STRONG DYNAMICS WORKING GROUP SUMMARY

Pushpa Bhat
Estia Eichten

Fermi National Accelerator Laboratory

Muon Collider Workshop, Nov. 6-9, 1997

MOTIVATION FOR STRONG DYNAMICS

Success of the Standard Model has been Spectacul.

But, New Physics seems inevitable because The cause for Electroweak Symmetry Breaking and the origin of fermion masses and mixing are unknown.

Broadly, there are two main routes taken to understand EWSB

- → Supersymmetry
- → New Strong Interactions/ Strong Dynamics

Charge:

- What direct searches and detailed measurements for low energy signatures of the new dynamics can be done at the FMC? How do these compare with what is attainable at the Tevatron, LHC and the possible NLC machines?

- What about indirect tests for strong dynamic. such as, compositeness tests, strong WW interactions, rare B & K decays, anomalous couplings, etc.

- What are the long range opportunities with higher energy muon colliders, to discover and study new strong dynami

List of Participants

E. Eichten
P. Bhat
K. Lane
C. Hill
G. Burdman
S. Parke
S. Keller
B. Dobrescu
G. Pacetetta
D. Dominici
P. Mackenzie
K. Maeshima
T. Handa
R. Vilar
J. Womersley
G. Farrar

Talks

11/6/97	• Technicolor & Muon Colliders	K. Lane
	• Top and Strong Dynamics	C. Hill
11/7/97	• Compositeness tests at the FMC	Eichten/Kell
	• Detector & Background Issues	P. Lebrun
	• Strong WW Scattering	J. Gunio
	• Effective Lagrangian Parametrization of SEWS & Strong Dynamics @ FMC	Dominic
	• Constraints on Strong Dynamics from rare B and K decays	G. Burdm
11/8/97	• Low-scale Walking Technicolor	J. Womers
	• Technicolor with scalars @ FMC	B. Dobres
	• Search for technicolor particles in W+2 jets with b-tag channel	Handa/Maes Valls/Vila for CDF
	• Trilinear Gauge Boson Couplings	U. Baur
	• Quartic Gauge Boson Couplings	H. He

TEC NICOLOR

and

its cousins

Technicolor model starts with massless technifermions (T) that interact strongly at a scale Λ_{TC} (~ 1 TeV) and acquire a dynamical mass $O(\Lambda_{TC})$

→ produces techniparticles (massless technipion π_T)

← No masses for SM particles

Quarks and leptons need to <u>couple</u> to technifermions via Extended Technicolor gauge interaction in order to acquire masses

$$G_{ETC} \rightarrow G_{TC} \otimes G_{QCD} \otimes G_F$$

$$@ \; M_{ETC} \gtrsim 100 \text{ TeV}$$

If FCNC rates are to be low,

$$m_{q,\ell,T} \leq \text{few MeV} \; ; \; M_{\pi_T} \lesssim \text{few GeV}$$

A possible solution is to make the technico "walk" instead of "run" ← $\beta\left(\frac{dg_{TC}}{dt}\right) \approx 0$

⇒ Walking Technicolor

$$m_{q,\ell,T} \lesssim \text{few GeV} \; ; \; M_{\pi_T} \simeq \text{few 100 GeV}$$

TOPCOLOR-ASSISTED TECHNICOLOR (TC2)

Top quark is very massive and so may be very special!

"Top quark is the elementary particle most strongly coupled to the agent or the dynamics of EWSB"

So, top may have unique dynamics

Invoke TOPCOLOR with $\Lambda_{top} \lesssim 1$ TeV to generate large $\langle t\bar{t} \rangle$, m_t

Replace $SU(3) \otimes U(1)$

$$\rightarrow SU(3)_{1,2} \otimes SU(3)_3 \otimes U(1)_{1,2} \otimes U($$

subscripts denote generations

Signatures

Walking Technicolor

Technipions $(m \gtrsim 100\ \mathrm{GeV})$

$$\pi_T^0 \to t\bar{t},\ b\bar{b},\ \tau\tau\ ;\ \pi_T^\pm \to t\bar{b},\ b\bar{c},\ \tau\nu$$

Color-singlet technirhos $(m \sim 200-400\ \mathrm{GeV})$

$$\rho_{T1}^\pm \to W^\pm Z,\ W^\pm\pi_T^0,\ Z\pi_T^\pm,\ \pi_T^\pm\pi_T^0$$

$$\rho_{T1}^0 \to WW,\ W\pi_T,\ \pi_T\pi_T$$

Color-octet technirhos $(m \sim 200-600\ \mathrm{GeV})$

$$\rho_{T8} \to \pi_T\pi_T,\ gg$$

Color-singlet techniomega

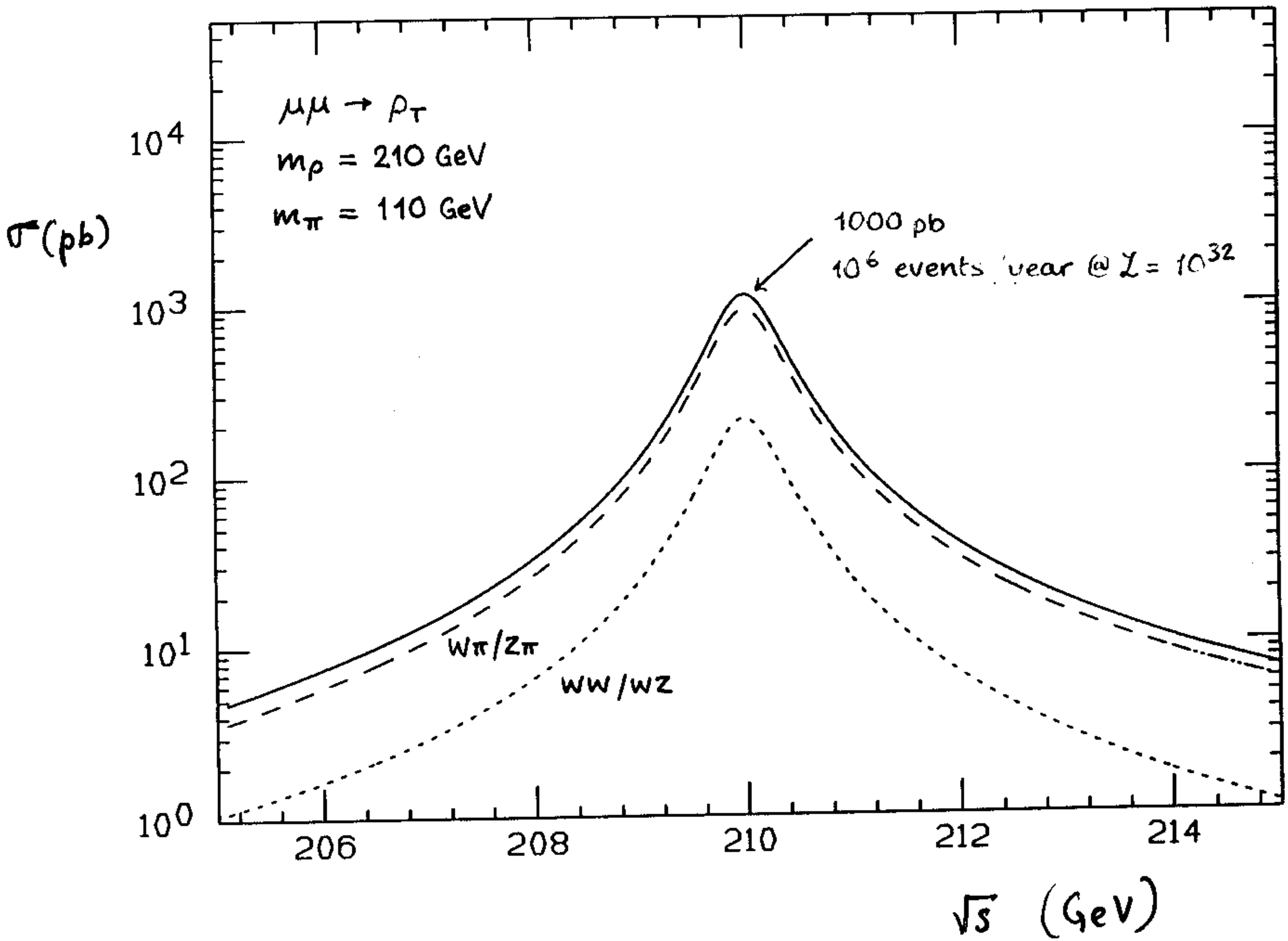
$$\omega_T^0 \to \gamma\pi_T^0,\ Z\pi_T^0,\ q\bar{q},\ \ell^+\ell^-$$

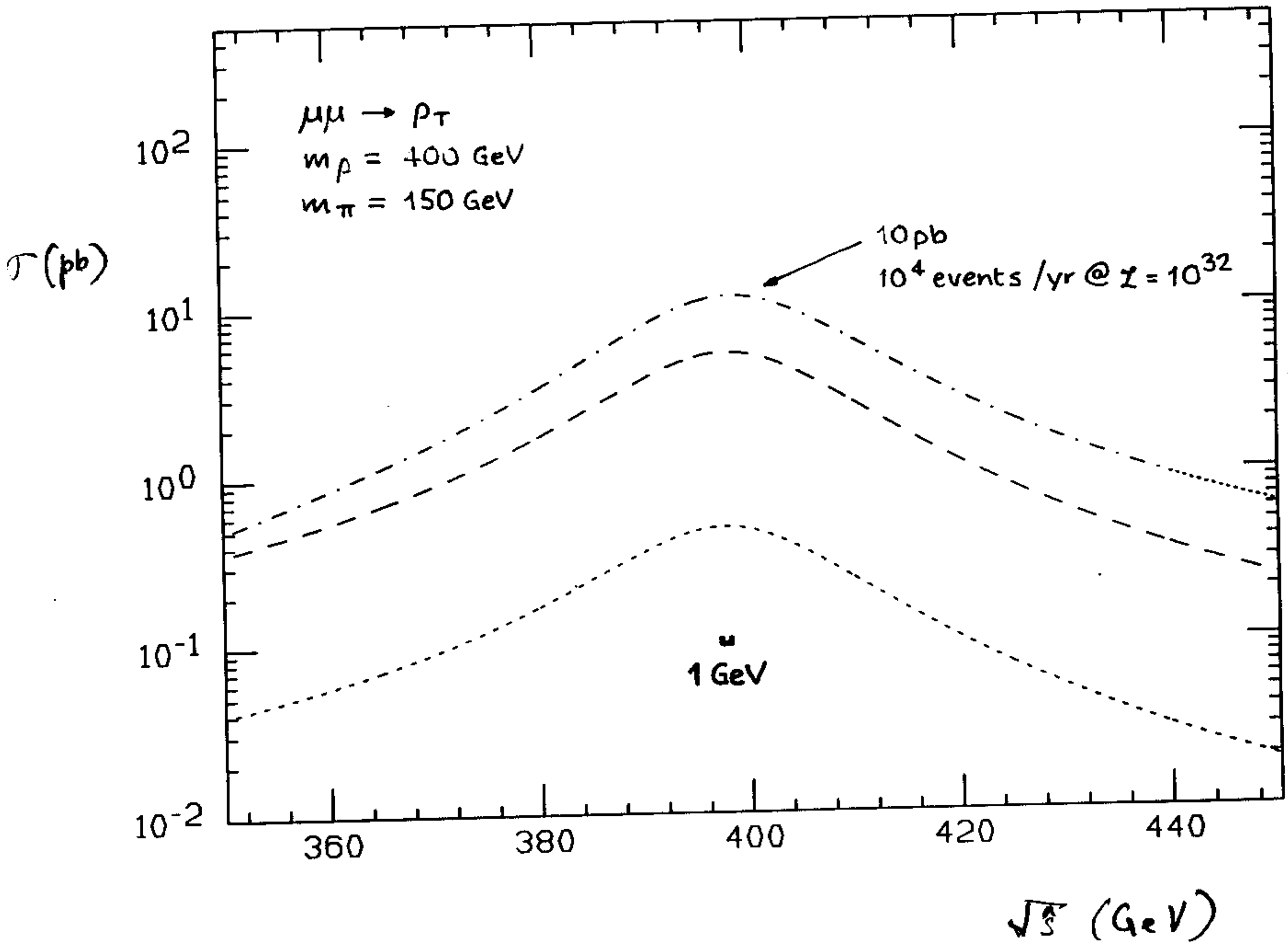
Topcolor-Assisted Technicolor

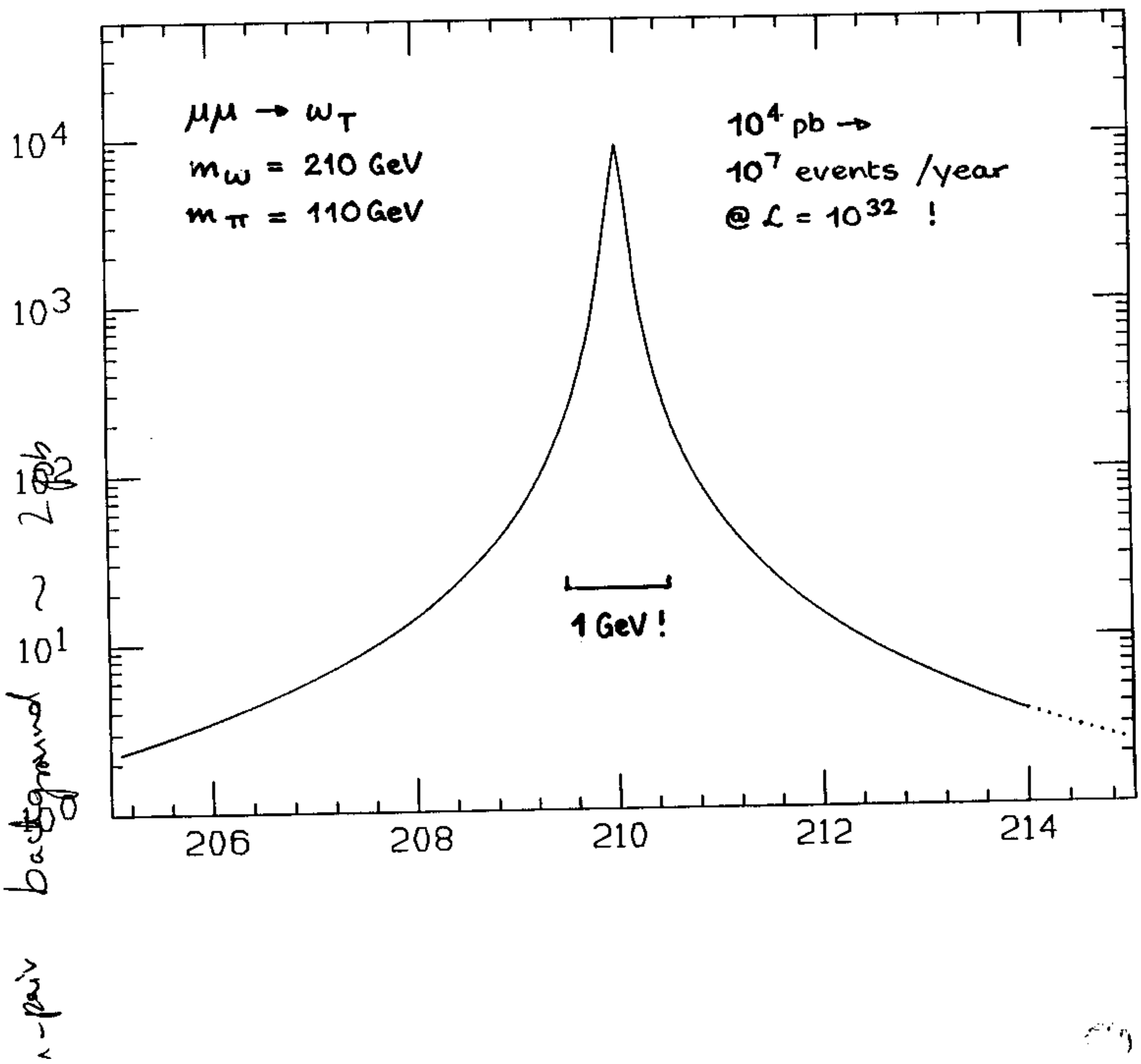
Top-pions $\quad \pi_t \to t\bar{b} \quad$ or $\quad t \to \pi_t b$

Top-gluons $\quad B \to b\bar{b},\ t\bar{t}$

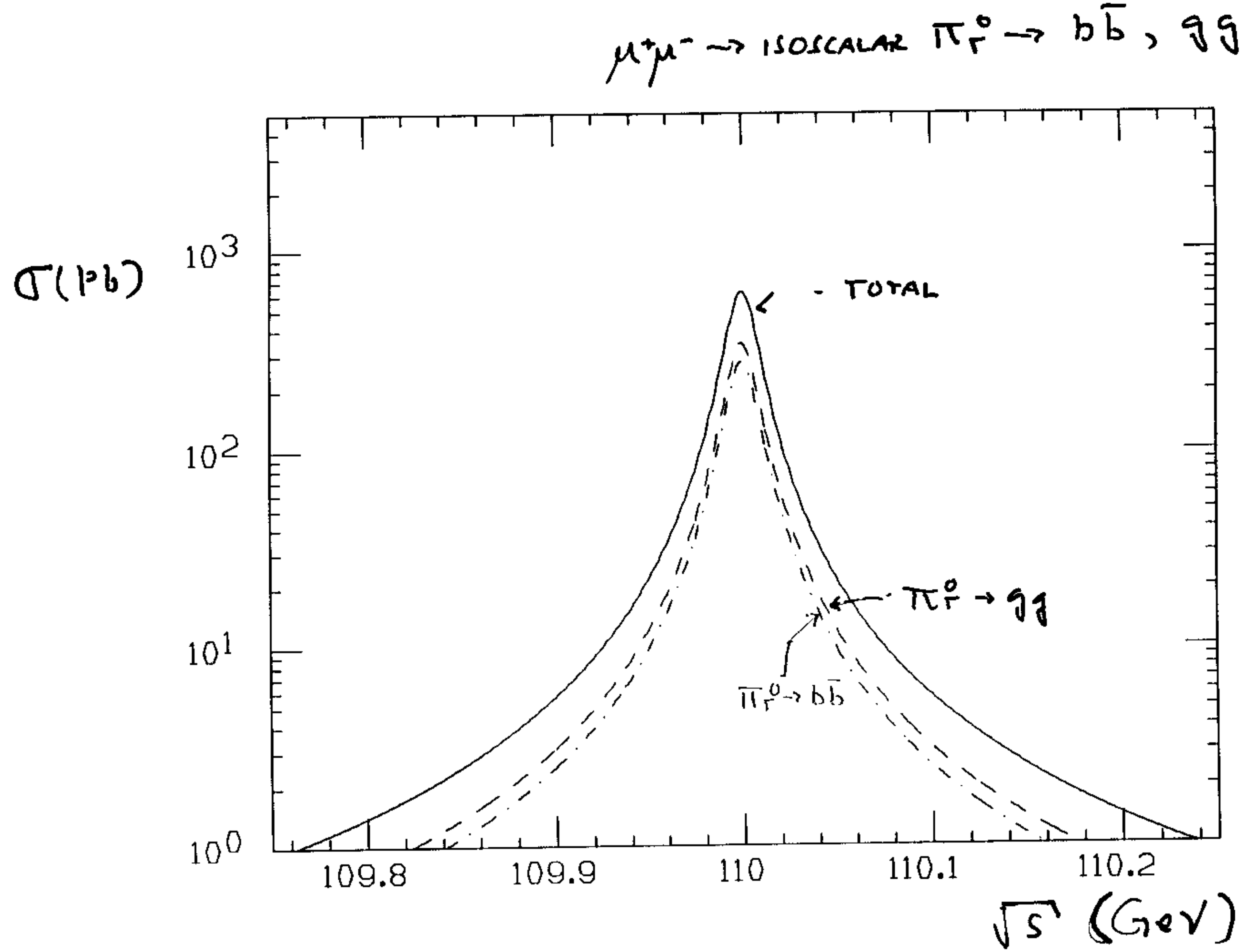
Topcolor Z' $\quad Z_t' \to t\bar{t}$


$\mu\mu \to \rho_T$
m_ρ = 210 GeV
m_π = 110 GeV
1000 pb
10^6 events/year @ $\mathcal{L} = 10^{32}$
$W\pi/Z\pi$
WW/WZ
σ(pb)
10^4
10^3
10^2
10^1
10^0
206
208
210
212
214
$\sqrt{s}$ (GeV)

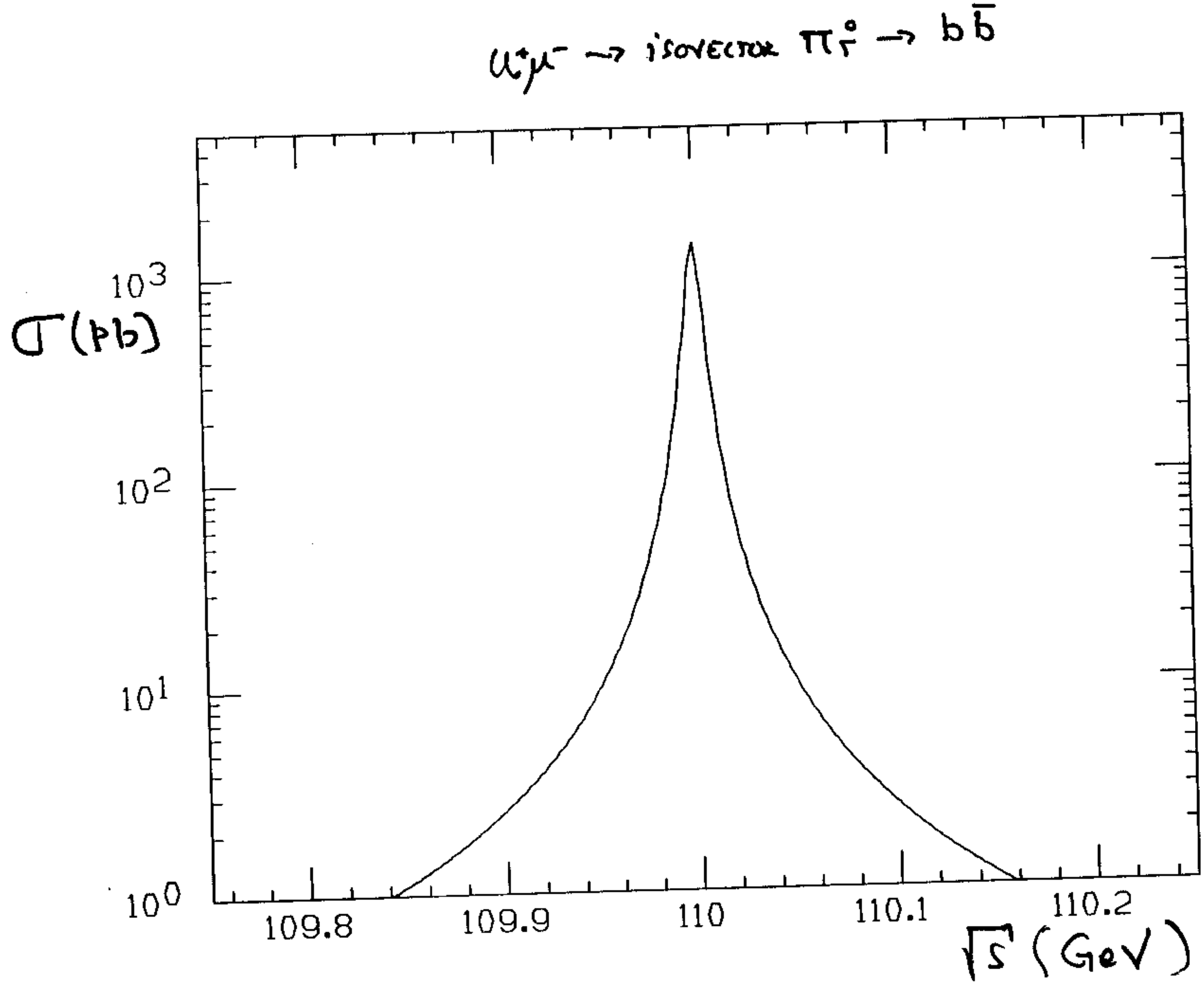

$\mu\mu \to \rho_T$
m_ρ = 400 GeV
m_π = 150 GeV
10pb
10^4 events /yr @ $\mathcal{L} = 10^{32}$
1 GeV
σ (pb)
10^2
10^1
10^0
10^{-1}
10^{-2}
360
380
400
420
440
$\sqrt{\hat{s}}$ (GeV)



$\mu\mu \to \omega_T$
m_ω = 210 GeV
m_π = 110 GeV
10^4 pb →
10^7 events /year
@ $\mathcal{L} = 10^{32}$!
1 GeV !
10^4
10^3
10^2
10^1
206
208
210
212
214

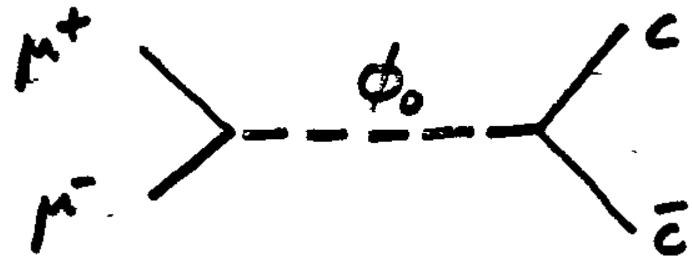


μ+μ- → ISOSCALAR π_T^0 → bb̄ , gg
σ (pb)
10^3
10^2
10^1
10^0
TOTAL
π_T^0 → gg
π_T^0 → bb̄
109.8
109.9
110
110.1
110.2
√s (GeV)



$\mu^+\mu^- \to$ isovector $\pi_T^0 \to b\bar{b}$
10^3
σ (pb)
10^2
10^1
10^0
109.8
109.9
110
110.1
110.2
$\sqrt{s}$ (GeV)

s-channel ϕ_0 production at the FMC



Cross section

$$\sigma(\mu\bar{\mu} \to \phi_0 \to c\bar{c}) = 4\pi \frac{\Gamma(\phi_0 \to \mu^+\mu^-)\Gamma(\phi_0 \to c\bar{c})}{(\hat{s} - M_\Phi^2)^2 + M_\Phi^2 \Gamma_\Phi^2}$$

At peak:

$$\begin{aligned} \sigma_p(\mu\bar{\mu} \to \phi_0 \to c\bar{c}) &\approx \frac{4\pi}{3M_\Phi^2}\left(\frac{m_\mu}{m_c}\right)^2 \frac{1}{(1+r)^2} \\ &\approx 60\,\mathrm{pb}\frac{1}{(1+r)^2}\left(\frac{400\,\mathrm{GeV}}{M_\Phi}\right)^2 \end{aligned}$$

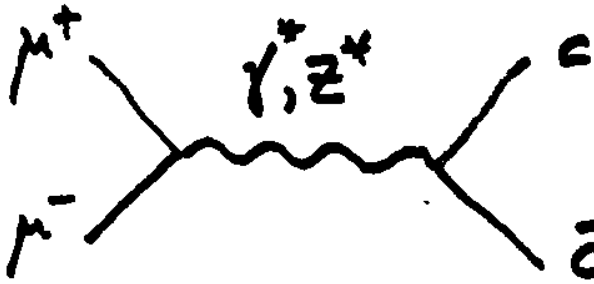
$0 < r < 1$

$$\mathcal{L}_{\mathrm{average}} = 7 \times 10^{32}\ cm^{-2}s^{-1}$$

5×10^5 events/year $\times$ c-tagging efficiency

(15% ?)

Background



$$\sigma_B(\mu\bar{\mu} \to c\bar{c}) = 2\,\mathrm{pb}\frac{(300\,\mathrm{GeV})^2}{s}$$

Discovery

$$L = 7\,\mathrm{fb}^{-1}/y$$

$$\frac{\sigma(\mu\bar{\mu} \to \phi_0 \to c\bar{c})\,L}{\sqrt{\sigma_B(\mu\bar{\mu} \to c\bar{c})\,L}} \geq 5$$

$$\Rightarrow\ \sigma(\mu\bar{\mu} \to \phi_0 \to c\bar{c}) \geq 90\,\mathrm{fb}$$

Two scan points (300 and 500 GeV) are sufficient to find a ϕ_0 with mass between 200 − 600 GeV.

What can be done at The FMC?

- Technihadrons low enough in mass to be produced at the FMC will probably be first seen at the Tevatron – certainly at the LH(

So, discovery is not The goal but precision measurements, although for single π_T, Higgs-like scalars FMC may be the best bet!

→ sit on the resonance(s) and study all decay and BR's of the ρ's ω's and π's
(all-hadronic modes hard at hadron colliders)
Explore the full spectrum of hadrons

→ Good mass resolution from beam constrai
can scan and determine widths (~ [illegible]?)

→ Study ρ, ω interference

Detector Requirements

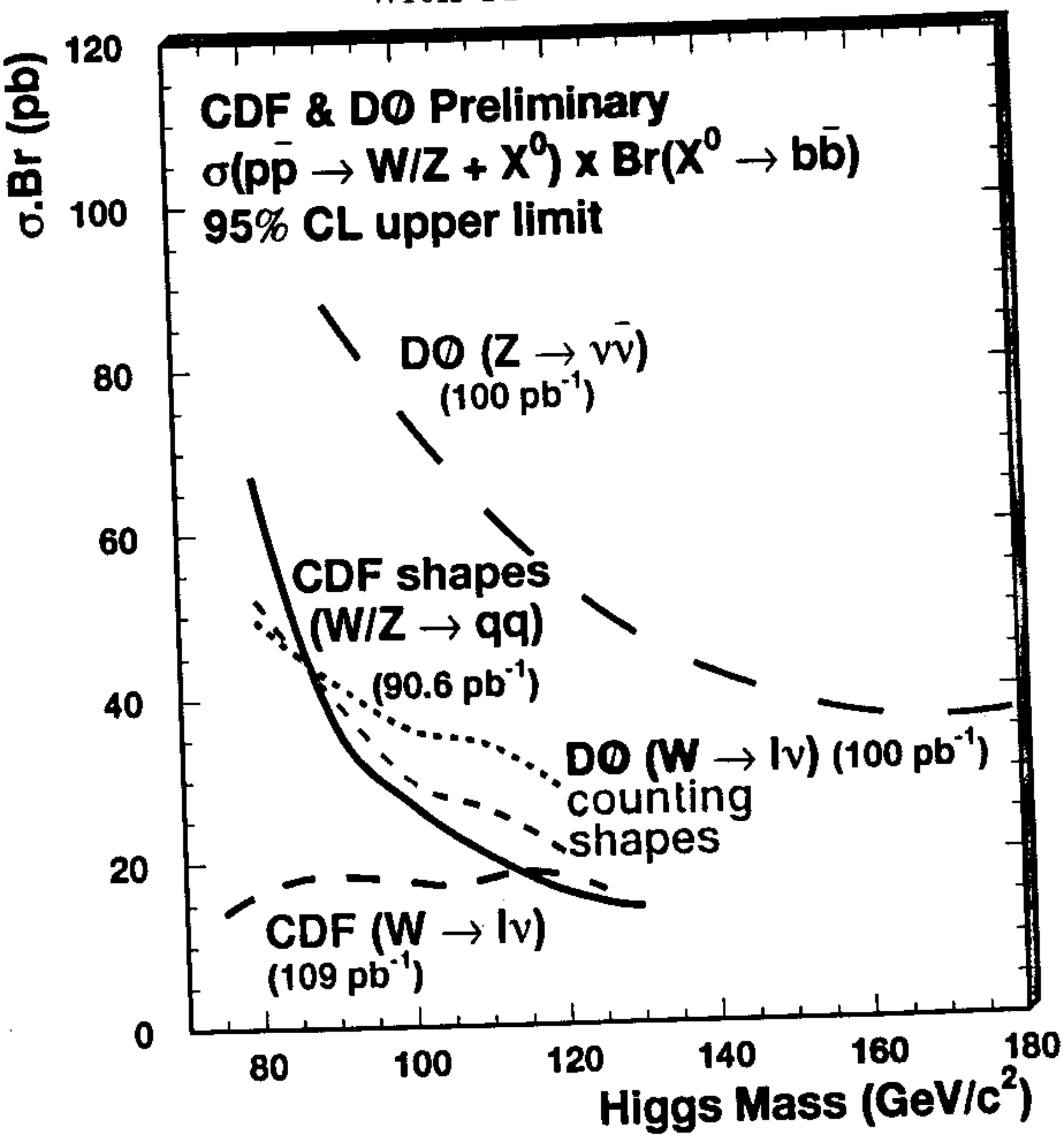
→ e, μ, τ

→ jets, $\not{E}_T$

→ tagging heavy flavor

LIMITS ON NEW HEAVY SCALARS

Limits for $\sigma(p\bar{p} \to W^{\pm}/Z^0 + X^0)$
with $X^0 \to b\bar{b}$



(For Standard Model Higgs $\sigma \cdot \mathrm{Br} \lesssim 1$ pb)

Search for Technicolor particles in W + 2 jet with b-tag channel

Workshop on Physics at the First Muon Collider and at Front End of a Muon Collider
Strong Dynamics Working Group 11/08/97

- ⋆ Takanobu Handa Hiroshima University
- ⋆ Kaori Maeshima Fermilab
- ⋆ Juan Valls Rutgers University
- ⋆ Rocio Vilar Fermilab

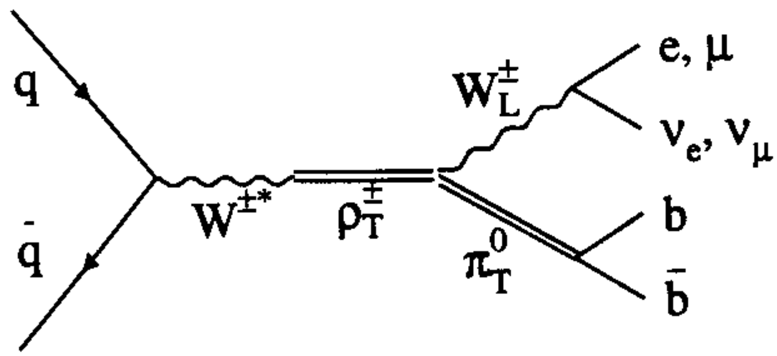
(Representing CDF Collaboration)

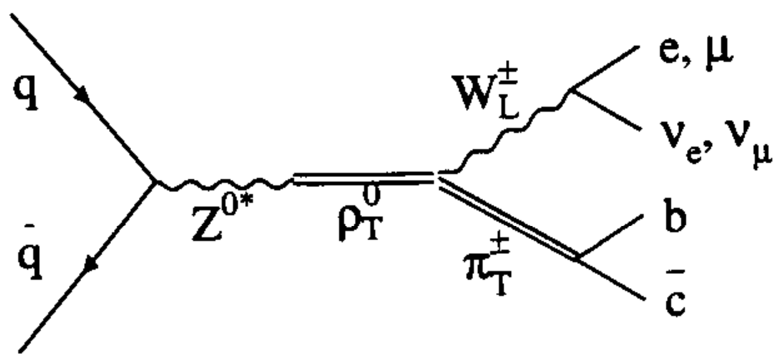
Outline

1. Production Cross Section
2. W+2jet with SECVTX b-tag Selection
3. TC Signal Acceptance
4. Background
5. 2jet Topology Cuts $\Delta\phi_{jj}$ and $p_{T_{jj}}$
6. π_T, ρ_T Mass Window Cuts
7. Systematic Uncertainties
8. Number of Events and Cross Section Limits
9. Summary Plots

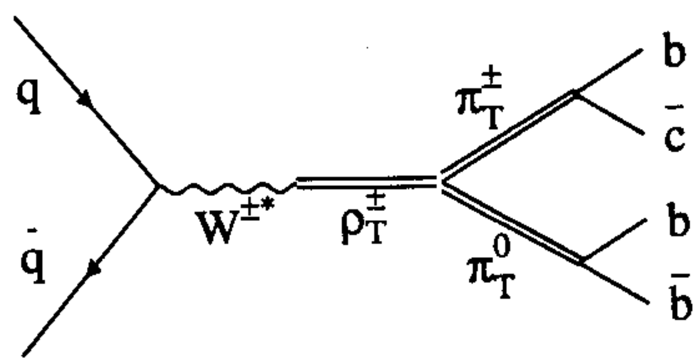
Technicolor Signatures

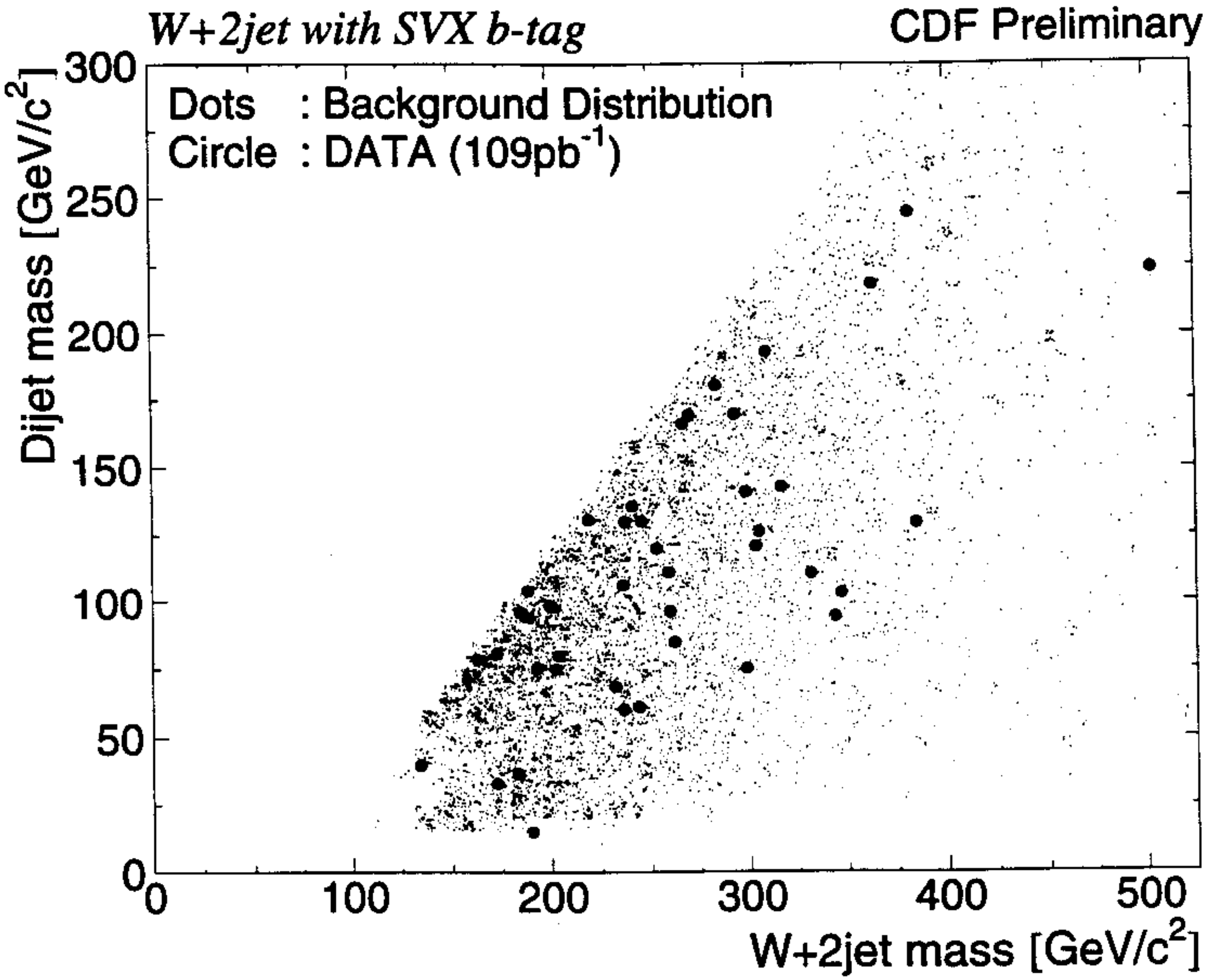
This analysis : W + 2jet with b-tag





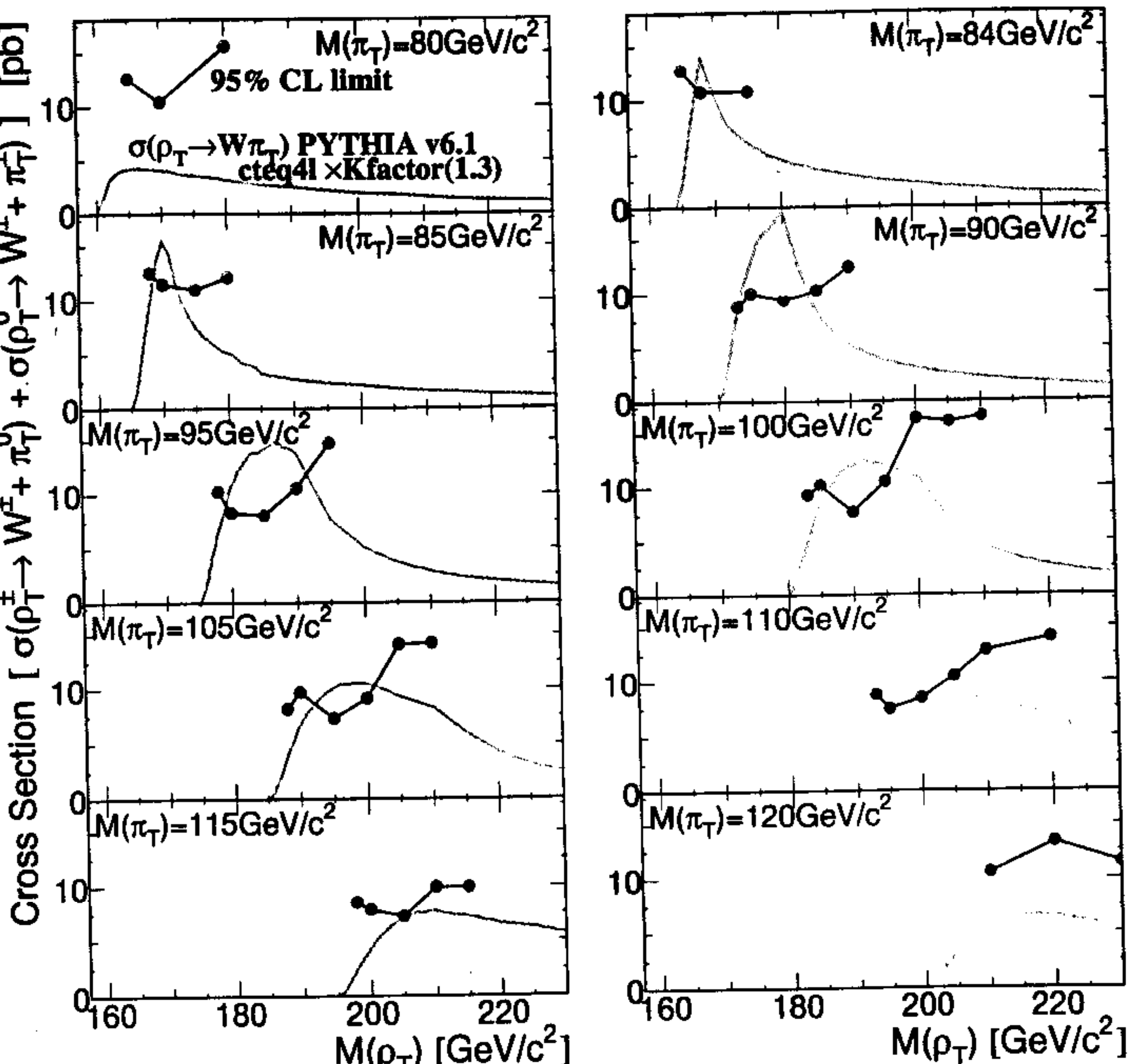
Another analysis : Multijet with Double b-tag



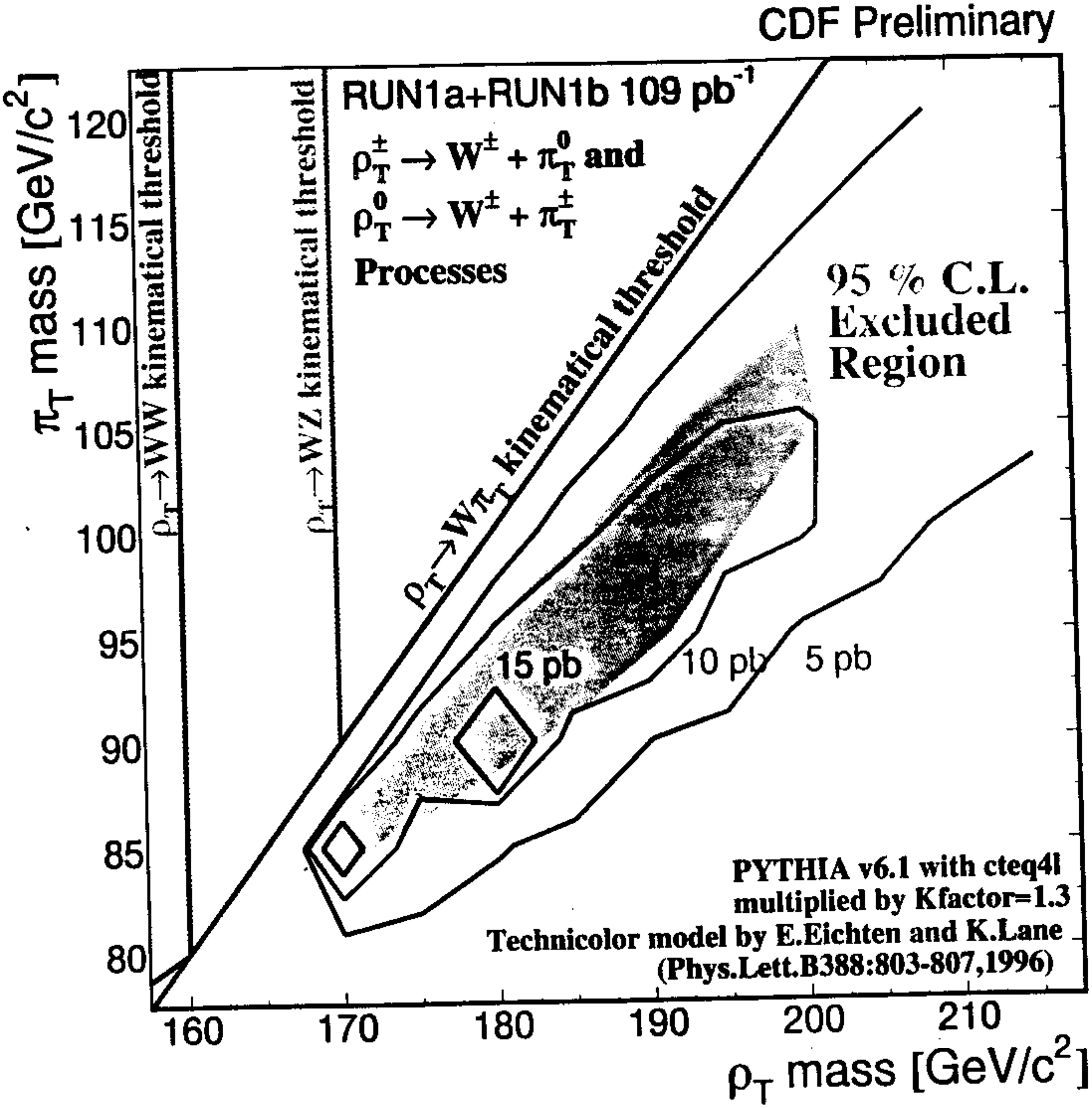


W+2jet with SVX b-tag
CDF Preliminary
Dots : Background Distribution
Circle : DATA (109pb-1)
Dijet mass [GeV/c2]
W+2jet mass [GeV/c2]
0
50
100
150
200
250
300
0
100
200
300
400
500

CDF Preliminary



Technicolor Particle Search



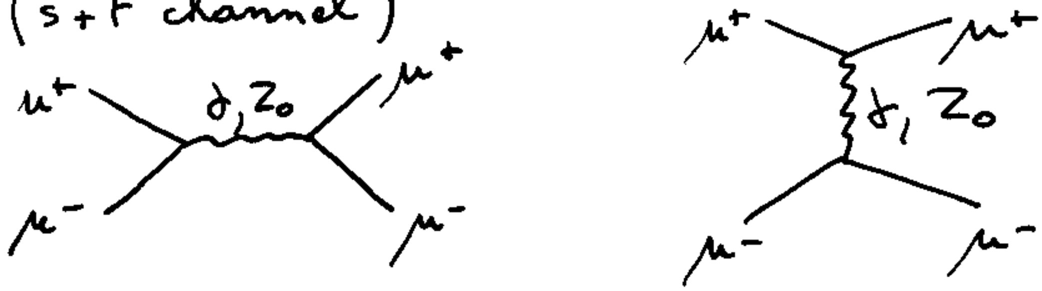
Compositeness test at the FMC with Bhabha Scattering

E. Eichten, S.K.

Goal: look at one case in some details

[illegible]

(s+t channel)



+ [illegible] (E. Eichten, K. Lane, M. Peskin

$$\mathcal{L}_{eff} = \frac{g^2}{2\Lambda^2}\left(\eta_{LL}\, J_L J_L + \eta_{RR}\, J_R J_R + 2\eta_{RL}\, J_R J_L\right)$$

strong interaction $\frac{g^2}{4\pi} = 1 \qquad \eta = \pm 1$

4 cases:

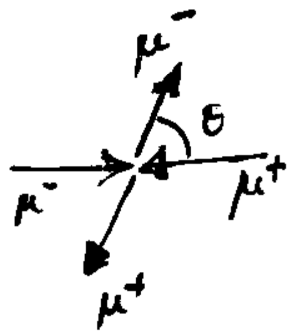
LL $\quad \eta_{LL} = \pm 1 \qquad \eta_{RR} = \eta_{RL} = 0$

RR $\quad \eta_{RR} = \pm 1 \qquad \eta_{LL} = \eta_{RL} = 0$

VV $\quad \eta_{LL} = \eta_{RR} = \eta_{RL} = \pm 1$

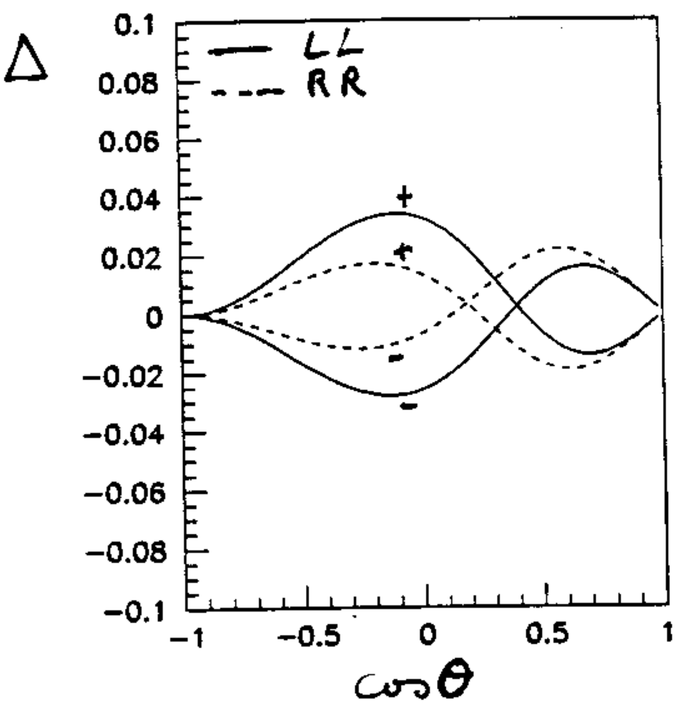
AA $\quad \eta_{LL} = \eta_{RR} = -\eta_{RL} = \pm 1$

$$\Delta = \frac{\left(\frac{d\sigma}{d\cos\theta}\right)_{\Lambda+EW} - \left(\frac{d\sigma}{d\cos\theta}\right)_{EW}}{\left(\frac{d\sigma}{d\cos\theta}\right)_{EW}}$$

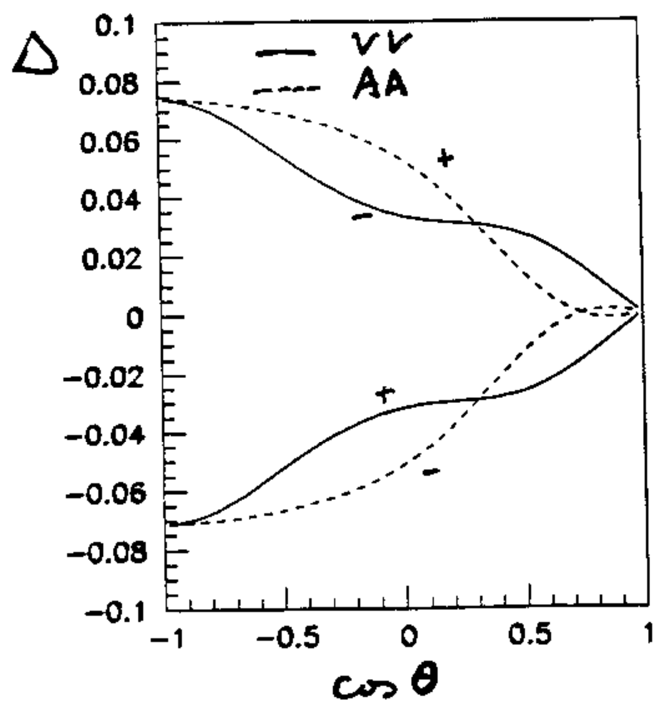


$E_{coll} = 100$ GeV

$\Lambda_\pm = 3$ TeV



$\Lambda_\pm = 6$ TeV



➡ get limits on $\Lambda_\pm$ from shape of the distribution.

(lowest uncertainty in a bin is ~ 10% if one use 20 bins)

$|\cos\theta| < .95$ (LEP I, LEP II)

	LEP I	LEP II	100	200	350	500	4000 (GeV)
$\mathcal{L}$ (fb^{-1})	.4	.02	.6	1	3	7	450 (TeV)
LL	4.0	3.8	4.4	9.4	18	27	222
RR	4.4	3.8	4.6	9.2	17	26	208
VV	8.0	7.6	11.2	19.1	33	50	[redacted]39
AA	4.5	4.6	11.1	11.5	19	29	241
N points (10^3)	$1.1\,10^3$	3.3	73	33	32	37	37

Conclusions:

- $|\cos\Theta| < .8$ fine $\qquad \Theta_{min} = 35°$
- Reach at 500 GeV $\quad \Lambda_\pm \geq 25-50$ TeV

  (4 TeV $\quad \Lambda_\pm \geq 200-400$ TeV)
- polarization will help to differentiate between LL, RR, AA, VV
- add systematic uncertainties

STRONG WW SCATTERING PHYSICS

If no light Higgs boson exists, then EW gauge bosons develop strong interactions by 1-2 TeV

⇐ A logical cause for EWSB

To fully explore this physics and uncover the possible underlying dynamics muon collider with $\sqrt{s} \sim 3$-4 TeV is needed

- Study all isospin channels as a function of WW mass
- Separate models using M_{VV} spectrum

No hope at FMC

TECHNICOLOR & THE BIG MUON COLLIDER

OR — THE PHYSICS OF THE TC2 Z′

- Z′ MASS

$$M_{Z'} \simeq 1\text{-}3 \text{ TeV}$$

  - BOUNDED BELOW BY Z-Z′ MIXING.
  - BOUNDED ABOVE BY FINE-TUNING.

- COUPLINGS (NEGLECTING ψ_i-ψ_j MIXING!)

$$\mathcal{L}_{Z'\bar\psi\psi} = g_{Z'} \sum_{\psi_i = \ell, f, T} Z'^{\mu} \left[(Y_{iL} - \epsilon Y)\, \bar\psi_{iL} \gamma_\mu \psi_{iL} + (Y_{iR} - \epsilon Q)\, \bar\psi_{iR} \gamma_\mu \psi_{iR} \right]$$

$$Y_{iL,R} = O(1) \,, \quad \epsilon = O(\tfrac{1}{10})$$

$$\alpha_{Z'} Y_{iL} Y_{iR} \approx 0.3 \ (?) \text{ FOR } t, b$$

- Z′ WIDTH (FOR $m_\psi \ll M_{Z'}$)

$$\Gamma(Z' \to \bar\psi_i \psi_i) \cong \frac{N_i}{12} \alpha_{Z'} (Y_{iL}^2 + Y_{iR}^2) M_{Z'}$$

— PROBLEMATIC !?!

TC2 Z' PHYSICS PROGRAM

* DETERMINE Z' MASS, WIDTH, COUPLINGS Y_{iL}, Y_{iR} TO QUARKS + LEPTONS.

** MEASURE $\Gamma(Z' \to \bar{T}_i T_i)$!

HOW WILL THESE DECAYS APPEAR? AS $\pi_T \pi_T$? AS TECHNIBARYONS ?? AS TECHNI<u>JETS</u> ???

*** DISCOVER (THE ONLY WAY!) THE <u>HIGHER</u>-<u>DIMENSIONAL</u> <u>TECHNIFERMIONS</u> THAT GIVE MASS TO Z' (BUT NOT W, Z).

THESE NEED <u>HIGH</u> $\sqrt{s}$, <u>HIGH</u> $\int \mathcal{L} dt$, A <u>CLEAN</u> ENVIRONMENT. CAN A BMC PROVIDE ALL THAT?

SUMMARY

- Technicolor signatures may be found at the Tevatron or at the LHC, but, the First Muon Collider will be a remarkable facility to make detailed studies and precision measurements

- Muon Collider has a big advantage over other colliders for s-channel resonance production of new particles and hence their discovery and study (ϕ_0, π_T^0, ..) (explored at the Workshop)

- Compositeness tests give unparallel reaches at the BMC of the scale at which we would be probing the structure of the dynamics that gives rise to the fermion masses and mixings

- Exploration of the Strong WW sector will require the Big Muon Collider ($\sqrt{s} \sim 3-4$ TeV)