



Status of $H \rightarrow Z \gamma$ Analysis

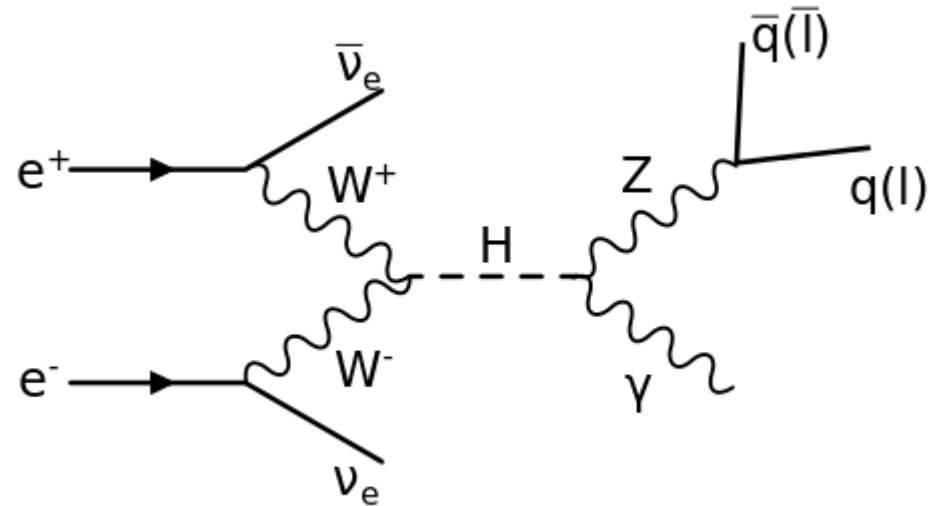
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On behalf of the CLIC Detector and Physics Study CERN

CLIC Workshop, CERN
Physics & Detectors: Physics Analysis
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Signal $H \rightarrow Z \gamma$

- Signal

- Vector boson fusion
- Higgs decay: $H \rightarrow Z \gamma$
- Z decay: $Z \rightarrow q \bar{q}$ or $l \bar{l}$
- e^+e^- @ $\sqrt{s} = 1.4$ TeV
- $M_H = 126$ GeV/c², ISR,
- CLIC Beam spectrum



- $\sigma(e^+e^- \rightarrow H \nu_e \bar{\nu}_e) \approx 271$ fb

- $BR_{H \rightarrow Z \gamma} \approx 1.5 \cdot 10^{-3}$

- $BR_{Z \rightarrow \text{visible}} \approx 0.8$

- $\sigma(e^+e^- \rightarrow H \nu_e \bar{\nu}_e) \cdot BR_{H \rightarrow Z \gamma} \cdot BR_{Z \rightarrow \text{visible}} \approx 0.33$ fb $\rightarrow N_{\text{signal}} \approx 495 / 1.5$ ab⁻¹



Main Z Decay Channels

- $BR_{Z \rightarrow e e} \approx (3.363 \pm 0.004) \%$
- $BR_{Z \rightarrow \mu \mu} \approx (3.366 \pm 0.007) \%$
- $BR_{Z \rightarrow \tau \tau} \approx (3.367 \pm 0.008) \%$
- $BR_{Z \rightarrow \text{invisible}} \approx (20.00 \pm 0.06) \%$
- $BR_{Z \rightarrow \text{hadrons}} \approx (69.91 \pm 0.06) \%$

Lepton channels

- $Z \rightarrow l l$
- Using $l = e, \mu, \tau$



Visible BR
 ≈ 0.8

- $BR_{Z \rightarrow (uu+cc)/2} \approx (11.6 \pm 0.6) \%$
- $BR_{Z \rightarrow (dd+ss+bb)/3} \approx (15.6 \pm 0.4) \%$
- $BR_{Z \rightarrow cc} \approx (12.03 \pm 0.21) \%$
- $BR_{Z \rightarrow bb} \approx (15.12 \pm 0.05) \%$
- $BR_{Z \rightarrow bbbb} \approx (3.4 \pm 1.3) 10^{-4} \%$
- ...

Quark channels

- $Z \rightarrow q Q$
- Using $q = u, d, s, c, b$

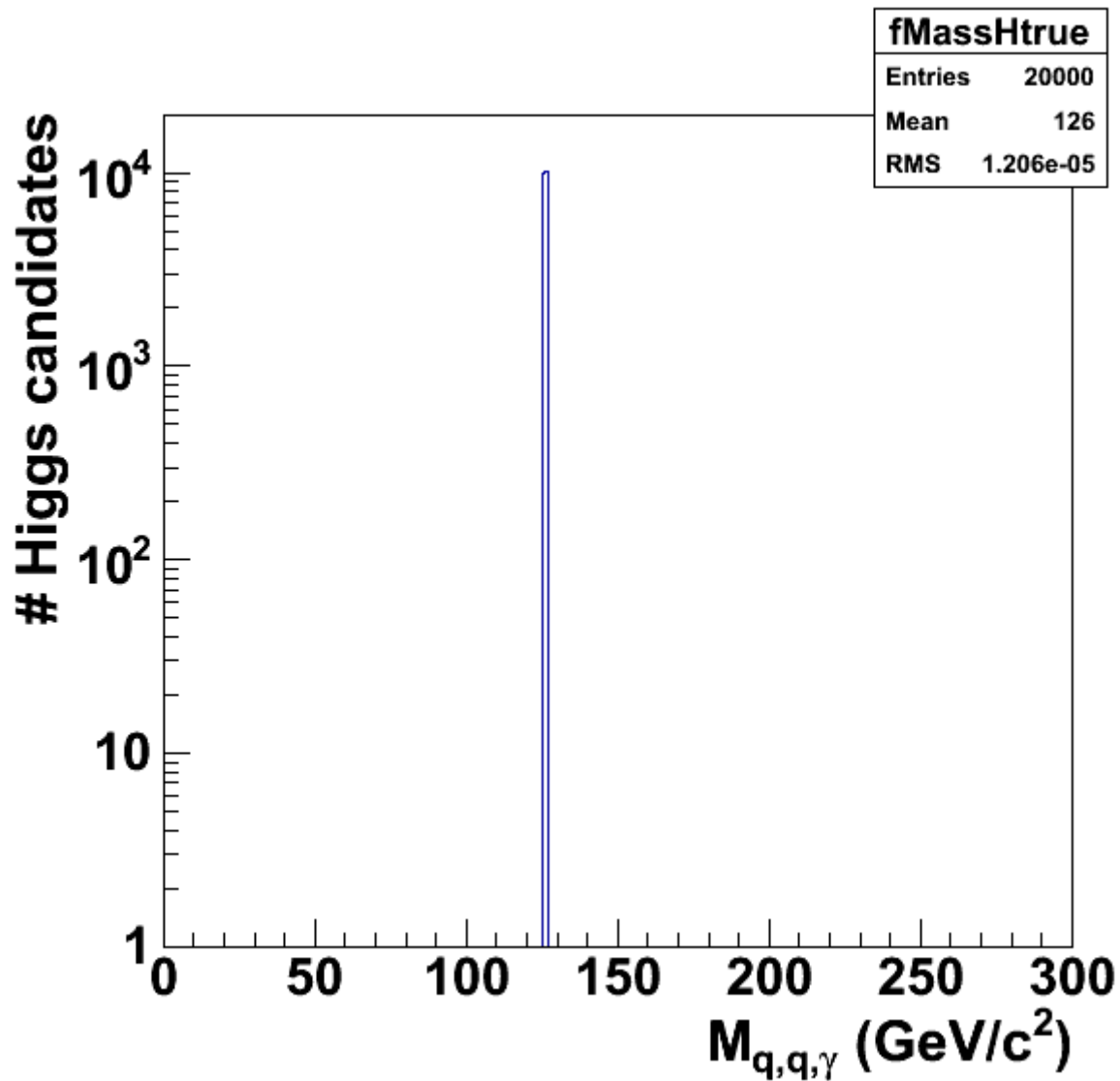


WHIZARD 2 Simulation Settings

- $M_H = 126 \text{ GeV}/c^2$
- $e^+ e^-$ collision, beam energy 14 TeV, CLIC beam spectrum
- ISR photons switched on, ISR recoil switched on
- Production: $e^+ e^- \rightarrow H \nu \nu$, decay: $H \rightarrow Z \gamma$
 - $Z \rightarrow q Q$ ($q = u, d, s, c, b$)
 - $Z \rightarrow l L$ ($l = e, \mu, \tau$)
 - $M_l = 0, M_q = 0$
- Start values for generator level cuts
 - $E_{\text{photon}} > 5 \text{ GeV}$
 - $E_{\text{quarks,leptons}} > 5 \text{ GeV}$
 - $100 \text{ GeV}/c^2 < M_{\text{Higgs candidate}} < 150 \text{ GeV}/c^2$
- **Note:** WHIZARD cuts do not apply on ISR photons



True Higgs Signal: $M(q,Q,\gamma)$

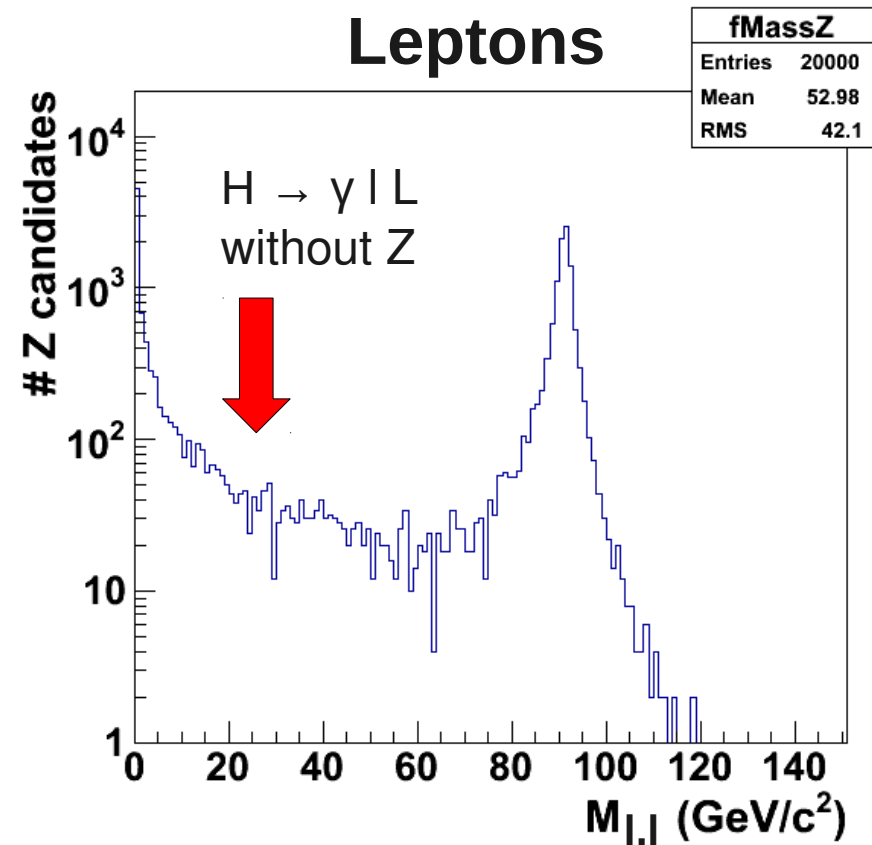
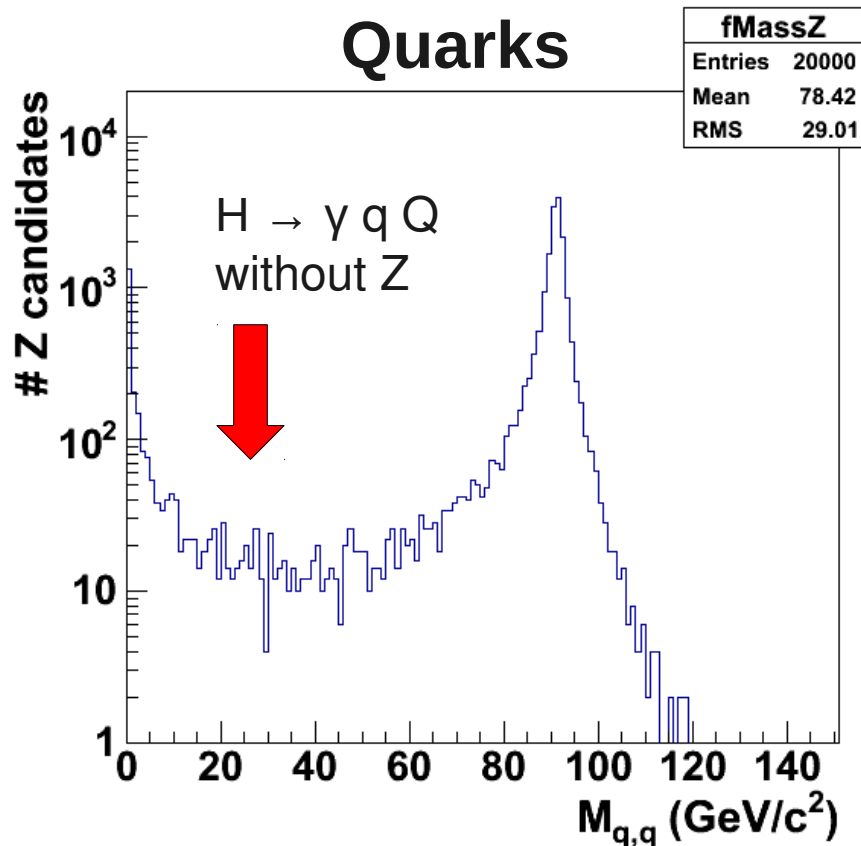


- Build invariant mass of of true H-daughters:
 - q, Q, γ
(same for l, L, γ)
- Double count each Higgs due to double loop
- Clean Higgs peak at $M_H = 126 \text{ GeV}/c^2$



True Higgs Daughter Z

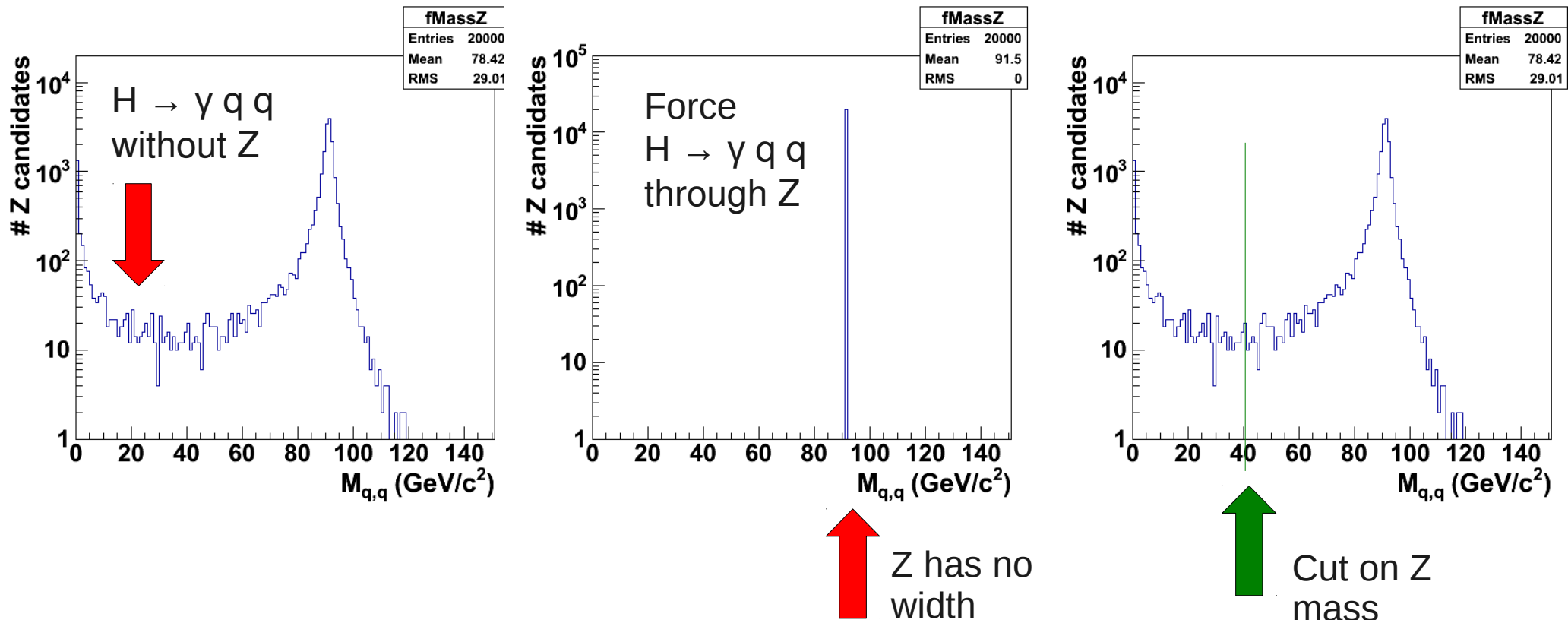
- $H \rightarrow q Q \gamma$ ($l L \gamma$) without forcing decay through Z
- Then also processes **without Z** are allowed
- For measurement of $H \rightarrow Z \gamma$, these events needs to be rejected



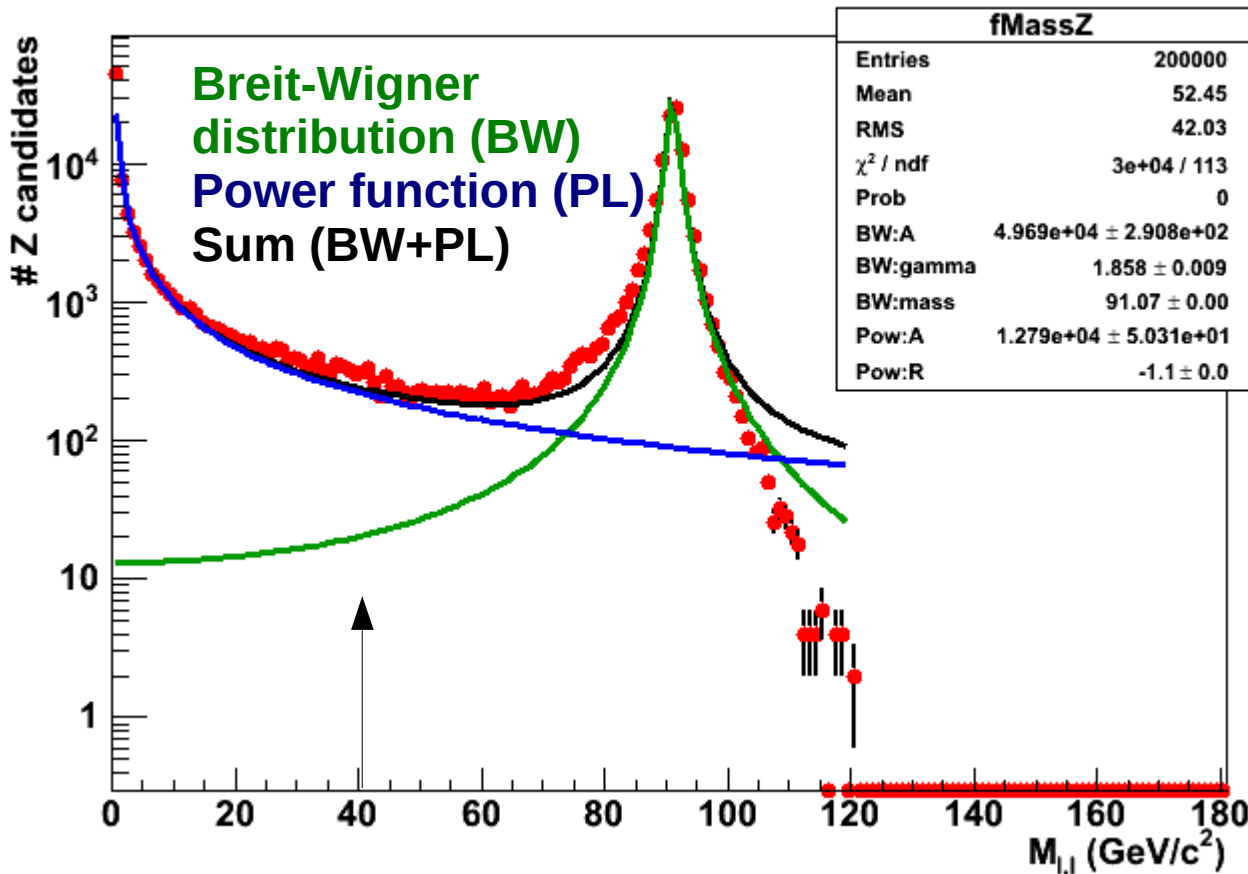


Z in Higgs $\rightarrow \gamma q Q$

- Instead of $H \rightarrow \gamma q Q$ force decay through Z ($H \rightarrow \gamma Z ; Z \rightarrow q Q$)
 - When forcing decay through Z, **Z has no width**
- **Solution:** Cut on invariant Z-mass in Whizard
 - $M_{Z \text{ candidate}} = M(q, Q) > 40 \text{ GeV}/c^2$



Contributions to $M_{Z \text{ cand.}}$ -distribution



- Get rough idea of contributions to $M(q,Q)/M(l,L)$ distribution using fit function
- Note: Function does not include interference terms between the two contributions

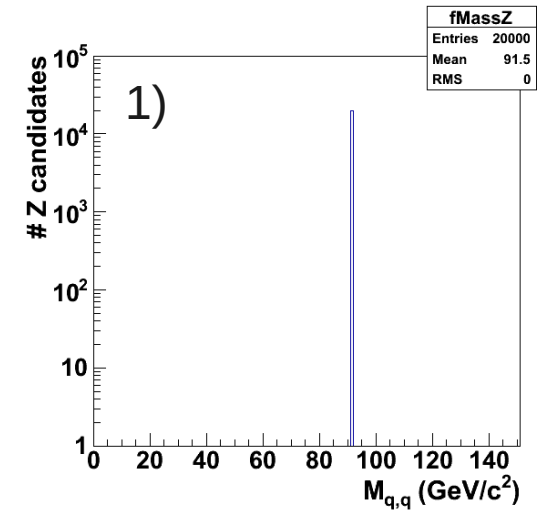
- Power function describes contributions from $\gamma \rightarrow q Q$ (I L) and off-shell processes
- Breit-Wigner describes $Z \rightarrow q Q$ (I L)
- Impact of cut on $M_{Z,\text{cand}} > 40\text{GeV}/c^2$
 - would remove $\sim 0.7\%$ of full BW for both quark and lepton channel
- Contributions to integral after $M_{Z,\text{cand}}$ -cut (from fit):
 - Leptons: $\sim 91\%$ BW, $\sim 9\%$ PL
 - Quarks: $\sim 98\%$ BW, $\sim 2\%$ PL



Impact of M_Z -Cut on Cross Sections

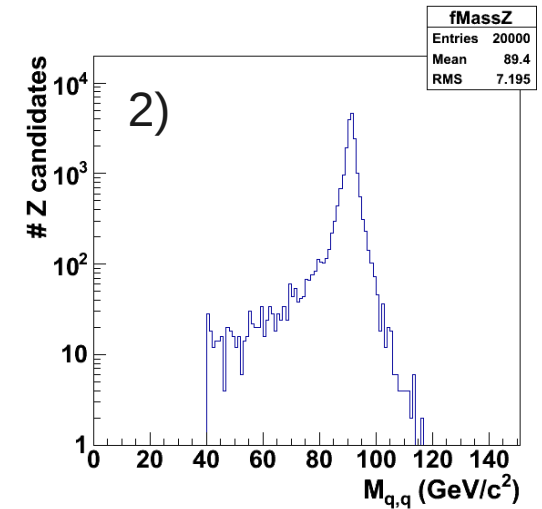
1) Force Higgs to decay through Z

- $e^+ e^- \rightarrow H \nu \nu$,
 $H \rightarrow Z \gamma$,
 $Z \rightarrow q Q$ (l L)
- $\sigma_{\text{quark}} = (273.4 \pm 0.1) \text{ fb}$,
 $\sigma_{\text{lepton}} = (273.8 \pm 0.1) \text{ fb}$



2) Free Higgs decay to $q Q \gamma$ (l L γ) + cut on invariant mass of Z

- $e^+ e^- \rightarrow H \nu \nu$,
 $H \rightarrow q Q \gamma$ (l L γ) ($M > 40 \text{ GeV}/c^2$)
- $\sigma_{\text{quark}} = (273.7 \pm 0.1) \text{ fb}$,
 $\sigma_{\text{lepton}} = (273.9 \pm 0.1) \text{ fb}$

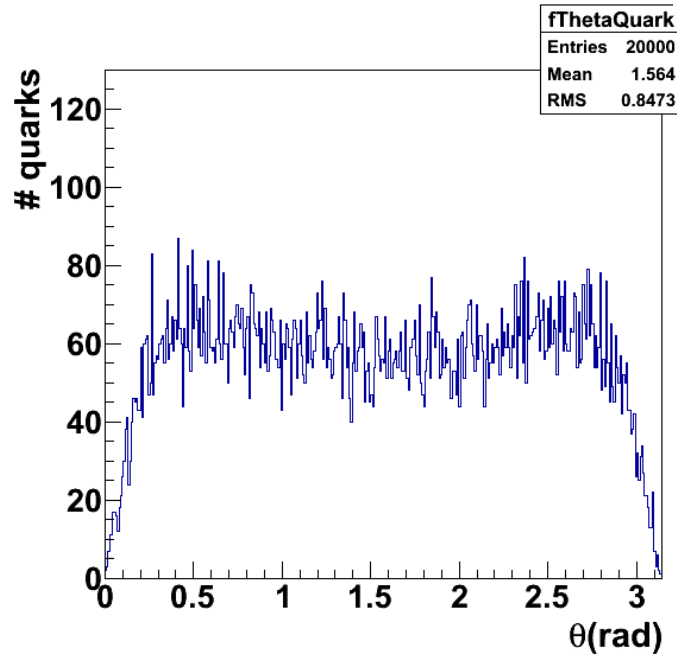
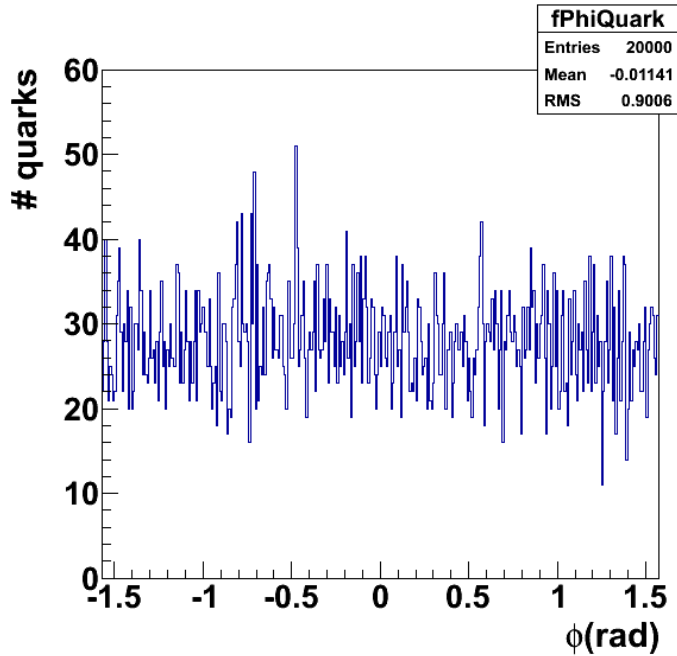
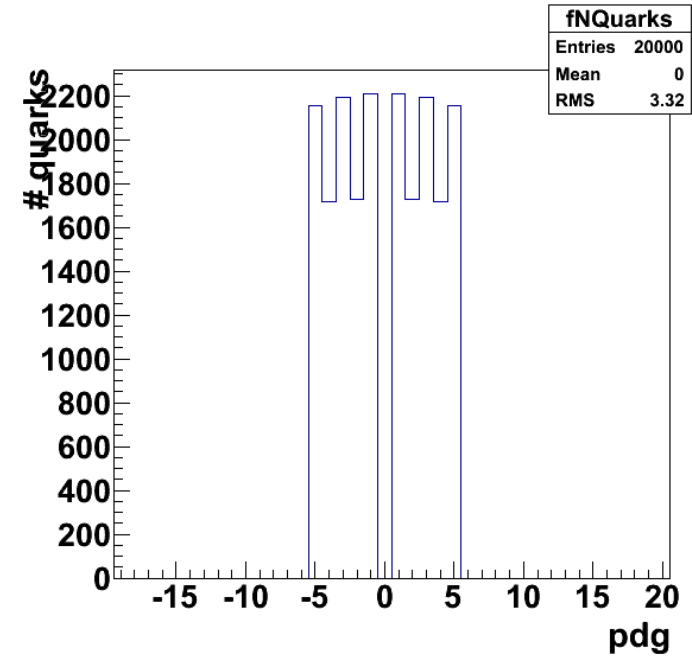
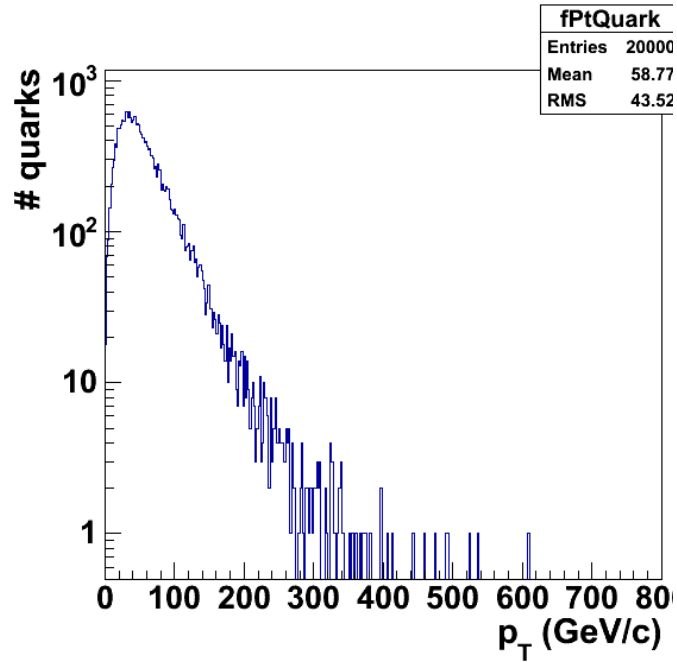
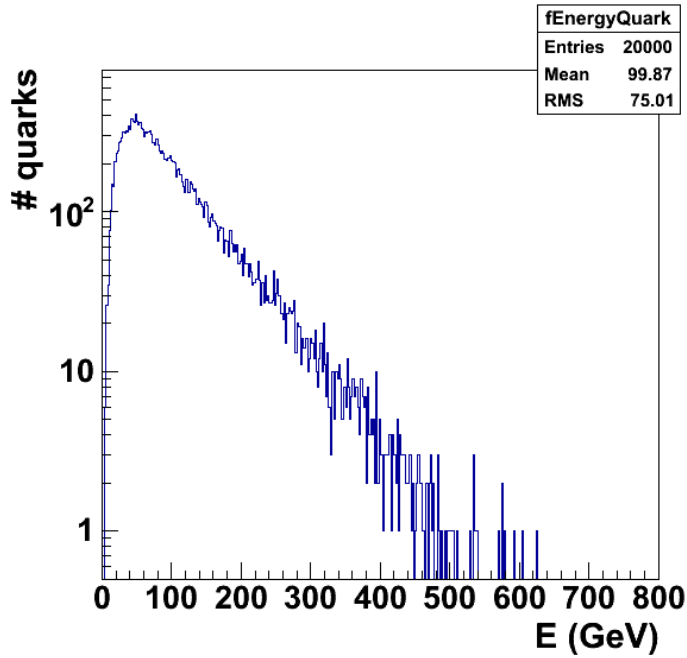


- Cross sections of process 1) and 2) agree with each other within uncertainties
- Use M_Z -cut in definition of Higgs measurement

Whizard
n-integrations:
20:100000

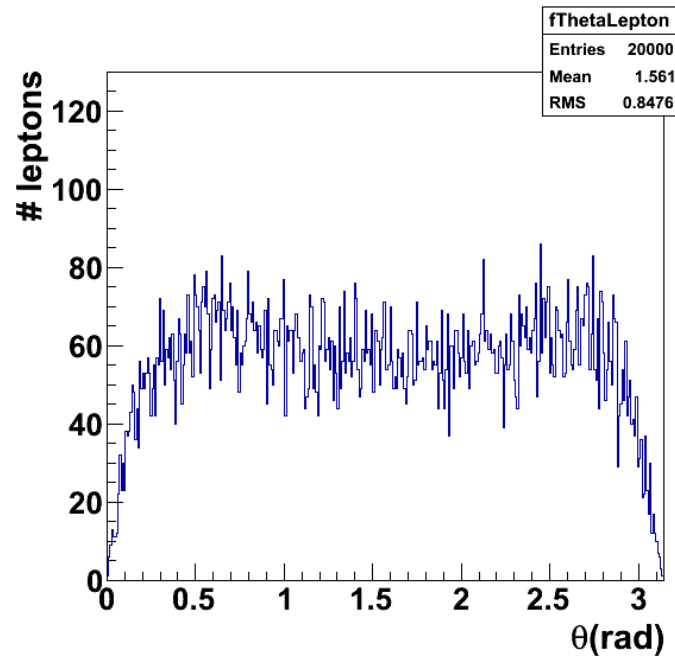
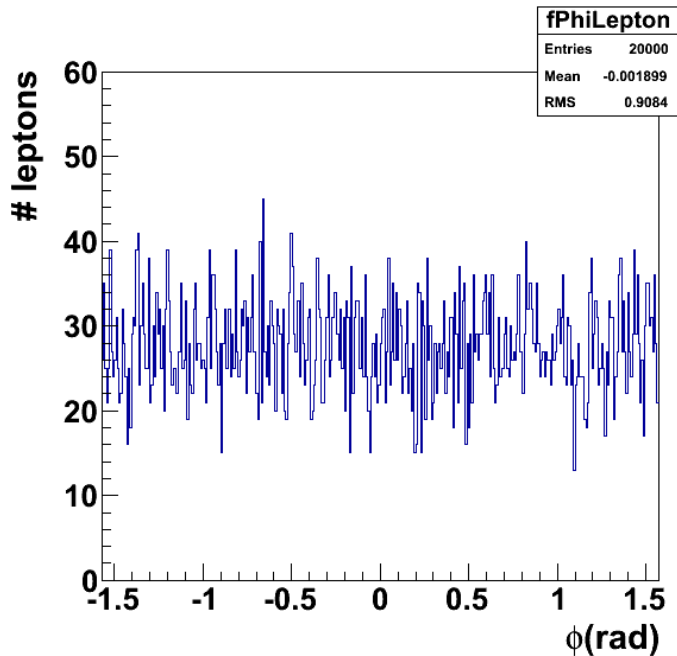
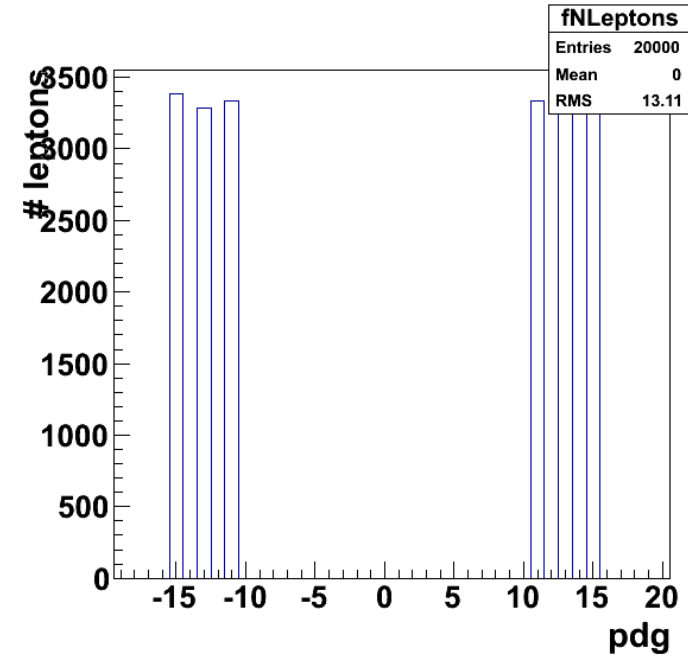
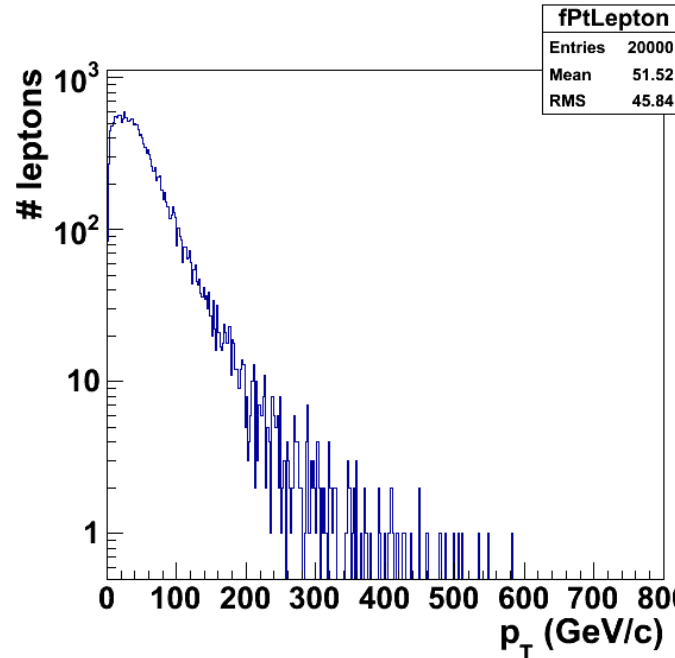
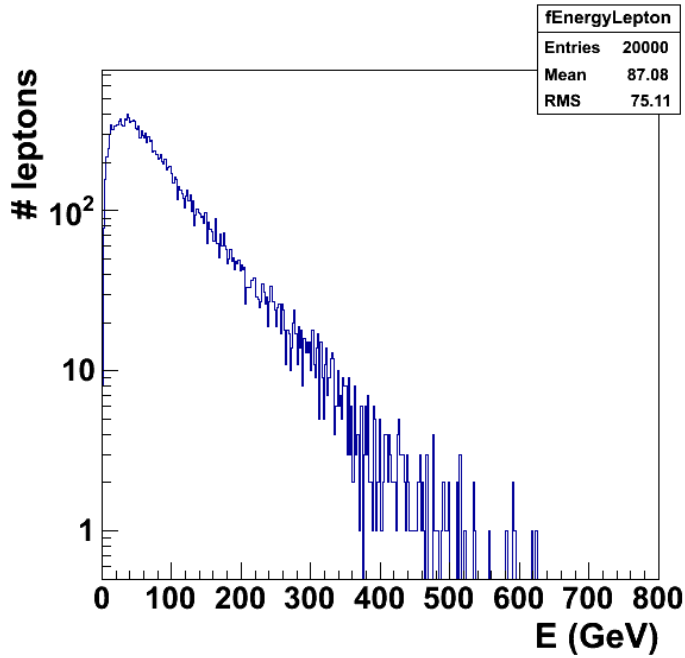


True Z Daughters: Quarks



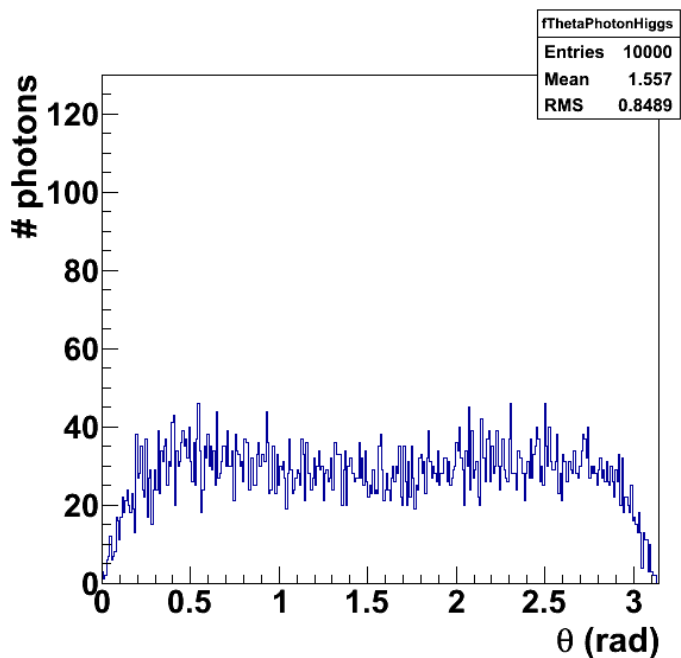
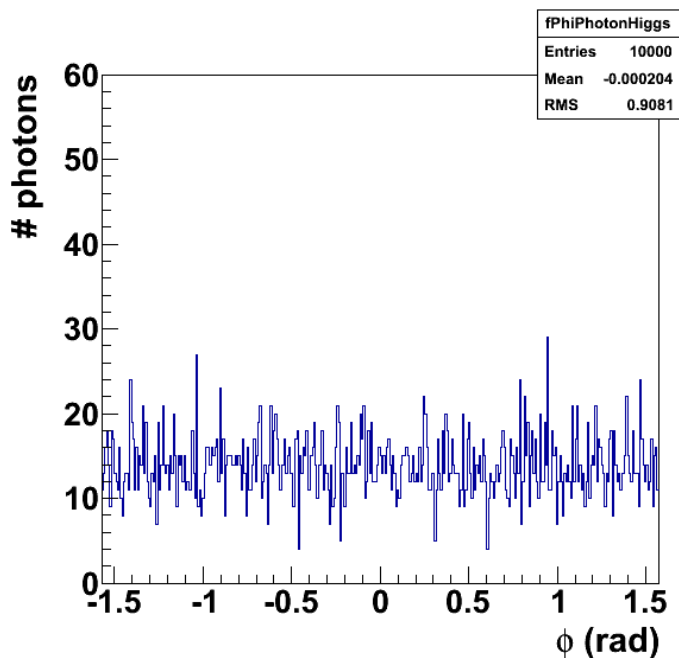
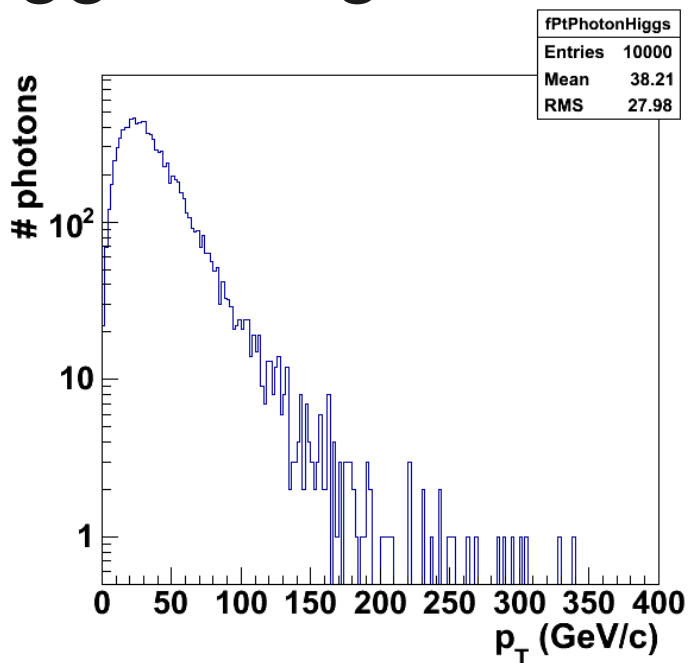
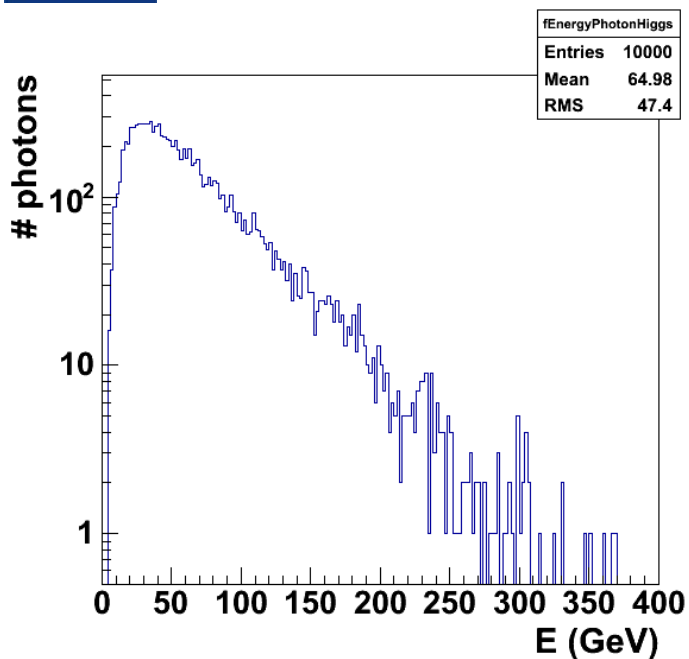


True Z Daughter: Leptons



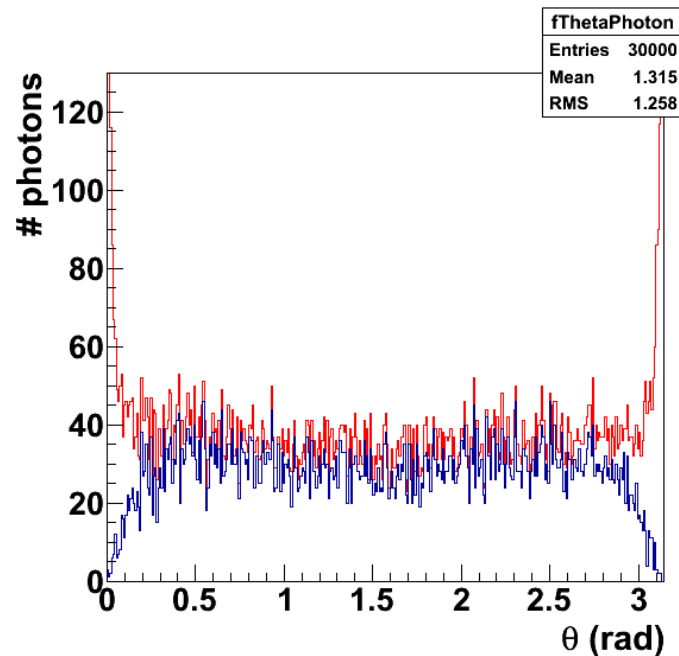
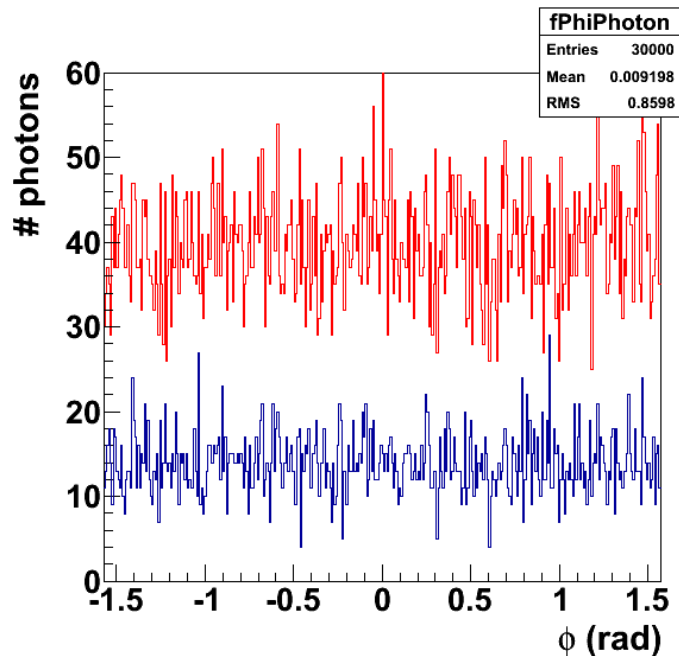
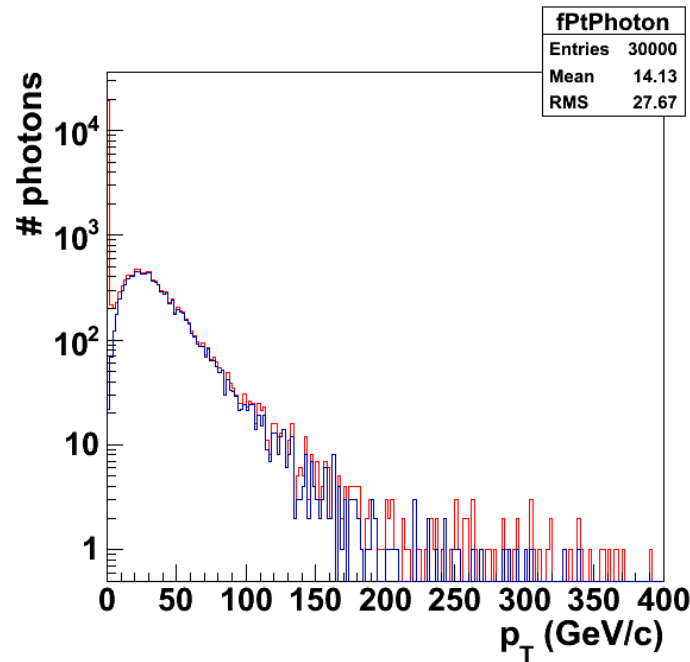
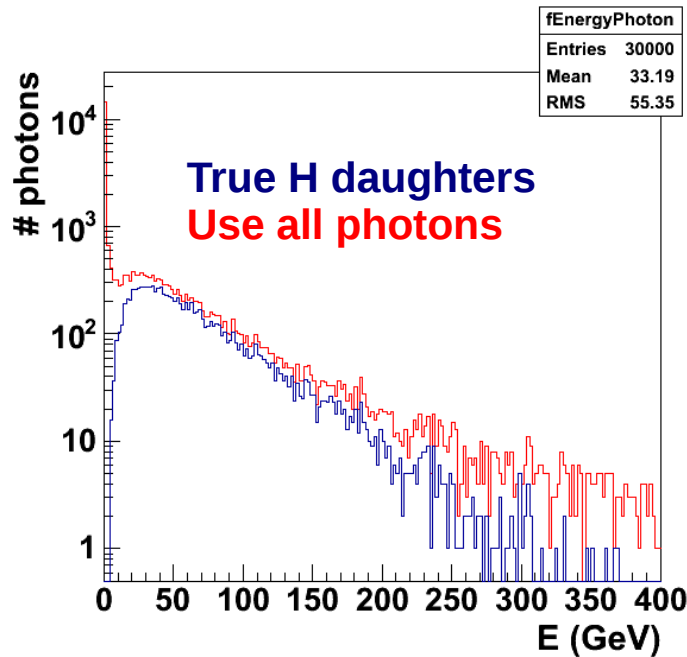


True Higgs Daughters: Photon





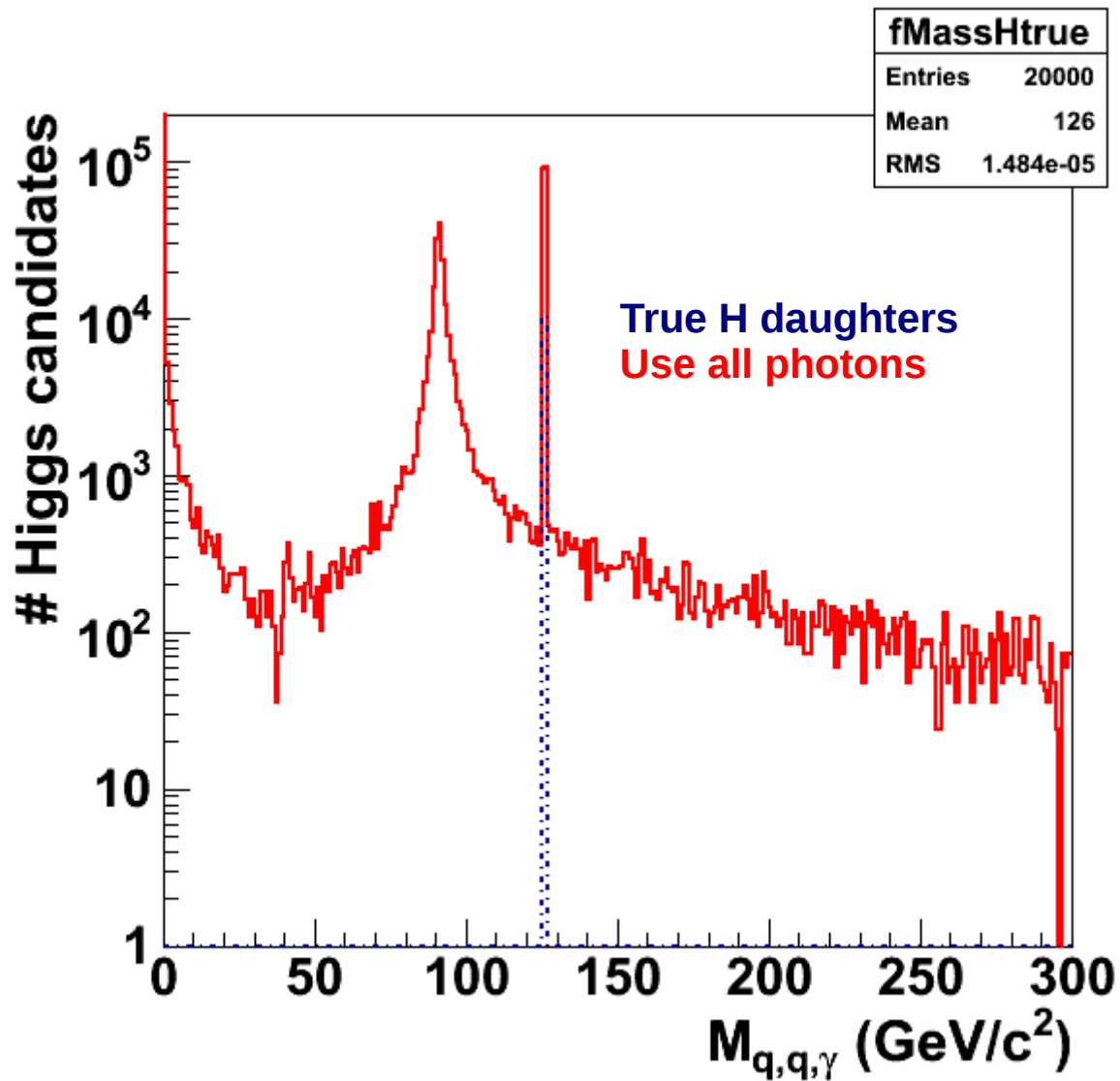
Impact of Initial State Radiation



- ISR gives to each event 2 additional ISR photons
- ISR photons have mostly low E and p_T
- **Note:** Whizard cuts do not apply on ISR photons
- Cut on photon E and p_T needs to be implemented after whizard simulation and before transport simulation
→ STDHEP cuts



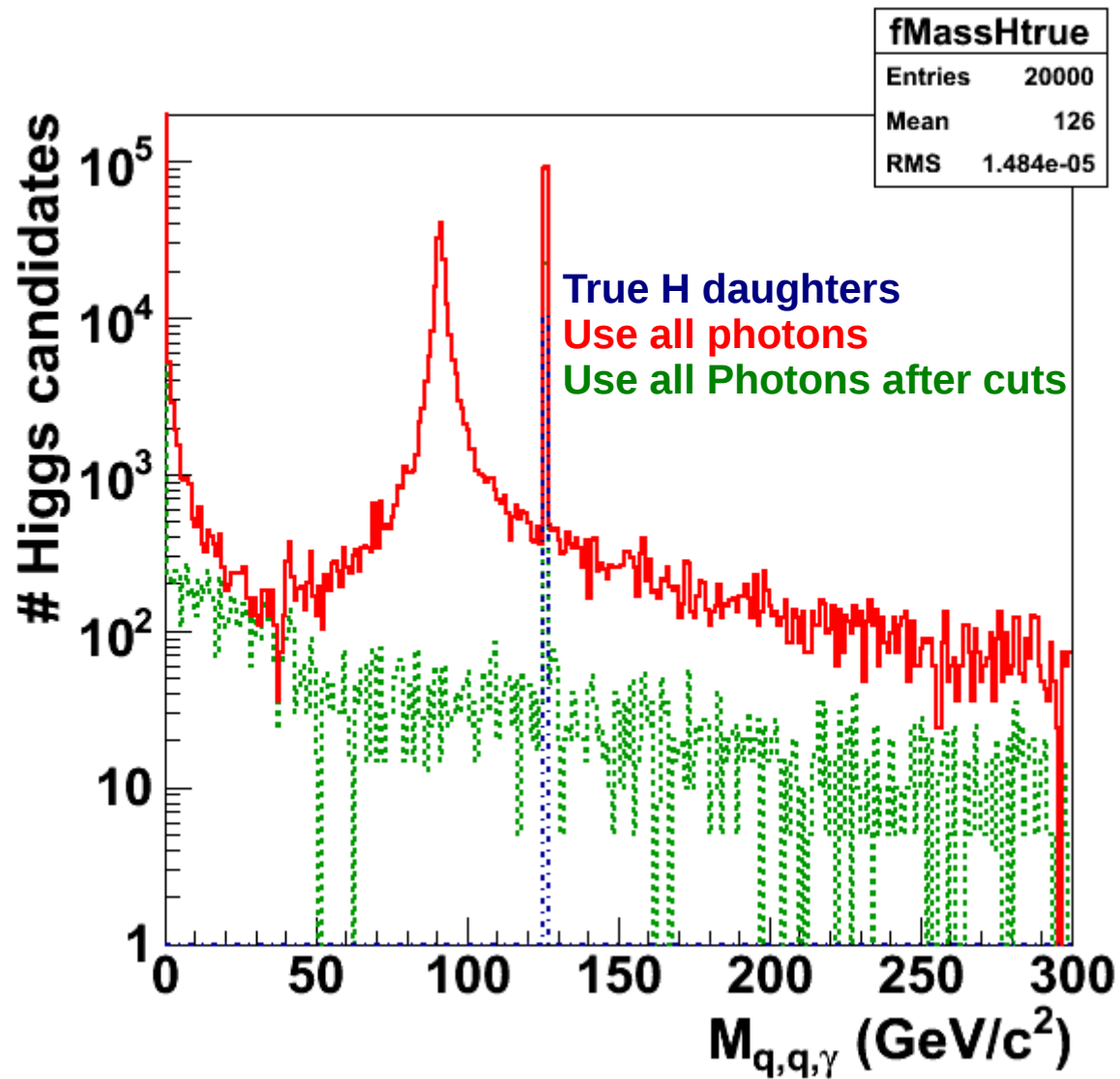
Higgs Signal including ISR Photons



- Build invariant mass of q, Q, γ (also ISR)
- Higgs peak
- peak for Z +low energetic ISR photons close to Z peak
- Study STDHEP cuts on E and p_T of photons in order to reduce the fake Higgs candidates of ISR photons



Higgs Signal + ISR Photons + Cuts



- STDHEP cuts on photon E and p_T
 - $E > 10$ GeV
 - $p_T > 5$ GeV/c
- Reminder: cuts in Whizard on photons
 - $E > 5$ GeV
- After STDHEP cuts
 - background reduced by $\approx 90\%$
 - No Z peak left after cuts



Proposed Cuts from Signal Analysis + ISR

- Generator level cuts

- $E_{\text{photon}} > 5 \text{ GeV}$
- $E_{\text{quarks, leptons}} > 5 \text{ GeV}$
- $M_{Z \text{ candidate}} > 40 \text{ GeV}/c^2$
- $100 \text{ GeV}/c^2 < M_{\text{Higgs candidate}} < 150 \text{ GeV}/c^2$

- STDHEP cuts

- Purpose: rejection of ISR photons
- $E_{\text{photon}} > 10 \text{ GeV}$
- $P_{T, \text{photon}} > 5 \text{ GeV}/c$
- $90 \text{ GeV}/c^2 < M_{\text{Higgs cand. (q, Q, photon)}} < 160 \text{ GeV}/c^2$



Background Channels (WHIZARD 2)

- Using all discussed generator level cuts if applicable
- ISR always switched on (always two extra photons, mostly low-E)
- Here: $q = u, d, c, s, b$, **and** e, μ, τ !
- All generator level cuts ($E_{\text{photon}}, E_{\text{quarks,leptons}}, M(q,Q), M(q,Q,\gamma)$)
 - $e^+ e^- \rightarrow \nu \nu q Q \gamma \rightarrow (159 \pm 8) \text{ fb}$
 - $e^+ e^- \rightarrow q Q \gamma \rightarrow (6 \pm 3) \text{ fb}$
- No generator level cuts on photon: E_{photon} and $M(q,Q,\gamma)$
 - $e^+ e^- \rightarrow \nu \nu q Q \rightarrow (7.38 \pm 2) 10^7 \text{ fb}$
 - $e^+ e^- \rightarrow q Q \rightarrow (2.2 \pm 0.8) 10^8 \text{ fb}$
 - $e^+ e^- \rightarrow q Q q Q \rightarrow (1.29 \pm 0.2) 10^4 \text{ fb}$
- Use STDHEP cuts in order to reduce σ of background channels



Summary

- Analysis of signal channel $H \rightarrow Z \gamma; Z \rightarrow q Q (l L)$
 - Contamination from events with $H \rightarrow q Q \gamma$ without Z
 - Solution: Cut on Z mass
 - $M_{Z \text{ cand.}} > 40 \text{ GeV}/c^2$
- Huge background due to initial state radiation
 - Can be reduced by STDHEP cuts after generation and before transport simulation
- Large cross sections for background channels
 - Can be reduced substantially by suitable STDHEP cuts