Automated BSM at NLO

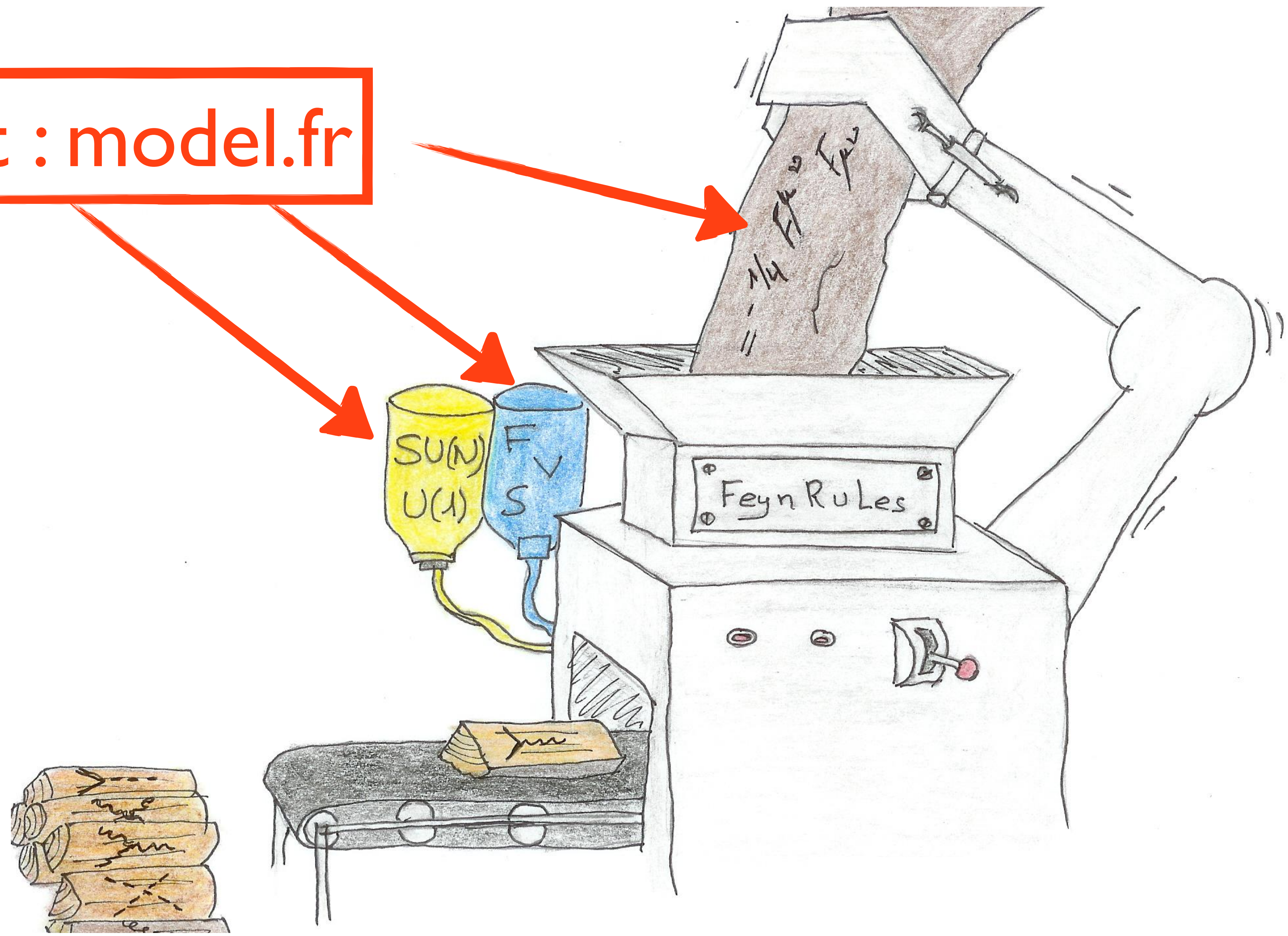
Celine Degrande
CERN, 21 October 2016

Plan

- Framework : From FeynRules to Madgraph5_aMC@NLO
- Examples :
  - Charged Higgs production
  - Spin 2
  - Top FCNC
- Final remarks

FeynRules

Input : model.fr



Output : vertices

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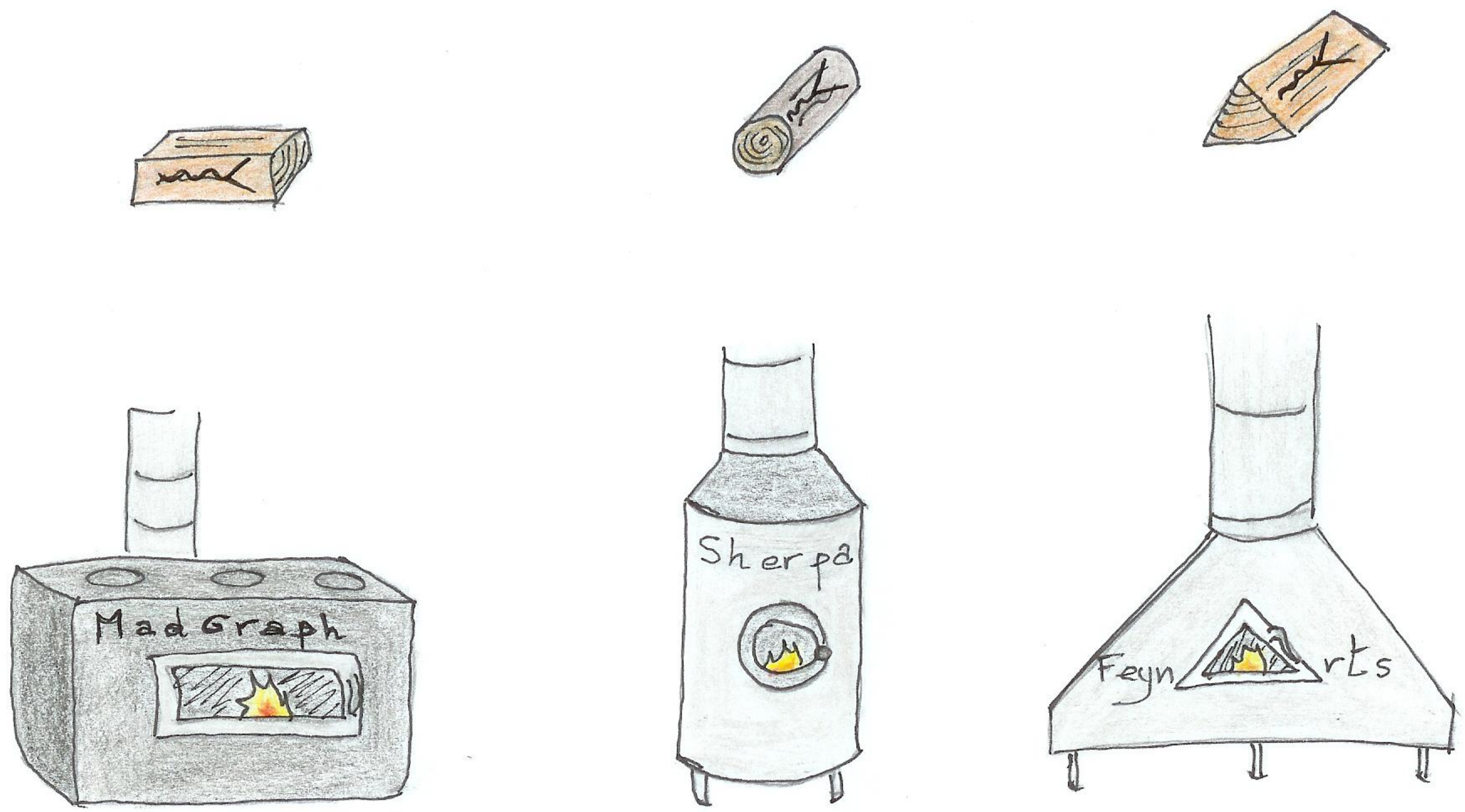
FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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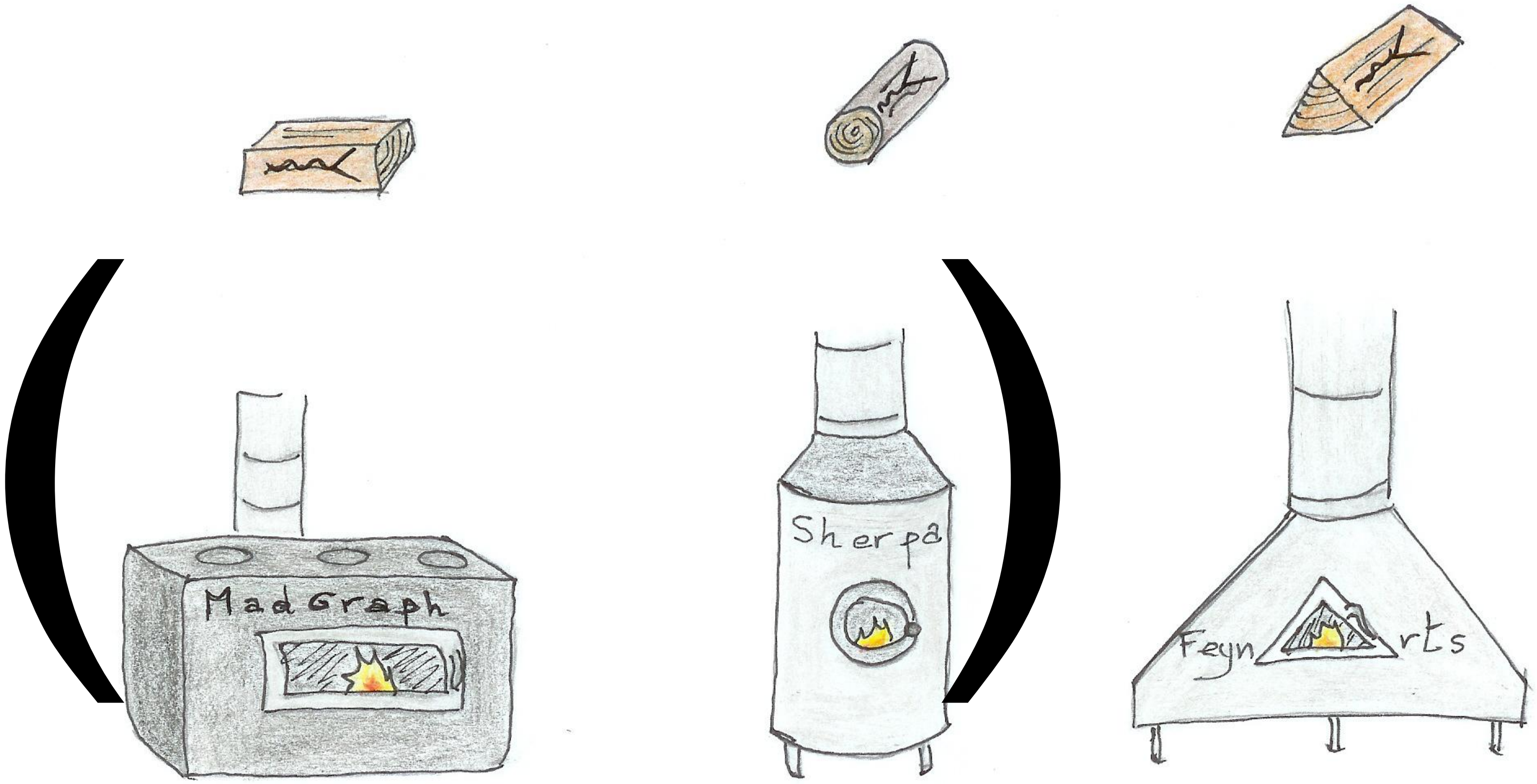
FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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UFO

- Generator independent output with full model information
- Contains the list of particles, parameters, vertices, decays (1to 2), coupling orders
- vertices are split into Lorentz structures, colours and couplings and all are included in the model!

$$-ig_s \quad T^a_{ij} \quad \gamma_\mu$$

- Used in MG5, Herwig, Gosam, Sherpa

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Madgraph5_aMC@NLO

Automated NLO computation

MG5

- Computation of the born

MadFKS (IR)

- Computation of the real

MadLoop

- Computation of the loop
- Matching with parton shower ‘à la’ MC@NLO

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MadLoop

$$\mathcal{A}^{1-loop} = \sum_i d_i \ \mathrm{Box}_i + \sum_i c_i \ \mathrm{Triangle}_i + \sum_i b_i \ \mathrm{Bubble}_i + \sum_i a_i \ \mathrm{Tadpole}_i + R$$

- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Tensor reduction (OPP)
- R : rational terms should be partially provided
- UV counterterm vertices have to be provided

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To be provided : R_2

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}, \qquad \bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$$

$$\bar{N}(\bar{q}) = N(q) + \widetilde{N}(\tilde{q}, q, \epsilon)$$

d 4 ε

$$R_2 \equiv \lim_{\epsilon\to 0}\frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\tilde{N}(\tilde{q}, q, \epsilon)}{\overline{D}_0\overline{D}_1\ldots\overline{D}_{m-1}}$$

Finite set of vertices that can be computed once for all

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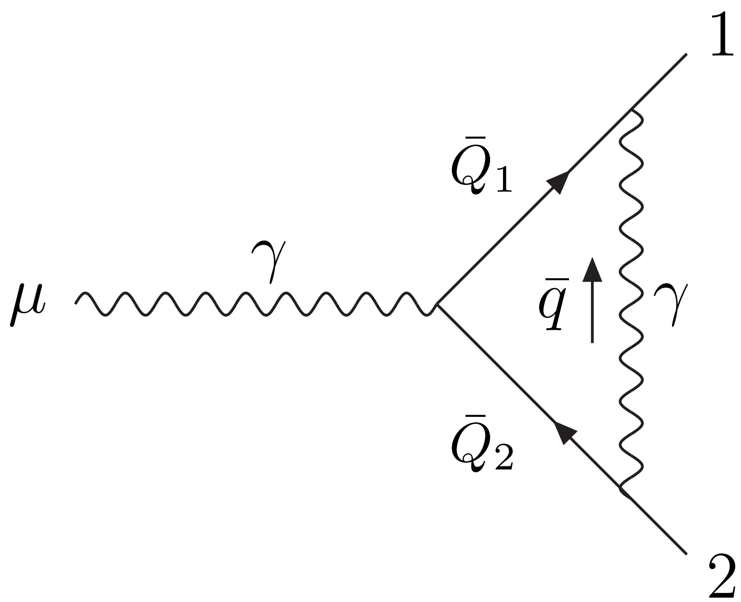
R_2 example



$$\bar{Q}_1 = \bar{q} + p_1 = Q_1 + \tilde{q}$$
$$\bar{Q}_2 = \bar{q} + p_2 = Q_2 + \tilde{q}$$

$$\bar{D}_0 = \bar{q}^2$$
$$\bar{D}_1 = (\bar{q} + p_1)^2$$
$$\bar{D}_2 = (\bar{q} + p_2)^2$$

't Hooft Veltman scheme

$$\bar{\eta}^{\bar{\mu}\,\bar{\nu}}\bar{\eta}_{\bar{\mu}\,\bar{\nu}} = d,$$
$$\bar{\gamma}^{\bar{\mu}}\bar{\gamma}_{\bar{\mu}} = d\,\mathbb{1},$$

$$\begin{aligned}
\bar{N}(\bar{q}) &\equiv e^3 \left\{\bar{\gamma}_{\bar{\beta}}\ (\bar{\not{Q}}_1 + m_e)\ \gamma_\mu\ (\bar{\not{Q}}_2 + m_e)\ \bar{\gamma}^{\bar{\beta}}\right\} \\
&= e^3 \left\{\gamma_\beta(\not{Q}_1 + m_e)\gamma_\mu(\not{Q}_2 + m_e)\gamma^\beta\right. \\
&- \left.\epsilon\,(\not{Q}_1 - m_e)\gamma_\mu(\not{Q}_2 - m_e) + \epsilon\tilde{q}^2\,\gamma_\mu - \tilde{q}^2\,\gamma_\beta\gamma_\mu\gamma^\beta\right\}
\end{aligned}$$

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2} + \mathcal{O}(\epsilon)\,,$$
$$\int d^n\bar{q}\frac{q_\mu q_\nu}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2\epsilon}g_{\mu\nu} + \mathcal{O}(1)$$

$$\mathrm{R}_2 = -\frac{ie^3}{8\pi^2}\gamma_\mu$$

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Computed in MadLoop :R_1

Due to the ε dimensional parts of the denominators

Like for the 4 dimensional part but with a different set of integrals

$$
\begin{aligned}
\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j} &= -\frac{i\pi^2}{2}\left[m_i^2+m_j^2-\frac{(p_i-p_j)^2}{3}\right]+\mathcal{O}(\epsilon)\,,\\
\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} &= -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,\\
\int d^n\bar{q}\frac{\tilde{q}^4}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} &= -\frac{i\pi^2}{6}+\mathcal{O}(\epsilon)\,.
\end{aligned}
$$

Only $R = R_1+R_2$ is gauge invariant ⇨ Check

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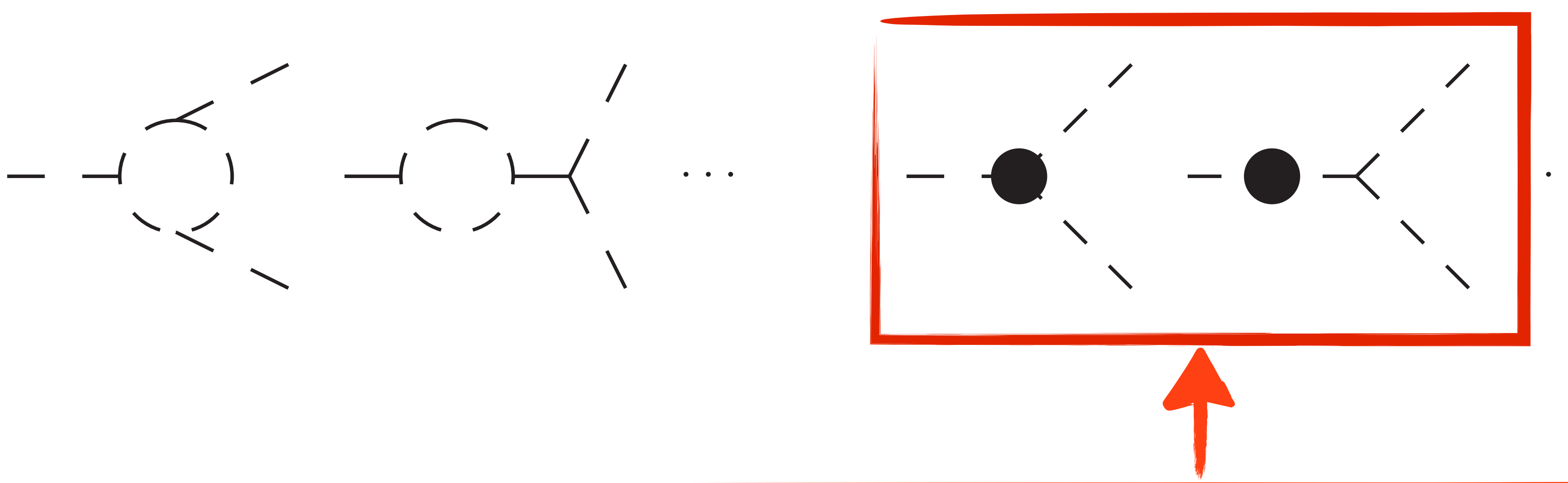
UV

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}} = K\frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$



$$= 0\tfrac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$

Relations fixed by the Lagrangian (finite part)

Finite set of vertices that can be computed once for all

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Renormalization

External parameters

$$x_0 \rightarrow x + \delta x,$$
$$\phi_0 \rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi$$

Same for the conjugate field

Internal parameters are renormalised by replacing the external parameters in their expressions

$$gg \quad (1 + \delta Z_{gg})\, TL$$
$$ggg \quad \left(1 + \tfrac{1}{2}\delta\alpha_s + \tfrac{3}{2}\delta Z_{gg}\right) TL$$
$$gggg \quad (1 + \delta\alpha_s + 2\delta Z_{gg})\, TL$$

Fixed by

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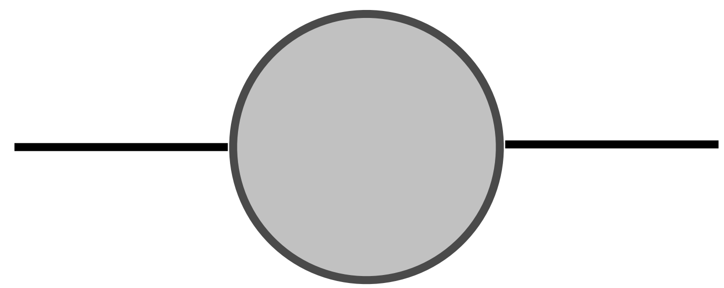
Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

Two-point function vanishes on-shell (No external bubbles)



$$i\delta_{ij}\left(\not{p}-m_i\right)+i\left[f_{ij}^{L}\left(p^2\right)\not{p}\gamma_-+f_{ij}^{R}\left(p^2\right)\not{p}\gamma_++f_{ij}^{SL}\left(p^2\right)\gamma_-+f_{ij}^{SR}\left(p^2\right)\gamma_+\right]$$

$$\begin{aligned}
\tilde{\Re}\left[f_{ij}^{L}\left(p^2\right)m_i+f_{ij}^{SR}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\tilde{\Re}\left[f_{ij}^{R}\left(p^2\right)m_i+f_{ij}^{SL}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\tilde{\Re}\left[2m_i\frac{\partial}{\partial p^2}\left[\left(f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right)m_i+f_{ii}^{SL}\left(p^2\right)+f_{ii}^{SR}\left(p^2\right)\right]+f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0
\end{aligned}$$

Similar for the vectors and scalars

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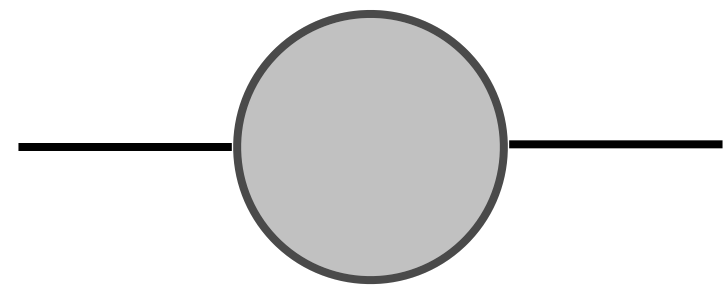

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\end{aligned}$$

Similar for the vectors and scalars

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Renormalization conditions

Zero momentum scheme available for the gauge couplings

$$\Gamma^{\mu}_{FFV}\left(p_1,p_2\right) = igT^a\delta_{f_1,f_2}\left[\gamma^\mu\left(\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{1}{2}\delta Z^R_{FF}+\frac{1}{2}\delta Z^L_{FF}+\frac{g'_V}{2g}\delta Z_{V'V}\right)\right.$$

$$+\gamma^\mu\gamma_5\left(\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}\right)$$

$$\left.+\left(\gamma^\mu h^V\left(k^2\right)+\gamma^\mu\gamma_5 h^A\left(k^2\right)+\frac{(p_1-p_2)^\mu}{2m}h^S\left(k^2\right)+\frac{k_\mu}{2m}h^P\left(k^2\right)\right)\right]$$

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{1}{2}\delta Z^R_{FF}+\frac{1}{2}\delta Z^L_{FF}+\frac{g'_V}{2g}\delta Z_{V'V}+h^V(0)+h^S(0) = 0$$

$$\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}+h^A(0) = 0.$$

By gauge invariance

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{g'_V}{2g}\delta Z_{V'V}+\frac{g'_A}{2g}\delta Z_{V'V}=0$$

Only from two-point functions

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Renormalization conditions

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$$+\gamma^\mu\gamma_5\left(\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}\right)$$
$$+\left(\gamma^\mu h^V\left(k^2\right)+\gamma^\mu\gamma_5 h^A\left(k^2\right)+\frac{(p_1-p_2)^\mu}{2m}h^S\left(k^2\right)+\frac{k_\mu}{2m}h^P\left(k^2\right)\right)\Bigg]$$

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{1}{2}\delta Z^R_{FF}+\frac{1}{2}\delta Z^L_{FF}+\frac{g'_V}{2g}\delta Z_{V'V}+h^V(0)+h^S(0) = 0$$
$$\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}+h^A(0) = 0.$$

By gauge invariance

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{g'_V}{2g}\delta Z_{V'V}+\frac{g'_A}{2g}\delta Z_{V'V}=0$$

Only from two-point functions

$\overline{\text{MS}}$ scheme for everything else (option for all)

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BSM@NLO

- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices — Done(FeynRules)
  - R2 vertices (OPP)
  - UV counterterm vertices — Missing
- Solution : UFO at NLO

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How does it work?

FeynRules

Renormalize the Lagrangian

model.mod

model.gen

FeynArts

Write the amplitudes

NLOCT.m

Compute the NLO vertices

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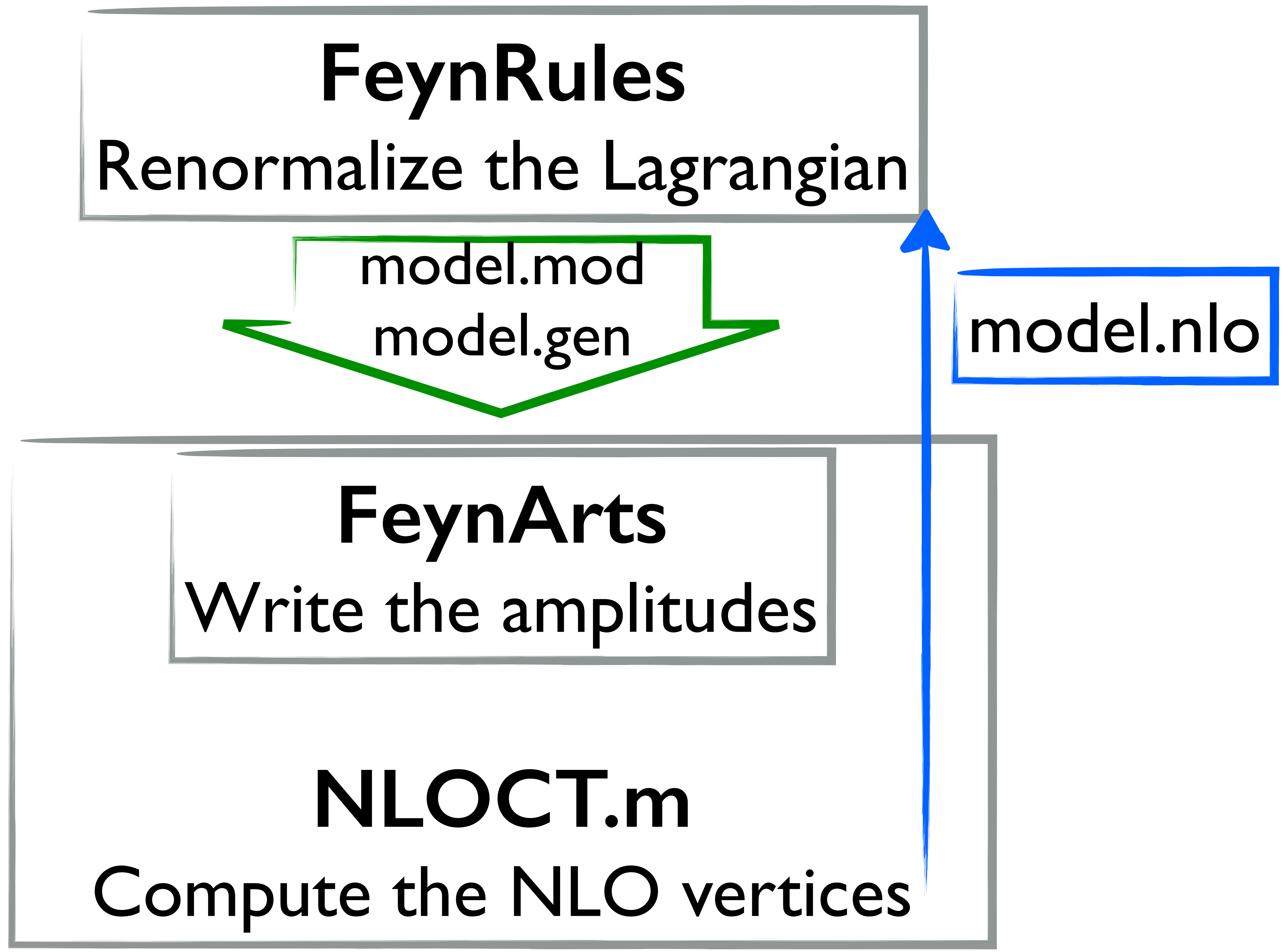
How does it work?



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How does it work?

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model.mod
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FeynArts
Write the amplitudes

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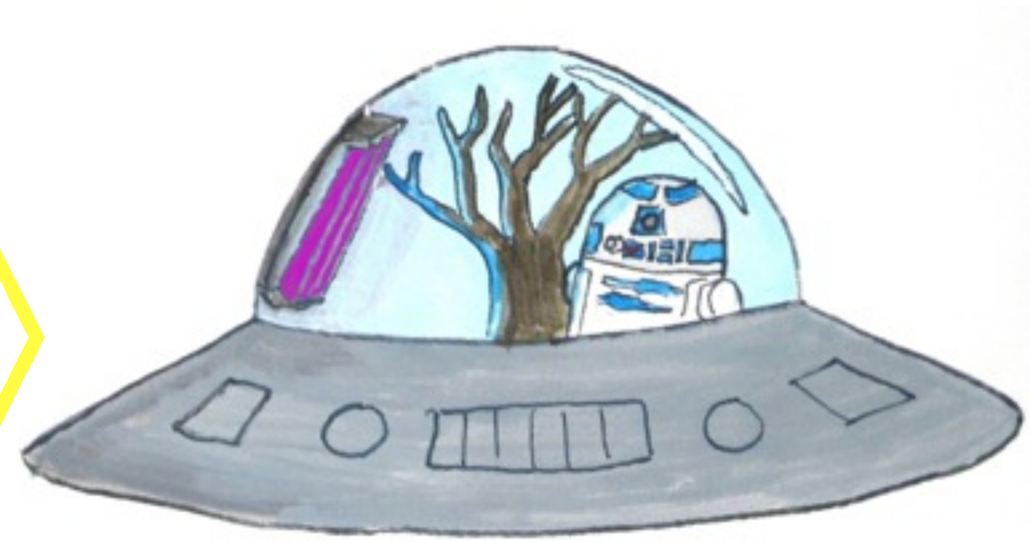
Compute the NLO vertices

model.nlo



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How does it work?

FeynRules :

...

```
Lren  =  OnShellRenormalization[  LSM  ,   QCDOnly ->True];
WriteFeynArtsOutput[  Lren   ,  Output -> "SMrenoL",
GenericFile -> False]
```

FeynArts / NLOCT :

```
WriteCT[  "SMrenoL/SMrenoL" ,      "Lorentz",  Output->
“SMQCDreno",   QCDonly -> True]
```

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"SMQCDreno",  QCDonly -> True]
```

FeynRules :

...

```
Get["SMQCDreno.nlo"];
WriteUFO[ LSM , UVCounterterms -> UV$vertlist ,
 R2Vertices -> R2$vertlist]
```

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How does it work?

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Restrictions/Assumptions

- Renormalizable Lagrangian, maximum dimension of the operators is 4
- Feynman Gauge
- $\{\gamma_\mu, \gamma_5\} = 0$
- ‘t Hooft-Veltman scheme
- On-shell scheme for the masses and wave functions
- $\overline{\text{MS}}$ by default for everything else (zero-momentum possible for fermion gauge boson interaction)

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Restrictions/Assumptions

- Renormalizable Lagrangian, maximum dimension of the operators is 4 → EFT with max 4F
- Feynman Gauge → any gauge
- $\{\gamma_\mu, \gamma_5\} = 0$
- ‘t Hooft-Veltman scheme
- On-shell scheme for the masses and wave functions
- $\overline{\text{MS}}$ by default for everything else (zero-momentum possible for fermion gauge boson interaction)

→ MZ scheme for EW coupling

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EFT at NLO (QCD)

B. Grzadkowski et al, JHEP 1010 (2010) 085

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

No QCD particle

C. Degrande

EFT at NLO (QCD)

B. Grzadkowski et al, JHEP 1010 (2010) 085

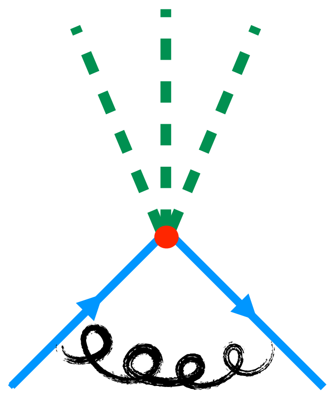
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

No QCD particle

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

C. Degrande

EFT at NLO



In the loop:
same as SM

$$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$$

$$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$$

$$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$\varphi^\dagger\varphi \, G_{\mu\nu}^A G^{A\mu\nu}$$

More momenta: higher rank of the integral numerator (NLOCT/MadLoop✓)

Additional gamma algebra (NLOCT✓)

$$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$$

C. Degrande

EFT at NLO

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

C. Degrande

EFT at NLO

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	~~$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$~~	Q_{ee}	~~$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$~~	Q_{le}	~~$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$~~
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

C. Degrande

EFT at NLO

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	~~$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$~~	Q_{ee}	~~$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$~~	Q_{le}	~~$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$~~
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Same as SM

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

C. Degrande

EFT at NLO

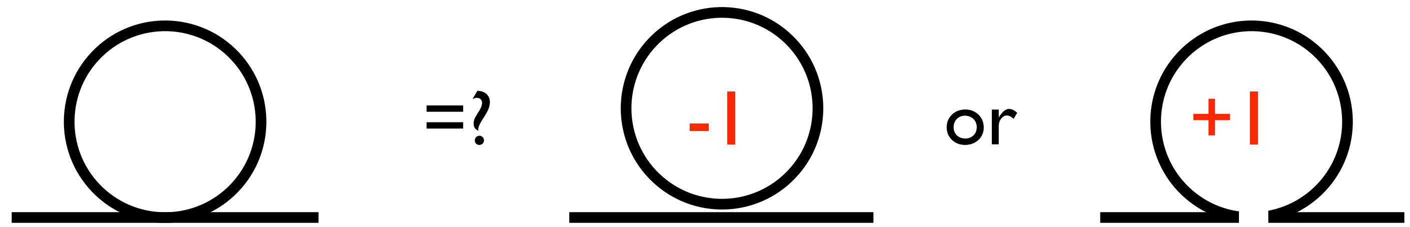
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	~~$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$~~	Q_{ee}	~~$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$~~	Q_{le}	~~$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$~~
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

Same as SM

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

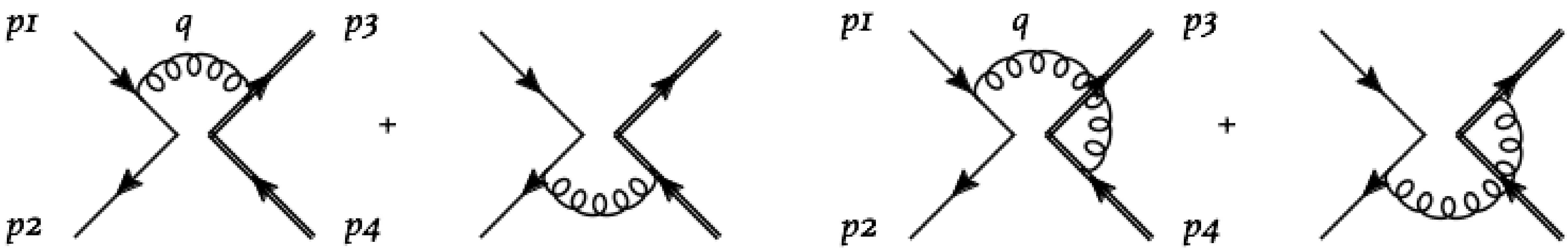
C. Degrande

EFT at NLO



In MG5_aMC

Evanescent operators: $O_{ut}^{(8)} = \left(\bar{u}\gamma^{\mu}T^{A}u\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right)$



$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\mu}\gamma_{\nu}\gamma_{\rho}P_R = E + (16 - 4a\varepsilon)\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$
$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\rho}\gamma_{\nu}\gamma_{\mu}P_R = -E + [4 - (12 - 4a)\varepsilon]\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$

Extra R2 (gauge invariant)
Change the UV matching

C. Degrande

EFT at NLO

- UV counterterms :
  - Basis reduction needed for the anomalous matrix (By Liam Moore)
    - Check (R. Alonso, E. E. Jenkins, A. V. Manohar, M. Trott, JHEP 1404 (2014) 159)
  - MSbar : $1/\varepsilon$ from the amplitudes not from the renomalization
  - Running (UFO 2.0)

R2 :Validation

- tested* on the SM (QCD:P. Draggiotis et al. +QED:M.V. Garzelli et al)
- tested* on MSSM (QCD:H.-S. Shao, Y.-J. Zhang) : test the Majorana

*Analytic comparison of the expressions

UV Validation

- SM QCD : tested* (W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper)
- SM EW : tested* (expressions given by H.-S. Shao from A. Denner)

*Analytic comparison of the expressions

C. Degrande

Tests in event generators

- aMC@NLO
- The SM QCD has been tested by V. Hirschi (Comparison with the built-in version)
- SM EW (MZ scheme): comparison to published results for ME by H.-S. Shao and V. Hirschi
- Various BSM
  - gauge invariance
  - pole cancelation

SM QCD tests

=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	3.0015206007e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-5.3971186943e+01	-5.3971193753e+01	-5.3971189940e+01	6.3091071914e-08	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	6.4168774056e-05	6.4168764370e-05	6.4168764370e-05	7.5467680882e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-3.7439549398e+01	-3.7439549398e+01	-3.7439549397e+01	6.8122965983e-12	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	2.2443585452e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-5.3769573669e+01	-5.3769573347e+01	-5.3769566412e+01	6.7475496780e-08	Pass

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SM QCD tests

=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	3.0015206007e-14	Pass

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-5.3769573669e+01	-5.3769573347e+01	-5.3769566412e+01	6.7475496780e-08	Pass

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SM QCD tests

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	3.1531233900e-04	3.1531235770e-04	3.1531235770e-04	2.9654886777e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-3.7464897007e+01	-3.7464897007e+01	-3.7464897007e+01	4.2333025503e-12	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	2.1316282073e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-5.9990384275e+00	-5.9990511729e+00	-5.9990379587e+00	1.1013604745e-06	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	2.2616997126e-06	2.2617000449e-06	2.2617000449e-06	7.3450366526e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-1.5469587040e+01	-1.5469587040e+01	-1.5469587040e+01	1.5226666708e-11	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	2.6645352591e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	2.9740187004e+01	2.9740187005e+01	2.9740187036e+01	5.3265970697e-10	Pass

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SM QCD tests

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	1.1079653971e-07	1.1079653974e-07	1.1079653974e-07	1.3190849004e-10	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	-7.0825709000e+00	-7.0825709000e+00	-7.0825709000e+00	5.0901237085e-13	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	-6.0000000000e+00	-6.0000000000e+00	-6.0000000000e+00	1.7023419711e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	3.6409017466e+01	3.6409021125e+01	3.6409021117e+01	5.0242920154e-08	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	7.0723041711e-07	7.0723046101e-07	7.0723046101e-07	3.1039274206e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	-7.1948086812e+00	-7.1948086773e+00	-7.1948086773e+00	2.7349789963e-10	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	-6.0000000000e+00	-6.0000000000e+00	-6.0000000000e+00	2.5165055225e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

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SM QCD tests

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	3.0015206007e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-1.1504816412e+01	-1.1504816557e+01	-1.1504815497e+01	4.6089385415e-08	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	2.3138920858e-06	2.3138920858e-06	2.3138920858e-06	4.3012538015e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-2.8637049838e+01	-2.8637049838e+01	-2.8637049838e+01	1.5718407645e-13	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	1.7421961310e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-1.0306105482e+01	-1.0306105654e+01	-1.0306102645e+01	1.4600800434e-07	Pass

+2/3

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Test EW

```
== a a > t t~ ['QED'] ==
== a a > t t~ a ['QED'] ==
== a a > w+ w- ['QED'] ==
== a b > t w- ['QED'] ==
== d~ d > w+ w- ['QCD'] ==
== d~ d > w+ w- ['QED'] ==
== d~ d > z z ['QCD'] ==
== d~ d > z z ['QED'] ==
== e+ e- > t t~ a ['QED'] ==
== e+ e- > t t~ g ['QED'] ==
== g b > t w- ['QED'] ==
== g g > h h ['QCD'] ==
== g g > t t~ ['QED'] ==
== g g > t t~ g ['QED'] ==
== g g > t t~ h ['QCD'] ==
== g g > t t~ h ['QED'] ==
== h h > h h ['QED'] ==
== h h > h h h ['QED'] ==
== t t~ > w+ w- ['QED'] ==
```

```
== u b > t d ['QED'] ==
== u d~ > t b~ ['QED'] ==
== u g > t d b~ ['QED'] ==
== u u~ > a a ['QED'] ==
== u u~ > e+ e- ['QED'] ==
== u u~ > g a ['QCD QED'] ==
== u u~ > u u~ ['QCD QED'] ==
== u u~ > u u~ a ['QCD QED'] ==
== u u~ > u u~ g ['QCD QED'] ==
== u u~ > w+ w- ['QED'] ==
== u u~ > z a ['QED'] ==
== u u~ > z z ['QED'] ==
== u~ d > w- z ['QCD'] ==
== u~ d > w- z ['QED'] ==
== u~ u > w+ w- ['QCD'] ==
== u~ u > w+ w- ['QED'] ==
== u~ u > z z ['QCD'] ==
== u~ u > z z ['QED'] ==
== ve ve~ > e+ e- ['QED'] ==
== w+ w- > h h ['QED'] ==
```

Massive and massless b

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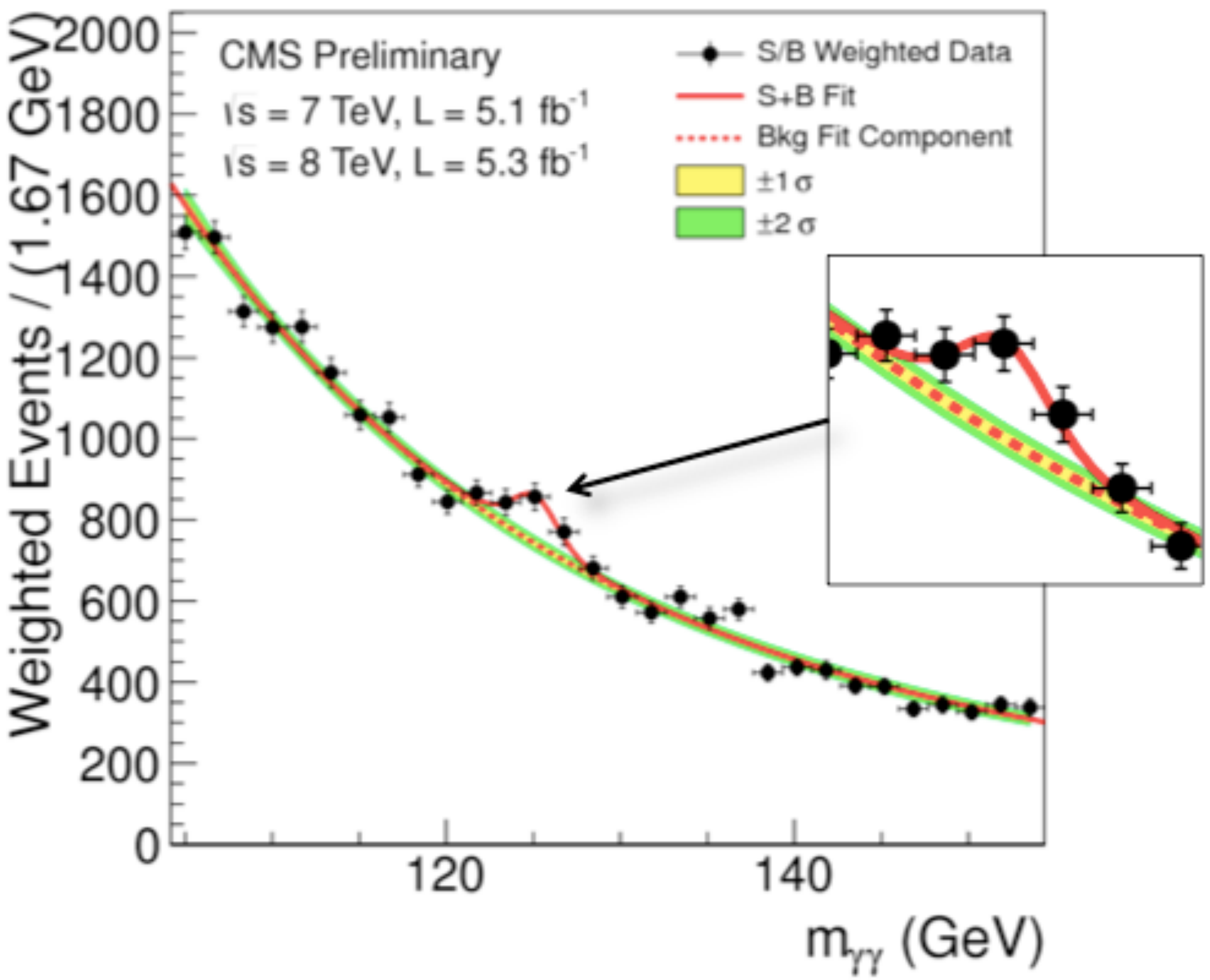
Future development

- UFO@NLO in Gosam (N. Greiner)
- DRED (asked by Gosam)
- UFO 2.0

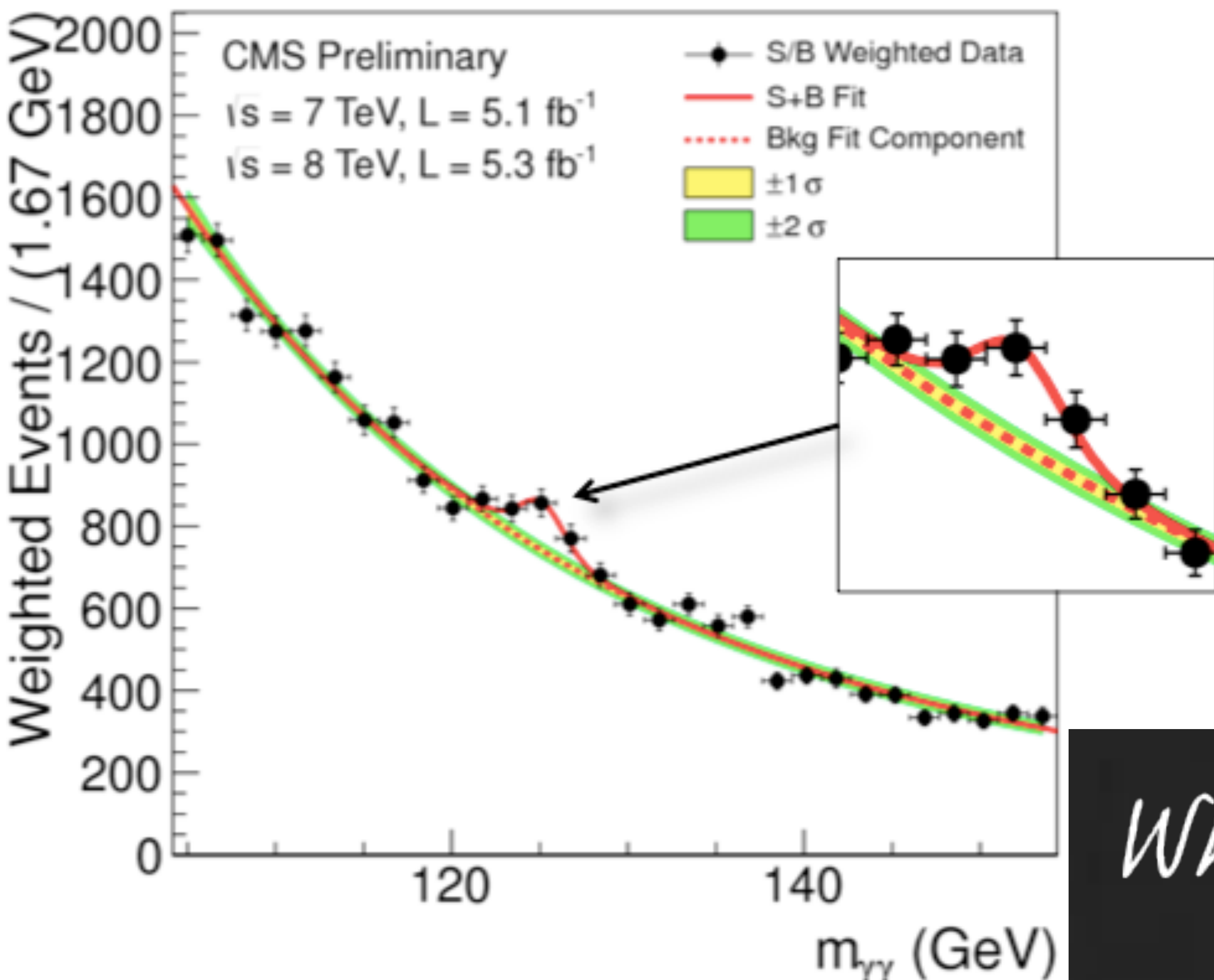
Plan

- Framework : From FeynRules to Madgraph5_aMC@NLO
- Examples :
  - Charged Higgs production
  - Spin 2
  - Top FCNC
- Final remarks

The Higgs discovery



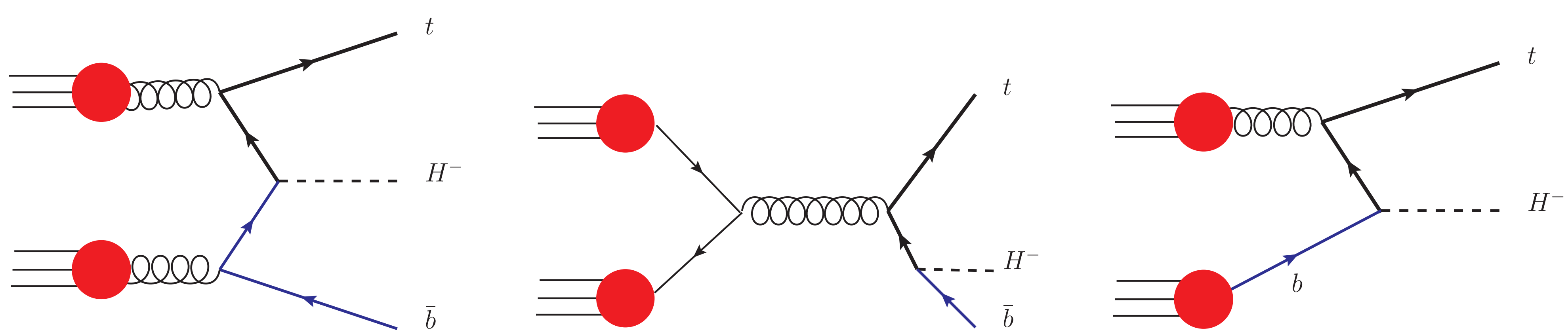
The Higgs discovery



Example 1: Charged Higgs production

C. D., M.Ubiali, M.Wiesemann and M.Zaro, JHEP 1510 (2015) 145

- Motivations :
  - needed for the LHC current and future runs
  - First searches in the high mass region
  - Threshold region (With R. Frederix)
- 4F NLO fully differential matched with parton shower

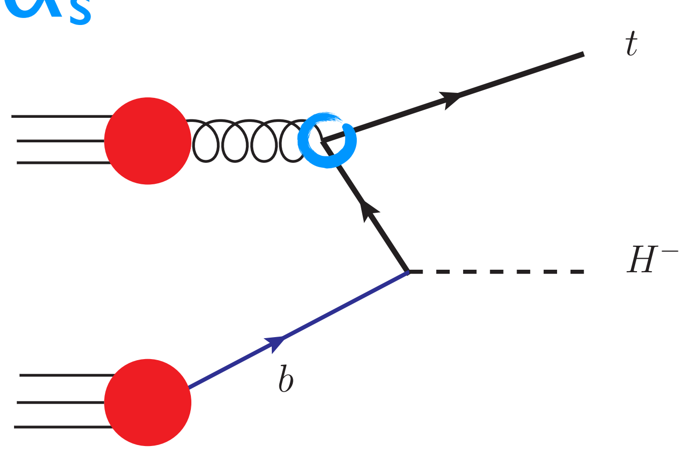


- Shape comparison with the 5F

Example 1: Charged Higgs production

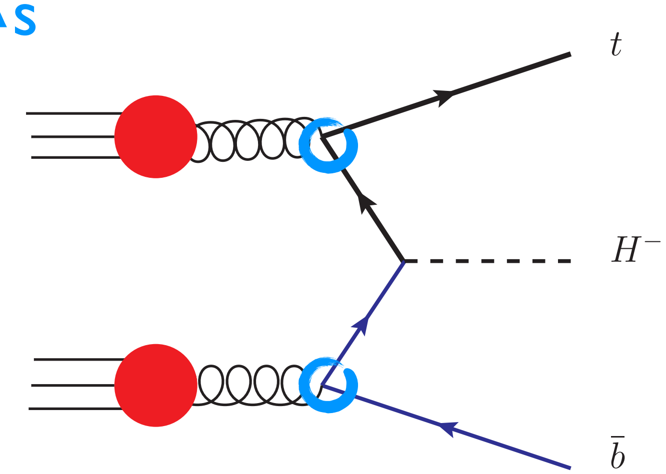
5 Flavours

- $m_b=0$ (but $m_b^y>0$)
- In the PDF
- In the running of α_s
- Handle collinear logarithms
- α_s



4 Flavours

- $m_b>0$
- Not in the PDF
- Not in the running of α_s
- Contribution to b observable at LO
- α_s^2



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Example 1: Charged Higgs production

Type-II 2HDM

$$V_{t\bar{b}H^-} = -i\left(y_t P_R \frac{1}{\tan\beta} + y_b P_L \tan\beta\right)$$

$$P_{R/L} = (1 \pm \gamma_5)/2$$

$$y_{t/b} \equiv \sqrt{2}\frac{m^y_{t/b}}{v}$$

$$\delta y_{t/b} = \sqrt{2}\frac{\delta m_{t/b}}{v}$$

On-shell sc.

$$\delta m_{t/b} = -\frac{g_s^2}{12\pi^2} m_{t/b}\left(\frac{3}{\bar{\epsilon}} + 4 - 6\log\frac{m_{t/b}}{\mu_R}\right)$$

$\overline{\text{MS}}$ sc.

$$\delta y_b = -\frac{\sqrt{2}}{v}\frac{g_s^2 m_b^y}{4\pi^2\bar{\epsilon}}$$

Input : -FR model
-running of the b yukawa mass

Validation : -Comparison with S. Dittmaier, M. Kramer, M. Spira and M. Walser, PRD 83 (2011) 055005
-Recover ttH

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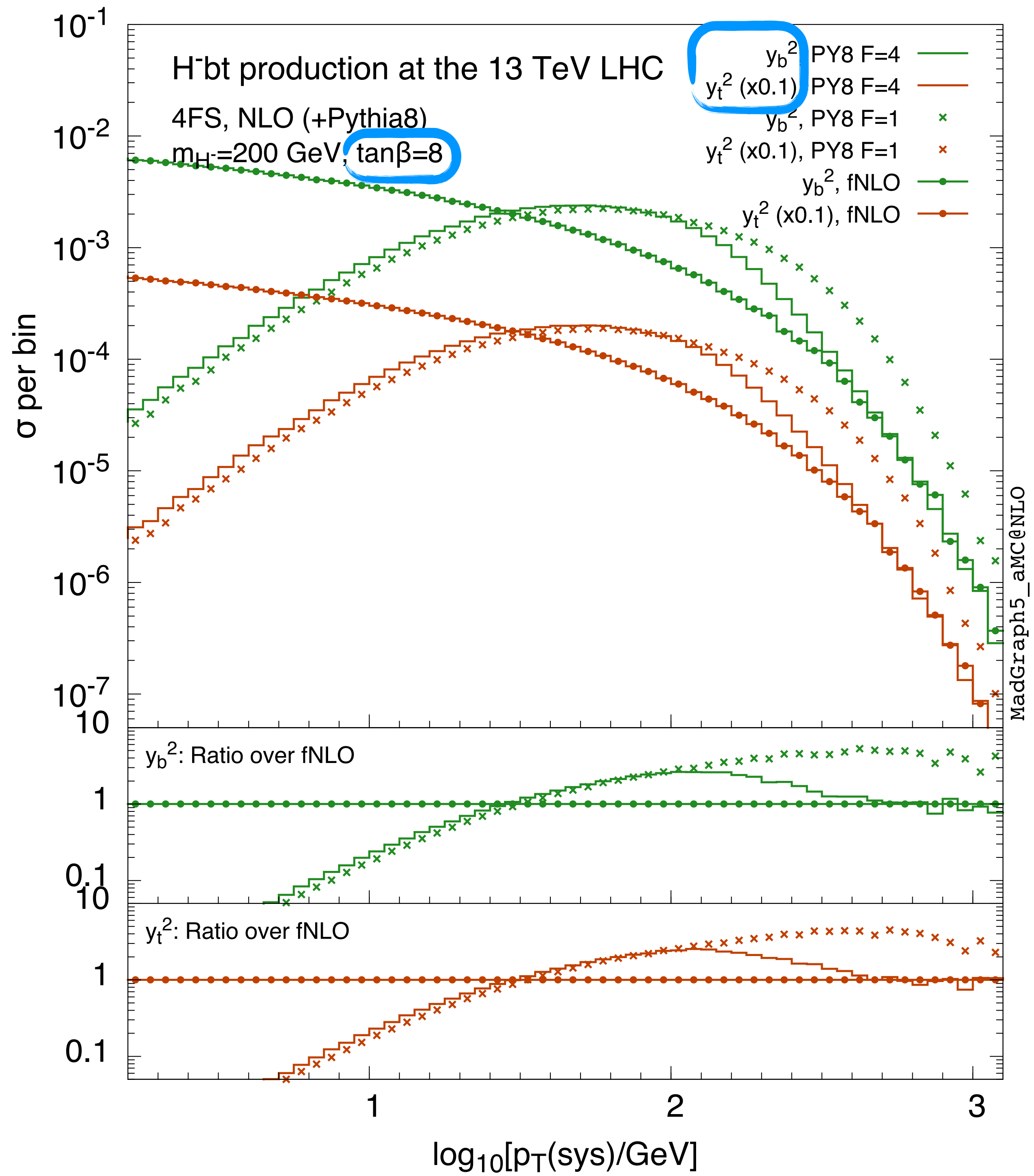
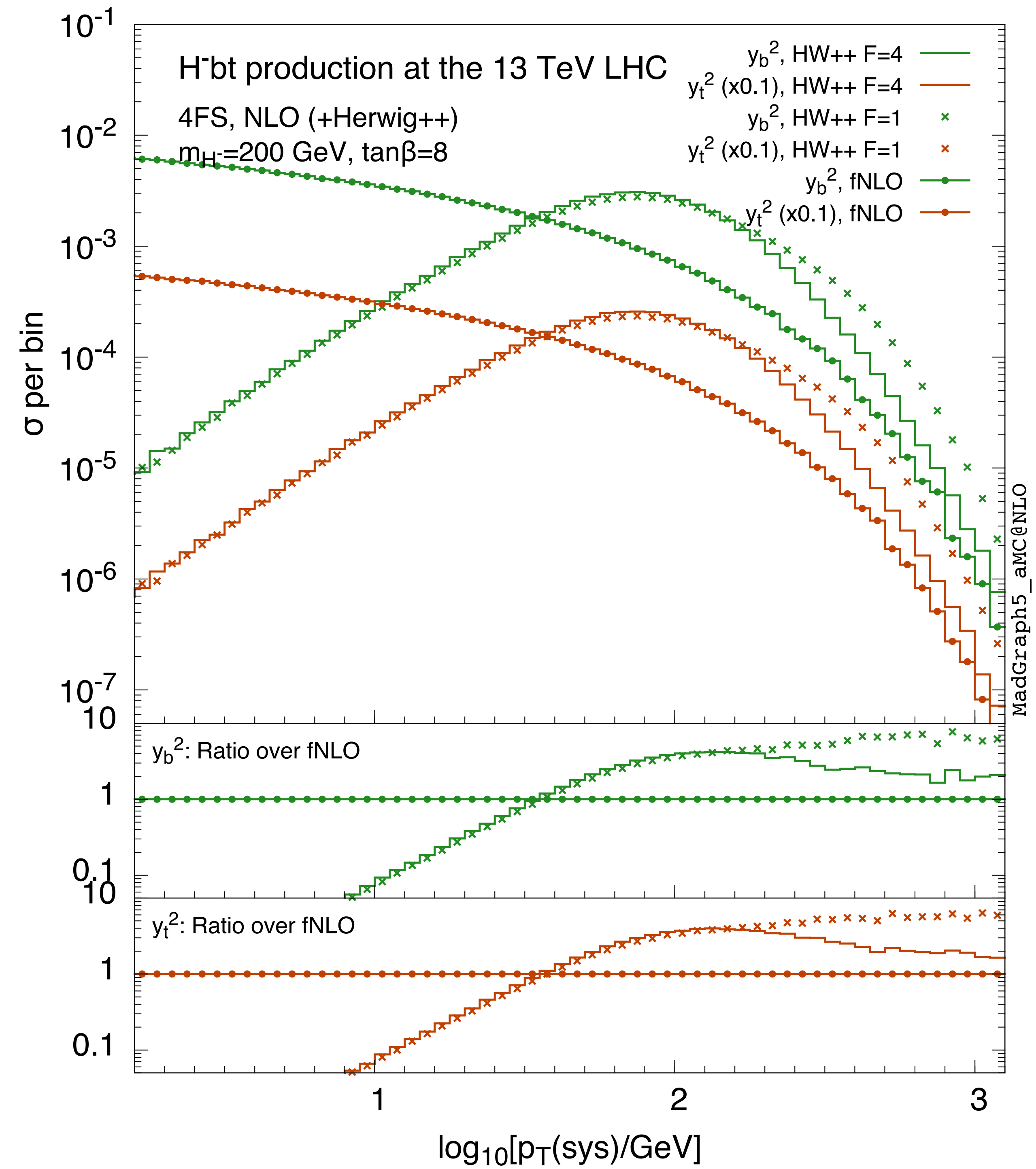
Example 1: Charged Higgs production





$$\mu_{R,F} = H_T/3 \equiv \frac{1}{3}\sum_i \sqrt{m(i)^2 + p_T(i)^2}$$

$$\frac{0.1}{F}\hat{s} \le \mu_{\rm sh} \le \frac{1}{F}\hat{s}$$

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Example 1: Charged Higgs production

$\sigma(m_{H^-} = 200\ \text{GeV})$ [fb]		NLO y_b^2	NLO y_t^2	LO y_b^2	LO y_t^2
	Inclusive	$50.40^{+17.8\%}_{-18.6\%}$	$42.43^{+12.4\%}_{-13.1\%}$	$42.12^{+52.2\%}_{-31.9\%}$	$28.68^{+36.3\%}_{-24.7\%}$
$\geq 1 j_b$	F.O.	$45.47^{+17.5\%}_{-18.4\%}$	$38.31^{+12.2\%}_{-13.0\%}$	$38.26^{+51.9\%}_{-31.8\%}$	$26.09^{+36.1\%}_{-24.6\%}$
	Pythia8	$43.44^{+17.4\%}_{-18.4\%}$	$36.67^{+12.0\%}_{-13.0\%}$	$36.81^{+52.0\%}_{-31.8\%}$	$25.09^{+36.1\%}_{-24.7\%}$
	Herwig++	42.64	36.04	36.08	24.61
$\geq 2 j_b$	F.O.	$11.55^{+10.9\%}_{-15.4\%}$	$9.76^{+6.5\%}_{-10.0\%}$	$11.22^{+50.4\%}_{-31.2\%}$	$7.79^{+35.0\%}_{-24.1\%}$
	Pythia8	$12.55^{+15.3\%}_{-17.4\%}$	$10.67^{+10.4\%}_{-12.1\%}$	$11.73^{+51.2\%}_{-31.5\%}$	$8.12^{+35.6\%}_{-24.4\%}$
	Herwig++	11.03	9.33	10.09	7.00

$\tan\beta = 8$

$\sigma(m_{H^-} = 600\ \text{GeV})$ [fb]		NLO y_b^2	NLO y_t^2	LO y_b^2	LO y_t^2
	Inclusive	$2.400^{+20.3\%}_{-20.1\%}$	$2.117^{+13.1\%}_{-14.2\%}$	$1.794^{+54.9\%}_{-33.0\%}$	$1.339^{+40.1\%}_{-26.5\%}$
$\geq 1 j_b$	F.O.	$2.187^{+19.9\%}_{-19.9\%}$	$1.925^{+12.6\%}_{-14.0\%}$	$1.649^{+54.7\%}_{-32.9\%}$	$1.232^{+39.9\%}_{-26.5\%}$
	PYTHIA8	$2.115^{+19.9\%}_{-19.9\%}$	$1.865^{+12.5\%}_{-14.0\%}$	$1.601^{+54.8\%}_{-32.9\%}$	$1.197^{+40.0\%}_{-26.5\%}$
	HERWIG++	2.077	1.836	1.570	1.175
$\geq 2 j_b$	F.O.	$0.630^{+12.6\%}_{-17.0\%}$	$0.548^{+5.9\%}_{-10.8\%}$	$0.548^{+53.8\%}_{-32.6\%}$	$0.413^{+39.2\%}_{-26.2\%}$
	PYTHIA8	$0.697^{+16.7\%}_{-18.6\%}$	$0.611^{+9.6\%}_{-12.6\%}$	$0.588^{+54.3\%}_{-32.8\%}$	$0.443^{+39.6\%}_{-26.3\%}$
	HERWIG++	0.602	0.532	0.498	0.376

Reduced

Top leptonic decay

$\simeq$

$\neq$ K-factor

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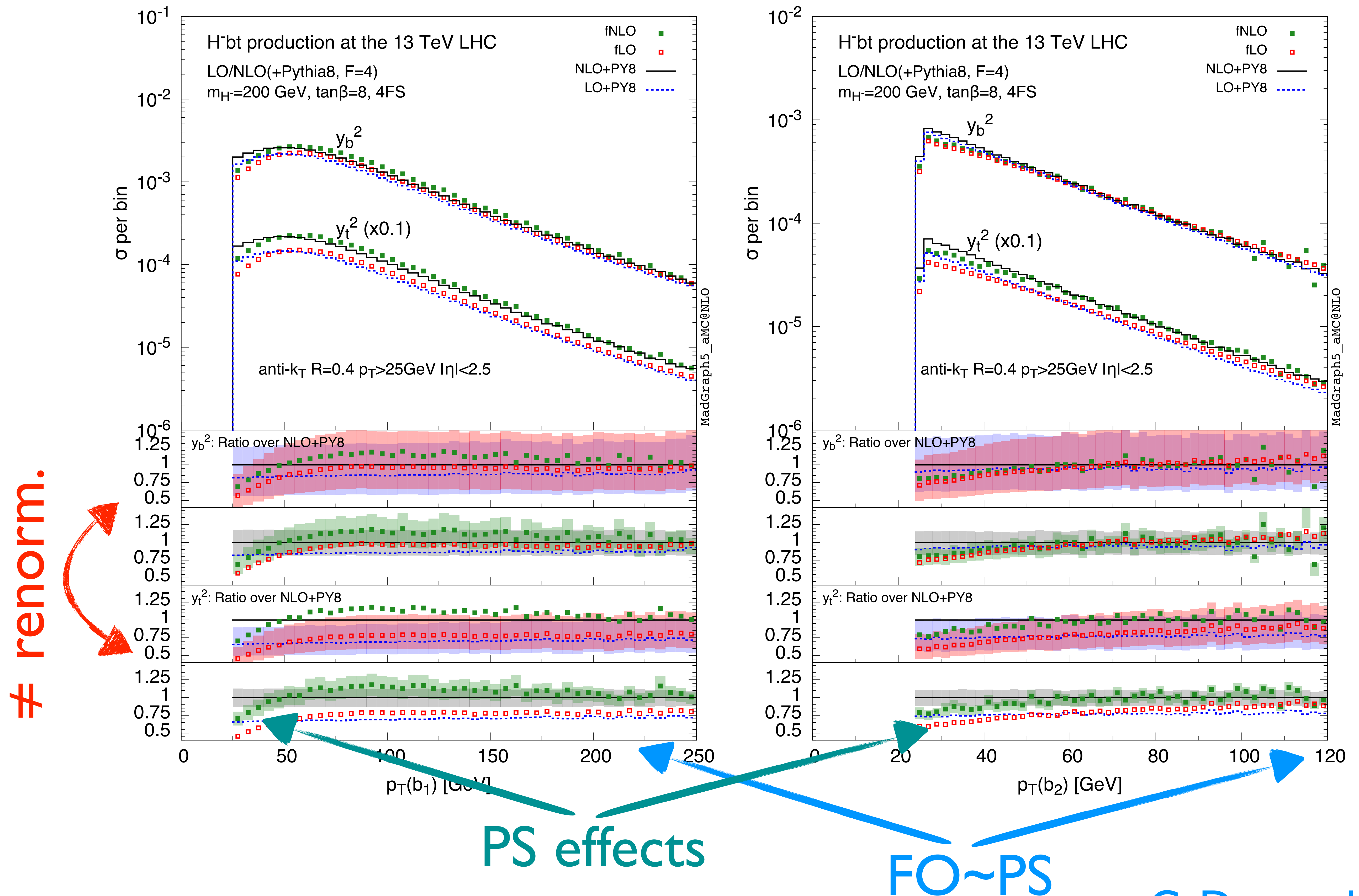
Example 1: Charged Higgs production



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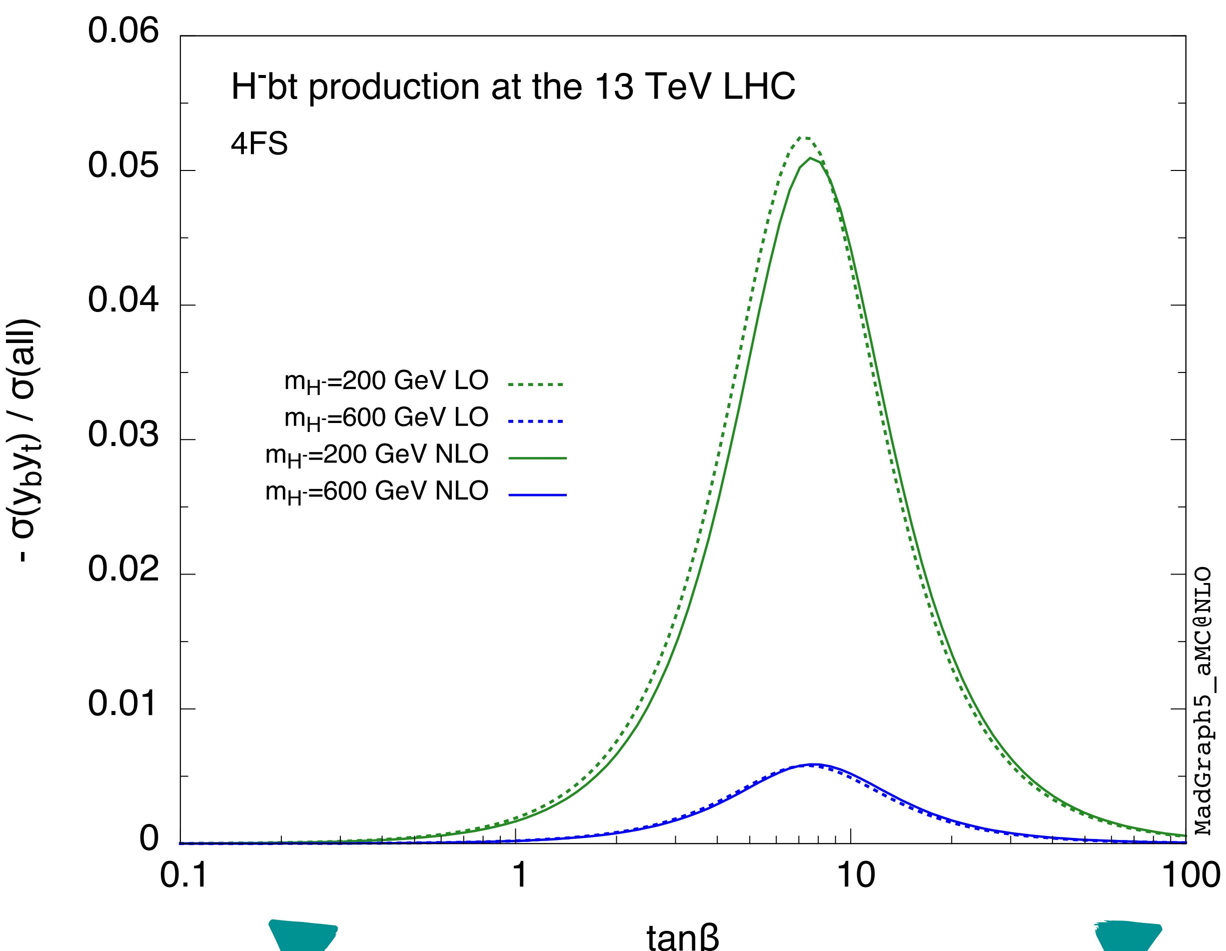
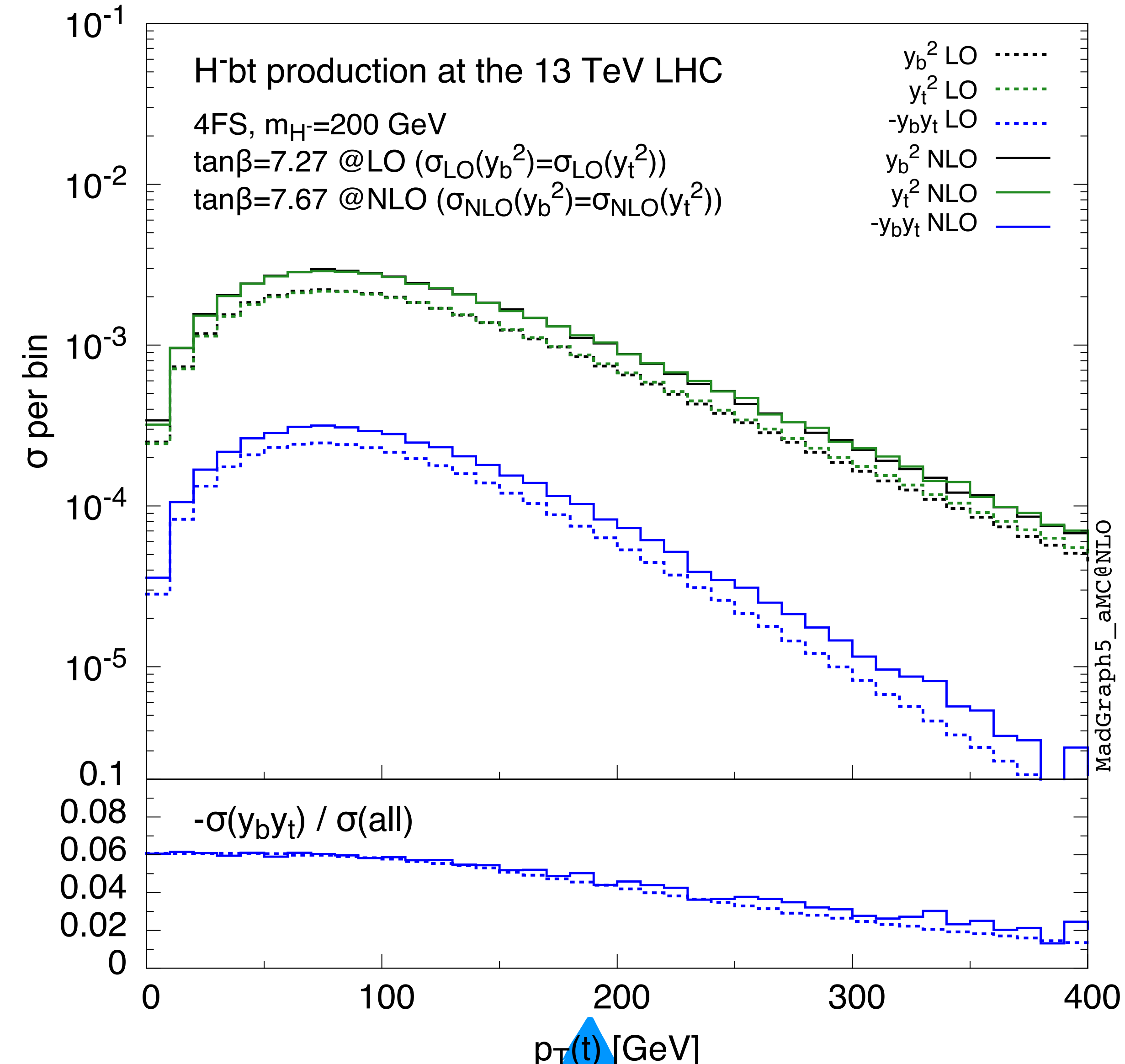
Example 1: Charged Higgs production

Interference : $\propto m_b$





Other terms are enhanced

More important at low energy

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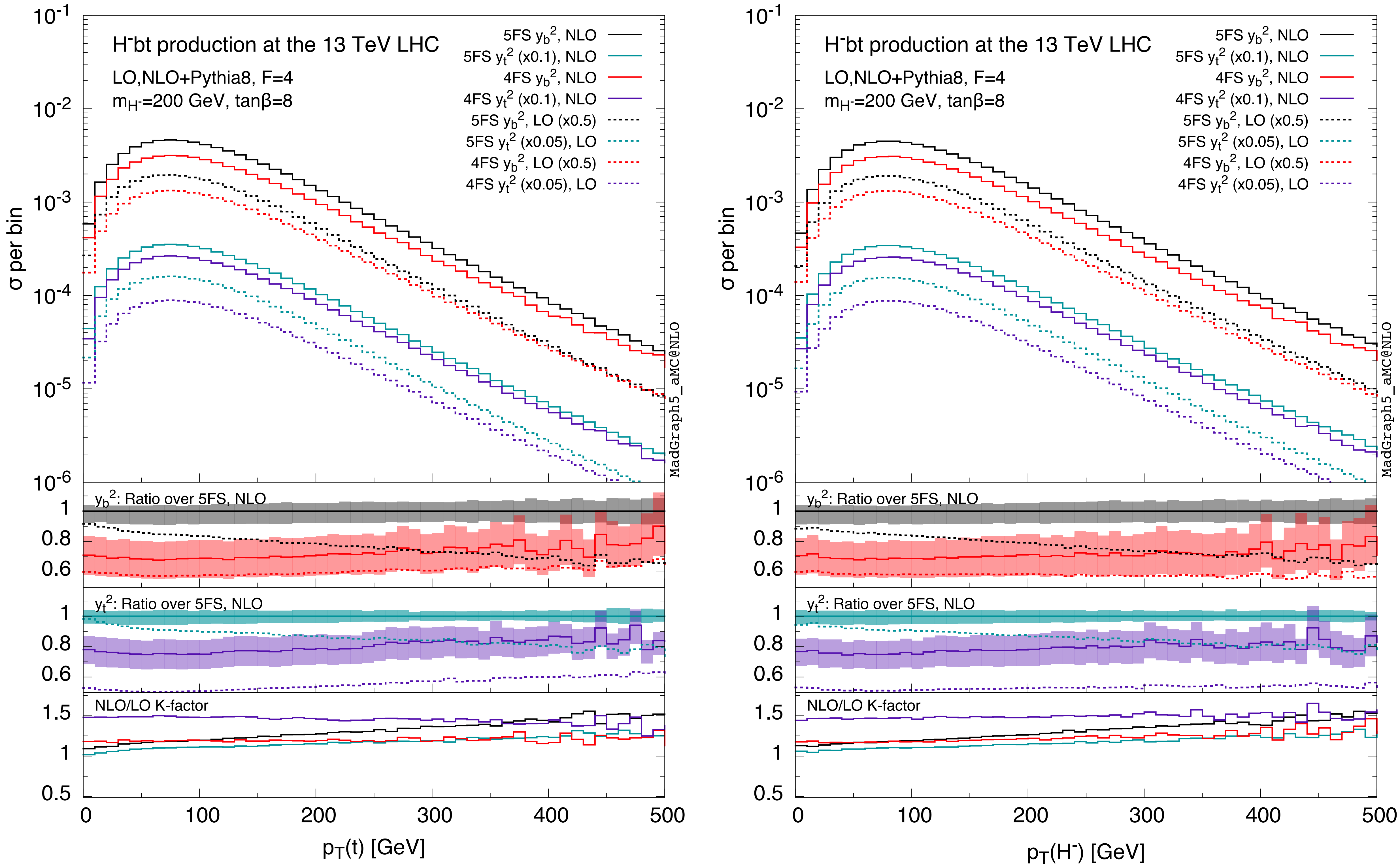
Example 1: Charged Higgs production

4F vs 5F



Closer (Shape) at NLO

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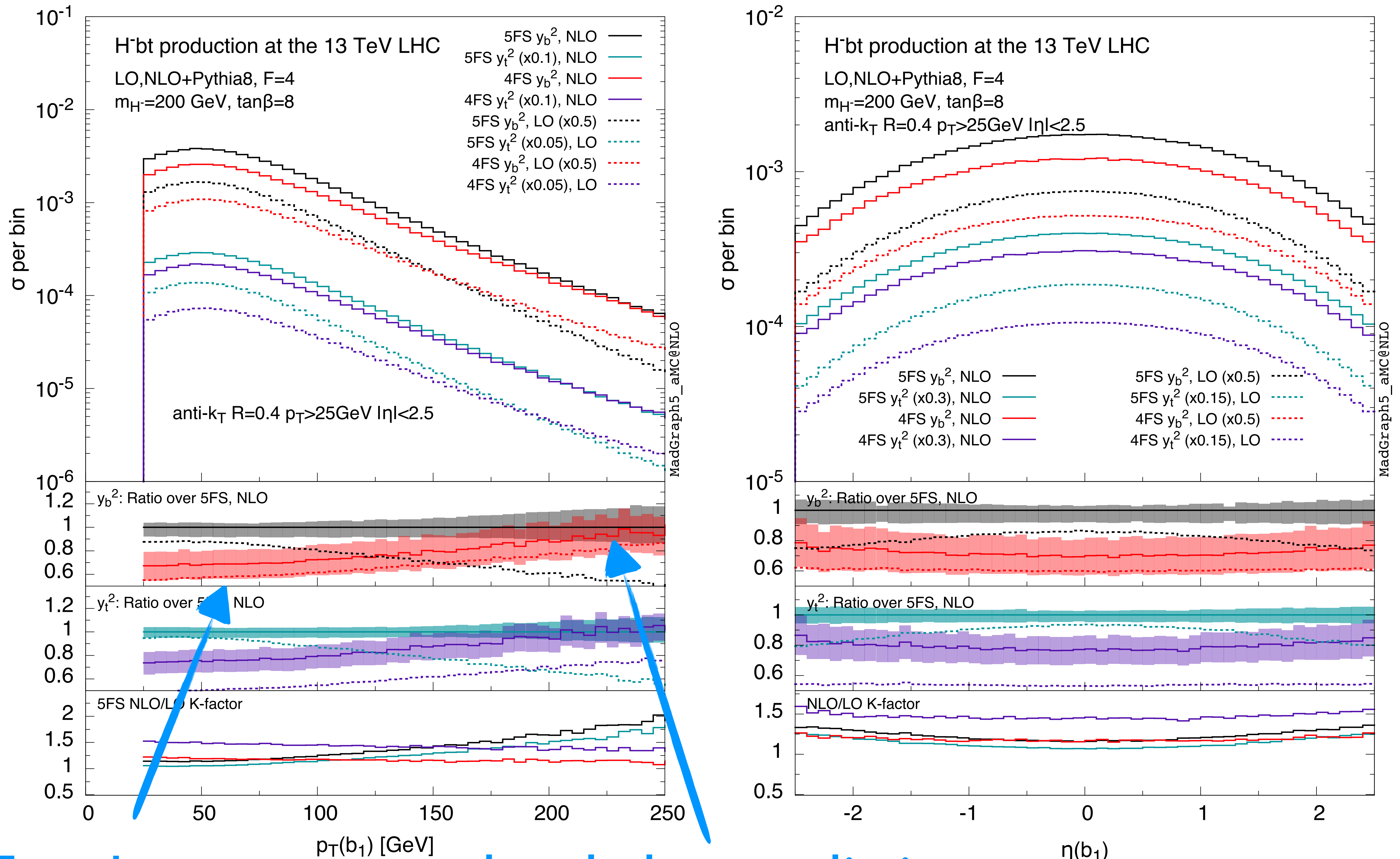
Example 1: Charged Higgs production



Top decay

hard gluon splitting

more exclusive in b more different

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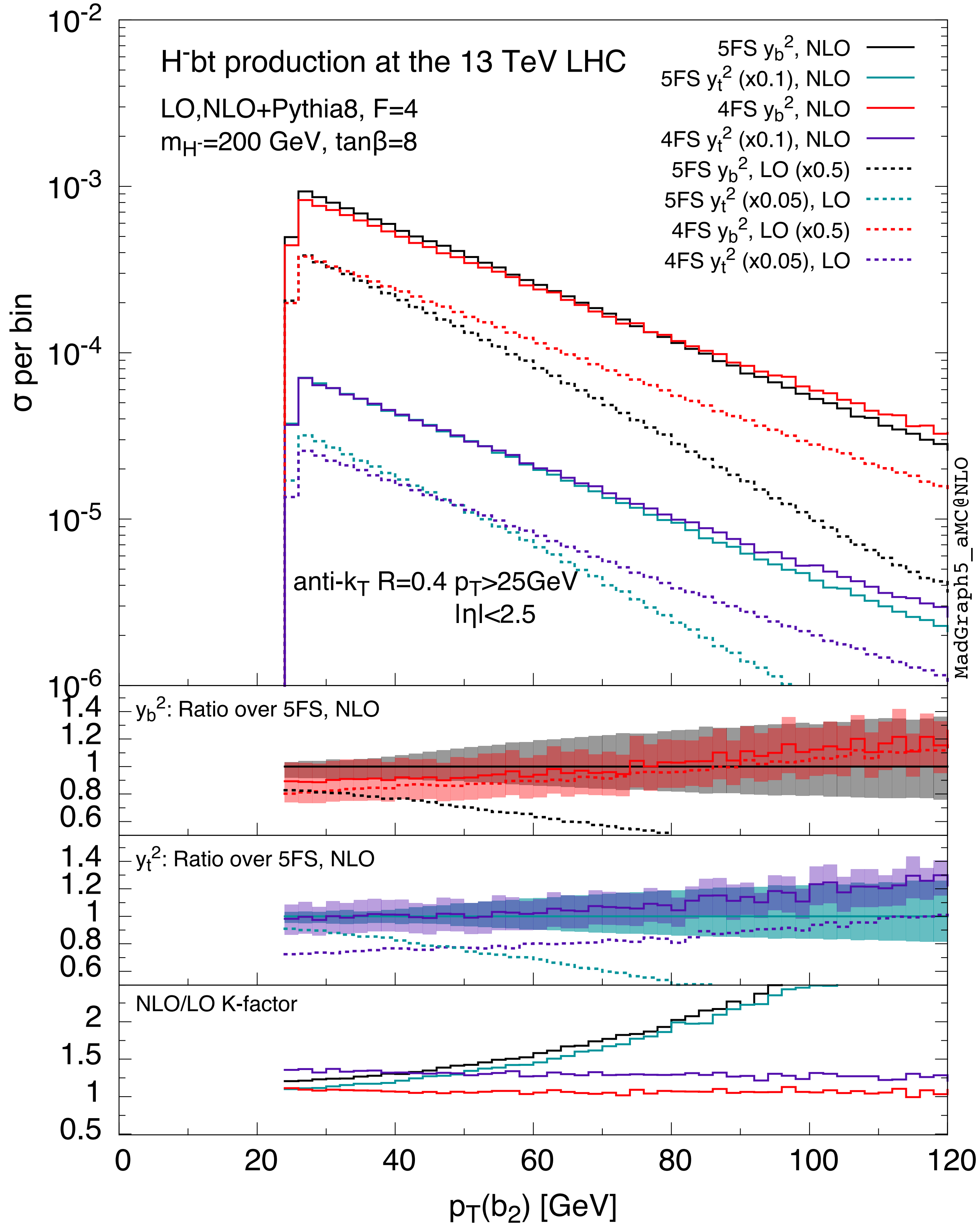
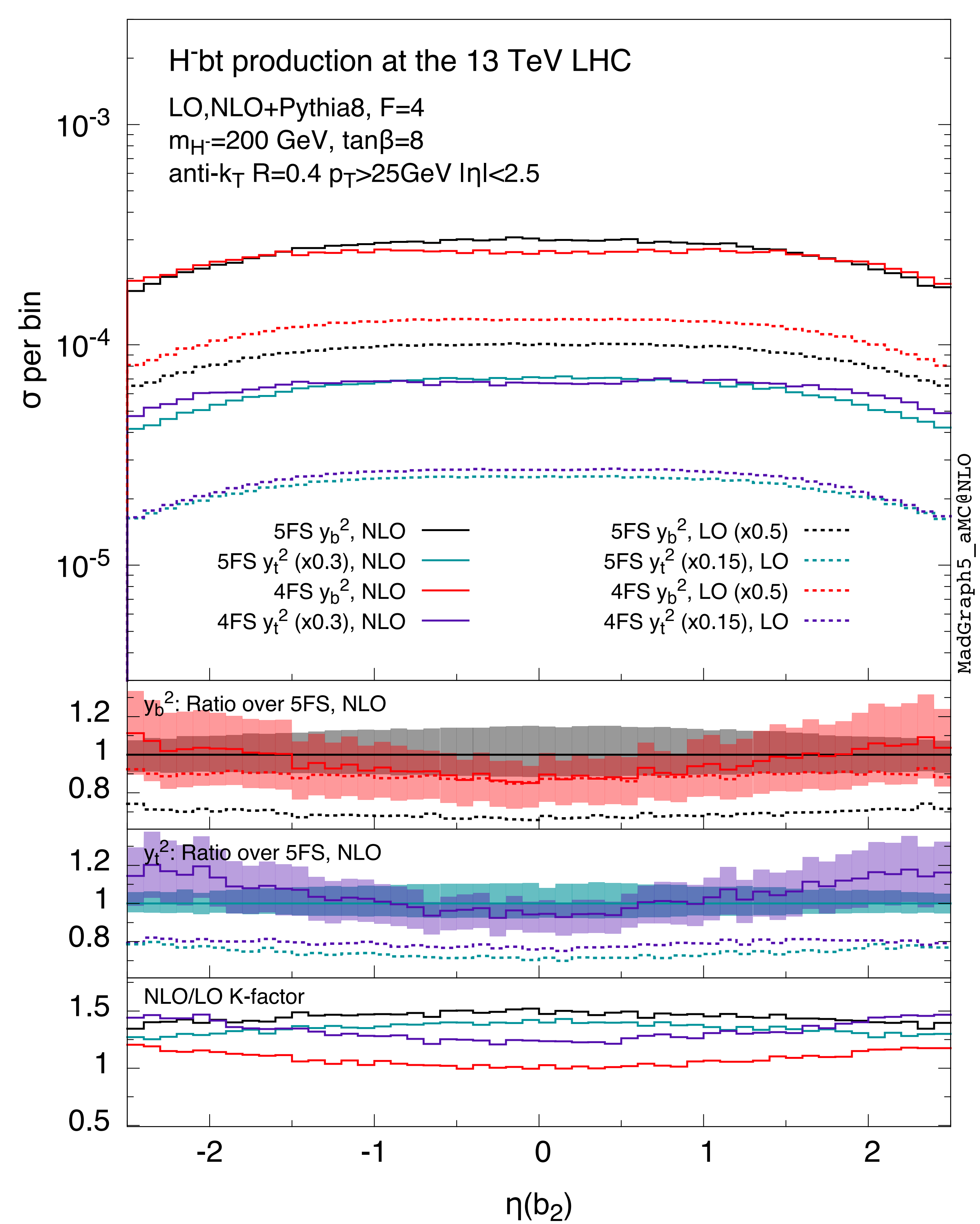
Example 1: Charged Higgs production





Only LO in 5F

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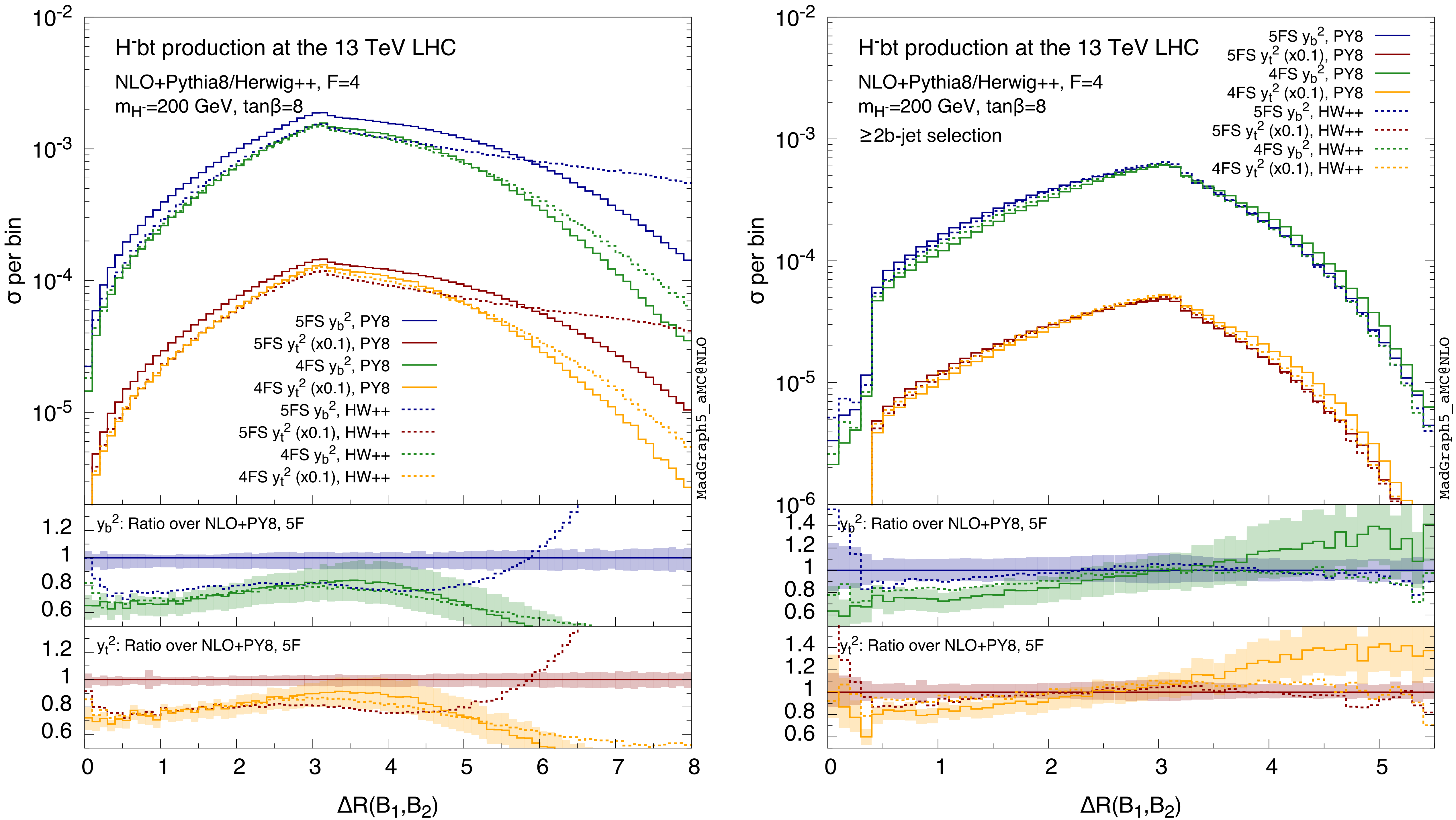
Example 1: Charged Higgs production



Shower dependent in 5F

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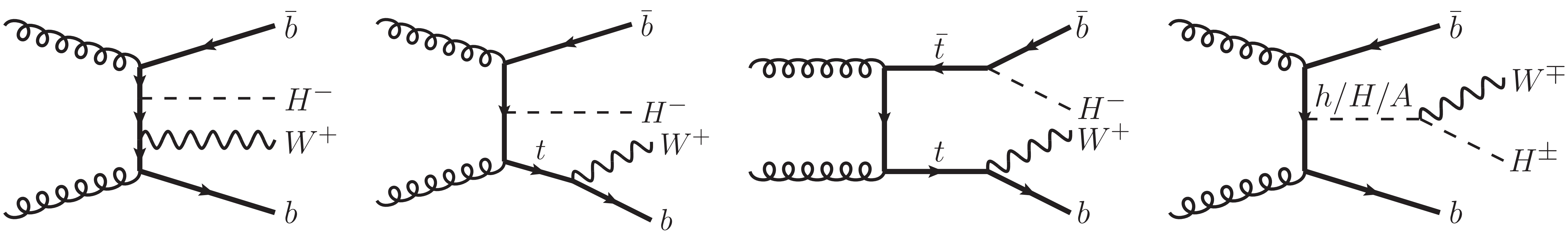
H^+ production : $m_H \sim m_t$

1607.05291 : C. D., R. Frederix ,V. Hirschi, M.Ubiali, M.Wiesemann and M.Zaro

NLO in QCD

Complex Mass Scheme (Top)



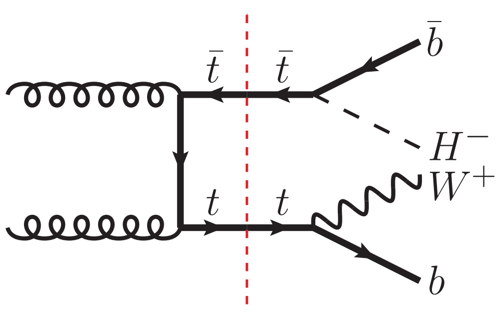
Single and double resonant

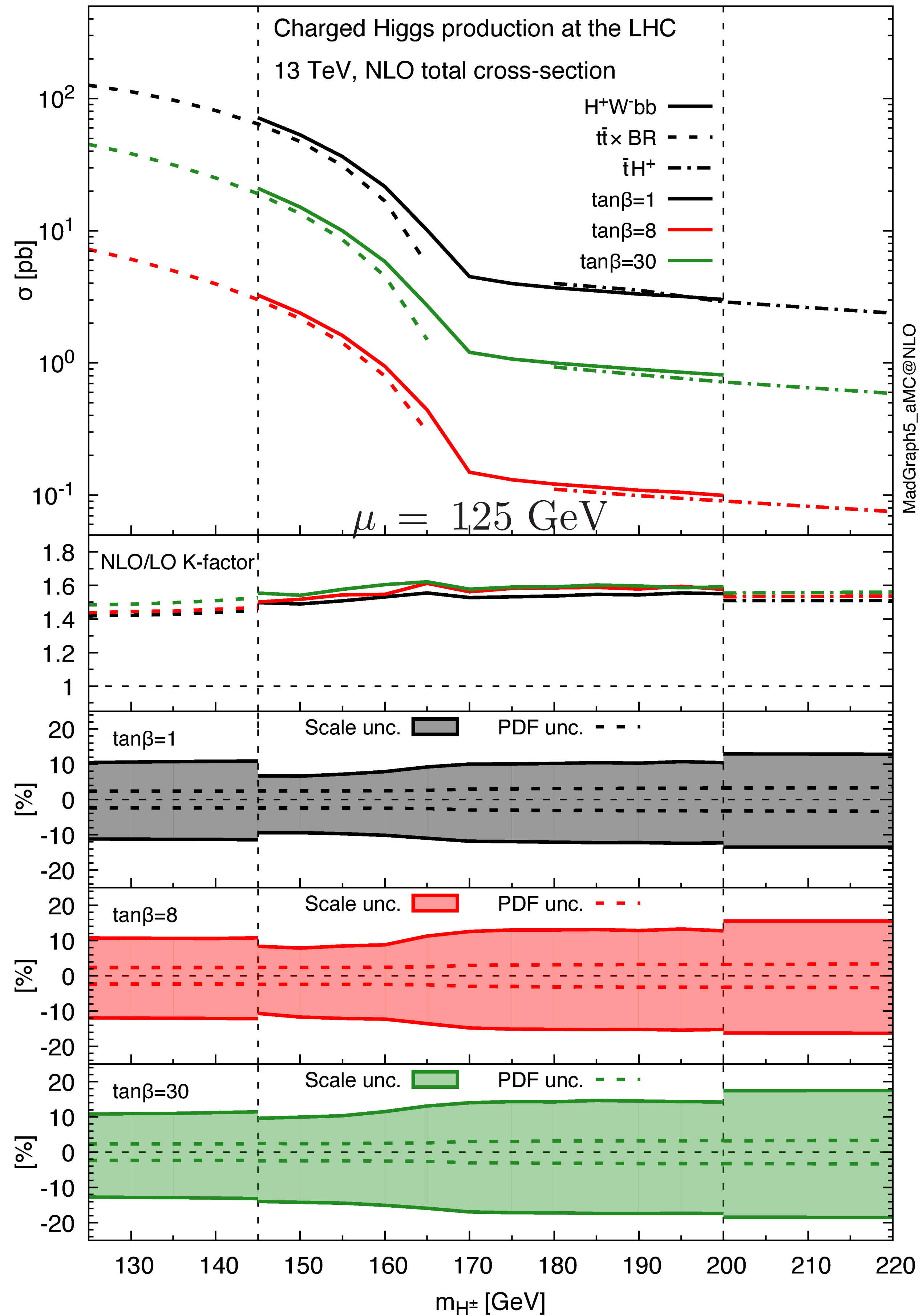
Neutral scalars (≲7%)

C. Degrande

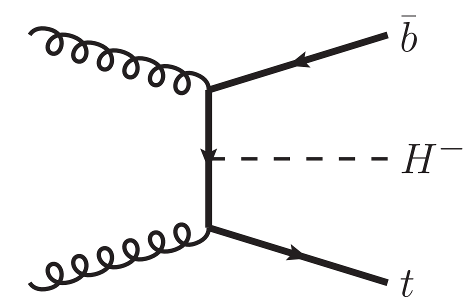
H^+ production : $m_H \sim m_t$

$$\frac{m_t}{2} \lesssim \mu \lesssim m_t$$





$$\mu = (m_t + m_{H^\pm} + m_b)/3$$



Errors are reduced by a factor ~2

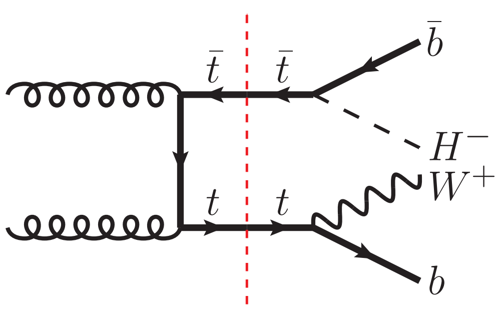
C. Degrande

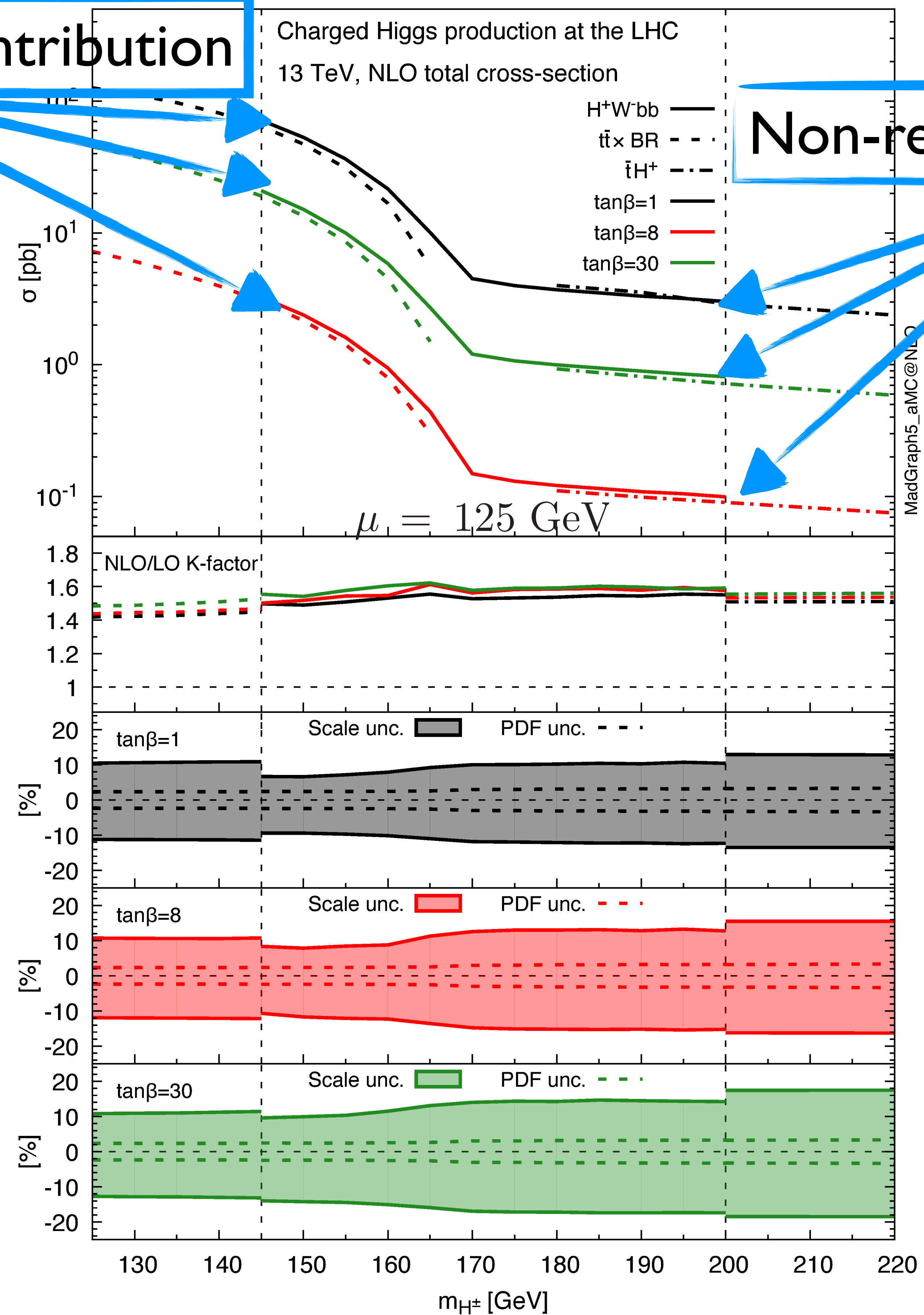
H^+ production : $m_H \sim m_t$

Single-resonant contribution

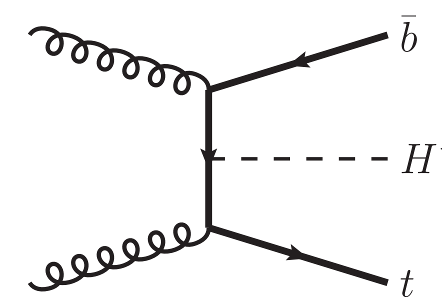
Non-resonant contribution

$$\frac{m_t}{2} \lesssim \mu \lesssim m_t$$





$$\mu = (m_t + m_{H^\pm} + m_b)/3$$



Errors are reduced by a factor ~2

C. Degrande

Spin-2

$$\mathcal{L}^{Y_2}_{\rm V,f} = -\frac{\kappa_{V,f}}{\Lambda} T^{V,f}_{\mu\nu} Y_2^{\mu\nu}$$

$$T^f_{\mu\nu} = -g_{\mu\nu}\left[\bar\psi_f\left(i\gamma^\rho D_\rho - m_f\right)\psi_f - \frac{1}{2}\partial^\rho\left(\bar\psi_f i\gamma_\rho\psi_f\right)\right] + \left[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu\left(\bar\psi_f i\gamma_\nu\psi_f\right) + (\mu\leftrightarrow\nu)\right],$$

$$T^\Phi_{\mu\nu} = D_\mu\Phi^\dagger D_\nu\Phi + D_\nu\Phi^\dagger D_\mu\Phi - g_{\mu\nu}(D^\rho\Phi^\dagger D_\rho\Phi - V(\Phi))$$

$$T^V_{\mu\nu} = -g_{\mu\nu}\left[-\frac{1}{4}F^{\rho\sigma}F_{\rho\sigma} + \delta_{m_V,0}\left(\left(\partial^\rho\partial^\sigma V_\sigma\right)V_\rho + \frac{1}{2}\left(\partial^\rho V_\rho\right)^2\right)\right] - F^\rho_\mu F_{\nu\rho} + \delta_{m_V,0}\left[\left(\partial_\mu\partial^\rho V_\rho\right)V_\nu + \left(\partial_\nu\partial^\rho V_\rho\right)V_\mu\right],$$

$$+$$

$$T^{\rm FP}_{\mu\nu} = -g_{\mu\nu}\left[\left(\partial^\rho\bar\omega^a\right)\left(\partial_\rho\omega^a\right) - g_s f^{abc}\left(\partial^\rho\bar\omega^a\right)\omega^b V^c_\rho\right] + \left[\left(\partial_\mu\bar\omega^a\right)\left(\partial_\nu\omega^a\right) - g_s f^{abc}\left(\partial_\mu\bar\omega^a\right)\omega^b V^c_\nu + (\mu\leftrightarrow\nu)\right]$$

- Simplified model for new resonance search
- Motivated by Extra Dimension
- Check : Known UV (P. Artoisenet et al, JHEP 1311 (2013) 043)

$$\delta\kappa_g = \frac{\alpha_s}{3\pi}T_F\sum_q\left(\kappa_g-\kappa_q\right)\left(\frac{1}{\epsilon} - \gamma_E + \log 4\pi + \log\frac{\mu_R^2}{m_{Y_2}^2}\right),$$

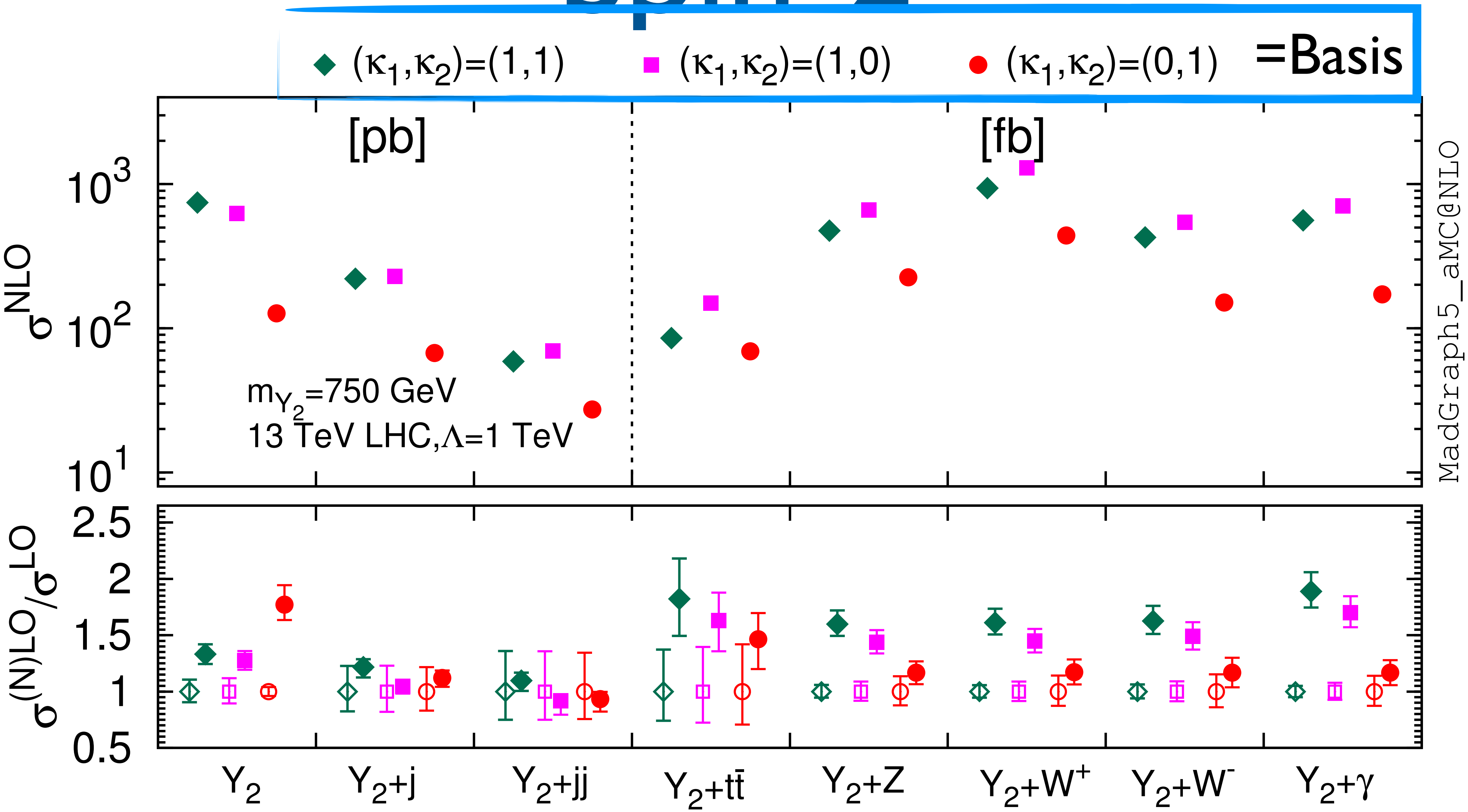
$$\delta\kappa_q = \frac{2\alpha_s}{3\pi}C_F\left(\kappa_q-\kappa_g\right)\left(\frac{1}{\epsilon} - \gamma_E + \log 4\pi + \log\frac{\mu_R^2}{m_{Y_2}^2}\right),$$

No running

- Production at the LHC (G. Das, CD, V. Hirschi, F. Maltoni, H.-S. Shao, arXiv:1605.09359 [hep-ph])

C. Degrande

Spin-2



Process	Couplings set
$pp \to Y_2, Y_2 + j, Y_2 + jj$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_{q,t}$
$pp \to Y_2 + t\bar{t}$	$\kappa_1 = \kappa_{g,q}, \kappa_2 = \kappa_t$
$pp \to Y_2 + Z$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + W^{\pm}$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + \gamma$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + H$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$Y_2 \to jj$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_{q,t}$
$Y_2 \to t\bar{t}$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_t$

Scale+pdf
+param. unc.

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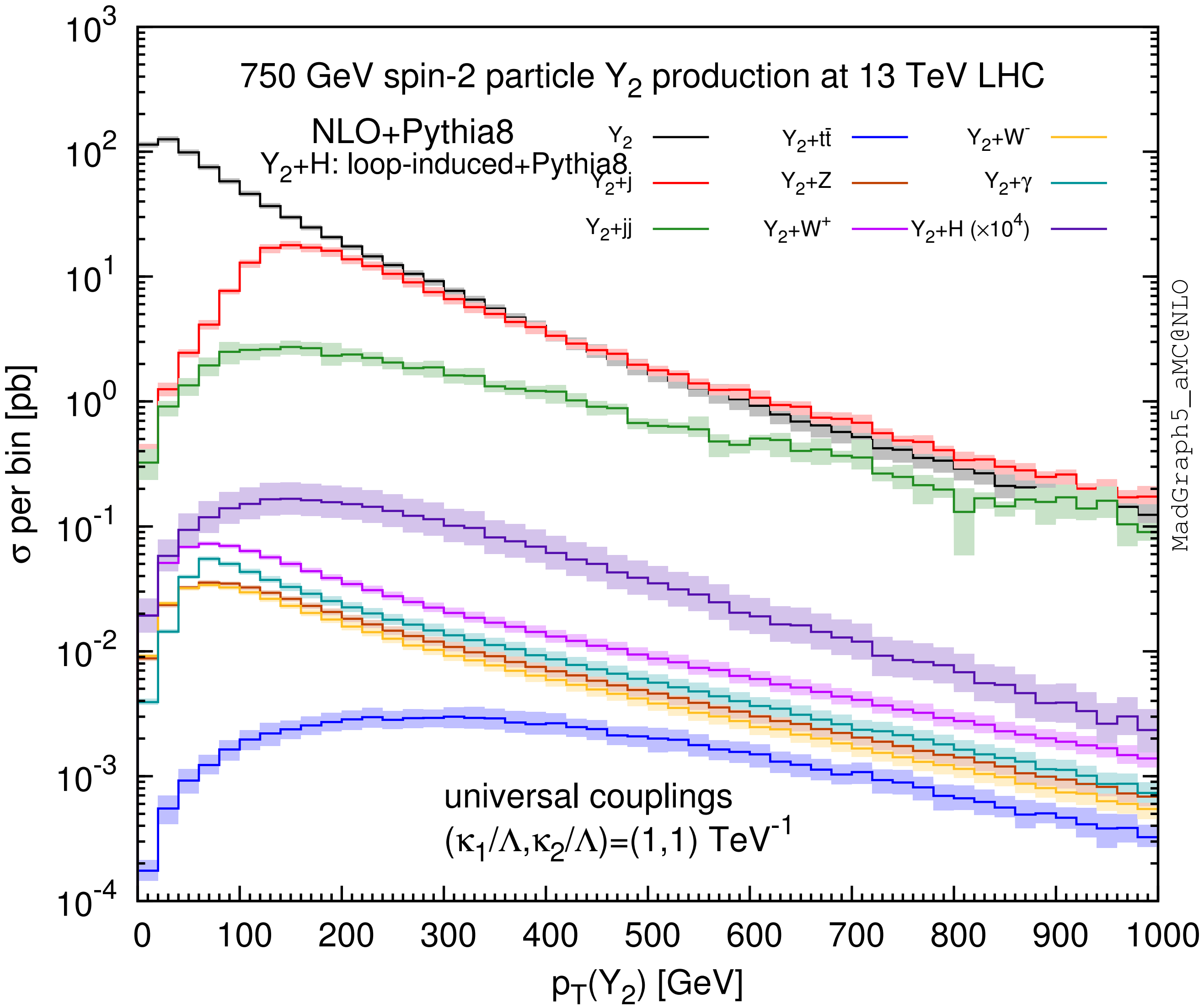
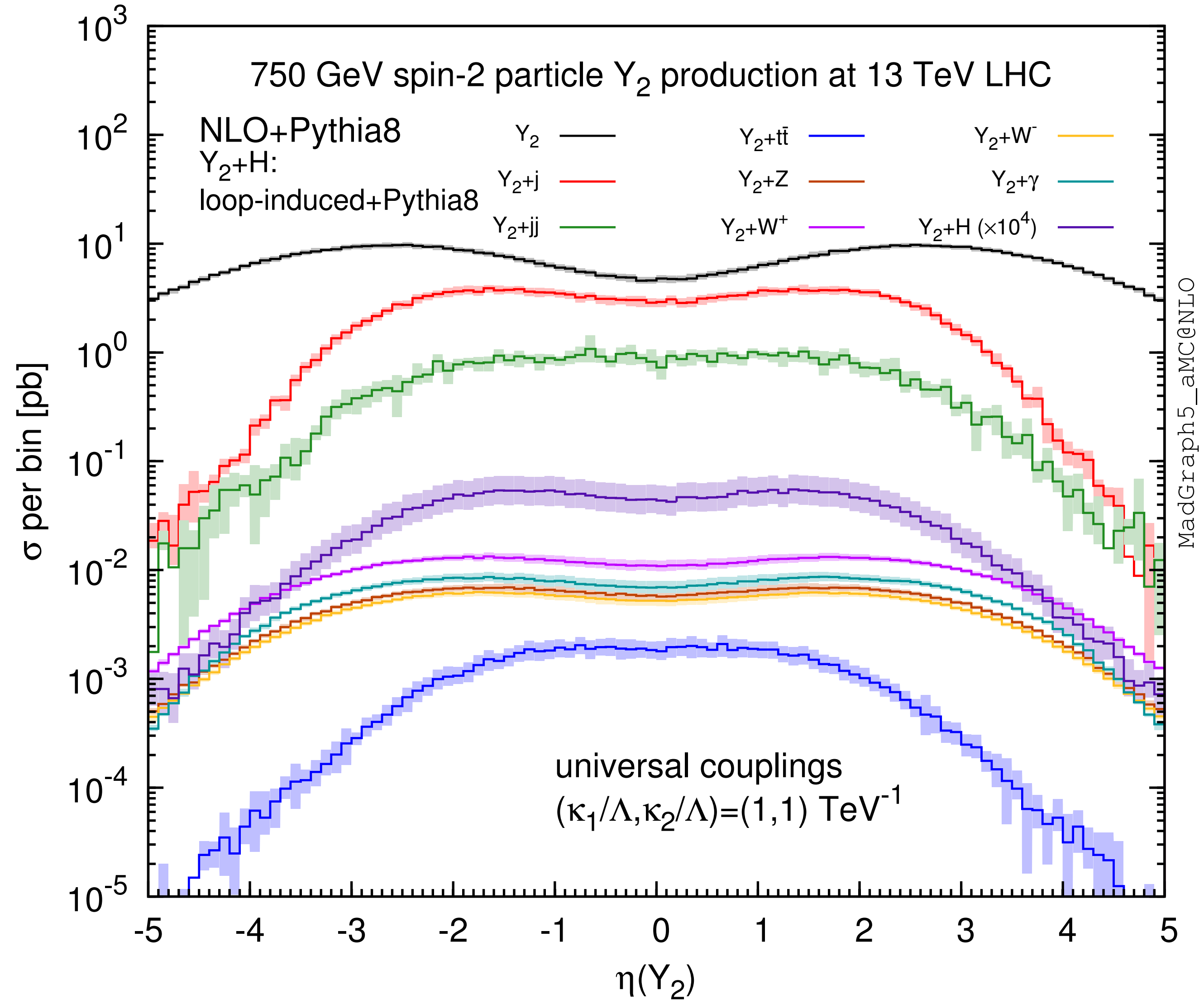
Spin-2





Y2+H is LO (Loop-induced)

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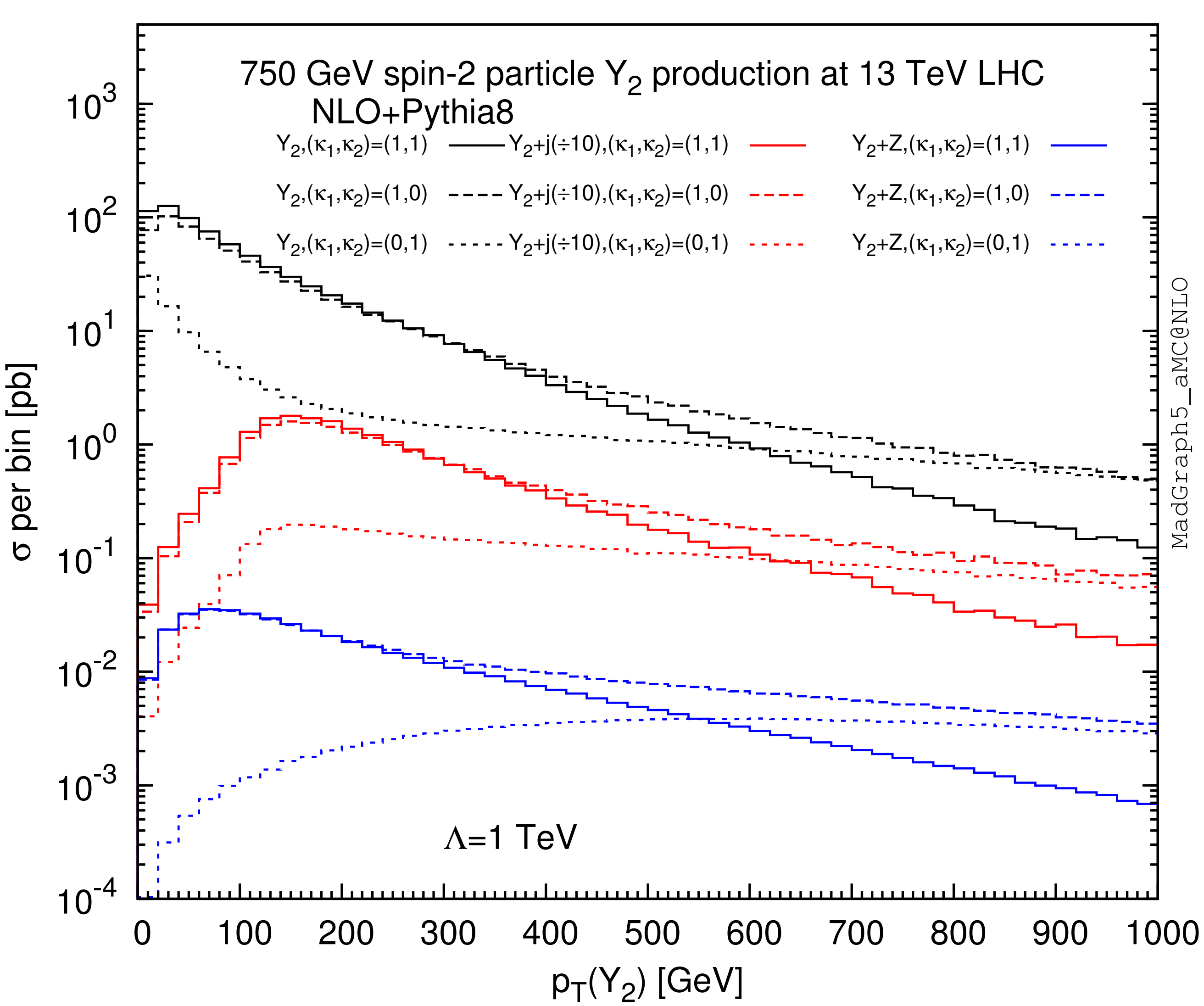
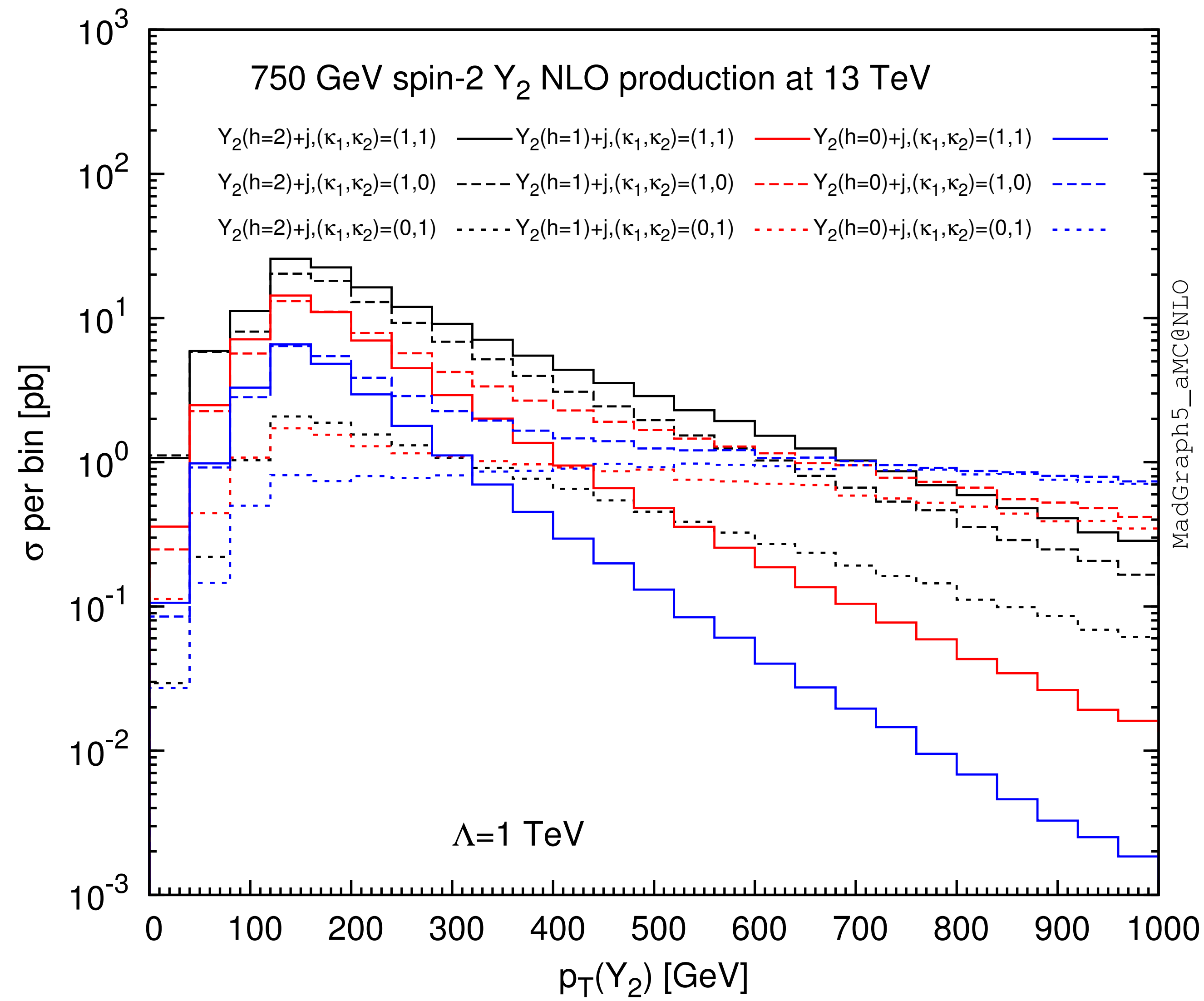
Spin-2 : Non-universal





$$\sim \frac{\hat{s}^3}{m_{Y_2}^4\Lambda^2} \qquad \sim \frac{\hat{s}^2}{m_{Y_2}^2\Lambda^2} \qquad \sim \frac{\hat{s}}{\Lambda^2}$$

C. Degrande

Top FCNC

CD, F. Maltoni, J. Wang, C. Zhang, PRD91 (2015) 034024

t u/c h/A/Z/g

$$qg \to tB$$

$$B = \gamma, Z, h$$

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + H.c.$$

$$O_{\varphi q}^{(3,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_i \gamma^\mu \tau^I Q)$$

$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu Q)$$

$$O_{\varphi u}^{(i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu t)$$

$$O_{uB}^{(i3)} = g_Y (\bar{q}_i \sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu},$$

$$O_{uG}^{(i3)} = g_s (\bar{q}_i \sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu},$$

$$O_{uW}^{(i3)} = g_W (\bar{q}_i \sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{u\varphi}^{(i3)} = (\varphi^\dagger \varphi)(\bar{q}_i t)\tilde{\varphi}$$

+4F

<u>Renorm.:</u>
c/u-t CT
mixing between
operators

Project : u/c g > t

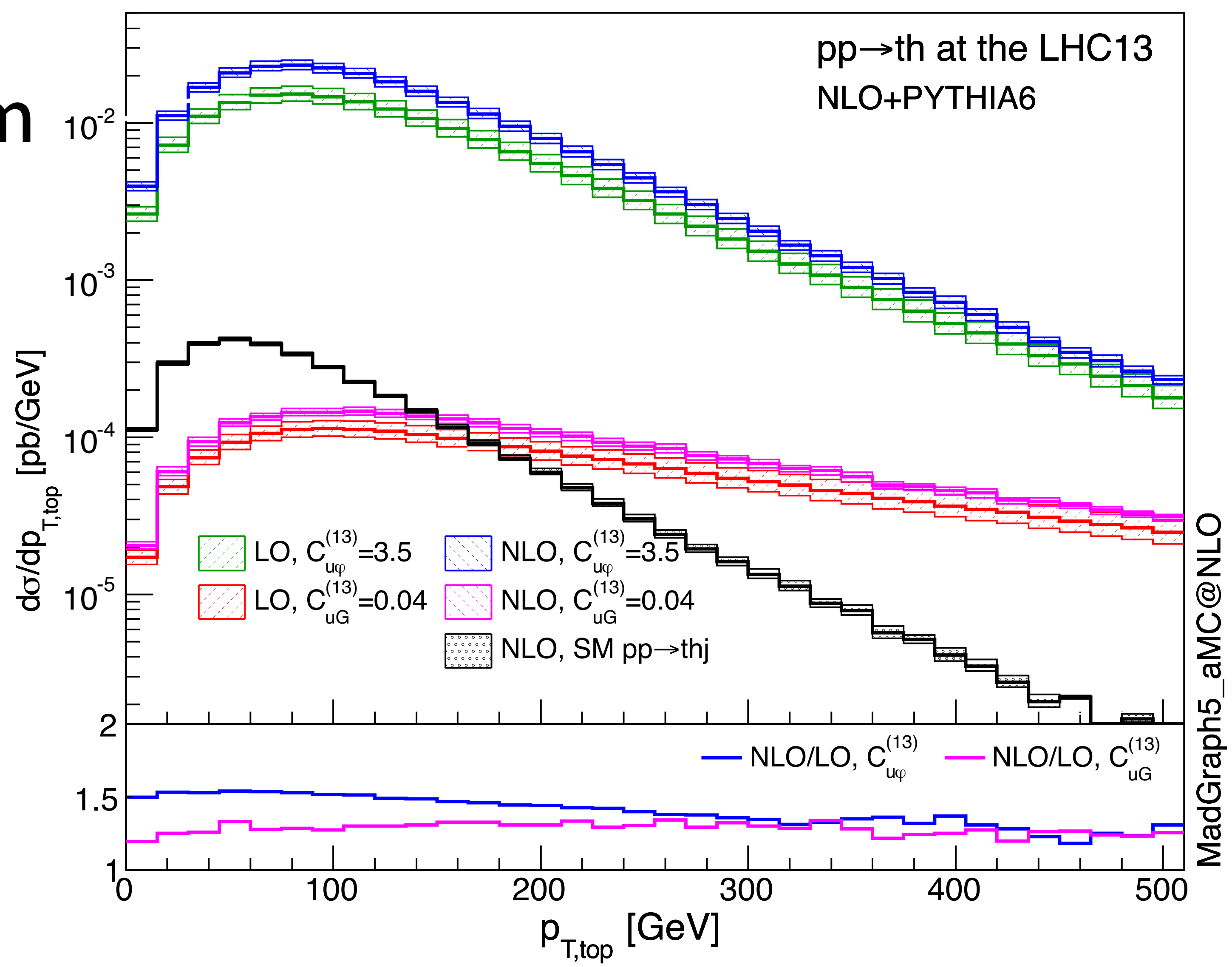
Decay the top with the CMS with flavour mixing

C. Degrande

Top FCNC

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{u\varphi}^{(13)} = 3.5$	2603	+13.0% -11.0%	3858	+7.4% -6.7%
$C_{uG}^{(13)} = 0.04$	40.1	+16.5% -13.2%	50.7	+4.0% -5.2%
$C_{u\varphi}^{(23)} = 3.5$	171	+9.7% -8.7%	310	+7.3% -6.3%
$C_{uG}^{(23)} = 0.09$	9.53	+11.0% -9.7%	16.6	+5.5% -5.1%

Small when constraints from $ug \to t$ are taken into account



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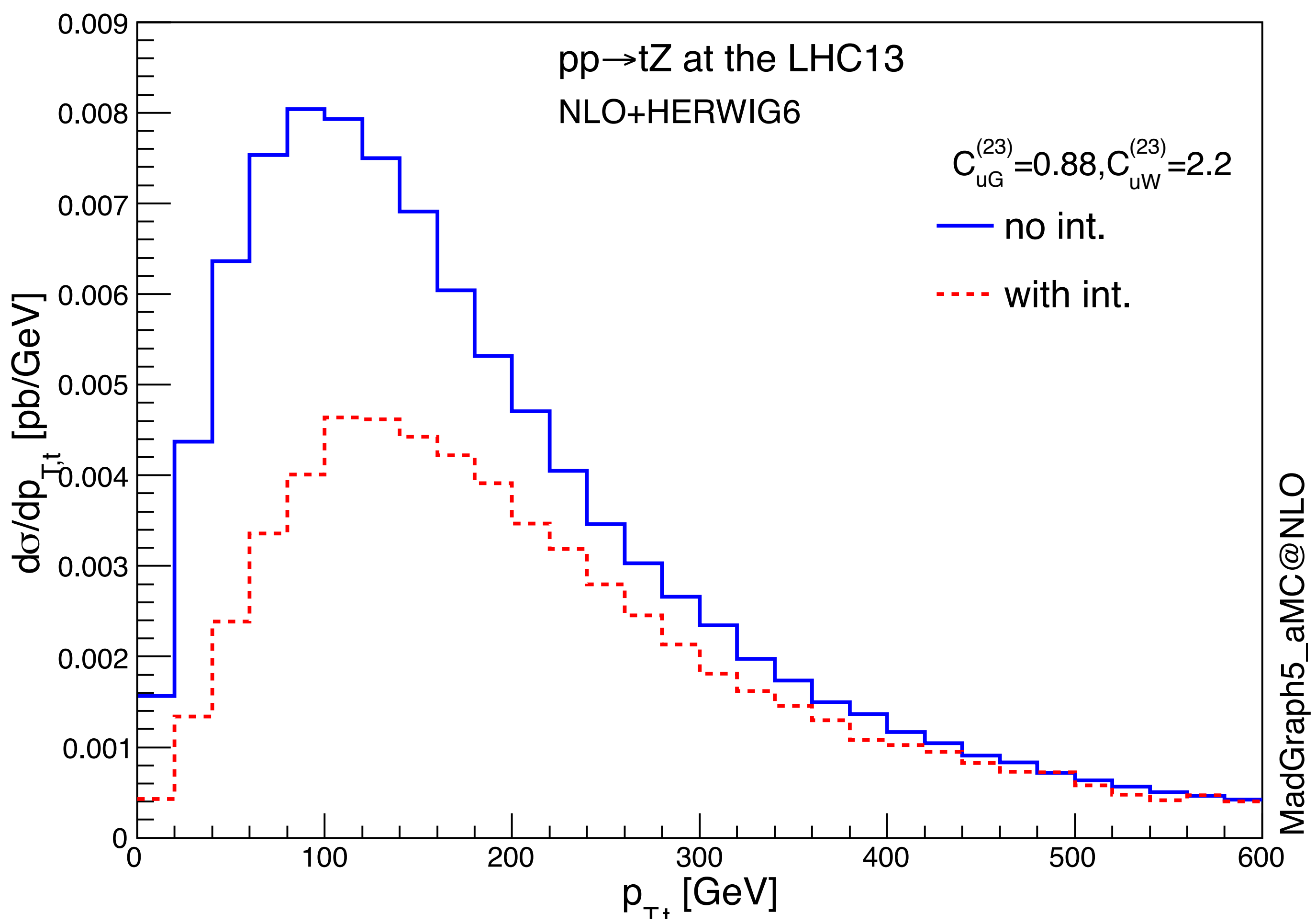
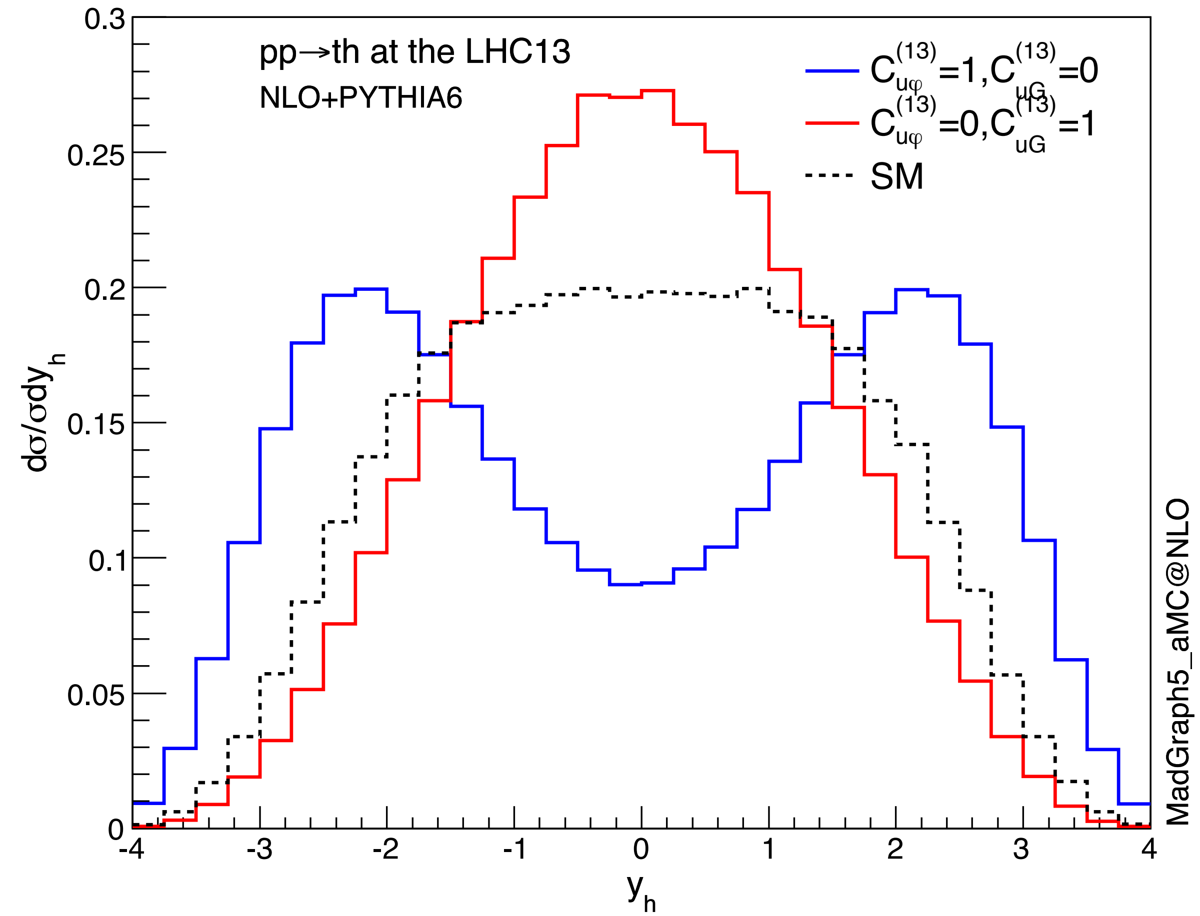
Top FCNC

Large interference between op.



Shape effect



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Plan

- Framework : From FeynRules to Madgraph5_aMC@NLO
- Examples :
  - Charged Higgs production
  - Spin 2
  - Top FCNC
- Final remarks

Final remarks

- Automatic BSM@NLO
  - Renormalizable (Public)
  - For EFT (Private)
- Pheno
  - Top EFT
  - Full EFT
  - …
- Jointly by FeynRules and Madgraph_aMC@NLO teams

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Back-up

Example 1: Charged Higgs production

$m_{H^\pm} = 200\,\mathrm{GeV}$ and $m_{H^\pm} = 600\,\mathrm{GeV}$

$\tan\beta = 8$ but $y_b^2,\ y_t^2$ and $y_b y_t$

NNPDF2.3 at NLO/ NNPDF3.0 at LO with 4/5F

$\alpha_s(M_Z) = 0.118$ (5F) $\alpha_s(M_Z) = 0.1226$ (4F)

$m_b^{\mathrm{pole}} = 4.75\,\mathrm{GeV}$ $m_t^{\mathrm{pole}} = 172.5\,\mathrm{GeV}$

$\bar{m}_b(\bar{m}_b) = 4.3377\,\mathrm{GeV}$

$$\mu_{R,F} = H_T/3 \equiv \frac{1}{3}\sum_i \sqrt{m(i)^2 + p_T(i)^2}$$

Anti-k_T $\Delta R = 0.4$ $p_T(j) \geq 25\,\mathrm{GeV},$ $|\eta(j)| \leq 2.5.$

C. Degrande