$t\bar{t}$ WORKING GROUP

Convenors: Berger
Winer

Speakers: Yang
Hughes
Raja
Berger
Hoang
Smith
Reina
Orr
Parke
Roser

Top Quark Processes at the Upgraded Tevatron to Probe New Physics

J. M. Yang

Datta, Hosch, Li, Oakes, Whisnant, Young, Zhang

* SINGLE TOP QUARK PRODUCTION

1) MODEL-INDEPENDENT ANALYSIS FOR SINGLE TOP QUARK PRODUCTION.

   A) CP - CONSERVING

   B) CP - VIOLATING

2) SUSY

   A) R-PARITY CONSERVING

   B) R-PARITY VIOLATING

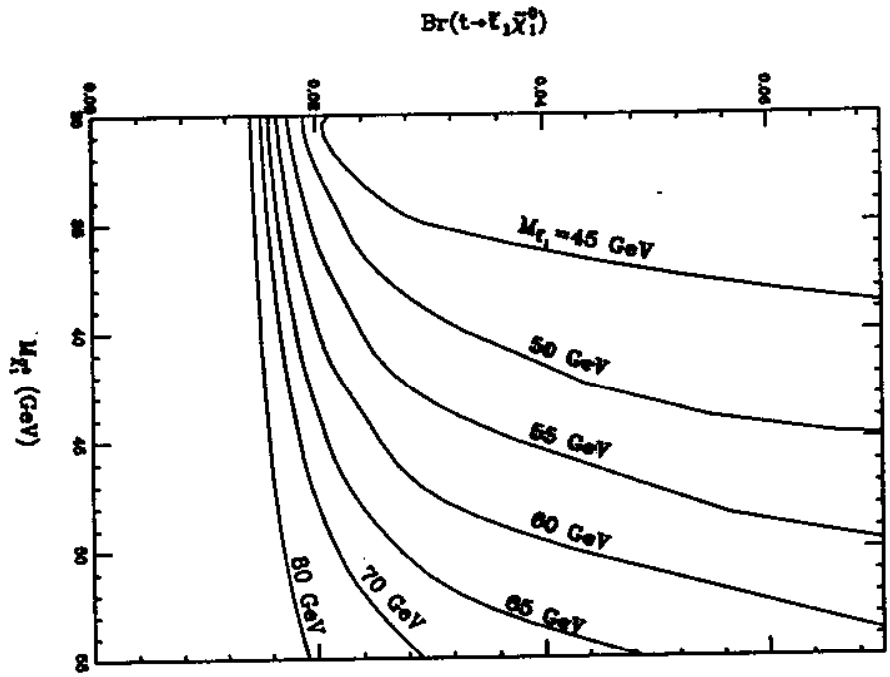
* EXOTIC DECAYS

a) $t \to cX \qquad X = g, \gamma, Z, h$

b) $t \to \tilde{t}_1 \tilde{\chi}_1^0$

YANG

$B(t \to \tilde{t}_1 \tilde{\chi}_1^0)$ versus $M_{\tilde{\chi}_1^0}$ for the signal to be observable at Run 2 under the criteria $S \geq 5\sqrt{B}$. The region above the curve is the observable region.



HUGHES

Parameters of Future Colliders

	Run I	Run II	Tev33	[redacted]
Energy (TeV/c^2)	1.8	2.0	2.0	14.0
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	2×10^{31}	2×10^{32}	10^{33}	10^{33}
$\int\mathcal{L}$ (fb^{-1})	0.11	2.0	30.0	10.0
$< n_{int} >$	2.0	2	9	2.0
$\sigma(t\bar{t})$ (pb)	4.7-5.5	7.0-7.7	7.0-7.7	800
$\sigma(t\bar{b})$ (pb)	2.5	3.7	3.7	400
dilepton	~ 6	~ 160	~ 2500	$\sim 50k$
$l+ \geq 3jets$ (≥ 1 tag)	~ 25	~ 1400	$\sim 20k$	$\sim 400k$
$l+ \geq 4jets$ (2 tags)	~ 5	~ 600	$\sim 9k$	$\sim 200k$

Muon-muon Collider

- Sharper beam energy profile - monochromaticity of the beams will prove critically important for some of the physics that can be done at a $\mu^+\mu^-$ collider.

  - Gaussian in shape.

  - RMS spread R naturally in range 0.04%-0.08%.

  - Additional cooling can yield 0.01%.

$$R_\mu = 0.01 - 0.1\% \qquad \mu\mu$$
$$R_e \sim 1\% \qquad ee$$

Then the rms deviation in the center-of-mass energy is

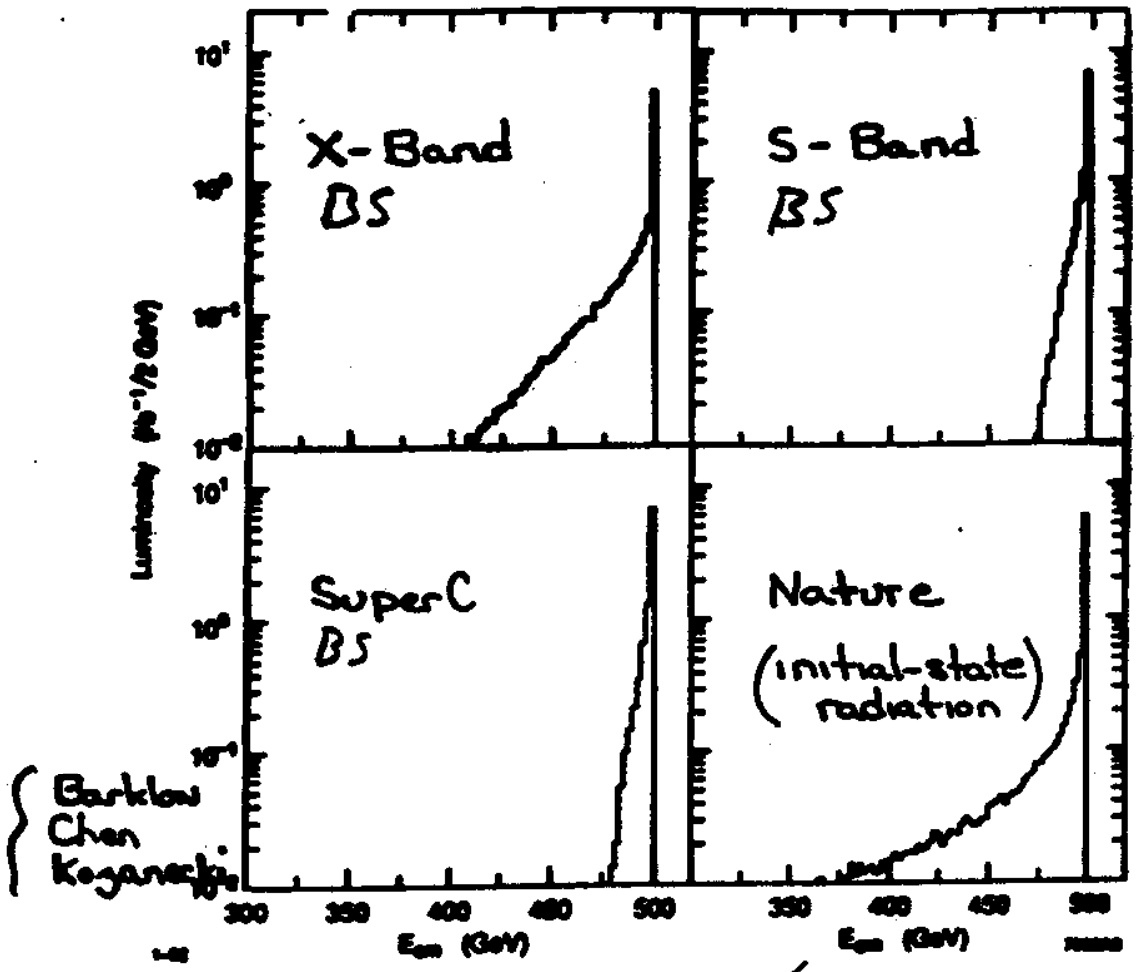
$$\sigma = (0.25 \text{ GeV}) \left(\frac{R}{0.1\%}\right) \left(\frac{\sqrt{s}}{360 \text{ GeV}}\right)$$

– Beamstrahlung (Bremsstrahlung from beam particles in the EM field of the opposing beam) is reduced.

- Initial State Radiation (ISR)

$\Rightarrow$ possibly more precise measurements of thresholds

RAJA



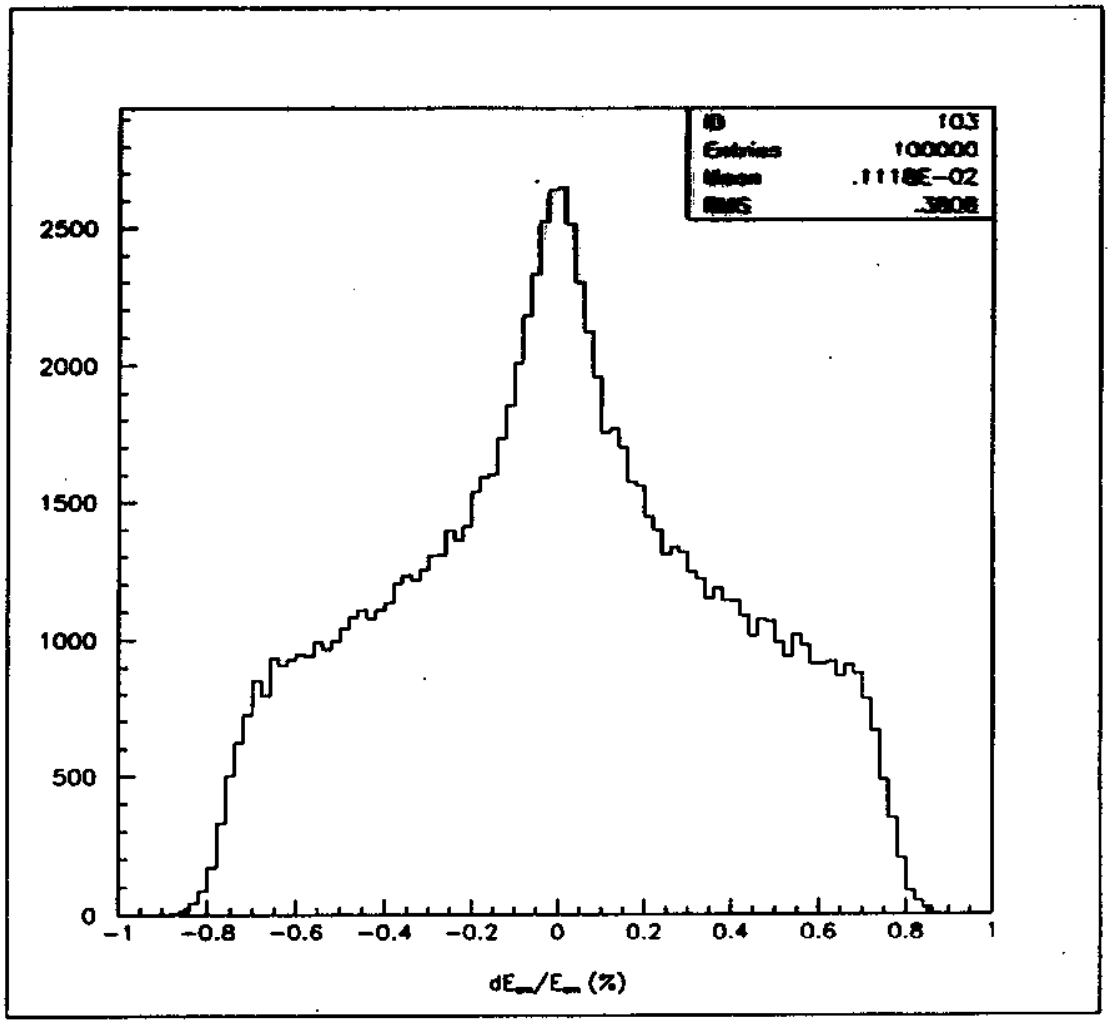
$$\sigma = \sigma_0(s)\left[1+\delta\right] K_0^{\beta} + \beta \int_{K_0}^{1} dK\, \sigma_0(s')\left[K^{\beta-1}(1+\delta) - 1 + \frac{K}{2}\right],$$

$$s' = s(1 - K/E_{beam})$$

$$\beta = \frac{2\alpha}{\pi}\left[\ln\frac{s}{m_e^2} - 1\right] \approx 1/8 \quad \text{at } \sqrt{s} = 500\,\text{GeV}$$

RAJA

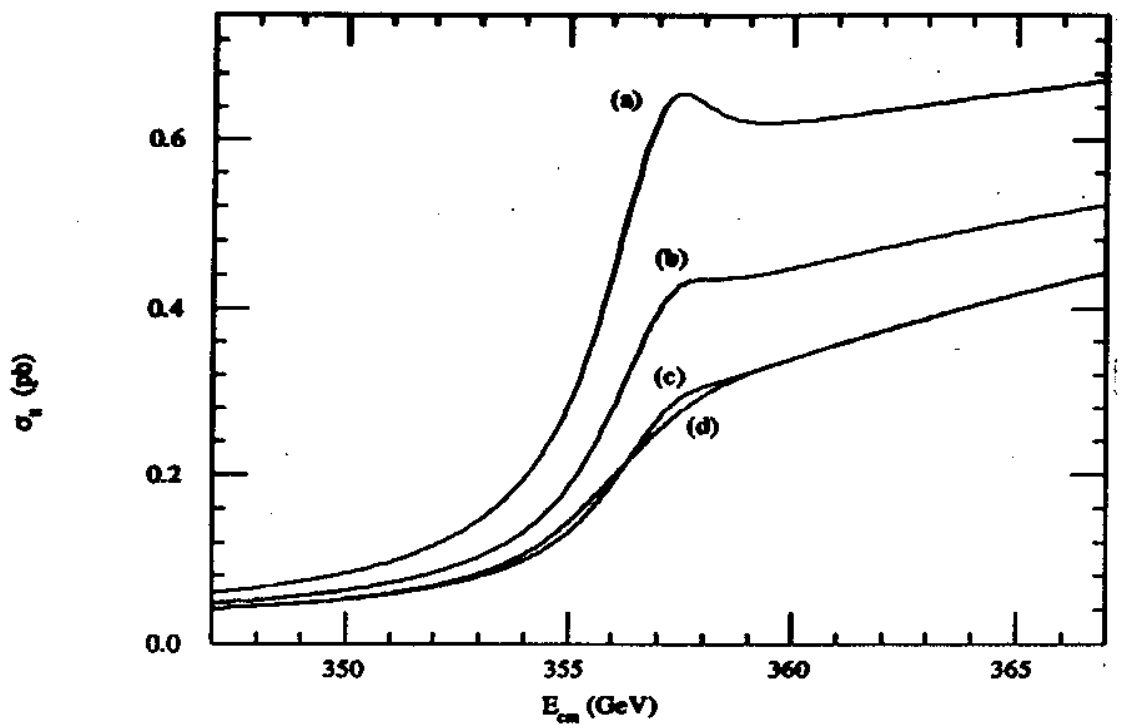
NLC Center of mass energy distribution



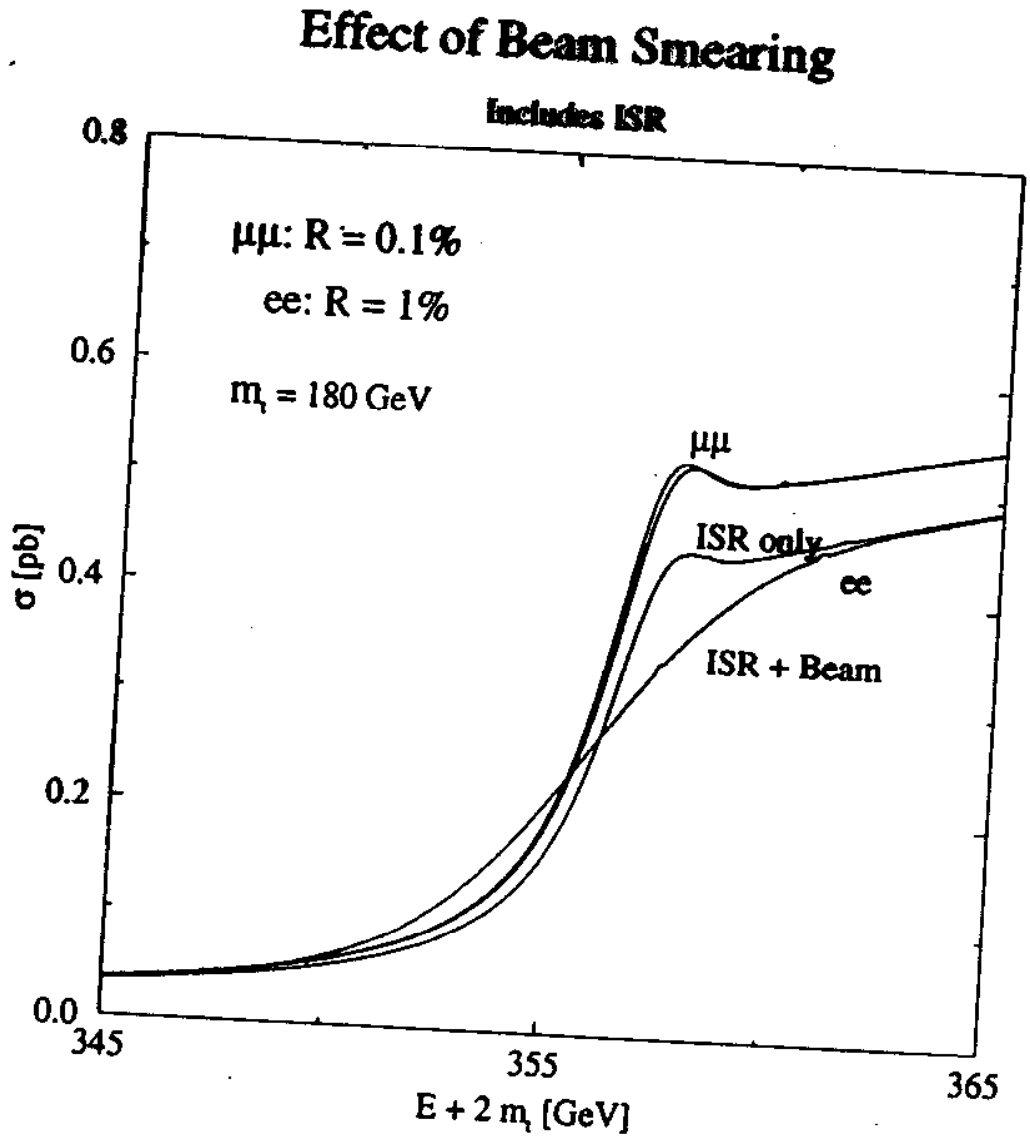
Convolute the single energy beam spreads of both beams

RAJA

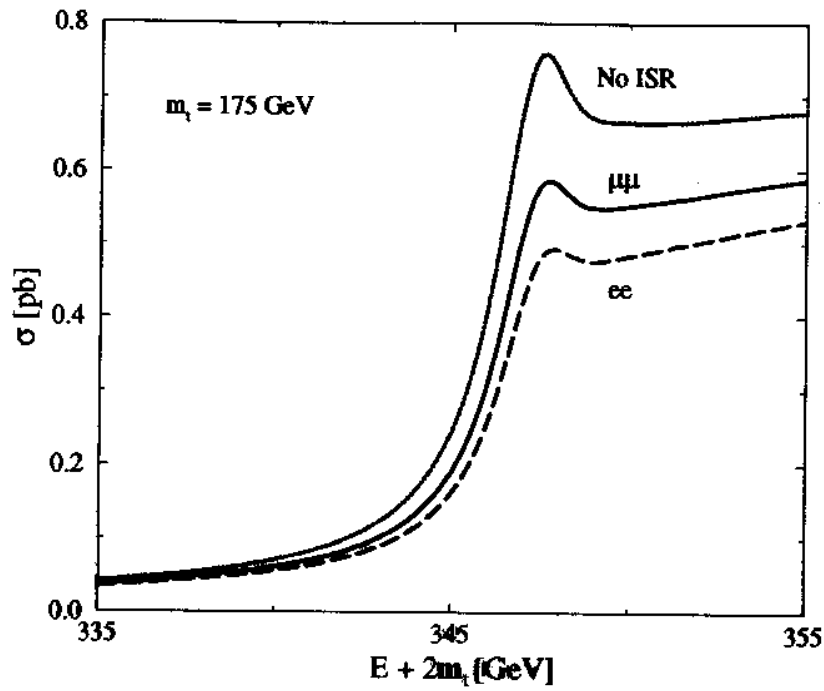
Top Production cross section



a) Theoretical cross section
b)Initial state radiation (ISR)
c)ISR + beamstrahlung
d)ISR beamstrahlung and beam energy spread


Effect of Beam Smearing
Includes ISR
μμ: R = 0.1%
ee: R = 1%
m_t = 180 GeV
μμ
ISR only
ee
ISR + Beam
σ [pb]
0.0
0.2
0.4
0.6
0.8
345
355
365
E + 2 m_t [GeV]

$\ell^+\ell^- \to t\bar{t}$



$$\left[-\frac{\Delta}{m_t} + V(r) - \left(E + i\frac{\Gamma_\Theta}{2}\right)\right] G(\mathbf{x}; E) = \delta^3(\mathbf{x})$$

where Γ_Θ is the (running) toponium width, and $E = \sqrt{s} - 2m_t$.

$$\sigma_{t\bar{t}} = \frac{96\pi^2\alpha^2}{s^2}\left\{1 - \frac{16\alpha_s}{3\pi}\right\}\left[(Q_e Q_t + v_e v_t \chi)^2 + (a_e^2 v_t^2 \chi^2)\right]$$
$$\times \mathrm{Im}\, G(\mathbf{x} = 0; E = \sqrt{s} - 2m_t)$$

where $\chi = s/(s - M_Z^2)$.

Initial State Radiation (ISR)

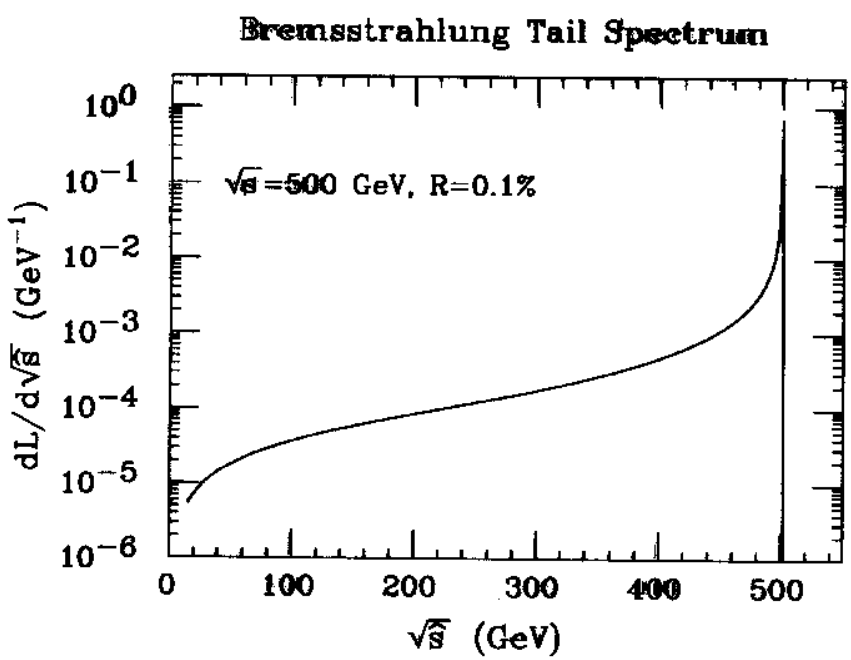
Convolute Radiator Function

$$\mathcal{D}(x) \;=\; 1 + \frac{2\alpha}{\pi}(\pi^2/6 - 1/4)\left[\beta x^{\beta-1}\left(1 + \frac{3}{4}\beta\right) - \beta\left(1 - \frac{x}{2}\right)\right]$$

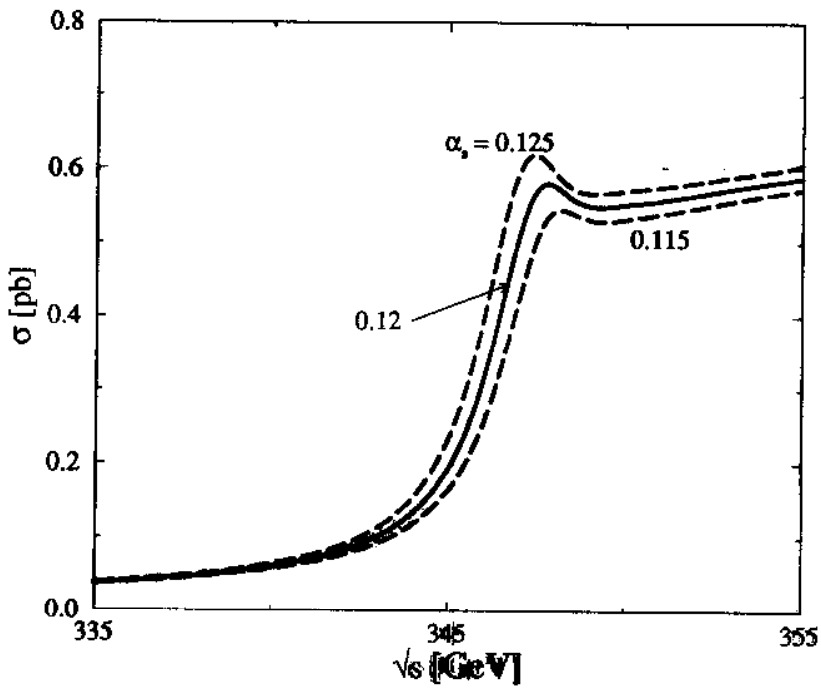
where

$$\beta \;=\; \frac{2\alpha}{\pi}\ln\left(\frac{s}{m_\ell^2} - 1\right)$$

- ISR reduces the size of the cross section at the threshold.
- ISR is reduced for muons.

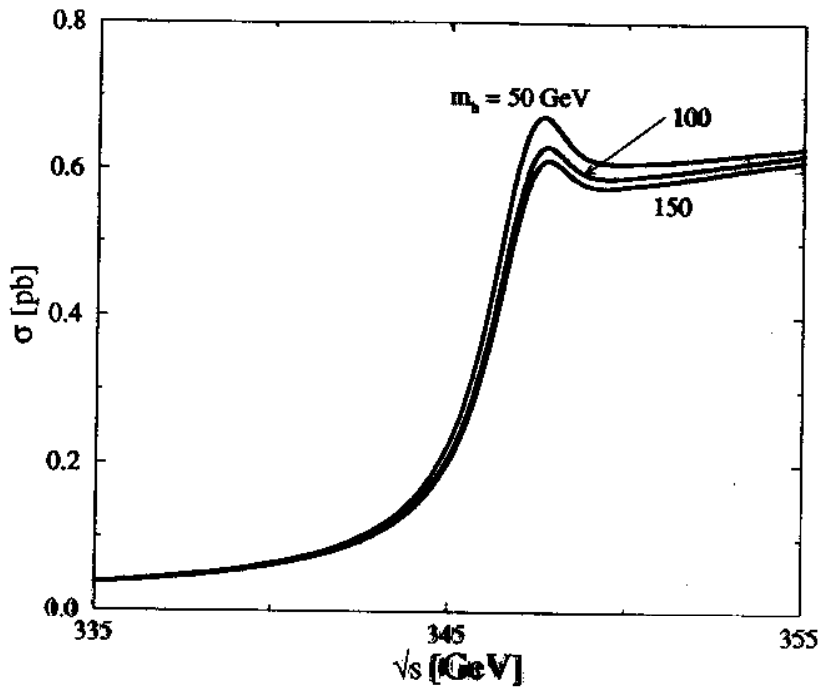


Dependence on the strong coupling $\alpha_s(M_Z)$



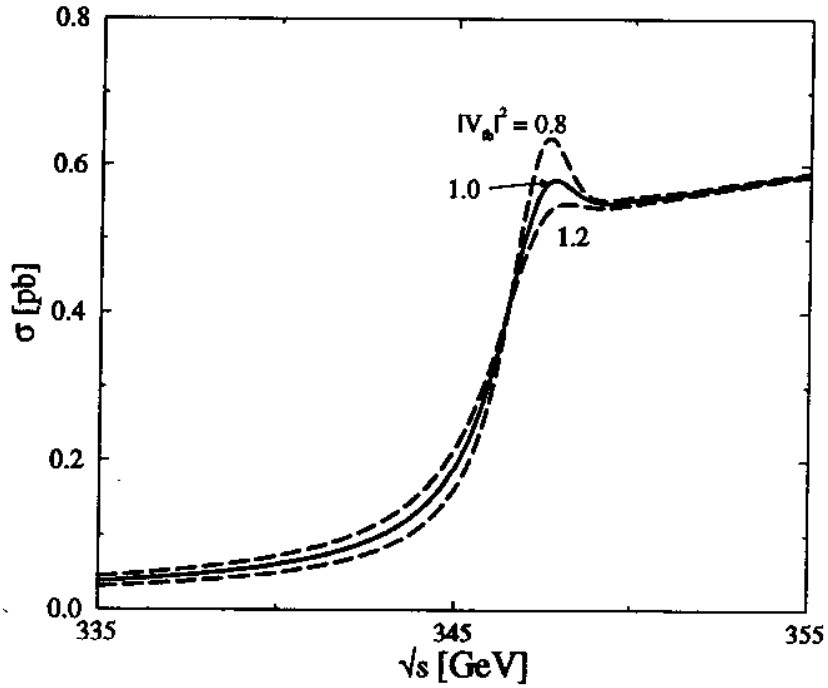
- Larger $\alpha_s \Rightarrow$ tighter binding
- Larger $\alpha_s \Rightarrow$ larger cross section

Dependence on m_h

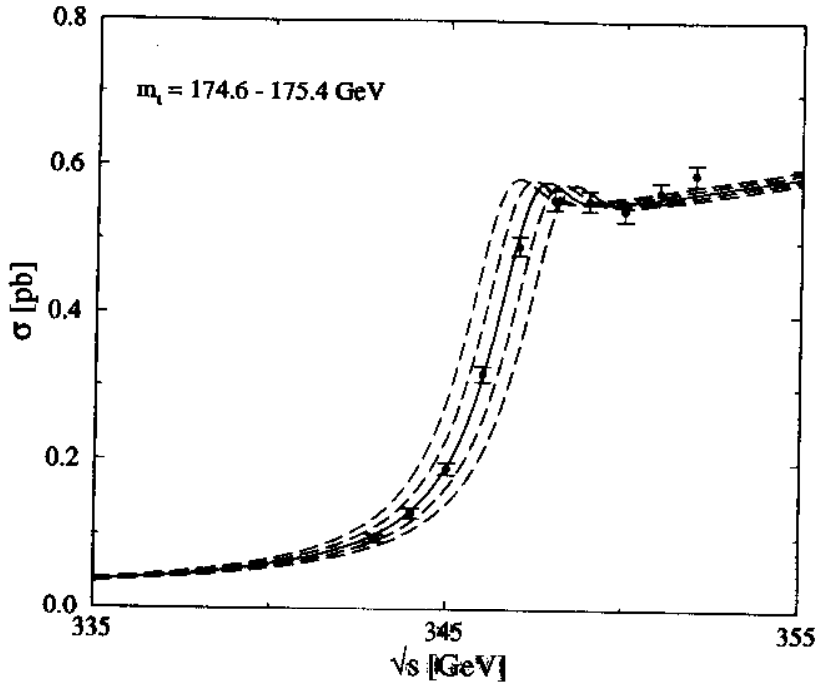


- Higgs mass
- Yukawa coupling

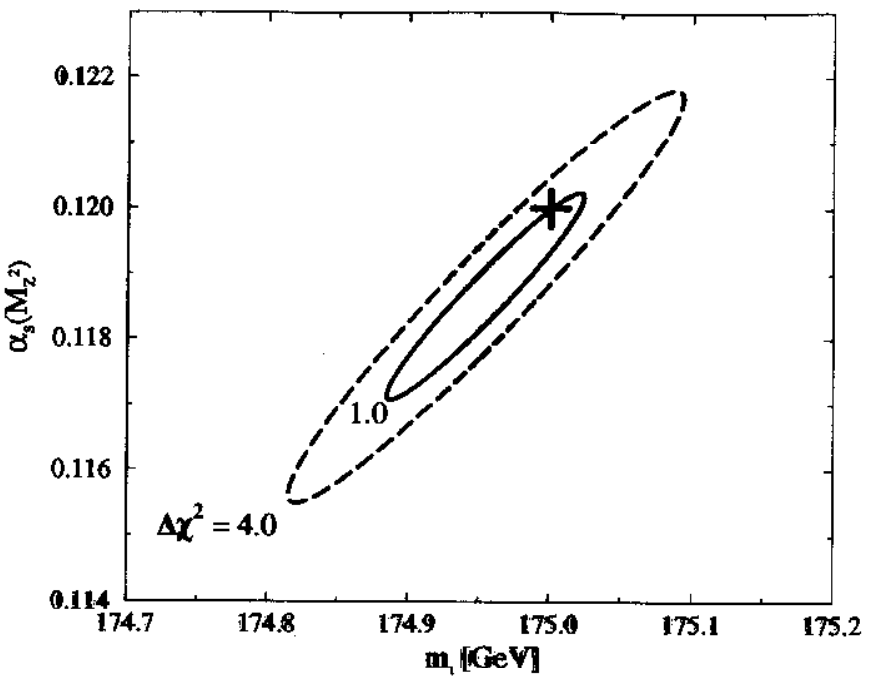
Top quark width



10 point scan



- Can't measure all undetermined variables at a single energy
- Scan can be optimized
- 10 fb^{-1} at 10 pts.
- Nominal values: $m_t = 175$ GeV, $\alpha_s(M_Z) = 0.120$



- $\Delta m_t \sim 70$ MeV, $\Delta\alpha_s \sim 0.0015$
- Theoretical ambiguity in the pole mass $\sim \Lambda_{QCD}$

$\mu^+\mu^- \to t\bar{t}$ THRESHOLD
$e^+e^- \to t\bar{t}$

FOR SAME LUMINOSITY, EFFICIENCIES AS AN e^+e^- MACHINE, THE m_t MEASUREMENT IMPROVES BY ALMOST A FACTOR 2.

$$\mu^+\mu^- : \quad \left.\begin{array}{l} \Delta m_t = 220 \text{ MeV} \\ \Delta m_t = 350 \text{ MeV} \end{array}\right\} \text{ for } \underline{\mathcal{L} = 10 \text{ fb}^{-1}}$$

THEORETICAL UNCERTAINTIES

- DEFINITION OF THE POLE MASS

$$\Delta m_t \sim \Lambda_{QCD} \quad \text{(M. SMITH)}$$

- NNLO CORRECTIONS (A. HOANG)

CALCULATED ONES ARE 4-7% IN THE CROSS SECTION

The Top Quark Mass and the Threshold

Martin C. Smith

— truncation

— scale dependence

— power corrections, condensates, etc.

— V, m_{pole} are not theoretically well-defined beyond perturbation theory. Defination relies on seperation of quarks at $r \to \infty$.

— Scale dependence is reduced when $\bar{m}(\mu)$ is substituted for m_{pole} in calculation of physical quantities.

STATUS OF NNLO CALCULATIONS

hep-ph – 9704325 Hoang

PRD 56 (1997) 5851

- Replace potential models with NRQCD
- NRQCD allows for systematic ~~calculate~~ calculation of NNLO effects

$$\left.\begin{array}{l} O(\alpha_s^2 C_F^2) \\ O(\alpha_s^2 C_F T) \end{array}\right\} \text{calculation Hoang } 4\text{–}7\,\%$$

$$\left.\begin{array}{l} O(\alpha_s C_A C_F) \\ O(\alpha_s C_F T u_\ell) \end{array}\right\} \text{in preparation Hoang, Teubner}$$

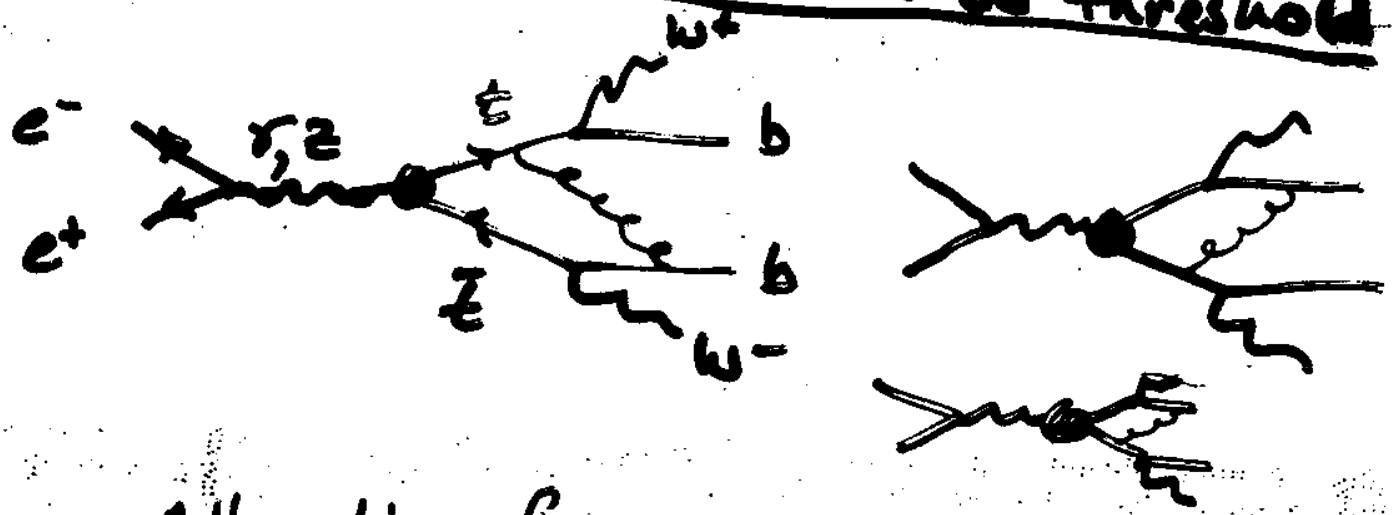
Mom dependent width

→ $t, \bar{t}$ not decaying freely

→ must be investigated to get full NNLO effects.

Final State Interactions at $t\bar{t}$ threshold

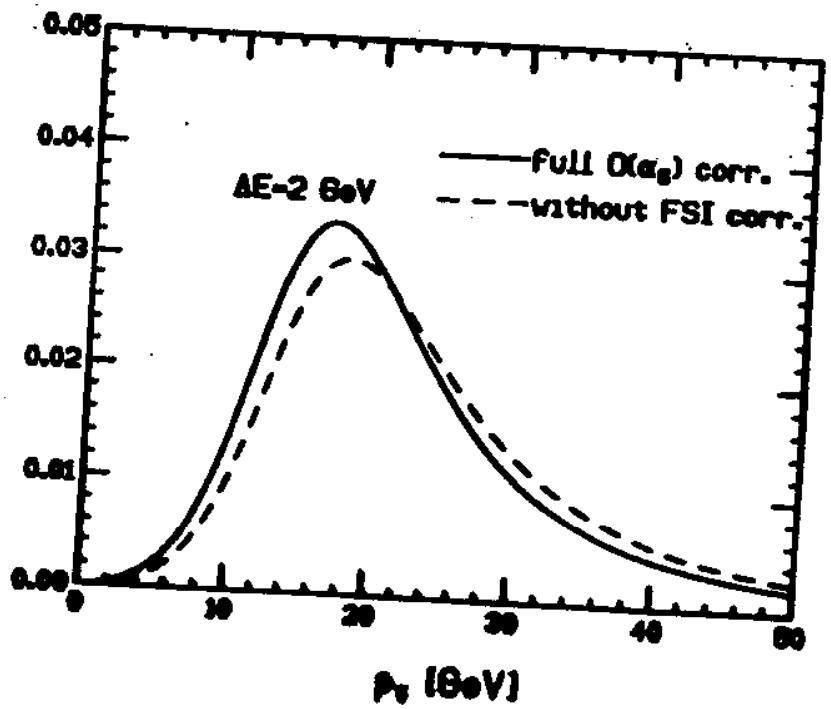
Peter + [illegible]



⇒ Attractive force

⇒ Changes momentum, polarization dist.

Top momentum distrib.



Top Loop Corrections to $t\bar{t}$ production at Higher Energies

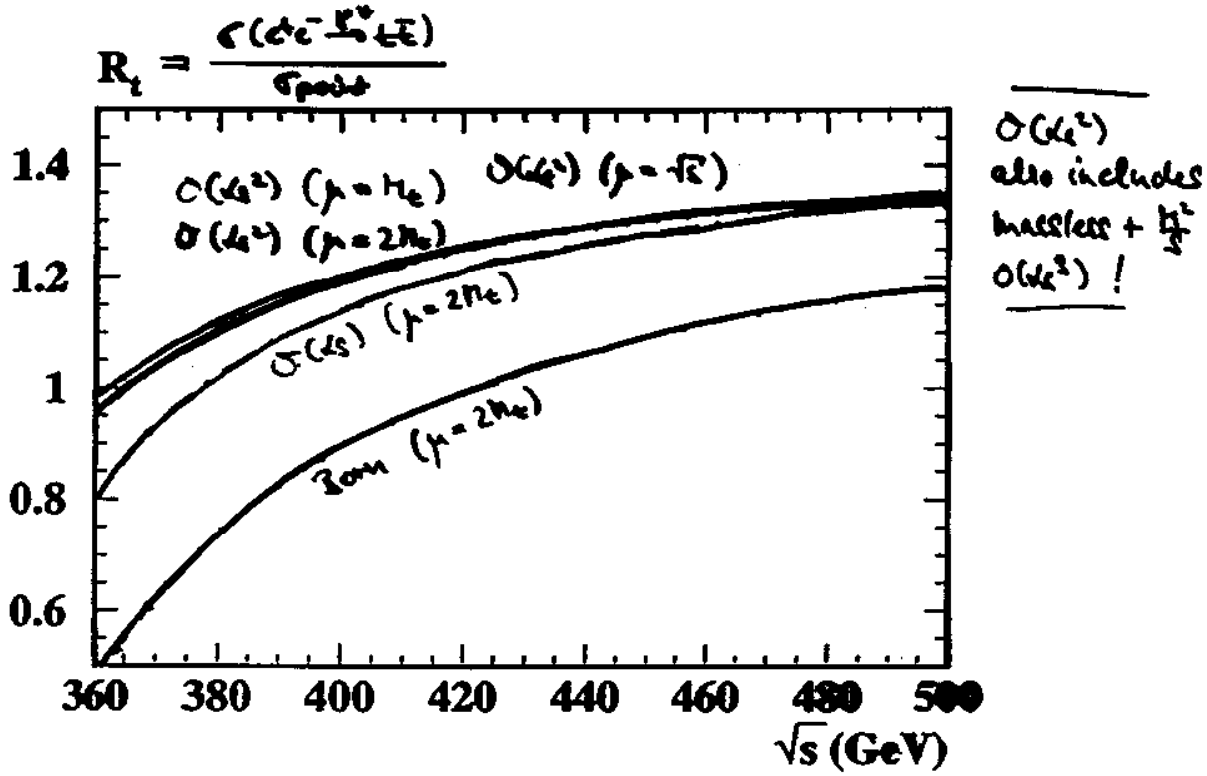
André H. Hoang

1) Calculation of terms $\left(\frac{M_t^2}{s}\right)^n$ $n \gg 1$

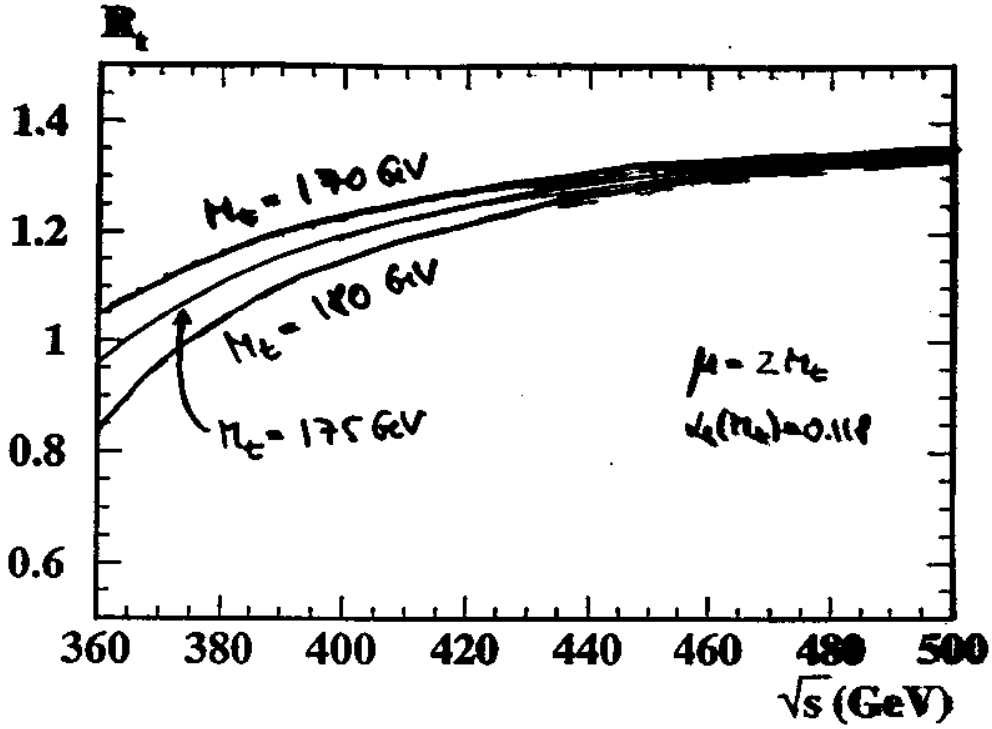
2) Complete analytic calculation of specific diagrams

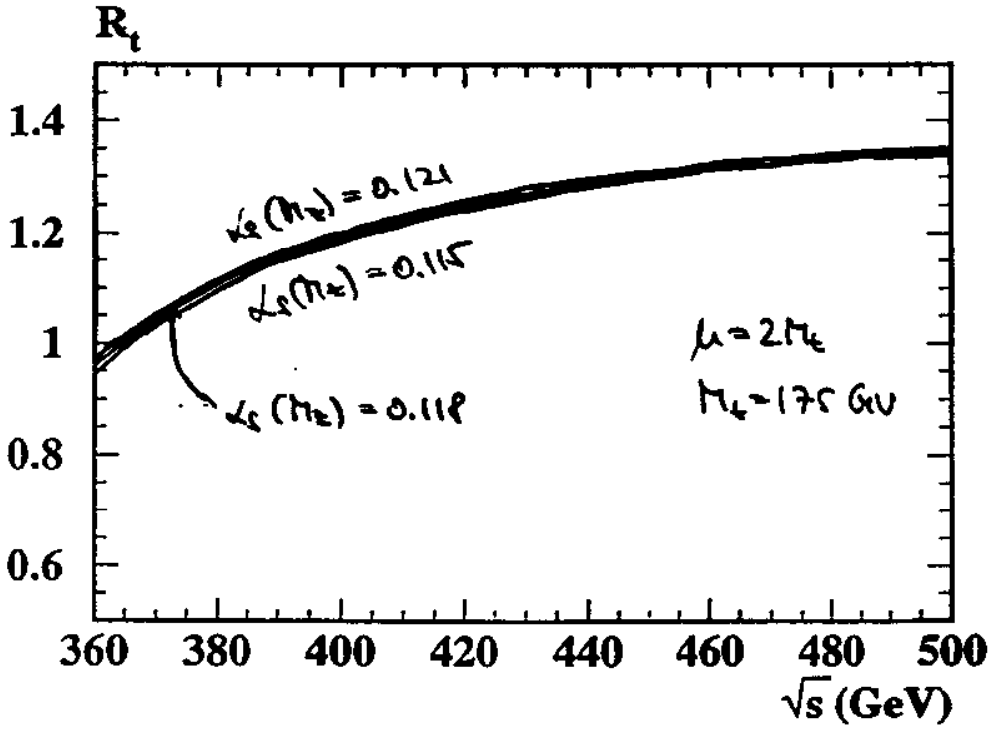
3) Padé - approximation

HOANG


$R_t = \frac{\sigma(e^+e^- \to t\bar{t})}{\sigma_{point}}$
1.4
1.2
1
0.8
0.6
360
380
400
420
440
460
480
500
$\sqrt{s}$ (GeV)
$O(\alpha_s^2)$ $(\mu = m_t)$
$O(\alpha_s^2)$ $(\mu = \sqrt{s})$
$O(\alpha_s^2)$ $(\mu = 2m_t)$
$O(\alpha_s)$ $(\mu = 2m_t)$
Born $(\mu = 2m_t)$
$O(\alpha_s^2)$ also includes massless + $\frac{m_t^2}{s}$ $O(\alpha_s^3)$!

HOANG


R_t
1.4
1.2
1
0.8
0.6
360
380
400
420
440
460
480
500
$\sqrt{s}$ (GeV)
M_t = 170 GeV
M_t = 180 GeV
M_t = 175 GeV
$\mu = 2M_t$
$\alpha_s(M_t)$=0.118


R_t
1.4
1.2
1
0.8
0.6
360
380
400
420
440
460
480
500
$\sqrt{s}$ (GeV)
$\alpha_s(M_t)$ = 0.121
$\alpha_s(M_t)$ = 0.115
$\alpha_s(M_t)$ = 0.118
$\mu = 2M_t$
M_t = 175 GeV

Flavor Changing Neutral Currents at $\mu^+\mu^-$ colliders

D. Atwood, L. Reina, A. Soni

PRL 75, 3800 (1995)

PRD 55, 3156 (1997) (review)

this workshop

REINA

THE MODEL

Two Higgs Doublet Model: Model III

Yukawa Lagrangian

$$\mathcal{L}_Y^{(III)} = \eta_{ij}^U \bar{Q}_{i,L} \tilde{\phi}_1 U_{j,R} + \eta_{ij}^D \bar{Q}_{i,L} \phi_1 D_{j,R} + \xi_{ij}^U \bar{Q}_{i,L} \tilde{\phi}_2 U_{j,R} + \xi_{ij}^D \bar{Q}_{i,L} \phi_2 D_{j,R} + h.c.$$

Discrete Symmetry $\longrightarrow$ No FCNC:
Model I and II (Glashow and Weinberg, 1977)

$$\phi_1 \to -\phi_1 \quad \text{and} \quad \phi_2 \to \phi_2$$
$$D_i \to -D_i \quad \text{and} \quad U_i \to \mp U_i$$

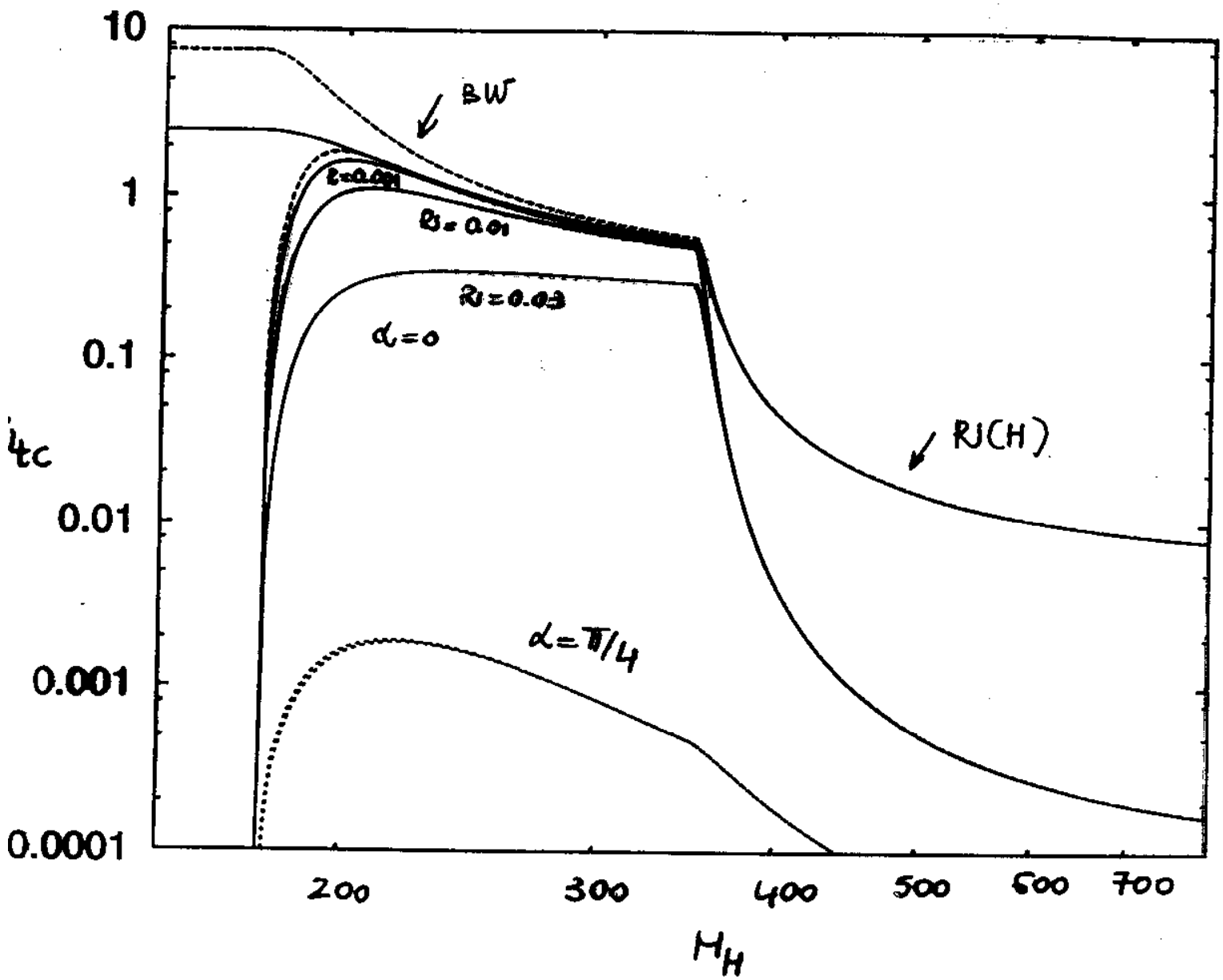
If we do not enforce it, and choose

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad , \quad \langle \phi_2 \rangle = 0 \ .$$

Then (Weinberg and Hall, Luke and Savage,...)

$\phi_1 \longrightarrow$ mass generation
$\phi_2 \longrightarrow$ new FC couplings

REINA



$$R_{tc} = \frac{\sigma_{tc}^{eff}(\mu^+\mu^- \to tc)}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$

REINA

TOP-CHARM PRODUCTION or $t \to cV$ DECAYS

The FIRST MUON COLLIDER

Some indicative results

$M_H = 300$ GeV and R=0.01%

($\sigma_0 \simeq 1$ pb)

- $\alpha = 0$

  i) $\mathcal{L} \simeq 10^{32}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1} \longrightarrow \simeq 10^2$ events

  i) $\mathcal{L} \simeq 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1} \longrightarrow \simeq 10^4$ events

- $\alpha = \pi/4$

  i) $\mathcal{L} \simeq 10^{32}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1} \longrightarrow$ a few events

  i) $\mathcal{L} \simeq 10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1} \longrightarrow \simeq 10^2$ events

Background : WW production and bb production

Detector & Background

P. Lebrun, R. Roser

— Lattice work: COSY & MAD.

— HEP detector simulation:

MARS and GEANT3

— HEP "Physics events"

Lund, Pythia, ...

ROSER

Backgrounds sources

Synchroton radiation:
(small from muons),
from electrons: absorbed by the shield

E.m. shower occuring close to the detector.
"The problem"

Hadrons from photoproduction at high energy.
Only relevant at ~ 2 TeV.

These hadrons generates also tertiary muons at
large radii.

Others, may be !..

Note:

The lattice in itself is, a sense the culprit:
by bringing the muons in focus at the I.P.,
we "spray" the detector, as the electrons do
not have the correct momentum to be kept
in the beam pipe.

TOP QUARK PHYSICS AT THE MUON COLLIDER ABOVE THE THRESHOLD REGION

PARKE

- CHECK STANDARD MODEL COUPLINGS & SEARCH FOR ANOMALOUS COUPLINGS
- NO HADRONIZATION: SPIN PRESERVED FROM PRODUCTION TO DECAY

– PRODUCTION
  COUPLINGS TO γ, Z

  σ, $\frac{d\sigma}{d\cos\theta^*}$, SPIN CORRELATIONS BETWEEN $t, \bar{t}$

– DECAY
  COUPLINGS TO W BOSON

  ANGULAR CORRELATIONS OF DECAY PRODUCTS WITH SPIN DIRECTIONS OF t AND $\bar{t}$

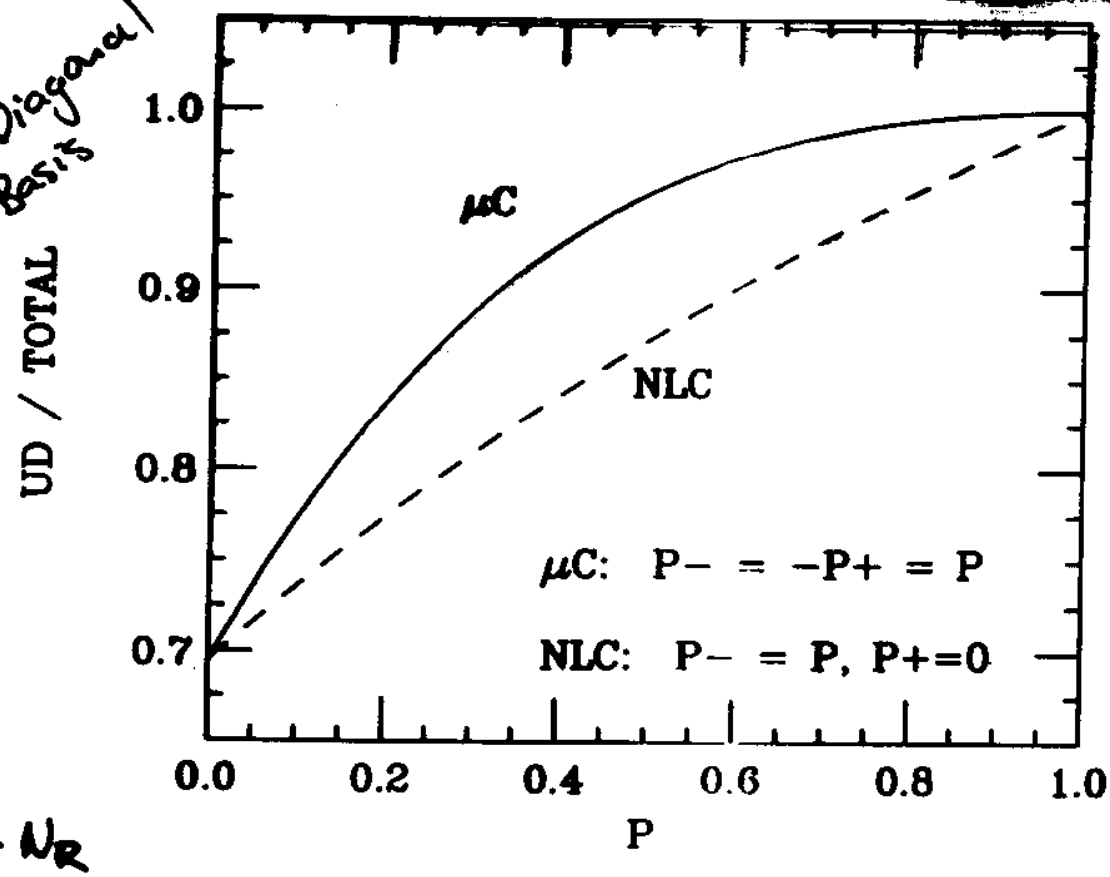
– SEARCH FOR NEW PARTICLES IN PRODUCTION AND DECAY

  $(\mu^+\mu^- \to X \to t\bar{t})$ $(t \to H^+ b)$

$\sqrt{s} = 400$ GeV $\quad \sigma_{TOTAL}/\sigma_{LR} = 0.44$ PARKE

POLARIZED BEAMS

Off-Diagonal Basis



$$P = \frac{N_L - N_R}{N_L + N_R}$$

μC	NLC	UD/TOTAL
0	0	0.69
0.20	0.40	0.84
0.30	0.55	0.89
0.50	0.80	0.95

in helicity basis

$$\frac{LR}{TOTAL} = 0.52 \quad \text{at } P^- = 1$$

otherwise smaller.

$$\frac{RL}{TOTAL} = 0.57 \quad \text{at } P^- = -1$$

TOP QUARK PAIRS ABOVE THE THRESHOLD REGION AT MUON COLLIDERS ARE A GREAT PLACE TO SEARCH FOR ANOMALOUS COUPLINGS OF THE TOP QUARK.

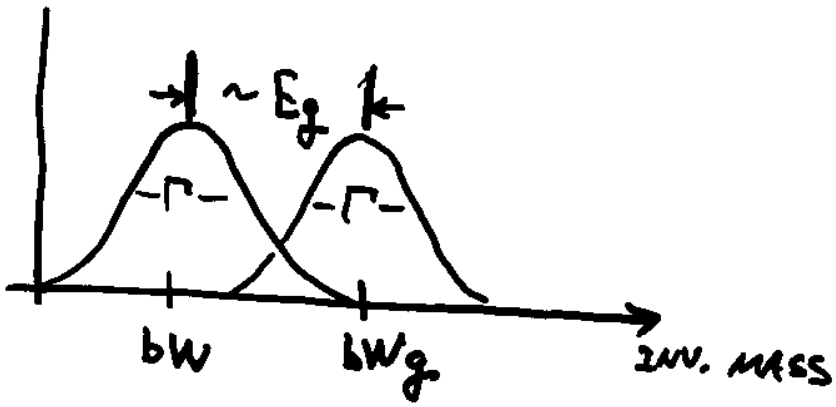
FOR $\sqrt{s} < 1$ TeV THE OFF-DIAGONAL BASIS IS FAR SUPERIOR TO HELICITY BASIS IN DESCRIBING THE EVENTS IN THEIR SIMPLEST POSSIBLE TERMS.

POLARIZATION OF THE INCOMING BEAMS ENHANCES THIS EFFECT.

GLUONS AND TOP AT $\mu^+\mu^-$ (ORR)

- NO ISR GLUONS, BUT STILL HAVE PRODUCTION- AND DECAY-STAGE RADIATION:

- PRODUCTION-DECAY INTERFERENCE FOR $E_{gluon} \sim \Gamma_t$ OR LESS.



$\Rightarrow$ SENSITIVITY TO Γ_t

- DIFFICULT TO MEASURE Γ_t; BUT IT IS WORTHWHILE LOOKING FOR
  - INTERFERENCE EFFECTS
  - CONSISTENCY

GLUON RADIATION CONCLUSION

OR

- We need to understand gluon radiation to make sense of top events, especially for M_t reconstruction.

- There are no significant differences between $\mu^+\mu^-$ and e^+e^- machines as far as gluon radiation is concerned.

- Relatively clean environment of lepton colliders allows for detailed experimental studies of QCD effects in $t\bar{t}$ physics both within SM and beyond.

COMPARING $\mu^+\mu^-$ AND e^+e^- MACHINES IN $t\bar{t}$ PHYSICS

SAME

1) GLUON RADIATION (ORR)

2) $t\bar{t}$ THRESHOLD - NNLO CORRECTIONS (HOANG)

3) 2-LOOP CORRECTIONS TO $t\bar{t}$ PRODUCTION ABOVE THRESHOLD (HOANG)

DIFFERENT

1) BEAM EFFECTS (RAJA)

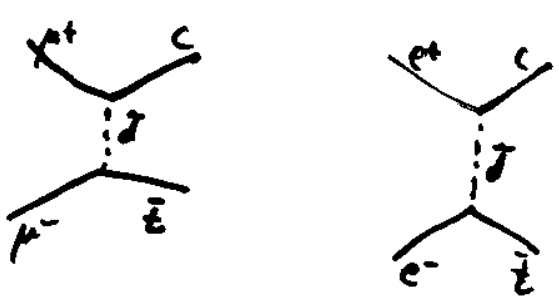
2) INITIAL STATE RADIATION (QED) (RAJA)

3) POLARIZATION (PARKE)
(TRADEOFF BETWEEN P AND $\mathcal{L}$)

4) $\mu^+\mu^- H$ COUPLING

$$\mu^+\mu^- \to H \to t\bar{t} + c\bar{t} \quad \text{(REINA)}$$

5)



DIFFERENT
~~BY~~ YUKAWAS
(REINA)

CONCLUSION

→ MUCH TOP QUARK PHYSICS REQUIRES HIGH LUMINOSITY

→ MORE COMPLETE THEORETICAL CALCULATIONS MAY BE NEEDED TO FULLY REALIZE PRECISION MEASUREMENTS

→ POLARIZATION

- HELPFUL FOR ELIMINATING BACKGROUNDS
- HELP WITH TOP QUARK SPIN MEASUREMENTS
- HOW DOES P TRADEOFF WITH $\mathcal{L}$ (LUMINOSITY)