Inclusive Higgs + jet

EF01 Working Group Meeting - SM21

Francesco Giovanni Celiberto

ECT* Trento & INFN-TIFPA

Based on 🔗 [F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa [arXiv:2008.00501]],
to appear in *Eur. Phys. J. C*

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

FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

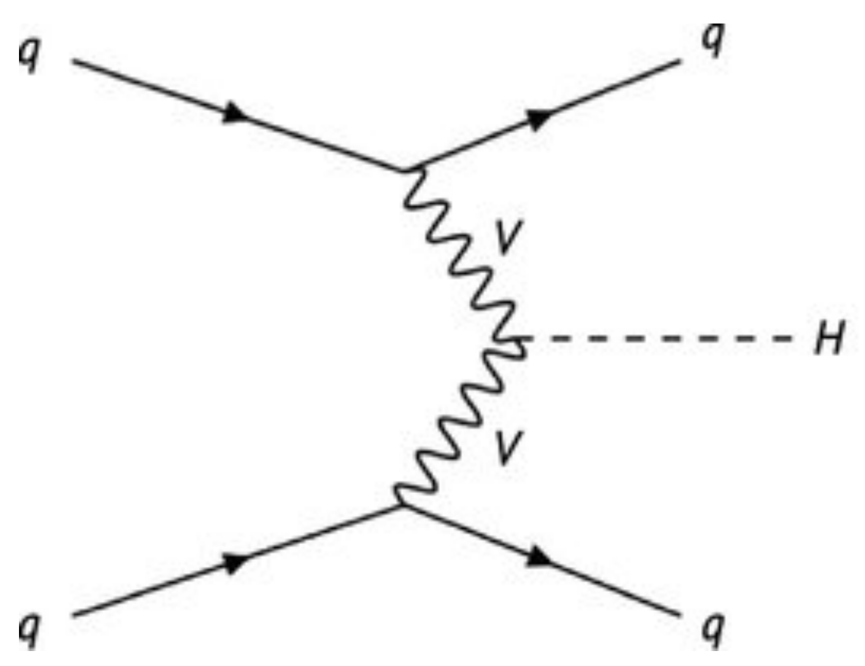
TIFPA Trento Institute for Fundamental Physics and Applications

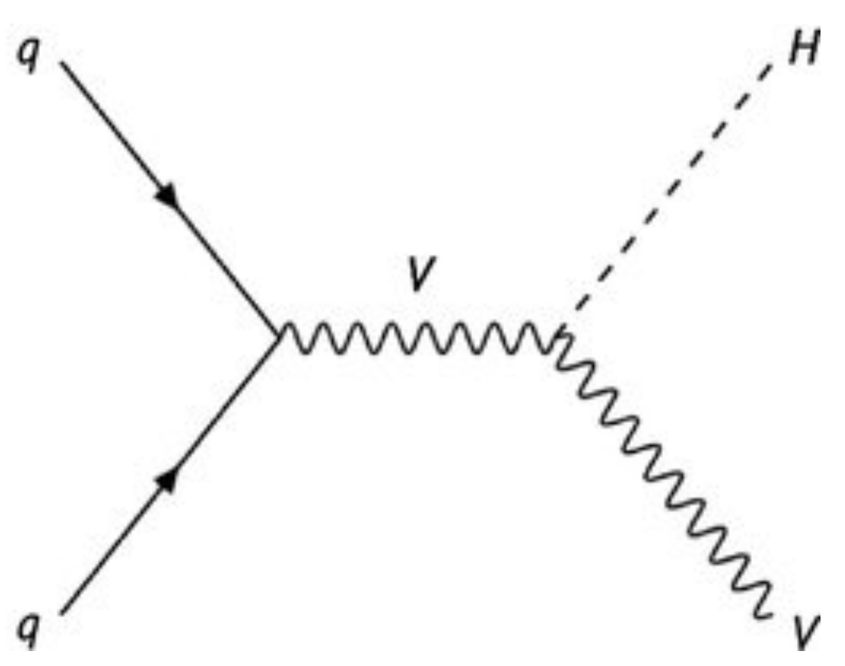
HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

Higgs sector(s): properties & production

Electroweak

* Golden channel to investigate Higgs decays
* VBF as extractor of *HWW* and *HZZ* couplings
* EWSB and CP studies
* Higgs with associated production of jets





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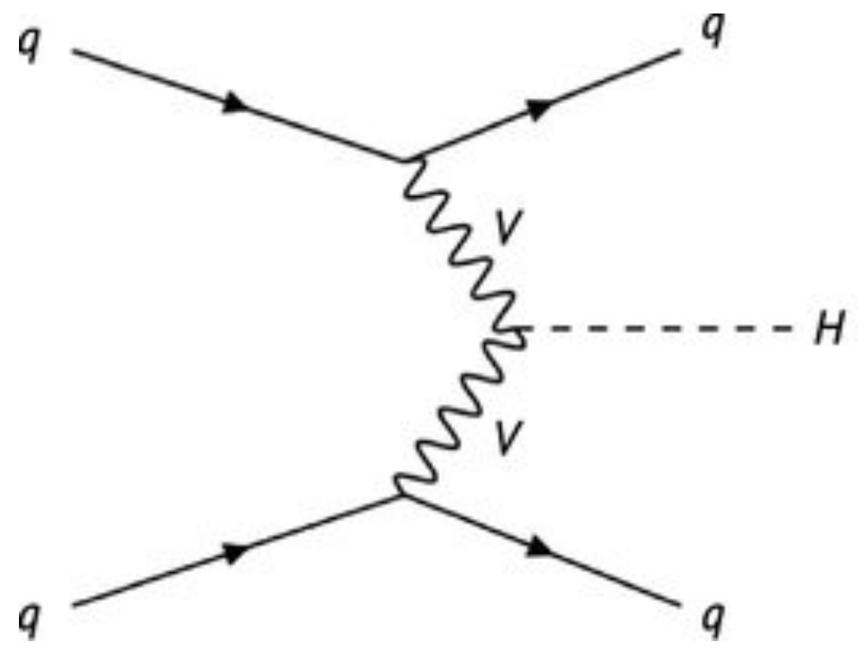
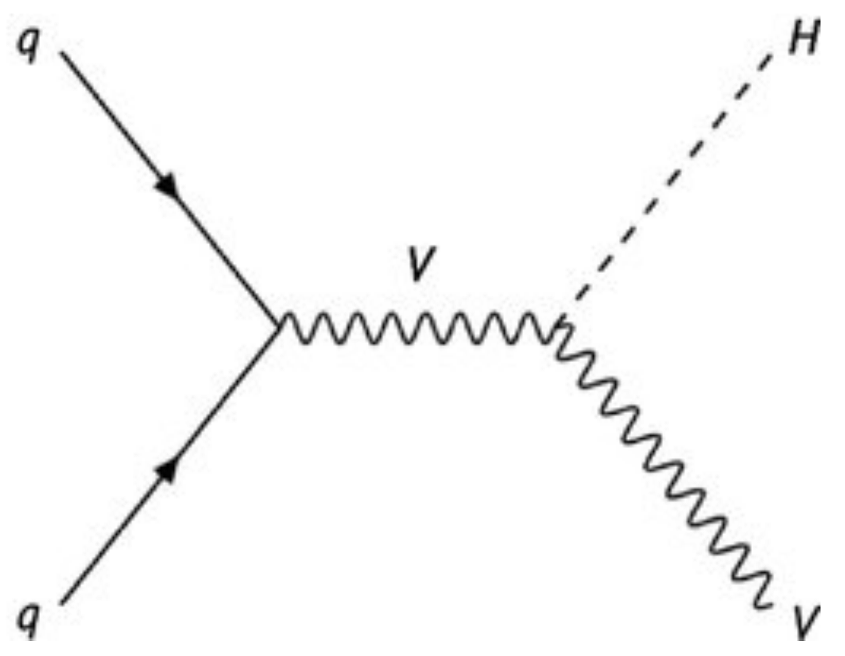
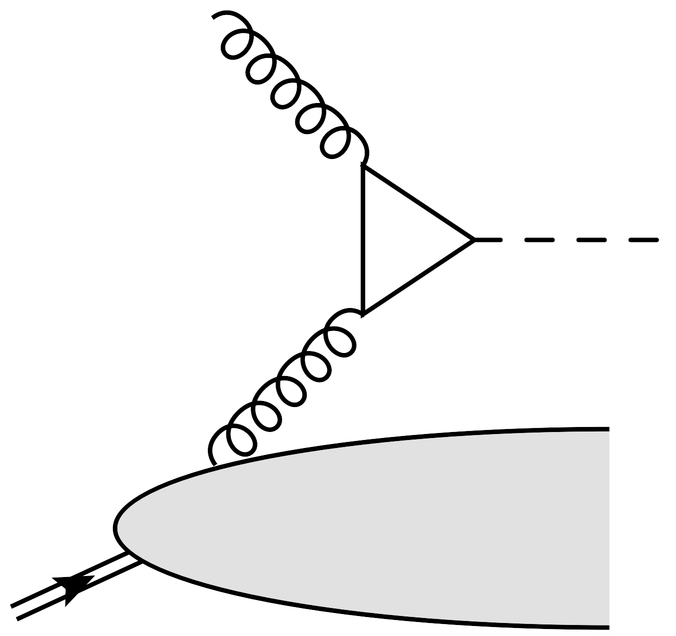
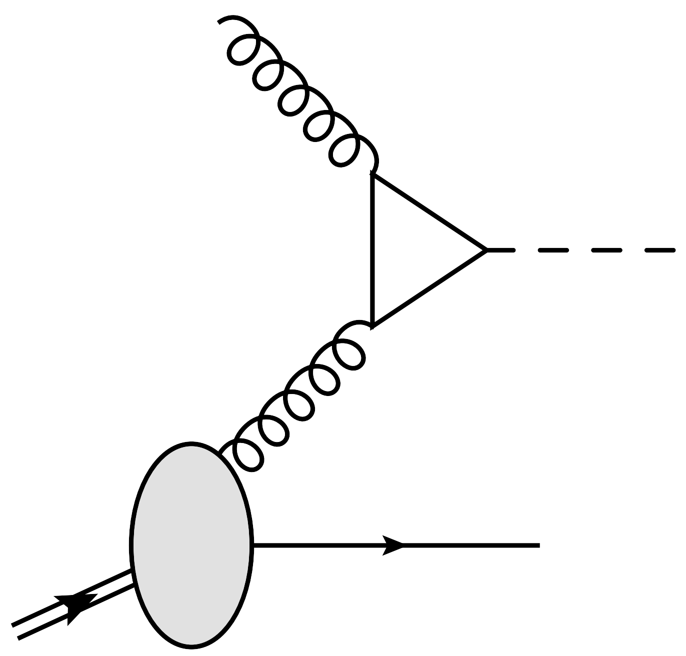




QCD gluon fusion

* Key ingredient for differential distributions
* Stringent tests of pQCD ↔ **resummations**
* Inclusive Higgs → hadronic structure (TMD)
* Inclusive Higgs + jet → high-energy QCD





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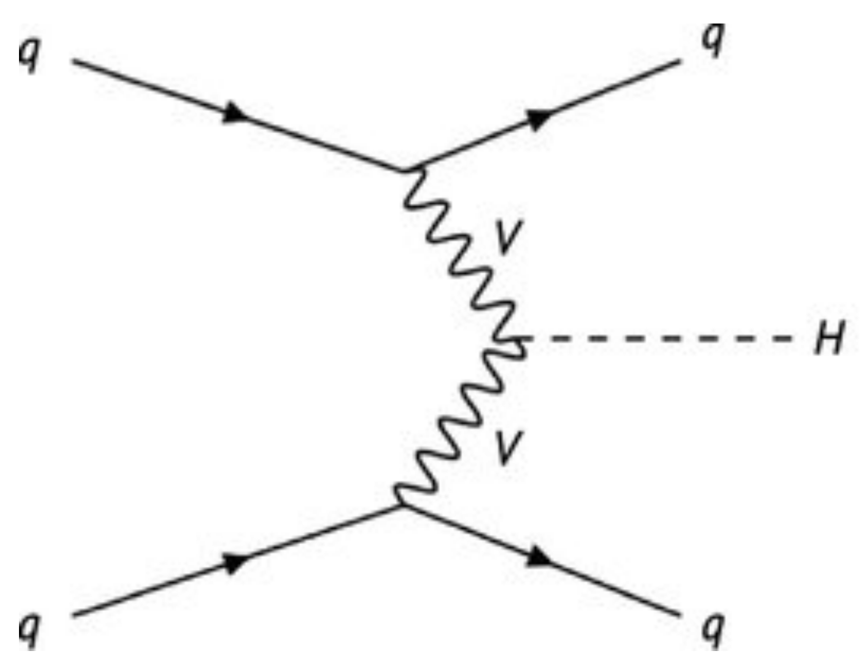

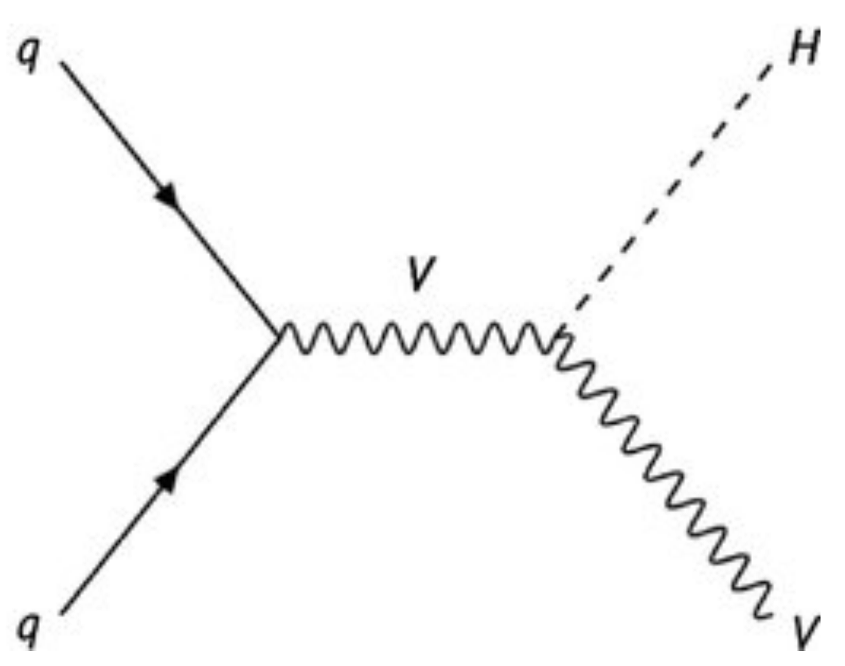

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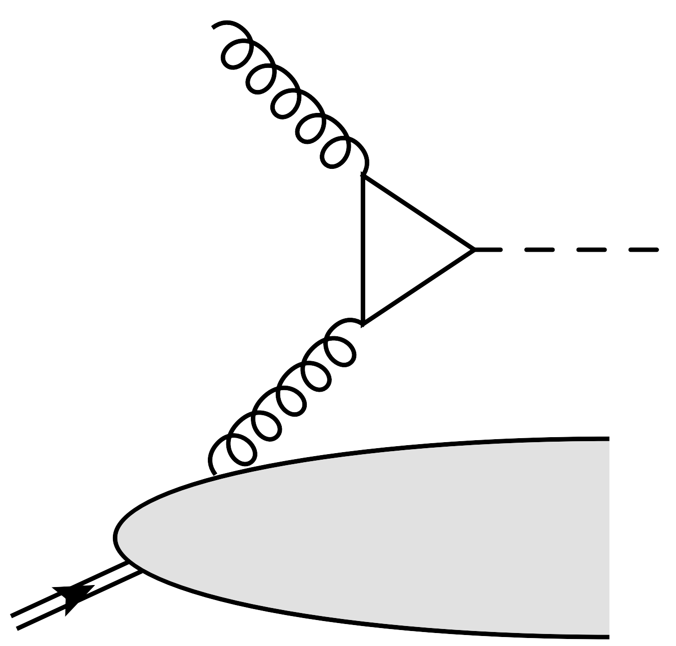
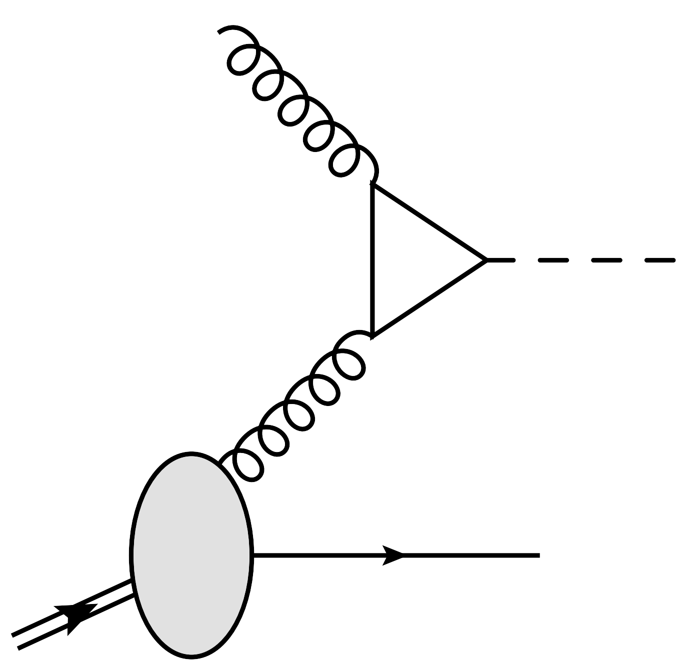




The high-energy resummation

- Enhanced *energy single logs* in fixed-order description of high-energy (HE) collisions
- Convergence of perturbative series spoiled when $\alpha_s \ln(s) \sim 1$
- *All-order resummation* $\rightarrow$ **BFKL** approach at LLA: $\alpha_s^n \ln(s)^n$, and NLA: $\alpha_s^{n+1} \ln(s)^n$
- *Golden channels* $\rightarrow$ **diffractive semi-hard reactions**: $s \gg \{Q^2\} \gg \Lambda_{\rm QCD}$
- HE resum. $\rightarrow$ essential ingredient to study production mechanisms of particles
- Parton content of proton at small-x $\rightarrow$ BFKL **UGD**, resummed PDFs, small-x TMDs

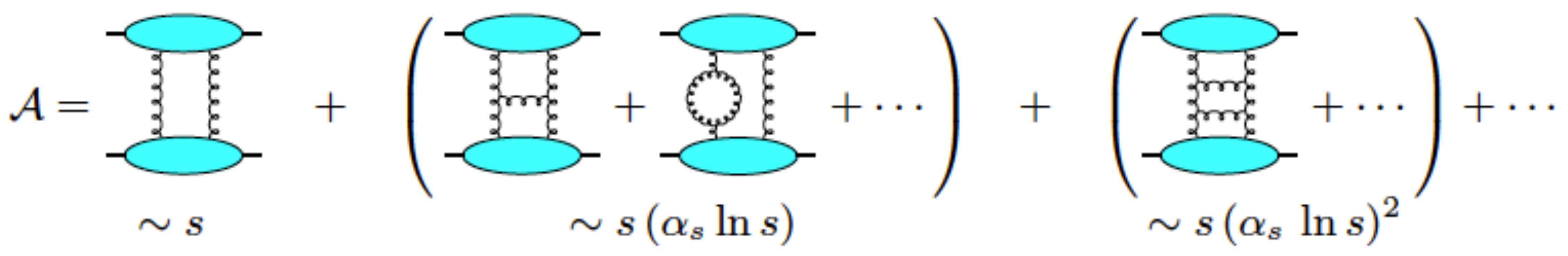
The high-energy resummation

The BFKL resummation

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

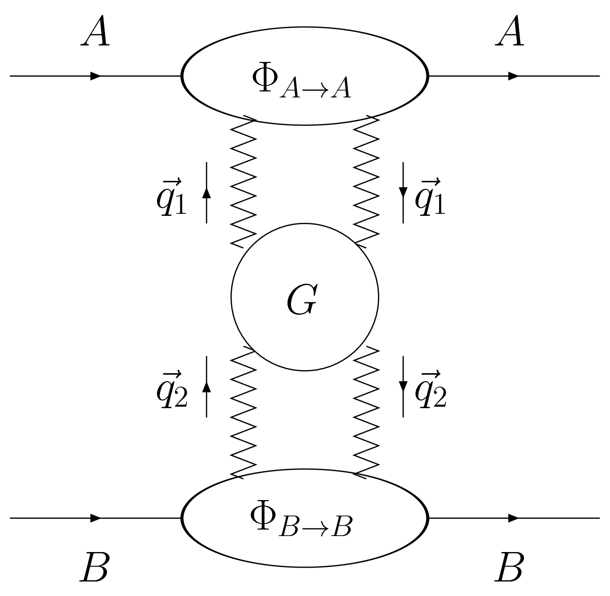
$\xrightarrow{\text{based on}}$ **gluon Reggeization**

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



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

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



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

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

The high-energy resummation

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

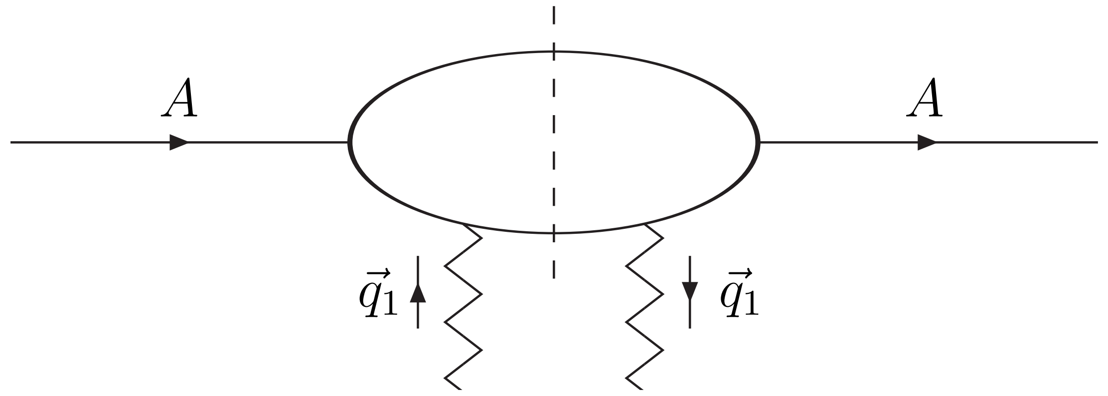
- **Green's function** is **process-independent** and takes care of the **energy dependence**

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

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

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

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



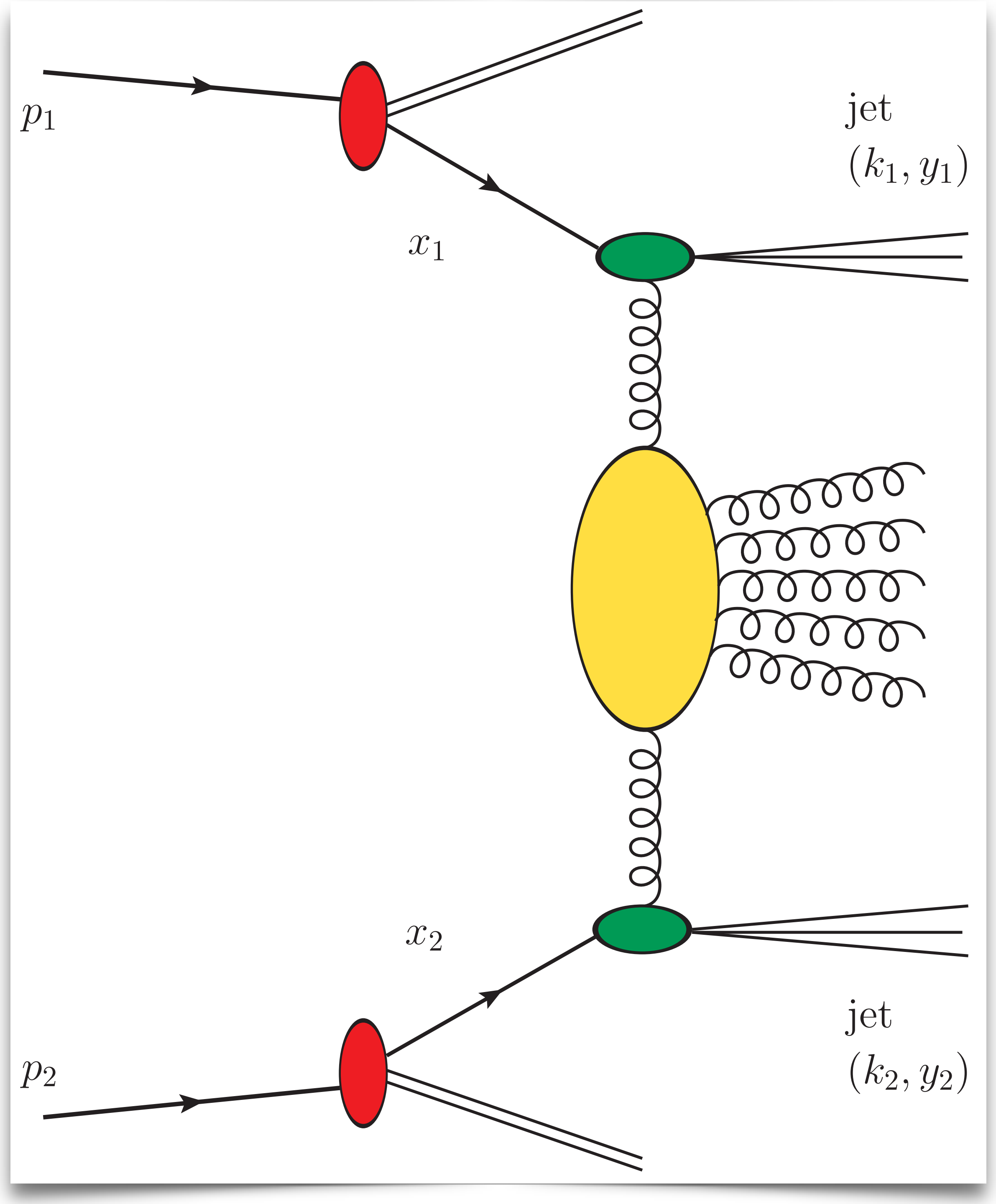
- Successful tests of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

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

Mueller-Navelet jets: hybrid factorization

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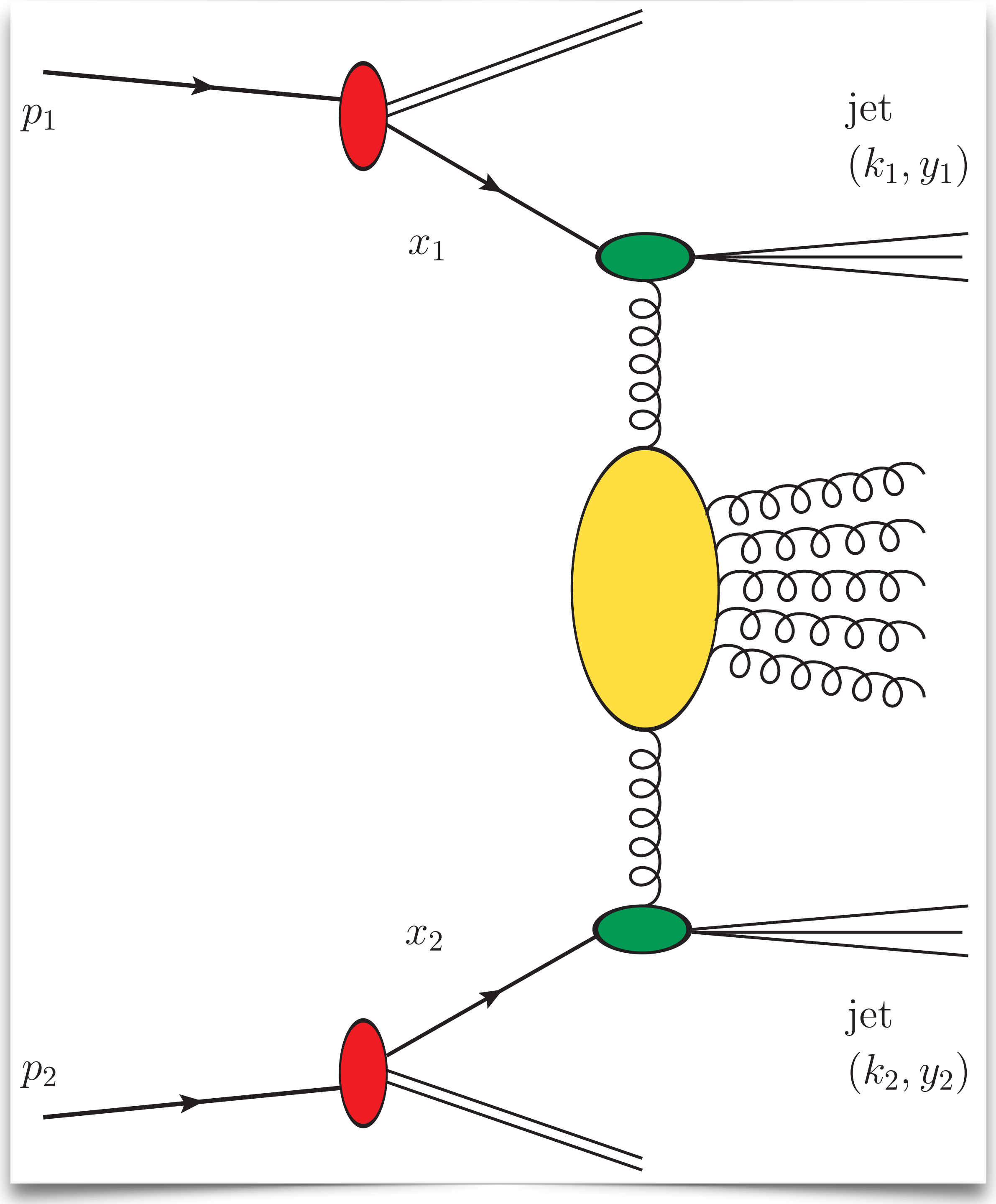

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \frac{1}{(2\pi)^2}$$
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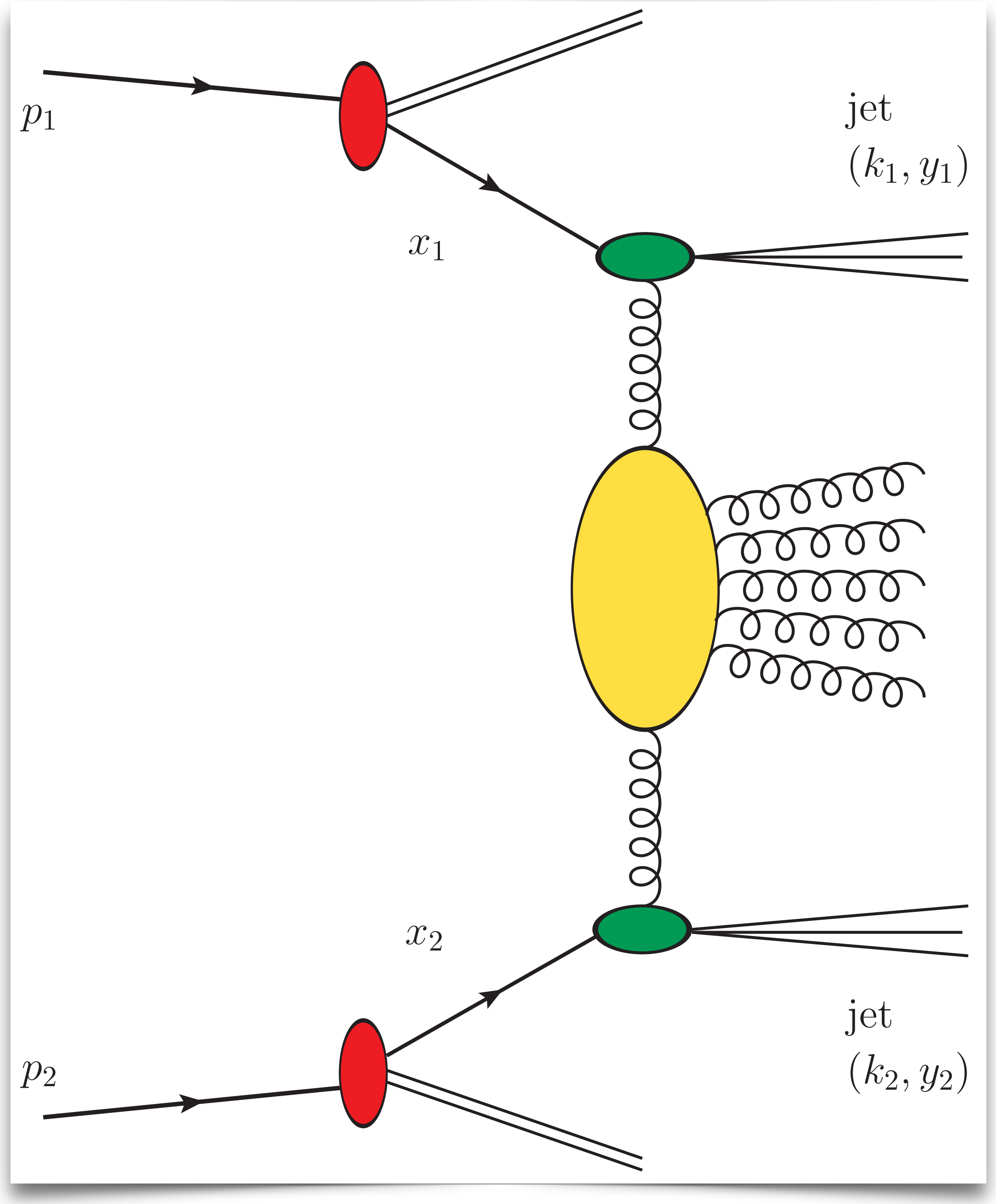

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jet vertices (off-shell amplitudes)

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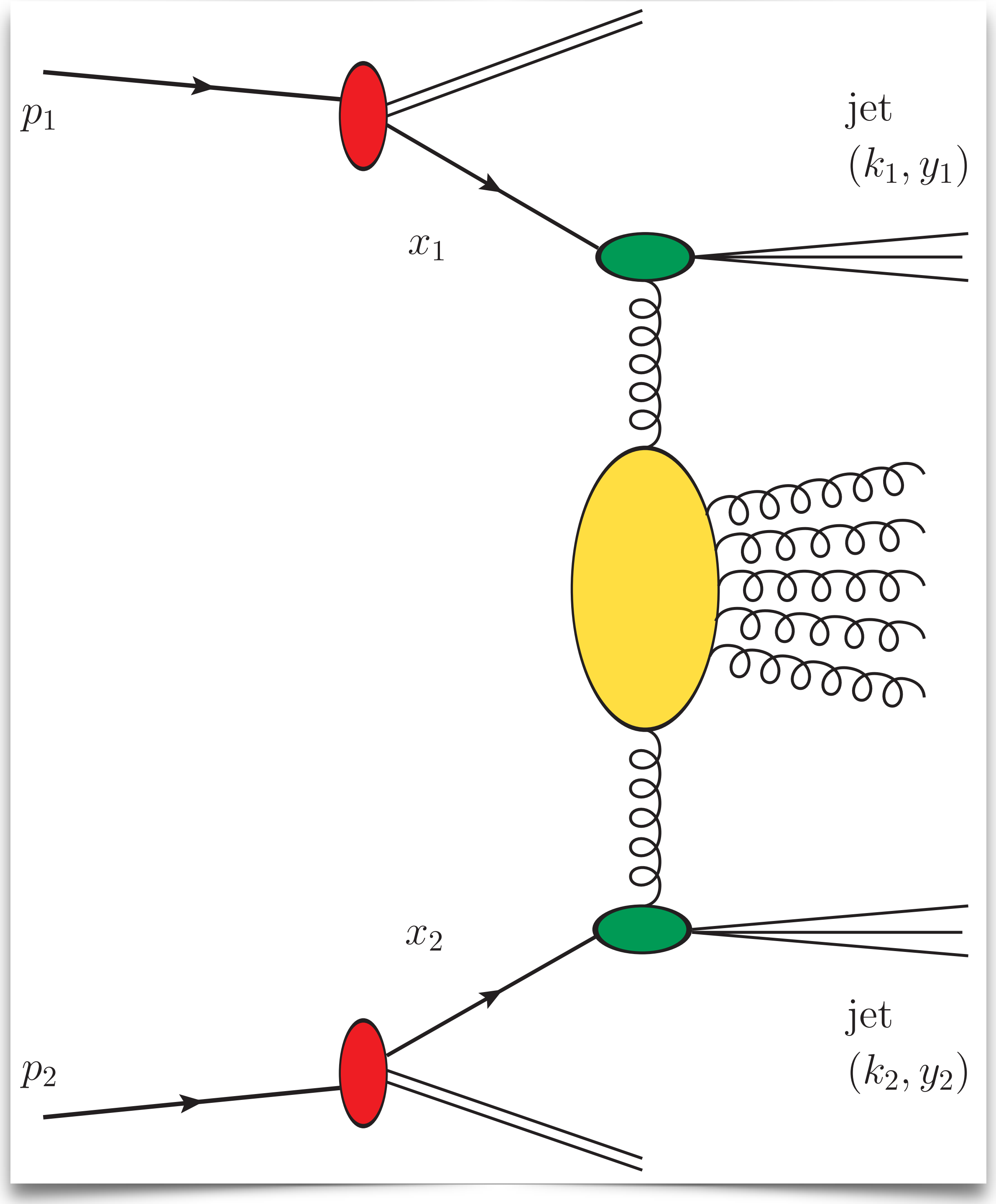

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Inclusive Higgs + jet

Resummed distributions

Closing statements

Mueller-Navelet jets: theory vs experiment

- Possibility to define *infrared-safe* observables and constrain PDFs
- Theory vs experiment: CMS @7TeV with **symmetric** p_T-ranges, **only!**
- LHC kinematic domain *in between* the sectors described by BFKL and DGLAP
- Clearer manifestations of high-energy signatures expected at increasing energies
- Need for *more exclusive* final states as well as *more sensitive* observables
- Strong manifestation of higher-order

  instabilities via *scale variation* (¡!)

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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

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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

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

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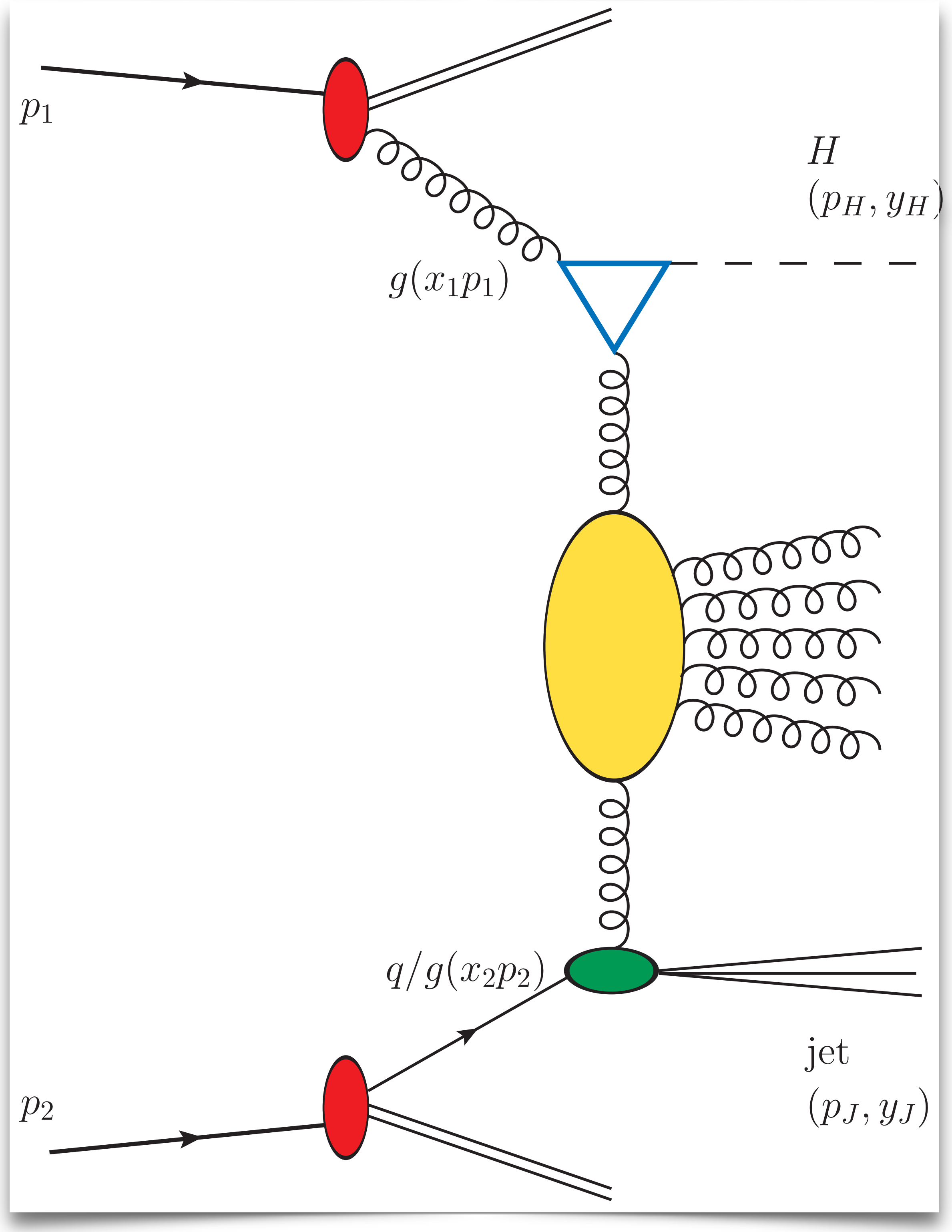

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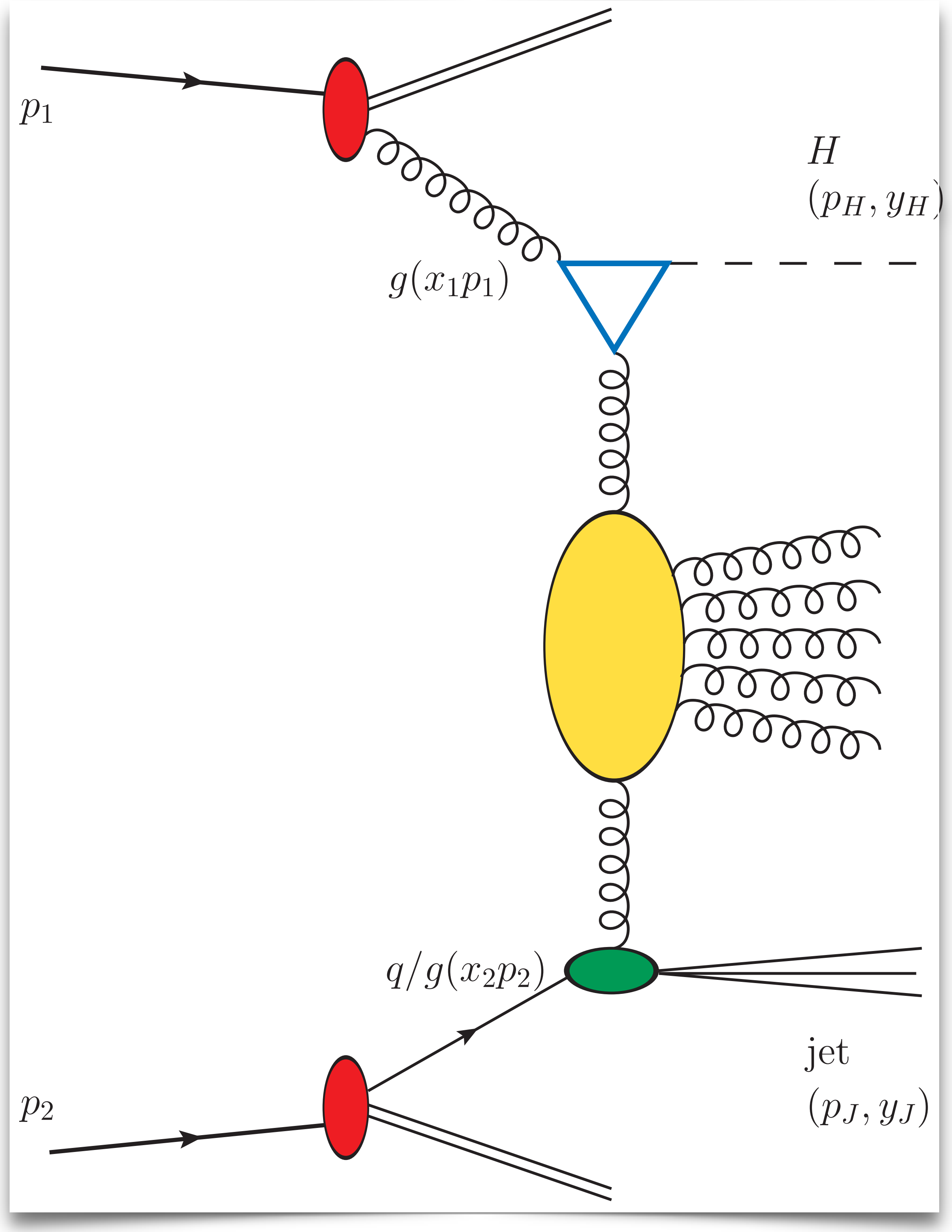

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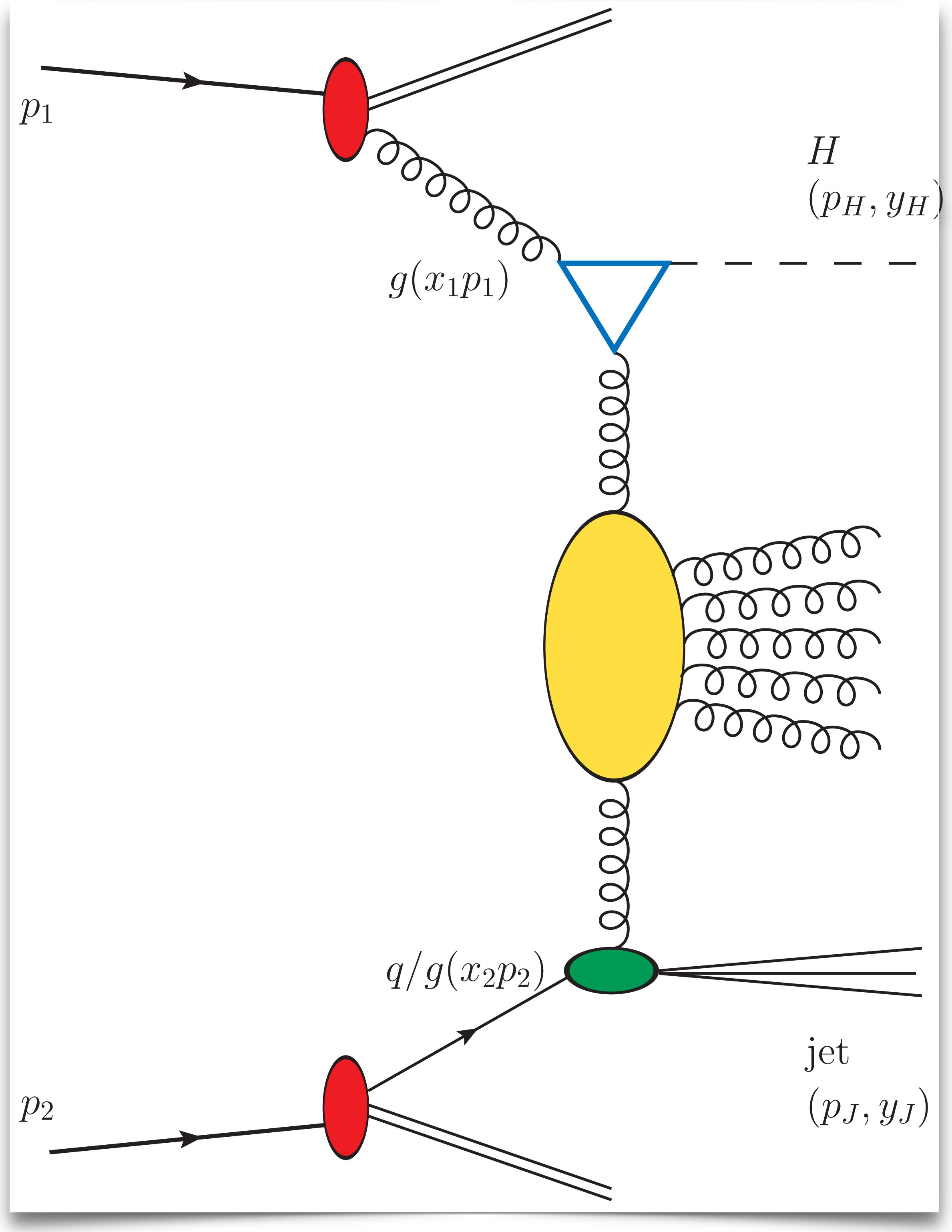

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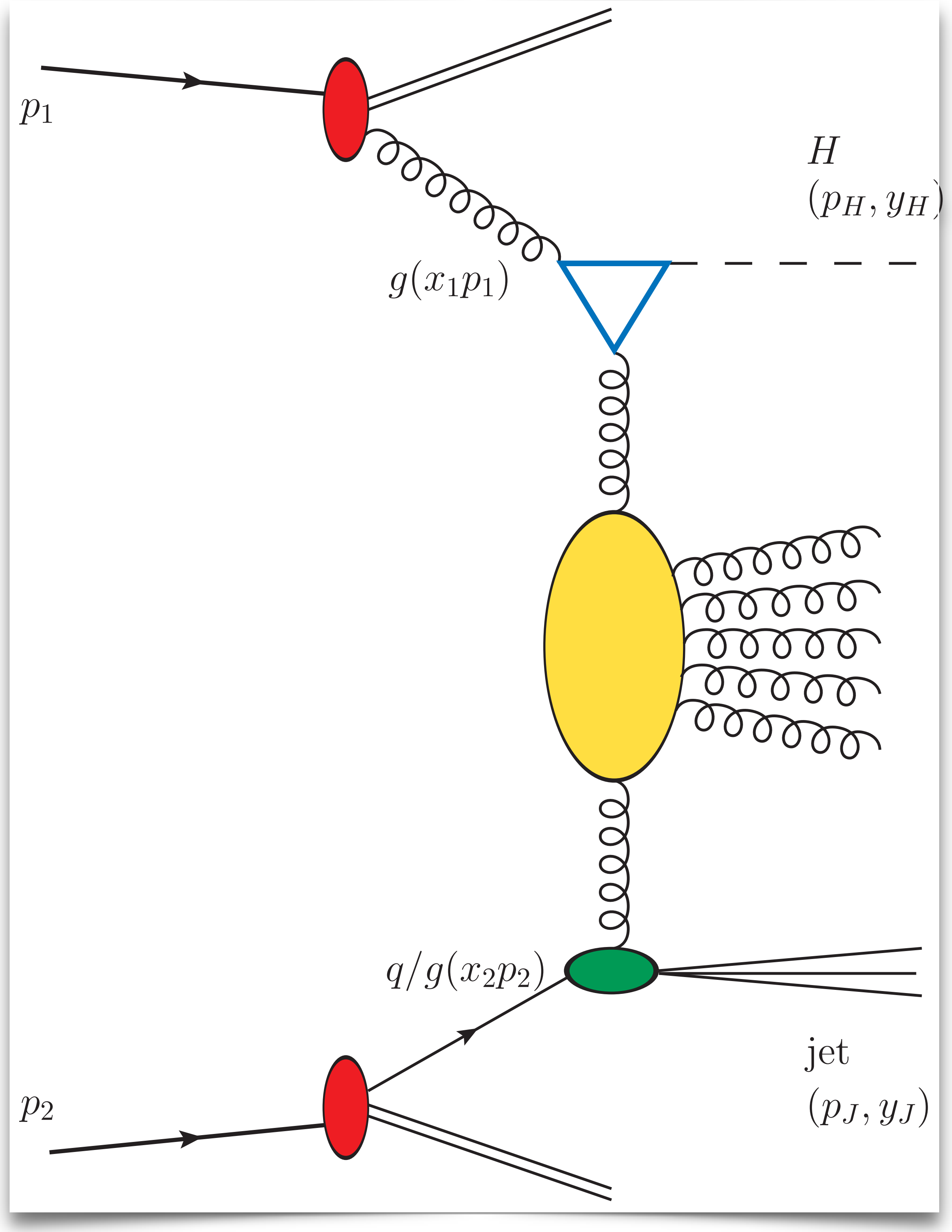

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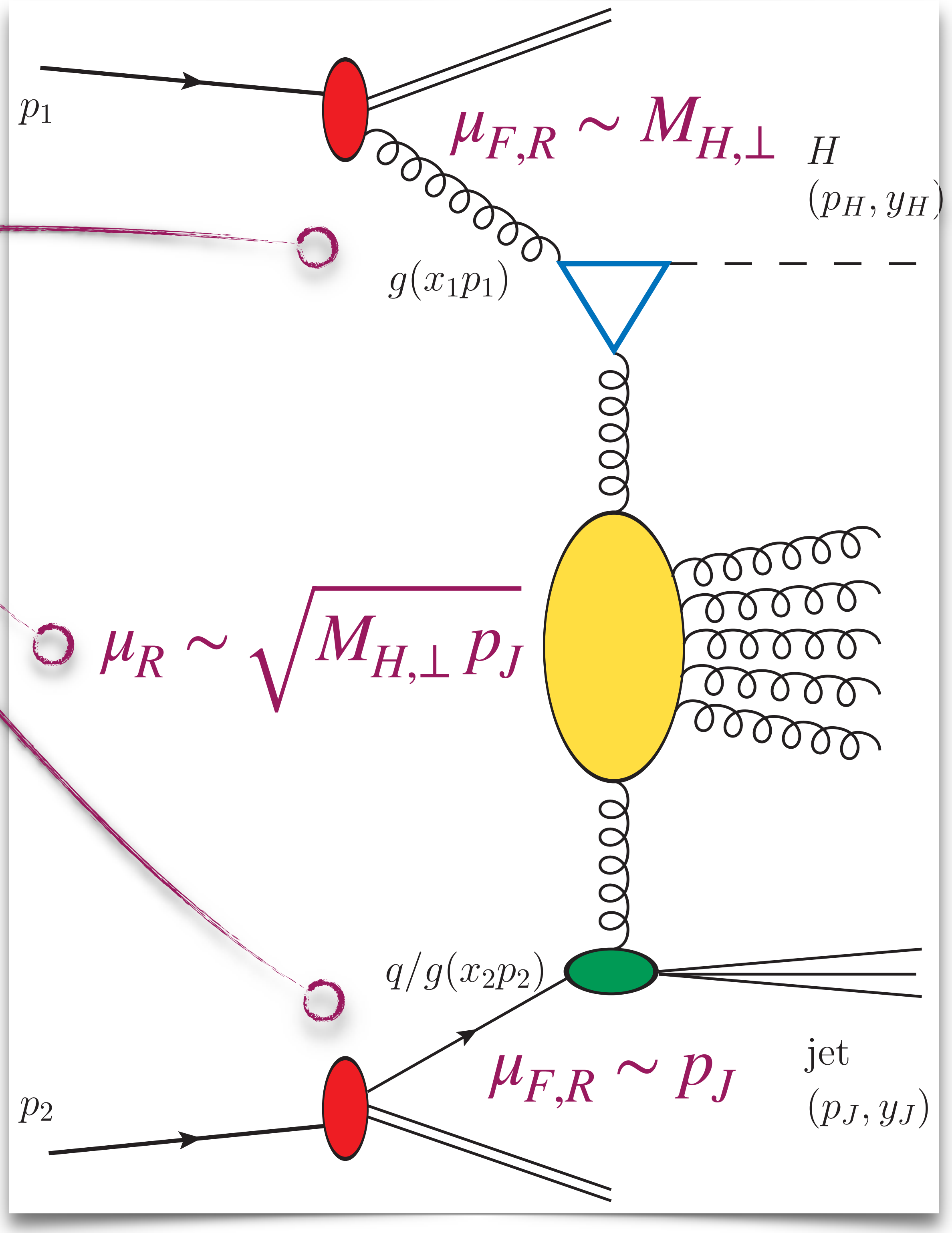

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φ-averaged cross section: C_0

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

φ-averaged cross section: C_0

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

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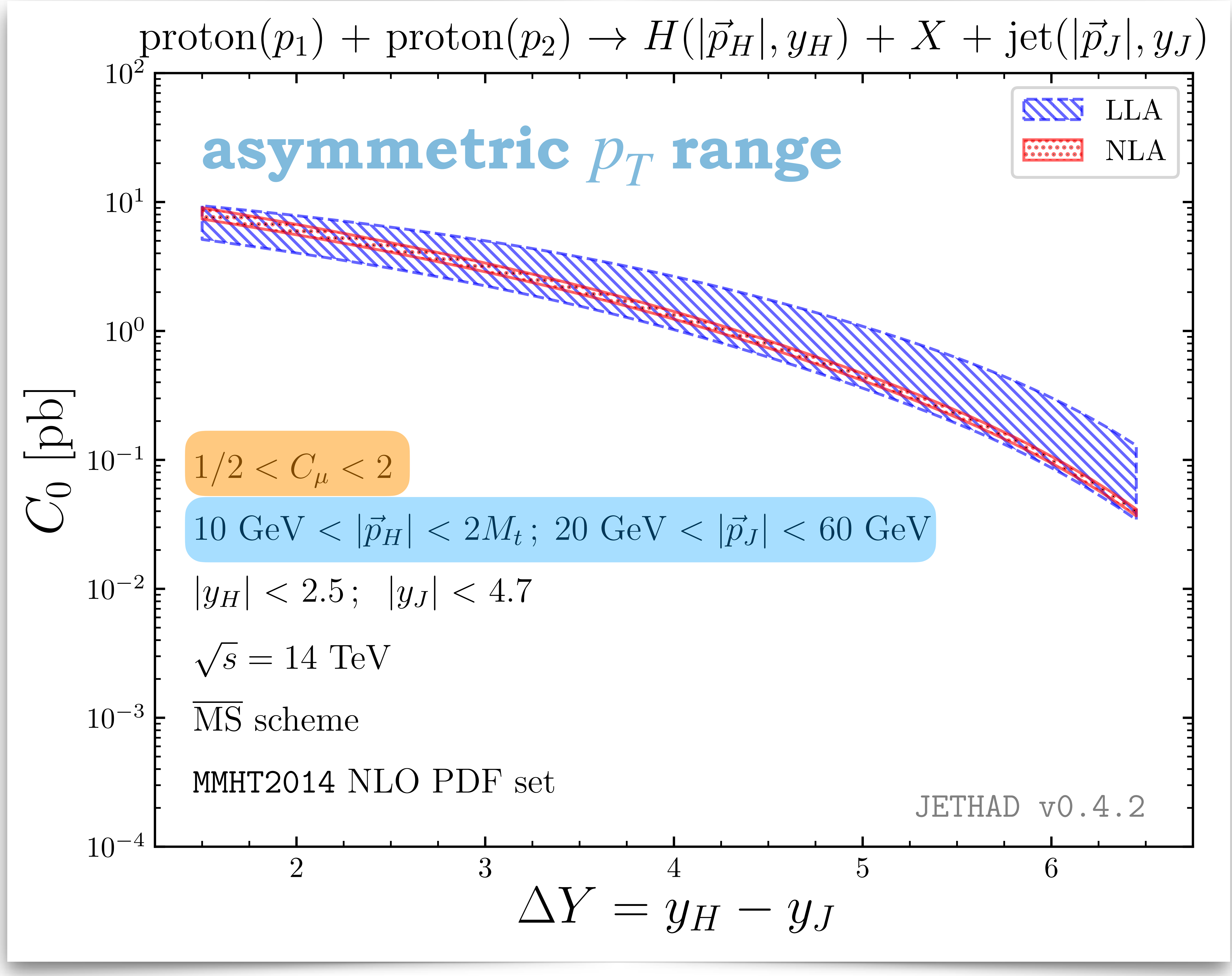

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Inclusive Higgs + jet

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

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

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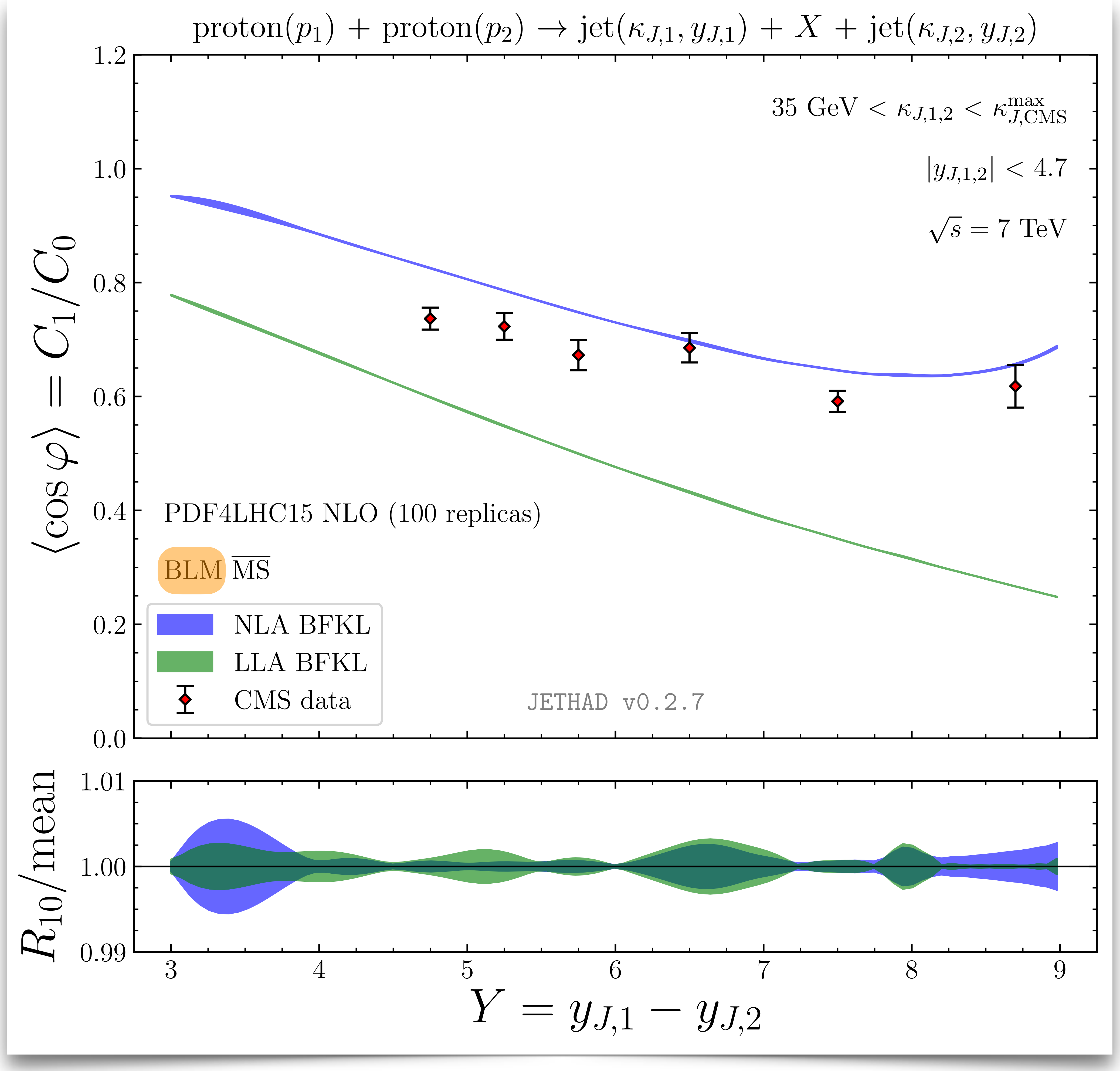
Mueller-Navelet jets

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

(figure below) [F. G. C. (2020)]



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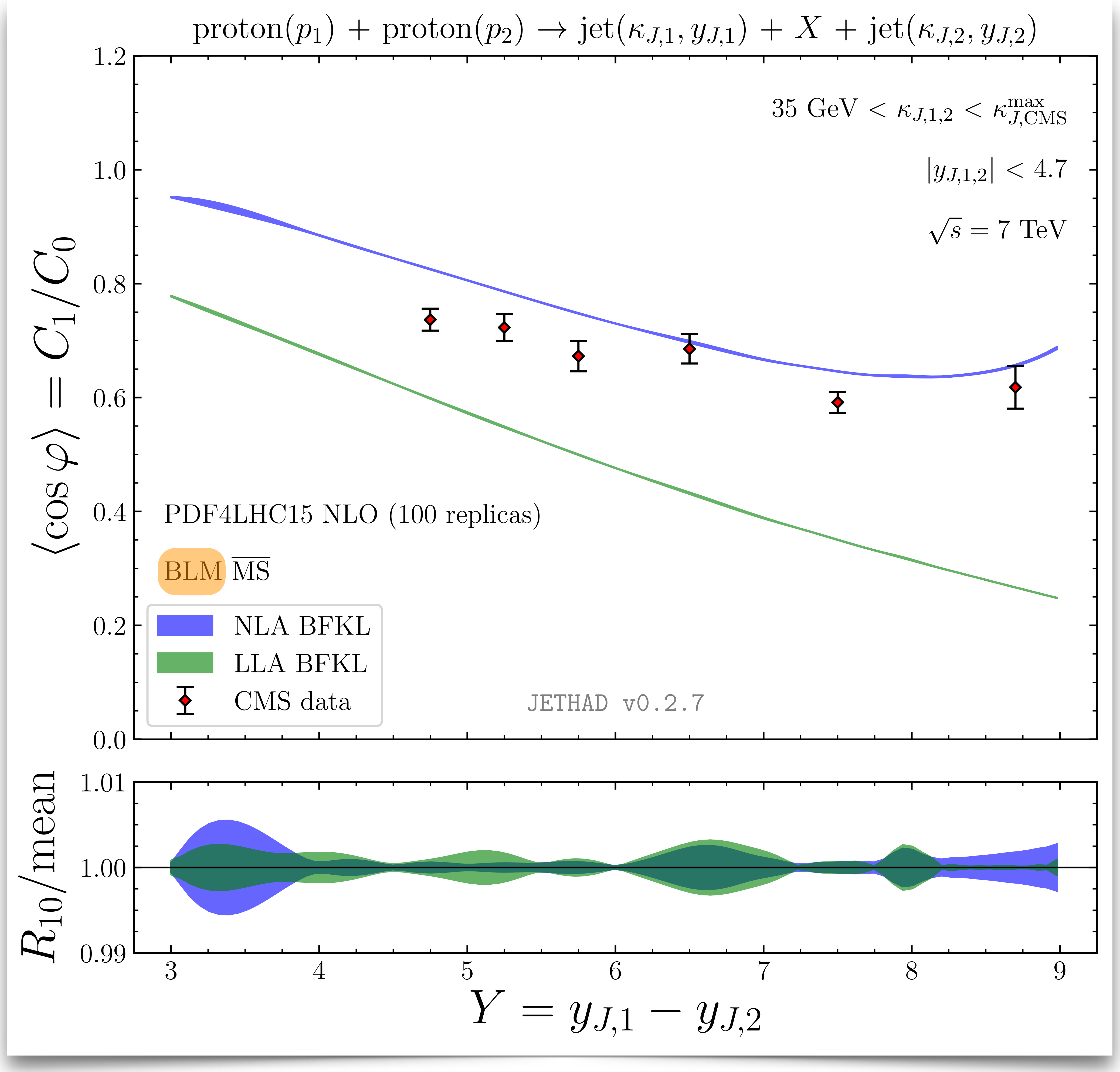
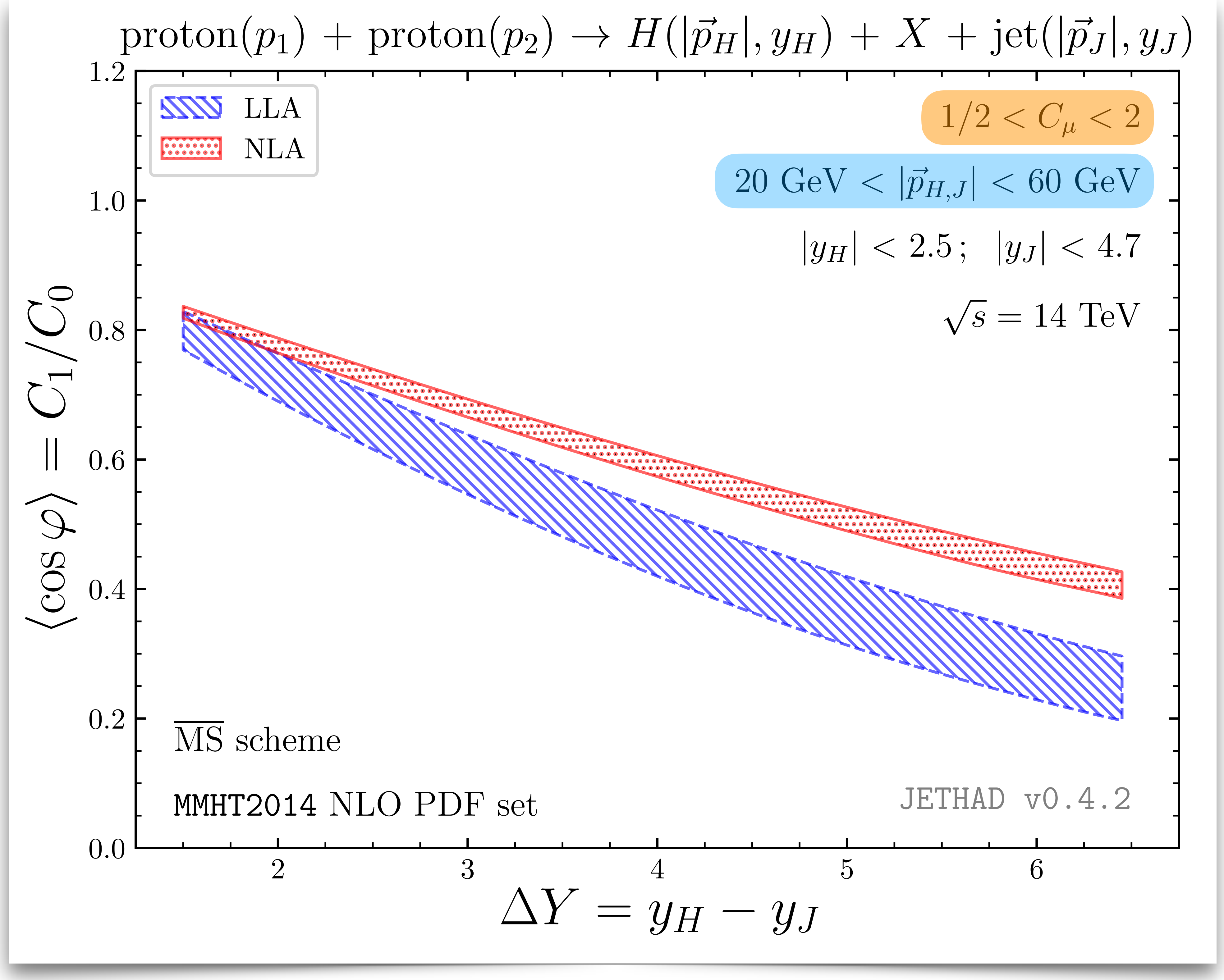


Higgs + jet



natural scales

symmetric p_T range

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Azimuthal correlations: $C_2/C_0 \equiv \langle \cos 2\varphi \rangle$

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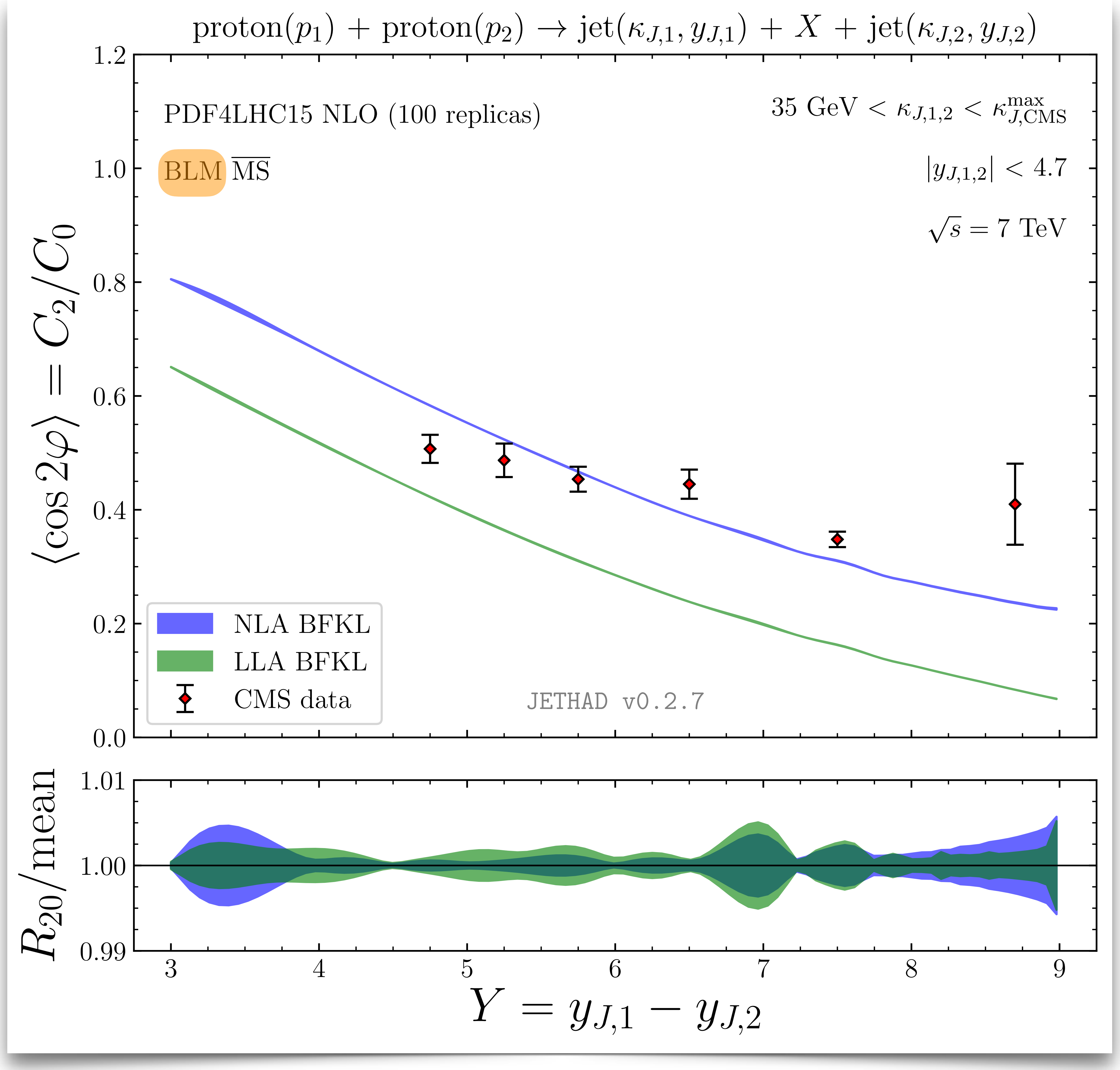

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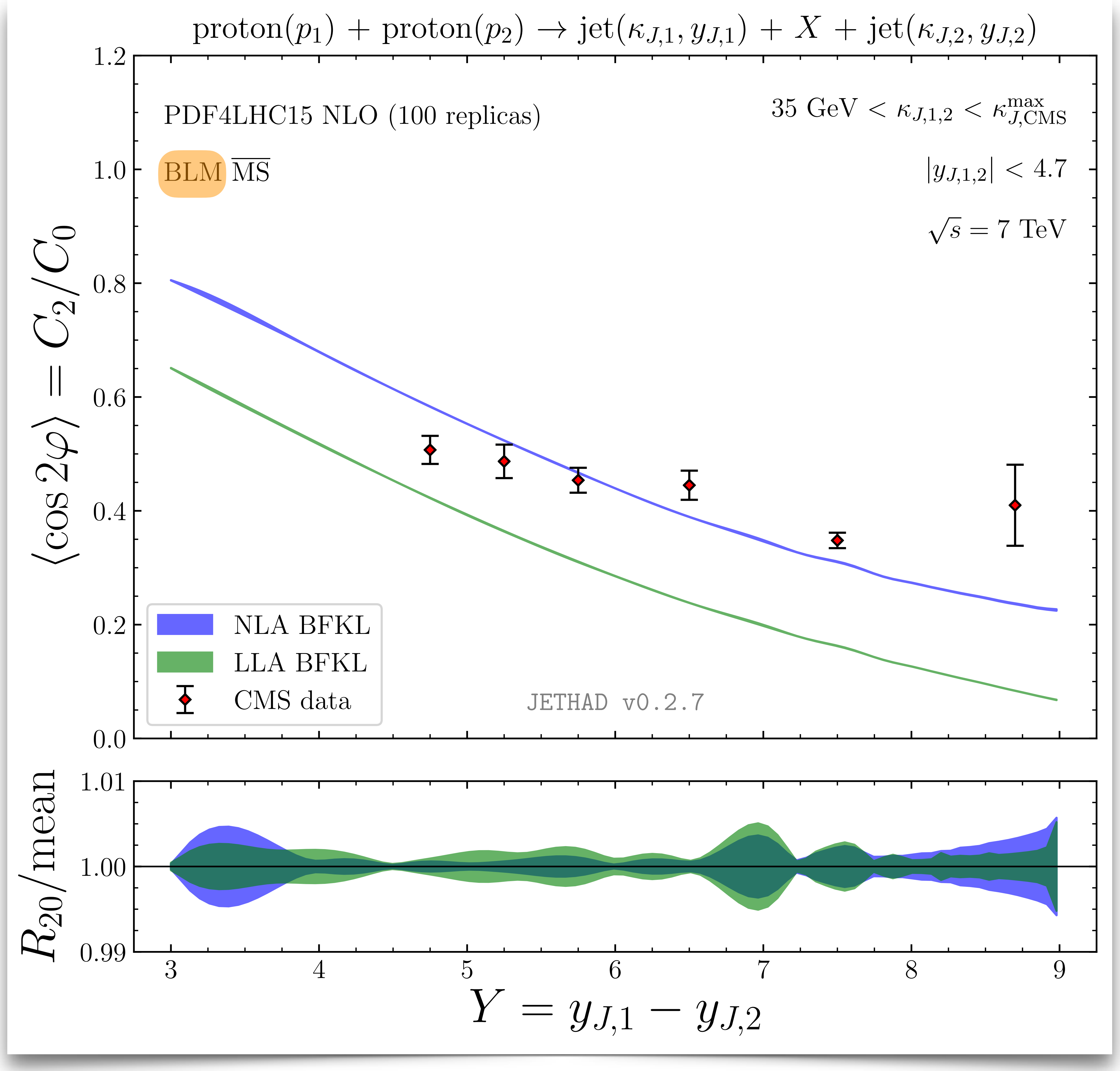

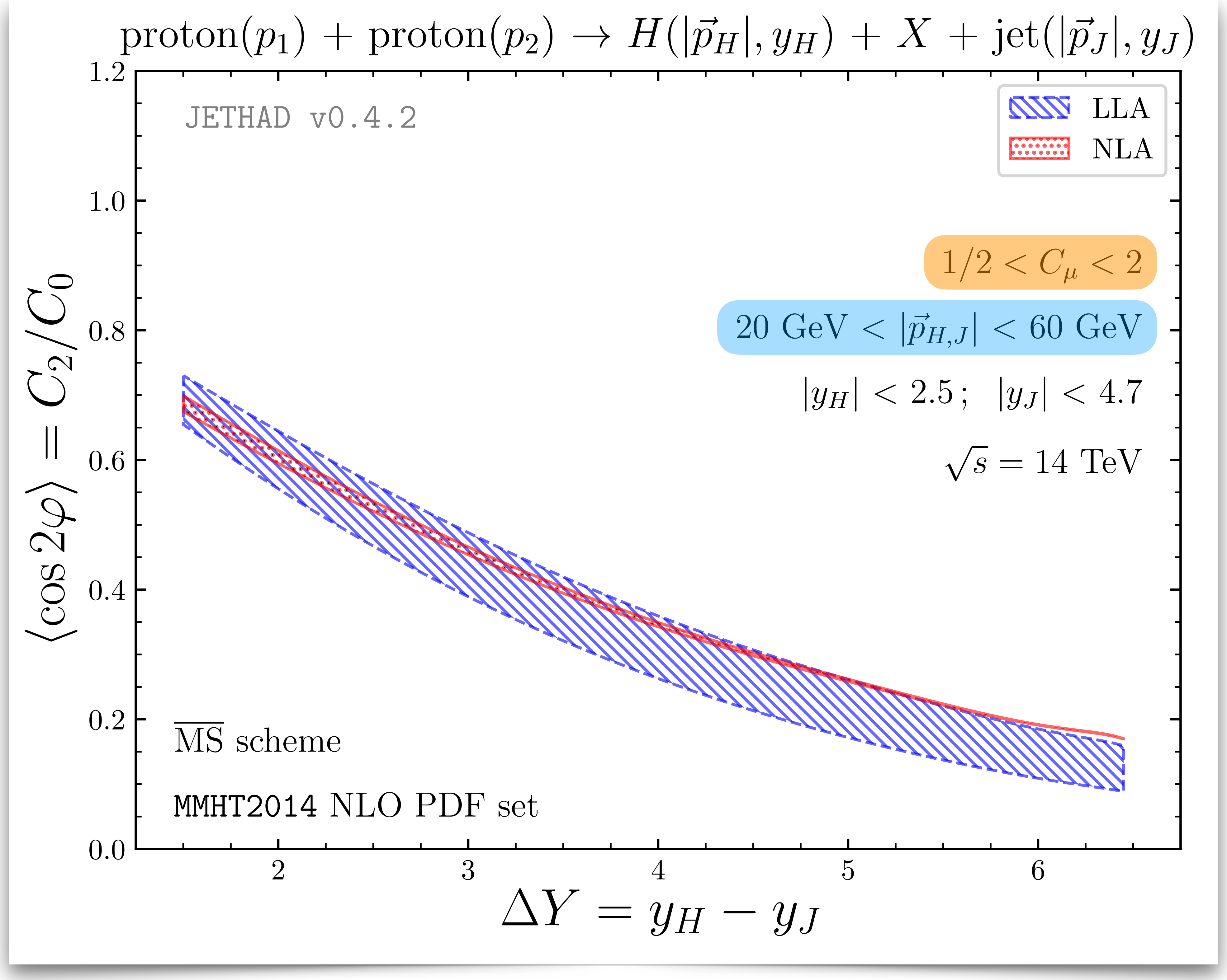

natural scales

symmetric p_T range

p_H-distribution: dC_0/dp_H

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

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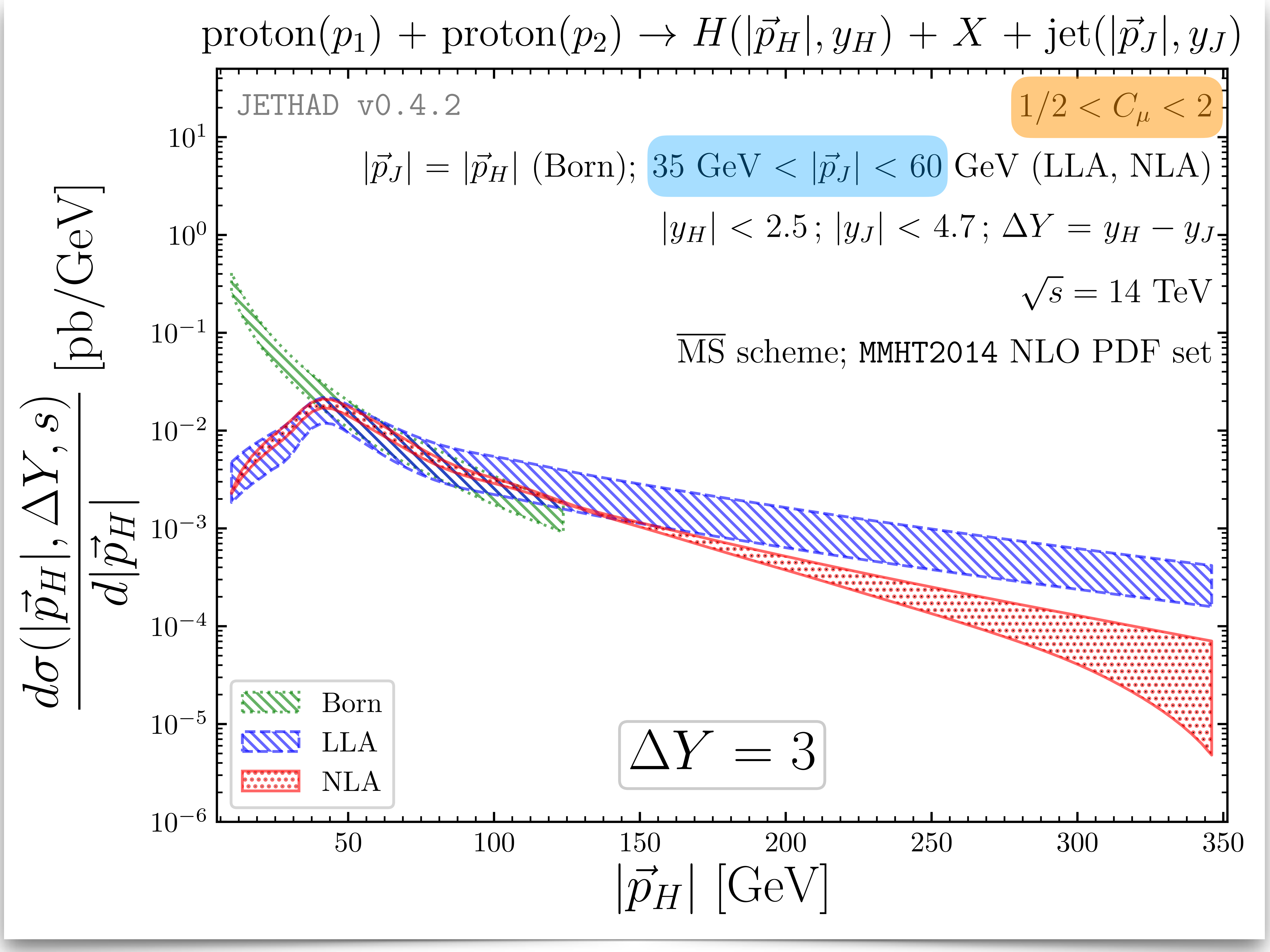

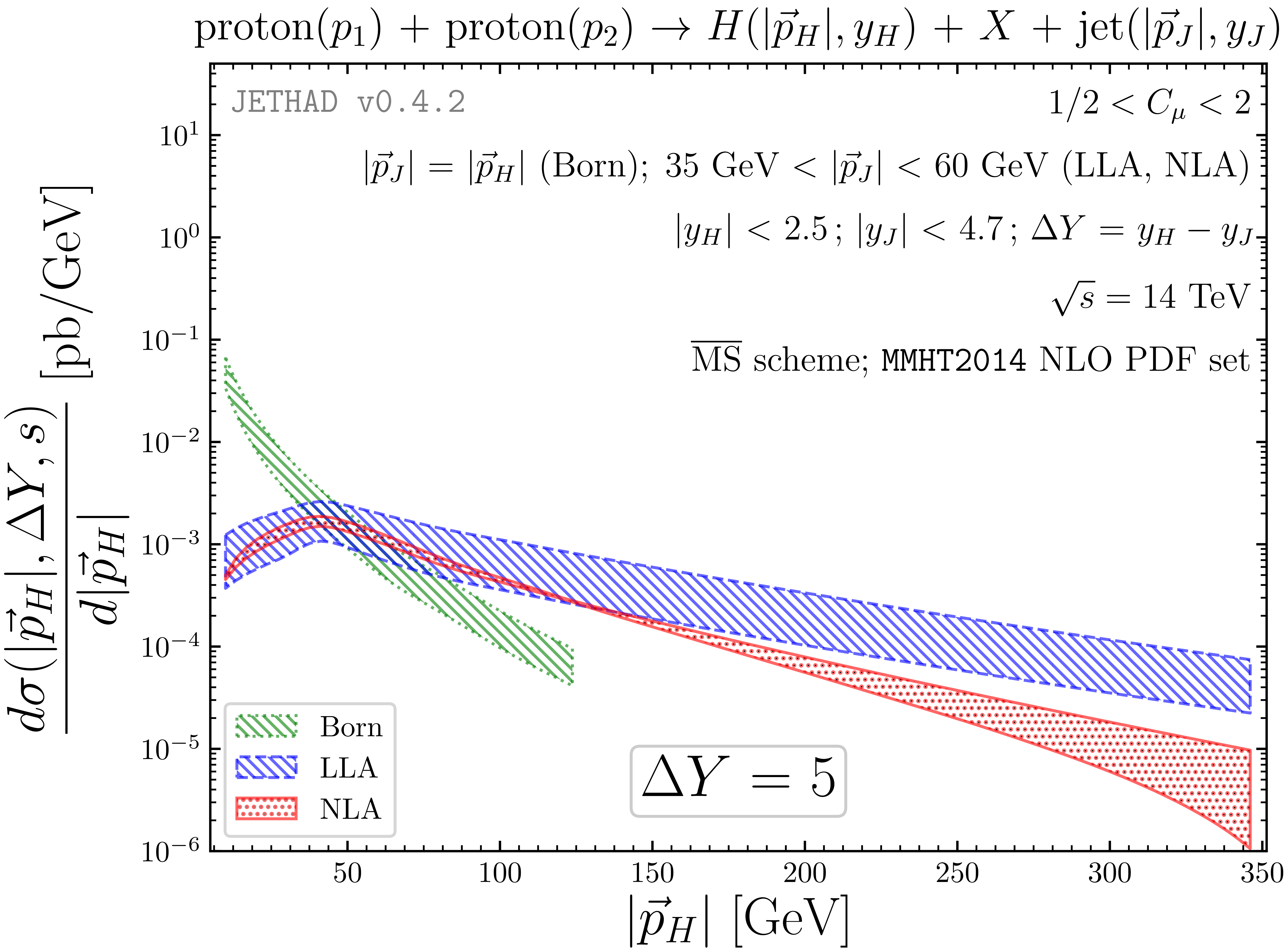
proton(p_1) + proton(p_2) → $H(|\vec{p}_H|, y_H)$ + X + jet($|\vec{p}_J|, y_J$)
JETHAD v0.4.2
$1/2 < C_\mu < 2$
$|\vec{p}_J| = |\vec{p}_H|$ (Born); 35 GeV $< |\vec{p}_J| <$ 60 GeV (LLA, NLA)
$|y_H| < 2.5$; $|y_J| < 4.7$; $\Delta Y = y_H - y_J$
$\sqrt{s} = 14$ TeV
$\overline{\text{MS}}$ scheme; MMHT2014 NLO PDF set
$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H|}$ [pb/GeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Born
LLA
NLA
$\Delta Y = 5$
50
100
150
200
250
300
350
$|\vec{p}_H|$ [GeV]

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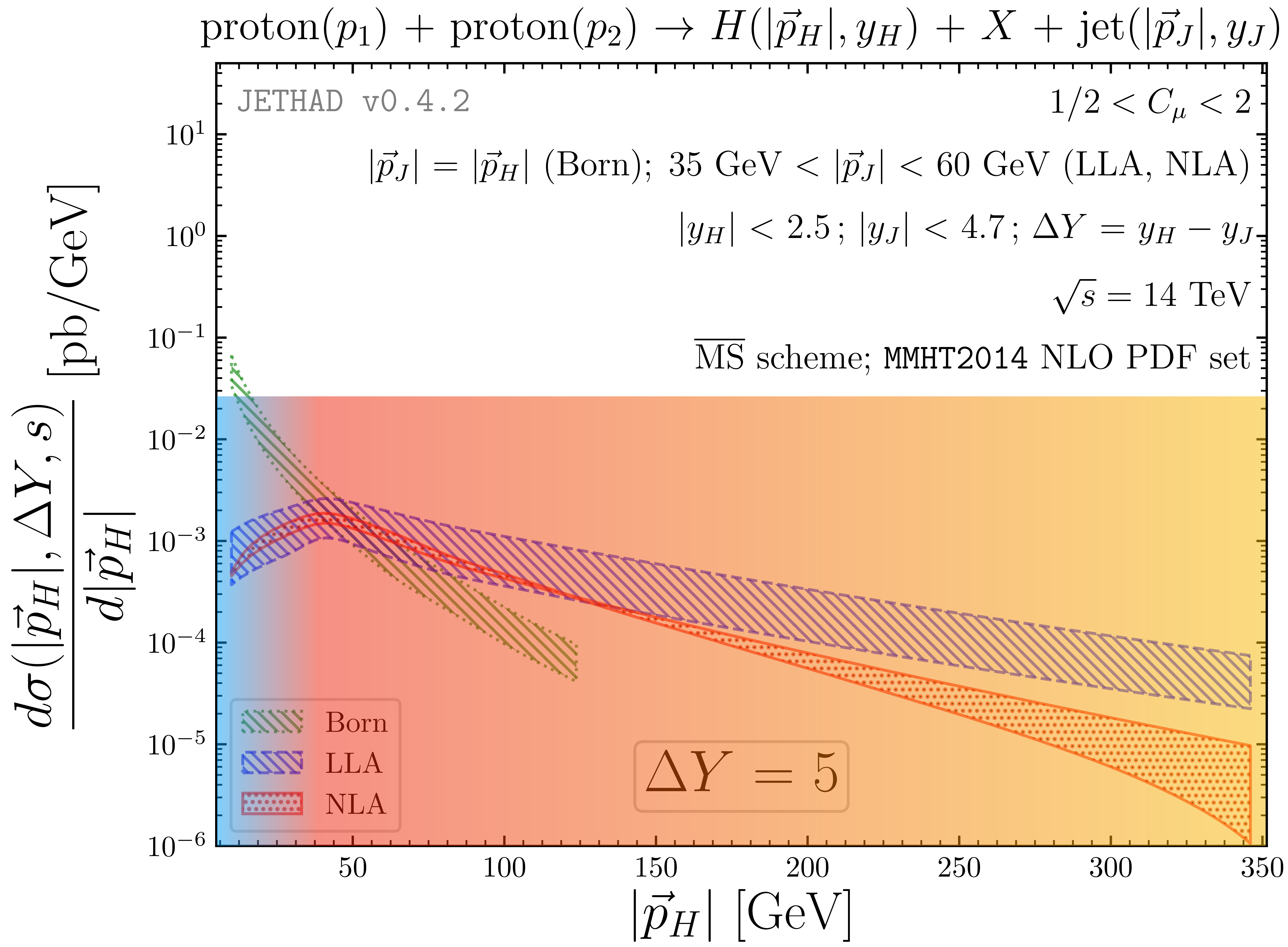

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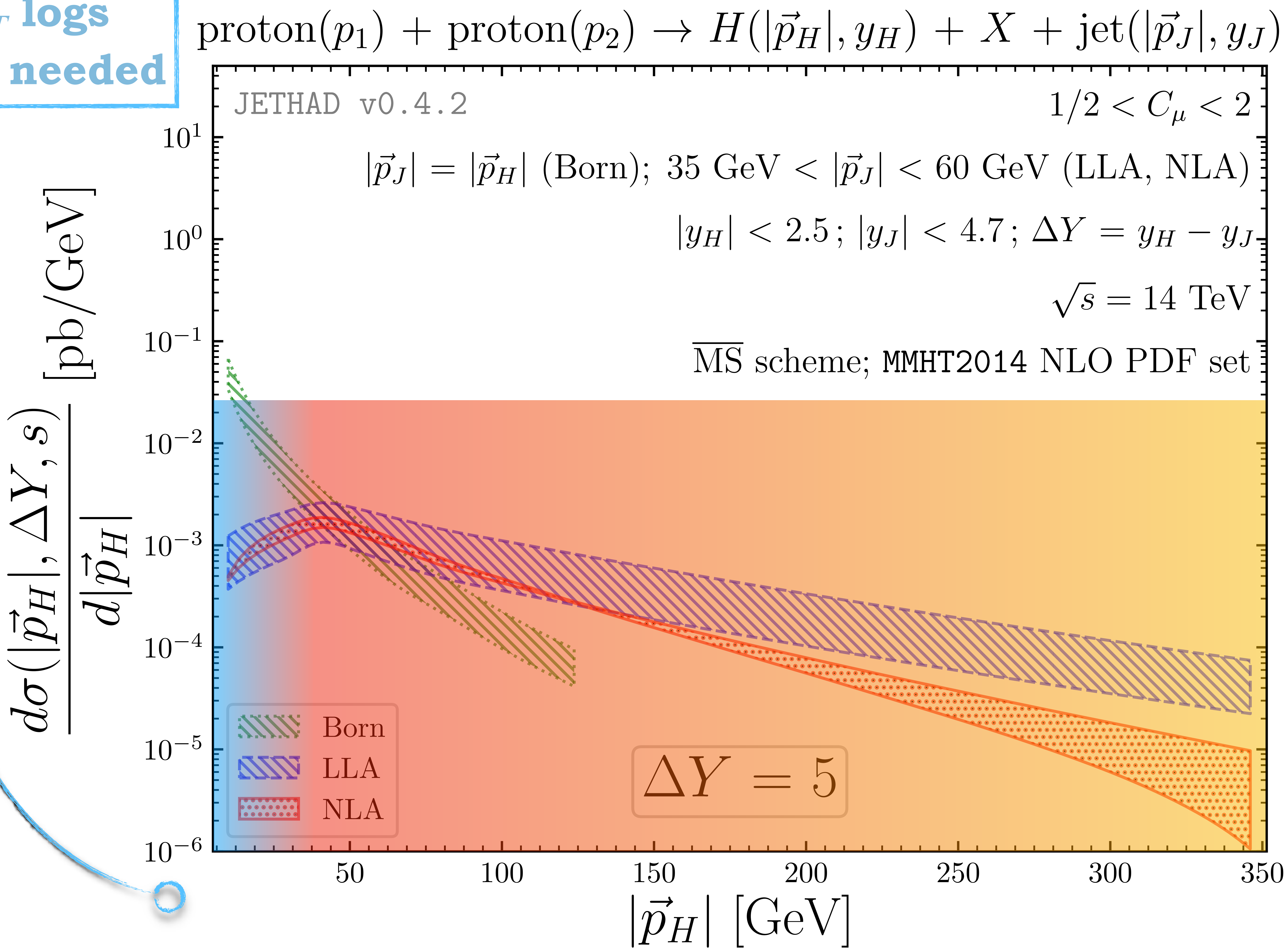
large p_T logs
p_T-resum. needed



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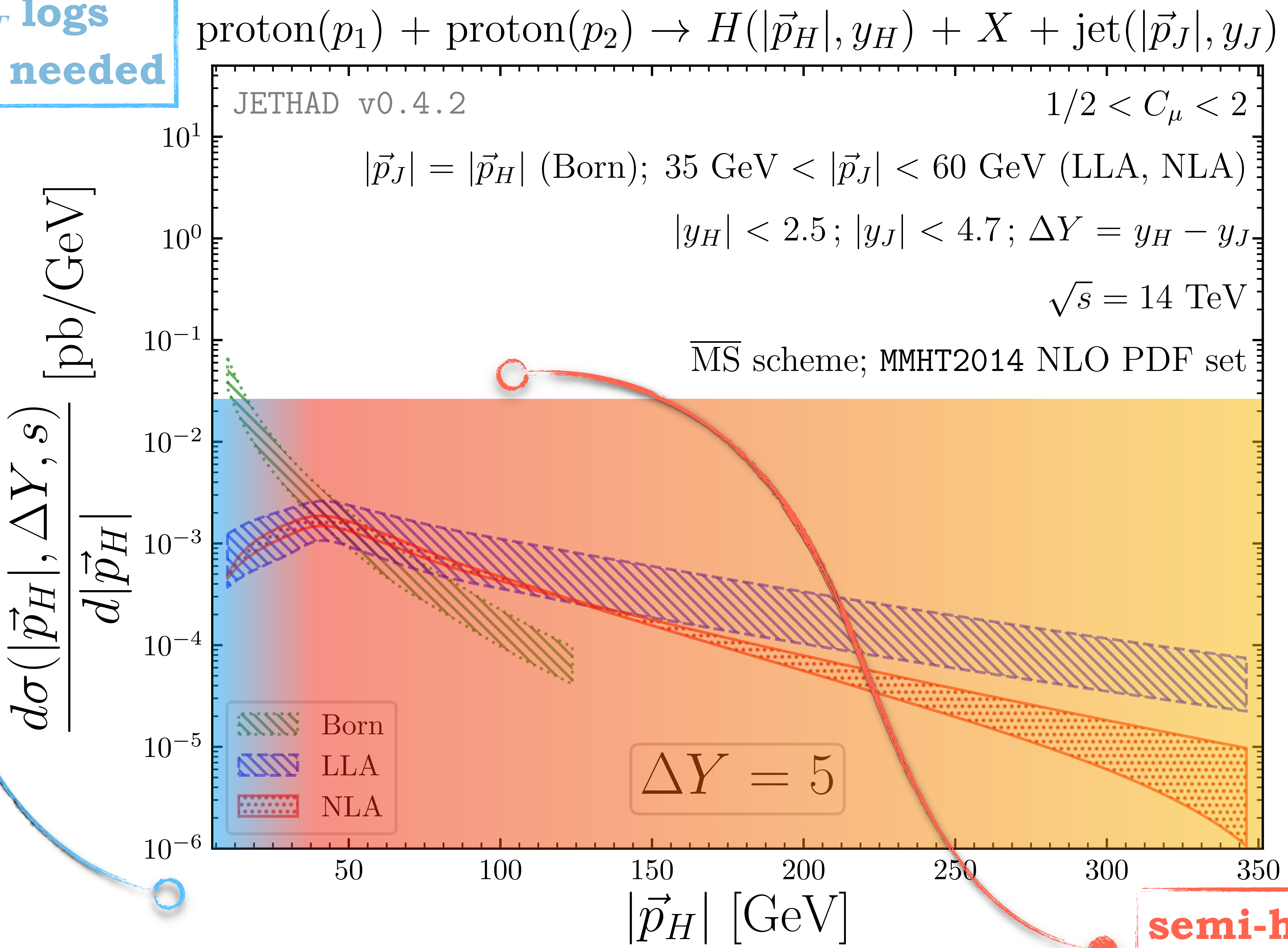
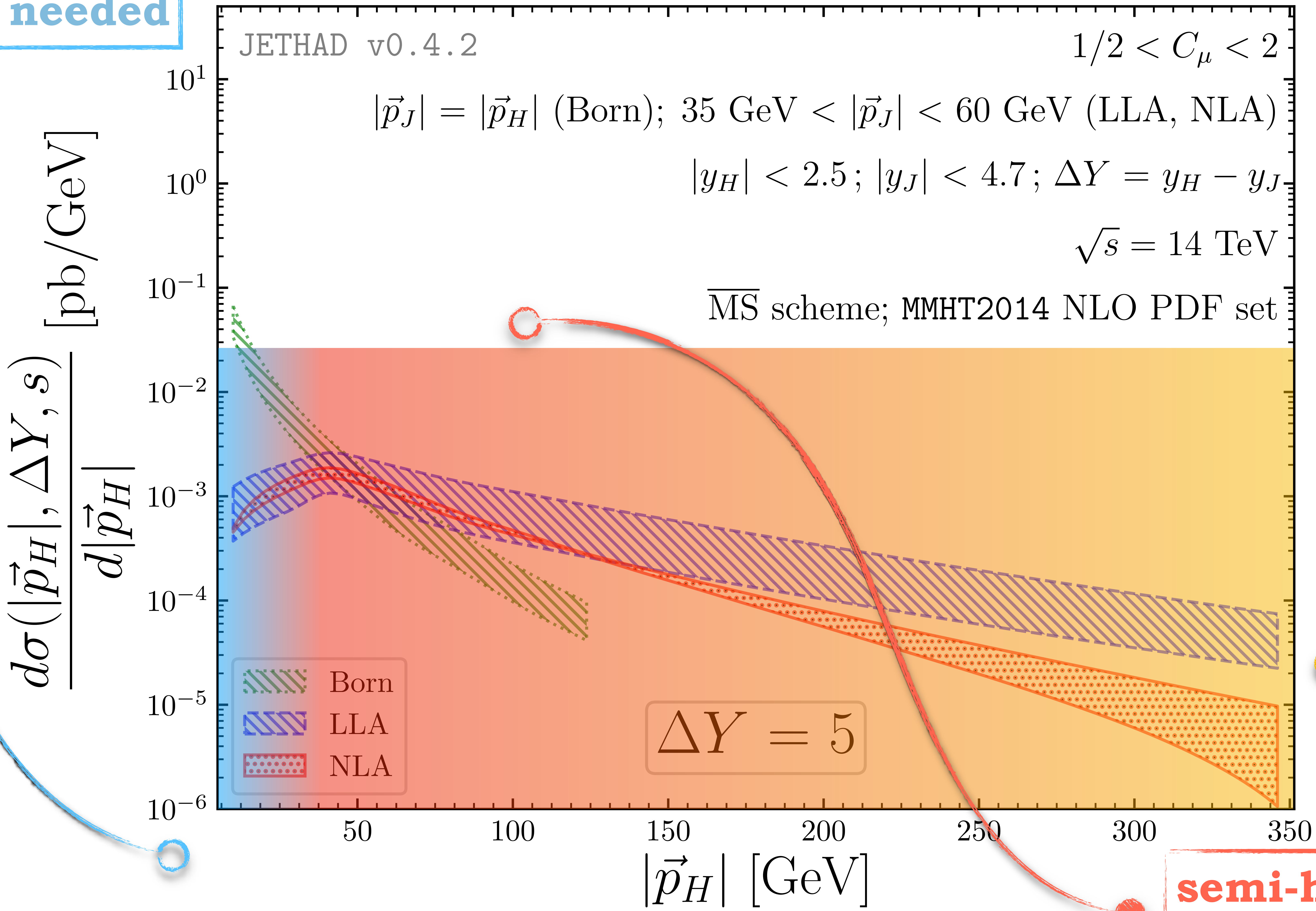


semi-hard regime
BFKL expected

DGLAP-type + threshold logs → BFKL decoupling

large p_T logs
p_T-resum. needed

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



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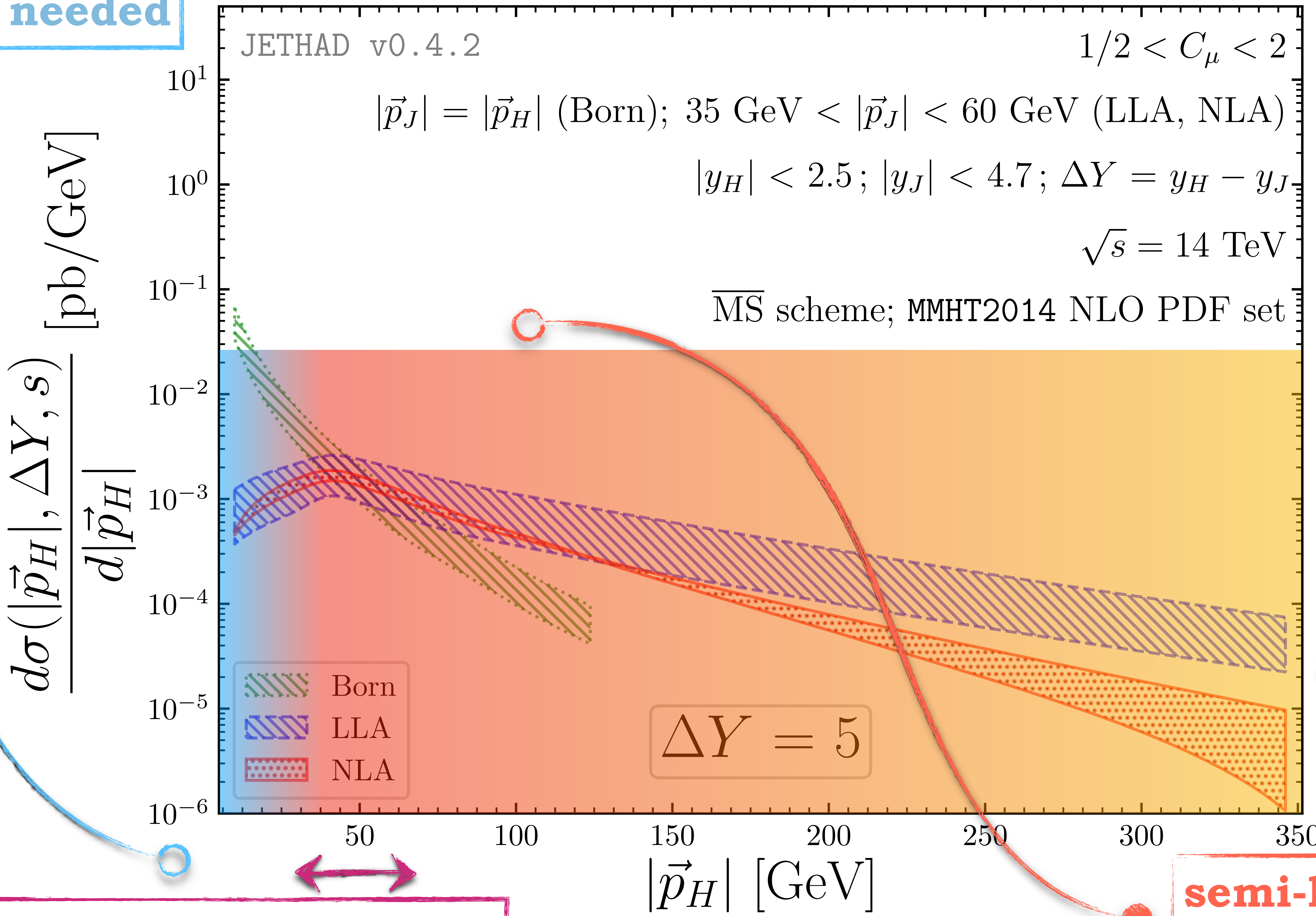

semi-hard regime
BFKL expected

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

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Closing statements

Closing statements

- ☑ Inclusive Higgs + jet as new **semi-hard** probe for **BFKL**
- ☑ Partial NLA BFKL accuracy: NLA kernel + LO IFs + NLO RG
- ☑ *Encouraging* statistics for rapidity and p_H-distributions
- ☑ **Fair stability** under *higher-order* corrections

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Resummed distributions

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- ☑ *Encouraging* statistics for rapidity and p_H-distributions
- ☑ **Fair stability** under *higher-order* corrections
- ☐ Feasibility of **precision measurements** to be *gauged*
- ☐ Full NLA BFKL analysis: NLO Higgs IF & jet-algorithm selection
- ☐ Distributions as *underlying staging* for several **resummations**
- ☐ *Transversal formalism* to **encode** distinct resummations

High-energy QCD at colliders: semi-hard reactions and unintegrated gluon densities

Letter of Interest for SnowMass 2021

Francesco G. Celiberto [1,2*], Michael Fucilla [3,4§], Dmitry Yu. Ivanov [5,6†], Mohammed M.A. Mohammed [3,4‡], and Alessandro Papa [3,4¶]

The search for evidence of New Physics is in the viewfinder of current and forthcoming analyses at the Large Hadron Collider (LHC) and at future hadron, lepton and lepton-hadron colliders. This is the best time to shore up our knowledge of strong interactions though, the high luminosity and the record energies reachable widening the horizons of kinematic sectors uninvestigated so far. A broad class of processes, called *diffractive semi-hard* reactions [1], *i.e* where the scale hierarchy, $s \gg \{Q^2\} \gg \Lambda^2_{\rm QCD}$ (s is the squared center-of-mass energy, $\{Q\}$ a (set of) hard scale(s) characteristic of the process and $\Lambda_{\rm QCD}$ the QCD scale), is stringently preserved, gives us a faultless chance to test perturbative QCD in new and quite original ways. Here, a genuine fixed-order treatment based on collinear factorization fails since large energy logarithms enter the perturbative series in

***

The research lines presented above are relevant in the search for high-energy effects via the description of an increasing number of hadronic and lepto-hadronic reactions at the LHC and at new-generation colliders, like the Electron-Ion Collider (EIC). At the same time, the BFKL resummation serves as a tool to address more general aspects of QCD, from the hadronic structure to other resummations and to the production mechanism of hadronic bound states. We believe that the inclusion of these topics in the *SnowMass 2021* scientific program would accelerate progress of our understanding of both formal and phenomenological aspects of strong interactions at high energies.

Backup slides

Parton densities: an incomplete family tree

Wigner distributions **5D**

$\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$

$\int d^2\mathbf{k}_T$

$\int d^2\mathbf{b}_T$

Generalized Parton Distributions

GPDs

Transverse Momentum Distributions

TMDs **3D**

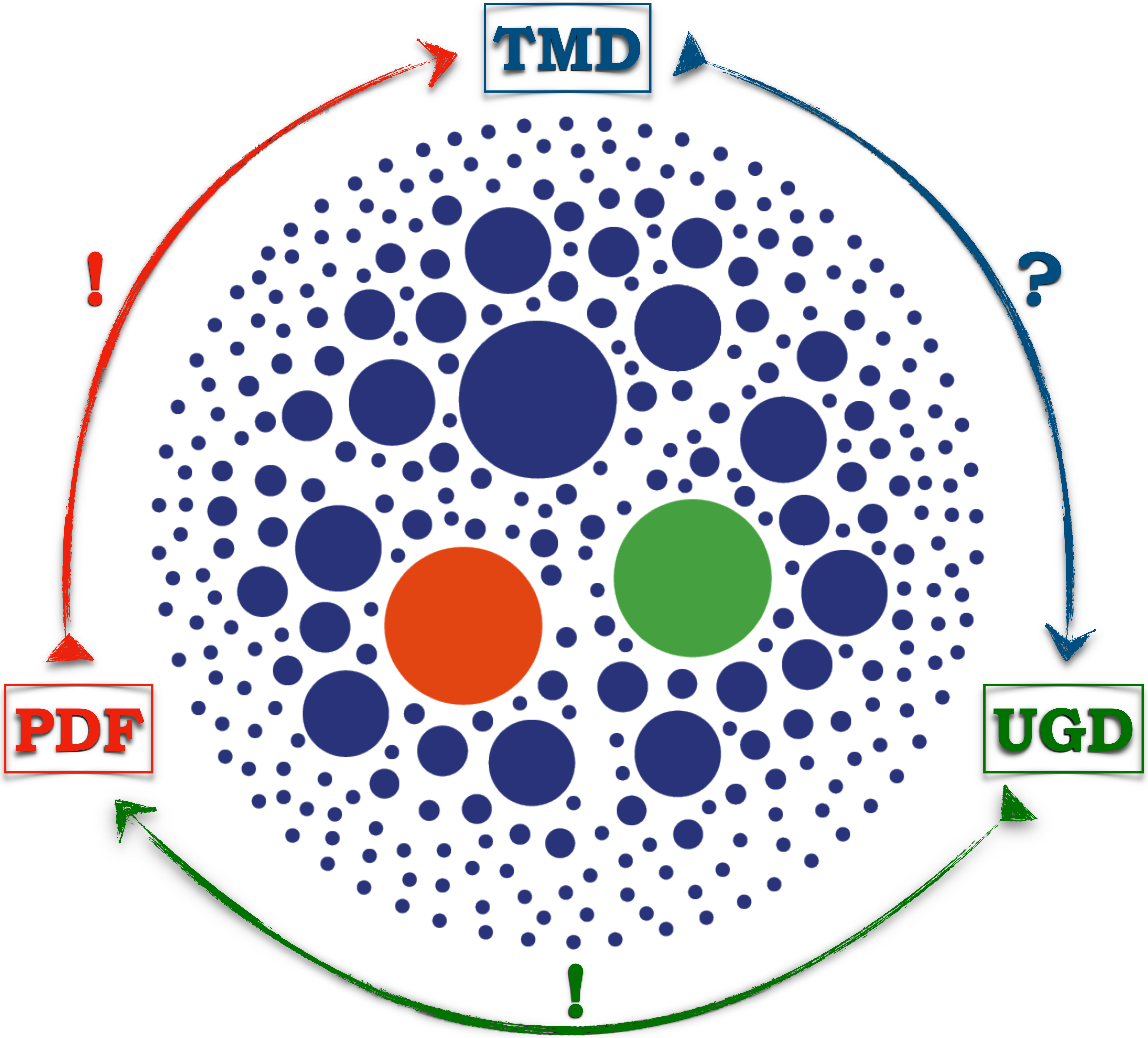
$\int d^2\mathbf{k}_T$

Parton Distribution Functions

PDFs **1D**

Backup

Mapping the proton content



Backup

The high-energy resummation

Gluon Reggeization in perturbative QCD

◇ Gluon quantum numbers in the t-channel: 8^- representation

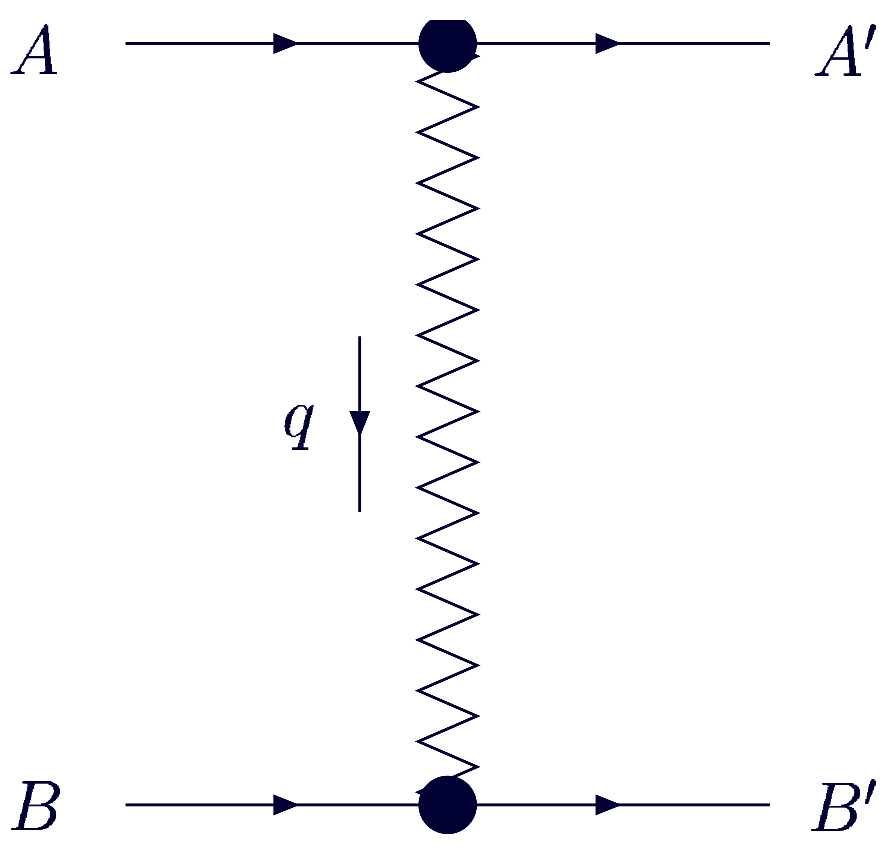
◇ Regge limit: $s \simeq -u \to \infty$, t not growing with s

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

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

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

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



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

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

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

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

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

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

The high-energy resummation

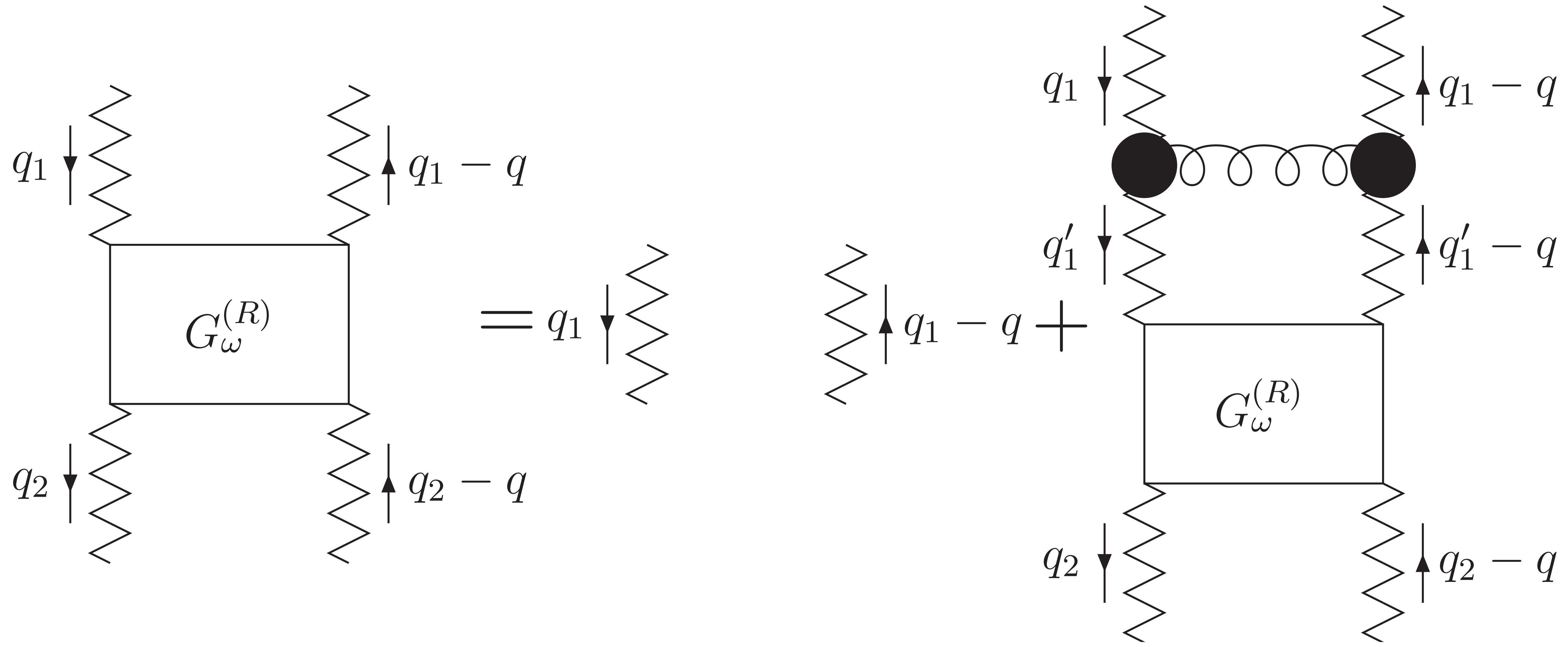
$$\mathcal{I}m_s\{\mathcal{A}\} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1,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

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

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

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

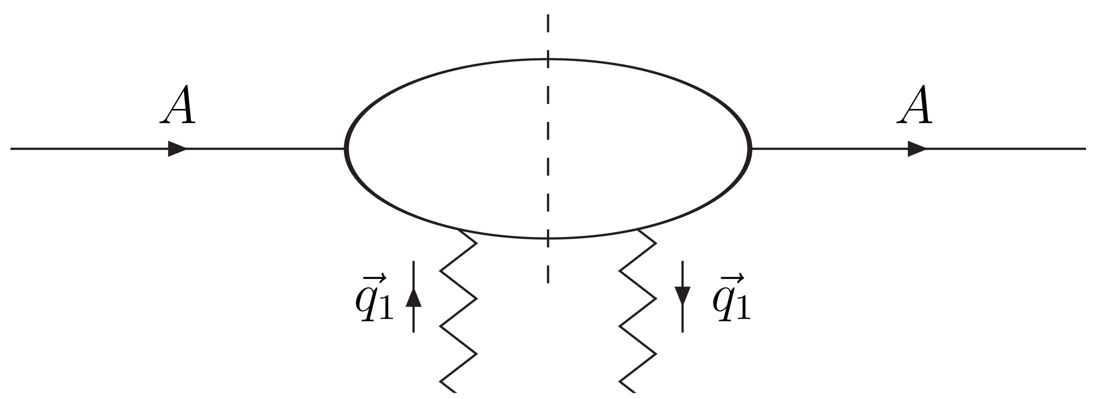
$$\omega\, G_\omega(\vec{q}_1, \vec{q}_2) = \delta^{D-2}(\vec{q}_1 - \vec{q}_2) + \int d^{D-2}q\, K(\vec{q}_1, \vec{q})\, G_\omega(\vec{q}, \vec{q}_1)\,.$$



Backup

The high-energy resummation

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



◇ **colliding partons**

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

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

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

◇ forward jet production

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

◇ forward identified hadron production

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

◇ $\gamma^* \longrightarrow \gamma^*$

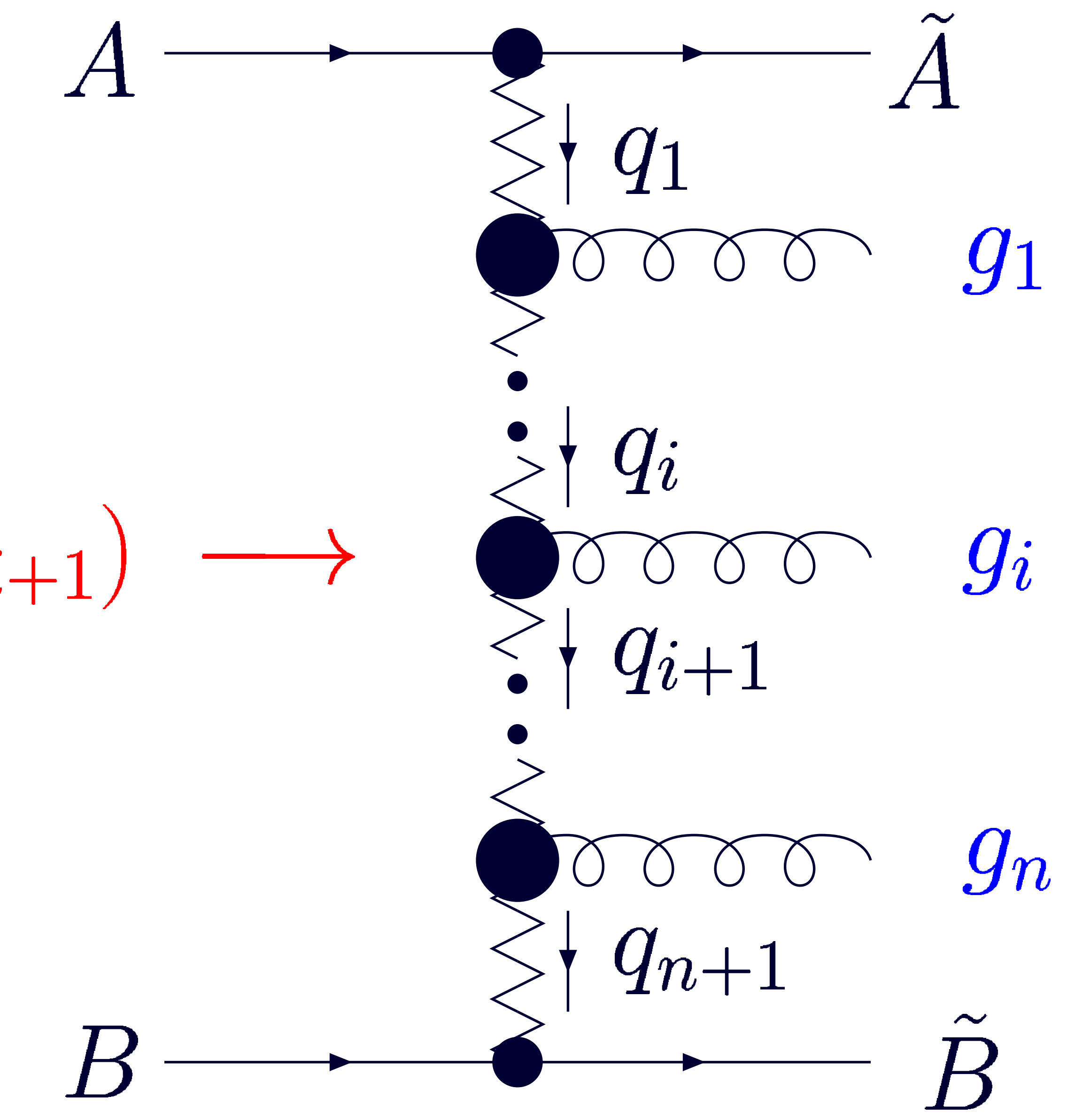
[J. Bartels *et al.* (2001), I. Balitsky, G.A. Chirilli (2011, 2013)]

The high-energy resummation

BFKL in the LLA (I)

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

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



multi-Regge kinematics

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

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

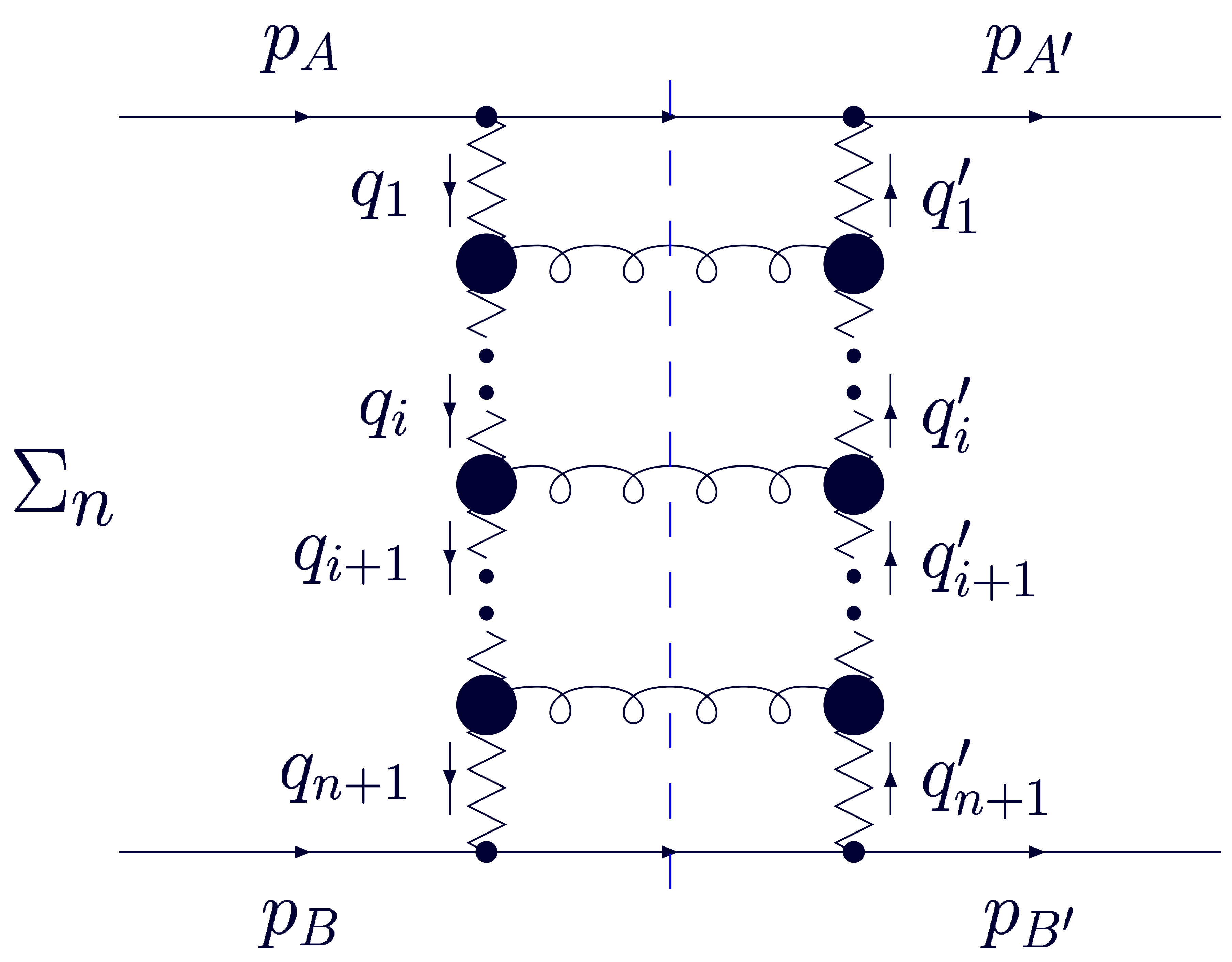
$s_R \;\; \rightarrow$ energy scale, irrelevant in the LLA

Backup

The high-energy resummation

BFKL in the LLA (II)

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



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

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

Backup

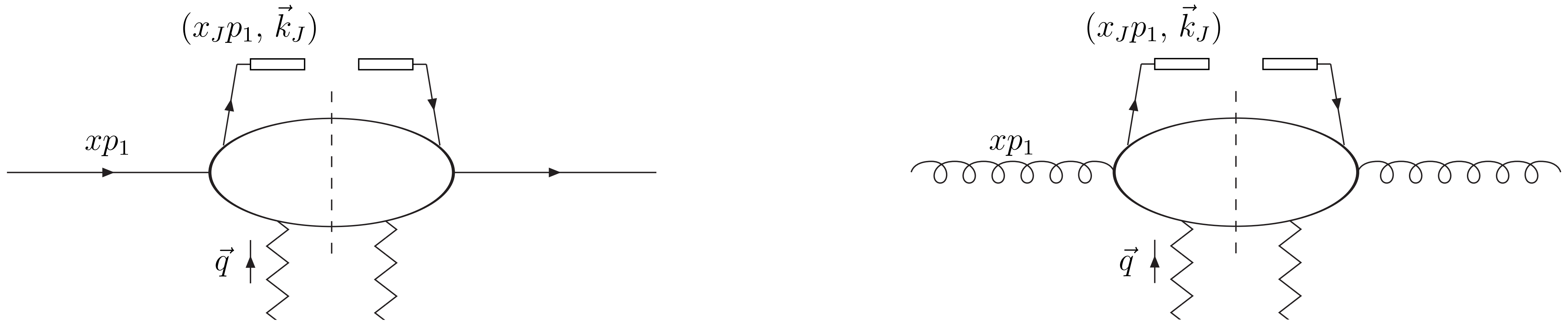
Hybrid factorization at work

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

Backup

φ-averaged cross section: C_0

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

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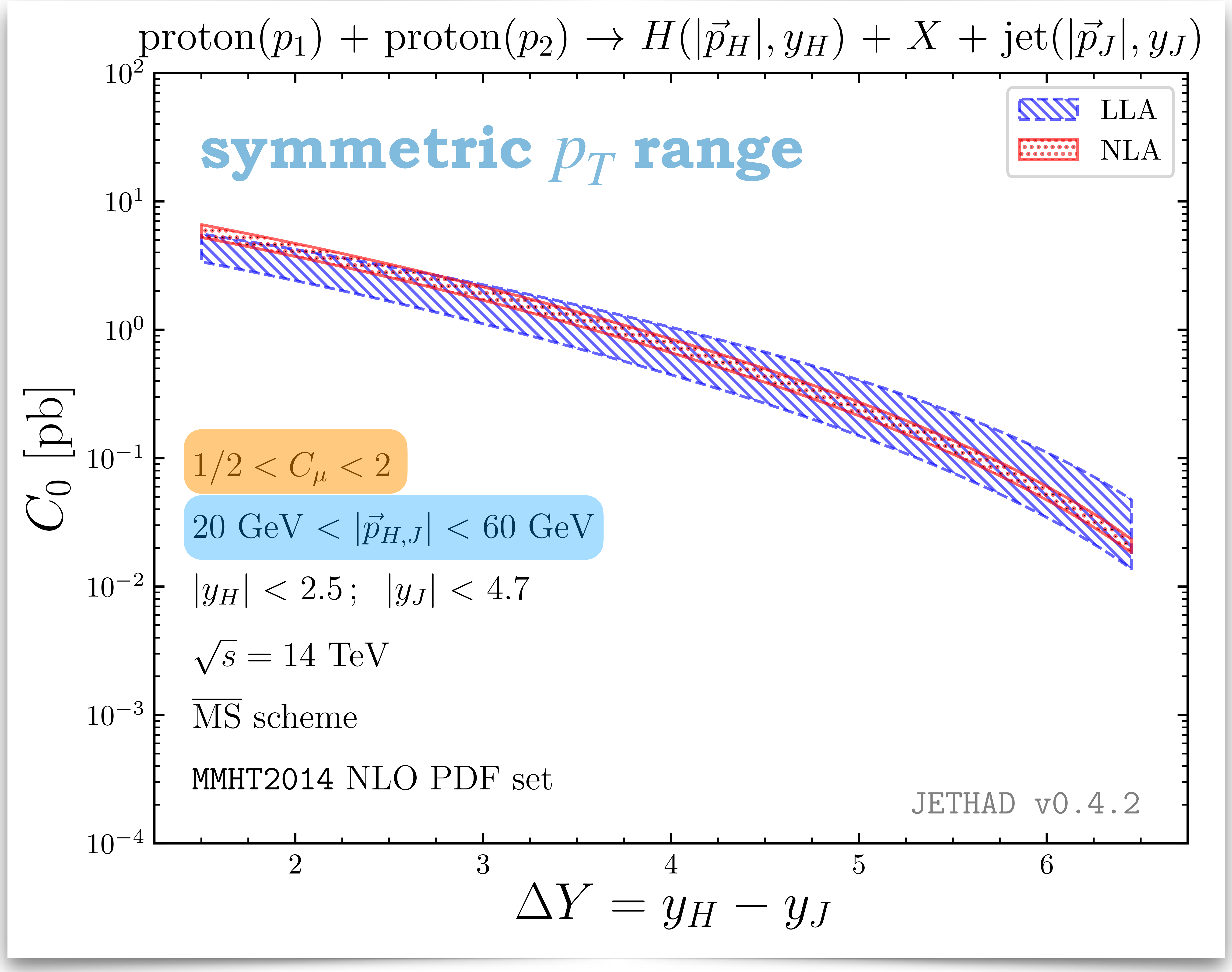

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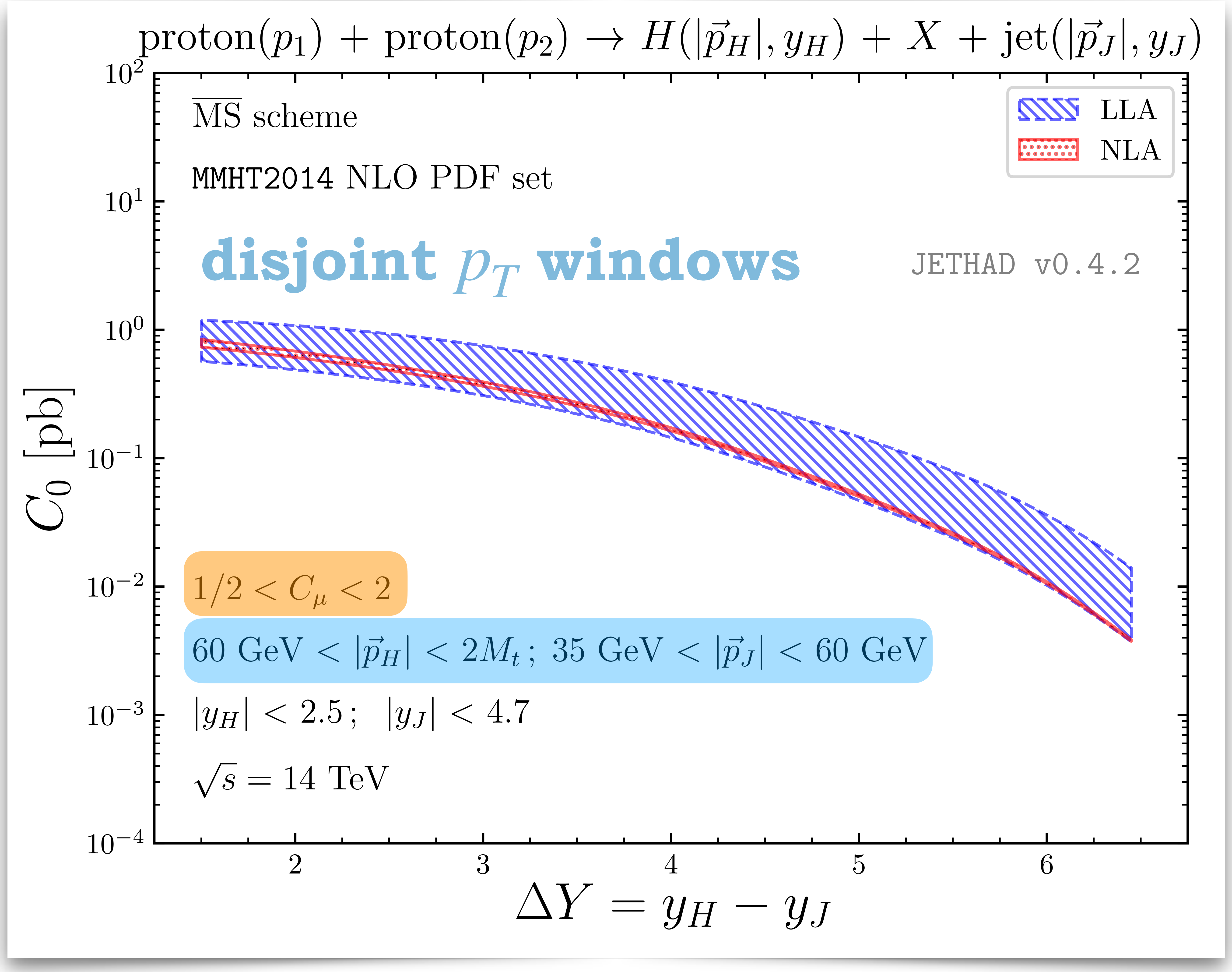

Backup

φ-averaged cross section: $C_0\,(M_t \to +\infty)$

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

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Closing statements

φ-averaged cross section: $C_0\,(M_t \to +\infty)$

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

Backup

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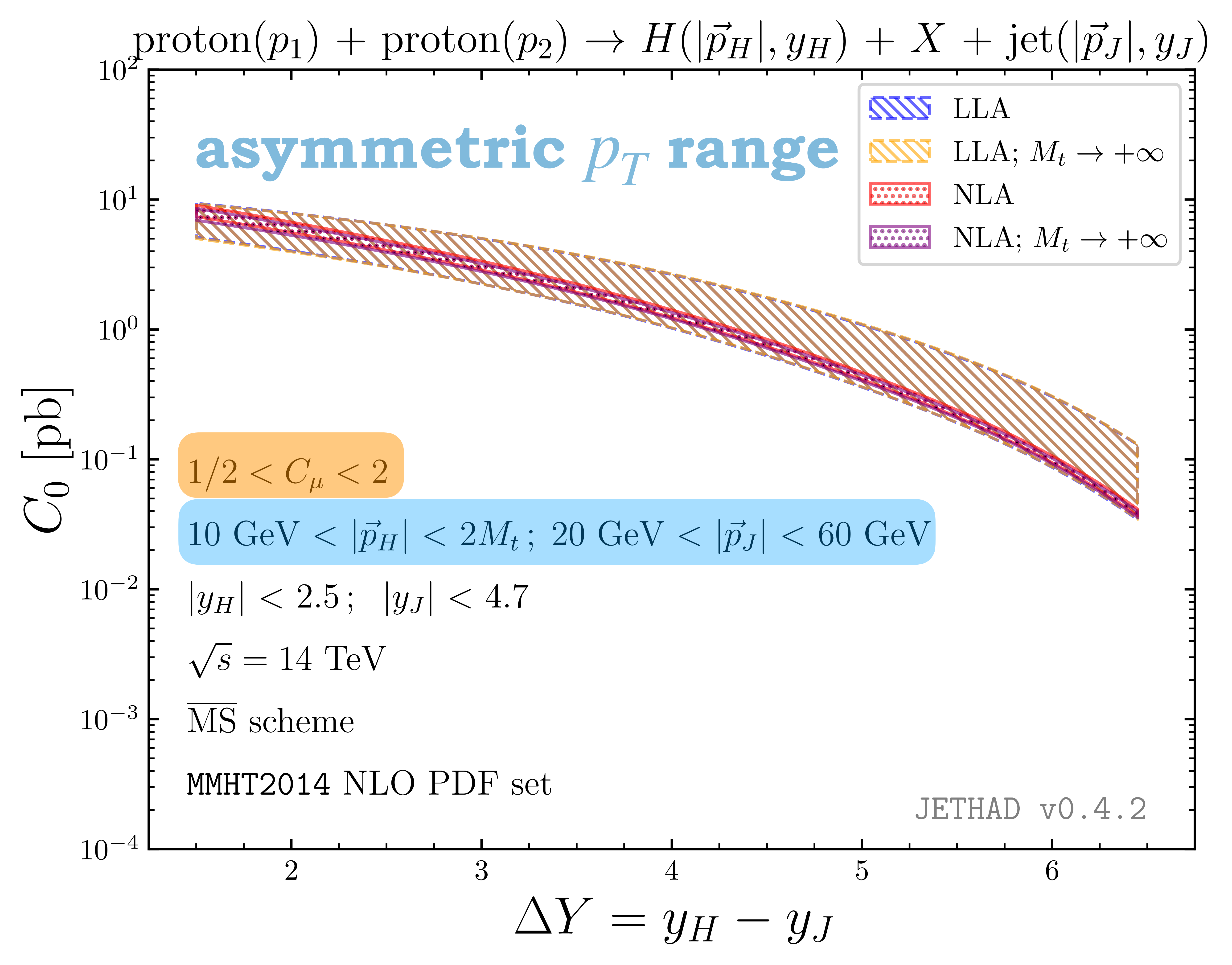

Backup

Azimuthal correlations: $C_1/C_0 \; (M_t \to +\infty)$

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

Backup

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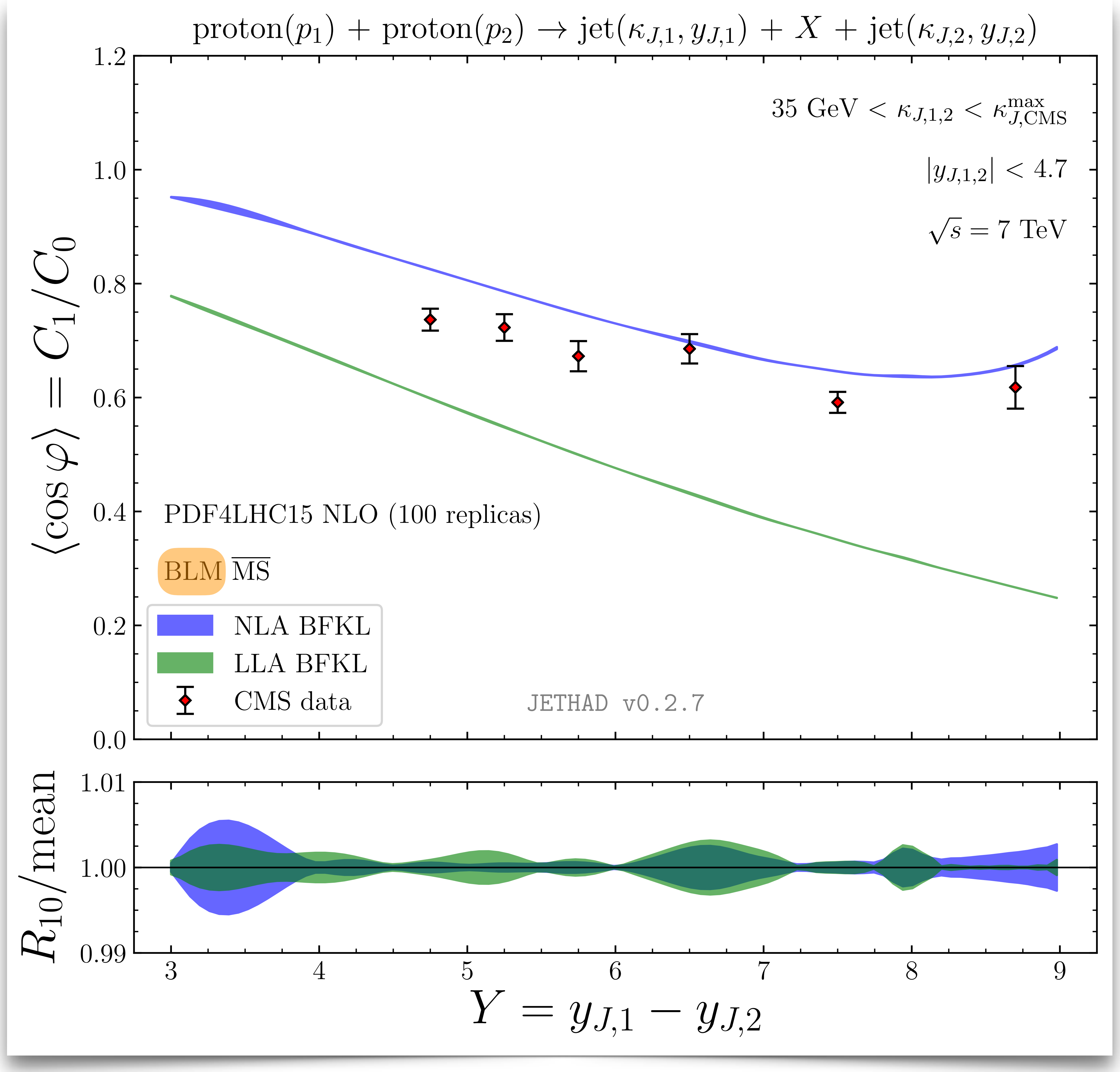
Mueller-Navelet jets

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

(figure below) 🔗 [F. G. C. (2020)]



Backup

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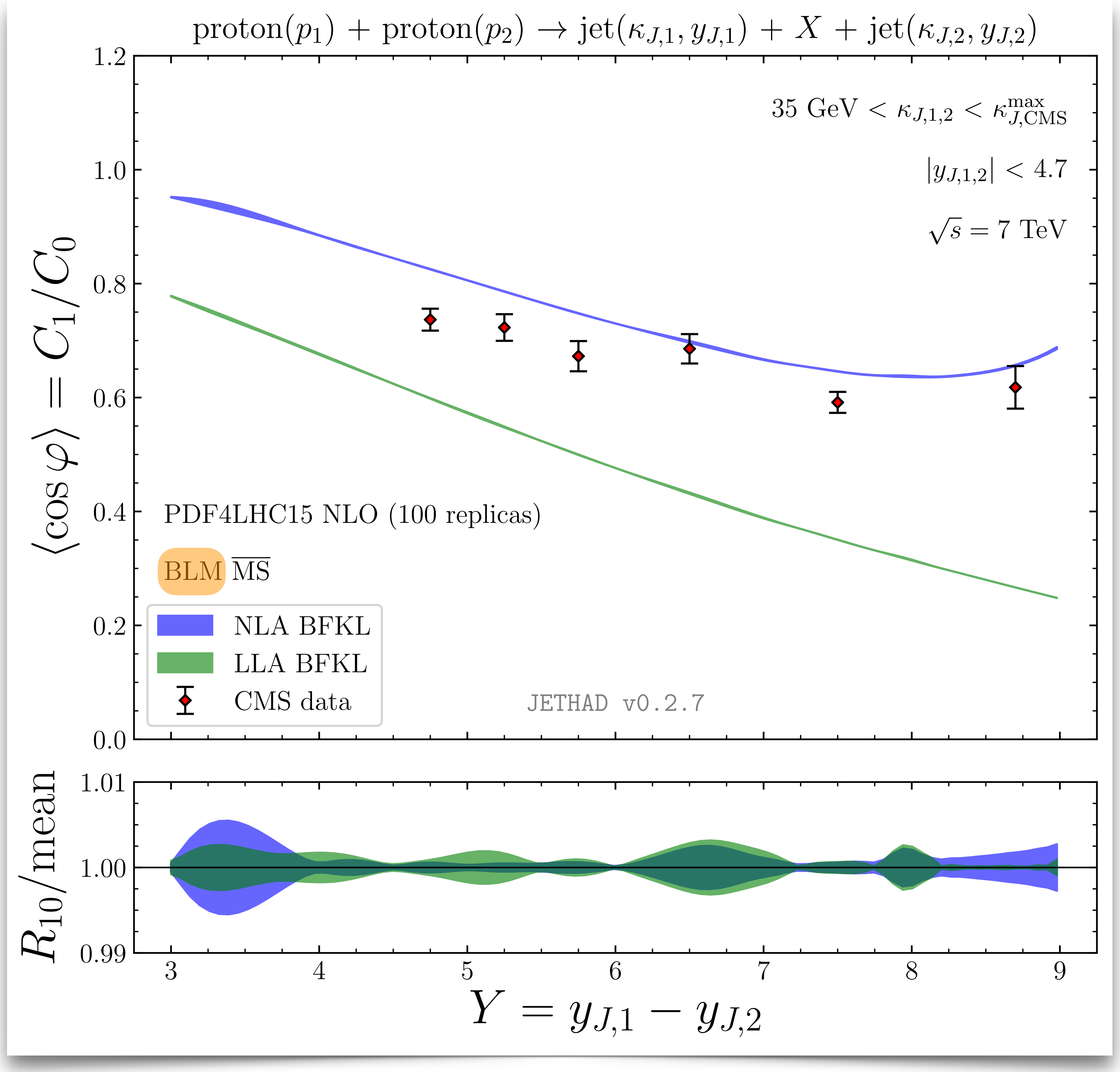
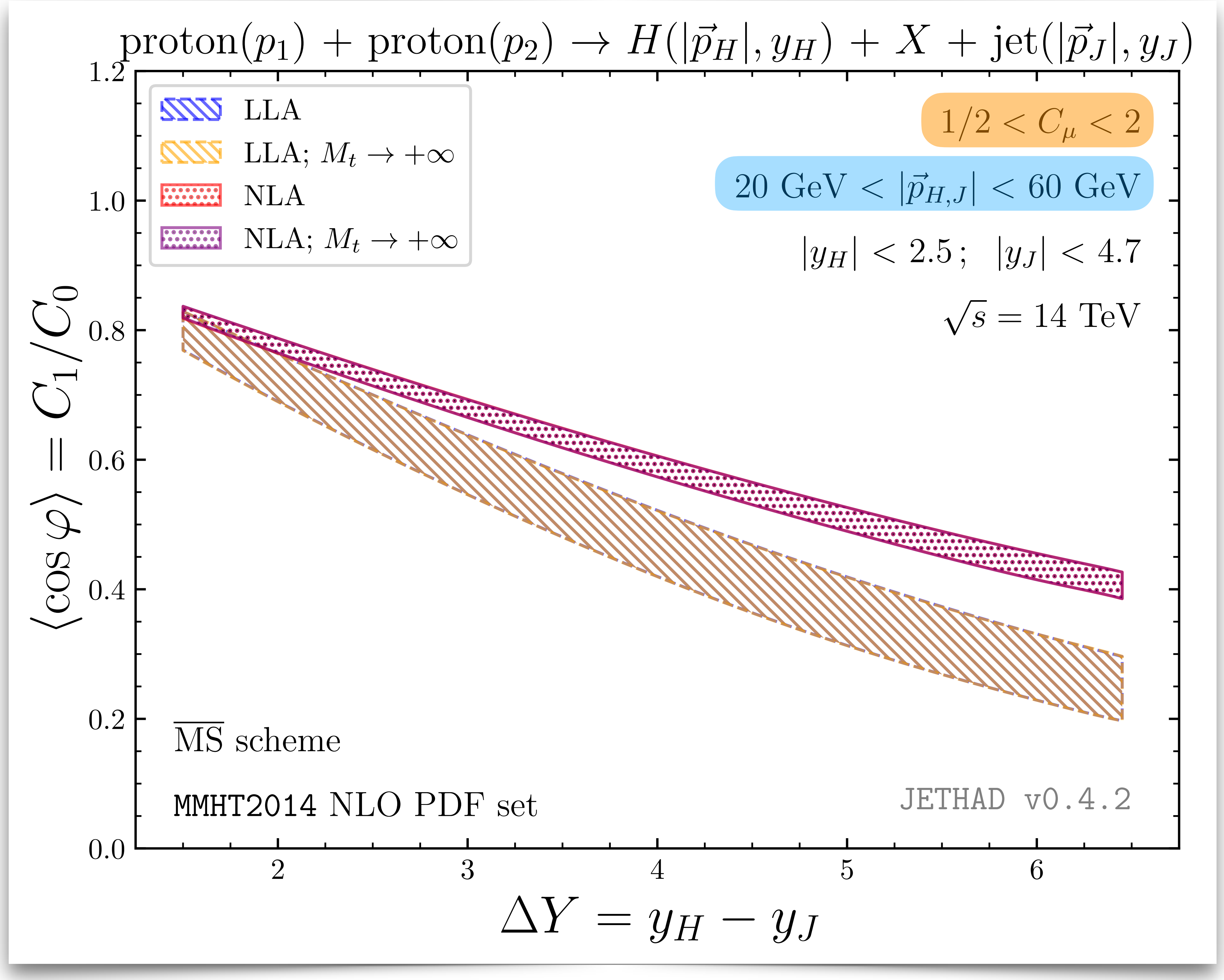


Higgs + jet



natural scales

symmetric p_T range

Backup

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

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

Backup

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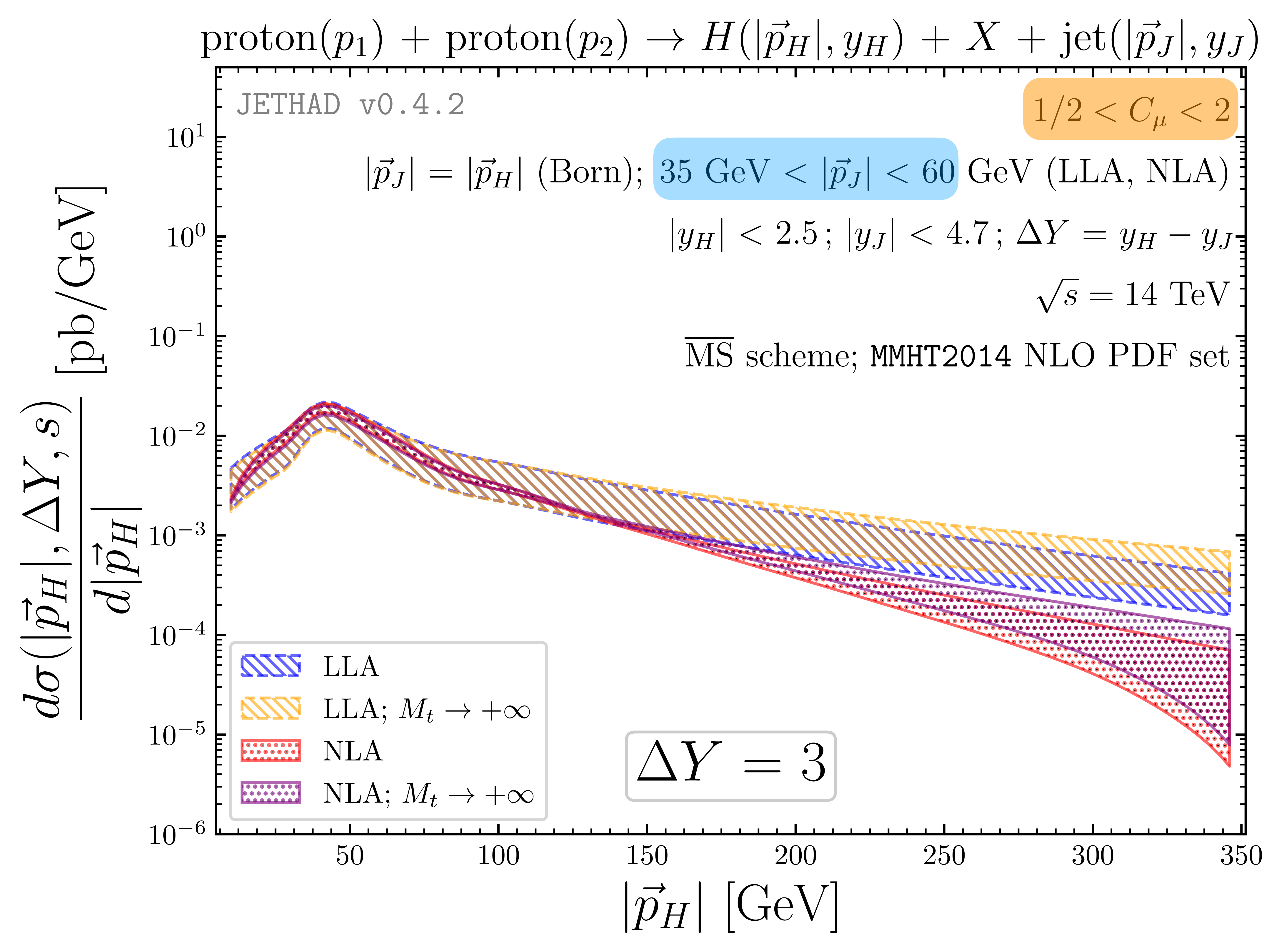

Backup

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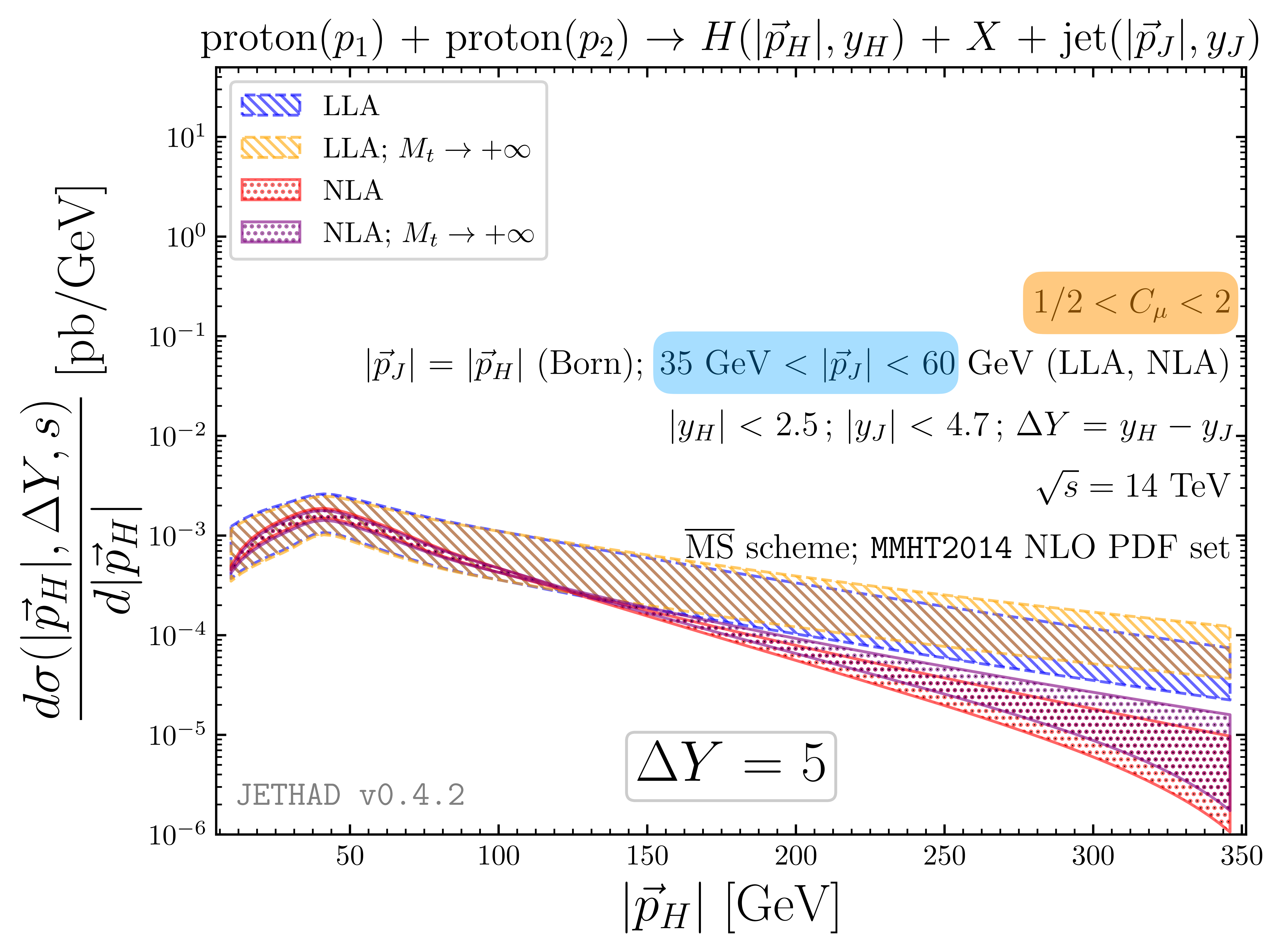

Backup