

The emerging importance of high energy logarithms for LHC studies

Sebastian Jaskiewicz

with High Energy Jets (HEJ) collaborators:

J. Andersen, A. Maier, A. Papaefstathiou, M. Rosca, G. Ruisi, J. Smillie

High Precision for Hard Processes 2026

Karlsruhe, Germany

9th October 2026

Introduction

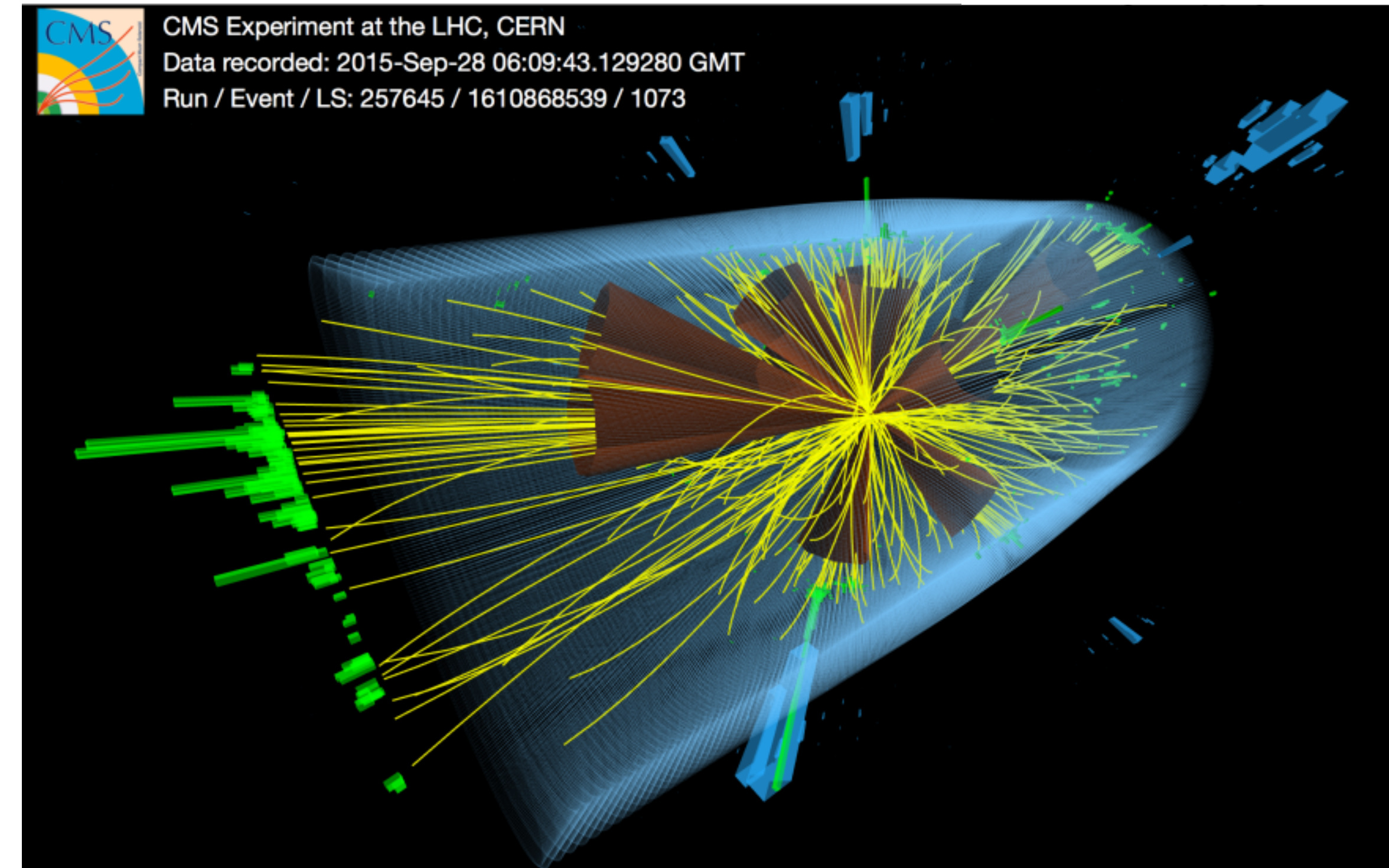
Control over logarithmic corrections is critical in describing the LHC phenomena.

Transverse momentum hierarchies, collinear splittings, MPI, and hadronization described by parton showers.

See talks Daniel Reichelt, Ignacio Borsa, Joanne Roper, Lois Flower..

All-order control is also needed over the large high-energy logarithms:

$$\alpha_s \ln\left(\frac{m_{ij}^2}{p_T^2}\right) \sim \alpha_s \Delta y$$



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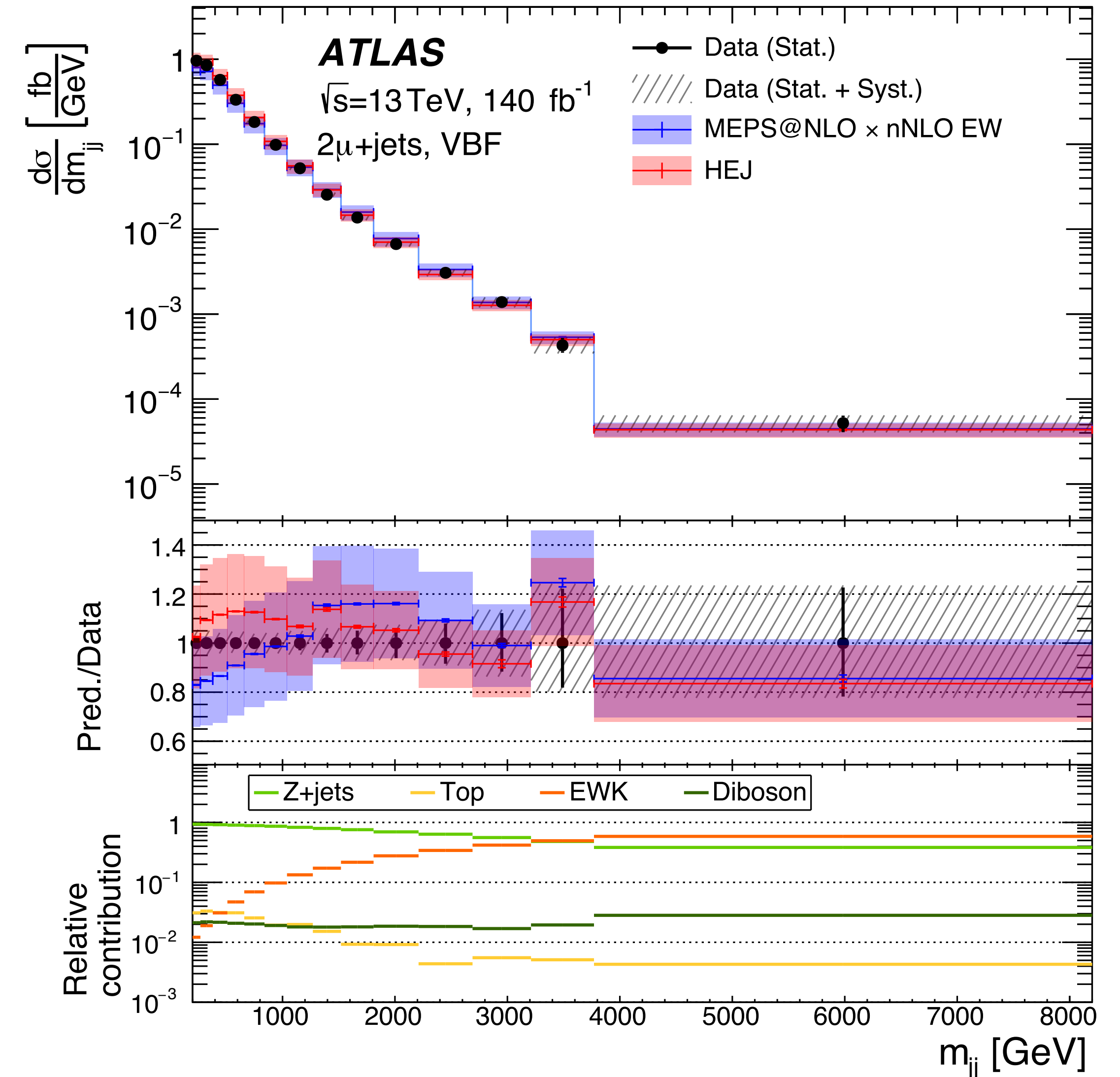
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High Energy Jets (HEJ)



[ATLAS, 2403.02793]

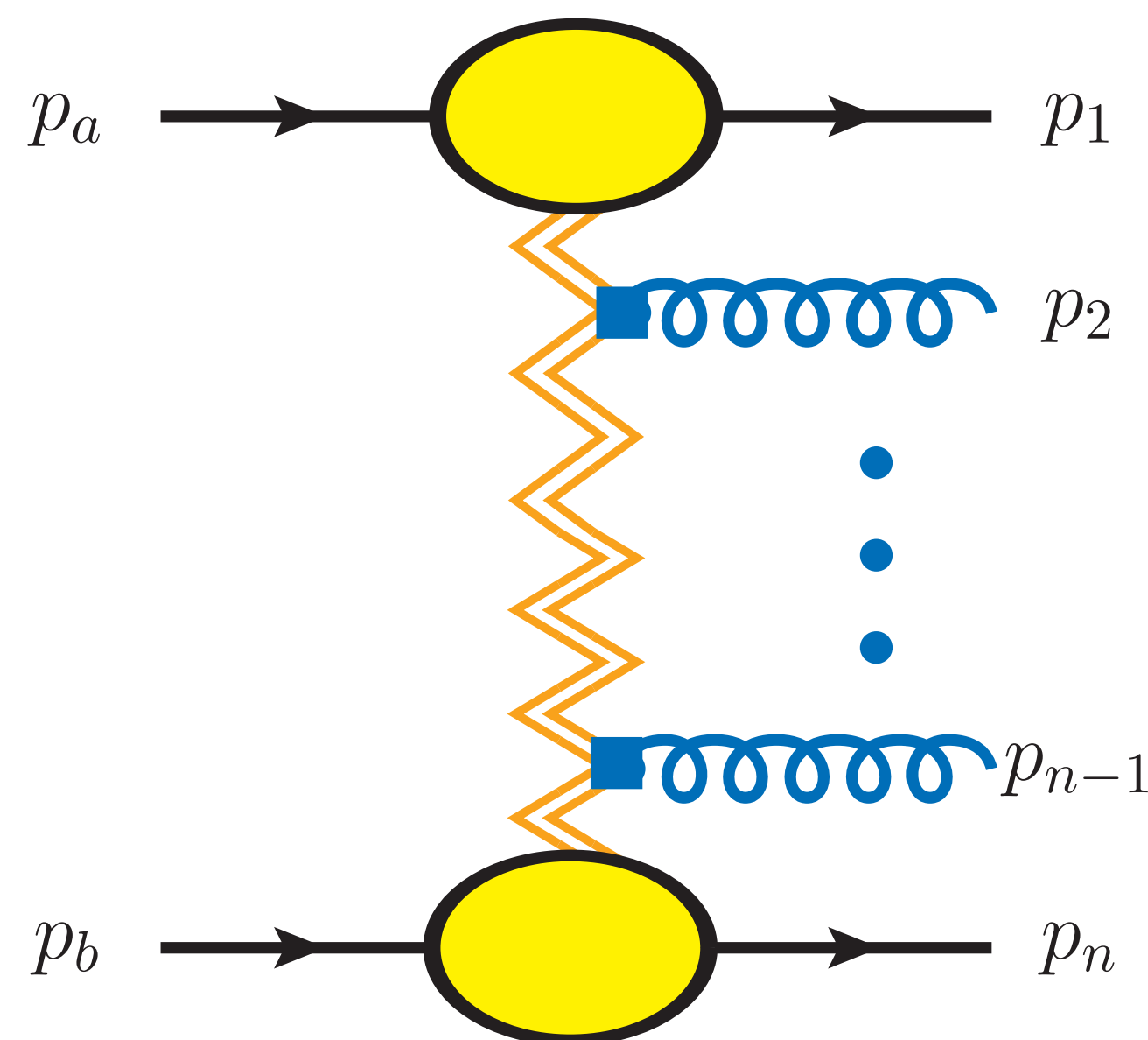
NLO + PS from MEPS@NLO
 [S. Höche, F. Krauss, M. Schönherr,
 F. Siegert, 1207.5030]

High Energy Jets (HEJ)

The High Energy Jets is built to describe effects from hard, wide angle emissions.

HEJ resums large logarithms in s/t , the same as BFKL equation

[J. Andersen, J. Smillie, 0908.2786]
 [J. Andersen, J. Smillie, 0910.5113]
 [J. Andersen, J. Smillie, 1101.5394]
 [J. Andersen, J. Black, H. Brooks, B. Ducloue,
 M. Heil, A. Maier, J. Smillie, 2110.15692]
 [J. Andersen, B. Duclou'e, H. Hassan,
 C. Elrick, A. Maier, G. Nail, J. Paltrinieri,
 A. Papaefstathiou, J. Smillie, 2303.15778]



High-energy limit for $2 \rightarrow n$ scattering. We are interested in the **Multi-Regge Kinematics (MRK)**

$$\hat{s} \gg m_{ij}^2 \gg p_{i\perp}^2 \quad m_{ij}^2 = (p_i + p_j)^2$$

The setup corresponds to a strong ordering in rapidities

$$y_1(p_1) \ll y_2(p_2) \ll \dots \ll y_n(p_n) \quad |p_{i\perp}| \sim \text{finite}$$

- Systematic classification of leading and sub-leading corrections based on Regge theory scaling
- Matrix elements are factorised into currents that retain analytic properties such as crossing symmetry
- Integration over loop momenta for virtual particles (Lipatov ansatz) and integration over phase-space for real emissions (Lipatov vertices)

High Energy Jets

Latest release: HEJ 2.4

[A. Maier, G. Ruisi, 2608.21195]

HEJ 2 overview: [arXiv:2303.15778](#)

[J. Andersen, B. Ducloue, H. Hassan, C. Elrick, A. Maier, G. Nail, J. Paltrinieri, A. Papaefstathiou, J. Smillie]

The HEJ code release is available at:

<https://hej.hepforge.org/>

Processes:

- pure multijet production, ≥ 2 jets
- gluon-fusion production of a Higgs boson with jets, H and ≥ 1 jets
- production of a W boson with jets, $W(\rightarrow l\nu)$ and ≥ 2 jets
- production of jets with a charged lepton-antilepton pair, via a virtual Z boson and/or photon
- production of two same-sign W bosons with jets, $W^\pm W^\pm$ and ≥ 2 jets
- production of jets with a neutrino-antineutrino pair via a virtual Z boson

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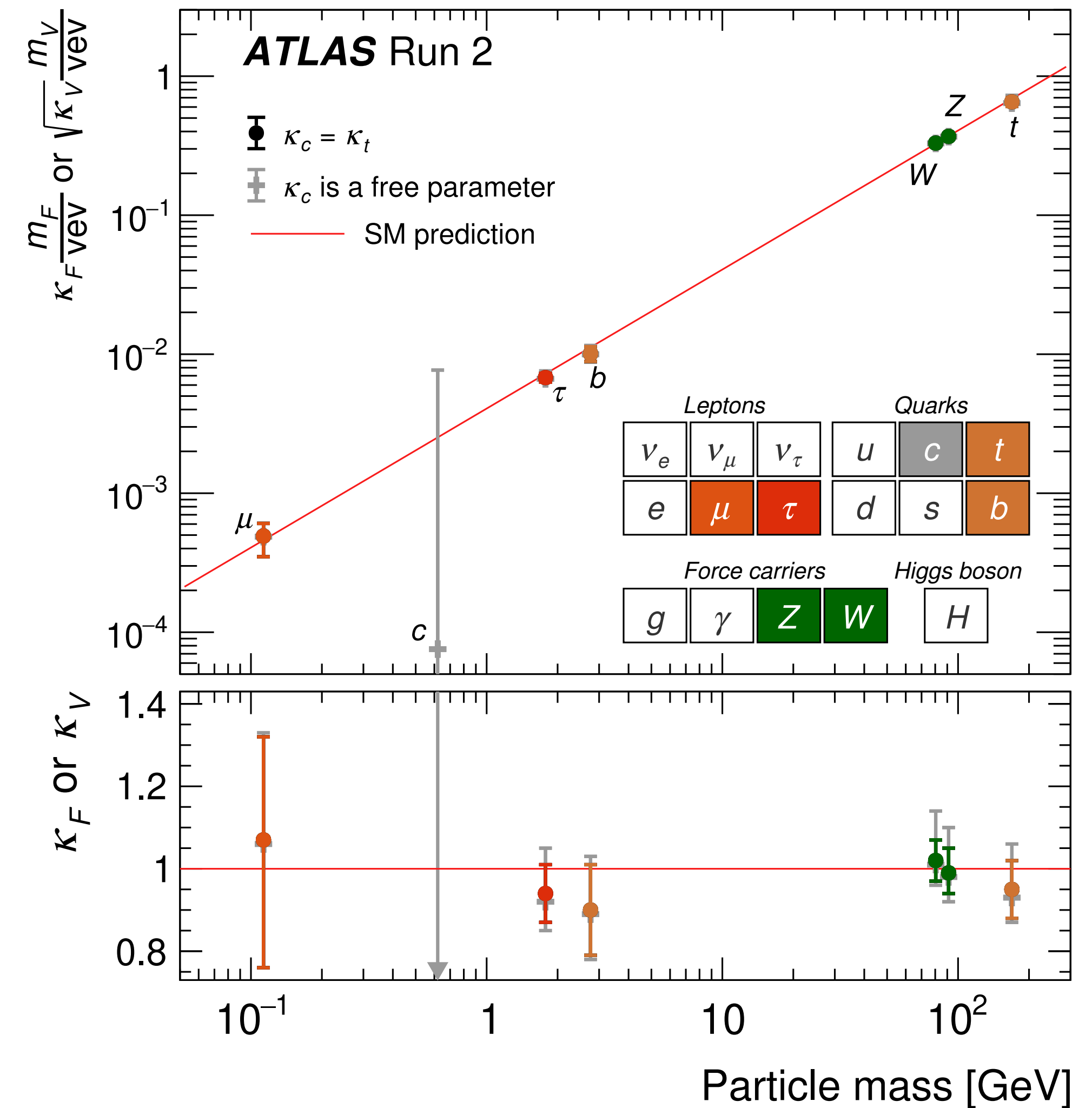
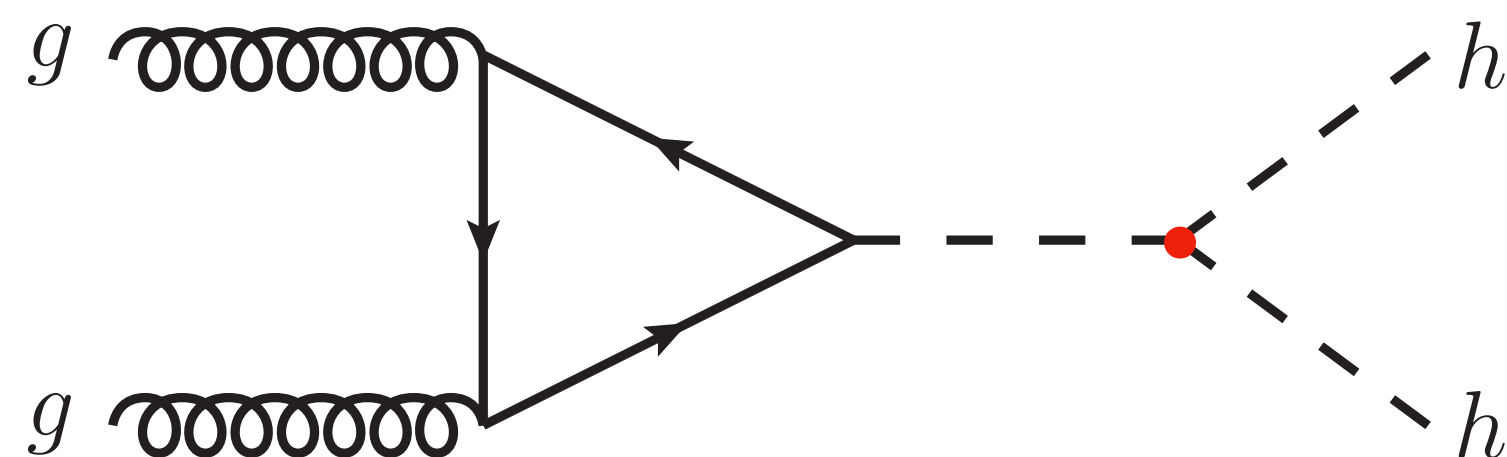
Recent progress:

- Including the photon plus jets process
[J. Andersen, A. Maier, M. Rosca, G. Ruisi, 2506.17438]
- Higgs Boson plus quark pair production for di-Higgs studies
[A. Maier, G. Ruisi, 2608.21195]
- $pp \rightarrow Z(\rightarrow e^+e^-) + \text{jets}$
[J. Andersen, S. Jaskiewicz, A. Maier, J. Smillie, 2609.36023]

Higgs couplings

- Top-quark Yukawa coupling first directly observed in 2018 ($t\bar{t}H$)
[ATLAS Collaboration, 1806.00425] [CMS Collaboration, 1804.02610]
- Higgs coupling to second generation leptons measured in 2020 ($H \rightarrow \mu^+\mu^-$)
[ATLAS Collaboration, 2007.07830] [CMS Collaboration, 2009.04363]
- Higgs coupling to second generation quarks measured in 2022 ($H \rightarrow c\bar{c}$)
[ATLAS Collaboration, 2201.11428] [CMS Collaboration, 2205.05550]
- The Higgs self-coupling is yet to be measured

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \quad m_H^2 = 2\lambda v^2$$

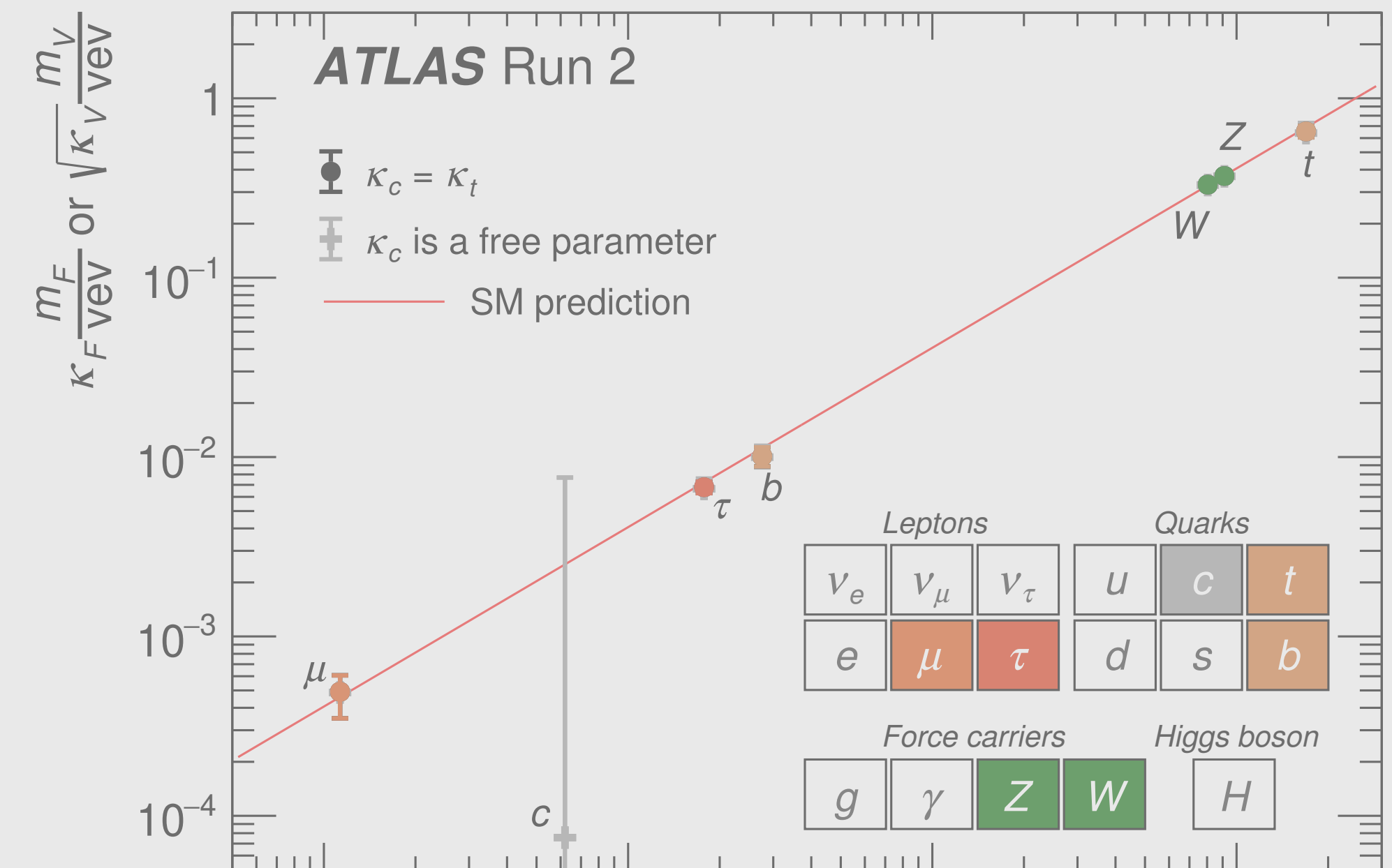
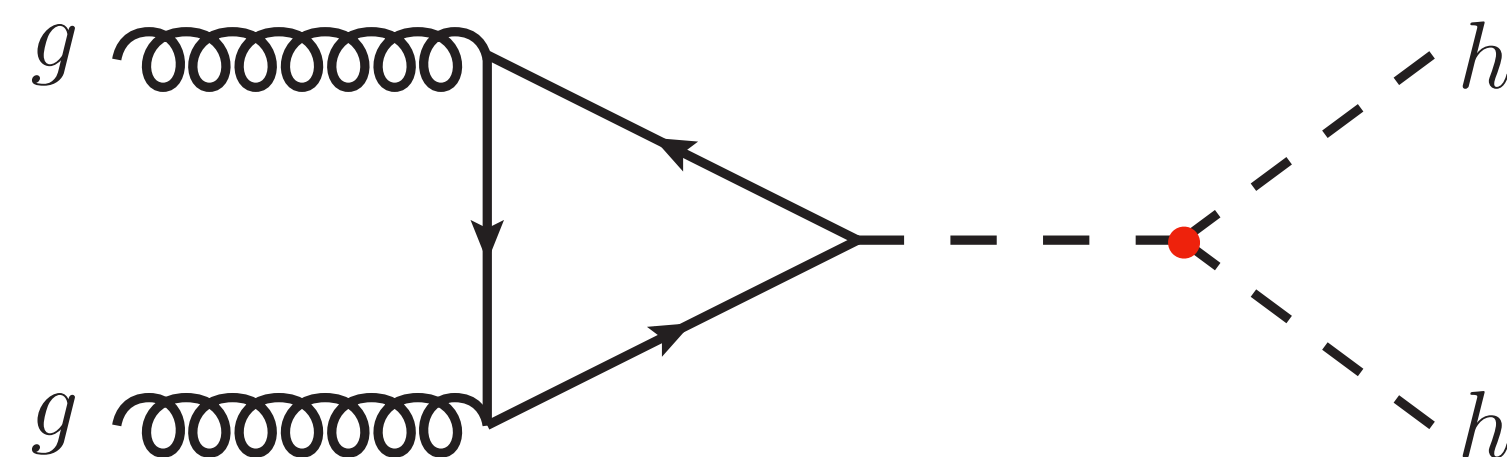


[ATLAS Collaboration, CERN-EP-2022-057, 2207.00092]

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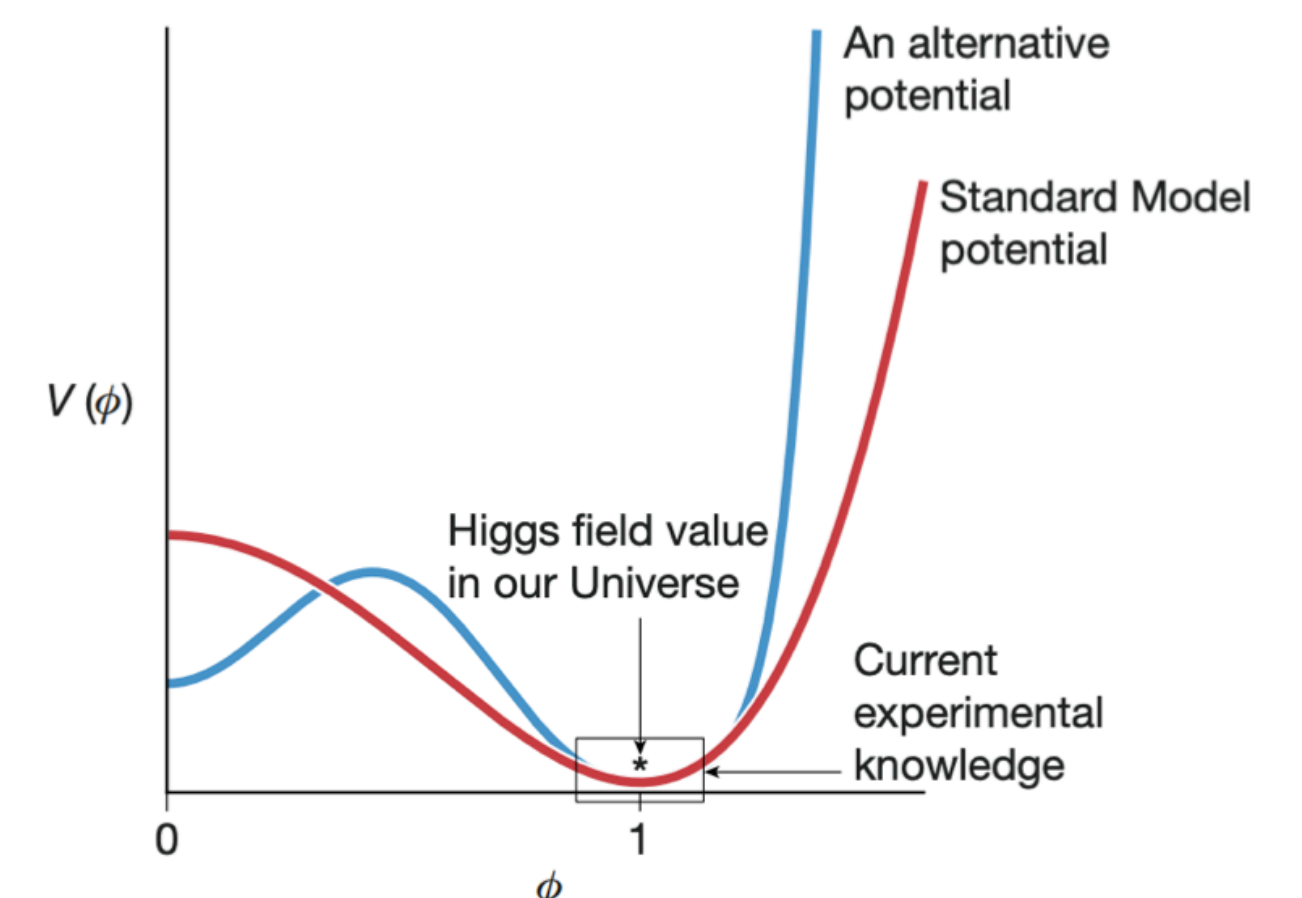
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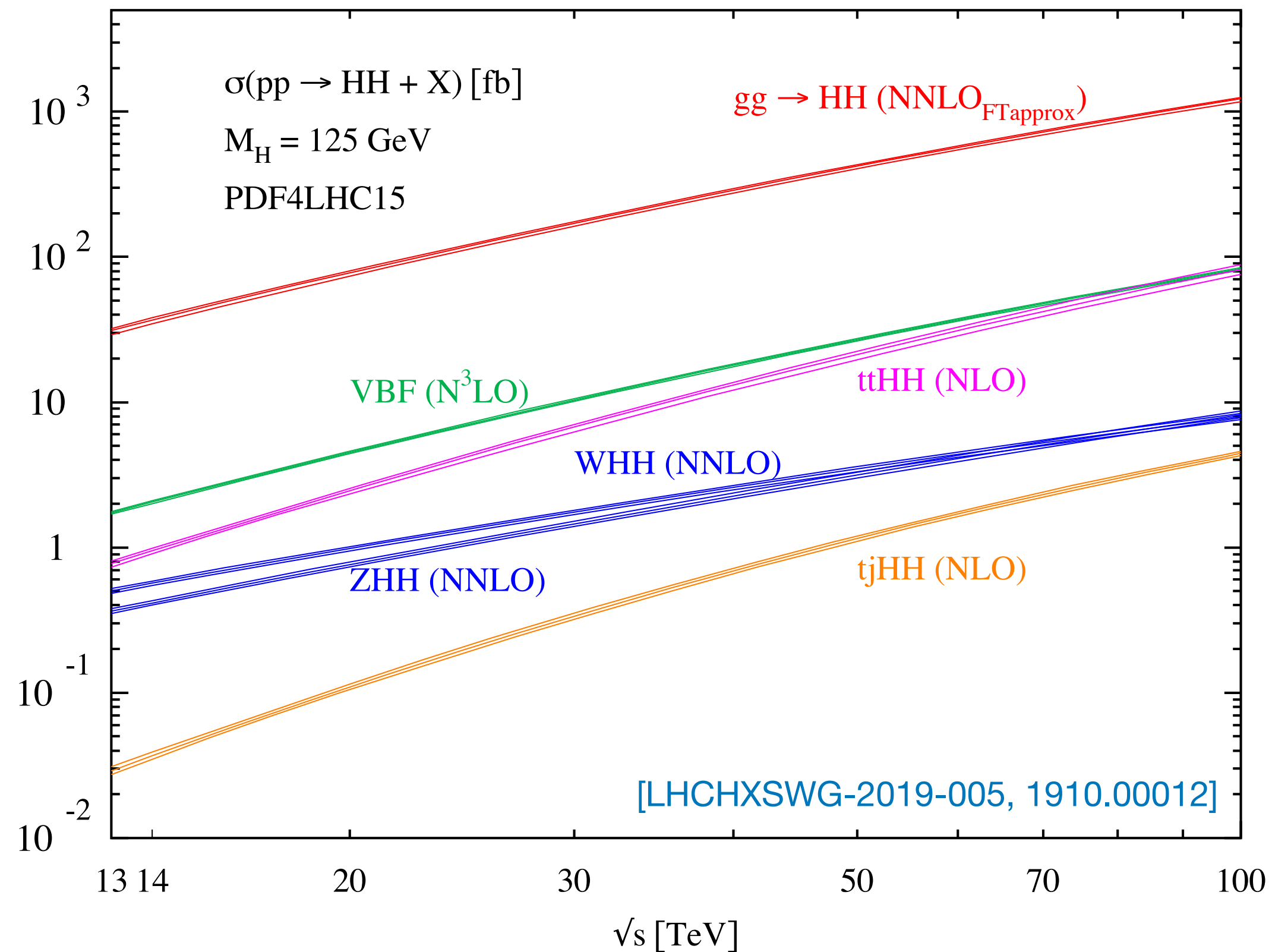
Tests of EW
symmetry breaking
mechanism

Major HL-LHC goal

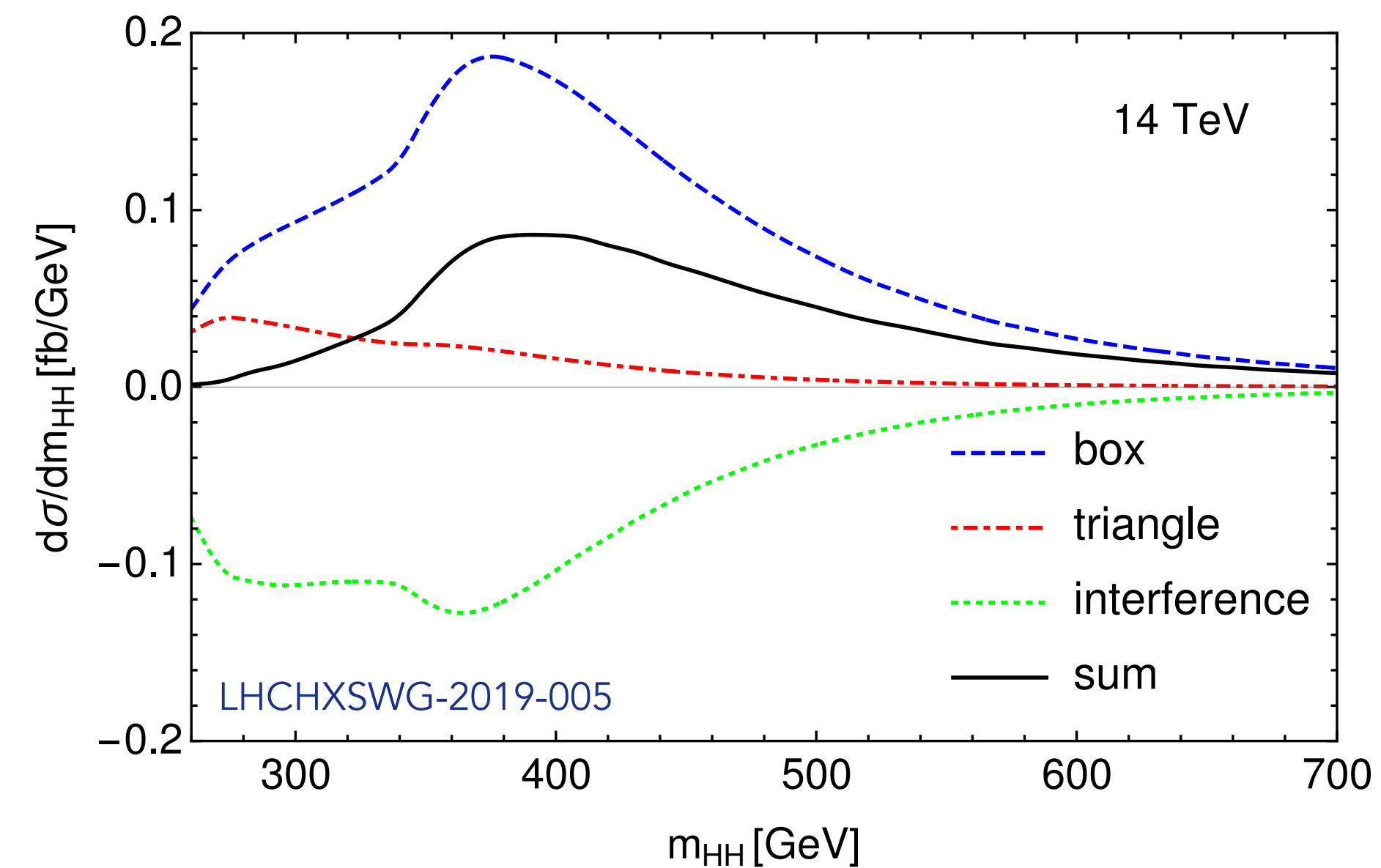
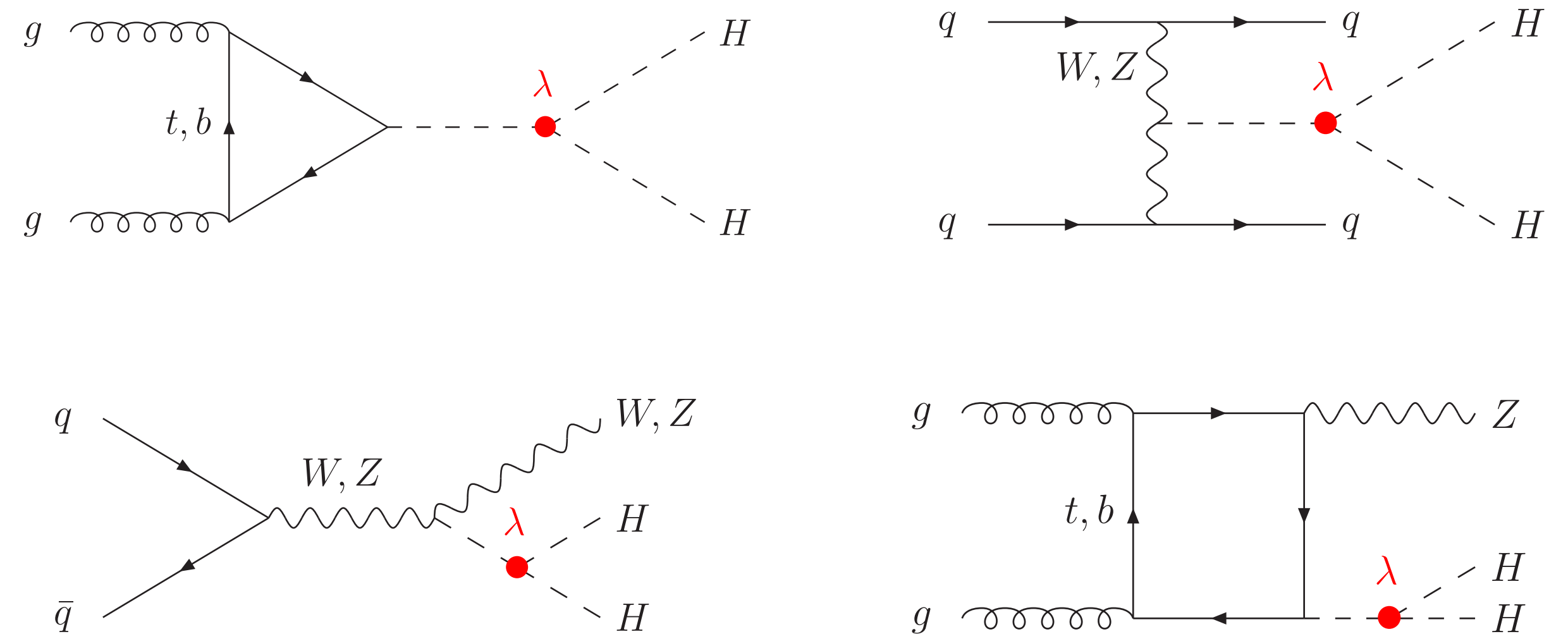
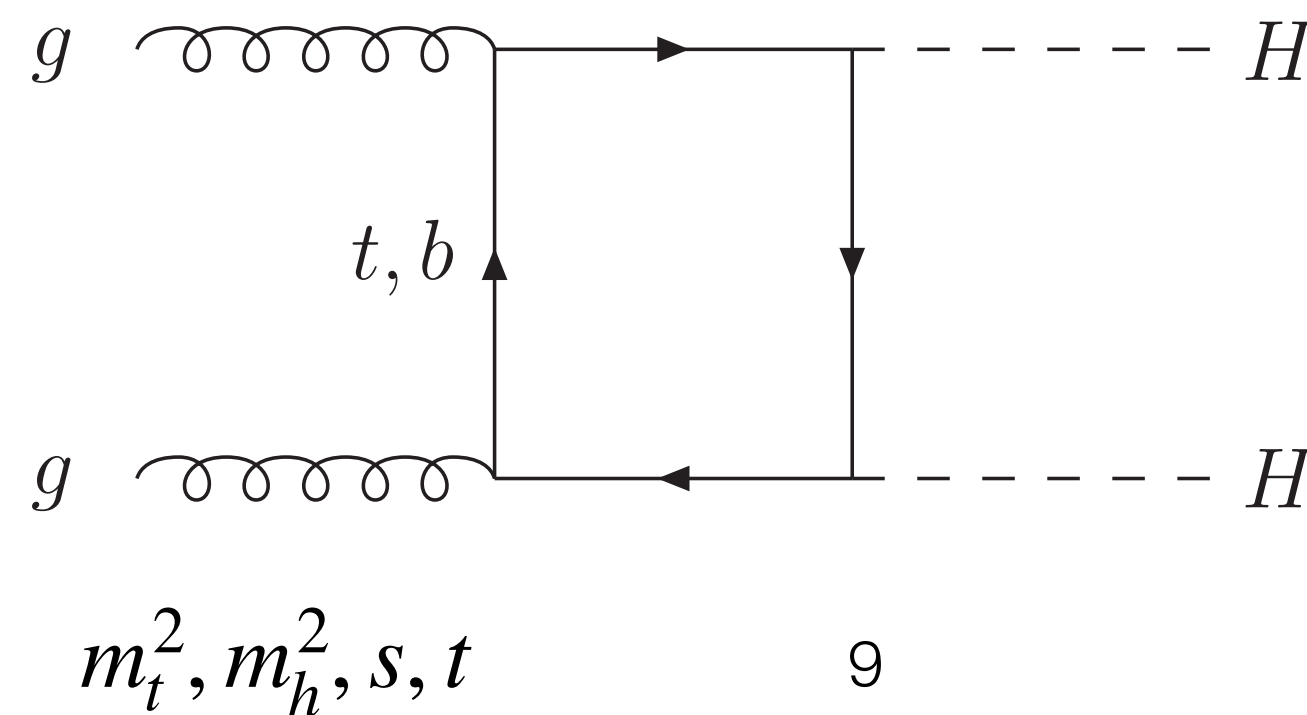


[G. Di Gregorio, Cometa Krakow]

Double Higgs production



The cross-section for
 $pp \rightarrow HH$ process is a
 factor 1000 smaller than
 $pp \rightarrow H$ production
 cross-section

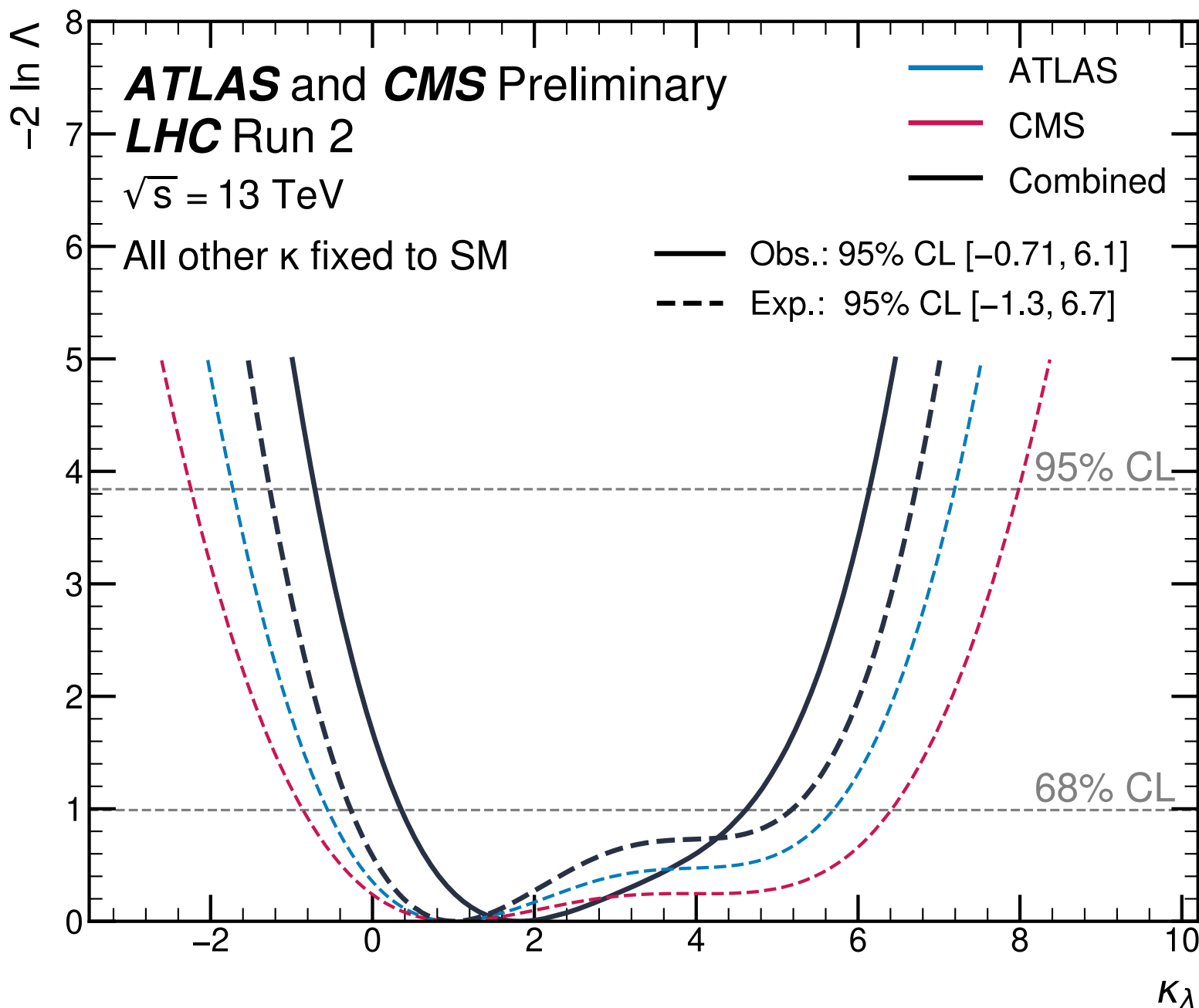


Experimental status and projections

Current Experimental Limits (Run 2) @ 95% CL

ATLAS: $-1.2(-1.6) < \kappa_\lambda < 7.2(7.2)$

CMS: $-1.39(-2.29) < \kappa_\lambda < 6.43(7.95)$



ATLAS-CONF-2025-012
[\[HIG-20-011-PAS\]](#)

Expected discovery
significance $\sim 3.8\sigma$ per
experiment

Combined
ATLAS+CMS
projections $\sim 7.6\sigma$

Theory systematics
halved in projections



ATL-PHYS-PUB-2025-018
CMS-HIG-25-002

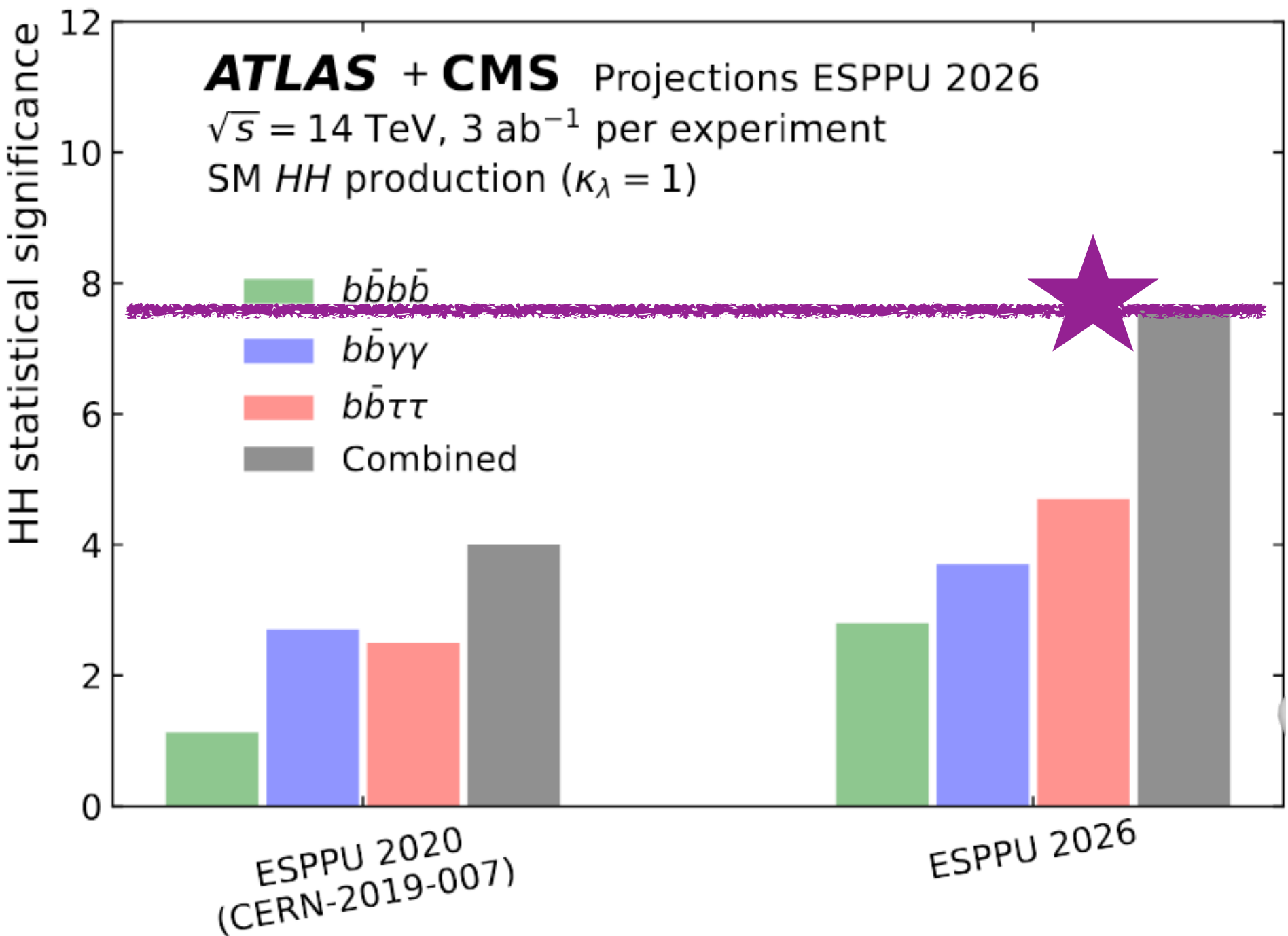
31st March 2025

ATL-PHYS-PUB-2025-018

**Highlights of the HL-LHC physics projections
by ATLAS and CMS**

The ATLAS¹ and CMS² Collaborations



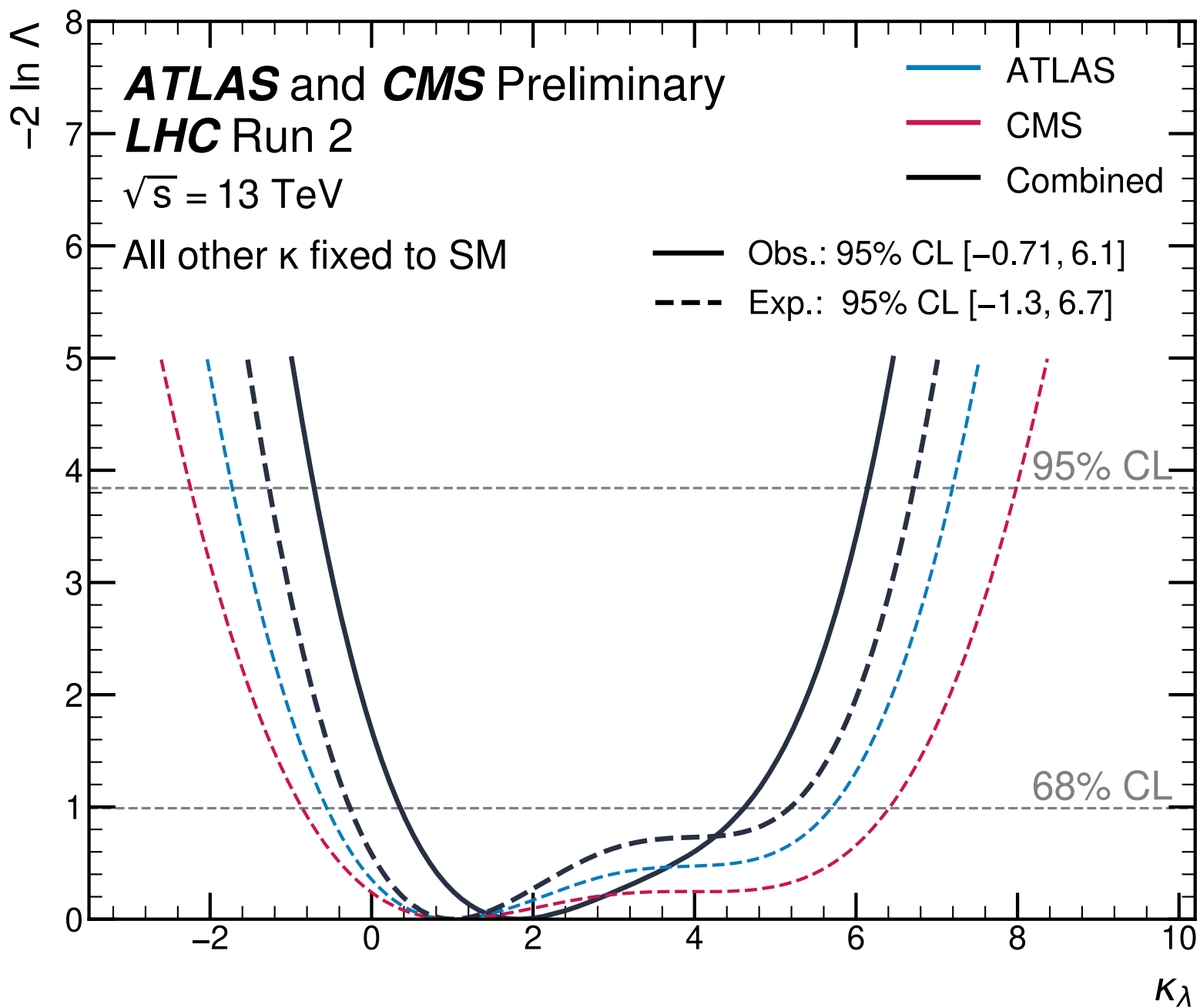


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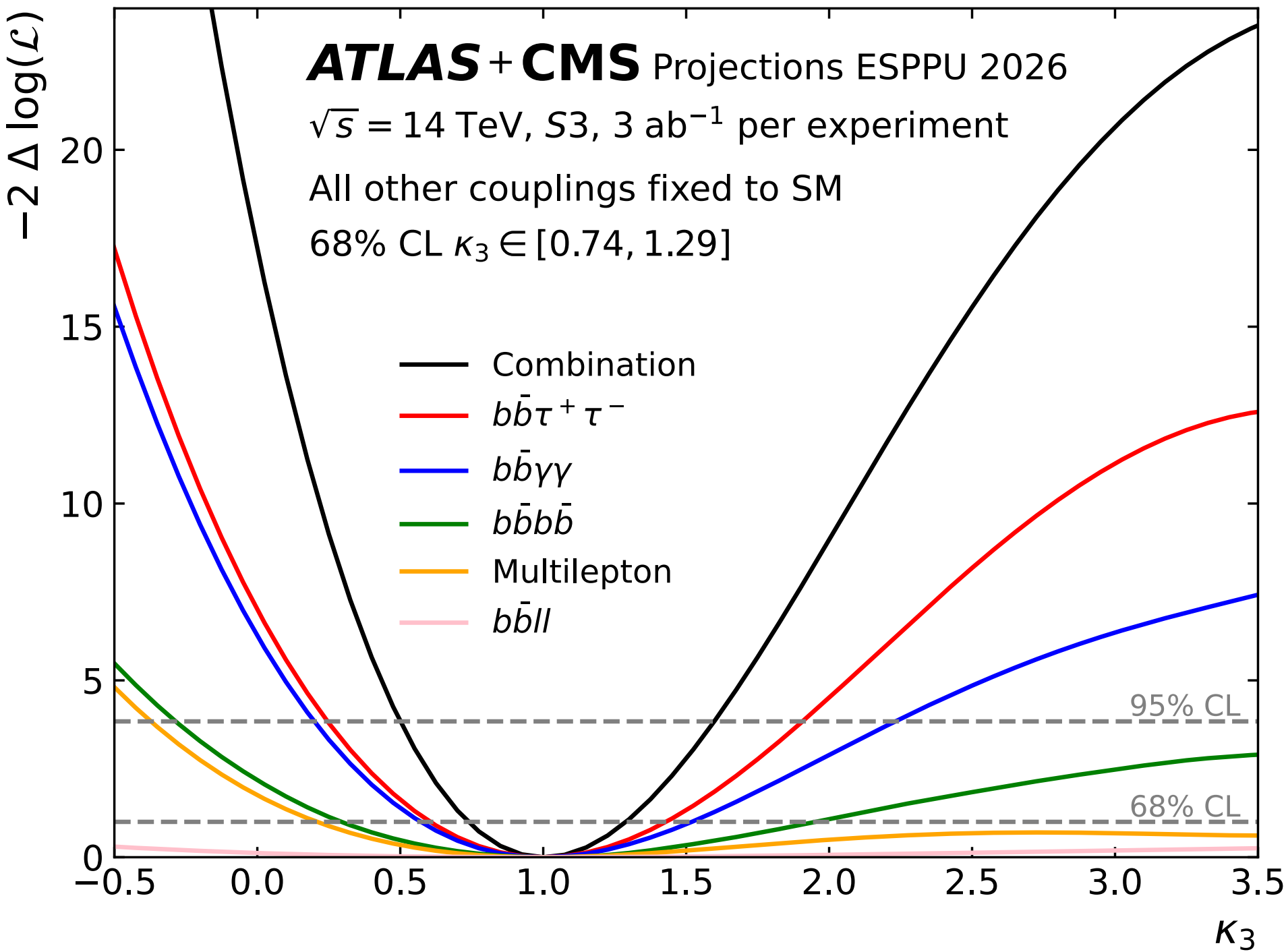
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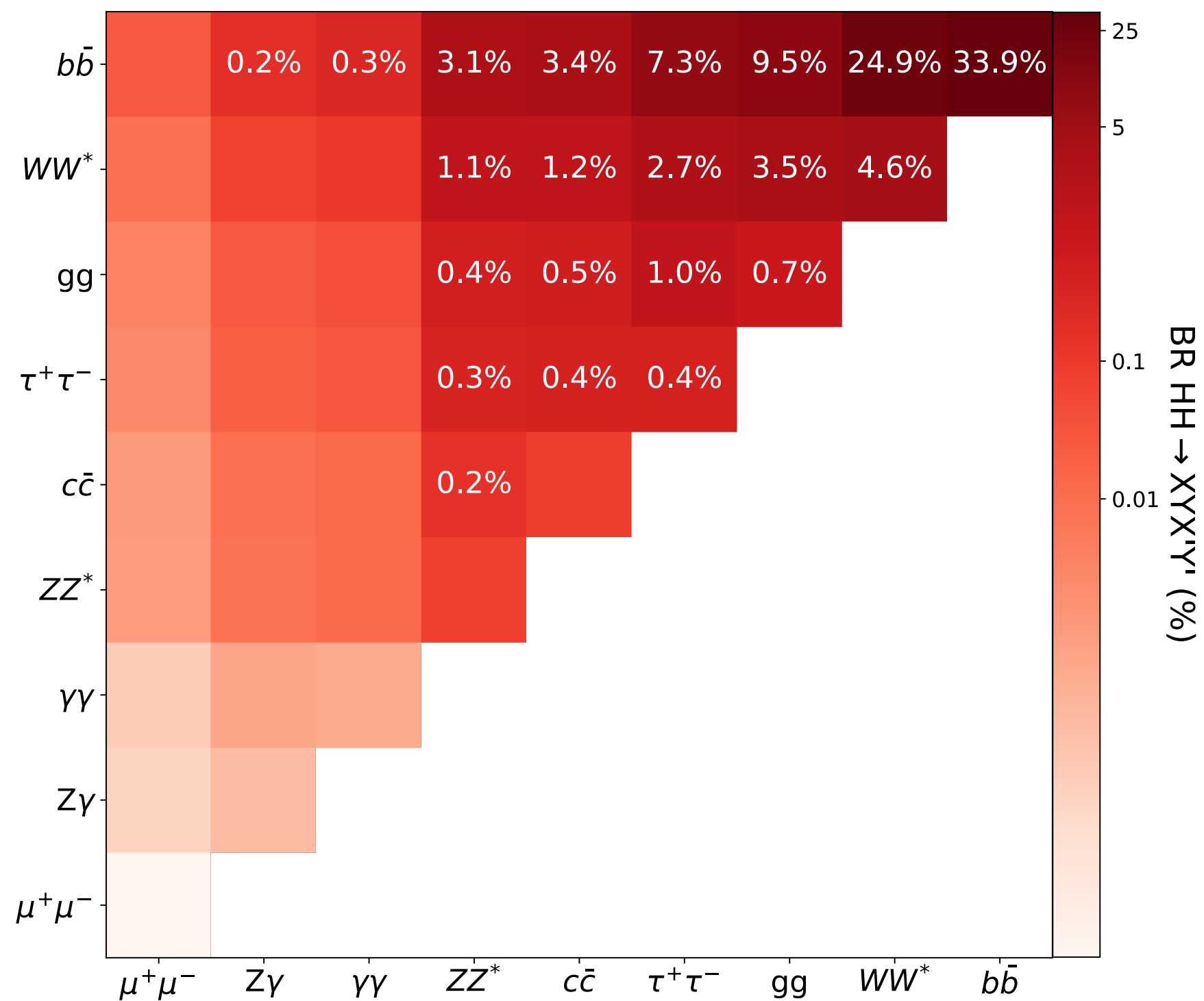


A precision on trilinear Higgs coupling below 30%

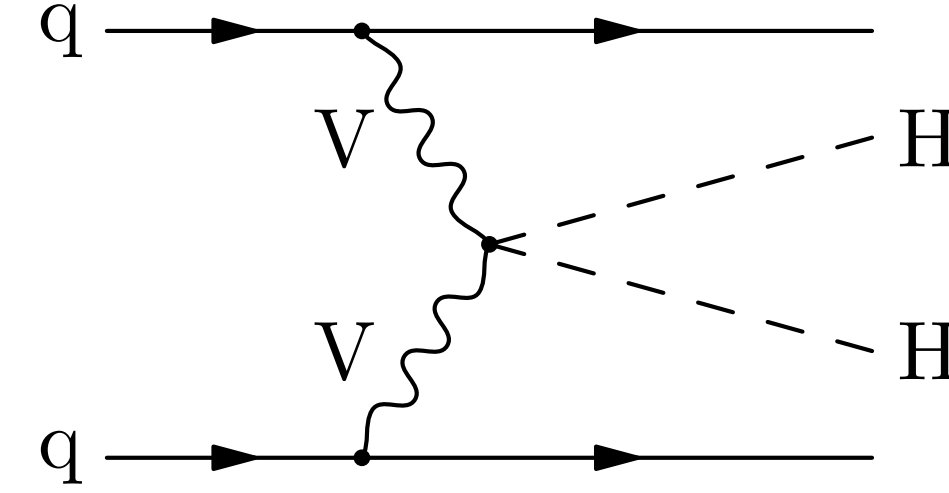
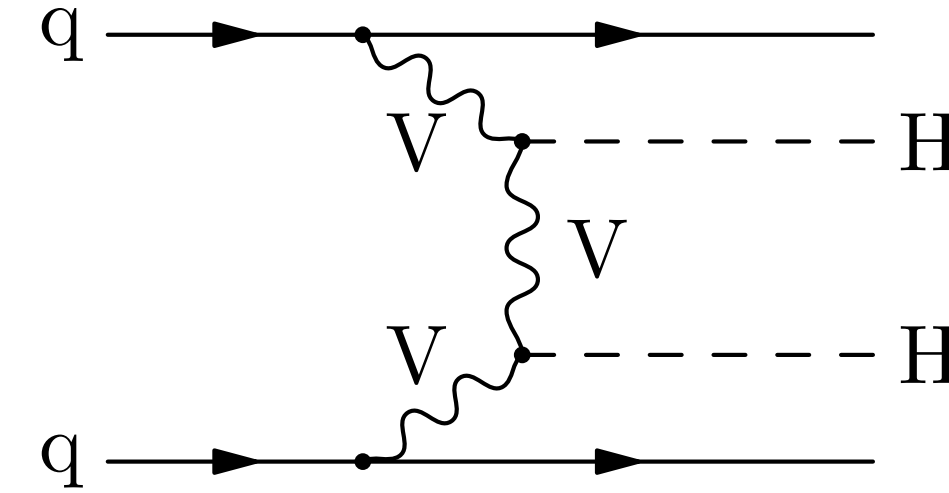
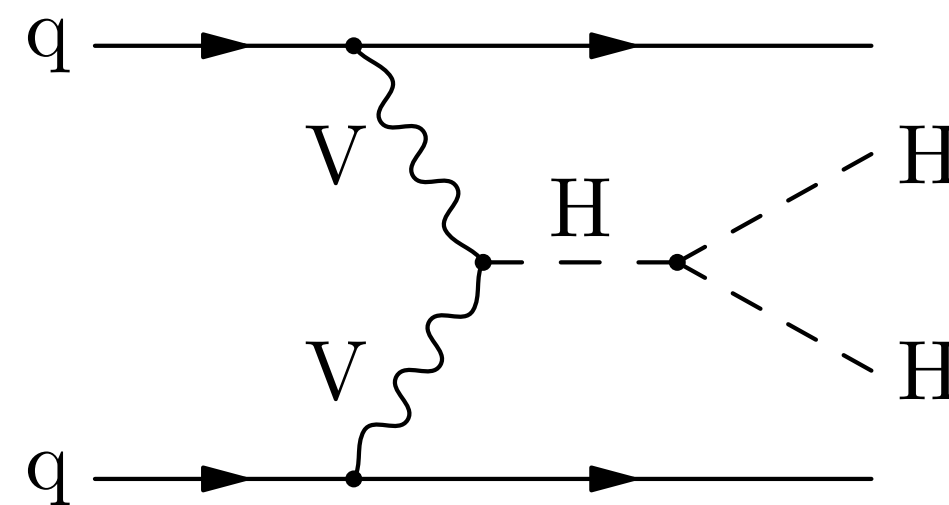
Higgs pairs in $\gamma\gamma b\bar{b}$

Recent search for non-resonant production of Higgs boson pairs via gluon-gluon and vector boson fusion processes in final states with two bottom quarks and two photons.

[\[CMS, 2011.12373\]](#) see also [\[ATLAS, 2507.03495\]](#)



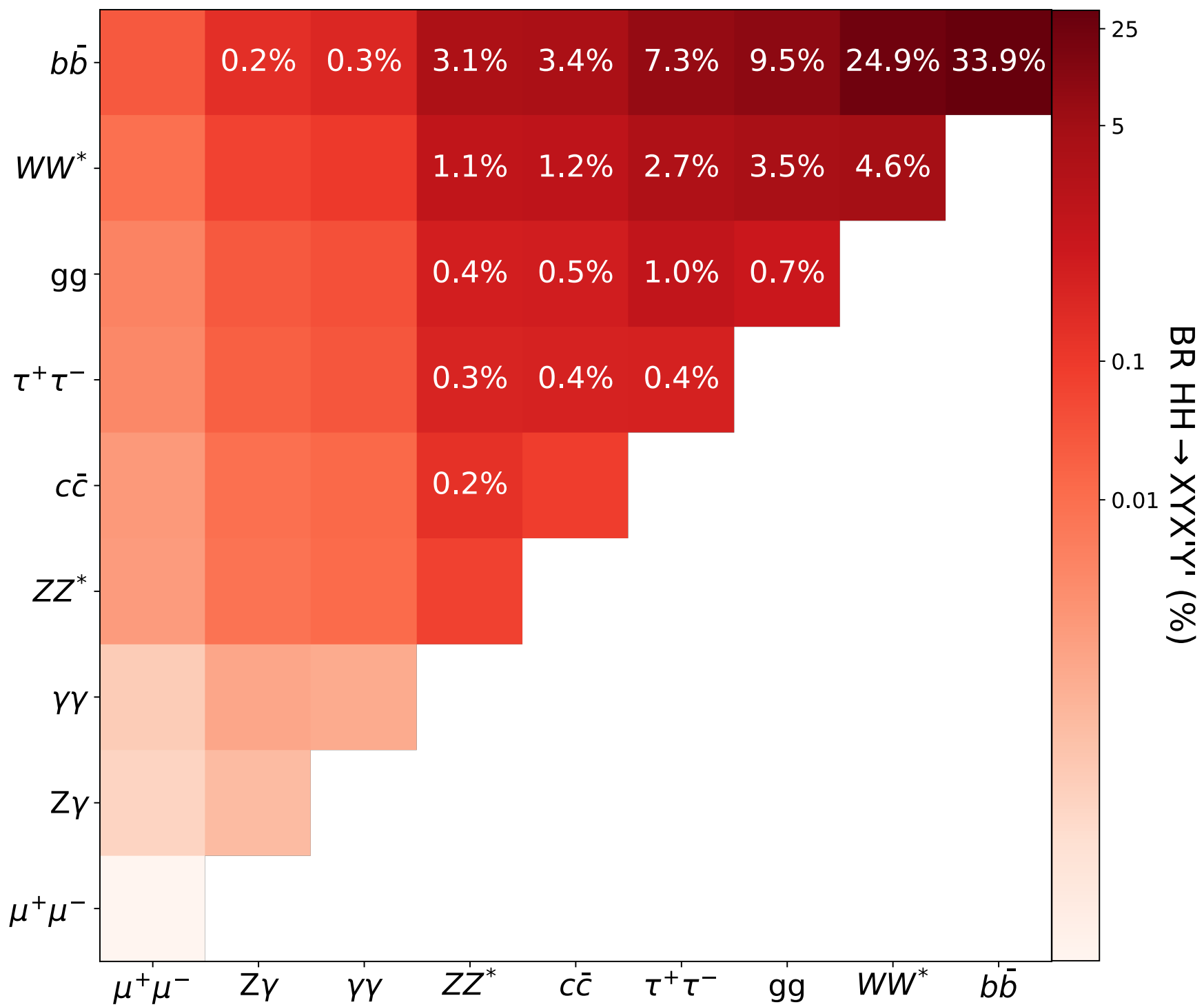
[Report: B. Di Micco, M. Gouzevitch,
J. Mazzitelli, C. Vernieri, 1910.00012]



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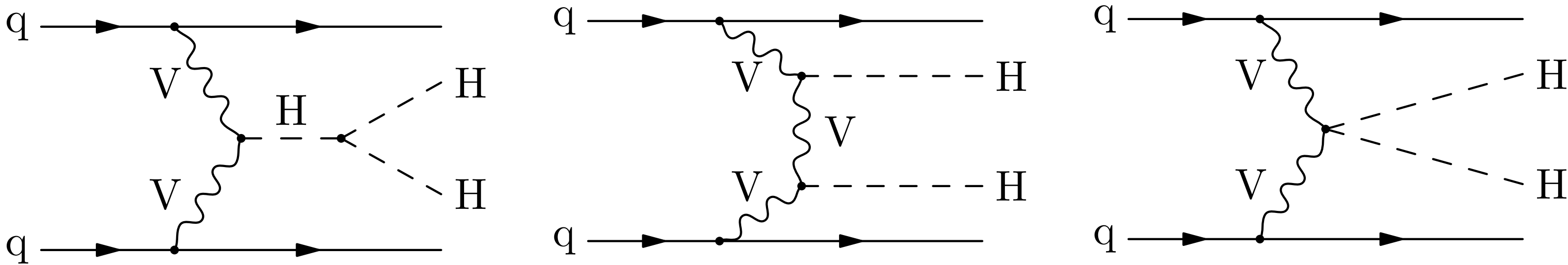
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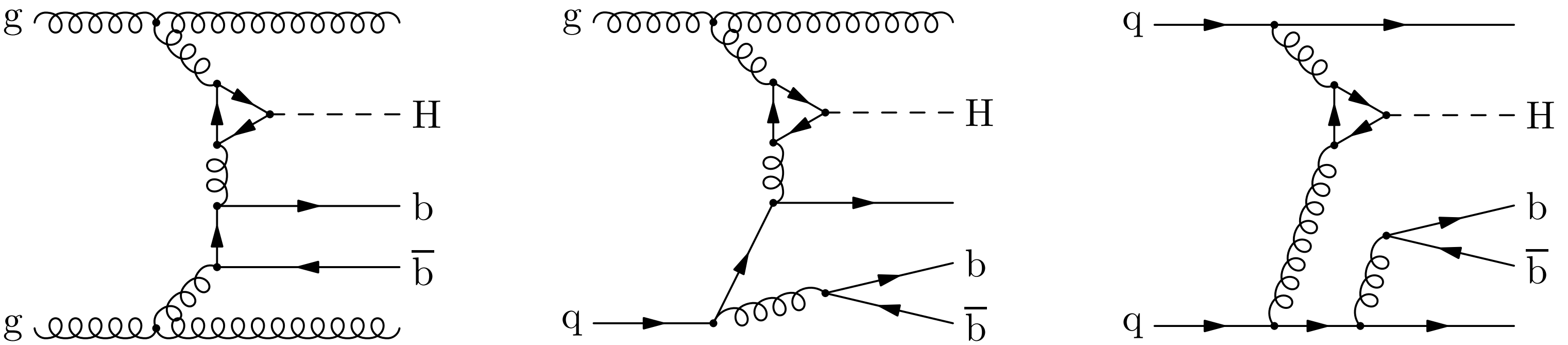


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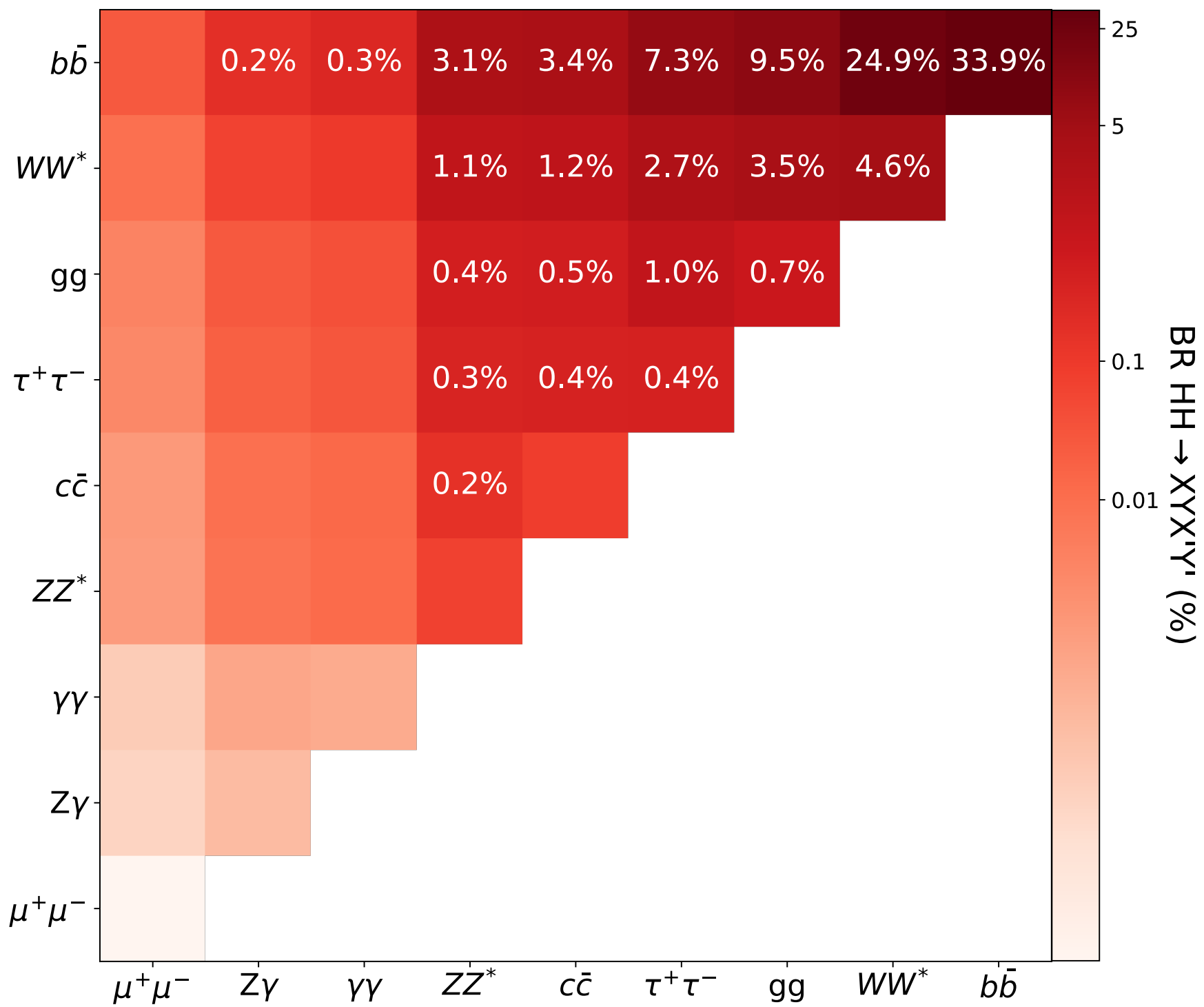
Important background from $pp \rightarrow H(\rightarrow \gamma\gamma) + b\bar{b} + 2j$



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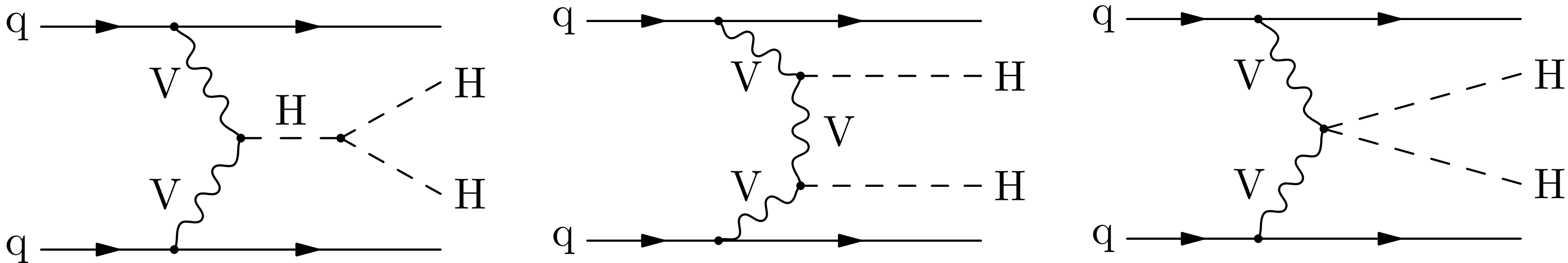
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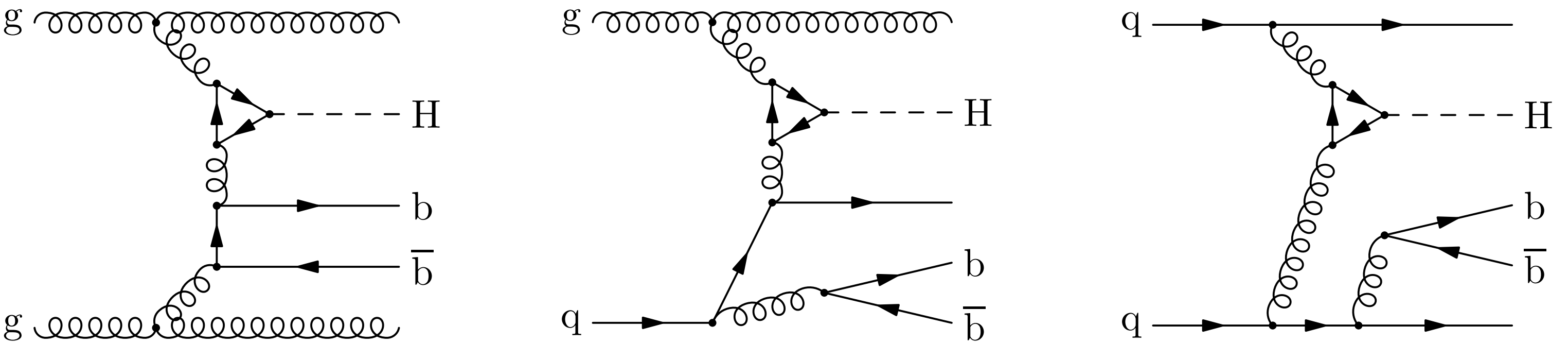


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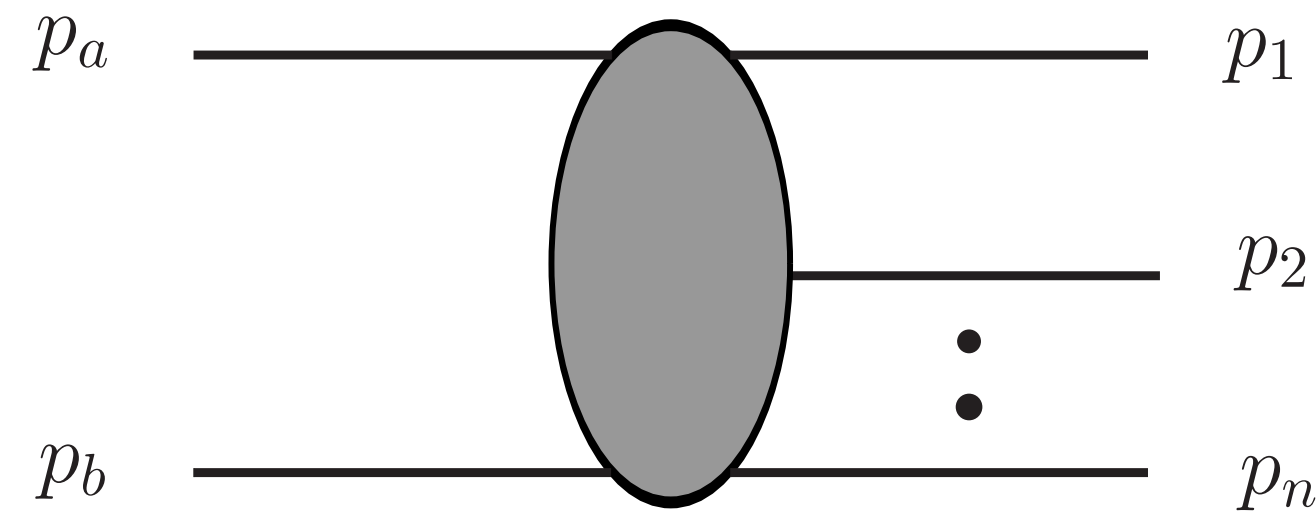
Central Higgs and b-jets $\rightarrow$ high-energy resummation region

Scaling of amplitudes

[R. Brower, C. DeTar, J. Weis, 1974]

In the Regge limit the amplitudes have the following scaling

[V. Fadin, R. Fiore, M. Kozlov, A. Reznichenko, 0602006]



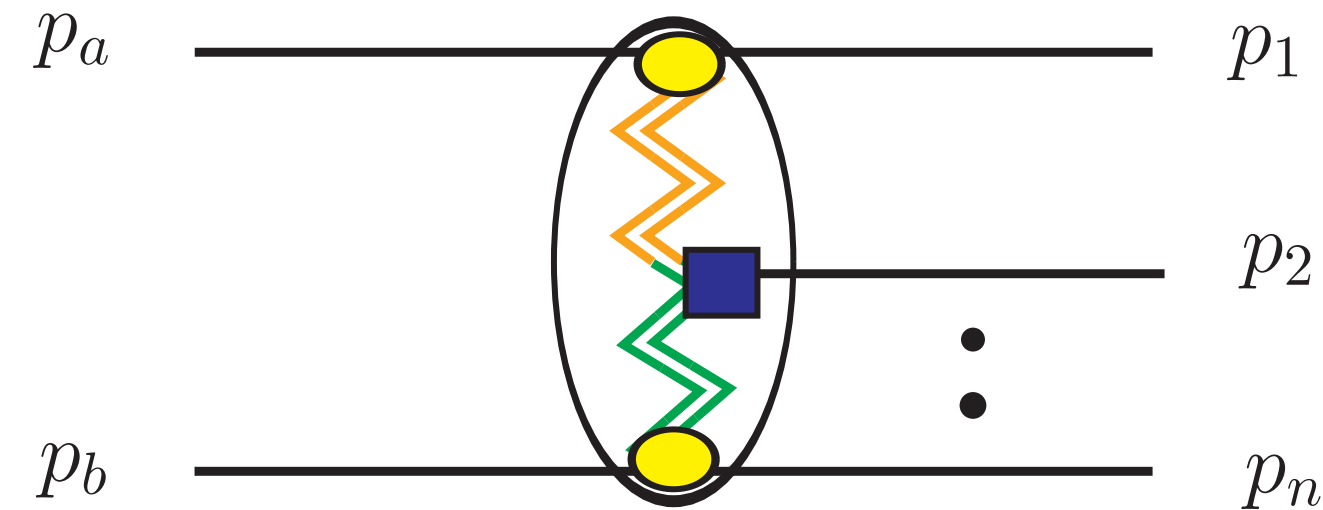
$$\mathcal{M} \propto s_{12}^{\alpha_{12}} s_{23}^{\alpha_{23}} \cdots s_{n-1,n}^{\alpha_{n-1,n}} f(\{p_{Ti}\})$$

$$s_{ij} = (p_i + p_j)^2$$

α_{ij} is the spin in the effective t-channel

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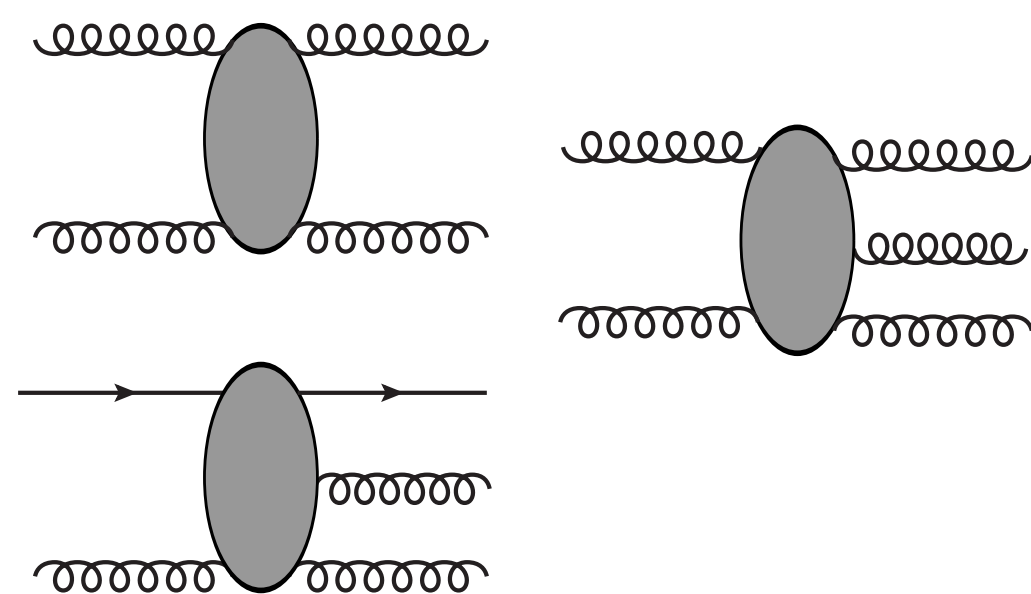


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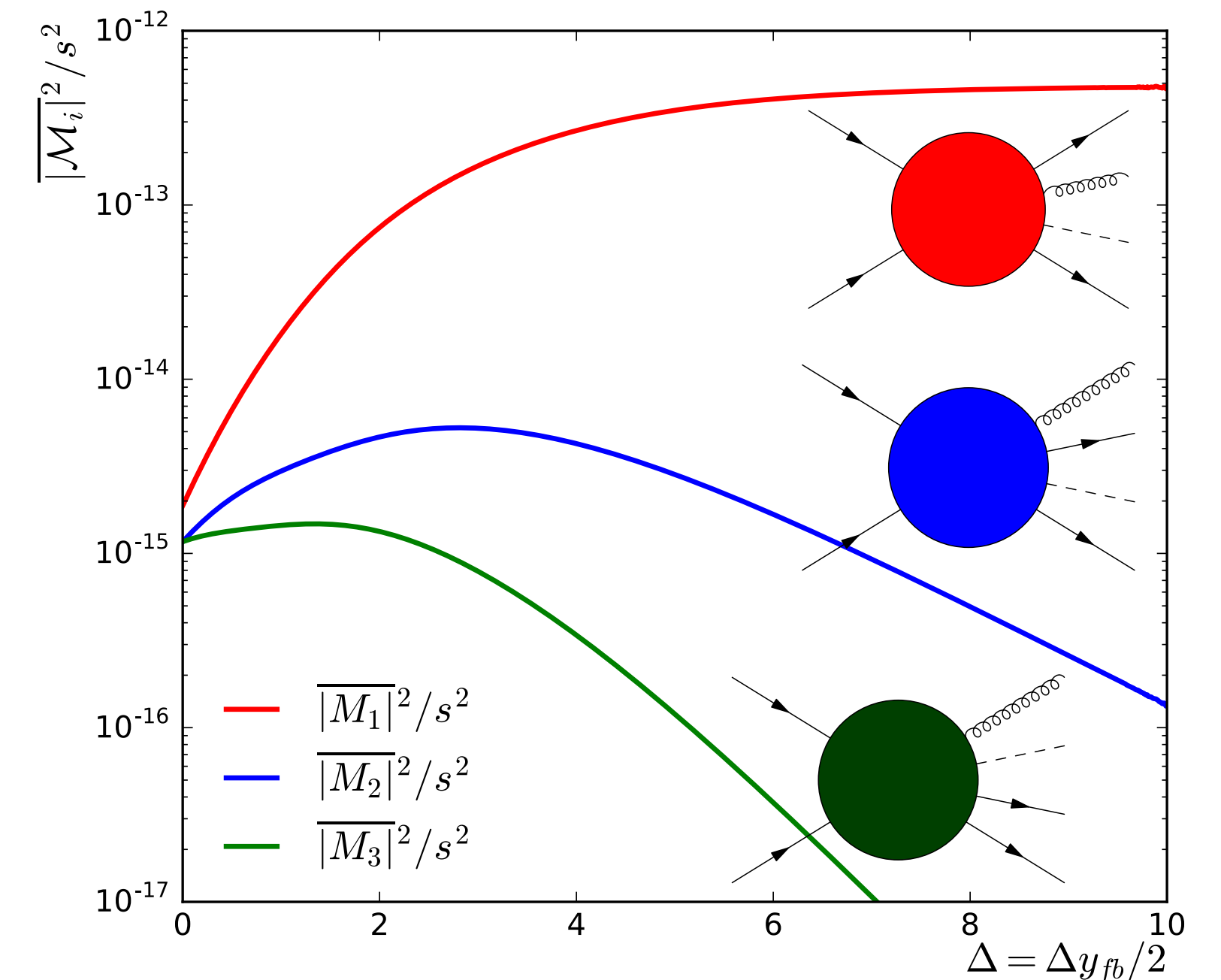
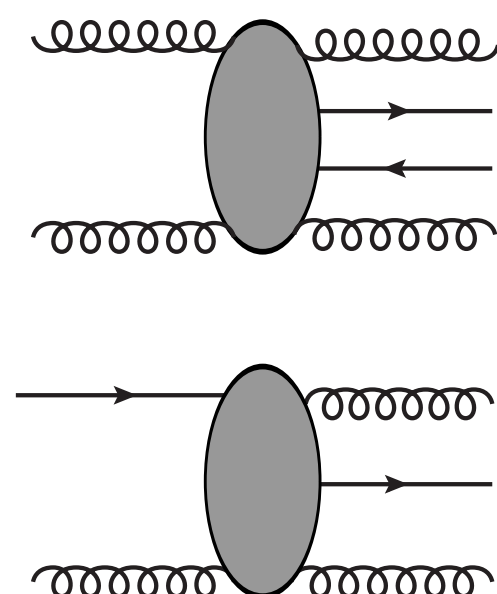
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Example configurations in HEJ:

Leading Logarithmic (LL)



NLL



HEJ developments

In order to describe the di-Higgs background

$$pp \rightarrow H(\rightarrow \gamma\gamma) + b\bar{b} + 2j$$

need to describe $q\bar{q}$ emissions along with the Higgs

In the MRK limit, scattering amplitudes factorise

$$\begin{aligned} |\mathcal{M}_{\text{HEJ}}^{f_a g \rightarrow f_a \cdots H \cdots q\bar{q}}|^2 &= \mathcal{B}_{f_a, H, q\bar{q}}(p_a, p_b, p_1, p_q, p_{\bar{q}}, q_j, q_{j+1}) \\ &\times \prod_{\substack{i=1 \\ i \neq j}}^{n-3} \mathcal{V}(p_a, p_b, p_1, p_q, p_{\bar{q}}, q_i, q_{i+1}) \\ &\times \prod_{i=1}^{n-2} \mathcal{W}(q_i, y_i, y_{i+1}) \end{aligned}$$

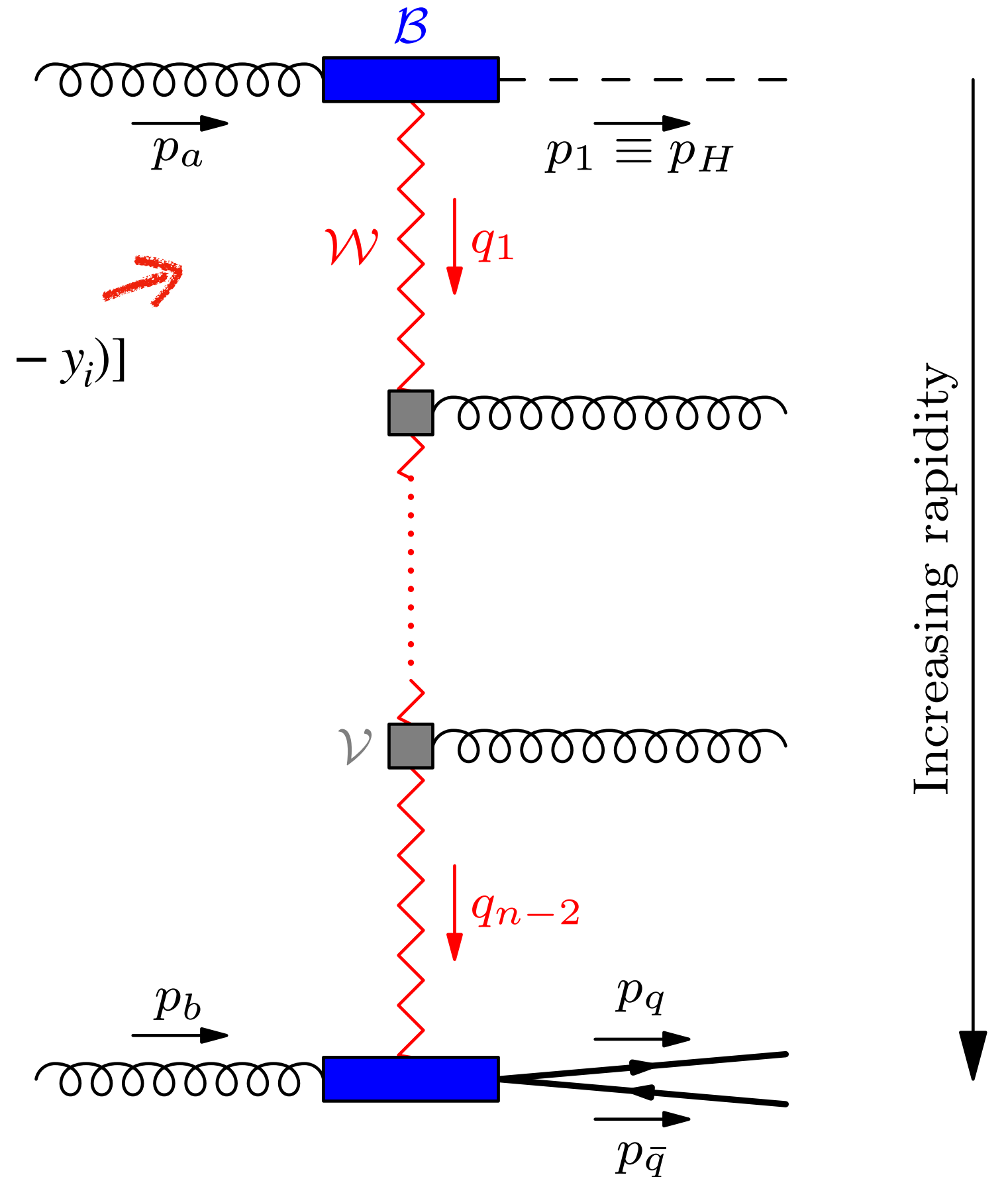
New derivation of HEJ amplitudes required to describe $H + q\bar{q}$

[A. Maier, G. Ruisi, 2608.21195]

$$\mathcal{M} \sim s_{hq} s_{q\bar{q}}^{1/2}$$

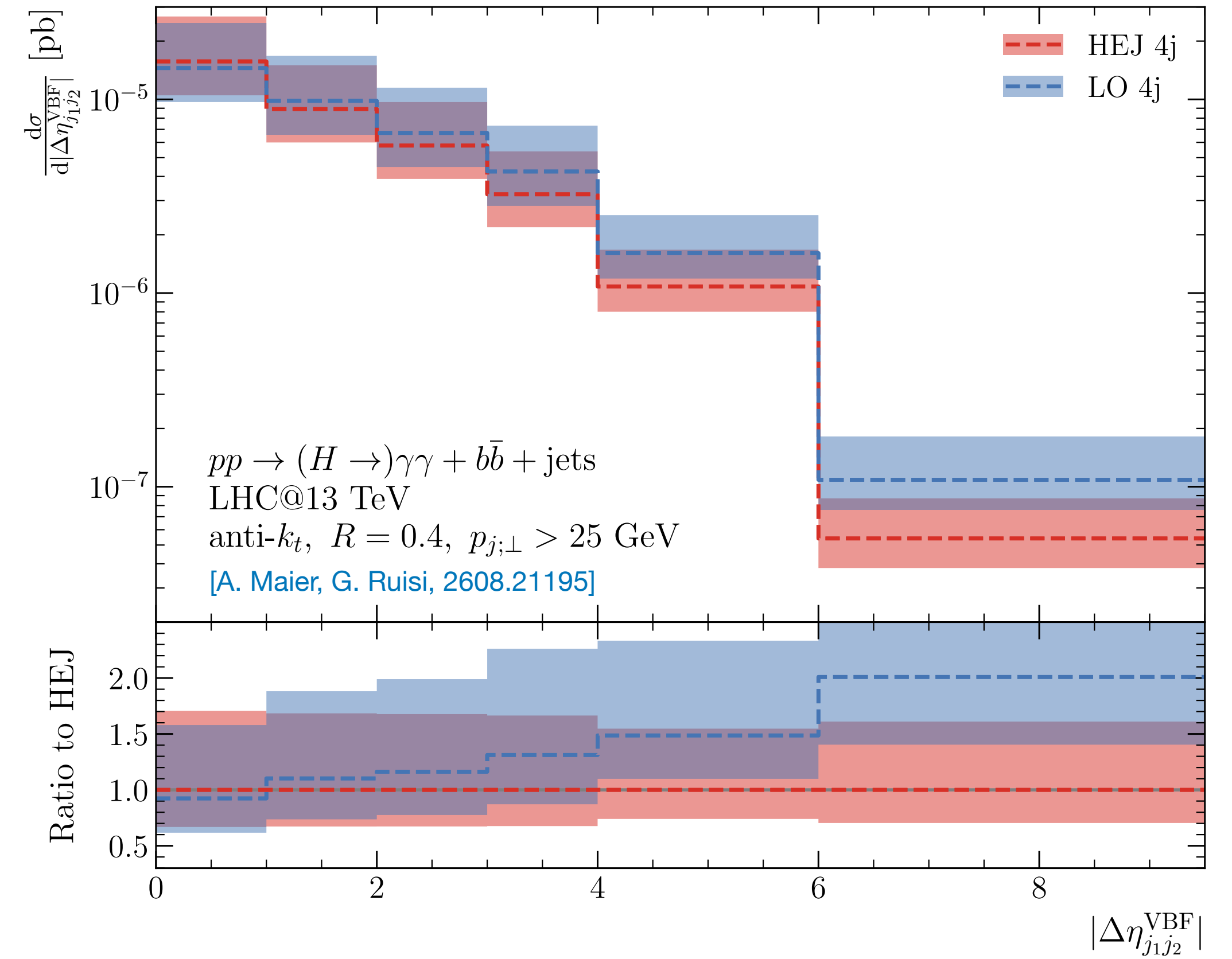
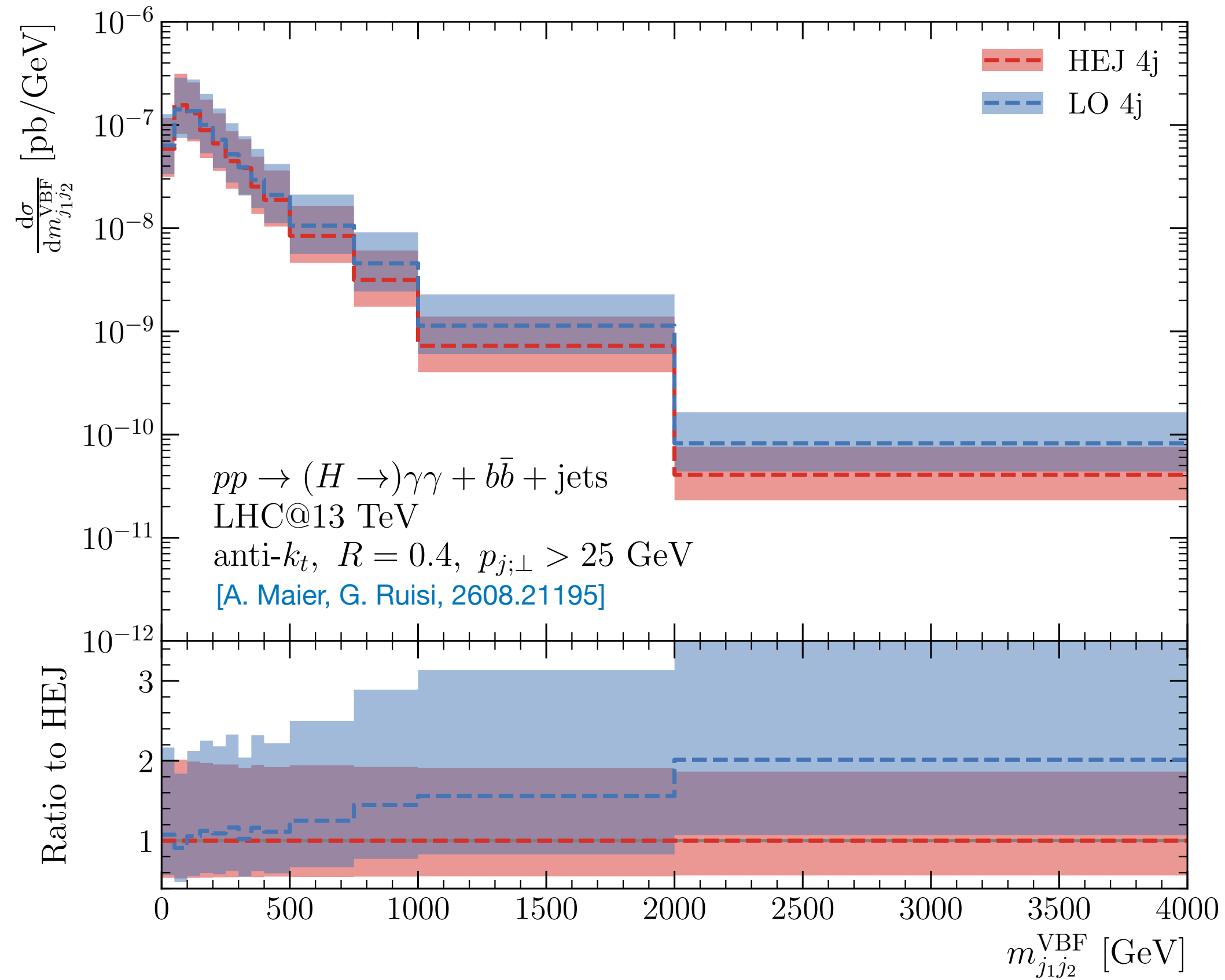
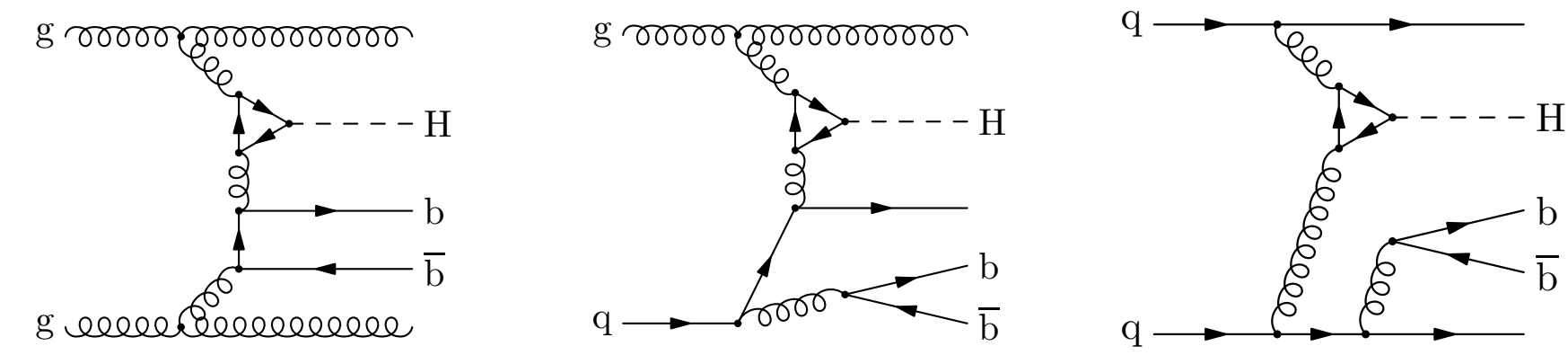
Reggeized gluon

$$\frac{1}{t_i} \rightarrow \frac{1}{t_i} \exp[\hat{\alpha}(q_i)(y_{i+1} - y_i)]$$



$$\begin{aligned} V^\mu(p_a, p_b, p_1, p_q, p_{\bar{q}}, q_i, q_{i+1}) &= -(q_i + q_{i+1})^\mu \\ &+ \frac{p_a^\mu}{2} \left(\frac{q_i^2}{p_{i+1} \cdot p_a} + \frac{p_{i+1} \cdot p_b}{p_a \cdot p_b} + \frac{p_{i+1} \cdot (p_q + p_{\bar{q}})}{p_a \cdot (p_q + p_{\bar{q}})} \right) + p_a \leftrightarrow p_1 \\ &- \frac{p_b^\mu}{2} \left(\frac{q_{i+1}^2}{p_{i+1} \cdot p_b} + \frac{p_{i+1} \cdot p_a}{p_b \cdot p_a} + \frac{p_{i+1} \cdot p_1}{p_b \cdot p_1} \right) - p_b \leftrightarrow (p_q + p_{\bar{q}}) \end{aligned}$$

Results for $\gamma\gamma b\bar{b}$ background



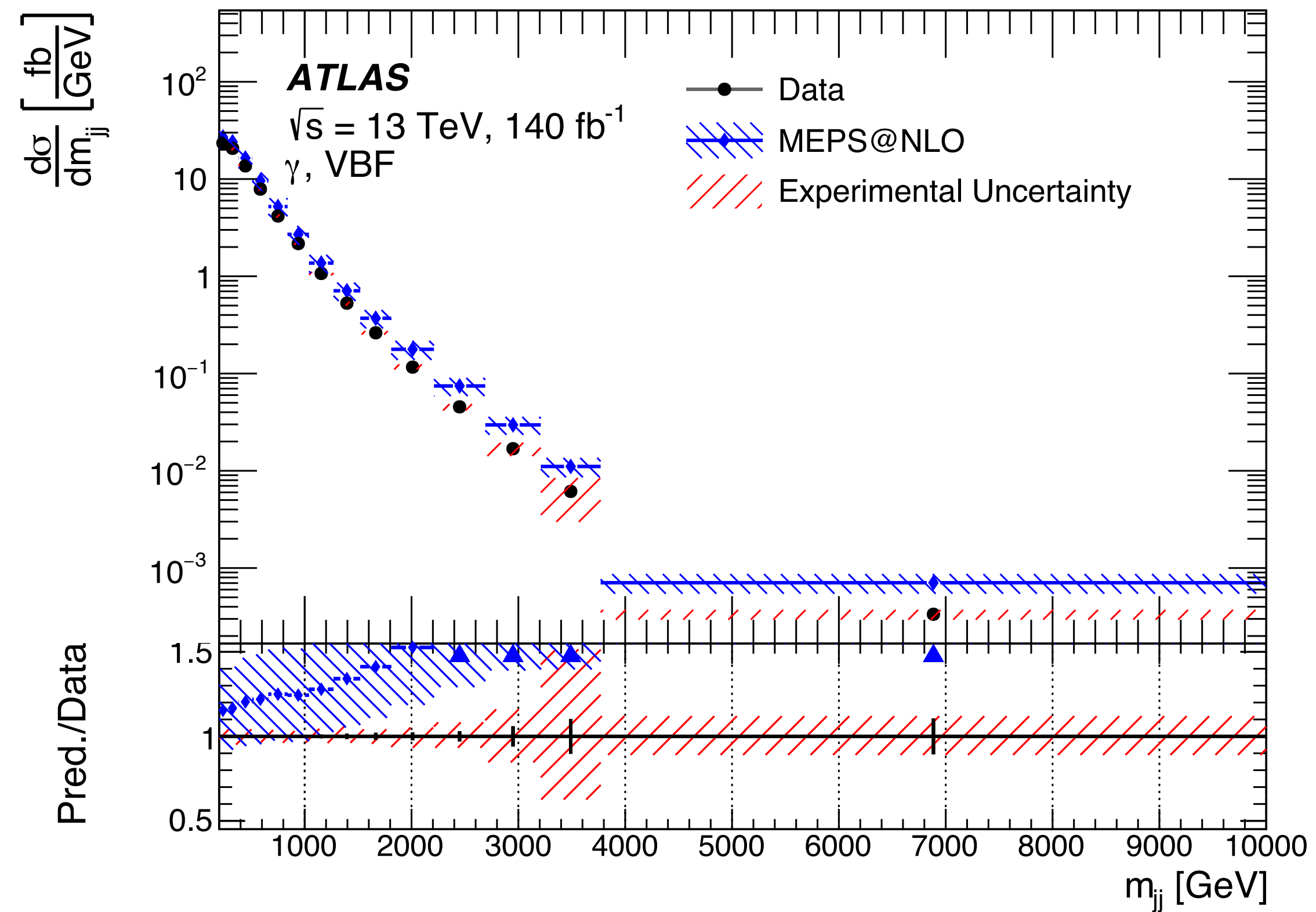
In the VBF region, resummation of high-energy logarithms suppresses the background further with respect to the leading order prediction.

The leading order predictions are obtained using Sherpa 2.2

[\[Sherpa, 1905.09127\]](#)

Photon + dijets

Recent measurement of the $pp \rightarrow \gamma + \text{dijets}$ by [\[ATLAS, 2403.02793\]](#)

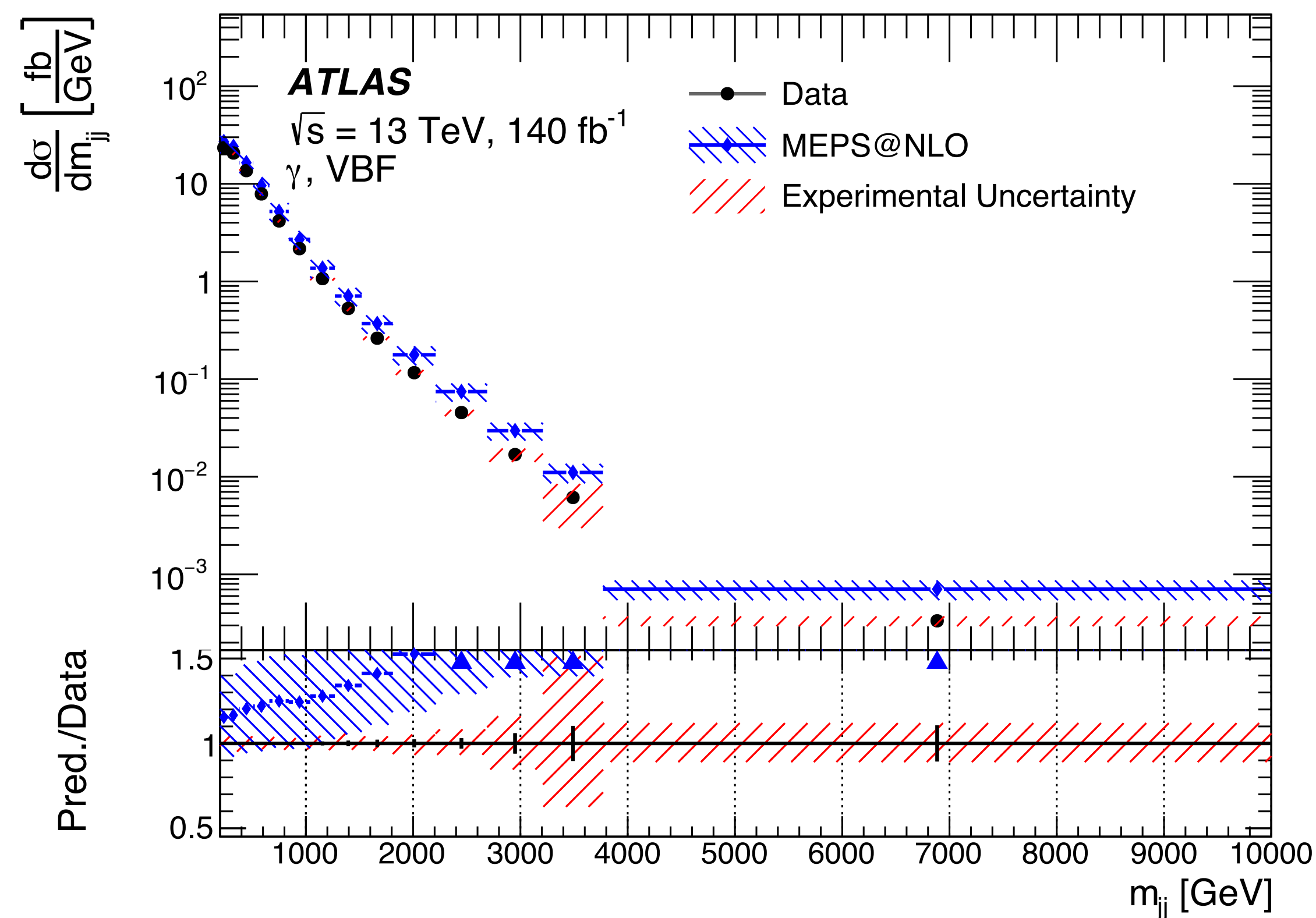


Interplay of QCD and electroweak processes, with QCD dominating up to $m_{jj} \sim 3 \text{ TeV}$

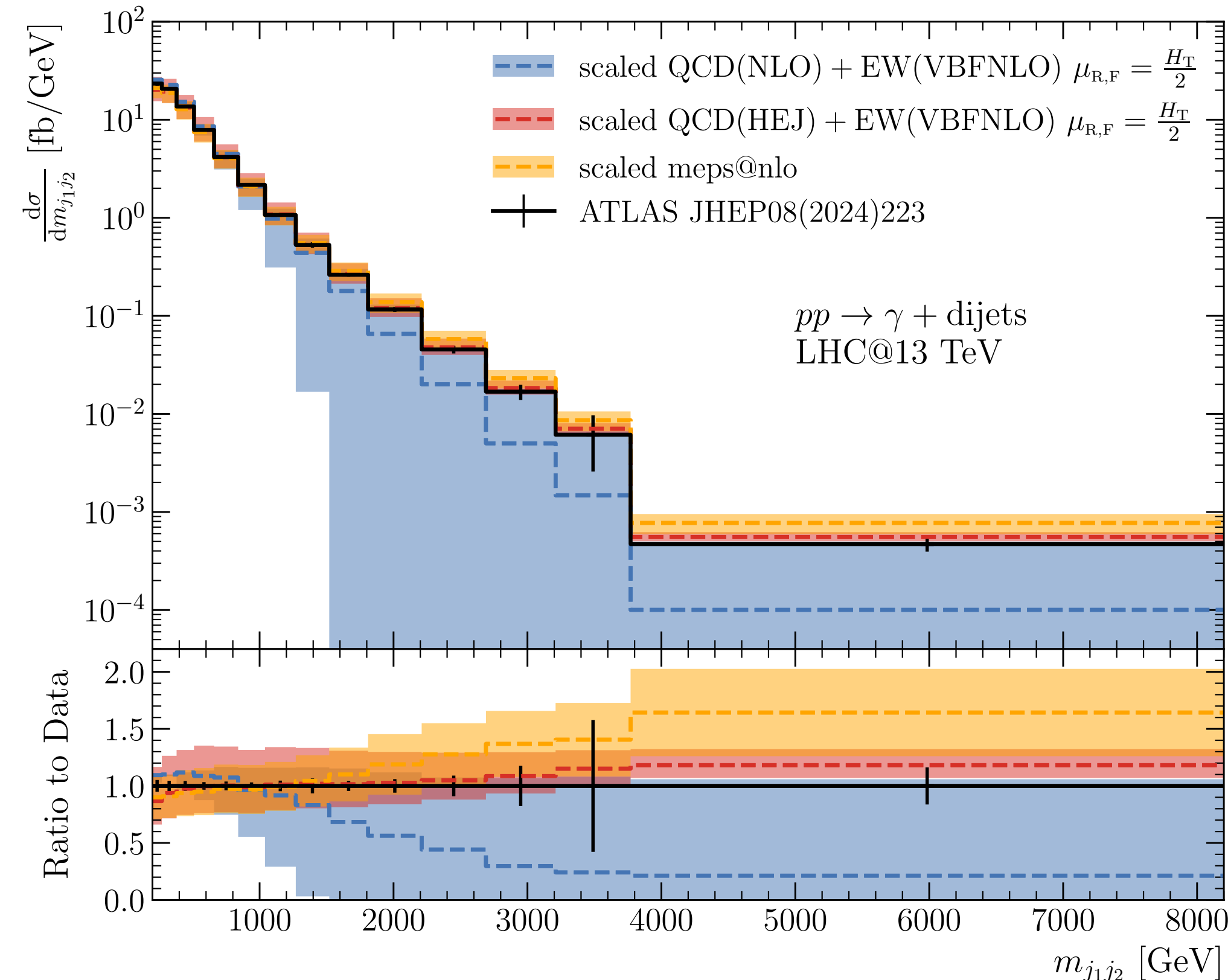
The state of the art prediction for this observable obtained using MEPS@NLO [\[S. Höche, F. Krauss, M.Schönherr, F. Siegert, 1207.5030\]](#)

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Prediction obtained with HEJ
[\[J. Andersen, A. Maier, M. Rosca, G. Ruisi, 2506.17438\]](#)



EW component computed with
VBFNLO 3.0

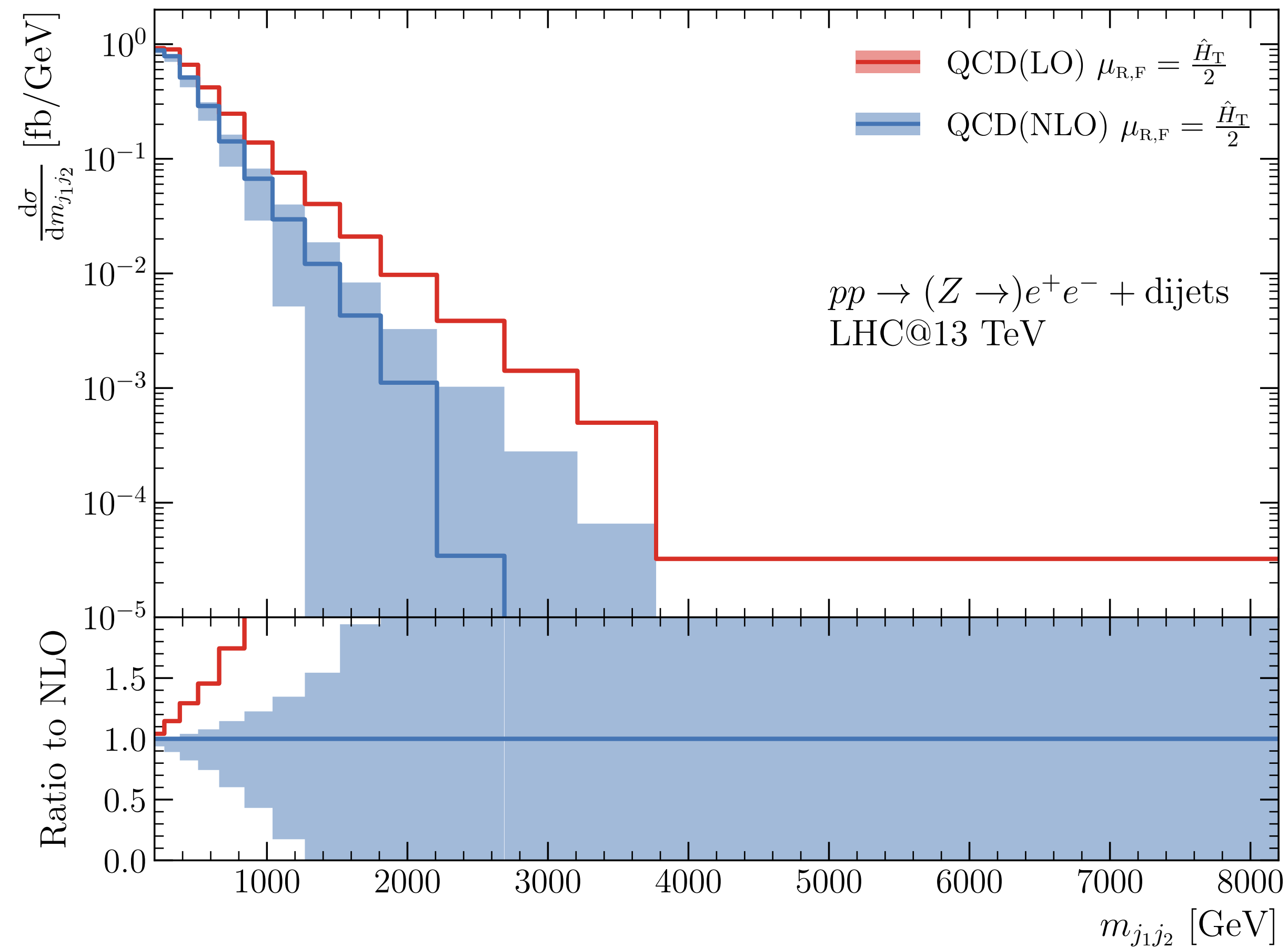
[\[J. Baglio et al., 2405.06990\]](#)

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[\[Sherpa, 1905.09127\]](#)

$pp \rightarrow Z(\rightarrow e^+e^-) + \text{dijets}$

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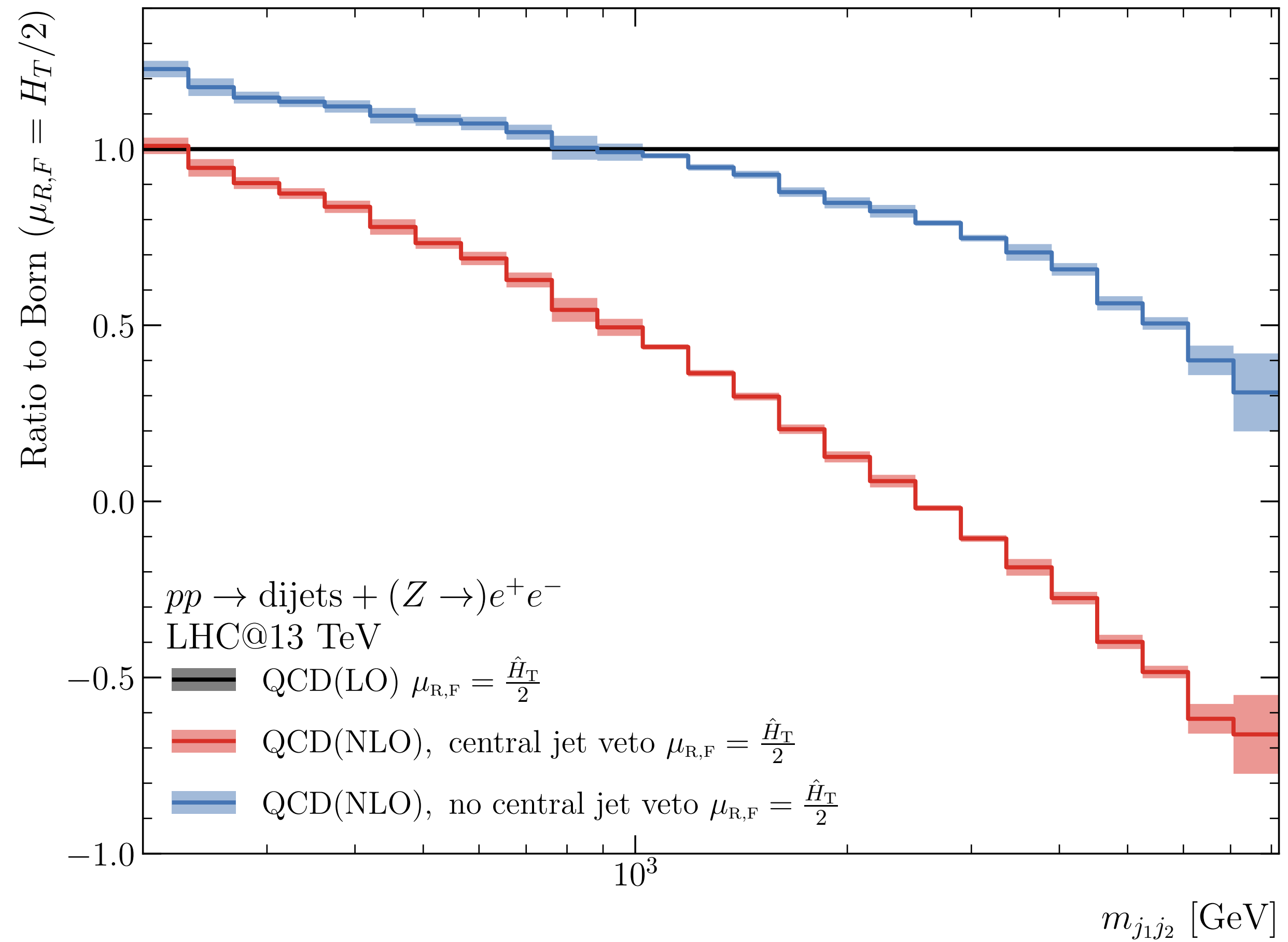
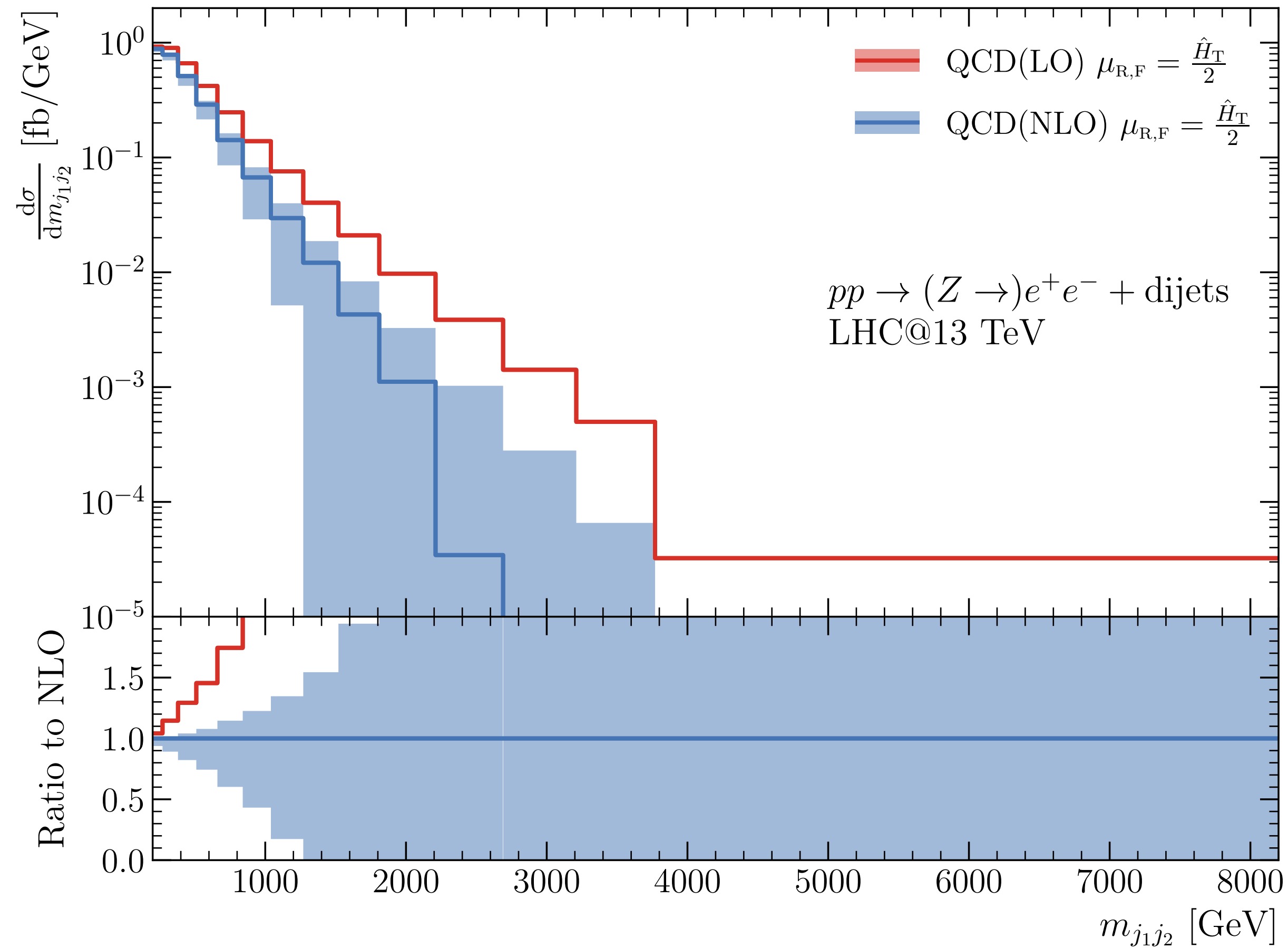


$$\hat{\sigma}_{2j}^{\text{NLO}} \sim C \alpha_s^2(\mu_r^2) \left(1 - \alpha_s(\mu_r^2) C_2 C_A \log m_{jj}^2/p_t^2 \right)$$

The NLO cross section even goes negative within the explored phase space

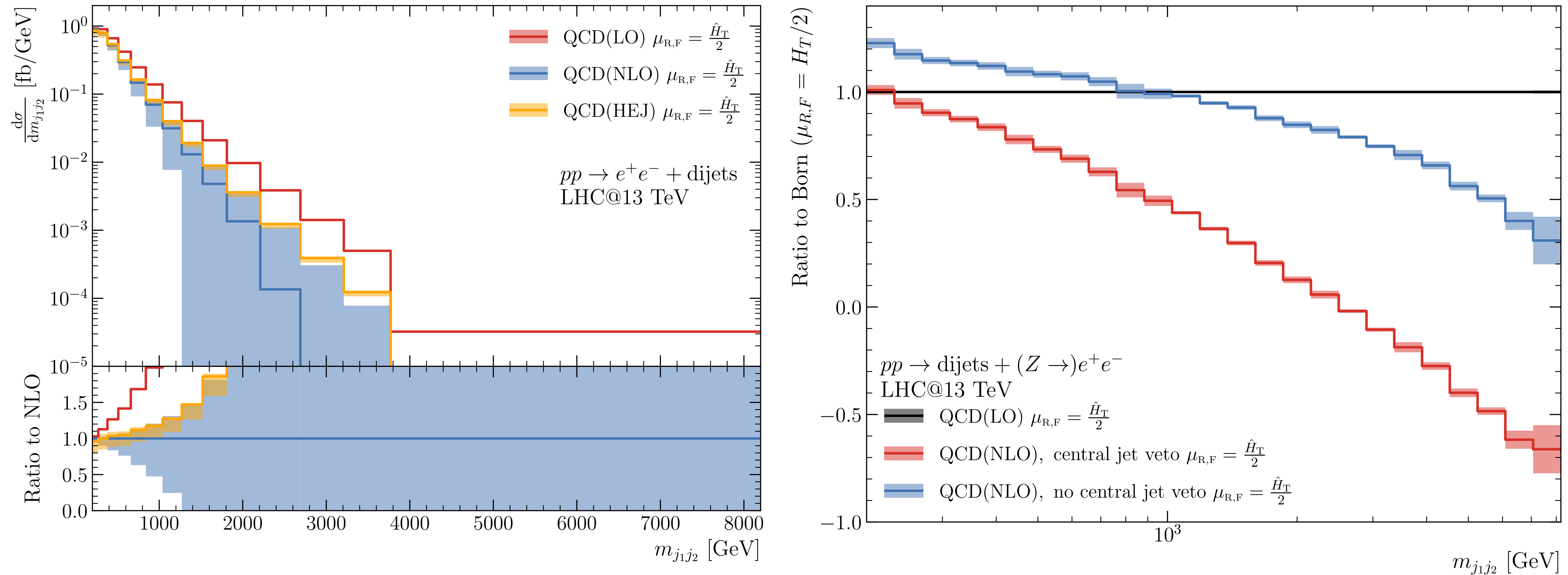
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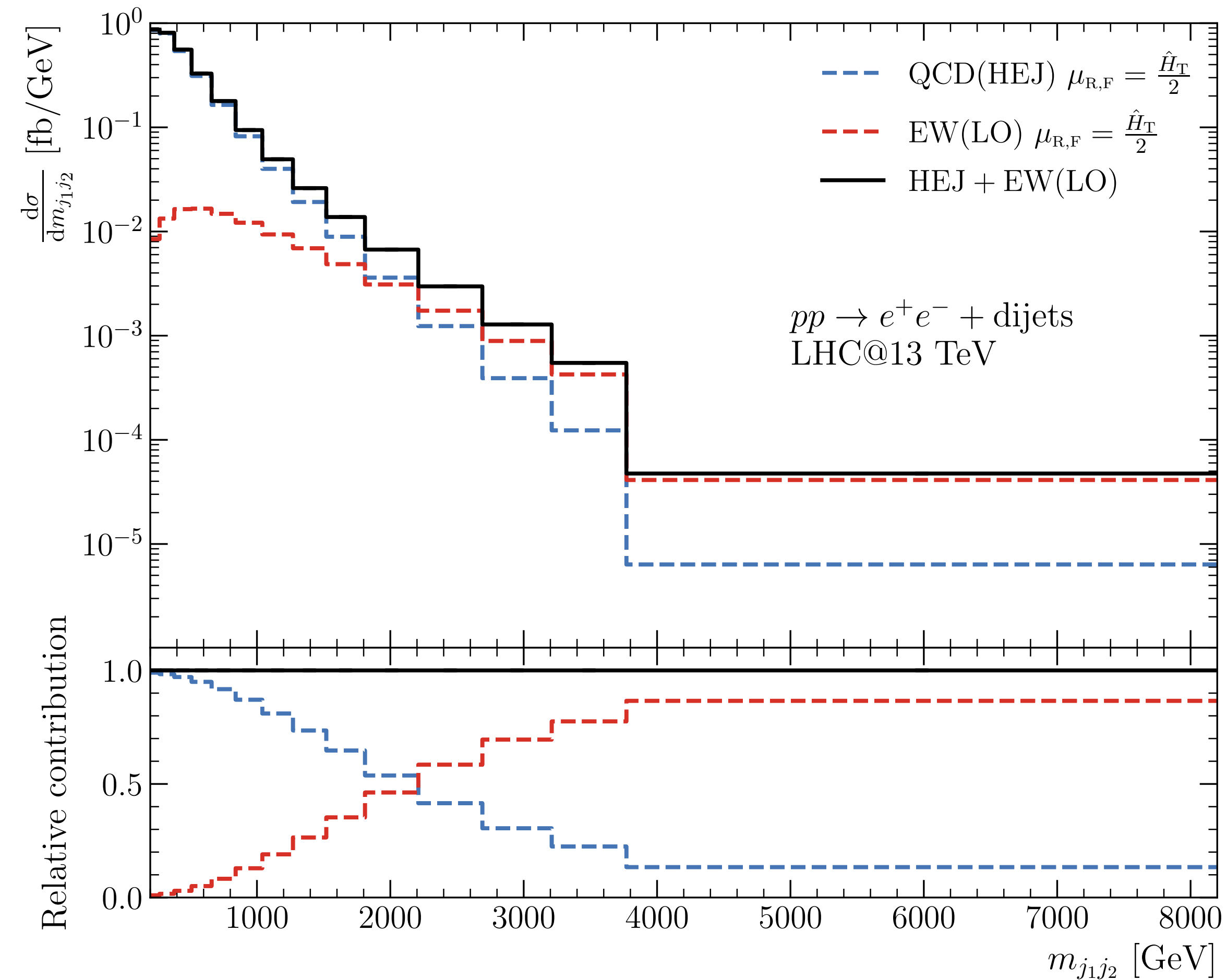
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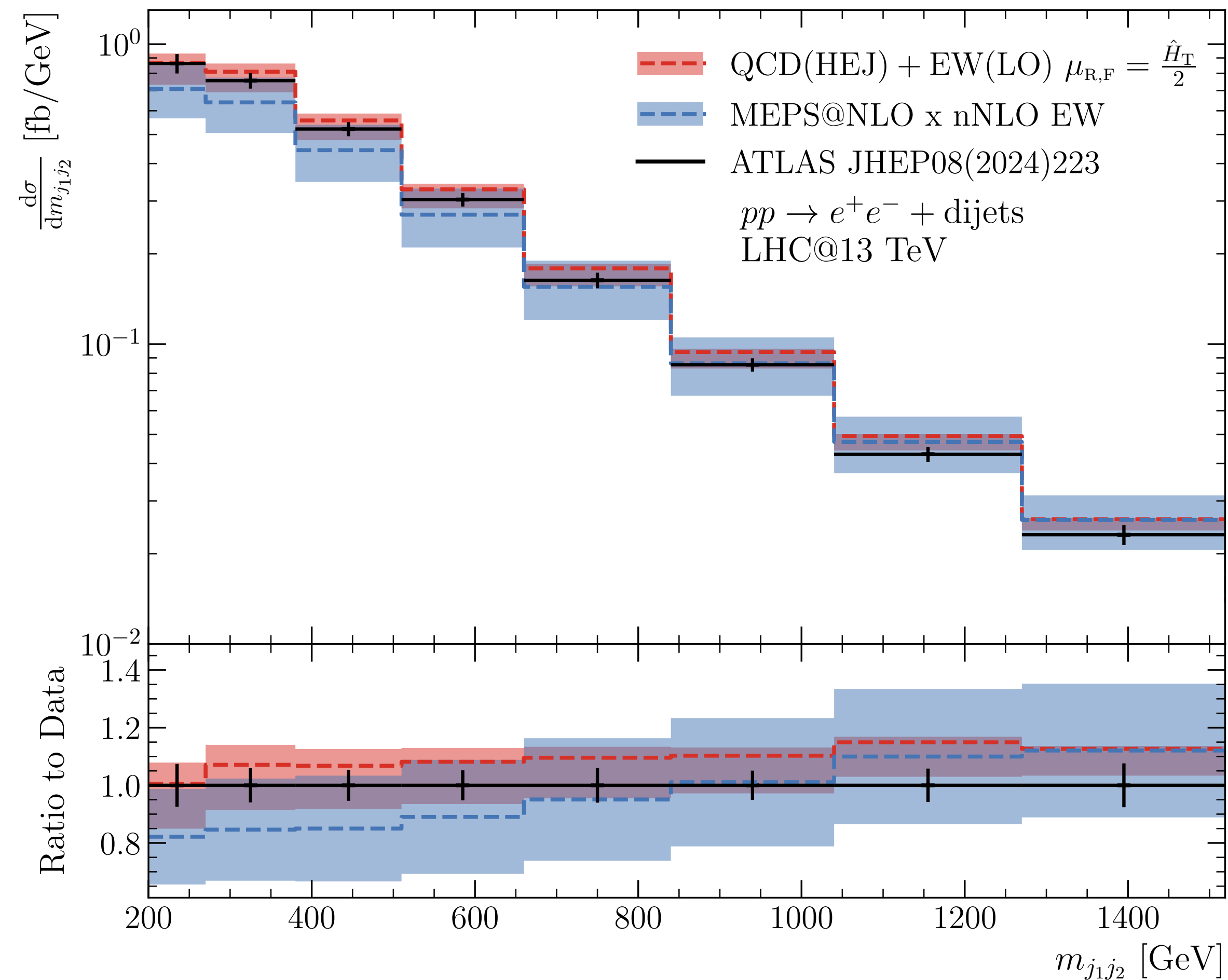
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Recent measurement of the $pp \rightarrow e^+e^- + \text{dijets}$ by [\[ATLAS, 2403.02793\]](#)



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The leading order predictions are obtained using Sherpa 2.2 with Openloops 2 MEPS@NLO

[\[Sherpa, 1905.09127\]](#)

[\[J. M. Lindert et al, 1705.04664\]](#)

[\[F. Buccioni, et al, 1907.13071\]](#)

Conclusions

- Improvement in the description of the radiation pattern can help in suppressing the QCD-background in VBF studies searching for the di-Higgs process
- Effects from high-energy corrections show up in experimental measurements! Description of these corrections requires dedicated resummation → **HEJ**
- Will be even more important with higher precision data, and at higher energies

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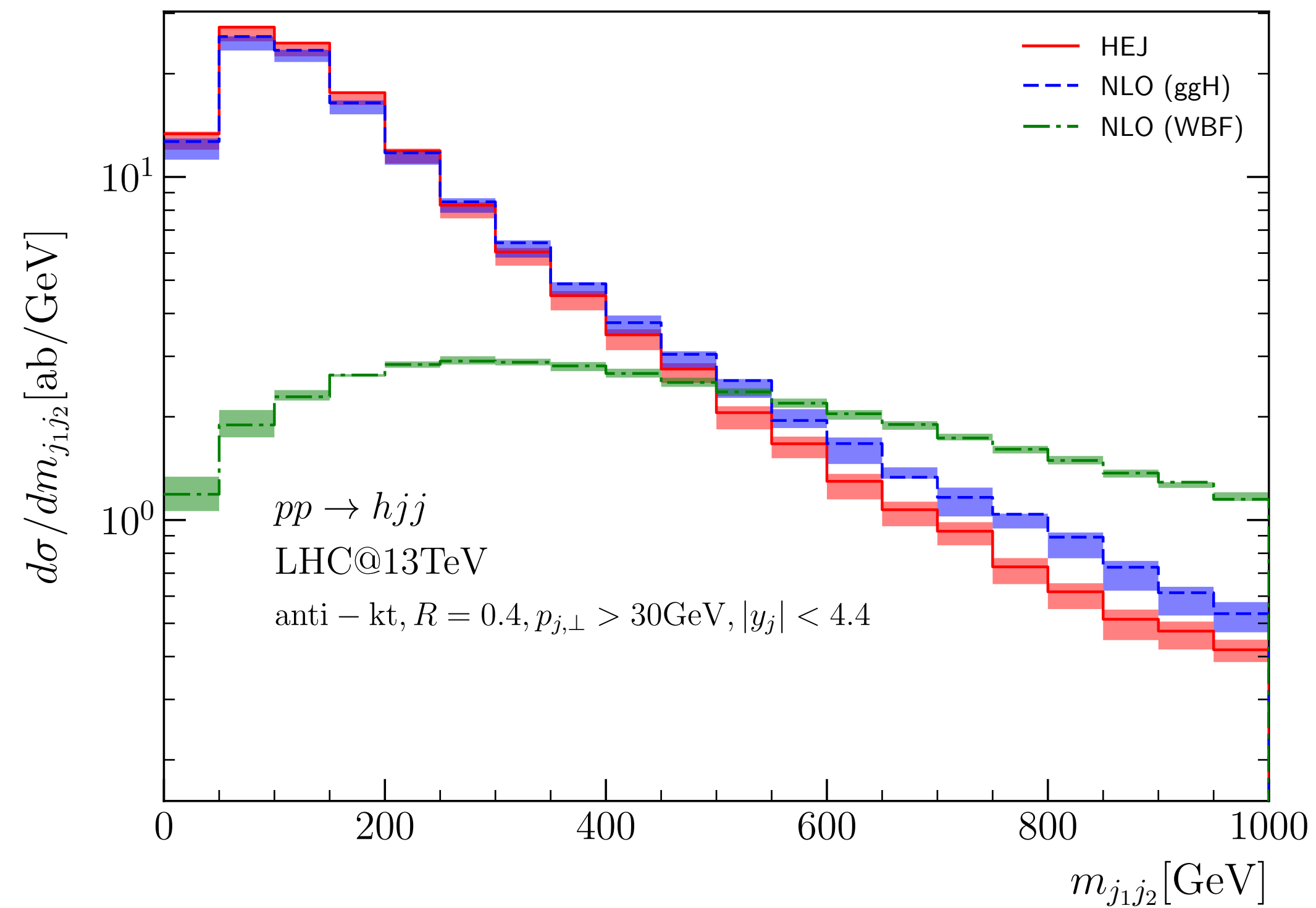
Thank you!

Auxiliary slides

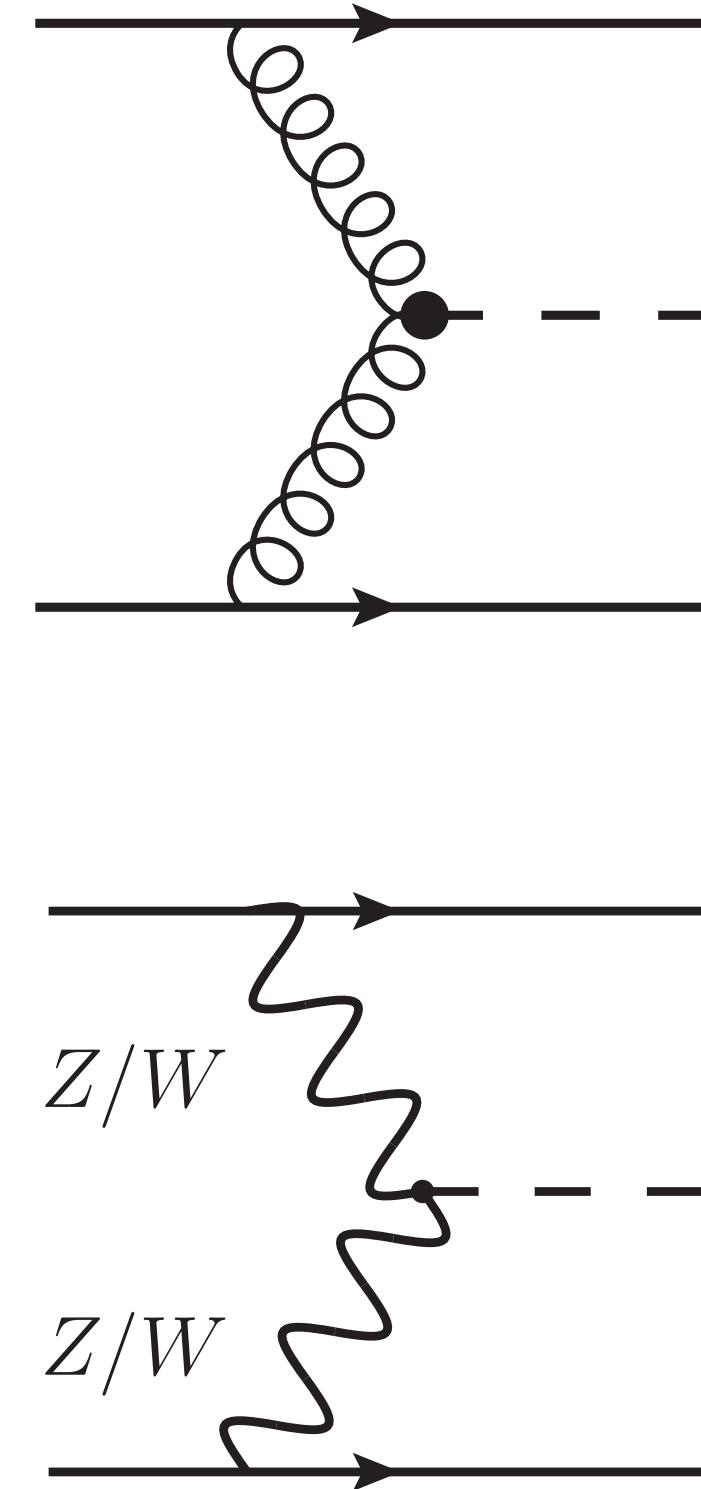
Higgs + dijets

High-energy logarithms are crucial in describing regions selected by VBF cuts

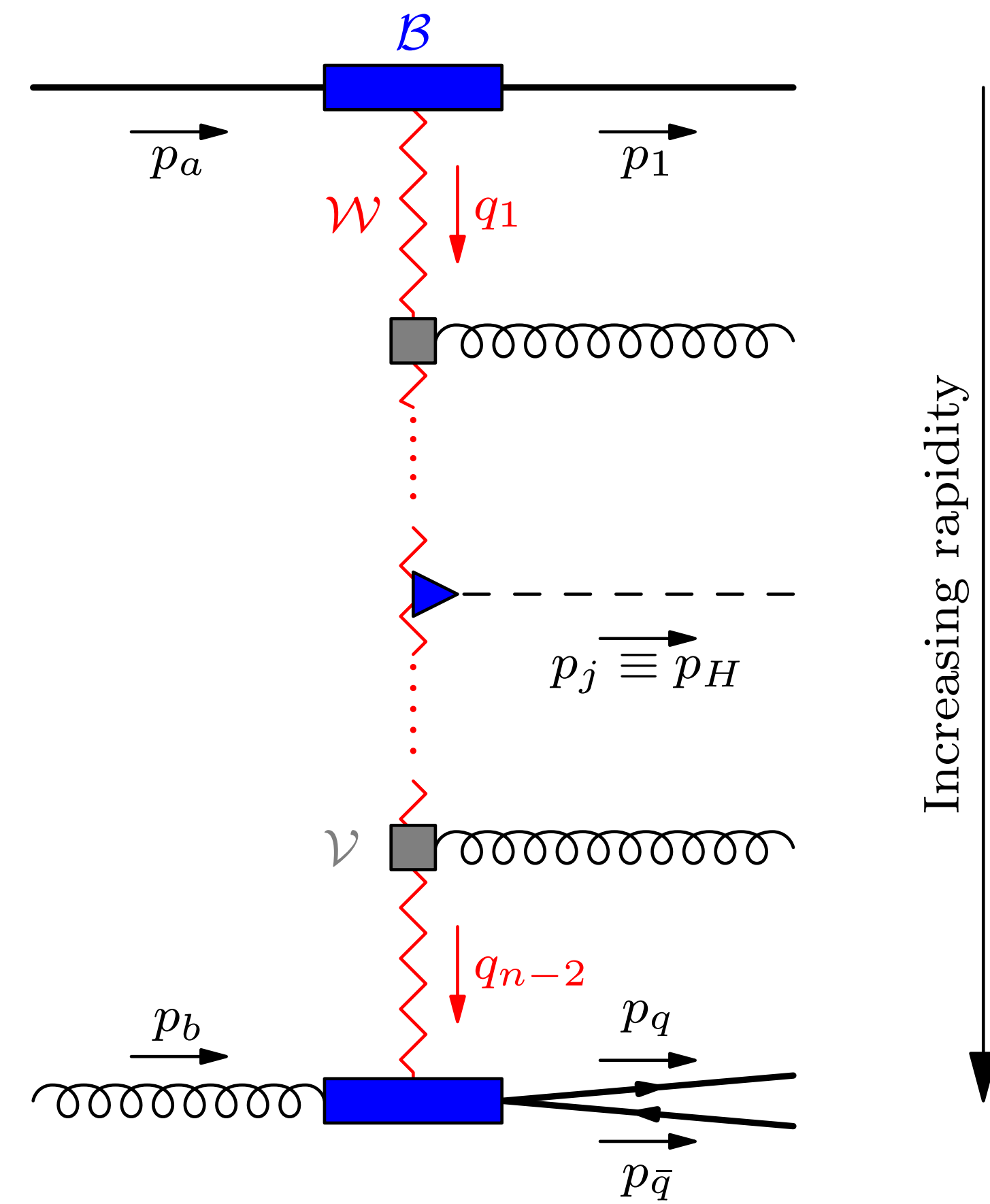
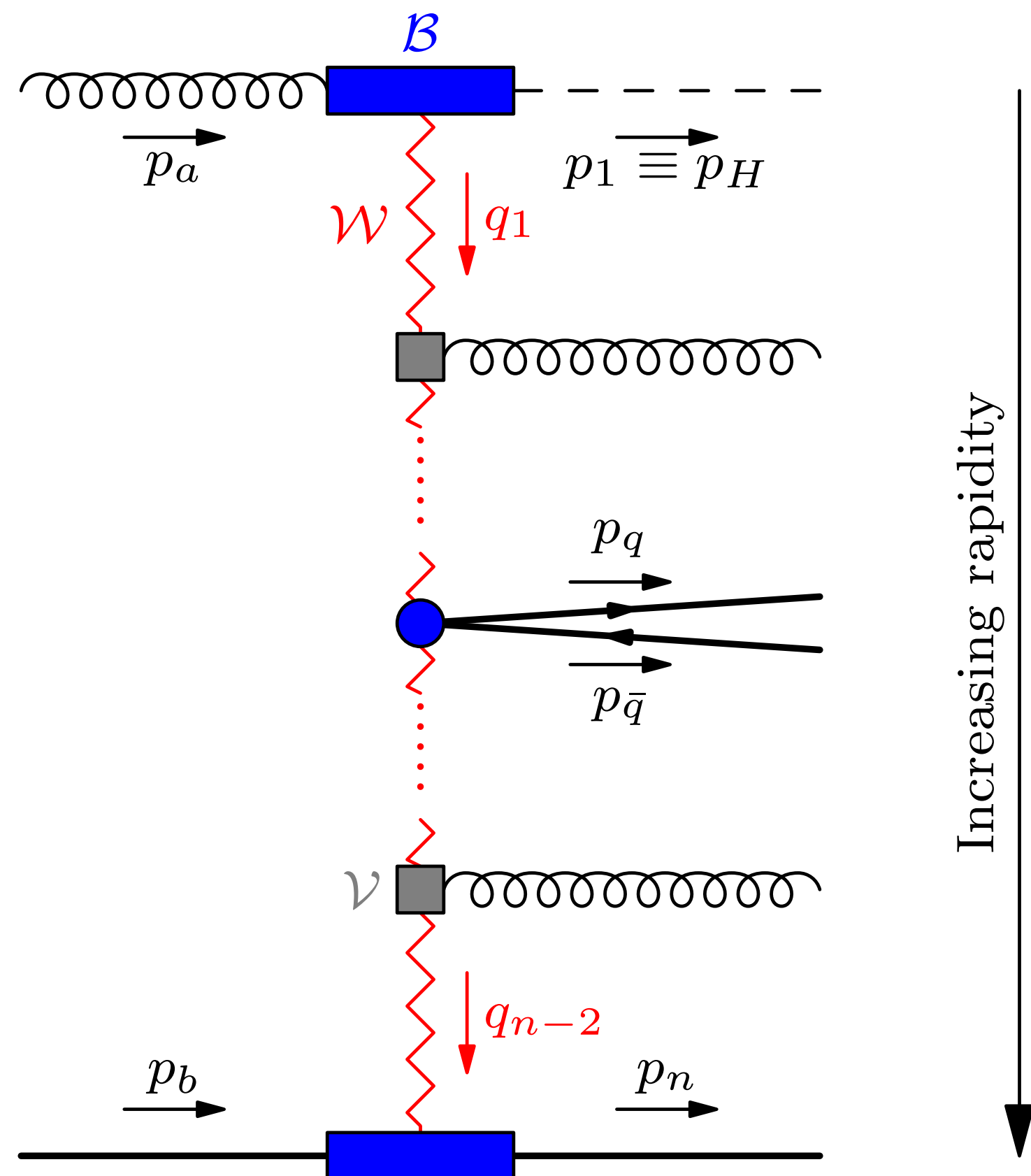
$$\Delta y_{jj} > 2.8 \quad m_{jj} > 400 \text{ GeV}$$



[J. Andersen, M. Heil, A. Maier, J. Smillie, in 1803.07977]



HEJ Developments



p_T and $\Delta\phi_{jj}$

