S. Dawson

June, 2000

QCD and New Physics

- The Higgs Sector
  - Motivation for precision Higgs studies
  - Corrections to production rates, branching ratios, etc
    Example 1: $gg \to h$, NLO result in heavy top quark limit
    Example 2: $h \to b\overline{b}$; which m_b?
  - Uncertainties in theoretical predictions
    pdf dependence, renormalization scale dependence,...
    How do uncertainties affect precision measurements of Yukawa couplings?
  - Backgrounds from multi-jet processes

- Non-Standard Model Interactions
  - Small effects: QCD uncertainties vs new physics
    Example 3: Three gauge boson interactions at the LHC
    How can we tell new physics effects from QCD uncertainties?
- Conclusions

Review of Standard Model

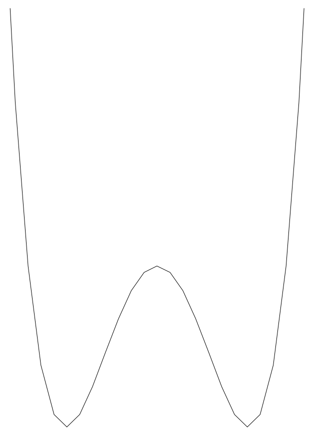
Standard model includes Higgs doublet, Φ

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

with scalar potential

$$V = \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

If $\mu^2 < 0$ then spontaneous symmetry breaking:



$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Couple Φ to $SU(2) \times U(1)$ gauge bosons

$$\mathcal{L}_s = \left(D^\mu \Phi\right)^\dagger \left(D_\mu \Phi\right) - V\left(\Phi\right)$$

$$D_\mu = \partial_\mu + i\frac{g}{2}\tau \cdot W_\mu + i\frac{g'}{2} B_\mu .$$

Generate mass for W, Z; h physical particle, $\phi_3 = (\frac{v+h}{\sqrt{2}})$
(Count degrees of freedom)

Scalar couplings to fermions:

$$\mathcal{L}_f = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

with left handed $SU(2)$ fermion doublet:

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

Effective Higgs-fermion coupling:

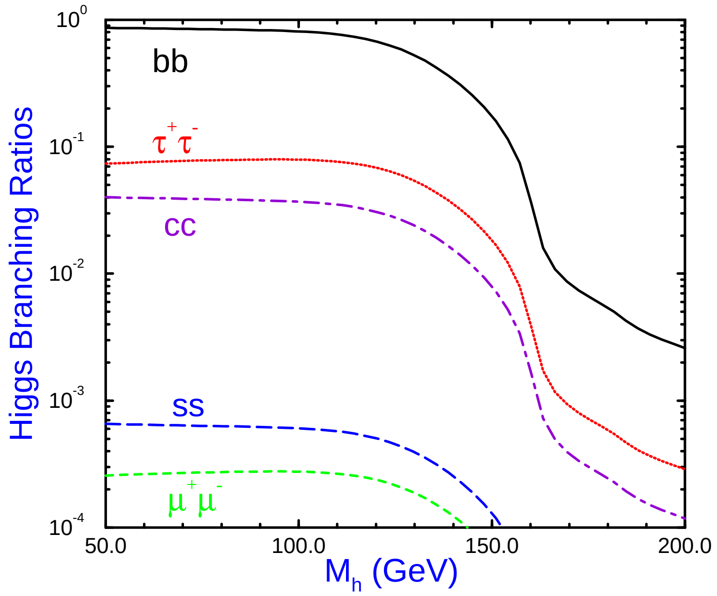
$$-\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \ \overline{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.$$

Mass term for down quark:

$$\lambda_d = \frac{m_d \sqrt{2}}{v}.$$

m_u from $i\sigma_2 \Phi^*$ (not allowed in SUSY)

- Fermion couplings fixed
- Higgs decays to heaviest fermion pair allowed (much more on this in Lecture 2)



Muon decay, $\mu \to e\nu_e\overline{\nu}_\mu$, fixes v:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

$v^2 = (\sqrt{2}G_F)^{-1} = (246\ GeV)^2$

Higgs potential has 2 free parameters, μ^2, λ
Trade for v^2, M_h^2:

$$\begin{aligned} v^2 &= -\frac{\mu^2}{2\lambda} \\ M_h^2 &= 2v^2\lambda \end{aligned}$$

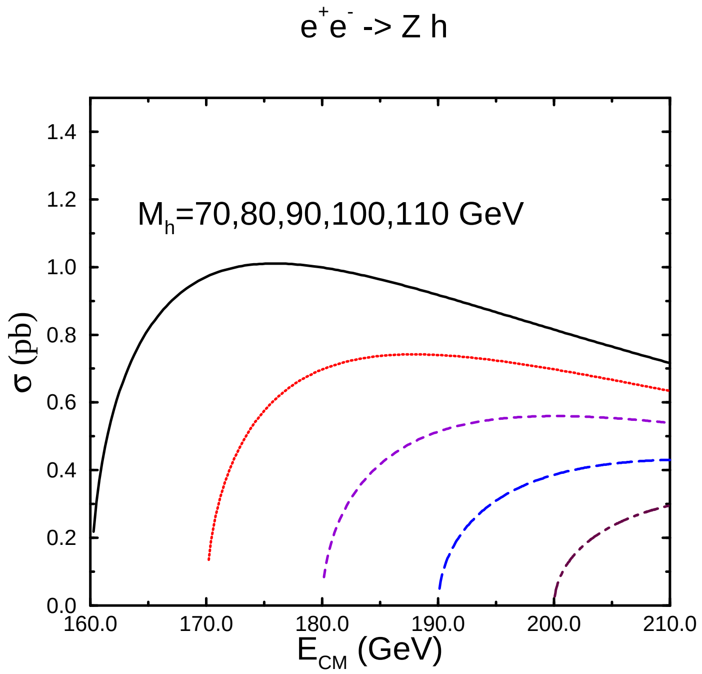
Higgs Theory testable because all couplings known!!

- Fermions: $\frac{m_i}{v}\overline{\psi}_i\psi_i h$
- Gauge Bosons, $W^{+\mu}W^{-\nu}h$: $gM_W g^{\mu\nu}$
  $Z^\mu Z^\nu h$: $\frac{gM_Z}{\cos\theta_W}g^{\mu\nu}$
- Self-couplings $\sim M_h^2$

$$V = \frac{M_h^2}{2}h^2 + \frac{M_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

- Higgs mass only free parameter; everything calculable
- Precise measurements of couplings test theory (eg, SUSY couplings can be very different from SM)

Direct Higgs Searches at LEP2



- $e^+e^- \to Zh$ (tests ZZh vertex)
- Rate turns on rapidly after threshold; best measurement at highest energy
- Searches include $Z \to e^+e^-, \mu^+\mu^-, \nu\overline{\nu}, q\overline{q}$
- Measure recoil mass of Higgs; result independent of Higgs decay

$$M_h^2 = s - 2\sqrt{s}E_Z + M_Z^2$$

- Current LEP2 limit (4 experiments):

$$\sqrt{s_{max}} = 202 \;\; GeV, \; \int \mathcal{L} = 900 \;\; pb^{-1}$$

$$M_h > 107.7 \;\; GeV$$

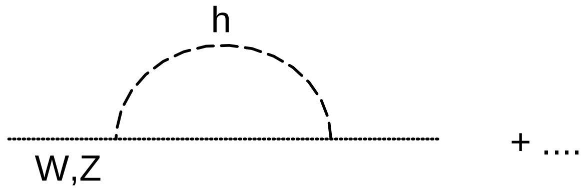
Limits from Precision Measurements

Higgs contributes to radiative corrections:

- Without a Higgs boson EW radiative corrections are infinite:

$$\frac{\delta M_W^2}{M_W^2} = \frac{3\alpha}{16\pi \sin^2\theta_W}\frac{1}{\epsilon}$$

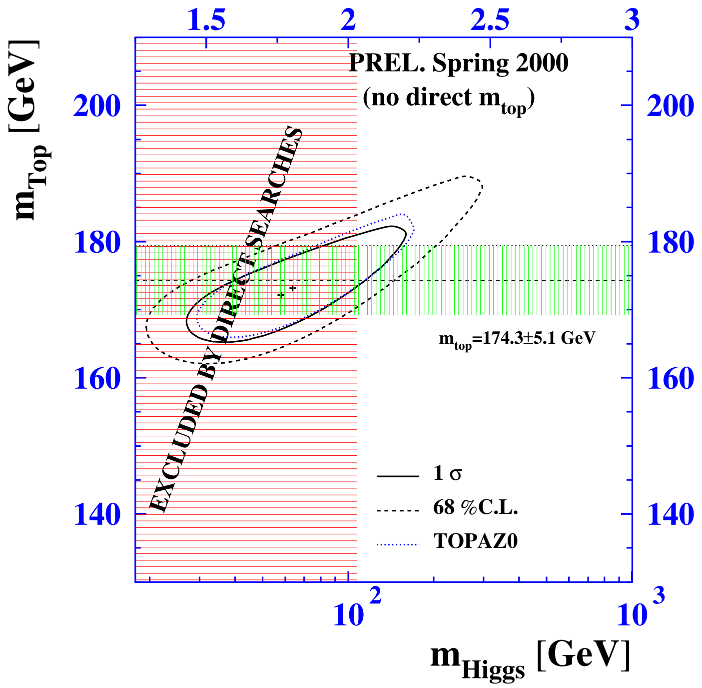
Singularity cancelled by Higgs:



- Contributions to EW observables $\sim log(M_h)$

$$\delta\rho = \frac{11 g^2}{96\pi^2 \tan^2\theta_W} \log\left(\frac{M_h}{M_W}\right)$$

- Limits on M_h from radiative corrections assume SM



Consistency of theory tells us more...

$$V \sim -\mid \mu^2 \mid h^2 + \lambda h^4$$

- This is potential at electroweak scale
- Parameters evolve with energy
- For large λ,

$$\frac{d\lambda}{d\log\left(\mu^2\right)} \sim \frac{3\lambda^2}{4\pi^2}$$

- Solve:

$$\frac{1}{\lambda\left(\Lambda^2\right)} = \frac{1}{\lambda\left(v^2\right)} - \frac{3}{4\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

- Need:

$$\frac{1}{\lambda\left(\Lambda\right)} > 0$$

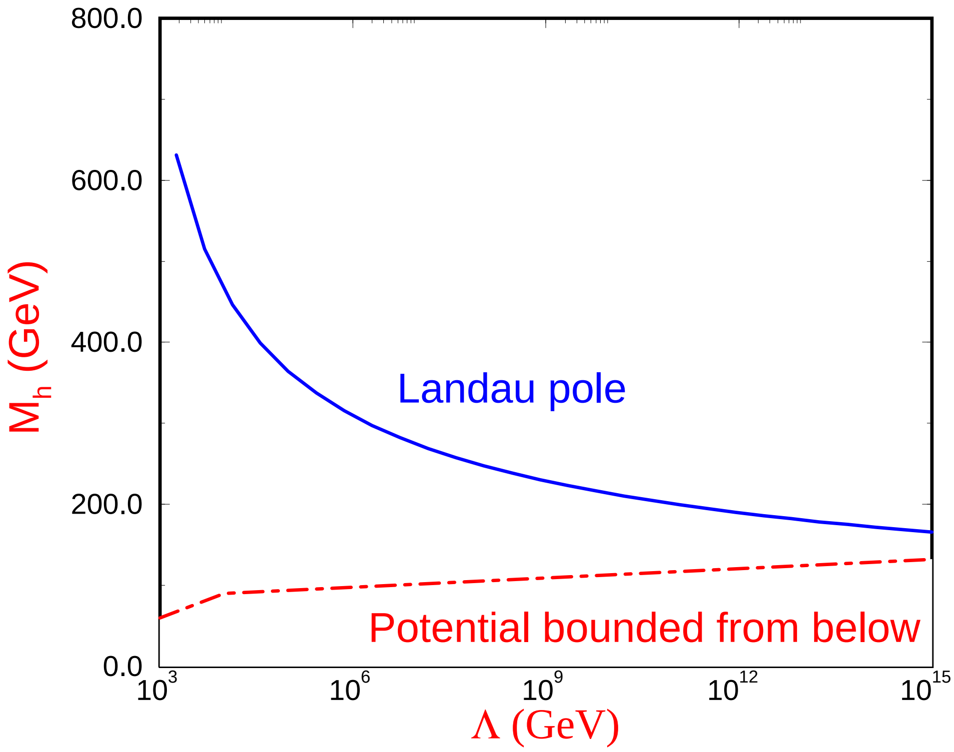
$$M_h^2 < \frac{8\pi^2 v^2}{3\log\left(\Lambda^2/v^2\right)}$$

- Suppose $\lambda(\Lambda) < 0$?

  $\longrightarrow$ potential unbounded from below

  $\longrightarrow$ lower bound on M_h

- For any given scale, Λ, theoretically consistent range for M_h



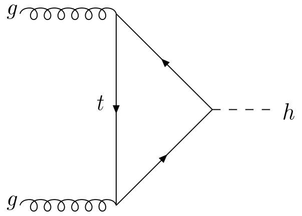
- SM direct search plus precision measurements

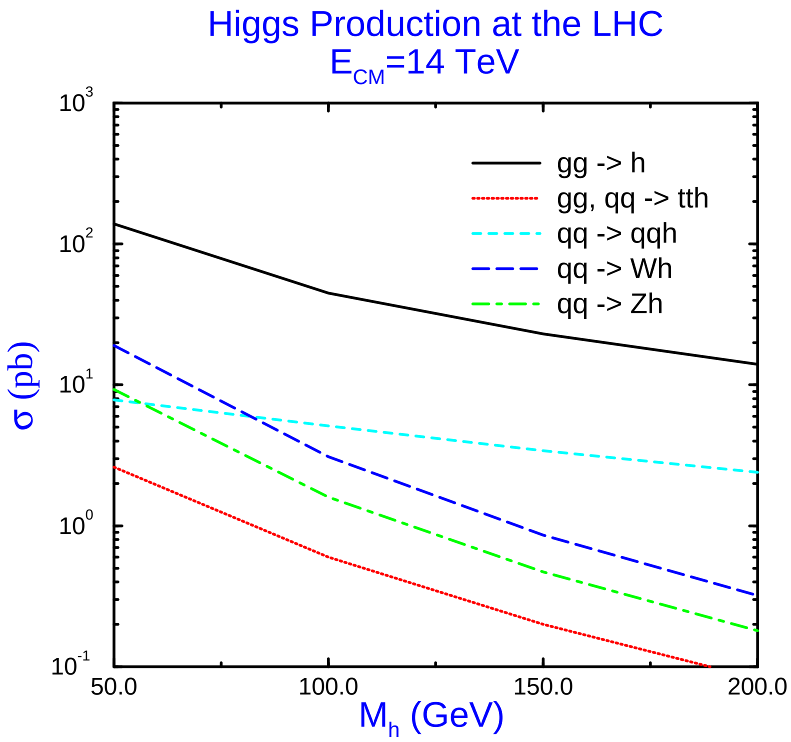
$$108\ GeV < M_h < 190\ GeV$$

- Extraordinary effort focused on $M_h \sim 100 - 200\ GeV$
- Either light Higgs or new physics at scale $\sim \Lambda$
- Can we avoid a light Higgs?

Searches at LHC

Gluon fusion dominant production mechanism at LHC





- Gluon fusion counts number of heavy quarks
- SM dominant contribution from top quark loop
- In SUSY models, b contribution can be enhanced
- $\int \mathcal{L} = 10^{34}/cm^2/sec$ gives about 10^5 Higgs/yr

Lowest order cross section:

$$\hat{\sigma}\left(gg \rightarrow h\right) = \frac{\alpha_s^2}{1024\pi v^2} \mid \sum_q F_{1/2}\left(\tau_q\right) \mid^2 \delta\left(1 - \frac{\hat{s}}{M_h^2}\right)$$
$$\equiv \hat{\sigma}_0\left(gg \rightarrow h\right) \delta\left(1 - \frac{\hat{s}}{M_h^2}\right)$$

- $\tau_q \equiv 4M_q^2/M_h^2$, $\hat{s}$ is gg center of mass energy
- Light quark contributions small

$$F_{1/2}\left(\tau_q\right) \equiv -2\tau_q\left[1 + \left(1 - \tau_q\right) f\left(\tau_q\right)\right]$$
$$f\left(\tau_q\right) = \left[\sin^{-1}\left(\sqrt{1/\tau_q}\right)\right]^2, \qquad \text{if } \tau_q \geq 1$$
$$= -\frac{1}{4}\left[\log\left(\frac{x_+}{x_-}\right) - i\pi\right]^2, \qquad \text{if } \tau_q < 1$$

with

$$x_\pm = 1 \pm \sqrt{1 - \tau_q}$$

Heavy quark limit, $(M_t/M_h) \rightarrow \infty$:

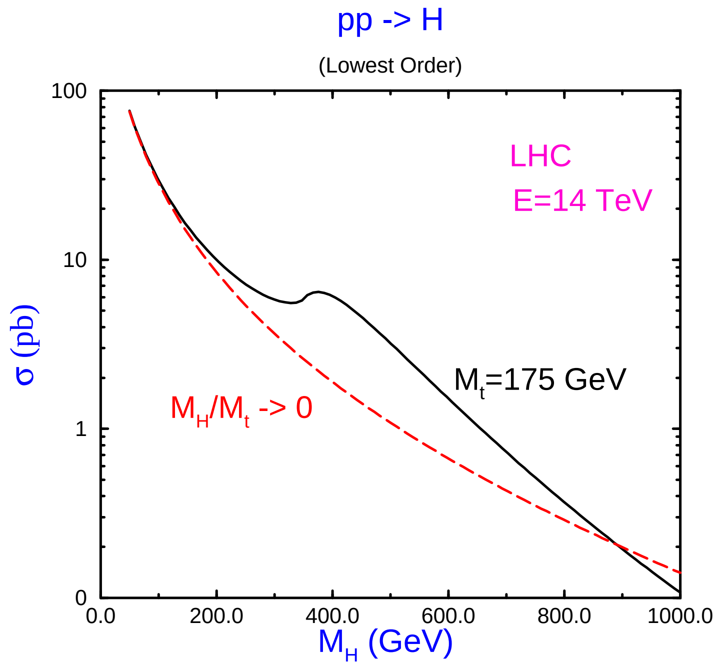
$$F_{1/2} \rightarrow -\frac{4}{3}$$
$$\hat{\sigma}_0\left(gg \rightarrow h\right) \rightarrow \frac{\alpha_s^2}{576\pi v^2}$$

- Good approximation to rate below $t\bar{t}$ threshold
- Higgs couplings violate unitarity for $M_h \sim 800\ GeV$

Integrate with gluon structure functions:

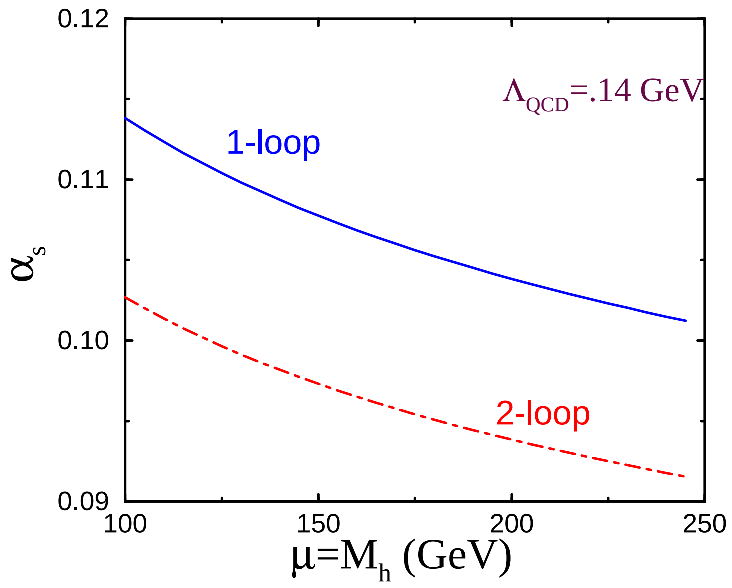
$$\sigma_0\left(pp \to h\right) = \hat{\sigma}_0 \tau \int_\tau^1 \frac{dx}{x} g\left(x\right) g\left(\frac{\tau}{x}\right),$$

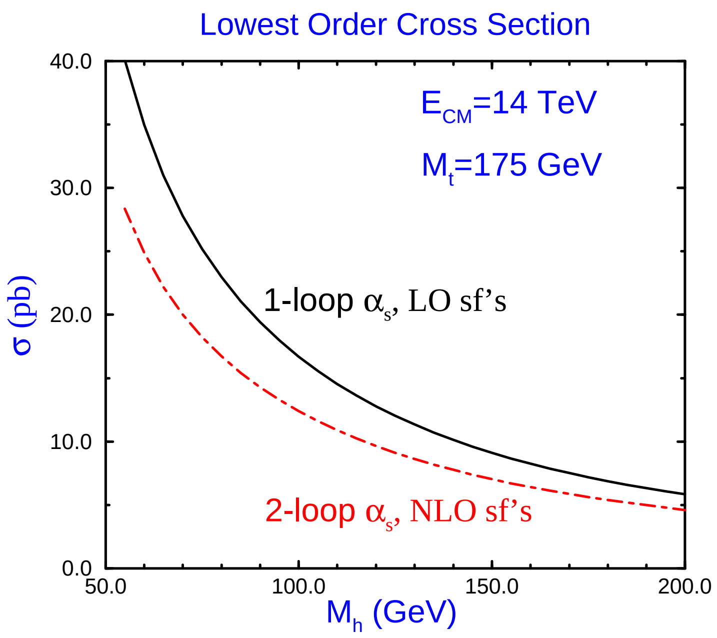
$\tau \equiv M_h^2/S$, S is the hadronic center of mass energy



$$\sigma(gg \to h) = \sigma_\infty (1 + \frac{7M_h^2}{120M_t^2} + ...)$$

- Obvious scale for structure functions is $\mu = M_h$
- Which α_s?, Which structure functions?





Compute QCD corrections to $gg \to h$ to $\mathcal{O}(\alpha_s^3)$

- Virtual corrections to 2-loops
- Singularities cancel with real diagrams $gg \to gh$, $q\overline{q} \to gh$, $qg \to qh$
- Real diagrams generate p_T spectrum for Higgs
- In $M_h \sim 100\ GeV$ region, expansion in $\frac{M_h}{M_t}$ may be reasonable
- Derive effective theory (integrate out top quark) for Higgs-gluon interactions
- Effective theory useful for t contributions to Higgs processes; eg $h \to b\overline{b}$. Also for NLO contributions to h+jet production
- Two loops $\to$ 1 loop
- Higgs mass effects only from kinematics
- Complete 2-loop calculation exists for comparison

Effective Lagrangian for Higgs Couplings:

$$\mathcal{L} = -\sum_i \left(1+\frac{h}{v}\right) m_i \overline{\psi}_i \psi_i$$

$p_h \to 0: \quad [\mathcal{P}_\mu, h] = i\partial_\mu h = 0$
Kinetic terms vanish $\to$ h is constant field

$$m_i \to \left(1+\frac{h}{v}\right) m_i$$

Low Energy Theorem:

$$\mathcal{A}\left(A \to B+h\right) \to \sum_i \frac{1}{v} m_i \frac{\partial}{\partial m_i} \mathcal{A}\left(A \to B\right)$$

for $p_h \to 0$

- True for $i =$ fermion or gauge boson

Diagramatic derivation

$Tr(\ldots\frac{i}{p-m}(-i\frac{m}{v})\frac{i}{p-p_h-m}\ldots)$

$Tr(\ldots.\frac{i}{p-m}\ldots.)$

$\frac{m}{v}\frac{\partial}{\partial m}(\ldots..) \longrightarrow \frac{m}{v}\frac{i}{(p-m)^2}$

Using low energy theorem find effective ggh coupling:

$$\mathcal{L}_0 = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{eff} = \frac{h}{v} m \frac{\partial}{\partial m} \mathcal{L}_0$$

Derivative of g is β-function:

$$\beta = \mu \frac{dg}{d\mu}$$

$$\mathcal{L} = -\frac{1}{4g^2} \left(1 - \frac{2\beta}{g} \frac{h}{v} \right) G^a_{\mu\nu} G^{a\mu\nu}$$

- Only heavy fermions contribute to β:

$$\frac{\beta_F}{g} = N_H \frac{\alpha_s}{6\pi}$$

- Obtain effective ggh vertex:

$$-\frac{i\alpha_s}{3\pi v} \delta_{AB} \left(g^{\mu\nu} p \cdot q - p^\nu q^\mu \right)$$

- Also $gggh$ vertex

Low Energy Theorems Beyond the Leading Order

$$\mathcal{L}_{gg} = -\frac{1}{4g^2} G^{a\mu\nu} G^a_{\mu\nu} \left(1 + \Pi^t_{gg}(0)\right)$$

$$\Pi^t_{gg}(0) = \frac{\alpha_s}{6\pi} \left(\frac{4\pi\mu^2}{M_t^{o\ 2}}\right)^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon}$$

- LET requires differentiation w.r.t. *bare mass*
- Don't differentiate w.r.t. mass dependent couplings

$$M_t = M_t^0 Z_m$$

$$M_t^o \frac{\partial}{\partial M_t^o} = \frac{M_t}{1+\gamma_m} \frac{\partial}{\partial M_t}$$

with

$$M_t^0 \frac{\partial}{\partial M_t^0} \Pi^t = \frac{2\beta_F}{g}$$

$$M_t \frac{\partial log \ \ (Z_m)}{\partial M_t} = \gamma_m$$

NLO Effective Lagrangian:

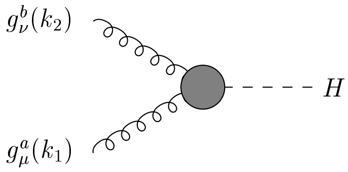
$$\mathcal{L}_{ggh} = \frac{\beta_F}{2g} \frac{h}{v} \left(\frac{1}{1+\gamma_m}\right) G^{a\mu\nu} G^a_{\mu\nu}$$

$$\frac{\beta_F}{g} = N_H \frac{\alpha_s}{6\pi} \left(1 + \frac{19\alpha_s}{4\pi}\right)$$

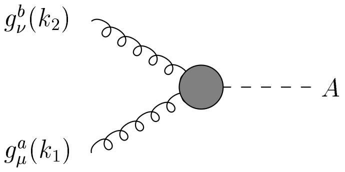
$$\gamma_m = \frac{2\alpha_s}{\pi}$$

$$\mathcal{L}_{ggh} = \frac{\alpha_s}{6\pi} \left(1 + \frac{11}{4}\frac{\alpha_s}{\pi}\right) \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

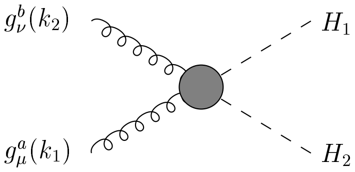
- $\mathcal{O}(\alpha_s^3)$ contribution to ggh vertex known



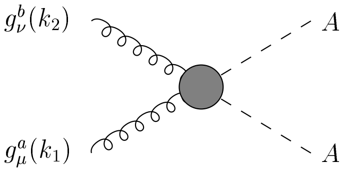
$$i\delta_{ab}\frac{\alpha_s}{3\pi v}g_t^H\left\{g^{\mu\nu}(k_1\cdot k_2)-k_1^\nu k_2^\mu\right\}\left(1+\frac{11}{4}\frac{\alpha_s}{\pi}\right)$$



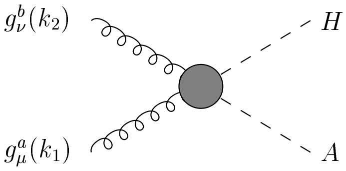
$$i\delta_{ab}\frac{\alpha_s}{2\pi v}g_t^A\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}$$



$$-i\delta_{ab}\frac{\alpha_s}{3\pi v}g_t^{H_1}g_t^{H_2}\left\{g^{\mu\nu}(k_1\cdot k_2)-k_1^\nu k_2^\mu\right\}\left(1+\frac{11}{4}\frac{\alpha_s}{\pi}\right)$$

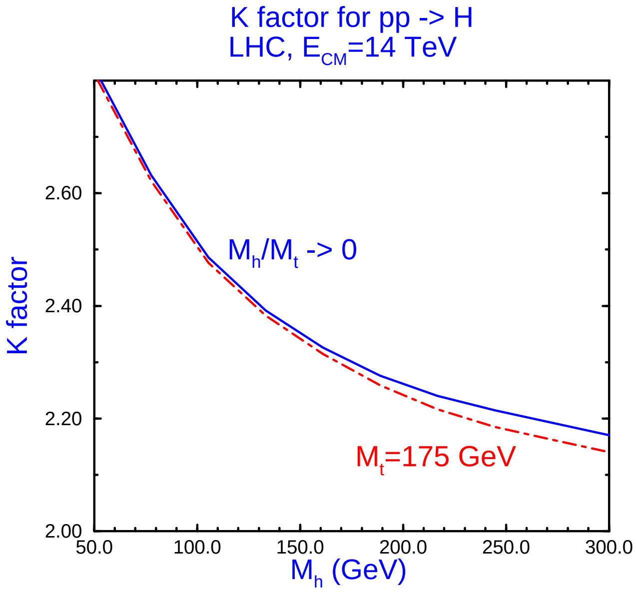


$$i\delta_{ab}\frac{\alpha_s}{3\pi v}(g_t^A)^2\left\{g^{\mu\nu}(k_1\cdot k_2)-k_1^\nu k_2^\mu\right\}\left(1+\frac{11}{4}\frac{\alpha_s}{\pi}\right)$$



$$-i\delta_{ab}\frac{\alpha_s}{2\pi v}g_t^H g_t^A\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}$$

- Effective ggh, $gghh$, ggA, $ggAA$ vertices



$$K \sim \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Why does heavy quark limit work so well?

Remember Drell-Yan:

$$\sigma\,(real) = (...) \left(\frac{4\pi\mu^2}{Q^2}\right)^{\epsilon} \left(-\frac{1}{\epsilon^2} + ...\right)$$

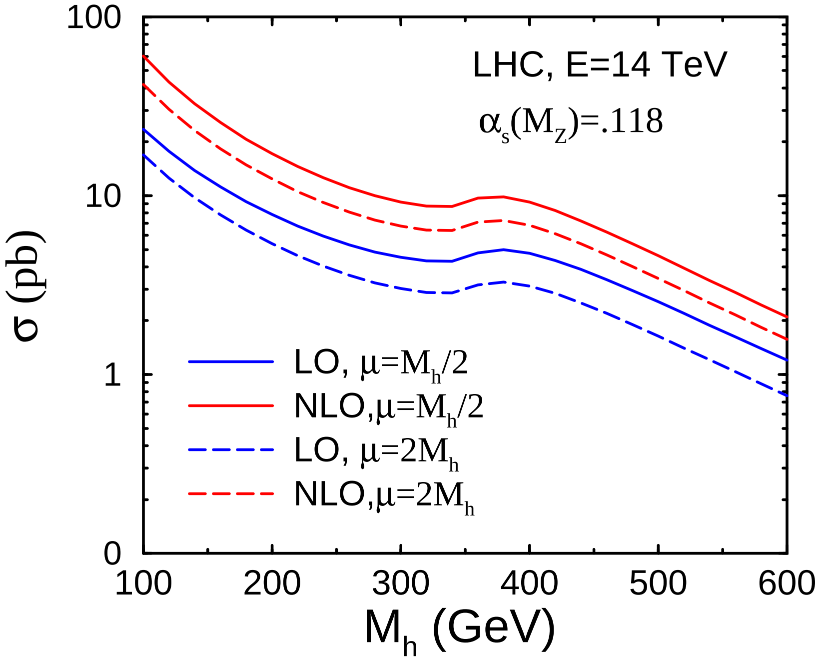
$$\sigma\,(virtual) = (...) \left(\frac{4\pi\mu^2}{-Q^2}\right)^{\epsilon} \left(\frac{1}{\epsilon^2} + ...\right)$$

$$(-1)^{\epsilon} \rightarrow \left(1 - \frac{\pi^2}{2}\epsilon^2\right)$$

$$\sigma_{ggh} \sim \sigma_{\infty} \left[1 + \frac{\alpha_s}{\pi}\left(\pi^2 + \frac{11}{2}\right)\right] + ...$$

$$\sim \sigma_{\infty}\,[1.9]$$

- Scale dependence from $\alpha_s(\mu)$, structure functions
- Roughly 30% uncertainty from scale dependence



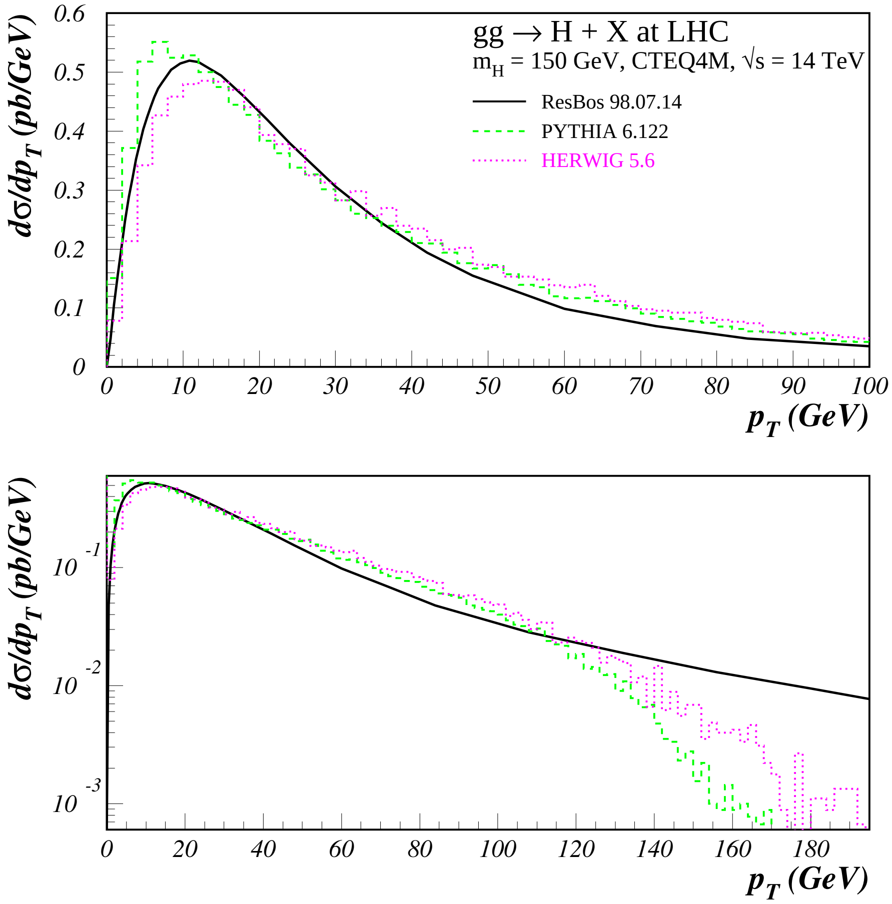
Spira program for NLO Higgs production: HIGLU.F

from http://mspira.home.cern.ch/mspira/proglist.html

Default is with σ_{LO} evaluated with NLO α_s

Higgs p_T distributions

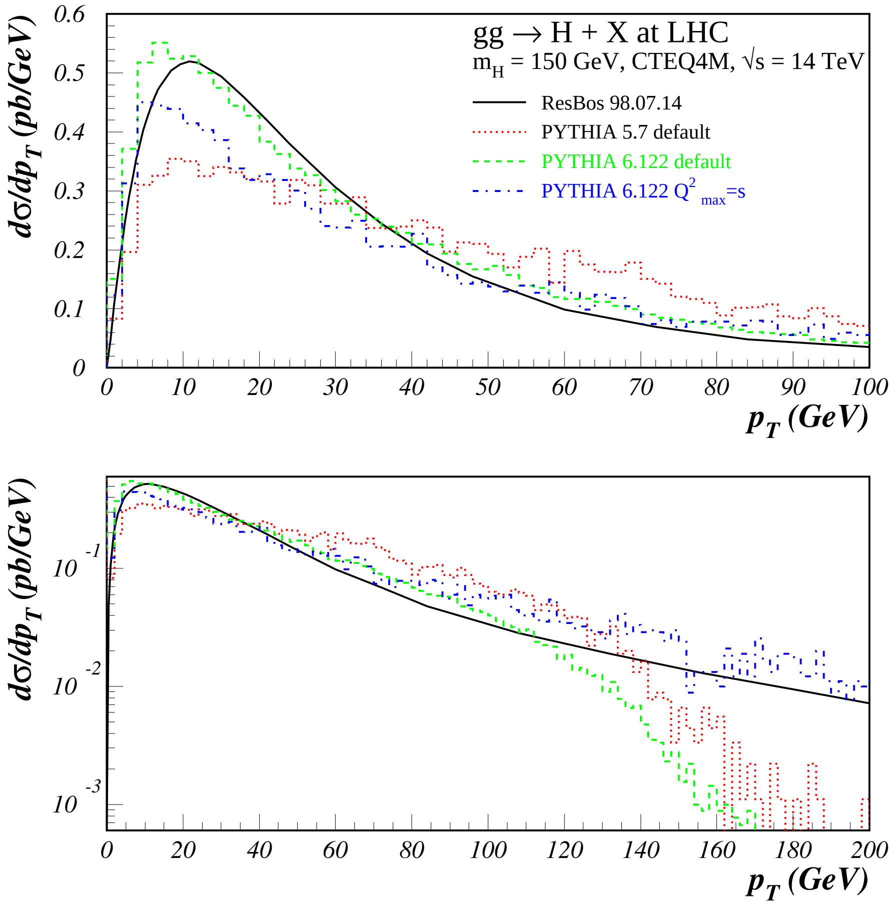
- LO Higgs σ, $gg \to h$, has no p_T
- High p_T contributions from $gg \to gh$, etc
- Most of p_T from initial state parton showers

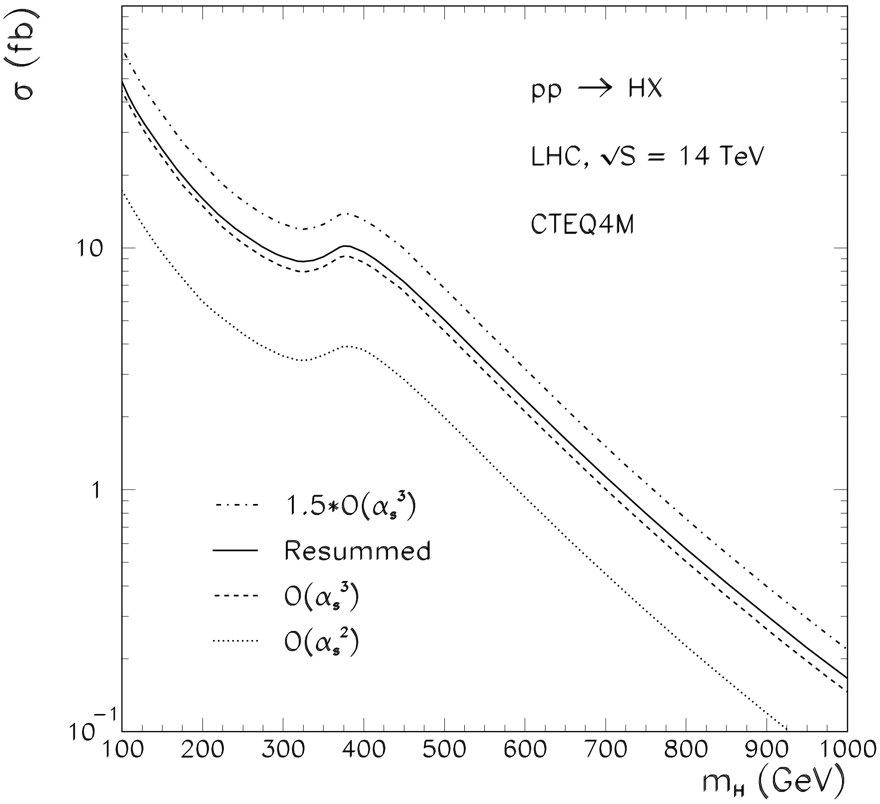


(Les Houche study, hep-ph/0005114)

- Pythia lower than ResBos at high p_T (assums $gg \to h$ is hardest process, so $p_T < M_h$)
- ResBos has analytic resummation of multiple soft gluon effects matched to NLO h + jet at high p_T

- Pythia agrees better with ResBos at high p_T with scale $\mu \sim \sqrt{\hat{s}}$ instead of M_h
- MCs need $qg \to qh$, $q\overline{q} \to gh$, $gg \to gh$ to get high p_T spectrum correct (matching problem)





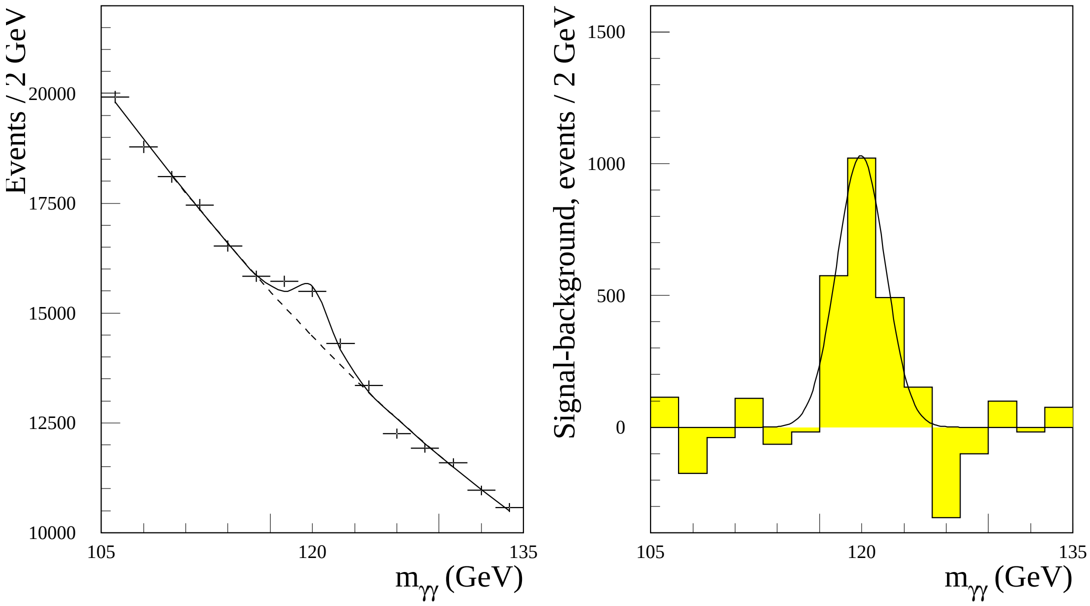
(Balazs, hep-ph/0001103)

How to Find Higgs at LHC

- Large QCD backgrounds to dominant $h \to b\bar{b}$ decay
- Look at rare decay, $h \to \gamma\gamma$

$$BR(h \to \gamma\gamma) \sim 10^{-3}$$

- Signal shows sharp peak in $M_{\gamma\gamma}$ since $\Gamma_h \sim$ MeV
- Large background from $q\overline{q} \to \gamma\gamma$, jet-jet; naively 8 orders of magnitude larger than signal. Need γ/jet rejection $\sim \mathcal{O}(10^{-4})$



(ATLAS with $M_h = 120\ GeV$, $\mathcal{L} = 100\ fb^{-1}$)

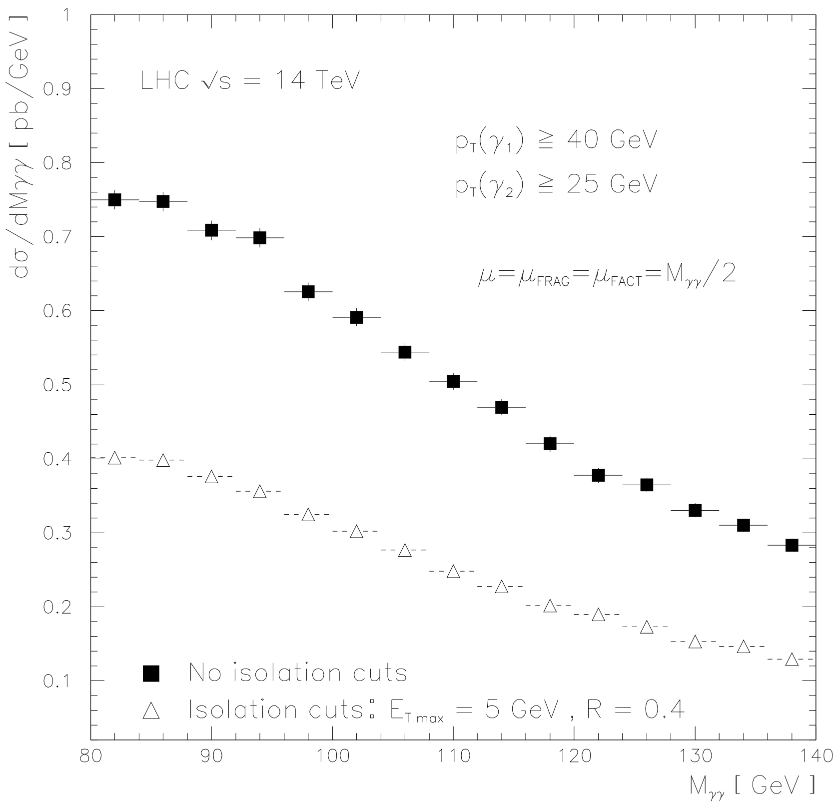
- NNLO process $gg \to \gamma\gamma$ same size as $q\overline{q} \to \gamma\gamma$ due to large gluon luminosity at LHC

Extra α_s^2 compensated by $\mathcal{L}_{gg} >> \mathcal{L}_{q\overline{q}}$

- Need background to NNLO!

$\gamma\gamma$ background to $h \to \gamma\gamma$

- Complete NLO calculation of $\gamma\gamma$ background exists; agrees well with Tevatron data
- Implemented in parton level Monte Carlo, DIPHOX
- Direct, fragmentation, meson decay contributions
- Also includes $gg \to \gamma\gamma$ box
- Fragmentation contributions reduced by isolation cuts



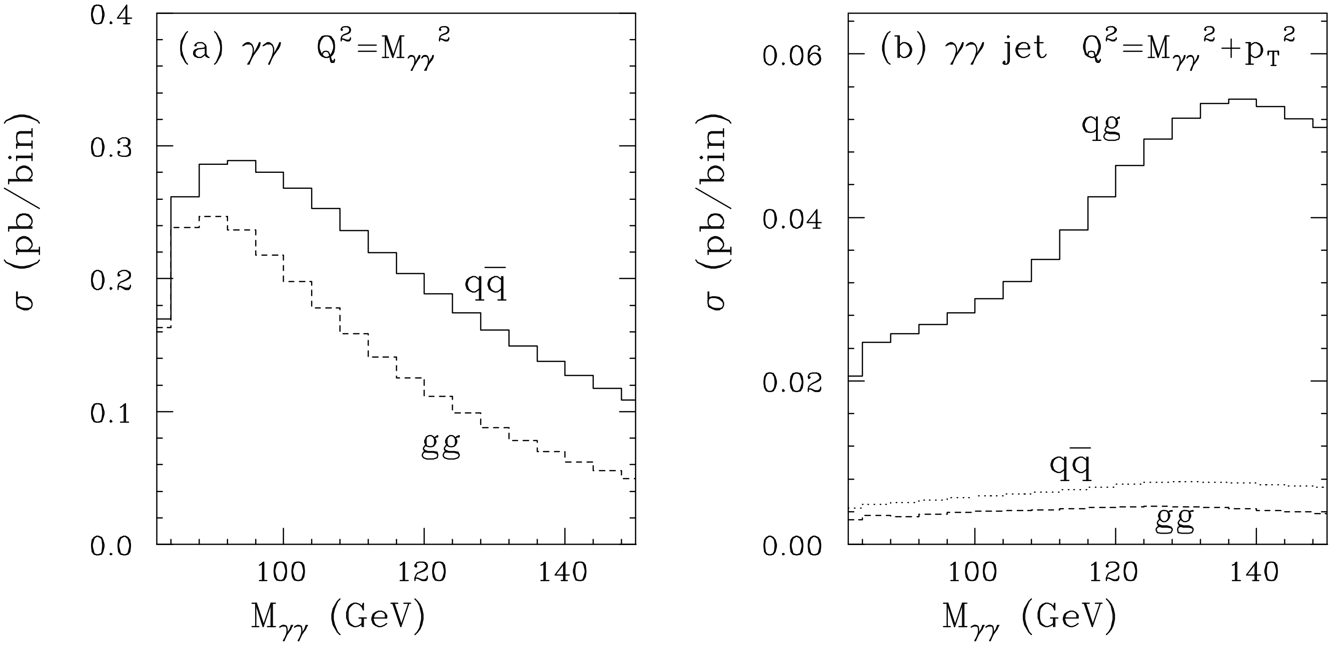
(Binoth, hep-ph/0005194)

Higgs + jet production:

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

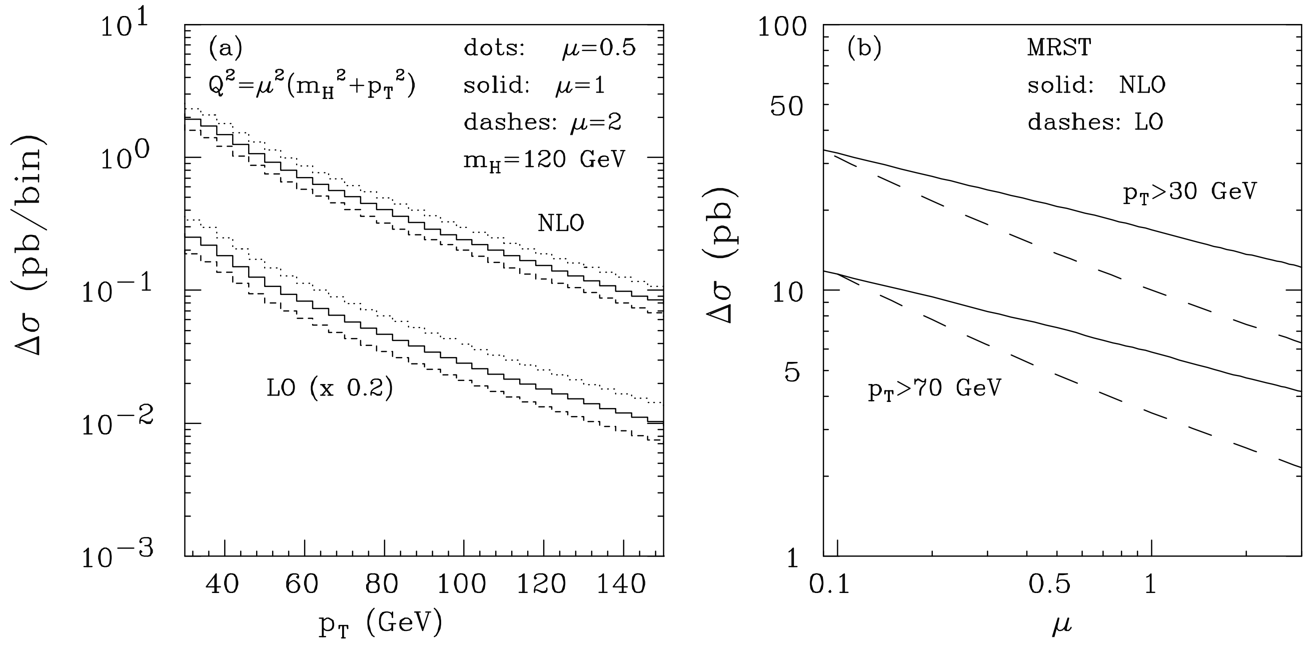
$$S/B \sim 1/2$$

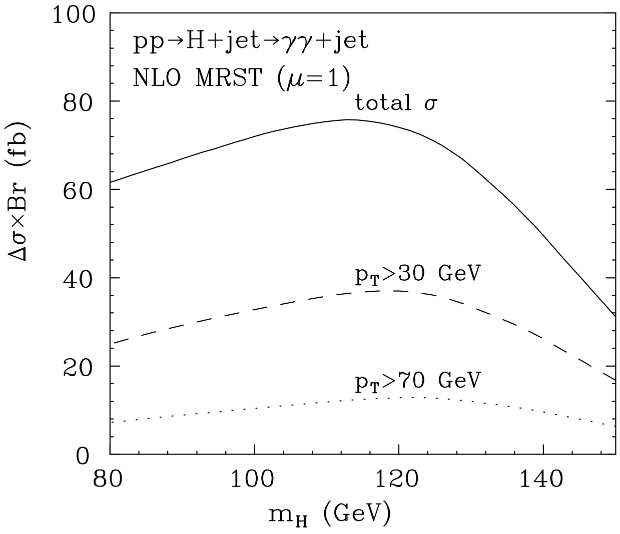
- Roughly 100 events with $\mathcal{L} = 30\ fb^{-1}$
- Can get K factor for signal using large M_t expansion; $K \sim 1.6$
- Need NLO calculation of background
- Dominant contribution to $\gamma\gamma$ jet from qg initial state, so higher order corrections to background under better control than inclusive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



(deFlorian, hep-ph/9905283)

$\gamma\gamma$ jet to NLO:



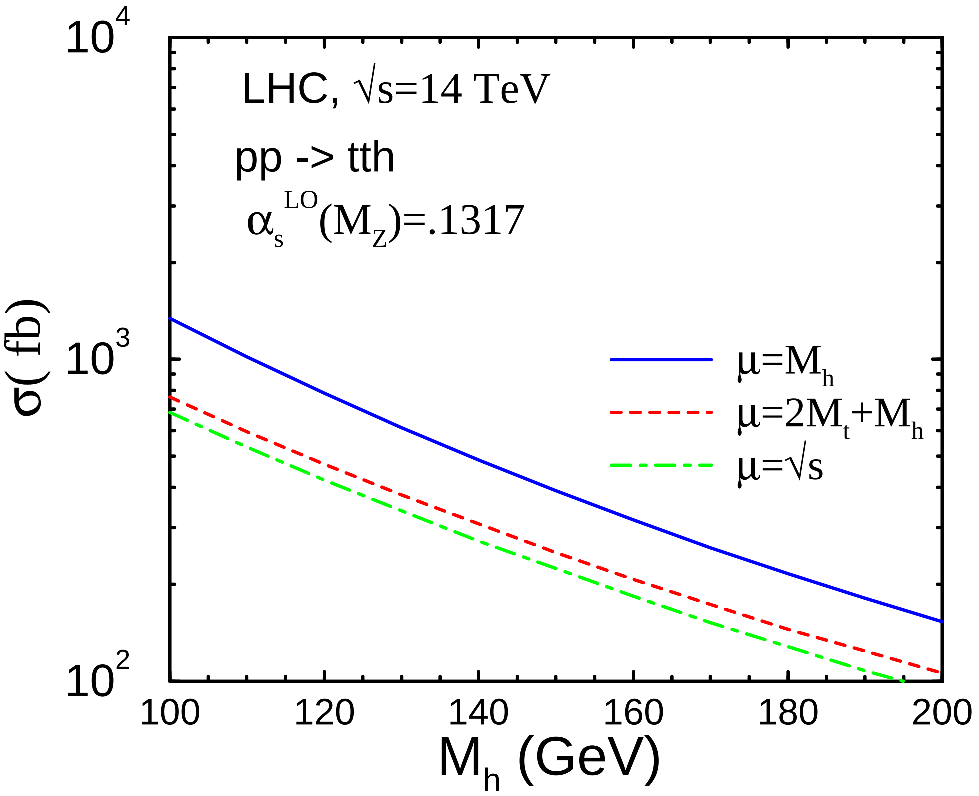


(deFlorian, hep-ph/9902483)

Observable signal in Higgs + jet

Important channel for $100\ GeV < M_h < 140\ GeV$ is $t\bar{t}h$:

- Direct measurement of $t\bar{t}h$ coupling
- Only Higgs production channel with uncalculated NLO QCD corrections

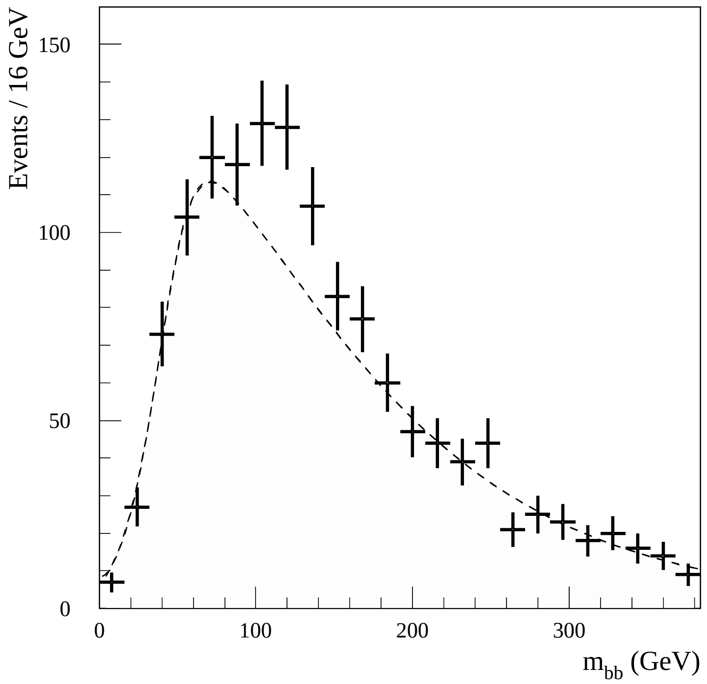


- Look for $h \to b\bar{b}$; final state is $W^+W^-b\bar{b}b\bar{b}$
- 1 W decays semi-leptonically, other hadronically; fully reconstruct both tops

ATLAS with $\mathcal{L} = 100 \ fb^{-1}$, $M_h = 120 \ GeV$

Background, dashed line; signal, data points

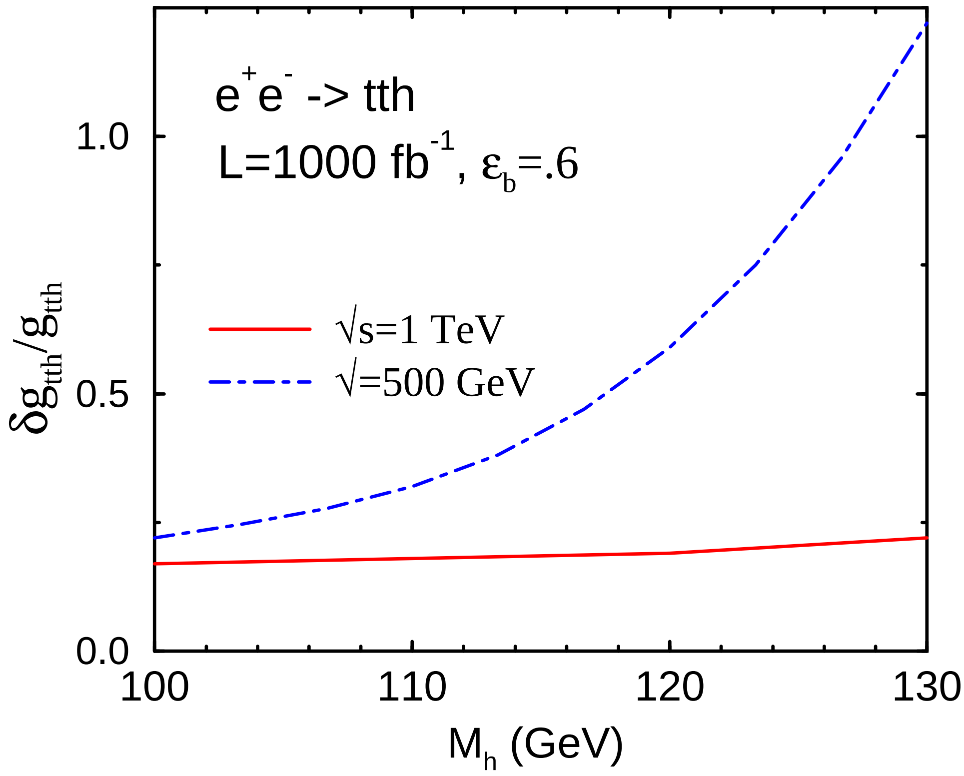
Can measure $\frac{\delta g_{tth}}{g_{tth}} \sim 16\%$



(LHC Top Study, hep-ph/0003033)

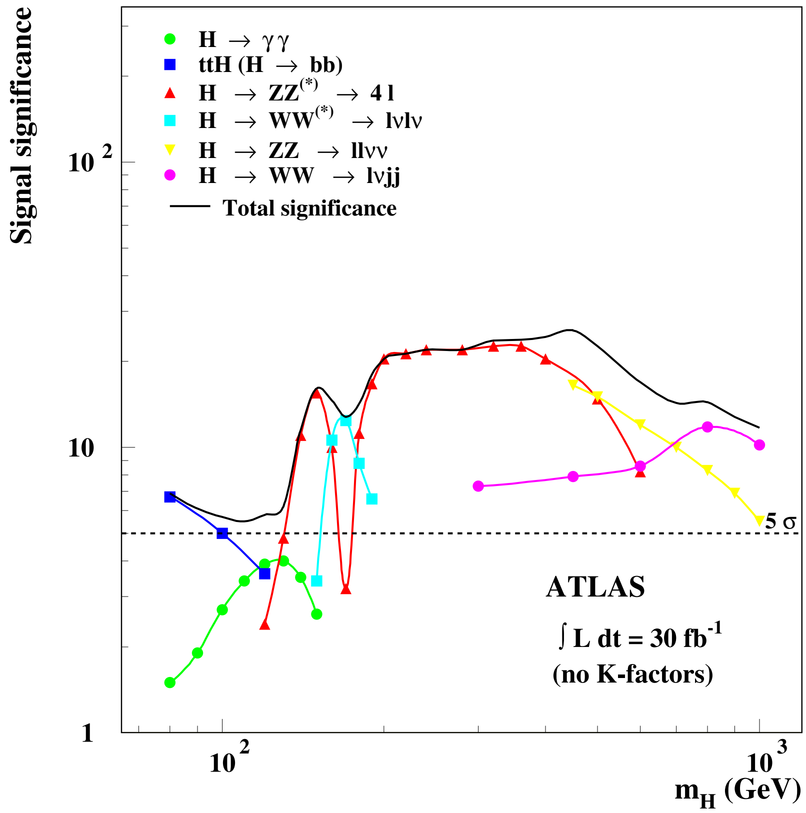
Compare $t\bar{t}h$ at e^+e^- collider:
NLO QCD corrections straightforward

$$\sqrt{s} = 500\ GeV: \qquad K \sim 1.4 - 2.4$$
$$\sqrt{s} = 1\ TeV: \qquad K \sim .8 - .9$$



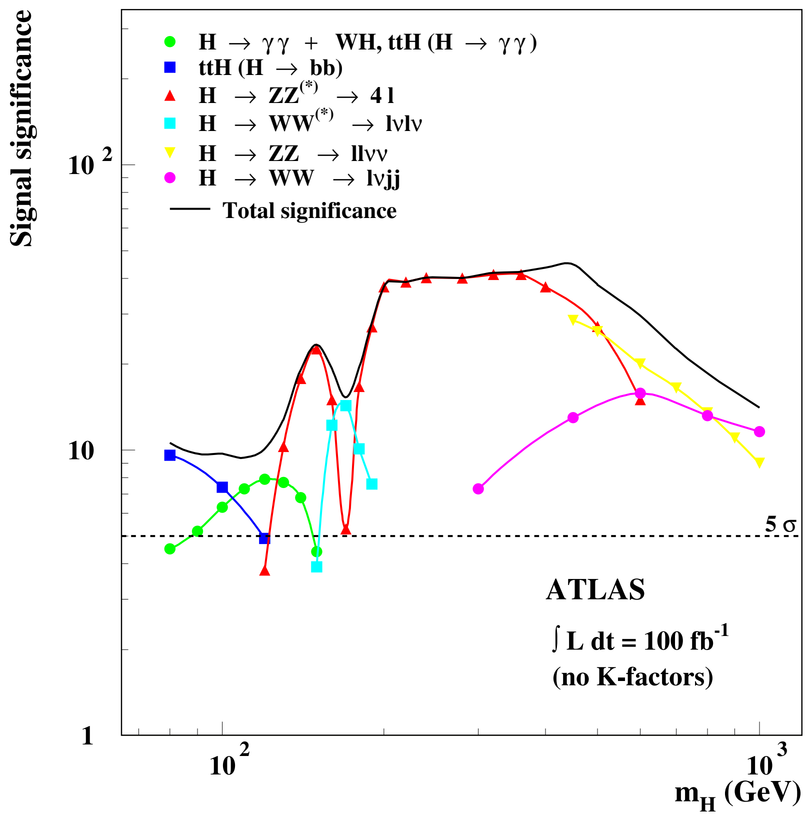
(Baer, hep-ph/9906419)

LHC will observe Higgs for all $M_h < 1\ TeV$

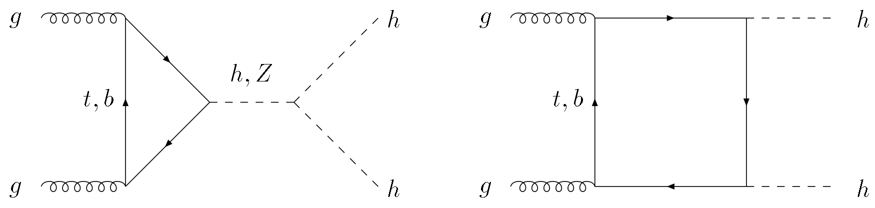


- Recent work suggests $qq \to qqh$, $h \to \gamma\gamma$, $\tau^+\tau^-$, W^+W^- may be observable in $M_h \sim 150\ GeV$ region
- Tag forward jets; veto central jet activity

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



Effective $\mathcal{L}$ to compute $gg \to hh$



$gg \to hh$

Higgs Potential:

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

- λ defines strength of Higgs interactions

$$\lambda_{hhh}^{SM} = -\frac{3M_h^2}{v}$$

- Want to verify Higgs self couplings to know that Higgs connected to spontaneous symmetry breaking

- At present, no experimental limits on λ

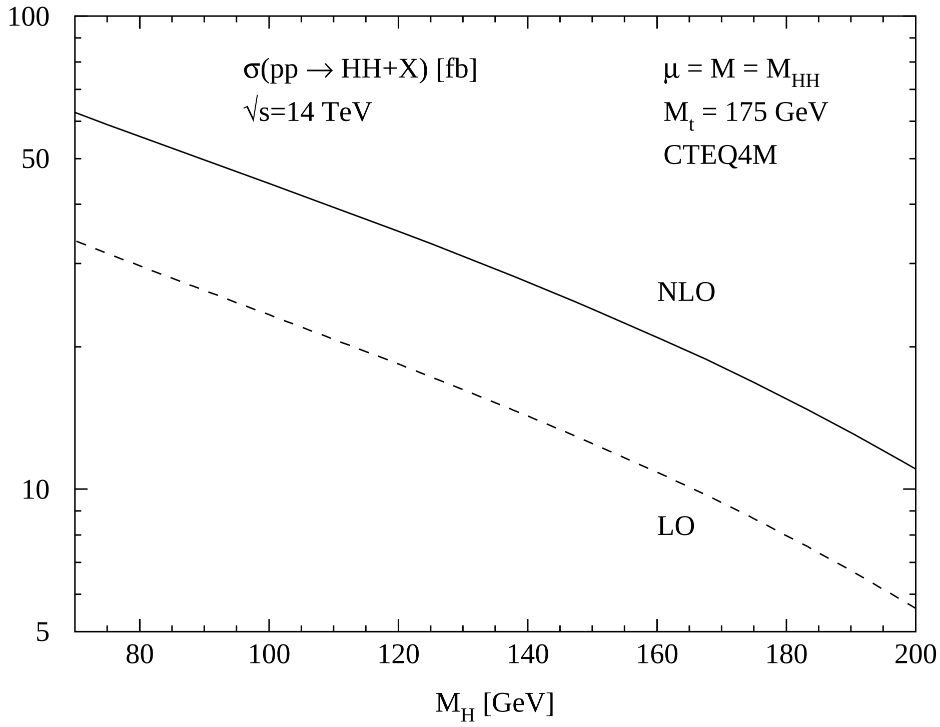
- Need multiple Higgs production to probe λ

NLO calculation of $pp \rightarrow hhX$

- Compute QCD corrections in heavy top quark limit, $M_h << M_t, \; M_b = 0$

$$\mathcal{L}_{h^n gg} = \frac{\alpha_s}{12\pi}\left(1 + \frac{11\alpha_s}{4\pi}\right) G^{a\mu\nu} G^a_{\mu\nu} log\left(1 + \frac{h}{v}\right)$$

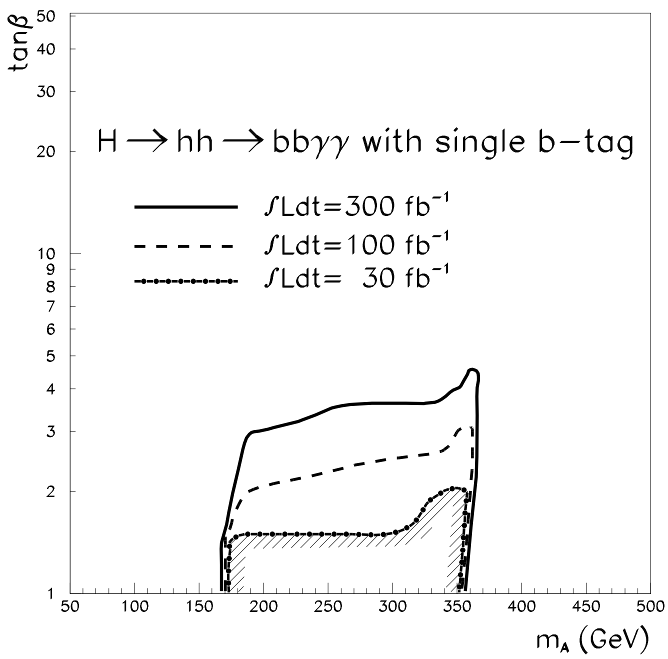
- Dominant corrections from soft and collinear gluon radiation



(Dawson, hep-ph/9805244)

- Double Higgs rate enhanced in SUSY models and is relevant for small $\tan\beta$

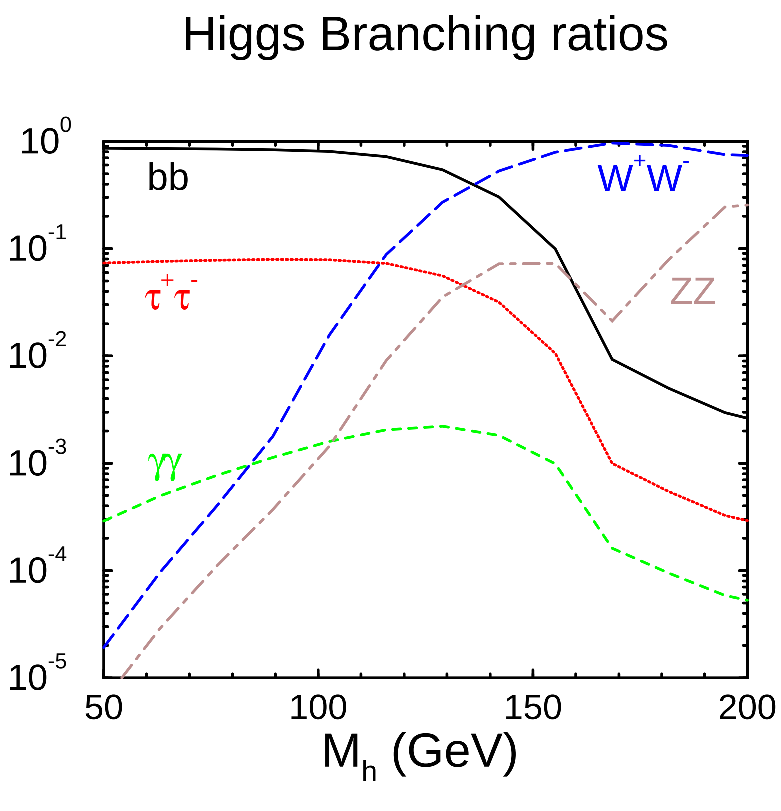
- SUSY models have resonance effects, $H \to hh$, etc



(ATLAS Physics TDR)

Higgs Branching Ratios

- After Higgs discovery, want to measure properties
- Measurements of couplings check SM properties
- Coupling to fermions $\sim$ mass in SM (no free parameters)
- For $m_b < 2M_W$, dominant decay is $\Gamma(h \to b\bar{b})$



$$\frac{\Gamma\left(h \to b\bar{b}\right)}{\Gamma\left(h \to \tau^+\tau^-\right)} \sim 3\frac{m_b^2}{M_\tau^2}$$

$$\Gamma\left(h \to b\bar{b}\right)_{LO} = \frac{N_c M_h}{8\pi v^2} m_b^2$$

m_b runs with scale ... which m_b?

Running of b mass:

To leading logarithm:

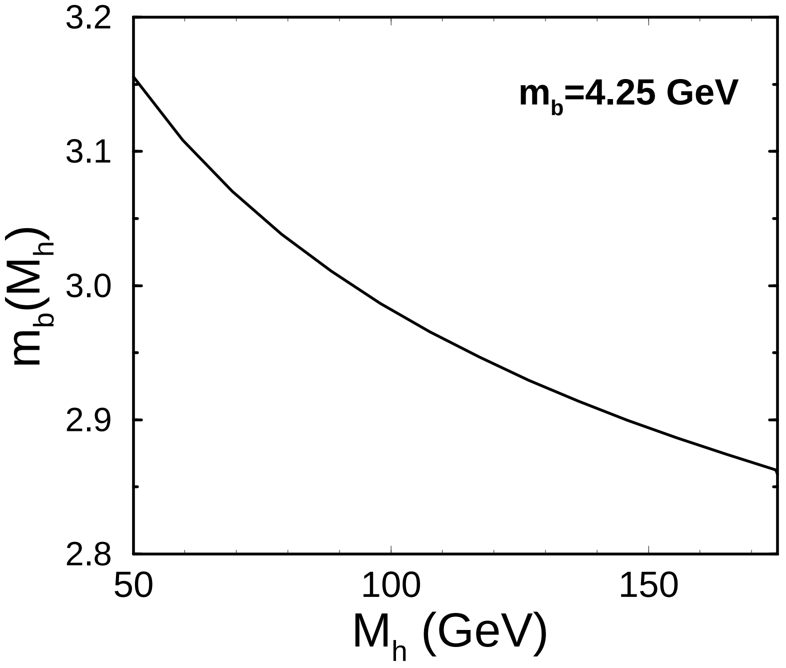
$$m_b\left(\mu\right) = m_b \left(\frac{\log\left(\frac{\mu^2}{\Lambda_{QCD}^2}\right)}{log\left(\frac{m_b^2}{\Lambda_{QCD}^2}\right)} \right)^{\frac{\gamma_0}{2b_0}} = m_b \left(\frac{\alpha_s\left(M_b^2\right)}{\alpha_s\left(\mu^2\right)} \right)^{\frac{\gamma_0}{2b_0}}$$

Sums large logarithms, $\log(\frac{M_h}{M_b})$

$m_b \equiv$ pole mass $\sim \quad \frac{M_\Upsilon}{2}$

$\gamma_0 = -8,\ \beta_0 = 11 - \frac{2}{3} n_f$

Including NLO contributions, b mass significantly reduced



$$\Gamma\left(h \to b\bar{b}\right) = \frac{N_c M_h}{8\pi v^2} m_b\left(M_h\right)^2 \left(\delta_{QCD} + \delta_t\right)$$

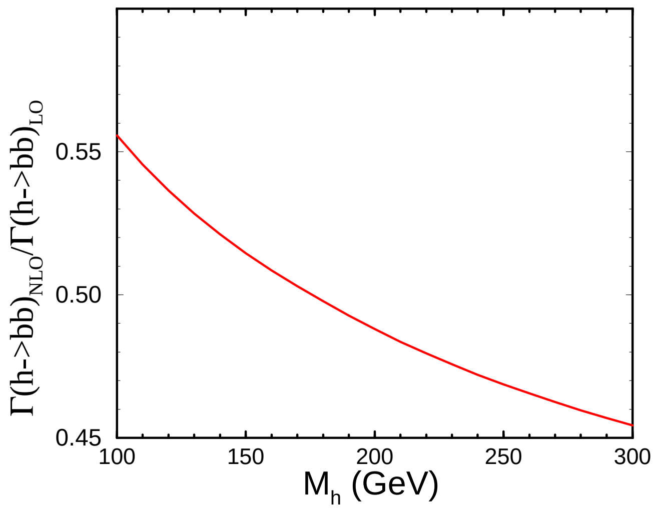
$$\delta_{QCD} = 1 + 5.67 \frac{\alpha_s\left(M_h\right)}{\pi} + ...$$

$$\delta_t = \left(\frac{\alpha_s\left(M_h\right)}{\pi}\right)^2 (1.57 + ...)$$

δ_{QCD} known to $\mathcal{O}(\alpha_s^3)$

Relevant M_h far above $b\bar{b}$ threshold

- QCD corrections decrease $\Gamma(h \to b\bar{b})$ by ~ 2
- *Increases* $\Gamma(h \to \gamma\gamma)$



- To compute Higgs branching ratios, including all known QCD corrections, use program HDECAY

http://mspira.home.cern.ch/mspira/proglist.html

- HDECAY can also do SUSY decays

Who cares about precision measurements of Γ_h?

- Higgs couplings can be significantly different in non-standard models
- Useful comparison is SUSY model
- *All* SUSY models have at least 2 Higgs doublets
- Minimal model has 2 Higgs doublets; 5 physical Higgs bosons

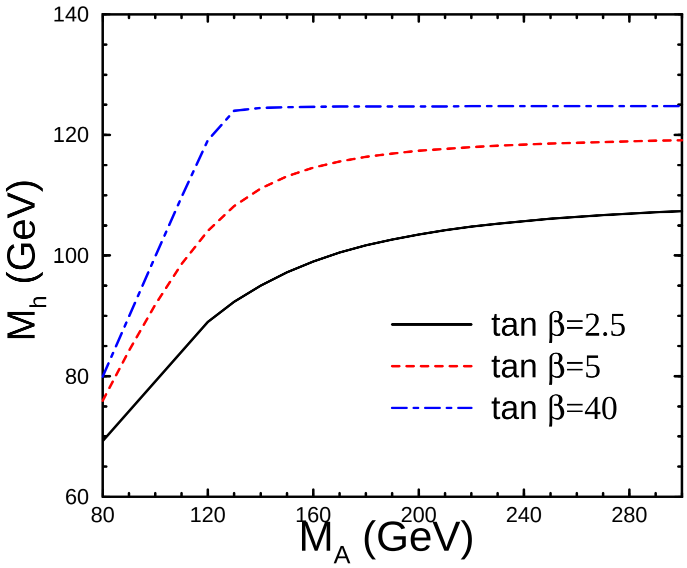
$$h, H, A, H^{\pm}$$

- SUSY Higgs potential has 2 free parameters which can be taken to be

$$M_A, \tan\beta = v_1/v_2$$

- All SUSY Higgs masses given in terms of M_A, $\tan\beta$ at LO
- Unlike SM, minimal SUSY model has absolute upper bound on Higgs mass (depends on M_{squark})

Upper bound on lightest SUSY Higgs mass:



LEP2 limit:

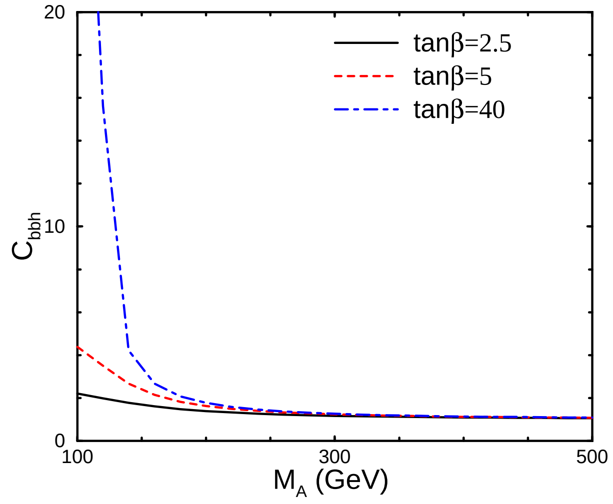
$$M_h > 88.3\ GeV, \quad for\ all\ \ \tan\beta$$

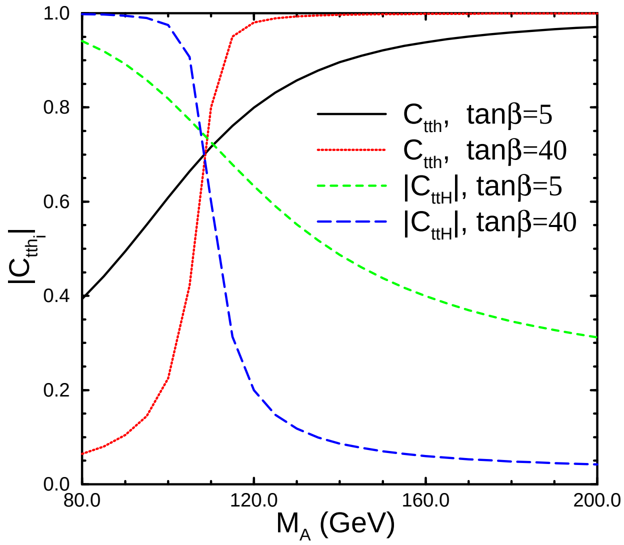
(Moriond, 2000)

- Couplings of SUSY Higgs to fermions altered,

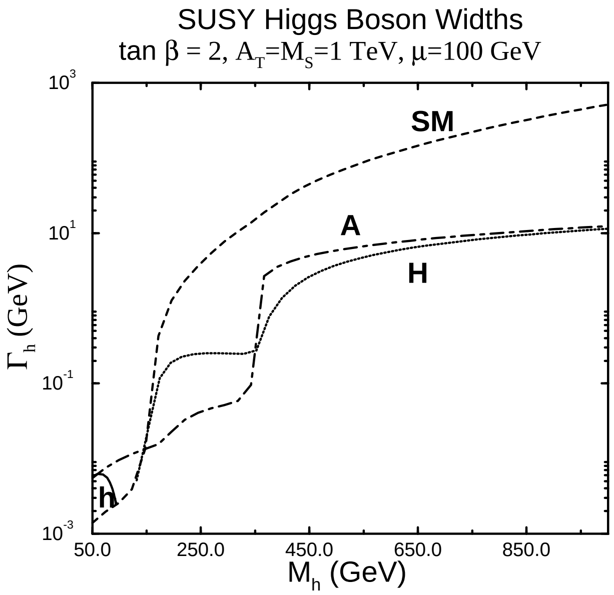
$$\mathcal{L} = -\frac{m_i}{v} C_i \overline{\psi}_i \psi_i h$$

- Higgs sector looks like SM for $M_A \to \infty$





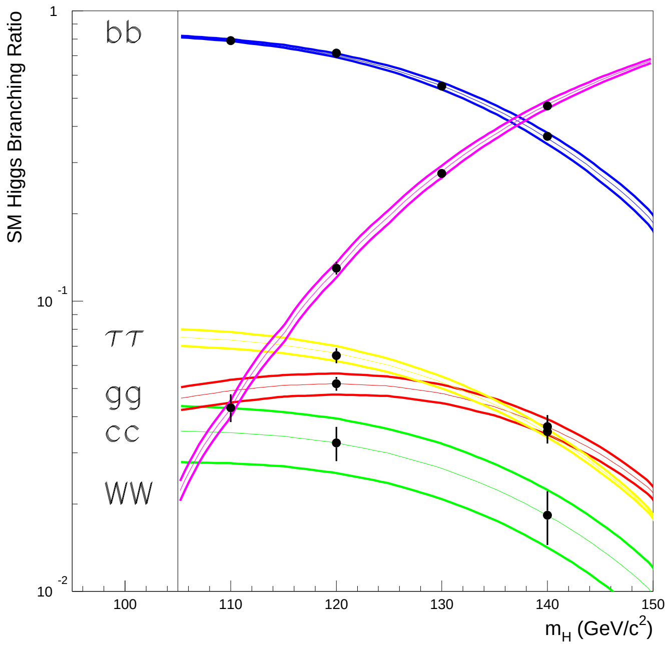
- Measurement of Higgs Branching ratios and widths can distinguish between models



- How well can we do?
- How well do we need to do?
- How well can we distinguish between models?

- Uncertainties on Higgs branching ratios from α_s, m_{quark}

$$\alpha_s\,(M_Z) = .1164 \pm .0025$$
$$m_b^{\overline{MS}} = (4.2 \pm .11)\ \ GeV \qquad \left(\text{sum rules} + \frac{m_\Upsilon}{2}\right)$$
$$m_b - m_c = (3.4 \pm .01)\ \ GeV \qquad \text{from HQET (Battaglia)}$$

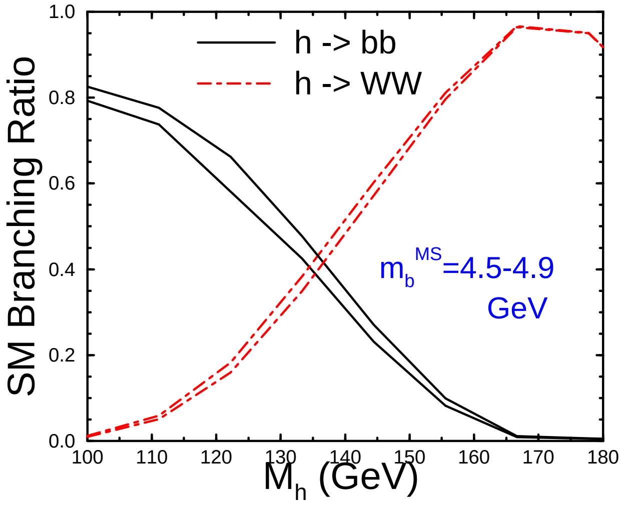


(Battaglia, hep-ph/9910271)

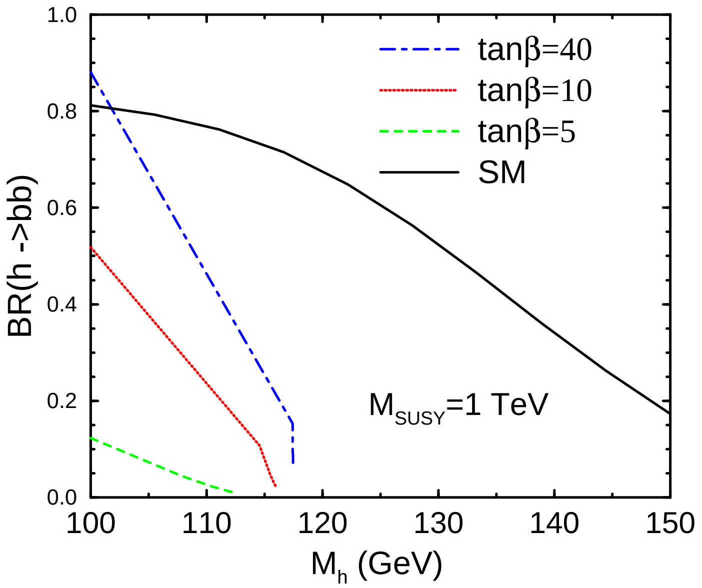
- Experimental points are TESLA study with $\sqrt{s} = 350\ \ GeV$, $\mathcal{L} = 500\ \ fb^{-1}$

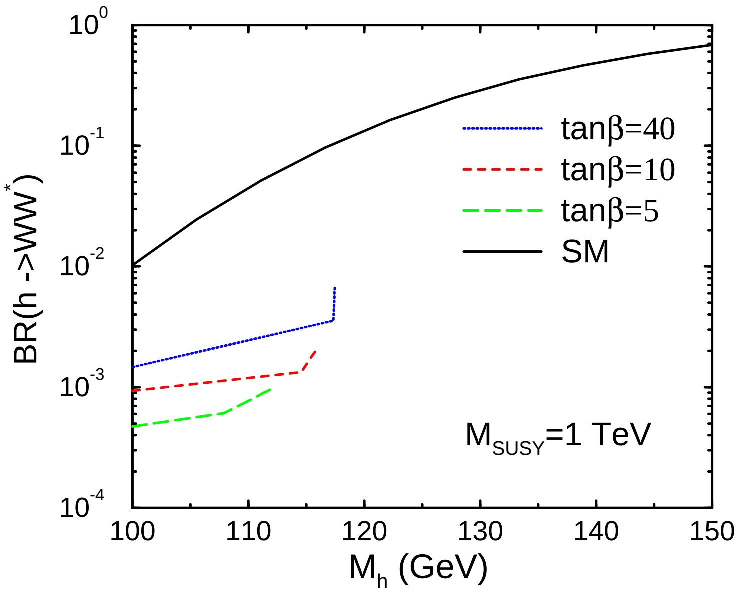
- Largest uncertainty is theoretical from m_b, m_c

- Probably larger error on branching ratios
- Particle Data book range for m_b^{MS} gives 20 % uncertainty on branching ratios



- $10 - 20\%$ measurement of branching ratios effective at distinguishing between SM and MSSM
- MSSM decouples for large M_A





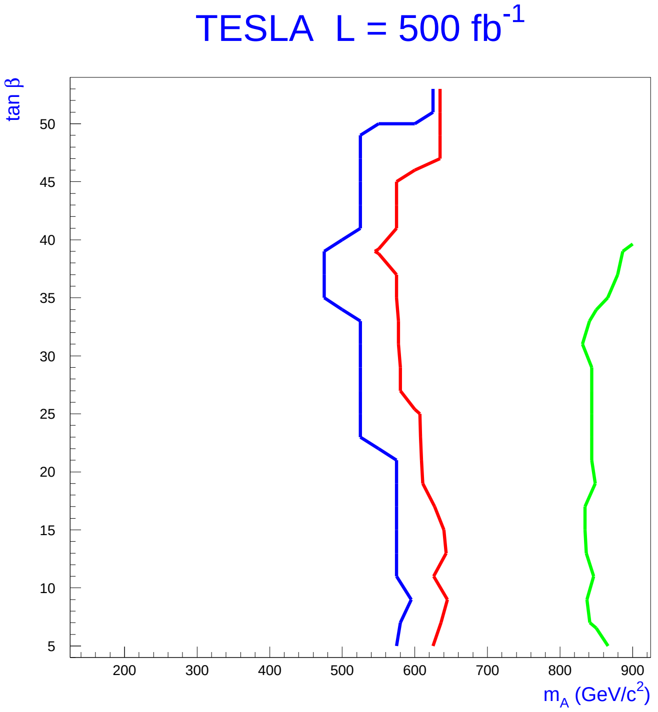
- TESLA study assumes specific detector design (charm tagging possible)

- Equivalent results for $\sqrt{s} = 350,\ \ 500\ \ GeV$

- Scan "reasonable MSSM" parameter space ($M_{SUSY} <$ $1.5\ \ TeV$

- Select solutions with $M_h = (120 \pm 2)\ \ GeV$ and compute MSSM BRs

- SM/MSSM discrimination defined to be portion of $M_A - \tan\beta$ plane with 68% , 90% , 95% of MSSM solutions outside SM 95% cl region:



(Battaglia, hep-ph/9910271)

How well can the LHC measure coupling constants?

- Production from gluon fusion:

$$\begin{array}{rl} gg \rightarrow h \rightarrow \gamma\gamma, & M_h < 150 \;\; GeV \\ gg \rightarrow h \rightarrow ZZ^* \rightarrow 4l & M_h > 130 \;\; GeV \\ gg \rightarrow h \rightarrow WW^* \rightarrow l\nu l\nu & M_h > 150 \;\; GeV \end{array}$$

- Assume $20-30\%$ errors on $\sigma \cdot BR$

- Production from WW fusion:

$$\begin{array}{rl} VV \rightarrow h \rightarrow \gamma\gamma, & M_h < 150 \;\; GeV \\ VV \rightarrow h \rightarrow \tau^+\tau^- & M_h < 140 \;\; GeV \\ VV \rightarrow h \rightarrow WW^* \rightarrow e\nu\mu\nu & M_h > 120 \;\; GeV \end{array}$$

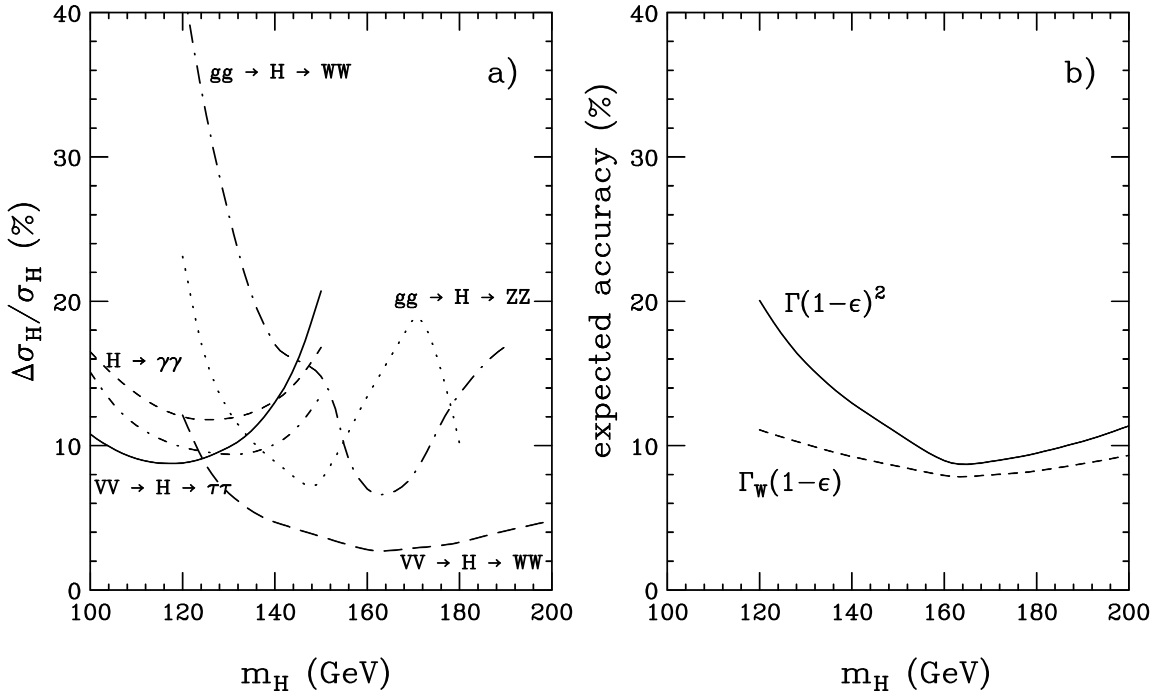
- VV production uses double forward jet tag; central jet veto to reduce background

- Smaller theoretical uncertainty on VV production ($\sim$ 5 %)

- VV results parton level only so far

- LHC measures combinations of coupling constants

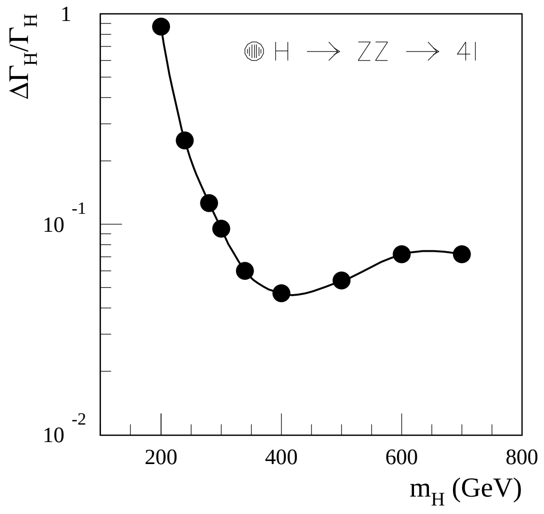
- With reasonable assumptions can get total width by combining gg and VV results

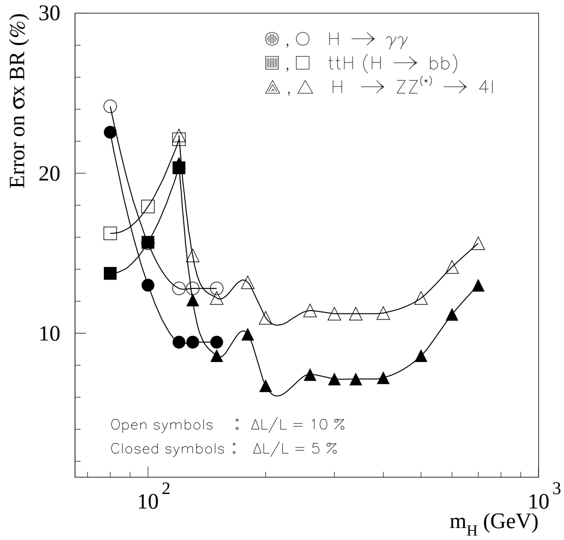


(Zeppenfeld, hep-ph/0005152)

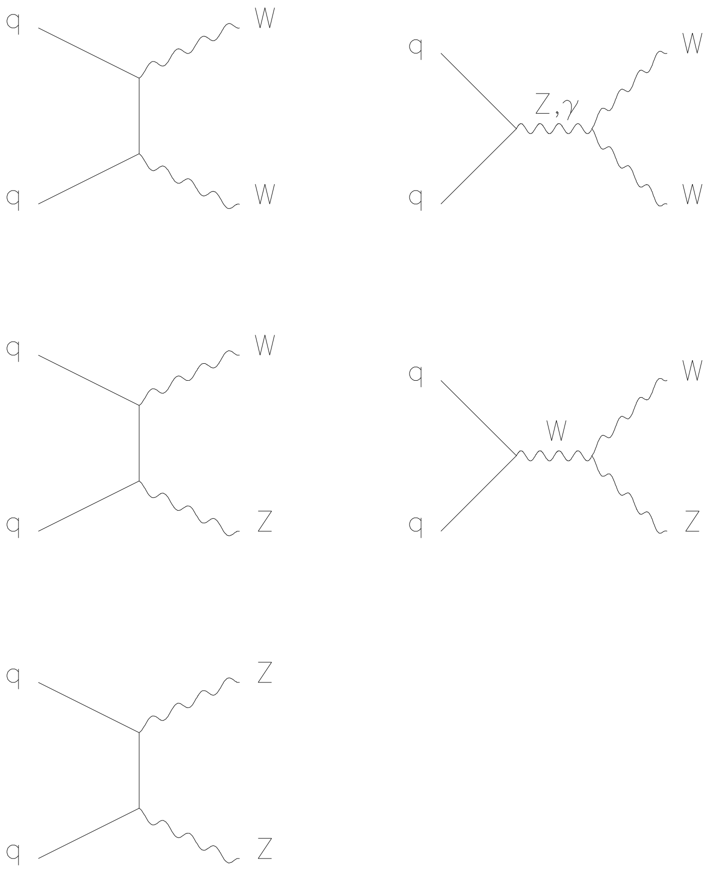
- Coupling constant measurements restricted to small M_h ranges
- Usually only measure a few channels
- Argument for NLC

ATLAS Physics TDR with $\int \mathcal{L} = 300\ fb^{-1}$:





$f\overline{f} \to W^+W^-$ and 3 Gauge Boson Vertices

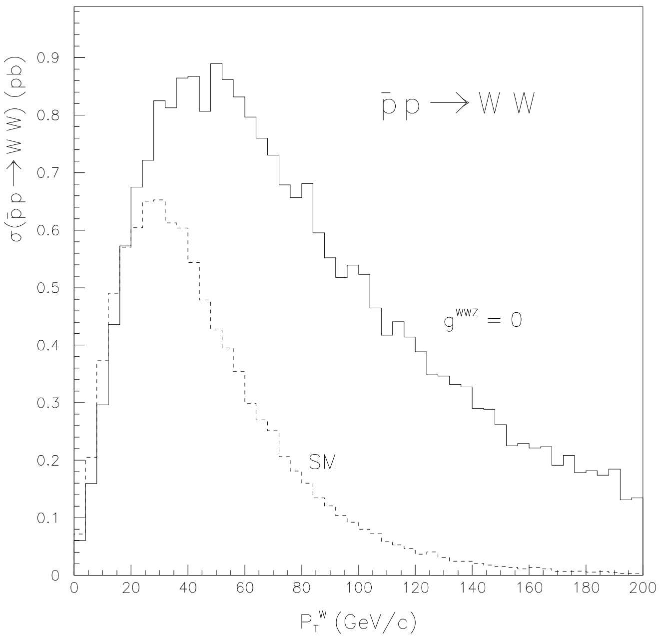


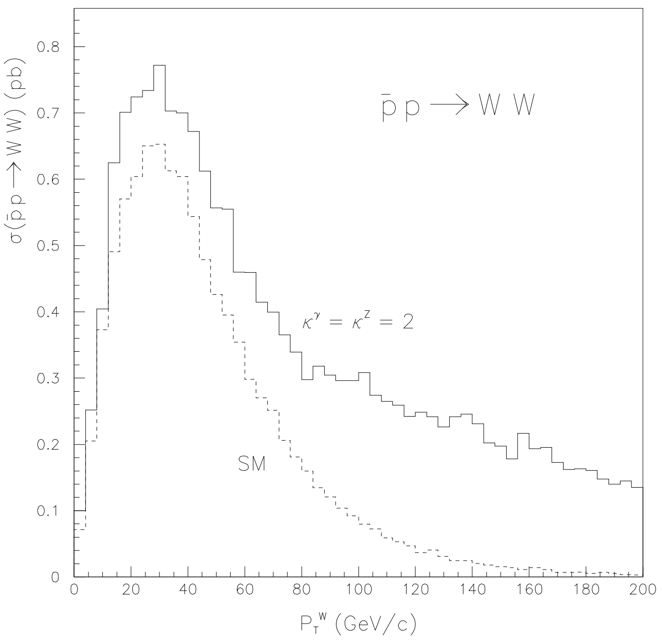
- W^+W^-, $W^\pm\gamma$, etc, production sensitive to new physics
- Expect effects which grow with energy

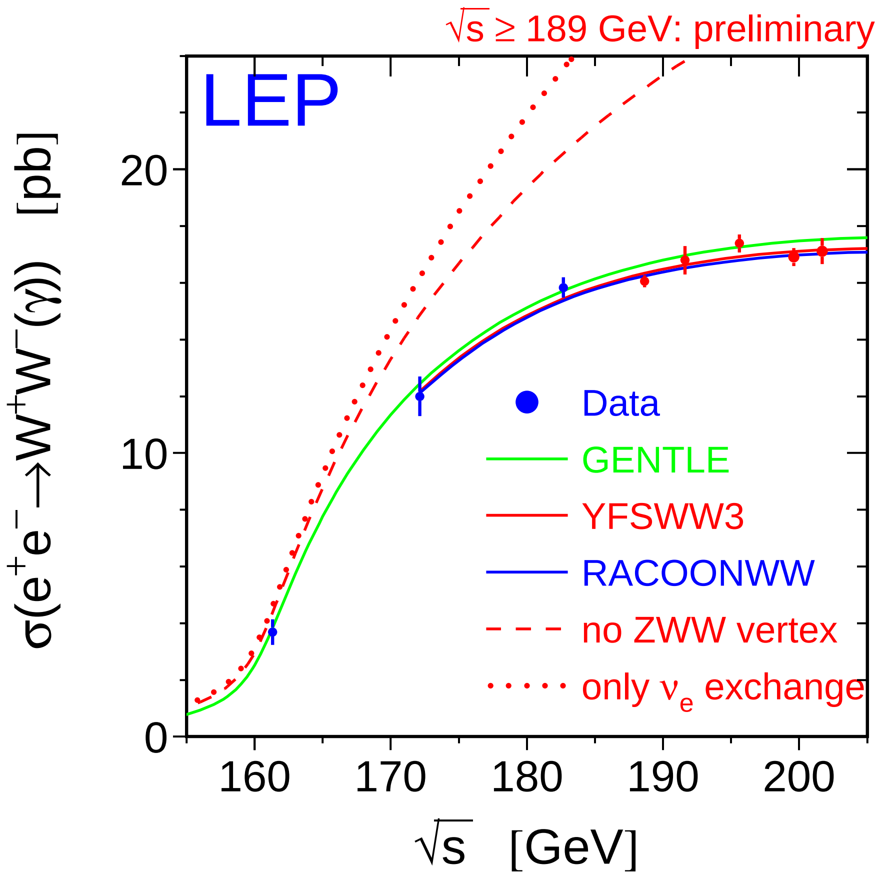
$$\mathcal{A}_t \sim (\ldots)\,\frac{s}{v^2} + \mathcal{O}\,(1)$$
$$\mathcal{A}_s \sim -\,(\ldots)\,\frac{s}{v^2} + \mathcal{O}\,(1)$$
$$\sigma_{tot} \sim \ \mathcal{O}\,(1)$$

- Interesting angular correlations; eg, $W\gamma$ has radiation zero at LO

- Existence of 3 gauge boson vertex confirmed by Tevatron, LEPII data







- LEP2 sensitive to relatively small M_{WW}
- Expect new physics effects grow with M_{WW}

Can we tell new physics from NLO QCD?

Consider W^+W^- production as example:

Need QCD corrections to $\mathcal{O}(\alpha_s)$ to:

$$pp \to W^+W^- \to l\nu l'\nu$$

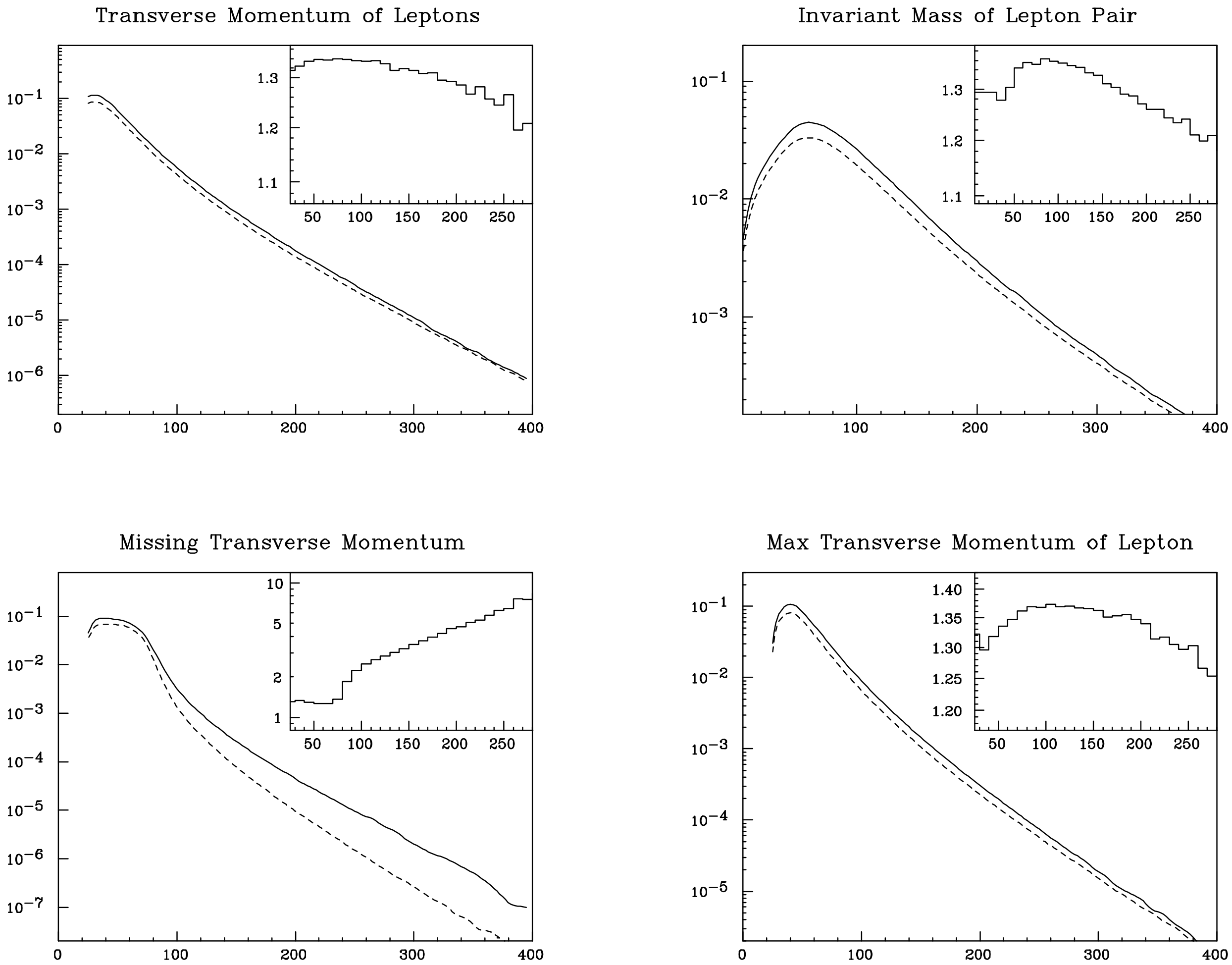
- Need spin and decay correlations
- Dominant contributions from double resonant Feynman diagrams
- Calculation straightforward using helicity amplitudes (remember V-A structure of W interactions)
- Large effects in tails of distributions due to

$$\begin{aligned} q\overline{q} &\to W^+W^-q \\ qg &\to W^+W^-q \end{aligned}$$

- qg contribution enhanced due to large gluon luminosity at LHC
- Need qg at 1-loop (NNLO) to get reliable predictions for large p_T
- Lacking NNLO impose "jet cut" on hadronic energy to cut out $qg \to W^+W^-q$

$p\bar{p} \to W^+W^- \to l\nu l'\nu$ **at Tevatron**

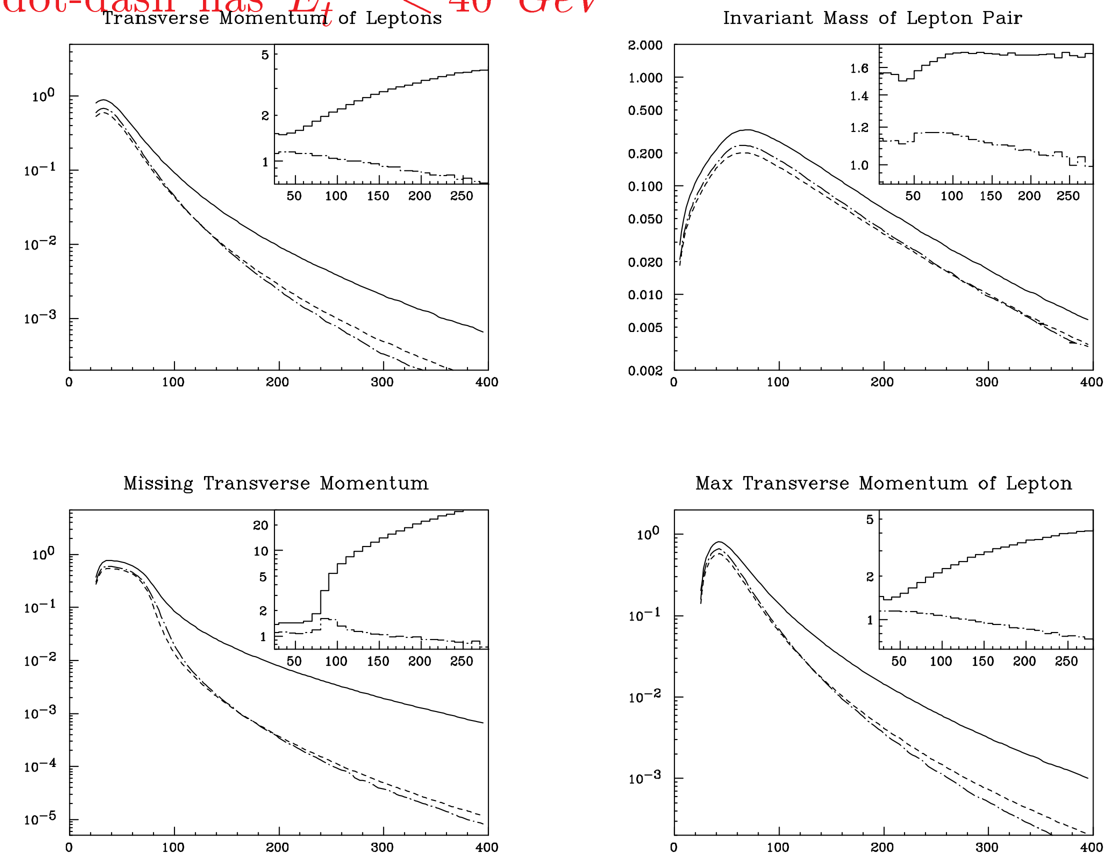
- LO (dashed); NLO (solid) in pb/GeV; inset $\frac{d\sigma_{NLO}}{d\sigma_{LO}}$



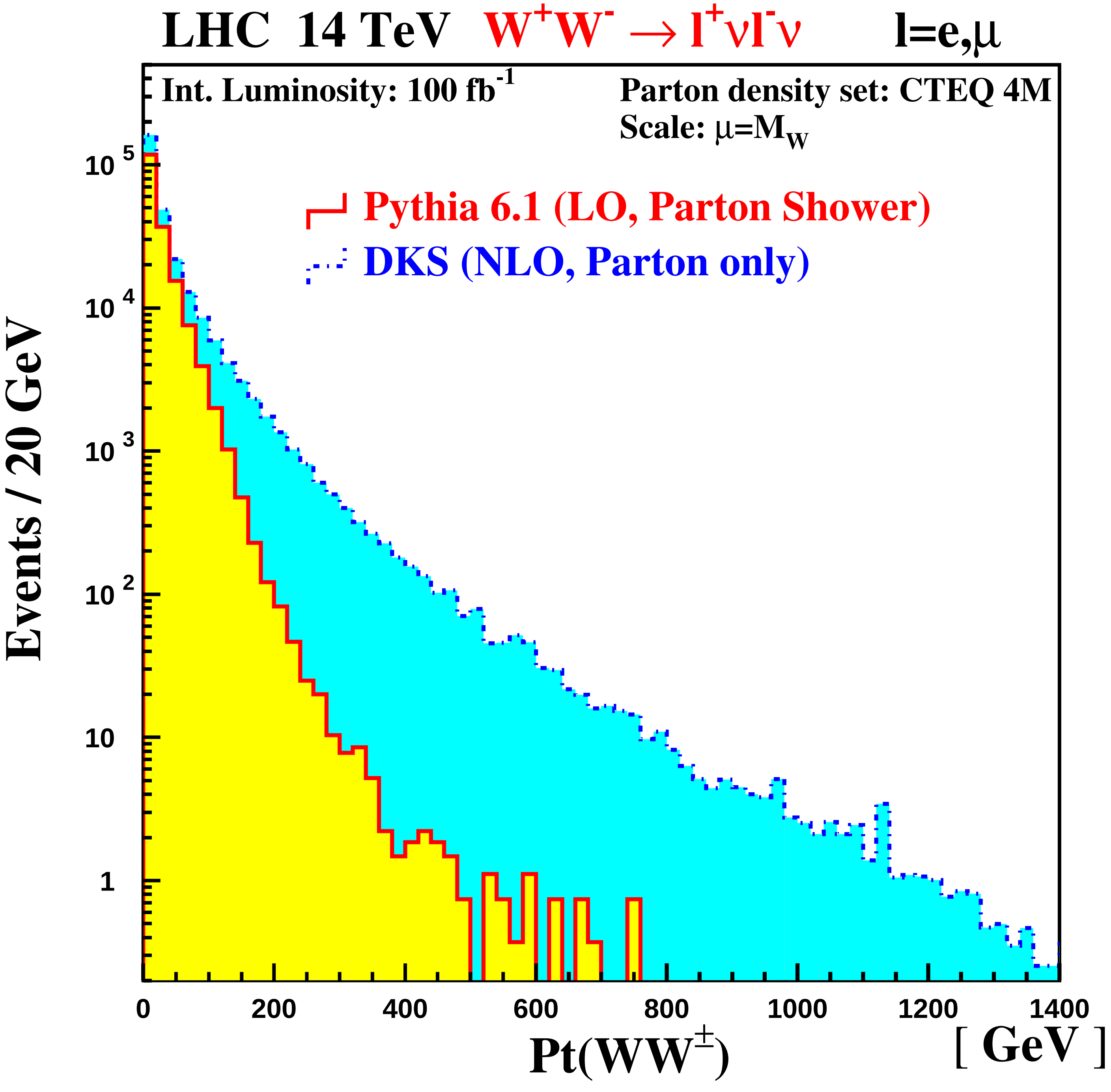
(Dixon, hep-ph/9907305)

$pp \to W^+W^- \to l\nu l'\nu$ **at LHC**

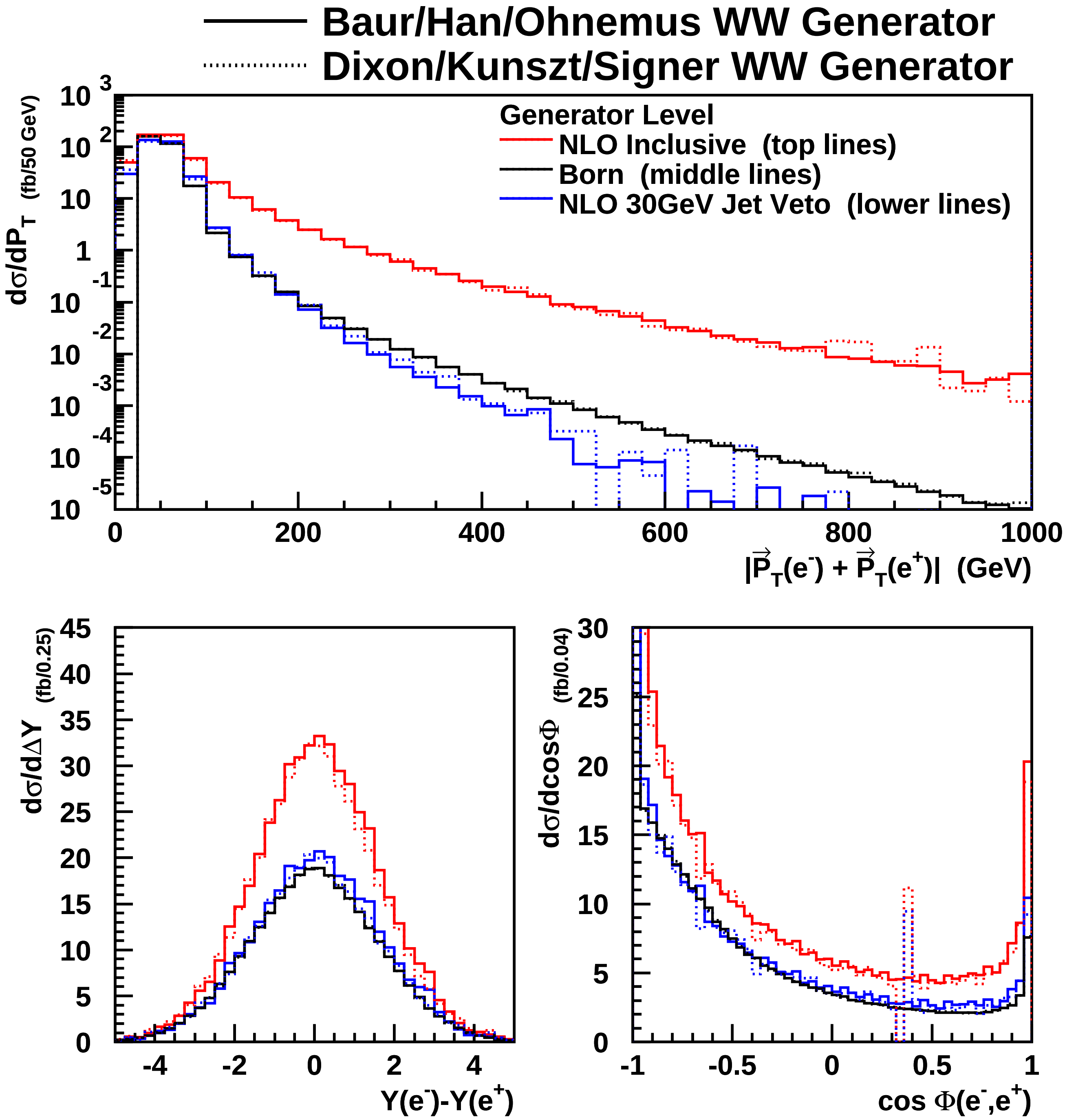
- LO (dashed); NLO (solid) in pb/GeV; inset $\frac{d\sigma_{NLO}}{d\sigma_{LO}}$; dot-dash has $E_t^{had} < 40\ GeV$



(Dixon, hep-ph/9907305)



(LHC Electroweak Study, hep-ph/0003275)


Baur/Han/Ohnemus WW Generator
Dixon/Kunszt/Signer WW Generator
Generator Level
NLO Inclusive (top lines)
Born (middle lines)
NLO 30GeV Jet Veto (lower lines)
dσ/dP_T (fb/50 GeV)
|P_T(e-) + P_T(e+)| (GeV)
dσ/dΔY (fb/0.25)
Y(e-)-Y(e+)
dσ/dcosΦ (fb/0.04)
cos Φ(e-,e+)

Consider Non-SM W^+W^-V Couplings

- Most general gauge and Lorentz invariant couplings with C and P separately conserved:

$$\frac{\mathcal{L}_{VVV}}{-ig_V} = \{g_1^V \left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_\rho^\mu\}$$

where $V = Z, \gamma$

- λ_V higher order in derivative expansion (often ignored)
- SM: $\kappa_\gamma = \kappa_Z = g_1^Z = g_1^\gamma = 1,\ \lambda_V = 0$
- EM gauge invariance requires $\Delta g_1^\gamma = 0$

Assume $SU(2)_C$ and neglect operators with dimension 8 or greater:

$$g_1^Z = \kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$$
$$\lambda_Z = \lambda_\gamma$$

Relationship (HISZ) violated at $\mathcal{O}(E^6)$

NLO corrections to W^+W^- under control with jet veto

Can hope to see small NSM effects:

- $p\overline{p} \to W^+W^- \to e^+e^-p_T^{miss}$ at $\sqrt{s} = 2\ TeV$, $p_T^e >$ $20\ GeV$, $|\eta_e| < 2.5$, $p_T^{miss} > 20\ GeV$, $p_T(jet) > 20\ GeV$, $|\eta_{jet}| < 2.5$

$$\begin{aligned} \sigma_{LO} &= 62 fb \\ \sigma_{NLO} &= 82\ fb \\ \sigma_{NLO} + \text{ Jet cut} &= 66\ fb \end{aligned}$$

With non-SM couplings,

$$\Delta g_1^Z = .5,\ \lambda_Z = \lambda_\gamma = .1,\ \Delta\kappa_Z = \Delta\kappa_\gamma = .3$$

$$\begin{aligned} \sigma_{LO} &= 83 fb \\ \sigma_{NLO} &= 107\ fb \\ \sigma_{NLO} + \text{Jet cut} &= 84\ fb \end{aligned}$$

(Tevatron, Run III study, hep-ph/0005226)

- At high energy, non-SM W^+W^-V interactions give cross sections which violate unitarity

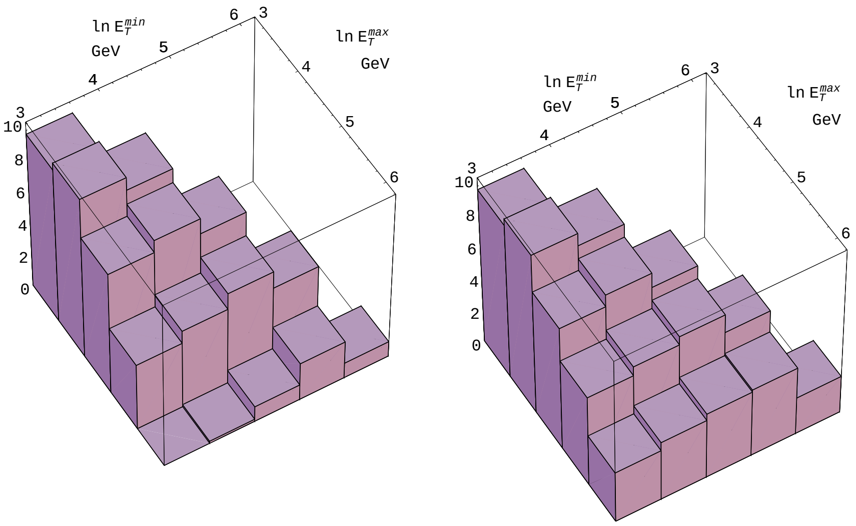
- Unitarity restored at high energy, Λ, by new physics

- Assume form factor dependence:

$$\Delta g_1^Z \to \frac{\Delta g_1^Z}{\left(1 + \frac{M_{WW}^2}{\Lambda^2}\right)^2}$$

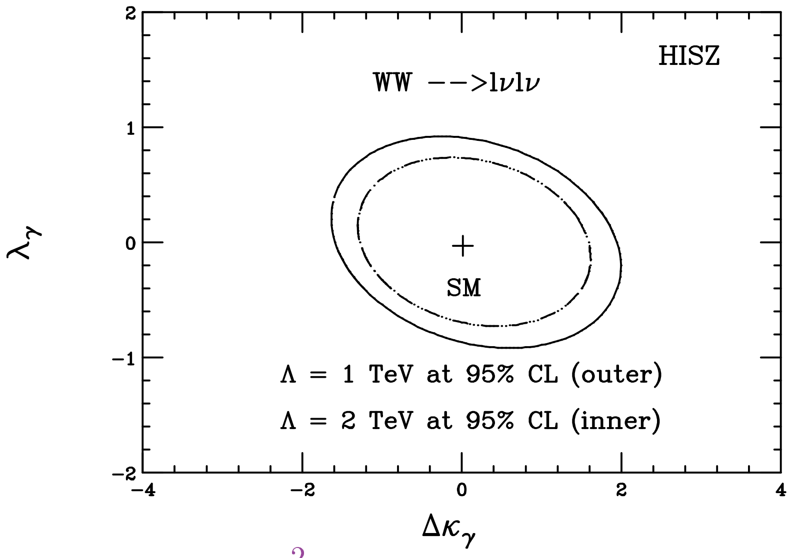
- Sample predictions with $\Delta g_1^Z = .13, \lambda^\gamma = \lambda^Z = .1, \Delta\kappa^\gamma = .2, \Delta\kappa^Z = .07, \Lambda = 2\ TeV$

$W^+W^- \to l\nu l'\nu$ at Tevatron: (SM, NSM)



Note excess of events at high p_T with non-SM couplings
(Dixon, hep-ph/9907305)

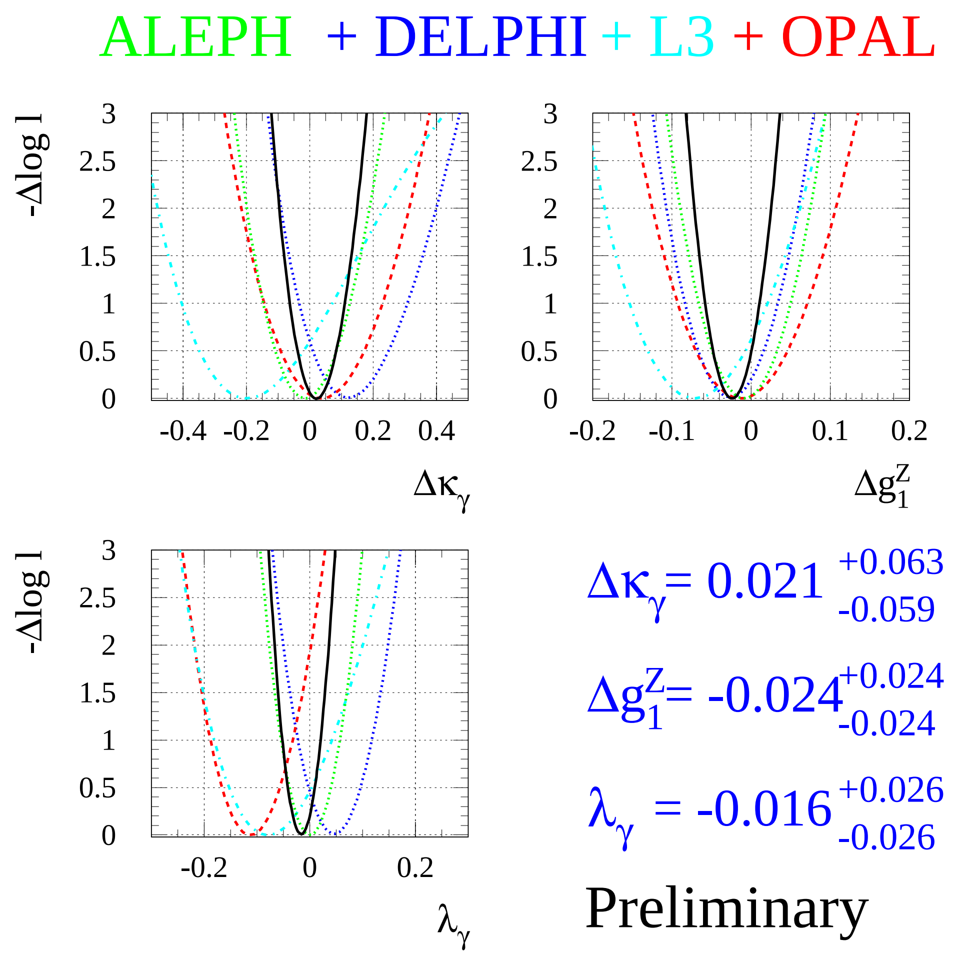
- Limits from measurement of W^+W^- cross section
- CDF with 108 pb^{-1}
- Search for isolated leptons; observe 5 events



- Expect couplings $\sim \frac{g^2}{16\pi^2} \sim .001$
- With $2fb^{-1}$, $p\overline{p} \rightarrow W^+W^- \rightarrow e\nu jj$ may achieve:

$$-.16 < \lambda_Z < .1$$
$$-.3 < \Delta g_1^Z < .3$$

LEP2 limits (Moriond, 2000) on 3GB couplings:



$(475 \ pb^{-1}; \ 6320 \ W + W^- \ \text{events})$

Conclusions

- Lots of QCD in Higgs physics!
- Starting to see need for NNLO calculations
- NLO VV pair production under control with jet veto; anomalous couplings measurable