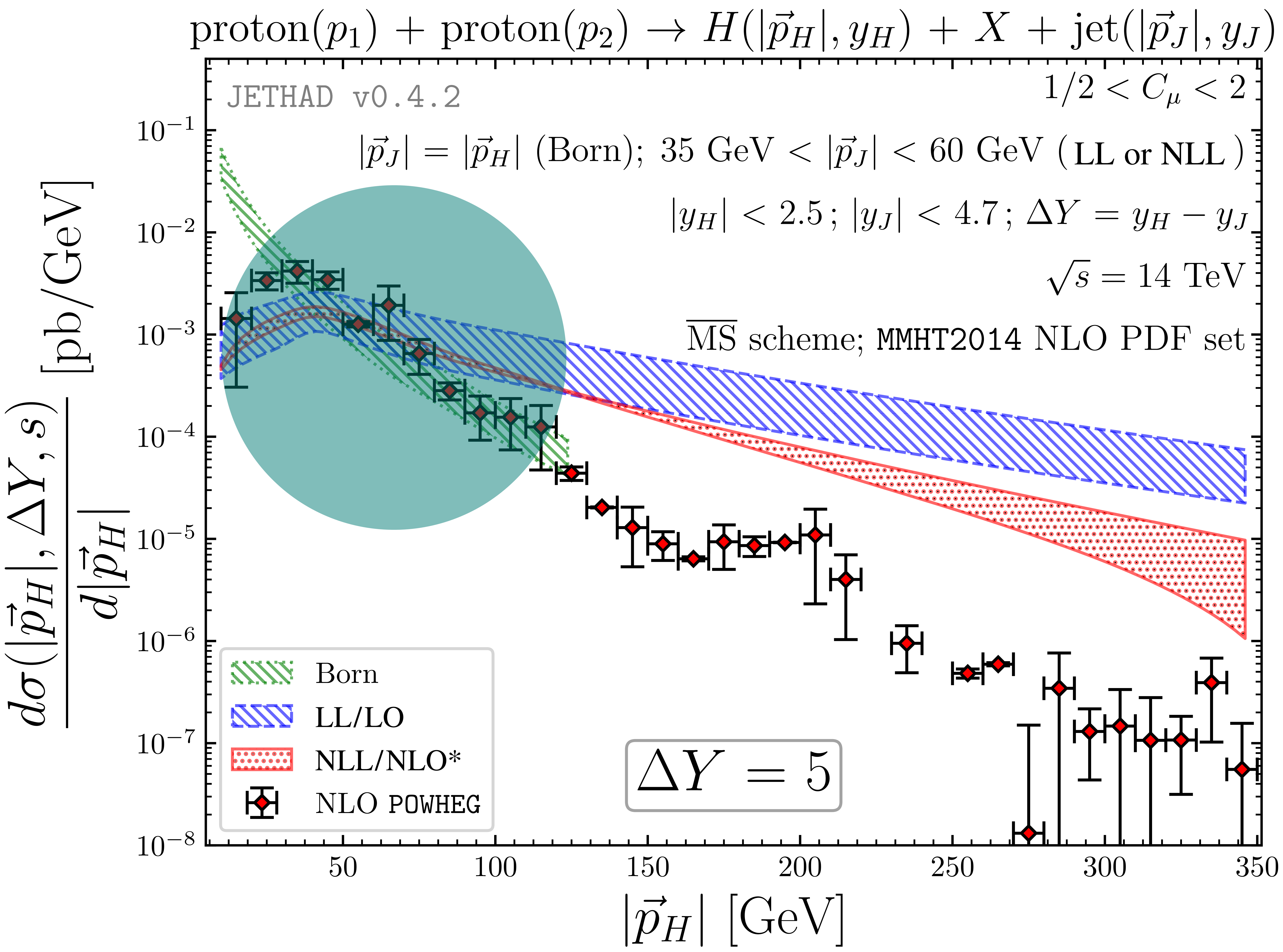


almost back-to-back emissions
large imbalance double logs

semi-hard regime
BFKL expected

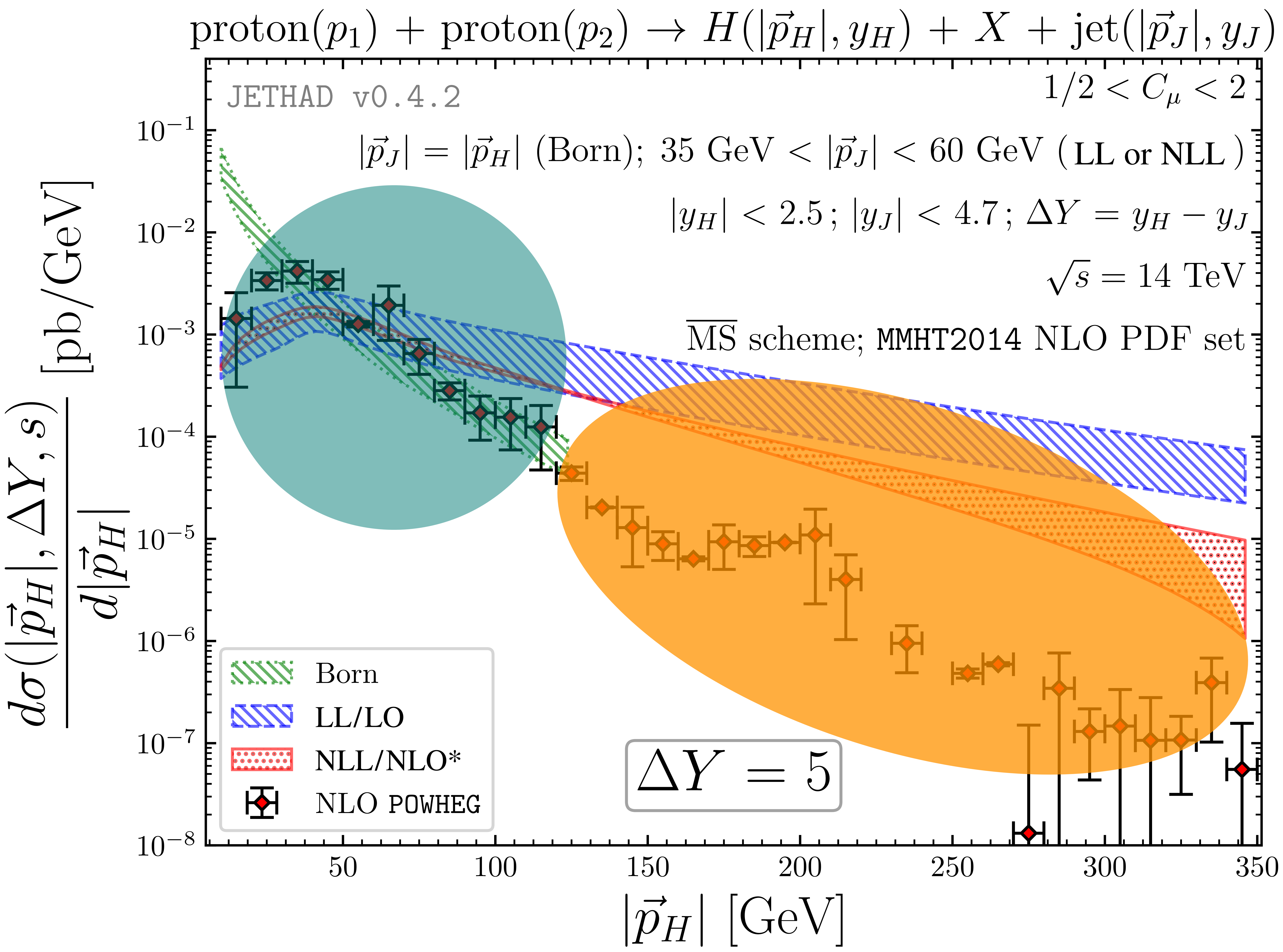
(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(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 **hybrid factorization** *predicts* **large deviations** from **f.o.** !

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)

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

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Matching NLL to NLO with JETHAD

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HELL + ggHiggs

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

Inclusive Higgs

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

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HELL + ggHiggs

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Inclusive Higgs

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

HEJ framework

$\mathrm{LL_{sx}^{+}/NLO}$

Higgs + jet(s)

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

[Today's talks by Jeppe & Andreas]

Matching NLL to NLO with JETHAD

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HEJ framework

LL_{sx}^{+}/NLO

Higgs + jet(s)

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

RadISH + MCFM-8.3

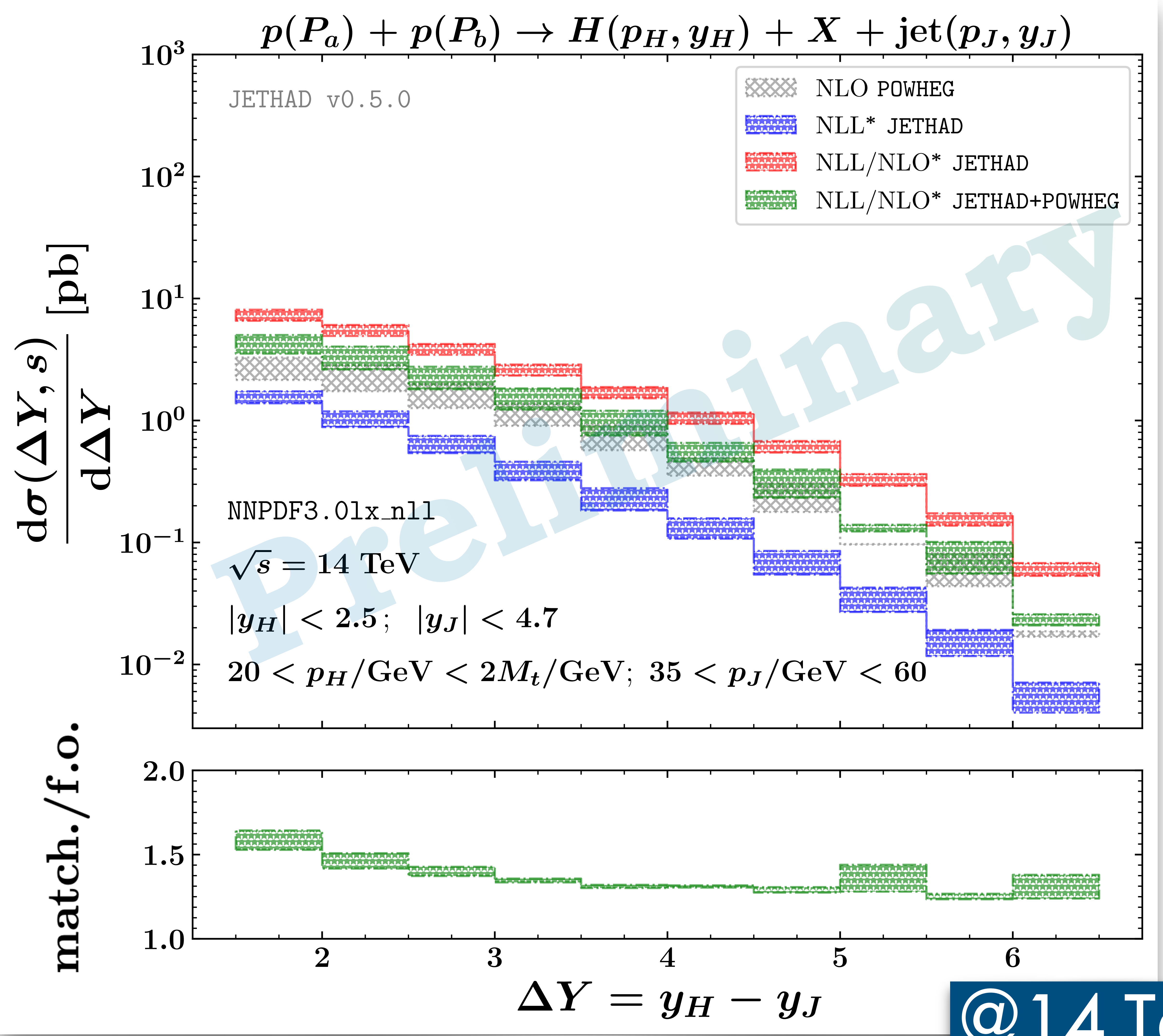
$NNLL_{TM}/NLO$

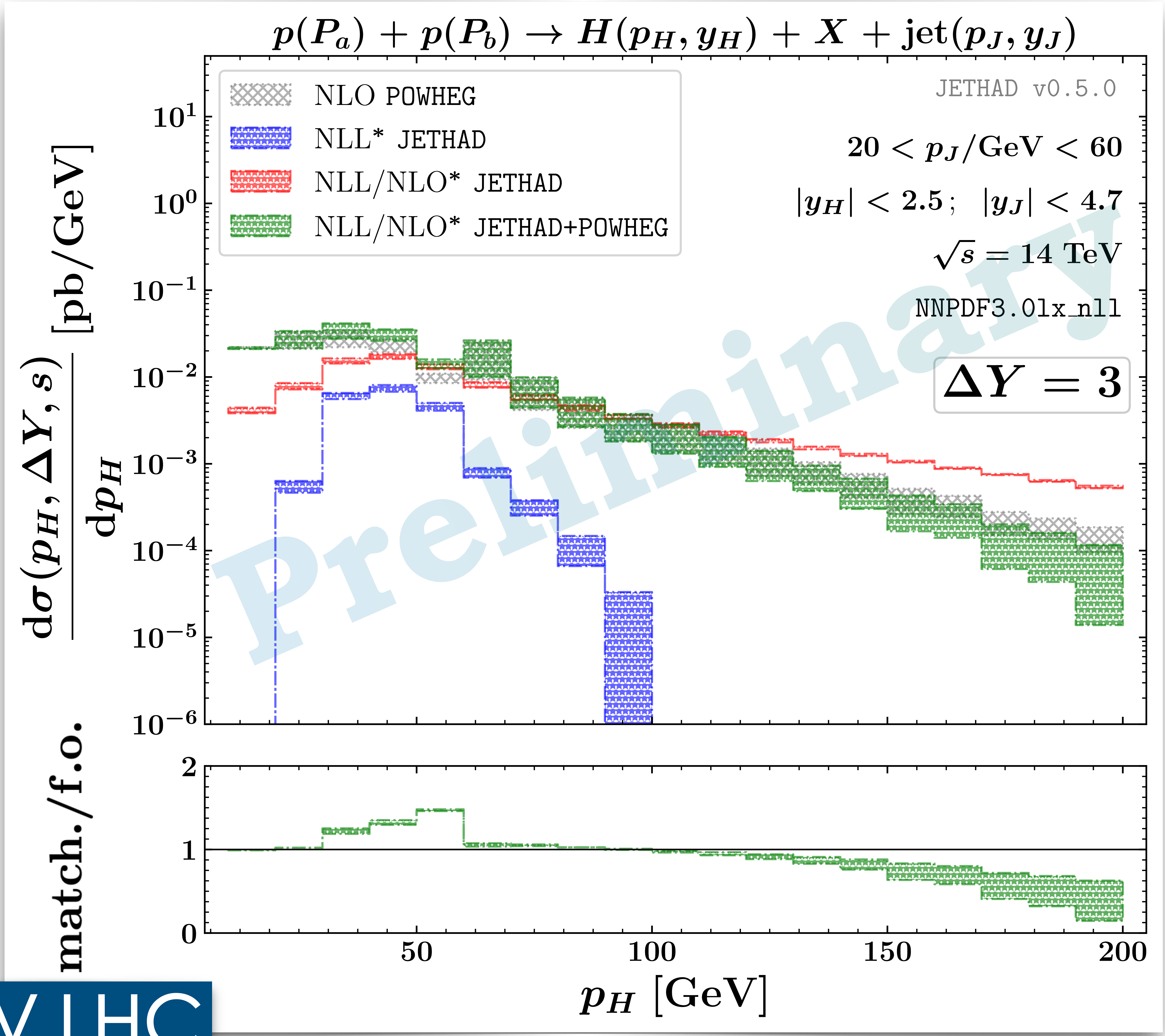
Higgs + jet

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

[Today's talks by Jeppe & Andreas]

The Higgs + jet spectrum from POWHEG + JETHAD

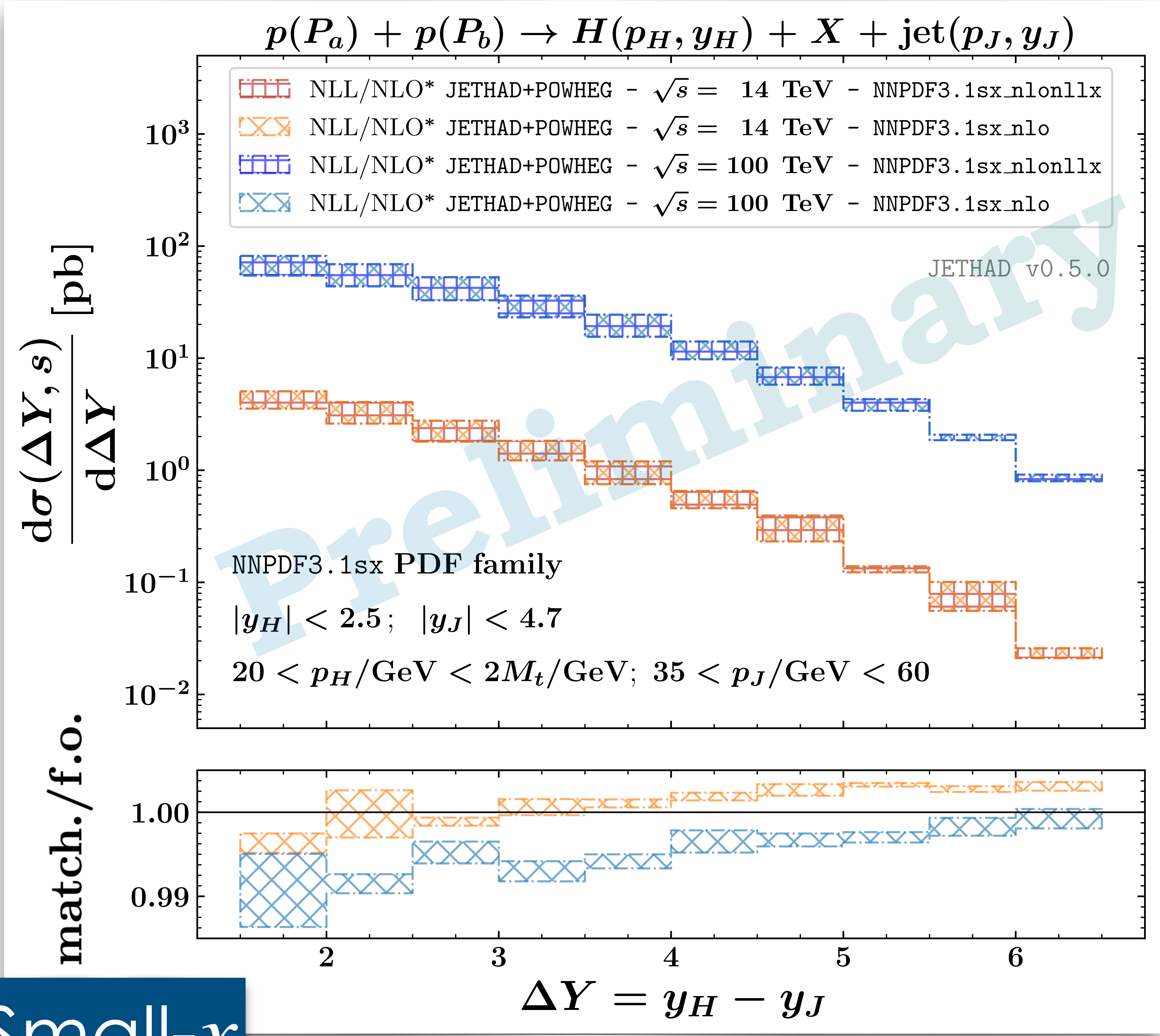




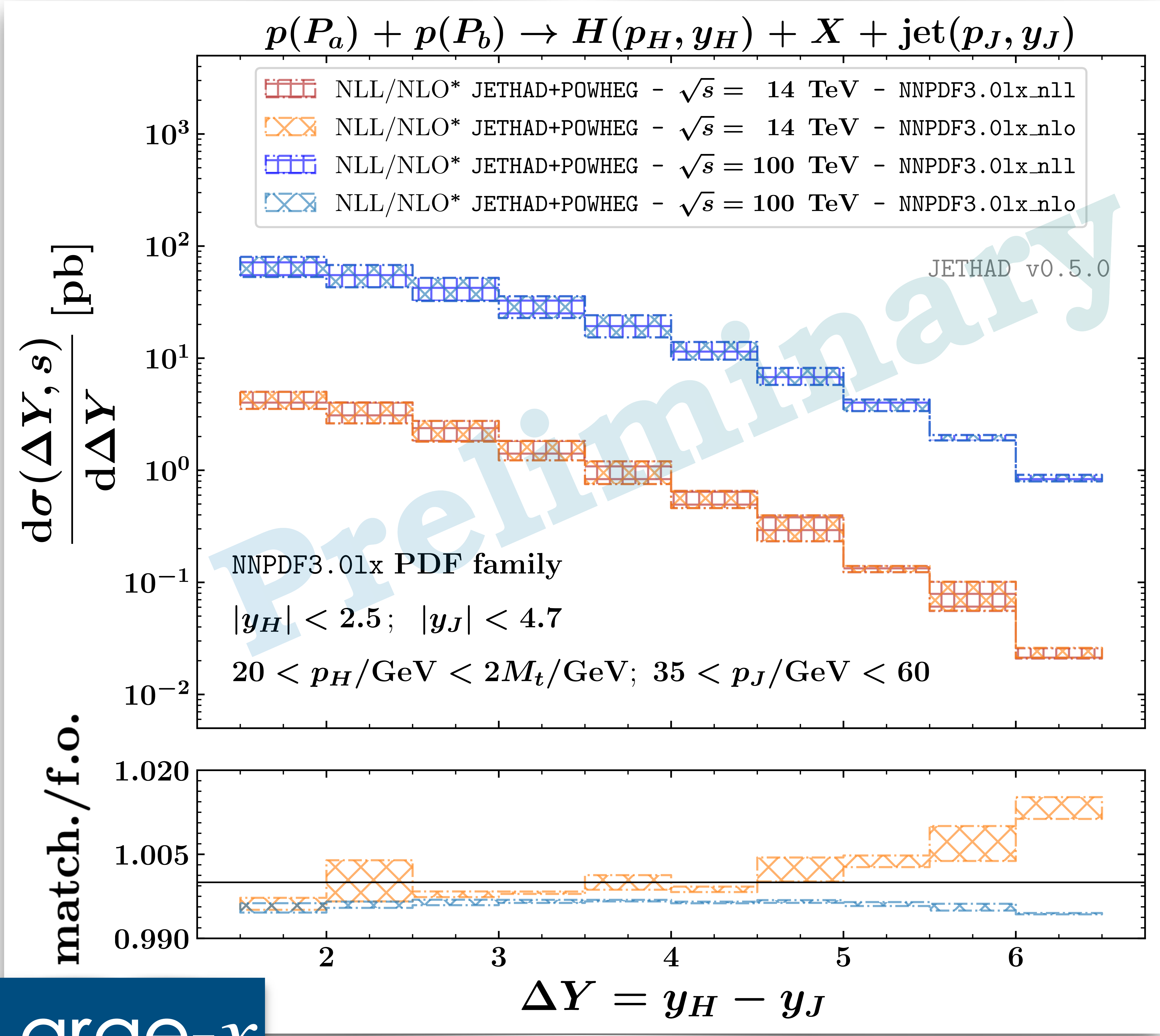
@14 TeV LHC

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

Small-x and large-x enhancement from PDFs



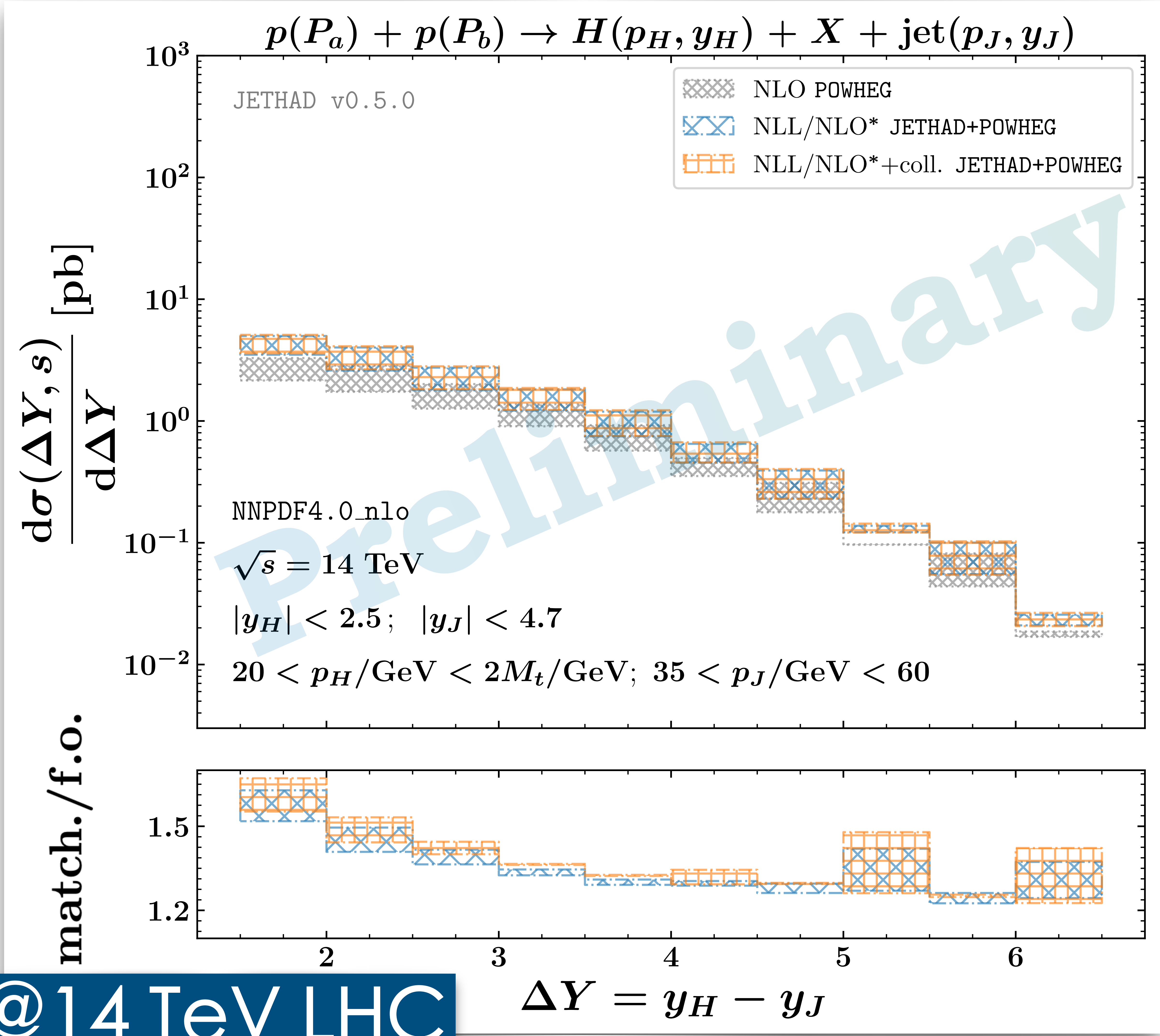
Small-x



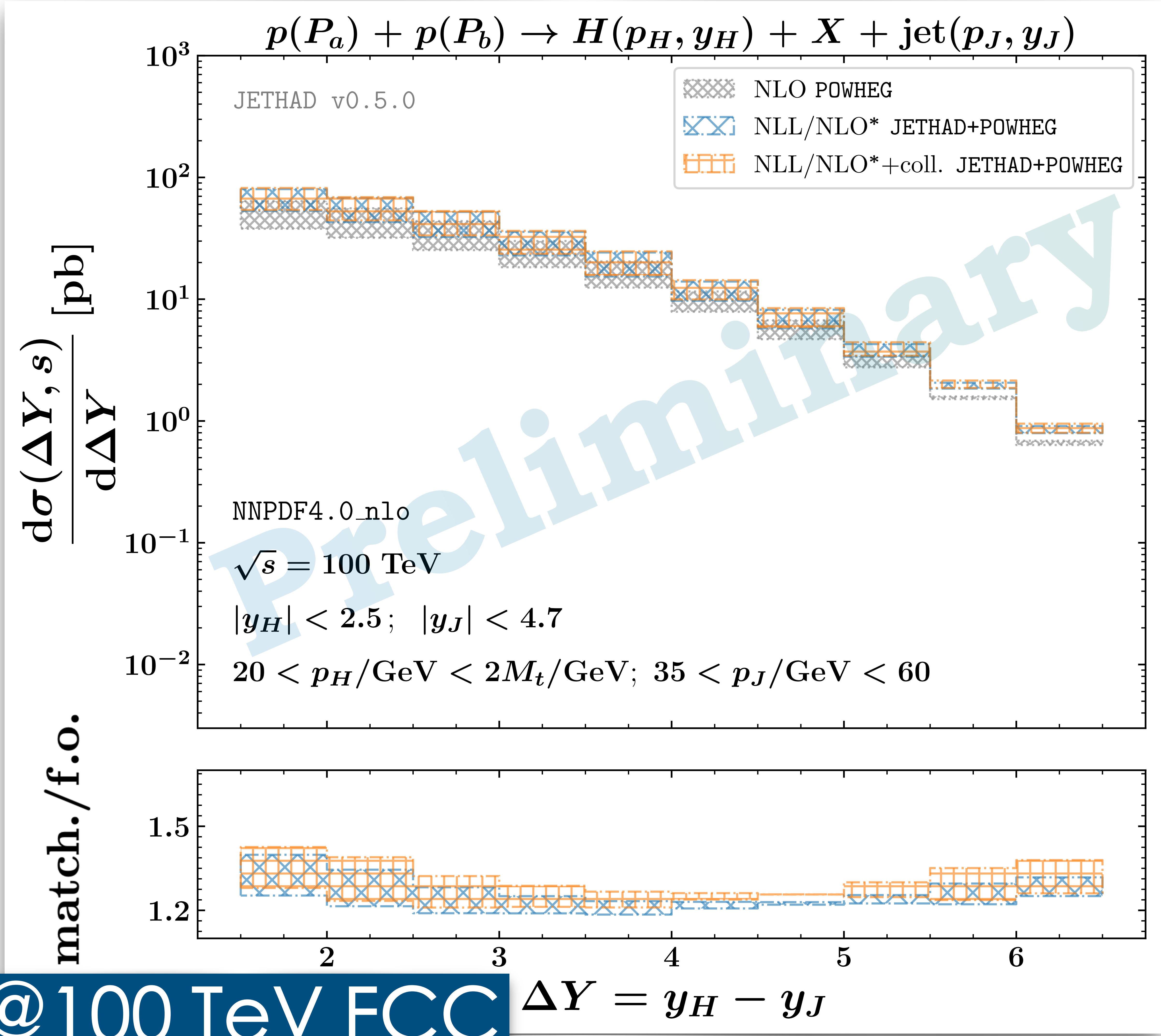
Large-x

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

Effect of collinear improvement on NLL BFKL kernel



@14 TeV LHC

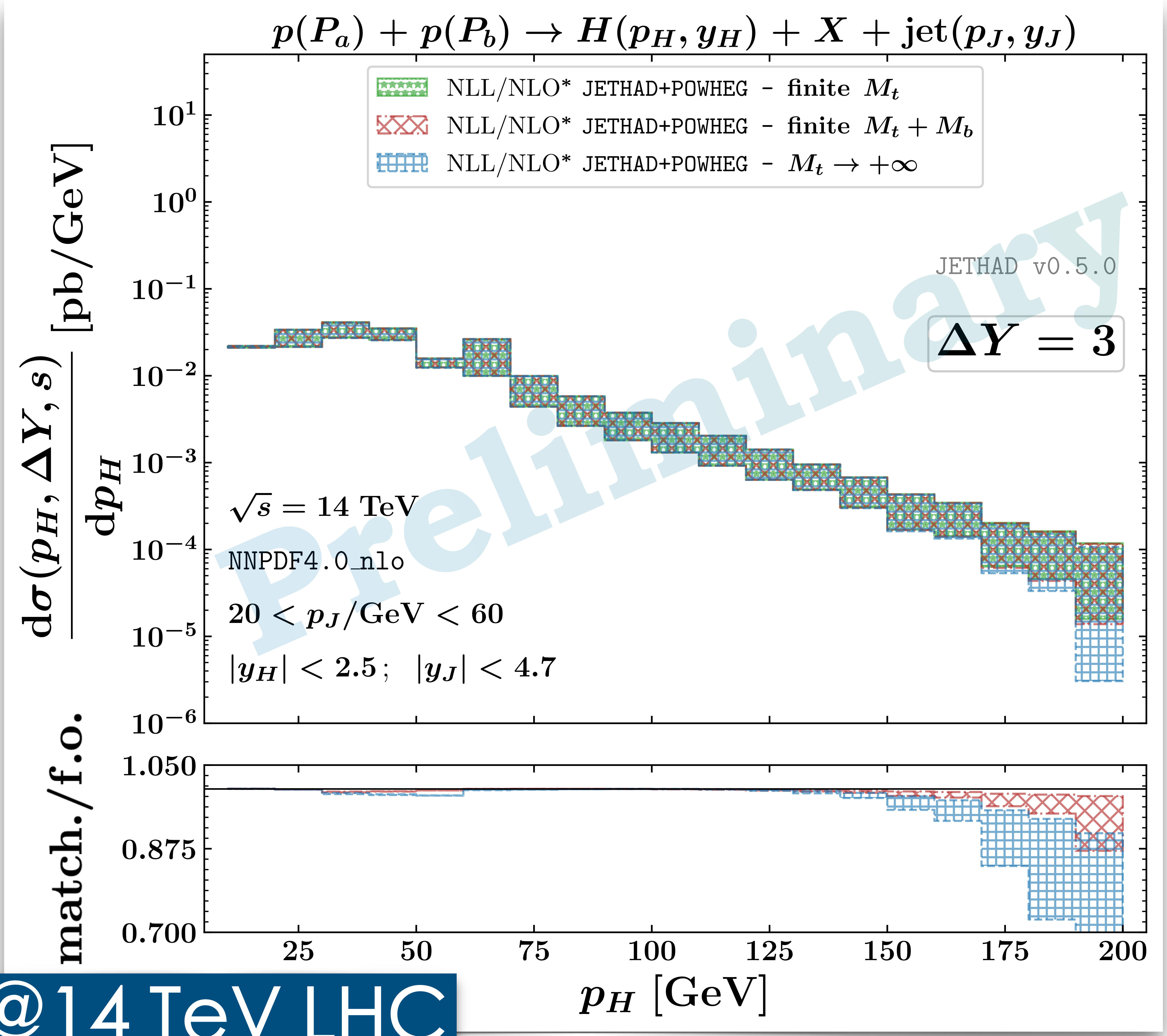


@100 TeV FCC

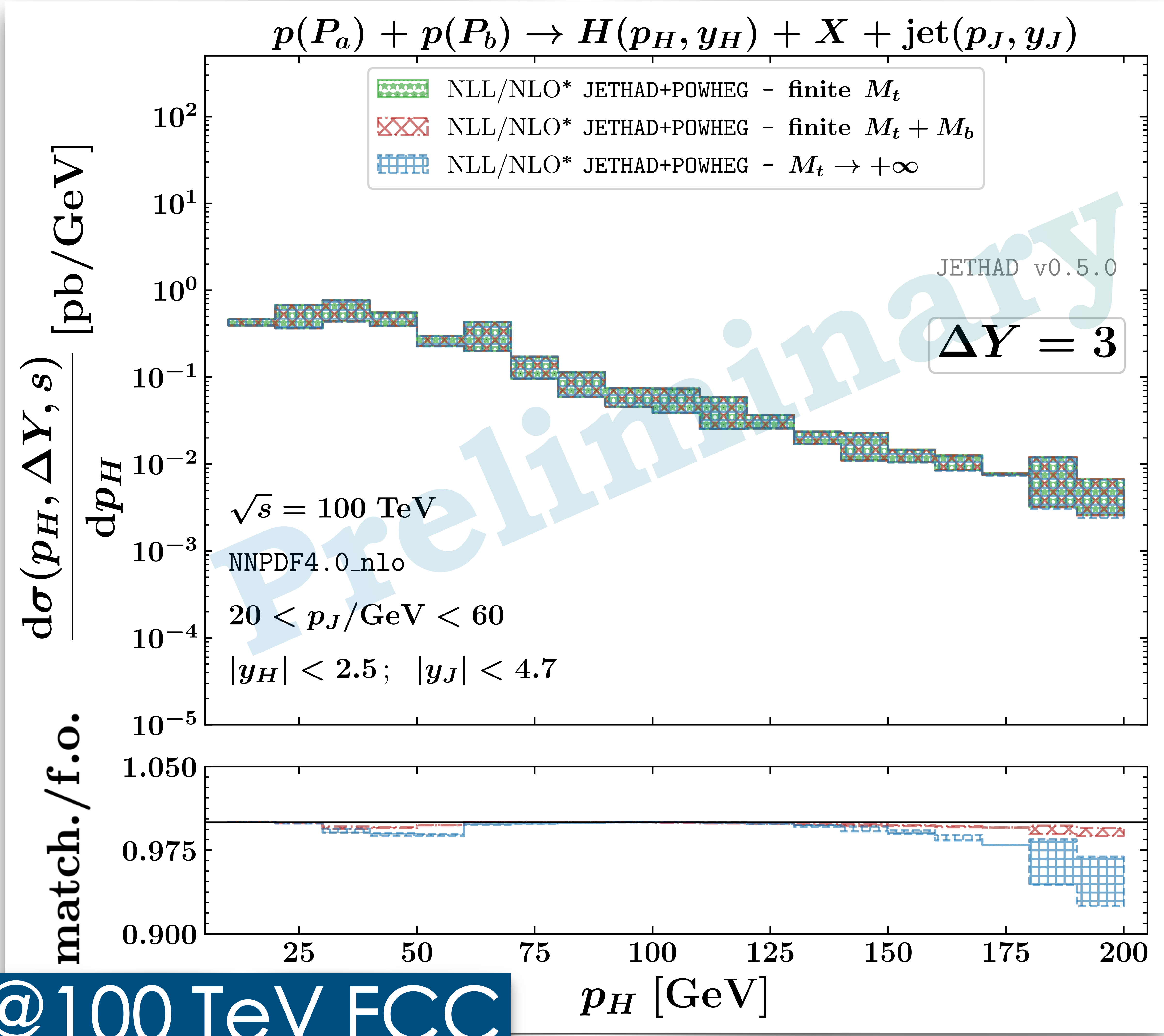
(Collinear improvement) [G.P. Salam, JHEP 07 (1998) 019]; [M. Ciafaloni et al., Phys.Lett.B 587 (2004) 87-94]; [A. Sabio Vera, Nucl.Phys.B 722 (2005) 65-80]

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

Finite top- and bottom-mass corrections



@14 TeV LHC



@100 TeV FCC

Effect of finite heavy-quark masses on NLO coeff. functions to be gauged

(NLO Higgs) 🔗 [F. G. C., M. Fucilla, D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, JHEP 08 (2022) 092]

Paving the way toward precision

- ☑ Semi-inclusive Higgs + jet as novel probe for High-Energy QCD
- ☑ Encouraging statistics for rapidity & transverse-momentum distributions
- ☑ Fair stability under NLL corrections

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- ☐ Precision studies ⇔ NLL/NLO Matching via the JETHAD Method
- ☐ Full NLL/NLO analysis: NLO Higgs [Michael's talk], jet algorithm
- ☐ Systematic uncertainties: top & bottom masses, PDF impact, Matching
- ☐ Transversal formalism as underlying staging for several resummations

Extras

Mueller-Navelet jets @LHC & 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

Mueller-Navelet jets @LHC & resummation instabilities

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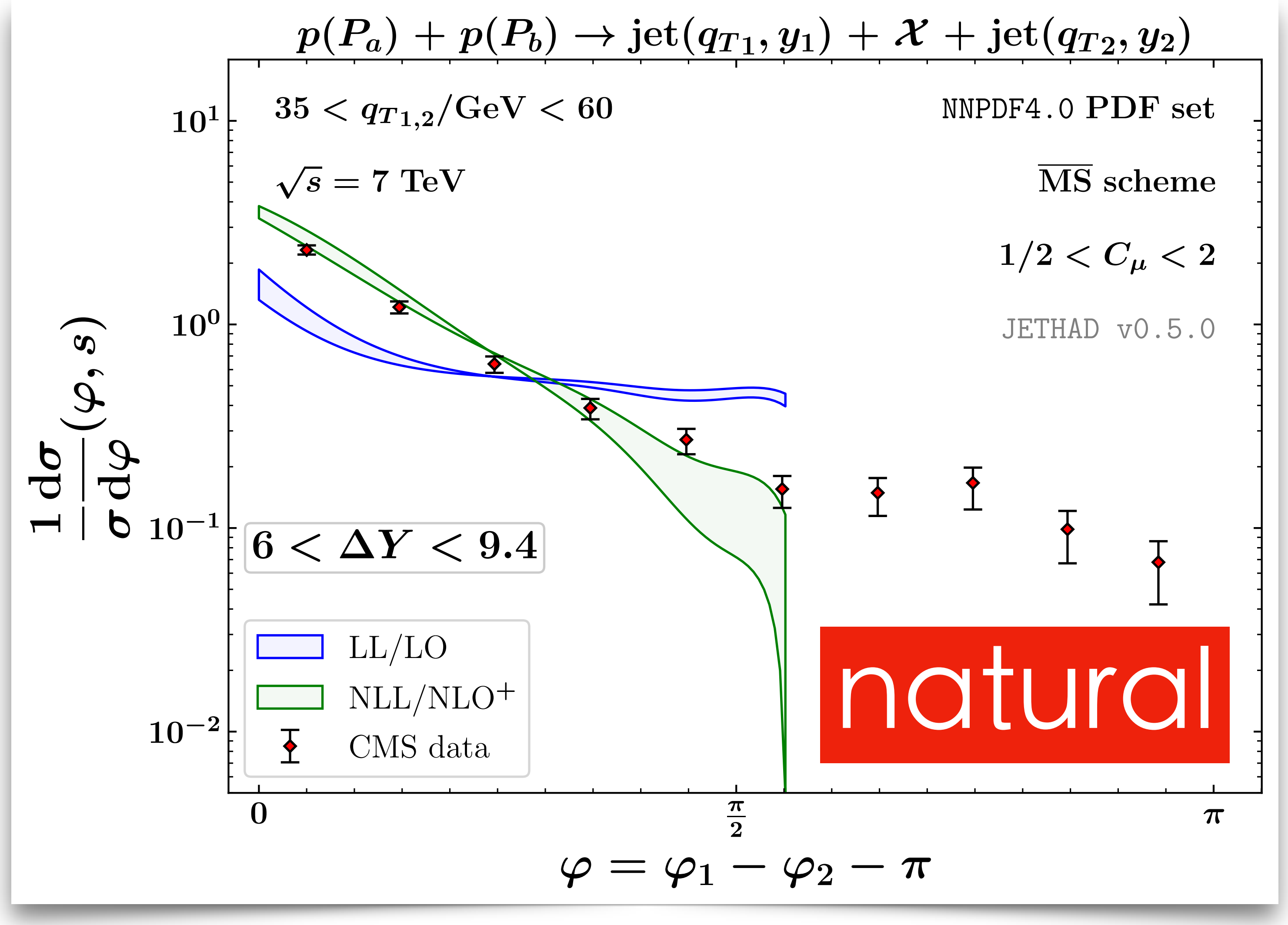
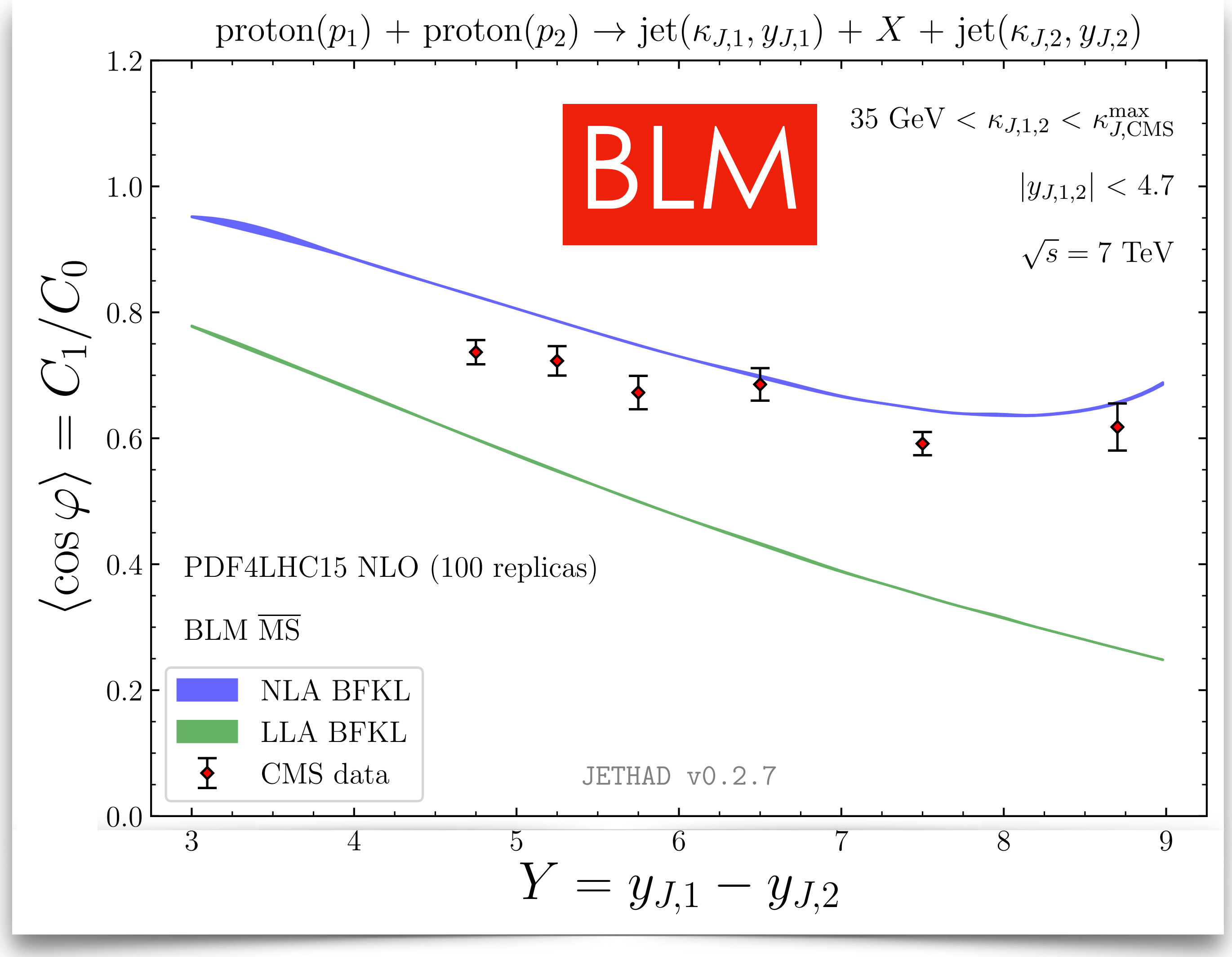
[CMS Collaboration, JHEP 08 (2016) 139]
[B. Ducloué et al., Phys. Rev. Lett. 112 (2014) 082003]
[F. Caporale et al., Eur. Phys. J. C 74 (2014) 10, 3084]





(left figure) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Backup

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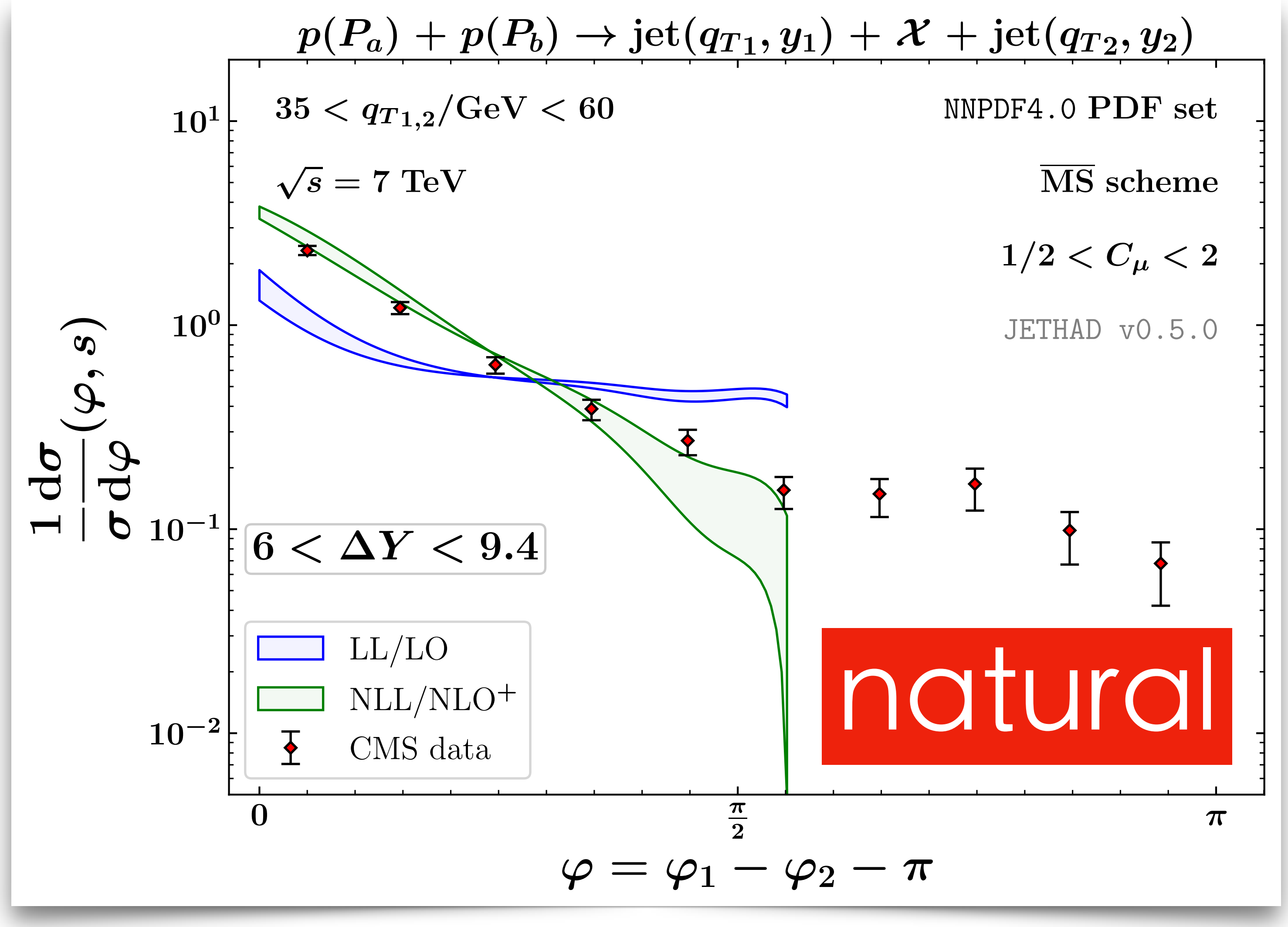
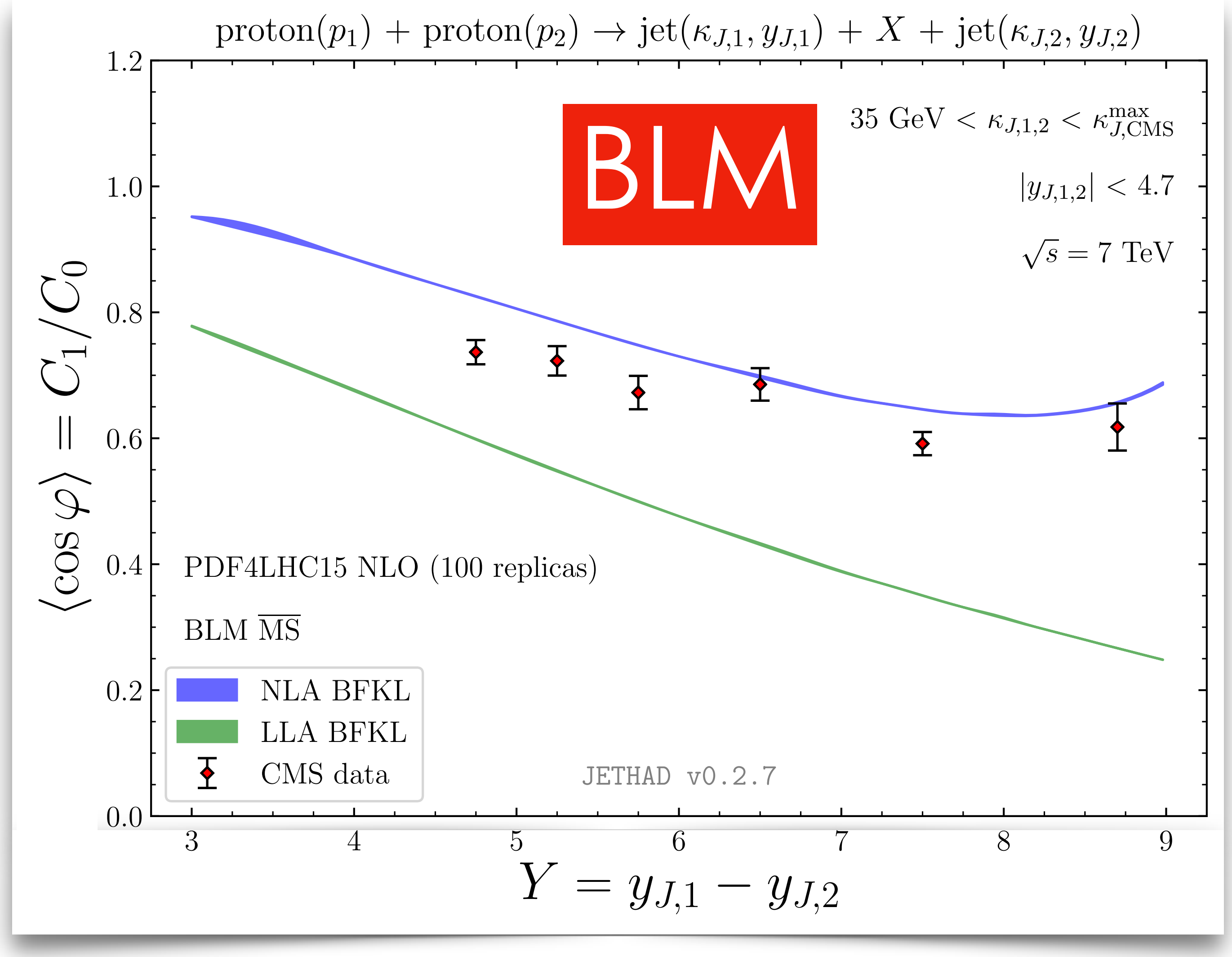


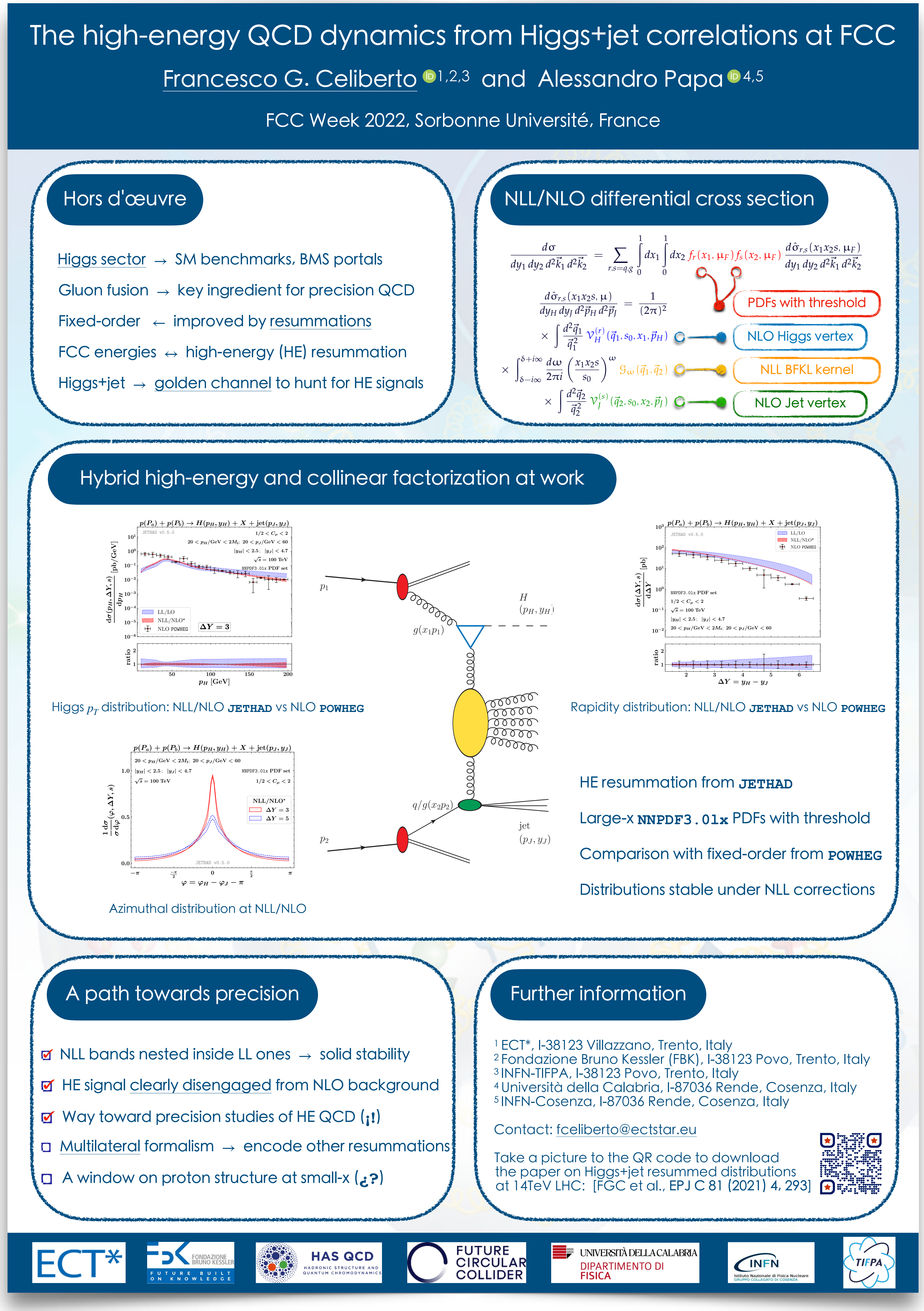


(left figure) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

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

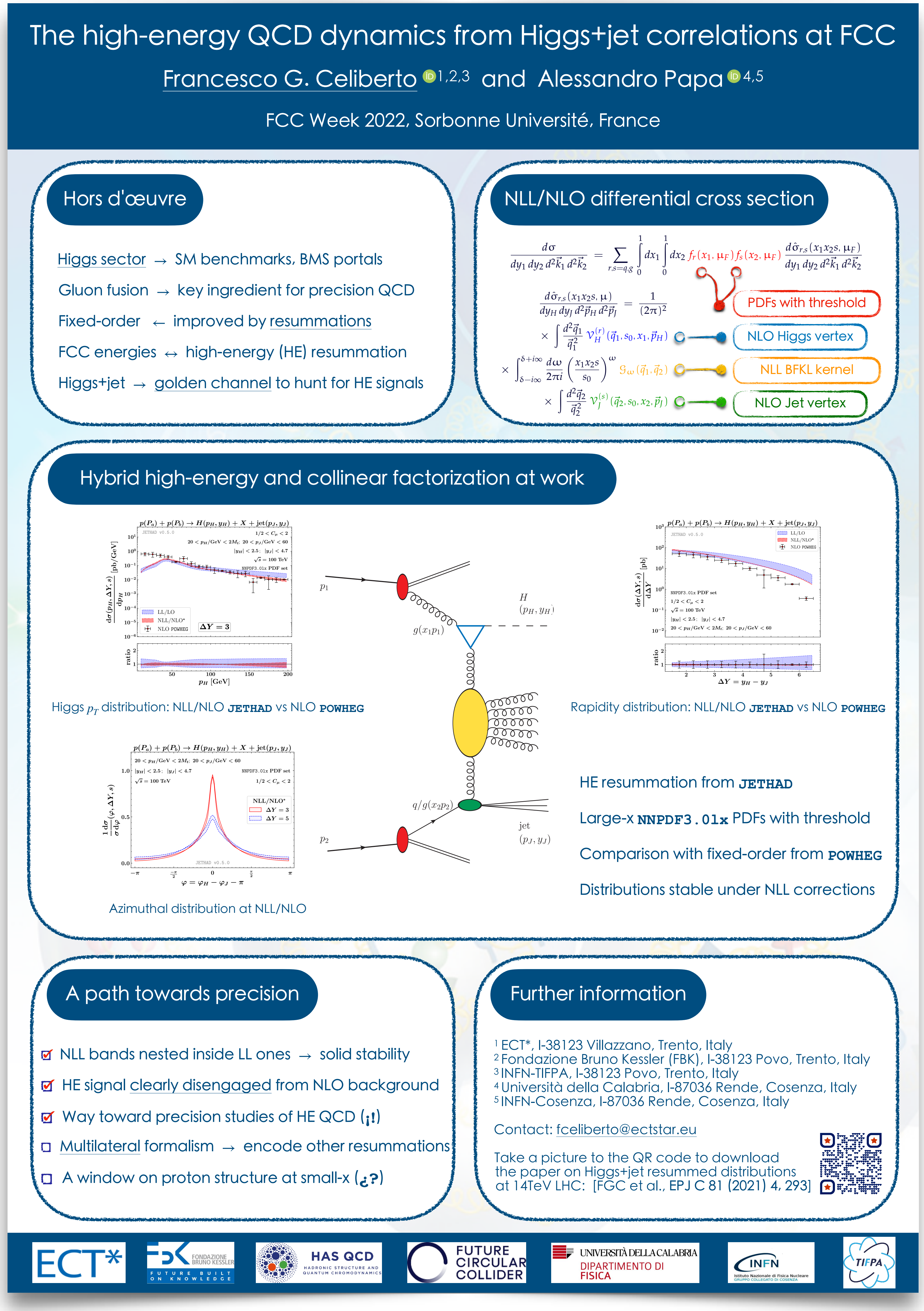
Backup

Higgs + jet highlights from the FCC Week 2022



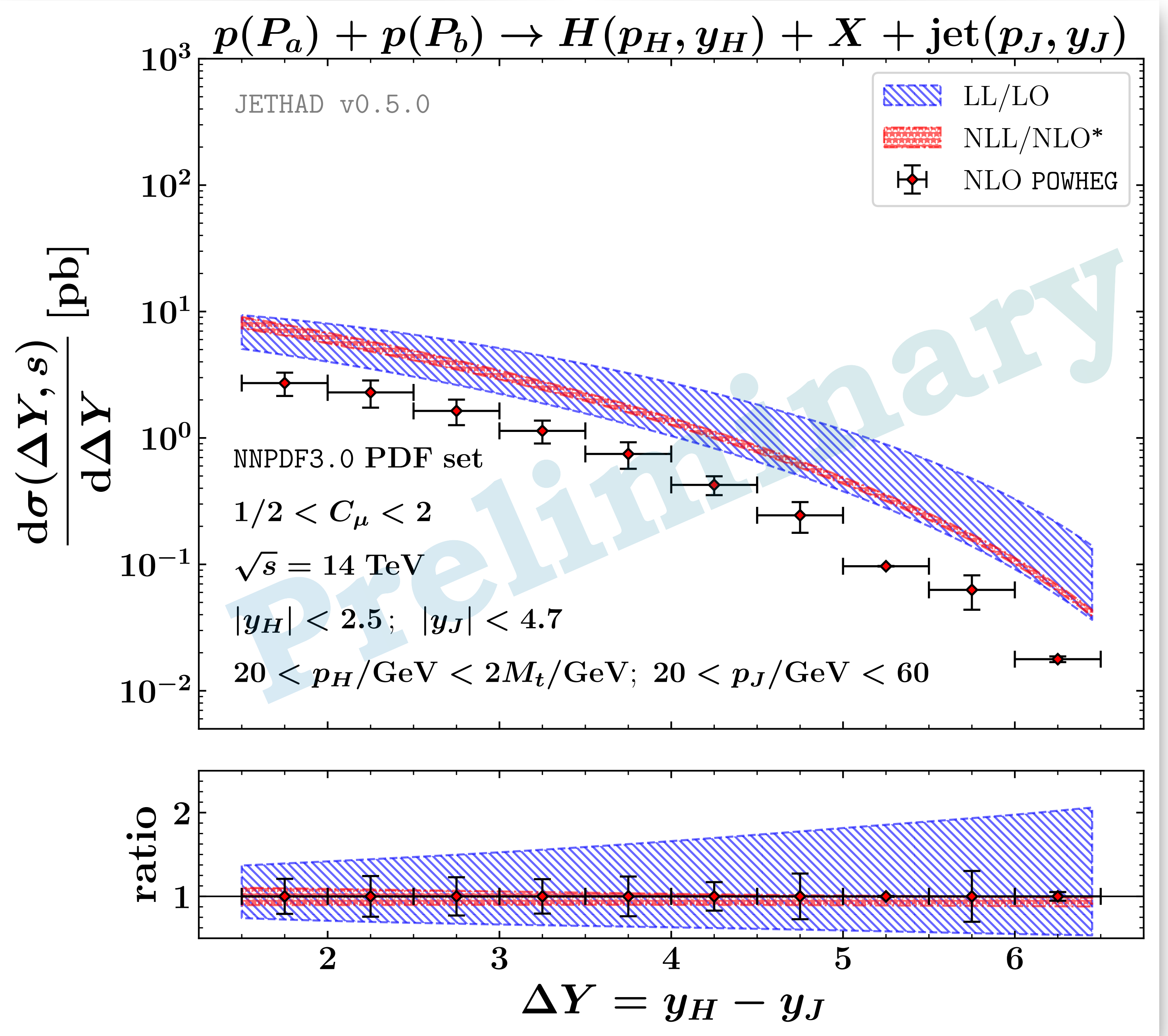
Backup

Higgs + jet highlights from the FCC Week 2022

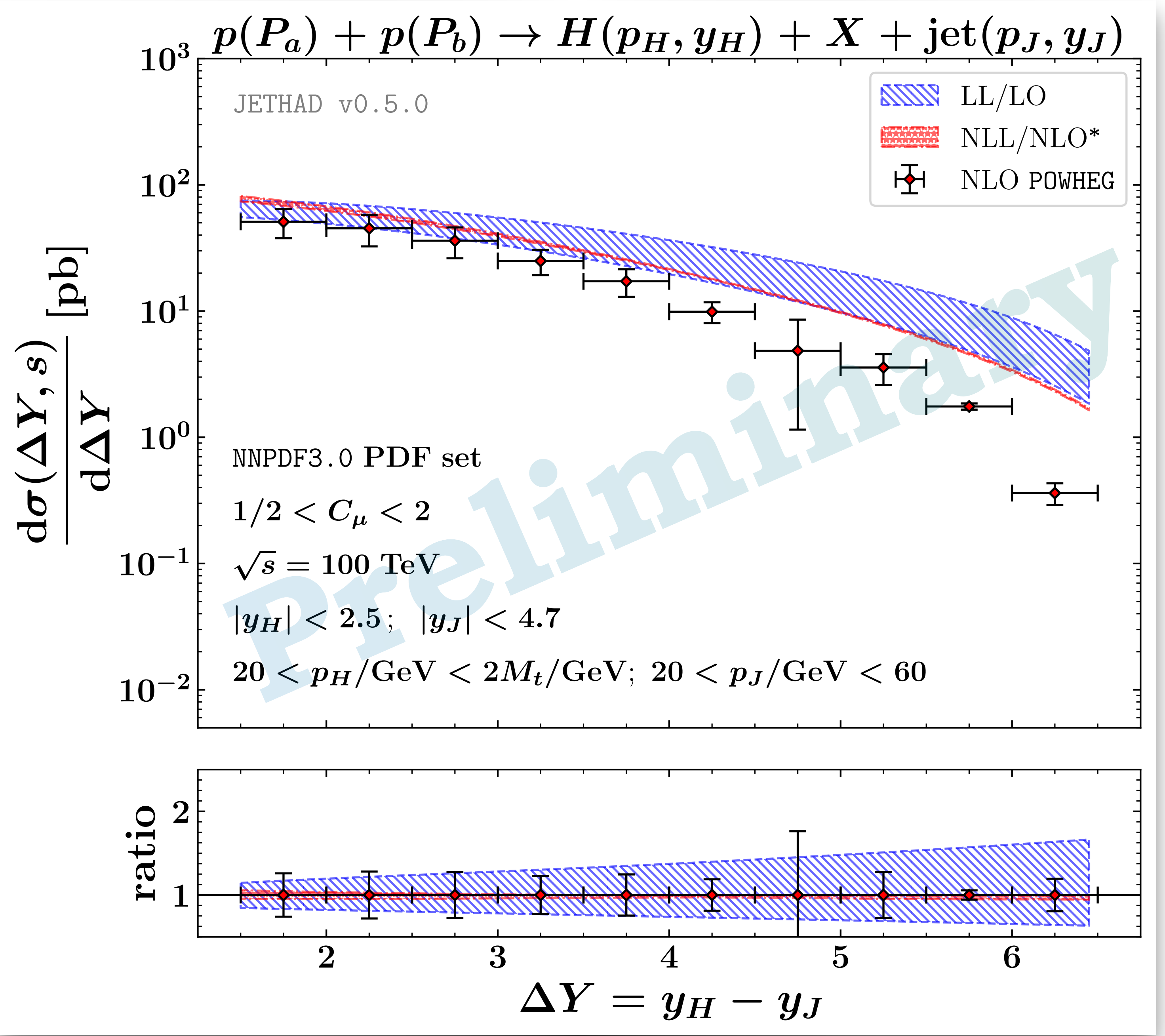


$$C_n(\Delta Y, s) = \int_{p_H^{\rm min}}^{p_H^{\rm max}} d|\vec p_H| \int_{p_J^{\rm min}}^{p_J^{\rm max}} d|\vec p_J| \int_{y_H^{\rm min}}^{y_H^{\rm max}} dy_H \int_{y_J^{\rm min}}^{y_J^{\rm max}} dy_J\, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$

Rapidity distribution: NLL/NLO* JETHAD vs NLO POWHEG



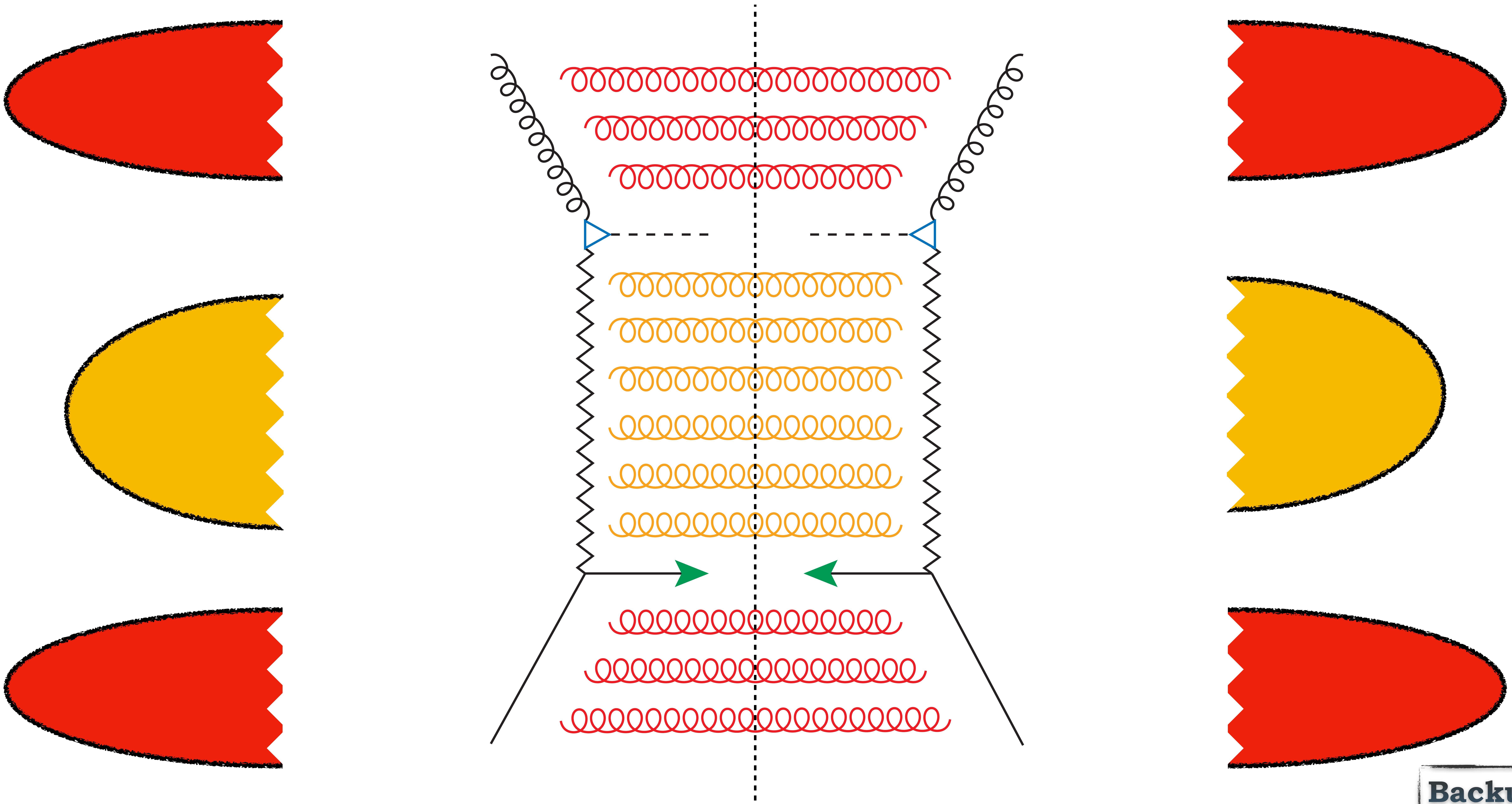
14 TeV LHC



100 TeV FCC

Backup

Anatomy of Higgs + jet in hybrid factorization (HyF)



Backup

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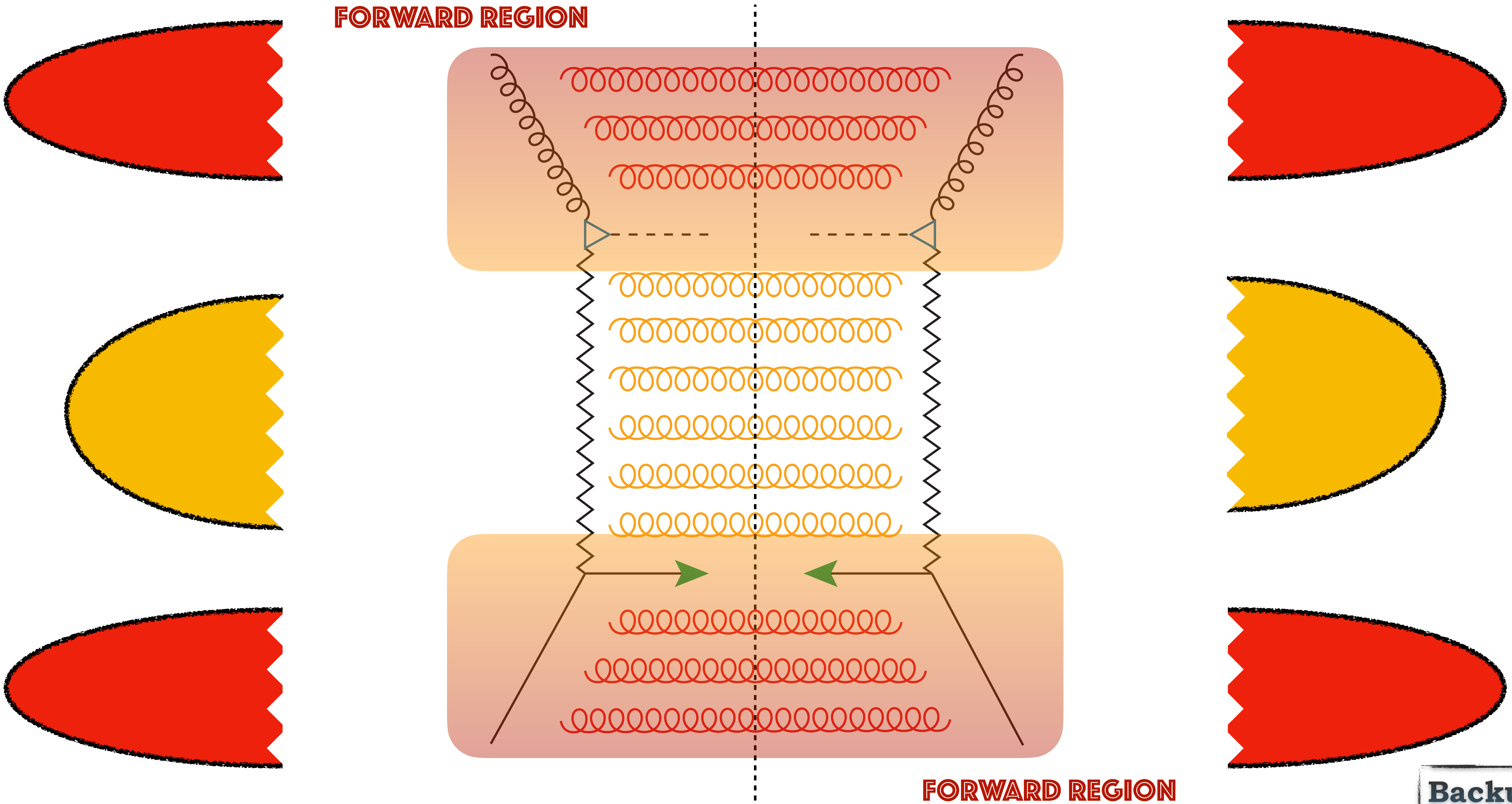

Backup

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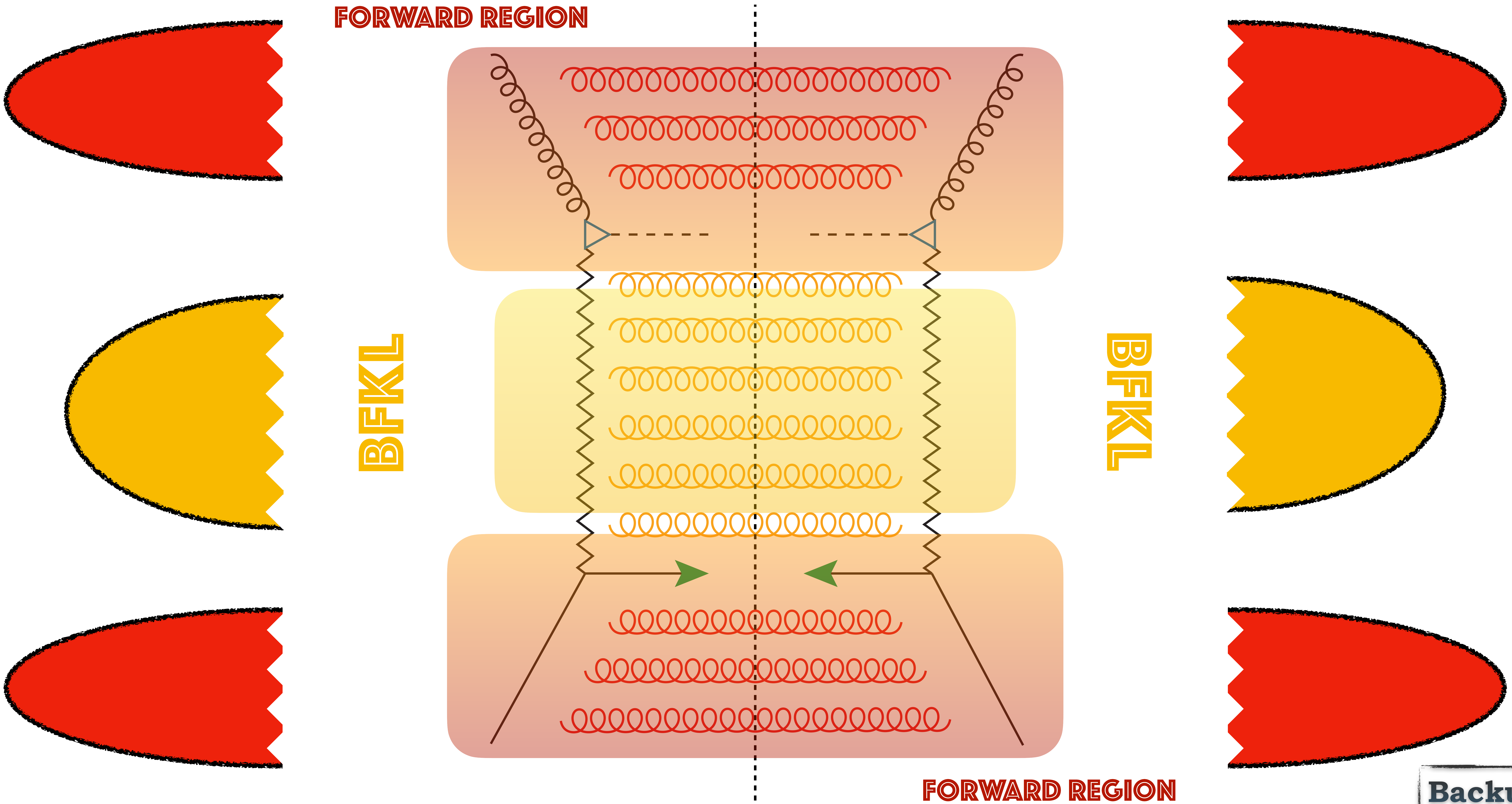

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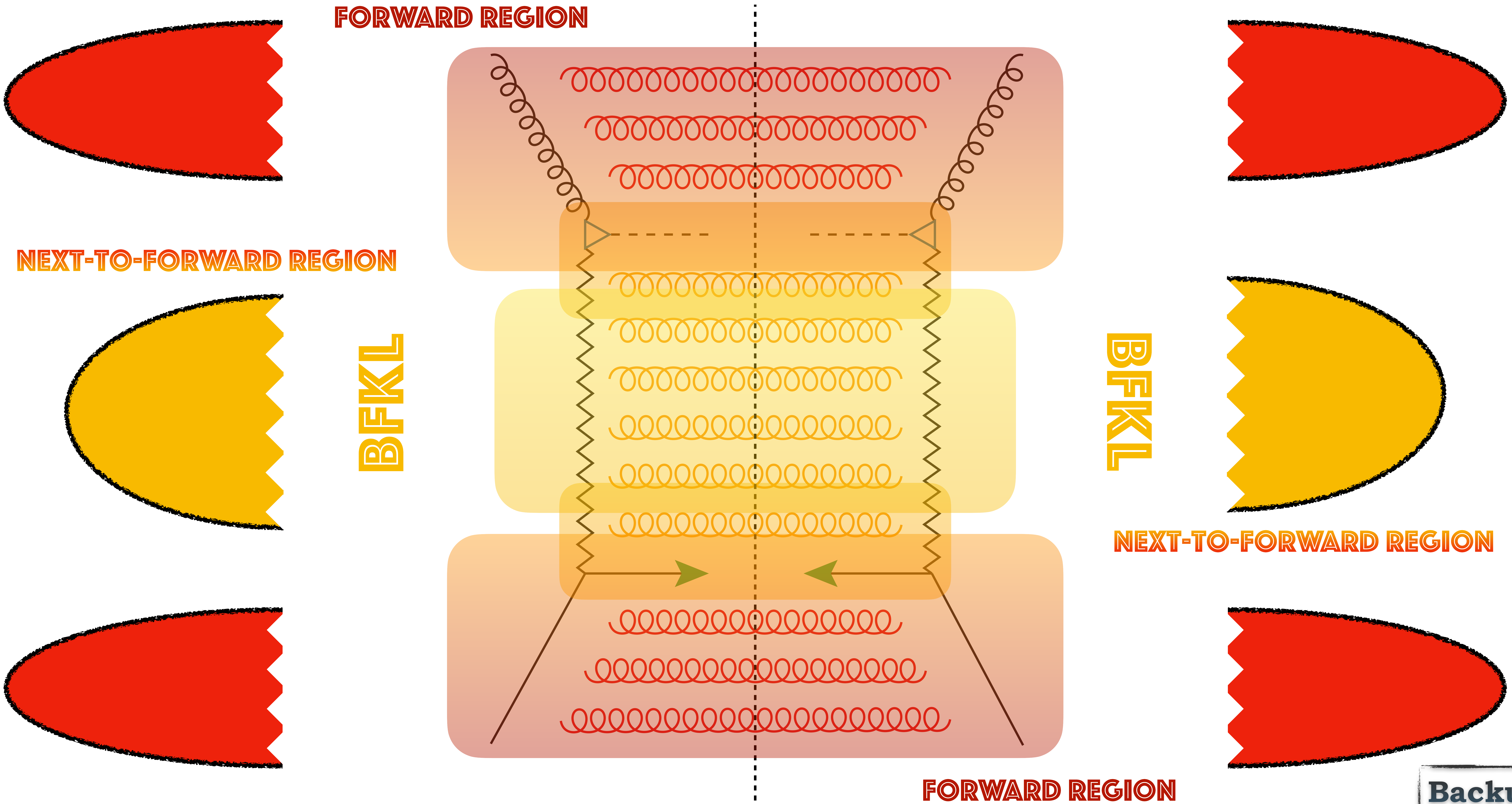
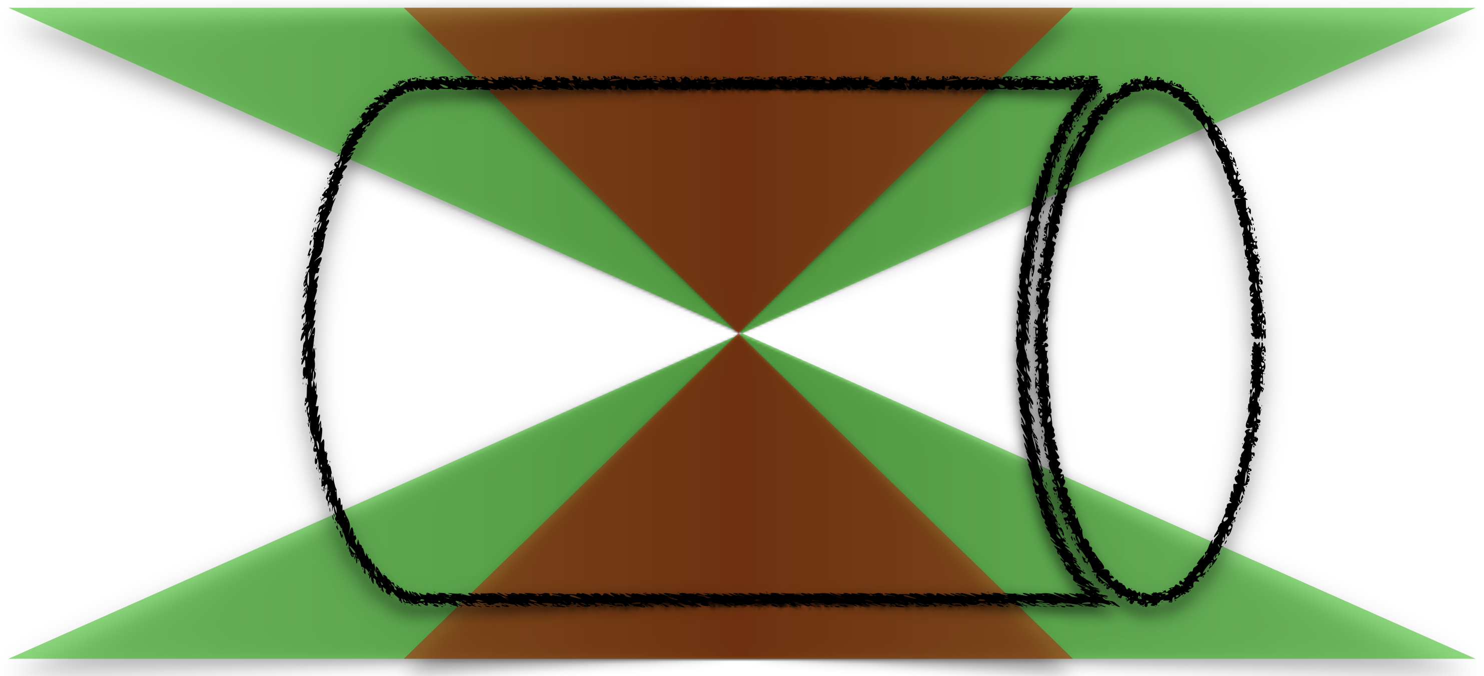


Backup

Ultraforward charm + Higgs production at 14 TeV FPF+ATLAS

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

Backup

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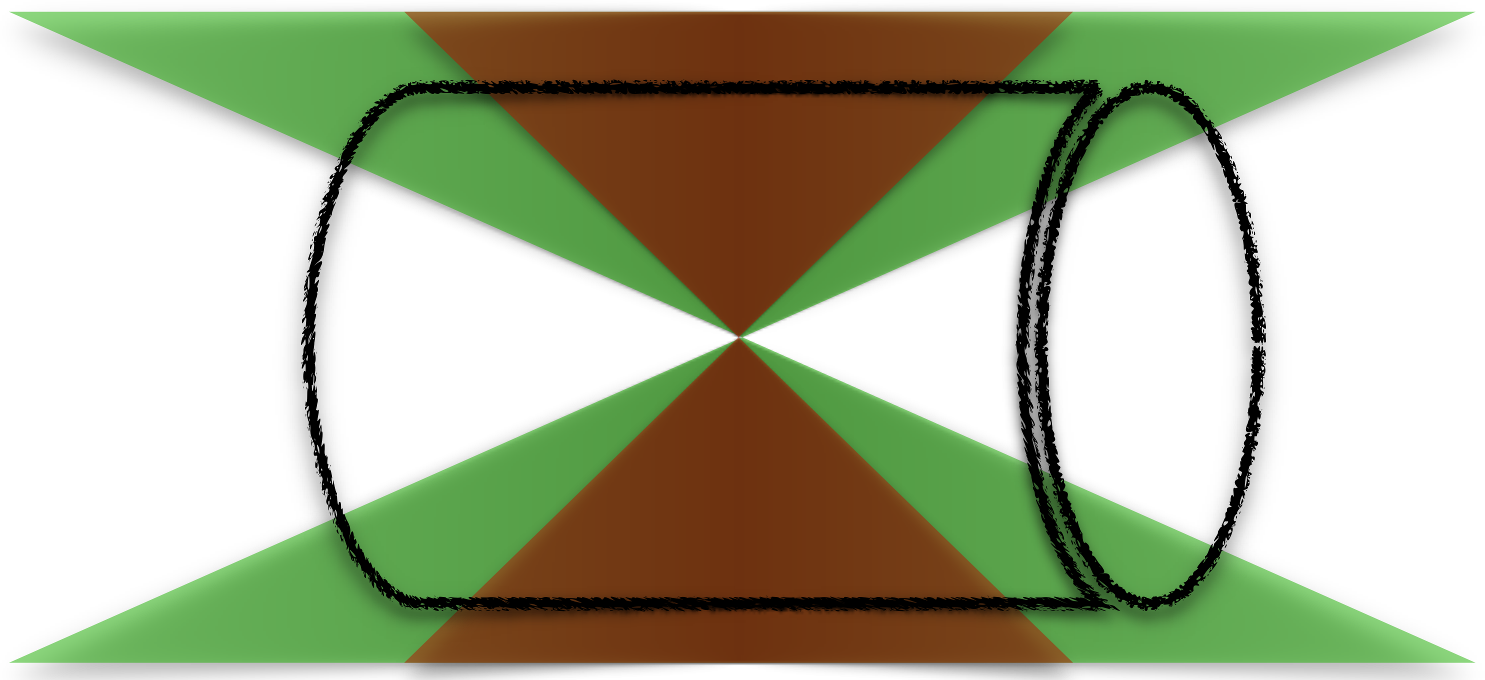


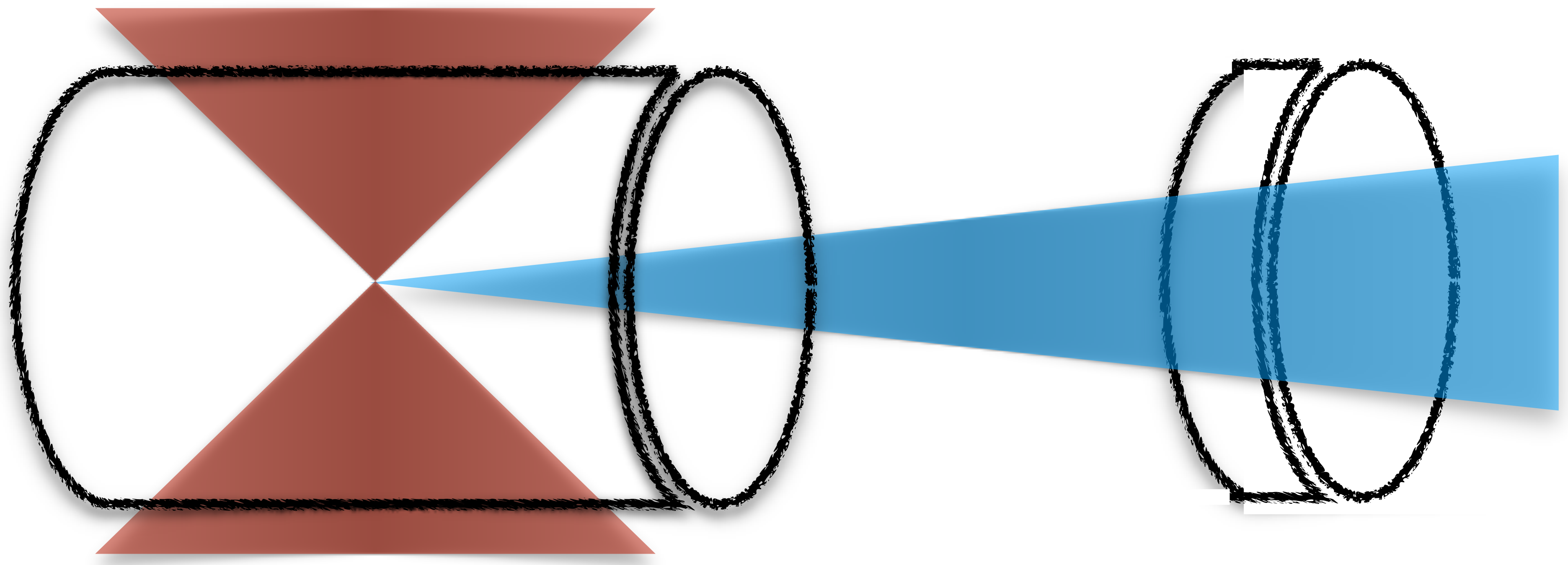
$|y_{\rm jet}| < 4.7$

barrel + endcap

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

barrel

- 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]

Backup

High-energy QCD in ultraforward directions

Backup


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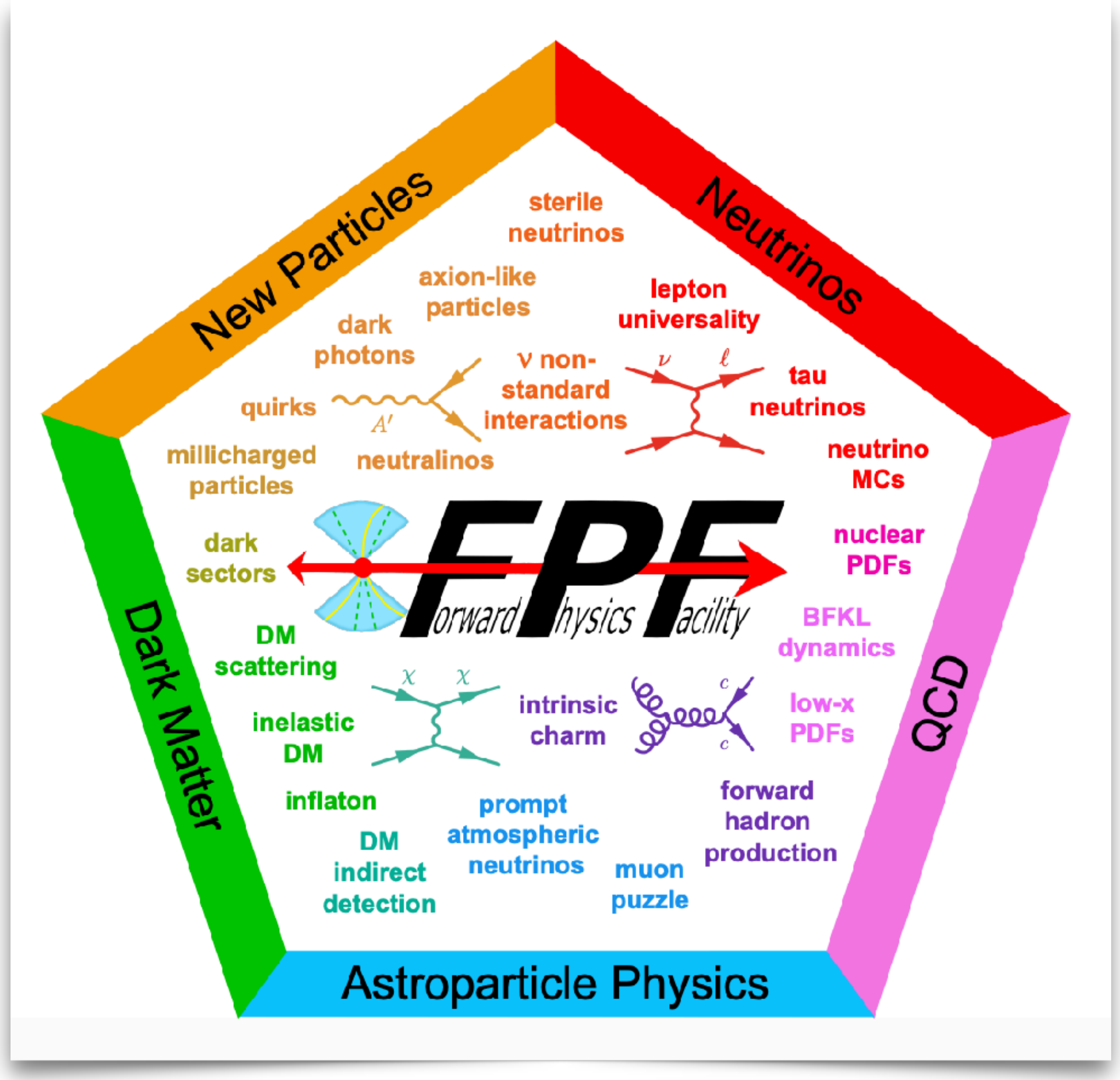
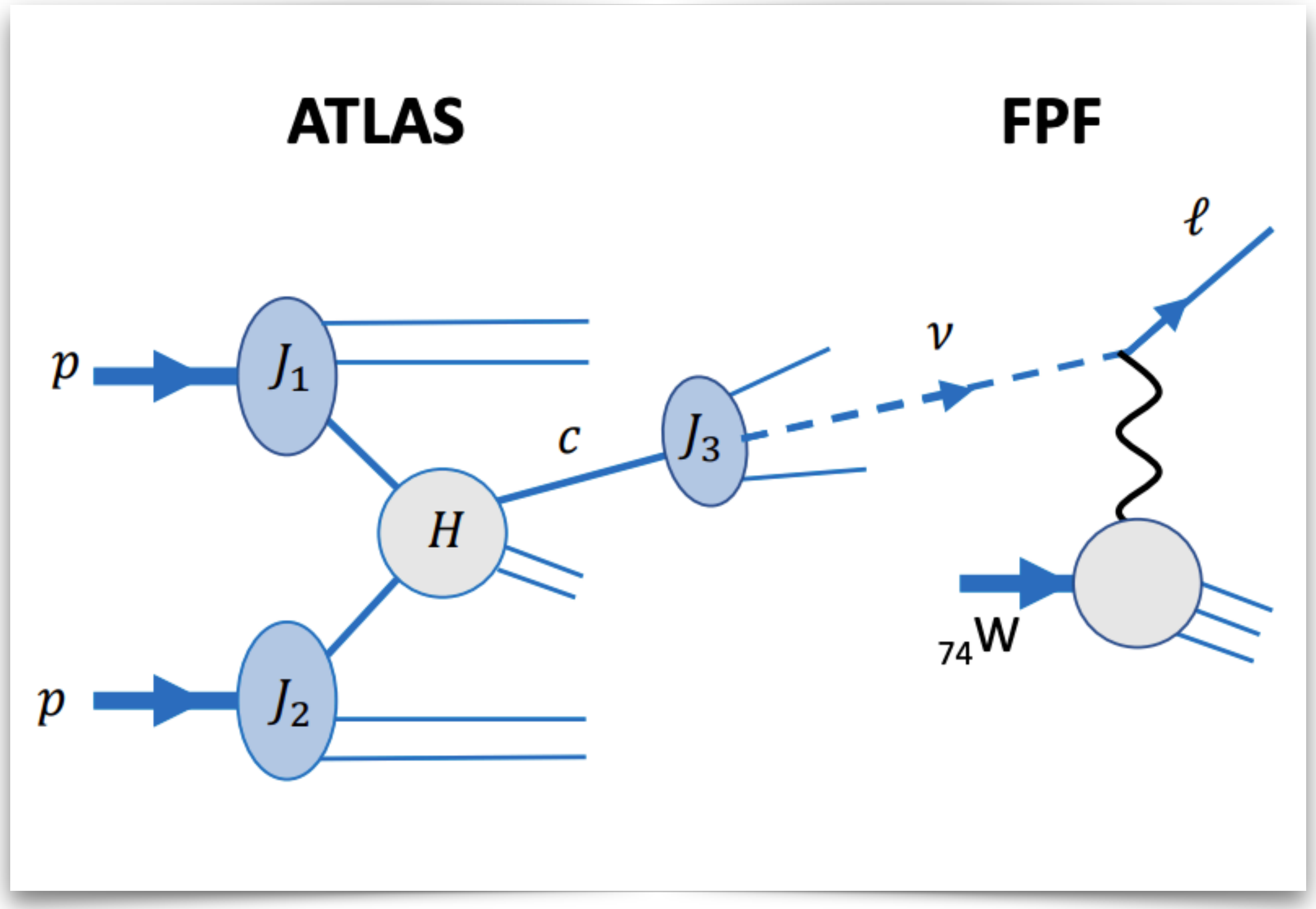
https://doi.org/10.1016/j.physrep.2022.04.004





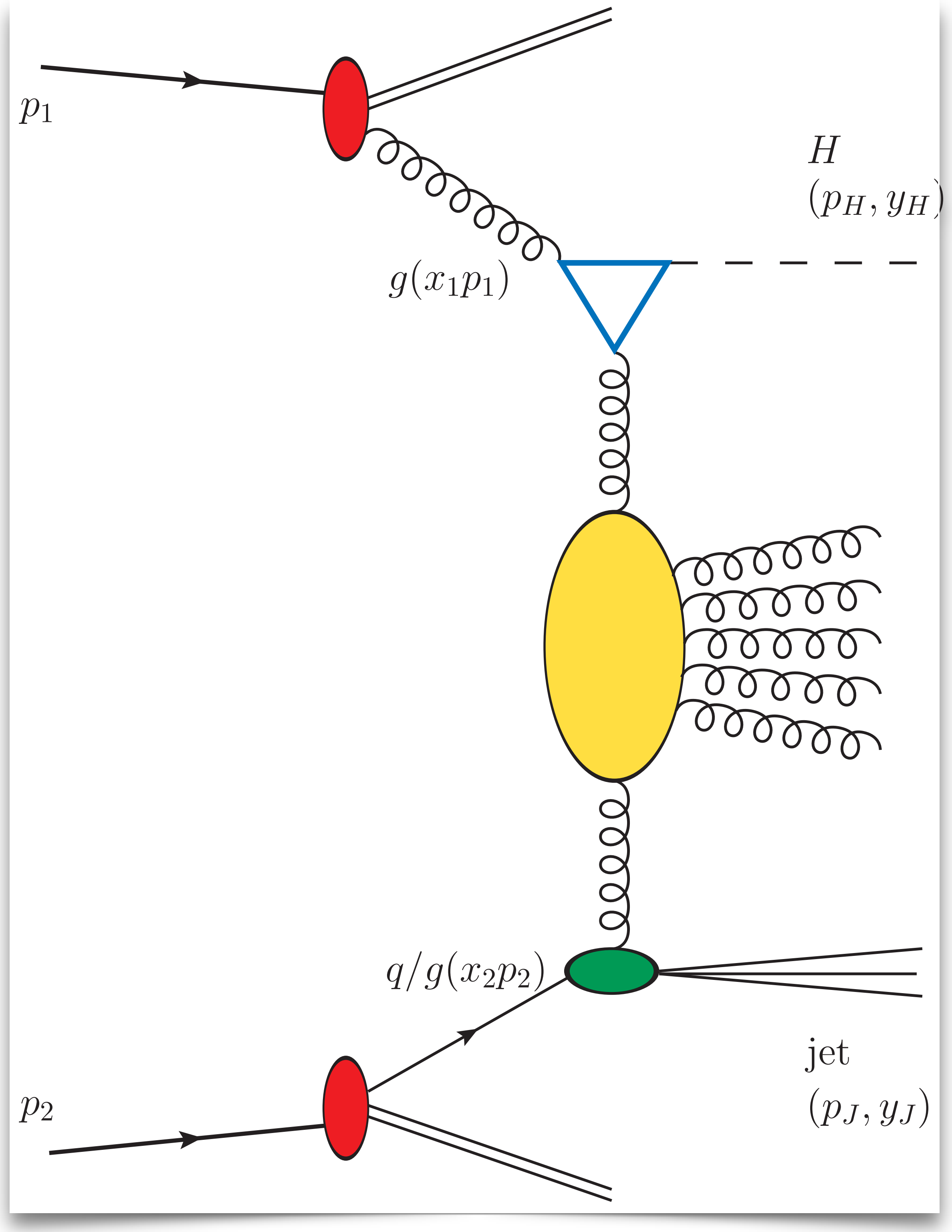
Higgs + jet distributions

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

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

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



Backup

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Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

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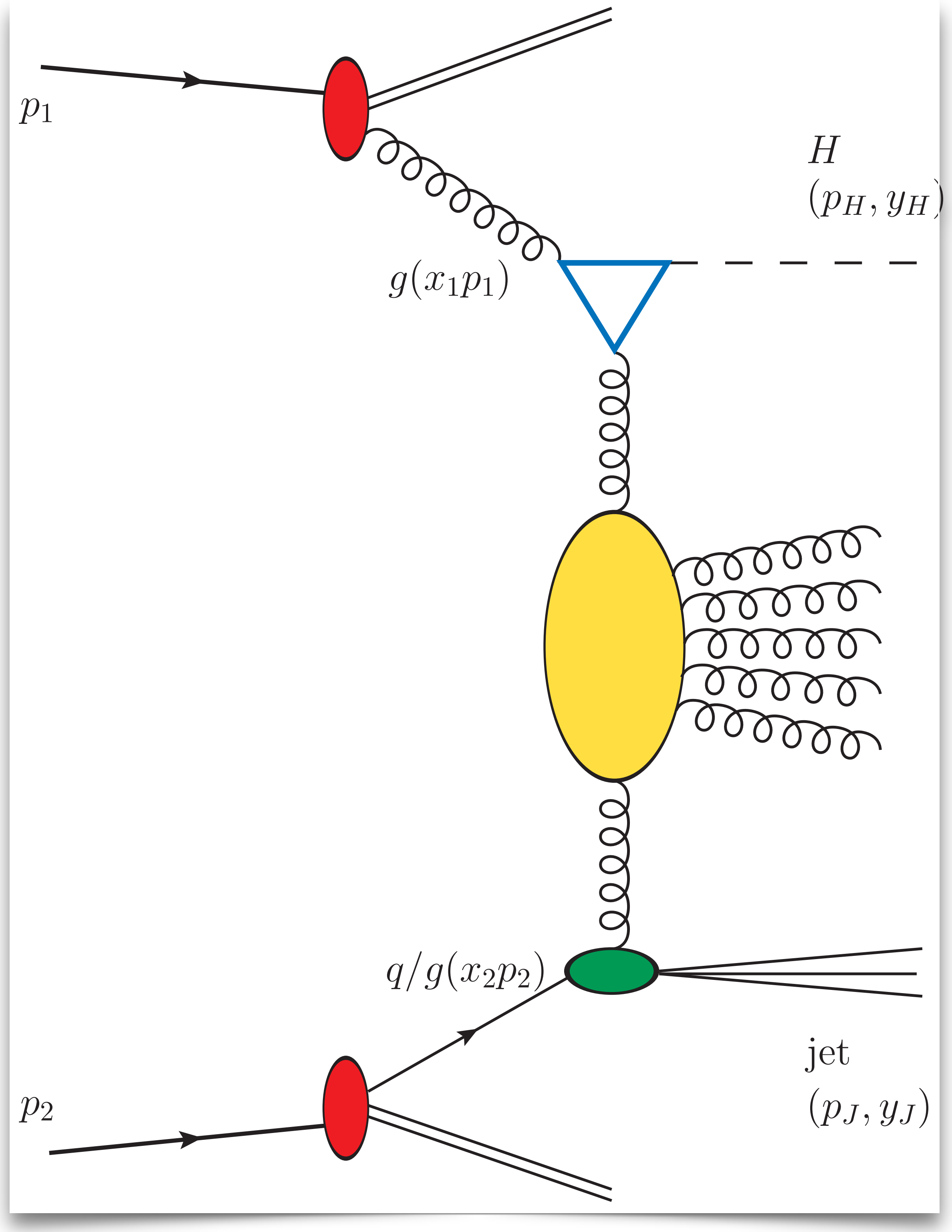

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$

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

BFKL Green's function

Backup

Inclusive Higgs + jet at the LHC

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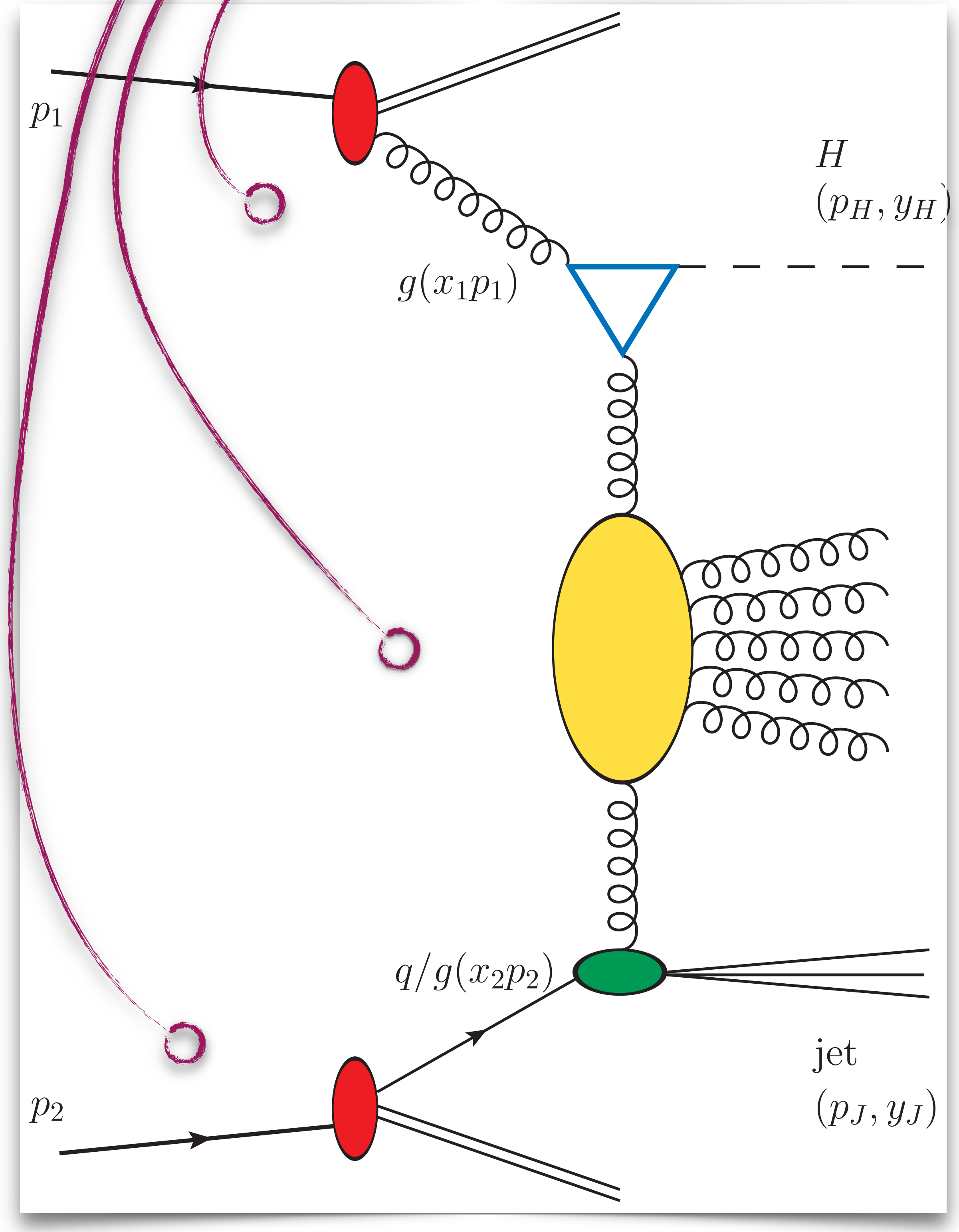

$\mu_{F,R} \sim M_{H,\perp}$

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

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

NLO*

NLL

NLO*

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

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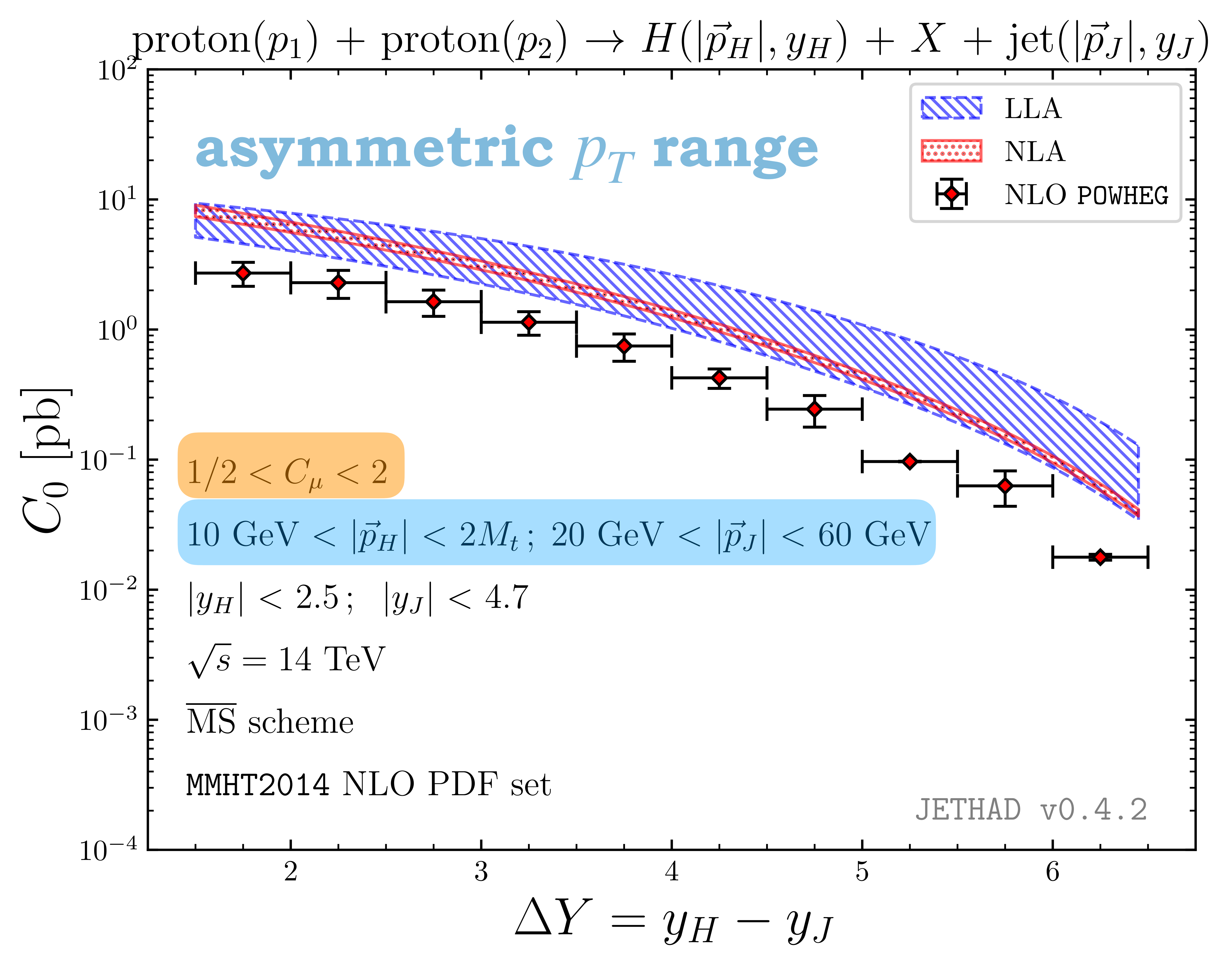
BFKL Green's function

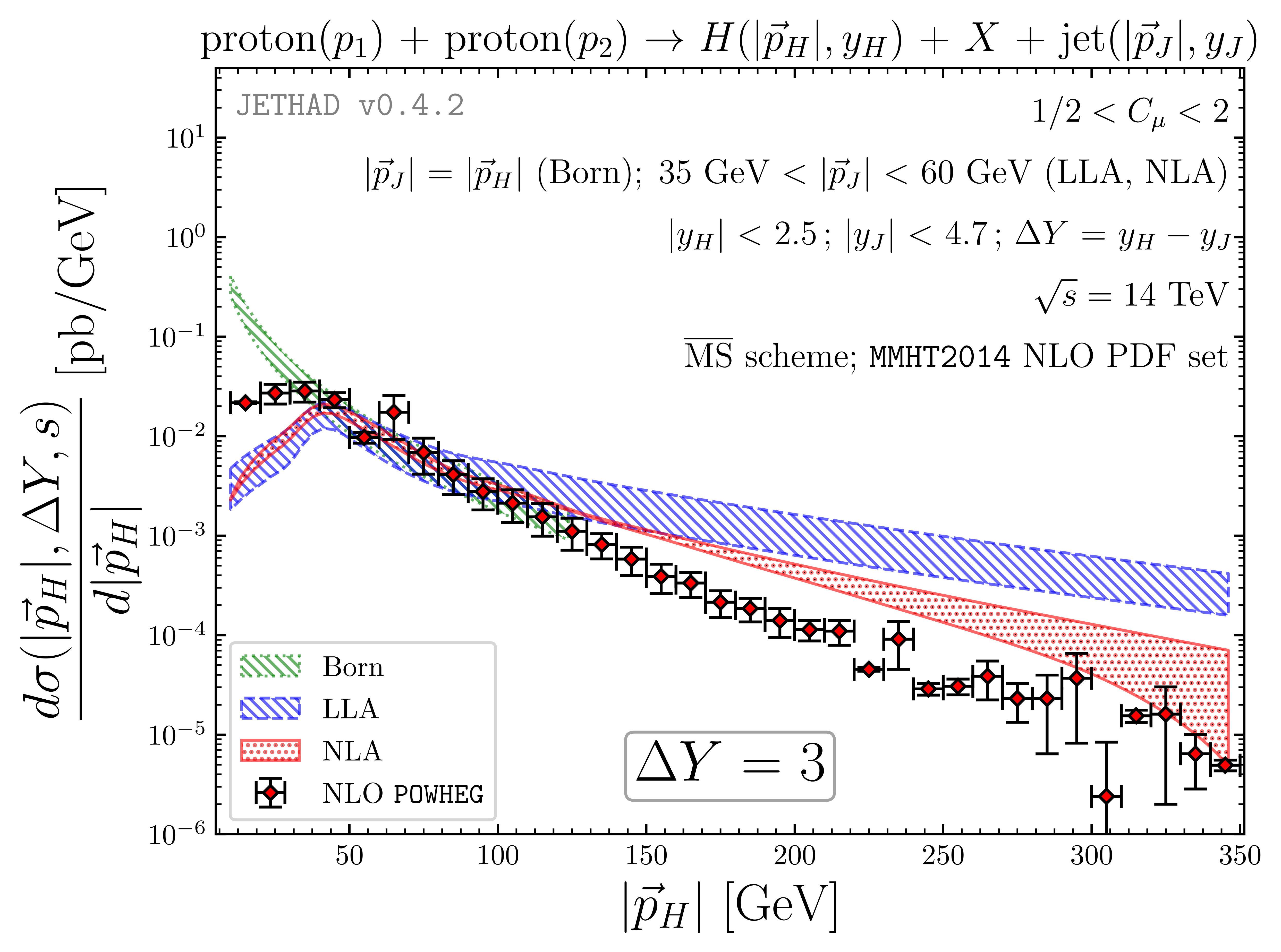
Backup

The Higgs + jet spectrum in hybrid factorization

ΔY spectrum



p_H spectrum



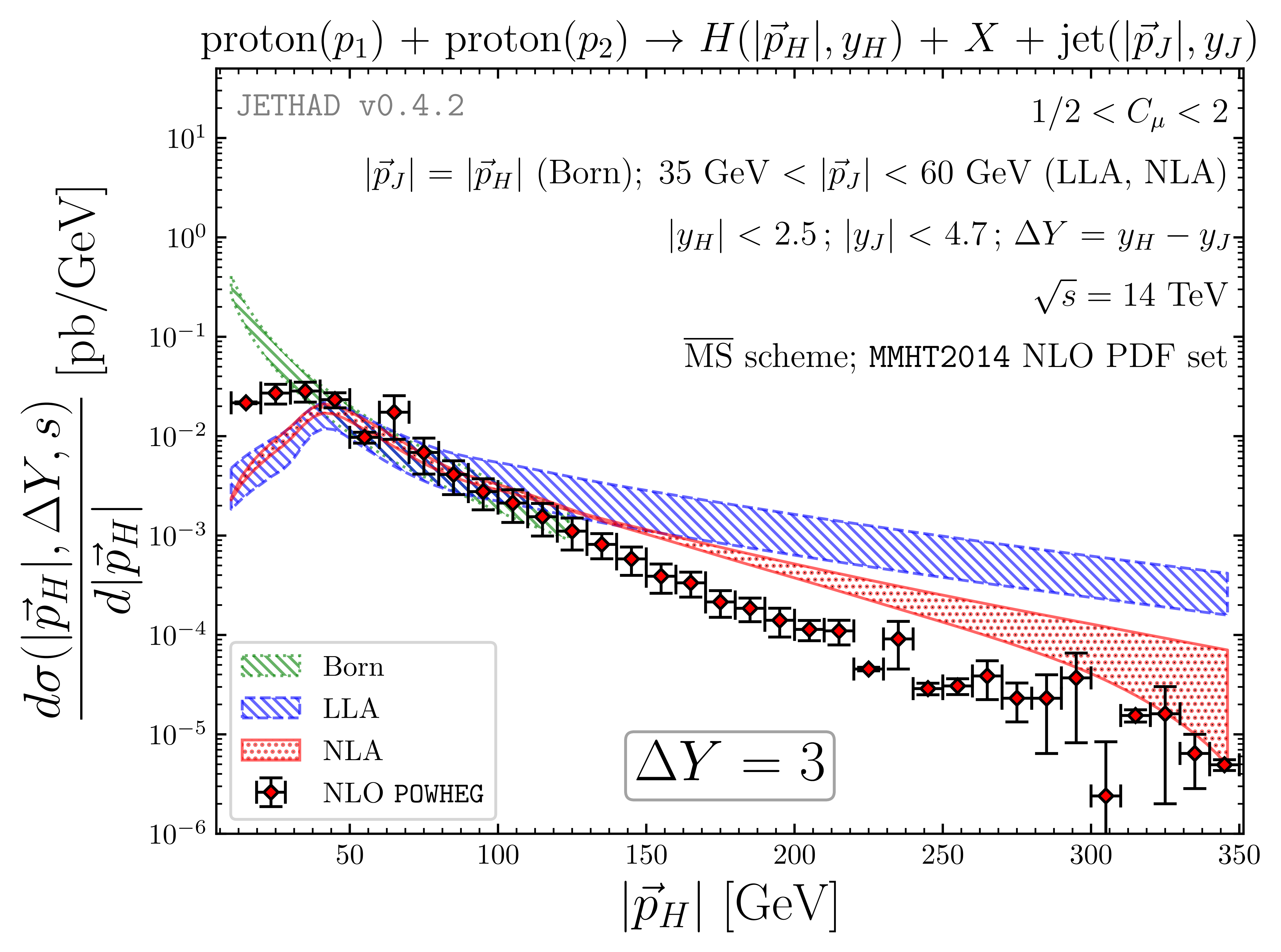
(in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

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

Backup

Higgs transverse-momentum distribution

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



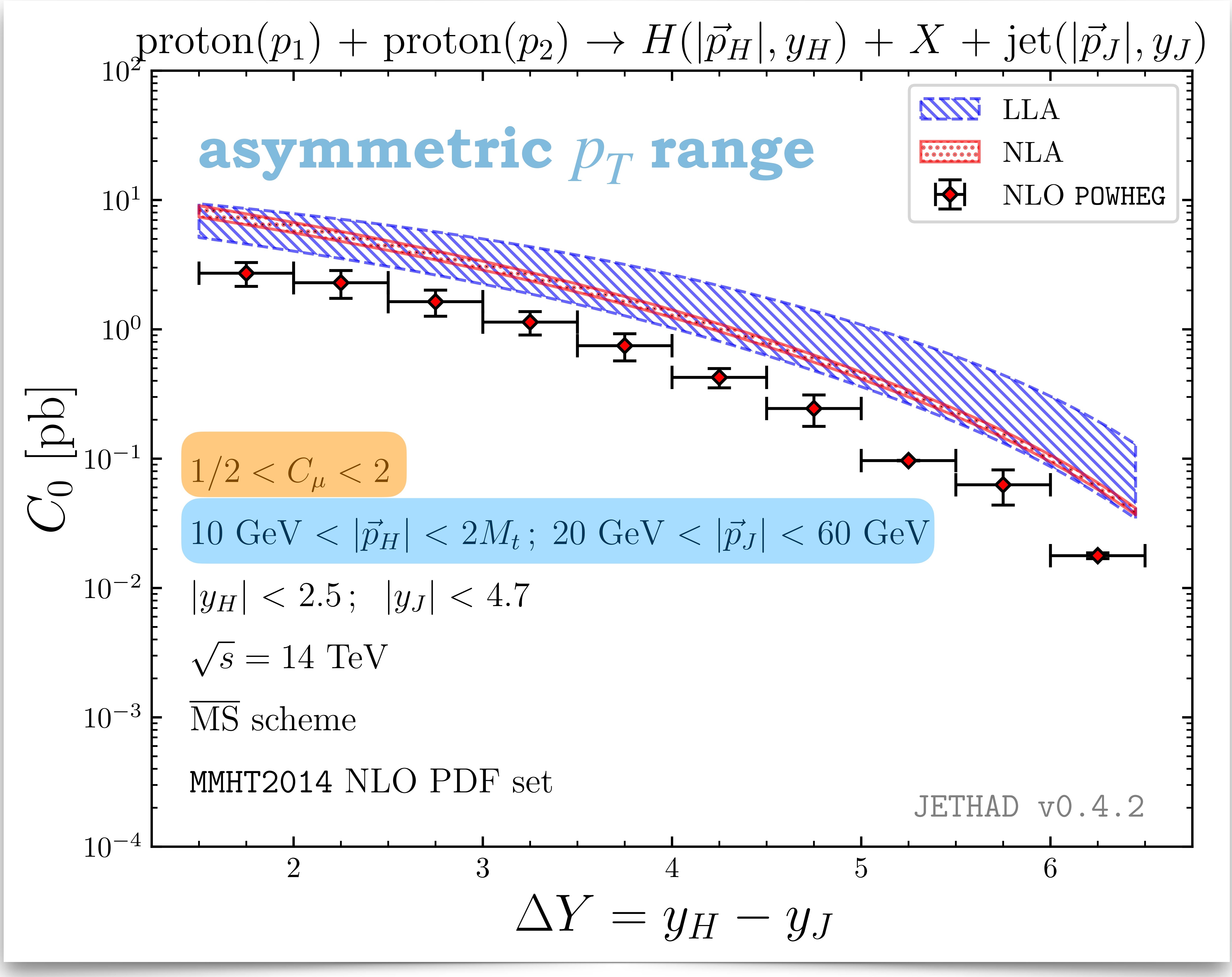
- HE resummation from JETHAD
- Comparison with fixed-order POWHEG
- Distributions stable under NLL corrections

Backup

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

ΔY-distribution

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



Backup

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

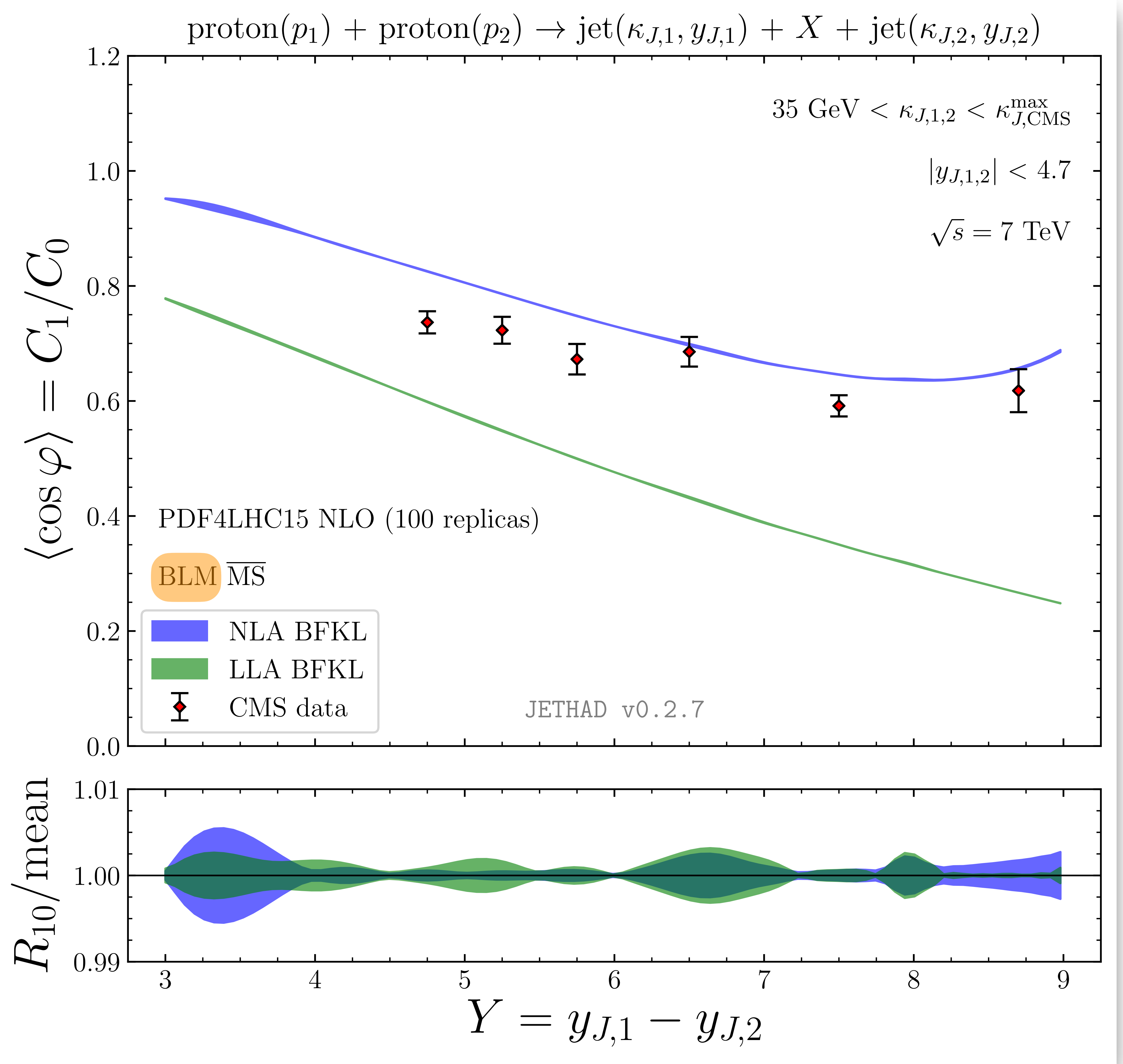
Angular correlations

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

Mueller-Navelet jets

[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

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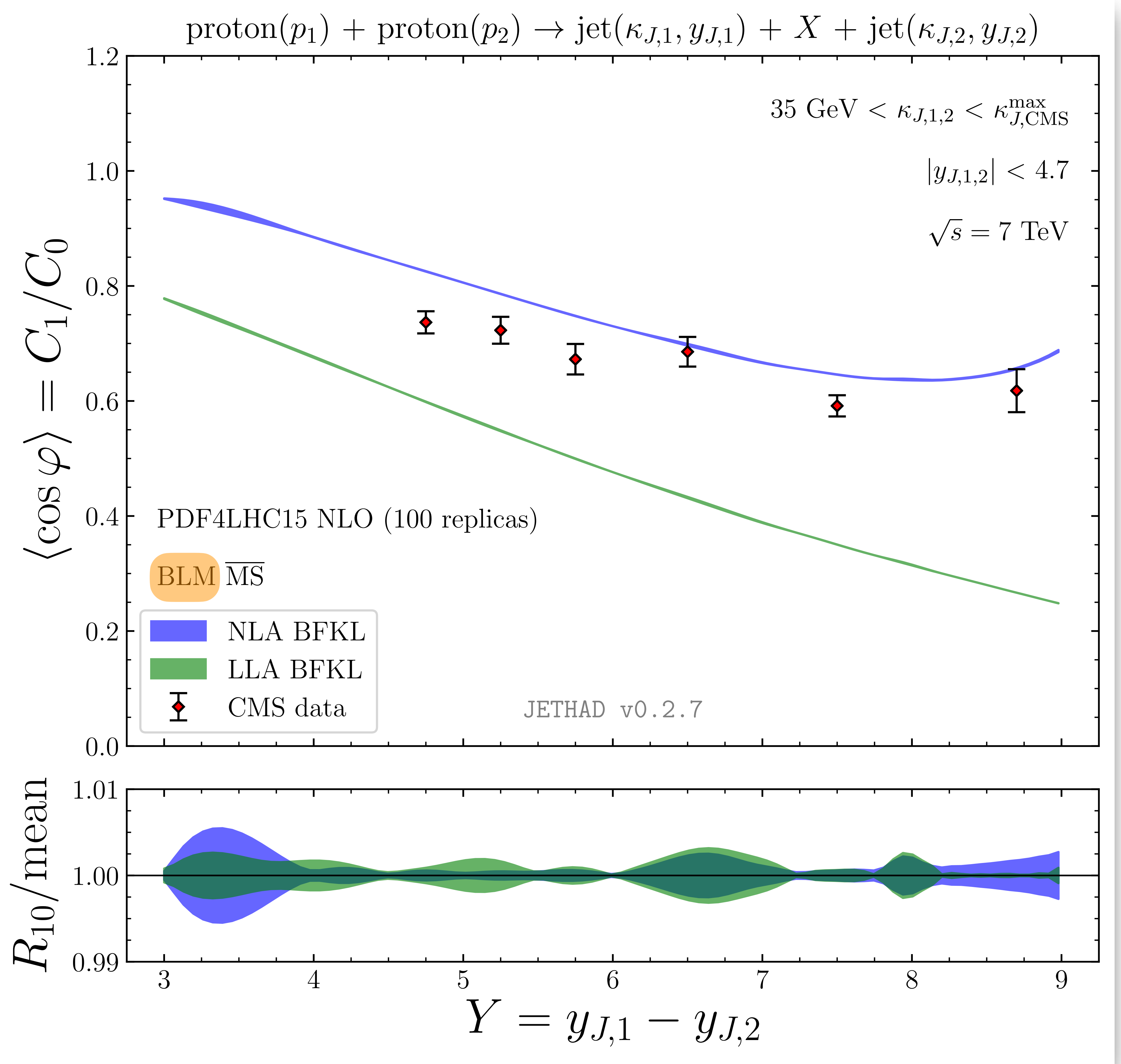

Higgs + jet

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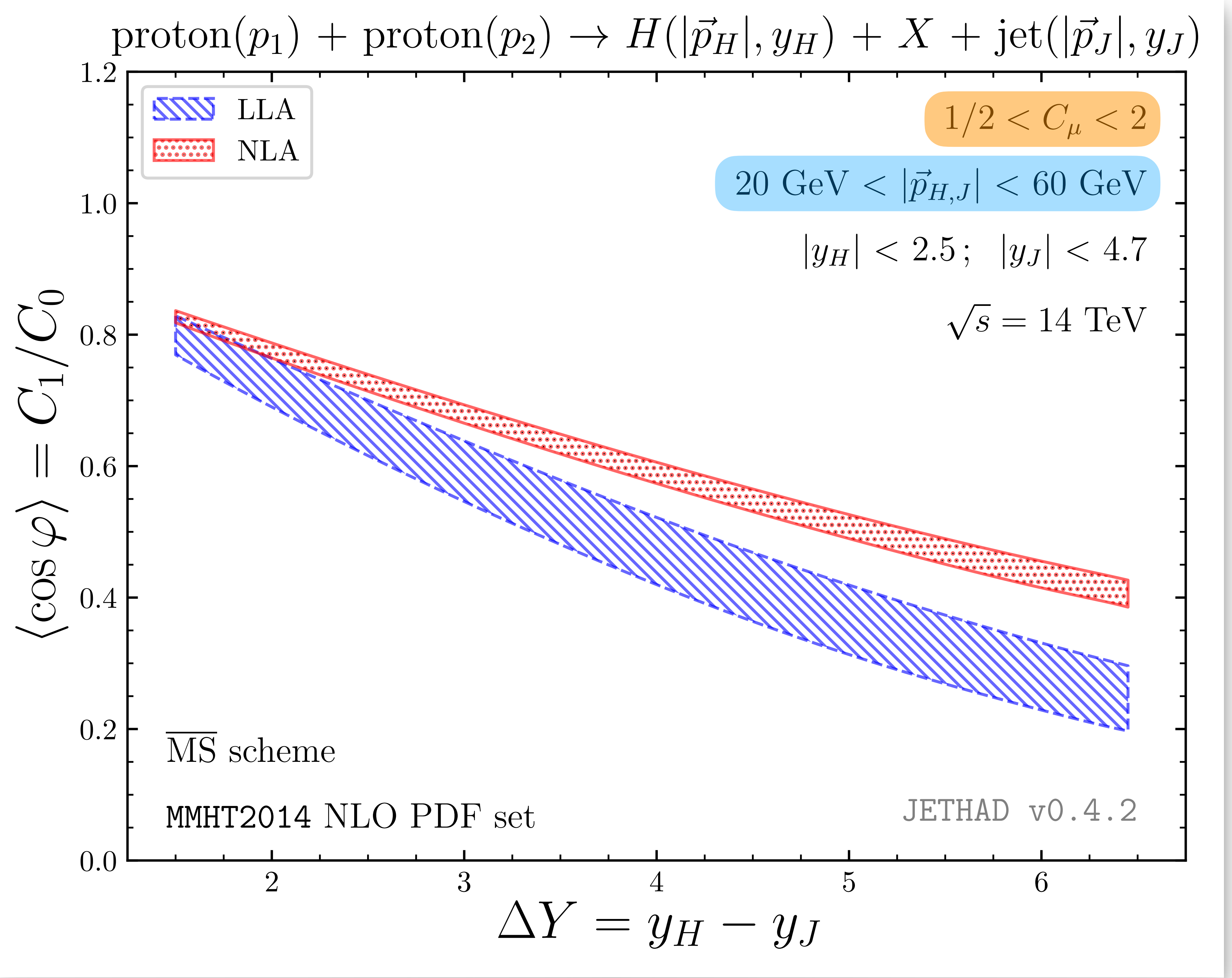
(NLO Higgs impact factor) [F. G. C. et al., under review (2022)]



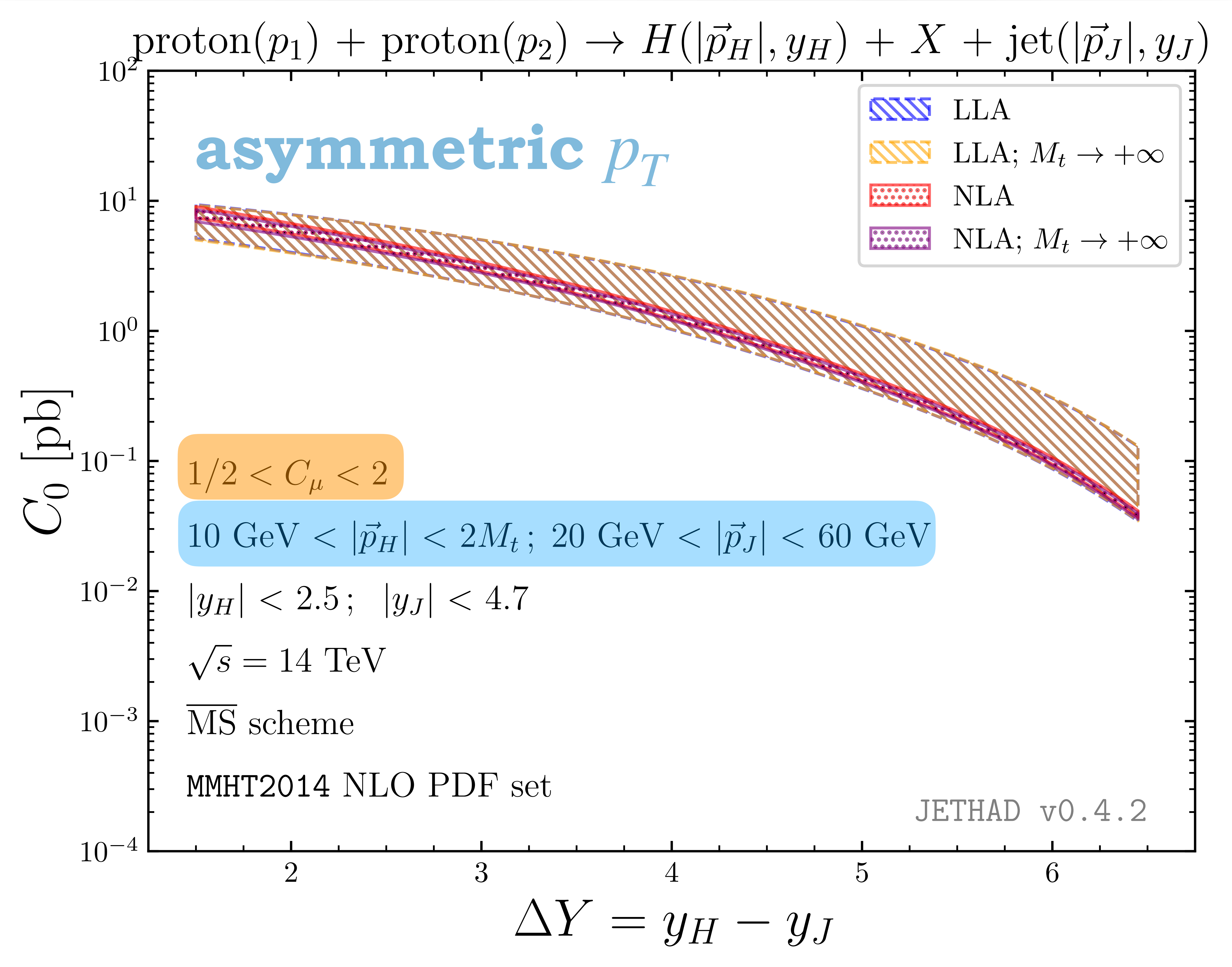
natural scales

symmetric p_T range

Backup

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]

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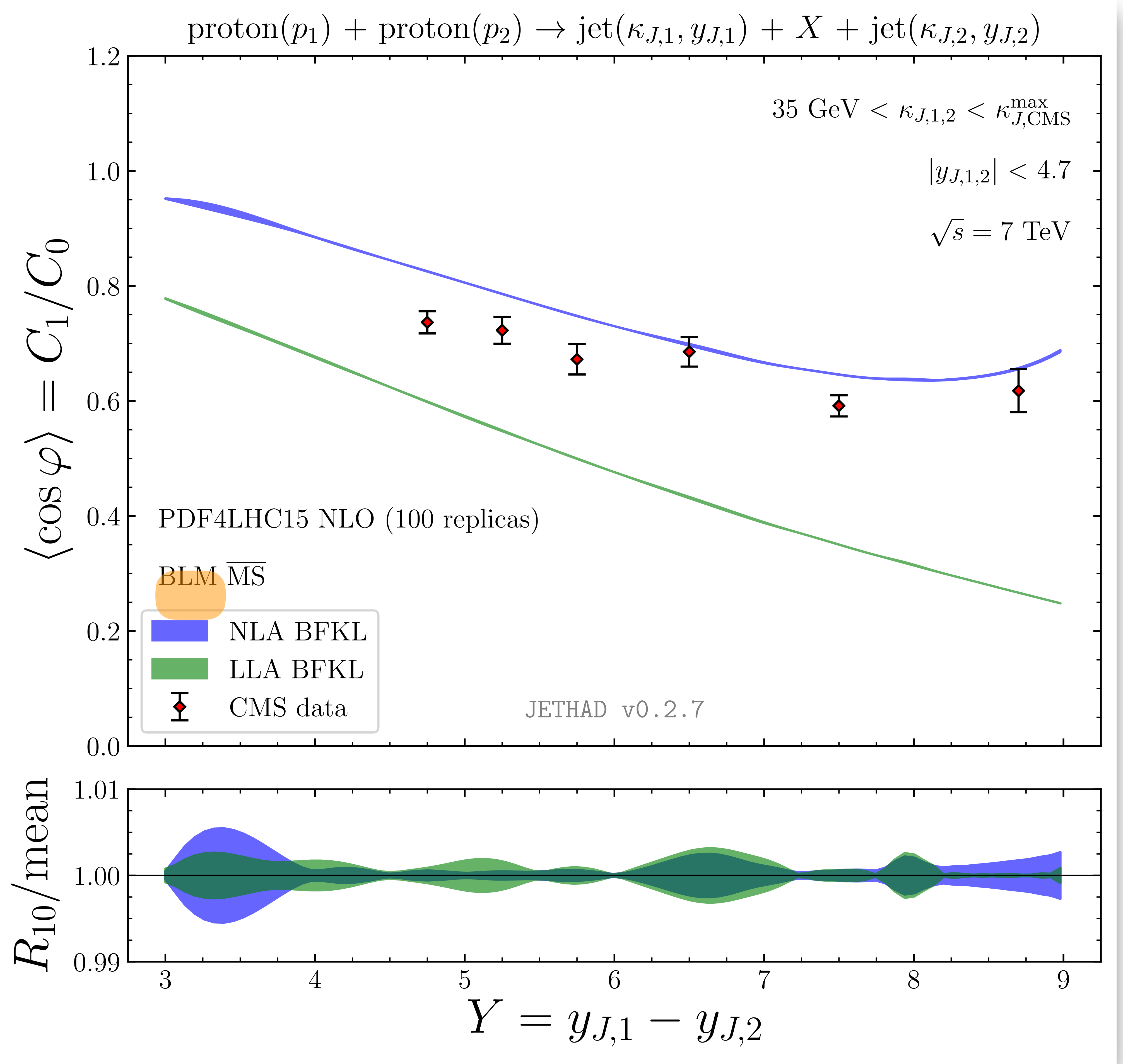

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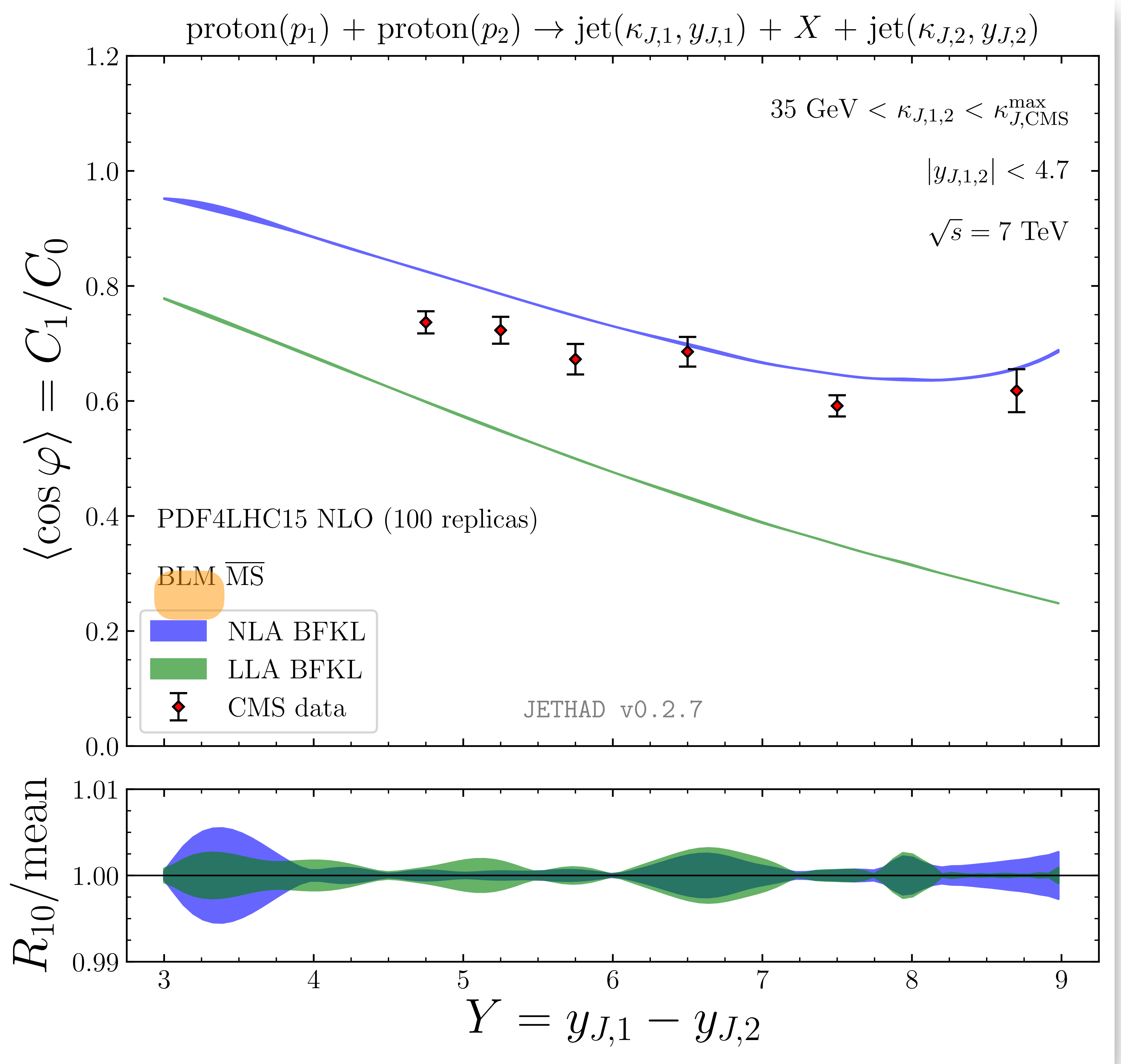

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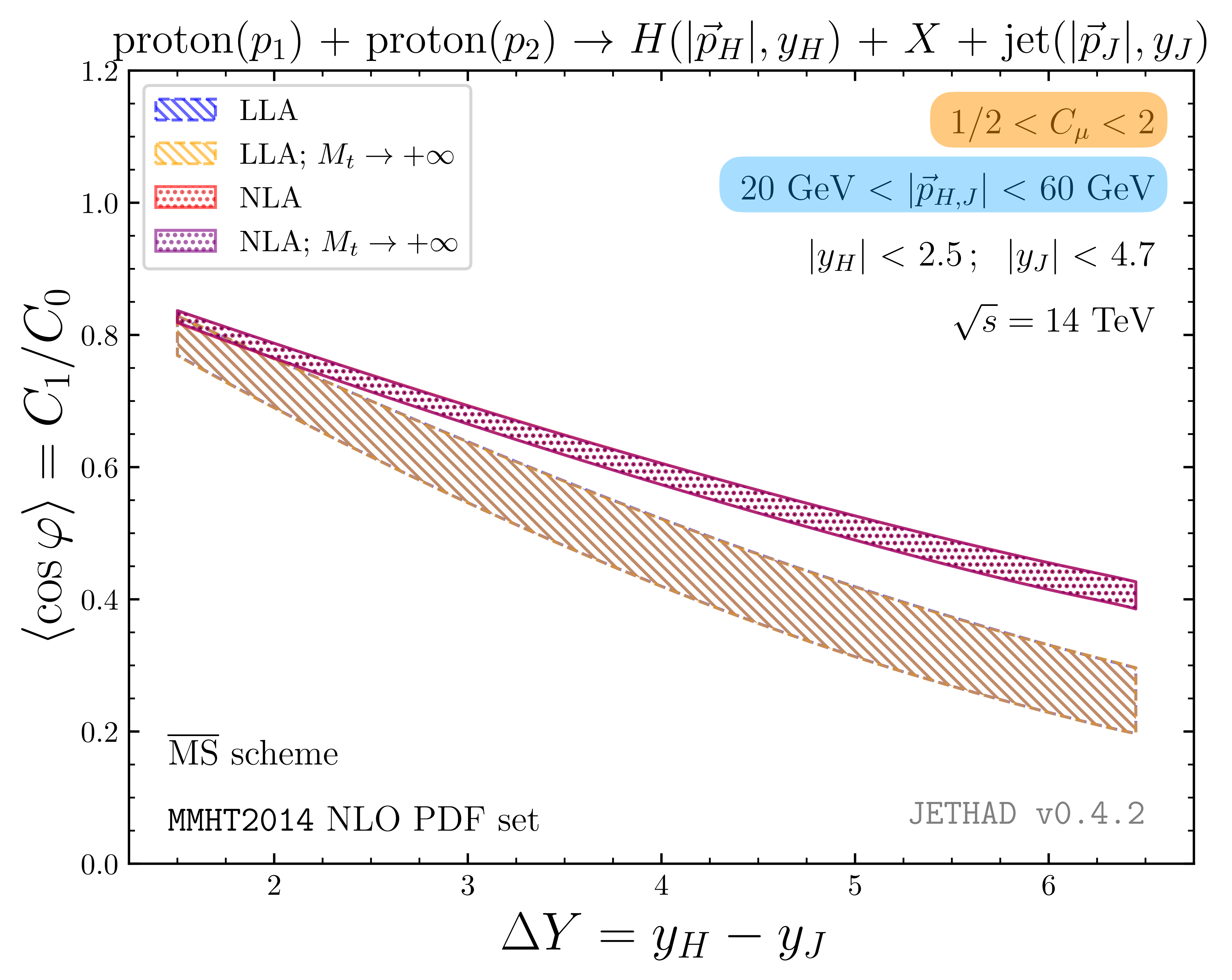
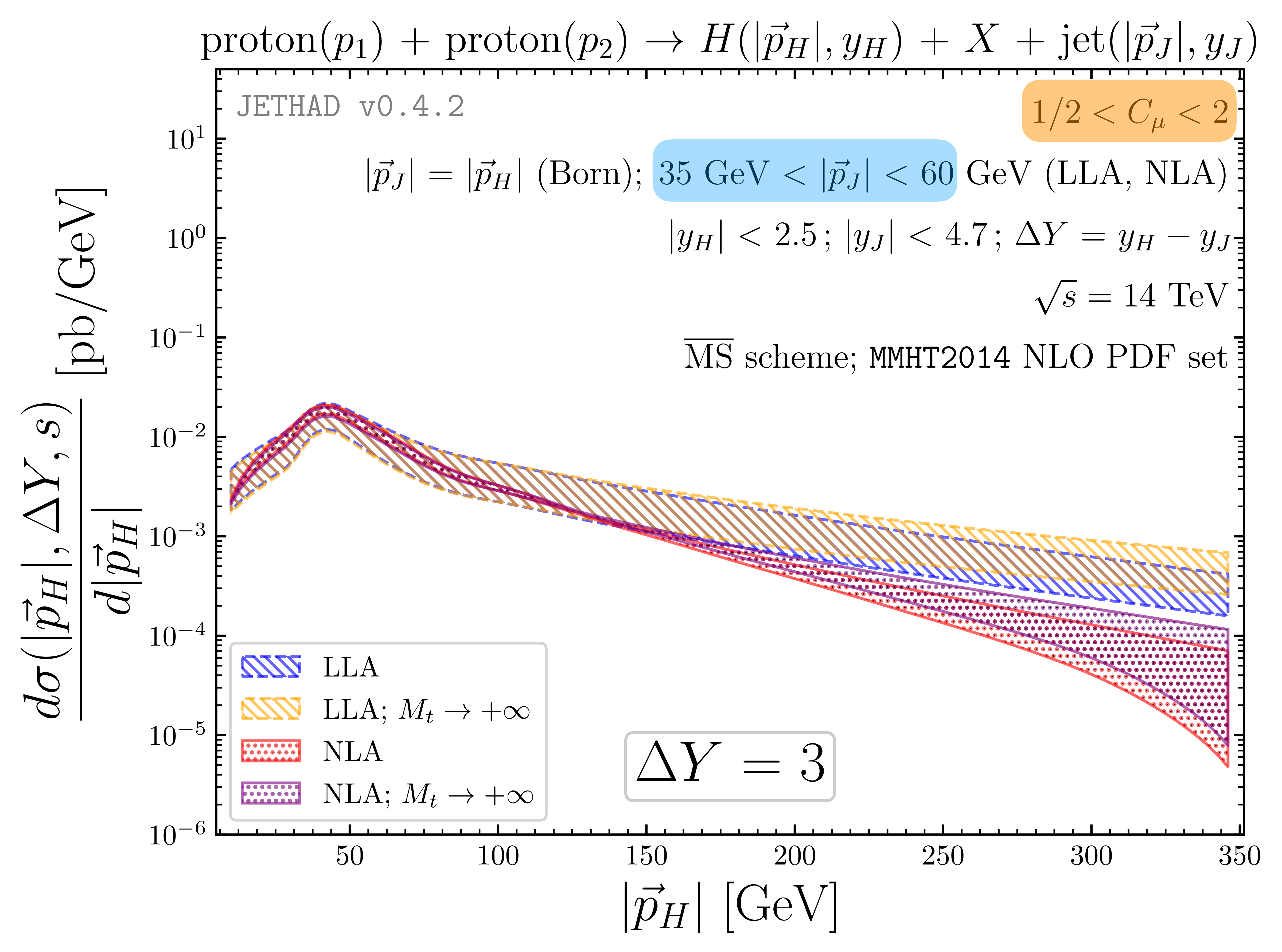


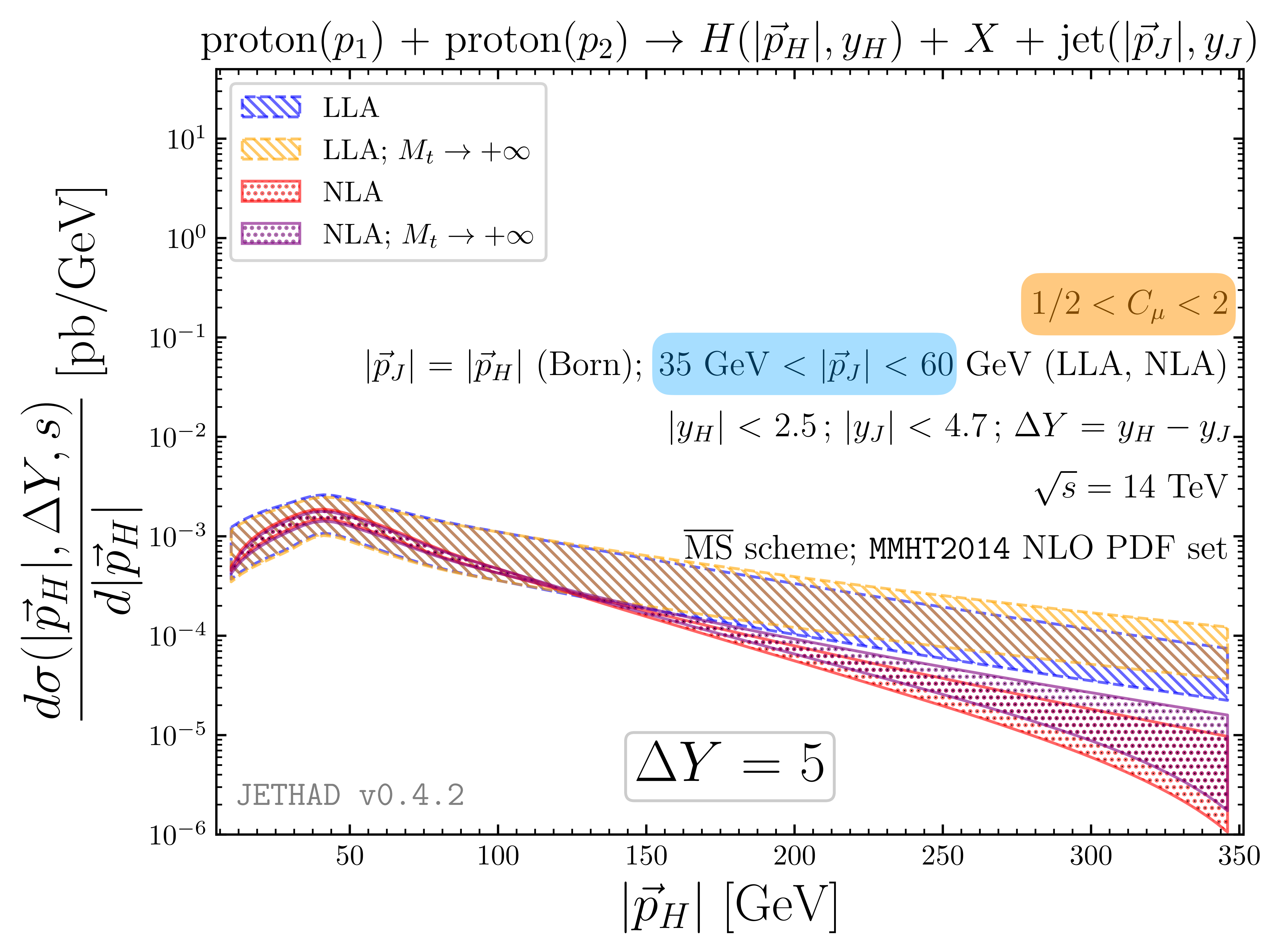
natural scales

symmetric p_T range

Backup

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



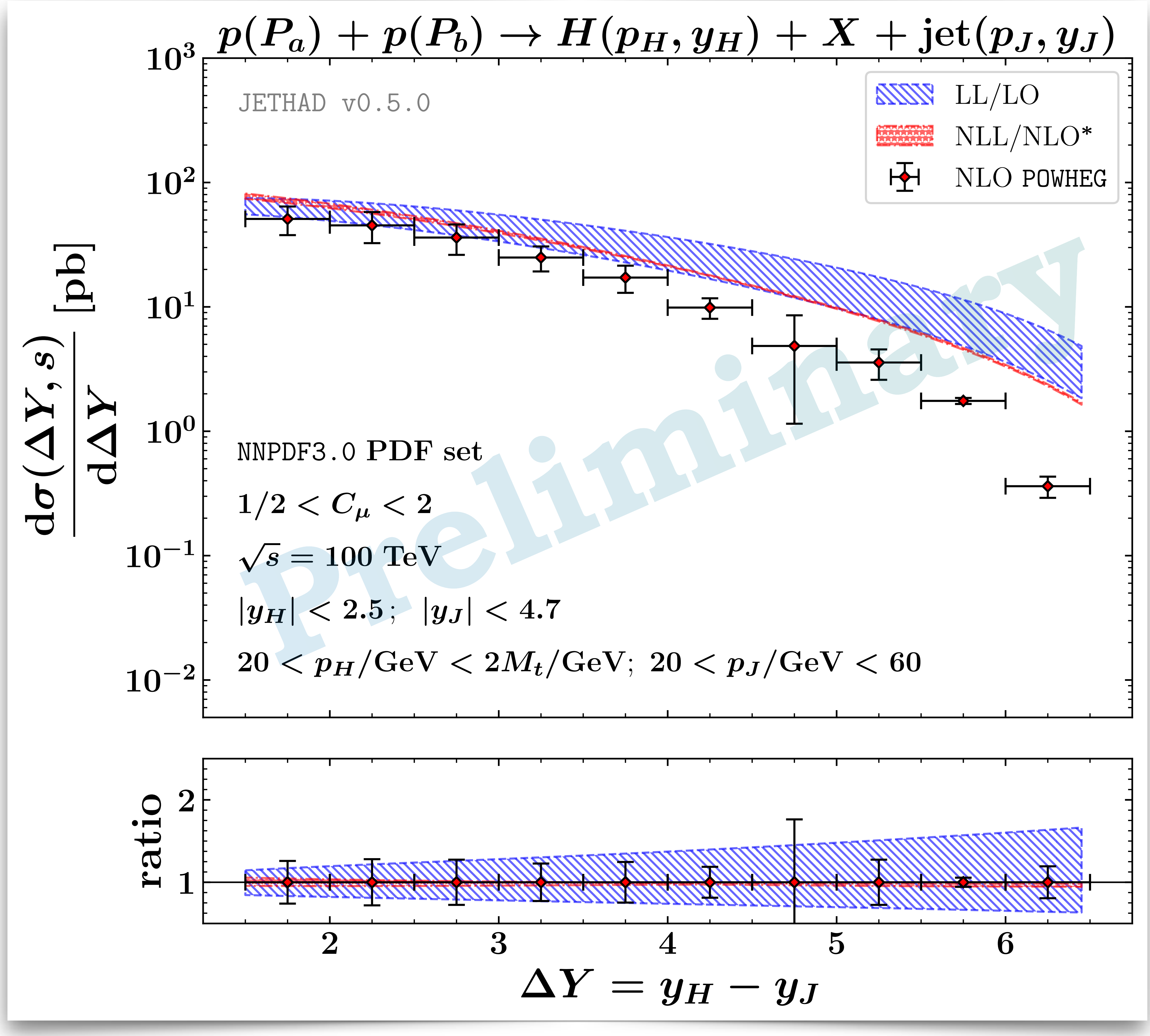


[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Backup

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

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



Backup

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

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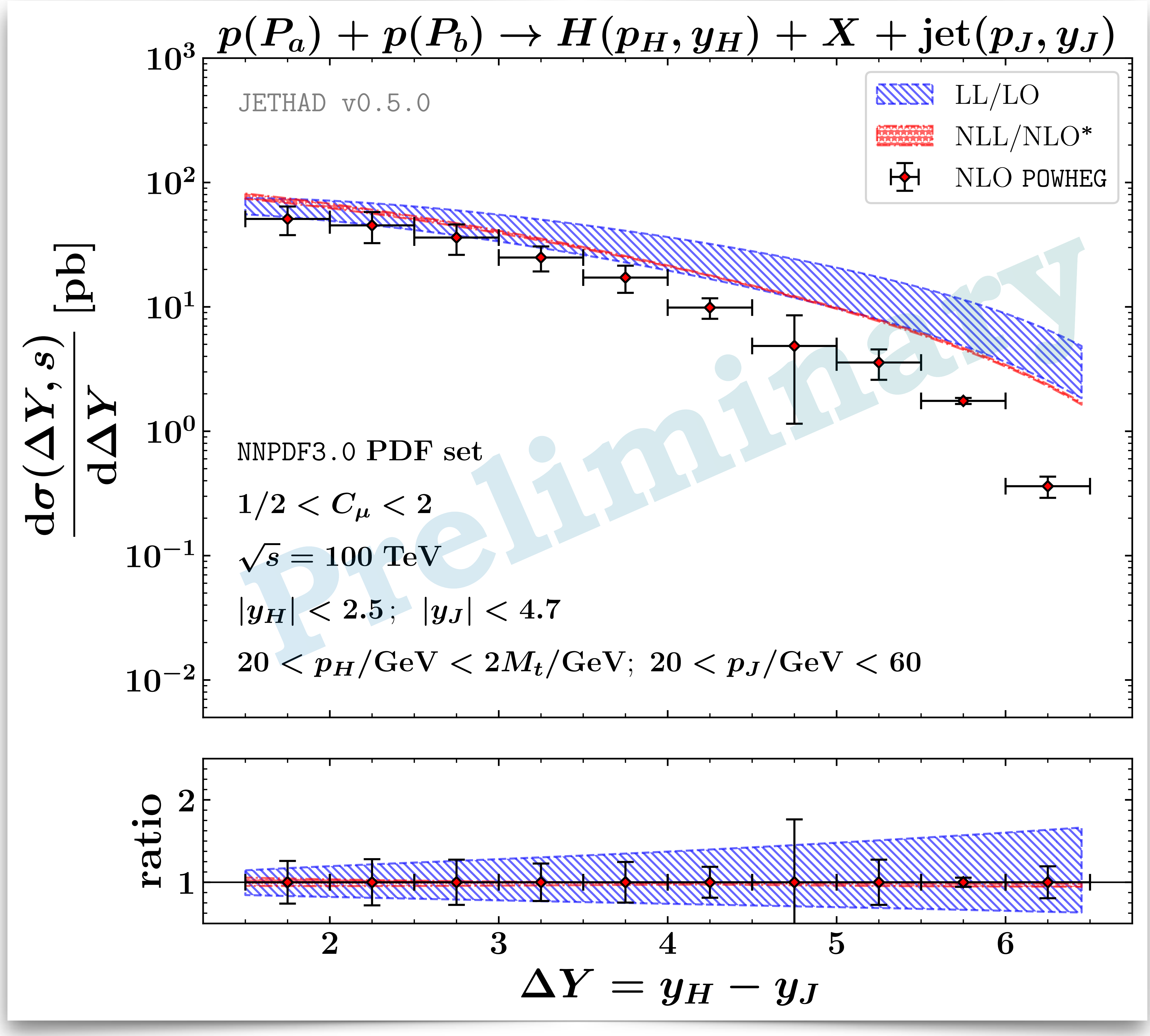
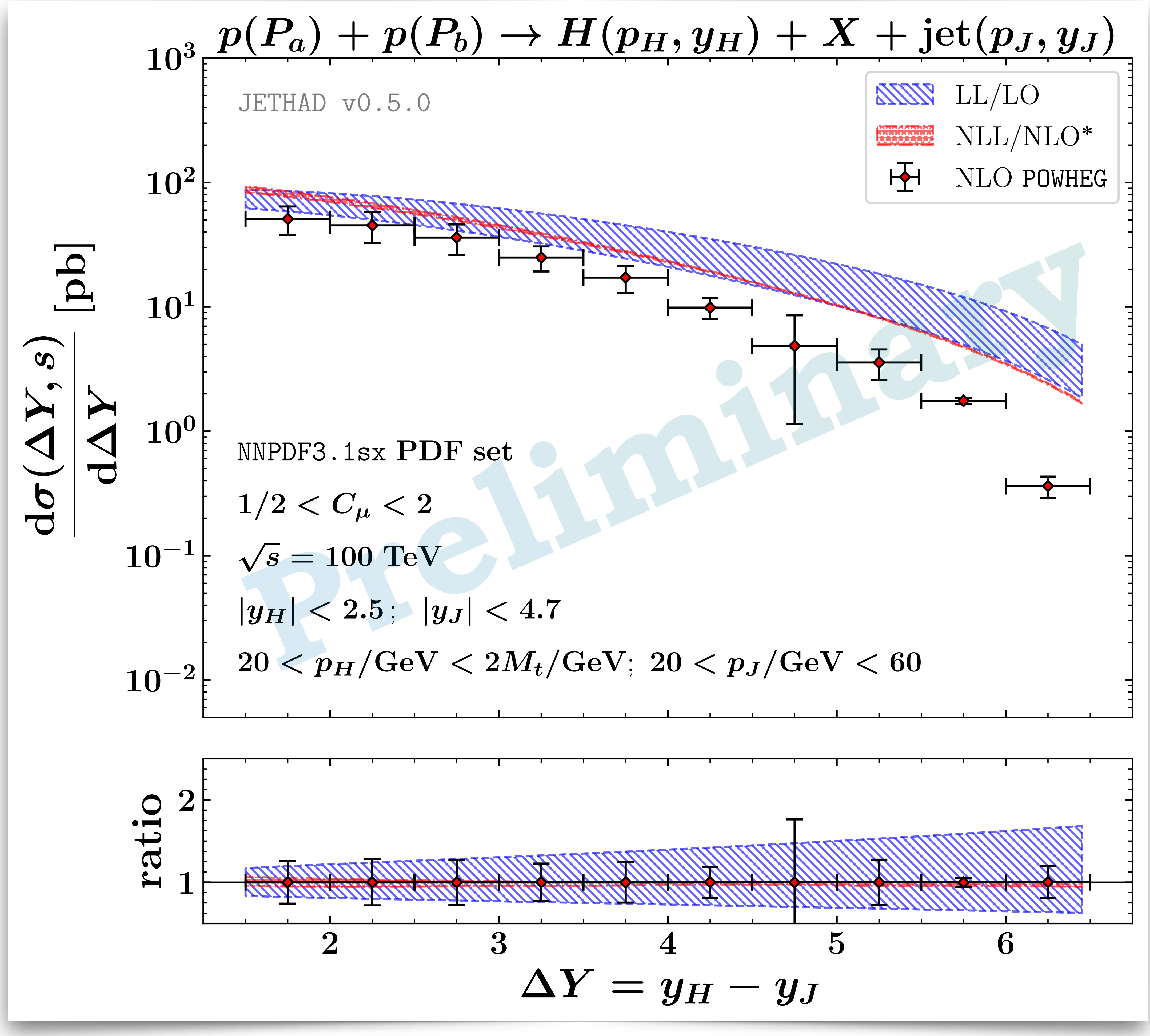


High-energy resummation + **NNPDF3.1sx**

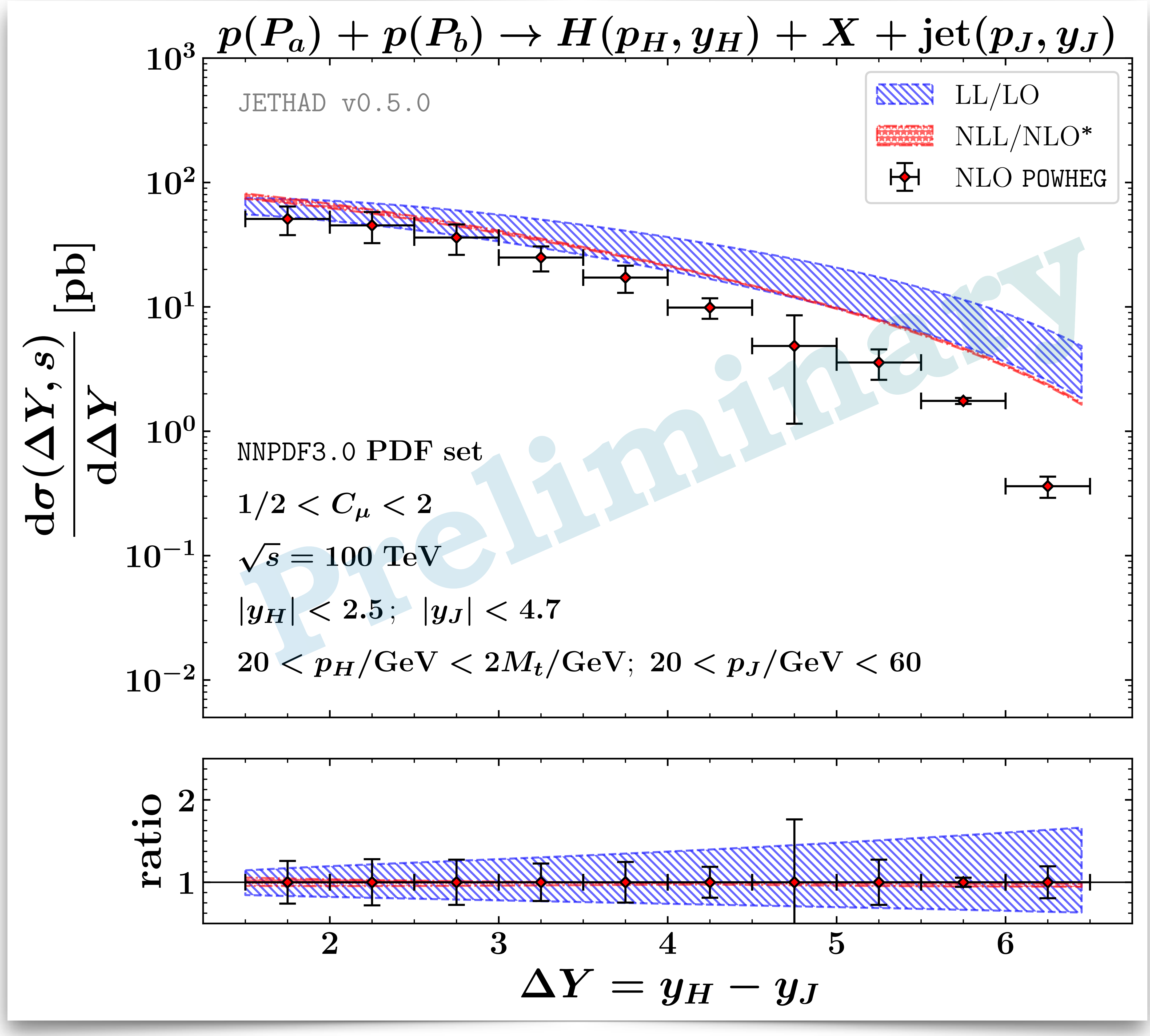


Backup

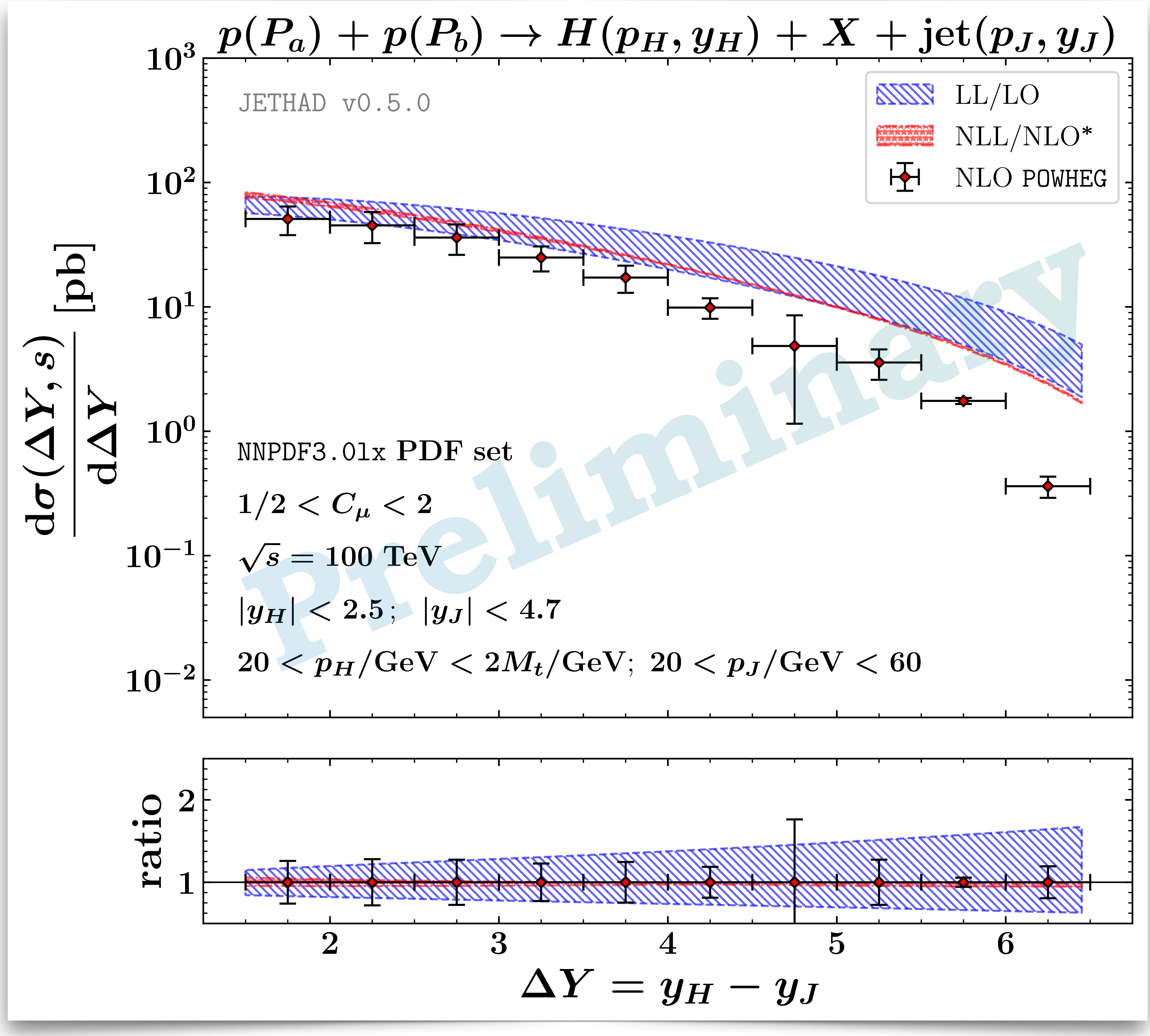
Small-x resummation on PDFs $\Rightarrow$ $+(13.5 \div 2.10)\,\%$ @NLL/NLO*

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

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



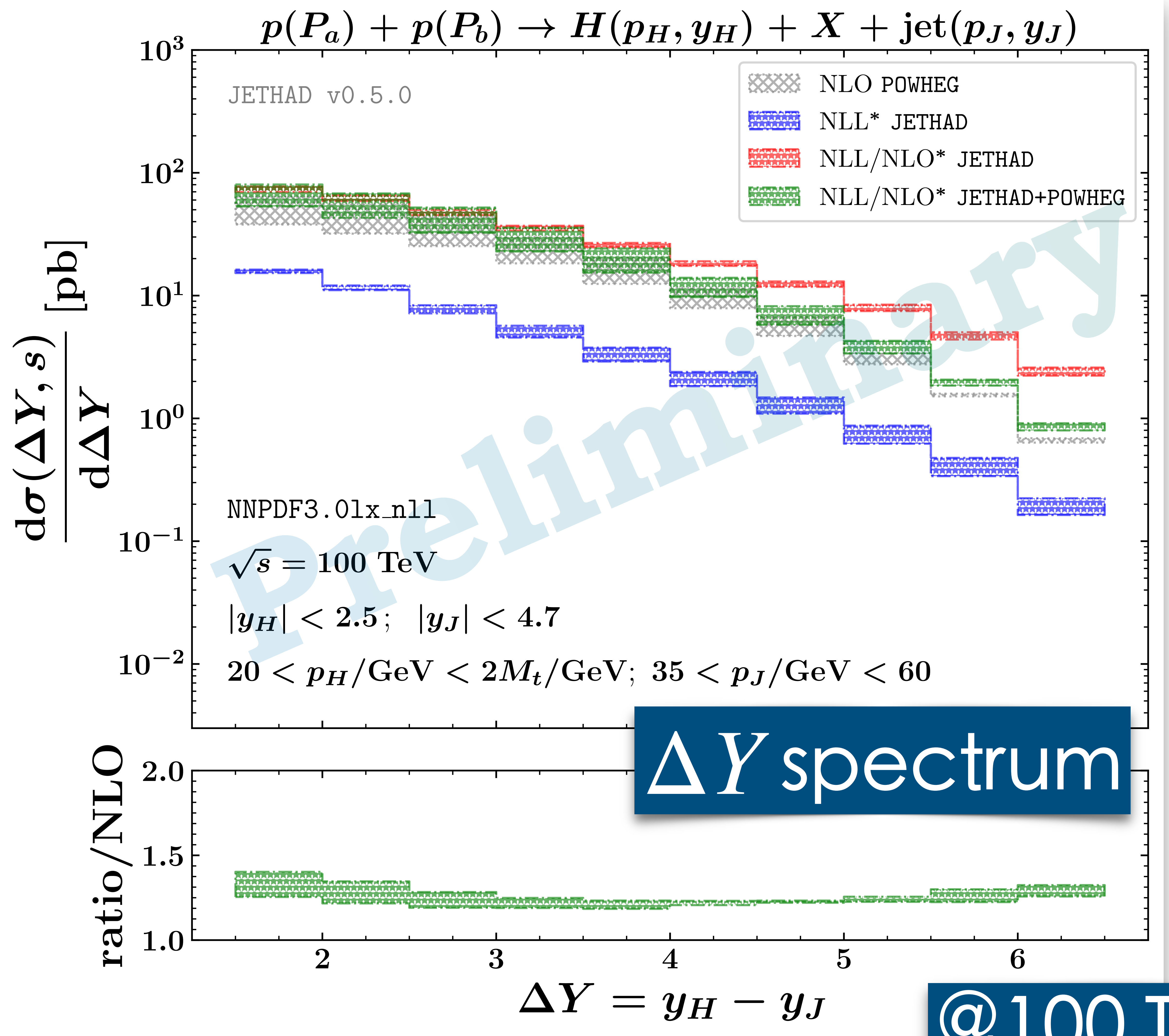
High-energy resummation + **NNPDF3.01x**



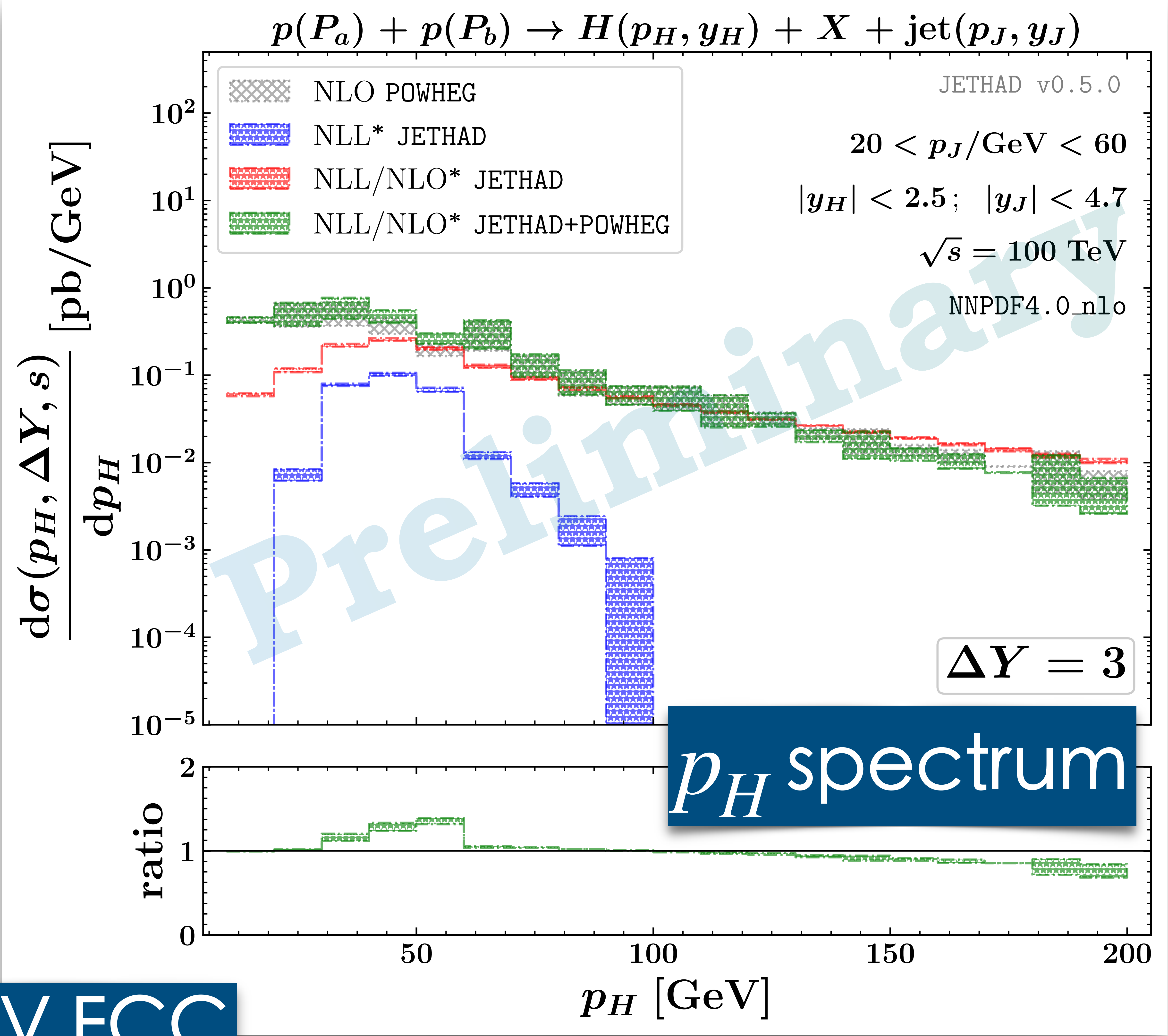
Threshold resummation on PDFs $\Rightarrow$ $+(10.7 \div 2.15)\,\%$ @NLL/NLO*

Backup

The Higgs + jet spectrum from POWHEG + JETHAD



ΔY spectrum



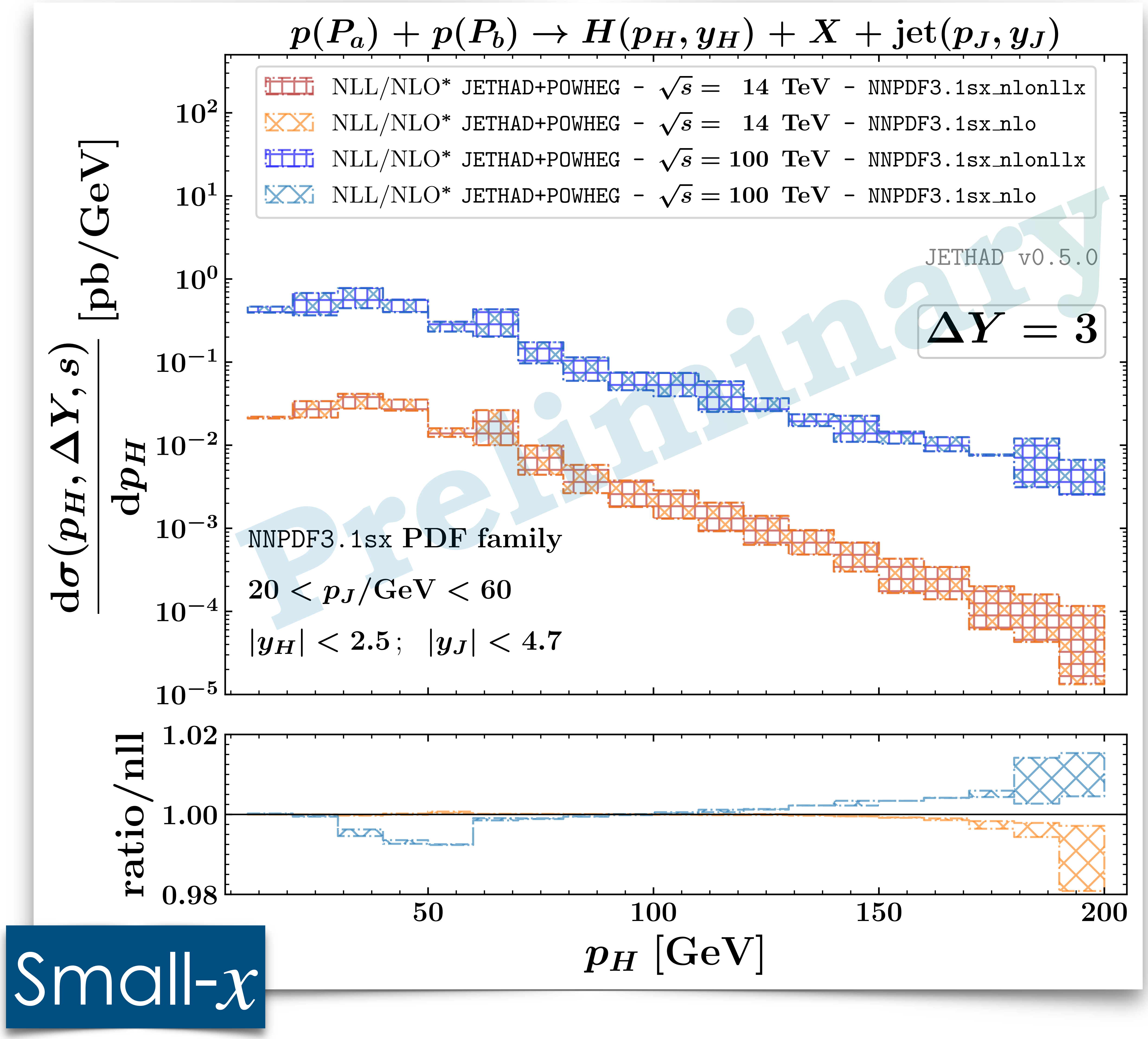
p_H spectrum

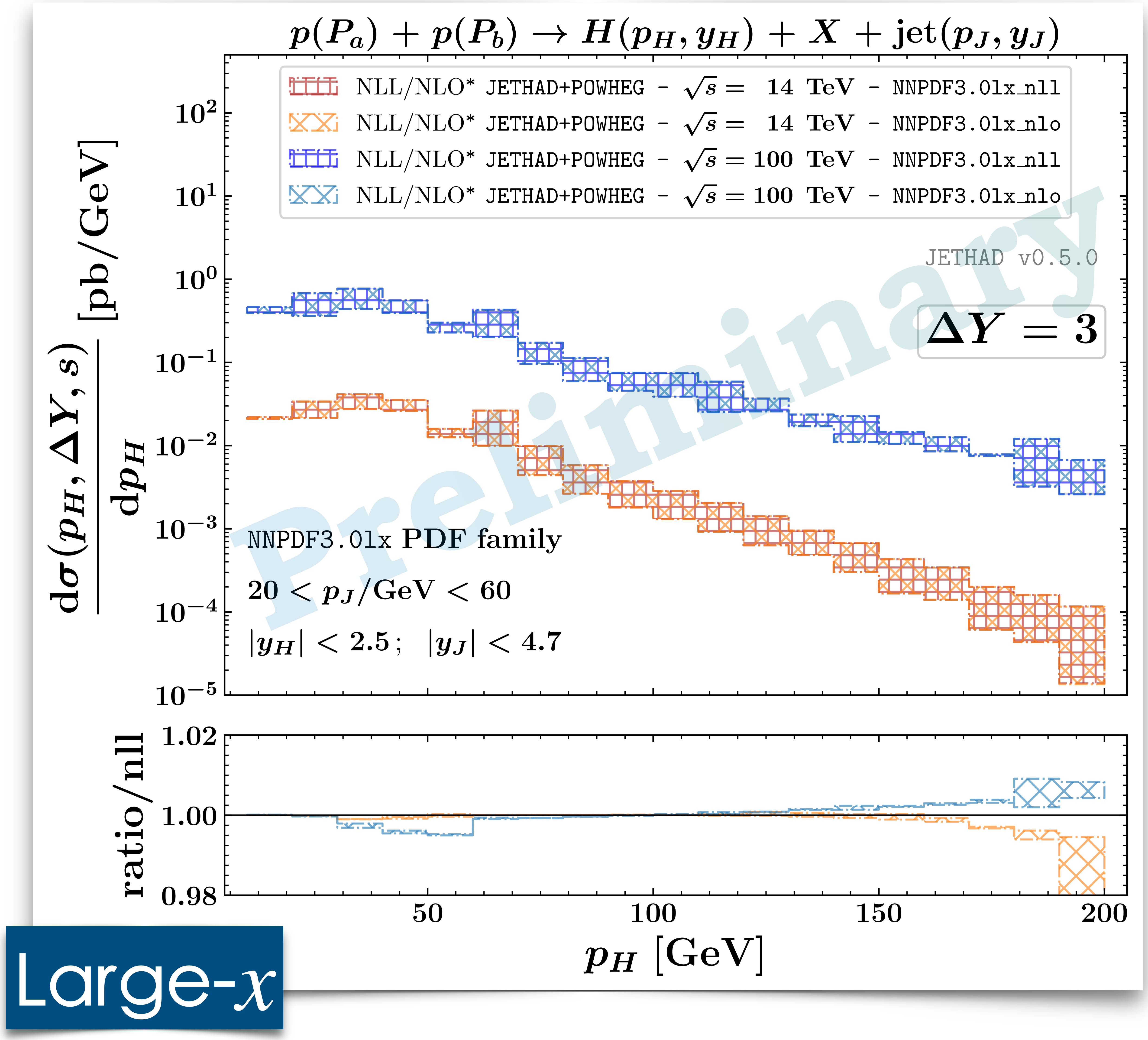
@100 TeV FCC

Backup

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

Small-x and large-x enhancement from PDFs





Backup

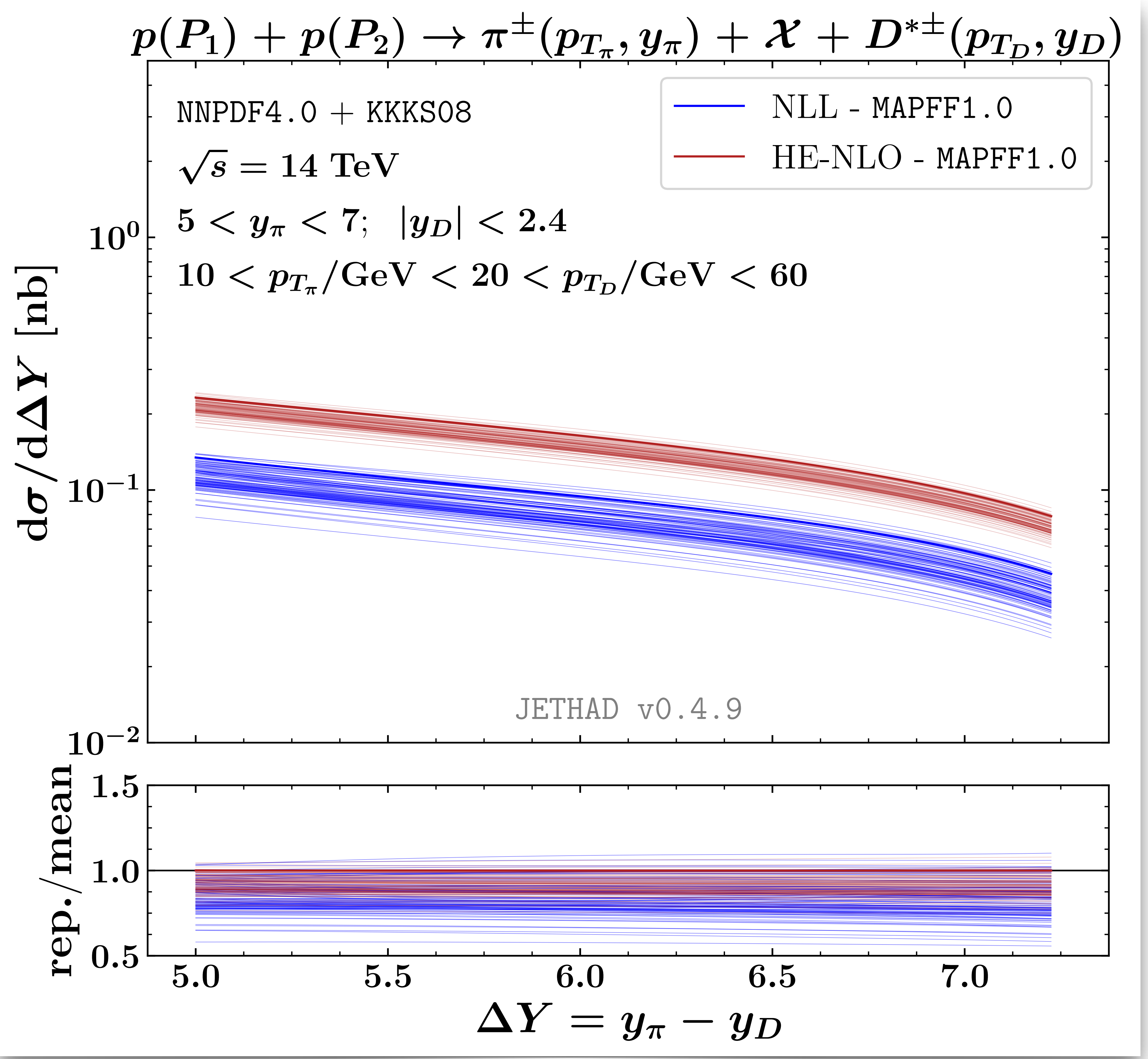
Impact of large-x threshold logs on NLO impact factors to be gauged

Heavy-light hadrons

Rapidity distributions @FPF+ATLAS

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

[FPF Snowmass Whitepaper]



Backup

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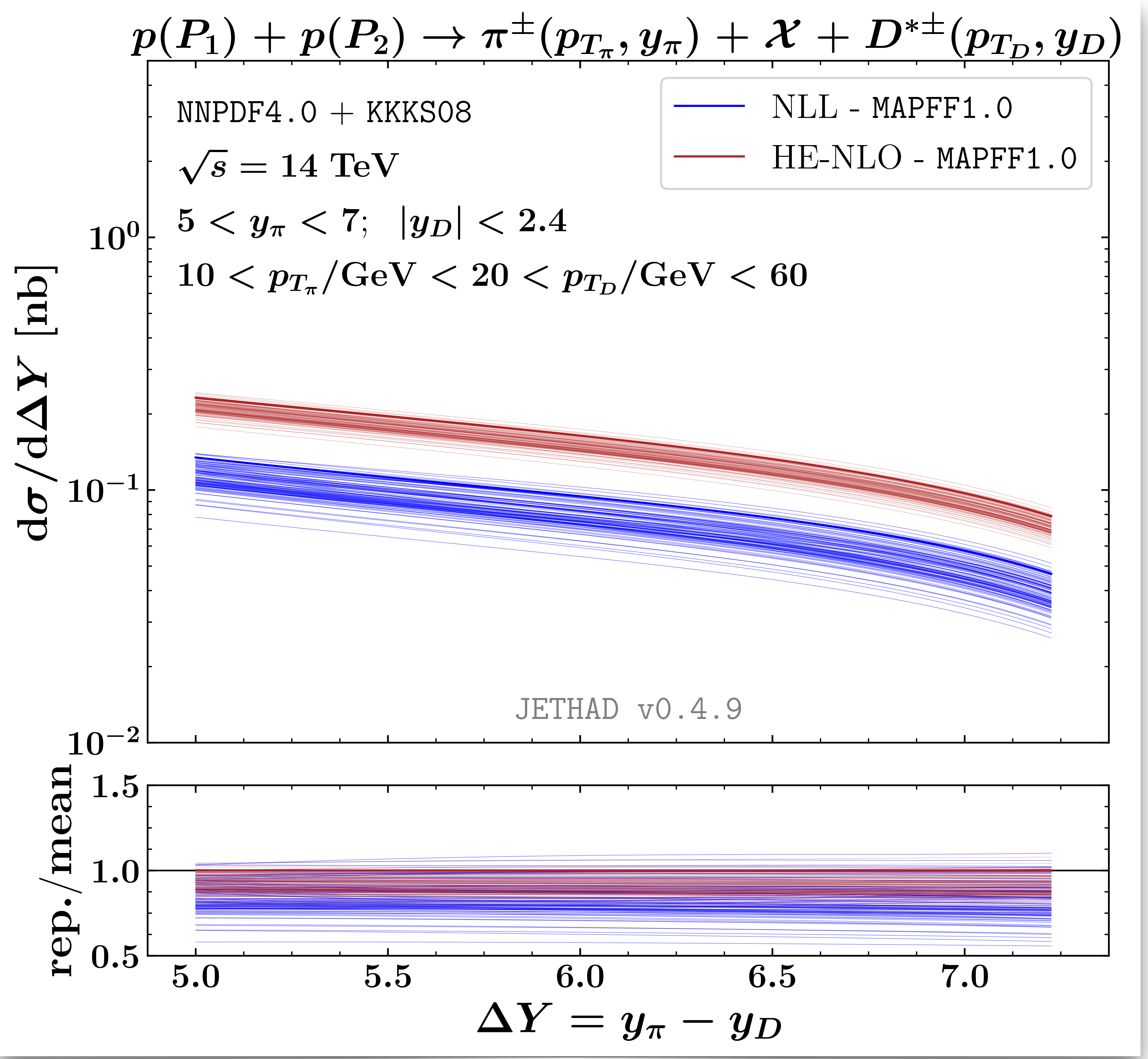

- ✱ Impact of collinear FFs on ΔY-distribution
- ✱ Replica method at work

Backup

Rapidity distributions @FPF+ATLAS

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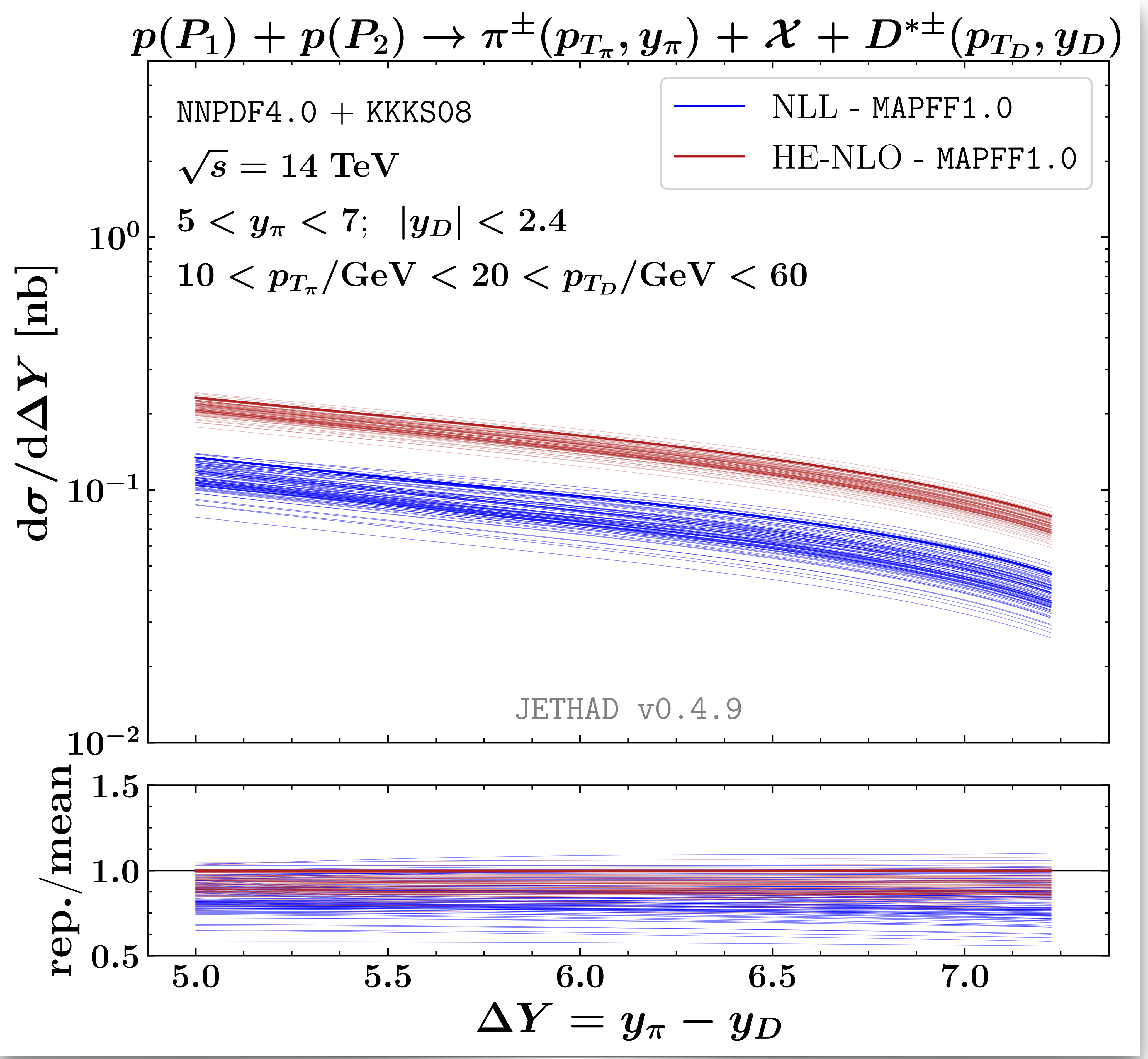


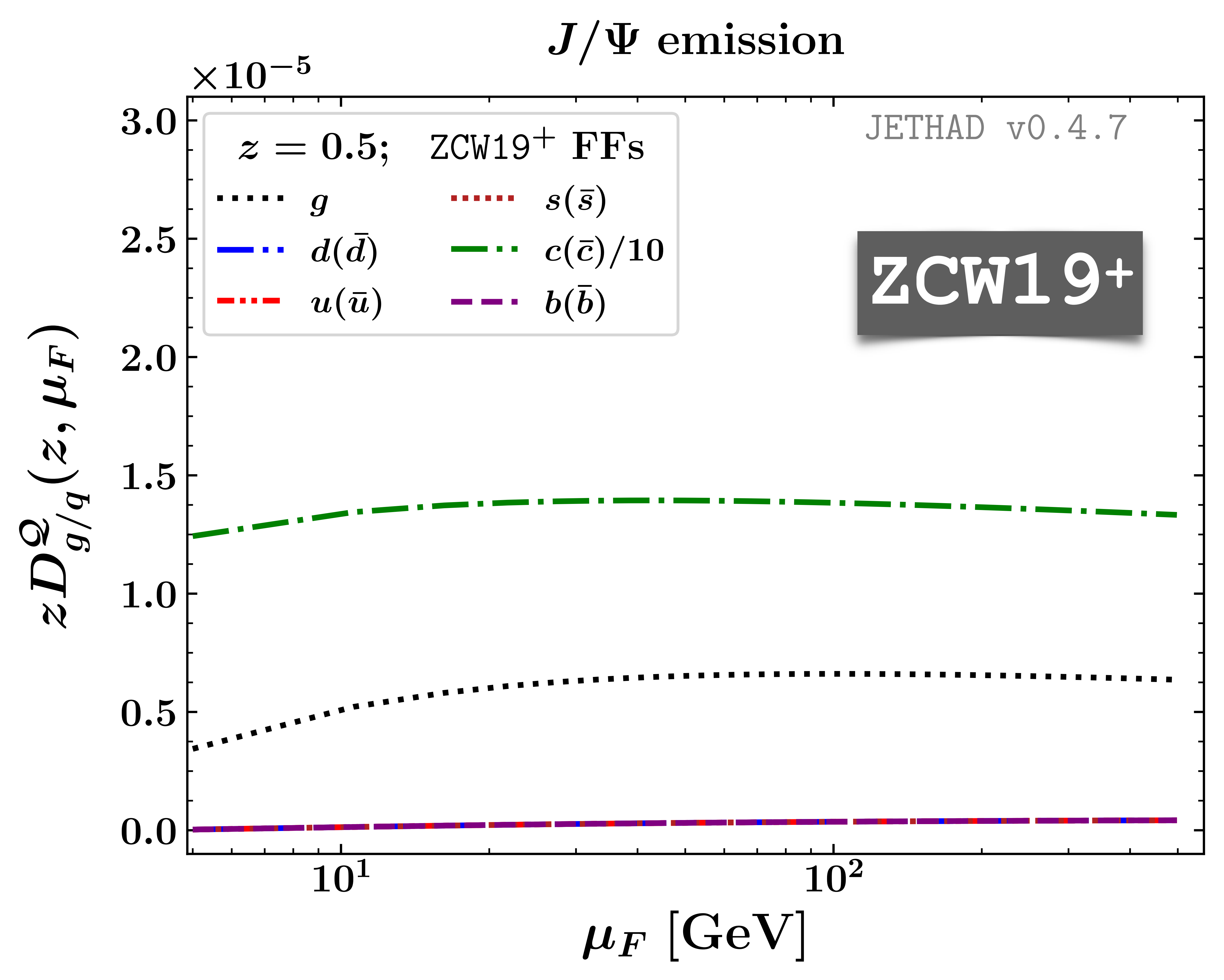
- ✱ Impact of collinear FFs on ΔY-distribution
- ✱ Replica method at work
- ✱ Larger spread of replicas at NLL
- ✱ Probe FFs in complementary ranges
  - Weight of FF replicas in the same set
  - Different sets via functional correlation?
- ✱ Complementary studies on FFs

Backup

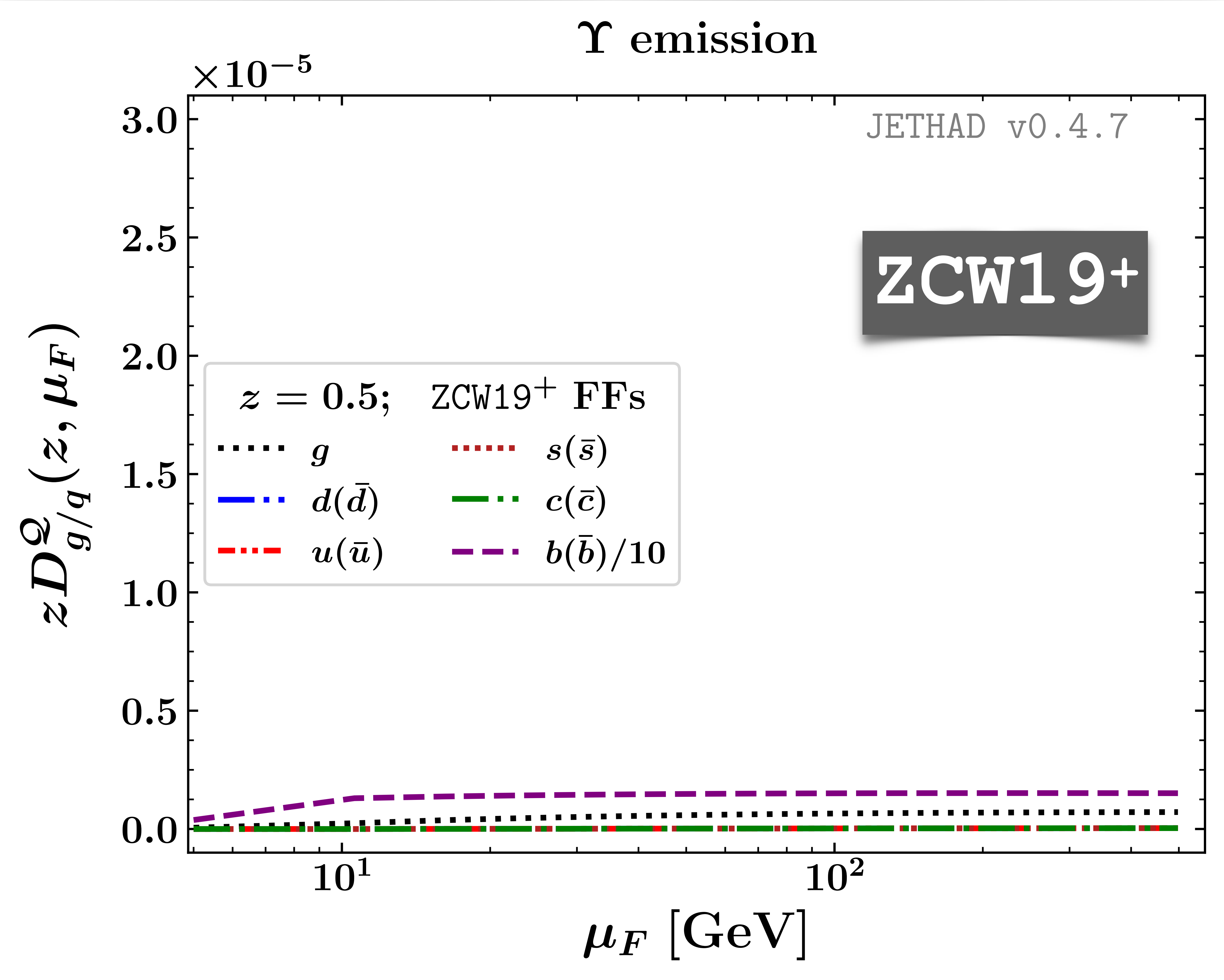
Vector quarkonia

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



Υ collinear FFs

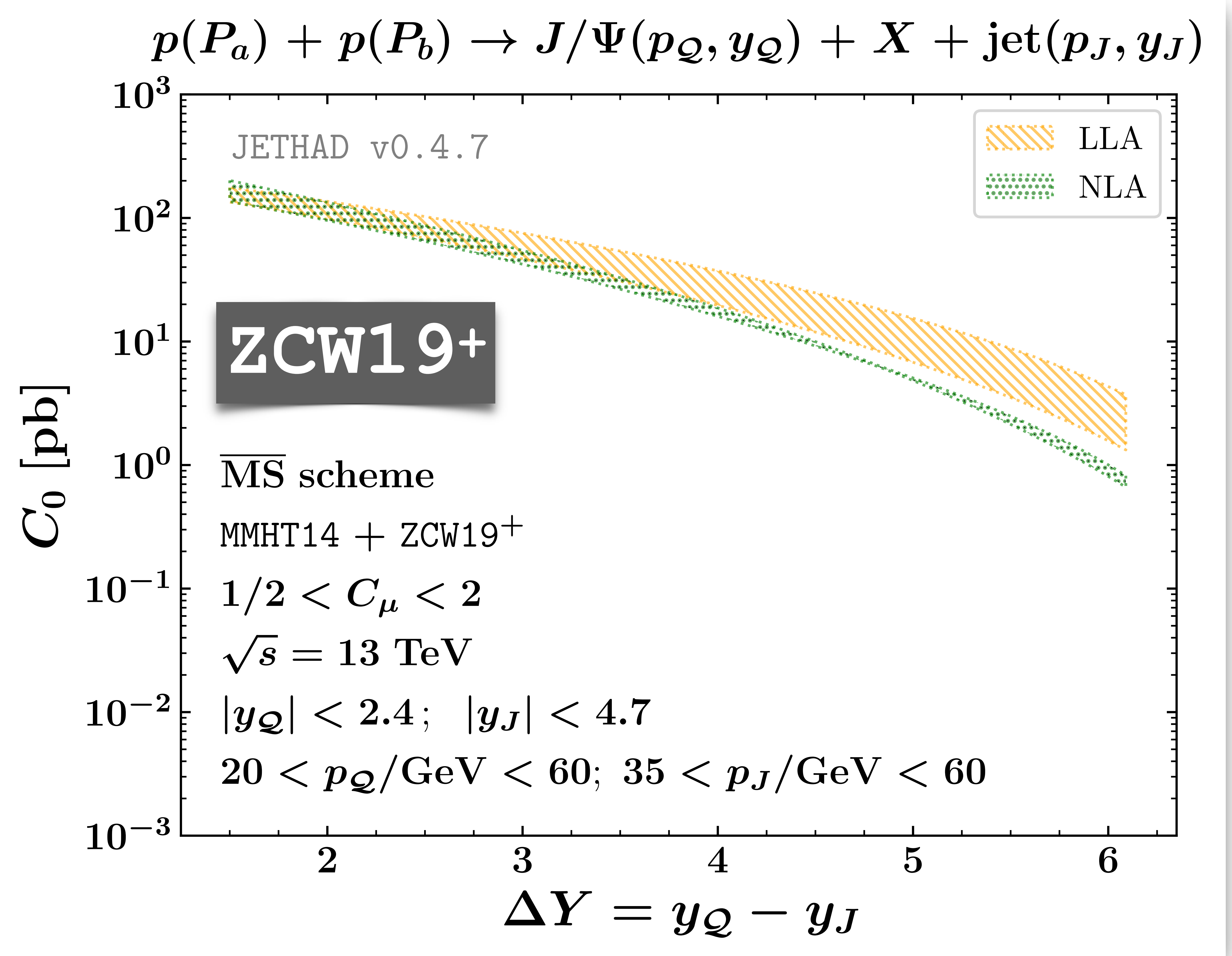


[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

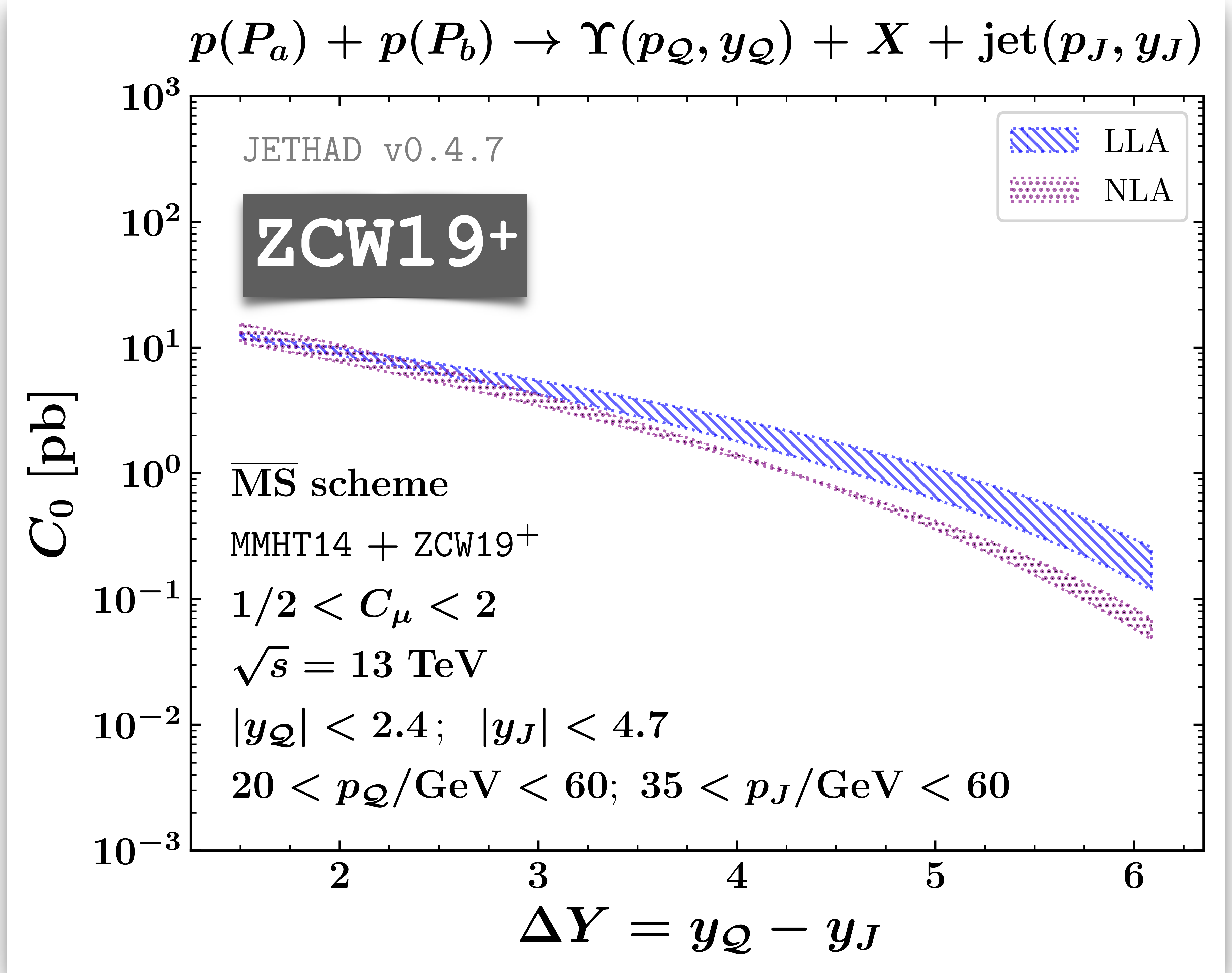
Backup

Vector quarkonium + jet at the LHC

J/ψ + jet



Υ + jet

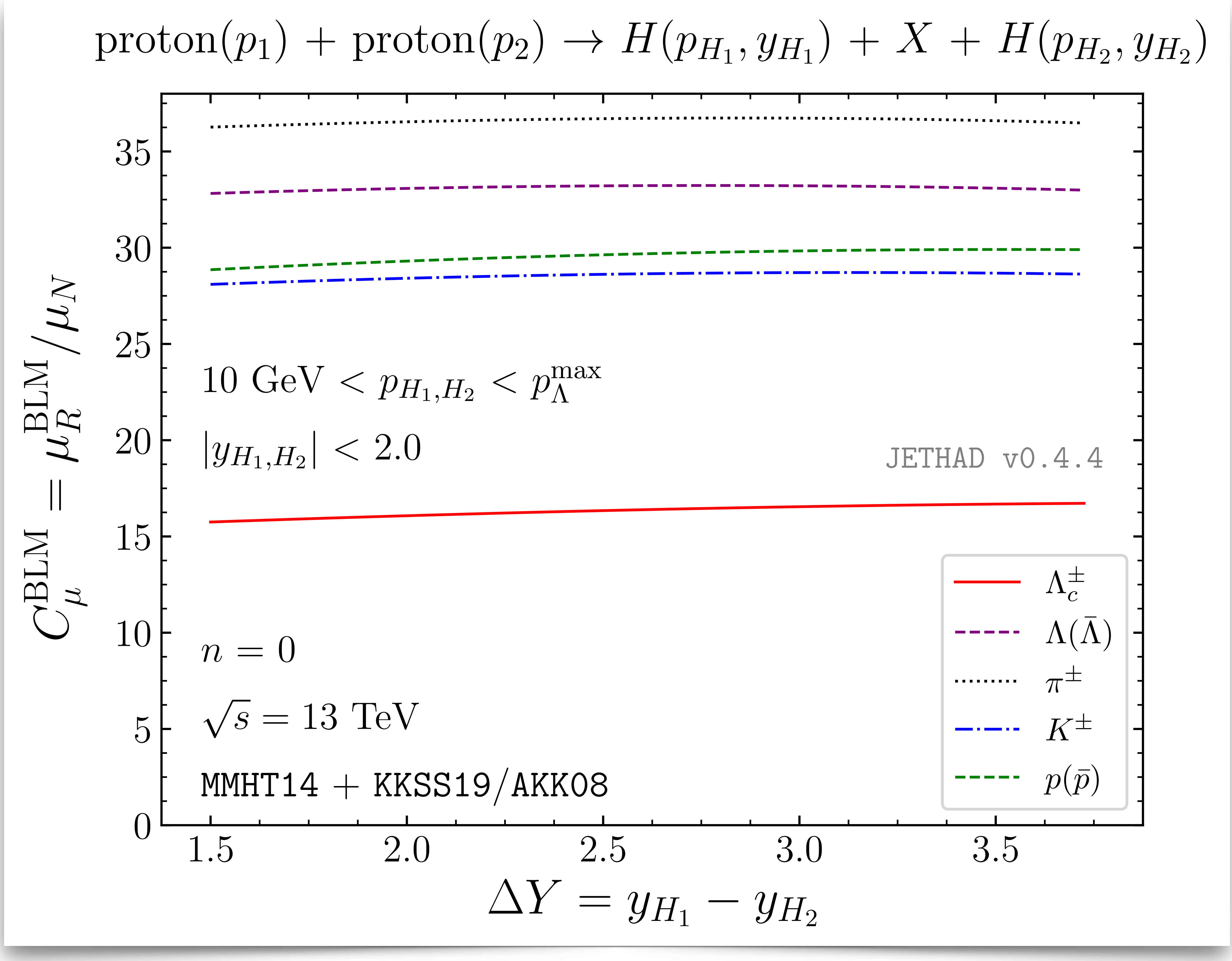


[F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

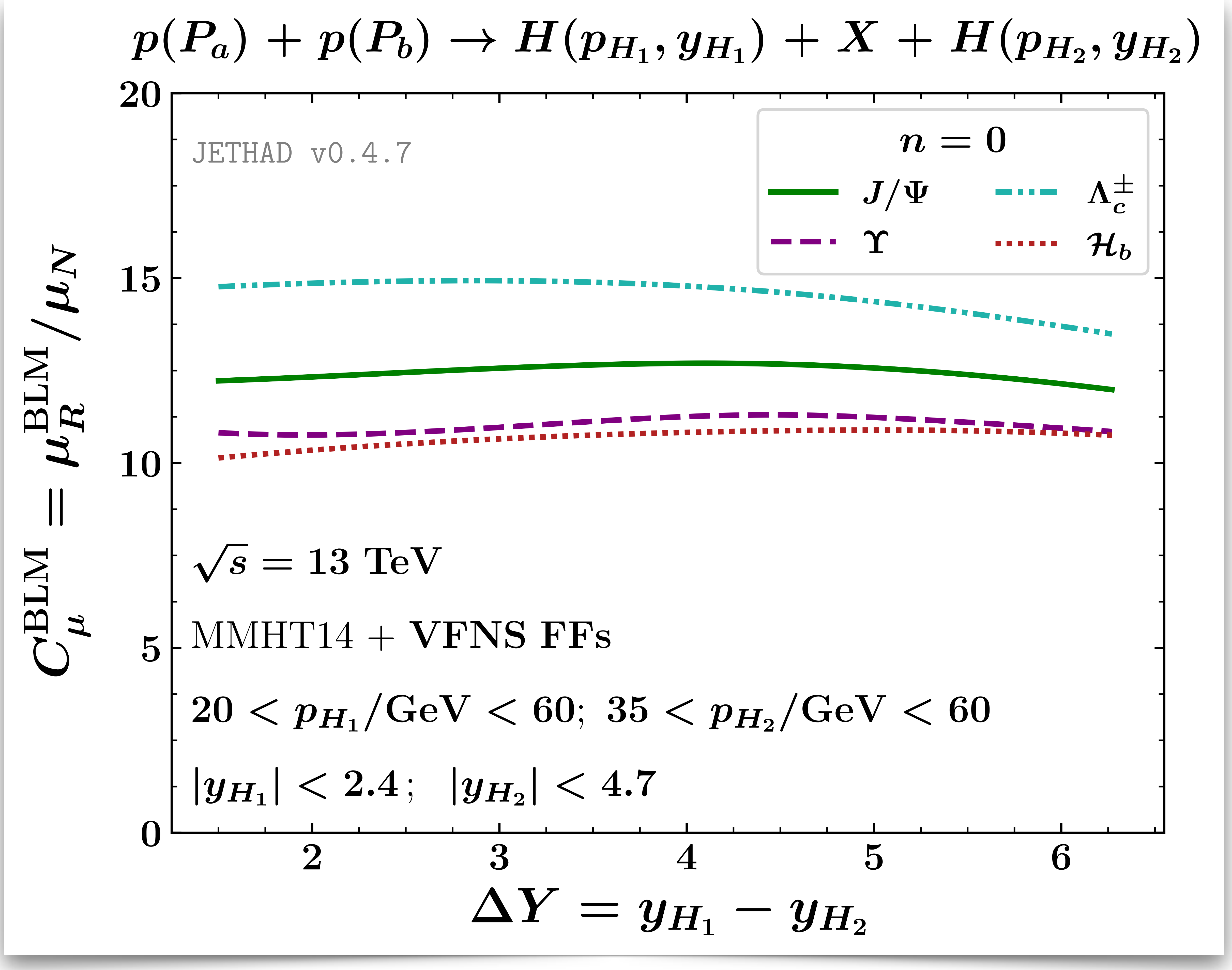
Backup

Heavy flavor at the LHC: BLM scales

Heavy-light hadrons



Vector quarkonia

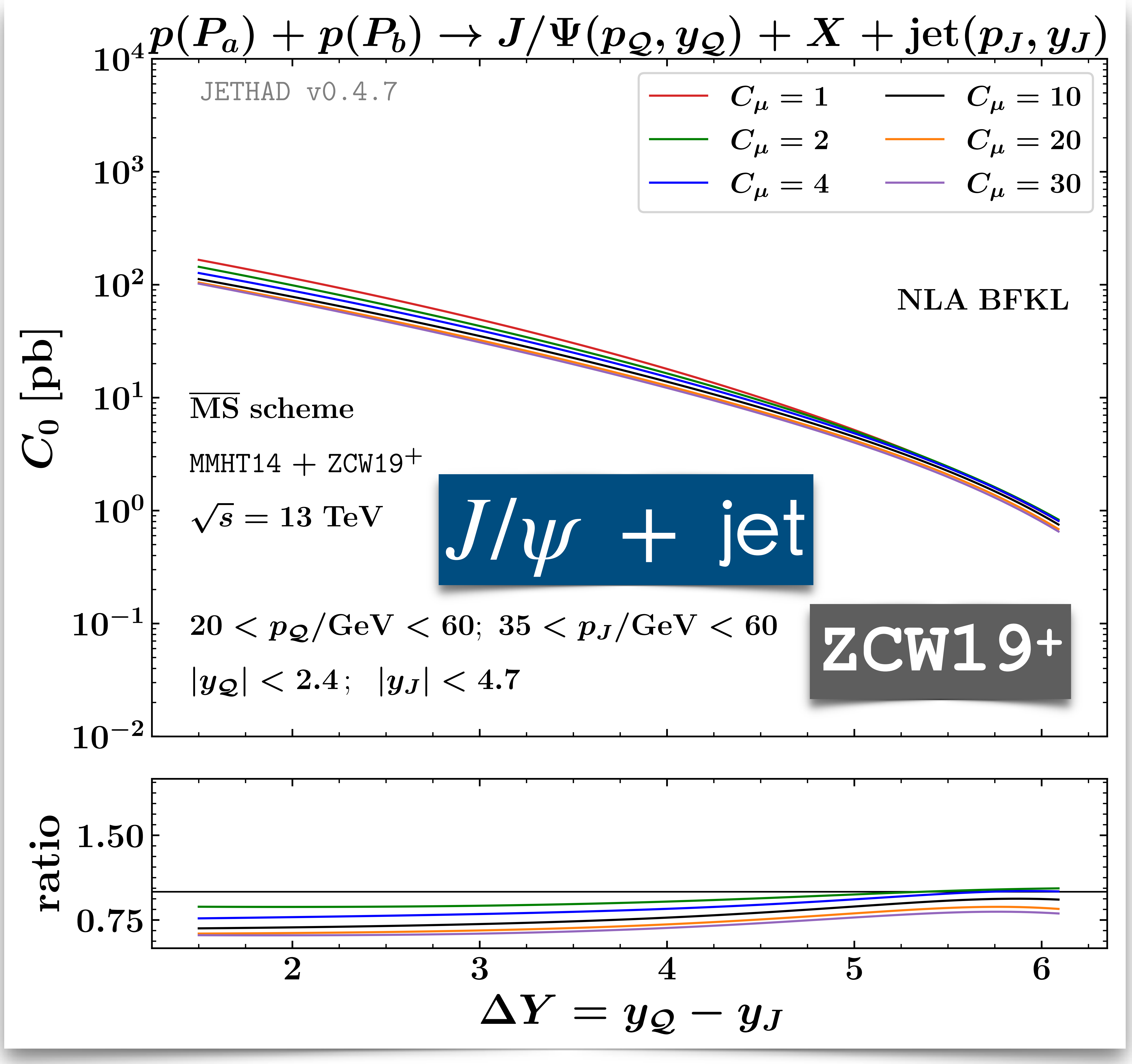


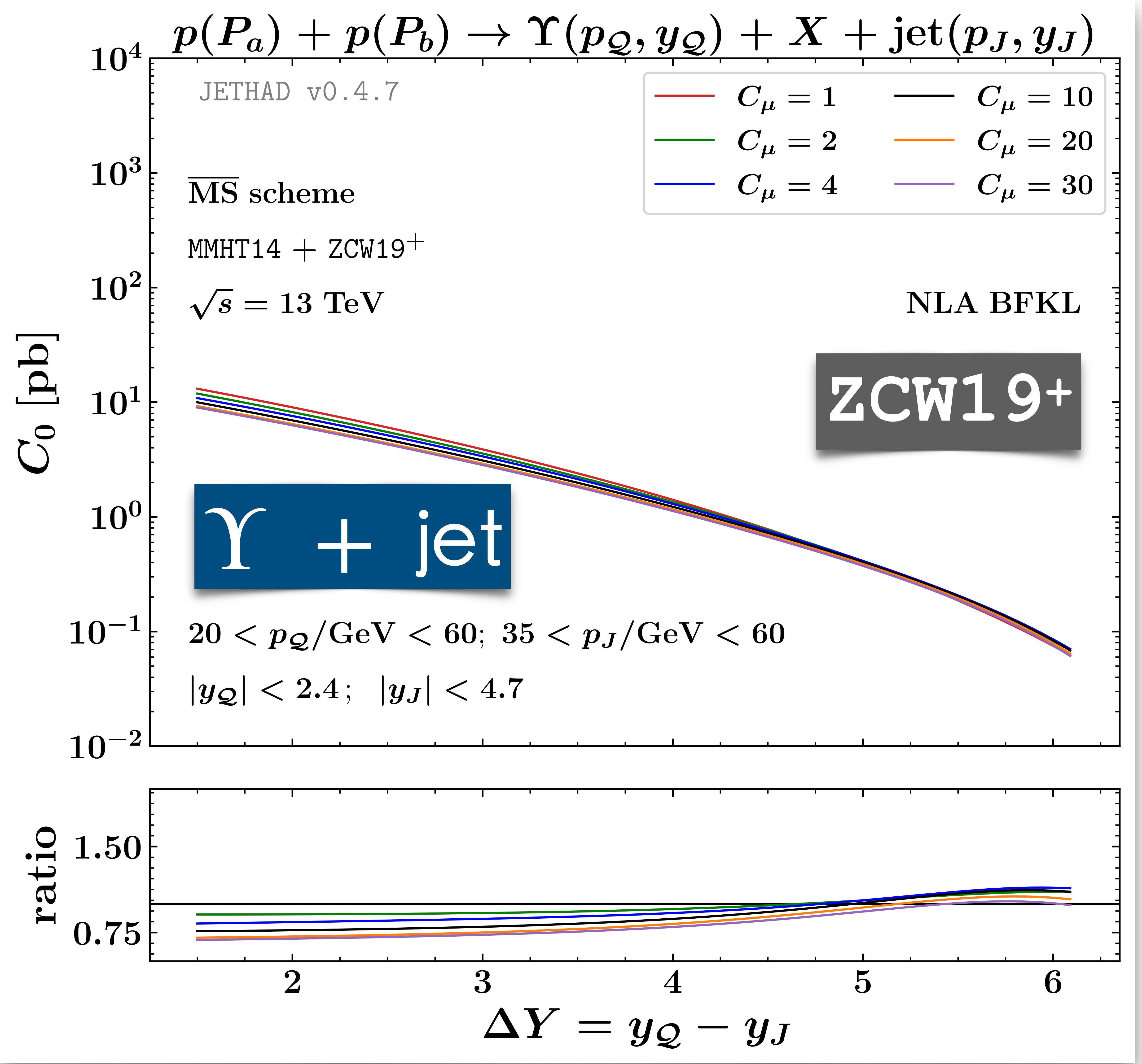
🔗 [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

Backup

🔗 [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]

Backup

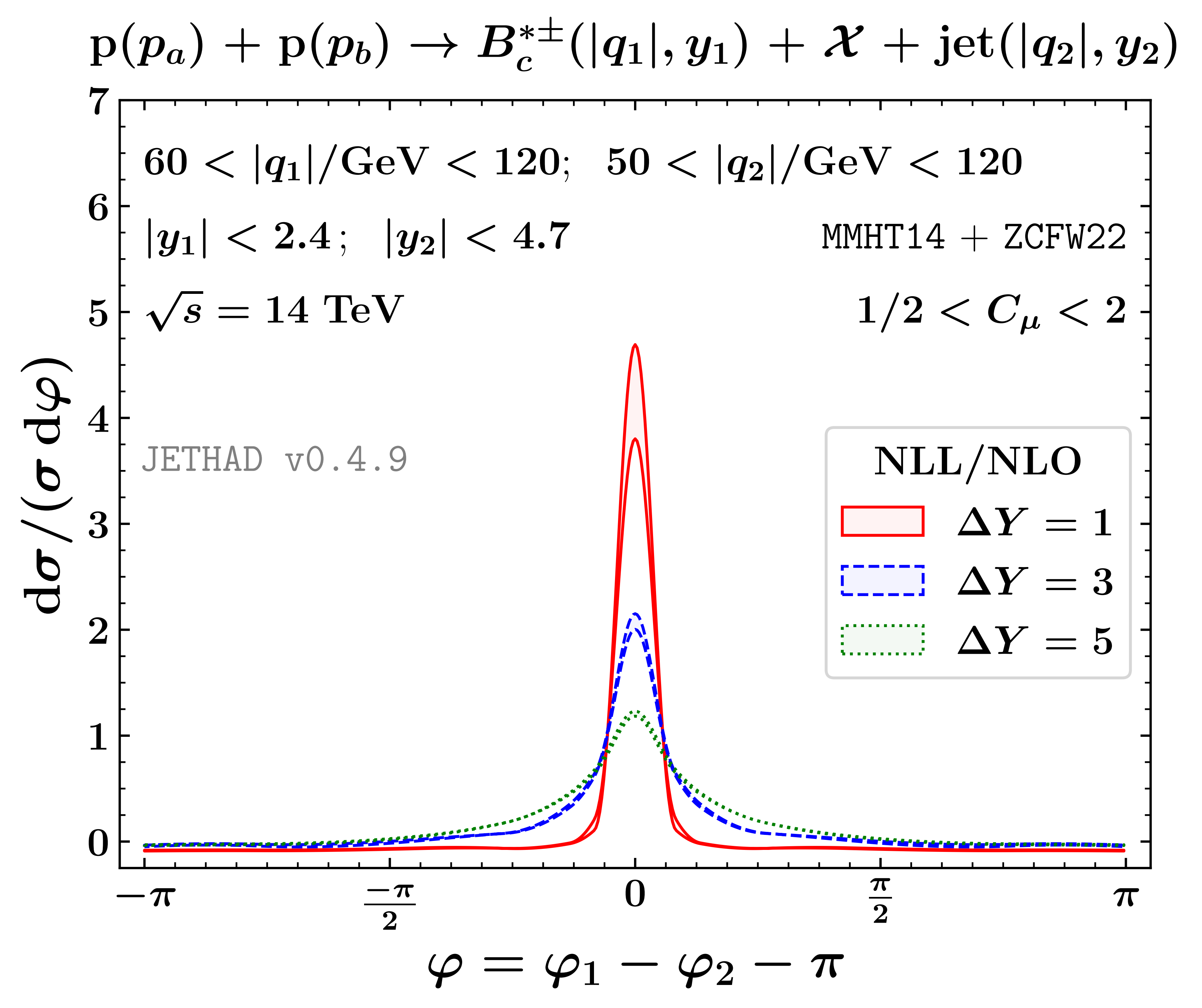
Charmed B-mesons

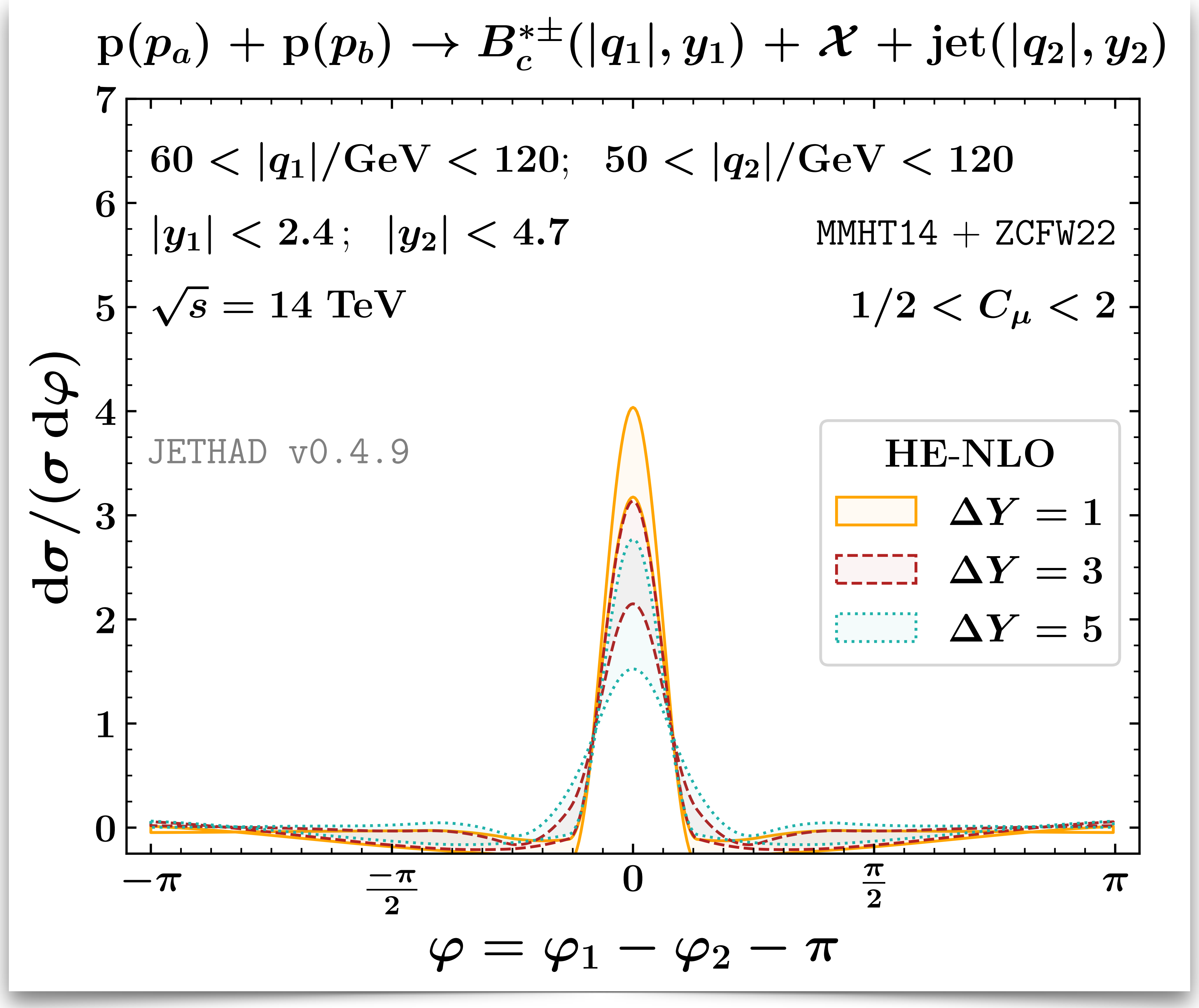
Charmed B-mesons from single-parton fragmentation

(2) ¡ *Let us consider* $B_c(^1S_0)$ *and* $B_c(^3S_1)$ *at large* p_T → *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]



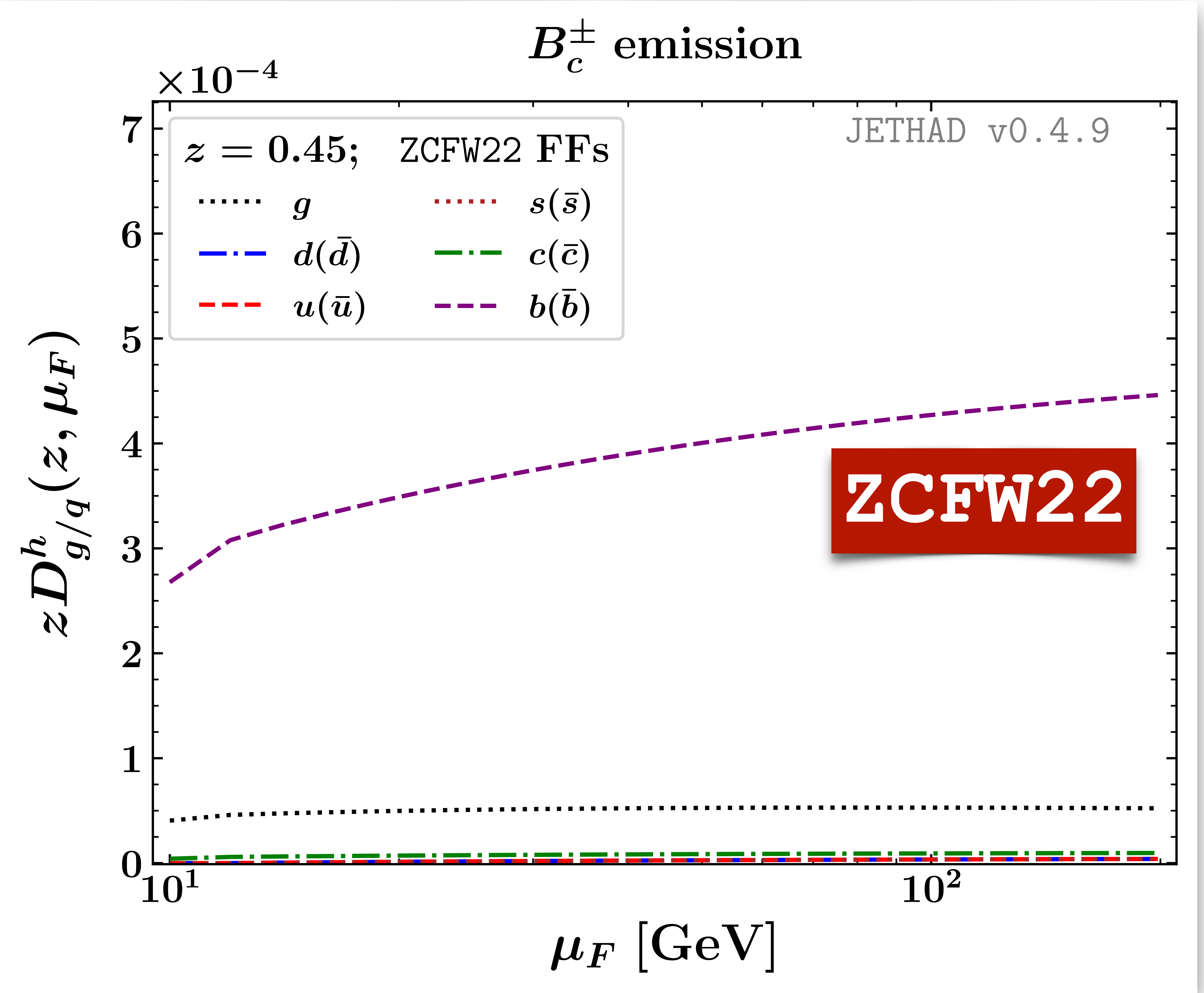


🔗 [F. G. C., Phys. Lett. B 835 (2022) 137554]

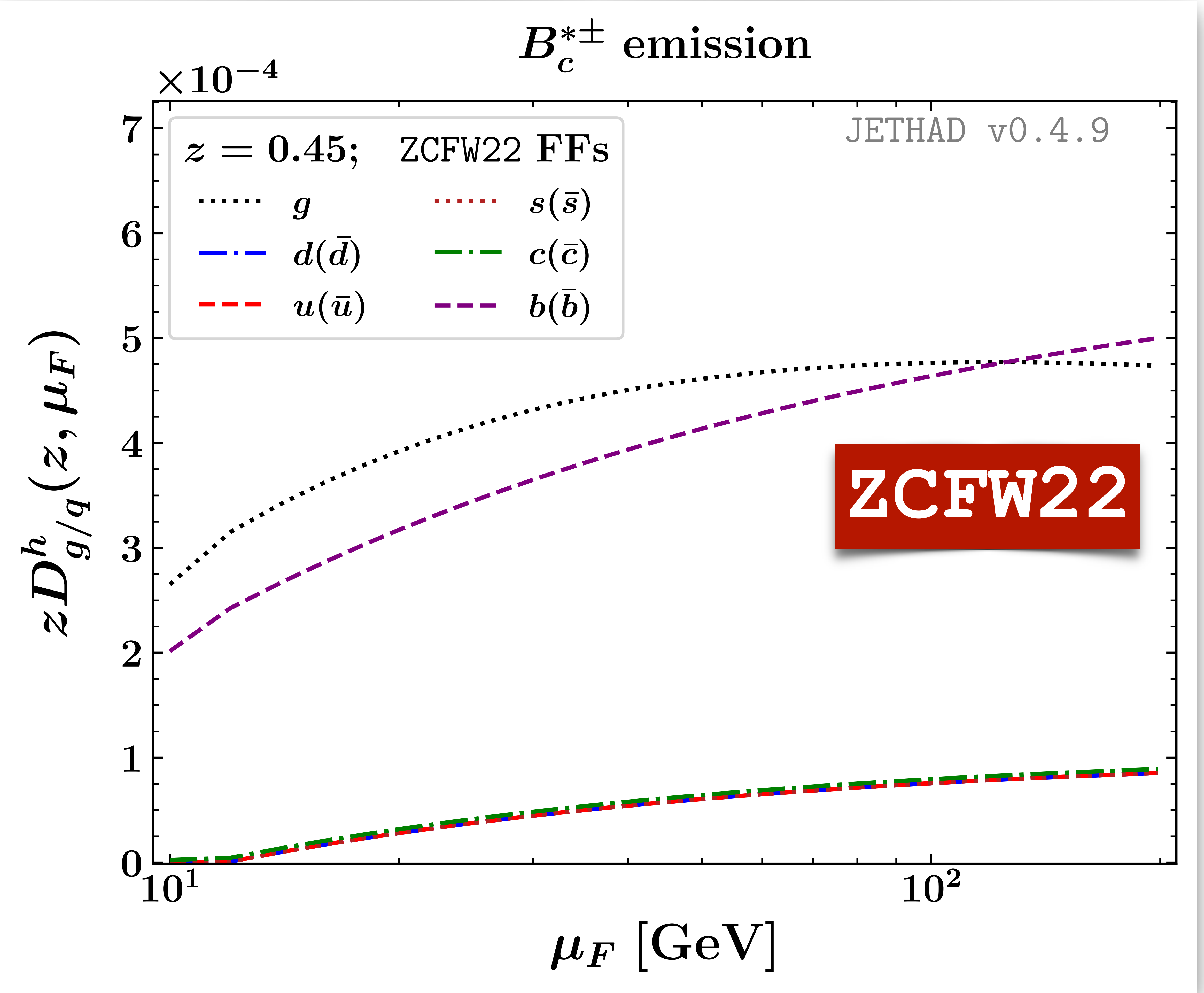
Backup

Charmed B-mesons + jet at the HL-LHC

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



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

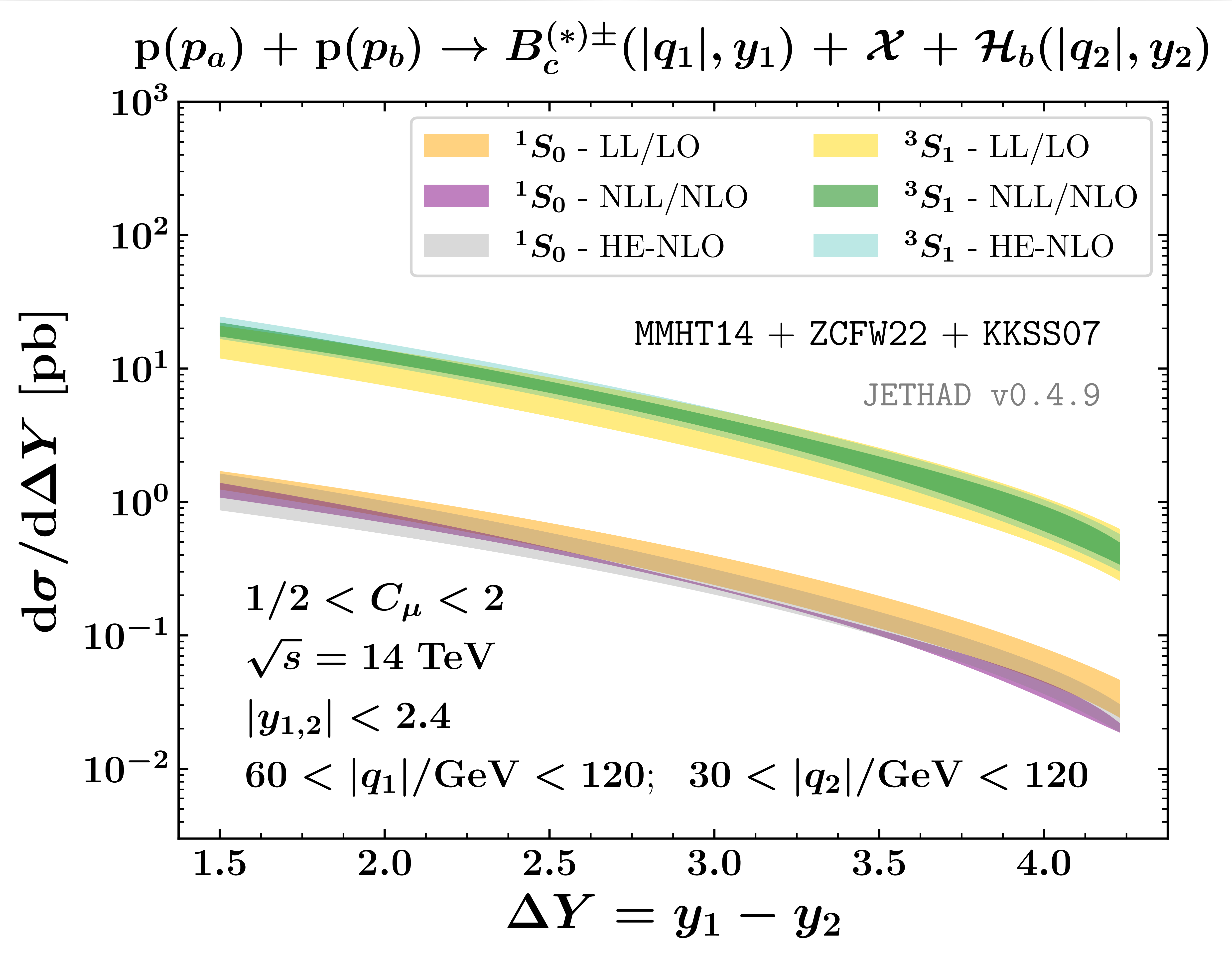


[F. G. C., Phys. Lett. B 835 (2022) 137554]

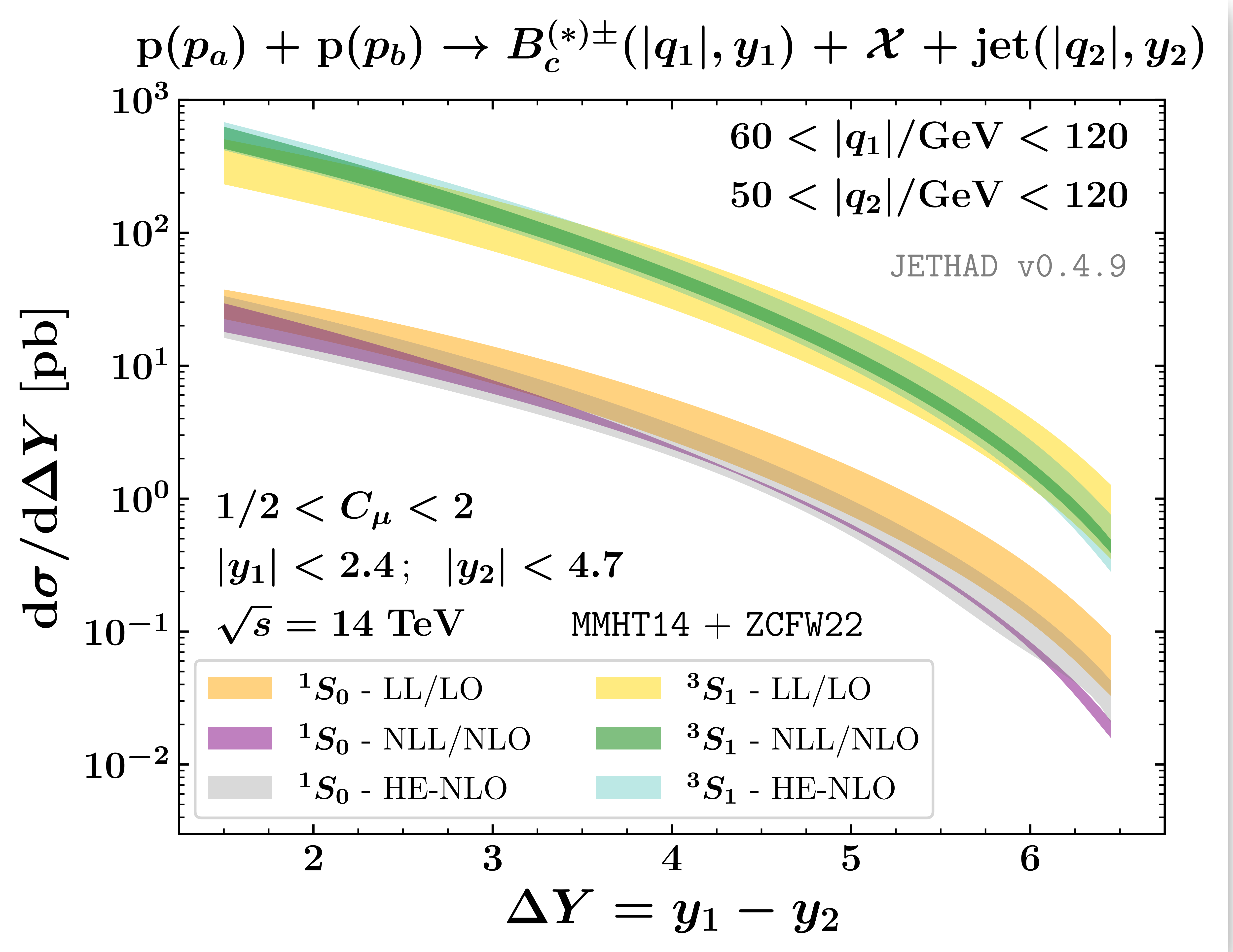
Backup

Charmed B-mesons + jet at the HL-LHC

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



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



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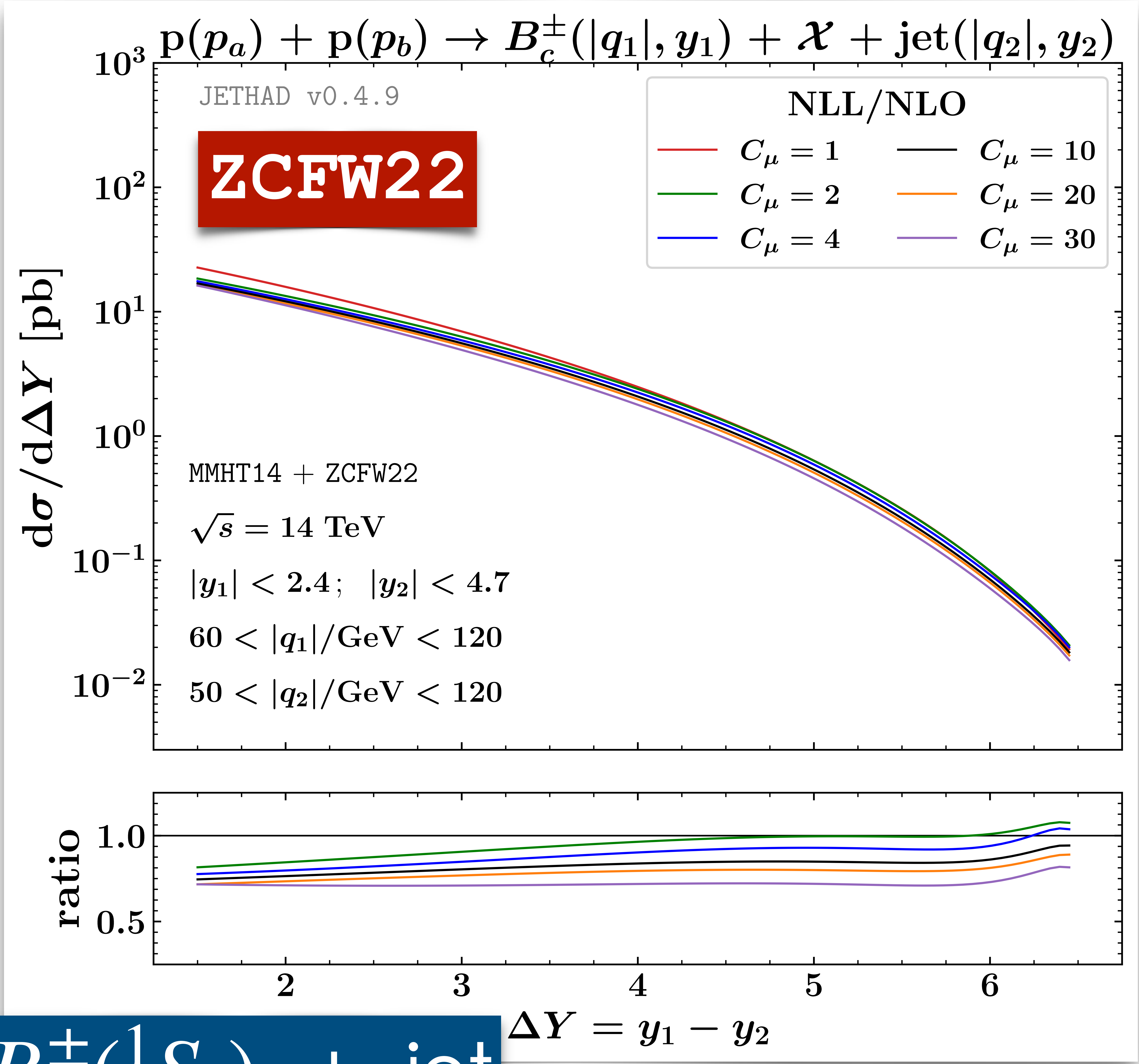
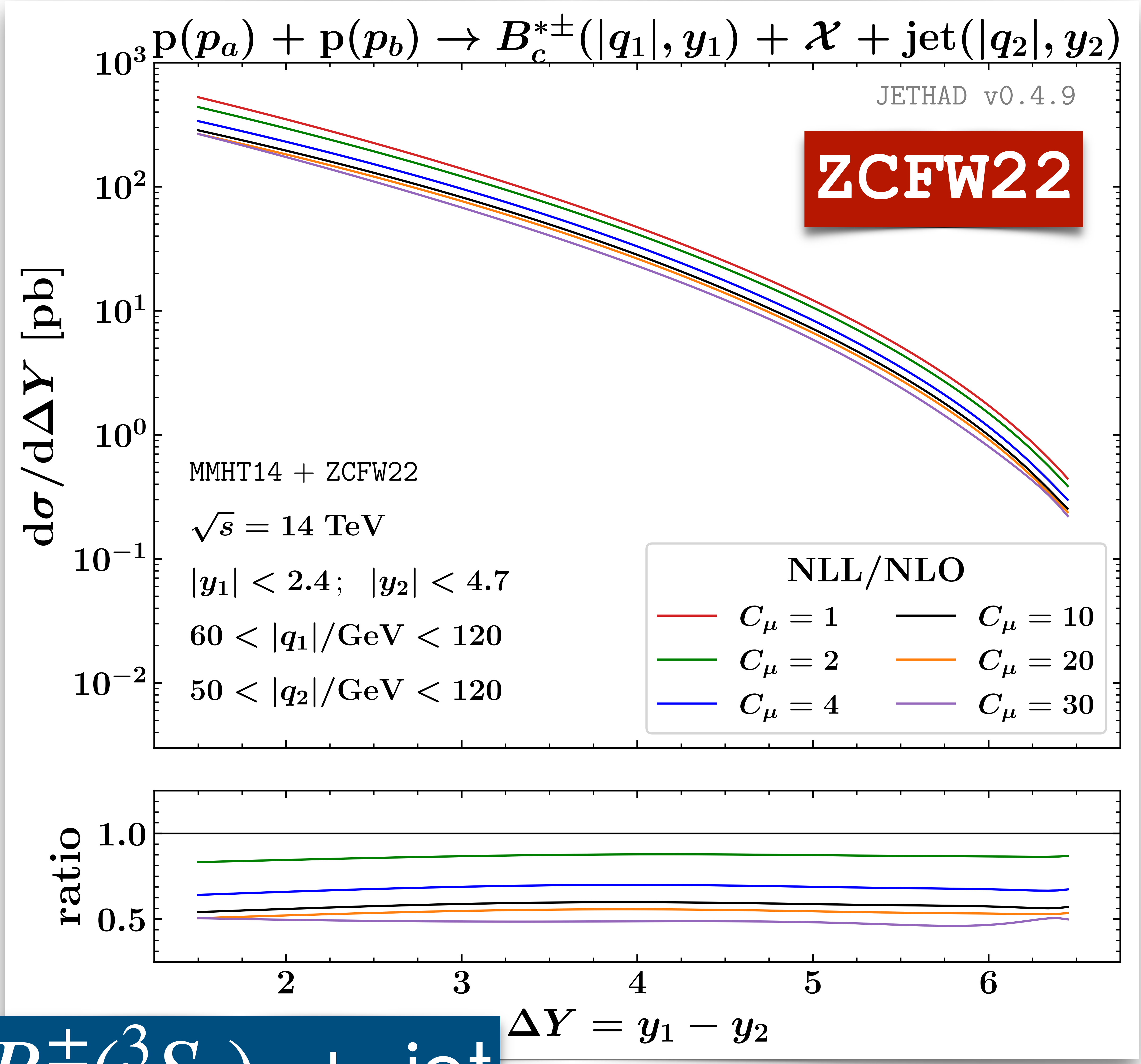
Backup

Charmed B-mesons + jet at the HL-LHC



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



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

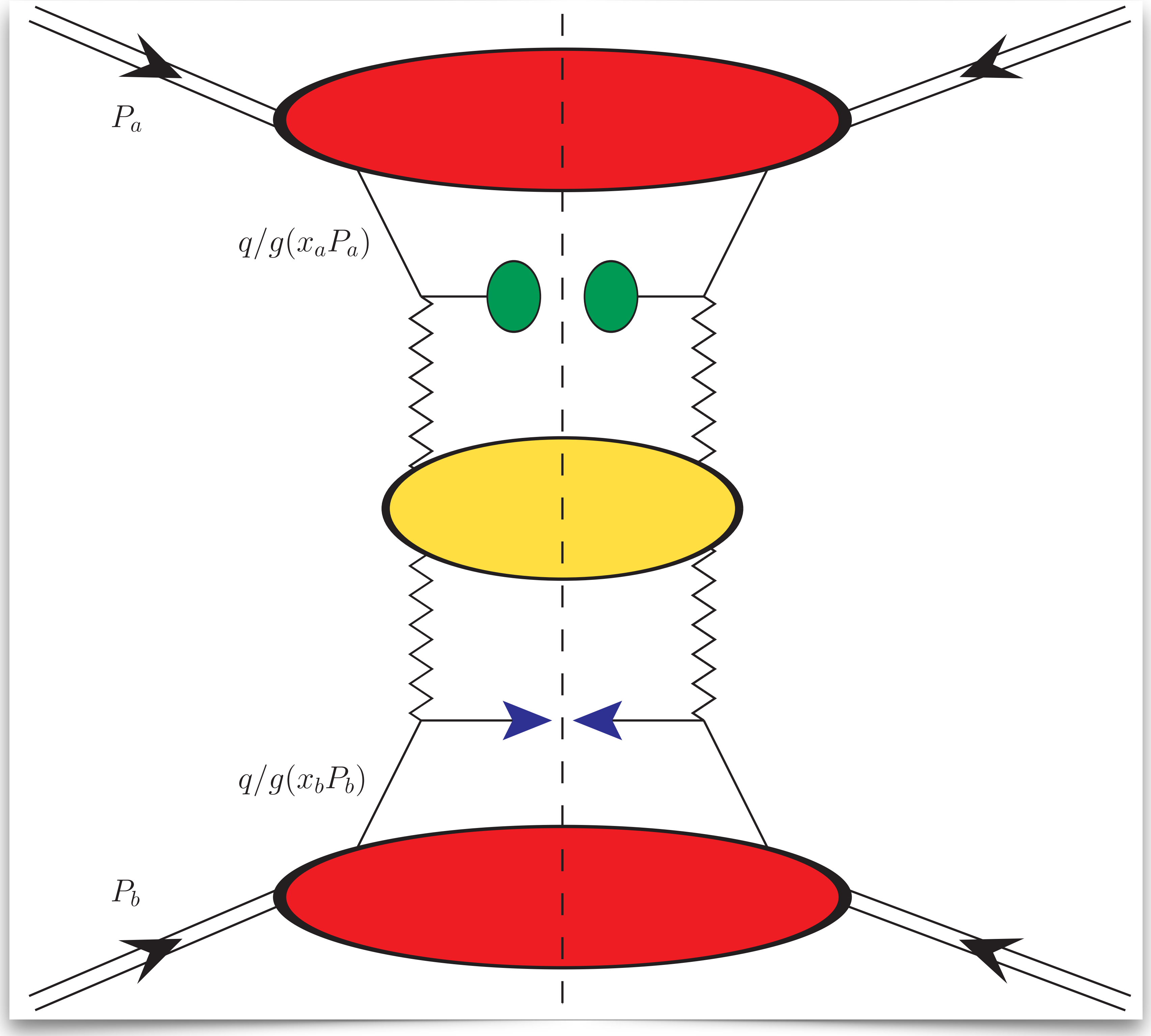
[F. G. C., Phys. Lett. B 835 (2022) 137554]

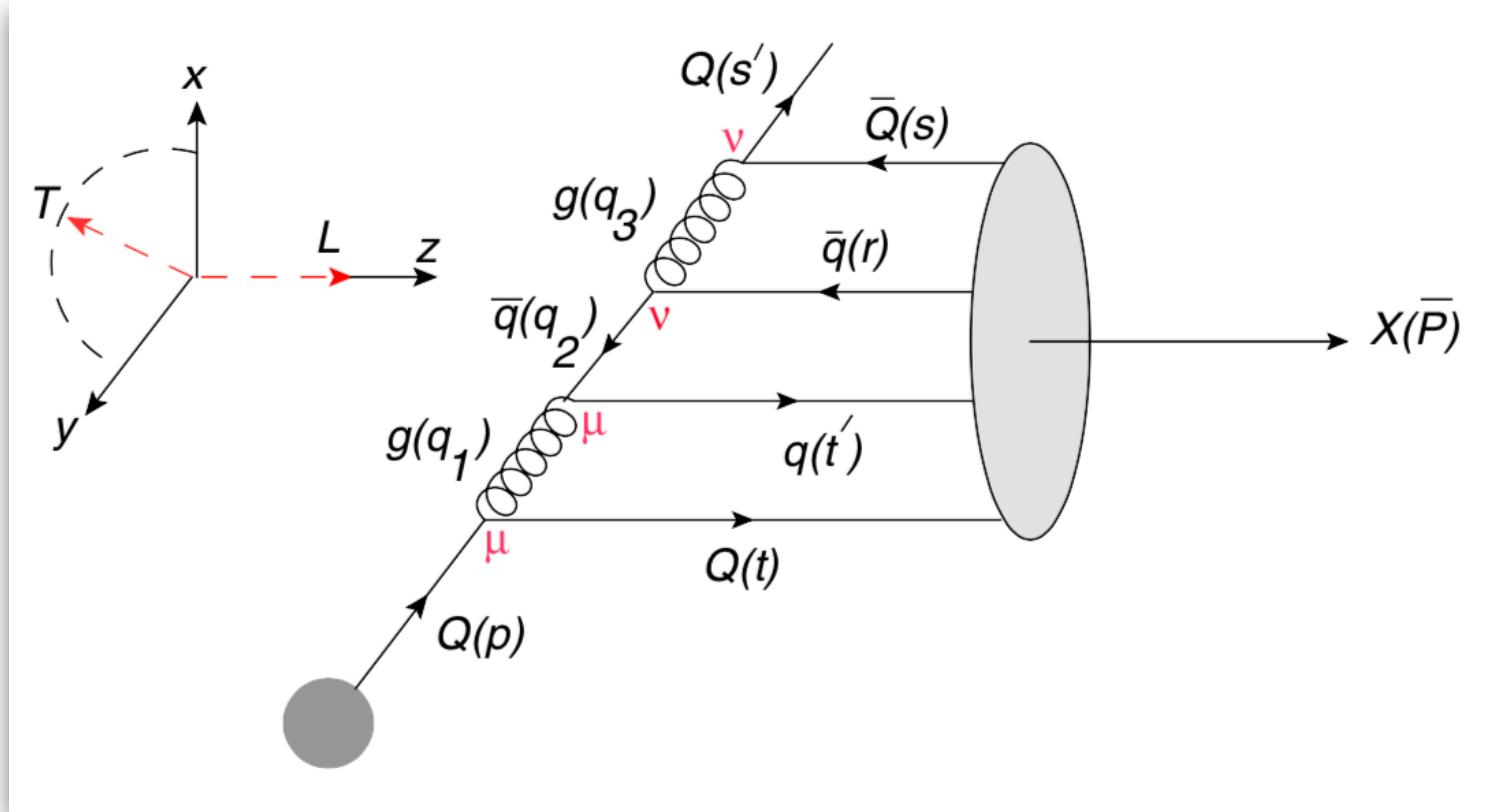
Backup

A high-energy QCD portal to exotic matter

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*** !



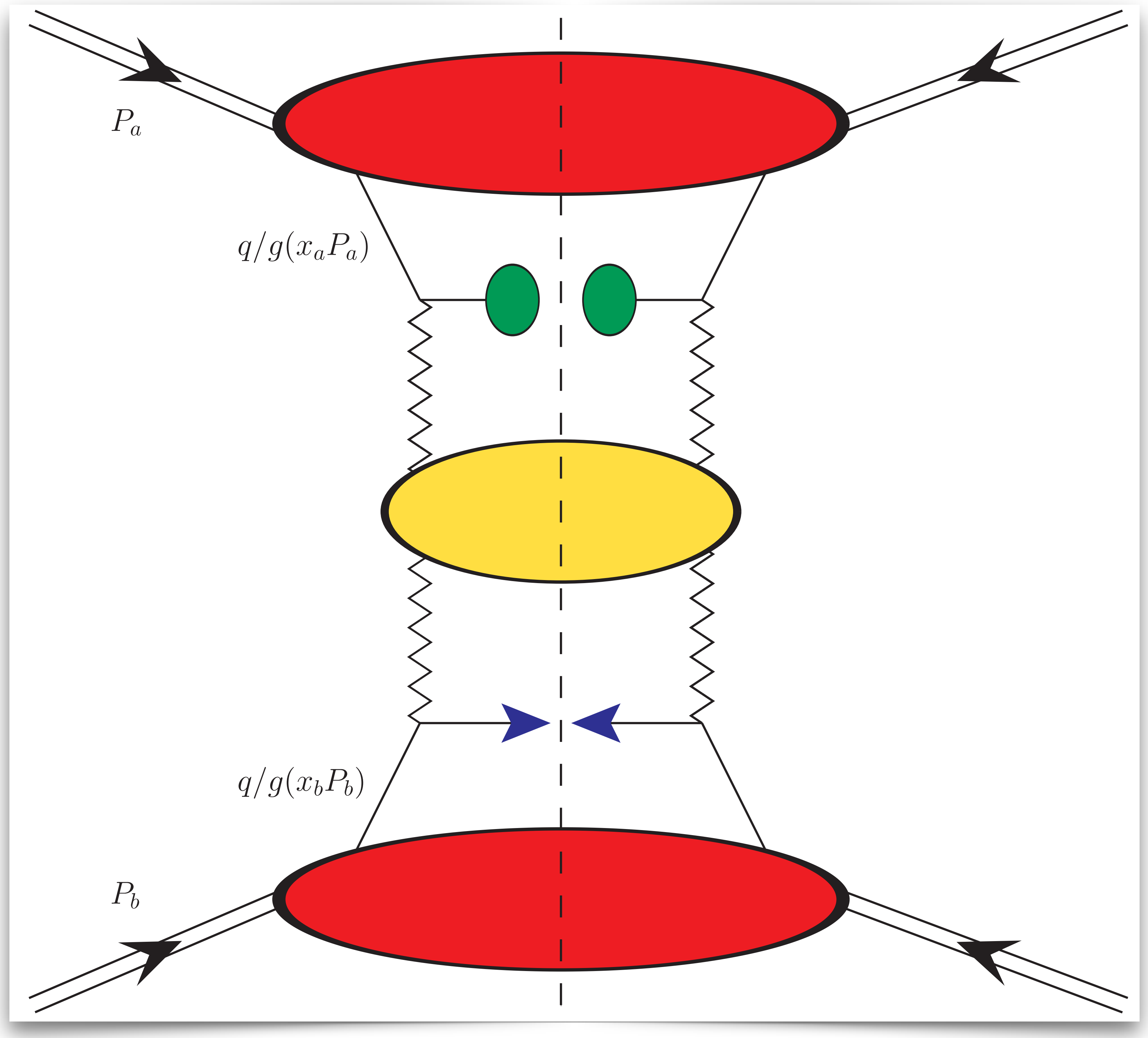


[F. G. C., A. Papa, in preparation]

Backup

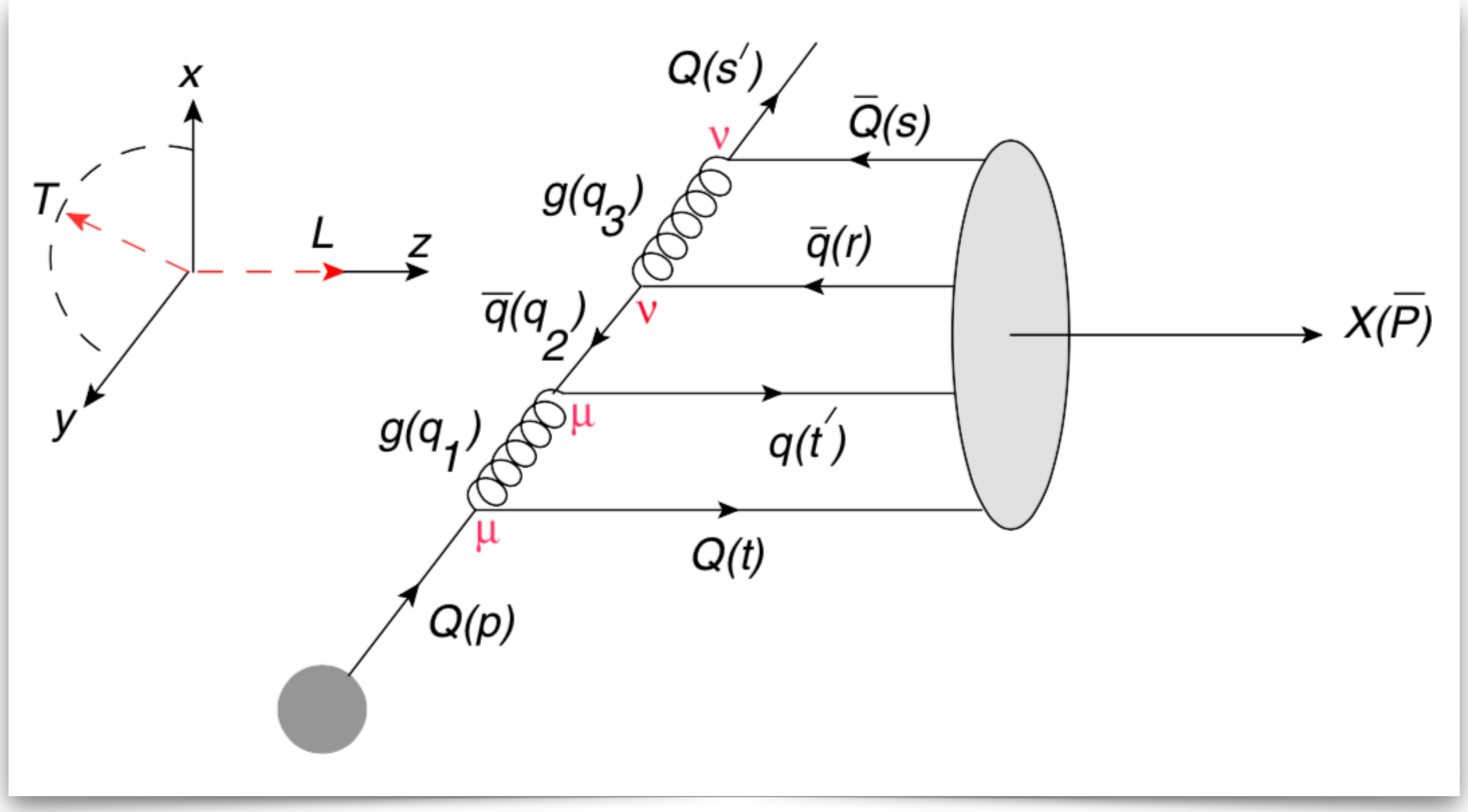
Heavy-light tetraquark from single-parton fragmentation

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



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

$[\mu_0 = m_X + m_Q]$



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

S-wave

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

$$= N \frac{z \times \Sigma_{\rm spin} \Gamma\bar{\Gamma}}{[m_X^2 - (m_Q^2 + \langle p_T^2 \rangle)(1 + z - \frac{1}{1-z})]^2}$$

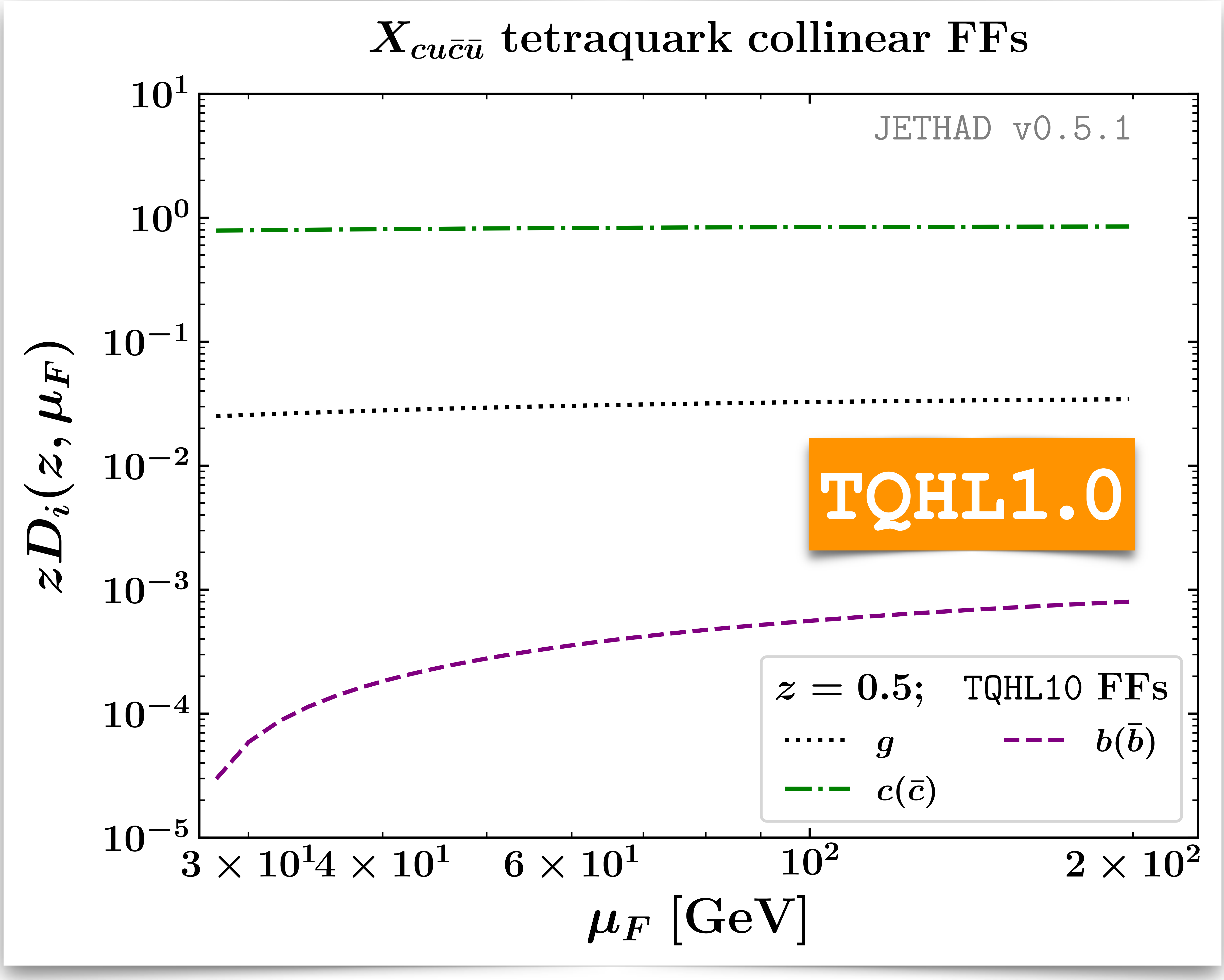
(LO) 🔗 [S. M. Moosavi Nejad, Phys. Rev. D 05 (2022) 3, 034001]

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

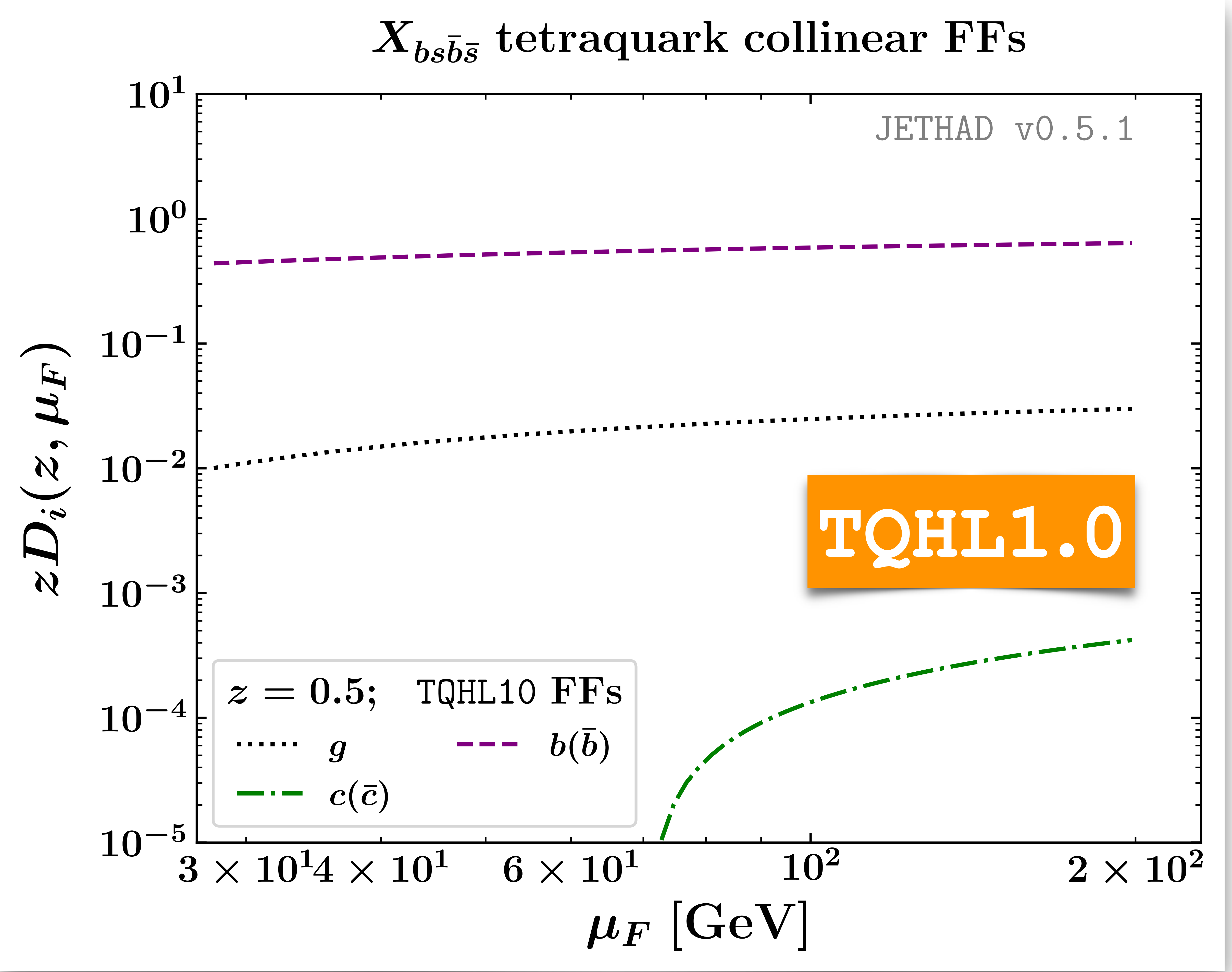
Backup

Heavy-light tetraquarks at the HL-LHC

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



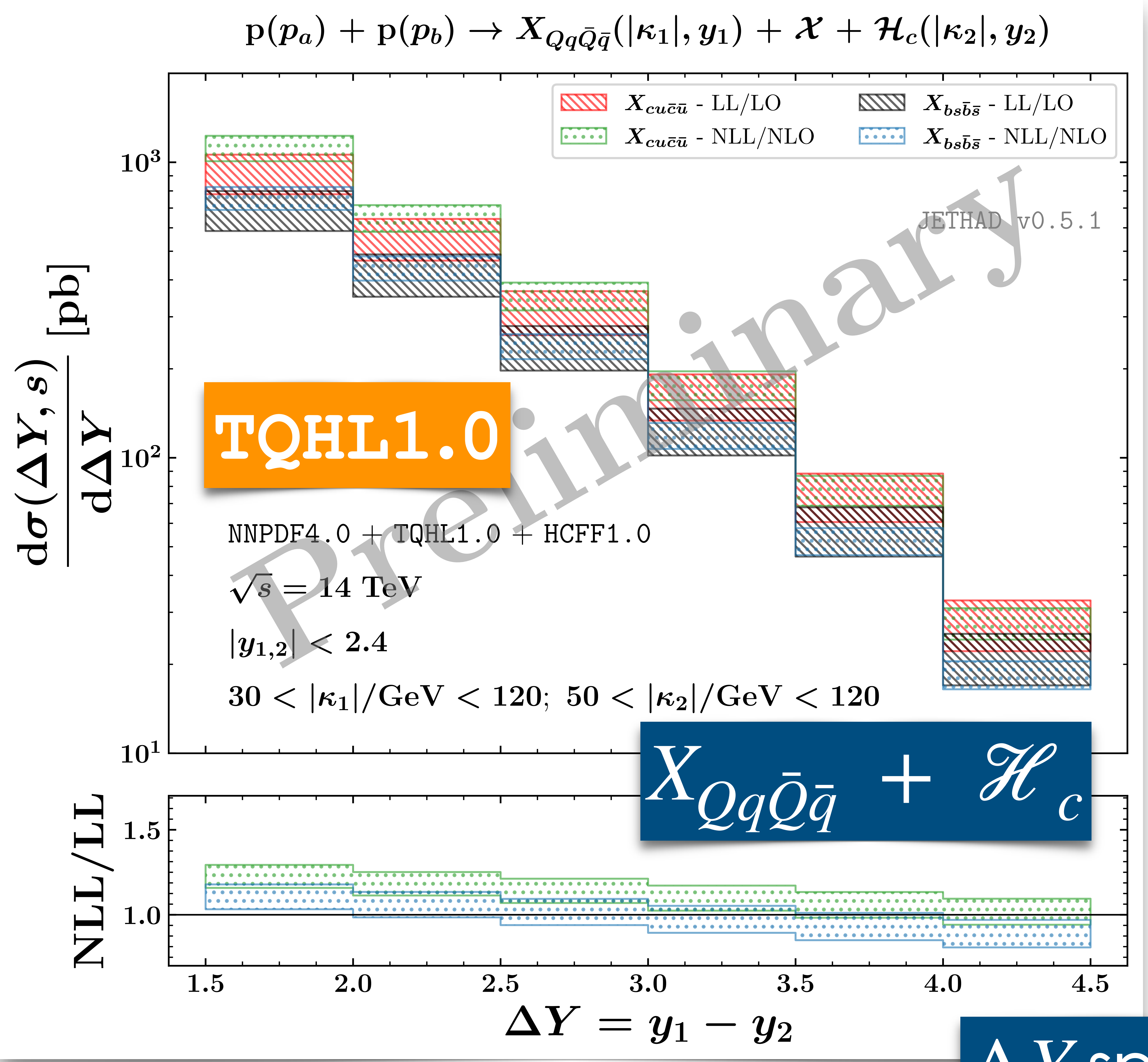
$X_{bs\bar{b}\bar{s}}$ collinear FFs

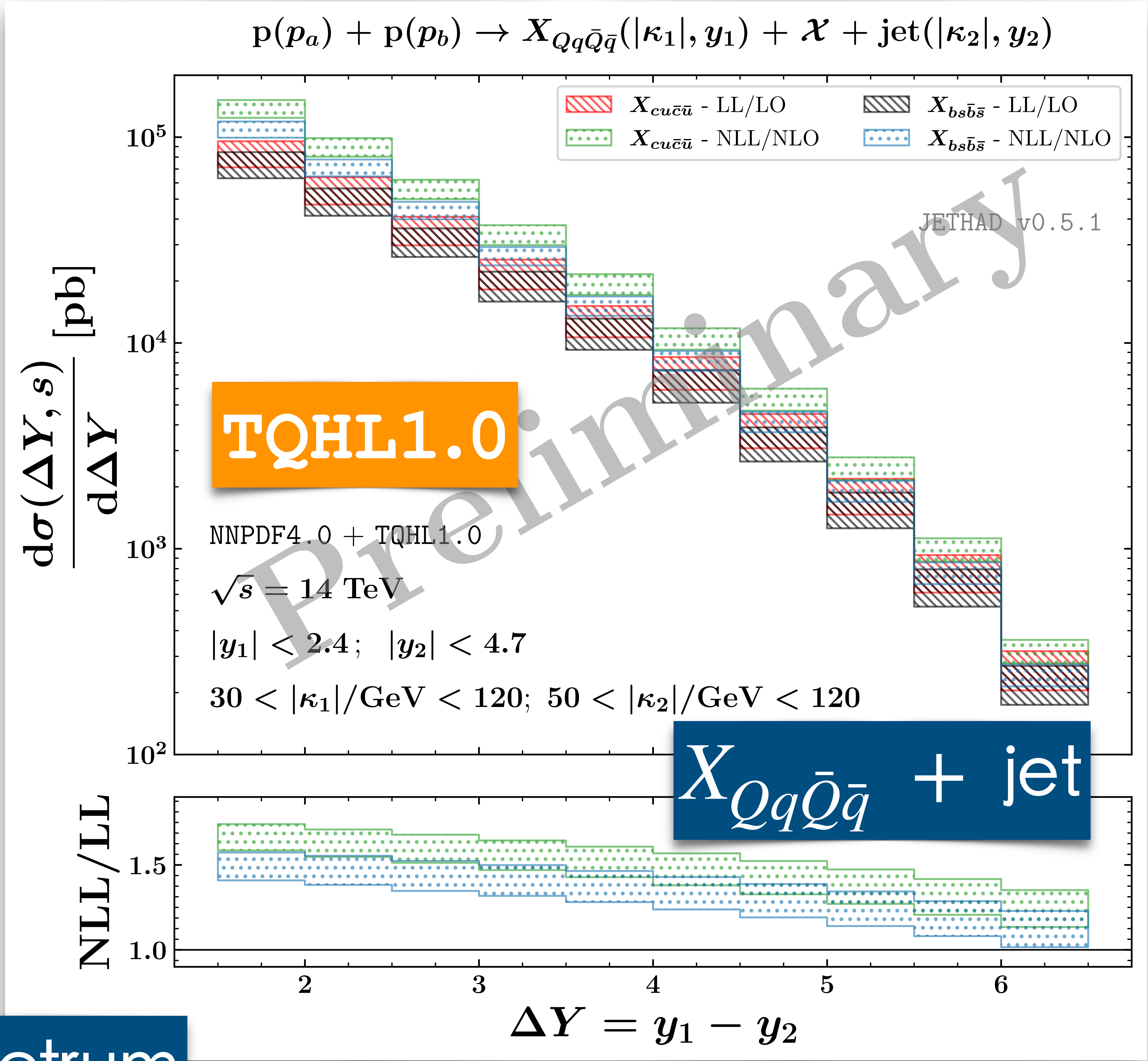


[F. G. C., A. Papa, in preparation]

Backup

Heavy-light tetraquarks at the HL-LHC



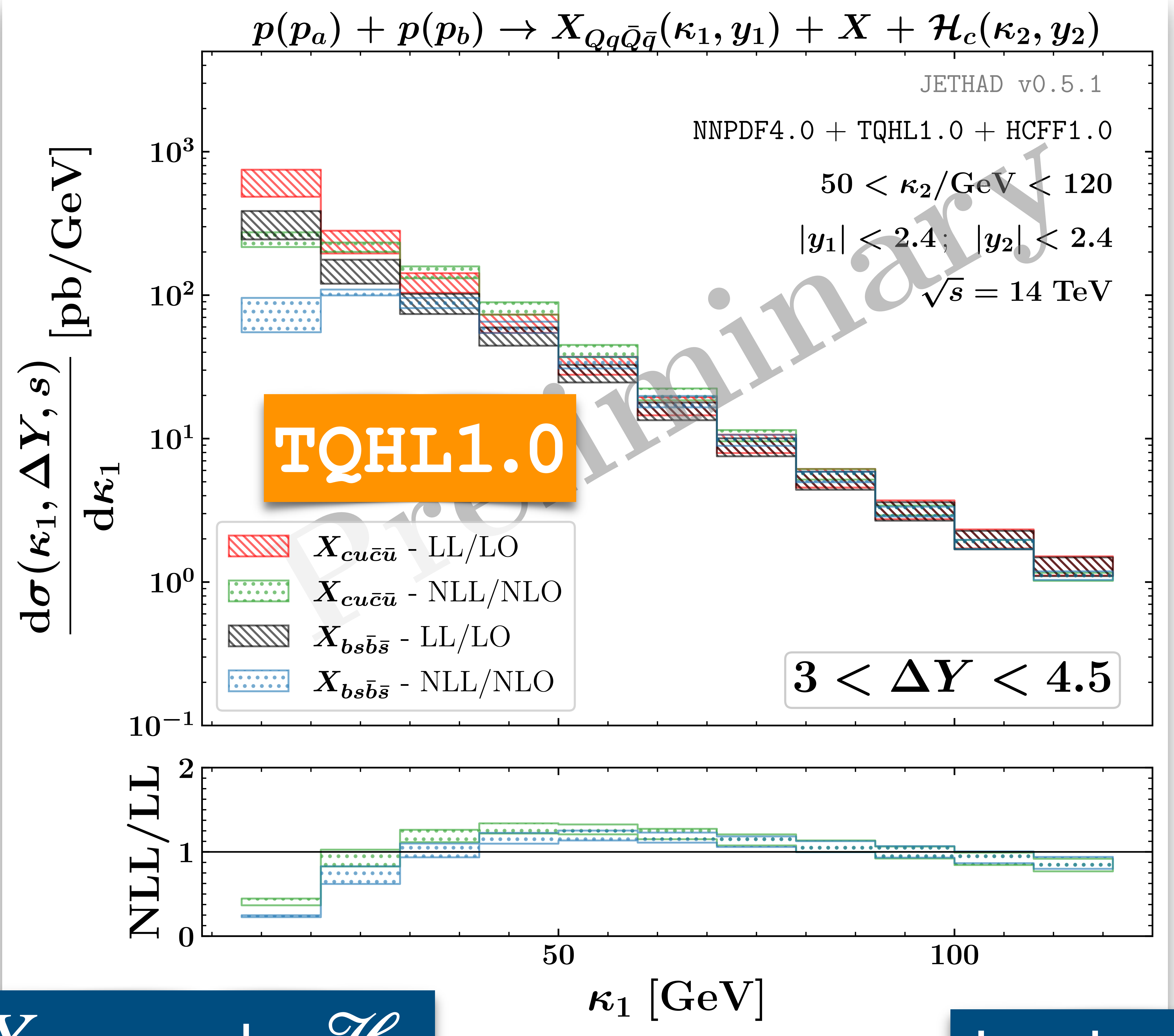


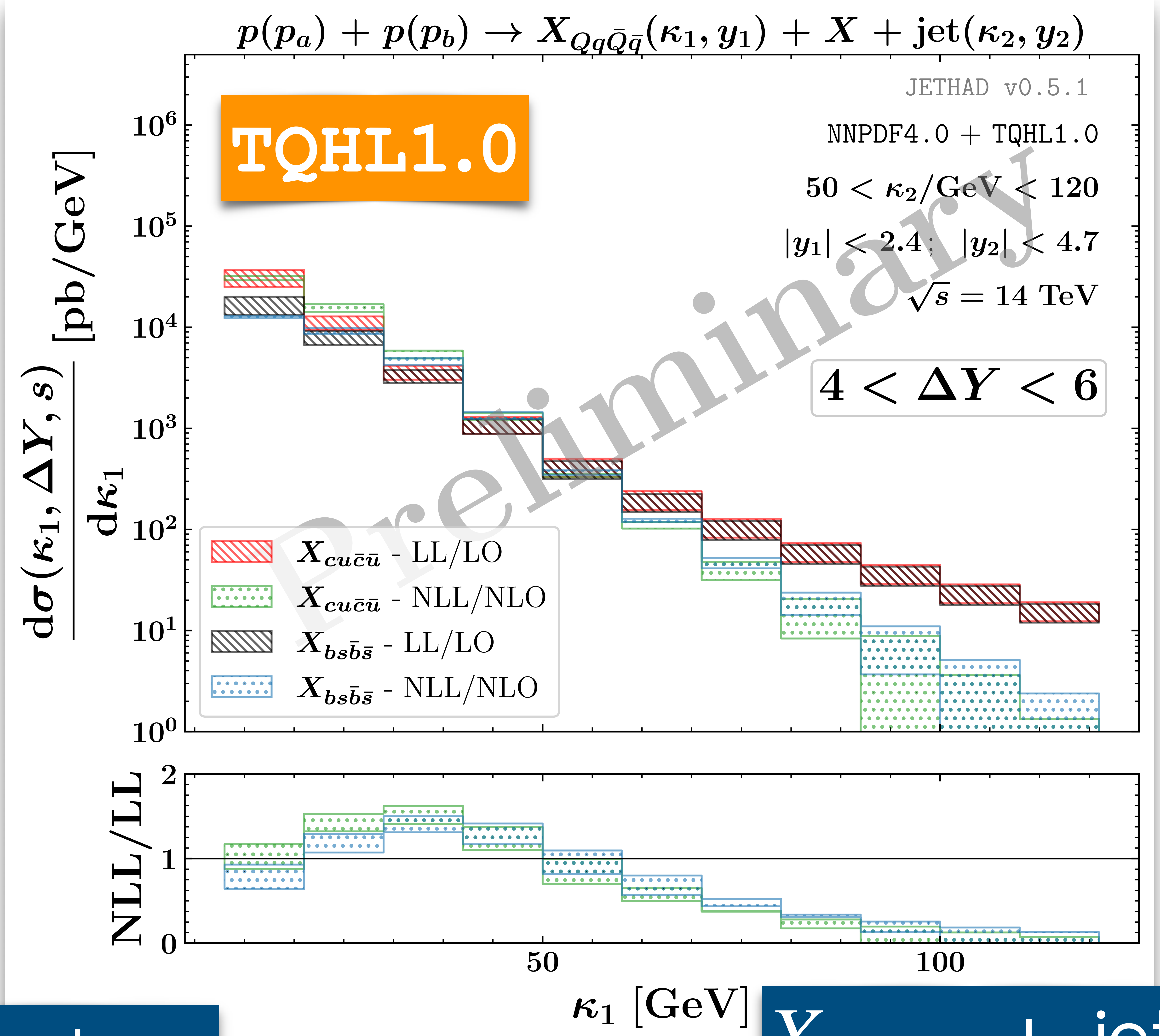
ΔY spectrum

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

Backup

Heavy-light tetraquarks at the HL-LHC





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

$|\kappa_1|$ spectrum

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

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

Backup

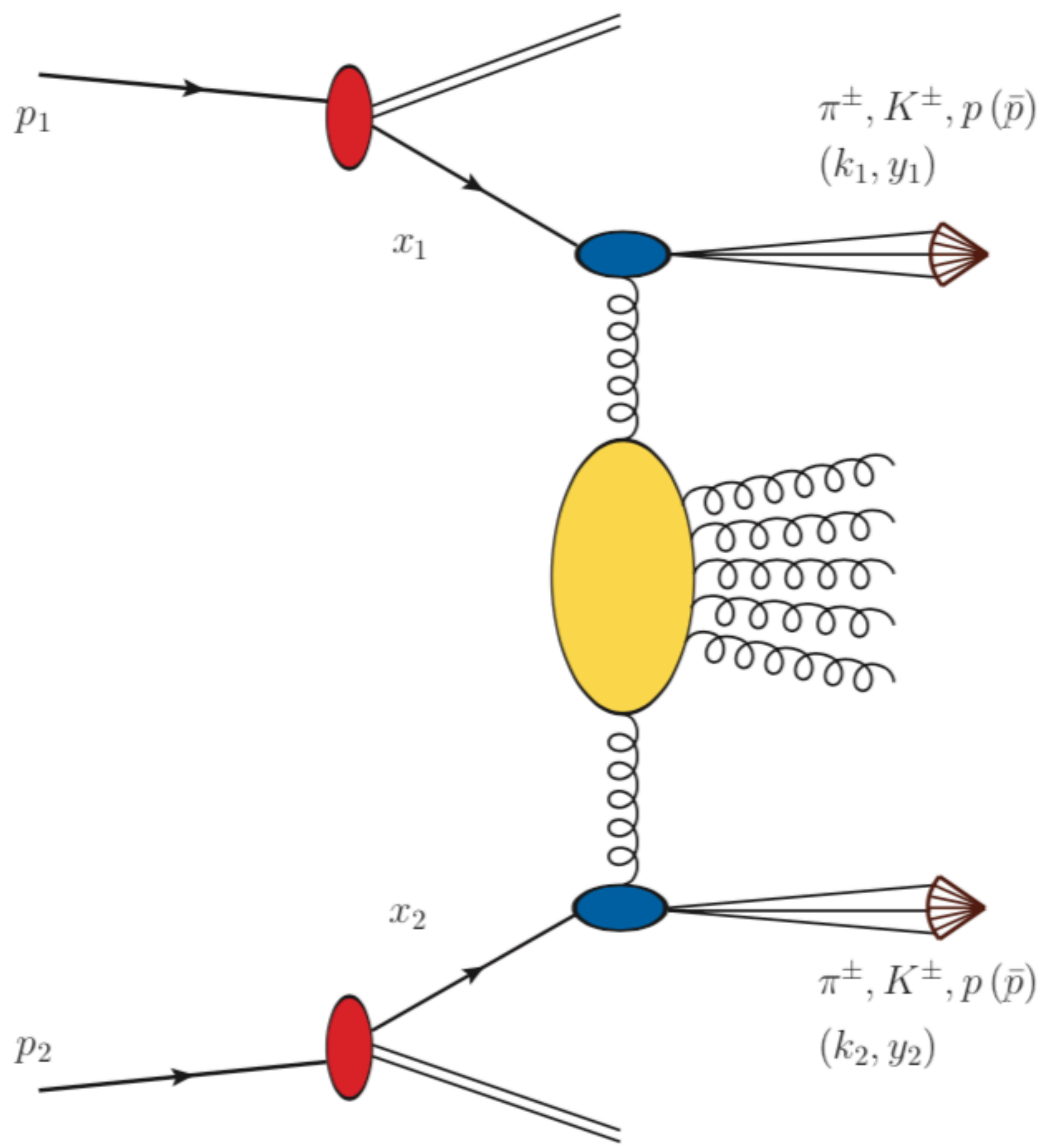
Heavy-flavored emissions

From Higgs + jet to bound states

Di-hadron and hadron-jet correlations

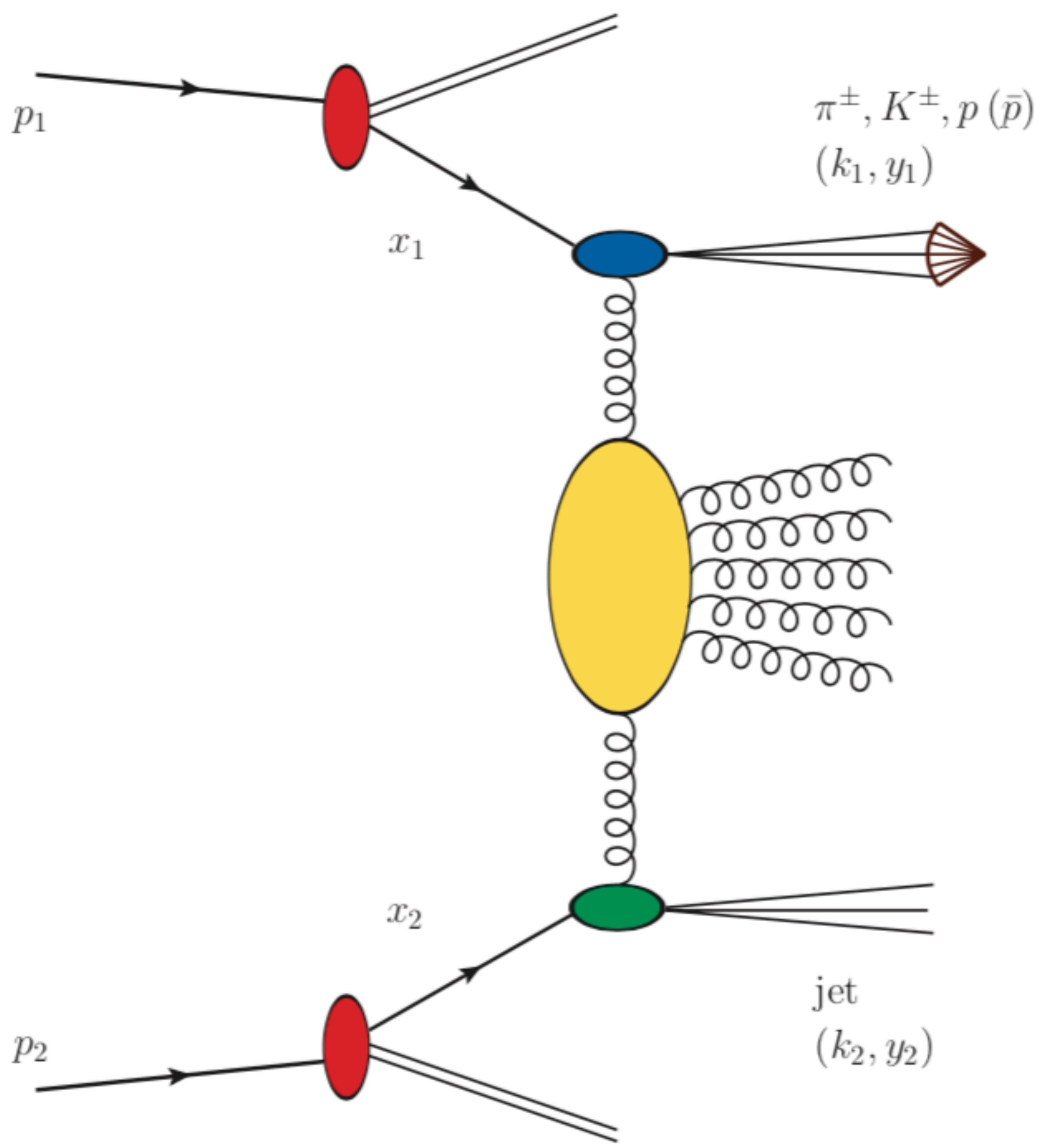
Inclusive di-hadron production

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



Inclusive hadron-jet production

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



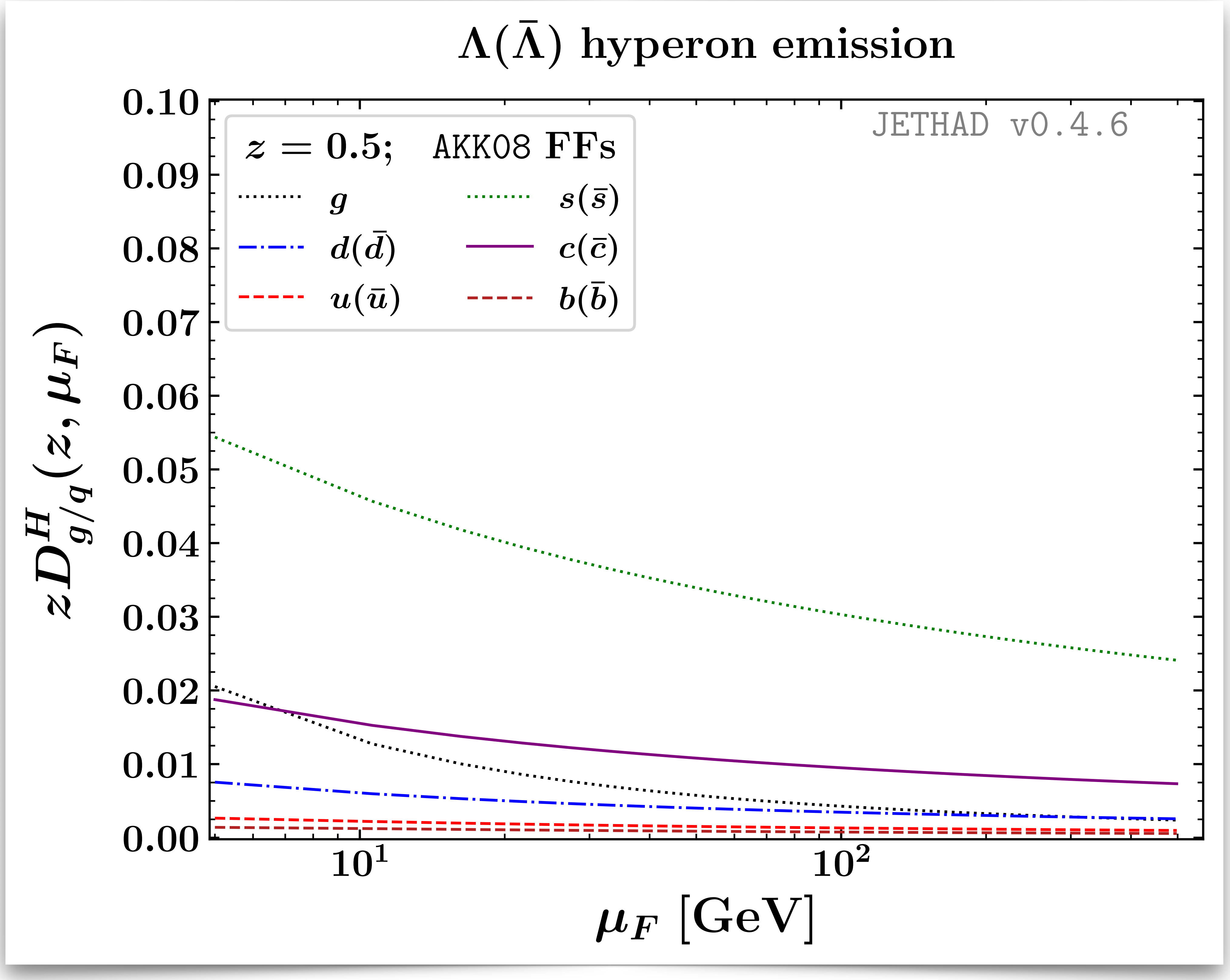
- ◇ NLO impact factors known $\Rightarrow$ full NLA BFKL analysis feasible
- ◇ PDFs + FFs at work (both), hadrons at smaller rapidities than jets (di-hadron)
- ◇ genuine *asymmetric* cuts in transverse momenta (hadron-jet)

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

Backup

Stabilizing effects of heavy-flavor fragmentation

AKK08 VFNS collinear FFs for Λ hyperon: $|uds\rangle$ [S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]



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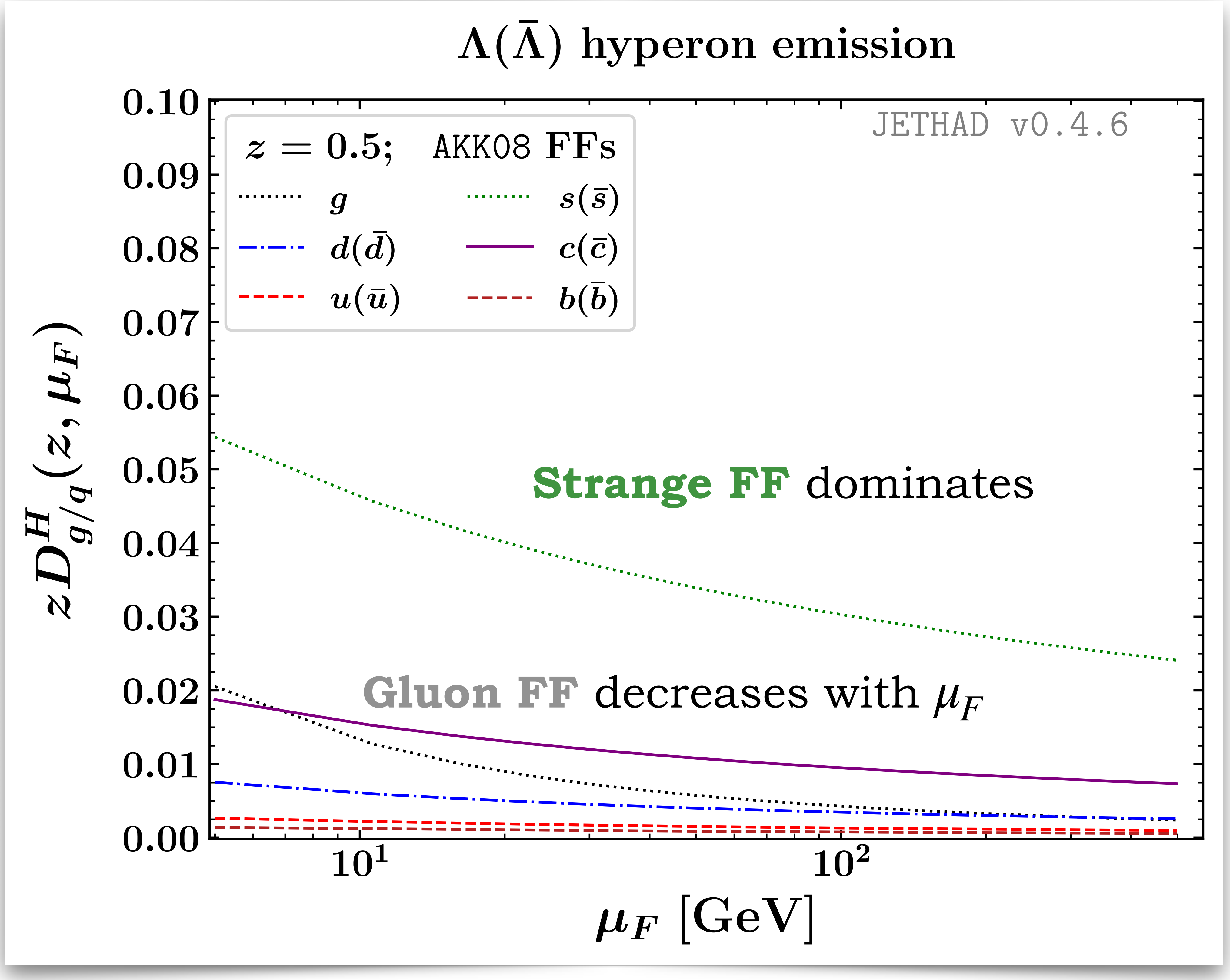

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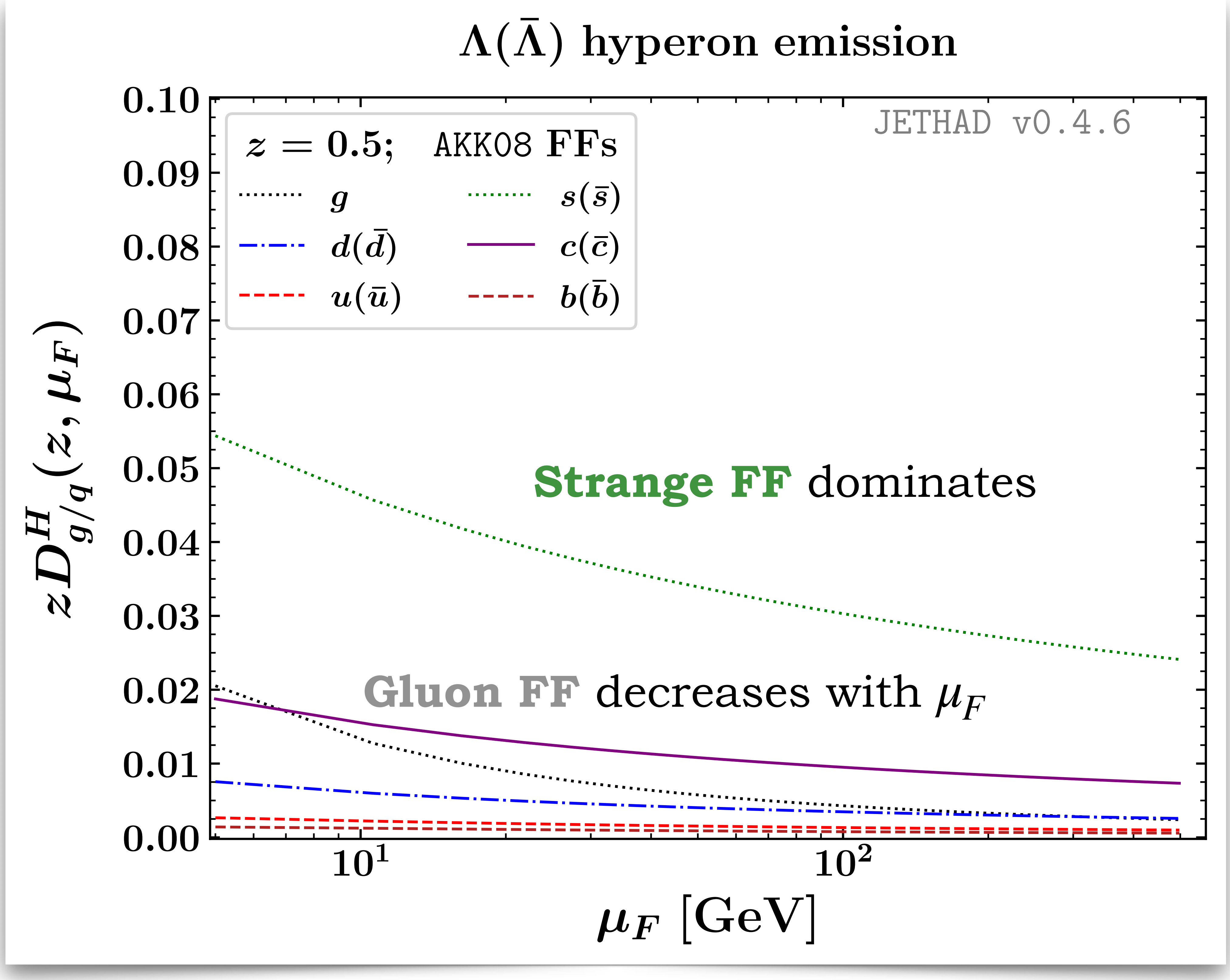
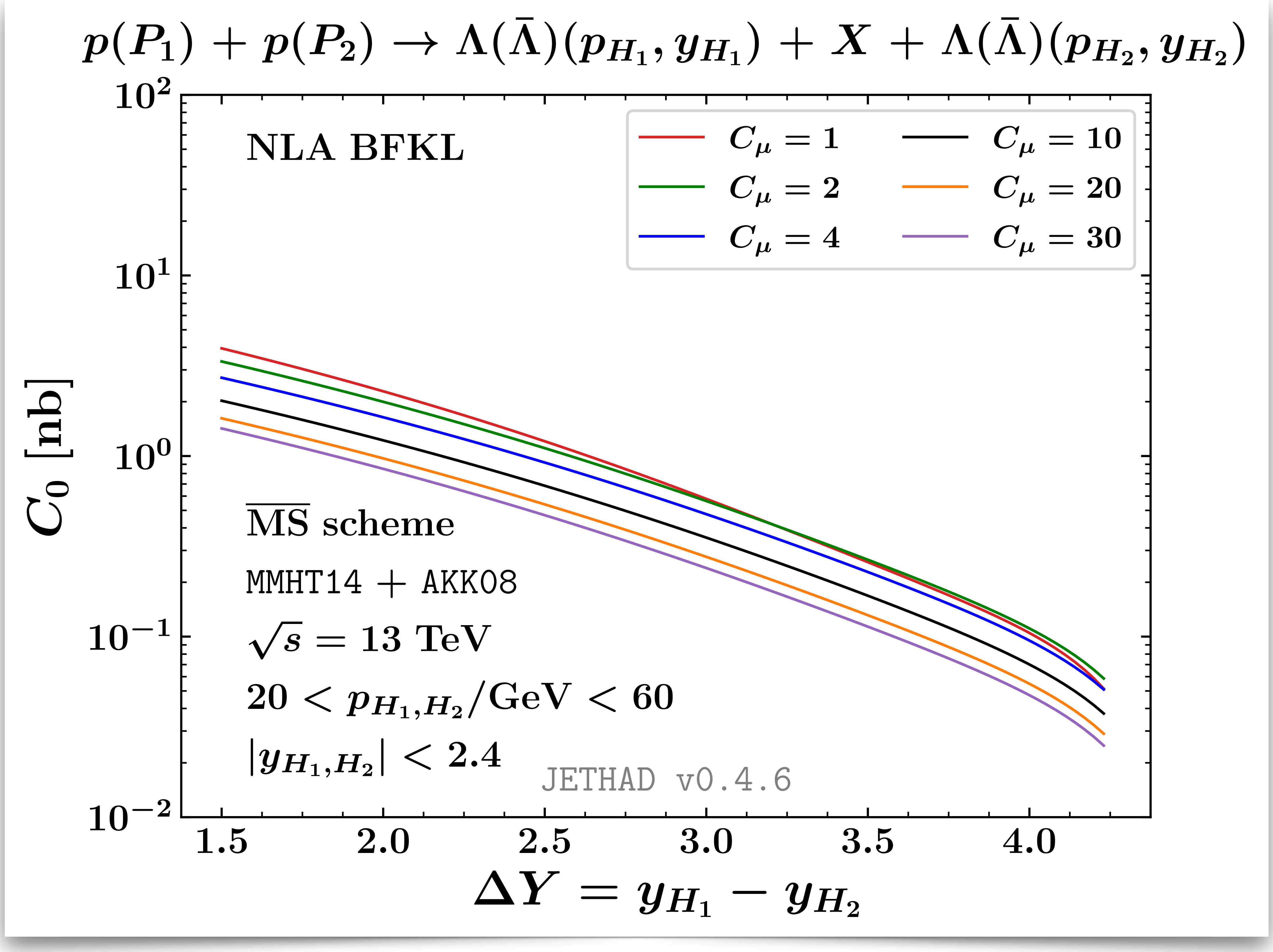




Rapidity distribution sensitive to scale variations

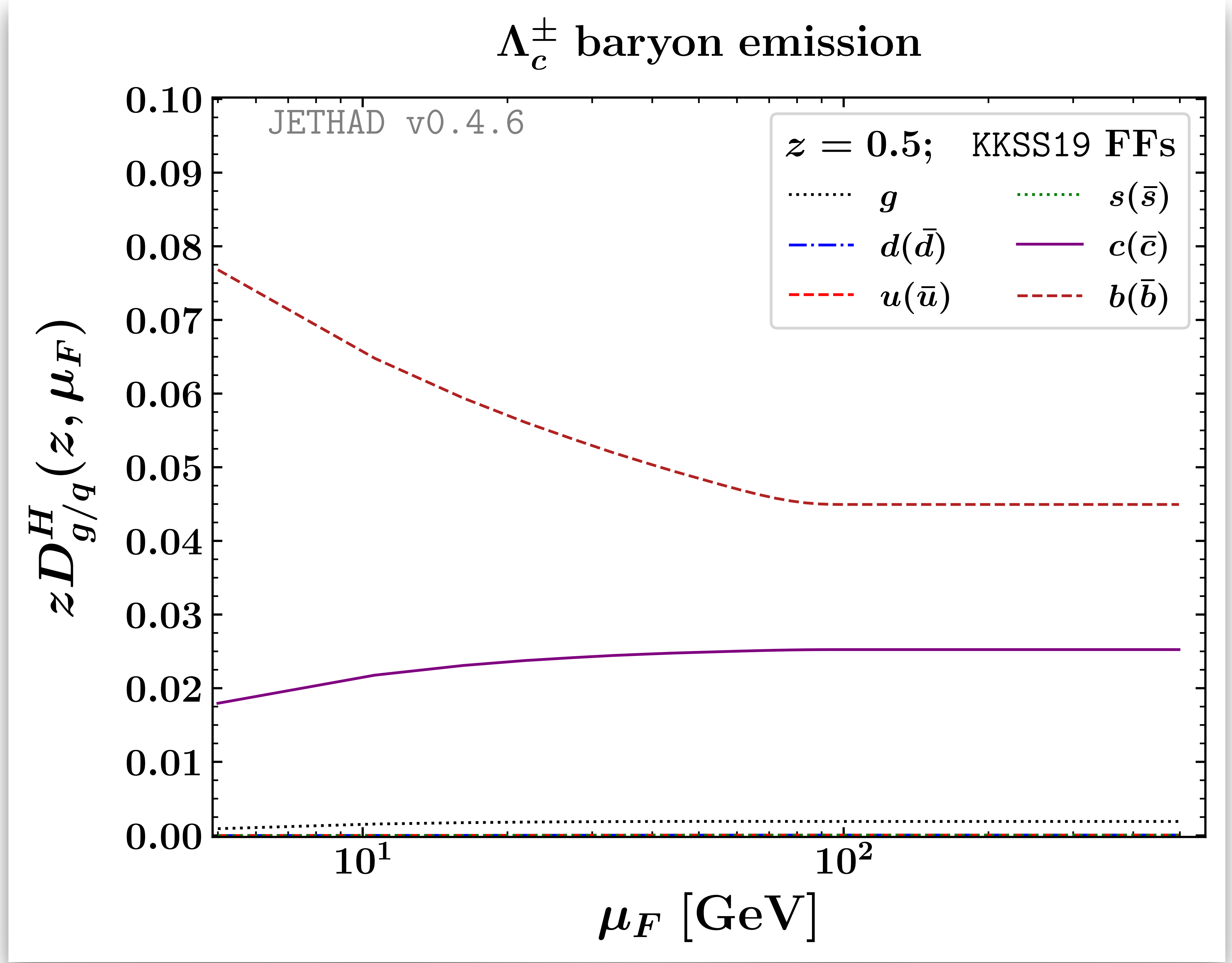
(Λ hyperons) [F. G. C. et al., Phys. Rev. D 102 (2020) 9, 094019]

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

Backup

Stabilizing effects of heavy-flavor fragmentation

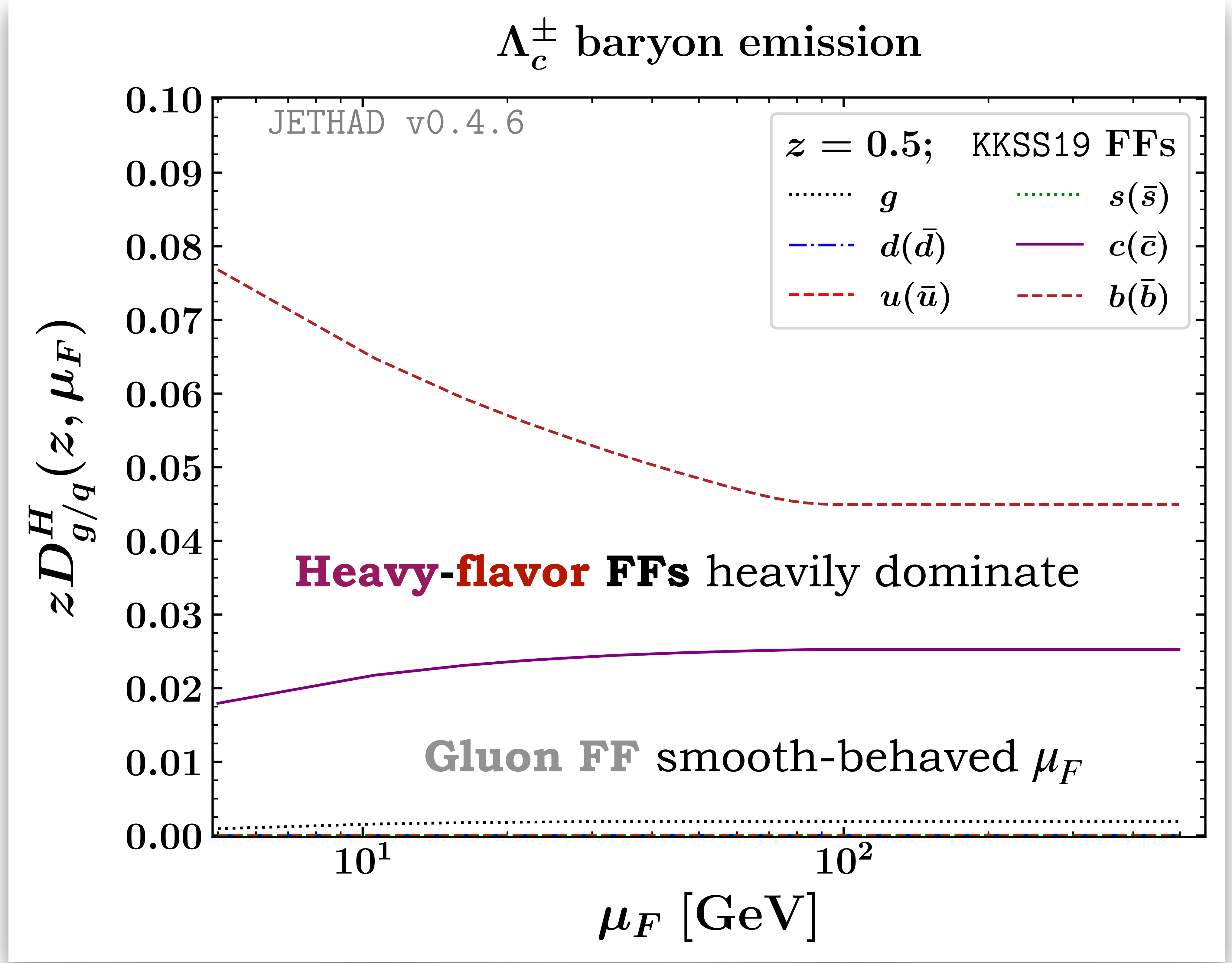
KKSS19 VFNS collinear FFs for Λ_c baryons: $|udc\rangle$ [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]



Backup

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]



Backup

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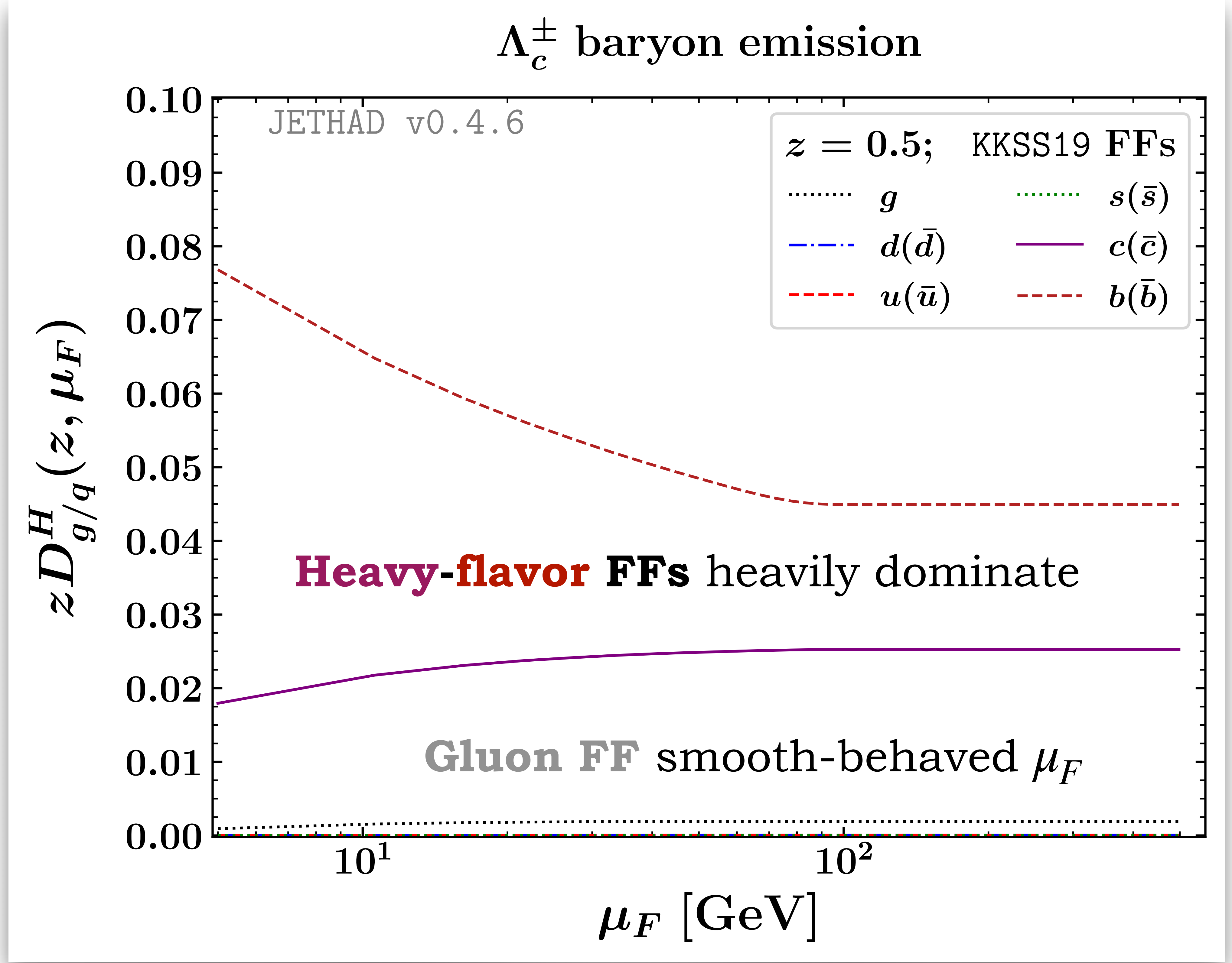
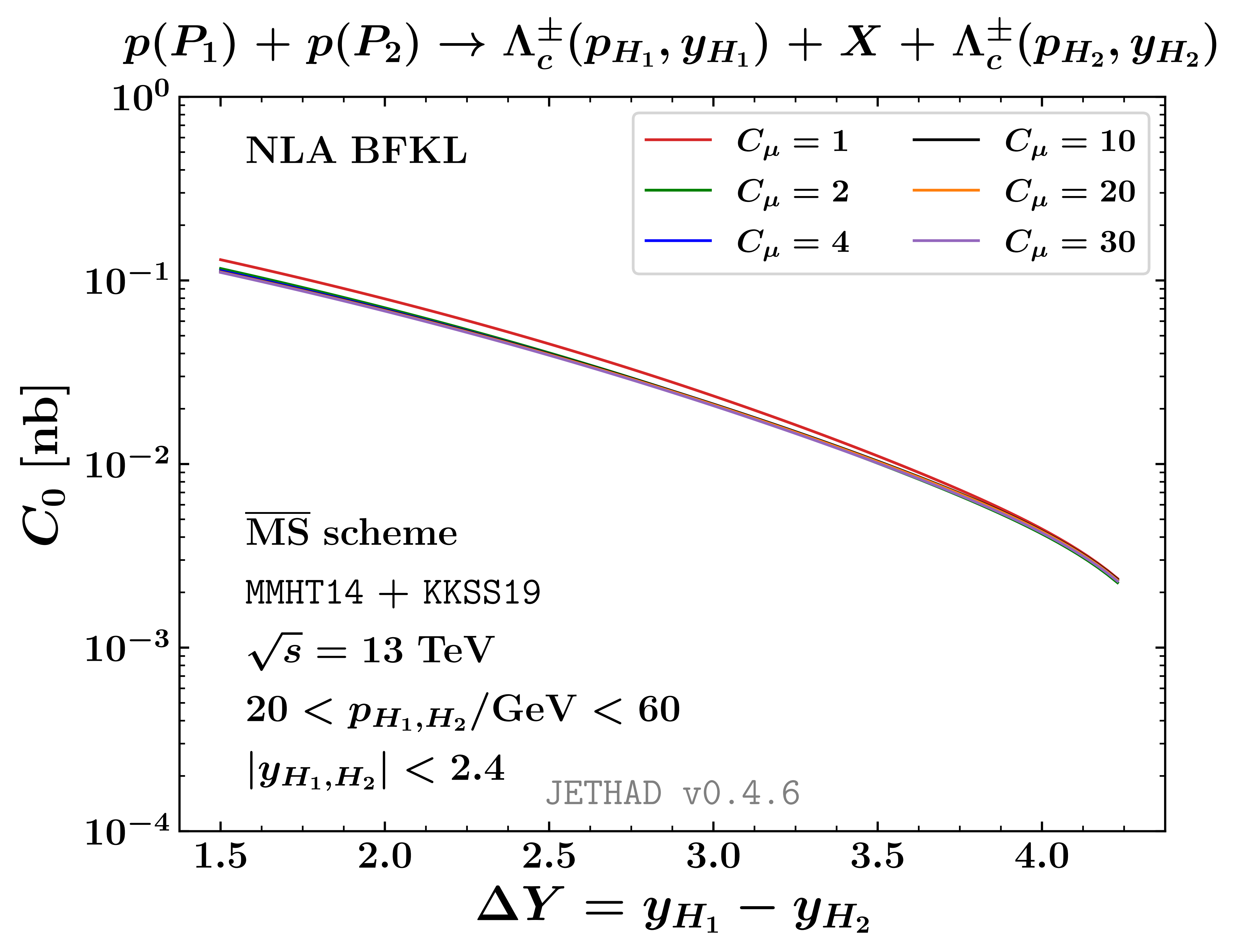




Rapidity distribution stable under scale variations

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

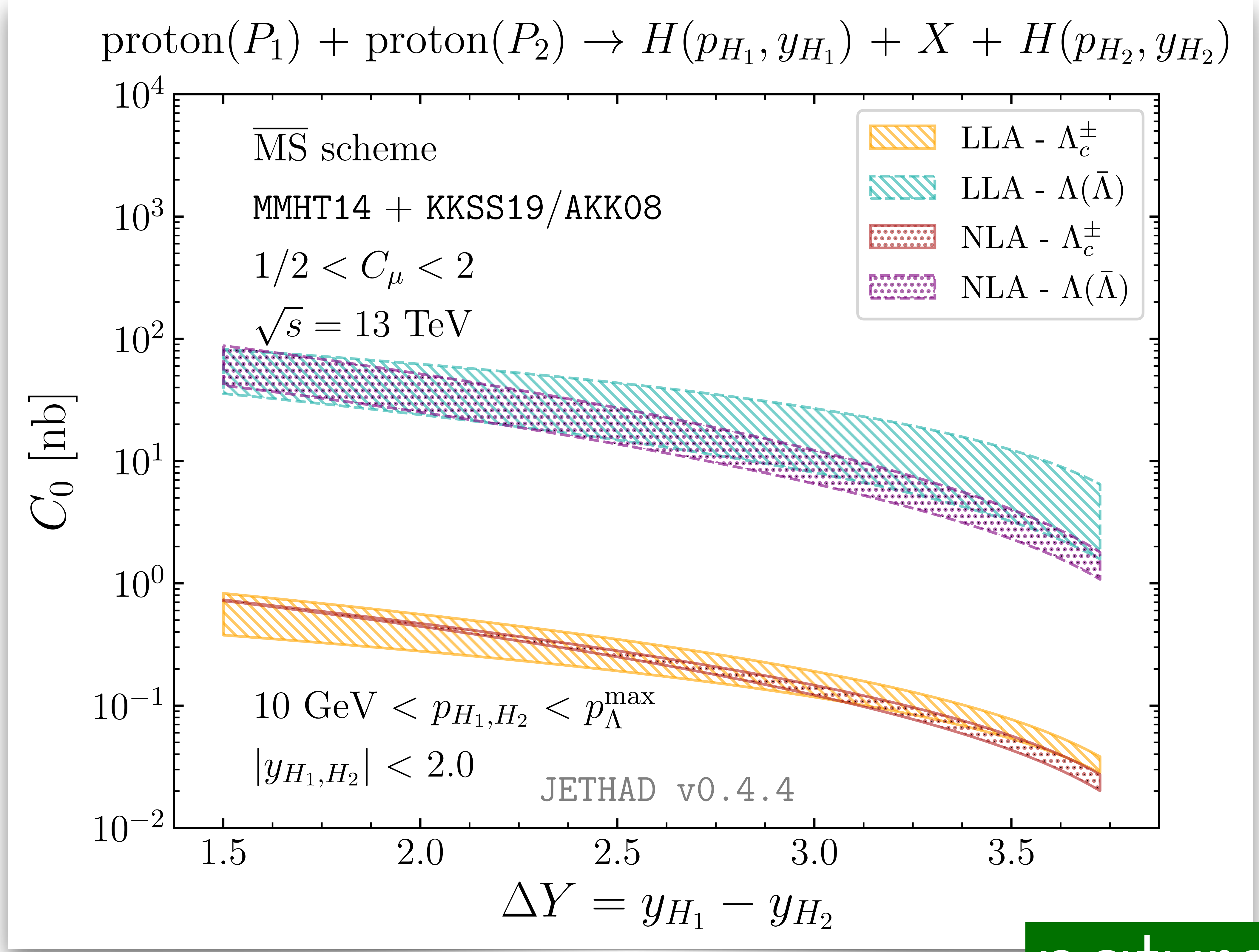
(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

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

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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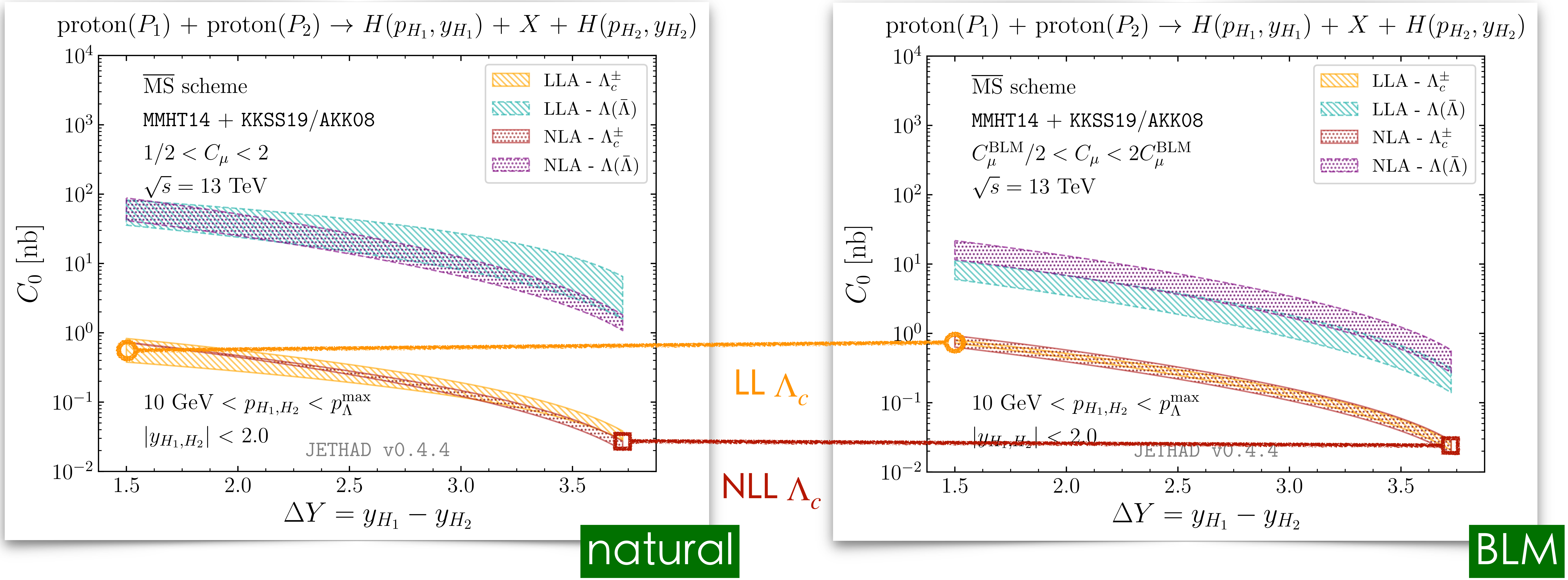

NLL corrections: rapidity distribution stable for Λ_c

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

Backup

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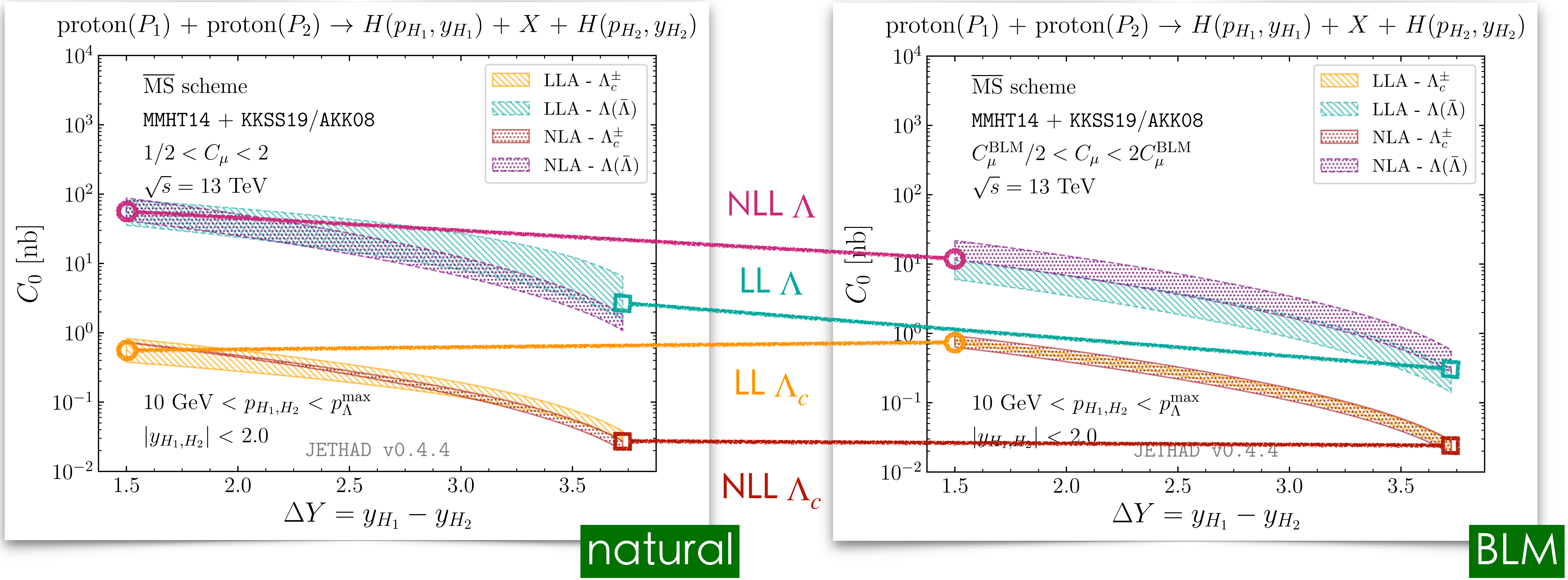


NLL corrections: rapidity distribution stable for Λ_c, loses $\sim 10^1$ magnitude for Λ

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

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

Backup

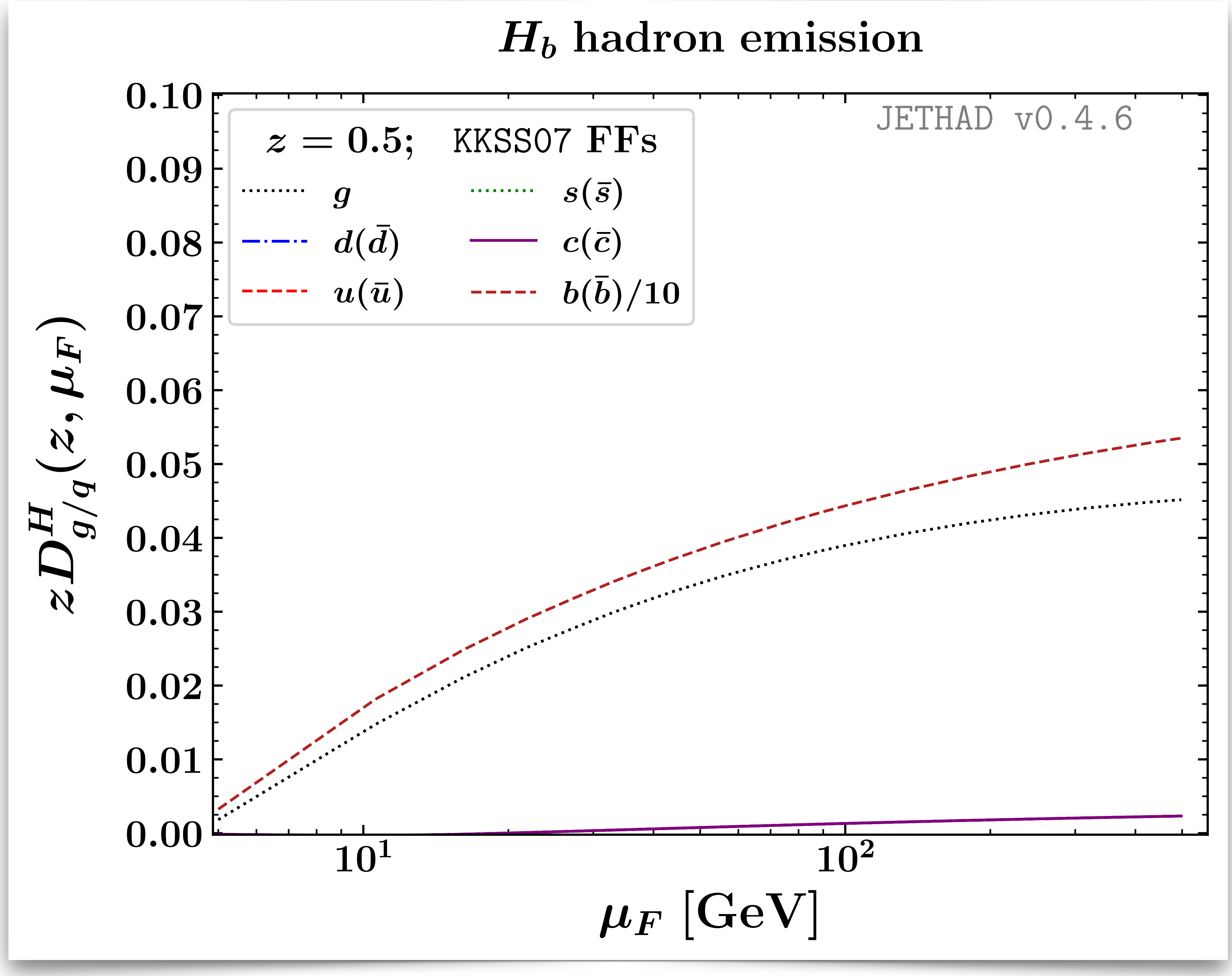
Stabilizing effects of heavy-flavor fragmentation

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]



Backup

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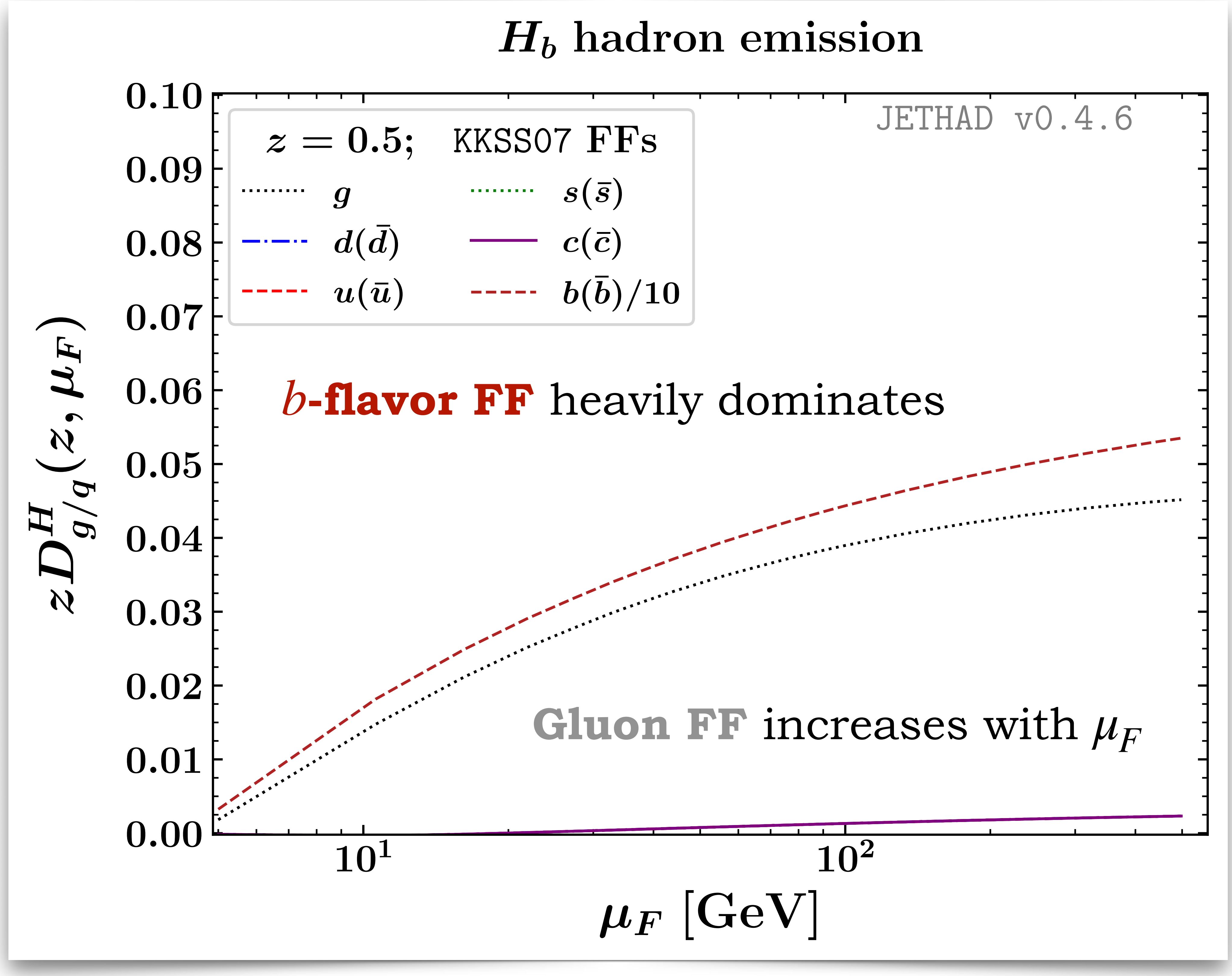

Backup

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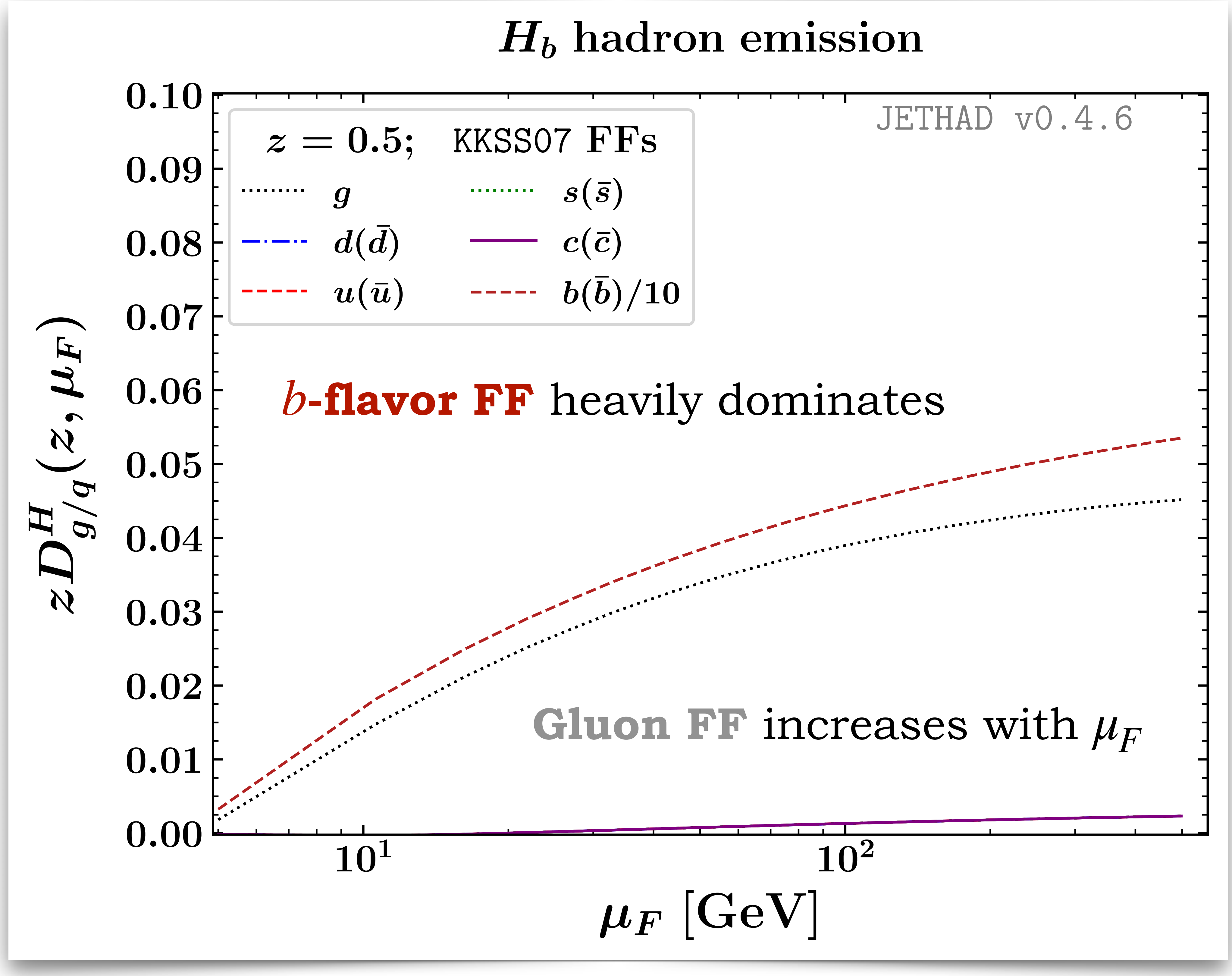

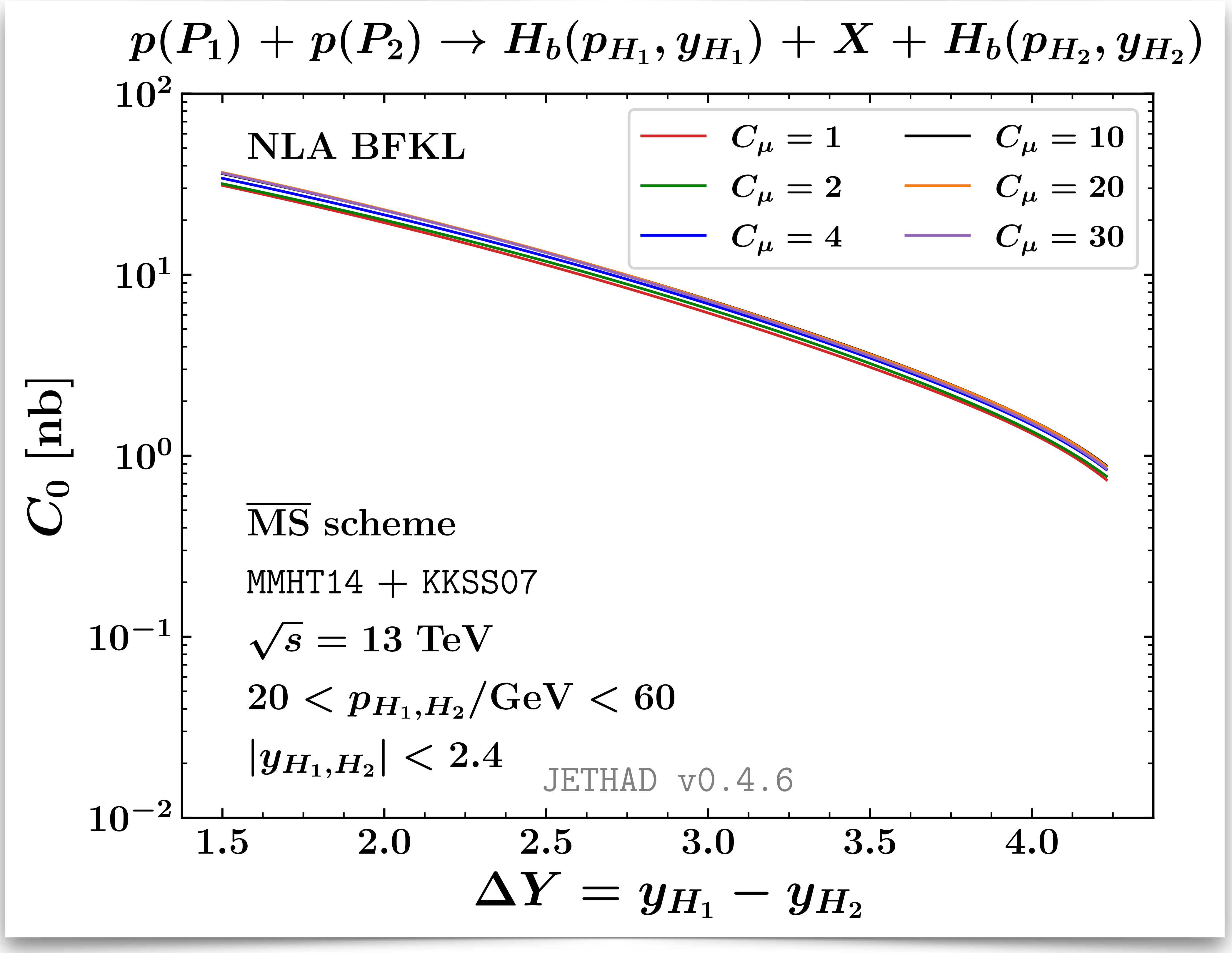

Rapidity distribution very stable under scale variations

(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]

Backup

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...

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

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

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

Backup

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

- Gluon FF rises with energy ⇒ this compensates PDF and BFKL kernel decreasing behavior

Backup

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

Quarkonia

Is the natural stability robust?

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

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

Backup

Is the natural stability robust?

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

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

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

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

Backup

Vector quarkonium from single-parton fragmentation

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

Backup

Vector quarkonium from single-parton fragmentation

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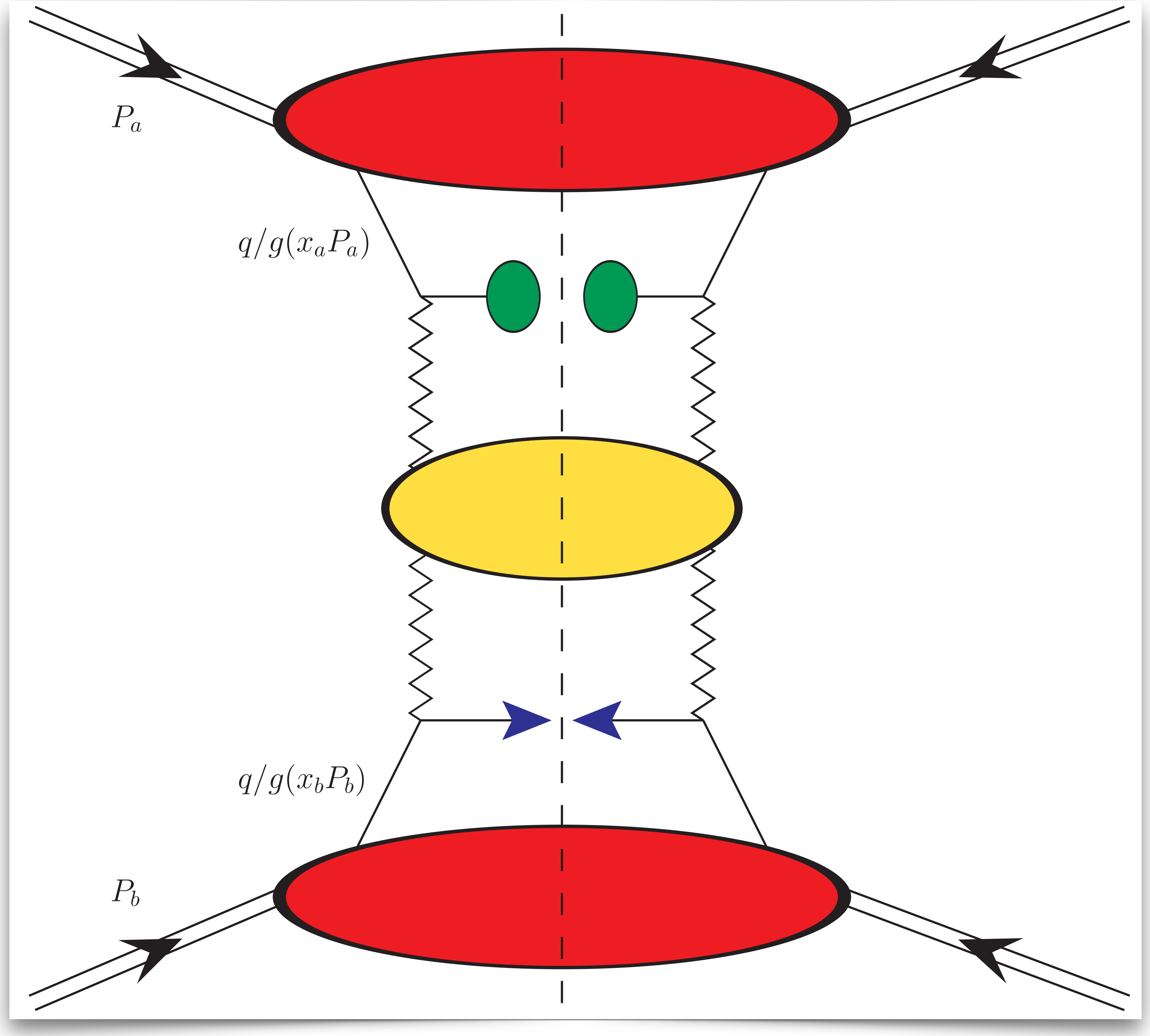


2.1 High-energy resummed cross section

The process under investigation is

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

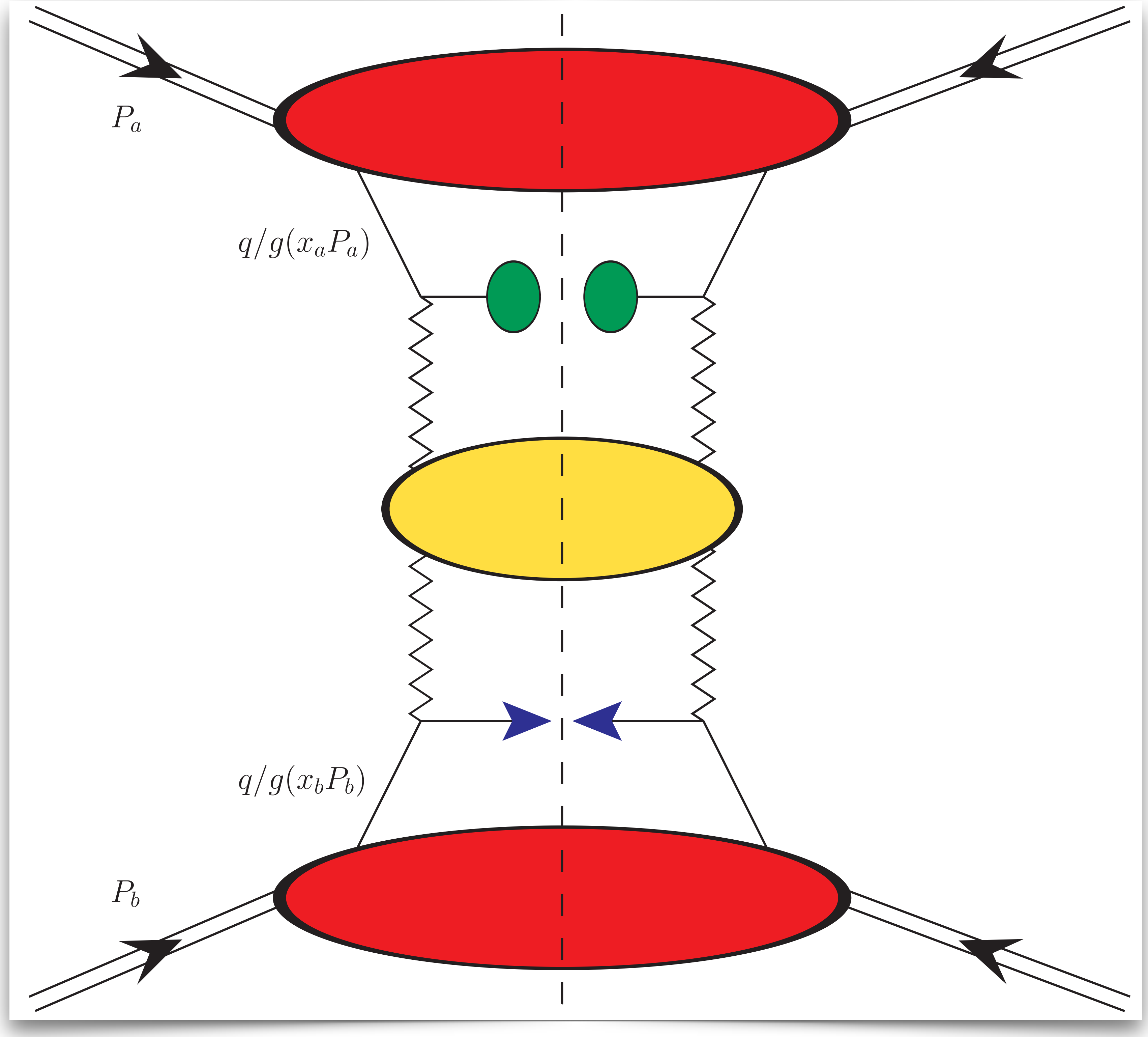
where $p(P_{a,b})$ stands for an initial proton with momentum $P_{a,b}$, $\mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q})$ is a J/ψ or a Υ emitted with momentum $p_\mathcal{Q}$ and rapidity $y_\mathcal{Q}$, the light jet is tagged with momentum p_J and rapidity y_J, and X denotes all the undetected products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

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

Backup

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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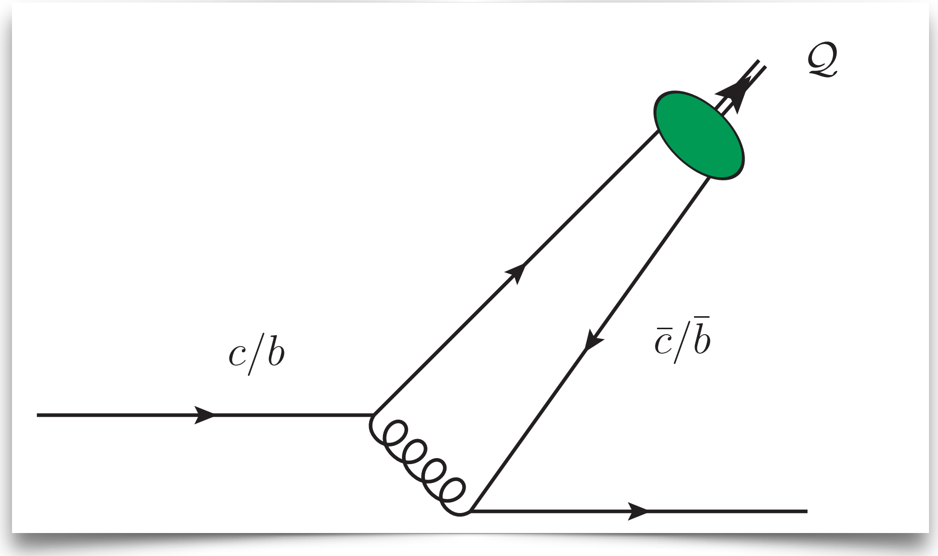


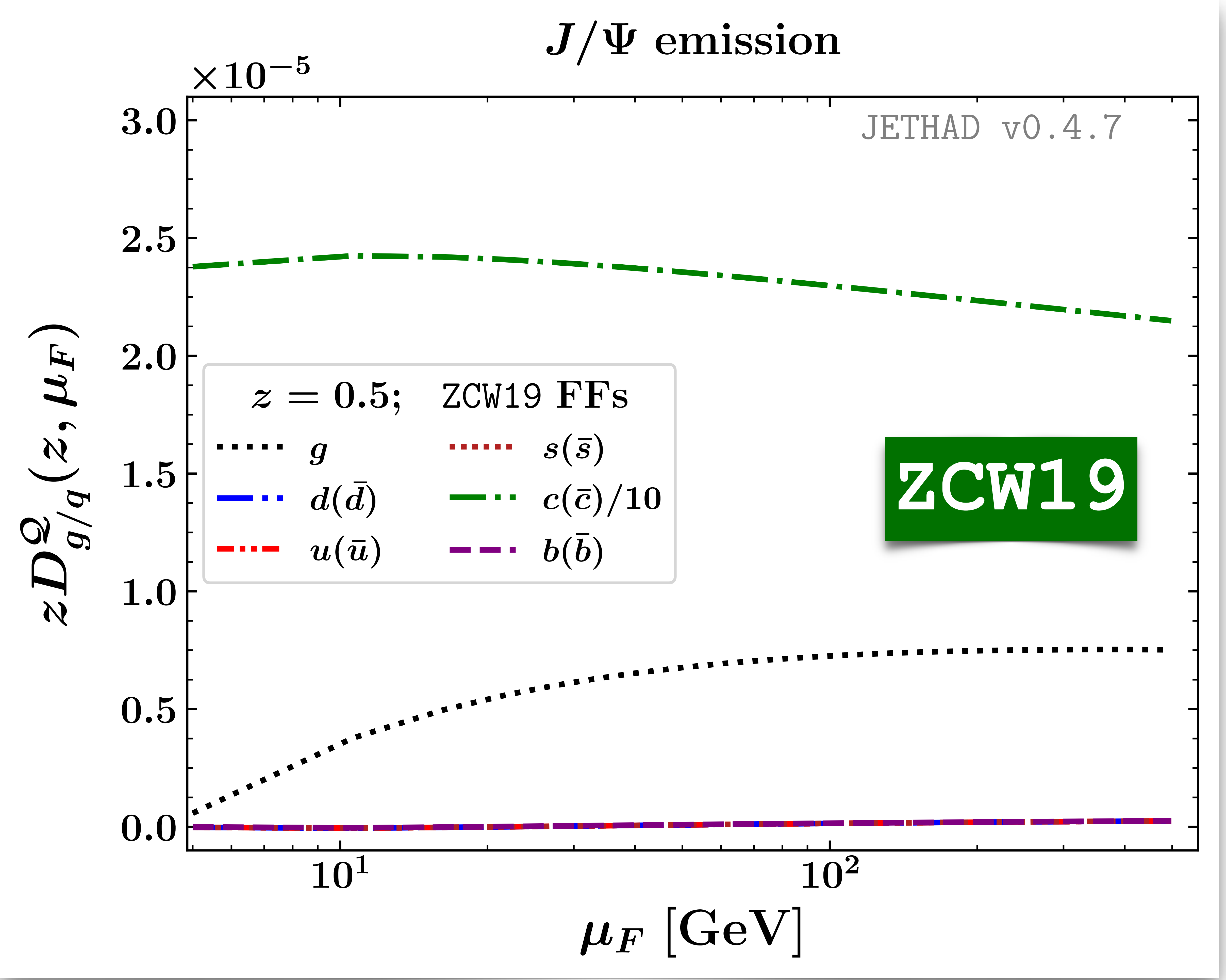
(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

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

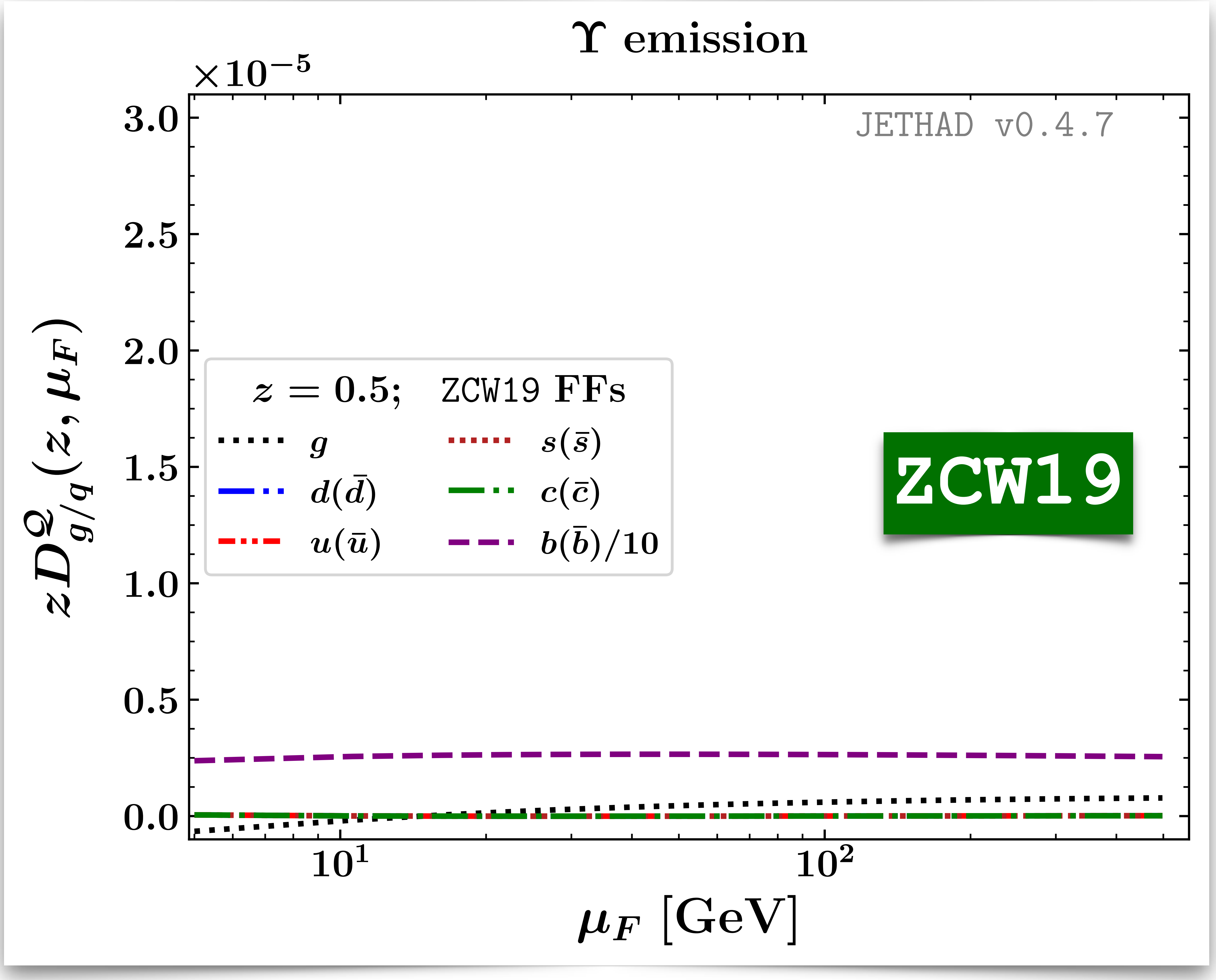
Backup

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



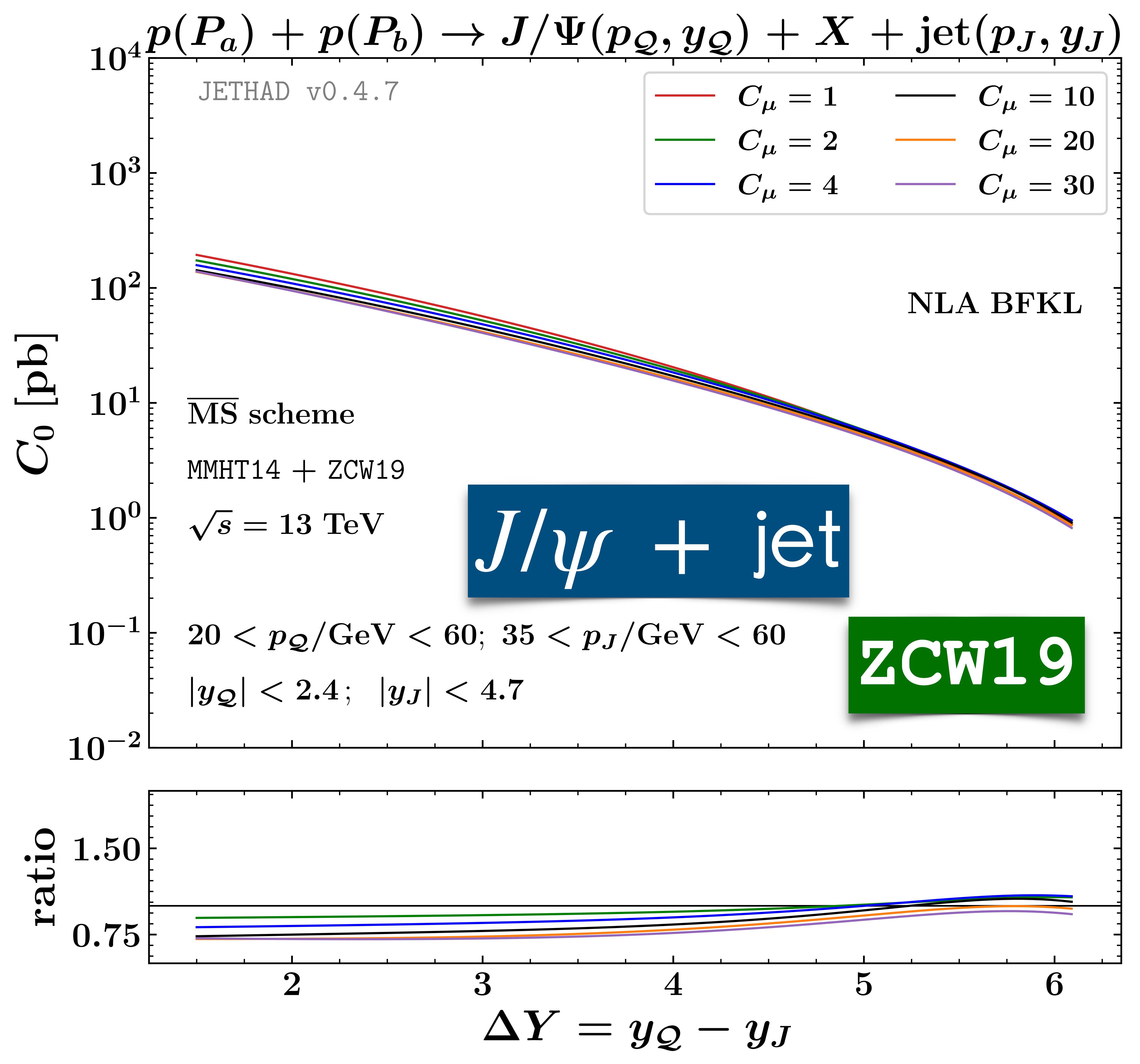
Υ collinear FFs

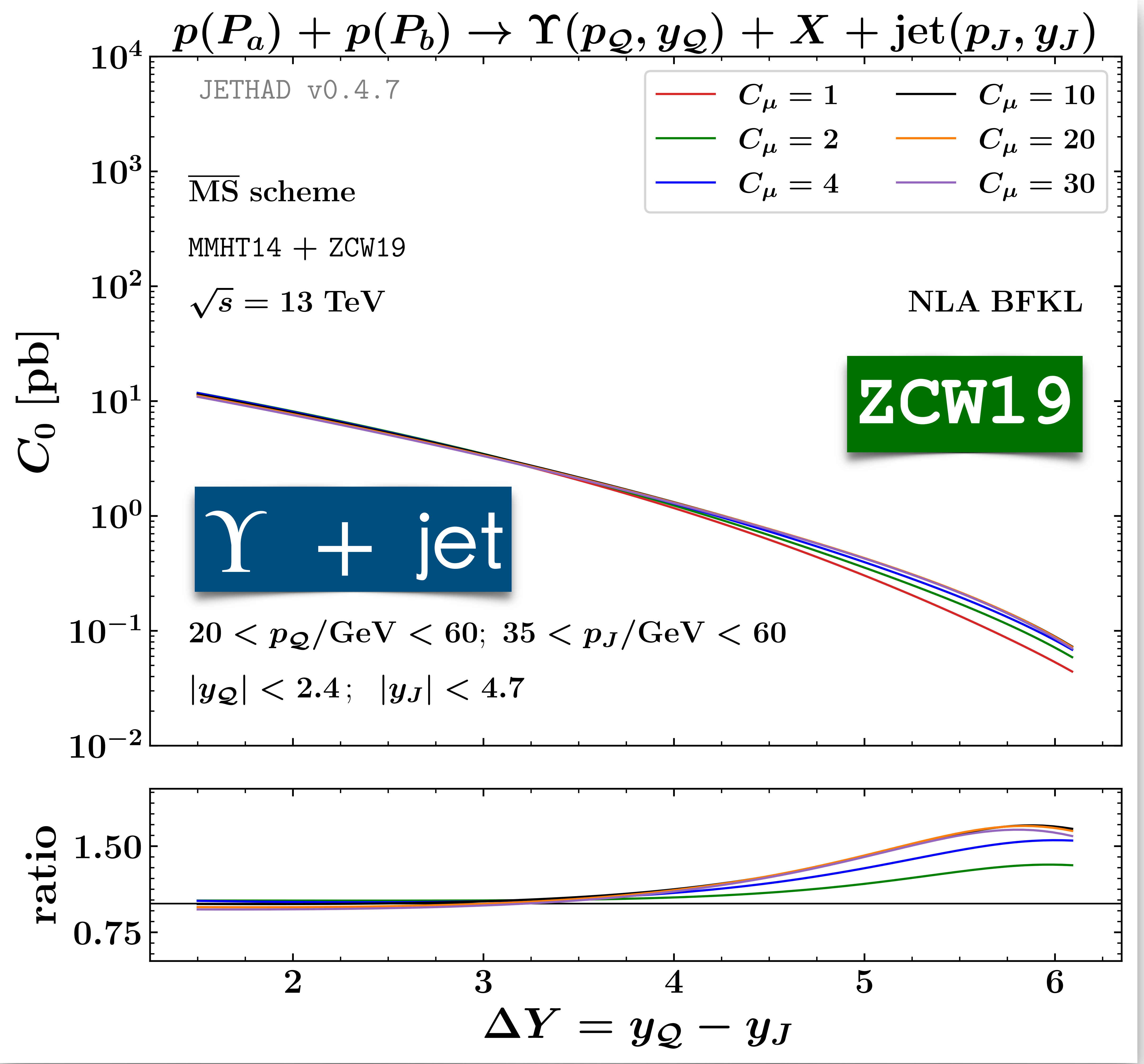


Backup

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

Vector quarkonium + jet at the LHC



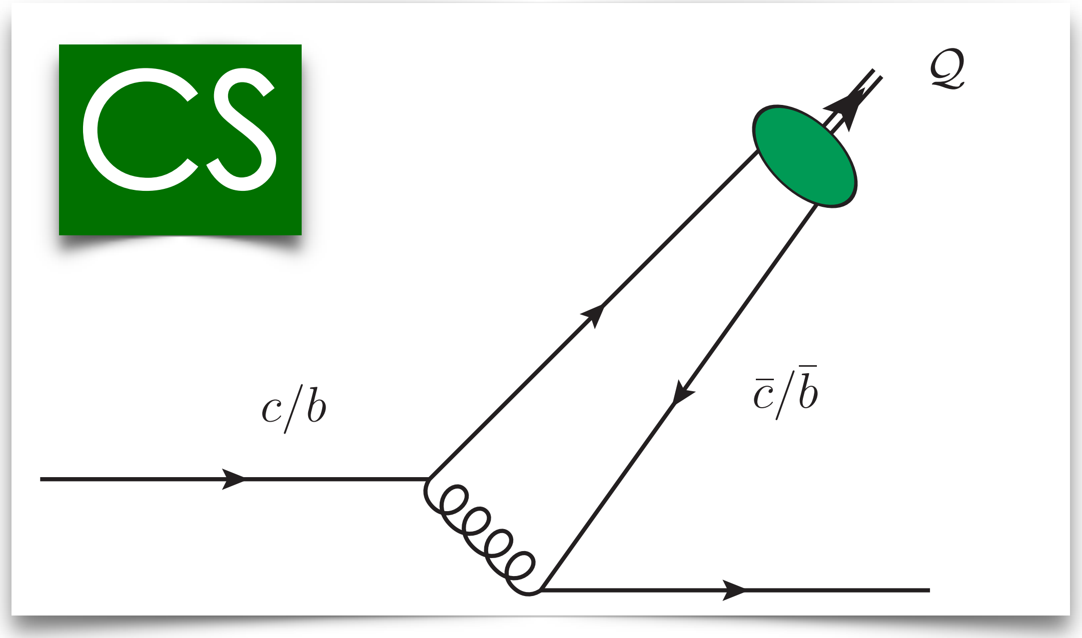


Backup

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

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 $\mu_0 = 3m_Q$

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

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

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

Backup

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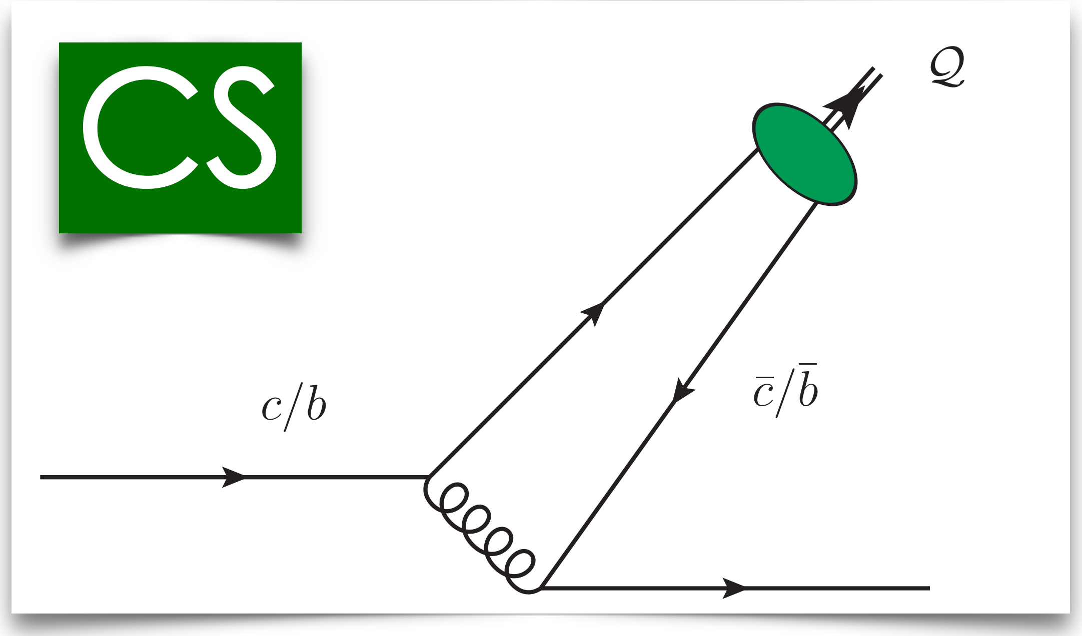

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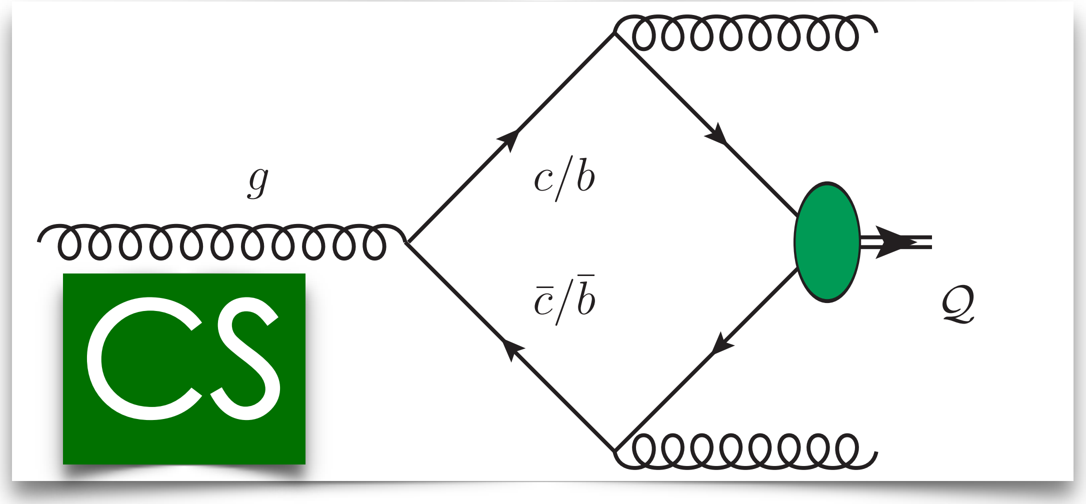
+



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

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

(LO) 🔗 [A. Braaten, T.C Yuan, Phys. Rev. Lett. 71 (1993), 1673]

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

Backup

Vector quarkonium from single-parton fragmentation

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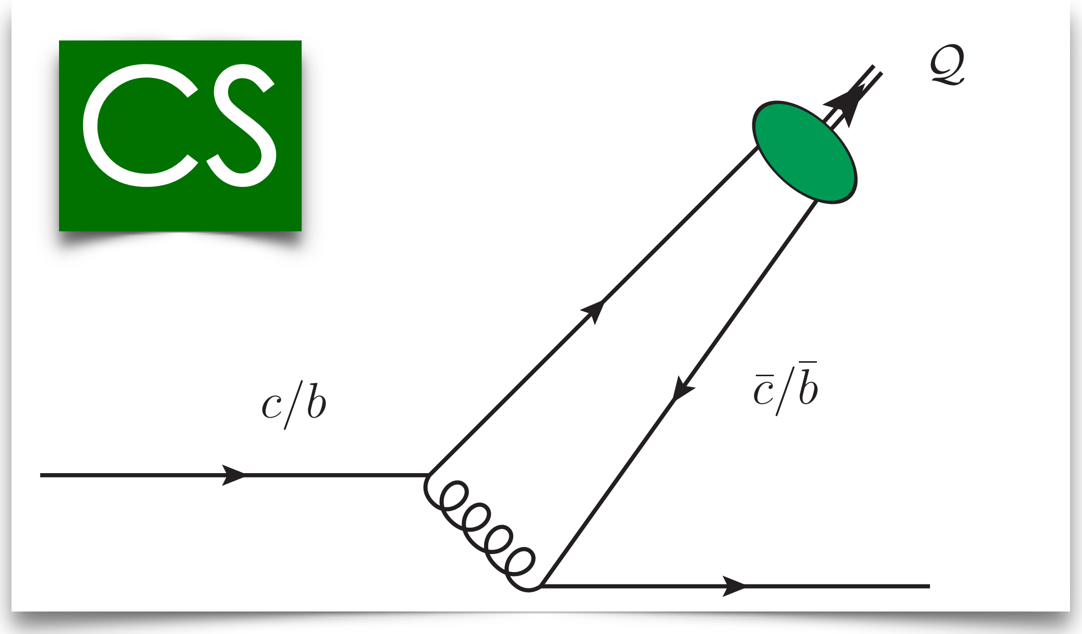

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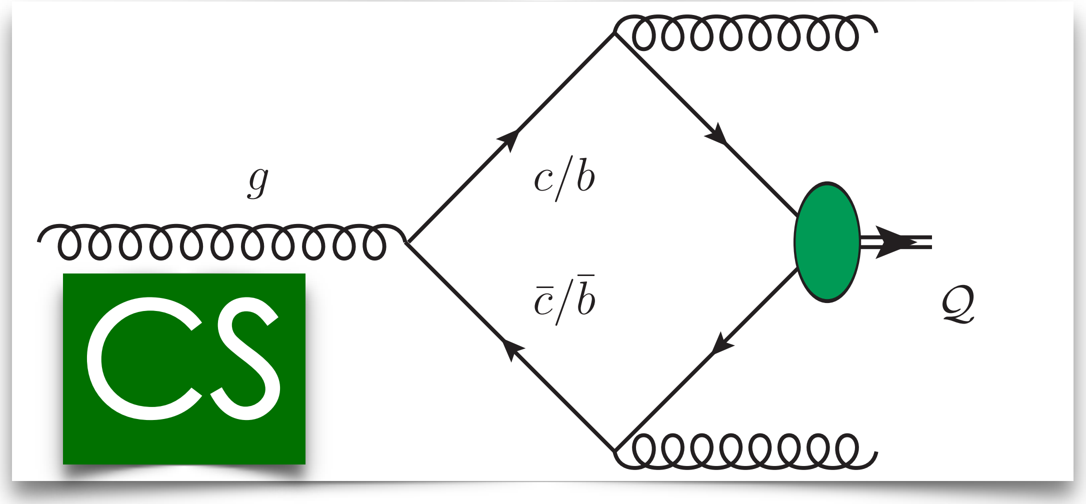

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$\otimes$

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

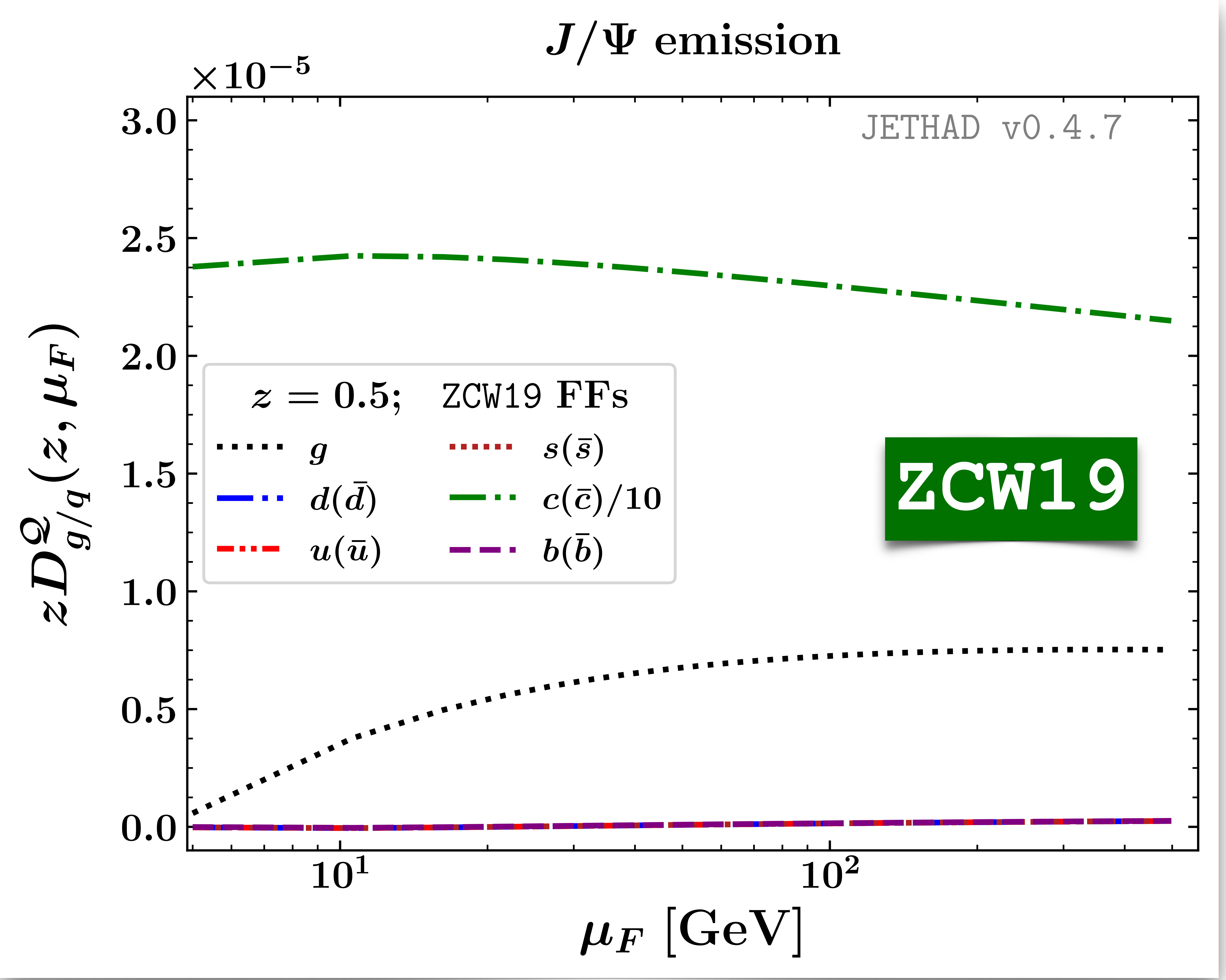
ZCW19+

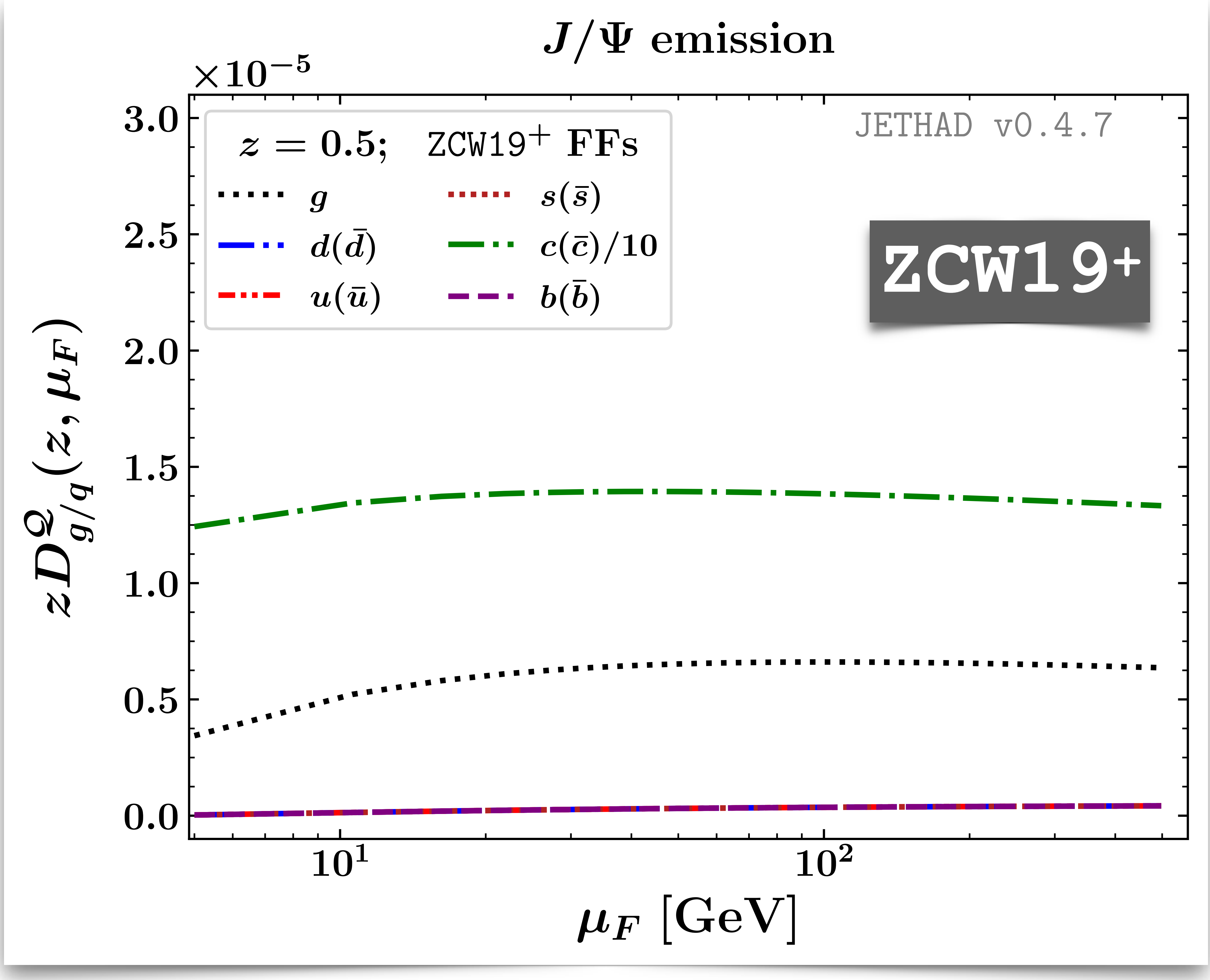
onium FFs = **APFEL++**

Backup

Vector quarkonium + jet at the LHC

J/ψ collinear FFs





Backup

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

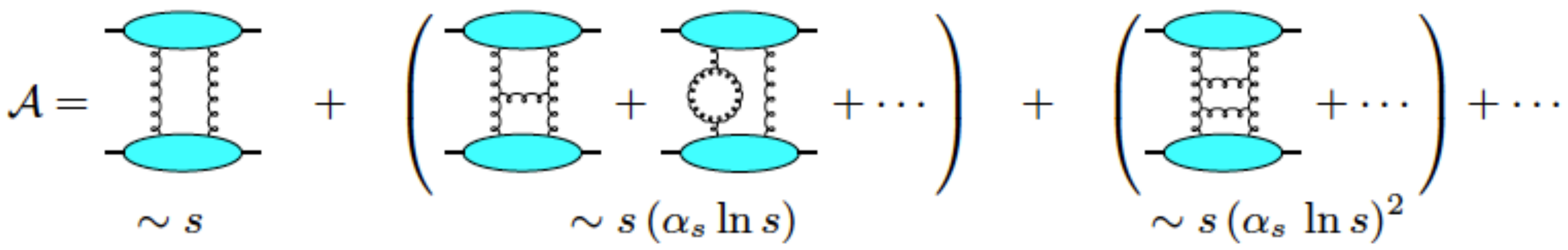
Basics of BFKL

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)]

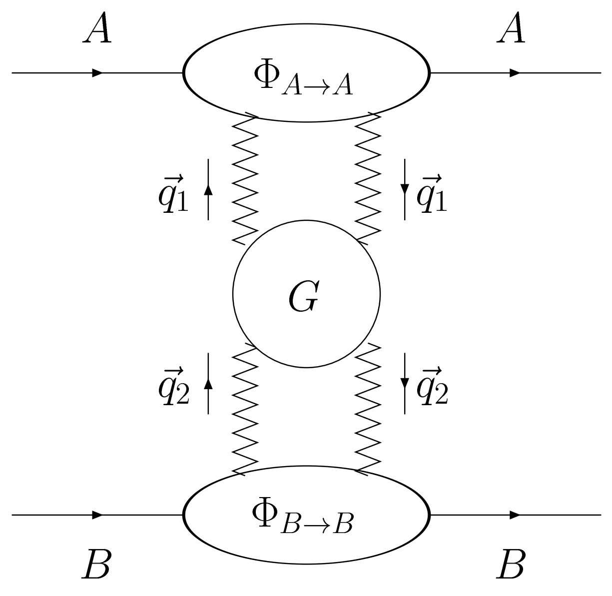
  $\xrightarrow{\text{based on}}$ **gluon Reggeization**

  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***



- $\mathcal{I}m_s\{\mathcal{A}_{AB}^{AB}\}$ 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**

Backup

The high-energy resummation

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

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

  ⟶ 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

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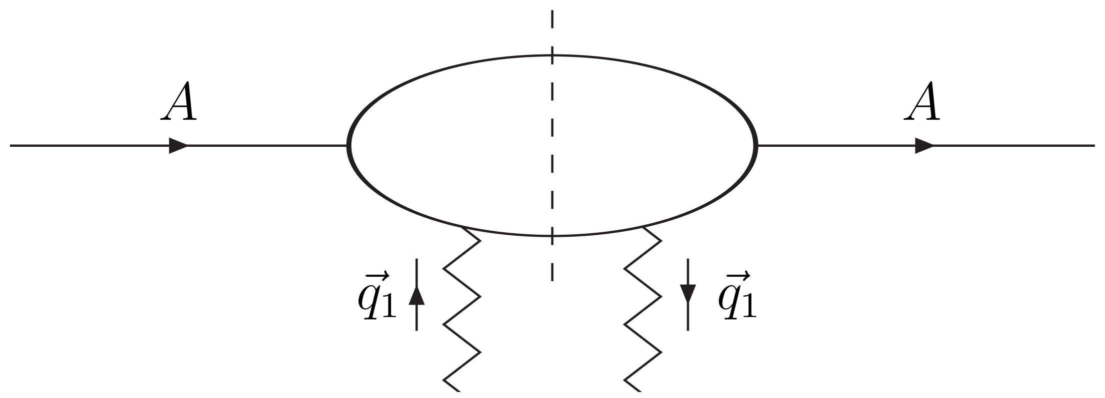

- Successful tests of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

(**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)]

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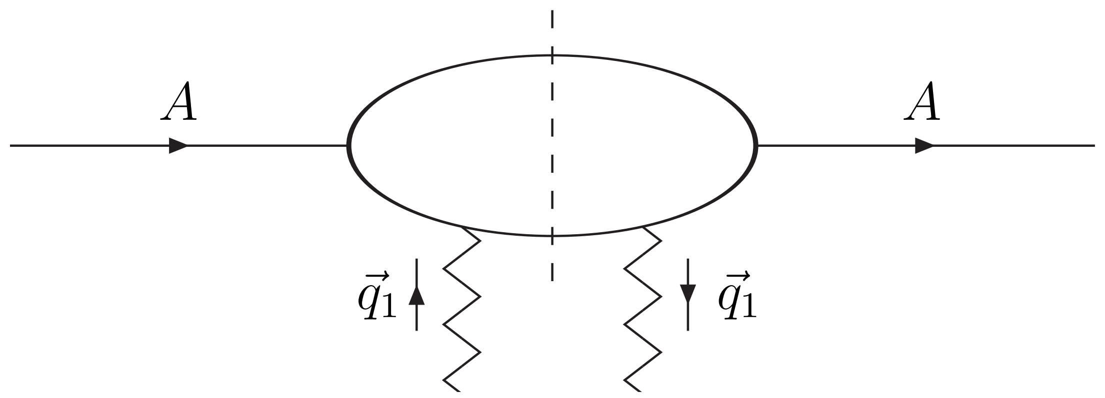

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¡ NEW ! NLO HIGGS

(κ_T space) 🔗 [M. Hentschinski, K. Kutak, A. Van Hameren (2021)]
(κ_T & Mellin) 🔗 [F.G.C., M. Fucilla, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2022)]

Backup

Gluon Reggeization in perturbative QCD

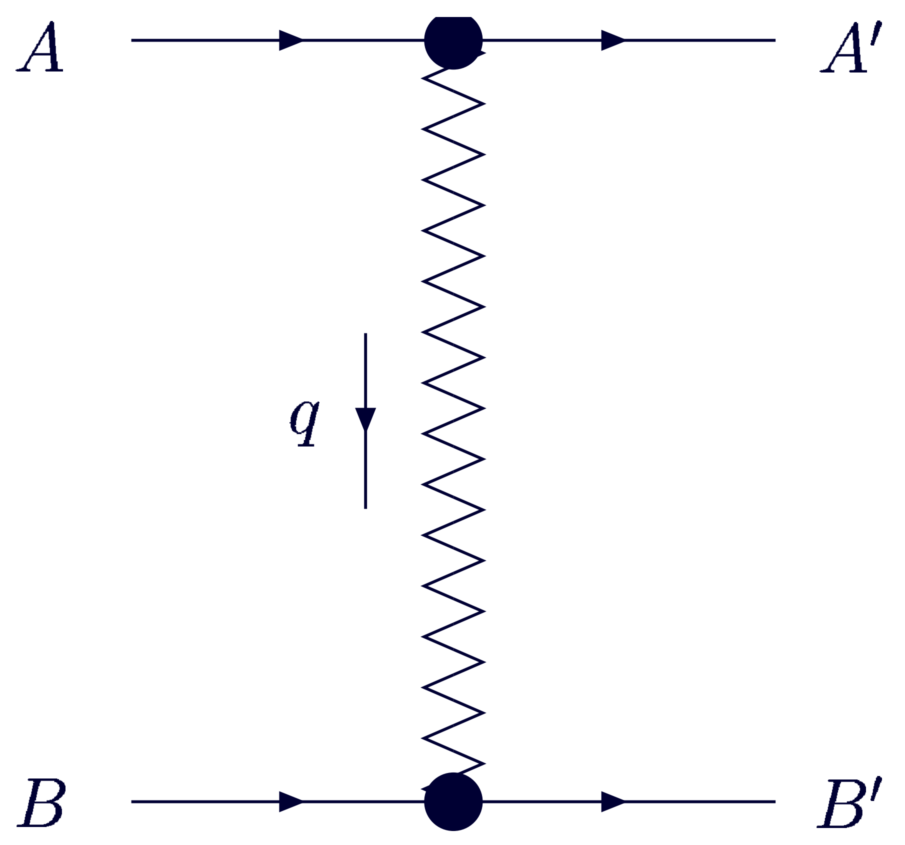
- Gluon quantum numbers in the t-channel: 8^- representation
- Regge limit: $s \simeq -u \to \infty$, t not growing with s

$\to$ 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,...

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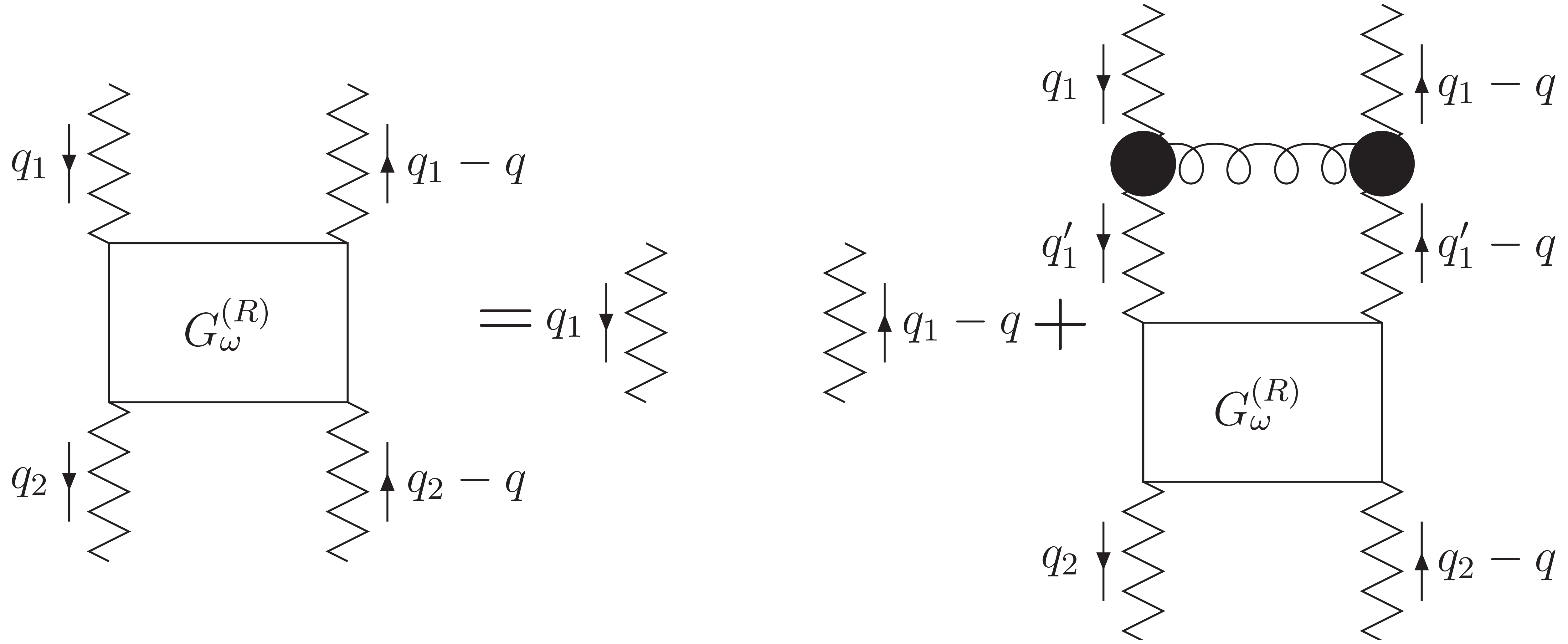
$\longrightarrow$ determined through the **BFKL equation**

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

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



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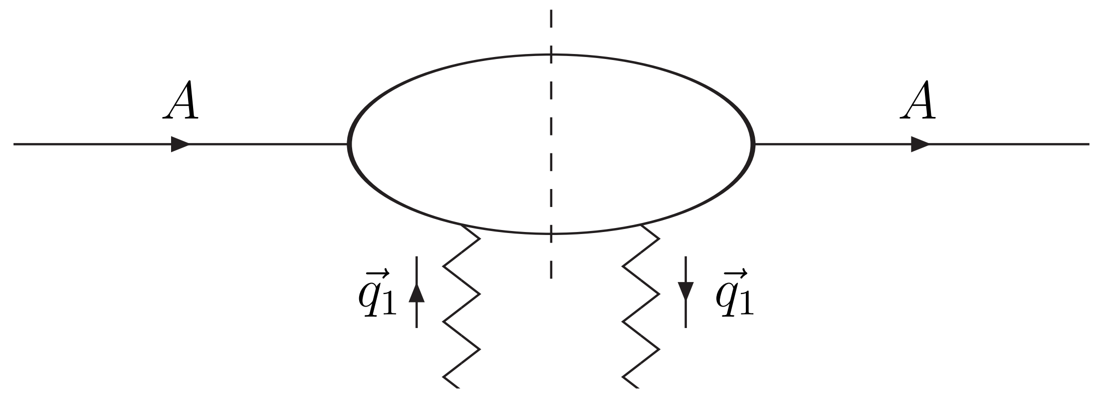


◇ **colliding partons**

[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)]

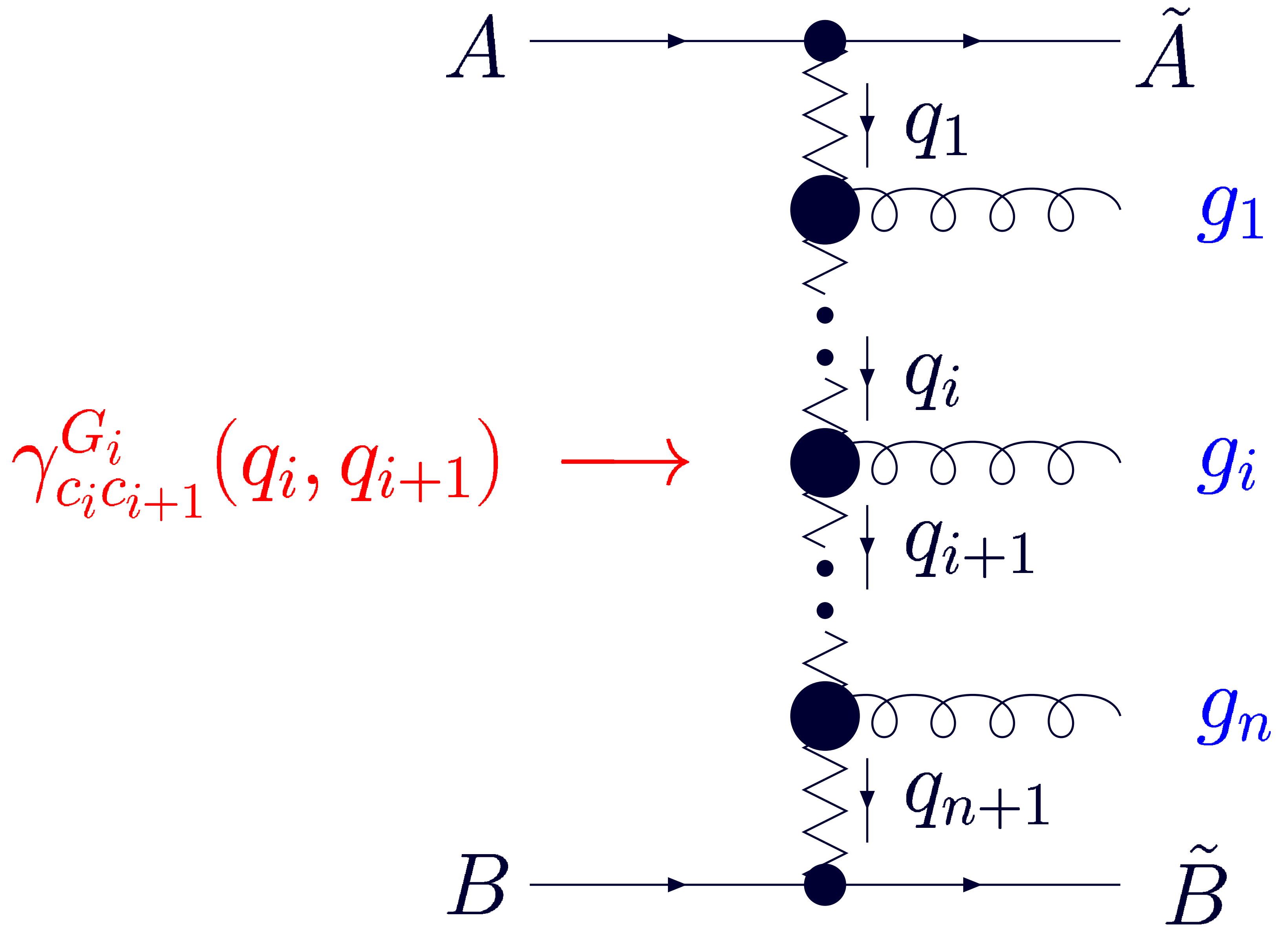
◇ $\gamma^* \longrightarrow \gamma^*$

[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



multi-Regge kinematics

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

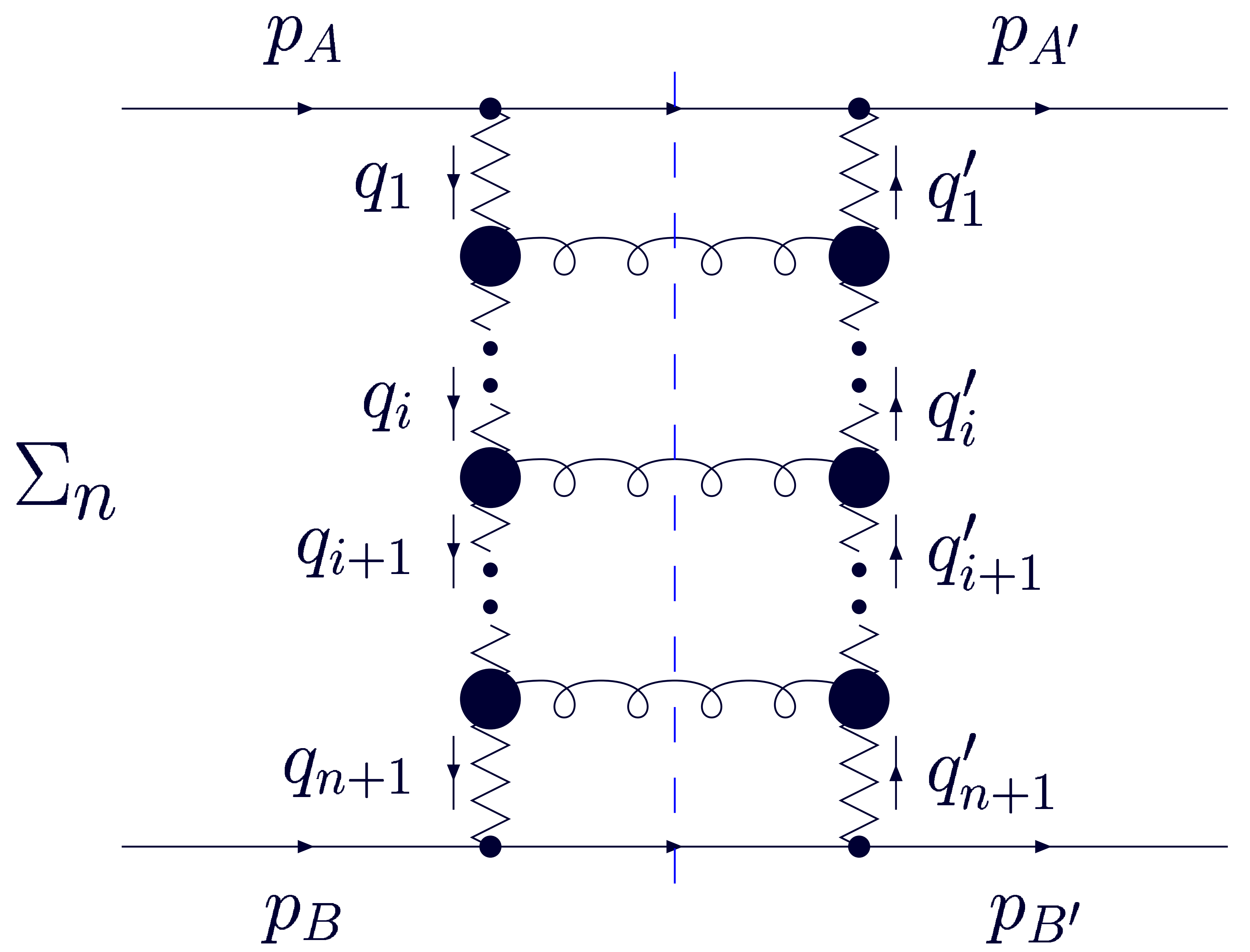
$\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \;\; \rightarrow$ RRG vertex

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

Backup

BFKL in the LLA (II)

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

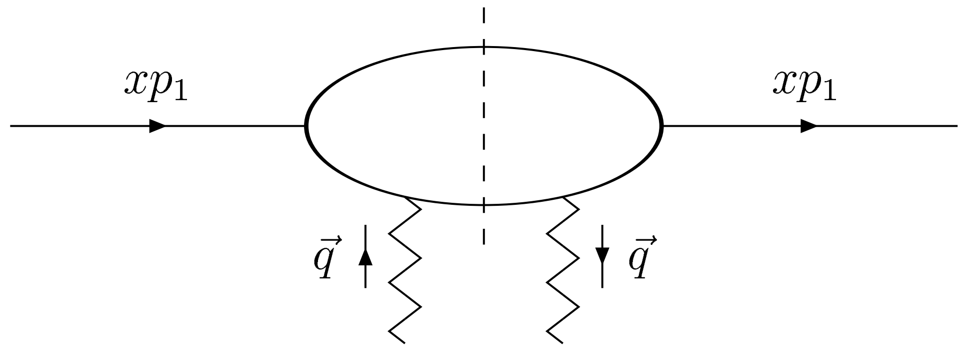


$$\mathcal{A}_{AB}^{A'B'} = \sum_{\mathcal{R}} (\mathcal{A}_{\mathcal{R}})_{AB}^{A'B'} \,, \qquad \mathcal{R} = 1 \text{ (singlet)}, 8^- \text{ (octet)}, \ldots$$

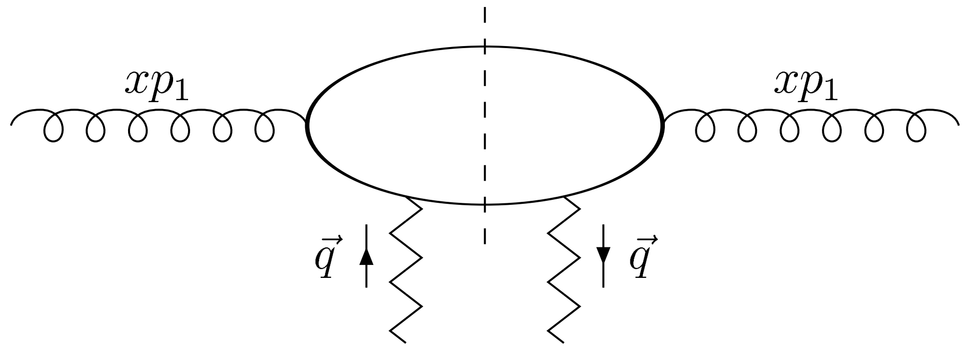
The 8^- color representation is important for the bootstrap, i.e. the consistency between the above amplitude and that with one Reggeized gluon exchange

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)]

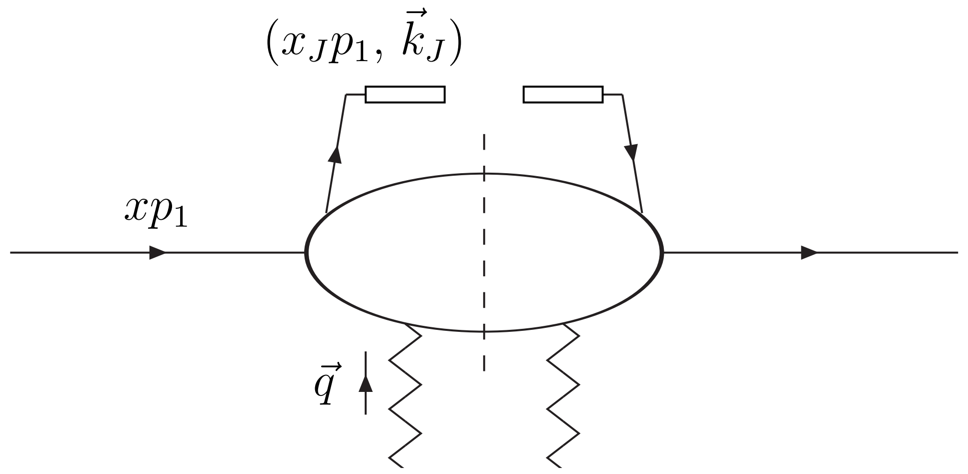


quark vertex

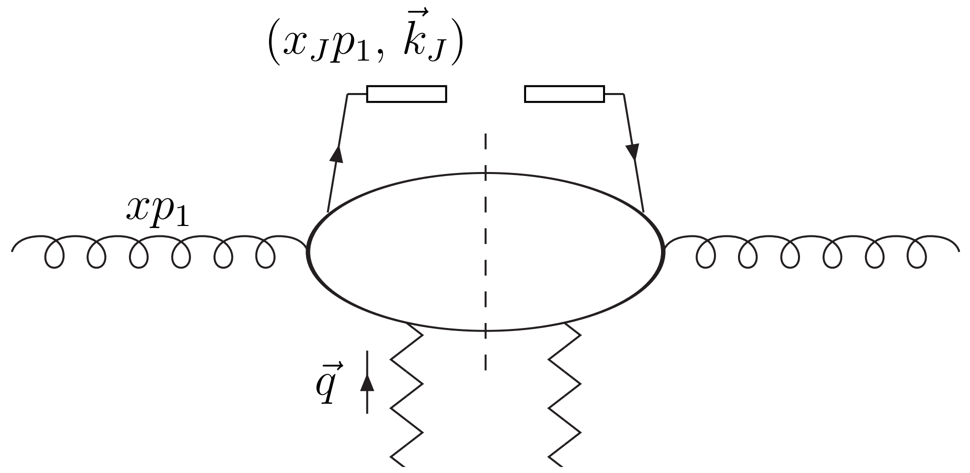


gluon vertex

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



quark jet vertex

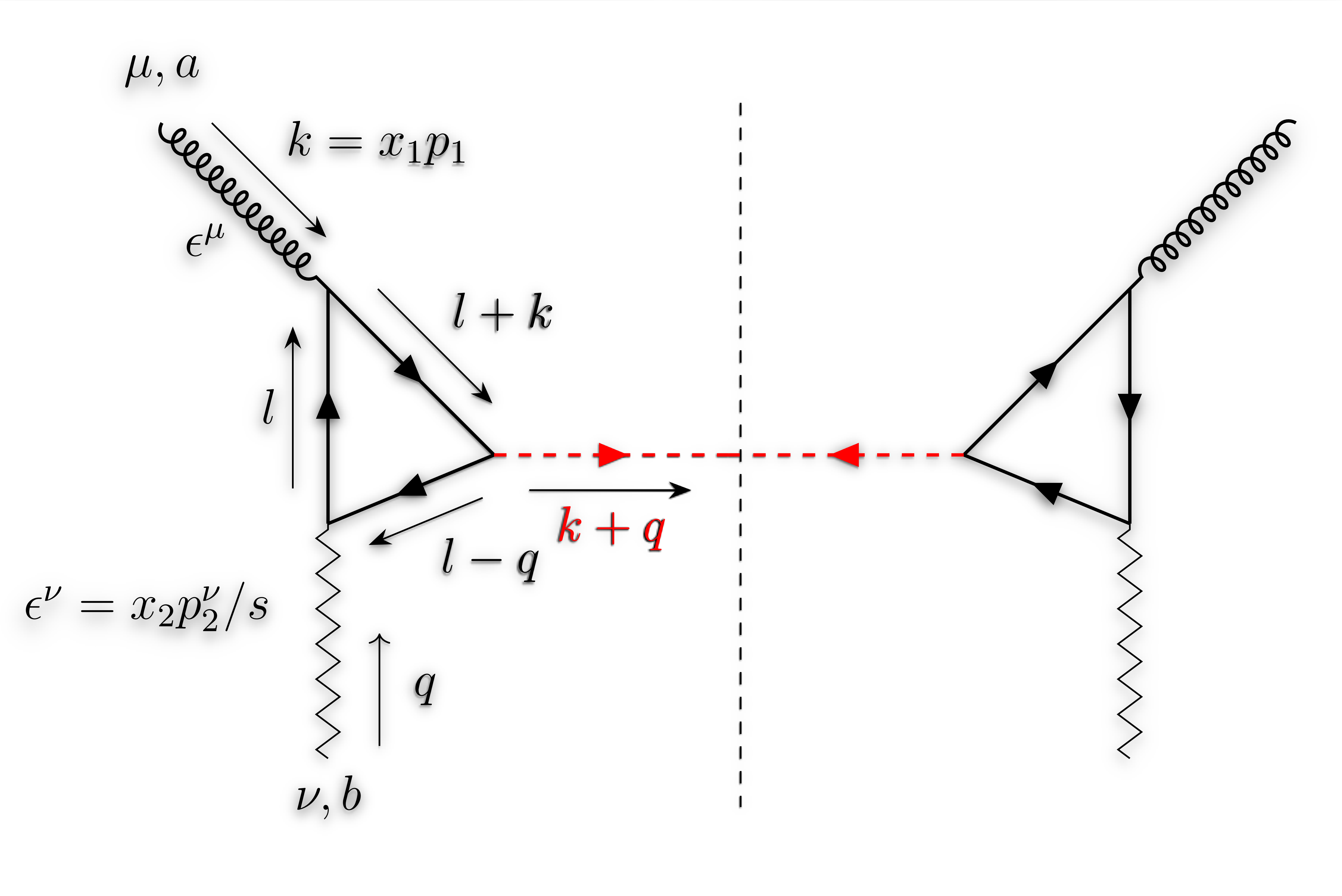


gluon jet vertex

- 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

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

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

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

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

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Inclusive Higgs + jet: NLL/NLO* azimuthal coefficients

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

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

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

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

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