Identifying the Top Quark:
collaborative work with Dick Dalitz

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Beginnings

- Previous work on e^+e^- into jets→mesons & spin correlations
  with R. Marshall (‘87-’89) (see ref.[1])
- LEP & CDF had not seen top by 1990
- LEP energy ~ 100 GeV x 2
- So m_{top} > 100 GeV → very fast decay ($\Gamma \propto m_{top}^5$)
- t→ W^+ + b (W on-shell)

  $W^+ \rightarrow \ell^+ + \nu$

  or →(***u,c***) + *anti(**d,s,b**)*

  particularly mostly $u\bar{d}$ or $c\bar{s}$ each with 3 colors

- So B.R. for one ℓ^+ is ~1/9 hadronic mode
- $\ell^+ \nu$ is rarer but cleaner - ℓ^+ is very energetic!
- What about missing ν 4-momentum? [2]

Top decays vs. mass

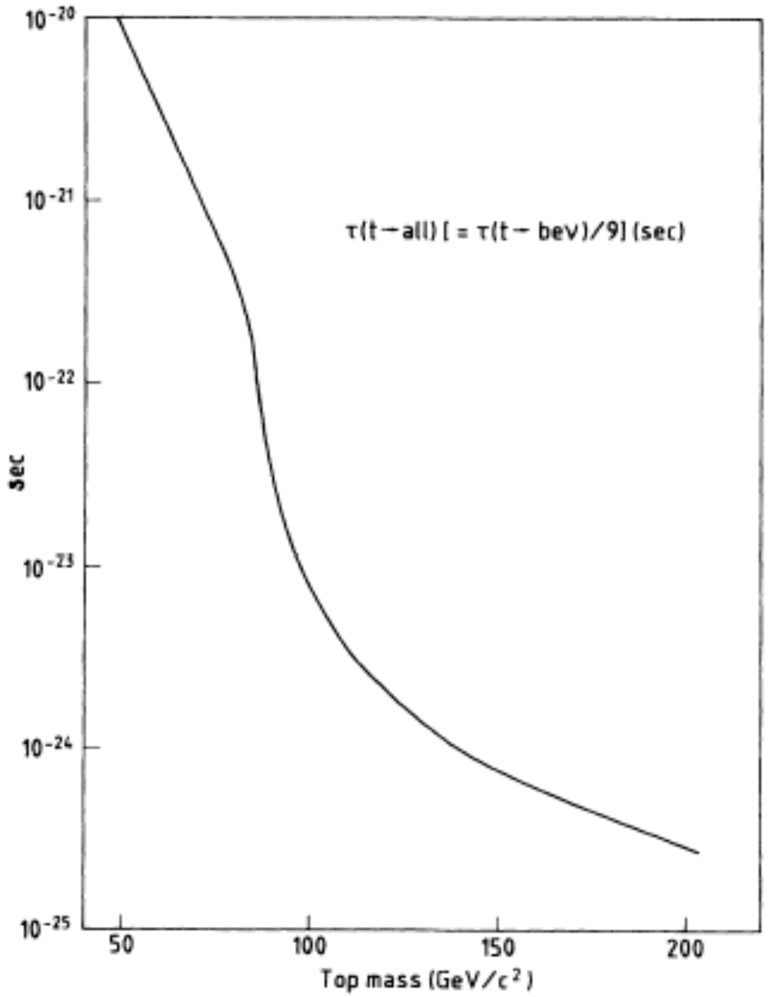


FIG. 1. Total top-quark lifetime as a function of its mass m_t.

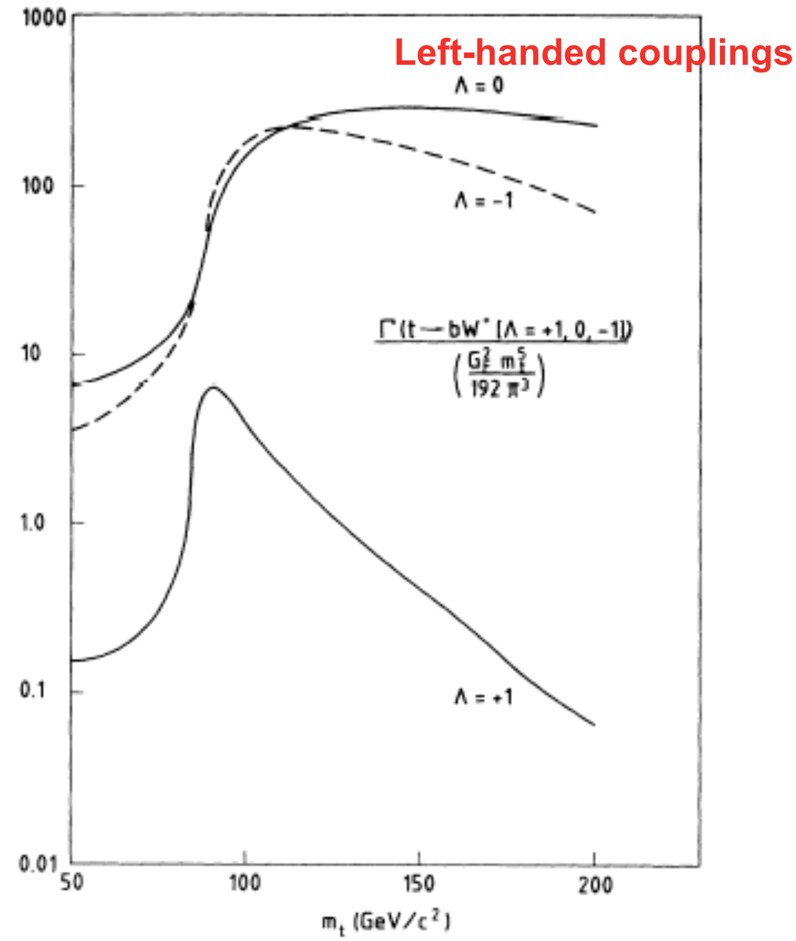
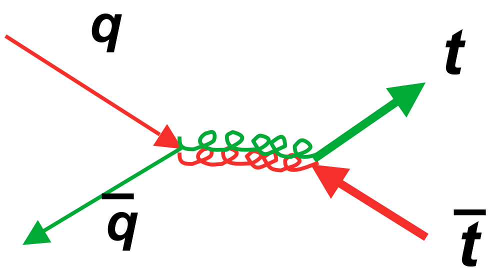


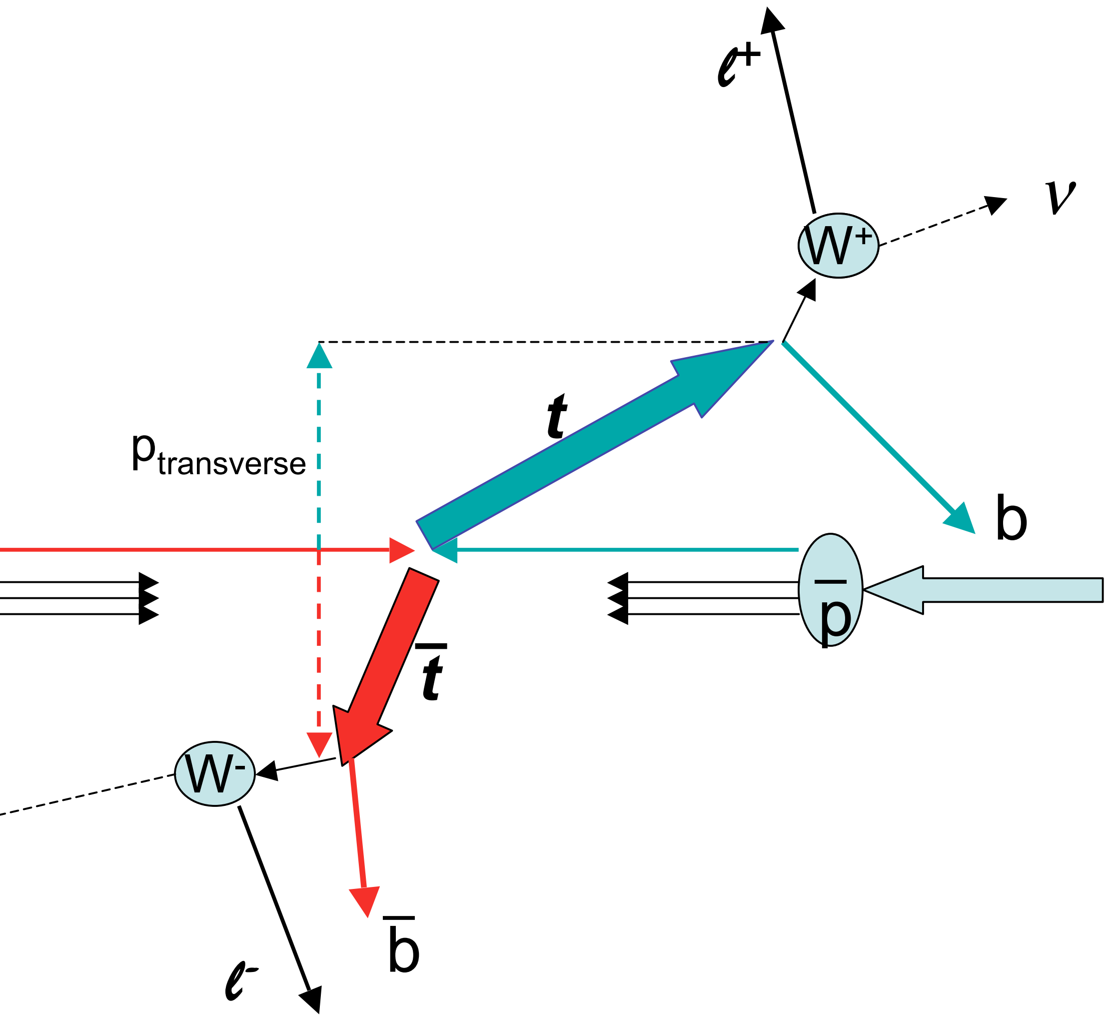
FIG. 2. Partial rates for top-quark decay to bW^+, for W helicity $\Lambda=+1$, 0, and -1 along its momentum in the top-quark rest frame.

See ref.[2]

Dilepton events

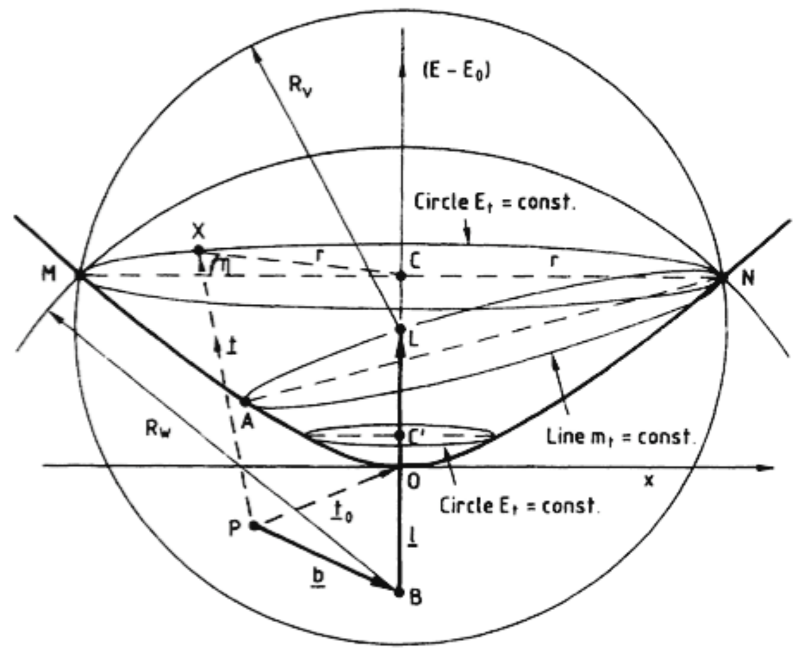


Tree-level QCD



Geometric construction

Consider one of *t + anti-t* pair. What is ***t*** 3-momentum?
Natural lab coordinate system with
z-axis in beam (+/-) direction.
Here use lepton 3-vector as *z-axis*



$$\left(\vec{t}-\vec{b}\right)^2 = \overrightarrow{W}^2 \rightarrow \text{ sphere centered on } \vec{b}$$

$$\left(\vec{t}-\vec{b}-\vec{l}\right)^2 = \vec{\nu}^2 \rightarrow \text{ sphere centered on } \vec{b}+\vec{l}$$

$$\overrightarrow{W}^2 = \left(E_t - E_b\right)^2 - M_W^2 \quad \text{fixes radius of } b \text{ } \textit{sphere} \text{ for } E_t$$

$$E_\nu^2 = \left(E_t - E_b - E_l\right)^2 \quad \text{fixes radius of } b+l \text{ } \textit{sphere} \text{ for } E_t$$

For fixed E_t the 3-vector $\vec{t}$ lies on circle of intersection

$$r^2 = \frac{M_W^2}{E_l}(E_t - E_0), \text{ where minimum } E_0 = E_b + \left(1+\frac{M_W^2}{4E_l^2}\right)E_l$$

$$\vec{t}\cdot\hat{l} = E_t - E_b + \vec{b}\cdot\hat{l} - \frac{M_W^2}{2E_l} \quad \rightarrow \text{plane} \perp \text{ to } \vec{l}$$

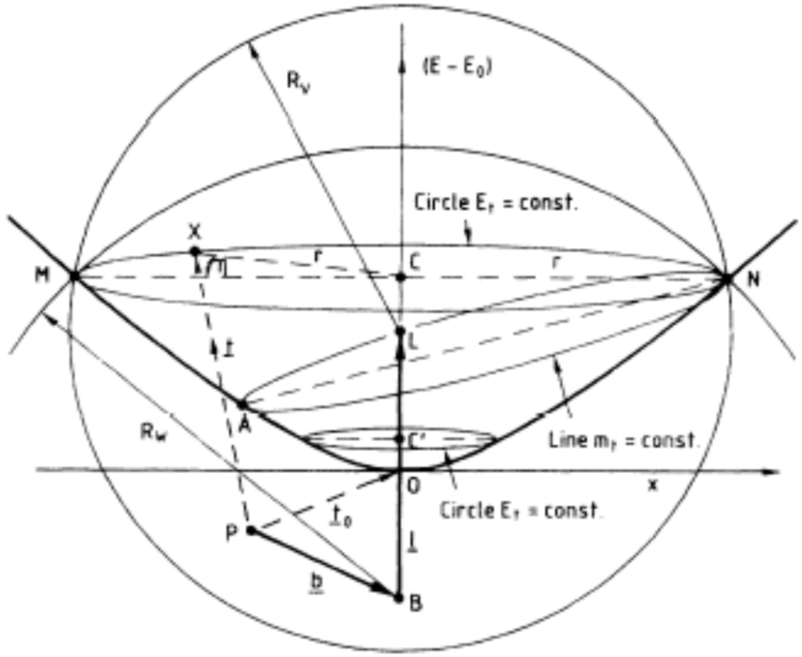
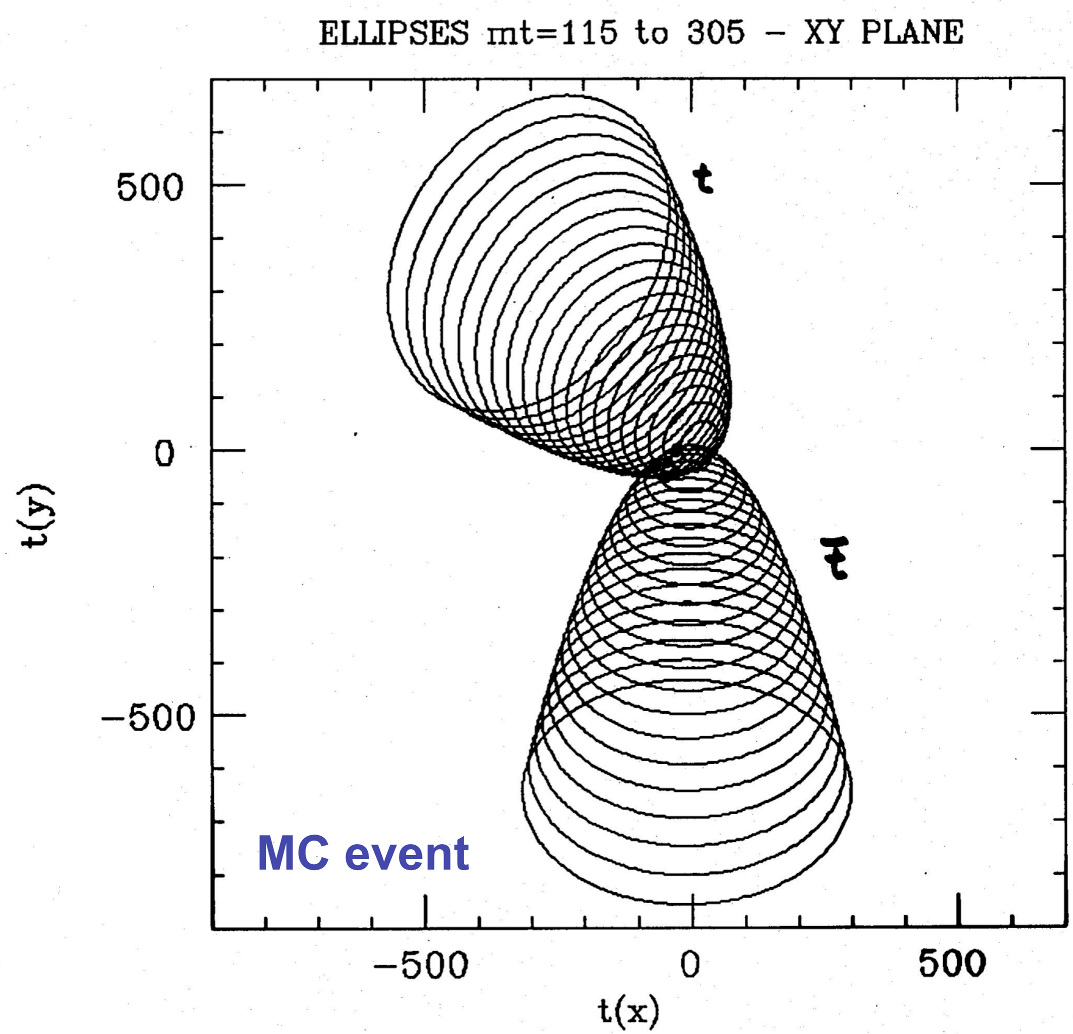


FIG. 5. Momentum vectors **b** and $\bar{l}$ observed in the laboratory frame for bottom quark and lepton, and the construction for locating all top-quark momenta **t** such that these three vectors can correspond to the decay sequence $t \to bW^+$, $W^+ \to \bar{l}^+ \nu_l$ for a given top-quark mass m_t.

Circles for all allowed E_t form paraboloid with axis along ***l***.
For fixed m_{top} & varying E_t , constrained ***t*** values fall on an inclined plane cutting paraboloid → ellipse
Varying m_{top} gives set of ellipses. ∃ $m_{top}{}^{\min}$ for given ***b·l***
Projecting onto transverse plane → parabola composed of ellipses [2]

Paraboloids & Intersections



For a given $\vec{t}_{Transverse}$ with m_{top} ellipse there should be ~ $-\vec{\bar{t}}_{Transverse}$ ellipse with *same* m_{top}.

Extra gluons can shift $\vec{p}^{(Total)}_{Transverse}$.

Allow t+$\bar{t}$ CM transverse momentum distribution.

0, 2 or 4 intersections for each m_{top} .

See ref.[3]

Probabilities

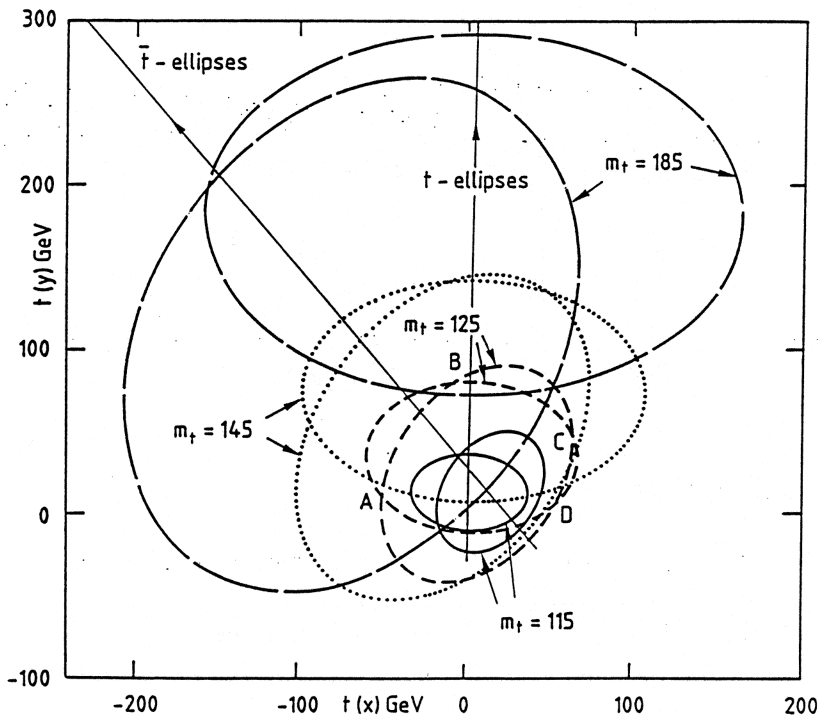
- For each ***t*** & anti-***t*** candidate event
- Measured (***b***(jet), anti-***l***) & (anti-***b***(jet), ***l***) determine parabolas, intersections $\rightarrow$ kinematically allowed $\mathbf{p}_{\mathbf{top}}$ & $\mathbf{p}_\nu$ with anti-$\mathbf{p}_{\mathbf{top}}$ & anti-$\mathbf{p}_\nu$ for each allowed value of m_{top}
- For each m_{top} ellipse intersection $\rightarrow$ kinematics

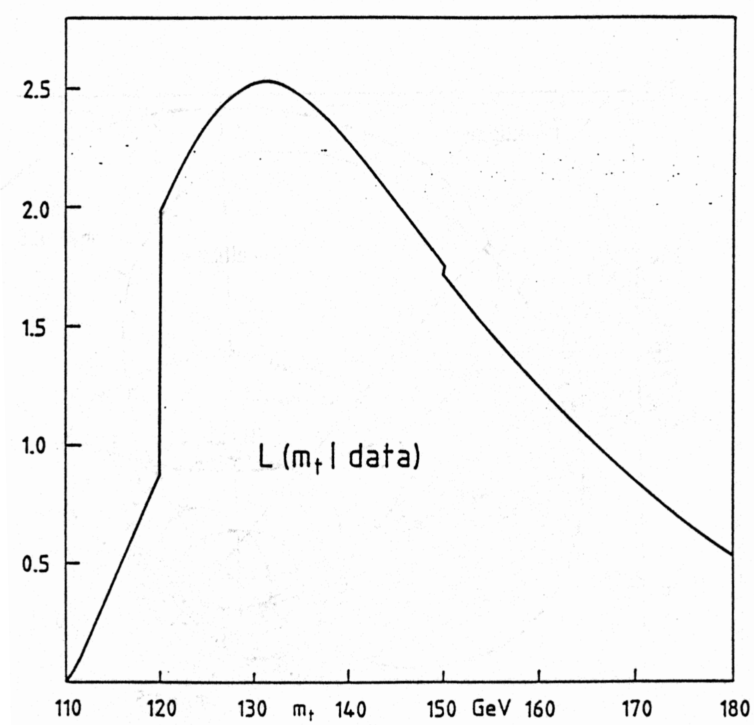
($\mathbf{p}_{\mathbf{top}}$ $\mathbf{p}_\nu$ ***b***(jet) anti-***l***) (anti-$\mathbf{p}_{\mathbf{top}}$ anti-$\mathbf{p}_\nu$ anti-***b***(jet) ***l***)

- $\rightarrow$ determines ***t*** +anti-***t*** CM $\rightarrow$ x and anti-x
- How probable is that set of particle momenta for that m_{top}?
- SM $\rightarrow$ $\mathcal{P}$(anti-***l***,m_{top}) $\times$ $\mathcal{P}$(***l***,m_{top}) in top & anti-top rest frames ($\mathcal{P}$'s in terms of invariants)
- $F_{quark}(x) \times F_{anti\text{-}quark}(\text{anti-}x)$ for q & anti-q probabilities
- $\mathcal{P}(m_{top}|\text{ data}) \propto \mathcal{P}(\text{anti-}\boldsymbol{l},m_{top}) \times \mathcal{P}(\boldsymbol{l},m_{top})$

$$\times \textstyle\sum_{\mathrm{q}} F_q(x) \times F_{anti\text{-}q}(\text{anti-}x) \times d\sigma(q\underline{q} \rightarrow t\underline{t})$$

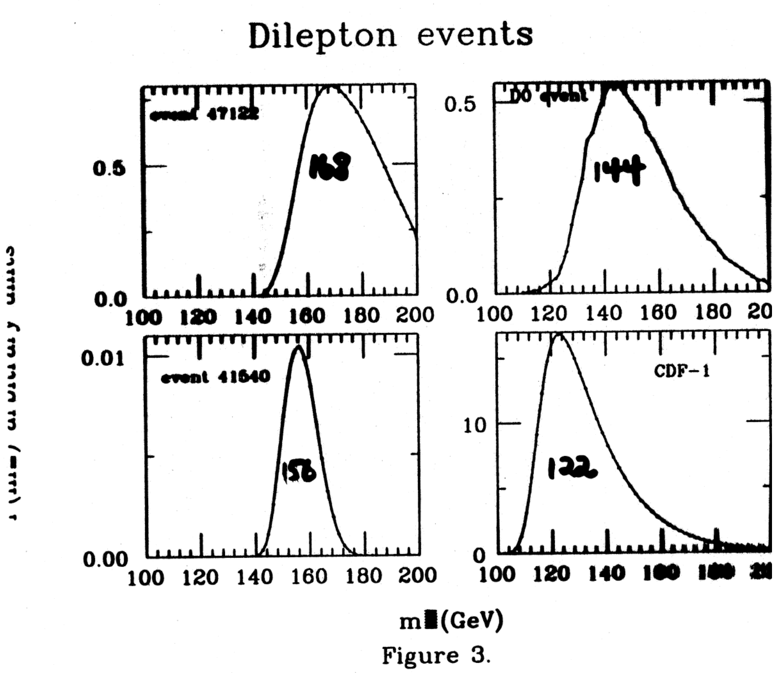
Analysis of CDF1

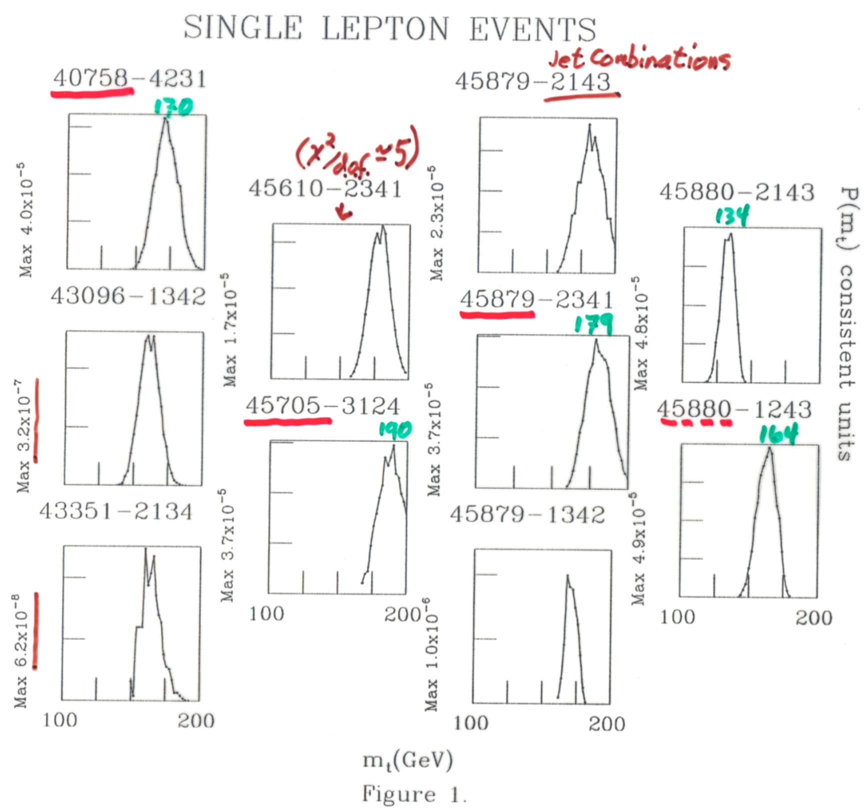




See ref.[2&4]

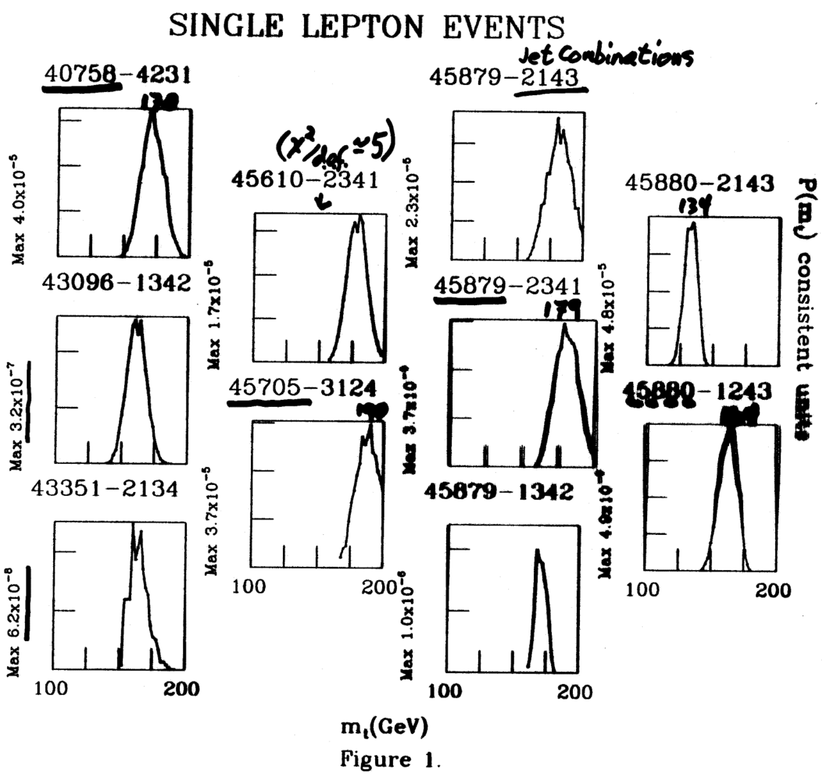
Real events

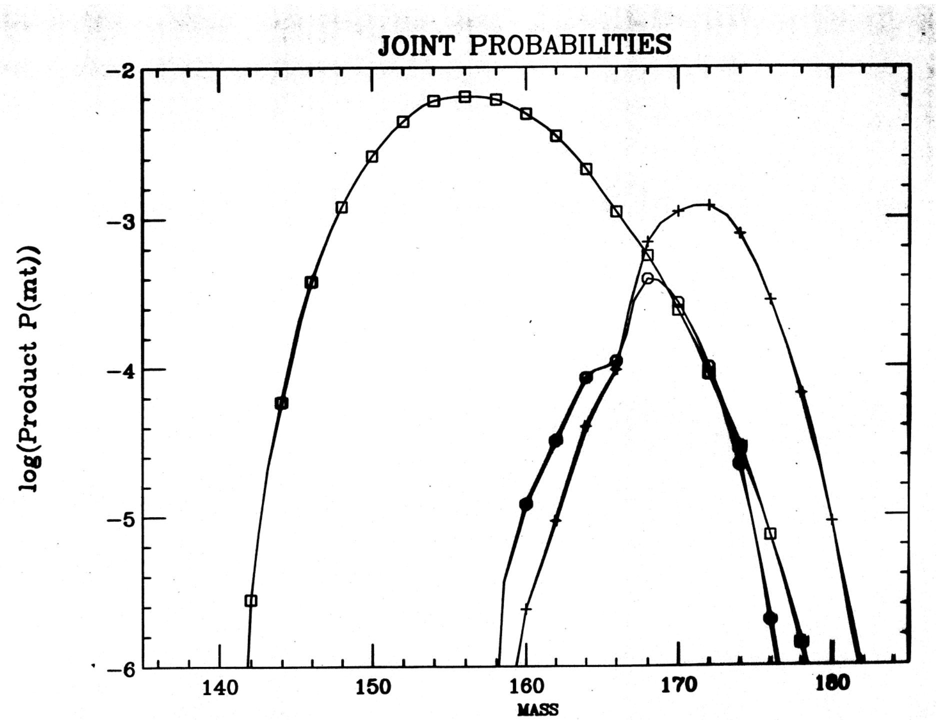




One lepton + 4 jets (b+ anti-b+q+q') => ***t*** or ***anti-t*** fixed
Worked with K. Sliwa on unileptons [3]

Combining probabilities





Masses?

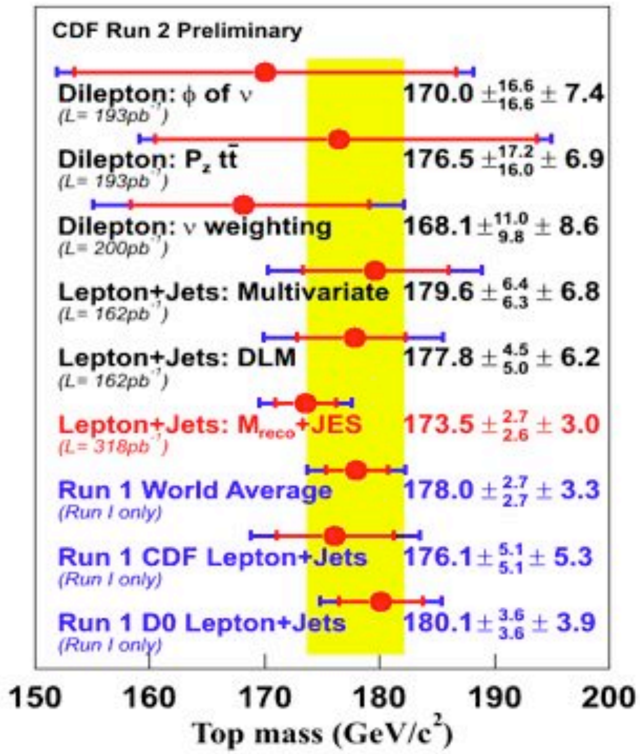
- m_t = 158 ±10 GeV/c^2 3 CDF dileptons 1995 or mean 155-160 for 15 combined D0 & CDF
- 172 ± 4 7 CDF unileptons Analyzed in [5]RHD&GRG PRS **A455**, 2803 (1999)

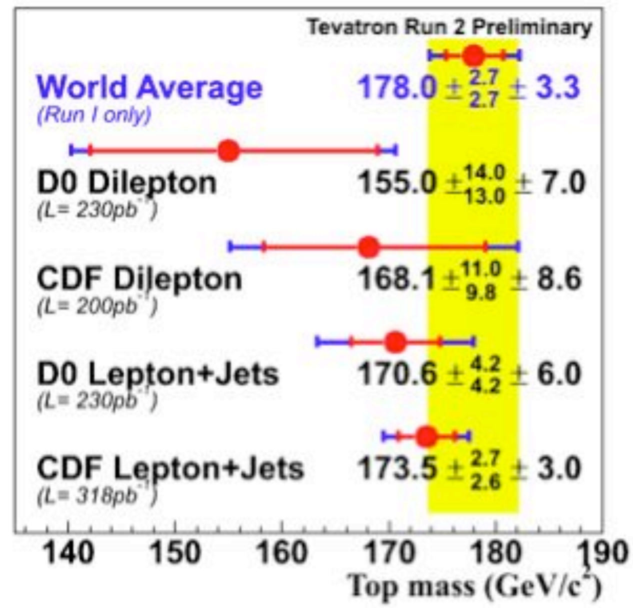
Monte Carlo shows that dilepton m will be lower - phase space fall-off of probability
- unless compensated ("pull")

Recent Experimental determinations

- m_t = 167.9 ± 5.2 stat ± 3.7 syst GeV/c^2 dileptons CDF II combined methods 33 events
- 165.2±6.1 GeV/c^2 likelihood method
- $m_t = 173.5^{+3.9}_{-3.8}$ GeV/c^2 unileptons CDF II 165 events
- m_t = 174.3 ± 5.1 GeV/c^2 PDG world average 2004
- m_t = 178.0 ± 4.3 GeV/c^2 D0 world ave (Nature 2004)
- 168.4 ± 12.3 (stat) ± 3.6 (syst) GeV/c^2 D0 Run I dilepton 6 events
- 180.1 ± 5.3 GeV/c^2 unileptons 71 events

TOP MASS MEASUREMENT IN LEPTON+JETS AND DILEPTON CHANNELS





DOE Review, October 26, 2005, Tufts University

From K. Sliwa 27

PHENO-2005 Symposium U.Wisc.

References to publications

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[2] R.H. Dalitz and G.R. Goldstein, “Decay and Polarization Properties of the Top Quark”, Phys. Rev. D45, 1531 (1992);
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[3] G.R. Goldstein, K. Sliwa and R.H. Dalitz, “On Observing Top Quark Production at the Tevatron”, Phys. Rev. D47, 957 (1993);
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[4] R.H. Dalitz and G.R. Goldstein, “Where is Top?”, in: "From Superstrings to the Real Superworld", Proceedings of the International School of Subnuclear Physics, The Subnuclear Series Vol. 30, editor A. Zichichi, World Scientific (Singapore, 1994);
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[5] R.H. Dalitz and G.R. Goldstein, “Test of analysis for top--antitiop production and decay events”, Proc. Royal Soc. of London, A455, 2803 (1999).