# THEORETICAL PROGRESS FOR HIGGS-BOSON PRODUCTION VIA VECTOR-BOSON FUSION
# ICHEP XLI 2022

Karlsruher Institut für Technologie

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*ITP, IAP, Karlsruhe Institute of Technology*
*Bologna, 8 July, 2022*

# SUCCESS OF LHC HIGGS EXPERIMENTS

- 10 years since Higgs Boson discovery
- A "bump" evolves to
  - Higgs mass at $125.35 \pm 0.14$ GeV
  - Fiducial total cross section at $\pm 10\,\%$ precision
  - Differential cross section at $\pm 10 \sim 25\,\%$ precision
  - Bosonic and 3rd generation fermionic couplings observed

4th July 2012 CERN main auditorium

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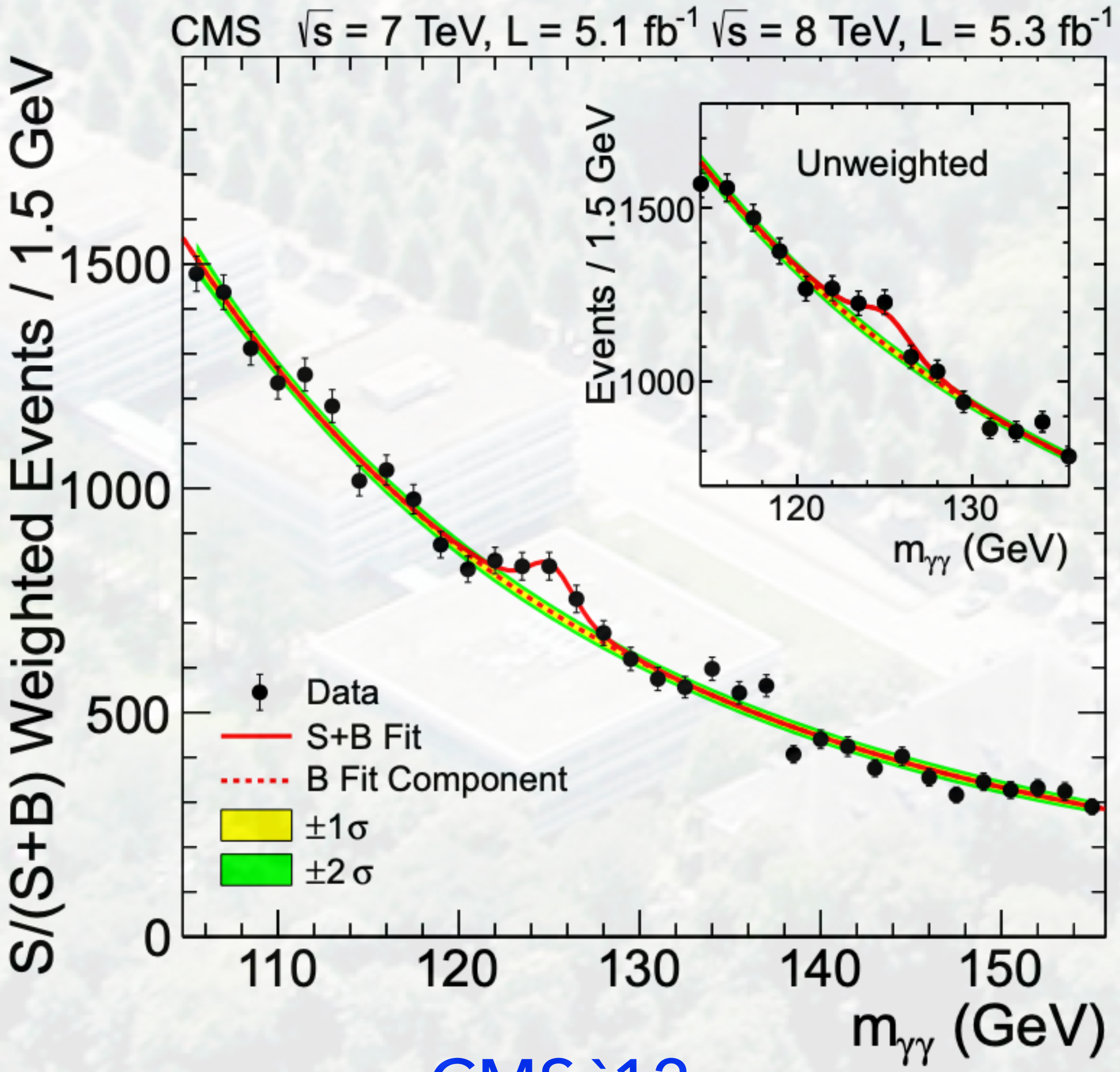


CMS `12

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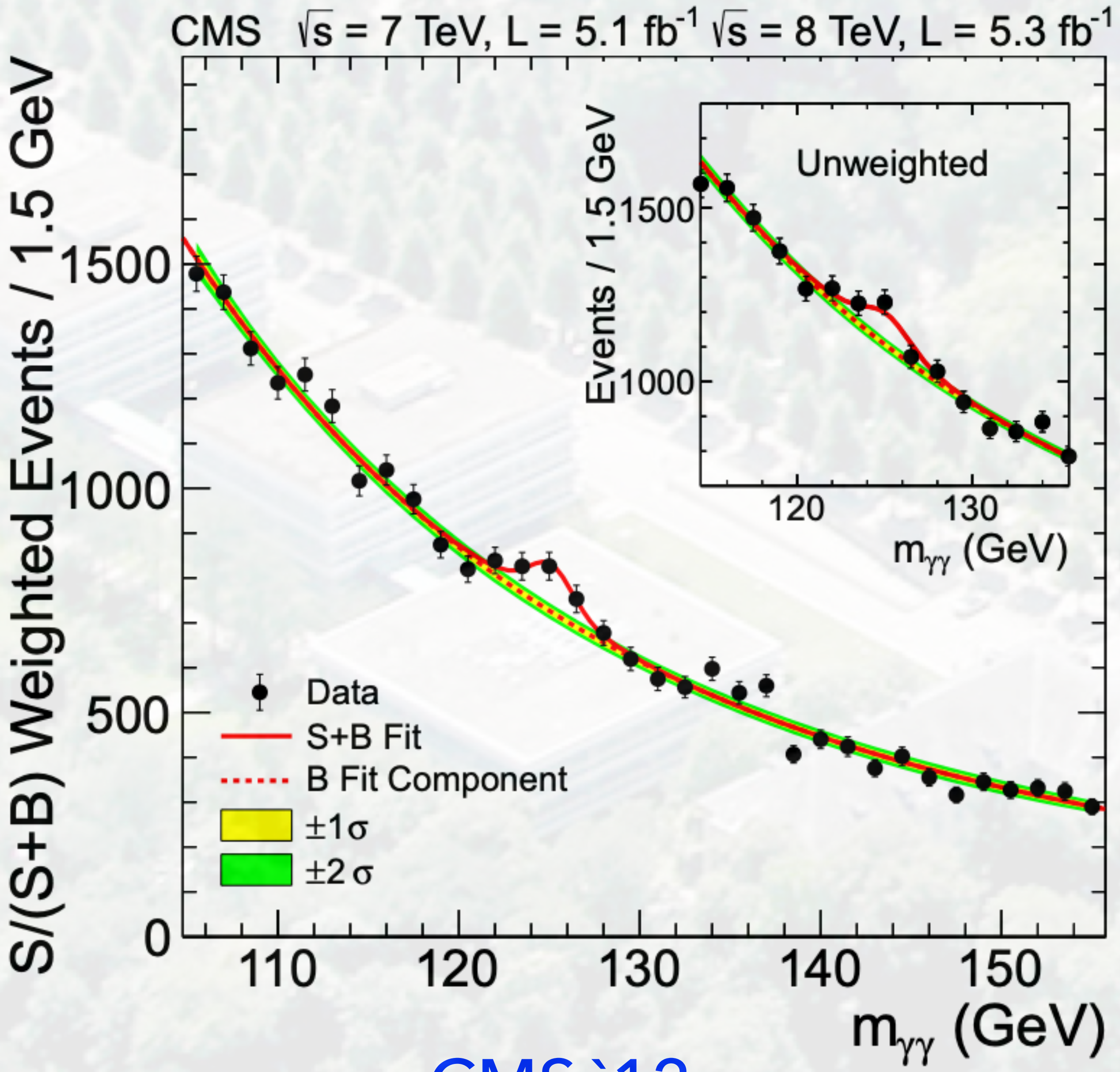


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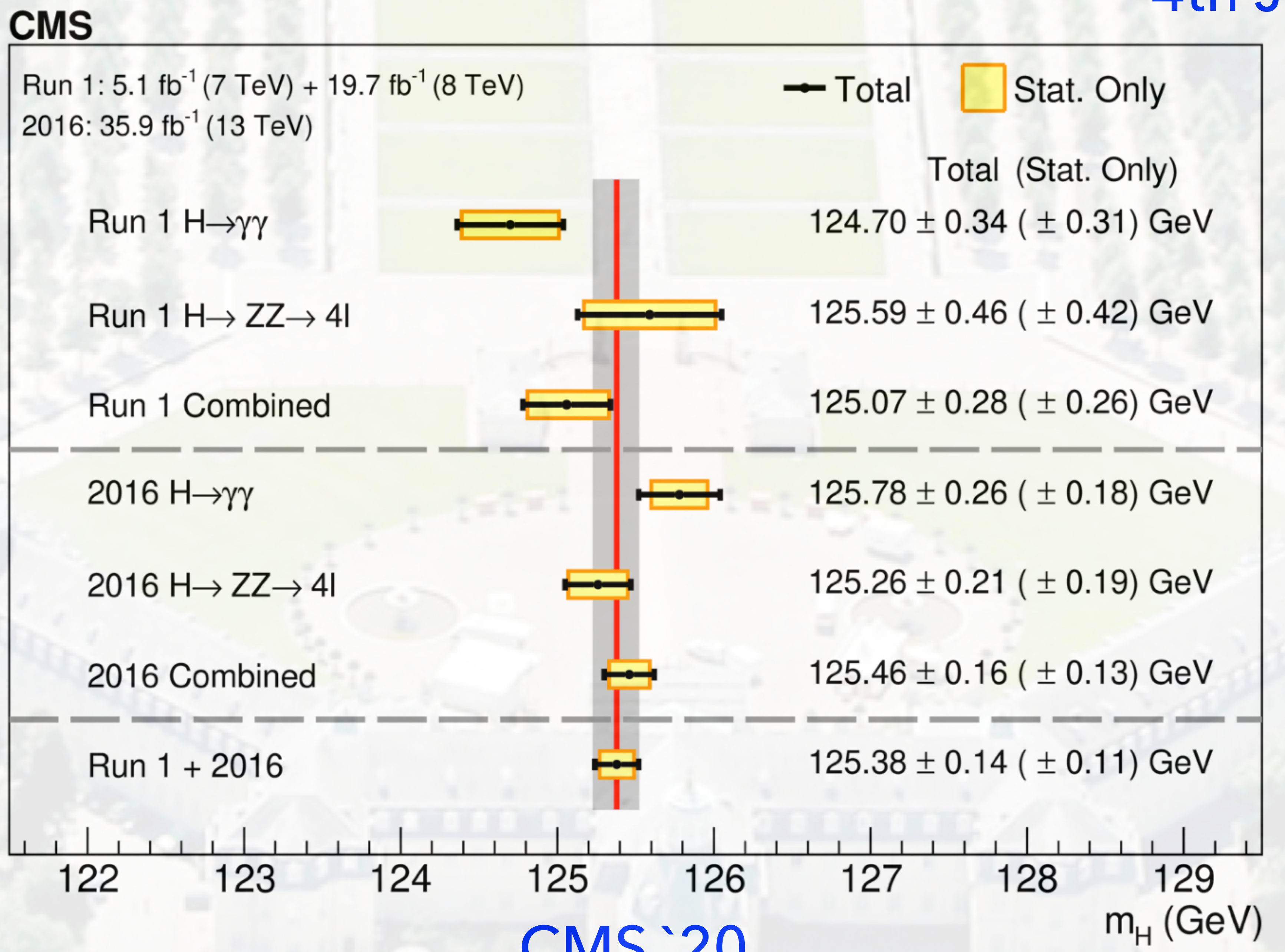
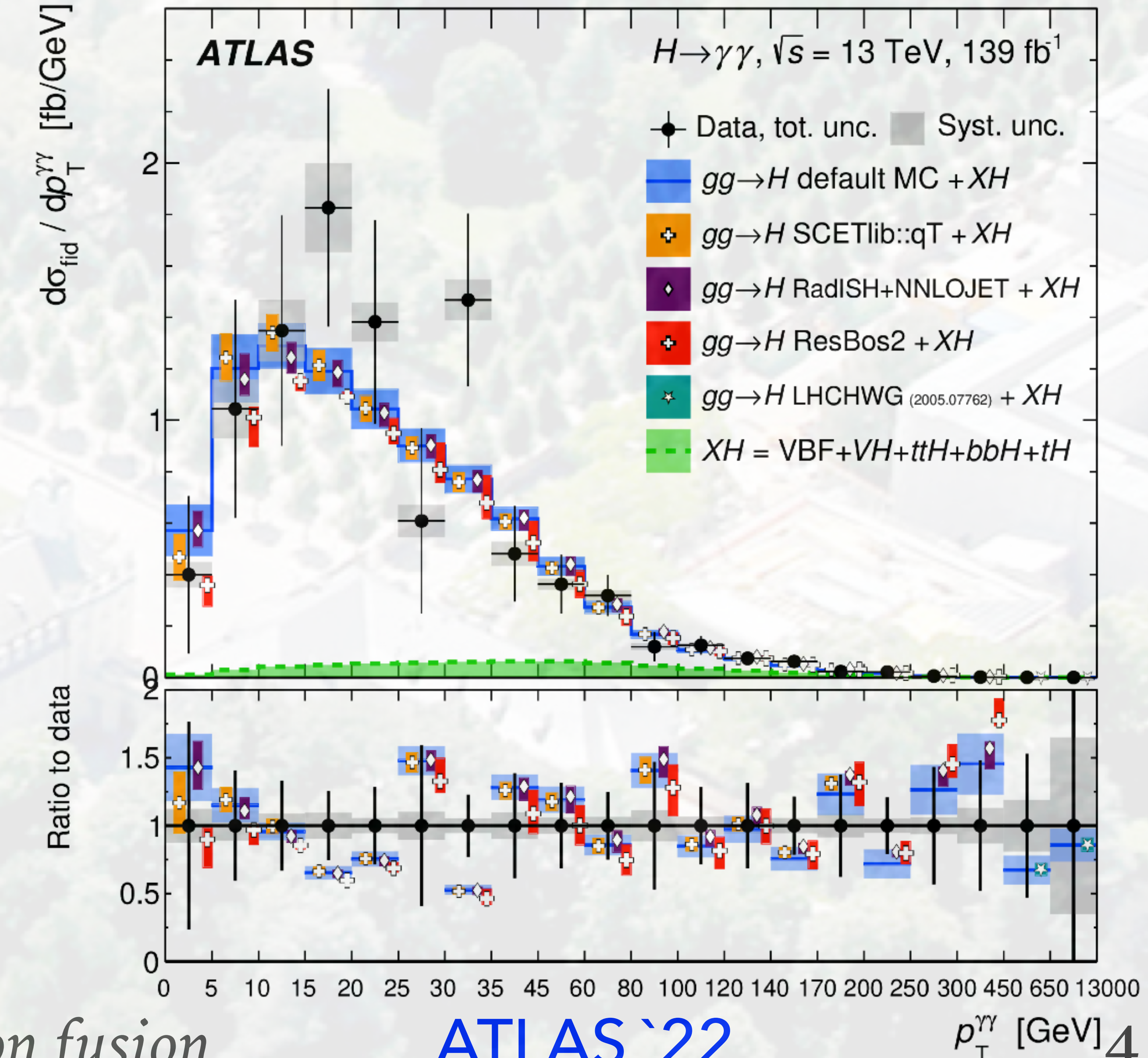



CMS `20




ATLAS `22

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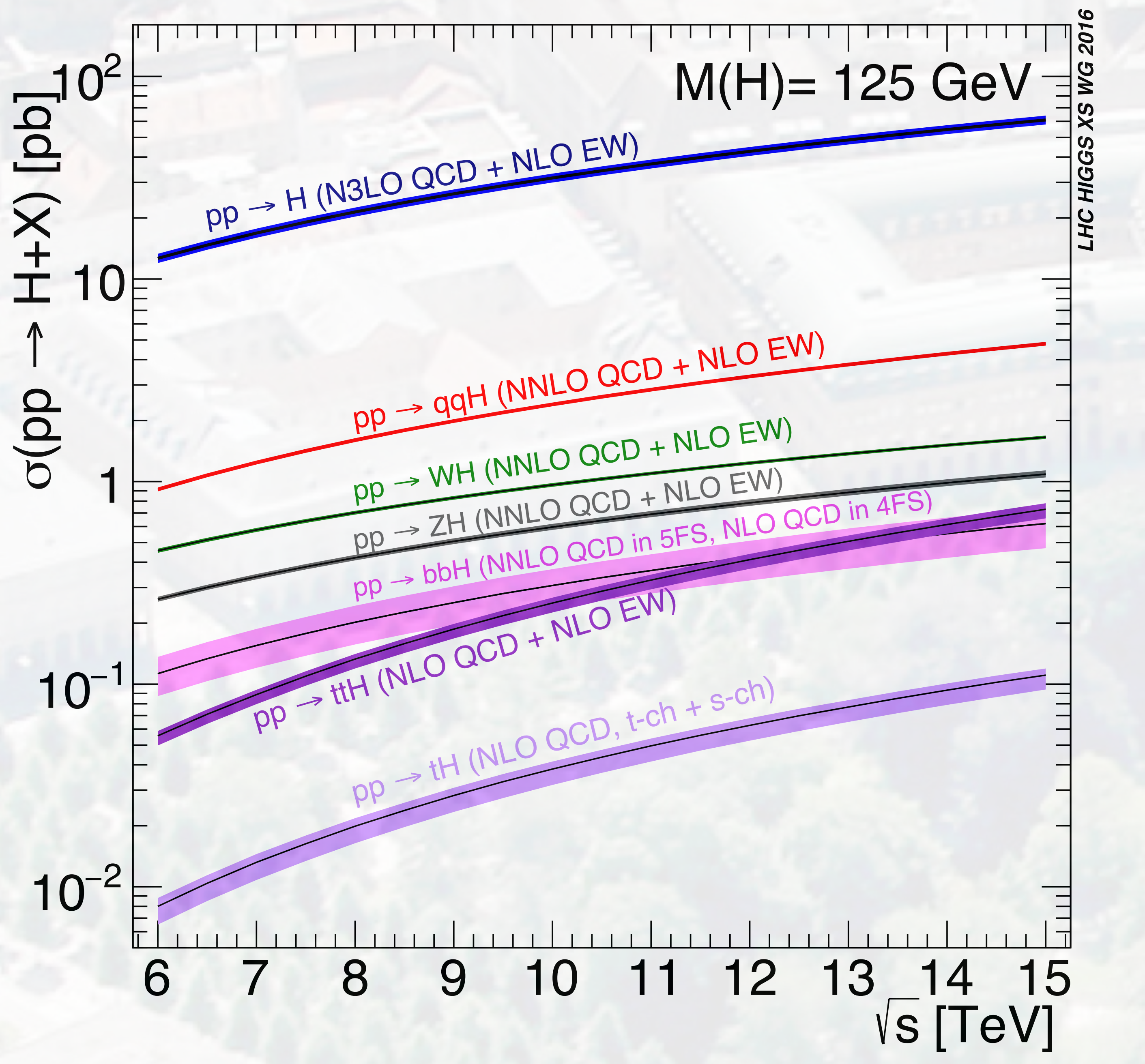

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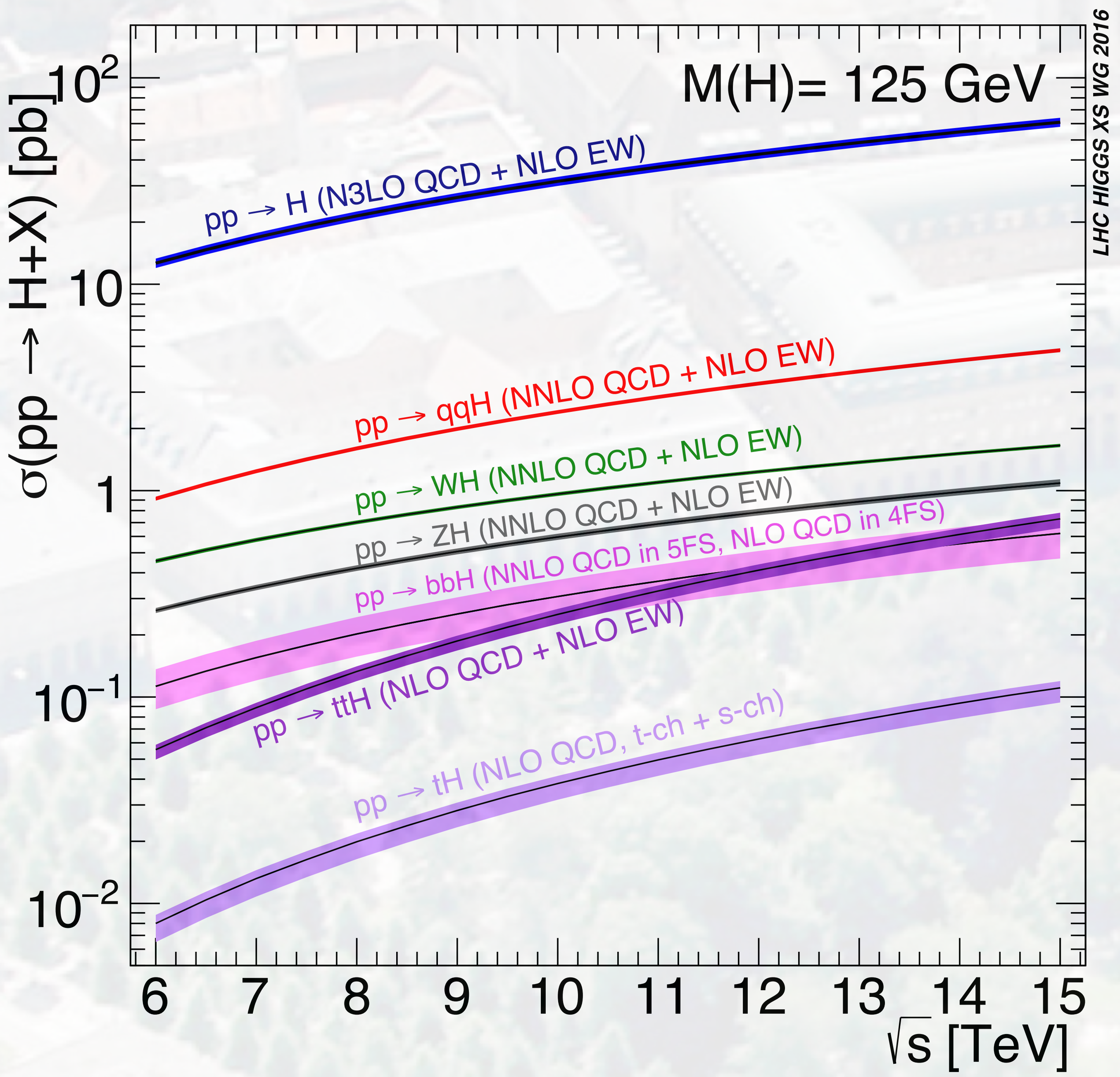
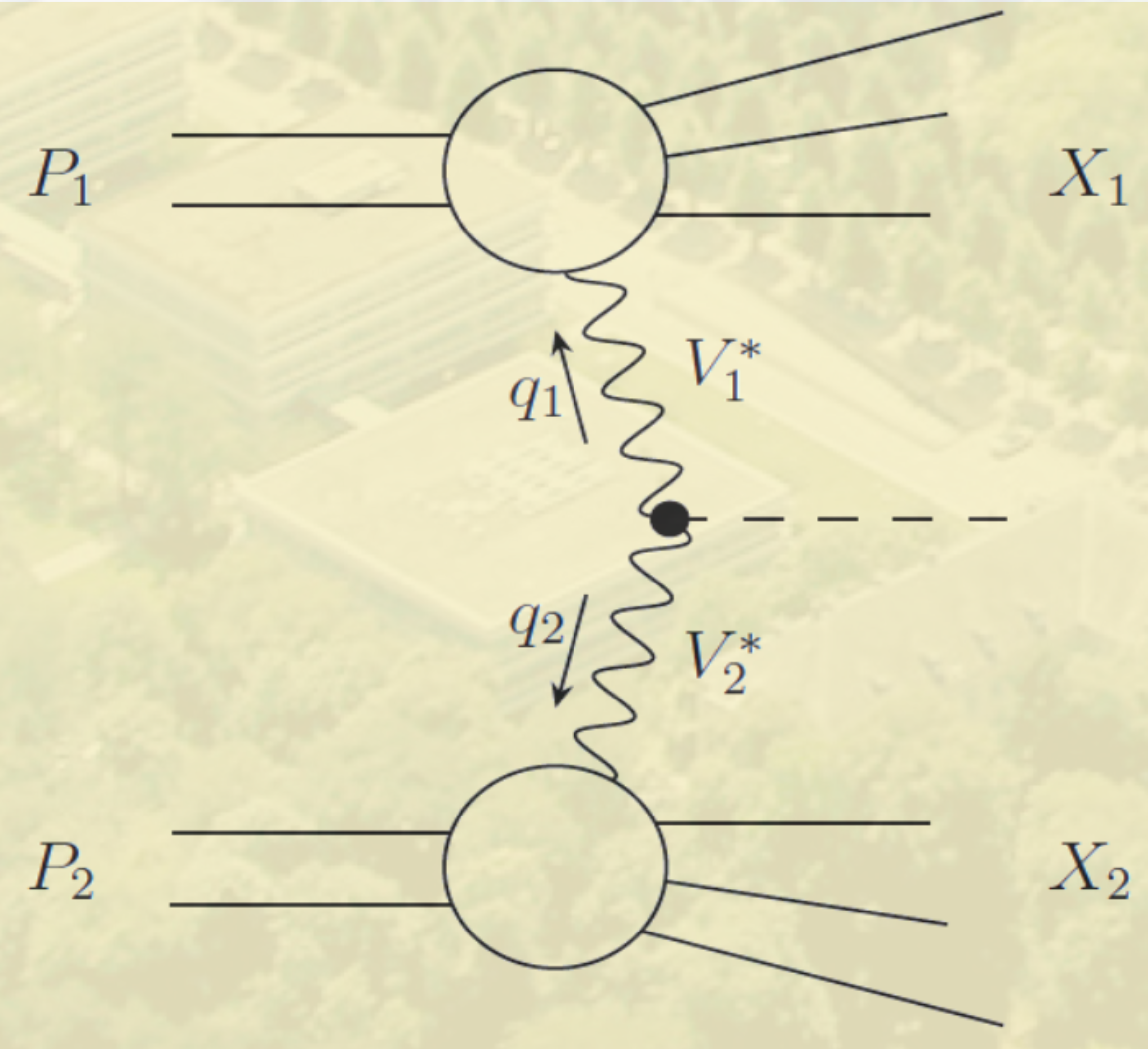



Image from VBF@NNLO package



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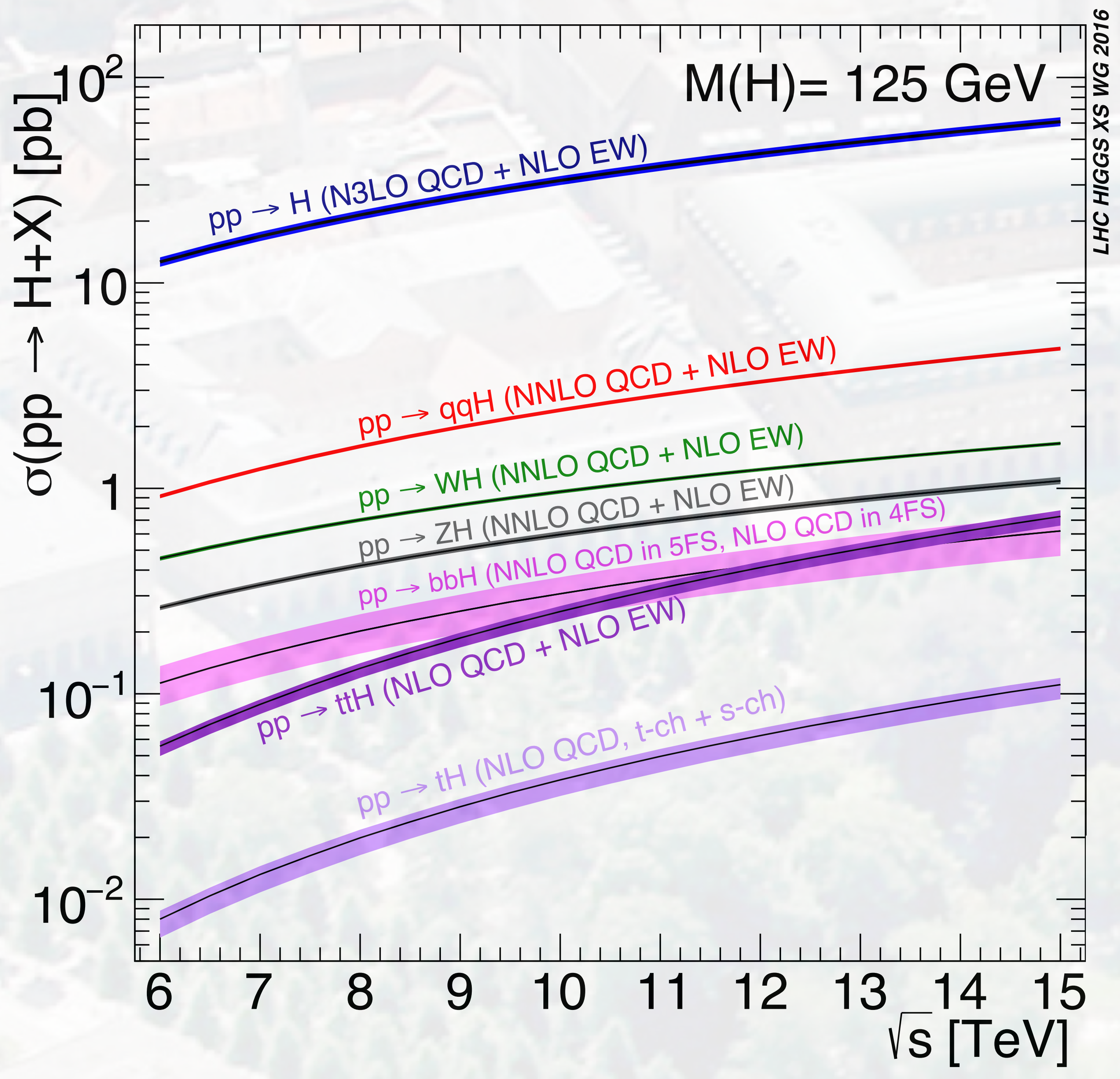
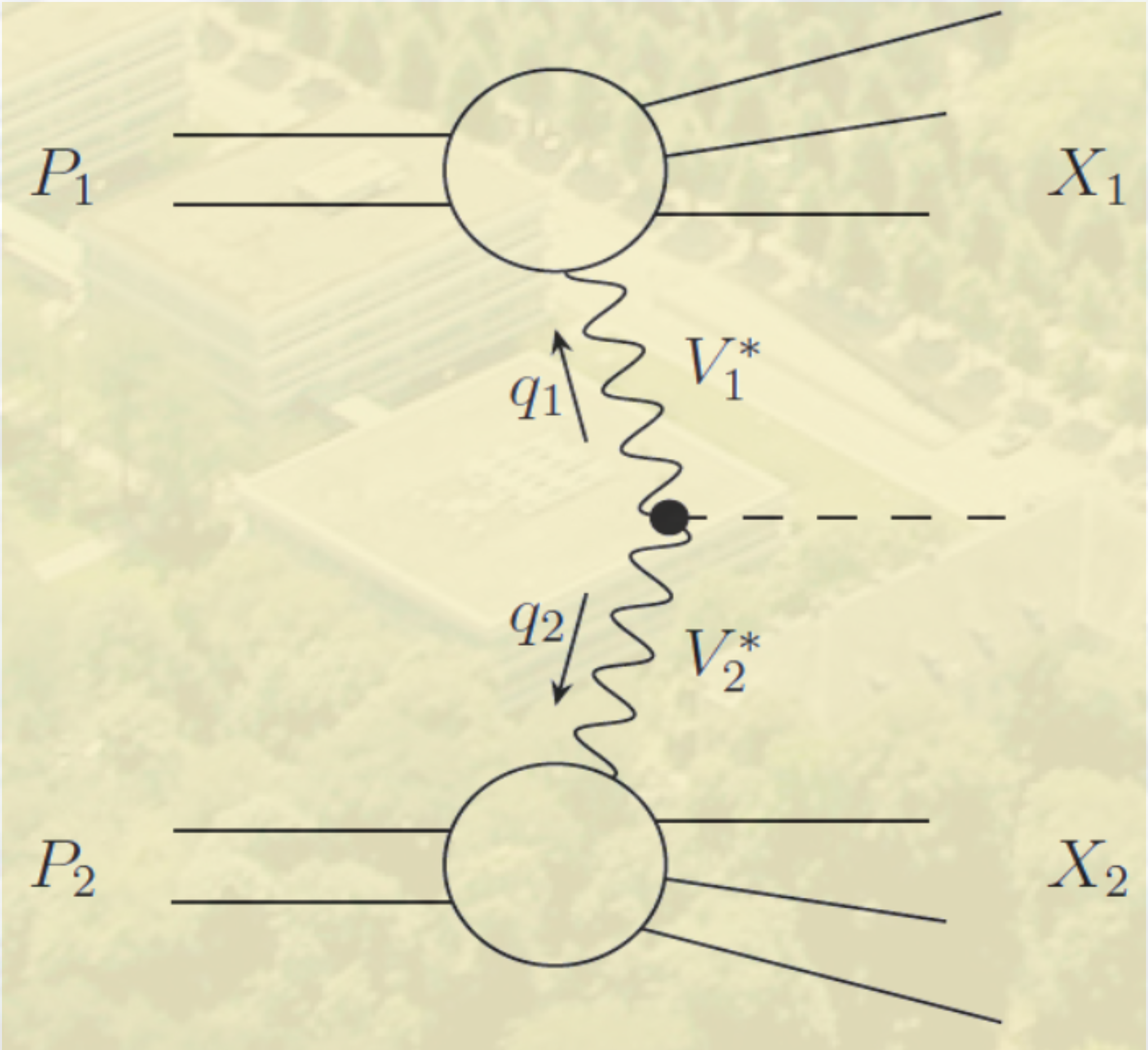



- The **V**ector **B**oson **F**usion **H**iggs production channel
- Measured via $H \to b\bar{b}$ at $\mu = \sigma/\sigma^{SM} = 0.99^{+0.36}_{-0.34}$ by ATLAS
- Measured via $H \to \gamma\gamma$ at $\mu = \sigma/\sigma^{SM} = 1.04^{+0.34}_{-0.31}$ by CMS
- Overlap with VH and ggF: $q\bar{q} \to V(\to q\bar{q}) + H, gg \to gg + H$
- Large QCD background

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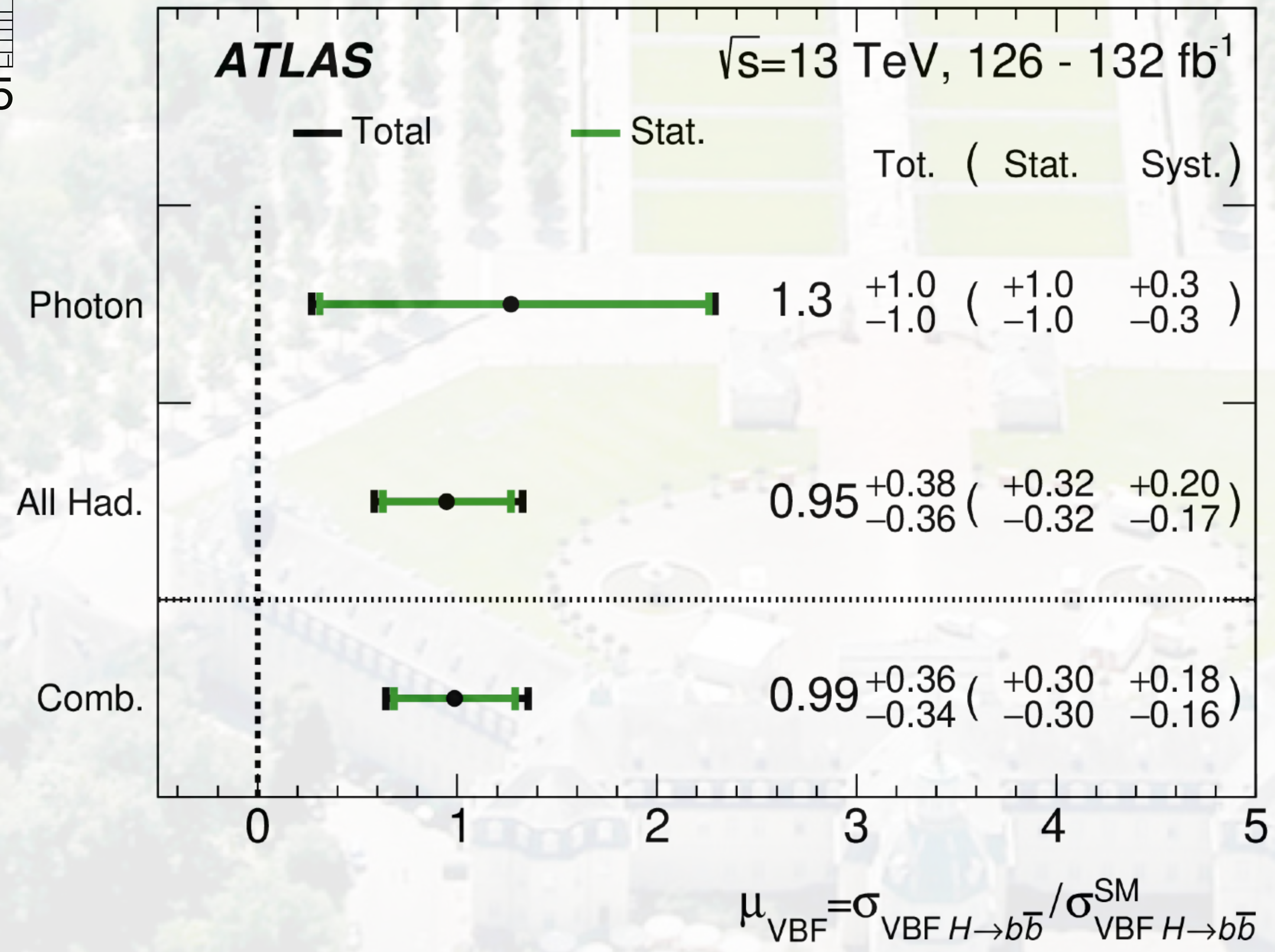
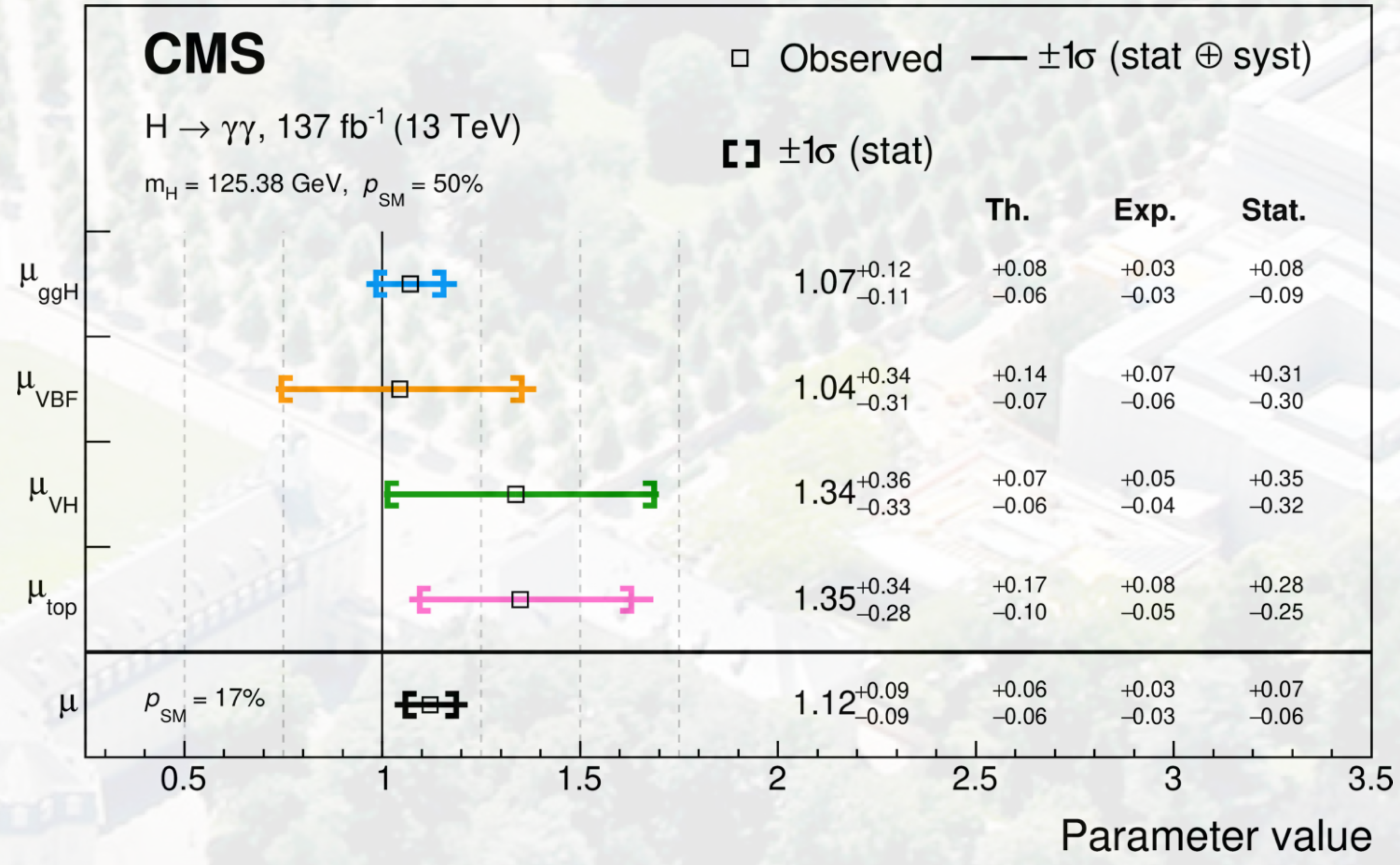
Eur. Phys. J. C. 81 (2021) 537

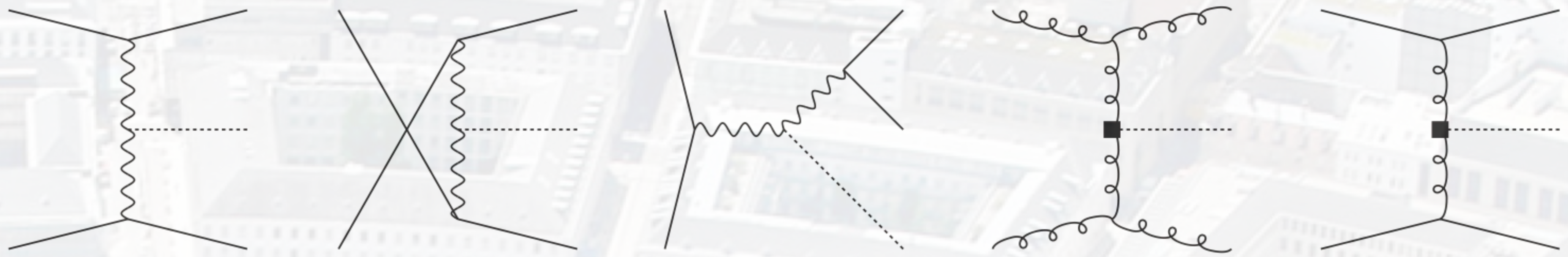



JHEP 07 (2021) 027



# DIFFERENTIAL SIGNATURE

- The Structure Function Approach (from NLO Han, Valencia, Willenbrock `92)
- Differential signature:→ ‘VBF cuts’:
  - 2-jet tagging, $m_{jj} > 350$ GeV, $\Delta y_{jj} > 4$ etc.
- Use Simplified Template Cross Section bins to enhance signal sensitivity
- Measured via $H \to WW^* \to 2l2\nu$ with various VBF fiducial bins



LO contribution from VBF, VH and ggF

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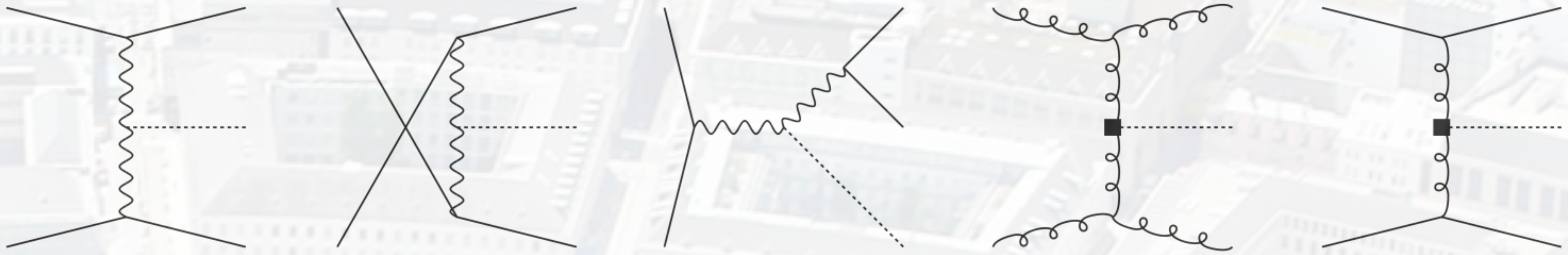

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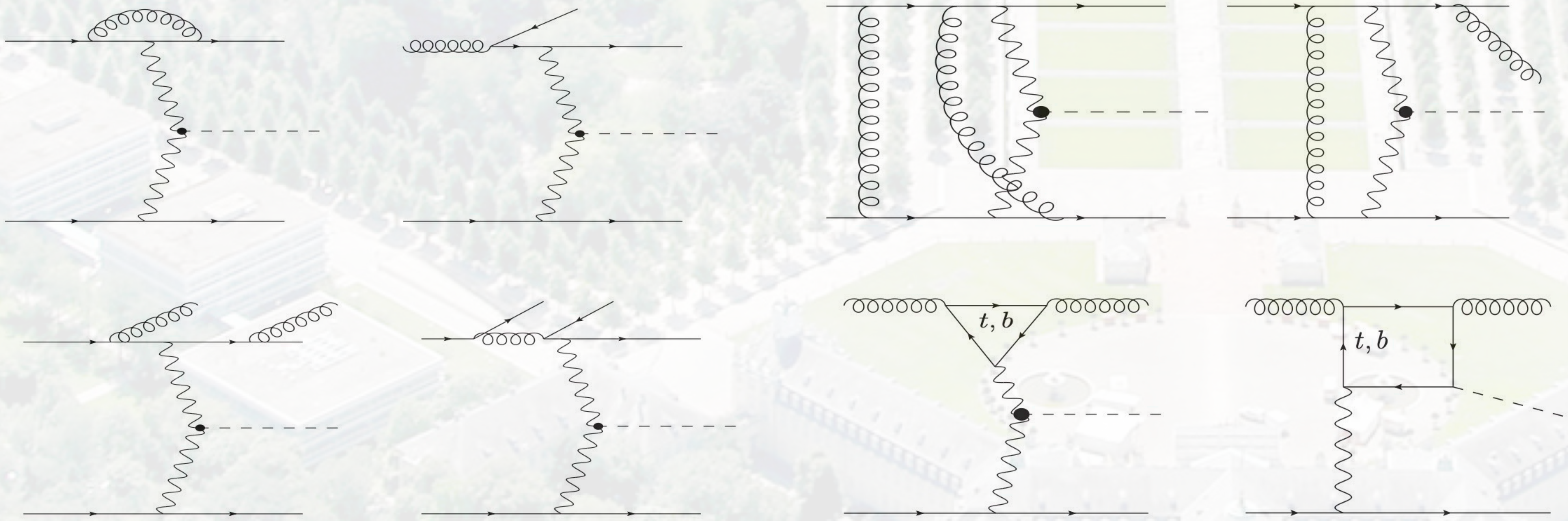


Example NLO  and NNLO contribution to VBF (Bolzoni, Maltoni, Much, Zero `10)

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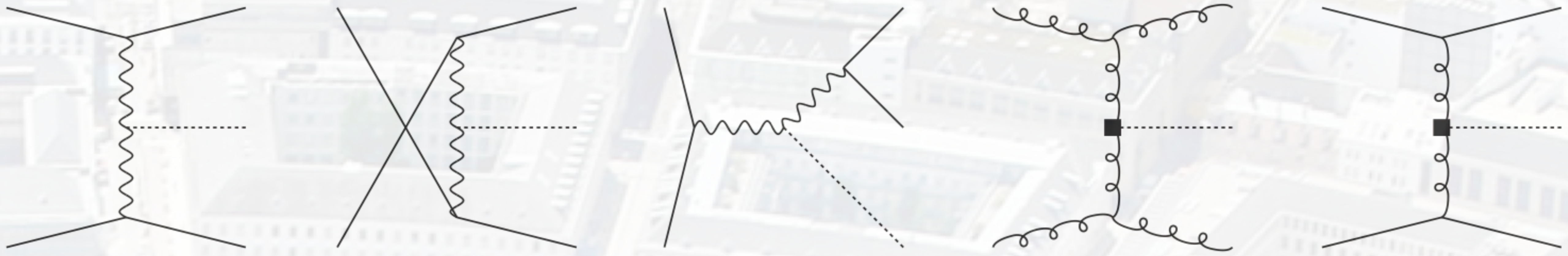

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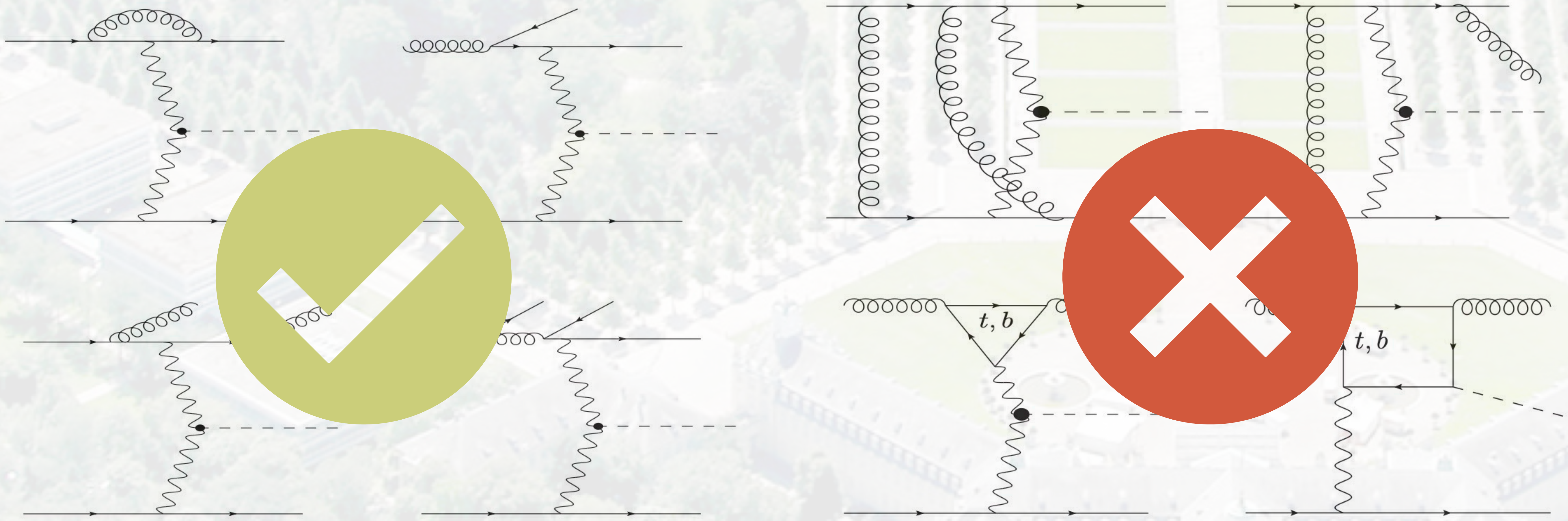


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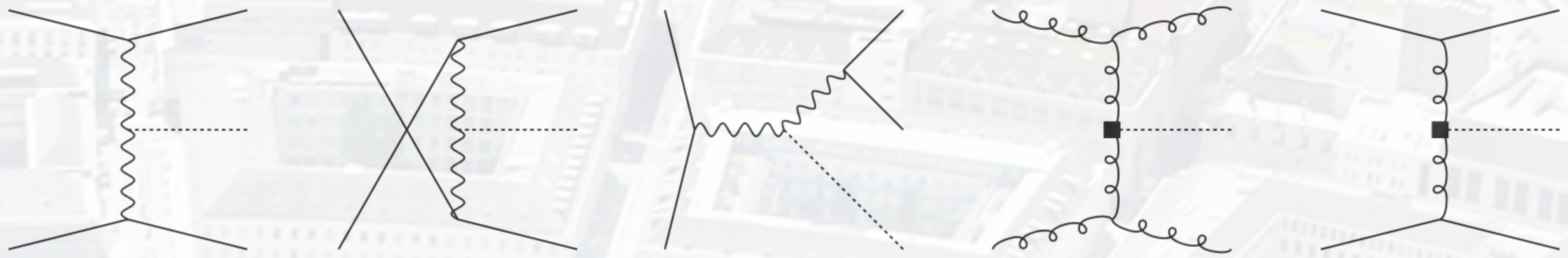

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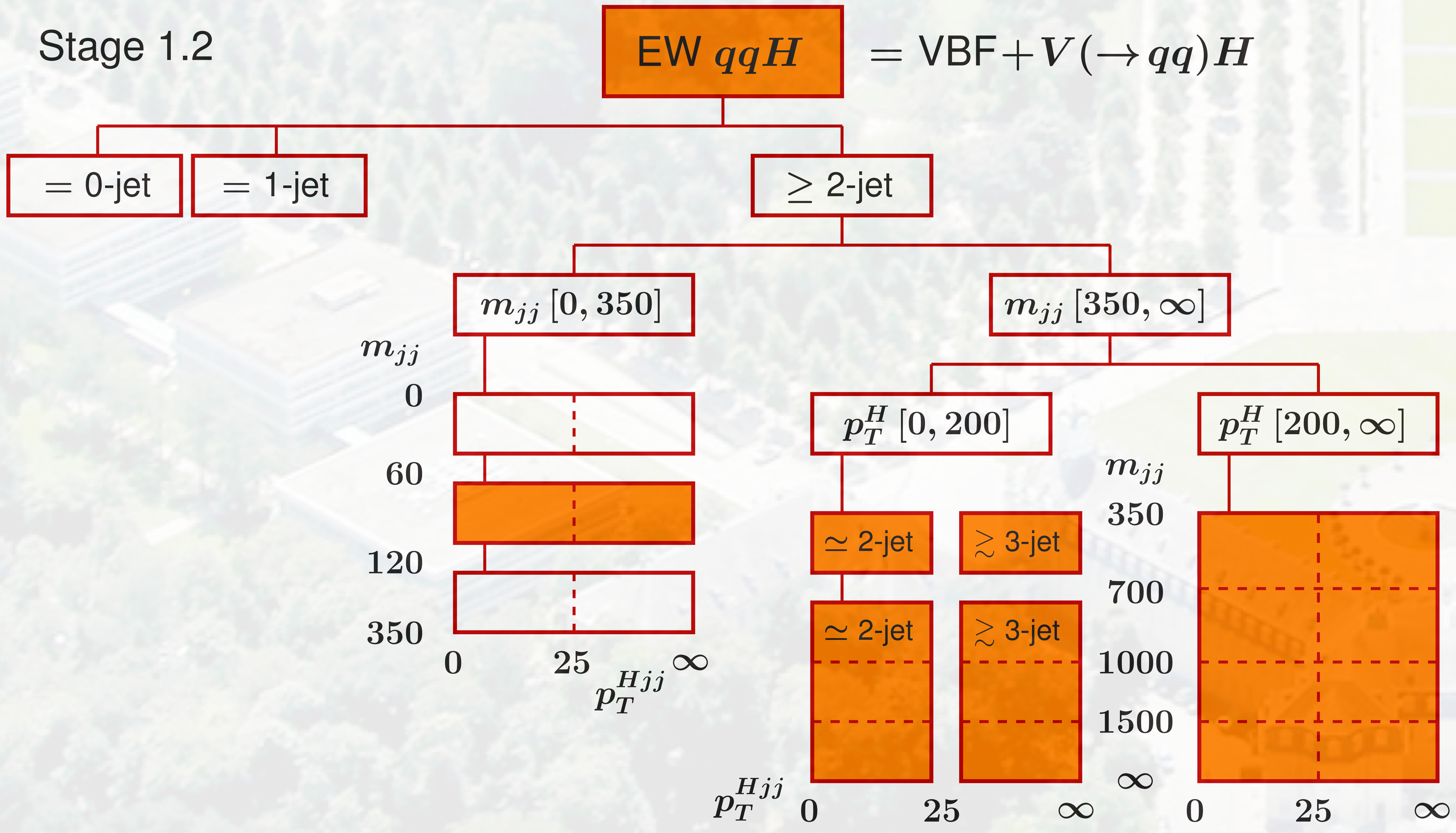

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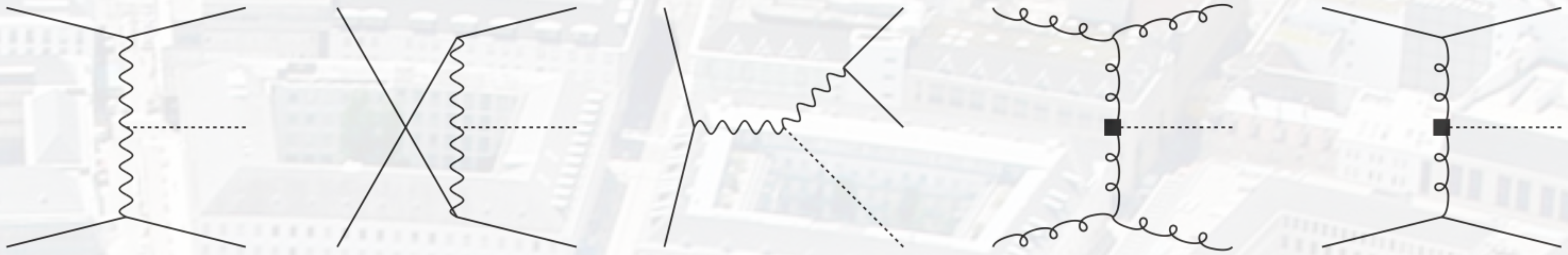

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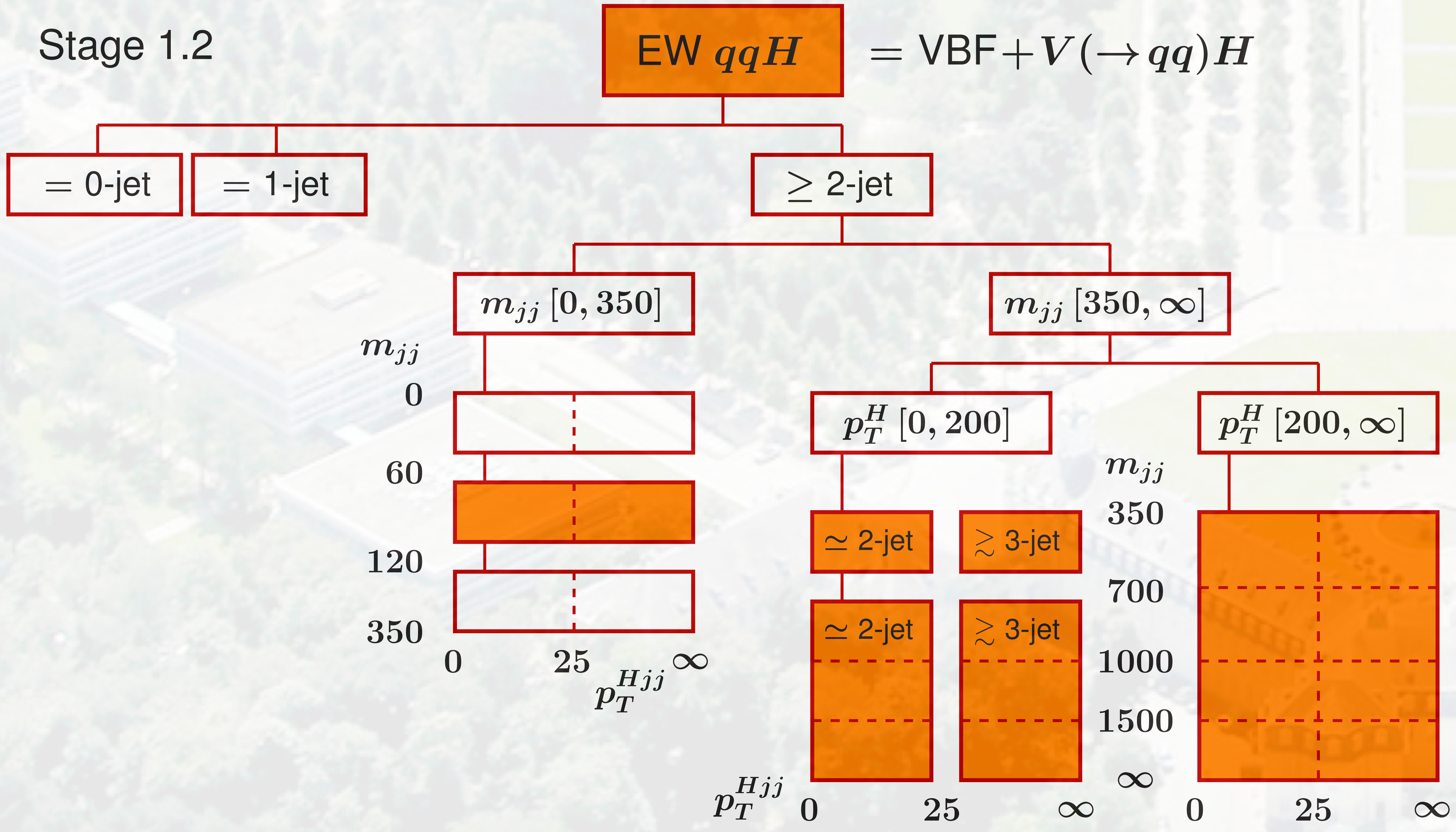


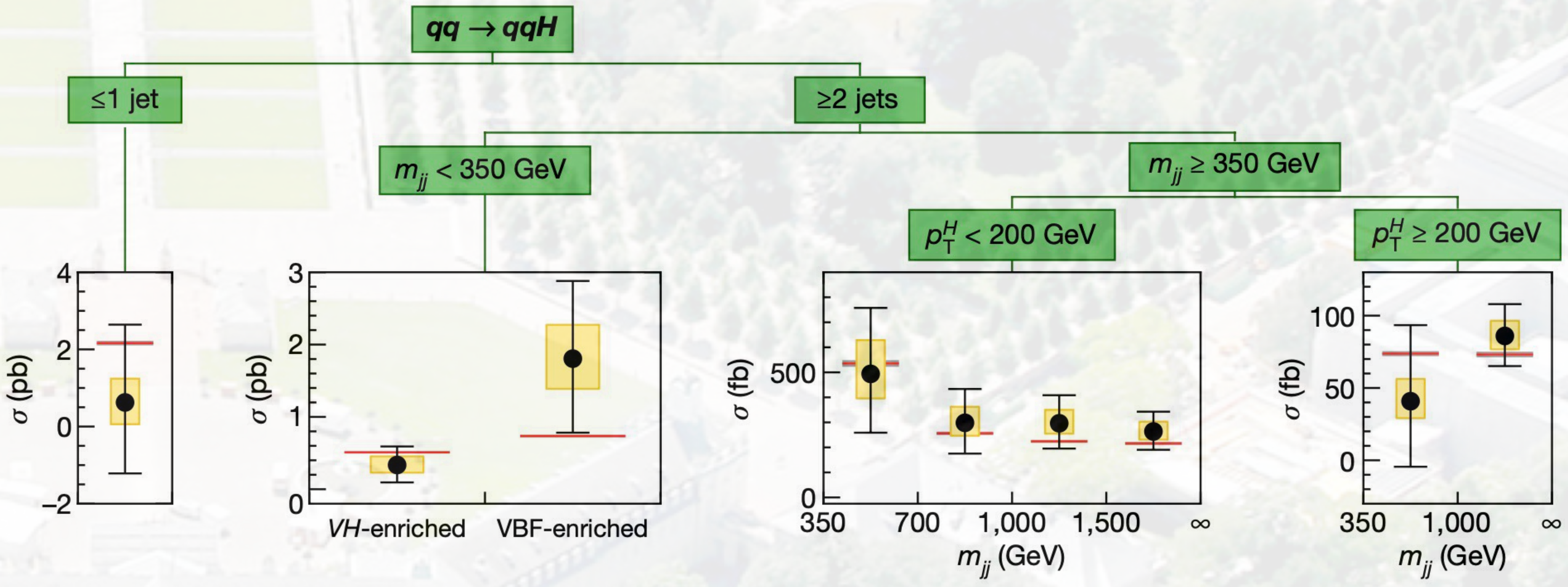


ATLAS, Nature 607 (2022)

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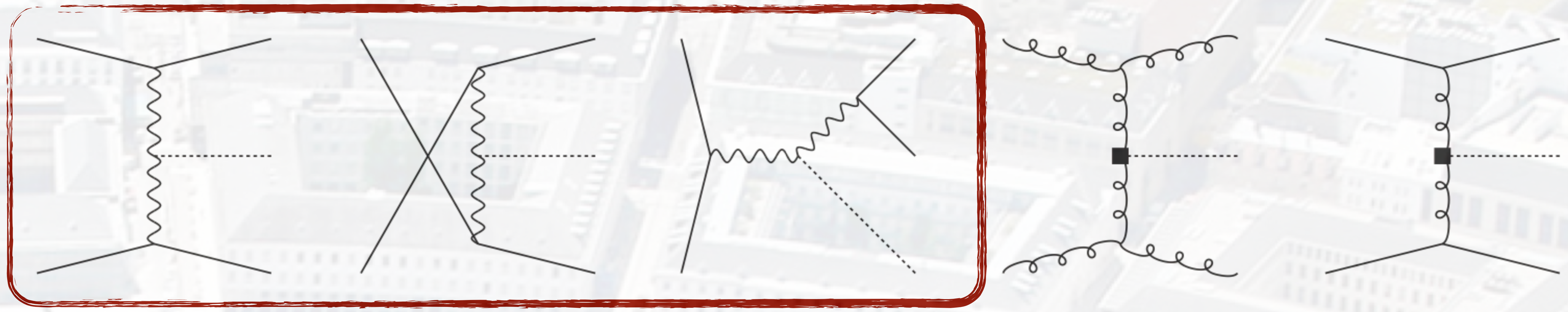

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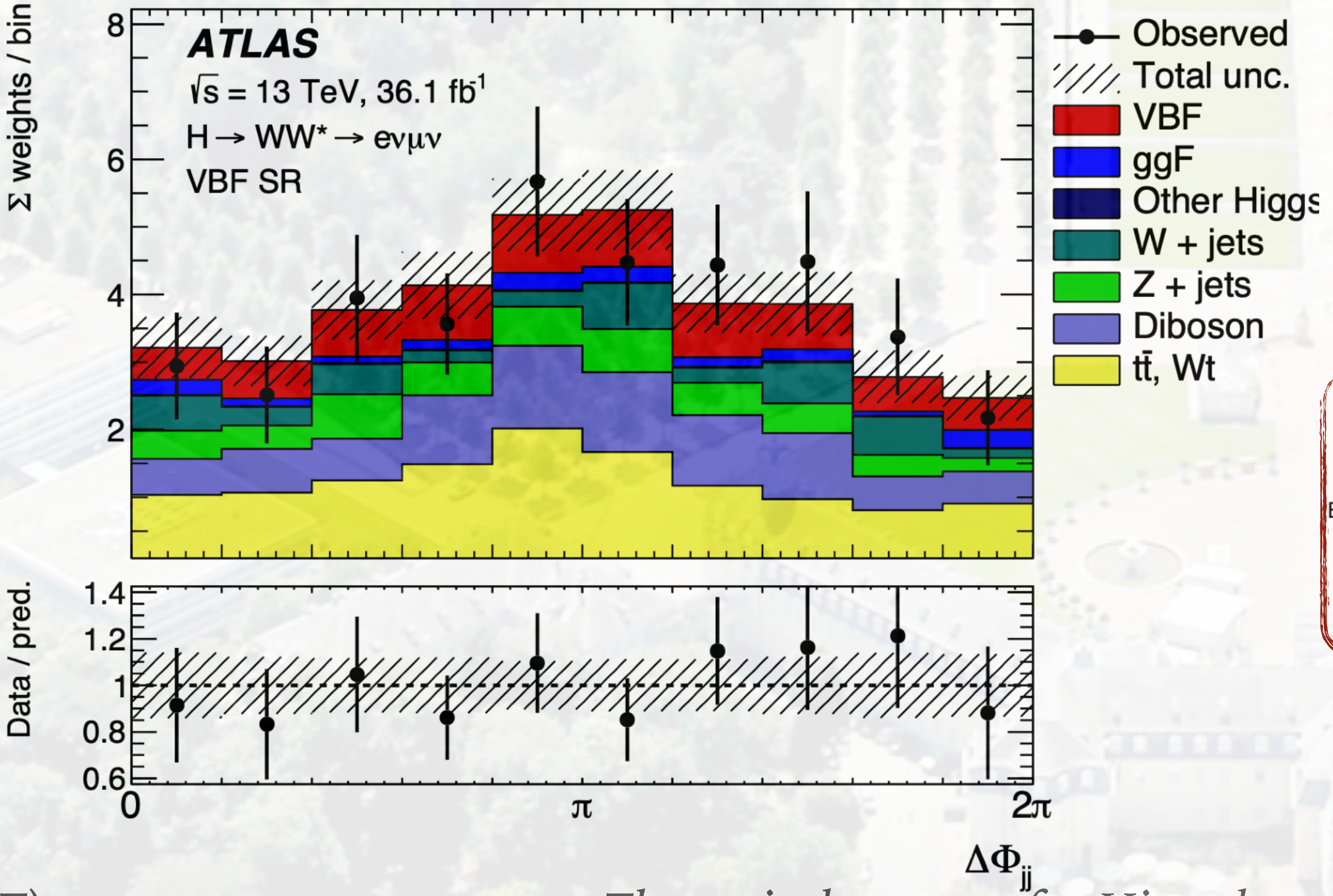


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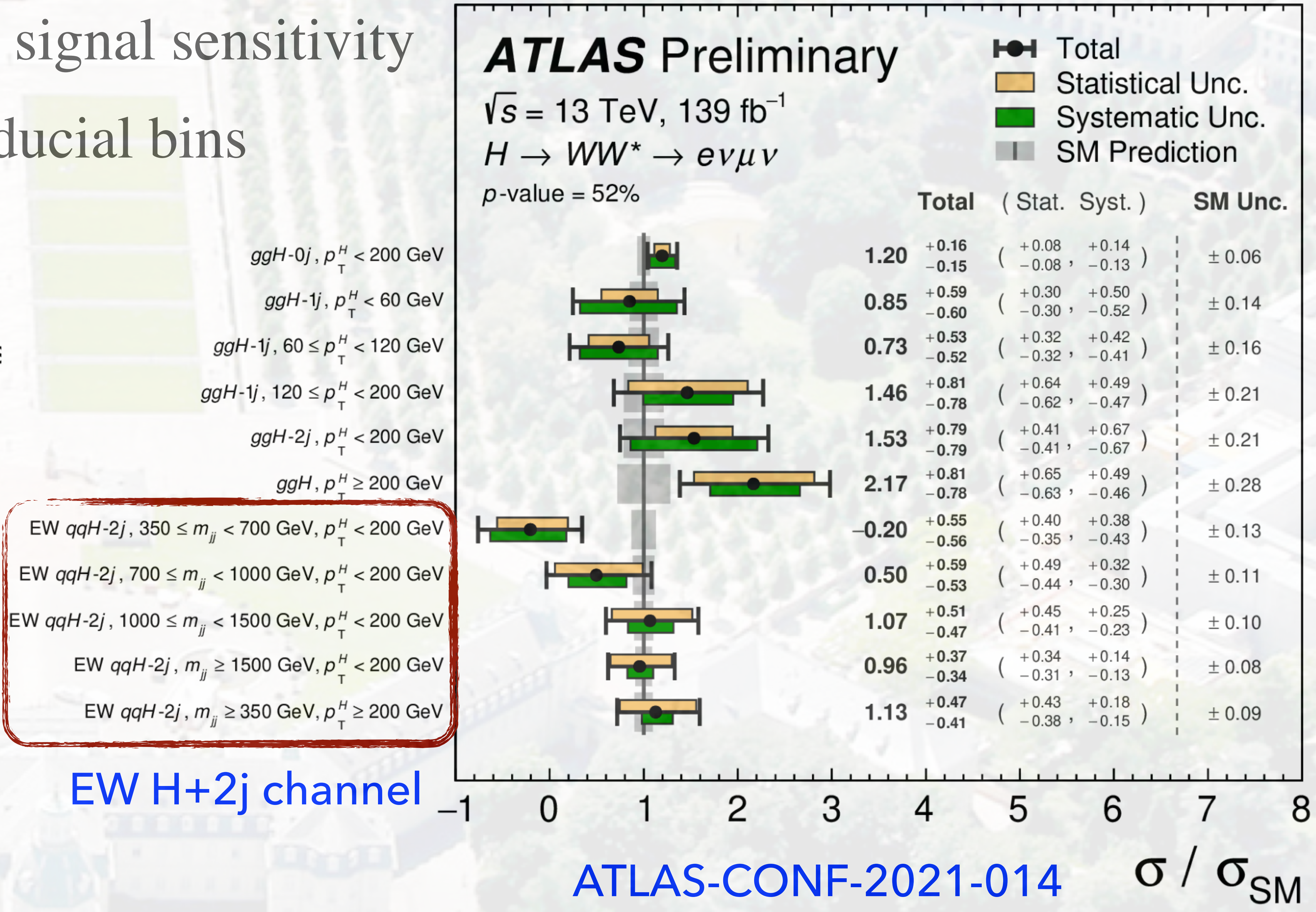



EW H+2j channel

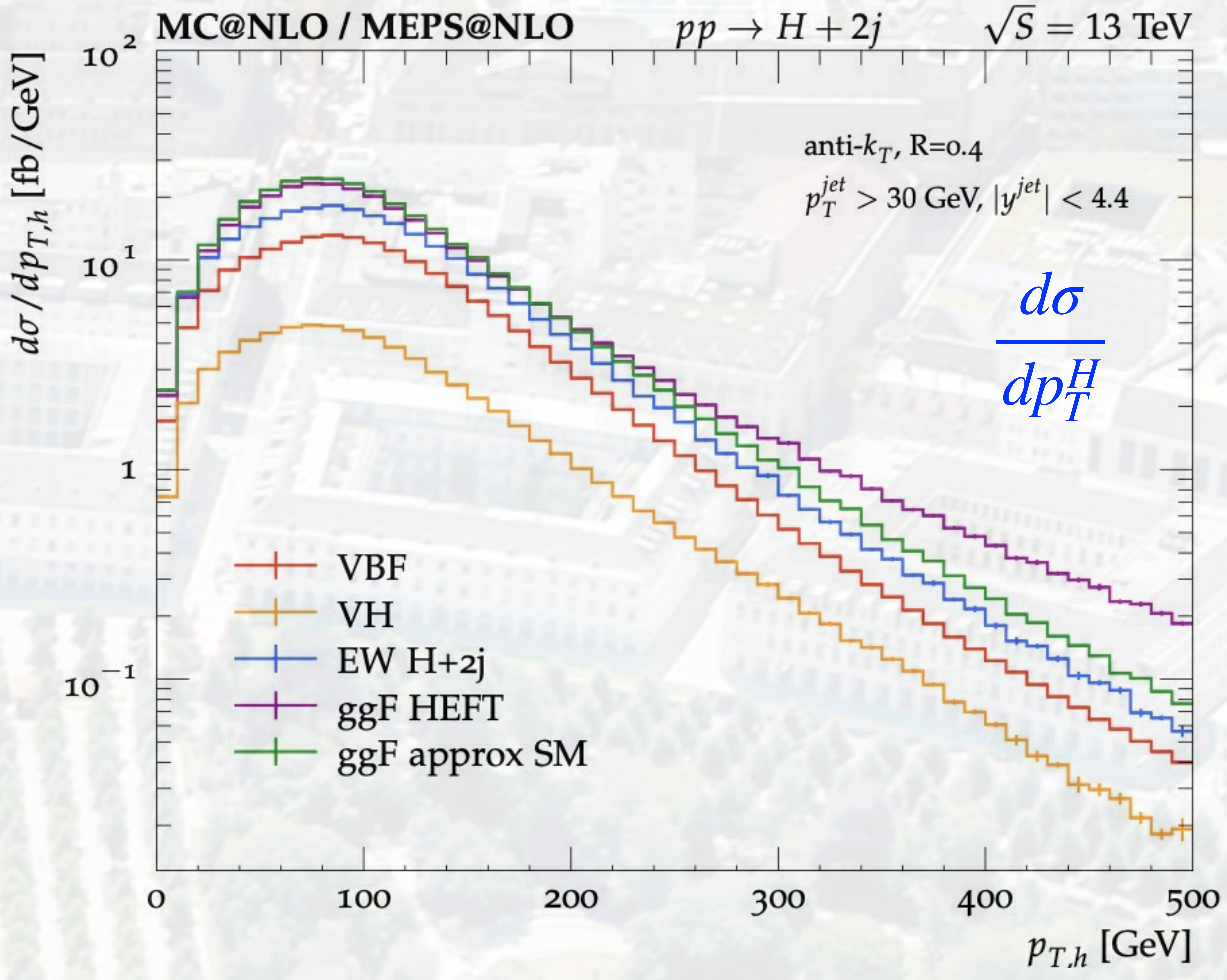
ATLAS-CONF-2021-014

# STATE-OF-THE-ART PREDICTIONS

- Tools at NLO (+PS) fully differential QCD accuracy:
  - VBFNLO Arnold, Bahr, Bozzi, Campanario, Englert et. Al. `08 + updates
  - POWHEG Nason, Oleari `09, HERWIG Plätzer, Gieseke `11, aMC@NLO Frixione, Torrielli, Zaro `13
- NNLO QCD correction in Structure Function Approach:
  - Total cross section: VBF@NNLO Bolzoni, Maltoni, Moch, Zaro `10
  - Fully differential: proVBFH Cacciari, Dreyer, Karlberg, Salam, Zanderighi `15, NNLOJET Cruz-Martinez, Gehrmann, Glover, Huss `18, Nested-Soft-Collinear scheme Asteriadis, Caola, Melnikov, Röntsch `21, `22
- N3LO QCD correction in Structure Function Approach (Total cross section): proVBFH Dreyer, Karlberg `16
- NLO EW correction (Fully differential): Ciccolini, Denner, Dittmaier `07, HAWK Denner, Dittmaier et. al.`14
- Non-factorizable correction:
  - Gluon exchange: VBF@NNLO Bolzoni, Maltoni, Moch, Zaro `10, `12
  - VBF-ggF interference: Andersen, Binoth, Heinrich et. al. `07 Gluon induced: Harlander, Vollinga, Weber `08
  - Leading power correction: Liu, Melnikov, Penin `19, proVBFH Dreyer, Karlberg, Tancredi `20

# DIFFERENTIAL SIGNATURES AT NLO

- Differential signatures at NLO → Reason of VBF cuts
  - Compare ggF, VBF, VH and EW H+2j (VBF+VH+interference) Buckley, XC, Cruz-Martinez, Ferrario Ravasio et. al. \`21
  - ggF approx SM include finite top mass effects up to NLO Jones, Kerner, Luisoni \`18, XC, Huss, Jones, Kerner et. al. \`21
  - VBF dominant in large $m_{jj}$, $\Delta y_{jj}$ region




$$\frac{d\sigma}{dp_T^H}$$

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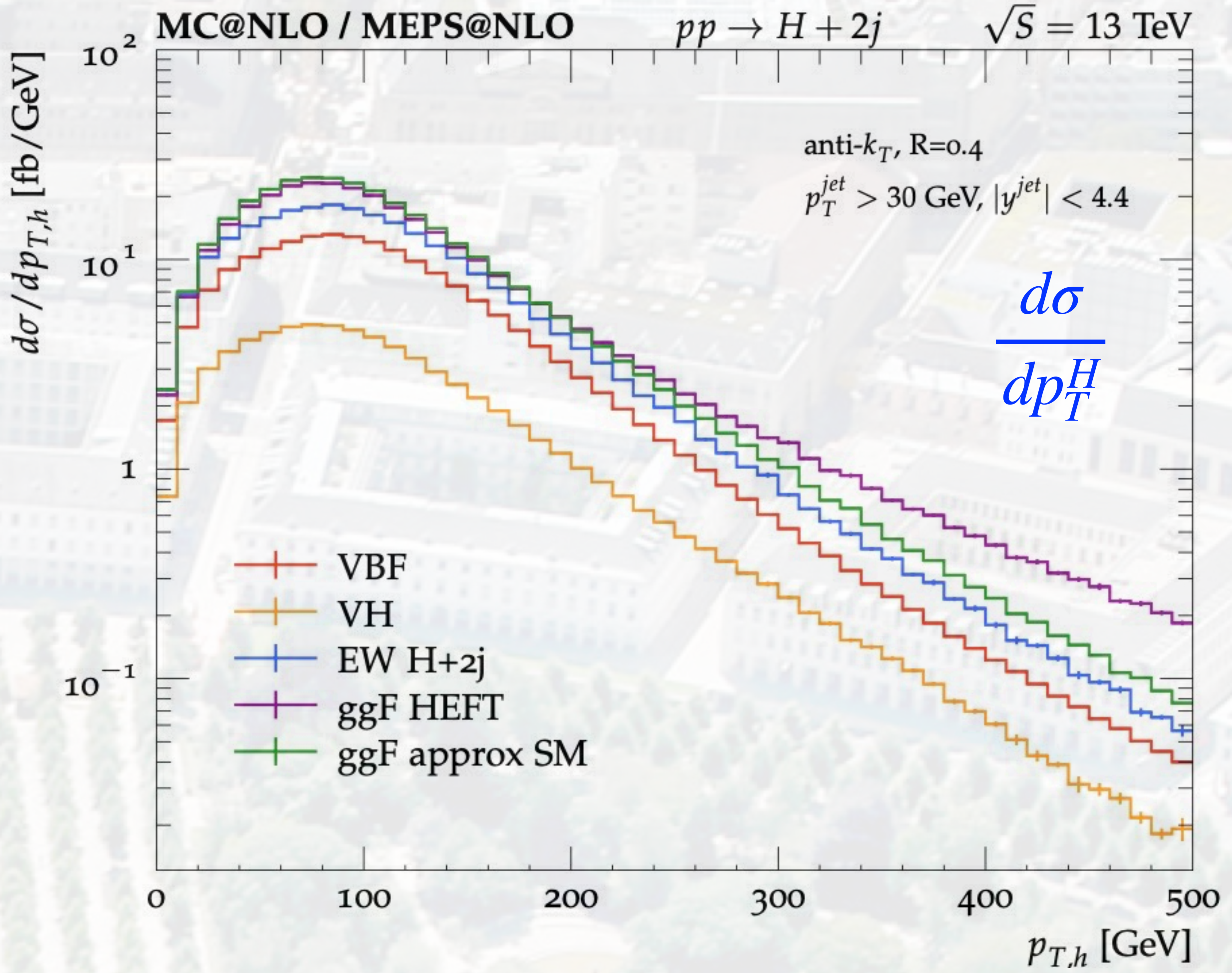
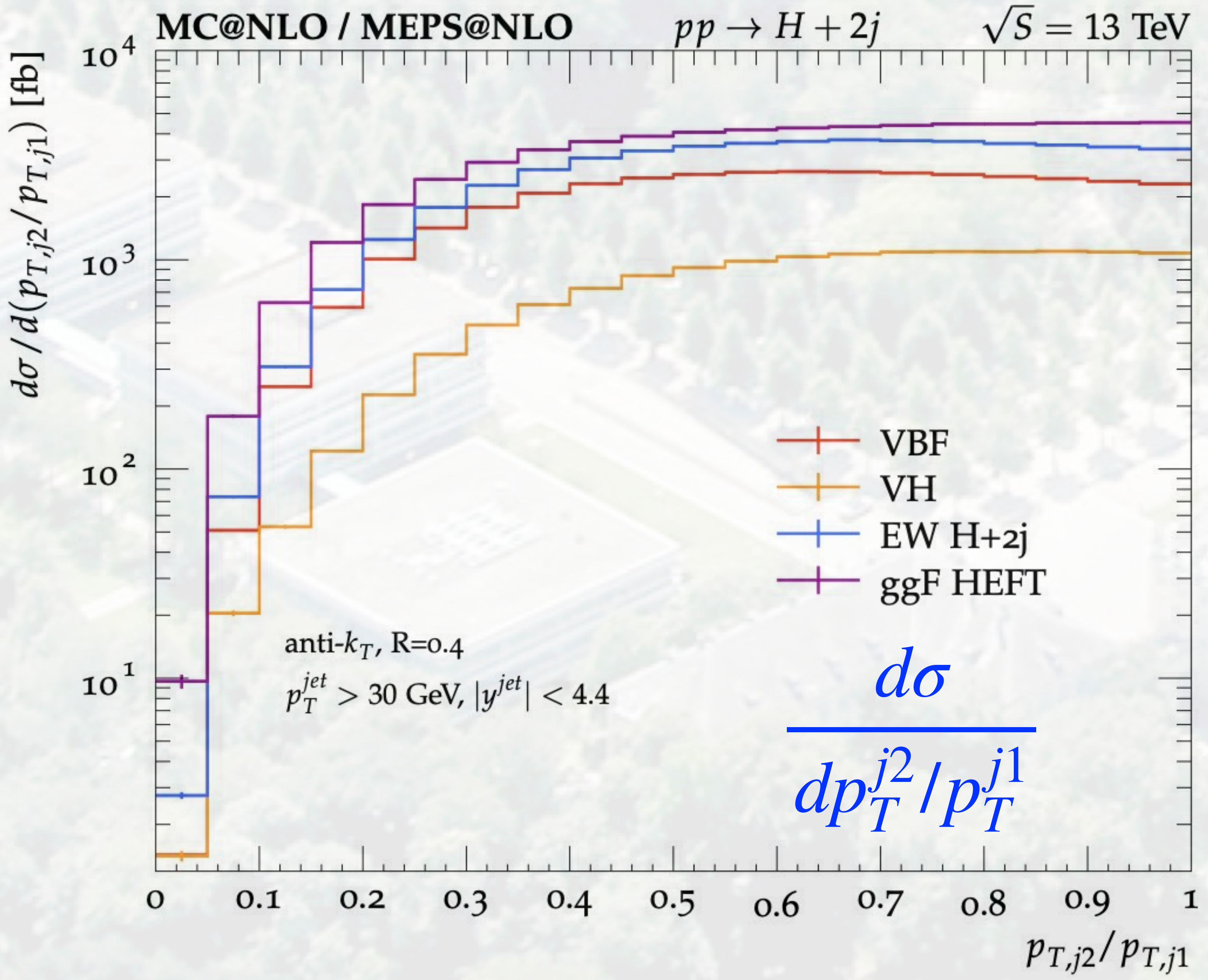
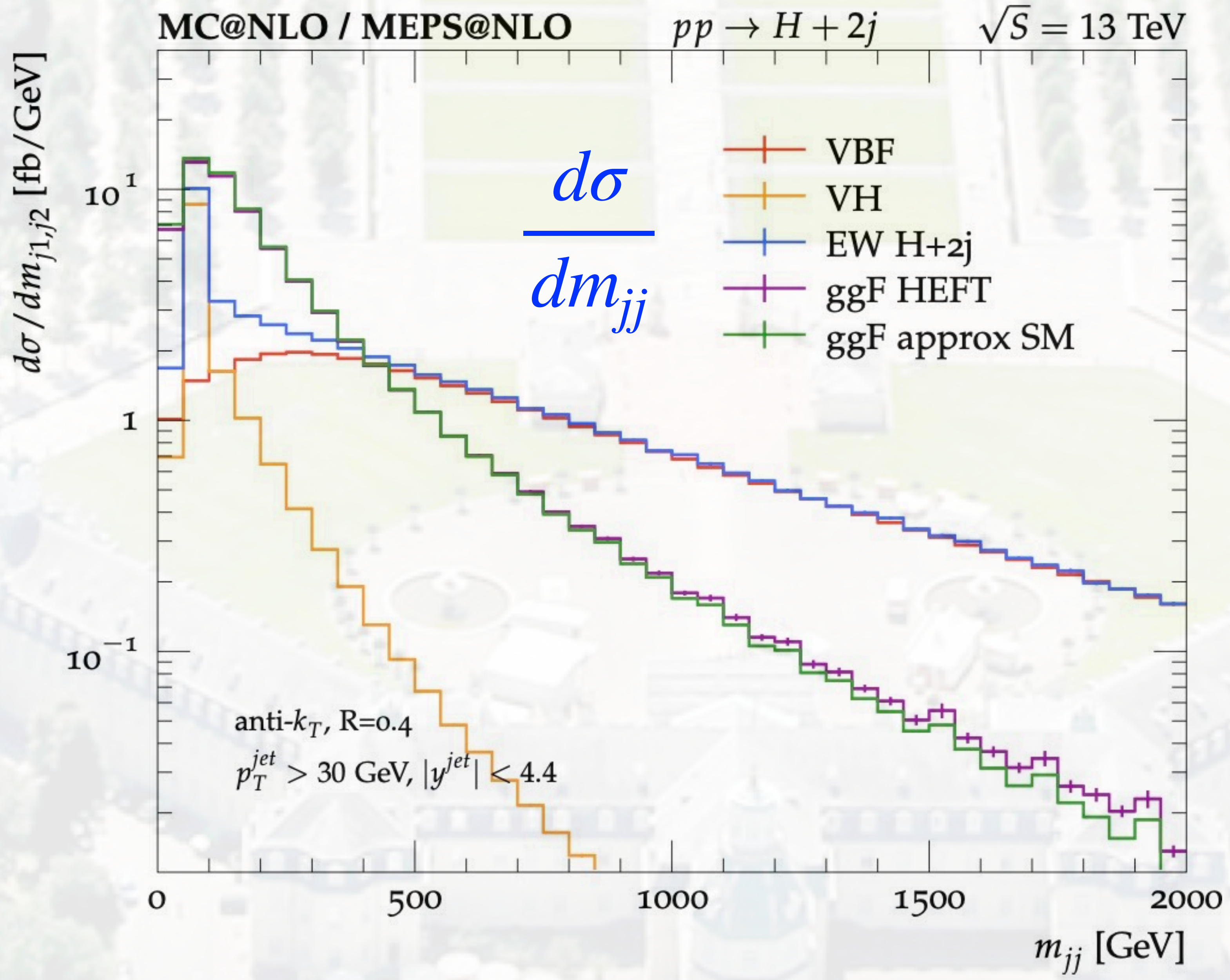
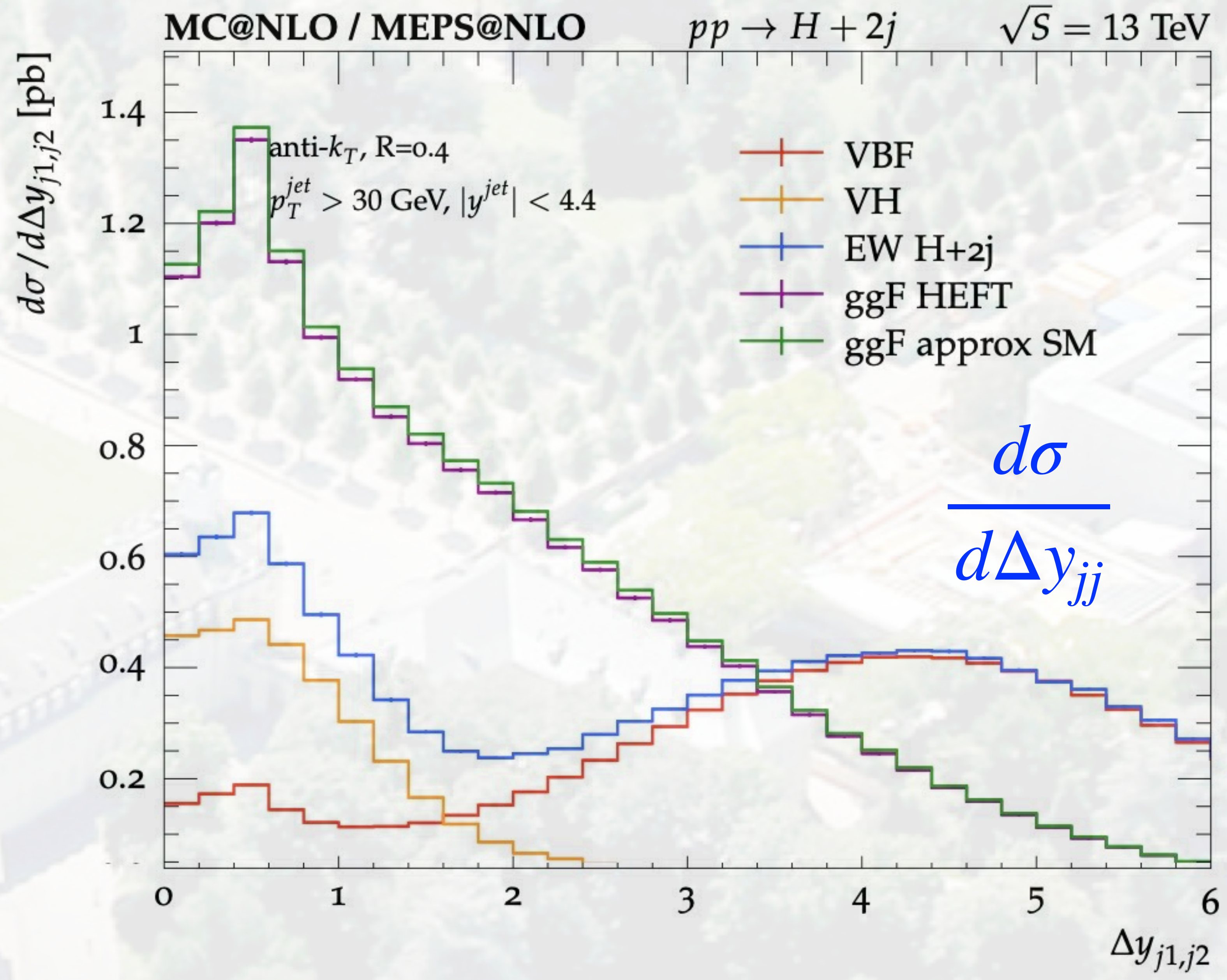


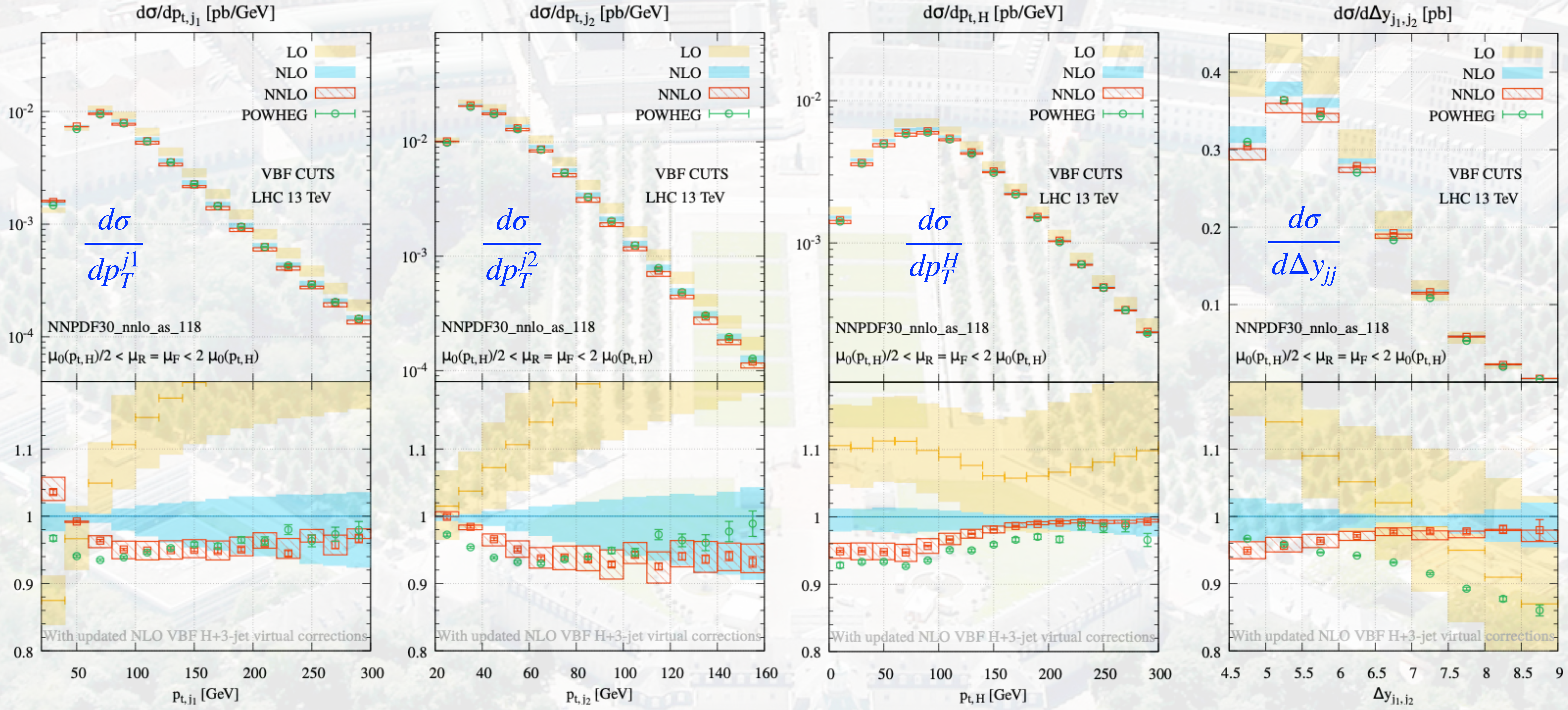



# DIFFERENTIAL SIGNATURES FROM HIGHER ORDERS

➤ Differential NNLO QCD corrections in Structure Function Approach: (VBF cuts: $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$)




Cacciari, Dreyer, Karlberg, Salam, Zanderighi `15 (erratum) `18

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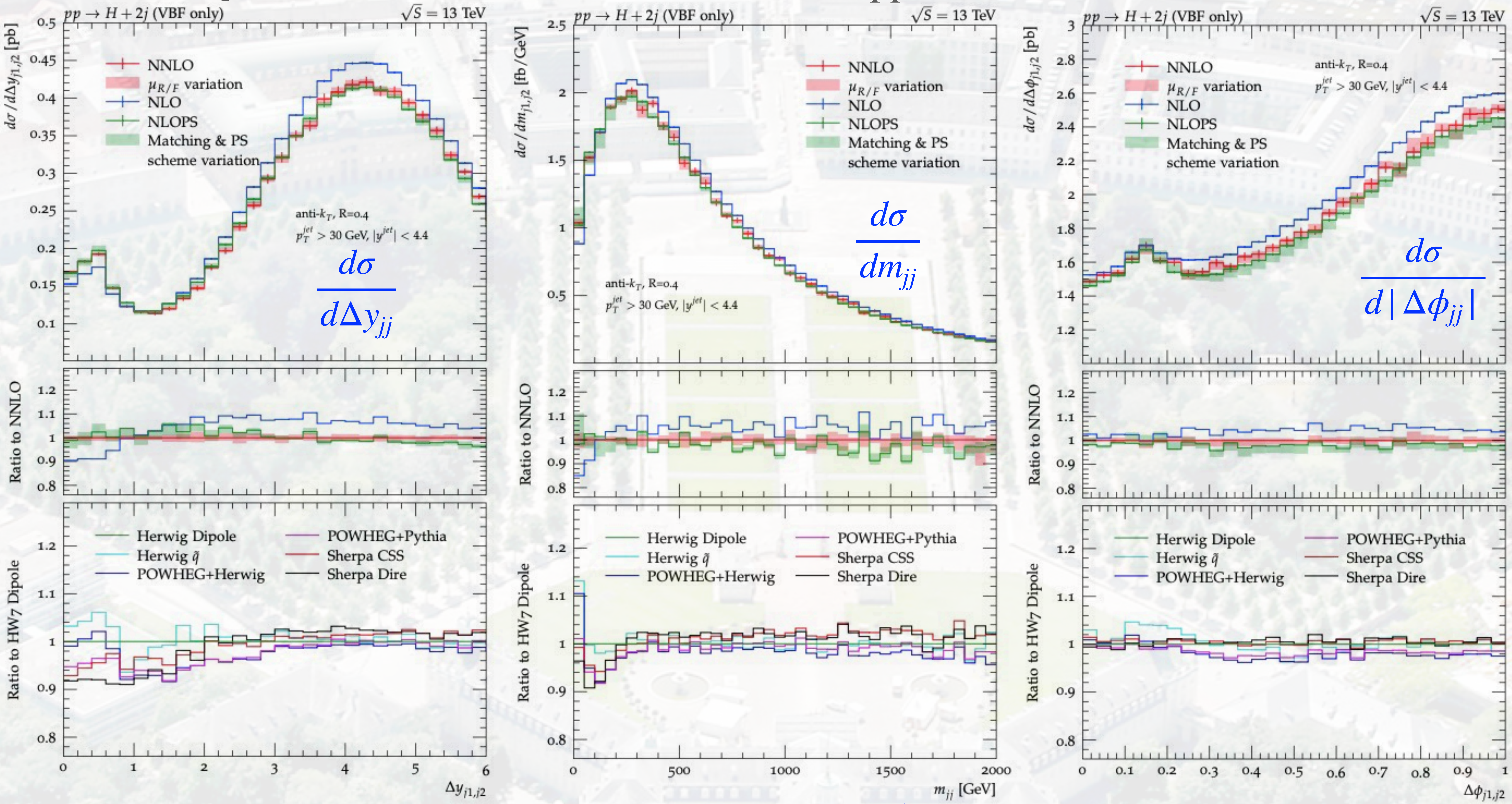


Buckley, XC, Cruz-Martinez, Ferrario Ravasio, Gehrmann, Glover, Höche, Huss, Huston, Lindert, Plätzer `21
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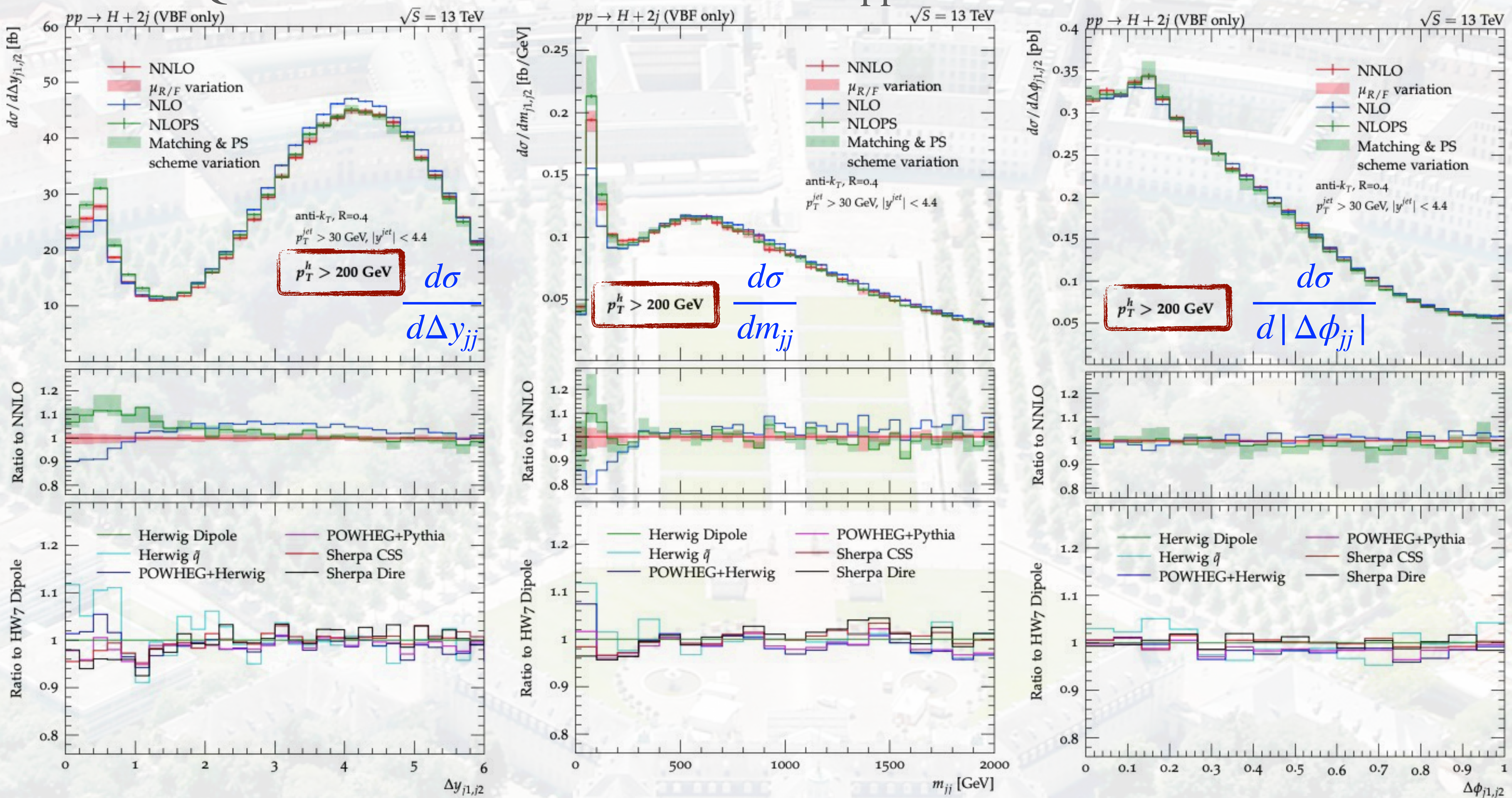


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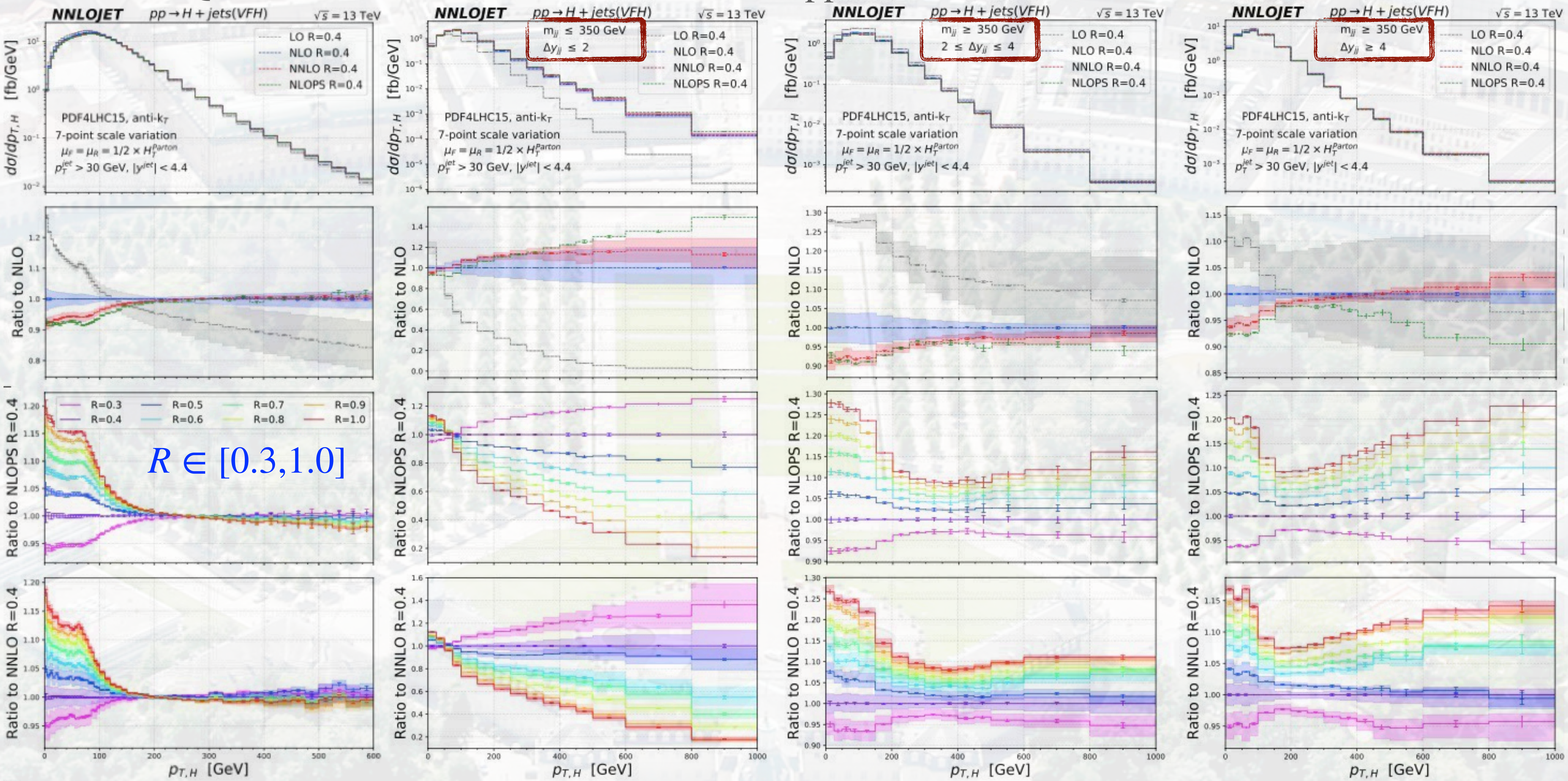
- Differential NNLO QCD corrections in Structure Function Approach:

$$\frac{d\sigma^{H+2J}(R)}{dp_T^H}$$




$R \in [0.3,1.0]$

Buckley, XC, Cruz-Martinez, Ferrario Ravasio, Gehrmann, Glover, Höche, Huss, Huston, Lindert, Plätzer `21

# DIFFERENTIAL SIGNATURES FROM HIGHER ORDERS

➤ Differential NNLO QCD corrections in Structure Function Approach:

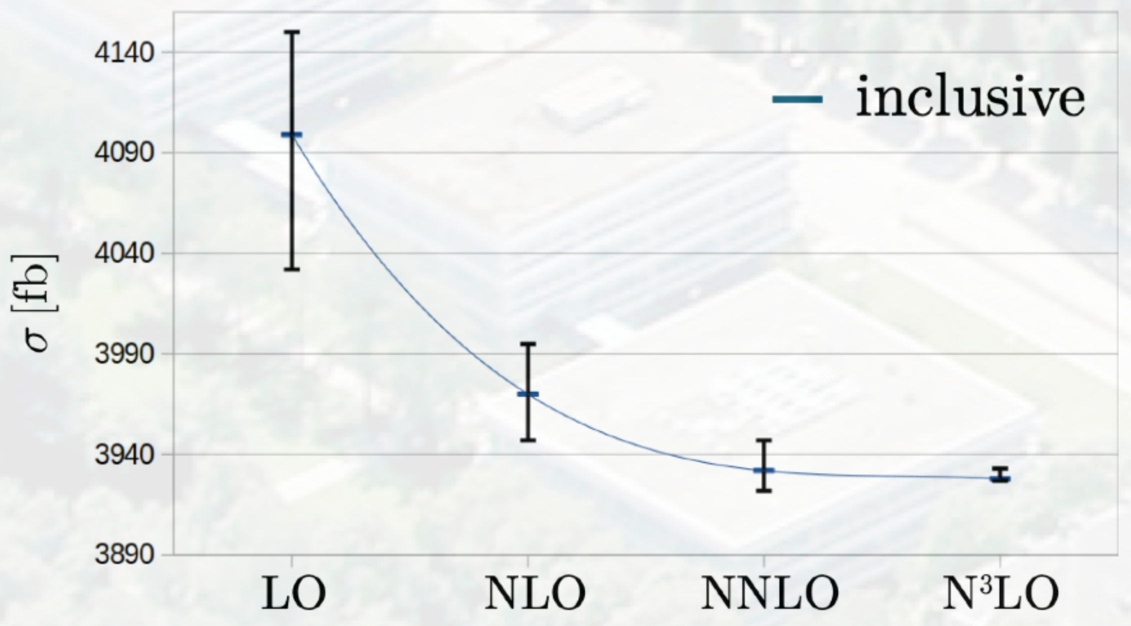

➤ $VBF \to H(\to b\bar{b}) + 2j$ with full b quark kinematic and $\Gamma_{H\to b\bar{b}}$

➤ $VBF \to H(\to WW^* \to 2l2\nu) + 2j$ with LO decay

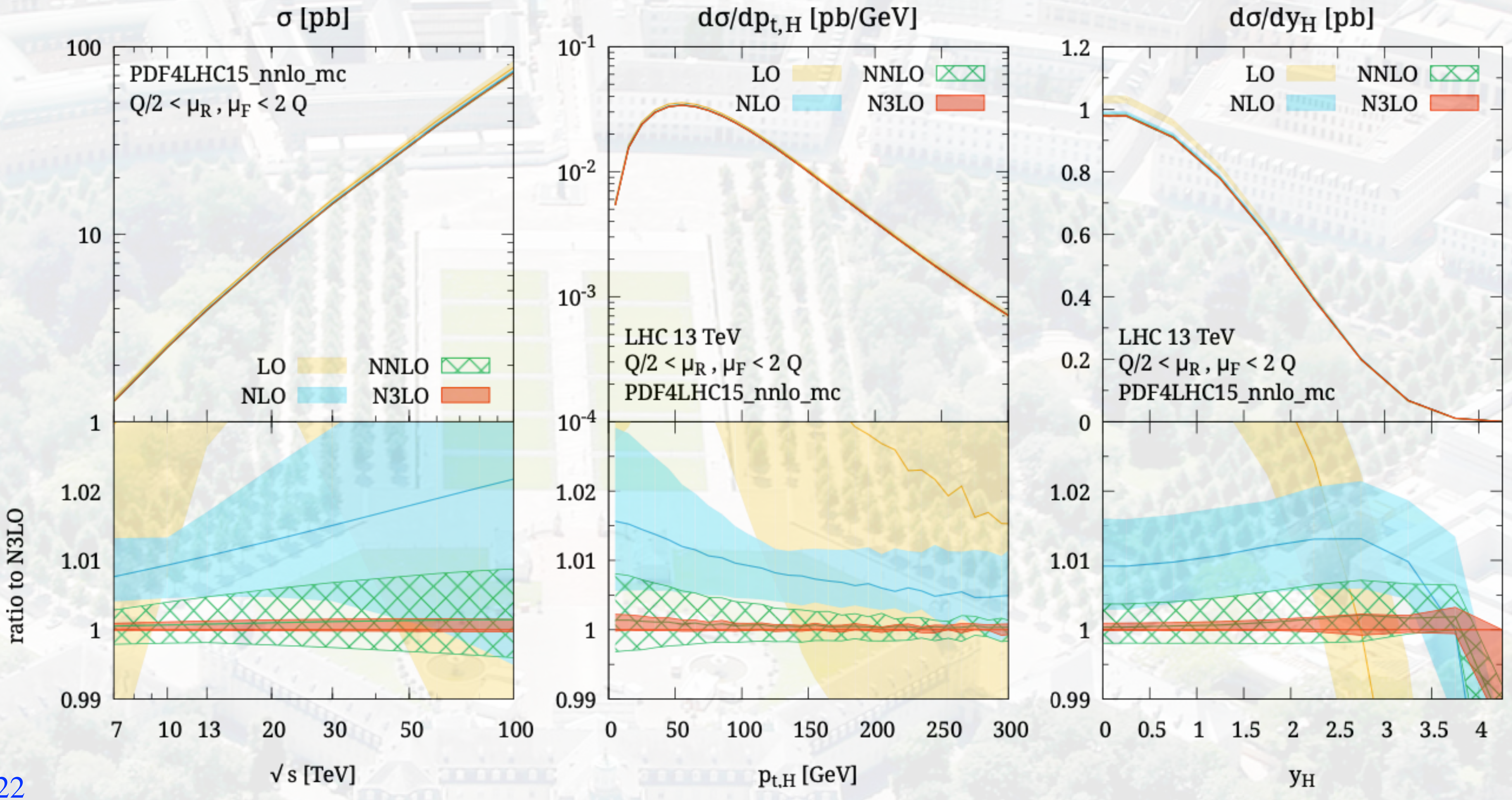
Asteriadis, Caola, Melnikov, Röntsch `21

# DIFFERENTIAL SIGNATURES FROM HIGHER ORDERS

- Inclusive N3LO QCD corrections in Structure Function Approach:
  - Differential in H
  - Inclusive in jets
  - Very good convergence of pQCD expansion
  - Extendable to fully differential N3LO




Plot by Asteriadis at LoopFest 2022




Dreyer, Karlberg `16

# DIFFERENTIAL SIGNATURES OF THE NON-FACTORIZABLE

- Non-factorizable contribution is colour and kinematic suppressed:
  - Eistmate gluon exchange via ekional approximation:
    - Expand loop integral via $\xi^2 = (p_T^{jet})^2/s \ll 1$ (valid for VBF cuts)
    - Keep leading power at $\xi^2 \rightarrow$ loop integral factorized from LO
    - $\pi^2$ enhancement from Glauber gluons in transverse space

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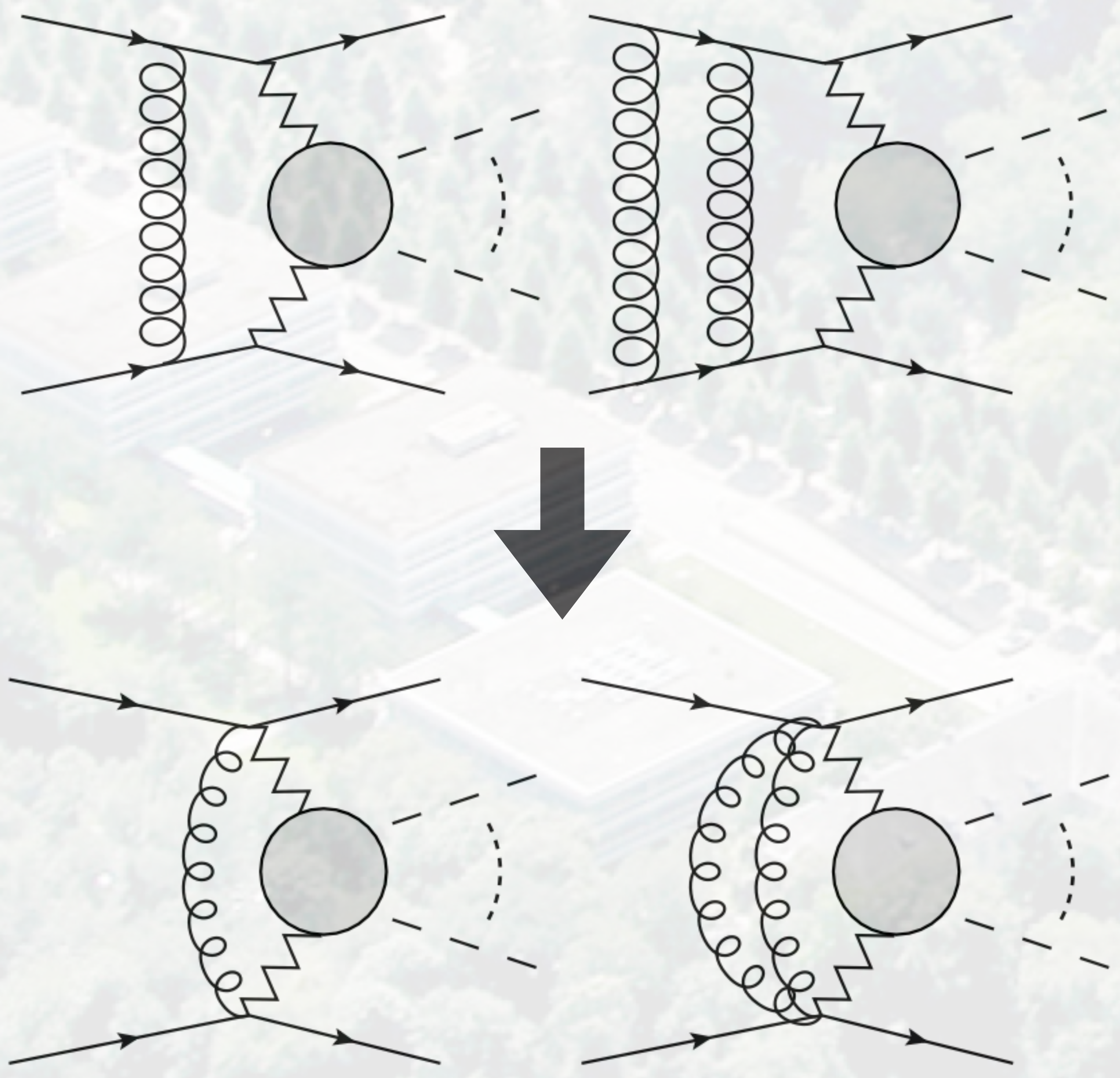

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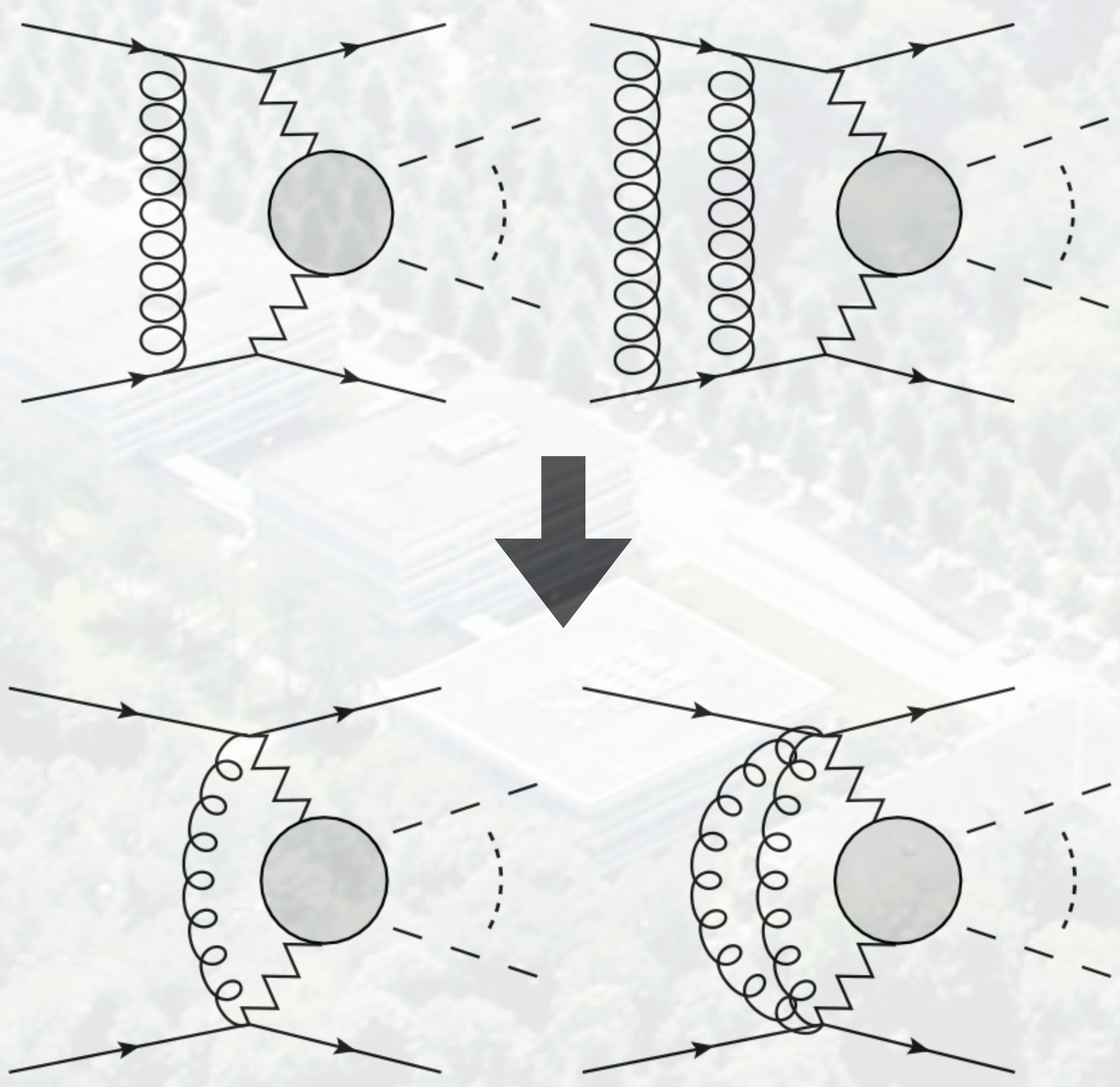
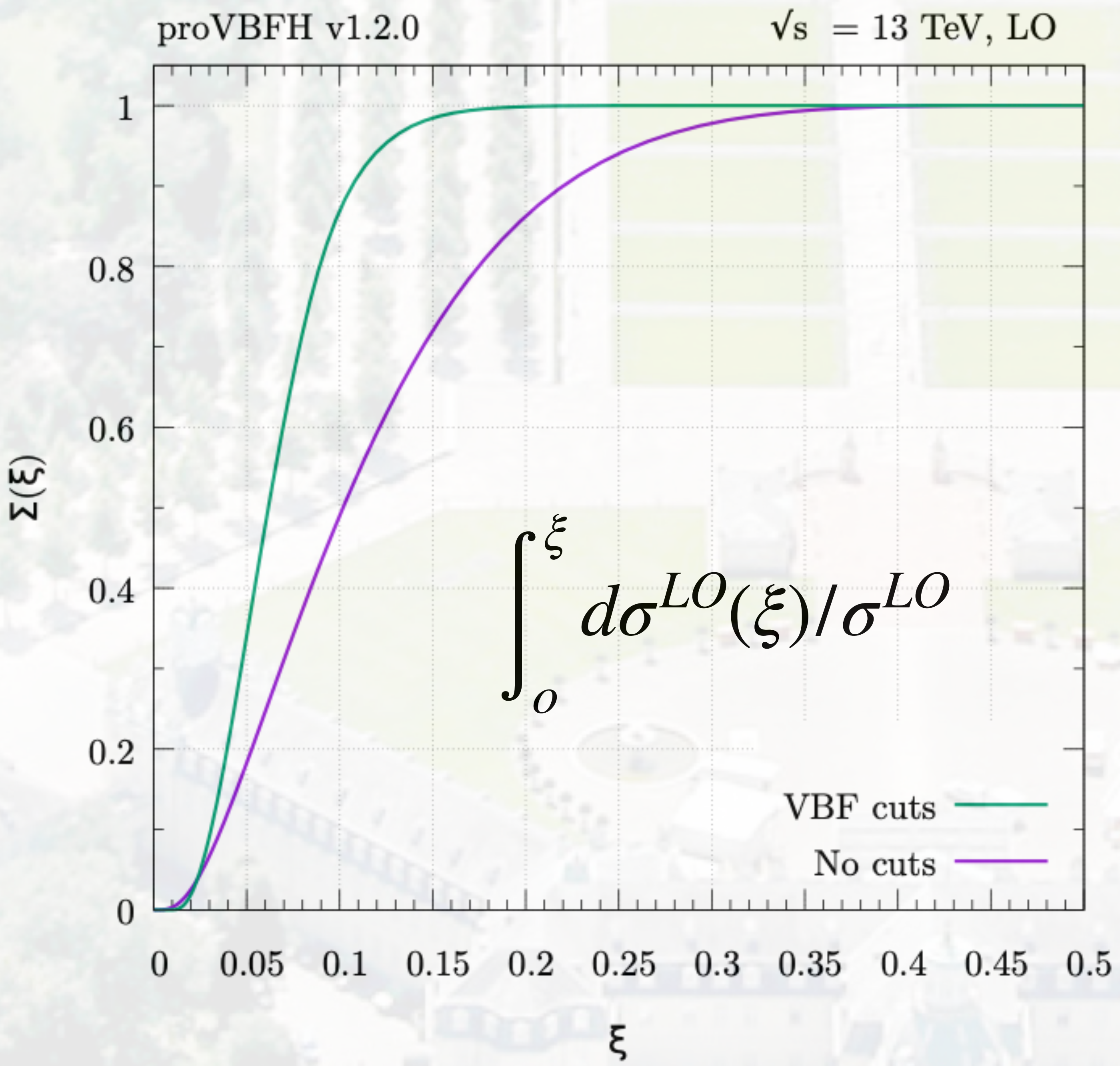
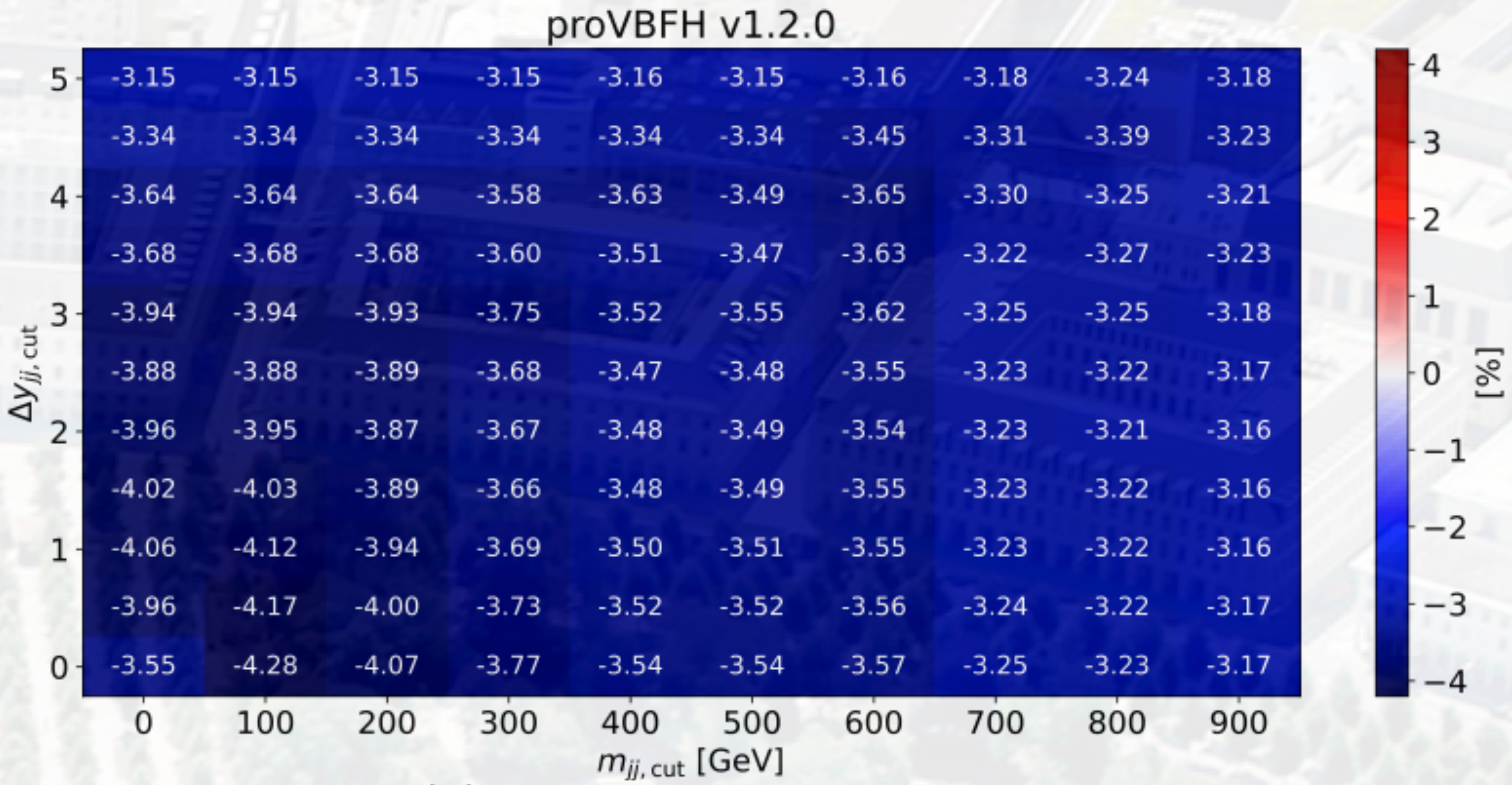
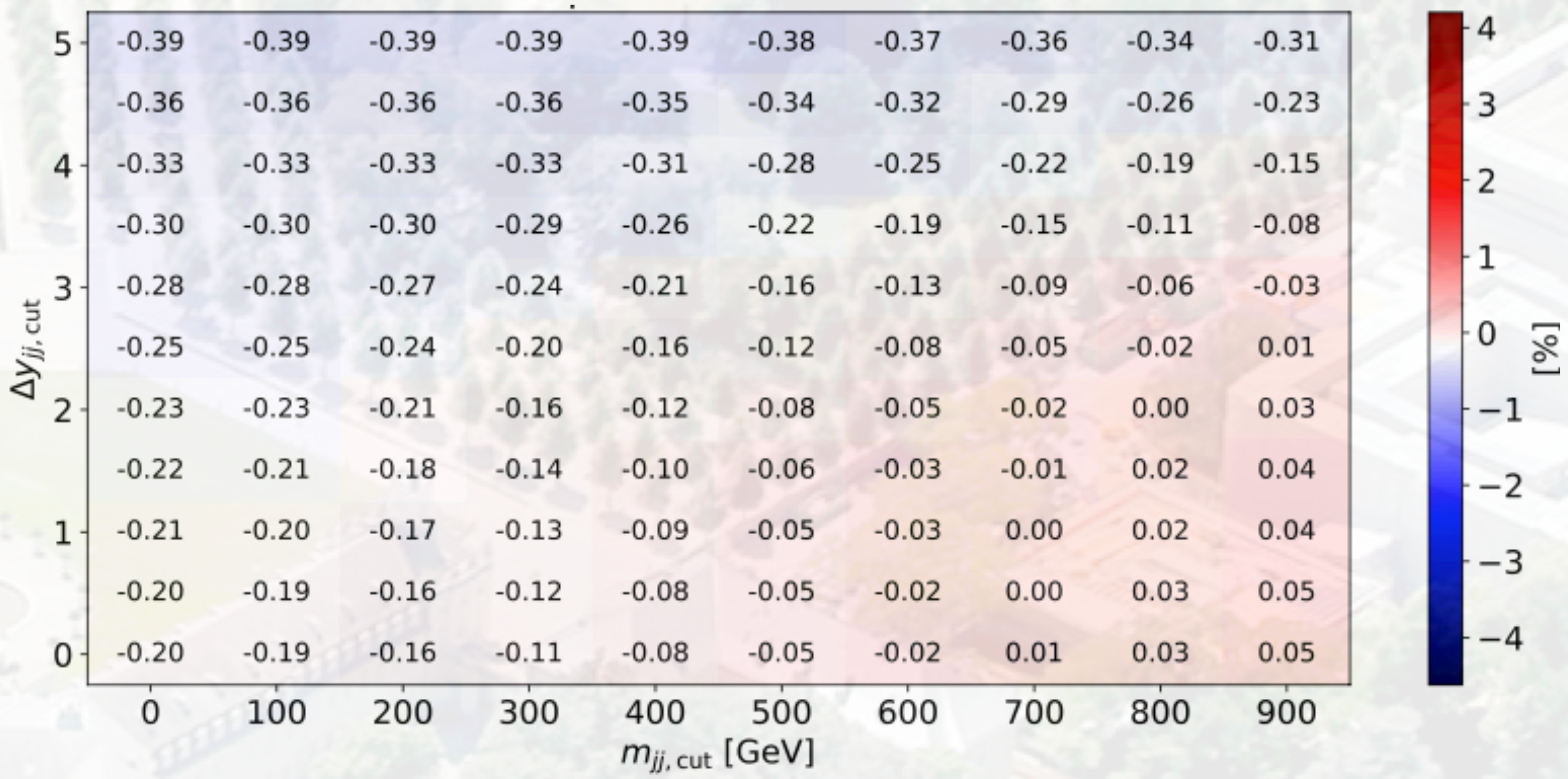




(a) Factorisable corrections



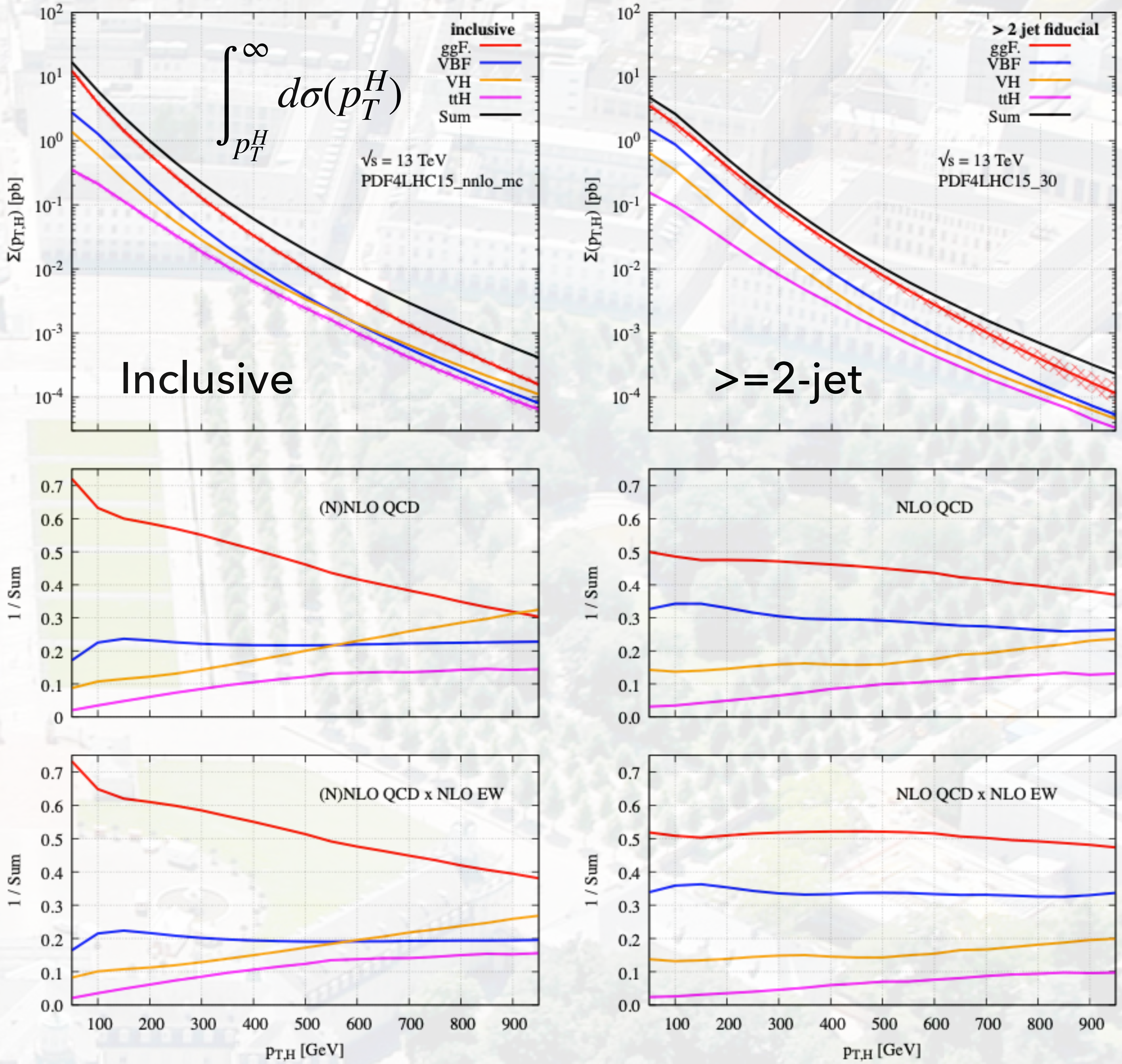
(b) Non-factorisable corrections

$$\left(\frac{\sigma^{NNLO}}{\sigma^{LO}} - 1\right)\%$$

proVBFH Dreyer, Karlberg, Tancredi `20

# DIFFERENTIAL SIGNATURES OF EW CORRECTION

- EW corrections to VBFH is available at NLO
  (HAWK Denner, Dittmaier, Kallweit, Mück `14)
- Relative large for VBFH at $5 \sim 15\,\%$ for high $p_T^H, m_{jj}$
  (Sudakov log dominant)
- Combine EW and QCD predictions in STXS bins:

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$$\sigma_{VBF} = \sigma^{N^nLO}_{QCD}(1+\delta_{EW}) + \sigma_\gamma \text{ with } (\delta_{EW} = \sigma_{EW}/\sigma^{LO}_{QCD})$$

| | STXS bin | $\sigma_{LO}$(fb) | $(1+\delta_{EW})$ | $\sigma_\gamma$(fb) | $\Delta_{EW}$ |
|---|---|---|---|---|---|
| | $0 < m_{jj} \leq 60$ | 6.67 | 0.981 | 0.081 | 0.012 |
| | $60 < m_{jj} \leq 120$ | 601.78 | 0.938 | 7.440 | 0.012 |
| | $120 < m_{jj} \leq 350$ | 540.59 | 0.981 | 6.567 | 0.012 |
| $p_T^H \leq 200$ | $350 < m_{jj} \leq 700$ | 659.75 | 0.955 | 9.056 | 0.014 |
| $p_T^H \leq 200$ | $700 < m_{jj} \leq 1000$ | 318.83 | 0.937 | 4.820 | 0.015 |
| $p_T^H \leq 200$ | $1000 < m_{jj} \leq 1500$ | 275.94 | 0.921 | 4.481 | 0.016 |
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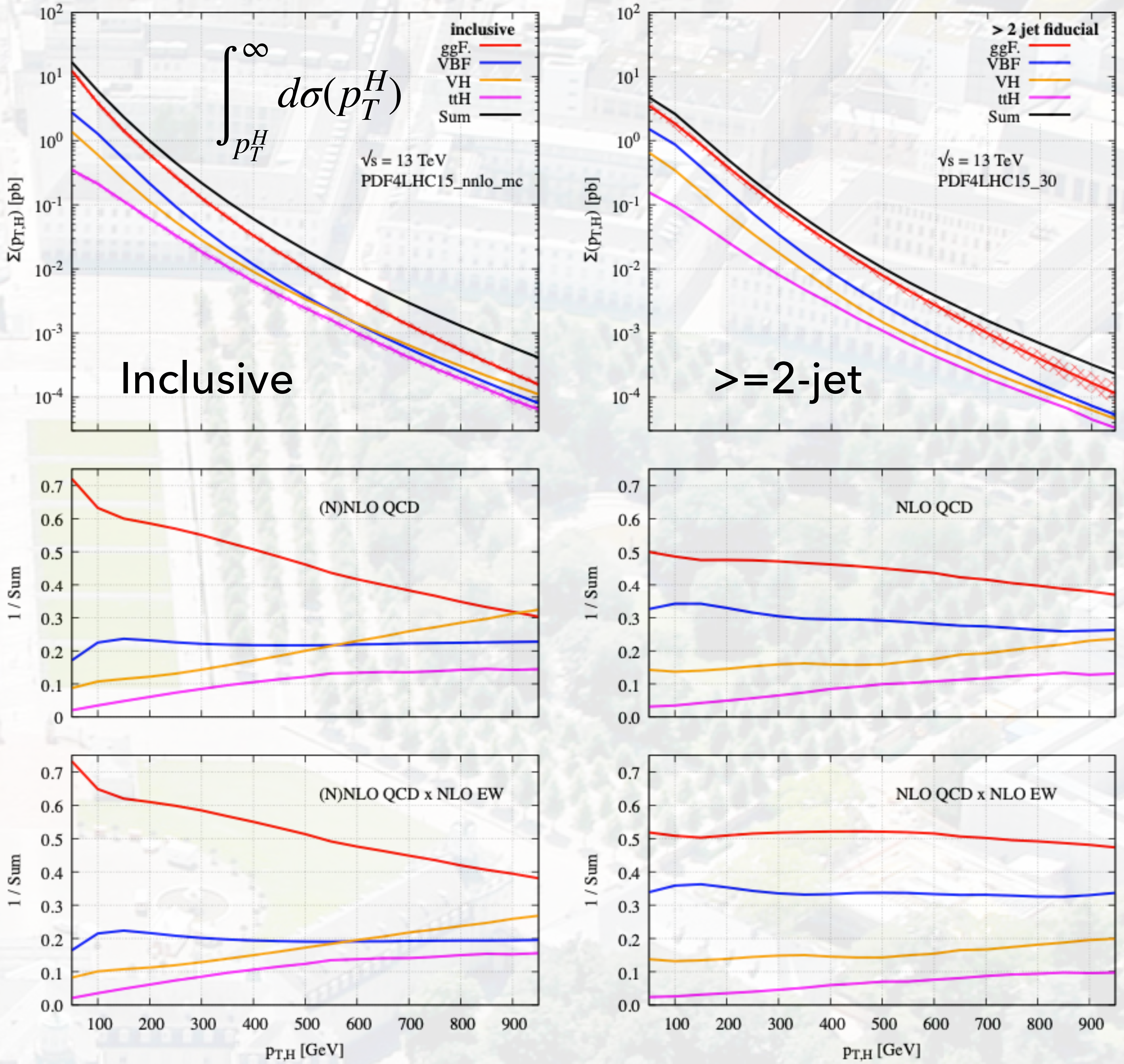
HAWK 3.0 to LHCHWVBF




Buckley, XC, Cruz-Martinez, Ferrario Ravasio, Gehrmann et. al. `21

# DIFFERENTIAL SIGNATURES OF EW CORRECTION

- EW corrections to VBFH is available at NLO (HAWK Denner, Dittmaier, Kallweit, Mück `14)
- Relative large for VBFH at 5 ~ 15 % for high $p_T^H, m_{jj}$ (Sudakov log dominant)
- Combine EW and QCD predictions in STXS bins:

$$\sigma_{VBF} = \sigma_{QCD}^{N^nLO} \boxed{(1+\delta_{EW})} + \boxed{\sigma_\gamma} \text{ with } (\delta_{EW} = \sigma_{EW}/\sigma_{QCD}^{LO})$$

| | STXS bin | $\sigma_{LO}$(fb) | $(1+\delta_{EW})$ | $\sigma_\gamma$(fb) | $\Delta_{EW}$ |
|---|---|---|---|---|---|
| | $0 < m_{jj} \leq 60$ | 6.67 | 0.981 | 0.081 | 0.012 |
| | $60 < m_{jj} \leq 120$ | 601.78 | 0.938 | 7.440 | 0.012 |
| | $120 < m_{jj} \leq 350$ | 540.59 | 0.981 | 6.567 | 0.012 |
| $p_T^H \leq 200$ | $350 < m_{jj} \leq 700$ | 659.75 | 0.955 | 9.056 | 0.014 |
| $p_T^H \leq 200$ | $700 < m_{jj} \leq 1000$ | 318.83 | 0.937 | 4.820 | 0.015 |
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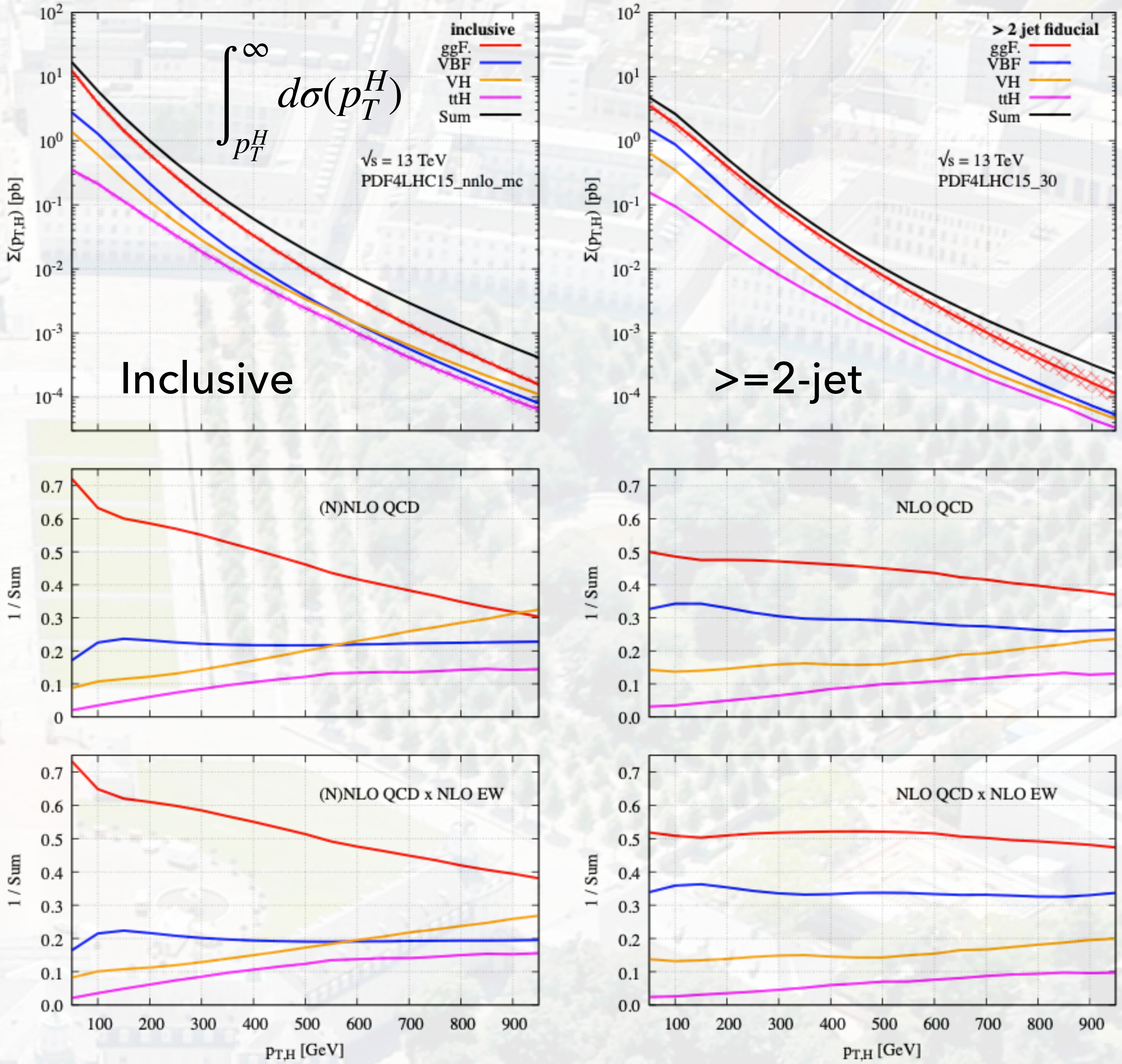


Buckley, XC, Cruz-Martinez, Ferrario Ravasio, Gehrmann et. al. `21

# DIFFERENTIAL SIGNATURES OF ANOMALOUS COUPLING

- VBFH is the largest production channel to search for HVV anomalous couplings:
  - CP even and odd anomalous couplings analysis at LO (Plehn, Rainwater, Zeppenfeld `02), NLO (Figy, Zeppenfeld `04, Hankele, Klämke, Zeppenfeld `06, Denner, Dittmaier, Kallweit, Muck `15)
  - SMEFT analysis for general HVV anomalous couplings at LO (JHU generator `20), NLO (Madgraph5 `11), NNLO (Asteriadis, Caola, Melnikov, Röntsch '22)
- Dimensionless anomalous couplings for D6 operators in SMEFT: $c^{(1)}_{HVV}$, $c^{(2)}_{HVV}$, $\tilde{c}_{HVV}$

$$= ig^{(SM)}_{HVV}\left[g^{\mu\nu}\left(1+\frac{m_H^2}{\Lambda^2}c^{(2)}_{HVV}+\frac{p_1^2+p_2^2}{\Lambda^2}c^{(1)}_{HVV}\right)+\frac{2p_1^\nu p_2^\mu}{\Lambda^2}c^{(1)}_{HVV}-\tilde{c}_{HVV}(6\pi)\epsilon^{\mu\nu\rho\sigma}\frac{p_{1,\rho}p_{2,\sigma}}{\Lambda^2}\right]$$

- Use VBF cuts and assume $\Lambda = 1$ TeV with fix anomalous couplings in two scenarios:

- Compatible fiducial cross section from LO to NNLO.

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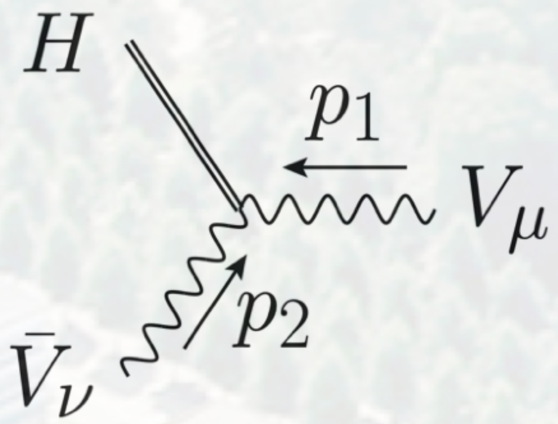


$$= i g^{(SM)}_{HVV}\left[ g^{\mu\nu}\left(1+\frac{m_H^2}{\Lambda^2}c^{(2)}_{HVV}+\frac{p_1^2+p_2^2}{\Lambda^2}c^{(1)}_{HVV}\right)+\frac{2p_1^\nu p_2^\mu}{\Lambda^2}c^{(1)}_{HVV}-\tilde{c}_{HVV}(6\pi)\epsilon^{\mu\nu\rho\sigma}\frac{p_{1,\rho}p_{2,\sigma}}{\Lambda^2}\right]$$

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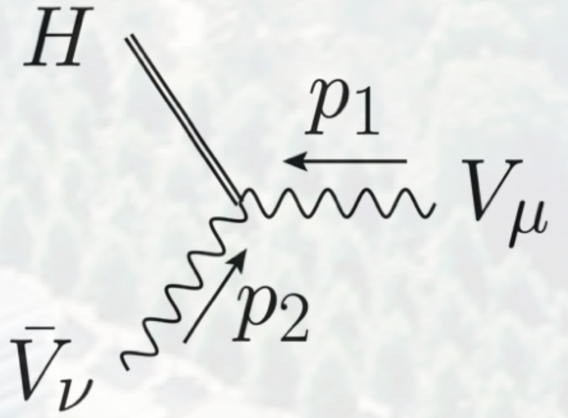



$$= i g^{(SM)}_{HVV}\left[ g^{\mu\nu}\left(1 + \frac{m_H^2}{\Lambda^2} c^{(2)}_{HVV} + \frac{p_1^2 + p_2^2}{\Lambda^2} c^{(1)}_{HVV}\right) + \frac{2 p_1^\nu p_2^\mu}{\Lambda^2} c^{(1)}_{HVV} - \tilde{c}_{HVV}(6\pi)\epsilon^{\mu\nu\rho\sigma}\frac{p_{1,\rho} p_{2,\sigma}}{\Lambda^2}\right]$$

- Use VBF cuts and assume $\Lambda = 1$ TeV with fix anomalous couplings in two scenarios:

$$\text{Sce. A:} \quad c^{(1)}_{HVV} = +1.5\,, \quad c^{(2)}_{HVV} = -1.9\,, \quad \tilde{c}_{HVV} = +0.6\,;$$
$$\text{Sce. B:} \quad c^{(1)}_{HVV} = -1.8\,, \quad c^{(2)}_{HVV} = -0.1\,, \quad \tilde{c}_{HVV} = -1.5\,.$$

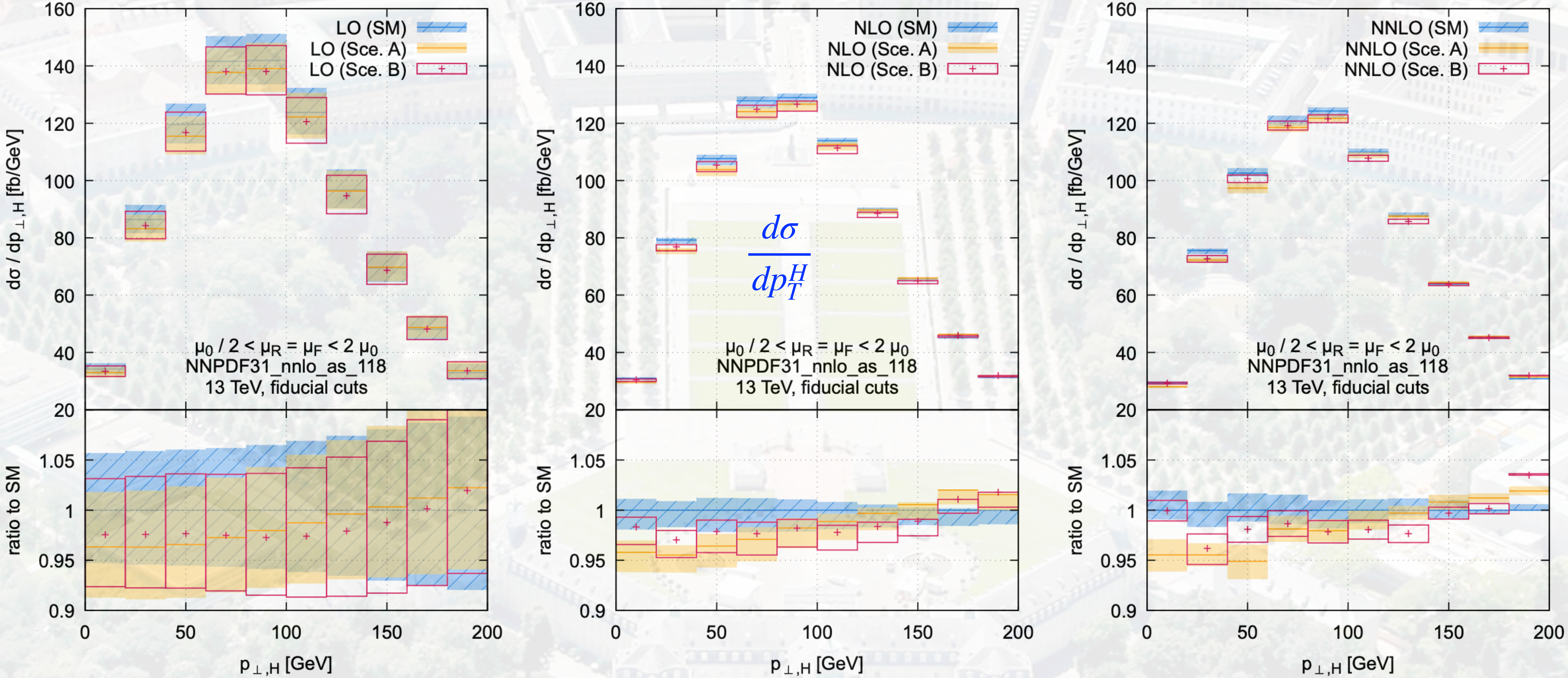
| $\sigma_{\text{fid}}$ (fb) | SM | Sce. A | Sce. B |
|---|---|---|---|
| LO | $971^{-61}_{+69}$ | $960^{-61}_{+68}$ | $965^{-63}_{+71}$ |
| NLO | $890^{+8}_{-18}$ | $882^{+7}_{-17}$ | $890^{+6}_{-17}$ |
| NNLO | $859^{+8}_{-10}$ | $851^{+9}_{-8}$ | $860^{+8}_{-8}$ |

- Compatible fiducial cross section from LO to NNLO.

(Asteriadis, Caola, Melnikov, Röntsch '22)

# DIFFERENTIAL SIGNATURES OF ANOMALOUS COUPLING

➤ Differential observable at high precision resolve BSM scenarios:




Asteriadis, Caola, Melnikov, Röntsch ’22

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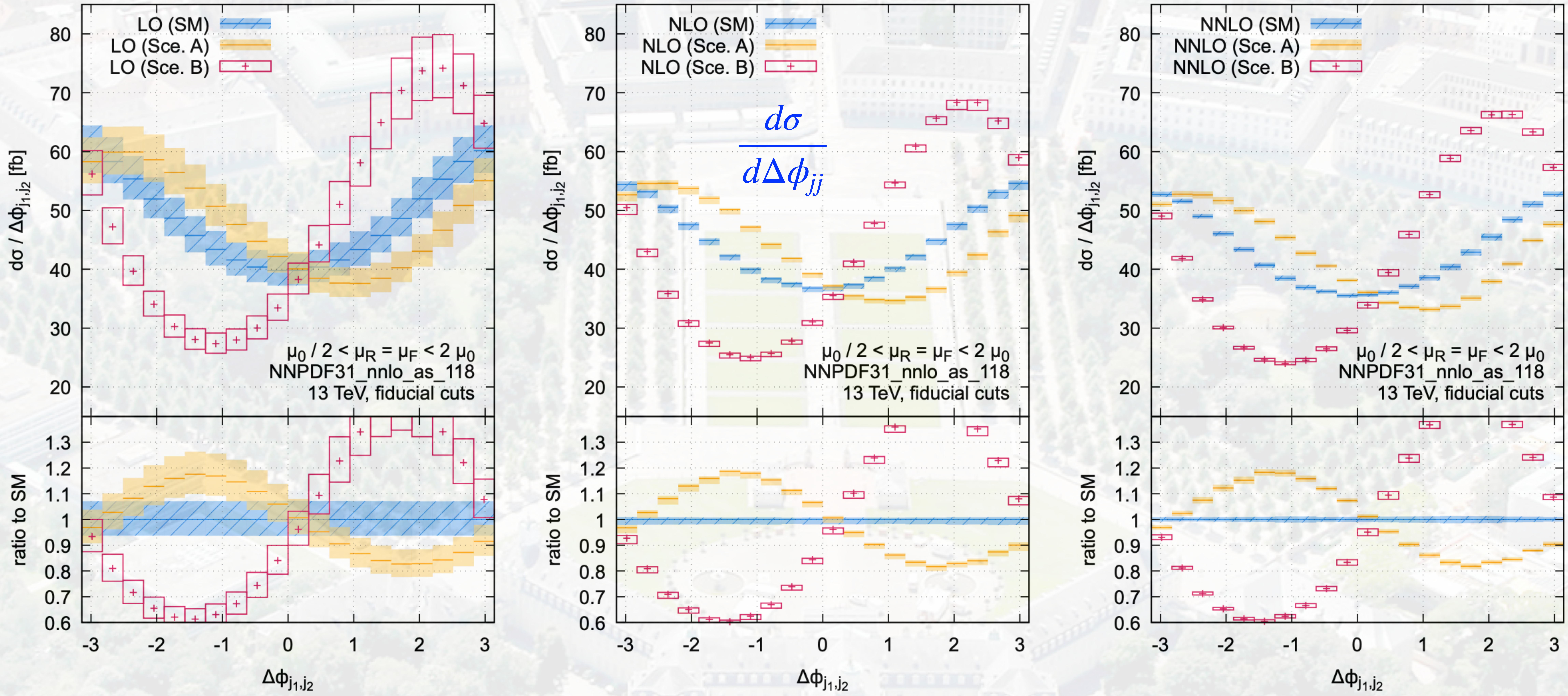


Asteriadis, Caola, Melnikov, Röntsch ’22

# CONCLUSION AND OUTLOOK

- We learned a lot in the past 10 years about VBFH production channel
- LHC precision starts to reveal details of VFBH production channel.
- STXS at stage 1.2 is mature for data analysis to improve extraction of signal.
- Rich phenomenology in various kinematic regions: SFA, eikonal approximation …
- Valuable data/cross sections away from VBF cuts can be understood.
- Fully differential NNLO QCD and NLO EW predictions available with N3LO QCD and QCD-EW mixed corrections desired in the future.
- Parton Shower in good agreement with NNLO QCD, upgrade to N(N)LL in the future.
- Precision tool could also be discovery tool to resolve BSM scenarios.
- Many public tools available each with its own speciality in precision frontier.
- Collaboration via LHCHWVBF to combine state-of-the-art predictions for Run 3.

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*Thank You for Your Attention*

# DIFFERENTIAL SIGNATURES AT NLO

- Differential signatures at NLO → Reason of VBF cuts
  - Compare ggF, VBF, VH and EW H+2j (VBF+VH+interference) Buckley, XC, Cruz-Martinez, Ferrario Ravasio et. al. `21
  - ggF approx SM include finite top mass effects up to NLO Jones, Kerner, Luisoni `18, XC, Huss, Jones, Kerner et. al. `21
  - VBF dominant in large $m_{jj}$, $\Delta y_{jj}$ region
  - However the signatures change for $p_T^H > 200$ GeV