CHARGED HIGGS AND QCD

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- QCD issue — bottom partons
- associated production with top
- associated production with W
- pair production

CHARGED HIGGS PRODUCTION

Why look for a charged Higgs?

- single Higgs multiplet (plus conjugate) only minimal solution
- neutral scalars mixing with Higgs not unique [e.g. radion–Higgs mixing]
- charged Higgs couplings sign of doublet/triplet and flavor structure [Spannofski]

Production processes, mostly known to NLO–QCD [sorry, only few NLO citations]

- associated with top: $gg \to \bar{b}tH^-$ [Zhu; TP; Berger, Han, Jiang, TP; Alwall & Rathsman, Peng et al;...]
- associated with W: $gg \to b\bar{b}W^+H^-$ [Hollik & Zhu; Barrientos Bendezu & Kniehl;...]
  pair production: $gg \to b\bar{b}H^+H^-, q\bar{q} \to H^+H^-$ [Sheng et al; Alves & TP;...]
- leading order loop: $gg \to H^+H^-$ [Willenbrock; Krause, TP, Spira, Zerwas; Brein & Hollik;...]
  leading order loop: $gg \to W^+H^-$ [Barrientos Bendezu & Kniehl; Brein, Hollik, Kanemura;...]

$\Rightarrow$ (1) bottom Yukawa coupling $\sigma \sim y_b^2 \tan^2\beta + ...$ [SUSY, see Jaume Guasch and Oliver Brein]
(2) gluon splitting into bottom partons [purely QCD in 2HDM]

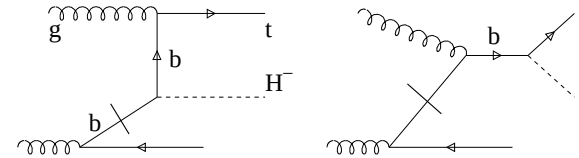
Decay processes

- bottom Yukawa definition and higher orders [too many QCD loop papers to list here]

$\Rightarrow$ Hdecay with everything you need [thanks, Michael S!]

COLLINEAR GLUON SPLITTING

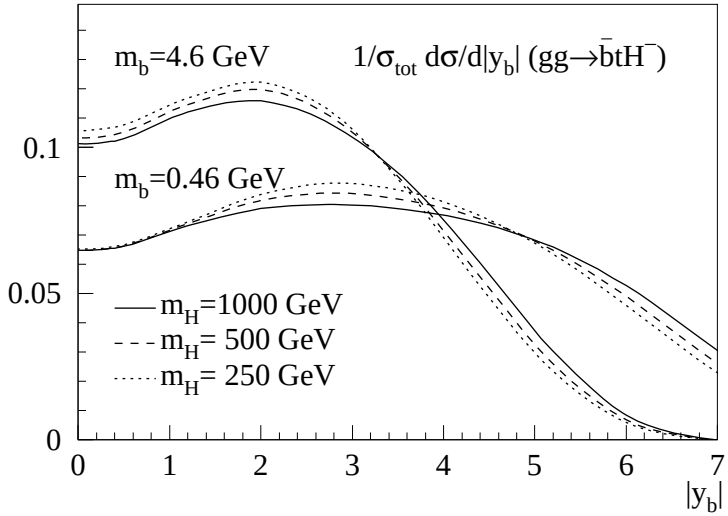
Problem with gluon splitting [one final–state bottom: $gg \to \bar{b}tH^-$]

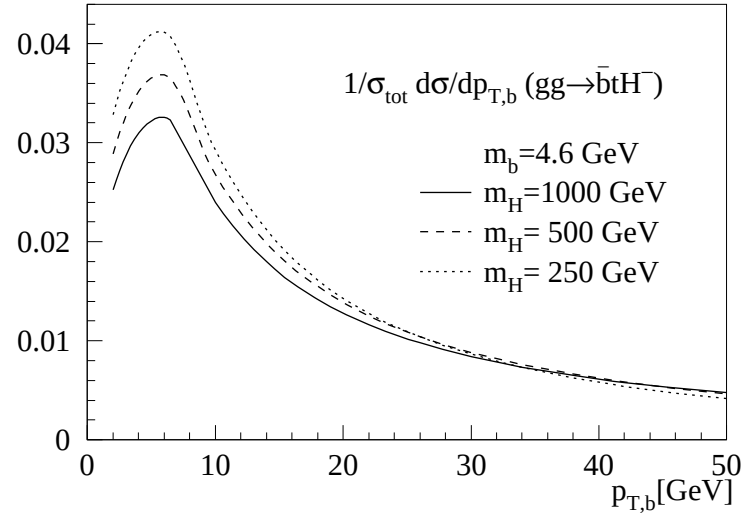


- e.g. Madevent output: forward jets, $p_{T,b}$ peaked at m_b
- bottom–inclusive cross section for $gg \to \bar{b}tH^-$?
- QCD: collinear bottom from gluon splitting, IR–regularized by m_b
- asymptotic behavior $d\sigma/dp_{T,b} \propto p_{T,b}/m^2_{T,b}$

$\Rightarrow$ inclusive total rate $\sigma \propto \log p^{max}_{T,b}/p^{min}_{T,b} \sim \log p^{max}_{T,b}/m_b$

$\Rightarrow$ how large logarithms? resum?





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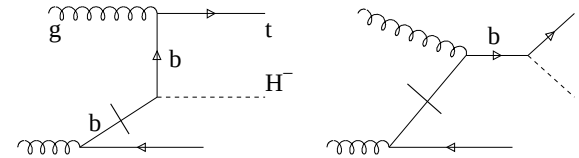

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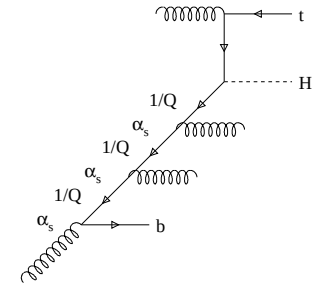


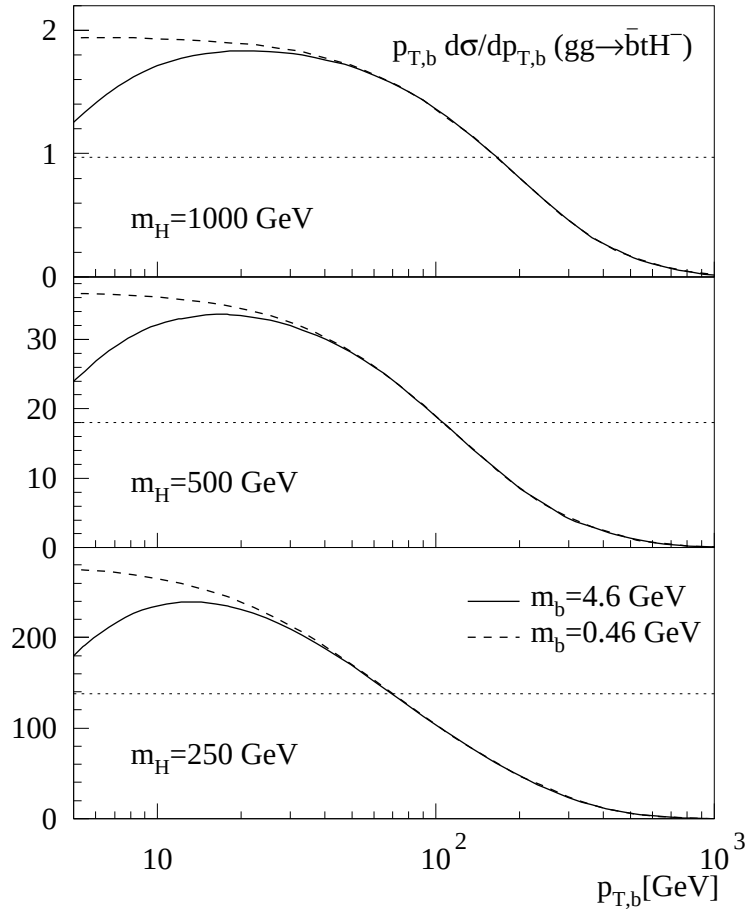
Bottom partons [Aivazis, Collins, Olness, Tung, Willenbrock]

- collinear description of gluon splitting valid below $p^{max}_{T,b}$ [Johan Alwall's talk]
- resummation defines bottom parton density [e.g. $bg \to tH^-$]
- $\mu_{F,b}$ 'transverse momentum size' of inclusive bottom parton [$\mu_{F,b} \equiv p^{max}_{T,b}$ perturbative!]
- usually matrix elements in limit $m_b \to 0$

$\to$ (1) check bottom–inclusive total rate
(2) check bottom–inclusive distributions

COMPUTING BOTTOM PARTONS

Before tests: understand $p_{T,b}$ and $\mu_{F,b}$



COMPUTING BOTTOM PARTONS

Before tests: understand $p_{T,b}$ and $\mu_{F,b}$

- QCD factorization: start with virtuality Q for $gg \to \bar{b}X_M$
- Russian style approximation: [$\mathcal{L} = \mathcal{L}_0/x^2$, etc; Boos & TP]

$$\sigma = \frac{2\sigma_0\mathcal{L}_0}{16\pi} \int_0^{S-M^2} \frac{dQ_b}{Q_b} F(Q_b)$$

- $F(Q_b)$ correction to asymptotic behavior $d\sigma/dQ_b \sim 1/Q_b$

$\Rightarrow$ $Q_b^{max} \sim M/2$ at turning point of $F(\log Q)$ [usually only $Q_b^{max} \propto M$, see also Alwall & Rathsman]

$\Rightarrow$ $Q_b \to p_{T,b}$ point by point: $\mu_{F,b} \equiv p_{T,b}^{max} \sim Q_b^{max}/2 \sim M/4$ [same as numerical results]

Bottom partons in perturbative QCD

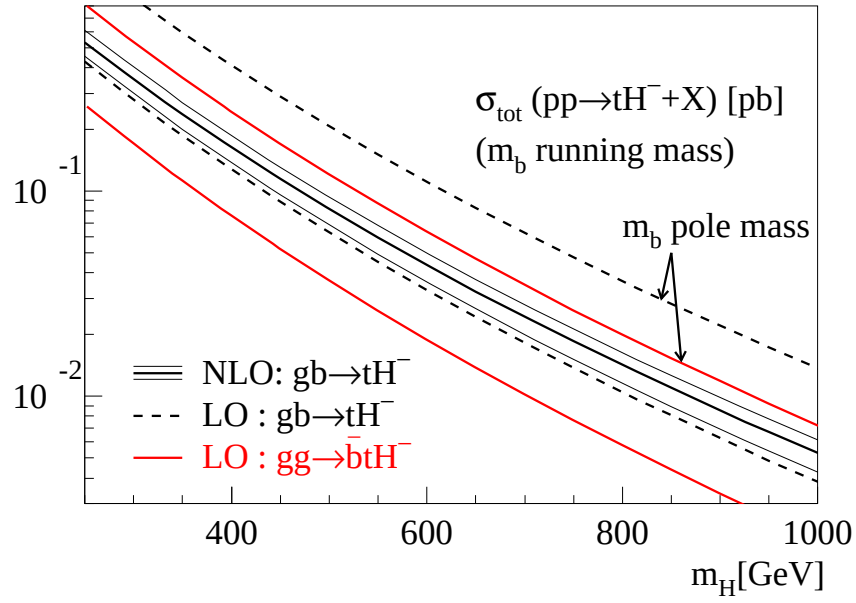
- 'large' logs at maximum $\log p_{T,b}/m_b < \log M/(5m_b)$ [also: Maltoni & Willenbrock]
- inclusive $gg \to \bar{b}X_M$ factorization scale $\mu_{F,b} \sim M/5$
- confirmed by NNLO calculations for $b\bar{b} \to h$ [Harlander & Kilgore]
- not valid for (quark–induced) single top production

$\Rightarrow$ cross section with bottom partons understood

Top–Higgs Total Cross Section at NLO

Bread–and–butter NLO corrections to $bg \to tH^-$

- leading order uncertainty large, as usual [running or pole Yukawa, etc.]
- NLO correction $+30\% \cdots 40\%$ with $\sim 20\%$ error [Zhu; TP]



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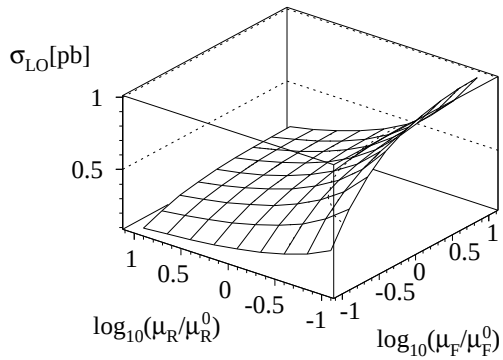
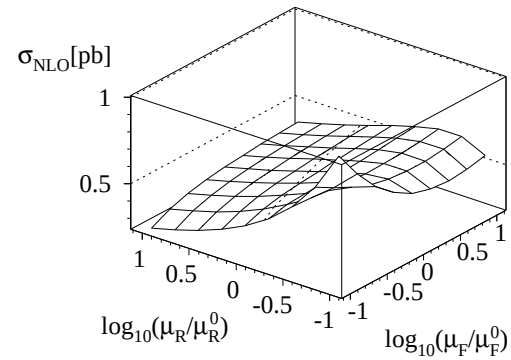
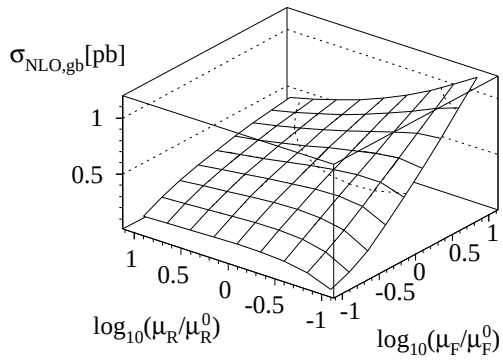
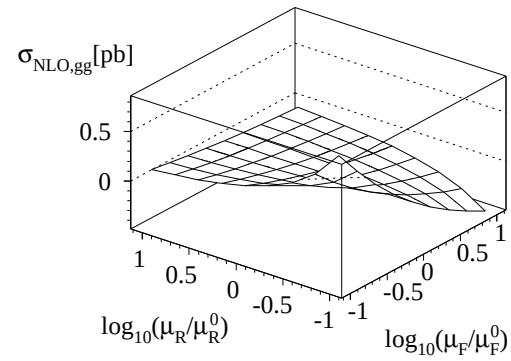
  $\Rightarrow$ problems with bottom partons butcher NLO perturbative expansion









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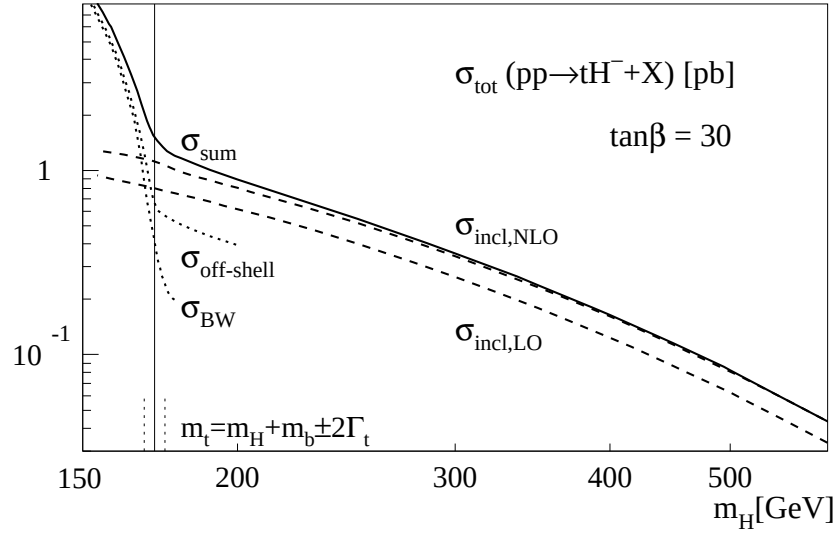
- double counting of $pp \to t\bar{t}^* \to t(\bar{b}H^-)$
  $\Rightarrow$ subtract on-shell $t\bar{t}$ from $bg \to tH^-$ at NLO [Berger, Han, Jiang, TP]
  $\Rightarrow$ simply add samples with NLO normalization



Top–Higgs Distributions at NLO

As far I know only checked in $bg \to tH^-$ [Berger, Han, Jiang, TP]

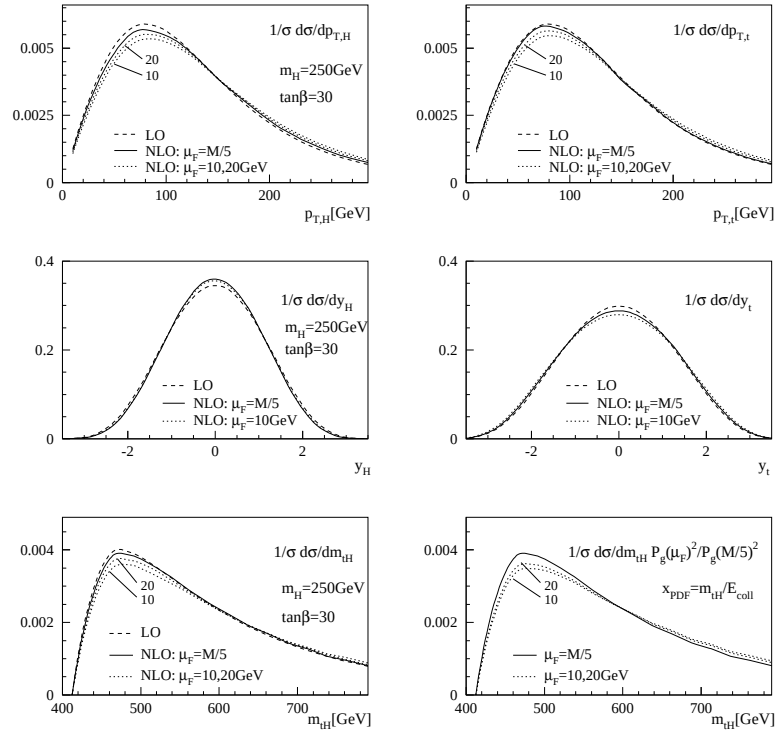
- bottom parton description appropriate for total rate [review on $b\bar{b} \to h$: Dawson, ...]
- Higgs and top distributions?

Approximation $p_{z,b} \gg p_{T,b} \to 0$

- compare $gb \to tH^-$ and $gg \to \bar{b}tH^-$ [as part of NLO]
- switch on/off bottom partons via $\mu_F \to m_b$

$\Rightarrow$ slightly harder distributions

[gluon PDF, not bottom partons]



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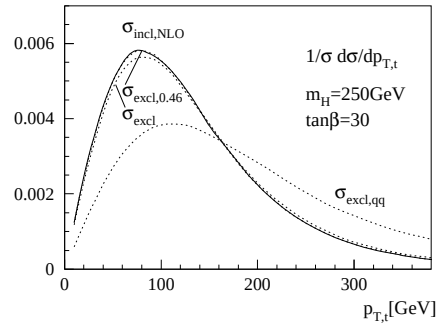
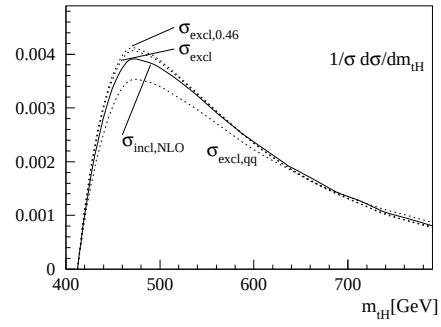
Approximation $m_b \to 0$

- bottom mass dependence of $pp \to \bar{b}tH^-$
- collinear log subtraction
  instead of dimensional regularization

  [Krämer, Olness, Soper]
- perfect agreement

$\Rightarrow$ bottom parton picture established





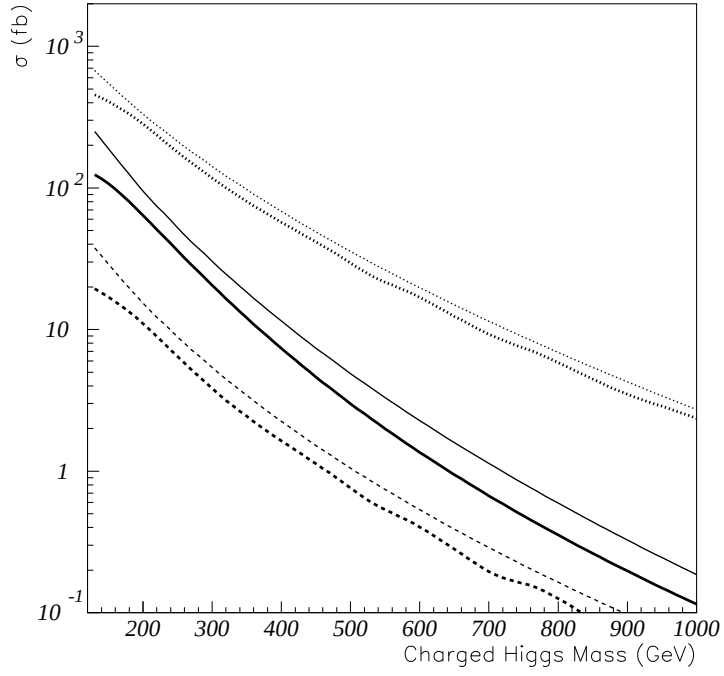
W–Higgs Cross Section at NLO

Similarly for $gg \to b\bar{b}W^+H^-$ [Hollik & Zhu]

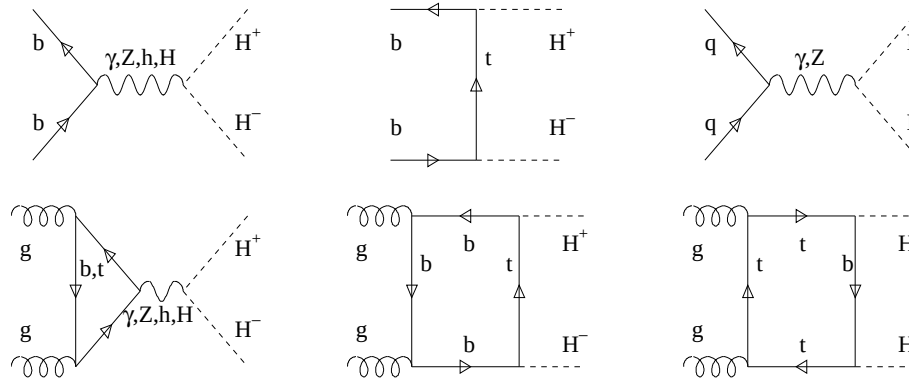
- competing with loop-induced $gg \to W^+H^-$ [see Oliver's talk]
- two bottom partons $b\bar{b} \to W^+H^-$ [each proportional to $\log \mu_{F,b}/m_H$]
- same scale argument applicable because of initial–state gluons
- NLO computed before bottom parton issues were resolved

$\Rightarrow$ too large $\mu_{F,b}$ compensated by NLO corrections: $K < 1$

[There is no really 'correct scale' in QCD, but there are wrong, perturbative unstable ones...]



Higgs–Pair Cross Sections at NLO



Charged Higgs pairs [Alves & TP]

– bottom fusion $b\bar{b} \to H^+H^-$

  $\tan^4\beta$ beta enhancement of rate
  QCD as $bg \to tH^-$ and $b\bar{b} \to H^+H^-$
  NLO corrections small and positive for appropriate $\mu_{F,b}$

– Drell–Yan process $q\bar{q} \to H^+H^-$

  valence quarks for heavy masses
  no $\tan\beta$ enhancement
  (N)NLO corrections just like Drell–Yan [Anastasiou, Melnikov, Petriello; Kilgore]

– loop–induced gluon fusion

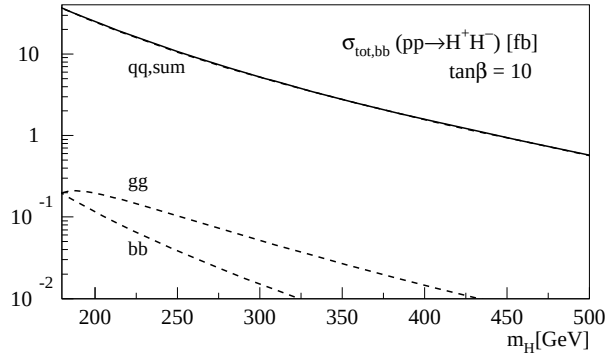
  $\tan^4\beta$ beta enhancement of box
  no effective higher–dimensional coupling for Madevent
  loop sensitive to particle content of model [SUSY talks by Jaume and Oliver]
  NLO (probably) similar to neutral pairs [Dawson, Dittmaier, Spira]

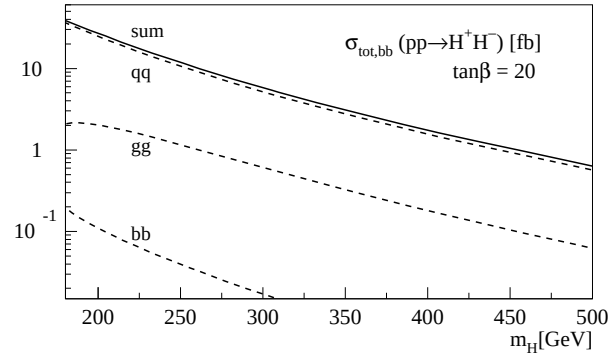
Higgs–Pair Cross Sections at NLO

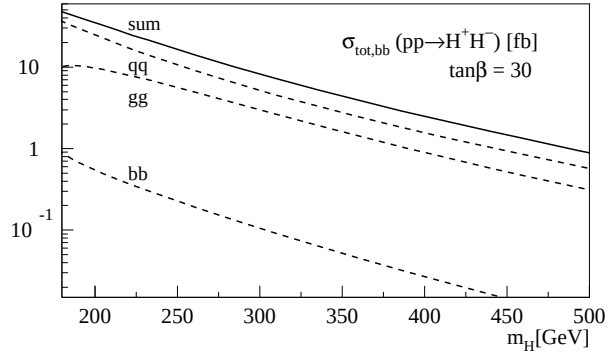
Total cross sections []Alves, TP]

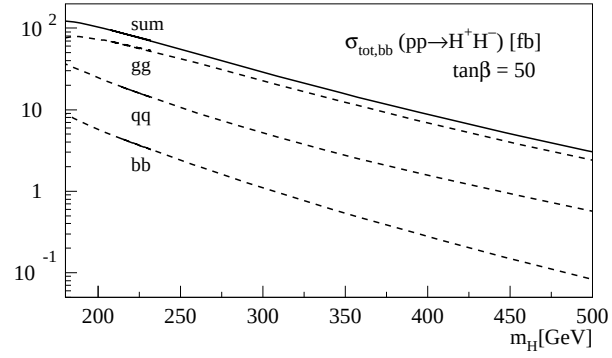
- bottom factorization scale argument as before [It's QCD, stupid!]
- bottom approximations quantitatively tested [m_b and $p_{T,b}$ approximations fine]
- reliable cross section values to compare [NLO to loop process hard without effective coupling]

$\Rightarrow$ race between loop amplitude and Drell–Yan [$b\bar{b}$ process killed]









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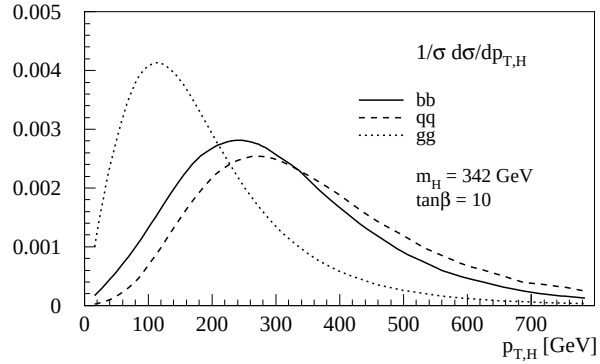
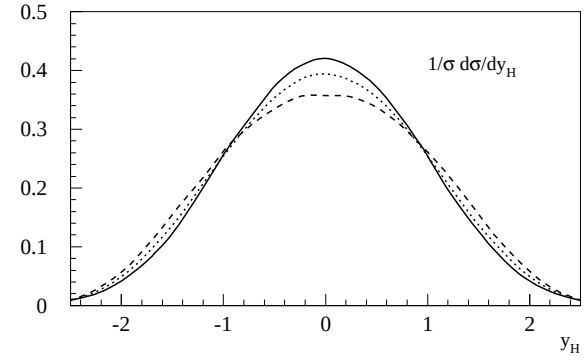
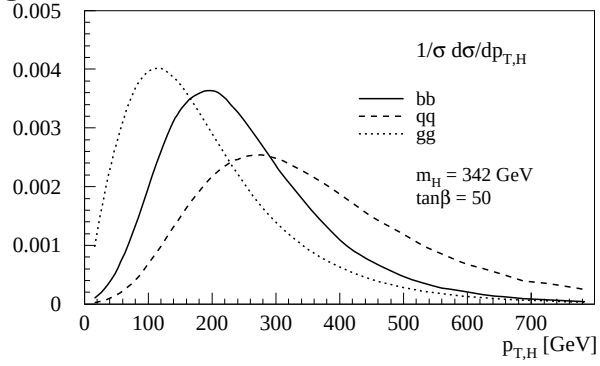
Distributions

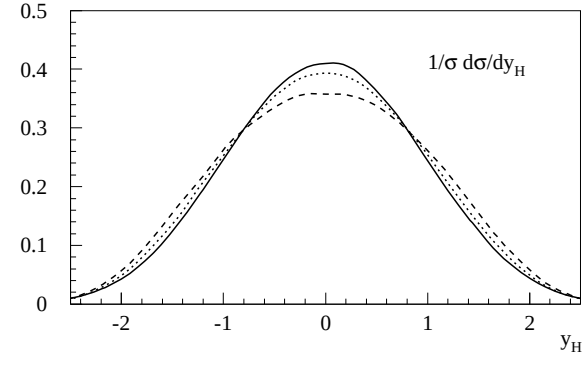
- gg process soft
- $b\bar{b}$ harder
- Drell–Yan process hard

$\Rightarrow$ add samples at given order





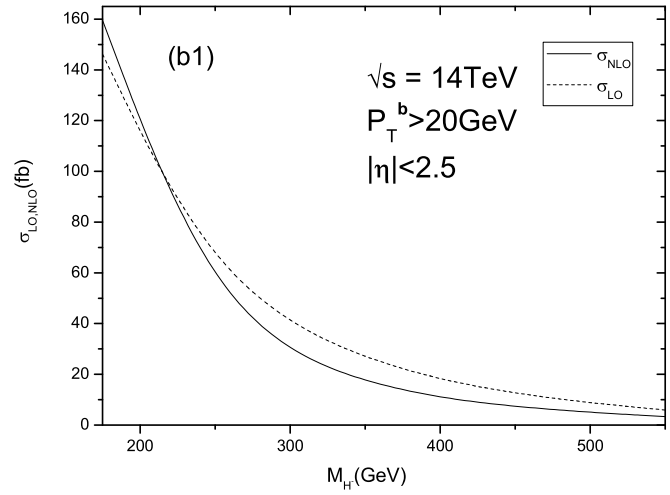




What Else

Further reading and checking

- threshold resummation at NNNLO
  possible rate enhancement of $\sim 15\%$ [Kidonakis]
- NLO corrections to exclusive $gg \to \bar{b}tH^-$ [Peng et al]



Outlook

- charged Higgs physics exciting from QCD and SUSY point of view
- many channels computed, what else do you need us to think about?

$\Rightarrow$ Let's go and find that thing!