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# report from the e x t e n d e d workshop

**Chip Brock**  
Michigan State University  
*for: Dan Amidei and the  
workshop participants*

## what we were...

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**October, 1994 a group of 100 users & friends dedicated time they didn't have to unraveling the physics potential of an upgraded Fermilab**

- **Two goals:**
  - to quantify the physics reactions of interest, quantify the signal and background sensitivities, and identify the primary detector challenges *and*
  - to create a literature which documented that work
- **we think that we've succeeded**
- **The efficiency of completion was high: about 100 physicists attended the original workshop and there are >70 authors to the report.**
  - This says something about this laboratory's unique user community and support base.
  - There is considerable loyalty to U.S. - based hadron physics.

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## 3 premises:

1. It didn't make sense to ignore Fermilab's physics potential in any discussion of the future  
**many of us have a concern for**
  - the possible timeliness of important physics,
  - the schedule of LHC, and
  - the maintenance of a healthy and balanced U.S. program at home.
2. Top Physics should remain a dominant focus of an FNAL program
3. Something unusual could happen - *it does all the time*  
**the strengths of the fermilab facility are:**
  - **THERE'S DATA HERE**
  - and there appears to be a breadth and depth to the physics accessible at a high luminosity Tevatron upgrade -

**it is a Program**

## accelerator parameters

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### Scenarios (*both proton-antiproton, 2 TeV in the cm*)

- Run II (proposed CDF/DØ upgrades)
  - Luminosity  $L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - bunch characteristics 36 bunches; 396 ns; 3 int/crossing
  - Total exposure  $\int L dt = 2 \text{ fb}^{-1}$
- way beyond (“reasonable” CDF/DO upgrades)
  - Luminosity  $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
  - bunch characteristics 99 bunches; 192 ns; 9 int/crossing
  - Total exposure  $\int L dt = 100 \text{ fb}^{-1}$
- intermediate (“incremental” CDF/DO upgrades)
  - Luminosity  $L = > 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - bunch characteristics 36 bunches; 396 ns; 3 int/crossing
  - Total exposure  $\int L dt \geq 10 \text{ fb}^{-1}$ 
    - or ~99 bunches; 132ns?; 1 int/crossing?

(caveats include increased cm energy and/or 19r

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# Top Quark Physics

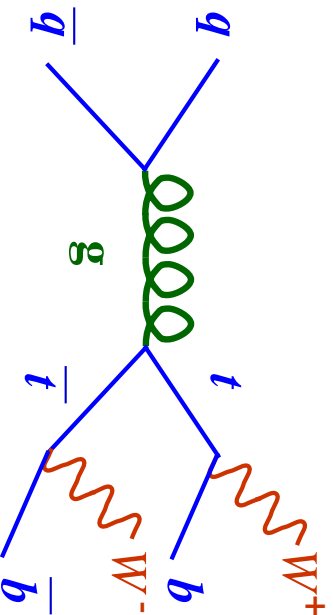
*D. Amidei, University of Michigan*

## top quark physics

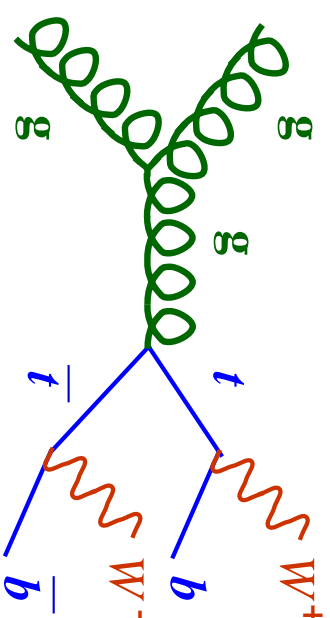
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**now that we've found it...**

- we understand the gross properties, but the decades of the top quark are just beginning
- we know generally how it's made here and “there”....



for high mass,  
dominant at Fermilab



*of lesser importance at Fermilab...  
dominant at LHC*

• *quick summary* •

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**top quark physics at fermilab will be timely and unique**

- a detector with rate capability comparable to CDF/DØ upgrades with  $\int L dt \geq 10 \text{ fb}^{-1}$  will
  - determine  $m_t$  to 2 GeV/c<sup>2</sup> per experiment
  - measure  $\sigma(tt)$  to 6%
  - measure  $\text{BR}(t \rightarrow b)$  to 5%
  - probe for  $t$  resonant states to 1 TeV/c<sup>2</sup>
  - probe  $Wtb$  couplings with few % precision
  - isolate single-top produced final states and
    - determine  $\sigma$  to 10%
    - determine  $\Gamma(t \rightarrow Wb)$  to 12%
    - determine  $V_{tb}$  to 6%
  - search for anomalous couplings and  $\mathcal{CP}$
- probe for rare decays to levels of  $10^{-3}$  -  $10^{-4}$

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## detector assumptions (CDF):

- Run 1b benchmark, extrapolation to Run II parameters:
- geom. acceptance improvements to lepton id and SVX
- third-view addition to SVX

$$m_t = 170\text{-}175 \text{ GeV}/c^2$$

	Run 1b (%)	→	Run II (%)
b-tag eff. incl geometrical acc.			
b(SVX)	44	→	60
b(SLT)	13	→	13
+ det. acc., for SVX or S			
$\epsilon(t\bar{t} \rightarrow 1b+X)$	53	→	85
$\epsilon(t\bar{t} \rightarrow 2b+X)$	13	→	42

+

	Run 1b (%)	→	Run II (%)
kinematical cut acceptance			
$\epsilon(\ell\ell)$	16	→	23
$\epsilon(\ell+3j)$	29	→	35
$\epsilon(\ell+4j)$	25	→	30

	Run 1b (%)	→	Run II (%)
at least one b tagged			
$t\bar{t} \rightarrow \ell+3j$ & 1b	15	→	29
$t\bar{t} \rightarrow \ell+4j$ & 1b	13	→	25
both b's tagged			
$t\bar{t} \rightarrow \ell+4j$ & 2b	3.2	→	13

→

BR • eff	Run 1b (%)	→	Run II (%)
no b tagged			
$t\bar{t} \rightarrow \ell\ell$	0.8	→	1.1
$t\bar{t} \rightarrow \ell+3j$	8.7	→	10
$t\bar{t} \rightarrow \ell+4j$	7.5	→	8.9
at least one b tagged			
$t\bar{t} \rightarrow \ell+3j$ & 1b	4.5	→	8.6
$t\bar{t} \rightarrow \ell+4j$ & 1b	3.9	→	7.6
both b's tagged			
$t\bar{t} \rightarrow \ell+4j$ & 2b	1.0	→	3.8

yields, cont.

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large quality samples are conceivable

	1	10	100	1000
t <sub>p</sub> produced	6800	68,000	680,000	6,800,000
t <sub>e</sub> → ℓℓ	82	820	8200	82000
t <sub>e</sub> → ℓ+3 j	680	6800	68,000	680,000
t <sub>e</sub> → ℓ+4 j	605	6000	60,500	605,000
t <sub>e</sub> → ℓ+3 j & 1k	584	5800	58,400	584,000
t <sub>e</sub> → ℓ+4 j & 1k	517	5200	51,700	517,000
t <sub>e</sub> → ℓ+4 j & 2k	258	2600	25,800	258,000

**mass:  $\ell + j$**

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**we know how to do this:**

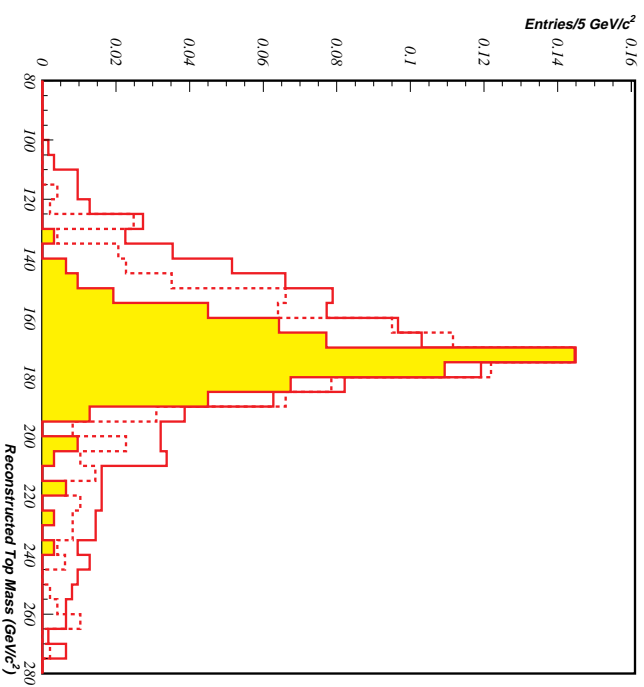
$$m_t = 176/170 \pm 8/15 \pm 10/10 ; \text{CDF/D}\emptyset$$

●...and we know how to make it systematically better

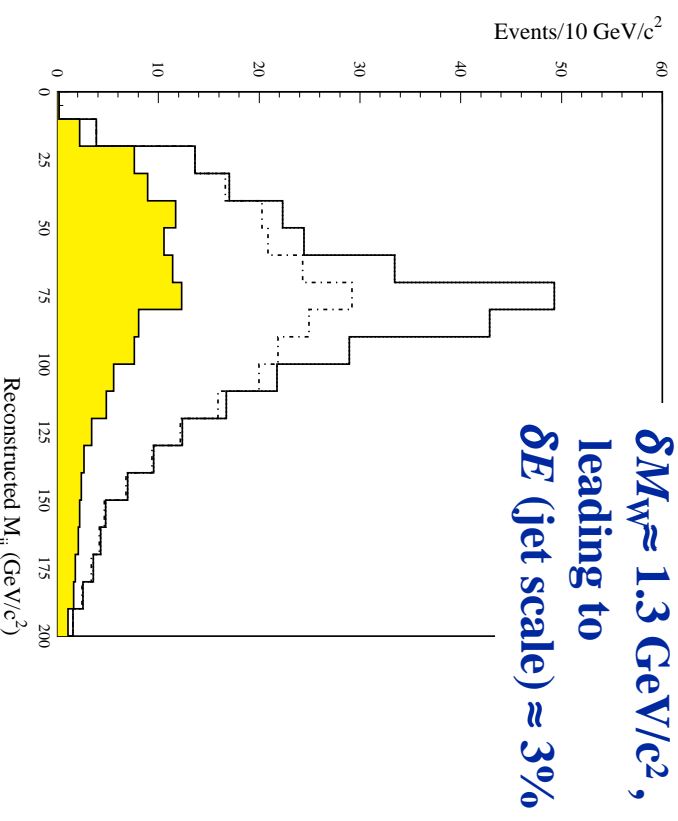
**reduction of combinatoric effects & jet energy scale**

● double tagging

●  $Z \rightarrow ee + 1j$  and  $W \rightarrow jj - \delta m_t [\text{GeV}/c^2] \approx (1.0) \times \delta E(\text{jetscale})[\%]$



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5/23/96 4:46 PM

# mass: $\ell + j$ , cont.

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**precision anticipated:**

	0.7 fb	1 fb	10 fb	
jet scale - QCD	7.7	2.0	0.6	"SQRT(N)"
jet scale - cal	3.1	0.8	0.3	"SQRT(N)"
jet scale - total	8.1	2.1	0.7	"SQRT(N)"
jet scale - total	8.1	3.3	1.0	"realistic"
b - tagging	8.4	0.6	0.2	
background sk.p	1.6	1.6	0.6	
fitting	3.1	0	0	
MC stat	3.1	0	0	
TOTAL	10	3.7	1.2	"realistic"



	0.7 fb	1 fb	10 fb	
statistical uncertainties (GeV/c)				
$\ell\ell jj$	12	1.6	0.5	"SQRT(N)"
$\ell\ell jj$ & $1b$	8	1.5	0.5	"SQRT(N)"
$\ell\ell jj$ & $2b$	25	1.7	0.5	"SQRT(N)"
systematic uncertainties (GeV/c)				
$\ell\ell jj$ & $1b$	10	2.5	0.8	"SQRT(N)"
$\ell\ell jj$ & $1b$	10	3.7	1.2	"realistic"
TOTAL (GeV/c)	13	4.0	1.3	"realistic"

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**we know how to do this too...harder?**

- ...and we know how to make it systematically better - same problems

reduction of combinatoric effects

- future double tagging

jet energy scale & QCD modeling

- currently,  $\delta E$  (jet scale)  $\approx 10\% \Rightarrow \delta m_t \approx 7\%$
- same studies as before
- anticipate significant reduction...  $\delta m_t \rightarrow 1\%$

	0.7 fb <sup>-1</sup>	1 fb <sup>-1</sup>	10 fb <sup>-1</sup>	
	statistical uncertainties (GeV/c)			
$t \rightarrow \ell\ell$	25	6.2	2	"SQRT(N)"
	systematic uncertainties (GeV/c)			
jet energy scale	1	2.7	0.9	
QCD generator	9	-	-	
bcgnd norm.	4	1	0.3	
MC statistics	5	-	-	

## production: $\sigma$ & $tt$ resonances

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### we know how to do this

- ...and we know how to make it systematically better (eg,  $\ell$  + jets)
- better understanding of acceptance (now  $\approx 30\%$ )
- ISR, jet energy scale, b-tagging efficiency (sound familiar?)
- better understanding of backgrounds (now  $\approx 35\%$ )
- heavy flavor content of  $W$  + jets events (sound familiar?)
- need to measure  $c$  and  $b$  content vs  $n_j$  with  $c\tau$  distributions

### better understanding of $\int L dt$ (now $\approx 10\%$ )

	1 fb <sup>-1</sup> %	10 fb <sup>-1</sup> %	100 fb <sup>-1</sup> %
acceptance	8.4	2.7	0.9
backgrounds	10	3.3	1.0
$\int L dt$	5	5	5
overall $tt$ precision	11	5.9	5.1

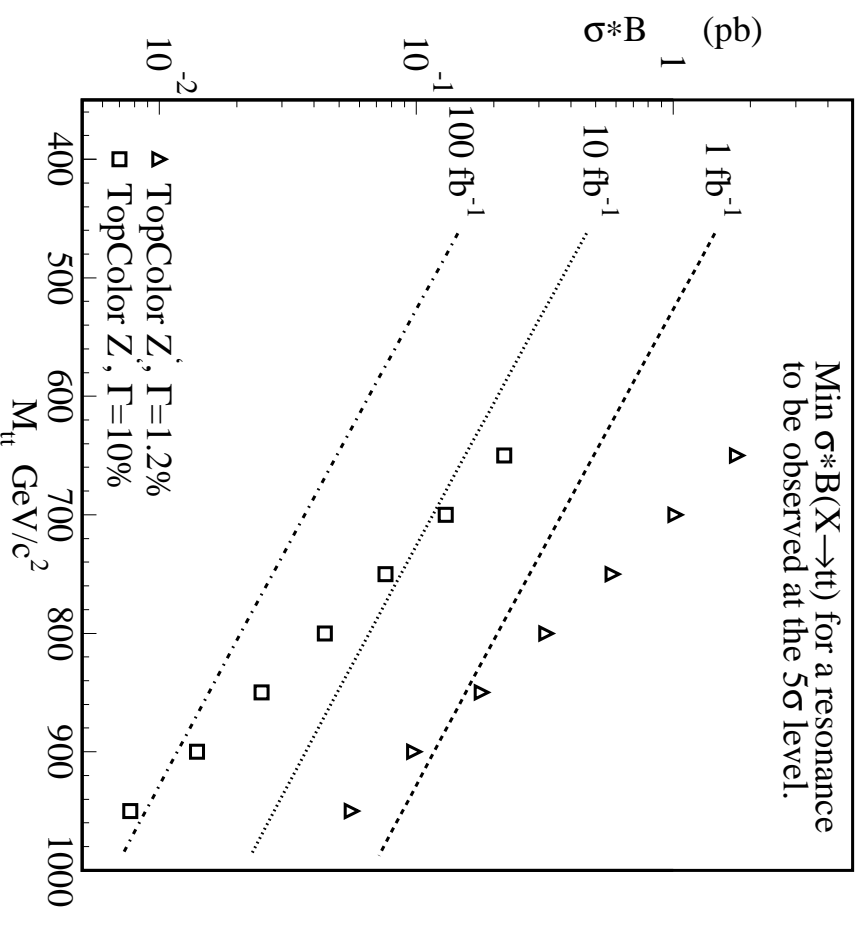
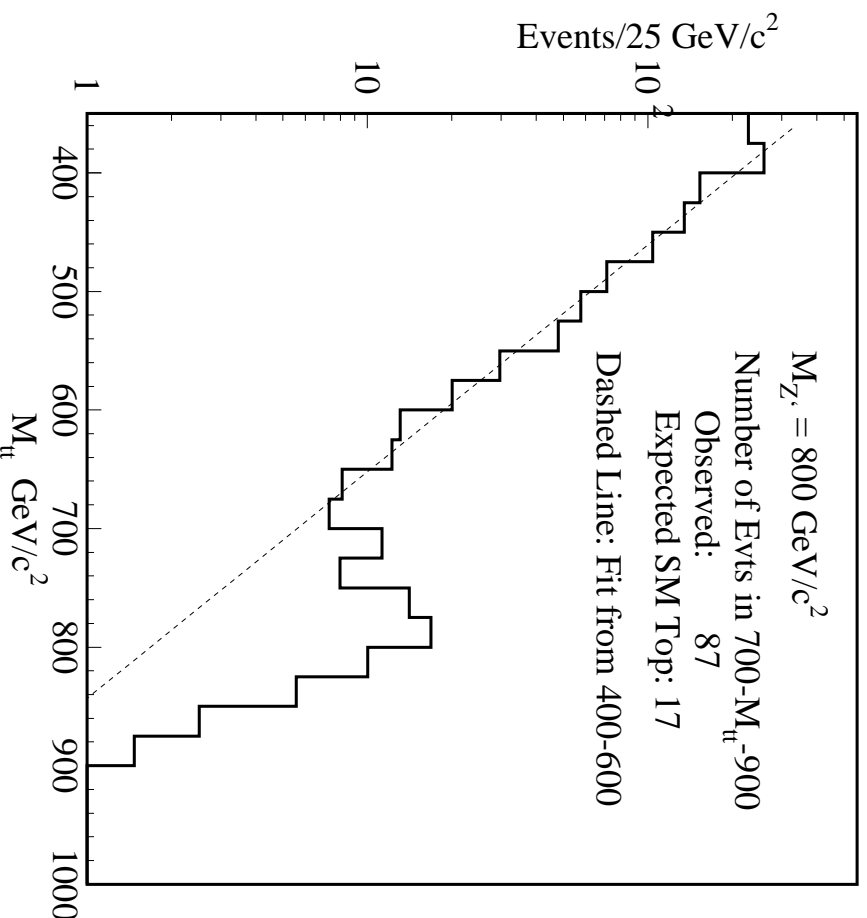
current theoretical prediction  $\approx 10 - 14\%$

# production: $t\bar{t}$ resonances

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**we're learning how to do this**

- crucially important to search -  $q\bar{q}$  annihilation unique
- models with predictions: color octet  $V$ ; multiscale technicolor...



# decays: $Wtb$ vertex

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**don't have experience here... Michel analysis**

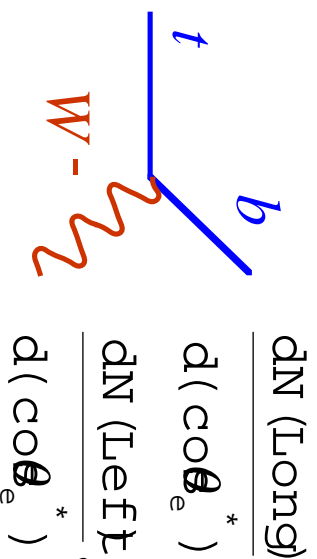
- SM fixes the vertex:

$$\text{standard V-A } \Gamma(t \rightarrow Wb) = \frac{G_F m_t^3}{8\sqrt{2}\pi} |V_{tb}|^2 \left[ 1 - \frac{M_W^2}{m_t^2} \right]^2 \left[ 1 + 2 \frac{M_W^2}{m_t^2} \right]$$

= 1.8 GeV

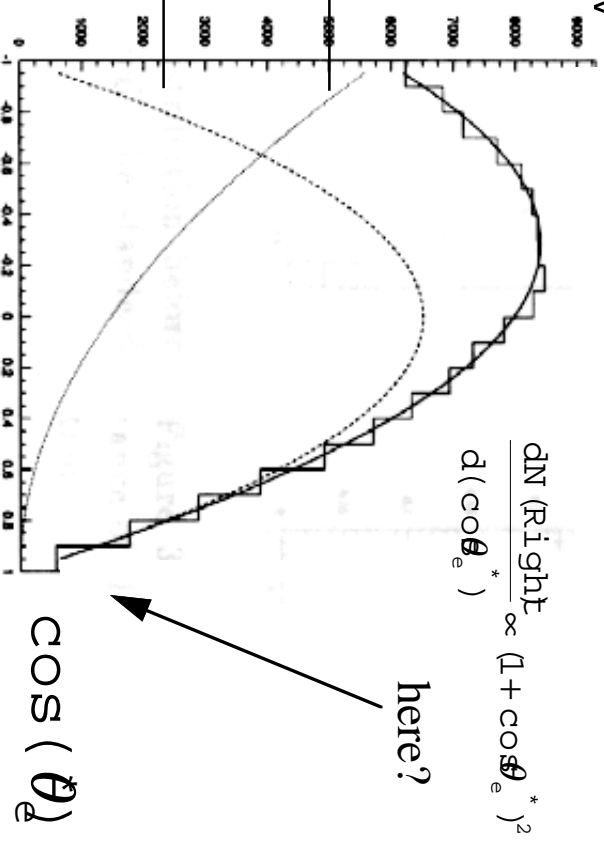
rather strict predictions:

$\text{BR}(t \rightarrow b W_{\text{Long}})$  fixed, dep. on  $m_t$



$$\frac{dN(\text{Long})}{d(\cos\theta_e^*)} \propto \sin^2\theta_e^*$$

$$\frac{dN(\text{Left})}{d(\cos\theta_e^*)} \propto (1 - \cos\theta_e^*)^2$$



$\delta_{\text{BR}[t \rightarrow bW(\text{Long})]}$	1 fb <sup>4</sup>	10 fb <sup>4</sup>	100 fb <sup>4</sup>
]	6.5	2.1	0.7
$\delta_{\text{BR}[t \rightarrow bW(\text{Right})]}$	2.6	0.8	0.3

statistical errors

# decays: $B(t \rightarrow b)$ , $V_{tb}$ , & $B(t \rightarrow W)$

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**we know how to do this**

- 3 methods: (double b-tags); (single b-tags); ( $\ell\ell$  w/tag;  $\ell\ell$  w/out tag); & intersection of tagging algorithms - all give:

$$BR(t \rightarrow W (b)) \simeq \frac{t \rightarrow W \text{ and } \bar{b}}{t \rightarrow \text{all } W} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

which can be extrapolated to  $|V_{tb}|$

	1 fb <sup>1</sup>	10 fb <sup>1</sup>	100 fb <sup>1</sup>
ratio	0.94 $\pm$ .07	0.895 $\pm$ .0222.19 $\pm$ .08	0.895 $\pm$ .022.189 $\pm$ .0255.10 $\pm$ .15
$\delta_B(t \rightarrow b)$	4%	1.8%	0.56%
overall $\delta_B(t \rightarrow b)$	3.3%	1.0%	0.33%
Limits on $ V_{tb} $   95%CL	> 0.22	> 0.40	> 0.71

for  $\delta_B(t \rightarrow b)$ , all methods combined, CDF already has  $\pm 30\%$  (stat) and  $\pm 11\%$  (sys) in 67 pb<sup>-1</sup>

## decays: $B(t \rightarrow W)$ & sensitivity to rare decays

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it must be tested that  $W$ 's occur in all top final states

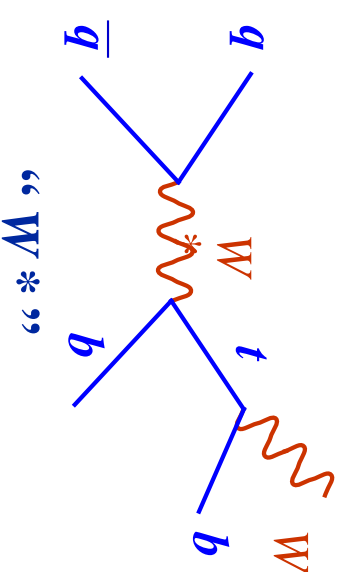
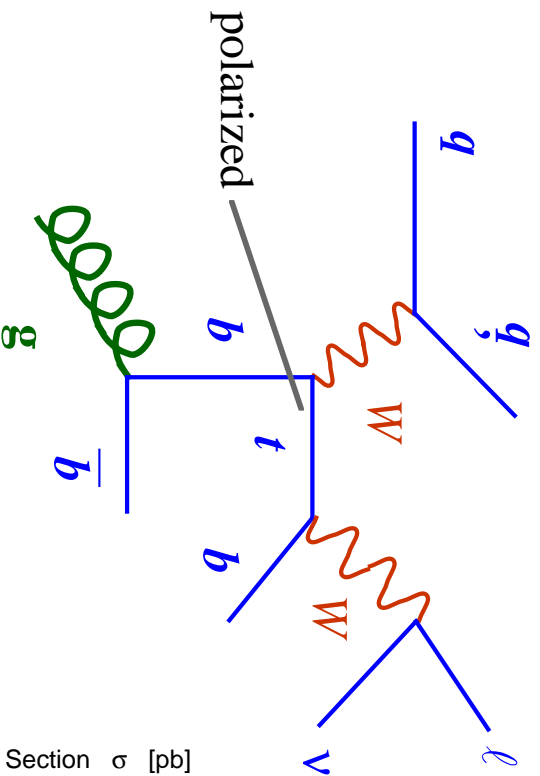
- SM decays would require that  $R_\rho = \ell\ell / \ell$  events be = 1/6  
represent as  $BR(t \rightarrow b \text{ "with a } W\text{")}$
- also, specific model-dependent sensitivities can be estimated...

	1 fb <sup>1</sup>	10 fb <sup>1</sup>	100 fb <sup>1</sup>
$\delta BR(t \rightarrow b \text{ with } W)$	10%	3.5%	1.0%
$t \rightarrow H \bar{t} b$			
$BR(t \rightarrow H \bar{t} b)$ @ 95% CL	15%	6%	1.7%
$t \rightarrow c \gamma$			
$\ell + \gamma + 2j$ limit- $\gamma \times 10^5$	7	0.62	0.13
$\gamma + 4j$ limit- $\gamma \times 10$	6.5	1.1	0.24
overall limit- $\gamma \times 10$	3.0	0.4	0.084
$t \rightarrow Z c$			
$3\ell + 2j$ limit- $\gamma \times 10$	43	7.4	1.0
$2\ell + 4j$ limit- $\gamma \times 10$	26	7.9	1.7
overall limit- $\gamma \times 10$	15	3.8	0.63

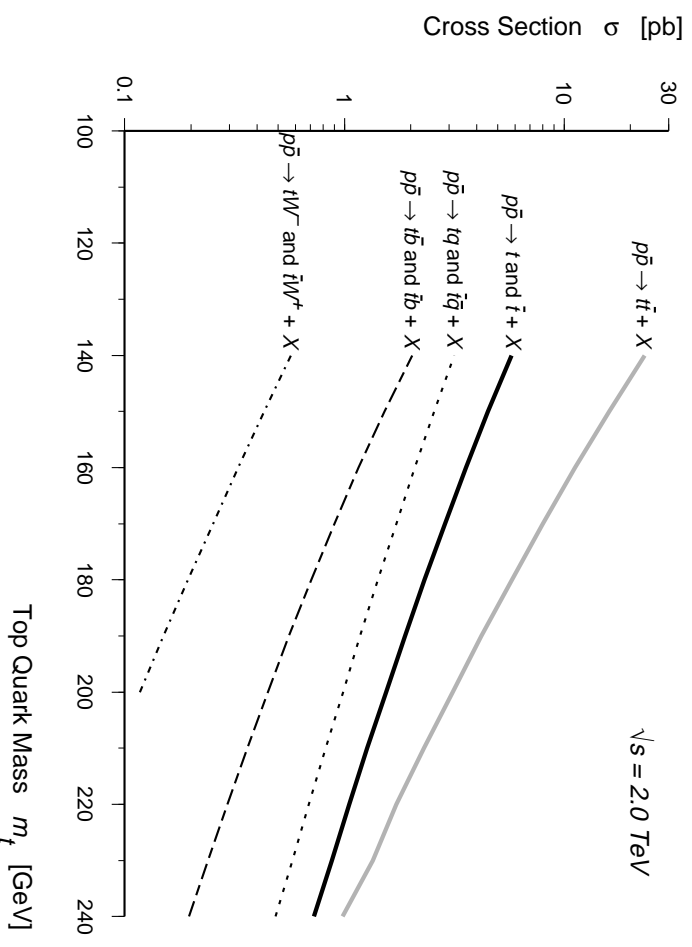
# electroweak production of top

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**variations on 2 themes:**



“W- gluon fusion”



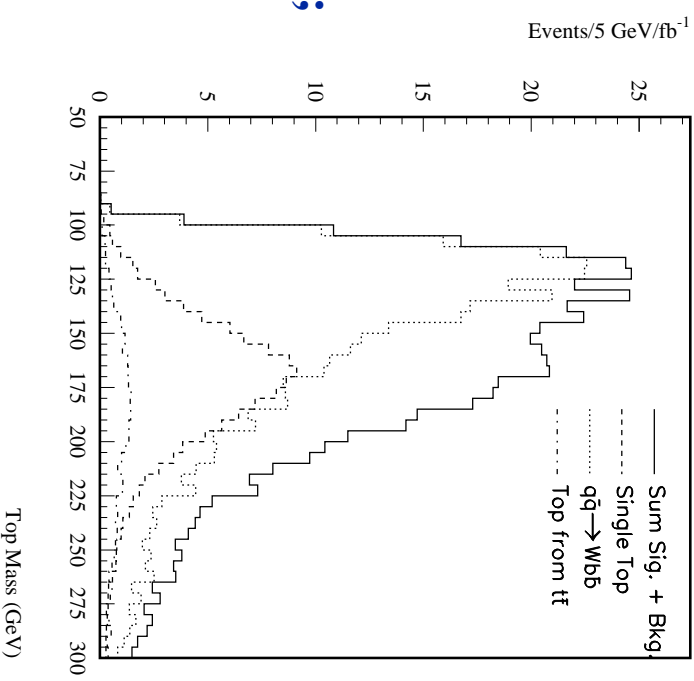
# yields, backgrounds

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**this will become important with increasing luminosity**

- $D\emptyset$  resolutions;
- 50% b-tagging efficiency + 0.4% mistag rate;
- $Wbb$  backgrounds scaled to CDF measurements;
- strategy for assignment of tagged  $b$ 's;
- sign of top can be inferred, and used to suppress background.

$M(Wb)$  within 50 GeV/ $c^2$  window of  $m_t$



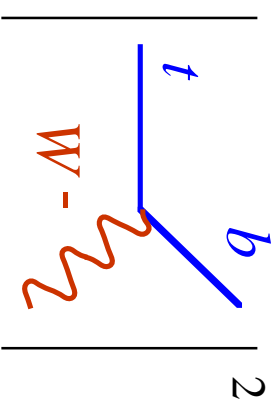
$m_t = 170$ GeV/ $c$	1 $fb^{-1}$	10 $fb^{-1}$	100 $fb^{-1}$
W b bckgnd	109	1000	10,000
W j bckgnd	109	1000	10,000
ttbckgnd	21	200	2000
single top	107	1000	10,000

$\Gamma, W^*, V_{tb}$

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**among measurements:**

- width - total rate is proportional to



so, get a direct measure of total width (within SM) to compare to  $t\bar{t}$  measurement of  $BR(t \rightarrow b)$  and  $V_{tb}$ .

- $W$ - $g$  fusion and  $W^*$ ...(latter less prone to theoretical uncertainties)

$m_t = 170 - 175$	2 fb <sup>3</sup>	10 fb <sup>3</sup>	100 fb <sup>3</sup>
GeV/ $\mathcal{L}$			
W-gluon fusion			
S/B = 0.45			
stat error %	12.3	5.5	1.7
$\delta\sigma$ %	26	10	7
$\delta\Gamma(t \rightarrow Wb)$ %			
$\delta V_{tb}$ %	14	6	5
$W^*$			
S/B = 0.69			
stat error %	39	17	5.5
$\delta V_{tb}$ %		5	

...plus, Long  $W$  and  $\mathcal{CP}$

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## LHC

- done during early running (capable b-tagging there)
  - significant statistical advantage
  - what are the uncertainties which don't scale as  $\text{SQRT}(N)$ ?
    - QCD modeling...hard gluon radiation?
    - systematics from top  $p_t$ ? from gluon source, as opposed to  $\bar{q}q$ ?
- much of this work can be done at fermilab first, and with full systematic control based on immediate experience.
- $W^*$  for  $V_{tb}$  will be hard at LHC - a gluon collider

## NLC

- no onia resonance, so production cross section is smooth
- threshold measurements dependent on beam systematics...likely late in the program
  - 500 MeV/c<sup>2</sup> precision advertised at  $E_{\text{cm}} = 500$  GeV

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## **Intermediate Vector Boson Physics**

***U. Baur, University of New York, Buffalo***

***M. Demarteau, Fermilab***

***S. Errede, University of Illinois***

## IVB physics: yields

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**$W$ 's,  $Z$ 's and  $\gamma$ 's - masses, decay's, and couplings:  
FNAL is a vector boson factory.**

- standard CDF/DO cuts, efficiencies, lepton id...

$p\bar{p} \rightarrow X +$	additional cuts	1 fb <sup>-1</sup>	10 fb <sup>-1</sup>
$W \rightarrow e\nu$		0.6M	6.4M
$Z \rightarrow ee$		74k	0.74M
$W (\rightarrow e\nu)\gamma$	$E_T(\gamma) > 10\text{GeV}$	480	4800
$Z (\rightarrow ee)\gamma$	$E_T(\gamma) > 10\text{GeV}$	150	1500
$Z (\rightarrow \nu\nu)\gamma$	$E_T(\gamma) > 40\text{GeV}$	110	1100
$W (\rightarrow e\nu)W (\rightarrow \mu\nu)$		50	500
$W (\rightarrow \ell\nu)Z (\rightarrow \ell\ell)$		20	200
$Z (\rightarrow \ell\ell)Z (\rightarrow \ell\ell)$		3	30

a staggering sample size, a source of physics in and of itself as well as a systematics toolkit for top, higgs, susy, exotics studies.

• *quick summary* •

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**IVB physics at fermilab will be timely and complementary to other future facilities**

- with 10 fb<sup>-1</sup>, a measurement of  $M_W$  to 20-30 MeV/c<sup>2</sup>
  - combined with 2 GeV/c<sup>2</sup> top measurement, bounding of  $M_H$  is possible to 40-50% of  $M_H$
  - in good time for direct searches
- $\Gamma(W)$  to 15 MeV - much better than LEP II
- asymmetries (W and Z) as constraint on pdfs
- $WWV$  &  $Z\gamma$  ( $g_Z$ ) couplings comparable or much better than LEP II
- radiation zero in  $W\gamma$  production - unique potential
- rare W decays
- $\cancel{P}$
- quartic gauge couplings

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**we know how to do this...**

$$M_W = 80.41 / 80.33 \pm 0.180 / 0.270 \text{ CDF/DØ}$$

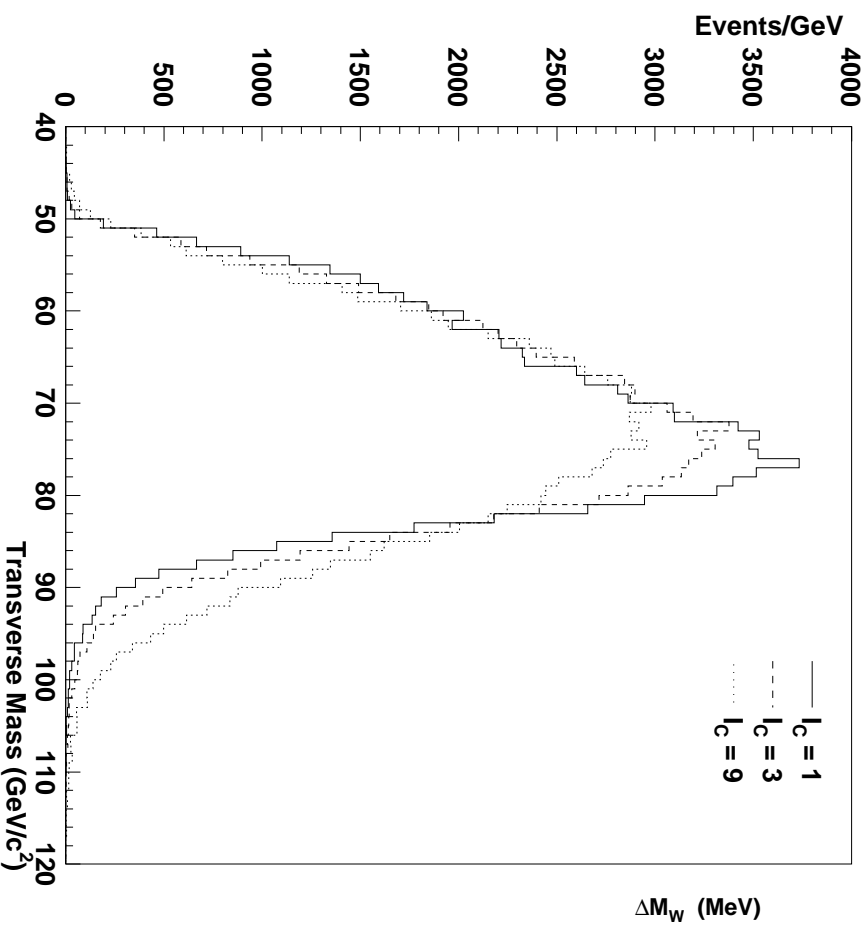
- ...and we know how to make it systematically better  
**more Z statistics**  
**better understanding of model uncertainties**
  - both will come for “free” with more running
- However, at higher instantaneous luminosities, effects from multiple interactions will become serious
  - will degrade the  $E_T$  resolution and therefore  $m_T$
- $I_C \approx 3[9]$  for  $L = 10^{32}$  [ $10^{33}$ ]  $\text{cm}^{-2}\text{s}^{-1}$  at 395 [132] ns bunch spacing
- group found roughly that:  $\Delta M_W|_{\text{sys}} \approx (17.9 \text{ GeV}/c^2) \sqrt{(I_C/N)}$

	1 $\text{fb}^{-1}$	10 $\text{fb}^{-1}$
$I_C$	3	9
statistical $\text{MeV}/c$	29	17
systematic $\text{MeV}/c$	42	23
Total $\text{MeV}/c$	51	29

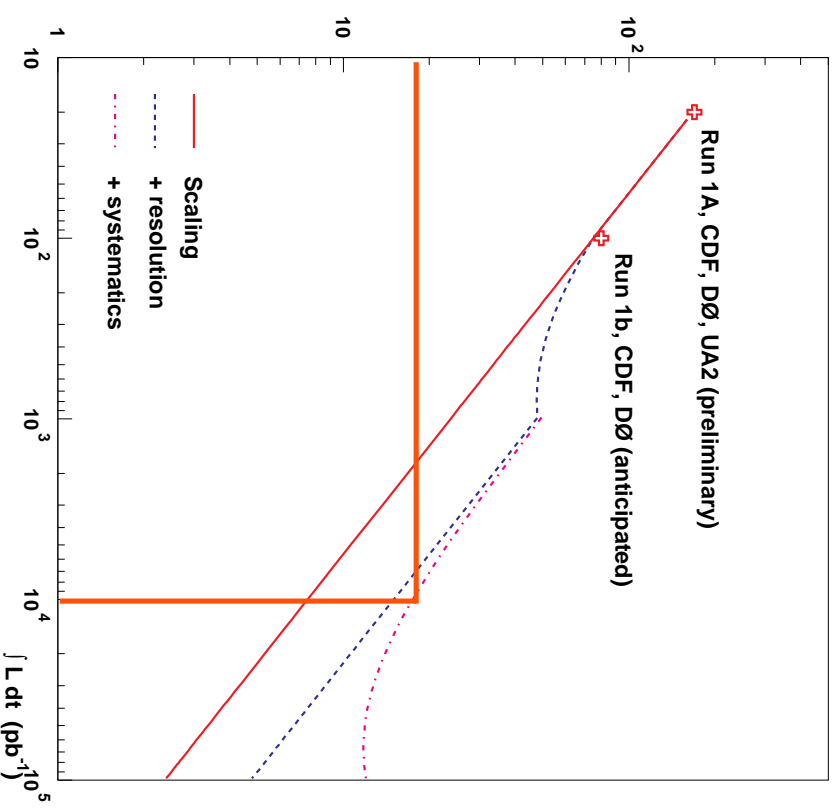
# $M_W$ cont.

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- multiple interactions were simulated by overlapping min bias events



Scaling of W-mass error



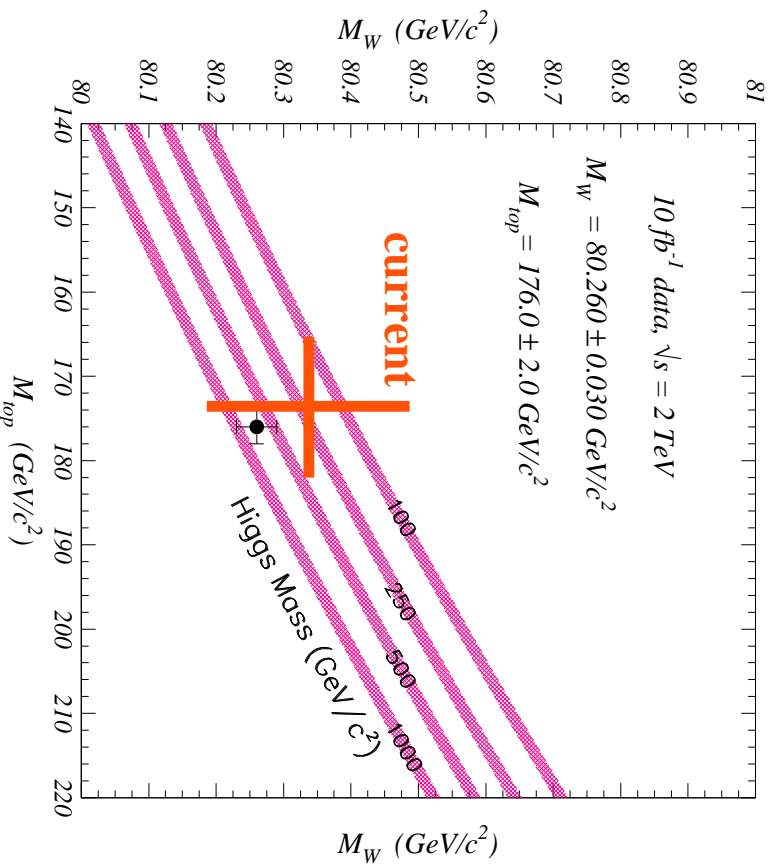
- sufficient statistics to measure  $M_W$  in alternative ways;  $p_T(\ell)$ ,  $E_\nu$ , etc.

closing in...

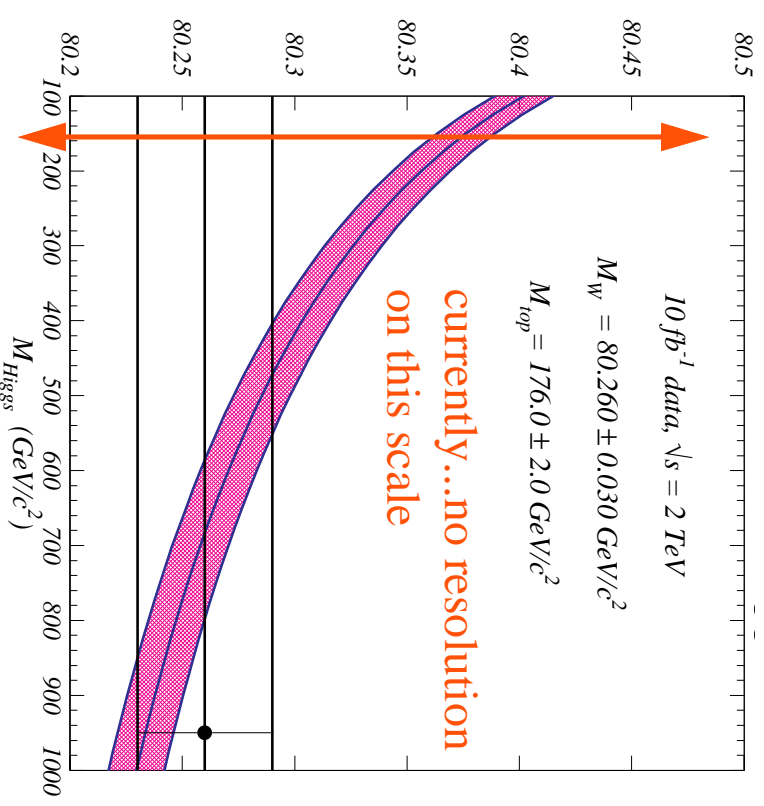
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**stressing the SM is the game**

“Fermilab Measurables”



...a different slice



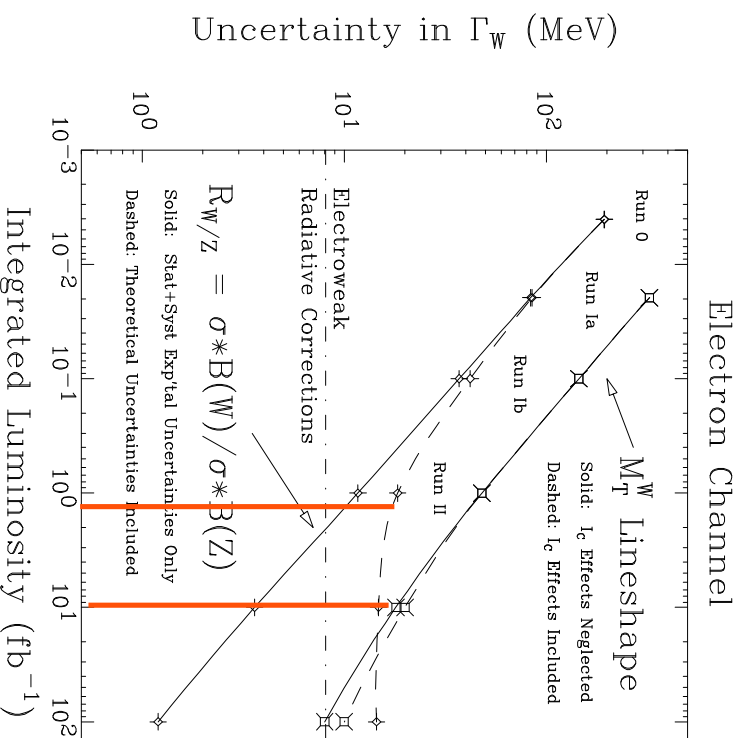
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**we know how to do this...**

- traditional method will bottom out on theoretical uncertainties
- direct measurement from the  $m_T$  distribution will win

direct measurement of  $\Gamma(W)$

	1 fb <sup>-1</sup>	10 fb <sup>-1</sup>
$\Gamma_c$	3	9
statistical MeV	40	13
background MeV	8	5
$p_T(W)$ MeV	17	8
energy scale MeV	6	3
electron energy resolution MeV	10	8
$E_T$ resolution MeV	14	8
Total MeV	48	20

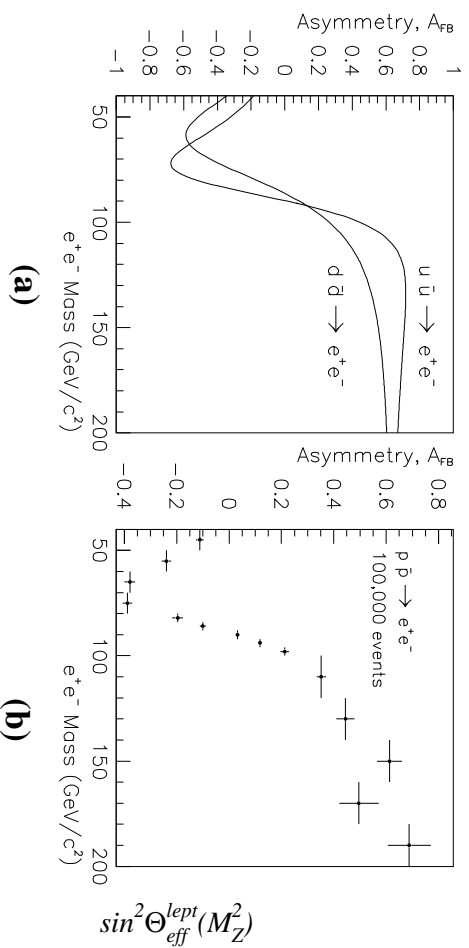


# asymmetries

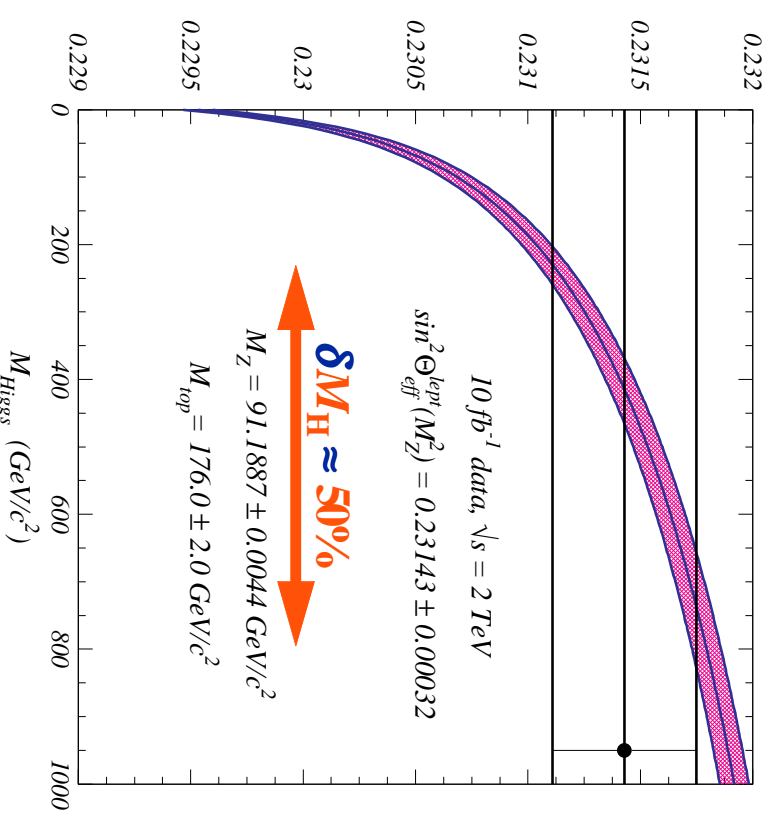
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**we know how to do this...**

- **W asymmetries** now are a definitive constraint on pdf's
- **Z asymmetries** will likewise restrict allowable pdf's
- **both timely and in pace with the pursuit of 30 MeV/c<sup>2</sup> in  $\delta M_W$**
- **also a complementary, largely uncorrelated EW constraint**



	1 fb <sup>-1</sup>	10 fb <sup>-1</sup>	100 fb <sup>-1</sup>
$\delta \sin^2 \Theta_{eff}^{lept}$ (stat)	$\pm 0.001$	$\pm 0.00032$	$\pm 0.00010$



# $p\bar{p}$ is a CP eigenstate

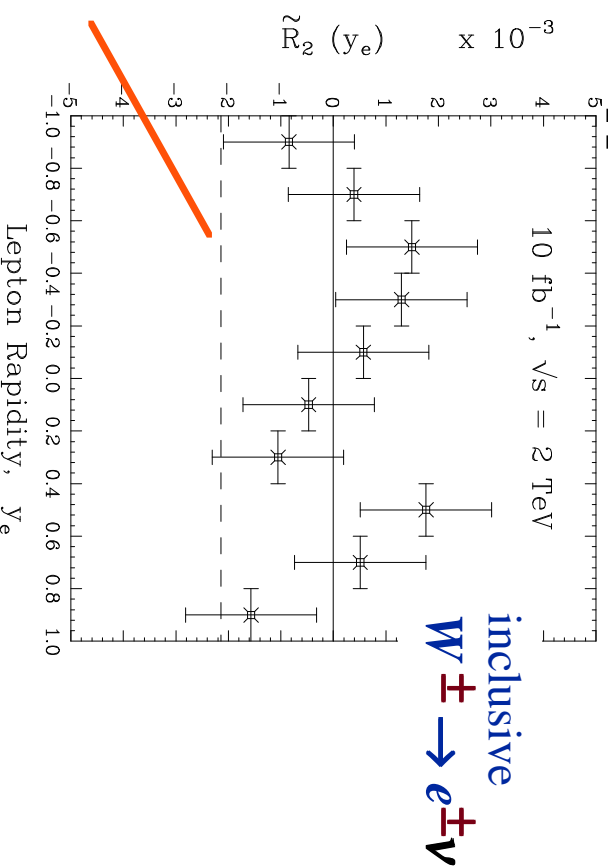
- uniquely Fermilab situation, top physics...

$$A_t = \frac{\sigma(p\bar{p} \rightarrow tX) - \sigma(p\bar{p} \rightarrow \bar{t}X)}{\sigma(p\bar{p} \rightarrow tX) + \sigma(p\bar{p} \rightarrow \bar{t}X)} \approx A_{\text{DW}} = \frac{\Gamma(t \rightarrow bW^+) - \Gamma(\bar{t} \rightarrow \bar{b}W^-)}{\Gamma(t \rightarrow bW^+) + \Gamma(\bar{t} \rightarrow \bar{b}W^-)}$$

- 10k events  $\rightarrow$  few % asymmetries, some model discrimination
- ...plus out-of-decay-plane/ in-plane measurements in  $t\bar{t}$

- a similar asymmetry is measurable in  $p\bar{p} \rightarrow W^\pm X \rightarrow \ell^\pm \nu X \equiv \sigma^\pm$

$$\tilde{R}_2(y_0) \equiv \frac{\frac{d\sigma^+}{dy_\ell} \Big|_{y_\ell=y_0} - \frac{d\sigma^-}{dy_\ell} \Big|_{y_\ell=-y_0}}{\frac{d\sigma^+}{dy_\ell} \Big|_{y_\ell=y_0} + \frac{d\sigma^-}{dy_\ell} \Big|_{y_\ell=-y_0}}$$



$A = 1 \text{ TeV} \ \& \ \sin\phi = 1$

— *tev\_2000*

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## we know how to do this

- steady accumulation of low-background data crucial

- glossary:

### most general $WWV$ ( $\gamma$ or $Z$ ) interactions:

- $(\partial W)WV$                       proportional to  $g_1^V$  ( $= 1$  in SM)
- $WWV$                               proportional to  $\kappa_V$  ( $= 1$  in SM)
- $(\partial W)(\partial W)(\partial V)$               proportional to  $\lambda_V$  ( $= 0$  in SM)
- $\epsilon_{\mu\nu\rho\sigma} \partial_\rho W_\mu W_\nu V_\sigma$       proportional to  $g_5^V$  ( $= 0$  in SM)

### most general $Z\gamma V$ ( $\gamma$ or $Z$ ) vertex

- characterized by two free parameters  
 $h_3^V$  and  $h_4^V$  ( $= 0$  in SM)

- $W\gamma$ ,  $Z\gamma$ ,  $WW$ , and  $WZ$  candidates have been seen

$W\gamma$  and  $Z\gamma$  have backgrounds from  $W/Z + j$  (fluctuating to  $\pi^0$ )

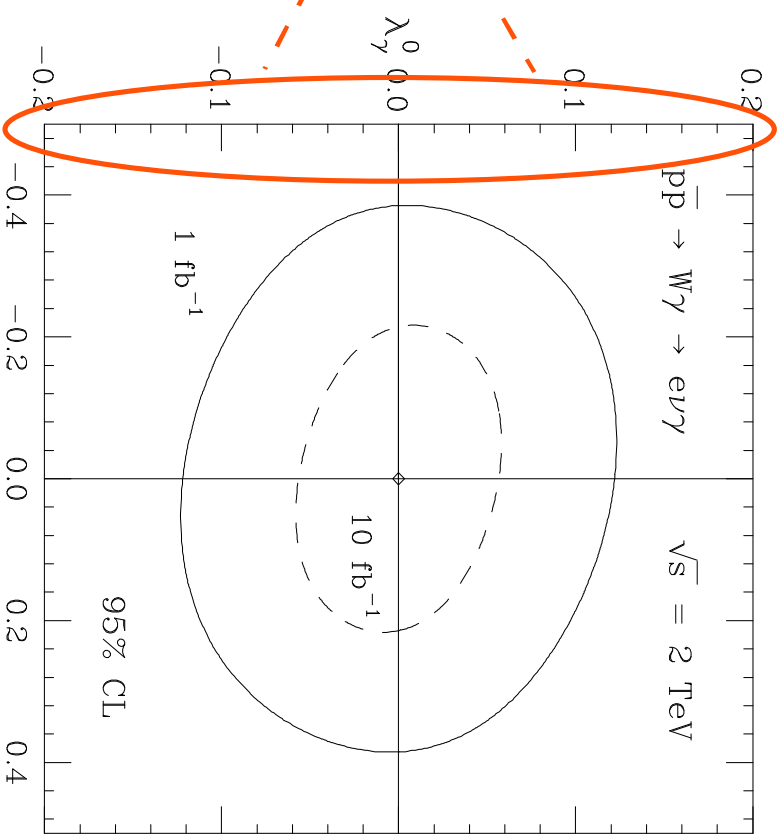
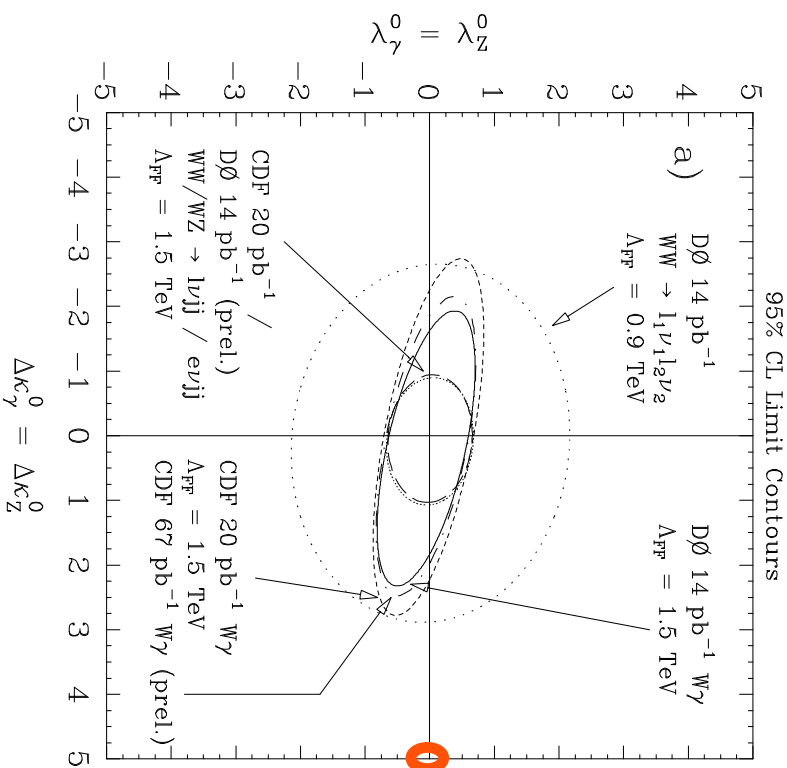
$WW$ ,  $WZ \rightarrow \ell\nu jj$  and  $ZW \rightarrow \ell\ell jj$  likewise (involves  $jj$  cuts)

$WW \rightarrow \ell\nu \ell\nu$  has  $t\bar{t}$  backgrounds

— *tev\_2000*

# limits will improve dramatically

WWV Anomalous Couplings from  $p\bar{p} \rightarrow WW, WZ, W\gamma$



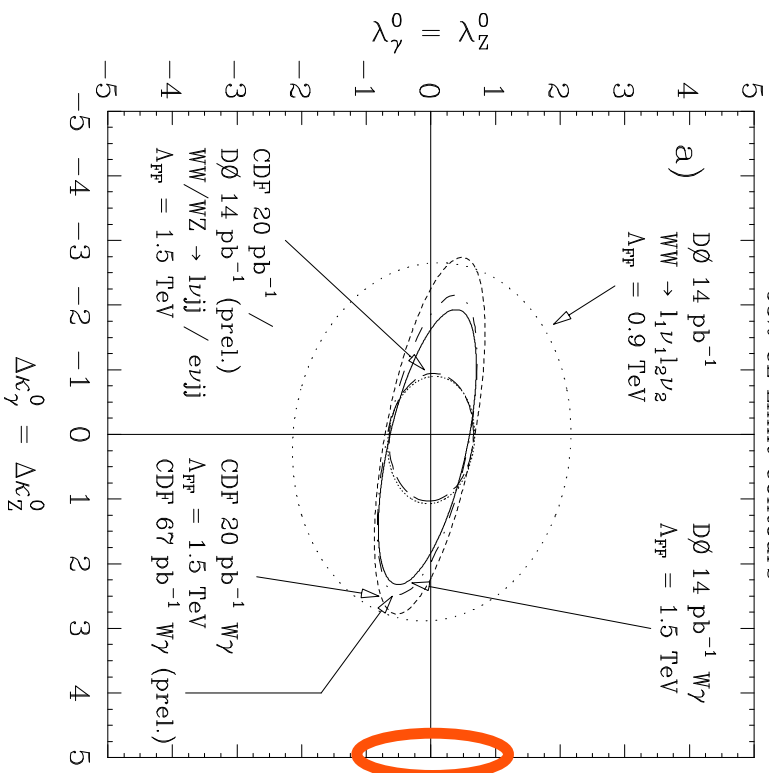
current limits

W $\gamma$

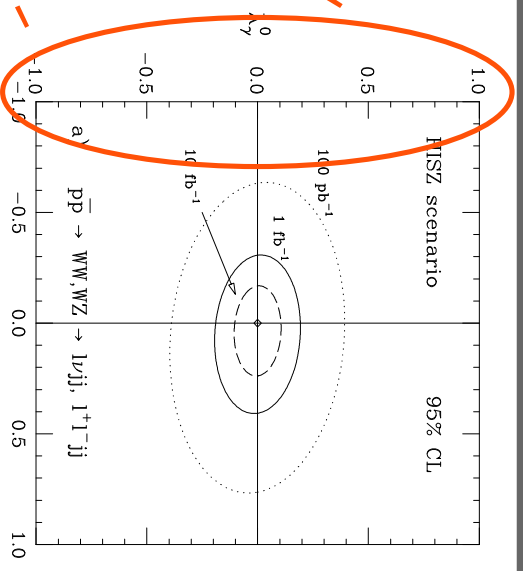
# WW, WZ

— **tev\_2000**

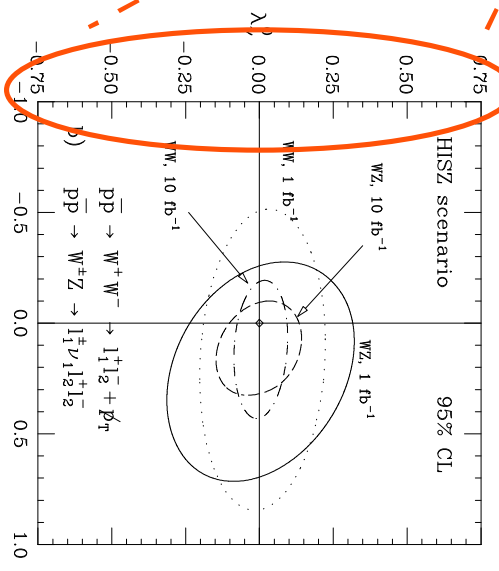
WWV Anomalous Couplings from  $p\bar{p} \rightarrow WW, WZ, W\gamma$   
95% CL Limit Contours



**current limits**



**WW, WZ → lνjj and ZW → lljj**



**WW → lνlν and WZ → ll + p\_T**

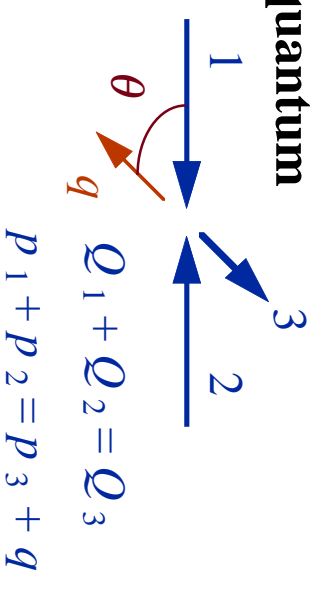
## radiation zero

— *tev\_2000*

**classically: dipole radiation for the scattering of two charged particles vanishes when  $Q_1/m_1 = Q_2/m_2$**

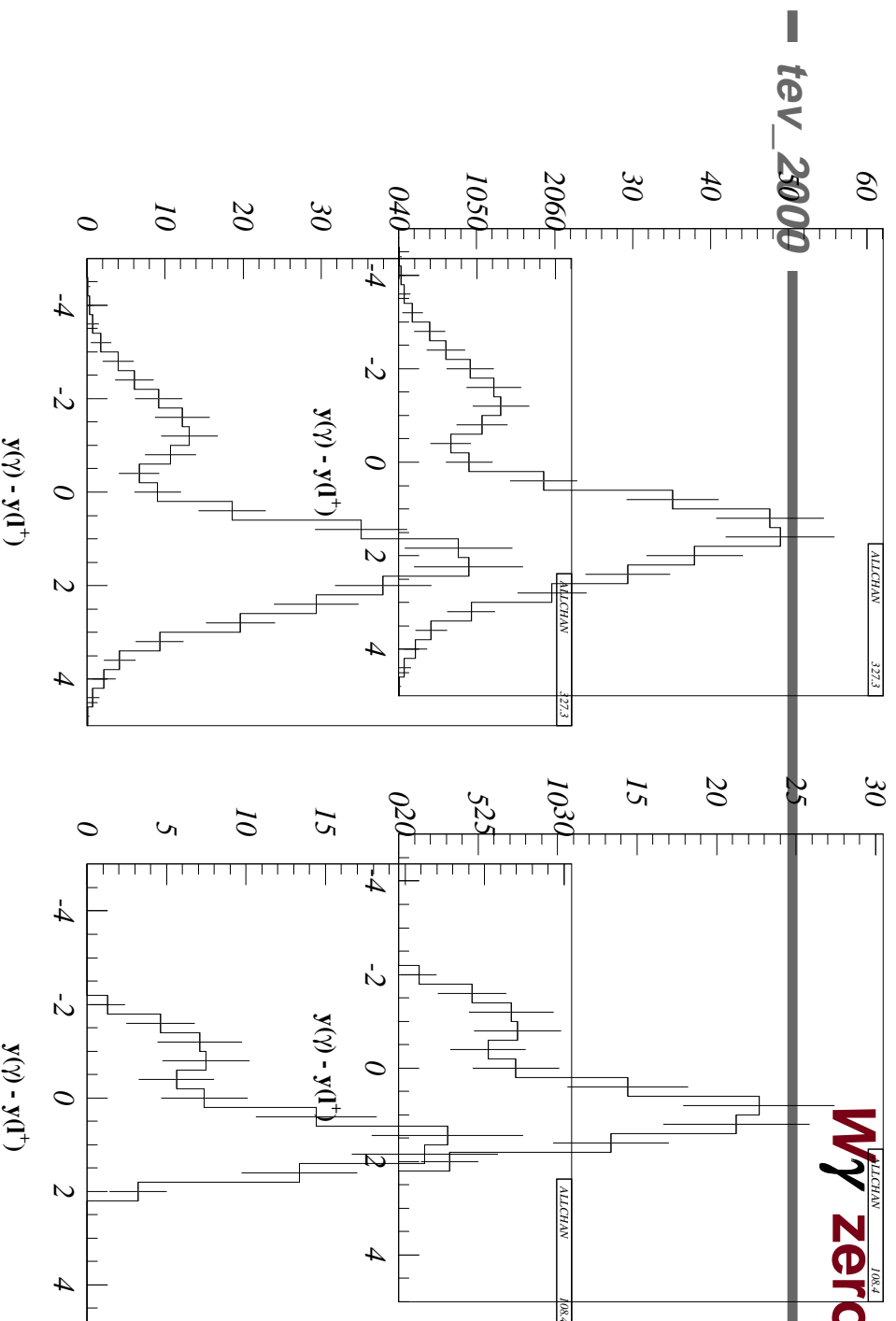
- this “radiation zero” persists to relativistic and quantum mechanical situations where the condition for

the “null zone” is  $\frac{Q_1}{P_1 \cdot q} = \frac{Q_2}{P_2 \cdot q}$  which



for  $E_1 = E_2$ , happens at  $\cos \theta = \frac{Q_1 + Q_2}{Q_1 - Q_2} = \pm \frac{1}{3}$  for  $u$  and  $\bar{d}$  annihilation,  $u \bar{d} \rightarrow W \gamma$

- a variety of non-standard effects will spoil this null zone, and confirmation is a fundamental test of the gauge invariance and structure of the SM
- the cm angle is difficult, but rapidity correlations in the laboratory frame
- this is a  $p\bar{p}$  favorable measurement...unaffected by NLO corrections, doable with precision lepton id.



— **tev\_2000**

central + endcap electrons

central electrons only

one of the numerous places that high-premium may be placed on large-rapidity leptons in the upgrades (top, MW, asymmetries, di-bosons, etc.)

## LEP II, LHC

### — *tev\_2000*

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- $M_W$ : important  $tev_{33}$  measurement, maybe unique
  - LEP II advertises  $\approx 40 \text{ MeV}/c^2$  from threshold ( $tev_{33}$ , 20-30  $\text{MeV}/c^2$ )
- $\Gamma_W$ : unique  $tev_{33}$  measurement
  - LEP II advertises  $\approx 400 \text{ MeV}$  ( $tev_{33}$ , few 10's  $\text{MeV}$ )
- $A_{FB}$ : complementary  $tev_{33}$  measurements, systematic tool
  - LEP II/SLD now at 0.00028 ( $tev_{33}$ , comparable)
  - LHC projected to be few  $\times 10^{-5}$ , more difficult
- $\mathcal{P}$ : complementary, model dependent for interpretation
  - only doable at  $tev_{33}$
- diboson couplings: timely  $tev_{33}$  measurements
  - LEP II, comparable for  $\Delta\kappa\gamma$  ( $tev_{33}$  better for  $\ell\gamma$ )
  - LHC better
- radiation zero: possibly unique  $tev_{33}$  measurement
  - LHC hard... QCD corrections difficult

**millions of  $W$ 's and  $Z$ 's are critical, high quality, high statistics systematics tools**

— *tev\_2000* —

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# Light Higgs Physics

*U. Heintz, Fermilab*

*D. Kuhlmann, Argonne*

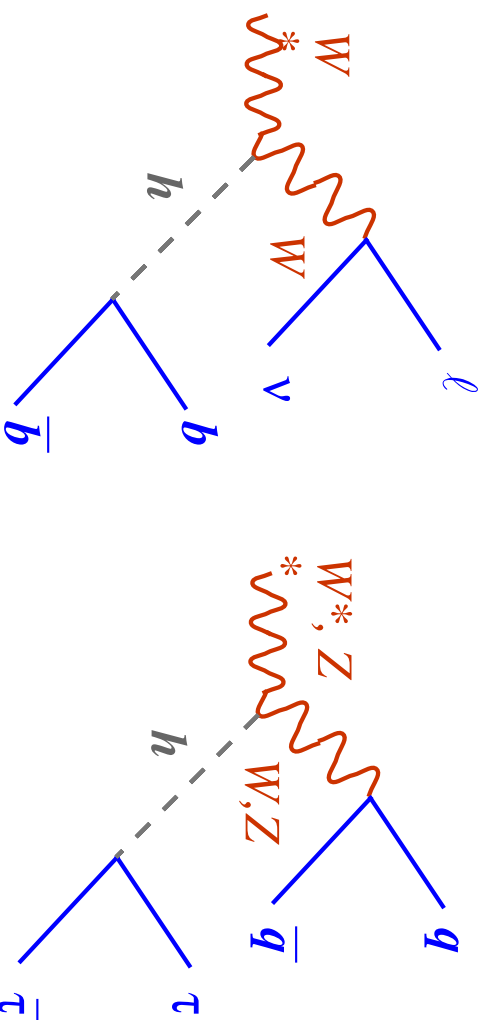
*S. Willenbrock, University of Illinois*

## light higgs physics

— *tev\_2000*

**books have been written on how to do this...**

- conventional wisdom became broader a few years ago with the outlining of the potential for associated light Higgs production



- if minimal supersymmetry is viable, then there would be an expectation for a Higgs spectrum which included a light, SM-like neutral scalar. Constraints would suggest,  $m_H < 125 \text{ GeV}/c^2$
- the canonical  $\gamma\gamma$  mode would be invisible to LHC in this range and backgrounds might fatally compromise associated production at LHC
- this has become an important component of a **tev33** program

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- *quick summary*

— *tev\_2000*

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## **light higgs physics at fermilab may be timely and unique**

- study has concluded that there is a luminosity threshold of 5-25 fb<sup>-1</sup> for the detection of a light higgs in the range 60-120 GeV/c<sup>2</sup>
  - $q\bar{q} \rightarrow WH \rightarrow b\bar{b}\ell\nu$  is the best mode for discovery
  - depends on *b*-tagging and jet fitting, and *W*+ heavy flavor backgrounds, just like the top program
- the  $q\bar{q} \rightarrow (W,Z)H \rightarrow \tau\bar{\tau}j\bar{j}$  modes are very difficult
  - $q\bar{q} \rightarrow ZH \rightarrow \nu\nu b\bar{b}$  mode has not been investigated
  - combined significance with *W* mode might improve overall discovery power
- intermediate mass Higgs may be discoverable at LHC, but disconfirmation as SUSY Higgs is compromised due to uncertain model-dependent BR( $H \rightarrow \gamma\gamma$ )
- $q\bar{q} \rightarrow WH$  is complementary to  $e^+e^- \rightarrow ZH$

# $WH \rightarrow b\bar{b}$

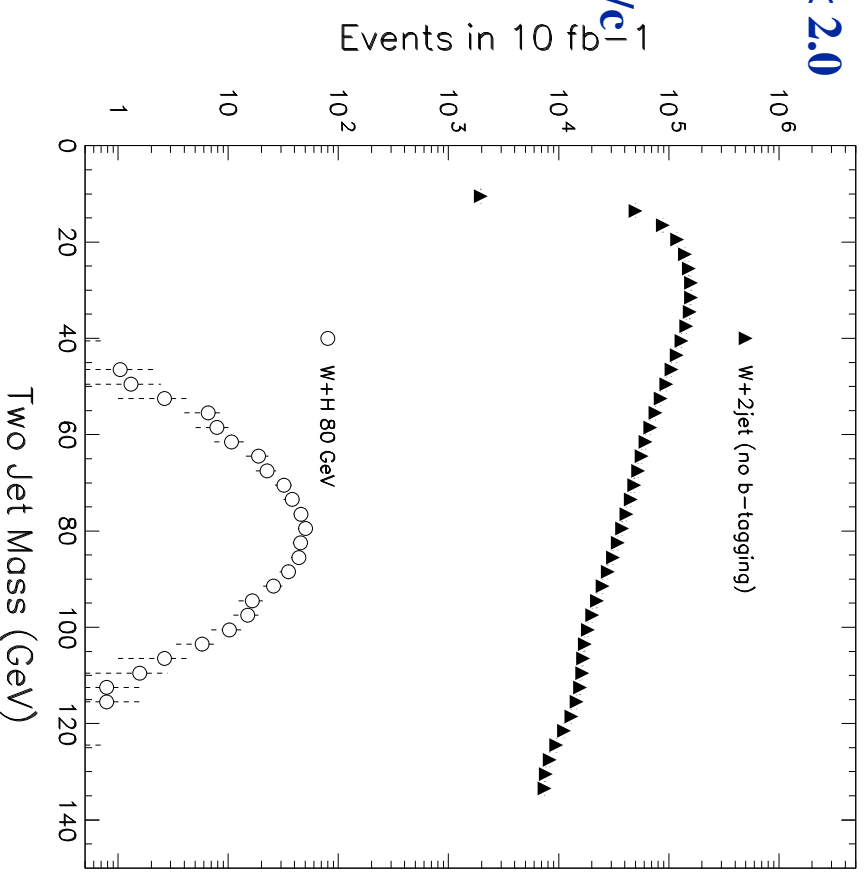
—  $tev\_2000$

**only a few people seem to know how to do this!**

● evolving study which has largely confirmed early theoretical calculations

- typical  $W$  cuts/selection
- $p_T > 15$  GeV/c for both  $b$  jets;  $|\eta| < 2.0$
- no extra jets with  $p_T > 30$  GeV/c (or 2 extra jets above 15 GeV/c)
- no extra leptons with  $p_T > 20$  GeV/c
- CDF calorimeter simulation

double  $b$  tagging required



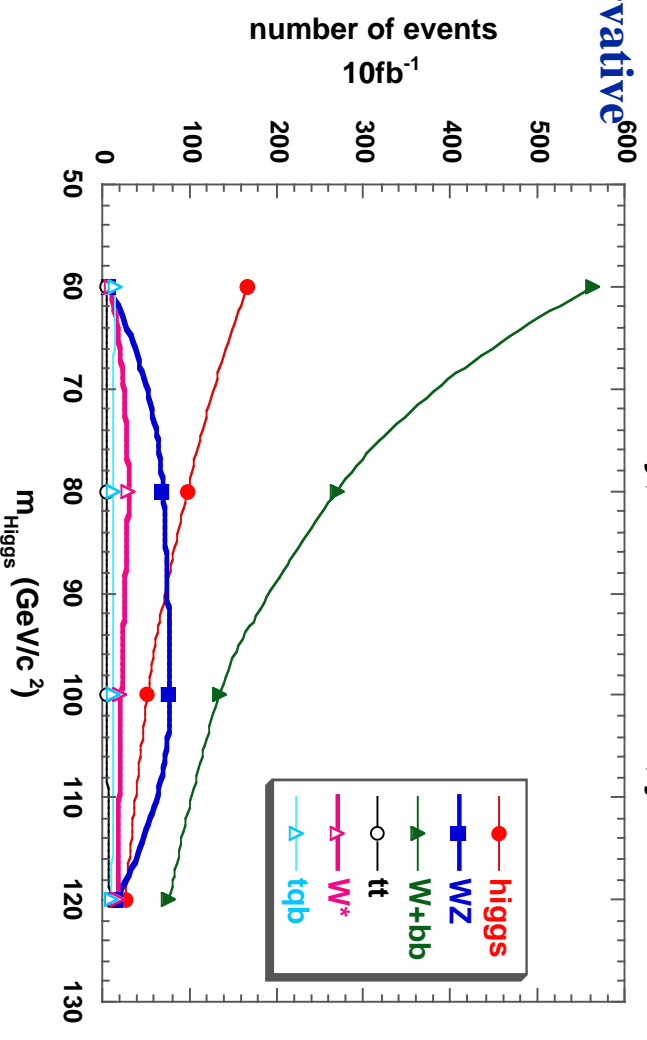
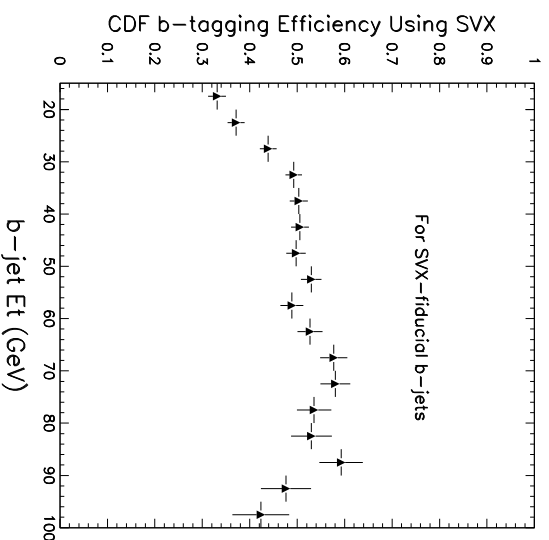
# backgrounds and b-tagging

— *tev\_2000*

## backgrounds are the issue

- $W + b\bar{b}$ ;  $WZ$  ( $Z \rightarrow b\bar{b}$ );  $W^* \rightarrow$  single top; gluon fusion single top,  $t\bar{t}$
- S/B different among proponents -  $M_H$  dependent cuts provide x4 improvement. This study assumed x2 improvement, without optimized cuts.

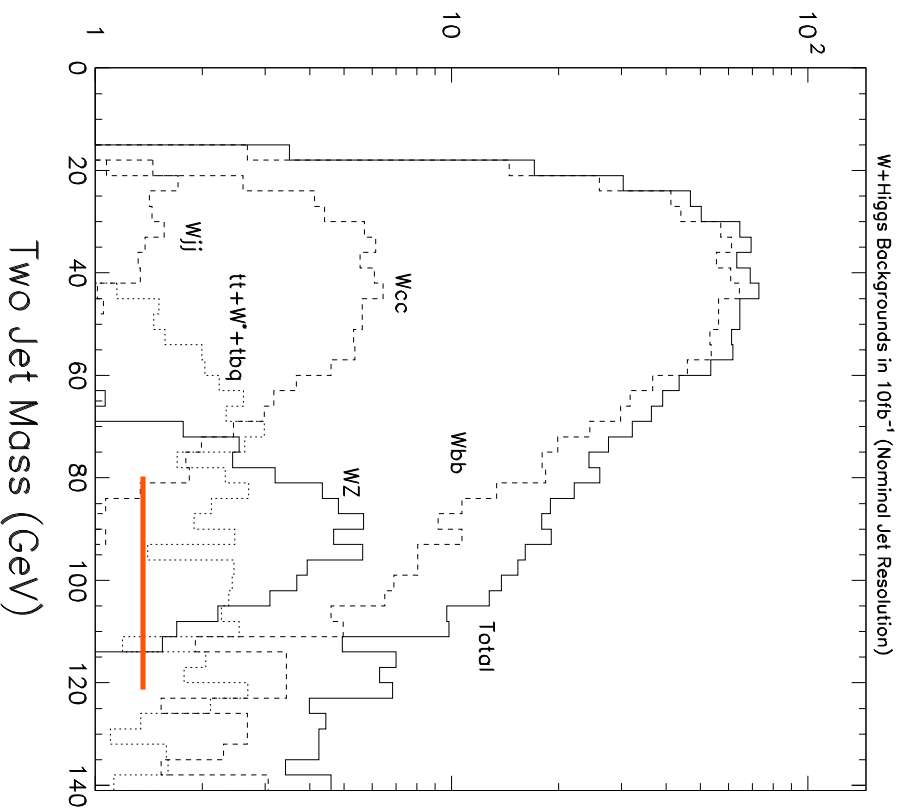
- b-tagging based directly on CDF experience and measurement
- strategy of trying to show convincing mass bump on optimum background shape
- double b-tagging, conservative



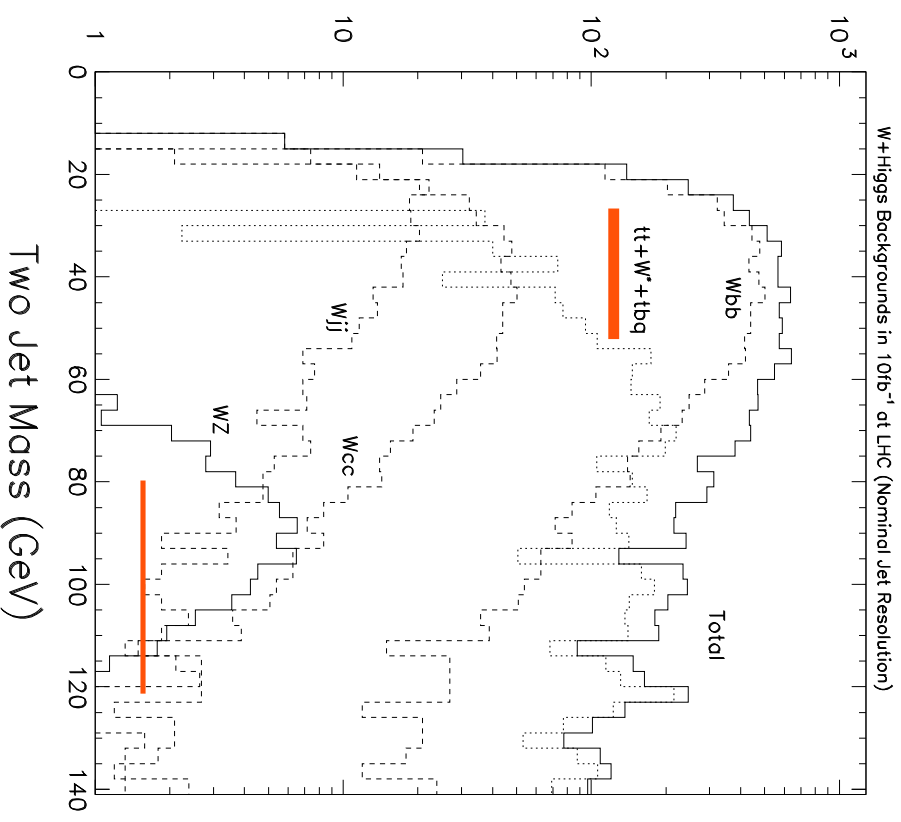
# all backgrounds

— *tev\_2000*

## tev33 has better background control



### Tevatron



### LHC

# results $WH \rightarrow b\bar{b}$

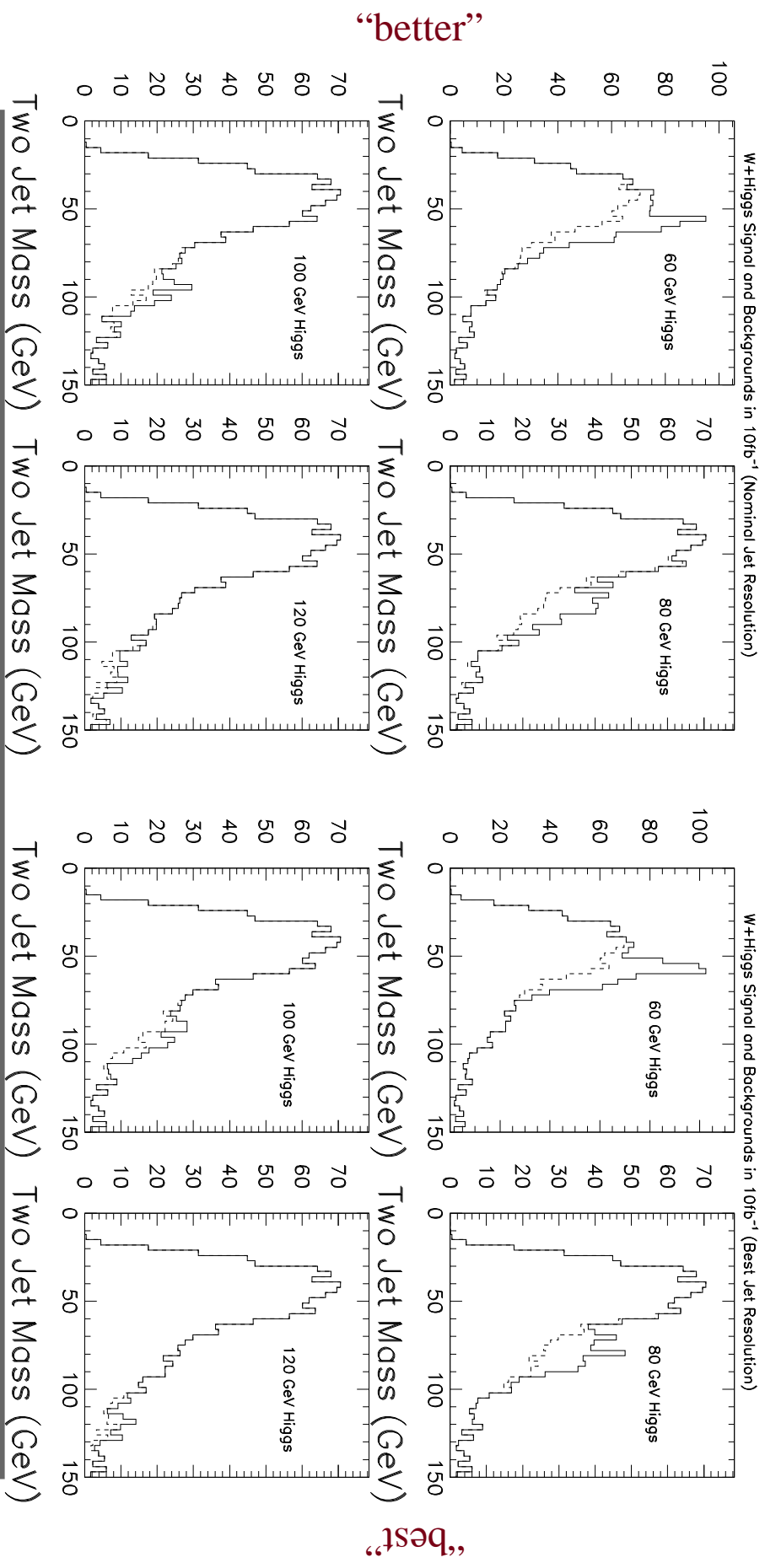
— *tev\_2000*

**the key will be  $m(jj)$  resolution**

- three options studied:

“best”, “better”, “worst” ... like Sears.

$m_H$ “better”	significance 10 $\text{fb}^{-1}$
60 GeV/ $\rho_c$	9 $\sigma$
80 GeV/ $\rho_c$	7 $\sigma$
100 GeV/ $\rho_c$	4.9 $\sigma$
120 GeV/ $\rho_c$	uncertain



# ZH $\rightarrow$ tt jj

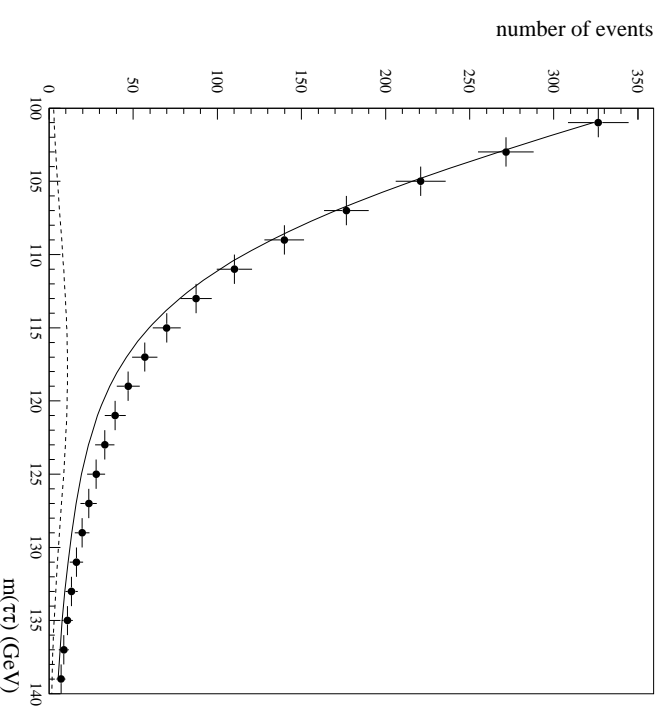
— *tev\_2000*

**strategy here is to combine the lower-statistics tau channel with the bottom.**

- backgrounds are totally different, maybe important for highest mass range in WH where top begins to become serious and irreducible
- nonetheless, the background

from  $Z \rightarrow tt$  jj is huge

- strategy
- calculate  $m(\tau\tau)$  from direction and  $p_T$  of the  $\tau\tau$  system in one-prongs
- DO resolutions and rejection power
- in  $10 \text{ fb}^{-1}$ , yield is about 10 events with S/B of 0.1
- resolution is obviously critical



# LEP II, LHC, NLC

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— *tev\_2000*

## LEP II

- by 1992,  $\sqrt{s} = 192 \text{ GeV}$  which will reach to  $m_H \approx 95 \text{ GeV}/c^2$   
the entire  $m_H$  range is accessible with significant RF and cryo upgrades...probably in conflict with LHC.

## LHC

- $\gamma\gamma$  mode still plated with gold, but associated production is conceivable...but with very difficult top backgrounds

## NLC

- discovery is straightforward in the  $ZH$  mode.

— *tev\_2000* —

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# Supersymmetric Physics

*K. De, University of Texas, Arlington  
T. Kamon, Texas A & M*

## Supersymmetry

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— *tev\_2000*

**many people think they know how to do this!**

- SUSY is a theory which has been “refined” over recent years into a model
  - containing 32 new particles, in addition to the current particle spectrum, with masses which must lie in the range  $100 \text{ GeV}/c^2 - 1 \text{ TeV}/c^2$
  - including 2 Higgs doublets with 5 physical states one of which is “light” ( $< \sim 130 \text{ GeV}/c^2$ ) and SM-like (see previous discussion!).
  - There are some versions of the model which correlate many masses which makes the theory Highly Predictive and can be made to be consistent with LEP results
- Supersymmetry cannot be ruled out by direct searches at Fermilab. However, promising models, coupled with the Light Higgs opportunities make the Tevatron a crucial, timely tool.
- strategies for discovery include chargino pair production, gluino pair production, and stop pair production...

• *quick summary* •

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– *tev\_2000*

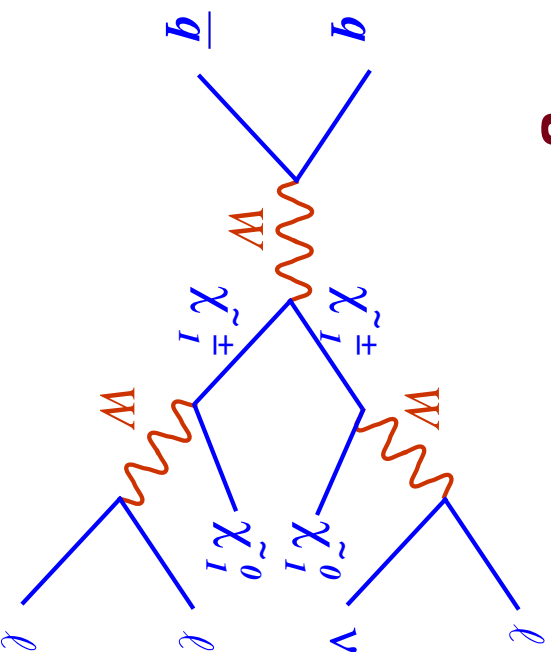
**supersymmetric physics at fermilab will be timely, complementary, and possibly unique**

- Within the Minimal Model, charginos of masses up to 250 GeV/c<sup>2</sup> can be discovered.
- gluinos of masses up to 300-400 GeV/c<sup>2</sup> can be discovered
  - with varying degrees of model-dependence
- stops can be detected up to masses of 180 GeV/c<sup>2</sup>.
- SUSY searches at tev33 will be complementary to those of LEP II and NLC.

## lightest chargino

— *tev\_2000*

**diagrams like:**



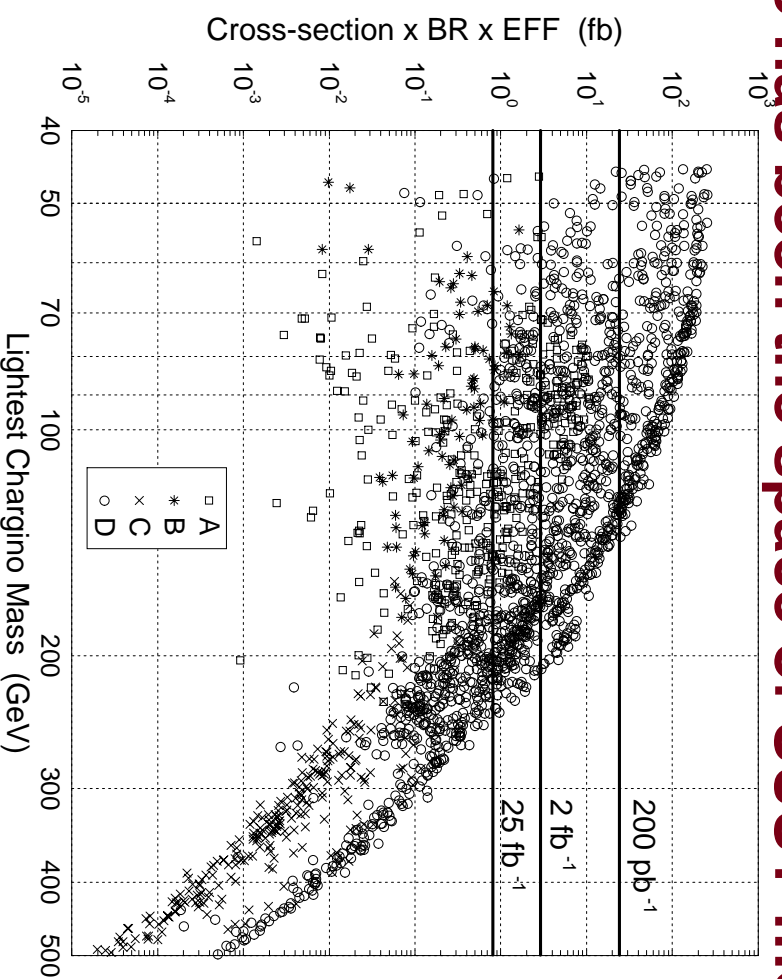
showing the characteristic signal of:

- 3 leptons
  - $\cancel{E}_T$
- various attempts at modeling of this “trilepton signal” and the relevant backgrounds have been made
  - dominant backgrounds are DY or Z dileptons with a fluctuating hadronic shower which fakes an electron
  - other backgrounds such as WZ, ZZ, and  $t\bar{t}$  can be controlled through dilepton mass cuts and  $\cancel{E}_T$  cuts
  - different background estimates have been reconciled in the study

## model space...

— *tev\_2000*

**instructive has been the space of SUSY models**



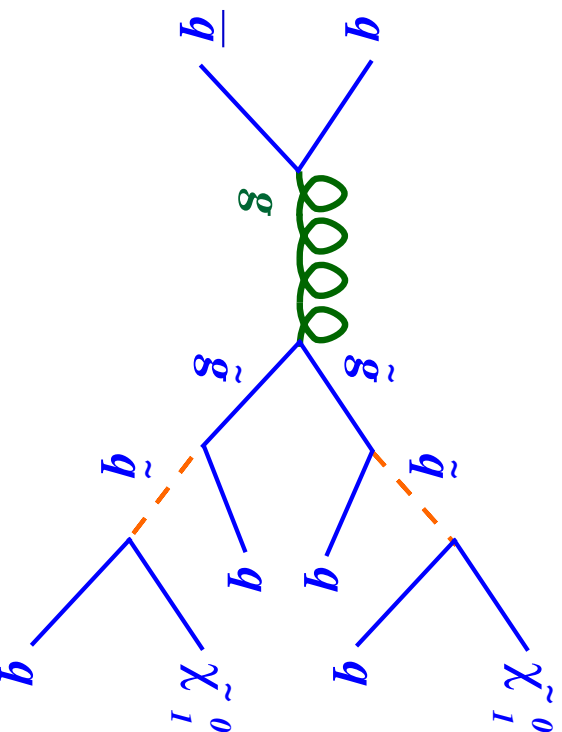
- these are  $5\sigma$  “discovery limits” above a presumed total background of about  $0.6 \text{ fb}$ .
- an attempt has been made to evaluate the effect of multiple interactions in degrading the signal (and background) detection efficiencies...this seems to decrease the mass limit by about  $10 \text{ GeV}/c^2$

## gluino search

— *tev\_2000*

...the “**traditional gluino search**”

- comes from diagrams such as:

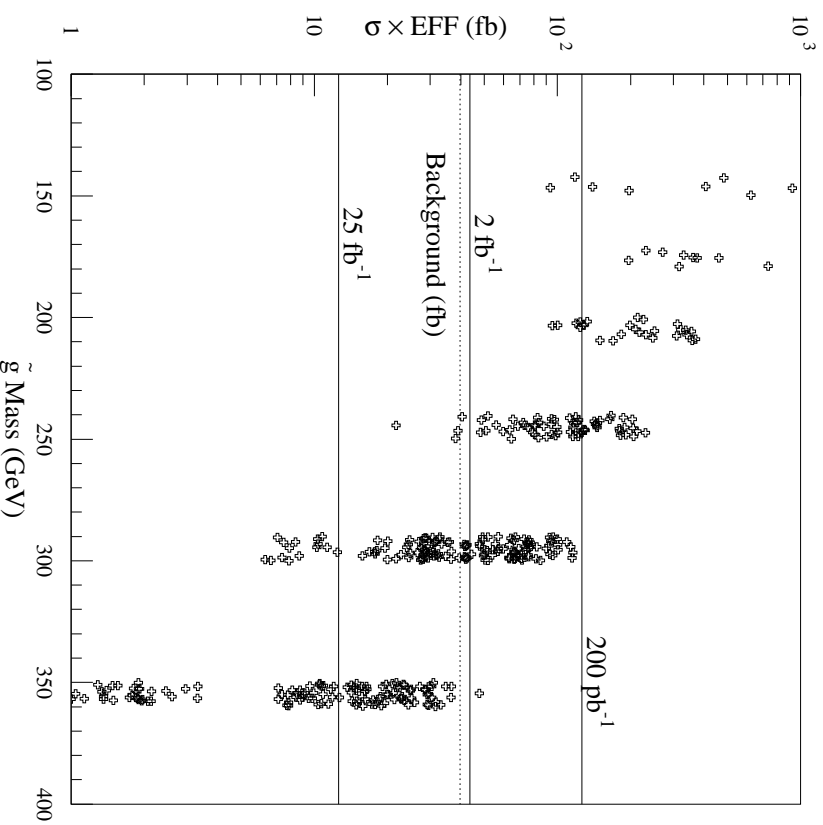


showing the characteristic signal of

- multiple jets
  - $E_T$
- various attempts at modeling this signal and the dominant backgrounds have been made
  - largest background is  $W$  plus jets and  $Z$  plus jets...which can be reduced substantially by requiring  $E_T(j_1) + E_T(j_2) + E_T \tilde{\chi}_1^0 > 300$  GeV

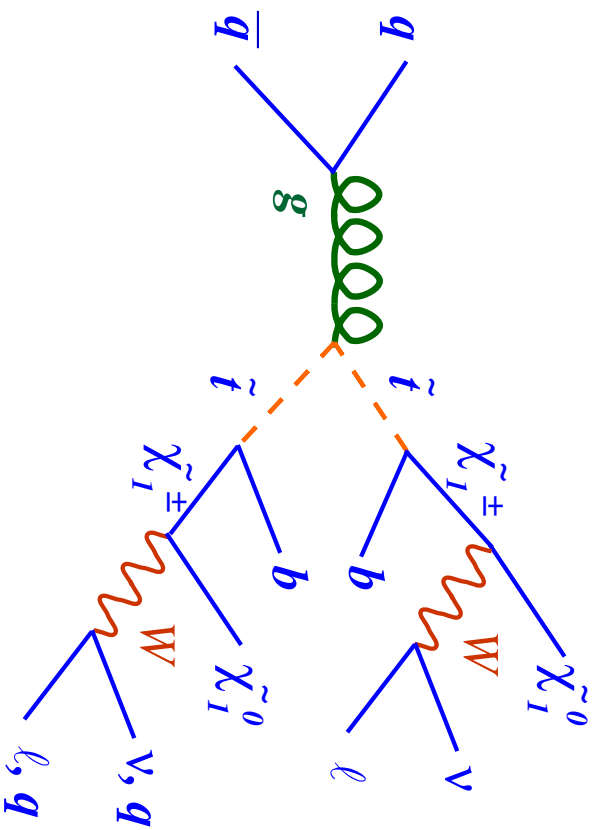
## more model space...

— *tev\_2000*



- these are  $10\sigma$  limits above backgrounds which are of order 40 fb.
- with a high cut on  $E_T$  of 75 GeV, the effect of multiple interactions may be small...no degradation of efficiencies has been applied.
- the effect of pileup in “creating” extra jets is assumed to be small.

## light top squark search



- Here there are two possible strategies with different signals:
- 1) single-lepton channel
    - one lepton
    - $E_T$
    - at least one tagged b
  - 2) dilepton channel
    - 2 leptons
    - $E_T$
    - $>1$  jet

- Roughly speaking, the range of  $m(\text{stop})$  to  $\sim m(\text{top})$  can be roughly covered in  $10 \text{ fb}^{-1}$
- In addition, if  $m(\text{stop}) < m(\text{top})$ , then the decay  $\tilde{t} \rightarrow \tilde{\chi}_1^0 c$  is kinematically favored: 2 colinear jets plus  $E_T$
- this search peaks in sensitivity in Run II at just below  $m(\text{top})$

# LEP II, NLC, LHC

— *tev\_2000* —

● maximum reaches by all of the players:

	current	tev33	100fb <sup>1</sup>	LEP II	NLC	
maximum mass limit:	1fb <sup>-1</sup>	10fb <sup>-1</sup>	100fb <sup>1</sup>	500pb <sup>1</sup> , 190 GeV	20fb <sup>1</sup> , 500 GeV	
$\tilde{\chi}_{\pm 1}^0$ GeV/c <sup>2</sup>	65 (LEP 140)	205	235	265	90	248
$\tilde{g}$ GeV/c <sup>2</sup>	173 (DØ, CDF)	350	400	>400	85 (100 pb <sup>-1</sup> )	≈ 250
$\tilde{f}_1$ GeV/c <sup>2</sup>	48 (LEP 140)	150	155	210	83	≈ 250
$\tilde{f}_1 (\rightarrow c)$ GeV/c <sup>2</sup>	100 (DØ)	150	150	150	na	≈ <b>250</b>

LHC does considerably better.

● The issue is not one of setting a limit, but in creating

1. a timely opportunity for discovery,
2. credible limits, and
3. a bank of experience which applies to future experiments, should discovery not occur.

**The Light Higgs opportunity ⊗ with the above direct SUSY sensitivity are a formidable assault on the most promising supersymmetric models.**

— *tev\_2000* —

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# Exotic Physics

***R. Harris, Fermilab***

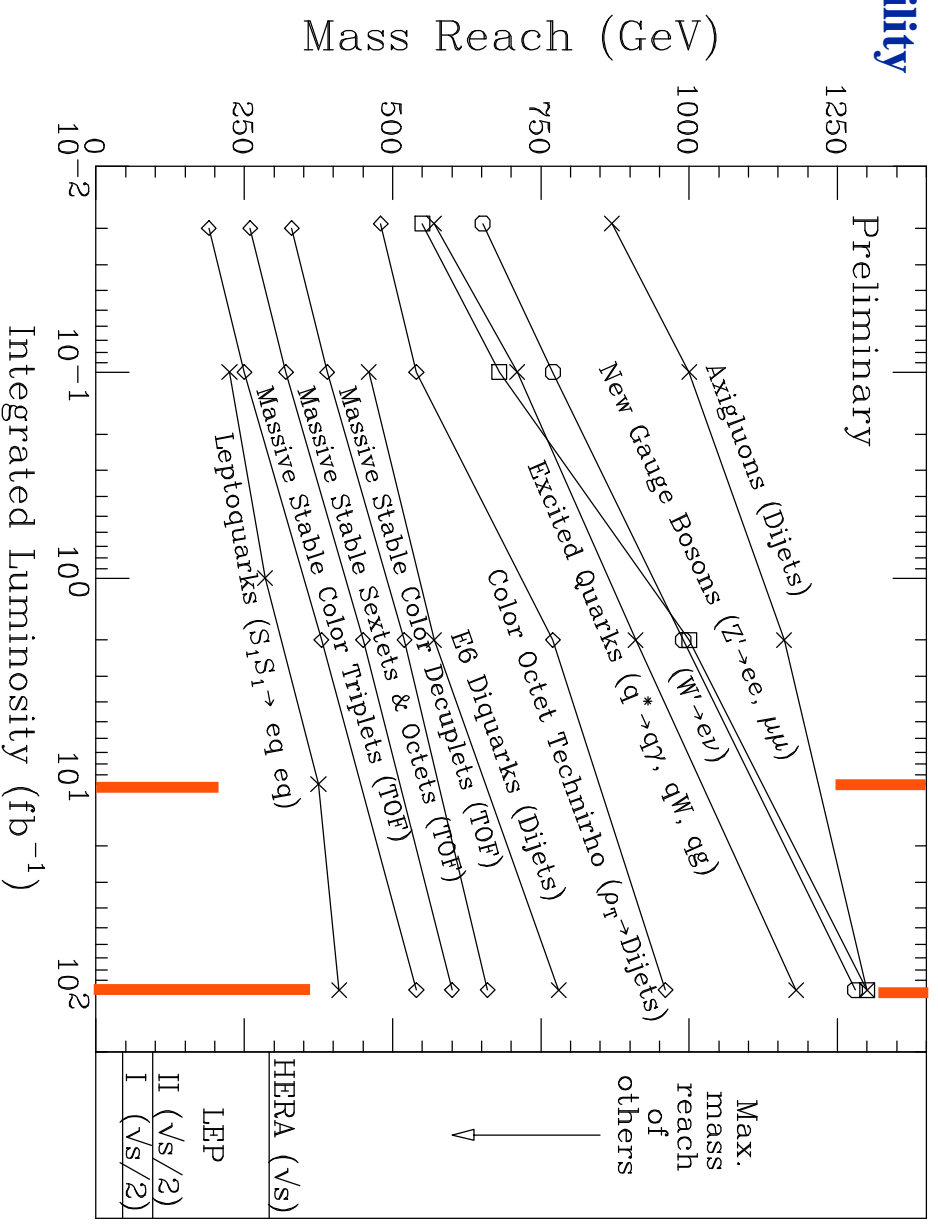
# exotics... • real quick summary •

— *tev\_2000*

## exotic searches at fermilab will be timely and complementary to other facilities

- effectively a doubling of current capability in RunII and a superluminous exposure

Searches for New Physics at Fermilab ( $\sqrt{s}=2$  TeV)



— *tev\_2000* —

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# **Physics with a Polarized Proton Beam**

*R. Brock, Michigan State University*

*G. Ladinsky, Michigan State University*

*H. Weerts, Michigan State University*

— *tev\_2000* — **polarized beams...** • *real quick* summary •

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**polarized colliding beam physics at fermilab would clearly be unique**

- It may be feasible to polarize the proton beam, transversely and longitudinally at high luminosity. The \$ cost is not unreasonable, but the question is on overall performance.
- non-negligible improvement of S/B for certain measurements might be obtainable - esp. QCD backgrounds
- There is a sizeable reduction in  $L_{\perp}$  ...hence, polarizing one beam now is not compelling
  - However, this might not be the whole story
  - physics opportunities should continue to be explored
- If it were possible to polarize both the  $p$  and the  $\bar{p}$  beams, without sizeable negative effects on luminosity, the S/B issues and distinct EW physics opportunities might arise.

# Detector Requirements

*J. Womersley, Fermilab*

## detector issues

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— *tev\_2000*

**The real questions...are detector/collaboration(s) questions.**

- watch out. The technical problems are probably solvable.
- the fiscal, organizational, sociological, and political issues may be much harder!
  - how many upgrades start out at one level and then evolve into something much more ambitious? this situation may not tolerate that.
  - there was no effort to consider the 1 detector or 2 detector or staged detectors or any of the other obvious conflicts that result when a calendar is mapped onto this project!

In most instances this workshop was a joint CDF/DO effort.

This level of cooperation may have to continue in order to achieve the physics goals

■ Ask yourselves: could the physics be more important than either CDF or DO? If you haven't already, you will find yourself confronting difficult issues like this in discussing detector upgrades for tev33! *having said that, I'll ignore it.*

• *quick summary* •

— *tev\_2000* —

## **high luminosity will be challenging...not crippling**

- tracking and vertex tagging appear to be feasible based on current experience and sensible extrapolations in a variety of worldwide scenarios
  - efficiencies <sup>a</sup> 50% and mistag rates < 1% seem reasonable
- existing calorimeter resolutions and acceptance seems sufficient
- lepton isolation will degrade in the high luminosity environment...how much?
- muon performance of existing detectors will likely be sufficient
  - **increased backgrounds seem inevitable and that will affect triggering**
- early looks at triggering capabilities suggest a match with the physics menu. Again, multiple interactions may surprise...
- offline processing will likely be capable with some 21st century extrapolation

— *tev\_2000*

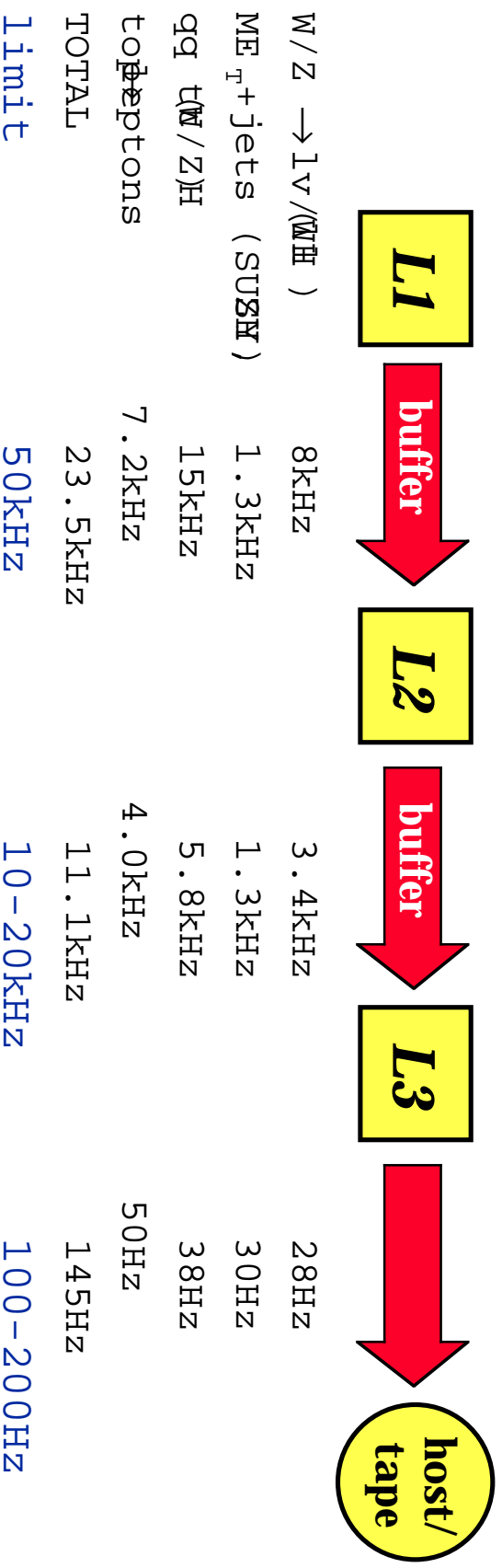
**The detector challenges are significant...solutions are consistent with an evolving accelerator.**

- calorimeter
  - EM: isolated electrons |  $\eta$  | < 2.5 → hard with pileup?  
soft electron b tags  
isolated electron triggering  $p_T > 15\text{-}20$  GeV/c  
resolution  $\sim 15\%/ \sqrt{E}$  adequate
  - Had: id & measure jets  
missing  $E_T$   
0.1x0.1 segmentation adequate  
resolution  $\sim 70\%/ \sqrt{E}$  adequate  
triggering on jets and missing  $E_T$
- tracking  
magnetic, 3D tracking  
SVX<sup>n</sup> disp. vertices |  $\eta$  |  $\sim 2$  with CDF performance @  $10^{33}$
- muons  
id & measure soft muon b tags  
isolated  $\mu$  trigger, |  $\eta$  | < 2.5,  $p_T > 15\text{-}20$  GeV/c

— *tev\_2000*

## A TRIGGER CASE STUDY:

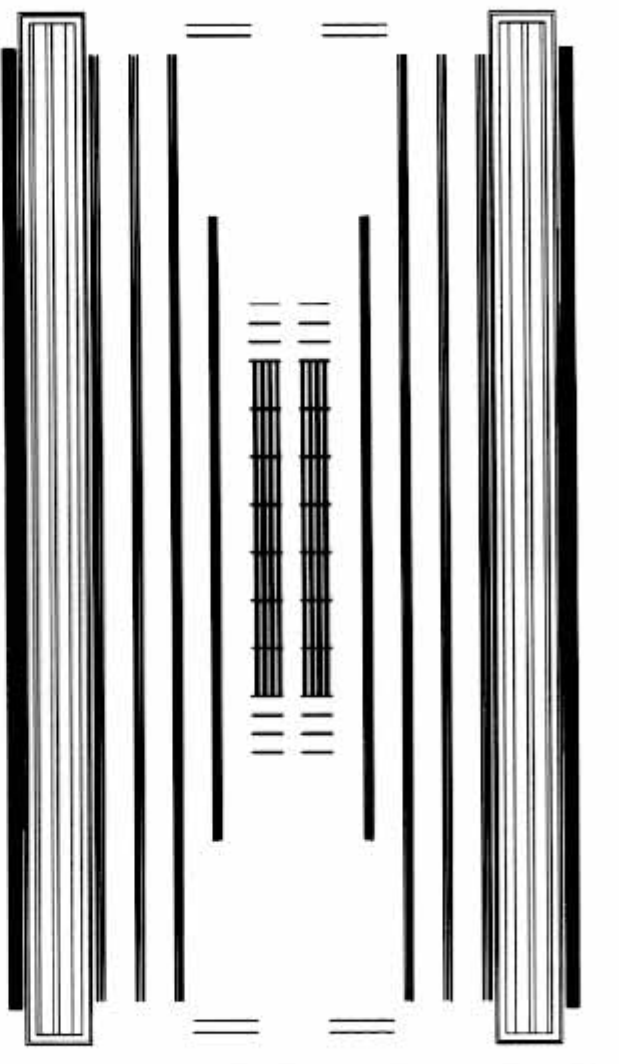
- Straw-man trigger system considered:
  - three level system (1: analog hardware; 2: DSP's; 3: software)
  - primitives: (isolated electrons; isolated muons; charged tracks; jets; missing  $E_T$ ..displaced vertices?)



- pileup? studies suggest that MET > 20 GeV still okay with 9 minbias overlap

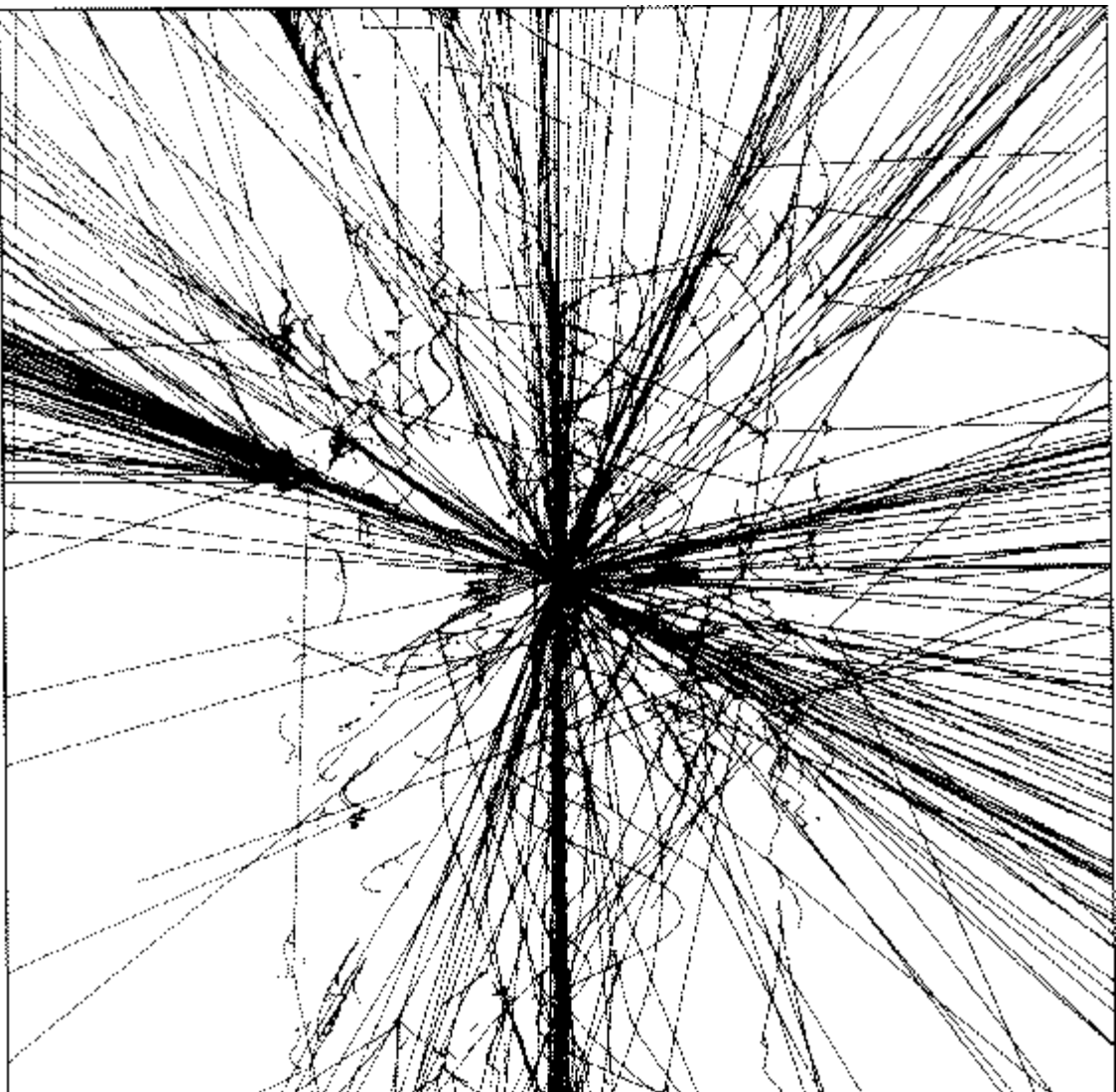
**everyone's favorite:**

— *tev\_2000* —



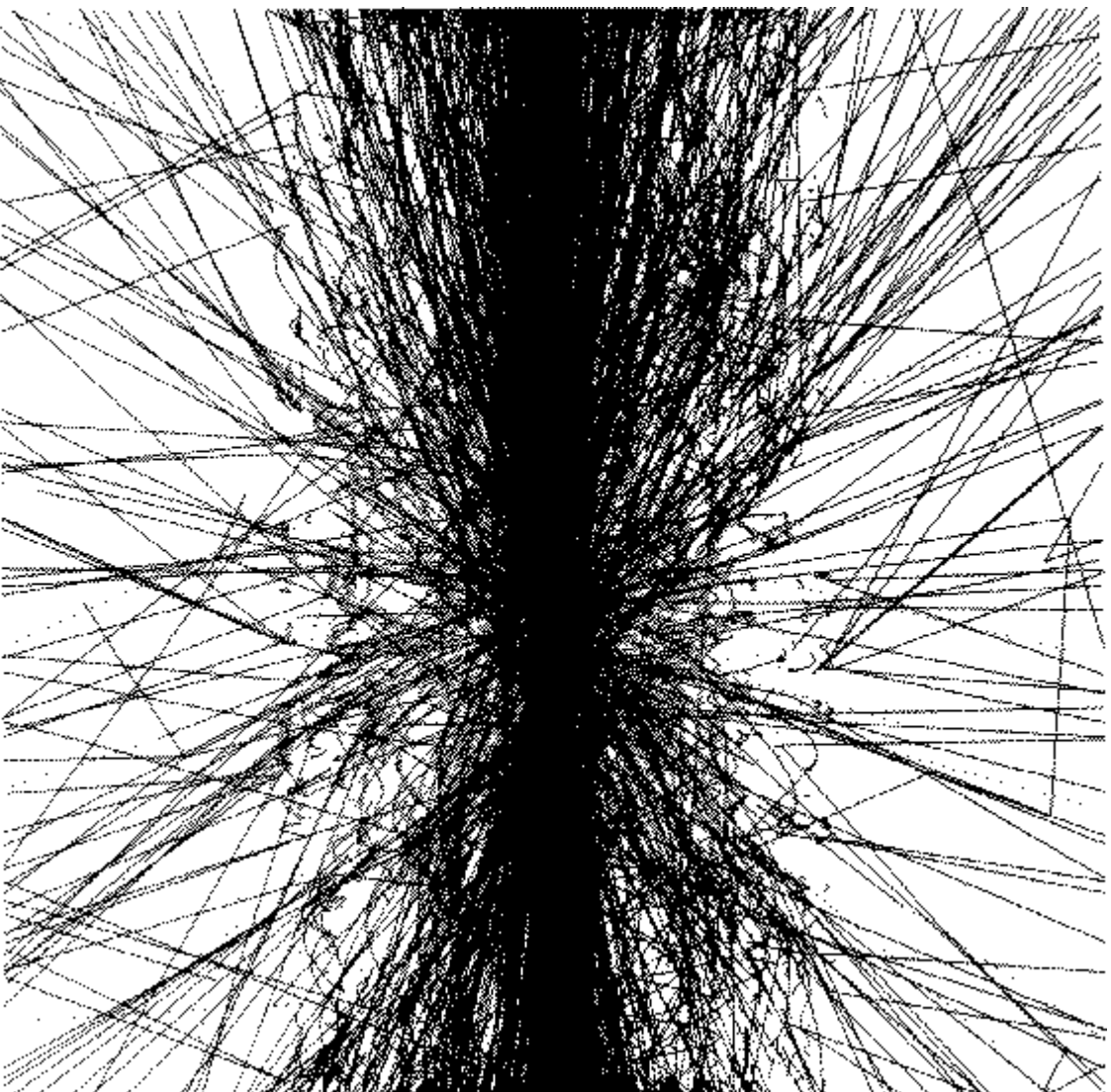
# 1 tt event

— tev\_2000



**+ 9 min bias**

— *tev\_2000* —



**we are not unaware of the difficulties**

*Chip Brock*

*tev\_2000 Workshop*

*5/23/96 4:46 PM*

## **primary conclusions of the workshop**

- Fermilab will be the Top Quark factory for a decade or more...as with other unusual quarks, the beginning of many decades of work and surprises. It is essential that this opportunity be realized.
- Speculation that there may be a ‘luminosity threshold’ for the discovery of a light Higgs scalar appears to be borne out... 5 - 25 fb<sup>-1</sup> level. More work is still required.
  - a strategy for confirming and realizing this threshold necessary. *this workshop?*
- A Tevatron program can either discover supersymmetry, or severely constrain it. Actual discovery potential still requires more work.
- High luminosity conditions are still not adequately understood as they effect detector performance. Better understanding, including a serious R&D program seems critical.
- The physics overall is tantalizing...simply waiting for LHC is unwise. Maximizing the physics return of the Tevatron is an effort which ought to be vigorously pursued with management, accelerator, and user participation.

## where are there some common themes?

— *tev\_2000*

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### there seem to me to be a few important correlations

- we ought to be as confident as possible that we understand them
- *W* plus heavy flavor - recurs in almost all topics. efficiencies, rejection, geometrical acceptance, pattern recognition in *b*-detection make or break much of this
- lepton acceptance and efficiency - not really emphasized, but figures into many issues, not the least of which is the pdf uncertainty in  $M_W$ . Are the detection efficiencies and the tracking and vertexing capabilities of the upgraded detectors completely understood?
- QCD uncertainties and jet scale issues. An all-out attack on this will be required - everyone knows that. However, the degree to which one physics topic scratches the back of another physics topic (horrible metaphor...) ought to be well understood.
- Is there substantive benefit to  $\bar{p}p$  - induced global EW fitting ( $M_W, \Gamma_W, A_{FB}, A_W, M_H, \dots$ )? A modest program could be imagined which parallels much of the broader (highly correlated) LEP global fitting...
- pileup. There is a nervous calm about the effects of overlapping events in many of the topics. Has this really been understood?

— *tev\_2000*

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## sentiments of the editors/organizers:

### think of the physics themes:

Top and electroweak physics, symmetry breaking, generational mixing among quarks and leptons,  $\mathcal{CP}$  in  $s$ ,  $b$ , and  $t$  (?) systems, spectroscopy and rare decays in  $s$ ,  $c$ ,  $b$ , and  $t$  systems, hadronic structure in high and low  $p_T$  regimes, and the Zoo.

**The fermilab complex is guaranteed to significantly impact each of these areas**

from the collider to the fixed target area to the oscillation program, this wonderful facility can continue a vigorous and comprehensive program, wholly and efficiently within the scope of the US borders.

We have outlined here a **program** of research specifically for the Tevatron collider at Fermilab. It is **rich in guaranteed physics** (top, IVB), **surprising in its reach to the next level** (SUSY, Higgs, exotics), fertile in the different configurations which are feasible, **stimulating to continued R&D** in\_ accelerator and detector technologies, and **stable as a platform for the far future** of high energy physics (ultra-high energy *pp* or *pp*, and *e<sup>+</sup>e<sup>-</sup>*-linear collider, or a  $\mu$ -collider). **Much work still remains to be done**, but we hope that those who have not considered the **evolutionary opportunities** at the Fermilab complex will begin to look deeper with us. We urge our colleagues, the Fermilab management, the Department of Energy, the National Science Foundation, and members of Congress to take seriously a Physics Program for the United States which builds on the significant investment of millions of dollars and thousands of physicist-years to continue to **Follow the Physics**.