P2: Top Quark Physics
Summary

Lynne H. Orr
University of Rochester

LCWS2000
Fermilab
Oct. 24-28, 2000

Co-conveners: M. Martinez (Barcelona)
X. Zhang (ITP, Beijing)

Outline

1. Introduction
2. Top at Threshold
3. Continuum Top Production
   - couplings
   - QCD
4. Top at $\gamma\gamma$ colliders

Introduction

- Top is uniquely heavy:

  $m_t = 175$ GeV

  ⇒ largest fermion–Higgs coupling

  ⇒ special role in EWSB? (why $\lambda_t \simeq 1$?)

- Top decays very fast:

  $\Gamma_t = 1.4$ GeV

  ⇒ decays before hadronizing

  ⇒ parton level treatment justified

  e.g., spin info passed to decay prod.

⇒ Top is prime system to study new physics

⇒ LC is excellent, clean place to do it!

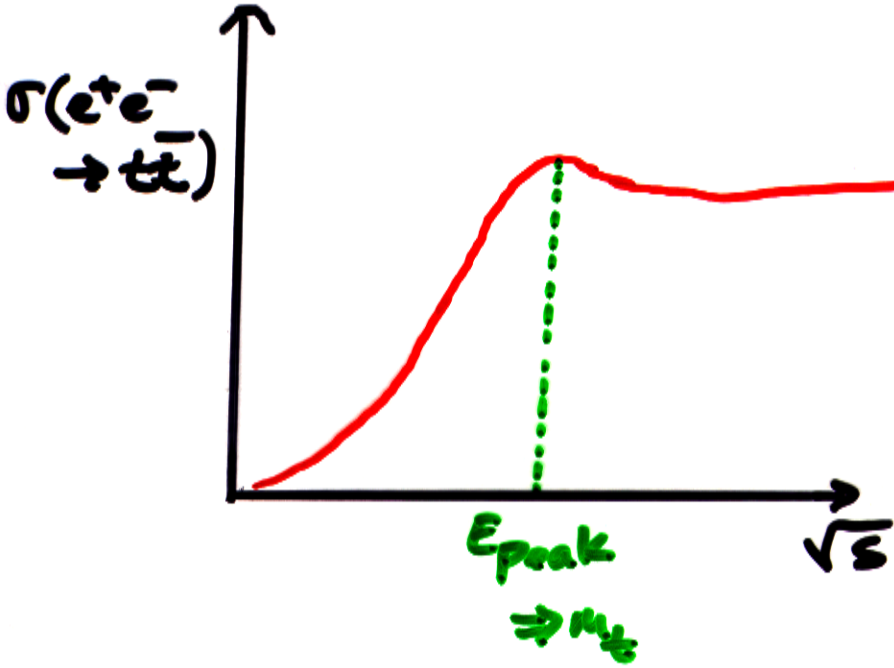
- See also:
  - Higgs (Yukawa coupl.)
  - Electroweak (Strong WW)
  - New phenomena (extra dim.)
  - SUSY ($t \to H^+ b$ etc)

... but you must understand SM top first!

Top at Threshold

Talks by:
Sumino
Yakovlev

- No toponium, but Coulomb-like QCD interaction ⇒ threshold structure:



⇒ measure

m_t
α_s
λ_t (Yukawa)
Γ_t

Thresh. scan: m_t to 50 MeV (stat.)

- Sitges: NNLO corr's calculated

Problem: corr's large (normalization)

peak position keeps moving
~600-800 MeV shift!

renorm scale dependence no better than NLO

← fig

Good news: peak position/mass problem solved

[Bad news: other two problems not solved]
needed for couplings

Sumino

"Toponium" 1S-state spectrum

For $\hat{m}_t = 165$ GeV ($\Leftrightarrow m_{pole} = 174.79$ GeV)

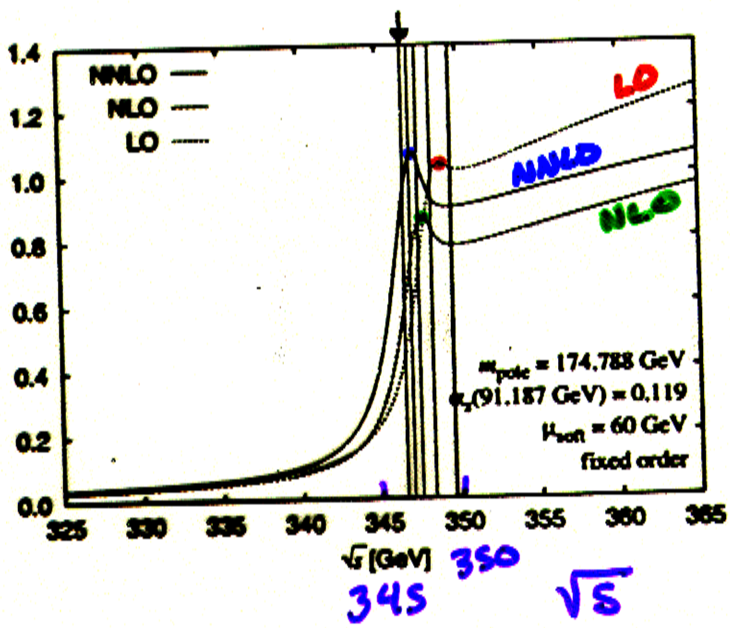
expansion parameter $= \alpha_s^{(5)}(\hat{m}) = 0.1092$

$$M_{1S} = 2 \times (174.79 - 0.46 - 0.39 - 0.28 - 0.19^{*})\ \text{GeV} : \text{Pole-mass scheme}$$

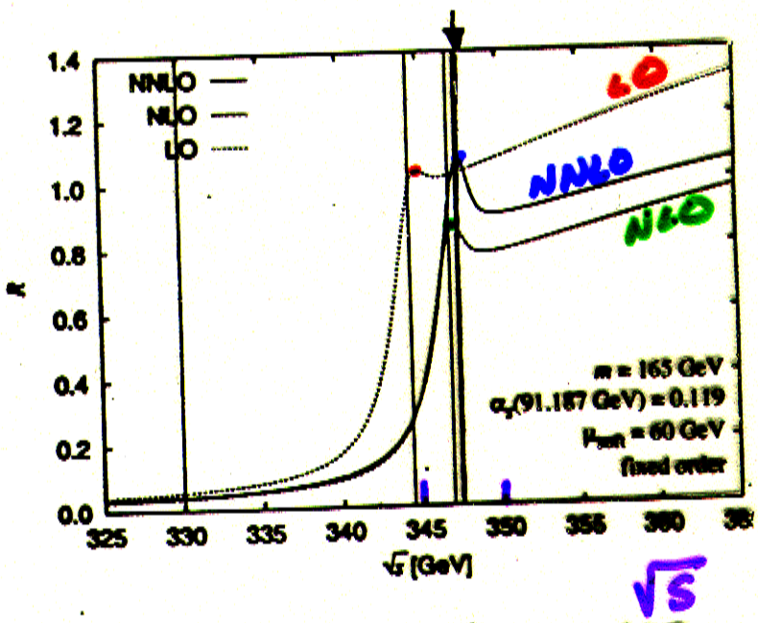
$$= 2 \times (165.00 + 7.21 + 1.24 + 0.22 + 0.052^{*})\ \text{GeV} : \overline{\text{MS}}\ \text{scheme}$$

Kiyo + Y.S.

Pole mass:



$\overline{\text{MS}}$ mass:



Nagano + Y.S.

* new result

Top masses

Pole mass m_{pole}

- position of pole in top propagator
- meas. in top reconstruction (CDF, DØ)
- sensitive to long dist/low energy (cf hadronization)

⇒ "renormalon ambiguity" $\mathcal{O}(\Lambda_{QCD})$

⇒ shift in NNLO peak position

Solution:

Short distance/threshold masses m_{SD}*

$$m_{pole} \simeq m_{SD} + \frac{1}{2}\int_{|q|<\mu} (\text{renormalon pole})$$

⇒ renormalon pole cancels in binding En.!

$$E_{tot} = 2m_{pole} - \int (\text{renorm pole}) + \int \text{well-behaved}$$

$$\boxed{E_{tot} = 2m_{SD} + \int \text{well-behaved}}$$

← fig

* $m_{\overline{MS}}$, m_{1S}, m_{kin}, m_{PS}

Sumino: Now we understand mass ambiguity. Let's try to reduce theoretical errors to $\mathcal{O}(50\ \text{MeV})$

cf 1-2 GeV at LHC

⇒ renormalon cancellation to higher orders

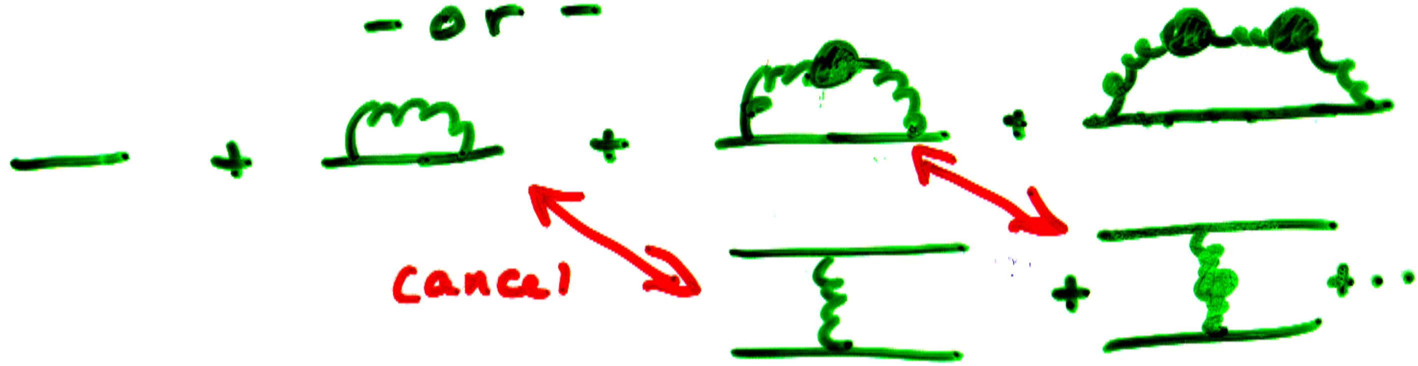
Cancellation takes place at different orders in $E_{binding}$ and $m_{pole} - m_{\overline{MS}}$ rel'n:

$$2m_{pole} = 2m_{\overline{MS}}\left[1 + (\,)\alpha_s + (\,)\alpha_s^2 + (\,)\alpha_s^3 + \ldots\right]$$

cancel

$$E_{binding} = 2m_{\overline{MS}}\left[\qquad (\,)\alpha_s^2 + (\,)\alpha_s^3 \qquad\right]$$

- or -



Result: For $\mathcal{O}(\alpha_s^4)$ in mass, need $\mathcal{O}(\alpha_s^5)$ in $E_{binding}$

⇒ $E_{binding}$ to α_s^5 in large β_0 approx.

What's still needed for m_t:

- $\mathcal{O}(\alpha_s^4 m)$ rel'n btwn m_{pole} + $m_{\overline{MS}}$
  4 loops
- FSI at NNLO
- EW corr's
- ISR + peak position

Yakovlev: "$\overline{PS}$" mass

Modification to PS ("potential subtracted") short dist mass

- includes recoil corrections ($\frac{1}{m}$)
- improves behavior of c.s.

also: nonfactorizable corr's to c.s. cancel at NNLO

... and in anticip....

... ation of European Working Group threshold results, Stay tuned for

TESLA TDR

Top at Threshold : Expt   Ikematsu

- Previously : threshold scan (total c.s.)
- Want p_{top} near threshold for anom. coupling studies (CP̸)

Ikematsu: Top reconstruction

- $\sqrt{s} = 2m_t + 2\,\text{GeV}$
- ISR, Beamstrahlung, QCD thresh. corr

⇒ momentum reconstruction

vs.

Kinematic fit (+ likelihood function)

⇒ Kinematic fit improves energy resolution, top direction resolution ← fig

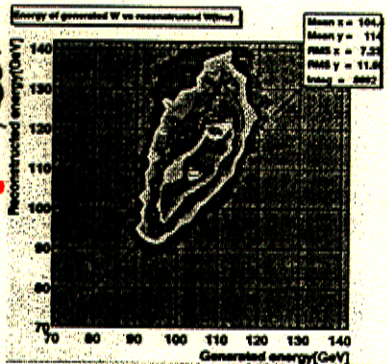
In progress : extension below threshold
improved jet clustering

Effects of Kin. Fit

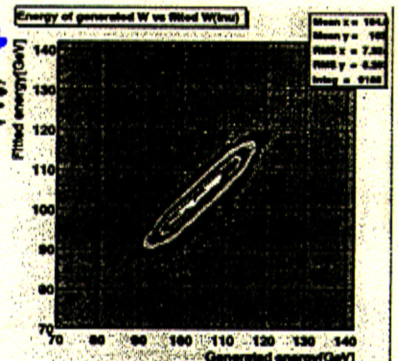
Ikematsu

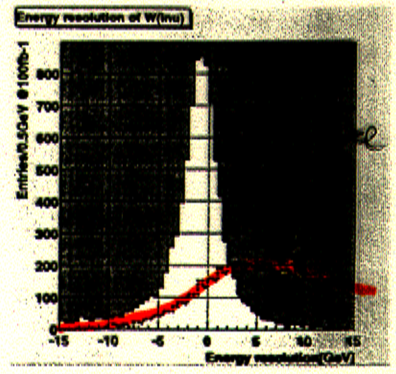
Energy of leptonic decayed W

Resolution



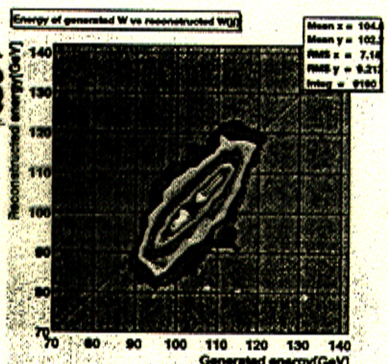
Fit →



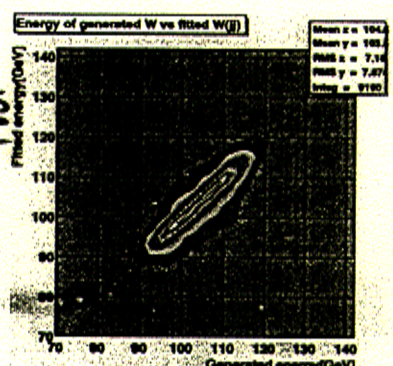


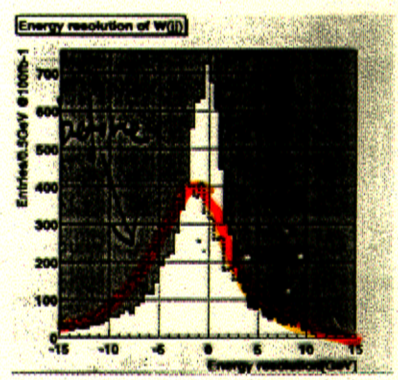
Energy of hadronic decayed W

Resolution



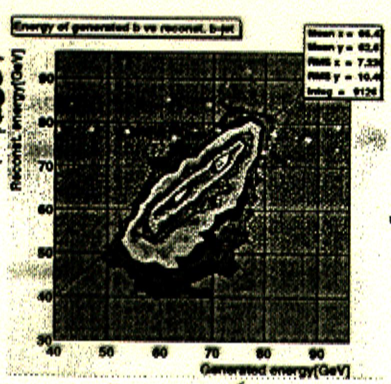
Fit →



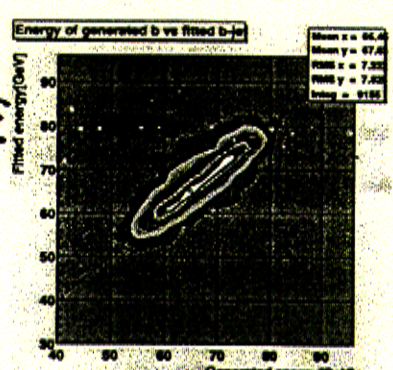


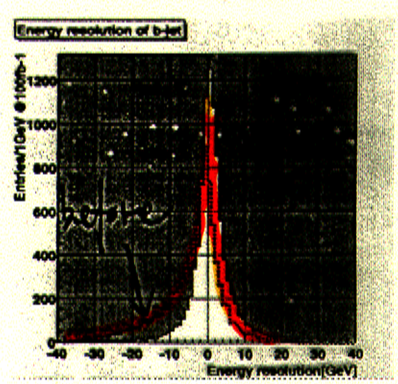
Energy of b-jets

Resolution



Fit →



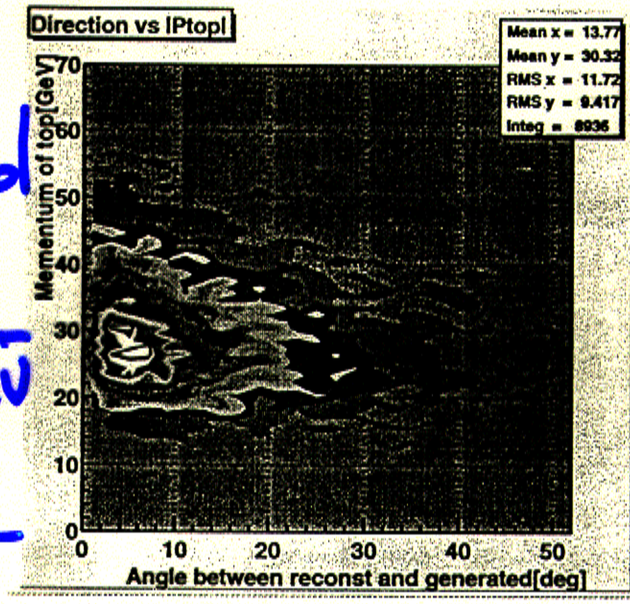


Effect on Top Direction

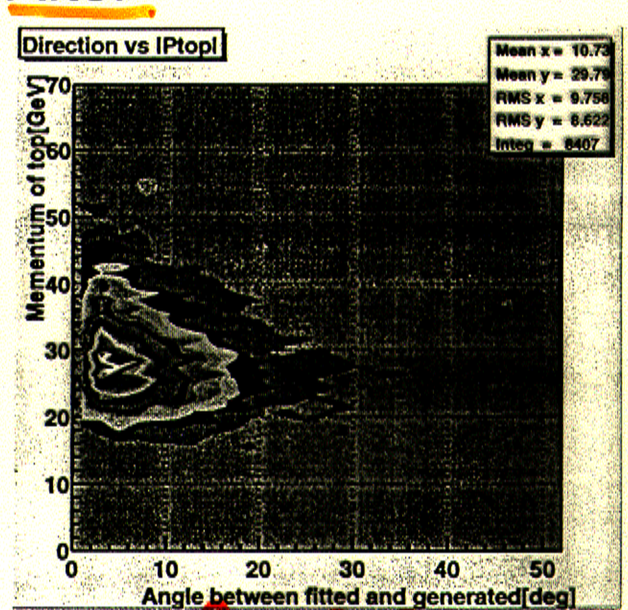
Ikematsu

Angular resolution vs top momentum

Before



After



Overall Selection Eff. ~ 11 %

Appreciable improvement
of top quark direction

or

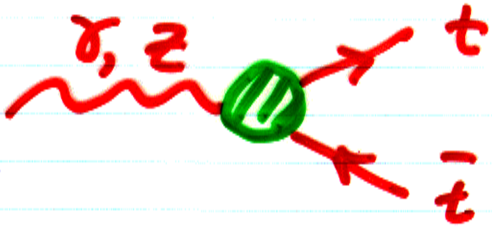
If we are to achive the same
angular resolution for top momenta,
~ 35% gain in the selection efficiency

Anomalous Couplings

Kiyo Iwasaka

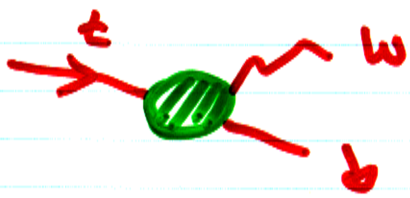
At LC, prob top prod. + decay couplings :

prod.



can't do at LHC

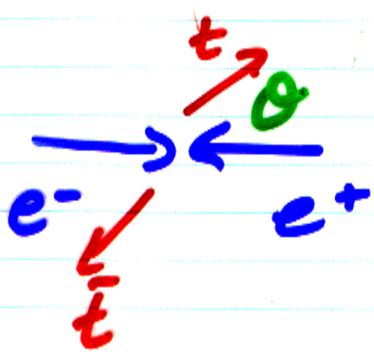
decay:

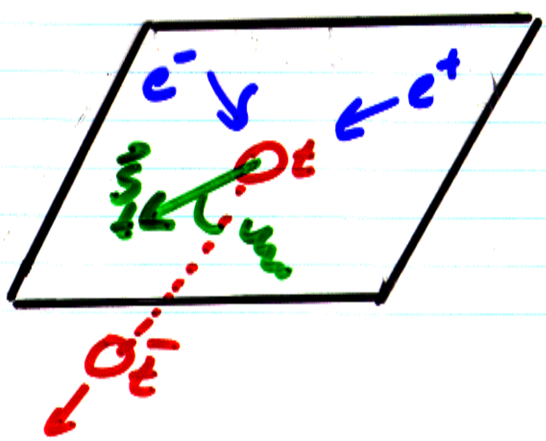


In particular, look for $\not{C}\not{P}$ in EDM, WDM (electric + weak dipole moments)

Kiyo: Spin correlations ⇒ angular corr. in top production + decay

"Off-diagonal" basis of Parke + Shadmi





t rest frame

$e_L^- e_R^+ \to t_\uparrow \bar{t}_\uparrow,\ t_\downarrow \bar{t}_\downarrow$

$$= \mp 4\pi\alpha \left[A_{LR} \cos\xi - B_{LR} \sin\xi \right]$$

at leading order. Define ξ_t so this is <u>zero</u>:

$$\tan\xi = A_{LR}/B_{LR}$$

$\Rightarrow$ **$t_\uparrow \bar{t}_\downarrow$ dominates cross sect.** *

Add t decay density matrix
$\not{C}\!\!P$ coupling

$\Rightarrow$ azimuthal angle dependence for lepton

$\leftarrow$ figs

<u>N.B.</u> Requires reconstructing top direction

Knowing up-vs. down-type W decay products helps too.

* QCD corr's don't make much difference

Kiyo

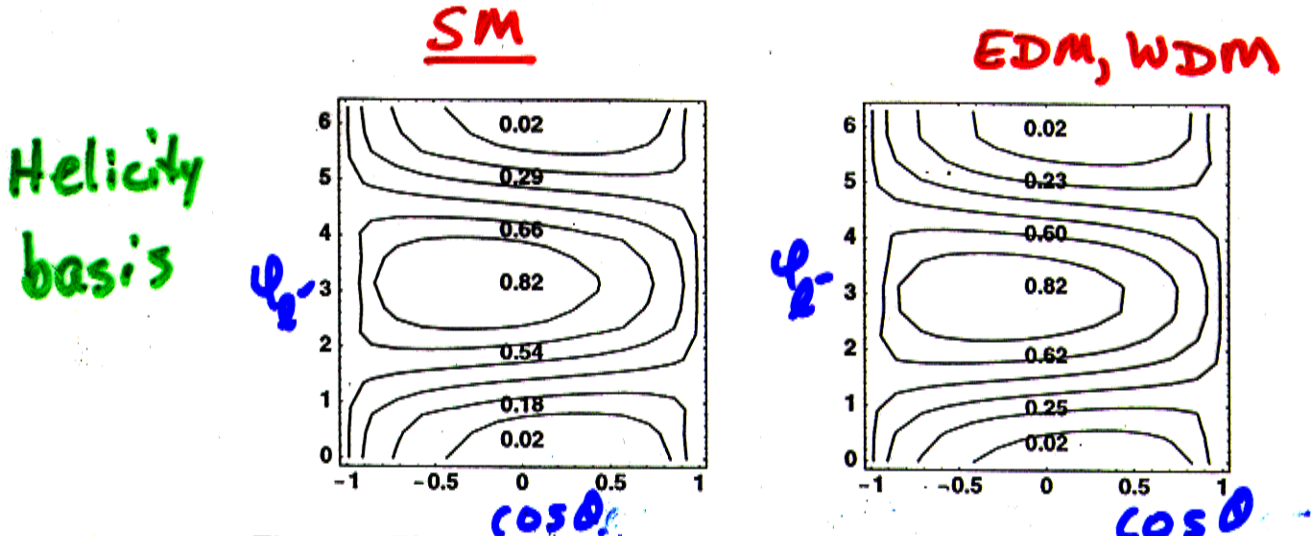


Figure 3: The double differential cross section $d\sigma/d\cos\theta_{\bar{l}}d\phi_{\bar{l}}$ in the helicity basis. The left (right) figure correspond to the cross section without (with) the anomalous $f_3^{\gamma,Z}$ coupling. Vertical and horizontal axes correspond to the azimuthal $\phi_{\bar{l}}$ and the polar angle $\cos\theta_{\bar{l}}$, respectively.

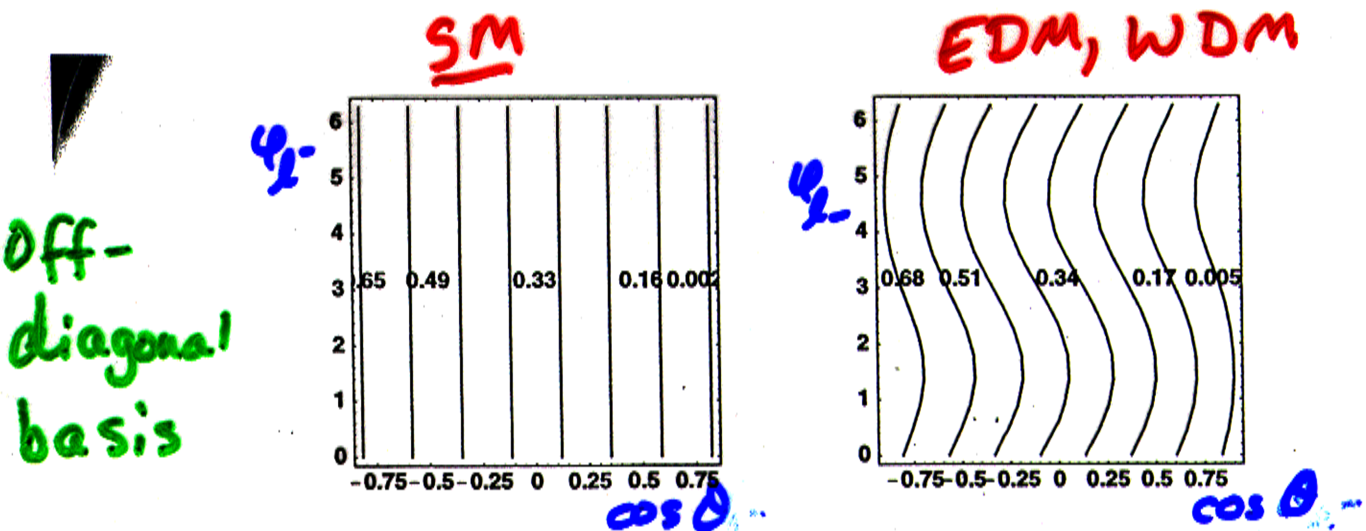


Figure 4: The double differential cross section in the off-diagonal basis. The left (right) figure correspond to the cross section without (with) the anomalous $f_3^{\gamma,Z}$ coupling. The axes are the same as in Fig.3

Kiyo

$$A = \frac{\int_{\varphi_\ell=0}^{\pi} d\varphi \frac{d\sigma}{d\cos\theta\, d\varphi_\ell} - \int_{\varphi_\ell=\pi}^{2\pi} (\quad)}{+}$$

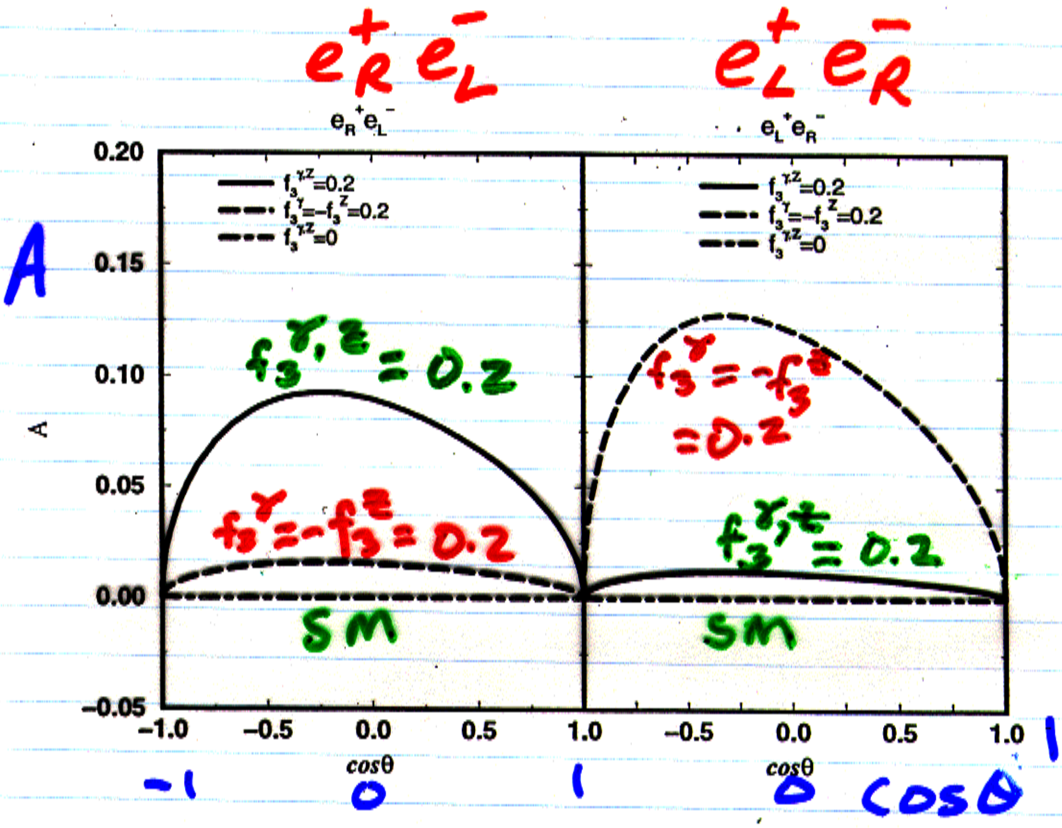
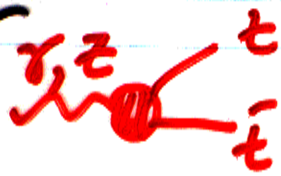


Figure 5: Azimuthal asymmetry as a function of $\cos\theta$ in the off-diagonal basis.

$$|f_3| = 1 \leftrightarrow 10^{-16}\, e\ \text{cm in EDM}$$



$$= g_V \left\{ Q_L^{\gamma,Z} \gamma_\mu L + Q_R^{\gamma,Z} \gamma_\mu R + \frac{(t-\bar{t})_\mu}{2m_t} \left[G_L^{\gamma,Z} L + G_R^{\gamma,Z} R \right] \right\}$$

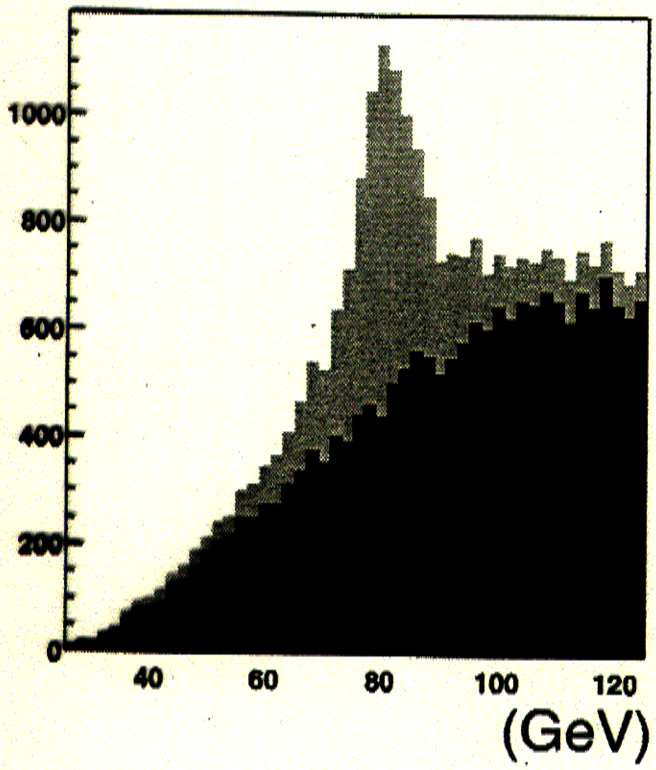
$i f_3 = G_R - G_L$

Iwasaki: Top Production + Decay Vertices w/ LCD fast simulation

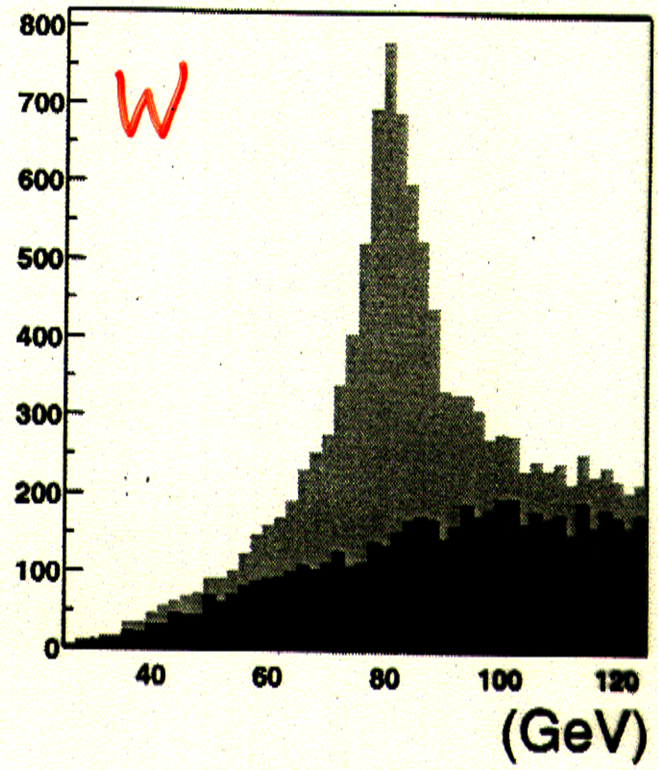
- How well can we
  - reconstruct $t, \bar{t}$ momentum?
    + know which is which
  - identify I_z of W decay products?
  - use this info to constrain couplings?
- LCD fast sim. w Pandora - Pythia
  ISR, beams., QCD rad. incl.
- ℓ + jets - features
  - energy flow: charged tracks + neutral clusters
  - b tagging: p_T corrected mass of vtx > 1.8 GeV
    # sig tracks in jet
  - ℓ charge gives I_z ← fig
- all jets
  - en. clusters

ℓ+jets Iwasaki

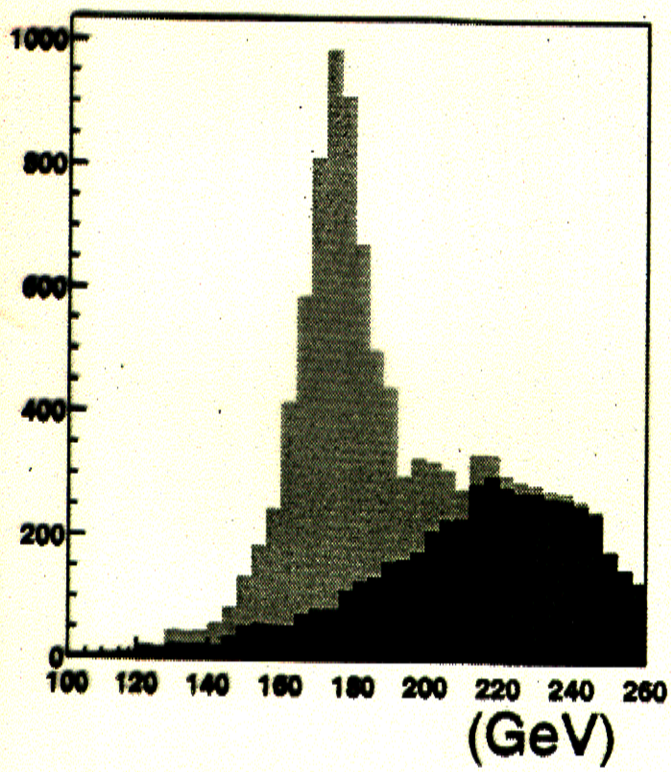
Reconstructed W with 2 jets



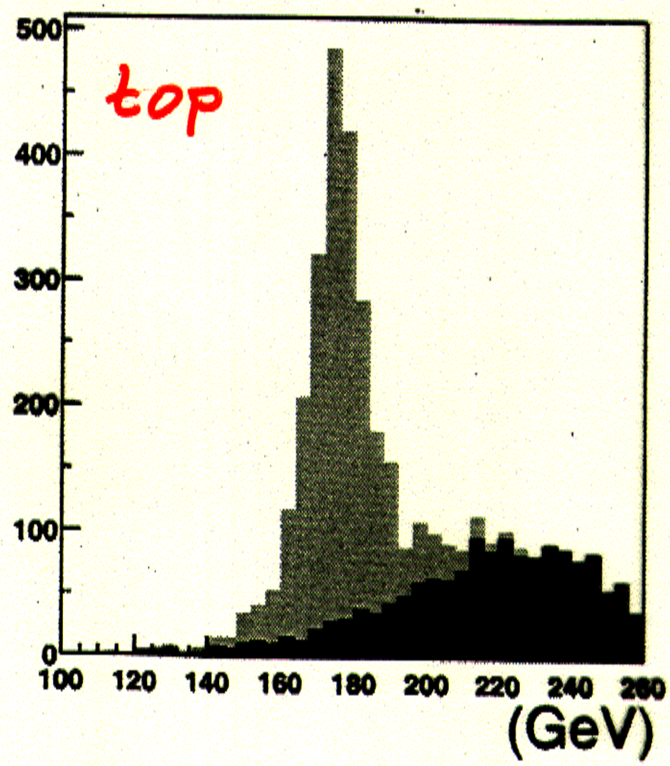
With flavor-tag



Reconstructed top with 3 jets



With flavor-tag



- all jets, cont.
  - b tagging: mass tag
    vertex charge (b vs. $\bar{b}$)
  - W decay products
    ⇒ charm tag!! → Can't do at LHC ← fig

    N.B.: Sensitive to vertex det. performance

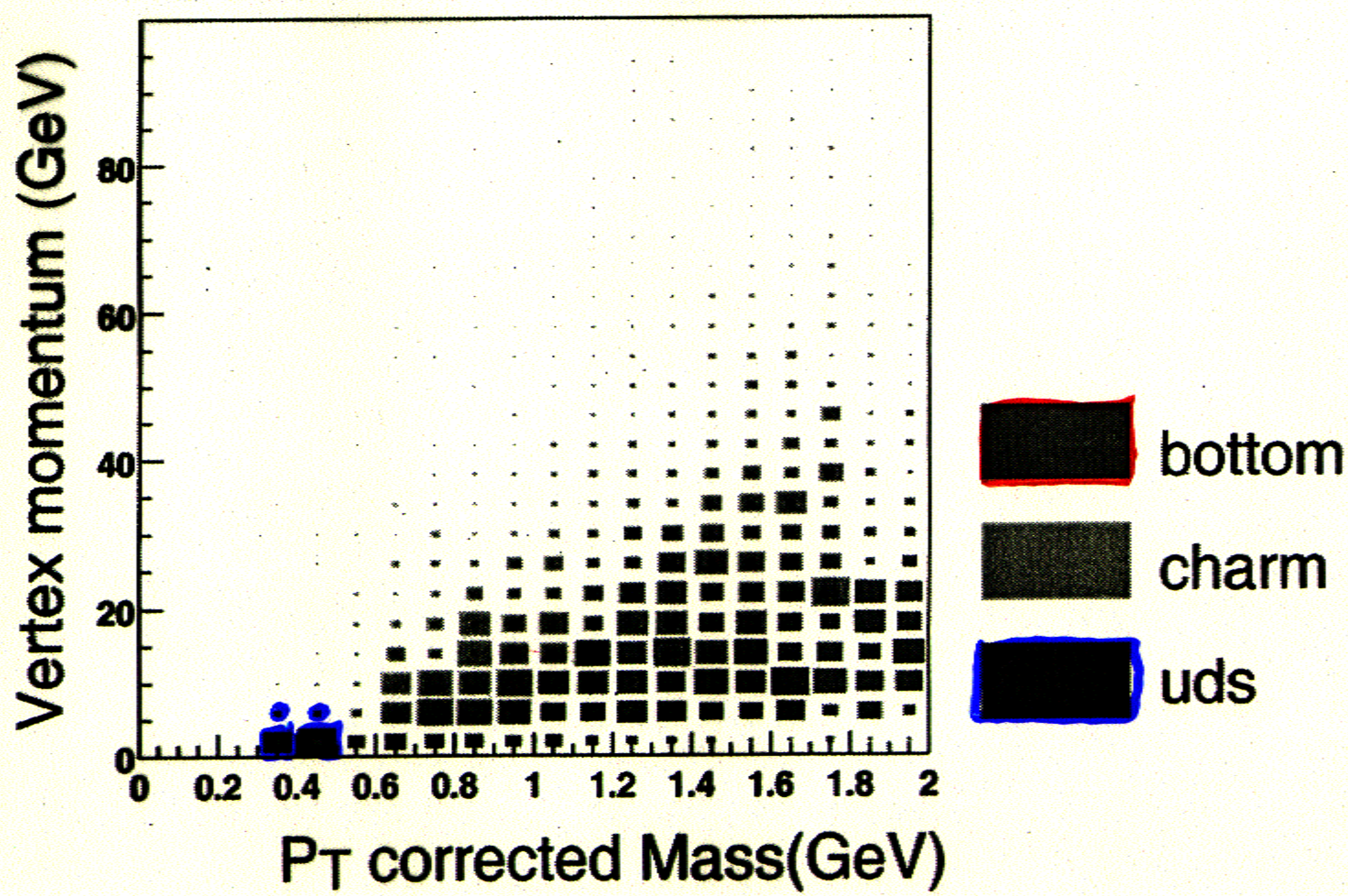
- Status
  - sensitivity to top prod. vertex

    axial coupling
    F_{1A}^{γ} to ~ 2×10^{-2}, 4×10^{-2} for Z
  - vector coupling coming soon
  - decays also to come

  (This is ℓ + jets. Stay tuned for 6 jets)

Can we tag $W \to q\bar{q}'$?

... Using the P_T corrected mass + Vertex momentum we can tag <u>c-quark</u>.

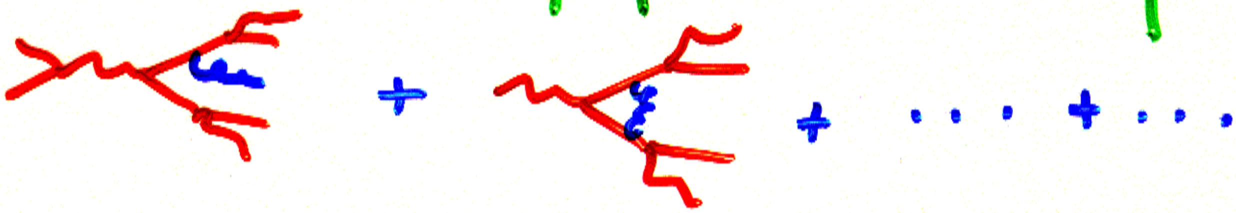


$\varepsilon_c = 28\ \%$ $\pi_c = 69\ \%$

QCD

talks by Macesanu
Corcella
Sjostrand

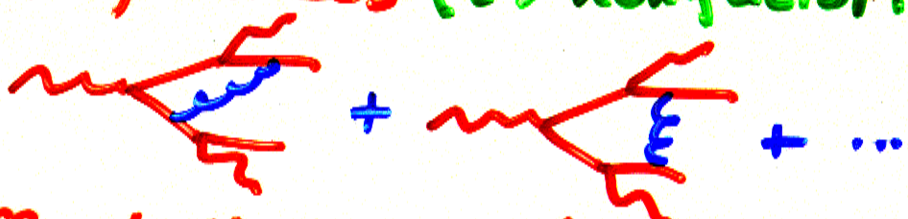
- QCD corr's to top prod. + decay



Previously: - Separate calcs for prod
decay

- Combined in on-shell approx

Macesanu: Full loop corr's including
- interferences (⇔ nonfactorizable)



- off-shell top, in "double pole approximation": keep terms w/ two resonant top quarks

⇒ cf RacoonWW for W pair prod

Coming soon: Full NLO corr's to top prod. + decay

Gluon Radiation in Monte Carlos

Corcella
Sjostrand

Parton showers (PS):

Use splitting functions to evolve in Q^2

- soft/collinear approx includes leading QCD effects (incl. higher orders)
- works well for massless particles
- massive particles - more complicated
  ⇒ no collinear radiation ("dead cone")
  ⇒ problem populating large angles, approximating dead cone
  ⇒ Matrix element corr's to PS

Corcella ME corr's to top decay in HERWIG

← fig

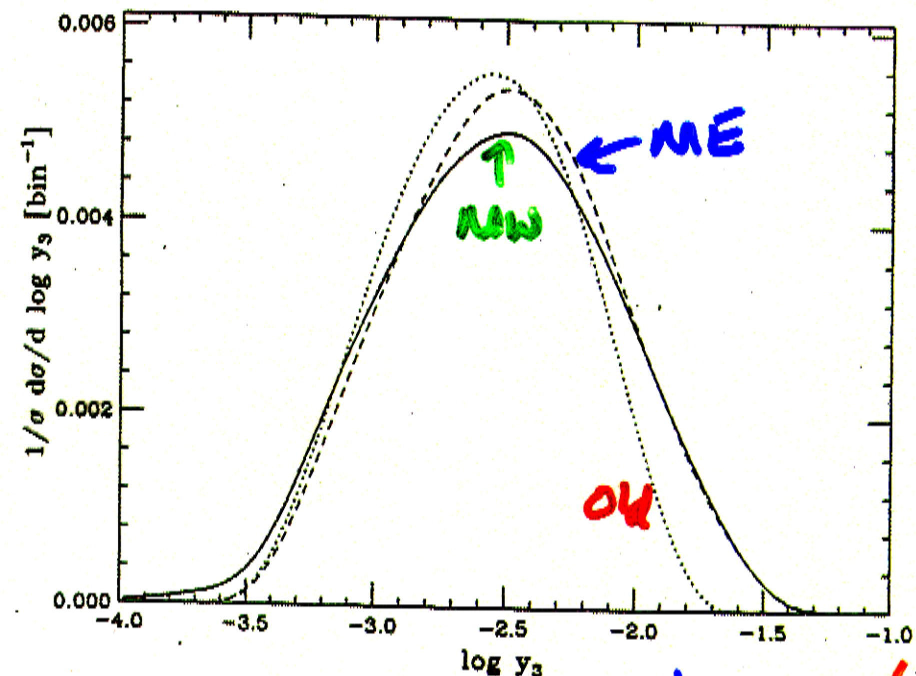
Coming soon: ME corr's to prod. (hadron colliders)

ISR, beams.
Spin corr.

$e^+e^- \to t\bar{t}$ $\sqrt{s} = 360$ GeV

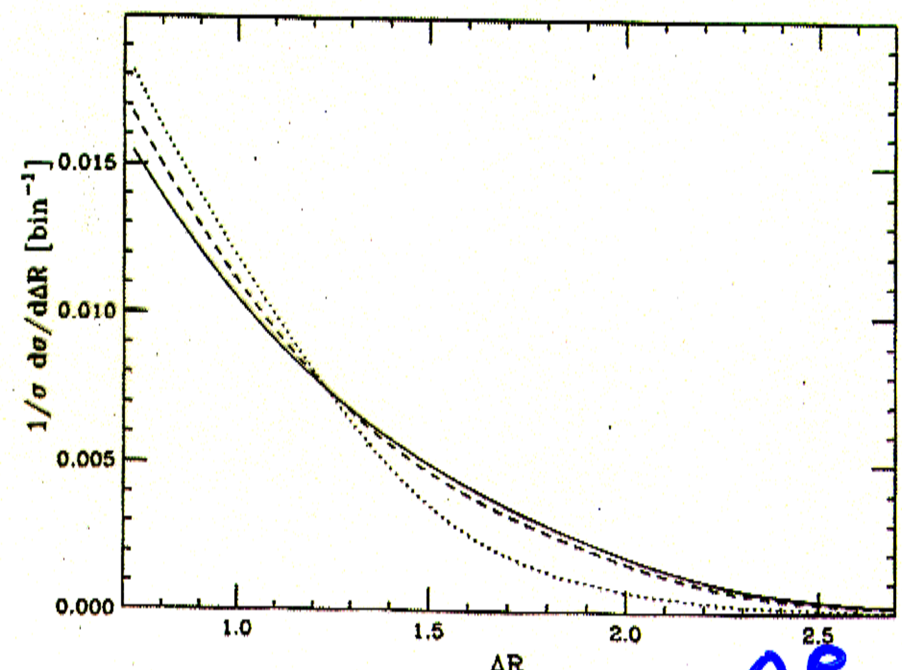
3-JET EVENTS $y_{ij} = \frac{2}{s} \min(E_i^2, E_j^2)(1-\cos\theta_{ij})$

— 6.1 .... 6.0 - - - $e^+e^- \to t\bar{t} \to W^+ b W^- \bar{b} g$



$E_T > 10$ GeV

$\Delta R > 0.7$



GOOD AGREEMENT AT LARGE y_3 AND ΔR

G.C. AND M.H. SEYMOUR, PLB 442 (1998) 417

Sjostrand ME corr's to radiation from *all* heavy particles in Pythia (including SUSY)

⇒ dependence on spin structure ← fig

Coming soon: width effects

Mass reconstruction in dilepton mode

Corcella Use Herwig, Pythia to look for distributions sensitive to m_t. Not easy!

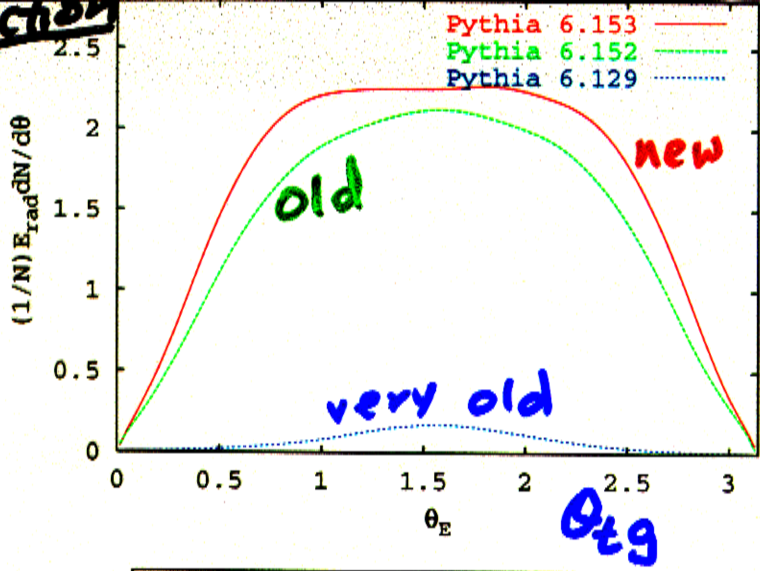
$m_{b\ell}$ not very good

E_ℓ no good

E_b near threshold promising

N.B.: Herwig–Pythia diffs can be hundreds of MeV

Production



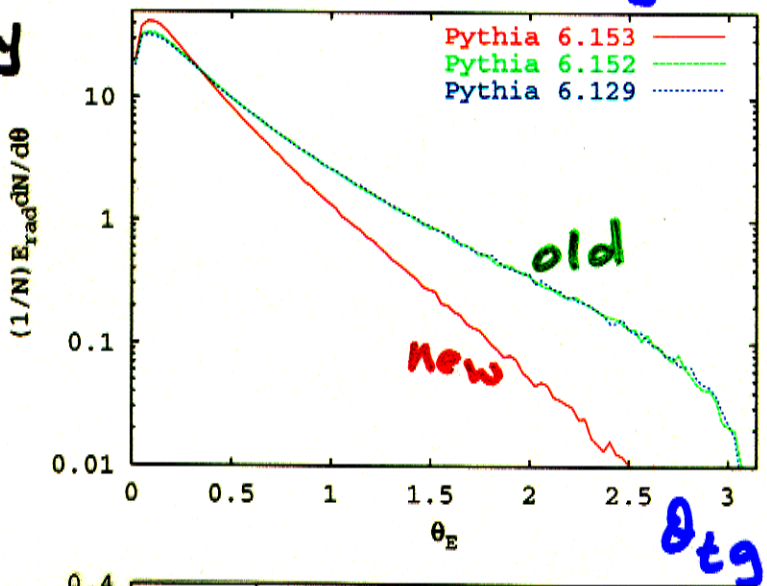
$\gamma^*/Z^* \to t\bar{t}$ Sjostrand

$E_{CM} = 500$ GeV

Increased gluon emission off $t\bar{t}$ . . .

(θ_E w.r.t. original $t\bar{t}$ axis)

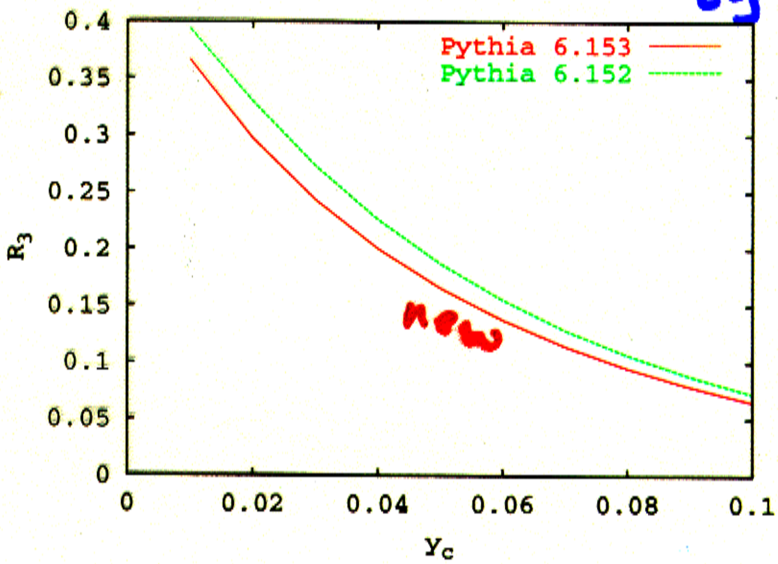
Decay



. . . but decreased off b in t decay (at large angles) . . .

(θ_E w.r.t. original b axis ⇒ W at 180°)

Total



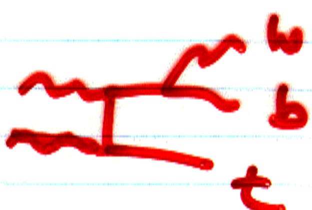
. . . gives net decrease in 3-jet rate for $t\bar{t} \to bW^+\bar{b}W^-$

(not counting W decay products)

Top at $\gamma\gamma$ Colliders : Boos

Many processes/meas similar to e^+e^-

- Pair prod. cross sect.
  - can be $> \sigma(e^+e^-)$ ← fig
  - NLO corr's increase $\sigma(\gamma\gamma)$
  - threshold has similar NNLO problems to ee
- $\gamma t\bar{t}$ coupling
  - comes in to 4th power
  - separate from $Zt\bar{t}$ coupling
- CP of higgs ($t\bar{t}$ decay)
- large extra dimensions
- Single top



probes Wtb vertex*

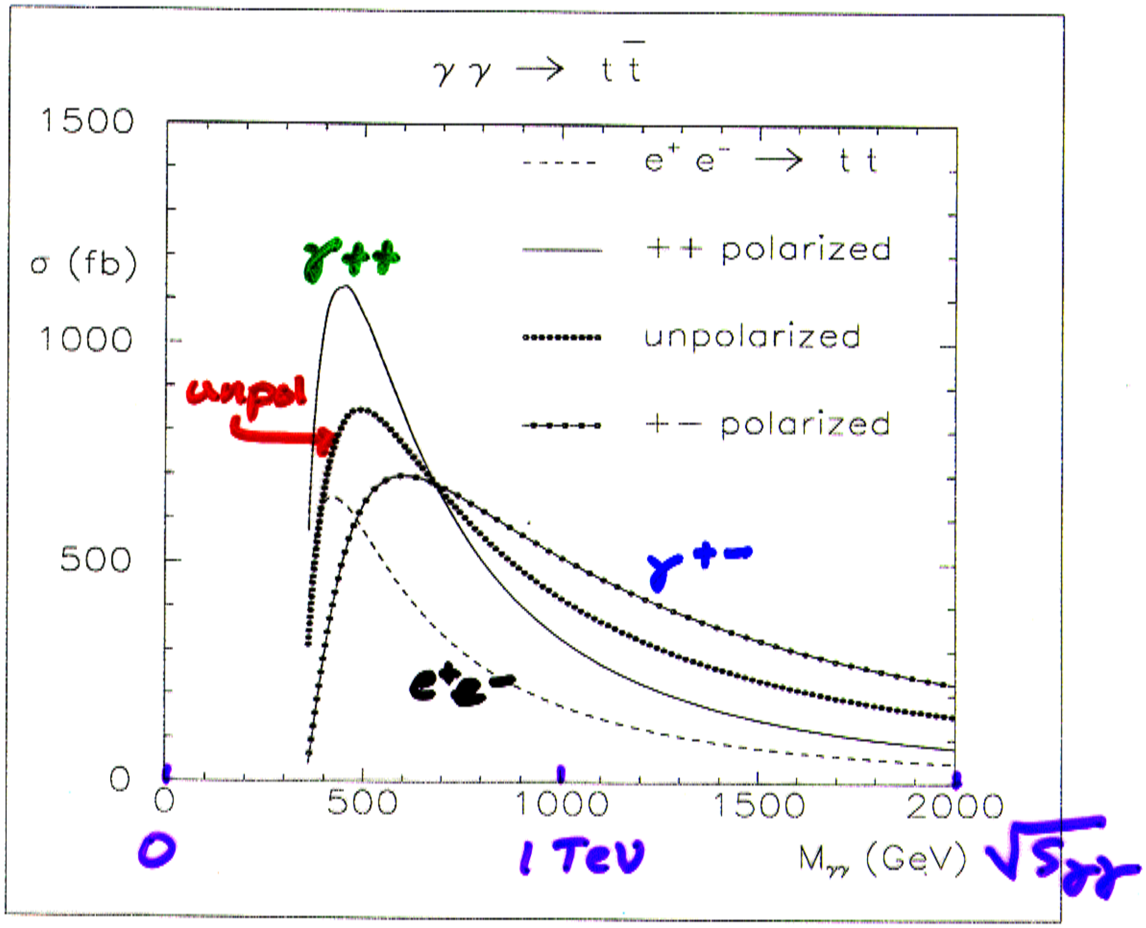
  - $t\bar{t}$ pair prod. is biggest b.g.!

* also some TC models

BOOS

$\gamma\gamma \to t\bar{t}$

CompHEP



The $(++) = (--)$ helicity configuration $(J_z = 0)$ dominates at energies less than about 680 GeV while the $(+-) = (-+)$ or $J_z = 2$ configuration starts to dominate at higher energies.

Summary

Lots of good progress in precision top studies

- Thresh. theory under control
- QCD corrections becoming more sophisticated
- Anom couplings being studied in detail
- Top reconstruction coming under control exptally

... and more to come!