A feasibility study of top-quark Yukawa coupling measurement in e^+e^- -> ttH at sqrt(s)=500GeV

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for

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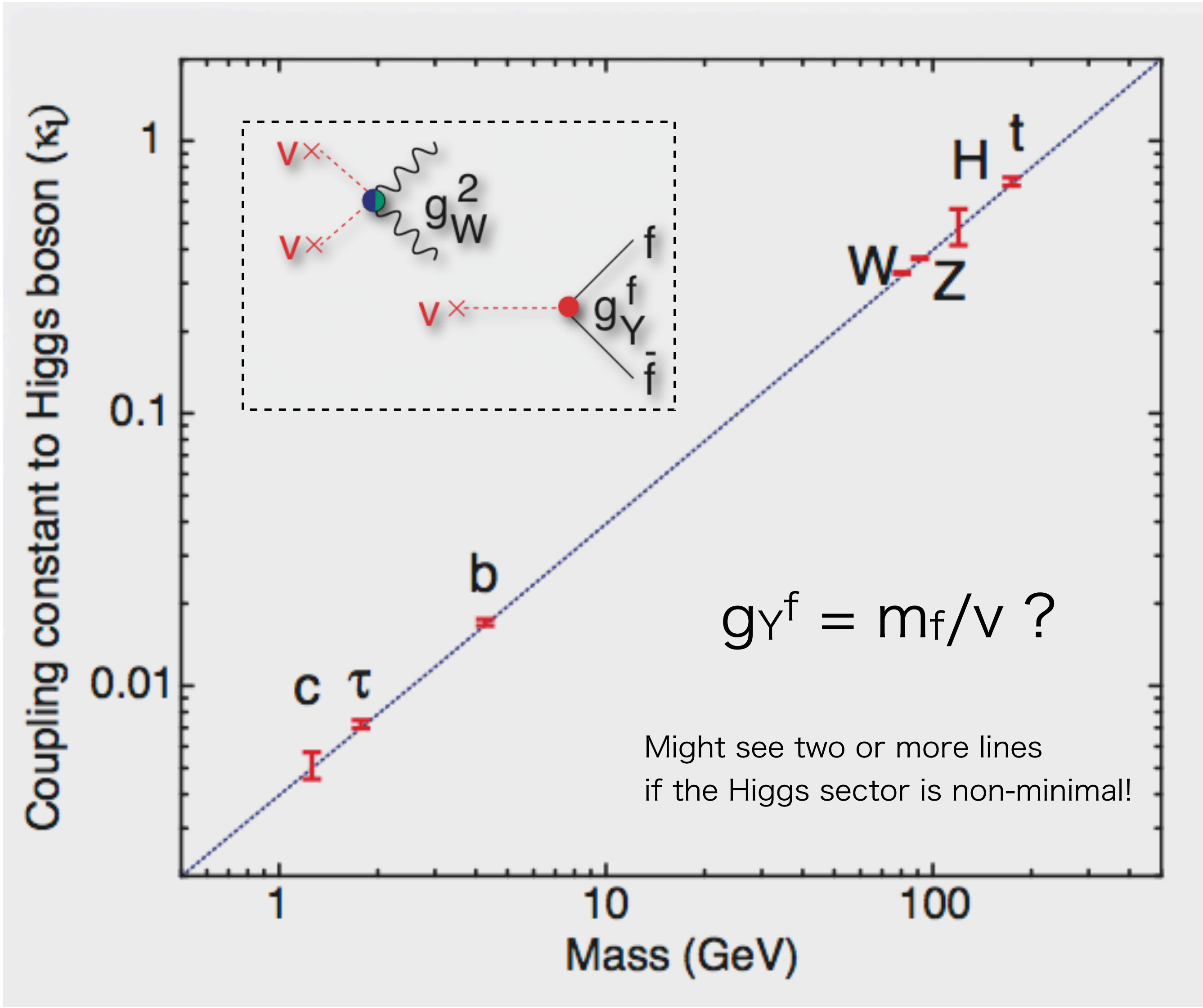
Introduction

- Unique role of the top quark for Electroweak symmetry breaking (EWSB) studies
  - Top mass is by far the largest and approximates the EWSB scale
  - Suggests top couples strongly to the physics that breaks the EW symmetry
  - Important to investigate properties of the top in detail, for the purpose of probing the EWSB physics as well as to gain deeper understanding of the origin of the flavor structure
  - Measurement of top-quark Yukawa coupling will be the most decisive test of the mass generation mechanism for matter particles!

- Goal of our study: evaluate measurement accuracy for the direct measurement of the top Yukawa coupling at 500GeV
  - Need to demonstrate its feasibility in the first phase of the ILC project!

If the Higgs boson is the one to give masses to all the SM particles, we need to observe proportionality between mass and coupling



Measurement of top Yukawa coupling

- **LHC** (2 x 300 fb^{-1})
  - Cross section for Gluon fusion -> H

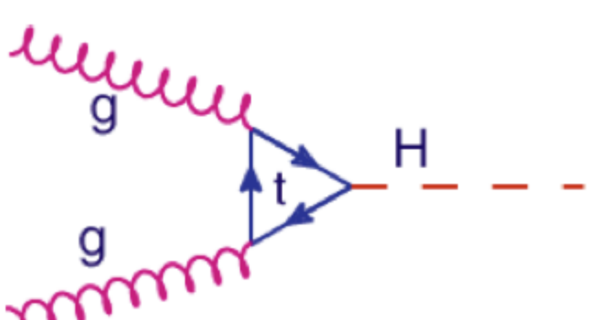
$$\sigma_{ggH} = \alpha_{ggH} \cdot g_t^2$$

  - Cross section for Gluon fusion -> ttH (seems difficult...)

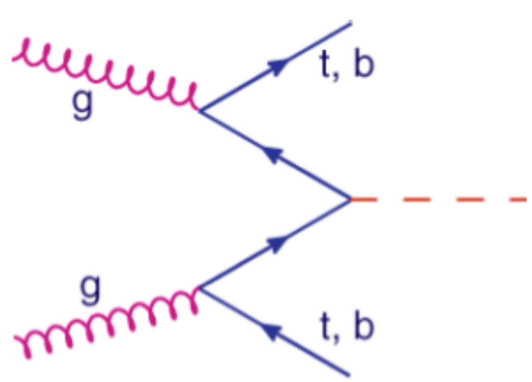
$$\sigma_{ttH} = \alpha_{ttH} \cdot g_t^2$$

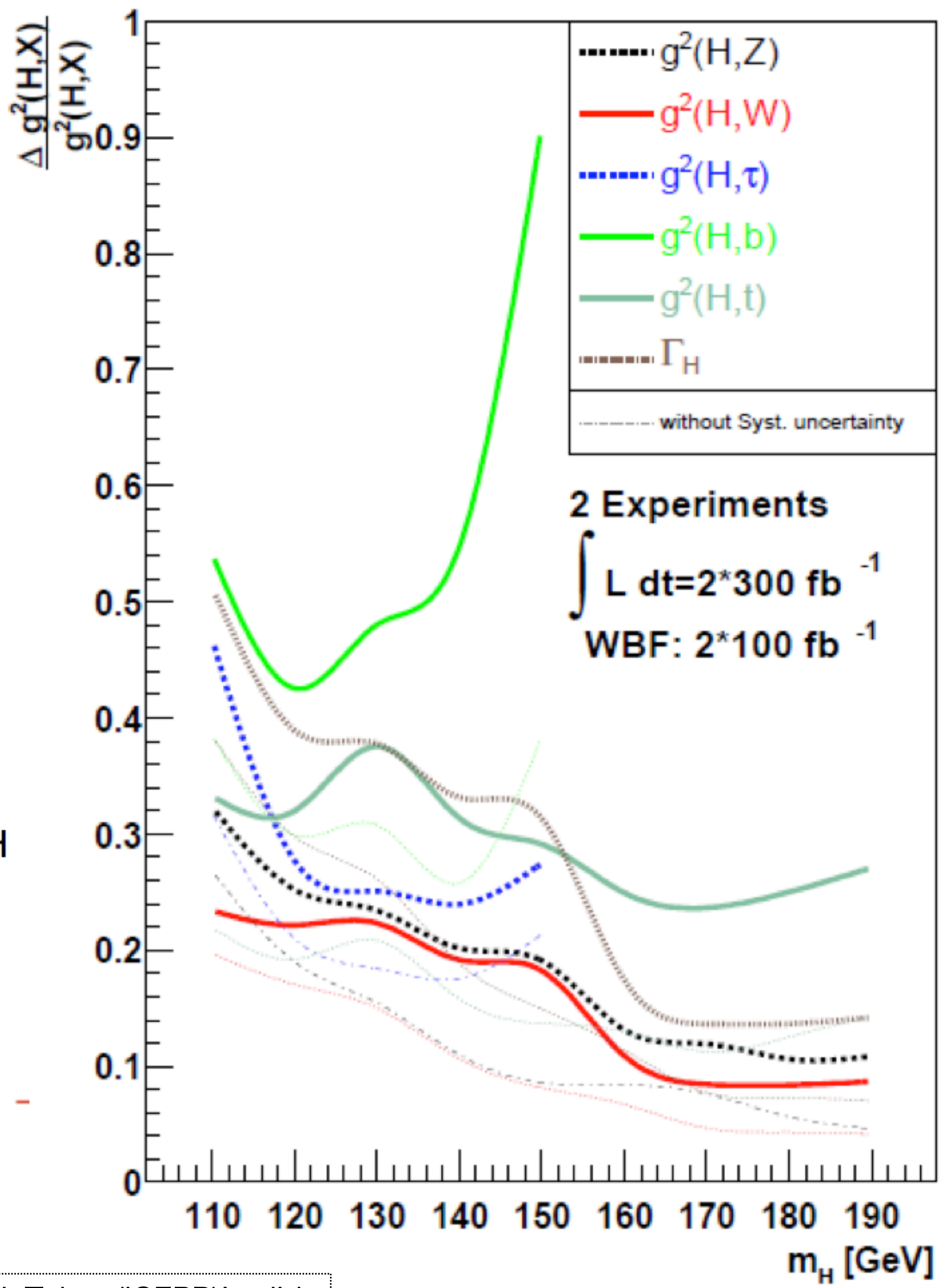
  - Branching ratio for H -> $\gamma\gamma$

$$BR(H\text{->}\gamma\gamma) = (\beta_{\gamma W} \cdot g_W - \beta_{\gamma t} \cdot g_t)^2 / \Gamma_H$$



via loop -> assume SM

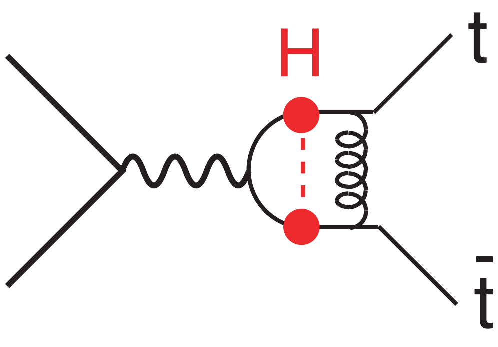




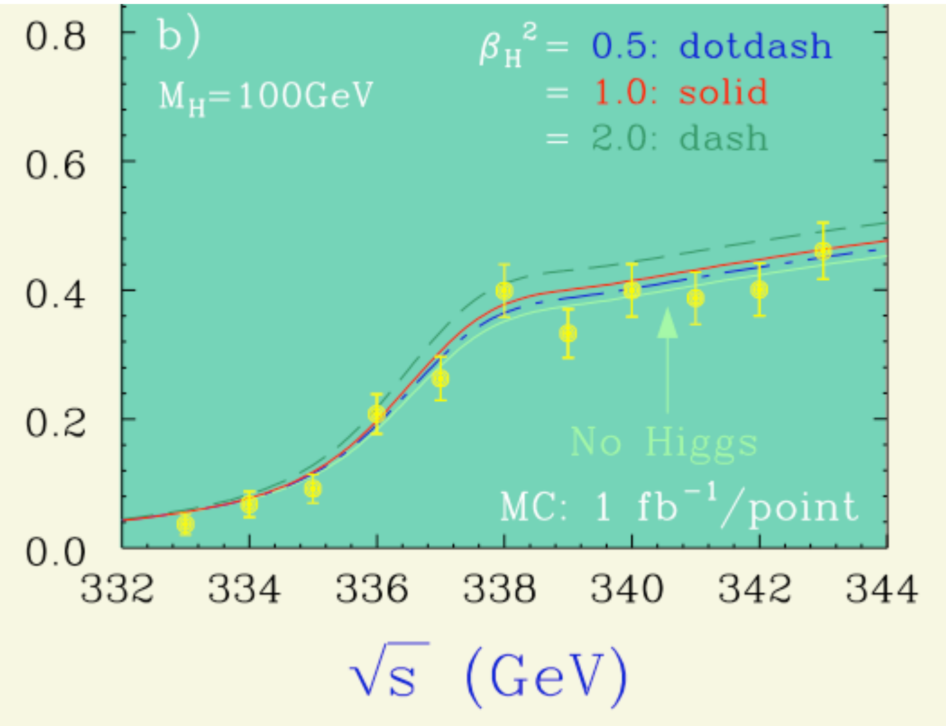
From J. Tanaka (U. Tokyo/ICEPP)'s slide

Measurement of top Yukawa coupling

- **ILC**: indirect measurement
  - Higgs exchange between tops affects the potential near ttbar threshold
  - 11 points ttbar threshold scan => σ_{tt} (m_H, g_Y^t)
  - Need theoretical progress in the predictions of ttbar threshold observables



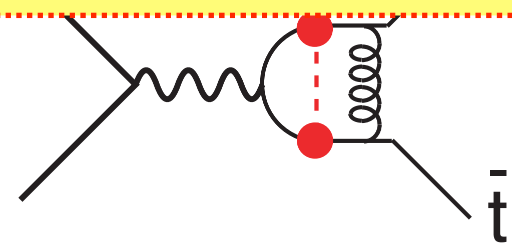
√s ~ 350 GeV



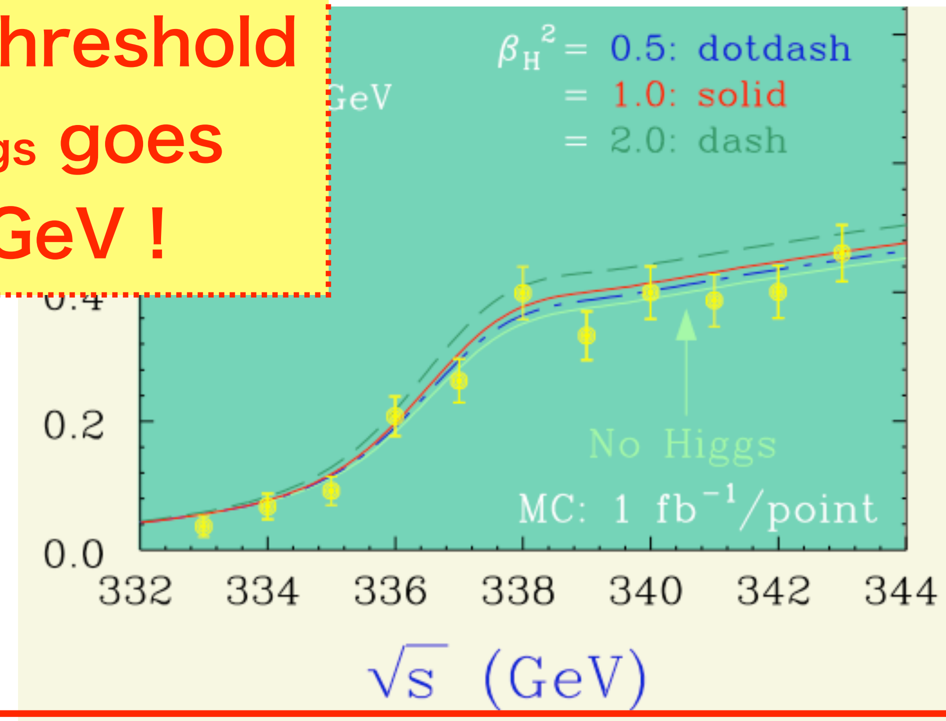
Measurement of top Yukawa coupling

- **ILC**: indirect measu
  - Higgs exchange betwee
    the potential near ttbar
  - 11 points ttbar thresho
    => σ_{tt} (m_H, $g_Y{}^t$)
  - Need theoretical progress in the predictions of ttbar threshold observables

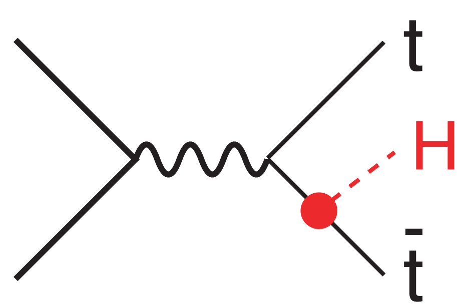
top Yukawa effect at tt threshold quickly vanishes as M_{Higgs} goes up from 110GeV to 120GeV !

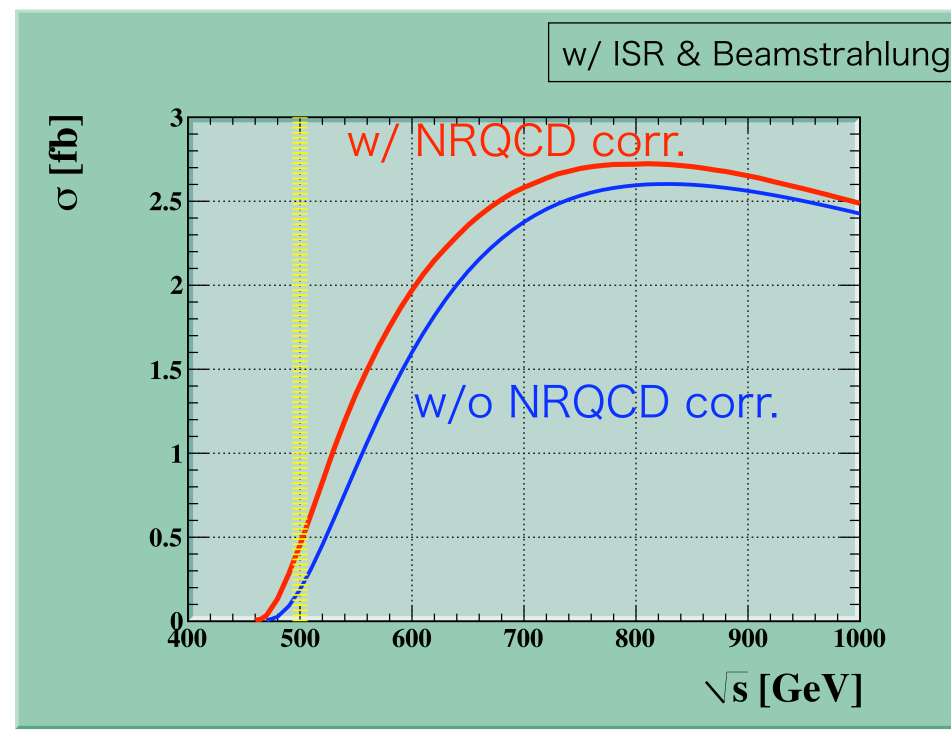


√s ~ 350 GeV



- **ILC: direct measurement**
  - Most of the past studies were done assuming at √s ~700GeV since the cross section for e^+e^- -> ttH attains its maximum around this energy region
  - However, pointed out that the NRQCD threshold correction enhances the cross section significantly and might open the possibility of directly measuring $g_Y{}^t$ **at √s = 500GeV**

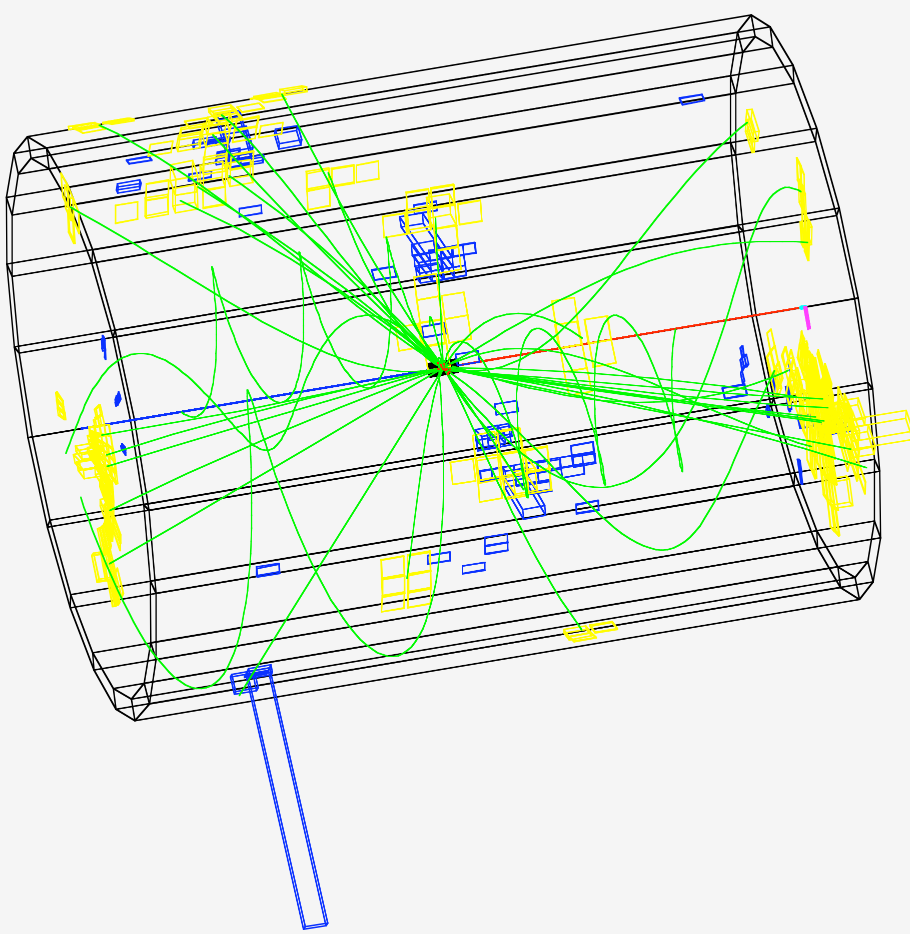




e^+e^- -> ttH event display

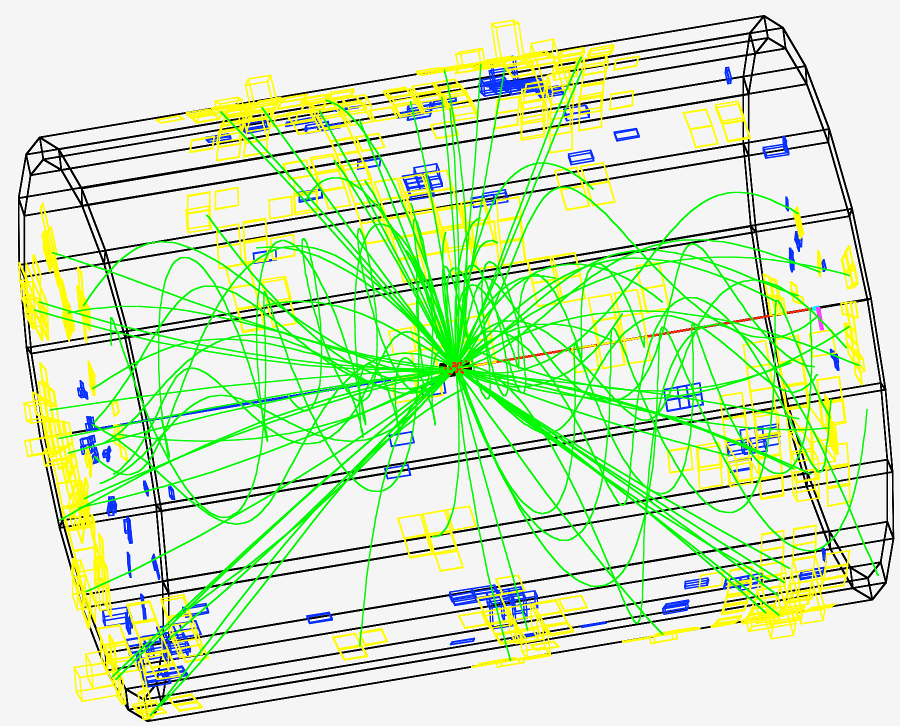
- Dense 8-fermion (H->bb) and/or 10-fermion (H->WW*) events
- Challenging for correct jet-parton association w/ quad b-tagging
  - Di-jet & Tri-jet invariant masses: $M_W(jj)$, $M_t(bjj)$ & $M_H(bb)$ for background events rejection

Lepton + 6-jets mode



ttH -> (bW)(bW)(bb) -> (bcs)(blν)(bb)

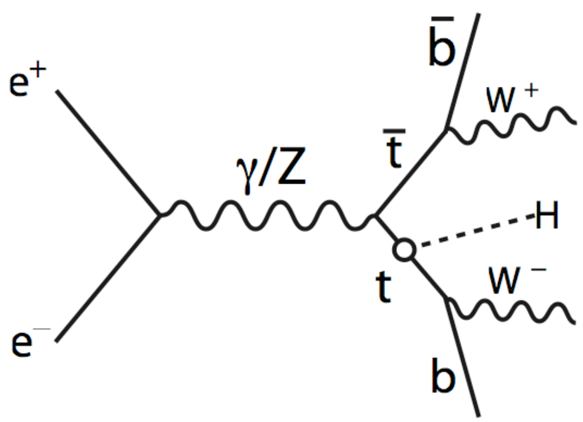
8-jets mode



ttH -> (bW)(bW)(bb) -> (bcs)(bcs)(bb)

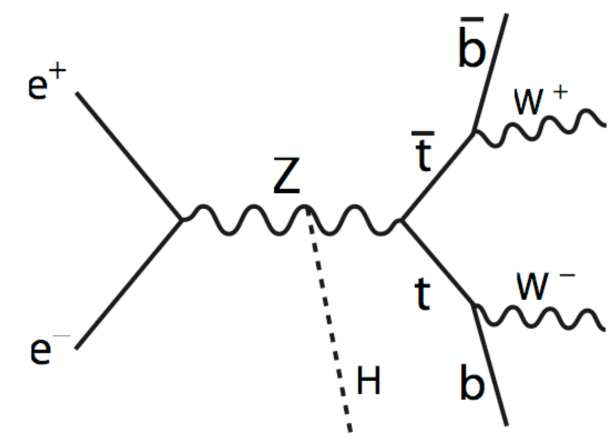
Signal processes: e^+e^- -> ttH

- In this study: concentrate on the dominant decay mode H(120GeV) -> bb (68%)
  - ttH (-> bW^+bW^- bb) signal events can be classified into 3 groups
    - 8-jets, 1-lepton + 6-jets, and 2-leptons + 4-jets



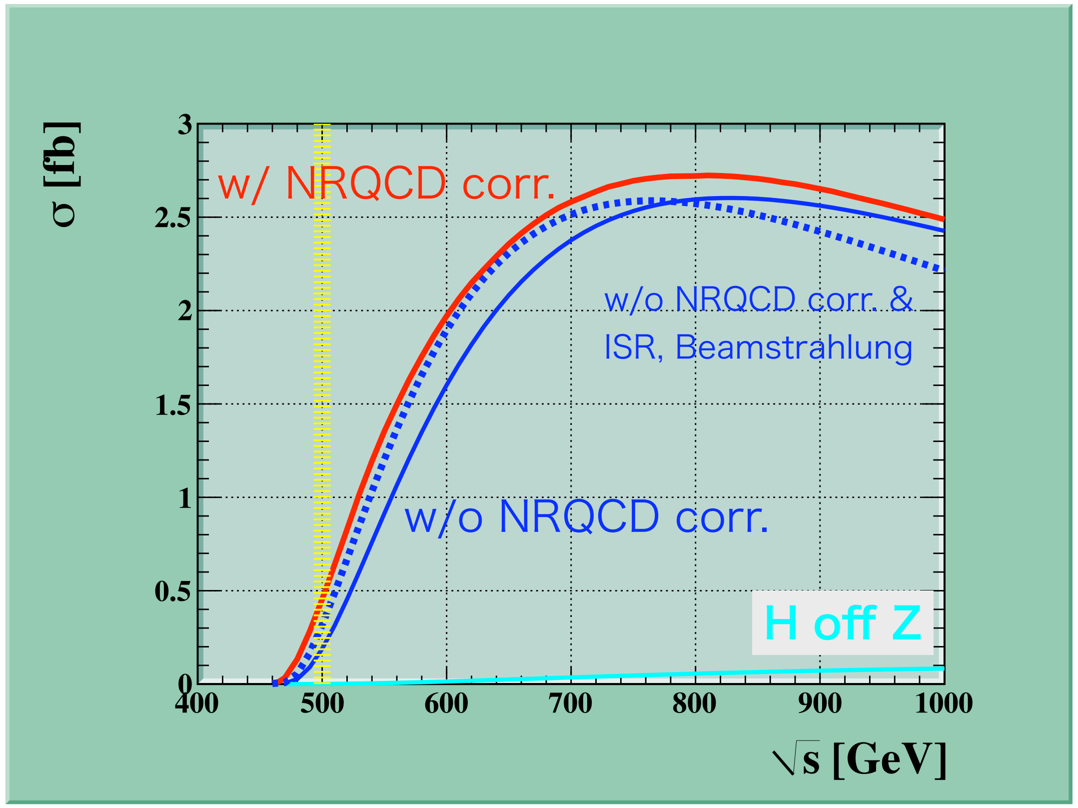
Contains the top Yukawa coupling

$$\sigma_{ttH} \propto (g_Y^t)^2$$



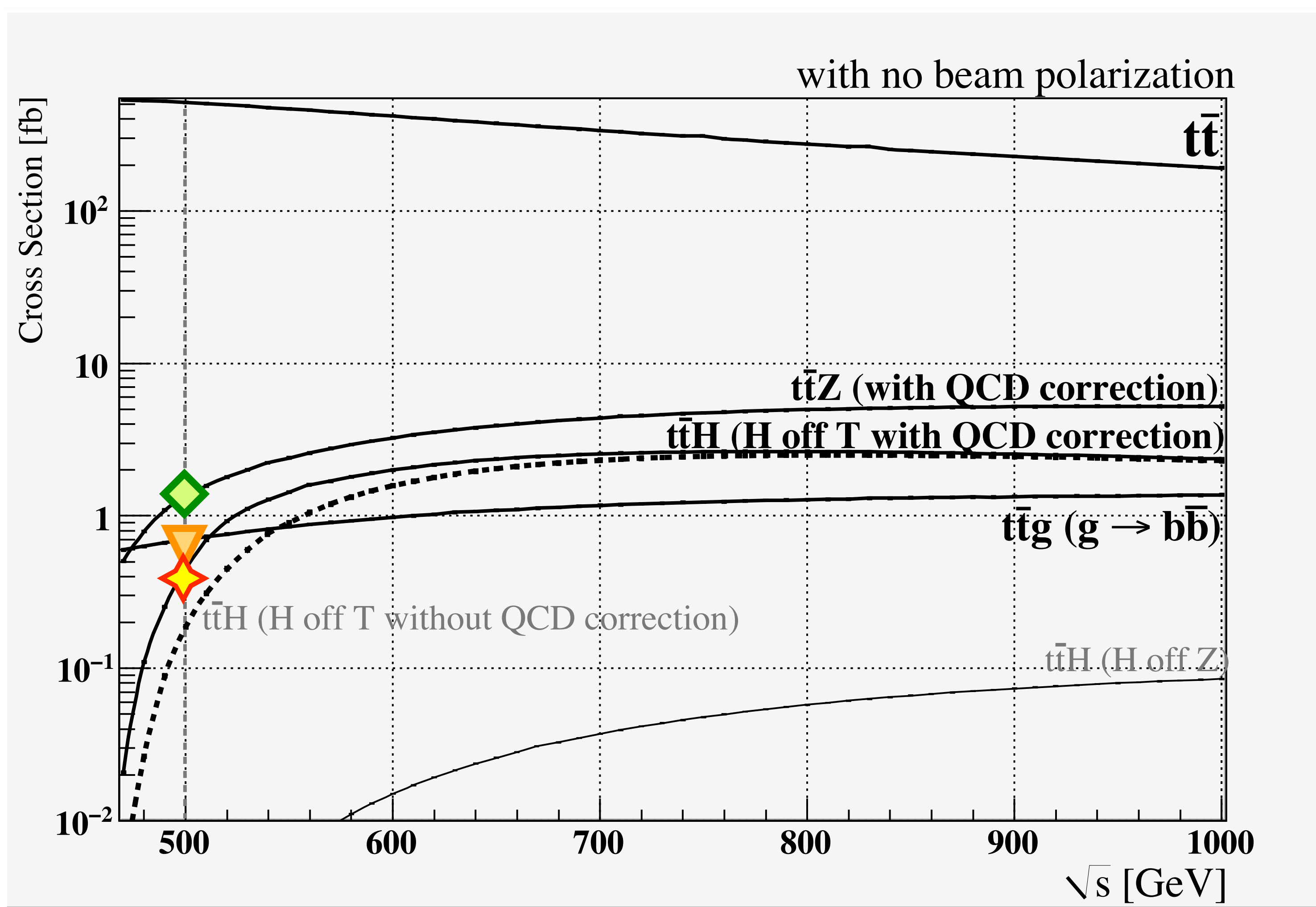
Dose not contain top Yukawa coupling

- Dominant contribution to ttH production at $\sqrt{s}$ = 500GeV is γ/Z exchange (= very small contribution from Higgs radiated off the Z)
  - Can determine g_Y^t by just counting the number of signal events
  - But the signal cross section is sub-fb order...
- Initial state radiation (ISR) and Beamstrahlung
  - σ_{ttH} decreases by a factor ~2 at $\sqrt{s}$ = 500GeV
- NRQCD threshold correction (to ttbar system)
  - Enhances σ_{ttH} significantly: σ_{ttH} = 0.45fb (with no beam pol.)



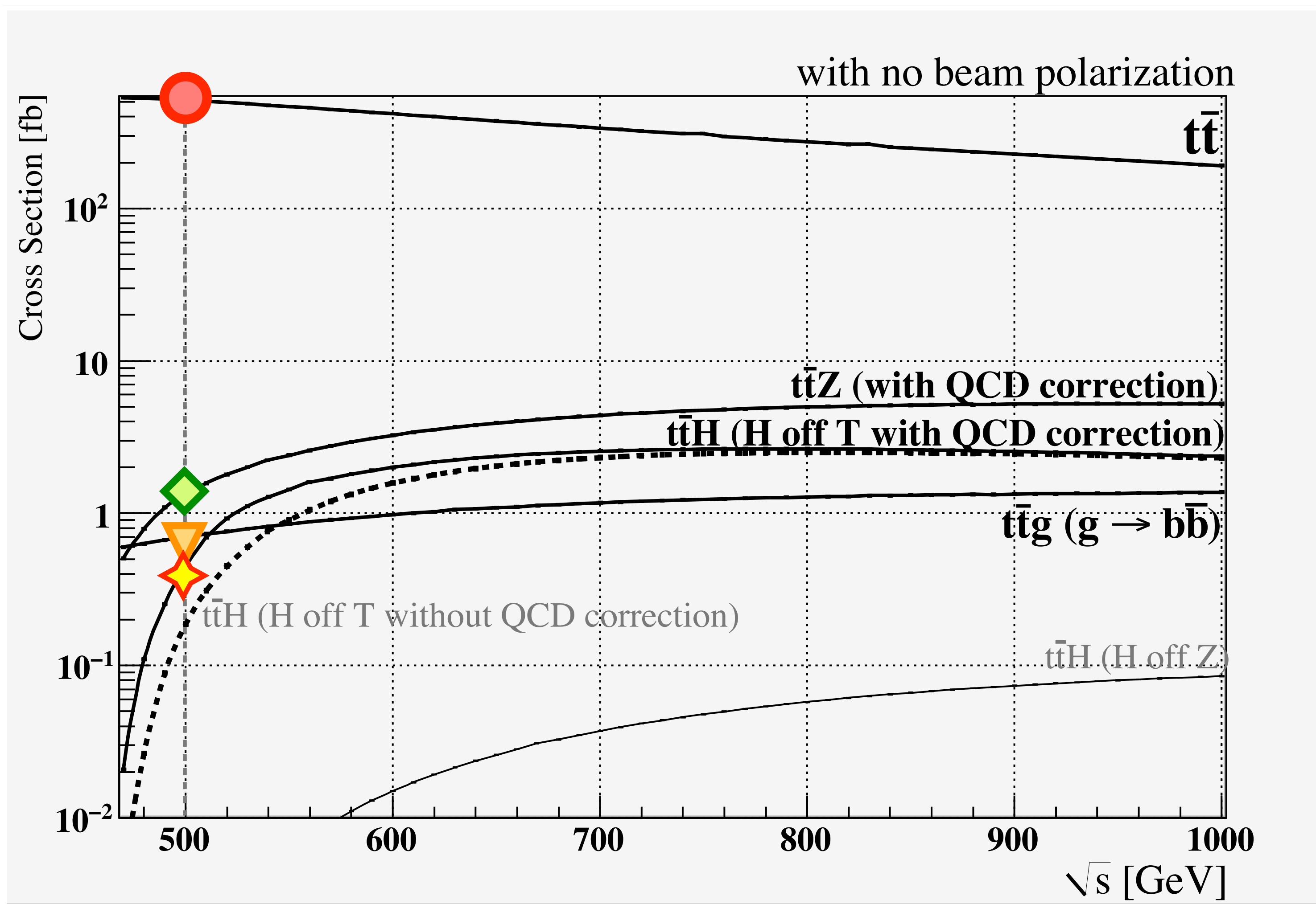
Possible BGs (Interfering)

- Interfering BGs (same final state: ttbb -> bqq blν bb)
  - Electroweak: ttZ -> ttbb (Z -> bb: 15%) ~ 0.2fb with no beam polarization
    - NRQCD threshold correction enhances σ_{ttz} from 0.7fb to 1.3fb
    - Dangerous if M_{Higgs}(120GeV) is close to M_{bb}
  - Electroweak: W*W*/ZZ* -> ttbb: small contribution (< 0.01fb)
  - QCD: ttg -> ttbb (g -> bb: dominant) ~ 0.7fb with no beam polarization
    - Not so dangerous when M_{bb} < M_{Higgs}(120GeV)



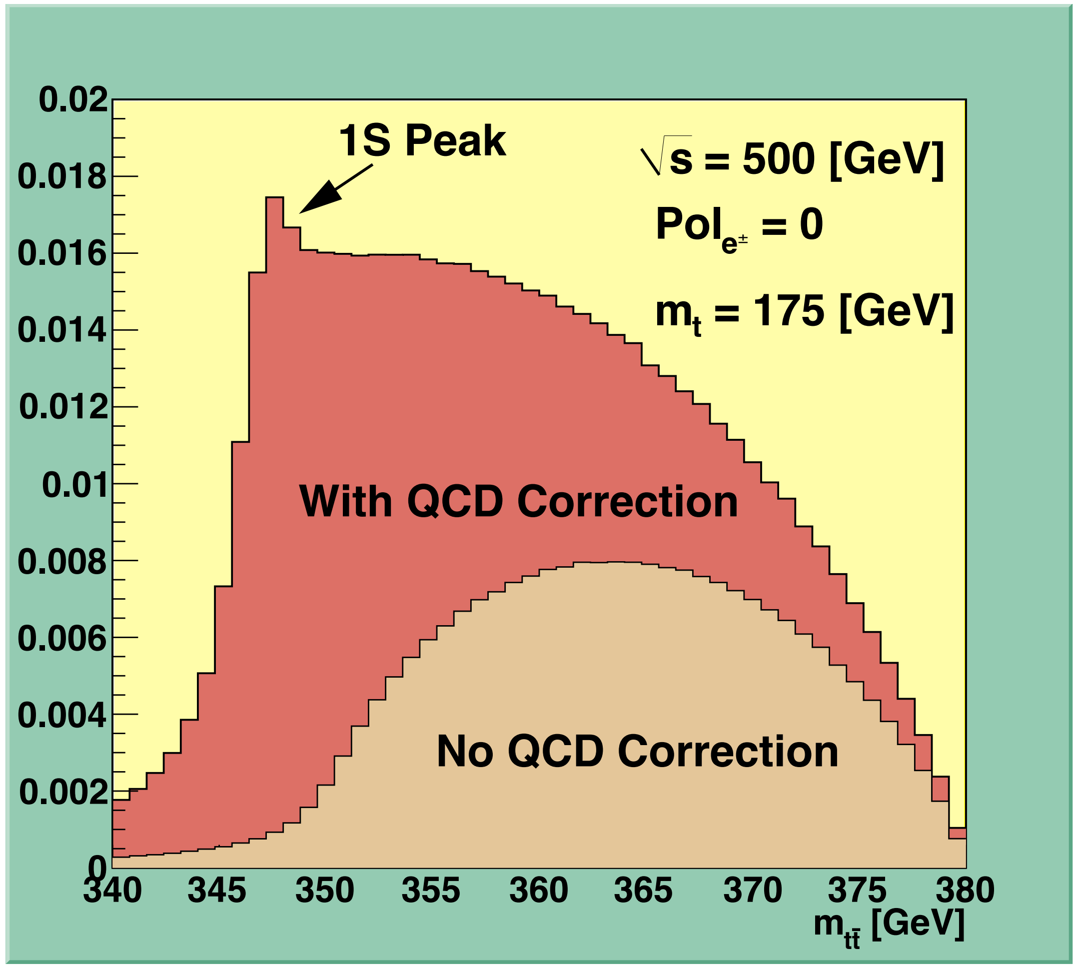
Possible BGs (Non-interfering)

- Non-interfering BGs (but, huge cross sections)
  - ttbar ~ 500fb with no beam polarization
    - Hard gluon emission from bottom quarks
    - Small fraction of mis-reconstruction and/or failure in b-tagging may led to significant BG contamination
  - qq (5 flavors) ~ 4pb: negligible <= 1-isolated lepton + 6-jets (w/ quad b-tagging)
  - WW ~ 8pb: negligible w/ quad b-tagging / ZZ ~ 0.58pb: not huge = negligible



Analysis framework

- Event generator
  - **physsim** package: based on full helicity amplitudes (6 or 8-fermion final states) calculated with **HELAS** including gauge boson decays (correctly taking into account angular distribution of the decay products)
  - **BASES/SPRING**: MC phase pace integration / 4-momenta of the final-state quarks and leptons
  - Included ISR & Beamstrahlung
  - NRQCD threshold enhancement to the ttbar system (ttH/ttZ)

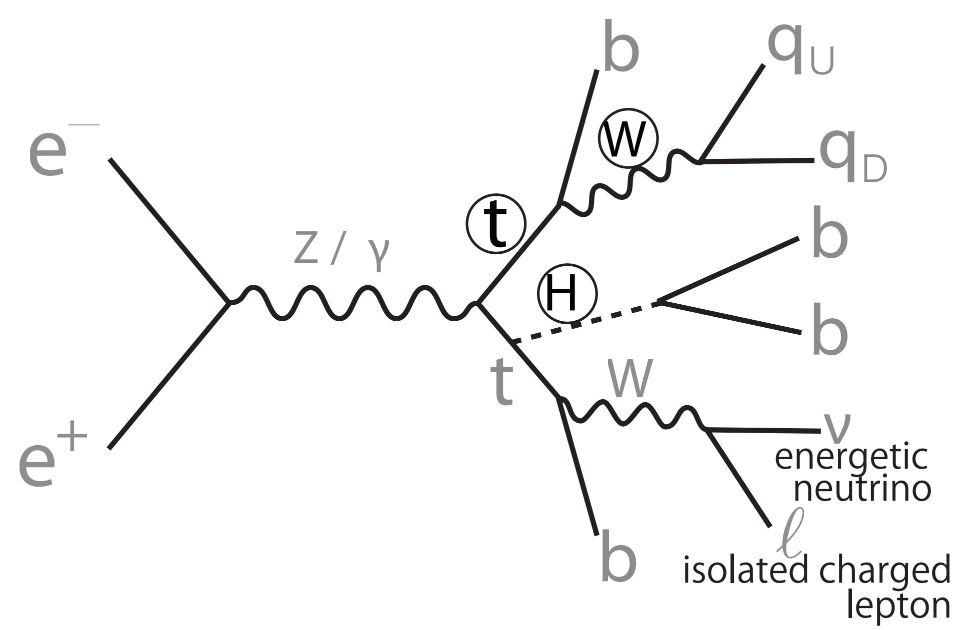


- Parton shower / Hadronization
  - **Pythia 6.4**
- Detector simulator / energy flow reconstruction
  - **JSFQuickSim** (smearing based fast MC simulator) / Track-cluster matching

Detector	Performance	Coverage
Vertex detector	$\sigma_b = 7.0 \oplus (20.0/p)/\sin^{3/2}\theta \mu m$	$\lvert\cos\theta\rvert \leq 0.90$
Central drift chamber	$\sigma_{P_T}/P_T = 1.1 \times 10^{-4} p_T \oplus 0.1\%$	$\lvert\cos\theta\rvert \leq 0.95$
EM calorimeter	$\sigma_E/E = 15\%/\sqrt{E} \oplus 1\%$	$\lvert\cos\theta\rvert \leq 0.90$
Hadron calorimeter	$\sigma_E/E = 40\%/\sqrt{E} \oplus 2\%$	$\lvert\cos\theta\rvert \leq 0.90$

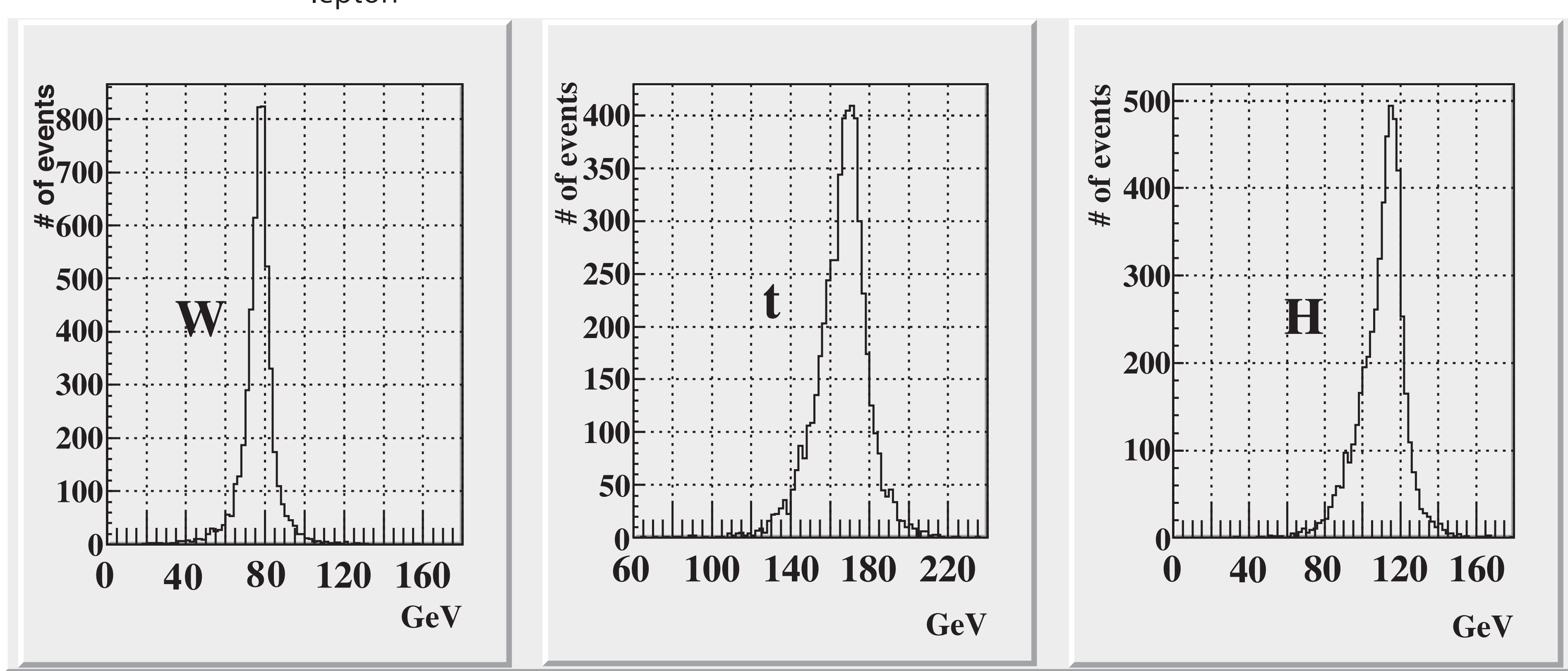
Event selection

- Concentrate on 1-lepton + 6-jets mode as our first step
  - not so low branching ratio: 35% where the lepton is required to be either $e^{\pm}$ or $\mu^{\pm}$
  - not so high jet multiplicities



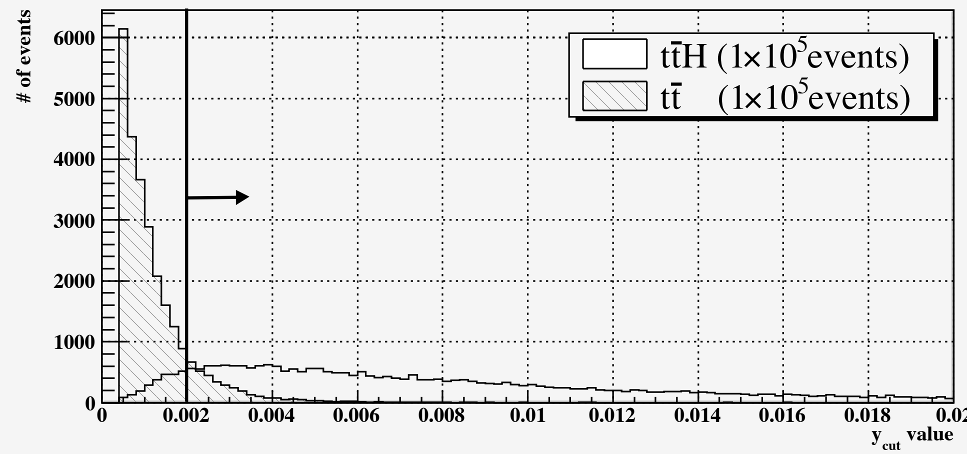
- Signatures of the 1-lepton + 6-jets mode
  - 1 isolated energetic $e^{\pm}$ or $\mu^{\pm}$
  - 6 jets including 4 b-jets, 2 of which form a Higgs
  - Remaining 2-jets being consistent with a W
  - 1 of the 2 unused b-jets together with this W candidate comprising a top

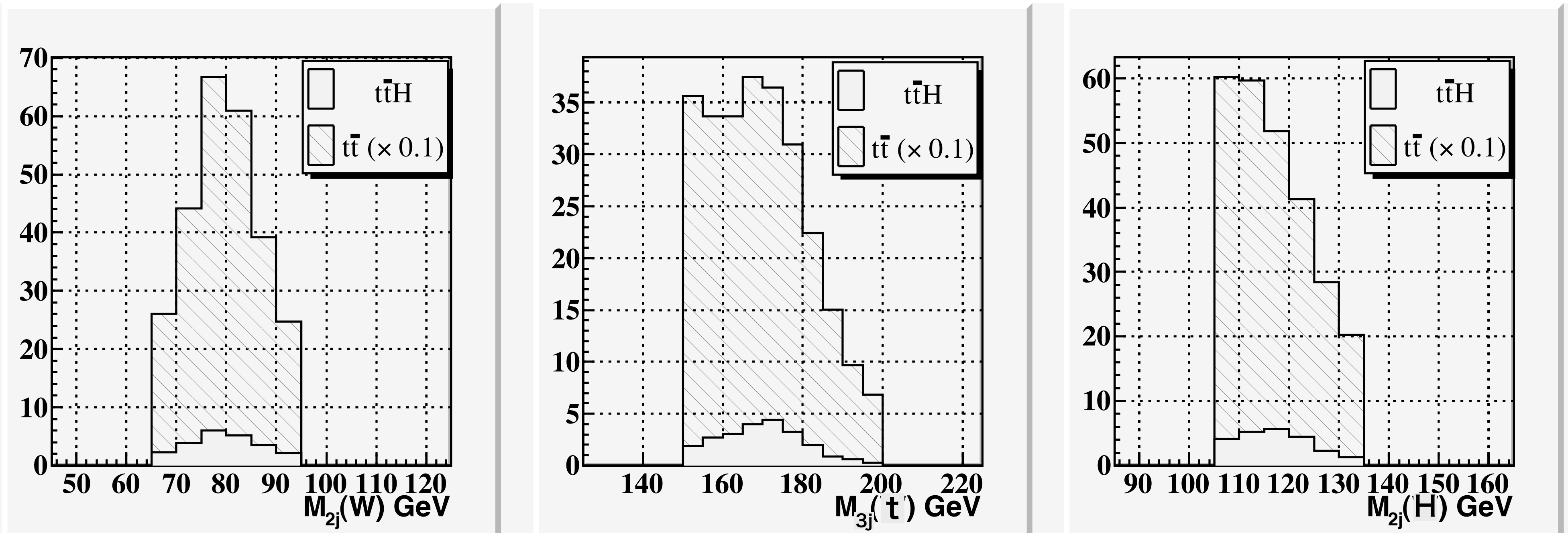
Reconstructed mass dists. using generator information (Cheated jet-finder = perfect jet-parton association)



Reduction of huge tt BGs

1) Finding and eliminating an energetic isolated lepton
2) Force the events to cluster into 6 jets by choosing an appropriate Y_{cut} value on the event-by-event basis (**force 6-jet clustering**)
3) **Ycut cut**
   - Y_{cut} value for a tt BG event to form 6-jets should be lower than the one for a signal (ttH -> ttbb)
   - Effective tt BG rejection by cutting Y_{cut} values at 0.002





Mass dists. for the best combinations

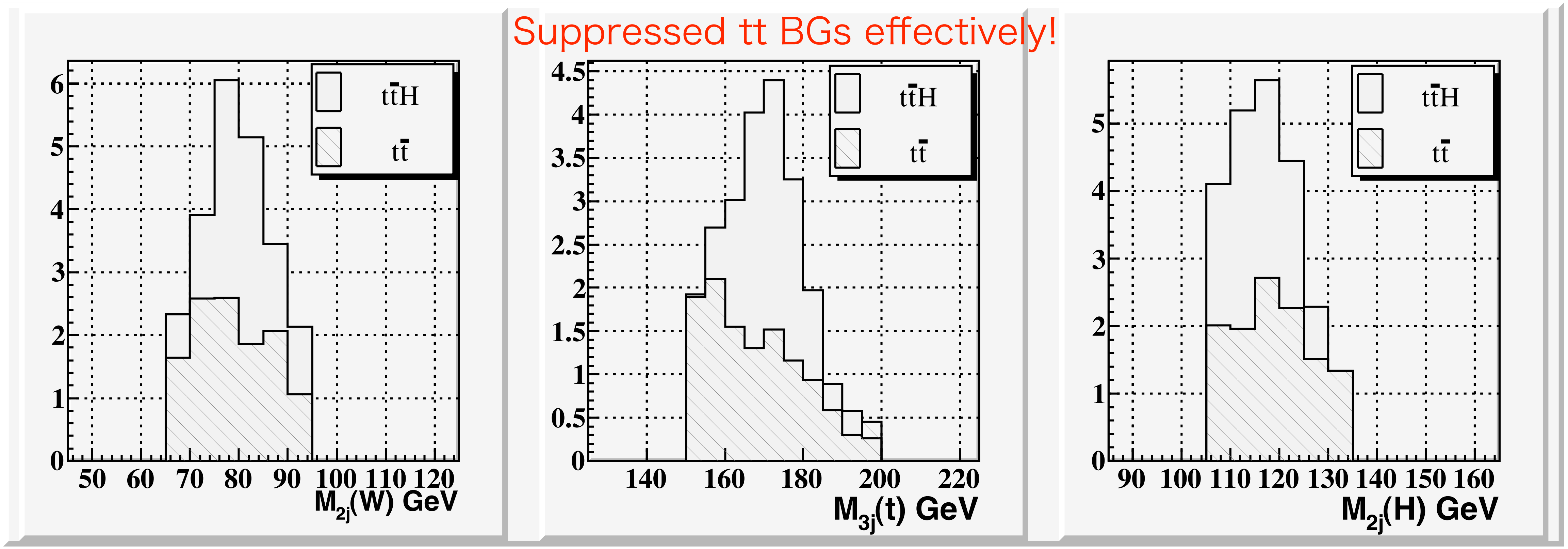
4) **Jet-parton association => Mass cut**
   - Looping over all the 2-jet combinations => Look for a pair having an invariant mass => ±15GeV from M_W(80.0GeV)
   - From the remaining 4-jets => Pick up one and attach it to the pair making a W candidate => ±25GeV from M_t(175GeV)
   - Search a pair from the 3-jets left over => ±15GeV from M_H(120GeV)
   - Chance to have multiple combinations since these mass window cuts are rather loose
   - Select the combination with the smallest χ^2

$$\chi^2 = \left(\frac{M_{2\text{-jet}(W)} - M_W}{\sigma_{M_W}}\right)^2 + \left(\frac{M_{3\text{-jet}(t/\bar{t})} - M_t}{\sigma_{M_t}}\right)^2 + \left(\frac{M_{2\text{-jet}(H)} - M_H}{\sigma_{M_H}}\right)^2$$

Reduction of huge tt BGs (cont'd)

- For the tt BG rejection, quad b-tagging is very powerful since ttH has 4 b-jets, while tt BG has only 2 b-jets
- Use ordinary n-sig method for the quad b-tagging for the moment
- Defined tight b-tagging ($n_{\sigma b}$, $\#_{\text{off-vtx-trk}}$) = (3.0, 2) / loose b-tagging ($n_{\sigma b}$, #off-vtx-trk) = (2.0, 2)
- Require all of the 4 b-jet candidates have to satisfy the loose b-tagging condition and there has to be at least one tight b-tagged jet from each of the H and t/tbar candidates

Suppressed tt BGs effectively!



Mass dists. after using both mass cut and the quad b-tagging

- ttZ (Z->bb) and ttg (g->bb) BGs have similar signature as a ttH

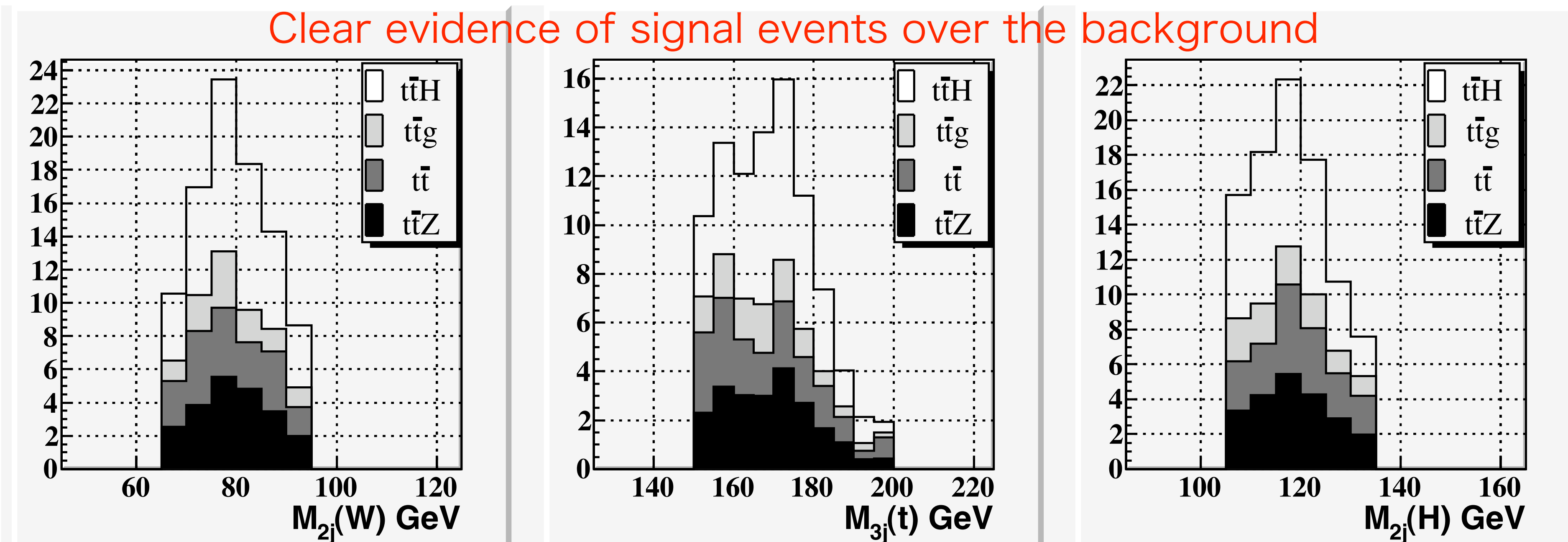
  ➡ can be separated only with the invariant mass of the H candidate

Final cut statistics

- Normalized to integrated luminosity: 1 ab^{-1}
  - # generated events: 5M for tt / 50k for ttH, ttZ, ttg (g->bb)

Beam Polarization	(0.0,0.0)				(-0.8,+0.3)			
Processes	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}$	$t\bar{t}g\,(b\bar{b})$	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}$	$t\bar{t}g\,(b\bar{b})$
No Cut	449.0	1340.0	514040.5	697.5	759.0	2407	863500.4	1159.6
$N_{iso.lep}$=1	159.4	435.9	209718.4	242.2	269.4	783.0	303879.0	397.7
Y_{cut} (6 jets) > 0.002	139.2	307.8	22851.3	152.5	235.4	552.9	38477.2	249.6
btag & mass cut	23.0	12.2	11.9	6.9	38.9	21.8	19.7	11.3

Mass dists. (cumulative) for the final selected samples for the beam polarization combination: (e^-, e^+) = (-0.8, +0.3)



Beam pol. combination	No beam pol.	(e^-, e^+) = (-0.8, +0.3)
Significance	4.1 σ	5.4 σ
$\Delta g_Y^t / g_Y^t$	±0.12	±0.093

Summary

- Performed a feasibility study of measuring the top-quark Yukawa coupling at $\sqrt{s}$ = 500GeV, taking advantage of the NRQCD threshold enhancement to the t-tbar sub-system
- Implemented the threshold correction in the ttH and ttZ event generators in the `physsim` package
- For 1-lepton + 6-jets mode of e^+e^- -> ttH process, signal significance 4.1 σ without beam polarization, and 5.4 σ with the beam polarization combination: (e^-, e^+) = (-0.8, +0.3) for an integrated luminosity of 1 ab^{-1}
- Measurement accuracy for the top-quark Yukawa coupling about 10% using only 1-lepton + 6-jets mode at $\sqrt{s}$ = 500GeV, which is the energy already available in the first stage of the ILC

Future prospects

- Increase signal statistics by analyzing 8-jets mode (45%)
- Introduce a multivariate analysis instead of cut-bases analysis
- Derive measurement accuracy for $\sqrt{s}$ dependence

- Apply full MC detector simulator => realistic particle flow algorithm
- Adopt a high performance flavor tagging by using **`LCFIVertex`** package
- Do full SM backgrounds scan