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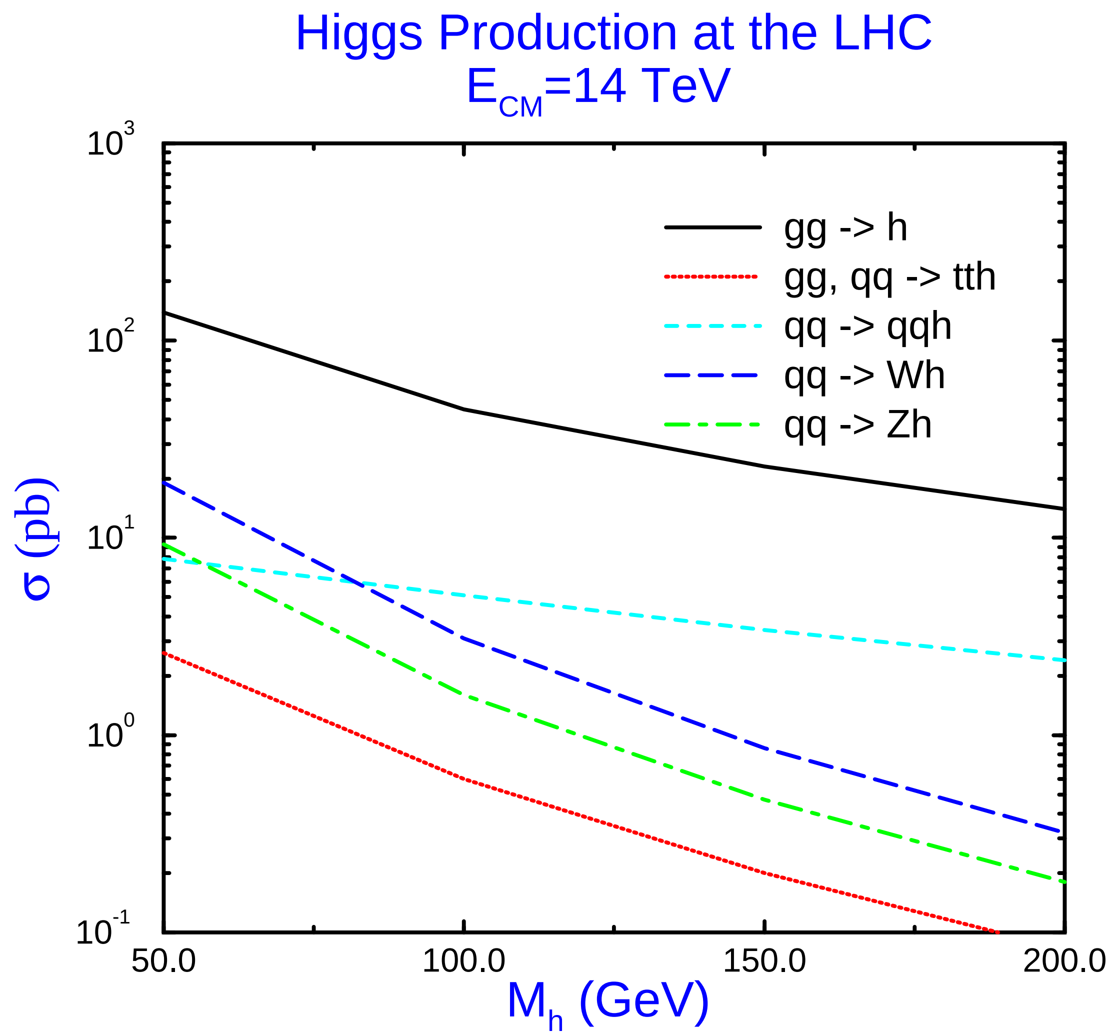
June, 2001

Higgs Boson Production Rates

- How well do we know production rates?
  - NLO, NNLO calculations
  - Dependence on scale, α_s, m_b...
- How well do we need to know rates?
- What about SUSY?
  - How to scan parameter space
  - Large SUSY radiative corrections?
- Action items for Snowmass

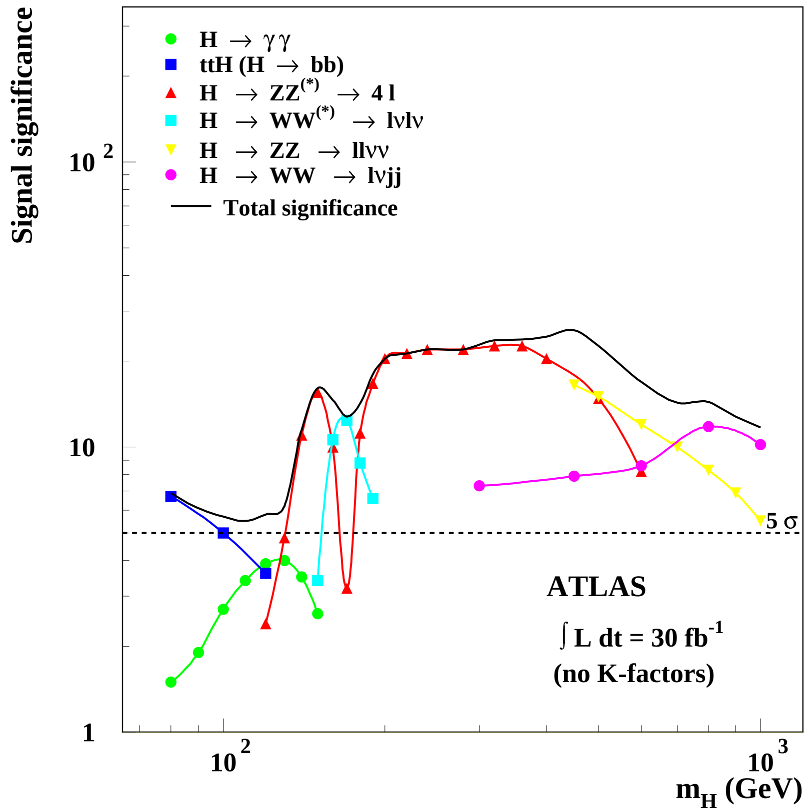
Searches at LHC

- $gg \rightarrow h, VV \rightarrow h$ most important channels for extracting Higgs couplings



(NLO results)

- NLO results exist for all signals
- K factors not included in analysis

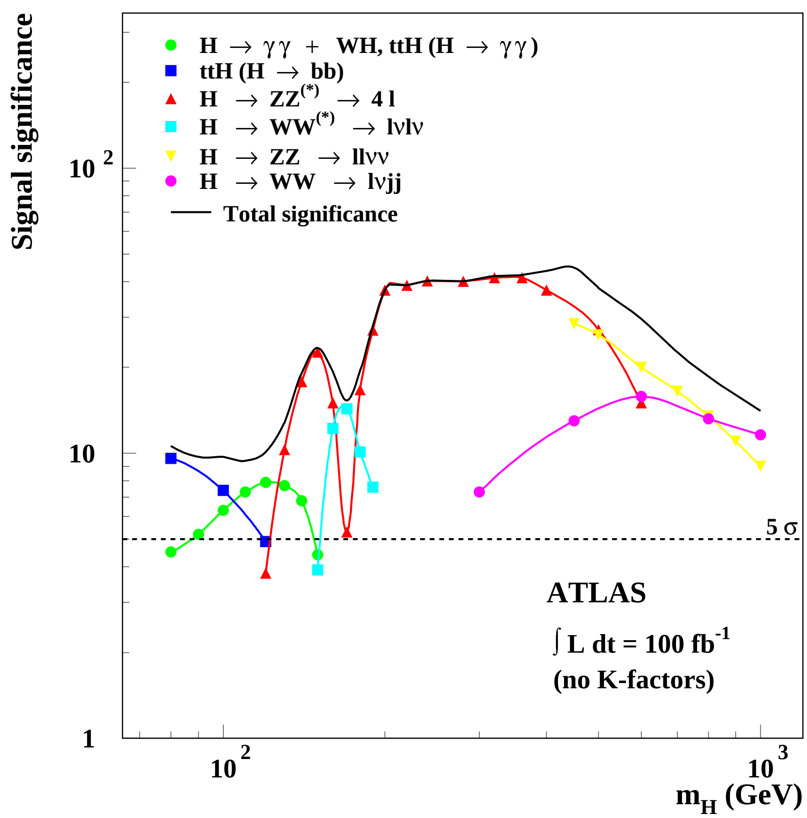


[ATLAS TDR]

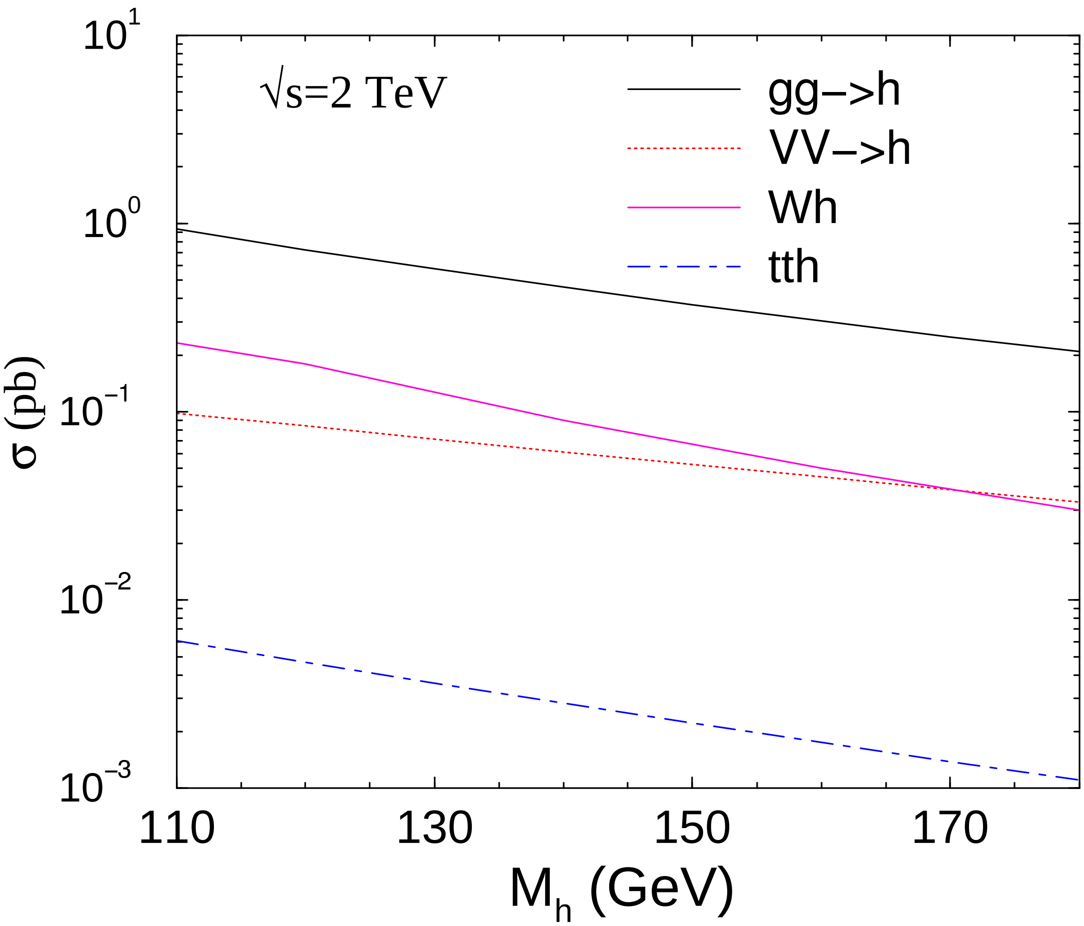
Action item for Snowmass:

- Understand which backgrounds need NLO corrections

- With higher luminosity, Higgs observable in several channels in most mass regions



Tevatron Rates:



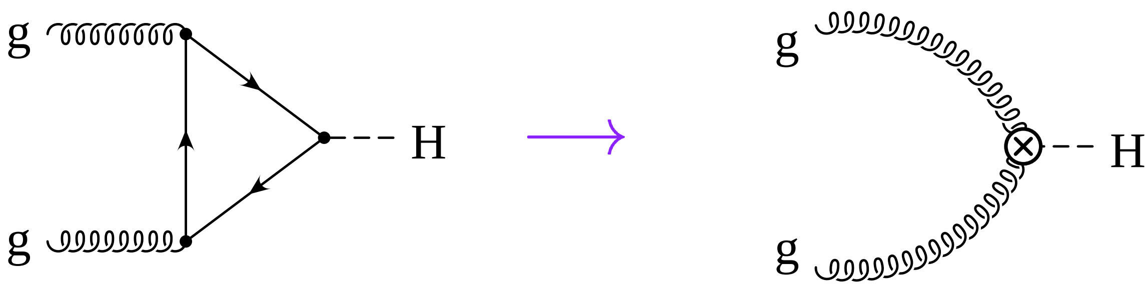
(NLO)

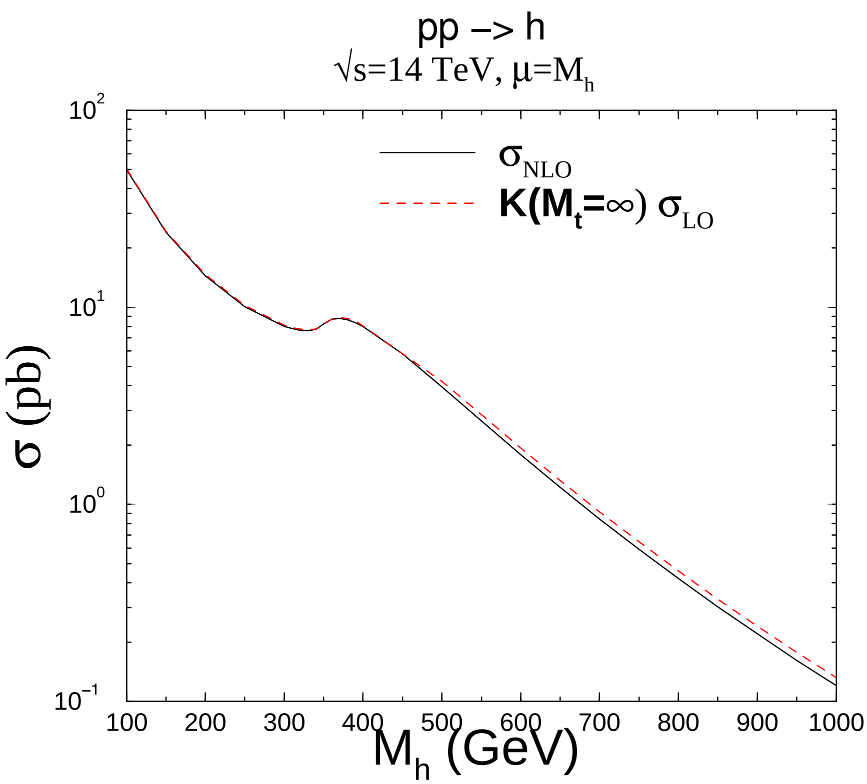
- NLO corrections to $gg \rightarrow h$ well known

[Dawson, NPB359 (1991) 283

Djouadi, Spira, Zerwas, PLB264 (1991) 440]

- $M_t \rightarrow \infty$ limit excellent approximation





Progress in NNLO calculations for $gg \to h$

- NLO results suggest $M_t \to \infty$ limit good approximation
- Virtual corrections: 3 loops $\to$ 2 loops for $M_t \to \infty$

  [Harlander, PLB492 (2000) 74]
- Soft terms included at NNLO

  [Harlander, Kilgore, hep-ph/0102241;

Catani, Florian, Grazzini, hep-ph/0102227]

- Leading contributions as $z = \frac{M_h^2}{\hat{s}} \to 1$:

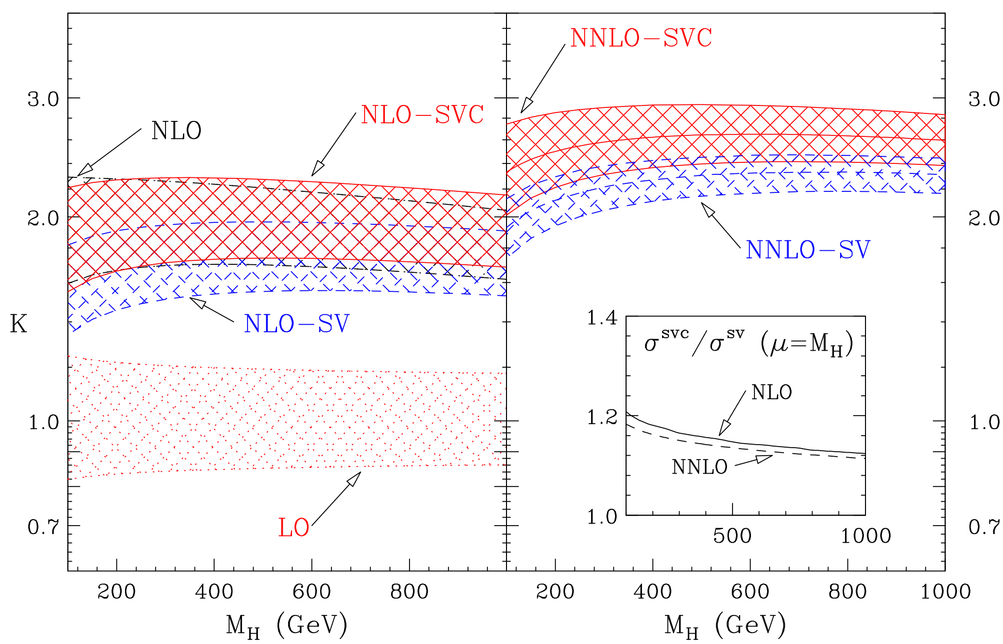
$$\delta\left(1-z\right), \left(\frac{\log^i\left(1-z\right)}{1-z}\right)_+$$

- At NLO, soft terms underestimate exact result by $\sim 15-20\%$

- Sub-leading collinear terms from resummation calculation:

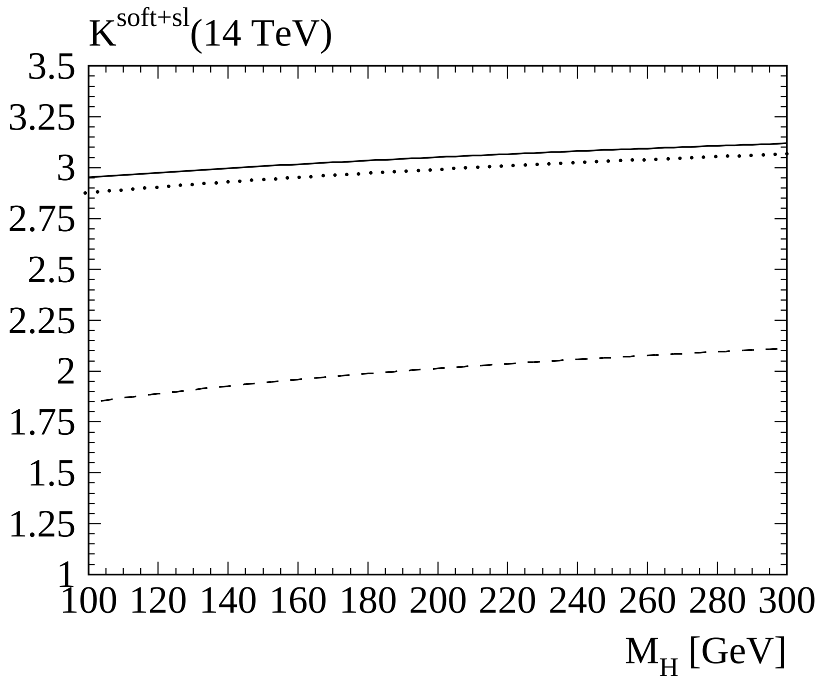
$$\log^3(1-z), \log^2(1-z), \log(1-z)$$

[Kramer, Laenen, Spira, NPB511 (1998) 523]



[Catani *etal*]

- Includes only $\log^3(1-z)$ term, uses MRST NNLO pdfs
- Bands correspond to $\frac{M_h}{2} < \mu < 2M_h$
- NNLO corrections are large

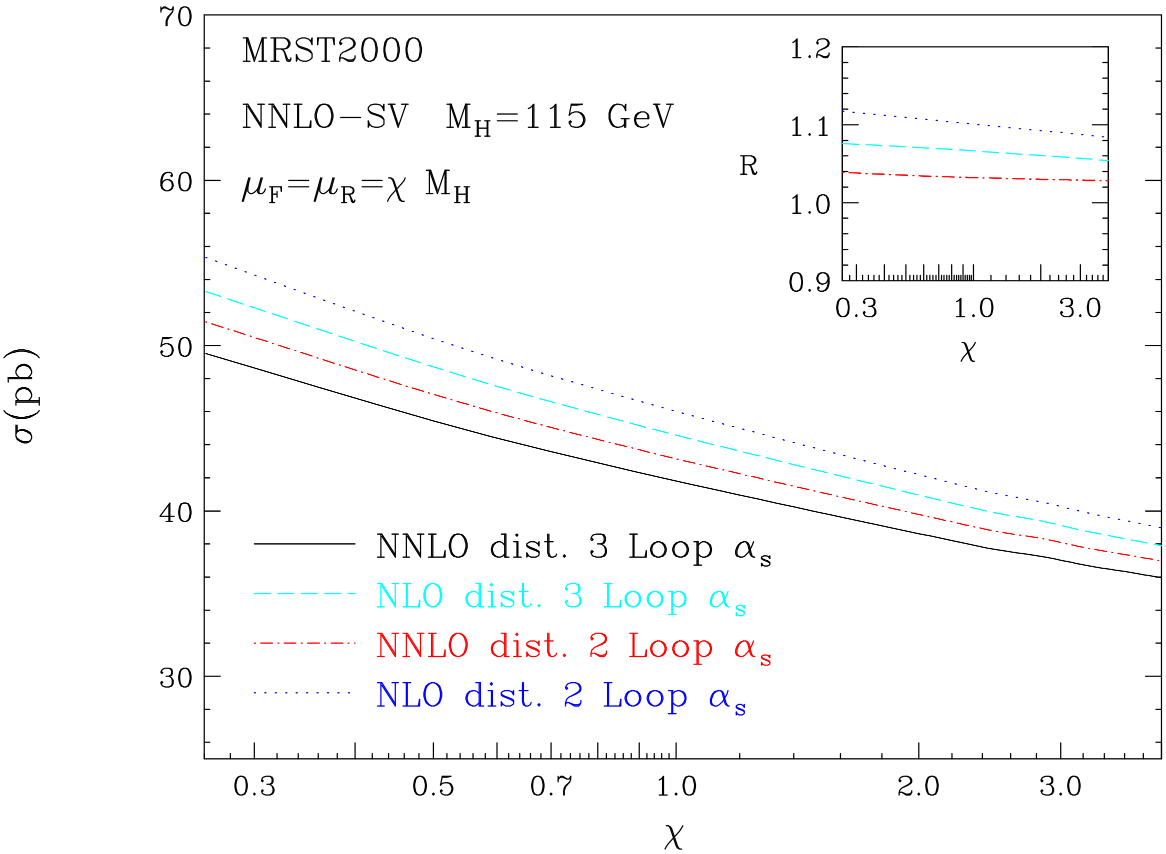


[Harlander and Kilgore]

- Exact analytic agreement between groups
- Includes $\log^i(1-z)$, i=1,2,3 terms, uses NLO pdfs
- $\sim$ 25% difference with Catani *etal*

Only partial NNLO pdfs exist

[MRST, Eur. Phys. J. C18 (2000)117]



8% difference between NNLO/NLO pdfs

Conclusions on gluon fusion:

- Need complete NNLO pdfs (8% difference between NNLO/NLO pdfs)
- Inclusion of subleading $log^2(1-z), log(1-z)$ terms 20% difference
- Need complete NNLO calculation!
- Best estimate: still have $\sim$ 35% uncertainty from scale dependence, unknown NNLO terms, pdfs, α_s

Action item for Snowmass:

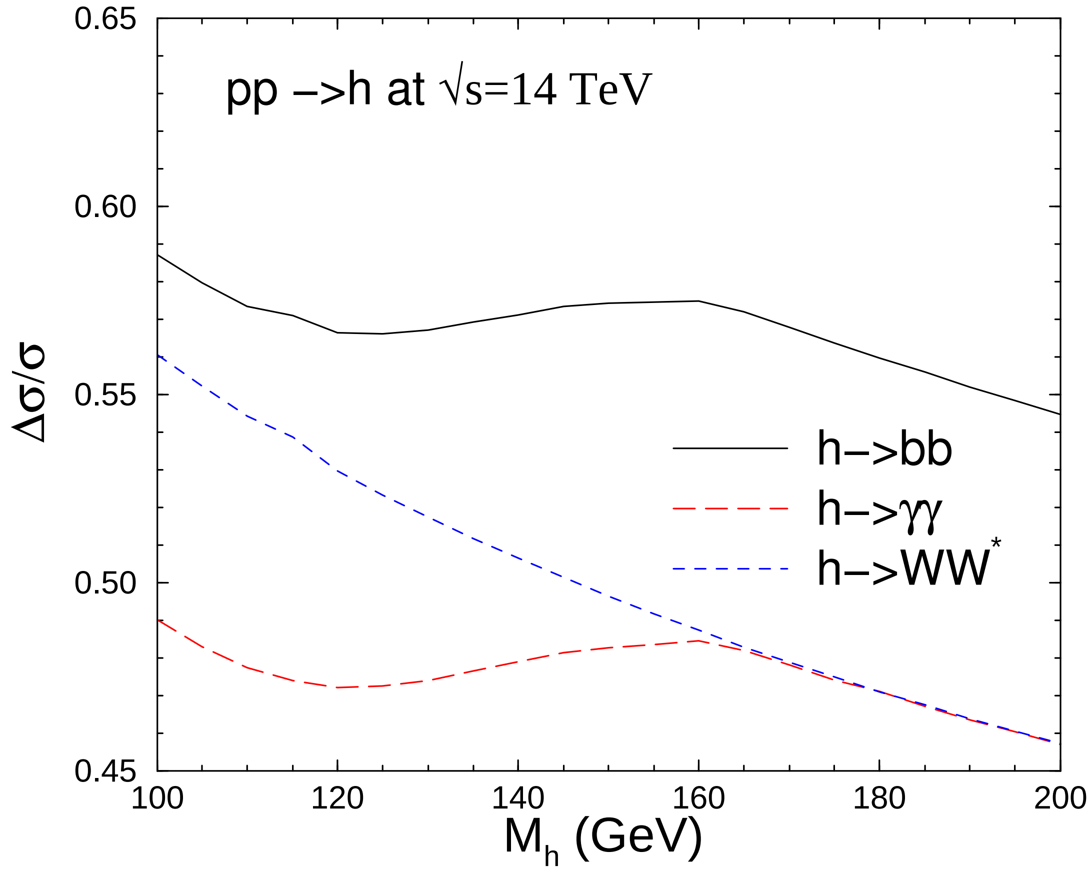
- Quantify uncertainty on $\sigma(gg \to h)$
- Feed into precision measurements group

Uncertainties on $gg \rightarrow h$

$$\frac{M_h}{2} < \mu < 2M_h$$

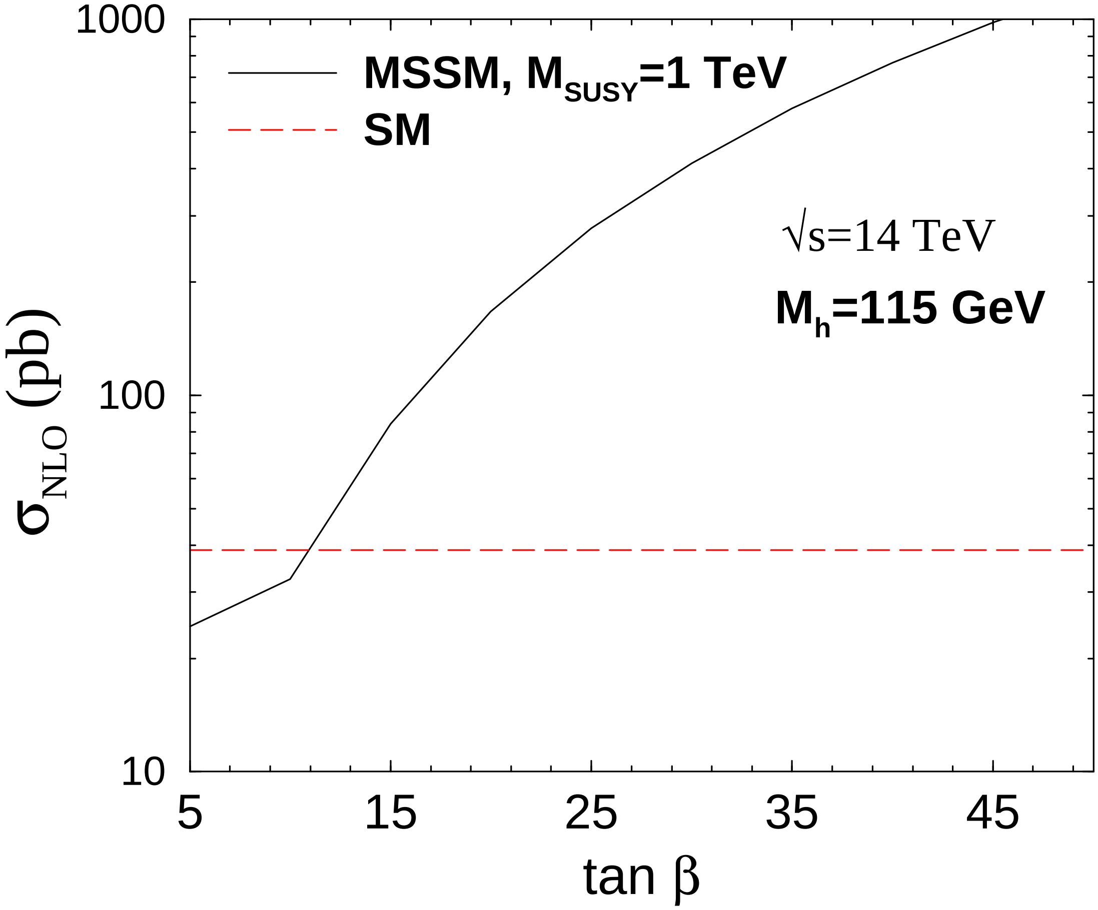
$$.115 < \alpha_s(M_Z) < .123$$

$$4.5\ GeV < m_b(m_b) < 5.0\ GeV$$

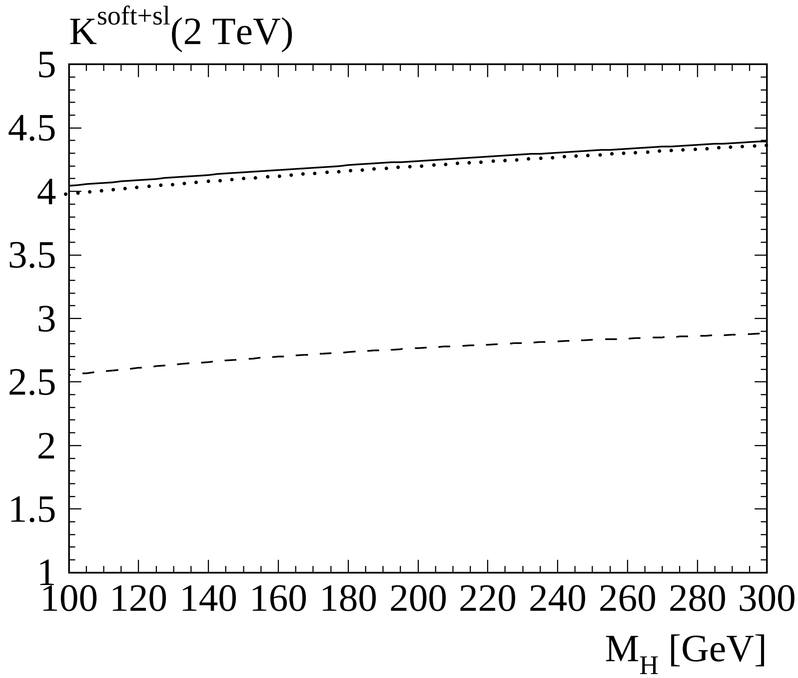


(NLO results)

- $gg \to h$ rate sensitive to SUSY parameters



- NNLO corrections to $gg \to h$ give huge effect at Tevatron:

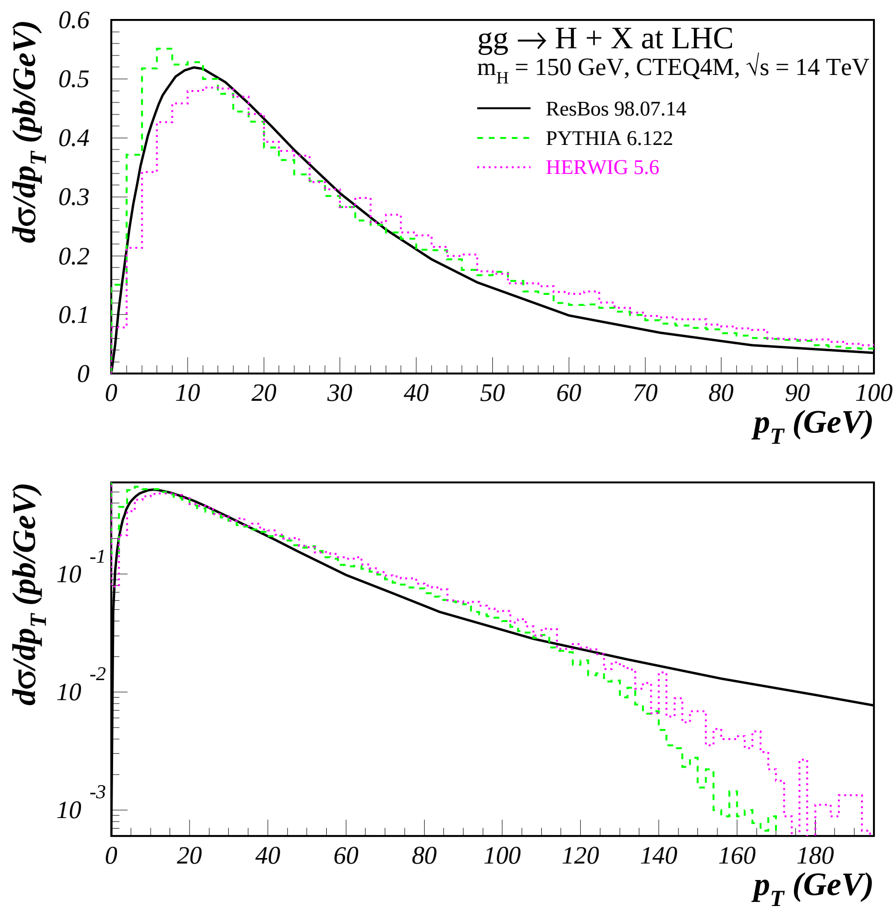


[Harlander and Kilgore]

- $gg \to h \to WW^*$ important near WW threshold at Tevatron

Higgs p_T distributions at LHC

- MCs need $qg \to qh$, $q\bar{q} \to gh$, $gg \to gh$ to get high p_T spectrum right



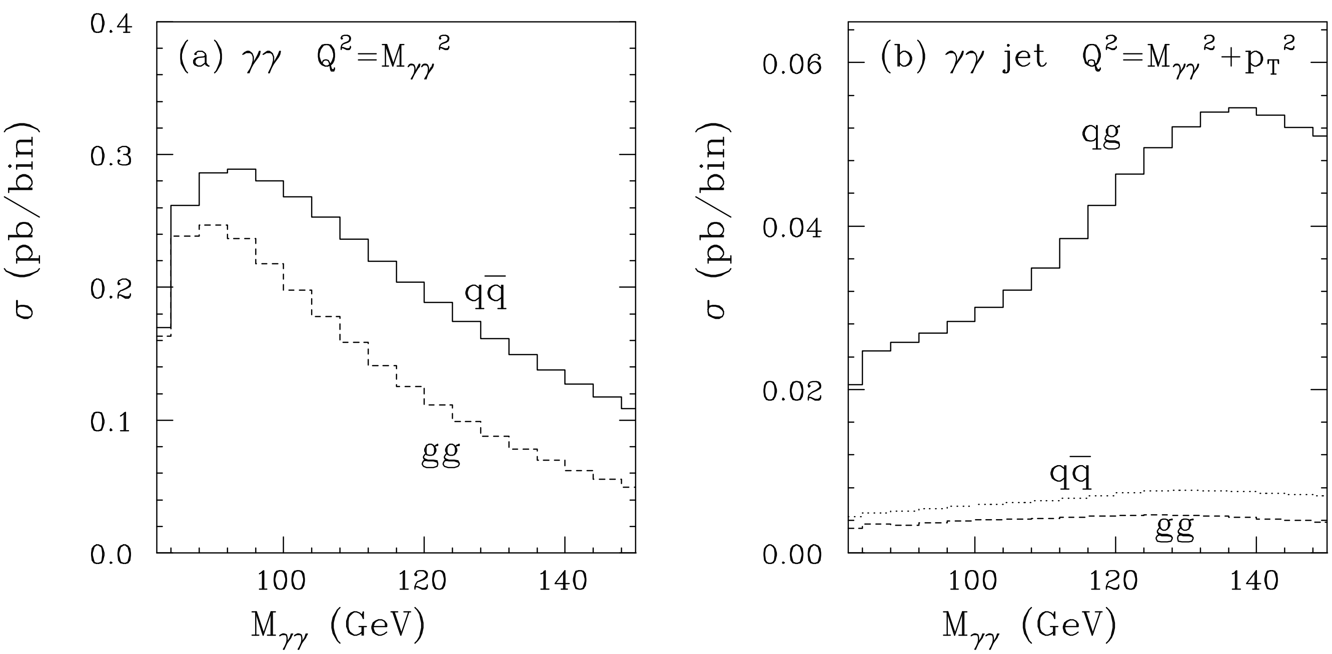
[Les Houche study, hep-ph/0005114; Balazs, Huston, Puljak, PRD63 (2001) 014021]

Higgs + jet production:

- Try to improve signal/background of $h \to \gamma\gamma$ by looking at $h \to \gamma\gamma$ plus jet production

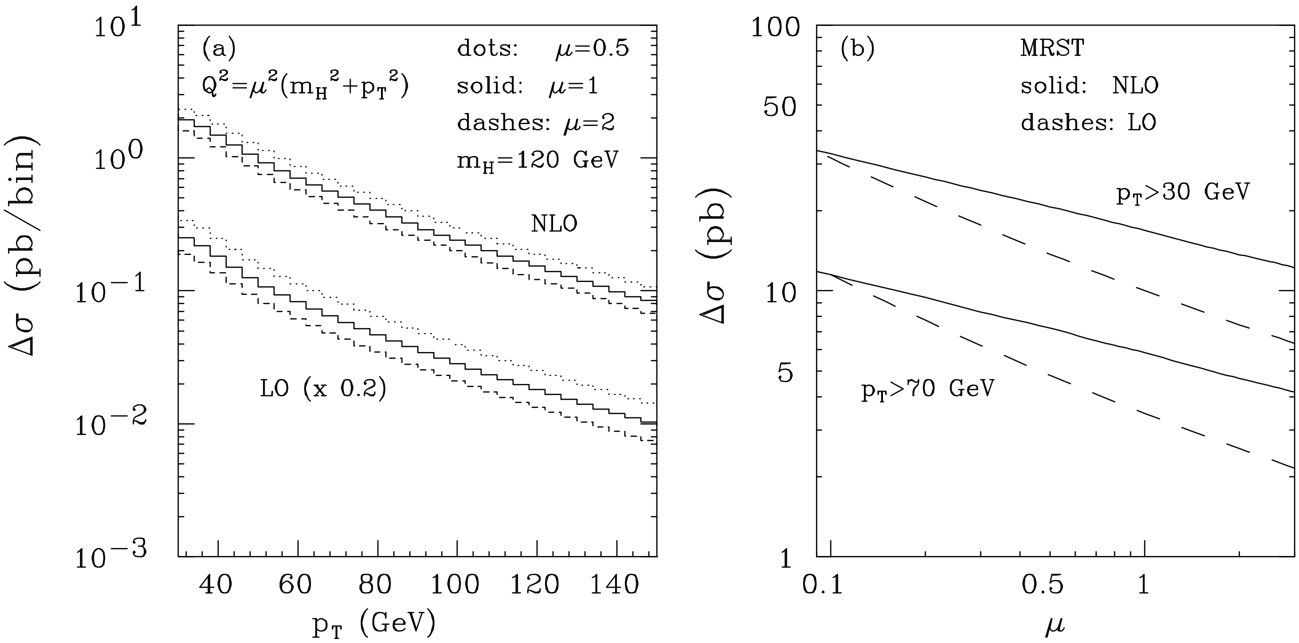
$$S/B \sim 1/2$$

- Roughly 100 events with $\mathcal{L} = 30 \ \ fb^{-1}$
- Can get K factor for signal using large M_t expansion; $K \sim 1.6$
- Need NLO calculation of background!
- Dominant contribution to $\gamma\gamma$ jet from qg initial state, so higher order corrections to background under better control than inclusive process



[deFlorian, Grazzini, Kunszt, PRL 82 (1999) 5209]

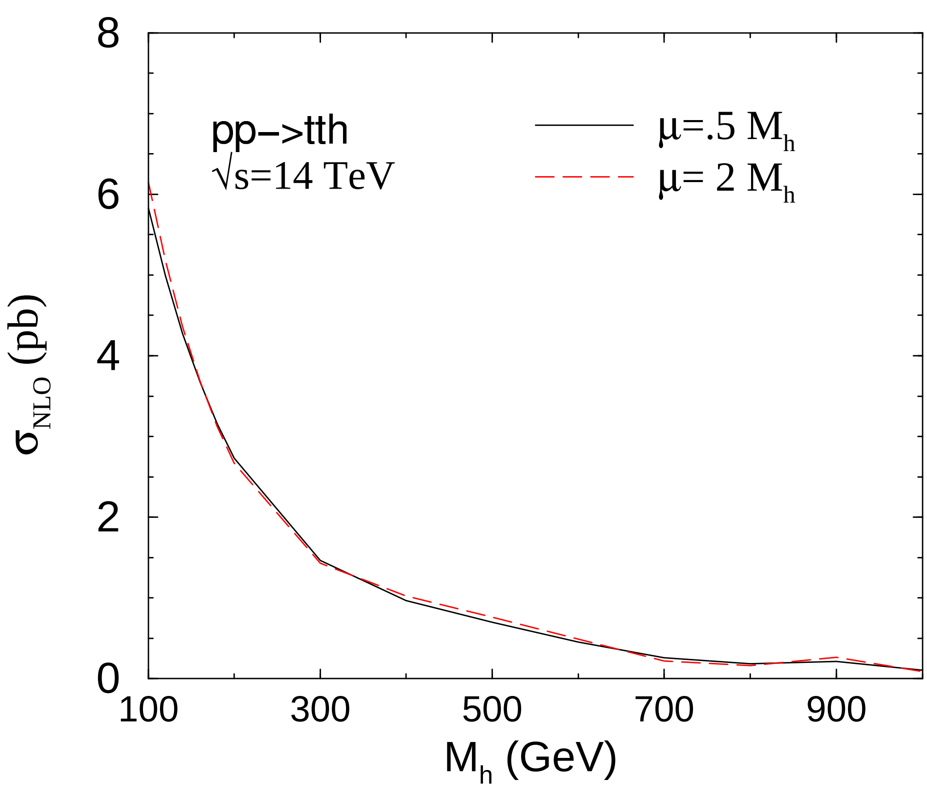
$\gamma\gamma$ jet to NLO:



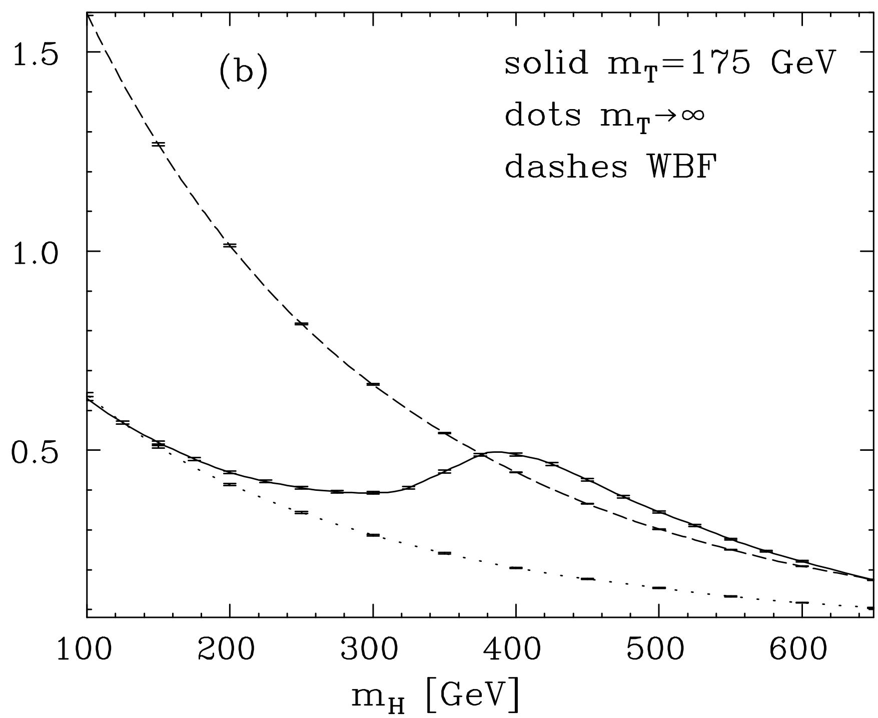
Vector Boson Fusion

$$pp \to qq'h$$

- WWh, ZZh useful for measuring h couplings
- Relatively insensitive to gluon pdfs, α_s, scale
- Theoretical uncertainty $\sim\ 1-2\%$



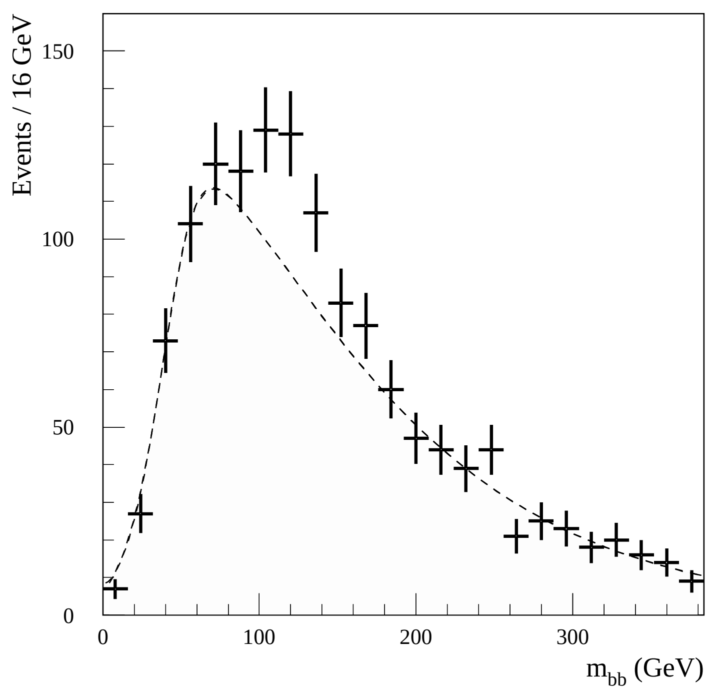
- Can we separate Vector Boson Fusion from QCD backgrounds?
- What about $gg \to q\bar{q}h$?
- Cuts designed to enhance VBF contribution



[DelDuca *etal*, hep-ph/0105129]

$pp(p\bar{p}) \rightarrow t\bar{t}h$

- Direct measurement of $t\bar{t}h$ coupling
- $h \rightarrow b\bar{b}$; final state is $W^+W^-b\bar{b}b\bar{b}$
- 1 W decays semi-leptonically, other hadronically; fully reconstruct both tops
- ATLAS with $\mathcal{L} = 100\ fb^{-1}$, $M_h = 120\ GeV$ can measure $\frac{\delta g_{tth}}{g_{tth}} \sim 16\%$



[LHC Top Study, hep-ph/0003033]

- Complete NLO calculation of $pp \to t\bar{t}h$

  [Beenacker *et al*;

  Reina *et al* in progress]

- Dominant effect from:

$$gg \to t\bar{t}$$

$$t \to th$$

  (Effective Higgs Approximation)

  [Dawson and Reina, hep-ph/9712400]

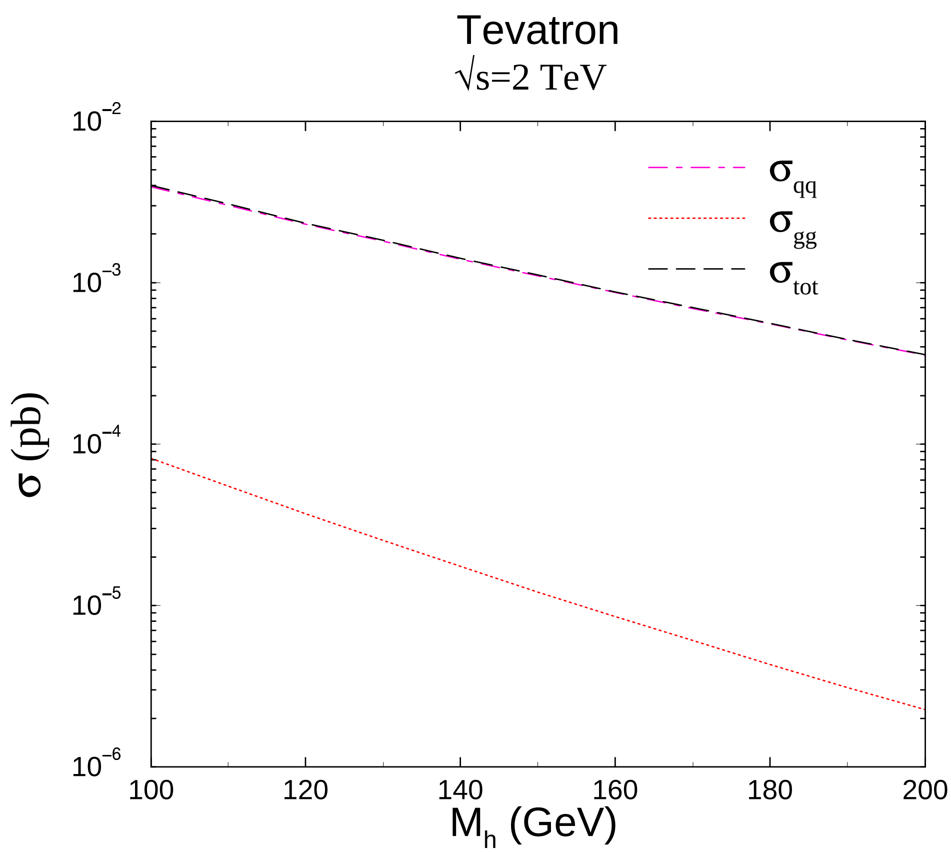
- $K_{LHC}(pp \to t\bar{t}h)^{EHA} \sim 1.2$

  (for $\mu = M_t + \frac{M_h}{2}, M_h \sim 120 \;\; GeV$)

- K factor defined using LO pdfs, 1-loop α_s for σ_{LO}, NLO pdfs, 2-loop α_s for σ_{NLO}

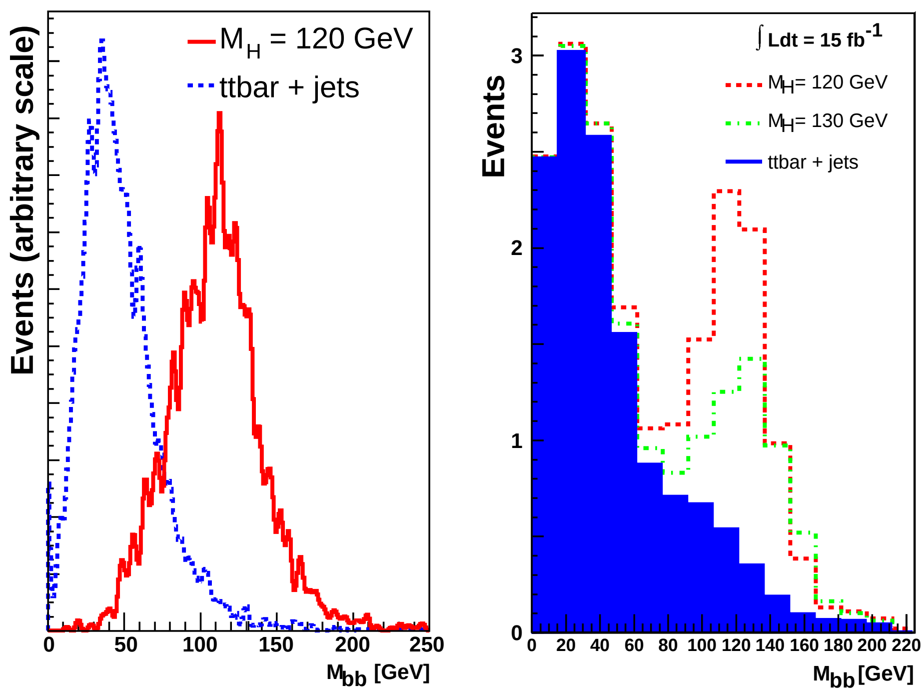
$t\bar{t}h$ at the Tevatron

- $q\overline{q}$ initial state dominant contribution at the Tevatron
- gg initial state dominates at LHC
- Note small rate!

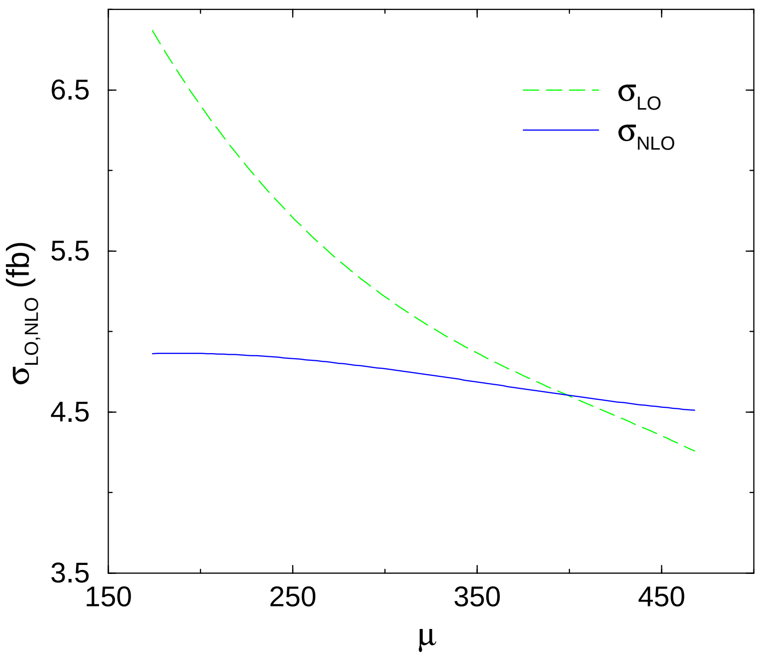


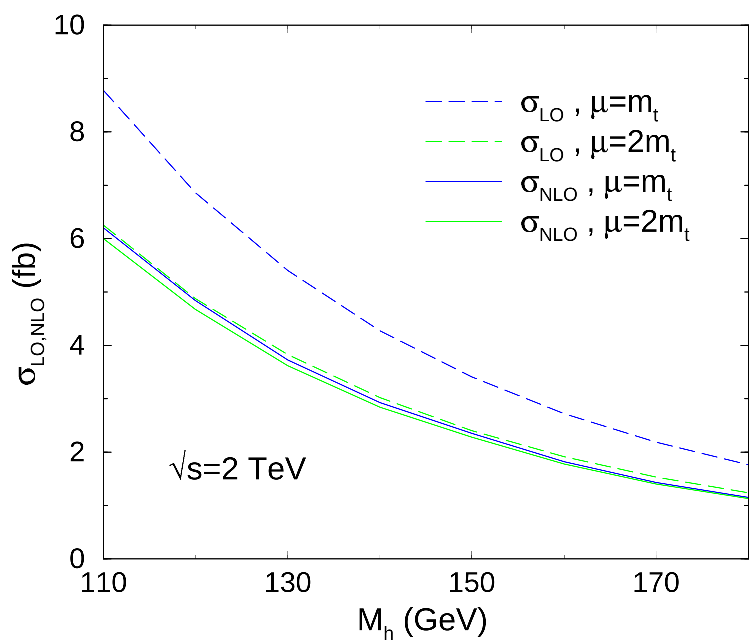
- Signal, background different shapes at Tevatron
- Small rate: 4 b tags, 15 fb^{-1} gives 7 signal and 40 background

[J. Goldstein et.al., hep-ph/0006311]



- NLO result shows reduced scale dependence; smaller rate





[Reina and Dawson; Beenacker *etal*]

More on NLO corrections to $p\bar{p} \rightarrow t\bar{t}h$

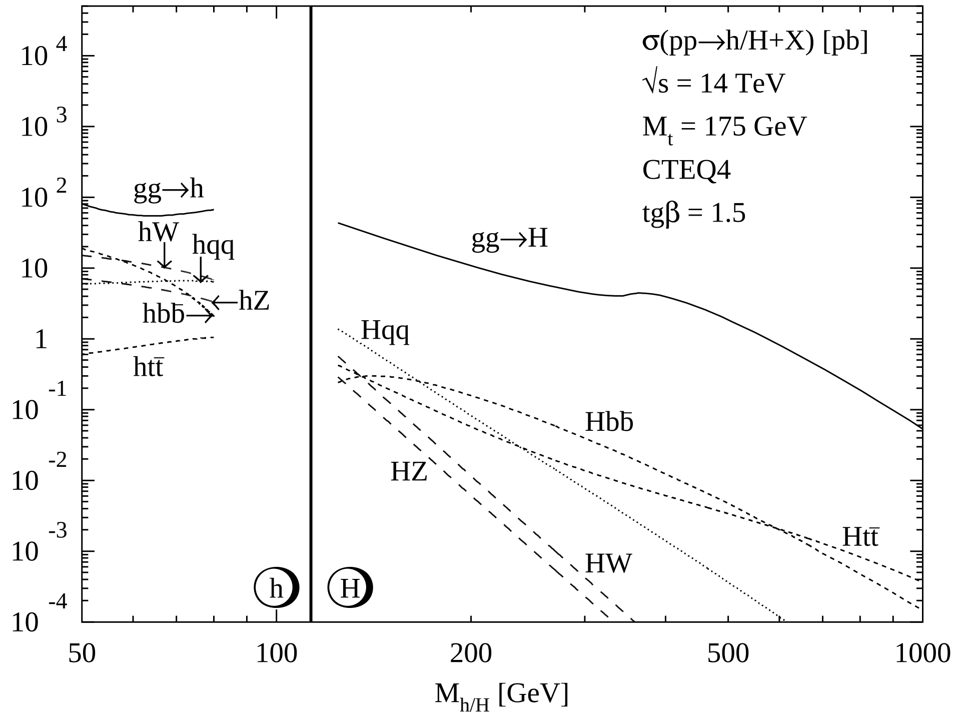
- Why is $K_{TeV} < 1$?
- At Tevatron, $t\bar{t}h$ produced close to threshold in color octet

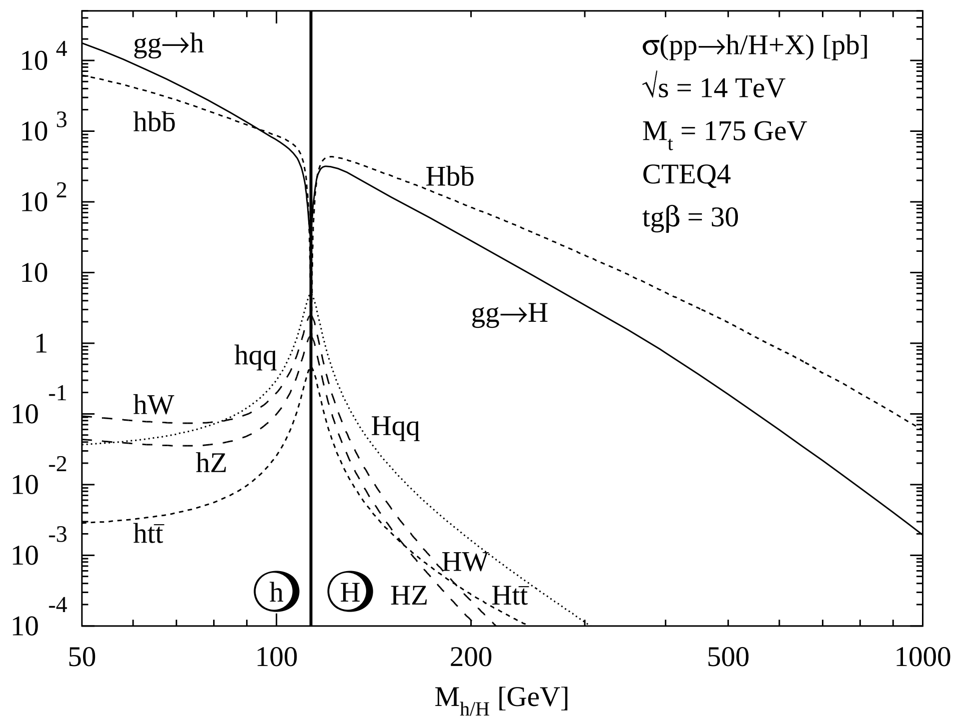
  $K_{threshold} \sim 1 - \frac{\alpha_s}{\beta}$
- At $\sqrt{s} >> M_t, M_H$, EHA $\longrightarrow$

$$K \sim K_{q\bar{q} \rightarrow t\bar{t}} K_{t \rightarrow th} < 1$$

See talk this afternoon by Reina

SUSY RATES:


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 1.5
gg→h
hW
hqq
hZ
hbb̄
htt̄
gg→H
Hqq
Hbb̄
HZ
HW
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_h/H [GeV]



[Spira, hep-ph/9711407]

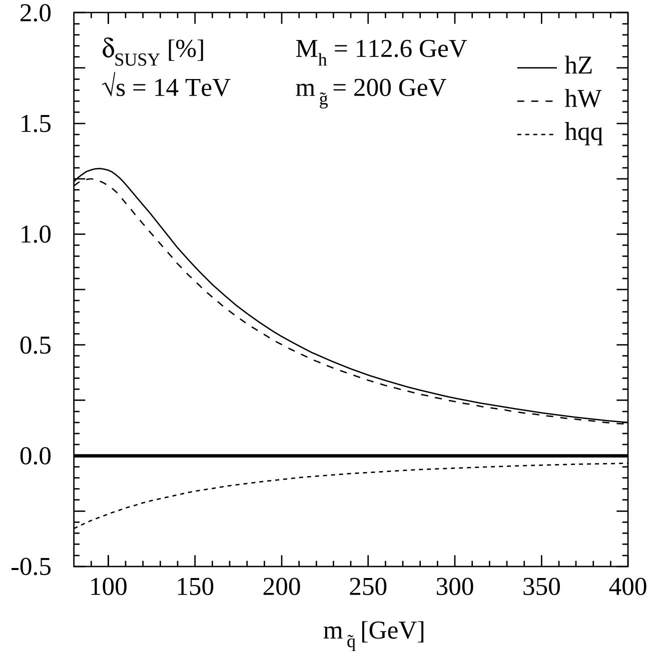
(NLO; except $t\bar{t}h$)

What about SUSY loop Corrections?

- SUSY is decoupling theory $\longrightarrow$ effects small for large SUSY masses
- Consider squark and gluino loops
- Effects $\sim .5 - 2\%$ at Tevatron, LHC

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} \equiv K_{QCD} + \delta_{SUSY}$$

[Djouadi and Spira; hep-ph/9912476]



2.0
1.5
1.0
0.5
0.0
-0.5
δ_{SUSY} [%]
$\sqrt{s}$ = 14 TeV
M_h = 112.6 GeV
$m_{\tilde{g}}$ = 200 GeV
hZ
hW
hqq
100
150
200
250
300
350
400
$m_{\tilde{q}}$ [GeV]

Conclusions

Action Items for Snowmass:

- Lots of QCD in Higgs physics!
- Understand uncertainties in predictions
- What can we learn from measurements?
- Starting to see need for NNLO calculations
- Need NNLO pdfs