Top mass effects in gluon fusion processes

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IPPP, Durham University

Ramona Gröber, AM, Thomas Rauh arXiv:1709.07799
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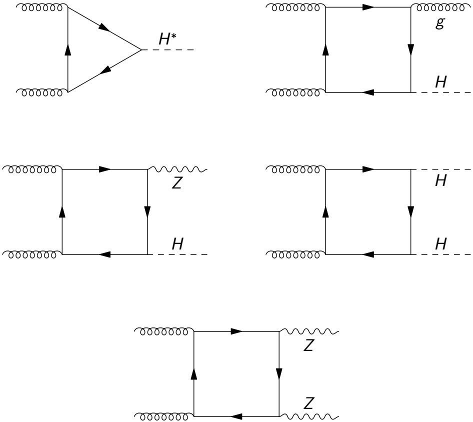
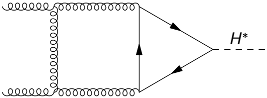
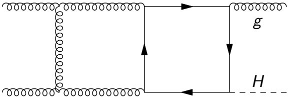
Gluon fusion processes at LO



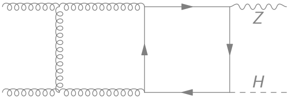
Gluon fusion processes at NLO

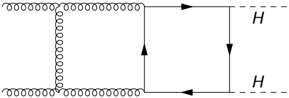


[Spira, Djouadi, Graudenz, Zerwas 1995; . . .]

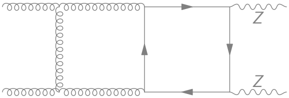


[Jones, Kerner, Luisoni 2018]



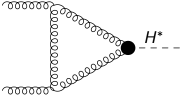


[Borowka et al. 2016]

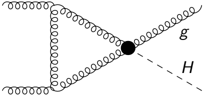


Gluon fusion processes at NLO

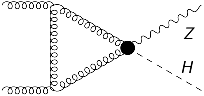
Large mass expansion (LME) $m_t \gg \hat{s}$



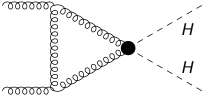
[Dawson 1991; Djouadi, Spira, Zerwas 1991]



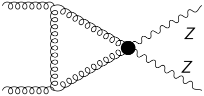
[Harlander, Neumann, Ozeren, Wiesemann 2012; . . .]



[Hasselhuhn, Luthe, Steinhauser 2016]



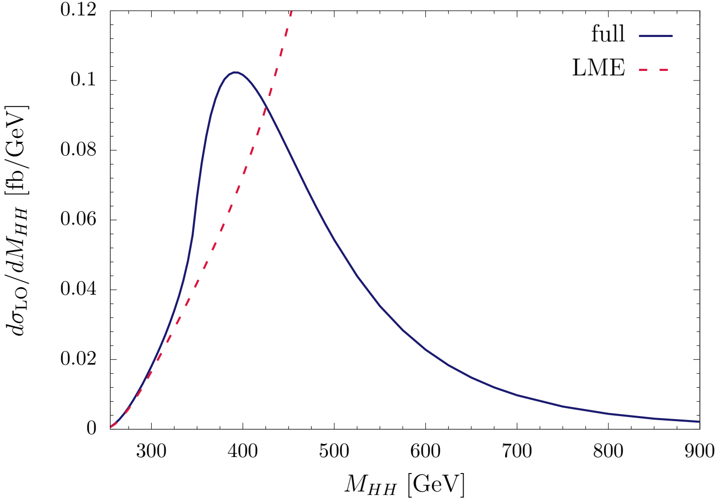
[Grigo, Hoff, Steinhauser 2015; Degrassi, Giardino, Gröber 2016]



[Melnikov, Dowling 2015; Campbell, Ellis, Czakon, Kirchner 2016; Caola et al. 2016]

Validity of the large mass expansion

Higgs pair production at LO



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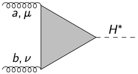
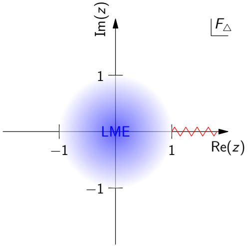
Padé Approximation

[Broadhurst, Fleischer, Tarasov 1993; Fleischer, Tarasov 1994; . . .]



$$= \frac{y_t \hat{s}}{\sqrt{2} m_t} \frac{\alpha_s}{2\pi} \delta_{ab} T_F A_1^{\mu\nu} F_\triangle(z)$$

$$z = \frac{\hat{s}}{4 m_t^2}$$



Padé Approximation

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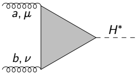

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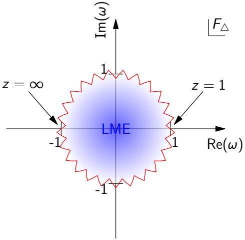
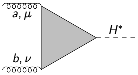
Conformal mapping: $z = \frac{4\omega}{(1+\omega)^2}$



Padé Approximation

[Broadhurst, Fleischer, Tarasov 1993; Fleischer, Tarasov 1994; . . .]



$$= \frac{y_t \hat{s}}{\sqrt{2} m_t} \frac{\alpha_s}{2\pi} \delta_{ab} T_F A_1^{\mu\nu} F_\triangle(z)$$

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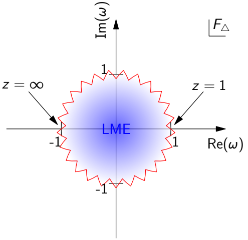

Padé approximation: $[n/m](\omega) = \frac{\sum_{i=0}^{n} a_i \omega^i}{1+\sum_{i=1}^{m} b_i \omega^i}$

Ansatz:

$$F_\triangle(z) = \frac{[n/m](\omega(z))}{1 + a_R z}, \quad a_R \in [0.1, 10]$$

Fix a_i, b_i from LME

from $F_\triangle \xrightarrow{z\to\infty} 0$

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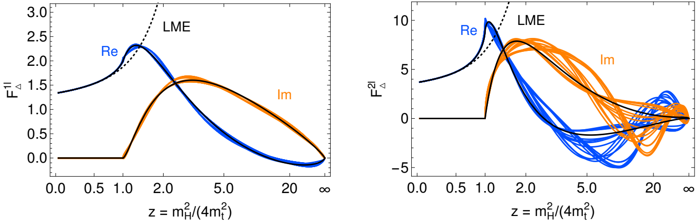
Padé Approximation for $gg \to H^*$



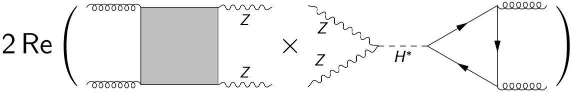
20 Padé approximants [1/3], [2/2], [3/1] from LME up to $\frac{1}{m_t^8}$

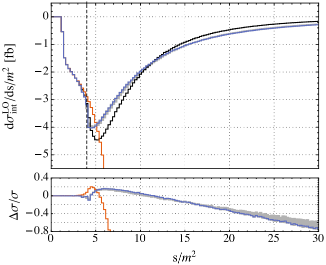
Exclude approximants with poles for

$\mathrm{Re}(z) \in [0, 8], \mathrm{Im}(z) \in [-1, 1]$

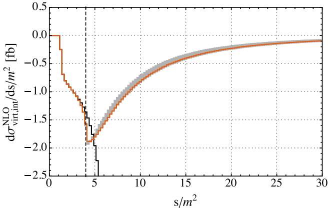
Padé Approximation for $gg(\to H^*) \to ZZ$

[Campbell, Ellis, Czakon, Kirchner 2016]





— exact
— LME up to $\frac{1}{m_t^{12}}$
— [3/3]
— [n/m] with $n, m \in \{2, 3\}$



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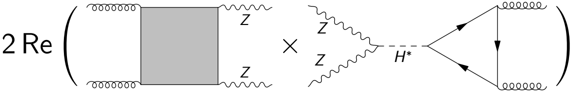
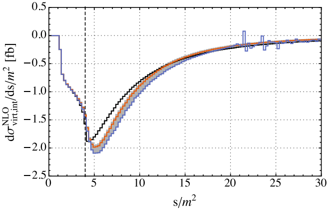
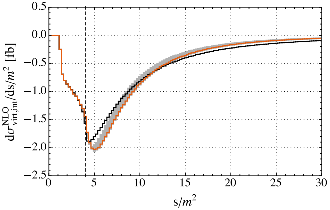






Left:

— [3/3]

— $d\sigma^{LO}_{exact} \times \frac{d\sigma^{NLO}_{LME}}{d\sigma^{LO}_{LME}}$ up to $\frac{1}{m_t^{\{2\ldots12\}}}$

Right:

— [3/3]

— $d\sigma^{LO}_{exact} \times \frac{d\sigma^{NLO}_{[3/3]}}{d\sigma^{LO}_{[3/3]}}$

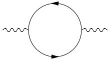
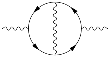
— $d\sigma^{LO}_{exact} \times \frac{d\sigma^{NLO}_{[n/m]}}{d\sigma^{LO}_{[n/m]}}$

Threshold expansion

$$F_\triangle \xrightarrow{z\to 1} \sum_{i=4-n}^{\infty} \sum_{j\geq 0} K_{i,j} \sqrt{1-z}^{\,i} \log^j(1-z)$$

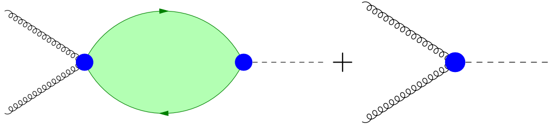
$\log(1-z)$ incompatible with Padé approximation
$\hookrightarrow$ extended ansatz

$$F_\triangle = \frac{[n/m](\omega(z))}{1+a_R z} + s(z)$$

- $\log(1-z)$ absorbed into subtraction function s
- s analytic for $z \to 0$, constructed from  , 

Threshold expansion

Expansion by regions or **Nonrelativistic QCD:**

$F_{\triangle} \xrightarrow{z \to 1}$ 

resonant + nonresonant

resonant:

- on-shell, nonrelativistic $t\bar{t}$ resonance
- $p_t^0 \sim m_t + m_t\,(z-1)$, $\mathbf{p}_t \sim m_t\,\sqrt{z-1}$
- non-analytic terms with $\sqrt{1-z}$, $\log(1-z)$

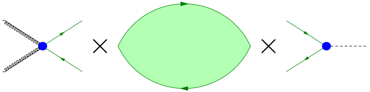
nonresonant:

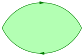
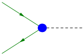
- off-shell t, $\bar{t}$
- no imaginary part, analytic in $(1-z)$

Threshold expansion

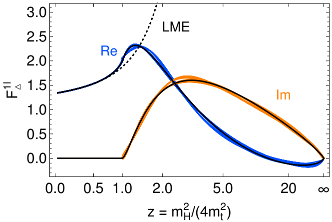
Resonant contribution

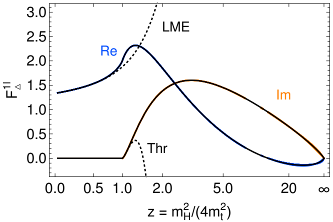
Factorisation:

$F^{\text{res}}_{\triangle} =$  $+ \cdots$

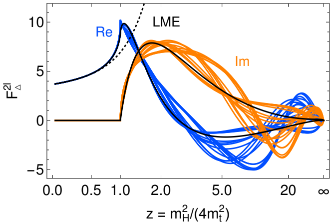
- P-wave Coulomb Green Function 
  known to all orders in α_s
  $\hookrightarrow$ leading term in threshold expansion
- only  depends on (colour singlet) final state

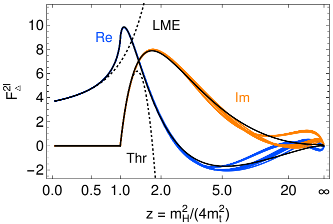
Padé Approximation with threshold expansion





threshold
excl. $(1-z)^i \log^0$





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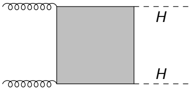
Padé approximation for $gg \to HH$



$$= y_t^2 \frac{\alpha_s}{2\pi} \delta_{ab} T_F \, z \left[A_1^{\mu\nu} F_1 + A_2^{\mu\nu} F_2\right]$$

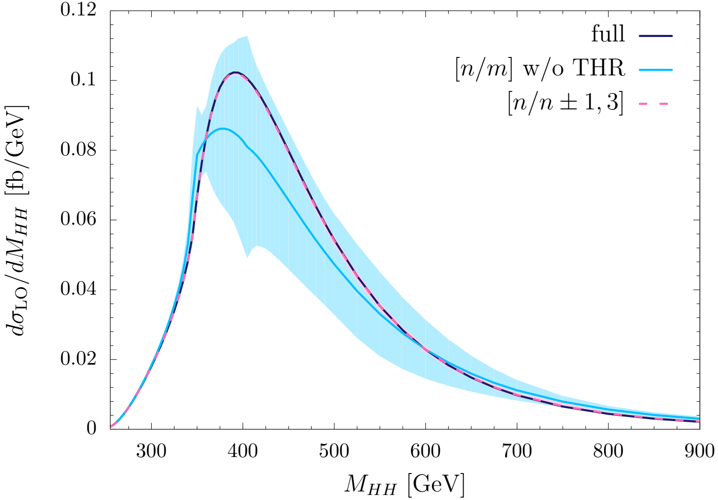
Three ratios: $z = \frac{\hat{s}}{4m_t^2}$, $r_H = \frac{m_H^2}{\hat{s}}$, $r_{p_T} = \frac{p_T^2}{\hat{s}}$

Given a phase space point (z, r_H, r_{p_T}):

1. Compute threshold and large mass expansion for given r_H, r_{p_T}
2. Construct 100 approximants in z
3. Evaluate approximants for given z

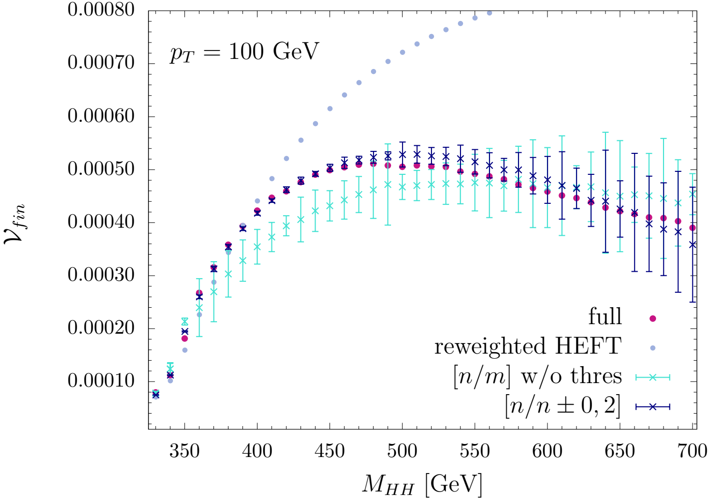
Padé approximation for $gg \to HH$

LO results



Padé approximation for $gg \to HH$

NLO results compared to [Borowka et al. 2016]



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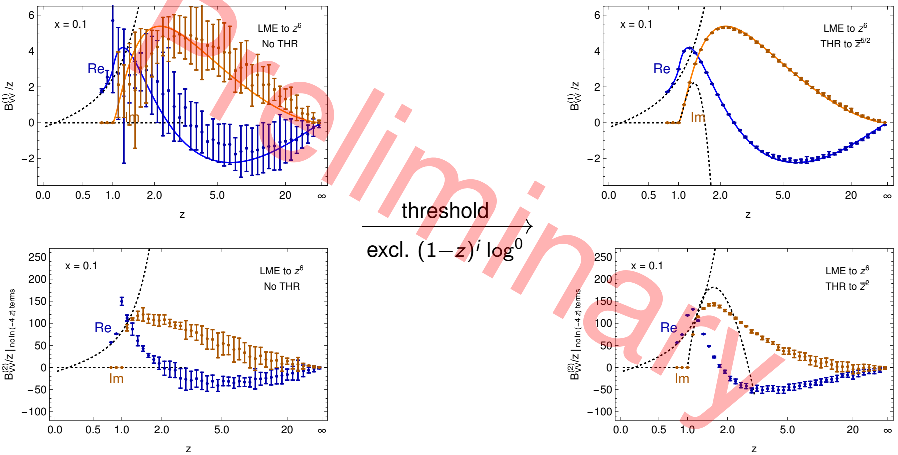
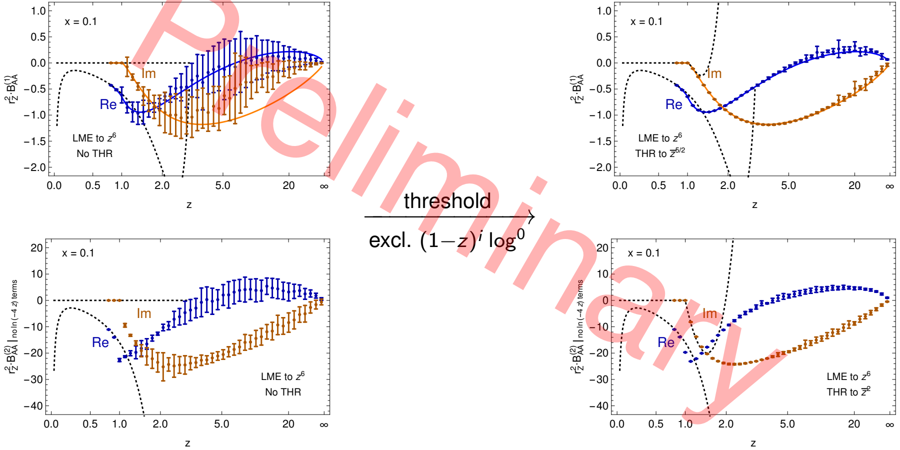
Padé approximation for $gg \to ZZ$

Vector coupling



Padé approximation for $gg \to ZZ$

Axial-vector coupling



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Conclusions

- Padé approximations can capture top mass corrections in gluon fusion processes
- Threshold expansion is necessary to model the peak region
- Systematic improvement through more expansion terms (LME, threshold expansion, small mass expansion)

Backup

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Padé approximation for vacuum polarisation

3 loop, $n + m = 60$