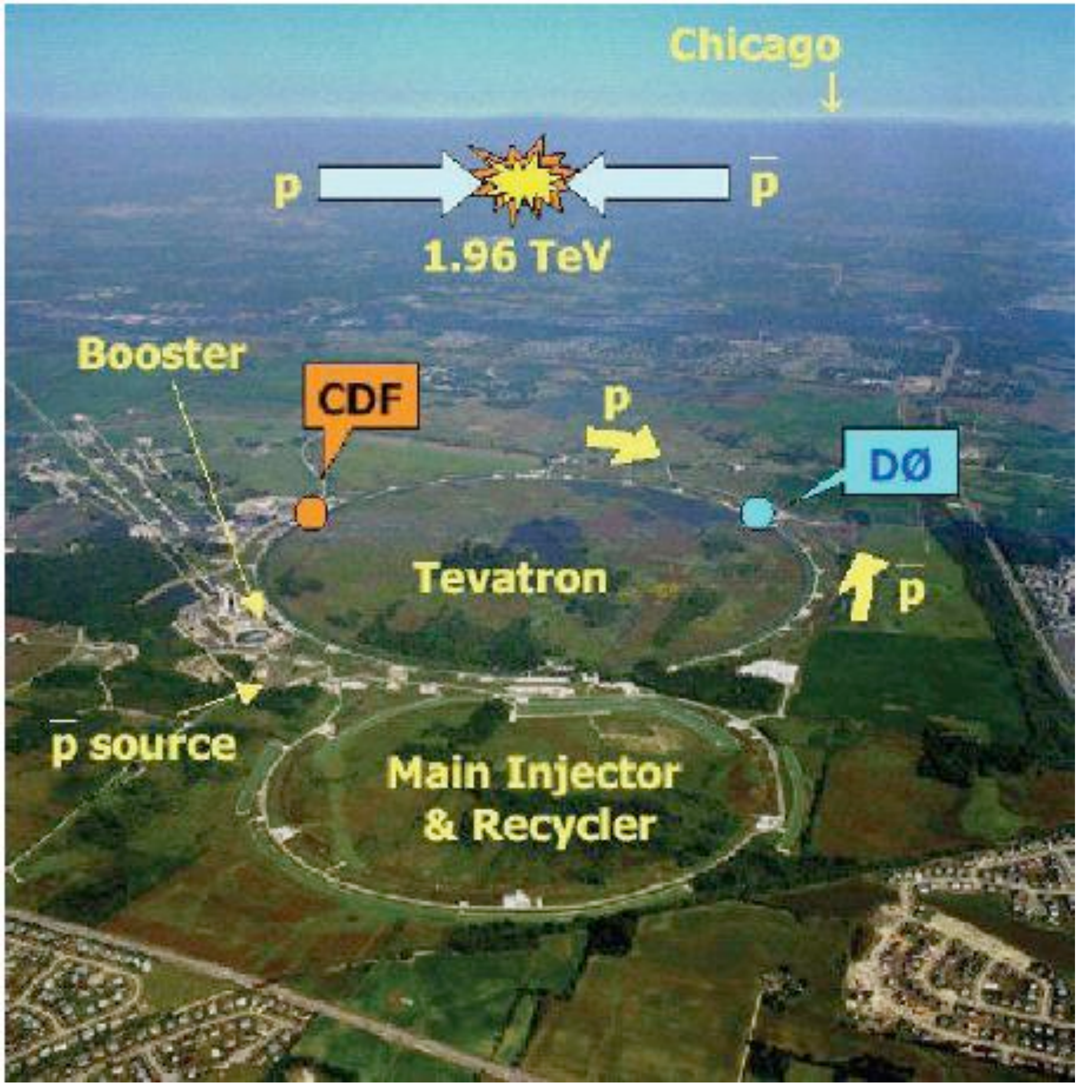
Higgs Searches at the Tevatron

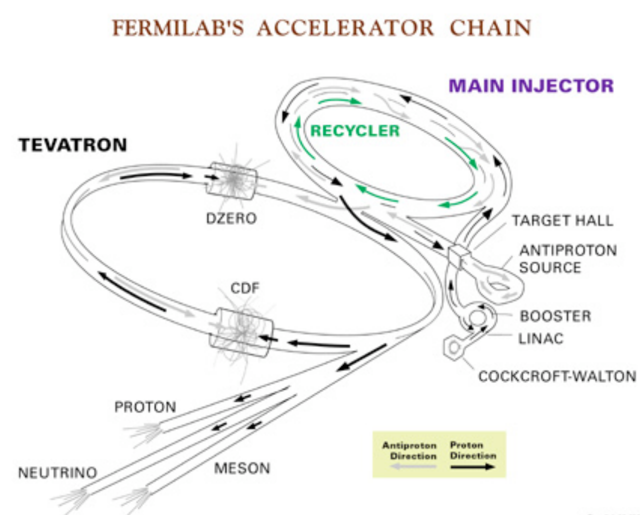
Venkat Kaushik

(Apr 18 2007)

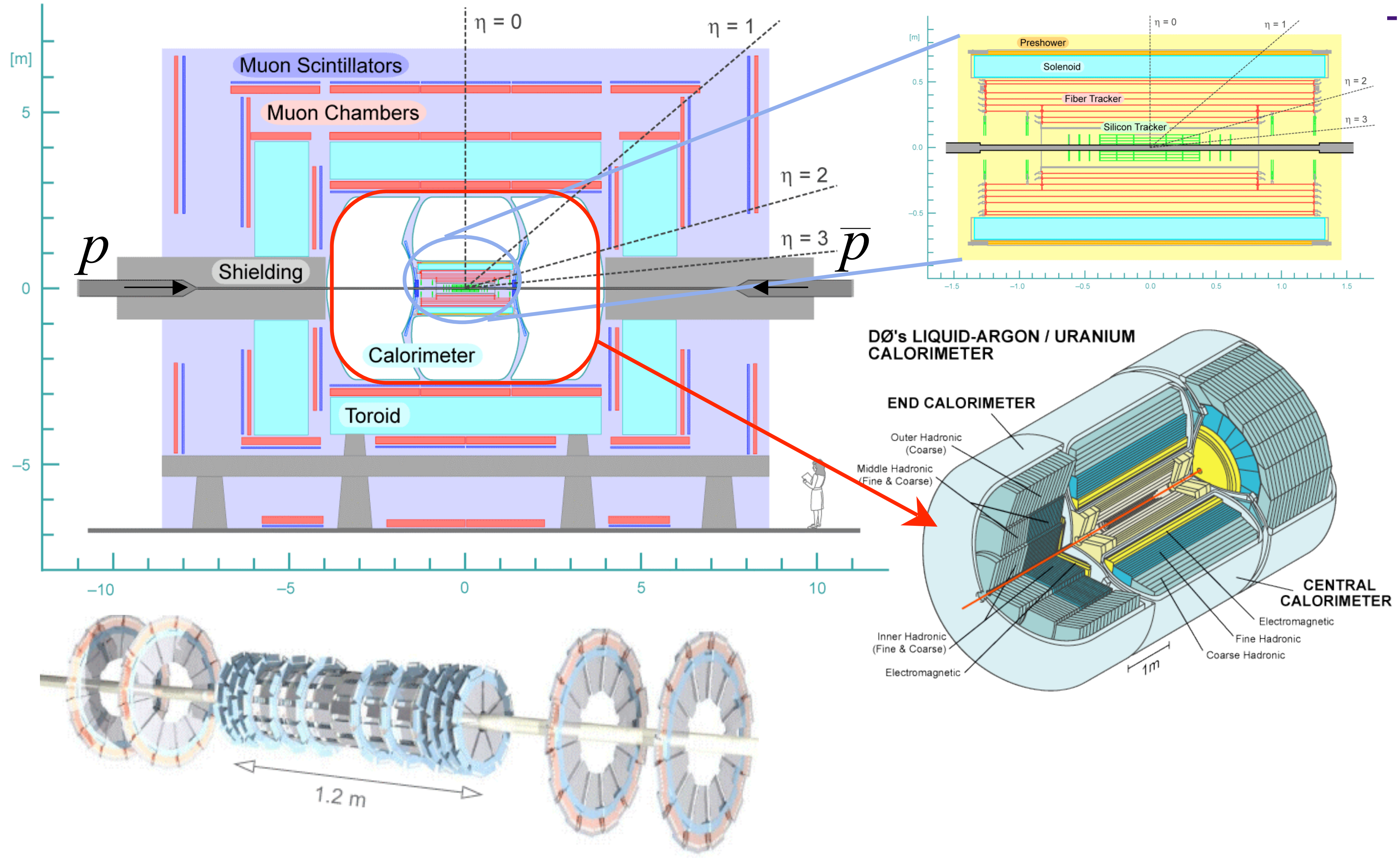
Experimental Apparatus - Tevatron



- Tevatron: Proton – Antiproton Collider
- $\sqrt{s} = 1.96\,\text{TeV}$
- DØ and CDF experiments among others
- Bunch crossing every 396ns
- W/Z factory – Precision electro weak measurements

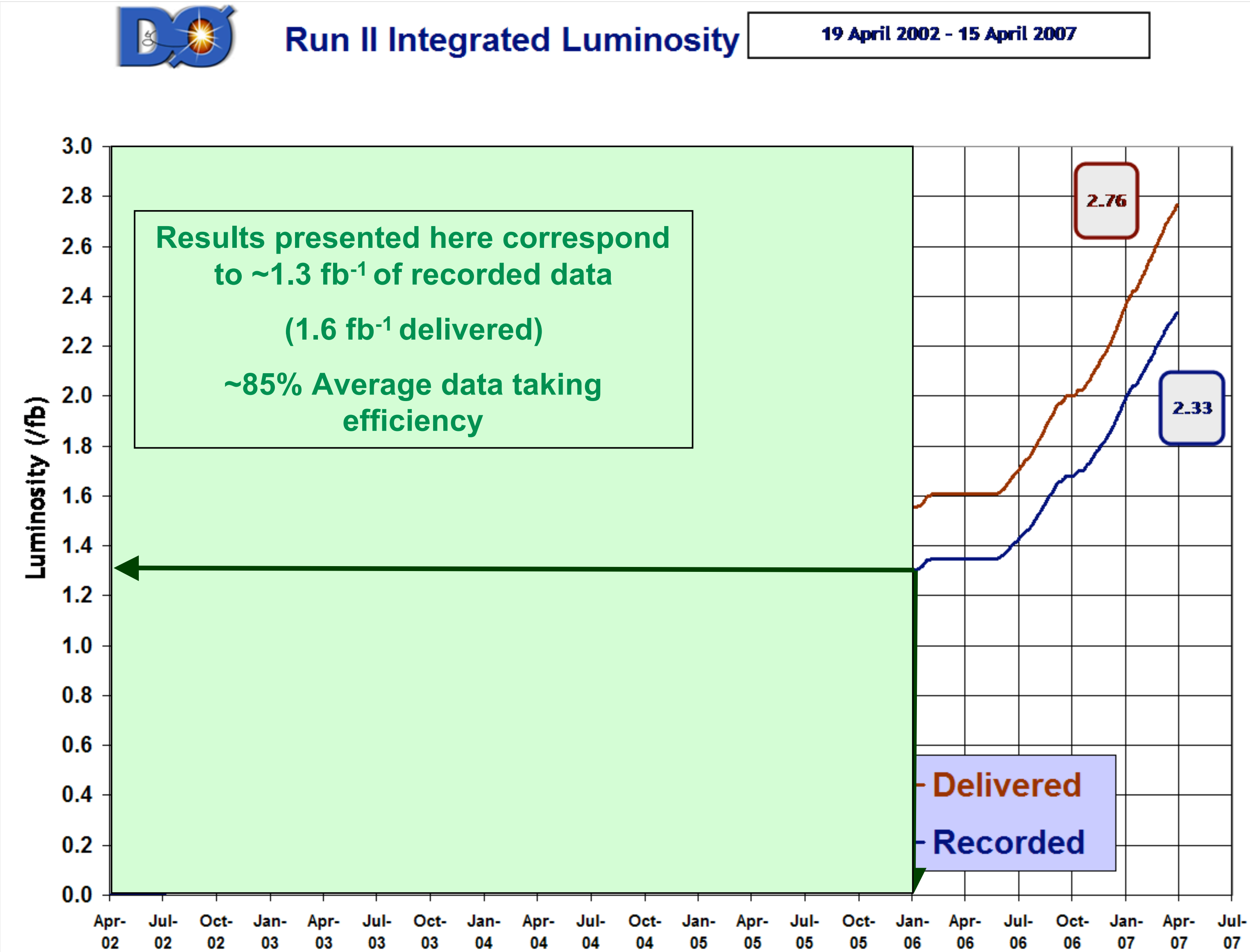


Experimental Apparatus – DØ Detector



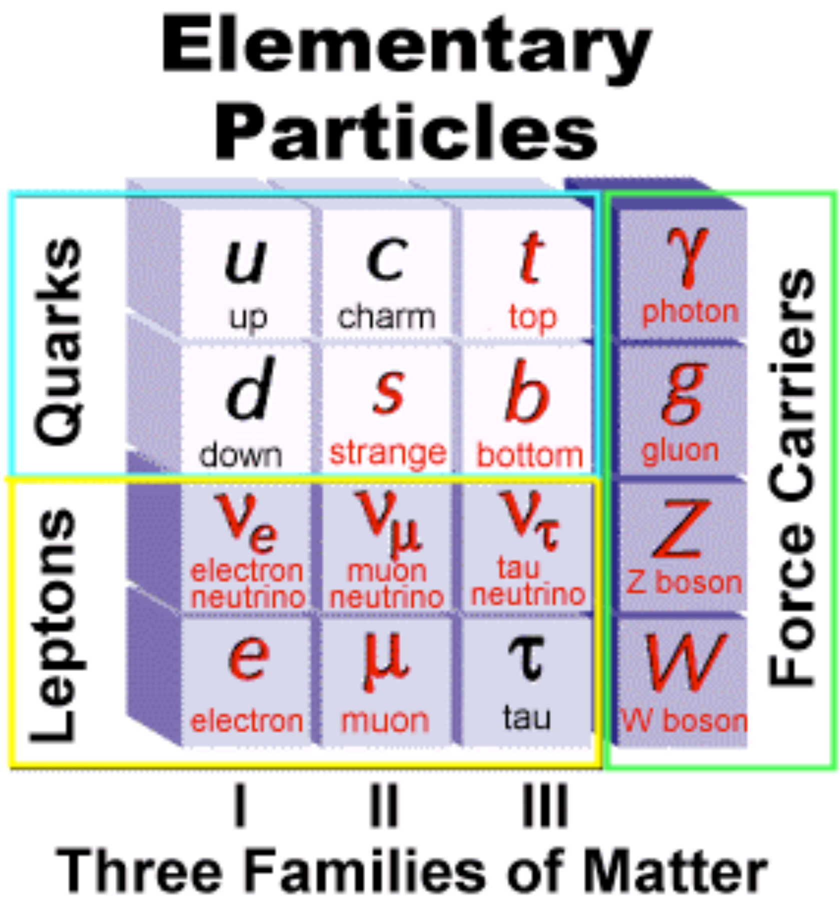

The
DØ
Collaboration
645 Scientists, 18 countries, 81 institutions

Dataset



Run II Integrated Luminosity
19 April 2002 - 15 April 2007
Results presented here correspond to ~1.3 fb-1 of recorded data
(1.6 fb-1 delivered)
~85% Average data taking efficiency
Luminosity (/fb)
2.76
2.33
Delivered
Recorded

Why Search for Higgs?



- Many years of work has lead to our understanding of matter and its interactions: **The Standard Model**
- Ingredients of the Standard Model
  - Matter Particles (fermions):
    - Quarks and Leptons
  - Force Carriers (bosons):
    - Gluon, photon, $W^{\pm}$ / Z^0
- This model is not the complete description of nature:
  - Does NOT explain the particle masses!
  - But we observe masses on an everyday basis!

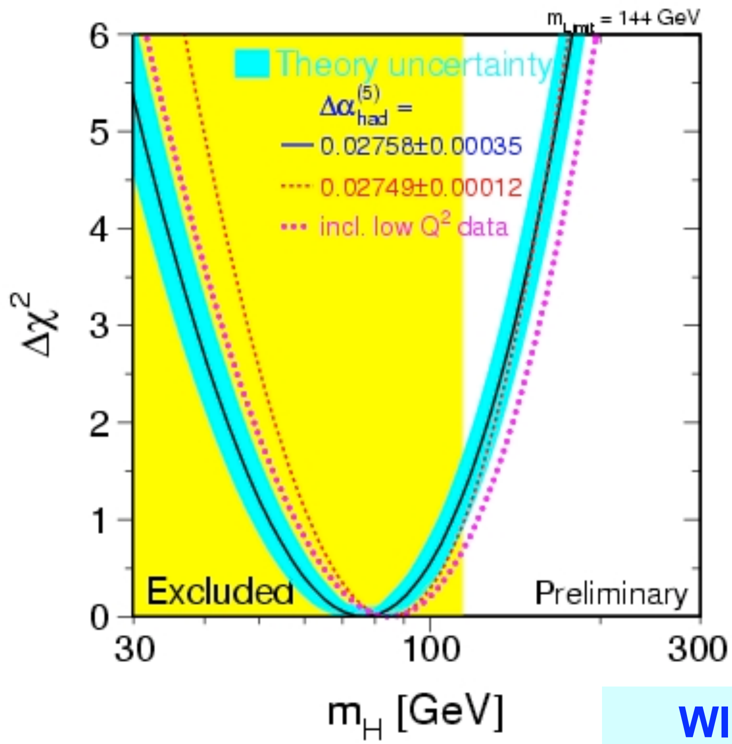
Why Search for Higgs?

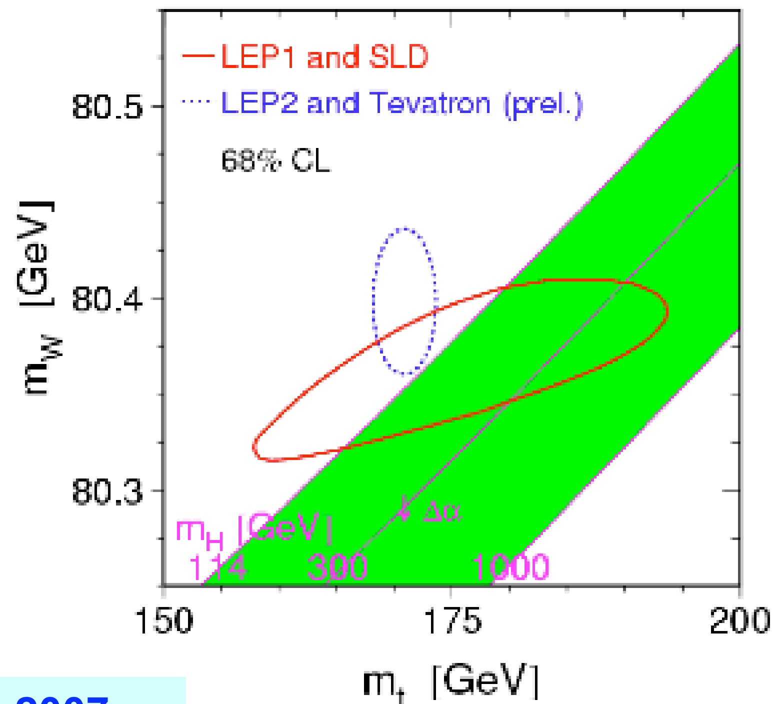
- Electroweak (EW) theory is well understood
  - $SU(2)_L \times U(1)_y$: very precisely tested by collider experiments
  - Its not a symmetry of our vacuum. Otherwise all the quarks, leptons and the gauge bosons would be massless!
  - 1964: Peter Higgs proposed a simple model
    - Add one complex doublet of scalar fields in a ϕ^4 potential

$$L_{Higgs} = \left| \left(\partial_\mu - i g W_\mu^\alpha T^\alpha - \frac{i}{2} k B_\mu \right) \phi \right|^2 - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

    - Symmetric solution: Unstable
    - Broken EW symmetry creates non-zero VEV
    - $W^\pm$ / Z^0 absorb three degrees of freedom
    - Remaining becomes a neutral scalar
    - Mass of Higgs Boson not predicted!

How massive is Higgs?





WINTER 2007

Precision EW Fits

m_H< 144 GeV @ 95% CL

m_H< 182 GeV with LEP II Limit

Tevatron Measurements

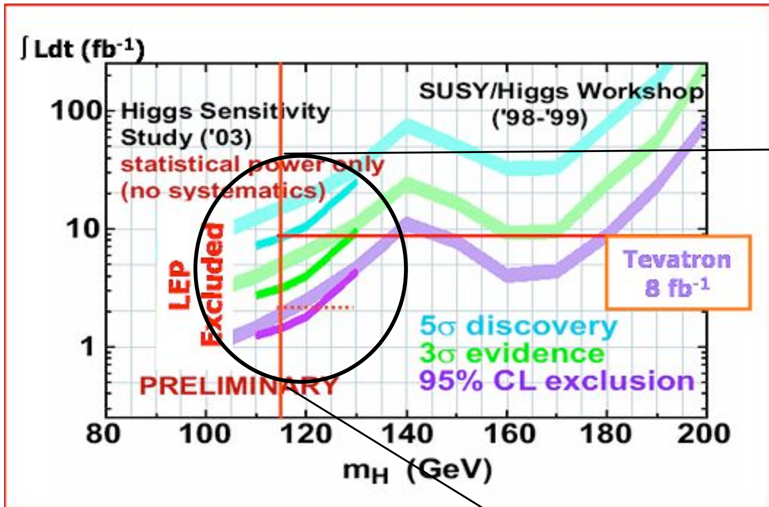
m_{top} = 170.9 ± 1.8 GeV

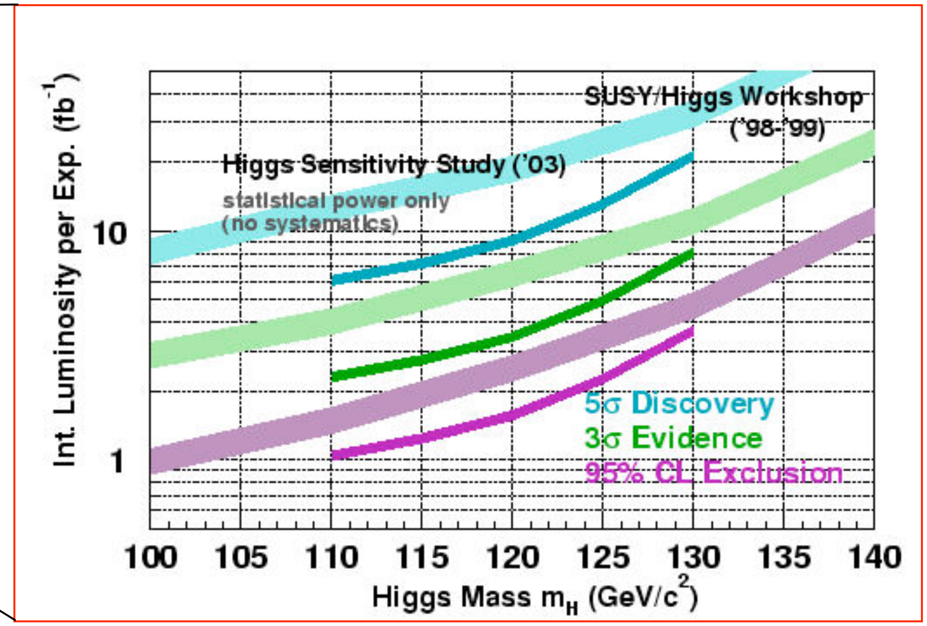
m_W = 80.398 ± 0.025 GeV

Direct Searches at LEP II

m_H> 114.4 GeV @ 95% CL

Higgs Search at the Tevatron





Studies by DØ and CDF experimental groups

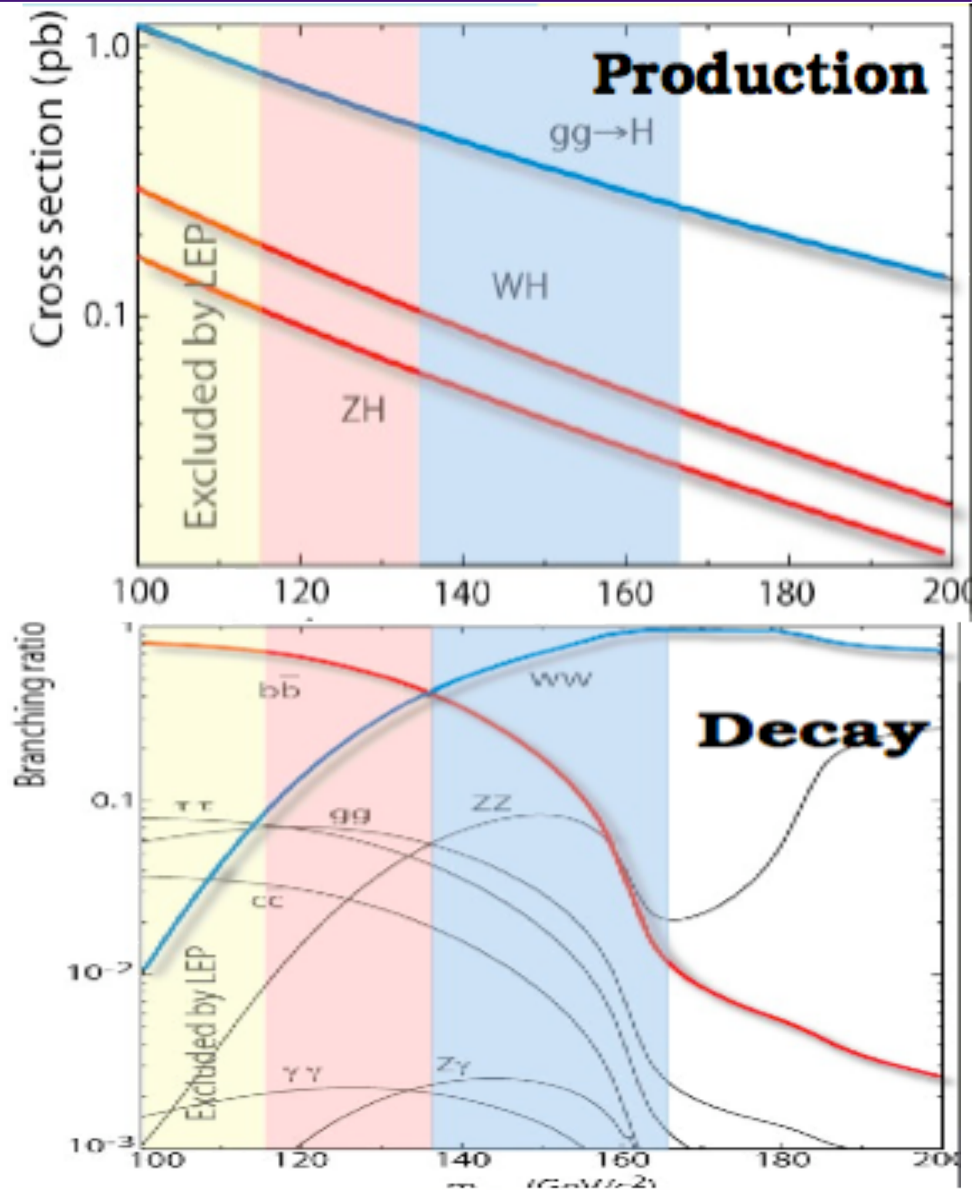
SUSY Higgs Working Group (SHWG) 10/2000

Higgs Sensitivity Group (HSG) 6/2003

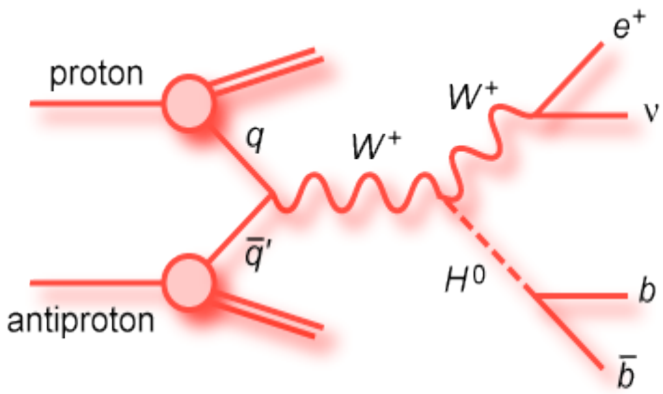
- *Higgs search feasible at Tevatron*
  - *No golden channel*
  - *Rely on equally two sensitive experiments*

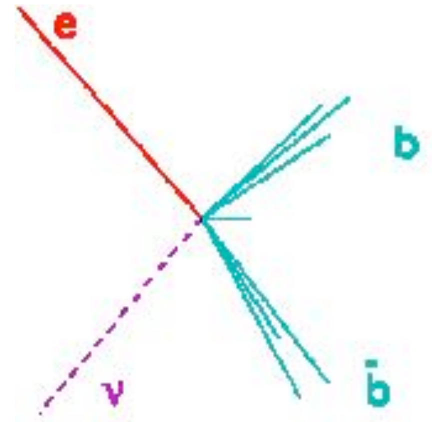
Higgs Search at the Tevatron

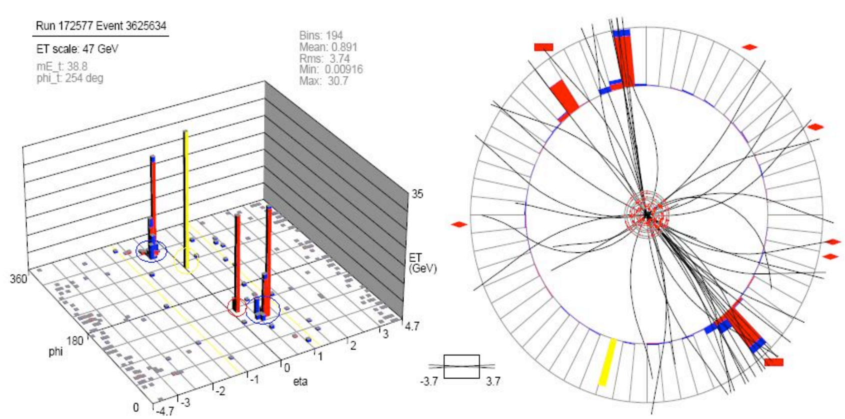
- o Gluon Fusion dominates for hadron colliders
  - ✓ Large backgrounds to Higgs decay
- o Associated Production with vector bosons
  - ✓ Best at low mass (m_H < 135 GeV)
  - ✓ Leptonic decays of W / Z bosons provide good handles for triggering and analysis
  - ✓ Low mass Higgs prefers to decay to bottom quark pairs
  - ✓ Need efficient identification of bottom quarks to reduce backgrounds



Experimental Event Signature

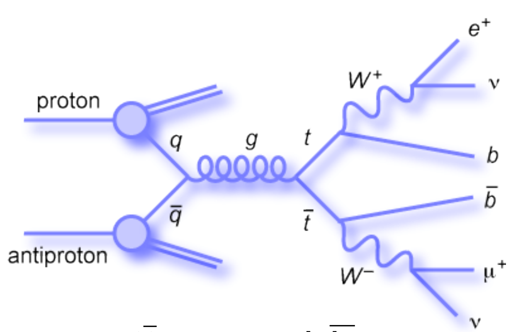




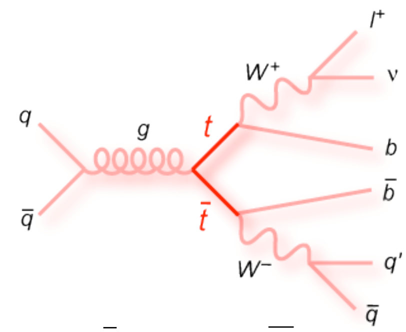


- Isolated Lepton
  - electron/muon
- Large Missing Transverse Energy
  - MET or $\not\!E_T$
- Exactly two Jets (tagged as b-jets)

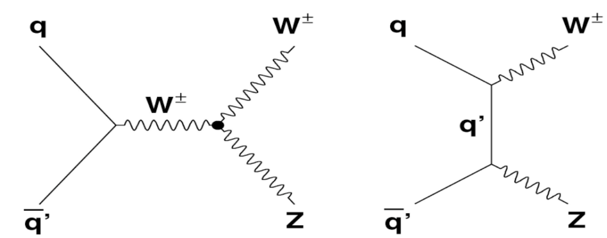
Physics Background to WH Signal



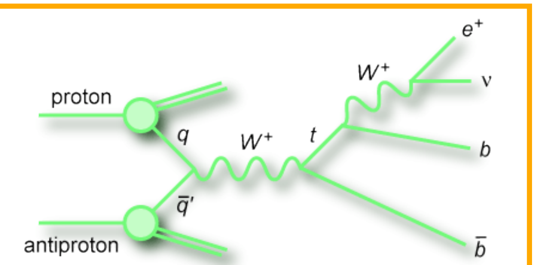
$t\bar{t} \rightarrow \ell\ell\nu\nu b\bar{b}$



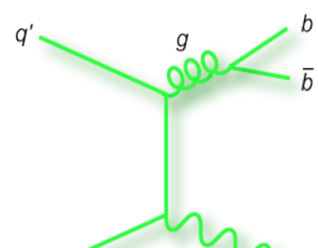
$t\bar{t} \rightarrow \ell\nu jjb\bar{b}$



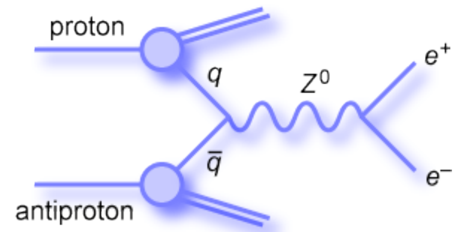
$\text{Di-Boson}(WZ/ZZ)$



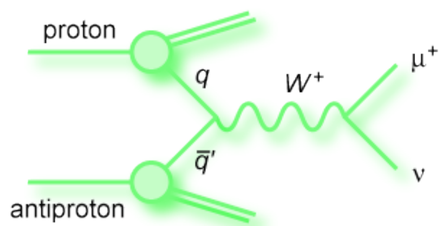
$t\bar{b} \rightarrow e\nu b\bar{b}$



$Wb\bar{b}$



$Z \rightarrow ee + 2lp$



$W \rightarrow e\nu + 2lp$

Other Backgrounds

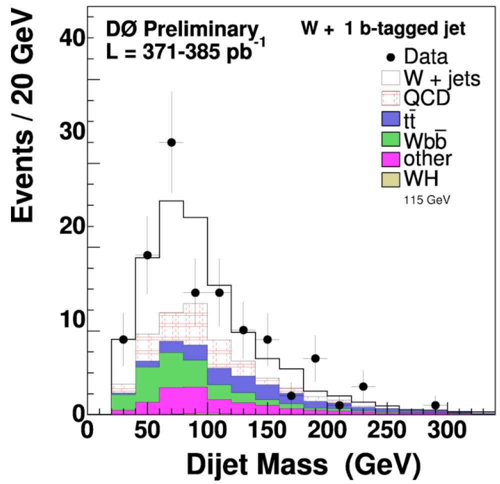
- $W(\rightarrow \tau\nu \rightarrow e\nu\nu) + 2lp$
- $Z(\rightarrow \tau\tau \rightarrow e\nu\nu + \text{hadrons}) + \text{jets}$

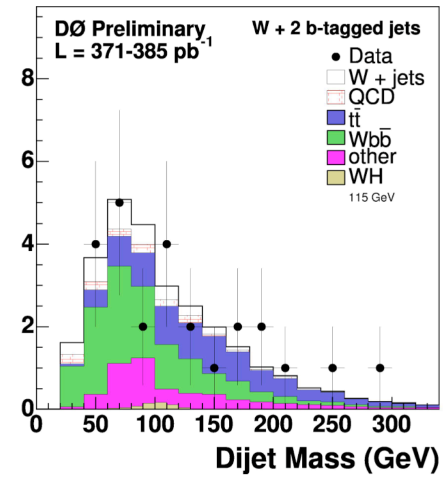
Simulated Background Samples

Process	Generator	$\sigma(\times BR)$[pb]	# events
$Wb\bar{b} \to e\nu bb$	ALPGEN + PYTHIA	3.35	205328
$Wb\bar{b} \to \tau\nu bb$	ALPGEN + PYTHIA	3.35	205328
$HW \to b\bar{b} + e\nu$, $m_H = 105$ GeV	PYTHIA (CS compliant)	0.0222	48250
$m_H = 115$ GeV		0.0150	30650
$m_H = 125$ GeV		0.0093	32057
$m_H = 135$ GeV		0.0045	46734
$m_H = 145$ GeV		0.0022	53131
$HW \to b\bar{b} + \tau\nu$, $\tau \to e$, $m_H = 105$ GeV	PYTHIA (CS compliant)	0.0039	46497
$m_H = 115$ GeV		0.0026	51751
$m_H = 125$ GeV		0.0016	48054
$m_H = 135$ GeV		0.00078	49330
$m_H = 145$ GeV		0.00038	45779
$Wjj \to e\nu + jj$	ALPGEN + PYTHIA	287.3	1476040
$Wjj \to \tau\nu + jj$	ALPGEN + PYTHIA	287.3	89060
$Zjj \to ee + jj$	ALPGEN + PYTHIA	27.2	706330
$\gamma^*/Z \to \tau\tau, \hat{m} \in (60, 130\,\mathrm{GeV})$	PYTHIA (CS compliant)	255.0	189342
$W \to \tau\nu_\tau$	PYTHIA (CS compliant)	2775	277366
$t\bar{t} \to b\bar{b} + \ell^+\ell^- + \not{E}_T$, $m_t = 175$ GeV	ALPGEN + PYTHIA	0.70	91402
$t\bar{t} \to b\bar{b} + 2j + \ell + \not{E}_T$, $m_t = 175$ GeV	ALPGEN + PYTHIA	2.90	76433
Single top s-channel ($tb \to e\nu\ bb$)	CompHEP + PYTHIA	0.115	137824
single top t-channel ($tqb \to e\nu\ bqb$)	CompHEP + PYTHIA	0.258	86742
$WW \to l\nu jj$	PYTHIA	2.672	95520
$WZ \to l\nu jj$	PYTHIA	0.824	92315
$WZ \to lljj$	PYTHIA	0.243	91460
$ZZ \to lljj$	PYTHIA	0.205	92560

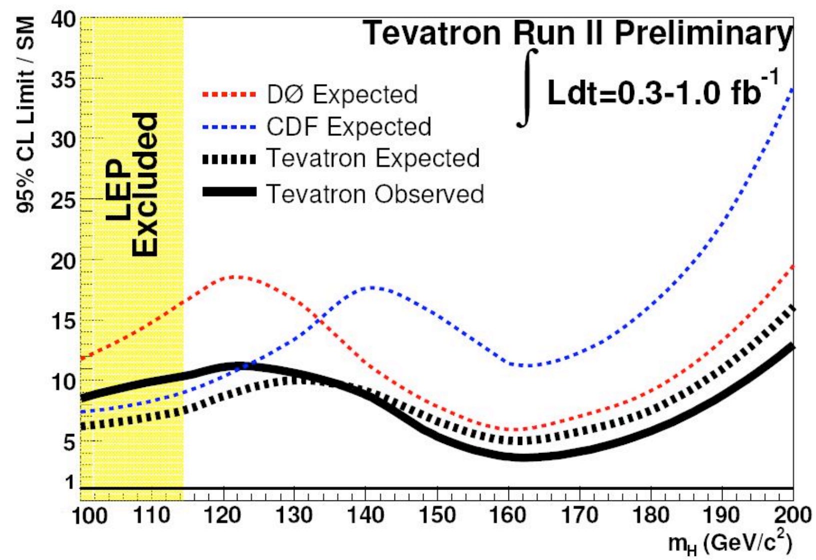
Current Results on SM Higgs Search at Tevatron

Higgs mass	105 GeV	115 GeV	125 GeV	135 GeV	145 GeV
WH	0.4	0.27	0.17	0.09	0.04
WW, WZ, ZZ	3.3	2.5	1.1	0.4	0.15
$Wb\bar{b}$	6.6	6.6	4.5	3.4	2.5
$t\bar{t}$	3.9	4.3	4.4	4.5	4.5
Single top	2.3	2.3	2.4	2.4	2.2
QCD / W or Z +jets	19.2	30.6	23.3	19.0	16.4
Total expectation	50.9	45.1	35.7	29.7	25.7
Data	40	32	32	27	27
WH	0.37	0.28	0.17	0.09	0.04
WZ	1.4	1.0	0.60	0.22	0.05
$Wb\bar{b}$	4.2	3.6	3.0	2.4	2.0
$t\bar{t}$	2.0	2.1	2.4	2.2	2.3
Single top	0.89	0.89	0.92	0.89	2.0
QCD / W or Z +jets	1.8	1.6	1.4	1.2	1.0
Total expectation	10.5	9.3	8.1	6.9	6.3
Data	7	6	7	6	6
Combined Cross section limit (pb)	2.4	2.4	2.9	2.8	2.6
Expected Cross section limit (pb)	4.0	3.5	3.4	3.0	2.8

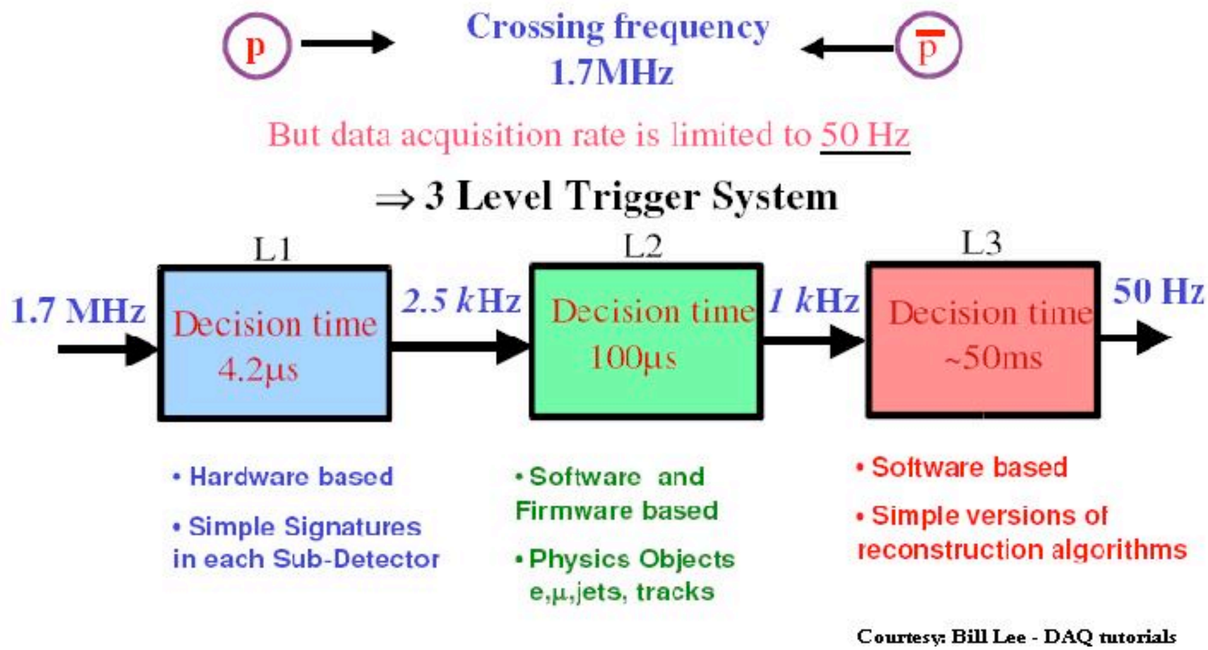




- WH e/μ channels combined
- Combination yields upper limits on cross section ranging from 2.4pb to 2.9pb for single tag
- $p\bar{p} \to W/ZH \to \ell\nu b\bar{b} / \nu\bar{\nu}b\bar{b} / \ell^+\ell^- b\bar{b}$
- $p\bar{p} \to WH \to WW^+W^-$
- $p\bar{p} \to H \to W^+W^-$



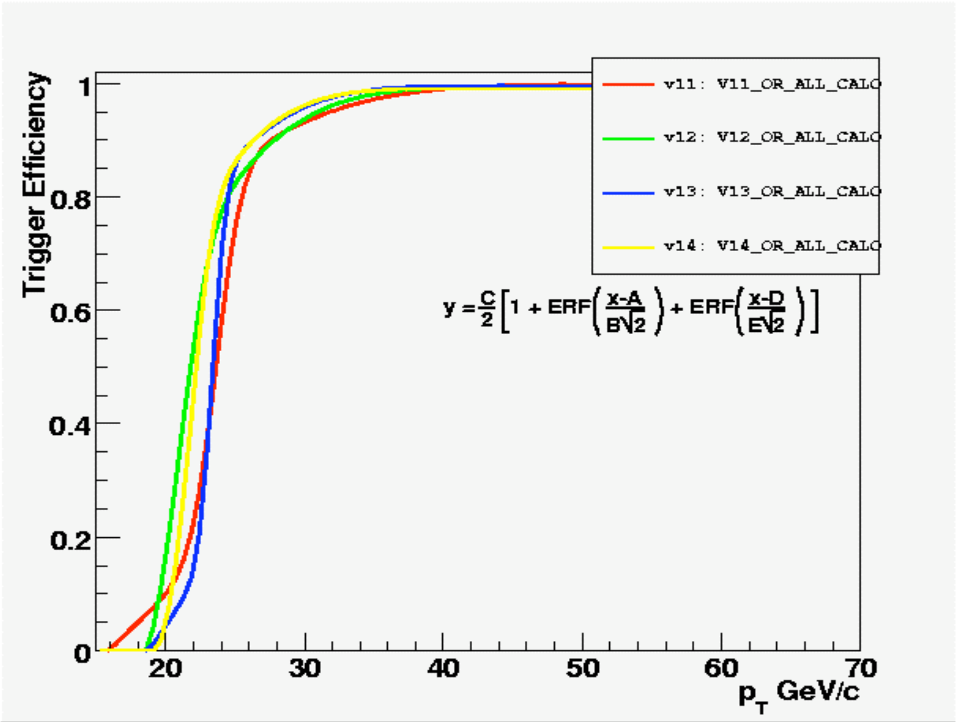
Triggering on Single Electon – Example



E1_SHT20

- **L1→ one calorimeter EM trigger tower with Et>11 GeV. Veto on cal_unsuppressed condition.**
- **L2→ Requires a standard L2 EM cluster with a threshold >= 15 GeV.**
- **L3→ The trigger bit set to true if an electron is found satisfying tight shower shape requirements with Et>20. GeV**
- Some triggers are selectively prescaled

Single EM "OR" Triggers - Parameterization

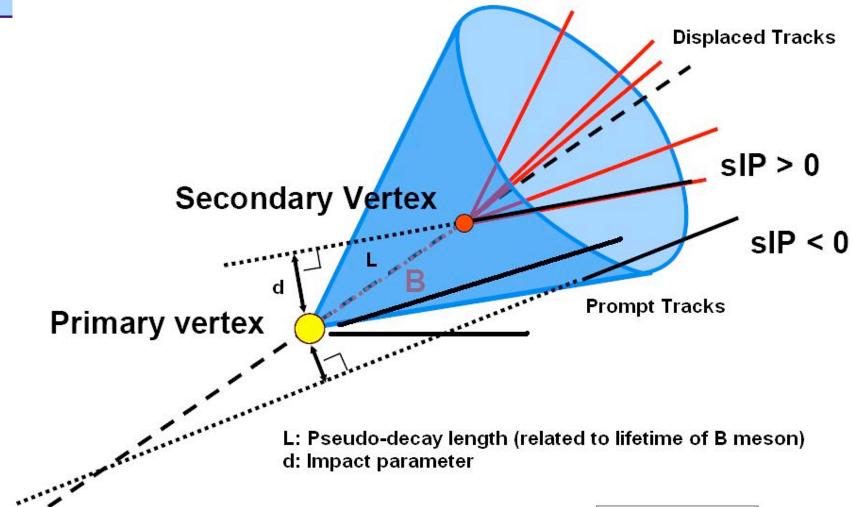


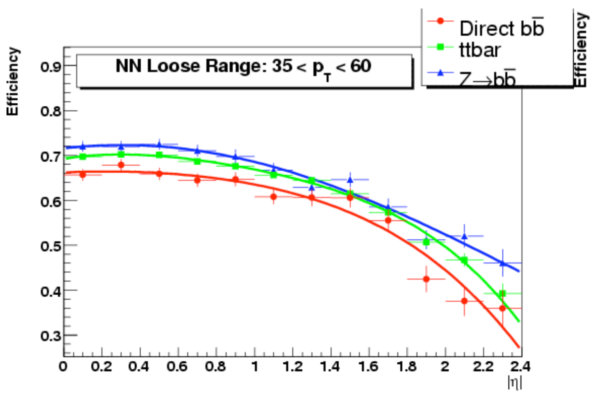
- Using "**OR" of all calorimeter based triggers**
- Applied luminosity weighted trigger efficiency as an event weight to MC events
- Average Luminosity weighted Trigger Probability:
  - 84% (v8-11)
  - 87% (v12-13)
  - 87% (v14)

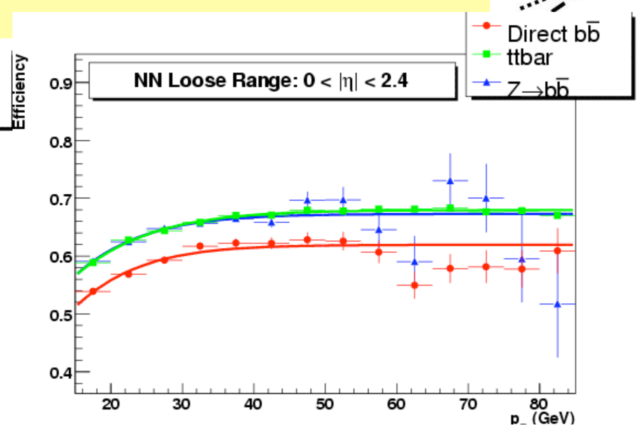
	A	B	C	D	E
V8_OR_ALL_CALO	**23.66 ± 0.23**	1.46 ± 0.23	0.67 ± 0.00	**15.92 ± 1.21**	11.10 ± 1.00
V12_OR_ALL_CALO	**21.11 ± 0.27**	1.66 ± 0.23	0.66 ± 0.00	**20.10 ± 0.75**	7.23 ± 0.49
V13_OR_ALL_CALO	**23.38 ± 0.08**	0.80 ± 0.10	0.66 ± 0.00	**18.83 ± 0.18**	7.10 ± 0.19
V14_OR_ALL_CALO	**21.90 ± 0.20**	1.20 ± 0.22	0.66 ± 0.00	**19.75 ± 0.47**	6.05 ± 0.41

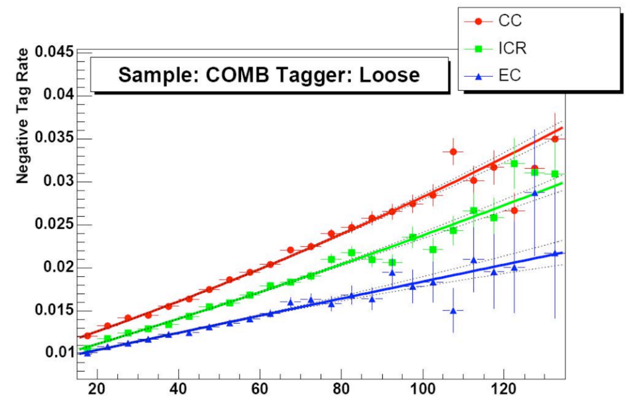
Tagging b-Jets

- Neural Net Tagging combines the different variables from three different tagging algorithms
  - Counting Signed IP (CSIP)
  - Jet LIfetime Probability (JLIP)
  - Secondary Vertex Tag (SVT)
- Various operating points are defined based on NN output
- Fake Rate (Negative Tag Rate) and Efficiency are measured for each operating point









Name	Tight	Medium	Loose	L2	L3	L4
NN Cut	> 0.775	> 0.65	> 0.5	> 0.325	> 0.25	> 0.2
Fake Rate	0.3	0.5	1.0	2.0	3.0	4.0

Region	L4	L3	L2	Loose	Medium	Tight
CC	5.36%	4.13%	2.96%	1.54%	0.884%	0.501%
ICR	4.92%	3.75%	2.65%	1.34%	0.75%	0.415%
EC	4.74%	3.58%	2.48%	1.18%	0.613%	0.304%

Single EM Triggers and Luminosity - RunIIA

[from	to[	Trigger	Del	Rec	Good
V8.0	V9.0	EM_MX	42.59	33.45	26.66
V9.0	V10.0	EM_MX	47.89	41.78	24.78
V10.0	V11.0	EM_MX	21.44	19.36	10.75
V11.0	V12.0	EM_MX	79.17	74.24	65.78
V12.0	V13.0	E1_SH30	276.90	254.75	230.99
V13.0	V13.3	E1_SH30	82.01	74.15	55.44
V13.3	V14.0	E1_SH30	381.85	350.42	322.83
V14.0	V15.0	E1_SHT25	416.89	388.95	333.74
			1348.74	**1237.10**	**1070.97**

- EM_MX, EM_HI, EM_MX_SH, EM_HI_SH, EM_MX_EMFR8, EM_HI_EMFR8 - V8-11
- E1_L50 E1_L70 E1_NC90 E1_SH30 E1_SHT20 E1_VL70 E2_SH30 E2_SHT20 E3_SH30 E3_SHT20 E4_SH30 E4_SHT20 - V12/V13
- 2CEM12_E15_SH30 2CEM12_E15_SHT22 2CEM6_E15_SH30 2CEM6_E15_SHT22 E1_ISH30 E1_ISHT22 E1_SH35 E1_SHT25 E3_ISH30 E3_ISHT22 E3_SH35 E3_SHT25 E4_ISH30 E4_ISHT22 E4_SH35 E4_SHT25 - V14

Single Electron Efficiency in Data / MC

PRESELECTION

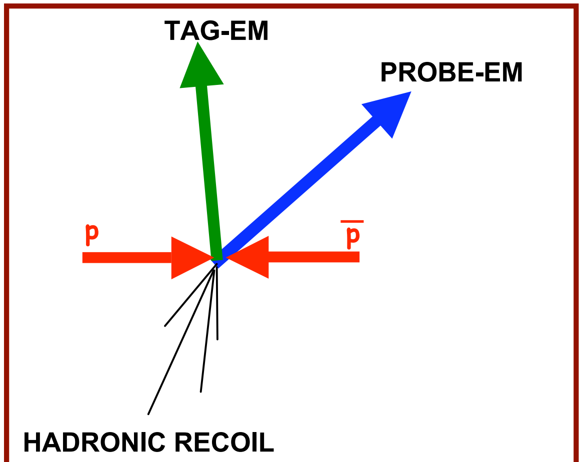
- EMID = 10, ± 11
- Electromagnetic fraction > 0.9
- Calorimeter isolation < 0.2
- H-Matrix(7) < 50
- Spatial track match χ^2 prob > 0
- Likelihood > 0.85
- $p_T > 15$ GeV/c

TIGHT_TRK

$$f_{em} = \frac{E_{EM}(0.2)}{E_{TOT}(0.4)}$$

$$f_{iso} = \frac{E_{tot}(0.4) - E_{EM}(0.2)}{E_{EM}(0.2)}$$

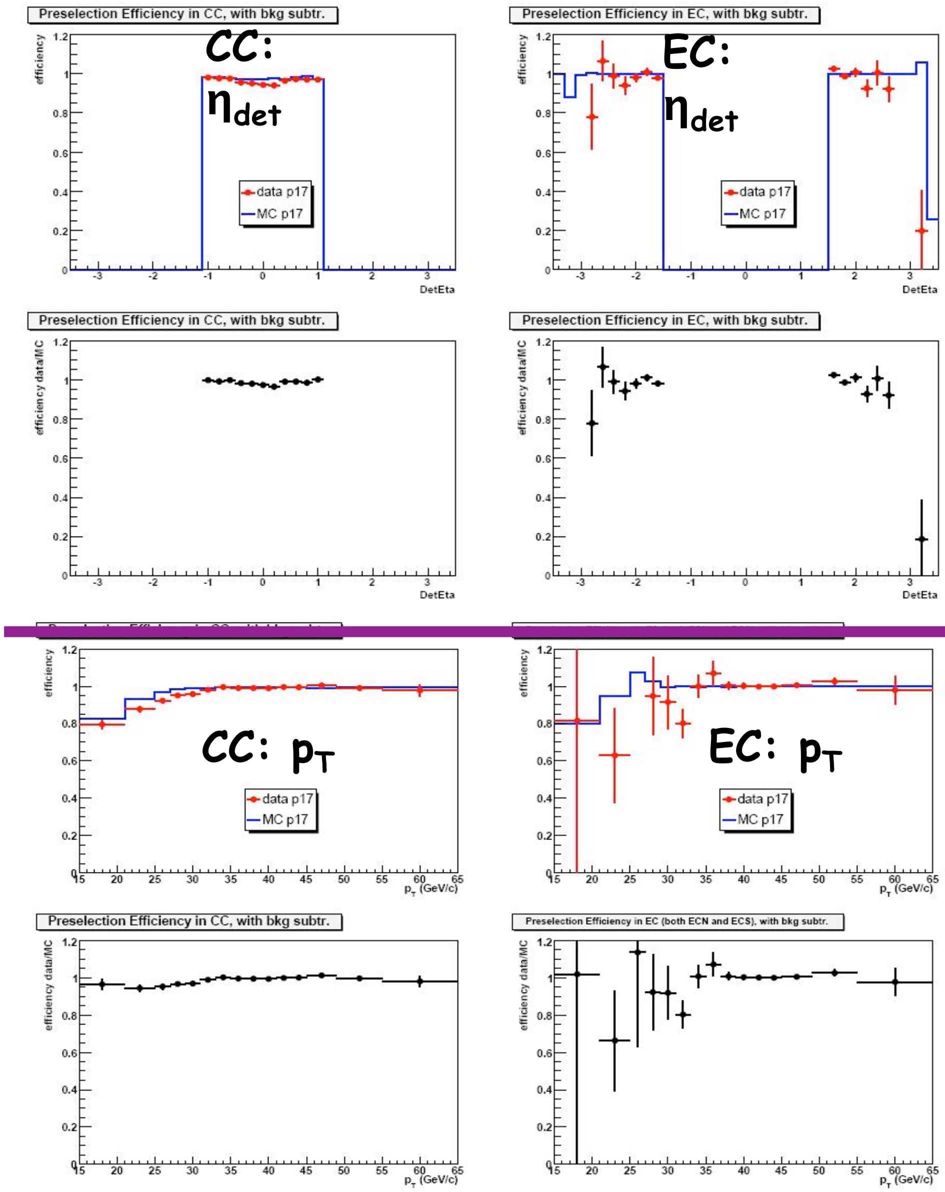
$$\varepsilon_{pre} = \frac{N_{pass}}{N_{pass} + N_{fail}}$$



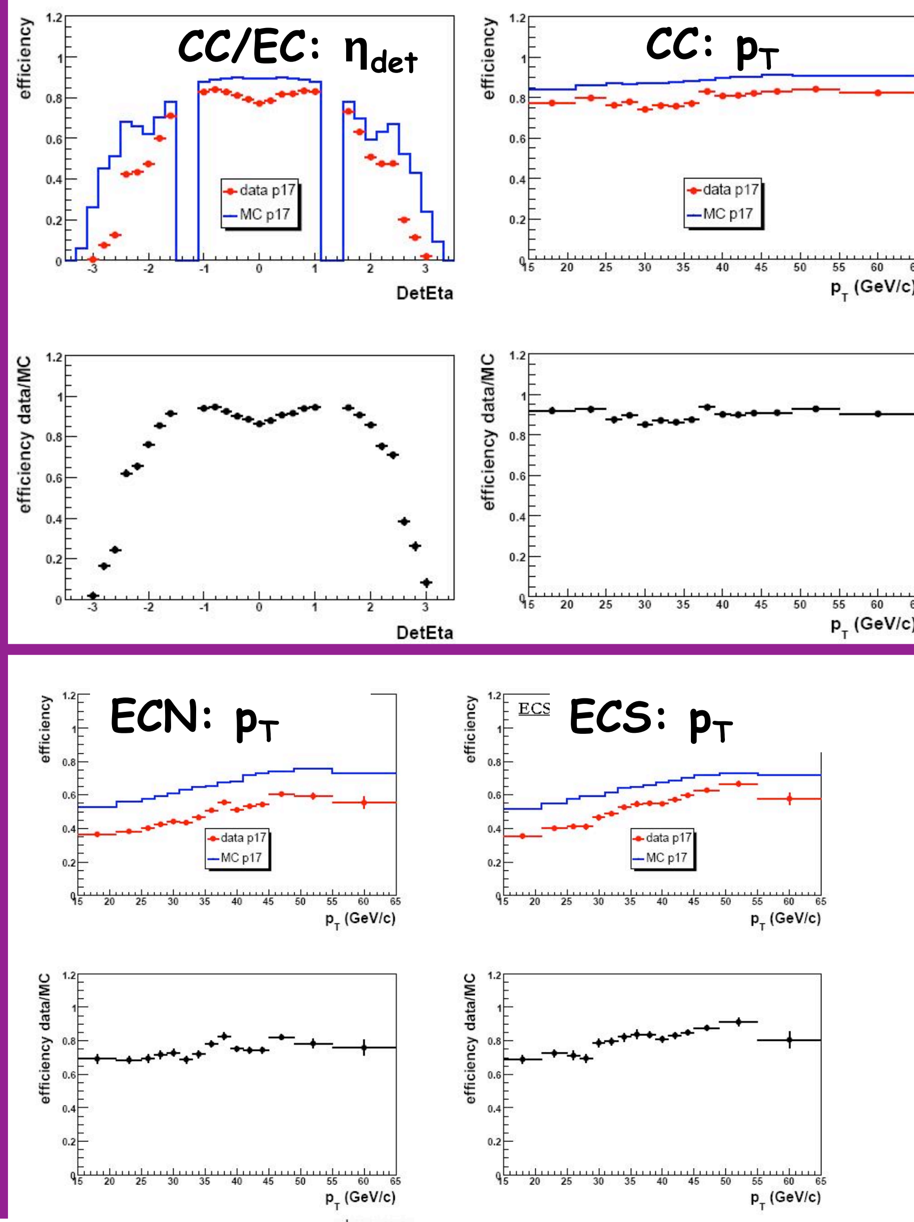
TAG/PROBE METHOD

- Require two electron candidates
- Dielectron invariant mass should be consistent to that of Z boson
- One of the electrons is required to pass stringent cuts – TAG
- The other candidate is required to pass cuts relevant to the efficiency to be determined
- Preselection efficiency is first determined
- All other efficiencies are relative to preselection efficiency
- Efficiencies are calculated per electron rather than per event to avoid bias
  - Each electron that forms the leg of Z boson can be a tag or a probe
- Signal Hypothesis: Voigtian
- Background Hypothesis : Exponential

Preselection Efficiency

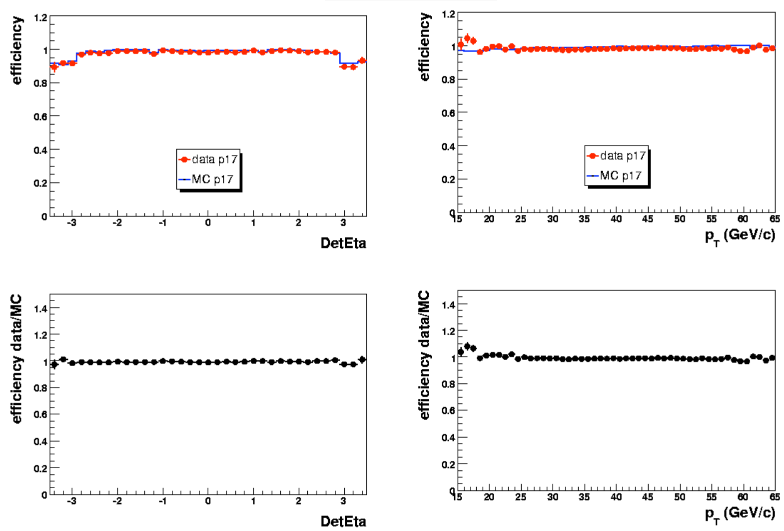


Tight_Trk Efficiency

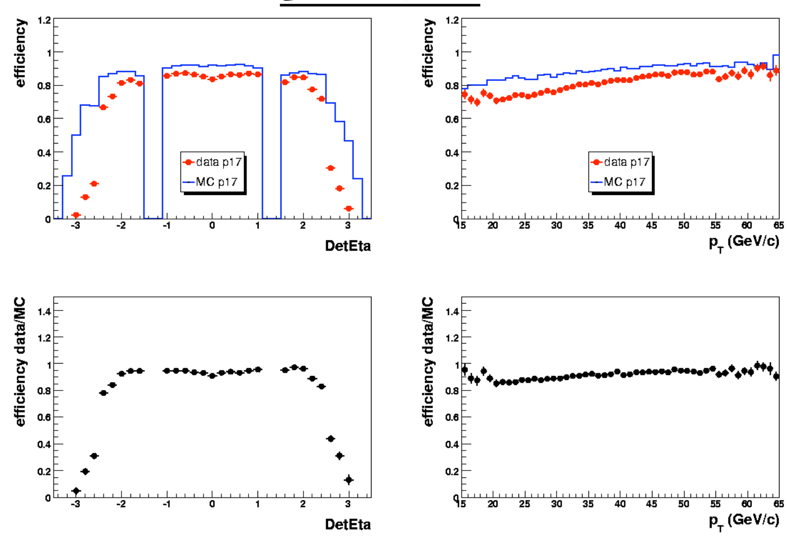


Single Electron Efficiency – Object ID Results

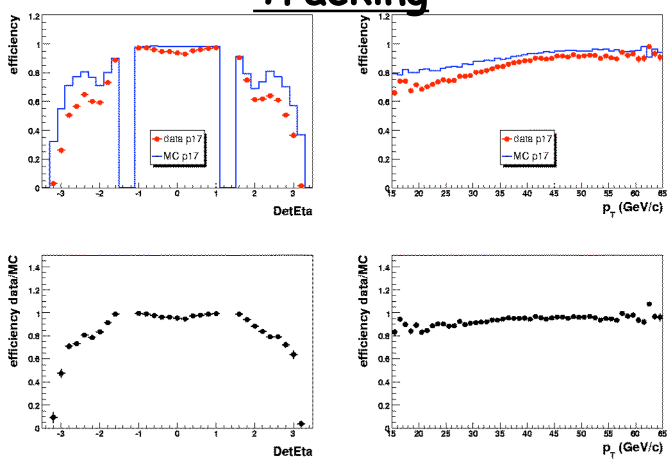
HMatrix



Likelihood



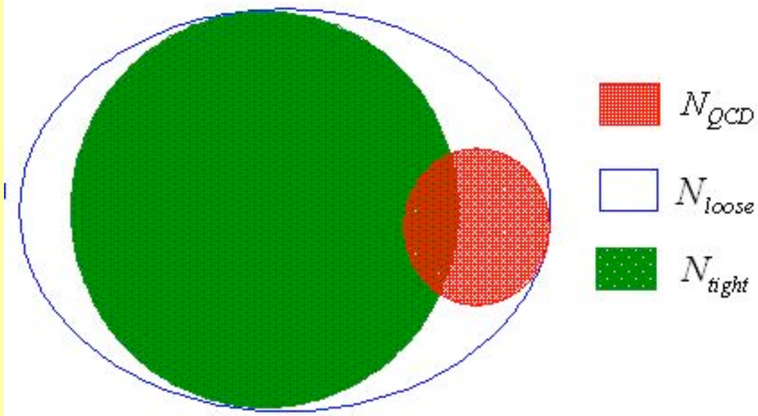
Tracking



Efficiency (Tight)	ECS		ECN		CC	
	Data	MC	Data	MC	Data	MC
HMatrix	98.492 ±0.094	98.864 ±0.060	98.103 ±0.105	98.875 ±0.060	98.205 ±0.059	99.237 ±0.027
Tracking	68.916 ±0.343	77.495 ±0.173	67.558 ±0.350	77.841 ±0.173	95.540 ±0.078	98.057 ±0.031
Likelihood	74.199 ±0.395	82.353 ±0.253	71.987 ±0.412	82.902 ±0.251	86.038 ±0.139	91.639 ±0.091

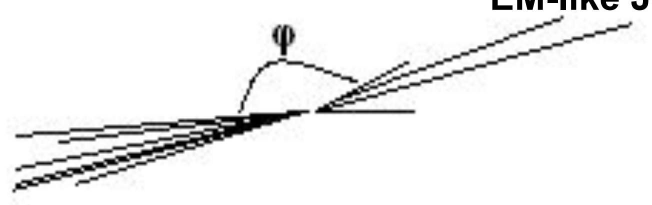
Background Modeling - Matrix Method for QCD

- Define two samples – (loose/ tight) based on likelihood discriminant
  - (N_{loose}, N_{tight}) and $N_{tight} \subset N_{loose}$
- Measure the electron likelihood efficiency (ϵ_{lk})
  - ($Z \rightarrow ee$) tag/probe method
- Measure fake rate (p_{fake})
  - Dijet events with two back to back jets in azimuth
  - No. of Events with atleast 1 fake electron passing likelihood cut (num)
  - No. of Events with atleast 1 fake electron (den)
  - (num/den) = the probability that a jet fakes an electron (p_{fake})
- Obtain the N_e and N_{QCD} by solving the matrix equations



$$N_{loose} = N_e + N_{QCD}$$

$$N_{tight} = \varepsilon_{lk} N_e + p_{fake} N_{QCD}$$

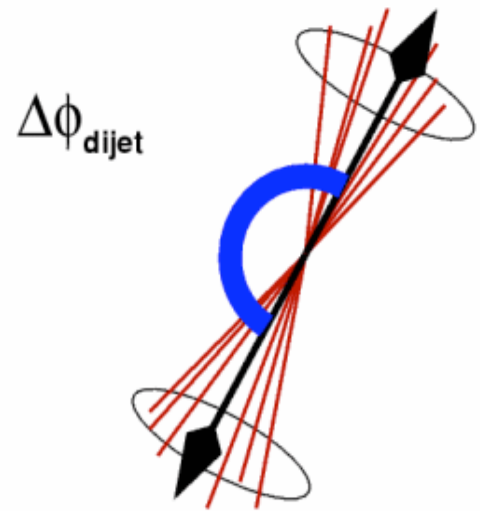


Estimation of Fake Rate (p_{fake})

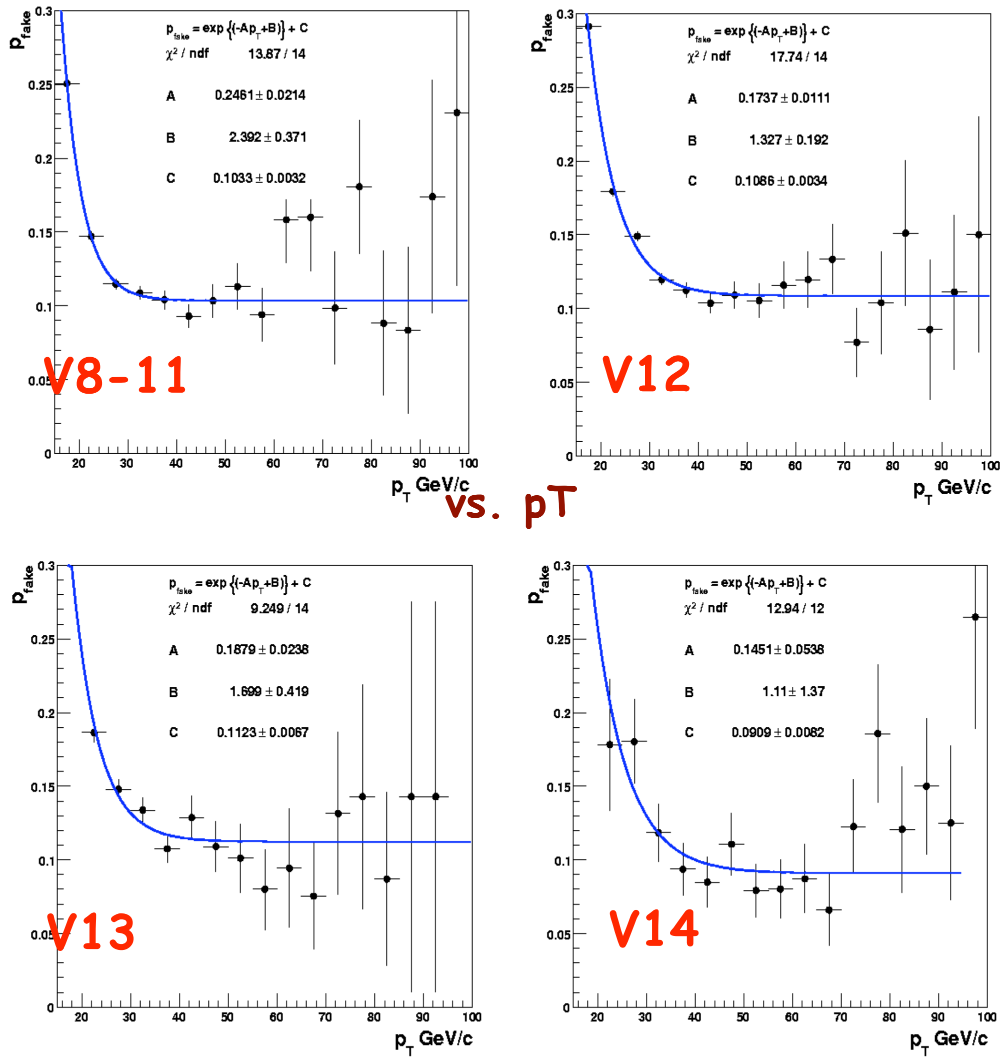
- Look for Dijet events
  - One good jet (JCCB) with
    - pT > 15 GeV/c
    - EMF(jet) < 0.7 (To Reject Zs)
    - # tracks >= 5
  - The other jet is (fake electron)
    - Back to back with the first jet (i.e., $|\Delta\varphi(j,j)| > 2.5$)
    - Passes all em-id cuts except likelihood
      - pT > 15 GeV/c
      - EMF > 0.9
      - ISO < 0.2
      - HMx7(χ^2) < 50
    - Is in the central calorimeter region ($|\eta| < 1.1$)
  - MET in the event < 10 GeV (To reject W+j events)

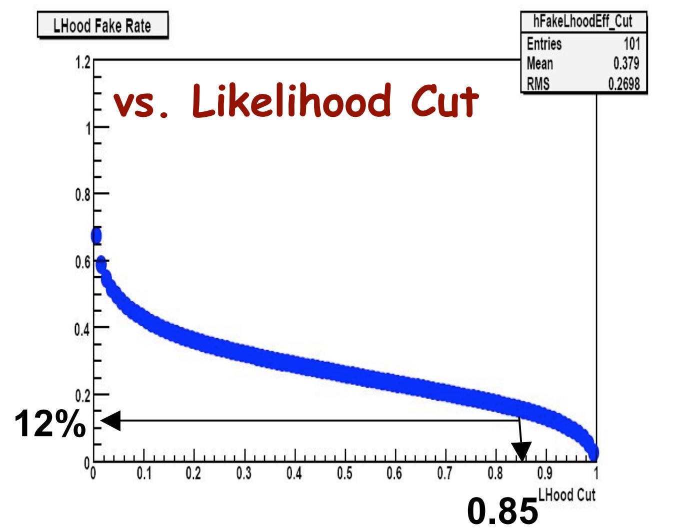
- For a given likelihood value (e.g,0.2 / 0.85) determine

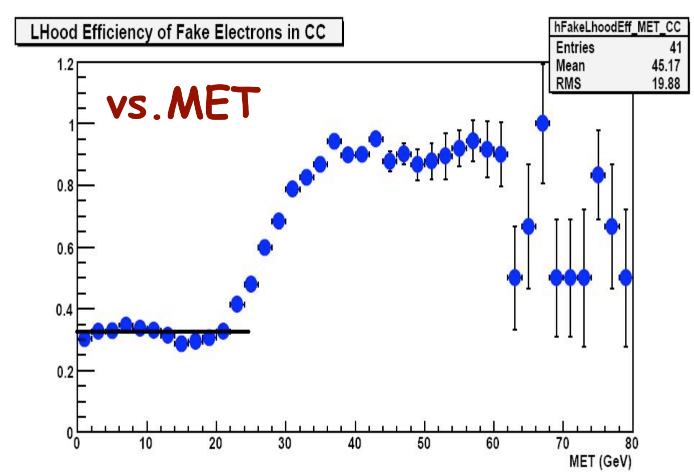
$$p_{fake} = \frac{\left(N_{lk>0.85}^{fake-em}\right)}{\left(N^{fake-em}\right)}$$



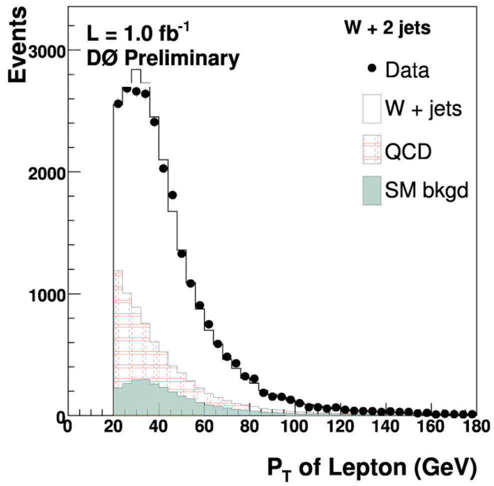
Fake Rate - Results

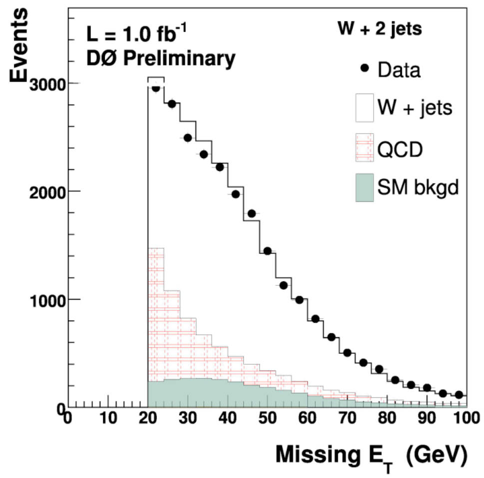


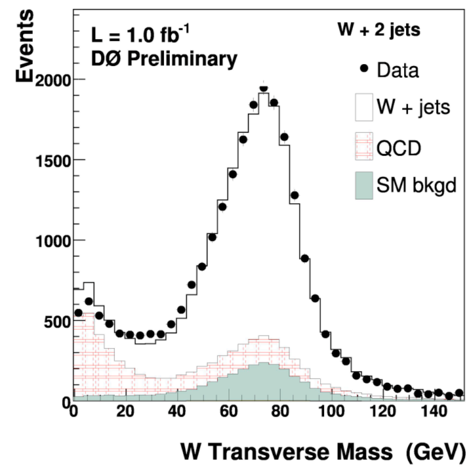


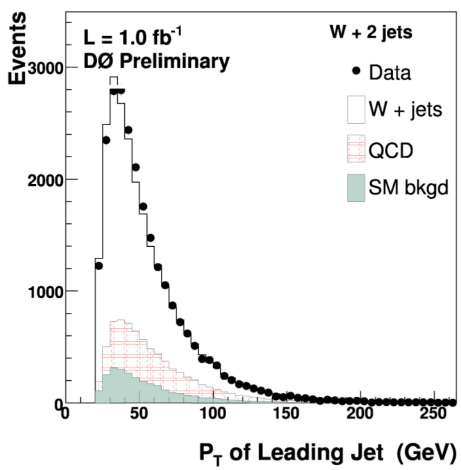


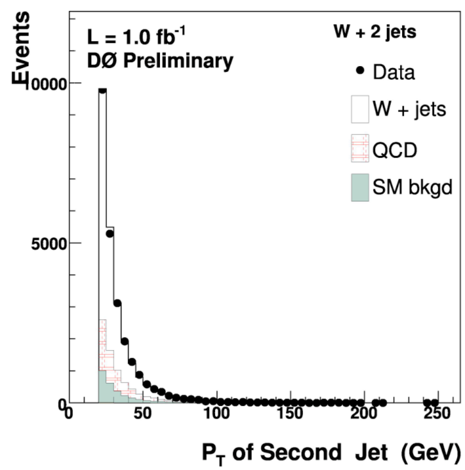
Data / Simulation Comparison

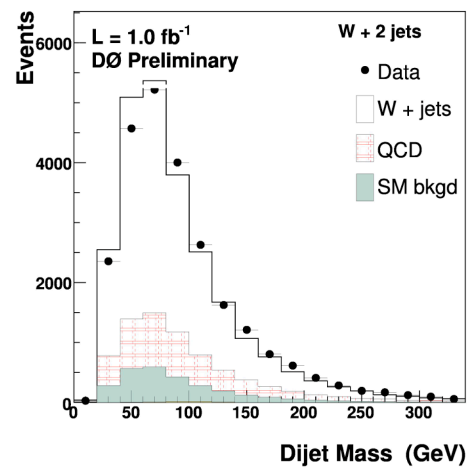




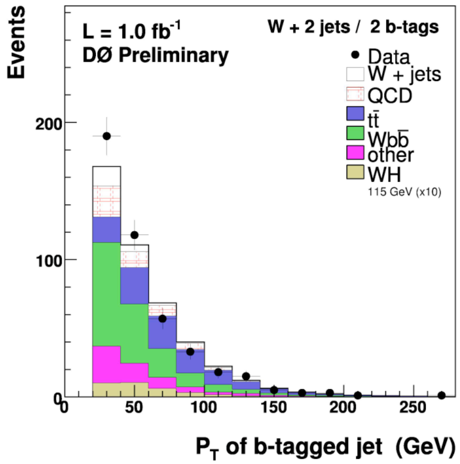


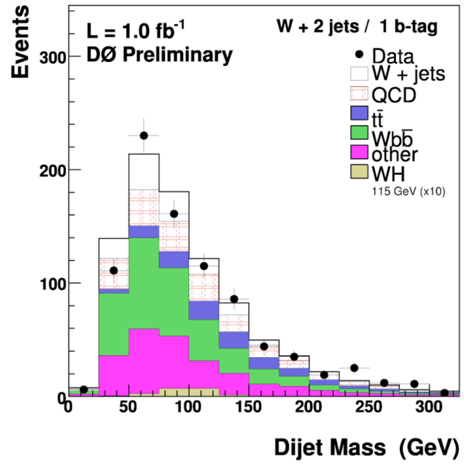


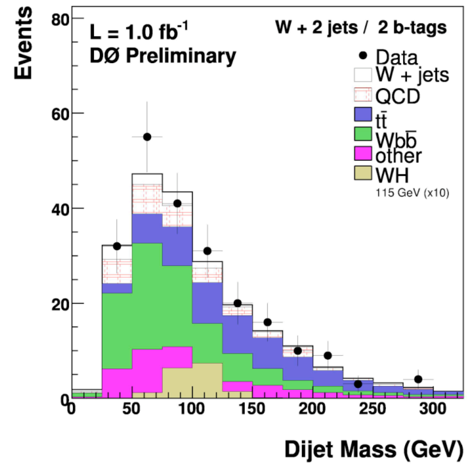


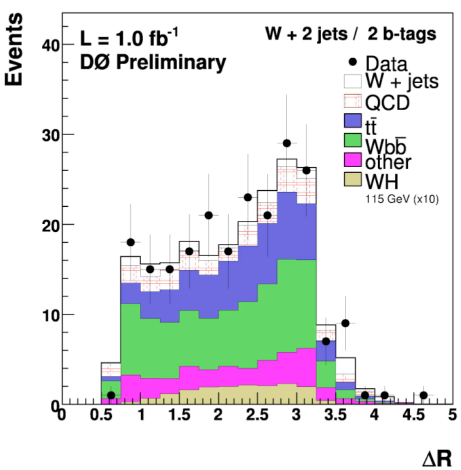


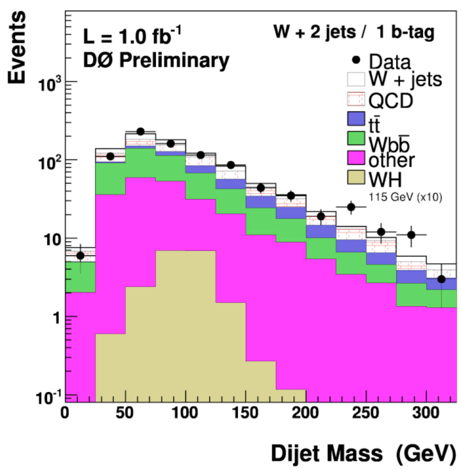
Data / Simulation Comparison

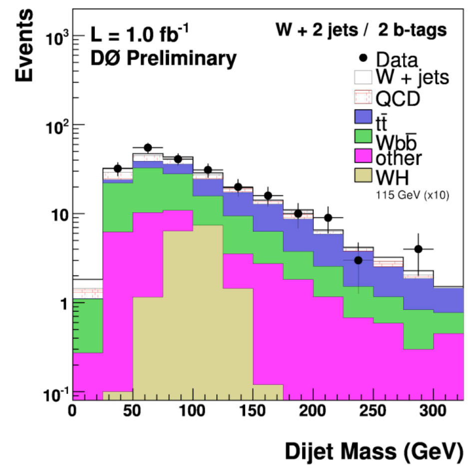












Limits on Production of Higgs

- In the absence of signal, we set limits on Standard Model Higgs boson production
  - We calculate limits via the CLs prescription:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

  - Using a Log-Likelihood Ratio test statistic:

$$Q(\vec{s}, \vec{b}, \vec{d}) = \prod_{i=0}^{N_{Chan}} \prod_{j=0}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{(s+b)_{ij}}}{d_{ij}!} / \frac{b_{ij}^{d_{ij}} e^{b_{ij}}}{d_{ij}!} \qquad LLR = -2 \times Log Q$$

- Distributions of simulated outcomes are populated via Poisson trial with mean values given by B-only or S+B hypotheses
  - Systematics are folded in via Gaussian marginalization
  - Correlations held amongst signals and backgrounds

Tools for Limit-setting

- To counteract the degrading effects of systematic uncertainties, we actually integrate over the Profile Likelihood distributions
  - Obtained by fitting MC expectations to “data” for each outcome
  - Capitalizes on shape and statistics of data to constrain background fluctuations
- Must define the best fit of our MC model to data
  - **Assume:** $B_i \to B_i \prod_k (1+\sigma_i^k S_k)$

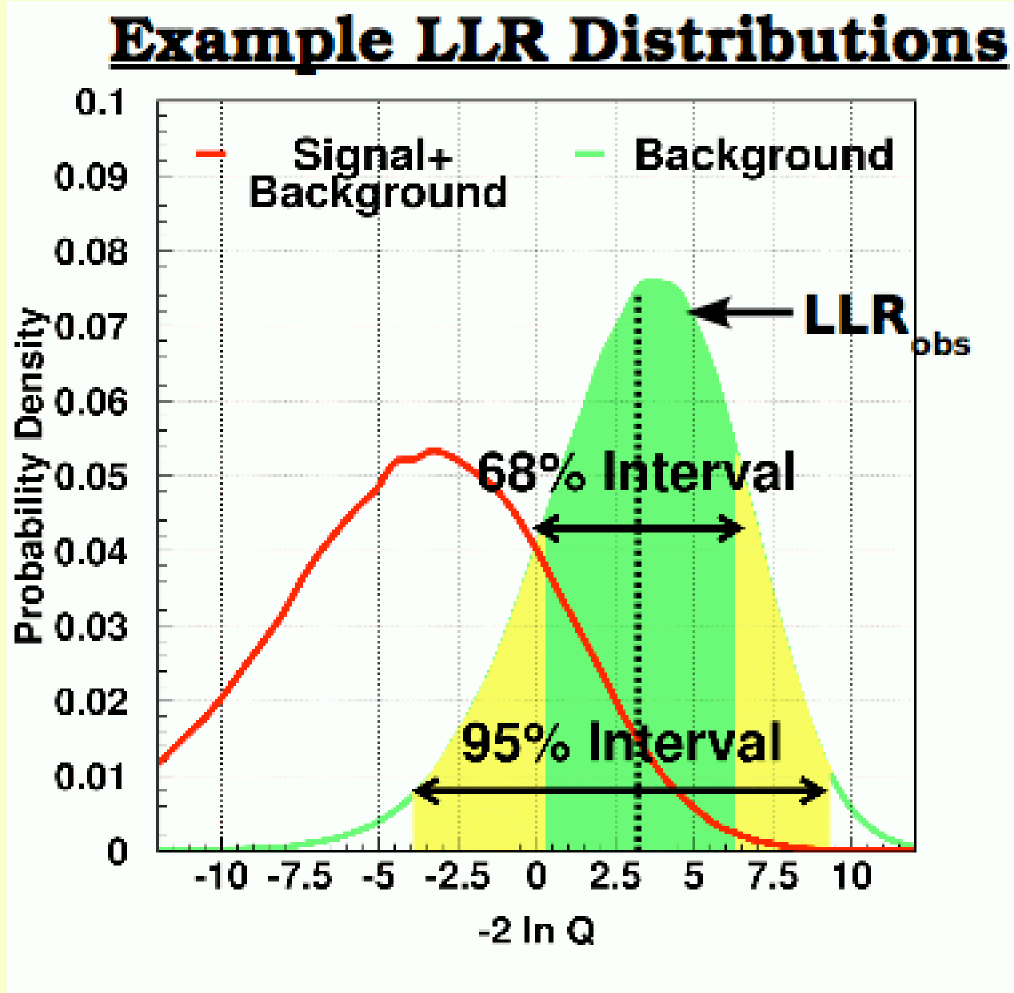
    Where S_k has a mean of 0 and width of 1

    Marginalizing!
  - Minimize Poisson estimator by varying S_k values

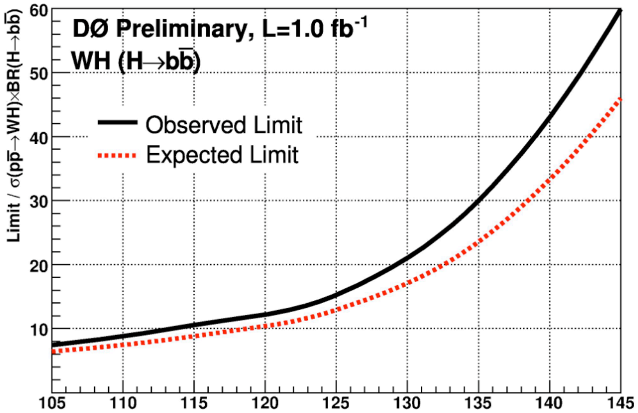
$$\chi^2 = 2\sum_i (B_i - D_i) - D_i \ln\left(\frac{B_i}{D_i}\right) + \sum_k S_k^2$$

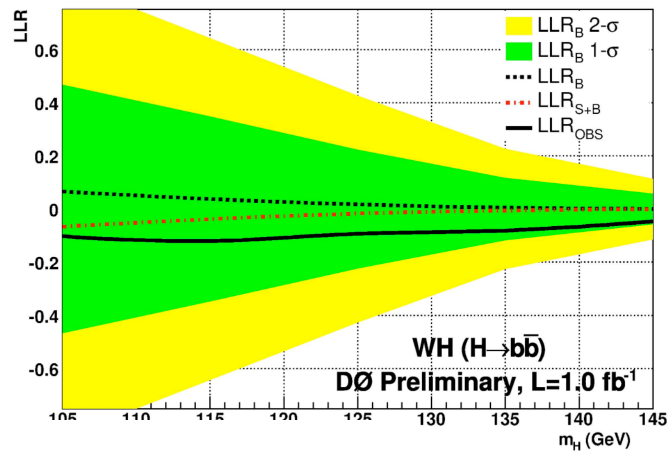
CLs in Pictures

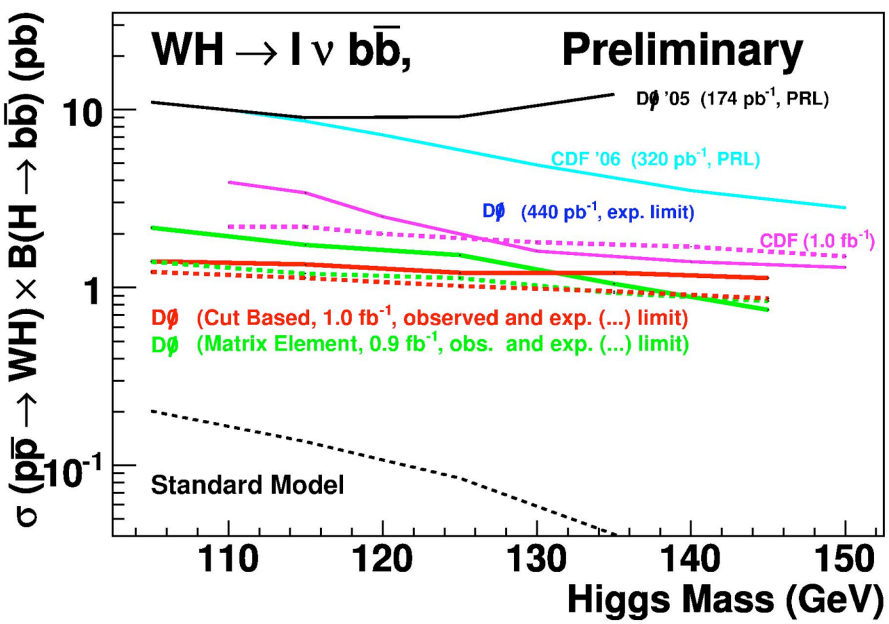
- ✗ Black dashed line: Observed LLR value (LLR_{obs})
- ✗ Green: Bkgd-only hypothesis
  - ✗ CL_b is region to right of LLR_{obs}
  - ✗ Equals ~50% for good bkgd/data agreement
- ✗ Red: Signal+bkgd hypothesis
  - ✗ CL_{s+b} is region to right of LLR_{obs}



W(H) → lνbb Limits

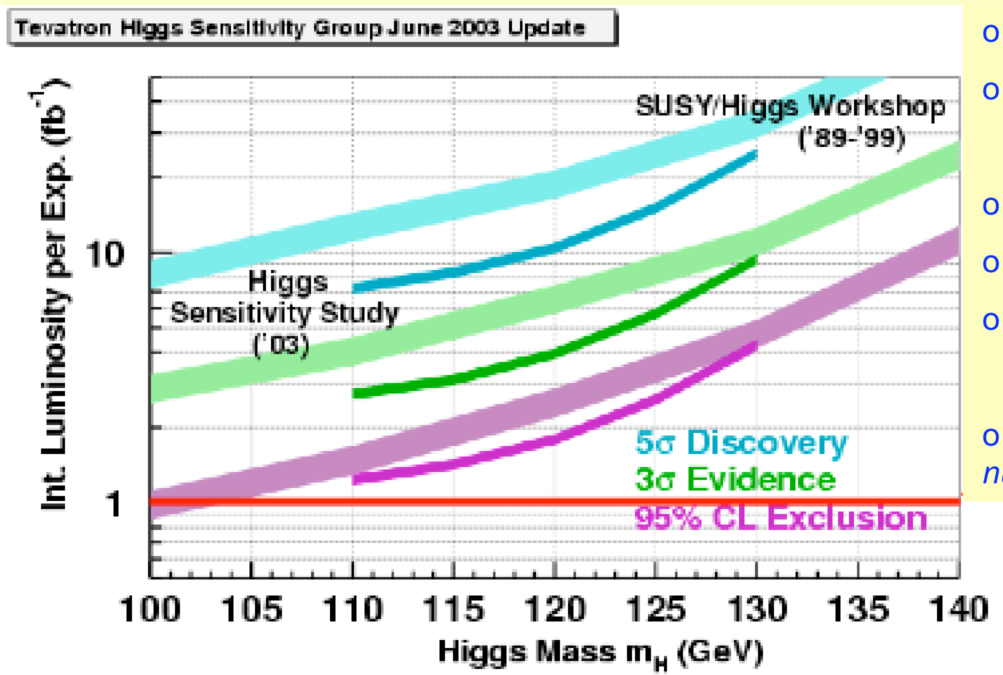






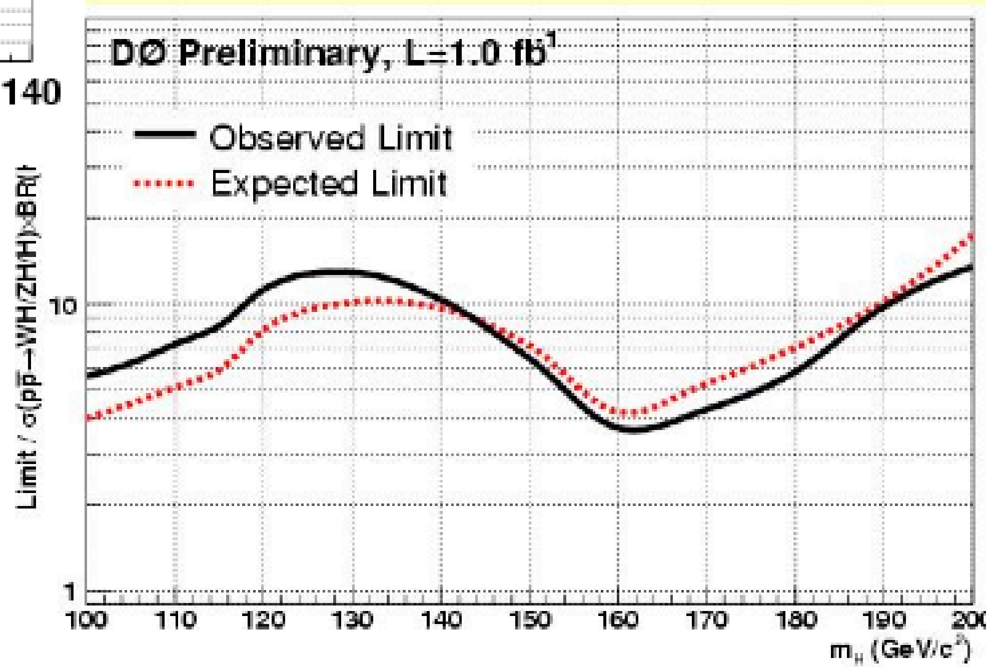
- Limits presented as ratios to the expected Standard Model cross section
  - 95% CL exclusion when ratio=1.0
  - Facilitates flexible combination of channels, interpretation of model

Where are we at the moment?



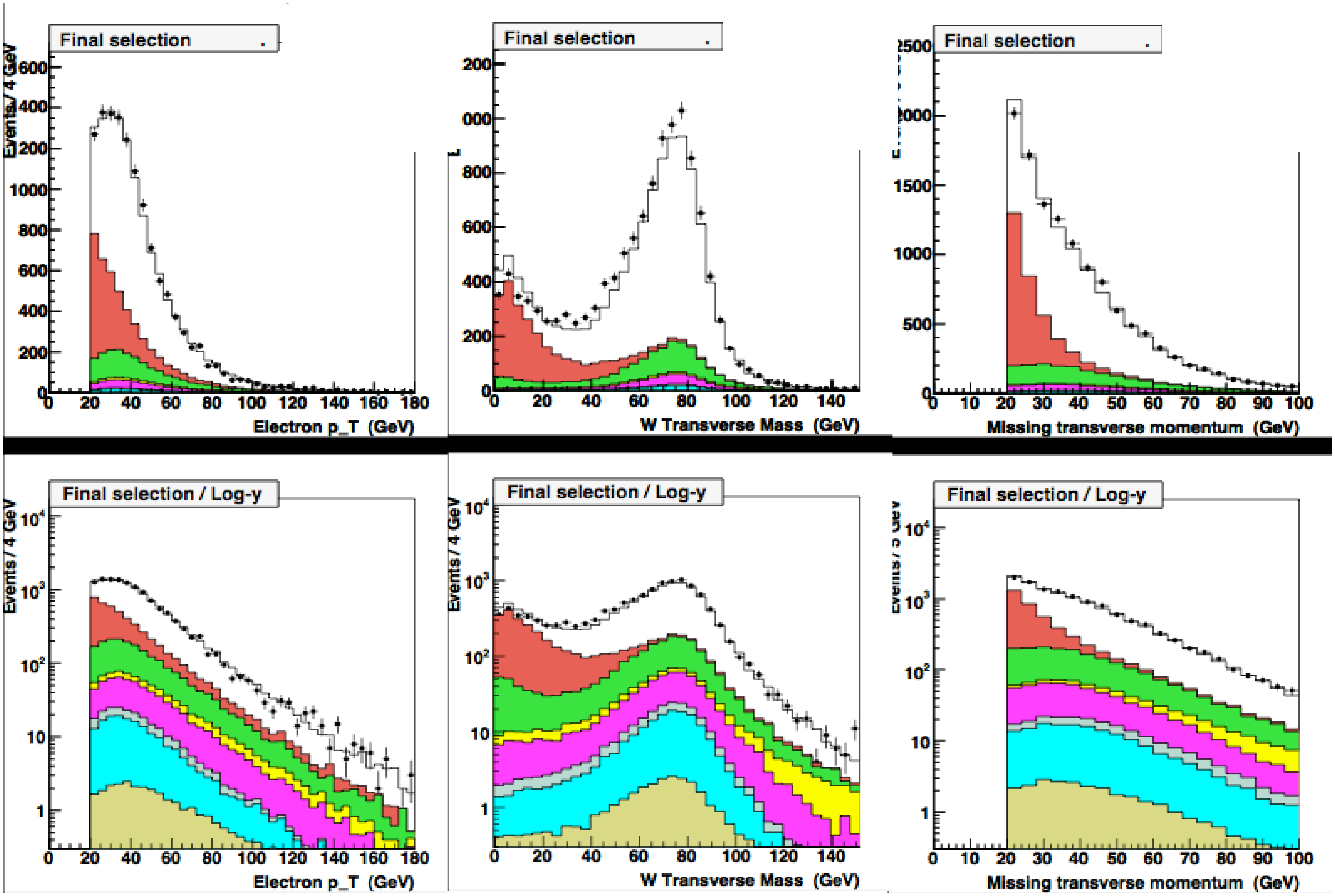
- o *We are not there yet!*
- o *Success at the Tevatron could be*
  - o *Exclusion / Discovery of SM Higgs*
- o *Either way we need to go beyond*
- o *LHC is the next logical step*
- o *Need to investigate other possibilities*
  - o *SUSY Higgs searches*
- o *If discovered we need to measure properties, quantum numbers with precision - ILC*

- ✗ Prediction indicates sensitivity at m_H~100 GeV for 1.0fb^{-1}
  - ✗ We're about a factor of 4 away
  - ✗ Prediction too aggressive?
  - ✗ Don't forget, need CDF!!

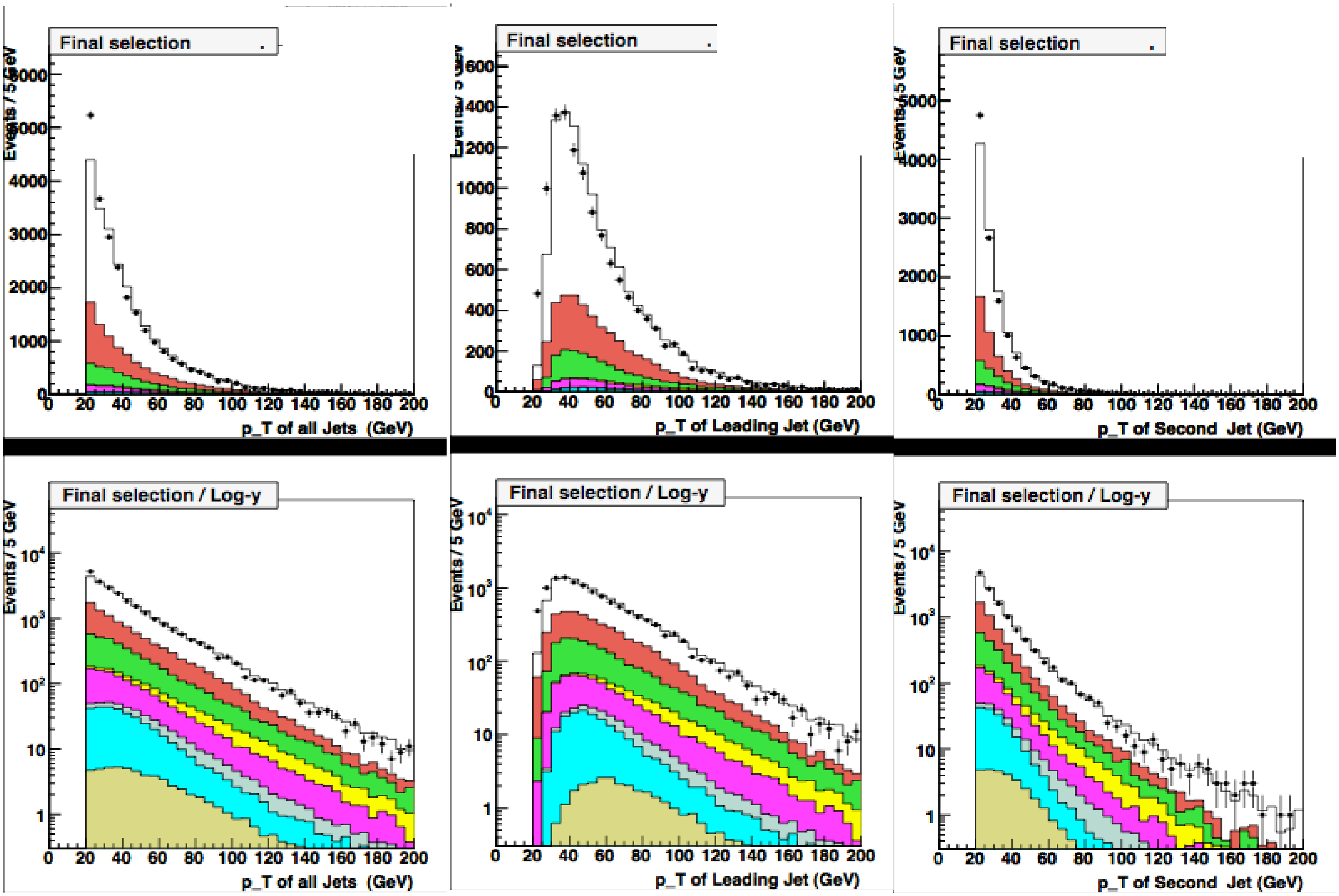


BACK UP SLIDES

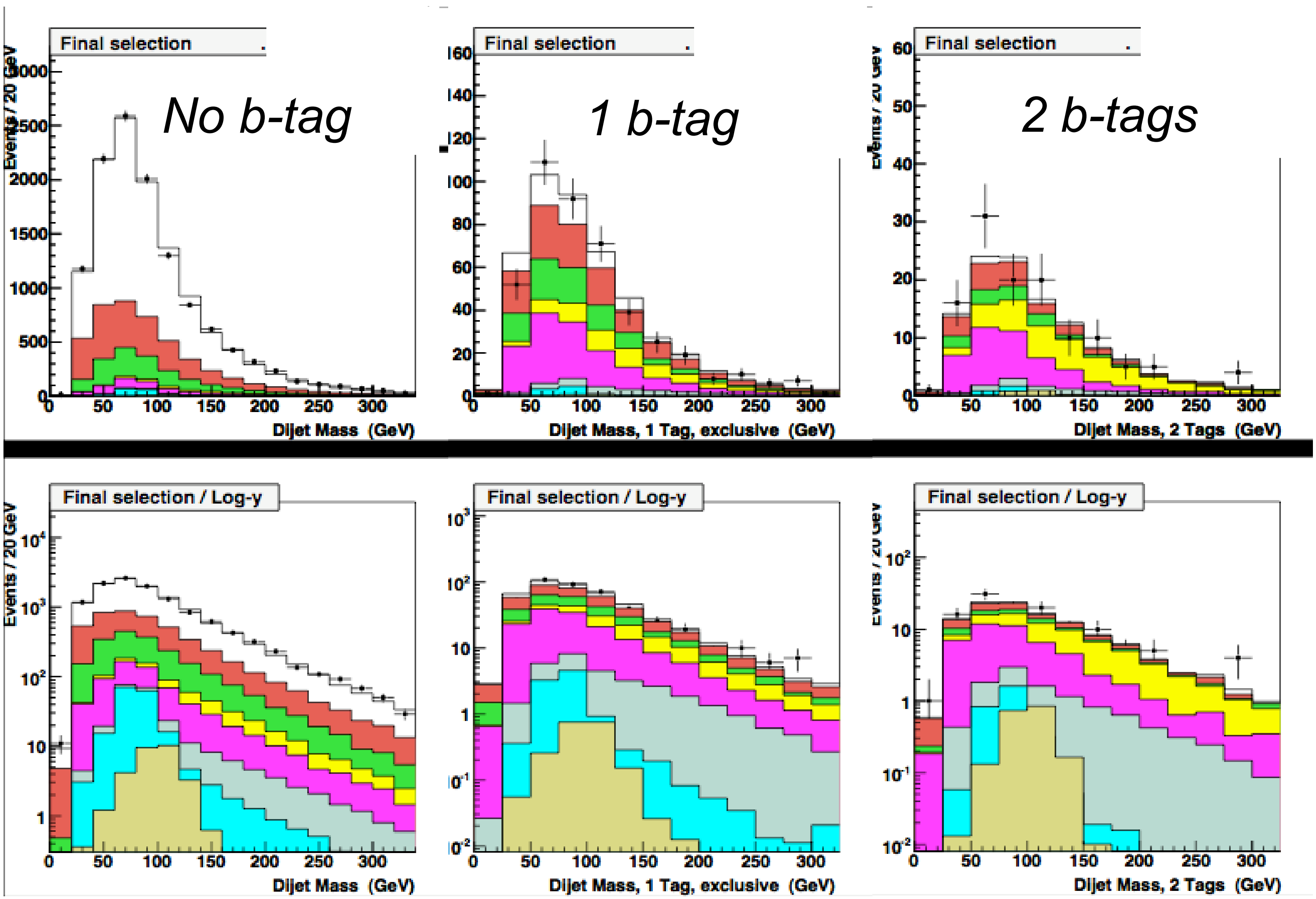
W + 2jets Properties (Single EM “OR”)



W + 2jets P_T of Jets (Single EM “OR”)



W+2jets Properties (Single EM “OR”) - Dijet Mass



Event Yield

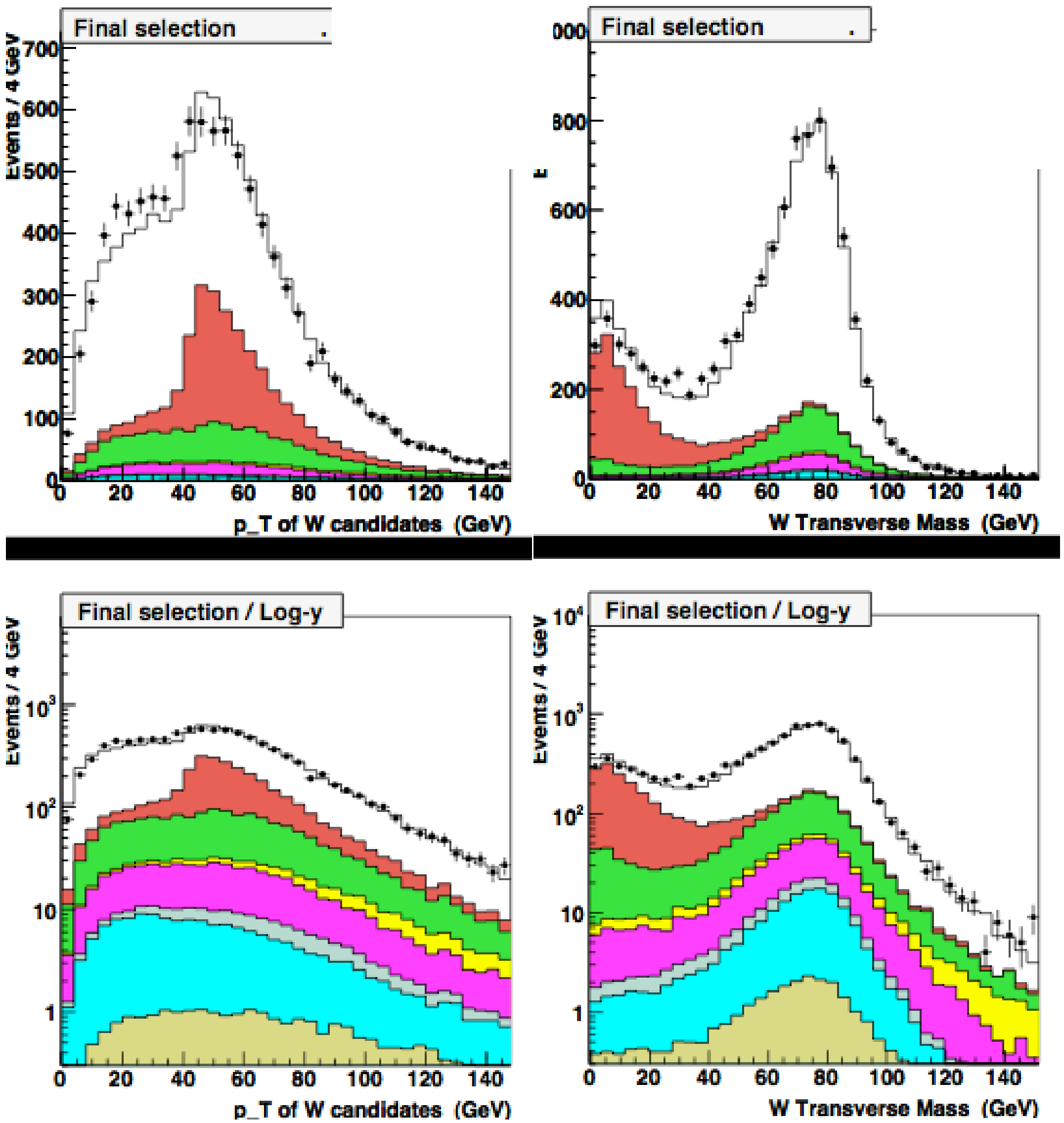
Event Yield: Single EM “OR”

	W(e) + 2jets	W(e) + 2jets (1 b jet)	W(e) + 2jets (2 b jet)
Data	12333	449	122
Exp. Bkg	12333.00	463.44	119.64
Signal (WH)	3.00 **(3.19)**	1.01 **(1.05)**	0.95 **(0.99)**

Event Yield: EM+JET Trigger (one per suite)

	W(e) + 2jets	W(e) + 2jets (1 b jet)	W(e) + 2jets (2 b jet)
Data	10027	384	100
Exp. Bkg	10027.00	384.40	95.00
Signal (WH)	2.65 **(3.19)**	0.89 **(1.05)**	0.84 **(0.99)**

W Properties - Before Reweighting W-pT



W Properties

→*all corrections applied to MC except pT re-weighting*

→*Disagreement between Data/MC in Pt spectrum (0,50) GeV*

→*QCD dominates the WTMass region below 40 GeV*

Selection Cuts

→*Nj ==2, pT > 20 GeV*

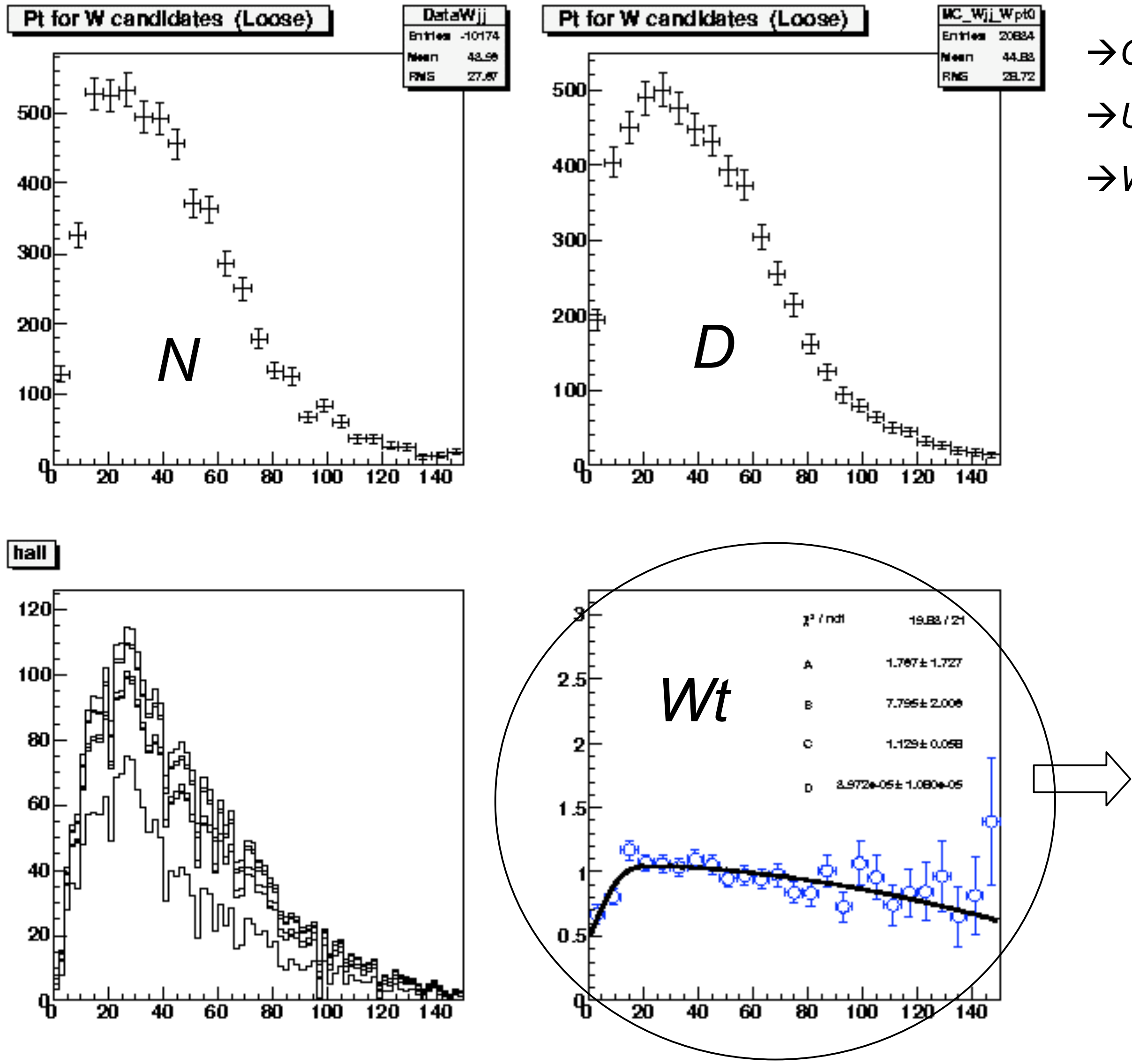
→*Mistag rate 0.3/0.03*

→*MET > 20 GeV*

Method

- Discrepancy b/w Data and MC
  - To study re-weighting, used additional cut
    - WTMass > 50 GeV
  - Major contribution to this discrepancy in pre-tagged samples is due to Wjj
- Define the weighting function: Wt = N / D where
  - N = Data - sum of all bkg except for Wjj (MC)
  - D = Wjj (MC)
- Fit Wt with: $0.5 [C + ERF\{(pT - A)/B\sqrt{2}\} + D(pT)^2]$
  - Fit Region of W-Pt (0,150) GeV
  - Similar study was done (Ref: D0 Note 5340)

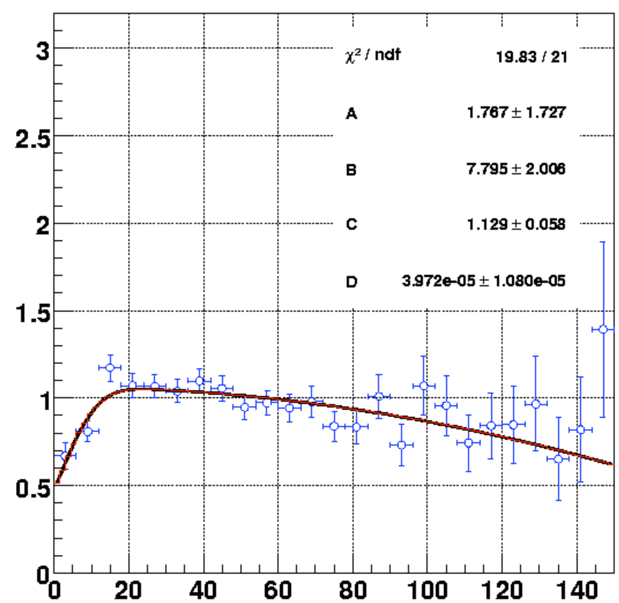
Results - W-pT Reweighting



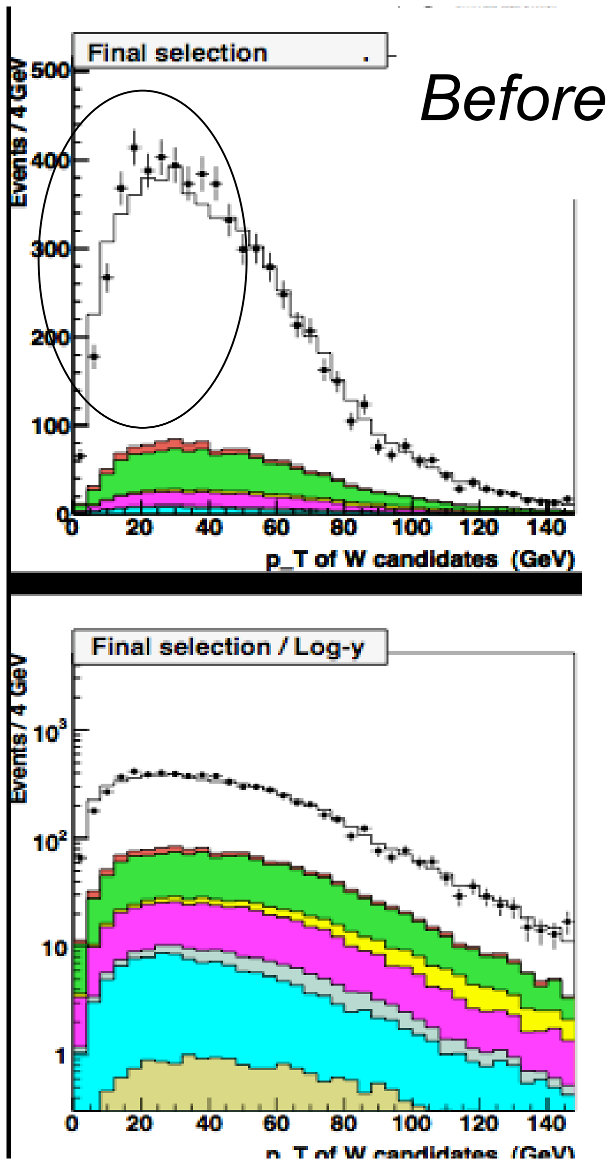
→ *Convert into spc file*

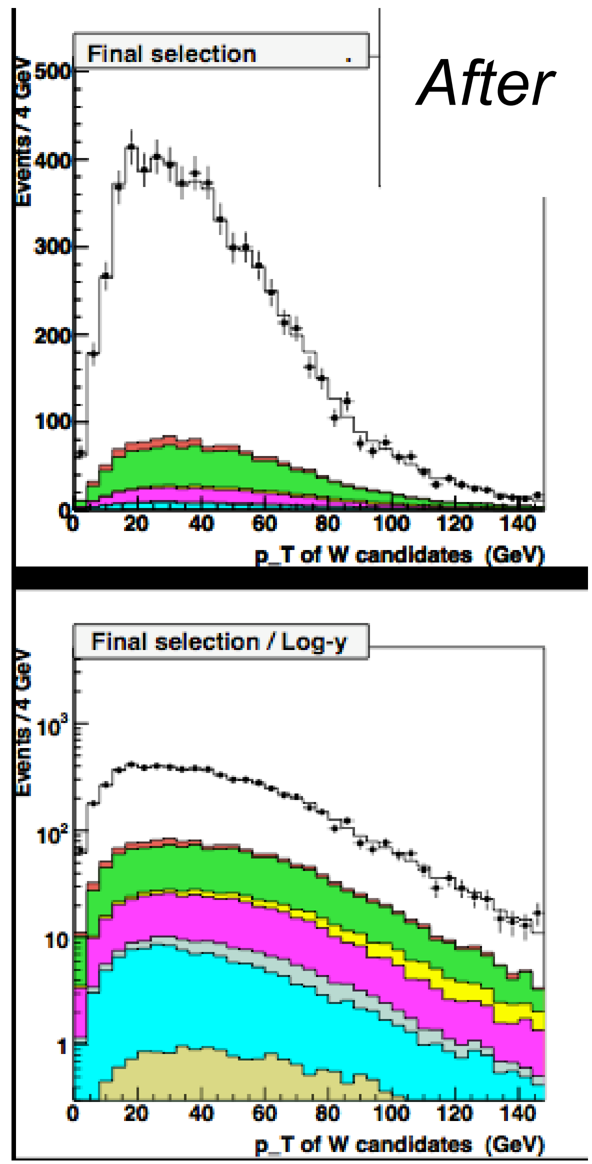
→ *Use it as an evt. Wt. to correct Wjj MC*

→ *Wt = N/ D*



Results - W-pT Reweighting





Conclusions/To Do List

"OR" of Calorimeter based triggers for each list with atleast one un-prescaled trigger in each list

This "OR" is actually an or of All CALO based EM trigger and EM+JET triggers.

- Average trigger efficiency is ≈95%
- Signal Efficiency increases by 13% (ST/DT)
- Luminosity increase: ~10%

TO DO:

- Triangle cut to remove QCD background and improve the $\Delta\varphi$ (em,met)
- Optimize Second lepton veto to reduce Z/ttbar contribution