ILC and LHC Physics

Edmond L. Berger

- 2005 Snowmass International Linear Collider Workshop
- Large Hadron Collider Physics
  - QCD ‘backgrounds’ for Higgs decay to $\gamma\gamma$
  - Higgs decay to W^+W^- to l^+l^- plus missing energy and the cocktail of standard model backgrounds

2005 Snowmass ILC Workshop

- I proposed at the 2004 Victoria LC workshop that we (ALCPG) host an extended international workshop to advance the detector concepts and sharpen the physics case; accelerator community then joined us
- Agreed to Co-Chair the LOC and the Executive Committee
- LOC of 6 individuals: ELB, J. Brau, S. Mishra, U. Nauenberg, M. Oreglia, and N. Phinney
  - Defined scientific program
  - Created the necessary infrastructure
- Scientific: charge for the workshop and for the working groups, advisory committees, working group topics and conveners, plenary speakers, summary speakers, special forums, ...
- Infrastructure: choice of Snowmass, funding from agencies and labs and other sources, assembled a secretariat, assembled a computer support team, obtained equipment, 22 meeting rooms, ..

2005 Snowmass ILC Workshop

- Took precedence over all other activities from 10/04 through 08/05
- Nearly 700 participants – scientists and engineers from all regions
- Achieved goals
  - Accelerator: Baseline Configuration Document; R&D plan; ....
  - Detectors: first full meeting of the 3 major concept groups; `detector outline documents'; PFA studies; MDI; ...
  - Physics: emphasis on benchmarking; precise calculations; simulations; ...
  - Outreach and Communication: engage (more of) the particle physics and engineering communities AND the greater public
- Since the workshop: invited article for the December 2005 CERN Courier, proceedings, financial reporting, ...
- Highly valued throughout the international linear collider community

2005 Snowmass ILC Workshop

Aug. 29 '05

Dear Ed,

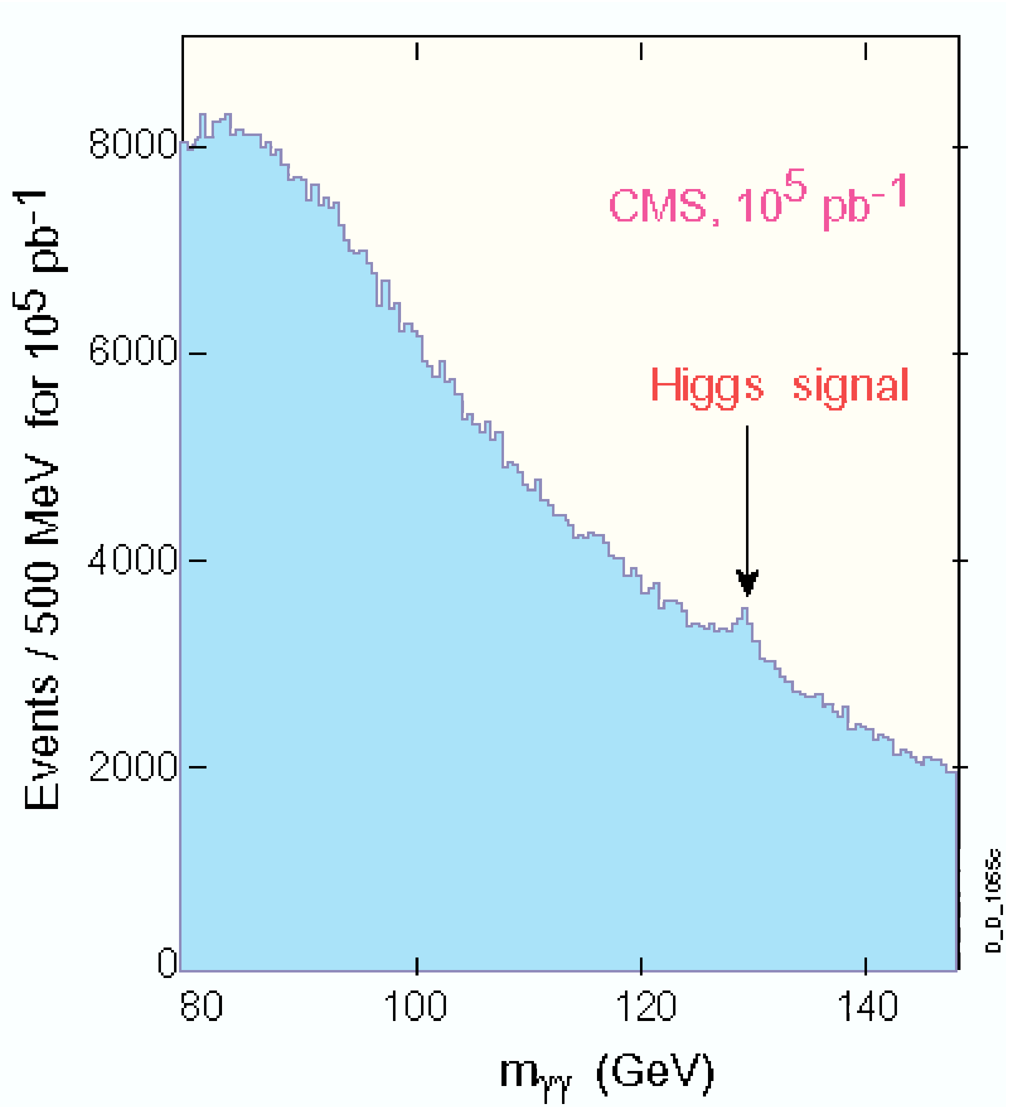
Please accept the profound and heart felt thanks from your Cornell colleagues for a superb Snowmass 2005.

Very best
Maury

Higgs Boson Search at the LHC

- Discover/understand the mechanism for electroweak symmetry breaking: a clear goal of LHC and ILC experiments during the next decade
- ATLAS and CMS plans:
  - Thorough search for Higgs bosons
  - Measure their properties and determine their couplings
- Help guide the search with theoretical predictions for the signal and backgrounds
- Focus today on the $\gamma\gamma$ and l^+l^- final states:
  - Signal $h \to \gamma\gamma$ and background from all QCD subprocesses
  - Signal $h \to W^+W^- \to l^+l^-X$ and backgrounds from a cocktail of standard model processes; including leptons from heavy flavor decays

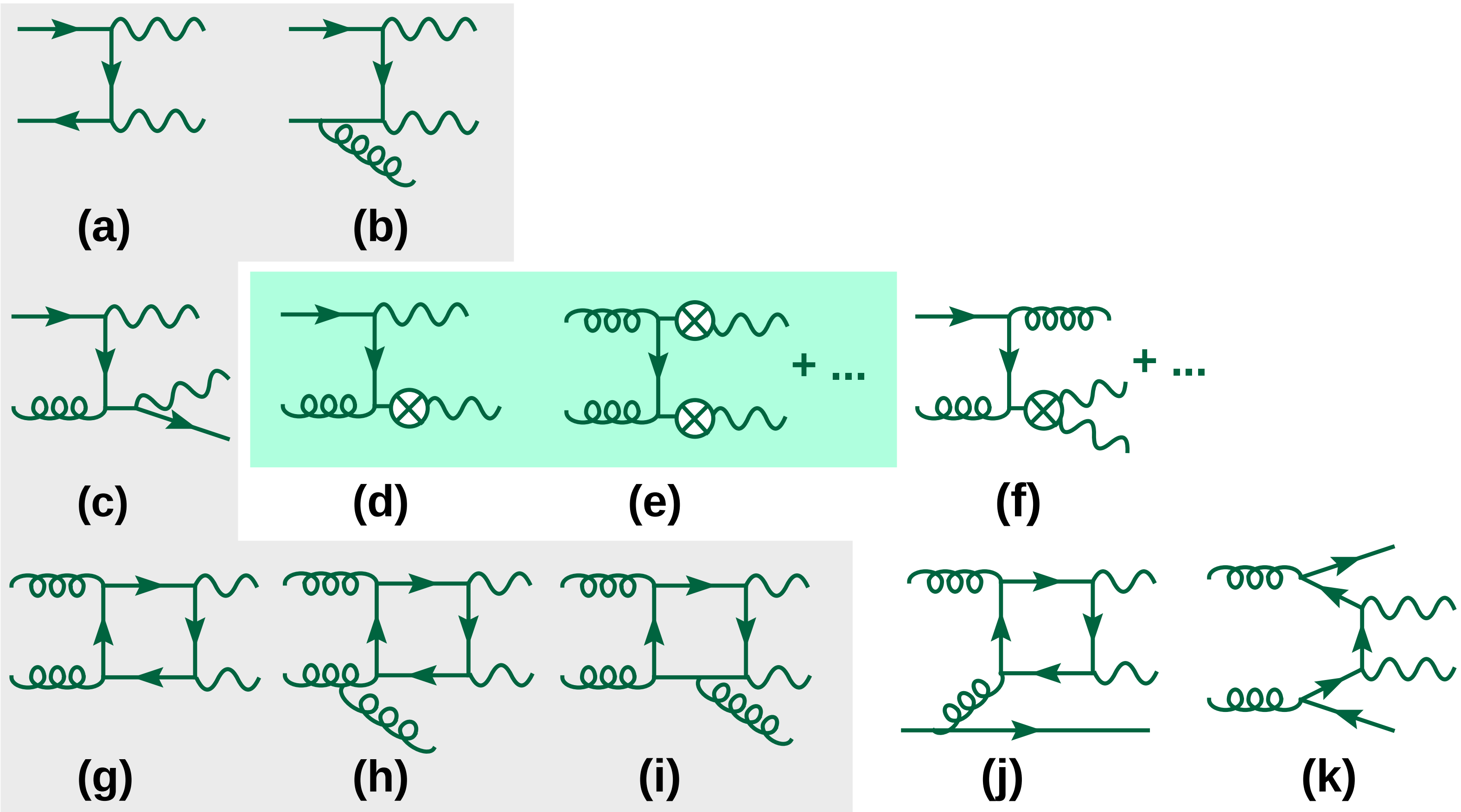
What do we expect to see in the $\gamma\gamma$ mass spectrum?



- Try to improve the signal to background by selecting events with 'large' pair transverse momentum Q_T

QCD Production of Photon Pairs

- QCD 'background' subprocesses initiated by $q\bar{q}$, qg and gg subprocesses



- Run 2 data from CDF at FNAL permit test of calculations
- Interesting QCD in its own right

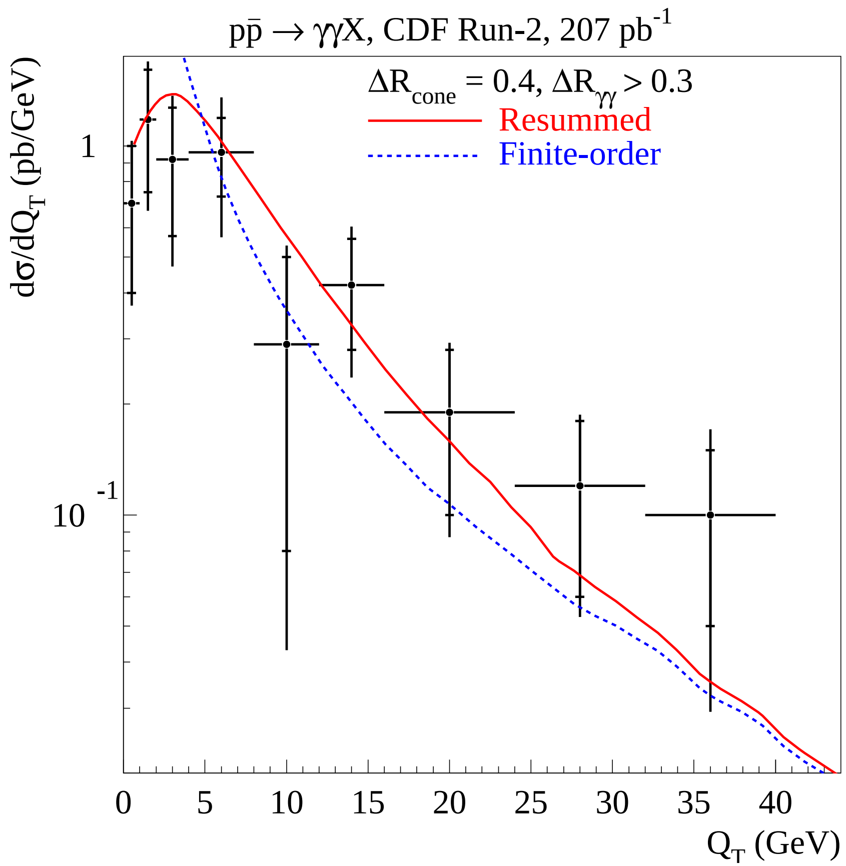
Differential cross section; fixed-order in α_s

- At fixed-order in α_s, the transverse momentum distribution behaves as $\frac{\alpha_s}{Q_T^2}\left[a + b\log(m_{\gamma\gamma}^2/Q_T^2)\right] \to \infty$ as $Q_T^2 \to 0$
  - $1/Q_T^2$ divergence is related to the light parton propagators
  - The logarithmic term $\log(m_{\gamma\gamma}^2/Q_T^2)$ remains after the usual cancellation of infra-red divergences and the absorption of collinear divergences into the renormalized parton densities
- In addition

  $\frac{\sigma^{\rm NLO}}{\sigma^{\rm LO}} = \mathcal{O}(\alpha_s \log^2(m_{\gamma\gamma}^2/Q_T^2))$ is not small $(\alpha_s(\mu)/\pi)\ln^2(m_h^2/Q_T^2) \sim 0.7$ if $\mu = m_h = 125$ GeV and $Q_T = 14$ GeV
- The large logarithmic terms spoil conventional factorization in QCD perturbation theory
- The physical cross section peaks below $Q_T \sim m_{\gamma\gamma}/3$.
  A reliable QCD calculation for small and intermediate Q_T requires that we resum the large logarithmic terms to all orders in α_s

Comparison with Run-2 Data

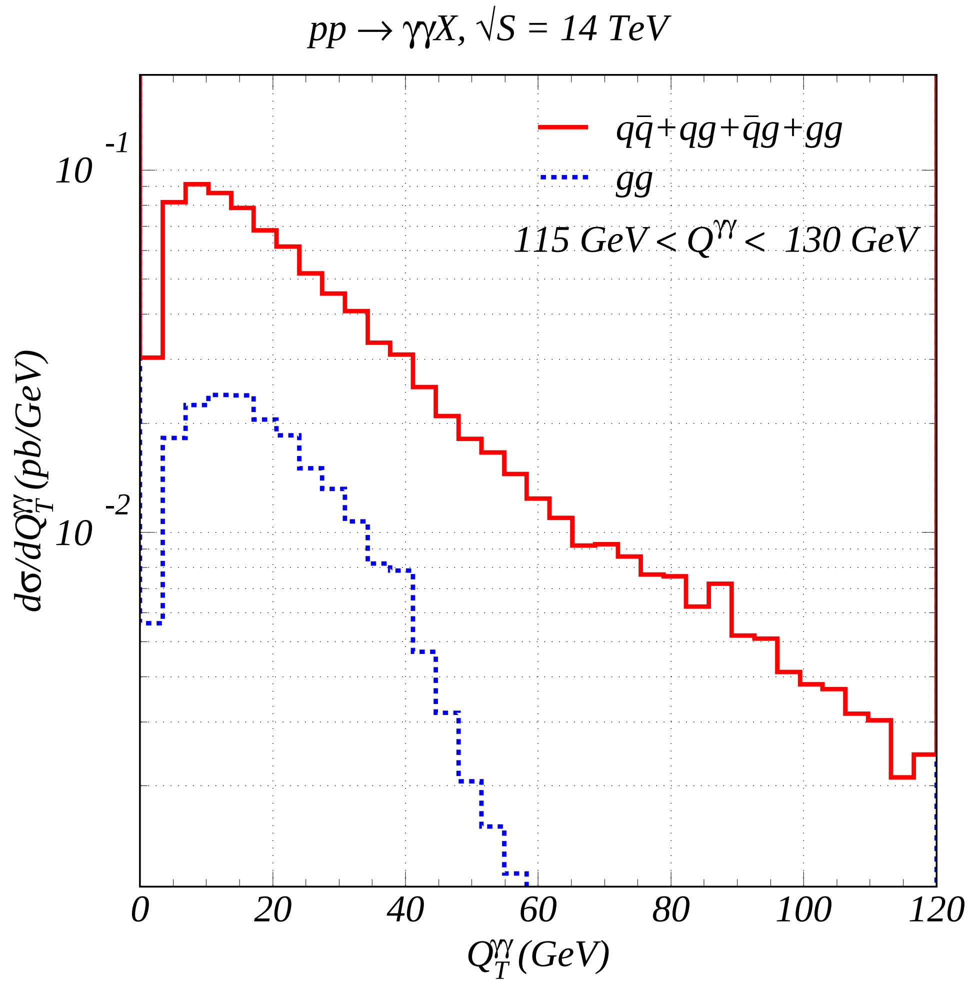
Balazs, Berger, Nadolsky, Yuan, hep-ph/0603037, Phys Letters B



- Our NNLL resummed Q_T calculation differs in shape and normalization from the finite-order perturbative result (P); it agrees well with the data
- Discrepancy at the larger values of Q_T is understood - related to the region of small $m_{\gamma\gamma}$ ($< Q_T$) and small $\Delta\phi$ where other (interesting) effects dominate - not of concern for Higgs physics at the LHC

Prediction for the LHC Balazs, Berger, Nadolsky, Yuan

- Q_T spectrum for $115 < m_{\gamma\gamma} < 130$ GeV



- The qg and $q\bar{q}$ subprocesses dominate. The glue glue subprocess is a small portion of the answer even at the LHC

$\gamma\gamma$ *Prediction for the LHC*

- The Q_T distribution of the background broadens with increasing $m_{\gamma\gamma}$, (as it does also for the signal for increasing m_h)
- For the SM Higgs boson mass range, 115 to 130 GeV, the $\gamma\gamma$ background peaks at a smaller value of Q_T than the Higgs boson signal. The QCD background has $\langle Q_T \rangle \sim 27$ GeV, vs. ~ 40 GeV for the Higgs boson signal
- The $qg \to \gamma\gamma X$ and $q\bar{q} \to \gamma\gamma X$ subprocesses that dominate QCD background have a softer Q_T spectrum than that for Higgs boson production because there is less gluon radiation in fermionic subprocesses
- Selection of events with large $Q_T^{\gamma\gamma}$ will help to improve S/B.

Balazs, Berger, Nadolsky, Yuan, hep-ph/0603037, Phys. Letters B

plus long paper to be issued within weeks

Higgs boson decay $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$

- $h \to W^+W^-$ branching fraction dominant when $m_h > 135$ GeV; at $m_h = 170$ GeV, $BR(h \to WW^* \to l^+l^-\nu\bar{\nu}) \sim 100 BR(h \to ZZ^* \to 4l)$
- The 'signal' is an excess of events above backgrounds from processes that provide l^+l^- plus missing transverse energy
- Standard model backgrounds:
  - 'irreducible' backgrounds have at least two 'isolated' leptons plus missing energy: continuum $WW^* \to l^+l^-\nu\bar{\nu}$; $WZ/ZZ \to l^+l^-\nu X$; $t\bar{t} \to WWb\bar{b}$; 'single top' $qg \to Wt \to WWb$;...
  - 'reducible' backgrounds in which the (second) lepton(s) and the missing energy arise from heavy flavor decay: $Wb\bar{b} \to l\nu b\bar{b}$; $Wc\bar{c}$, Wc,..., and inclusive $b\bar{b}/c\bar{c}$
- Heavy flavor backgrounds believed incorrectly to be removed by lepton isolation in prior studies

Higgs boson decay $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$

- 'Reducible' backgrounds: major issue is the extent to which lepton isolation and subsequent kinematic physics cuts can suppress them
- The problem:
  $\sigma B(h \to WW^* \to ll\nu\bar{\nu}) \sim 0.7$ pb for $m_h = 150$ to 190 GeV
  $\sigma^{b\bar{b}}_{\rm inclusive} \sim 5 \times 10^8$ pb
- 'Isolation' in $b \to lX$ (ΔR, $E_T^{\rm iso}$) even at the 0.5 % level leaves $l^+l^-E_T^{\rm miss}$ background that is 10^4 greater than the signal
- Questions of both magnitude and shape of the backgrounds
- Thorough (re)evaluation of the signal and backgrounds for $h \to WW^* \to ll\nu\bar{\nu}$: Berger and Sullivan, paper in draft form includes analysis of CDF and D0 cases
- Independent study of the ATLAS analysis chain but with all heavy flavor processes included
- Events generated with PYTHIA and put through a full detector simulation PGS (similar to ATLFAST)

Cross sections (fb) vs. cuts; $m_h = 160$ GeV

- Series of isolation and physics cuts on reconstructed objects (not parton level) (Table shows results of our analysis)
- 'Isolated' means $p_T^l > 10$ GeV, $\eta^l < 2.5$, plus generic ATLAS cone ΔR and $E_T^{\rm iso}$ choices

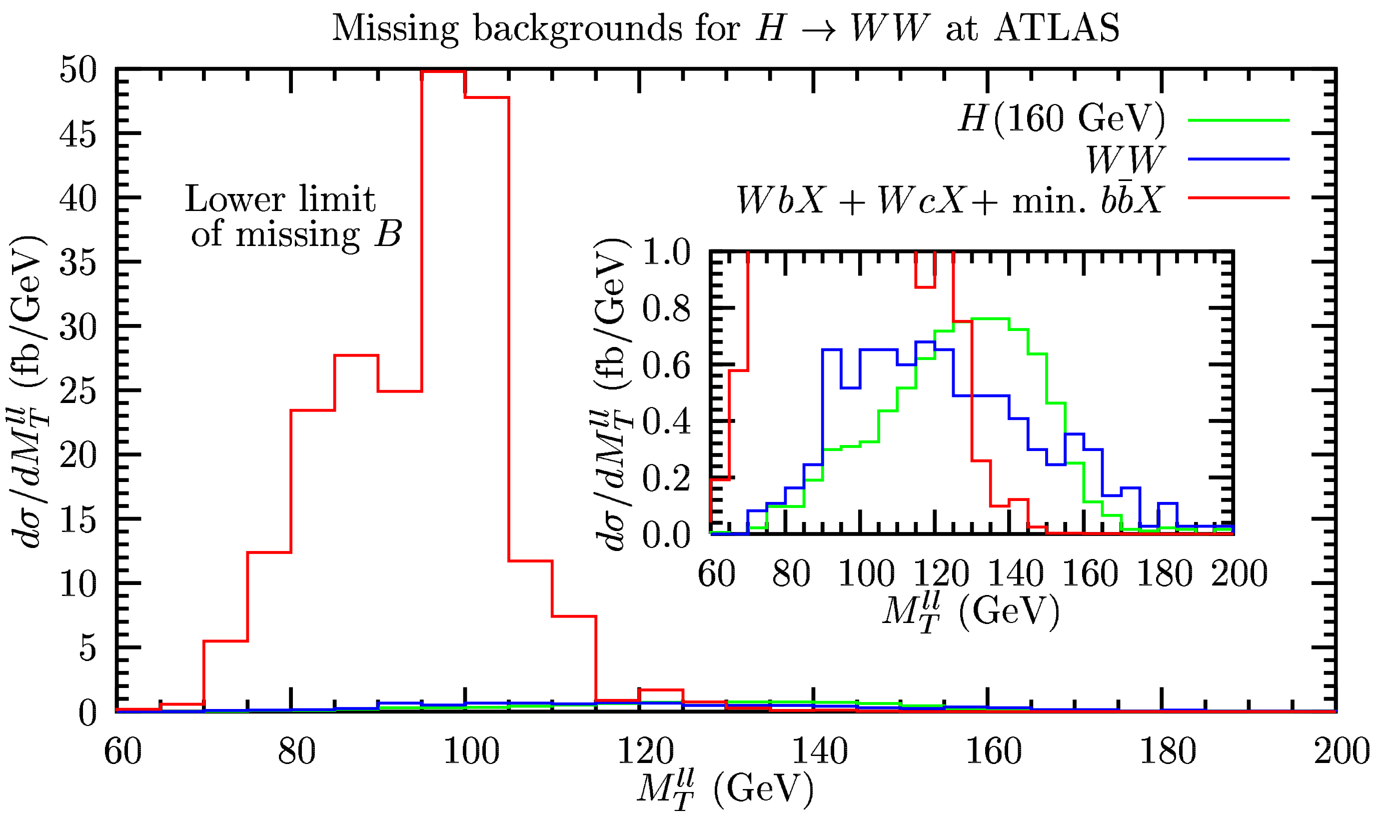
Table 1: Cross sections (in fb) for opposite-sign leptons as a function of cuts for the 160 GeV Higgs ATLAS analysis. $b\bar{b}$ production is a lower limit based on limited phase space, and $c\bar{c}$ production is not calculated. A dash indicates statistics were too small to estimate.

Cut level	$H \to WW$	WW	$b\bar{b}$	Wc	single-top	$Wb\bar{b}$	$Wc\bar{c}$
Isolated l^+l^-	336	1270	> 35700	12200	3010	1500	1110
$E_{Tl_1} > 20$ GeV	324	1210	> 5650	11300	2550	1270	963
$\not{E}_T > 40$ GeV	244	661	> 3280	2710	726	364	468
$M_{ll} < 80$ GeV	240	376	> 3270	2450	692	320	461
$\Delta\phi < 1.0$	136	124	> 1670	609	115	94	131
$\theta_{ll} < 0.9$	81	83	> 1290	393	68	49	115
$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 1.5$	76	71	> 678	320	48	24	104
Jet veto	41	43	> 557	175	11	12	7.4
$130 < M_T^{ll} < 160$ GeV	18	11	—	0.21	1.3	0.04	0.09

Transverse mass distribution after cuts

Berger, Sullivan

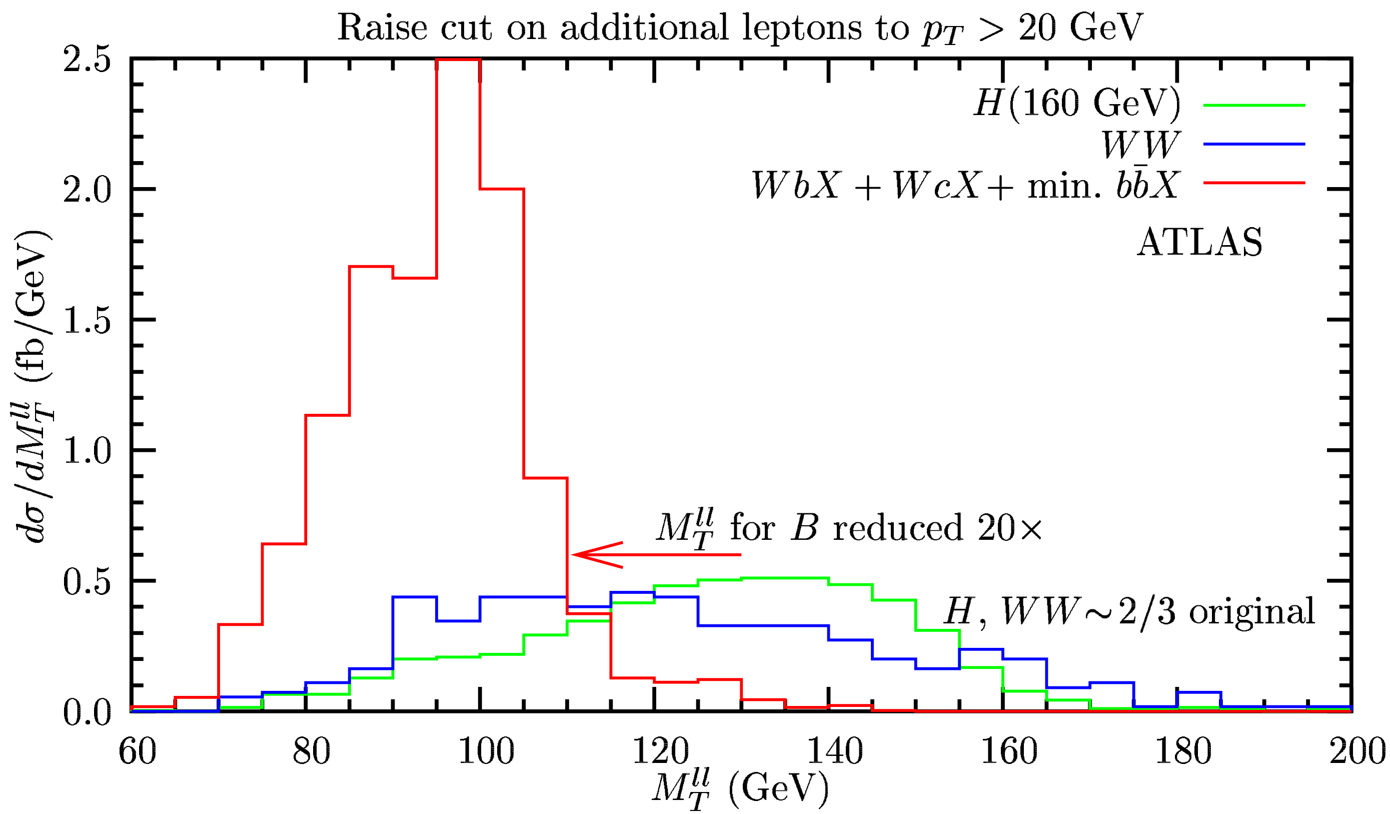
- Cannot reconstruct a Higgs boson mass peak from $h \to WW^* \to l^+ l^- \nu \bar{\nu}$; use 'transverse mass' as an estimator; $M_T^{l\bar{l}} = \sqrt{2 p_T^{l\bar{l}} E_T^{miss} (1 - \cos(\Delta\phi))}$



- Heavy flavor background is more than 10 times previous estimates of backgrounds when $M_T^{l\bar{l}} < 110$ GeV; a tail extends into the signal region

$M_T^{l\bar{l}}$ distribution with a harder p_T^l cut

Berger, Sullivan



- Harder cut on the p_T of the second lepton suppresses the heavy flavor background, by a factor of about 20, but has only a small effect on the $h \to WW$ and continuum WW contributions.
- The leading edge of the heavy flavor contribution drops to lower $M_T^{l\bar{l}}$

Summary $h \to W^+W^- \to l\bar{l}\nu\bar{\nu}$

- Previously omitted heavy flavor backgrounds are potentially huge: not killed by isolation
- Raising the p_T^l cut on the non-leading lepton appears essential
- Lepton identification criteria and isolation cuts will change once data are in-hand and real detector response is known
- Shape of the background is a limiting factor – not clear we can simulate tails well – could be worse
- 'Measure' the background?
- Heavy flavor backgrounds are an issue for all BSM signals with leptons in the final state; e.g., requirement to raise the p_T^l cut will affect SUSY studies with multi-lepton final state signatures

Future work

- Continue quantitative calculations (NLO, resummation, ..) of standard model and new physics processes at the energy of the Large Hadron Collider, including implications from Tevatron collider data, data challenges, full simulations, ...
- Keep the home fires burning for the International Linear Collider
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- Snowmass 2020

Higgs boson branching fractions