Chapter 3: ϕ_η^* observable for Higgs production

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A Higgstools collaboration

Outline

Chapter Overview

→ Chapter Overseer: Nigel

- Chapters 1,2,5,6: ϕ_η^* in the Standard Model

  → Stephen (theory: one massive loop in the SM, heavy top limit)

  → Hjalte (theory: two loops in the SM)

  → Juan (pheno: higher orders in EFT)

- Chapters 3,4: Experimental study of ϕ_η^*

  → Theo ($H \to \tau\tau$)

  → Yacine ($H \to \gamma\gamma$)

- Chapters 7,8: ϕ_η^* Beyond Standard Model

  → Shruti (review p_T^H distributions in the MSSM)

  → Matias (compare p_T^H and ϕ_η^* in the MSSM)

The search for new observables: $Z \to \ell^+\ell^-$

- Already in Tevatron, measurements of the transverse momentum of the Z boson (p_t^Z) were limited by event selection and lepton energy resolution rather than event statistics.
- In particular, at low p_t^Z, bin sizes were limited by energy resolution on the leptons after unfolding.

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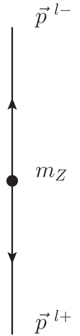


$$p_T^{\ell^\pm} \sim \frac{m_Z}{2}$$

$$\vec{p}_T^{\,Z} = \vec{p}_T^{\,\ell^-} + \vec{p}_T^{\,\ell^+}$$

$$\delta p_T^Z \sim \sqrt{2}(\delta p_T^{\ell^\pm})$$

this will be true even when $p_T^Z << p_T^{\ell^-}$

Definition of ϕ^*_η

- New observables were proposed to bypass these systematic uncertainties while accessing the same physics as p_t^Z like a_T^Z or ϕ^*_η
- The ϕ^*_η observable was proposed (hep-ex/1009.1580[1]). This observable corresponds to the transverse momentum at very low p_T through a trivial relations.
- We are looking for an observable independent on the energy of the final states that allow us to probe the same physics as the transverse momentum
- ϕ^*_η , depending only on the direction of the two final state leptons allows us to access the physics in the low p_t^Z regime while being independent of the energy of the leptons.

[1] Banfi A., Redford S., Vesterinen M., Waller P., Wyatt T.R.

Definition of ϕ^*_η

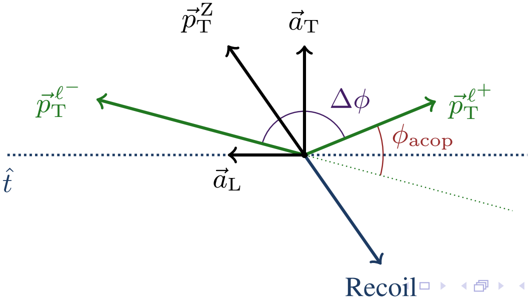
ϕ^*_η is defined by:

$$\phi^*_\eta \equiv \tan\left(\frac{\phi_{\text{acop}}}{2}\right)\sin(\theta^*_\eta).$$

The acoplanarity angle (ϕ_{acop}) is given by the azimuthal angle between the two leptons ($\Delta\phi$) as:

$$\phi_{\text{acop}} \equiv \pi - \Delta\phi,$$

Graphically, in the plane transverse to the beam direction:



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Whereas θ^*_η :

$$\cos(\theta^*_\eta) \equiv \tanh\left(\frac{\eta^{\ell^-} - \eta^{\ell^+}}{2}\right)$$

θ^*_η is the scattering angle of the leptons with respect to the proton beam in a reference frame boosted along the beam direction such that the two leptons are back to back.

Definition of ϕ^*_η

ϕ^*_η is defined by:

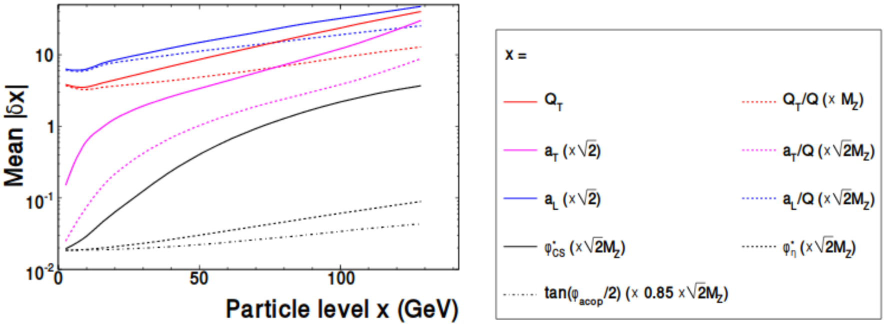
$$\phi^*_\eta \equiv \tan\left(\frac{\phi_{\text{acop}}}{2}\right)\sin(\theta^*_\eta).$$

- ϕ^*_η will vanish at Born level (Z plus no jet production), as p_T^Z goes to 0 and azimuthal angle between the two leptons tends to π ($\phi_{acop} = 0$). Therefore, ϕ^*_η measures deviations from "back-to-backness" of the two leptons.
- Ie, any deviations from $\phi^*_\eta = 0$ will be generated by the same mechanisms that generate a finite p_T^Z.

Experimentally

We can illustrate the improvement by showing the mean resolution of several observables in experimental measurements. Plots taken from hep-ex/1009.1580[2]).

Tracker



[2] Banfi A., Redford S., Vesterinen M., Waller P., Wyatt T.R.

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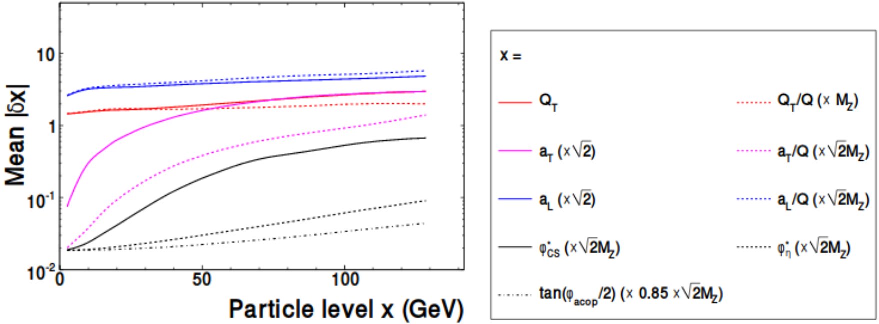
Calorimeter:



[2] Banfi A., Redford S., Vesterinen M., Waller P., Wyatt T.R.

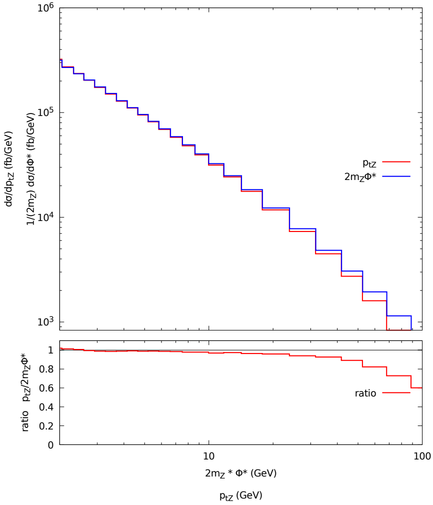
p_T and ϕ^*_η relationship

In the small p_T (and ϕ^*_η) region, we can approximate the value of ϕ^*_η as:

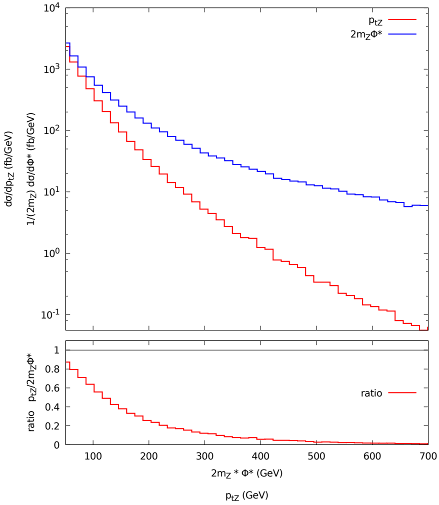
$$\phi^*_\eta \approx \frac{p_T}{2m_{\ell^-\ell^+}} \tag{1}$$

Let us see what's the actual range of application of this approximation and when does it start to break down.

p_T^Z and ϕ_η^* relationship

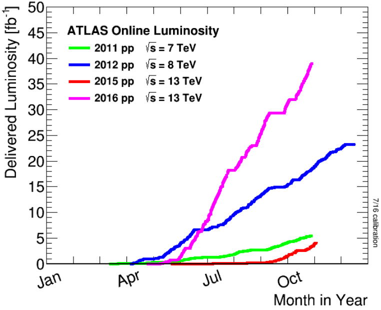


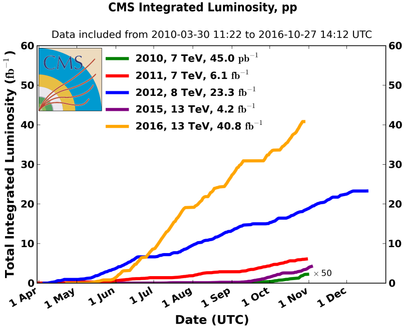
Low p_T^Z regime



Moderate to high p_T^Z regime

Extension to H production



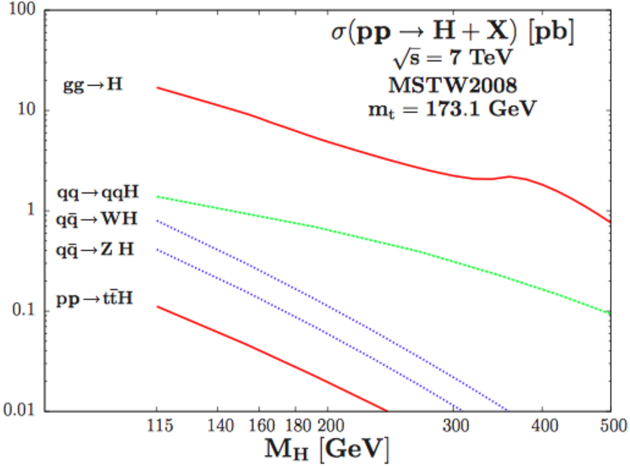


Source: ATLAS/CMS twiki pages

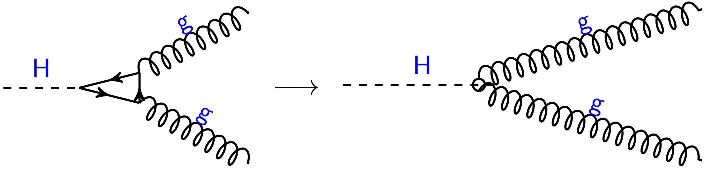
The LHC will provide enough statistics for Higgs production so that energy resolution could again become more relevant that event statistics.

Higgs Effective Theory

Even though the Higgs boson does not couple directly to gluon, due to the nature of protons, in the LHC gluon fusion is the dominant channel for Higgs production (through a massive quark loop).



Higgs Effective Theory



With an effective lagrangian such as:

$$\mathcal{L} \propto \lambda H G^{\mu\nu} G_{\mu\nu},$$

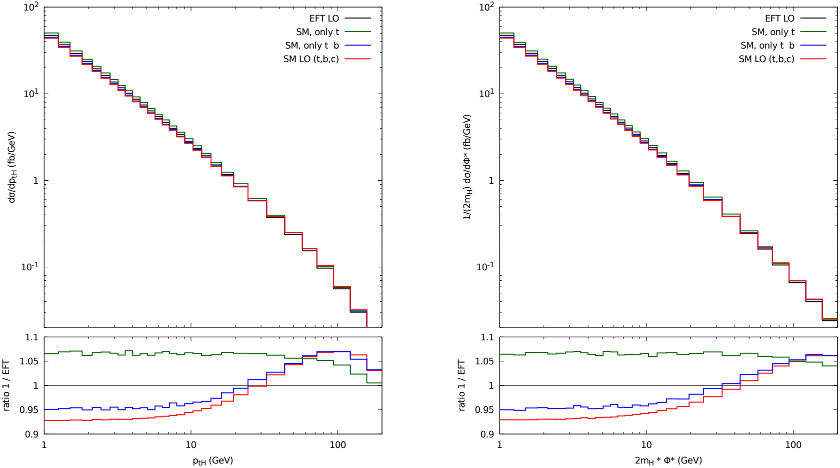
with $\lambda = \frac{\sqrt{G_F\sqrt{2}}}{6\pi}\alpha_s$.
Retaining top mass effect we find (at LO): $\mathcal{M}^2 \propto G_F \alpha_s m_H^4 \mid I(\frac{m_t^2}{m_H^2}) \mid^2$
where $I(x) \simeq 1 + \frac{1}{4x}$.

Higgs Effective Theory

- This approximation holds quite well at low p_T^H
- As the bulk of the cross section is concentrated at low p_T^H , it also yields a good approximation (5%) of the inclusive cross section.
- However, it performs quite badly as p_T^H grows.

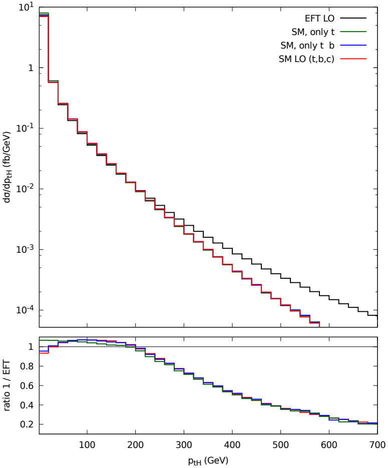
Let us see this explicitly:

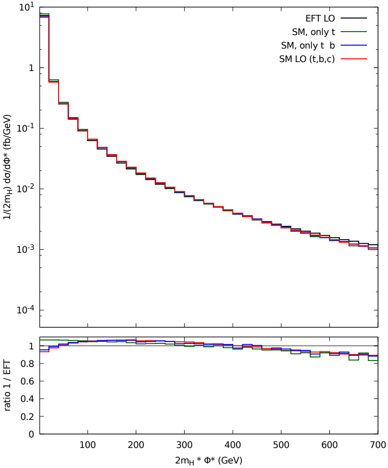
Low p_T^H (ϕ^*_η) regime



At low p_T^H the EFT approach works quite well for both distributions
Including the mass of the quarks running in the gg to H loop yields a small correction, which depends on the quarks included.

Moderate to high p_T^H (ϕ_η^*) regime

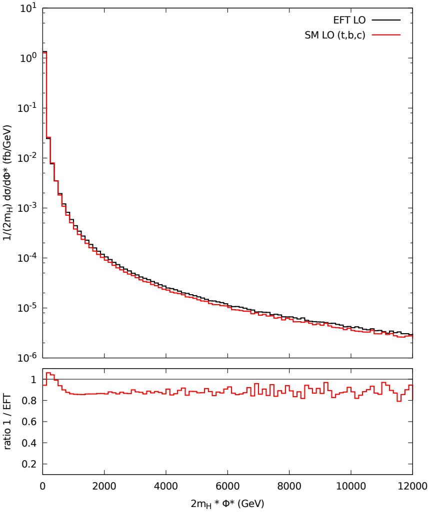




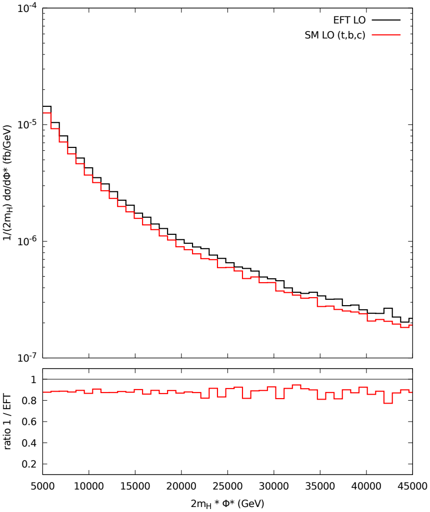
The p_T^H distribution for the Effective Theory quickly becomes an unreliable estimate

ϕ_η^* remains stable even at very high ϕ_η^*

High ϕ^*_η regime



(very) High ϕ^*_η regime



Different approaches in order to capture the effect of the massive loop

- Higher order corrections for p_T^H are not available yet for the Standard Model with finite quark masses.

$\rightarrow$ We need to use the Effective Field Theory approach.

$\rightarrow$ We need a way to estimate the associated uncertainty.

$EFT \otimes M$

For the inclusive cross section (σ) it has been observed we can account for the corrections due to quark running in the loop multiplying the higher order inclusive EFT cross section by:

$$R = \frac{\sigma^{M}_{LO}}{\sigma^{EFT}_{LO}}$$

We can extend this same approach to non inclusive quantities so for any observable $\mathcal{O}(\phi^*_\eta\ ,\ p_T^H\ )$ we can perform the same reweighting bin-by-bin.

$$R(\mathcal{O}) = \left(\frac{d\sigma^{M}_{LO}}{d\mathcal{O}}\right) / \left(\frac{d\sigma^{EFT}_{LO}}{d\mathcal{O}}\right)$$

$$\frac{d\sigma^{EFT \otimes M}_{NNLO}}{d\mathcal{O}} = R(\mathcal{O}) * \frac{d\sigma^{EFT}_{NNLO}}{d\mathcal{O}}$$

$EFT \oplus M$

Since at Leading Order we know the complete result for the Standard Model with finite quark masses for Higgs plus jet production, we can do the following:

$$\frac{d\sigma^{EFT\otimes M}_{NNLO}}{d\mathcal{O}} = \frac{d\sigma^{EFT}_{NNLO}}{d\mathcal{O}} + (R(d\mathcal{O}) - 1)\frac{d\sigma^{EFT}_{LO}}{d\mathcal{O}}$$

We can use these two approaches, $EFT \otimes M$ and $EFT \oplus M$, in order to estimate our lack of knowledge about the process.

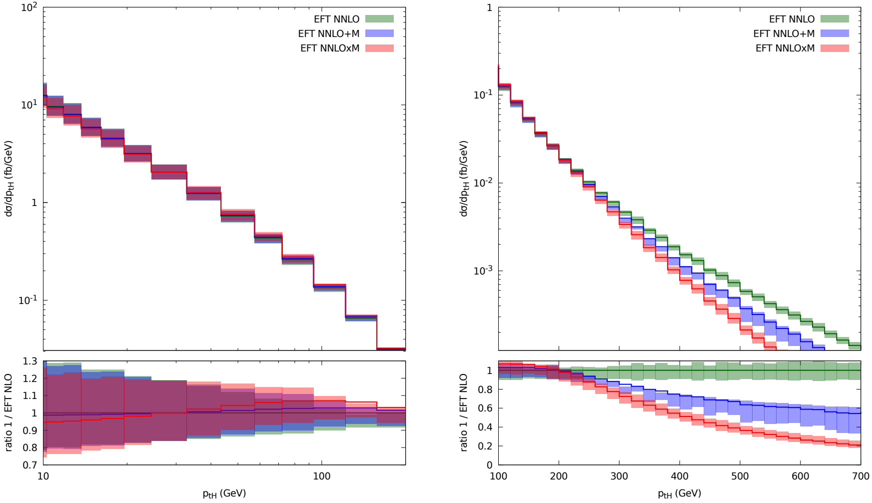
Comparisons of $EFT \otimes M$ and $EFT \oplus M$ for p_T^H

In order to compare the results of the EFT at NNLO we use the following factorisation and renormalisation scales in order to estimate the associated uncertainty:

$$\mu_F = \mu_R = [0.25, 0.5, 1] * \sqrt{(p_T^H)^2 + m_H^2}$$

- We are interested on whether the difference between these approaches is actually bigger than the scale uncertainty.

Comparisons of $EFT \otimes M$ and $EFT \oplus M$ for p_T^H



Comparisons of $EFT \otimes M$ and $EFT \oplus M$ for p_T^H

- As expected, at low p_T^H all approaches yield comparable results
- At high p_T^H , however, the difference between them is greater than the scale uncertainty
- This suggest our knowledge about the process is not enough to provide predictions for the p_T^H distribution at high p_T^H .

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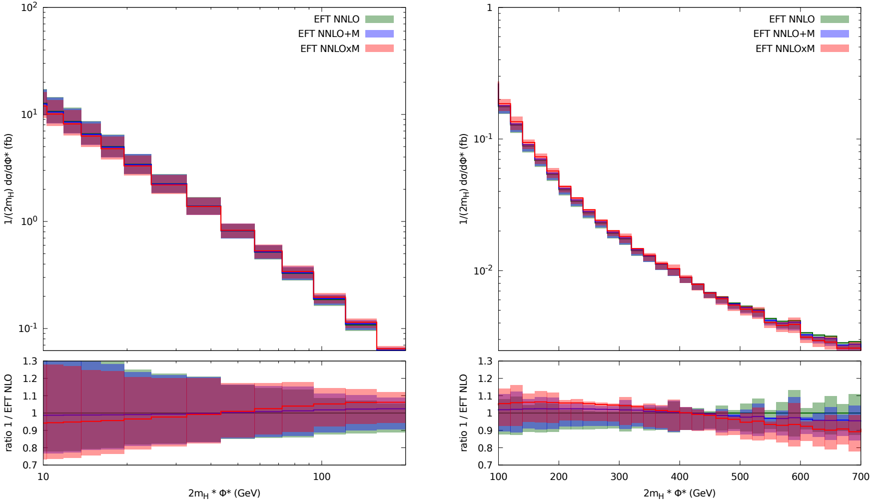
And if we look at the ϕ_η^* distribution:

Comparisons of $EFT \otimes M$ and $EFT \oplus M$ for ϕ^*_η



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And if we look at the ϕ_η^* distribution:
It offer us a more reliably way of modelling Higgs processes in the EFT, as the effects of the loop are smeared over the distribution.

Conclusions

- We see that ϕ^*_η offer us a new observable, effectively doubling our available statistics.

To come:

Conclusions

- We see that ϕ_η^* offer us a new observable, effectively doubling our available statistics.

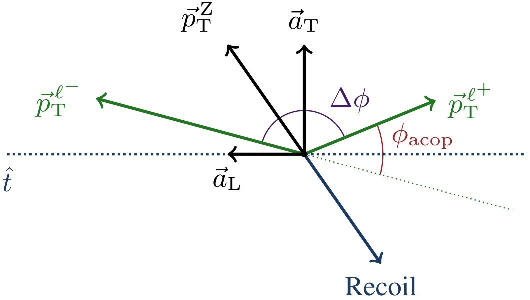
To come:

→ ϕ_η^* in the context of BSM physics

→ More on ϕ_η^* in experimental settings

Thanks!

The thrust axis



$$\hat{t} = \frac{\left(\vec{p}_T^{\ell-} - \vec{p}_T^{\ell+}\right)}{|\vec{p}_T^{\ell-} - \vec{p}_T^{\ell+}|}, \tag{2}$$