4th Forward Physics Facility Meeting
February 1st, 2022

Towards precision studies of high-energy QCD via a FPF+ATLAS tight timing coincidence

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ECT*/FBK Trento & INFN-TIFPA

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

FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

TIFPA Trento Institute for Fundamental Physics and Applications

HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

High-energy resummation at the FPF

Collinear factorization → well-established formalism, successes in QCD pheno

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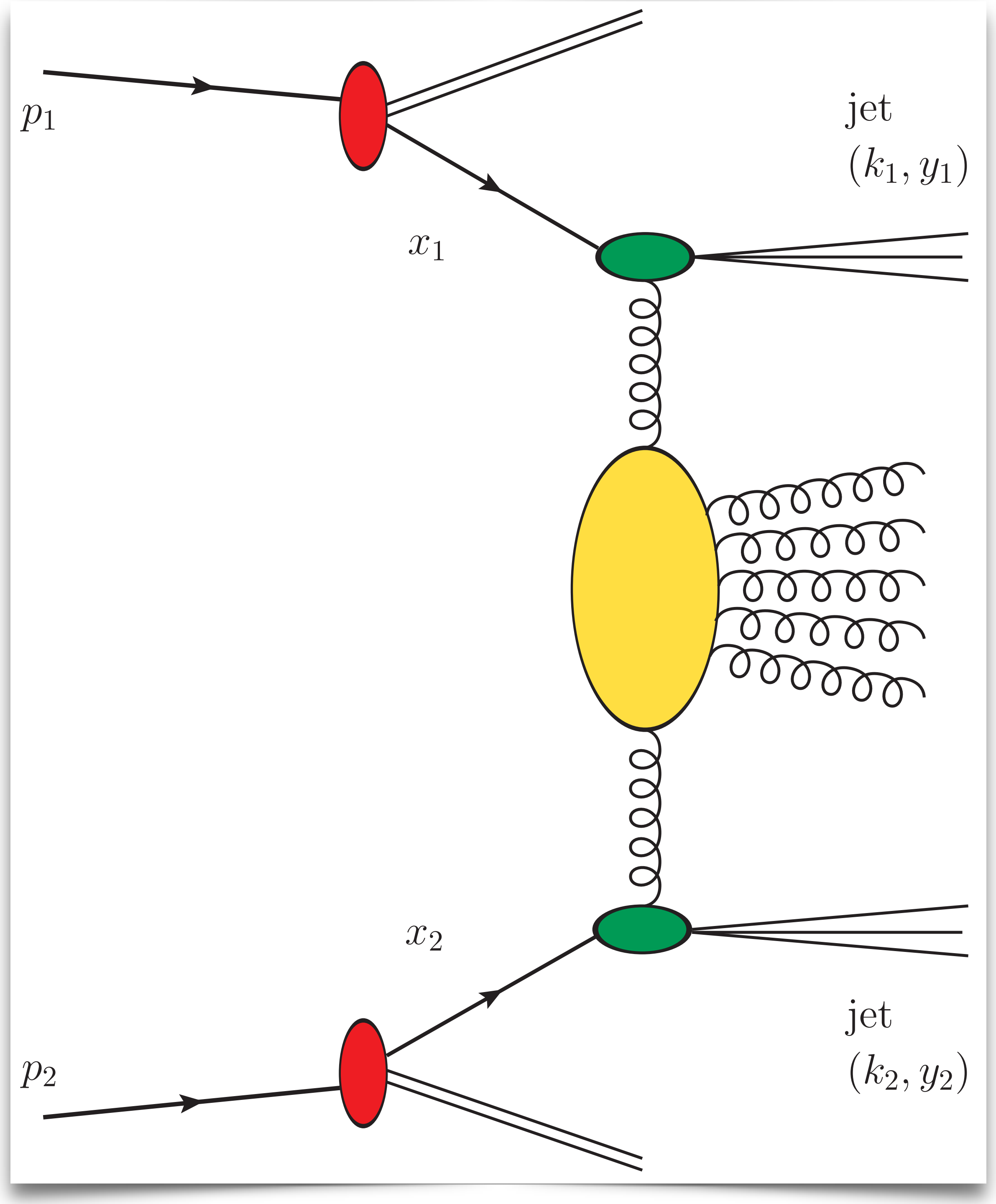
- Parton content of proton at small-x → BFKL UGD, resummed PDFs, small-x TMDs

Mueller-Navelet jets: hybrid factorization

- Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY
- Moderate x (*collinear PDFs*), but t-channel p_T (*HE factorization*) $\rightarrow$ **hybrid** approach

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



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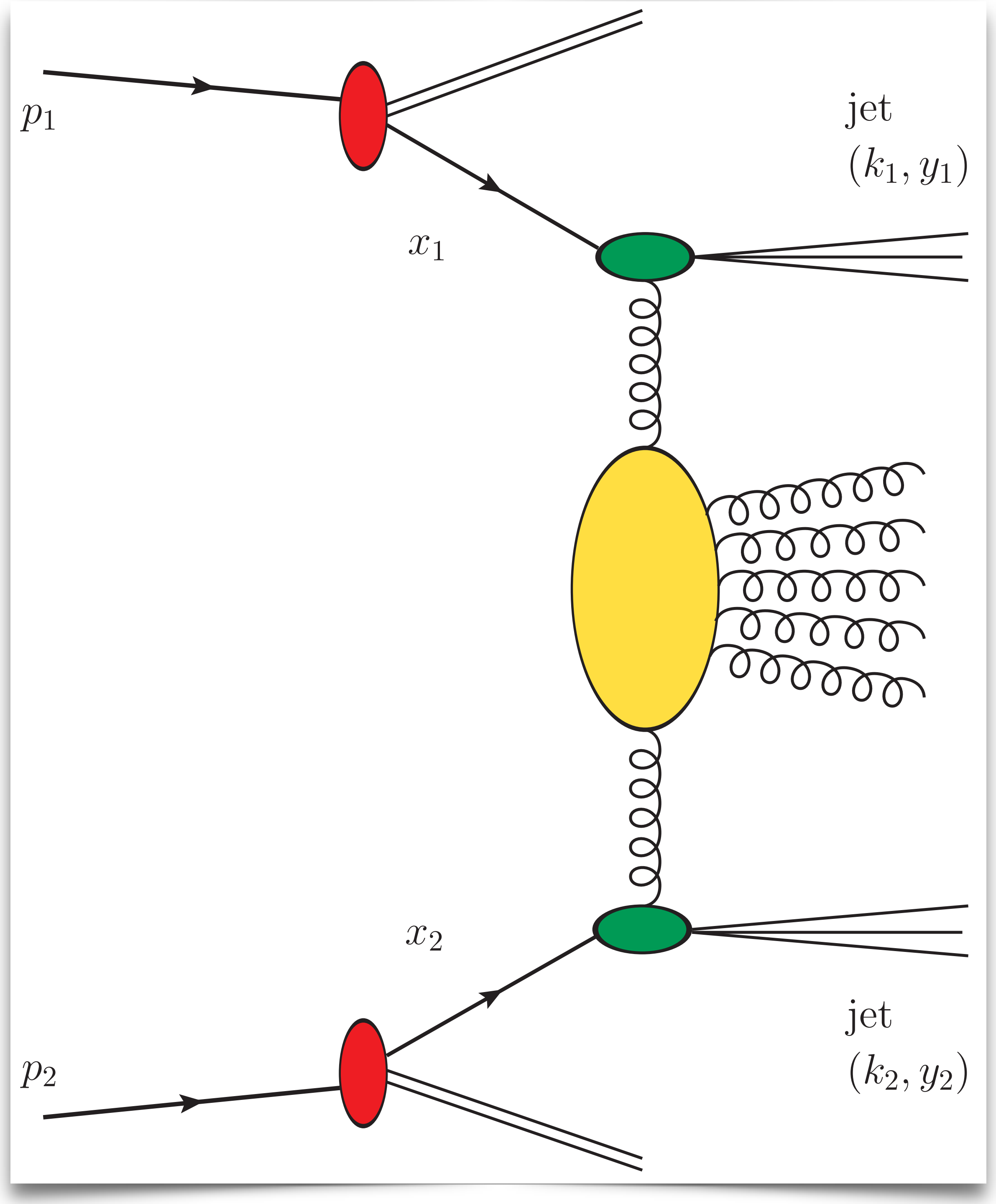

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \frac{1}{(2\pi)^2}$$
$$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_J^{(r)}(\vec{q}_1, s_0, x_1, \vec{k}_1)$$
$$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1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

jet vertices (off-shell amplitudes)

BFKL gluon Green's function

Mueller-Navelet jets & resummation instabilities

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- ¡ At *natural* scales: NLL/LL large, no agreement with data, unphysical values !

NLA BFKL corrections to cross section with opposite sign with respect to the leading order (LO) result and large in absolute value...

- ◇ ...call for some optimization procedure...
- ◇ ...choose scales to mimic the most relevant subleading terms

- **BLM** [S.J. Brodsky, G.P. Lepage, P.B. Mackenzie (1983)]
  - ✓ preserve the conformal invariance of an observable...
  - ✓ ...by making vanish its β_0-dependent part

* "Exact" BLM:
  suppress NLO IFs + NLO Kernel β_0-dependent factors

- **BLM** scales, theory vs experiment: CMS @7TeV with **symmetric** p_T-ranges, **only!**

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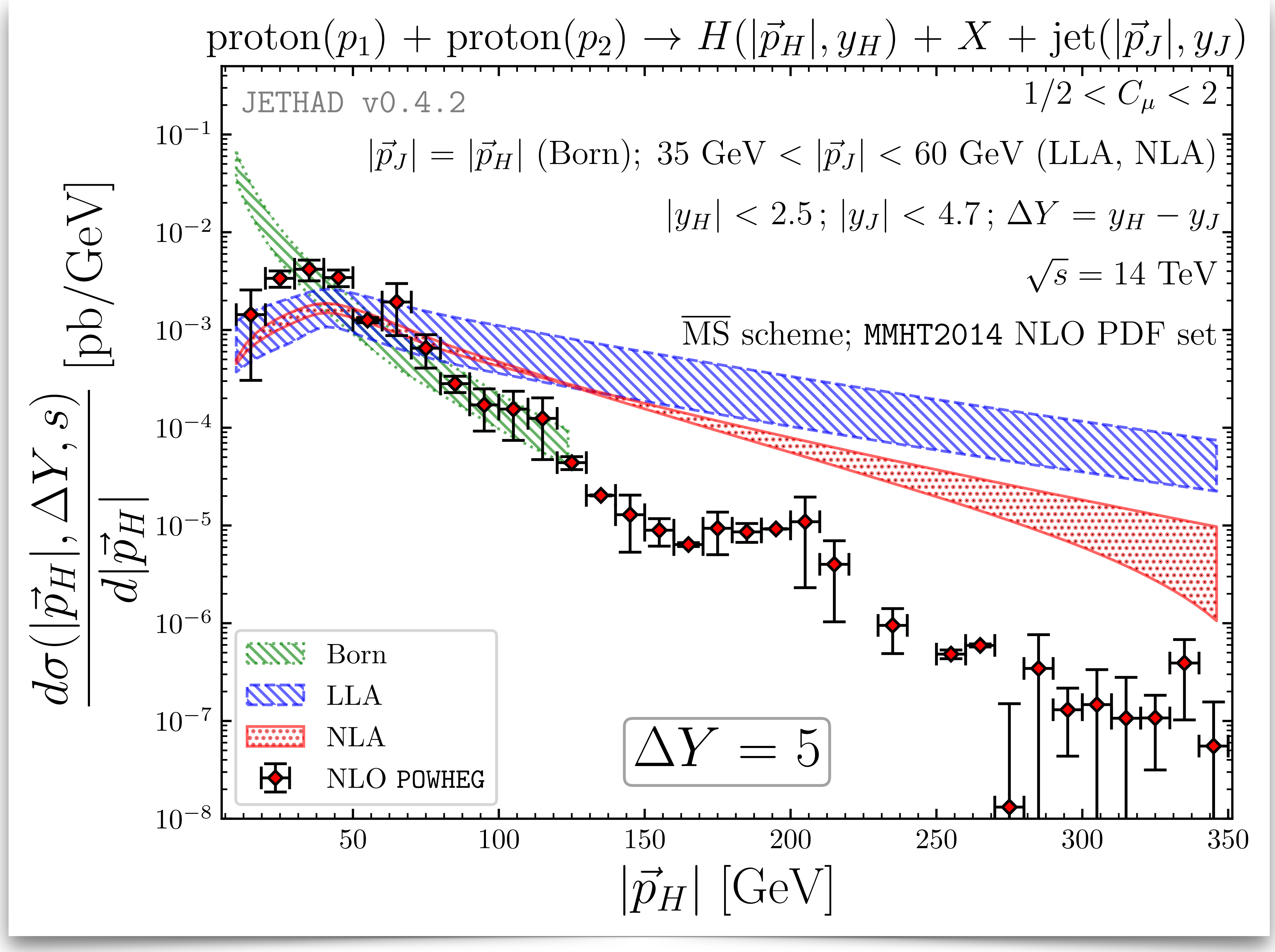
- *Unsuccessful* scale optimization → processes featuring *natural stability* (¿?)

Natural stability of the HE resummation

Higgs + jet ⇔ large transverse masses, partial NLL

🔗 [F. G. C. *et al.* (2021)]



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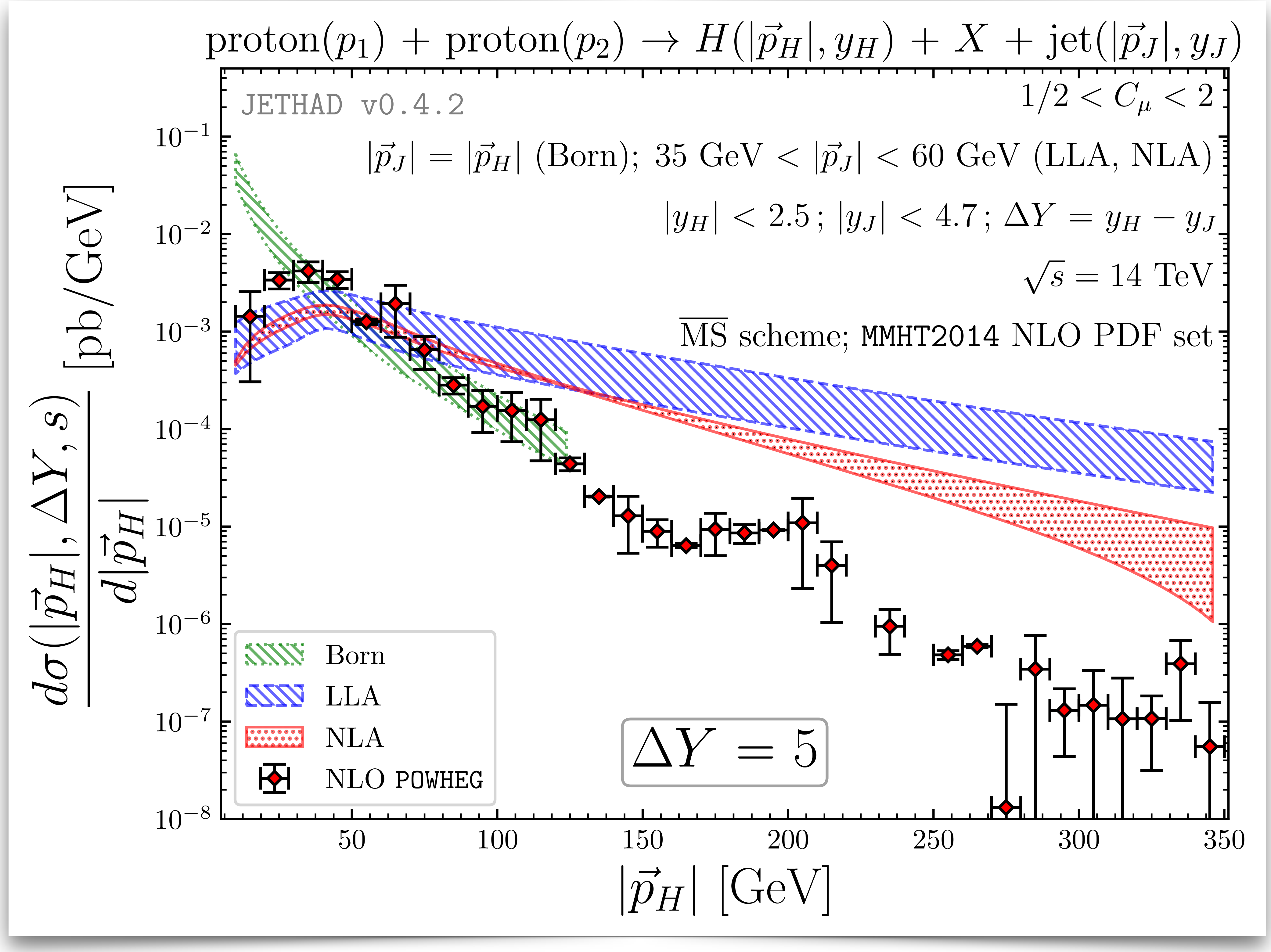

Heavy flavor ⇔ $D^*/\Lambda_c/H_b$ VFNS FFs, full NLL

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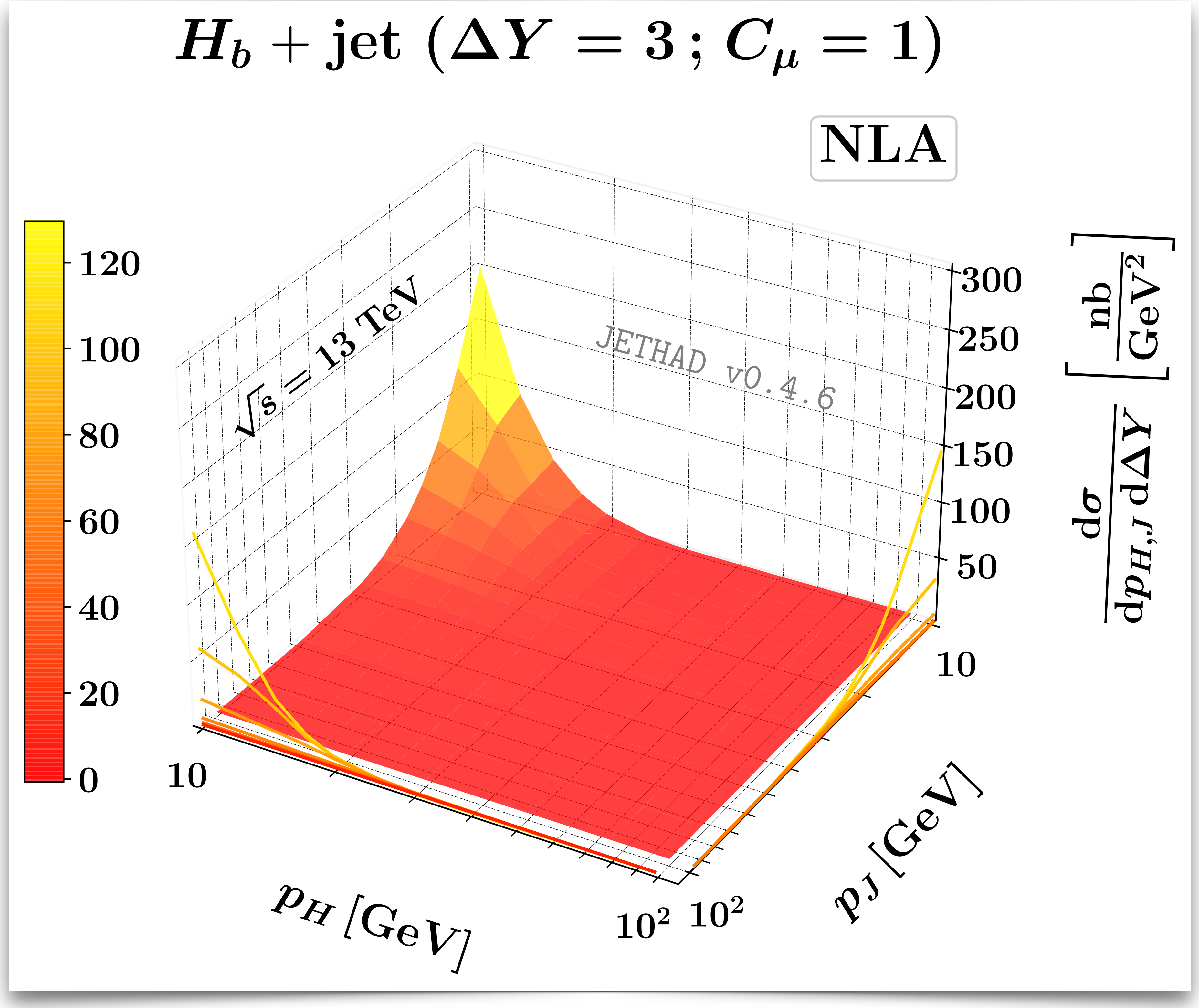

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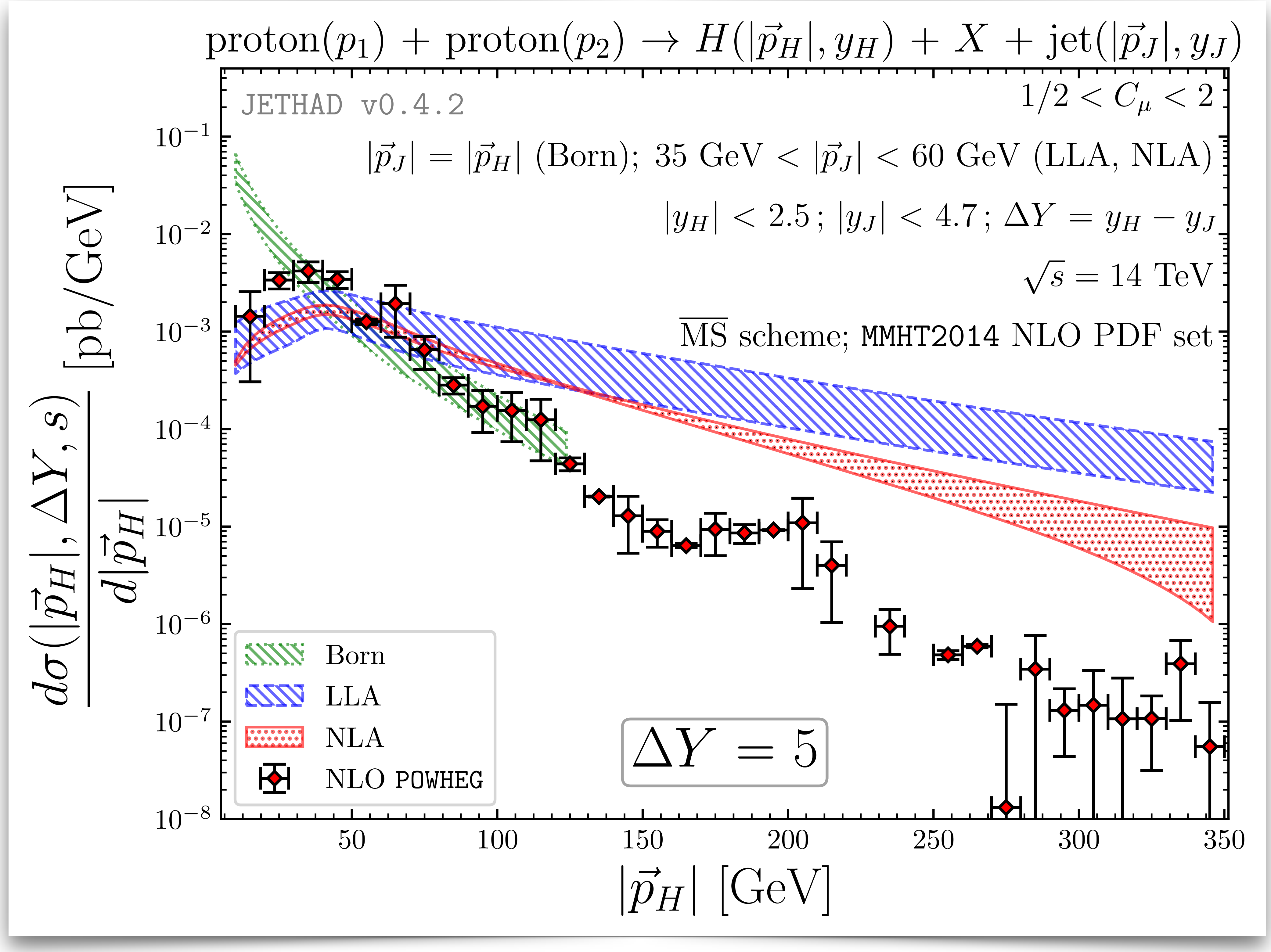

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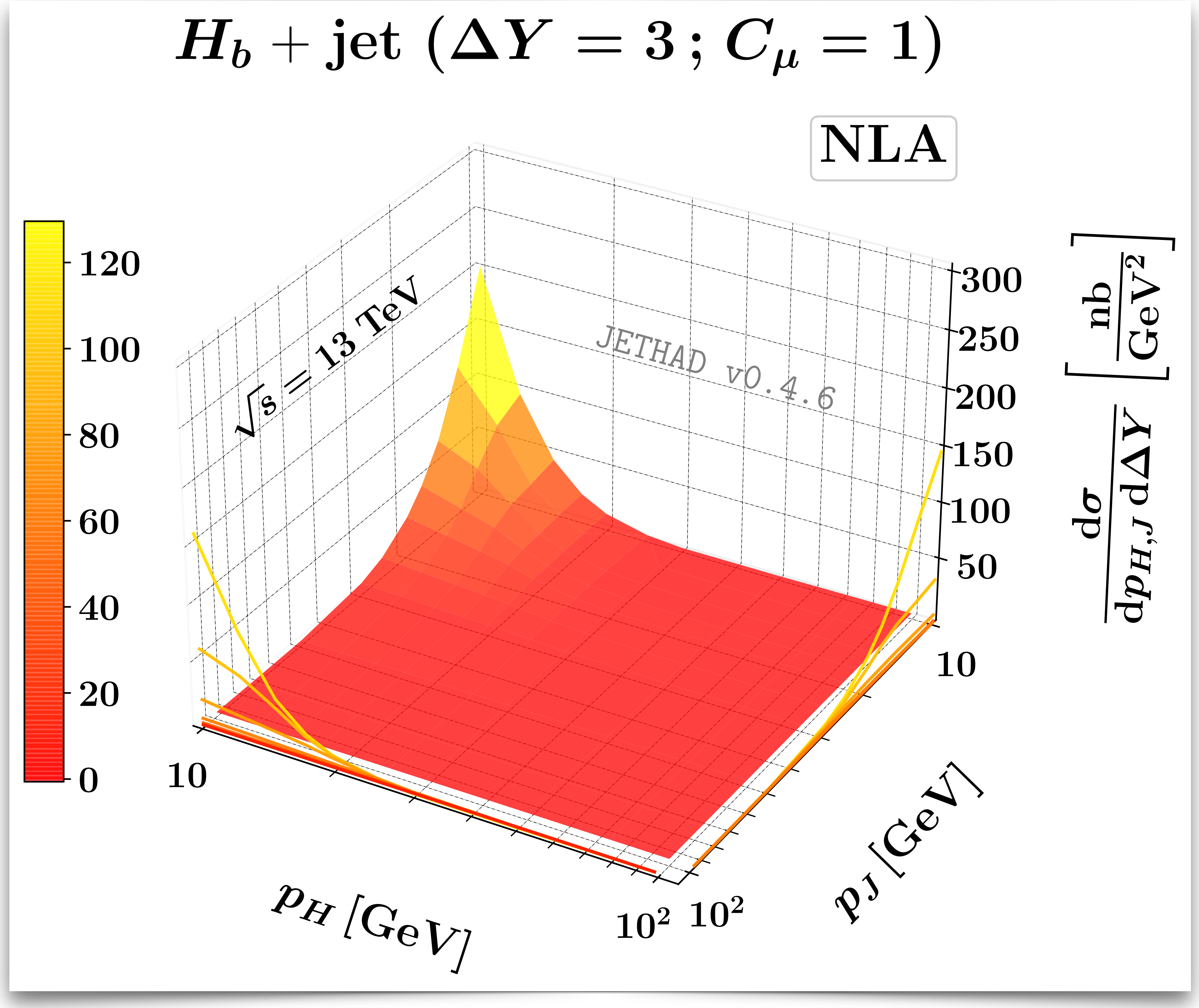
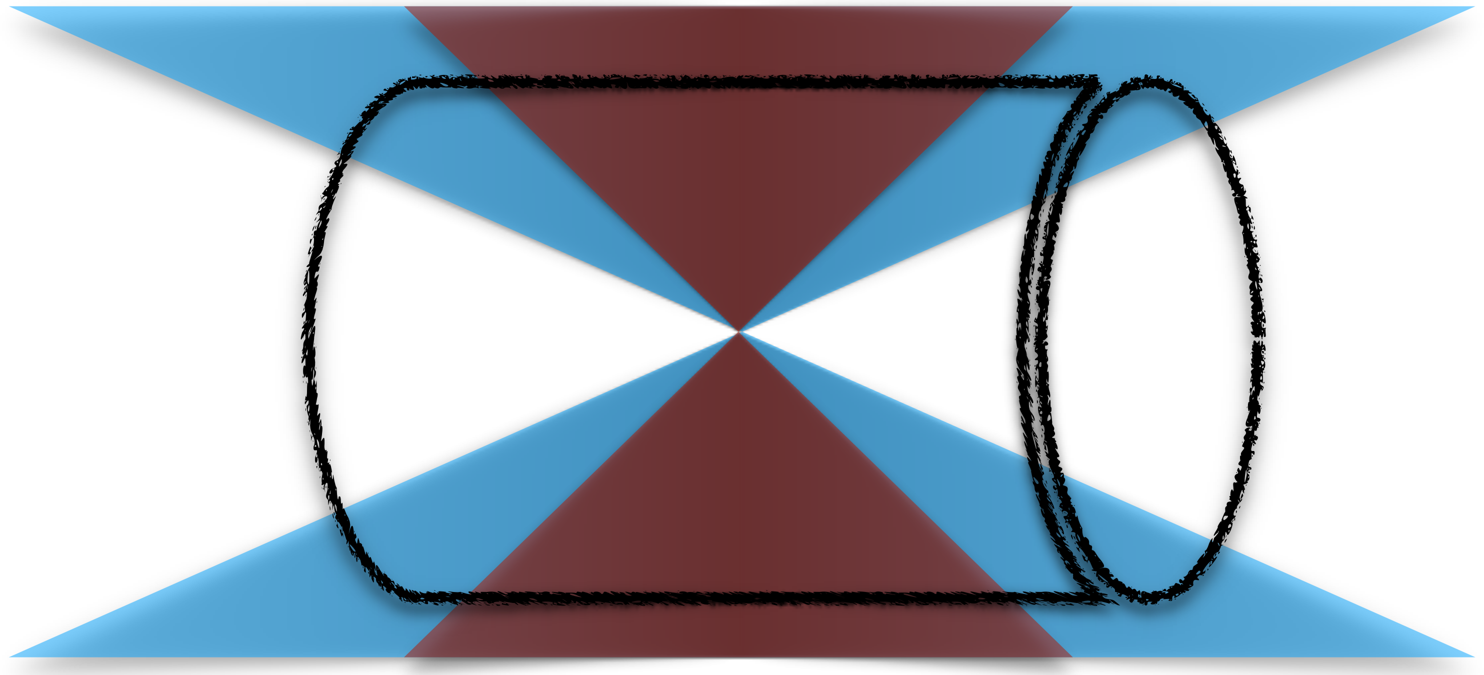


Natural stability *as a tool* to investigate HE dynamics of QCD at the **FPF**

Light mesons @FPF + heavy flavor @ATLAS

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



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

barrel + endcap

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

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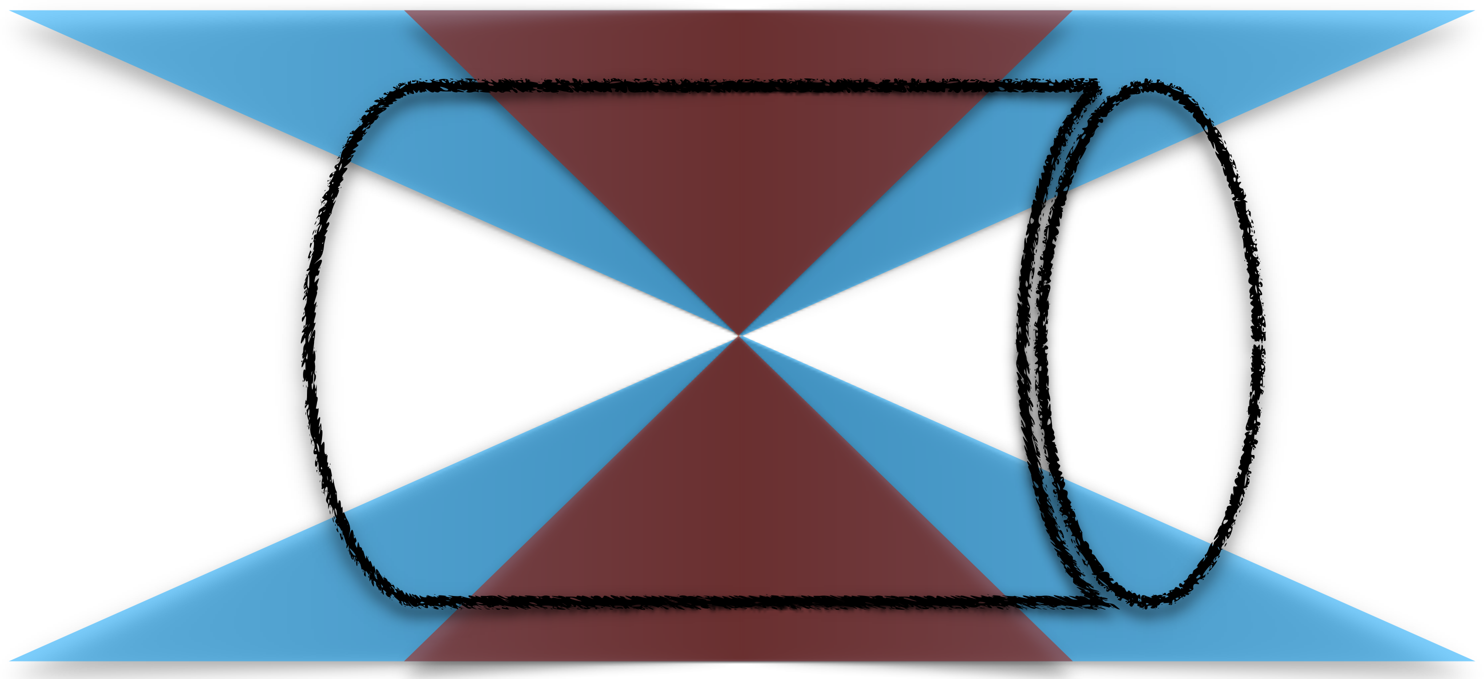

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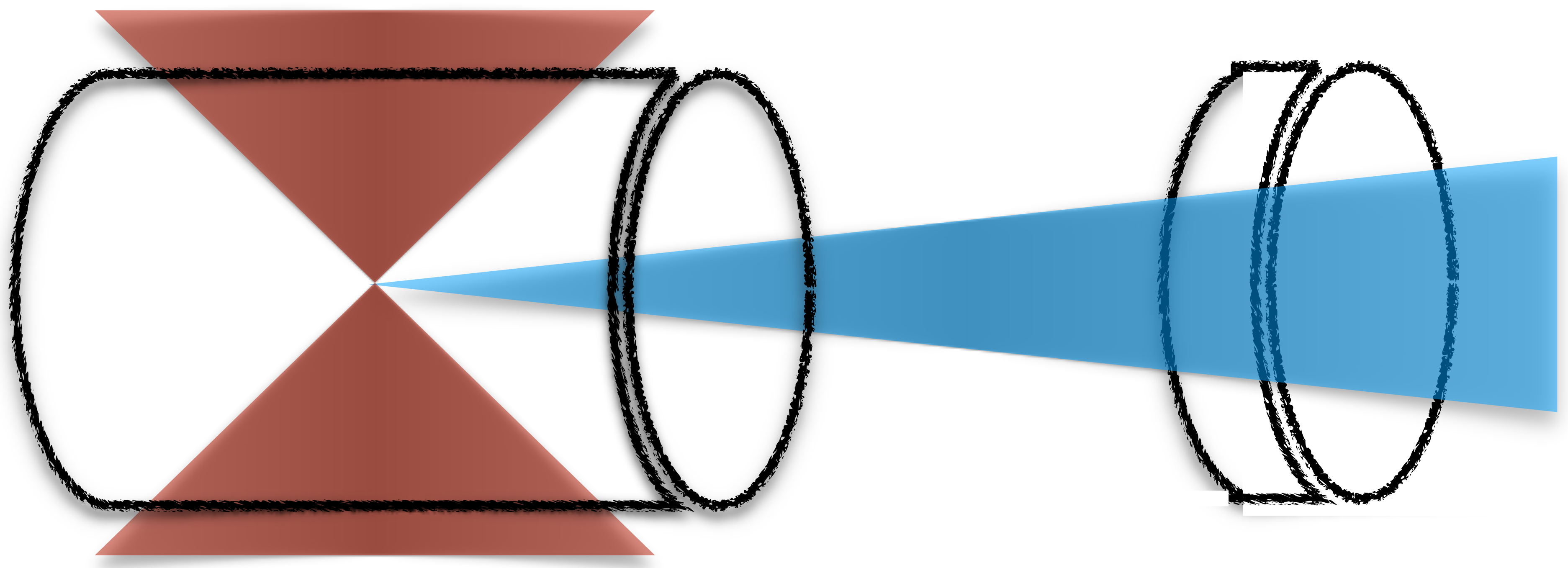

$5 < y_{\pi, K} < 7$

FPF

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ATLAS barrel

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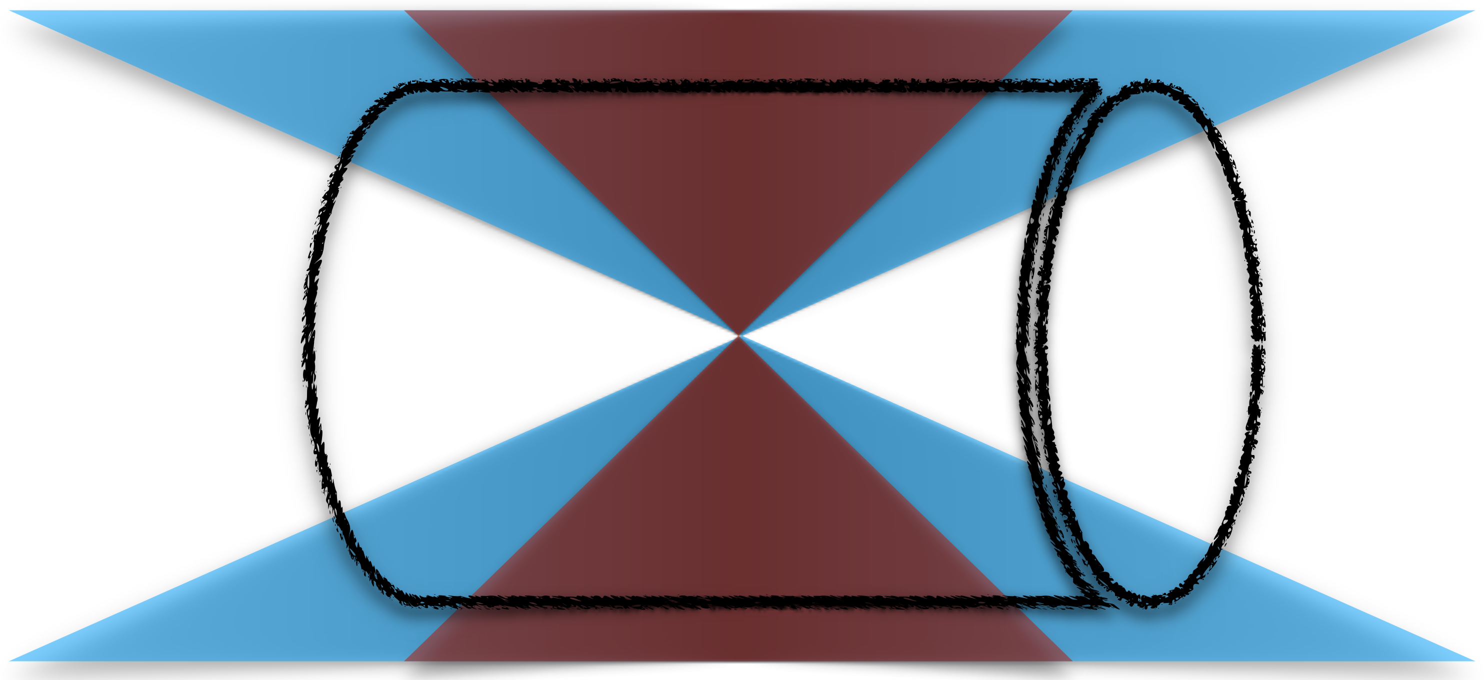

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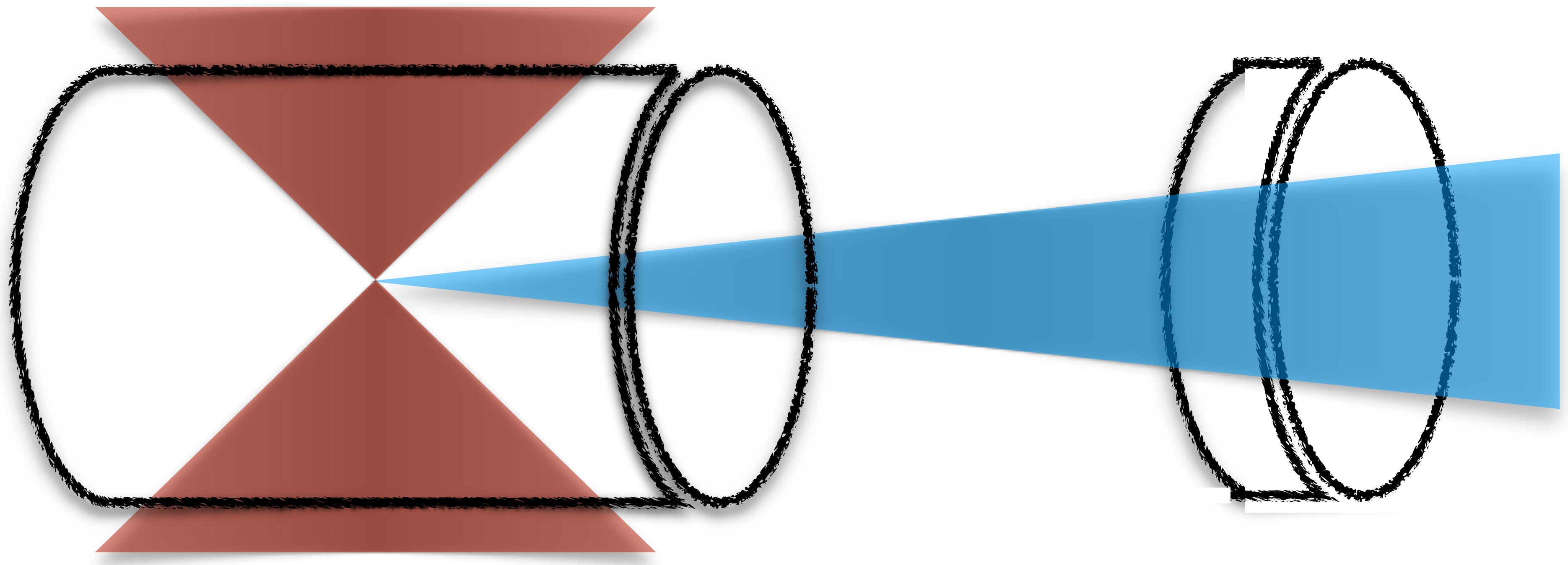

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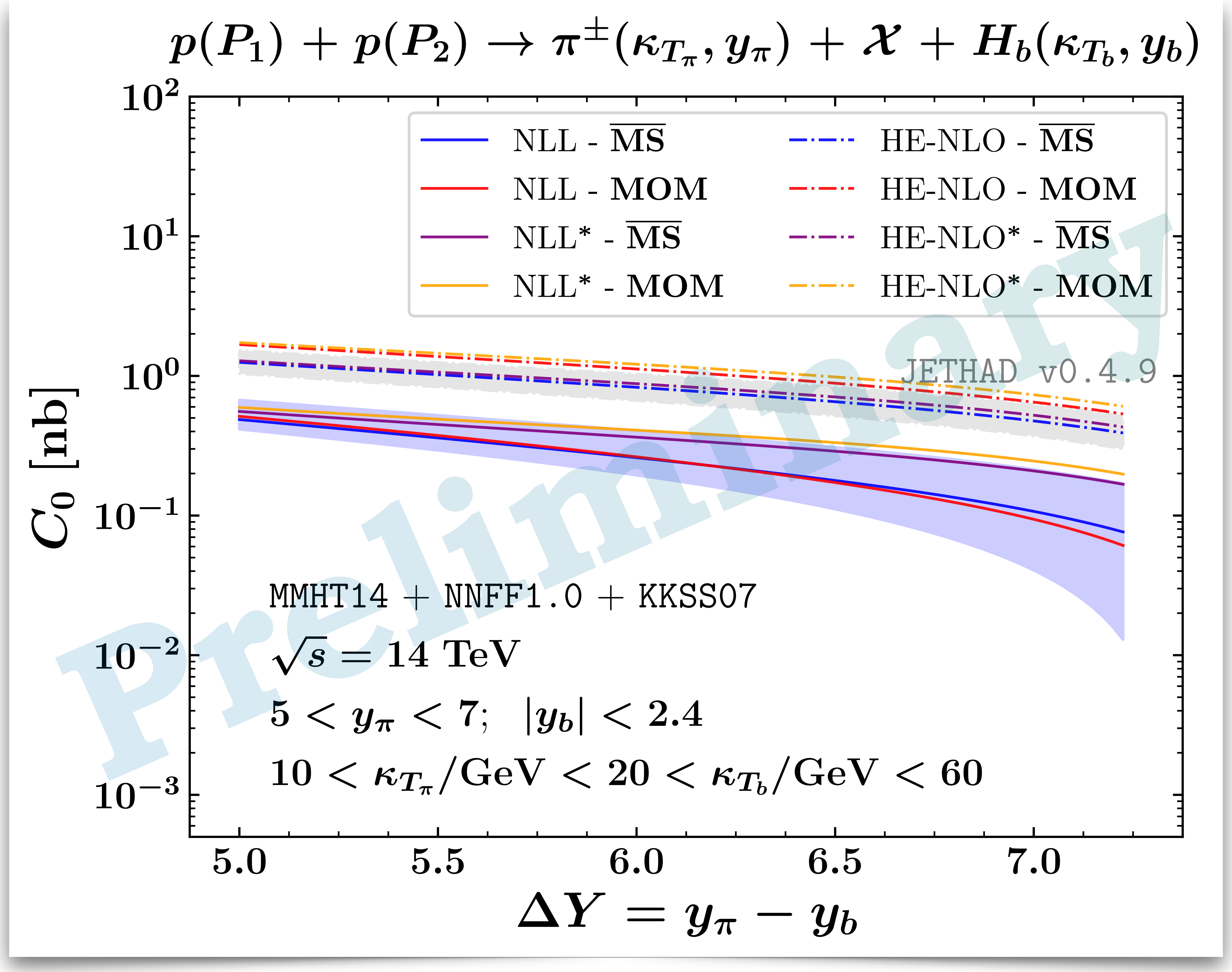
- Hybrid NLL/collinear factorization vs HE-NLO via the JETHAD method [F. G. C. (2021)]

Rapidity distribution @FPF+ATLAS

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

[F. G. C. (in preparation)]



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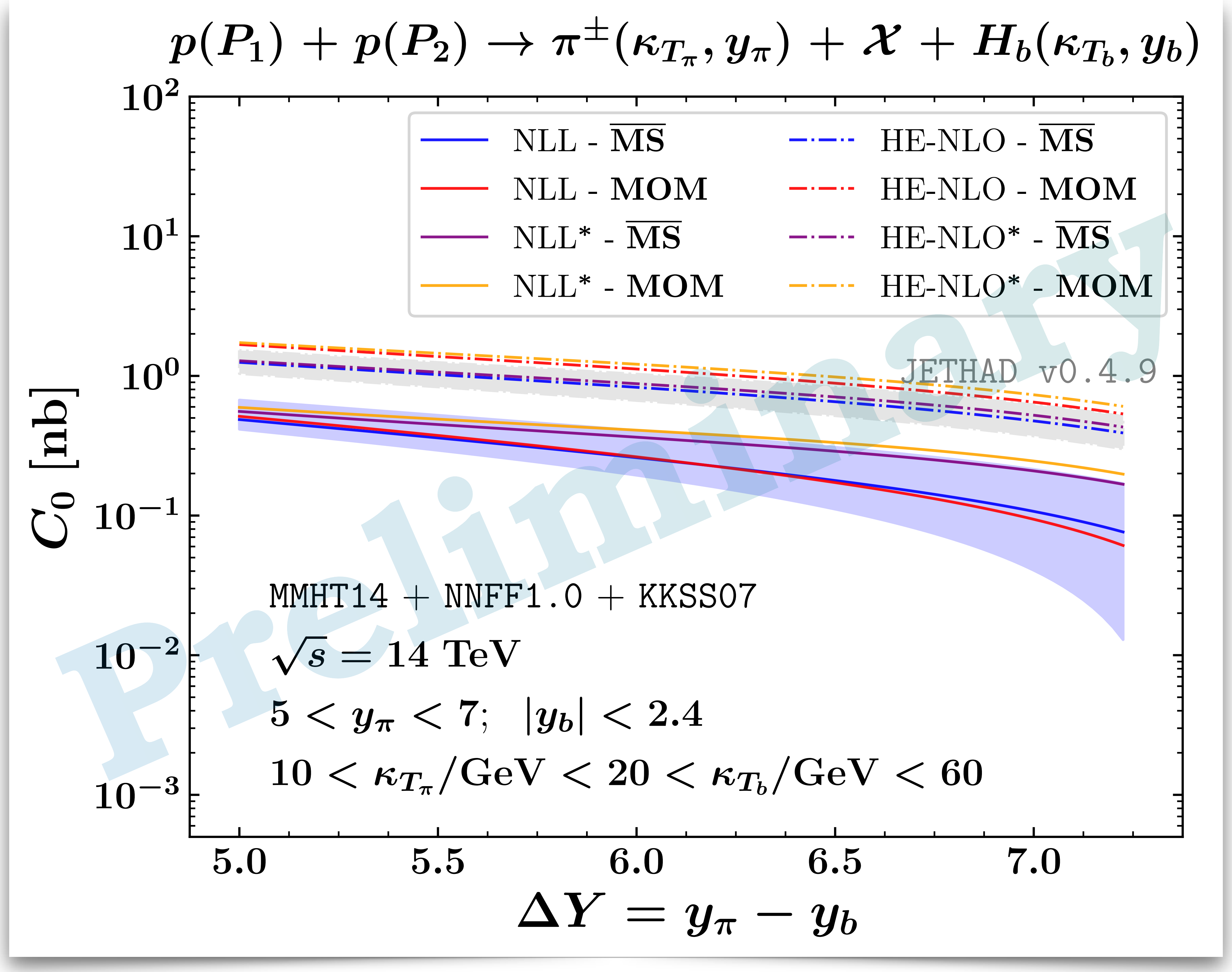

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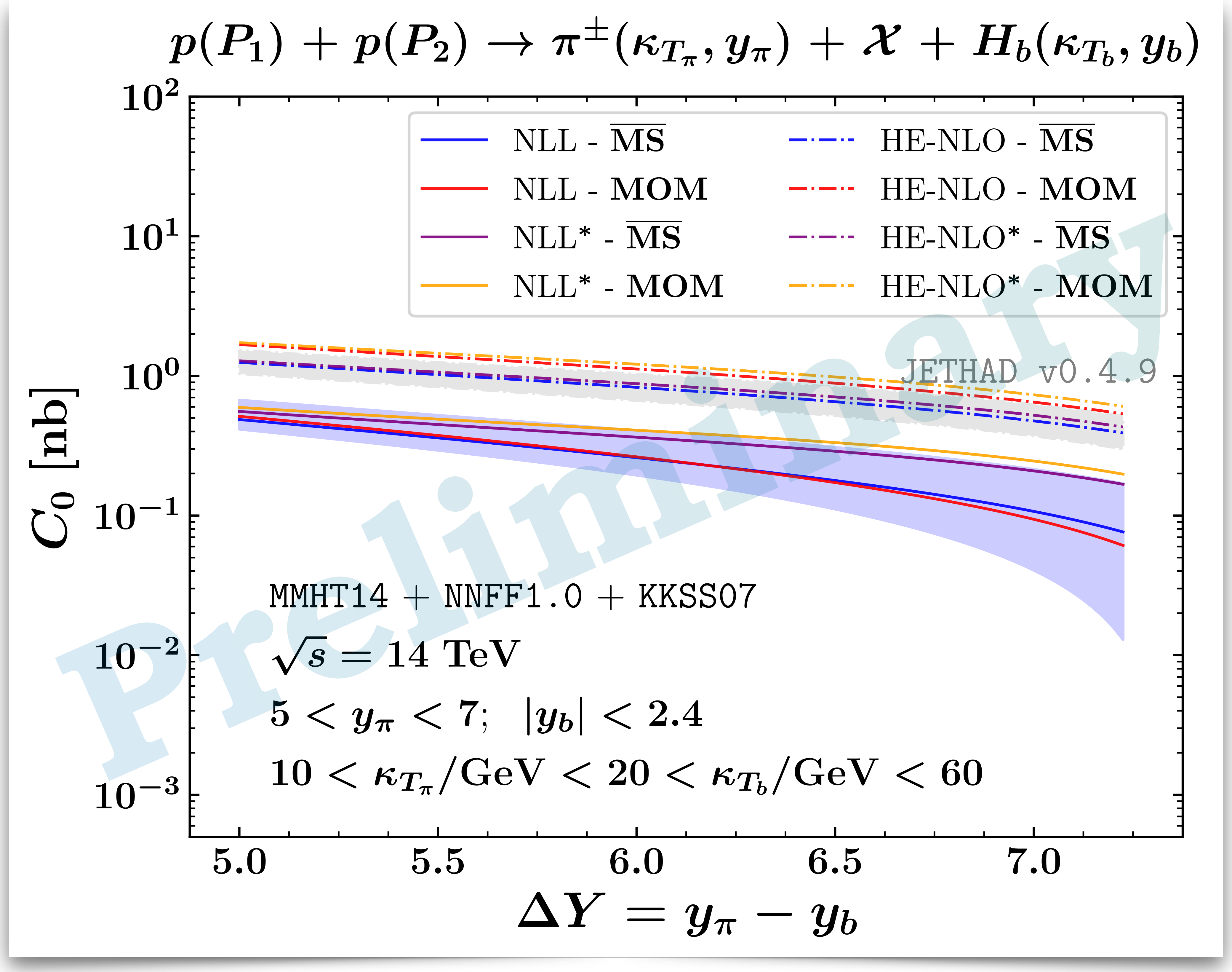

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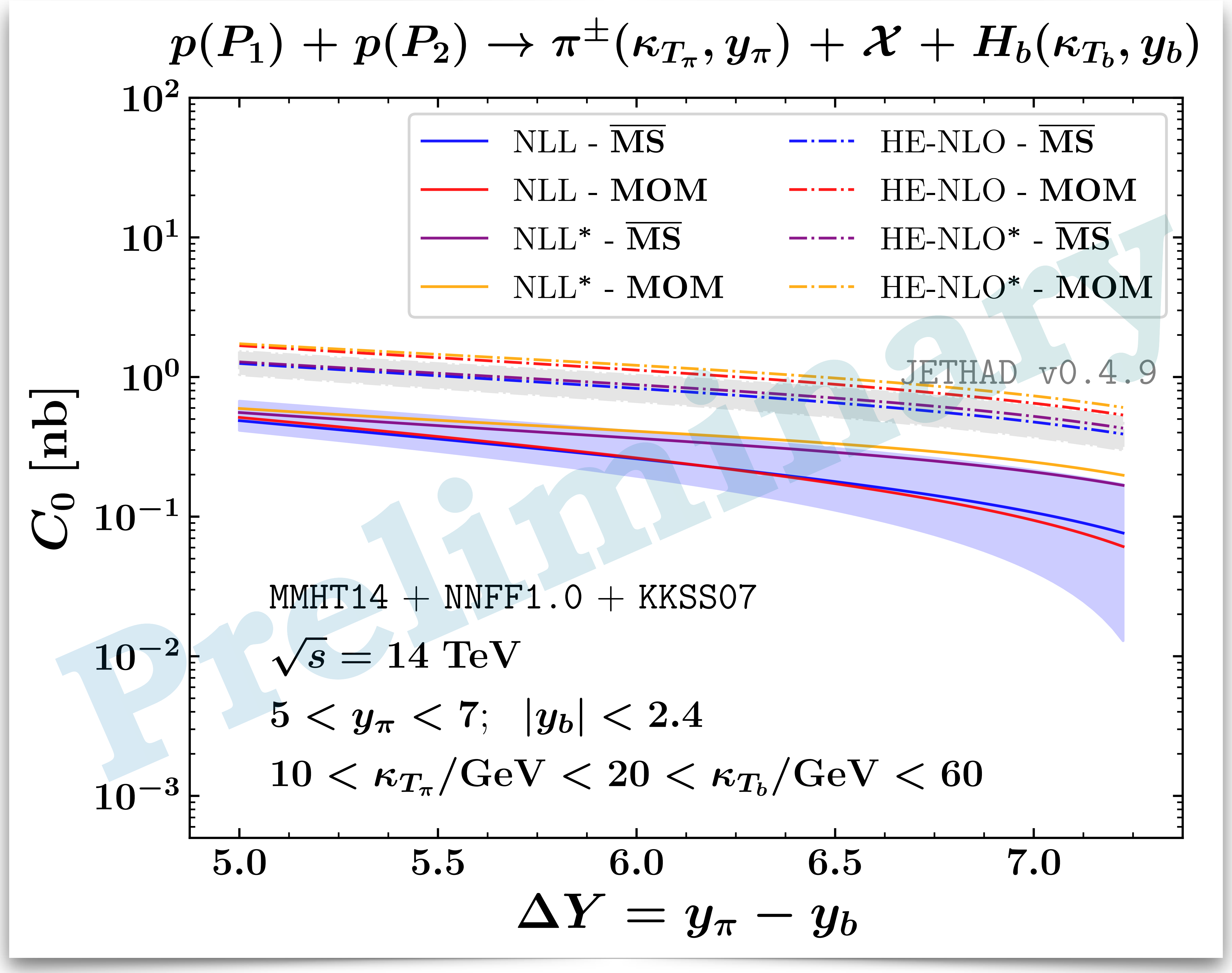

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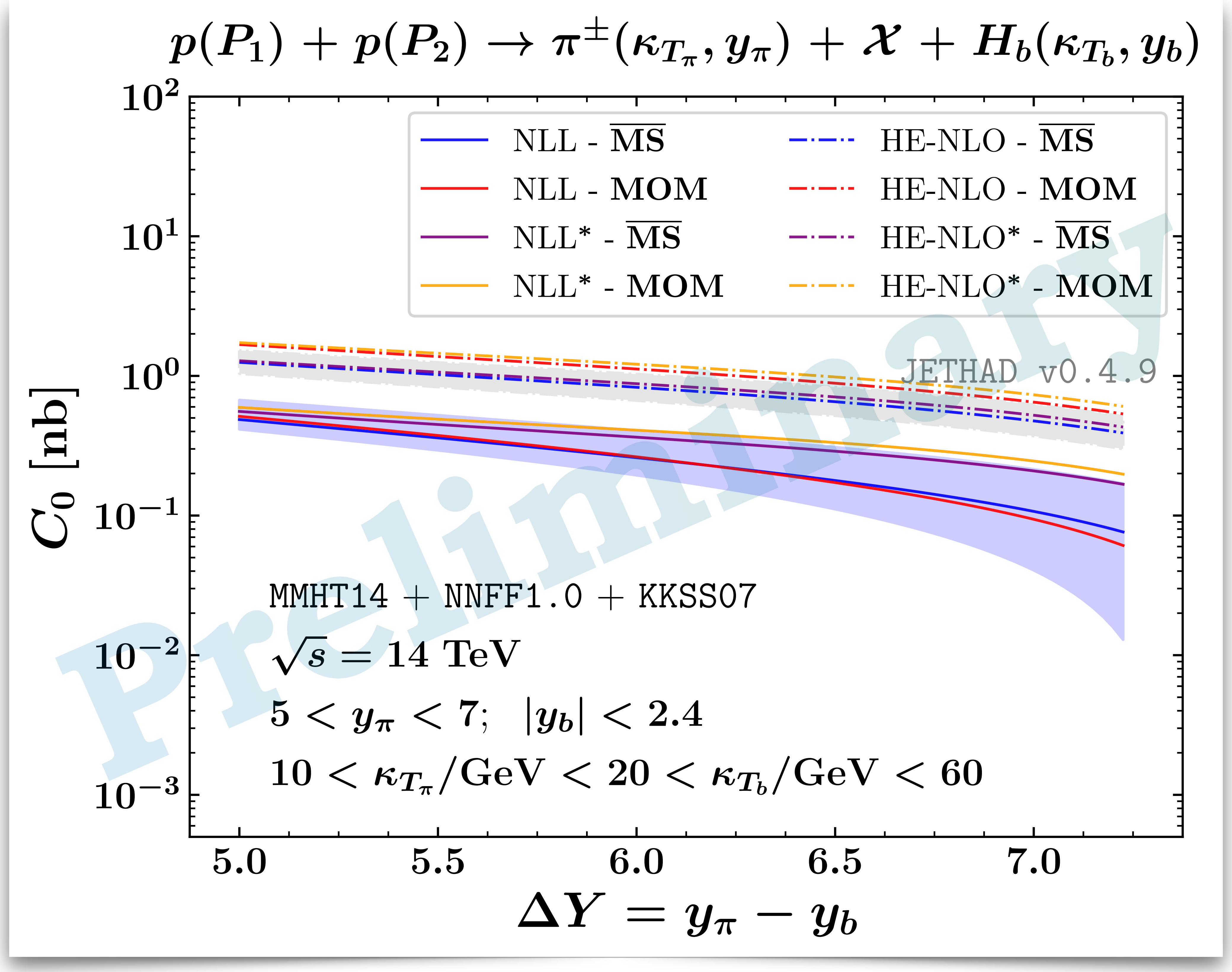

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  NLL*: NNLL effects via BFKL repres.

  MOM scheme: upper limit (overestimate)
- **HE resummation** plays a **key role**
- **Chance to probe PDFs and FFs**

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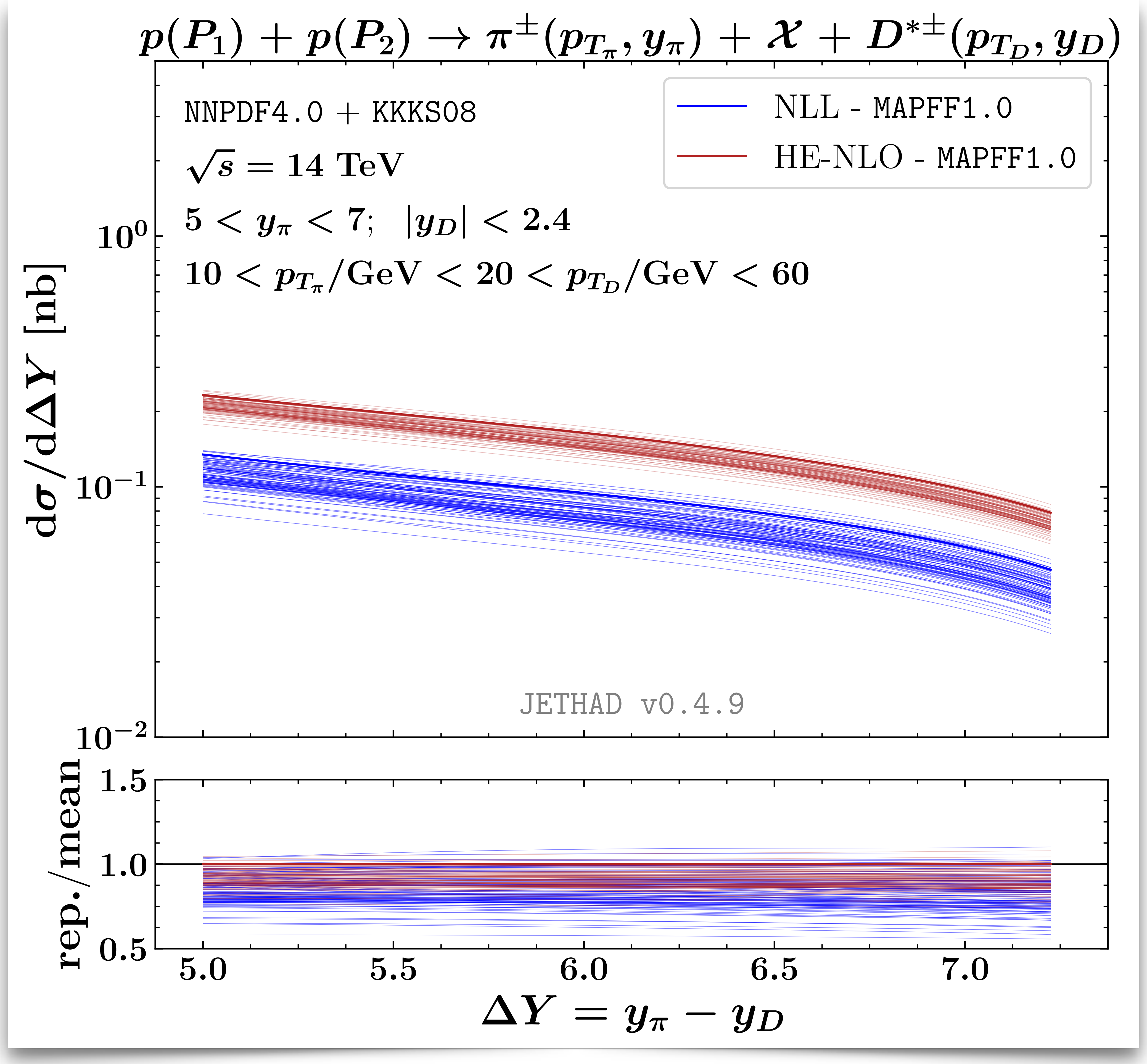
Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]



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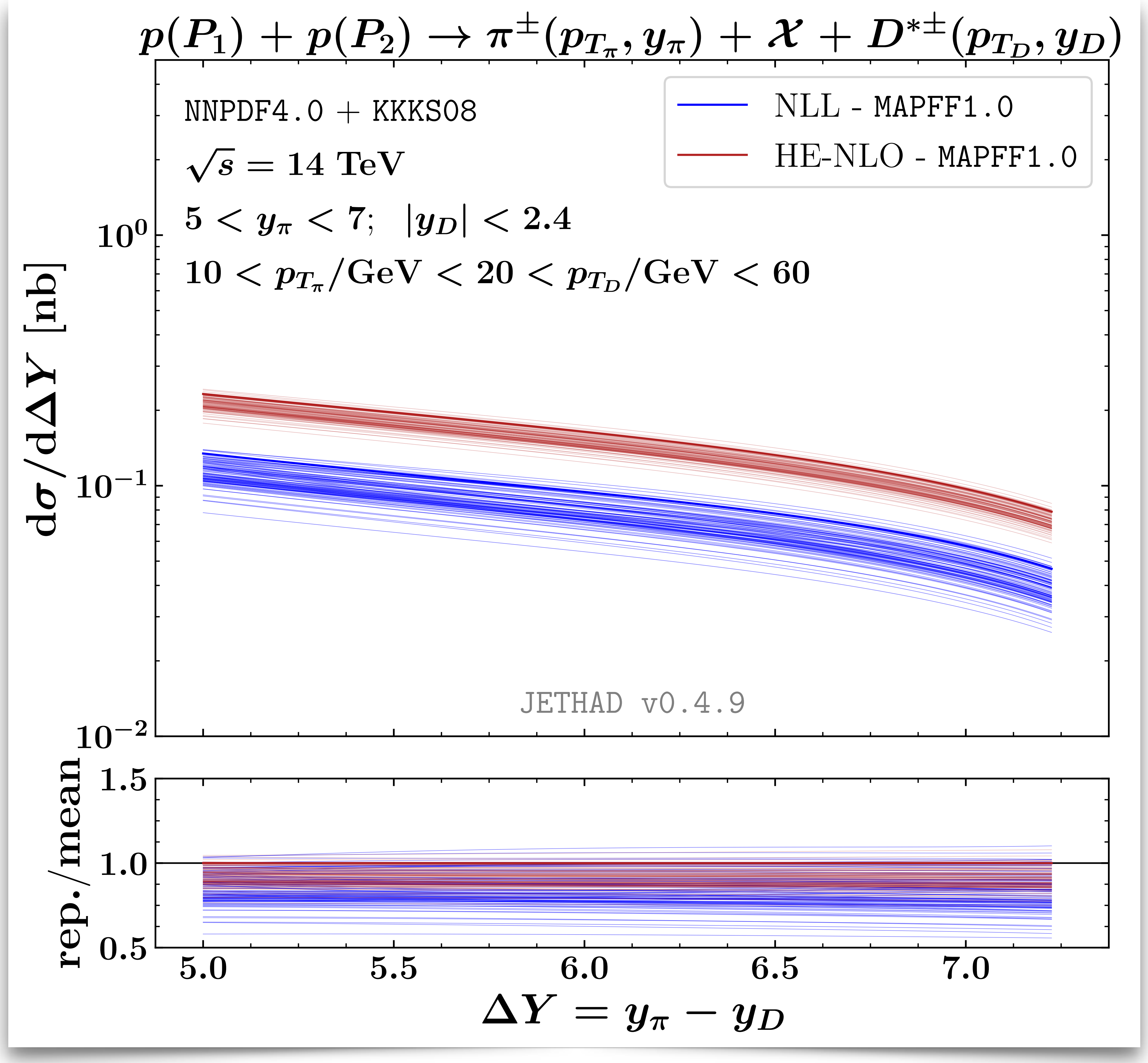

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- **Replica method** at work

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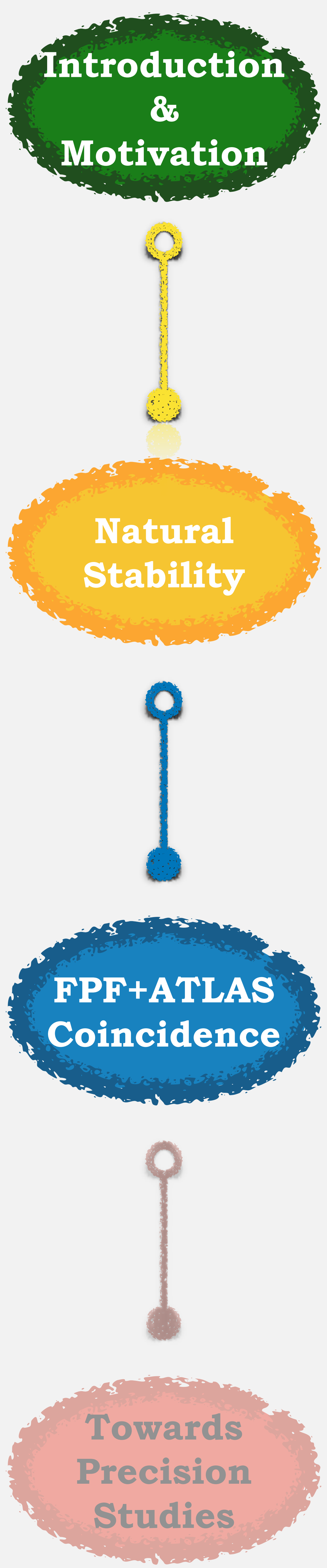

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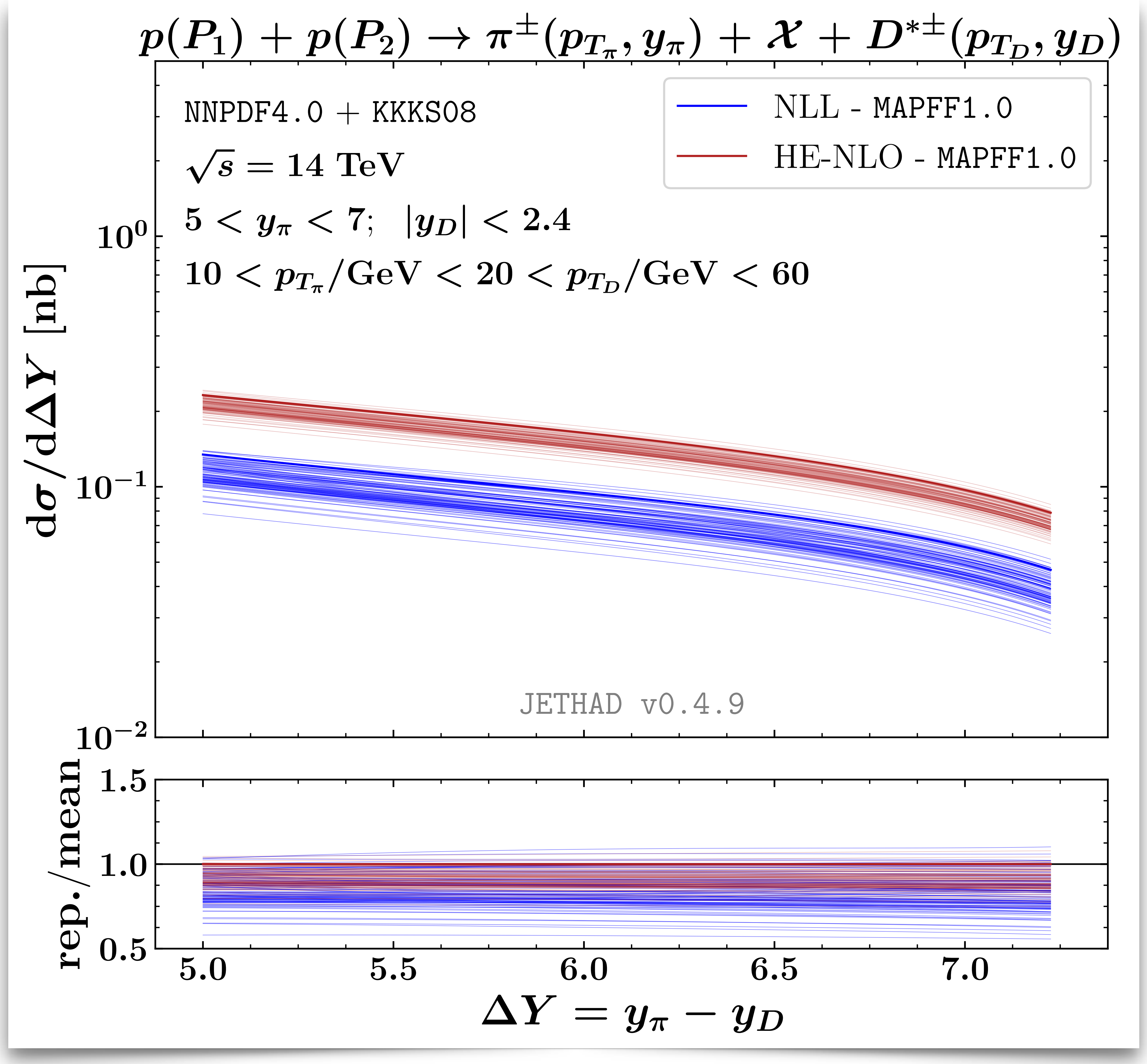

- Impact of collinear FFs on ΔY-distribution
- **Replica method** at work
- Larger spread of replicas at NLL
- Probe FFs in complementary ranges

  Weight of FF replicas in the same set

  Different sets via *functional correlation*?

- **Complementary studies on FFs**

Azimuthal distribution @FPF+ATLAS

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

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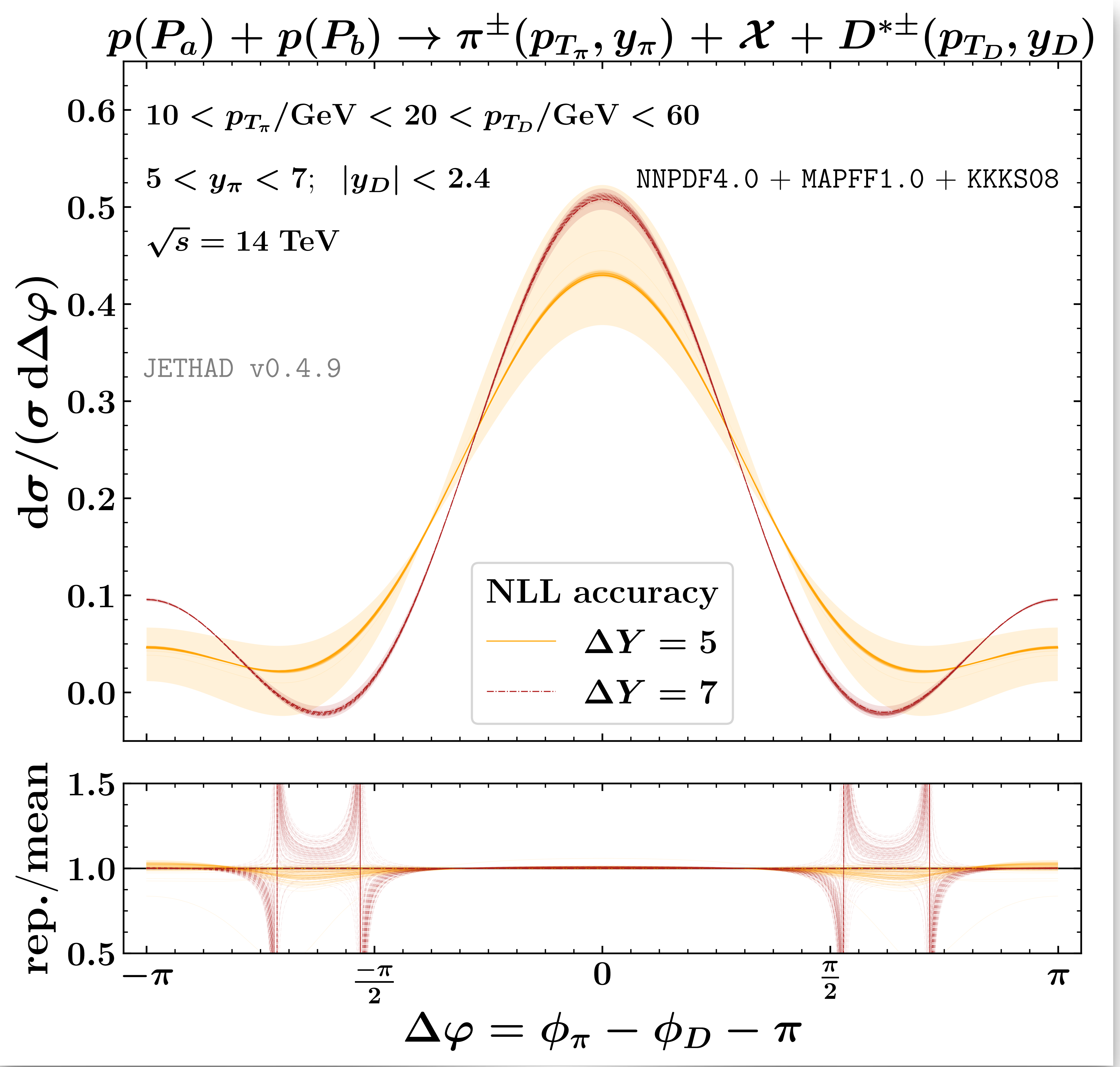

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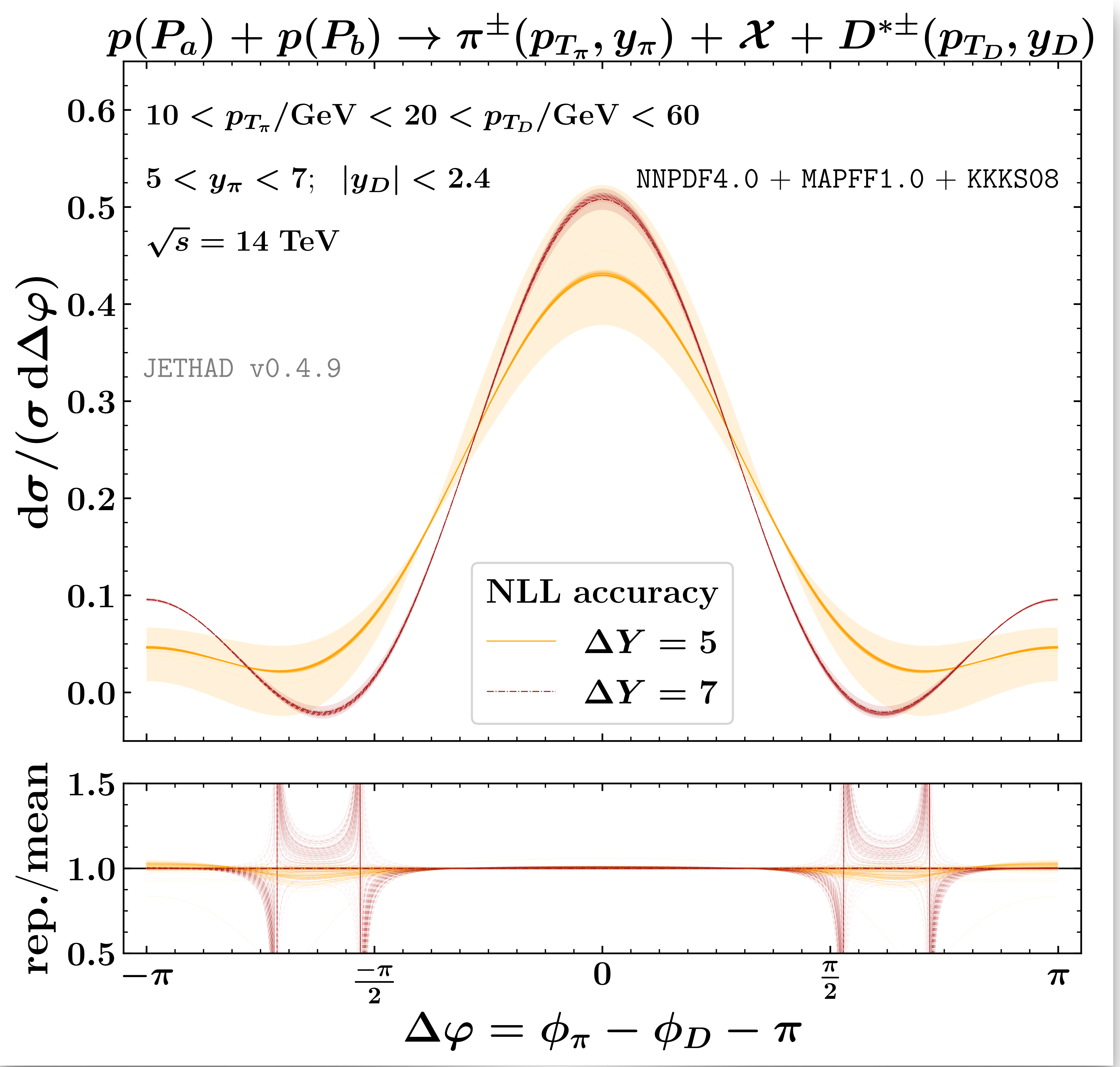

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- Easy to be analyzed from data
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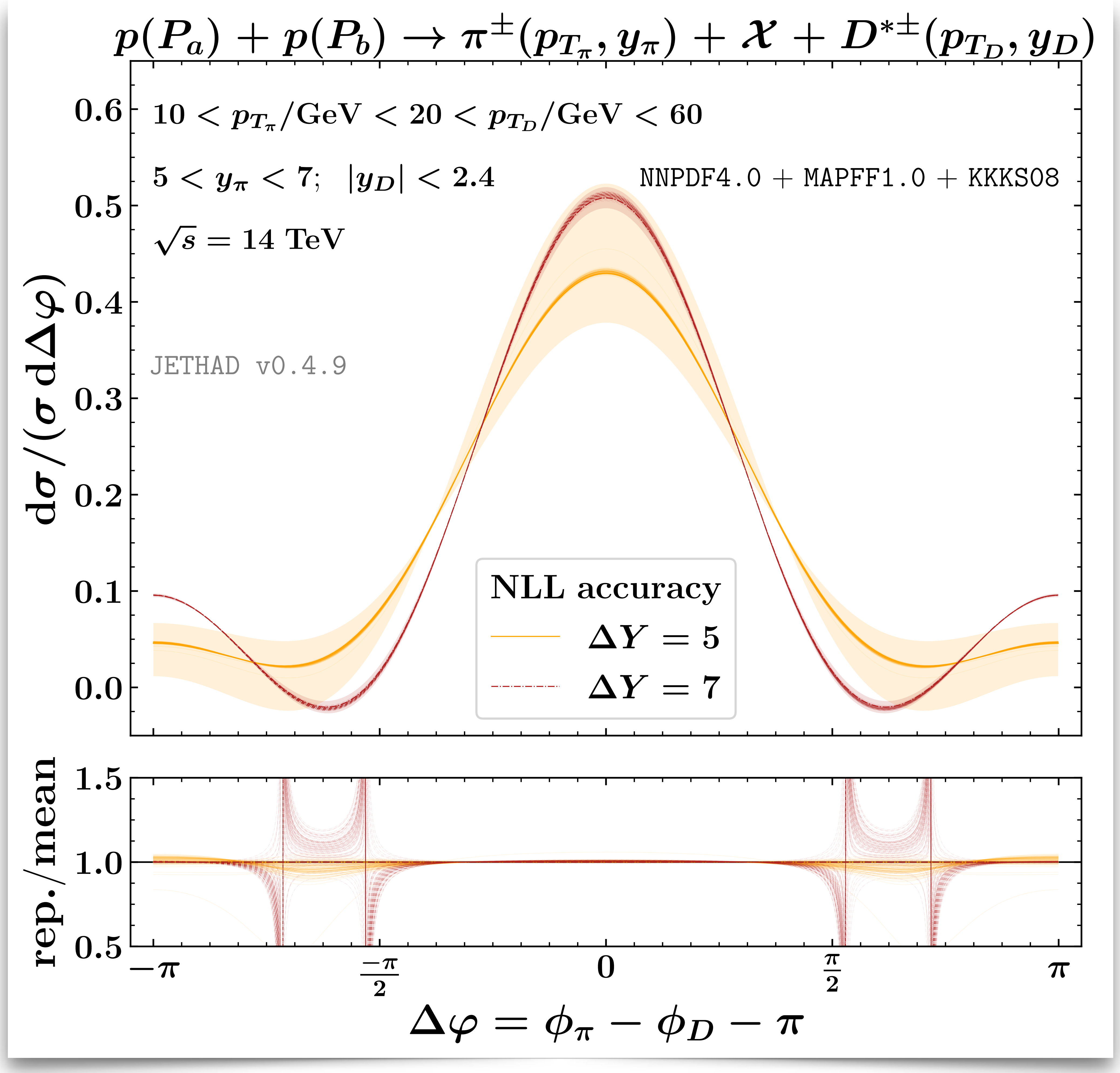

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- * *Novel* and *unexpected* features

Peak beavior → **re-correlation** pattern

Possible **threshold** contamination

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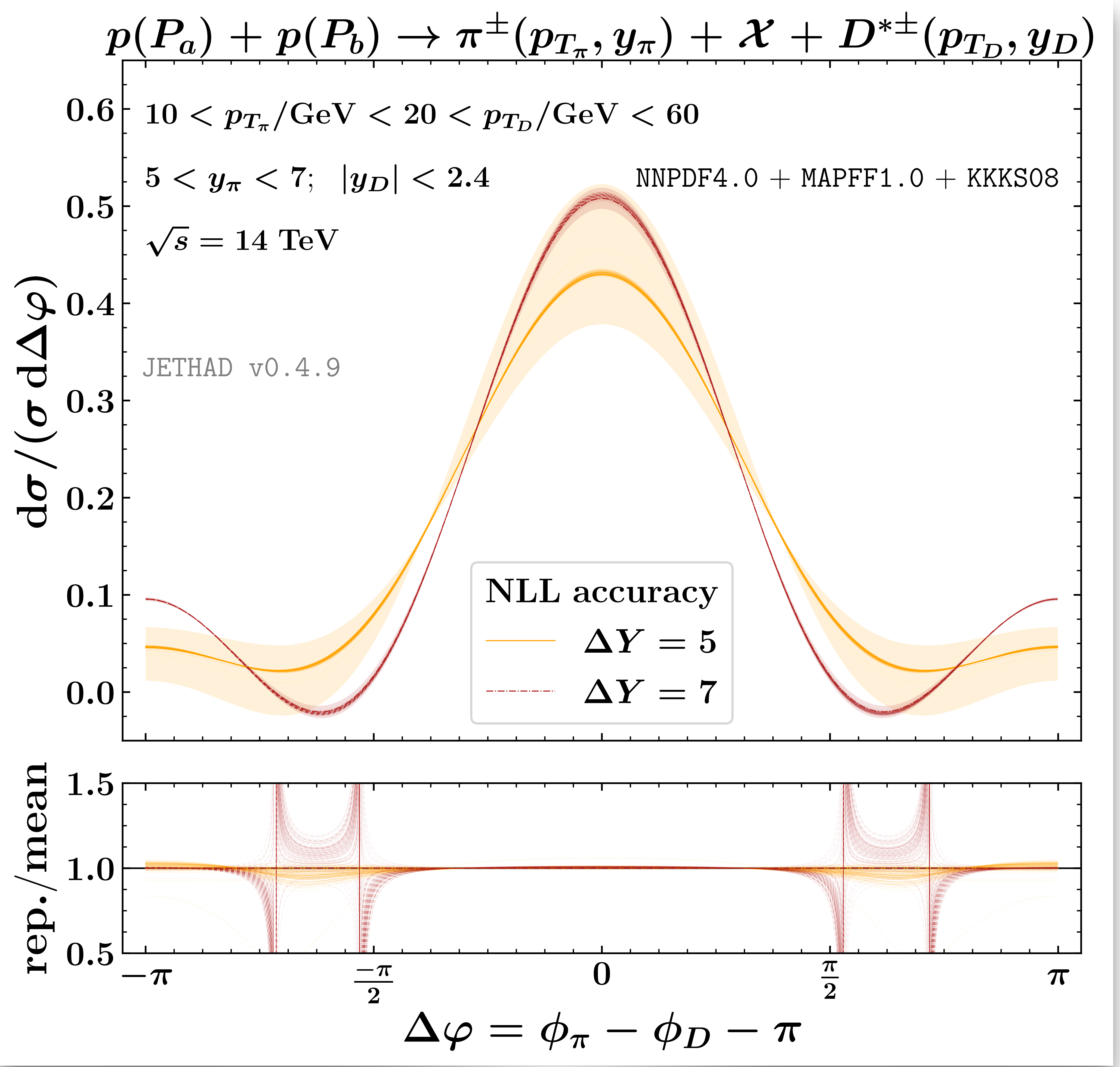

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- *Stringent* tests of **HE resummation**
- **Chance to explore other resummations**

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Towards new directions

- ☑ *FPF + ATLAS coincidence* → **high discovery potential** of QCD
- ☑ **Significant impact** of *HE dynamics* on *fixed-order* calculations
- ☑ *Rapidity distribution* → constrain **FFs** in **complementary** ranges
- ☑ *Azimuthal distribution* → hunt for **novel HE features**

  → explore **interplay** with other **resummations**

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- ☐ Theory: *multi-lateral formalism* → **encode** those resummations
- ☐ Pheno: *Heavy-hadron* production at the FPF → **flavor** studies

  Hadronic structure at the FPF → **HE/coll./TMD interplay**

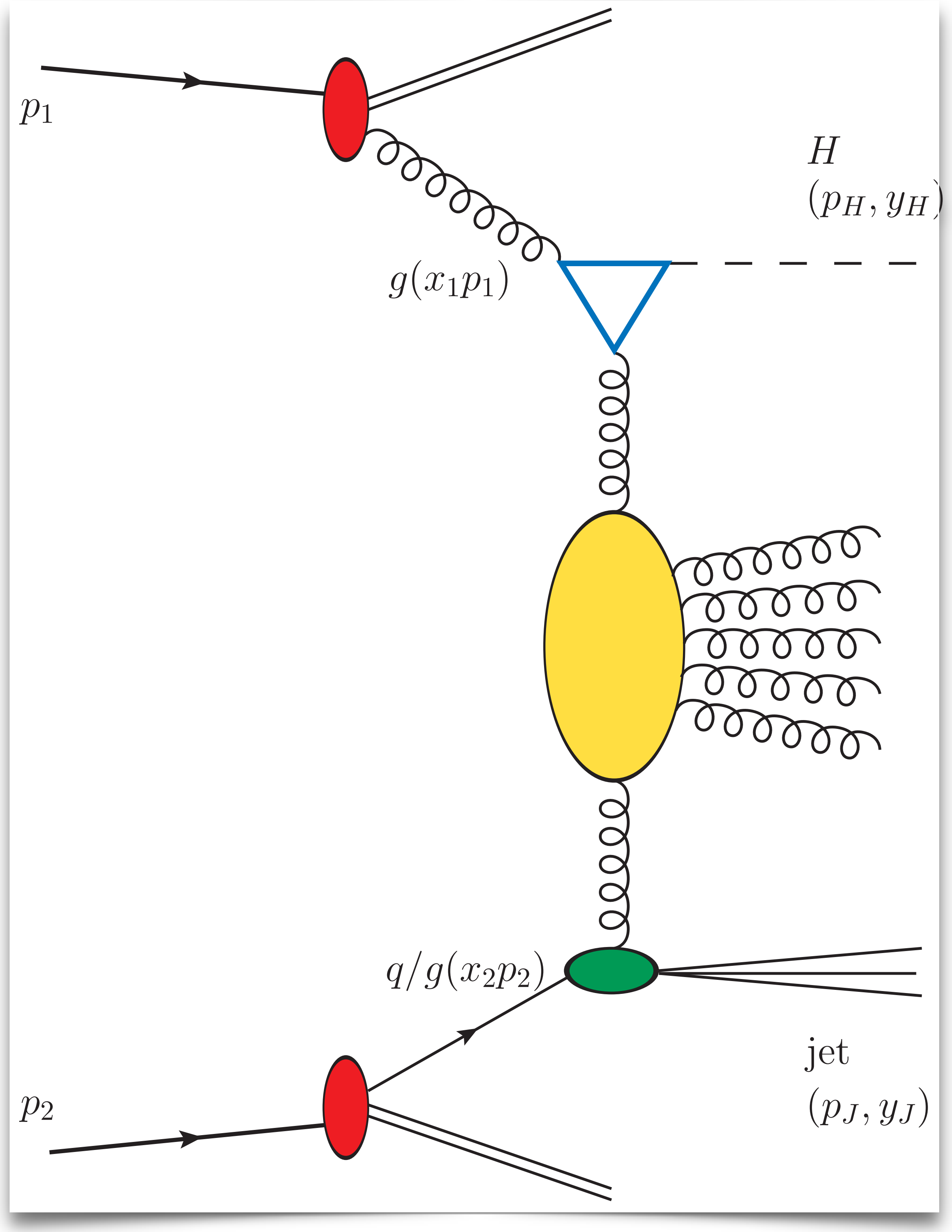
Backup slides

Inclusive Higgs + jet: azimuthal coefficients

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

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

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



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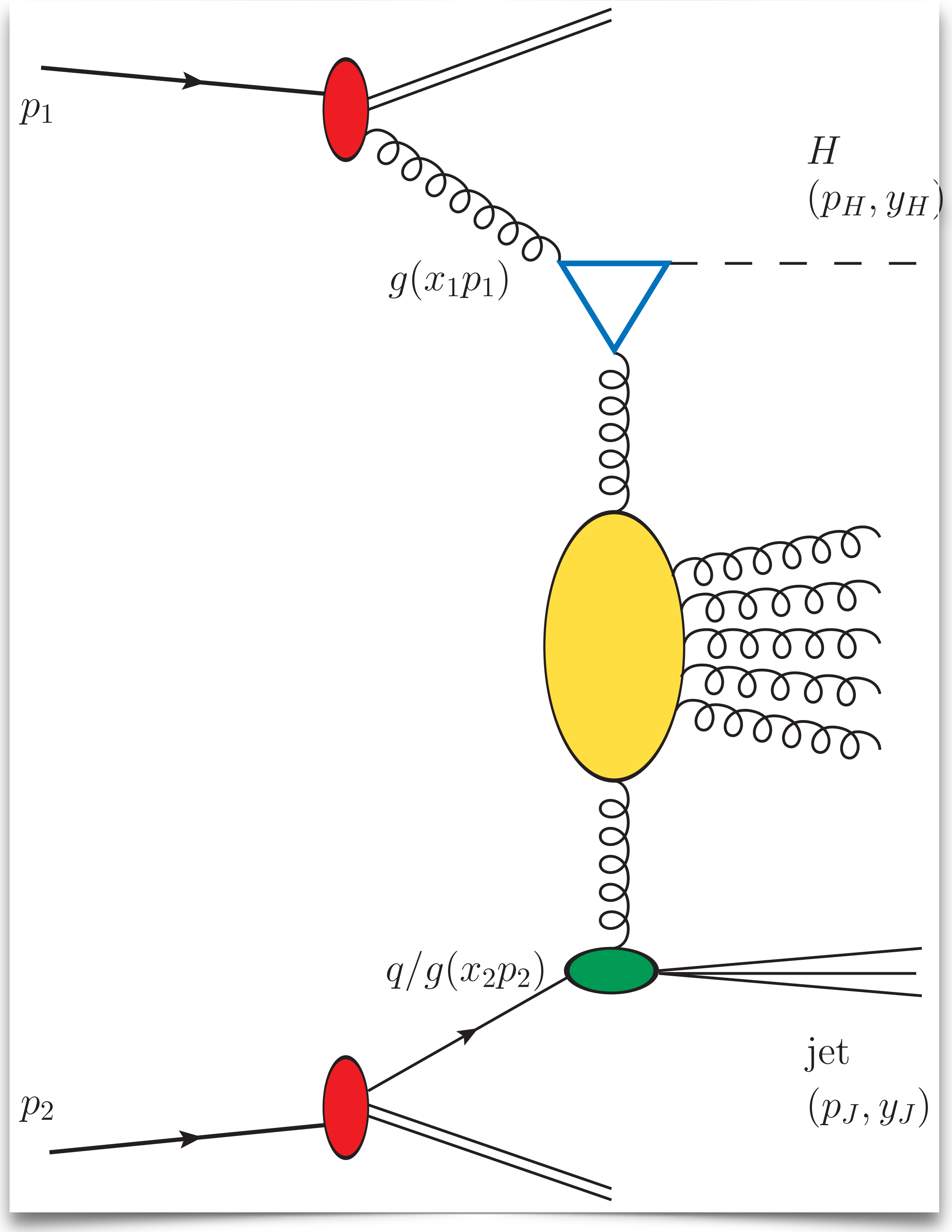


$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$
$$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H)$$
$$\times \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$
$$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

Higgs vertex (off-shell amplitude)

jet vertex (off-shell amplitude)

BFKL gluon Green's function

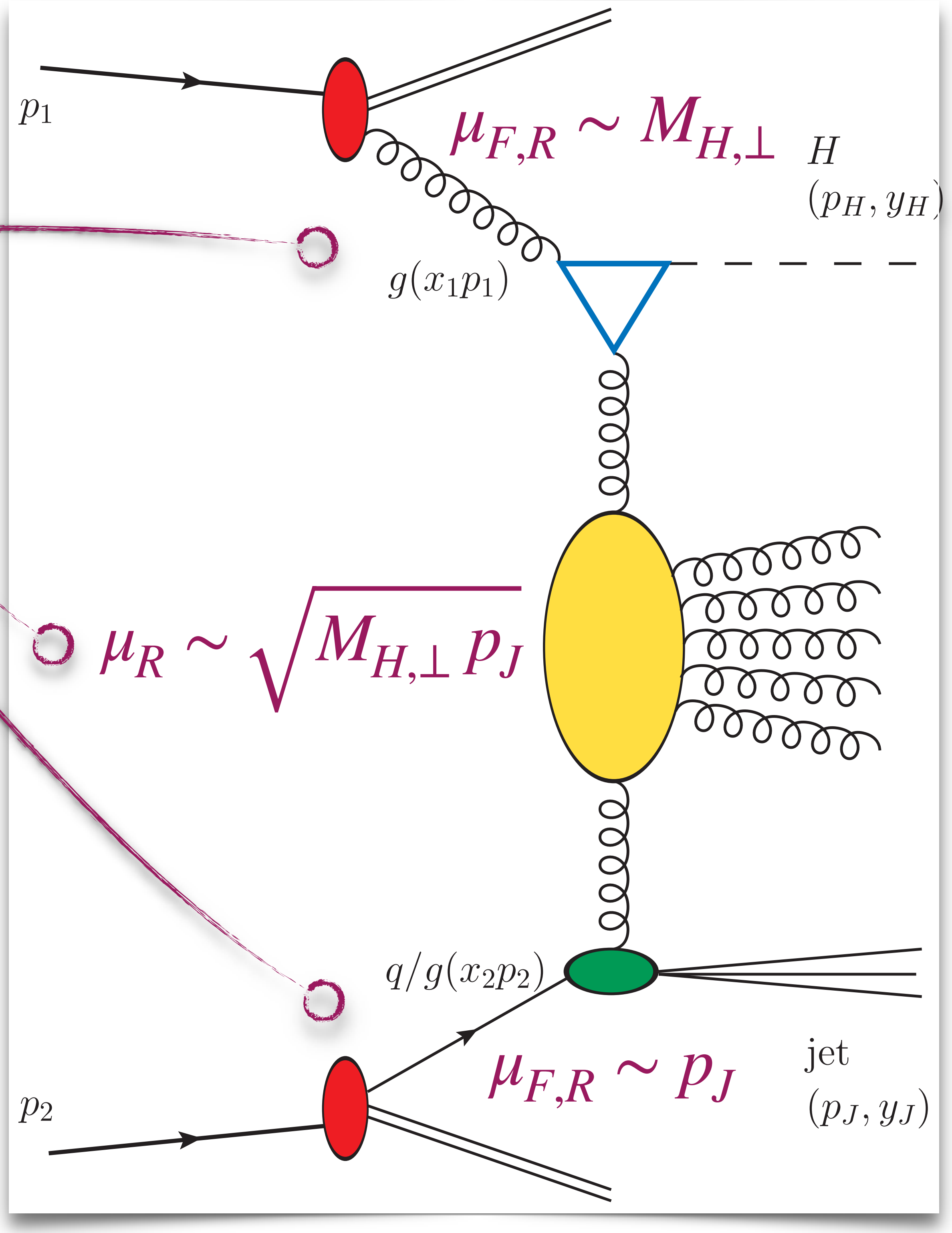
Backup

Inclusive Higgs + jet: azimuthal coefficients

- 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

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

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



Higgs vertex (off-shell amplitude)

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BFKL gluon Green's function

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Azimuthal correlations: $C_1/C_0 \equiv \langle \cos \varphi \rangle$

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$$\varphi = \varphi_1 - \varphi_2 - \pi$$

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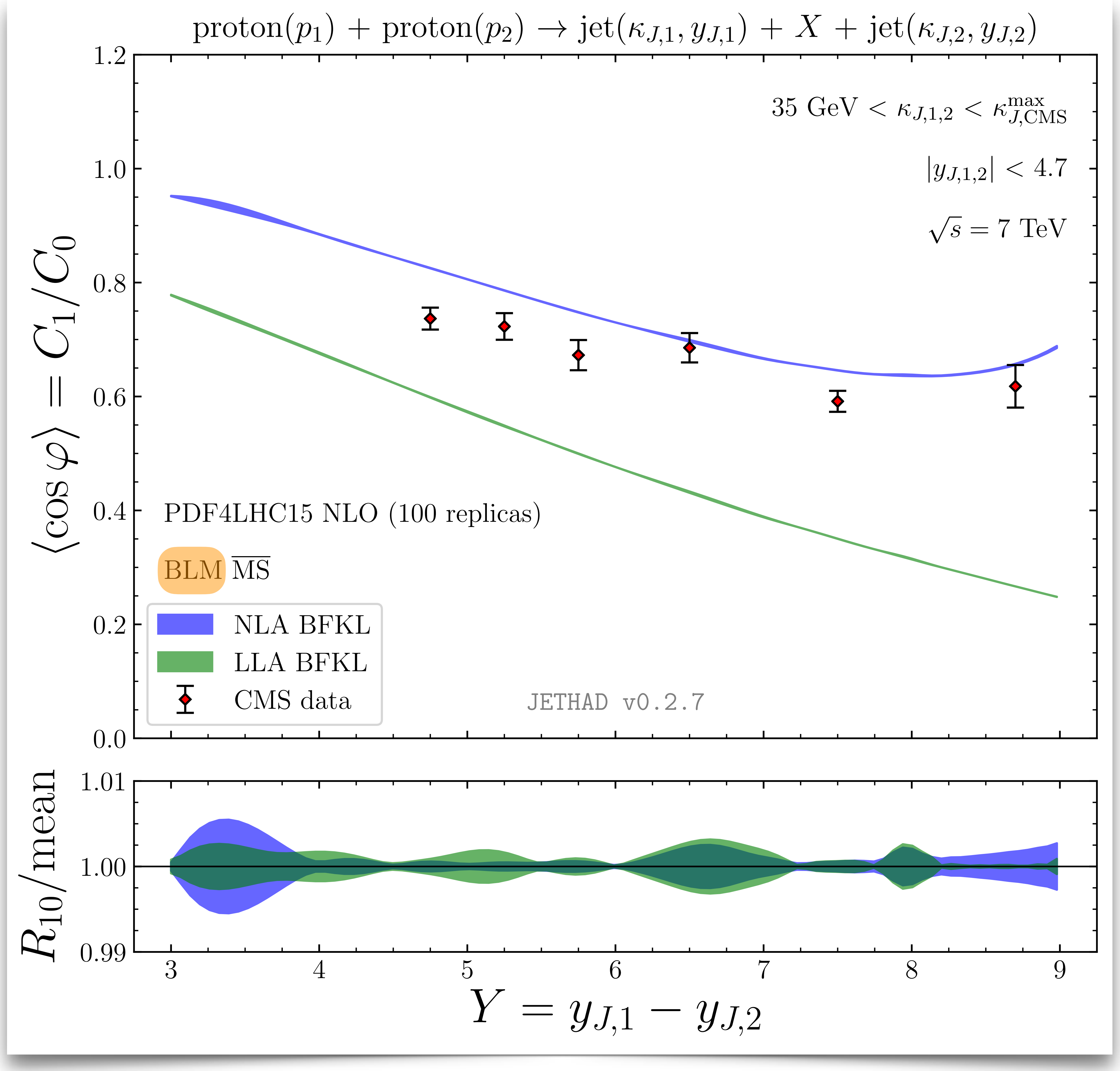
Azimuthal correlations: $C_1/C_0 \equiv \langle \cos\varphi \rangle$ Backup

$$\varphi = \varphi_1 - \varphi_2 - \pi$$

Mueller-Navelet jets

🔗 [B. Ducloué, L. Szymanowski, S. Wallon (2014)]

(figure below) 🔗 [F. G. C. (2021)]



Azimuthal correlations: $C_1/C_0 \equiv \langle \cos \varphi \rangle$

Backup

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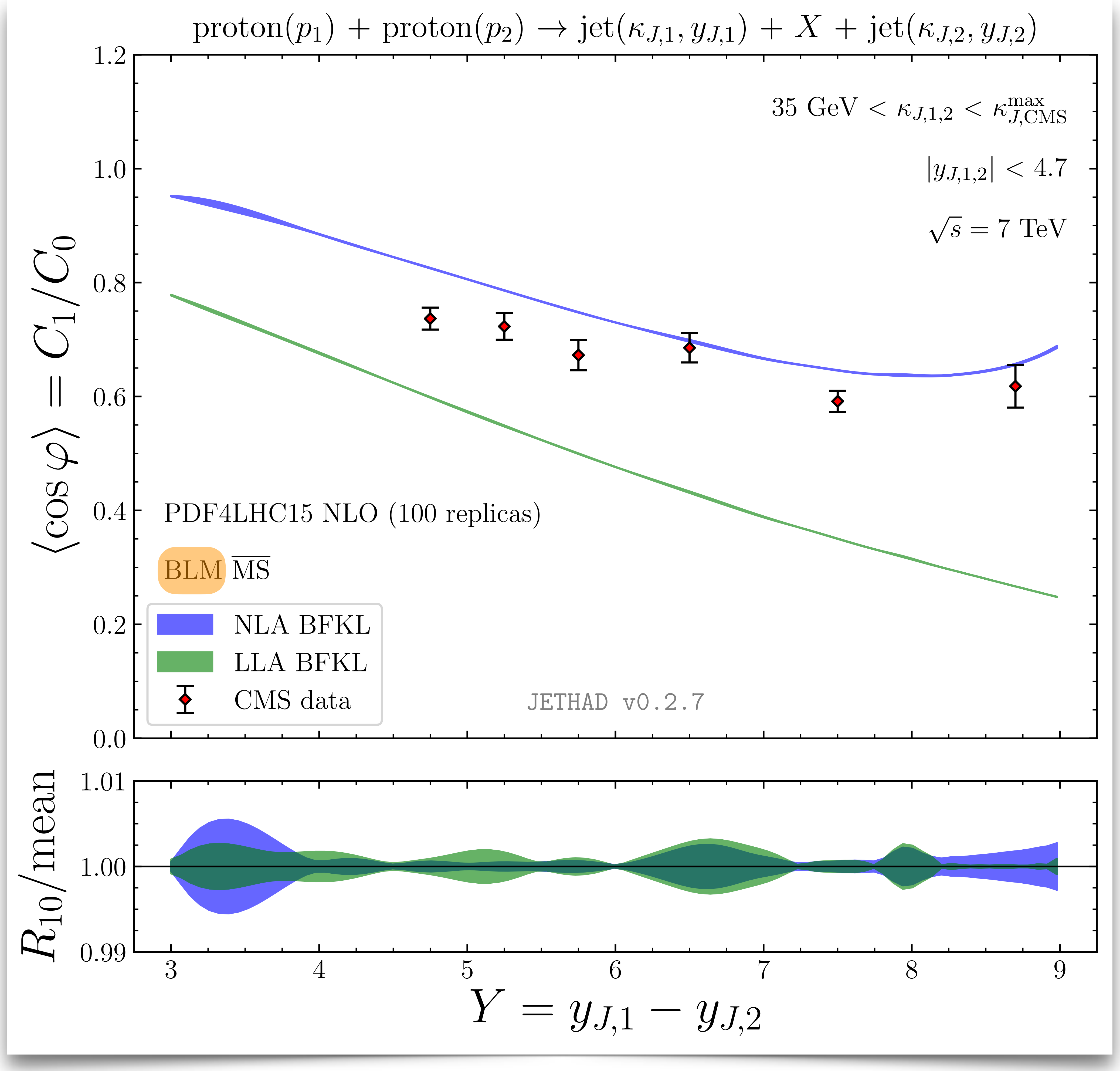
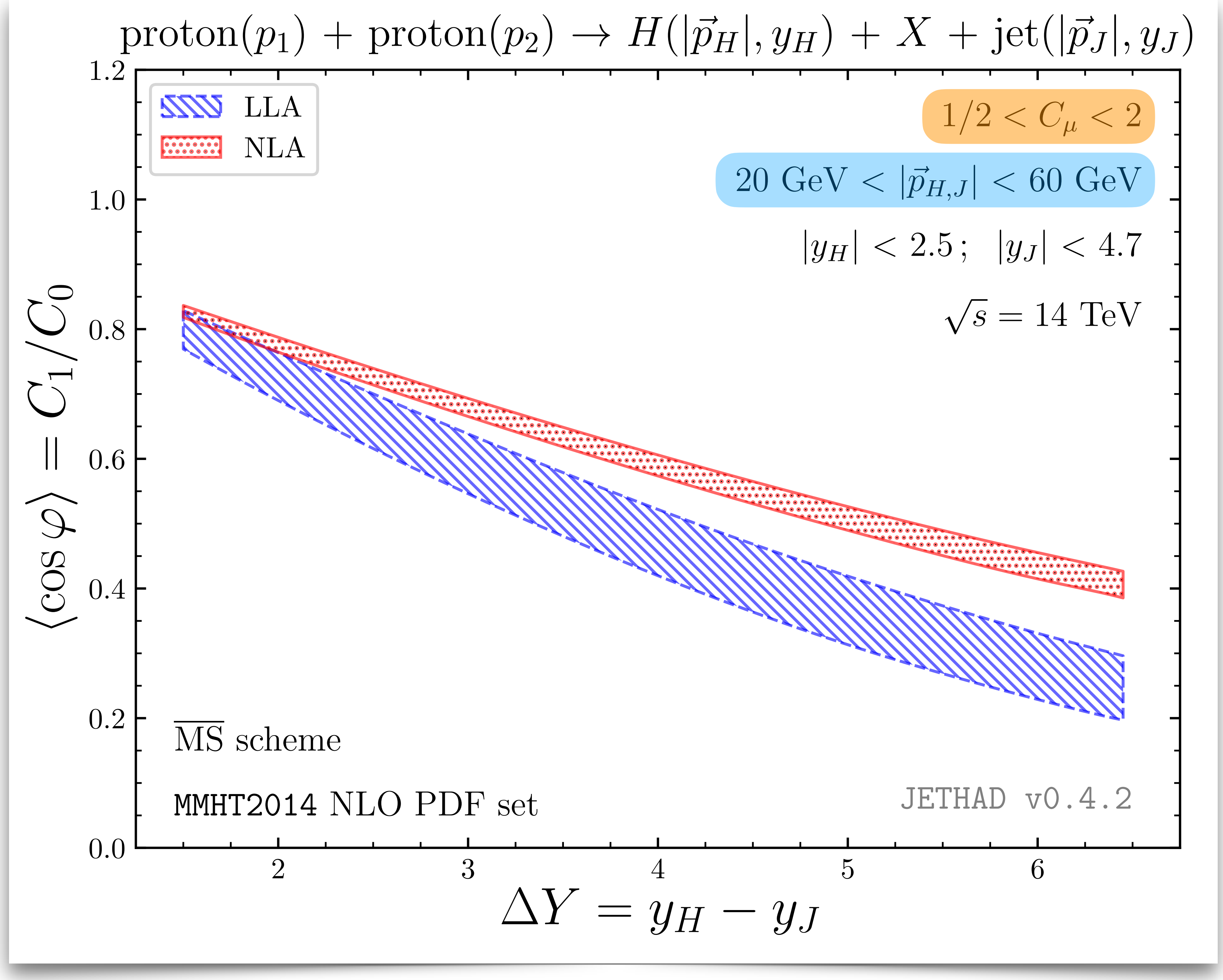


Higgs + jet

🔗 [F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]



natural scales

symmetric p_T range

φ-averaged cross section: C_0

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

Backup

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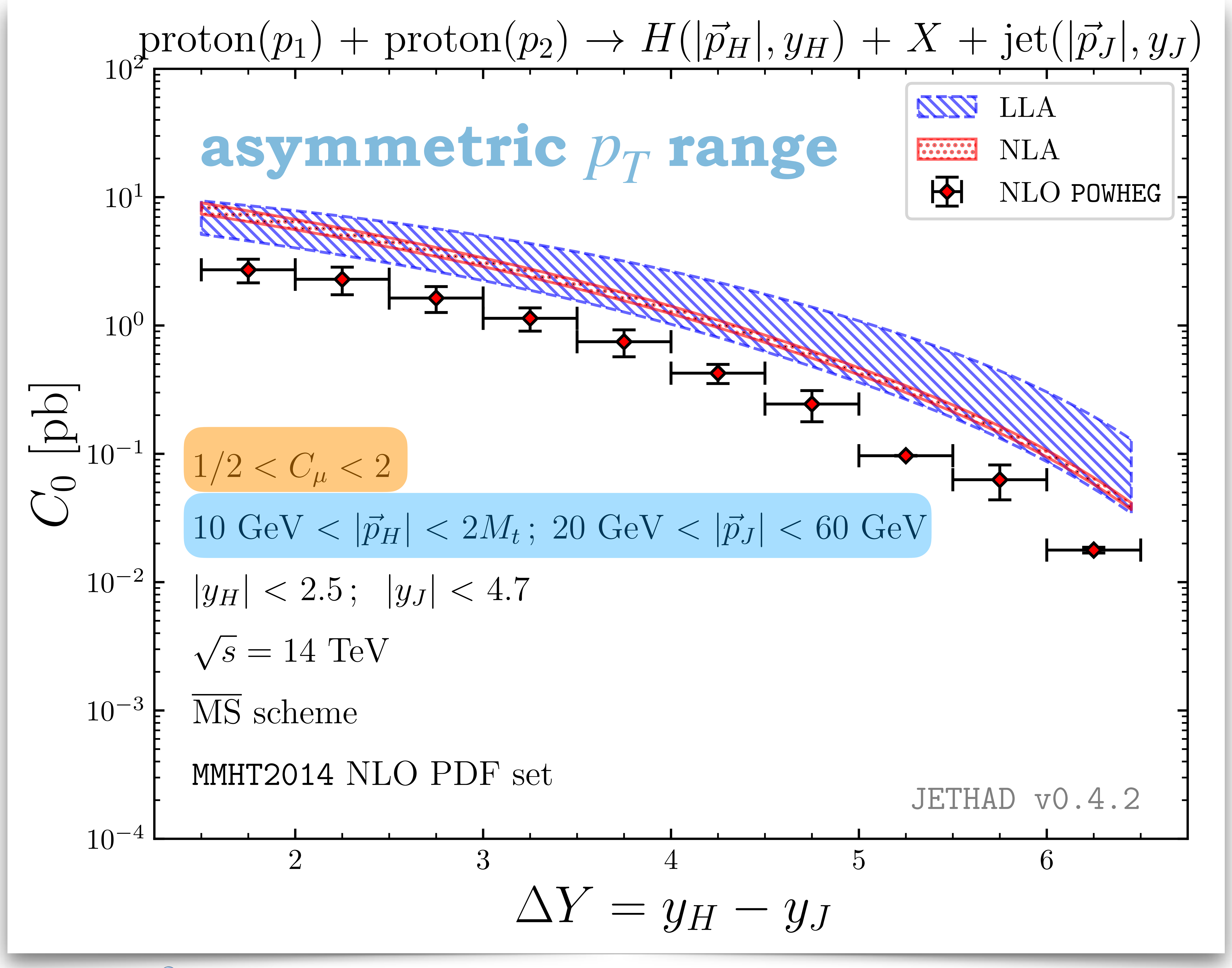
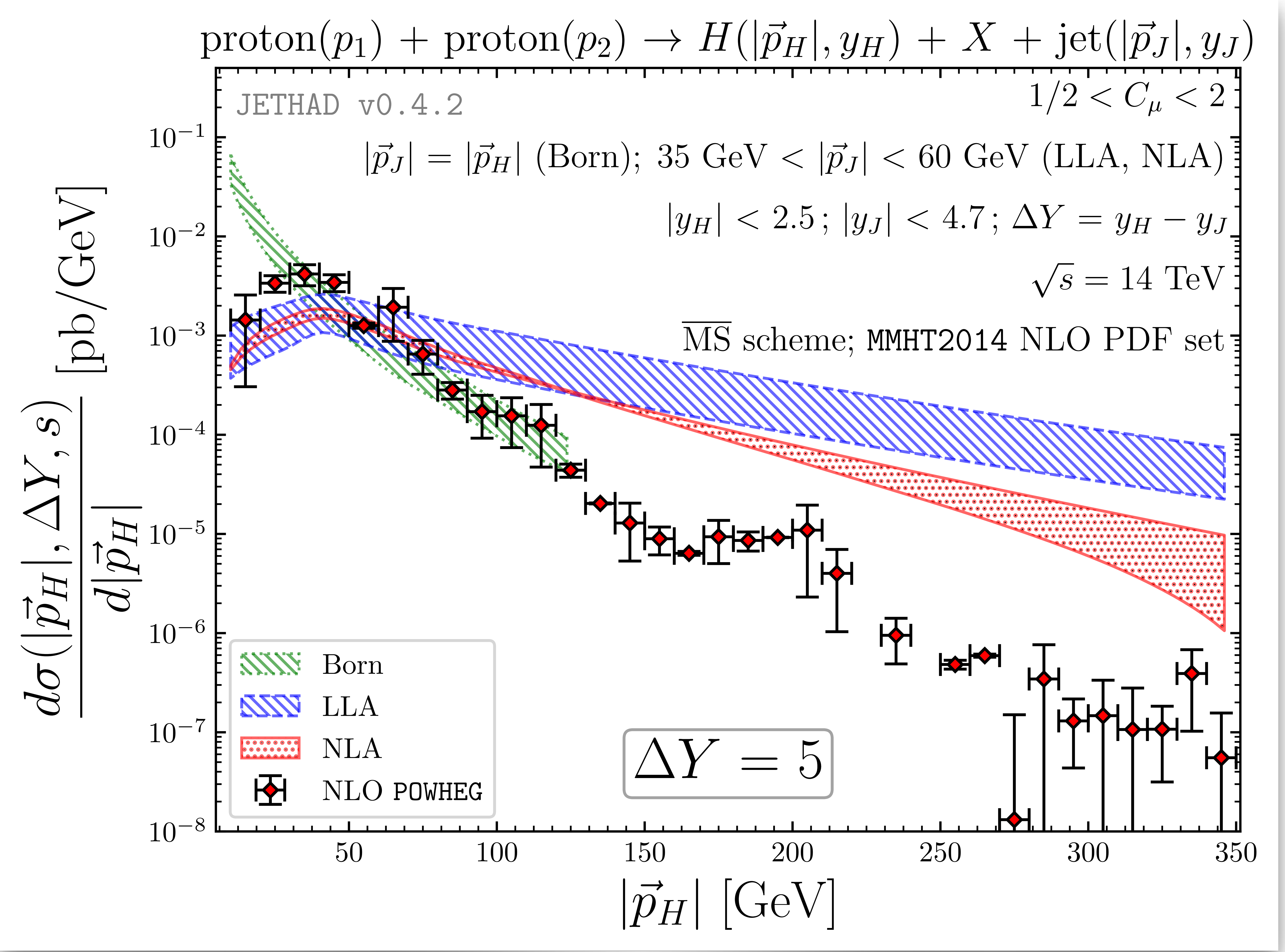


[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]

Backup

p_H-distribution: dC_0/dp_H

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



[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]

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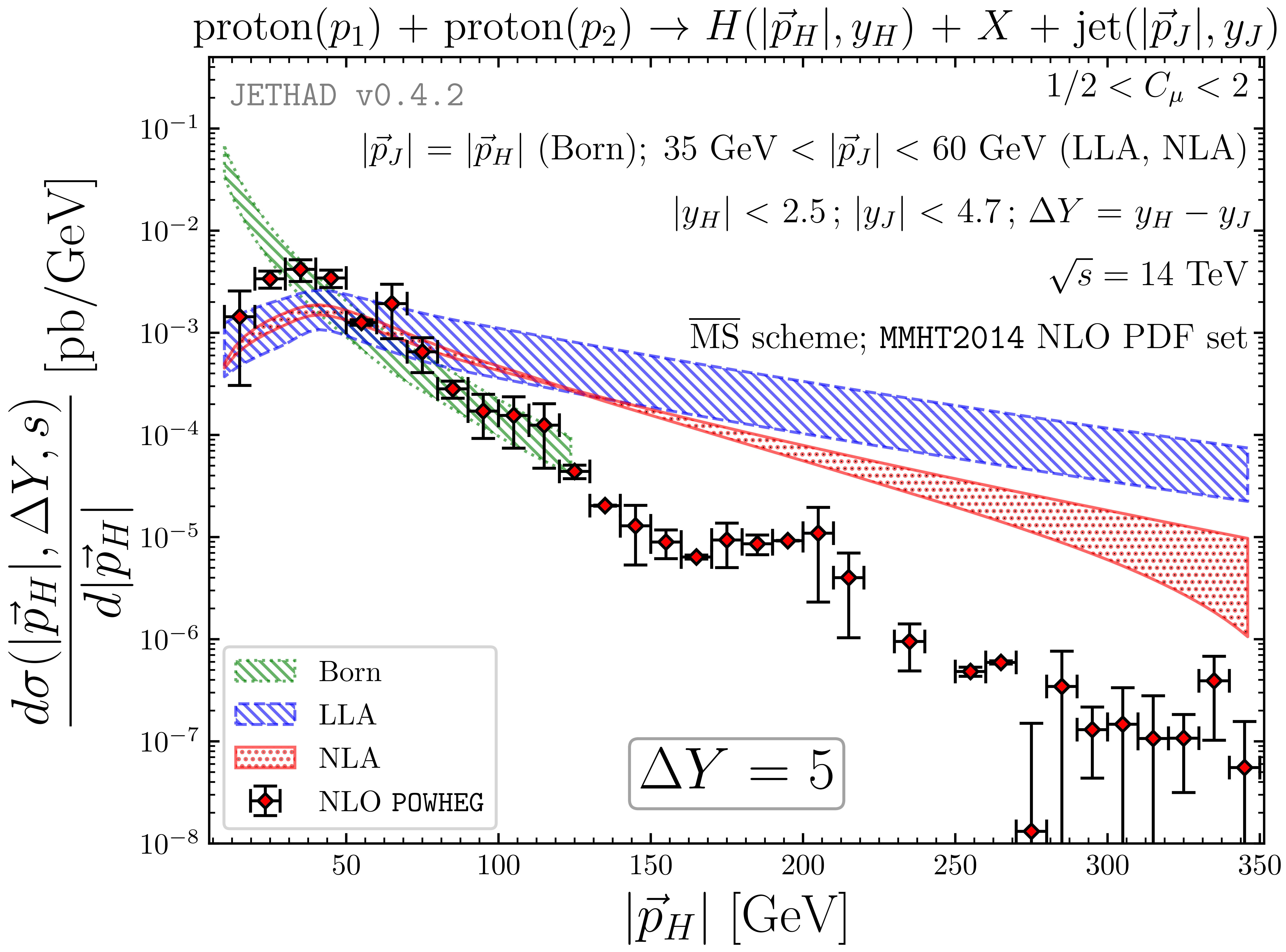

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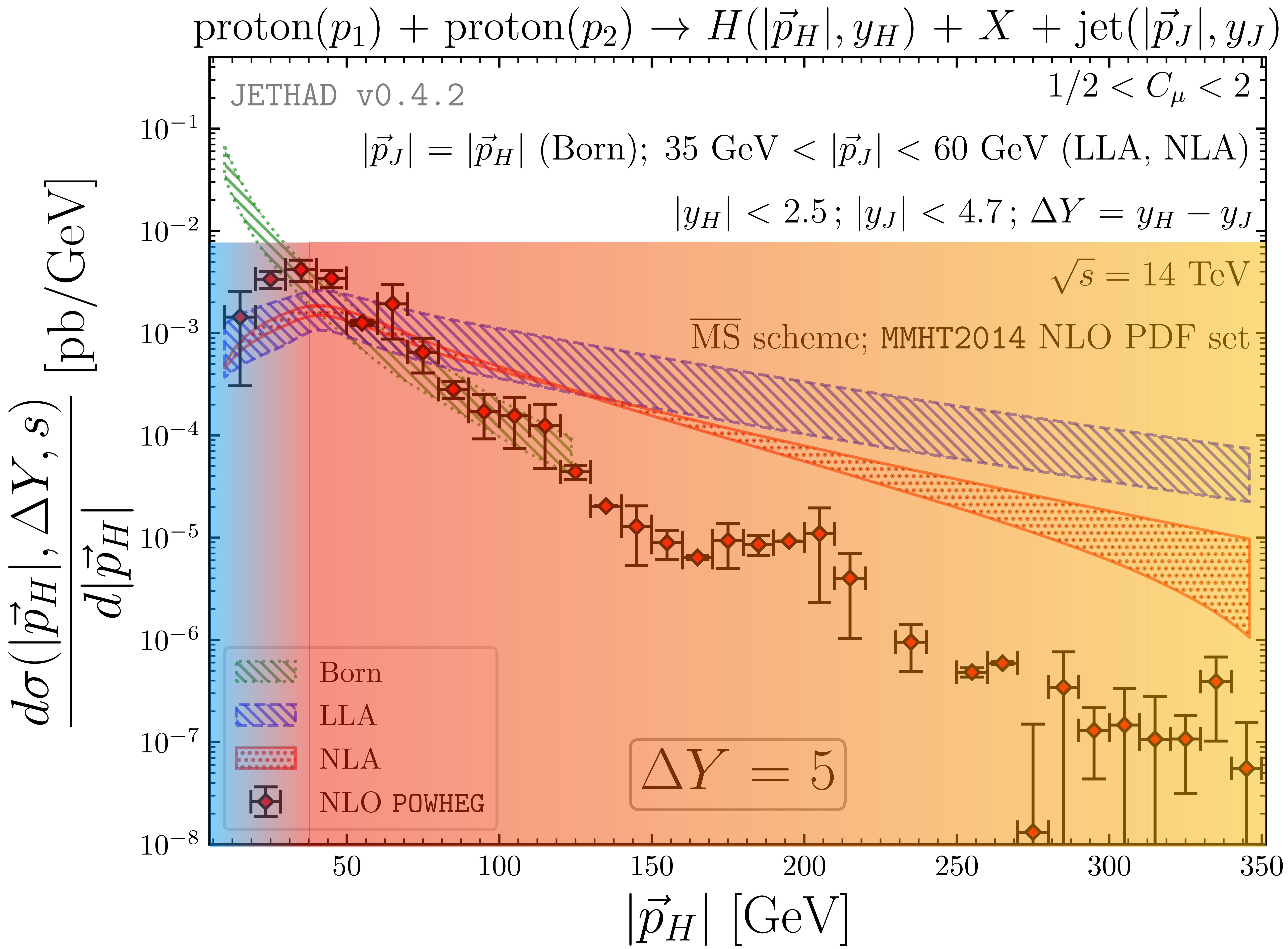
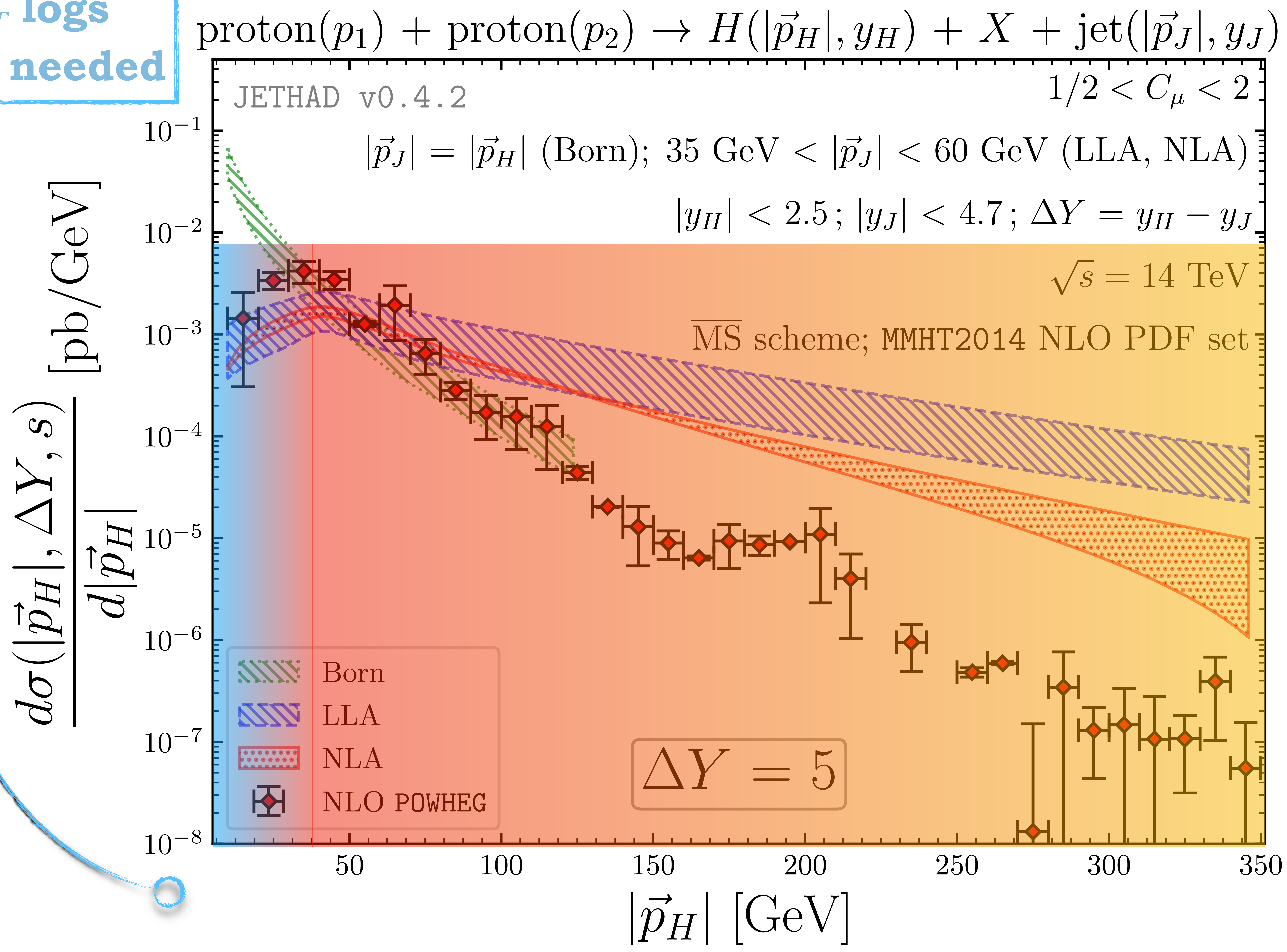


Backup

[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]

large p_T logs
p_T-resum. needed



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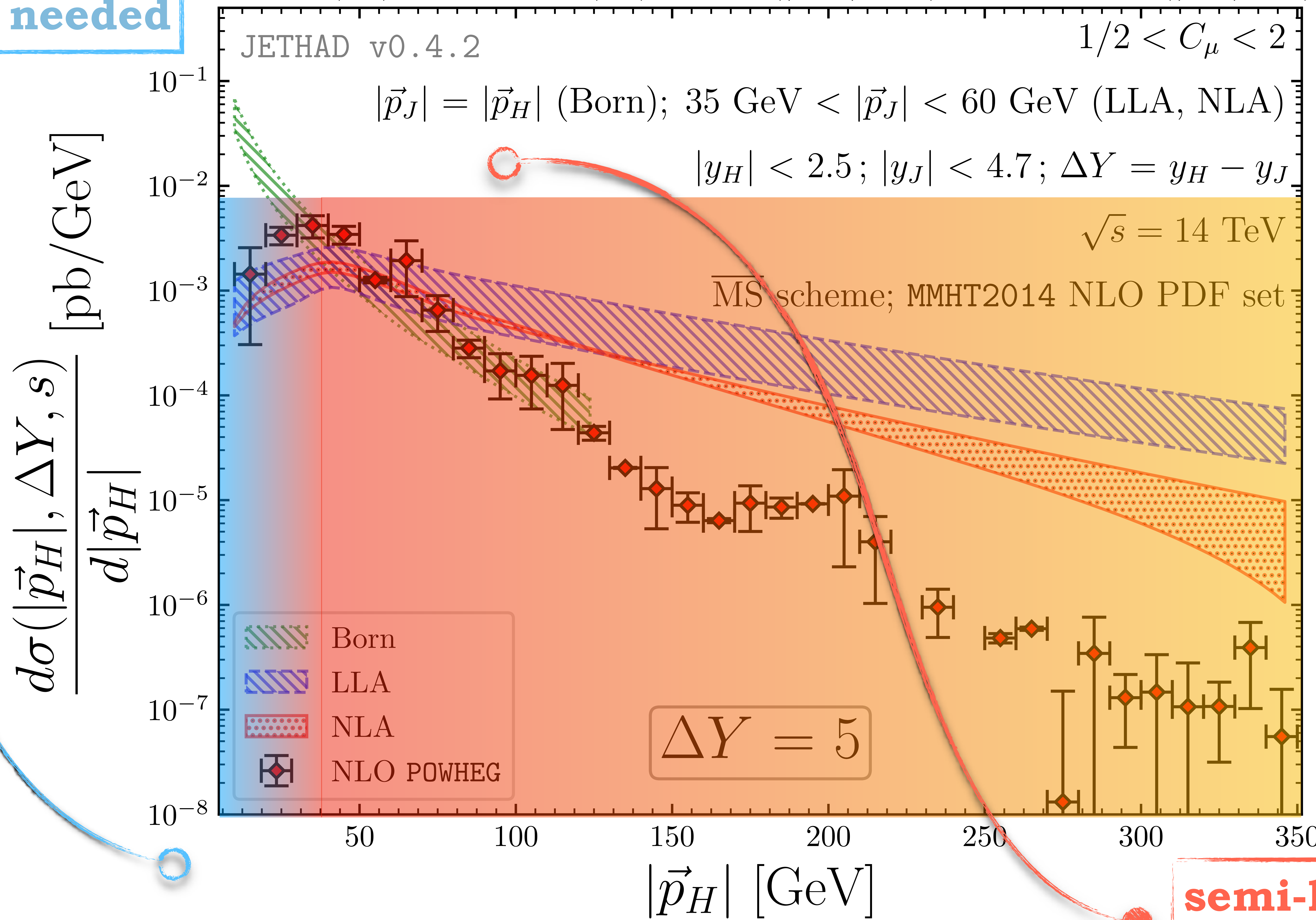
large p_T logs
p_T-resum. needed

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



semi-hard regime
BFKL expected

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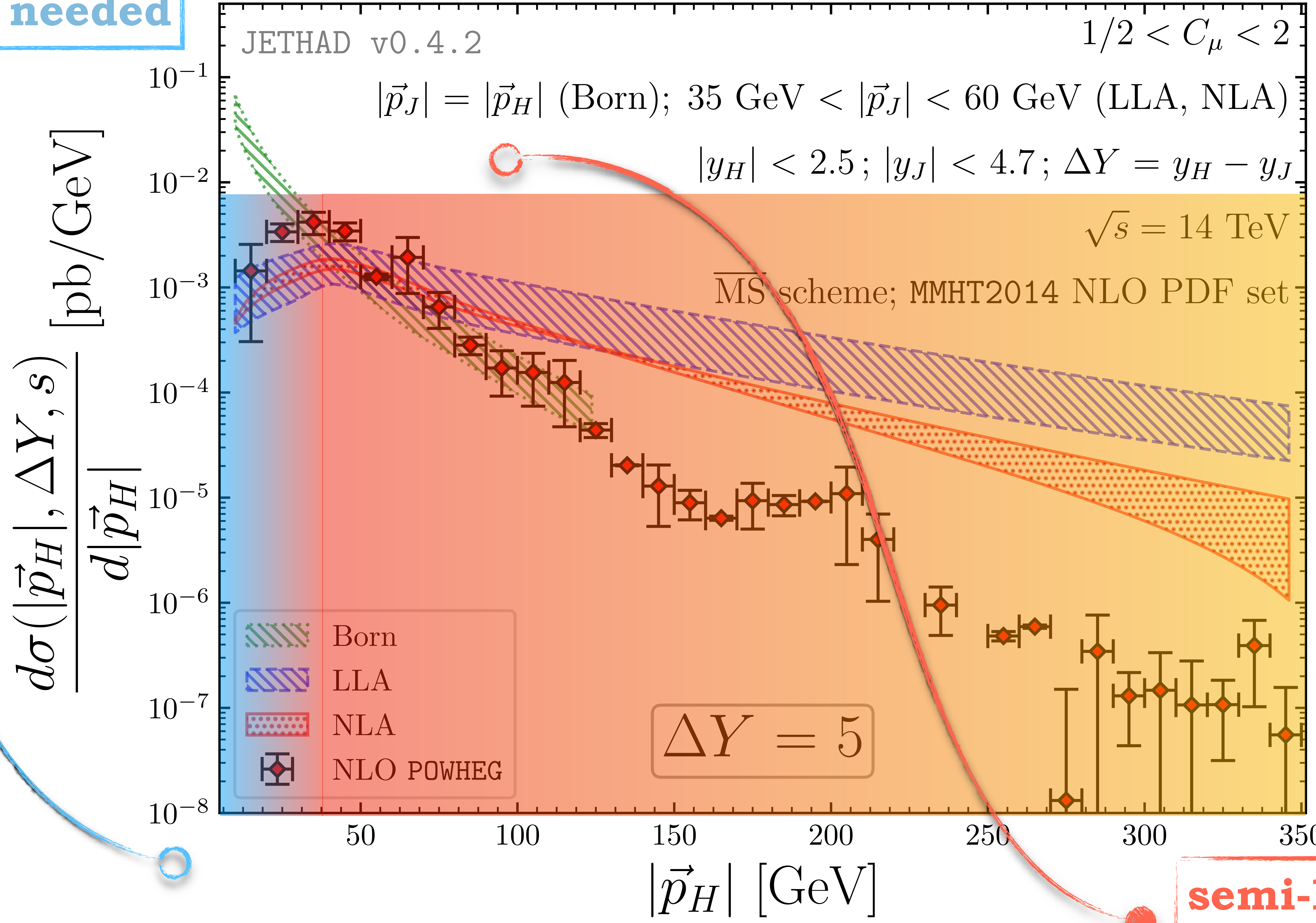
[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]

DGLAP-type + threshold logs → BFKL decoupling

large p_T logs
p_T-resum. needed

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



semi-hard regime
BFKL expected

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[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa (2021)]

p_H-distribution: $dC_0/dp_H\ (M_t \to +\infty)$

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

Backup

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Backup

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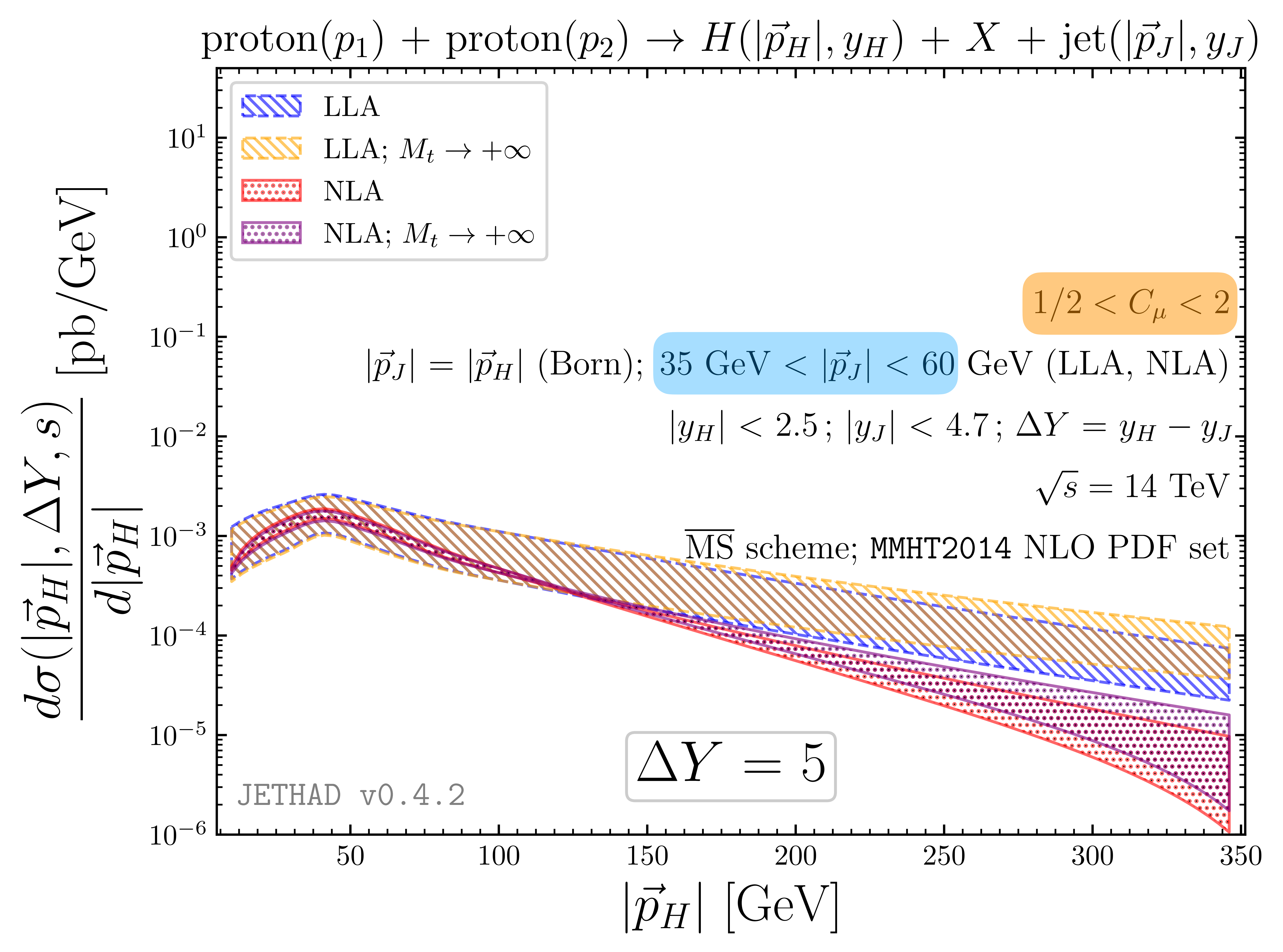


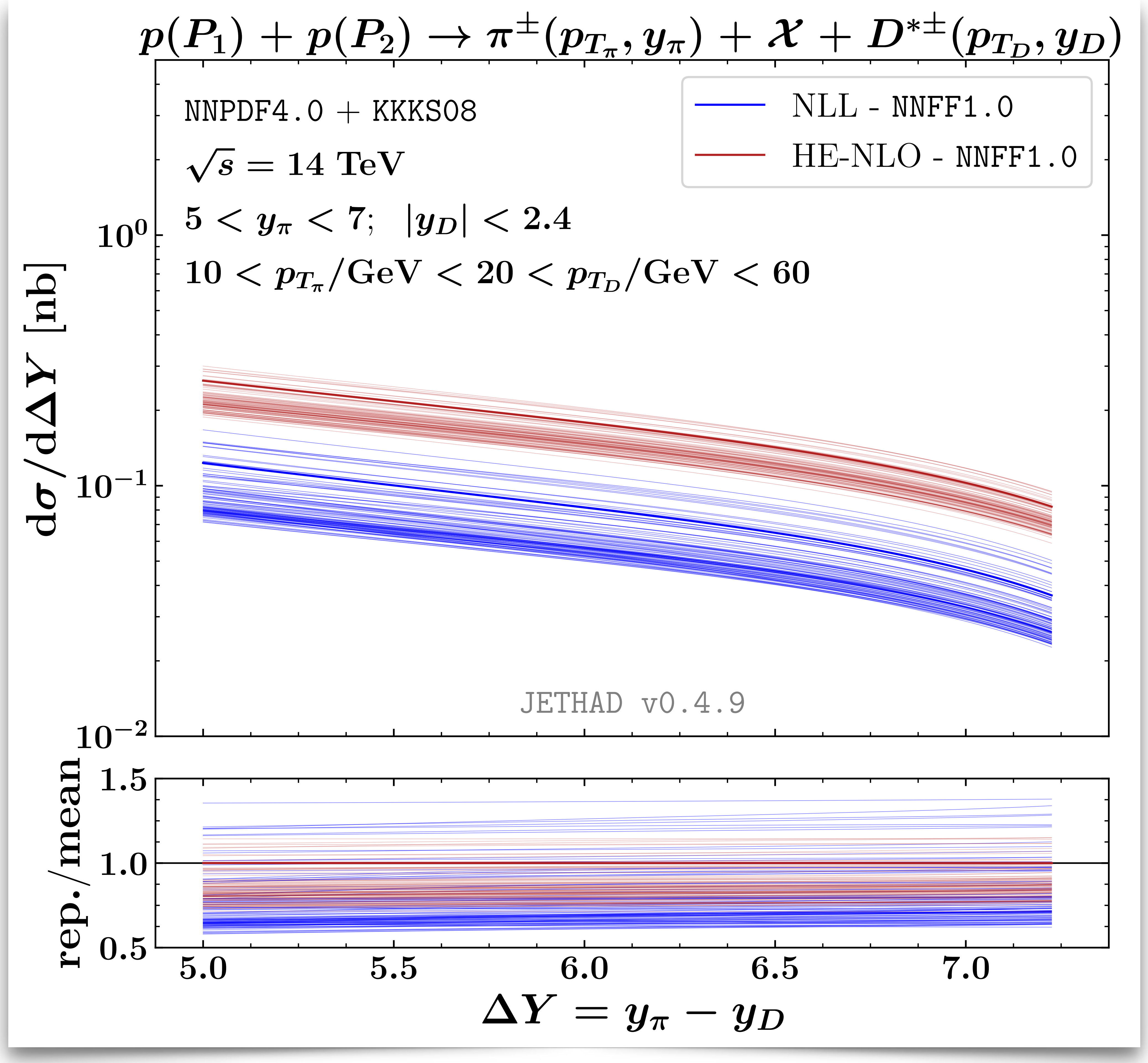
Backup

Rapidity distribution @FPF+ATLAS

Backup

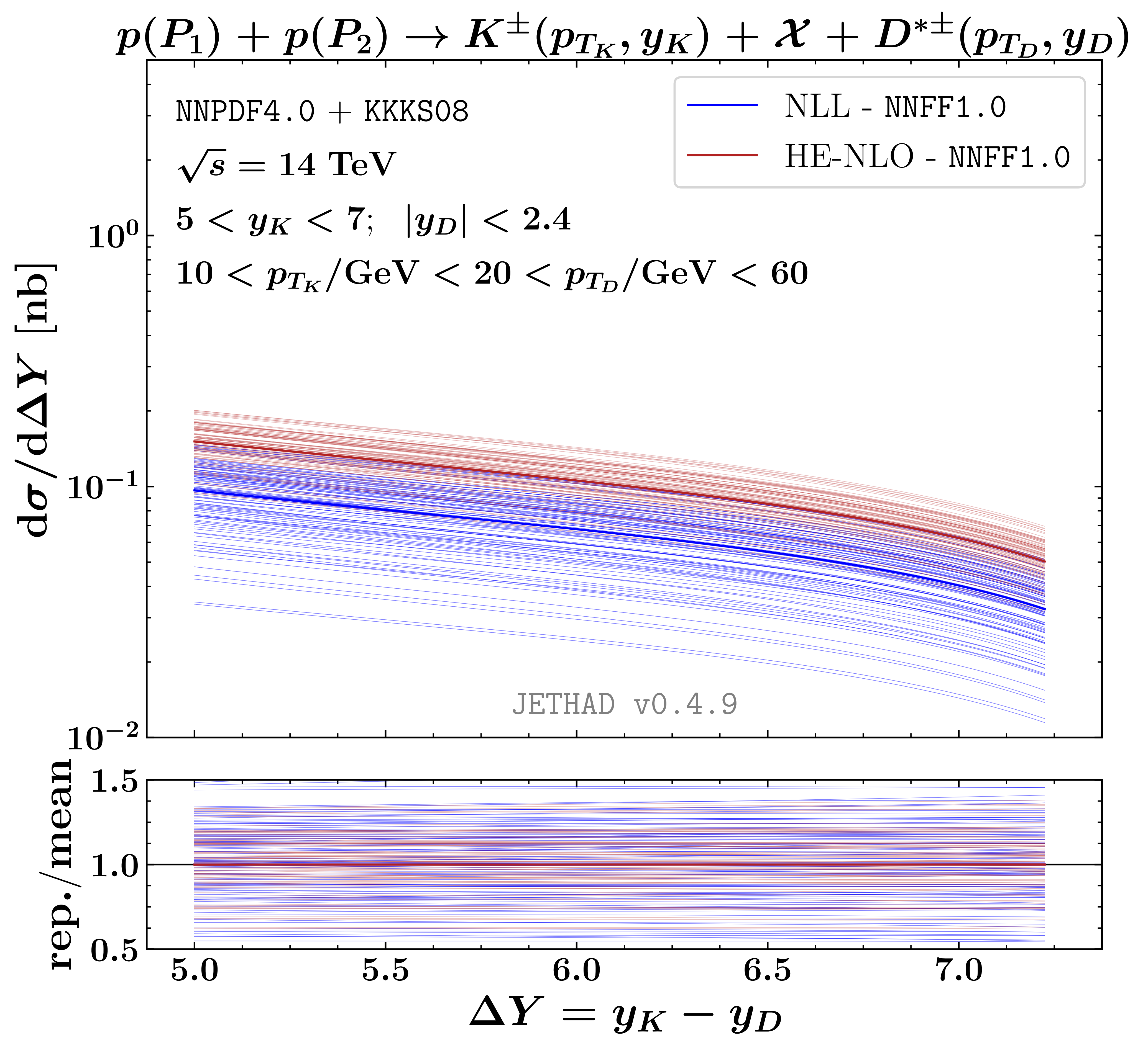
Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]



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

[FPF Snowmass Whitepaper]

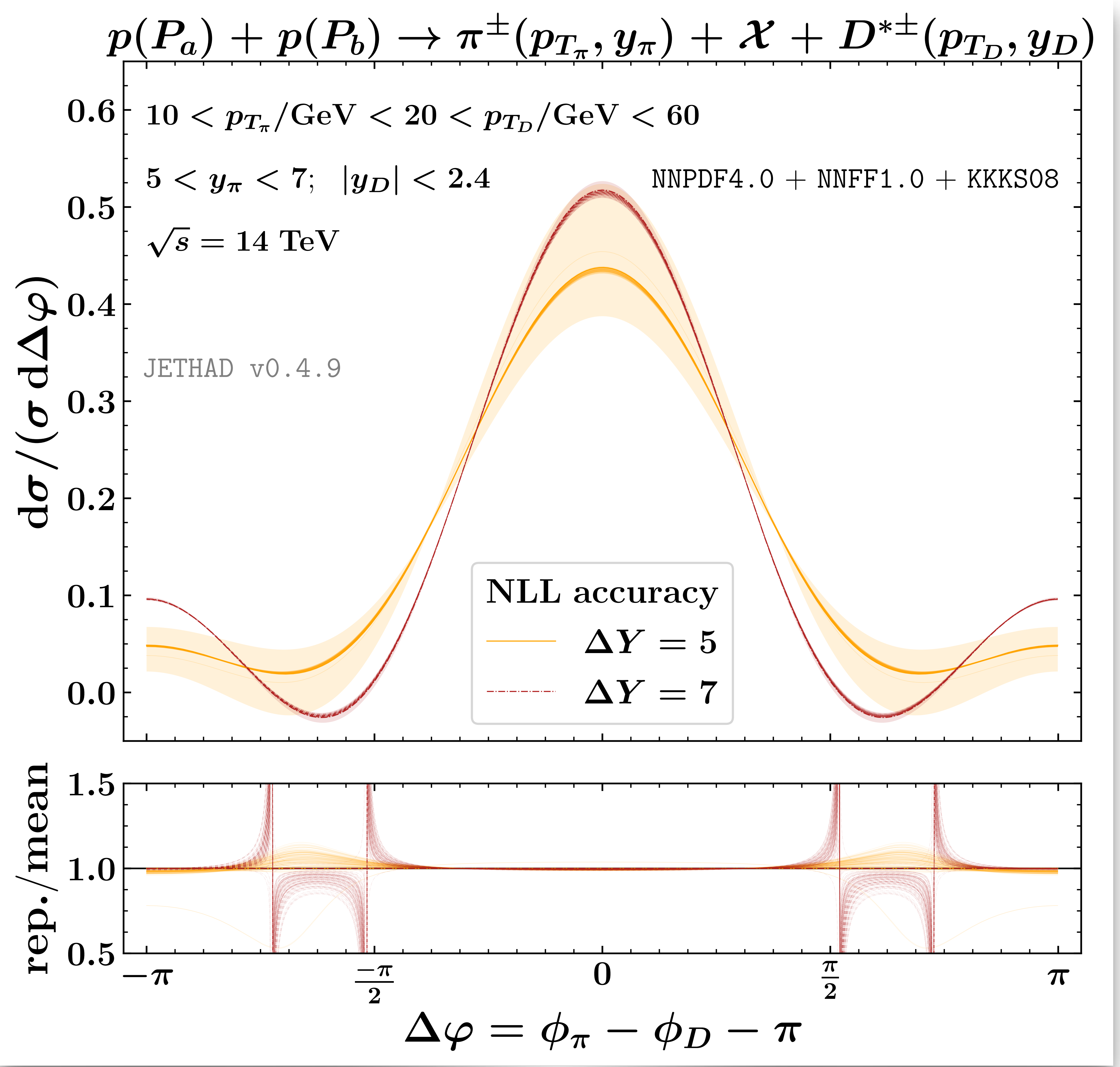


Azimuthal distribution @FPF+ATLAS

Backup

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

[FPF Snowmass Whitepaper]



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

[FPF Snowmass Whitepaper]