Measurement of the Top Quark Mass in Final States with Two Charged Leptons at D0

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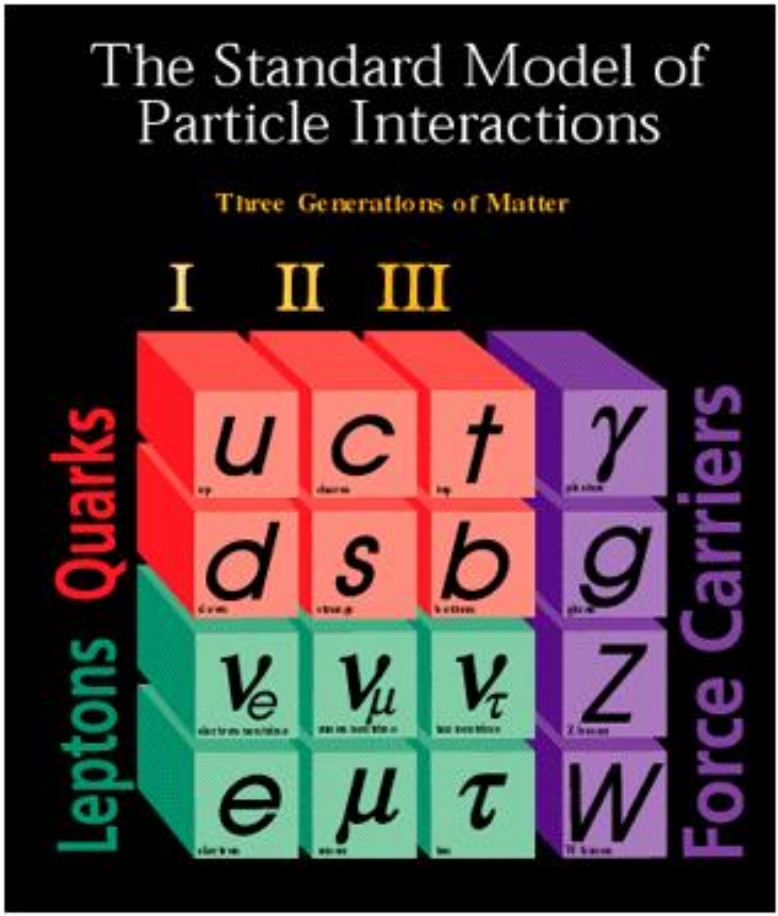
Outline

- Standard Model, the top quark, m_t
- Producing, detecting, selecting dileptons
- Measuring m_t in dileptons
- Result with data

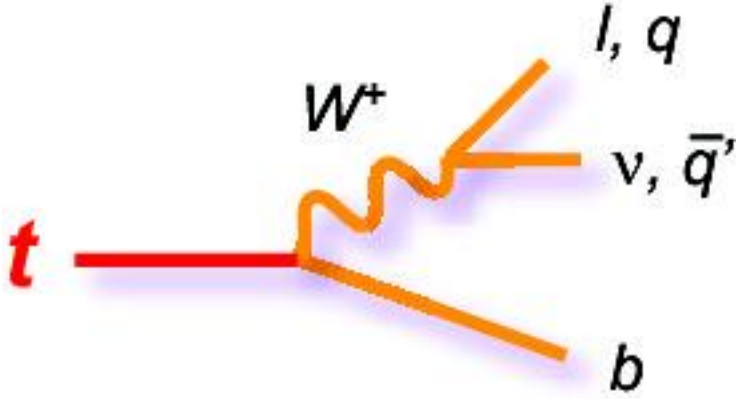
Standard Model

- 3 forces
  - Strong, Weak, EM
  - $\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$
  - Higgs Mechanism
  - gluon, $W^{\pm}/Z$, photon
- Fermions:
  - quarks , leptons
  - L doublets, R singlets
  - 3 generations
    - identical except larger masses



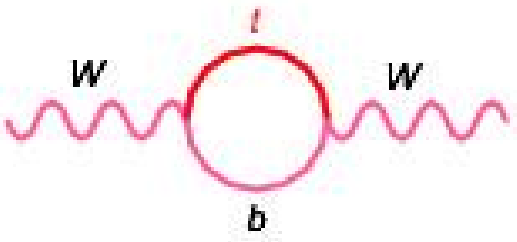
top quark

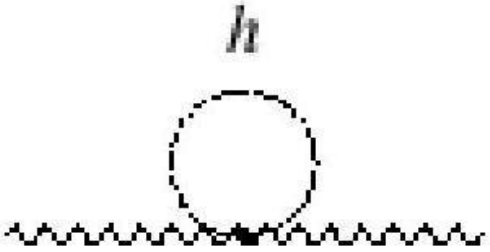
- most massive fermion
- $m_t \sim 173$ GeV
- mass 40 times m_b
  - mass of Tungsten
- $\Gamma_t >> \Lambda_{QCD}$
  - tops decay before hadronization
  - no toponium, T hadron
  - possible to measure m_t Γ_t Q_t



Precision EW Measurements

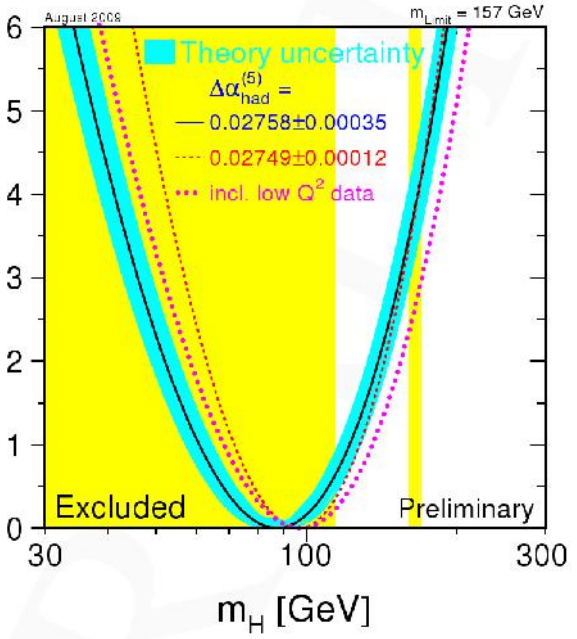
- SM has limited number of parameters:
  - $g_s(\Lambda)$, $g_L(\Lambda)$, $g_Y(\Lambda)$
  - $\upsilon = 246$ GeV
  - m_f^i , V_{CKM}
- Precision measurements:
  - G_F , $\alpha_{EM}(M_Z)$, M_Z , $\alpha_S(M_Z)$
- loop corrections:
  - Fermion loop: m_t^2
  - Higgs loop: $\log(m_H)$

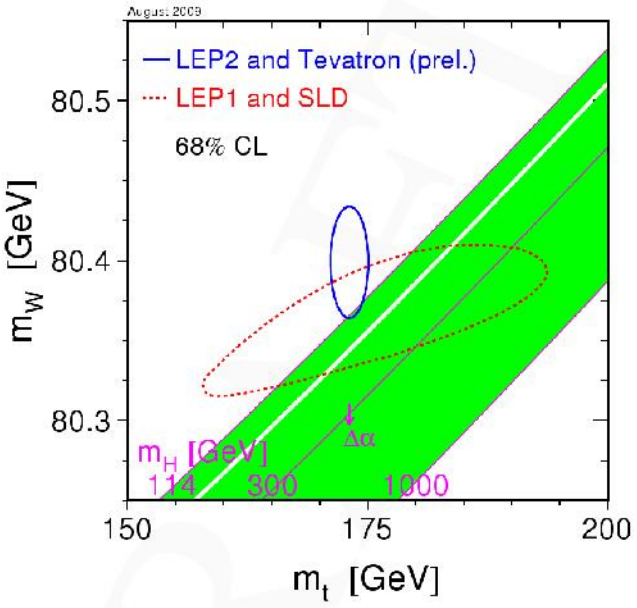




Constraint on Higgs Mass

- In SM Lagrangian:
  - $M_W = \frac{v|g_L|}{2} \qquad M_Z = \frac{v\sqrt{g_L^2 + g_Y^2}}{2}$
- Constraint on m_H from m_W:
  - m_t=173.1 ± 1.3 GeV
  - m_W= 80.399 ± 0.023 GeV
  - m_H =87 +35 -26 GeV
- m_H excluded by LEP?





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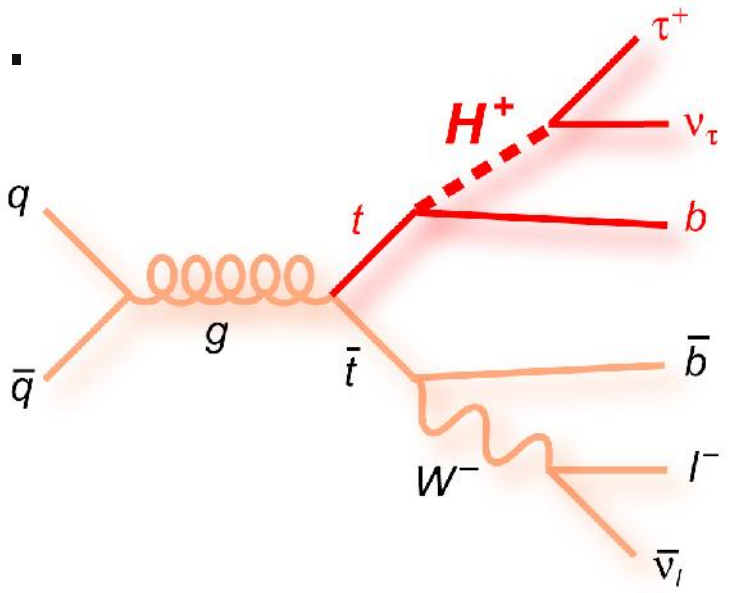
Why m_t with Dileptons?

- Different systematics
  - l+jets, alljets have W->qq
- Different Backgrounds
- Consistency Check
- Non SM t decays could affect channels differently.
  - t->H^+b for instance



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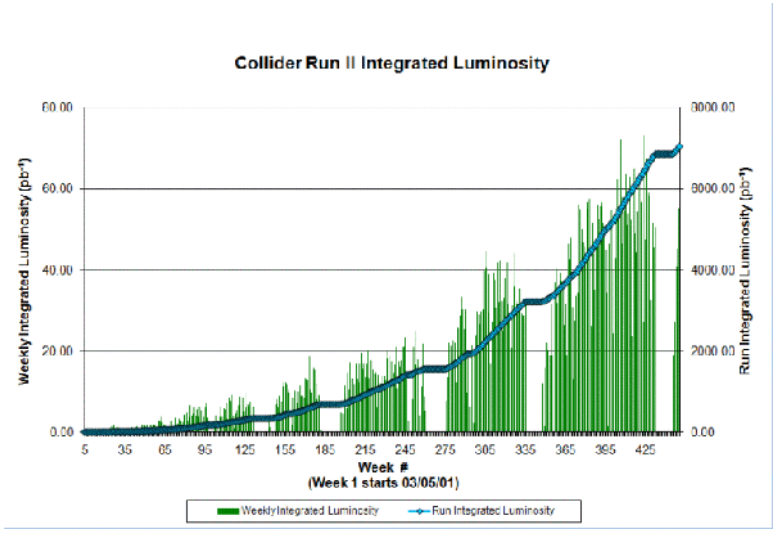
Tevatron

- $p\bar{p}$ collider
  - 1.96 TeV
- Run I : 1992-1996
  - ~0.4fb^{-1}
- Run IIa : 2001-2006
  - ~1fb^{-1}
- Run IIb : 2006-2011?
  - ~5fb^{-1} so far



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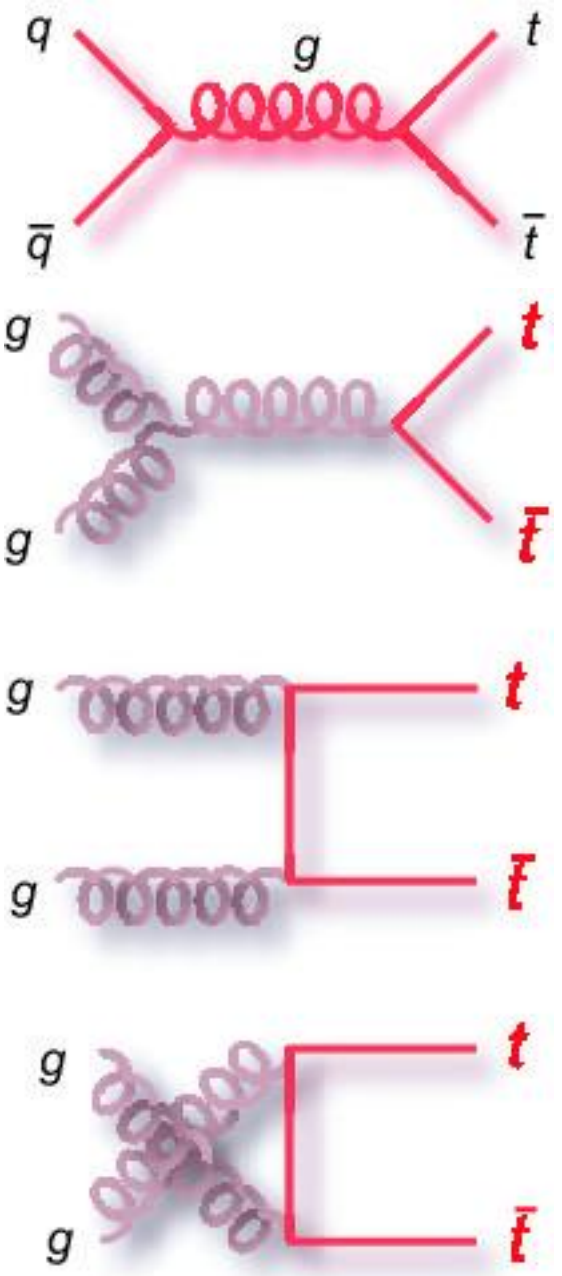
Top Pair Production

- 2 modes at leading order:
  - $q\bar{q}$: 85% at TeV
  - gg : 15% at TeV
- At Tevatron:
  - valence $u\bar{u}$->$t\bar{t}$ $d\bar{d}$->$t\bar{t}$
- At LHC:
  - gg->$t\bar{t}$

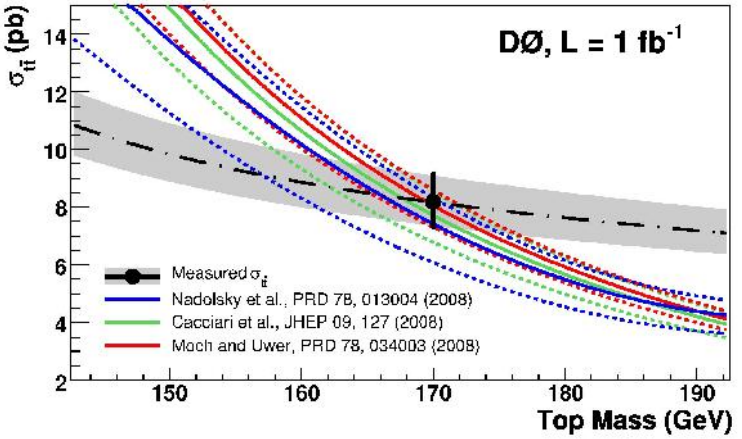


$t\bar{t}$ Production Cross Section

- Total cross section:
  - 7.45 pb for m_t=172.5 GeV

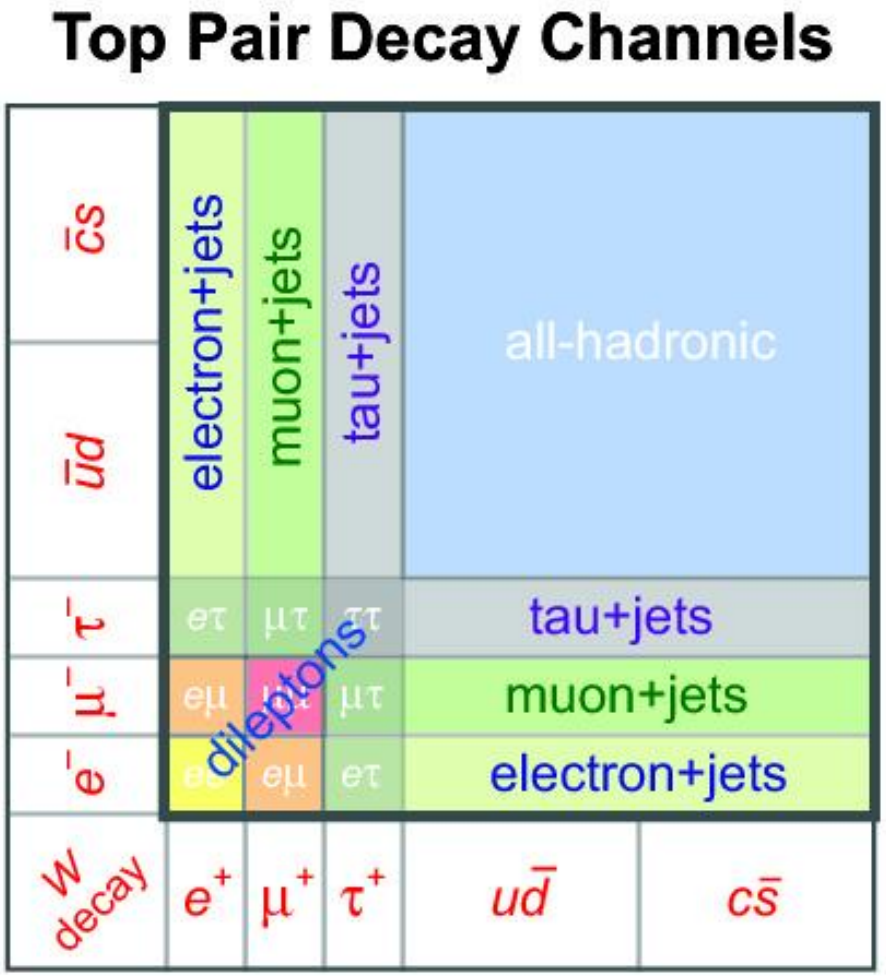
    PRD 78, 034003 (2008)
- Can constrain m_t using measured cross section.
  - m_t=169.1 +5.9 -5.2 GeV

    PRD 80,071102 (2009)



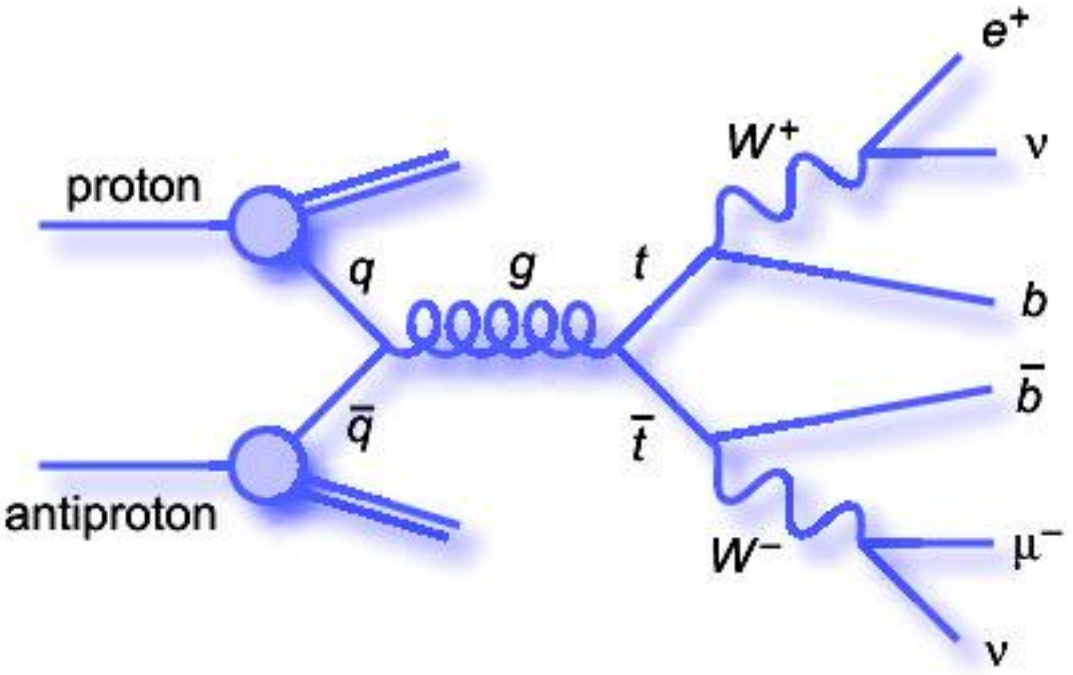
Decay Channels

- Br(t->bW) >99%
- W->lν or $q\bar{q}'$
- W decay-> 3 modes
  - alljets WW->4q
  - l+jets WW->lν qq
  - dilep WW->lν lν
  - τ+jet,l+τ,τ+τ
    - τ->lν + ν
    - τ->h's + ν



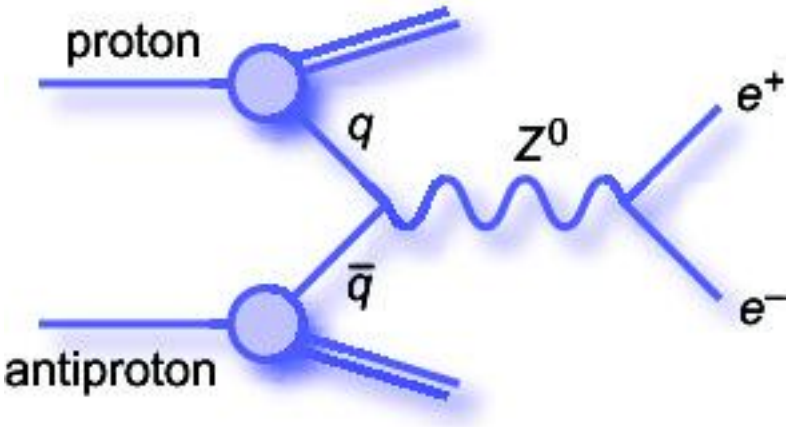
Dilepton Channel

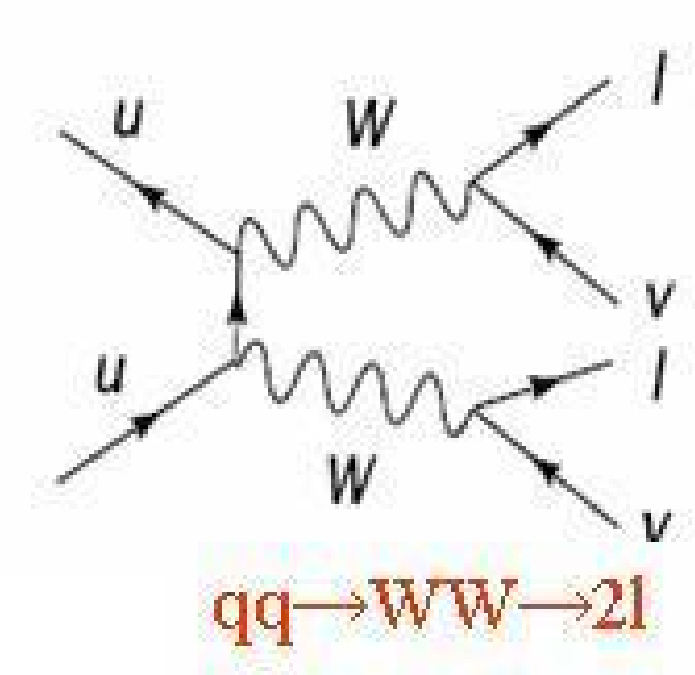
- 2 leptons from W's
  - (τ->lνν included)
  - ee , eμ , μμ
- Missing Transverse Energy from ν's
  - aka MET
- 2 jets from b-quarks



Backgrounds

- Backgrounds:
  - Instrumental
  - Z->ee/μμ
    - no MET
  - Z->ττ->2l 4ν
  - WW->lνlν
  - WZ->ll lν
  - ZZ->ll νν



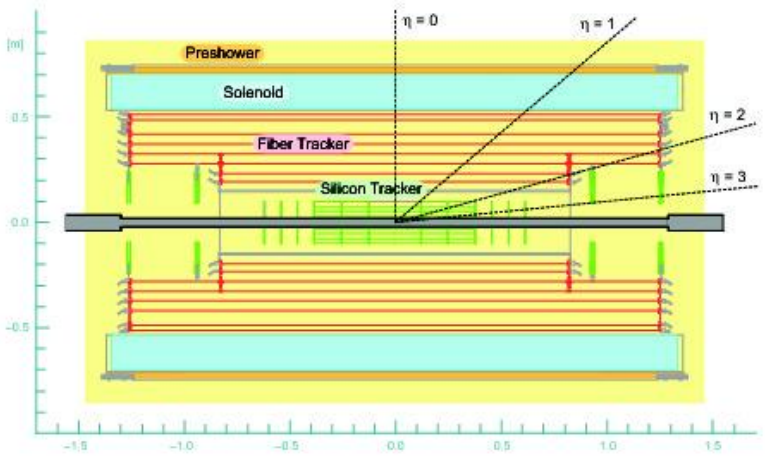


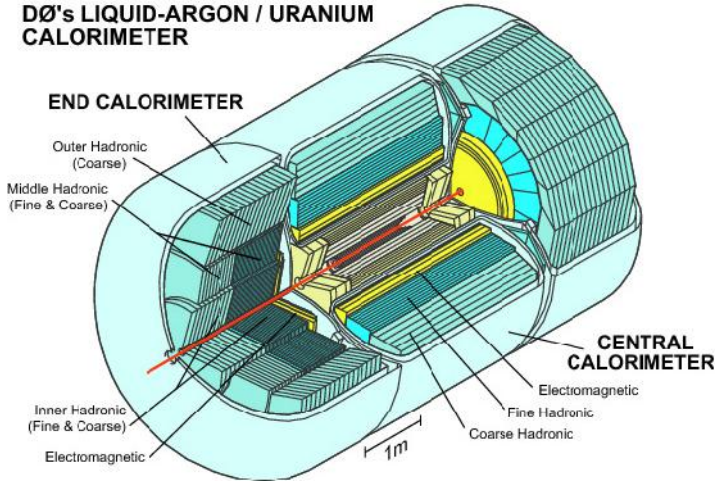
Monte Carlo Simulation

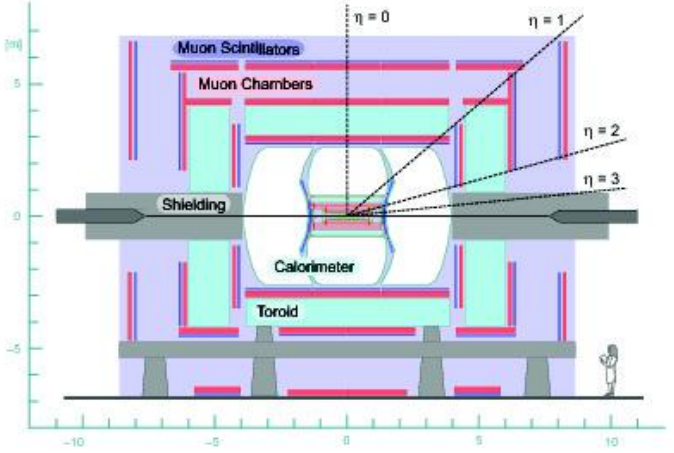
- PDF's
- Matrix Element
  - Hard Interactions
  - ALPGEN+PYTHIA
- Parton Shower
  - q -> qg , g -> qq
  - parton jet
- Hadronization
  - q,g -> hadrons
  - particle jet
- Particle Decay's
  - B-hadrons
  - τ leptons
- GEANT
- Detector Simulation
- Recontruction
  - e,μ,jet,MET

D0 Detector

- Central Tracker:
  - 2T B-field
  - Silicon Tracker
  - Fiber Tracker
- Calorimeter: |η|<4
  - EM, Hadronic
  - Central, Endcap, Scintill. Detector
- Muon: |η|<2
  - Central, Forward







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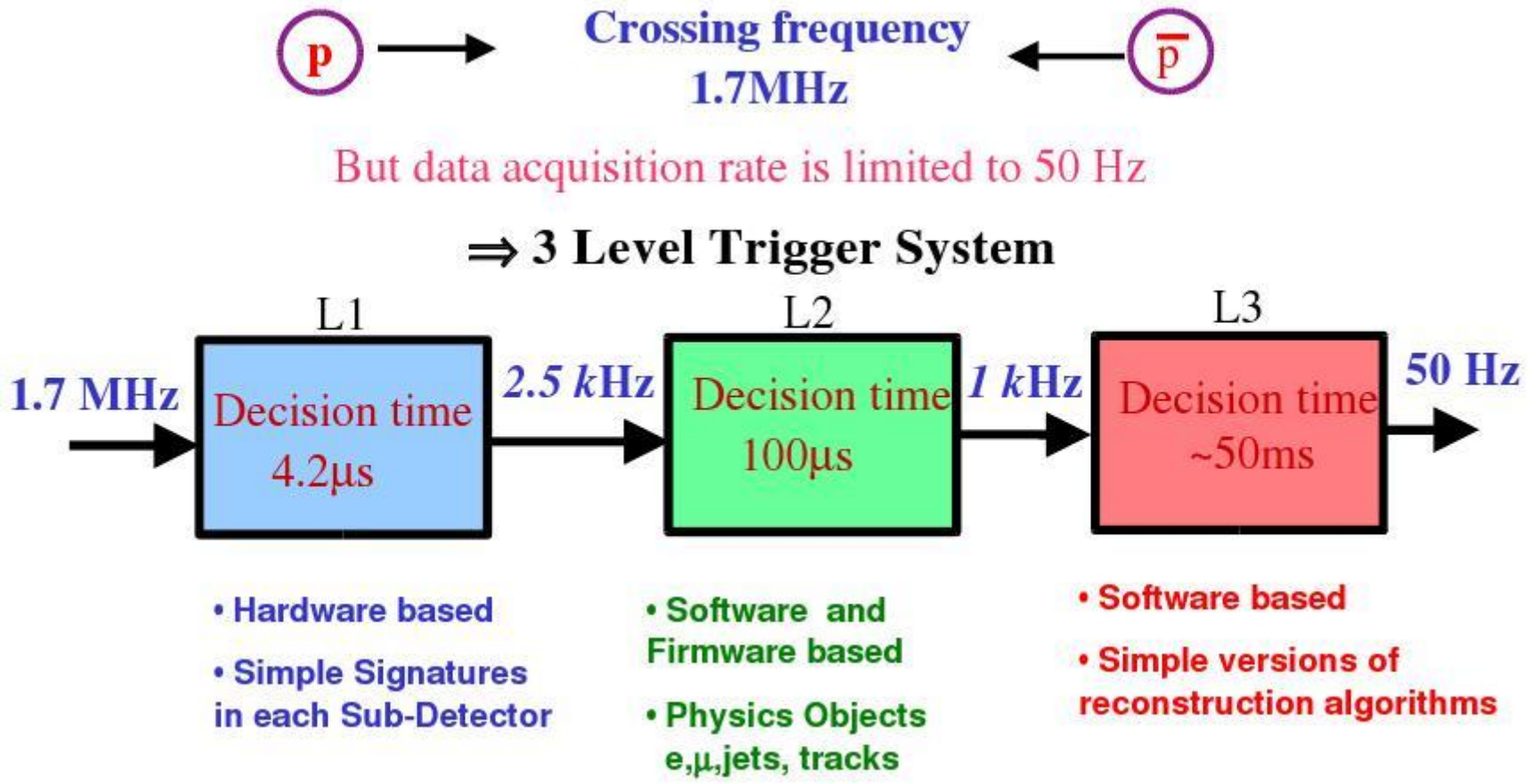
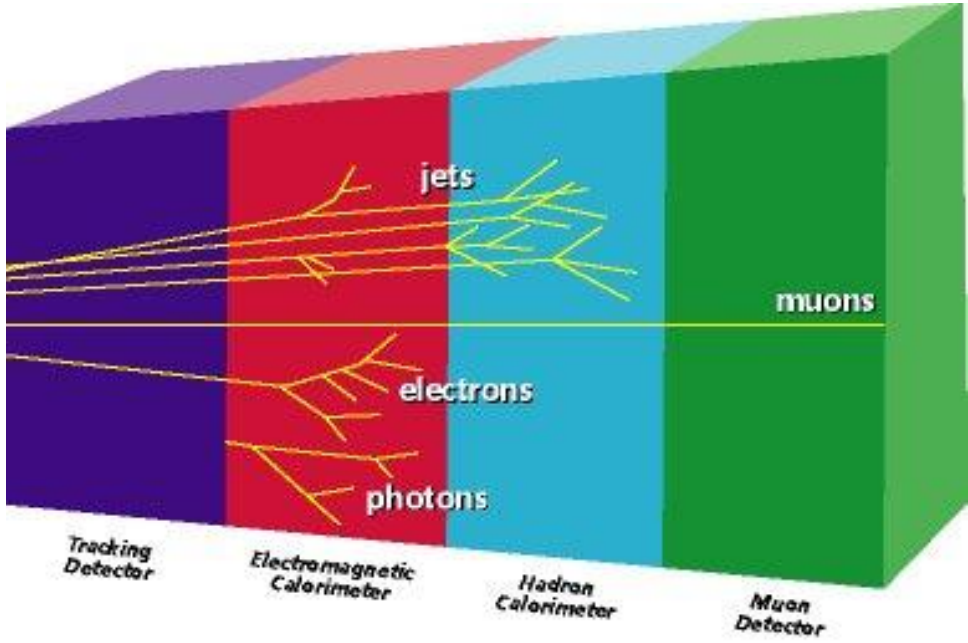
$$\eta = \tanh^{-1}(\cos\theta)$$

Trigger


p
Crossing frequency
1.7MHz
p̄
But data acquisition rate is limited to 50 Hz
⇒ 3 Level Trigger System
L1
L2
L3
1.7 MHz
Decision time
4.2μs
2.5 kHz
Decision time
100μs
1 kHz
Decision time
~50ms
50 Hz
• Hardware based
• Simple Signatures
in each Sub-Detector
• Software and
Firmware based
• Physics Objects
e,μ,jets, tracks
• Software based
• Simple versions of
reconstruction algorithms

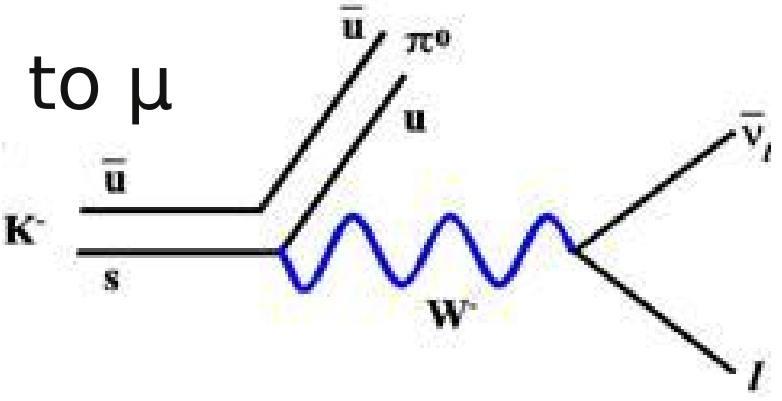
e/μ/Jet/MET Reconst.

- Electron:
  - Track + EM
- Muon:
  - Track + Muon Hits
- Jet:
  - Cone using EM/HAD CAL
- MET:
  - Vector sum E in CAL,
  - adjusted for e, μ, jet



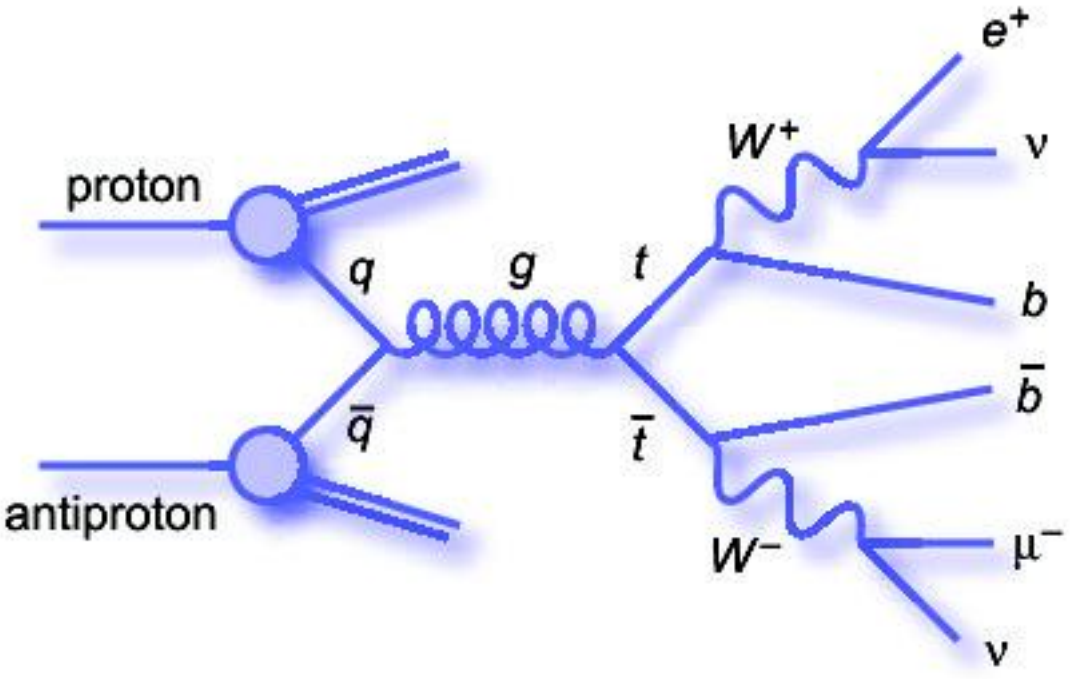
Instrumental Backgrounds

- Fake Electrons:
  - Isolated EM cluster + track
    - γ + track
    - γ -> e^+e^-
    - π^0->γγ + track
    - π^++n->π^0+p->γγ
    - jet shower fluctuations
- Fake Muons:
  - Hadrons ($\pi^{\pm}$,$K^{\pm}$) decaying to μ

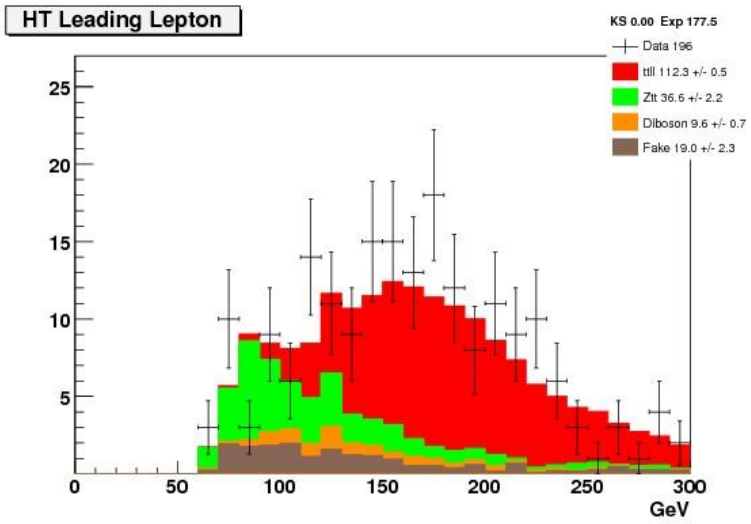


Event Selection

- Quality cuts reduce instrumentals
- 2 Leptons p_T>15 GeV
  - e: |η|<1.1
    or 1.5<|η|<2.5
  - μ: |η|<2
- 2 Jets p_T>20 GeV
  - |η|<2.5



Event Selection: eμ channel

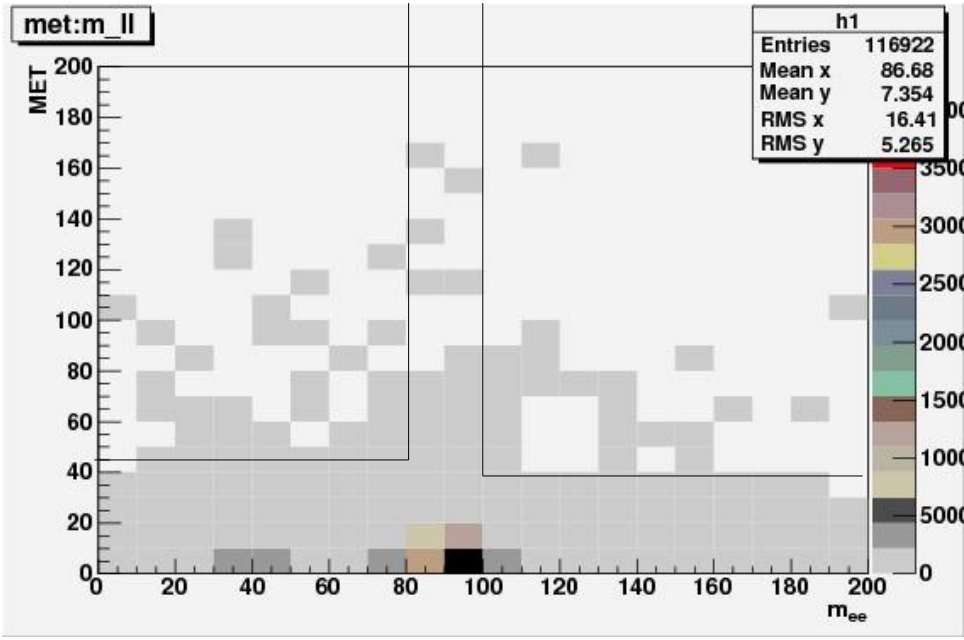


- Dominant Background:
  - Z->ττ
  - large MET
  - soft leptons, jets
- $H_T^l = \max(p_T^e, p_T^\mu) + p_T^{j1} + p_T^{j2} > 105$ GeV
- No cut on MET

	inc	≥ 1 jet	≥ 2 jets	$H_T^l > 105$ GeV
$Z \to \tau\tau$	1585 ± 22.5	271.4 ± 8.3	37.4 ± 2.2	19.6 ± 1.5
$WW/WZ/ZZ$	254.8 ± 3.6	51 ± 1.6	10.1 ± 0.7	7.9 ± 0.6
fake	202.2 ± 3.6	72.7 ± 2.4	20.7 ± 0.9	14 ± 0.7
$t\bar{t} \to l\bar{l}$	154.5 ± 0.5	152.6 ± 0.5	120.2 ± 0.5	115.5 ± 0.6
total	2196.5 ± 23.1	547.7 ± 8.8	188.4 ± 2.6	157 ± 1.8
data	2131	601	201	173

ee channel

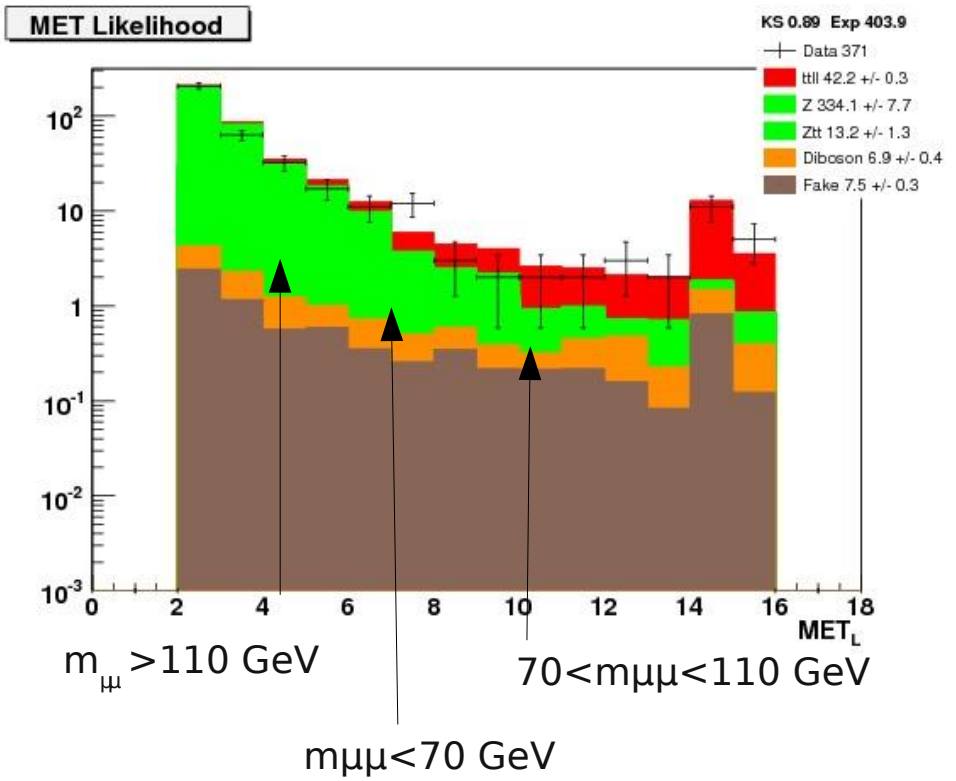
- Main Background:
  - Z->ee
  - no real MET
  - good energy resolution



	inclusive	≥ 1 jet	≥ 2 jets	Z veto $\not{p}_T > 30$ GeV	final selection
$Z \to ee$	123235 ± 207	17748 ± 62	2566.4 ± 19.6	22.0 ± 1.9	2.2 ± 0.3
$Z \to \tau\tau$	532.8 ± 12.5	74.0 ± 4.0	10.7 ± 1.1	6.4 ± 0.9	3.2 ± 0.6
$WW/WZ/ZZ$	179.0 ± 2.3	88.2 ± 1.3	41.2 ± 0.8	1.9 ± 0.3	1.3 ± 0.2
fake	291.8 ± 118.5	90.2 ± 17.2	16.7 ± 2.7	2.7 ± 0.1	1.3 ± 0.1
$t\bar{t} \to l\bar{l}\nu\bar{\nu}b\bar{b}$	55.7 ± 0.4	54.7 ± 0.4	41.4 ± 0.3	29.3 ± 0.3	24.4 ± 0.3
total expected	124294 ± 239	18056 ± 65	2676.3 ± 19.8	62.3 ± 2.1	32.3 ± 0.7
data	116496	16630	2489	49	34

μμ channel

- Dominant Background:
  - Z->μμ
  - no real MET
  - poor momentum resolution



$$\mathrm{MET_L} = \frac{\not{E}_\mathrm{T}^2}{2\sigma^2} \qquad \sigma = \sqrt{\sum_{i=objects} [\sigma_i^E \cos\Delta\phi_{i\not{E}_T}]^2 + \sigma_\mathrm{UE}^2}$$

	inclusive	≥ 1 jet	≥ 2 jets	$\not{p}_T^\sigma > 2$	final selection
$Z \to \mu\mu$	174729 ± 225	26344 ± 71	4128.4 ± 23.0	334.1 ± 7.7	2.7 ± 0.6
$Z \to \tau\tau$	861.1 ± 14.9	142.4 ± 5.0	23.5 ± 1.8	13.2 ± 1.3	3.3 ± 0.7
$WW/WZ/ZZ$	242.2 ± 2.5	121.0 ± 1.4	60.7 ± 0.9	6.9 ± 0.4	2.2 ± 0.3
fake	152.9 ± 89.0	246.4 ± 18.6	58.6 ± 3.8	7.6 ± 0.4	2.1 ± 0.1
$t\bar{t} \to l\bar{l}\nu\bar{\nu}b\bar{b}$	70.7 ± 0.4	70.0 ± 0.4	57.4 ± 0.4	44.3 ± 0.3	25.6 ± 0.2
total expected	176054 ± 244	26860 ± 73	4311.5 ± 23.3	406.1 ± 7.8	36.0 ± 1.0
data	167368	27386	4388	371	32

Fake Rate Determination

- Create loose and tight lepton cuts.
- Form system of equations to extract number of non-instrumental events.

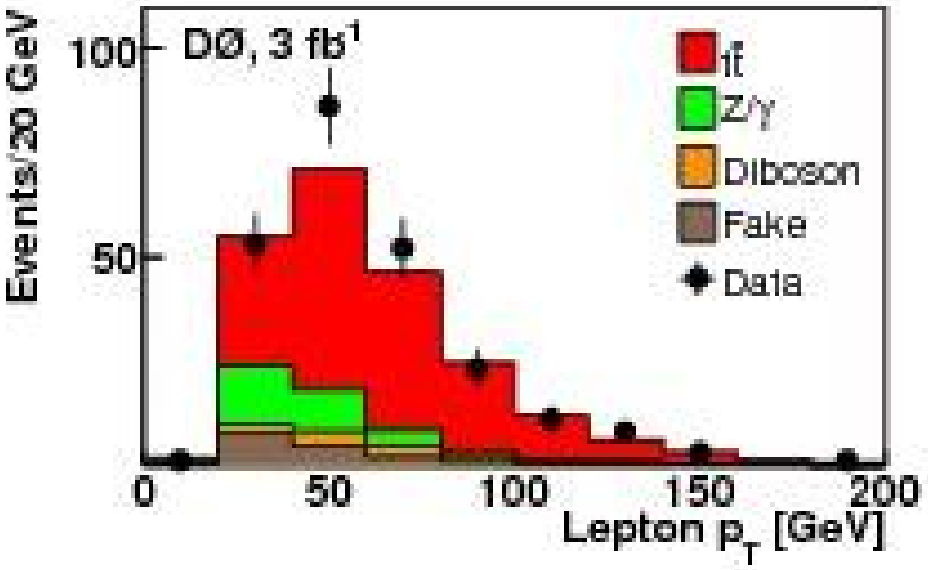
loose / tight

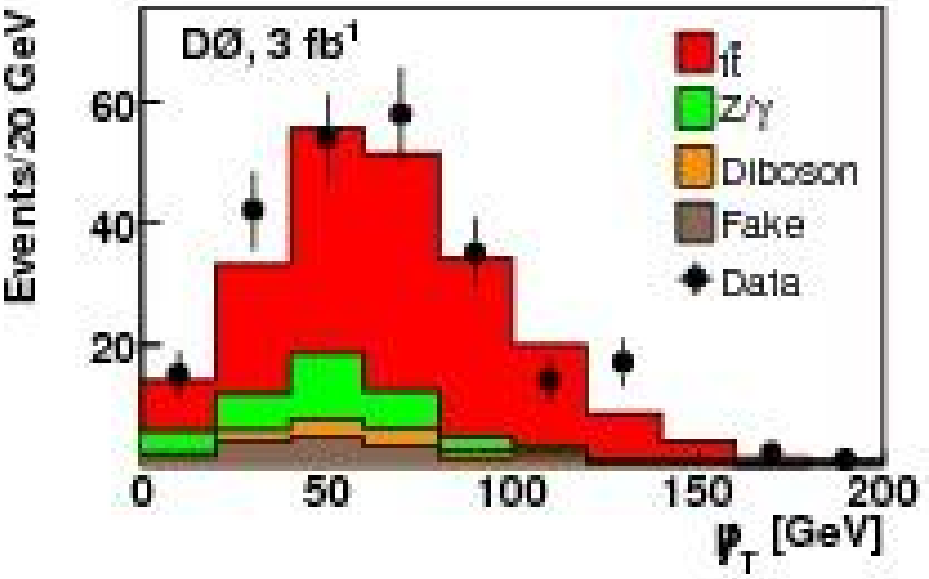
real/fake(instrumental)

$$\begin{pmatrix} N_{ll} \\ N_{tl} \\ N_{lt} \\ N_{tt} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ \epsilon_{r1} & \epsilon_{r1} & \epsilon_{f1} & \epsilon_{f1} \\ \epsilon_{r2} & \epsilon_{f2} & \epsilon_{r2} & \epsilon_{f2} \\ \epsilon_{r1}\epsilon_{r2} & \epsilon_{r1}\epsilon_{f2} & \epsilon_{f1}\epsilon_{r2} & \epsilon_{f1}\epsilon_{f2} \end{pmatrix} \begin{pmatrix} N_{rr} \\ N_{rf} \\ N_{fr} \\ N_{ff} \end{pmatrix}$$

- Invert matrix to obtain N_{rr} , $N_{f}=N_{rf}+N_{fr}+N_{ff}$

Final Yield





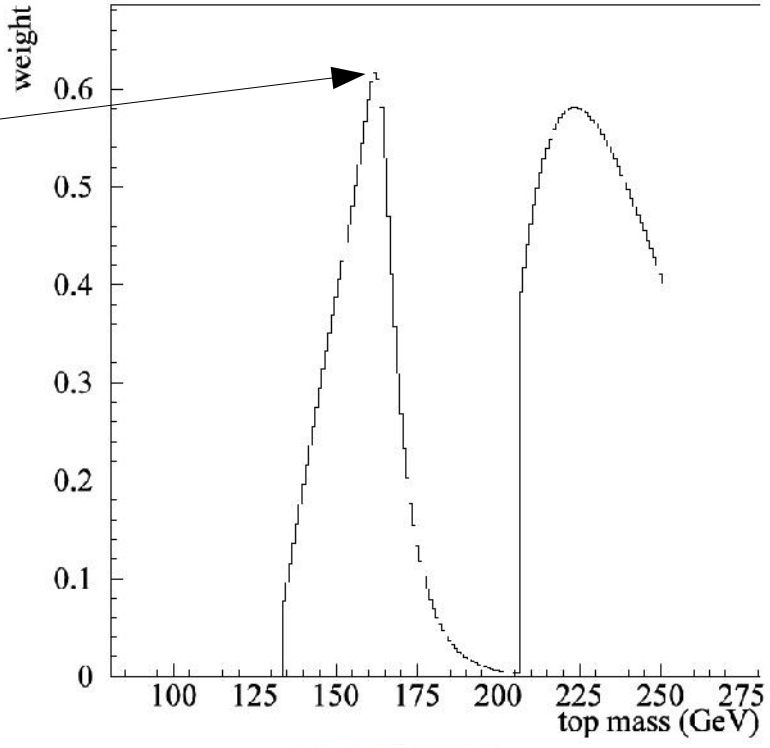
	ee	$e\mu$	$\mu\mu$	combined
$Z \to ee/\mu\mu$	2.2 ± 0.3		2.7 ± 0.6	4.9 ± 0.7
$Z \to \tau\tau$	3.2 ± 0.6	19.6 ± 1.5	3.3 ± 0.7	26.1 ± 1.8
$WW/WZ/ZZ$	1.3 ± 0.2	7.9 ± 0.6	2.2 ± 0.3	11.4 ± 0.7
fake	1.3 ± 0.1	14.0 ± 0.7	2.1 ± 0.1	17.4 ± 0.7
total background	8.0 ± 0.7	41.5 ± 1.7	10.3 ± 0.9	59.8 ± 2.1
$t\bar{t} \to l^- \bar{\nu}\bar{b}\ l'^+\nu' b$ $\sigma_{t\bar{t}} = 7.45$ pb	24.4 ± 0.3	115.5 ± 0.6	25.6 ± 0.2	165.5 ± 0.7
total expected	32.4 ± 0.7	157.0 ± 1.77	36.0 ± 1.0	225.3 ± 2.2
data	34	173	32	239

Top Kinematic Reconstruction

- Momenta of neutrinos aren't measured
  - 6 unknown quantities
  - Measured MET → 2 constraints
  - Fix mass of W's → 2 constraints
  - same mass for t and $\bar{t}$ → 1 constraint
  - 1 remaining unknown → m_t
    - no 1st order guess at m_t
    - must scan over m_t values
- For given $l^+, l^-, b, \bar{b}$, MET -> 0,2 or 4 solutions
- Each jet can be b or $\bar{b}$ -> up to 8 solutions

MWT Weight Distribution

- Assign weight to each allowed solution:
  - weight = PDF's × Prob(t->l^+) × Prob($\bar{t}$->l^-)
  - PDF's = F(x) × F($\bar{x}$)
  - Prob(t->l^+) = $\frac{4E_\ell^* m_t(m_t^2 - m_b^2 - 2E_\ell^* m_t)}{(m_t^2 - m_b^2)^2 - m_W^2(m_t^2 + m_b^2) - 2m_W^4}$
- For given m_t sum weights:
  - for all solutions
  - m_t^{max}



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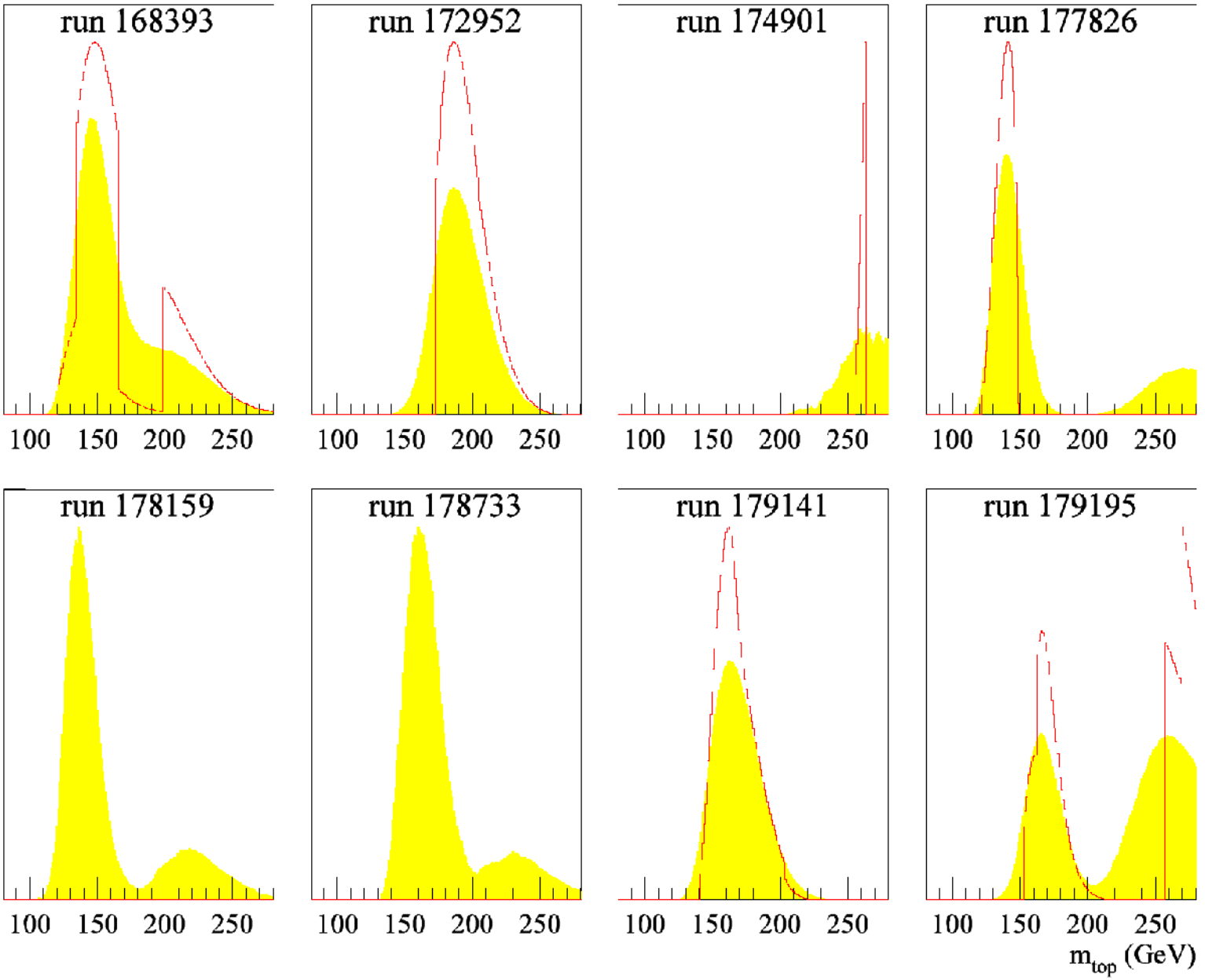
Detector Resolutions

- measured momenta very different from parton momenta
- sample parton momenta consistent with detector resolution
  - repeat 150 times
  - sum w

- e res:
  - $\sigma(E)/E \sim 0.005$
- mu res:
  - $\sigma(p_T^{-1})/p_T^{-1} \sim 0.1$
- jet res:
  - $\sigma(E)/E \sim 0.2$
- MET res:
  - $\sqrt{}$Unclustered E
  - $\sigma(\sqrt{}UE) \sim 5\text{-}10$ GeV

Detector Resolutions



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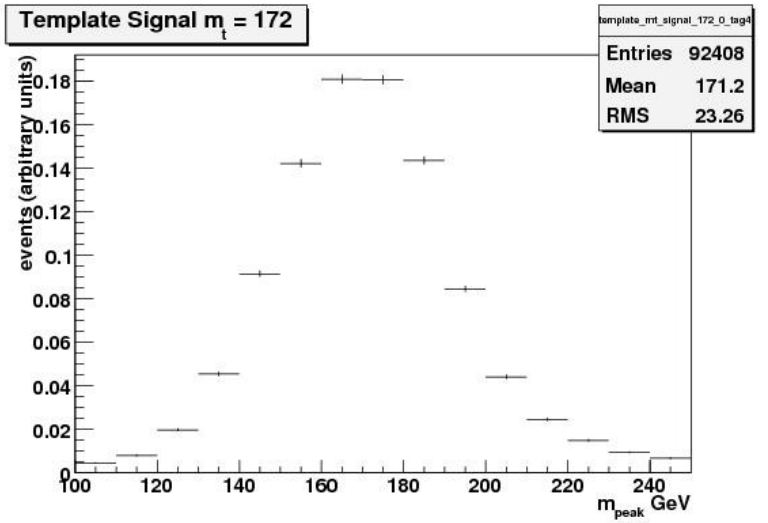
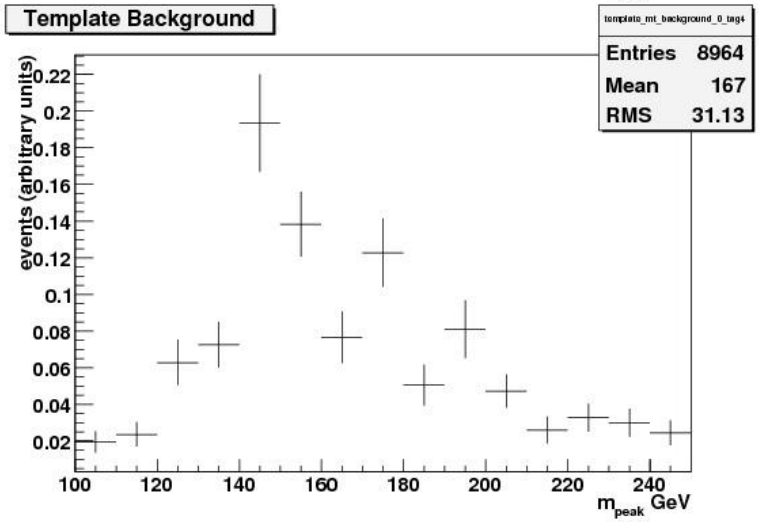
Templates, Likelihood

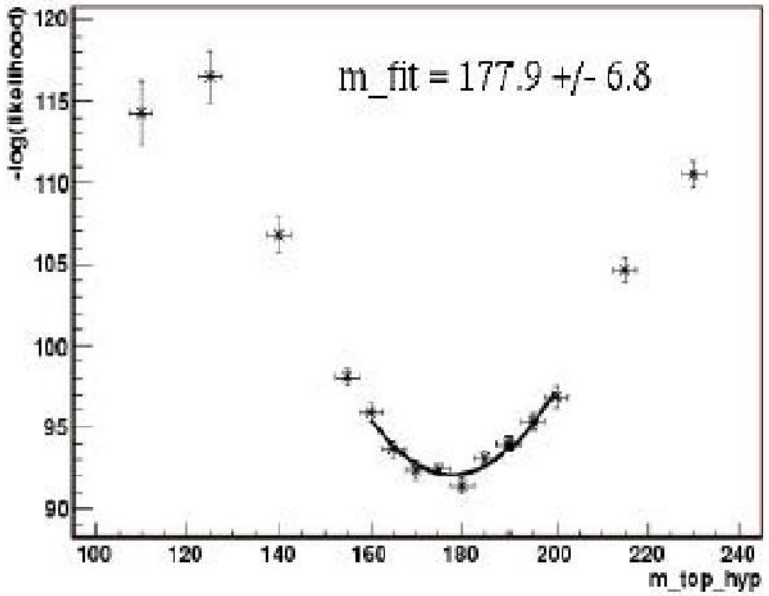
- Template
  - put all m_t^{max} from a given sample into histogram, normalize
- Samples:
  - each m_t sample
  - backgrounds
- Form likelihood: $\mathcal{L}(m_t) = \prod_{i=1}^{n_{bin}} \left[\frac{n_s s_i(m_t) + n_b b_i}{n_s + n_i} \right]^{n_i}$
- Fit -logL to measure m_t

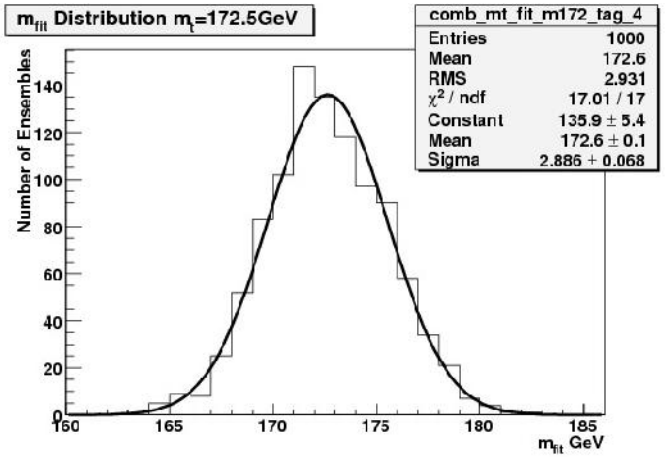


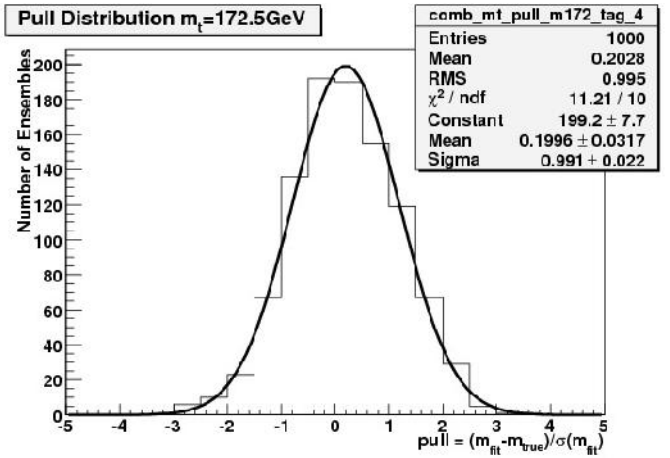


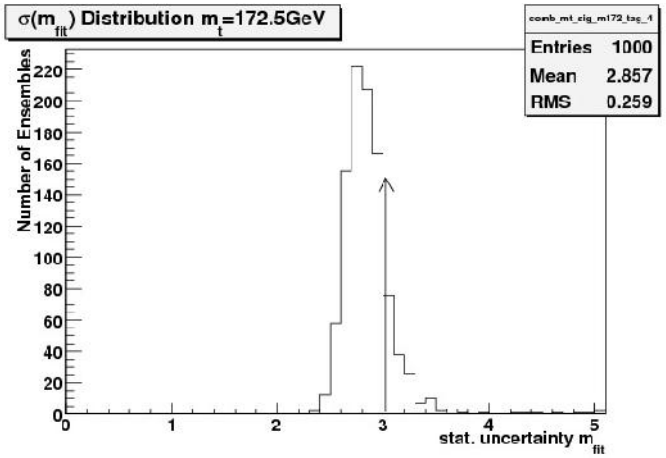
Statistical Calibration

- Form pseudoexperiments:
  - match expected sample composition in data
- Measure m_t, δm_t
- PULL=$(m_t - m_t^{true})/\delta m_t$



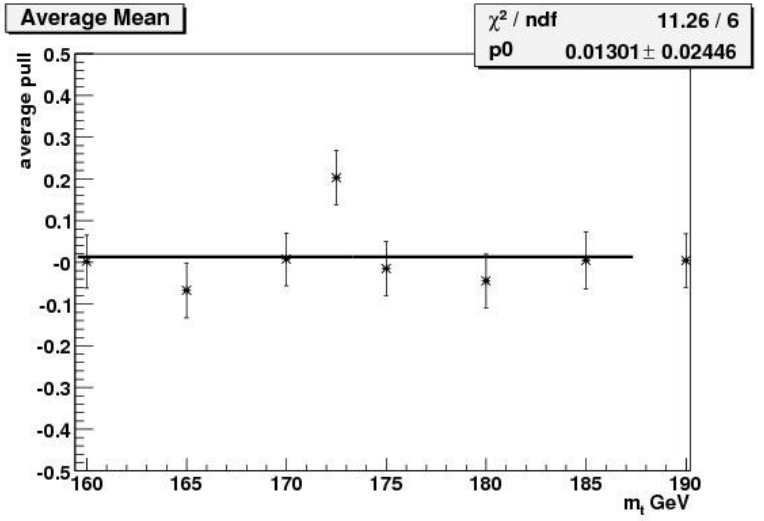


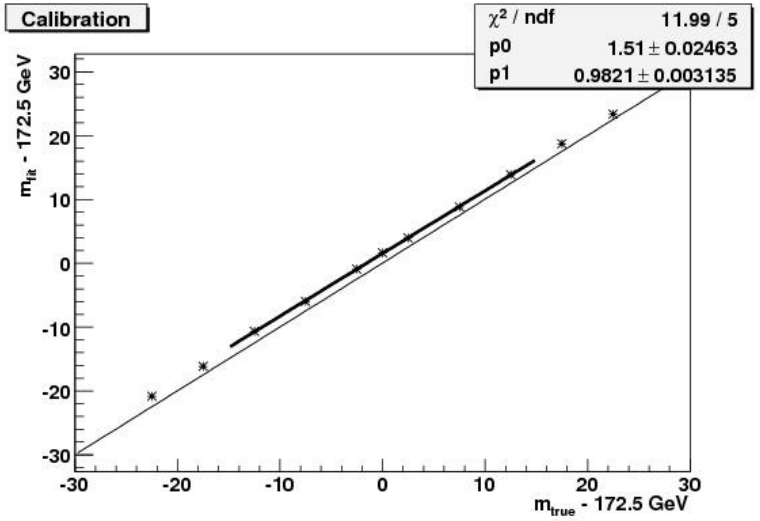


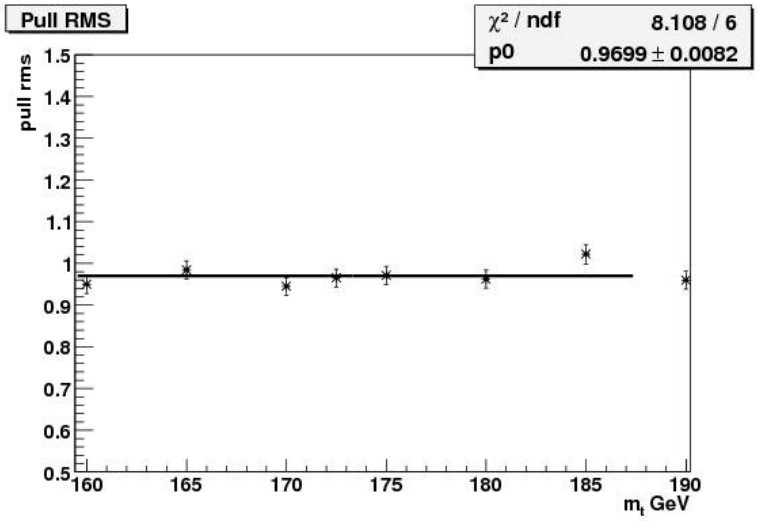


Statistical Calibration

- $<m_t>$ vs m_t^{true}
- RMS(pull)
- Calibrate out bias on m_t, δm_t

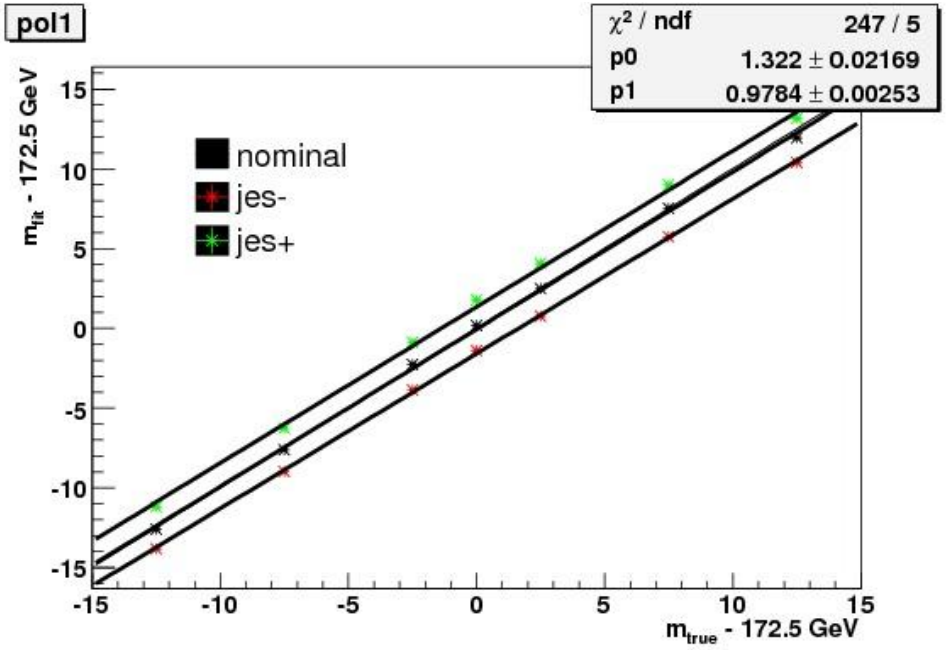






Systematics: Jet Energy Scale

- Change in measured mt when changing samples in pseudoexperiments



- Scale set using γ+j events:
  - γ well measured
  - calibration of data and simulation
  - collaboration-wide effort
  - systematics as function of p_T/η
- $\Delta m_t = \pm 1.5$ GeV

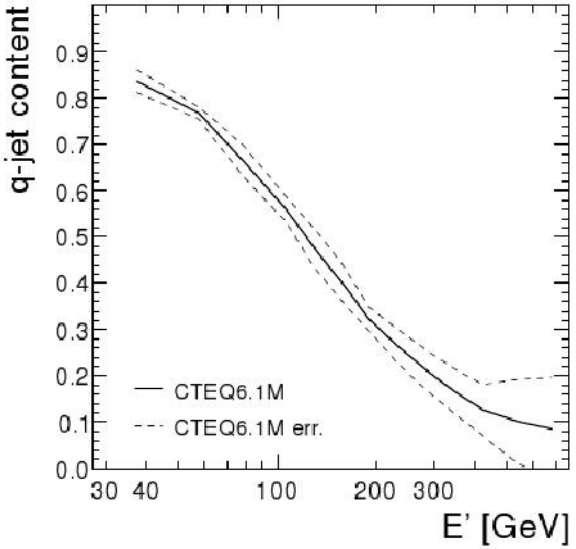
Sample Dependent JES

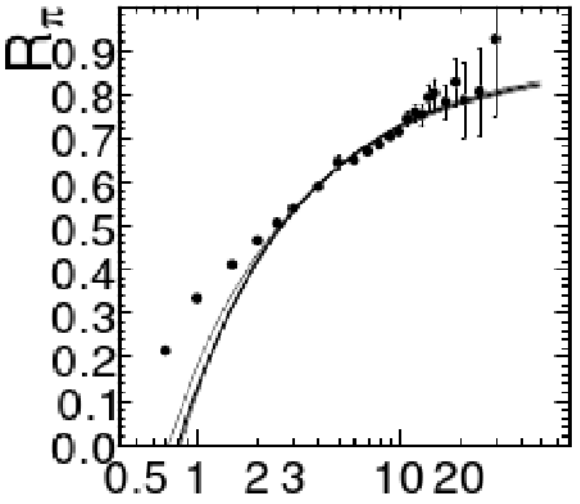
- JES strictly true for γj
  - different response for gluon, quark jets
  - b,c jets as well
- Tune response of detector to individual hadrons in data/MC
- Measure correction using MC particle jets:

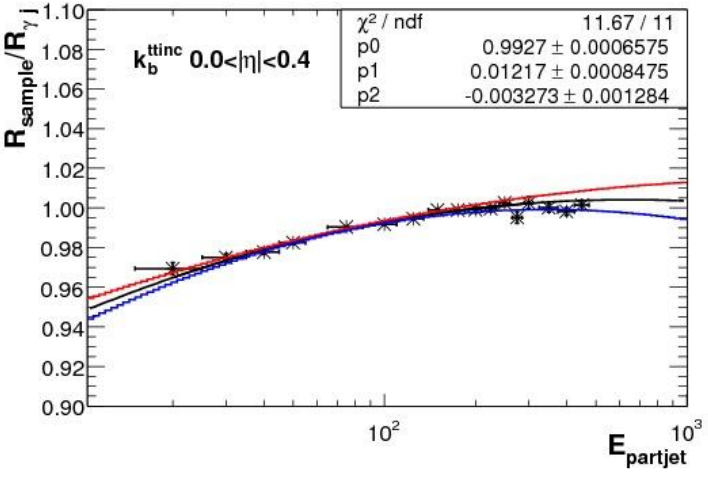
$$E_S^{Data} = k_S E_S^{MC}$$

$$k_S(E,\eta) = \frac{E_S^{Data}/E_S^{MC}}{E_{\gamma j}^{Data}/E_{\gamma j}^{MC}}$$

- $\Delta m_t = \pm 0.4$ GeV







Other Systematic Uncertainties

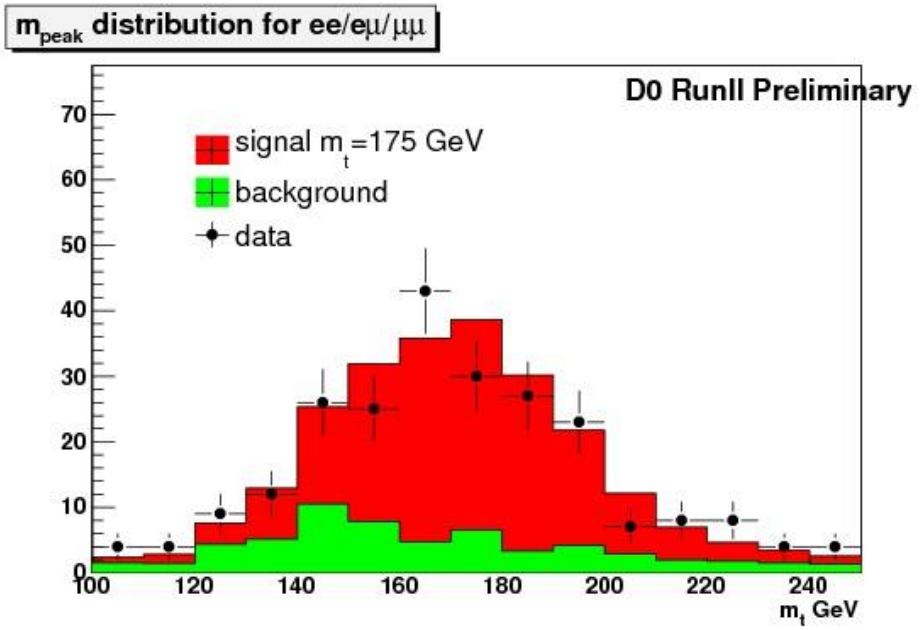
- MC generator / PDF
- Detector Effects
  - Momentum Scale/Resolution
  - ID Efficiency
- Signal/Background Normalization
- Template/Ensemble Statistics

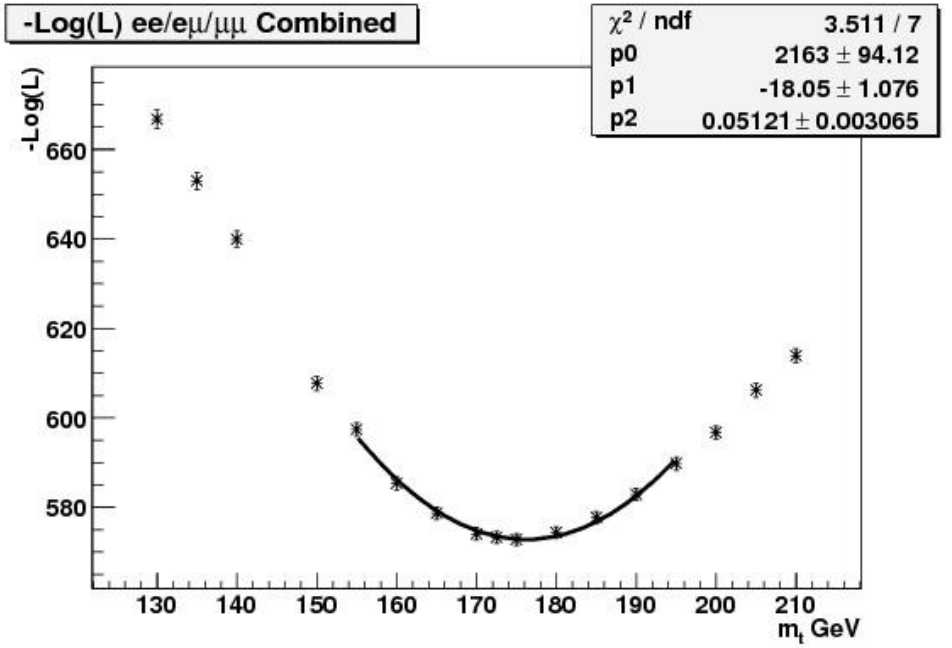
TABLE II: Summary of uncertainties.

source	uncertainty
jet energy scale	1.5 GeV
b/l response ratio + sample dependence	0.4 GeV
signal model: color reconnection	0.1 GeV
signal model: particle showering tune	0.3 GeV
higher order effects (MC@NLO)	0.3 GeV
hadronization	0.6 GeV
ISR/FSR	0.1 GeV
multiple interactions	0.01 GeV
pdf	0.4 GeV
jet energy resolution	0.03 GeV
jet identification	0.01 GeV
electron identification	0.02 GeV
μ identification	0.02 GeV
beam $\|z\|$ reweighting	0.01 GeV
μ momentum resolution	0.02 GeV
electron energy resolution	0.1 GeV
μ momentum scale	0.1 GeV
electron energy scale	0.2 GeV
background yield	0.2 GeV
background model	0.2 GeV
fake background shape	0.1 GeV
template statistics	0.1 GeV
Monte Carlo statistics	0.04 GeV
total systematic error	1.8 GeV
expected statistical error	3.0 GeV
observed statistical error	3.0 GeV
total expected error	3.5 GeV
total observed	3.6 GeV

Result in Data

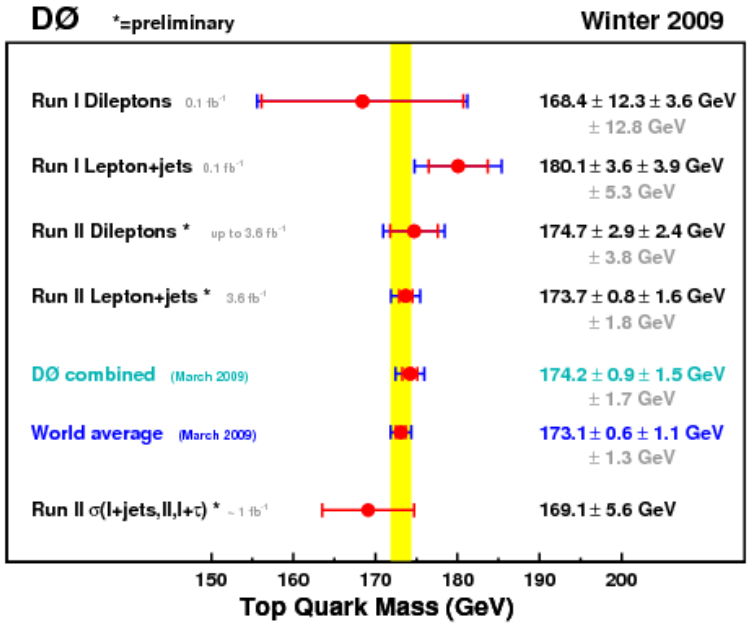
- PLB 655,7 (2007), 0.37fb:
  - mt=178.1+/-6.7(stat)+/-4.8(syst) GeV
- arxiv:0904.3195 (accepted by PRD) $1fb^{-1}$:
  - mt=174.7+/-4.4(stat)+/-2.0(syst) GeV
- Combined $1fb^{-1}$ + $3fb^{-1}$:
  - mt=174.8+/-2.5(stat)+/-1.8(syst) GeV

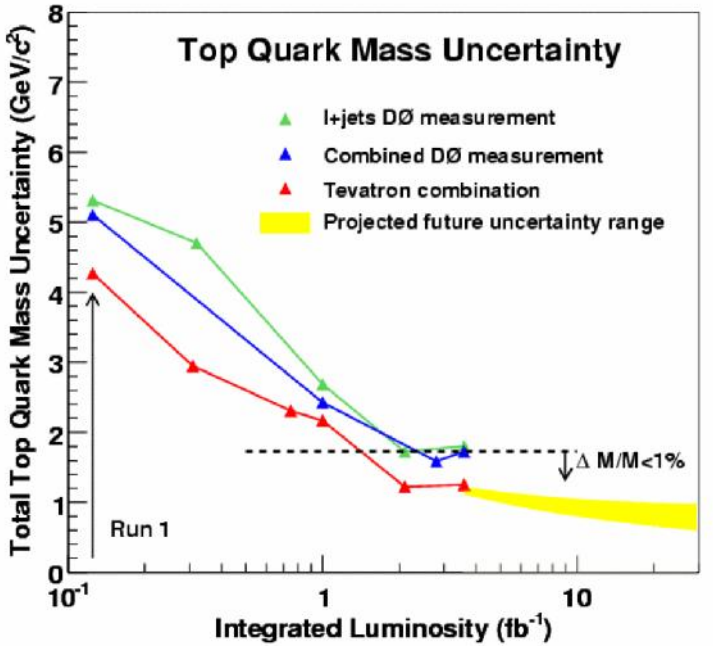




Conclusion

- Consistent with l+jets, world average
  - Potential constraint on new physics
- 2.5 GeV stat. uncertainty with 4 fb^{-1},
- 1.5 GeV stat. uncertainty with 11 fb^{-1} (2011)





Thanks

- To my adviser: Ulrich Heintz
- To Vivek, Shabnam, and Dookee
- To my fellow D0 collaborators
- To everyone responsible for the smooth operation of the Tevatron

Backup

Monte Carlo Simulation

- PDF's:
  - Distribution of quarks/gluons within proton
- Matrix Element Generator:
  - Perturbative treatment of hard interaction
  - ALPGEN+PYTHIA for ttbar/Z+jets
  - PYTHIA for WW/WZ/ZZ
- Parton Shower:
  - parton shower, hadronization
  - PYTHIA
- GEANT, detector simulation

Event Selection: μμ channel

- Dominant Background:
  - Z->μμ
  - no real MET
  - poor momentum resolution
- S>7.5 : $m_{\mu\mu}$<70 GeV
- S>10.2 : 70<$m_{\mu\mu}$<110 GeV
- S>4.2 for $m_{\mu\mu}$>110 GeV

$$\sigma = \sqrt{\sum_{i=objects} [\sigma_i^F \cos \Delta\phi_{i\not{E}_T}]^2 + \sigma_{\rm UE}^2} \qquad S = \frac{\not{E}_T^2}{2\sigma^2}$$

	inclusive	≥ 1 jet	≥ 2 jets	$p_T^{\sigma} > 2$	final selection
$Z \to \mu\mu$	174729 ± 225	26344 ± 71	4128.4 ± 23.0	334.1 ± 7.7	2.7 ± 0.6
$Z \to \tau\tau$	861.1 ± 14.9	142.4 ± 5.0	23.5 ± 1.8	13.2 ± 1.3	3.3 ± 0.7
$WW/WZ/ZZ$	242.2 ± 2.5	121.0 ± 1.4	60.7 ± 0.9	6.9 ± 0.4	2.2 ± 0.3
fake	152.9 ± 89.0	246.4 ± 18.6	58.6 ± 3.8	7.6 ± 0.4	2.1 ± 0.1
$t\bar{t} \to l\bar{l}\nu\bar{\nu}b\bar{b}$	70.7 ± 0.4	70.0 ± 0.4	57.4 ± 0.4	44.3 ± 0.3	25.6 ± 0.2
total expected	176054 ± 244	26860 ± 73	4311.5 ± 23.3	406.1 ± 7.8	36.0 ± 1.0
data	167368	27386	4388	371	32

Fake Rate Determination

- Create loose and tight lepton cuts.
- Form system of equations to extract number of non-instrumental events.

loose / tight

$$\begin{pmatrix} N_{ll} \\ N_{tl} \\ N_{lt} \\ N_{tt} \end{pmatrix}$$

real/fake(instrumental)

$$\begin{pmatrix} N_{rr} \\ N_{rf} \\ N_{fr} \\ N_{ff} \end{pmatrix}$$

Top Kinematic Reconstruction

- Assume qq -> tt -> WbWb -> lνb lνb
  - no ISR/FSR or extra jets
- Start with l's,b's and MET
  - solve system of equations for tt momenta
    - need to fix m_t
  - lepton bjet ambiguity
  - at most 8 solutions