MATCHING TO NLL TO NLO IN HIGGS AND Z PLUS JET AT THE LHC AND FCC

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In collaboration with: Luigi Delle Rose, Alessandro Papa

Marseille
- T08 -
Higgs Physics

2025, July 7th

Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

EUGLOH

Higgs production from LHC to FCC

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

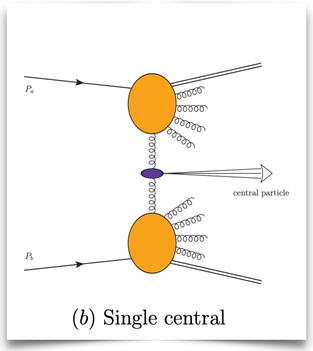
Double Resummation for Higgs Production

Marco Bonvini[1,*] and Simone Marzani[2,†]
[1]*INFN, Sezione di Roma 1, Piazzale Aldo Moro 5, 00185 Roma, Italy*
[2]*Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy*

(Received 26 February 2018; published 16 May 2018)

We present the first double-resummed prediction of the inclusive cross section for the main Higgs production channel in proton-proton collisions, namely, gluon fusion. Our calculation incorporates to all orders in perturbation theory two distinct towers of logarithmic corrections which are enhanced, respectively, at threshold, i.e., large x, and in the high-energy limit, i.e., small x. Large-x logarithms are resummed to next-to-next-to-next-to-leading logarithmic accuracy, while small-x ones to leading logarithmic accuracy. The double-resummed cross section is furthermore matched to the state-of-the-art fixed-order prediction at next-to-next-to-next-to-leading accuracy. We find that double resummation corrects the Higgs production rate by 2% at the currently explored center-of-mass energy of 13 TeV and its impact reaches 10% at future circular colliders at 100 TeV.

DOI: 10.1103/PhysRevLett.120.202003



(*b*) Single central

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

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

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

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

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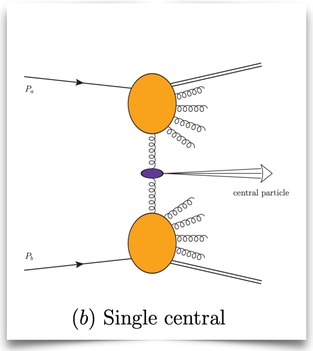

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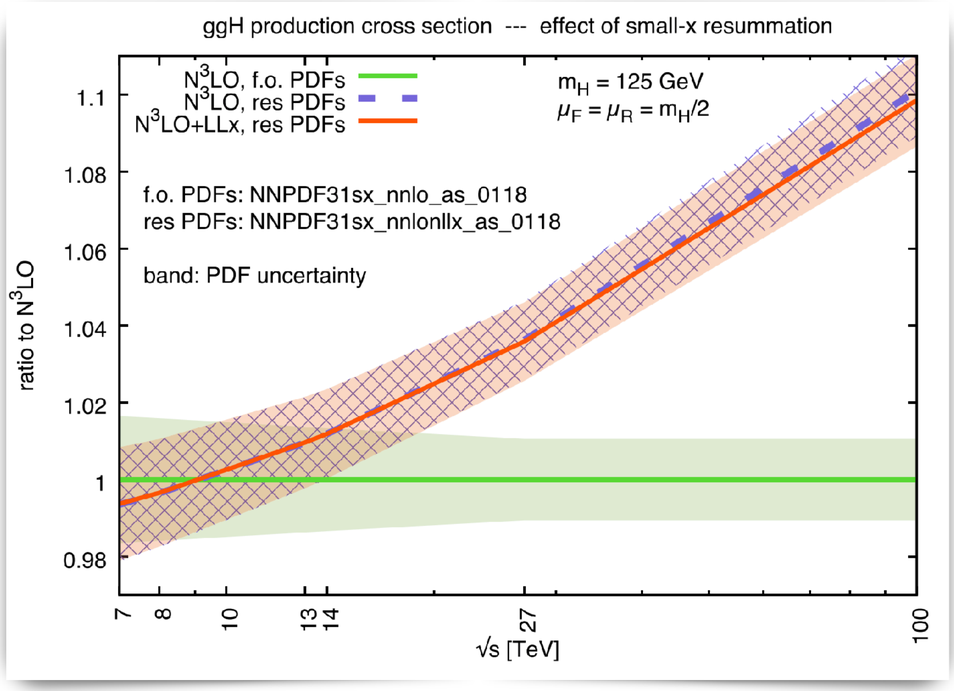

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(¡!) 100 TeV EW physics ⇔ small-x physics!

(¿?) Can LHC physics be resummation physics?

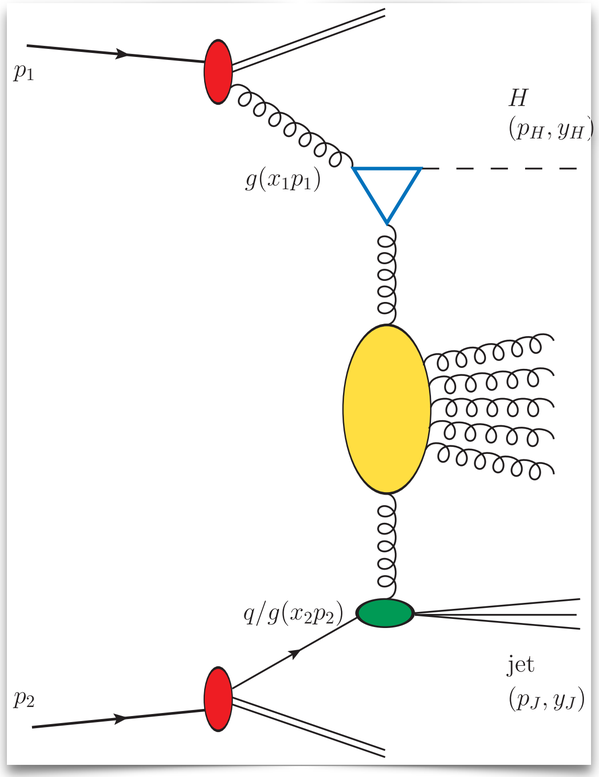
$$C_{ij}(x,\alpha_s) = C_{ij}^{\mathrm{fo}}(x,\alpha_s) + \Delta C_{ij}^{\mathrm{lx}}(x,\alpha_s) + \Delta C_{ij}^{\mathrm{sx}}(x,\alpha_s)$$

From Mueller-Navelet to Higgs and heavy flavor

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

HIGGS BOSON

Stabilizers ⇔ large Higgs transverse masses



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

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

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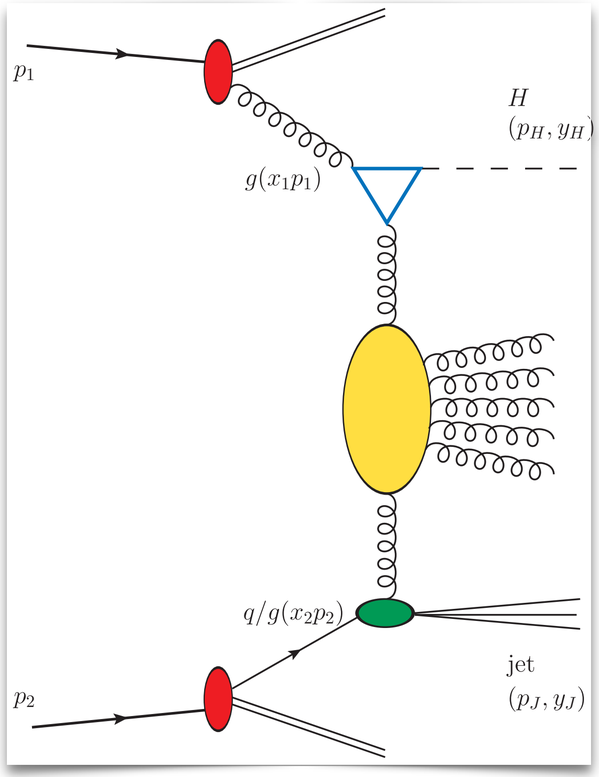

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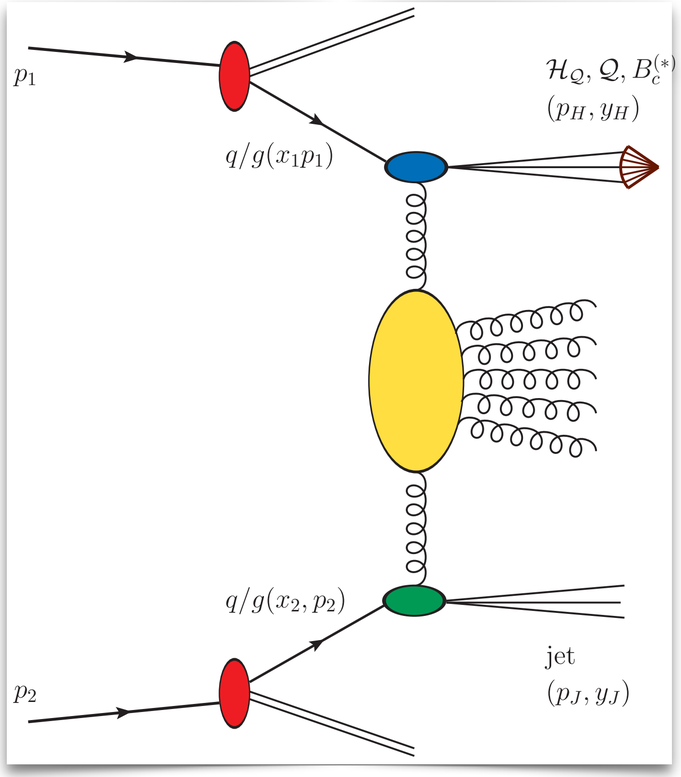
HEAVY FLAVOR AT LARGE P_T

Stabilizers ⇔ gluon fragmentation channels



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

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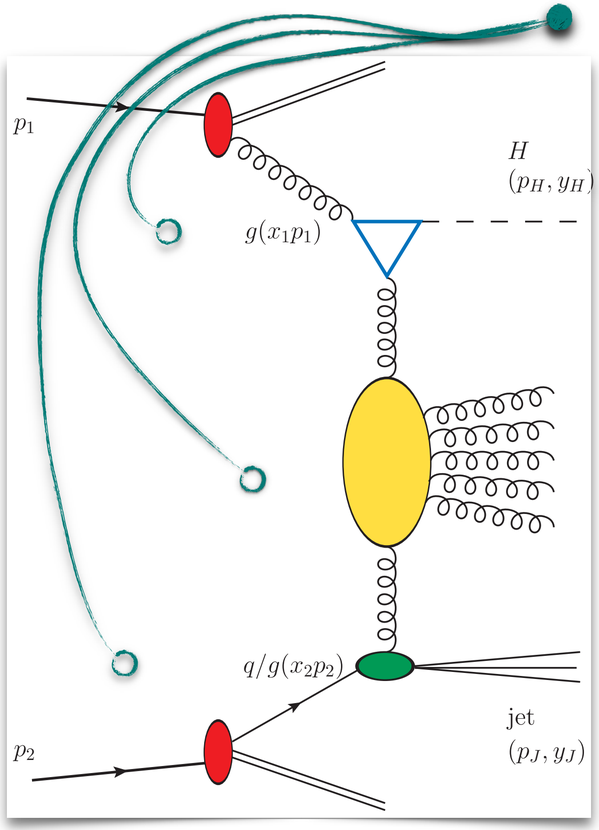

$\mu_{F,R} \sim M_{H,\perp}$

NLO*

= LO + NLO$^{\text{RGE}}$

NLL

NLO

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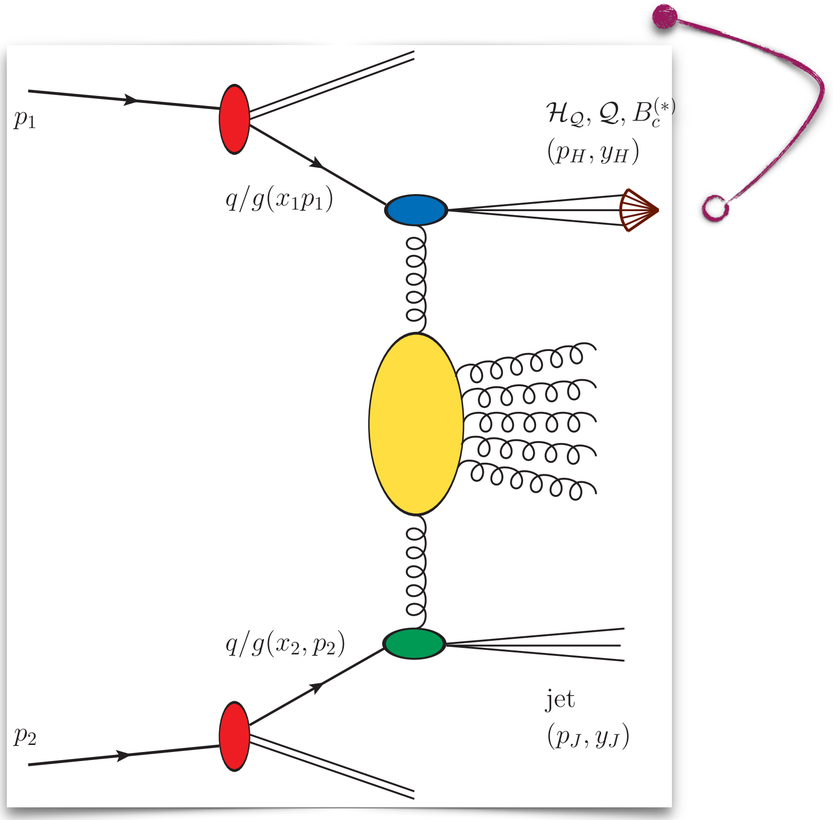

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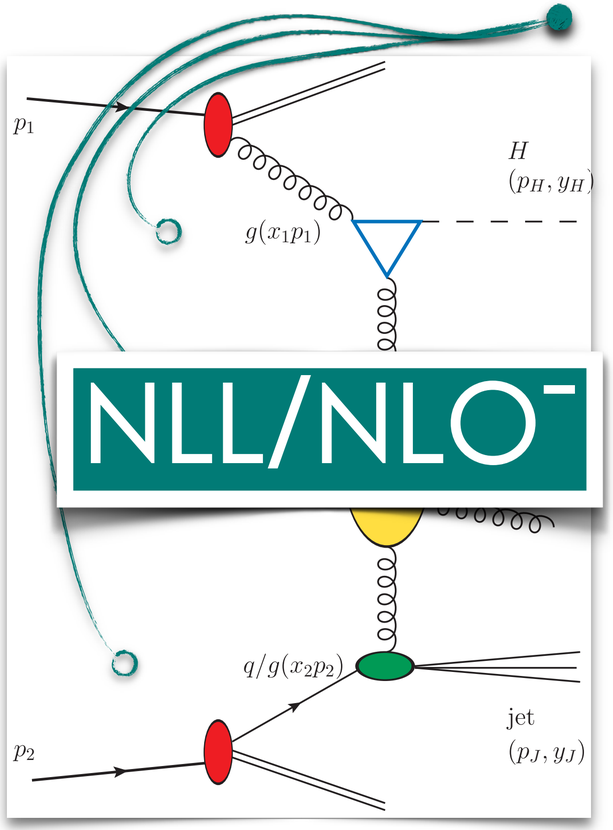

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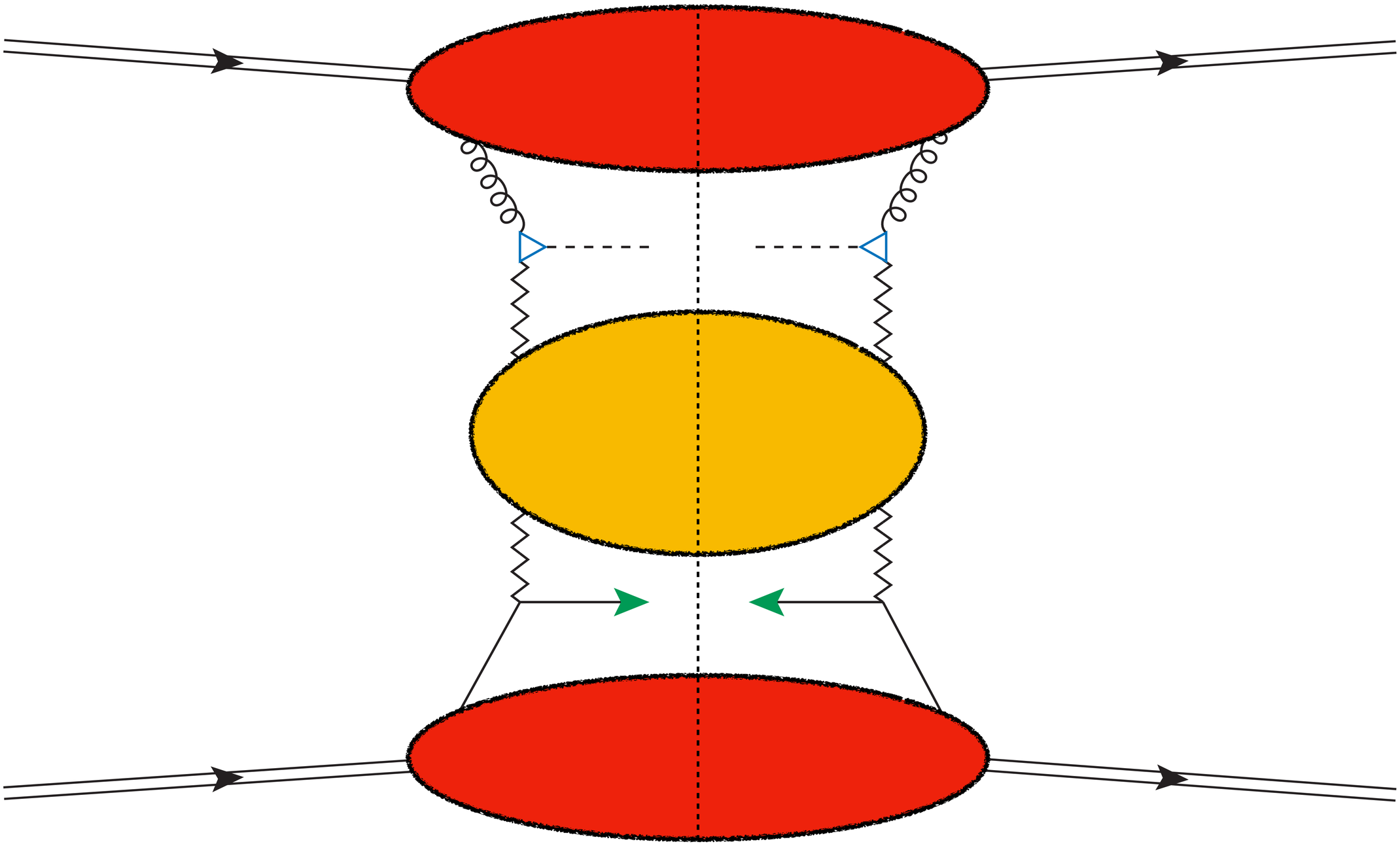
Anatomy of Higgs + jet in hybrid factorization (HyF)



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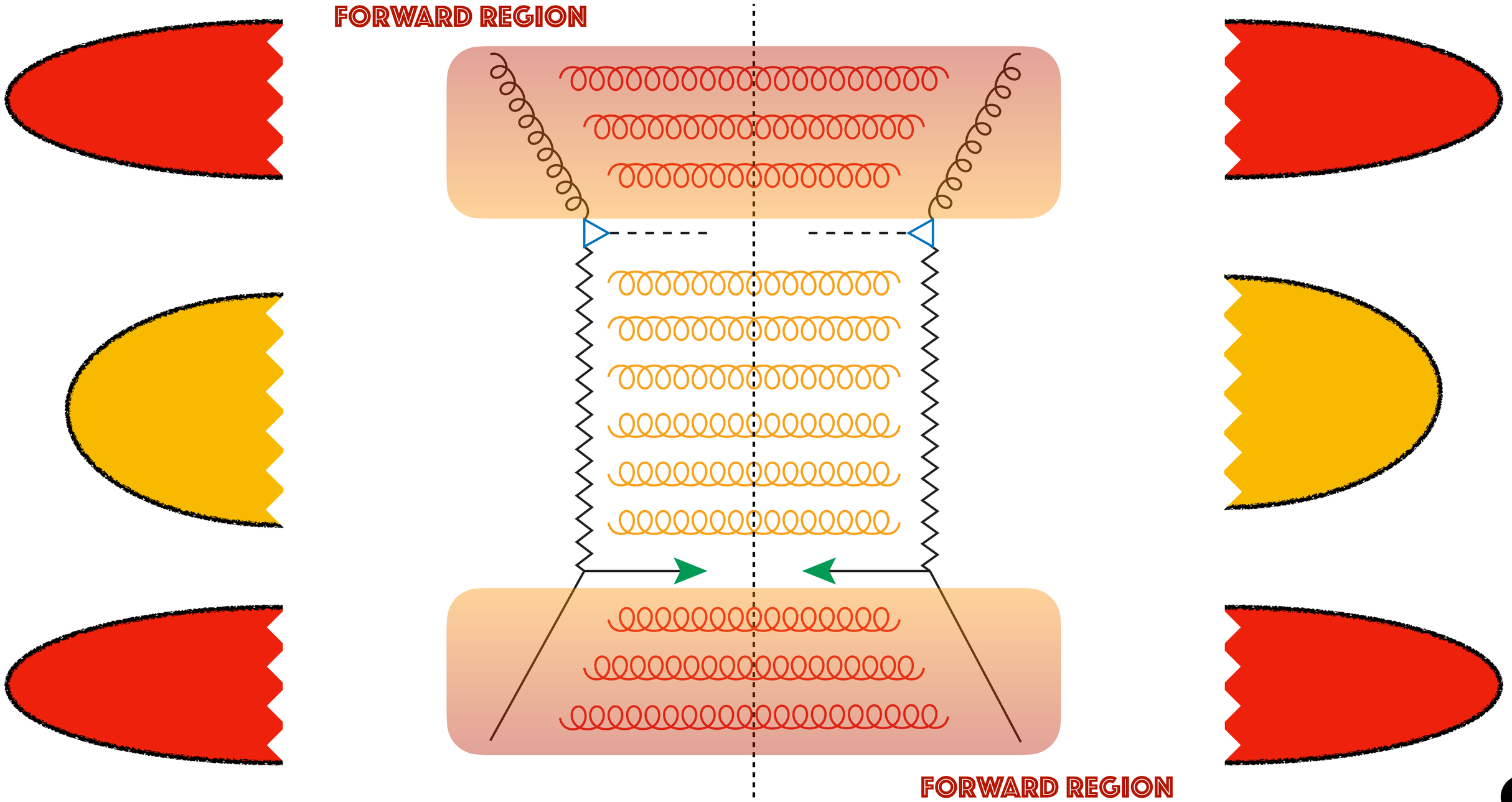

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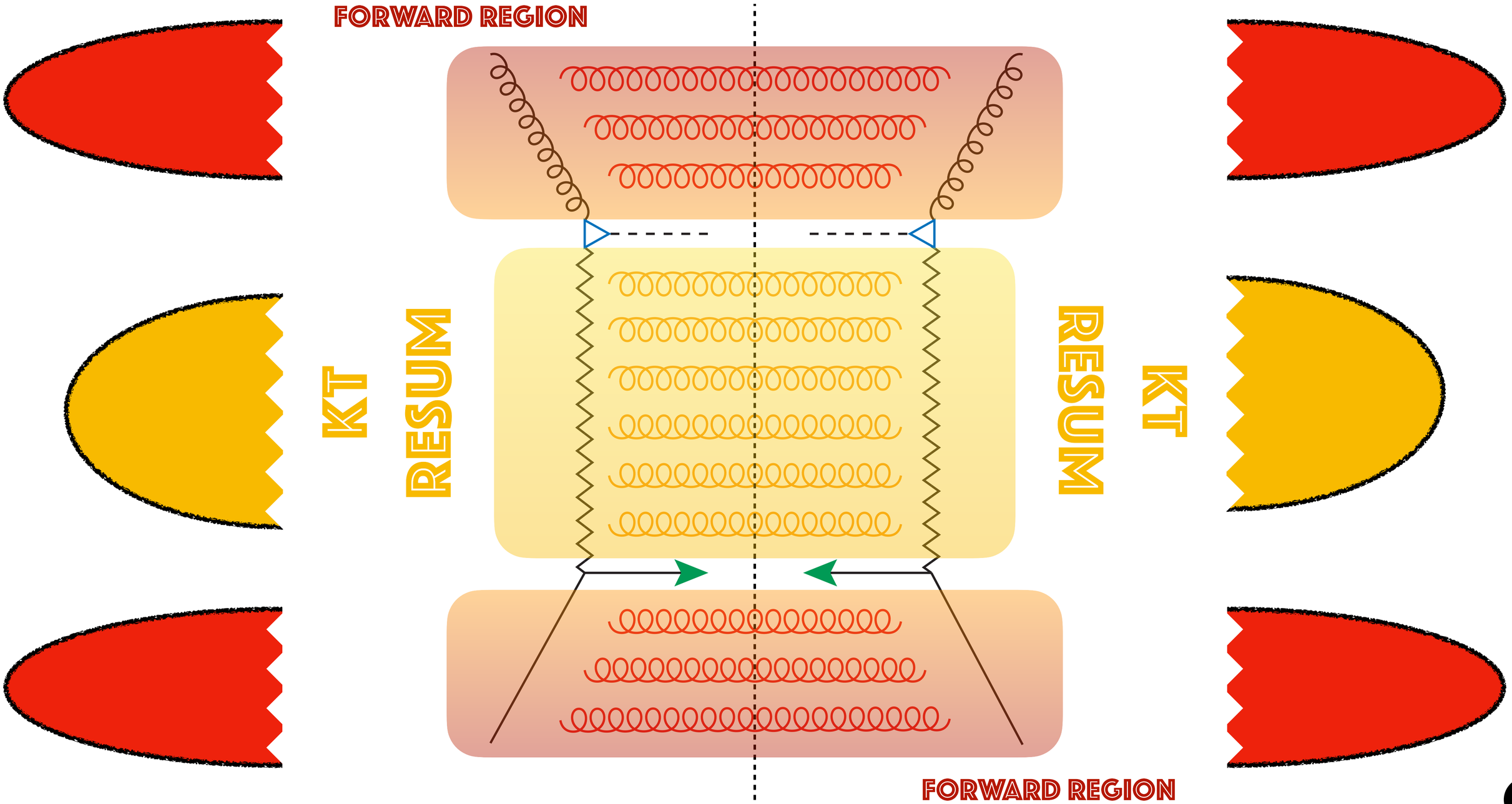

NLL accurate predictions matched to NLO via the JETHAD Method

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

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

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$\Delta\mathrm{d}\sigma^{\mathrm{NLL/NLO^{-}}}$: NLO POWHEG w/o PS

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NLO POWHEG w/o PS

NLL⁻ JETHAD w/o NLO⁻ double counting

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HELL + ggHiggs

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

Inclusive Higgs

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

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HEJ framework

NLL_{sx}^{-}/NLO

Higgs + jet(s)

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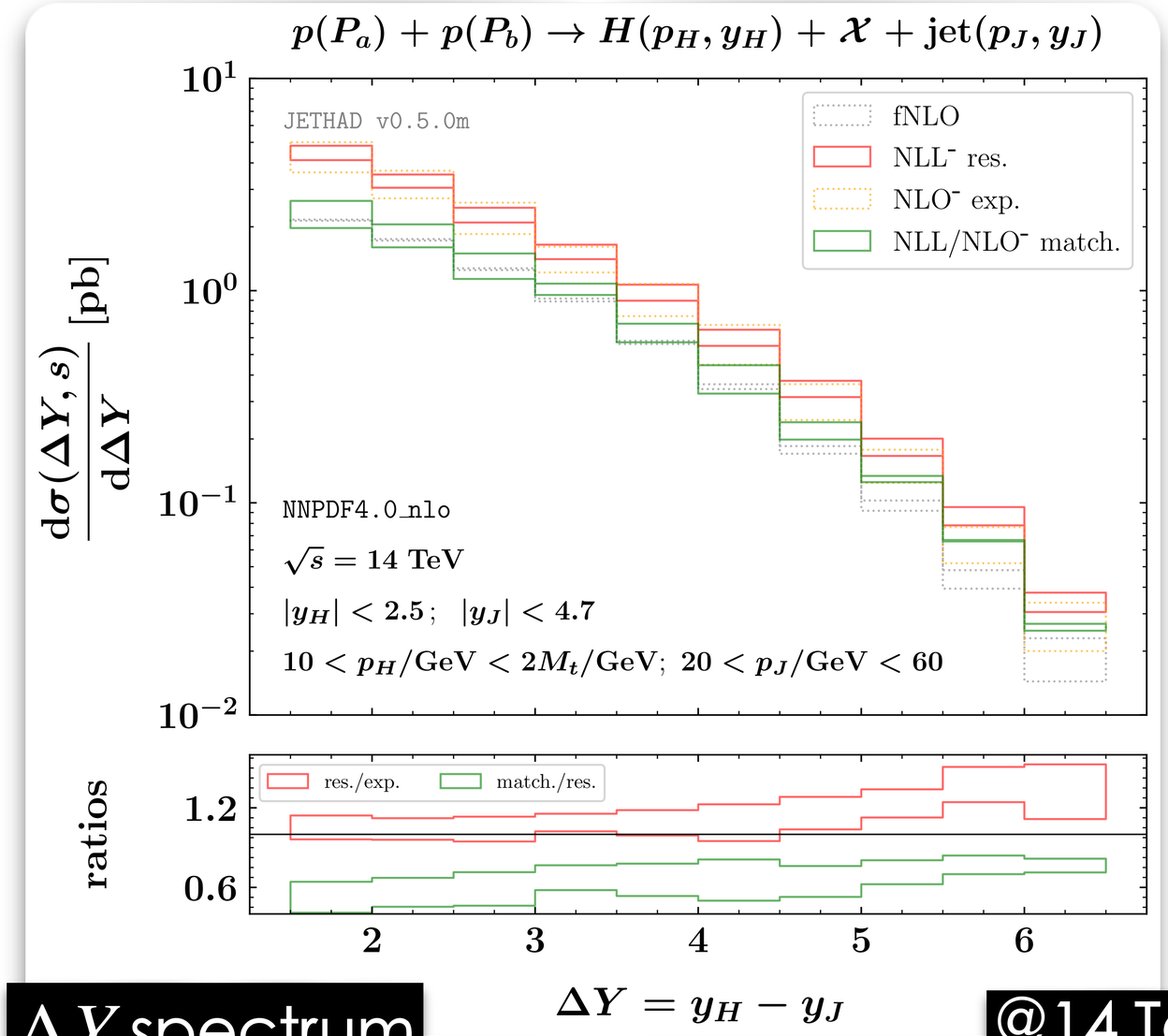
RadISH + MCFM-8.3

$NNLL_{TM}/NLO$

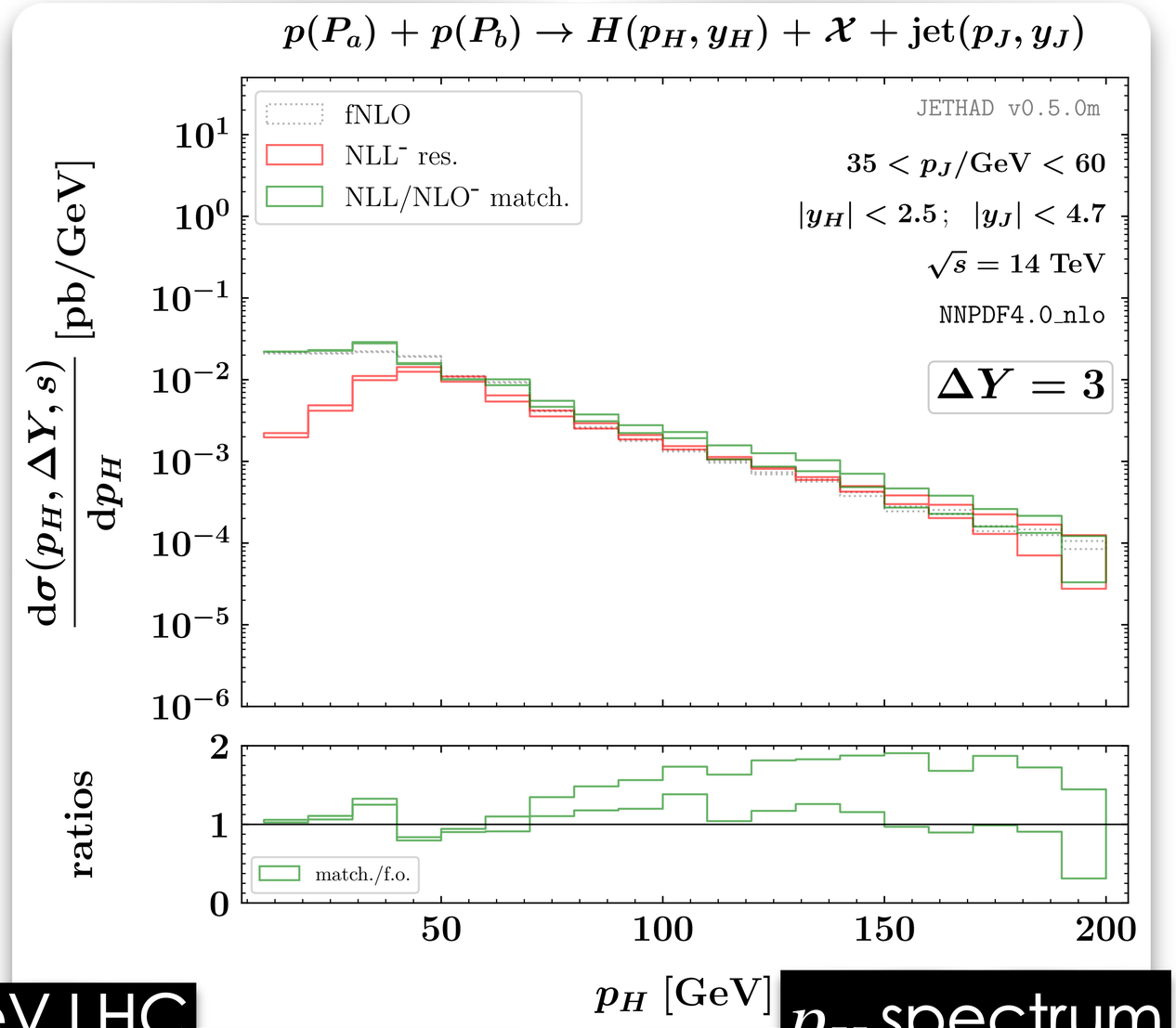
Higgs + jet

🔗 [P.F. Monni et al. (2020)]

The Higgs + jet spectrum from POWHEG + JETHAD



ΔY spectrum



p_H spectrum

@14 TeV LHC

2.2 POWHEG + JETHAD distributions

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

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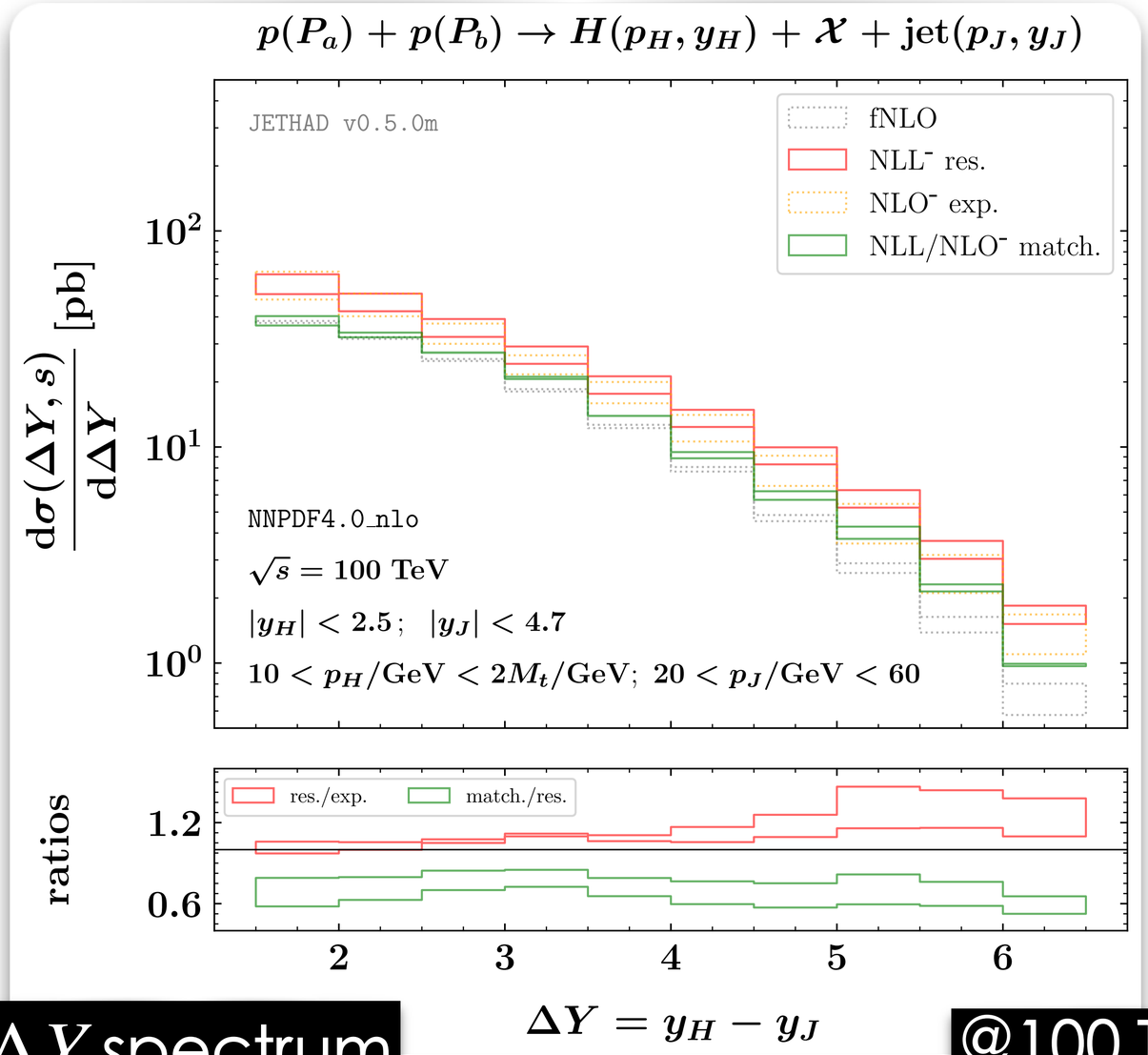

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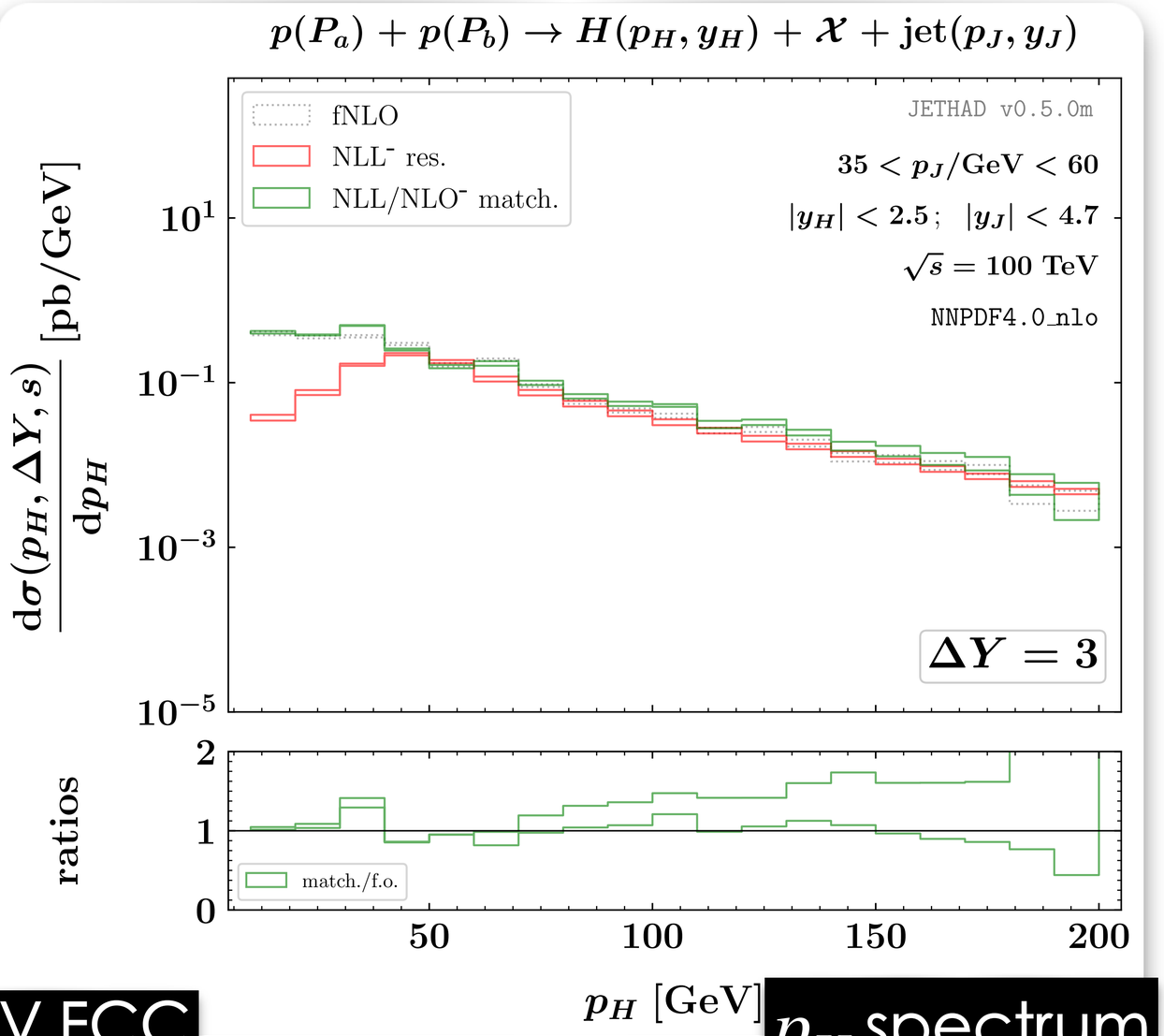
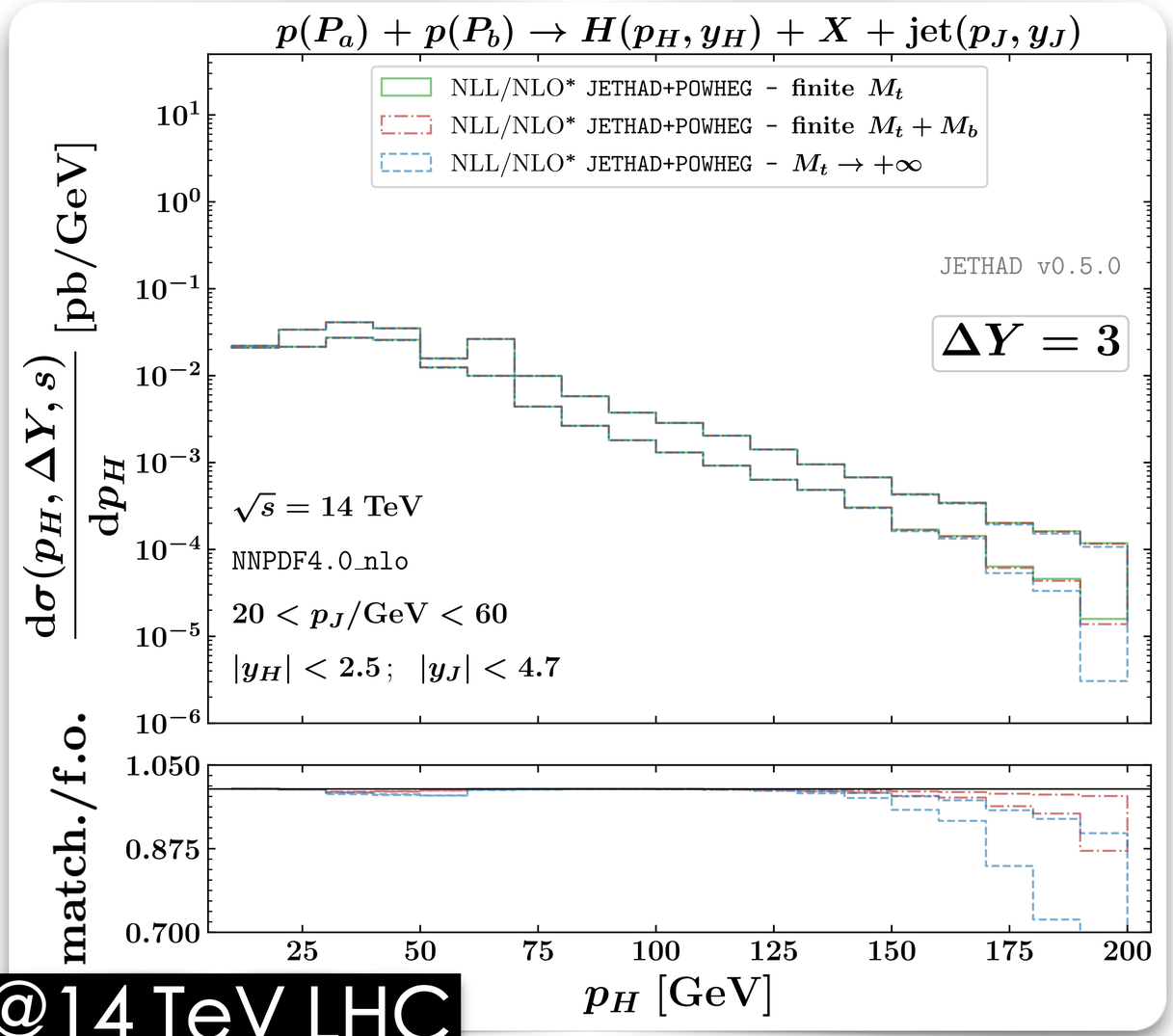


p_H spectrum

@100 TeV FCC

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

Finite top- and bottom-mass corrections



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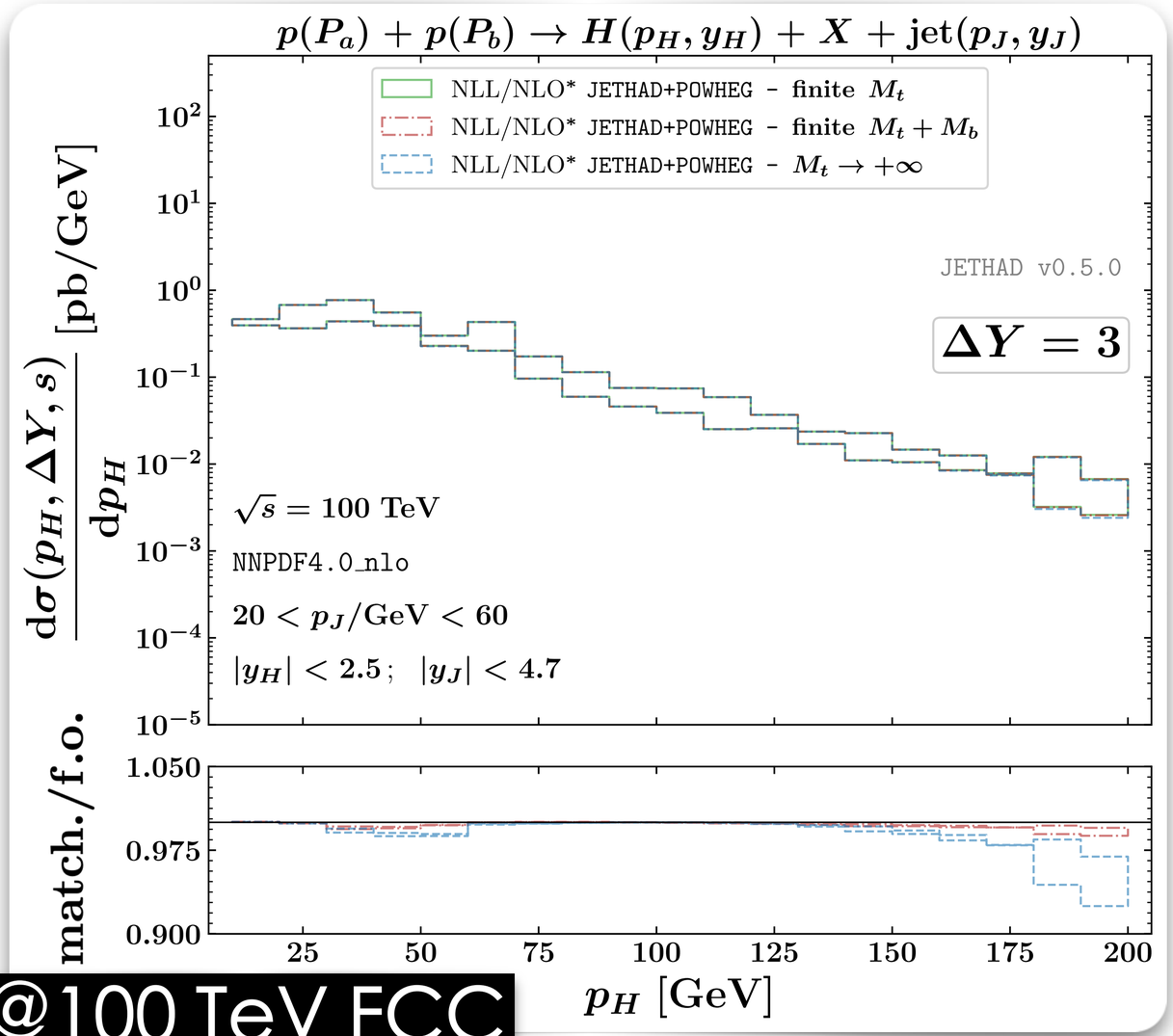

@100 TeV FCC

2.2 POWHEG + JETHAD distributions

(Physical masses at NLO) [F. G. C., L. Delle Rose, M. Fucilla, G. Gatto, A. Papa (2024)]

Towards Z + jet at NLL/NLO^{+} via the JETHAD Method

Forward Drell-Yan production

- LHC, **forward region** $\rightarrow$ $(l^+ l^-)$ produced in the fragmentation region of h_2
  - ◇ Asymmetric configuration: $x_1 \gg x_2$, down to $x_2 \simeq 10^{-6}$

$\Longrightarrow$ **possible small-x resummation effects expected!**

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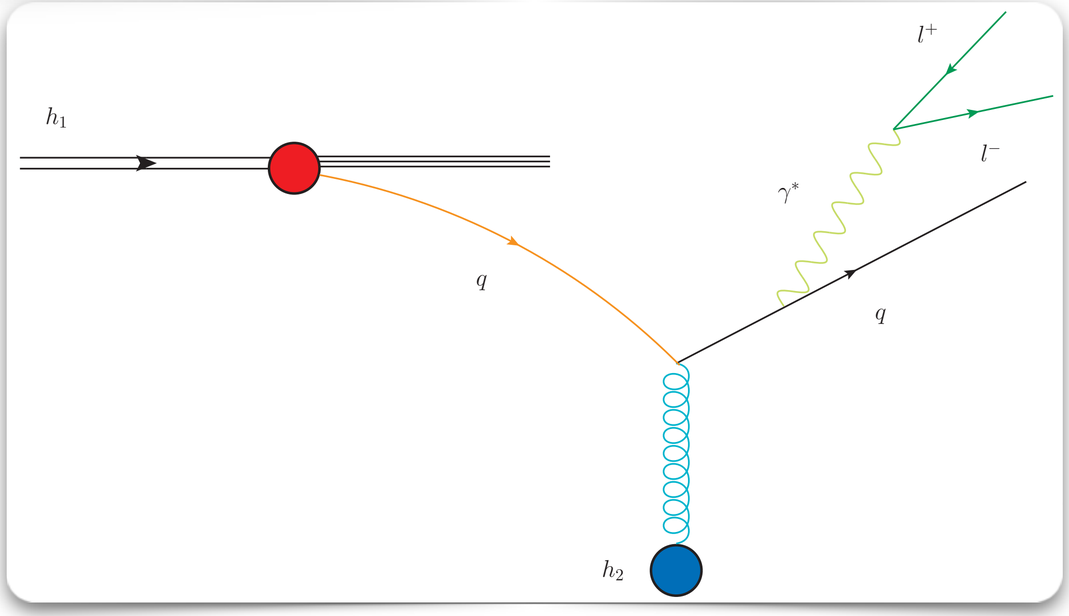
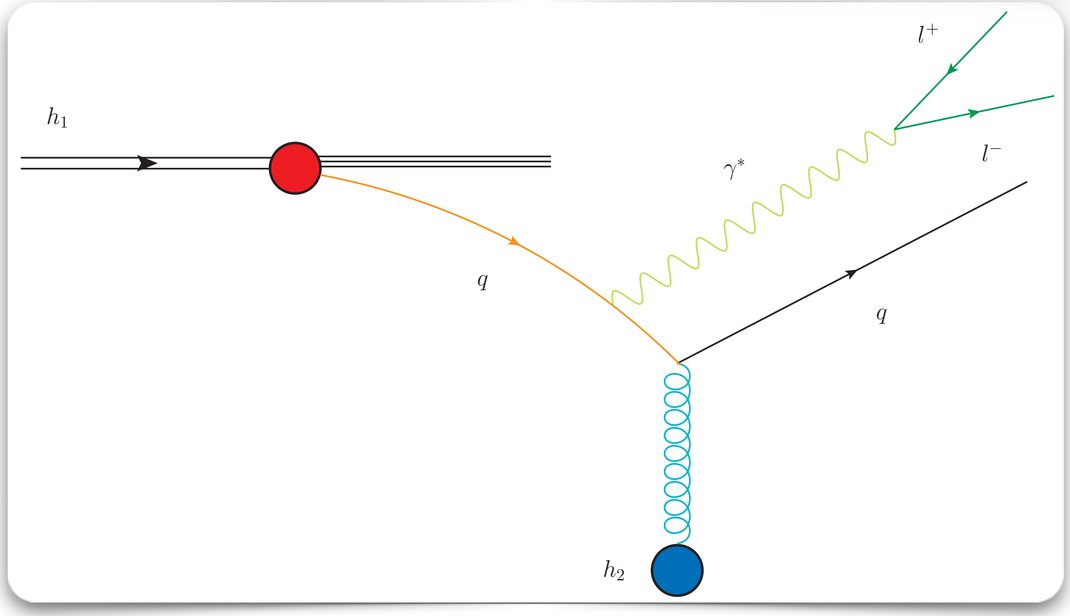


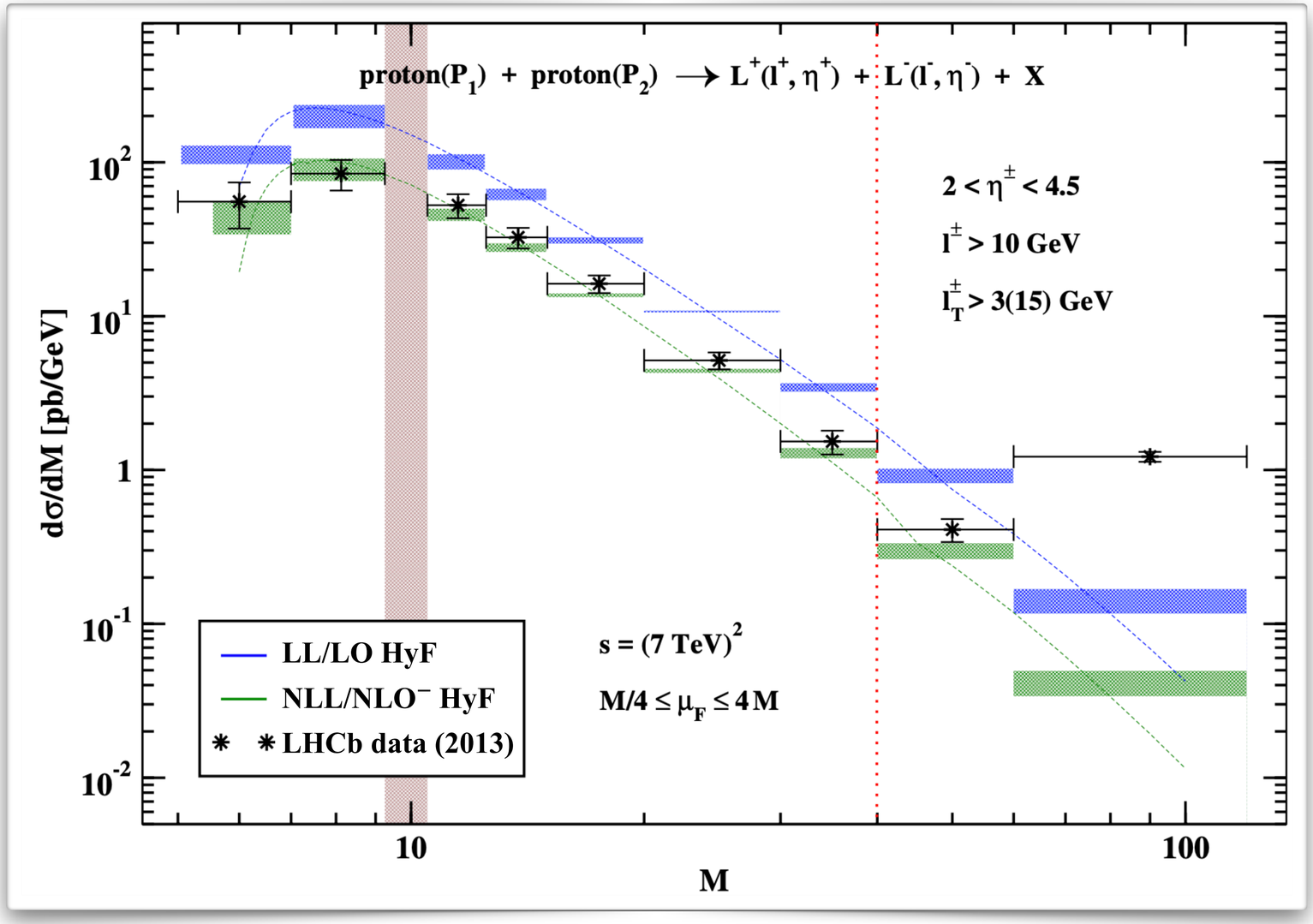


(LO DY emission functions + Mellin) [G. Golec-Biernat, E. Lewandowska, A. M. Stasto, Phys. Rev. D 82 (2010) 094010]

(LO DY emission functions + Mellin) [L. Motyka, M. Sadzikowski, T. Stebel, JHEP 05 (2015) 087]

(Twist decomposition + pheno) [D. Brzemiński, L. Motyka, M. Sadzikowski, T. Stebel, JHEP 01 (2017) 005]

Forward Drell-Yan production @LHC (2018)



NLL/NLO^{-} studies @7TeV LHCb

[F. G. C., D Gordo Gómez, A. Sabio Vera, Phys. Lett. B 786 (2018) 201-206]

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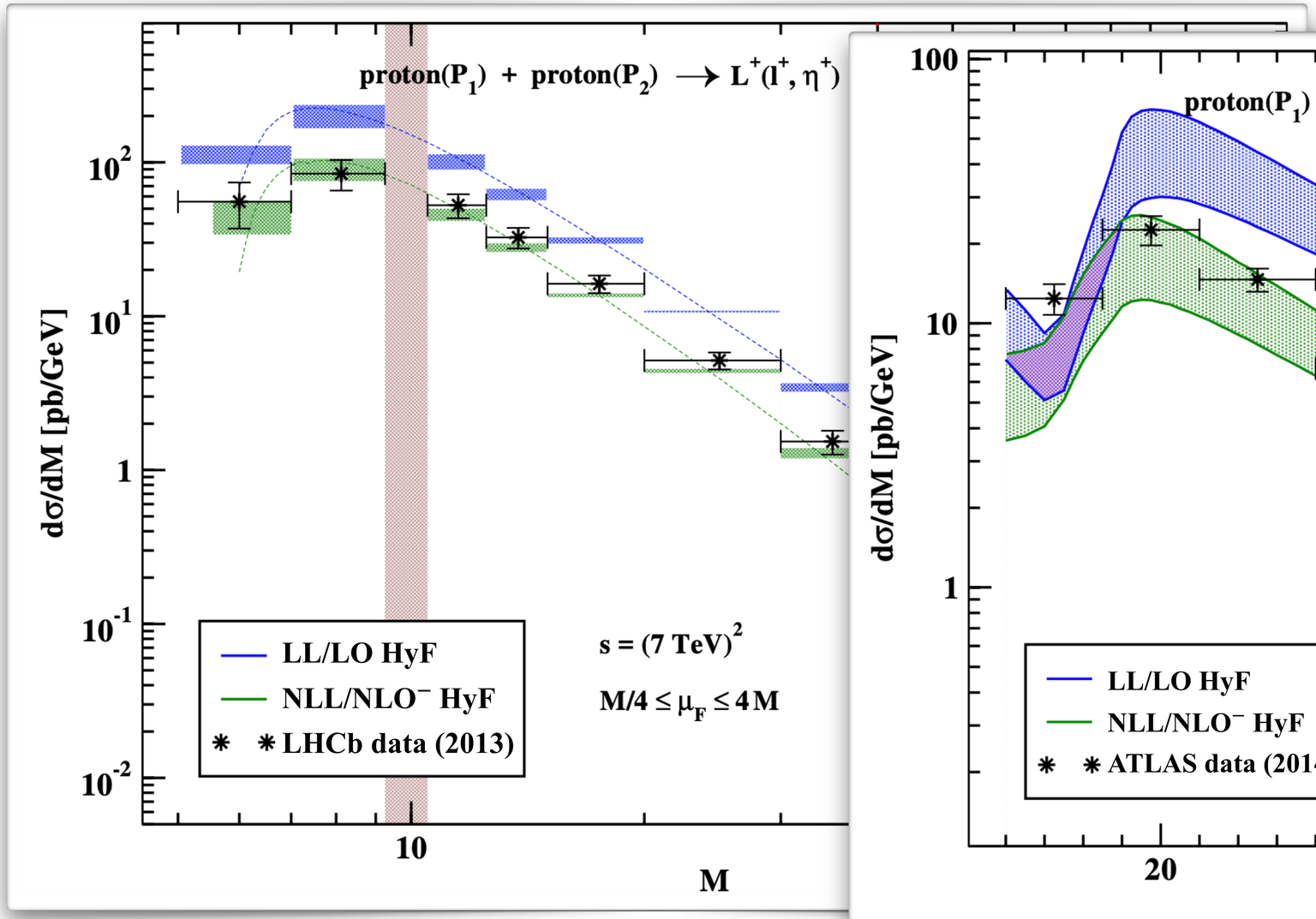

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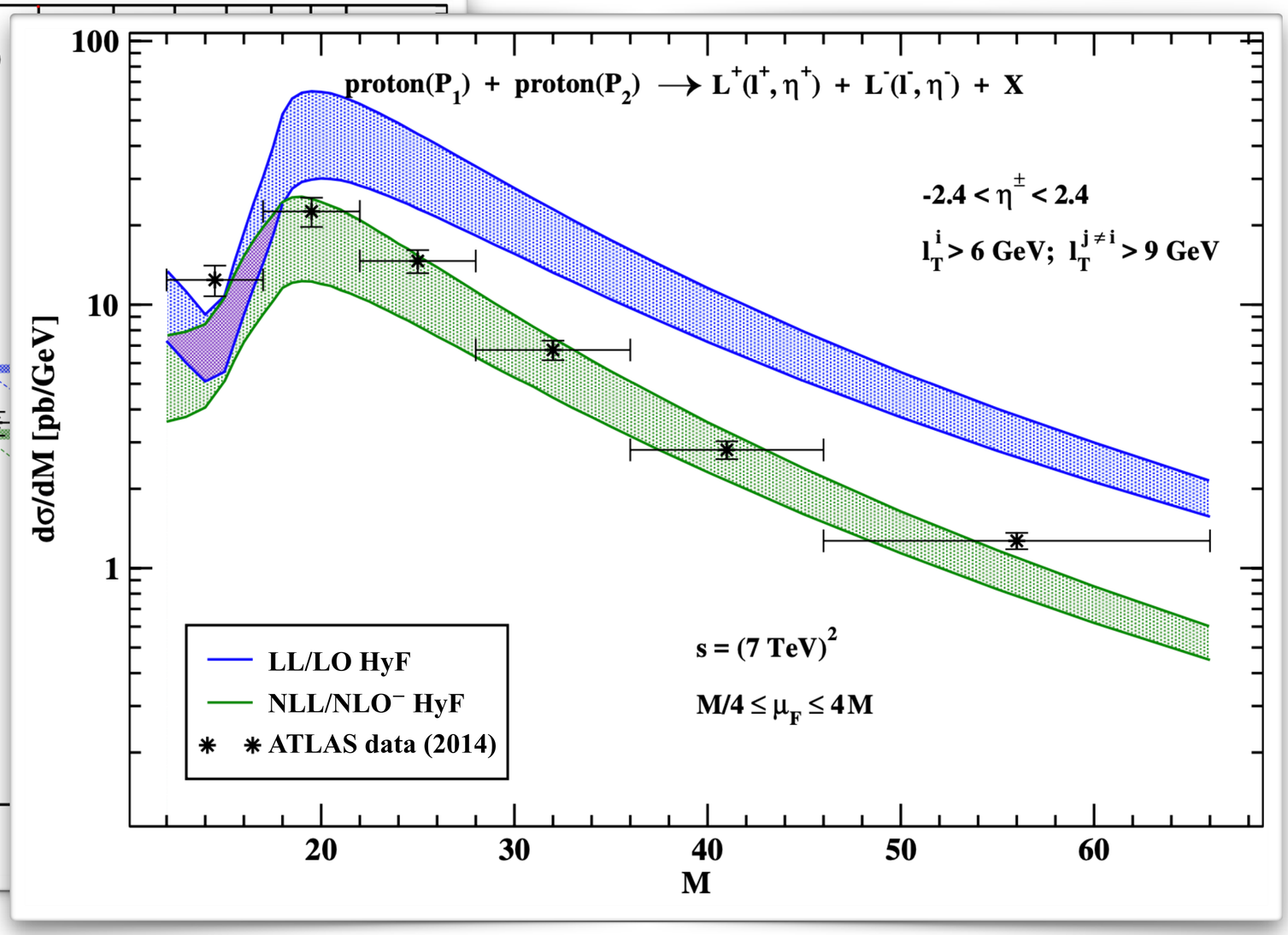

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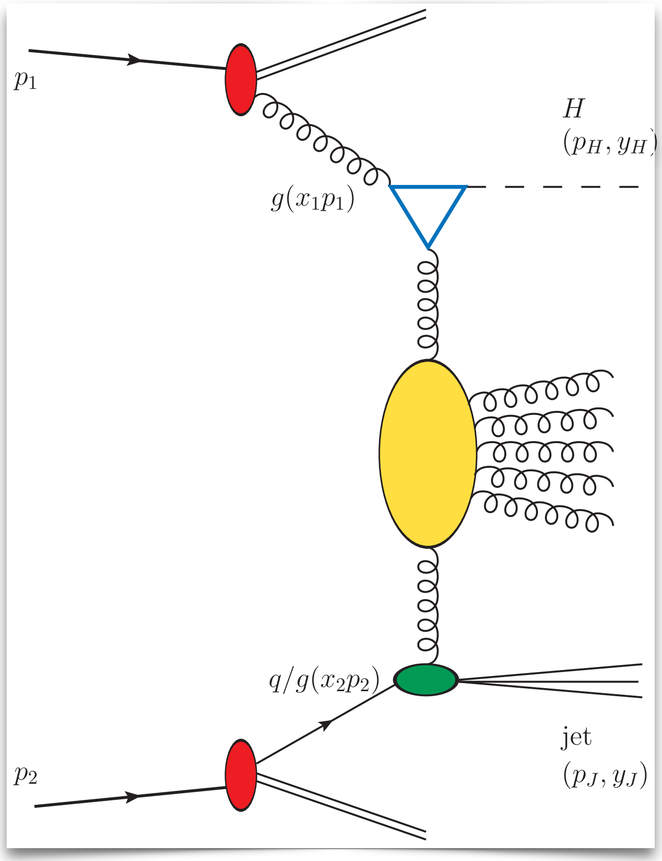
From Mueller-Navelet to Higgs and heavy flavor

HIGGS BOSON + JET



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

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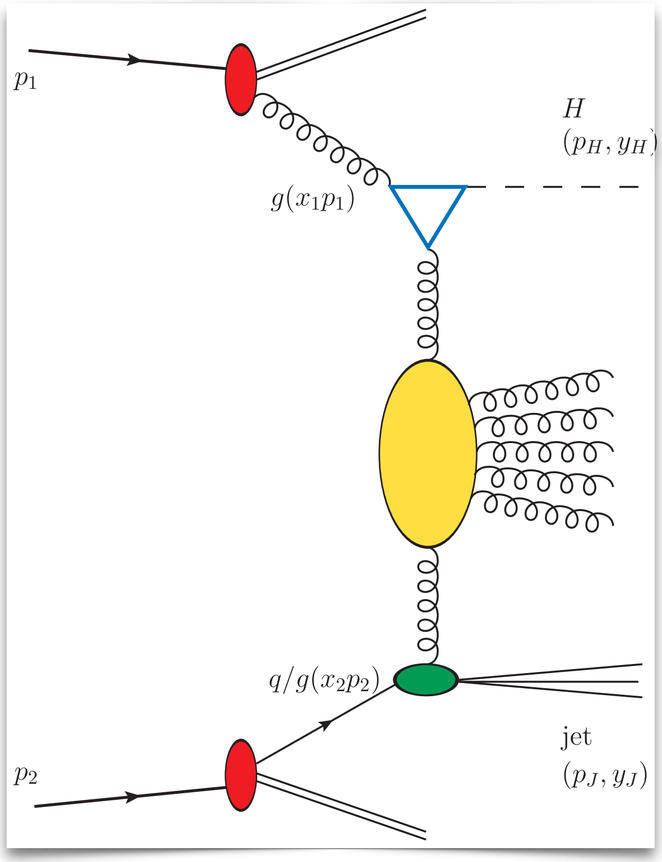

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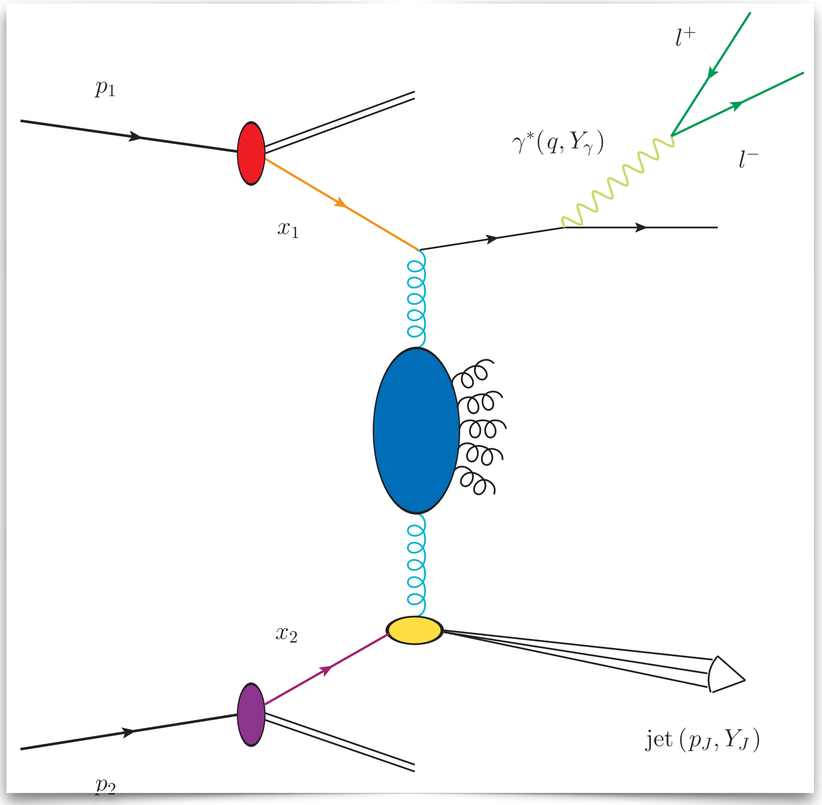

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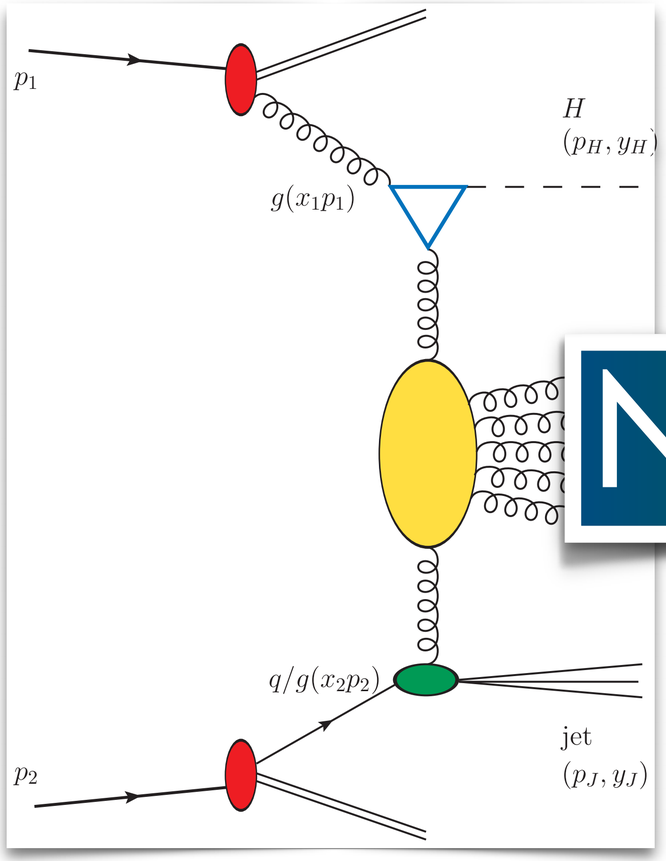

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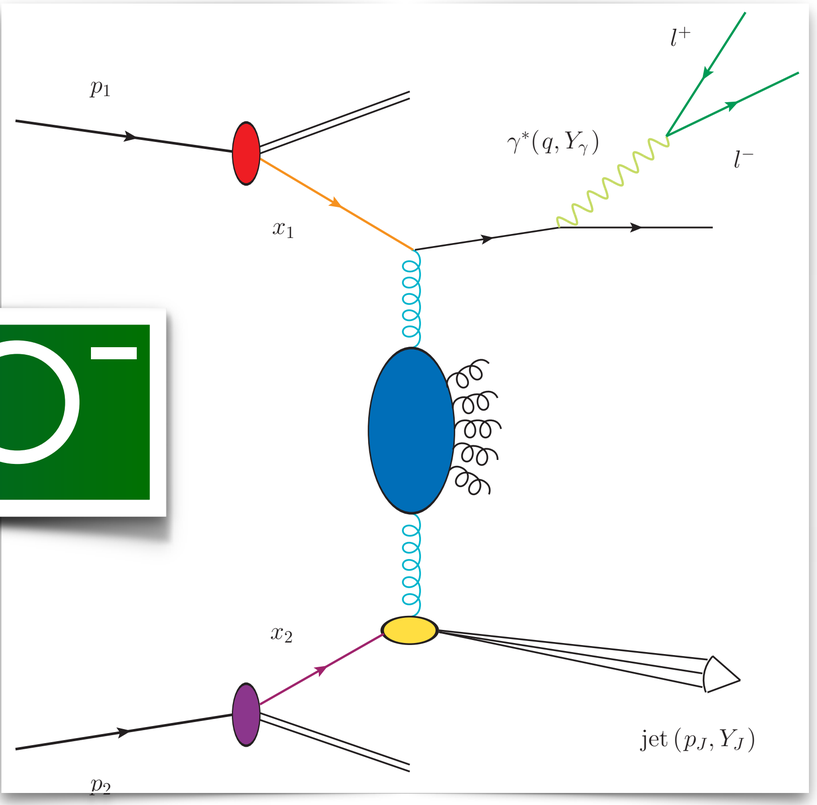

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Paving the way towards precision

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

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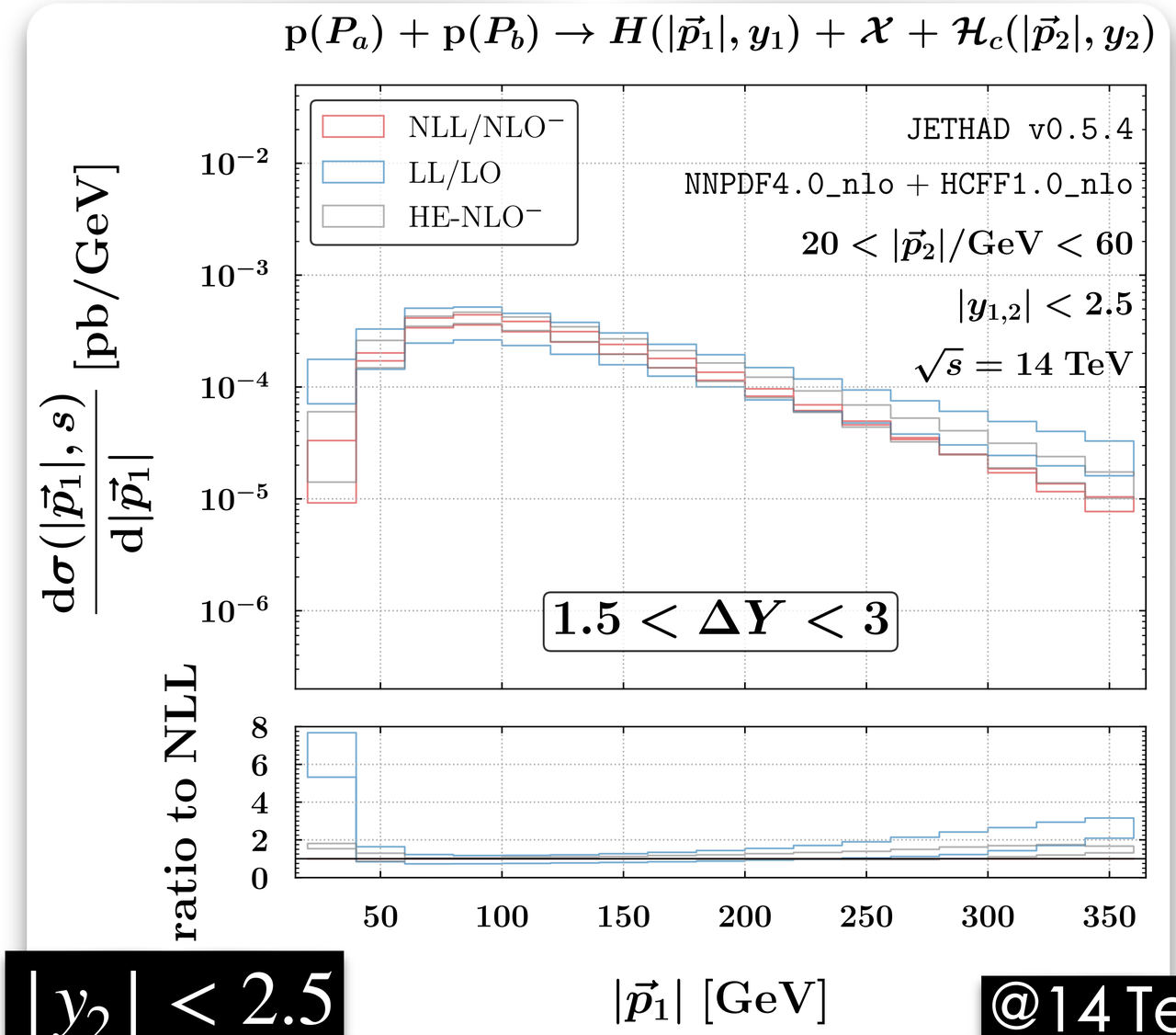
- ☐ Precision studies ⇔ NLL/NLO Matching via the JETHAD Method
- ☐ Systematic uncertainties: top & bottom masses, PDF impact, Matching
- ☐ Compare TM spectrum with Parton Shower, then Match/Merge with NLL_{sx} (¿?)
- ☐ Higgs + jet and at Z + jet from NLL/NLO^{-} to NLL/NLO^{+}

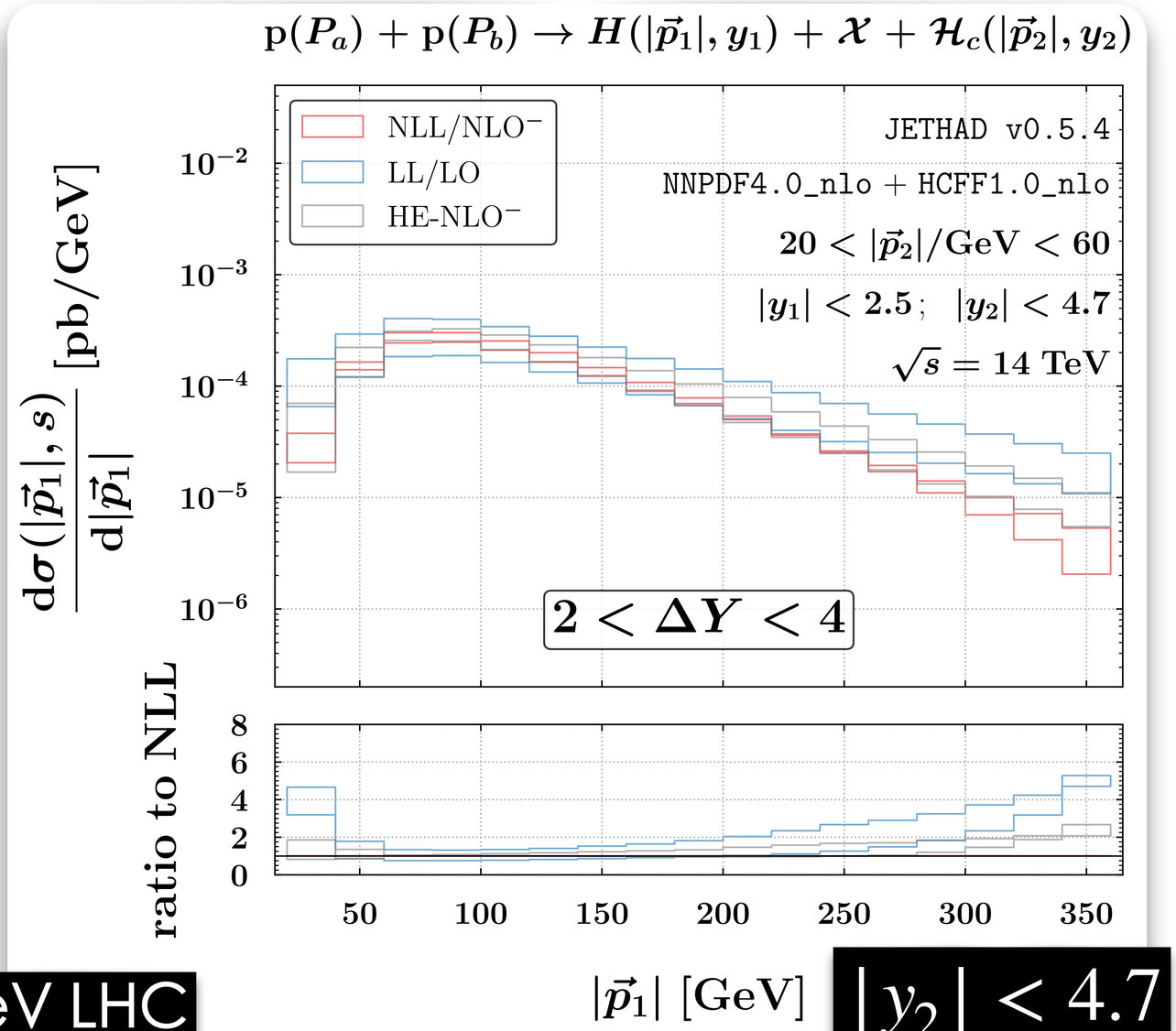
EXTRAS

The NLL/NLO^{-} spectrum of Higgs + charm

The Higgs + charm spectrum at NLL/NLO$^-$ HyF



$|y_2| < 2.5$



$|y_2| < 4.7$

@14 TeV LHC

(NLL/NLO$^+$ HyF) [F. G. C., L. Delle Rose, M. Fucilla, G. Gatto, A. Papa (in progress)]

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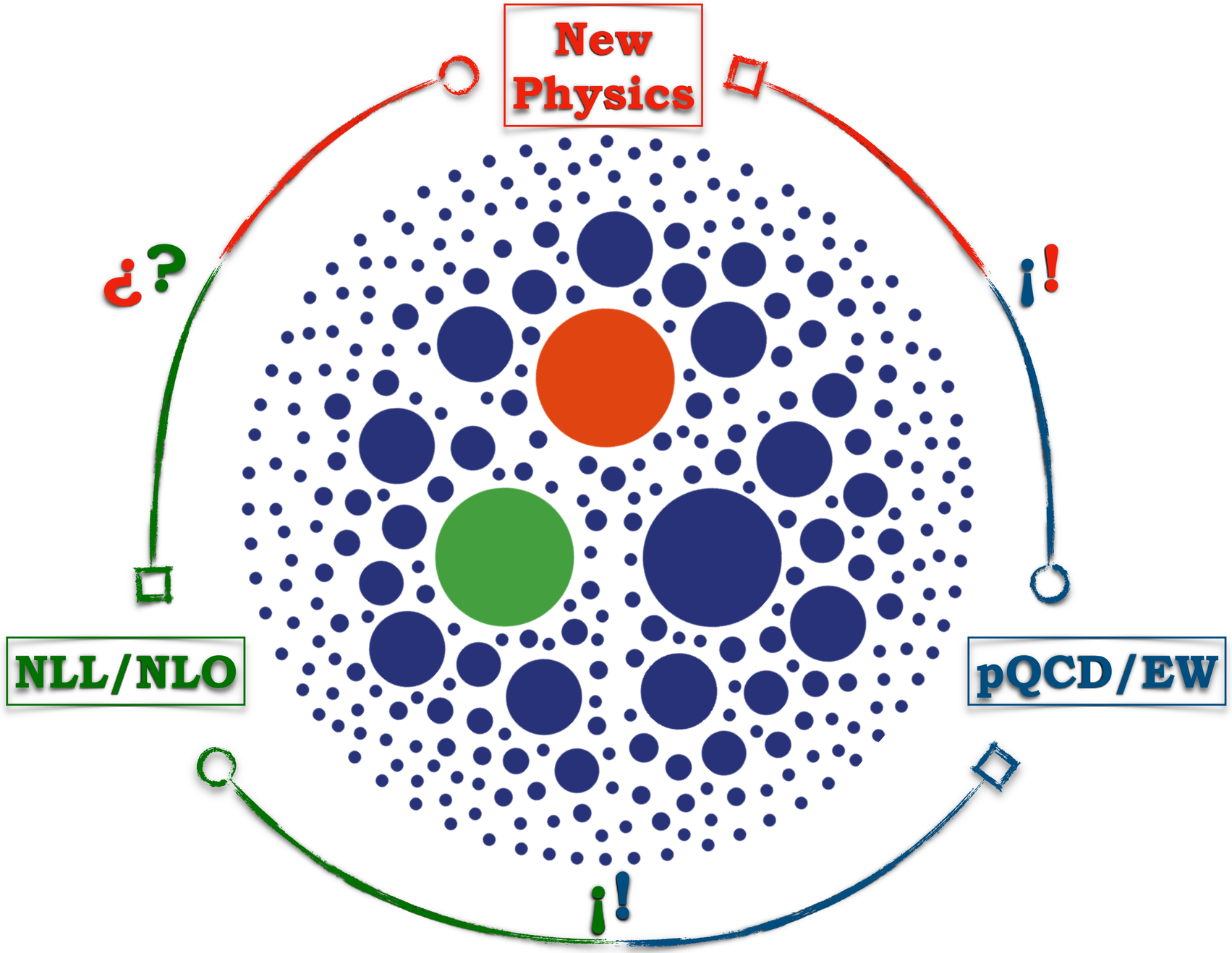

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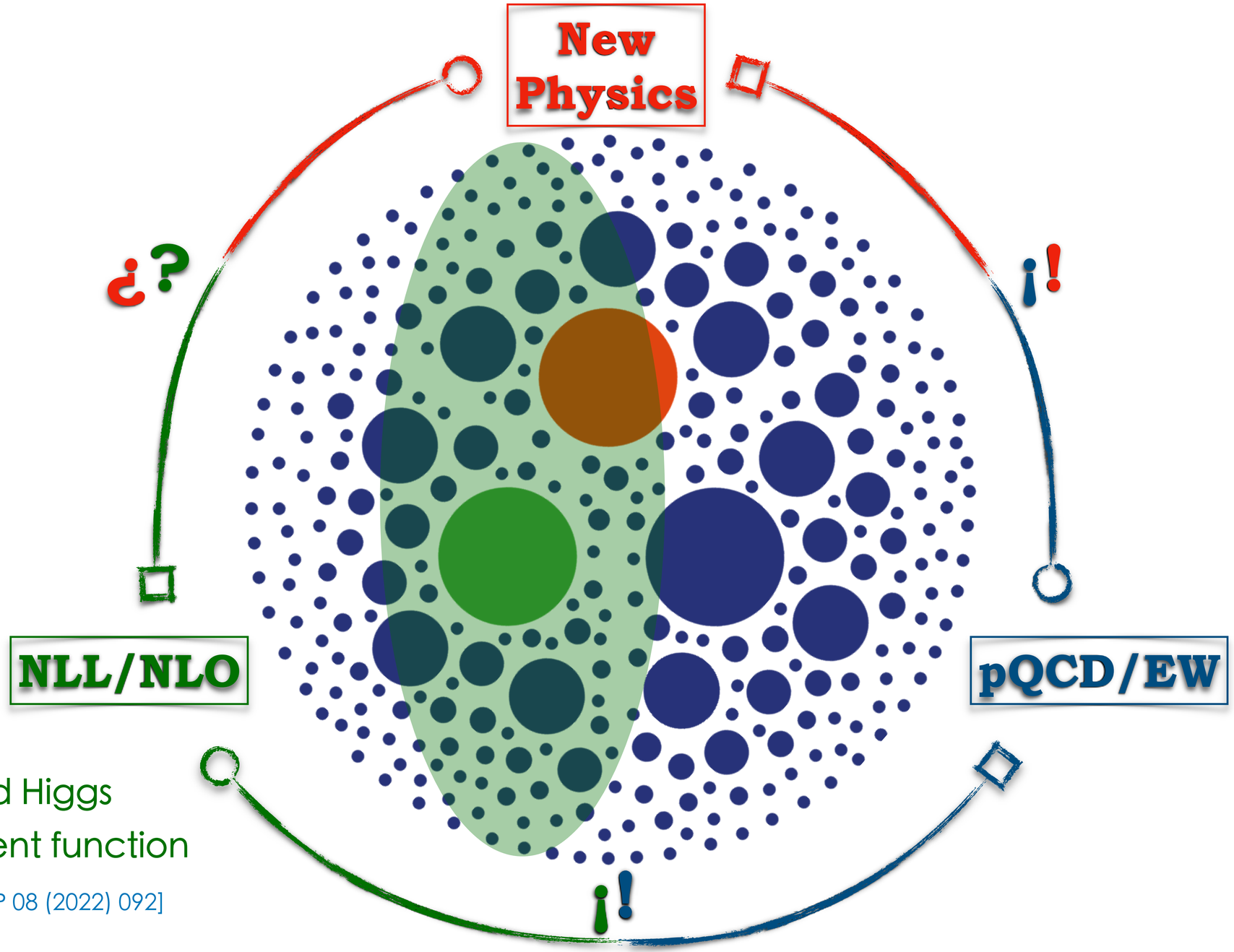

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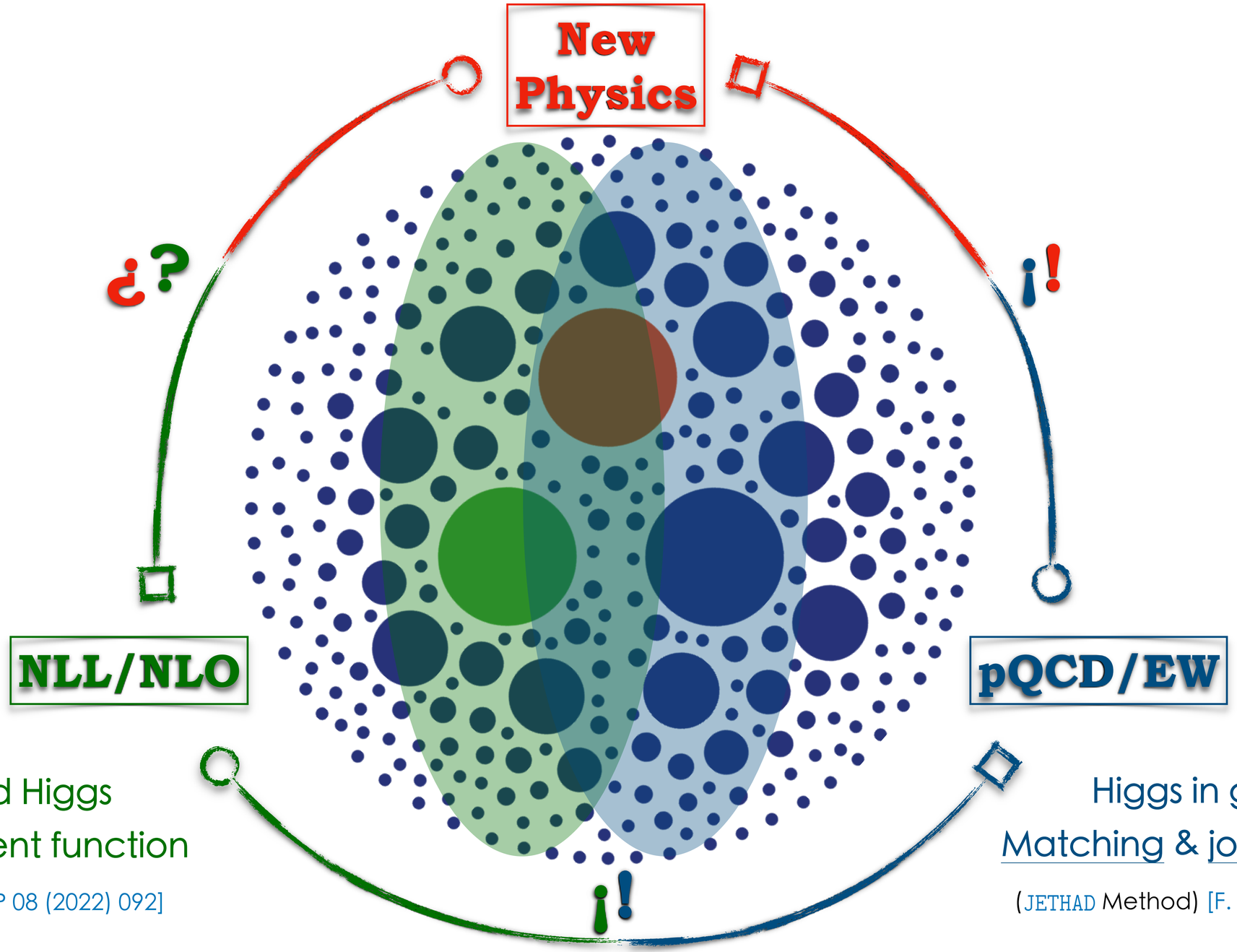

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Higgs in gluon fusion
Matching & joint resummations

(JETHAD Method) [F. G. C. et al., in progress]

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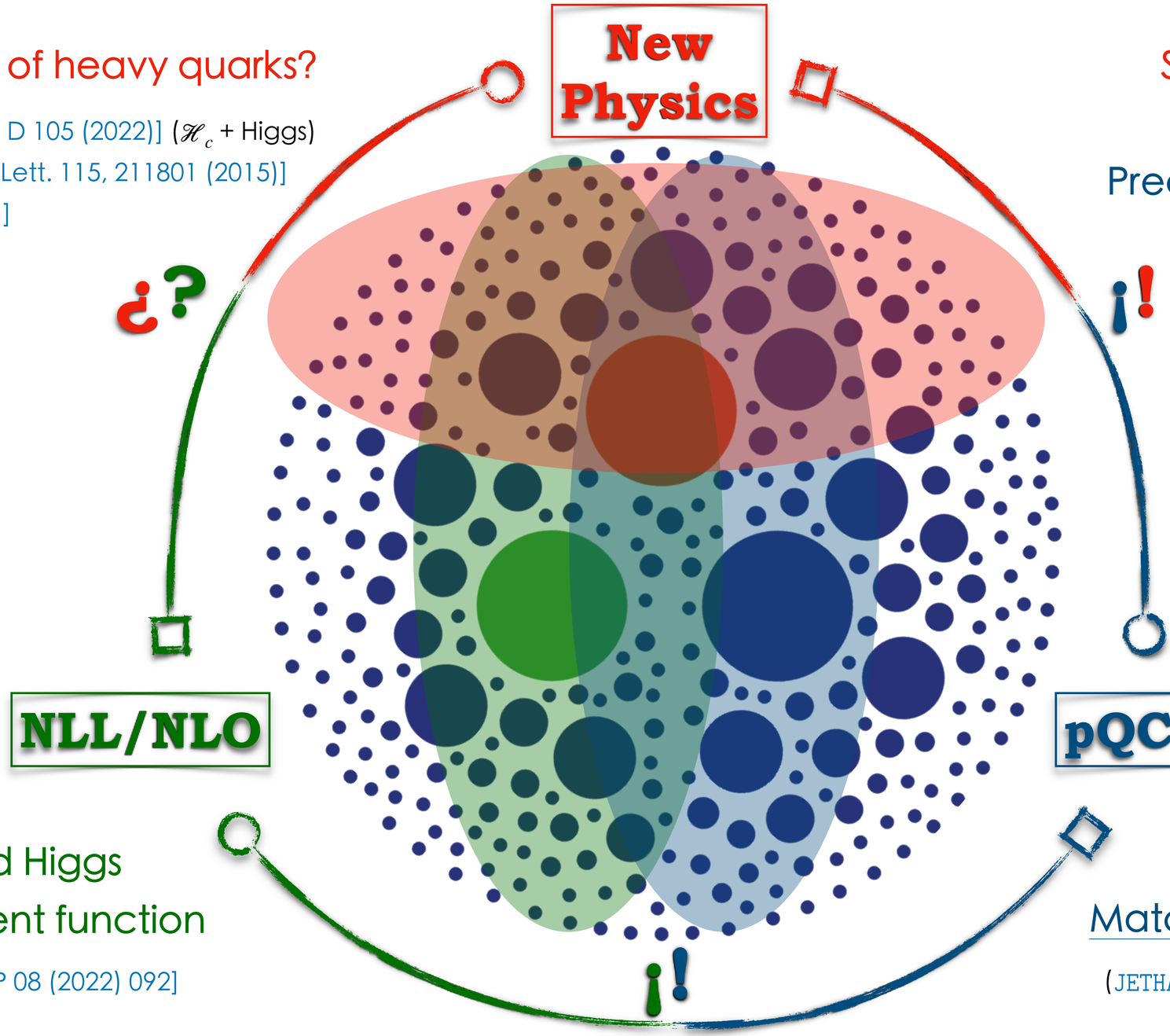
Yukawa coupling of heavy quarks?

- [F. G. C. et al., Phys. Rev. D 105 (2022)] ($\mathscr{H}_c$ + Higgs)
- [I. Brivio et al., Phys. Rev. Lett. 115, 211801 (2015)]
- [E. Chaubey et al. (2022)]



Search for New Physics needs Precision knowledge of QCD

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- Golden channel to investigate Higgs decays
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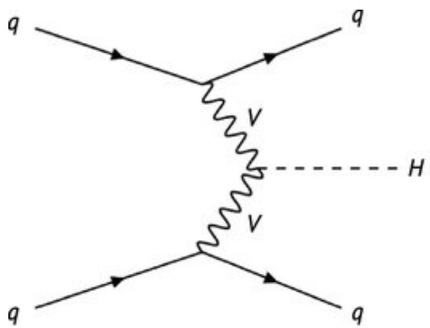

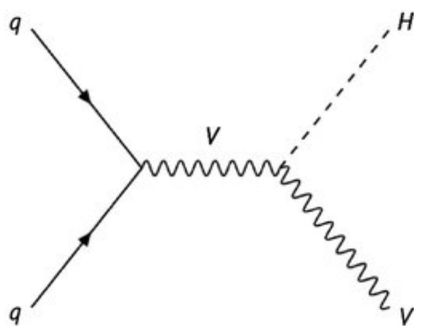

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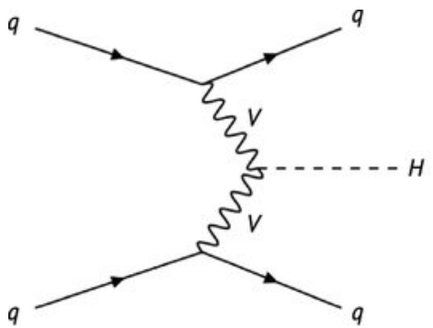

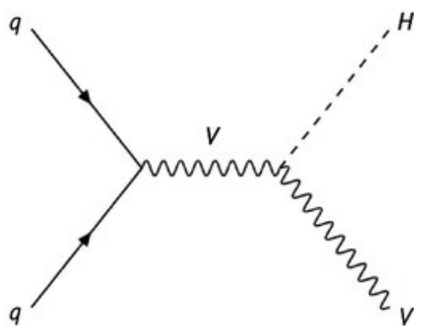

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- Stringent tests of pQCD ↔ **resummations**
- Inclusive Higgs → hadronic structure (TMD)
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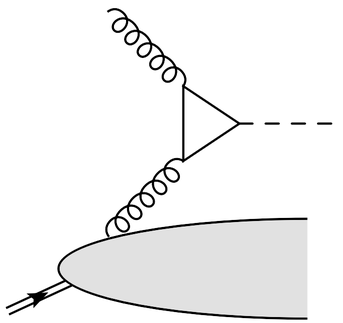

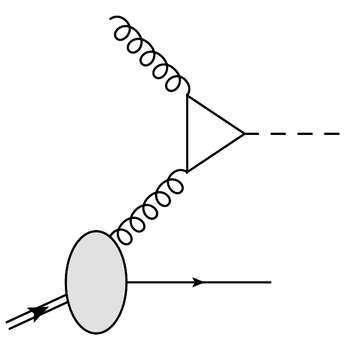

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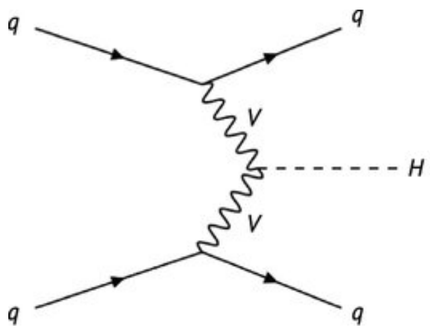

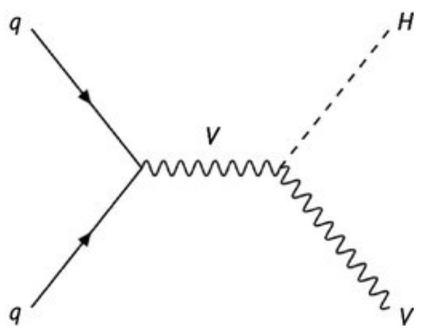

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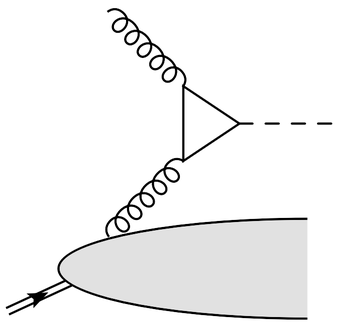

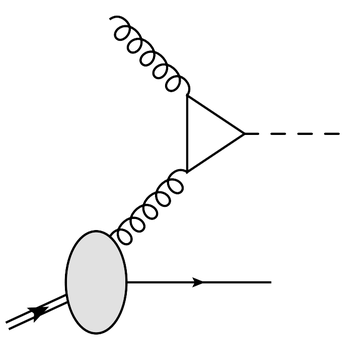

The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

`ERIS` super-module

$$\alpha_s \ln(s) \lesssim 1$$

JETHAD

v0.5.0m

python + F

🔗 [Eur. Phys. J. C 81 (2021) 8, 691]

🔗 [Phys. Rev. D 105 (2022) 11, 114008]

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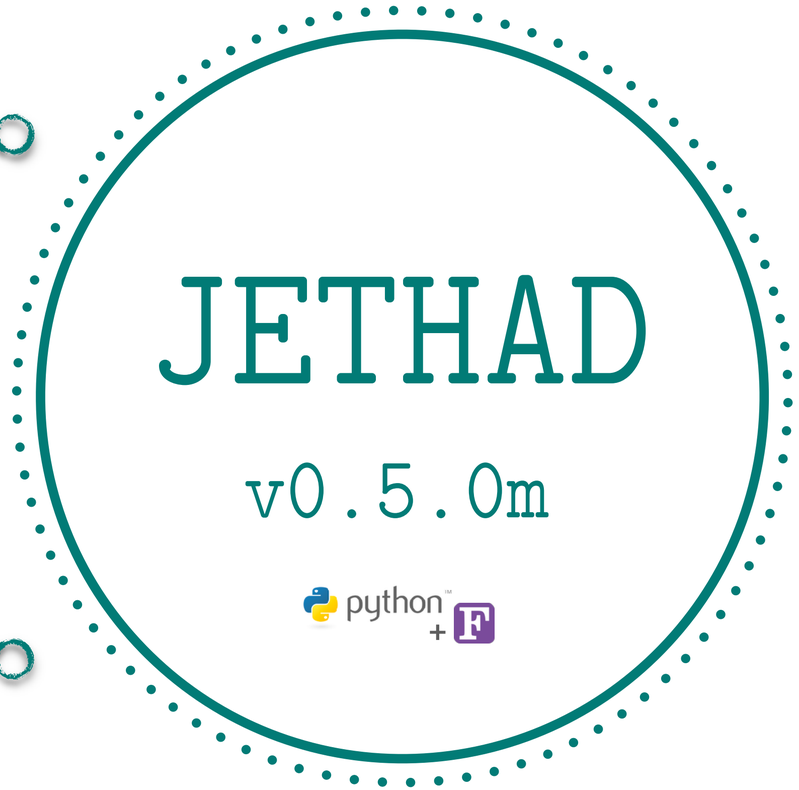

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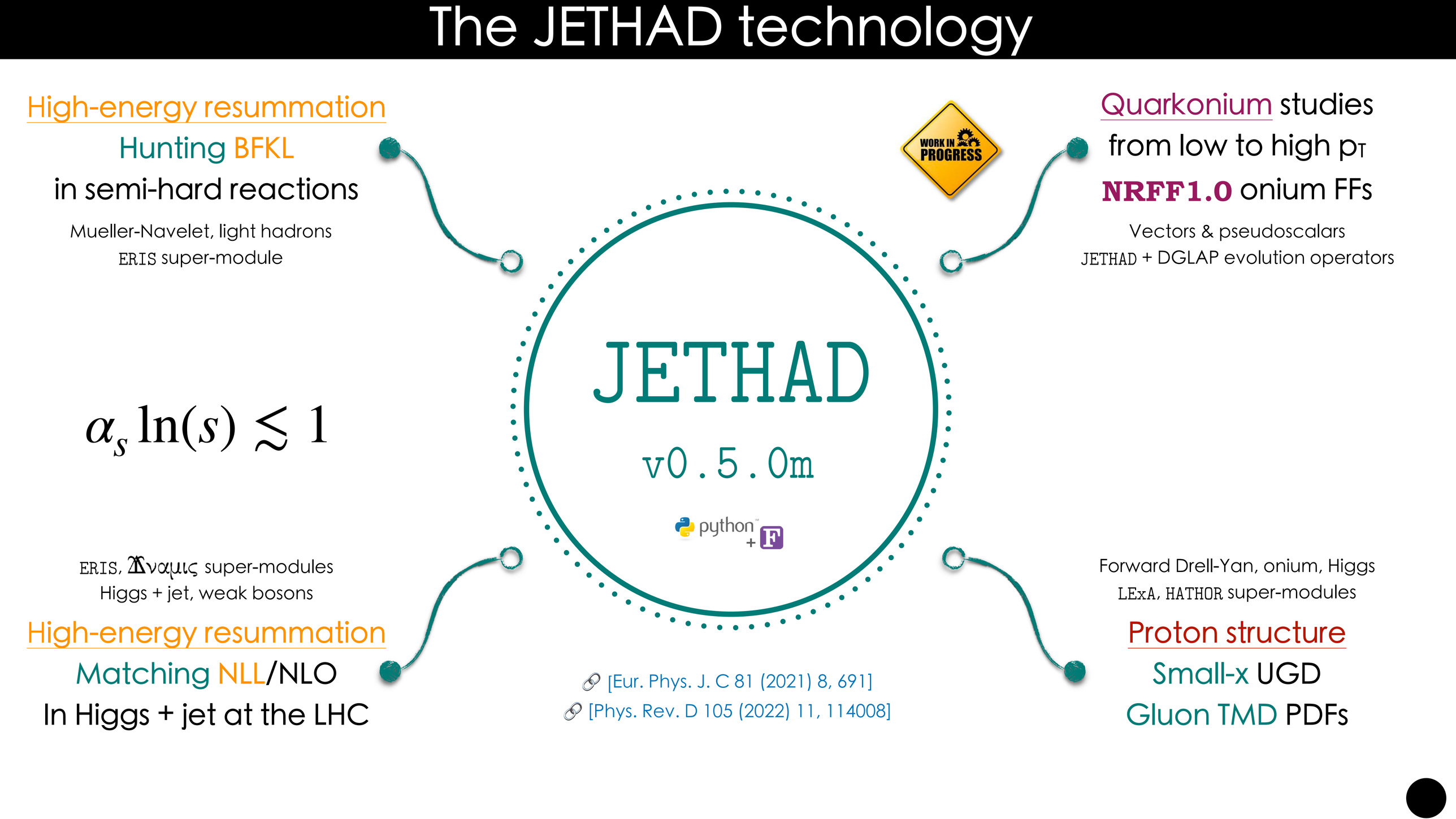

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The high-energy QCD dynamics from Higgs+jet correlations at FCC

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

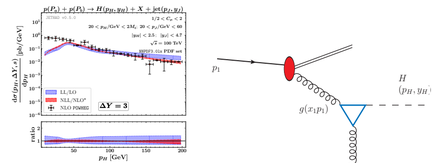
$$\frac{d\sigma}{dy_1\,dy_2\,d^2\vec{k}_1\,d^2\vec{k}_2} = \sum_{r,s=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2\, f_r(x_1,\mu_F) f_s(x_2,\mu_F)\, \frac{d\hat{\sigma}_{rs}(x_1x_2s,\mu_F)}{dy_1\,dy_2\,d^2\vec{k}_1\,d^2\vec{k}_2}$$

PDFs with threshold

$$\frac{d\hat{\sigma}_{rs}(x_1x_2s,\mu)}{dy_H\,dy_j\,d^2\vec{p}_H\,d^2\vec{p}_j} = \frac{1}{(2\pi)^2} \times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_H^{(r)}(\vec{q}_1,s_0,x_1,\vec{p}_H) \times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1x_2s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1,\vec{q}_2) \times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_j^{(s)}(\vec{q}_2,s_0,x_2,\vec{p}_j)$$

NLO Higgs vertex · NLL BFKL kernel · NLO Jet vertex

Hybrid high-energy and collinear factorization at work



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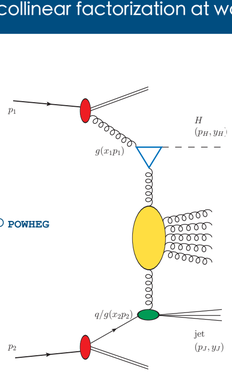
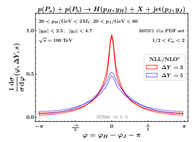
Rapidity distribution: NLL/NLO JETHAD vs NLO POWHEG



- HE resummation from JETHAD
- Large-x NNPDF3.01x PDFs with threshold
- Comparison with fixed-order from POWHEG
- Distributions stable under NLL corrections



Azimuthal distribution at NLL/NLO

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]

ECT* · FBK Future Built on Knowledge · HAS QCD Hadronic Structure and Quantum Chromodynamics · Future Circular Collider · Università della Calabria Dipartimento di Fisica · INFN Istituto Nazionale di Fisica Nucleare · TIFPA

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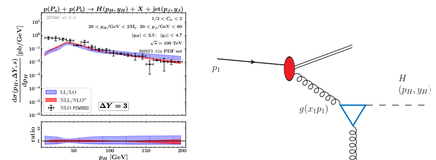

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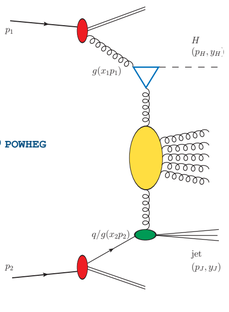
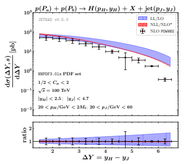
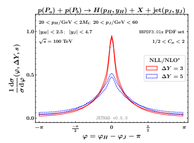




Rapidity distribution: NLL/NLO JETHAD vs NLO POWHEG



Azimuthal distribution at NLL/NLO

- HE resummation from JETHAD
- Large-x NNPDF3.01x PDFs with threshold
- Comparison with fixed-order from POWHEG
- Distributions stable under NLL corrections

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

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[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]

ECT* · FBK · HAS QCD · FUTURE CIRCULAR COLLIDER · UNIVERSITÀ DELLA CALABRIA DIPARTIMENTO DI FISICA · INFN · TIFPA

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

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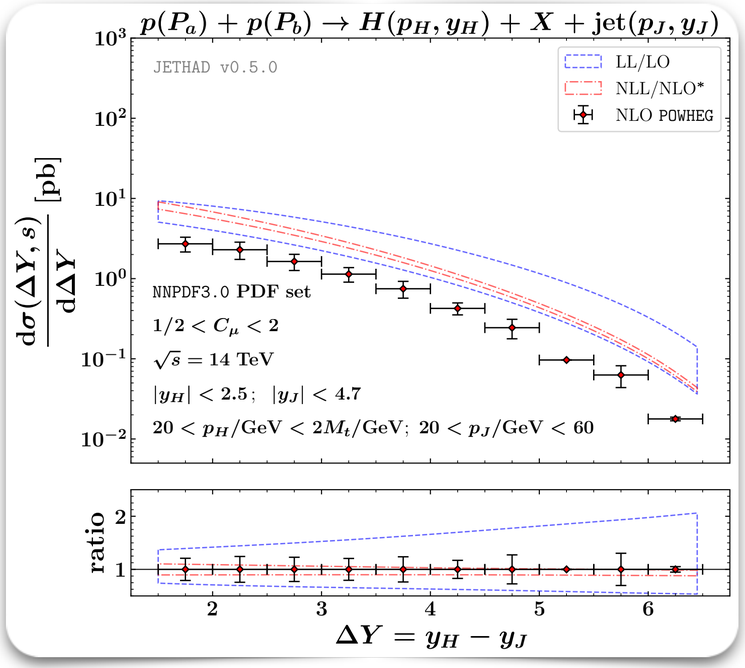
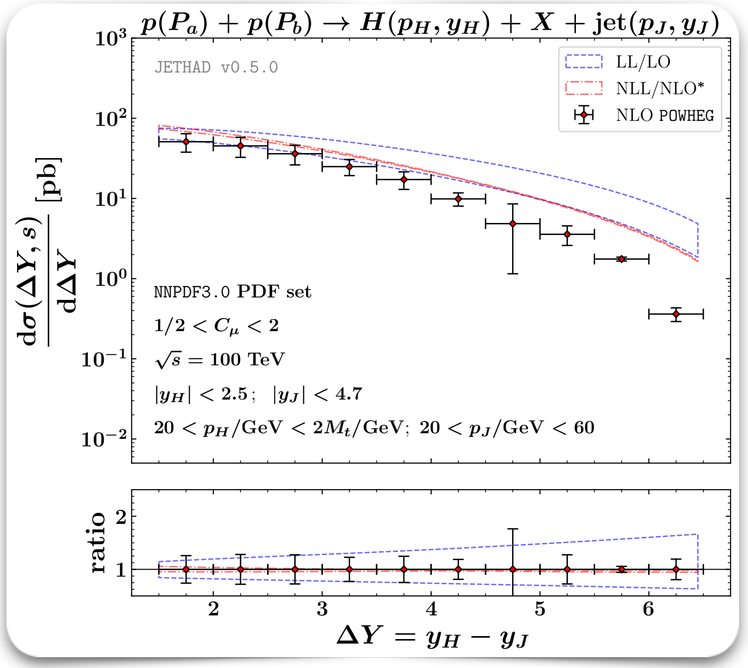
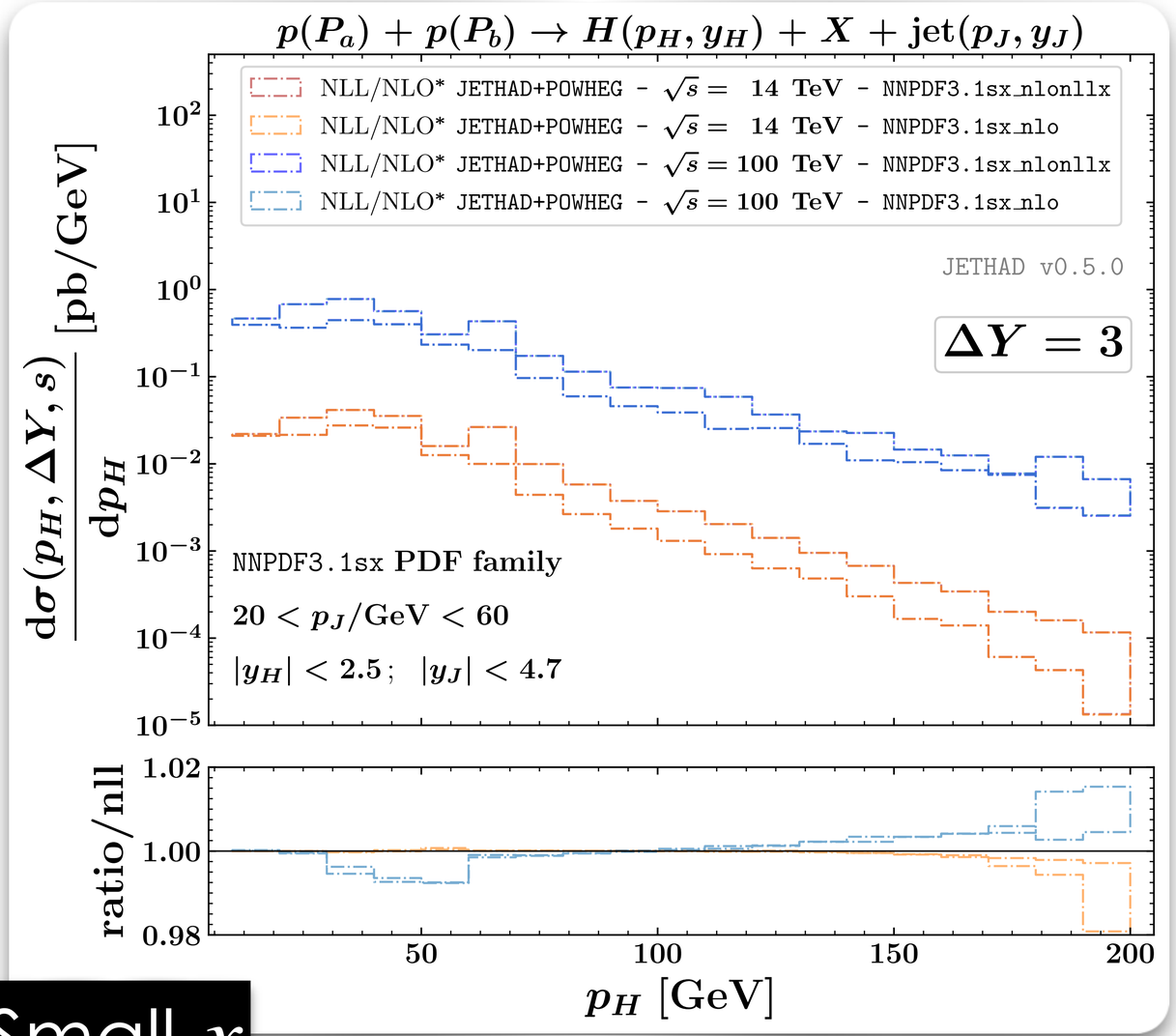


14 TeV LHC

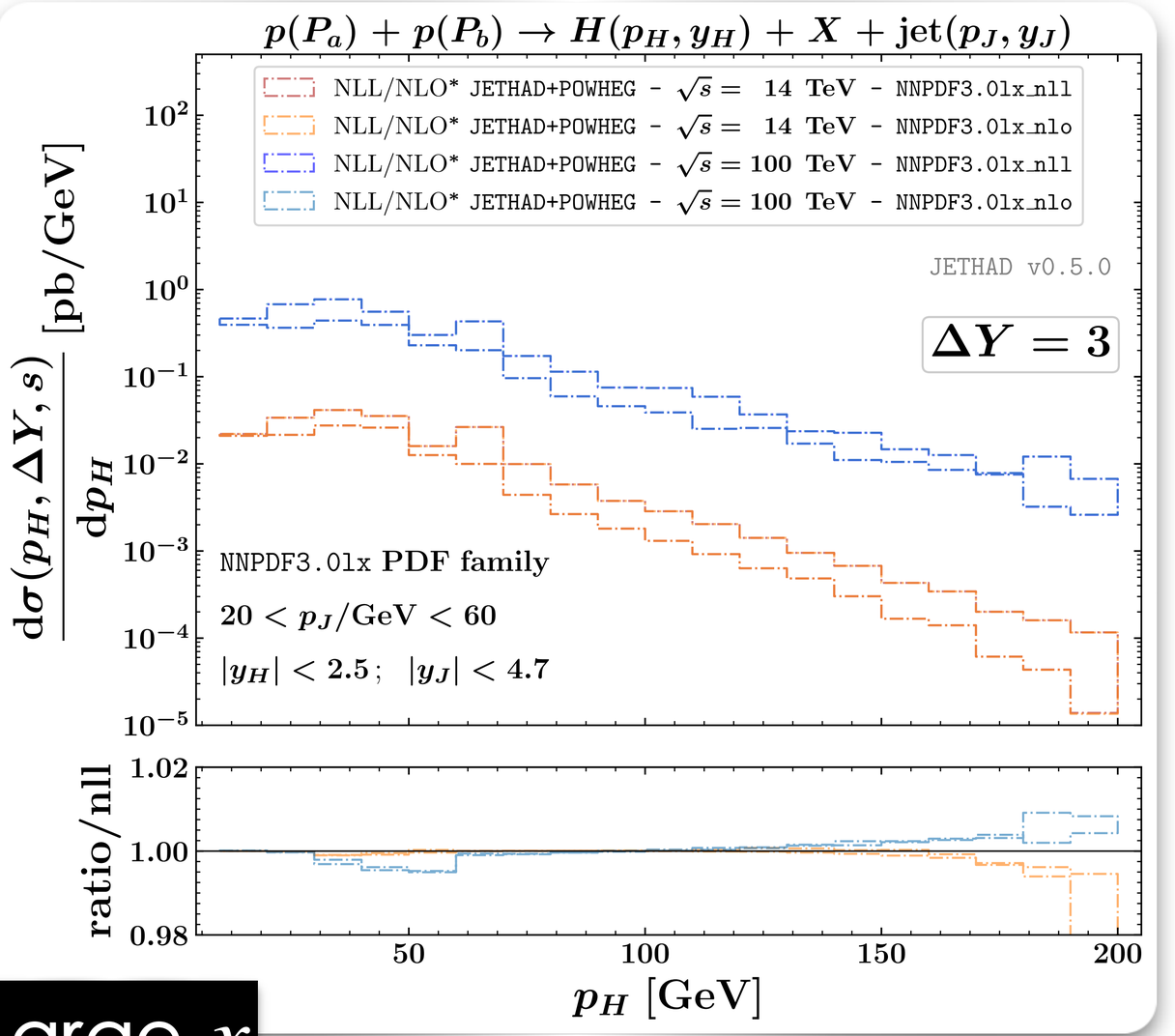


100 TeV FCC

Small-x and large-x enhancement from PDFs



Small-x



Large-x

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

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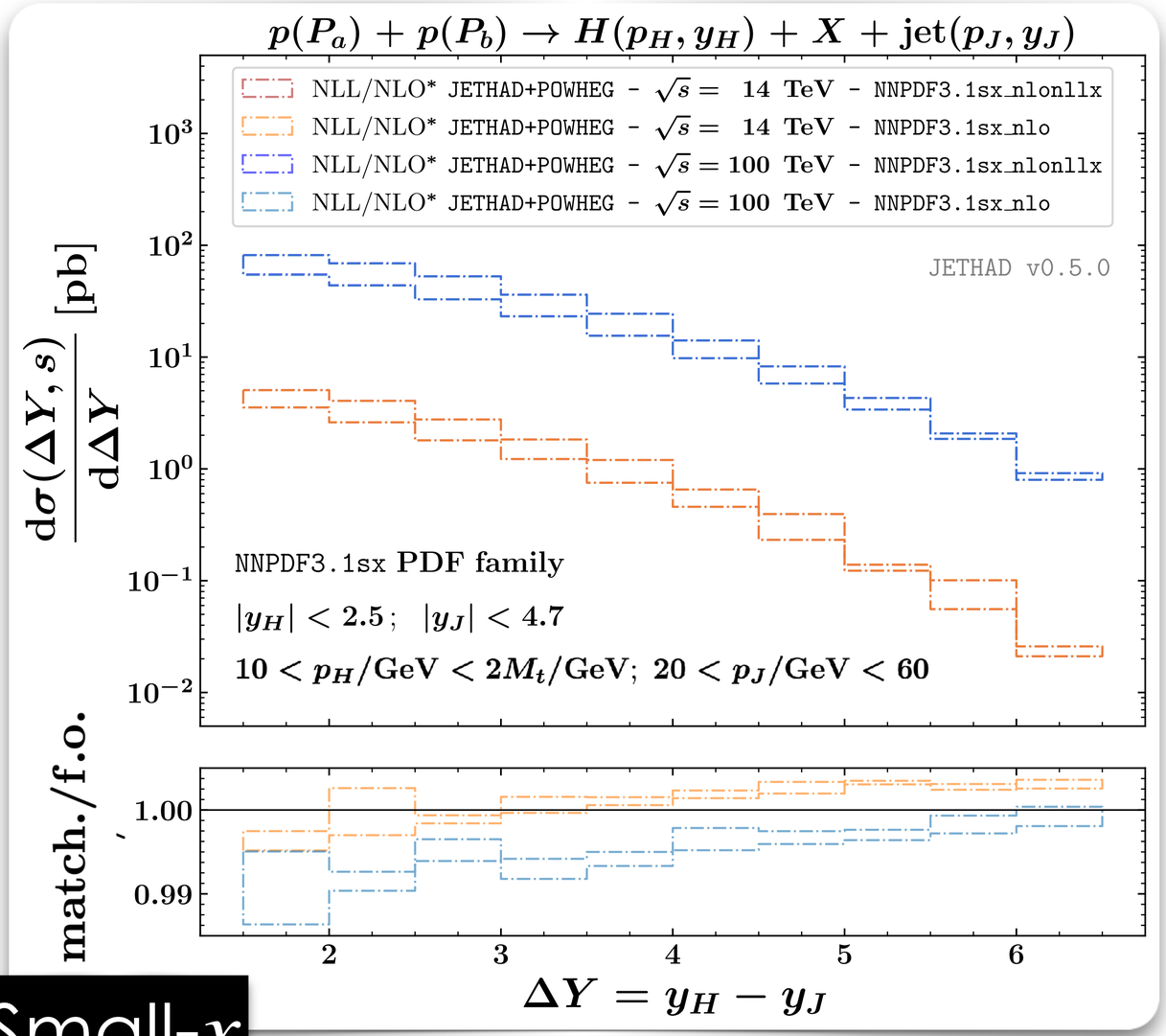

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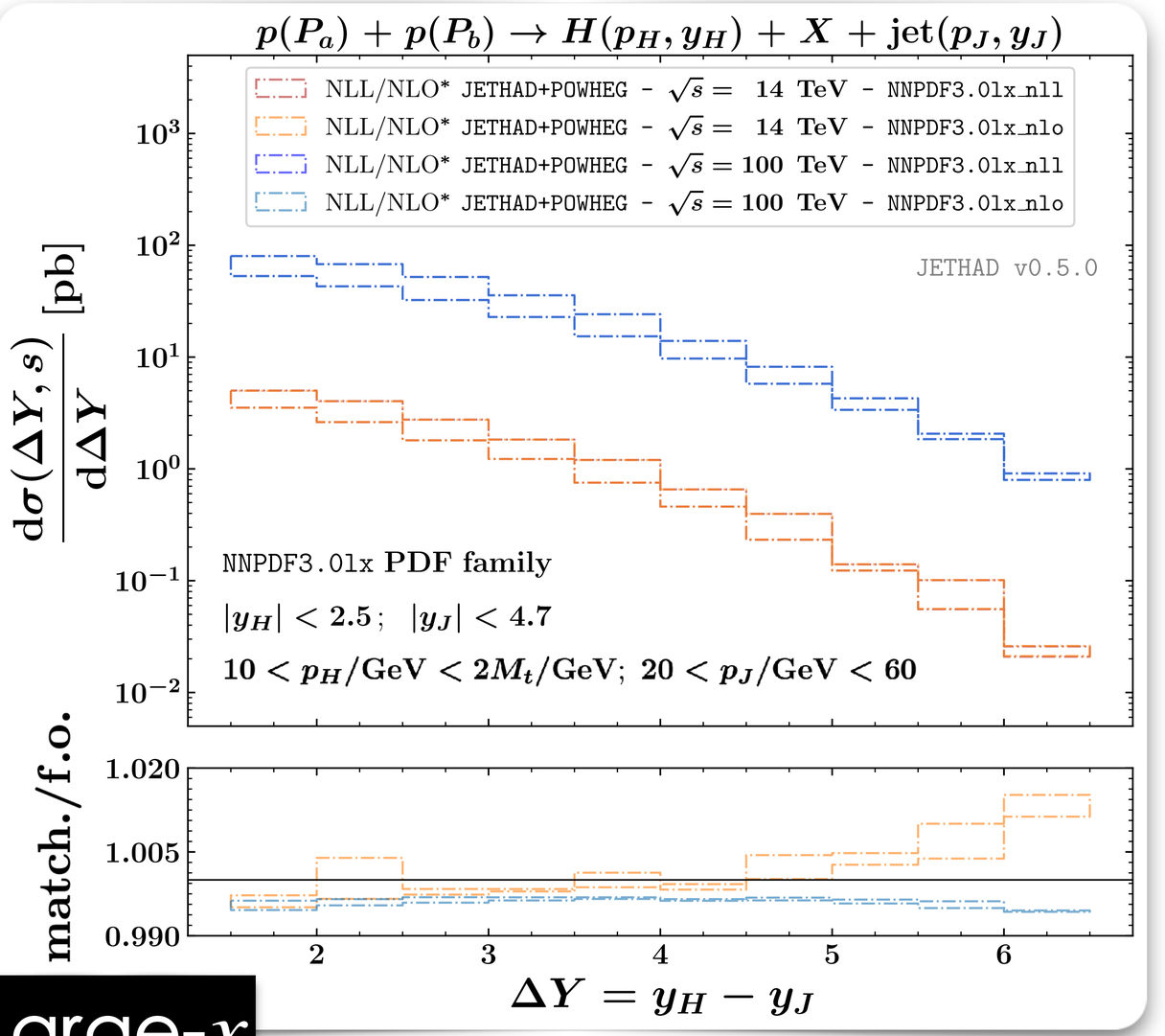

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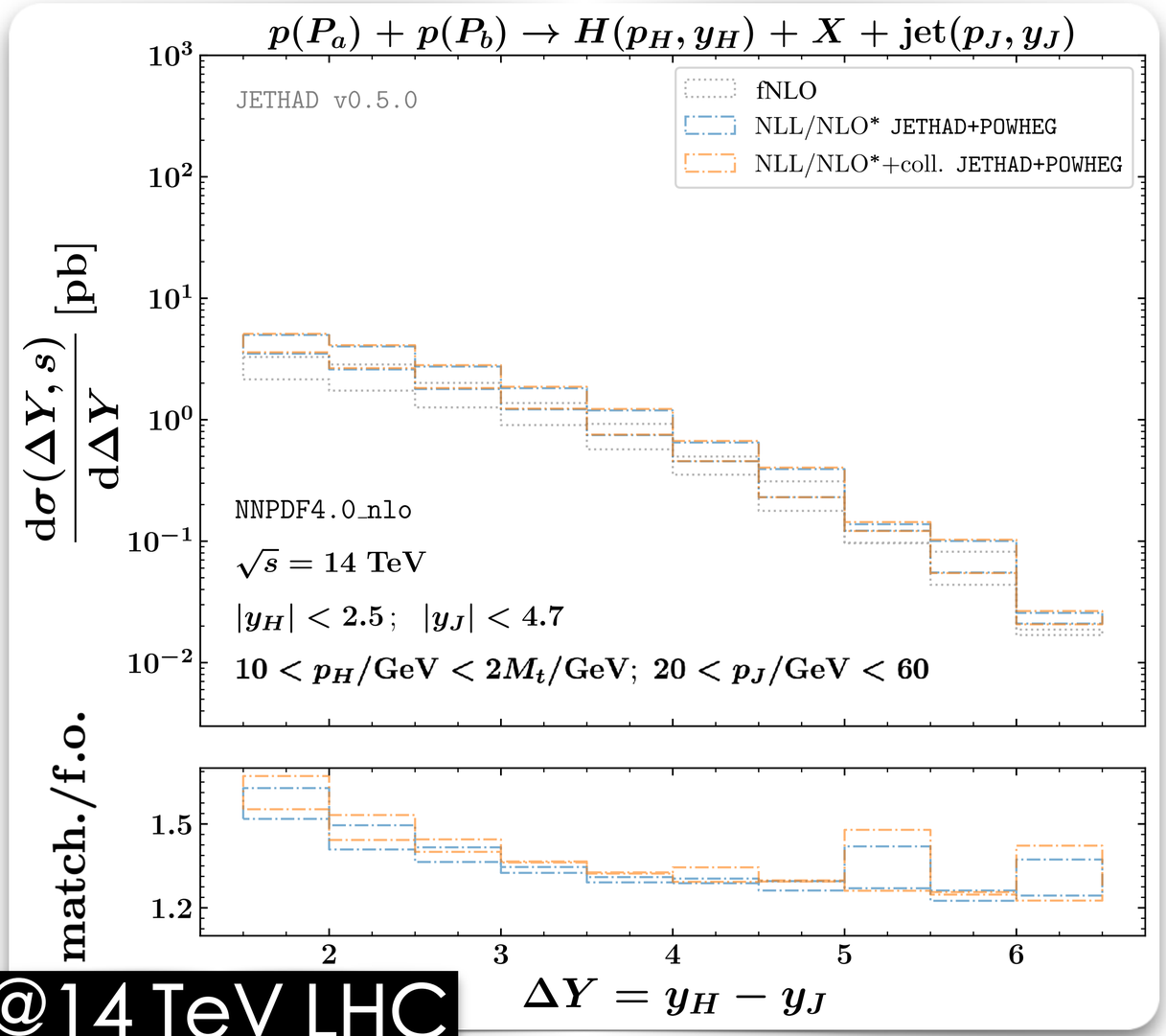
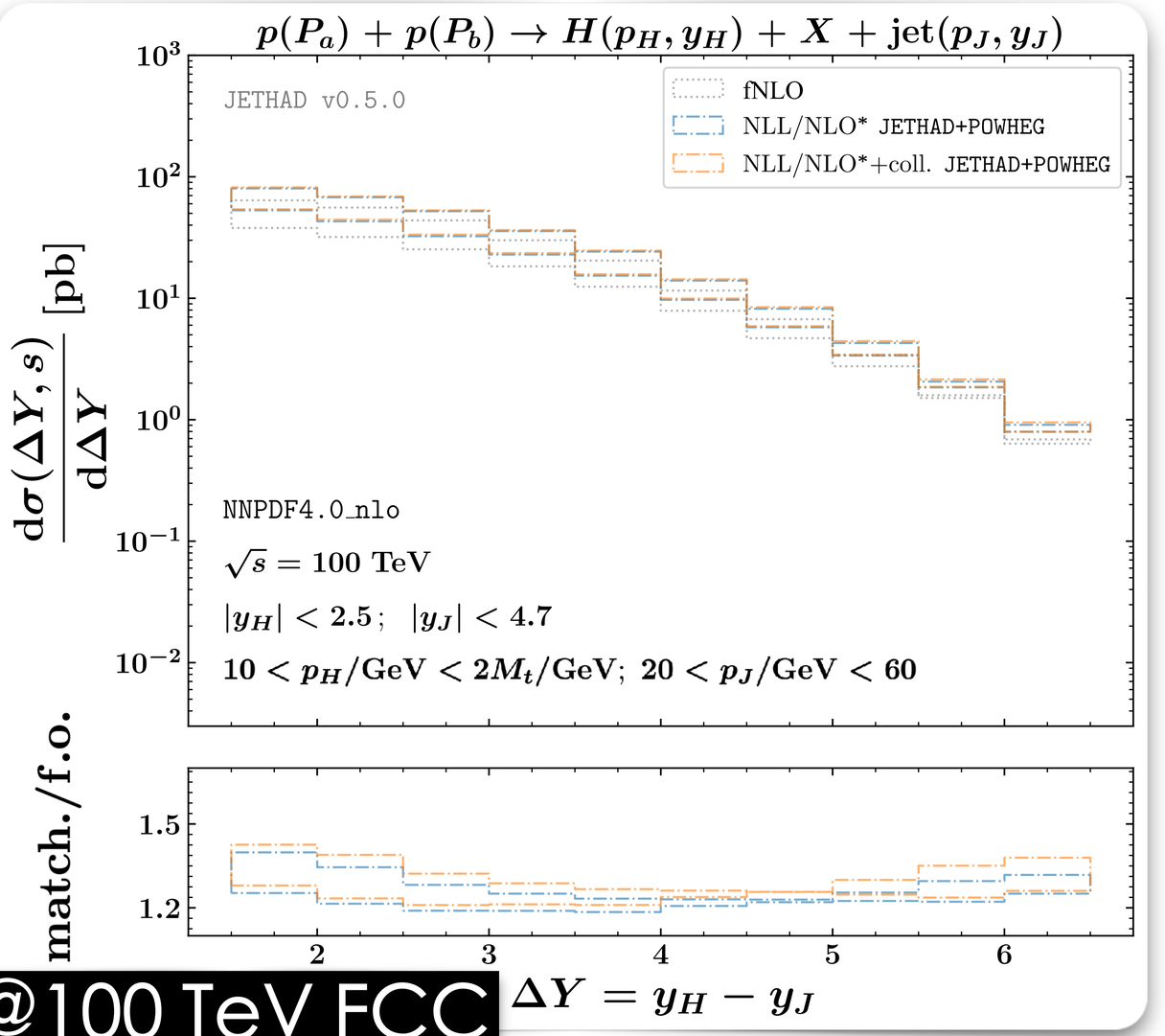
Effect of collinear improvement on NLL BFKL kernel



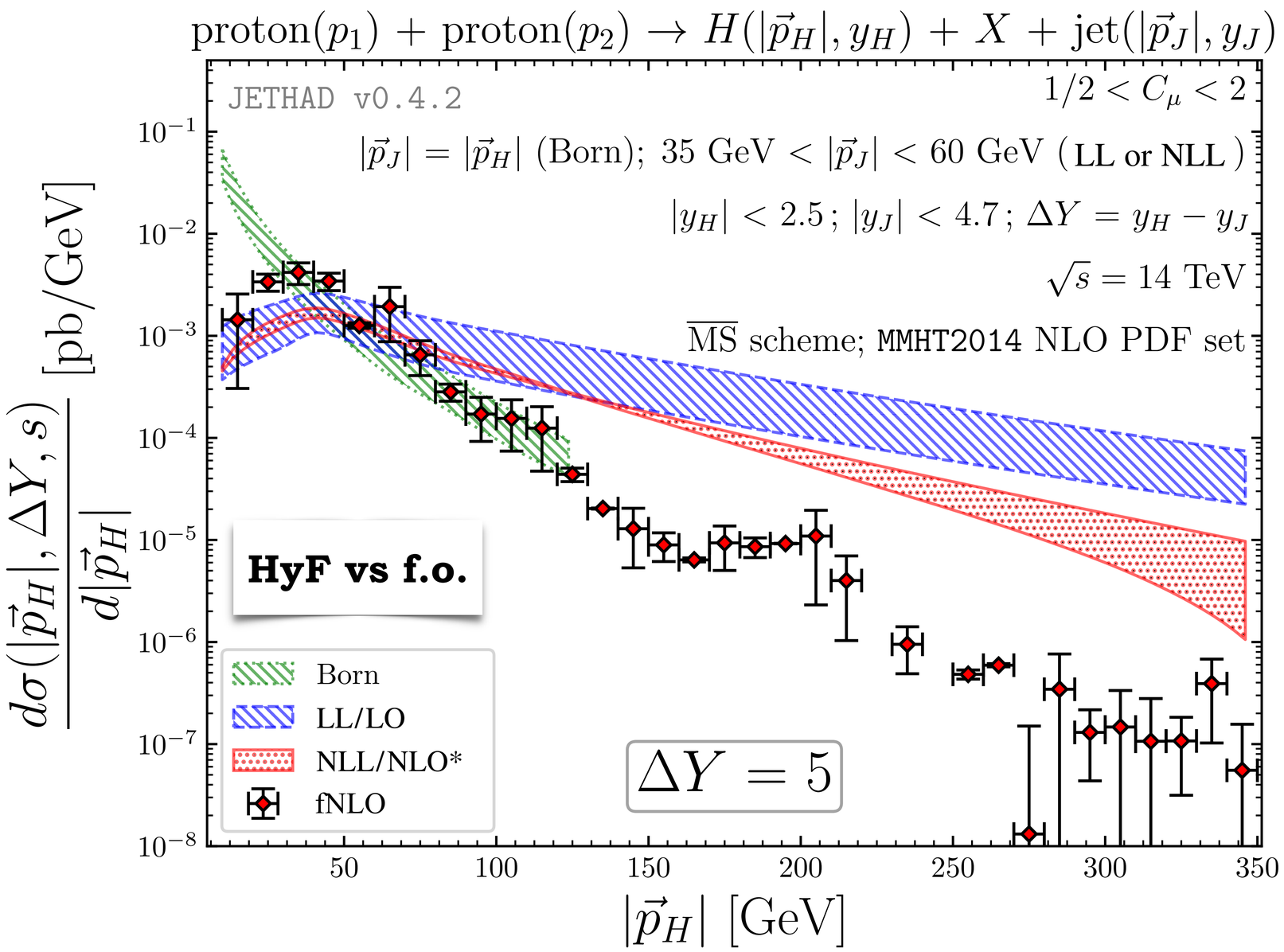
@14 TeV LHC



@100 TeV FCC

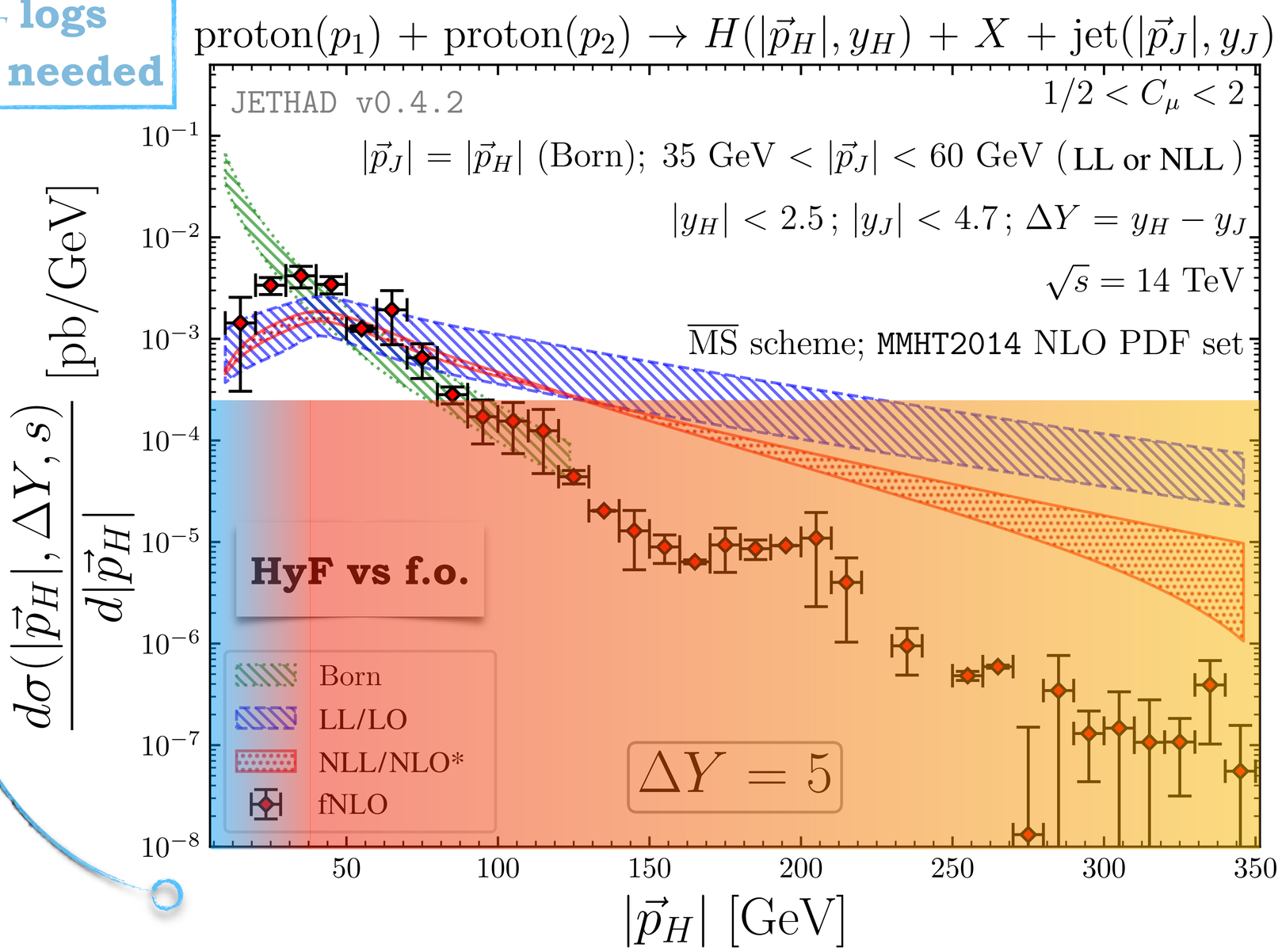
(Collinear improvement) [G.P. Salam, JHEP 07 (1998) 019]; [M. Ciafaloni et al., Phys.Lett.B 587 (2004) 87-94]; [A. Sabio Vera, Nucl.Phys.B 722 (2005) 65-80]

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



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

large p_T logs
p_T-resum. needed



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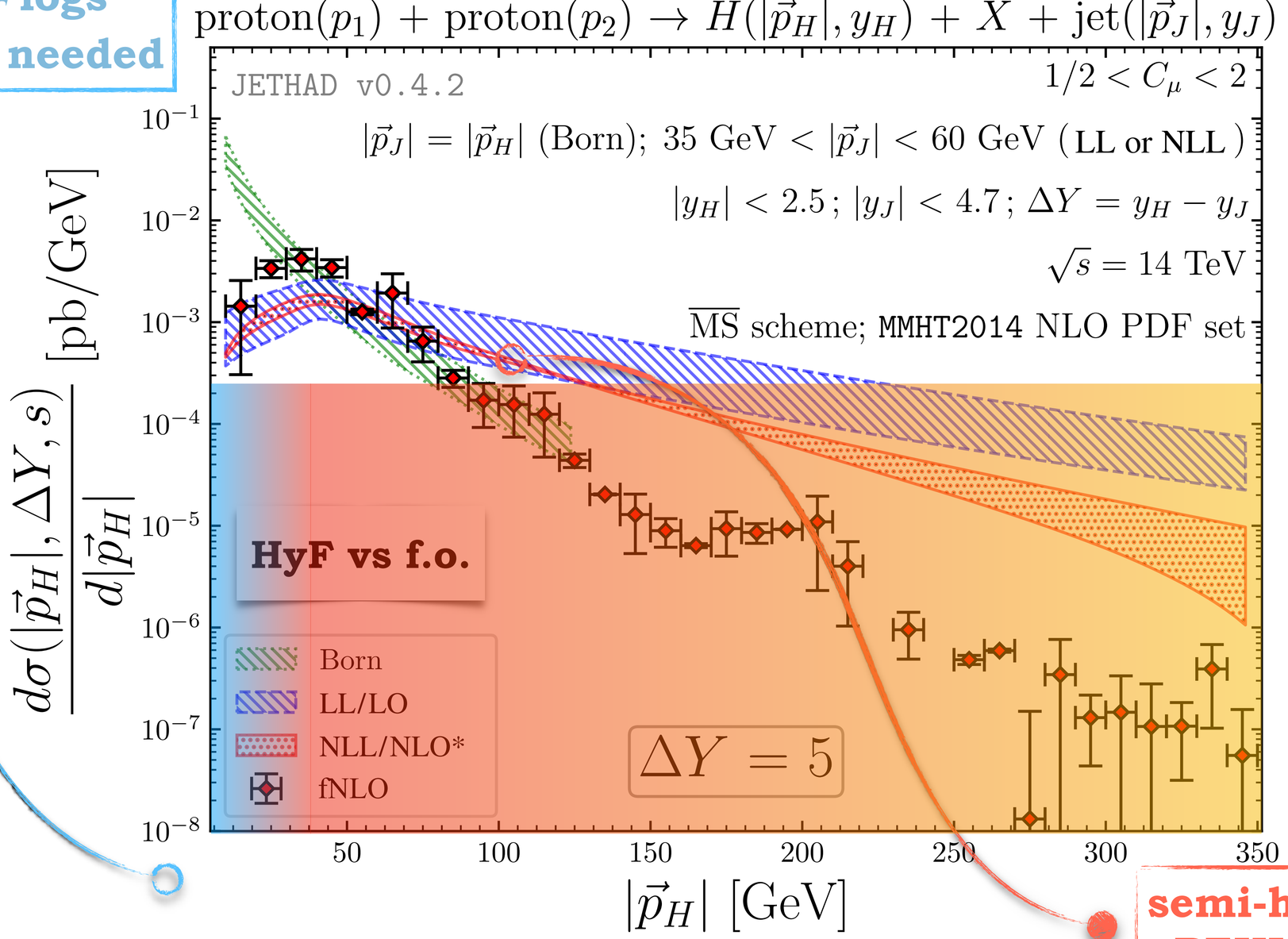

semi-hard regime
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DGLAP-type + large-x threshold logs → BFKL decoupling

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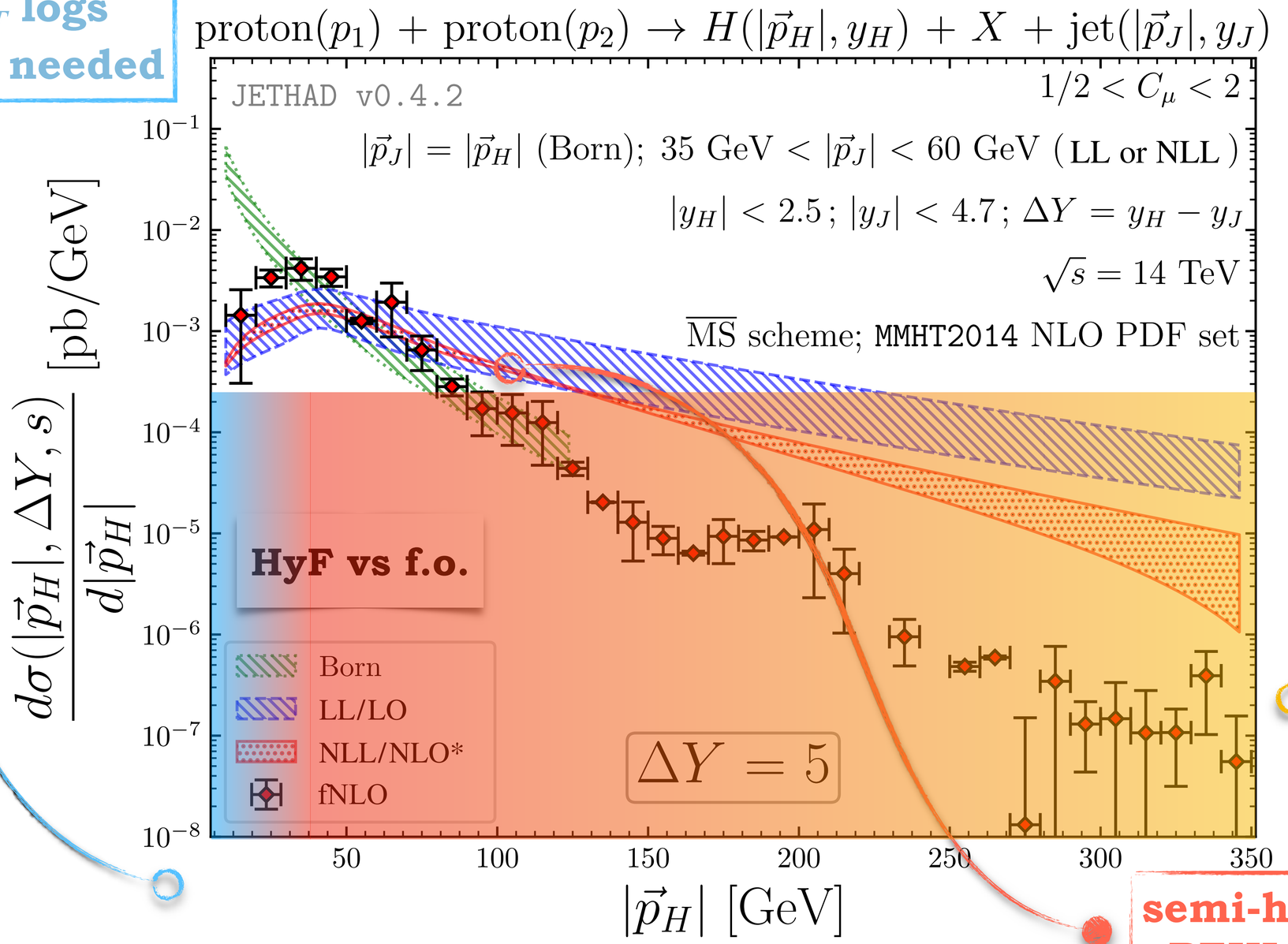

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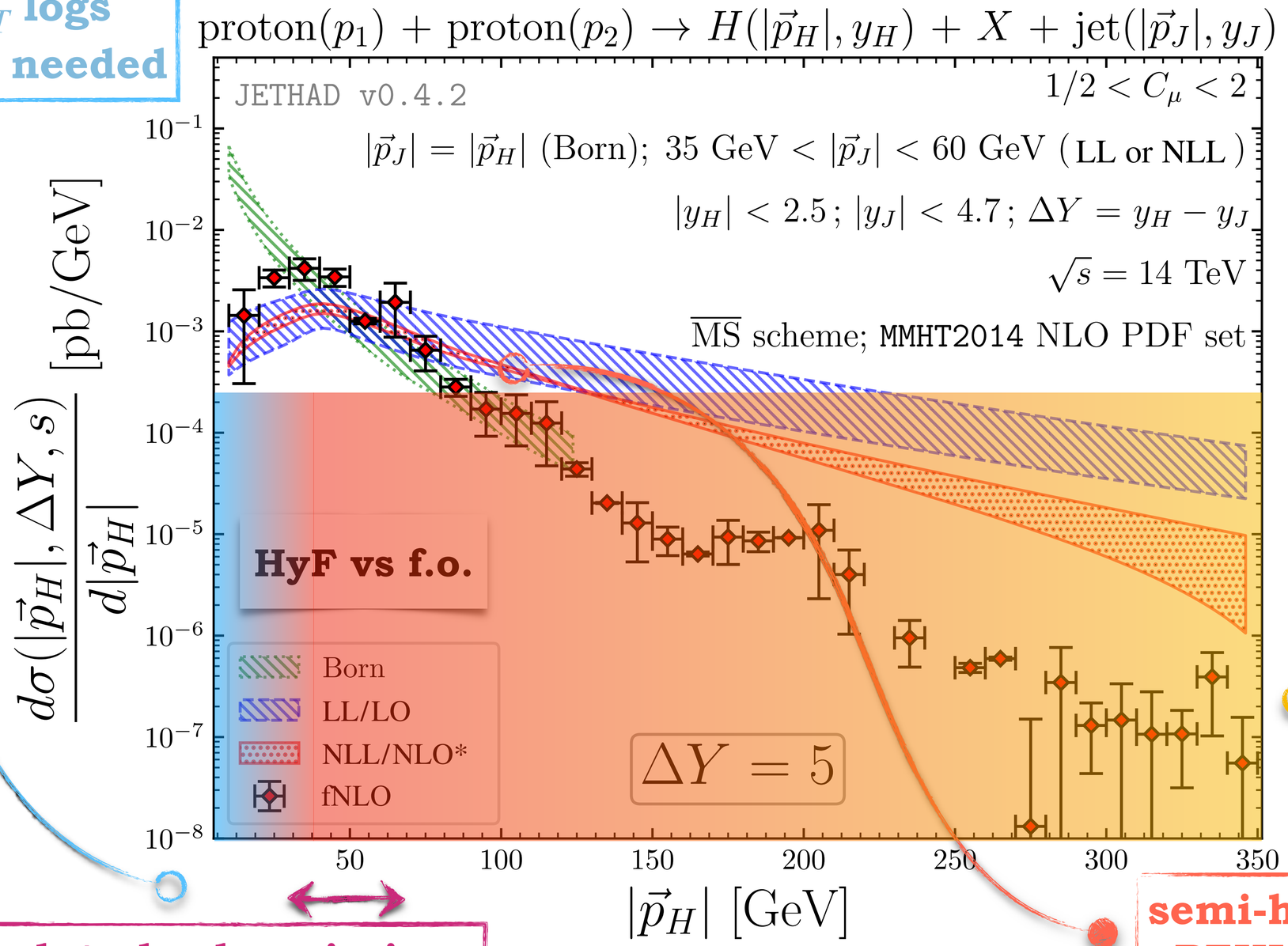
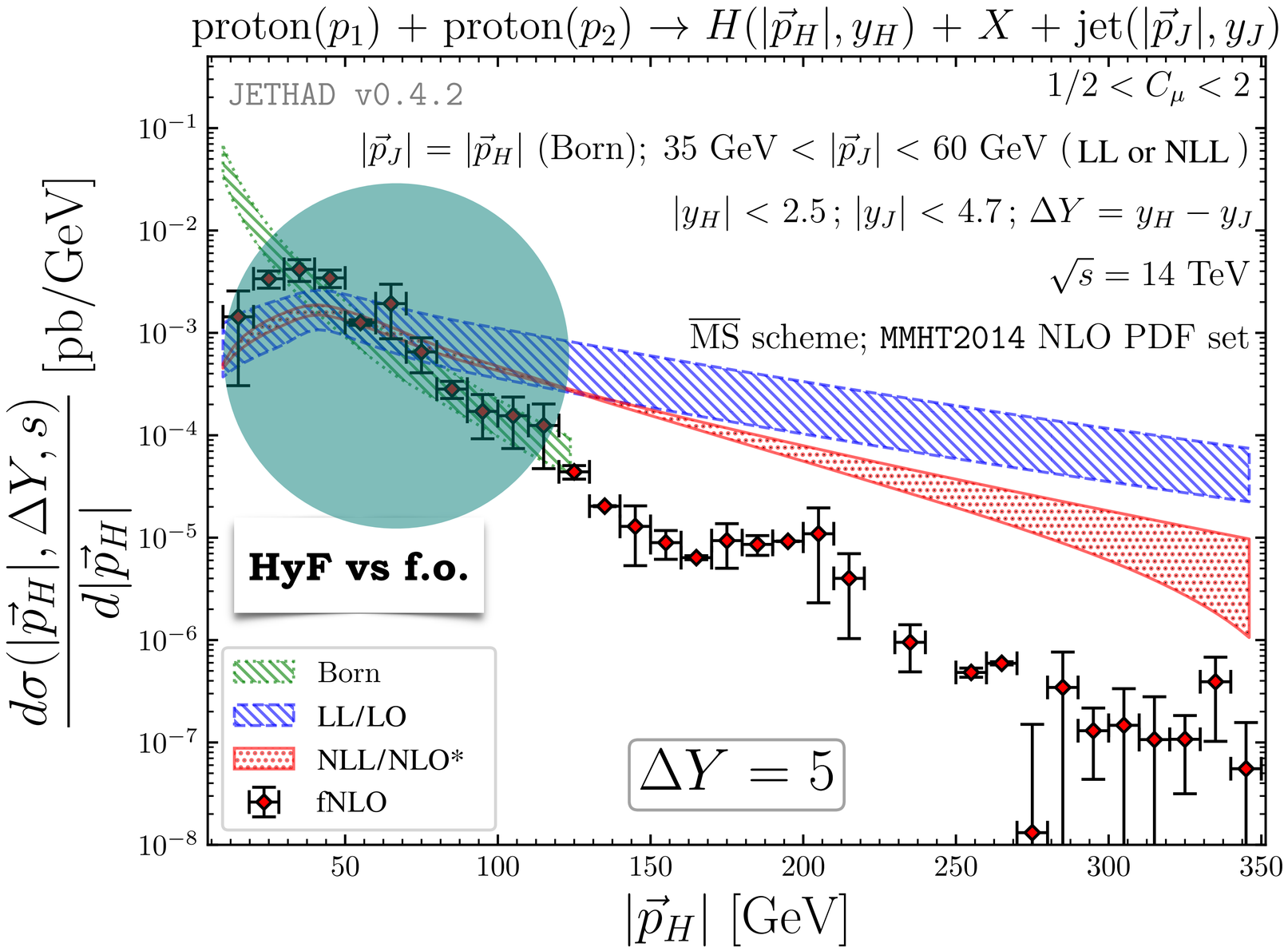


semi-hard regime
BFKL expected

almost back-to-back emissions
large imbalance double logs

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

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C., D Yu. Ivanov, M, M. A. Mohammed, A. Papa, Eur. Phys. J. C (2021) 8, 780]



¡ **Precision corrections** *expected*

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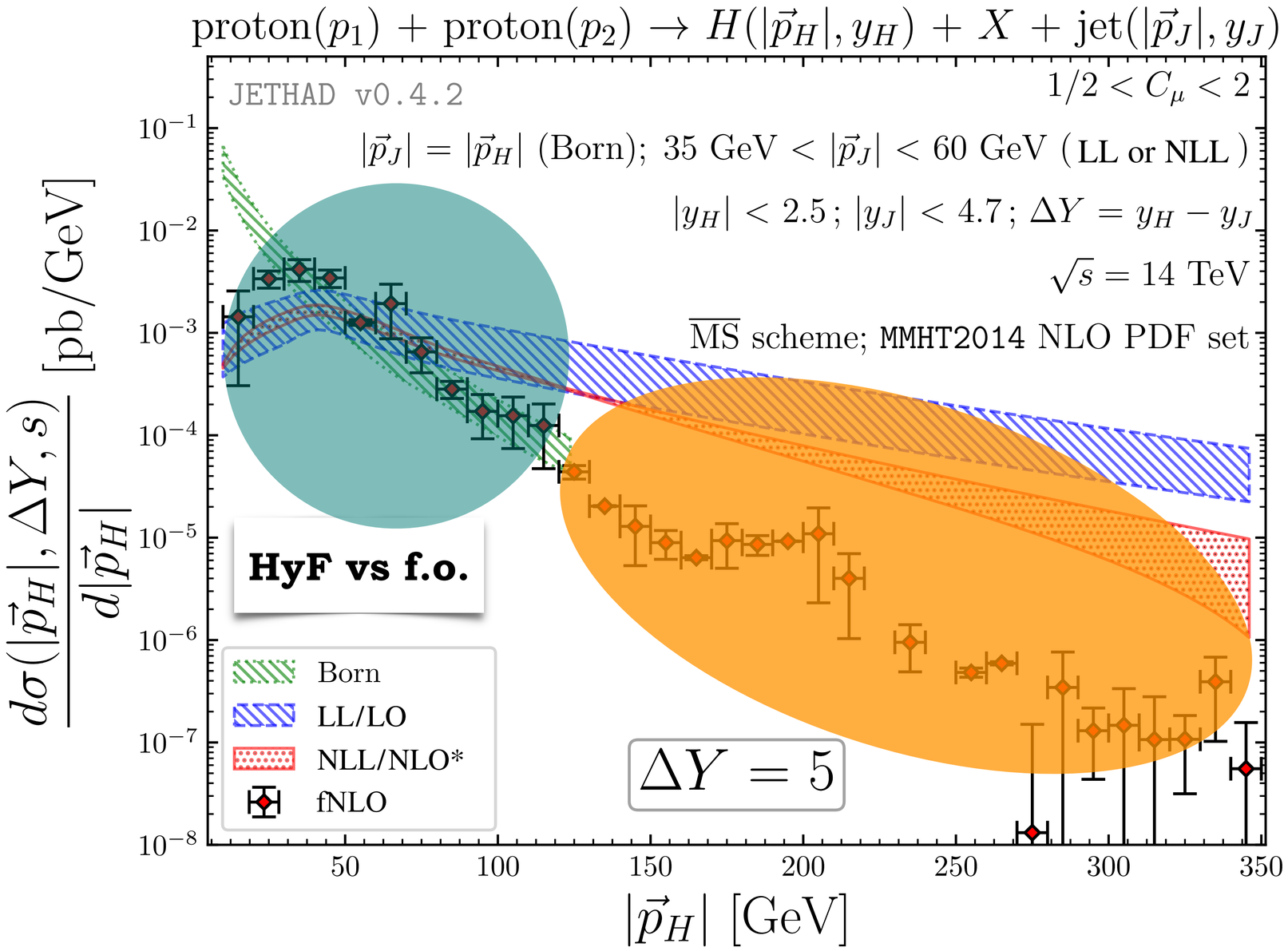
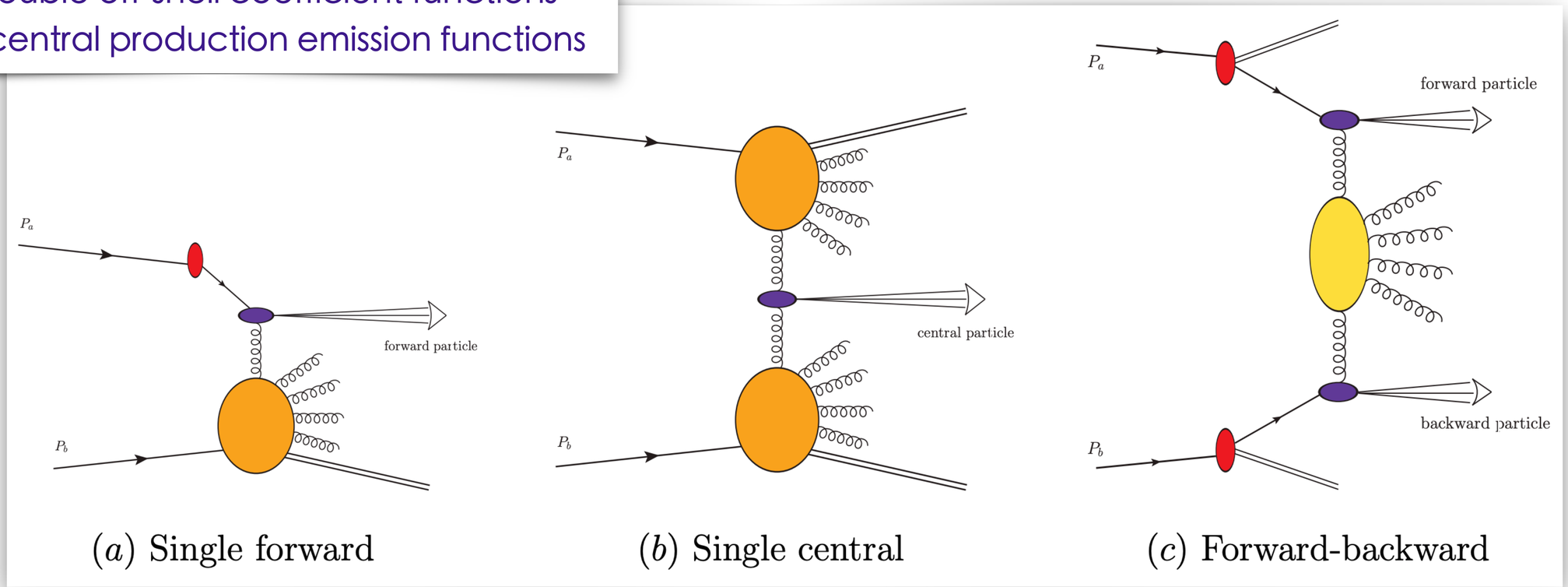


¡ **Precision corrections** *expected*, but **HyF** *predicts* **large deviations** from **f.o.** !

High-energy factorization at a glance

Singly/double off-shell coefficient functions
Forward/central production emission functions



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

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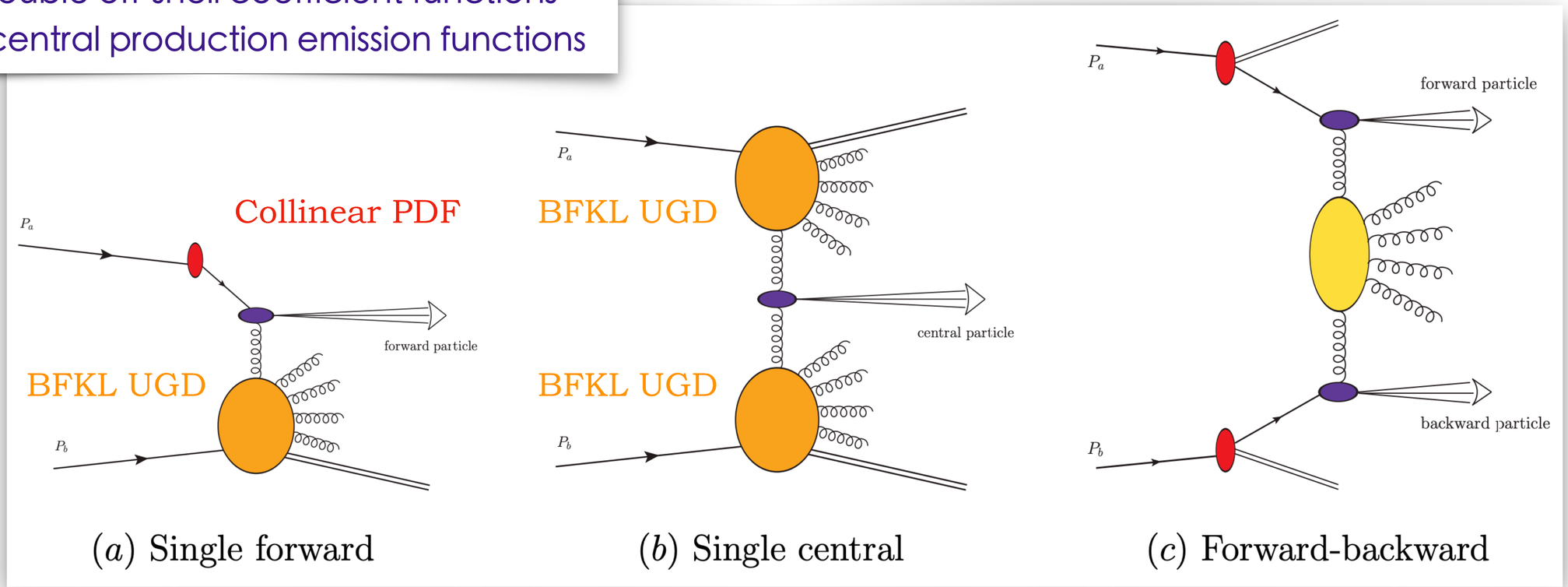

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Fast q/g + small-x g

Hybrid factorization

BFKL + Threshold

gg induced

High-energy factorization

BFKL or small-x improved PDFs

🔗 [M. Bonvini, S. Marzani (2018)]

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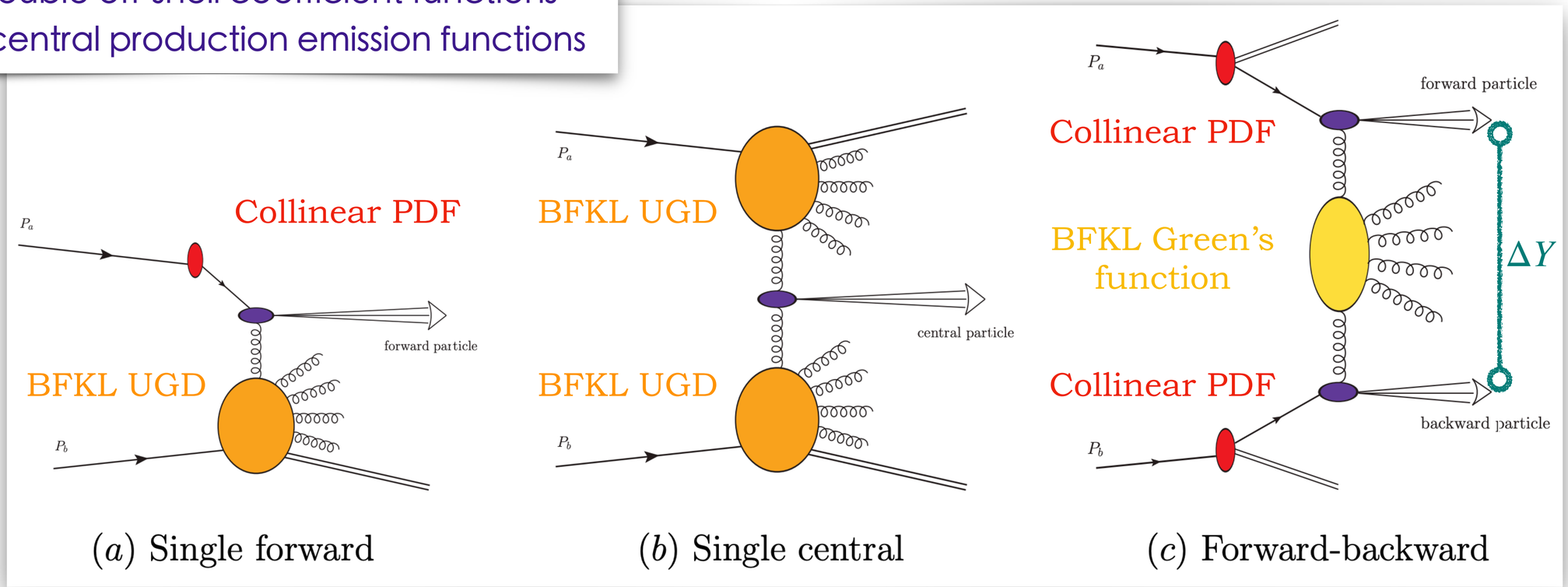

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Large rapidity distances, $\Delta Y \gg 1$

High energies, moderate x

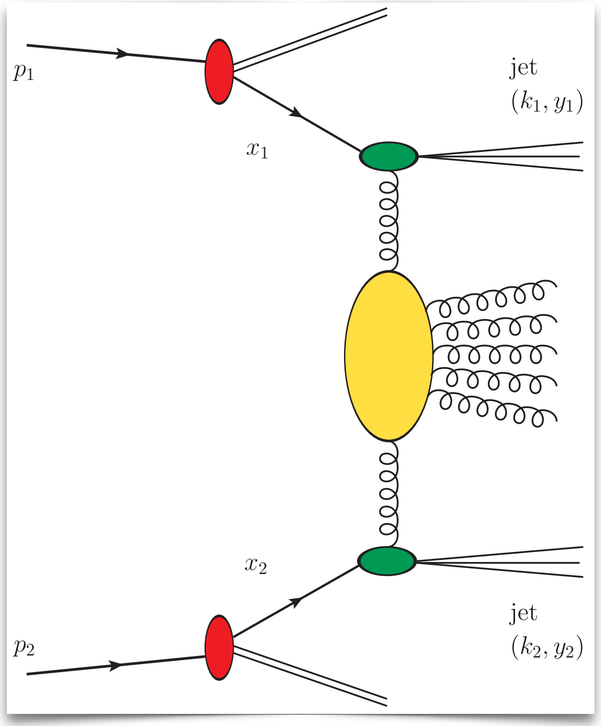
PDFs + t-channel BFKL (NLL/NLO HyF)

Imbalance logs ← back-to-back

Mueller-Navelet jets @LHC & resummation instabilities

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

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



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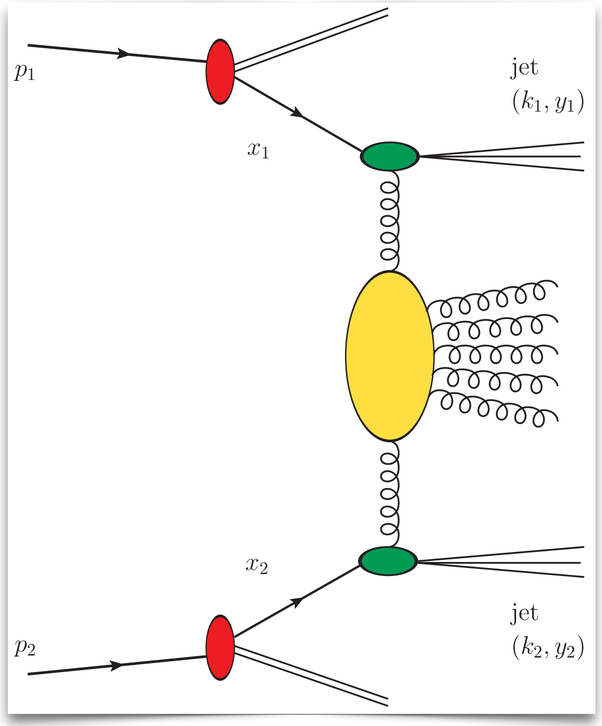

NLO(+)

NLL

NLO(+)

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

jet vertices (off-shell coefficient functions)

BFKL Green's function

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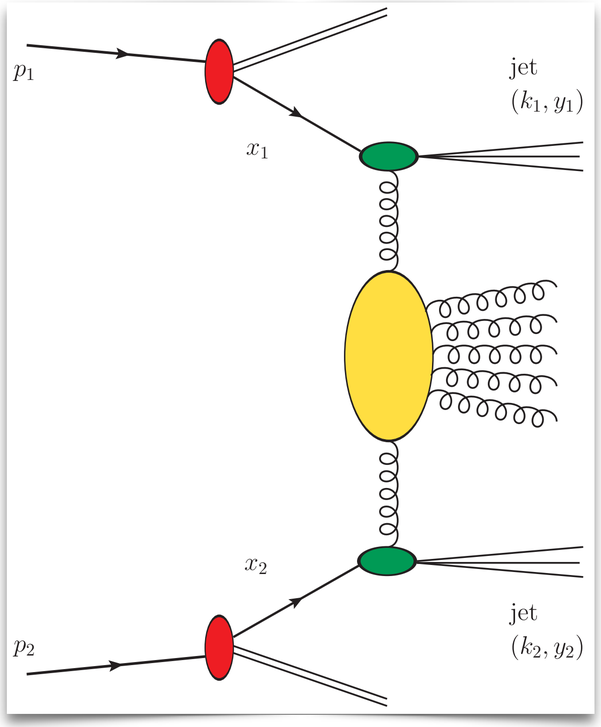

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- NLL/LL instabilities + NLO missing threshold ⇒ precision studies hampered

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- ¡ 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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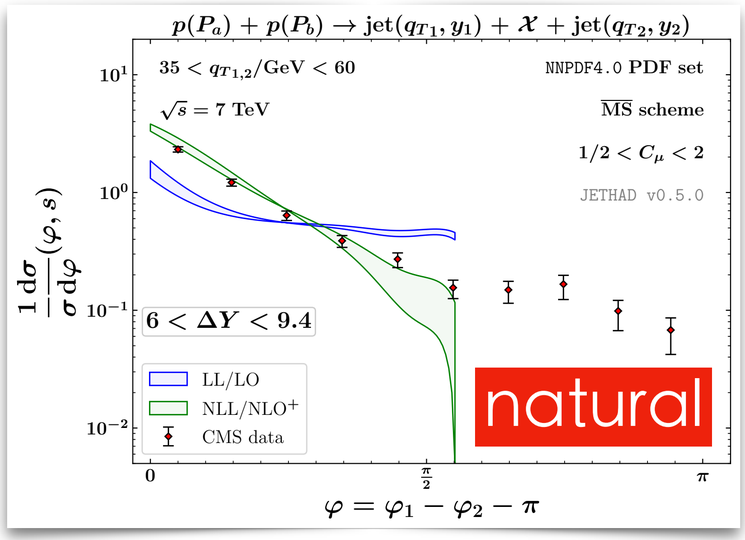

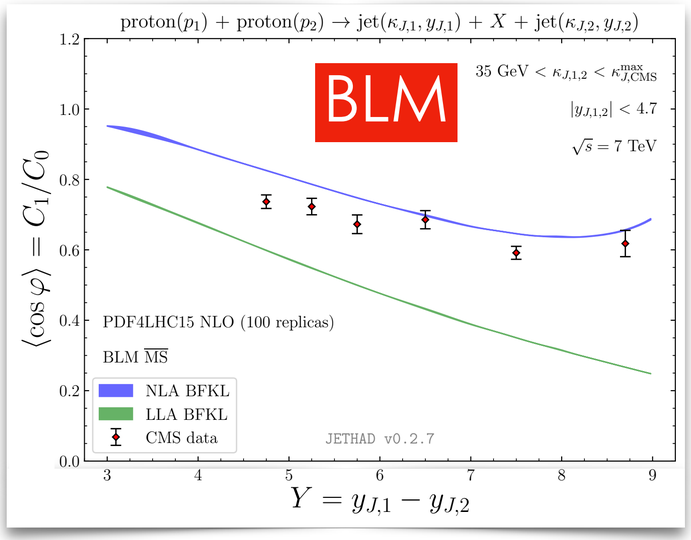

(left figure) 🔗 [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]

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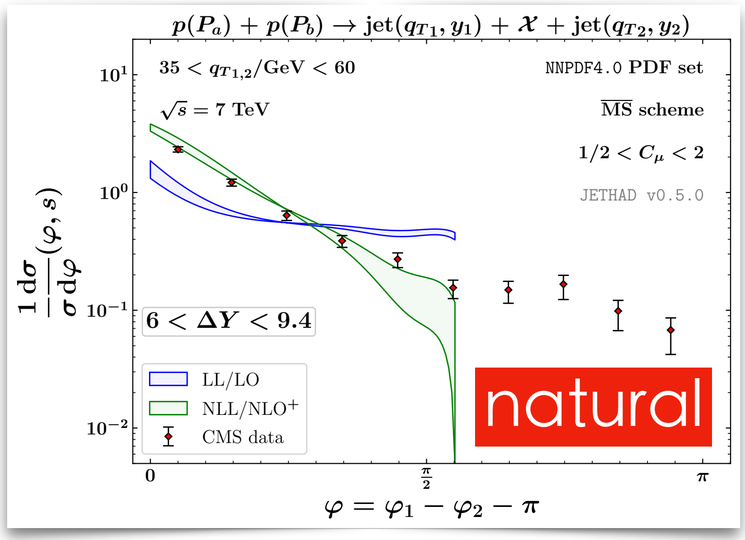

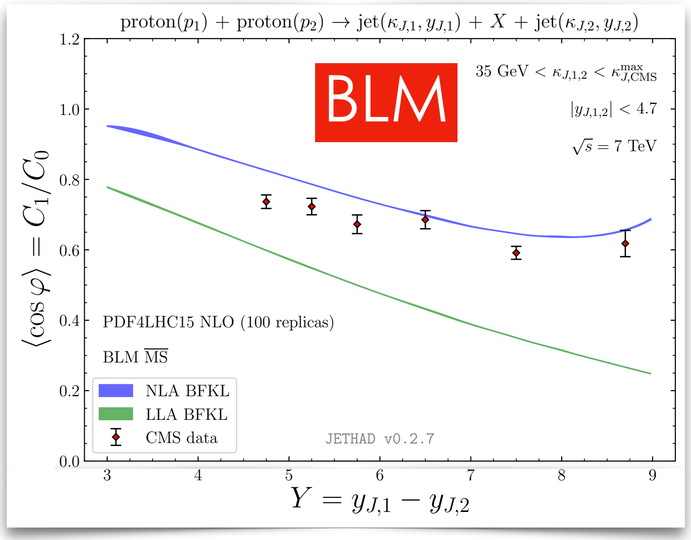

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- $\mu_R^{\mathrm{BLM}} \gg \mu_R^{\mathrm{nat.}} \Rightarrow d\sigma^{\mathrm{BLM}}/d\sigma^{\mathrm{nat.}} \sim 10^{-(1\div 2)} \Rightarrow$ precision studies hampered

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

Azimuthal-angle multiplicity

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

MUELLER-NAVELET JETS

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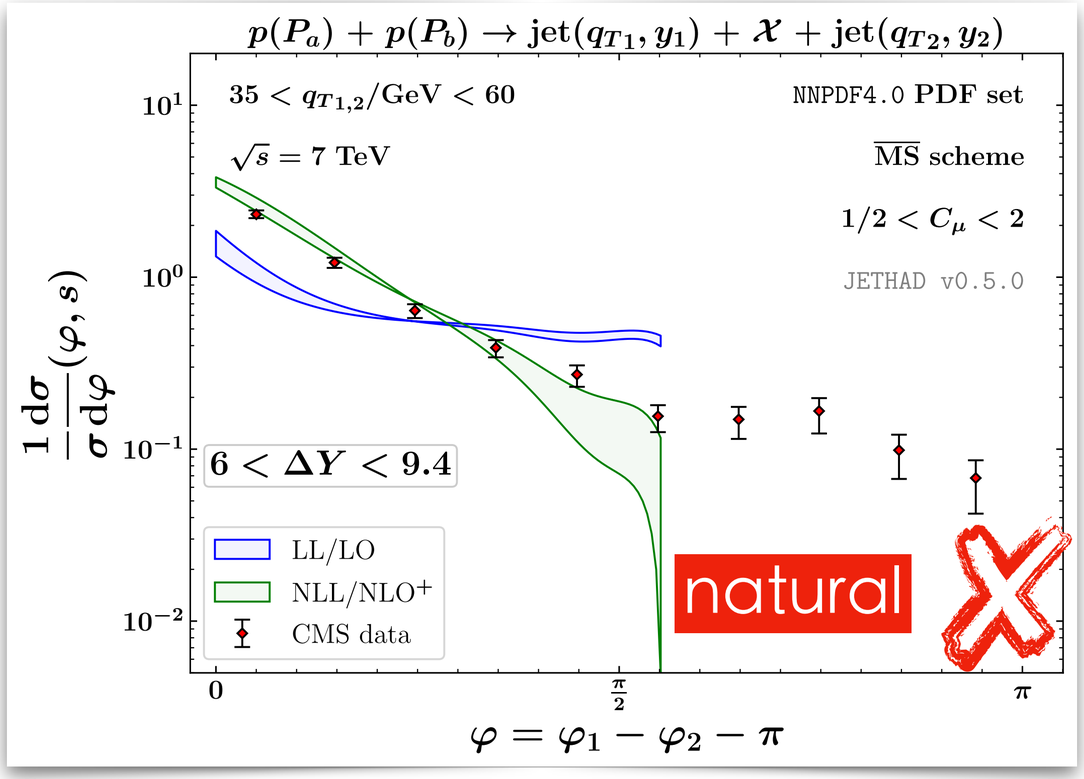

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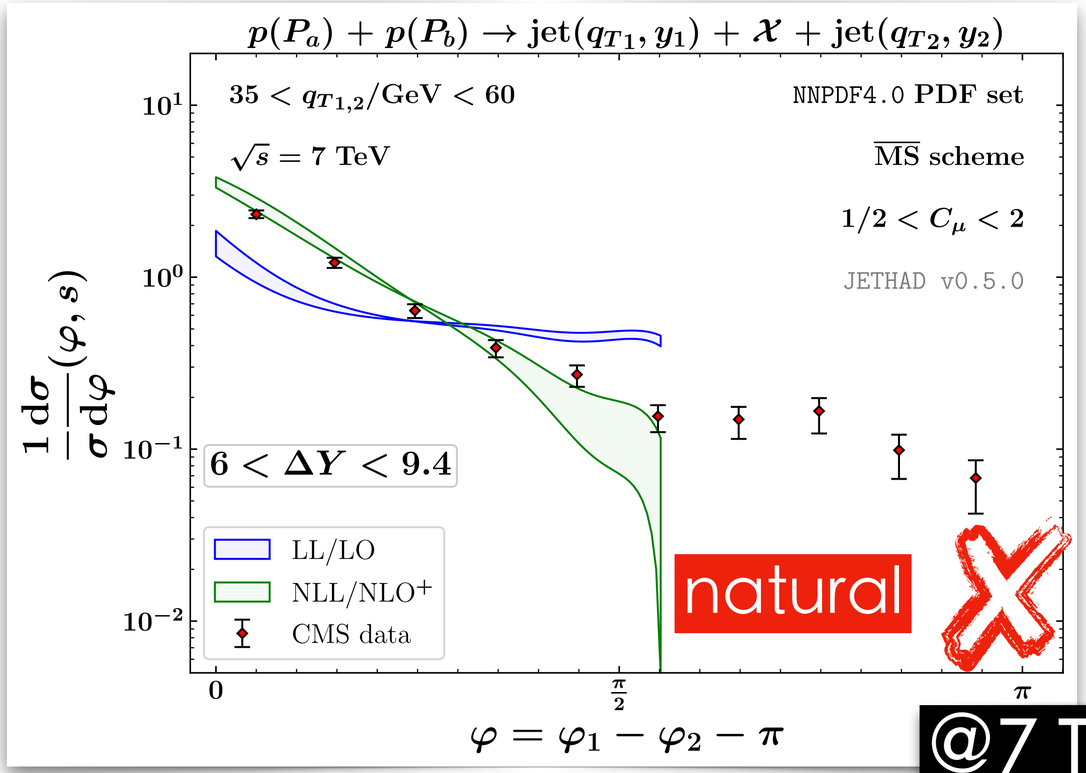
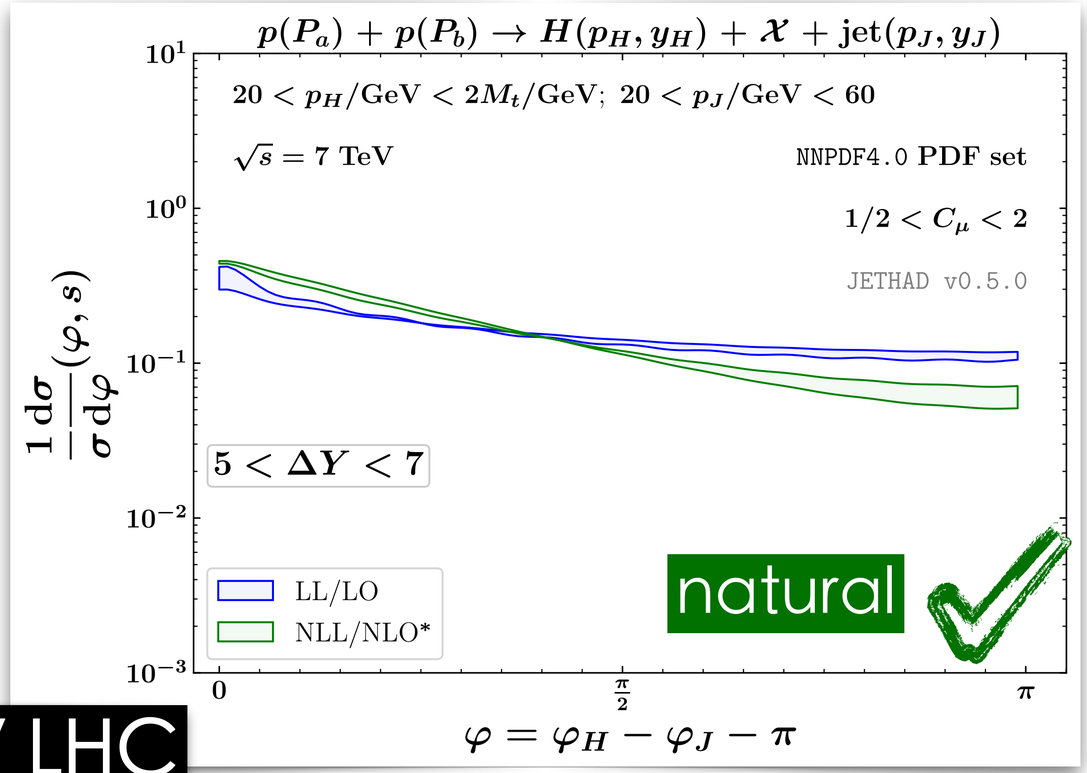
HIGGS + JET

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

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



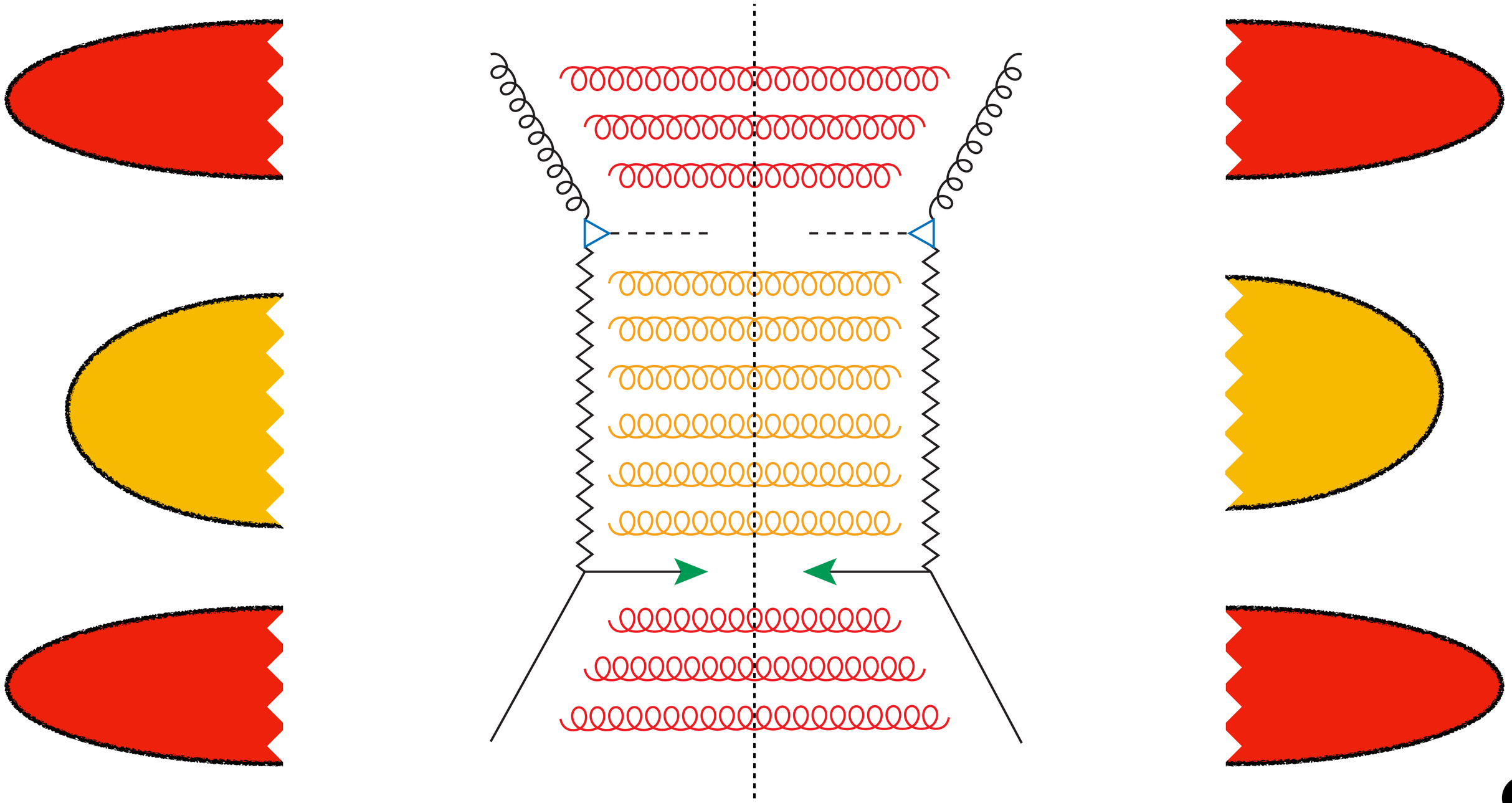


@7 TeV LHC

Hybrid factorization via the JETHAD code

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

Anatomy of Higgs + jet in hybrid factorization (HyF)



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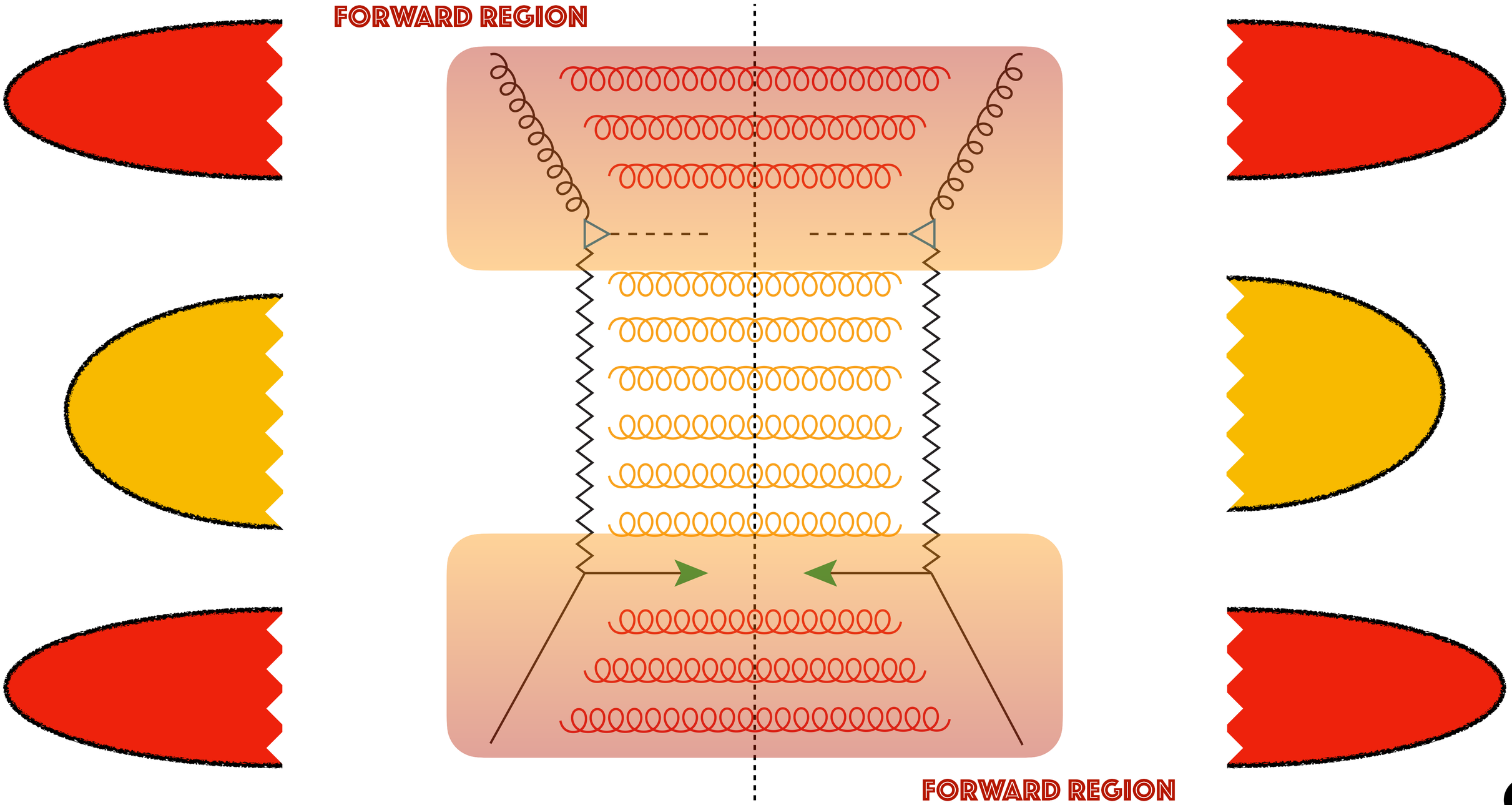
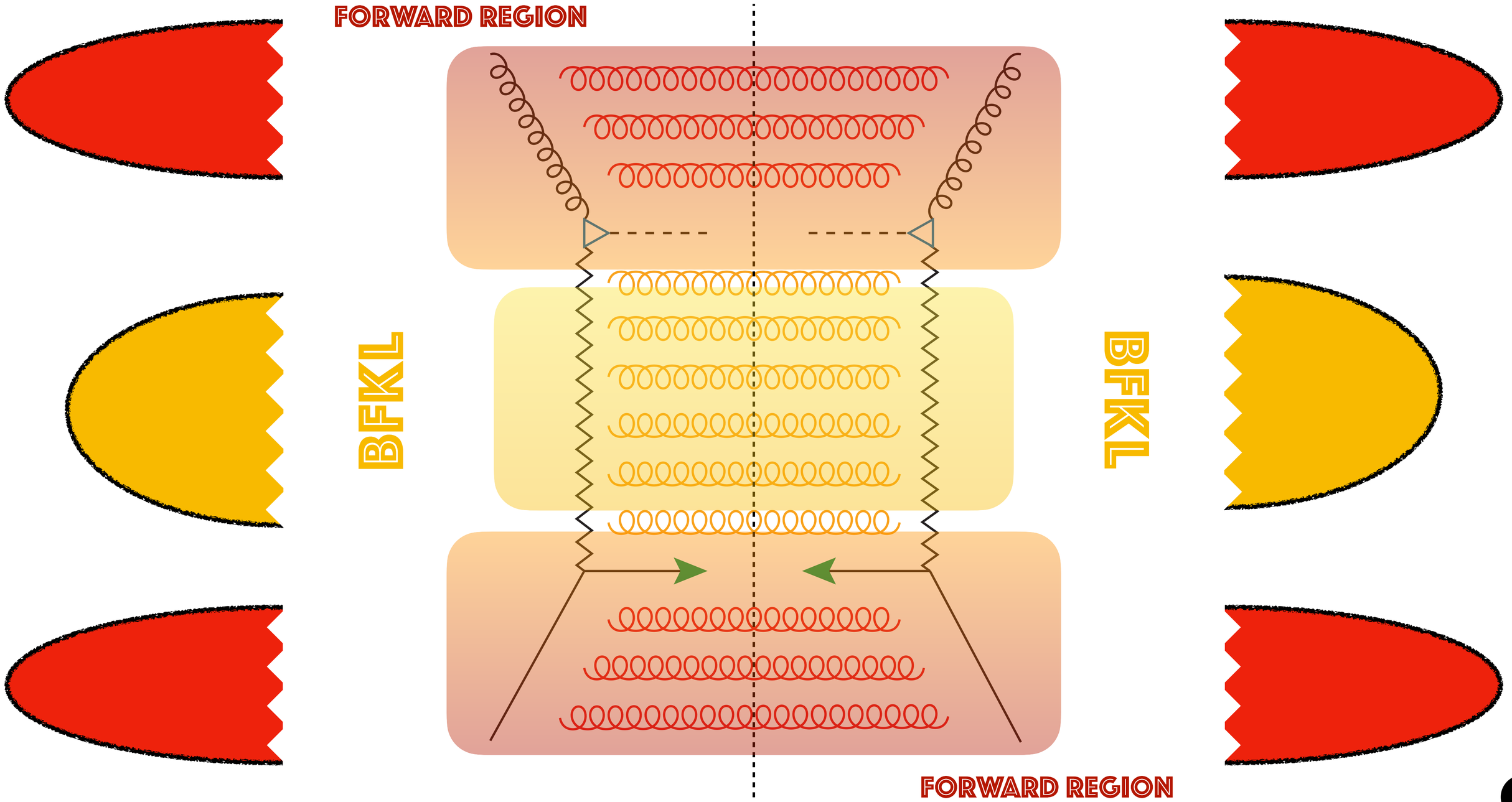
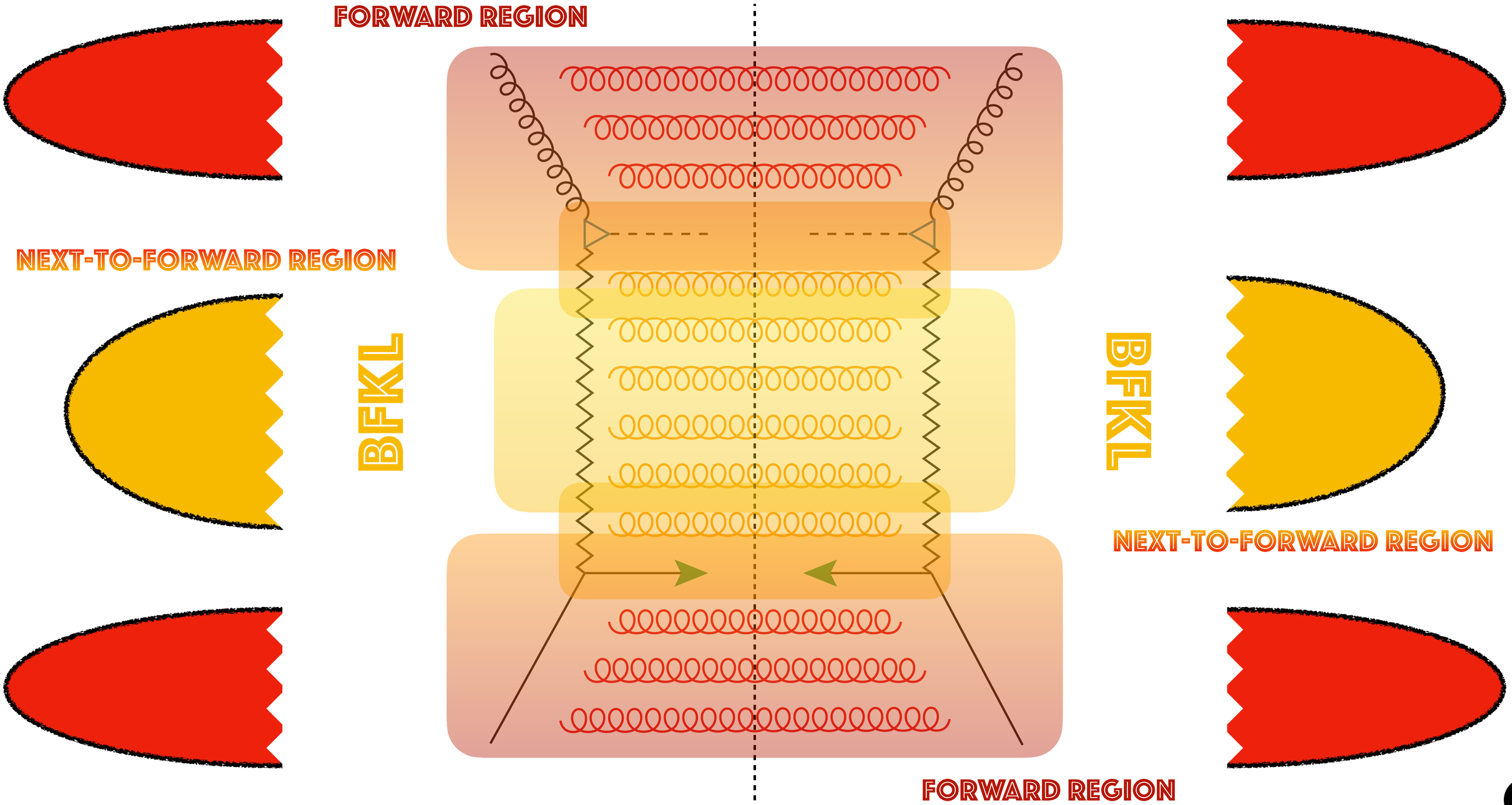


Anatomy of Higgs + jet in hybrid factorization (HyF)



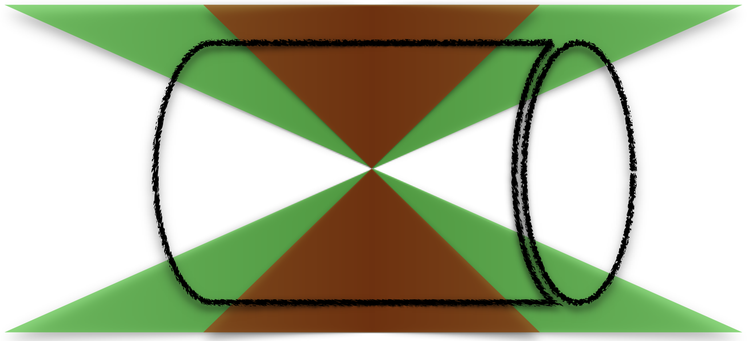
Anatomy of Higgs + jet in hybrid factorization (HyF)



Ultraforward charm + Higgs production @14 TeV FPF+ATLAS

High-energy QCD at new-gen Forward Facilities

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



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

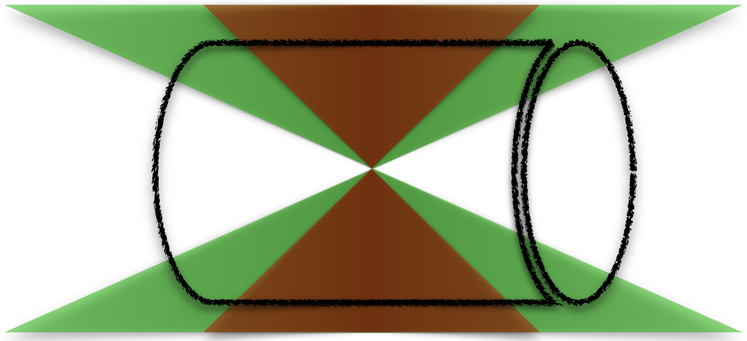
barrel + endcap

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

barrel

High-energy QCD at new-gen Forward Facilities

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



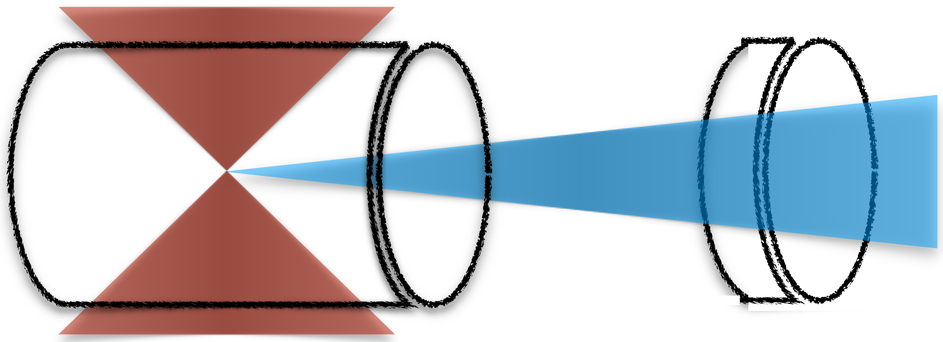
$|y_{\text{jet}}| < 4.7$

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]

High-energy QCD in ultraforward directions

Physics Reports 968 (2022) 1–50

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The Forward Physics Facility: Sites, experiments, and physics potential

Luis A. Anchordoqui [1], Akitaka Ariga [2,3], Tomoko Ariga [4], Weidong Bai [5], Kincso Balazs [6], Brian Batell [7], Jamie Boyd [6], Joseph Bramante [8], Mario Campanelli [9], Adrian Carmona [10], Francesco G. Celiberto [11,12,13], Grigorios Chachamis [14], Matthew Citron [15], Giovanni De Lellis [16,17], Albert De Roeck [6], Hans Dembinski [18], Peter B. Denton [19], Antonia Di Crecsenzo [16,17,6], Milind V. Diwan [20], Liam Dougherty [21], Herbi K. Dreiner [22], Yong Du [23], Rikard Enberg [24], Yasaman Farzan [25], Jonathan L. Feng [26,*], Max Fieg [26], Patrick Foldenauer [27], Saeid Foroughi-Abari [28], Alexander Friedland [29], Michael Fucilla [30,31], Jonathan Gall [32], Maria Vittoria Garzelli [33,*], Francesco Giuli [34], Victor P. Goncalves [35], Marco Guzzi [36], Francis Halzen [37], Juan Carlos Helo [38,39], Christopher S. Hill [40], Ahmed Ismail [41], Ameen Ismail [42], Richard Jacobsson [6], Sudip Jana [43], Yu Seon Jeong [44], Krzysztof Jodłowski [45], Kevin J. Kelly [46], Felix Kling [29,47,**], Fnu Karan Kumar [20], Zhen Liu [48], Rafał Maciuła [49], Roshan Mammen Abraham [41], Julien Manshanden [33], Josh McFayden [50], Mohammed M.A. Mohammed [30,31], Pavel M. Nadolsky [51], Nobuchika Okada [52], John Osborne [6], Hidetoshi Otono [4], Vishvas Pandey [53,46], Alessandro Papa [30,31], Digesh Raut [54], Mary Hall Reno [55], Filippo Resnati [6], Adam Ritz [28], Juan Rojo [56], Ina Sarcevic [57], Christiane Scherb [58], Holger Schulz [59], Pedro Schwaller [60], Dipan Sengupta [61], Torbjörn Sjöstrand [62], Tyler B. Smith [26], Dennis Soldin [54], Anna Stasto [63], Antoni Szczurek [49], Zahra Tabrizi [64], Sebastian Trojanowski [65,66], Yu-Dai Tsai [26,46], Douglas Tuckler [67], Martin W. Winkler [68], Keping Xie [7], Yue Zhang [67]

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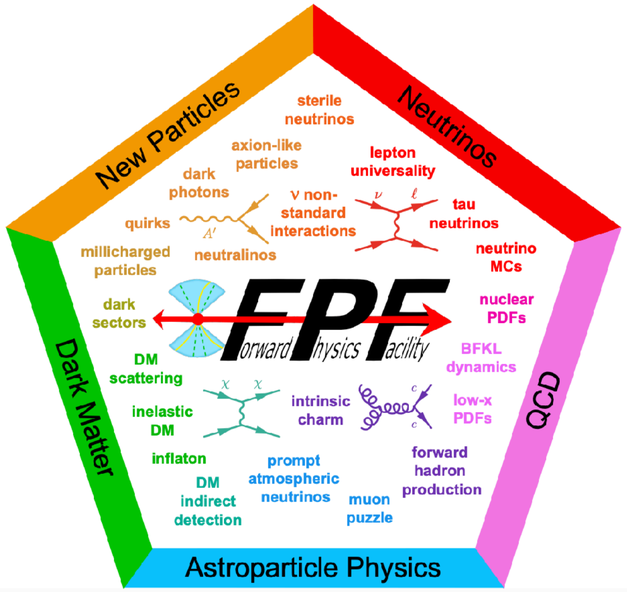
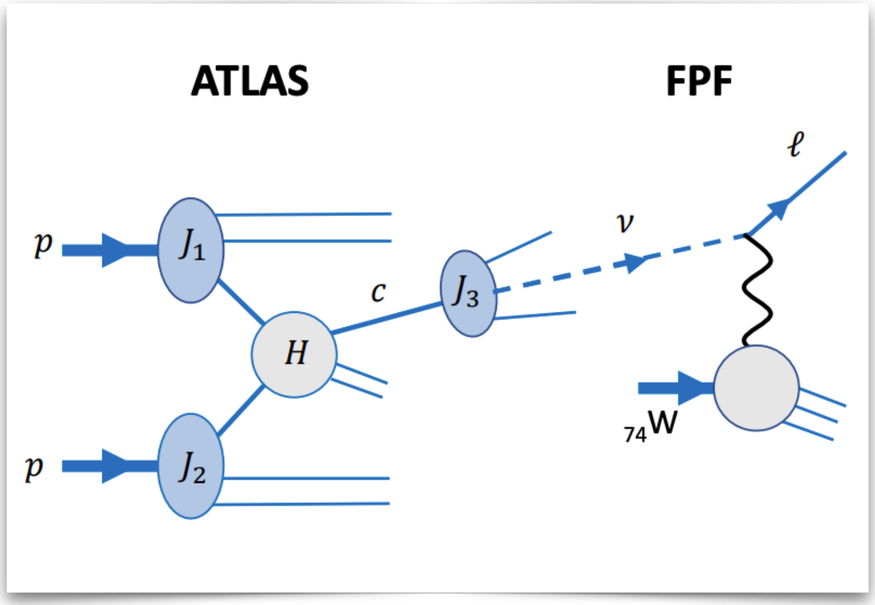


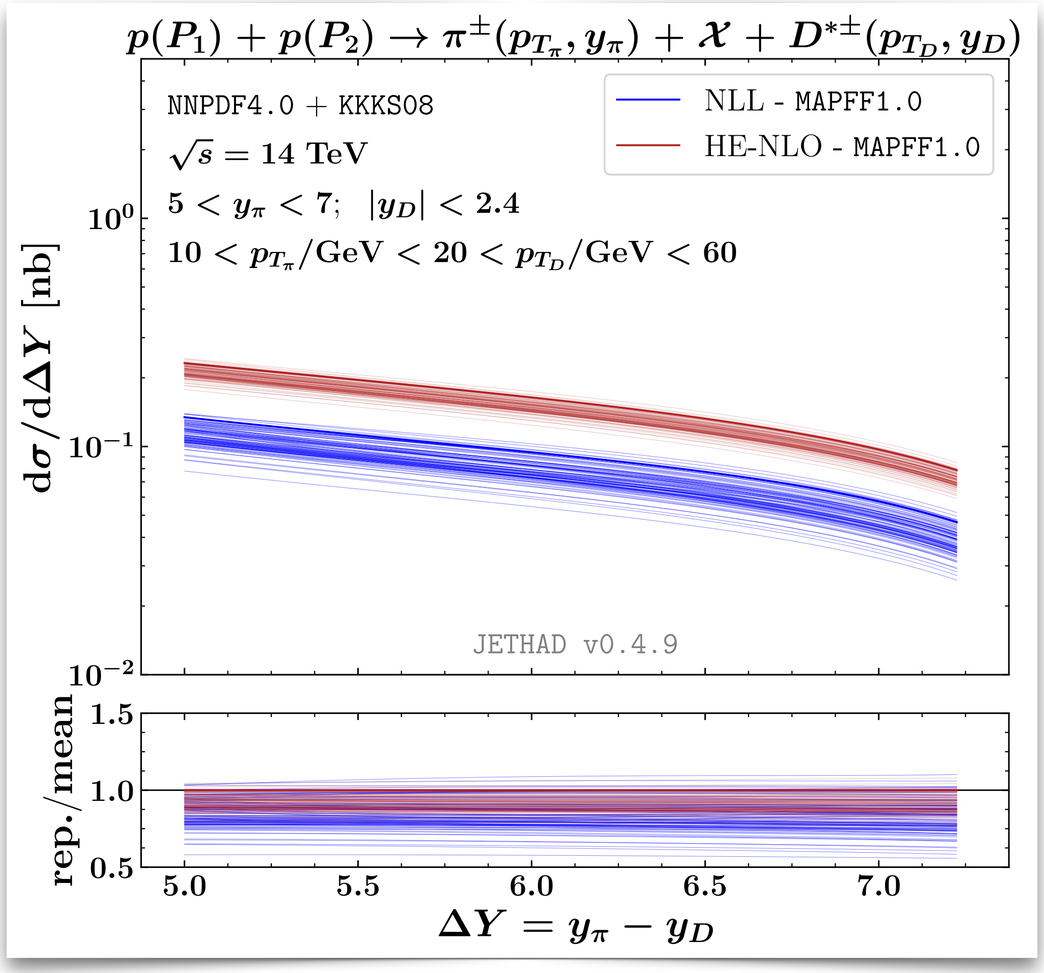
[FPF Snowmass Whitepaper]



Rapidity distributions @FPF+ATLAS

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

🔗 [FPF Snowmass Whitepaper]



Rapidity distributions @FPF+ATLAS

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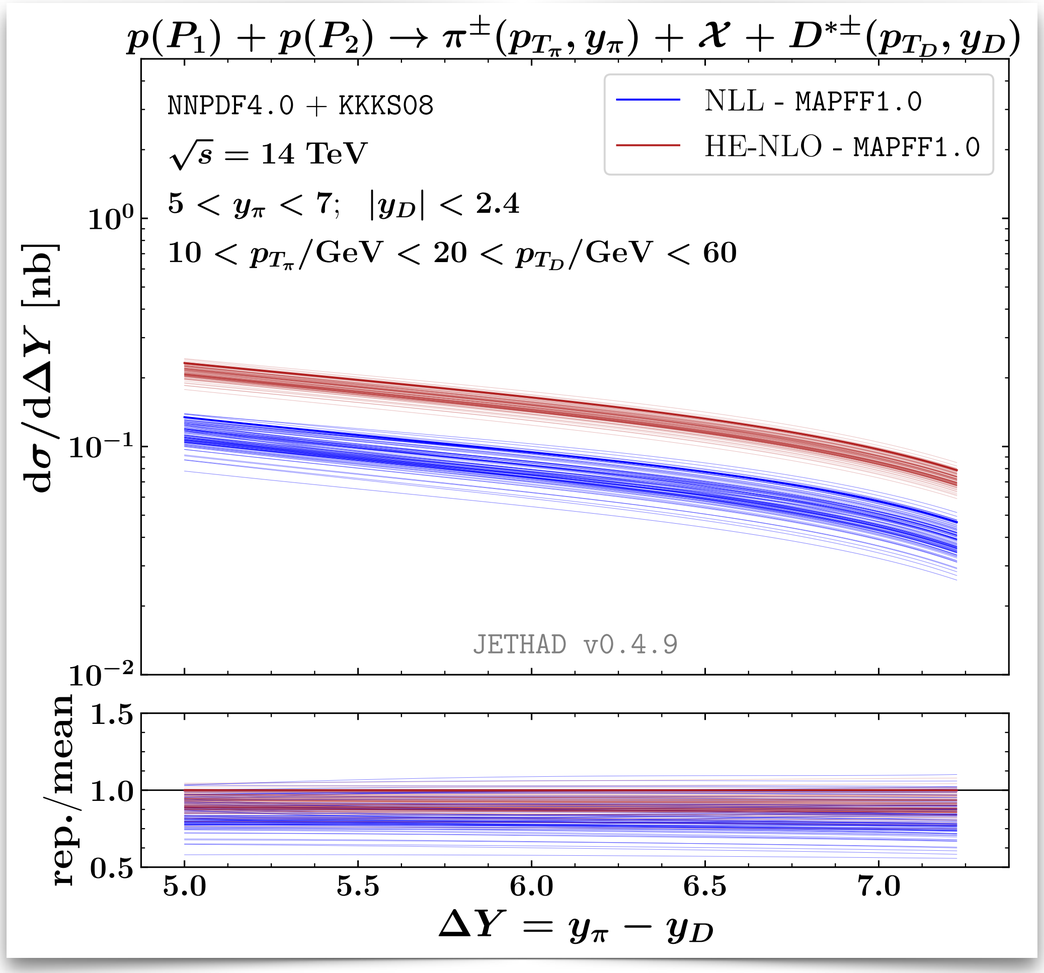

- Impact of collinear FFs on ΔY-distribution
- Replica method at work

Rapidity distributions @FPF+ATLAS

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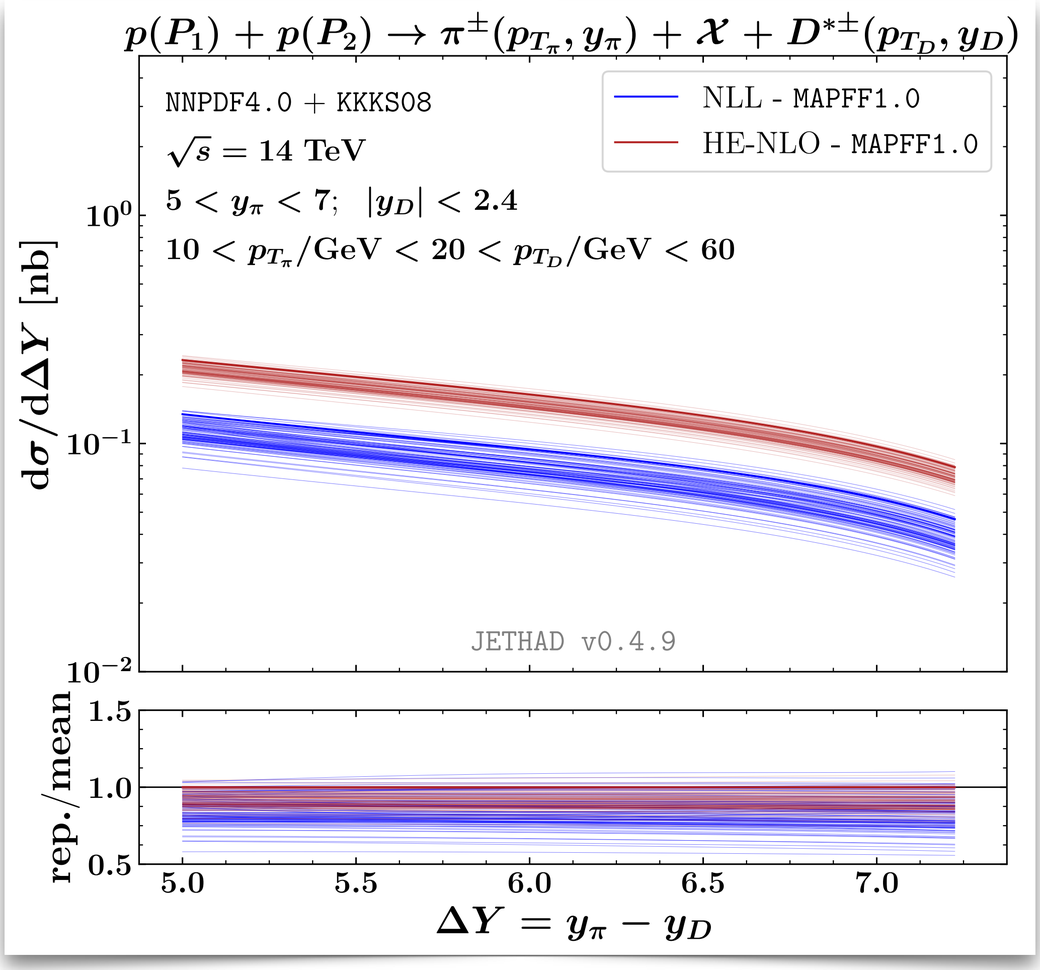
🔗 [FPF Snowmass Whitepaper]



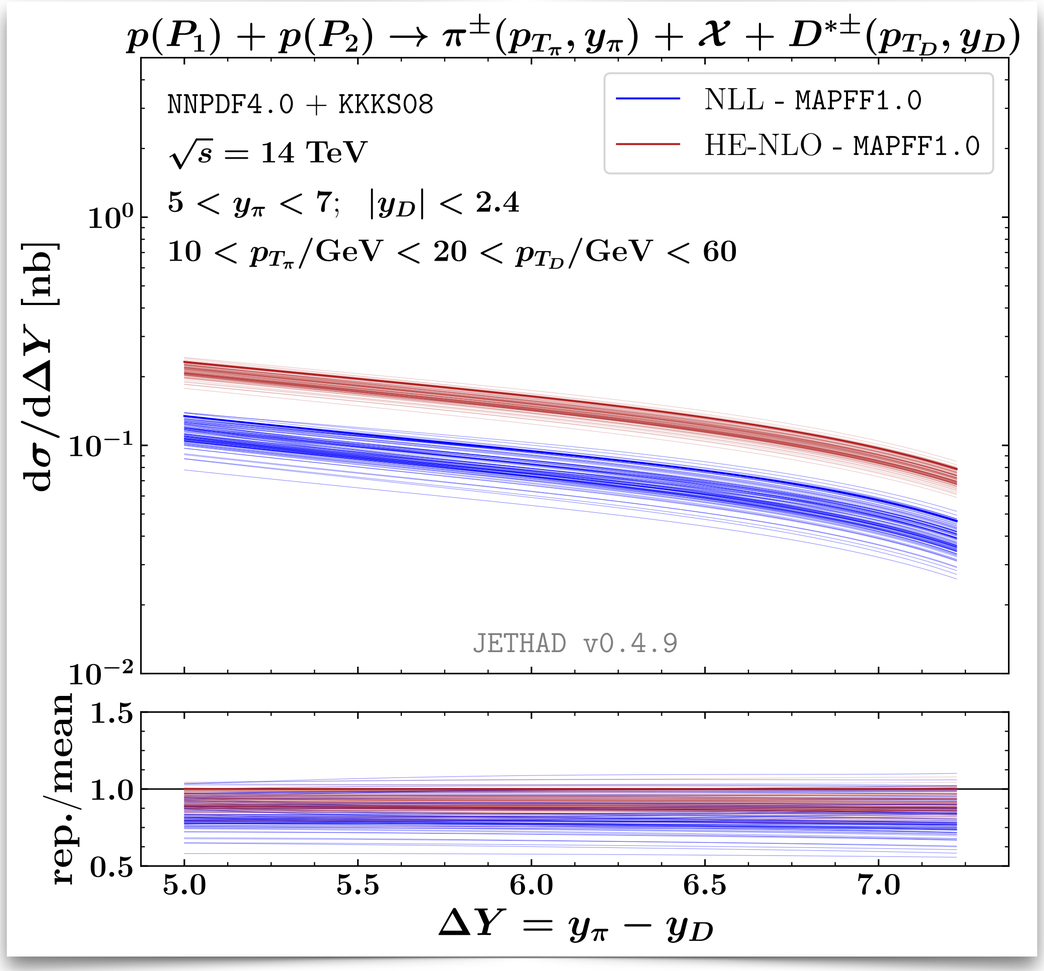
- Impact of collinear FFs on ΔY-distribution
- Replica method at work
- Larger spread of replicas at NLL
- Probe FFs in complementary ranges

  Weight of FF replicas in the same set

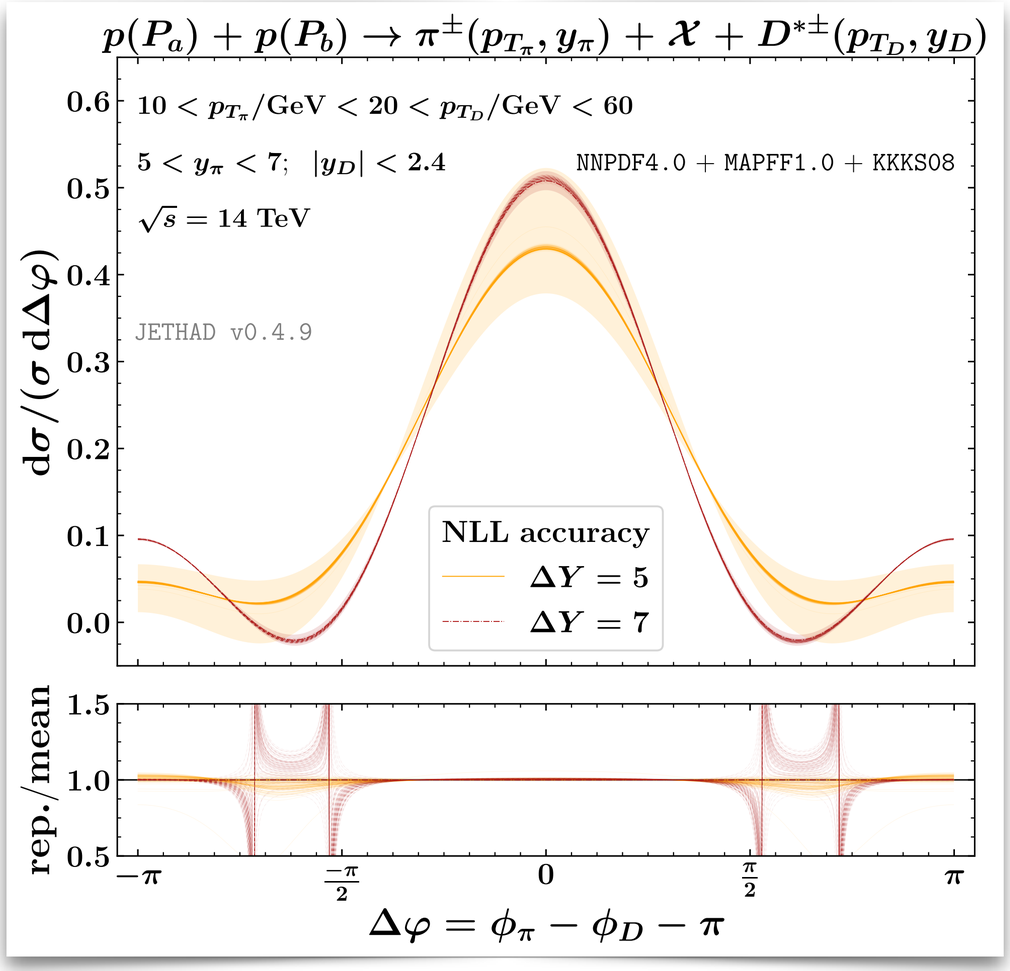
  Different sets via functional correlation?
- Complementary studies on FFs

Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) ΔY-spectrum



Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) $\Delta\varphi$-spectrum



🔗 [FPF Snowmass Whitepaper]

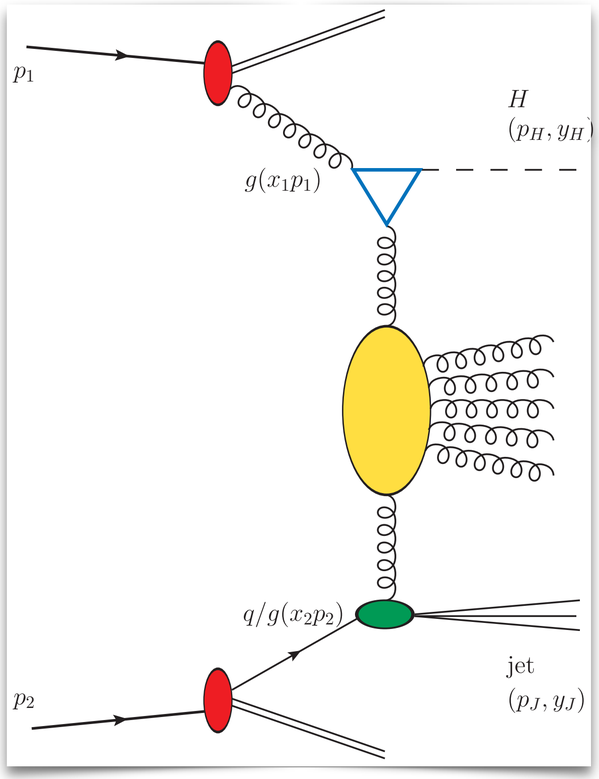
HIGGS + JET DISTRIBUTIONS

Inclusive Higgs + jet at the LHC

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

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

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



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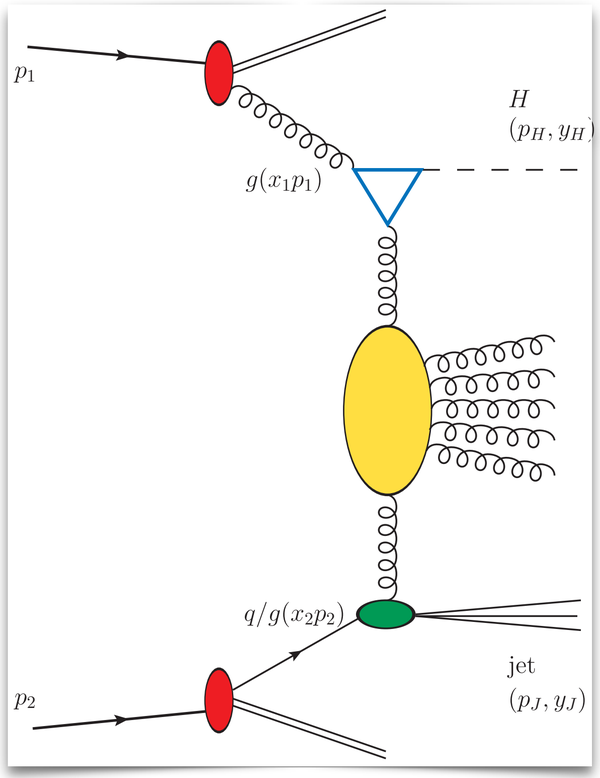


$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\,\mathcal{C}_n\right]$$

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

Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

NLO*

NLL

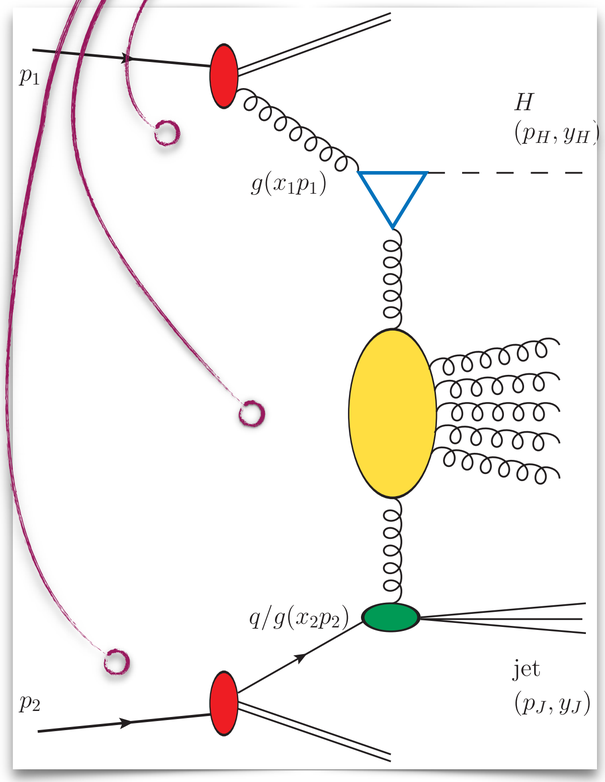
NLO*

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

BFKL Green's function

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



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

Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

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

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

NLO*

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

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

NLL

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

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

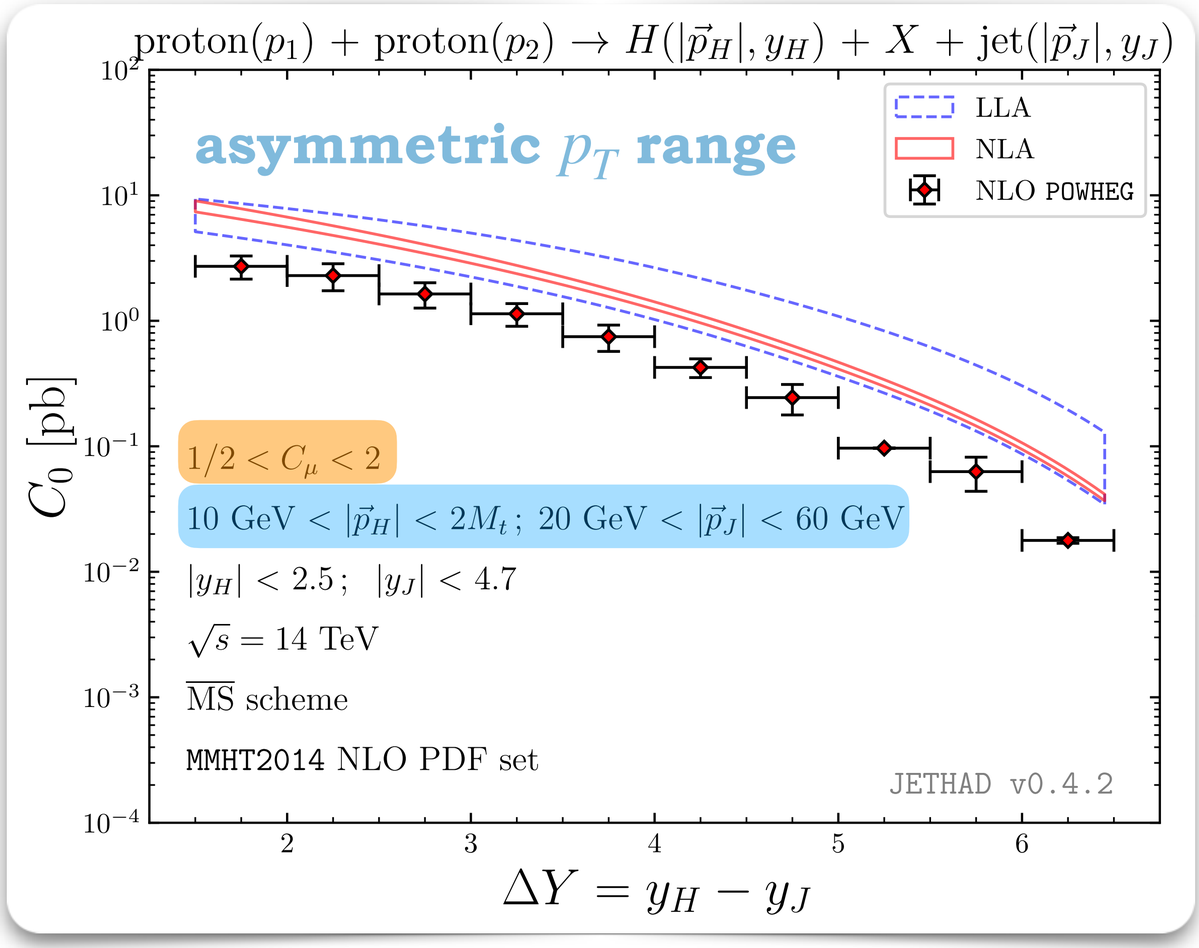
NLO*

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

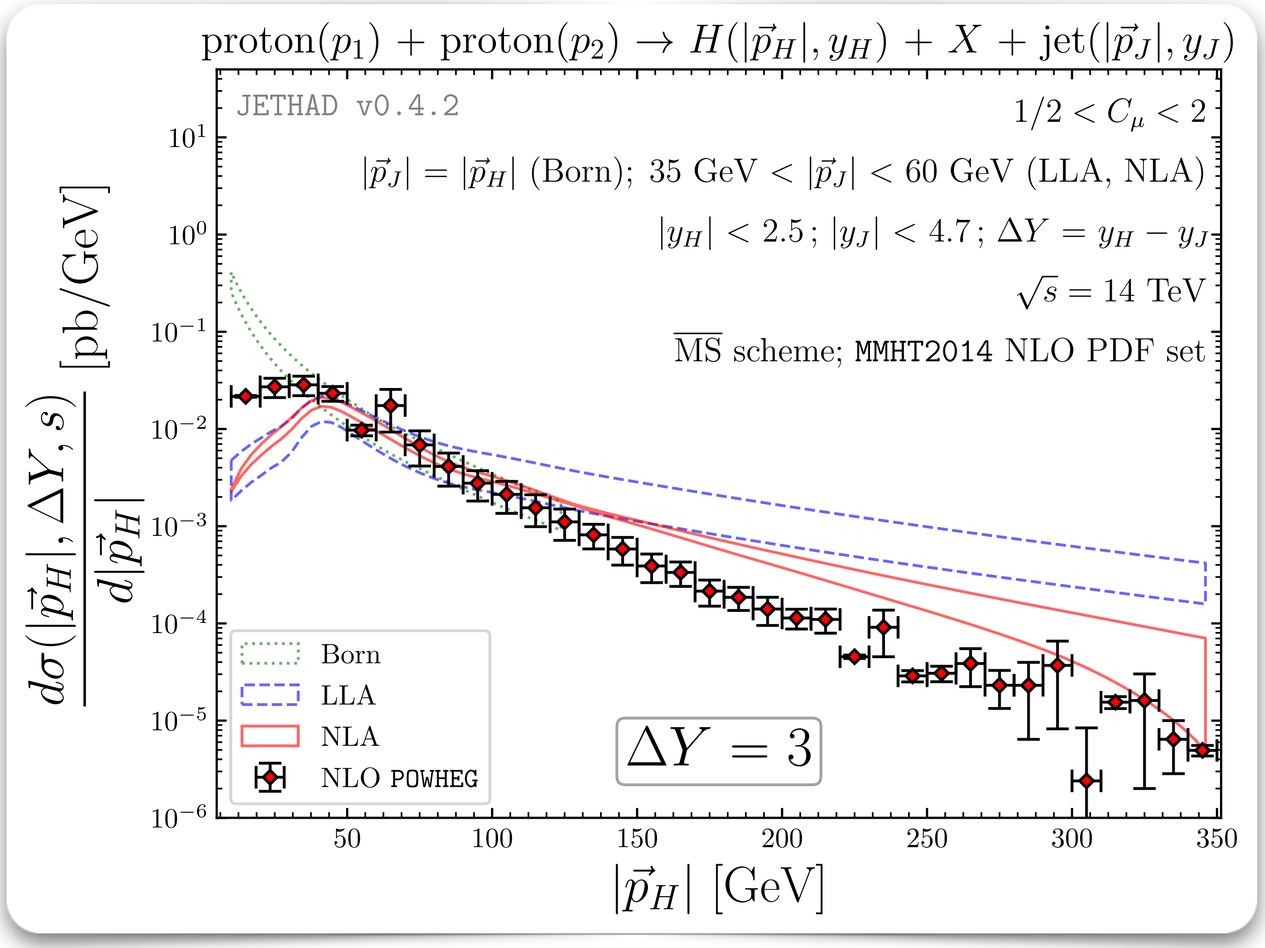
BFKL Green's function

The Higgs + jet spectrum in hybrid factorization

ΔY spectrum



p_H spectrum

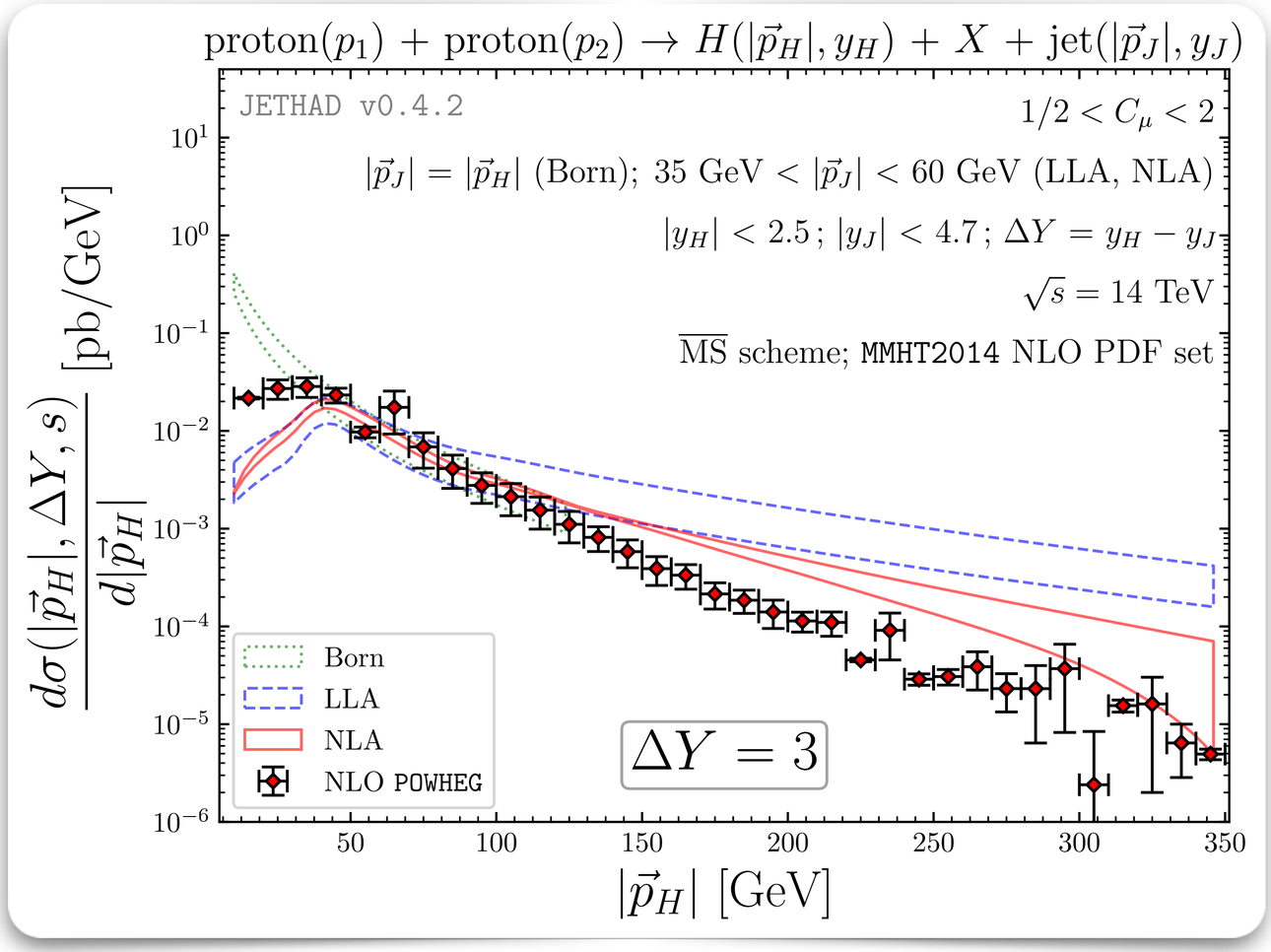


(in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

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

Higgs transverse-momentum distribution

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

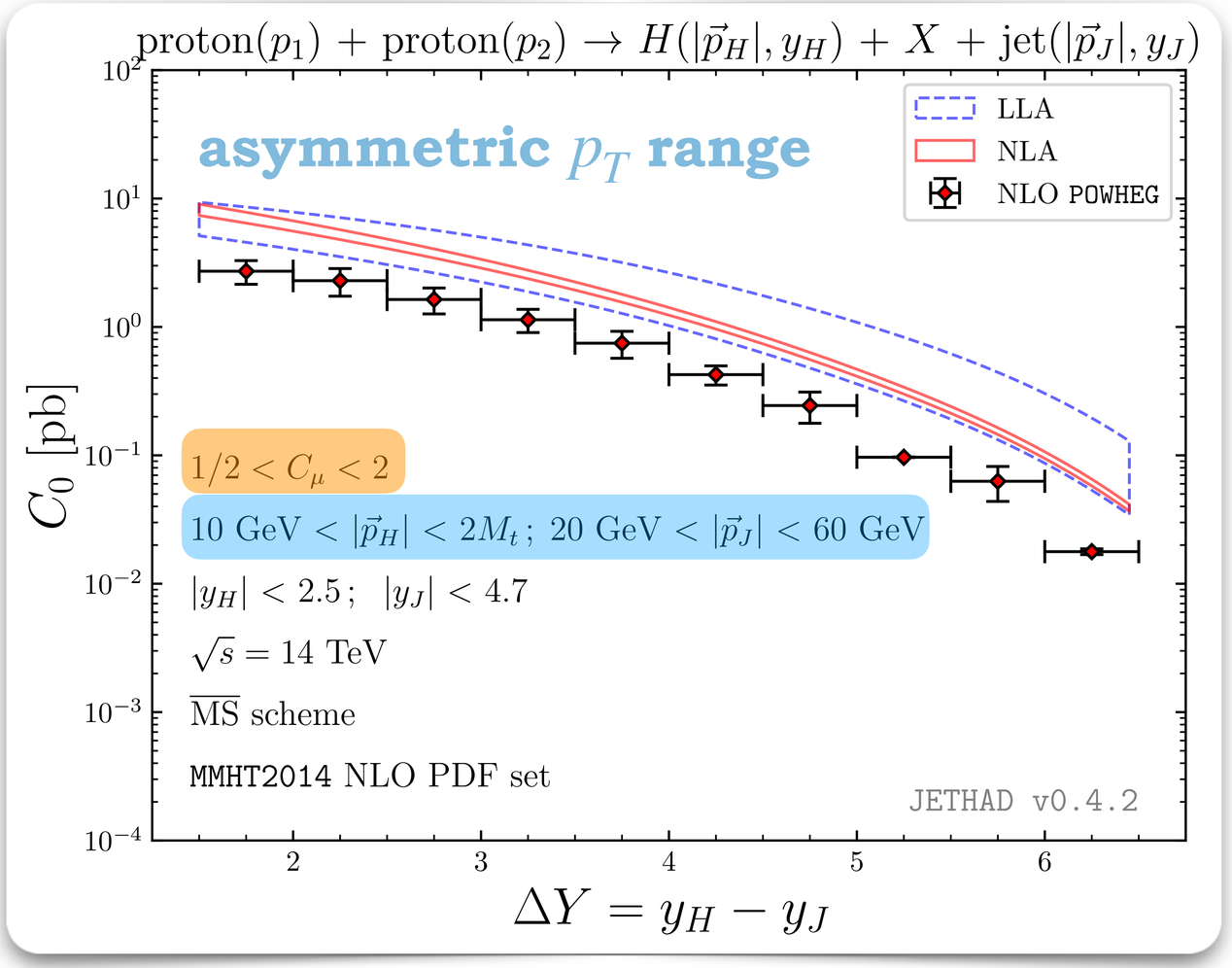


- ☑ HE resummation from JETHAD
- ☑ Comparison with fixed-order POWHEG
- ☑ Distributions stable under NLL corrections

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

ΔY-distribution

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



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

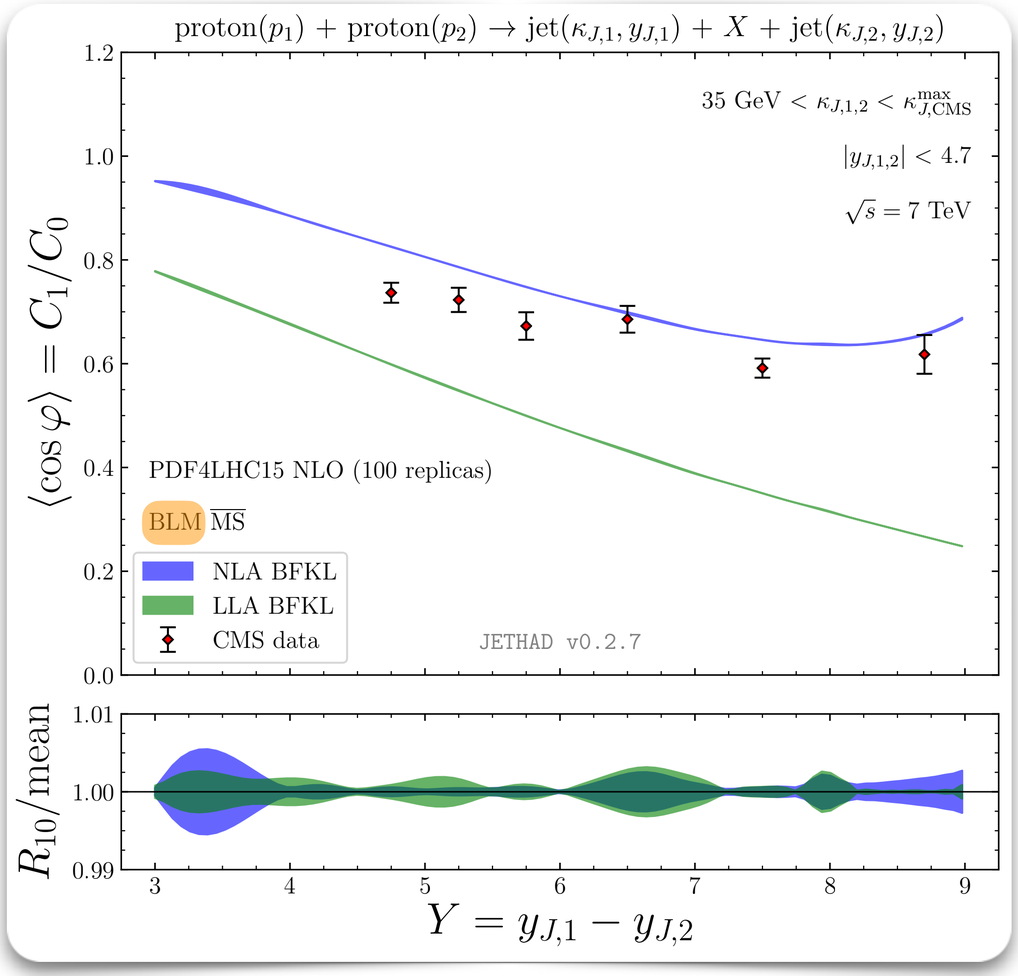
Angular correlations

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

Mueller-Navelet jets

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

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



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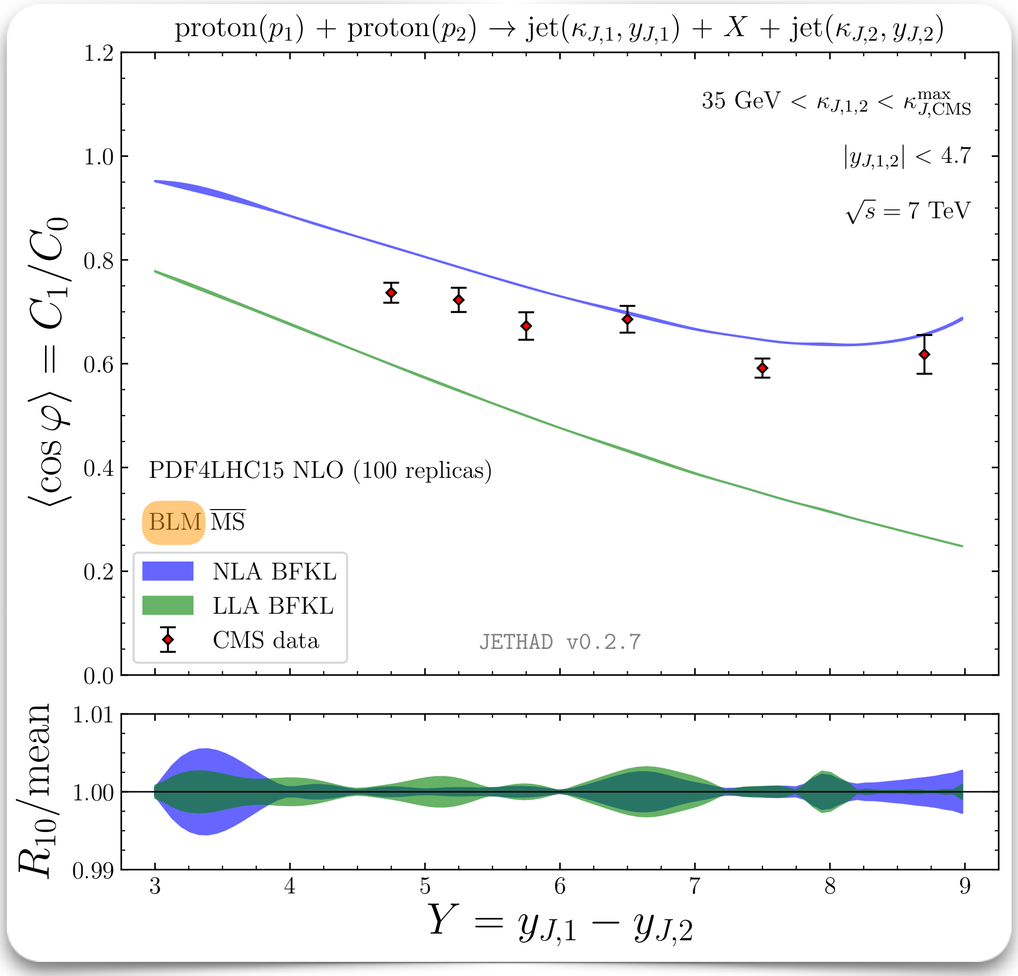
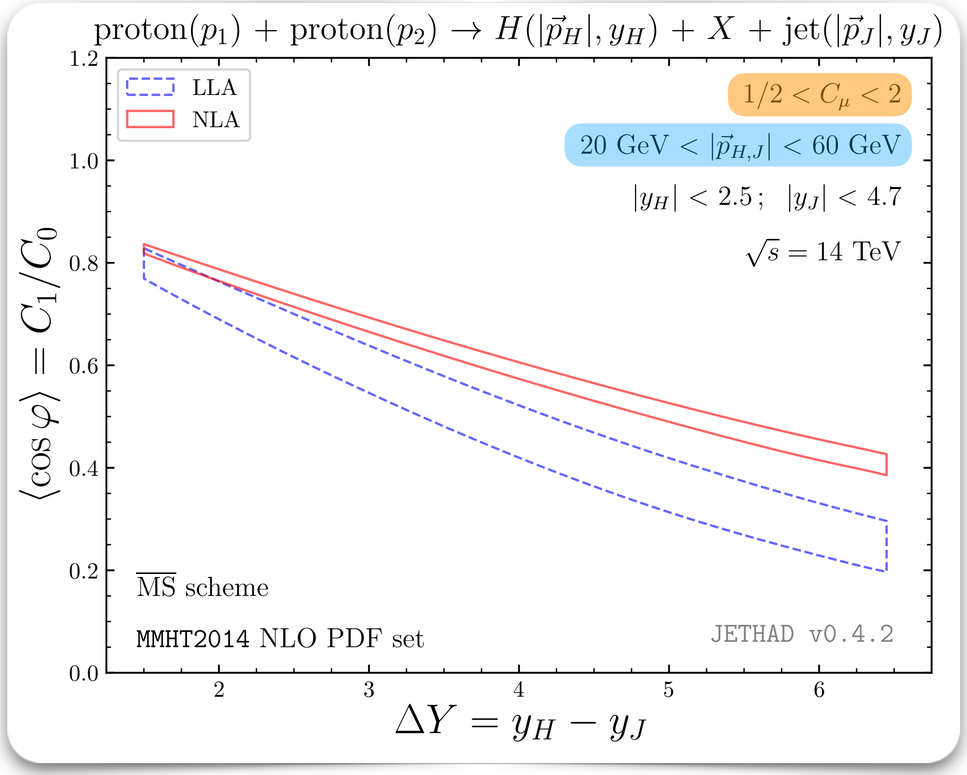


Higgs + jet

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

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

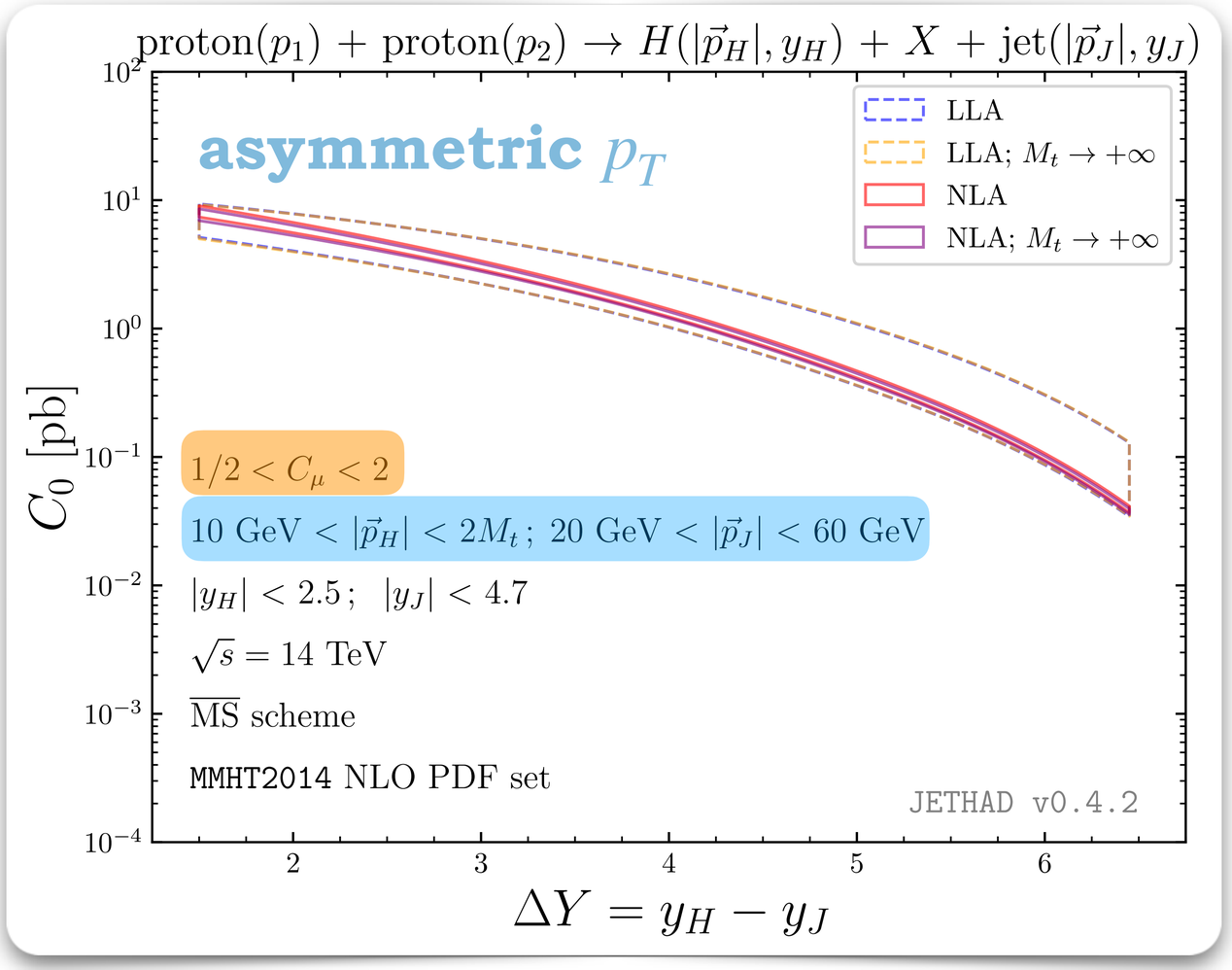


natural scales

symmetric p_T range

ΔY-distribution in the infinite top-mass limit

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



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

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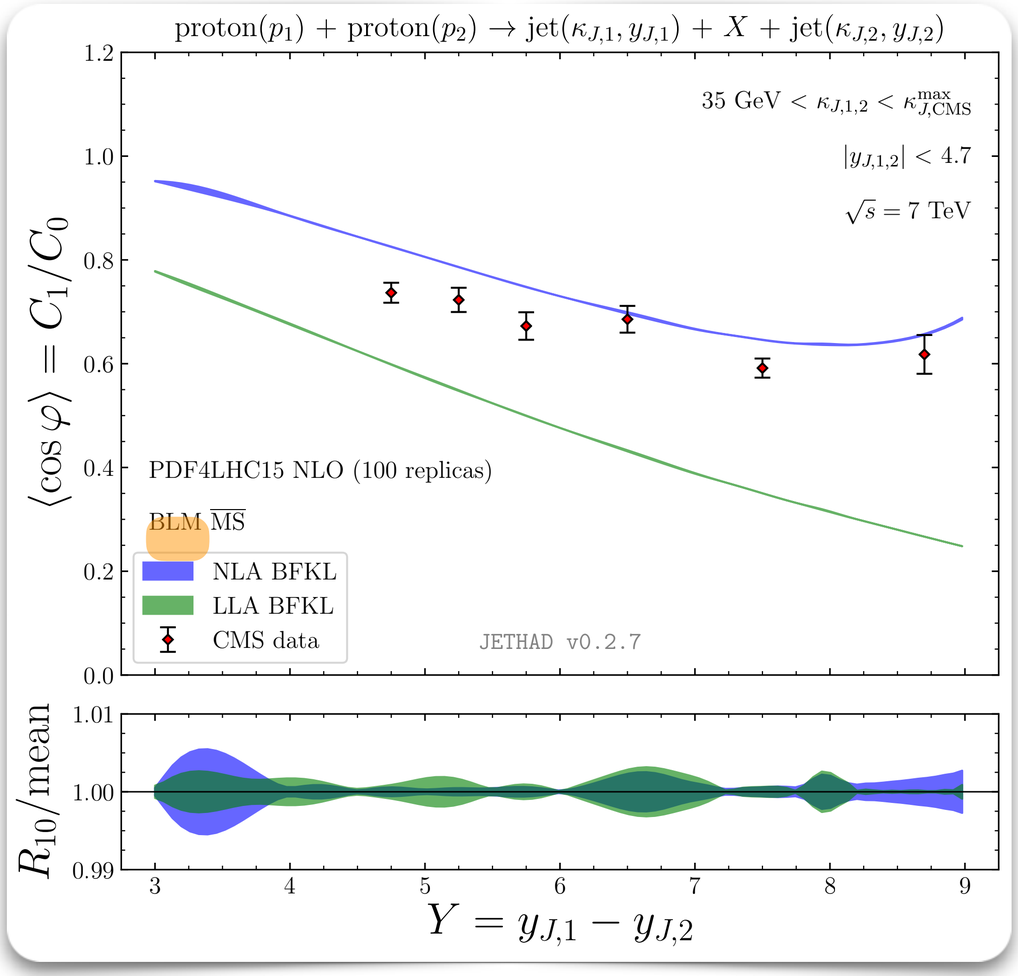

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Mueller-Navelet jets

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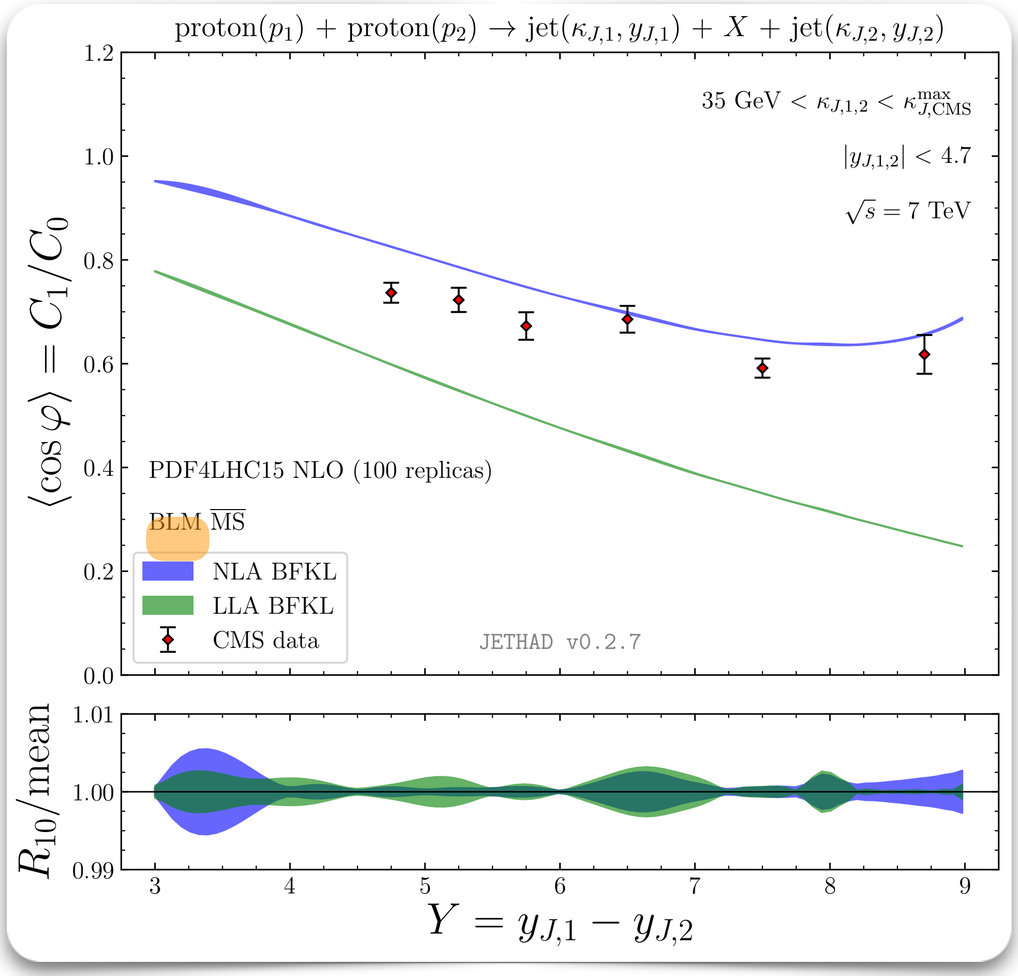
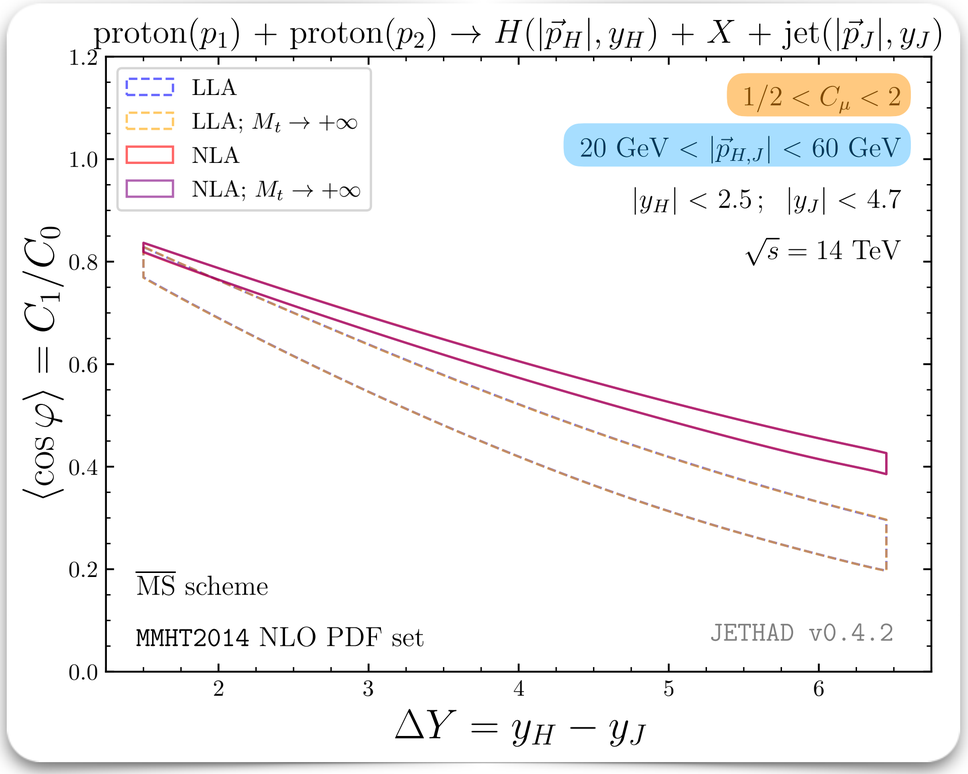


Higgs + jet

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

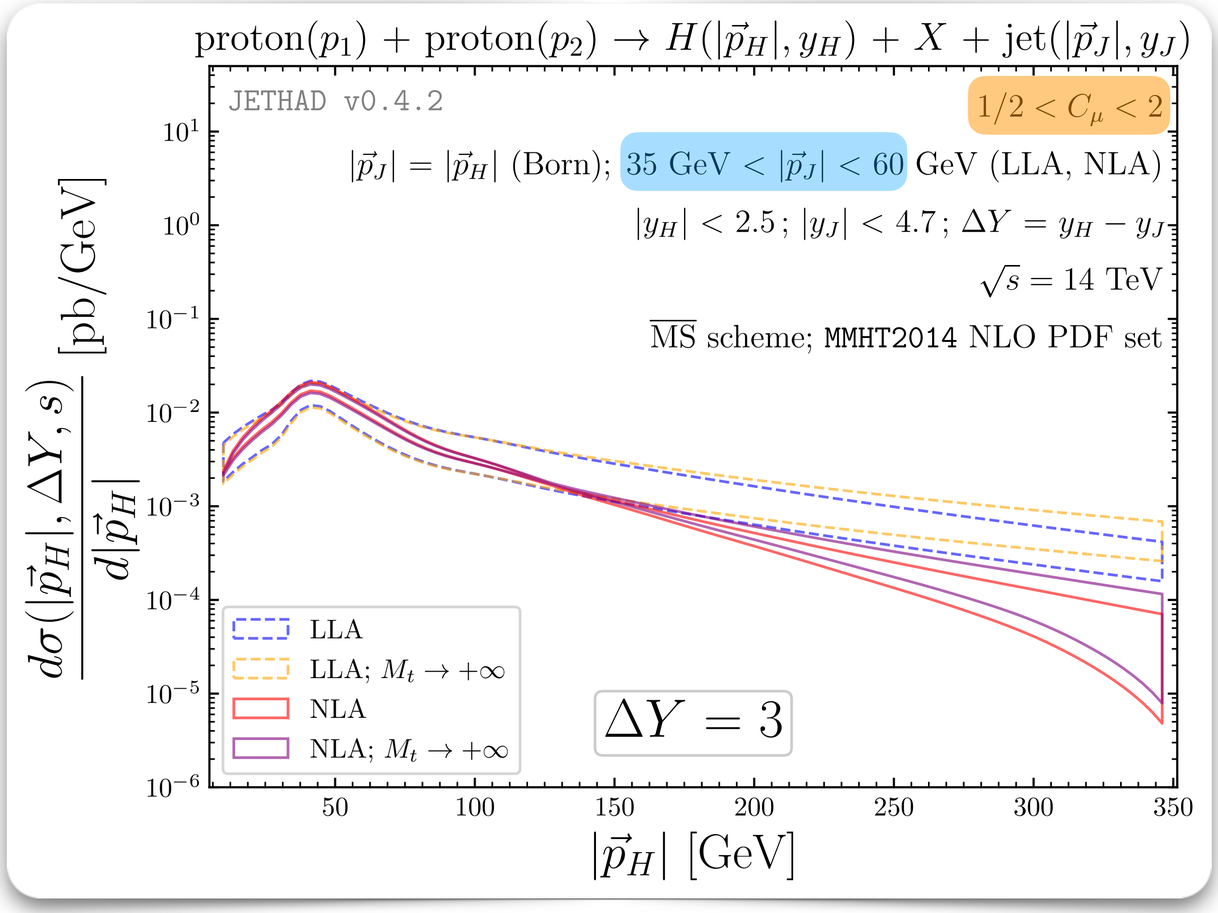
(NLO Higgs impact factor) 🔗 [F. G. C. et al., under review (2022)]

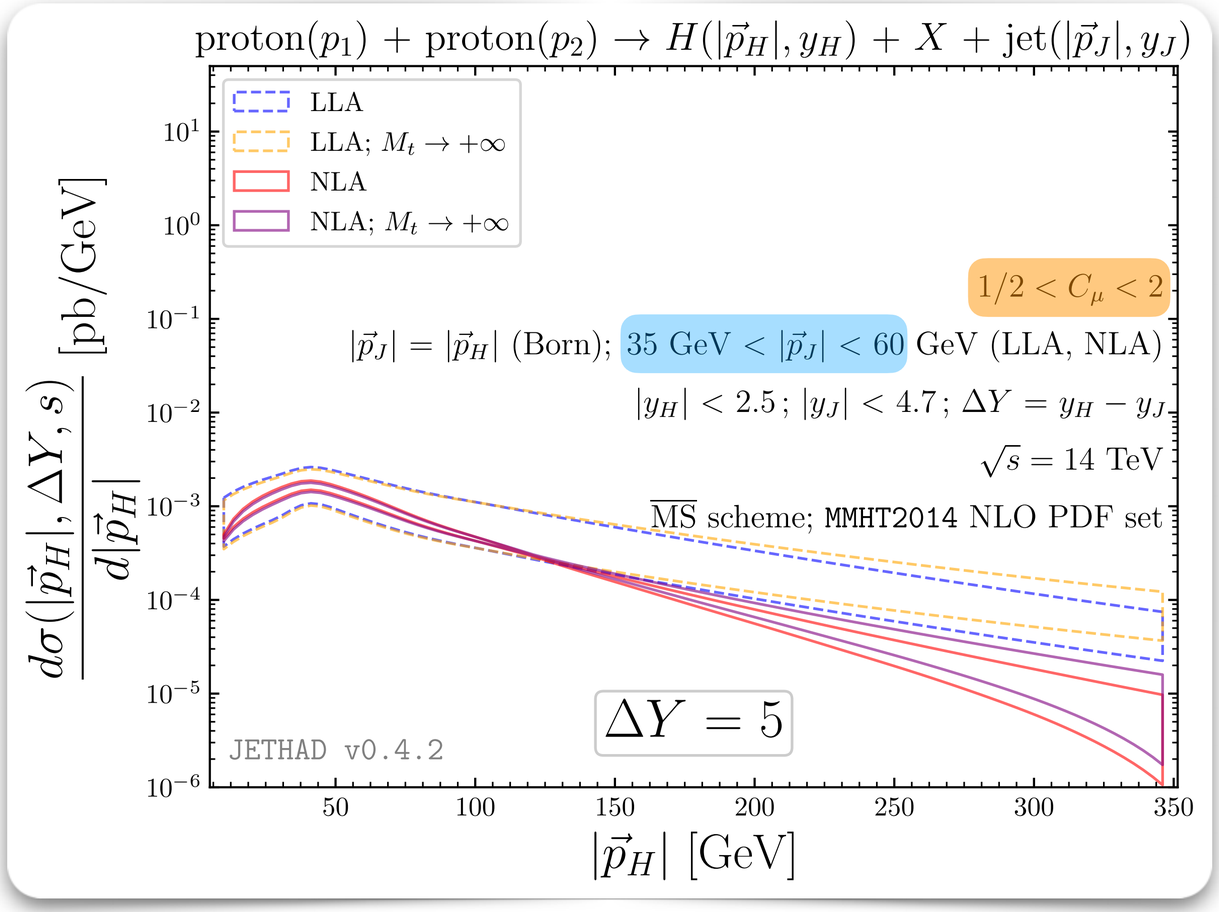


natural scales

symmetric p_T range

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

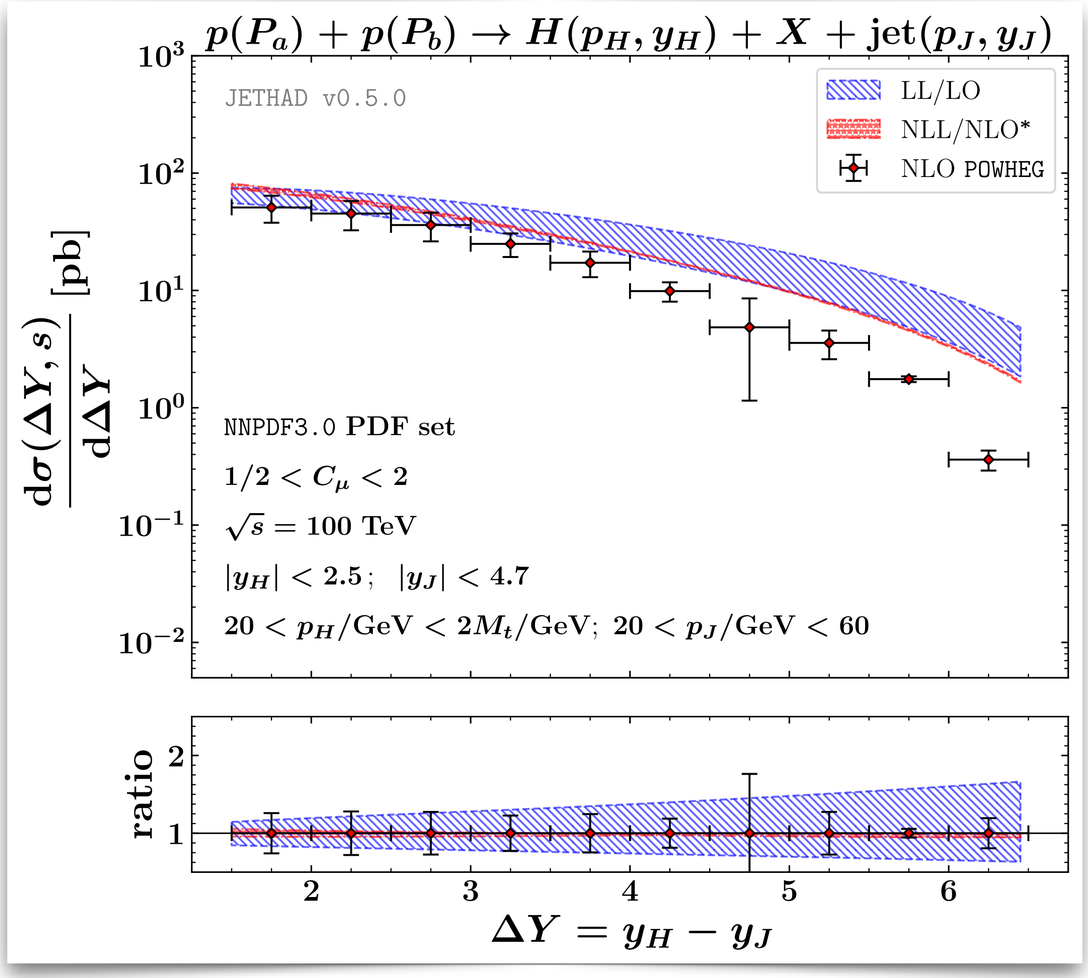




🔗 [F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

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

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



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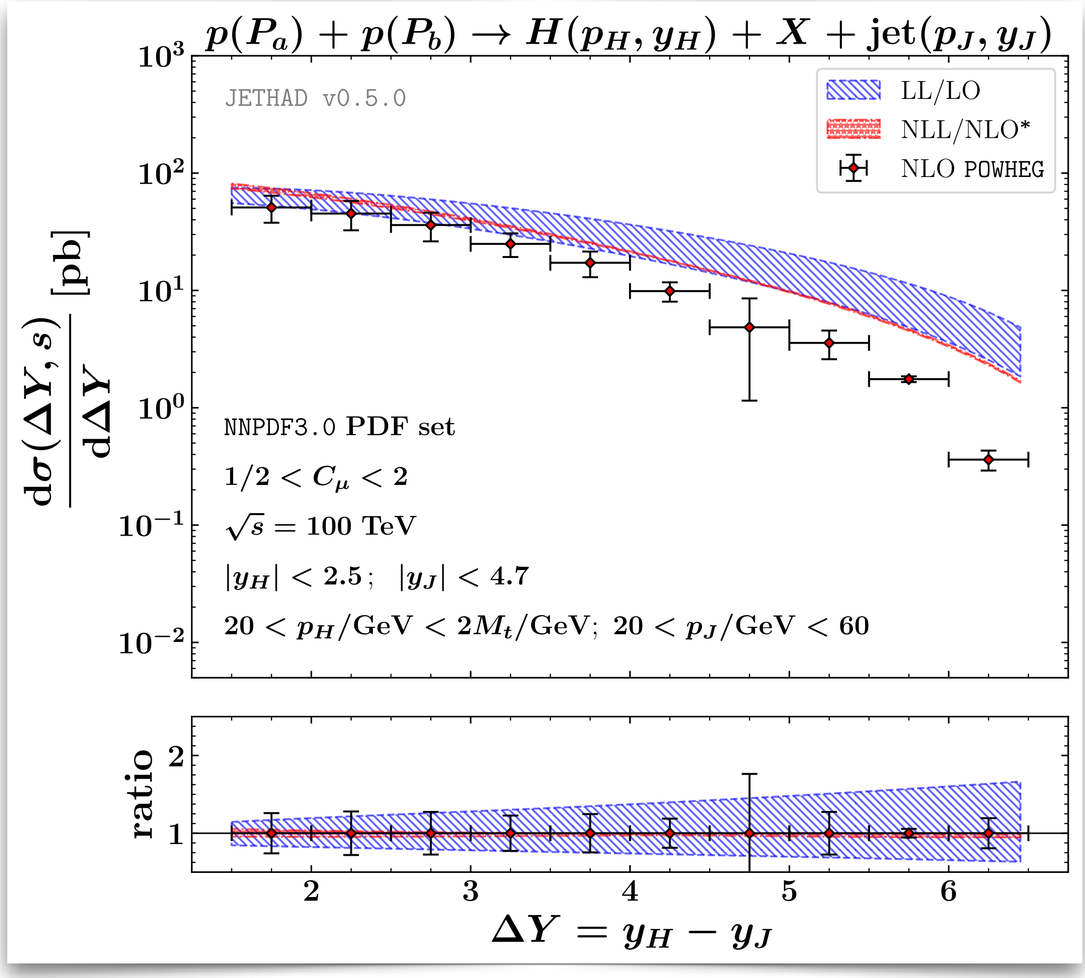
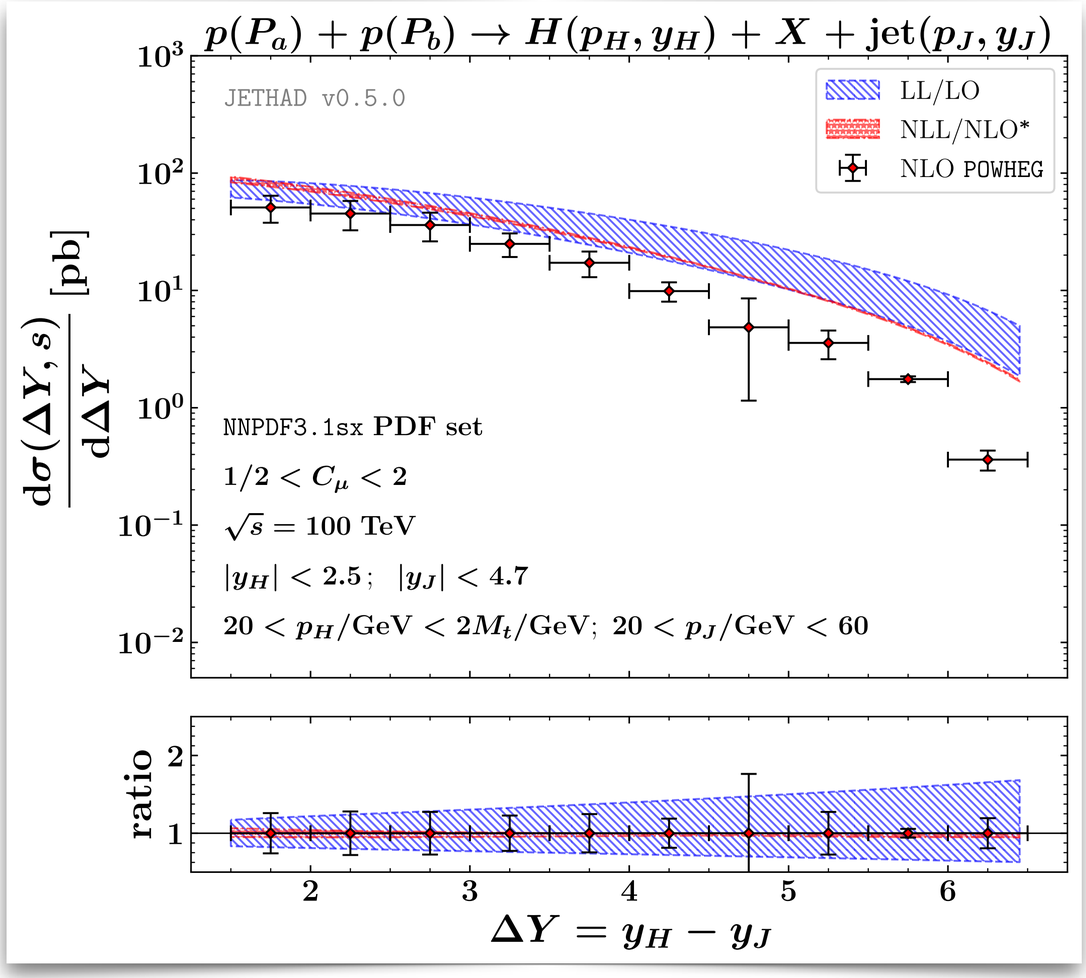


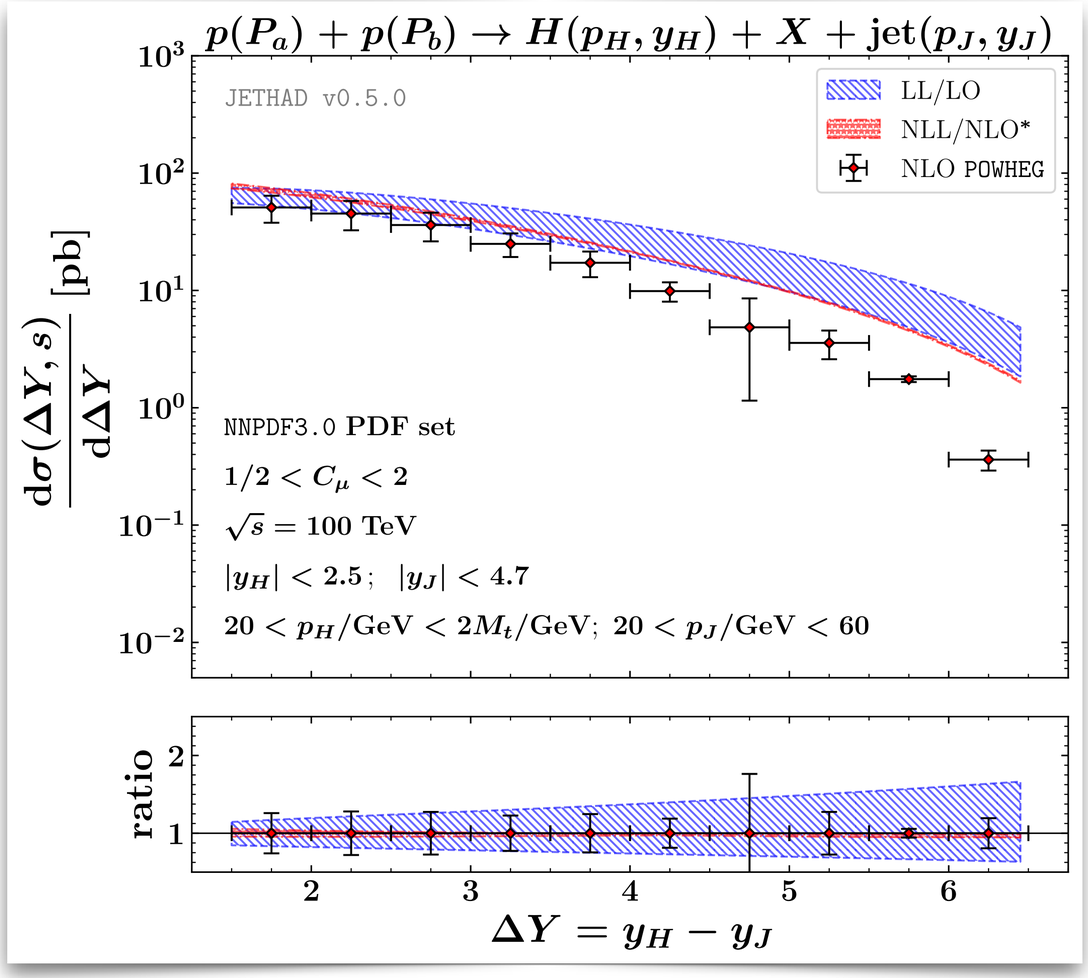
High-energy resummation + **NNPDF3.1sx** 🔗



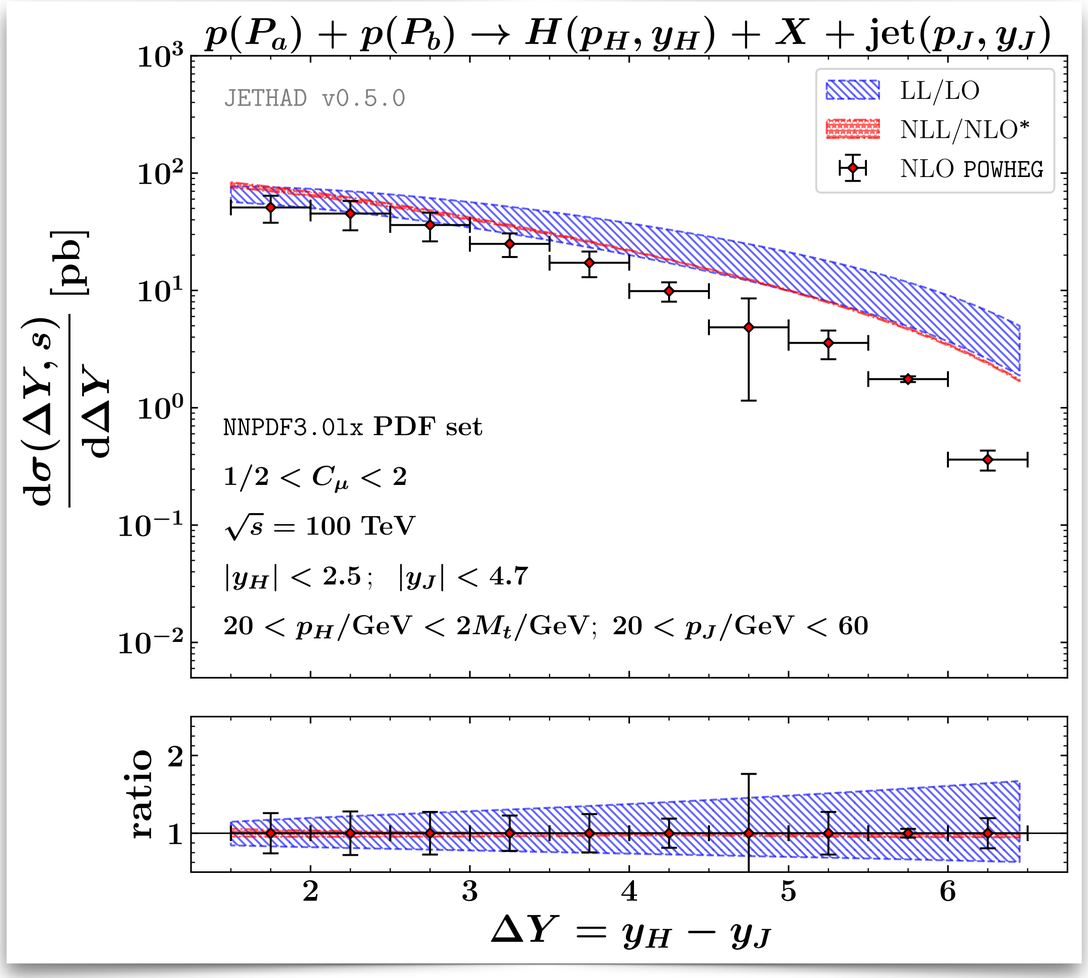
Small-x resummation on PDFs ⇒ $+(13.5 \div 2.10)\,\%$ @NLL/NLO*

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

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



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



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

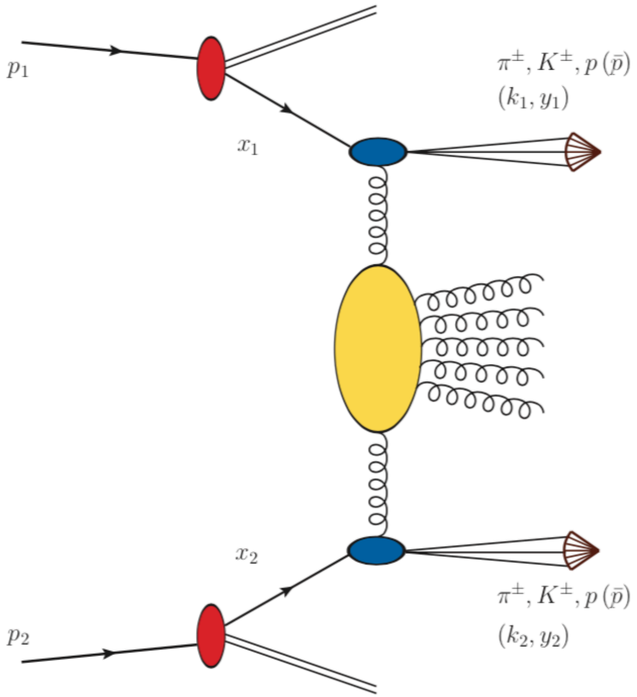
HEAVY-LIGHT HADRONS

From Higgs + jet to bound states

Di-hadron and hadron-jet correlations

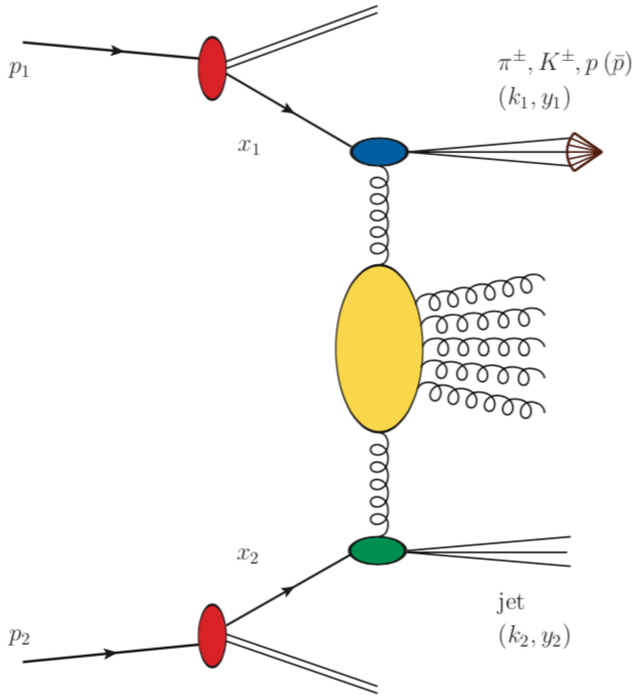
Inclusive di-hadron production

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



Inclusive hadron-jet production

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



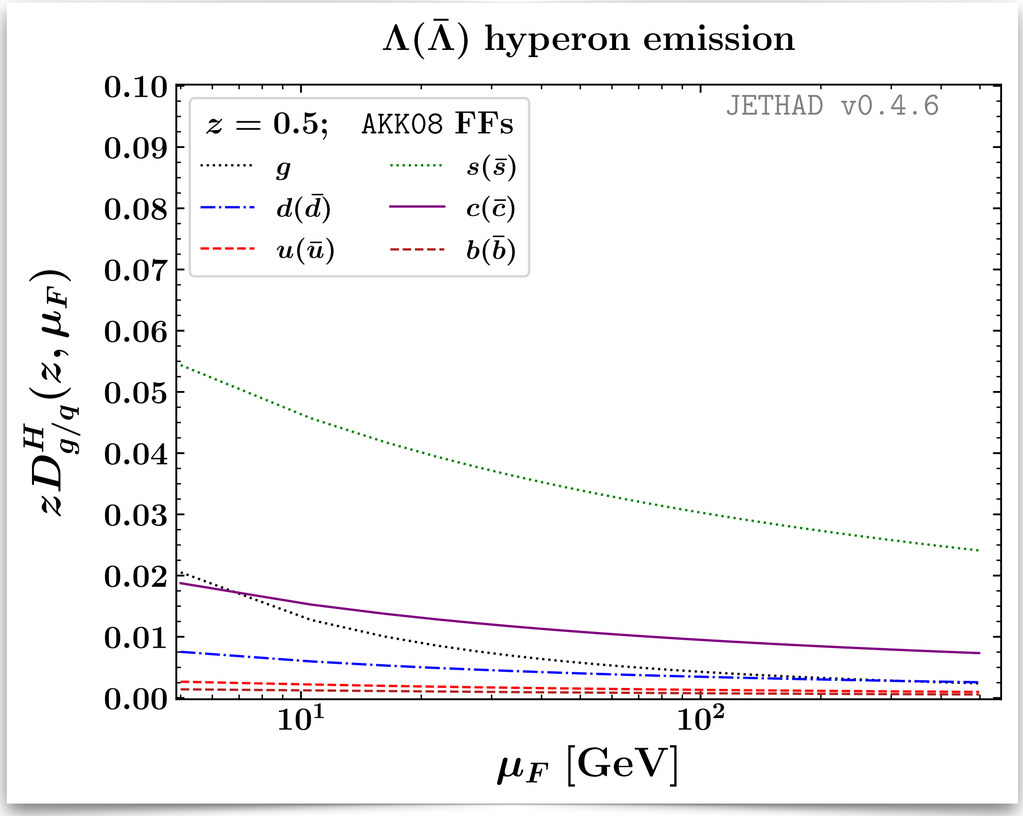
- NLO impact factors known $\Rightarrow$ full NLA BFKL analysis feasible
- PDFs + FFs at work (both), hadrons at smaller rapidities than jets (di-hadron)
- genuine *asymmetric* cuts in transverse momenta (hadron-jet)

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

Stabilizing effects of heavy-flavor fragmentation

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

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



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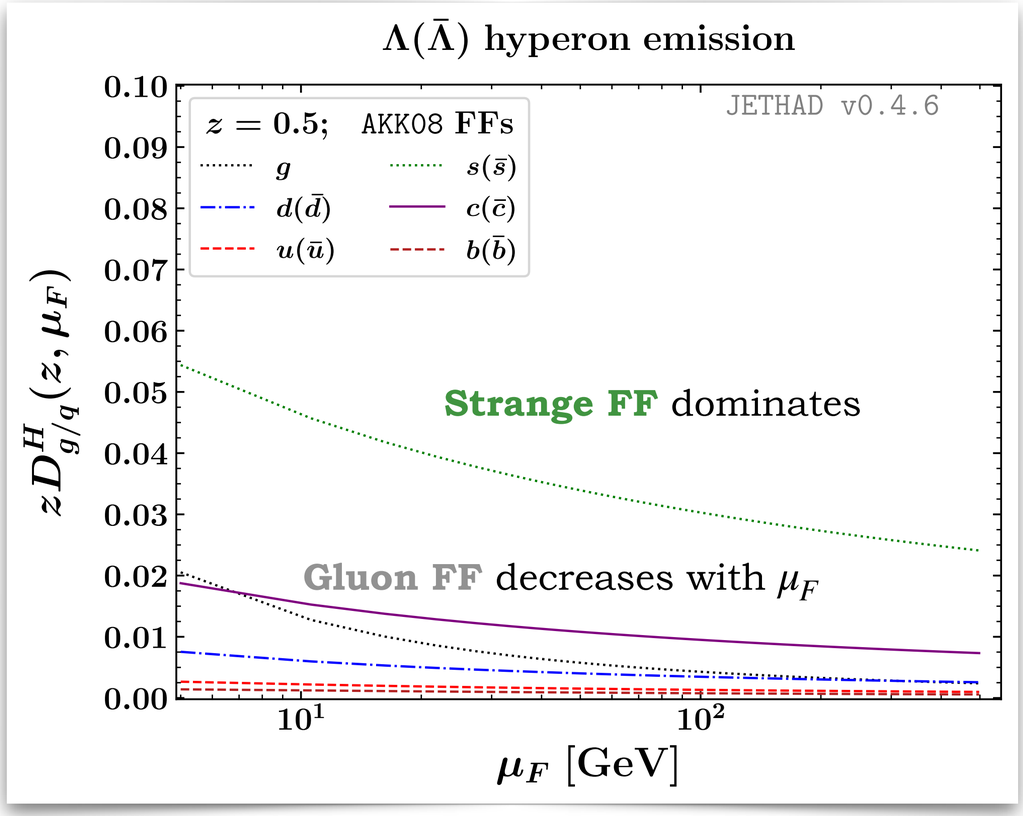

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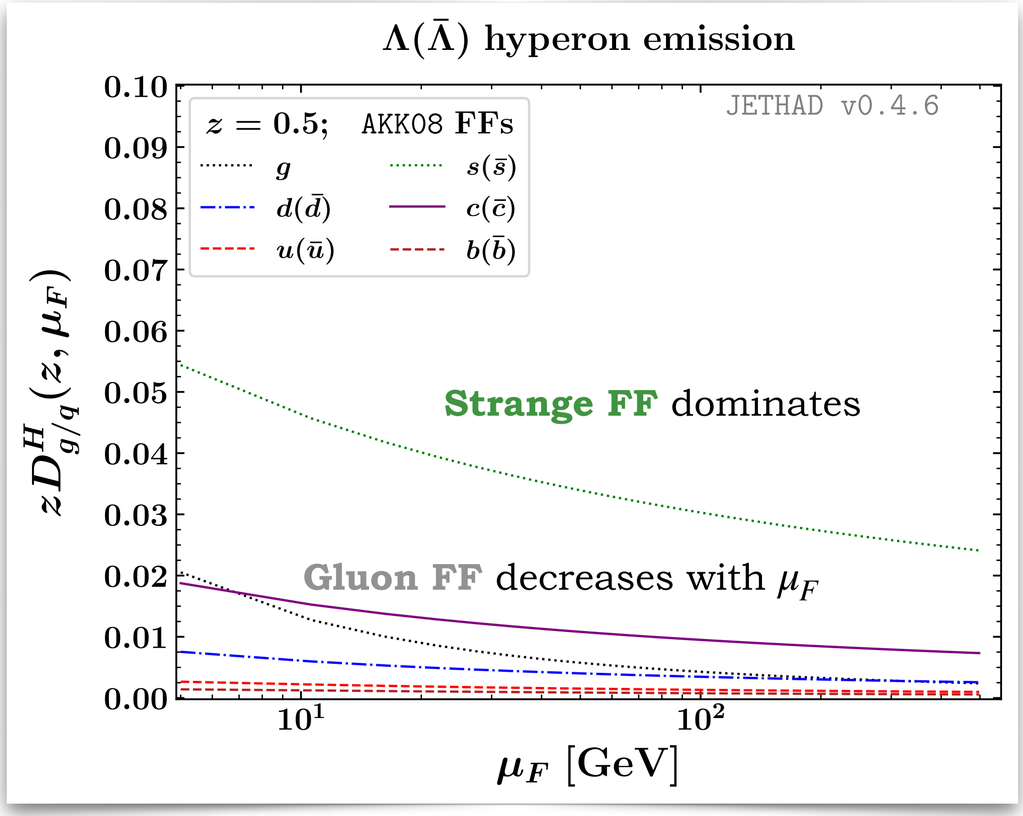
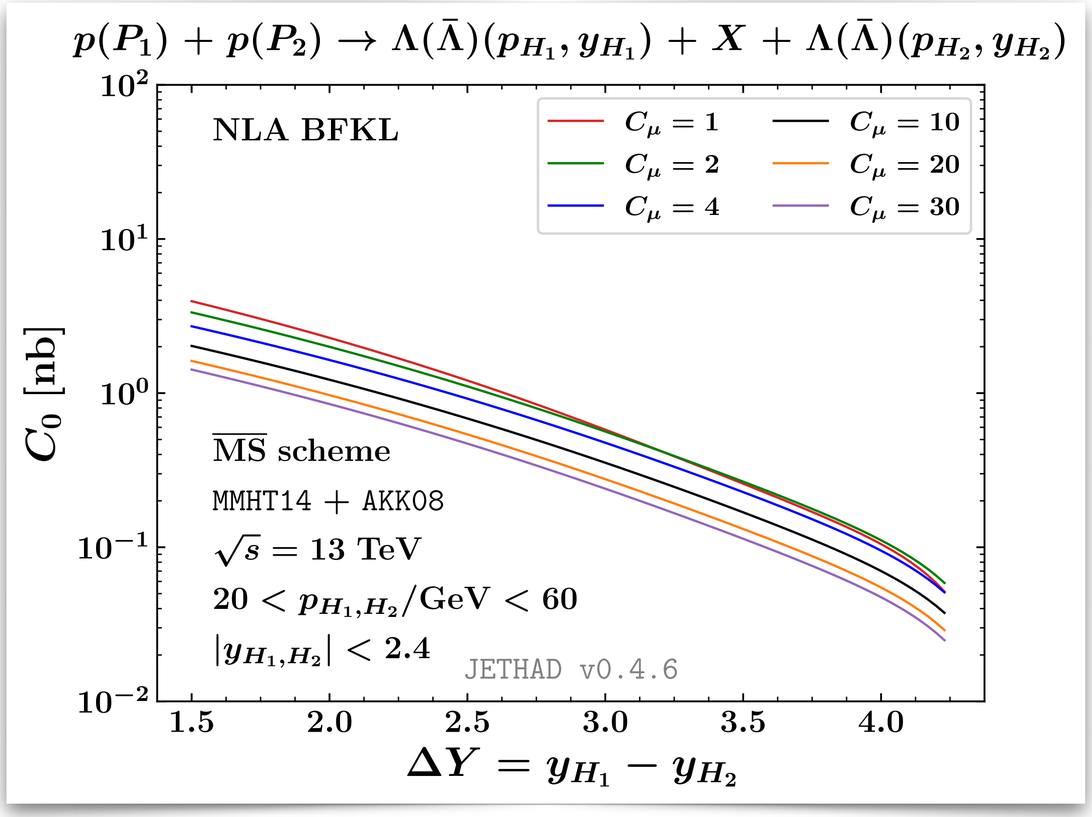




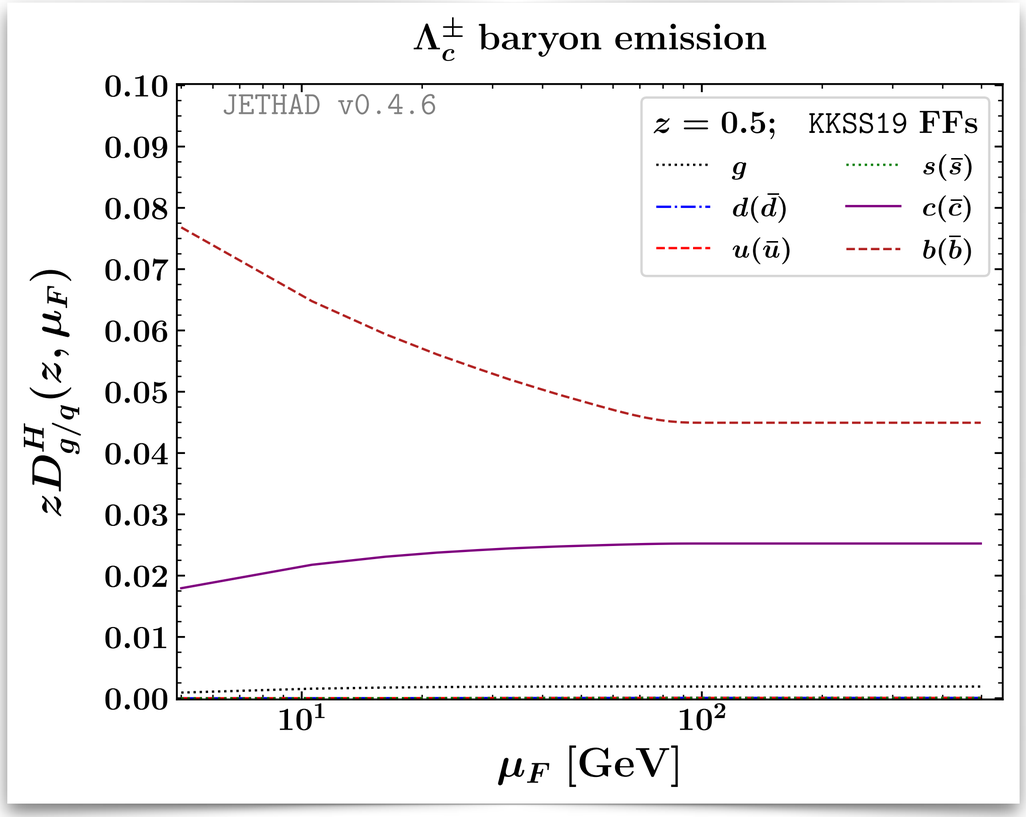
Rapidity distribution sensitive to scale variations

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

(cascade Ξ baryons) [F. G. C., Eur. Phys. J. C 83 (2023) 4, 332]

Stabilizing effects of heavy-flavor fragmentation

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



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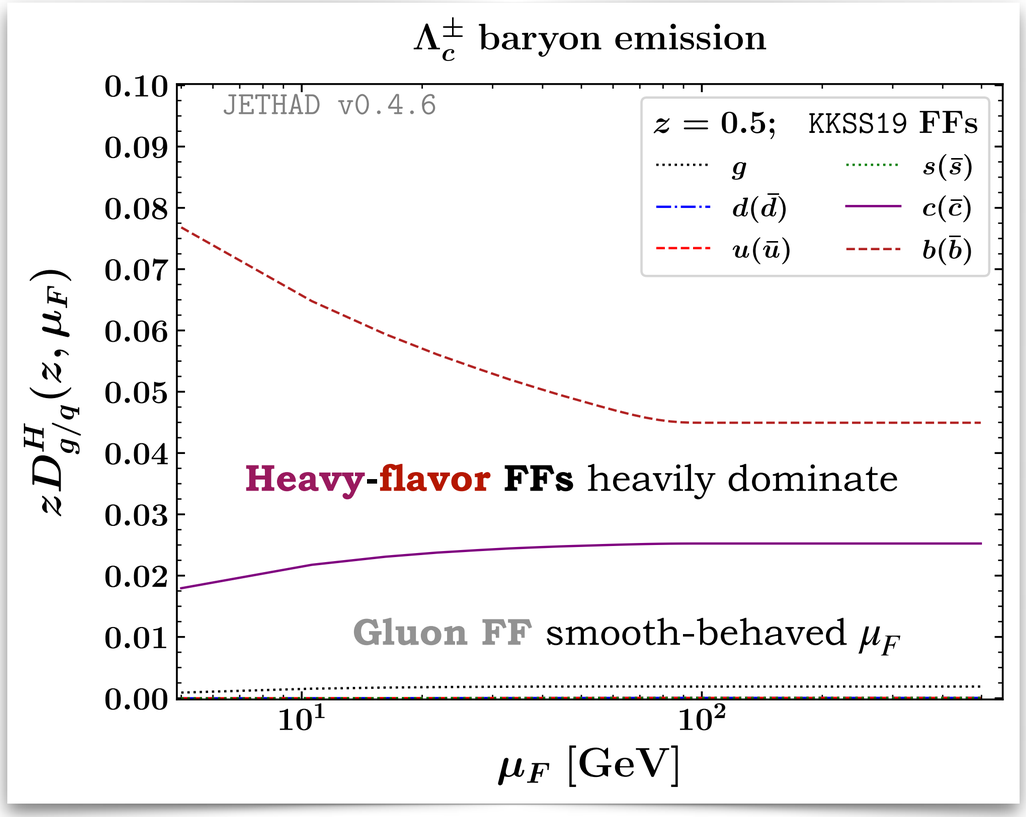

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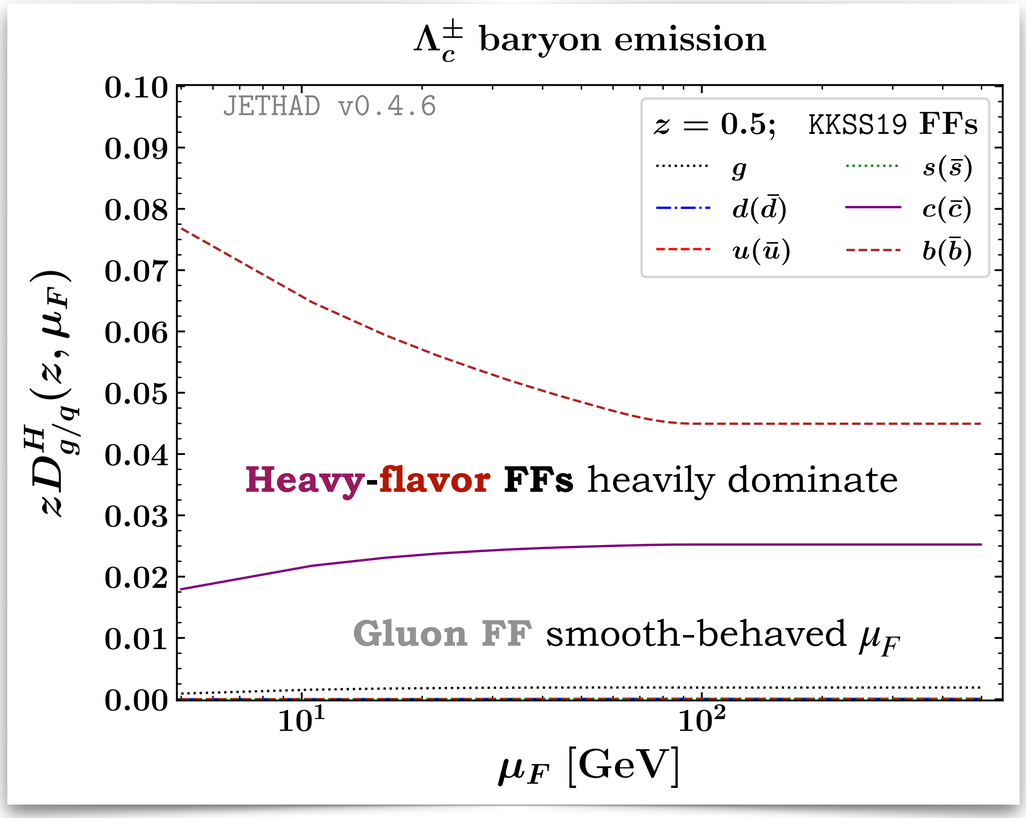
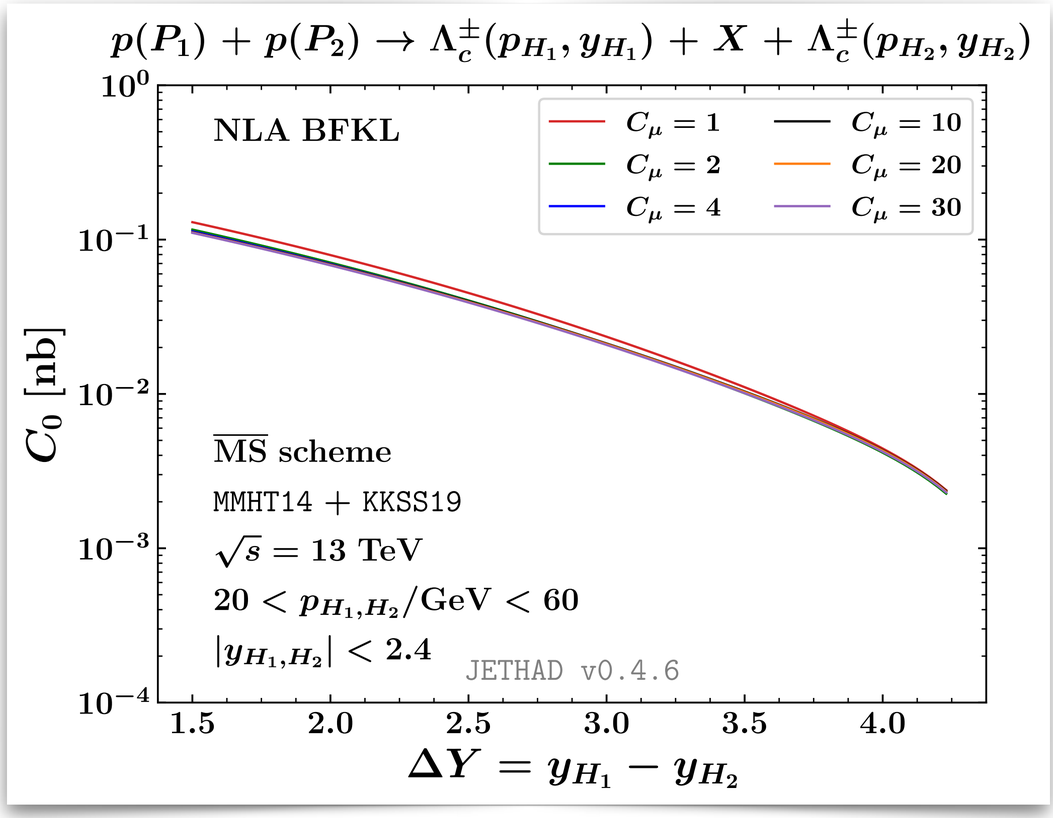




Rapidity distribution stable under scale variations

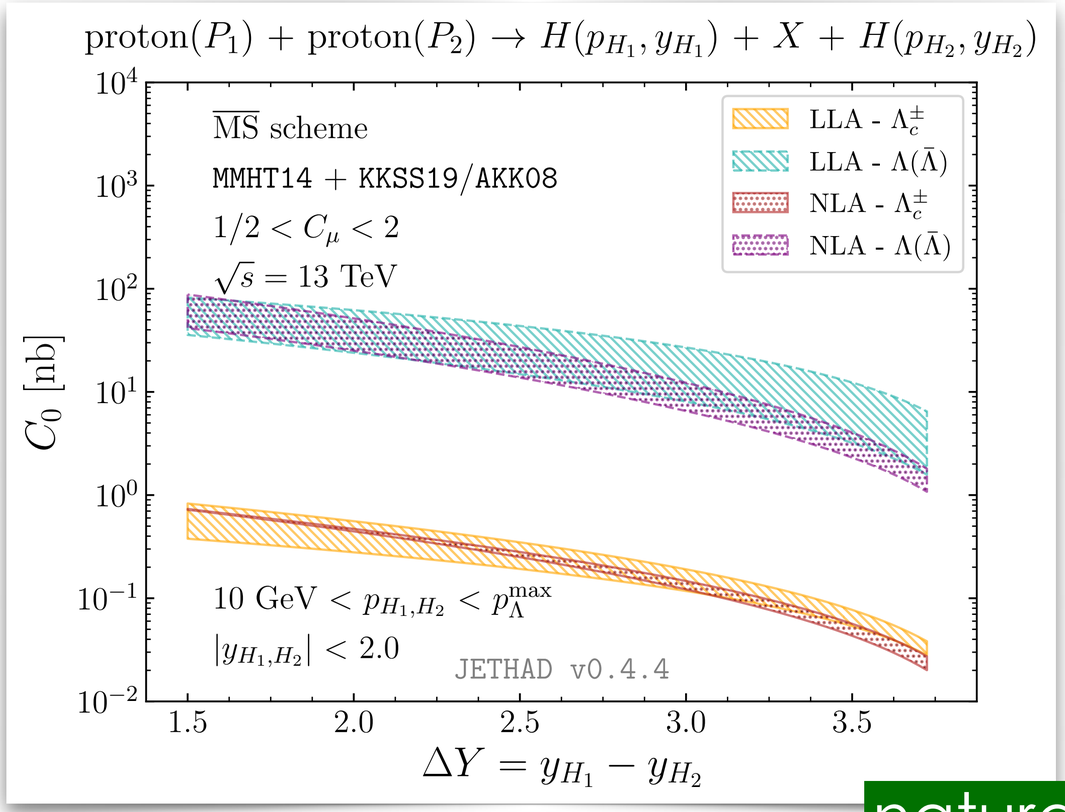
($B_c^{(*)}$ hadrons) 🔗 [F. G. C., Phys. Lett. B 835 (2022) 137554]

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

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

Stability under scale variations & NLL corrections

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



natural

Stability under scale variations & NLL corrections

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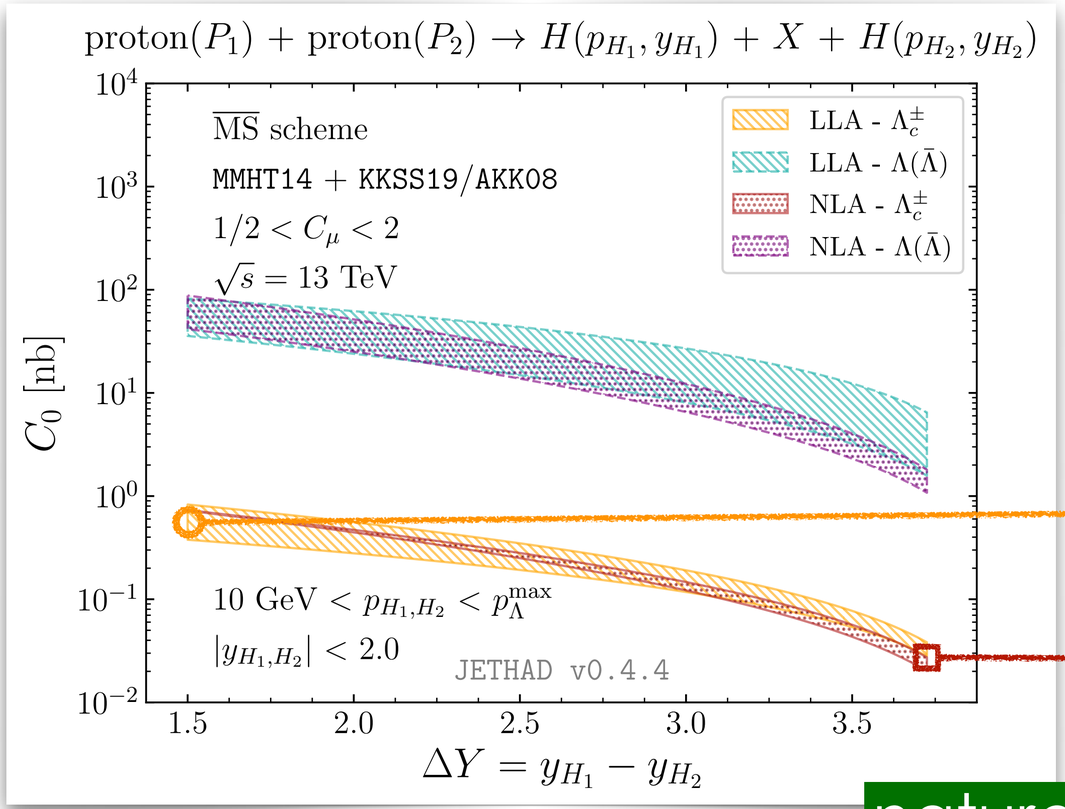

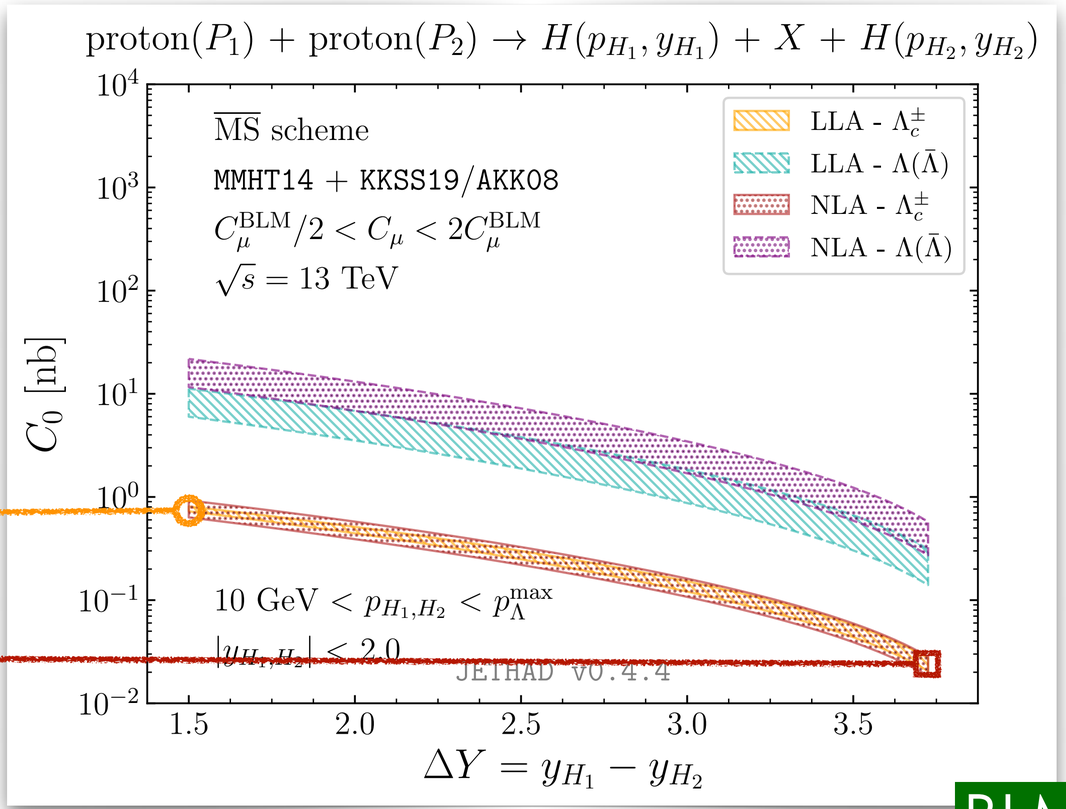

LL Λ_c

NLL Λ_c

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

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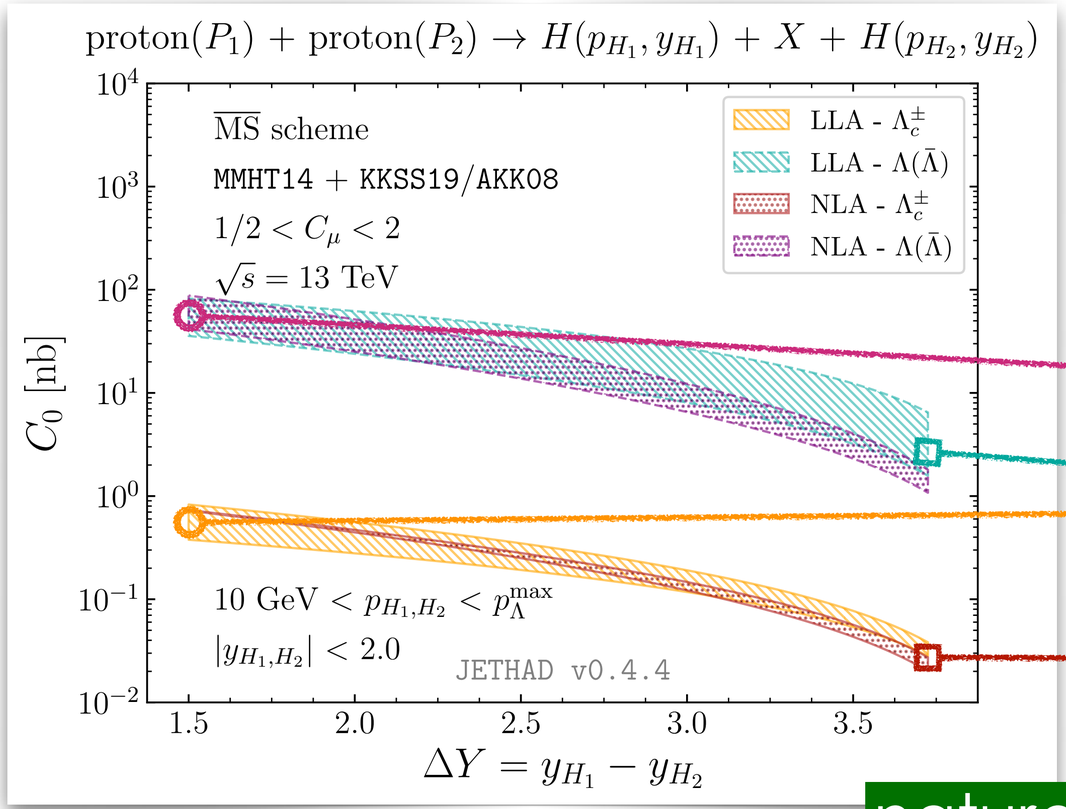
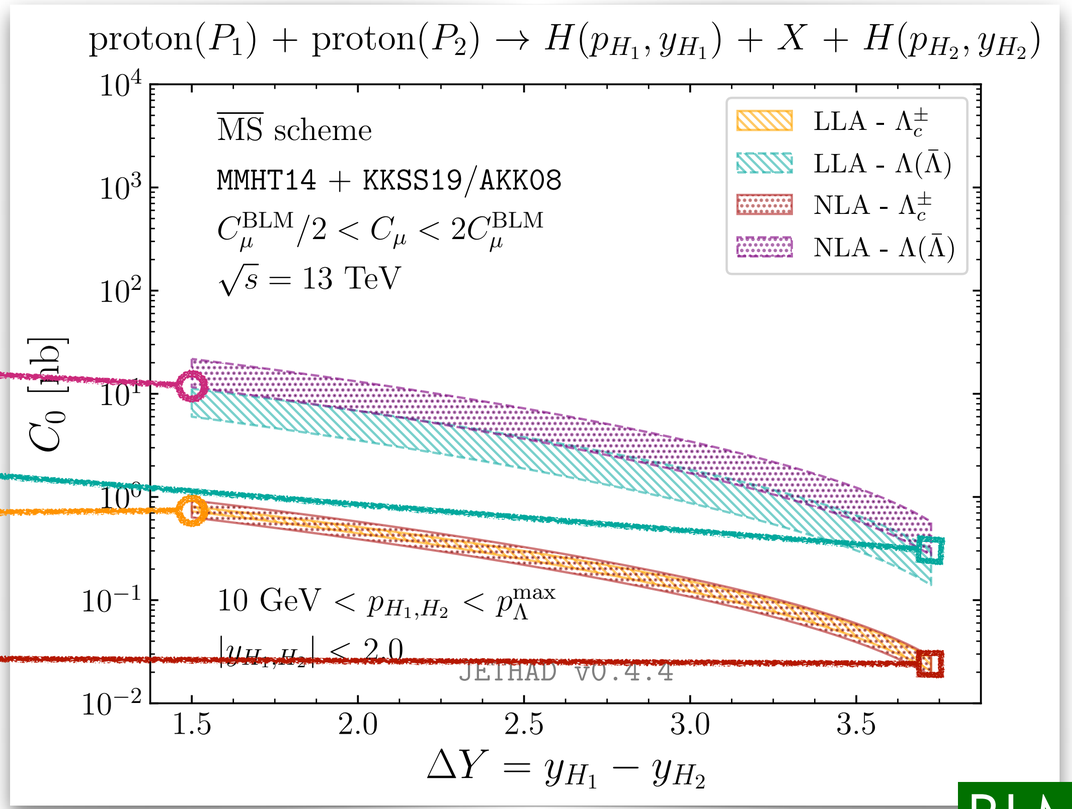


NLL Λ

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

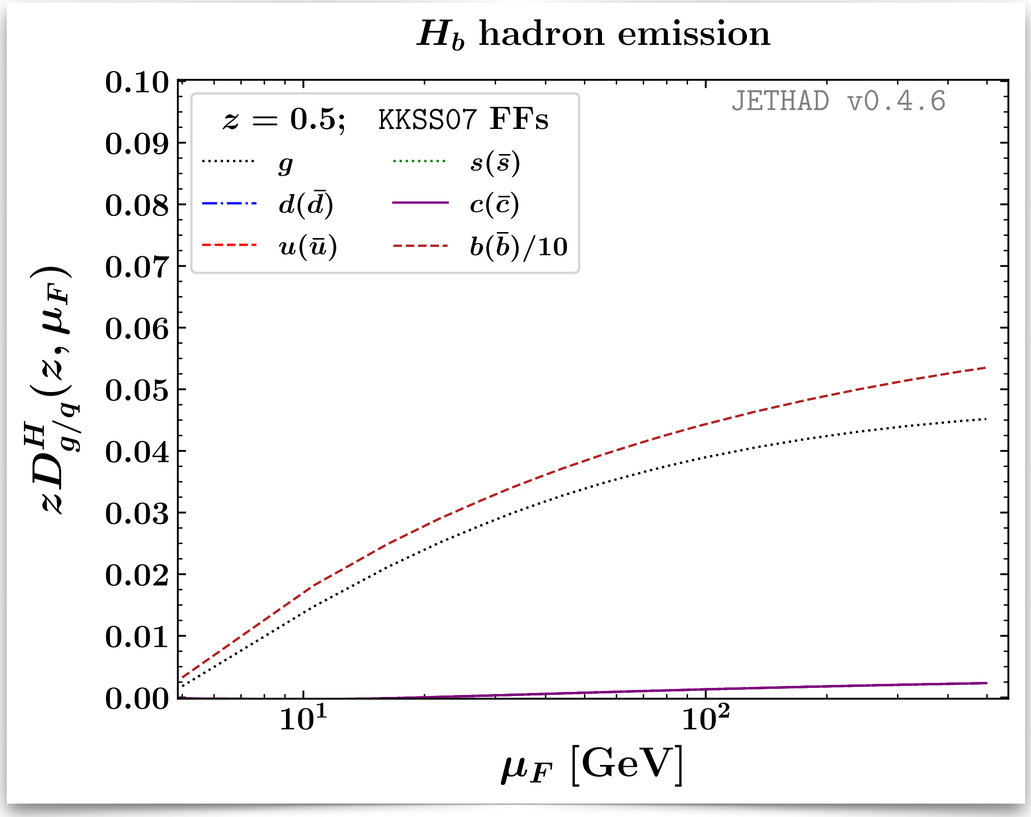
(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

(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]

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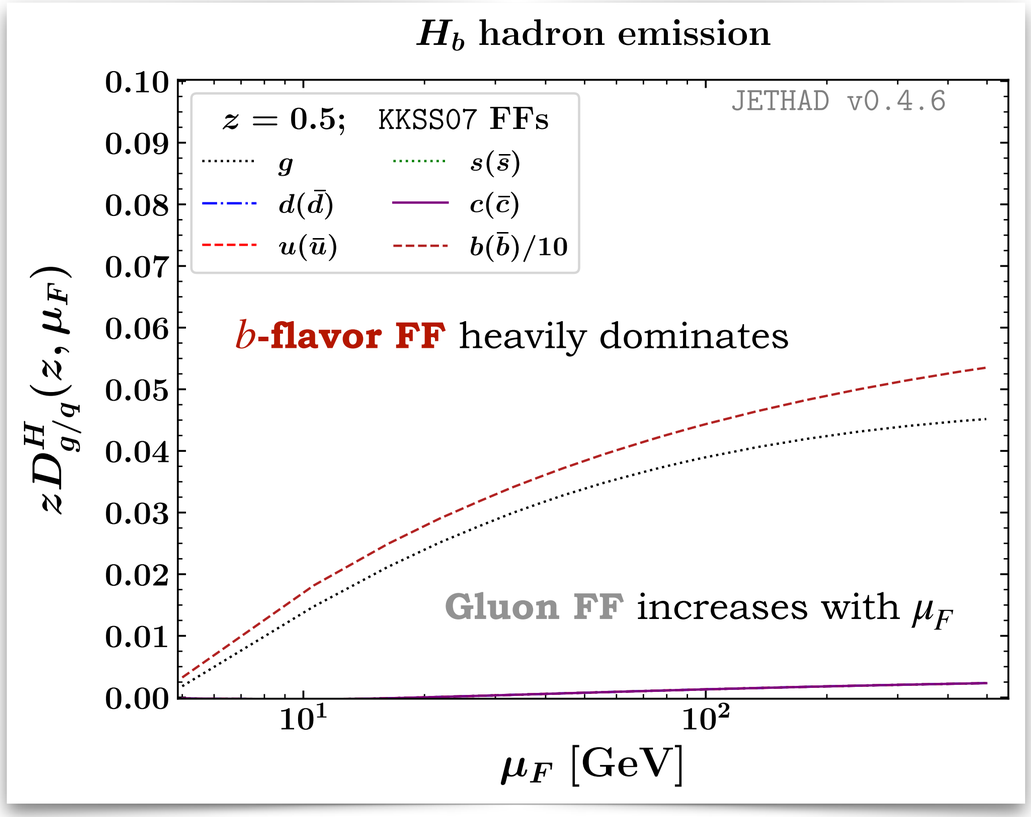

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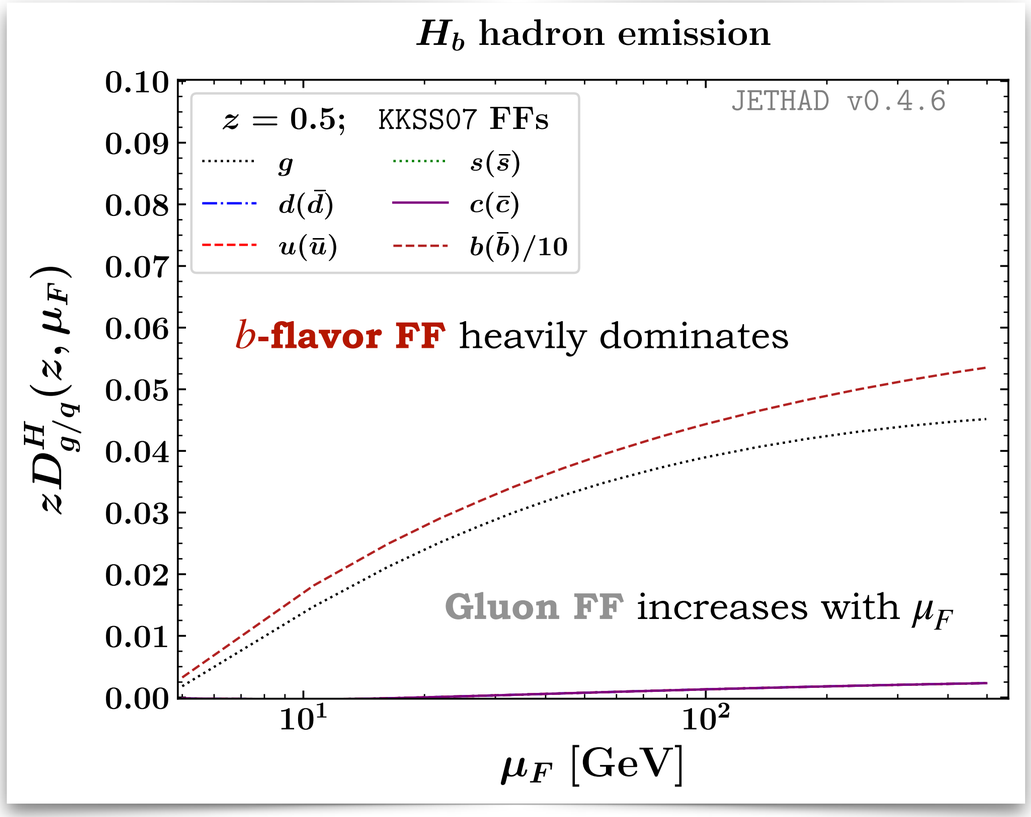

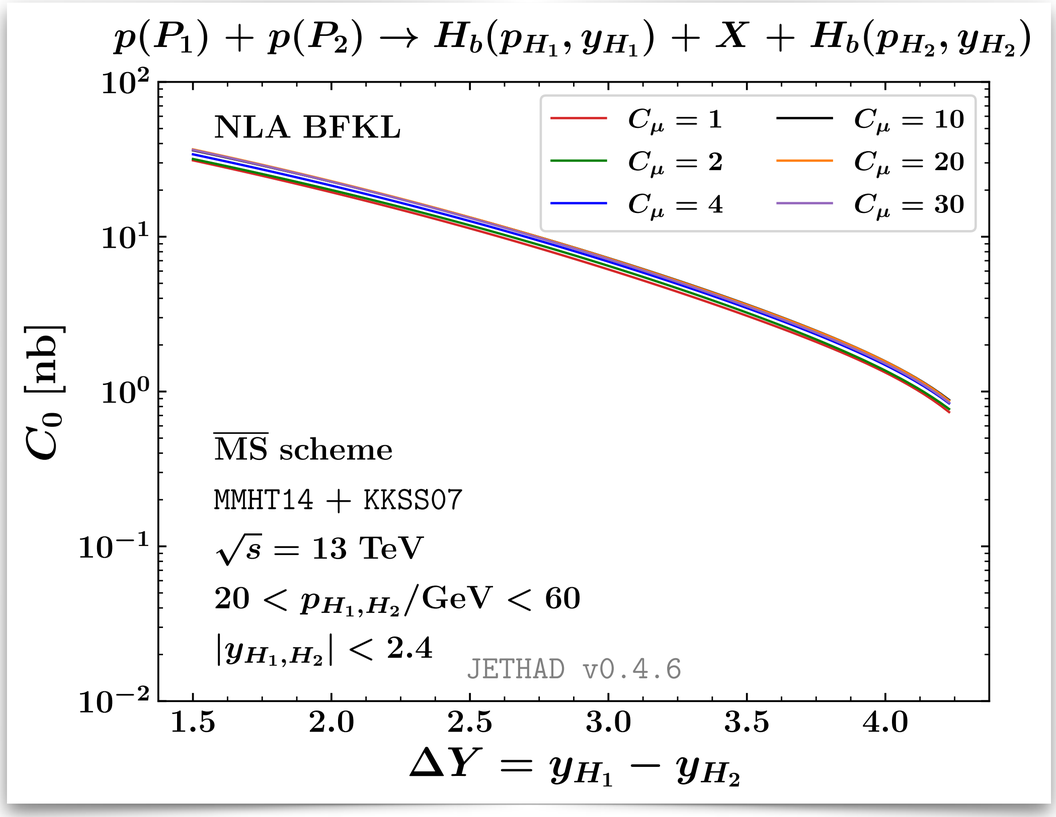

Rapidity distribution very stable under scale variations

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

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

Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

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

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

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- Forward-hadron NLO impact factor ⇒ a non-diagonal heavy-flavor channel open...

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

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

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

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

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

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

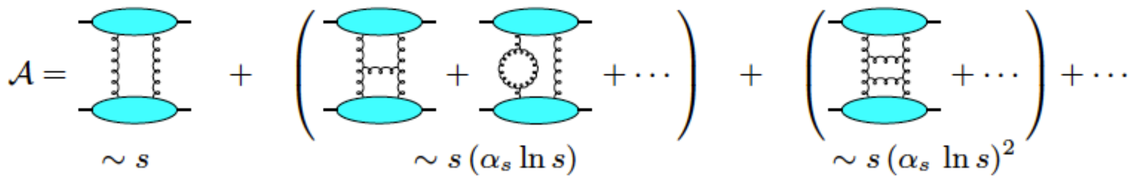
BASICS OF BFKL

The high-energy resummation

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

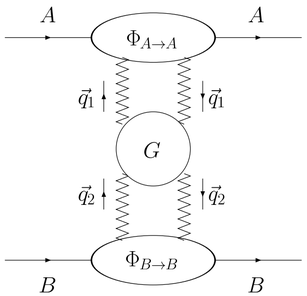
  based on ⟶ **gluon Reggeization**

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



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

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



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

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

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

The high-energy resummation

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

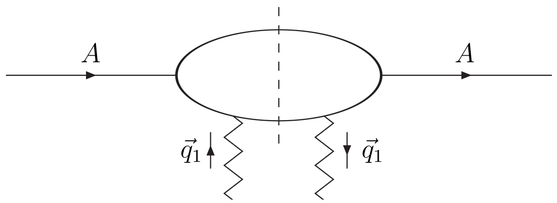
- **Green's function** is **process-independent** and takes care of the **energy dependence**

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

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

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

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



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

(**MN jets**) [B. Ducloué, L. Szymanowski, S. Wallon (2014); F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2015, 2016)]
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(**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)]
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The high-energy resummation

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

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

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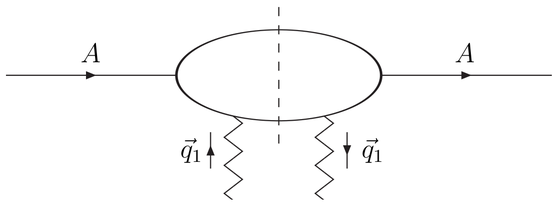

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¡NEW! NLO HIGGS

(κ_T space) 🔗 [M. Hentschinski et al. (2021)]

(κ_T & Mellin) 🔗 [F.G.C. et al. (2022)]

Gluon Reggeization in perturbative QCD

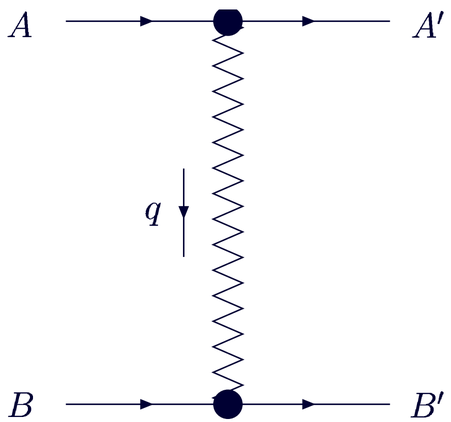
- ◇ Gluon quantum numbers in the t-channel: 8^- representation
- ◇ Regge limit: $s \simeq -u \to \infty$, t not growing with s

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

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

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

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



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

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

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

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

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

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

The high-energy resummation

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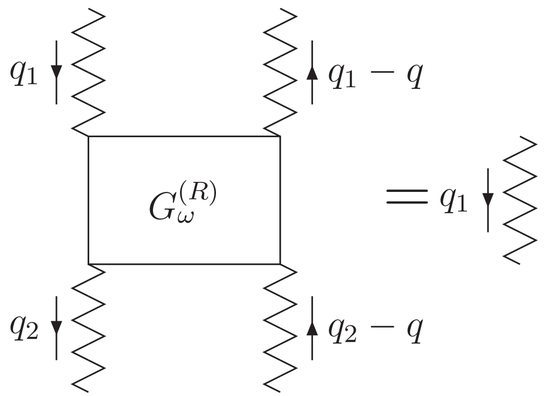
  [Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

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



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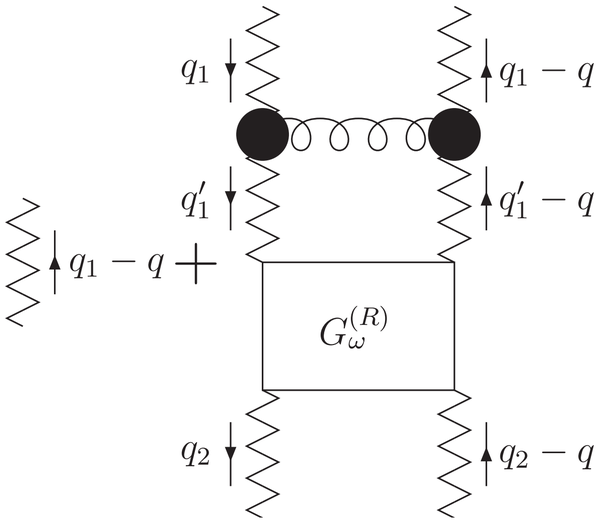

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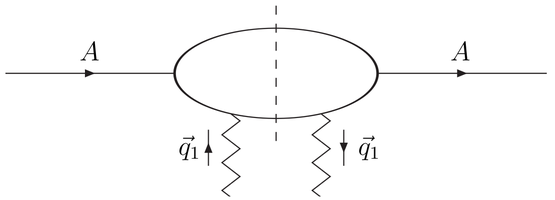


◇ **colliding partons**

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

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

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

◇ forward jet production

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

◇ forward identified hadron production

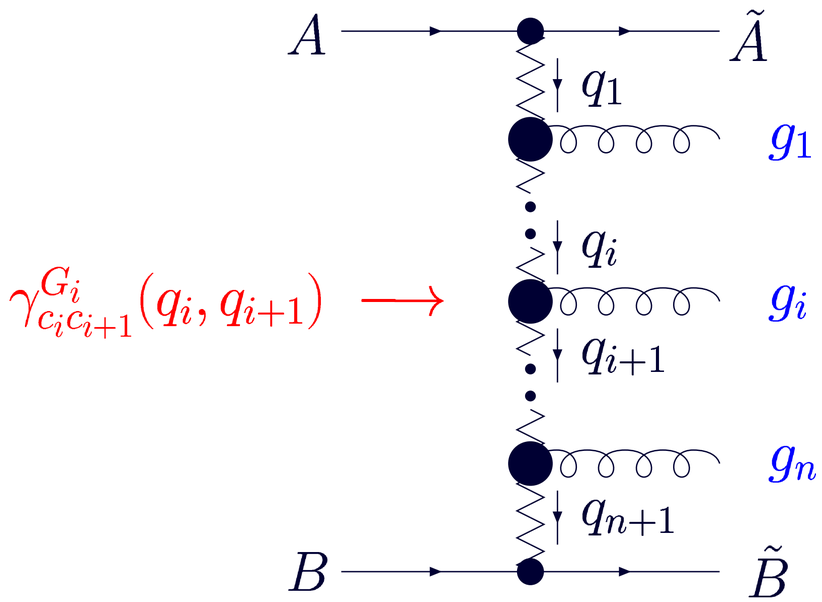
[D.Yu. Ivanov, A. Papa (2012)]

◇ $\gamma^* \longrightarrow \gamma^*$

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

BFKL in the LLA (I)

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



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

multi-Regge kinematics

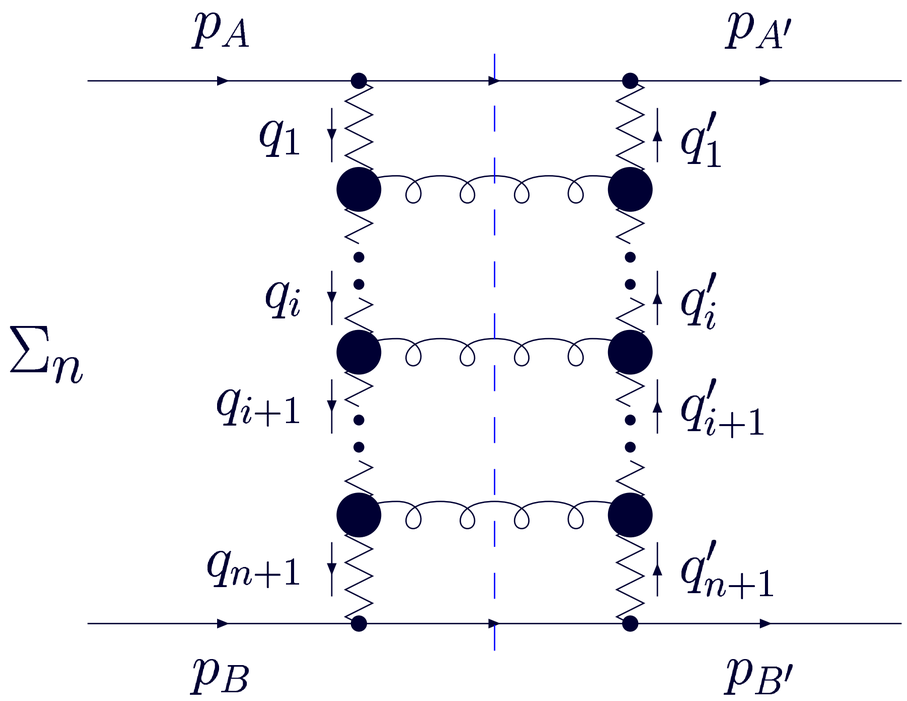
$$\mathrm{Re}\mathcal{A}^{\tilde{A}\tilde{B}+n}_{AB} = 2s\,\Gamma^{c_1}_{\tilde{A}A}\left(\prod_{i=1}^{n}\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1})\left(\frac{s_i}{s_R}\right)^{\omega(t_i)}\frac{1}{t_i}\right)\frac{1}{t_{n+1}}\left(\frac{s_{n+1}}{s_R}\right)^{\omega(t_{n+1})}\Gamma^{c_{n+1}}_{\tilde{B}B}$$

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

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

BFKL in the LLA (II)

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



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

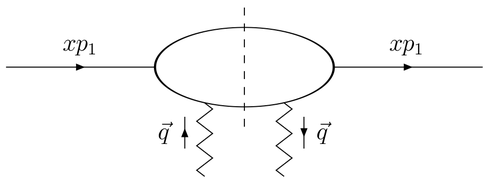
The 8^- color representation is important for the bootstrap, i.e. the consistency between the above amplitude and that with one Reggeized gluon exchange

Hybrid factorization at work

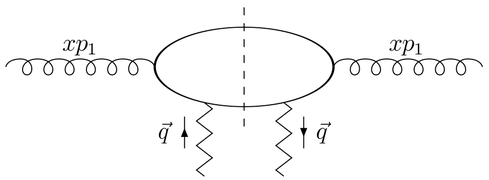
Forward-jet impact factor

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

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

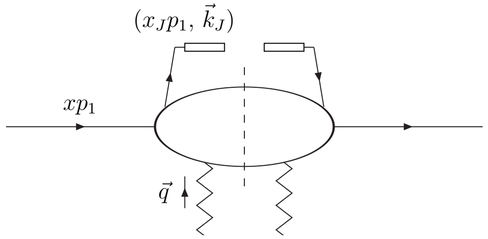


quark vertex

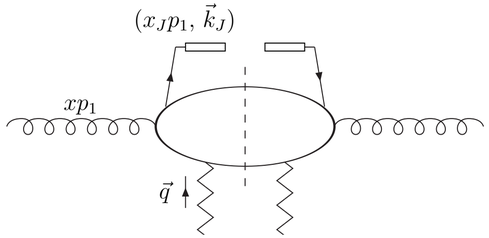


gluon vertex

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



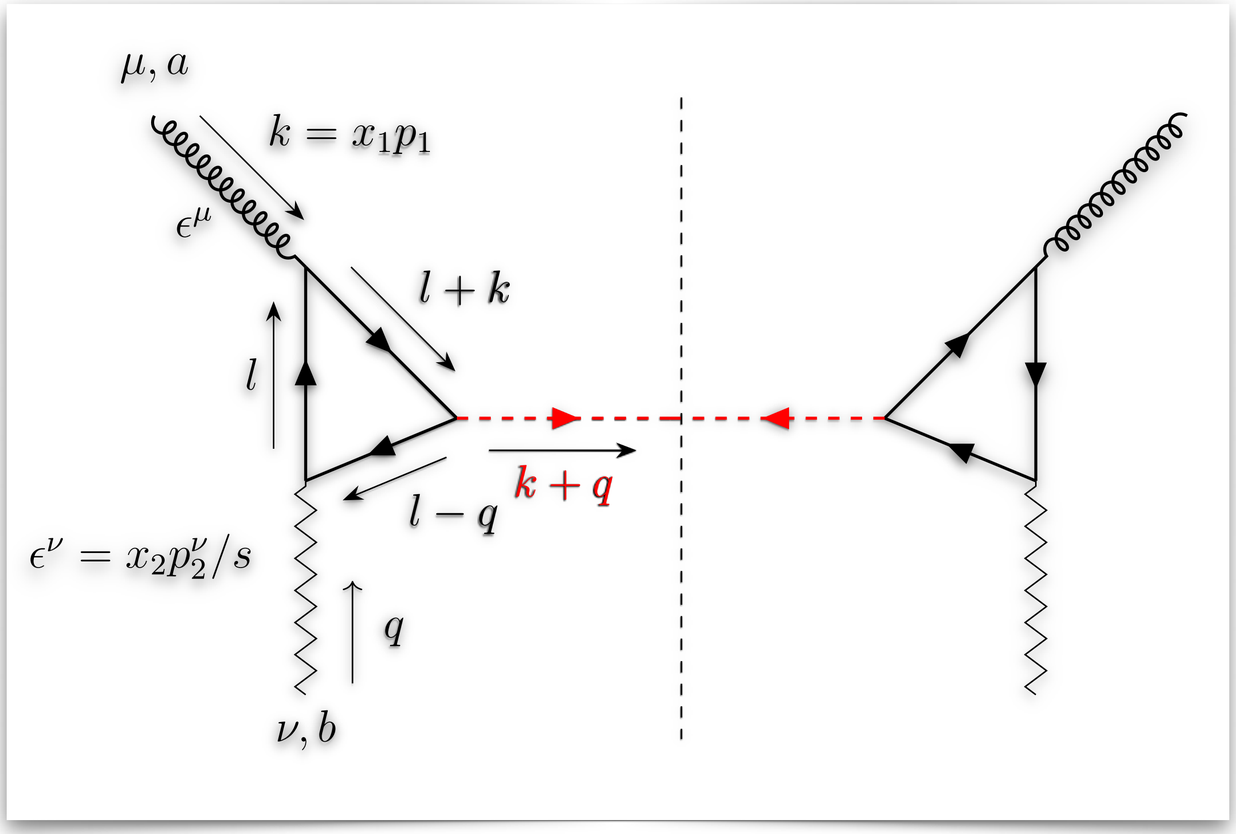
quark jet vertex



gluon jet vertex

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

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

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

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

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

Forward-jet NLO-RG impact factor

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

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

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

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

Inclusive Higgs + jet: NLL/NLO* azimuthal coefficients

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

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

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

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