Studies of $e^+e^- \rightarrow H^0A^0$ Processes

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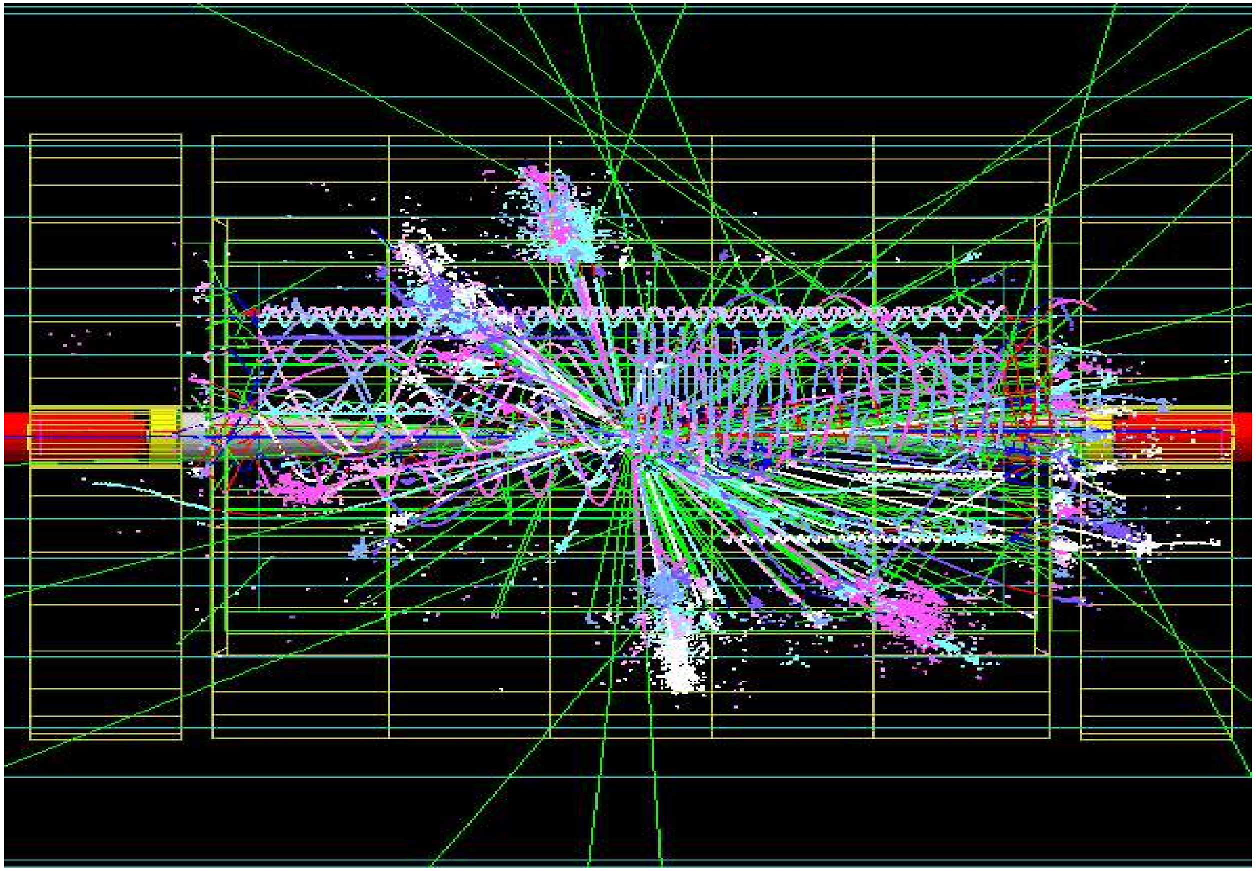
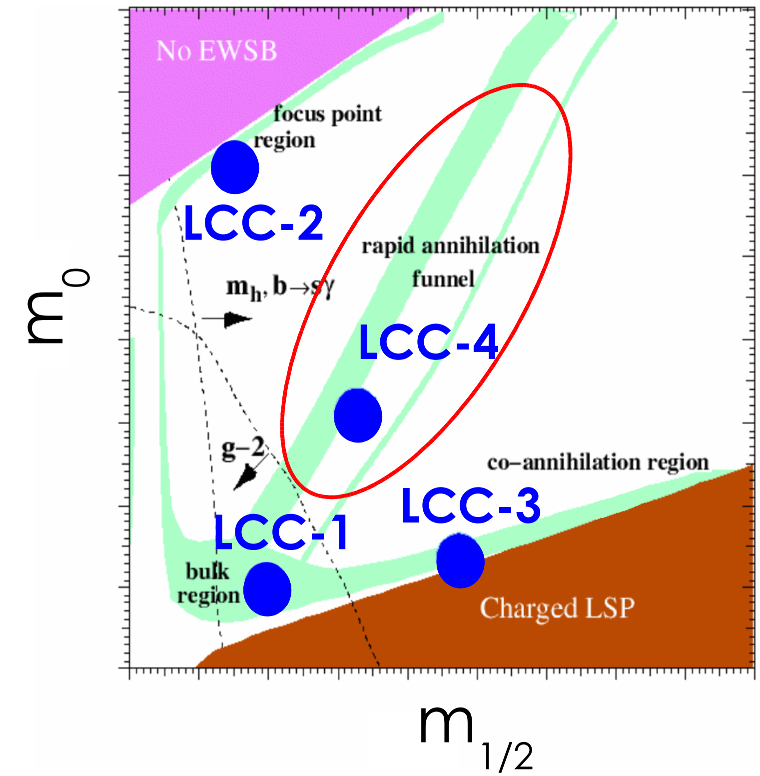


Introduction and Motivation

- CDM Motivated cMSSM scenario:
  - LCC-4 rapid annihilation funnel benchmark point
  - $\Omega_{CDM}h^2$ controlled by properties of A^0 heavy Higgs boson
- A^0 discovery @ LHC, precision measurement @ ILC
- Measure A^0 properties using $H^0A^0 \rightarrow b\bar{b}b\bar{b}/b\bar{b}\tau^+\tau^-$ @ 1 TeV
- b,τ tagging to reduce background
- Require b tagging in high multiplicity hadronic environment, τ tagging against jets and leptons over full kinematic range
- Analysis has been previously performed with fast sim (hep-ph/0410123)
- This analysis uses full Geant4 simulation+Marlin reconstruction

The LCC-4 Benchmark Point

- Assess detector performance, optimize detector design: need full sim+reco of multiple benchmark points
- LCC points (Baltz et al. Phys.Rev.D74:103521,2006.) compliant with $\Omega_{CDM}h^2$ from WMAP
- $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$ at LCC-4 proposed as benchmark process for the ILC detector optimization by the WWS ILC Benchmark Panel (Battaglia et al. hep-ex/0603010)
- H^0A^0 production @ LCC-4 at kinematic edge of ILC 1 TeV

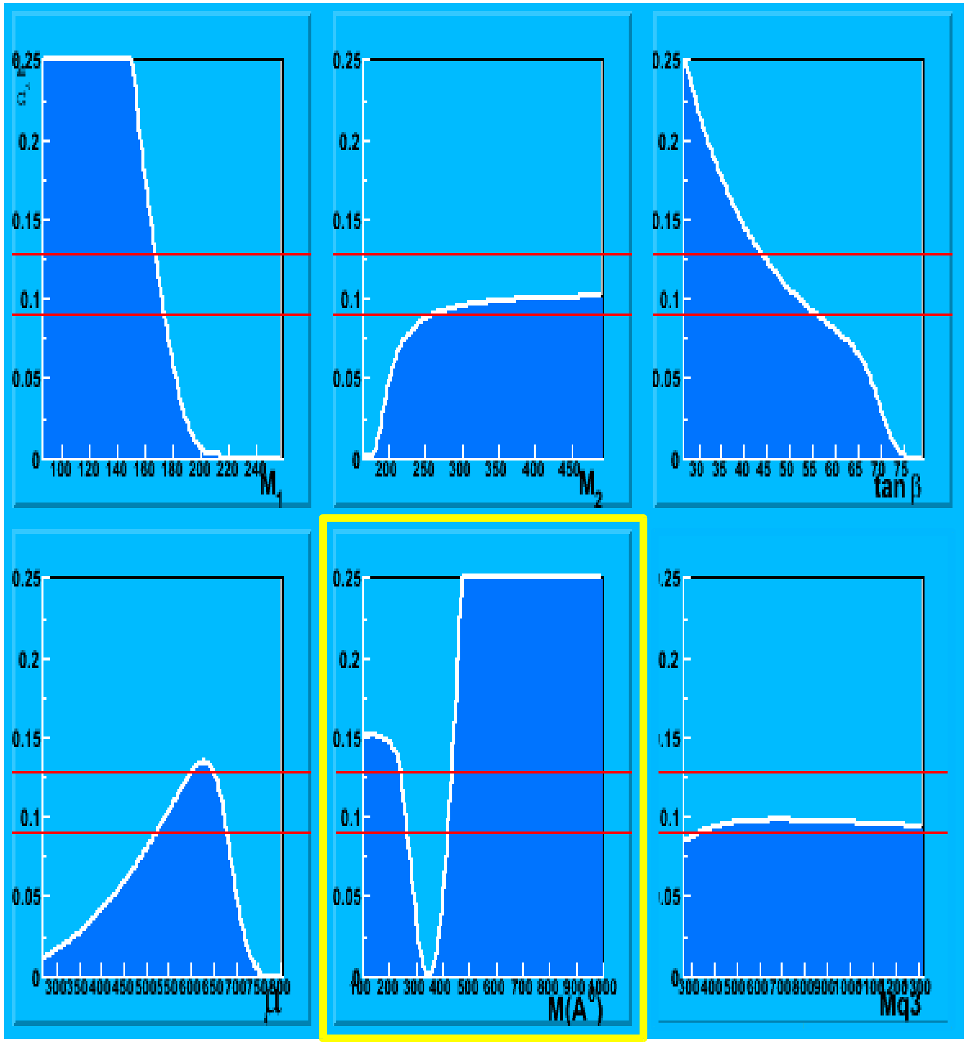


- m_0=380 GeV, $m_{1/2}$=420 GeV, A=0, tan β=53, sign(μ)=+1, M_{top}=178 GeV
- **M(H^0)=420 GeV, M(A^0) = 419 GeV**, M(h^0)=119 GeV, M(χ^0_1)=169 GeV, M($\tilde{\tau}_1$)=195 GeV

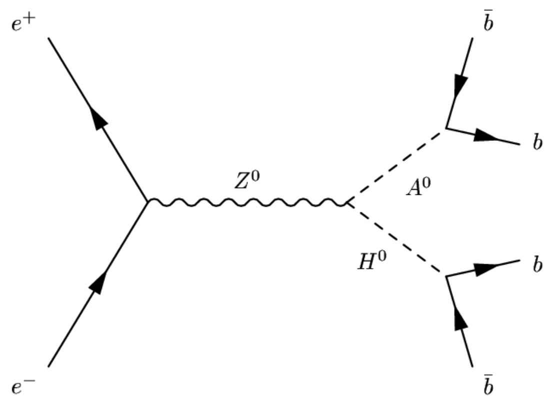
LCC-4 and $\Omega_{CDM}h^2$

- **LCC-4 Rapid annihilation funnel:** χ^0_1 LSP, $\Omega_\chi h^2$ controlled by $\chi\chi \rightarrow A^0$
- σ_{ANN} depends on $R = M(\chi^0_1)/M(A^0)$ and $\Gamma(A^0)$, enhanced for $R \approx 1/2$
- 0.5 TeV: $M(\tilde{\tau}_1)$ from threshold scan, $M(\chi^0_1)$ from $\Delta M = M(\tilde{\tau}_1) - M(\chi^0_1)$ from $\tilde{\tau}_1 \rightarrow \tau\, \chi^0_1$ kinematics
- **Goal of this analysis: measure A^0 properties using $e^+e^- \rightarrow H^0A^0$ @ 1 TeV**
- ~10% uncertainty on $\Omega_{CDM}h^2$ requires ~0.5% uncertainty on $M(A^0)$, $M(\chi^0_1)$
- Required accuracy achievable at ILC 1TeV?

Scan single parameter in MSSM space while fixing all other parameters to LCC-4 Values



$e^+ e^- \to H^0 A^0 \to b\bar{b}b\bar{b}$



	CP	M (GeV)	Γ(GeV)
A^0	+	419.3	15.3
H^0	-	421.7	15.3

- $\sigma(e^+e^- \to H^0A^0) = 1.4$ fb
- 2800 events for $\int L\,dt = 2.0\,\mathrm{ab}^{-1}$
- $BR(H^0/A^0 \to b\bar{b}) = 0.87$
- $BR(H^0/A^0 \to \tau^+\tau^-) = 0.13$
- $BR(H^0/A^0 \to \text{other}) < 2\times10^{-3}$

- H^0, A^0 heavy Higgs poles nearly degenerate in mass
- H^0, A^0 discovery @ LHC, but $H^0/A^0 \to \mu^+\mu^-$ not available and $H^0/A^0 \to \tau^+\tau^-$ precision limited to few % by τ jet energy calibration uncertainty: need ILC @ 1TeV!
- Reconstruct di-jet masses in $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ channel to measure $M(A^0)$, $\Gamma(A^0)$

Backgrounds

- $W^+W^- \rightarrow q\bar{q}q\bar{q}$ (w/ mis-identified q)
  - $\sigma_{WW} / \sigma_{HA} =$ **2300**
- $Z^0Z^0 \rightarrow q\bar{q}q\bar{q}/q\bar{q}b\bar{b}$ (w/ mis-identified q), also $Z^0Z^0 \rightarrow b\bar{b}b\bar{b}$
  - $\sigma_{ZZ} / \sigma_{HA} =$ **170**
- Irreducible 4b
  - $(\sigma_{4b} / \sigma_{HA})_{EW} =$ **2.4**, $(\sigma_{4b} / \sigma_{HA})_{QCD} =$ **1.5**
  - calculated with CompHEP, simulation underway
- Reduce background with kinematic and event shape cuts (ε_{BKG} = few $\times\ 10^{-2}$)
- b tagging needed to further reduce background

Full Simulation and Reconstruction

Pythia 6.58+ISASUGRA 7.69: Event Generation

e^+e^- collider @ 1 TeV, LCC-4, Circe beamstrahlung

↓ .stdhep

GEANT4/Mokka 6.03: Detector Simulation

LDC00_02Sc: LDC detector concept w/ realistic VTX

↓ .slcio

Marlin 00.09.06: Reconstruction

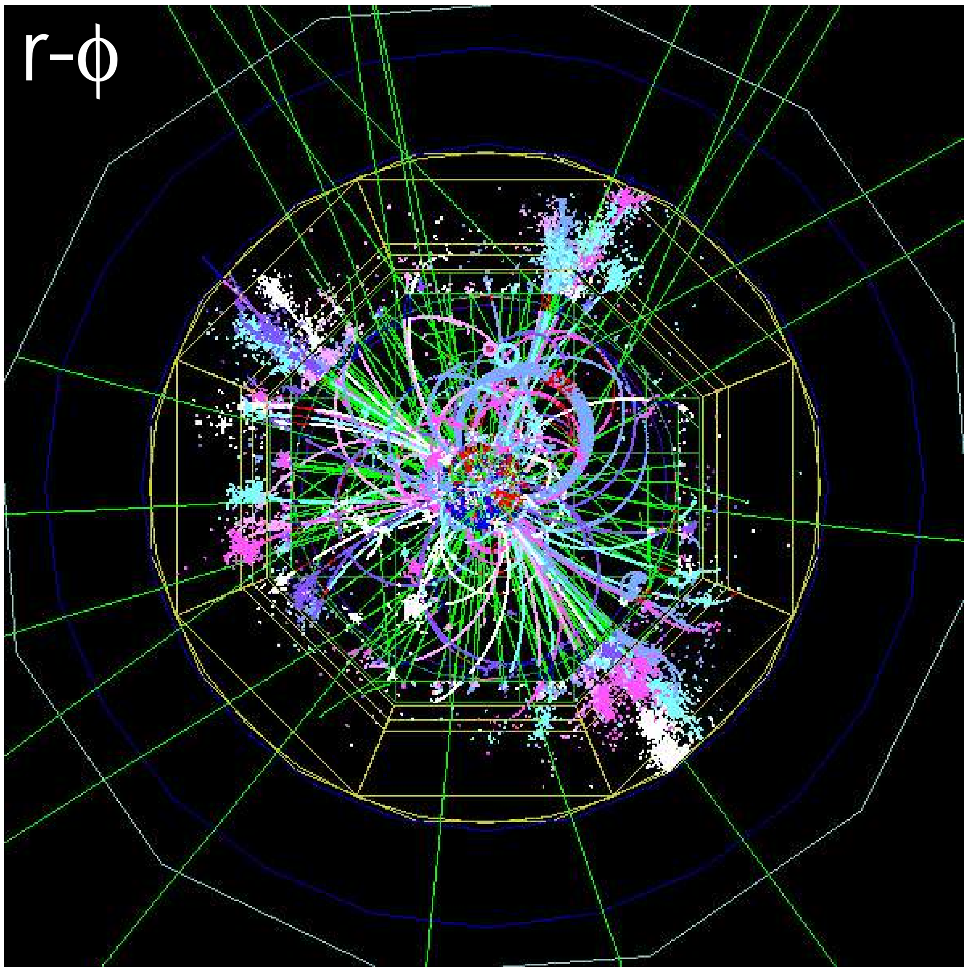
LCIO-based C++ framework: hit digitization, tracking/clustering, particle flow, jet clustering, b-tagging

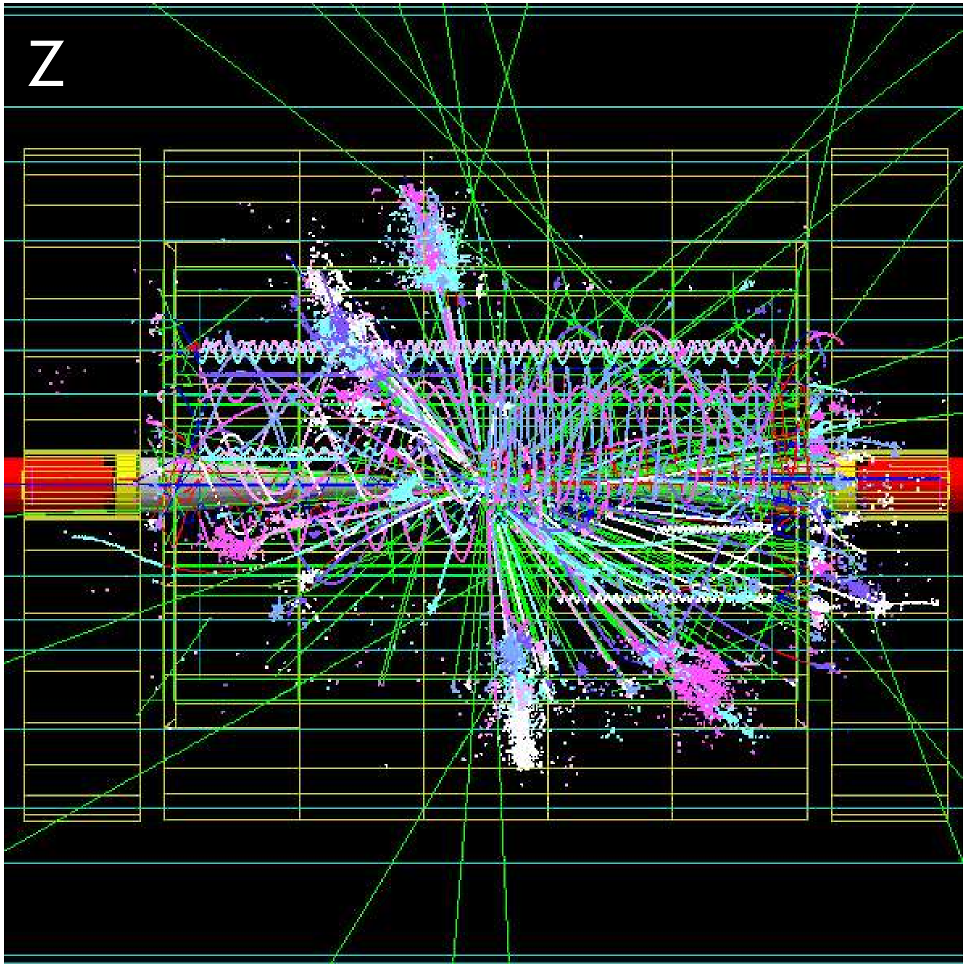
↓ .root ntuple

Root: Data Analysis

GEANT4/Mokka Event Display

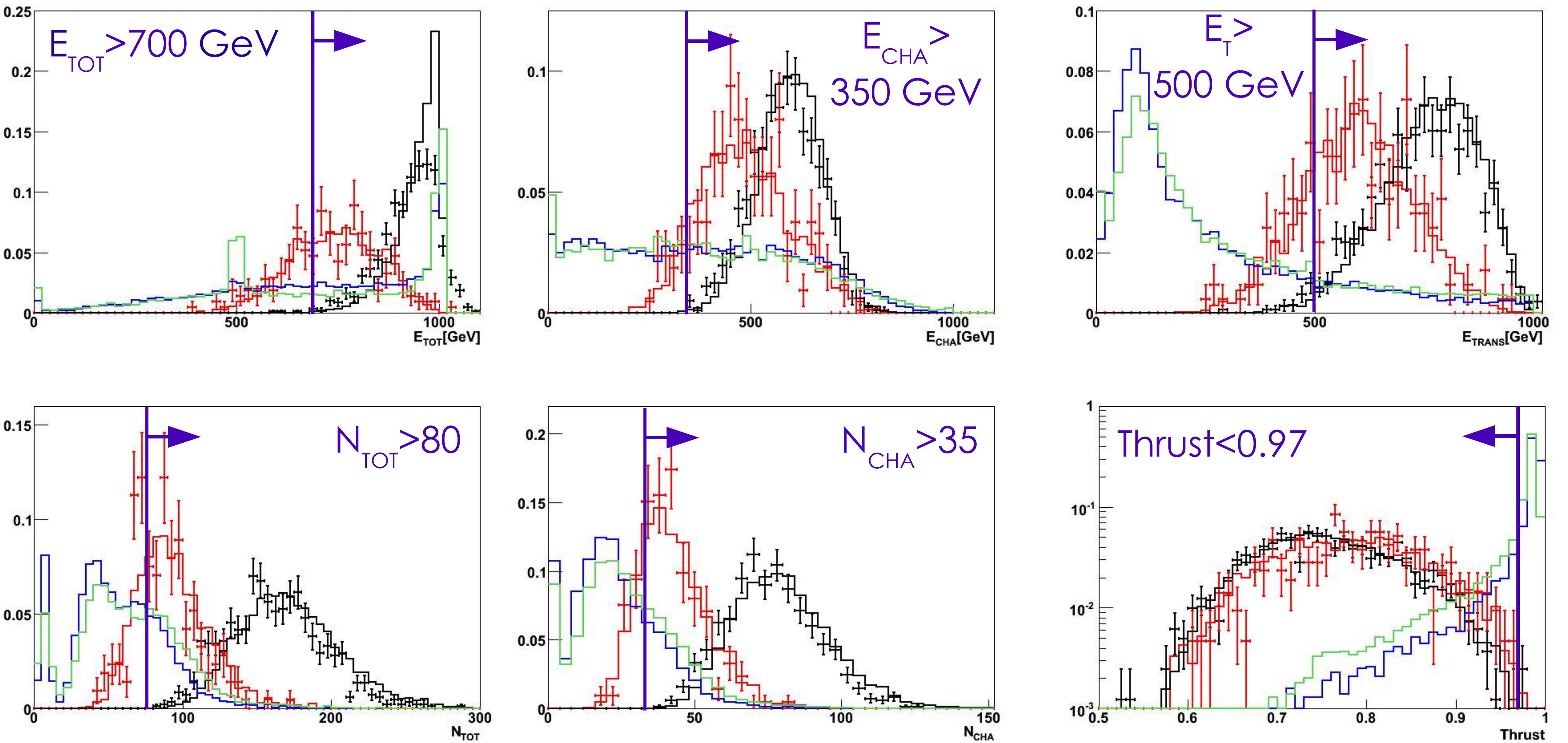
$$e^{+}e^{-}\rightarrow H^{0}A^{0}\rightarrow b\bar{b}b\bar{b}$$





Kinematic/Event Shape Cuts

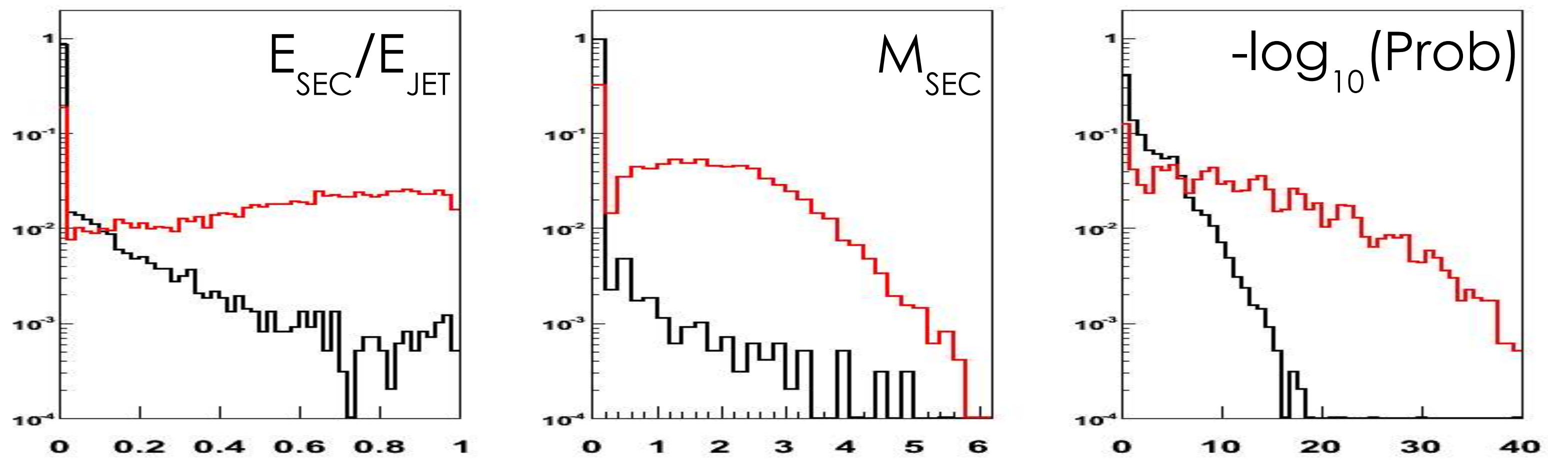
$\varepsilon(H^0A^0 \to b\bar{b}b\bar{b})=0.97$, $\varepsilon(H^0A^0 \to b\bar{b}\tau^+\tau^-)=0.33$, $\varepsilon(W^+W^-)=0.03$, $\varepsilon(Z^0Z^0)=0.04$



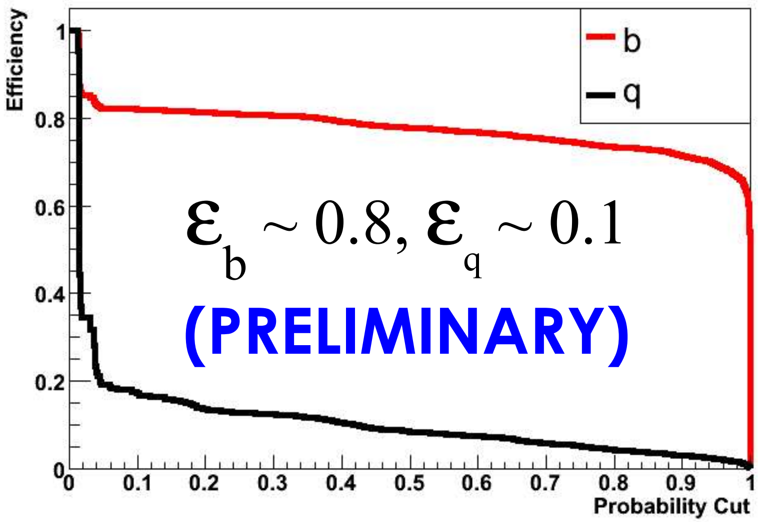
Solid lines are generated quantities, points with error bars are reconstructed quantities.
All histograms normalized to unity.

b Tagging

b vs. q distributions



- Reconstruct E_{SEC}/E_{JET}, M_{SEC}, $-\log_{10}(\text{Prob})$
- Obtain probability associated to each of 3 discriminant variables
- Normalized product of probabilities: single discriminant variable peaked at 1 for b, 0 for q



The Constrained Kinematical Fitter

- Problem: 4 jet final state ($\frac{\Delta E}{E}$ ~ .03-.05, lost or mis-assigned particles, ν's)
- PUFITC algorithm (DELPHI at LEP2 N Kjaer, M Mulders): Use constraints from total energy/momentum conservation to adjust jet momenta
- Implemented in Marlin module CKFit

Adjust jet momenta given by: $\vec{p}_F = e^a \vec{p}_M + b\,\vec{p}_B + c\,\vec{p}_C$

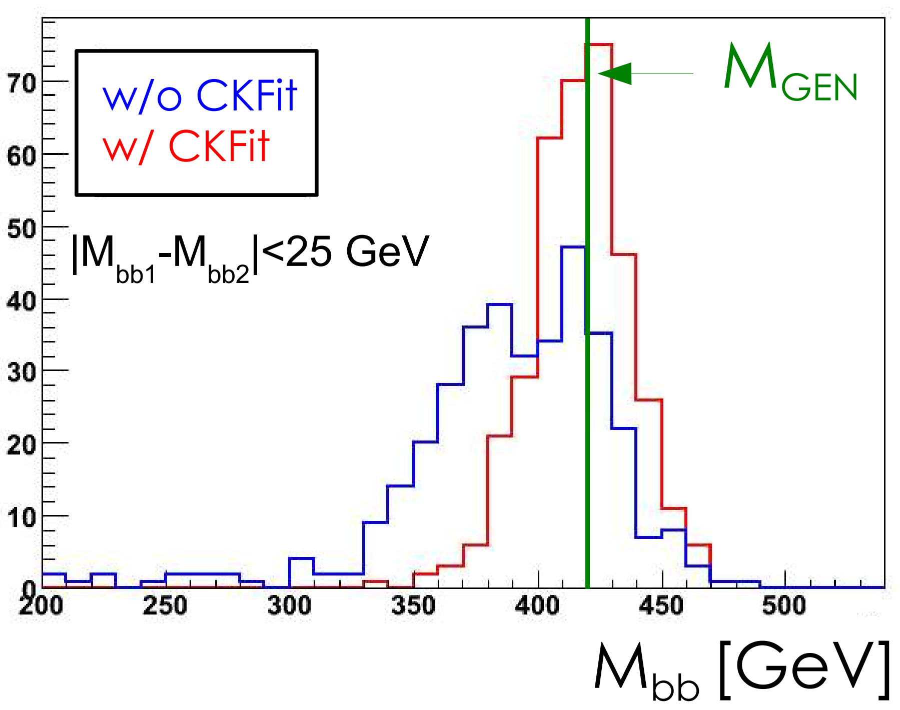
while satisfying: $p_X^{TOT} = p_Y^{TOT} = 0, E^{TOT} + |p_Z^{TOT}| = \sqrt{s}$

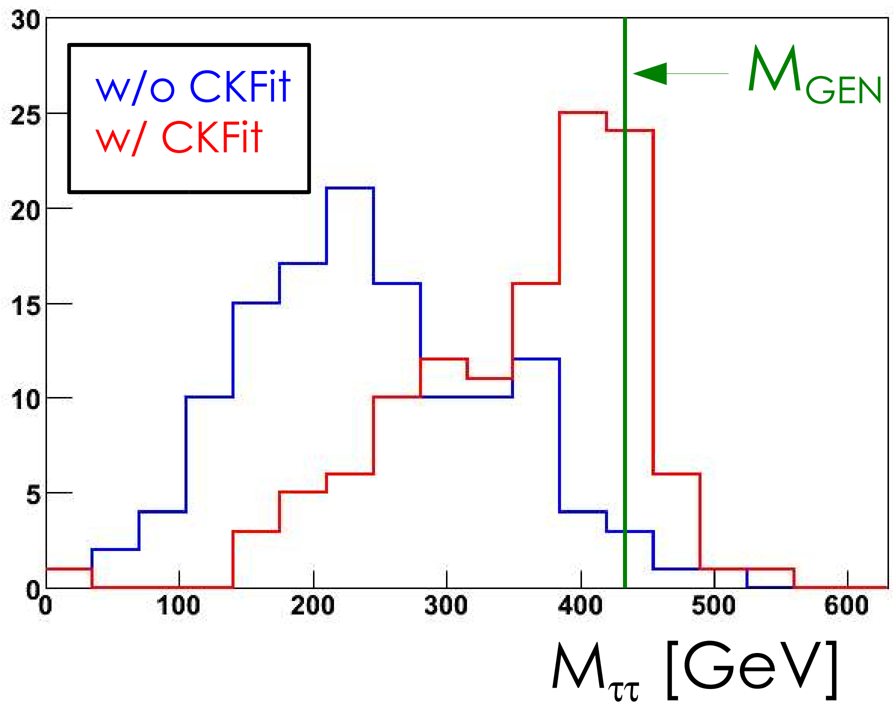
and minimizing: $\chi^2 = \Sigma_i \frac{(a_i - a_0)^2}{\sigma_a^2} + \frac{b_i^2}{\sigma_b^2} + \frac{c_i^2}{\sigma_c^2}$

$\vec{p}_F$ = fitted jet momentum
$\vec{p}_M$ = measured jet momentum
$\vec{p}_{B,C}$ = unit vectors $\perp$ to $\vec{p}_M$
a, b, c = fit parameters
a_0 = energy loss parameter
σ_a = energy spread param
$\sigma_{b,c}$ = trans mom spread params

CKFit Sample Results

Measure M_{bb} ($M_{\tau\tau}$) from $H^0A^0 \to b\bar{b}b\bar{b}$ ($b\bar{b}\tau^+\tau^-$) signal only, apply CKFit



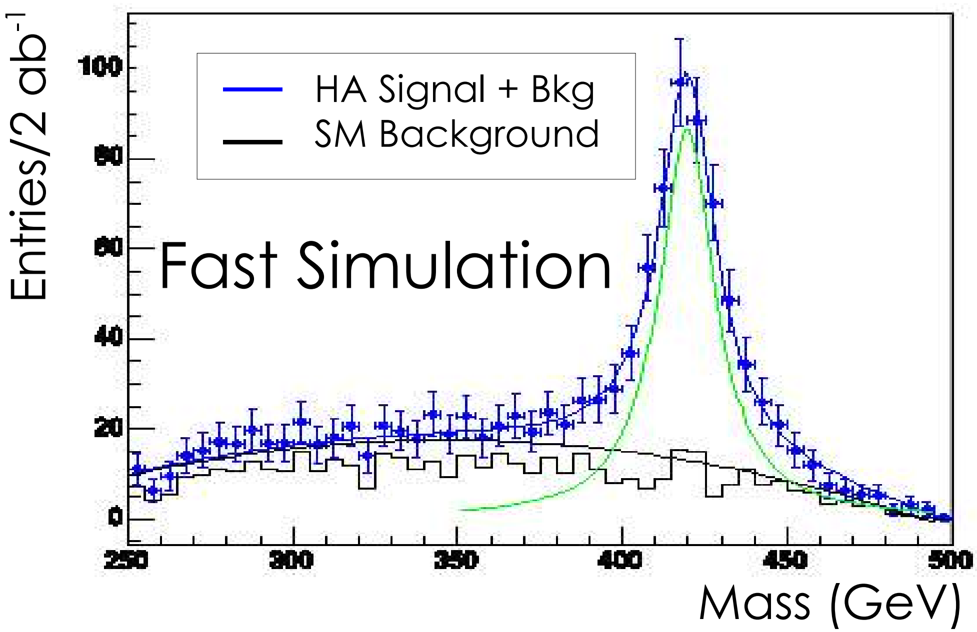


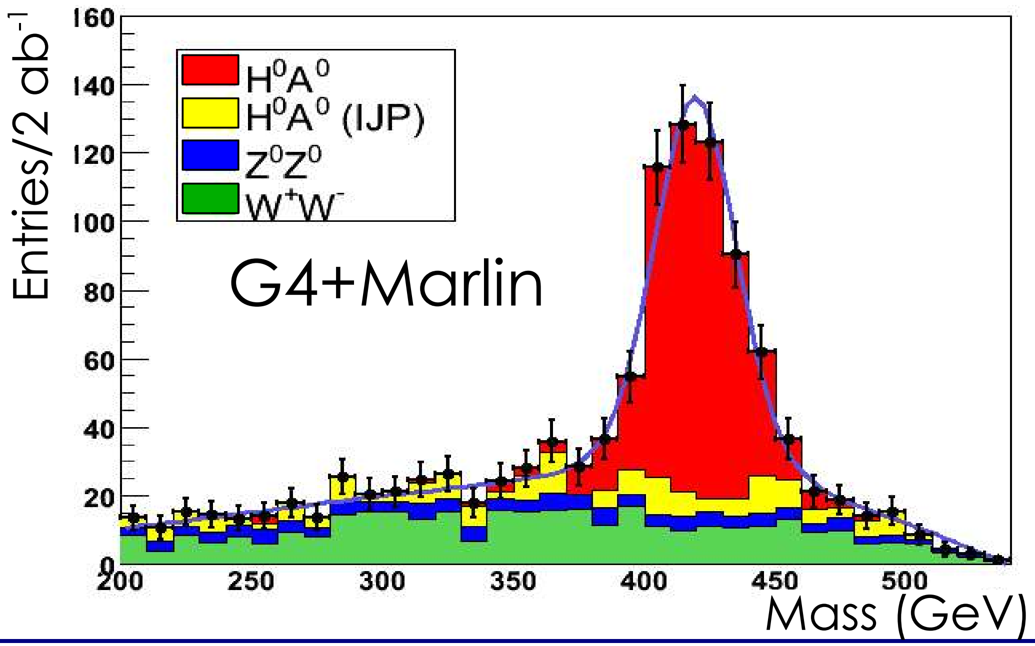
Results

- Plot dijet masses for each event (2 entries/event) using pairing which minimizes $|M_{JJ1}-M_{JJ2}|$
- Additional Cuts to maximize resolution: $|M_{JJ1}-M_{JJ2}| < 25$ GeV & $(\chi^2/ndf)_{CKFit} < 2$
- Background: fit 3rd order polynomial to $W^+W^- + Z^0Z^0 + H^0A^0$ events with incorrect jet pairing (IJP)
- Signal: 2 BW functions ⊕ Gaussian, σ_{GAUS} set to detector res, fix $M(H^0)-M(A^0)=1.4$ GeV, $\Gamma(H^0)=\Gamma(A^0)$

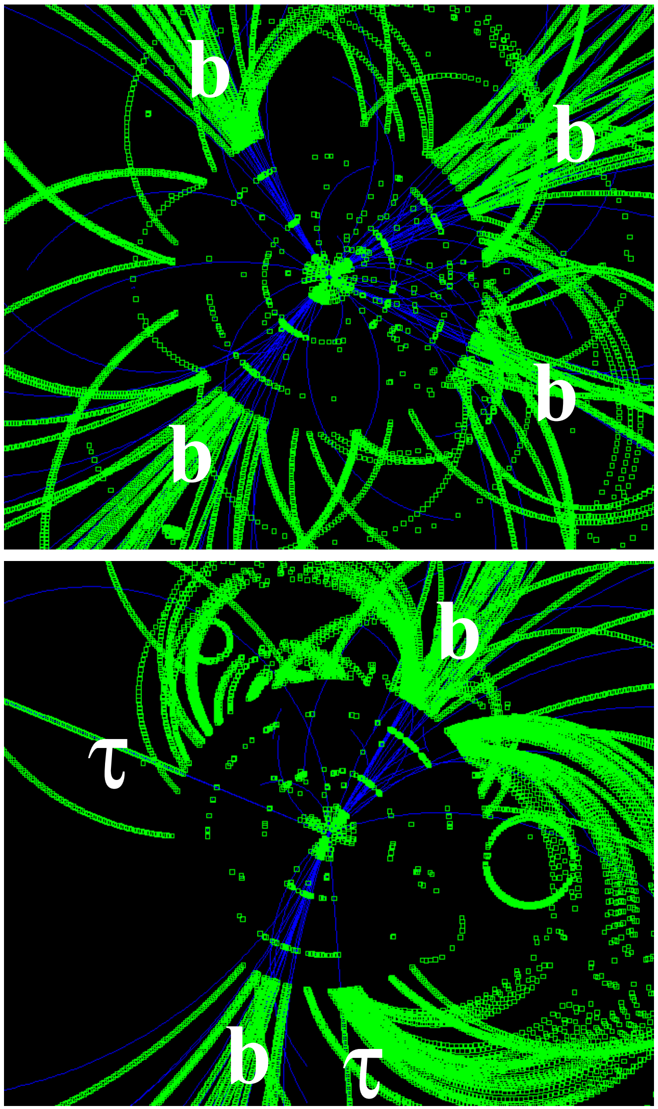
	#Events	ε
H^0A^0	2760	0.15
Z^0Z^0	4.7×10^5	1.2×10^{-4}
W^+W^-	6.5×10^6	2.7×10^{-5}

	X_{RECO} [GeV]	X_{GEN} [GeV]
$M(A^0)$	**418.8±1.1**	419.4
$\Gamma(A^0)$	**10.0±3.6**	15.3





A^0 BR Measurement



Mokka event display

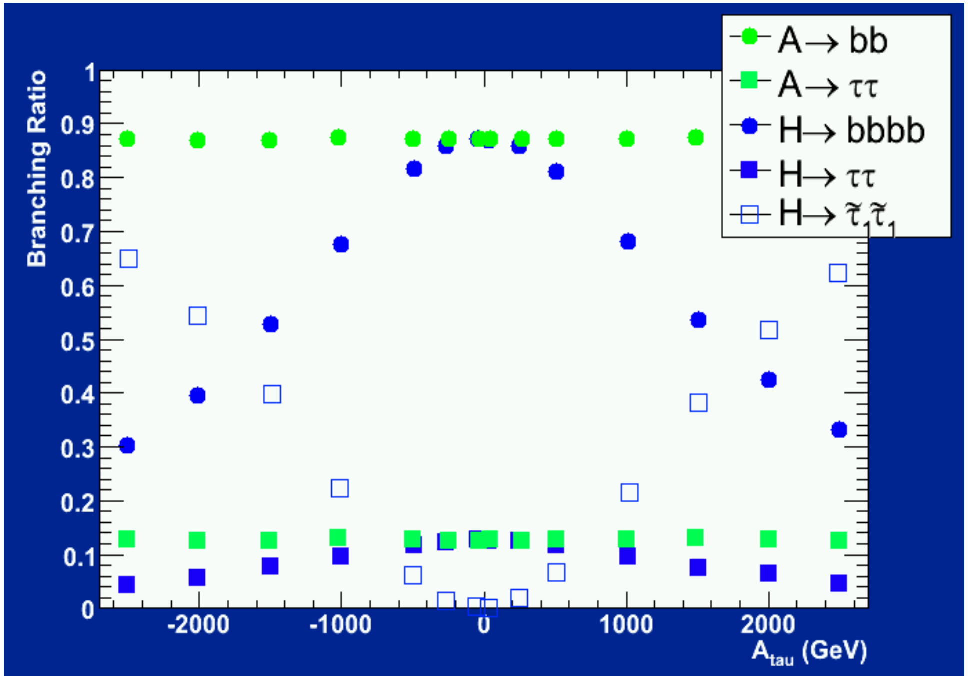
- Measure $BR(A^0 \to \tau^+\tau^-)$, $BR(A^0 \to b\bar{b})$ from rate of $H^0A^0 \to b\bar{b}\tau^+\tau^-$ vs $H^0A^0 \to b\bar{b}b\bar{b}$
- Consider W^+W^- and Z^0Z^0 background
- Kinematic/event shape cuts
- $b\bar{b}\tau^+\tau^-$: 2 b tags + 2 τ tags w/ $(M_{bb})_{CKFit}$, $(M_{\tau\tau})_{CKFit}$ > 250 GeV
- $b\bar{b}b\bar{b}$: 4 b tags with both $(M_{bb})_{CKFit}$ > 250 GeV
- Missing energy cut for $b\bar{b}\tau^+\tau^-$
- Estimate uncertainty in BR from $\left(\frac{Sig}{\sqrt{Sig+Bkg}}\right)^{-1}$
- **Preliminary results:**

$$\frac{\Delta BR(A^0 \to \tau^+\tau^-)}{BR(A^0 \to \tau^+\tau^-)} \approx 0.17 - 0.20 \qquad \frac{\Delta BR(A^0 \to b\bar{b})}{BR(A^0 \to b\bar{b})} \approx 0.04$$

- $\tau^+\tau^-$ result will be improved substantially with full τ tagging

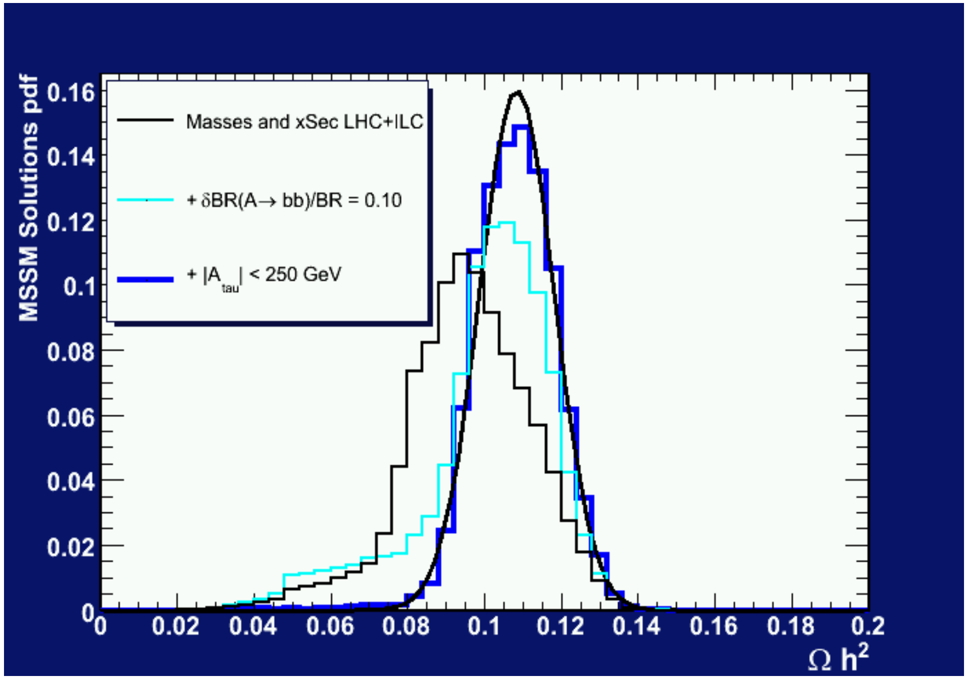
A_{tau} and $\Omega\, h^2$

- $BR(H\to\tilde{\tau}_1\tilde{\tau}_1)$ sensitive to A_{tau}
- Constrain $BR(H\to\tilde{\tau}_1\tilde{\tau}_1)$ with $b\bar{b}\tau^+\tau^-$ analysis
- $\Delta BR/BR = 0.15 \to |A_{tau}| < 250$ GeV



A_{tau} scan for LCC-4 with HDECAY 2.0

- Ωh^2 pdf from range of measurements @ LHC+ILC, low tail due to large $|A_{tau}|$
- $\Delta\Omega h^2/\Omega h^2 = 0.16 \to 0.08$ with $|A_{tau}|$ constraint



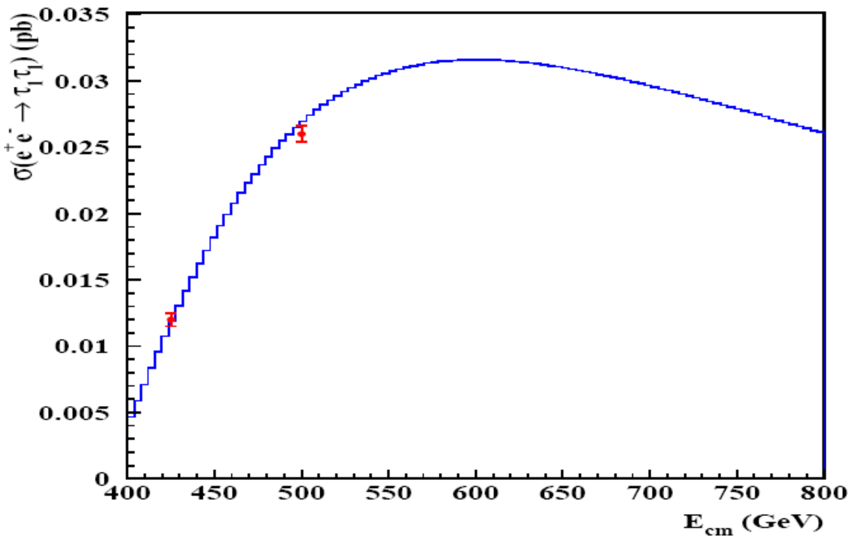
$\Omega\, h^2$ accuracy for LCC4 with HA analysis

Conclusions and Outlook

- Ported PUFITC algorithm to Marlin module CKFit
- Developed preliminary jet flavor tagging package,
- $M(A^0)$, $\Gamma(A^0)$ measured using $H^0A^0 \rightarrow b\bar{b}b\bar{b}$ with full G4+Marlin, required accuracy achievable @ ILC 1TeV
- $|A_{tau}|$ constraint improves $\Delta\Omega h^2/\Omega h^2$ to ~8%
- τ tagging to further improve $BR(A^0 \rightarrow \tau^+\tau^-)$ measurement
- Future work: study effect of varying vtx technology & parameters on performance

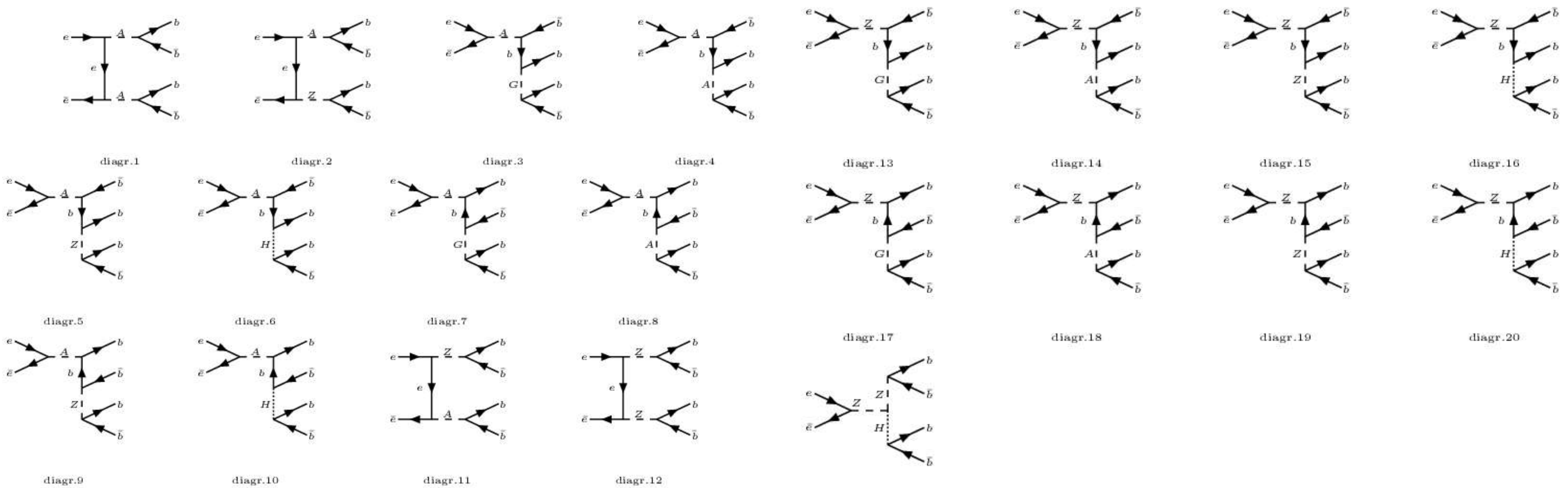
Additional Slides

LCC-4 Measurements



- Measure $M(\tau_1)$ from threshold scan
- .5 TeV
  - Measure $M(\tau_1)$-$M(\chi^0_1)$ from $\tau_1 \to \tau\, \chi^0_1$ kinematics
  - Estimate $\Gamma(A^0)$ from $\Gamma_{A^0} = \frac{BR(h^0 \to b\bar{b})}{BR(A^0 \to b\bar{b})} \Gamma_{h^0} \tan^2(\beta)$
- 1 TeV
  - Determine μ from $M(\chi_{2,3})$-$M(\chi_1)$
  - Precise measurement of $M(A^0)$,$\Gamma(A^0)$

Irreducible 4b Background



$H^0A^0 \rightarrow$staus

Stau coupling to H^0/A^0:

A^0: $A_{tau} \tan\beta + \mu$

H^0: $A_{tau} \cos\alpha / \cos\beta + \mu \sin\alpha / \cos\beta$

$M(A^0) < M(\tau_1) + M(\tau_2)$: no CP-allowed $A^0 \rightarrow$staus decay

$H^0 \rightarrow \tau_1 \tau_1$ probes A_{tau}