ElectroWeak corrections and Complex-Mass Scheme

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Review the status of

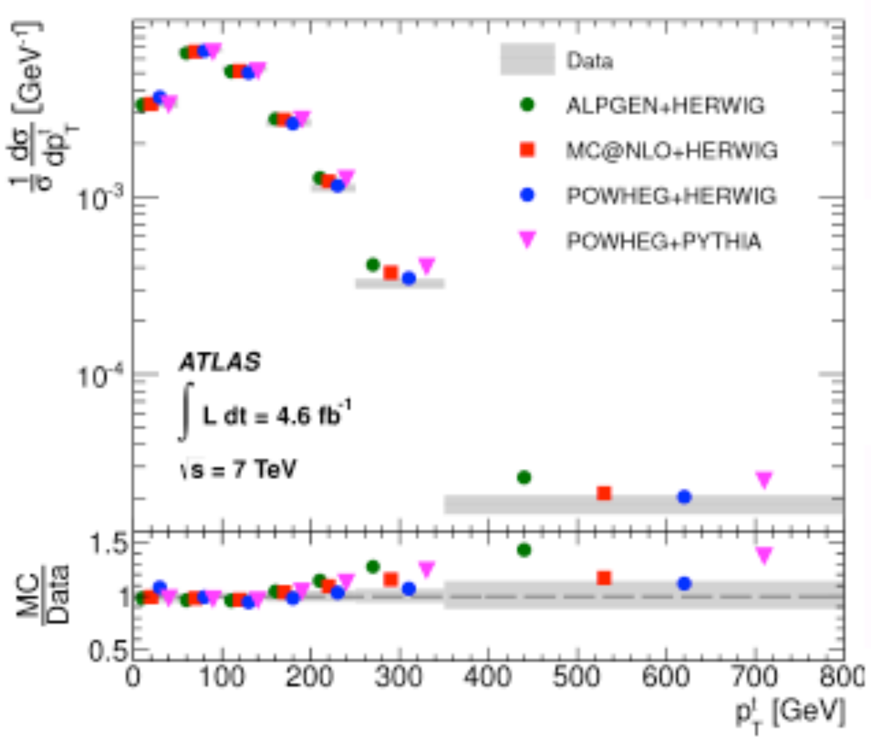
MadGraph5_aMC@NLO-EW

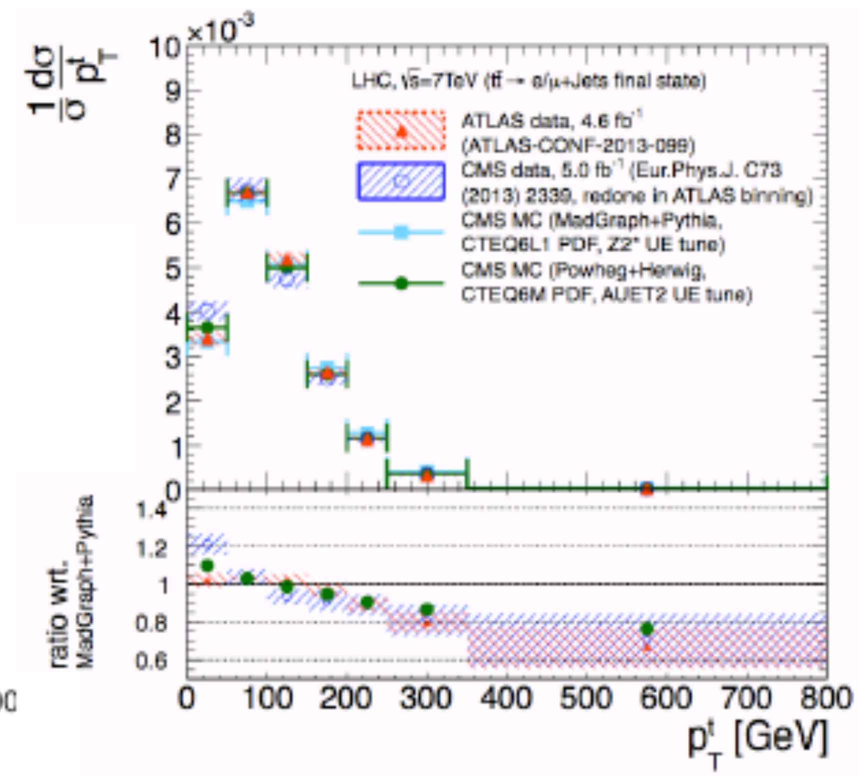
EW OVERVIEW

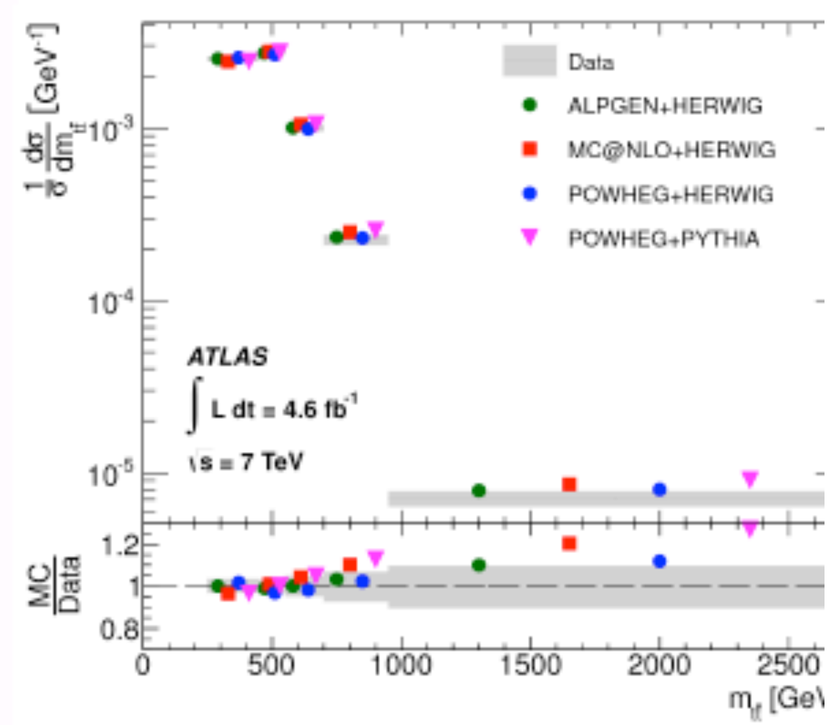
	Yes	No
MadLoop	*EW corrections to any SM process w or w/o b mass in two schemes; Order splitting in mixed order case; Decay processes;*	*Complex-Mass Scheme*
MadFKS	*FKS QED subtraction; Order splitting in mixed order case; Scale and PDF uncer.; MC over helicity;*	*Virtual Trick; Quasi-collinear subtraction; On-shell subtraction; More cross check (tT,tTV);*

EW corrections to $t\bar{t}$ production

- ATLAS and CMS see some ‘anomaly’ on the top p_T distribution and $t\bar{t}$ invariant mass
- Data are softer than NLO QCD MonteCarlos (up to 30-40%)

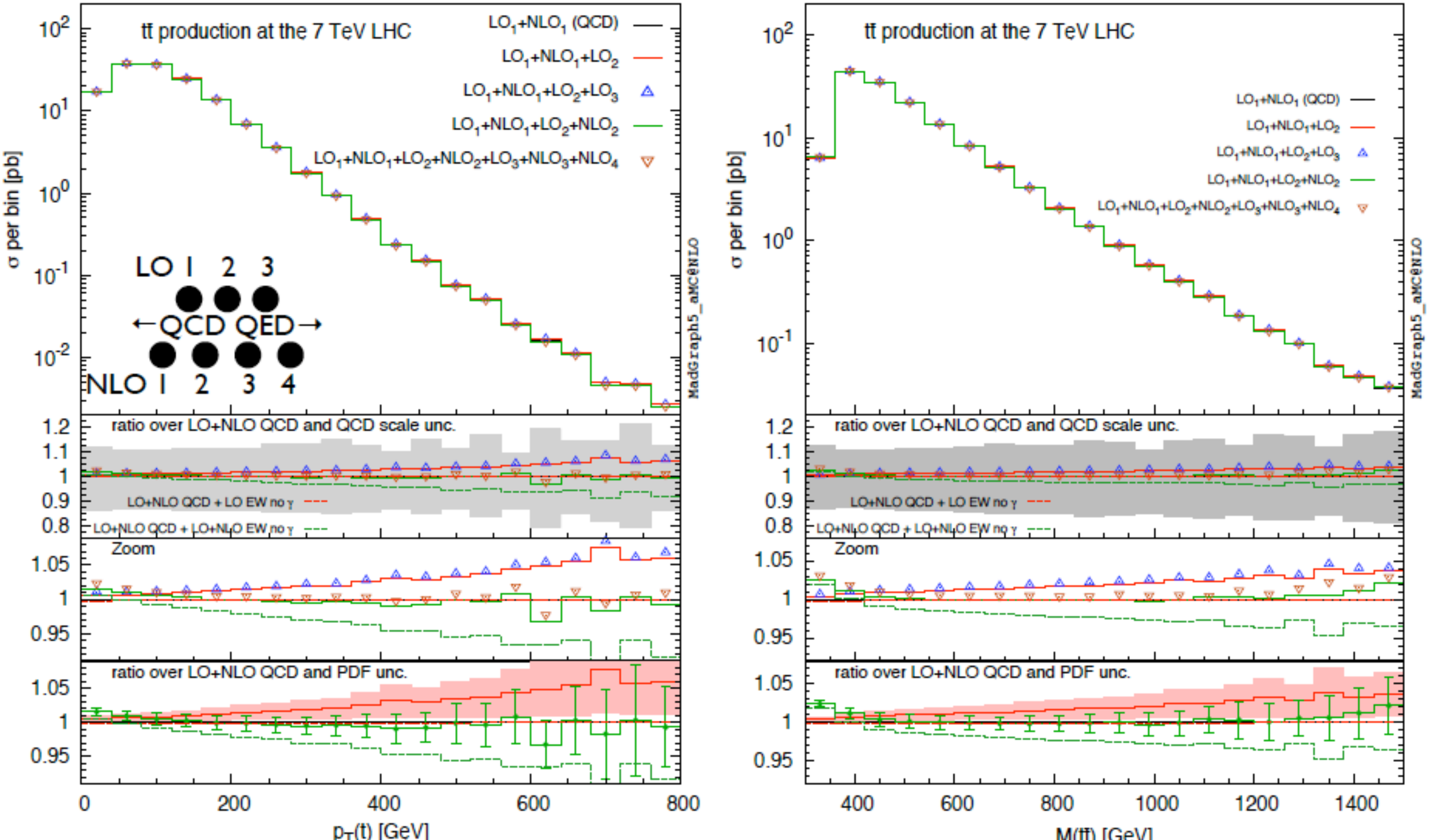






- Is it an EW effect?

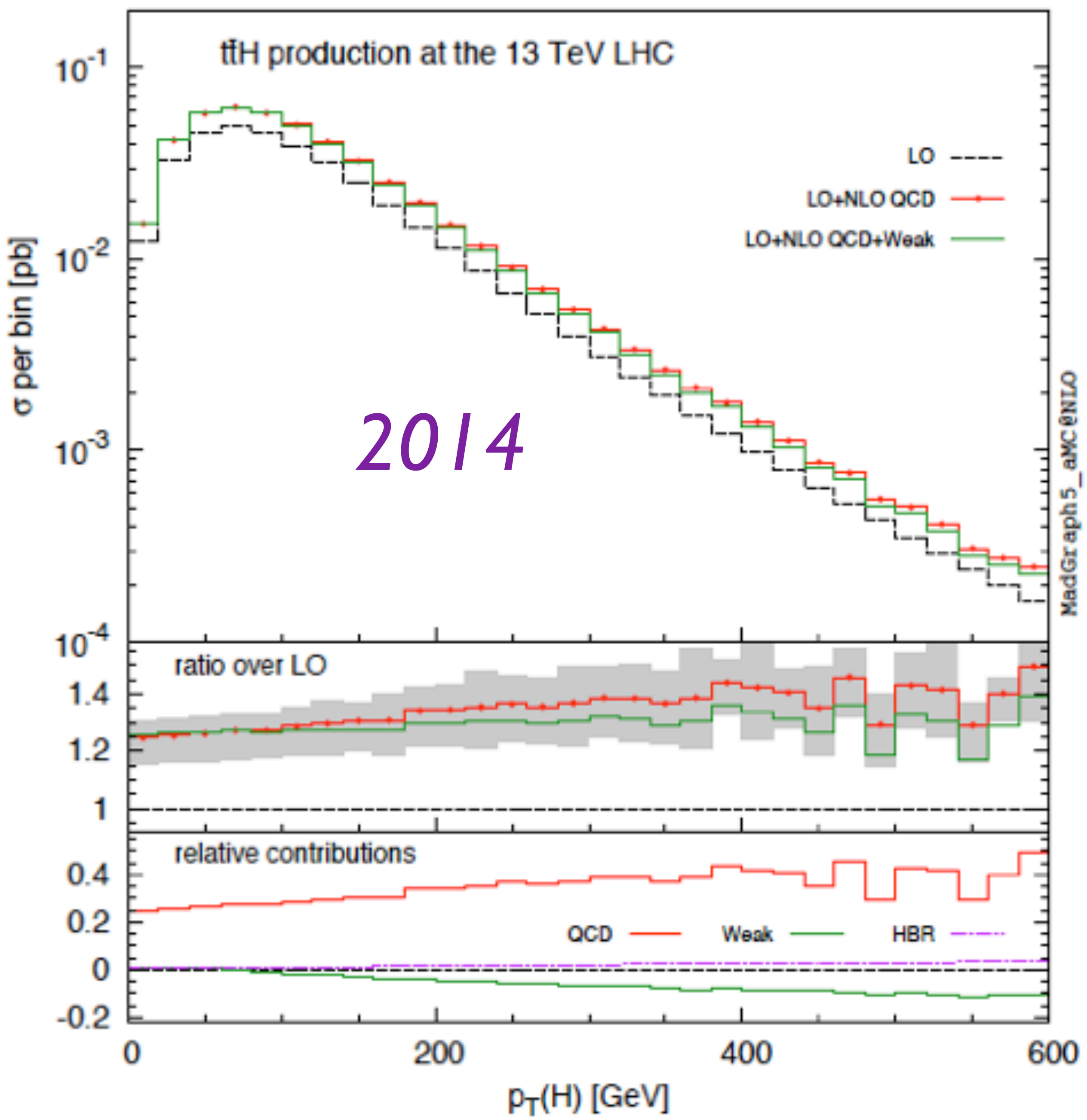
EW corrections to $t\bar{t}$ production

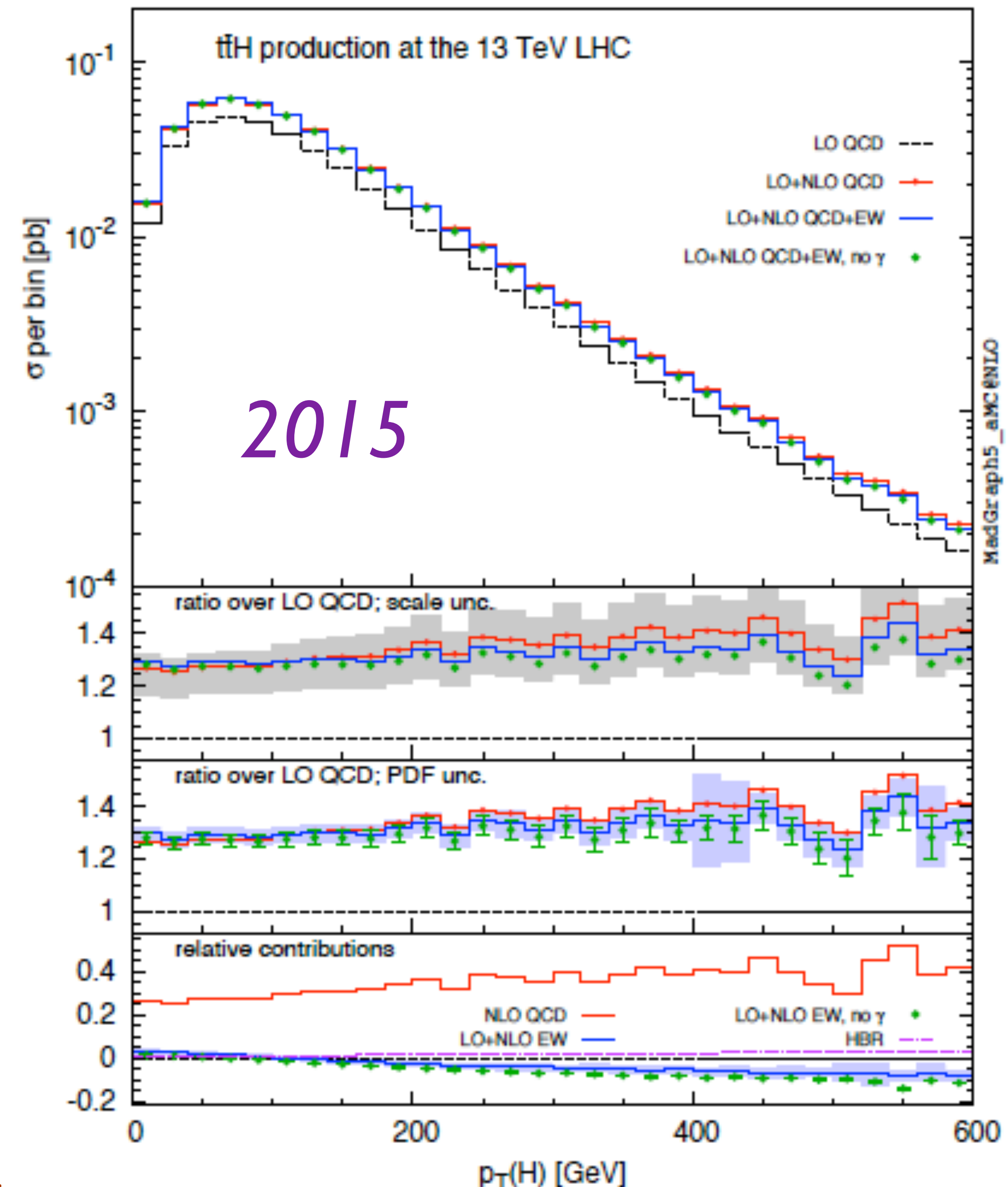


EW corrections to $t\bar{t}$ production

- EW corrections account at most -10% at large p_T, -5% at large mass
- Photon effect as large as EW corrections, but almost 100% uncertain
- Subleading corrections (LO_3, $NLO_{3,4}$) very small

FROM WEAK TO ELECTROWEAK





- **Improvements**: automated IR subtraction; photon emission; photon-induced process;

Monday, June 1, 15

TO DO/XCHECK LIST

- **Drell-Yan**
- **W+jet(s)** Openloops group arXiv:1412.5157
- **Z+jet(s)**
- **Di-jet (, 3-jets** t3/t2 to extract alphaS **)**
- **Single top**
- **tT+photon/jet** FB/charge asymmetry
- **...**

We are ready !!!

Next Step: Matching to Parton Shower ?

Complex-Mass Scheme: Concepts and Techniques

- CMS
  - A method to deal with unstable particle field in quantum field theories [A. Denner, S. Dittmaier etc]
  - Unlike unstable-particle effective field theory [M. Beneke, A. Chapovsky, A.Signer, G. Zanderighi] , the introduction of complex mass for unstable particle makes it applicable to the whole phase space directly and hence suitable for automation.
  - It reorganizes the bare Lagrangian -> same bare Lagrangian.
  - Change mass (like W, Z, top, Higgs etc) to be complex M^2->M^2-i G M (M is mass, G is width).

- CMS beyond LO
  - On-shell renormalization -> Complex renormalization

$$
\begin{aligned}
m_{cms}^2 &= M^2 - i\Gamma M,\\
m_{cms}^2 &= M_0^2 - \Sigma(m_{cms}^2),\\
\delta Z_{cms} &= -\Sigma'(p^2)|_{p^2=m_{cms}^2}.
\end{aligned}
$$

- CMS beyond LO

  - On-shell renormalization -> Complex renormalization

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BUT, is this the whole story ?

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BUT, is this the whole story ?

- Perturbation unitarity ? [Bauer, Gegelia etc; Denner, Lang]

- Relation between CMS and Narrow-Width Approximation ?

- Which level accuracy of width we need ?

- What cross-checks can we performed ?

ARCHITECTURES

- **Yes**
  - Change Mass to Complex Mass
  - Masses in one-loop integral can be complex -> ***OneLOop***, ***CutTools***, ***IREGI***, ***Golem95***, ***PJFry++***
- **No**
  - NLO width -> NLO accuracy -> ***SMWidth*** for SM
  - Extending Feynman integral/UV CTs to second RS

A CLOSER LOOK

- Dyson summation $$\frac{i}{p^2 - M_0^2 + \Sigma(p^2)}$$

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⇒ $\frac{\Gamma}{M} = \mathcal{O}(\alpha).$

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- Feynman integral:

physical region

$$p_i^2 \to p_i^2 + i\,\varepsilon\,,$$
$$s_{ij} \to s_{ij} + i\,\varepsilon\,,$$
$$m_i \to m_i - i\,\varepsilon\,.$$

non-physical region

$$p_i^2 \to p_i^2 - i\,\varepsilon\,,$$
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1st RS

$$\log\left(-\frac{p^2 + i\varepsilon}{m^2 - i\varepsilon}\right) = \log\frac{p^2}{m^2} - i\pi \qquad \log\left(-\frac{p^2 - i\varepsilon}{m^2 - i\varepsilon}\right) = \log\frac{p^2}{m^2} + i\pi$$

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1st RS $\log\left(-\frac{p^2 + i\varepsilon}{m^2 - i\varepsilon}\right) = \log\frac{p^2}{m^2} - i\pi$ $\quad \log\left(-\frac{p^2 - i\varepsilon}{m^2 - i\varepsilon}\right) = \log\frac{p^2}{m^2} + i\pi$

2nd RS $\log\left(-\frac{p^2 - i\varepsilon}{m^2 - i\varepsilon}\right) = \log\frac{p^2}{m^2} - i\pi$

- Narrow-Width Approximation:
  - XS level $\sigma(pp \to Z \to \ell^+\ell^-) = \sigma(pp \to Z)\frac{\Gamma(Z \to \ell^+\ell^-)}{\Gamma_Z^{\rm tot}}$
  - ME level $\mathcal{A}(e^+e^- \to Z \to \ell^+\ell^-) = \mathcal{A}(e^+e^- \to Z)\frac{i}{p^2 - M_Z^2}\mathcal{A}(Z \to \ell^+\ell^-)$
- Relation between CMS and Narrow-Width Approximation ?
  - Non-resonance region: CMS = NWA + higher-order effect
  - Resonance region: CMS = NWA + finite-width effect

$$\frac{1}{(p^2 - M^2)^2 + \Gamma^2 M^2} = \frac{\pi}{\Gamma M}\delta(p^2 - M^2) + \mathcal{O}(1)$$

NON-RESONANCE REGION

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- Born

$$= \mathcal{A}^{\mu}_{\rm CMS,Born,p}\left(-g_{\mu\nu} + (1-\xi)\frac{q_\mu q_\nu}{q^2-\xi M_W^2} - (1-\xi)i\frac{\xi\Gamma_W M_W}{q^2-\xi M_W^2}\frac{q_\mu q_\nu}{q^2-\xi M_W^2} + \mathcal{O}(\alpha^2)\right)\mathcal{A}^{\nu*}_{\rm CMS,Born,d}$$

$$\times\left[\frac{1}{(q^2-M_W^2)} - i\frac{\Gamma_W M_W}{(q^2-M_W^2)^2} + \mathcal{O}(\alpha^2)\right]$$

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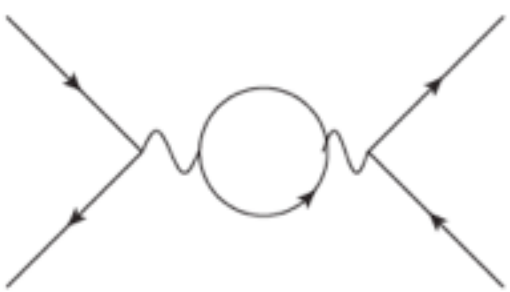
$$\times \left[\frac{1}{(q^2 - M_W^2)} - i \frac{\Gamma_W M_W}{(q^2 - M_W^2)^2} + \mathcal{O}(\alpha^2) \right]$$

- Virtual/UV



$$\sim \quad \mathcal{A}^{\mu}_{\text{CMS,Born,p}} \left(-g_{\mu\nu} \right) \mathcal{A}^{\nu}_{\text{CMS,Born,d}} \frac{i \Gamma_W M_W}{(q^2 - M_W^2)^2}$$

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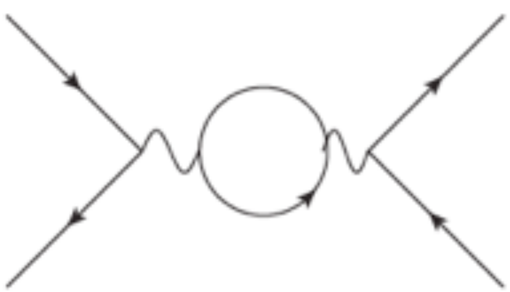

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a parameter from W propagator

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W width exp. from the imaginary part: optical theorem

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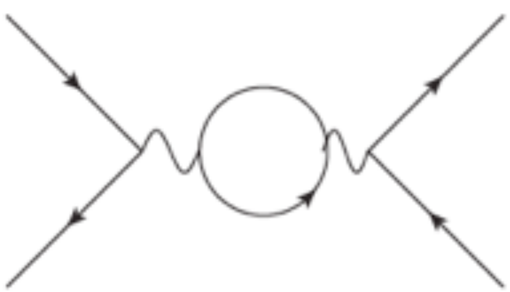

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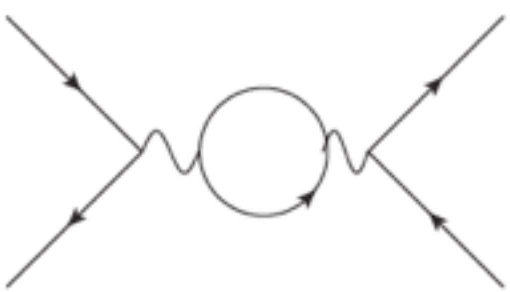

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- We need the exact (LO) width and the correct RS to guarantee it !
- It only contributes to the imaginary part. For a 2 > n (n <=2) process, this piece will cancel in ME2. -> We need trick to check a 2 > 2 process !

NON-RESONANCE REGION

- Cross-check method

  2 > n (n>=3):

$$\mathrm{CMS} = \left[2\Re\left(\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}\right) + |\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Born}}|^2 - |\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right] / \left(\alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right)$$

$$\mathrm{NWA} = 2\Re\left(\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{NWA}*}_{\mathrm{Born}}\right) / \left(\alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right),$$

$$\mathrm{diff} = (\mathrm{CMS} - \mathrm{NWA})/\alpha_{\mathrm{ew}},$$

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D.3 $e^+\nu_e \to t\bar{b} \to W^+ b\bar{b}$

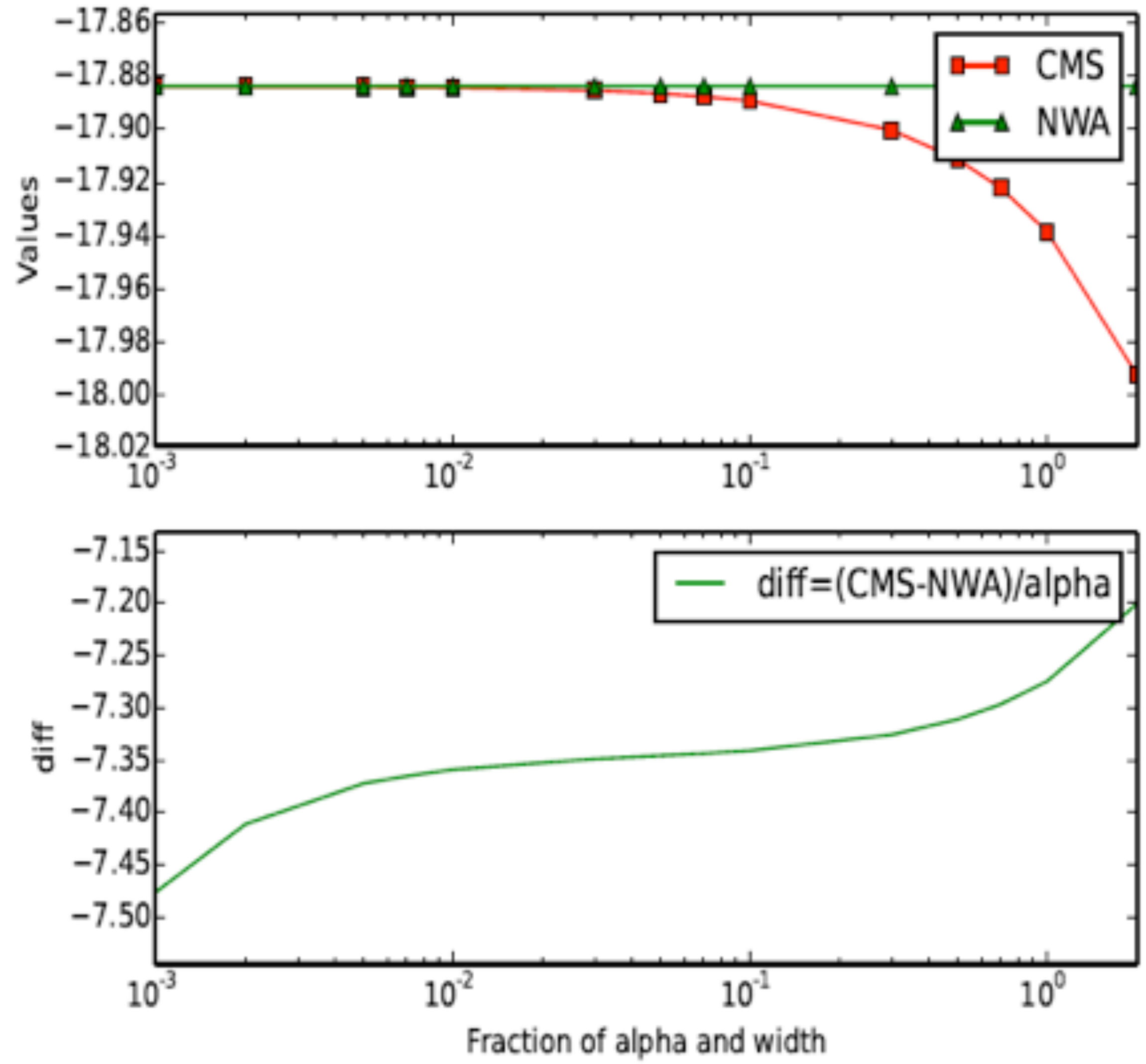

Figure 16: Cross checks for $e^+\nu_e \to t\bar{b} \to W^+ b\bar{b}$ in the non-resonance region with the correct LO width Γ_t^{LO}.

NON-RESONANCE REGION

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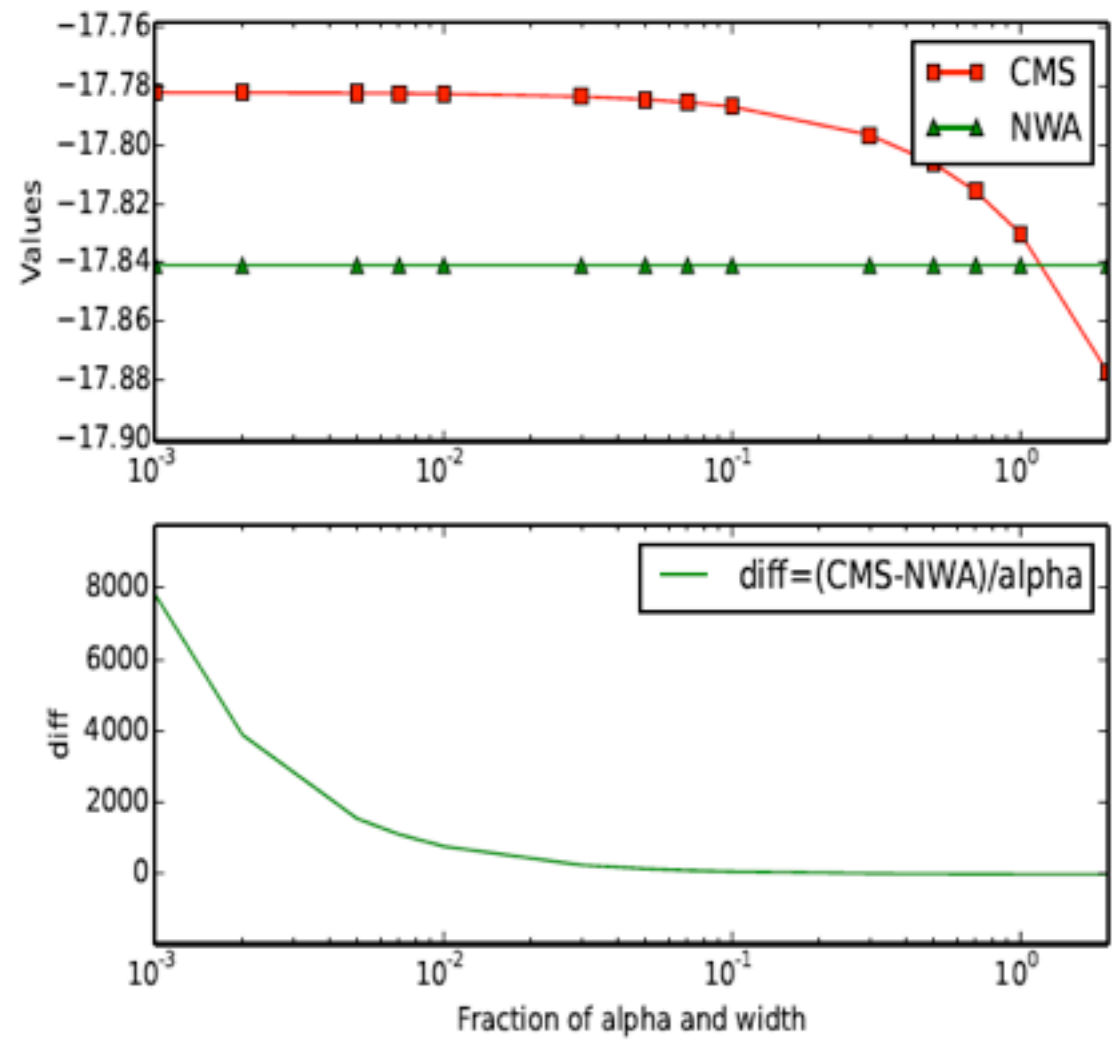

Figure 17: Cross checks for $e^+\nu_e \to t\bar{b} \to W^+ b\bar{b}$ in the non-resonance region with the wrong LO width,i.e. $\Gamma_t = 1.2\Gamma_t^{\text{LO}}$.

NON-RESONANCE REGION

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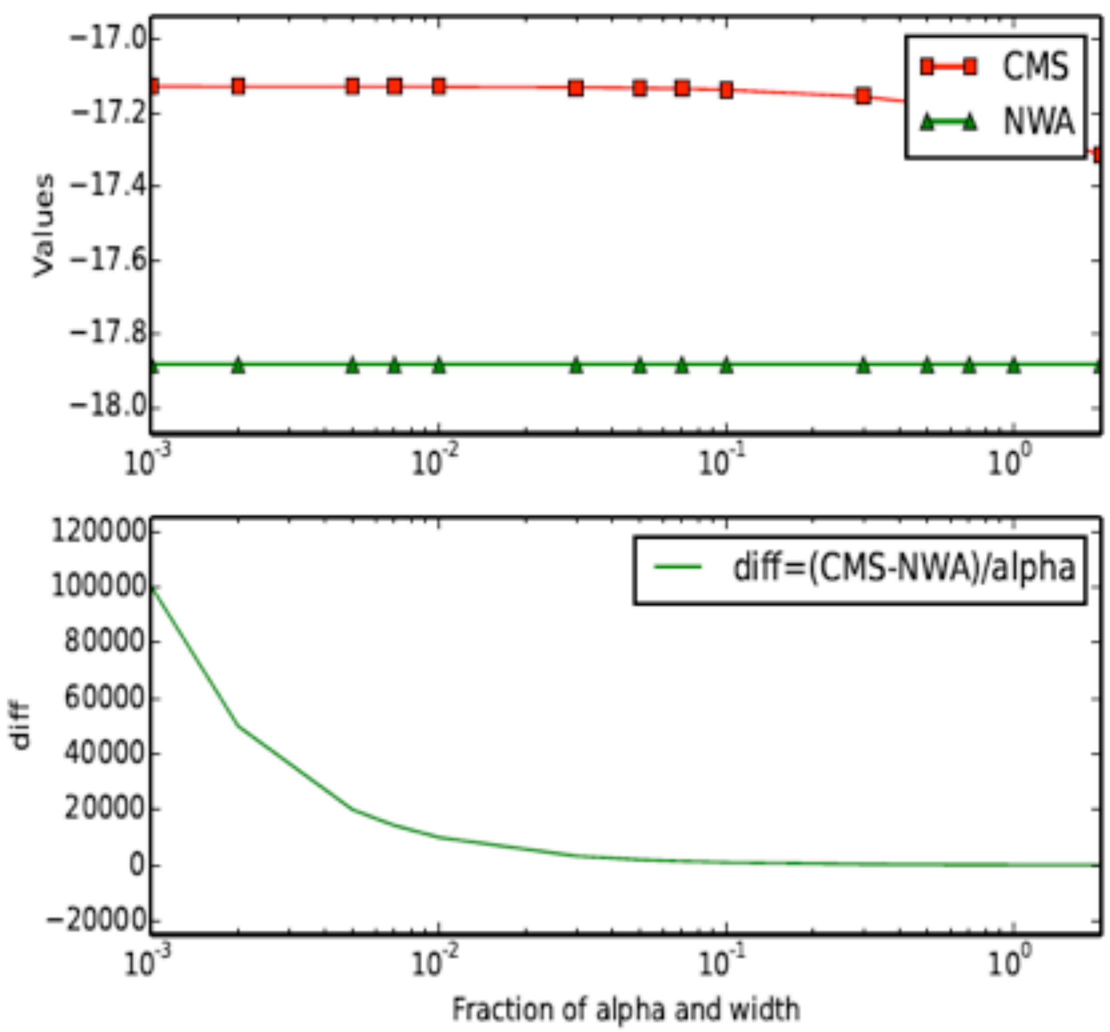

Figure 18: Cross checks for $e^+\nu_e \to t\bar{b} \to W^+b\bar{b}$ in the non-resonance region with the correct LO width but using the normal logarithms.

NON-RESONANCE REGION

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  2 > 2:

$$\begin{aligned}\mathrm{CMS} \times \alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2 &= 2\Im\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}|_{\delta Z_e=0,\delta s_w=0} \\ &+ 2\Im\mathcal{A}^{\mathrm{Born}}_{\mathrm{Virtual}}\left(\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}|_{(\Gamma_W=0 \text{ in W propagator only})}\right), \\ \mathrm{NWA} \times \alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2 &= 2\Im\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{NWA}*}_{\mathrm{Born}}, \\ \mathrm{diff} &= (\mathrm{CMS} - \mathrm{NWA})/\alpha_{\mathrm{ew}}. \end{aligned} \tag{D.2}$$

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- Cross-check method

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2 > 2:

$$\text{CMS} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{\delta Z_e}$$

$$+ 2\Im\mathcal{A}^{\text{Born}}_{\text{Virtual}}\,(\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{(\Gamma}$$

$$\text{NWA} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}},$$

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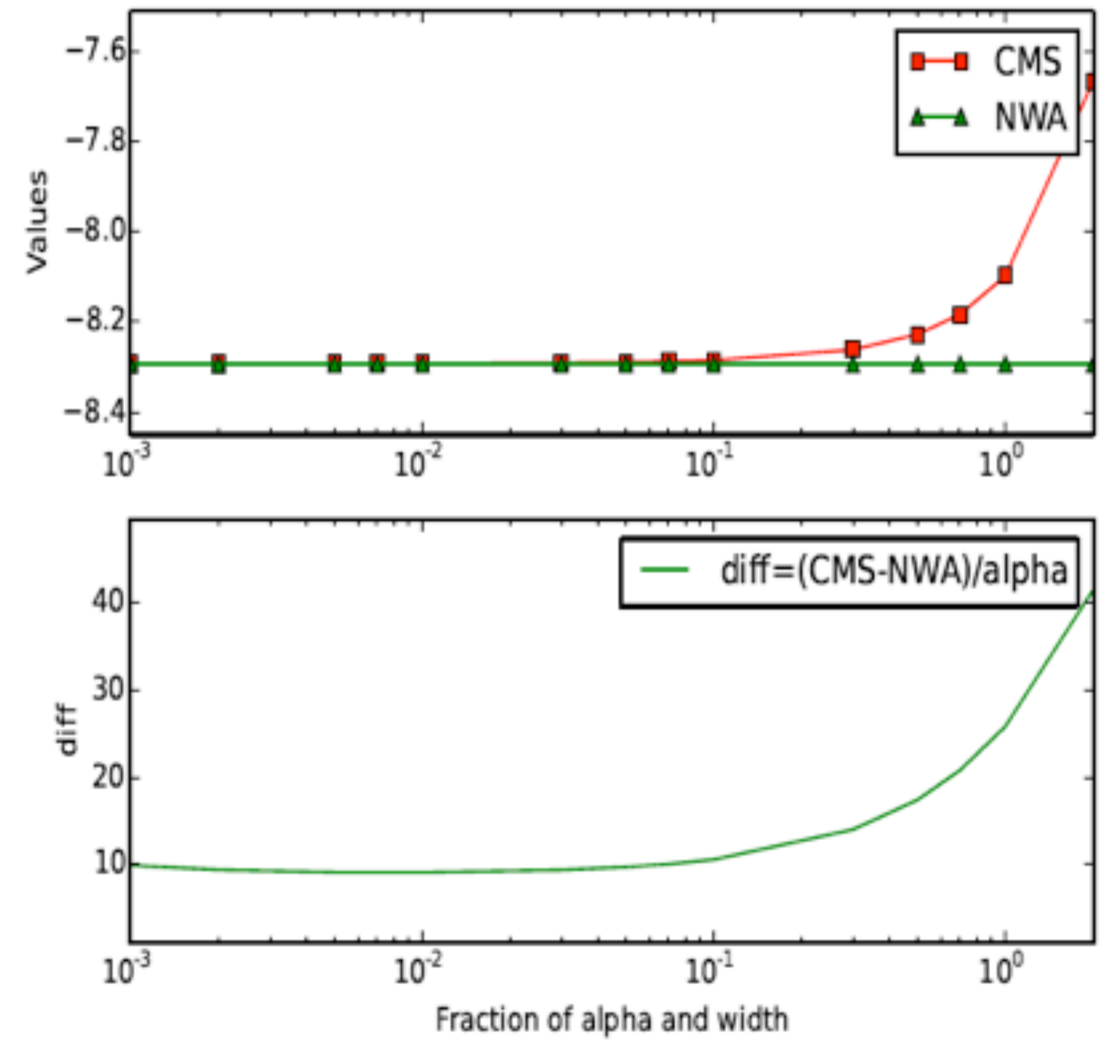

Figure 3: Cross checks for $e^+\nu_e \to W^+ \to \mu^+\nu_m$ in the non-resonance region with the correct LO width Γ^{LO}_W.

NON-RESONANCE REGION

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$$+ 2\Im\mathcal{A}^{\mathrm{Born}}_{\mathrm{Virtual}}\left(\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}|_{(\Gamma_V}\right.$$

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$$\mathrm{diff} = (\mathrm{CMS} - \mathrm{NWA})/\alpha_{\mathrm{ew}}.$$

D.1 $e^+\nu_e \to W^+ \to \mu^+\nu_m$

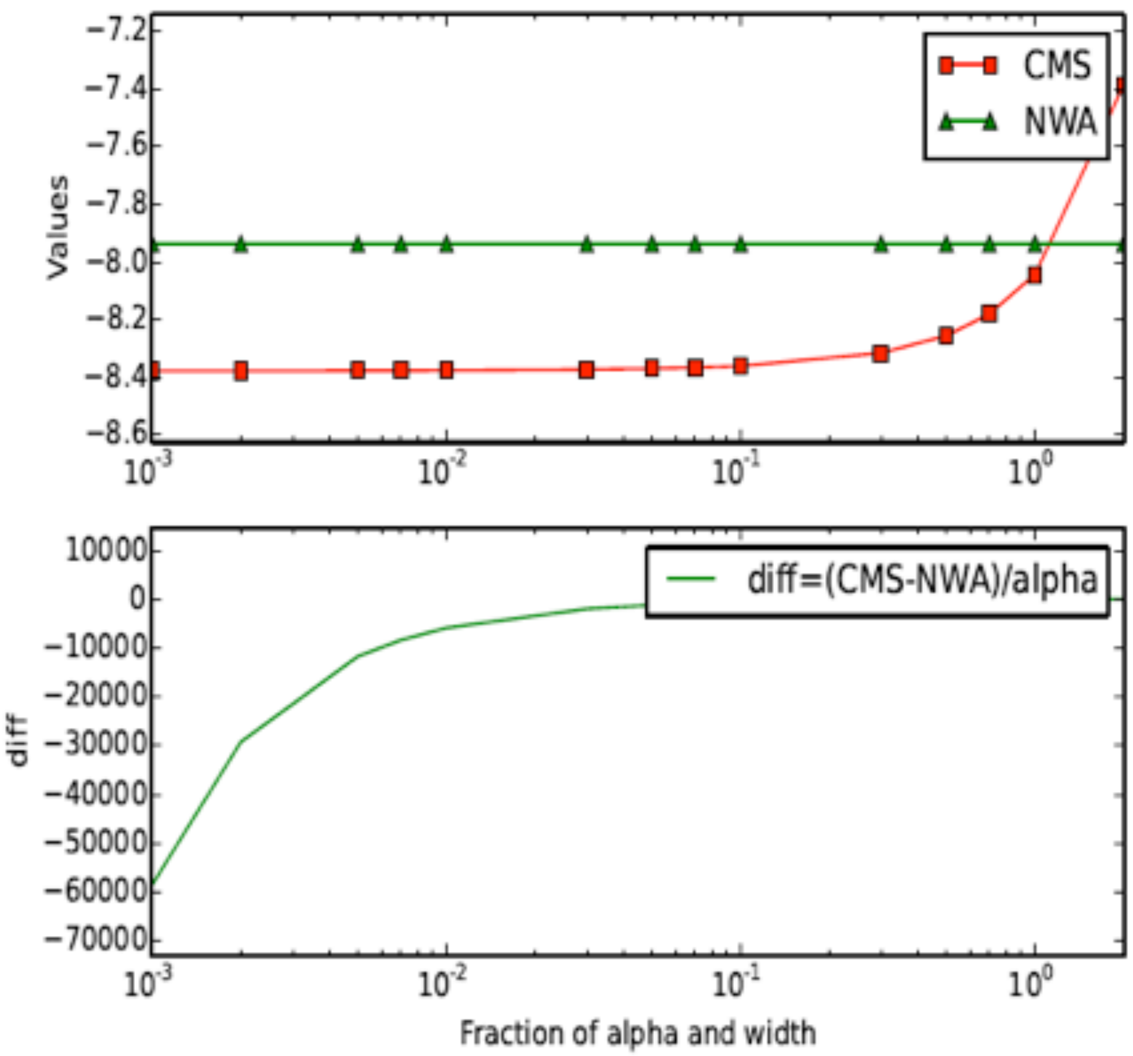

Figure 4: Cross checks for $e^+\nu_e \to W^+ \to \mu^+\nu_m$ in the non-resonance region with the wrong LO width,i.e. $\Gamma_W = 1.2\Gamma_W^{\mathrm{LO}}$.

NON-RESONANCE REGION

- Cross-check method

  2 > n (n>=3):

$$\text{CMS} = \left[2\Re\left(\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}\right) + |\mathcal{A}^{\text{CMS}}_{\text{Born}}|^2 - |\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right] / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right)$$

$$\text{NWA} = 2\Re\left(\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}\right) / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right),$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{ew}},$$

  2 > 2:

$$\text{CMS} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{\delta Z_e}$$

$$+ 2\Im\mathcal{A}^{\text{Born}}_{\text{Virtual}}\left(\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{(1}\right.$$

$$\text{NWA} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}},$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{ew}}.$$

D.1 $e^+\nu_e \to W^+ \to \mu^+\nu_m$

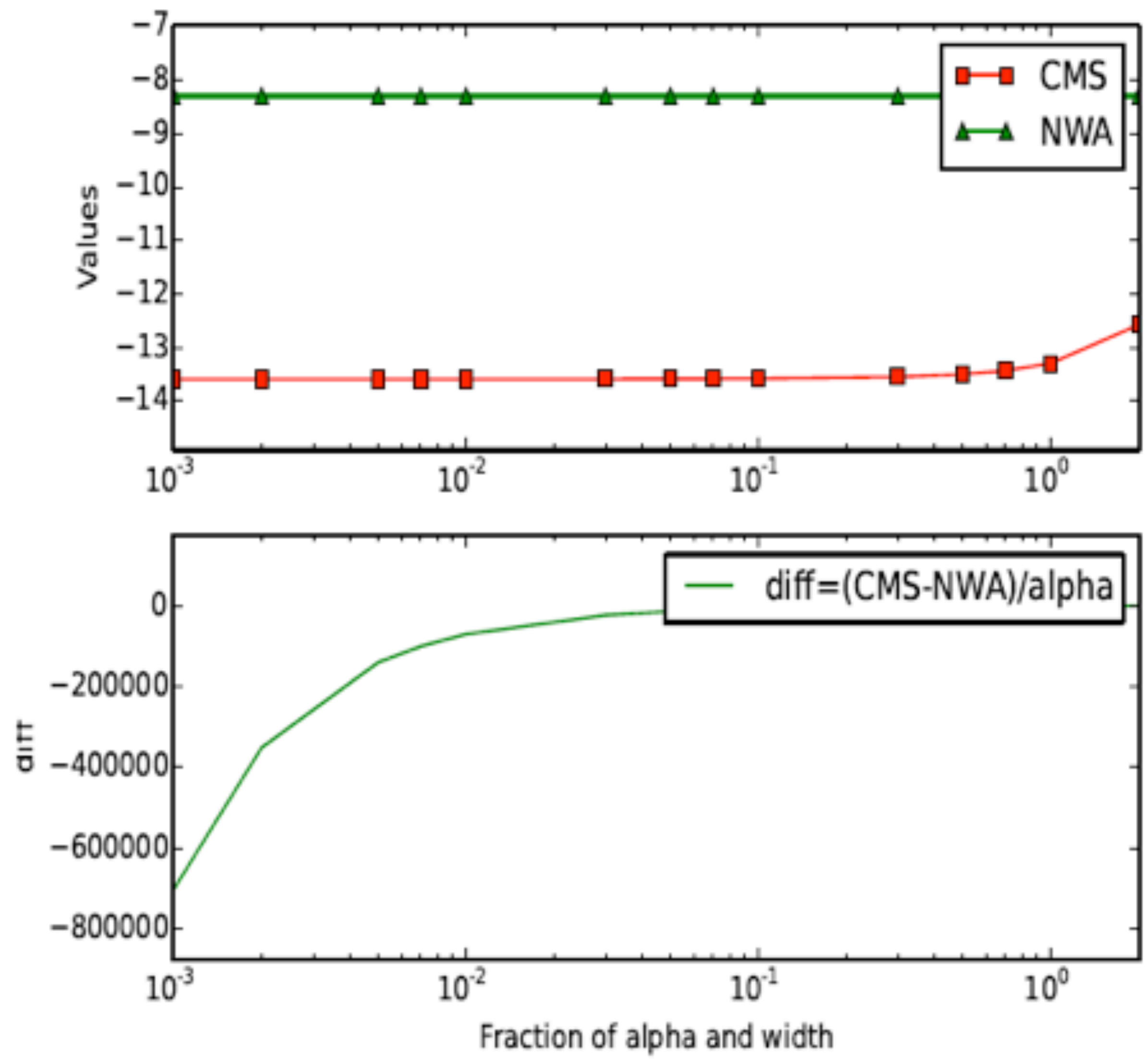

Figure 5: Cross checks for $e^+\nu_e \to W^+ \to \mu^+\nu_m$ in the non-resonance region with the correct LO width but using the normal logarithms.

NON-RESONANCE REGION

- Cross-check method

2 > n (n>=3):

$$\text{CMS} = \left[2\Re\left(\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}\right) + |\mathcal{A}^{\text{CMS}}_{\text{Born}}|^2 - |\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right] / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right)$$

$$\text{NWA} = 2\Re\left(\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}\right) / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right),$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{ew}},$$

2 > 2:

$$\text{CMS} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_\delta$$

$$+ 2\Im\mathcal{A}^{\text{Born}}_{\text{Virtual}}\left(\mathcal{A}^{\text{CMS}*}_{\text{Born}}\right.$$

$$\text{NWA} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}},$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{e}}$$

D.2 $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$

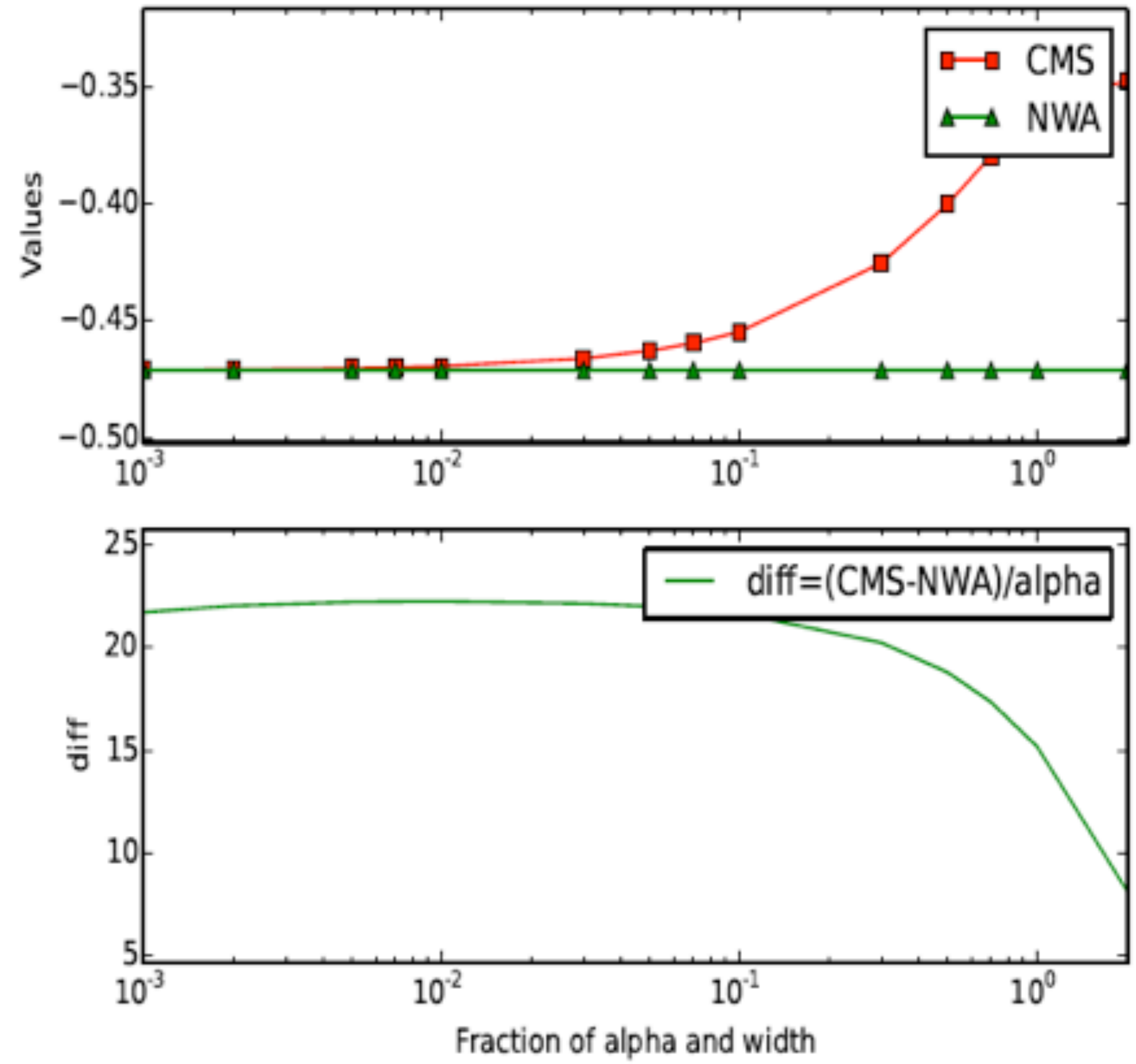

Figure 10: Cross checks for $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$ in the non-resonance region with the correct LO width Γ_Z^{LO}.

NON-RESONANCE REGION

- Cross-check method

2 > n (n>=3):

$$\text{CMS} = \left[2\Re\left(\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}\right) + |\mathcal{A}^{\text{CMS}}_{\text{Born}}|^2 - |\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right] / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right)$$

$$\text{NWA} = 2\Re\left(\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}\right) / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right),$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{ew}},$$

2 > 2:

$$\text{CMS} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}$$

$$+ 2\Im\mathcal{A}^{\text{Born}}_{\text{Virtual}}\,(\mathcal{A}^{\text{CMS}}_{\text{Born}}$$

$$\text{NWA} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 = 2\Im\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha$$

D.2 $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$

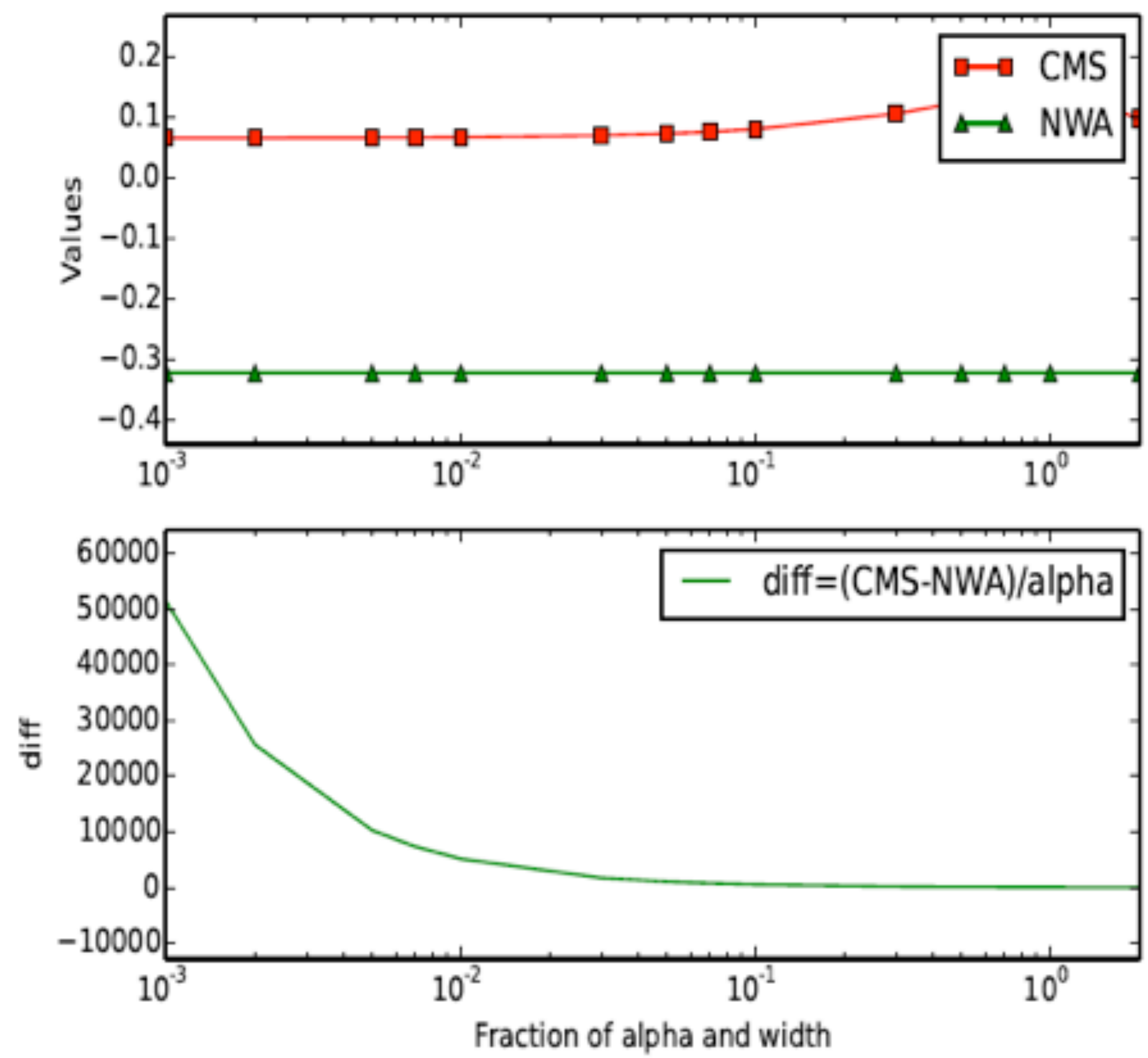

Figure 11: Cross checks for $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$ in the non-resonance region with the wrong LO width,i.e. $\Gamma_Z = 1.2\Gamma_Z^{\text{LO}}$.

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NON-RESONANCE REGION

- Cross-check method

2 > n (n>=3):

$$\mathrm{CMS} = \left[2\Re(\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}) + |\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Born}}|^2 - |\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right] / \left(\alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right)$$

$$\mathrm{NWA} = 2\Re(\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{NWA}*}_{\mathrm{Born}}) / \left(\alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2\right),$$

$$\mathrm{diff} = (\mathrm{CMS} - \mathrm{NWA})/\alpha_{\mathrm{ew}},$$

2 > 2:

$$\mathrm{CMS} \times \alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2 = 2\Im\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{CMS}*}_{\mathrm{Born}}|$$

$$+ 2\Im\mathcal{A}^{\mathrm{Born}}_{\mathrm{Virtual}}(\mathcal{A}^{\mathrm{CMS}}_{\mathrm{Born}}$$

$$\mathrm{NWA} \times \alpha_{\mathrm{ew}}|\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Born}}|^2 = 2\Im\mathcal{A}^{\mathrm{NWA}}_{\mathrm{Virtual}}\mathcal{A}^{\mathrm{NWA}*}_{\mathrm{Born}}$$

$$\mathrm{diff} = (\mathrm{CMS} - \mathrm{NWA})/\alpha$$

D.2 $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$

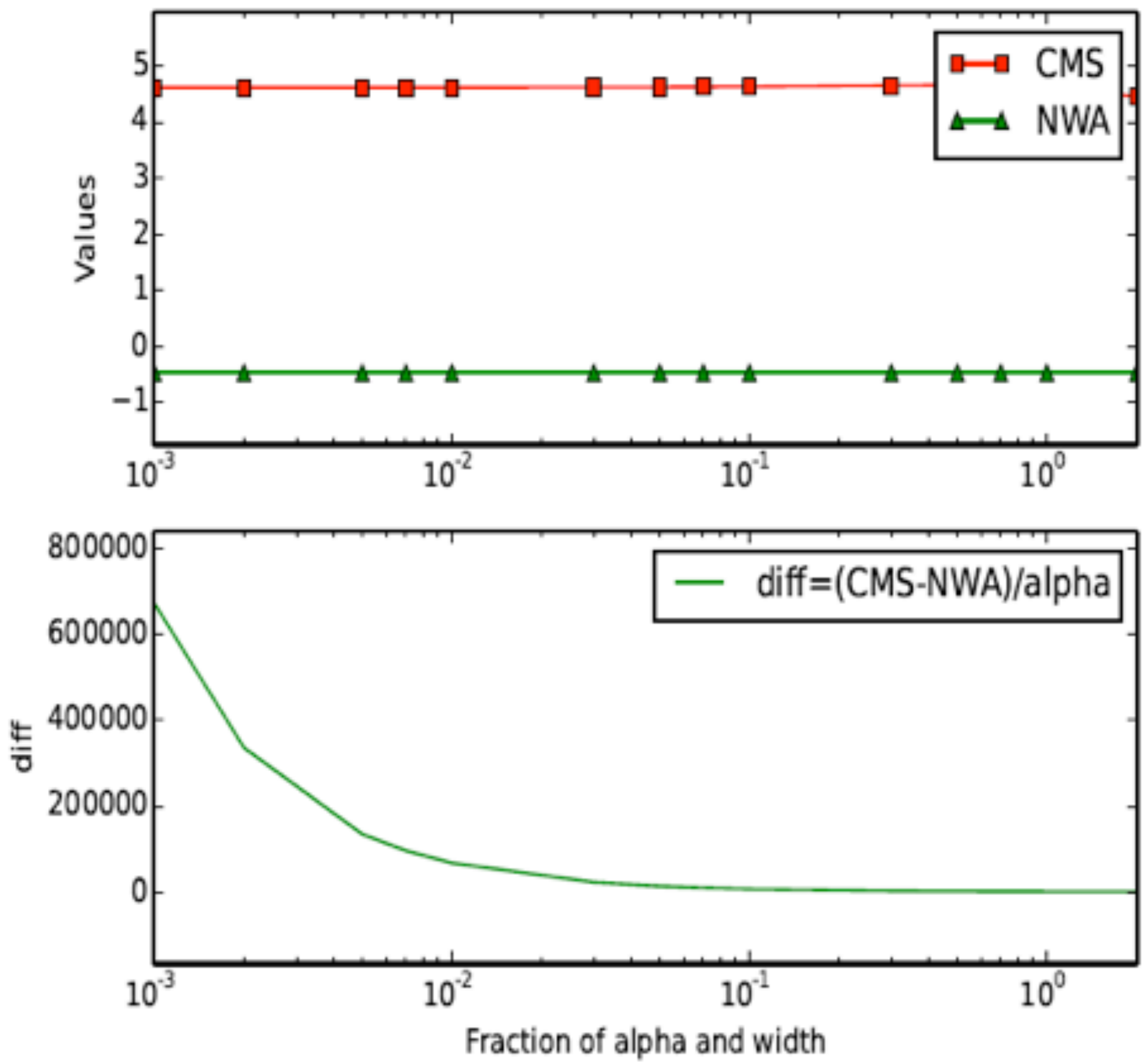

Figure 12: Cross checks for $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$ in the non-resonance region with the correct LO width but using the normal logarithms.

NON-RESONANCE REGION

- Cross-check method

  2 > n (n>=3):

$$\text{CMS} = \left[2\Re\left(\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}\right) + |\mathcal{A}^{\text{CMS}}_{\text{Born}}|^2 - |\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right] / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right)$$

$$\text{NWA} = 2\Re\left(\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}\right) / \left(\alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2\right),$$

$$\text{diff} = (\text{CMS} - \text{NWA})/\alpha_{\text{ew}},$$

  2 > 2:

$$\begin{aligned} \text{CMS} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 &= 2\Im\mathcal{A}^{\text{CMS}}_{\text{Virtual}}\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{\delta Z_e=0,\delta s_w=0} \\ &+ 2\Im\mathcal{A}^{\text{Born}}_{\text{Virtual}}\left(\mathcal{A}^{\text{CMS}*}_{\text{Born}}|_{(\Gamma_W=0 \text{ in W propagator only})}\right), \\ \text{NWA} \times \alpha_{\text{ew}}|\mathcal{A}^{\text{NWA}}_{\text{Born}}|^2 &= 2\Im\mathcal{A}^{\text{NWA}}_{\text{Virtual}}\mathcal{A}^{\text{NWA}*}_{\text{Born}}, \\ \text{diff} &= (\text{CMS} - \text{NWA})/\alpha_{\text{ew}}. \end{aligned} \tag{D.2}$$

RESONANCE REGION

- NLO accuracy in this region -> NLO accuracy width

$$\frac{1}{p^2 - M^2 + i\Gamma M} \rightarrow \frac{1}{i\Gamma M}$$

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    - XS level: difficult because of the spin correlation. Easier for a scalar resonance.
    - ME level: give a slight offshellness to avoid infinity in NWA. We have also cross checked in this region though it is much tricky:

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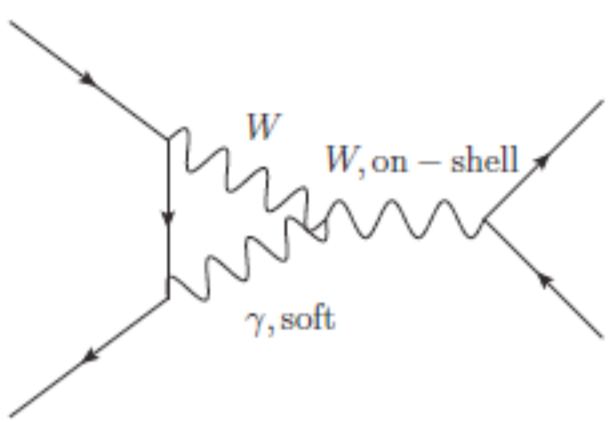

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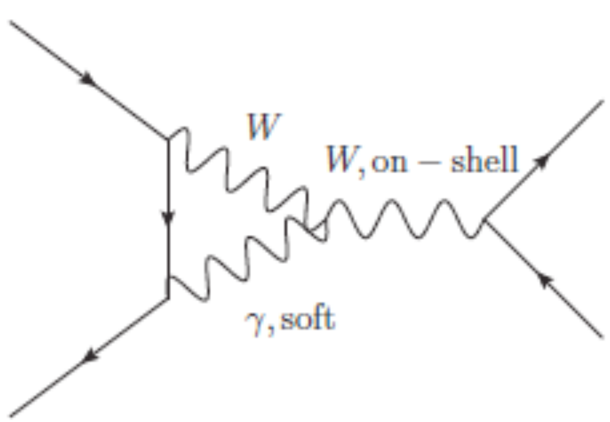

NWA: $\log \varepsilon$

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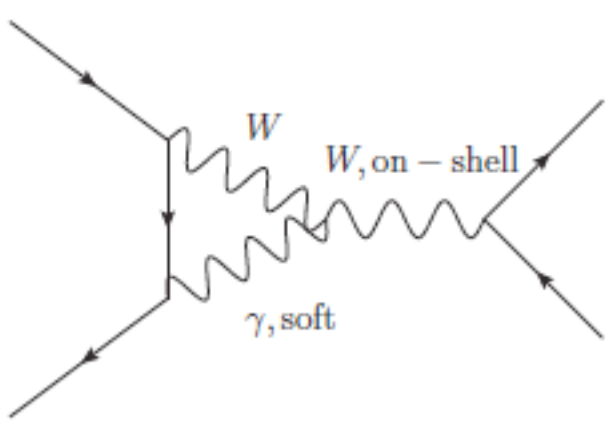

NWA: $\log \varepsilon$

CMS: $\log \Gamma_W$

RESONANCE REGION

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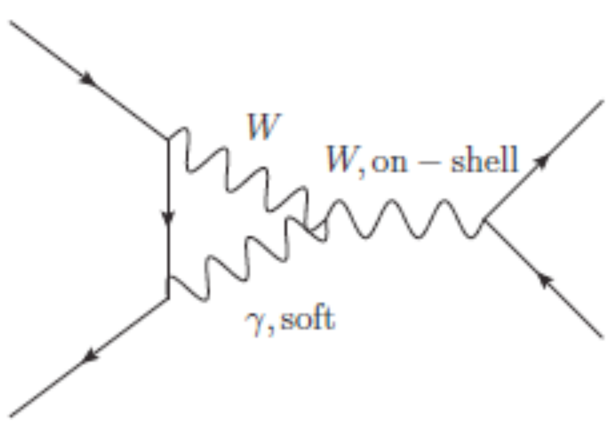

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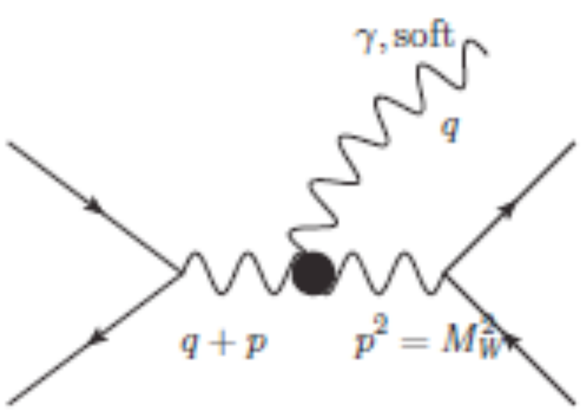
CMS: $\log \Gamma_W$



WIDTH

- Do we have to calculate the NLO-level top quark width with W decay ?
  - Not necessary !
  - NLO-level t > W+b in NWA
  - Finite width effect from lower-order diagrams (i.e. Born diagrams at NLO)

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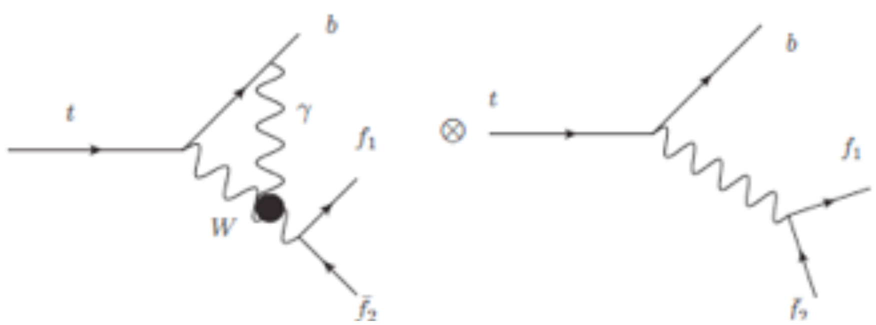

$$\frac{C_0(0,m_t^2,M_W^2,0,0,M_W^2-i\Gamma_W M_W)-C_0(0,m_t^2,M_W^2,0,0,M_W^2)}{i\pi^{2-\epsilon}\Gamma(1-\epsilon)^2\Gamma(1+\epsilon)\Gamma(1-2\epsilon)^{-1}}$$
$$=-\frac{1}{2(m_t^2-M_W^2)}\frac{1}{\epsilon_{\rm IR}^2}+\frac{1}{2(m_t^2-M_W^2)}\log\left(-\frac{\Gamma_W^2}{\mu^2}\right)\frac{1}{\epsilon_{\rm IR}}$$
$$+\frac{1}{2(m_t^2-M_W^2)}\left(-\frac{\pi^2}{2}-\frac{1}{2}\log^2\left(-\frac{\Gamma_W^2}{\mu^2}\right)\right).$$

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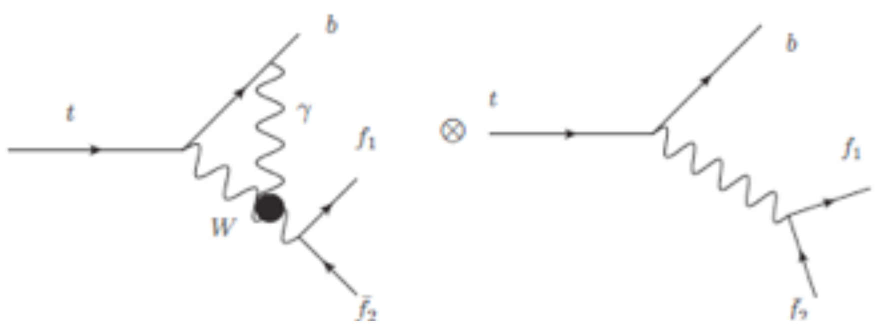

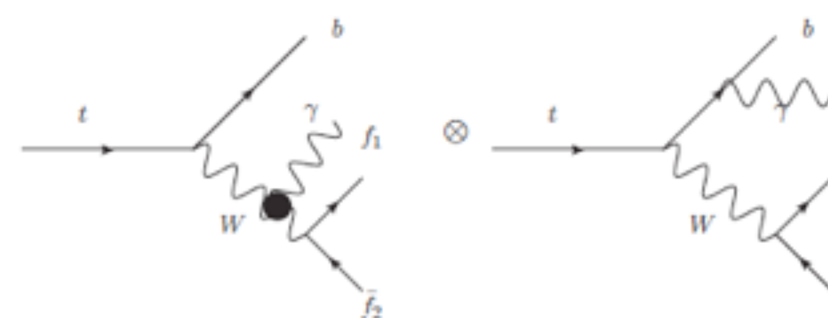

$$\frac{C_0(0,m_t^2,M_W^2,0,0,M_W^2-i\Gamma_W M_W)-C_0(0,m_t^2,M_W^2,0,0,M_W^2)}{i\pi^{2-\epsilon}\Gamma(1-\epsilon)^2\Gamma(1+\epsilon)\Gamma(1-2\epsilon)^{-1}}$$
$$= -\frac{1}{2(m_t^2-M_W^2)}\frac{1}{\epsilon_{\rm IR}^2}+\frac{1}{2(m_t^2-M_W^2)}\log\left(-\frac{\Gamma_W^2}{\mu^2}\right)\frac{1}{\epsilon_{\rm IR}}$$
$$+\frac{1}{2(m_t^2-M_W^2)}\left(-\frac{\pi^2}{2}-\frac{1}{2}\log^2\left(-\frac{\Gamma_W^2}{\mu^2}\right)\right).$$

$$\frac{\mathrm{Real}^{\pm}(\Gamma_W)-\mathrm{Real}^{\pm}(0)}{i\pi^{2-\epsilon}\Gamma(1-\epsilon)^2\Gamma(1+\epsilon)\Gamma(1-2\epsilon)^{-1}} \tag{3.100}$$
$$=\left(-\frac{1}{\epsilon_{\rm IR}}+\frac{\pi^2\epsilon}{6}\right)\times\left(-\frac{1}{2(m_t^2-M_W^2)}\frac{1}{\epsilon_{\rm IR}}+\frac{1}{2(m_t^2-M_W^2)}\log\left(-\frac{\Gamma_W^2}{\mu^2}\right)-\epsilon\frac{\frac{\pi^2}{3}+\frac{\log^2\left(-\frac{\Gamma_W^2}{\mu^2}\right)}{4}}{m_t^2-M_W^2}\right).$$

WIDTH

$$
\begin{aligned}
\Gamma_W &= \Gamma_W^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}\right),\\
\Gamma_Z &= \Gamma_Z^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}\right),\\
\Gamma_t &= \Gamma_t^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}+\delta_{\Gamma_W}\right).
\end{aligned}
\tag{5.1}
$$

	$\Gamma^{\rm LO}$ [GeV]	δ_{α_S} (%)	δ_α (%)	δ_{m_f} (%)	δ_{Γ_W} (%)
$W^\pm$	2.10490	2.55	−3.51	−0.0238	-
Z	2.51376	2.61	−3.34	−0.0374	-
t	1.54624	−8.58	−1.41	−0.239	−1.58

Table 1: The widths calculated by SMWidth in $\alpha(M_Z)$ renormalization scheme.

	$\Gamma^{\rm LO}$ [GeV]	δ_{α_S} (%)	δ_α (%)	δ_{m_f} (%)	δ_{Γ_W} (%)
$W^\pm$	2.04808	2.55	−0.364	−0.0238	-
Z	2.44591	2.61	−0.197	−0.0374	-
t	1.50450	−8.58	1.68	−0.239	−1.54

Table 2: The widths calculated by SMWidth in G_μ renormalization scheme.

WIDTH

$$\Gamma_W = \Gamma_W^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}\right),$$
$$\Gamma_Z = \Gamma_Z^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}\right),$$
$$\Gamma_t = \Gamma_t^{\rm LO}\left(1+\delta_{\alpha_S}+\delta_\alpha+\delta_{m_f}+\delta_{\Gamma_W}\right). \quad (5.1)$$

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EW OVERVIEW

	Yes	No
MadLoop	*EW corrections to any SM process w or w/o b mass in two schemes; Order splitting in mixed order case; Decay processes; Complex-Mass Scheme;*	*??*
MadFKS	*FKS QED subtraction; Order splitting in mixed order case; Scale and PDF uncer.; MC over helicity;*	*Virtual Trick; Quasi-collinear subtraction; On-shell subtraction; More cross check (tT,tTV);*