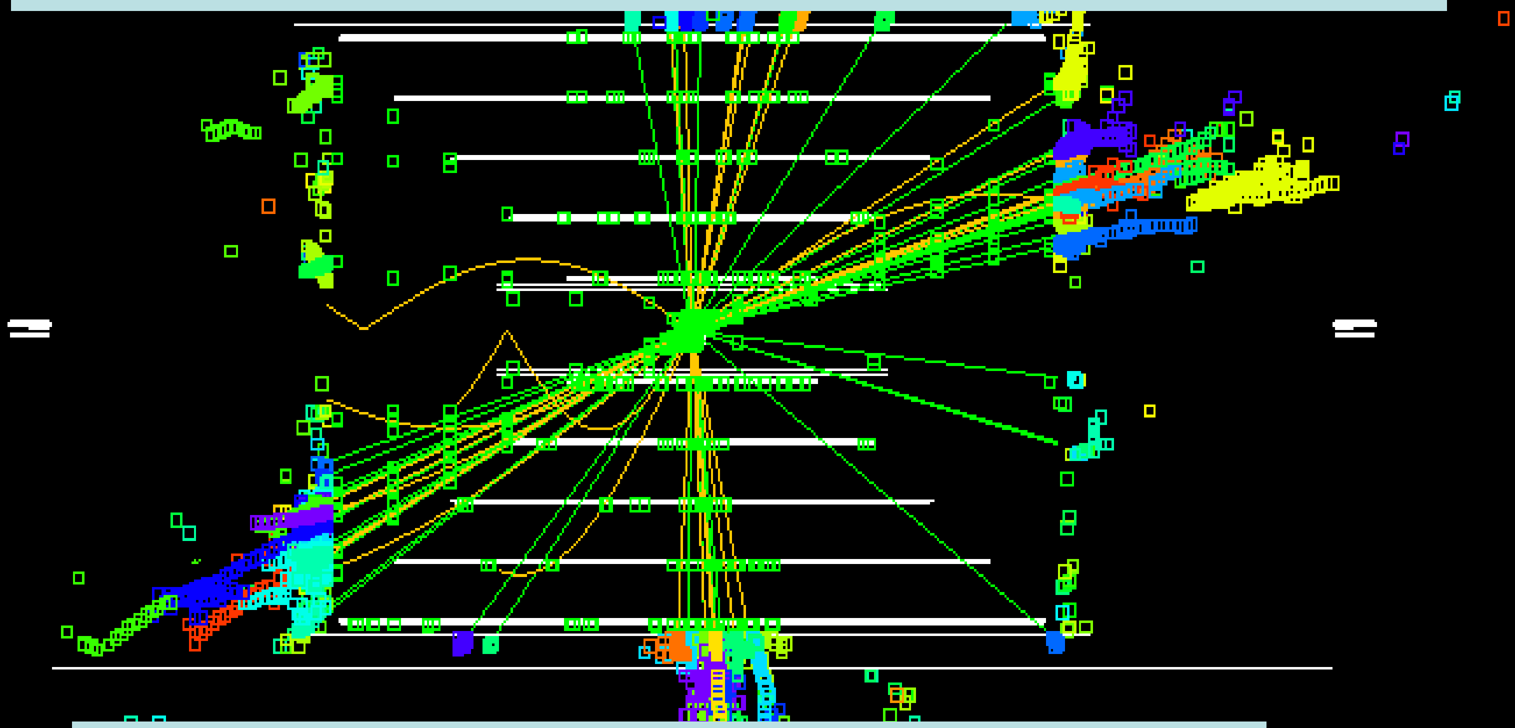
SiD LoI: Benchmarking



Andrei Nomerotski, University of Oxford
TILC09, Tsukuba, 17 April 2009

From Physics Studies to Benchmarking

- In LoI the emphasis of physics studies shifted towards
  - Realities required by engineering: material (amount and distribution)
  - Realities required by reconstruction algorithms: tracking & PFA

- Answer questions:
  - With added realism will it still deliver physics ?
  - How does it compare to other concepts ?

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Benchmarking Processes for LoI

Six compulsory processes proposed by WWS Software panel in consultation with the detector concepts

1. $e^+e^- \to e^+e^-H\,,\ \mu^+\mu^-H\,,\ \sqrt{s}$=250 GeV;
2. $e^+e^- \to ZH\,,\ H \to c\bar{c}\,,\ Z \to \nu\bar{\nu}\,, q\bar{q}\,,\ \sqrt{s}$=250 GeV;
3. $e^+e^- \to ZH\,,\ H \to \mu^+\mu^-\,,\ Z \to \nu\bar{\nu}\,, q\bar{q}\,,\ \sqrt{s}$=250 GeV;
4. $e^+e^- \to \tau^+\tau^-\,,\ \sqrt{s}$=500 GeV;
5. $e^+e^- \to t\bar{t}\,,\ t \to bW^+\,,\ W^+ \to q\bar{q}'\,,\ \sqrt{s}$=500 GeV;
6. $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-/\tilde{\chi}_2^0\tilde{\chi}_2^0\,,\ \sqrt{s}$=500 GeV.

Additional SUSY process

7. $e^+e^- \to \tilde{b}\tilde{b}\,,\ \tilde{b} \to b\tilde{\chi}_1^0, \sqrt{s}$=500 GeV.

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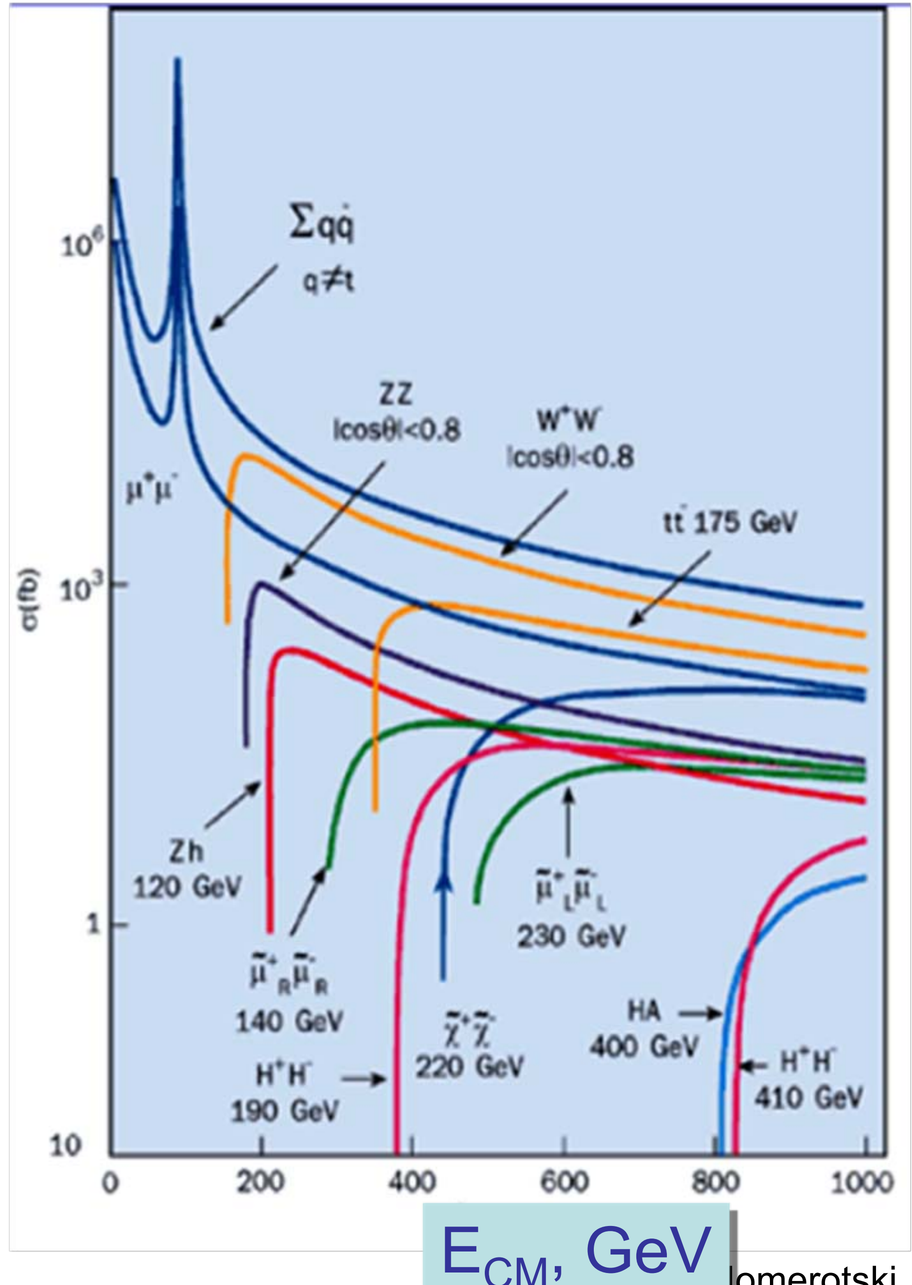
Standard Model Samples

- Generation of SM backgrounds
  - 250 and 500 GeV samples, 250 and 500 fb^{-1}
  - Large range of cross sections → Events are weighted

- All concepts used the same MC samples for benchmarking
  - WHIZARD Monte Carlo used to generate all 0,2,4,6-fermion and t-quark dominated 8-fermion processes

- SiD used premixed inclusive SM samples in all analyses



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LoI Data Analysis Flow

All analyses used :

- Java based org.lcsim framework
- Full simulation
  - GEANT4 based
  - Detector description consistent with LoI
    - Realistic amount of material
    - Some shape simplification
- Full reconstruction
  - Tracking: pattern recognition and fitting
  - SiD PFA
  - Lepton ID

- Data processing at SLAC, Fermilab and RAL using GRID
  - > 30 samples, ~ 50M events
  - Many issues encountered and efficiently resolved, many thanks to all involved!

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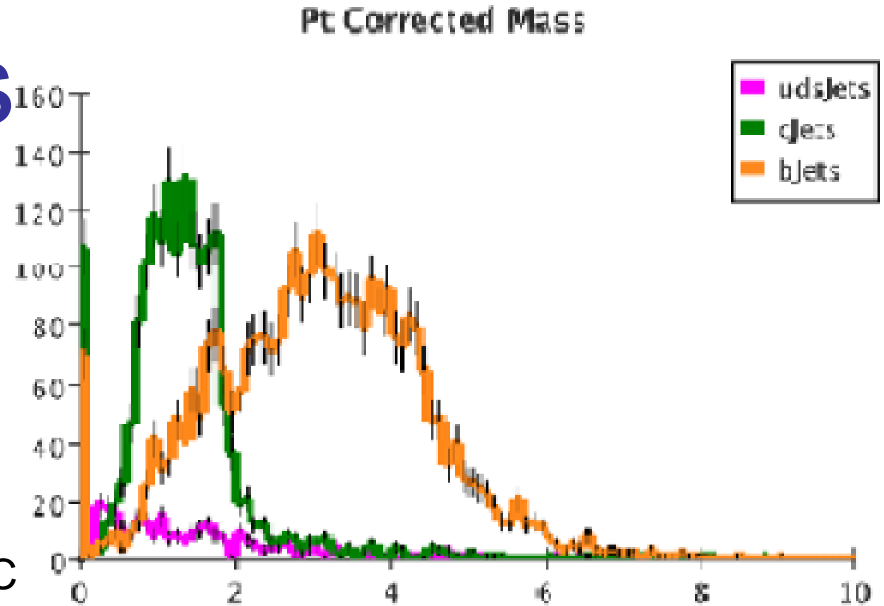
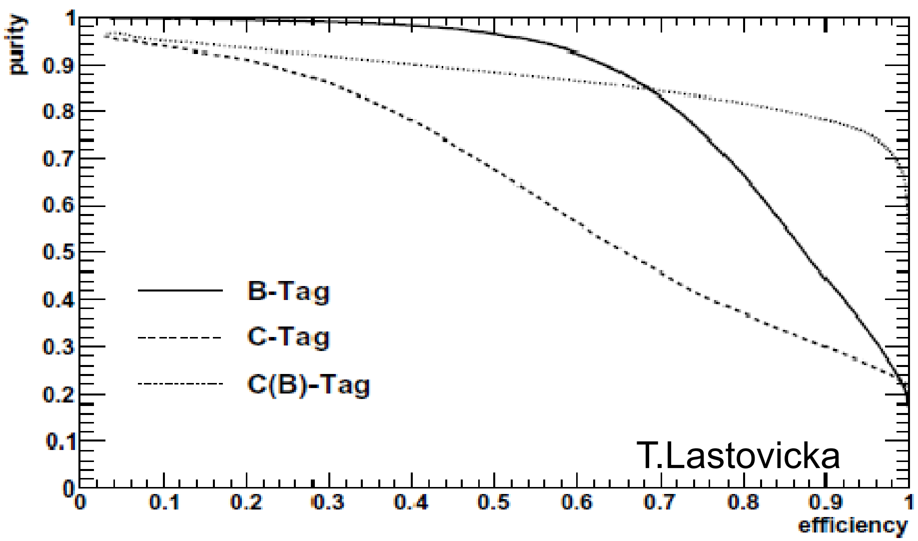
Analysis Tools

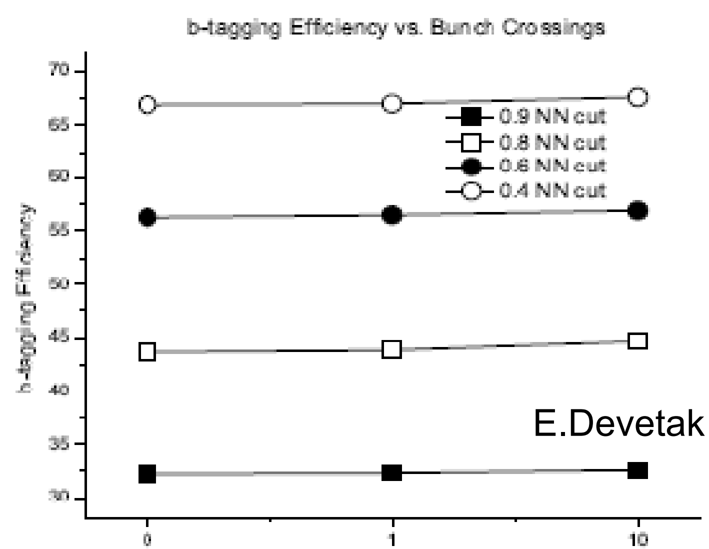
- Pythia jet clustering
- Marlin Kinematic Fitter
- Vertexing: LCFI package
  - NN based on flavour discriminants
  - Re-optimized for SiD
  - Beam-beam background study
    - One BC for Tracker, variable # of BC for VD



Corrected vertex mass, GeV



Purity vs Efficiency



Eff vs # BC in VD

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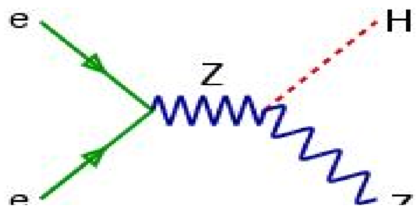
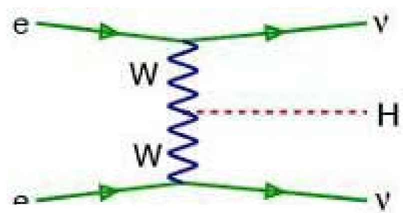
Highlights of Benchmarking Analyses

details will be discussed in five SiD presentations in the parallel session

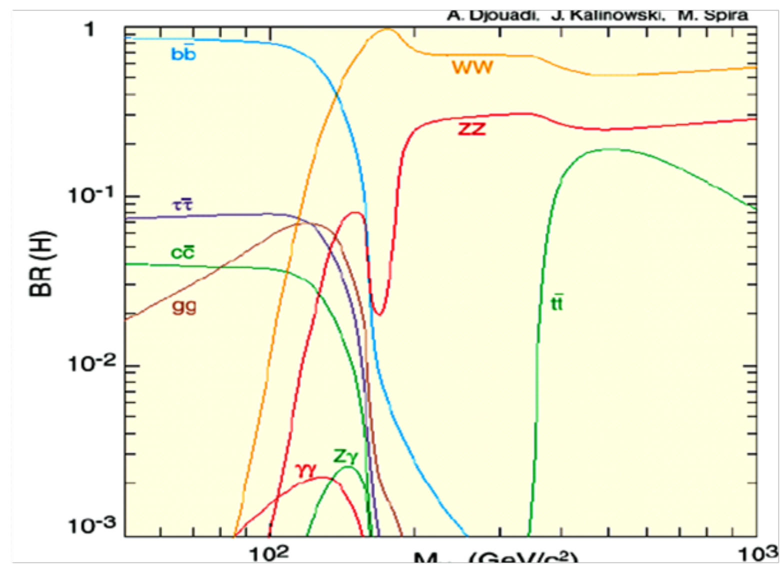
Higgs at ILC

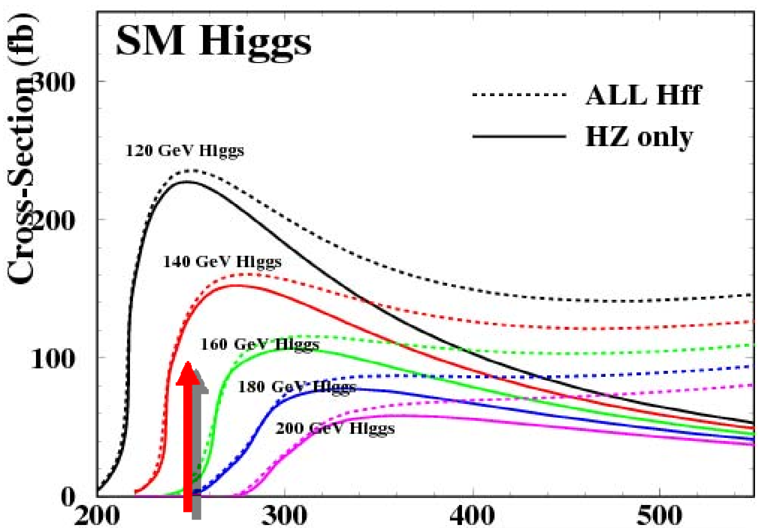
- Cornerstone of physics program
- Dominant production processes at ILC:





SM Higgs Branching Ratios





E_{CM}, GeV

Higgs mass, GeV

m_H = 120 GeV
E_{CM} = 250 GeV
L = 250 fb^{-1}

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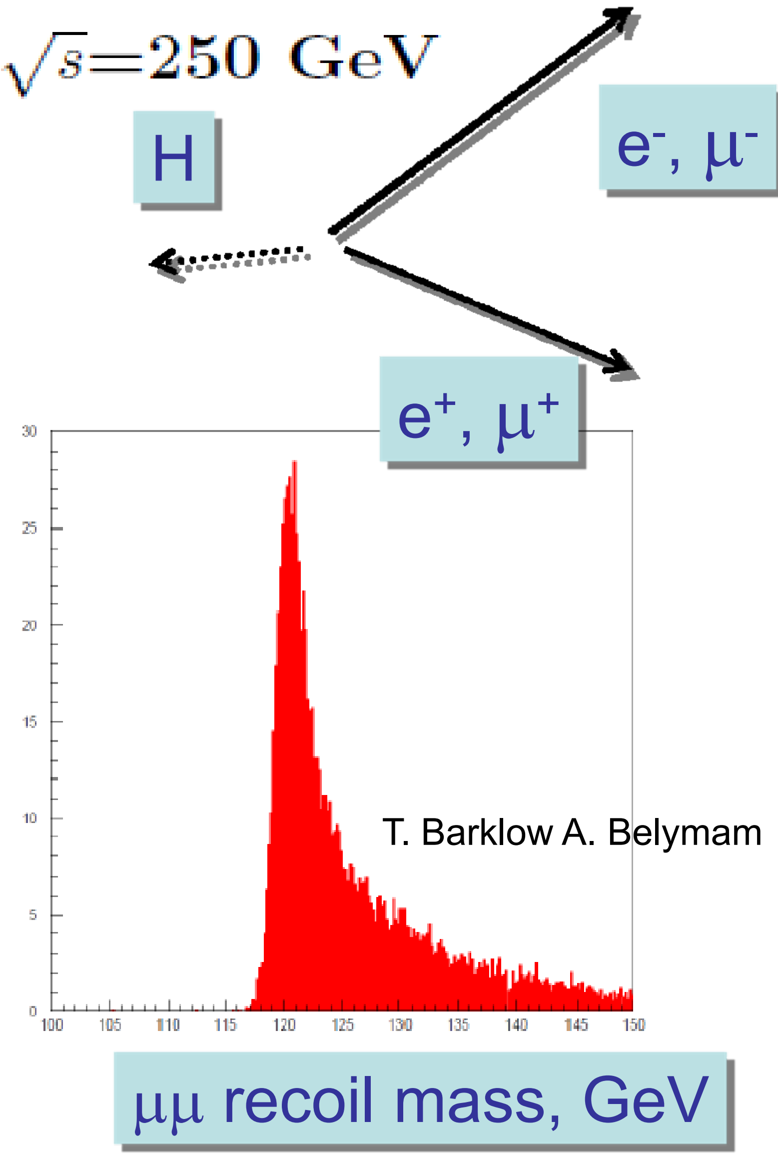
Higgs Recoil Mass (1)

$$e^+e^- \rightarrow e^+e^-H\ ,\ \ \mu^+\mu^-H\ ,\ \ \sqrt{s}{=}250\ \mathrm{GeV}$$

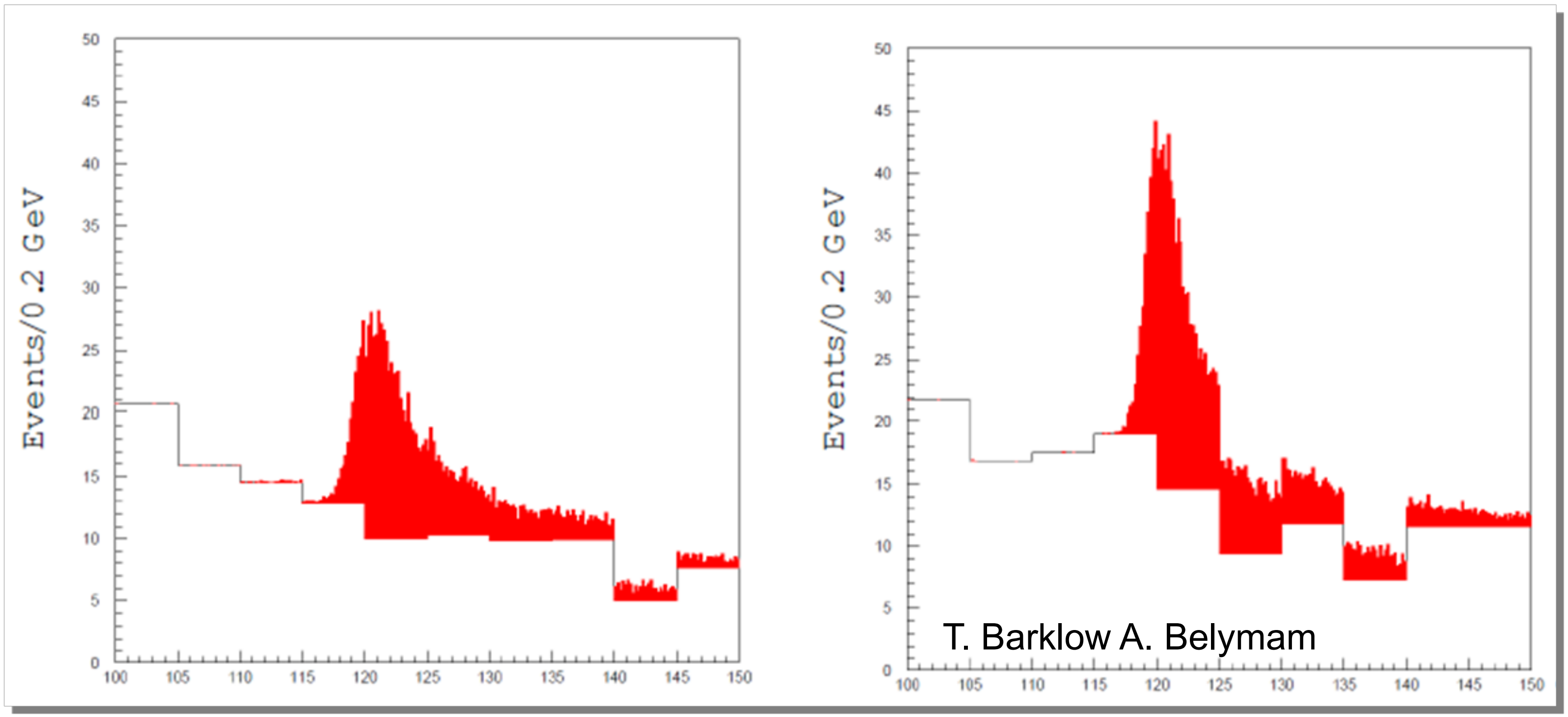
- Independent of Higgs decay modes
  - Sensitive to invisible modes
  - Precise determination of Higgs mass
- Reconstruct two leptons from Z decay, calculate invariant mass of recoiling object (Higgs)
- Lepton ID
  - Electron: track + EM object
  - Muon: track + MIP in CAL + stub in MUO
- Main selections
  - Two tracks
  - Acceptance selections
  - 87 < $M(l^+l^-)$< 95 GeV
- Polarization: 80%R e^-, 30%L e^+
  - Suppress WW background but lower xsection



Higgs Recoil Mass (2)

$$e^+e^- \rightarrow e^+e^-H\,,\ \mu^+\mu^-H\,,\ \sqrt{s}\text{=}\mathbf{250\ GeV}$$

- Main backgrounds: $\gamma\gamma\ l^+l^-$, W^+W^-, Z^*Z



ee recoil mass, GeV

μμ recoil mass, GeV

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Higgs Recoil Mass (3)

$$e^+e^- \rightarrow e^+e^-H\,,\ \mu^+\mu^-H\,,\ \sqrt{s}=250\ \mathrm{GeV}$$

- Higgs mass :
  - linear least squares fit for 117< M_H< 137 GeV
  - Two template samples: 120 and 119.7 GeV Higgs mass
  - 60 MeV uncertainty with 250 fb^{-1}
- Cross section :
  - 4.7% uncertainty

80eR lumi	80eL lumi	Mode	ΔM_H (GeV)	$\Delta\sigma_{l^+l^-H}$ (fb)
250 fb^{-1}	0 fb^{-1}	e^+e^-H	0.102	0.620
250 fb^{-1}	0 fb^{-1}	$\mu^+\mu^-H$	0.075	0.388
250 fb^{-1}	0 fb^{-1}	$e^+e^-H+\mu^+\mu^-H$	0.060	0.329
0 fb^{-1}	250 fb^{-1}	e^+e^-H	0.090	0.812
0 fb^{-1}	250 fb^{-1}	$\mu^+\mu^-H$	0.077	0.558
0 fb^{-1}	250 fb^{-1}	$e^+e^-H+\mu^+\mu^-H$	0.059	0.460

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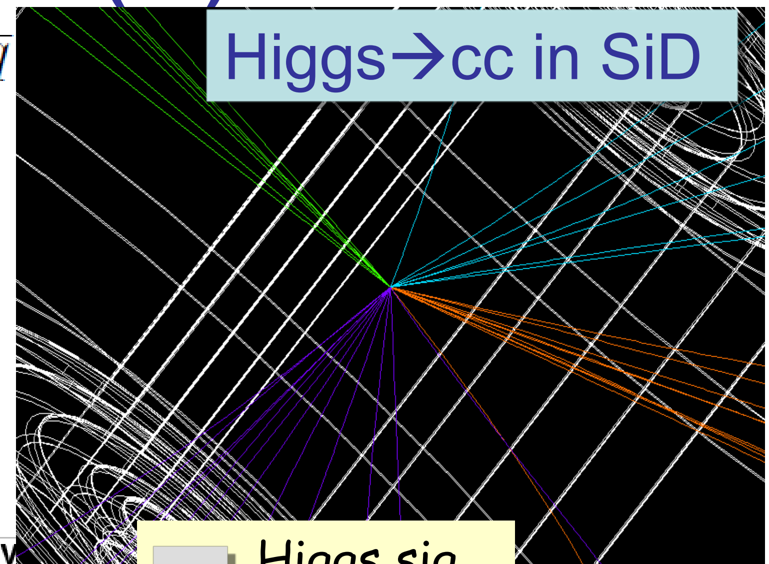
Higgs→cc (1)

$$e^+e^- \to ZH\,,\ \ H \to c\bar{c}\,,\ \ Z \to \nu\bar{\nu}\,,\ q\bar{q}$$

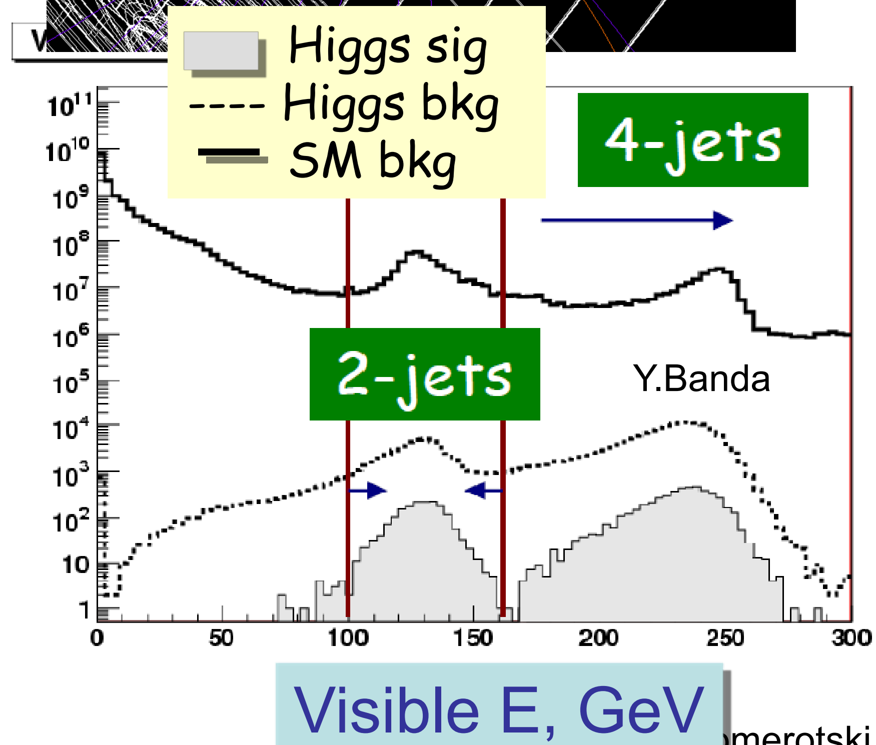


- Higgs couples to each particle in proportion to its mass
  - Discrimination between different BSM scenarios

- Signatures
  - 2 jets + Missing E
  - 4 jets

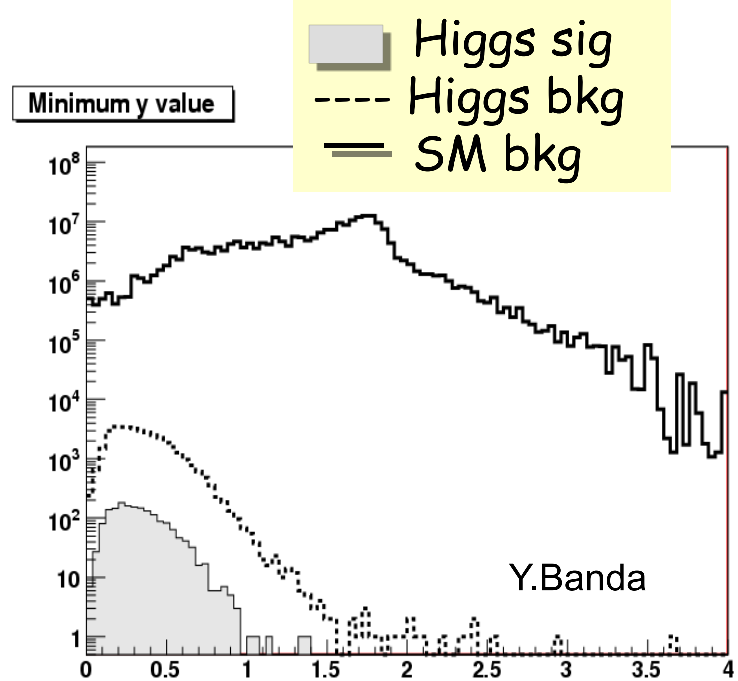
  - Two charm jets

- Preselections
  - Visible energy
  - No leptons with E > 15 GeV

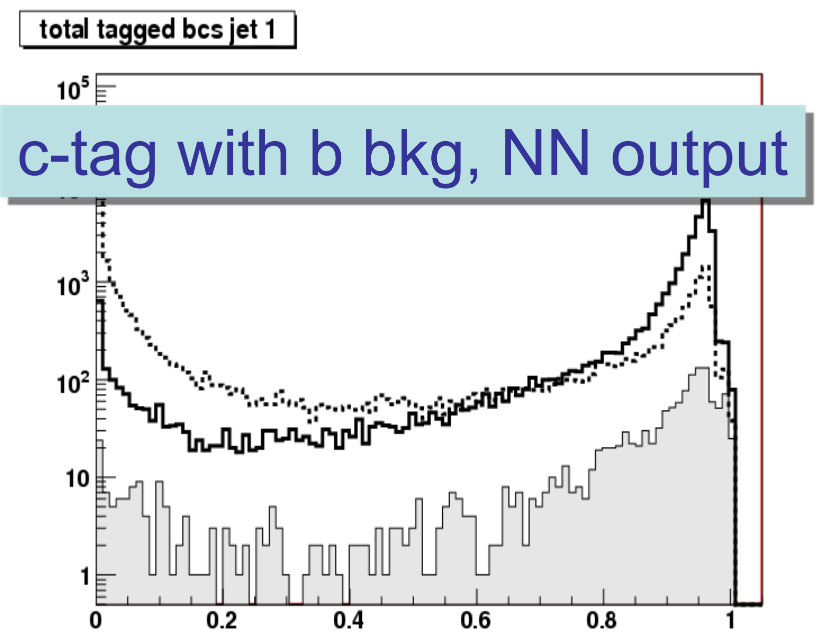


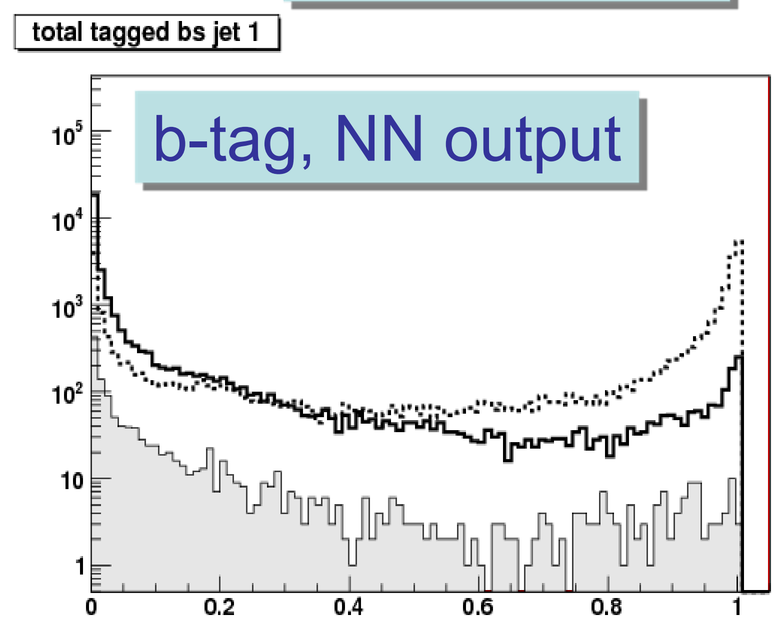
Higgs→cc (2)

- Neutrino channel selections
  - 20 < pT < 90 GeV
  - Two jets, -log (ymin) < 0.8
  - Thrust < 0.95
  - 100 < angle between jets < 170
  - 100 GeV < inv. Mass < 140 GeV
  - Energy of isolated photon < 10 GeV
- Important: c- and b- tagging



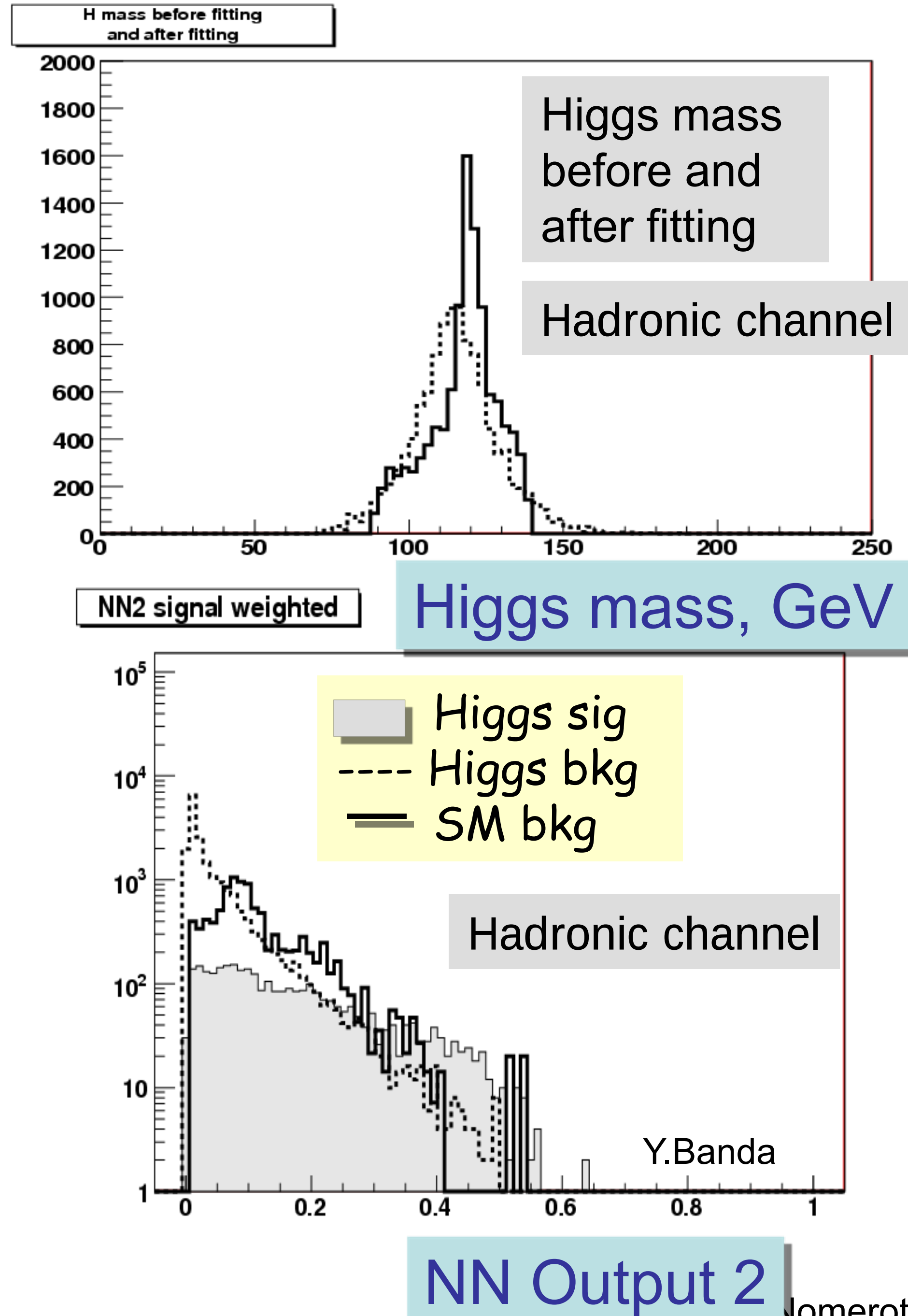
Minimum y cut





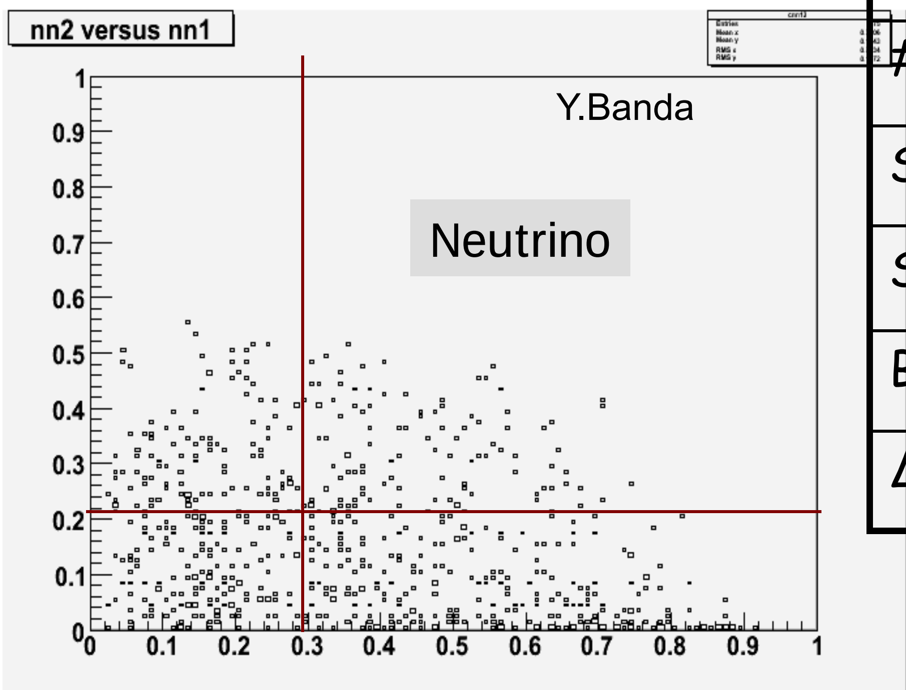
Higgs→cc (3)

- Hadronic channel
  - Kinematic and flavour tagging selections
  - Kinematic fit using mass constraints
- Variables combined in NN trained to discriminate
  - Inclusive Higgs and SM: NN Output 1
  - Signal Higgs and inclusive Higgs: NN Output 2



Higgs → cc : Results

- Final selections
  - NN Output 1 > 0.2
  - NN Output 2 > 0.3



NN 2 vs NN 1

	Neutrino	Hadronic
# Sig. events	476	814
# SM events	570	569
# Higgs bk events	246	547
Signal efficiency	28%	47%
Signal σ	6.8±0.7 fb	6.9±0.4 fb
Br (H->cc)	3.3±0.4%	3.3±0.2%
ΔBr/Br	~ 11%	~ 6%

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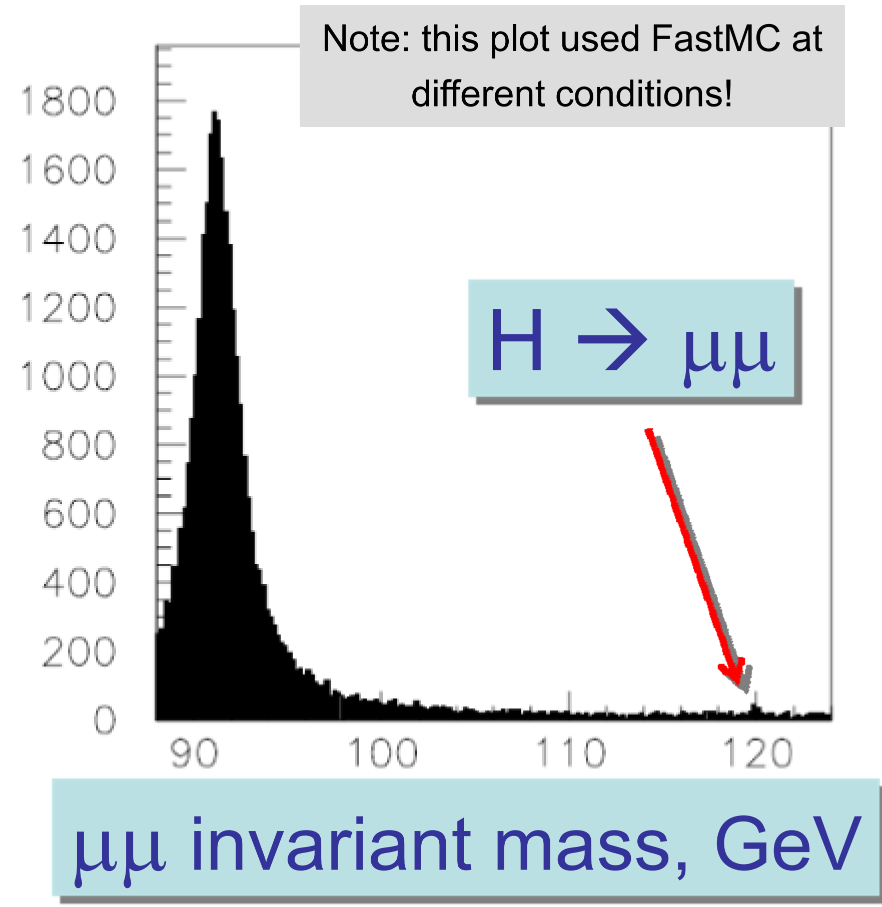
Higgs→μμ (1)

$$e^+e^- \rightarrow ZH\,,\ H \rightarrow \mu^+\mu^-\,,\ Z \rightarrow \nu\bar{\nu}\,,\, q\bar{q}\,,\ \sqrt{s}\mathbf{=250\ GeV}$$

- Rare Higgs decay
  - Br= 0.01%
  - Need excellent mass resolution
- Main challenge: overwhelming background from SM two- and four-fermions
  - Total 19 signal events at 250 fb^{-1}
- Considered only neutrino and hadronic channels
- Muon selections:
  - Two muons with standard muon ID
  - $E_{\mu 1}$ > 50 GeV
  - $E_{\mu 2}$ > 30 GeV



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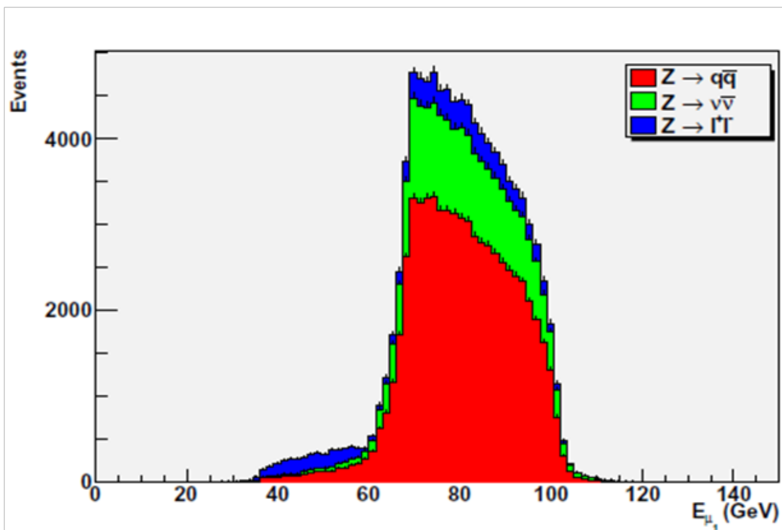
Higgs→μμ (2)

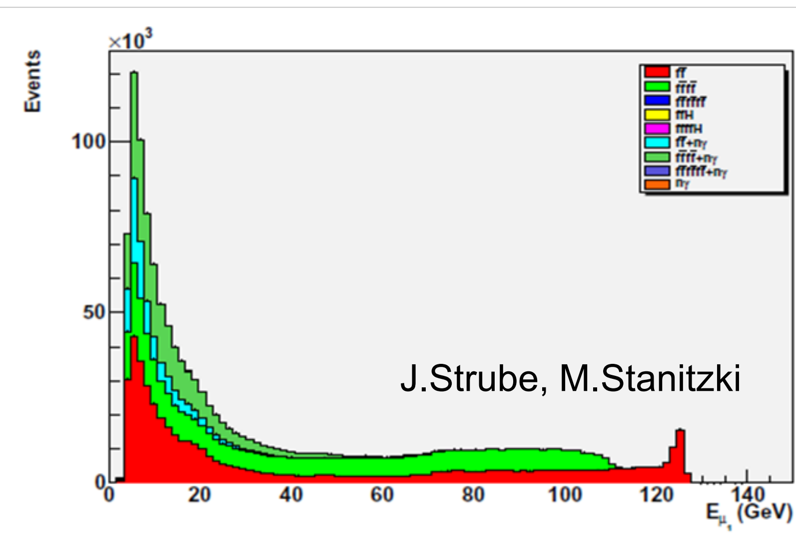
Hadronic channel: signature μμqq

Main selections:

- Force two jets, $y_{min} > 0.05$
- Number of charged tracks > 5
- Visible E > 140 GeV
- Jet energy and momentum selections
- Muon isolation and angular selections
- Di-muon mass compatible with Higgs mass 120 ± 20 GeV



Signal $E_{\mu 1}$, GeV



SM bkg $E_{\mu 1}$, GeV

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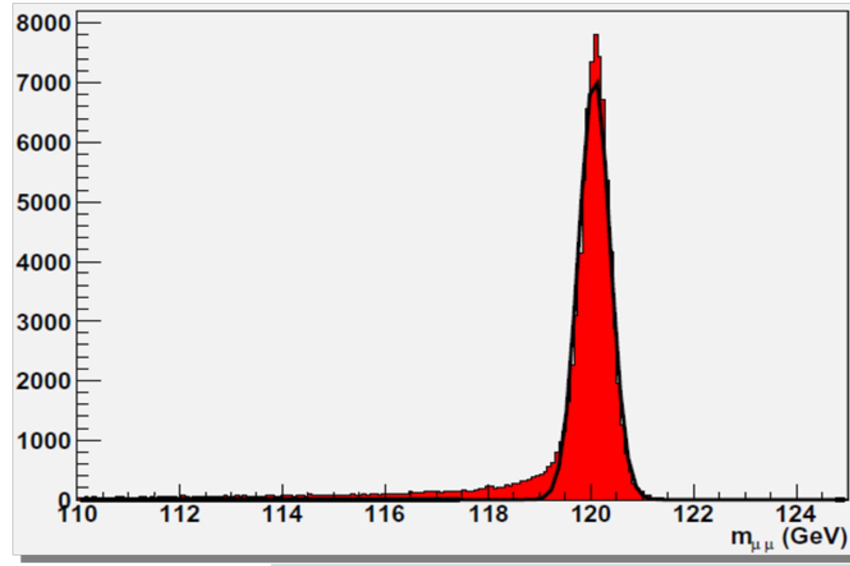
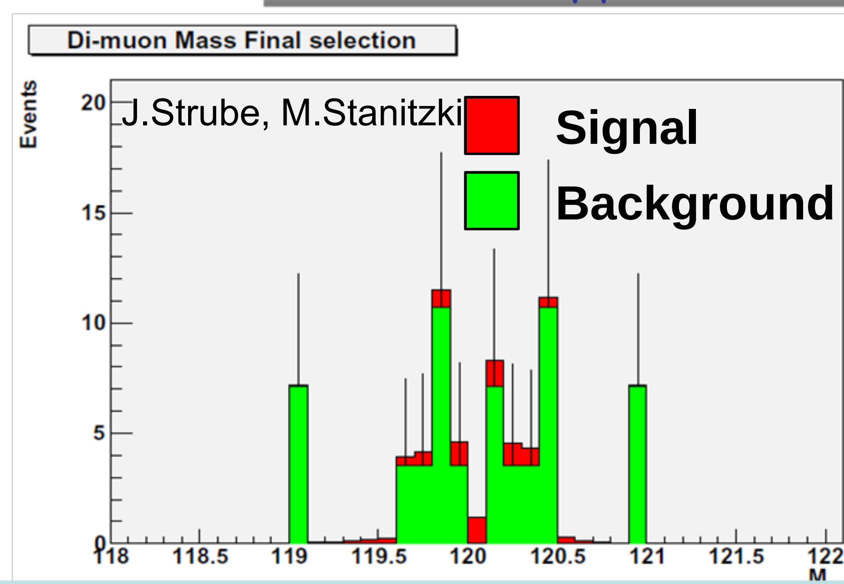
Higgs→μμ (3)

- Higgs mass resolution
  - 120.07 ± 0.30 GeV
- Di-jet mass resolution
  - 90.8 ± 7.6 GeV
- Main background: ZZ
- Construct chi2 to test ZH and ZZ hypothesis
  - Used for final selection
- Results
  - 7.7 signal events
  - 39.3 bkg events
  - Cross section
    - 0.074 ± 0.066 fb
- Expect considerable improvement with a NN approach, promising results with FastMC



Signal $M_{\mu\mu}$, GeV



Final selections: $M_{\mu\mu}$, GeV

Tau Production

$$e^+e^- \to \tau^+\tau^- \ , \ \sqrt{s}{=}500 \text{ GeV}$$

- Tau ID is a challenge for Tracker and calorimeter
  - π^0 reconstruction
- Used five tau decay modes to validate tau ID and measure cross section, asymmetry and polarization
  - Re-optimized PFA for tau objects
  - π^0 defined as a pair of photons with inv mass [0.06 – 0.18 GeV]
  - Two passes to account for merged π^0 photons

decay mode	# γ	# π^0	EPcut	other criteria
$e^-\bar{\nu}_e\nu_\tau$	0	0	-	HCAL energy $< 4\%$ of track energy.
$\mu^-\bar{\nu}_\mu\nu_\tau$	0	0	-	identified as μ by PFA
$\pi^-\nu_\tau$	0	0	2.5	-
$\rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau$	1	0	2.2	$0.6 \text{ GeV} < M_\rho < 0.937 \text{ GeV}, \quad E_\gamma > 10 \text{ GeV}$
$\rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau$	2	1	2.2	$0.4 \text{ GeV} < M_\rho < 0.93 \text{ GeV}$
$a_1^-\nu_\tau \to \pi^-\pi^0\pi^0\nu_\tau$	3	1	2.2	$0.8 \text{ GeV} < M_{a_1} < 1.5 \text{ GeV}, \quad E_\gamma > 10 \text{ GeV}$
$a_1^-\nu_\tau \to \pi^-\pi^0\pi^0\nu_\tau$	4	2	2.2	$0.8 \text{ GeV} < M_{a_1} < 1.5 \text{ GeV}$
$a_1^-\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$	0	0	2.5	$0.8 \text{ GeV} < M_{a_1} < 1.7 \text{ GeV}$

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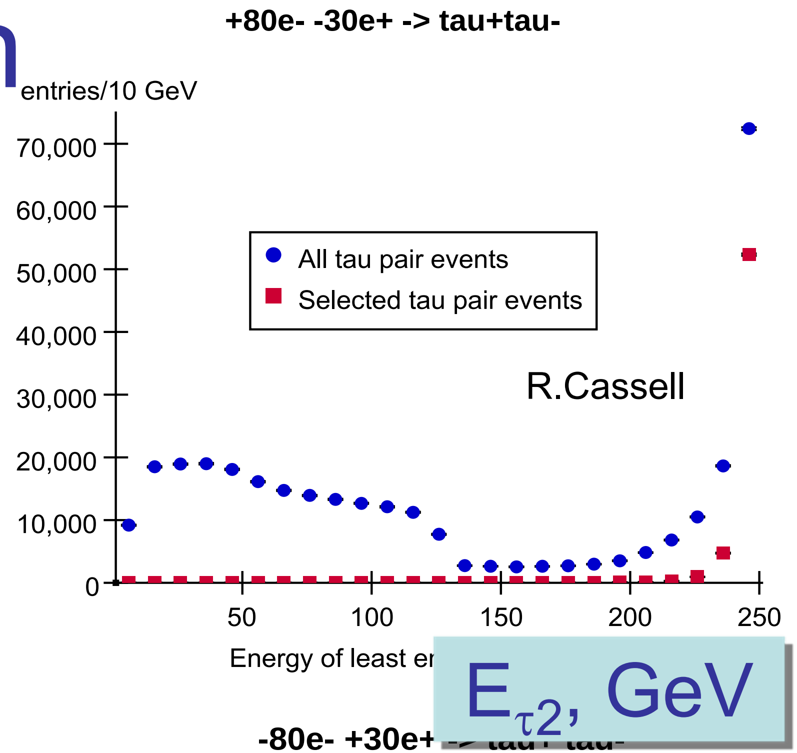
Tau Cross Section

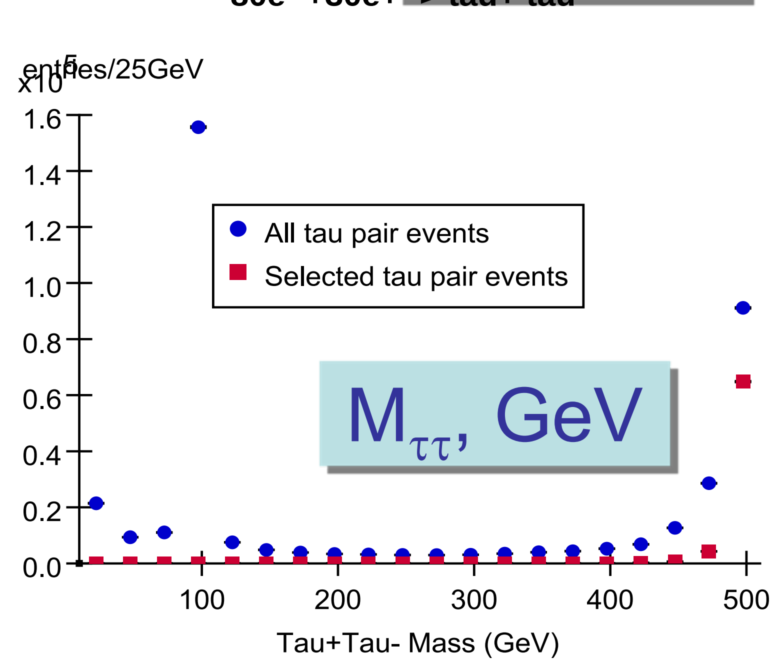
- Main selections for tau events:
  - Forced to two jets
  - Total # tracks <7
  - 40 < Visible E < 450 GeV
  - Veto if electrons or muons
  - Angle between jets > 178°
- Efficiency 17.9%
  - Clean tau sample for cross section measurement
- Cross section fit to

$$d\sigma/d\cos\theta \propto 1 + \cos\theta^2 + 8/3 \cdot A_{FB}$$

Precision ± 0.28%

$$A_{FB} = 0.4704 \pm 0.0024$$





Tau Polarization

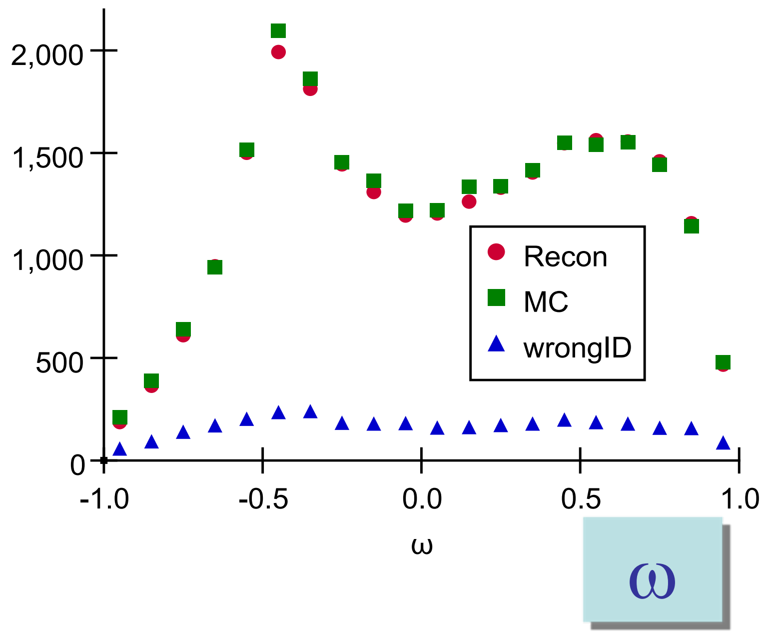
- Sensitive to new physics, for example multi-TeV Z'
  - Relies on tau ID and good 4-vector reconstruction
- Consider all but a_1 decay modes
- Achieved high efficiency and good purity
  - SM bkg below 2%

decay mode	Correct ID	Wrong ID	ID eff	ID purity	SM bgnd
$e^- \bar{\nu_e} \nu_\tau$	39602	920	0.991	0.977	1703
$\mu^- \bar{\nu_\mu} \nu_\tau$	39561	439	0.993	0.989	1436
$\pi^- \nu_\tau$	28876	2612	0.933	0.917	516
$\rho^- \nu_\tau \rightarrow \pi^- \pi^0 \nu_\tau$	55931	8094	0.790	0.874	1054
$a_1^- \nu_\tau \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	18259	11140	0.732	0.621	847
$a_1^- \nu_\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	21579	2275	0.914	0.905	141

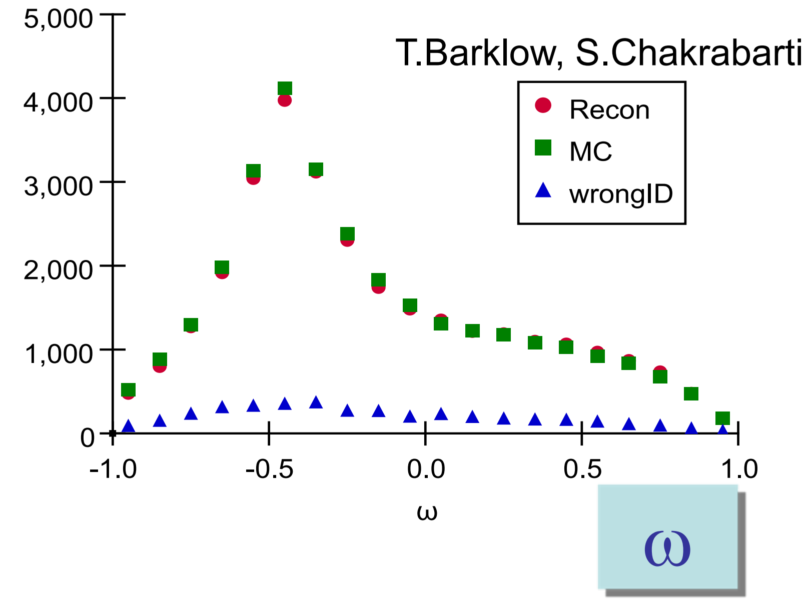
Tau Polarization

- Use optimal observable ω
  - For e or π decays: $\omega = E_e/E_{beam}$
  - For ρ decays: ω is a complicated function of ρ and π angles in τ and ρ rest frames
- Estimate the polarization using linear least squares fit of ω distribution
  - Dependence of ω on the polarization is obtained from an independent sample

80eR tau -> rho nu



80eL tau -> rho nu



$$< P_\tau > = -0.611 \pm 0.009 \text{ stat.} \pm 0.005 \text{ sys.}$$

$$< P_\tau > = 0.501 \pm 0.010 \text{ stat.} \pm 0.006 \text{ sys}$$

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Top Quark Properties

$$e^+e^- \to t\bar{t}\,,\ \ t \to bW^+\,,\ \ W^+ \to q\bar{q}'\,,\ \ \sqrt{s}=\mathbf{500\ GeV}$$

- Consider only hadronic decay mode:
  - Six jet final state
- Main selections

	selection	value
	E_{total}	> 400 GeV
	$\log(y_{min})$	> -8.5
	number of particles in event	> 80
	number of tracks in event	> 30
50 GeV <	W mass	< 110 GeV
	NN_{b-tag} output for the most b-like jet	> 0.9
	NN_{b-tag} output for the 2^{nd} most b-like jet	> 0.4
	Sum of NN_{b-tag} outputs for all jets	> 1.5

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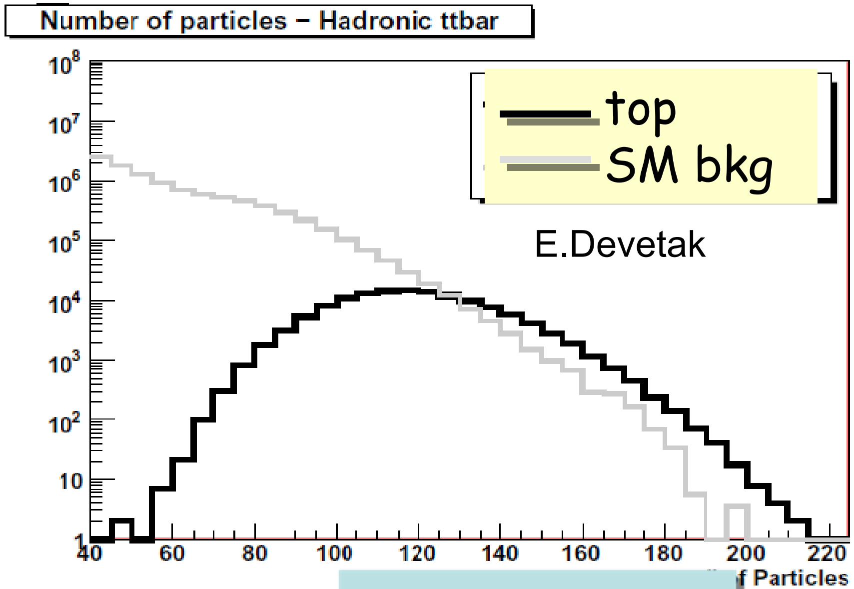
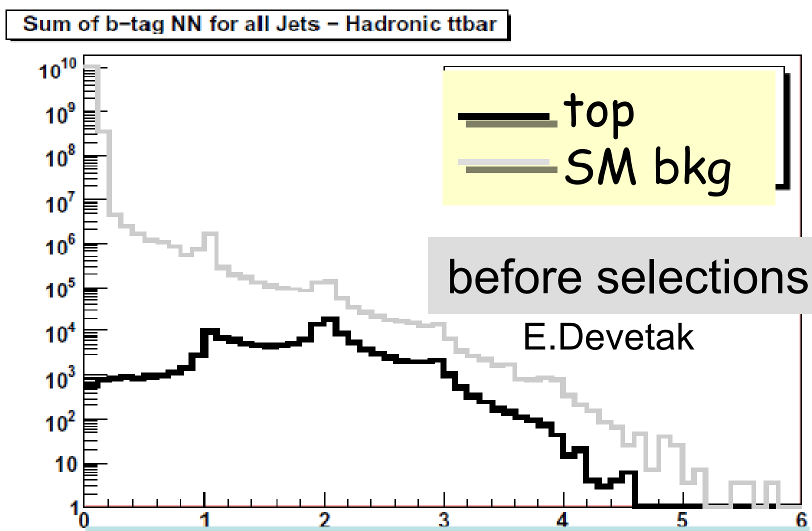
Top Mass Selections

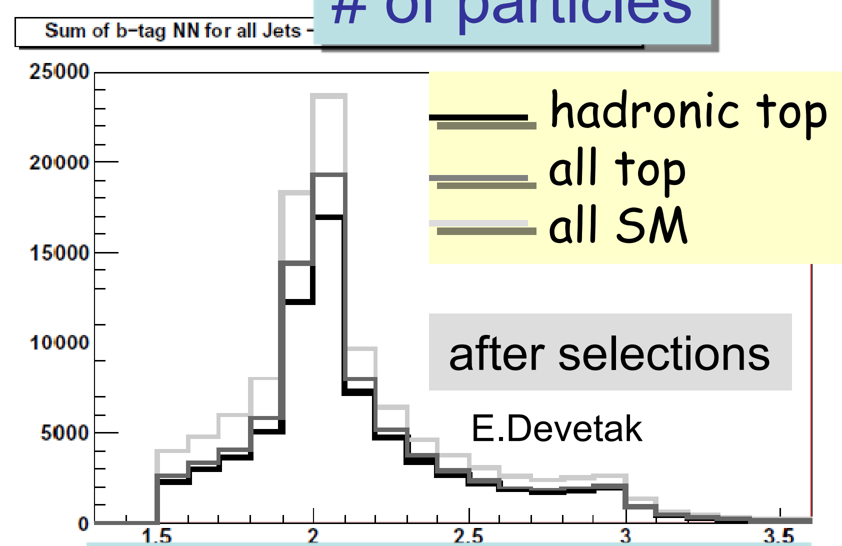
- B-tagging is important
  - Powerful discriminant
  - Reduce jet combinatorics
- After all selections:
  - Efficiency 31%, purity 85%



# of particles



Sum of b-tags for all jets



Sum of b-tags for all jets

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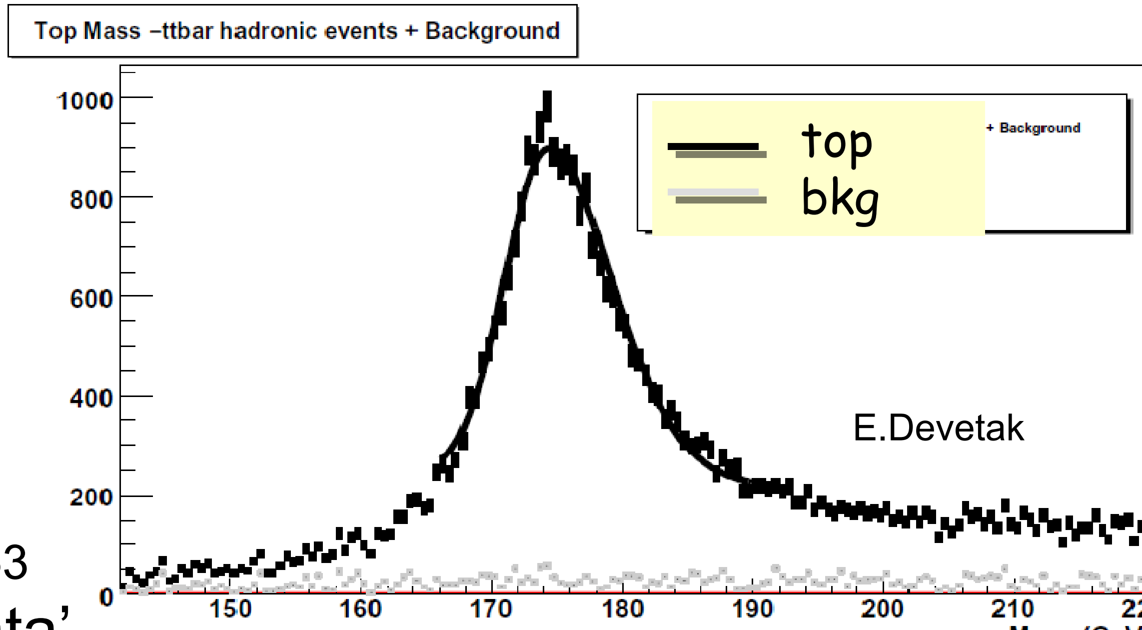
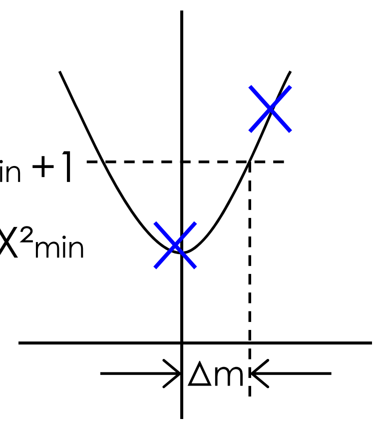
Top Mass



6 jet invariant mass, GeV

- Used kinematic fitter
  - Constraints: E_{CM}, M_W, $M_{top1} = M_{top2}$
- Two methods to determine m_{top}
  - Curve fitting
    - G1+G2+BW+P2
    - M_{top} = 173.918   0.053
- Template method: 'Data' compared to two template samples with M_{top} shifted by 0.5 GeV
  - Calculate χ^2
  - χ^2/NDF ≈ 1 for same M_{top}

$$\chi_1^2 = \sum_{i=0}^{Nbins} \frac{(y_{template1,i} - y_{data,i} + \delta_i)^2}{\sigma^2_{template1,i} + \sigma^2_{data,i} + \sigma^2_{SM,i}}$$



□ χ^2 + 1 used to estimate δM_{top} 0.038 GeV

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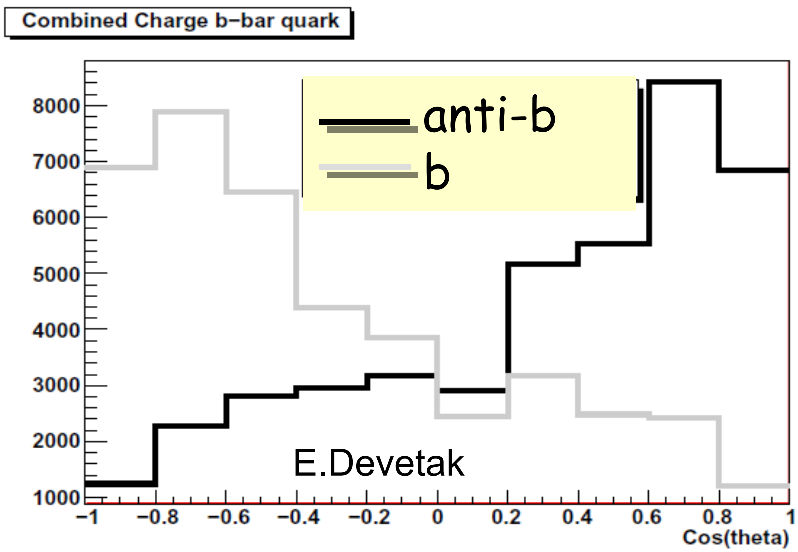
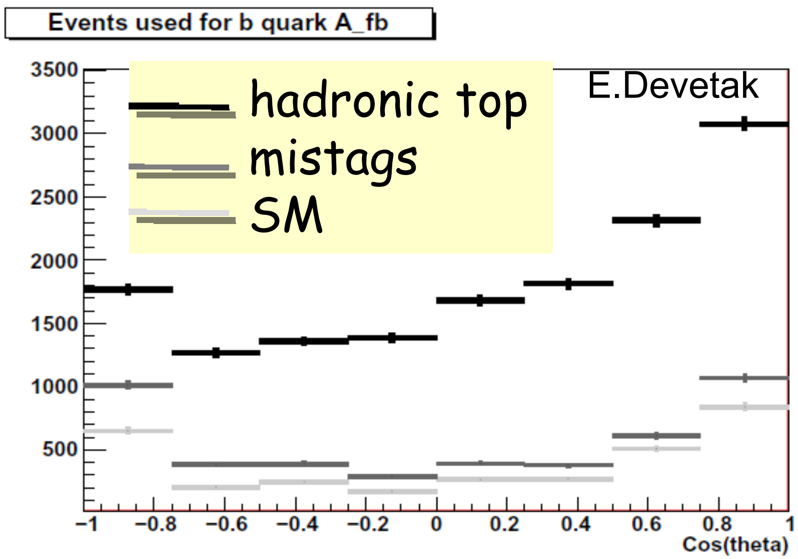
Top Forward-Backward Asymmetry

- Top anomalous coupling are sensitive to BSM physics
- Used combined discriminant sensitive to quark charge
  - Momentum weighted vertex and jet charges
- Plot cos Θ dependence, calculate A_{FB} for b- and t-quarks
  - t-quark requires correct pairing of b and W
  - Sensitive to performance of forward detectors, bins with extreme cos Θ have large SM bkg



b-quark charge discriminant



cos Θ dependence

$$A^b_{FB} = 0.272 \pm 0.015 \qquad A^t_{FB} = 0.342 \pm 0.015$$

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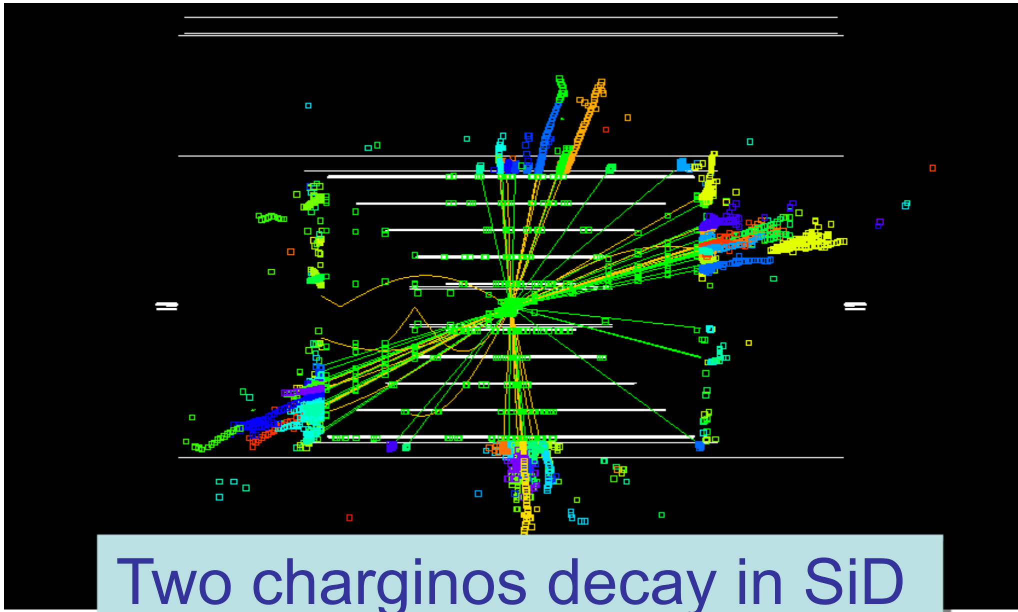
SUSY: Chargino/Neutralino

Select a particular SUSY model:

- Chargino/neutralino predominantly decay into on-shell W/Z
- W/Z energy distribution depends on the parent and LSP mass

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 q\bar{q}q\bar{q}$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 Z^0 Z^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 q\bar{q}q\bar{q}$$

- Signature:
  4 jets + missing energy
  - WW / ZZ separation
    tests PFA performance



Two charginos decay in SiD

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Chargino/Neutralino Selections

Main selections:

- Force 4 jets
- Apply cuts:

cut	value
E_{jet}	> 10 GeV
Fraction of EM energy in each jet	$< 80\%$
Number of tracks	> 20
Total visible energy	< 250 GeV
Thrust	< 0.85
$\cos\theta_{thrust}$	< 0.9
$\theta(1, 2)$	$> 60°$
$\theta(1, 3)$, $\theta(1, 4)$, $\theta(1, 3)$	$> 40°$
$\theta(2, 4)$, $\theta(3, 4)$	$> 20°$
Acoplanarity of two reconstructed gauge bosons	$> 10°$

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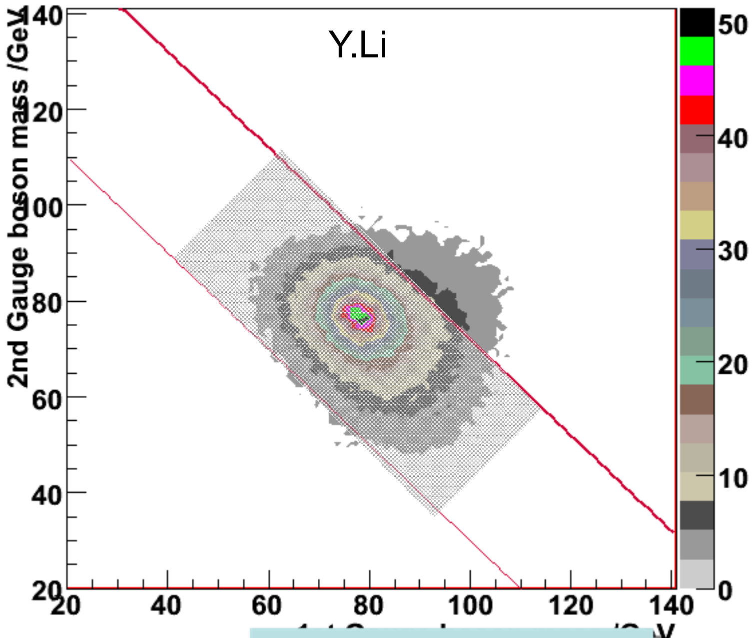
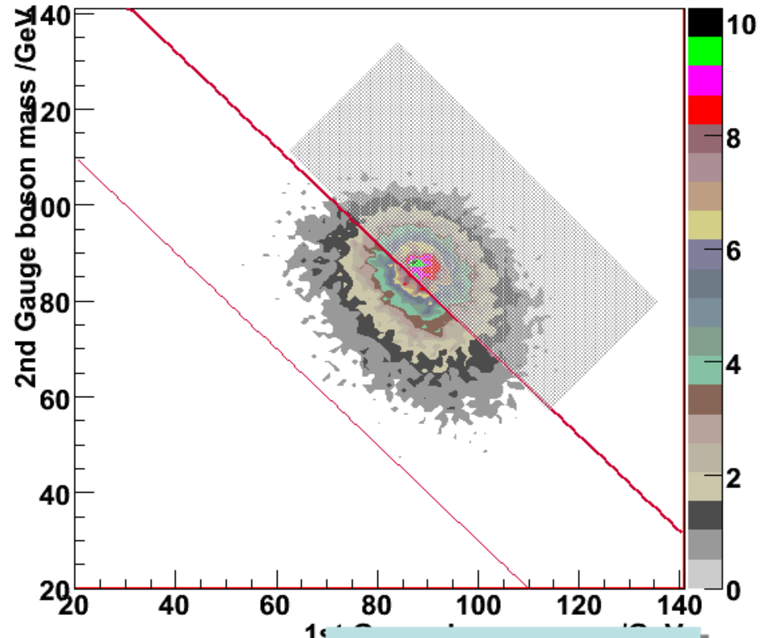
Chargino/Neutralino Separation

- Kinematic fitting to improve energy and mass resolution
- Correlation of two m_V is a powerful selection criteria
  - C1 xsection is x10 N2 xsection



m_{W1} vs m_{W2}



m_{Z1} vs m_{Z2}

Chargino events signal

130 GeV < M(W1) + M (W2) < 172 GeV

Neutralino events signal

M(Z1) + M (Z2) > 172 GeV

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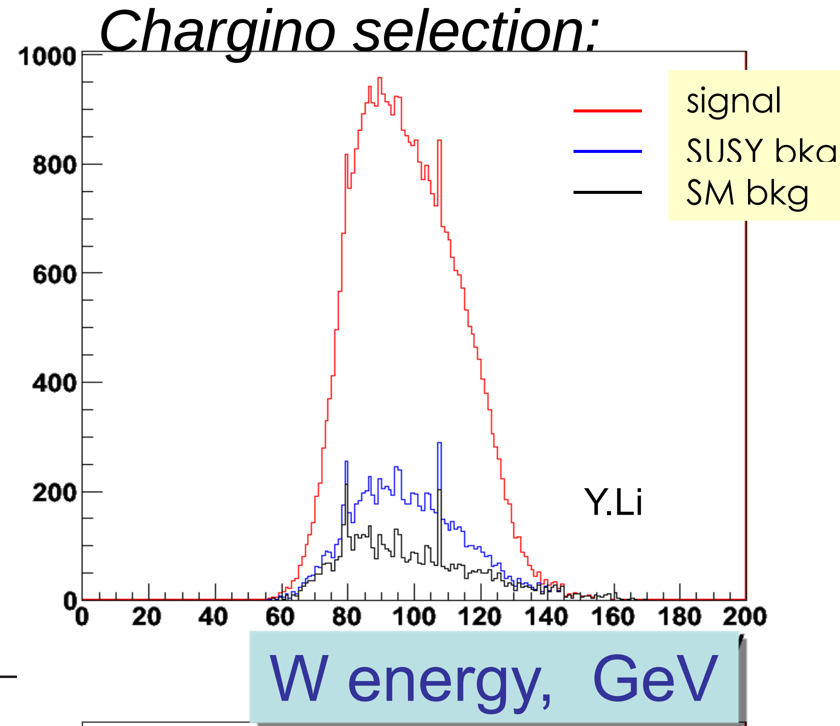
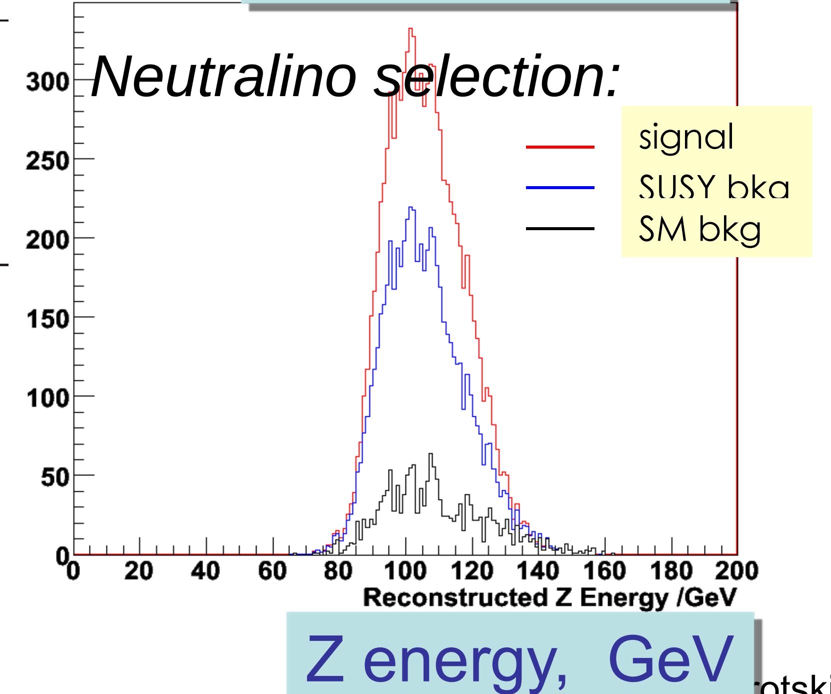
C1/N2 Samples

- Purity
  - Chargino 75%
  - Neutralino2 34%
- Generated several template samples to determine masses

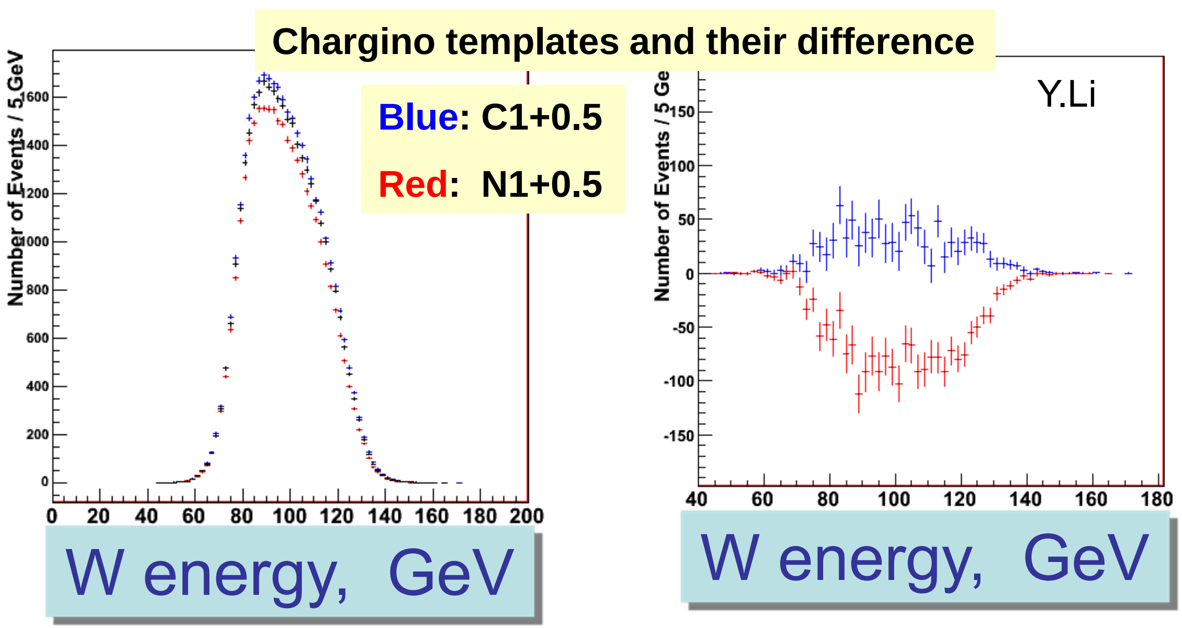
sample	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\chi}_2^0}$ (GeV)
Reference	115.7	216.7	216.5
$m_{\tilde{\chi}_1^0} + 0.5$	116.2	216.7	216.5
$m_{\tilde{\chi}_1^\pm} + 0.5$	115.7	217.2	216.5
$m_{\tilde{\chi}_2^0} + 0.5$	115.7	216.7	217.0





C1/N2 Mass Determination

- ‘Data’ compared to template samples
- $\chi^2 + 1$ used to estimate mass uncertainty :
  - C1 95 MeV
  - N2 369 MeV



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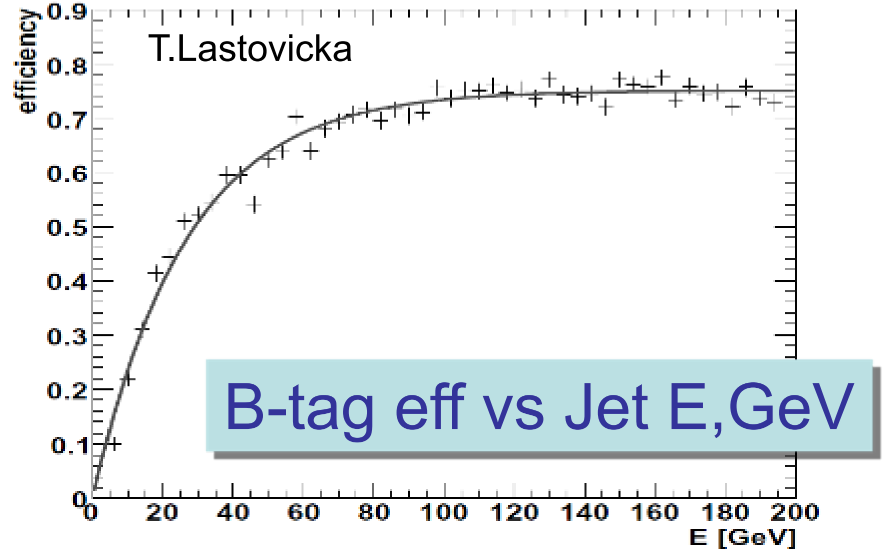
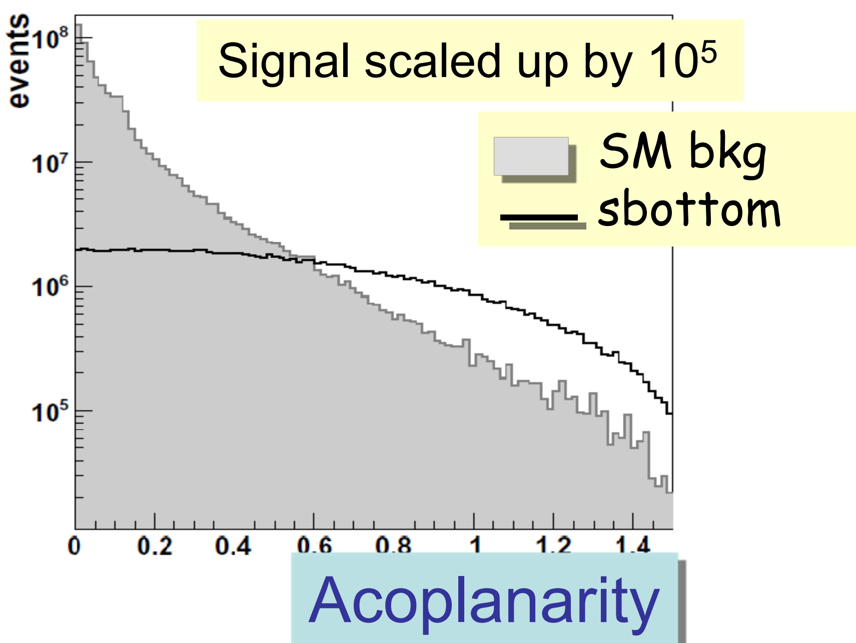
Sbottom Production

- Cosmology motivated SUSY predicts small mass split between LSP and NLSP
  - Small visible energy in the detector
  - Assume NLSP is sbottom
  - Two b-jets + MET
  - Jet clustering and b-tagging are challenging for low energy jets

- Huge jj$\gamma\gamma$ and jjγ backgrounds
  - Need to use forward calorimeter for rejection





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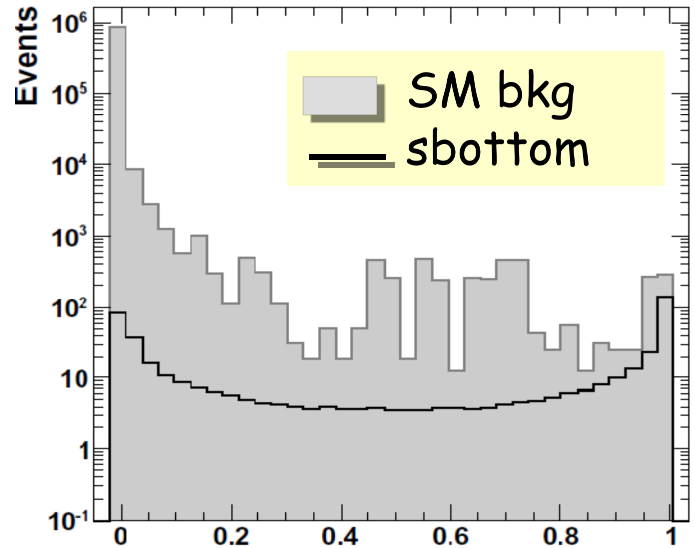
Sbottom Production

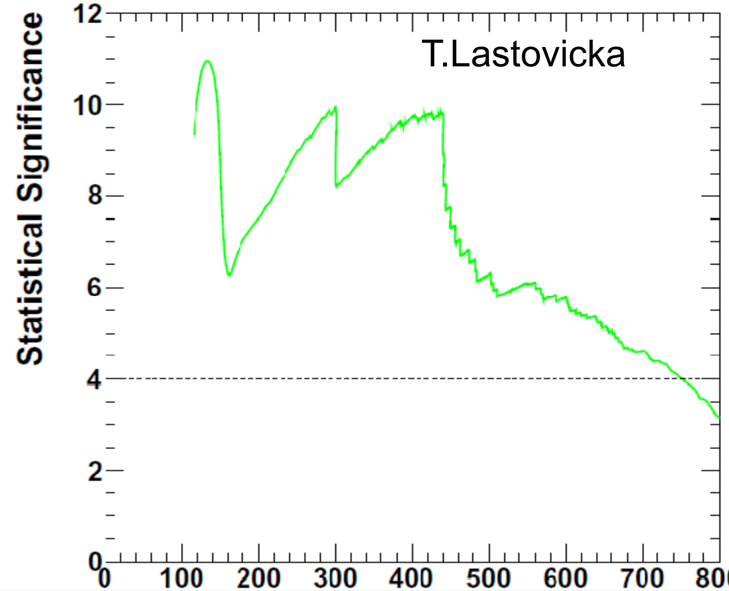
- Main selections
  - Visible energy < 80 GeV
  - Number of particle
  - Forward EM veto, acceptance 10 mrad, E > 300 MeV
- Main discriminating variables combined in NN, also adding
  - Acoplanarity
  - Maximum pseudorapidity
  - ΔR
- Results
  - 15% Cross section measurement for

$$m_{\tilde{b}} = 230\,\mathrm{GeV}\ \mathrm{and}\ m_{\tilde{\chi}_1^0} = 210\,\mathrm{GeV}$$

  - Sensitive to sbottom-neutralino mass difference down to 10 GeV



NN output



Significance vs # signal events

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Comments and Remaining Issues

- Analysis techniques are as important as properties of detectors
- Pleased to see little difference between fast and full simulations for one of the most difficult channels, top → 6 jets
- Focussed on compulsory LoI channels. Many analyses were limited by available time, resources and effort.
  - Some analyses could not be fully completed on this time scale; ex ZHH: have results but need more time to understand them
- Started but not finished studies of effects of beam beam background on
  - b-tagging studies: no effect if up to 10 BCs integrated in VD but need to add a point with 100 BCs
  - top mass measurement with 1 BC of beam-beam background
- Plan improvements for several analyses

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Summary

- Benchmarking analyses were key new ingredients of the SiD Letter of Intent
- We performed seven analyses using full simulation and reconstruction
- Big effort to process all data and obtain results with very limited time and resources. Many thanks to all involved for long hours and heroism!
- Pleased to see good results in all cases, insignificant deterioration due to realistic material description and realistic reconstruction algorithms

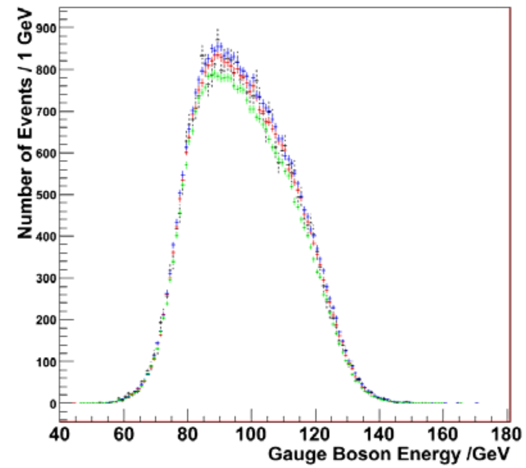
- Will need to finalize several things

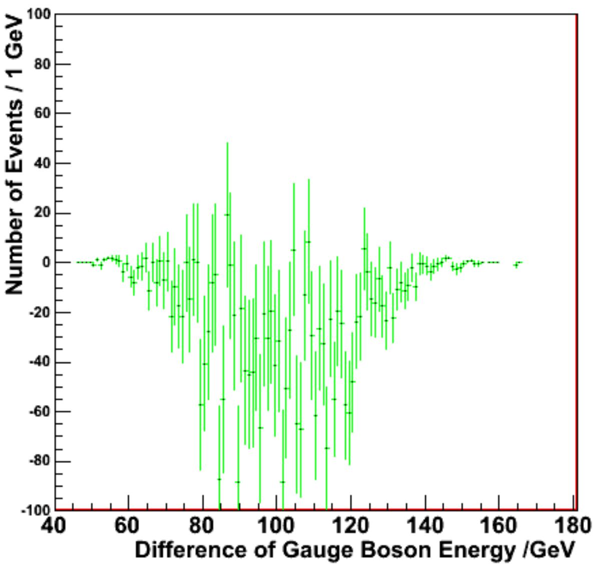
- Ready to move forward

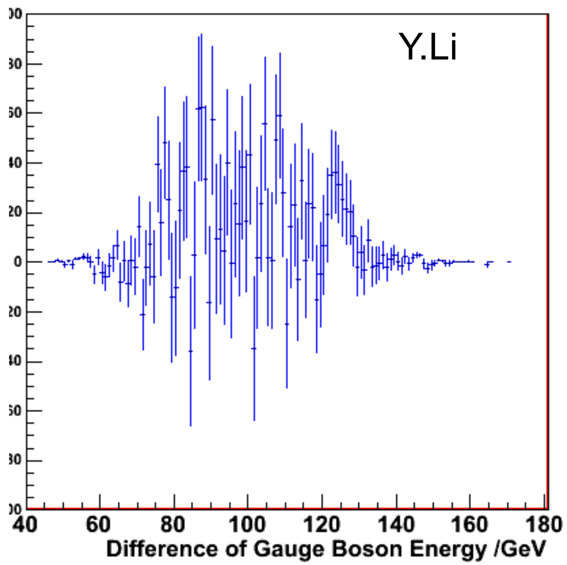
Backups

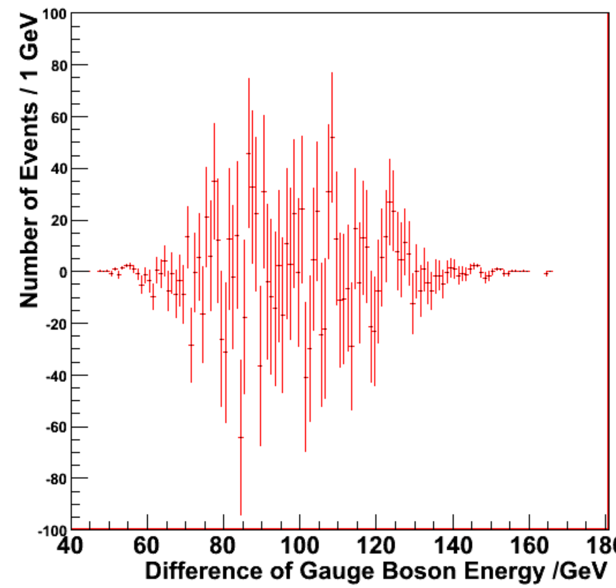
SUSY Mass Templates

- Templates have different SUSY masses
- Difference between ‘Data’ and templates









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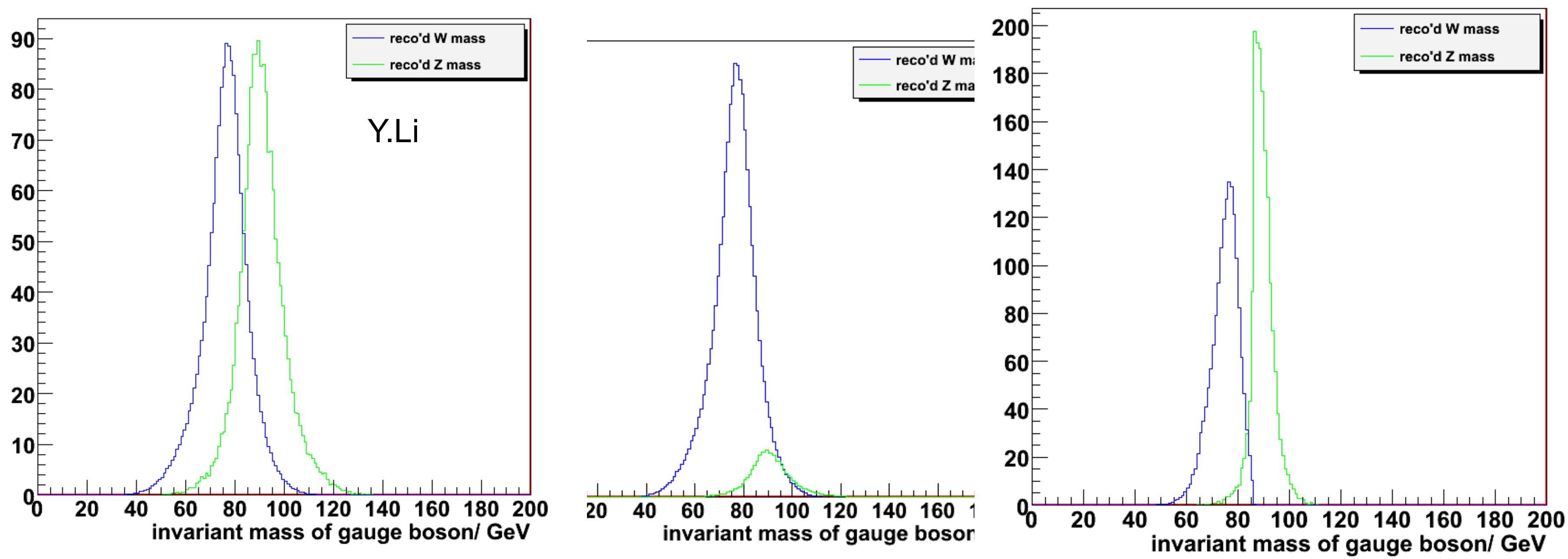
Di-jet Mass Resolution

- For SUSY analysis
- Resolution
  - ~8 GeV before KinFit
  - ~4 GeV after KinFit



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