Top pair production at the ILC

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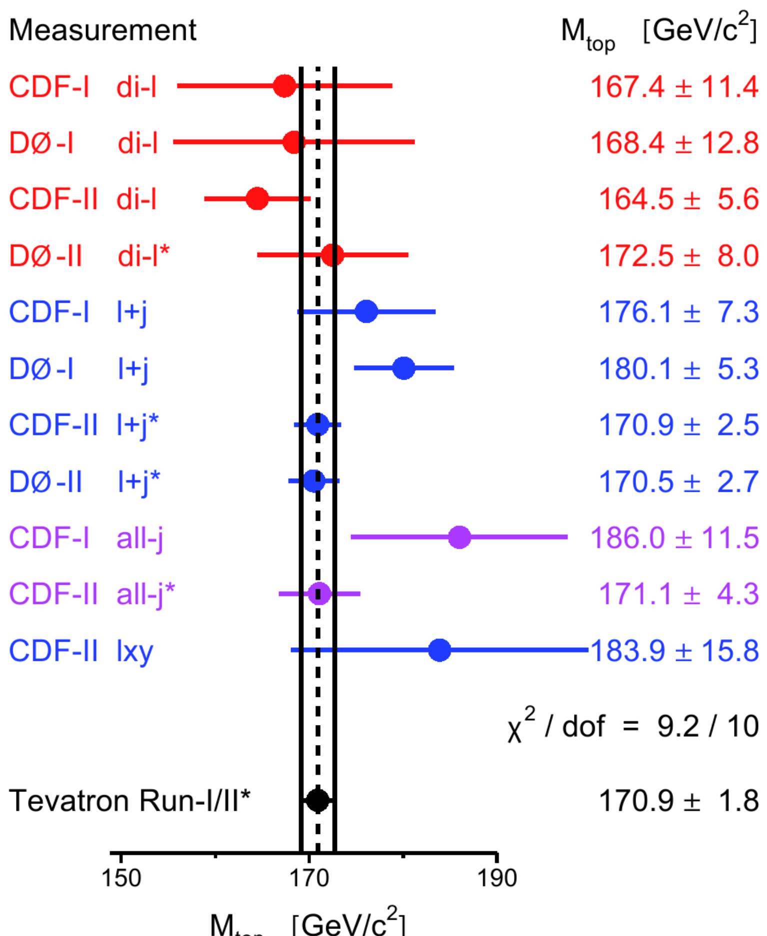
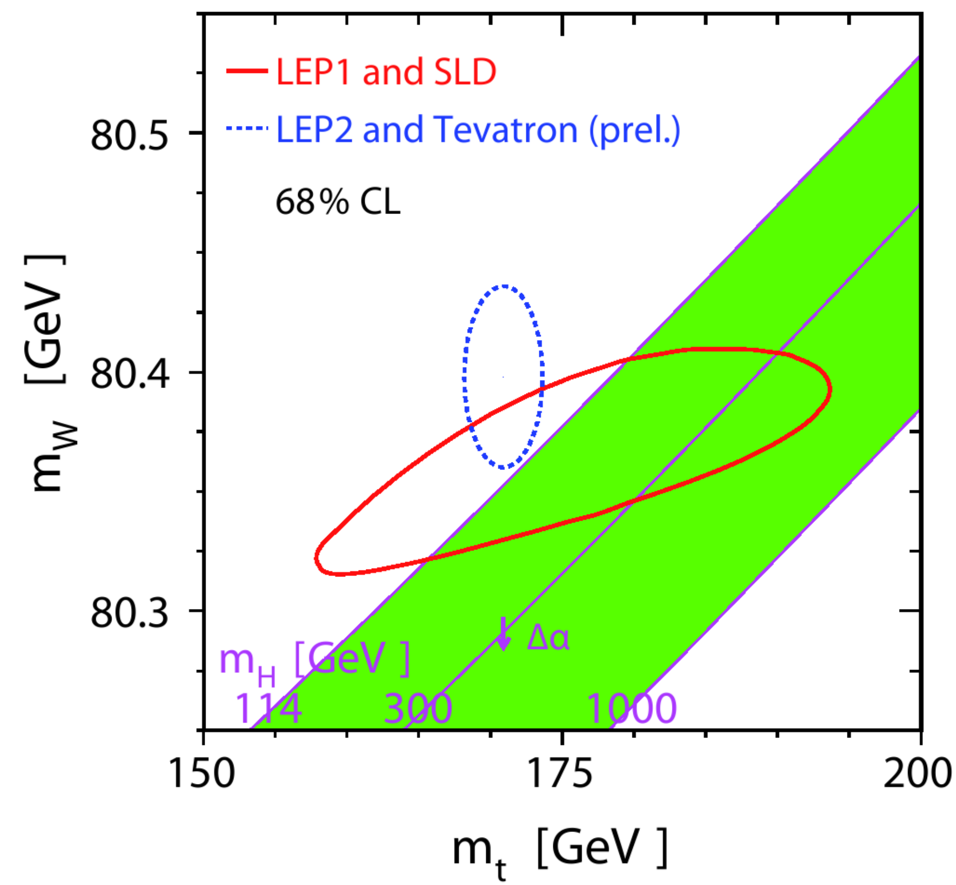
Why precise measurement of top invariant mass (m_t) ?

- m_t is free parameter of the Standard Model
- Electroweak observables including m_t depend on m_H $\sim \log(m_H^2)$

➡ m_t sets mass constraint on mass of **Higgs** particle

World average top mass:
$m_t = 170.9 \pm 1.8\, GeV$





Pictures taken from Stefan Kasselmann

Why $t\bar{t}$ production analysis for ILC ?

- calculate accuracy for top mass measurement at ILC
- $t\bar{t}$ benchmark reaction for detector optimization
- tuning and validation of the reconstruction software

LHC:

$int.\,luminosity = 1\,fb^{-1}(startup\,of\,LHC)$

$\delta m_t(stat.) \approx 1\,GeV\,(220\,MeV\,for\,20\mathrm{fb}^{-1})$

$\delta m_t(syst.) \approx 3\,GeV$

ILC:

$int.\,luminosity = 20\,fb^{-1}$

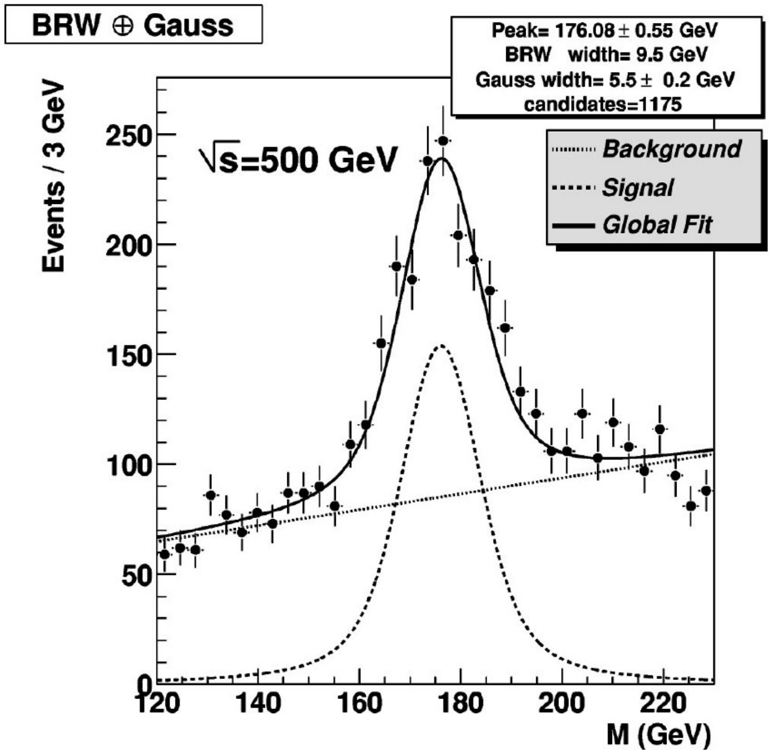
$\delta m_t(stat.) \approx\ ?$

Goal: estimate statistical error on m_t and width for ILC from direct reconstruction of t decays

The method used in this Analysis provides the consistency check and is complementary to the threshold scan technique.

S.V. Chekanov, V.L. Morgunov *Phys. Rev*. D 67, 074011 (2003)

- Detector simulation using Brahms (Fortran)
- Reconstruction optimized for TESLA design
- btag information not used
- no kinematic fits



$$int. luminosity = 16\, fb^{-1}$$
$$\delta m_t (stat.) \approx \;380\, MeV \; for \sqrt{s} = 500\, GeV$$

In the meantime detector design considerably changed.

⇒ *Revision of the analysis needed.*

Tools used in this analysis:

Mokka – flexible geant4 based detector simulation framework

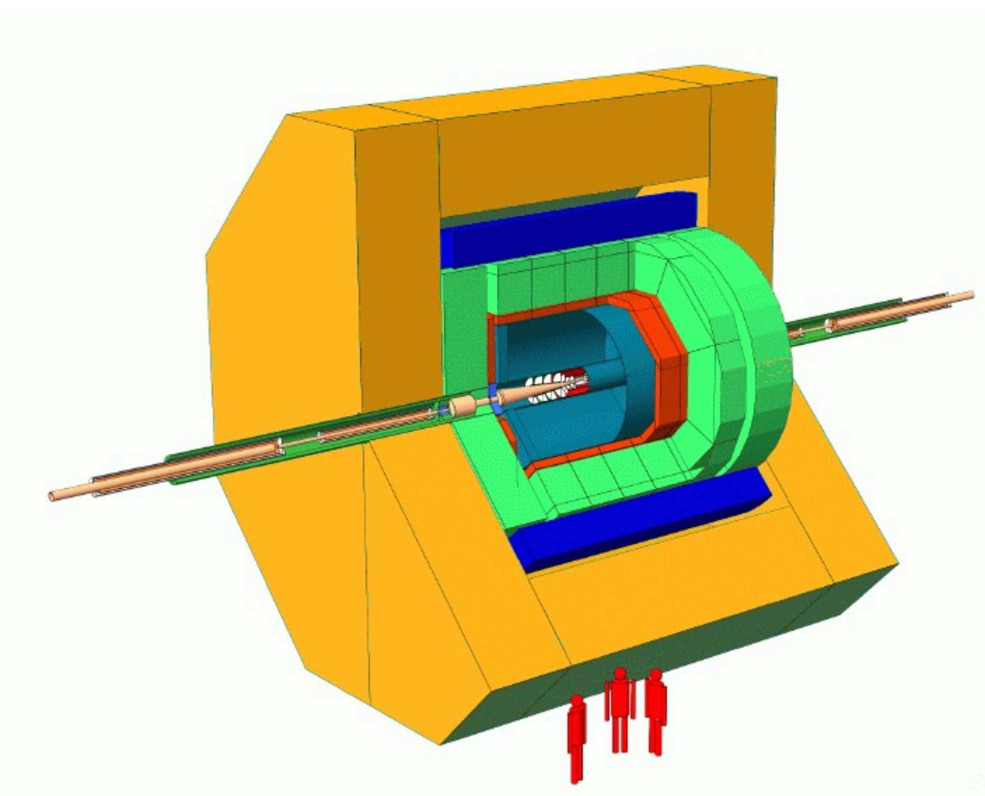
Marlin – modular and detector independent reconstruction software

- btag information from LCFIVertex package used
- kinematic fitting applied

Mokka: geant4 based framework for full detector simulation

Detector used for simulation with Mokka: **LDCPrime_02Sc_p01**

⇨ Interpolation between the two detector concepts GLD and LDC



Magnetic field: 3.5 T

Tracking:

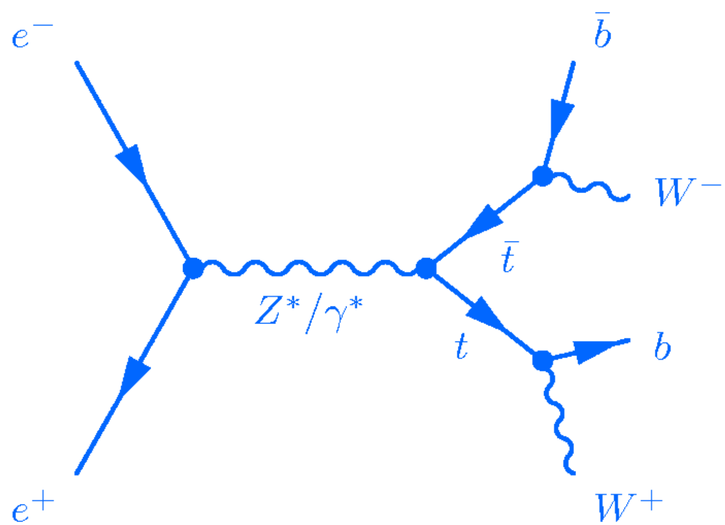
- *VTX* $(inner\ radius = 1.5\,cm)$
- *TPC* $(R = 1.7\,m, L = 4.4\,m)$
- *FTD* *(acceptance down to 7 degrees in polar angle)*

High granularity calorimeters:

- *ECAL* $W - Si, 23\,\chi_o, 1x1\,cm^2$
- *HCAL* $Iron - Scintillator, \sim 4\text{-}6\,\lambda, 3x3\,cm^2$

Studies done for center of mass energy of 500 GeV

500 GeV is the nominal energy for the first phase of ILC running (bulk of luminosity).



<table>
<tr><td rowspan="3" colspan="3">$t\bar{t} \to (W^+b)(W^-\bar{b})$</td><td colspan="9">$W^+ \to$</td></tr>
<tr><td rowspan="2">$e^+\nu_e$</td><td rowspan="2">$\mu^+\nu_\mu$</td><td rowspan="2">$\tau^+\nu_\tau$</td><td>$u\bar{d}$</td><td>$u\bar{d}$</td><td>$u\bar{d}$</td><td>$c\bar{s}$</td><td>$c\bar{s}$</td><td>$c\bar{s}$</td></tr>
<tr><td>$(r\bar{r})$</td><td>$(g\bar{g})$</td><td>$(b\bar{b})$</td><td>$(r\bar{r})$</td><td>$(g\bar{g})$</td><td>$(b\bar{b})$</td></tr>
<tr><td rowspan="9">$W^- \to$</td><td>$e^-\bar{\nu}_e$</td><td></td><td rowspan="3" colspan="3">9/81</td><td rowspan="3" colspan="6">18/81</td></tr>
<tr><td>$\mu^-\bar{\nu}_\mu$</td><td></td></tr>
<tr><td>$\tau^-\bar{\nu}_\tau$</td><td></td></tr>
<tr><td>$\bar{u}d$</td><td>$(r\bar{r})$</td><td rowspan="6" colspan="3">18/81</td><td rowspan="6" colspan="6">36/81</td></tr>
<tr><td>$\bar{u}d$</td><td>$(g\bar{g})$</td></tr>
<tr><td>$\bar{u}d$</td><td>$(b\bar{b})$</td></tr>
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<tr><td>$\bar{c}s$</td><td>$(b\bar{b})$</td></tr>
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$t\bar{t}$ decay mode used:

$$t\bar{t} \to (W^+b)(W^-\bar{b})$$

$$W^+W^- \to q\bar{q}q\bar{q} \qquad (\textit{fully hadronic})$$
$$W^+W^- \to q\bar{q}l\nu \qquad (\textit{semileptonic})$$

$$int.\,luminosity = 20\,fb^{-1}$$
$$\sigma = 3.07 \cdot 10^2\,fb \quad (for\ \sqrt{s} = 500\,GeV)$$
$$\#_{events} = 6140$$

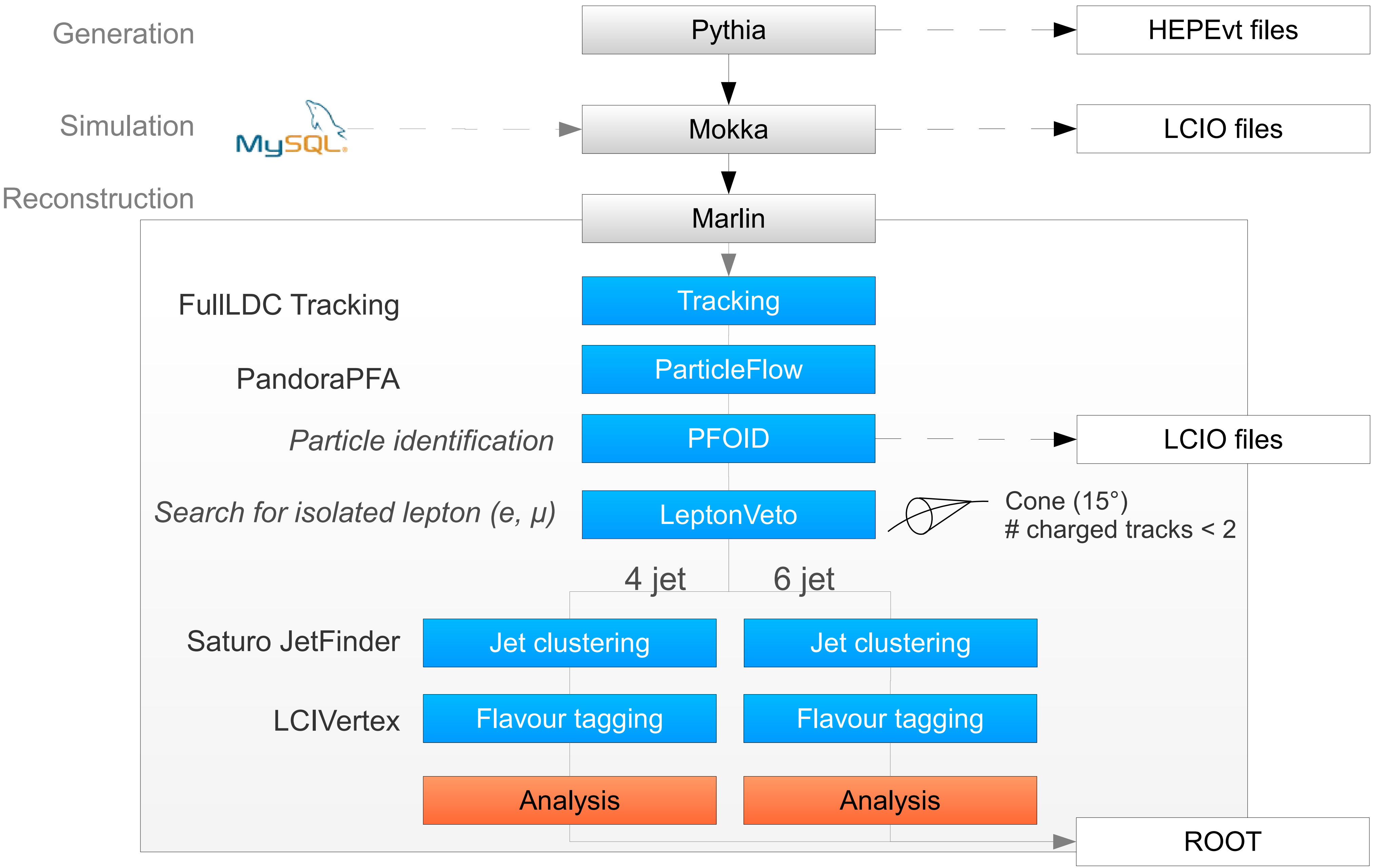
Values used in event production

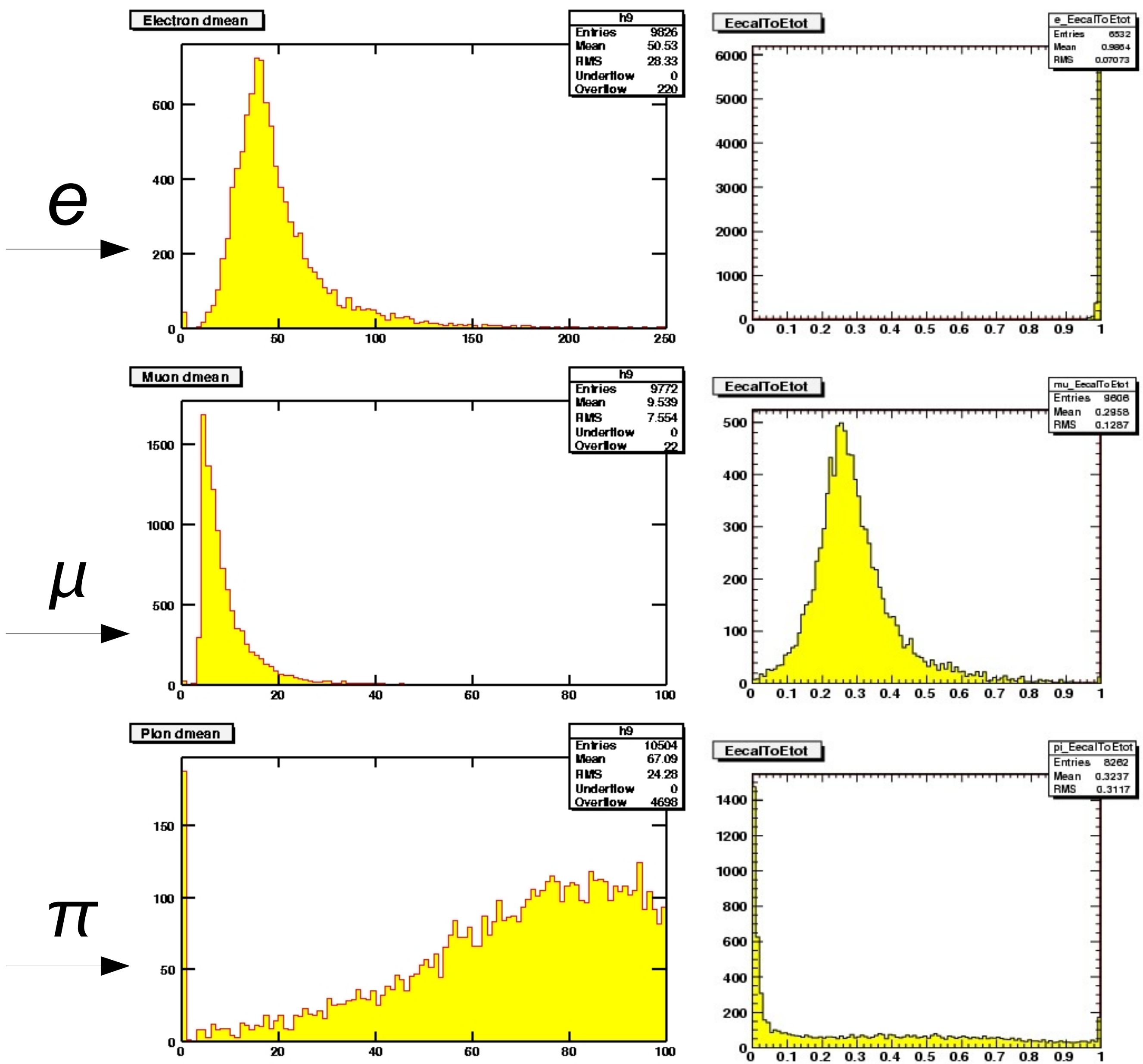
Picture taken from Stefan Kasselmann

Backgrounds were generated for $\sqrt{s}=500\,GeV$ and $int.luminosity=20\,fb^{-1}$

$e^+e^-\rightarrow WW\rightarrow q\bar{q}q\bar{q}$	$\sigma=4.15\cdot10^3\,fb$	$\#_{events}=\ 8.3\cdot10^4$	
$e^+e^-\rightarrow ZZ\rightarrow q\bar{q}q\bar{q}$	$\sigma=3.14\cdot10^2\,fb$	$\#_{events}=\ 6280$	
$e^+e^-\rightarrow Z/gamma\rightarrow q\bar{q}\ \ (+gluons)$	$\sigma=1.4\cdot10^4\,fb$	$\#_{events}=\ 2.8\cdot10^5$	*Cuts at the generator level to reduce the number of events:* $\#_{afterCuts}=\ 9080$
$e^+e^-\rightarrow WW\rightarrow q\bar{q}l\nu$	$\sigma=4.15\cdot10^3\,fb$	$\#_{events}=\ 8.3\cdot10^4$	
$e^+e^-\rightarrow ZZ\rightarrow q\bar{q}ll$	$\sigma=89\,fb$	$\#_{events}=\ 1794$	
$e^+e^-\rightarrow ZZ\rightarrow q\bar{q}\nu\nu$	$\sigma=1.79\cdot10^2\,fb$	$\#_{events}=\ 3588$	
$e^+e^-\rightarrow Ze^+e^-\rightarrow q\bar{q}e^+e^-$	$\sigma=4.13\cdot10^3\,fb$	$\#_{events}=\ 82600$	
$e^+e^-\rightarrow We\nu\rightarrow q\bar{q}e\nu$	$\sigma=4.26\cdot10^3\,fb$	$\#_{events}=\ 85200$	

It's all about the pipeline – Pythia, Mokka and Marlin





- Based solely on information from **calorimeter**
- Input: **pdf's** of the cluster shape variables, discriminating between **e**, **μ** and **π**
- Cluster shape variable pdf's ⇨ likelihood for the three **hypotheses**

  L(e) + L(μ) + L(π) = 1
- **Highest** likelihood defines particle ID

Discriminating variables x_i are combined into one **discriminant** (binned likelihood technique)

Final states are classified into **event classes** $(Signal, WW+ZZ, q\bar{q}(\gamma))$

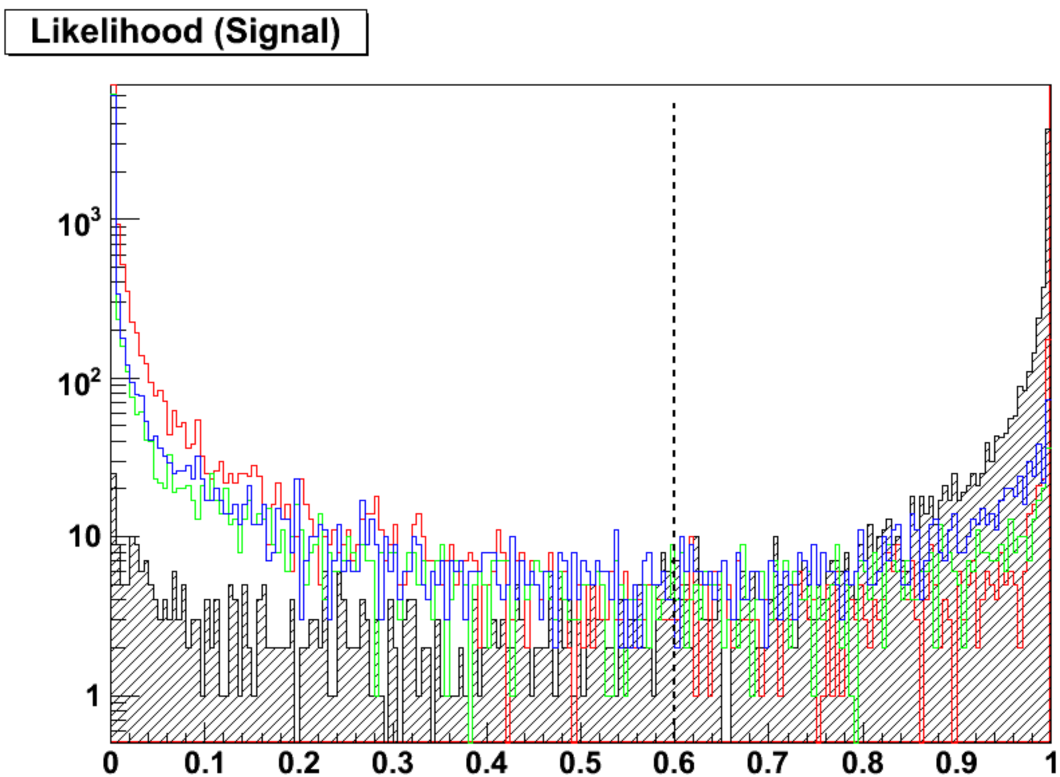
Each event class j consists of probability density functions $f^j(x_i)$

Probability of an event to belong to event class j:

$$p^j(x_i) = \frac{f^j(x_i)}{\sum_k f^k(x_i)}$$

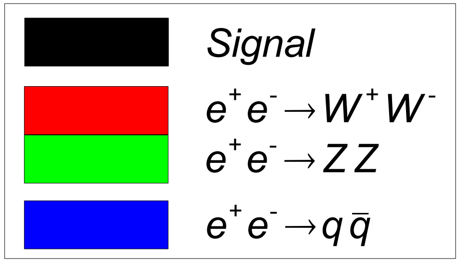
Individual probabilities are combined into a **likelihood L**.
The likelihood that an event belongs to signal class:

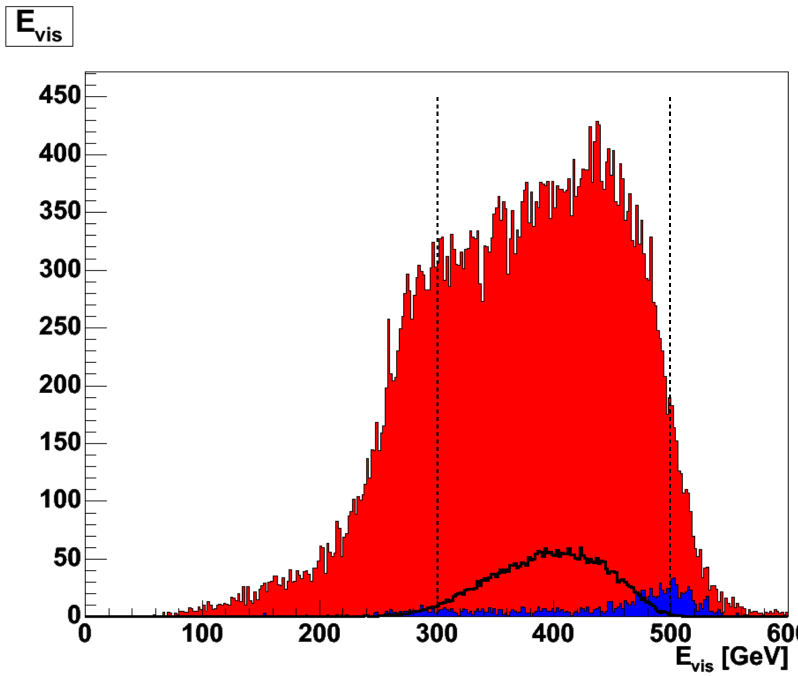
$$L_{Signal} = \frac{\prod_i p^{Signal}(x_i)}{\sum_k \prod_i p^k(x_i)}$$



Discriminating variables:

$btag_1, btag_2, y_{56}, m_W, \Delta m_{3j}, N_{Particles}$





Cuts used for selection of $t\bar{t}$ events:

$300.0\,GeV < E_{vis} < 500.0\,GeV$

$\log(y_{34}) > -3.0$ — *y_{ij} value for 4jets → 3jets*

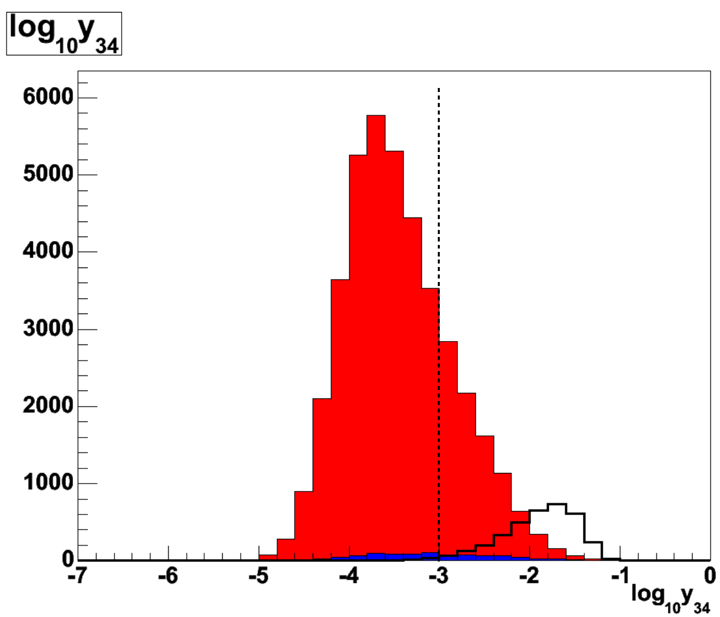
$m_W^{Leptonic} = 80.4 \pm 35\,GeV$

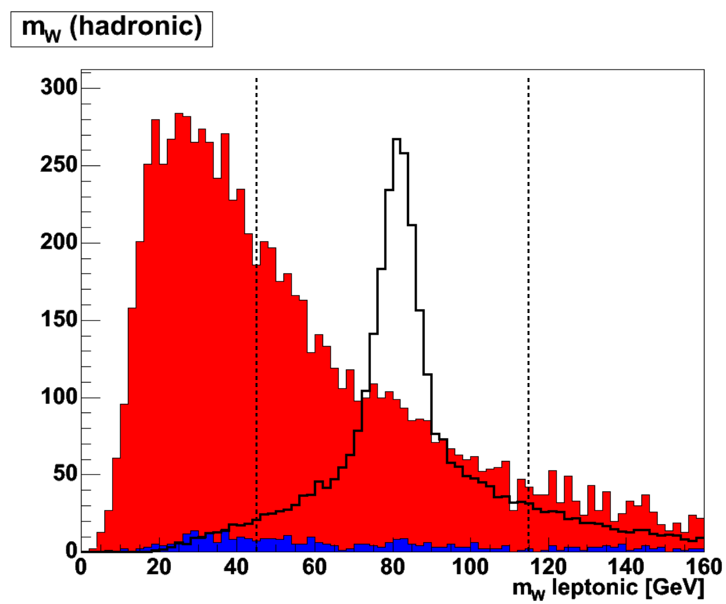
$m_W^{Hadronic} = 80.4 \pm 35\,GeV$

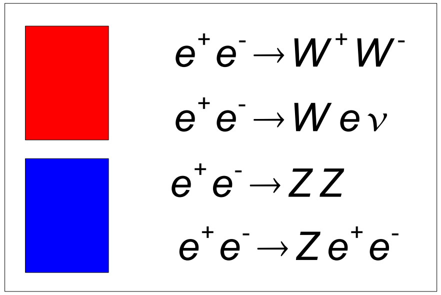
$bTag_{First} > 0.2$ — *highest bTag value*

$bTag_{Second} > 0.2$ — *second highest bTag value*

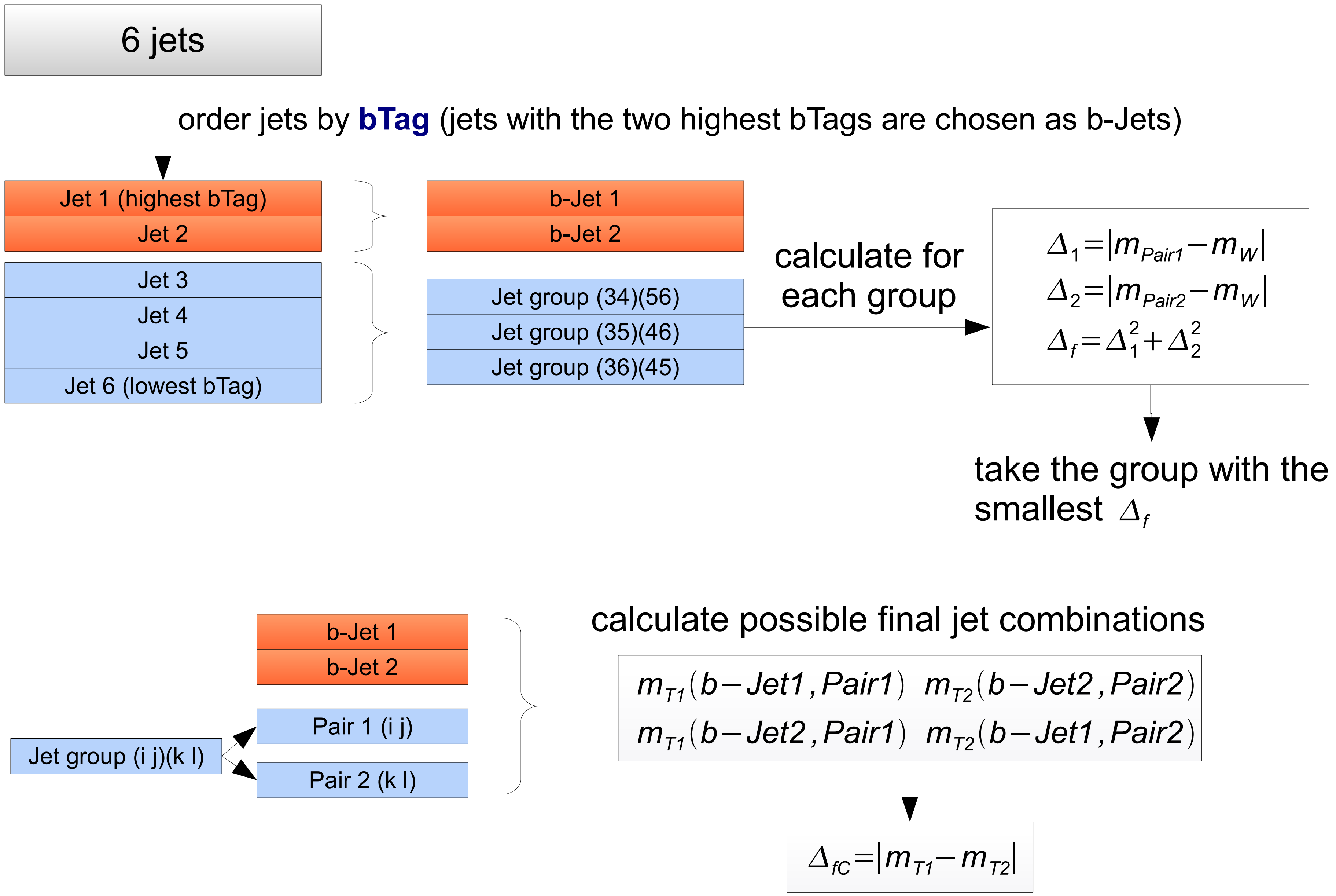
$\Delta m_{3j} < 40.0\,GeV$ — *mass difference tri – jets*







Finding the final jet combination – 6 jet



Take the Tri-Jet (b-Jet/Pair) combination with smallest Δ_{fC} as **final jet** state.

Finding the final jet combination – 4 jet

4 jets + lepton

order jets by **bTag** (jets with the two highest bTags are chosen as b-Jets)

- Jet 1 (highest bTag)
- Jet 2

→ b-Jet 1, b-Jet 2

- Jet 3
- Jet 4 (lowest bTag)

→ W (hadronic decay)

- Lepton
- Neutrino

calculate missing neutrino momentum from momentum conservation

$$\vec{p}_{Neutrino} = -\vec{p}_{b\text{-}Jet1} - \vec{p}_{b\text{-}Jet2} - \vec{p}_W - \vec{p}_{Lepton}$$

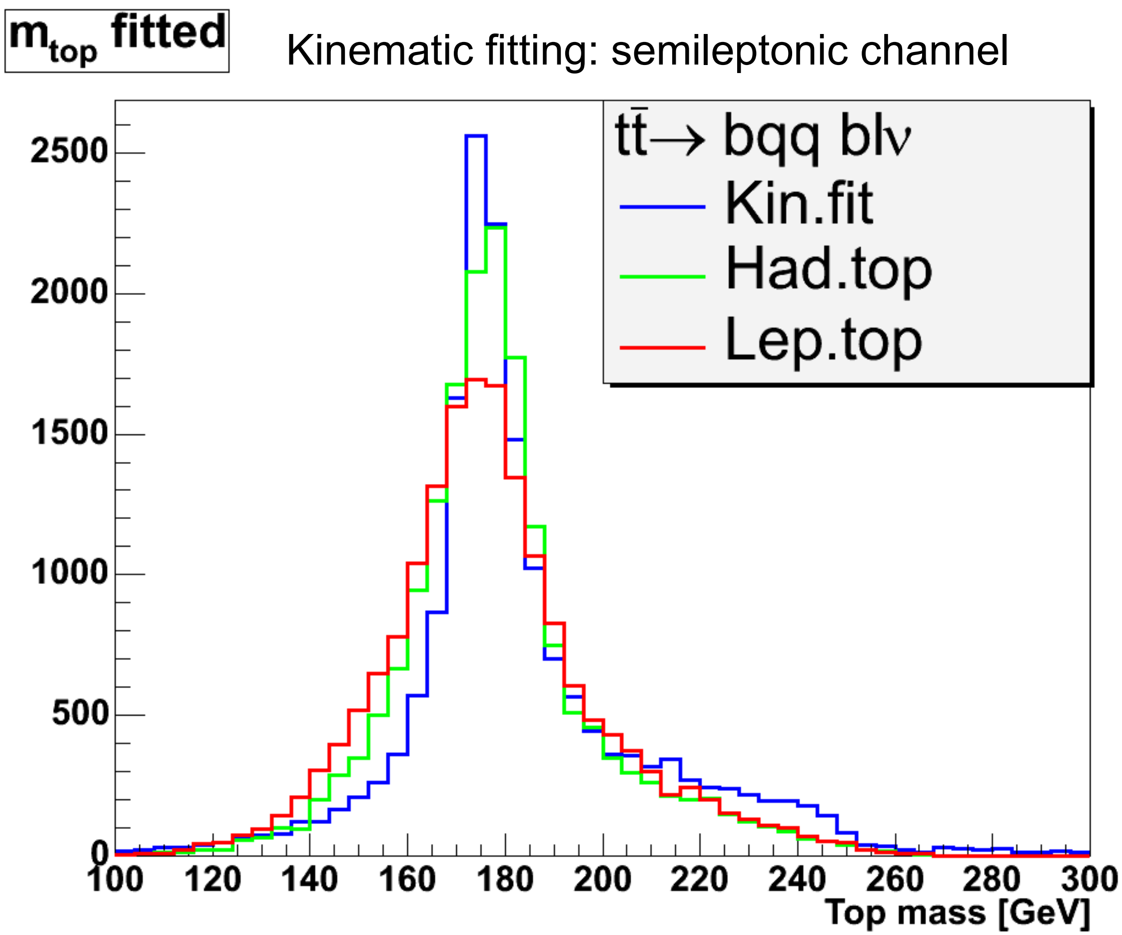
- b-Jet 1
- b-Jet 2
- Jet 3, Jet 4 → W (hadronic decay)
- Lepton, Neutrino → W (leptonic decay)

$$m_{T1}(b-Jet1, W_{Hadronic}) \quad m_{T2}(b-Jet2, W_{Leptonic})$$

$$m_{T1}(b-Jet2, W_{Hadronic}) \quad m_{T2}(b-Jet1, W_{Leptonic})$$

$$\Delta_{fC} = |m_{T1} - m_{T2}|$$

⇨ Take the combination with smallest Δ_{fC} as **final jet** state.



7 constraints were used for kinematic fitting:

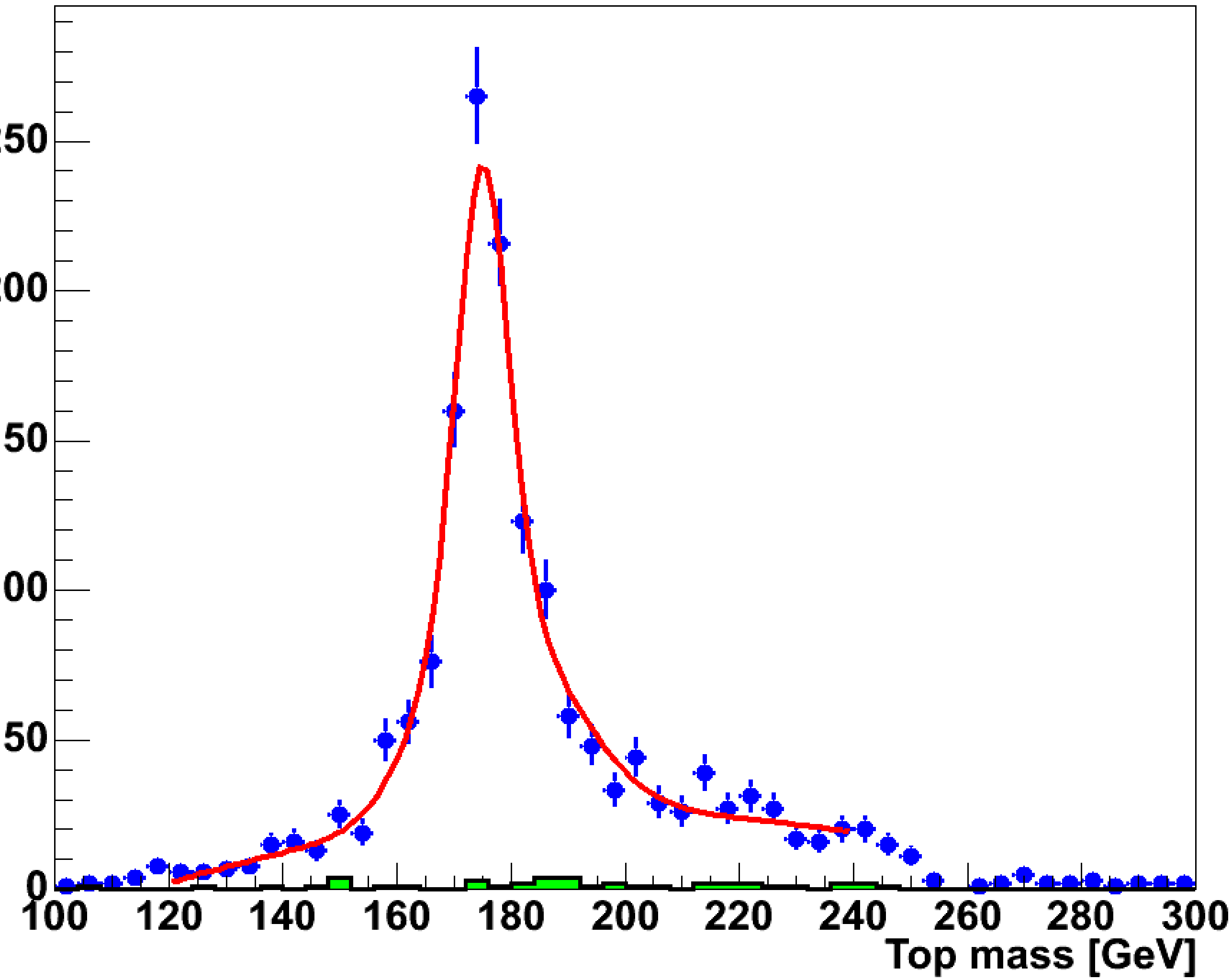
$$\sum_{i=1}^{6} \vec{p}_i = 0$$ *momentum conservation*

$$\sum_{i=1}^{6} E_i = \sqrt{s}$$ *energy conservation*

$$|m_{ij} - m_W| = 0$$
$$|m_{kl} - m_W| = 0$$ *mass difference W dijet and nominal W mass*

$$\Delta m_3 = 0$$ *same mass t and $\bar{t}$*

m_{top} fitted



$$L = 20\,fb^{-1}$$

$$\langle m_t \rangle \approx 174.93 \pm 0.27 \quad GeV$$

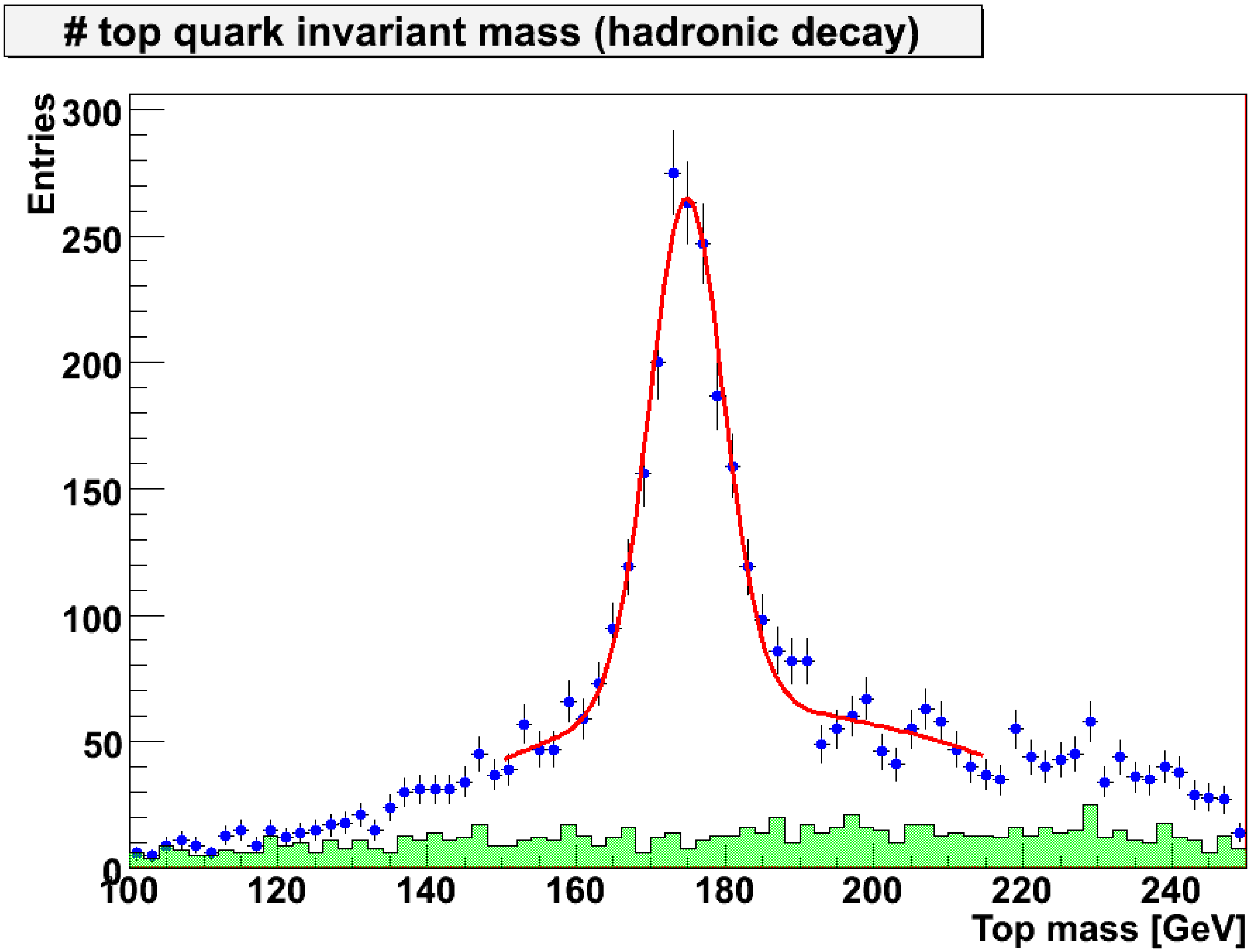
Selection efficiencies:

$W \rightarrow e\,\nu$ 37%

$W \rightarrow \mu\,\nu$ 41%

Fitting function: **Breit-Wigner** convoluted with the resolution function

Double Gaussian used as resolution function. Shape of the resolution function fixed.



$$L = 20\, fb^{-1}$$

$$\langle m_t \rangle \approx 175.07 \pm 0.21 \quad GeV$$

$$\Gamma = 1.6 \pm 0.13 \quad GeV$$

to improve quality, the typical CERN $e^+ e^-$ LEP **cuts** were applied

$$\left| \frac{E_{vis}}{\sqrt{s}} - 1 \right| < \Delta_E$$

$$\frac{\left| \sum \vec{p}_{\parallel i} \right|}{\sum \left| \vec{p}_i \right|} < \Delta_{PL}$$

$$\frac{\left| \sum \vec{p}_{Ti} \right|}{\sum \left| \vec{p}_i \right|} < \Delta_{PT}$$

Signal selection efficiency:	55.5 %	(cut based approach: 27.3 %)
Background rejection eff.:	99.1 %	

Invariant mass of top quark was reconstructed using

- full ILD detector simulation
- fully hadronic and semileptonic top quark channel and background
- complete reconstruction

Result (fully hadronic and semileptonic combined): $m_t = 175.02 \pm 0.16\,(stat.)\,GeV \quad (for\ 20\,fb^{-1})$

Extrapolated for higher luminosity: $m_t = 175.02 \pm 0.04\,(stat.)\,GeV \quad (for\ 300\,fb^{-1})$

Result by S.V. Chekanov and V.L. Morgunov: $m_t = 176.08 \pm 0.1\,(stat.)\,GeV \quad (for\ 300\,fb^{-1})$

Analysis will be used for detector optimization and performance studies and is supposed to be included in the Letter of Intent for the ILD detector.

Outlook:

Include additional background: $e^+e^- \rightarrow W\,W\,Z \rightarrow W\,W\,b\,\bar{b}$

⇨ Implementation of likelihood technique for semileptonic decay