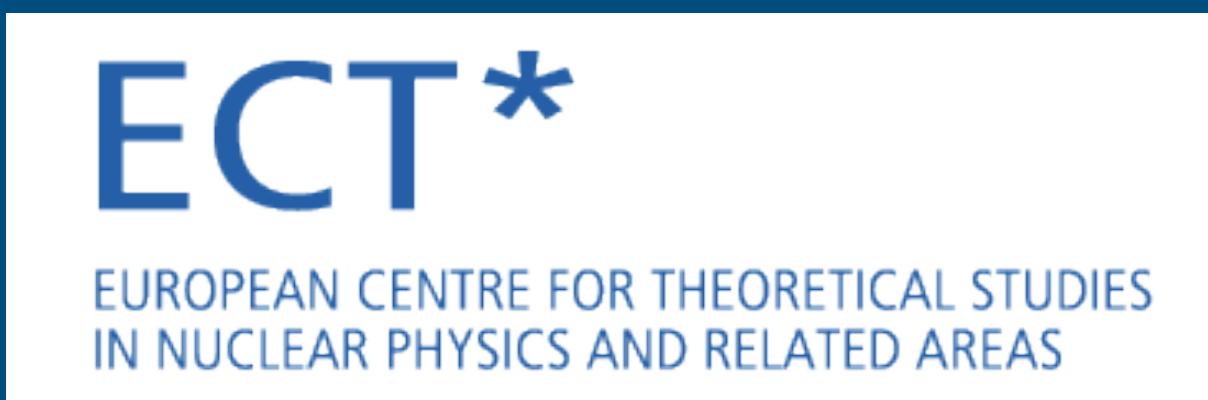


Precision studies of semi-inclusive Higgs production at new-gen Forward Facilities

LHC Forward Physics Meeting - CERN, 24th October 2022

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA



Trento Institute for
Fundamental Physics
and Applications



Higgs production from LHC to FCC

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

Double Resummation for Higgs Production

Marco Bonvini^{1,*} and Simone Marzani^{2,†}

¹INFN, Sezione di Roma 1, Piazzale Aldo Moro 5, 00185 Roma, Italy

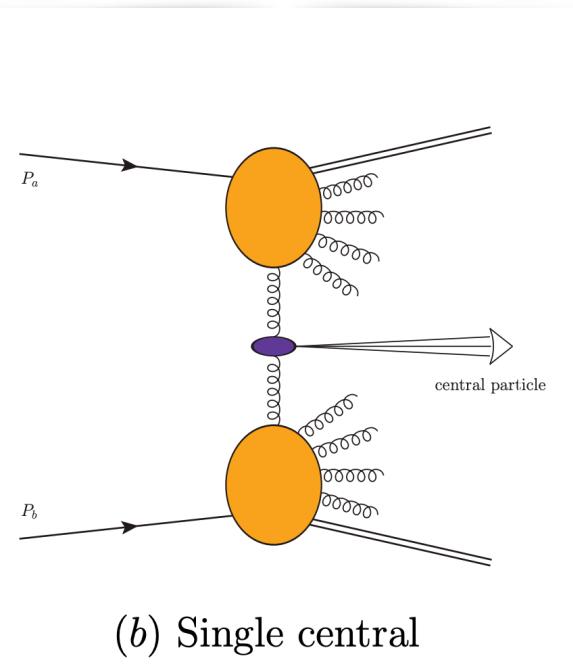
²Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy



(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](https://doi.org/10.1103/PhysRevLett.120.202003)



(b) Single central

BFKL used to determine small- x improved PDFs

ABF method to stabilize the NLLsx BFKL kernel

N³LL_{Ix}/LL_{Sx}/N³LO rapidity-inclusive coefficient functions

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

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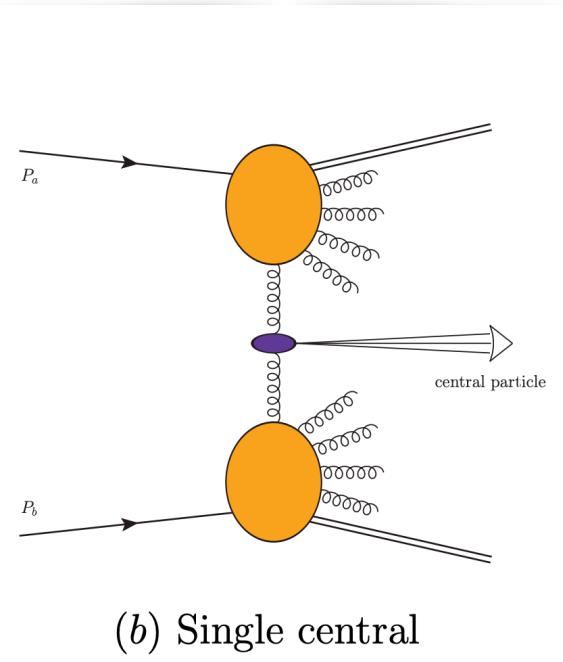
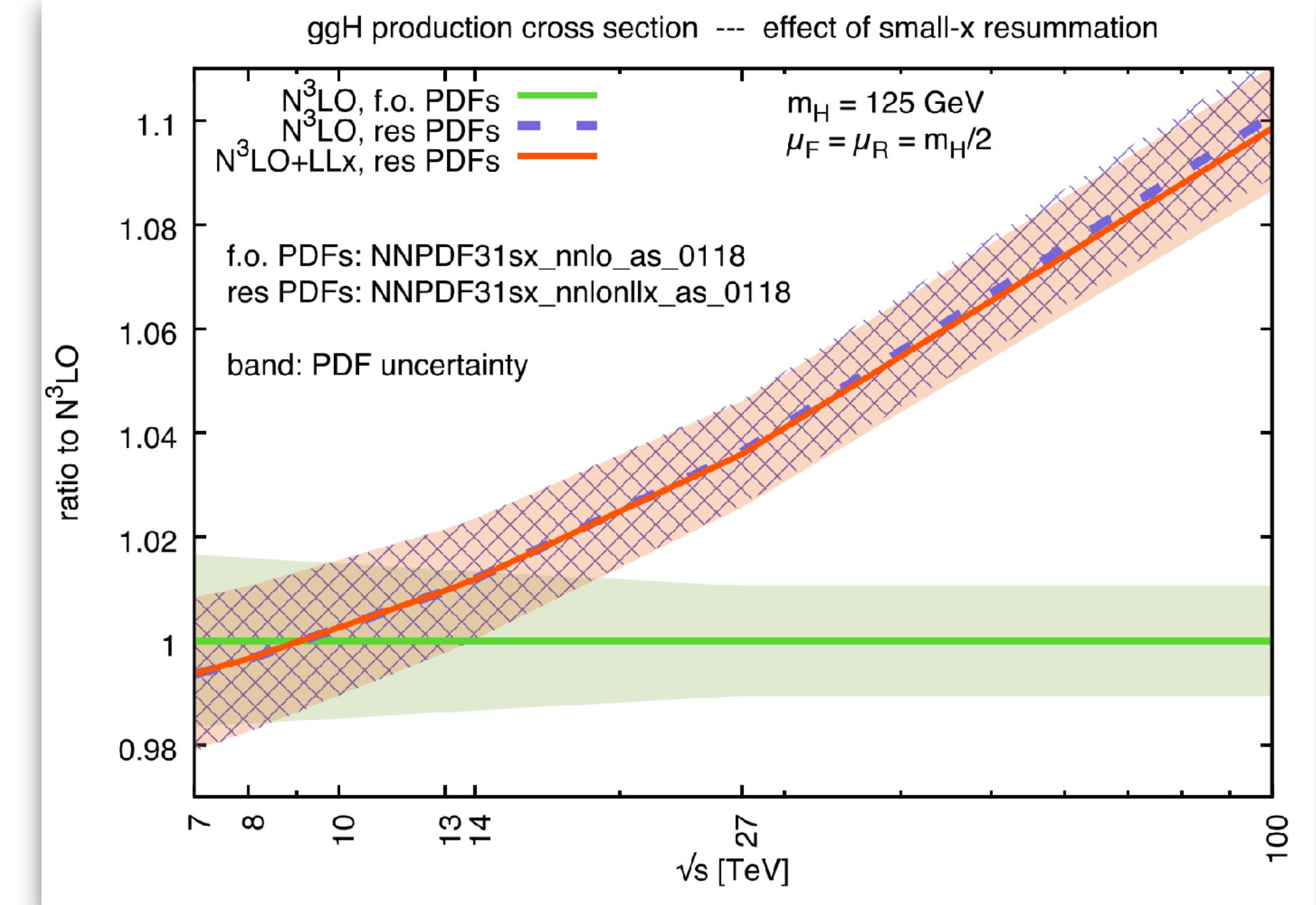
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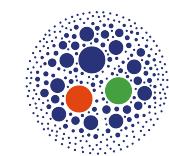
$N^3LL_{lx}/LL_{sx}/N^3LO$ rapidity-inclusive coefficient functions

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

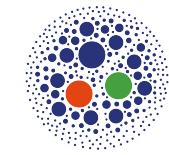
(ξ?) Can LHC physics be BFKL physics?

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

Mueller-Navelet jets at the LHC

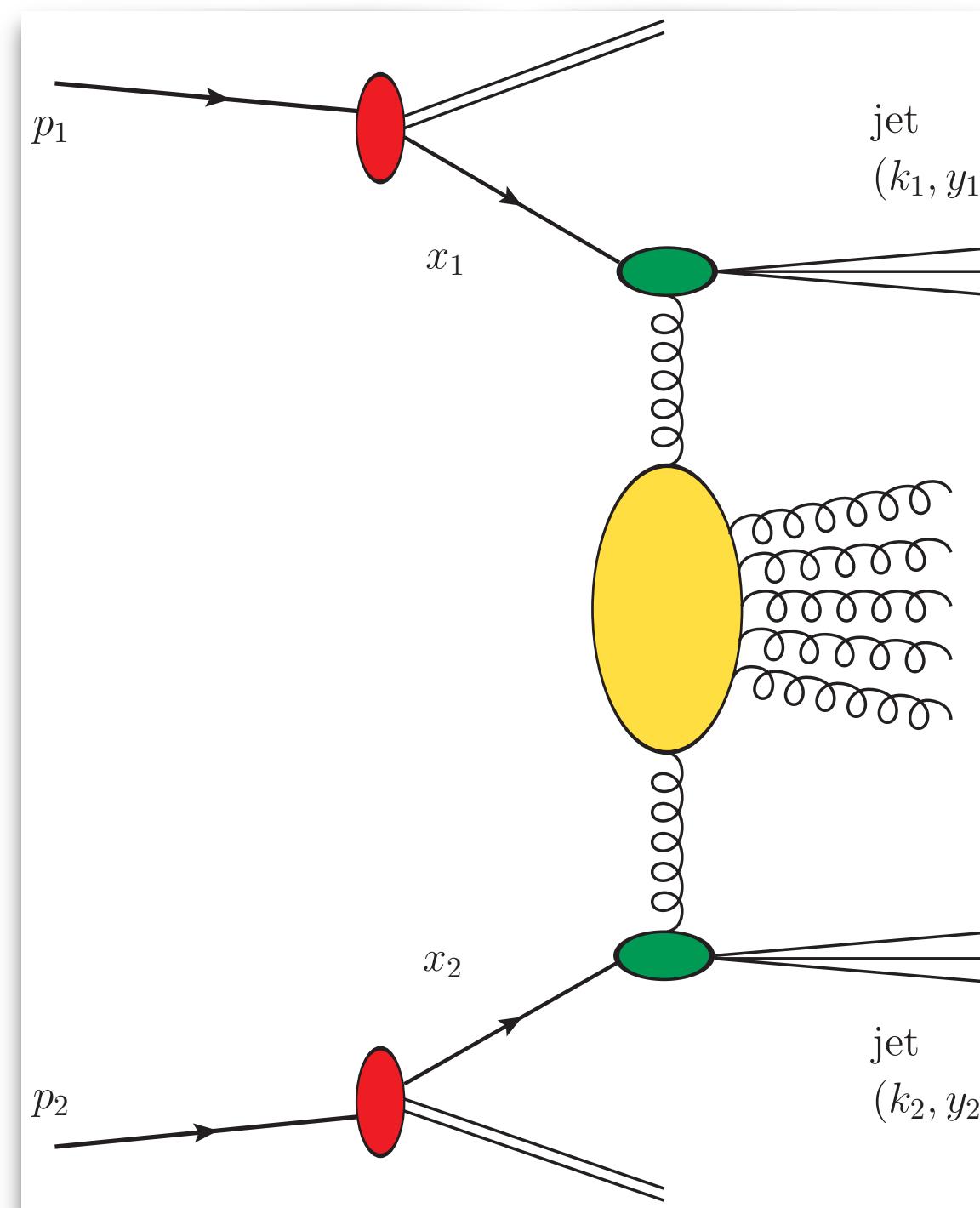


Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY

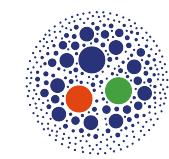


Moderate x (collinear PDFs), but t-channel p_T (BFKL resummation) → hybrid factorization

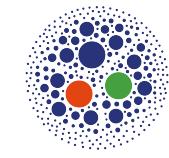
$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{k}_1 d^2\vec{k}_2} = \sum_{r,s=q,g} \int_0^1 dx_1 \int_0^1 dx_2 f_r(x_1, \mu_F) f_s(x_2, \mu_F) \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu_F)}{dy_1 dy_2 d^2\vec{k}_1 d^2\vec{k}_2}$$



Mueller-Navelet jets at the LHC



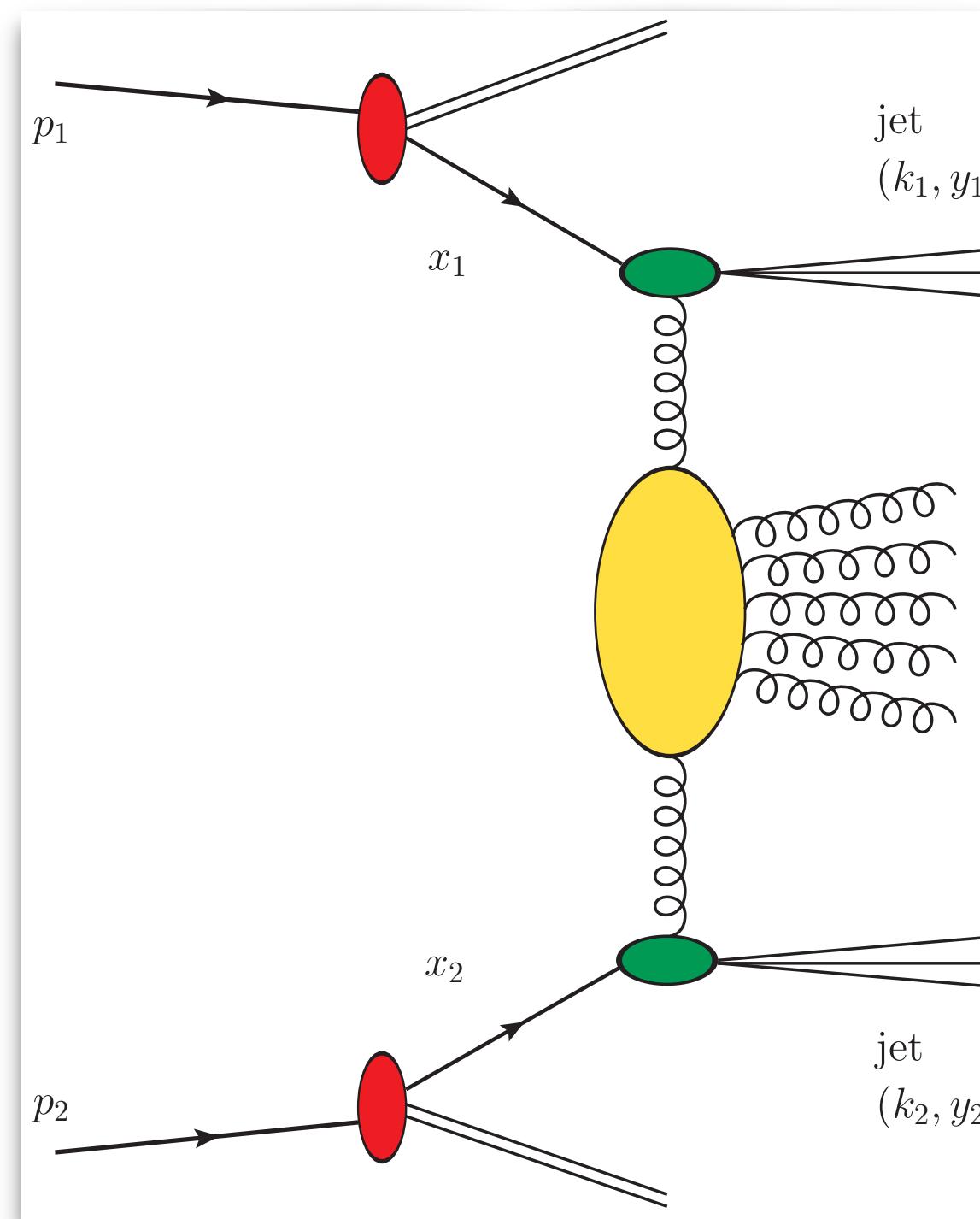
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jet vertices
(off-shell amplitudes)



NLO

NLL

NLO

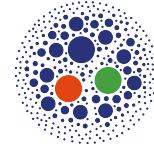
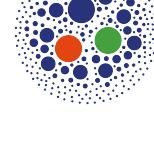
$$\begin{aligned} \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_1 dy_2 d^2\vec{k}_1 d^2\vec{k}_2} &= \frac{1}{(2\pi)^2} \\ &\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^2} \mathcal{V}_J^{(r)}(\vec{q}_1, s_0, x_1, \vec{k}_1) \\ &\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^\omega \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2) \\ &\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^2} \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{k}_2) \end{aligned}$$

BFKL Green's function

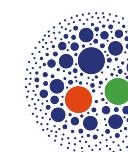


Hybrid NLL/collinear factorization via the **JETHAD** work package

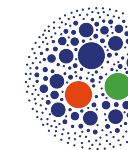
Mueller-Navelet jets & resummation instabilities

- 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

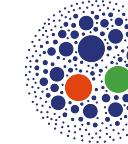
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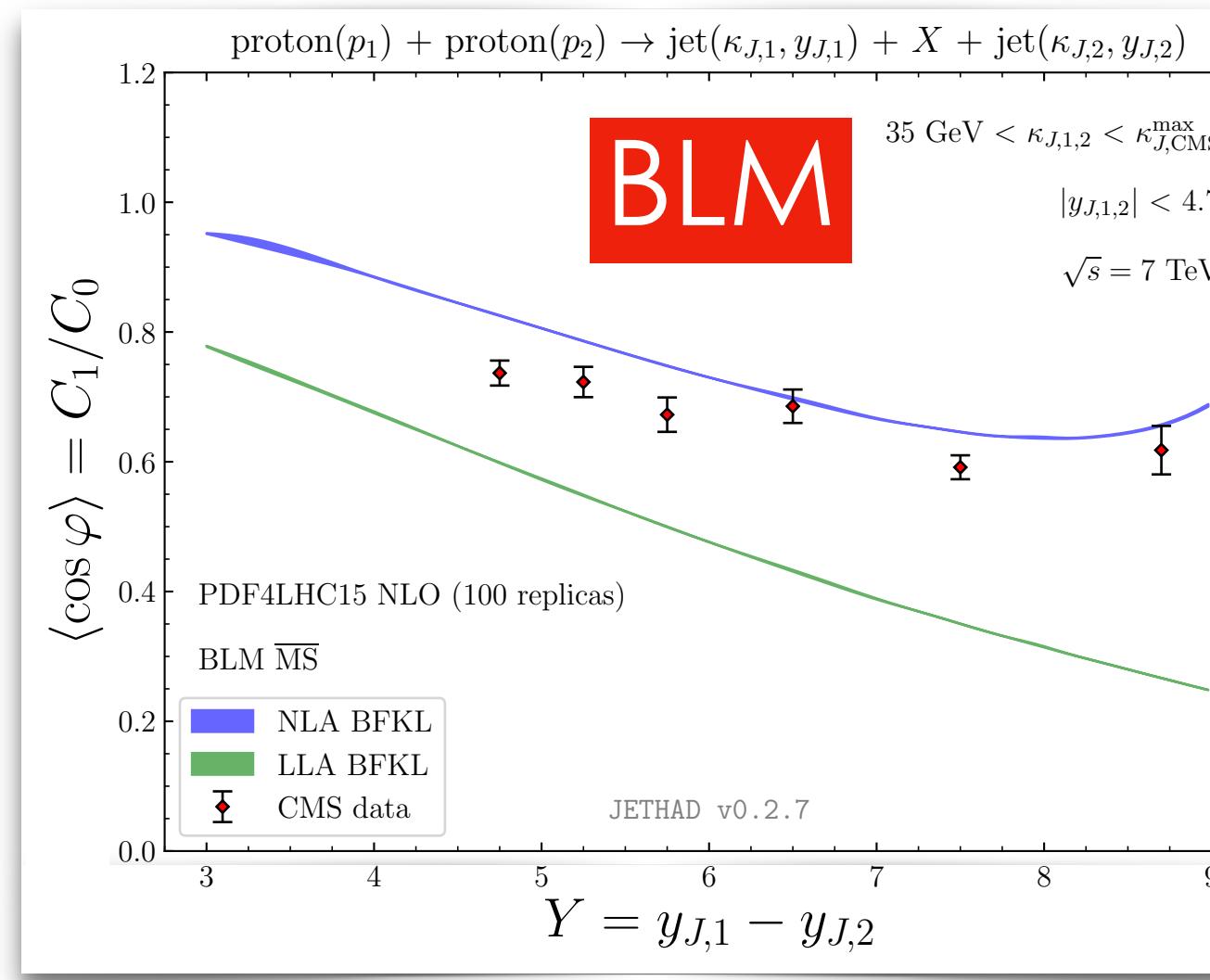
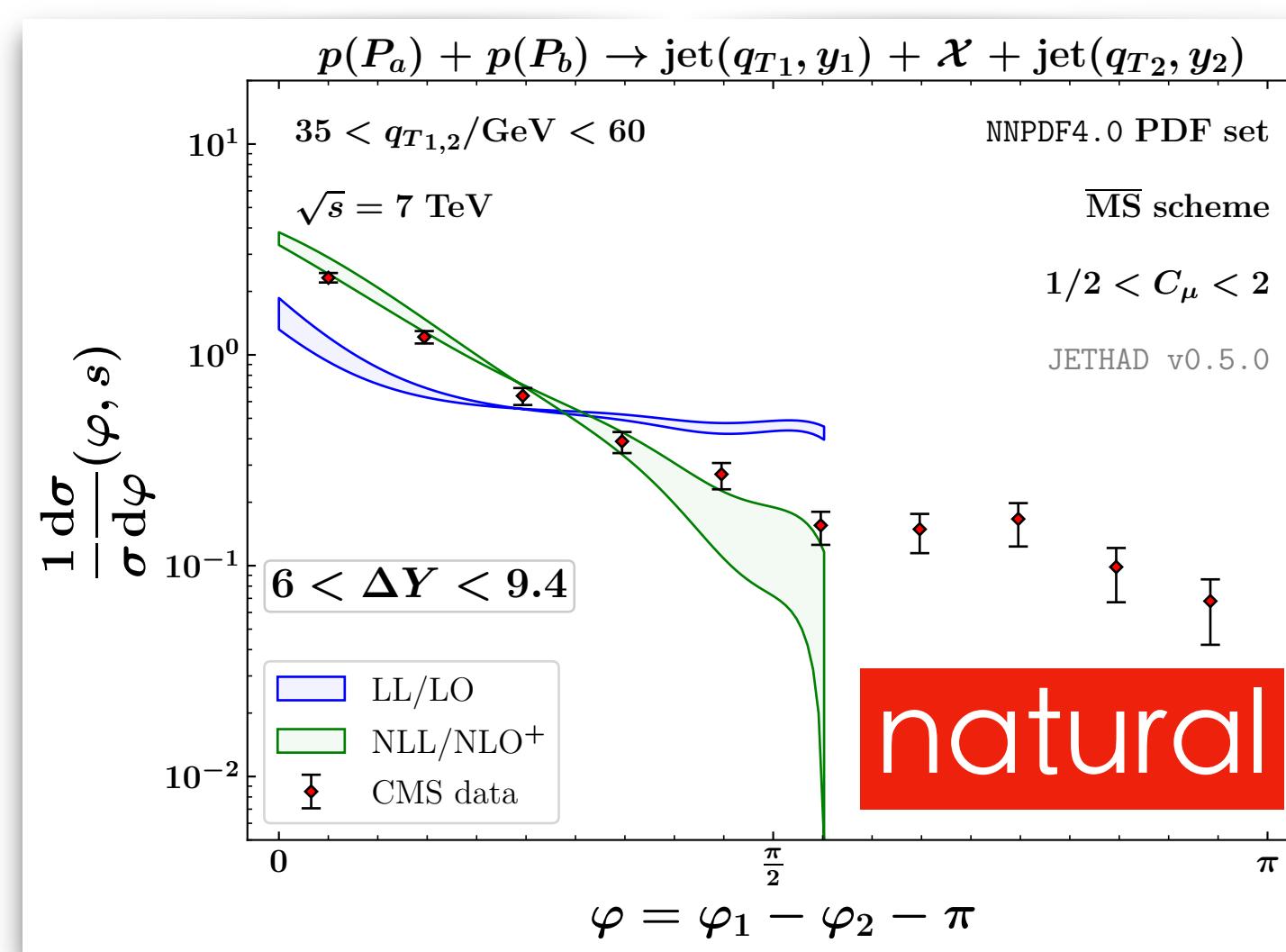
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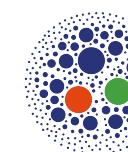
🔗 [B. Ducloué et al., Phys. Rev. Lett. 112 (2014) 082003]

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

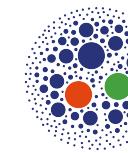
(left figure) 🔗 [F. G. C., A. Papa (2022)]

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

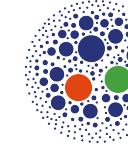
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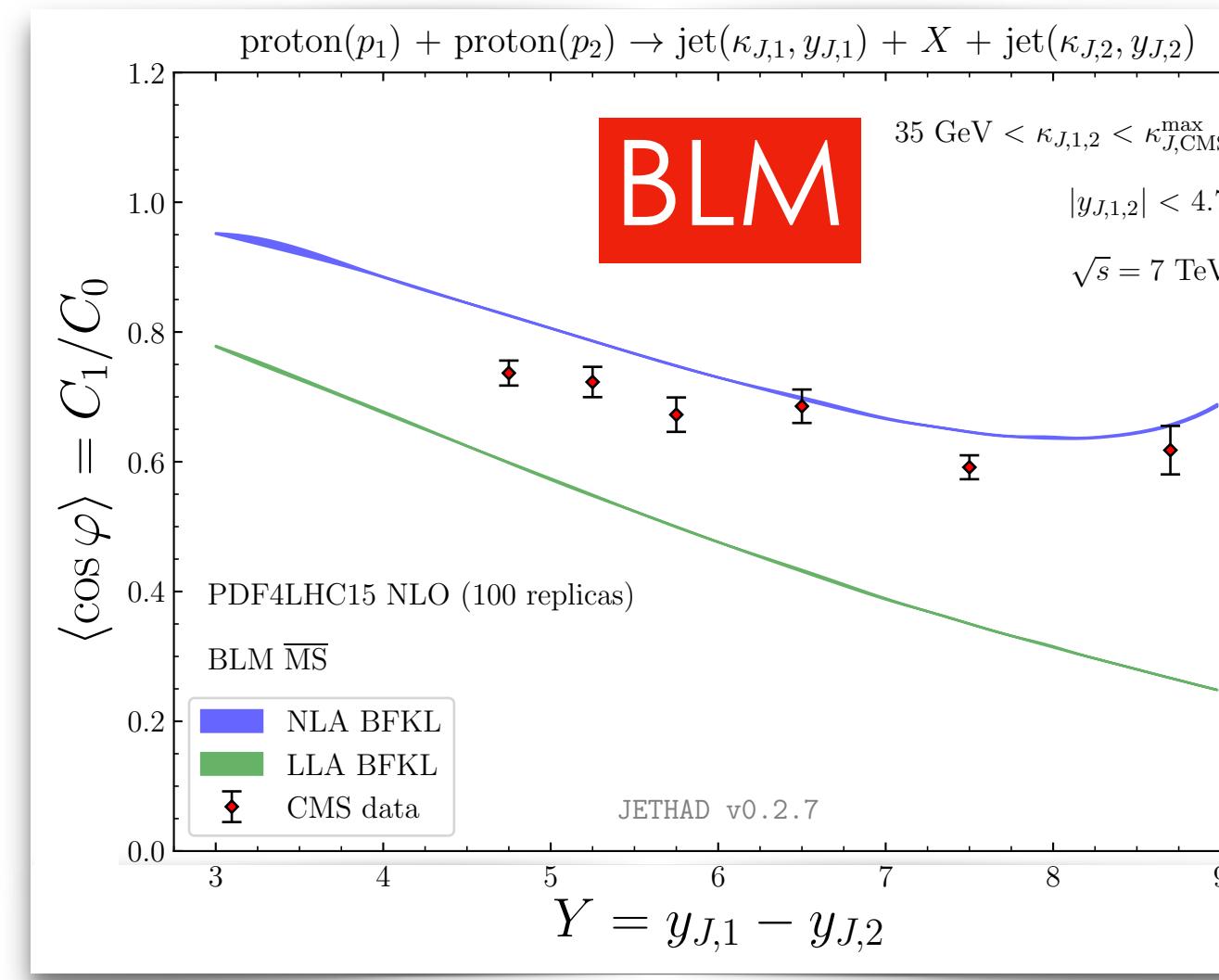
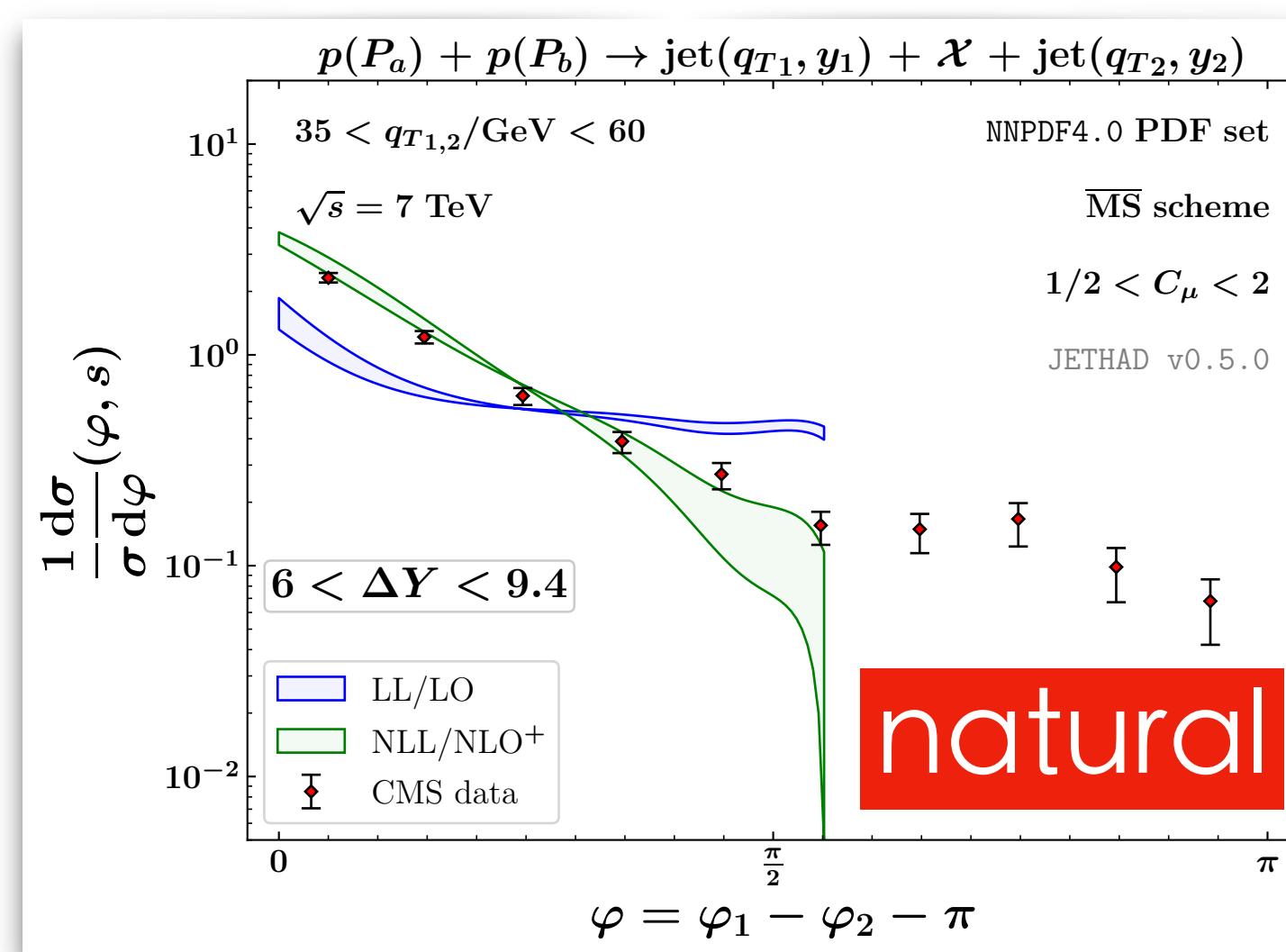
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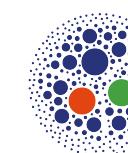


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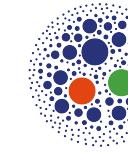
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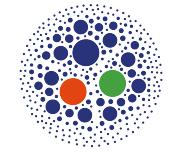


$\mu_R^{\text{BLM}} \gg \mu_R^{\text{nat.}} \Rightarrow d\sigma^{\text{BLM}}/d\sigma^{\text{nat.}} \sim 10^{-(1/2)} \Rightarrow$ **precision studies hampered**



Unsuccessful scale optimization \rightarrow processes featuring natural stability (**ξ?**)

From Mueller-Navelet to Higgs and heavy flavor



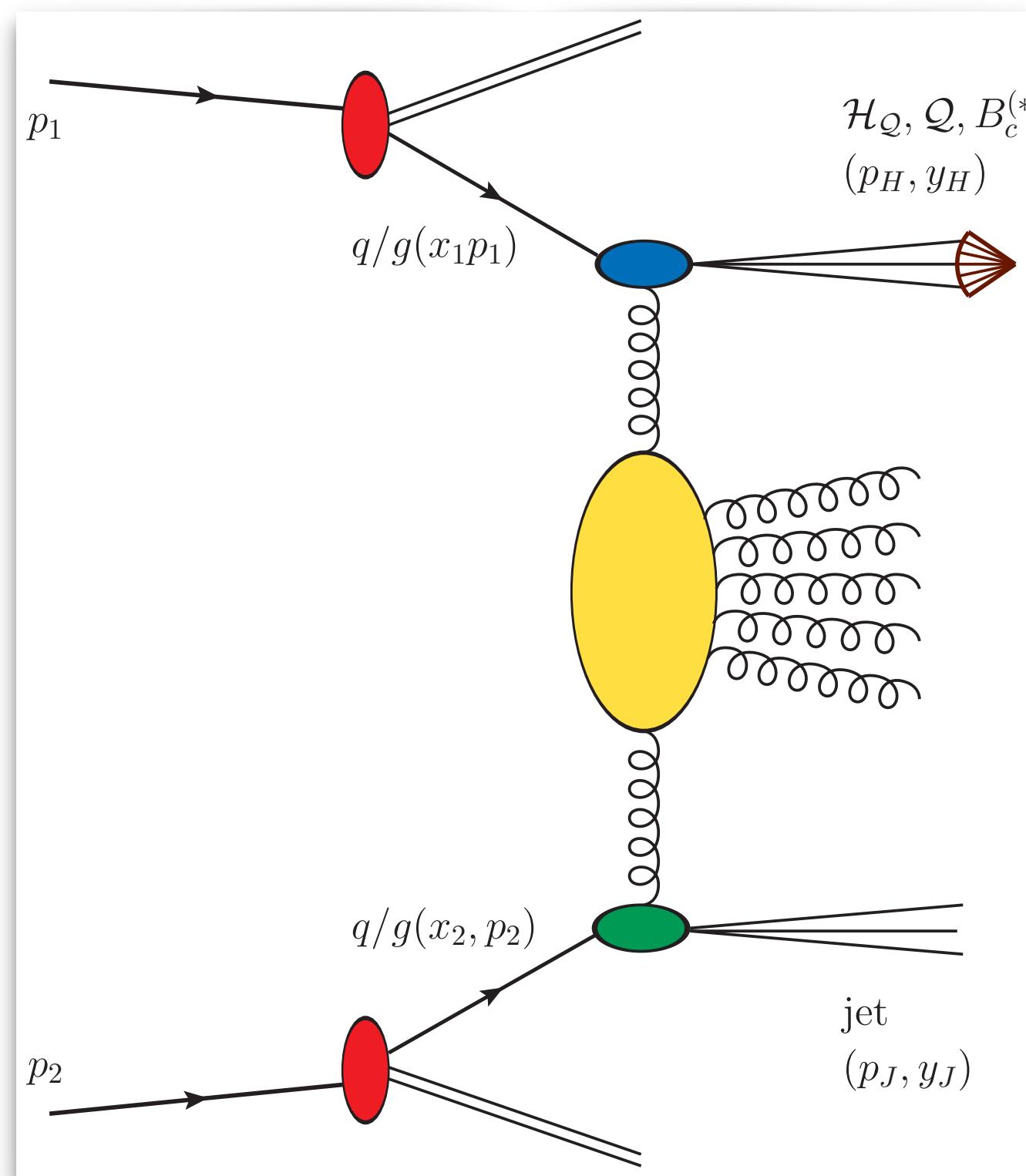
Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales ($i!$)

From Mueller-Navelet to Higgs and heavy flavor

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

Heavy flavor at large p_T

Stabilizers \Leftrightarrow gluon fragmentation channels

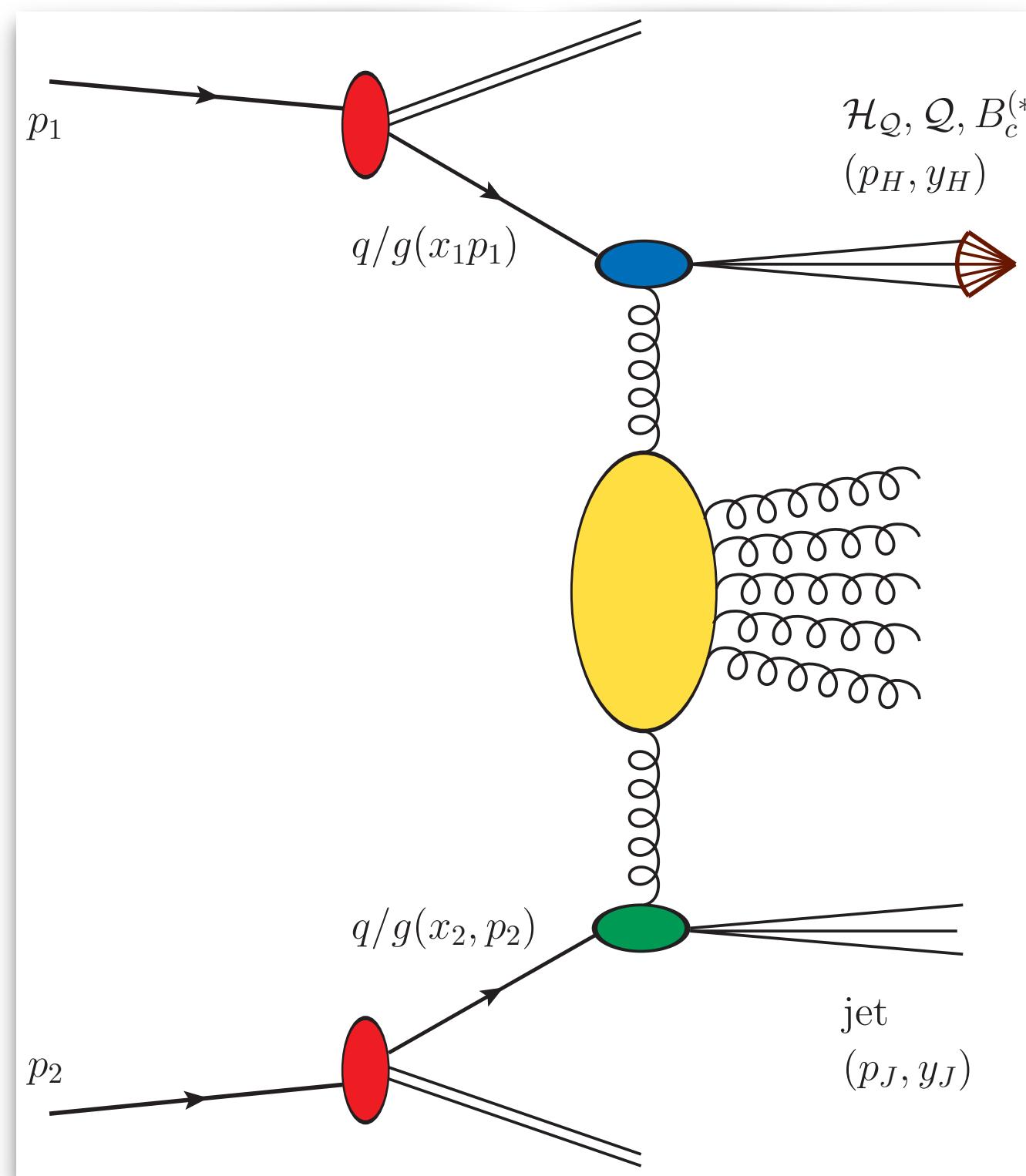


From Mueller-Navelet to Higgs and heavy flavor

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

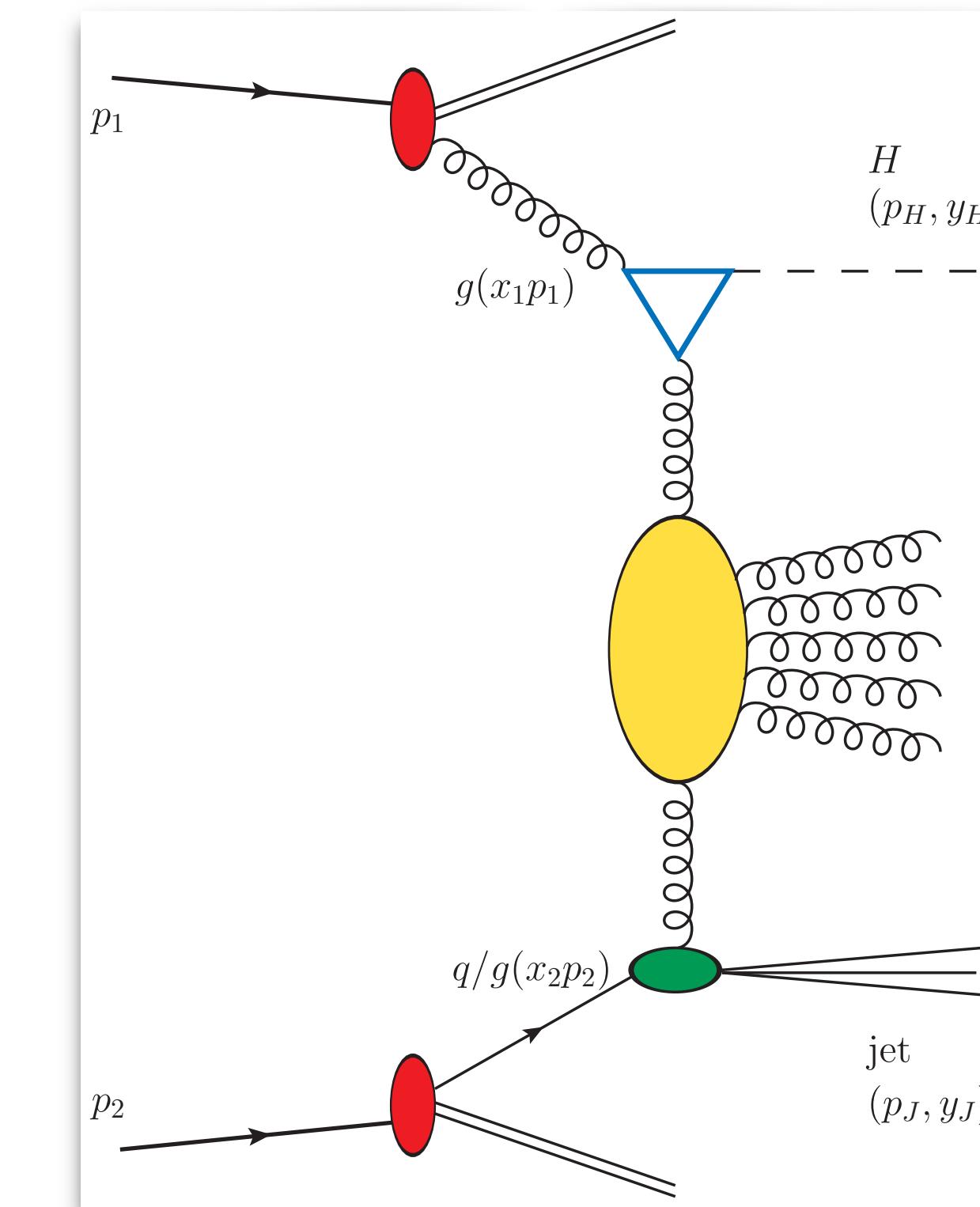
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Higgs boson

Stabilizers \Leftrightarrow large Higgs transverse masses

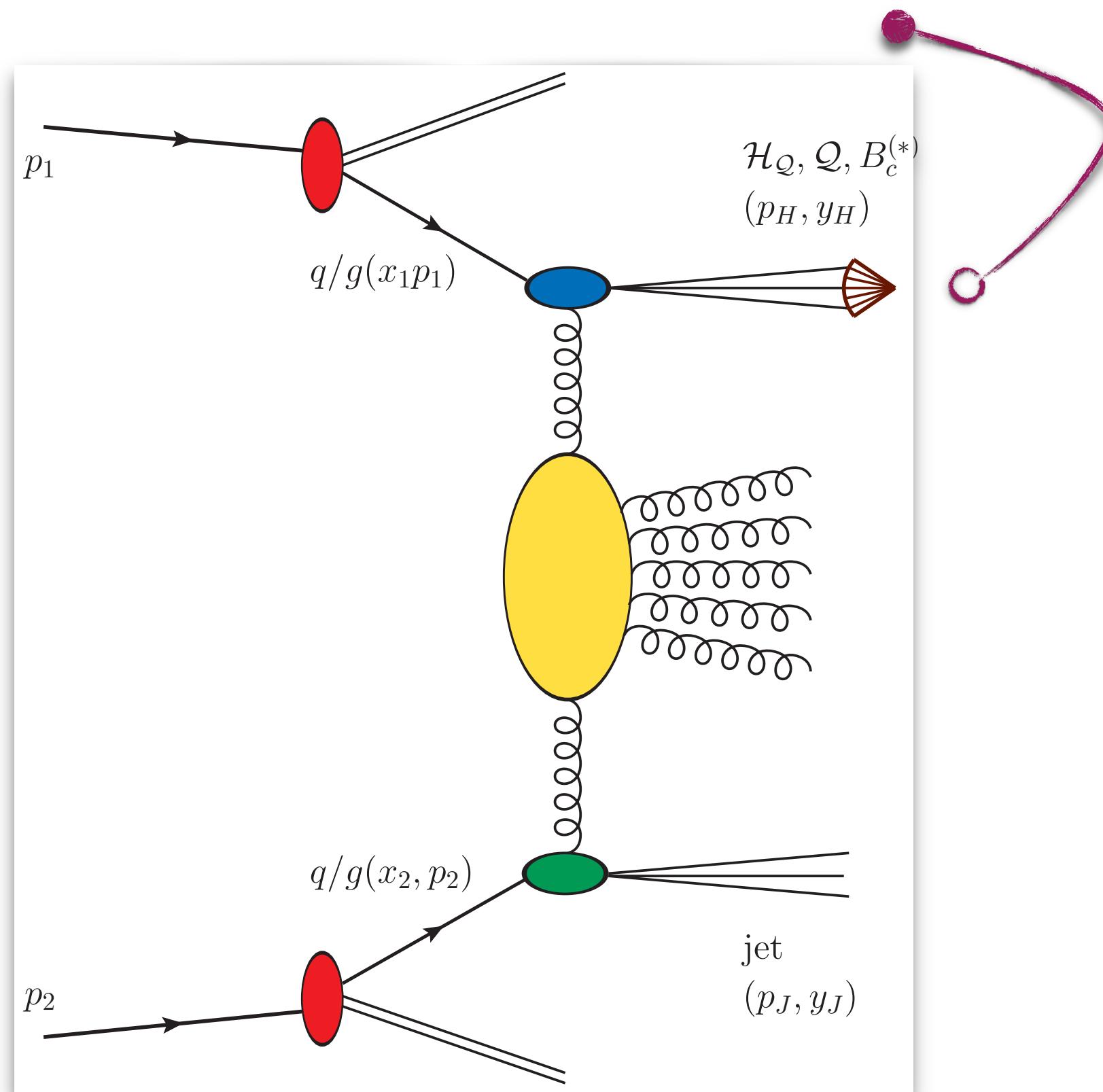


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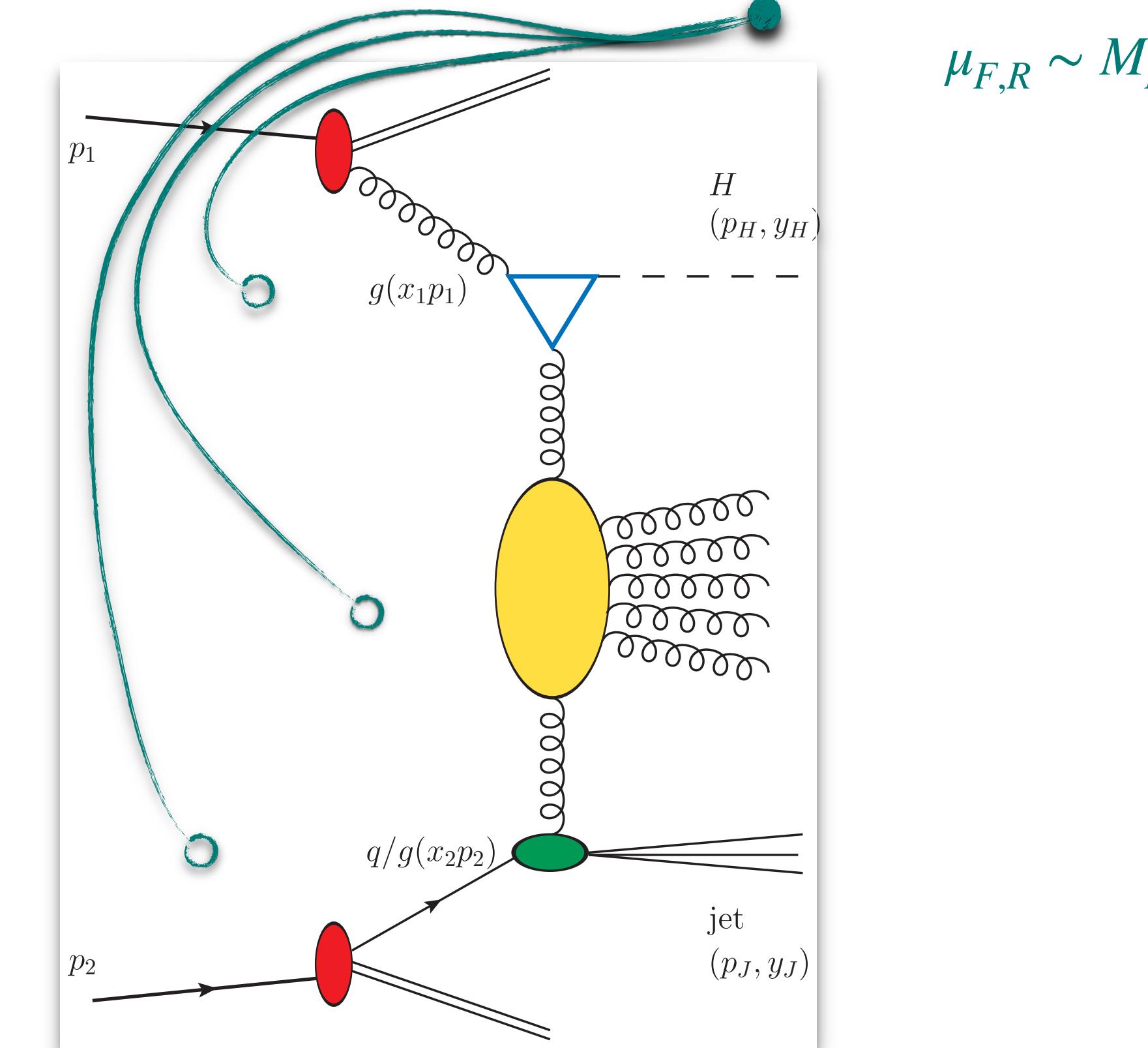
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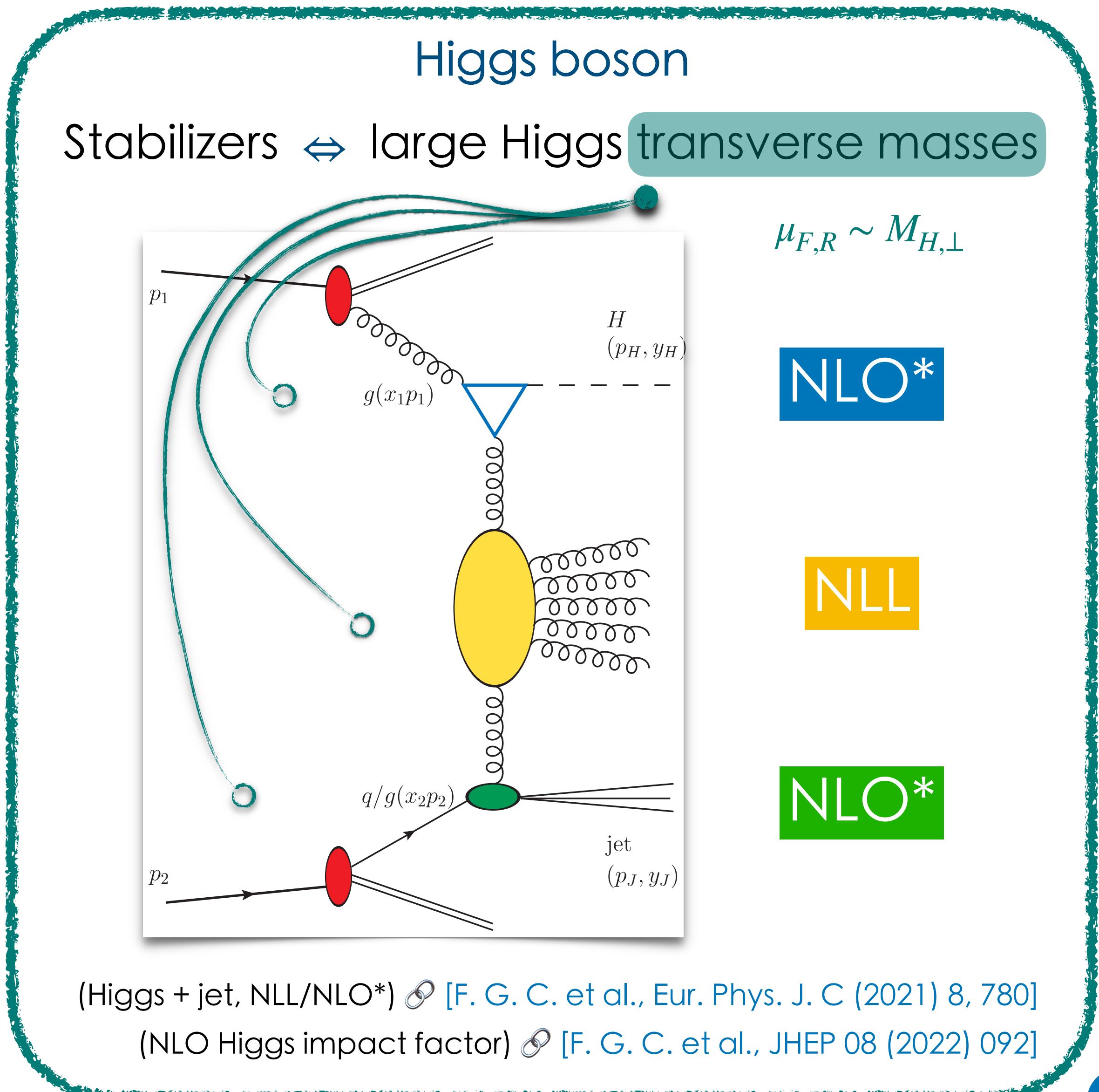
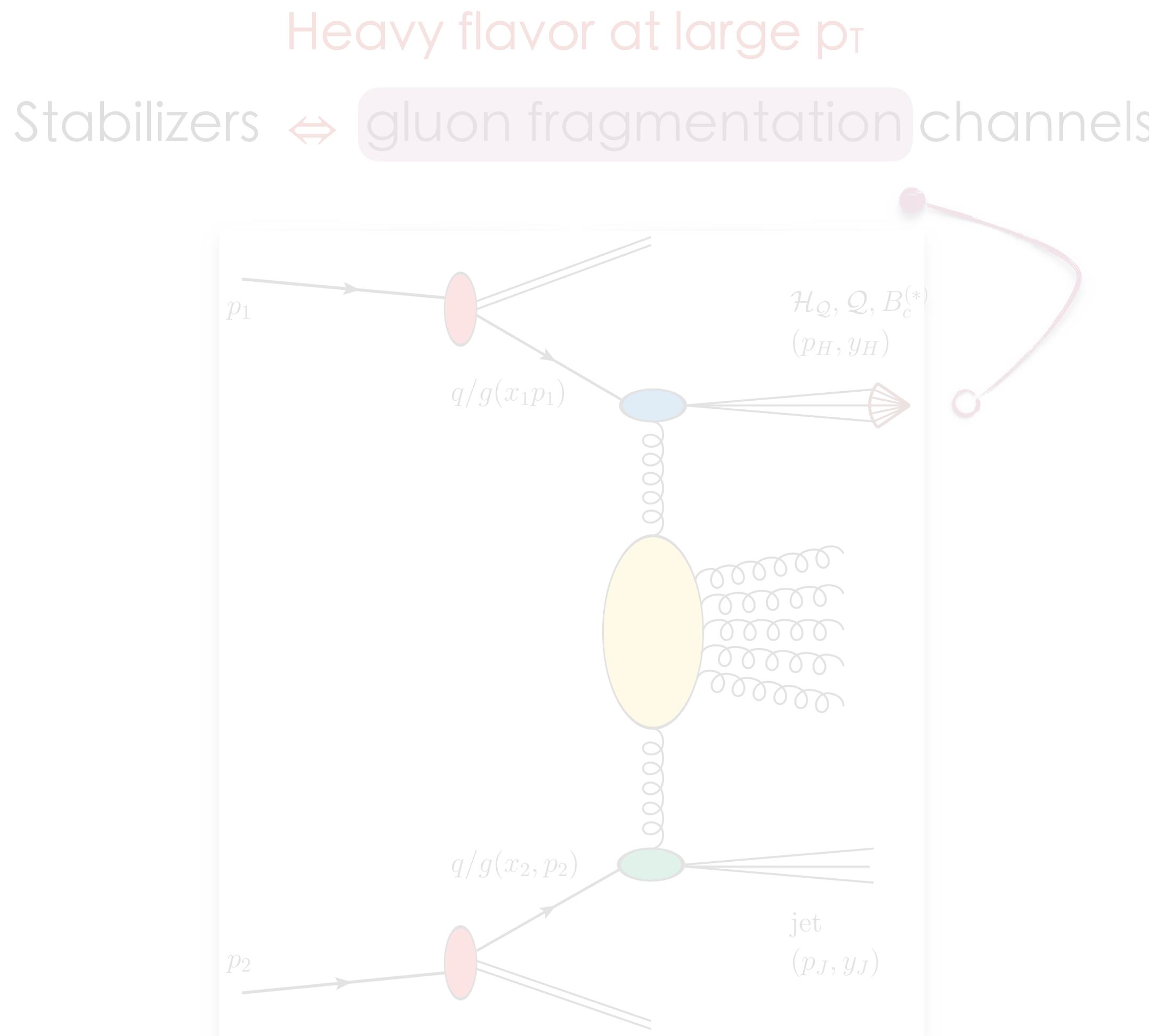
(Λ_c^\pm baryons, NLL/NLO) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

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



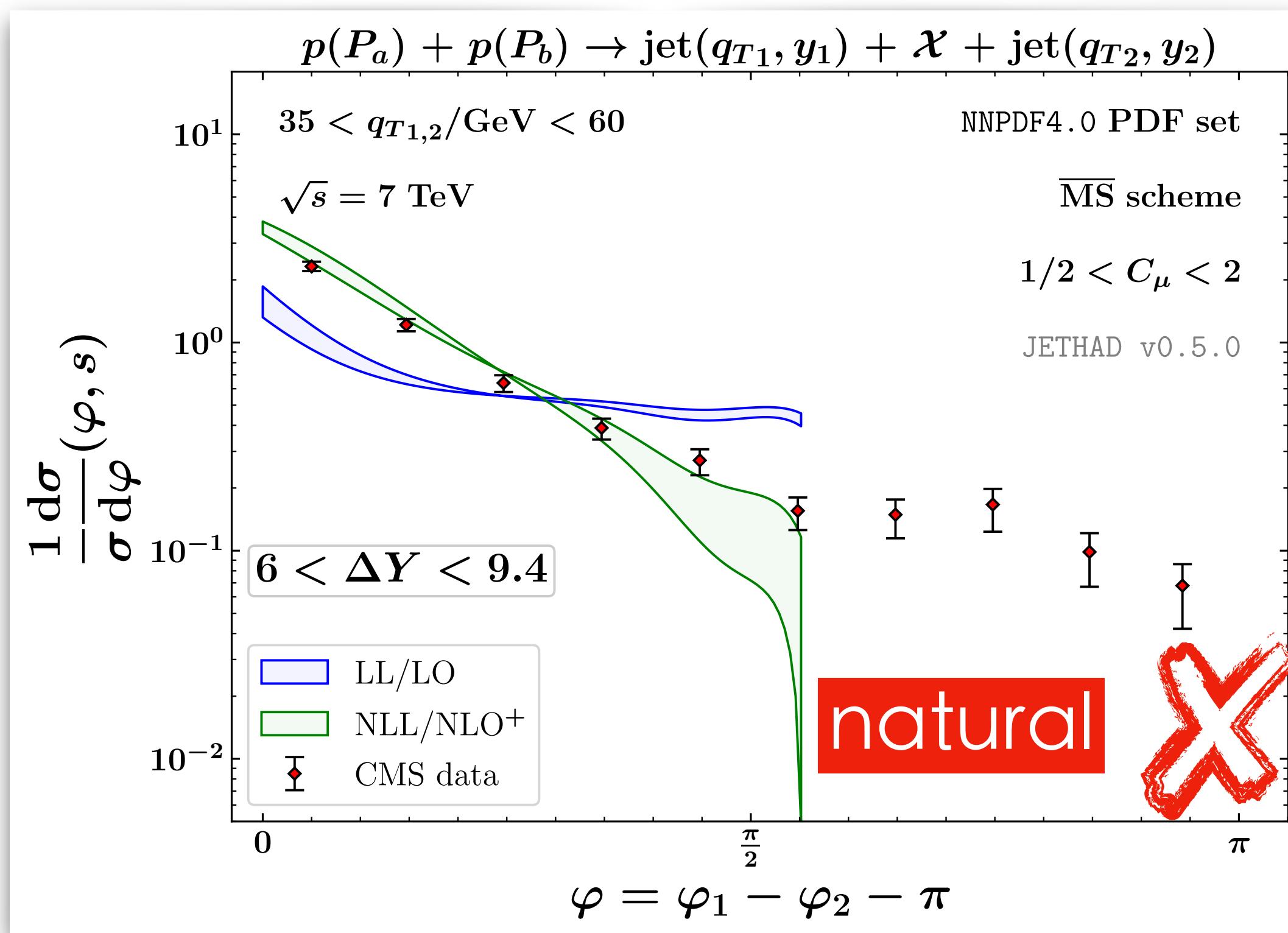
High-energy resummed Higgs + jet distributions from LHC to FCC

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)]



Azimuthal-angle multiplicity

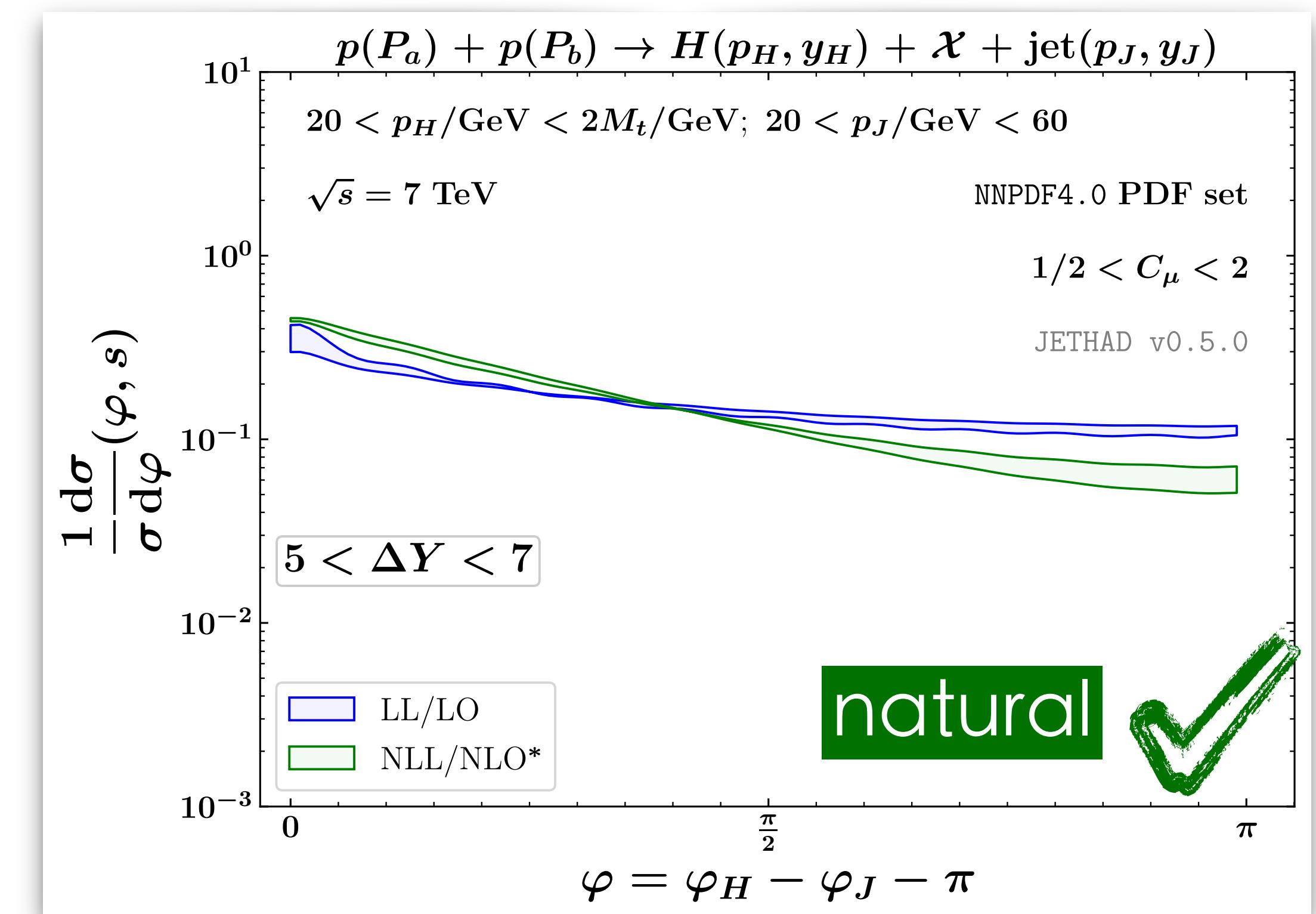
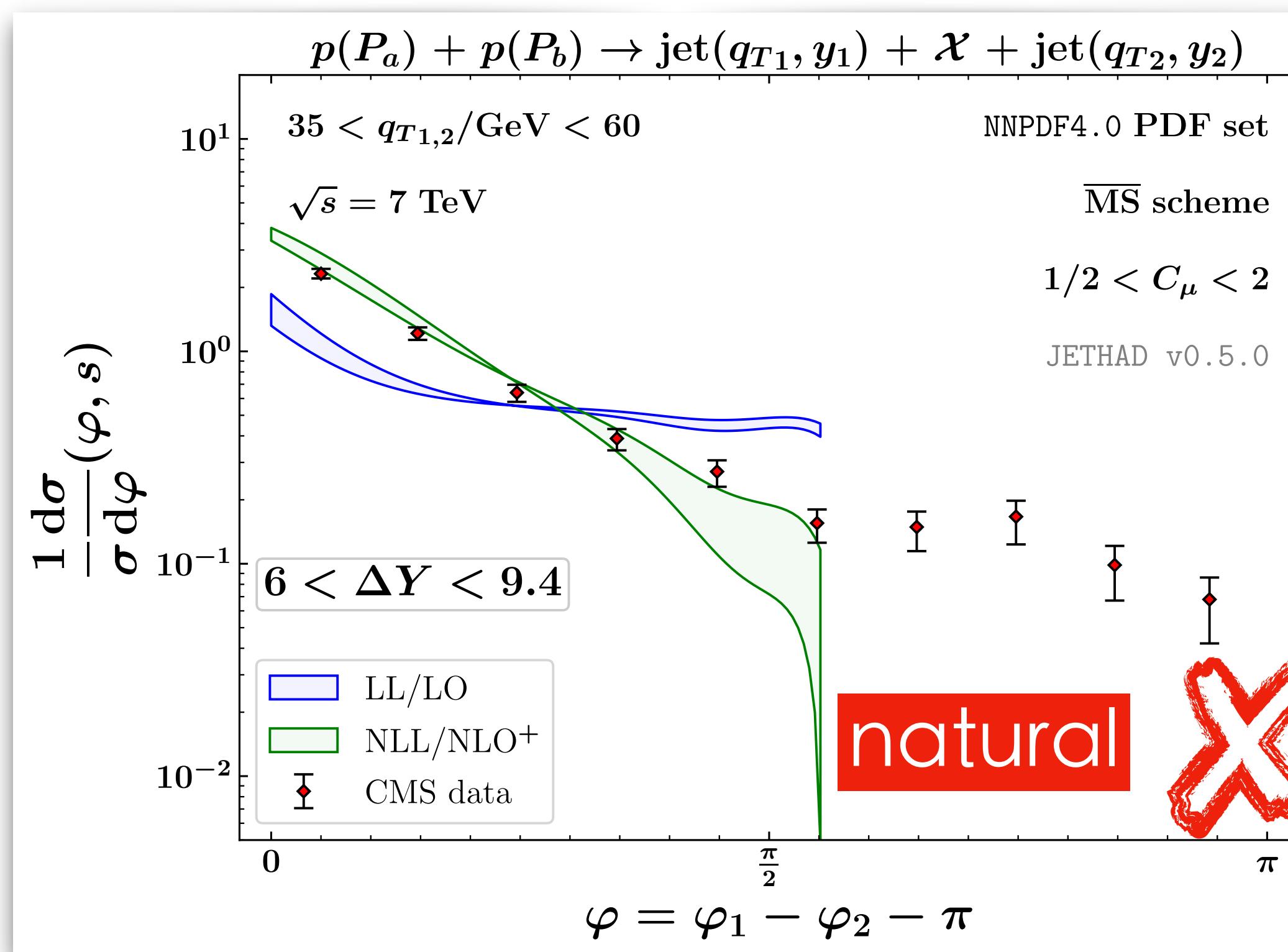
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 (figure below) [F. G. C., A. Papa (2022)]

Higgs + jet

(figure below) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]
 (NLL/NLO* Higgs) [F. G. C. et al., JHEP 08 (2022) 092]



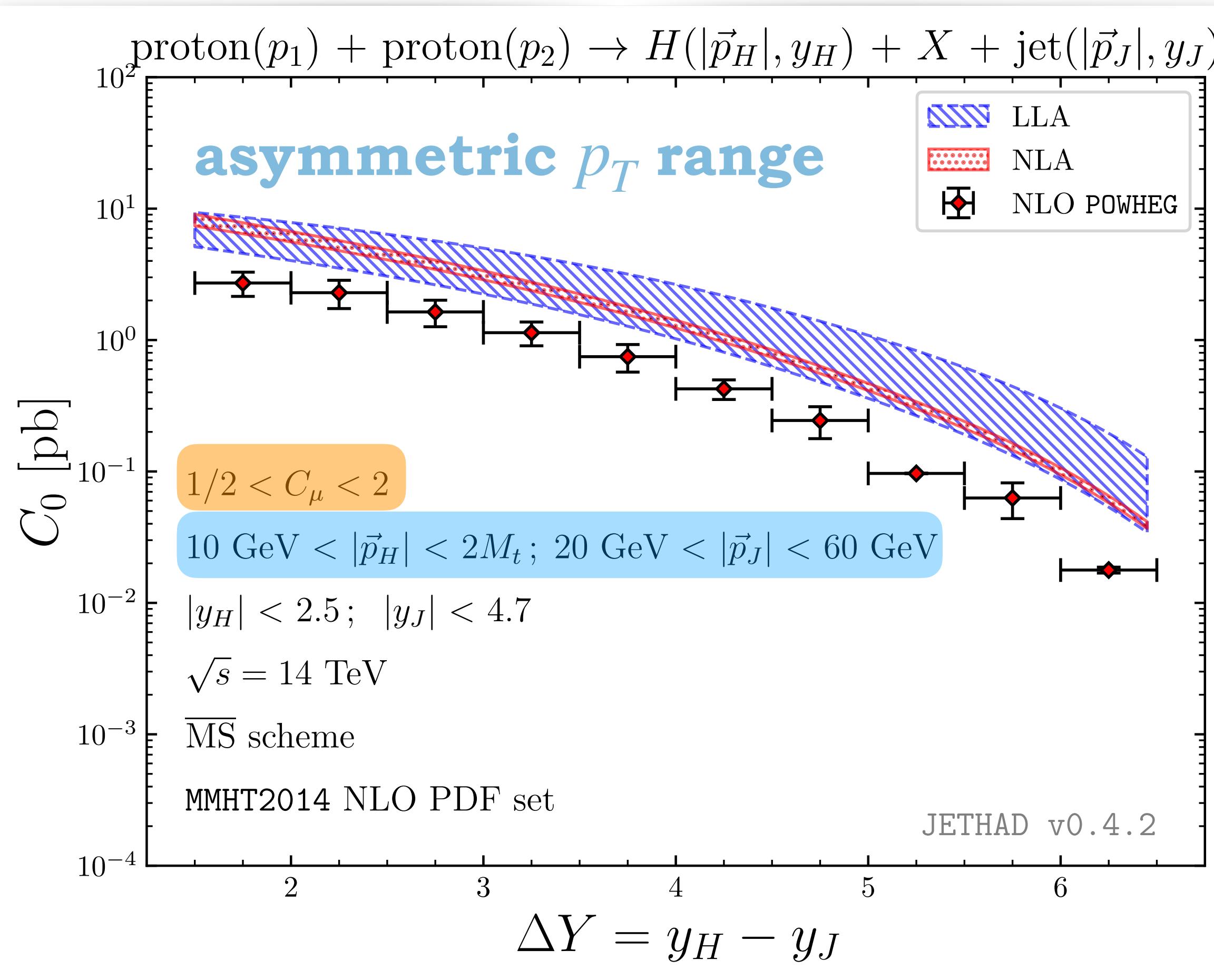
Hybrid factorization via the [JETHAD](#) code



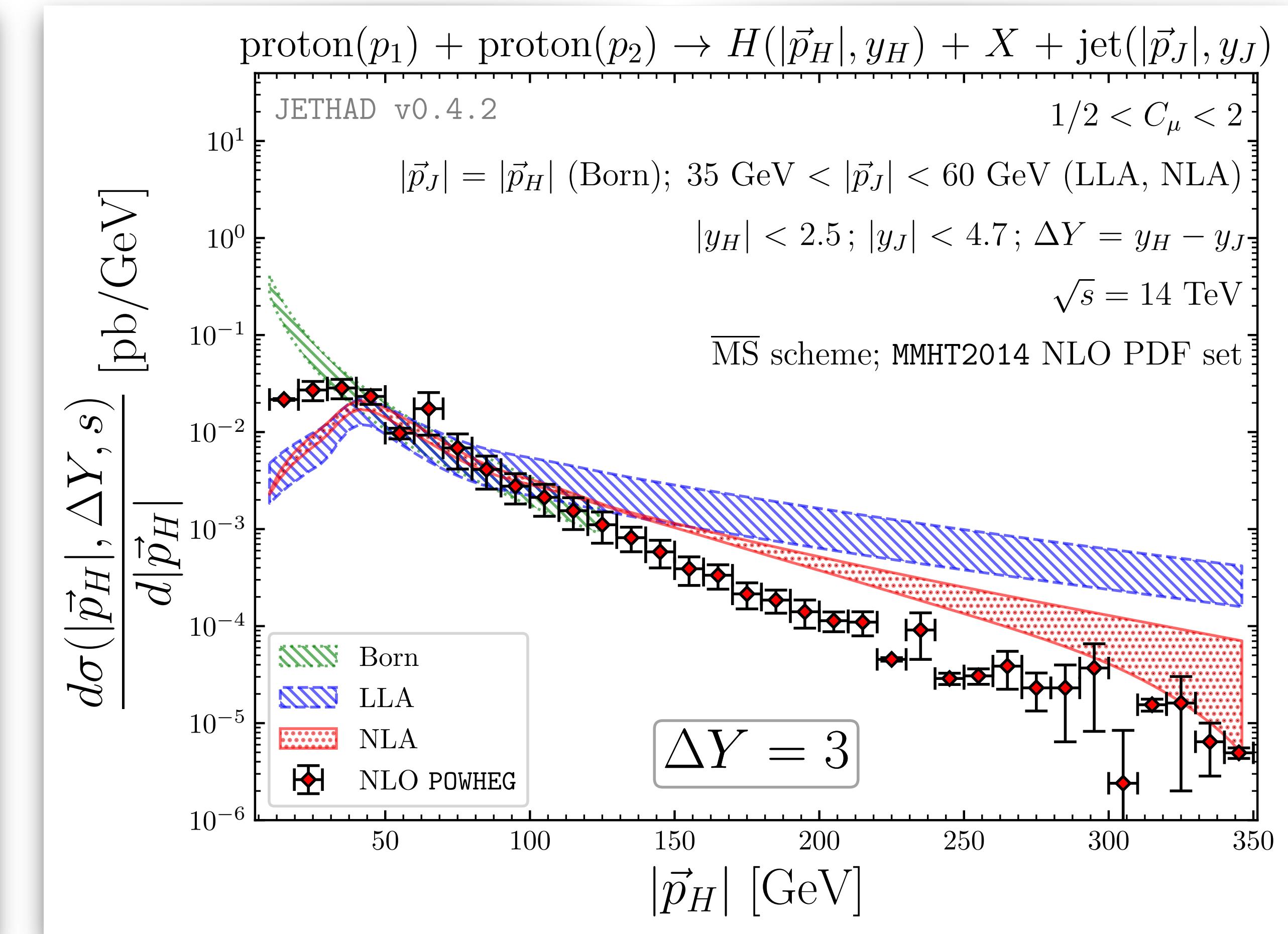
F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

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]

Higgs + jet highlights from the FCC Week 2022

The high-energy QCD dynamics from Higgs+jet correlations at FCC

Francesco G. Celiberto ^{1,2,3} and Alessandro Papa ^{4,5}

FCC Week 2022, Sorbonne Université, France

Hors d'œuvre

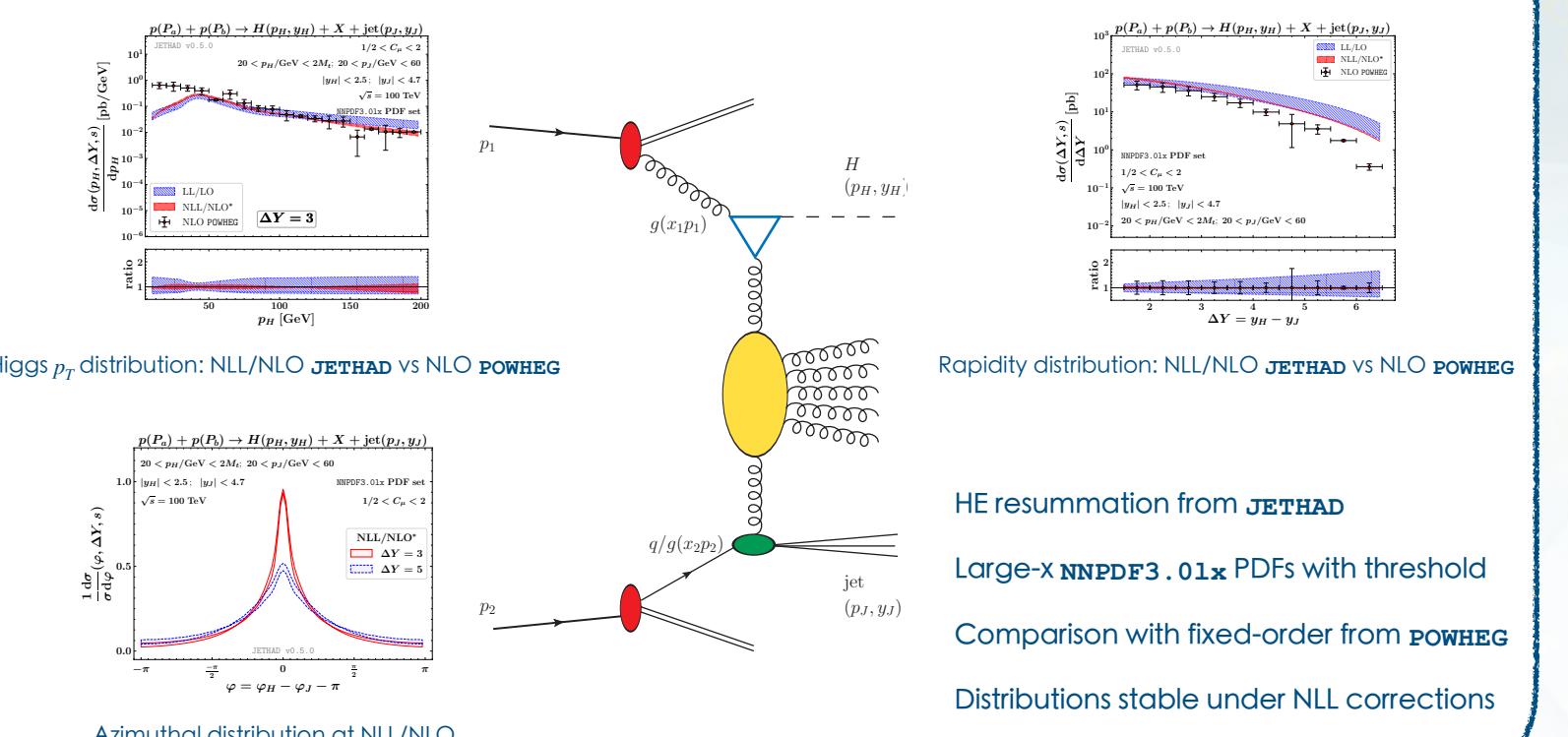
- Higgs sector → SM benchmarks, BMS portals
- Gluon fusion → key ingredient for precision QCD
- Fixed-order ← improved by resummations
- FCC energies ↔ high-energy (HE) resummation
- Higgs+jet → golden channel to hunt for HE signals

NLL/NLO differential cross section

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

$$\frac{d\hat{\sigma}_{rs}(x_1 x_2 s, \mu)}{(2\pi)^2} = \frac{1}{(2\pi)^2} \times \int \frac{d^2 \vec{q}_1}{\vec{q}_1^2} V_H^{(r)}(\vec{q}_1, s_0, x_1, \beta_H) \times \int_{\delta+ic\omega}^{\delta-ic\omega} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0} \right)^\omega g_\omega(\vec{q}_1, \vec{q}_2) \times \int \frac{d^2 \vec{q}_2}{\vec{q}_2^2} V_J^{(s)}(\vec{q}_2, s_0, x_2, \beta_J)$$

Hybrid high-energy and collinear factorization at work



A path towards precision

- NLL bands nested inside LL ones → solid stability
- HE signal clearly disengaged from NLO background
- Way toward precision studies of HE QCD (
- Multilateral formalism → encode other resummations
- A window on proton structure at small-x (

Further information

- ¹ ECT*, I-38123 Villazzano, Trento, Italy
² Fondazione Bruno Kessler (FBK), I-38123 Povo, Trento, Italy
³ INFN-TIFPA, I-38123 Povo, Trento, Italy
⁴ Università della Calabria, I-87036 Rende, Cosenza, Italy
⁵ INFN-Cosenza, I-87036 Rende, Cosenza, Italy
- Contact: fceliberto@ectstar.eu
- Take a picture to the QR code to download the paper on Higgs+jet resummed distributions at 14TeV LHC: [FGC et al., EPJ C 81 (2021) 4, 293]



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The high-energy QCD dynamics from Higgs+jet correlations at FCC

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Gluon fusion → key ingredient for precision QCD

Fixed-order ← improved by resummations

FCC energies ↔ high-energy (HE) resummation

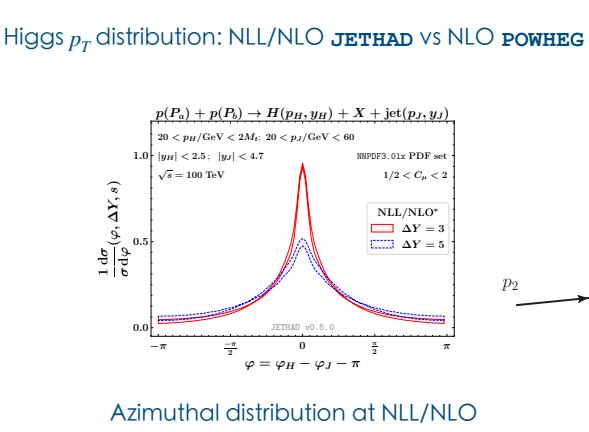
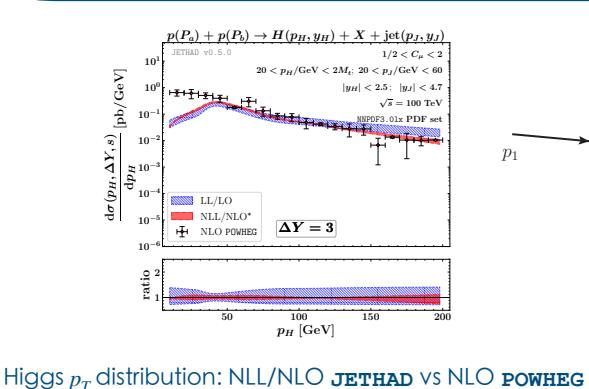
Higgs+jet → golden channel to hunt for HE signals

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$$\frac{d\hat{\sigma}_{f_1 f_2}(x_1 x_2 s, \mu_F)}{dy_1 dy_2 d^2 \vec{p}_H d^2 \vec{p}_J} = \frac{1}{(2\pi)^2} \times \int \frac{d^2 \vec{q}_1}{d\vec{q}_1^2} V_H^{(r)}(\vec{q}_1, s_0, x_1, \beta_H) \times \int_{\delta - i\epsilon_0}^{\delta + i\epsilon_0} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0} \right)^\omega G_\omega(\vec{q}_1, \vec{q}_2) \times \int \frac{d^2 \vec{q}_2}{d\vec{q}_2^2} V_J^{(s)}(\vec{q}_2, s_0, x_2, \beta_J)$$

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- Multilateral formalism → encode other resummations
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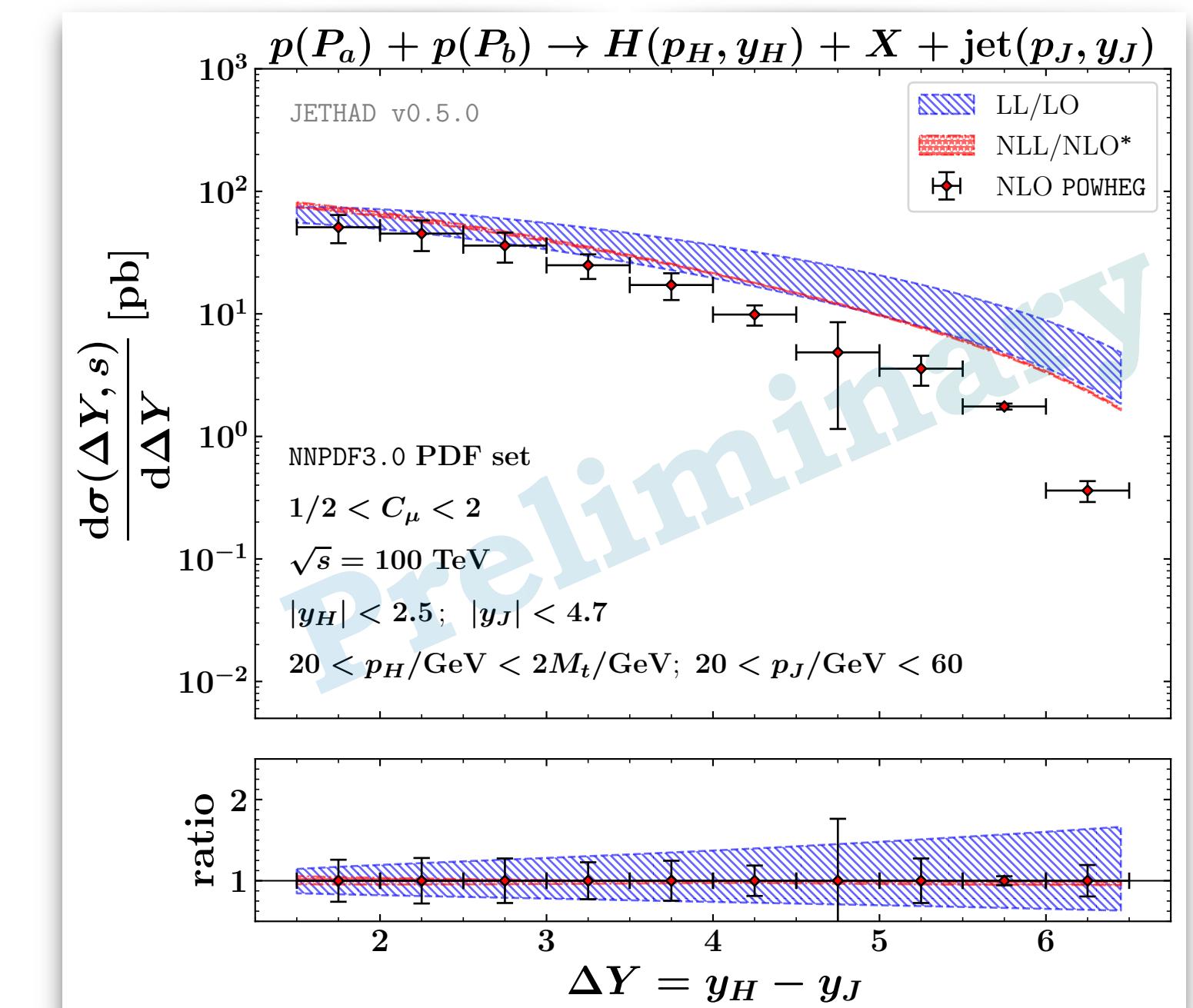
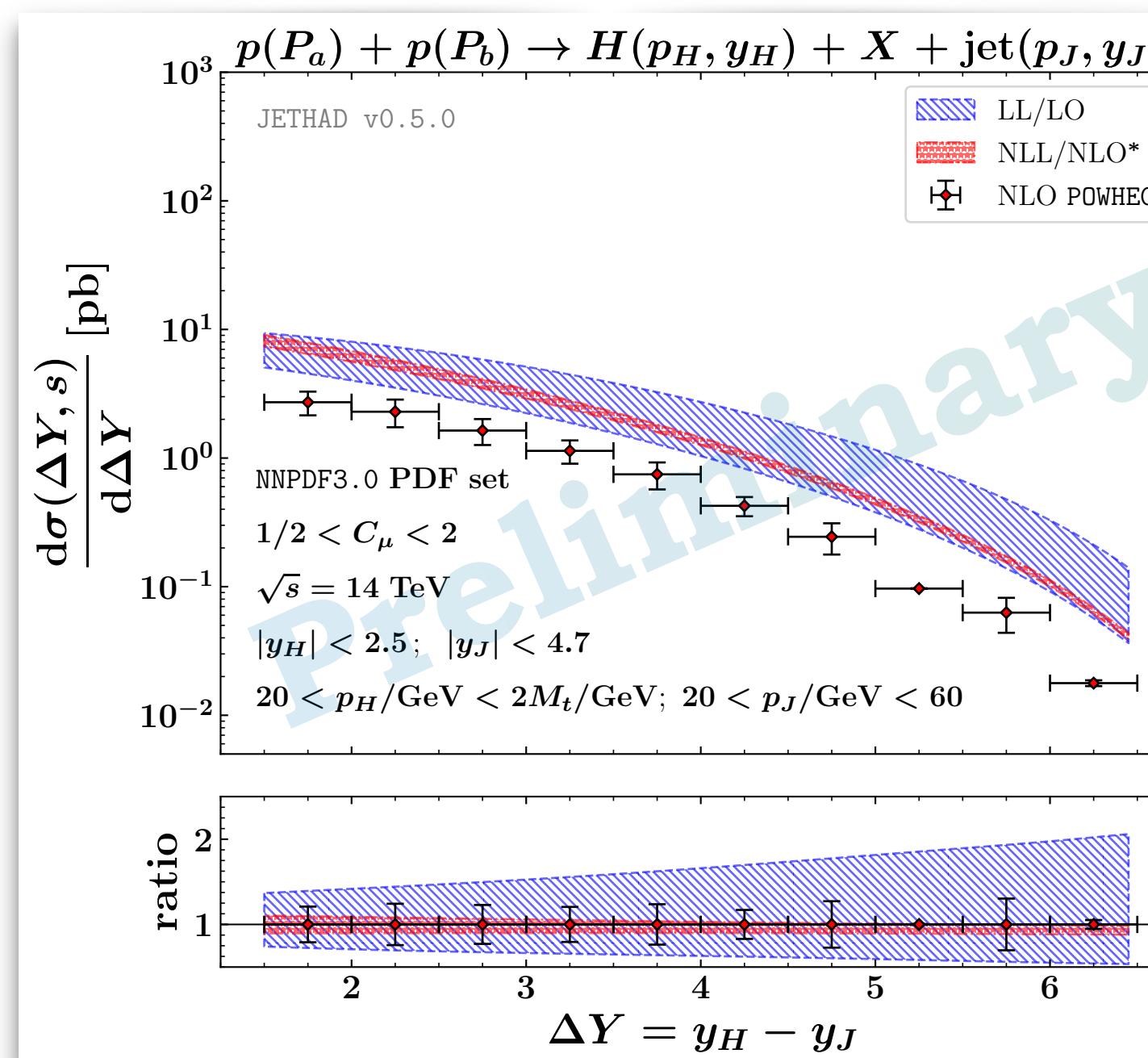
Further information

- ¹ ECT*, I-38123 Villazzano, Trento, Italy
 - ² Fondazione Bruno Kessler (FBK), I-38123 Povo, Trento, Italy
 - ³ INFN-TIFPA, I-38123 Povo, Trento, Italy
 - ⁴ Università della Calabria, I-87036 Rende, Cosenza, Italy
 - ⁵ INFN-Cosenza, I-87036 Rende, Cosenza, Italy
- Contact: fceliberto@ectstar.eu
- Take a picture to the QR code to download the paper on Higgs+jet resummed distributions at 14 TeV LHC: [FGC et al., EPJ C 81 (2021) 4, 293]



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

Rapidity distribution: NLL/NLO* JETHAD vs NLO POWHEG

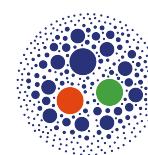


14 TeV LHC

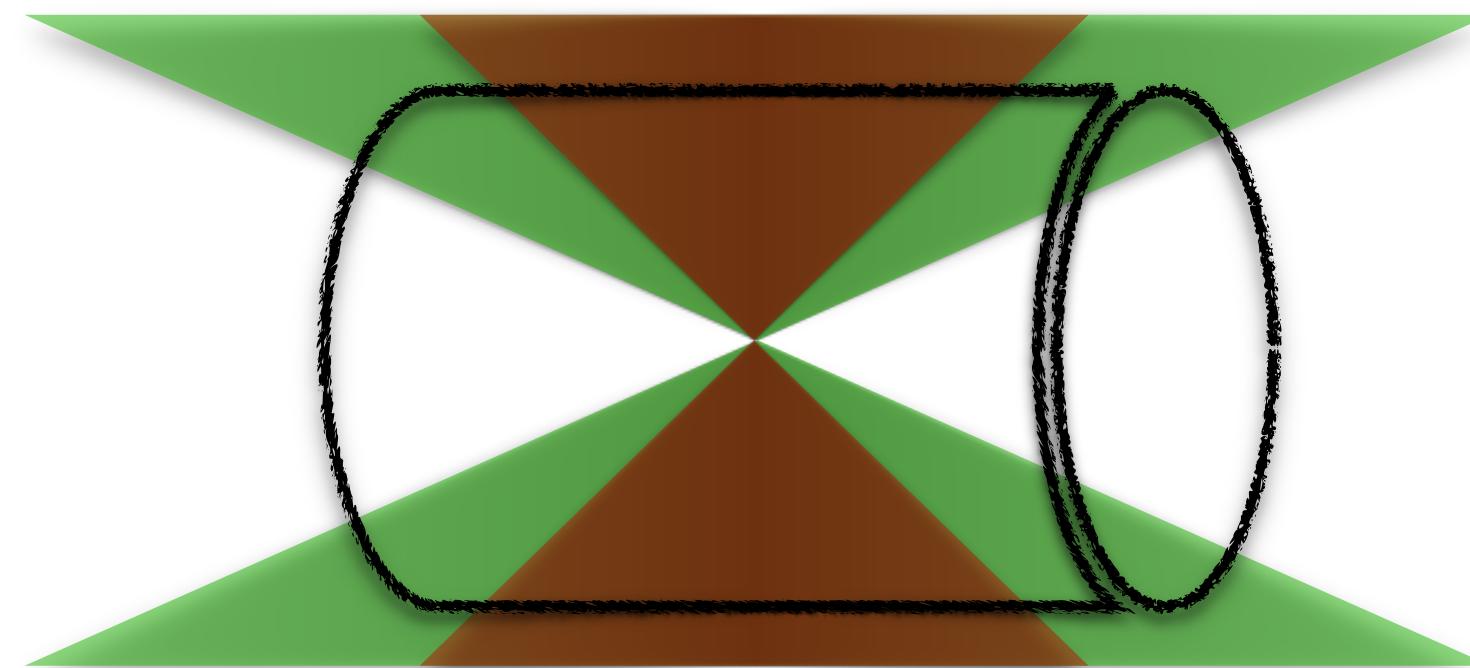
100 TeV FCC

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



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

barrel + endcap

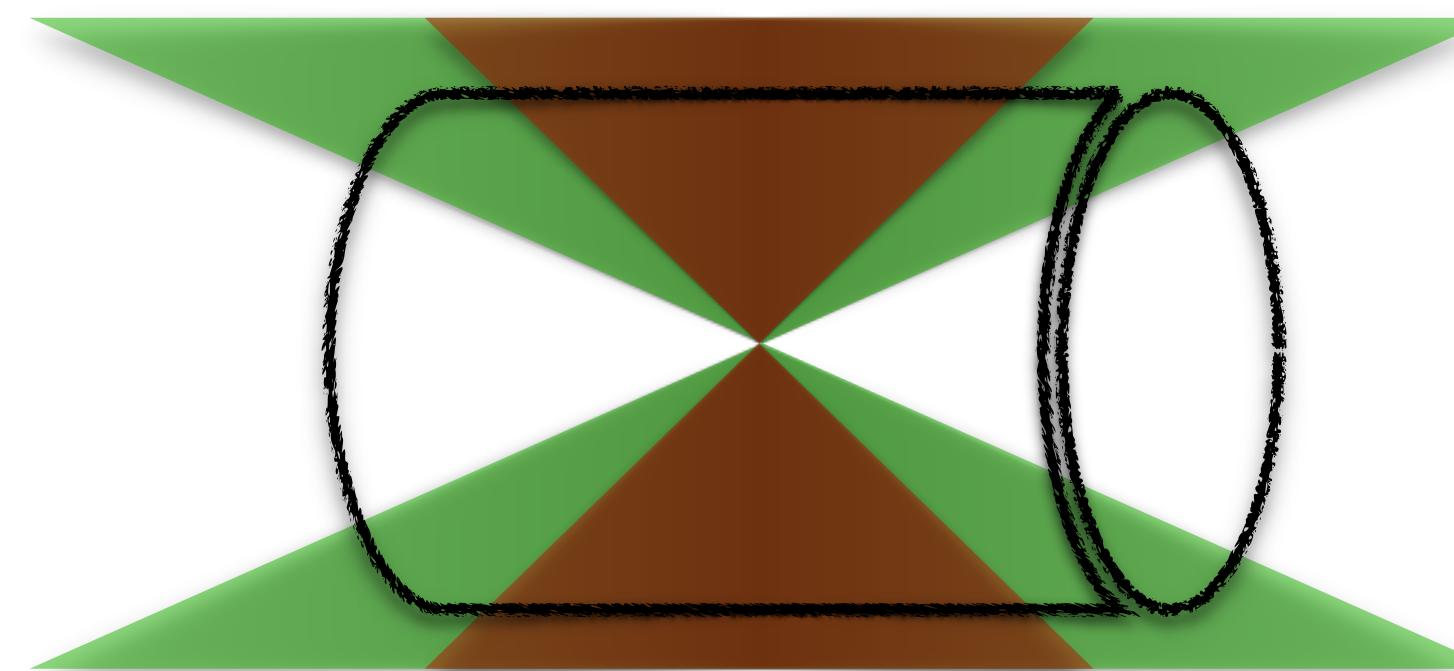
$$|y_{\text{hadron}}| < 2.4$$

barrel

High-energy QCD at new-gen Forward Facilities



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

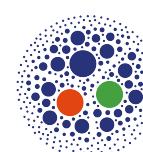


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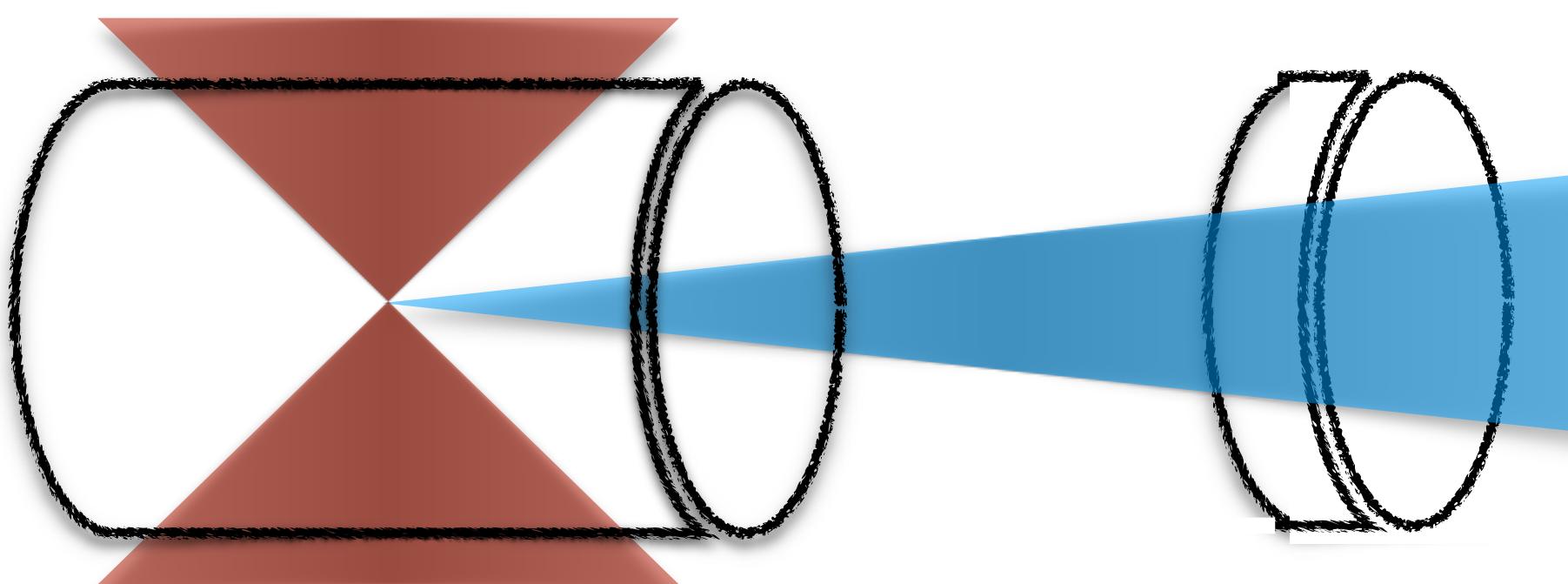
barrel + endcap

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

barrel



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



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

FPF

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

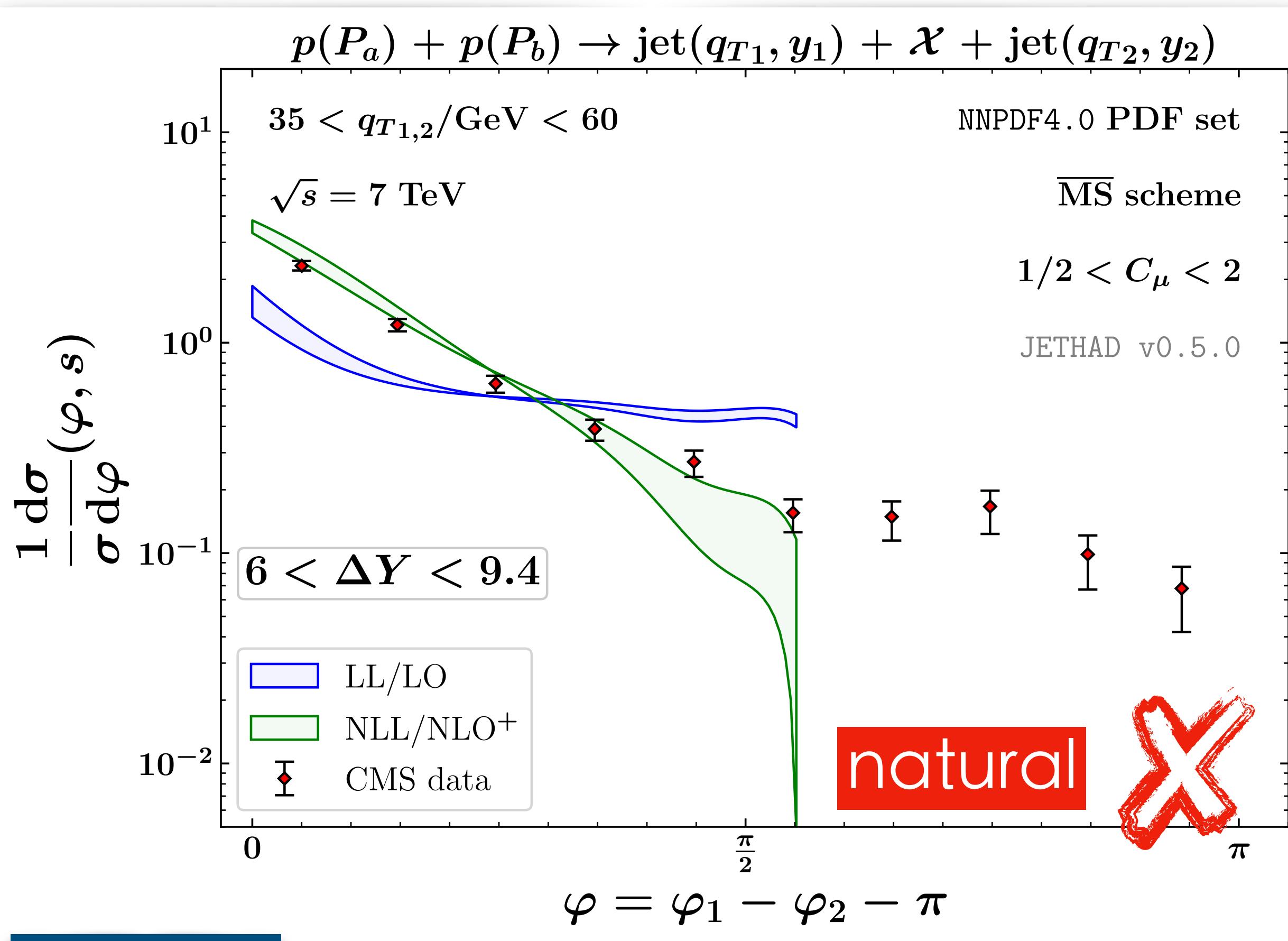
ATLAS barrel

(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]

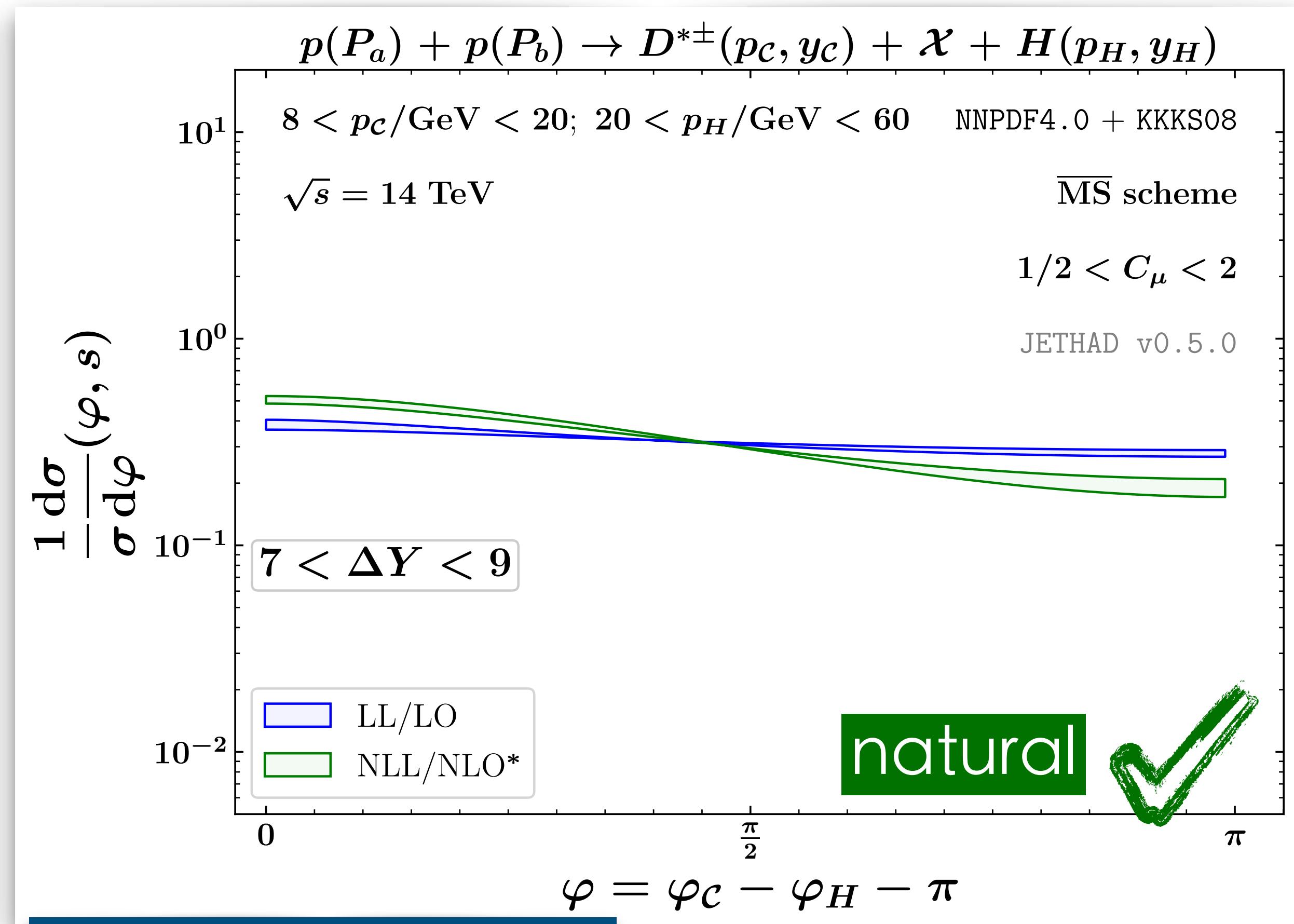
Benefits of natural stability from LHC to FPF

Mueller-Navelet jets



@CMS

Charm + Higgs

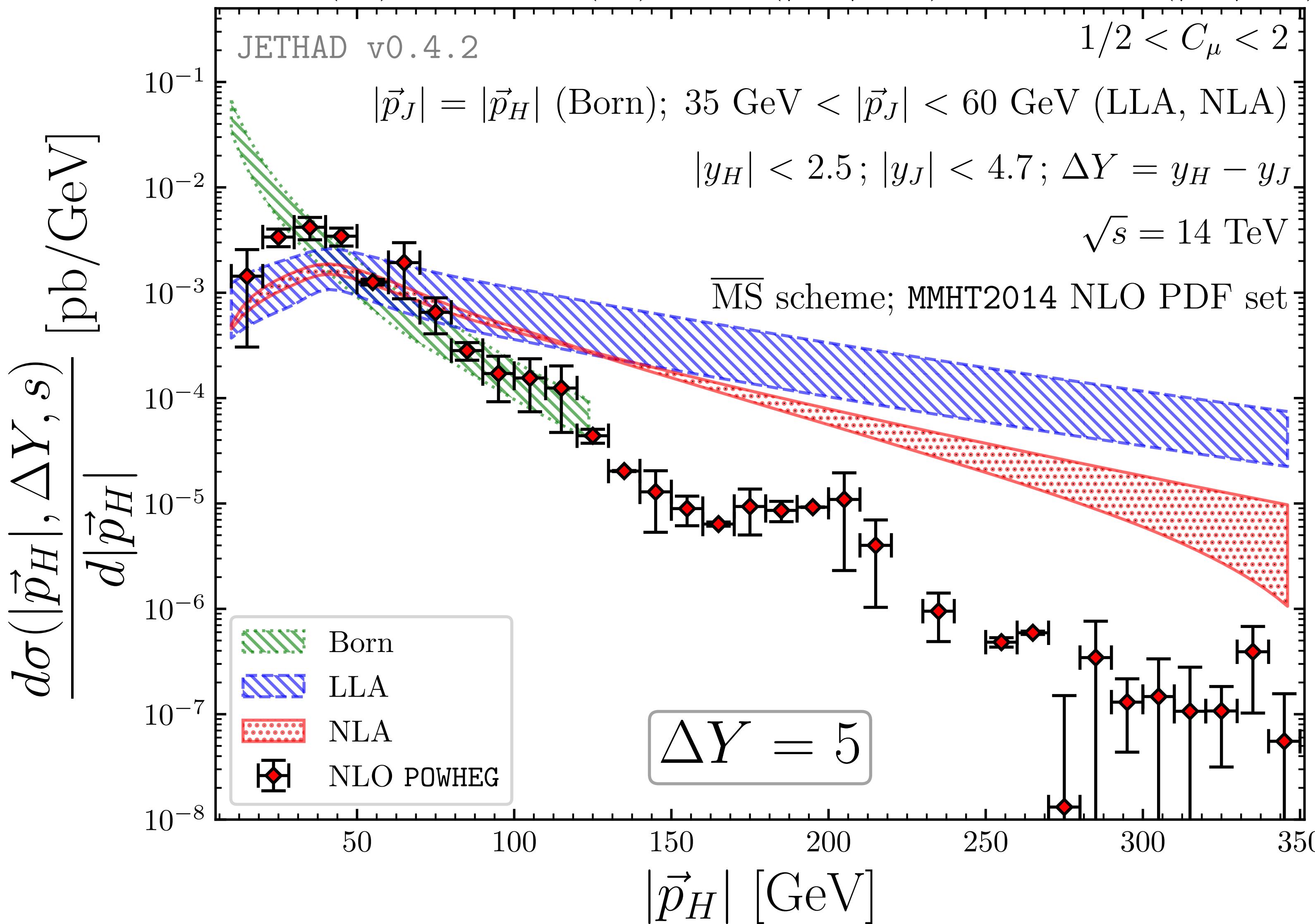


@[FPF + ATLAS]

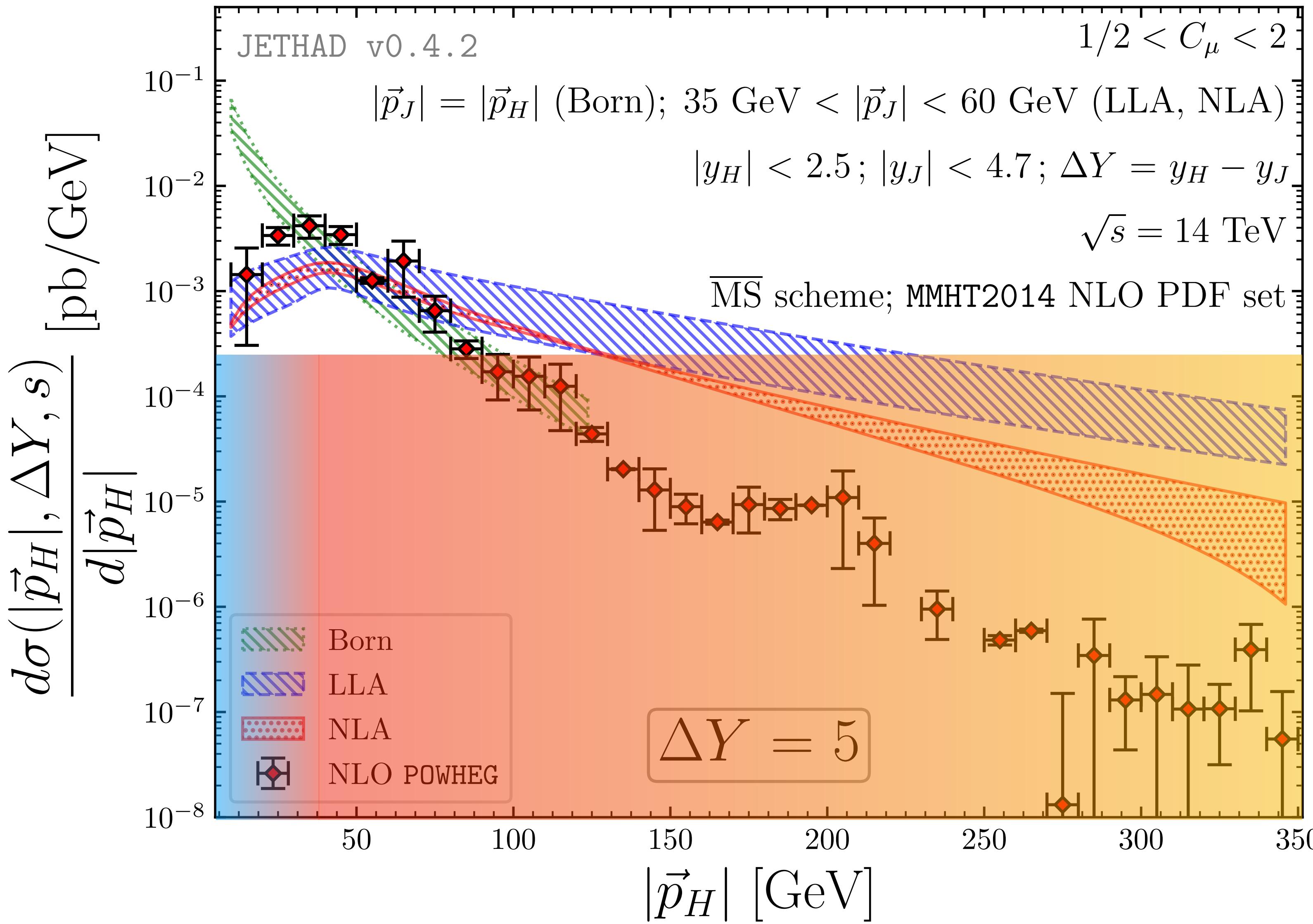


NLL accurate predictions
matched to NLO
via the JETHAD Method

$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$



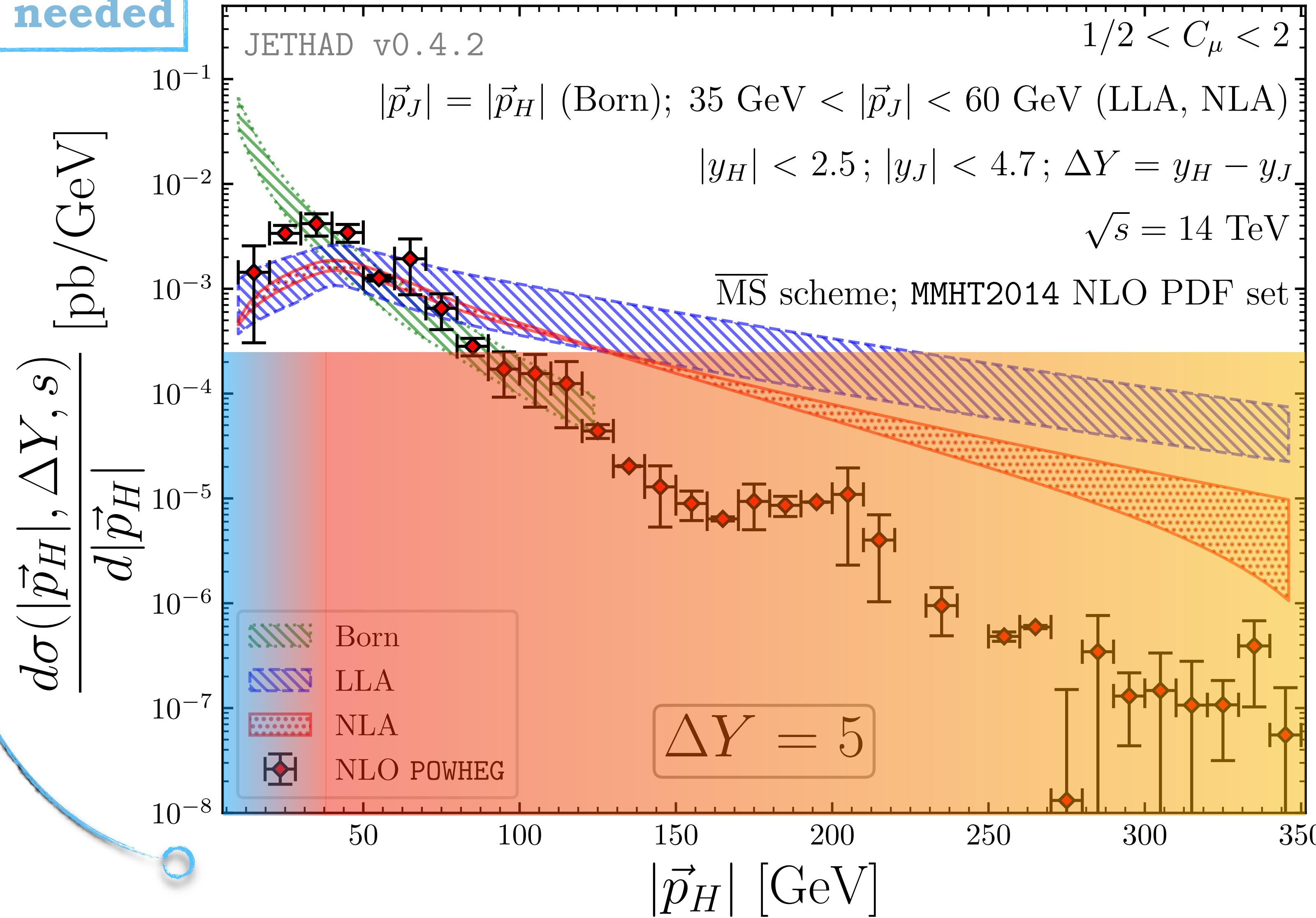
$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$



large p_T logs
 p_T -resum. needed

proton(p_1) + proton(p_2) $\rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$

$1/2 < C_\mu < 2$

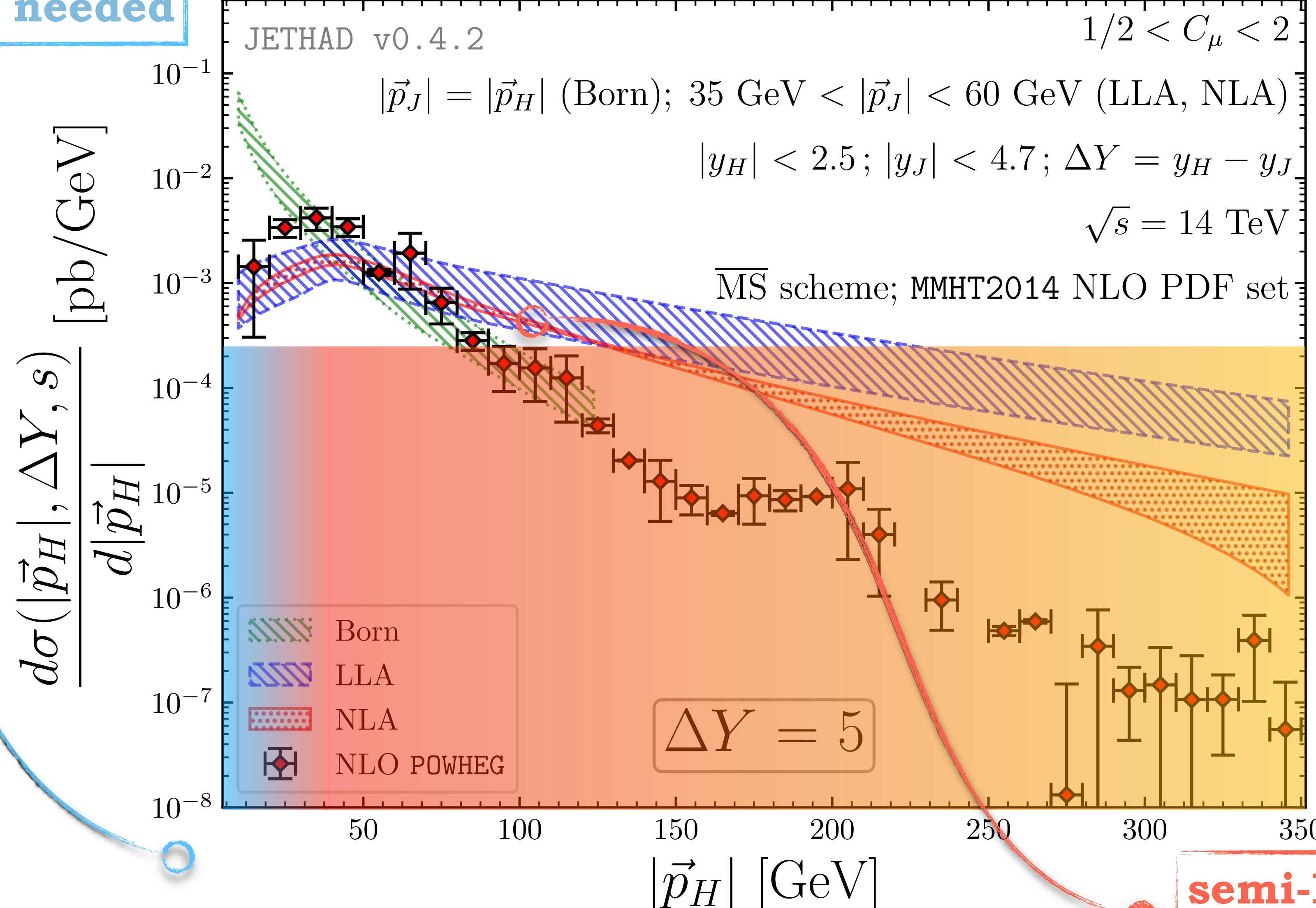


***p_T*-resum. needed**

large *p_T* logs

proton(p_1) + proton(p_2) $\rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$

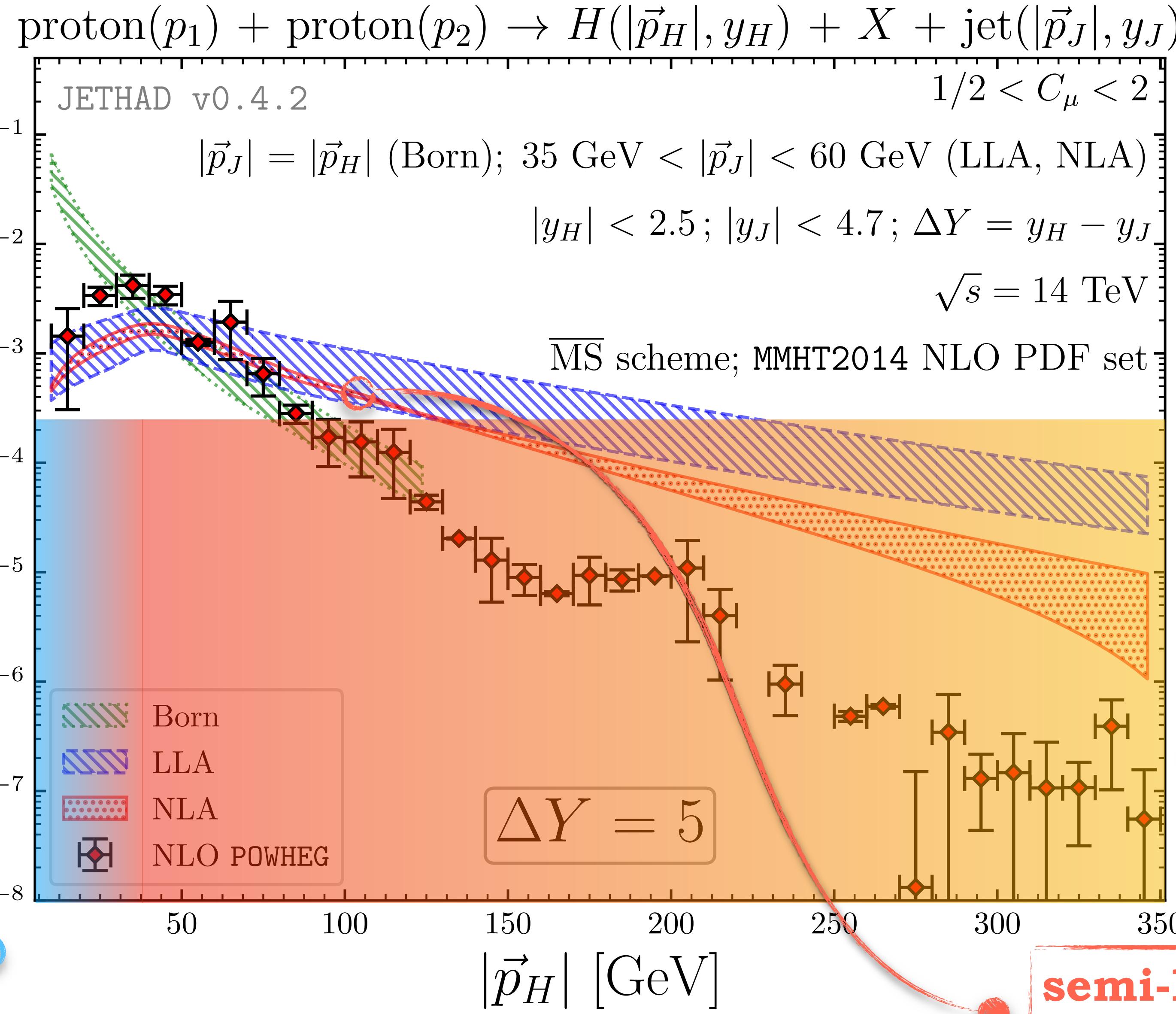
$1/2 < C_\mu < 2$



**semi-hard regime
BFKL expected**

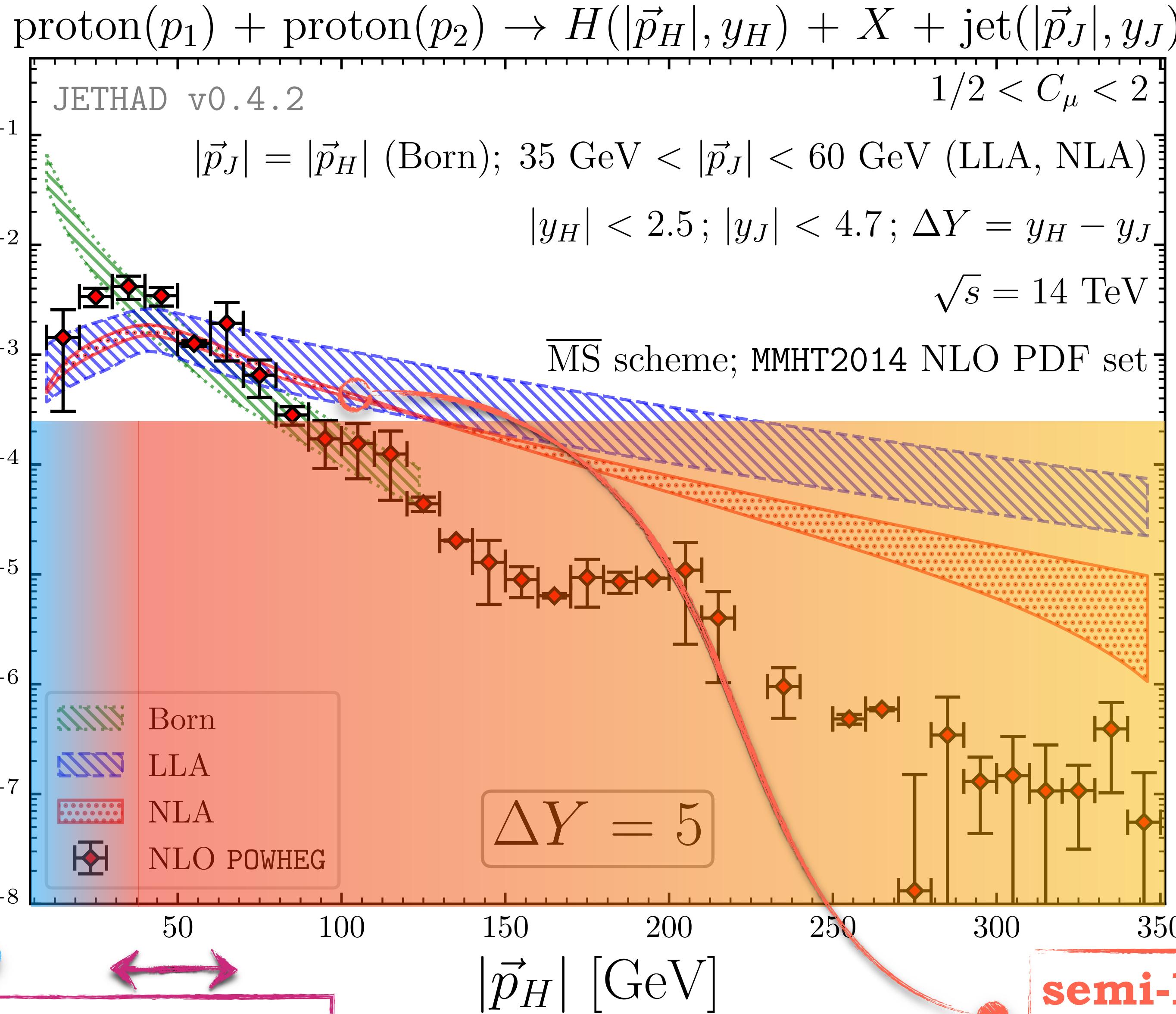
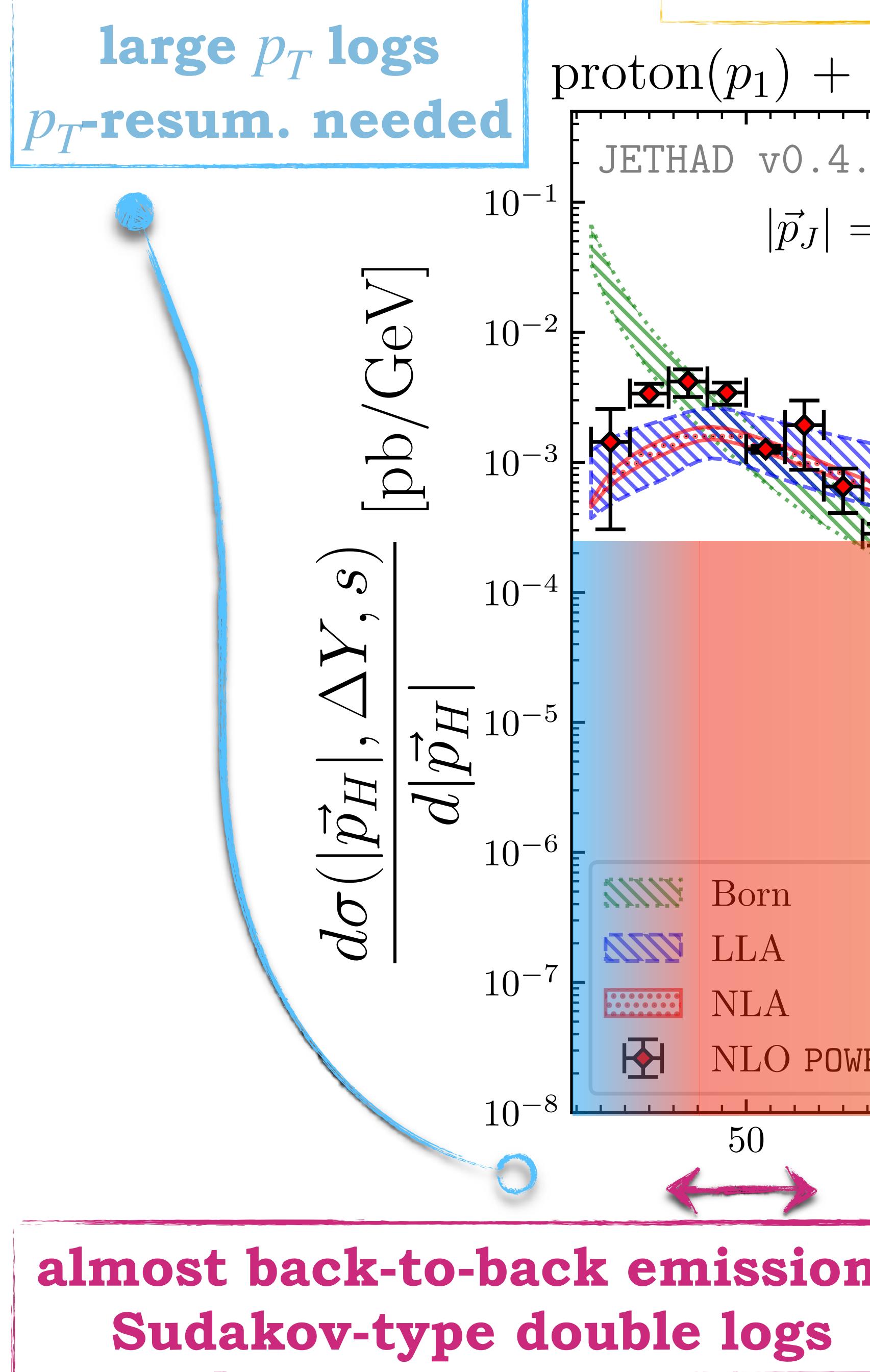
DGLAP-type + large- x threshold logs \rightarrow BFKL decoupling

**large p_T logs
 p_T -resum. needed**



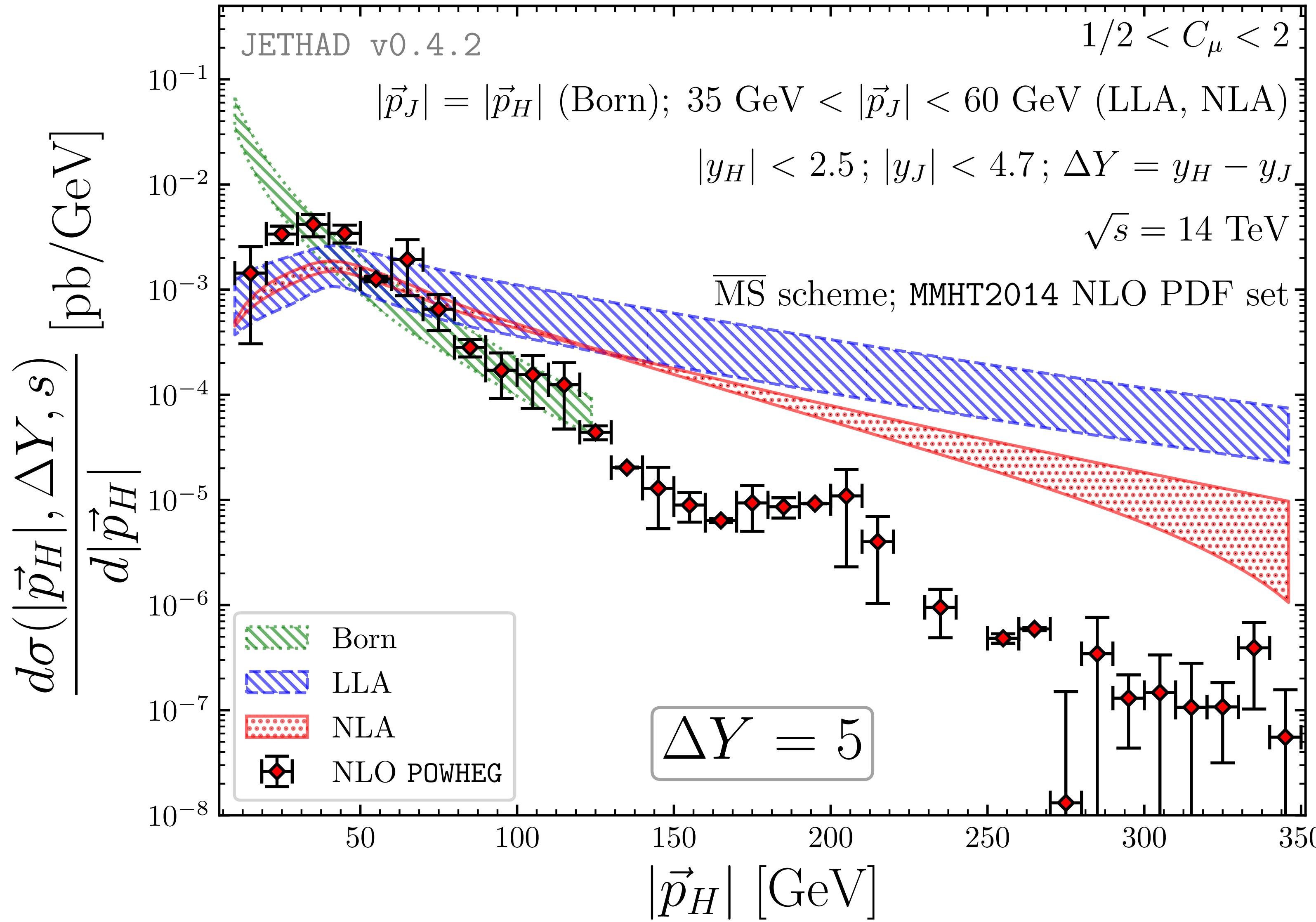
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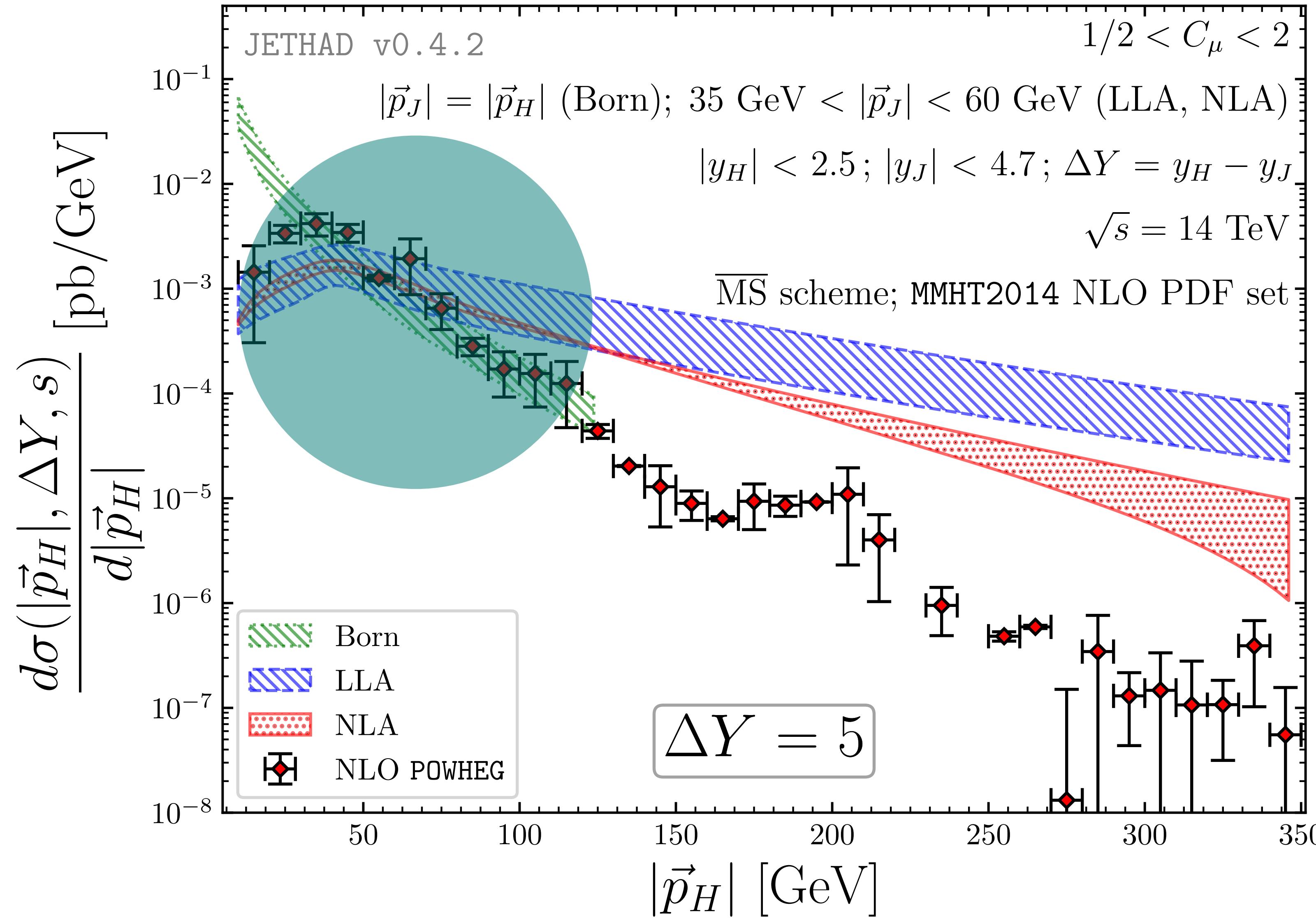


**semi-hard regime
BFKL expected**

proton(p_1) + proton(p_2) $\rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$

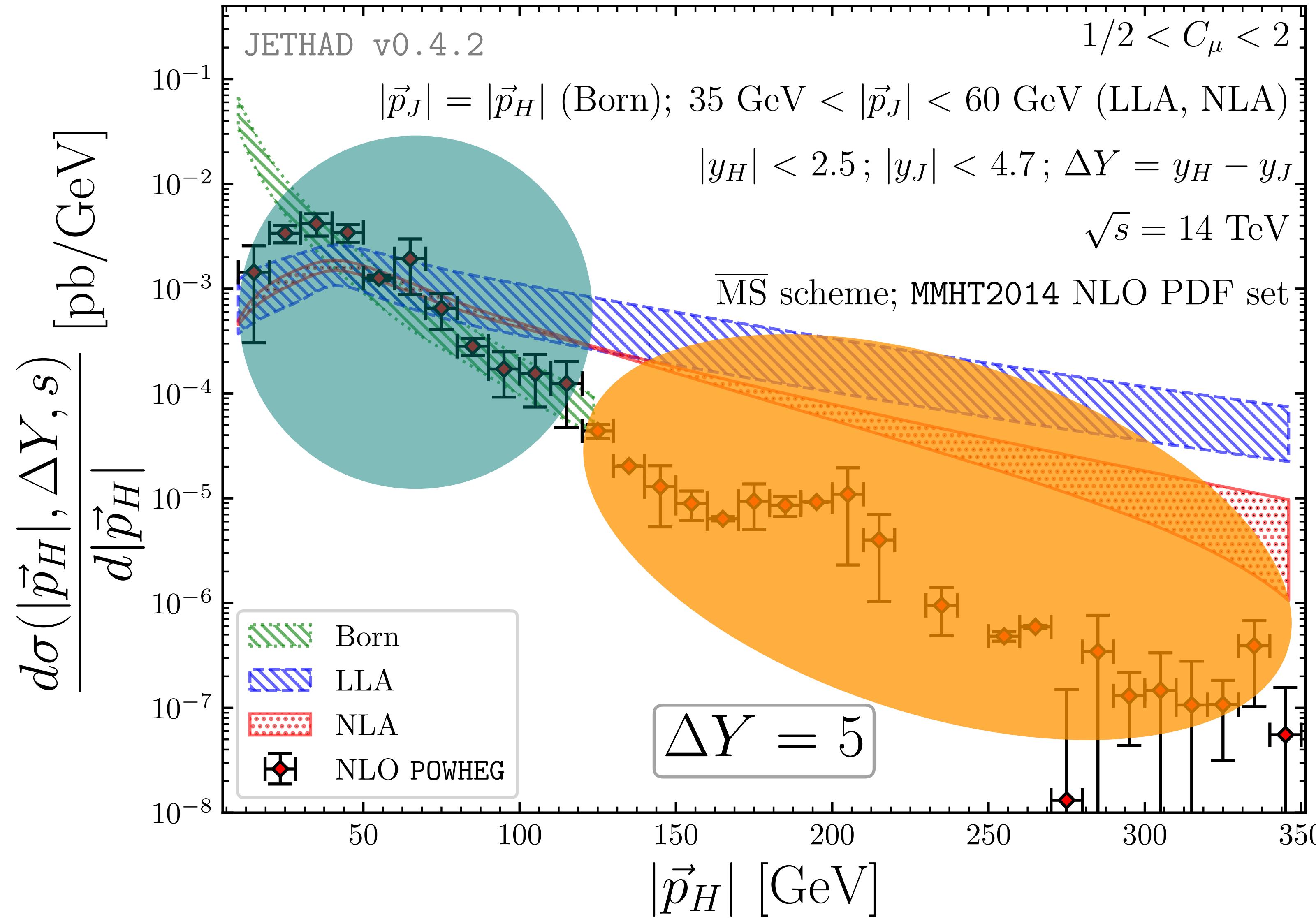


$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$



i Precision corrections expected

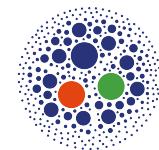
$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$



i Precision corrections expected, but hybrid factorization predicts large deviations from f.o. !

Matching NLL to NLO with JETHAD

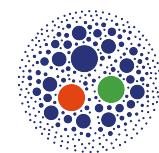
i Precision corrections expected \Leftrightarrow need for an accurate NLL-to-NLO Matching procedure !



JETHAD Method → NLL/NLO analytic (exact = BFKL kernel + impact factors) Matching

Matching NLL to NLO with JETHAD

i Precision corrections expected \Leftrightarrow need for an accurate NLL-to-NLO **Matching procedure !**

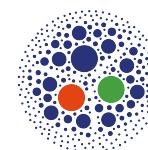


JETHAD Method → NLL/NLO analytic (exact = BFKL kernel + impact factors) Matching

$$d\sigma^{\text{NLL/NLO}}(\Delta Y, \varphi, s) = d\sigma^{\text{NLO}}(\Delta Y, \varphi, s) + d\sigma^{\text{NLL}}(\Delta Y, \varphi, s) - \Delta d\sigma^{\text{NLL/NLO}}(\Delta Y, \varphi, s)$$

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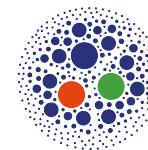
NLO POWHEG w/o PS



NLL JETHAD + removal of NLO double counting

Matching NLL to NLO with JETHAD

i Precision corrections expected \Leftrightarrow need for an accurate NLL-to-NLO Matching procedure !



JETHAD Method \rightarrow NLL/NLO analytic (exact = BFKL kernel + impact factors) Matching

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NLO POWHEG w/o PS



NLL JETHAD + removal of NLO double counting

HELL + ggHiggs

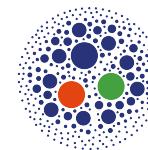
$\text{N}^3\text{LL}_{\text{Ix}}/\text{LL}_{\text{Sx}}/\text{N}^3\text{LO}$

Inclusive Higgs

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

Matching NLL to NLO with JETHAD

i Precision corrections expected \Leftrightarrow need for an accurate NLL-to-NLO Matching procedure !



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NLO POWHEG w/o PS

NLL JETHAD + removal of NLO double counting

HELL + ggHiggs

$\text{N}^3\text{LL}_{\text{Ix}}/\text{LL}_{\text{Sx}}/\text{N}^3\text{LO}$

Inclusive Higgs

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

HEJ framework

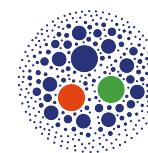
$\text{LL}_{\text{Sx}}/\text{LO}$

Higgs + jet(s)

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

Matching NLL to NLO with JETHAD

i Precision corrections expected \Leftrightarrow need for an accurate NLL-to-NLO Matching procedure !



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$$d\sigma^{\text{NLL/NLO}}(\Delta Y, \varphi, s) = d\sigma^{\text{NLO}}(\Delta Y, \varphi, s) + d\sigma^{\text{NLL}}(\Delta Y, \varphi, s) - \Delta d\sigma^{\text{NLL/NLO}}(\Delta Y, \varphi, s)$$



NLO POWHEG w/o PS

NLL JETHAD + removal of NLO double counting

HELL + ggHiggs

$\text{N}^3\text{LL}_{\text{Ix}}/\text{LL}_{\text{Sx}}/\text{N}^3\text{LO}$

Inclusive Higgs

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

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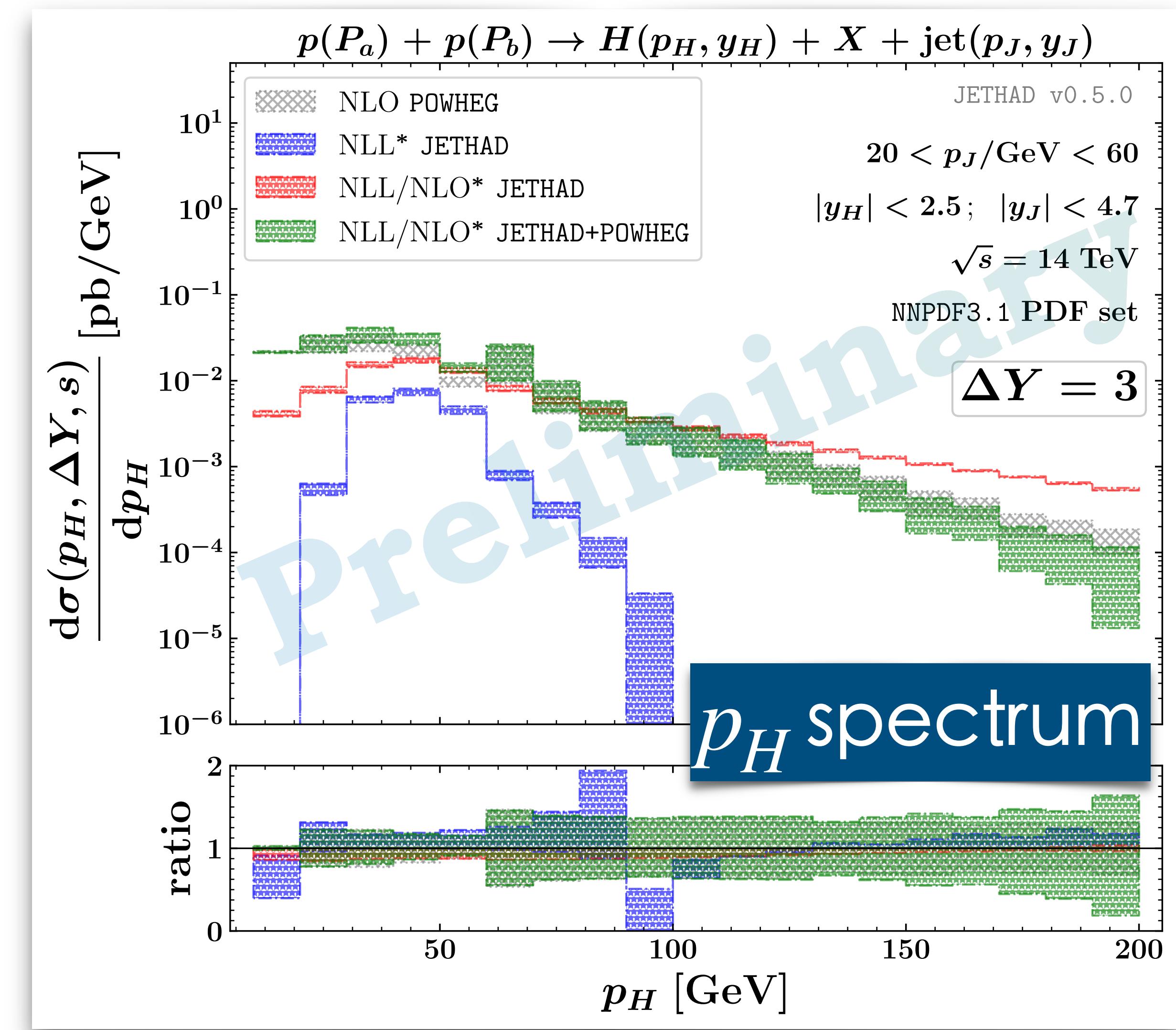
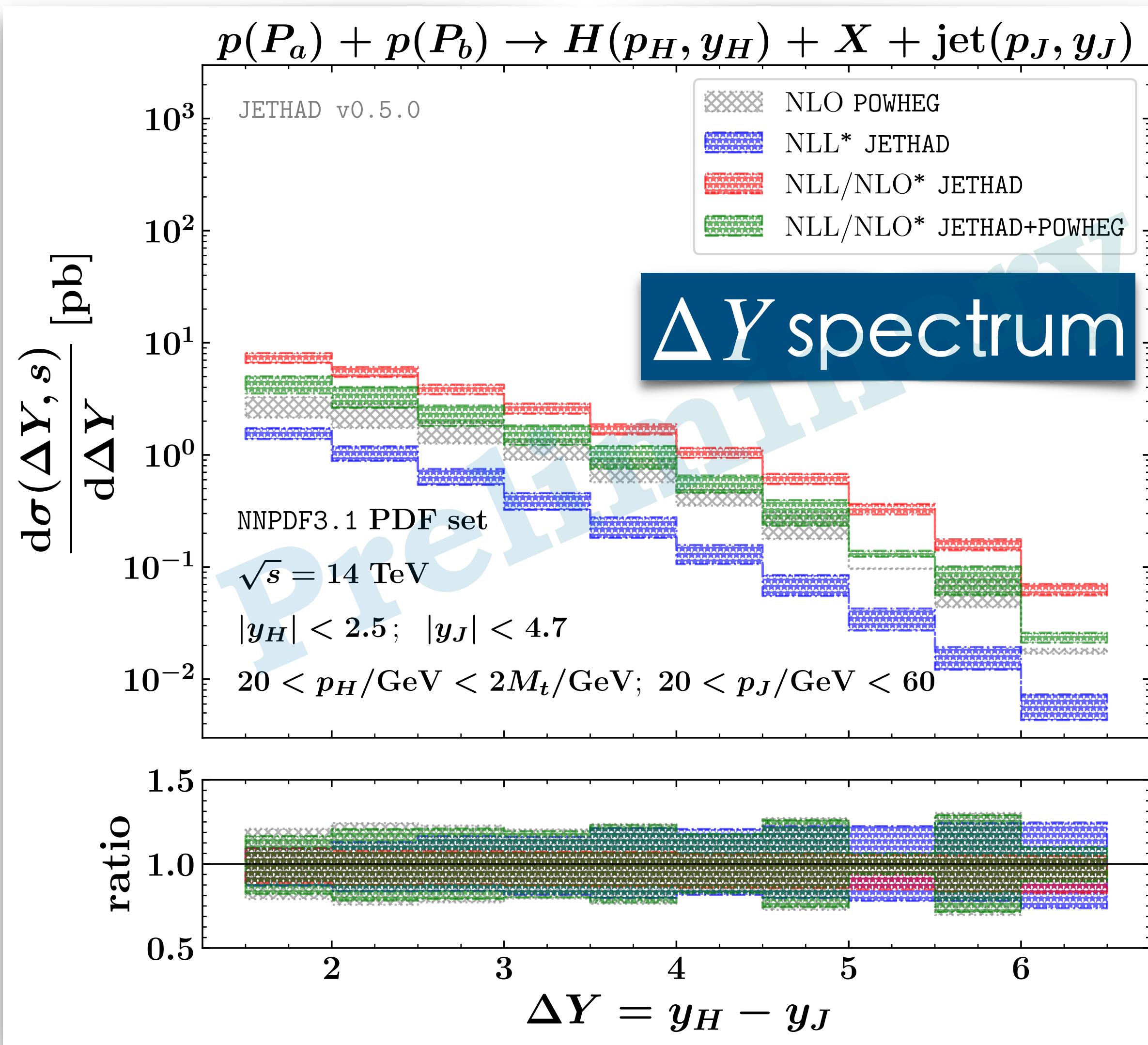
RadISH + MCFM-8 . 3

$\text{NNLL}_{\text{TM}}/\text{NLO}$

Higgs + jet

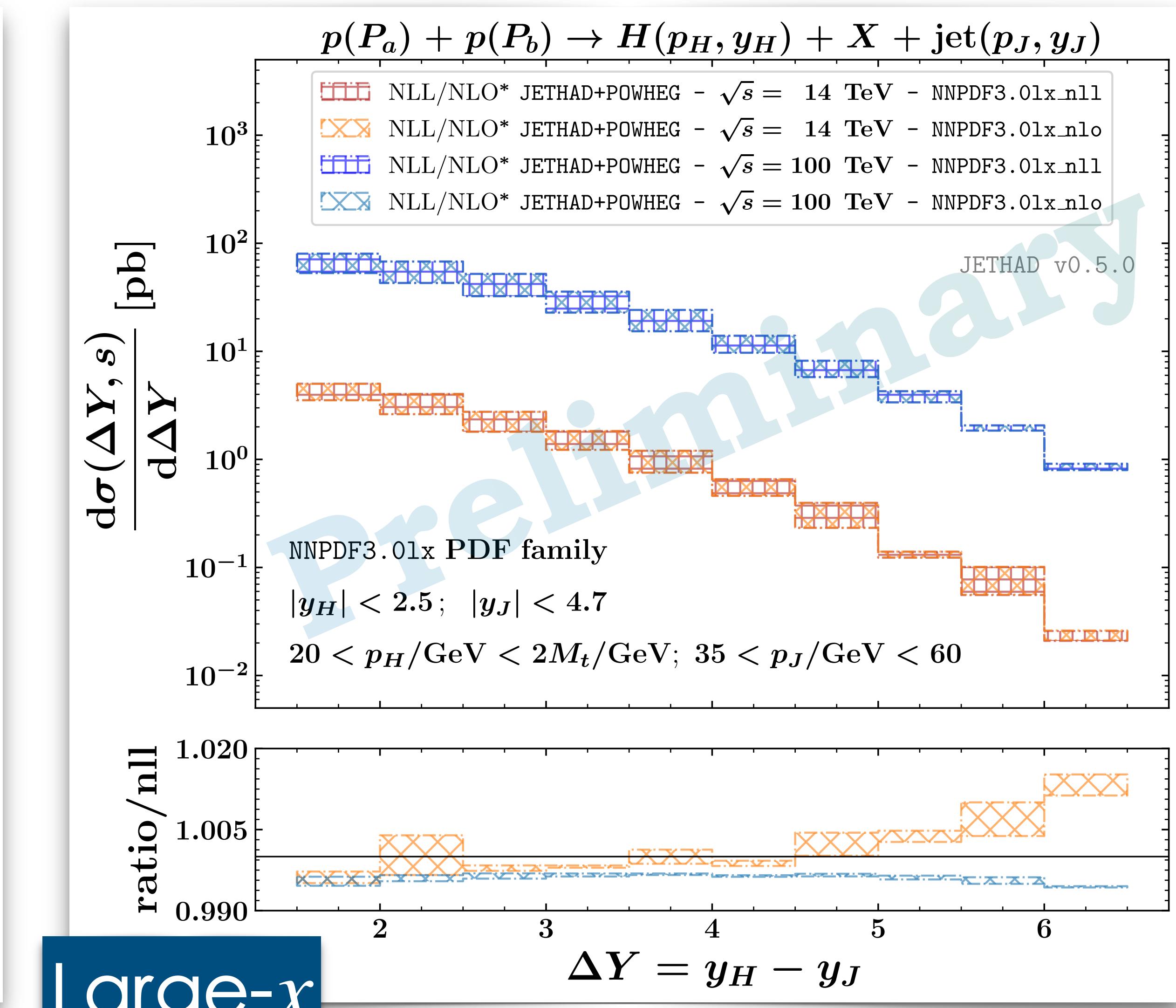
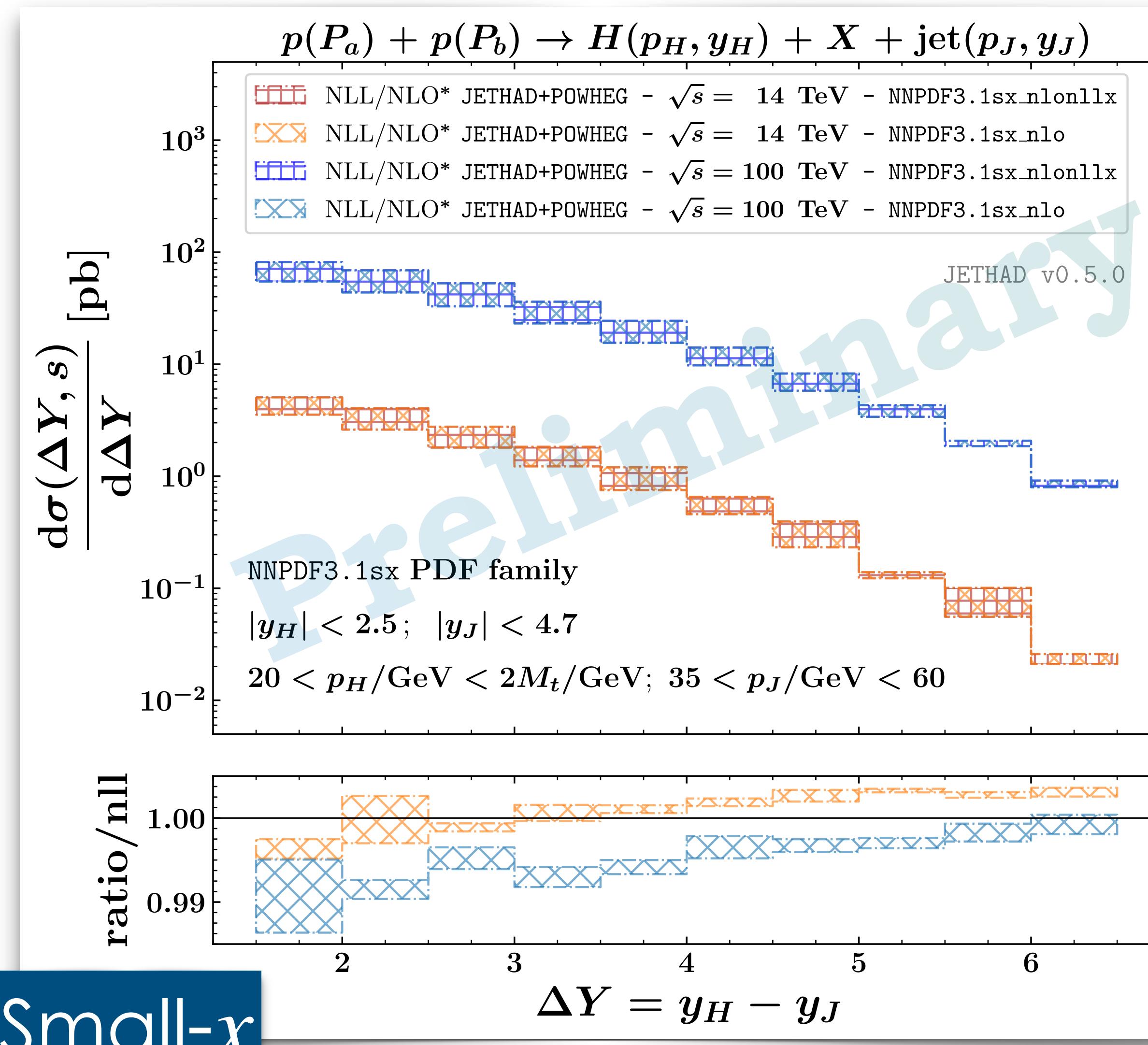
[P. F. Monni et al. (2020)]

The Higgs + jet spectrum from POWHEG + JETHAD

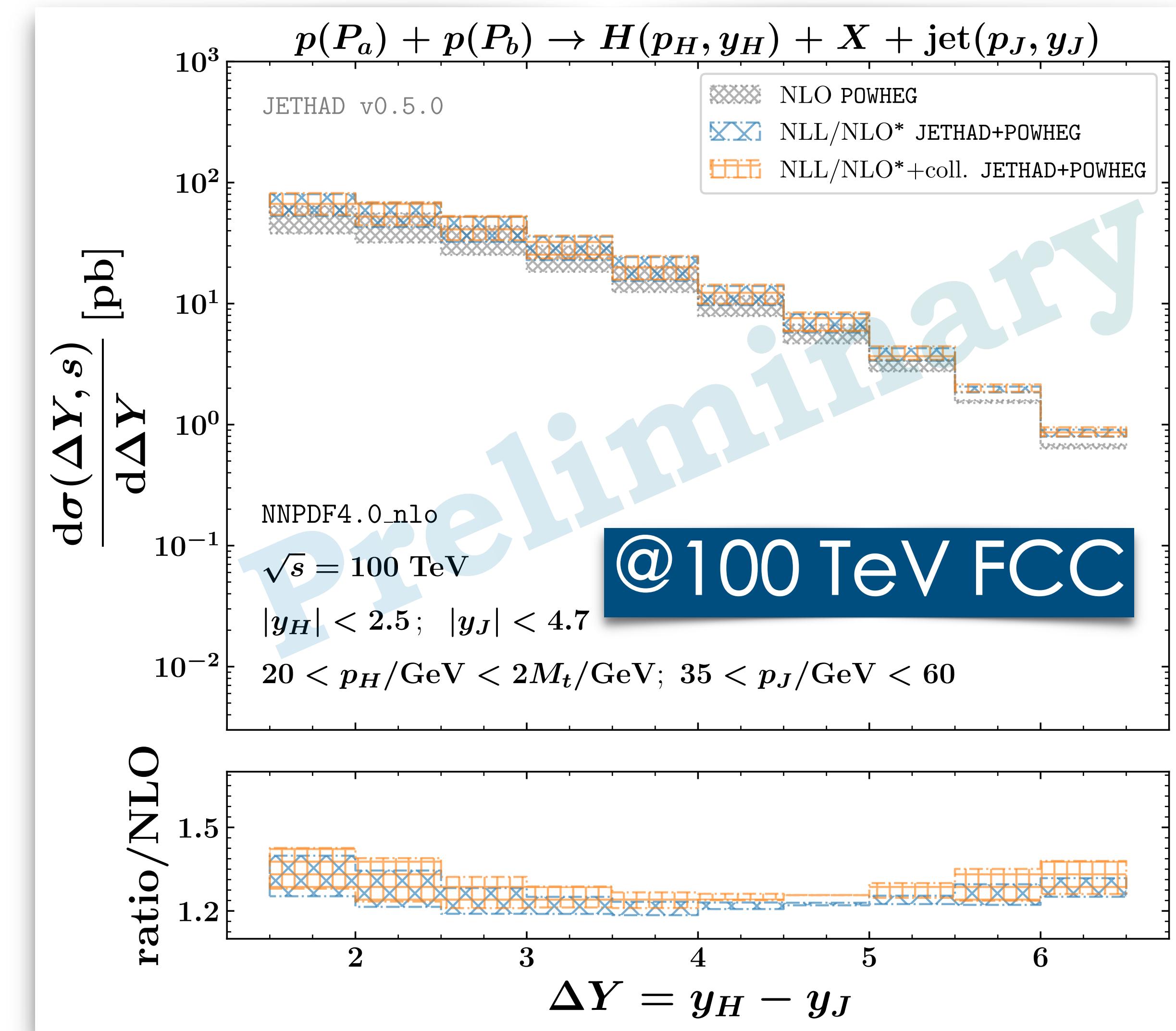
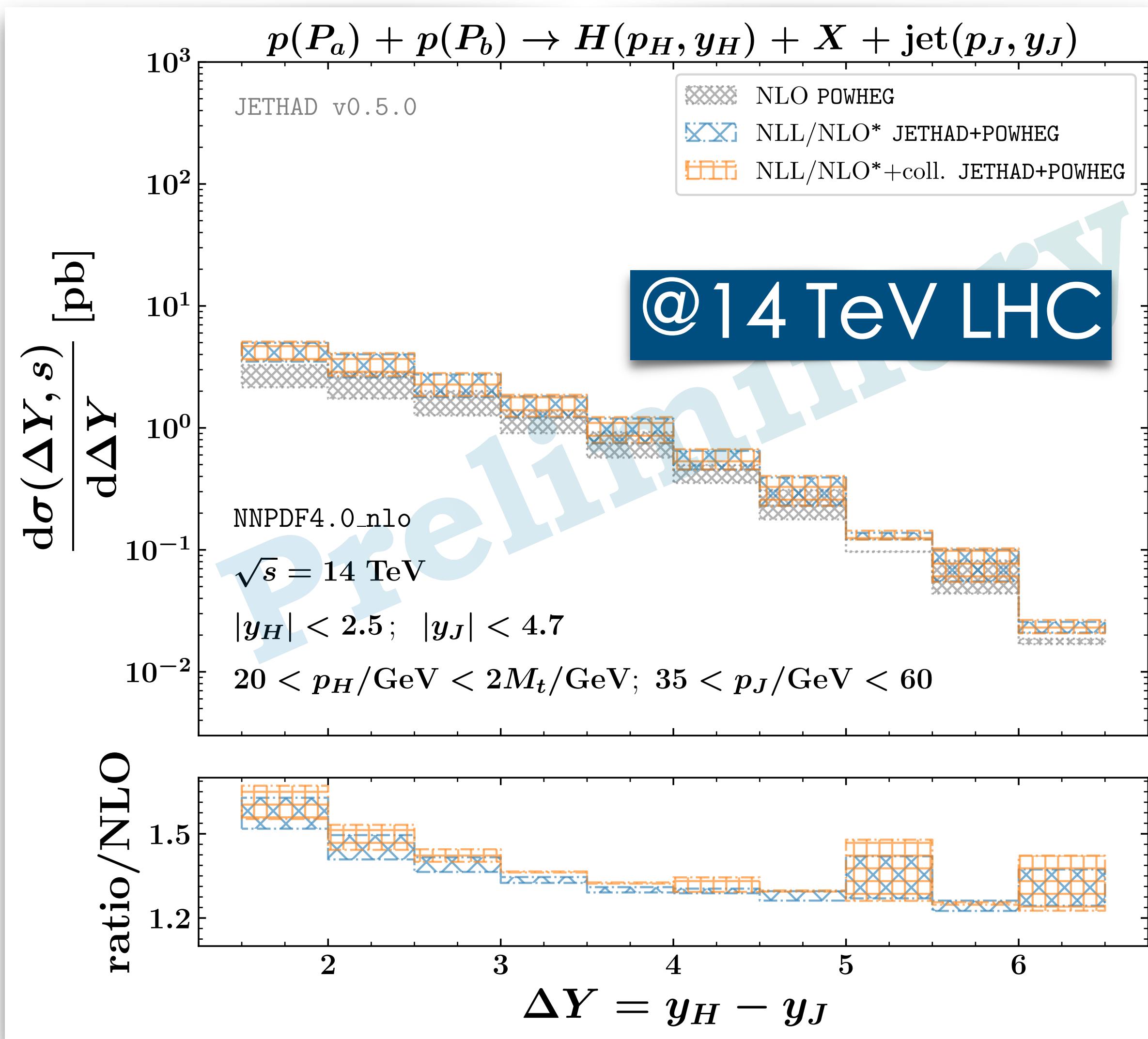


NLL matched to NLO fixed-order JETHAD + POWHEG (in progress)

Small- x and large- x enhancement from PDFs



Effect of collinear improvement on NLL BFKL kernel



Effect of collinear improvement on NLO impact factors to be gauged

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

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
- Precision studies \Leftrightarrow NLL/NLO Matching via the JETHAD Method
- Transversal formalism as underlying staging for several resummations
- Full NLL/NLO analysis: NLO Higgs impact factor & jet-algorithm selection
- Systematic uncertainties: top & bottom masses, PDF impact

Paving the way toward precision

HIGGS 2022

November 7-11 Pisa, Italy
<https://www.pi.infn.it/Higgs2022>



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Toward new horizons

Evidence of high-energy dynamics in Higgs-plus-jet distributions from LHC to FCC

10 Nov 2022, 15:55

15m

Sala Azzurra (Palazzo della Carovana)

Precision measure...

Thursday Session B

JETHAD Method

High-energy resummation for Higgs boson plus jets production

10 Nov 2022, 16:40

15m

Sala Bianchi (Palazzo della Carovana)

Precision measure...

Thursday Session A

HEJ Framework

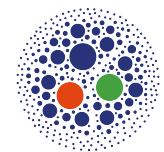
Extras

Higgs + jet distributions

Inclusive Higgs + jet at the LHC

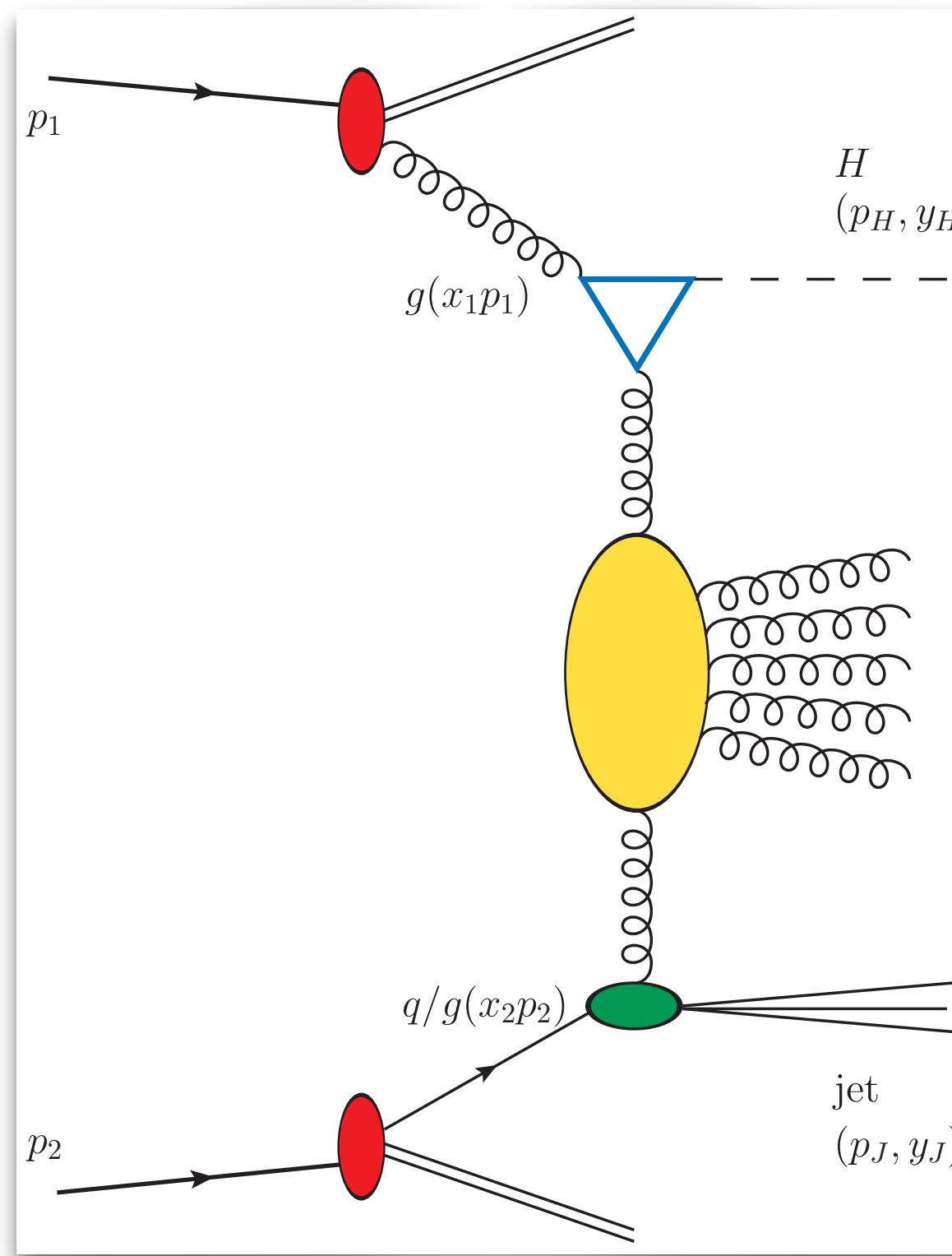


Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, ΔY



Large energy scales expected to stabilize the high-energy resummed series

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

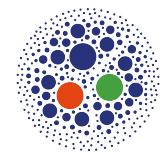


$$\varphi = \varphi_H - \varphi_J - \pi$$

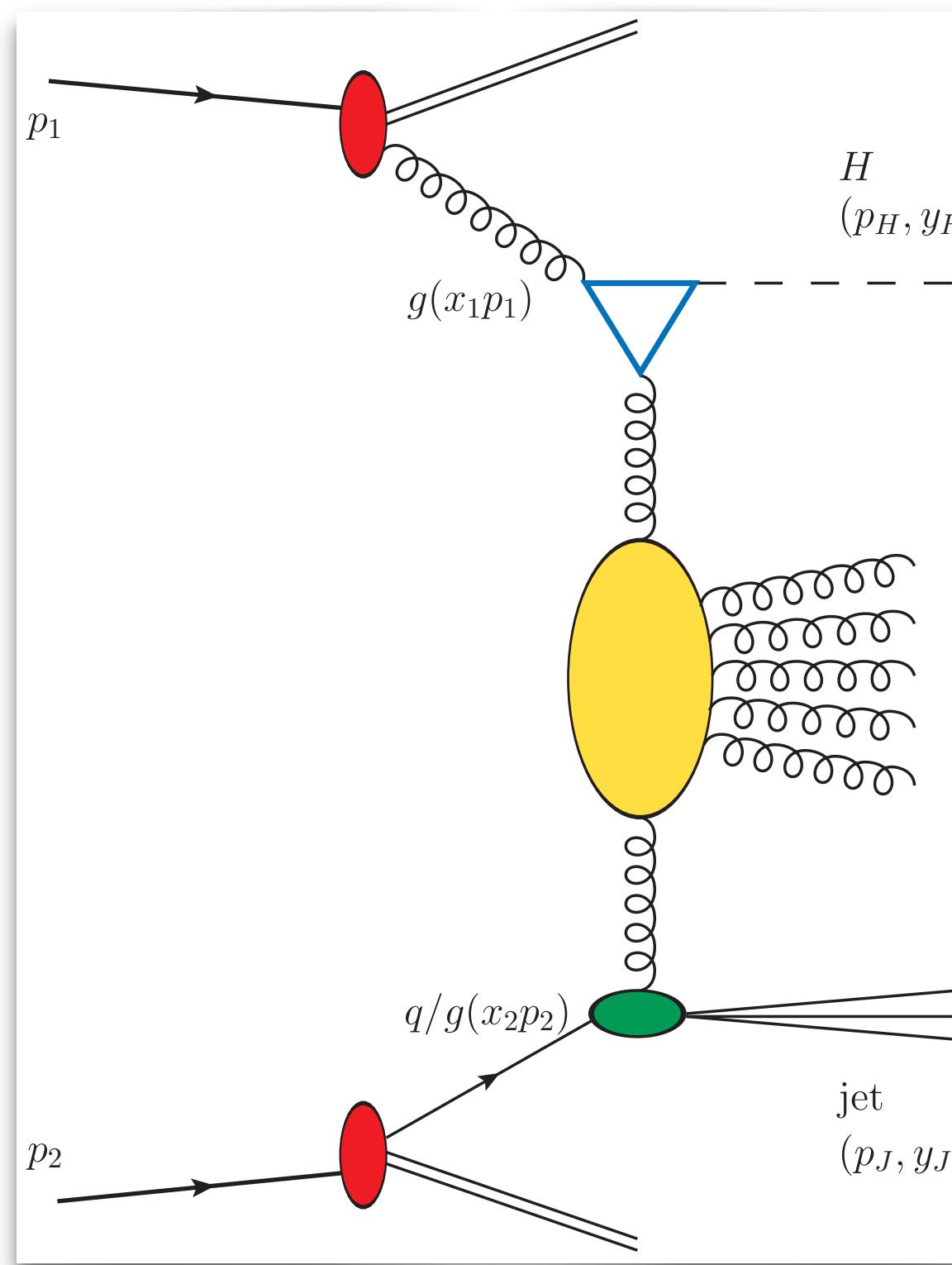
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$$\varphi = \varphi_H - \varphi_J - \pi$$

NLO*

NLL

NLO*

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

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

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

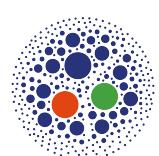
$$\times \int \frac{d^2 \vec{q}_2}{\vec{q}_2^2} \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

**Higgs vertex
(off-shell amplitude)**

**jet vertex
(off-shell amplitude)**

BFKL Green's function

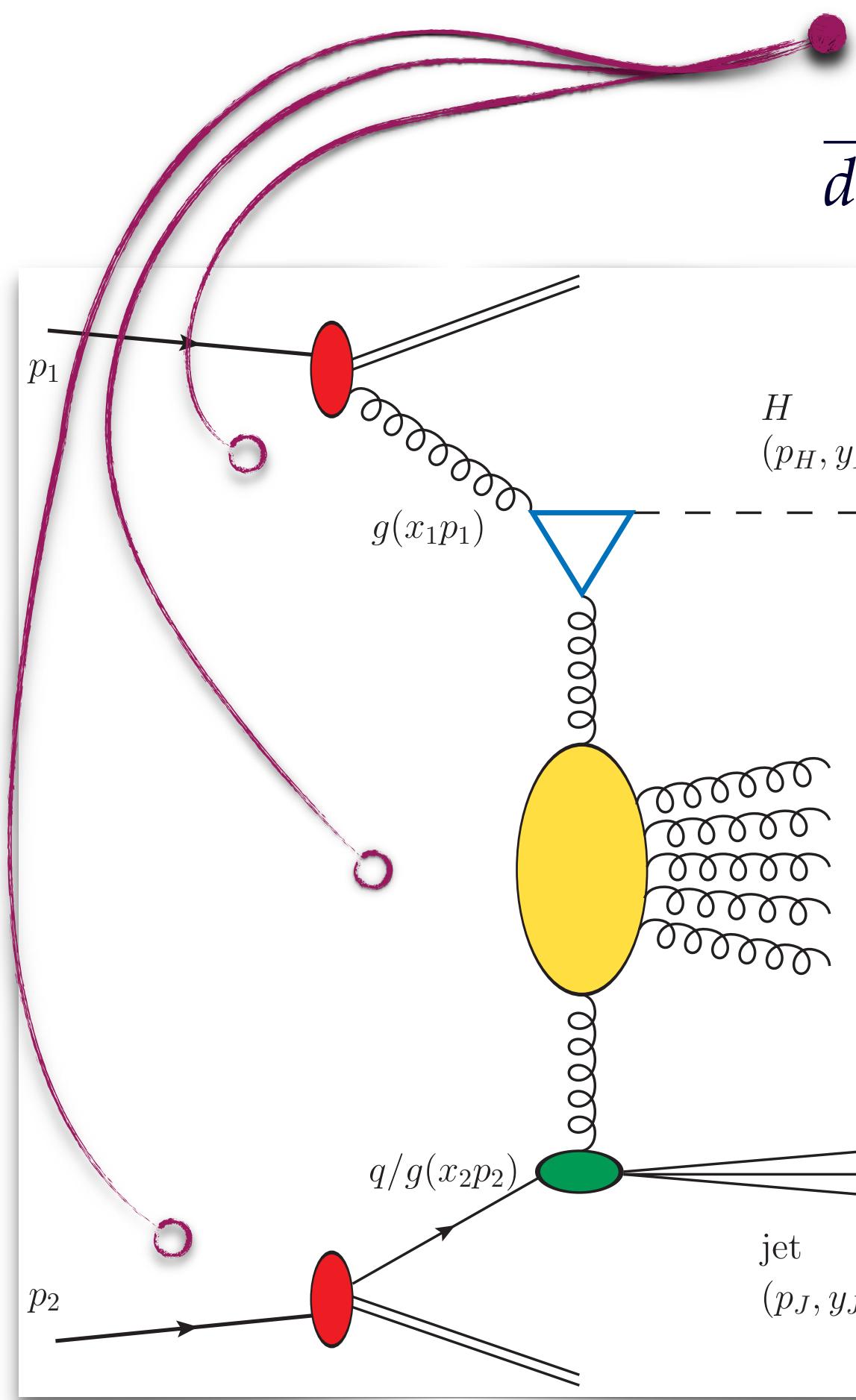
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$$\varphi = \varphi_H - \varphi_J - \pi$$

NLO*

NLL

NLO*

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H dy_J d^2 \vec{p}_H d^2 \vec{p}_J} = \frac{1}{(2\pi)^2} \times \int \frac{d^2 \vec{q}_1}{\vec{q}_1^2} \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H)$$

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Higgs vertex
(off-shell amplitude)

jet vertex
(off-shell amplitude)

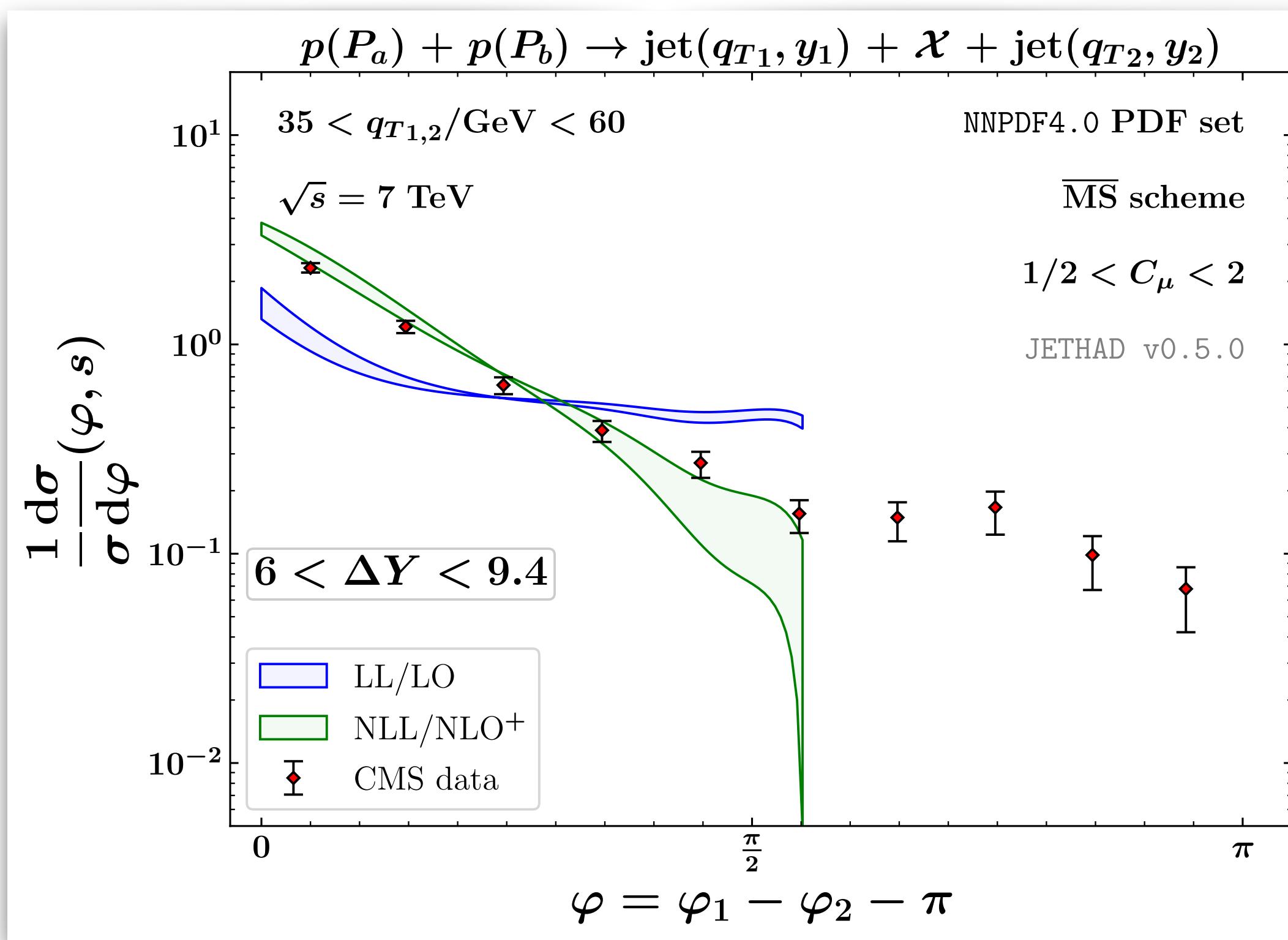
BFKL Green's function

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)]



Azimuthal-angle multiplicity

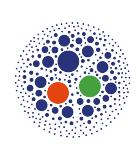
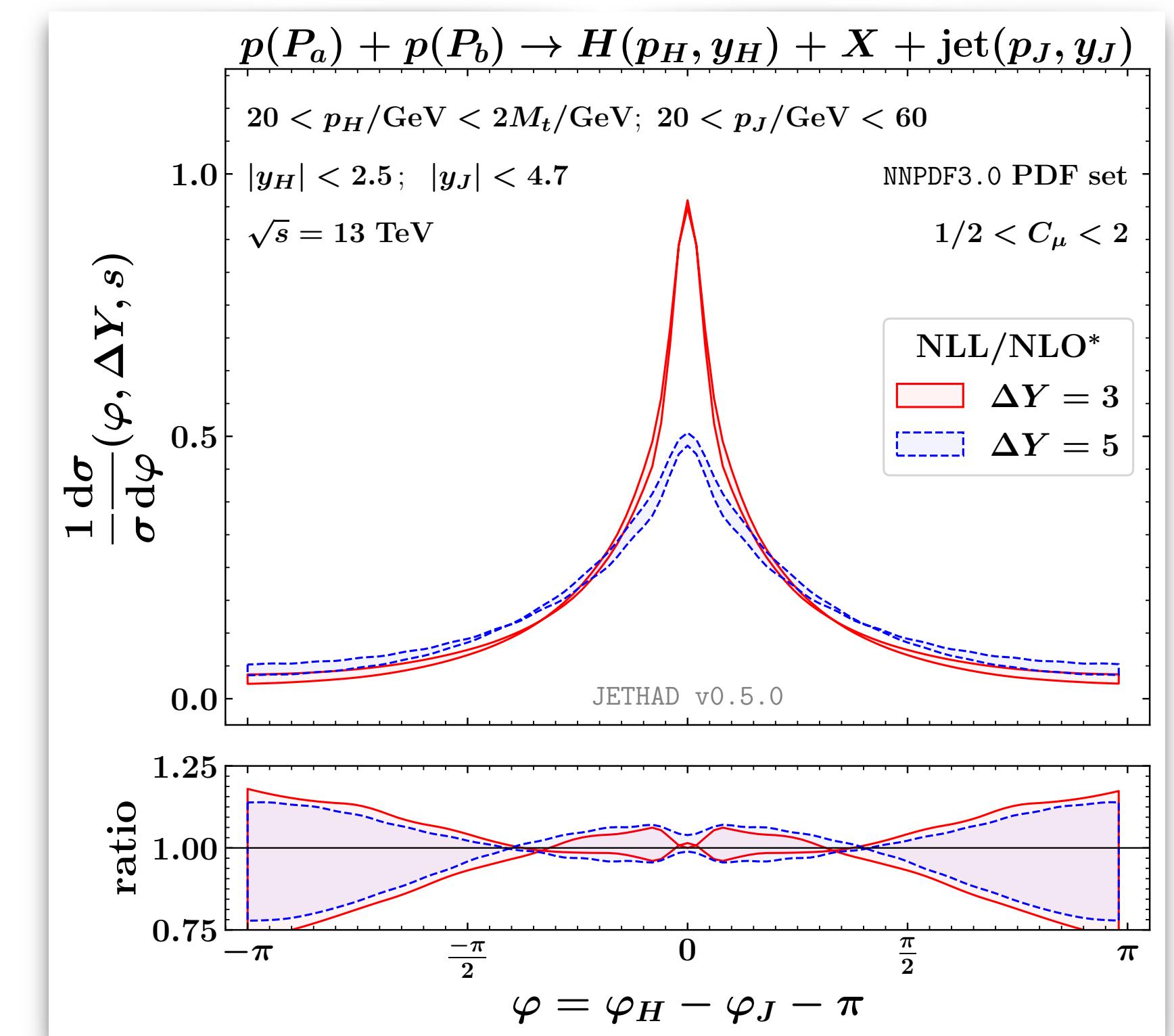
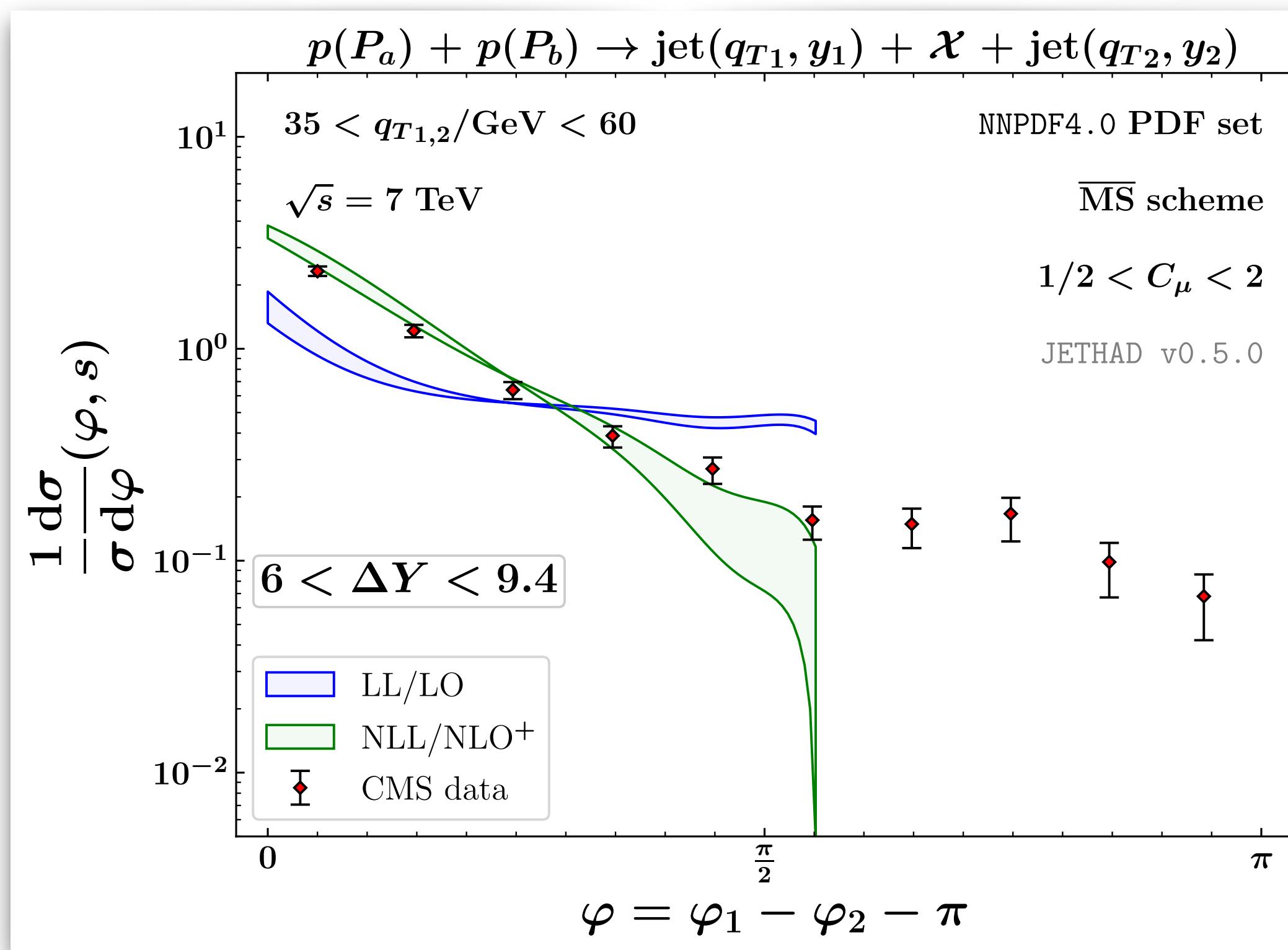
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[B. Ducloué, L. Szymanowski, S. Wallon, Phys. Rev. Lett. 112 (2014) 082003]
 (figure below) [F. G. C., A. Papa (2022)]

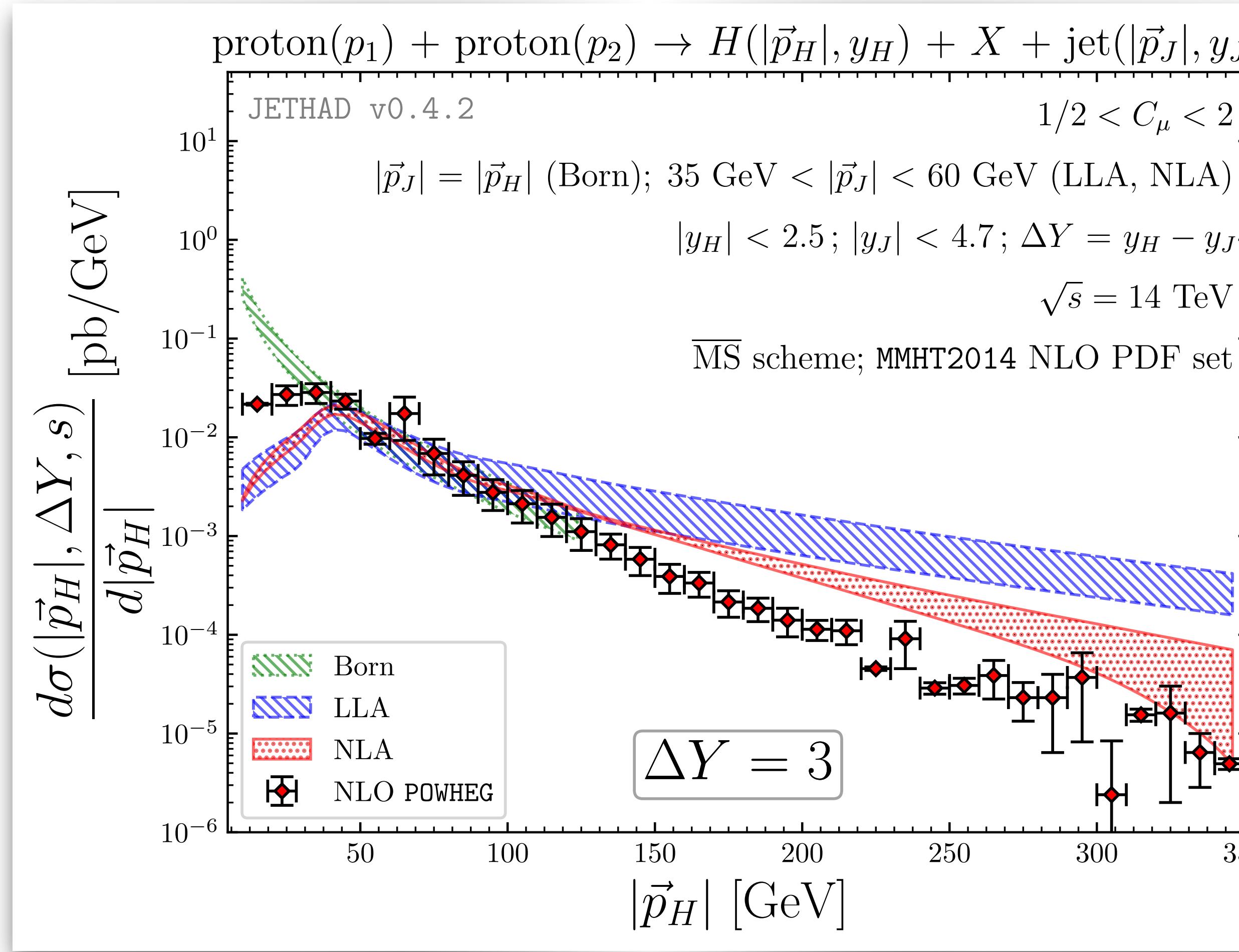
Higgs + jet

(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]

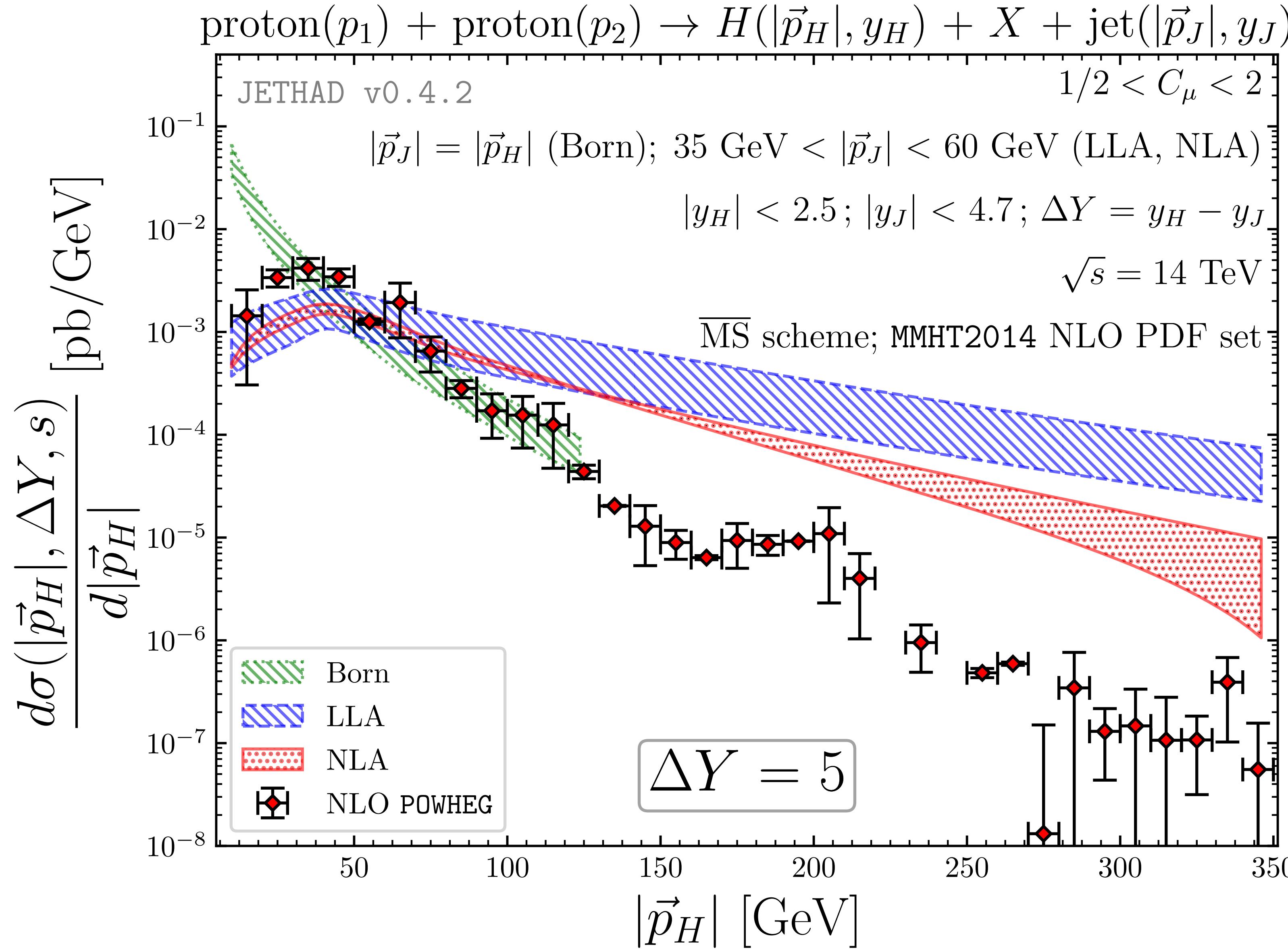


Higgs transverse-momentum distribution

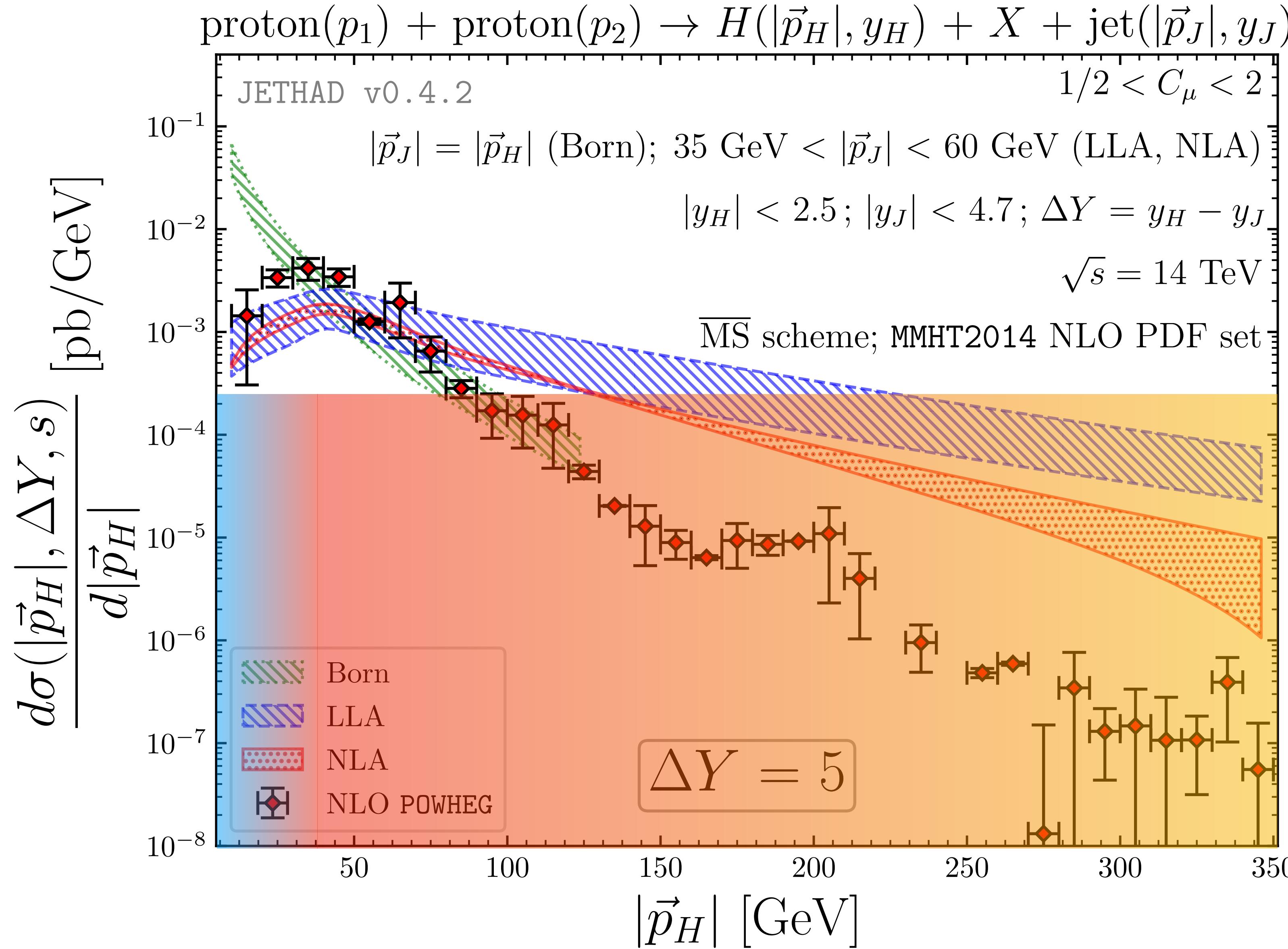
$$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_H - y_J - \Delta Y) \mathcal{C}_0$$



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



Backup



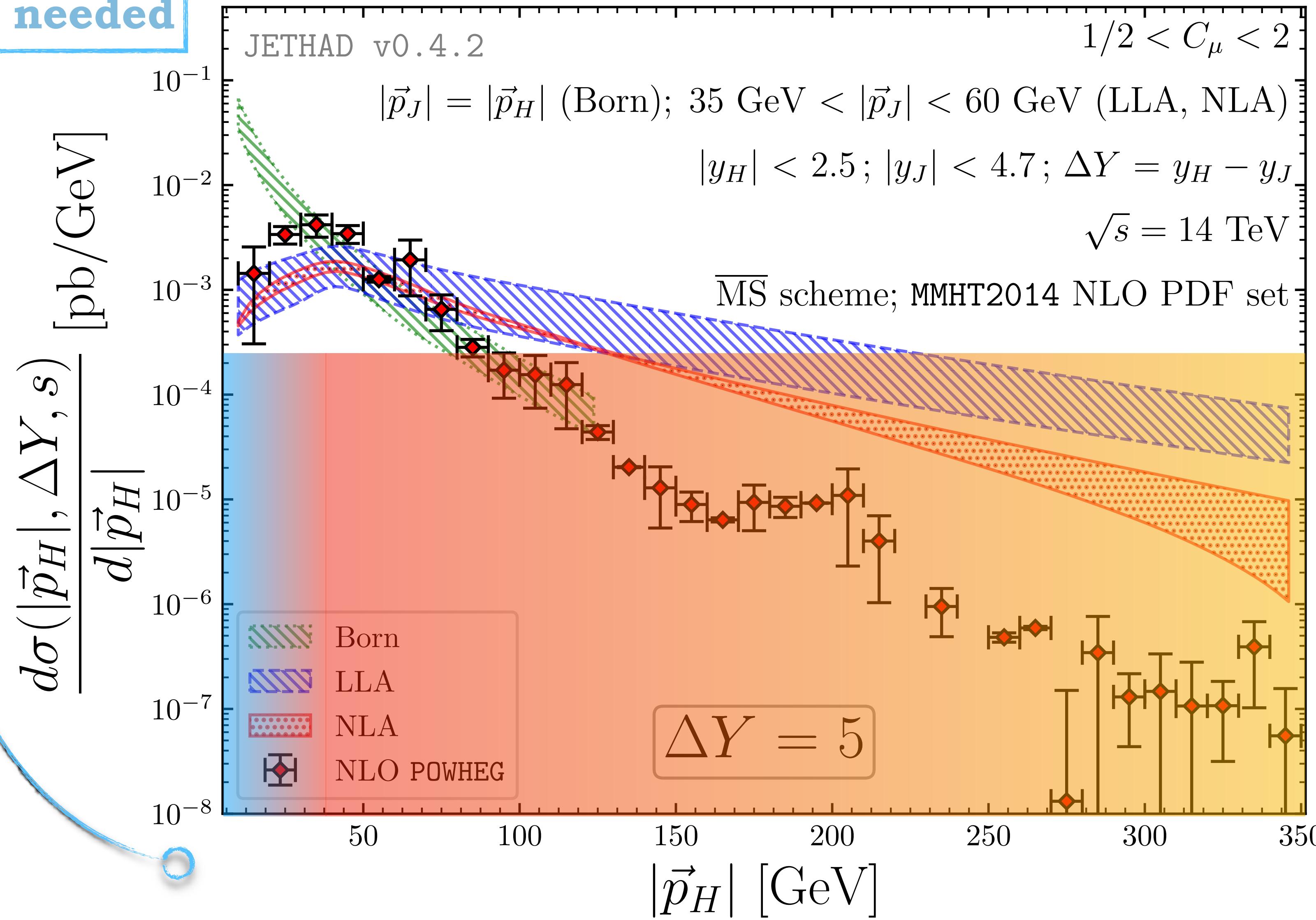
Backup

large p_T logs
 p_T -resum. needed

Backup

proton(p_1) + proton(p_2) $\rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$

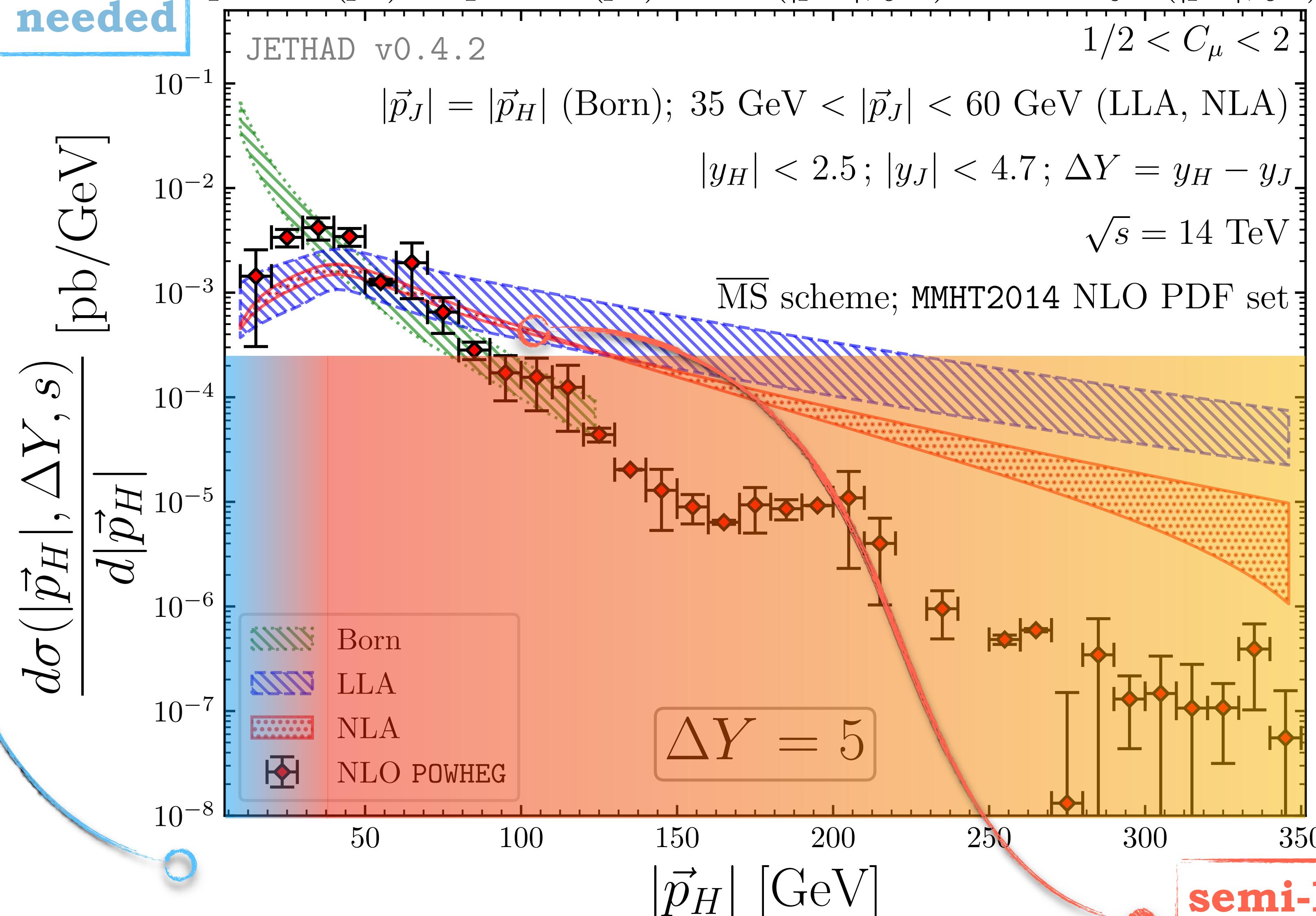
$1/2 < C_\mu < 2$



large p_T logs
 p_T -resum. needed

Backup

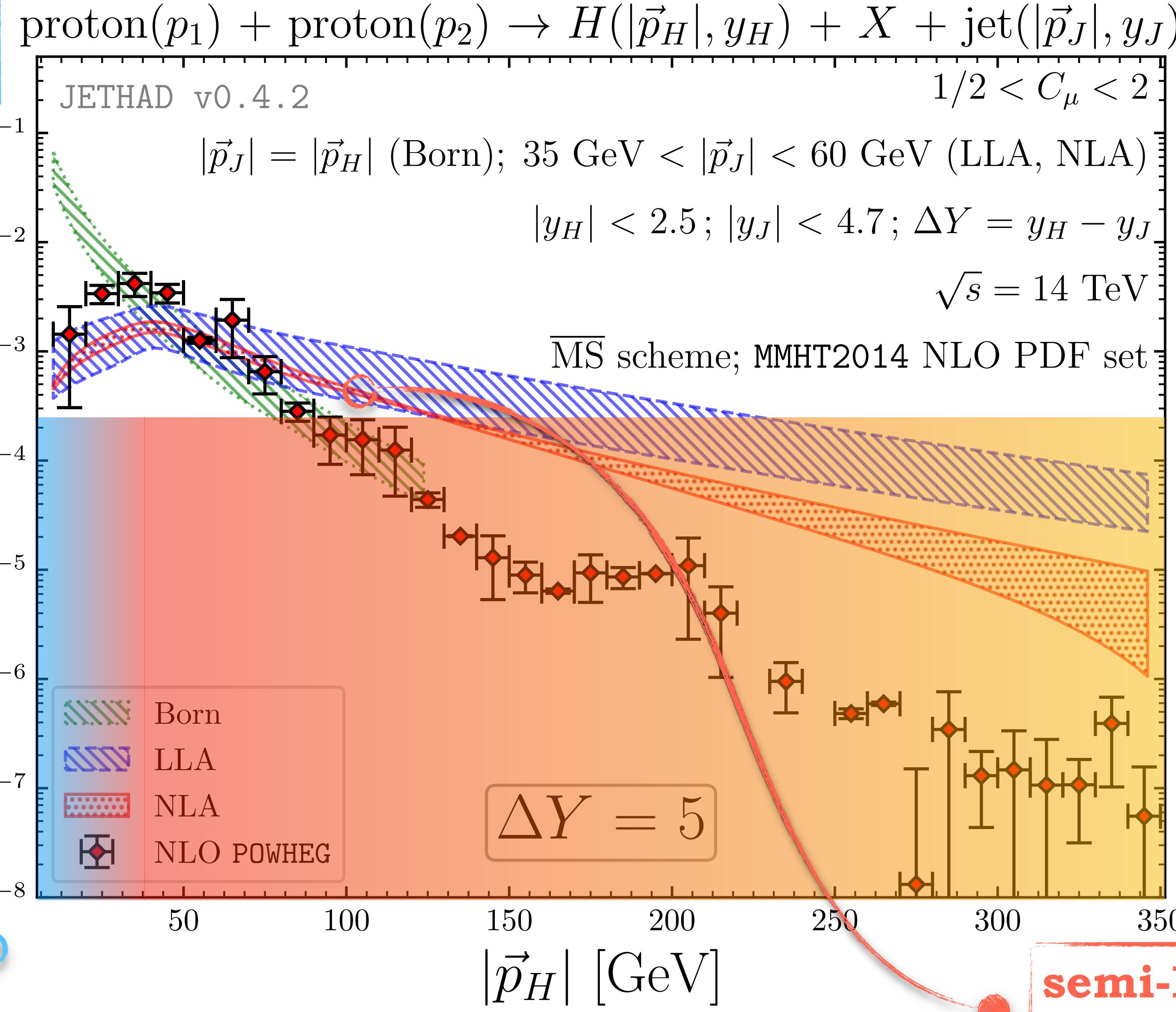
proton(p_1) + proton(p_2) $\rightarrow H(|\vec{p}_H|, y_H) + X + \text{jet}(|\vec{p}_J|, y_J)$
 $1/2 < C_\mu < 2$



DGLAP-type + large- x threshold logs \rightarrow BFKL decoupling

**large p_T logs
 p_T -resum. needed**

Backup

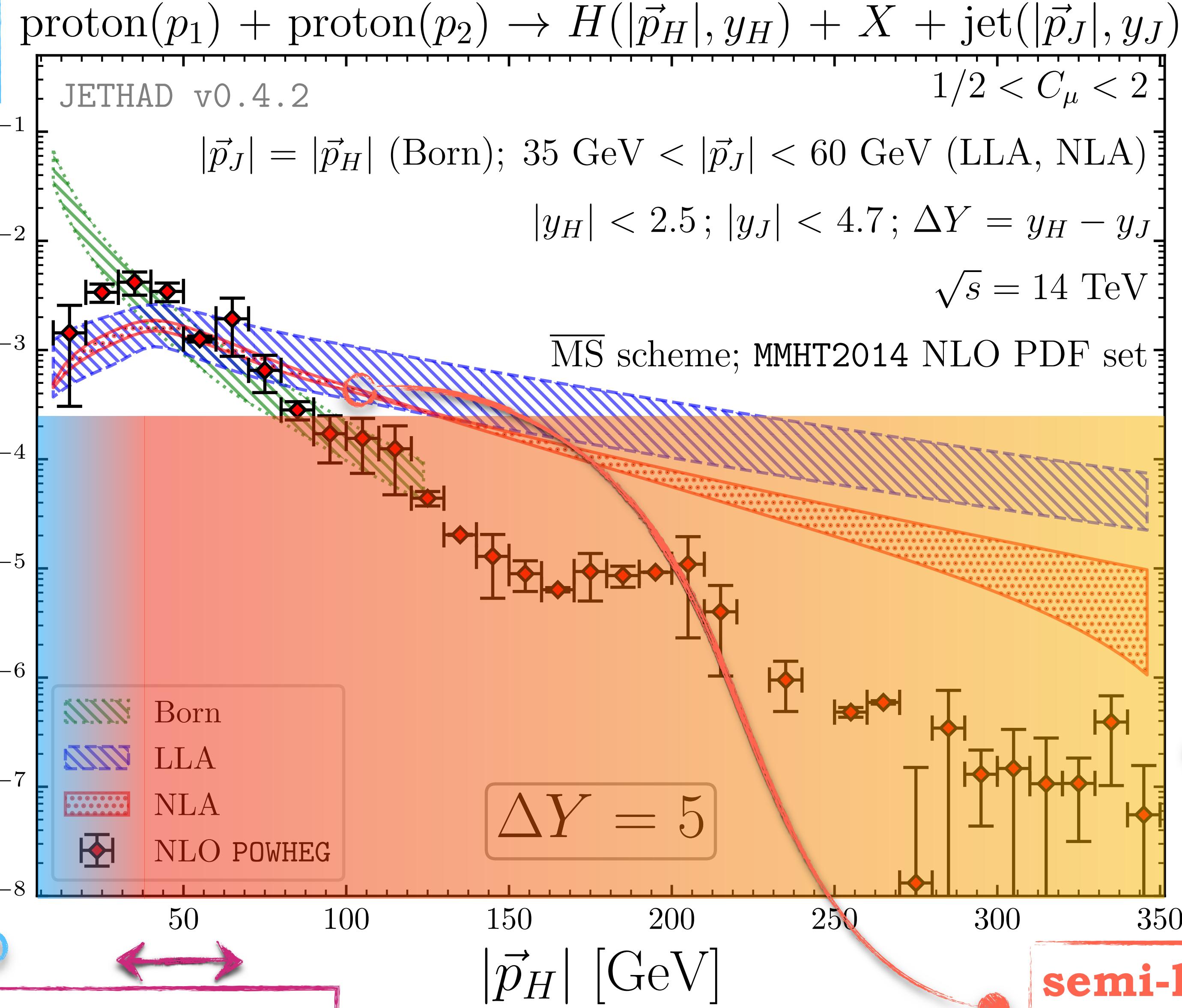


DGLAP-type + large- x threshold logs \rightarrow BFKL decoupling

**large p_T logs
 p_T -resum. needed**

Backup

$$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H|} [\text{pb}/\text{GeV}]$$

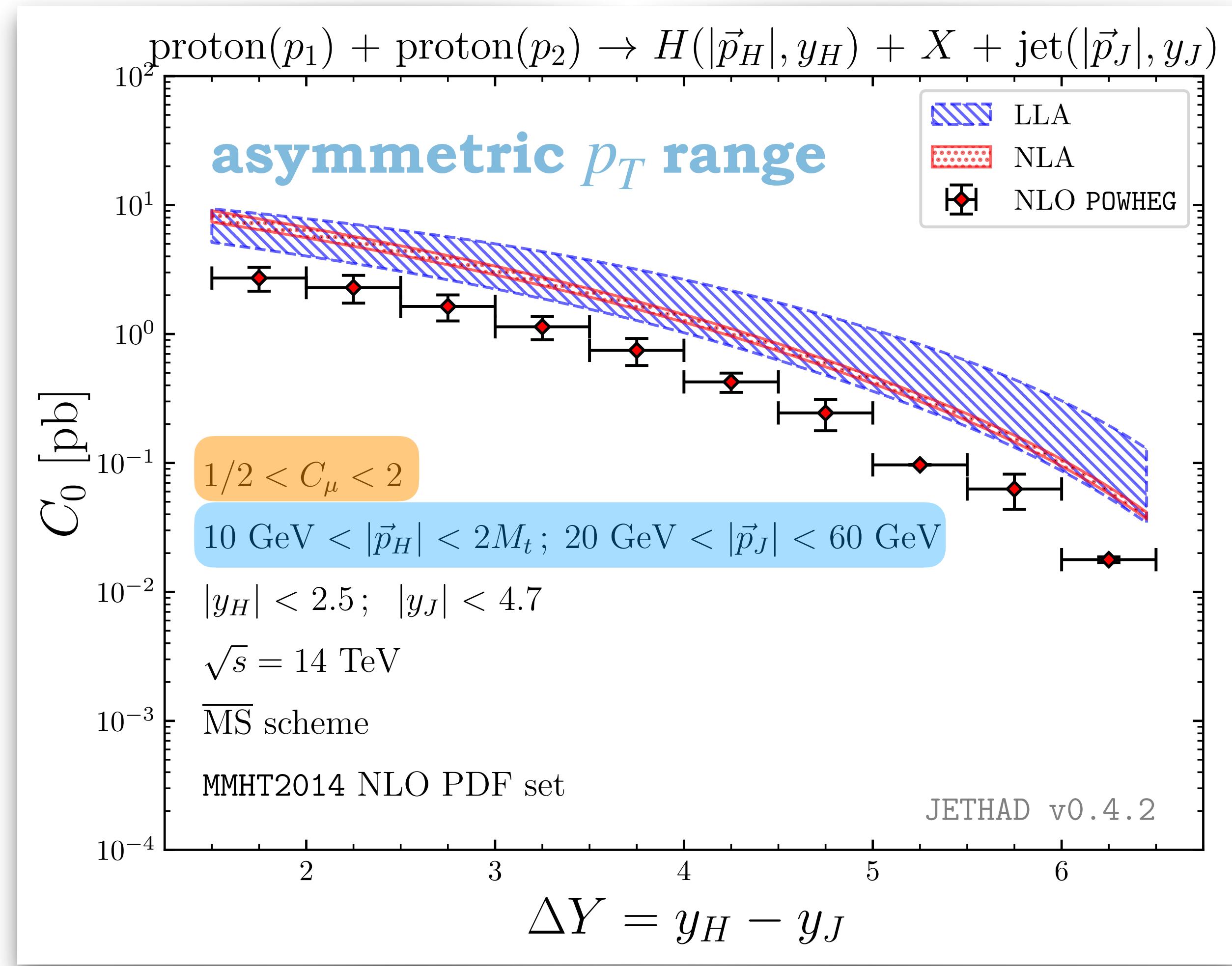


**almost back-to-back emissions
Sudakov-type double logs**

**semi-hard regime
BFKL expected**

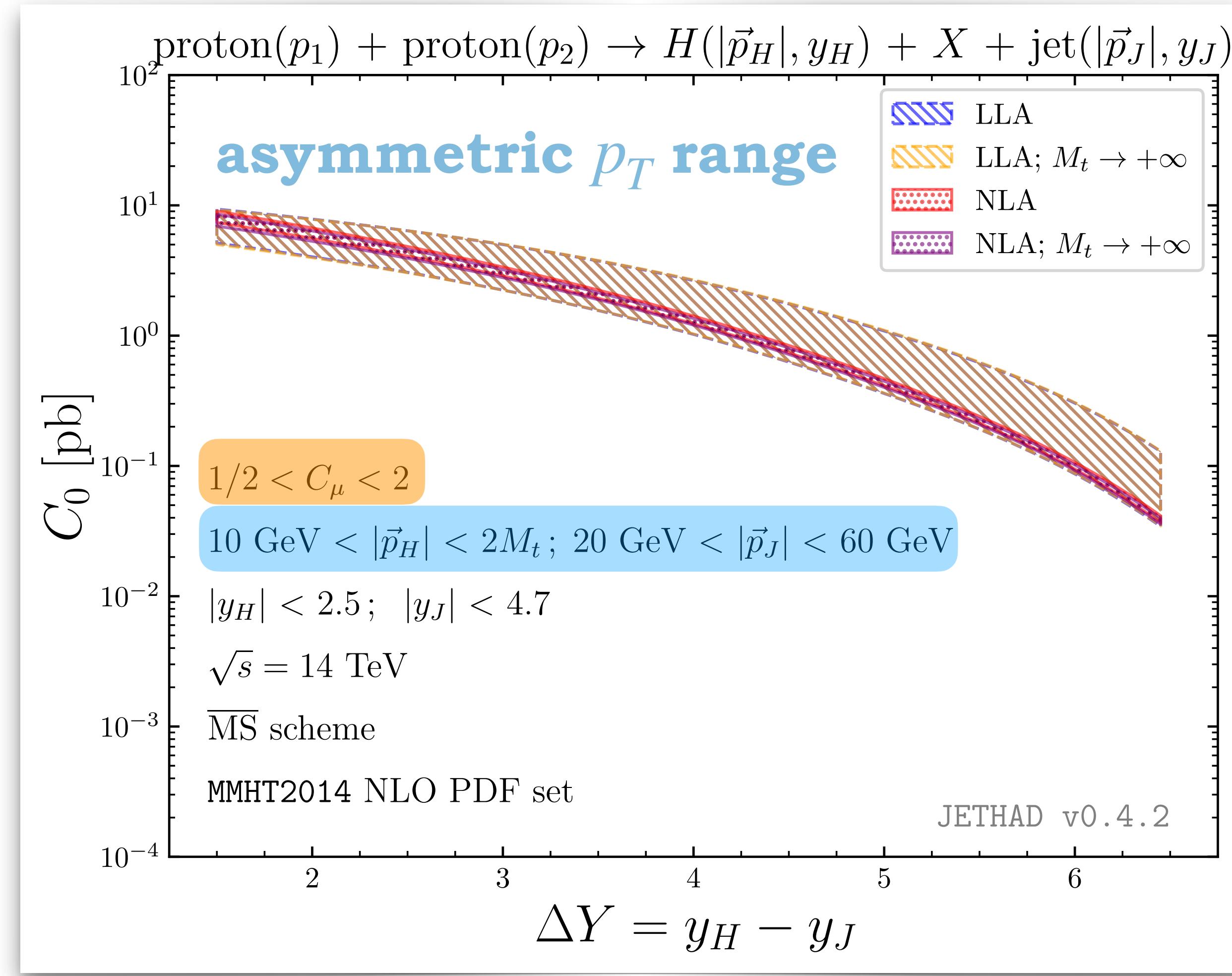
ΔY -distribution

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



ΔY -distribution in the infinite top-mass limit

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



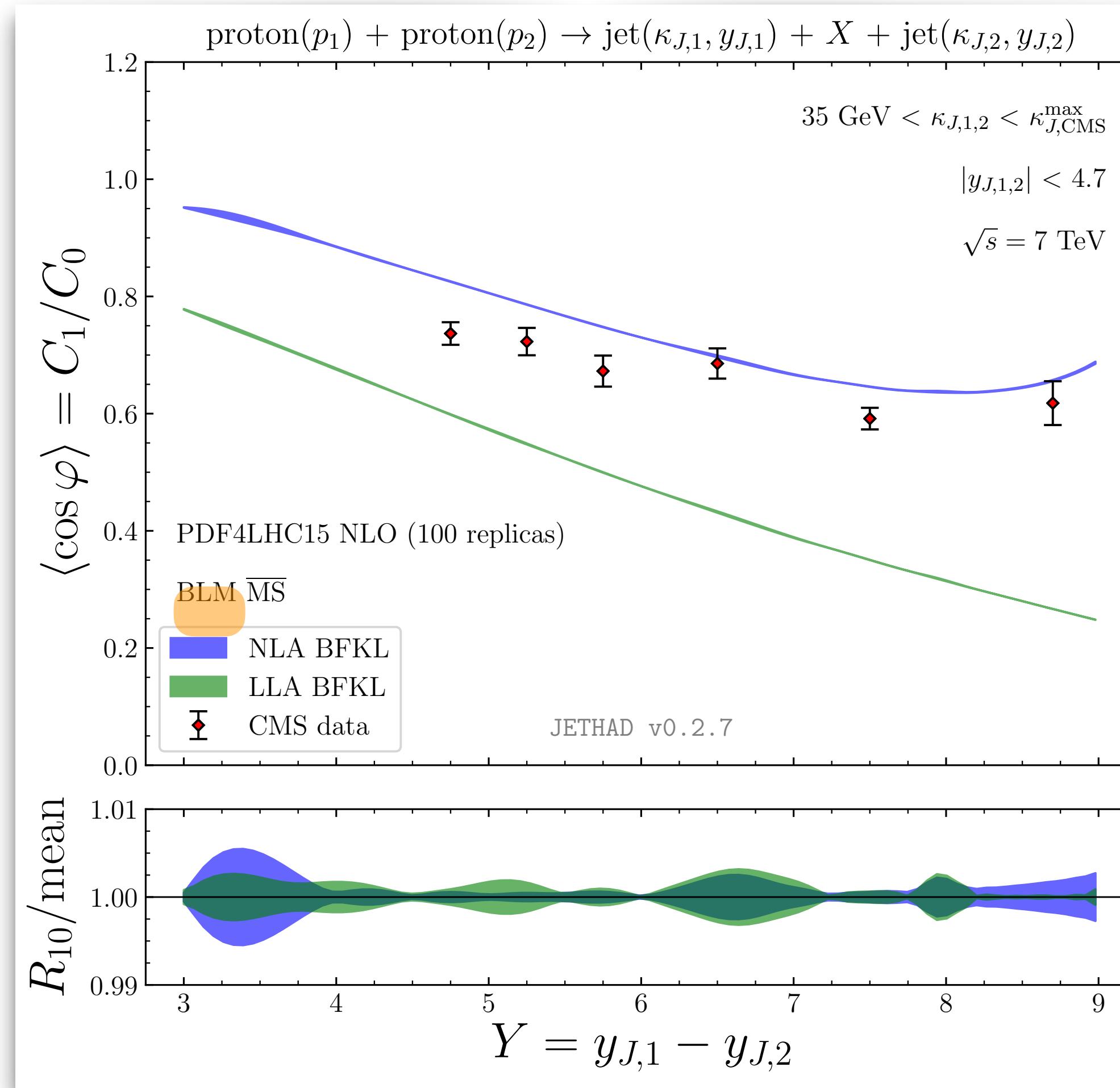
Angular correlations in the infinite top-mass limit

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

Mueller-Navelet jets

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

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

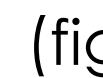


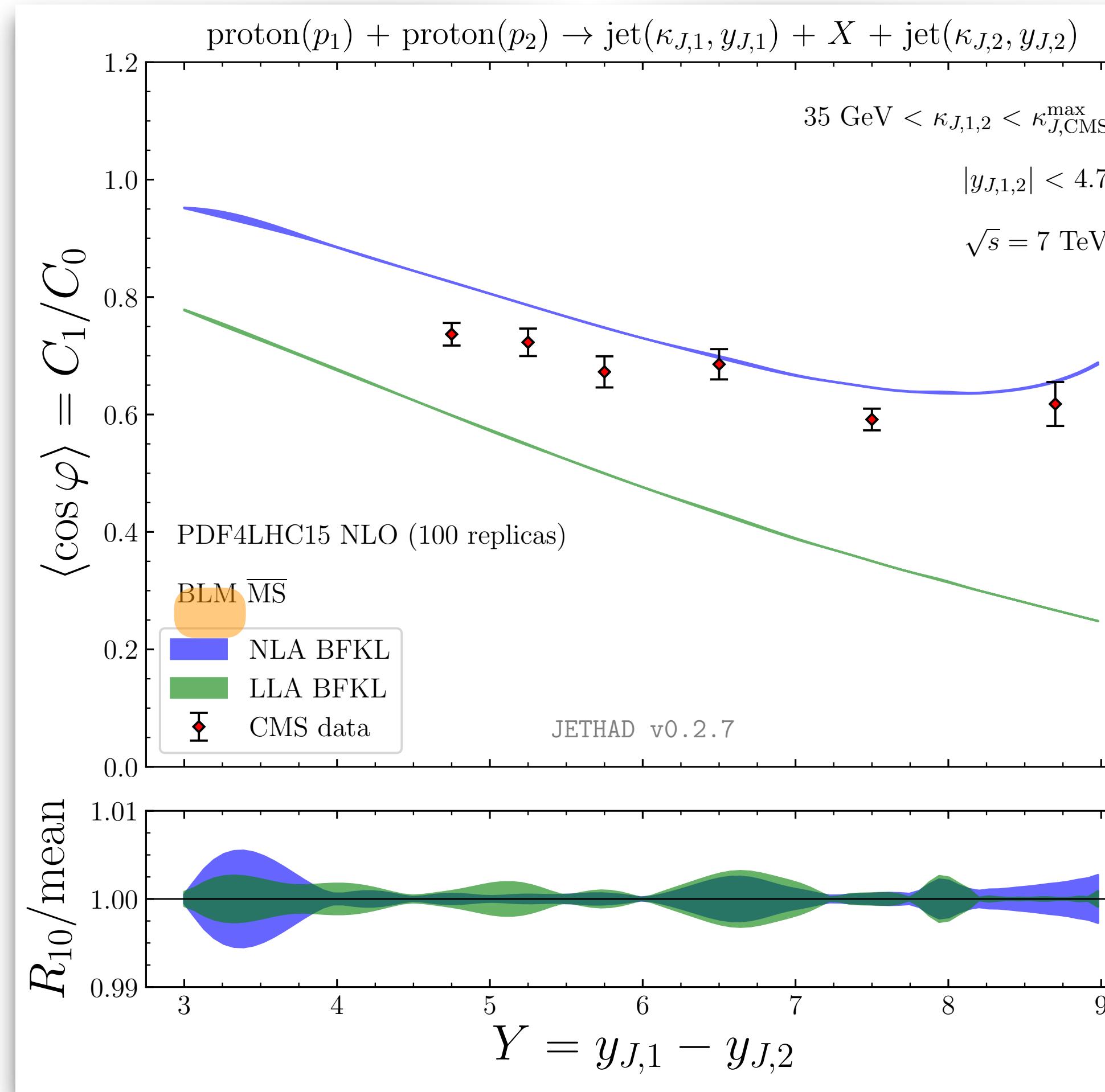
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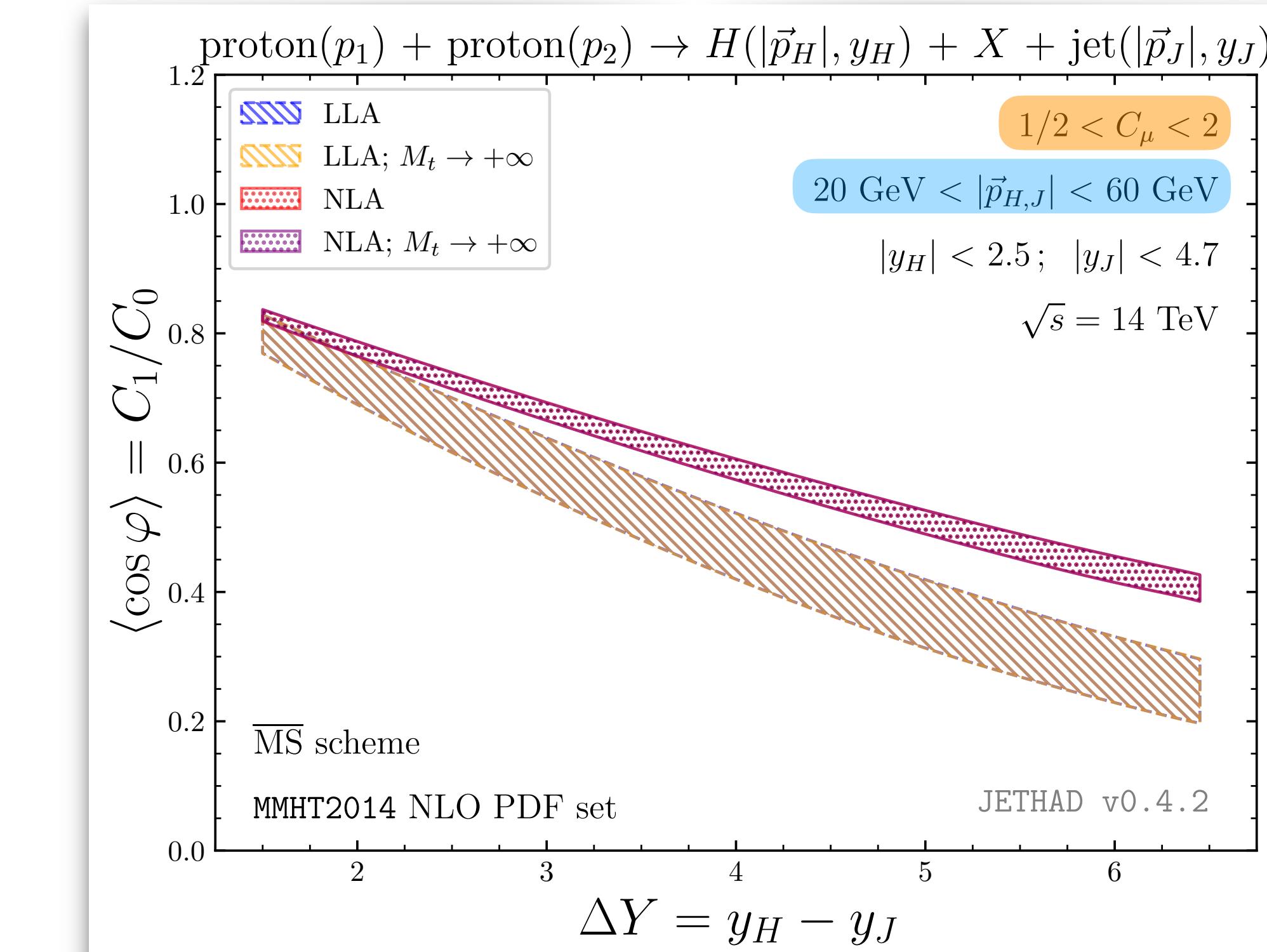
(figure below)  [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]



Higgs + jet

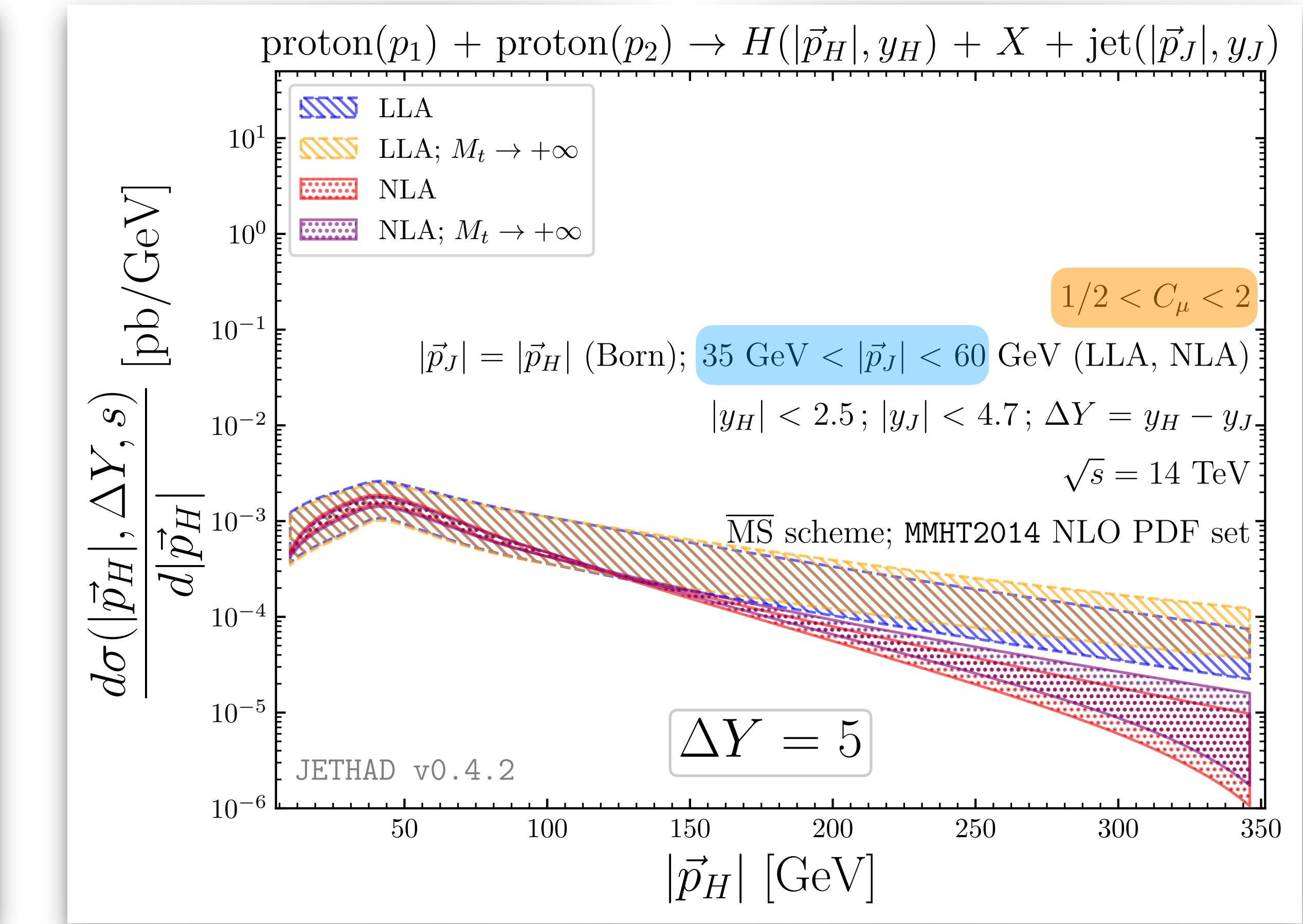
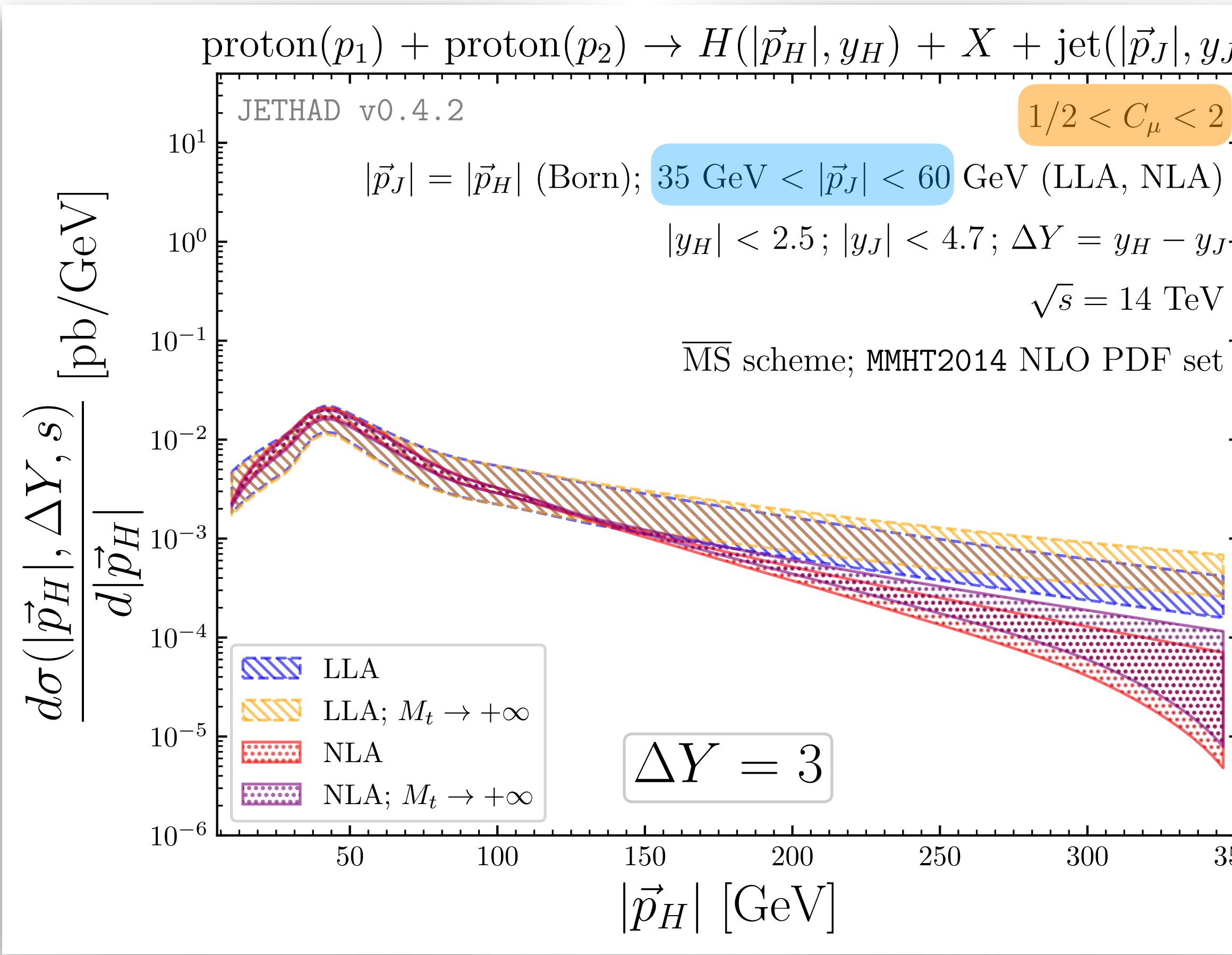
(figure below)  [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

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



natural scales
symmetric p_T range

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



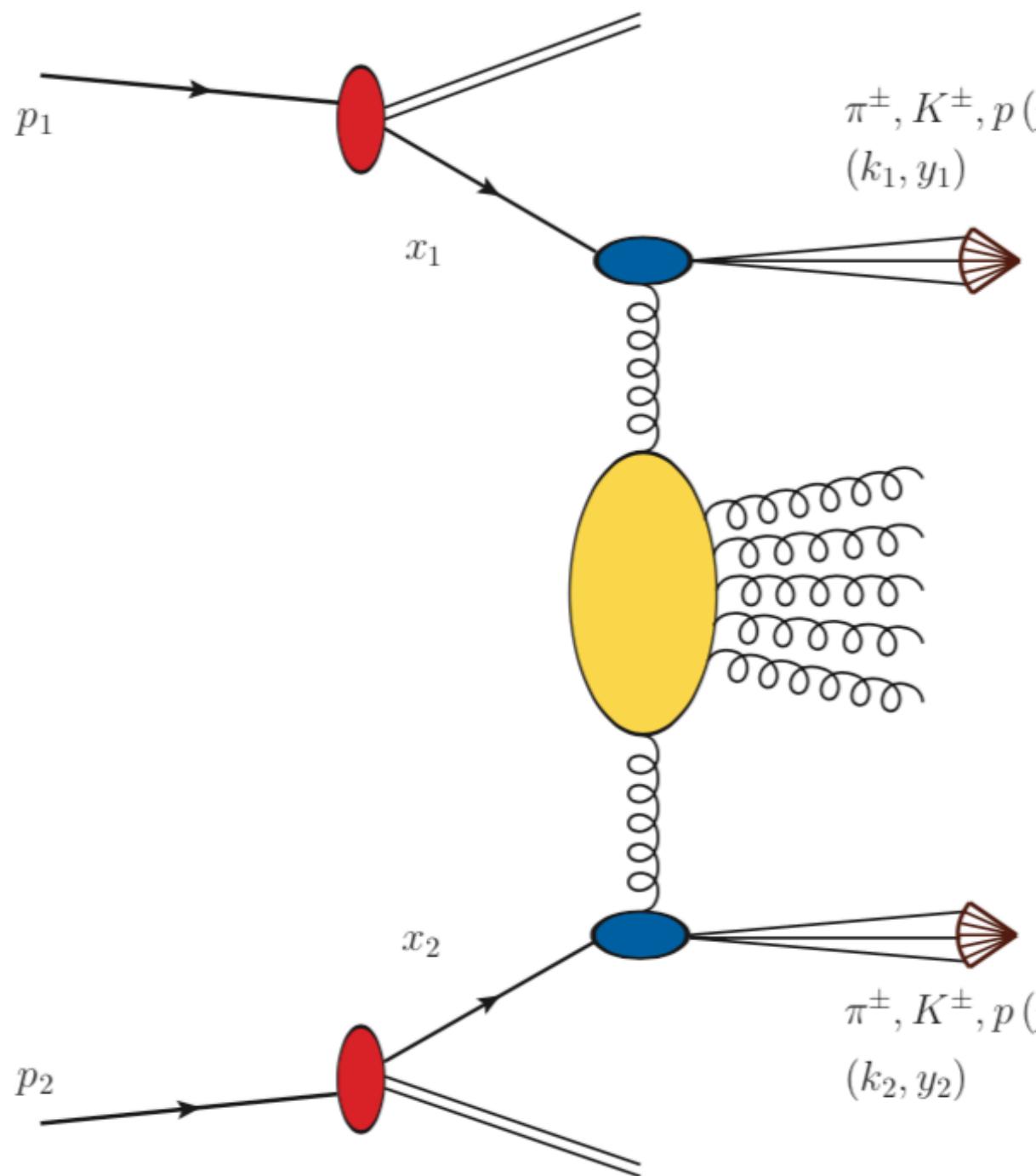
Heavy-light hadrons

From Mueller-Navelet jets to bound states

Di-hadron and hadron-jet correlations

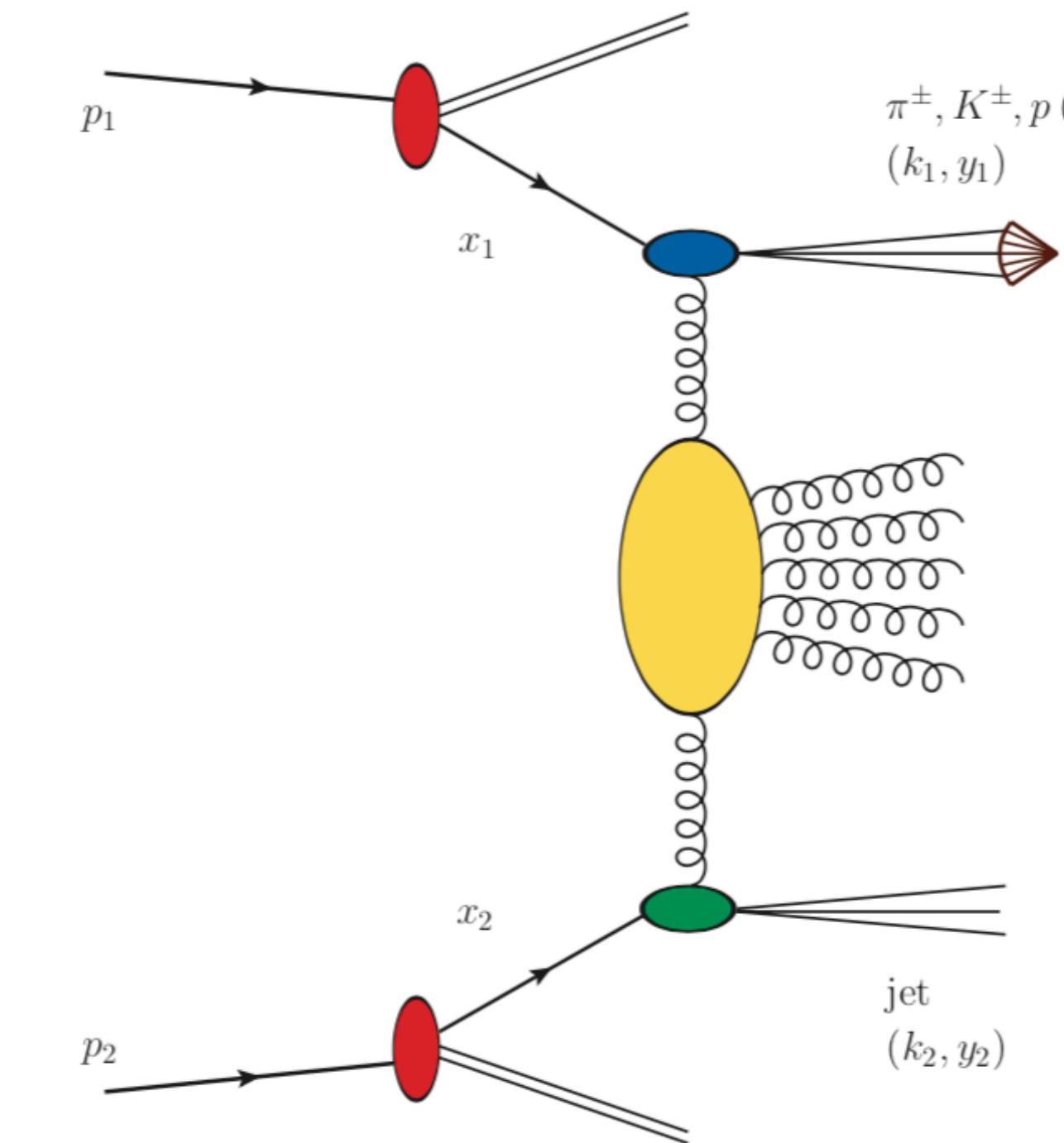
Inclusive di-hadron production

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



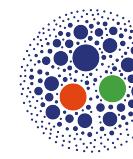
Inclusive hadron-jet production

[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)

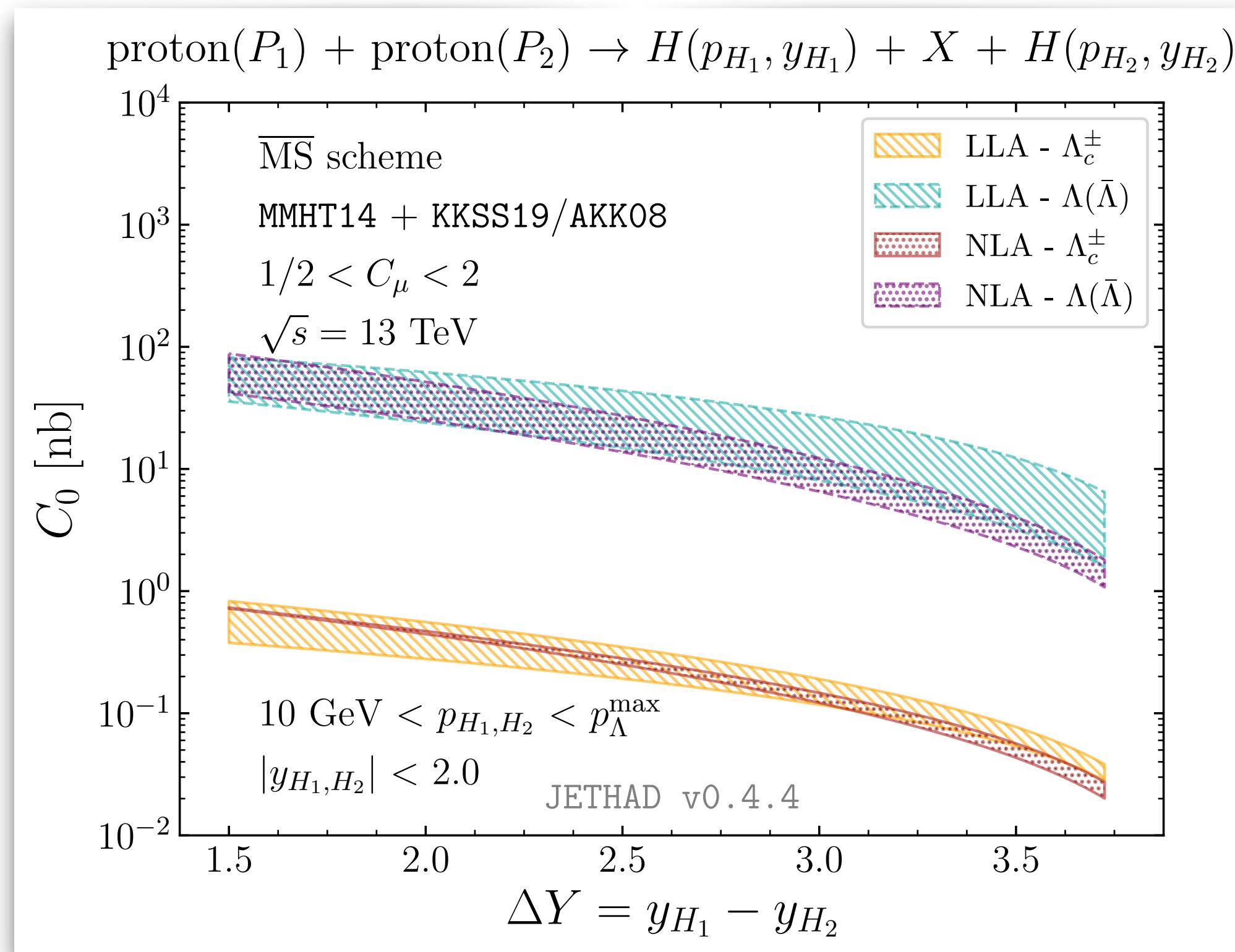
From light to heavy-light bound states



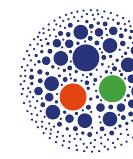
Light-hadron+jet: higher-order instabilities via scale variation, as in Mueller-Navelet (!)

Λ_c baryons

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



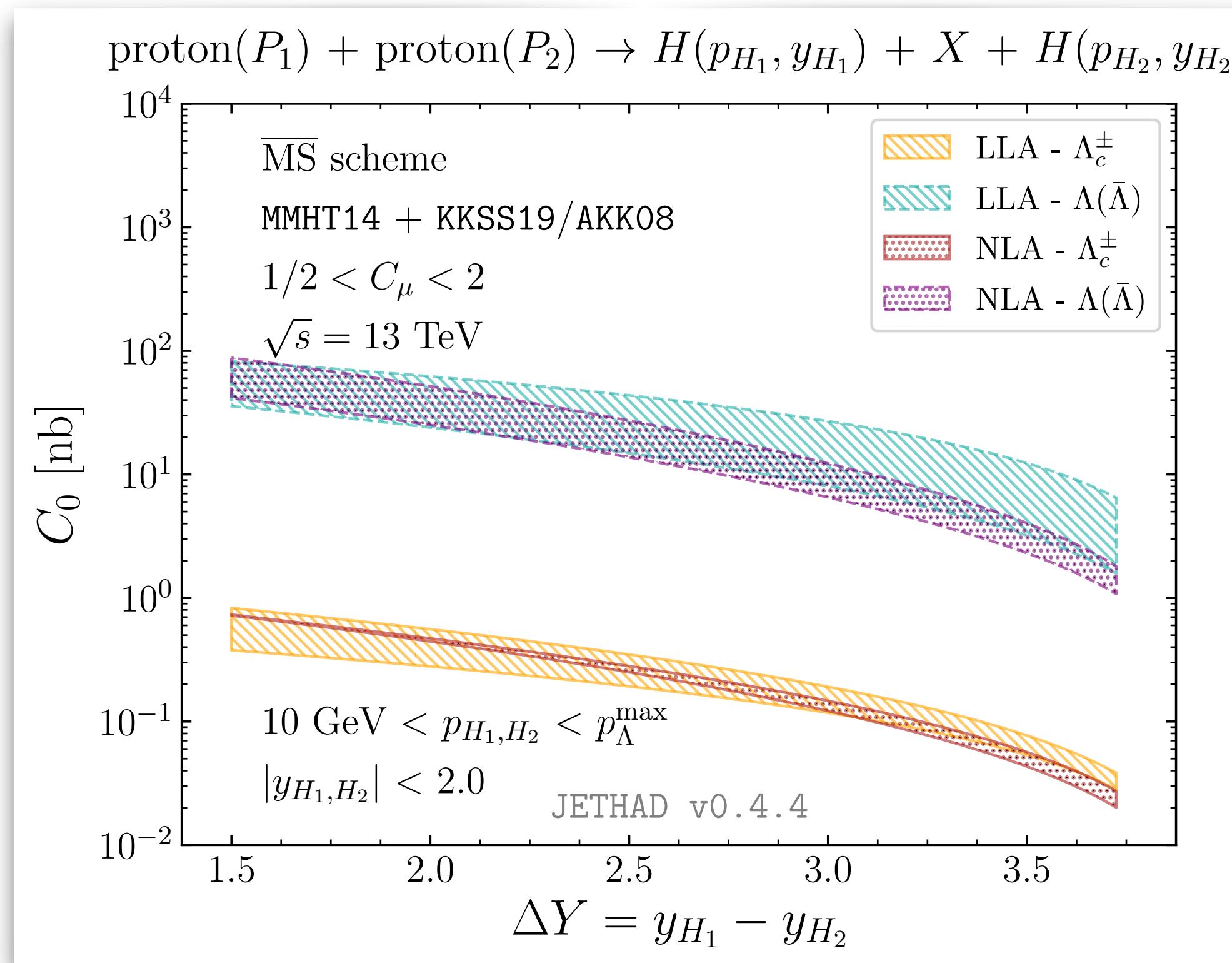
From light to heavy-light bound states



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

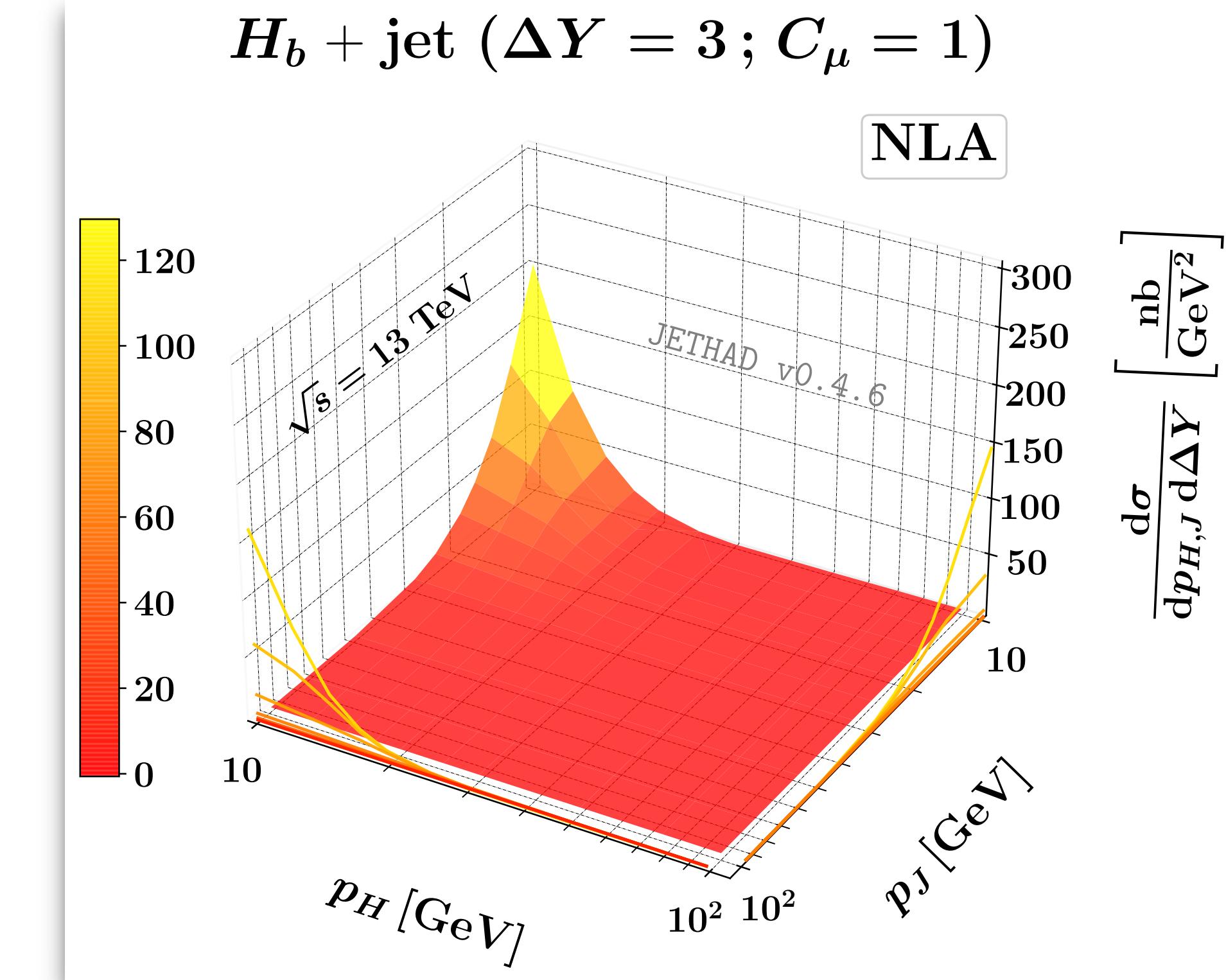
Λ_c baryons

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

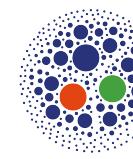


Bottom-flavored hadrons

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



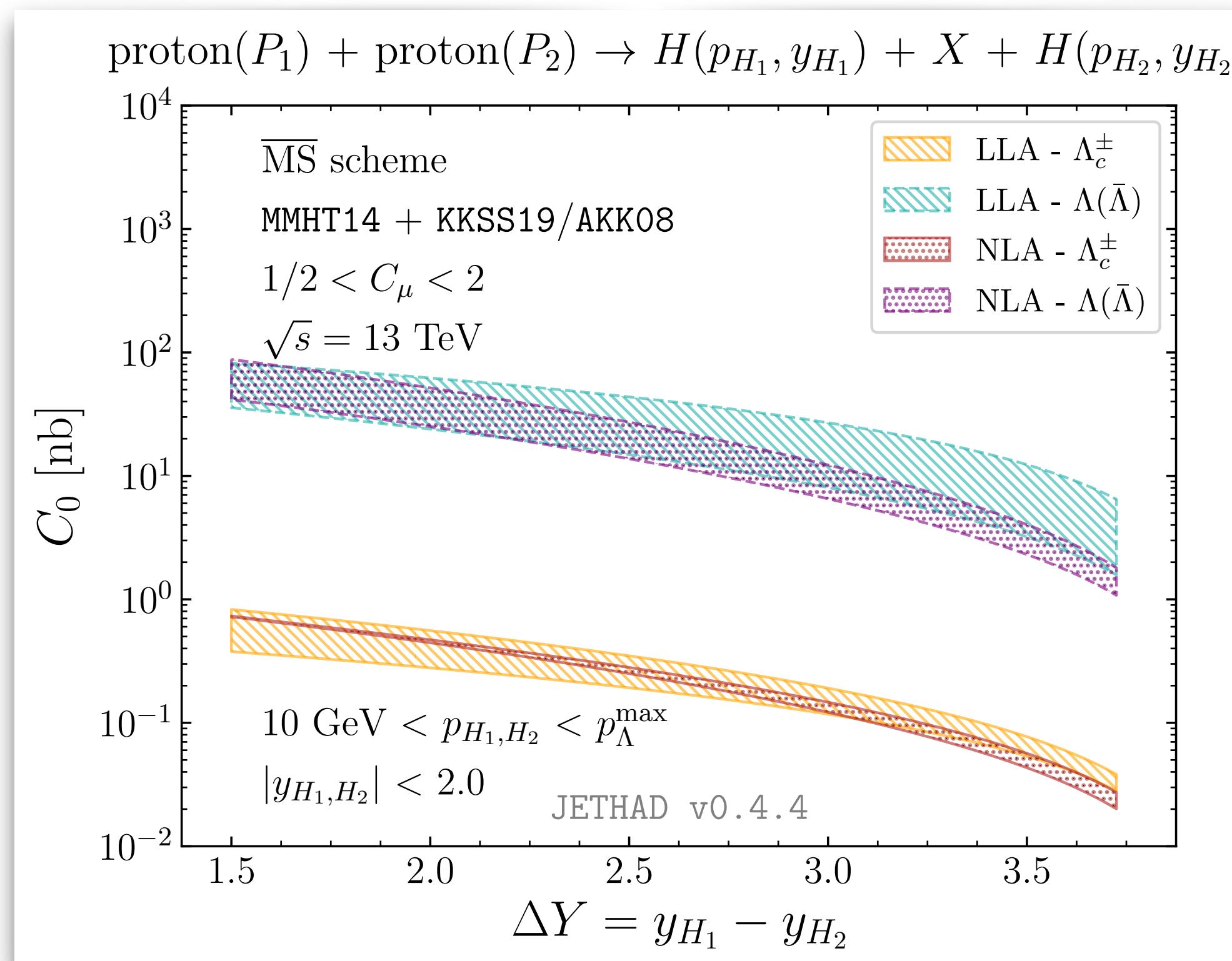
From light to heavy-light bound states



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

Λ_c baryons

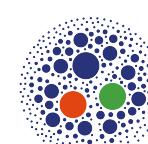
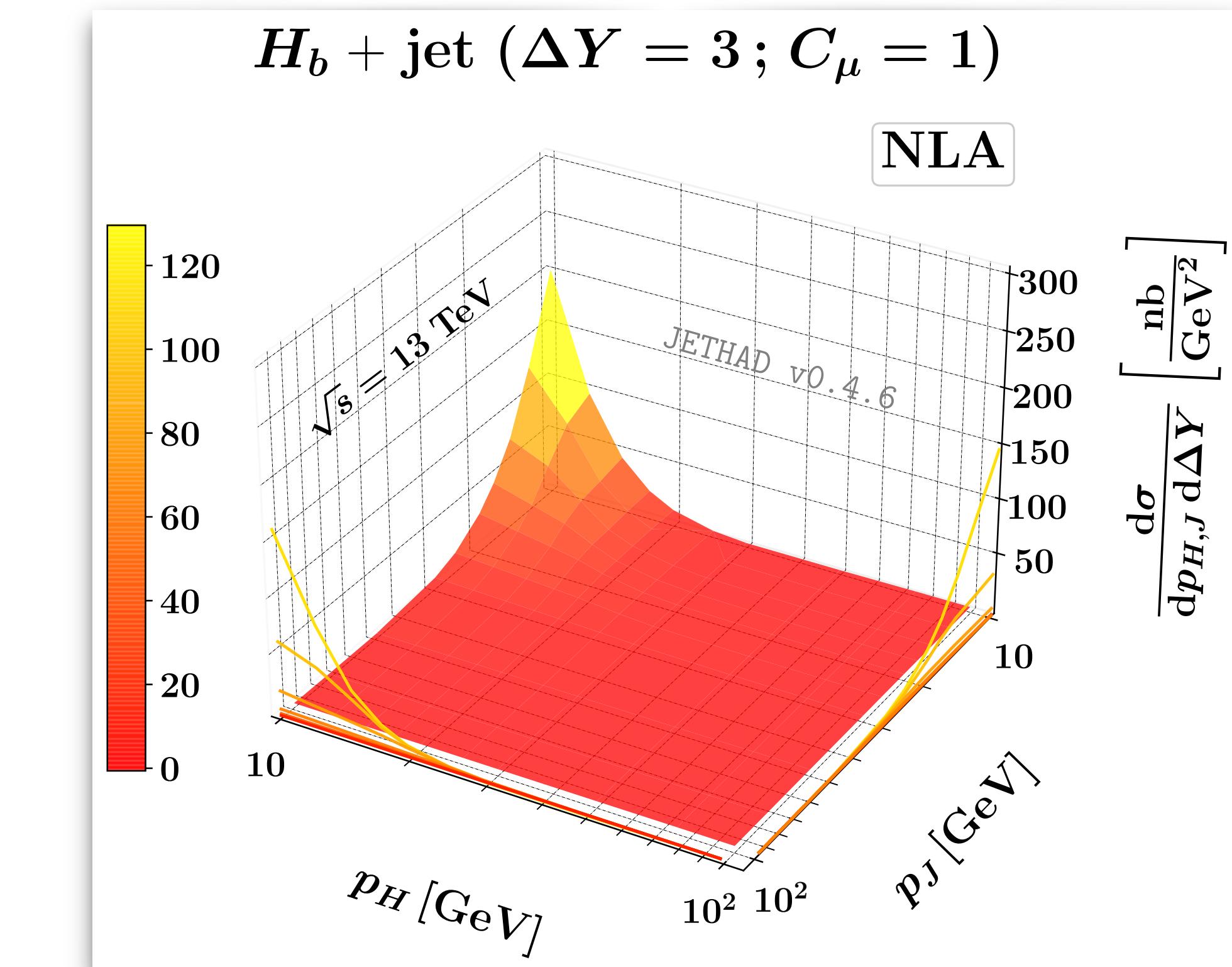
🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]



Bottom-flavored hadrons

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

$H_b + \text{jet } (\Delta Y = 3 ; C_\mu = 1)$



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

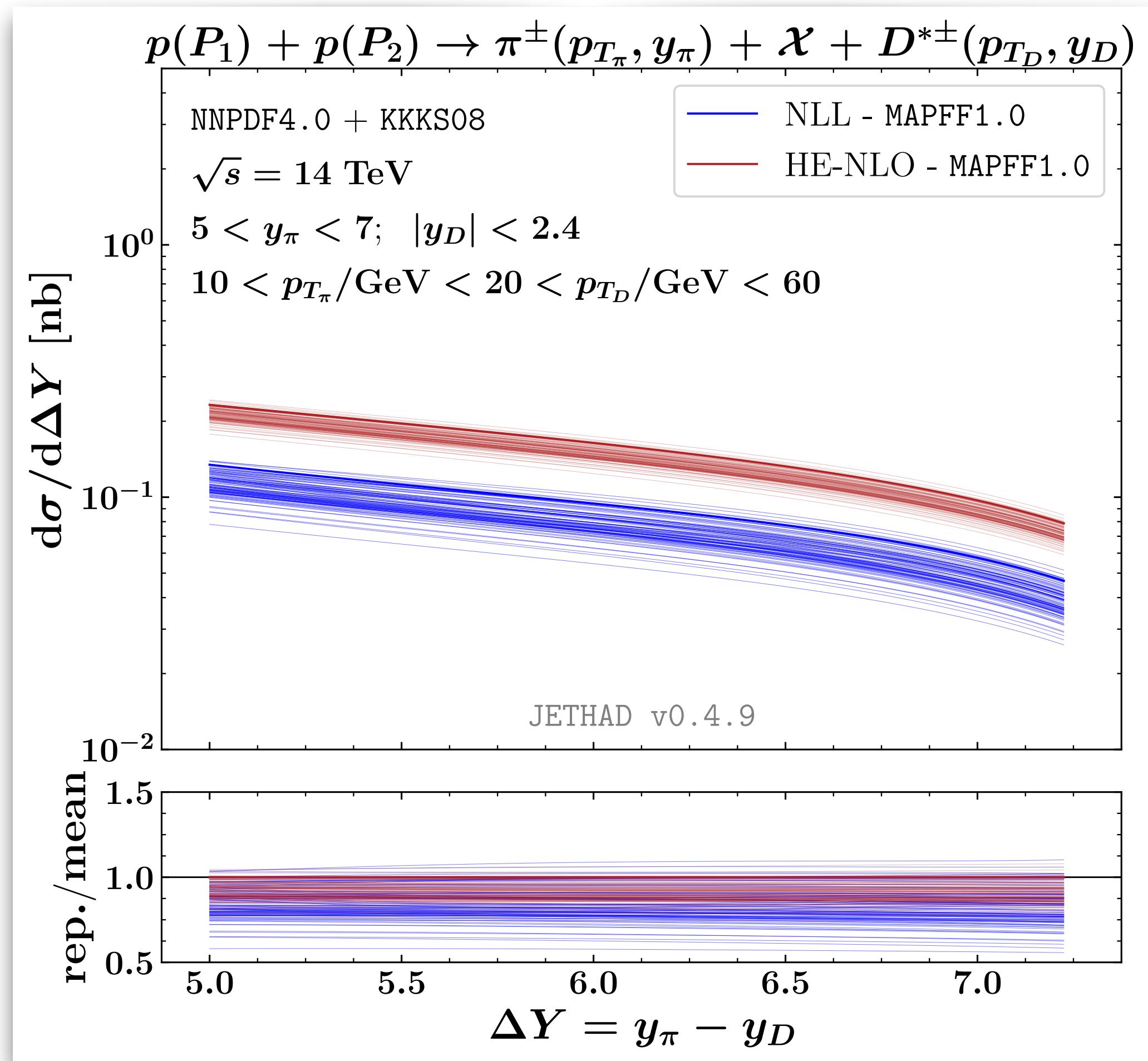


Backup

Rapidity distributions @FPF+ATLAS

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

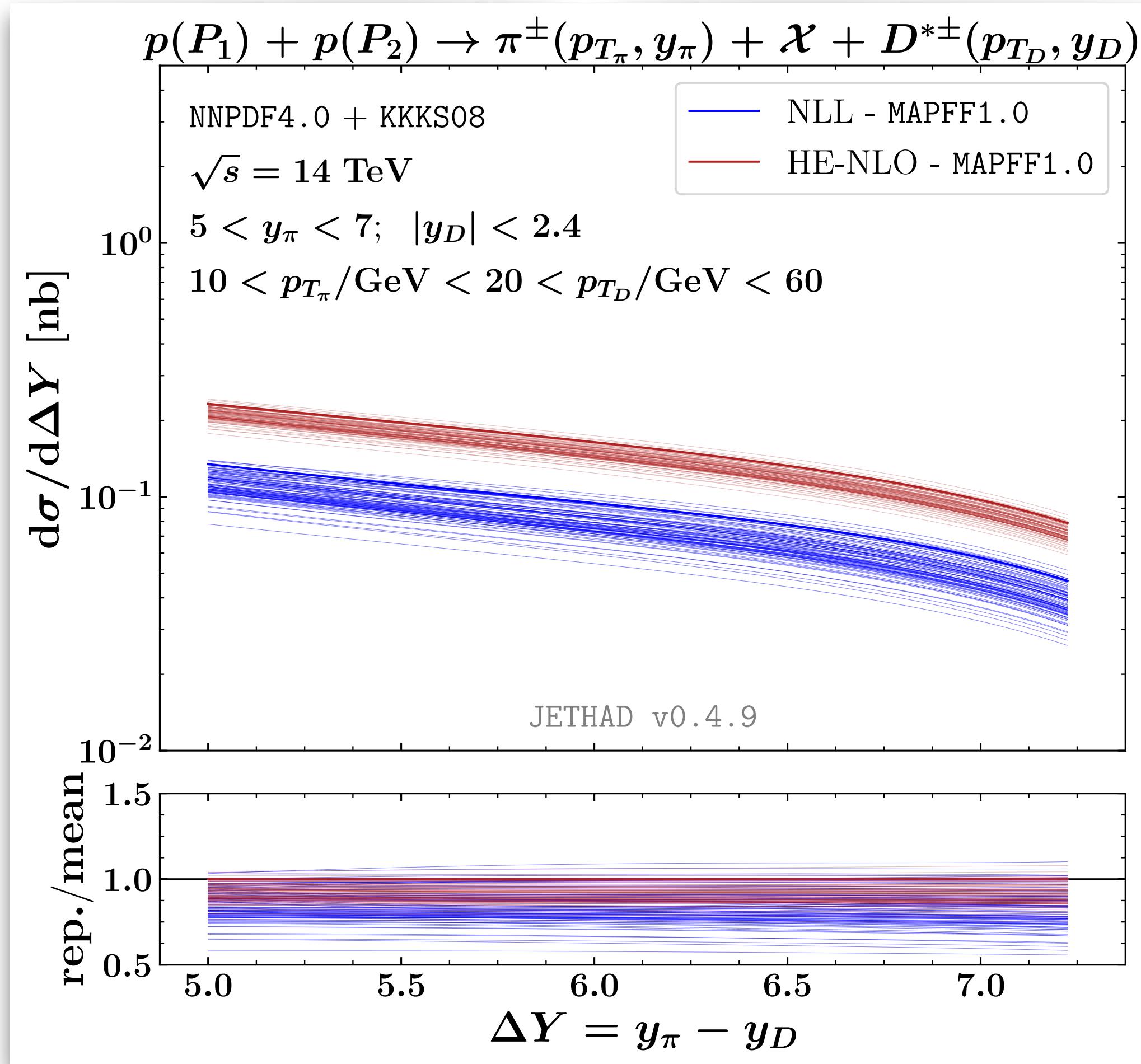
[FPF Snowmass Whitepaper]



Rapidity distributions @FPF+ATLAS

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

[FPF Snowmass Whitepaper]

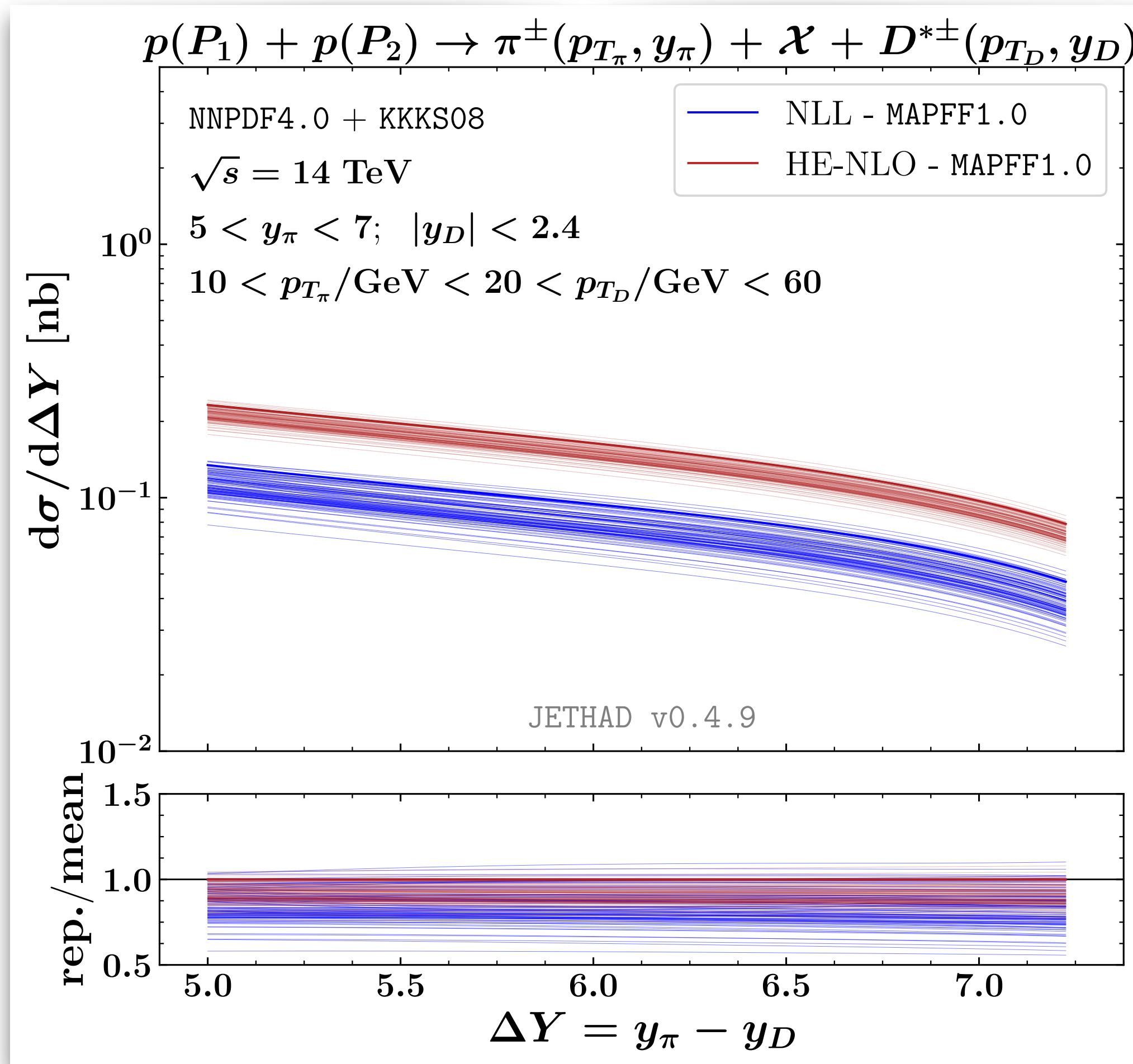


- * Impact of collinear FFs on ΔY -distribution
- * Replica method at work

Rapidity distributions @FPF+ATLAS

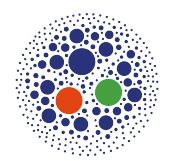
Inclusive π^\pm (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]



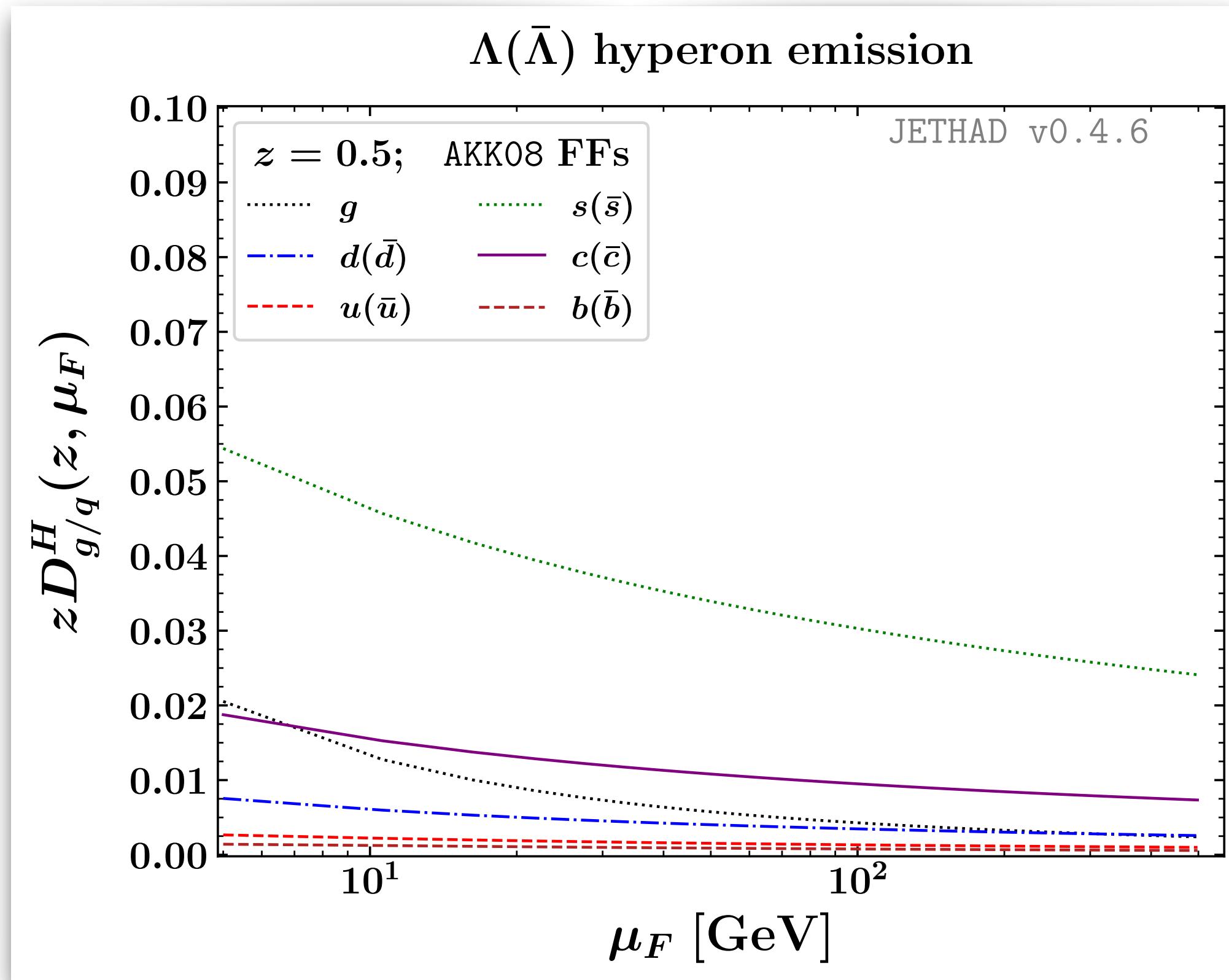
- * Impact of collinear FFs on ΔY -distribution
- * Replica method at work
- * Larger spread of replicas at NLL
- * Probe FFs in complementary ranges
 - Weight of FF replicas in the same set
 - Different sets via functional correlation?
- * Complementary studies on FFs

Stabilizing effects of heavy-flavor fragmentation

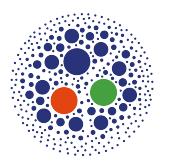


AKK08 VFNS collinear FFs for Λ hyperons: $|uds\rangle$

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

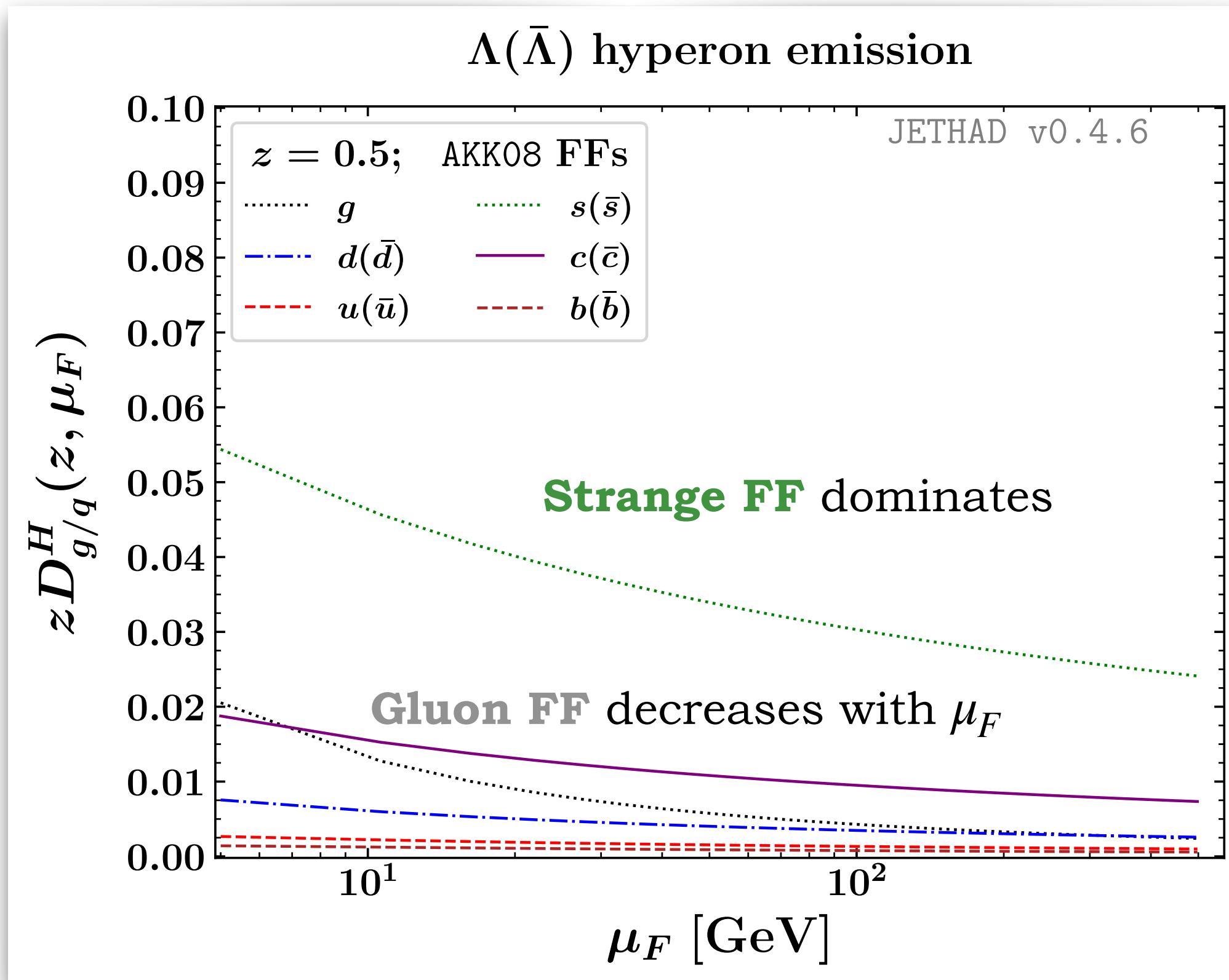


Stabilizing effects of heavy-flavor fragmentation

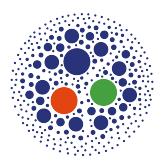


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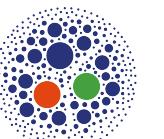
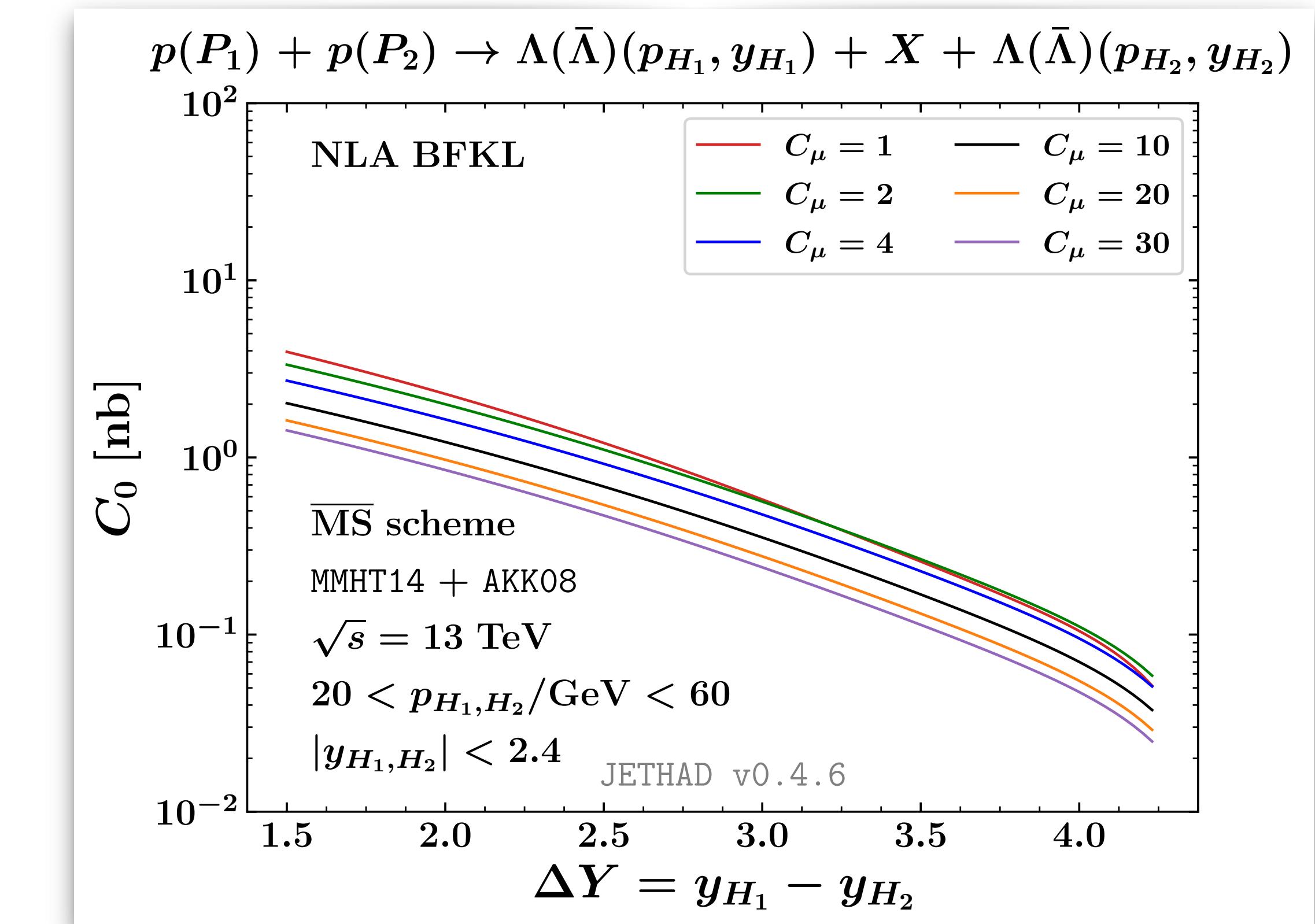
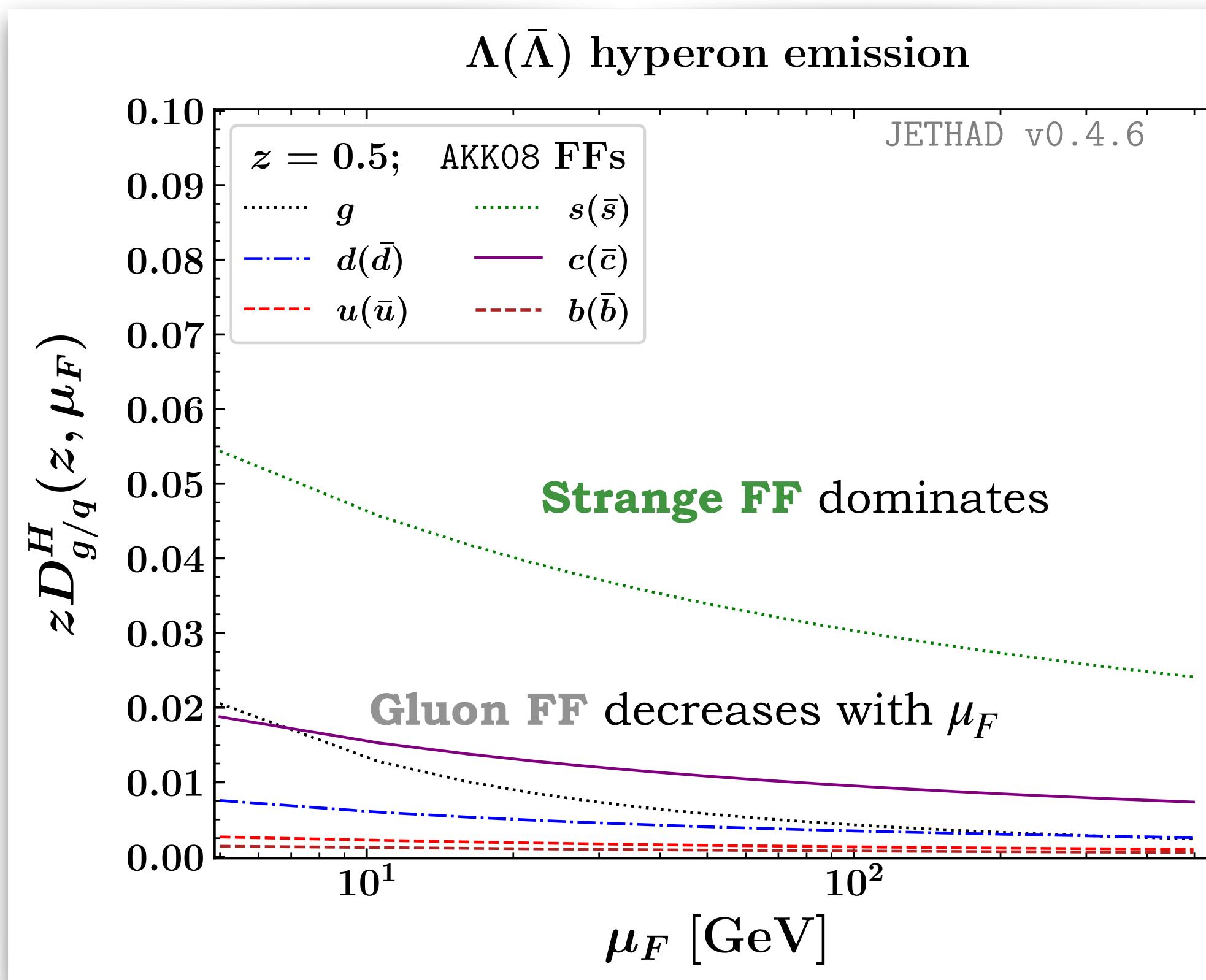


Stabilizing effects of heavy-flavor fragmentation



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

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Rapidity distribution **sensitive to scale variations**

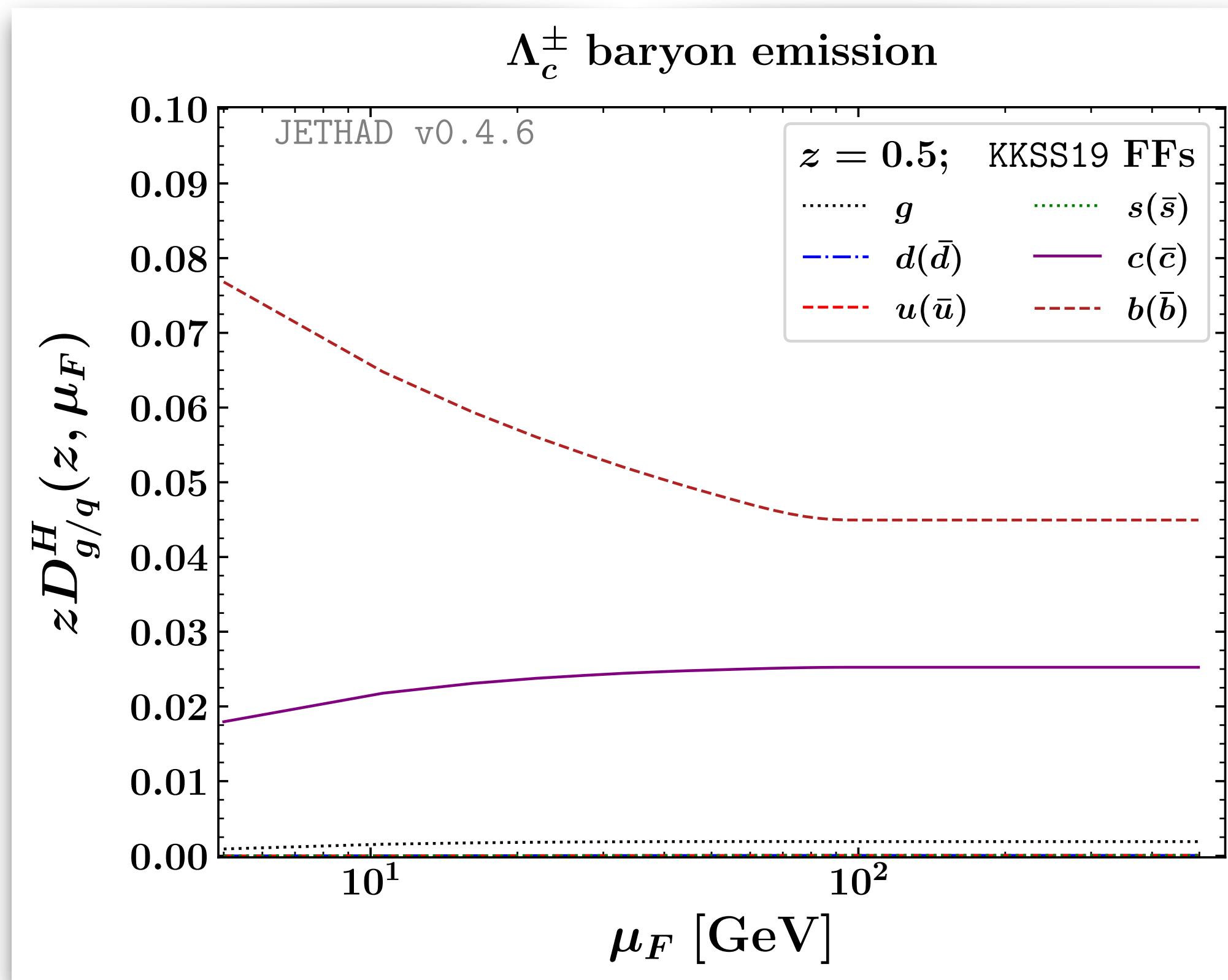
(Λ hyperons) 🔗 [F. G. C. et al., Phys. Rev. D 102 (2020) 9, 094019]

Stabilizing effects of heavy-flavor fragmentation



KKSS19 VFNS collinear FFs for Λ_c^\pm baryons: $|udc\rangle$

DOI [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]

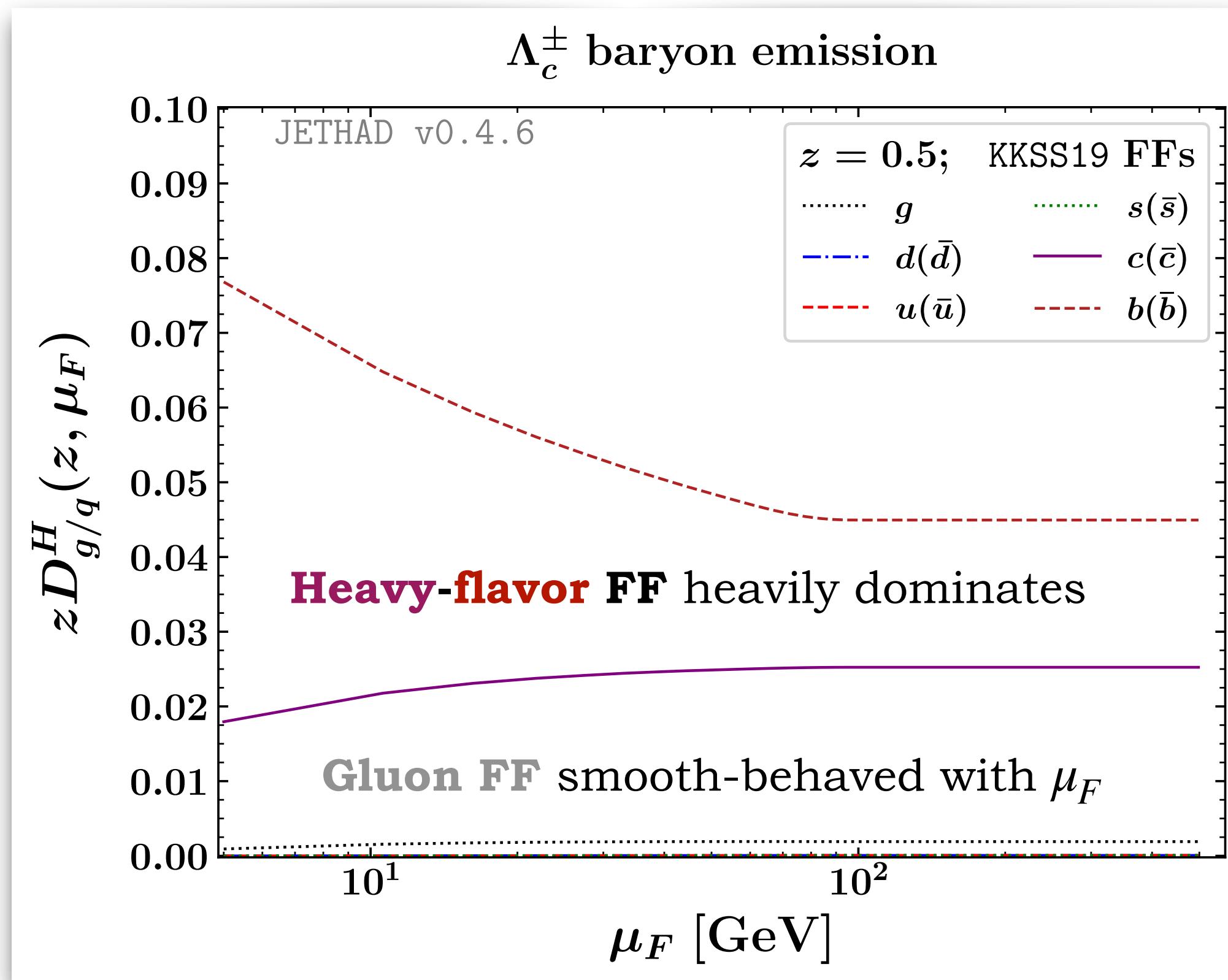


Stabilizing effects of heavy-flavor fragmentation

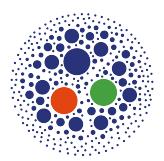


KKSS19 VFNS collinear FFs for Λ_c^\pm baryons: $|udc\rangle$

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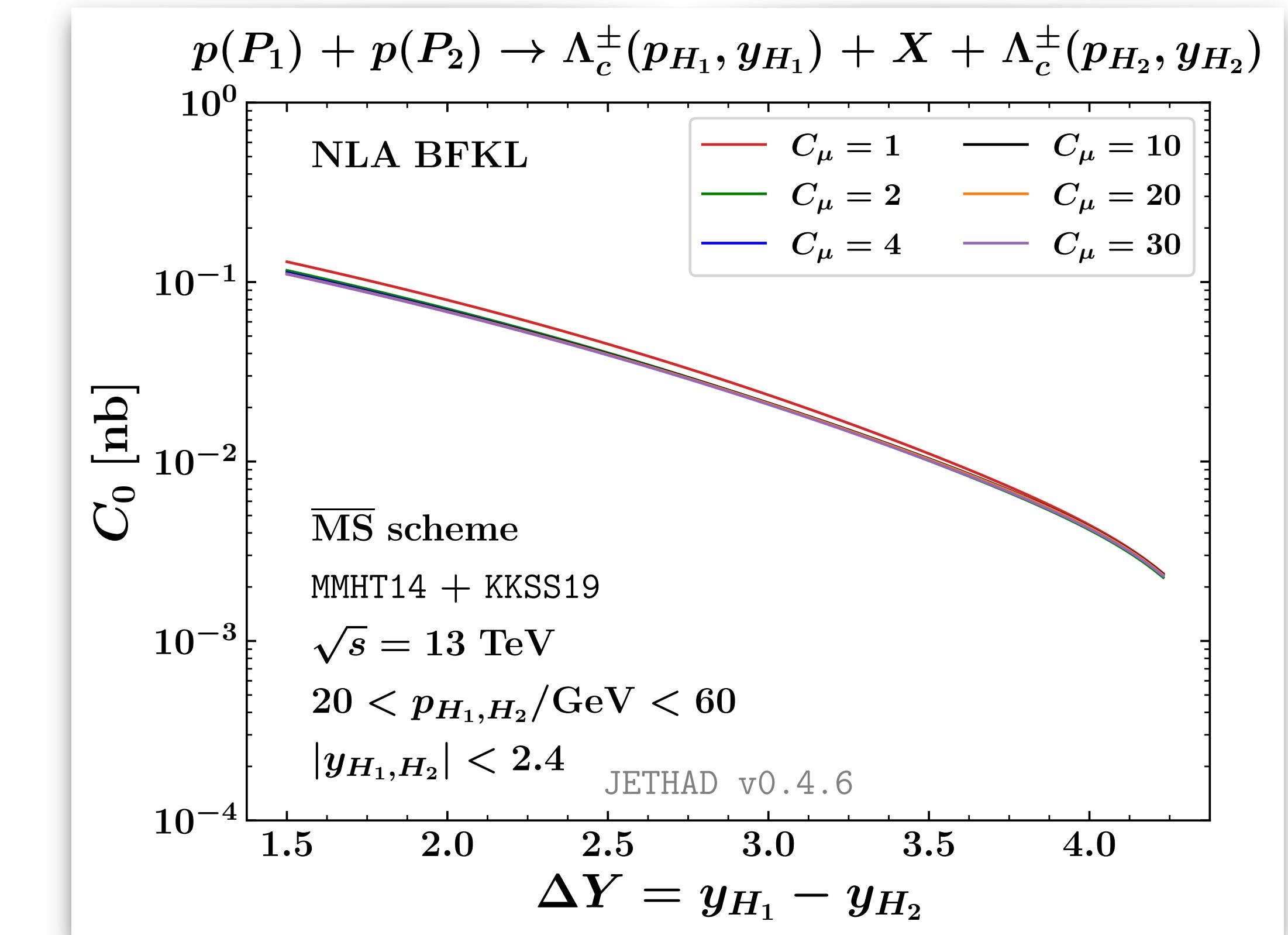
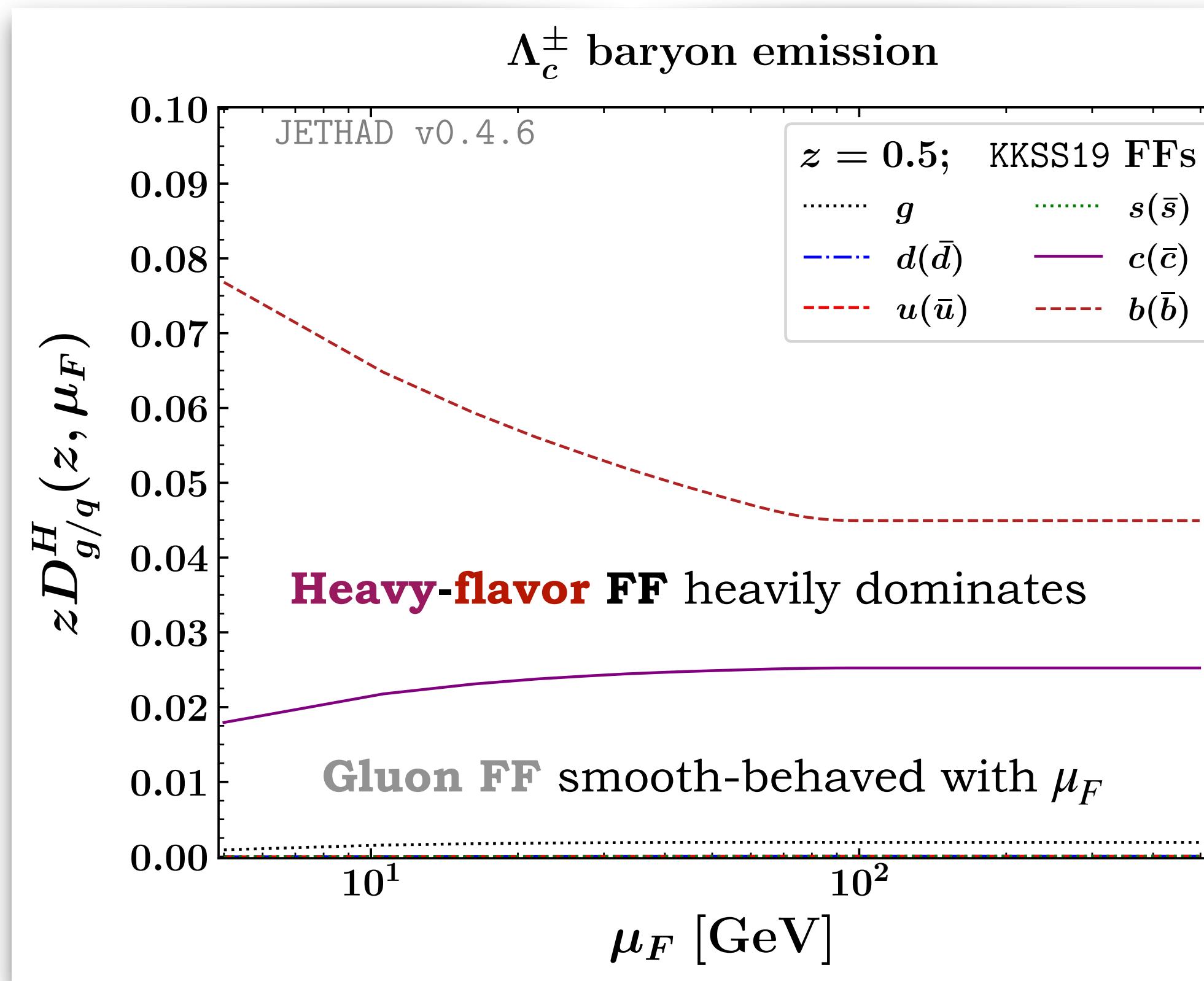


Stabilizing effects of heavy-flavor fragmentation



KKSS19 VFNS collinear FFs for Λ_c^\pm baryons: $|udc\rangle$

🔗 [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]



Rapidity distribution **stable** under scale variations

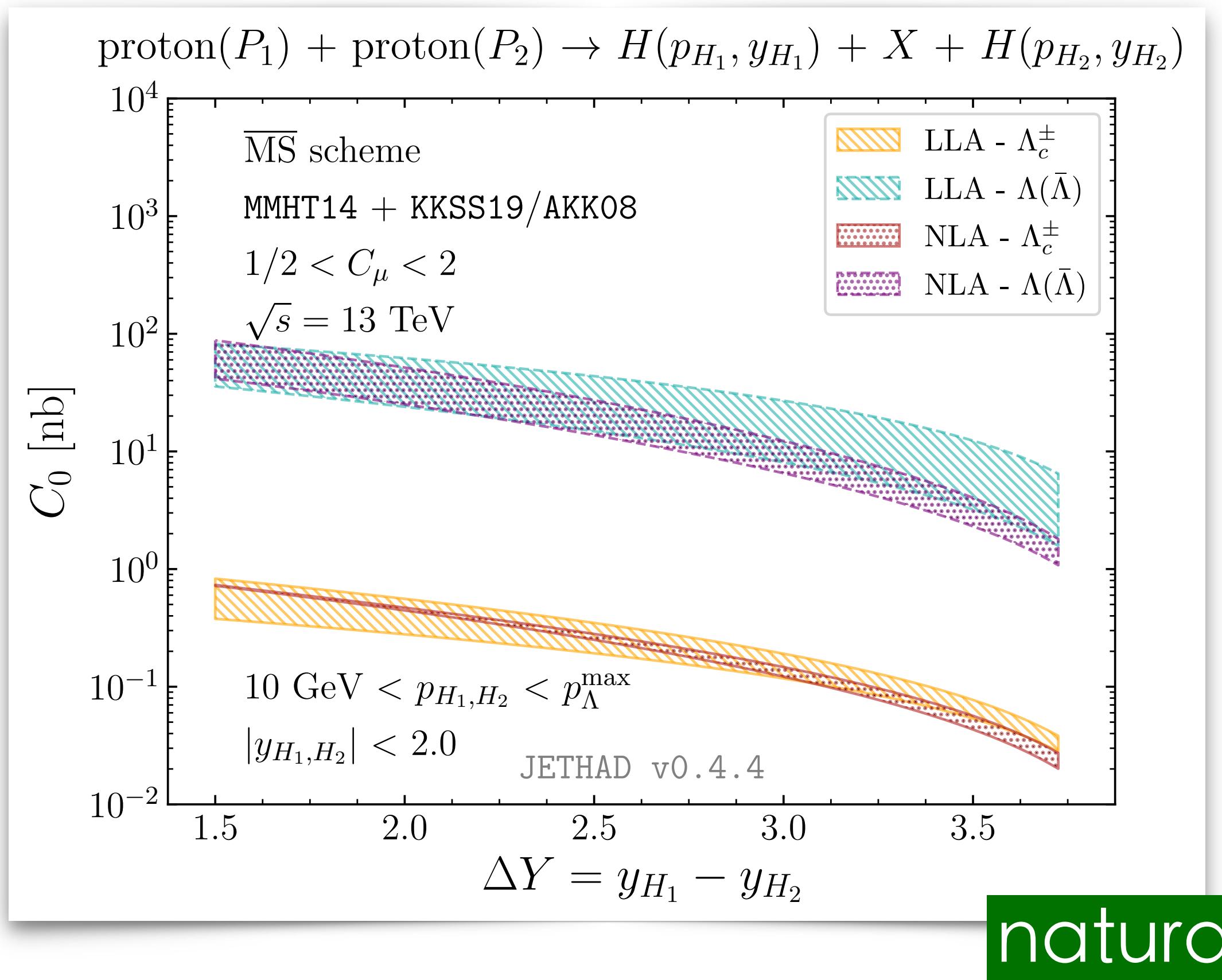
(Λ_c baryons, in this slide) 🔗 [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

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

Stability under scale variations & NLL corrections



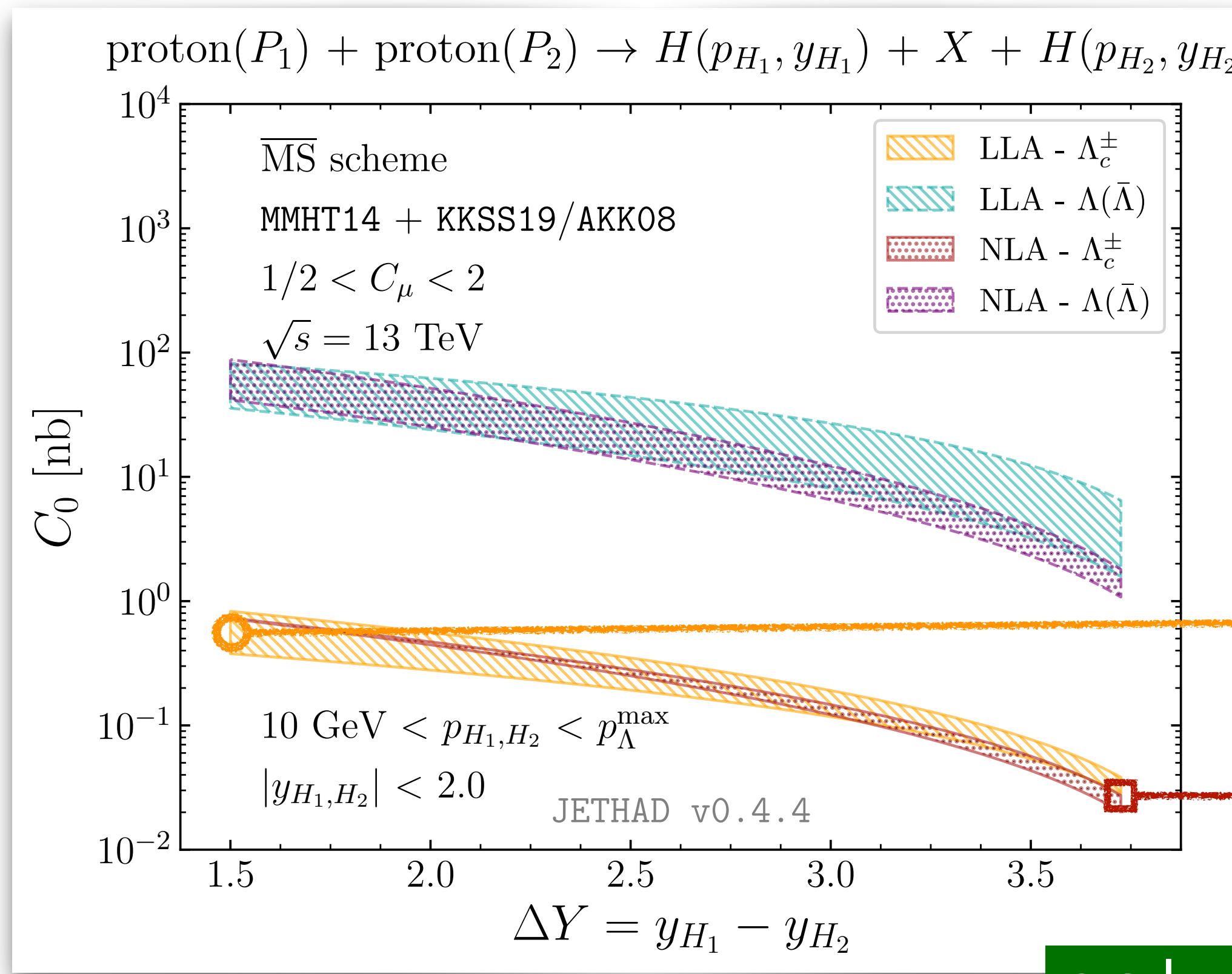
Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



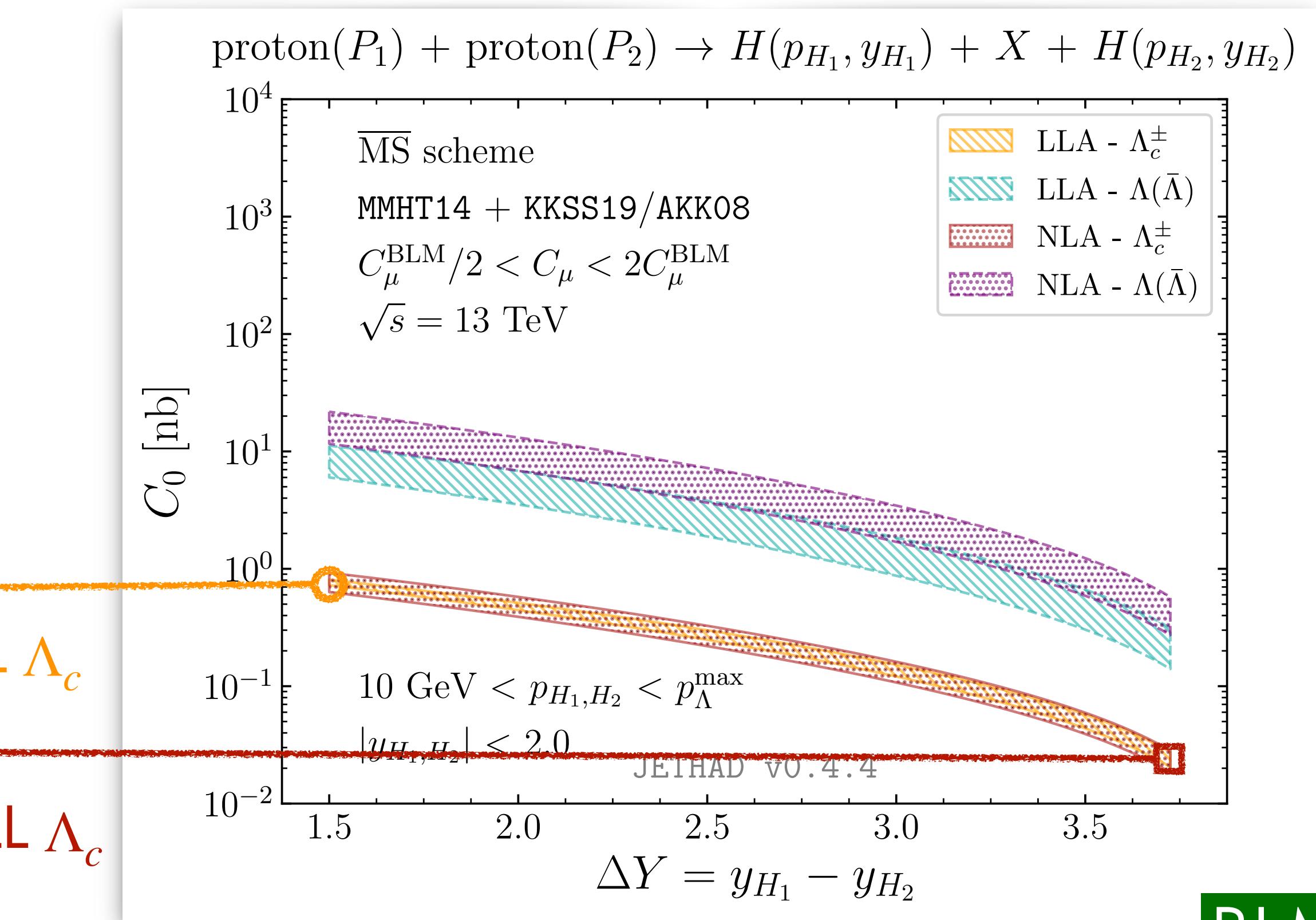
Stability under scale variations & NLL corrections



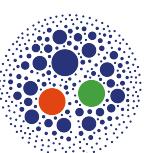
Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



natural



BLM



NLL corrections: rapidity distribution **stable** for Λ_c

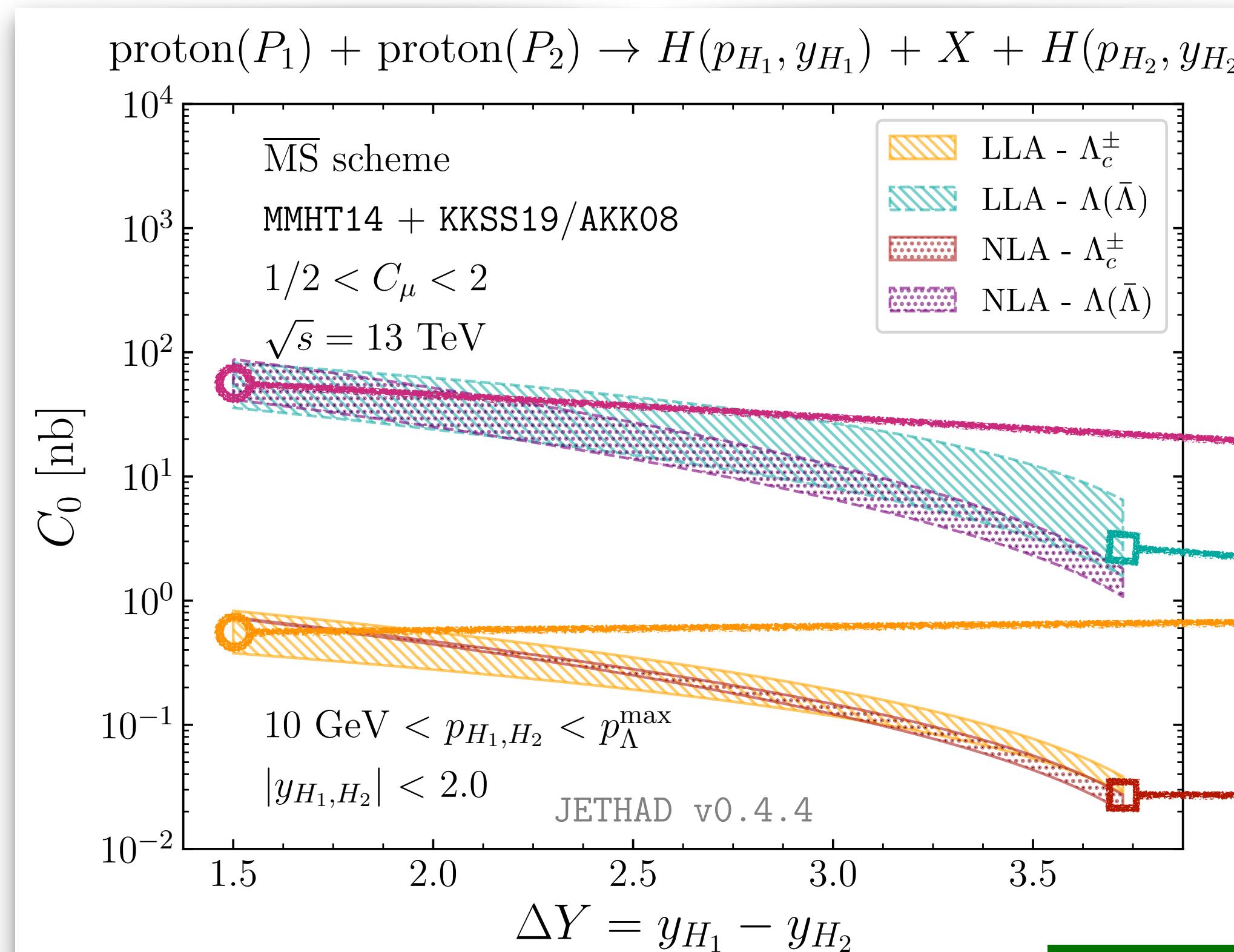
(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

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

Stability under scale variations & NLL corrections



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



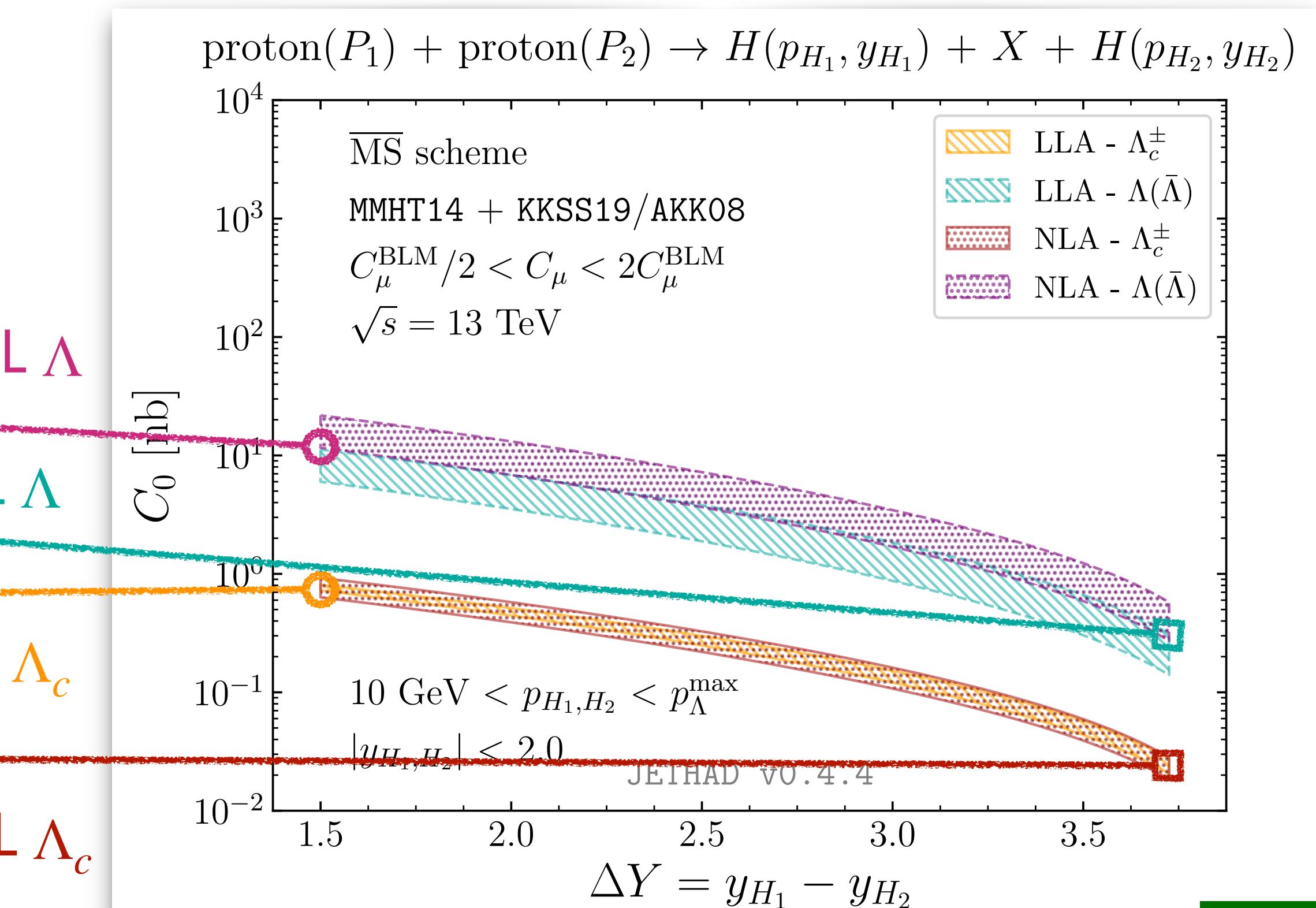
NLL Λ

LL Λ

LL Λ_c

NLL Λ_c

natural



BLM



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

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

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

Stabilizing effects of heavy-flavor fragmentation

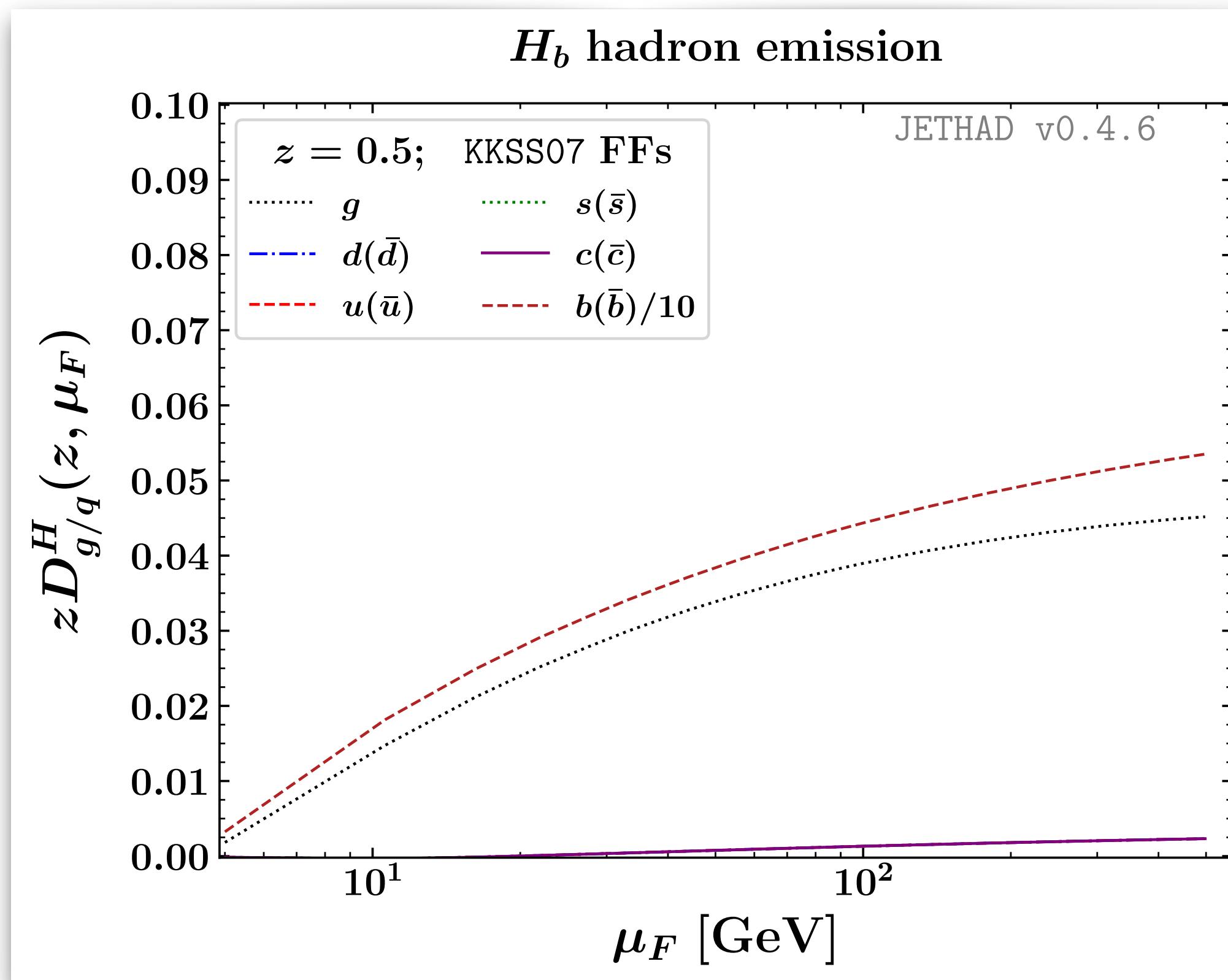


KKSS07 VFNS collinear FFs for:

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

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

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



Stabilizing effects of heavy-flavor fragmentation

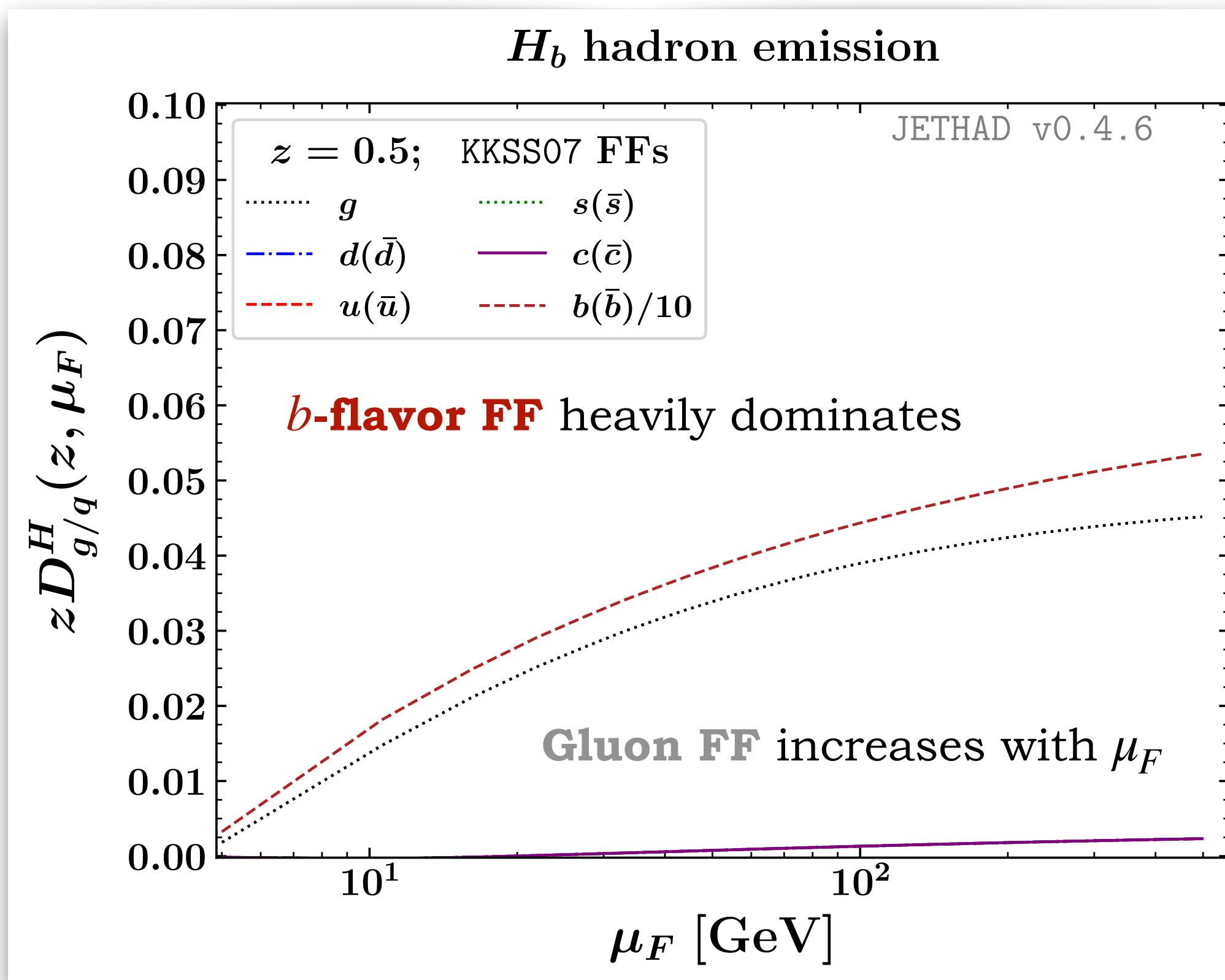


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Stabilizing effects of heavy-flavor fragmentation

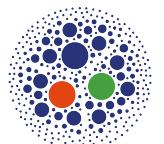
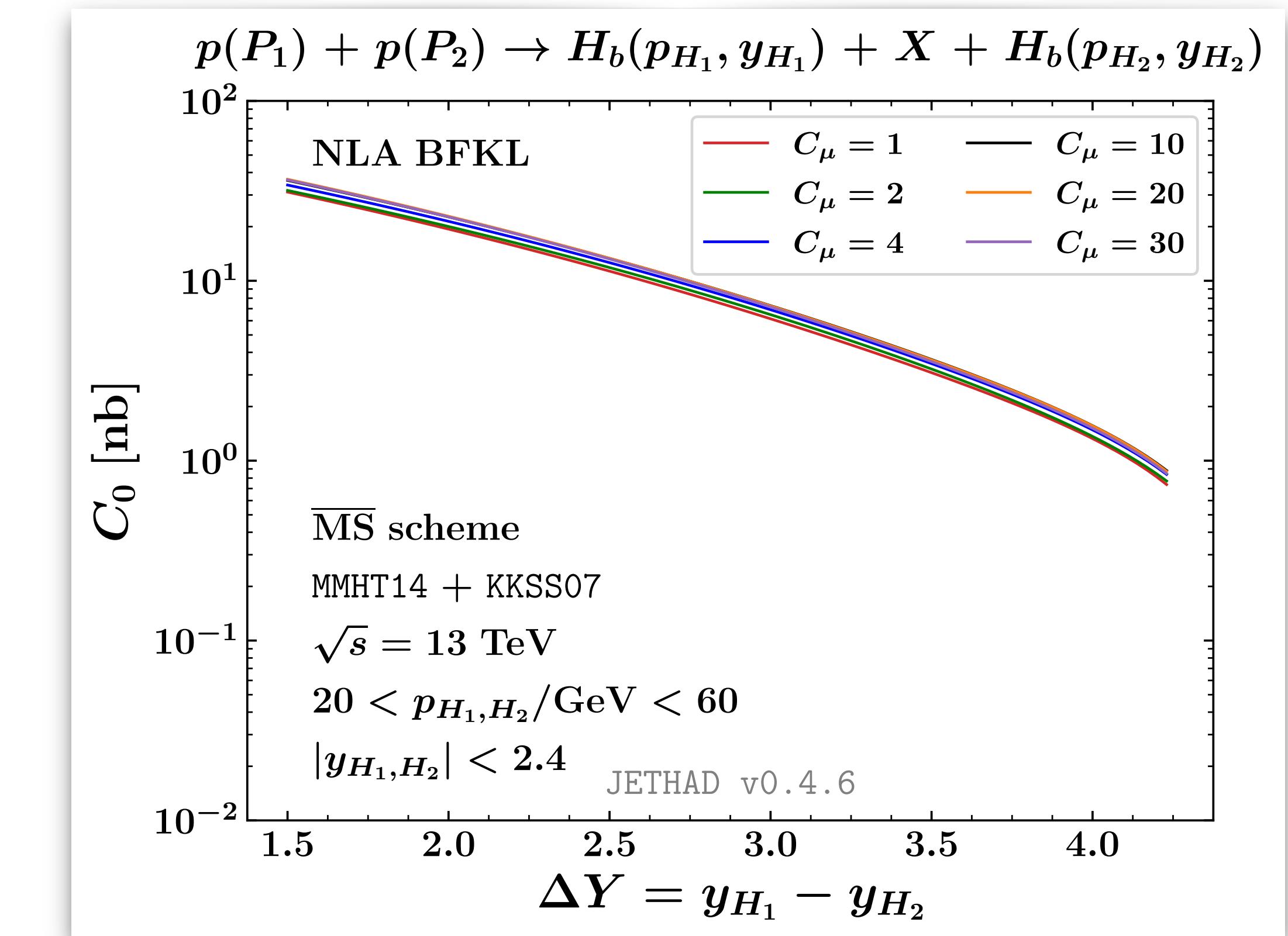
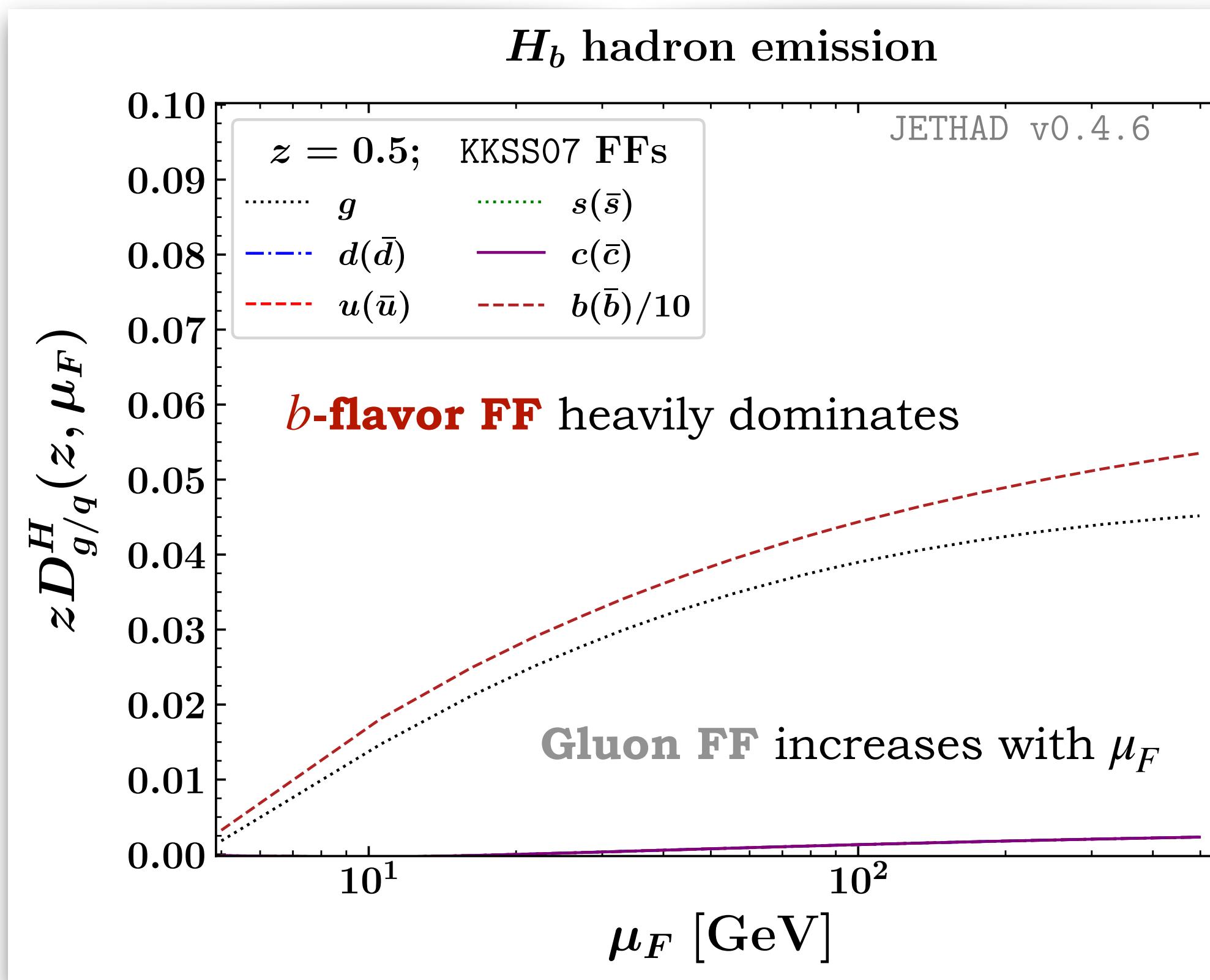


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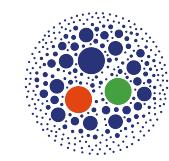
🔗 [B. A. Kniehl et al., Phys. Rev. D 77 (2008) 11, 014011]



Rapidity distribution **very stable** under scale variations

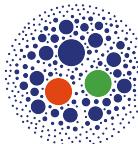
(H_b hadrons, in this slide) 🔗 [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

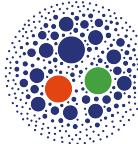
Stabilizing effects of heavy-flavor fragmentation



Stabilization mechanism encoded in the heavy-flavor gluon FF

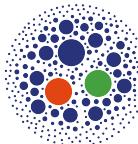
Stabilizing effects of heavy-flavor fragmentation

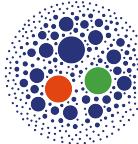
 Stabilization mechanism encoded in the heavy-flavor gluon FF

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

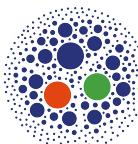
$$c_\Lambda(n, \nu, |\vec{p}|, x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec{p}|^2)^{i\nu-1/2} \int_x^1 \frac{dz}{z} \left(\frac{z}{x}\right)^{2i\nu-1} \left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar{q}} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right) \right]$$

Stabilizing effects of heavy-flavor fragmentation

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 Forward-hadron NLO impact factor \Rightarrow 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 $|C_{gg}| \sim 50 \div 10^4 |C_{gq}|$

Stabilizing effects of heavy-flavor fragmentation

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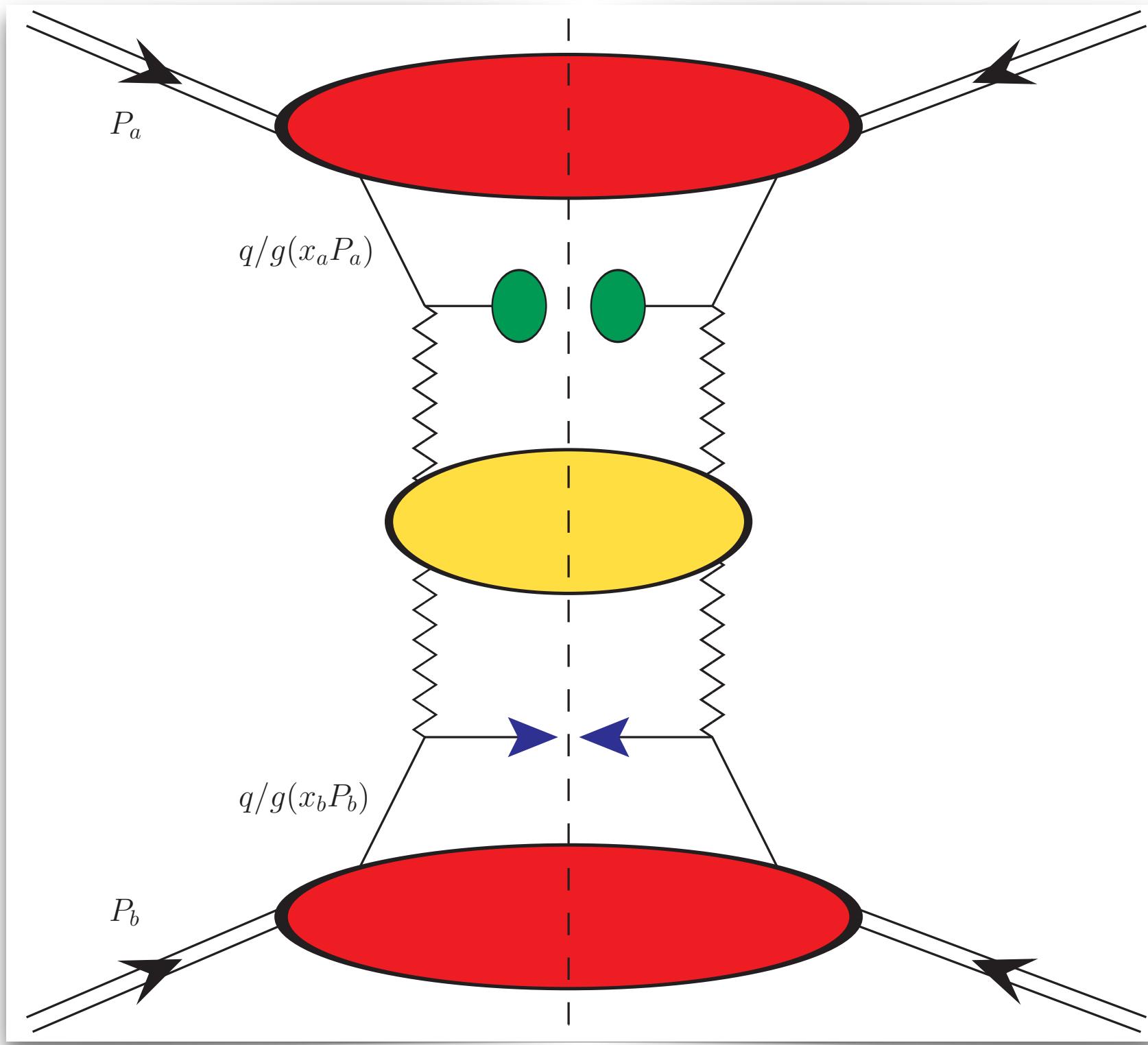
...but $|C_{gg}| \sim 50 \div 10^4 |C_{gq}|$

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

Quarkonia

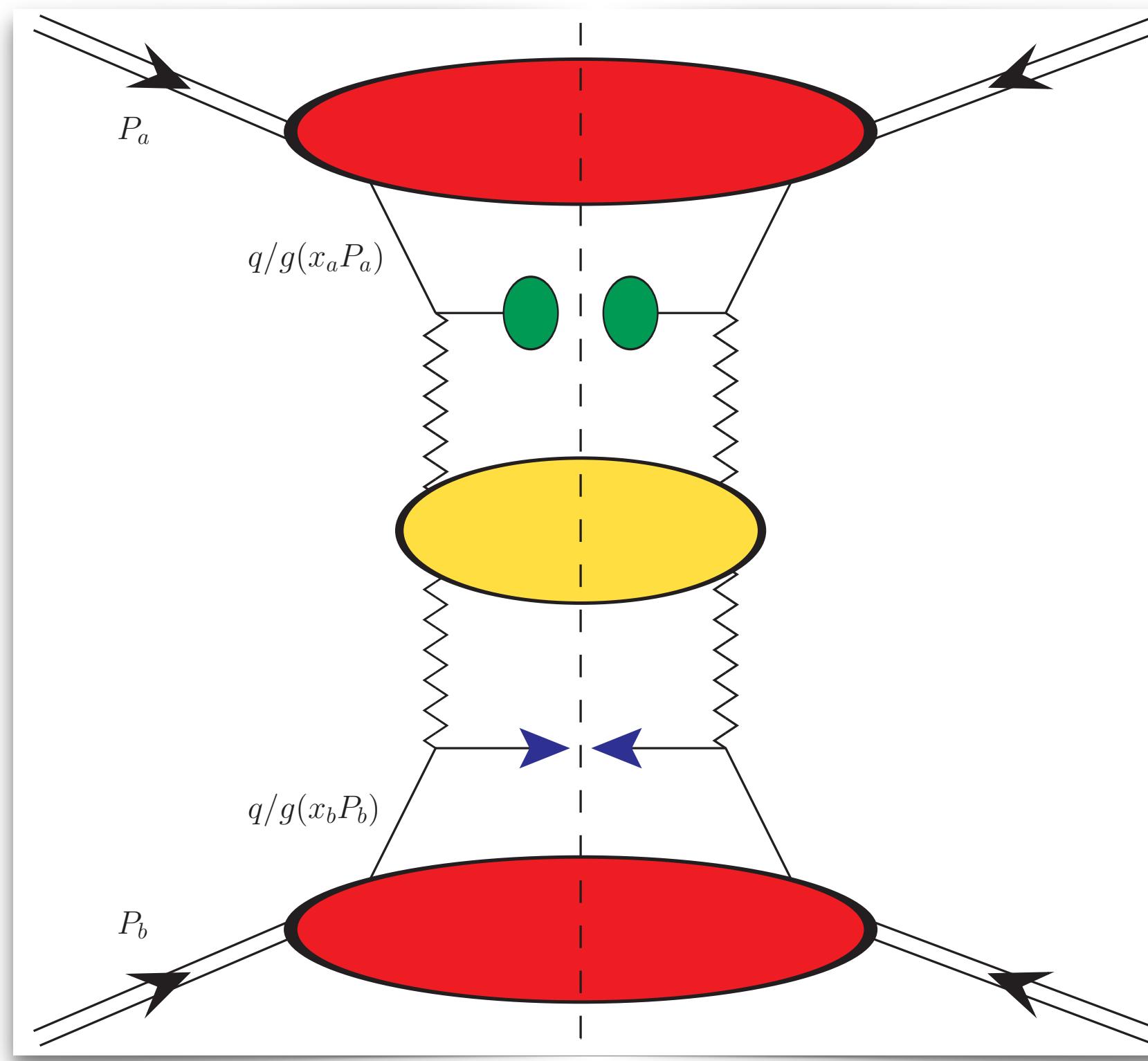
Vector quarkonium from single-parton fragmentation

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



Vector quarkonium from single-parton fragmentation

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ZCW19 onium FFs: $(Q \rightarrow Q\bar{Q}) \otimes \text{APFEL}++$
 $[\mu_0 = 3m_Q]$

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

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

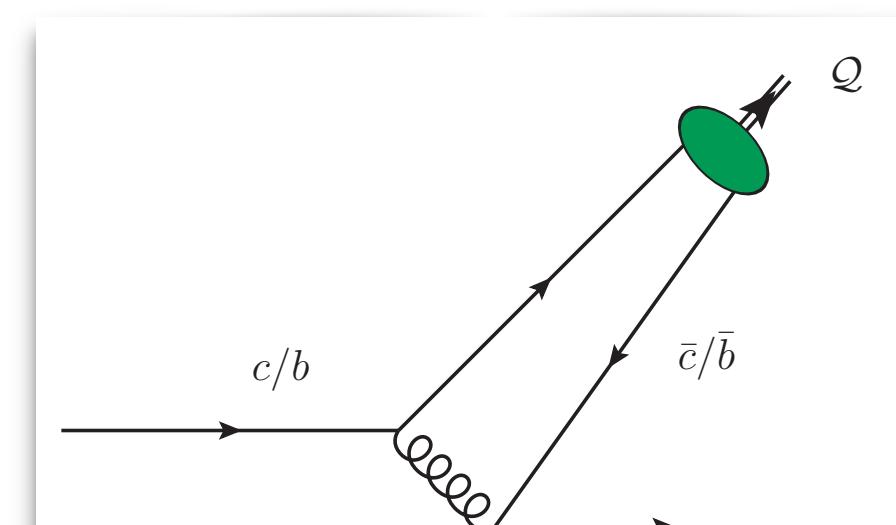
Diffractive semi-hard production of a J/ψ or a Υ from single-parton fragmentation plus a jet in hybrid factorization

Francesco Giovanni Celiberto ^{1,2,3,a} , Michael Fucilla ^{4,5,6,b}

¹ European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), 38123 Villazzano, Trento, Italy
² Fondazione Bruno Kessler (FBK), 38123 Povo, Trento, Italy
³ INFN-TIFPA Trento Institute of Fundamental Physics and Applications, 38123 Povo, Trento, Italy
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
⁶ Université Paris-Saclay, CNRS, IJCLab, 91405 Orsay, France

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



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

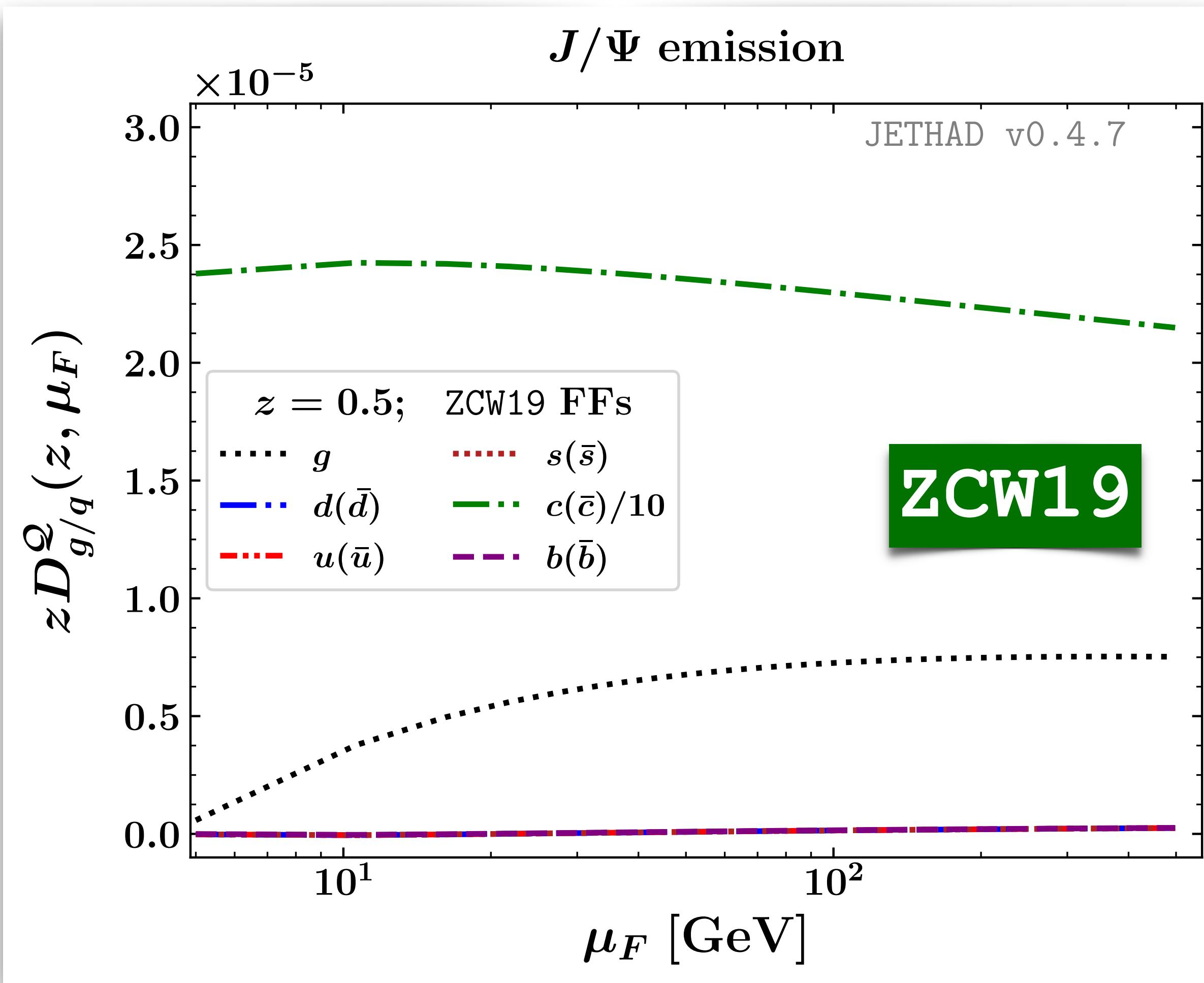
(LO) [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

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

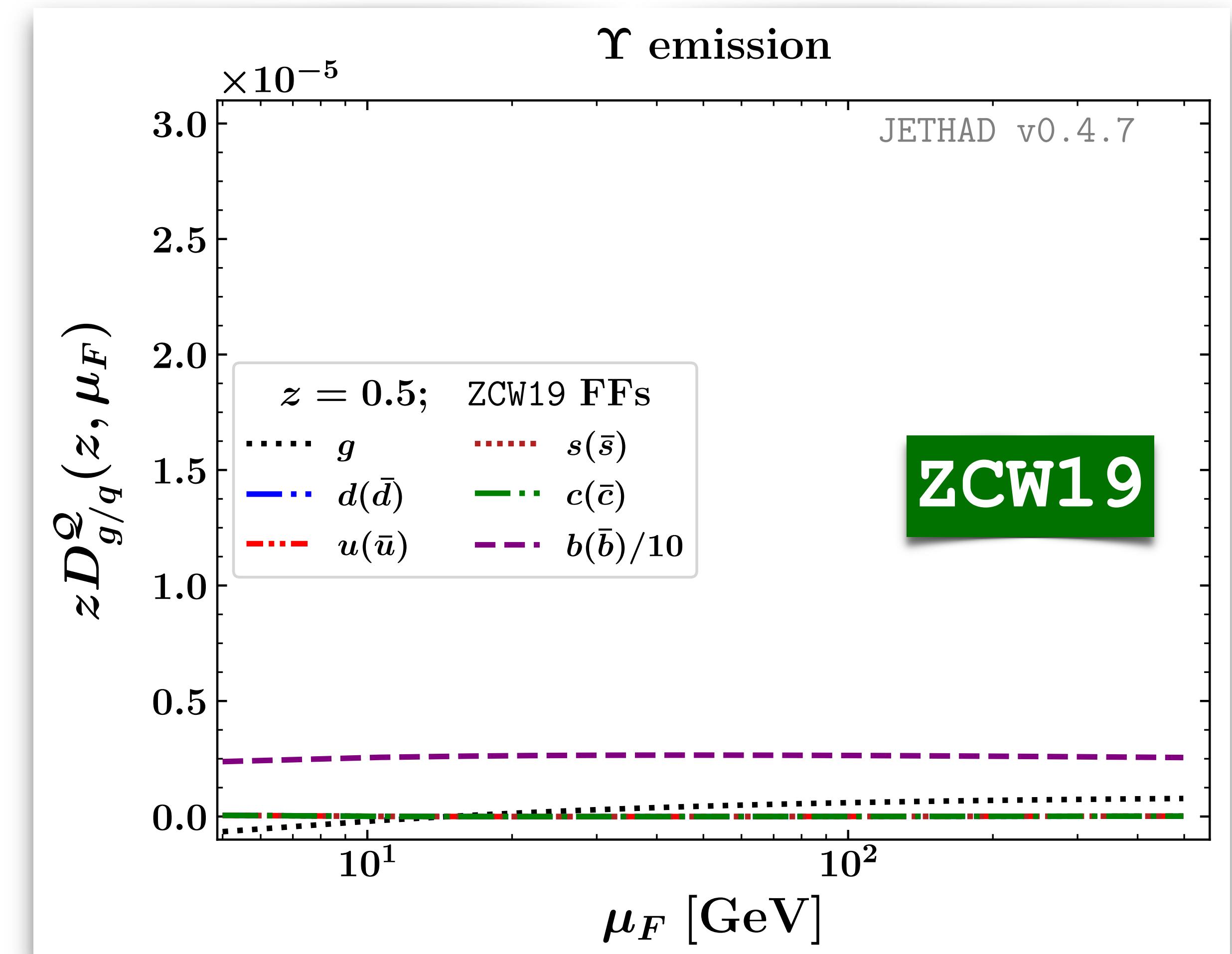
Color Singlet (CS)

Vector quarkonium + jet at the LHC

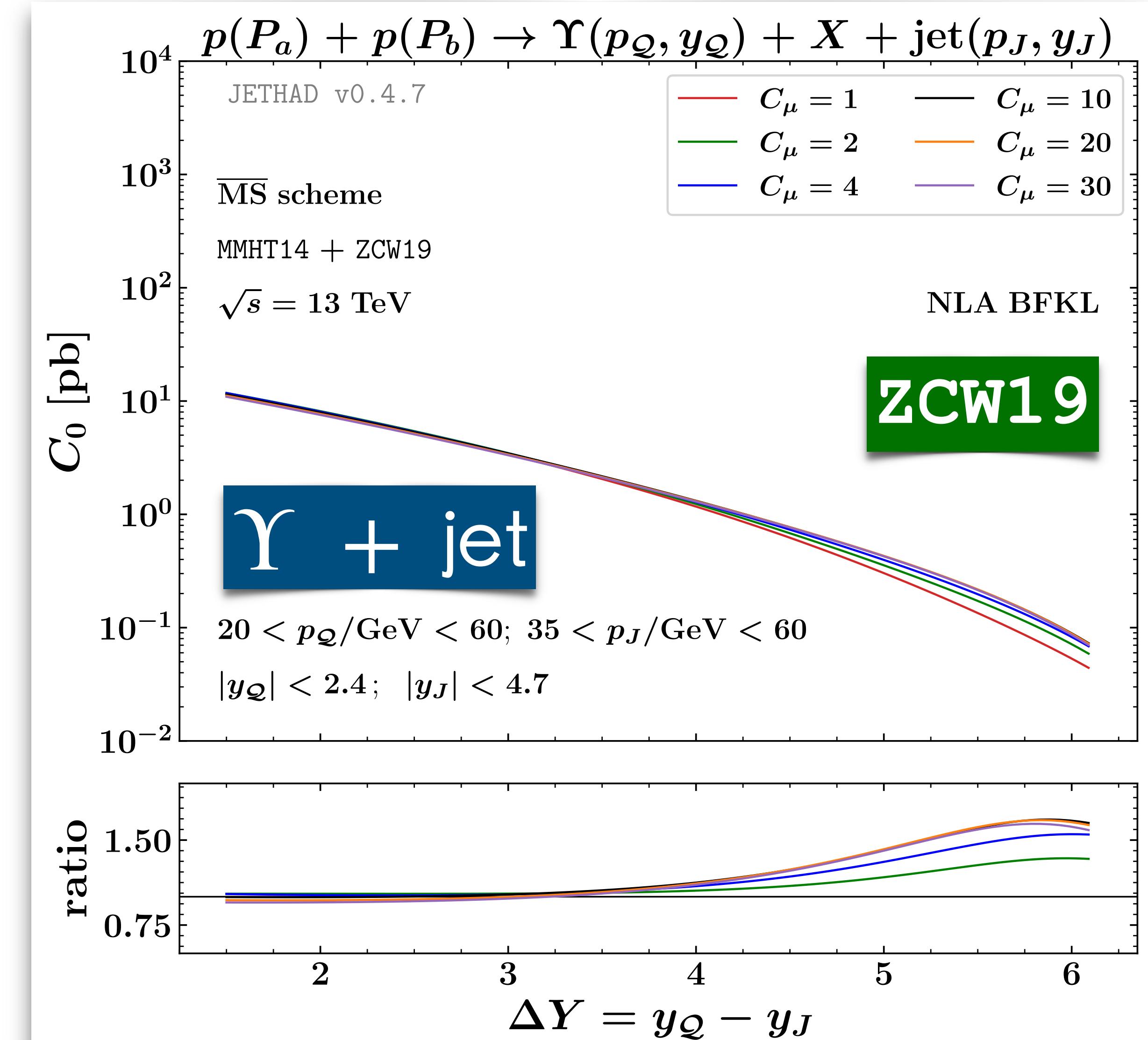
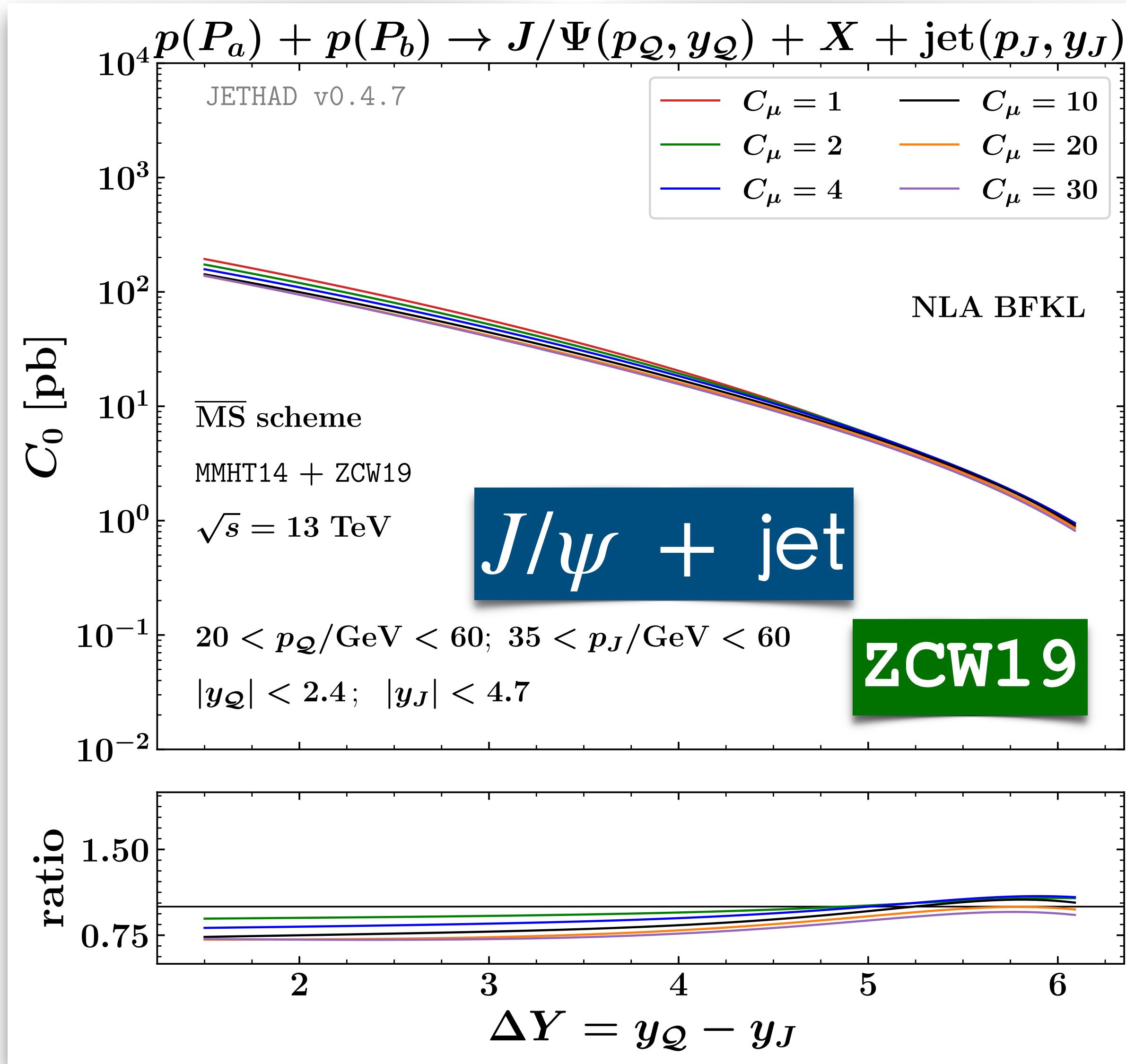
J/ψ collinear FFs



Υ collinear FFs

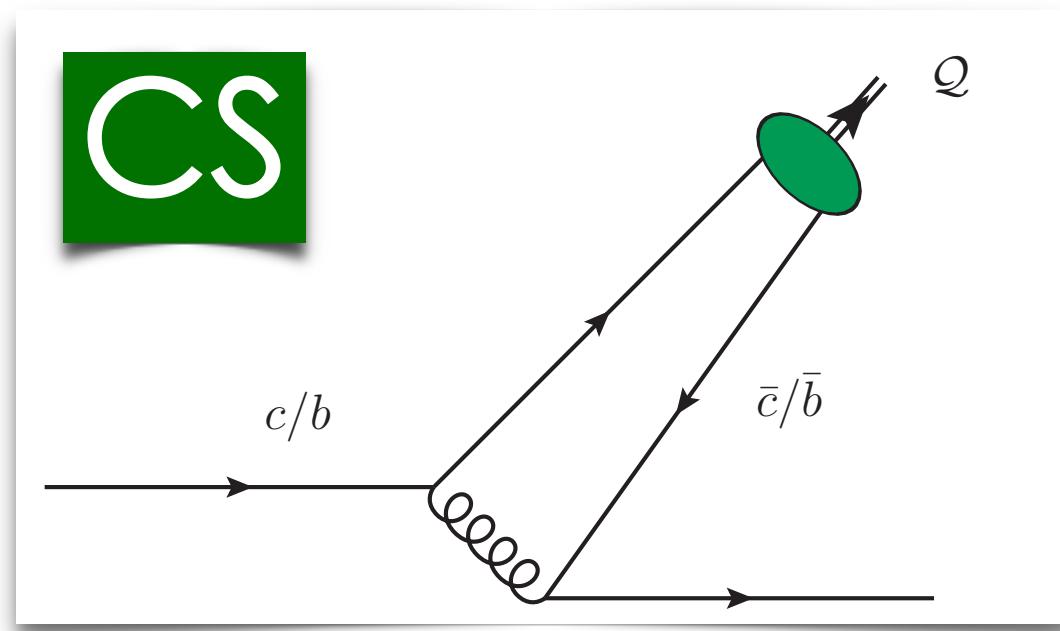


Vector quarkonium + jet at the LHC



Vector quarkonium from single-parton fragmentation

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



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

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

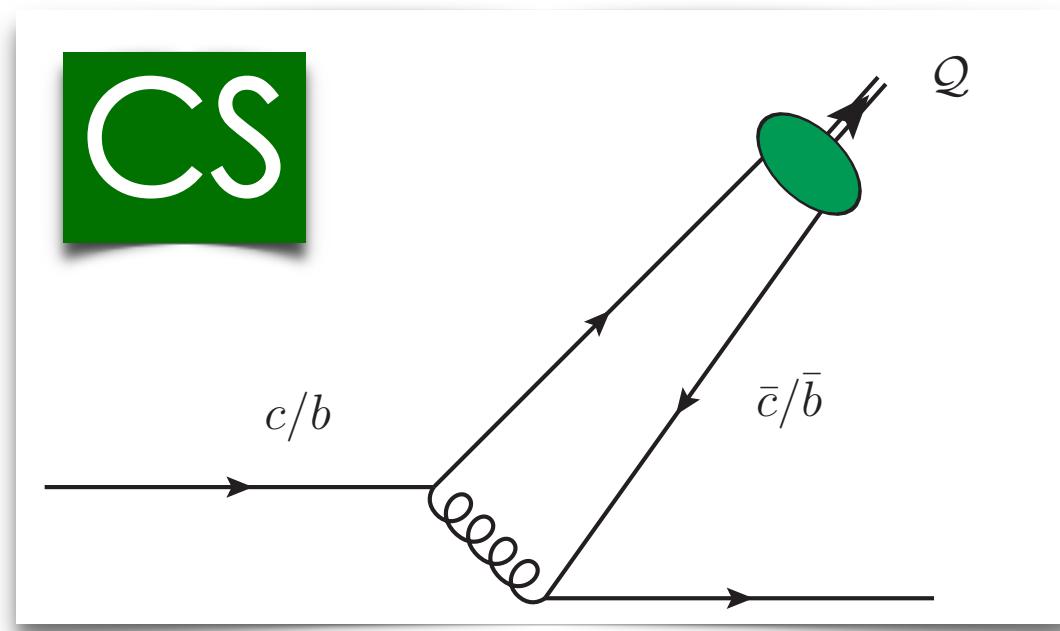
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⚡ [F. G. C., M. Fucilla, Eur. Phys. J. C 82 (2022) 10, 929]

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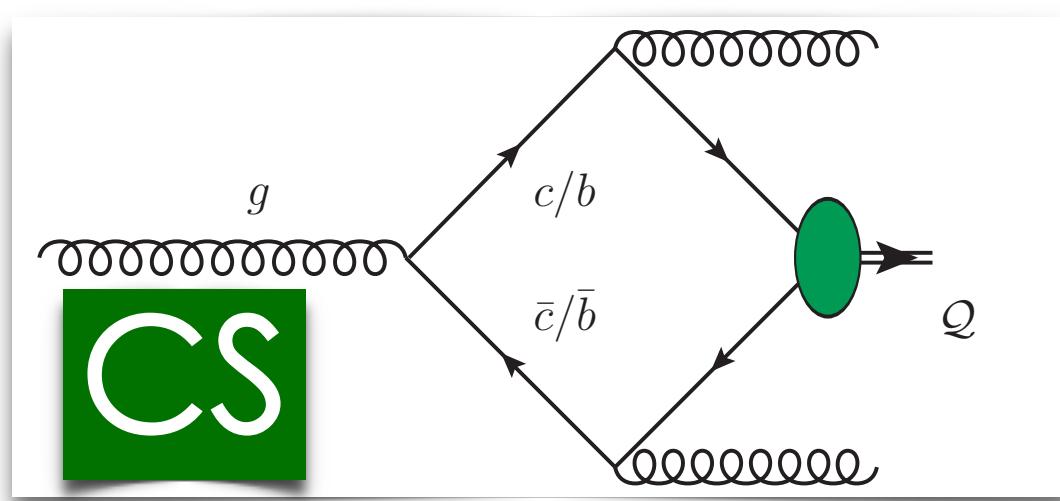


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+



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

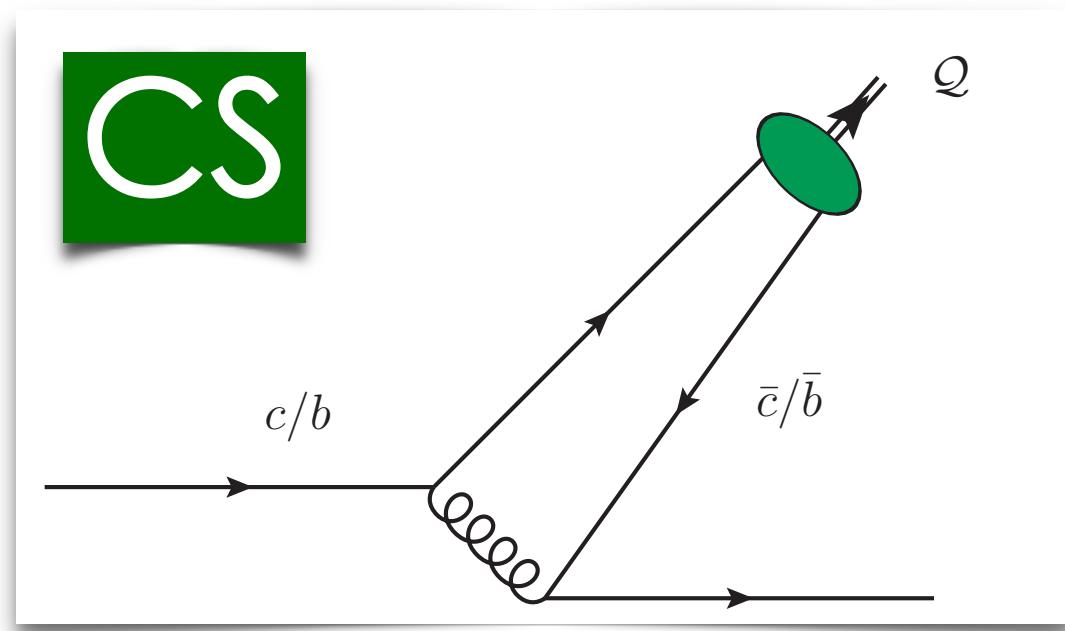
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Vector quarkonium from single-parton fragmentation

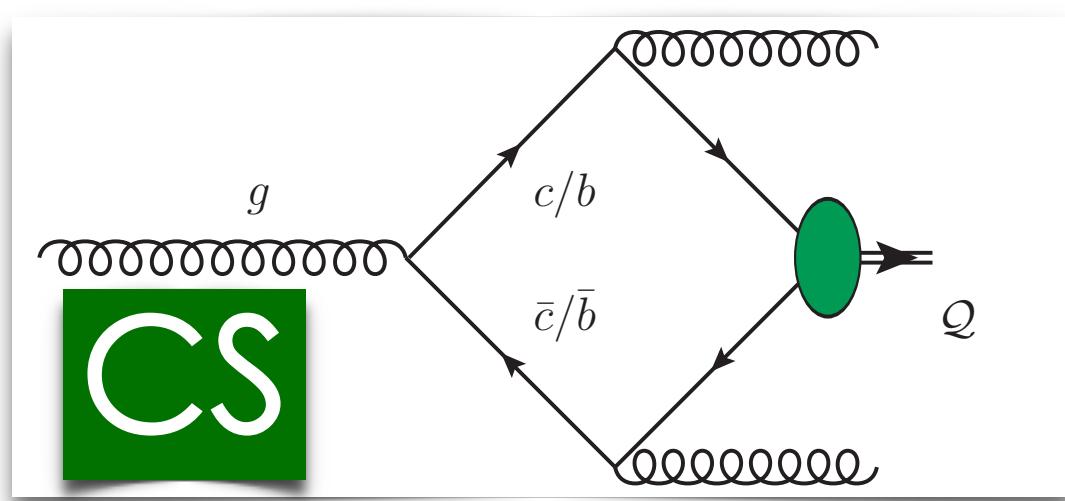
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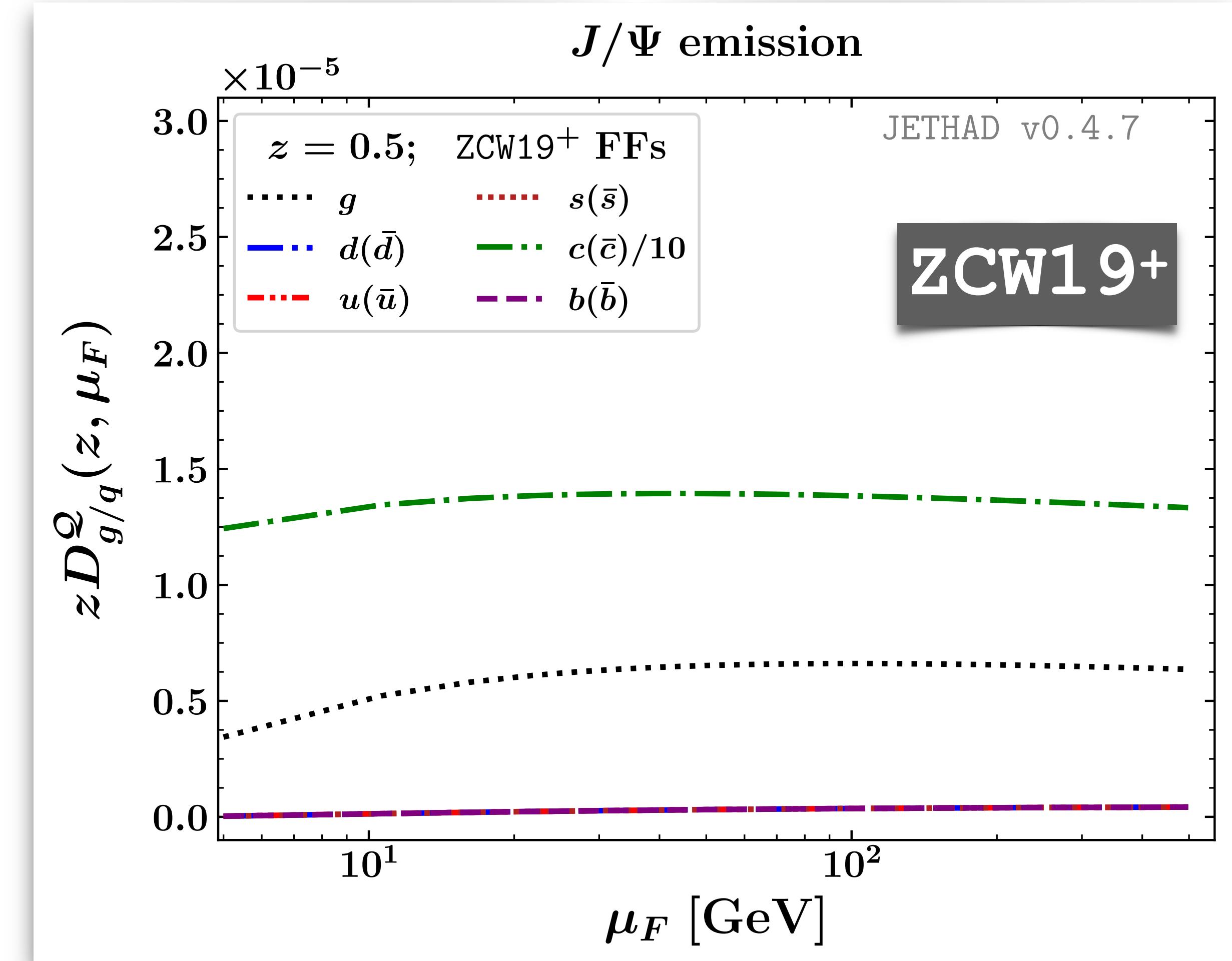
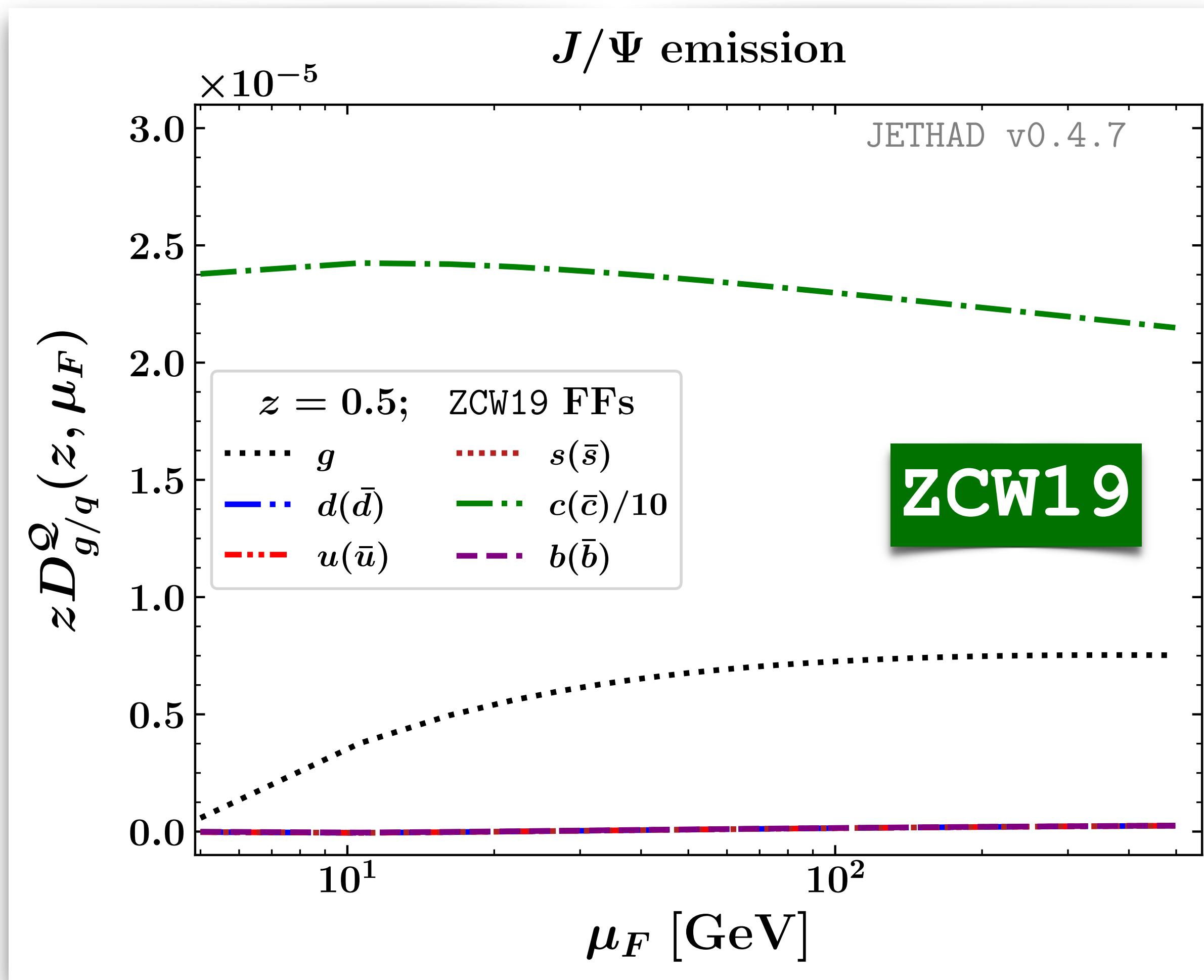
ZCW19⁺
onium FFs

=

APFEL++

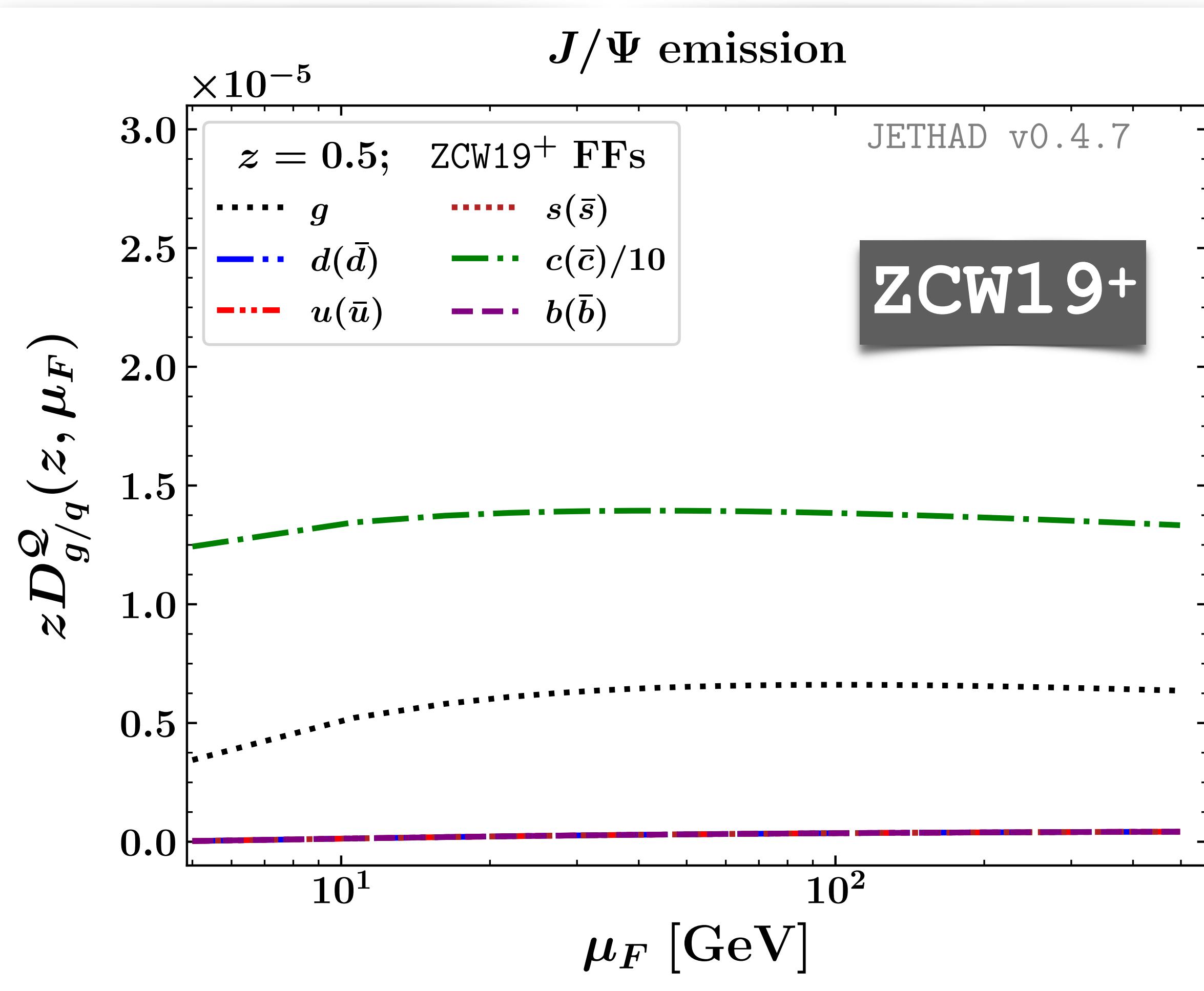
Vector quarkonium + jet at the LHC

J/ψ collinear FFs

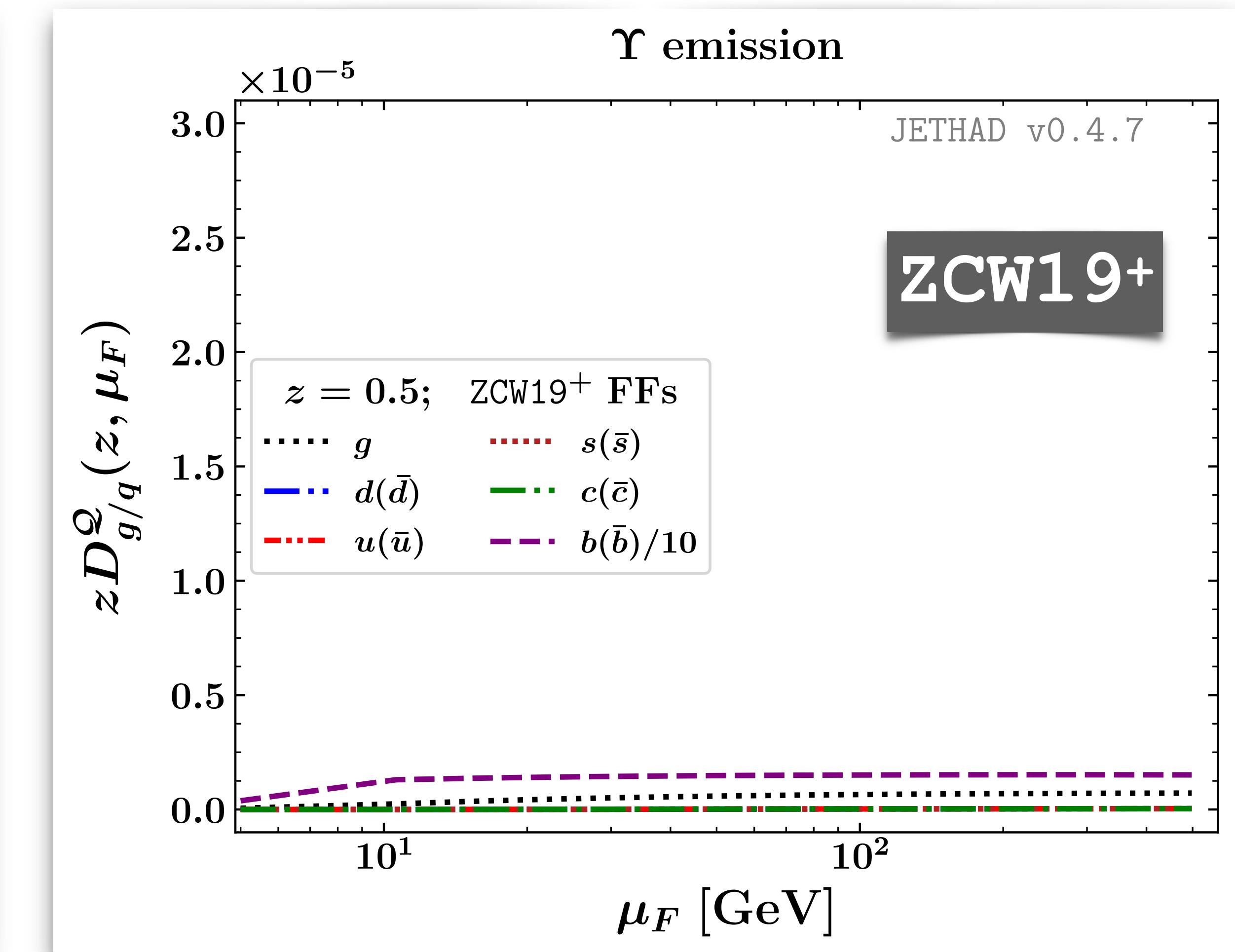


Vector quarkonium + jet at the LHC

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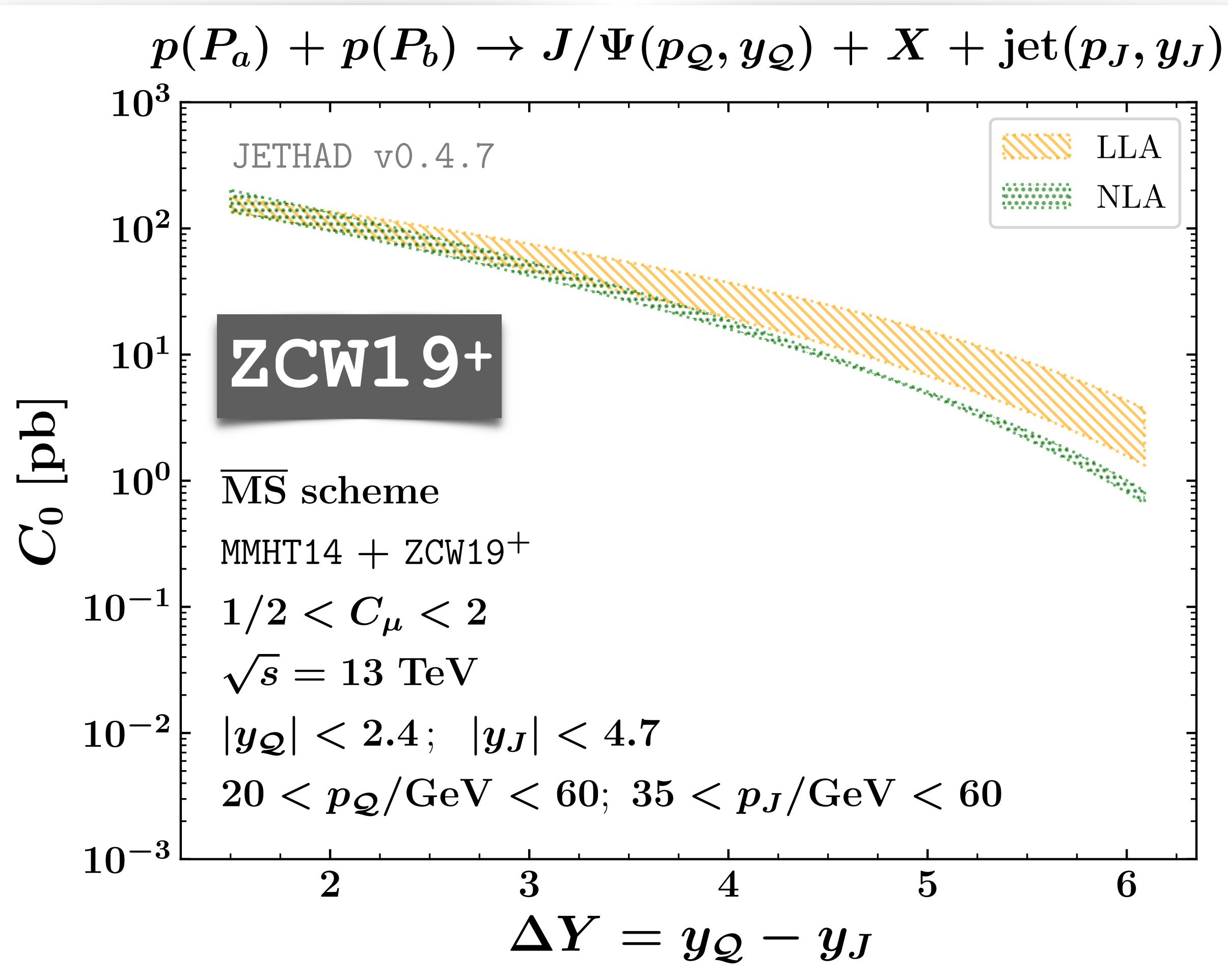


Υ collinear FFs

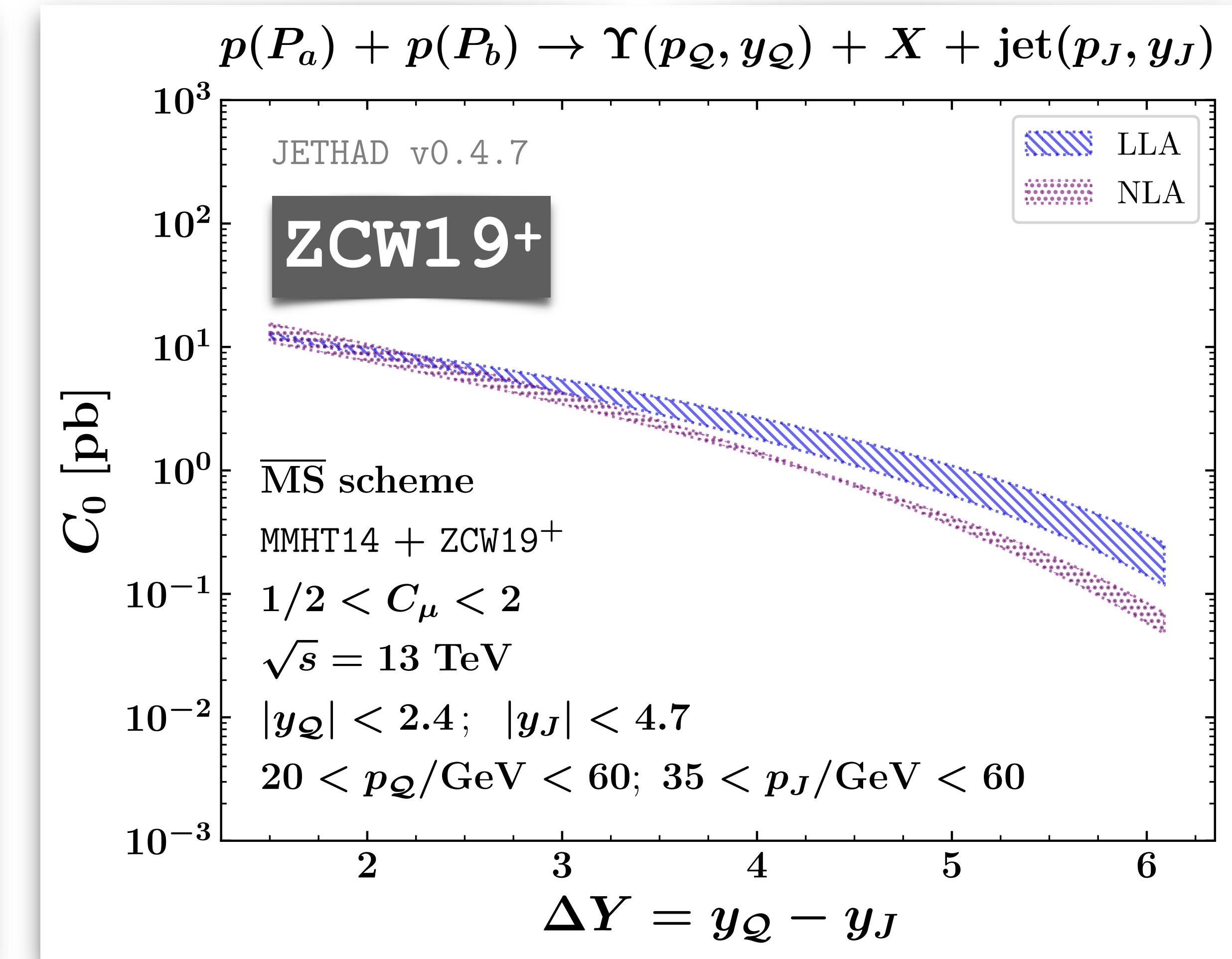


Vector quarkonium + jet at the LHC

$J/\psi + \text{jet}$

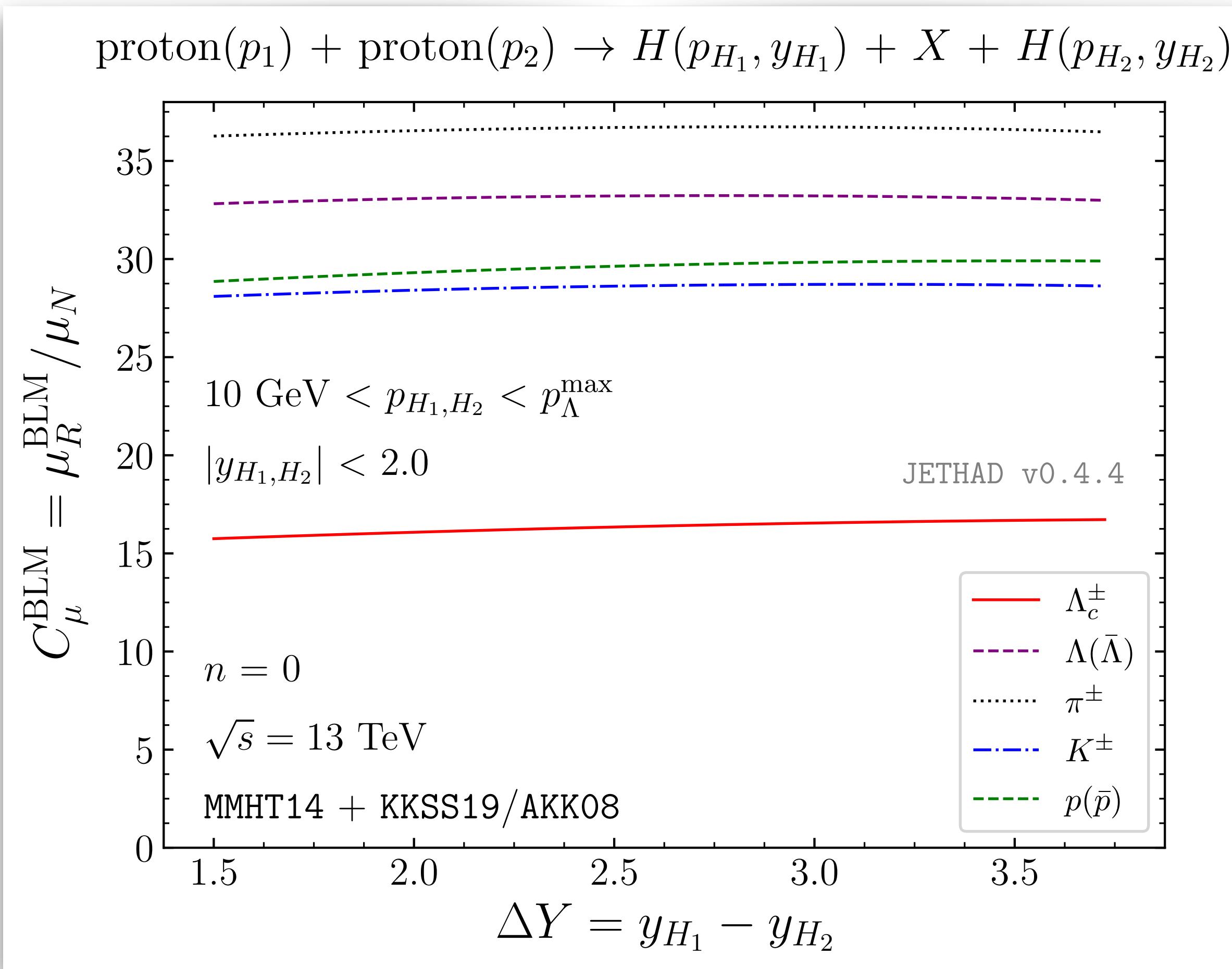


$\Upsilon + \text{jet}$

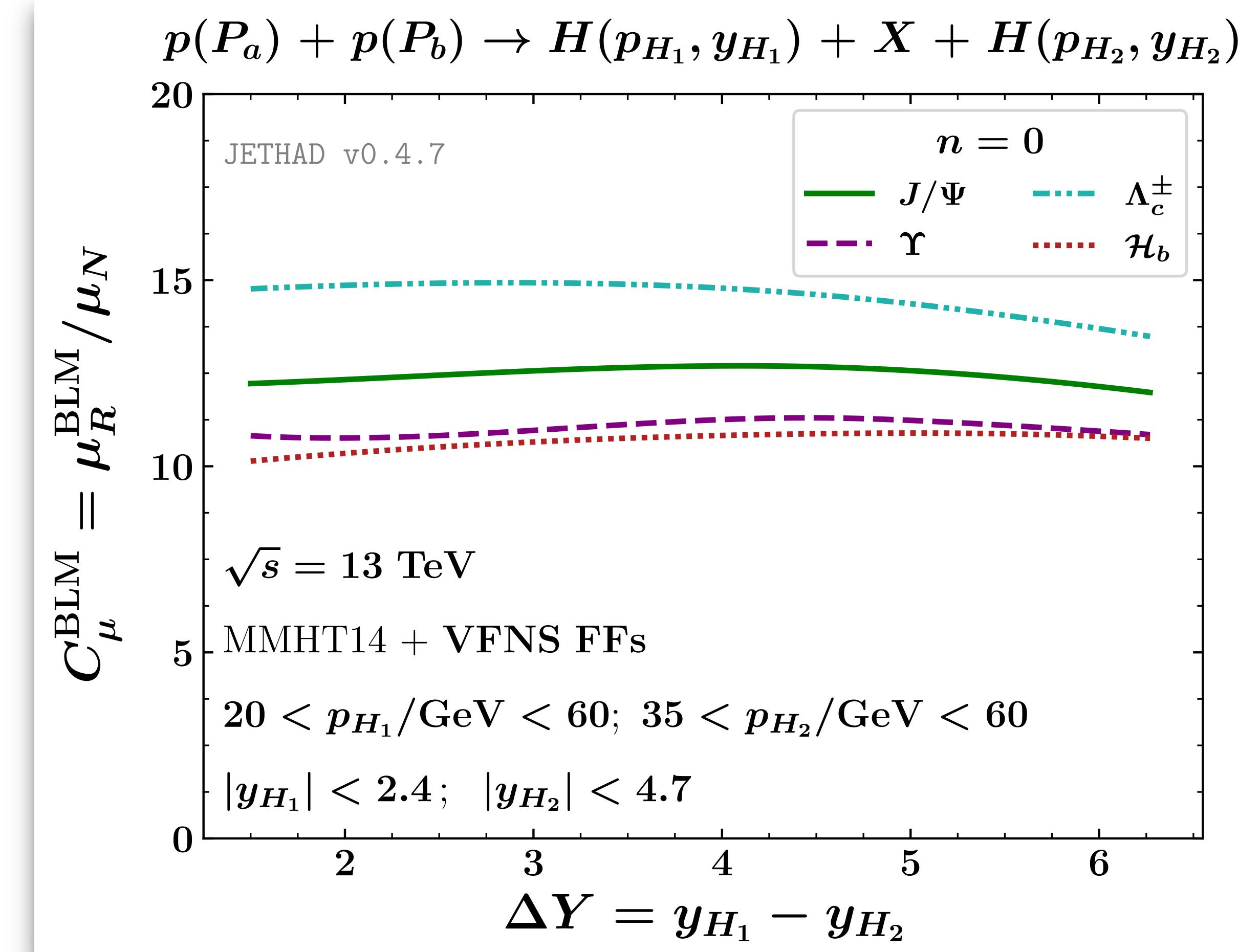


Heavy flavor at the LHC: BLM scales

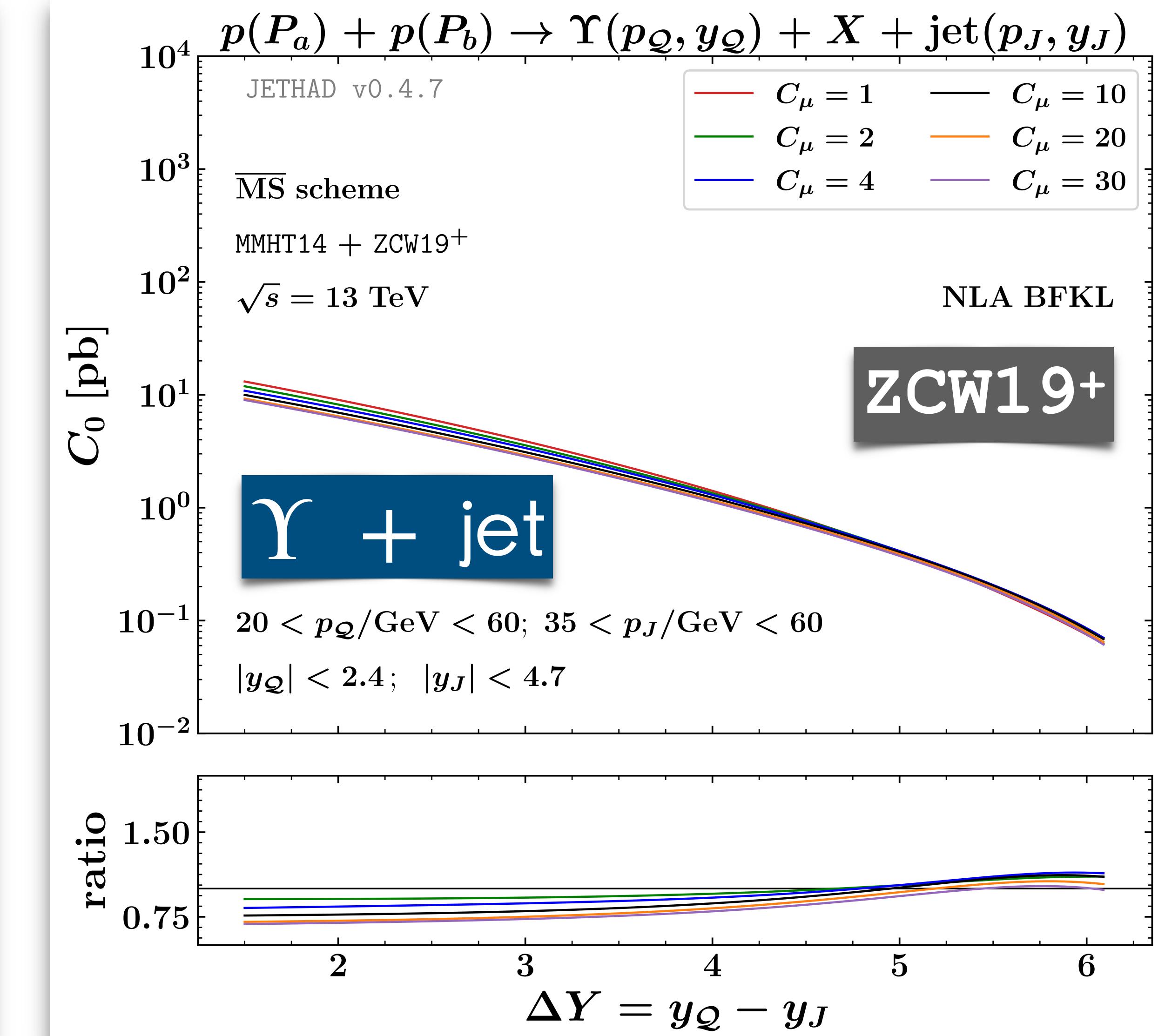
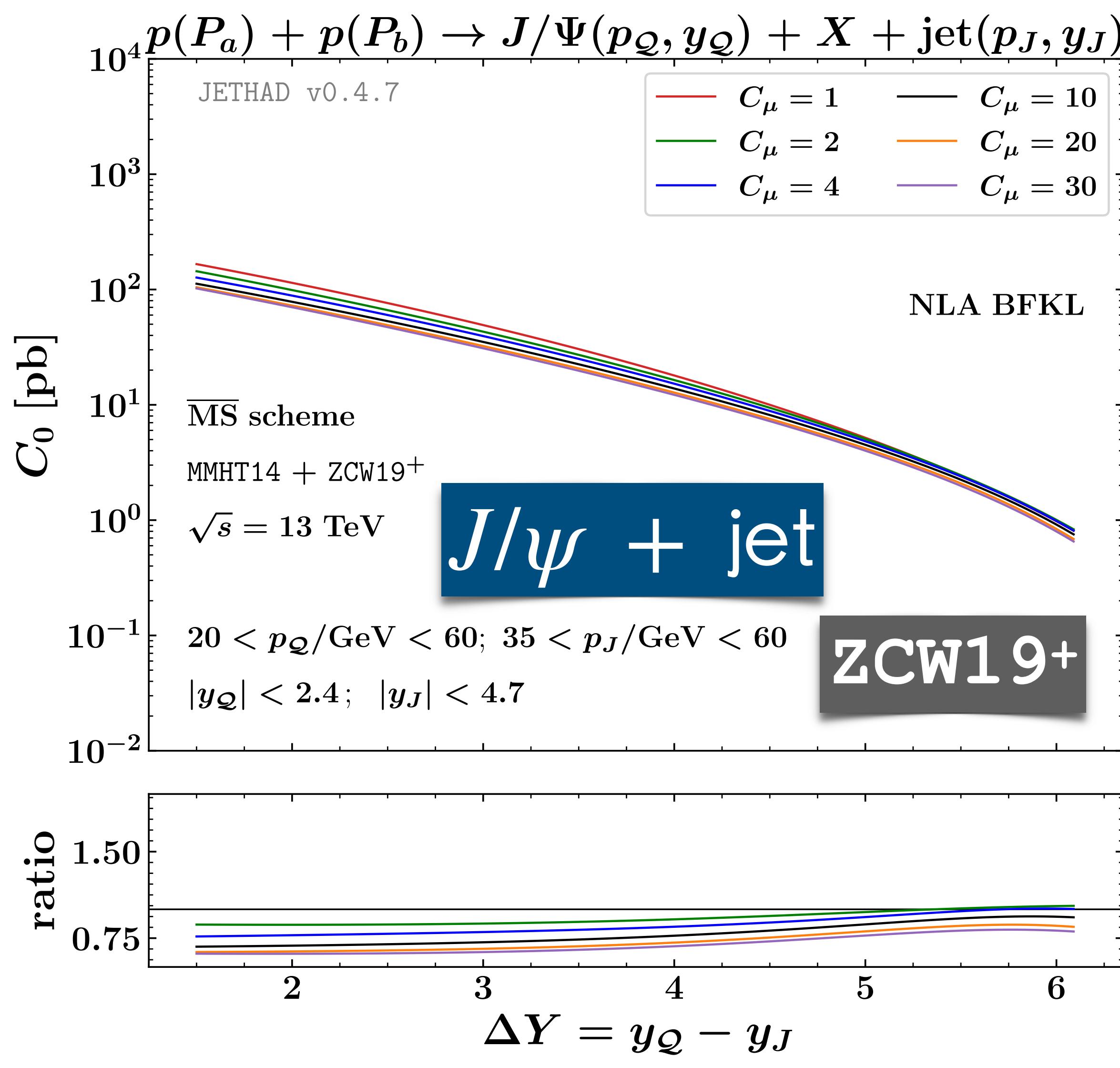
Heavy-light hadrons



Vector quarkonia



Vector quarkonium + jet at the LHC

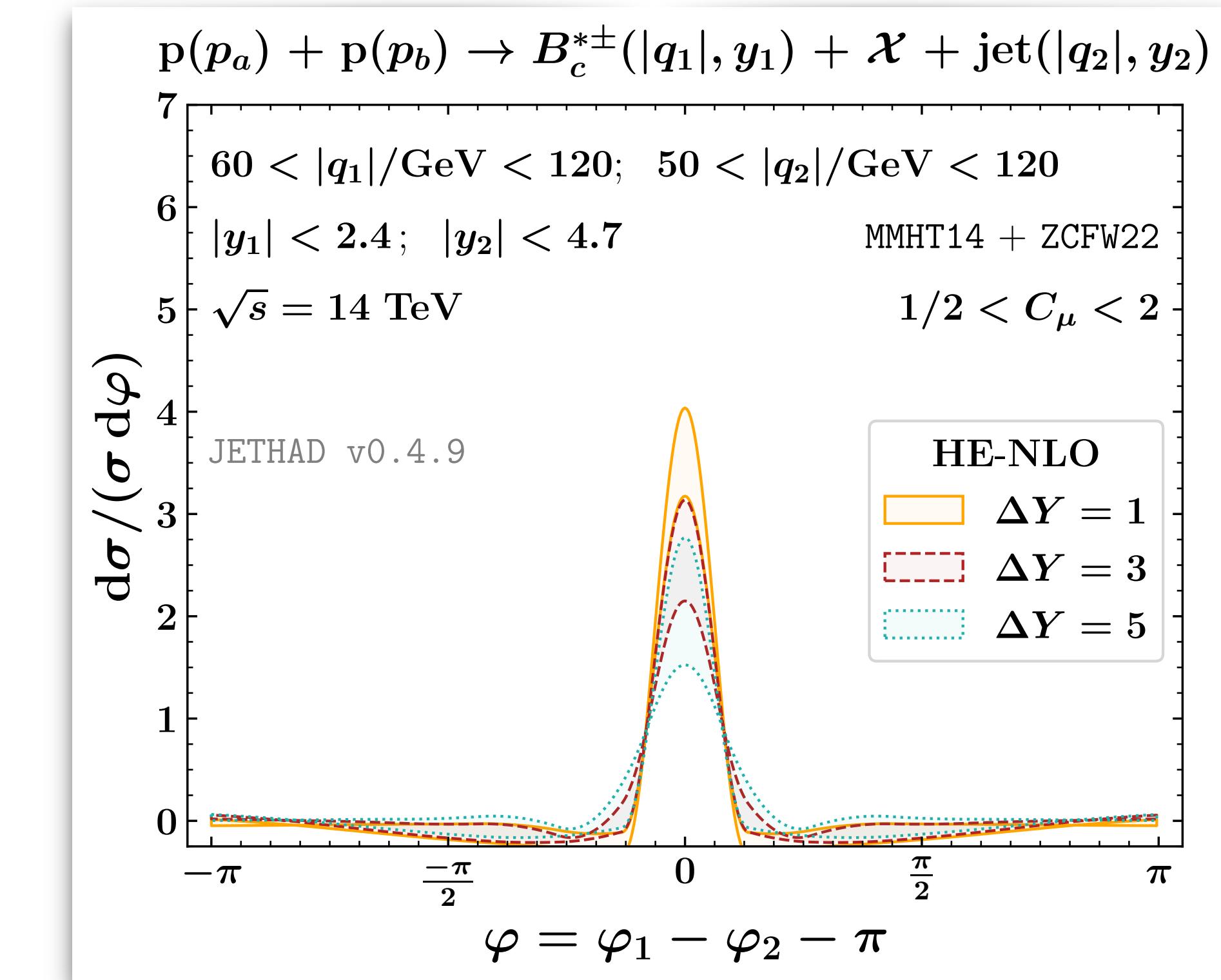
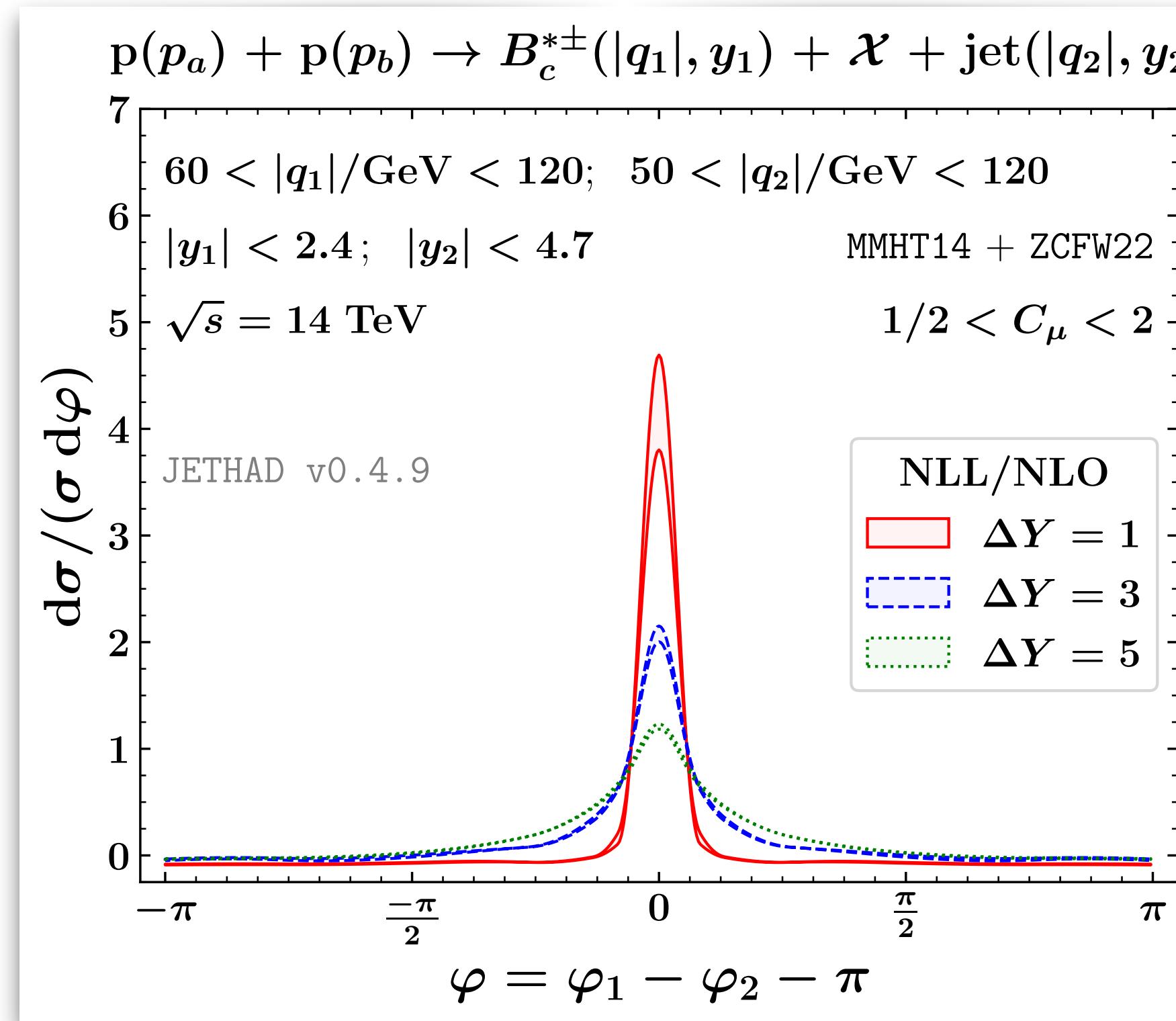


Charmed B -mesons from single-parton fragmentation

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

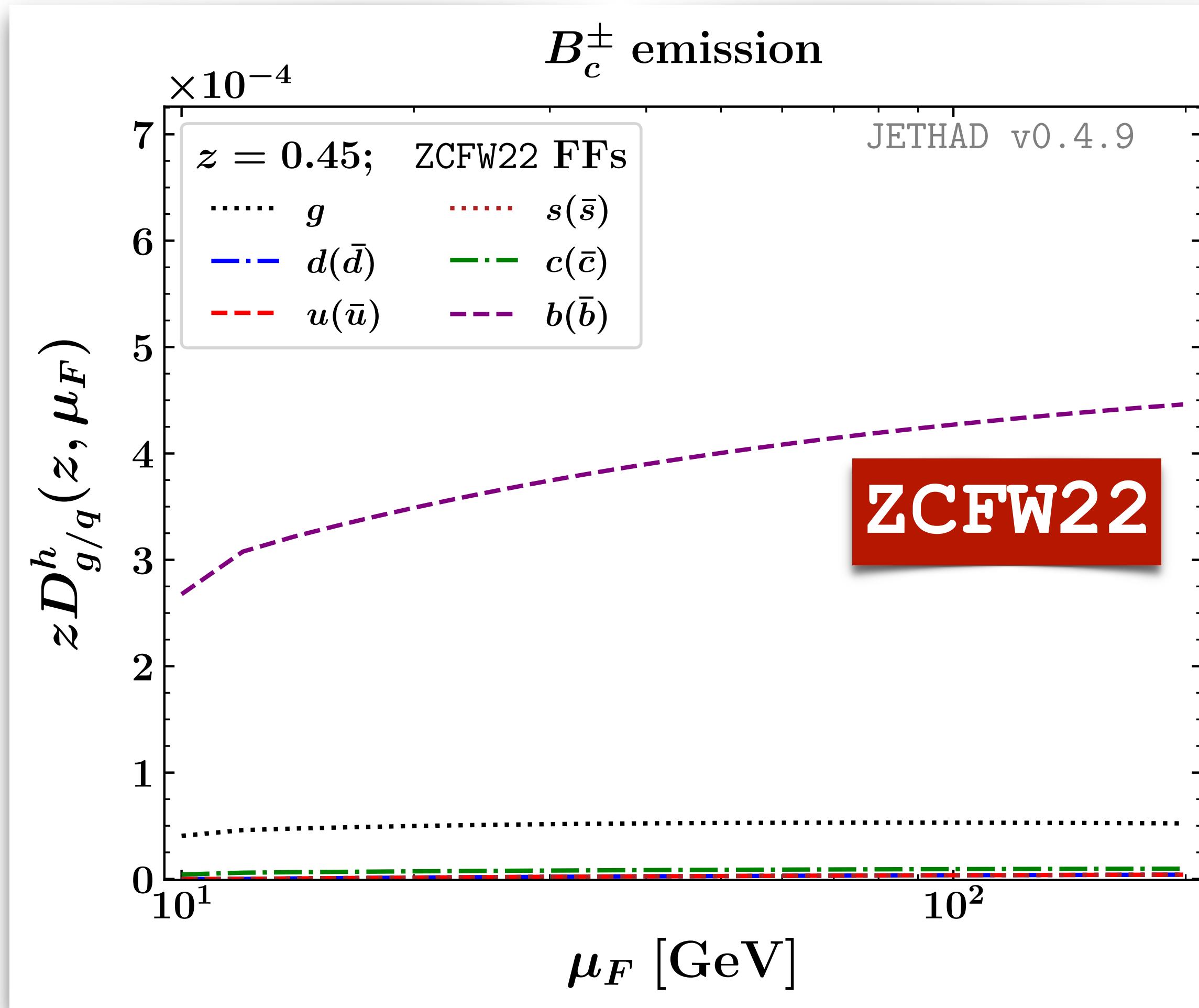
(NLO heavy quark)  [X. Zheng et al., Phys. Rev. D 100 (2019) 3, 034004]

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

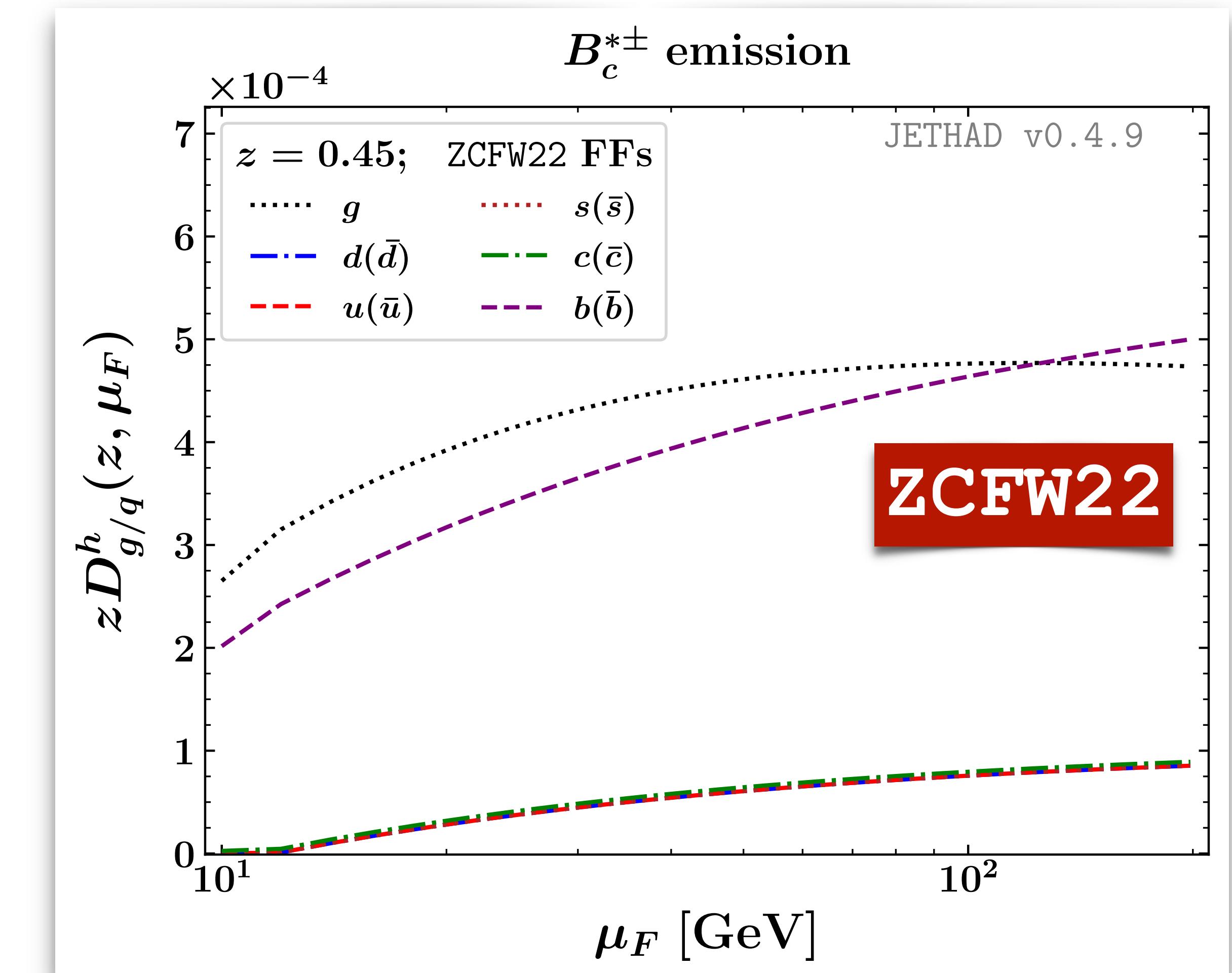


Charmed B -mesons + jet at the HL-LHC

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

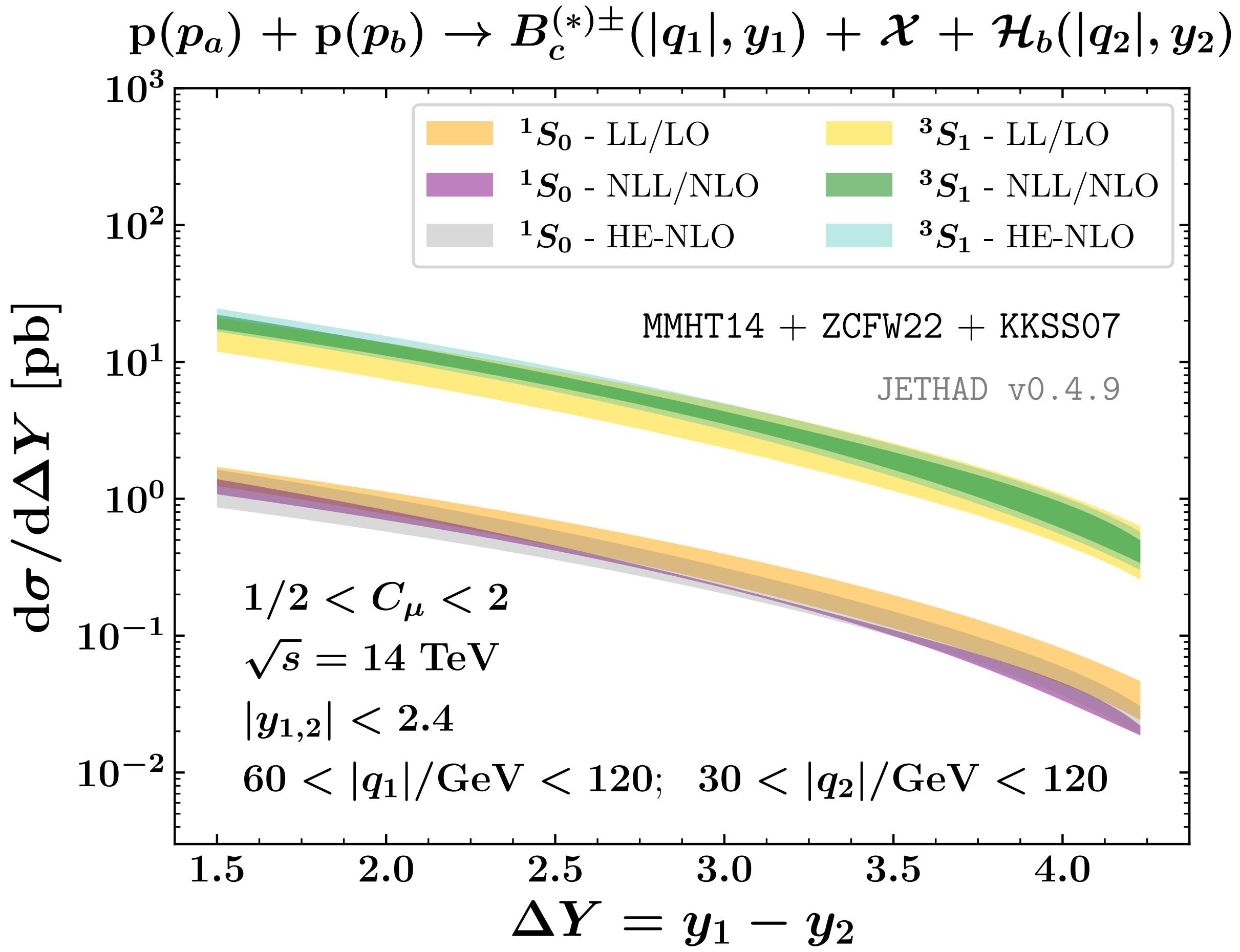


$B_c^\pm(^3S_1)$ collinear FFs

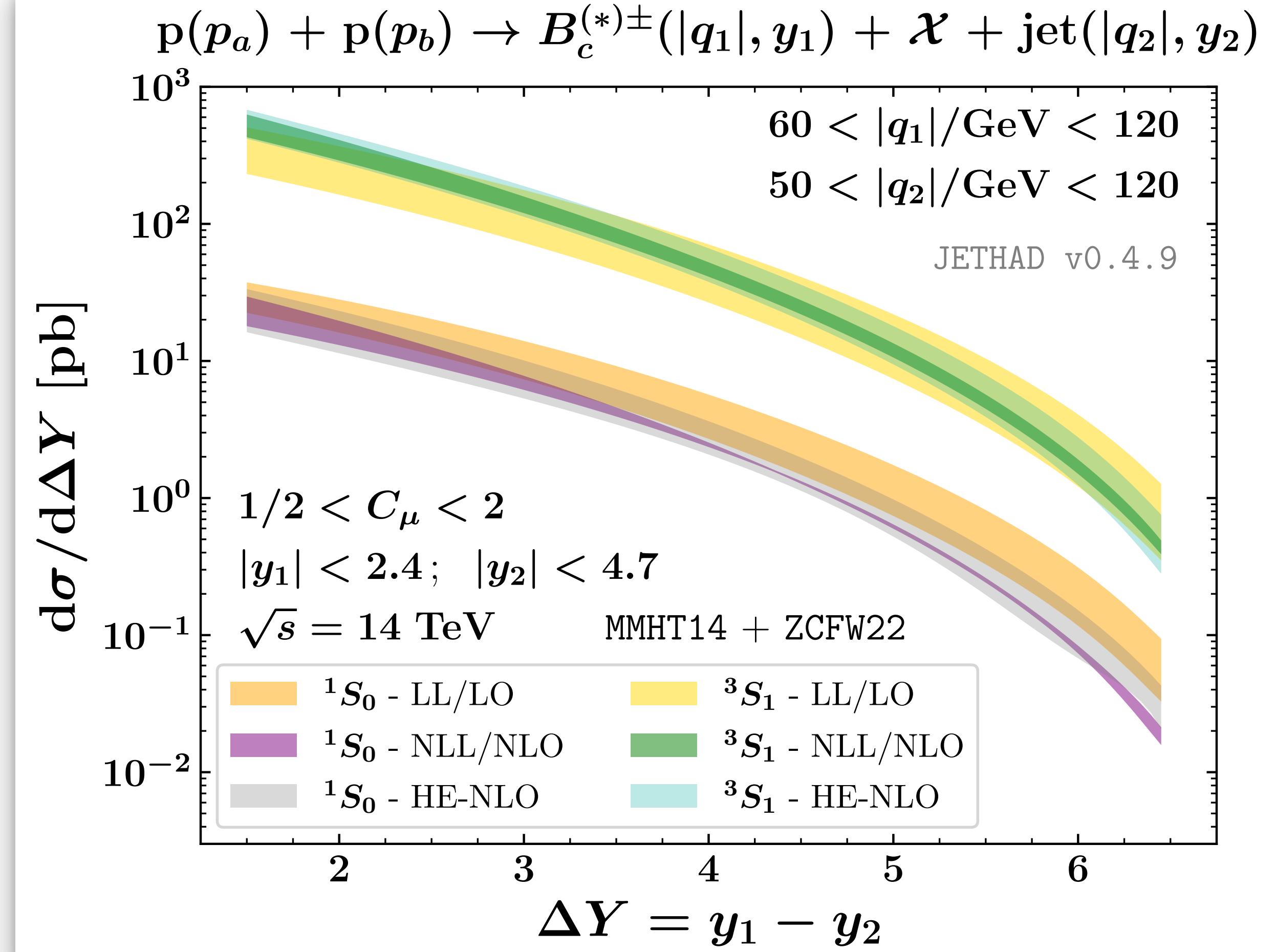


Charmed B -mesons + jet at the HL-LHC

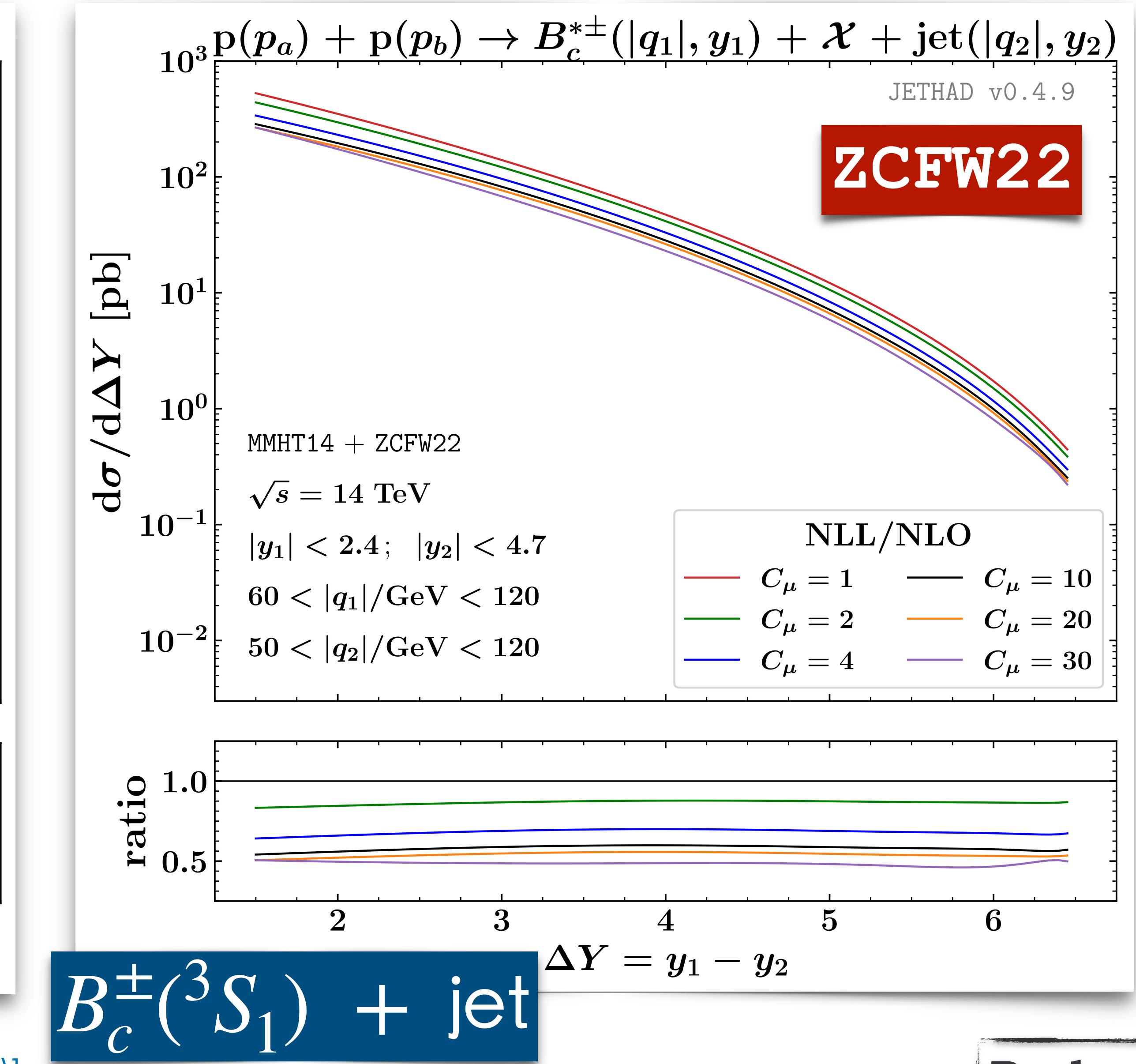
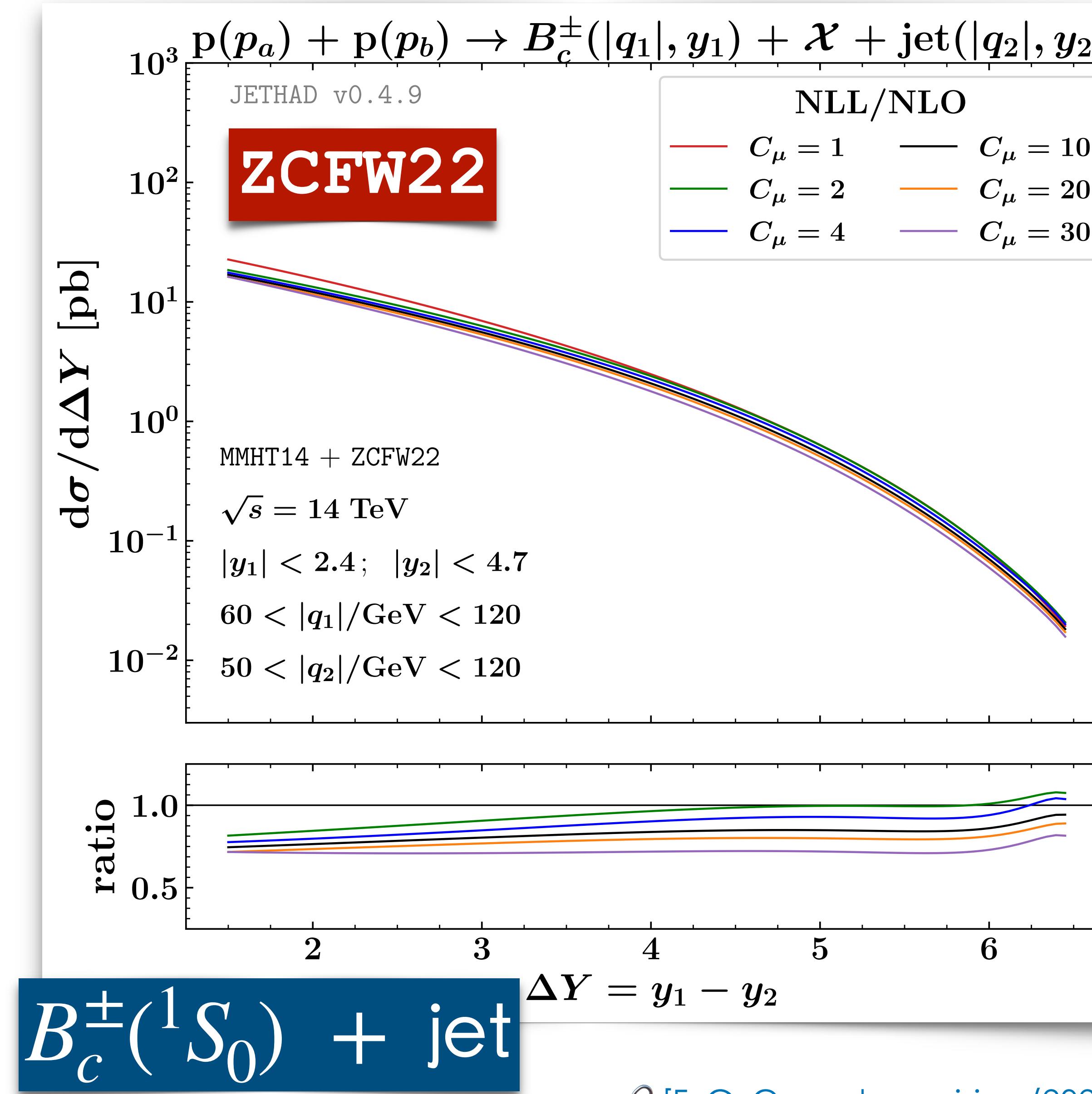
$B_c^\pm(^1S_0) + \text{b-hadron}$



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



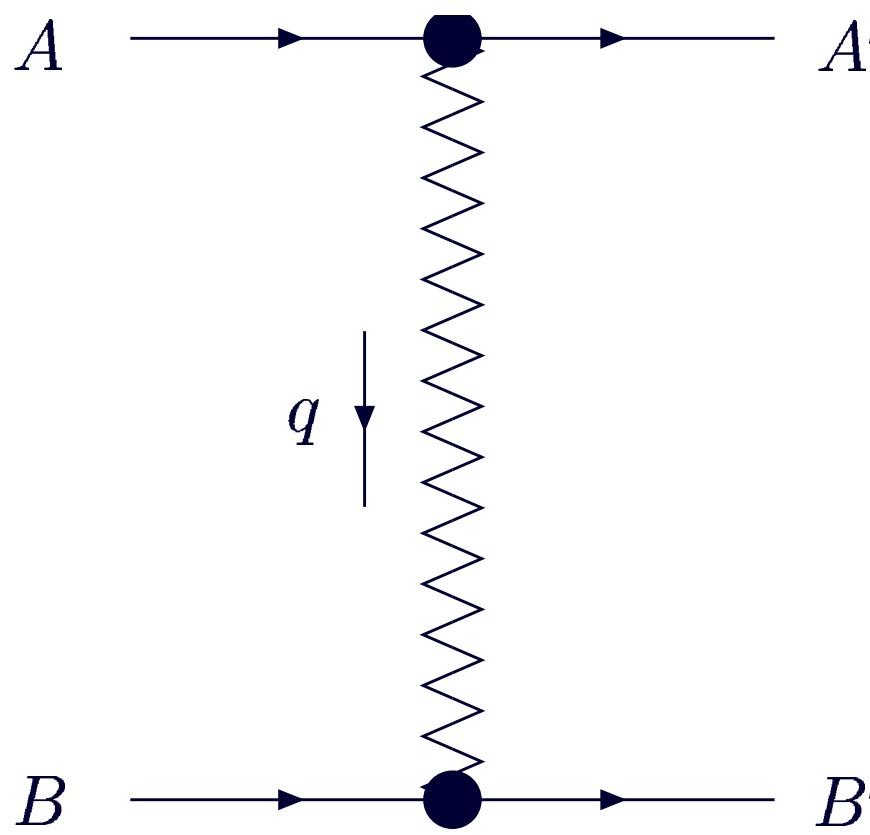
Charmed B -mesons + jet at the HL-LHC



Basics of BFKL

Gluon Reggeization in perturbative QCD

- ◊ Gluon quantum numbers in the t -channel: 8^- representation
- ◊ Regge limit: $s \simeq -u \rightarrow \infty$, t not growing with s
- amplitudes governed by **gluon Reggeization** → $D_{\mu\nu} = -i \frac{g_{\mu\nu}}{q^2} \left(\frac{s}{s_0} \right)^{\alpha_g(q^2)-1}$
 - $\xrightarrow{\text{feature}}$ 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: $A + B \longrightarrow A' + B'$



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

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

$\omega(t)$ → Reggeized gluon trajectory

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

T^c → fundamental (q) or adjoint (g)

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

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)]

based on
→ **gluon Reggeization**

leading logarithmic approximation (LL):

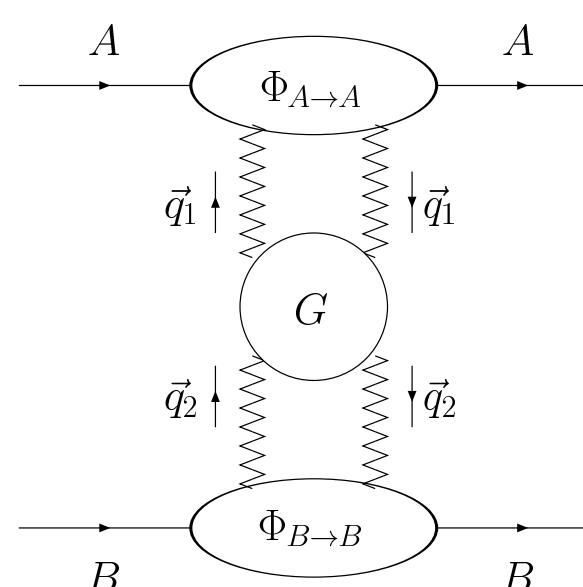
$$\alpha_s^n (\ln s)^n$$

$$\mathcal{A} = \text{diagram } \sim s + \left(\text{diagram } \sim s (\alpha_s \ln s) + \dots \right) + \left(\text{diagram } \sim s (\alpha_s \ln s)^2 + \dots \right) + \dots$$

next-to-leading logarithmic approximation (NLL):

$$\alpha_s^{n+1} (\ln s)^n$$

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



► $\Im m_s \{ \mathcal{A}_{AB}^{AB} \}$ 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**

The high-energy resummation

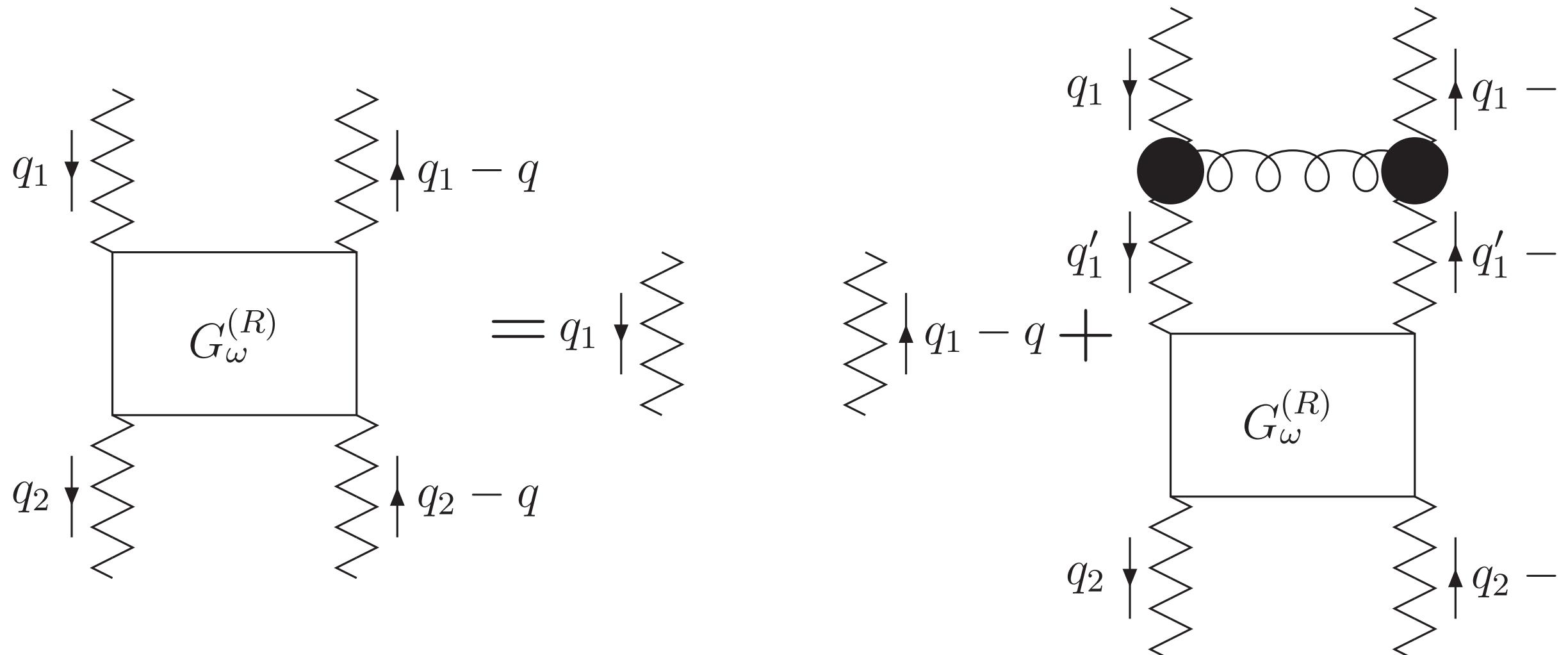
$$\mathcal{Im}_s \{\mathcal{A}\} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^2} \Phi_A(\vec{q}_1, \mathbf{s}_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^2} \Phi_B(-\vec{q}_2, \mathbf{s}_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{\mathbf{s}_0}\right)^\omega G_\omega(\vec{q}_1, \vec{q}_2)$$

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

→ determined through the **BFKL equation**

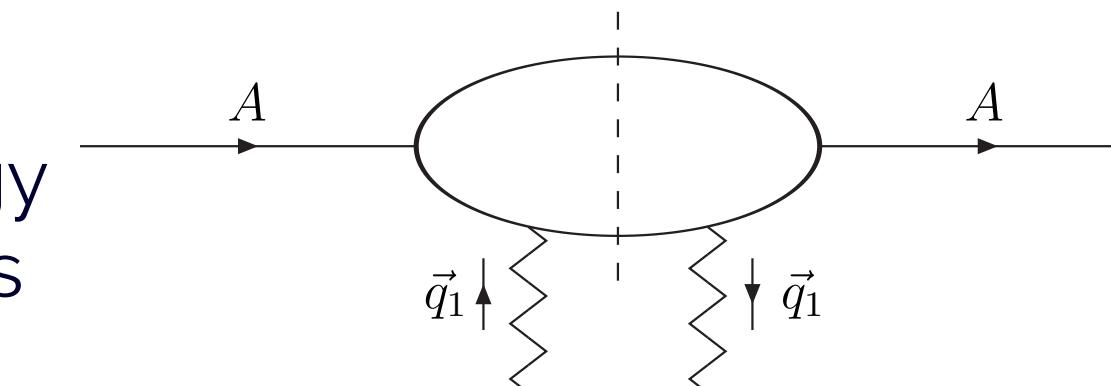
[Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

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



The high-energy resummation

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

- ◊ $\gamma^* \rightarrow V$, 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)]

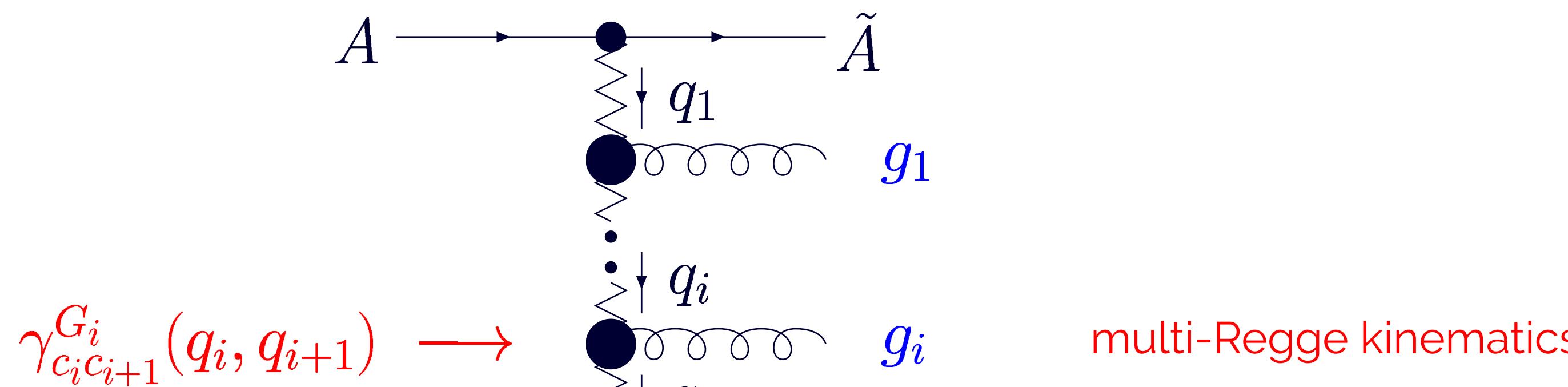
- ◊ $\gamma^* \rightarrow \gamma^*$

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

The high-energy resummation

BFKL in the LLA (I)

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



$$\gamma_{c_i c_{i+1}}^{G_i}(q_i, q_{i+1}) \rightarrow$$

multi-Regge kinematics

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

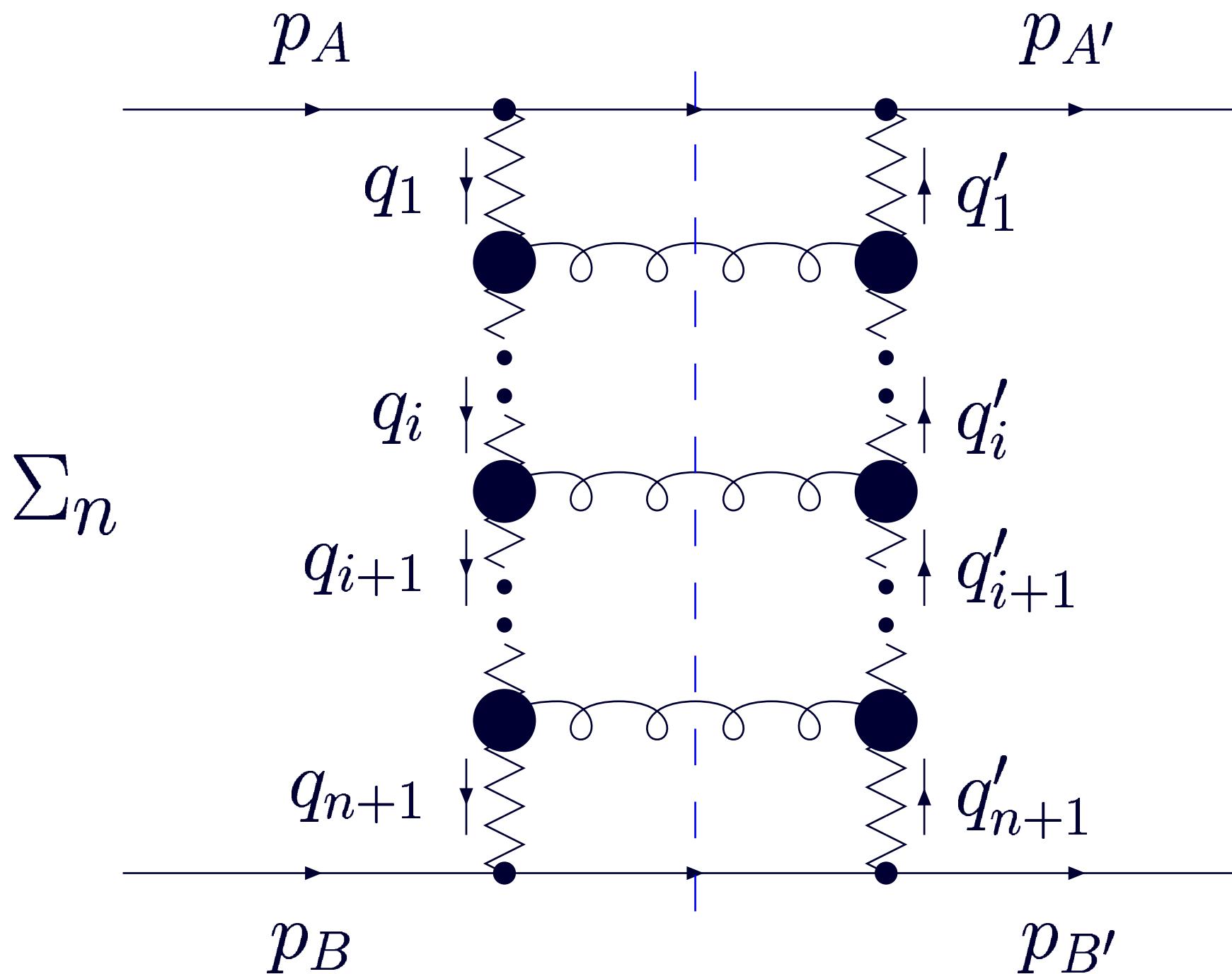
$$\gamma_{c_i c_{i+1}}^{P_i}(q_i, q_{i+1}) \rightarrow \text{RRG vertex}$$

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

The high-energy resummation

BFKL in the LLA (II)

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



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

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

The high-energy resummation

$$\text{Im}_s(\mathcal{A}) = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^2} \Phi_A(\vec{q}_1, \mathbf{s}_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^2} \Phi_B(-\vec{q}_2, \mathbf{s}_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{\mathbf{s}_0}\right)^\omega G_\omega(\vec{q}_1, \vec{q}_2)$$

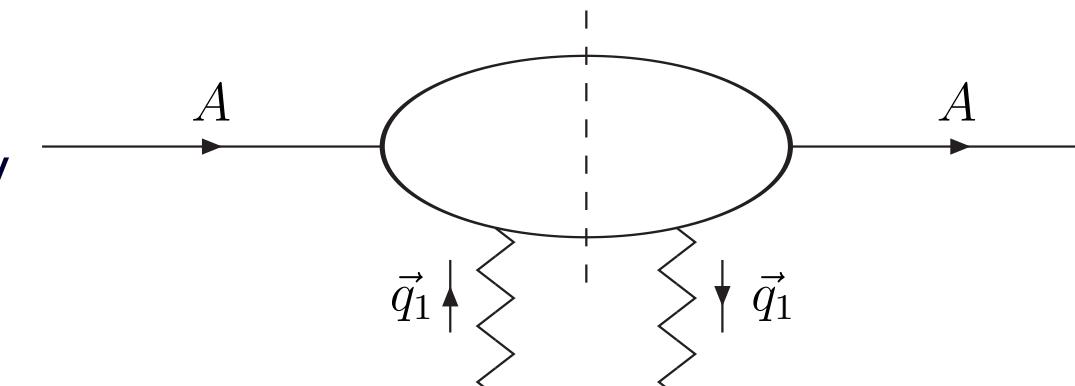
- **Green's function** is **process-independent** and takes care of the **energy dependence**

→ 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

→ 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)]

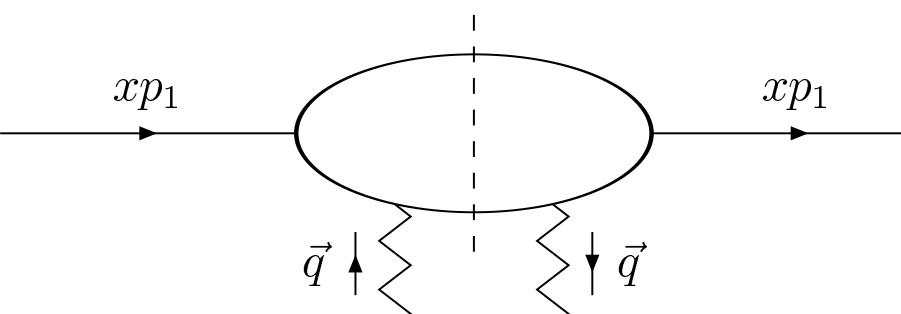
Hybrid factorization at work

Forward-jet impact factor

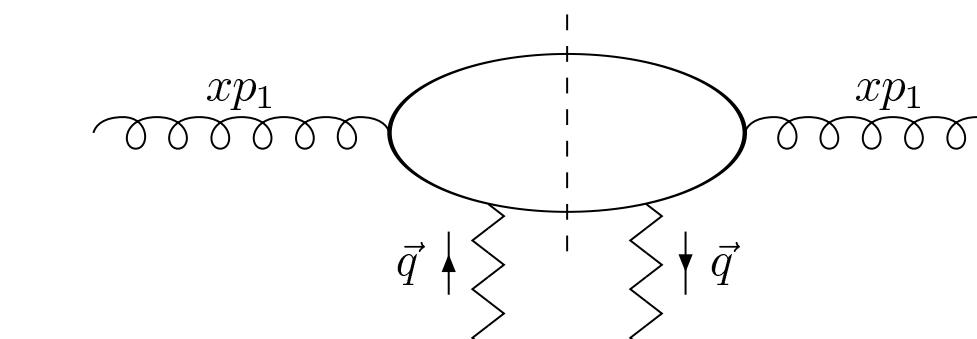
- take the impact factors for **colliding partons**

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

[M. Ciafaloni and G. Rodrigo (2000)]

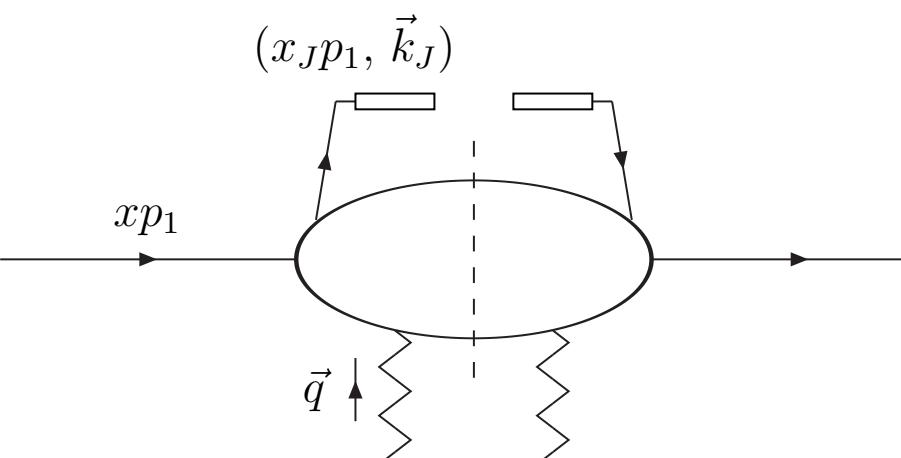


quark vertex

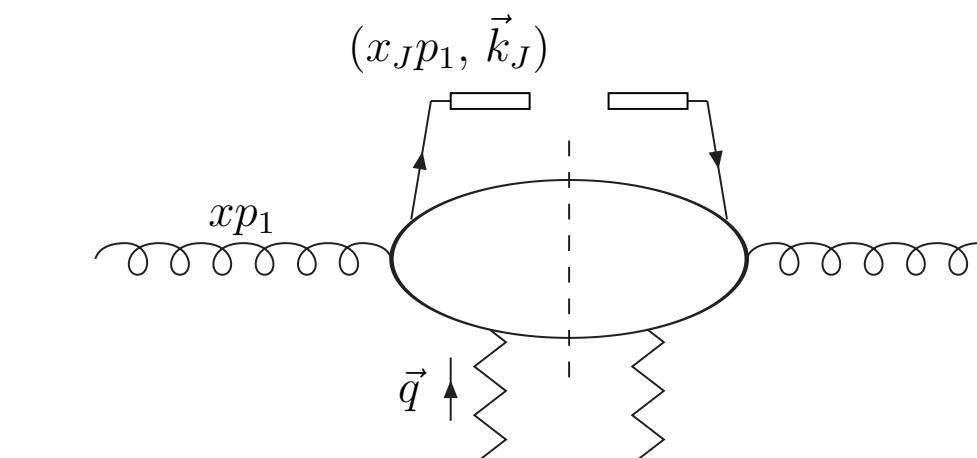


gluon vertex

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



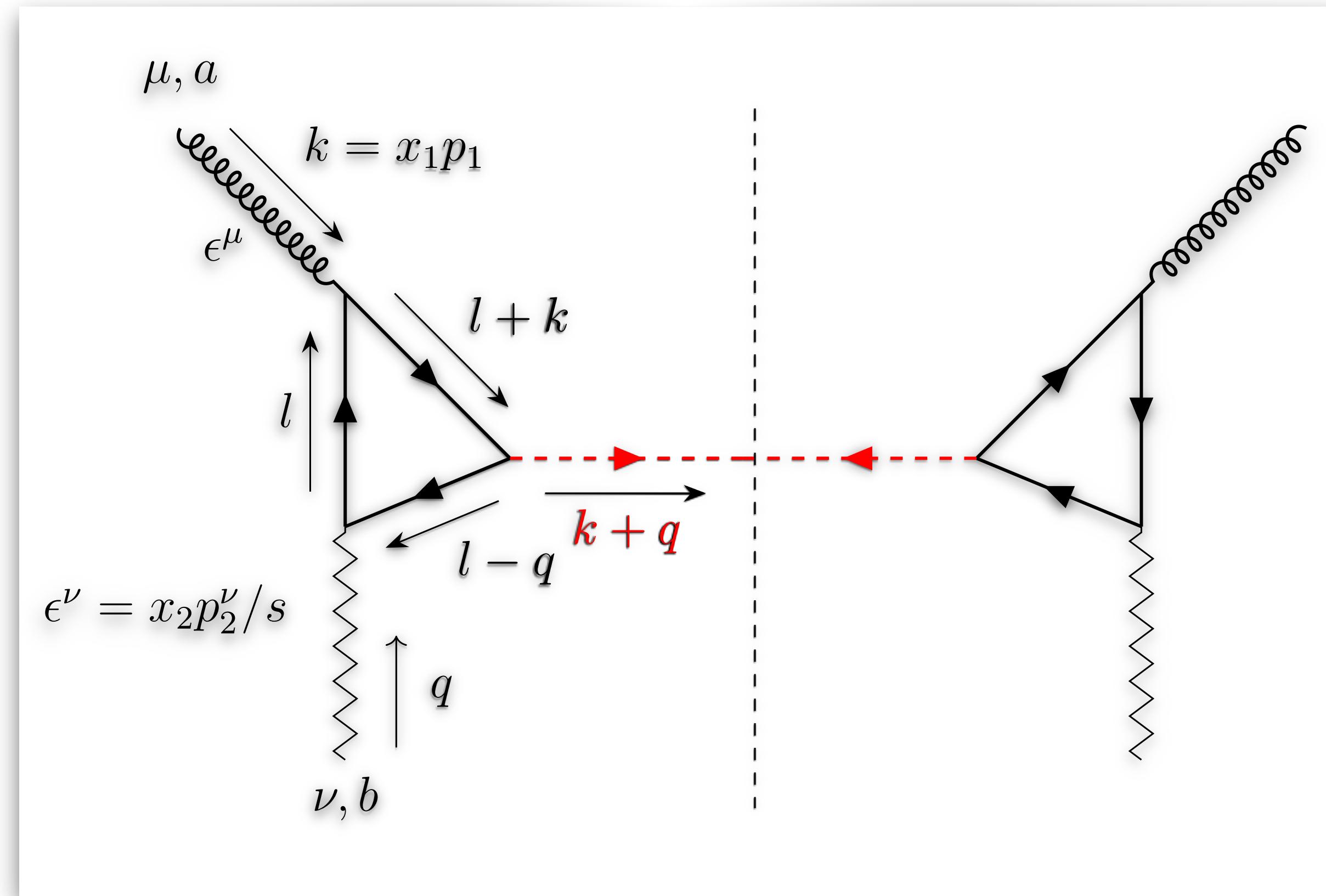
quark jet vertex



gluon jet vertex

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

Forward-Higgs LO impact factor



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

Forward-Higgs NLO-RG impact factor

$$\begin{aligned}\tilde{c}_H^{(1)}(n, \nu, |\vec{p}_H|, x_H) &= c_H(n, \nu, |\vec{p}_H|, x_H) \left\{ \frac{\beta_0}{4N_c} \left(2 \ln \frac{\mu_{F_1}}{|\vec{p}_H|} + \frac{5}{3} \right) + \frac{\chi(n, \nu)}{2} \ln \left(\frac{s_0}{M_{H,\perp}^2} \right) \right. \\ &\quad \left. + \frac{\beta_0}{4N_c} \left(2 \ln \frac{\mu_{F_1}}{M_{H,\perp}} \right) \right. \\ &\quad \left. - \frac{1}{2N_c f_g(x_H, \mu_{F_1})} \ln \frac{\mu_{F_1}^2}{M_{H,\perp}^2} \int_{x_H}^1 \frac{dz}{z} \left[P_{gg}(z) f_g \left(\frac{x_H}{z}, \mu_{F_1} \right) + \sum_{a=q, \bar{q}} P_{ga}(z) f_a \left(\frac{x_H}{z}, \mu_{F_1} \right) \right] \right\}\end{aligned}$$

Forward-jet NLO-RG impact factor

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

Inclusive Higgs+jet: NLL/NLO* azimuthal coefficients

$$\begin{aligned}
\mathcal{C}_n &= \frac{e^{\Delta Y}}{s} \frac{M_{H,\perp}}{|\vec{p}_H|} \\
&\times \int_{-\infty}^{+\infty} d\nu \left(\frac{x_J x_H s}{s_0} \right)^{\bar{\alpha}_s(\mu_{R_c})} \left\{ \chi(n, \nu) + \bar{\alpha}_s(\mu_{R_c}) \left[\bar{\chi}(n, \nu) + \frac{\beta_0}{8N_c} \chi(n, \nu) \left[-\chi(n, \nu) + \frac{10}{3} + 4 \ln \left(\frac{\mu_{R_c}}{\sqrt{\vec{p}_H \cdot \vec{p}_J}} \right) \right] \right] \right\} \\
&\quad \times \left\{ \alpha_s^2(\mu_{R_1}) c_H(n, \nu, |\vec{p}_H|, x_H) \right\} \left\{ \alpha_s(\mu_{R_2}) [c_J(n, \nu, |\vec{p}_J|, x_J)]^* \right\} \\
&\quad \times \left\{ 1 + \bar{\alpha}_s(\mu_{R_1}) \frac{\tilde{c}_H^{(1)}(n, \nu, |\vec{p}_H|, x_H)}{c_H(n, \nu, |\vec{p}_H|, x_H)} + \bar{\alpha}_s(\mu_{R_2}) \left[\frac{\tilde{c}_J^{(1)}(n, \nu, |\vec{p}_J|, x_J)}{c_J(n, \nu, |\vec{p}_J|, x_J)} \right]^* \right\}.
\end{aligned}$$