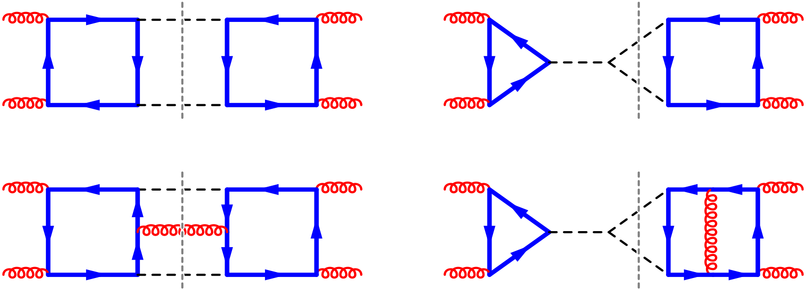
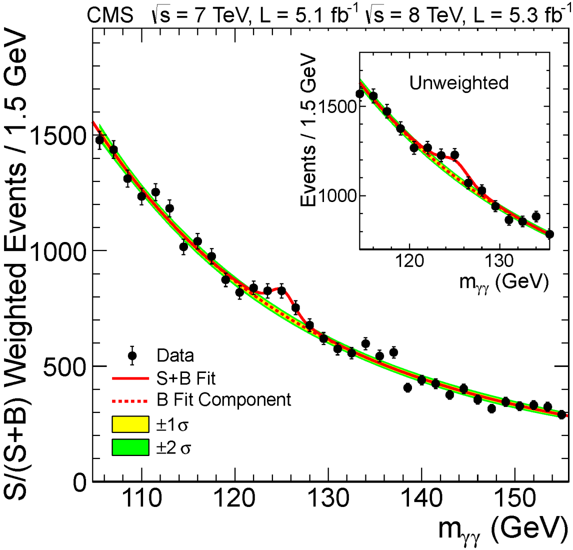
Higgs boson pair production at the LHC: top quark mass effects at NLO

Radcor 2013, September 22-27, Lumley Castle, Chester-le-Street

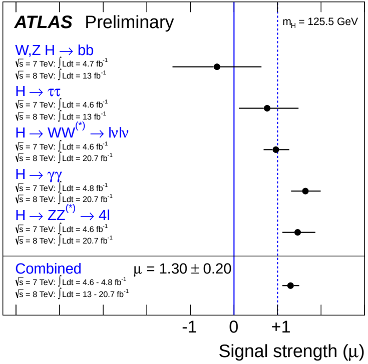
Matthias Steinhauser — TTP Karlsruhe | in collaboration with Jonathan Grigo, Jens Hoff, Kirill Melnikov

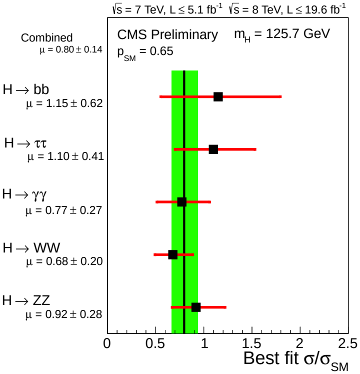


Higgs boson discovery



Higgs boson discovery





Open questions

- SM Higgs boson?
- Couplings to fermions?
- Couplings to bosons?
- Self-coupling?
- $V_{\text{Higgs}} = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$ $\qquad \lambda^{\text{SM}} = \frac{m_H^2}{2v^2} \approx 0.13$

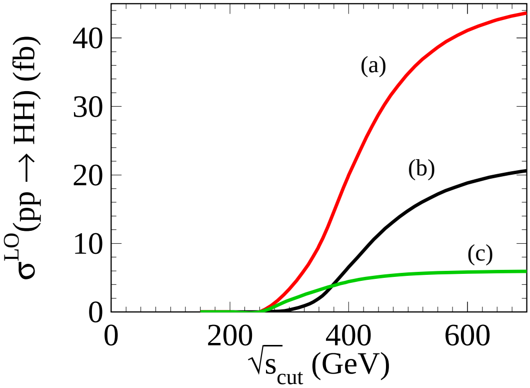
Information about λ_{HHH}

$$gg \to HH$$

$qq' \to HHqq'$, $q\bar{q}' \to ZHH/WHH$, $q\bar{q}, gg \to t\bar{t}HH$

➪ more than 10 times smaller

$gg \to HH$ at LO



box

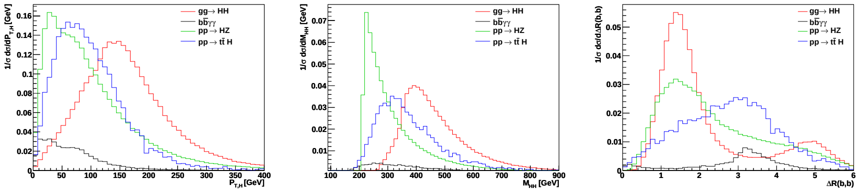
triangle

box + triangle

Promising channels/strategies

- $gg \to HH \to b\bar{b}\gamma\gamma$

[Baglio,Djouadi,Gröber,Mühlleitner,Quevillon,Spira'13]: $S/\sqrt{B} \approx 16$, 51 signal events for $\int \mathcal{L} = 3000\ \text{fb}^{-1}$

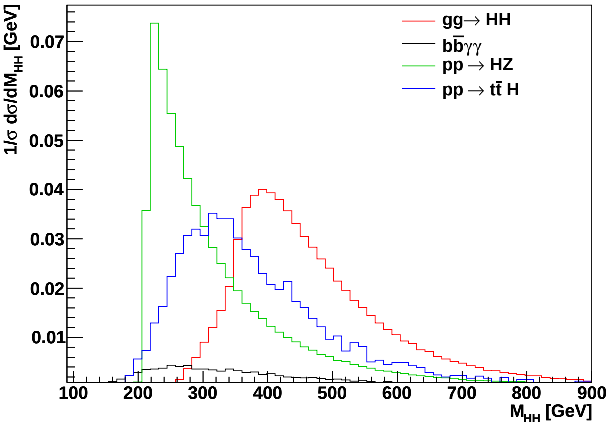


similar results: [Baur,Plehn,Rainwater'04]

Promising channels/strategies

- $gg \to HH \to b\bar{b}\gamma\gamma$

  [Baglio,Djouadi,Gröber,Mühlleitner,Quevillon,Spira'13]: $S/\sqrt{B} \approx 16$, 51 signal events for $\int \mathcal{L} = 3000\ \text{fb}^{-1}$

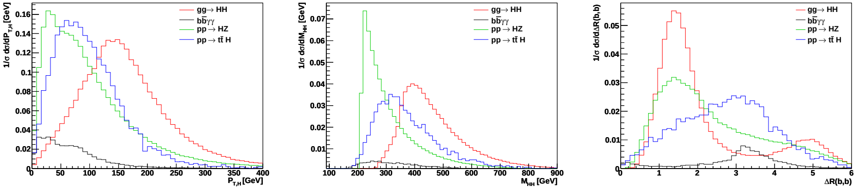


similar results: [Baur,Plehn,Rainwater'04]

Promising channels/strategies

- $gg \to HH \to b\bar{b}\gamma\gamma$

  [Baglio,Djouadi,Gröber,Mühlleitner,Quevillon,Spira'13]: $S/\sqrt{B} \approx 16$, 51 signal events for $\int \mathcal{L} = 3000\ \text{fb}^{-1}$



  similar results: [Baur,Plehn,Rainwater'04]

- $gg \to HH \to b\bar{b}\tau\tau$: "promising"; $gg \to HH \to b\bar{b}WW$??
- $\frac{\sigma(gg\to HH)}{\sigma(gg\to H)}$ ➪ $\lambda > 0$ at 95% C.L. with 600 fb^{-1} [Goertz,Papaefstathion,Yang,Zurita'13]

[Dolan,Englert,Spannowsky'12; Dawson,Furlan,Lewis'13,. . .]

$gg \to HH$: known results

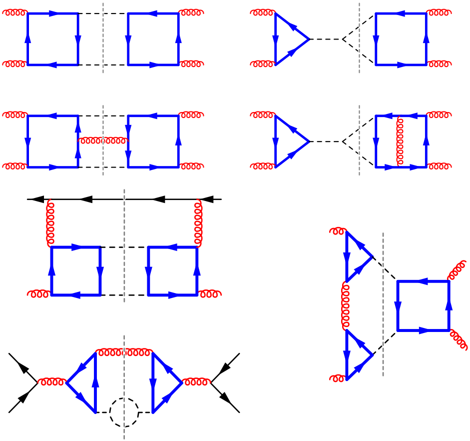
- LO [Glover, van der Bij'88; Plehn,Spira,Zerwas'96]
- NLO for $m_t \to \infty$ [Dawson,Dittmaier,Spira'98] $\approx +100\%$

this talk: $1/m_t$ terms at NLO [Grigo,Hoff,Melnikov,Steinhauser'13]

- NNLO soft-virtual approx., $m_t \to \infty$ [de Florian,Mazzitelli'13] $\approx +20\%$
- NNLL resummation [Shao,Li,Li,Wang'13] $\approx$ NLO $+20\%$

Technique

- forward scattering amplitude + optical theorem



Technique

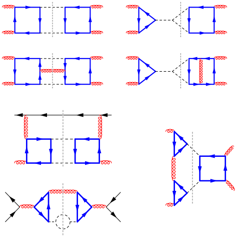
- forward scattering amplitude + optical theorem
- Asymptotic expansion for $m_t^2 \gg m_H^2, s$ with

  `exp` [Harlander,Seidensticker,Steinhauser'98]

  ➪ expansion in $\rho = m_H^2/m_t^2$

  ➪

$$\hat{\sigma}(gg \to HH) = \sum_n c(x) \left(\frac{m_H^2}{m_t^2}\right)^n , \quad x = \frac{4m_H^2}{s}$$



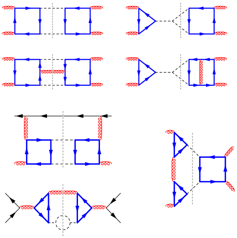
Technique

- forward scattering amplitude + optical theorem
- Asymptotic expansion for $m_t^2 \gg m_H^2, s$ with `exp` [Harlander,Seidensticker,Steinhauser'98]

  ➪ expansion in $\rho = m_H^2/m_t^2$

  ➪

$$\hat{\sigma}(gg \to HH) = \sum_n c(x) \left(\frac{m_H^2}{m_t^2}\right)^n , \quad x = \frac{4m_H^2}{s}$$



- `FORM` and `TFORM` [Vermaseren'90; ...; Tentyukov,Vermaseren'07; Kuipers,Ueda,Vermaseren,Vollinga'13]

Technique

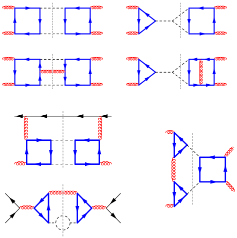
Karlsruhe Institute of Technology

- forward scattering amplitude + optical theorem
- Asymptotic expansion for $m_t^2 \gg m_H^2, s$ with `exp` [Harlander,Seidensticker,Steinhauser'98]

  ➪ expansion in $\rho = m_H^2/m_t^2$

  ➪

$$\hat{\sigma}(gg \to HH) = \sum_n c(x) \left(\frac{m_H^2}{m_t^2}\right)^n , \quad x = \frac{4m_H^2}{s}$$



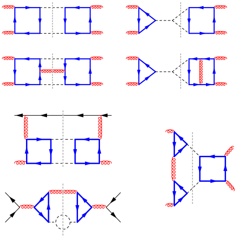
- `FORM` and `TFORM` [Vermaseren'90; ...; Tentyukov,Vermaseren'07; Kuipers,Ueda,Vermaseren,Vollinga'13]
- Reduction to MIs with `FIRE` [Smirnov'08; Smirnov^2'13]

Technique

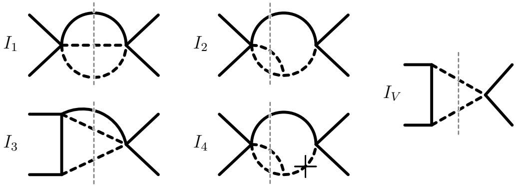
- forward scattering amplitude + optical theorem
- Asymptotic expansion for $m_t^2 \gg m_H^2, s$ with `exp` [Harlander,Seidensticker,Steinhauser'98]

  ➪ expansion in $\rho = m_H^2/m_t^2$

  ➪
$$\hat{\sigma}(gg \to HH) = \sum_n c(x) \left(\frac{m_H^2}{m_t^2}\right)^n, \quad x = \frac{4m_H^2}{s}$$

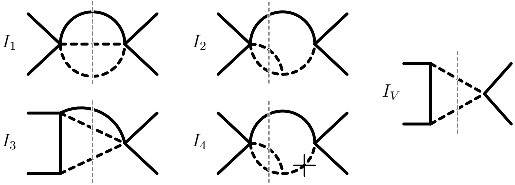


- `FORM` and `TFORM` [Vermaseren'90; . . . ; Tentyukov,Vermaseren'07; Kuipers,Ueda,Vermaseren,Vollinga'13]
- Reduction to MIs with `FIRE` [Smirnov'08; Smirnov^2'13]
- Master integrals (+ 2-loop tadpoles, . . .)



Master integrals

Karlsruhe Institute of Technology

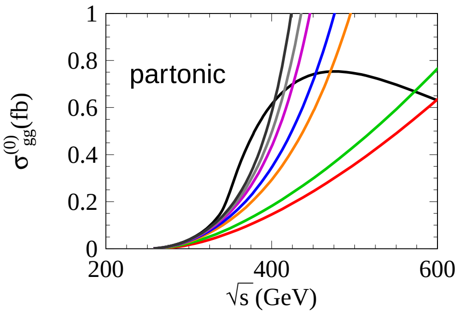


- derive 1-dimensional integral representation
- e.g.: $I_1 = \mathcal{N} s^{1-2\epsilon} \delta^{5/2-3\epsilon} \int_0^1 \frac{d\mu}{\sqrt{1-\mu\delta}} (1-\mu)^{1/2-\epsilon} \mu^{1-2\epsilon}$
- expand in $\delta = 1 - 4m_H^2/s = 1 - x$ ⇨ analytic results
-

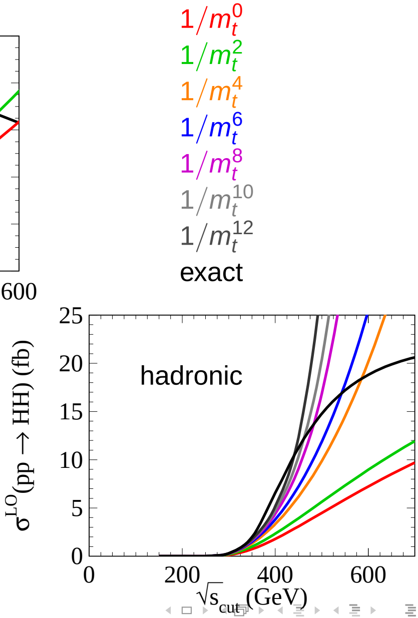
$$I_i = \sum_n^N c_n \, \delta^n \qquad N = 100, 200, \ldots$$

- σ^{partonic} in analytic from

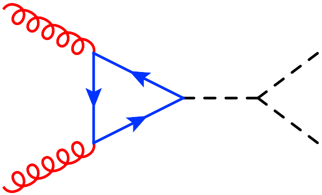
LO result



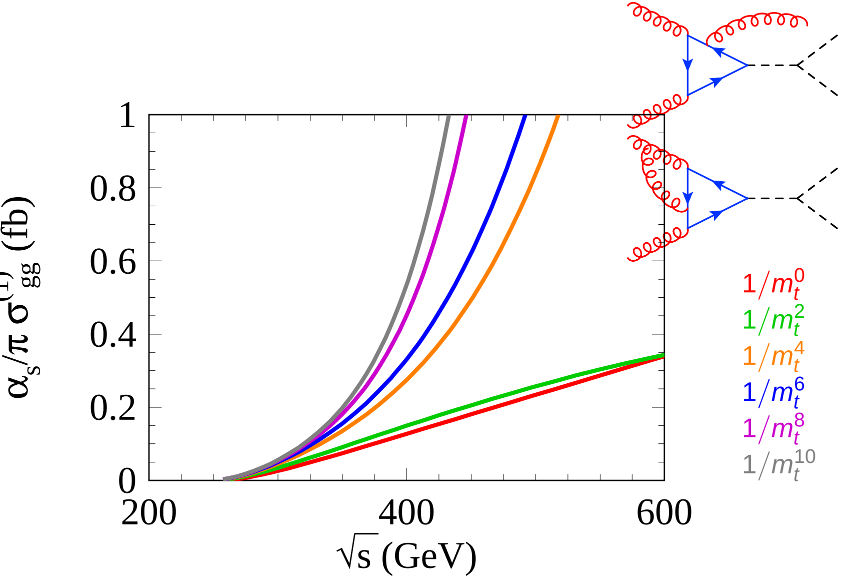
partonic
$\sigma^{(0)}_{gg}$(fb)
0
0.2
0.4
0.6
0.8
1
200
400
600
$\sqrt{s}$ (GeV)



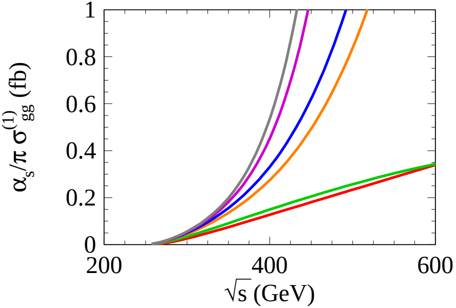
$1/m_t^0$
$1/m_t^2$
$1/m_t^4$
$1/m_t^6$
$1/m_t^8$
$1/m_t^{10}$
$1/m_t^{12}$
exact
hadronic
$\sigma^{LO}(pp \to HH)$ (fb)
0
5
10
15
20
25
0
200
400
600
$\sqrt{s_{cut}}$ (GeV)



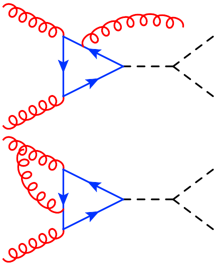
NLO contribution: gluon channel, partonic



NLO contribution: gluon channel, partonic

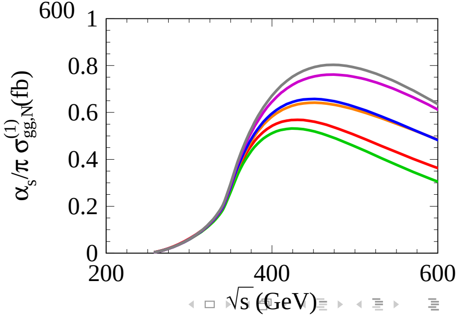


$1/m_t^0$
$1/m_t^2$
$1/m_t^4$
$1/m_t^6$
$1/m_t^8$
$1/m_t^{10}$

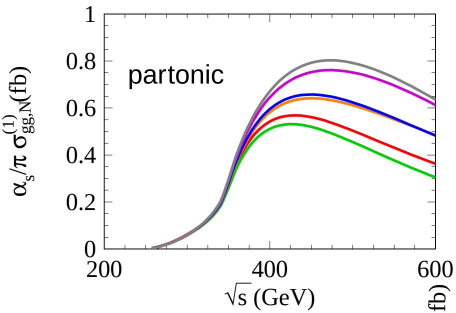


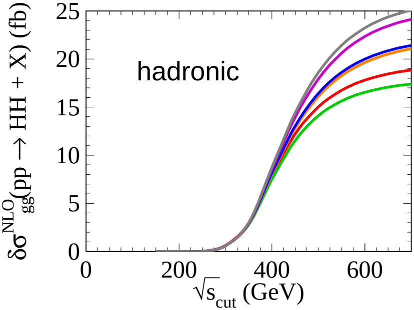
$$\sigma^{(1)}_{ij,N} = \sigma^{(0)}_{gg,\mathrm{exact}} \frac{\sigma^{(1)}_{ij,\mathrm{exp}}}{\sigma^{(0)}_{gg,\mathrm{exp}}} \quad \Rightarrow$$

N: use terms up to $(1/m_t^2)^N$

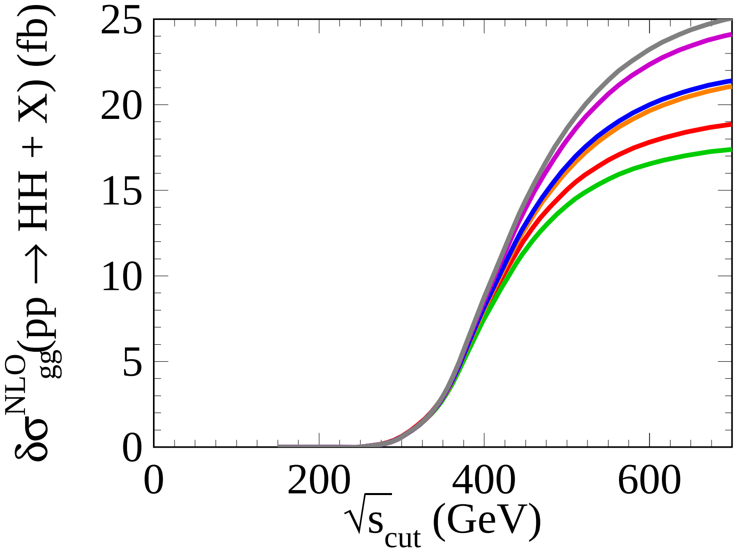


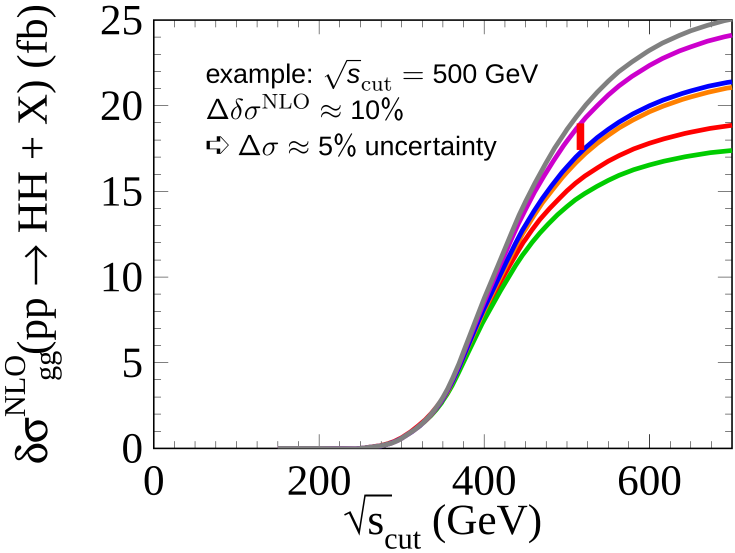
NLO contribution: gluon channel





$s_{\rm cut}$: upper limit on partonic center-of-mass energy $\approx m(HH)$ invariant mass

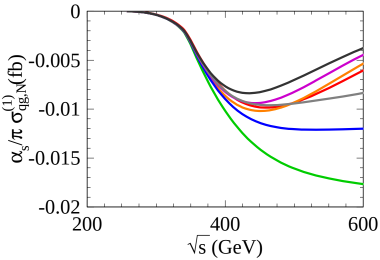

25
20
15
10
5
0
0
200
400
600
$\delta\sigma^{NLO}_{gg}(pp \to HH + X)$ (fb)
$\sqrt{s_{cut}}$ (GeV)

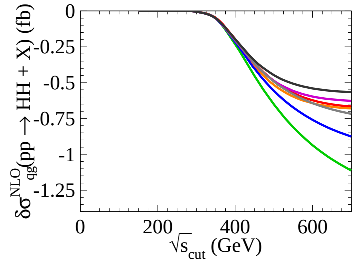

example: $\sqrt{s}_{\rm cut} = 500$ GeV
$\Delta\delta\sigma^{\rm NLO} \approx 10\%$
➪ $\Delta\sigma \approx 5\%$ uncertainty
$\delta\sigma^{\rm NLO}_{\rm gg}(\rm pp \to HH + X)$ (fb)
$\sqrt{s_{\rm cut}}$ (GeV)
0
5
10
15
20
25
0
200
400
600

NLO result: quark channels

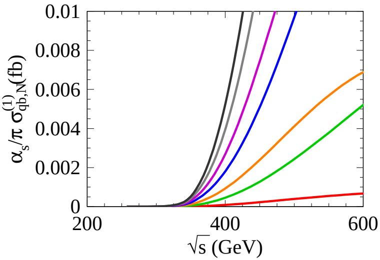
partonic | hadronic

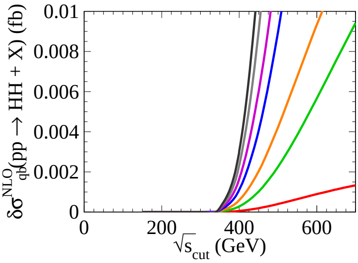
qg



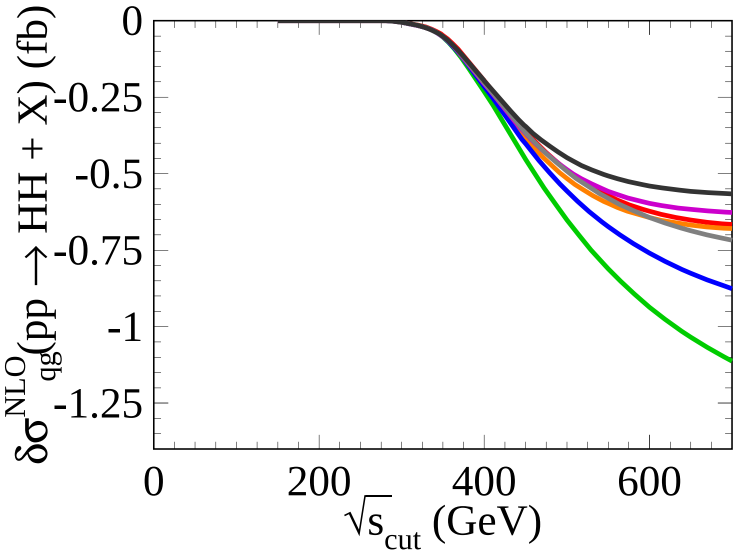


$q\bar{q}$



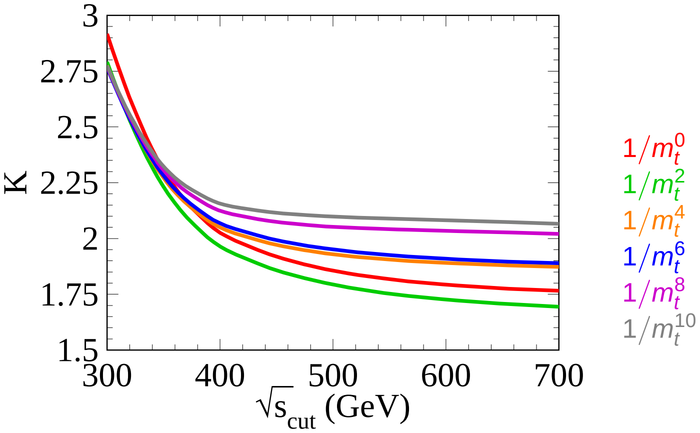


NLO result: quark channels



K factor

$$K = \frac{\sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{LO}}}$$



➪ enhancement close to threshold due to suppression of LO result

Partonic NLO *gg* contribution close to threshold

$$\rho = m_H^2/m_t^2,\ \delta = 1 - x = 1 - 4m_H^2/s$$

$$\sigma_{gg}^{\rm part} = \frac{G_F^2 m_H^2}{2\pi}\left(\frac{\alpha_s}{\pi}\right)^2 \Bigg\{ \delta^{5/2} + \#\ \rho\ \delta^{3/2} + \rho^2 \left(\#\ \delta^{1/2} + \#\ \delta^{3/2}\right)$$
$$+ \frac{\alpha_s}{\pi}\left[\#\ \delta^{3/2} + \rho\ \left(\#\ \delta^{1/2} + \#\ \delta^{3/2}\right) + \rho^2\left(\#\ \delta^{1/2}\ln^2\delta + \#\ \delta^{3/2}\right)\right]\Bigg\} + \ldots$$

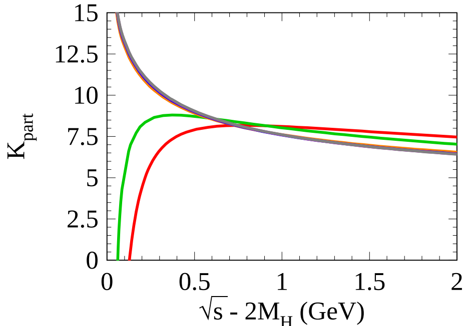
➪ K factor close to threshold strongly affected by power-suppressed $1/m_t$ terms

Partonic NLO *gg* contribution close to threshold

$$\sigma_{gg}^{\rm part} = \frac{G_F^2 m_H^2}{2\pi} \left(\frac{\alpha_s}{\pi}\right)^2 \Bigg\{ \delta^{5/2} + \# \, \rho \, \delta^{3/2} + \rho^2 \left(\# \, \delta^{1/2} + \# \, \delta^{3/2} \right)$$

$$+ \frac{\alpha_s}{\pi} \Bigg[\# \, \delta^{3/2} + \rho \, \left(\# \, \delta^{1/2} + \# \, \delta^{3/2} \right) + \rho^2 \left(\# \, \delta^{1/2} \ln^2 \delta + \# \, \delta^{3/2} \right) \Bigg] \Bigg\} + \ldots$$

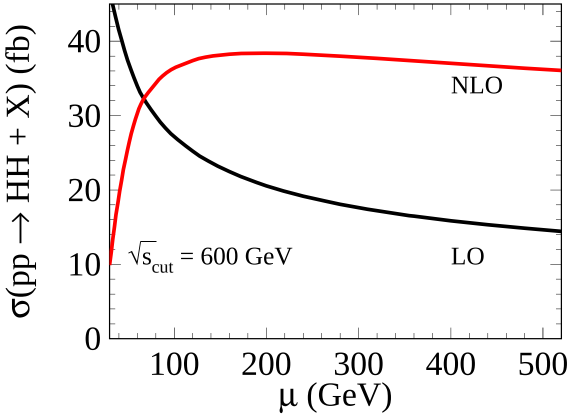
➪ K factor close to threshold strongly affected by power-suppressed $1/m_t$ terms



$$K_{\rm part} = \frac{\sigma_{\rm part}^{\rm NLO}}{\sigma_{\rm part}^{\rm LO}}$$

Scale dependence

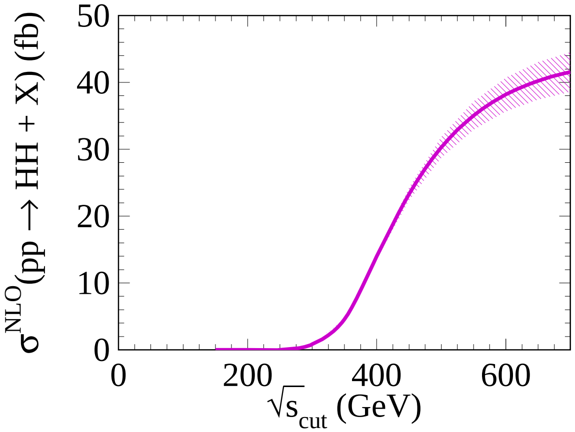
$\mu = \mu_f = \mu_r$



$\mu^{\rm central} = 2m_H$: $\sigma^{\rm LO} = 18^{+6}_{-4}$ fb ➪ $\sigma^{\rm NLO} = 38^{+0}_{-2}$ fb

Implication on extraction of λ_{HHH}

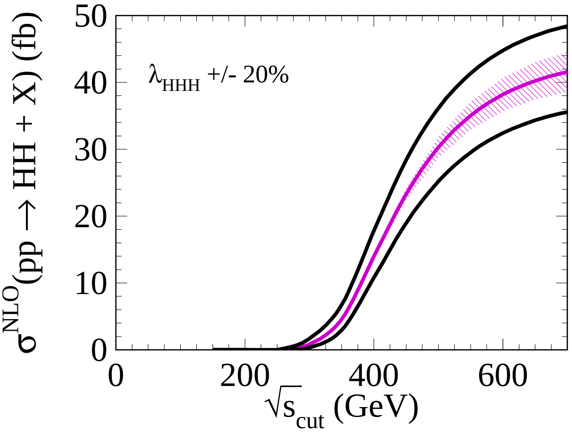
NLO prediction including $1/m_t^8$ terms
uncertainty band: compare with $1/m_t^6$ terms



➪ $\sigma^{\rm NLO}$ including $1/m_t$ corrections sufficient to detect $\mathcal{O}(10\%)$ deviations of λ from $\lambda^{\rm SM}$

Implication on extraction of λ_{HHH}

NLO prediction including $1/m_t^8$ terms
uncertainty band: compare with $1/m_t^6$ terms



➪ $\sigma^{\rm NLO}$ including $1/m_t$ corrections sufficient to detect $\mathcal{O}(10\%)$ deviations of λ from $\lambda^{\rm SM}$

Conclusions

- $\sigma(pp \to HH)$ SM cross section
- determination of λ_{HHH}
- NLO cross section
  independent check of [Dawson,Dittmaier,Spira'98]
- $1/m_t$ corrections ➪ 10% increase
- $K \nearrow$ for $s \to$ threshold ($1/m_t$ terms important!)
  ($\longleftrightarrow$ extraction of λ_{HHH})
- reliable error estimate at NLO