Higgs summary (theory)

Robert Harlander
RWTH Aachen University

Les Houches 2017

- 16 “official” sessions
- 35 “official” members

TTK Institute for Theoretical Particle Physics and Cosmology
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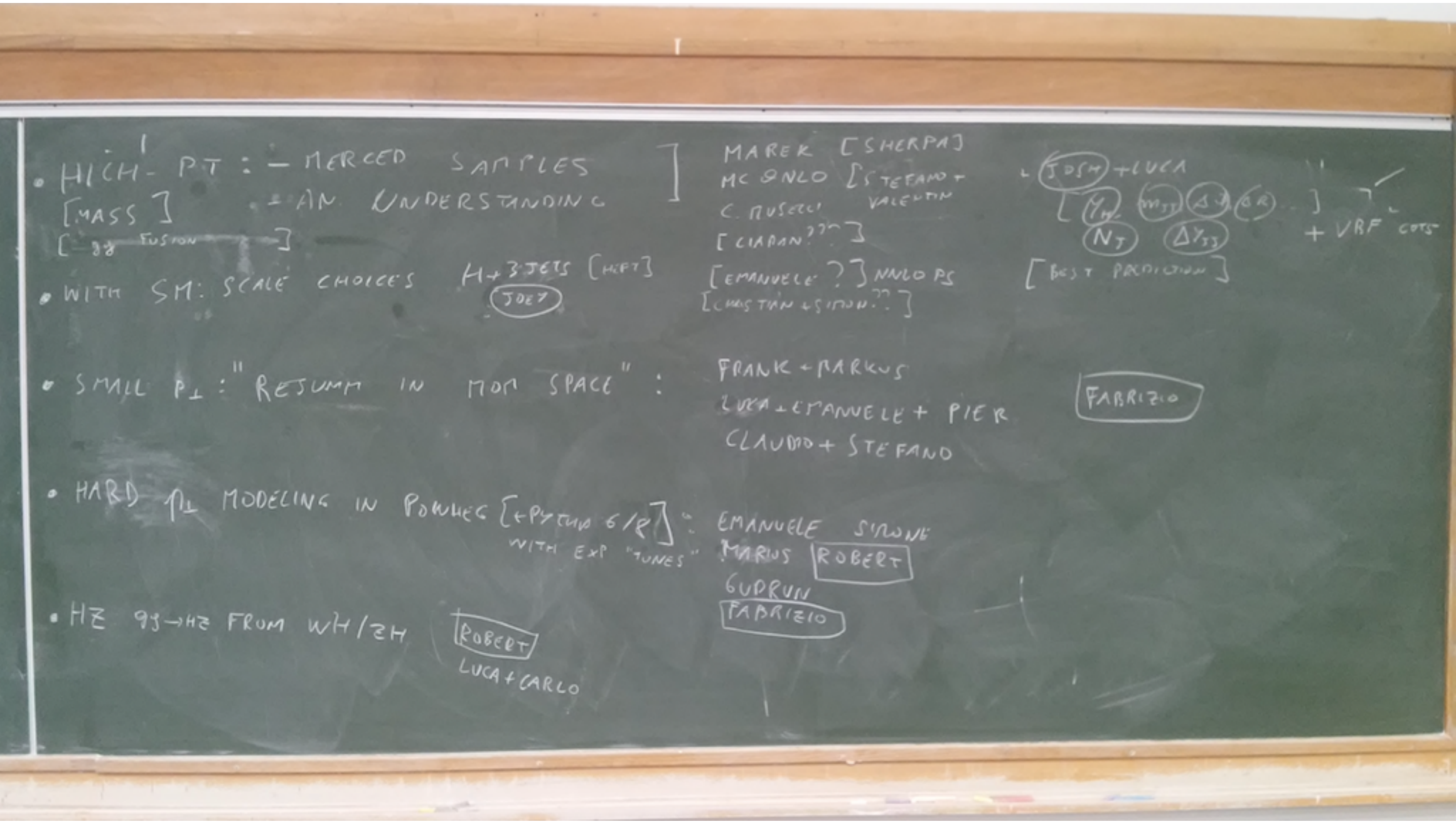

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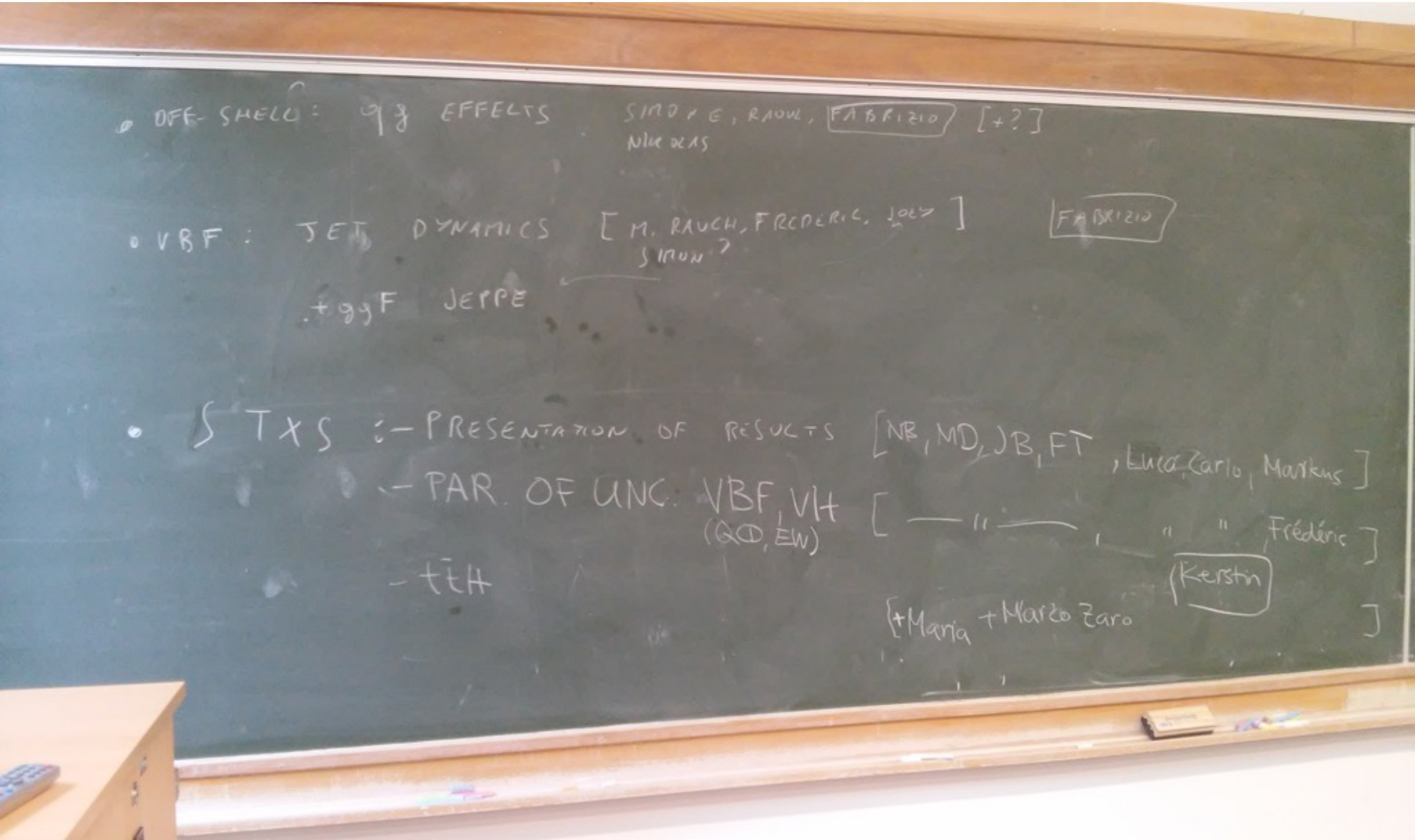
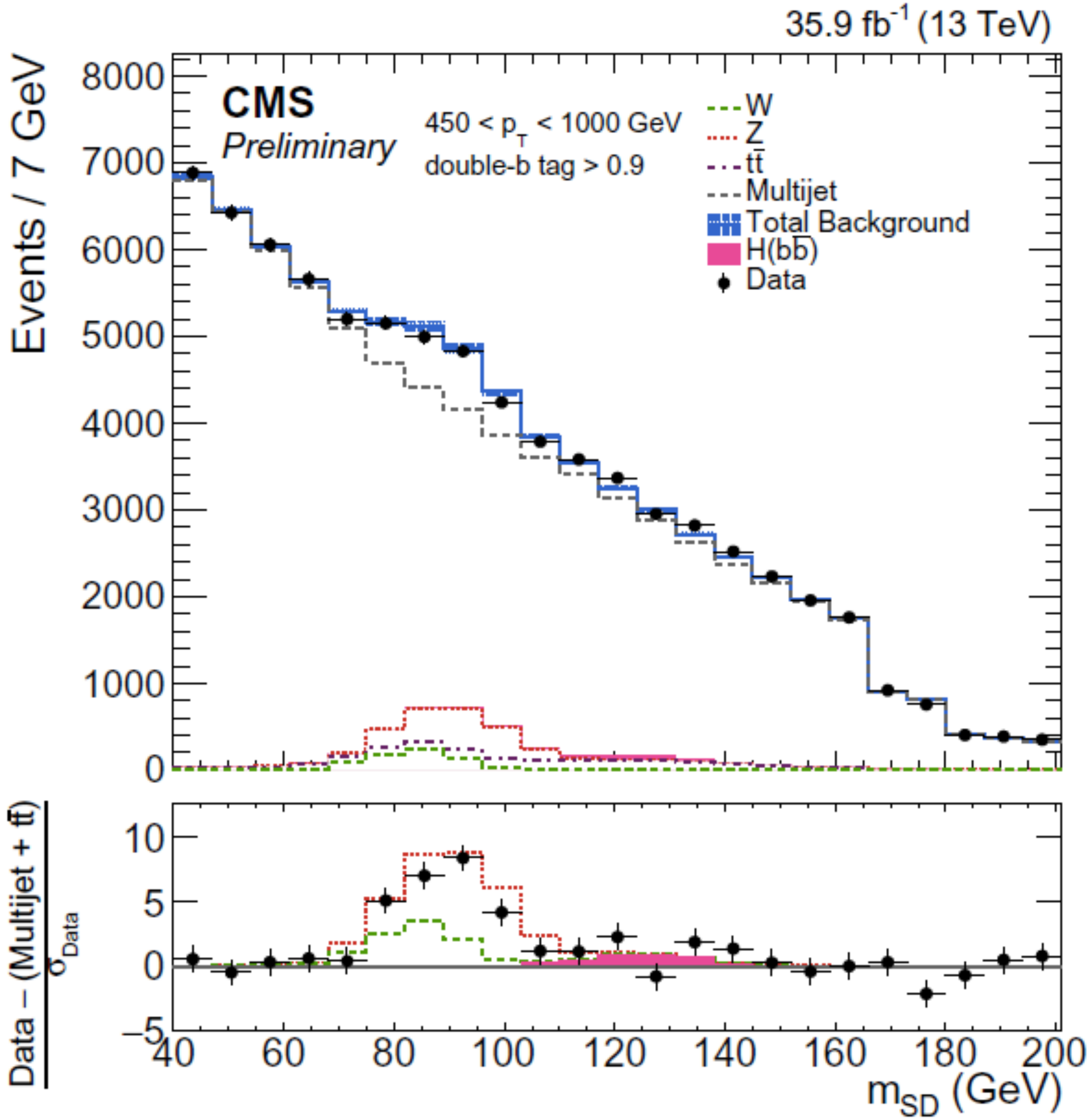

• OFF-SHELL: gg EFFECTS
SIMONE, RAOUL, FABRIZIO [+?]
NICOLAS
• VBF: JET DYNAMICS [M. RAUCH, FREDERIC,]
SIMON?
FABRIZIO
+ggF JEPPE
• STXS: - PRESENTATION OF RESULTS
[NB, MD, JB, FT, Luca, Carlo, Markus]
- PAR. OF UNC. VBF, VH
(QCD, EW)
[— " — , " " Frédéric]
- ttH
Kerstin
[+Maria +Marco Zaro]

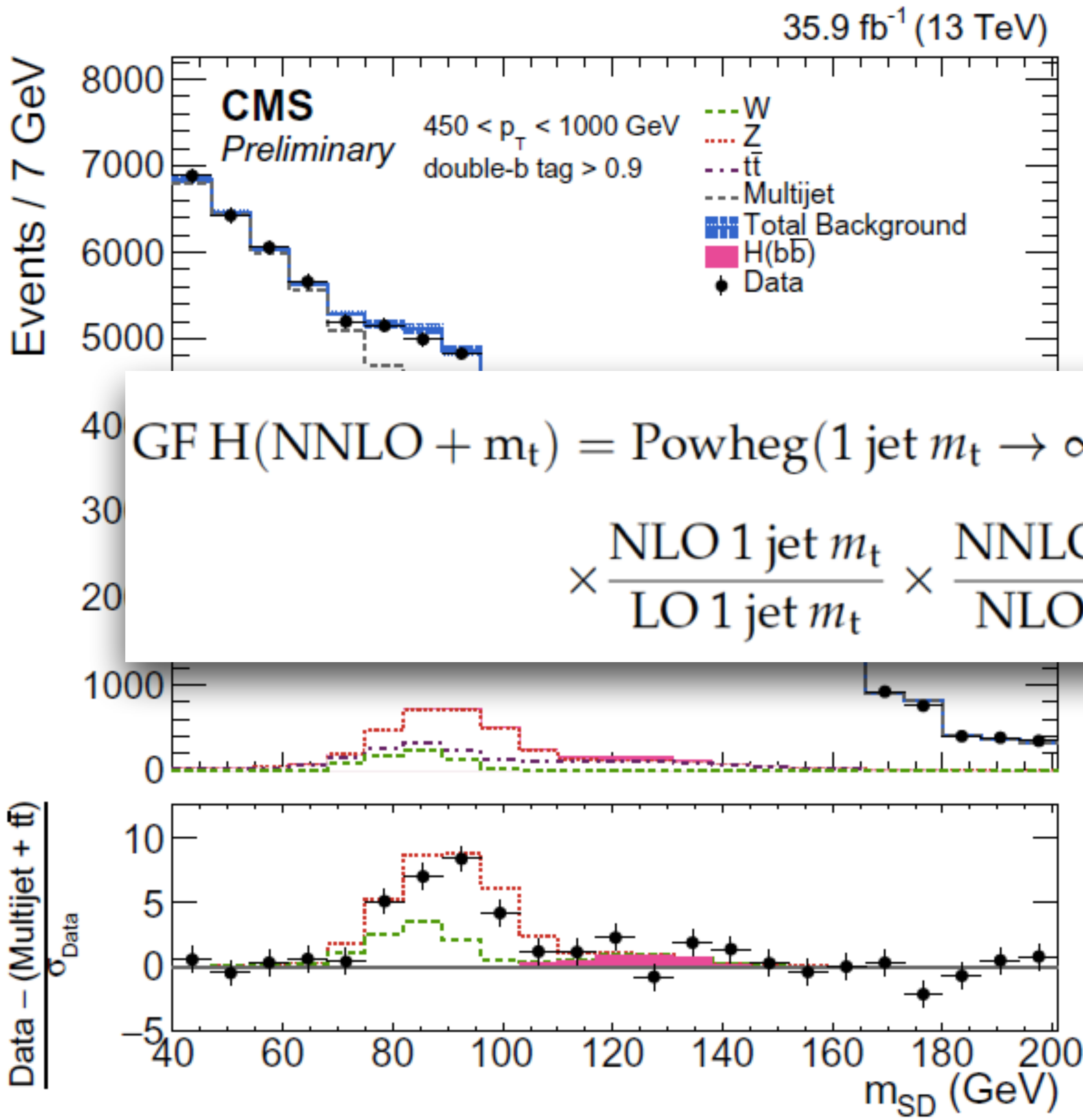
Higgs @ large p_T:

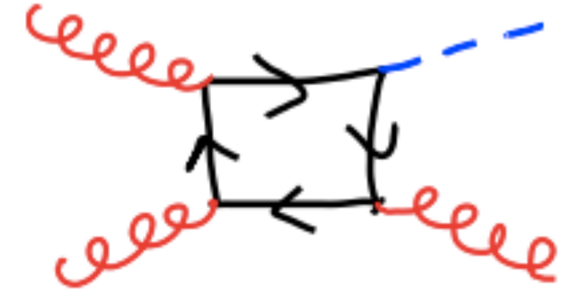


only known to LO!

CMS-PAS-HIG-17-010

Higgs @ large p_T:



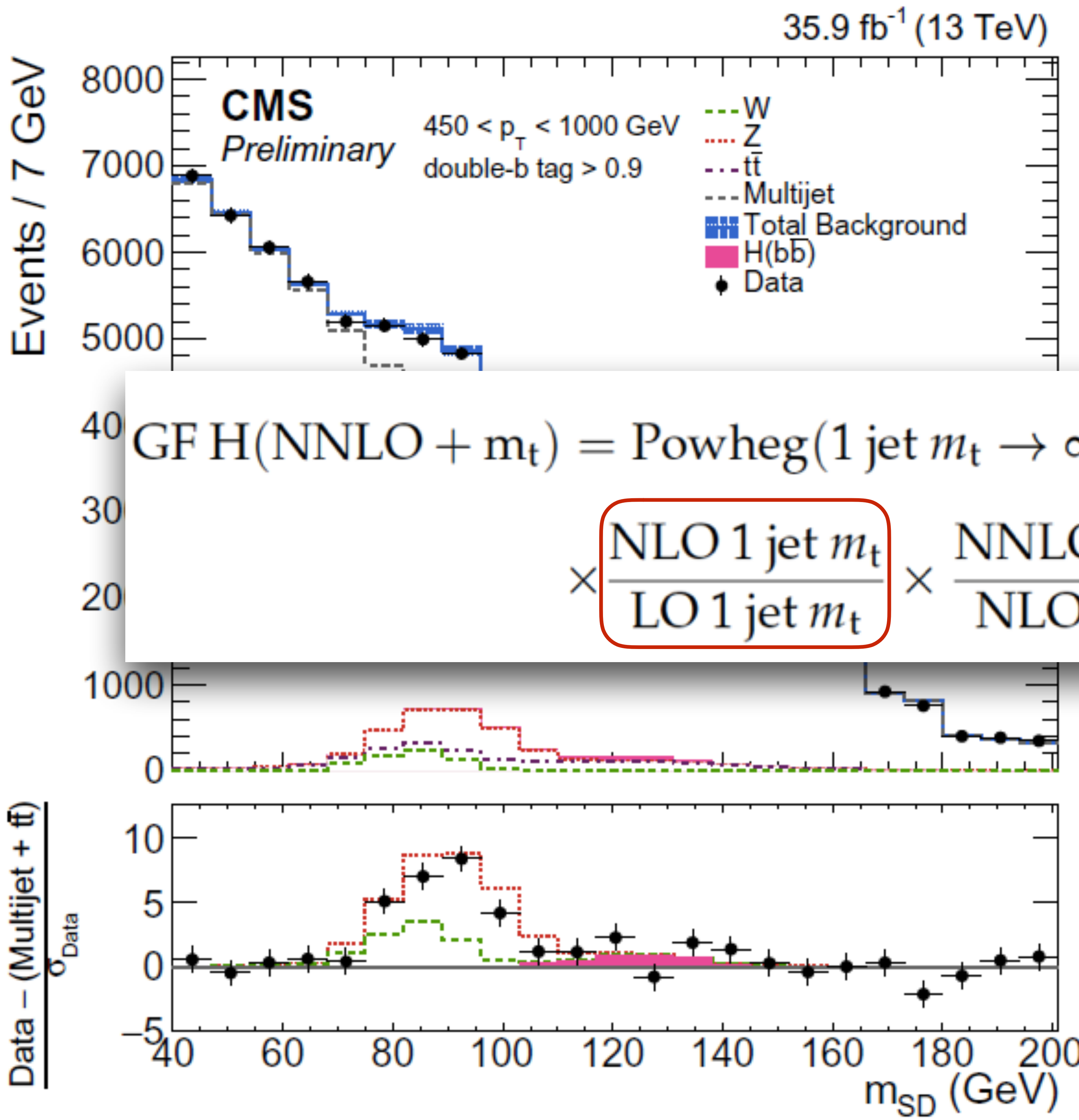


only known to LO!

$$\mathrm{GF\,H(NNLO+m_t)} = \mathrm{Powheg}(1\,\mathrm{jet}\; m_t \to \infty) \times \frac{\mathrm{MG\,LO}\;0-2\;\mathrm{jet}\; m_t}{\mathrm{Powheg}(1\,\mathrm{jet}\; m_t \to \infty)} \times \frac{\mathrm{NLO}\;1\;\mathrm{jet}\; m_t}{\mathrm{LO}\;1\;\mathrm{jet}\; m_t} \times \frac{\mathrm{NNLO}\;1\;\mathrm{jet}\; m_t \to \infty}{\mathrm{NLO}\;1\;\mathrm{jet}\; m_t \to \infty}.$$

CMS-PAS-HIG-17-010

Higgs @ large p_T:



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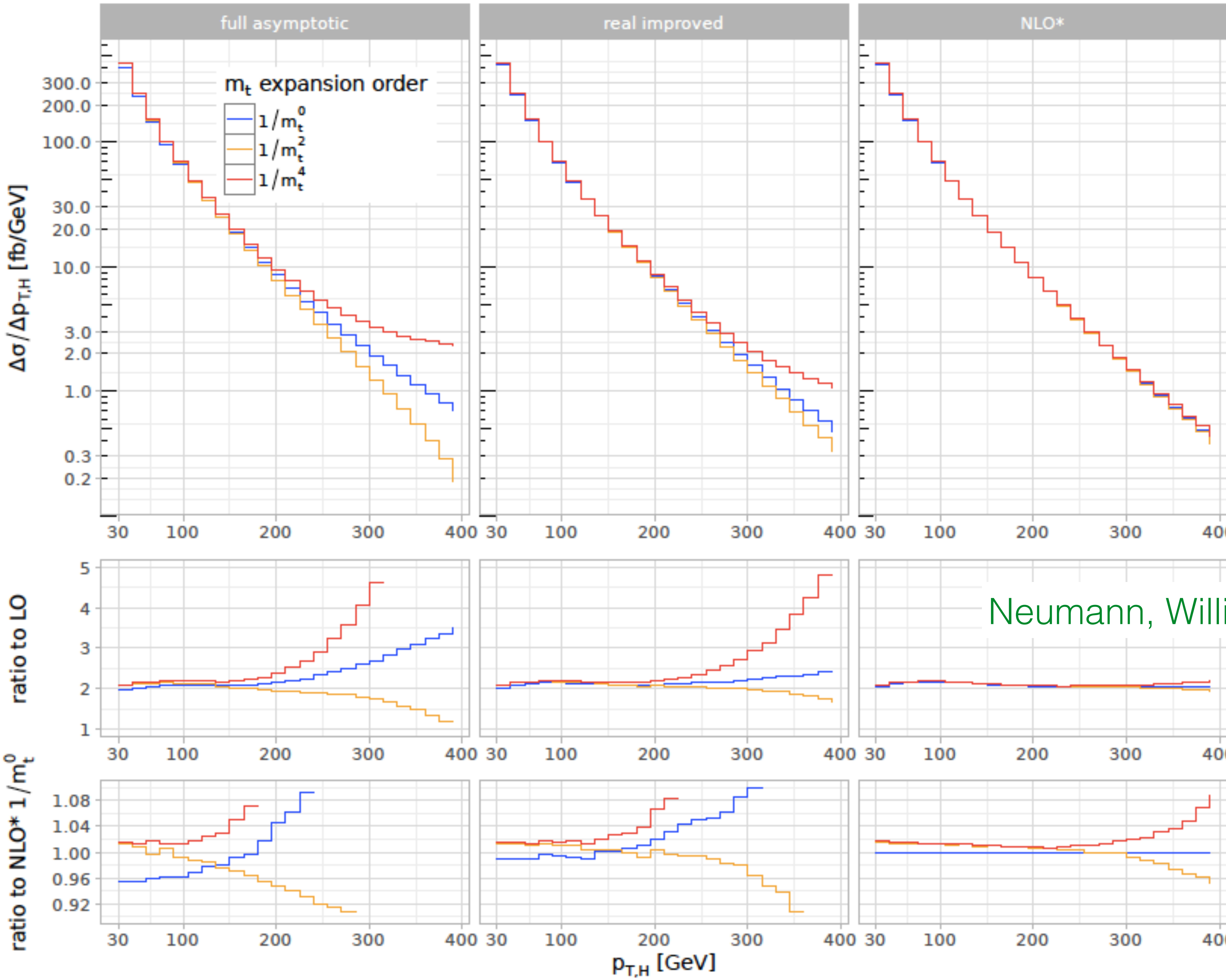
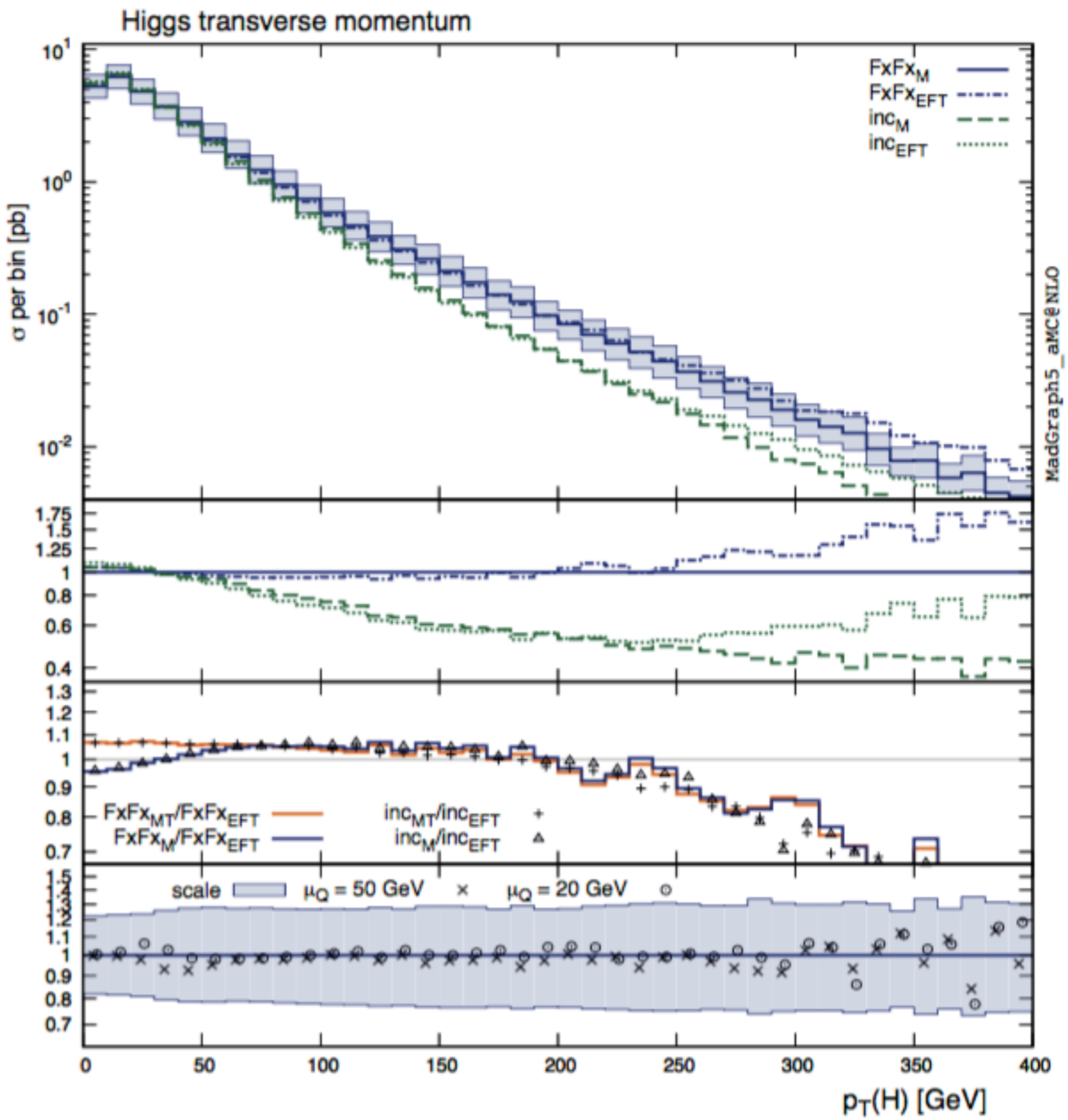
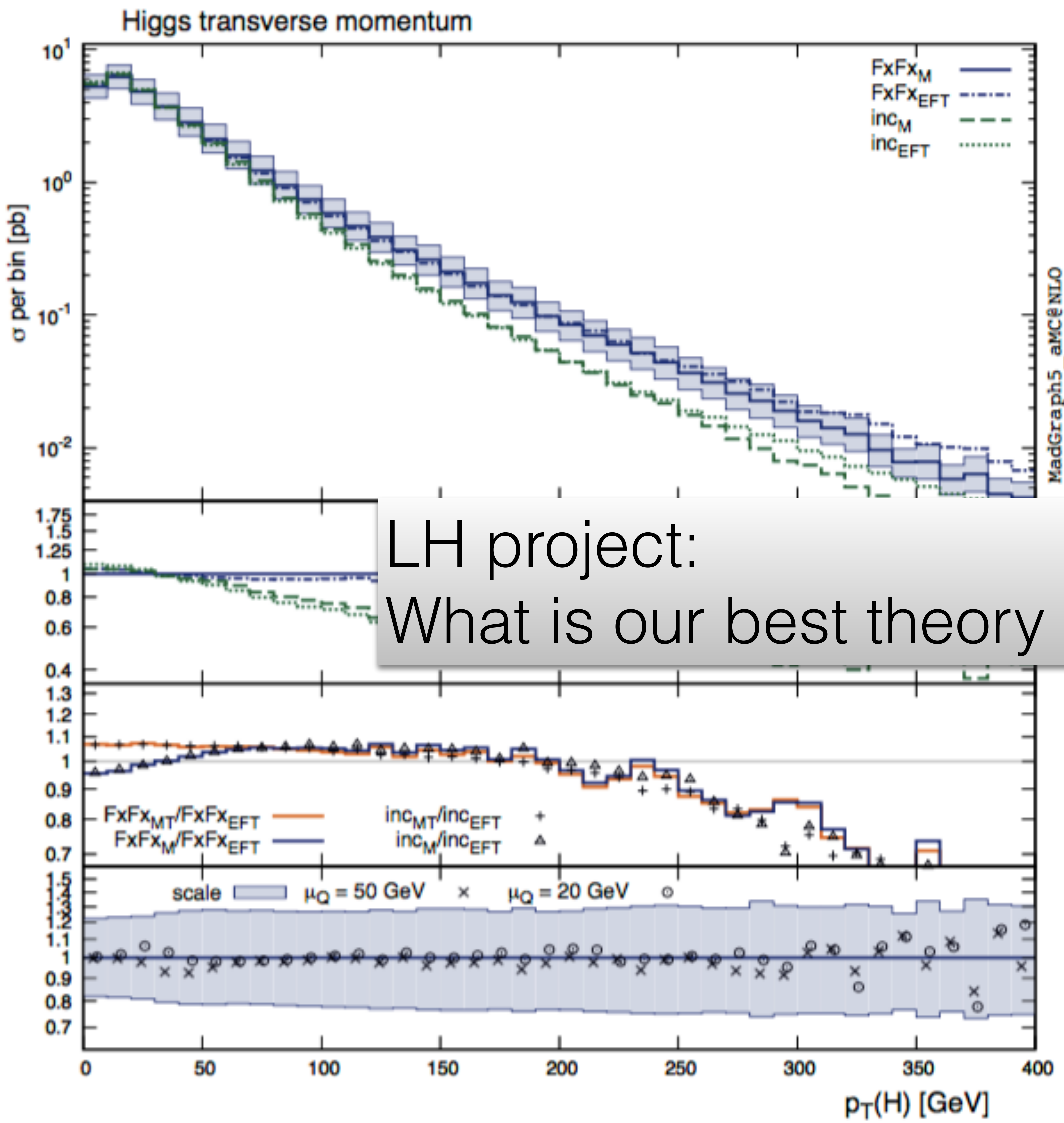


Neumann, Williams '16



Frederix, Frixione, Vryonidou, Wiesemann '17



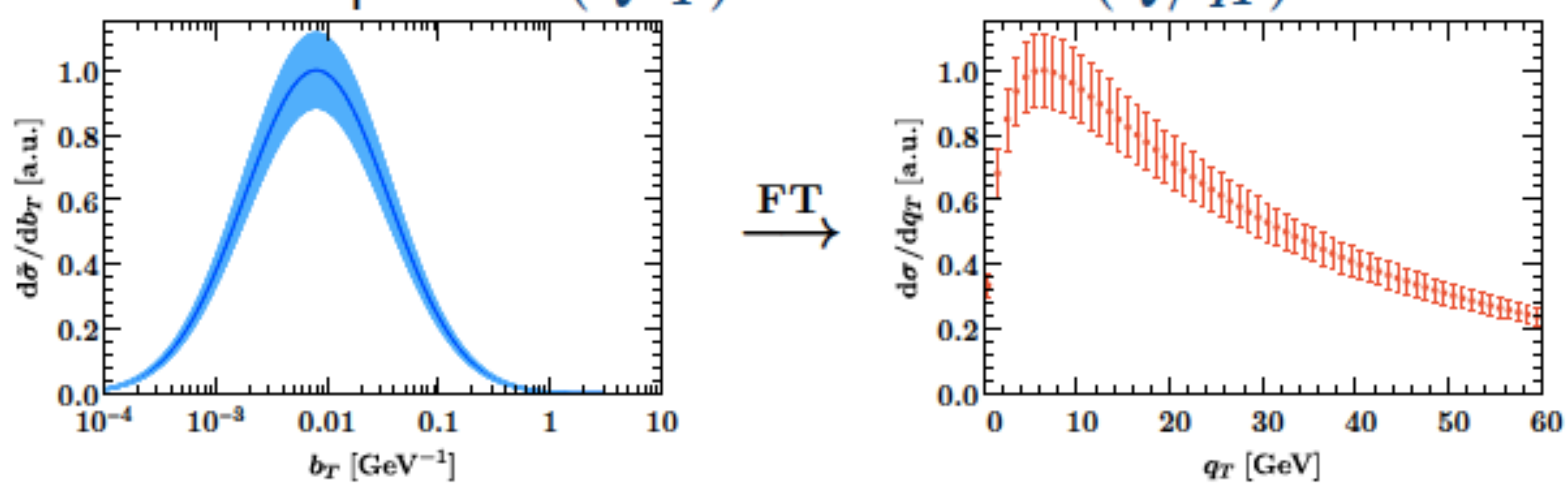
LH project:
What is our best theory prediction?

Frederix, Frixione, Vryonidou, Wiesemann '17

p_T resummation in p_T space:

Motivation.

- Transverse momenta $q_T \ll m_H$ are dominated by Sudakov logarithms $\alpha_s^n \ln^m(q_T/m_H)$, $m < 2n \to$ Resummation to all orders is necessary
- Resummation is well understood since [Collins, Soper, Sterman '85]
- Resummation carried out mostly in Fourier space $\vec{b}_T$
  DYRes [Catani, de Florian, Ferrera, Grazzini '15 ...], HRes [de Florian, Ferrera, Grazzini, Tommasini '12 ...], ResBos [Wang, Li^3, Yuan '12 ...], CuTe [Becher, Neubert, Wilhelm '12], [D'Alesio, Echevarria, Melis, Scimemi '14], [Echevarria, Kasemets, Mulders, Pisano '15], [Neill, Rothstein, Vaidya '15], arTeMiDe [Scimemi, Vladimirov '17], . . .
  - Resums $\ln(Qb_T)$ rather than $\ln(Q/q_T)$
  - Theory uncertainties are estimated in Fourier space:
    Scale variations probe $\ln(Qb_T)$ rather than $\ln(Q/q_T)$



p_T resummation in p_T space:

Motivation.

- Transverse momenta $q_T \ll m_H$ are dominated by Sudakov logarithms $\alpha_s^n \ln^m(q_T/m_H)\,,\ m < 2n \rightarrow$ Resummation to all orders is necessary
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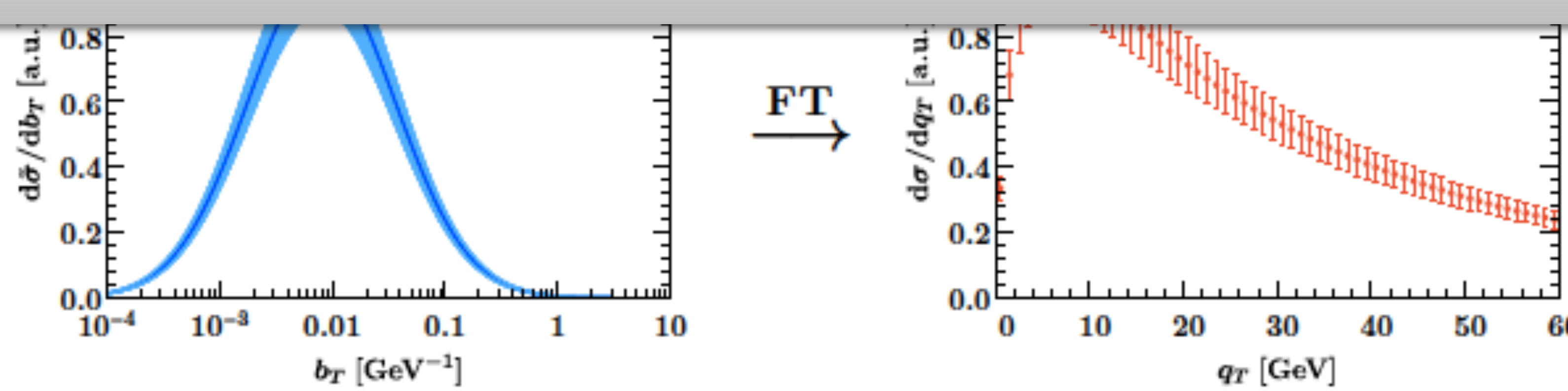
  - ▸ Resums $\ln(Qb_T)$ rather than $\ln(Q/q_T)$

- avoid Landau pole from $\alpha_s(1/b)$?
- need to treat azimuthal cancellations carefully



$$\sigma(\vec{q}_T) = \sigma_0\, H(Q, \mu_H) \frac{1}{2\pi q_T} \frac{\mathrm{d}}{\mathrm{d}q_T} \int_{|\vec{p}_T| \le q_T} \mathrm{d}^2\vec{p}_T$$

← distributional scale setting

$$\times \exp\left[\int_{\mu_H}^{\mu_T} \frac{\mathrm{d}\mu'}{\mu'} \gamma_H(Q, \mu')\right] \int \mathrm{d}^2\vec{k}_a\, \mathrm{d}^2\vec{k}_b\, \mathrm{d}^2\vec{k}_s\, \delta(\vec{p}_T - \vec{k}_a - \vec{k}_b - \vec{k}_s)$$

$$\times \int \mathrm{d}^2\vec{k}'_s \Big[\delta(\vec{k}_s - \vec{k}'_s)$$

$$+ \sum_{n=1}^{\infty} \prod_{i=1}^{n} \int_{k_{i-1}|_+}^{\nu_{i-1}} \frac{\mathrm{d}\nu_i}{\nu_i} \int \mathrm{d}^2\vec{k}_i\, \gamma_\nu(\vec{k}_{i-1} - \vec{k}_i, \mu_T)\, \delta\Big(\vec{k}_s - \vec{k}'_s - \sum_i \vec{k}_i\Big)\Big]$$

← ν evolution

$$\times B_a(\omega_a, \vec{k}_a, \mu_T, \nu_a)\, B_b(\omega_b, \vec{k}_b, \mu_T, \nu_b)\, S(\vec{k}'_s, \mu_T, k'_s|_+)$$

← ν-logs minimized

Ebert, F. Tackmann '17

Momentum space formulation

need some care in the treatment of the hard-collinear emissions

Result can be expressed as

$$\frac{d\Sigma(v)}{d\Phi_B} = \int_{\mathcal{C}_1} \frac{dN_1}{2\pi i} \int_{\mathcal{C}_2} \frac{dN_2}{2\pi i} x_1^{-N_1} x_2^{-N_2} \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} \mathbf{f}^T_{N_1}(\mu_0) \hat{\Sigma}^{c_1,c_2}_{N_1,N_2}(v) \mathbf{f}_{N_2}(\mu_0)$$

DGLAP anomalous dimensions

RG evolution of coefficient functions

$$\hat{\Sigma}^{c_1,c_2}_{N_1,N_2}(v) = \left[\mathbf{C}^{c_1;T}_{N_1}(\alpha_s(\mu_0)) H(\mu_R) \mathbf{C}^{c_2}_{N_2}(\alpha_s(\mu_0))\right] \int_0^M \frac{dk_{t1}}{k_{t1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi}$$
$$\times e^{-\mathbf{R}(\epsilon k_{t1})} \exp\left\{-\sum_{\ell=1}^{2}\left(\int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \frac{\alpha_s(k_t)}{\pi} \mathbf{\Gamma}_{N_\ell}(\alpha_s(k_t)) + \int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \mathbf{\Gamma}^{(C)}_{N_\ell}(\alpha_s(k_t))\right)\right\}$$
$$\sum_{\ell_1=1}^{2}\left(\mathbf{R}'_{\ell_1}(k_{t1}) + \frac{\alpha_s(k_{t1})}{\pi} \mathbf{\Gamma}_{N_{\ell_1}}(\alpha_s(k_{t1})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_1}}(\alpha_s(k_{t1}))\right)$$
$$\times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \sum_{\ell_i=1}^{2}\left(\mathbf{R}'_{\ell_i}(k_{ti}) + \frac{\alpha_s(k_{ti})}{\pi} \mathbf{\Gamma}_{N_{\ell_i}}(\alpha_s(k_{ti})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_i}}(\alpha_s(k_{ti}))\right)$$
$$\times \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right)$$

Result valid for all inclusive observables (e.g. p_T, φ^*)

$$V(k) = d_l g_l(\phi) \frac{k_T}{M}$$

unresolved emission + virtual corrections

resolved emission

Formulation **equivalent to b-space** result (up to a scheme change in the anomalous dimensions)

$$\frac{d^2\Sigma(v)}{d\Phi_B dp_t} = \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} \int b\, db\, p_t J_0(p_t b)\, \mathbf{f}^T(b_0/b) \mathbf{C}^{c_1;T}_{N_1}(\alpha_s(b_0/b)) H(M) \mathbf{C}^{c_2}_{N_2}(\alpha_s(b_0/b)) \mathbf{f}(b_0/b)$$
$$\times \exp\left\{-\sum_{\ell=1}^{2} \int_0^M \frac{dk_t}{k_t} \mathbf{R}'_\ell(k_t)\left(1 - J_0(bk_t)\right)\right\}$$

$$(1 - J_0(bk_t)) \simeq \Theta(k_t - \frac{b_0}{b}) + \frac{\zeta_3}{12} \frac{\partial^3}{\partial \ln(Mb/b_0)^3} \Theta(k_t - \frac{b_0}{b})$$

[Monni, Re, Torrielli, Phys.Rev.Lett. 116 (2016) no.24, 242001]
[Bizon, Monni, Re, LR, Torrielli, 1705.09127]

Verification: LL cross section without α_s-running

Solution in distribution space:

$$\sigma(\vec{q}_T) = \sigma_0 \frac{1}{2\pi q_T} \frac{\mathrm{d}}{\mathrm{d}q_T} \theta(q_T) f_a(\omega_a, q_T)\, f_b(\omega_b, q_T) \exp\left[-\frac{\Gamma_C}{2} \ln^2 \frac{Q^2}{q_T^2}\right]$$
$$\times \left[1 - 2\Gamma_C^2 \zeta_3 \ln \frac{Q^2}{q_T^2} + \Gamma_C^3 \left(\frac{2\zeta_3}{3} \ln^3 \frac{Q^2}{q_T^2} + 6\zeta_5 \ln \frac{Q^2}{q_T^2}\right)\right.$$
$$+ \Gamma_C^4 \left(-4\zeta_5 \ln^3 \frac{Q^2}{q_T^2} + 10\zeta_3^2 \ln^2 \frac{Q^2}{q_T^2} - 30\zeta_7 \ln \frac{Q^2}{q_T^2}\right)$$
$$\left. + \mathcal{O}(\Gamma_C^5)\right]$$

- Exponential resums $\ln(Q/q_T)$ at LL
- Many apparent-subleading terms arise from rapidity evolution
- These have no simple exponential structure

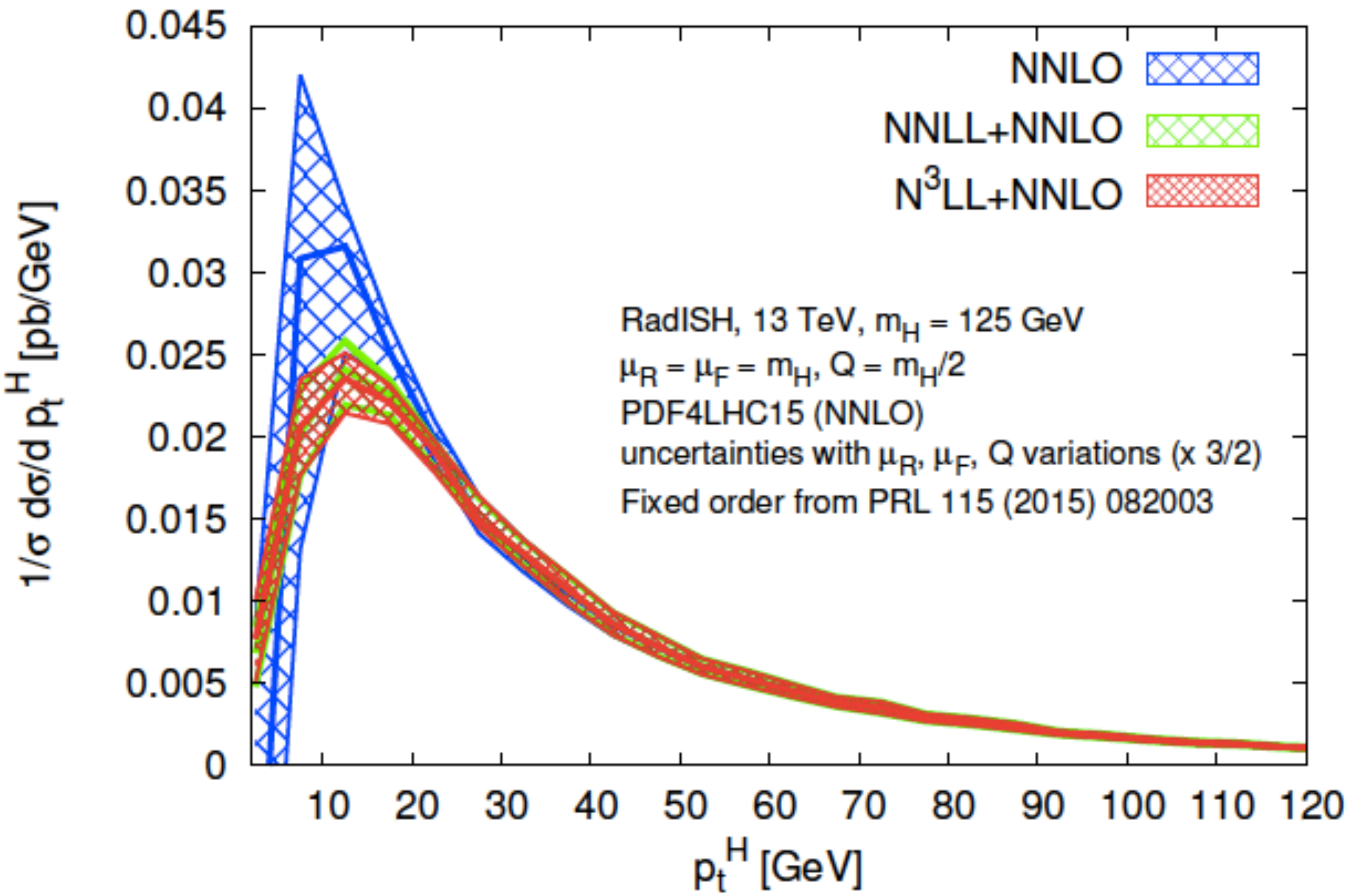
Verification: LL cross section without α_s-running

Solution in Fourier space:

$$
\begin{aligned}
\sigma(\vec{q}_T) &= \sigma_0 \frac{1}{2\pi q_T} \frac{\mathrm{d}}{\mathrm{d}q_T} \theta(q_T) f_a(\omega_a, q_T)\, f_b(\omega_b, q_T) \exp\Big[-\frac{\Gamma_C}{2} \ln^2 \frac{Q^2}{q_T^2}\Big] \\
&\quad \times \Big[1 - 2\Gamma_C^2 \zeta_3 \ln \frac{Q^2}{q_T^2} + \Gamma_C^3 \Big(\frac{2\zeta_3}{3} \ln^3 \frac{Q^2}{q_T^2} + 6\zeta_5 \ln \frac{Q^2}{q_T^2} - \frac{10}{3}\zeta_3^2\Big) \\
&\quad + \Gamma_C^4 \Big(-4\zeta_5 \ln^3 \frac{Q^2}{q_T^2} + 10\zeta_3^2 \ln^2 \frac{Q^2}{q_T^2} - 30\zeta_7 \ln \frac{Q^2}{q_T^2} + 28\zeta_3\zeta_5\Big) \\
&\quad + \mathcal{O}(\Gamma_C^5)\Big] \\
&= \sigma_0\, f_a(\omega_a, \mu)\, f_b(\omega_b, \mu) \int \frac{\mathrm{d}^2\vec{b}_T}{(2\pi)^2} e^{i\vec{b}_T\cdot\vec{q}_T} \exp\Big[-\frac{\Gamma_C}{2} \ln^2 \frac{Q^2 b_T^2}{4e^{-2\gamma_E}}\Big]
\end{aligned}
$$

- Simple Sudakov exponential in Fourier space → solution well-defined
- Induces same apparent-subleading terms as distributional solution
- Differ only by *constant* terms
  → Intrinsically different boundary condition than distribution space

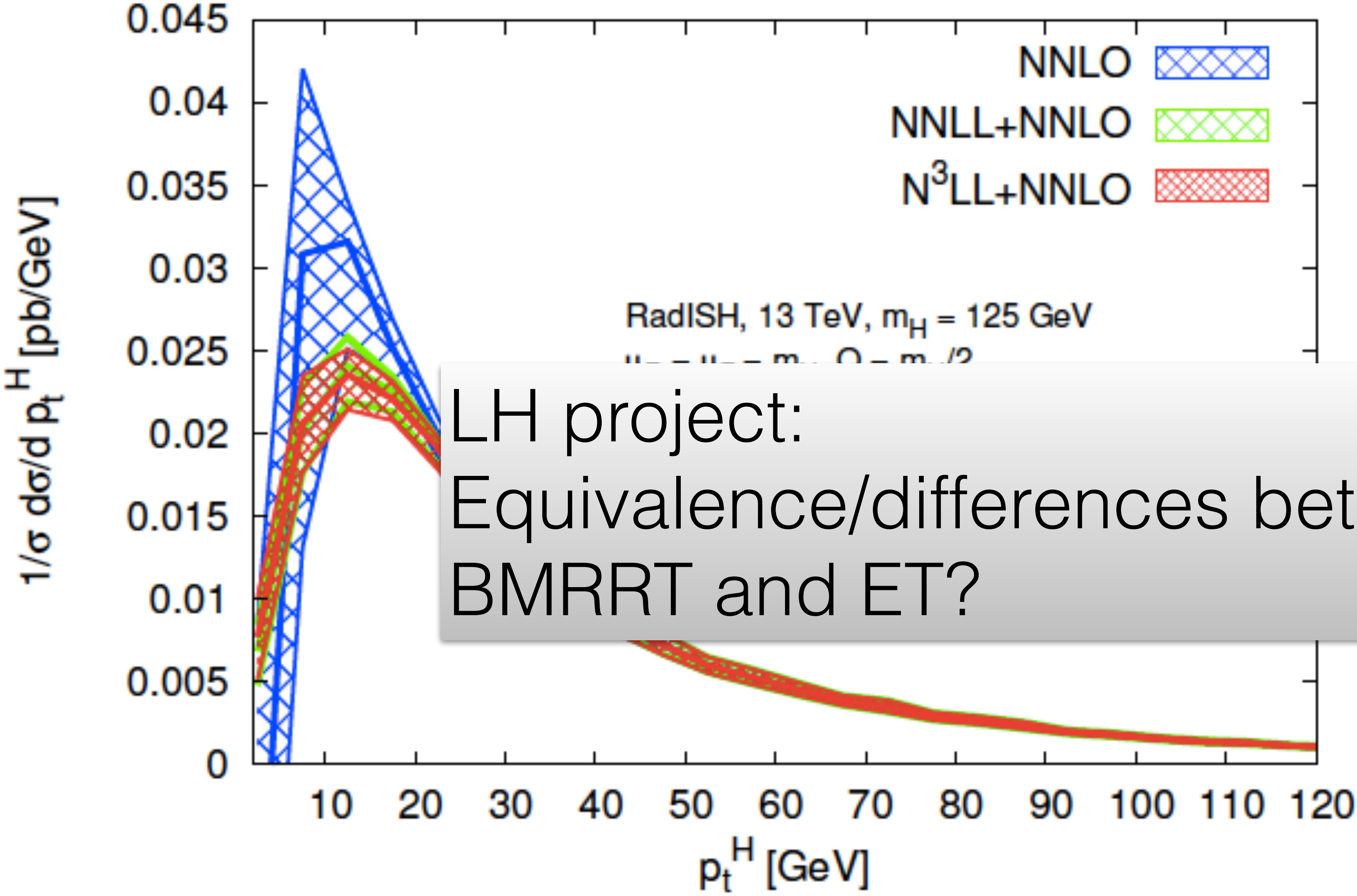
gg→H p_T distribution



Bizoń, Monni, Re, Rottoli, Torrielli '17

using NNLO from Boughezal, Caola, Melnikov, Petriello, Schulze '15

gg→H p_T distribution

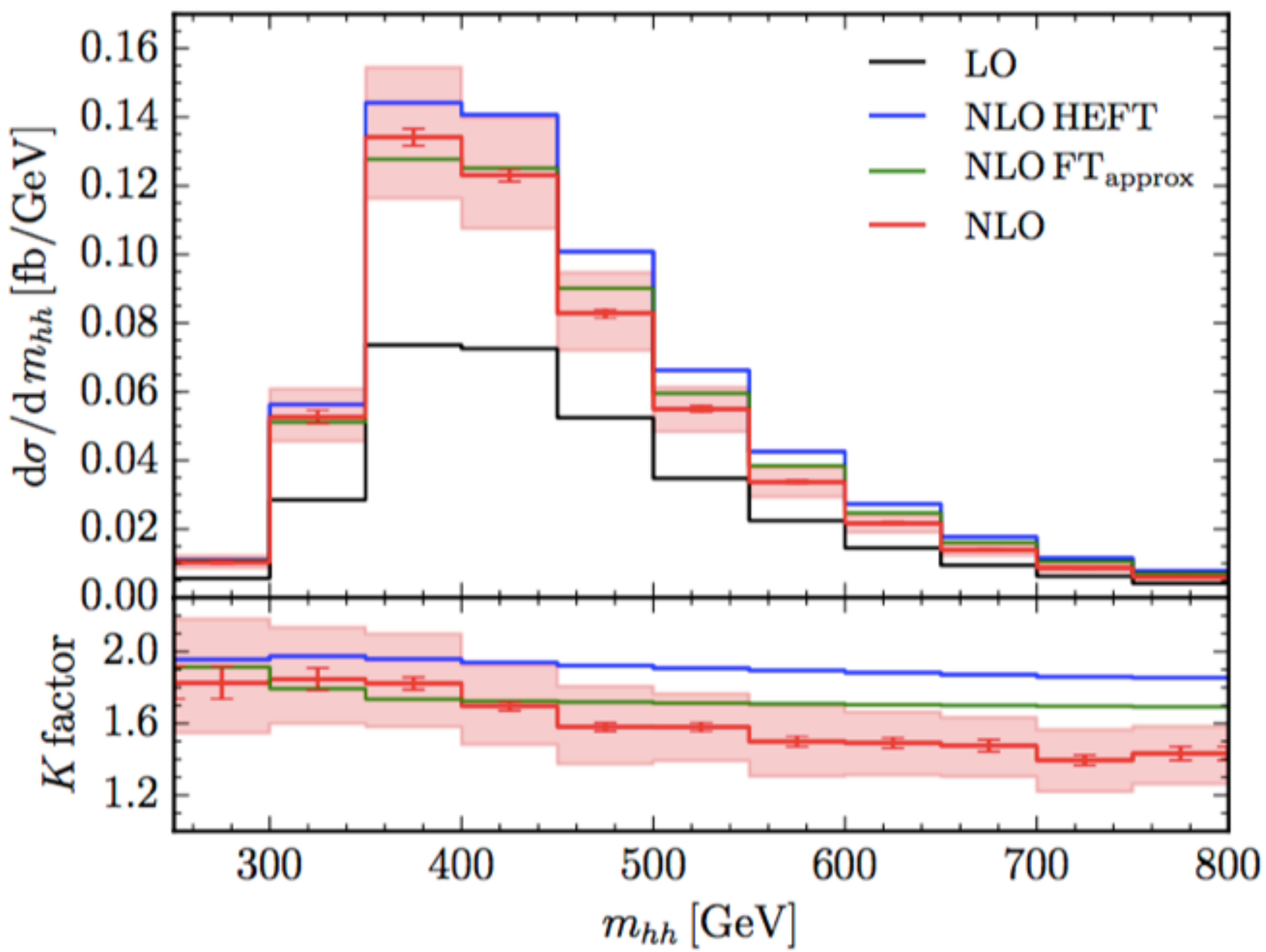


LH project:
Equivalence/differences between BMRRT and ET?

Bizoń, Monni, Re, Rottoli, Torrielli '17

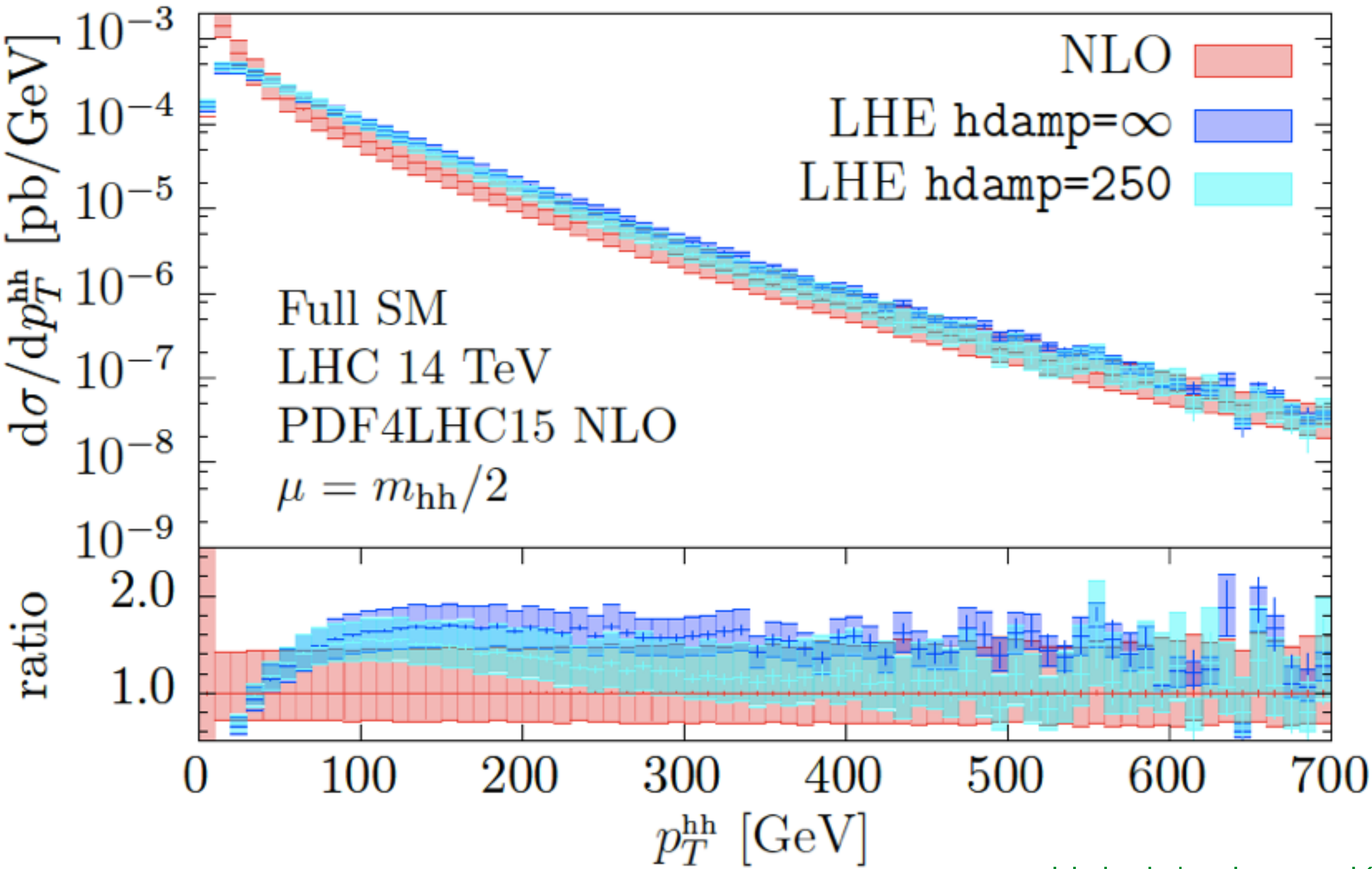
using NNLO from Boughezal, Caola, Melnikov, Petriello, Schulze '15

gg→HH @ NLO (with top mass dependence):



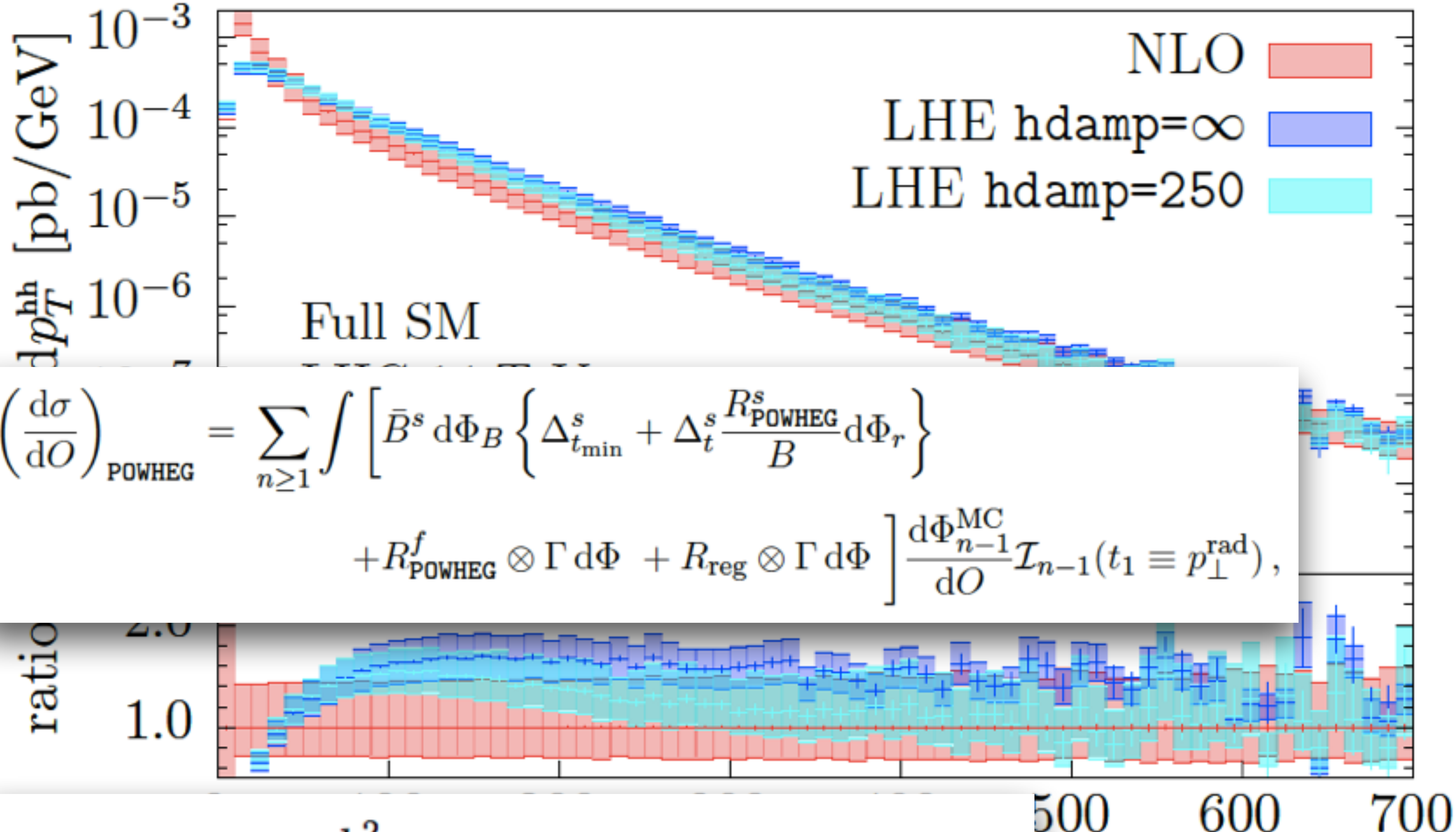
Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke '16

… with parton shower:



Heinrich, Jones, Kerner, Luisoni, Vryonidou ‘17

… with parton shower:

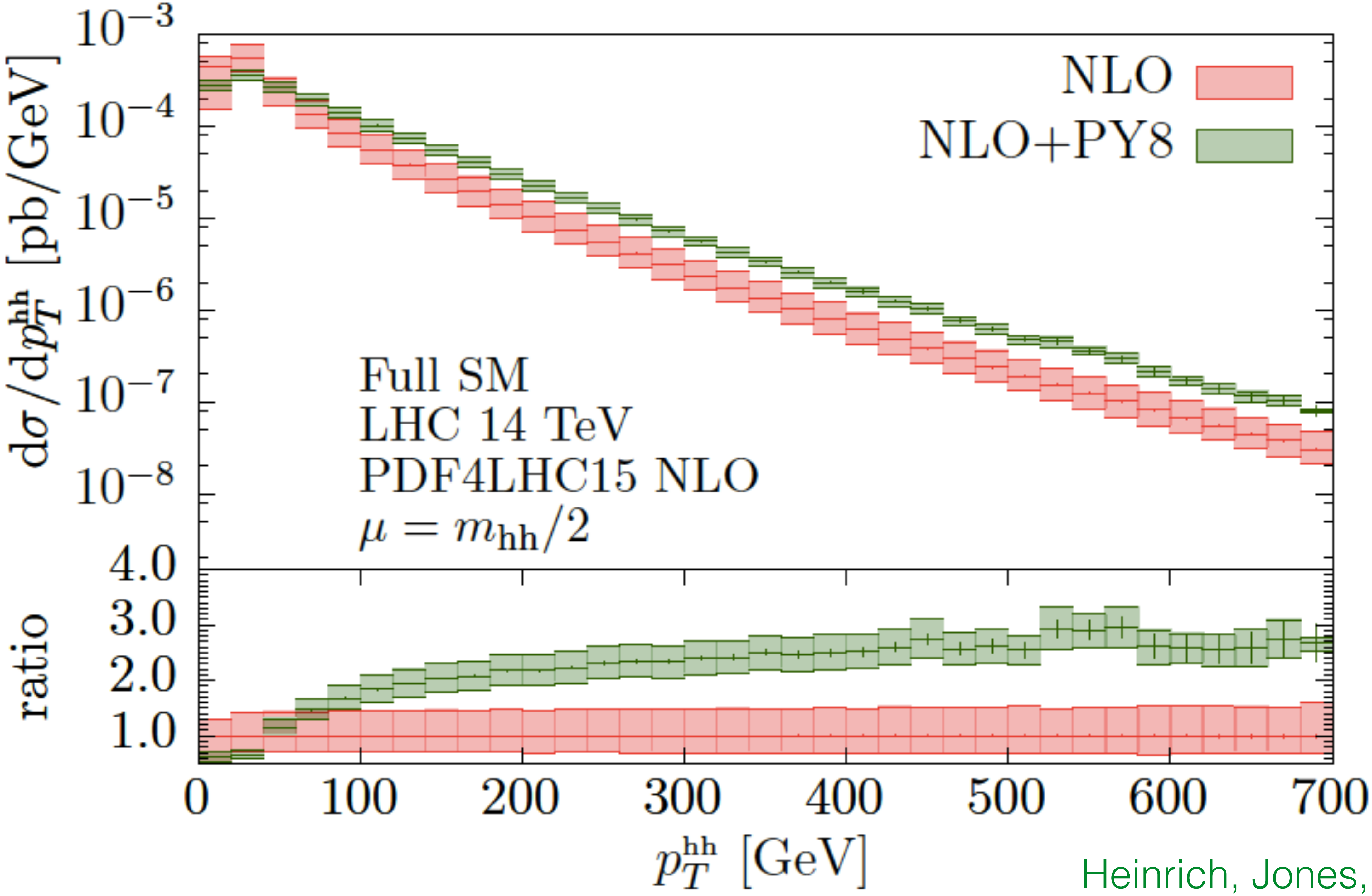


$$\left(\frac{d\sigma}{dO}\right)_{\texttt{POWHEG}} = \sum_{n\geq 1}\int \Bigg[\bar{B}^s\, d\Phi_B \left\{\Delta^s_{t_{\min}} + \Delta^s_t \frac{R^s_{\texttt{POWHEG}}}{B} d\Phi_r\right\} + R^f_{\texttt{POWHEG}} \otimes \Gamma\, d\Phi \; + R_{\rm reg} \otimes \Gamma\, d\Phi \Bigg] \frac{d\Phi^{\rm MC}_{n-1}}{dO} \mathcal{I}_{n-1}(t_1 \equiv p_\perp^{\rm rad})\,,$$

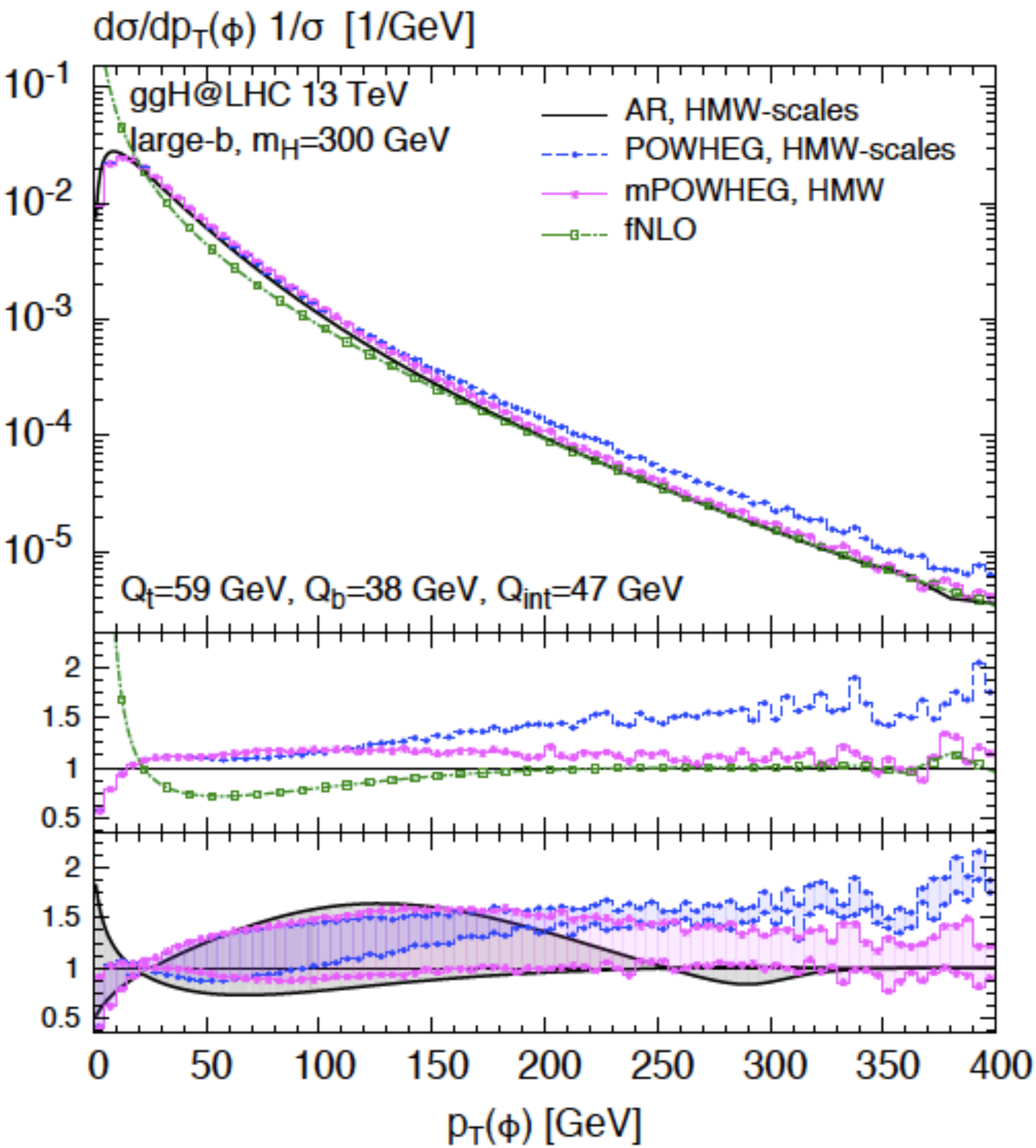
$$D_h \equiv \frac{h^2}{h^2 + (p_\perp)^2}\,,$$

$$R^s_{\texttt{POWHEG}} \equiv D_h R_{\rm div}\,, \qquad R^f_{\texttt{POWHEG}} \equiv (1 - D_h)\, R_{\rm div}\,.$$

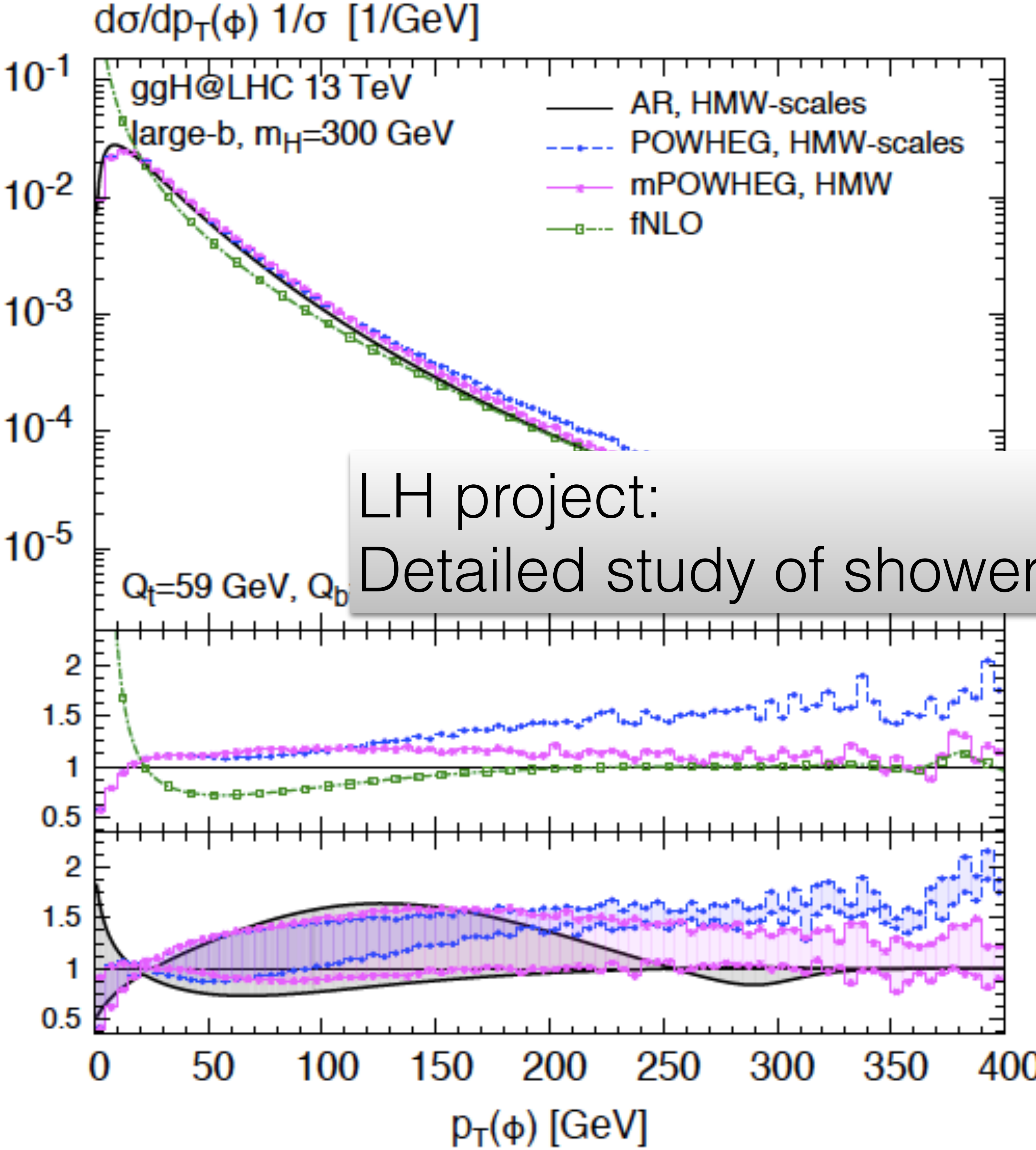
Heinrich, Jones, Kerner, Luisoni, Vryonidou '17



Heinrich, Jones, Kerner,
Luisoni, Vryonidou '17



Bagnaschi, RH, Mantler, Vicini, Wiesemann ‘15

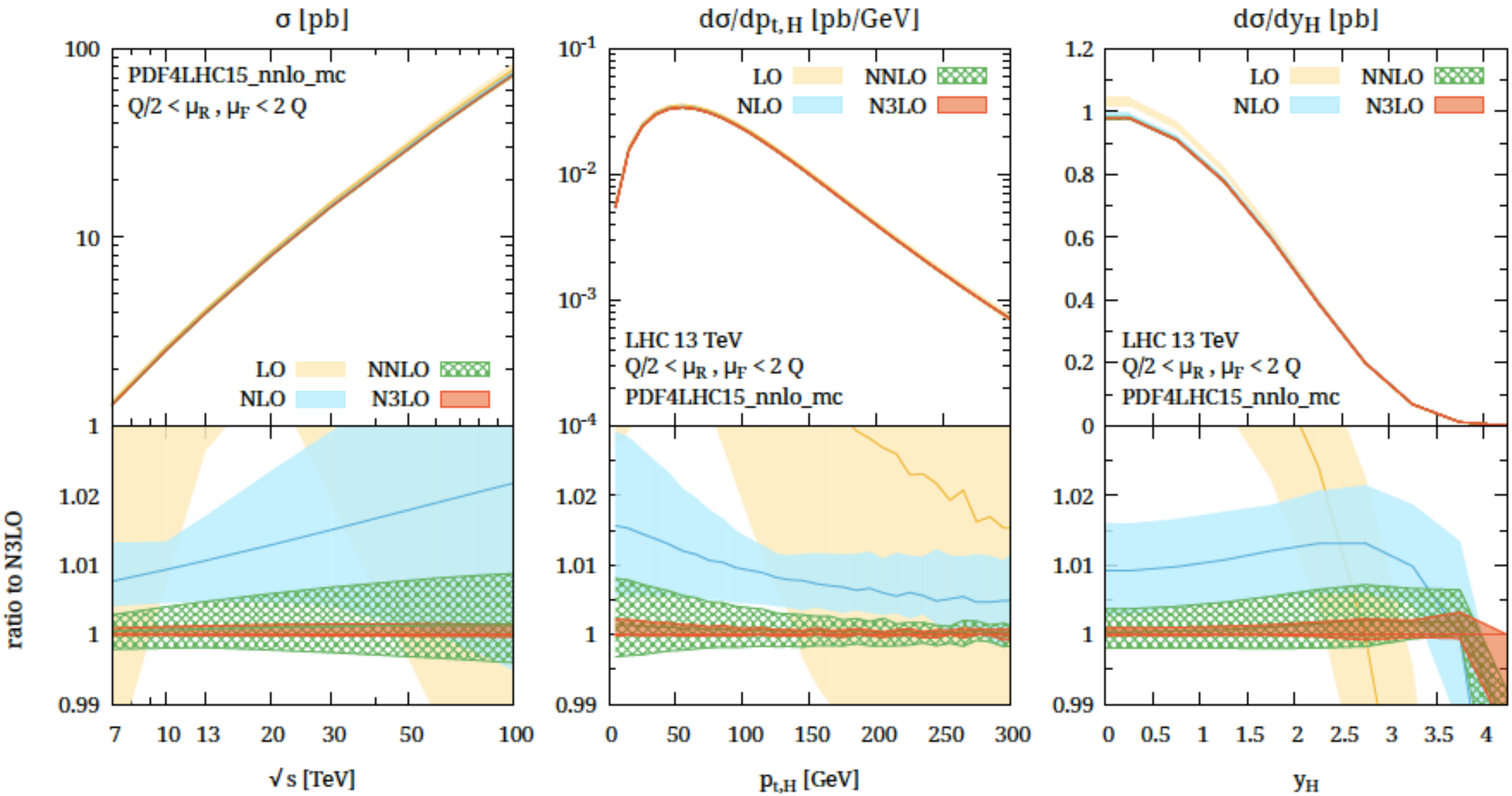


LH project:
Detailed study of shower effects at large p_T

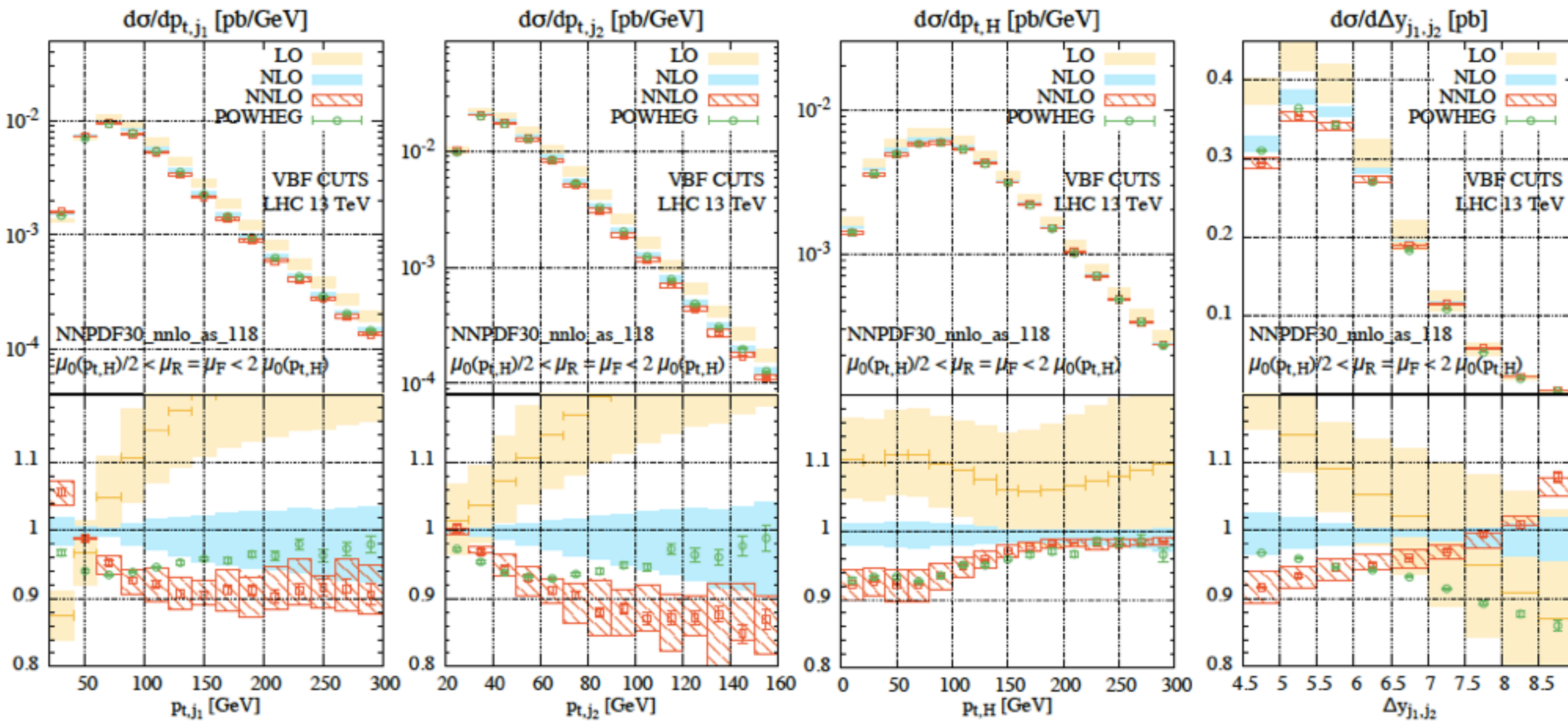
Bagnaschi, RH, Mantler, Vicini, Wiesemann ‘15

VBF N³LO inclusive:

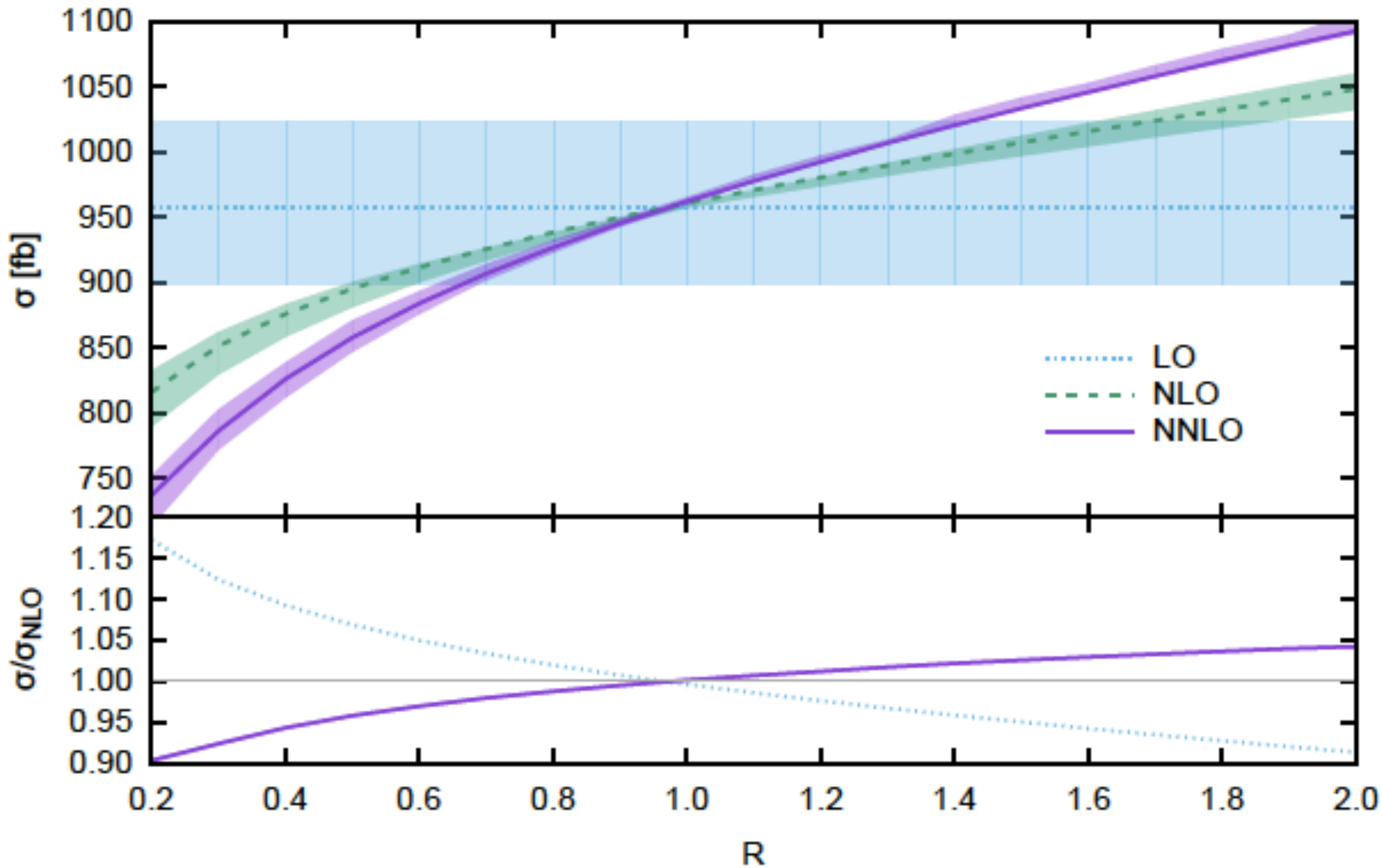
Dreyer, Karlberg '17



NNLO VBF distributions: Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15



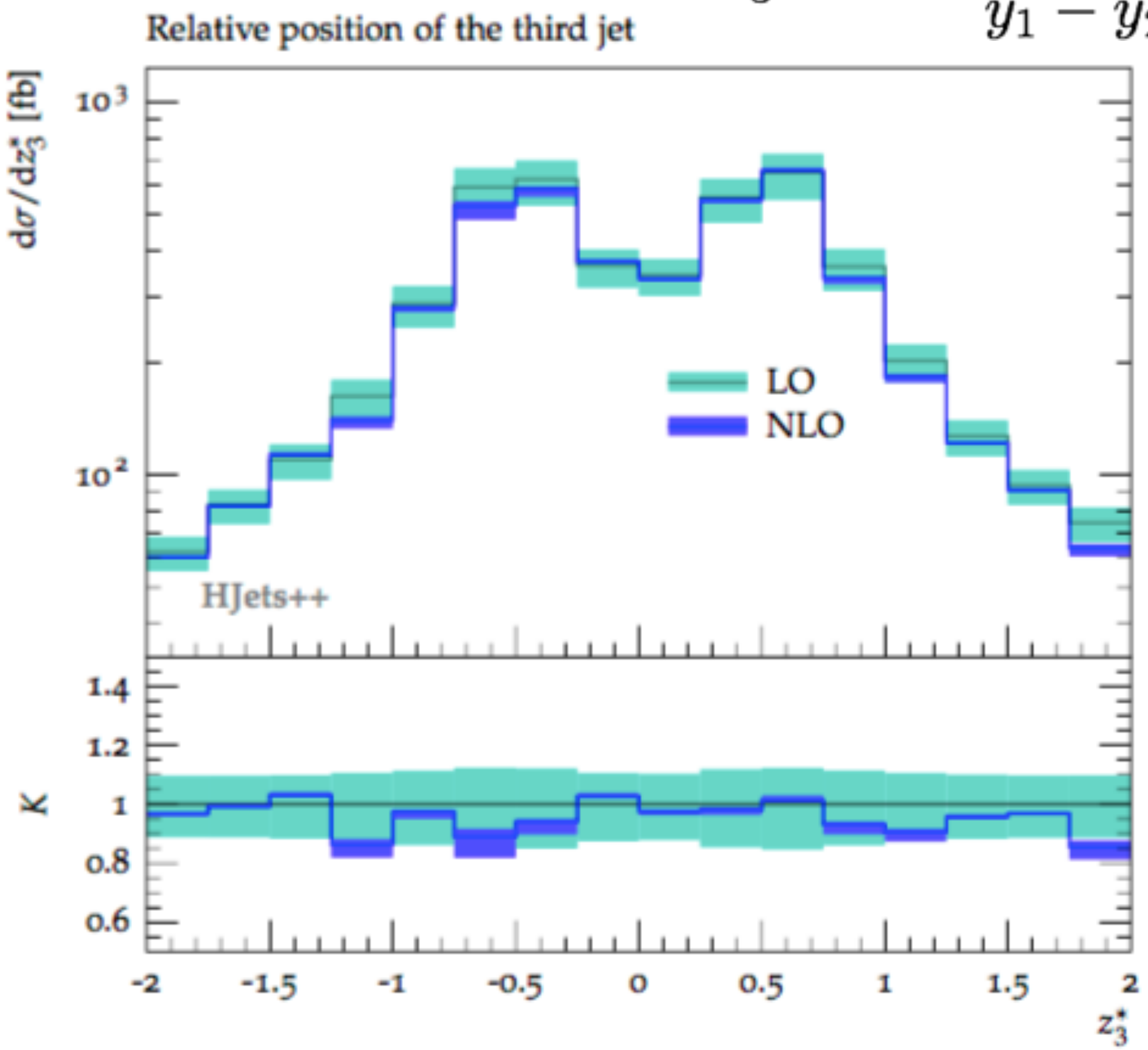
$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R,n) = \mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R{=}0.4, n{=}-1) \underbrace{-\mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R{=}0.4, n{=}-1) + \mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R,n)}_{=\Delta(R,n)} \,.$$

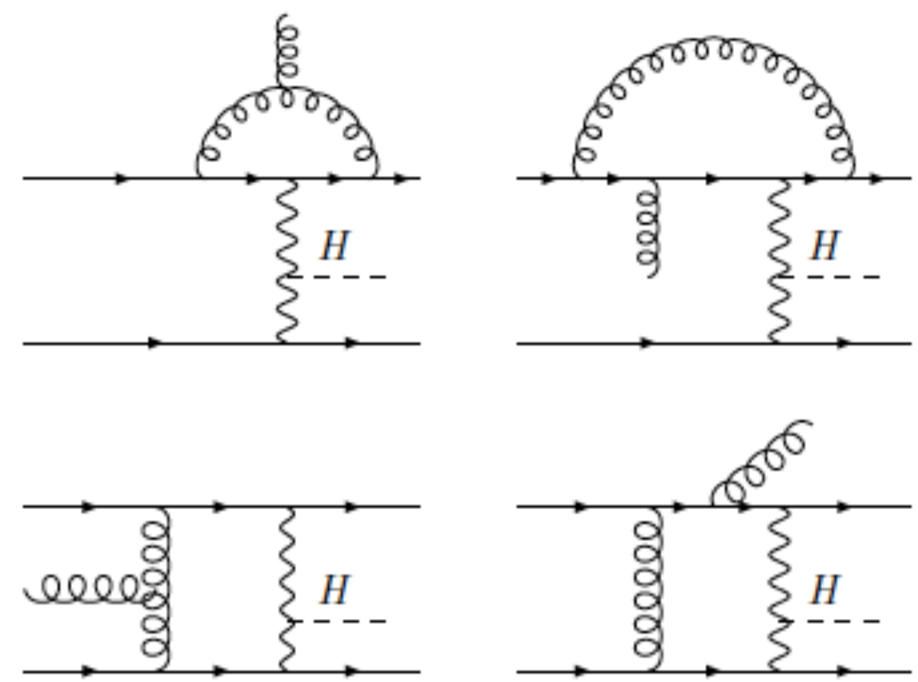


Rauch, Zeppenfeld '17

VBF+jet @ NLO

$$z_3^* = \frac{y_3 - (y_1 + y_2)/2}{y_1 - y_2}$$

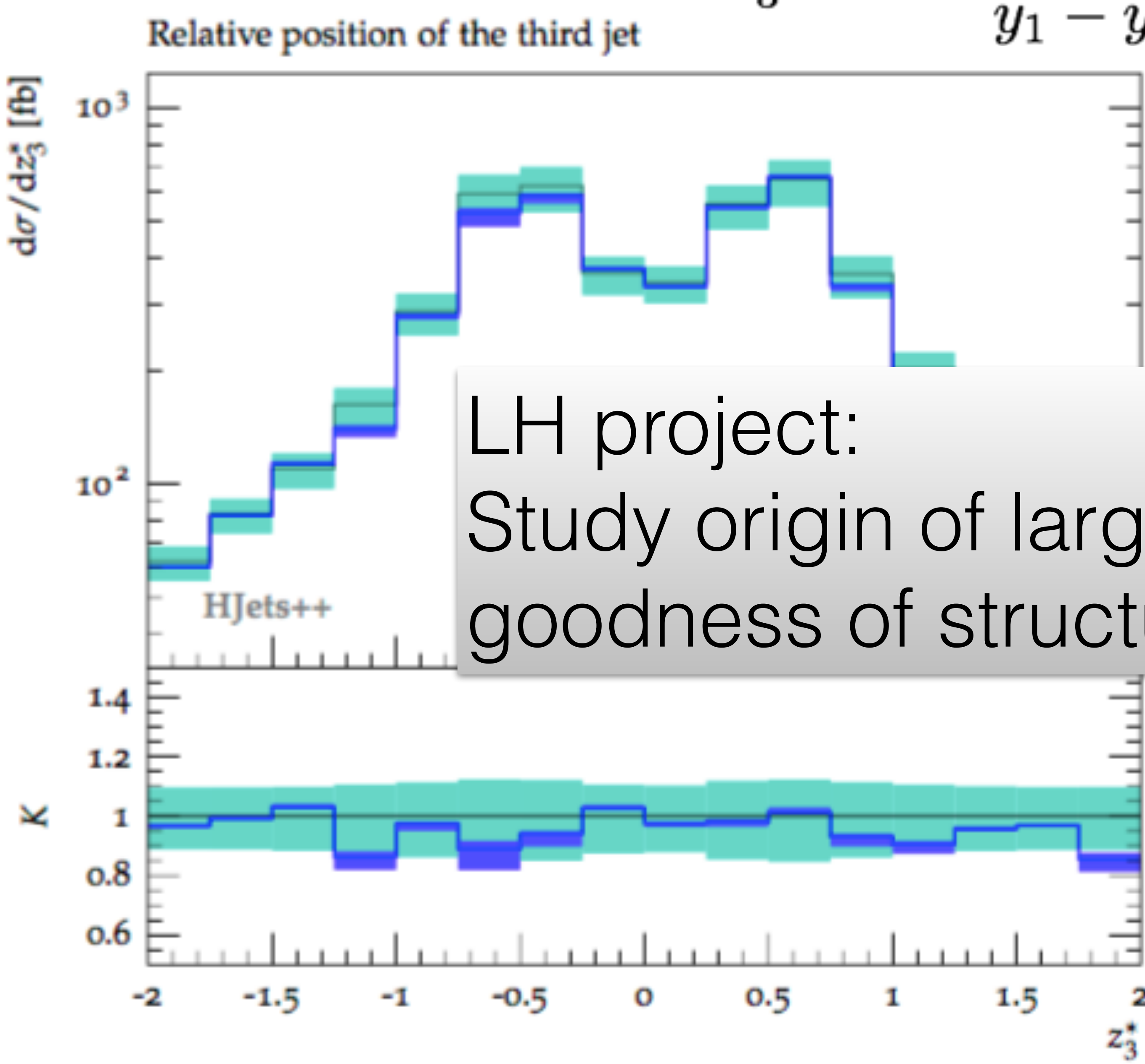


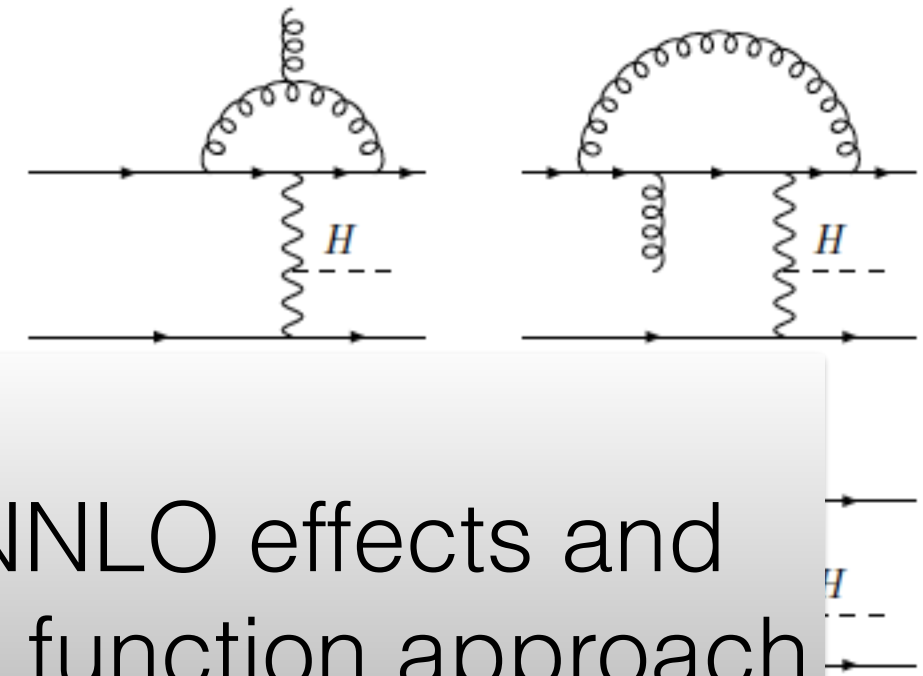


Campanario, Figy, Plätzer, Sjödahl '13

VBF+jet @ NLO

$$z_3^* = \frac{y_3 - (y_1 + y_2)/2}{y_1 - y_2}$$





LH project:
Study origin of large NNLO effects and goodness of structure function approach

Campanario, Figy, Plätzer, Sjödahl '13

Off-shell Higgs:

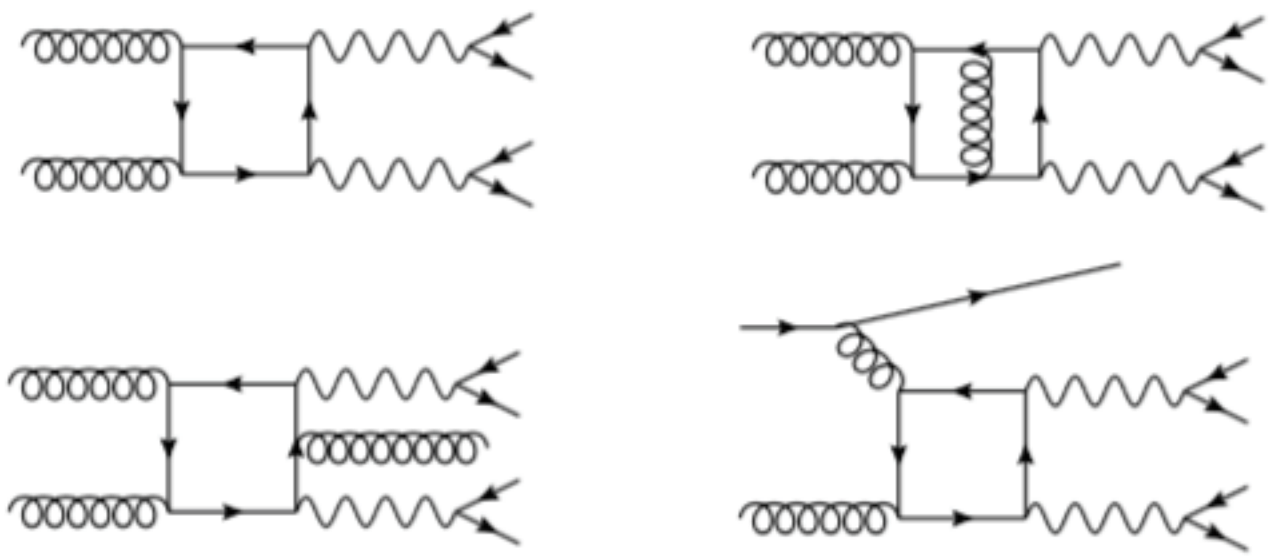
YR4 chapter (arXiv:1610.07922, 51 p.)

F. Caola, Y. Gao, NK, L. Soffi, J. Wang (eds.), A. Ballestrero, C. Becot, F. Bernlochner, H. Brun, A. Calandri, F. Campanario, F. Cerutti, D. de Florian, R. Di Nardo, L. Fayard, N. Fidanza, N. Greiner, A. V. Gritsan, G. Heinrich, B. Hespel, S. Höche, F. Krauss, Y. Li, S. Liebler, E. Maina, B. Mansoulié, C. O'Brien, S. Pozzorini, M. Rauch, J. Roskes, U. Sarica, M. Schulze, F. Siegert, P. Vanlaer, E. Vryonidou, G. Weiglein, M. Xiao, S. Yue

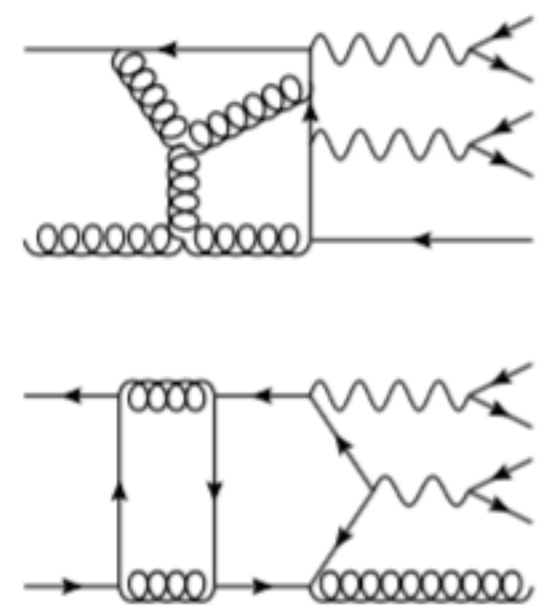
Future directions and discussion points

- Tools: high-mass NLO $gg \to VV$ (exact?) matched/merged with PS
  $\to$ public event generators for experimental studies
  (HERWIG7, MG5_AMC, POWHEG, SHERPA, ...)
- Comparing NLO+PS with. (merged) LO+PS predictions
- qg effects at NLO (overlap with $pp \to VV$ @ N^{3}LO)
- finite top mass corrections
- EW corrections
- BSM/EFT constraints

e.g. gg→ZZ × gg→H→ZZ



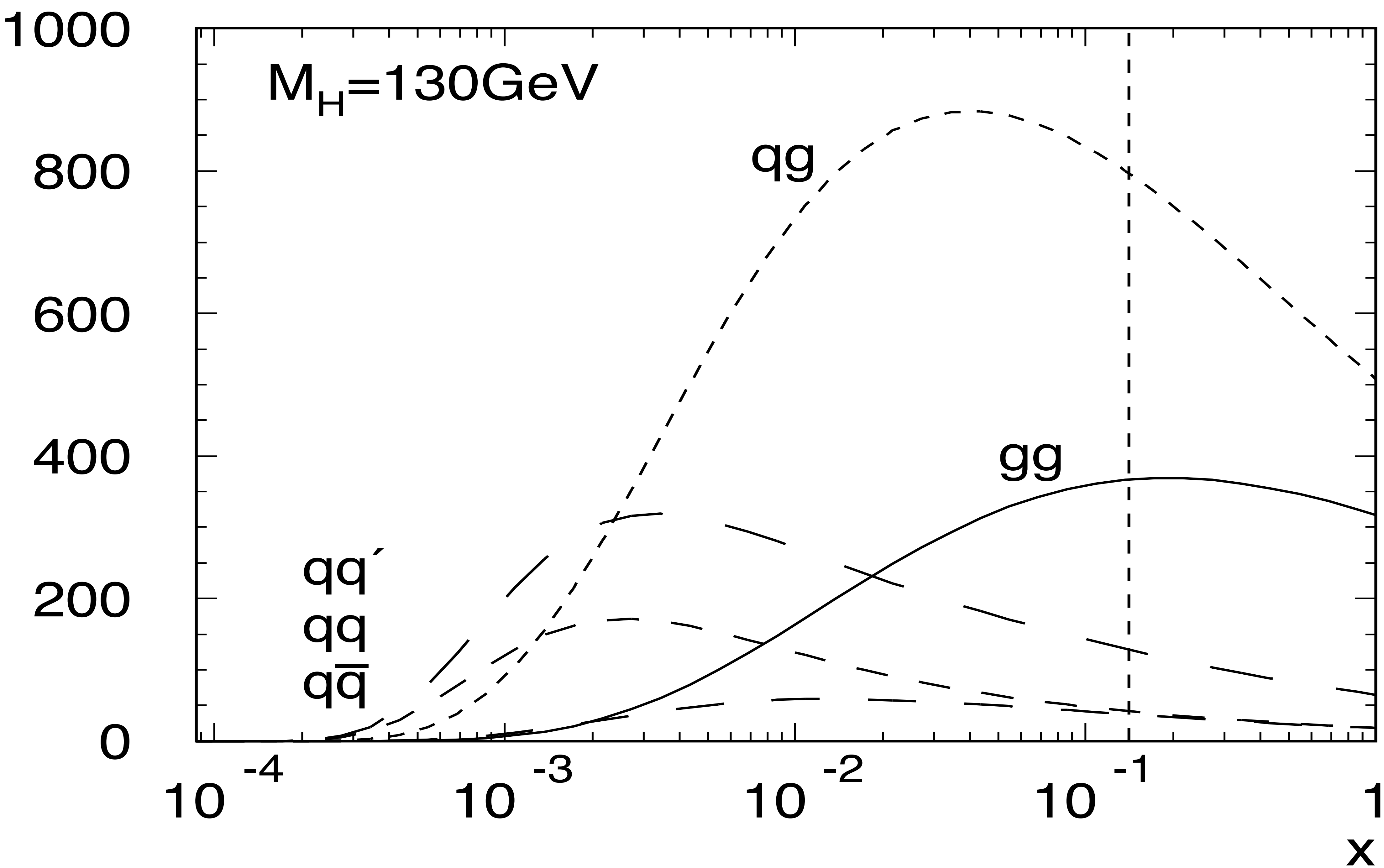
see Alioli, Caola, Luisoni, Röntsch ‘16



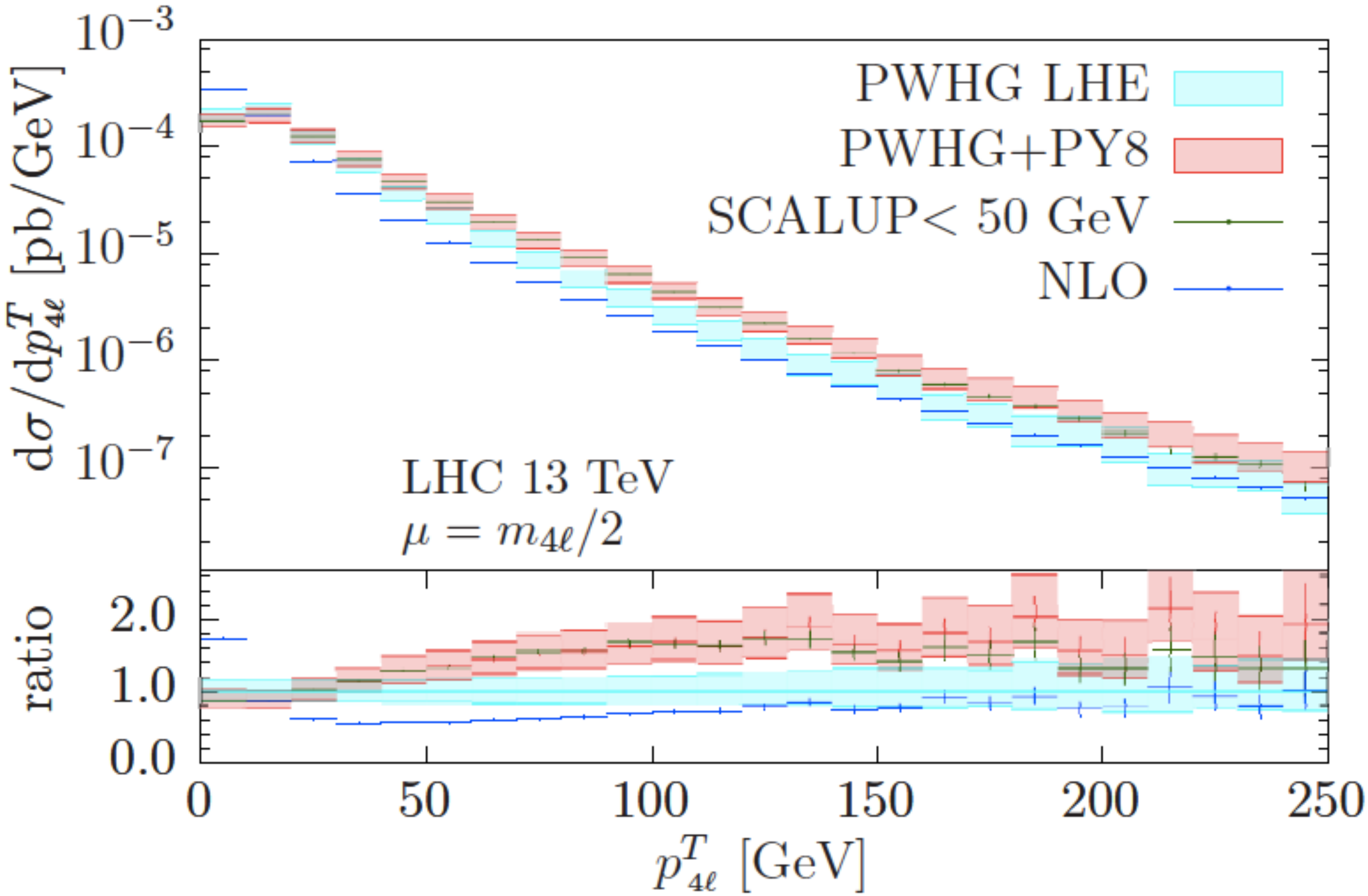
?

$$\sigma_{\alpha\beta}(z,\tau,l_{\rm F}) = \int_z^1 {\rm d}\omega\, \boxed{\mathcal{E}_{\alpha\beta}(\omega,\mu_{\rm F})}\, \hat{\sigma}_{\alpha\beta}(z/\omega,\tau,l_{\rm F})$$

$$\sigma_{\alpha\beta}(z,\tau,l_F) = \int_z^1 d\omega\, \mathcal{E}_{\alpha\beta}(\omega,\mu_F)\, \hat{\sigma}_{\alpha\beta}(z/\omega,\tau,l_F)$$

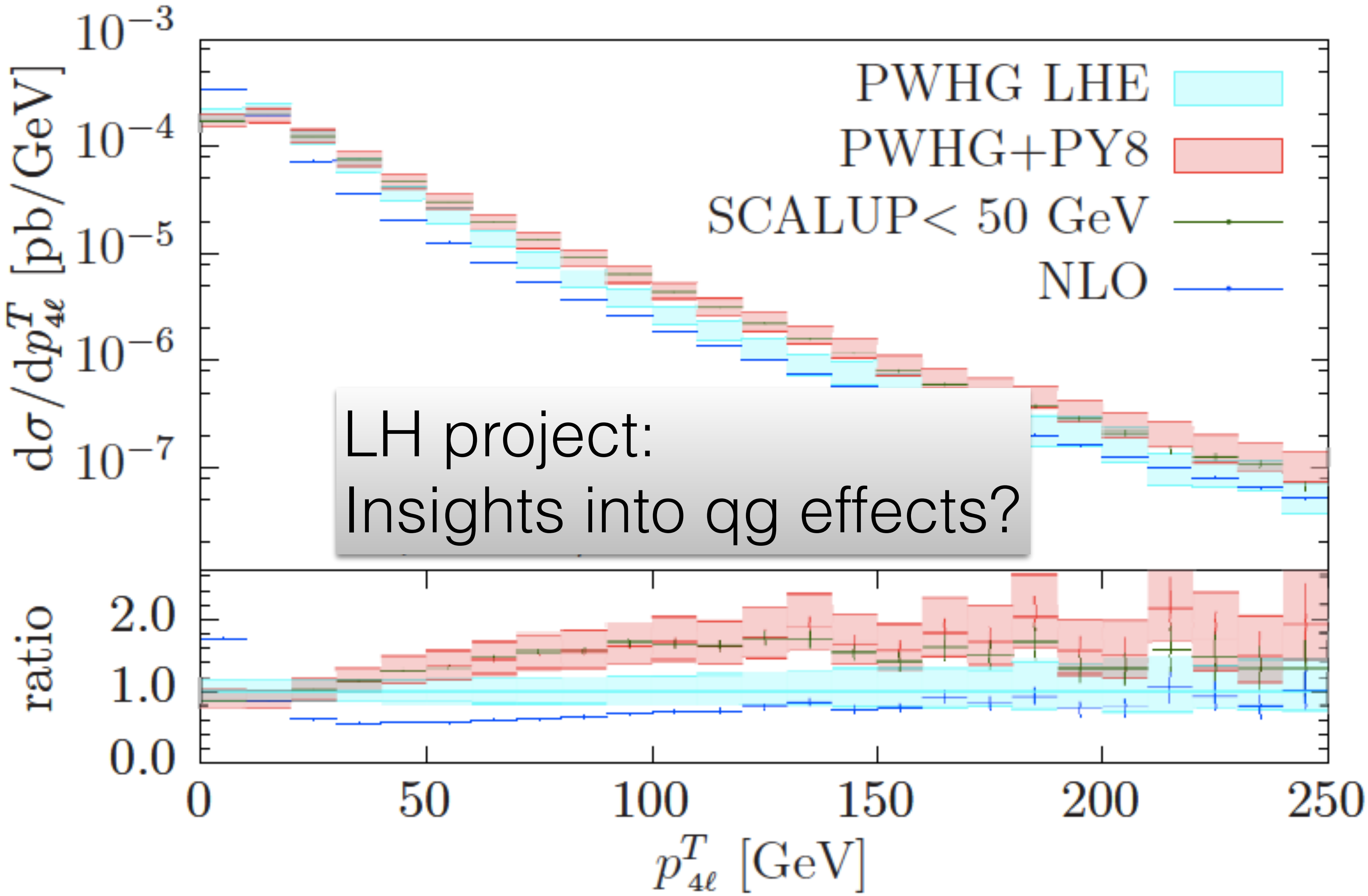


gg→ZZ @ NLO



Alioli, Caola, Luisoni, Röntsch '16

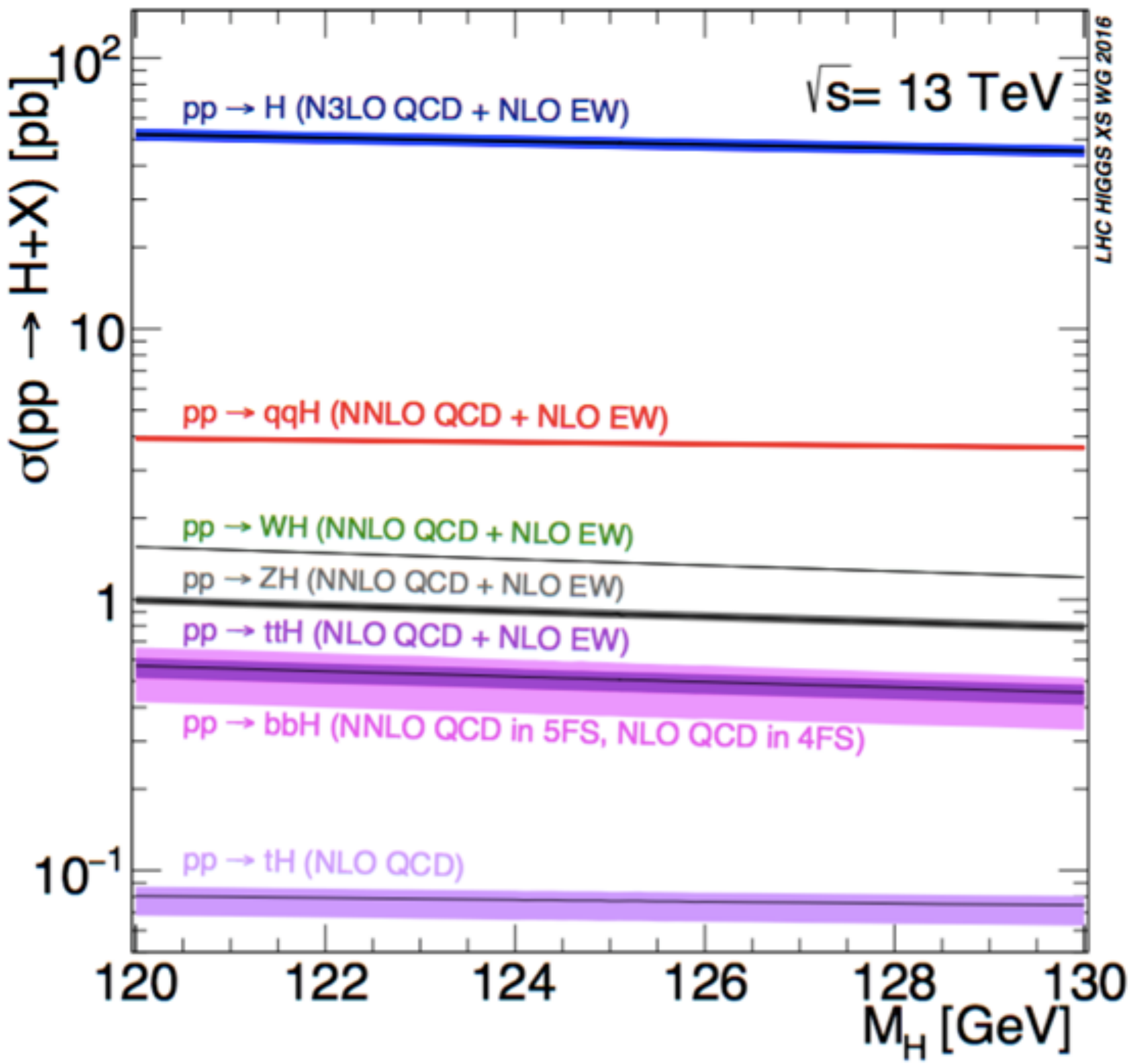
gg→ZZ @ NLO



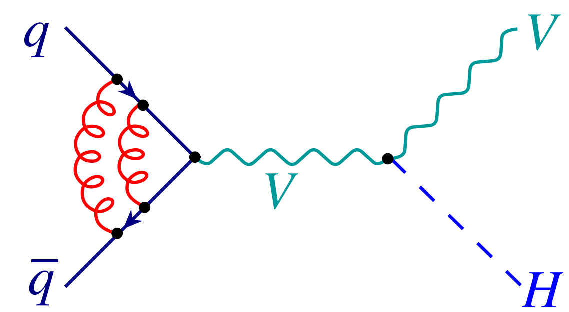
LH project:
Insights into qg effects?

Alioli, Caola, Luisoni, Röntsch '16

gg→HZ:

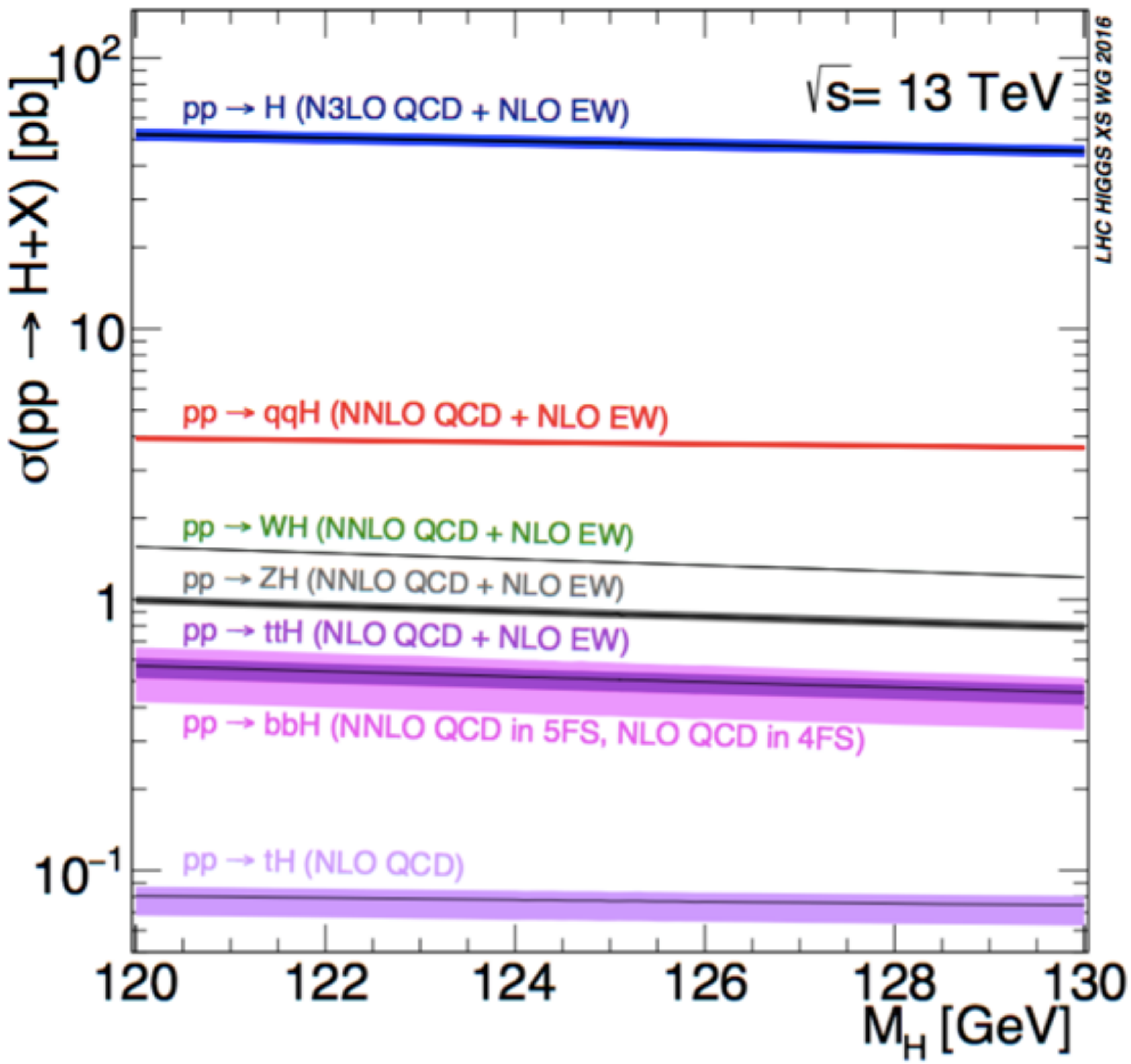


√s= 13 TeV
LHC HIGGS XS WG 2016
pp → H (N3LO QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → ttH (NLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → tH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]



q
q̄
V
V
H

gg→HZ:


√s= 13 TeV
LHC HIGGS XS WG 2016
pp → H (N3LO QCD + NLO EW)
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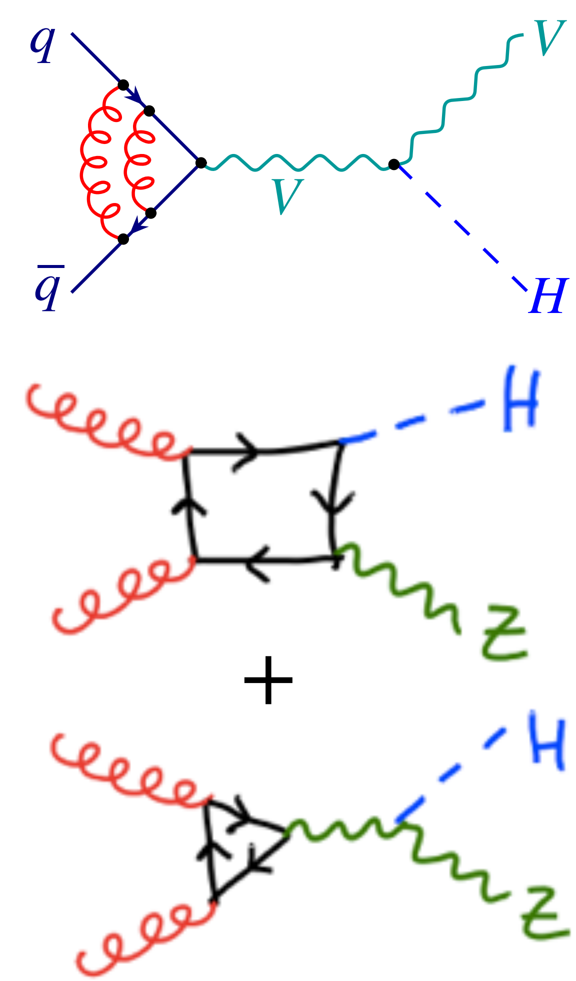
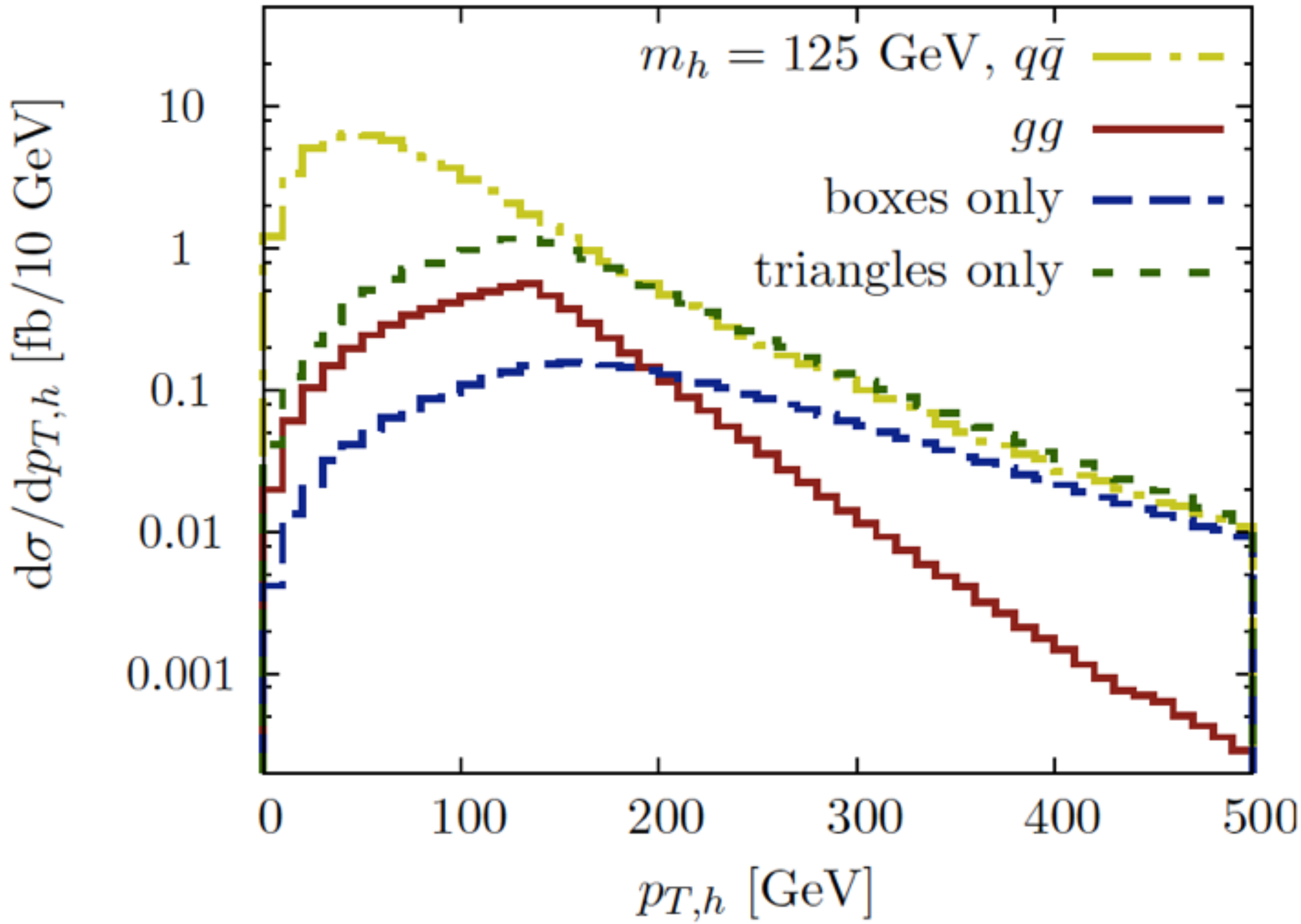
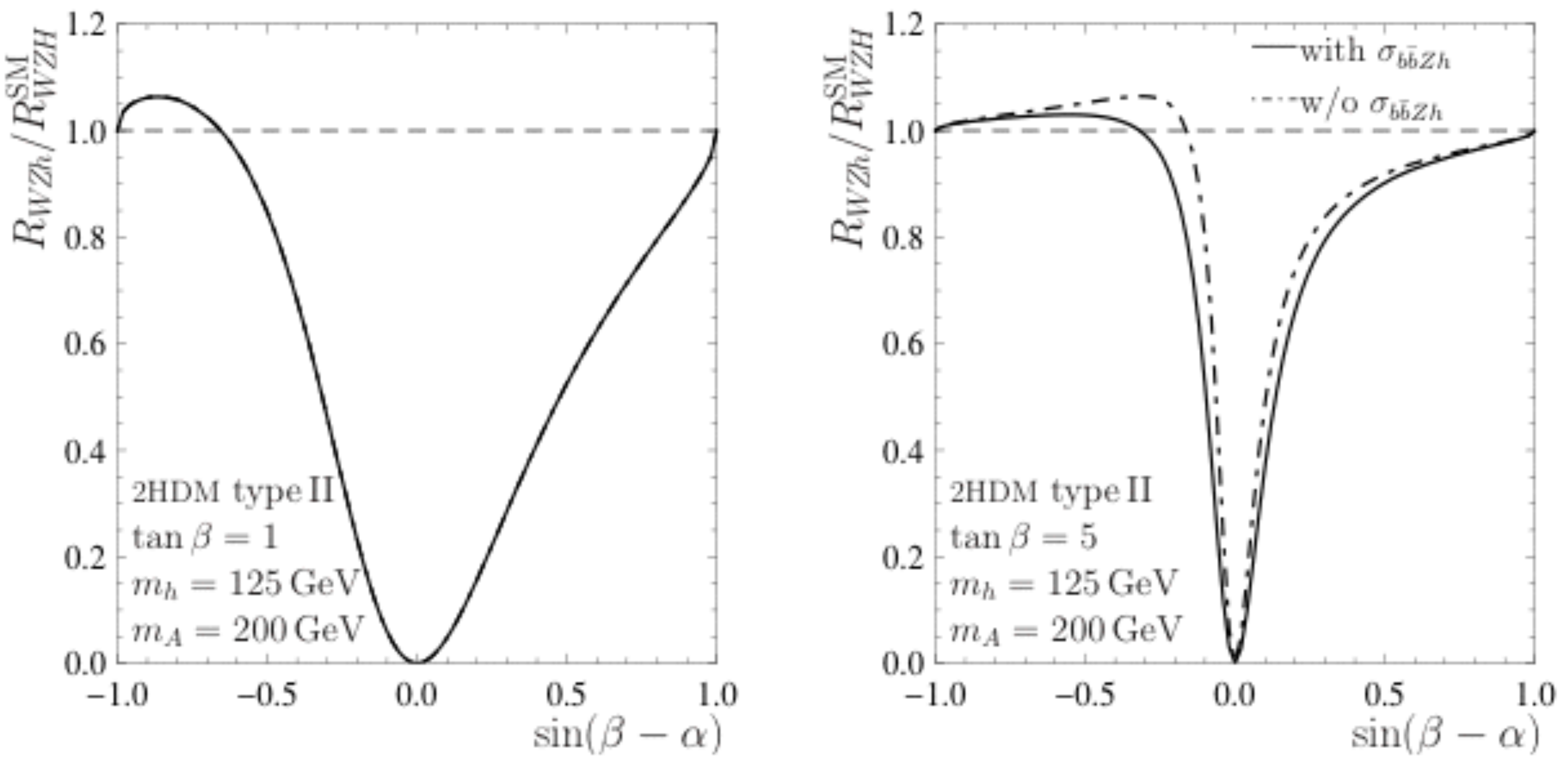
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → tH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]


q
q̄
V
V
H
H
Z
+
H
Z



Englert, McCullough, Spannowsky '14

consider ratio: σ_{WH}/σ_{ZH}

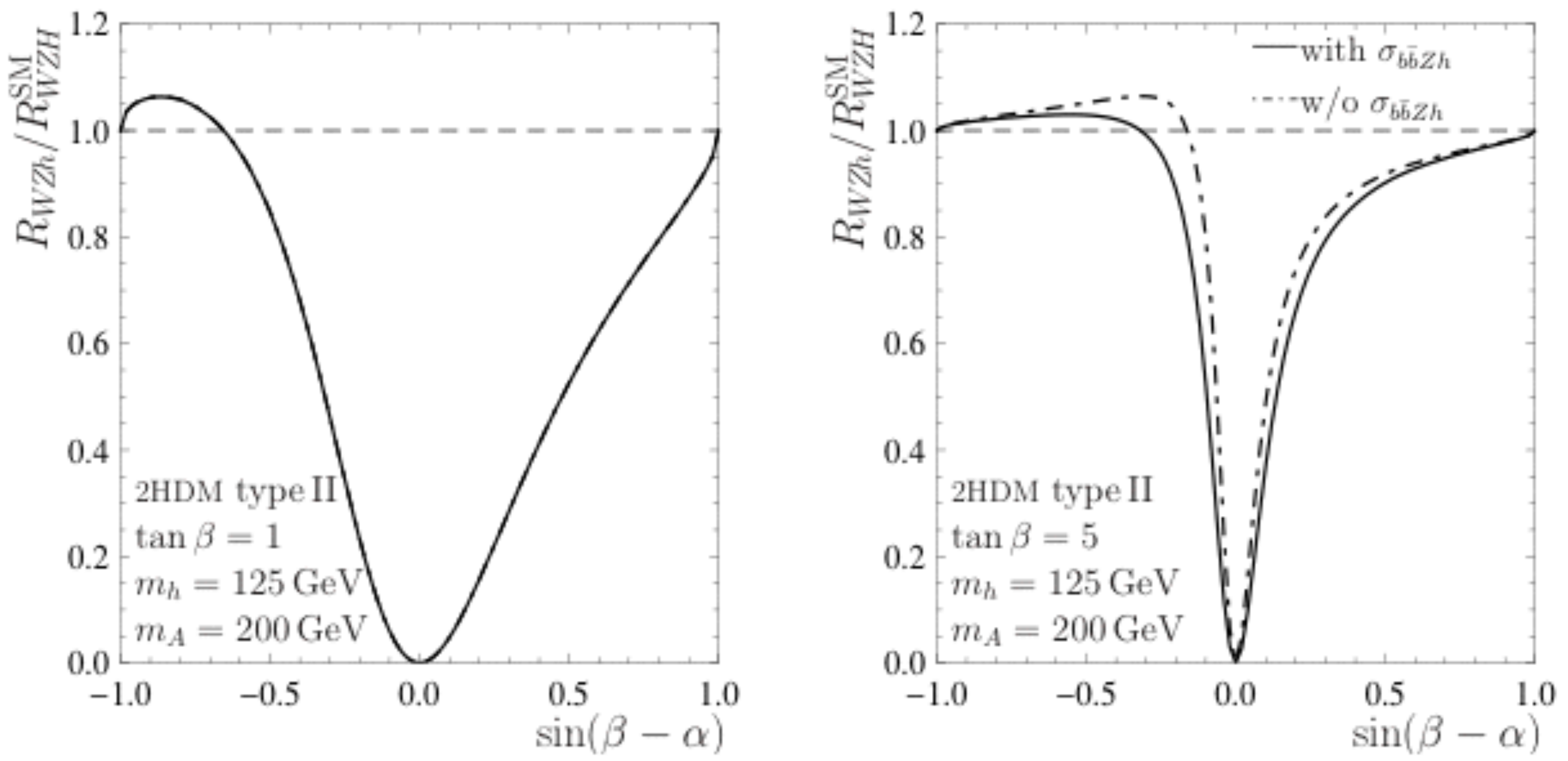


2HDM

RH, Liebler, Zirke '14

consider ratio: σ_{WH}/σ_{ZH}

- very weak dependence on PDFs
- very weak dependence on α_S
- reduced experimental uncertainties?



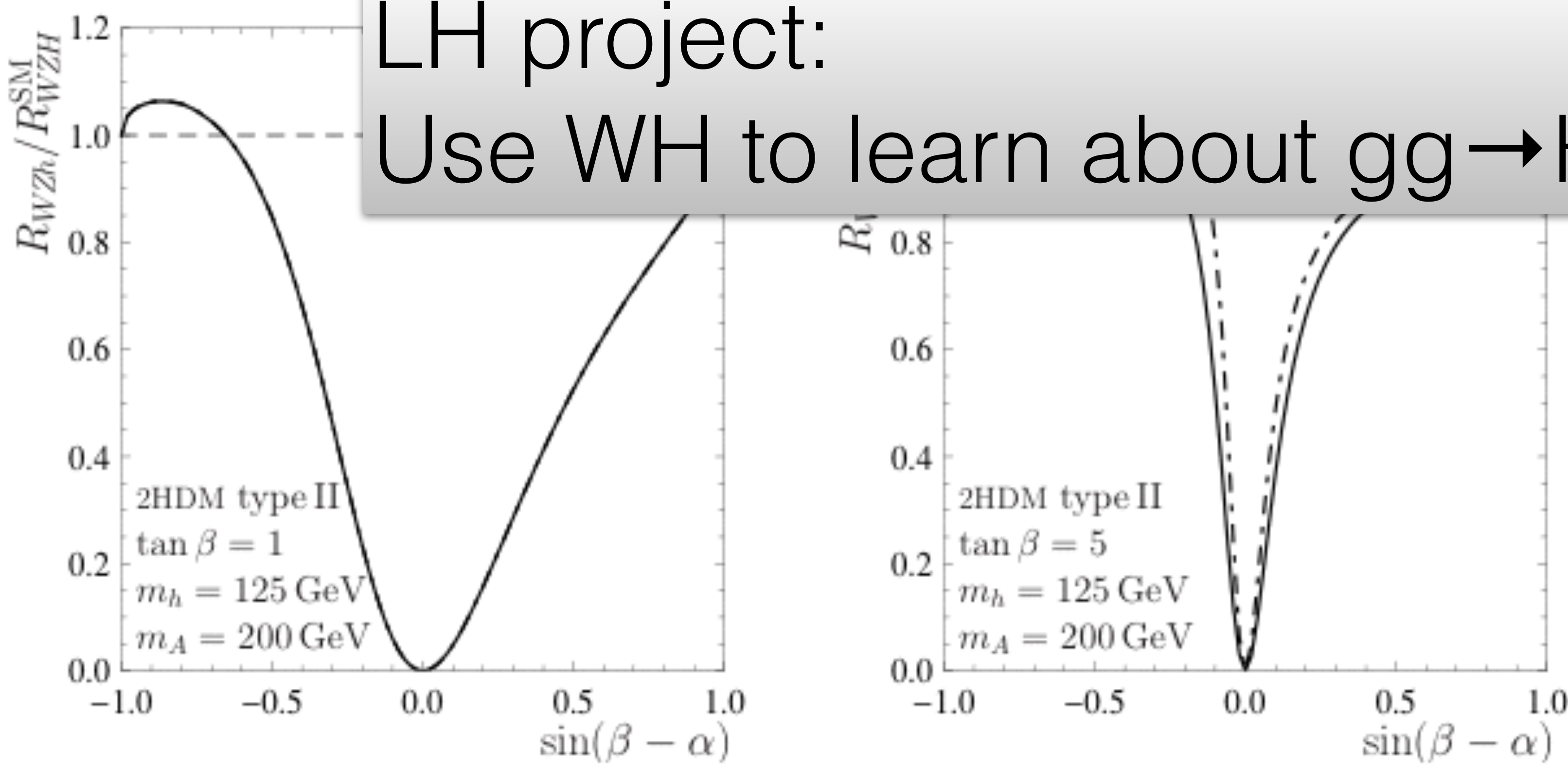
2HDM

RH, Liebler, Zirke '14

consider ratio: σ_{WH}/σ_{ZH}

- very weak dependence on PDFs
- very weak dependence on α_S
- reduced experimental uncertainties?

LH project:
Use WH to learn about gg→HZ.



2HDM

RH, Liebler, Zirke '14

Thanks to all who contributed!

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Even more thanks to all who *will* contribute!

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Most thanks to Fawzi + organizers for bringing us all together at Les Houches!

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