PART 1—INTRODUCTION TO TECHNICOLOR

I. WHY TECHNICOLOR?

- ELECTROWEAK SYMMETRY BREAKING:
  What dynamics are responsible for

$$SU(2)_{EW} \otimes U(1)_{EW} \longrightarrow U(1)_{EM} \quad ??$$

- FLAVOR: What is the origin of quark and lepton flavors?
  Why do flavors come in three identical generations?

- FLAVOR SYMMETRY BREAKING:
  What is the dynamical origin of the nontrivial quark and lepton masses and mixings?

- ENERGY SCALE of EWSB:

$$2^{-\frac{1}{4}} G_F^{-\frac{1}{2}} = 246\,\mathrm{GeV}$$

NEW PHYSICS **MUST** *OCCUR NEAR THIS ENERGY SCALE!*

$$\Lambda_{EW} \simeq 1\,\mathrm{TeV}$$

- *ENERGY SCALE of FLAVOR and FSB is* **UNKNOWN**:

$$\Lambda_{FL} \gtrsim \Lambda_{EW} \simeq 1\,\mathrm{TeV}$$

- **THE PROBLEMS OF HIGGS MODELS**

→ **DYNAMICS of EWSB:**

Higgs potential $V(\phi) = \lambda\,(\phi^\dagger\phi - v^2)^2$ provides no *dynamical* explanation for EWSB

— i.e., WHY $v = 246\,\text{GeV}$ instead of $v = 0$?

FUNDAMENTAL ENERGY SCALES MUST HAVE A DYNAMICAL EXPLANATION!

→ **NATURALNESS:**

$M_H \simeq \sqrt{2\lambda}v$ and $v = \langle\phi\rangle$ are *QUADRATICALLY UNSTABLE AGAINST RADIATIVE CORRECTIONS.* — Why $M_H,\ v \ll M_{Pl}$?

In SUSY, it's *"Set it and forget it!"*

→ **HIERARCHY:**

WHY NOT $v = M_{GUT}$ or $v = M_{Pl}$?

In SUSY .... AGAIN!

→ **TRIVIALITY:**

$$\lambda(M) \cong \frac{\lambda(\Lambda)}{1 + \frac{24}{16\pi^2}\lambda(\Lambda)\,\log\frac{\Lambda}{M}}$$
$$\Longrightarrow \lambda(M) \to 0 \quad \text{as} \quad \Lambda \to \infty$$

Equivalently, $V(\phi)$ describes an *EFFECTIVE THEORY*, valid for scales $M < \Lambda_\infty$, with the Higgs mass satisfying the triviality bound

$$M_H(\Lambda_\infty) \cong \sqrt{2\lambda(M_H)}\,v = \frac{2\pi v}{\sqrt{3\log(\Lambda_\infty/M_H)}}$$

LATTICE: $\quad \Lambda_\infty \gtrsim 2\pi M_H \Longrightarrow M_H \lesssim 700\,\mathrm{GeV}$

OR . . . NEW DYNAMICS NEAR 1 TeV !!

→ **FLAVOR:**

Number of quark–lepton generations??

Yukawa couplings $\Gamma^d_{ij}\,\bar{q}_{iL}\,\phi\,d_{jR} + \cdots$??

Arbitrary free parameters put in by hand —

NO DYNAMICAL UNDERSTANDING of FLAVOR, FSB!

II. TECHNICOLOR—NATURAL EWSB

- TC = *asymptotically free gauge theory* of *MASSLESS fermions* T with $\Lambda_{TC} \simeq 0.1$–$1.0\,\mathrm{TeV}$.

$\Longrightarrow$ $T_{iL,R} = (U_i, D_i)_{L,R}$ form N LH–doublets of $SU(2)_{EW}$ and $2N$ RH–singlets.
(*Assume $SU(3)_C$–singlets, for now.*)

$\Longrightarrow$ **DYNAMICAL EXPLANATION FOR EWSB:**
Just like chiral symmetry breaking in QCD —
At $\alpha_{TC}(\Lambda_{TC}) = \alpha_C = \mathcal{O}(1)$, critical value for χSB:

$$SU(2N)_L \otimes SU(2N)_R \to SU(2N)_V$$

$$\langle \bar{U}_{iL} U_{jR} \rangle = \langle \bar{D}_{iL} D_{jR} \rangle = -\delta_{ij} \Delta_T$$

$$\Delta_T \simeq \Lambda_{TC}^3$$

$$\Lambda_{TC} \sim F_T = F_\pi / \sqrt{N}$$

$$\Longrightarrow \quad M_W^2 = \tfrac{1}{2} g^2 N F_T^2$$

$$M_Z^2 = \tfrac{1}{2}(g^2 + g'^2) N F_T^2 \equiv M_W^2 / \cos^2\theta_W \quad (\text{to } \mathcal{O}(\alpha))$$

$\Longrightarrow$ **NATURAL:**

$$\Lambda_{EW} \equiv \Lambda_{\chi SB} \sim F_T \sim \Lambda_{TC} \sim M_{\rm techni} \quad \text{at } \alpha_{TC}(\Lambda_{TC}) = \mathcal{O}(1)$$

$\Longrightarrow$ **HIERARCHICAL:**

Logarithmic running from
$\alpha_{TC}(M_{\rm GUT}) \ll 1$ to $\alpha_{TC}(\Lambda_{TC}) \sim 1$
$\Longrightarrow \Lambda_{TC} \ll M_{\rm GUT}$.

$\Longrightarrow$ **NONTRIVIAL:**

$\beta(\alpha_{TC}) < 0 \Longrightarrow \alpha_{TC}(M)$ has no Landau pole at $M > 0$.

$\Longrightarrow$ **FLAVOR and FSB:** — *NOT addressed by TC alone!*

TECHNIHADRONS

Assume N doublets $U_{iL,R}$, $D_{iL,R} \in \underline{\mathbf{N_{TC}}}$ of $SU(N_{TC})$ and $SU(3)_C$ singlets.

- $\chi SB \Longrightarrow 4N^2 - 1$ *MASSLESS* Goldstone bosons π_T, decay constant F_T;
  3 become $W_L^\pm$, Z_L^0 via the Higgs mechanism.
  How do the others get mass?? (FSB again!)

- $4N^2$ ρ_T, ω_T decaying to ≥ 2 π_T.

- Other technimesons and baryons.

III. EXTENDED TECHNICOLOR (ETC) — A SCENARIO FOR FLAVOR PHYSICS

- *WHY EXTENDED TECHNICOLOR?*

→ Technicolor (and color) by itself leaves
too much chiral symmetry.

→ Explicit breaking of q, ℓ chiral symmetries —
required to give *hard* q, ℓ masses and
avoid massless Goldstone bosons — $\pi, K, \eta, \ldots$

→ Explicit breaking of technifermion chiral symmetries —
required to give hard masses to T_i and
avoid Goldstone technipions π_T (NO AXIONS!)

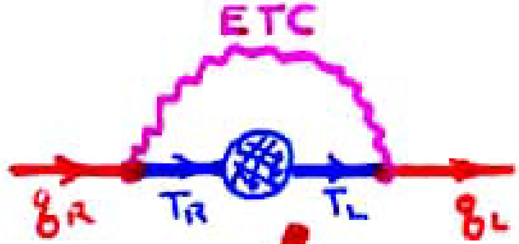
- *THE STRUCTURE OF ETC INTERACTIONS*

$\Longrightarrow$ ETC = gauge interaction of *MASSLESS* T_i, q_a, ℓ_a

$$\left\{ \underline{G_{ETC} \supset SU(N_{TC}) \otimes SU(3)_C \otimes \text{Flavor}} \right\}$$

$\Longrightarrow$ $G_{ETC} \longrightarrow SU(N_{TC}) \otimes SU(3)_C$ at $\underline{M_{ETC} \gg 1\,\text{TeV}}$ $\gtrsim \Lambda_{TC}$
explicitly breaking **ALL** global flavor symmetries.

$\Longrightarrow$ q, ℓ hard masses; π_T masses:



The KEY Equations of ETC:

- $$m_q,\, m_\ell,\, m_T(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T \rangle_{ETC}$$

- $$F_T^2 M_{\pi_T}^2 \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T\bar{T}T \rangle_{ETC}$$

- $$\langle \bar{T}T \rangle_{ETC} = \langle \bar{T}T \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

$\sim \underline{\underline{4\pi F_T^3}}$

- $$\gamma_m(\mu) = \frac{3 C_2(N_{TC})\, \alpha_{TC}(\mu)}{2\pi} + \cdots$$

→ Estimate M_{ETC} for $m_q = 1\,\mathrm{GeV}$ (N technidoublets).
ASSUME TC is QCD-like — precociously asymptotically free with α_{TC} decreasing rapidly above Λ_{TC}:

$$\Rightarrow \Lambda_{ETC} \equiv \frac{M_{ETC}}{g_{ETC}} \simeq \sqrt{\frac{4\pi F_\pi^3}{2m_q N^{3/2}}} \simeq \frac{10\,\mathrm{TeV}}{N^{3/4}}$$

→ ETC contribution to π_T mass:

$$F_T^2 M_{\pi_T}^2 \simeq m_T(M_{ETC})\,\langle \bar{T}T\rangle_{ETC}$$

$$\Longrightarrow M_{\pi_T} \simeq \frac{55\,\mathrm{GeV}}{N^{1/4}} \qquad (\text{for } M_T(M_{ETC}) = 1\,\mathrm{GeV})$$

ALL contributions to M_{π_T} add in quadrature.

→ Comment on ETC scales: Hierarchy? Tumbling?

→ Comment on $m_t > 100\,\mathrm{GeV} \Rightarrow$ (?) $\Lambda_{ETC} \sim 1\,\mathrm{TeV} \sim \Lambda_{TC}$

→ What breaks ETC?
Is it turtles all the way down? ?

IV. SHOW–STOPPERS !

→ FLAVOR CHANGING NEUTRAL CURRENTS

- Generic ETC models with *realistic* m_q-matrices have FCNC involving *mass eigenstate* q and/or ℓ:

$$[q^\dagger T\,,\, T^\dagger q'] = q^\dagger q' \Longrightarrow \frac{g_{ETC}^2\, V_{sd}^2}{M_{ETC}^2}\; \bar{s}\Gamma^\mu d\; \bar{s}\Gamma'_\mu d + \cdots$$

NO satisfactory GIM mechanism eliminates these FCNC.

- $|\Delta S| = 2$ FCNC $\Longrightarrow$ most stringent constraints on ETC:

$$\Delta M_{K^0} = 3.5 \times 10^{-18}\,\text{TeV} \;\Longrightarrow\; \frac{M_{ETC}}{g_{ETC}\sqrt{\text{Re}(V_{sd}^2)}} \gtrsim \underline{600\,\text{TeV}}$$

$$|\epsilon| = 2.3 \times 10^{-3} \;\Longrightarrow\; \frac{M_{ETC}}{g_{ETC}\sqrt{\text{Im}(V_{sd}^2)}} \gtrsim \underline{2000\,\text{TeV}}$$

Scaling condensates from QCD (for $\gamma_m \ll 1$)

$$\Longrightarrow\; m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T\rangle_{ETC} \lesssim \frac{0.25\,\text{MeV}}{|V_{sd}|^2 N^{3/2}}$$

$$\Longrightarrow\; M_{\pi_T} \simeq \sqrt{\frac{g_{ETC}^2}{2M_{ETC}^2}\frac{\langle \bar{T}T\rangle_{ETC}^2}{F_T^2}} \lesssim \frac{1.0\,\text{GeV}}{|V_{sd}|\, N}$$

→ PRECISION ELECTROWEAK TESTS

- *"Oblique" correction factor S* —

  ASSUMING all new physics scales such as $\Lambda_{TC} \gg M_{W,Z}$:

$$S = 16\pi \frac{d}{dq^2}\left[\Pi_{33}(q^2) - \Pi_{3Q}(q^2)\right]_{q^2=0} \equiv 16\pi\left[\Pi'_{33}(0) - \Pi'_{3Q}(0)\right]$$

Experimental limit (PDG):

$S = -0.07\,(-0.16) \pm 0.11$ for $M_H = 100\,(300)$ GeV.

- *ESTIMATES OF TC CONTRIBUTIONS TO S*

  ASSUME TC is QCD-like:

  → Spectrum of hadrons scaled from QCD.

  → Precocious asympototic freedom

  ⇒ rapid convergence of spectral function integrals.

  → Vector-meson dominance (VMD) of spectral functions.

  → Chiral perturbation theory accurate for technipions.

- *Peskin & Takeuchi, e.g.:* Use QCD as analog computer—
  VMD, spectral function sum rules:

$$S = 4\pi\left(1 + \frac{M^2_{\rho_T}}{M^2_{a_{1T}}}\right)\frac{F^2_T}{M^2_{\rho_T}} \simeq 0.25\,\frac{N_{TC}}{3}$$

$\longrightarrow$ **TOP QUARK MASS**

- $m_t \simeq 175\,\mathrm{GeV} \Longrightarrow M_{ETC} \simeq 1/N^{3/4}\,\mathrm{TeV} = \mathcal{O}(m_t)$!!
  (Note: FCNC on 3rd generation <u>are</u> less constraining.)

$\Rightarrow$ *Or* — <u>*unnatural*</u> fine–tuning of α_{ETC} to $\mathcal{O}(m_t/M_{ETC})$.

- $m_t \gg m_b \Longrightarrow$ <u>*large*</u> weak isospin breaking:

$\Rightarrow$ Trouble with $\rho = M_W/M_Z \cos\theta_W = 1$, $Z^0 \to \bar{b}b$, etc.

V. SHOW–SAVERS

⟶ WALKING TECHNICOLOR

- *THE BASIC IDEA*

The KEY Equations of ETC — Again:

$$m_q,\, m_\ell,\, m_T(M_{ETC}) \simeq \frac{g^2_{ETC}}{2M^2_{ETC}} \langle \bar{T}T \rangle_{ETC}$$

$$\langle \bar{T}T \rangle_{ETC} = \langle \bar{T}T \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\, \gamma_m(\mu) \right)$$

If TC = scaled–up QCD,

$$\gamma_m(\mu) \approx 3C_2(R)\alpha_{TC}(\mu)/2\pi \ll 1$$

$$\Longrightarrow \langle \bar{T}T \rangle_{ETC} \approx \langle \bar{T}T \rangle_{TC}$$

CAN γ_m BE LARGE — ENHANCING $\langle \bar{T}T \rangle_{ETC} / \langle \bar{T}T \rangle_{TC}$?

YES!

- Suppose $\alpha_{TC}(\mu) \simeq$ constant (strictly speaking, $\ll 1$). Solution to the linearized gap equation for $\Sigma(p)$ in *ladder approximation* (Landau gauge)

$$\Sigma(p) = 3C_2(R) \int \frac{d^4k}{(2\pi)^4} \frac{\alpha_{TC}((k-p)^2)}{(k-p)^2} \frac{\Sigma(k)}{k^2}$$

gives the gauge-invariant result for γ_m:

$$\gamma_m(\mu) = 1 - \sqrt{1 - \alpha_{TC}(\mu)/\alpha_C}\,; \qquad \alpha_C = \pi/3C_2(R)$$

- Ladder approximation "*indicates*" χSB occurs *iff*

$$\alpha_{TC} \geq \alpha_C = \pi/3C_2(R)$$

At the χSB scale Λ_{TC},

$$\alpha_{TC}(\Lambda_{TC}) = \alpha_C$$
$$\gamma_m(\Lambda_{TC}) = 1$$

<u>$\gamma_m = 1$ *is the signal for* χ*SB*</u> !

- To keep γ_m large ...

$$\beta(\alpha_{TC}(\mu)) \simeq 0 \text{ for } \mu > \Lambda_{TC}$$

$$\Longrightarrow \alpha_{TC}(\mu) \simeq \alpha_C \Longrightarrow \gamma_m(\mu) \simeq 1$$

HOW?

One simple way is $N \gg 1$

$\Longrightarrow F_T \ll F_\pi$, $\Lambda_{TC} \ll 1\,\text{TeV}$ (say $F_T \sim \Lambda_{TC} \sim 100\,\text{GeV}$).

i.e., *Low–Scale Technicolor!!* — See below.

→ **TC is a WALKING gauge theory.** ←

$\Longrightarrow$ *CONSEQUENCES OF WALKING TECHNICOLOR*

- In extreme walking limit *(problematic!)*, $\gamma_m = 1$ up to M_{ETC}

$$\Longrightarrow \langle \bar{T}T \rangle_{ETC} \simeq \frac{M_{ETC}}{\Lambda_{TC}} \times \langle \bar{T}T \rangle_{TC}$$

$$\Longrightarrow m_{q,\ell}(M_{ETC}) \simeq \frac{4\pi\alpha_{ETC}\langle \bar{T}T \rangle_{TC}}{2M_{ETC}\Lambda_{TC}} \simeq \frac{8\pi^2 F_\pi^2 \alpha_{ETC}}{N M_{ETC}}$$

$$\Rightarrow M_{ETC} = (70\,\mathrm{TeV} - 4 \times 10^5\,\mathrm{TeV}) \times \left(\frac{10}{N}\frac{\alpha_{ETC}}{0.75}\frac{F_T}{\Lambda_{TC}}\right)$$

for $m_q = 5\,\mathrm{GeV} - 1\,\mathrm{MeV}$

$$\Longrightarrow M_{\pi_T} \simeq \underbrace{\sqrt{1.5\pi}\, 4\pi F_\pi}_{7(!!)\,\mathrm{TeV}} \left(\frac{F_T}{\Lambda_{TC}}\right) \sqrt{\frac{\alpha_{ETC}}{0.75N}}$$

...π_T *may NOT be pseudo-Goldstone bosons,*

i.e., chiral perturbation theory may break down in walking TC.

In any case, the M_{π_T} *are significantly enhanced!*

$\longrightarrow$ **S in walking technicolor**

- Spectral integrals in $\Pi(q^2)$–calculation of S converge much slower in a walking gauge theory than in QCD.

- Spectrum of ρ_T, a_{1T} very different from QCD $\Longrightarrow$ spectral integrals not dominated by lowest–lying resonances.

- How to justify scaling arguments from QCD? Large–N_{TC} arguments break down when N is also large.

$\Longrightarrow$ S *cannot* be *reliably* estimated without WTC data!!

$\longrightarrow$ **TOPCOLOR–ASSISTED TECHNICOLOR (TC2)**

- **Topcolor** = *STRONG* interaction at 1 TeV of third generation (especially quarks).

- *Dynamically* generate large m_t (and condensate $\langle \bar{t}t \rangle$), but *not* m_b—*HOW??*

$\Longrightarrow$ "Simplest" TC2 scheme $\cdots$

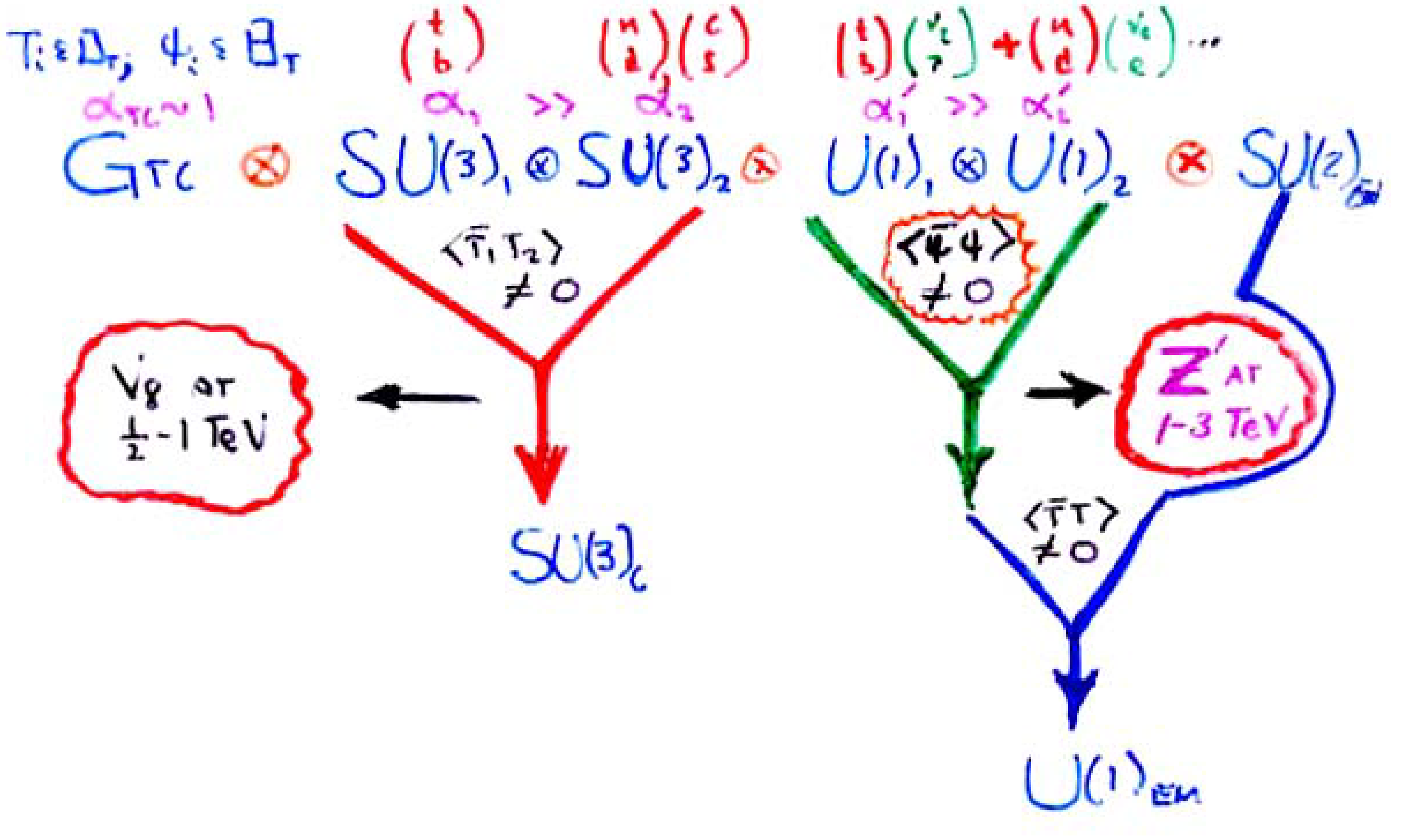
- $\langle \bar{t}t \rangle \neq 0$ produces 3 massless *top–pions* $\pi_t^{\pm,0}$ with $F_t \sim 70\,\mathrm{GeV} \ll F_\pi \Longrightarrow$ small breaking of $\rho = 1$.

- $m_t^{ETC} \simeq 5\,\mathrm{GeV}$ required to produce $M_{\pi_t} \gtrsim m_t$, preventing $t \to \pi_t^+ b$.

- Quark, lepton masses;
  mixing between generations 1,2 and 3;
  $\bar{B}_d^0$–B_d^0 mixing constraint; etc., etc.

$\Longrightarrow$ <u>$N \sim 10$ (!) T–doublets</u>

"Simplest" TC2 Scheme for $m_t \gg m_b$



Large m_t, but small m_b, because

- $SU(3)_1$ equally strong + attractive for t, b.
- $U(1)_1$ strong + attractive for t, repulsive for b.

PART 2—SIGNALS FOR TECHNICOLOR

I. LOW SCALE TECHNICOLOR!

- Walking TC ($\beta(\alpha_{TC}) \simeq 0$ from Λ_{TC} to $\sim M_{ETC}$)
  $\Longrightarrow N \gg 1$.

- TC2 phenomenology $\Longrightarrow N \gg 1$.

$\Longrightarrow$ *MANY* π_T, with decay constant $F_T = F_\pi/\sqrt{N} \lesssim 100\,\text{GeV}$
$M_{\pi_T} \sim 100\,\text{GeV}$ *and up*??

$\Longrightarrow$ $\Lambda_{TC} \sim F_T \ll 1\,\text{TeV}$, $\Longrightarrow$ *MANY* ρ_T, ω_T
$M_{\rho_T}, M_{\omega_T} \sim 200\,\text{GeV}$ *and up*!!

$\Longrightarrow$ **TC is accessible at the Tevatron!**

...maybe LEP...certainly at the LHC!

II. TECHNICOLOR STRAW–MAN MODEL

(Color Singlet Sector)

- **WTC** $\Longrightarrow M_{\rho_T}, M_{\omega_T} < 2M_{\pi_T}$

  $\Longrightarrow \rho_T \to \pi_T\pi_T,\ \omega_T \to \pi_T\pi_T\pi_T$ **CLOSED!**

  How do ρ_T, ω_T decay?

  Adopt the TCSM GROUND RULES:

- Lightest (T_U, T_D) are *color–singlets*.

- (T_U, T_D)–isospin breaking is small;
  charges are Q_U, $Q_D = Q_U - 1$.

- Consider bound states of lightest (T_U, T_D) *IN ISOLATION*:

  $\rho_T^{\pm,0}(I=1)$: $\quad \omega_T^0(I=0)$ with $M_{\rho_T} \cong M_{\omega_T}$

  $\Pi_T^{\pm,0}(I=1) = \pi_T^{\pm,0}\cos\chi + W_L^{\pm,0}\sin\chi$ with $\sin\chi = \dfrac{F_T}{F_\pi} \ll 1$

  $\Pi_T'^0(I=0) = \pi_T'^0\cos\chi' + \cdots$ with $\cos\chi' \simeq \cos\chi$??

  $W_L^{\pm,0}$ = isotriplet of longitudinal EW bosons.

- $\pi_T^+ \to c\bar{b}$ or $c\bar{s}$ or even $\tau^+\nu_\tau$
- $\pi_T^0 \to b\bar{b}$ and, perhaps $c\bar{c}$, $\tau^+\tau^-$
- $\pi_T^{0\prime} \to gg$, $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$
- π_T^0 and $\pi_T^{0\prime}$ may mix and share decay modes.

$\Longrightarrow$ Premium on heavy–flavor ID.

- **ρ_T and ω_T Decay Modes:**

  Consider technihadrons within Tevatron's (LEP's??) reach:

  $M_{\rho_T} \simeq M_{\omega_T} \sim 200$–$300\,\mathrm{GeV}$, $M_{\pi_T} \lesssim 200\,\mathrm{GeV}$.

- $\rho_T \to \Pi_T \Pi_T$ becomes

  $\rho_T \to \cos^2\chi\,(\pi_T\pi_T) + 2\sin\chi\,\cos\chi\,(W_L\pi_T) + \sin^2\chi\,(W_L W_L)$

  Competition between $\sin\chi (\sim 1/3?)$ and phase space — both suppress $\Gamma(\rho_T)$.

$\longrightarrow$ <u>*ALL*</u> $\omega_T \to \Pi_T\Pi_T\Pi_T$ modes are closed for $M_{\omega_T} \lesssim 250\,\mathrm{GeV}$!!

$\Longrightarrow$ <u>*Electroweak*</u> decay modes are <u>*competitive*</u>*!!*

$$\mathcal{O}(\alpha): \quad \rho_T, \omega_T \to G\pi_T \qquad (G = \text{transverse } \gamma, W^\pm, Z^0)$$

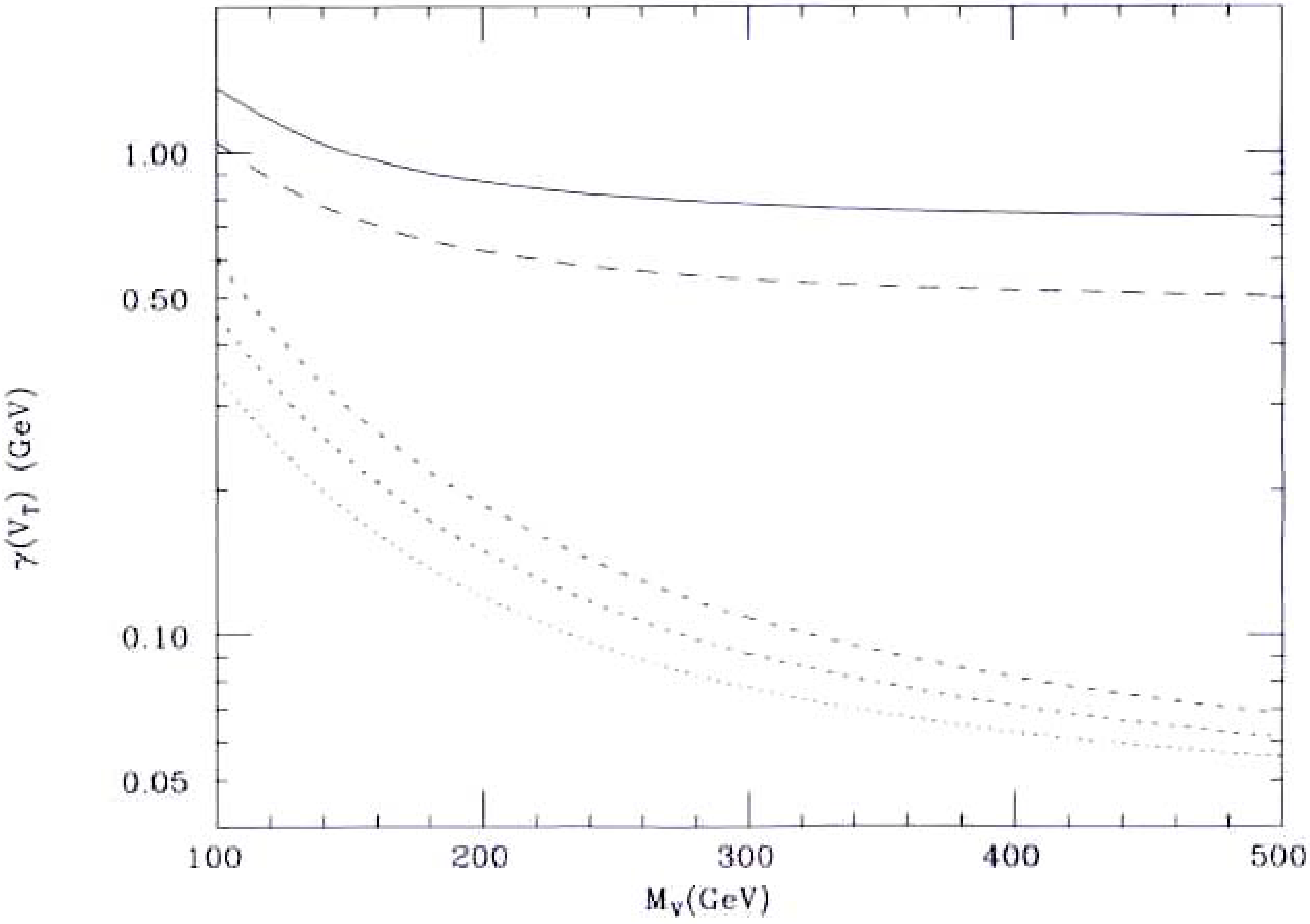
$$\mathcal{O}(\alpha^2): \quad \rho_T, \omega_T \to \bar{f} f' \qquad (f = \ell^\pm, \nu_\ell;\ q = u, d, s, c, b)$$

$\Longrightarrow$ ρ_T, ω_T are <u>**VERY NARROW**</u>

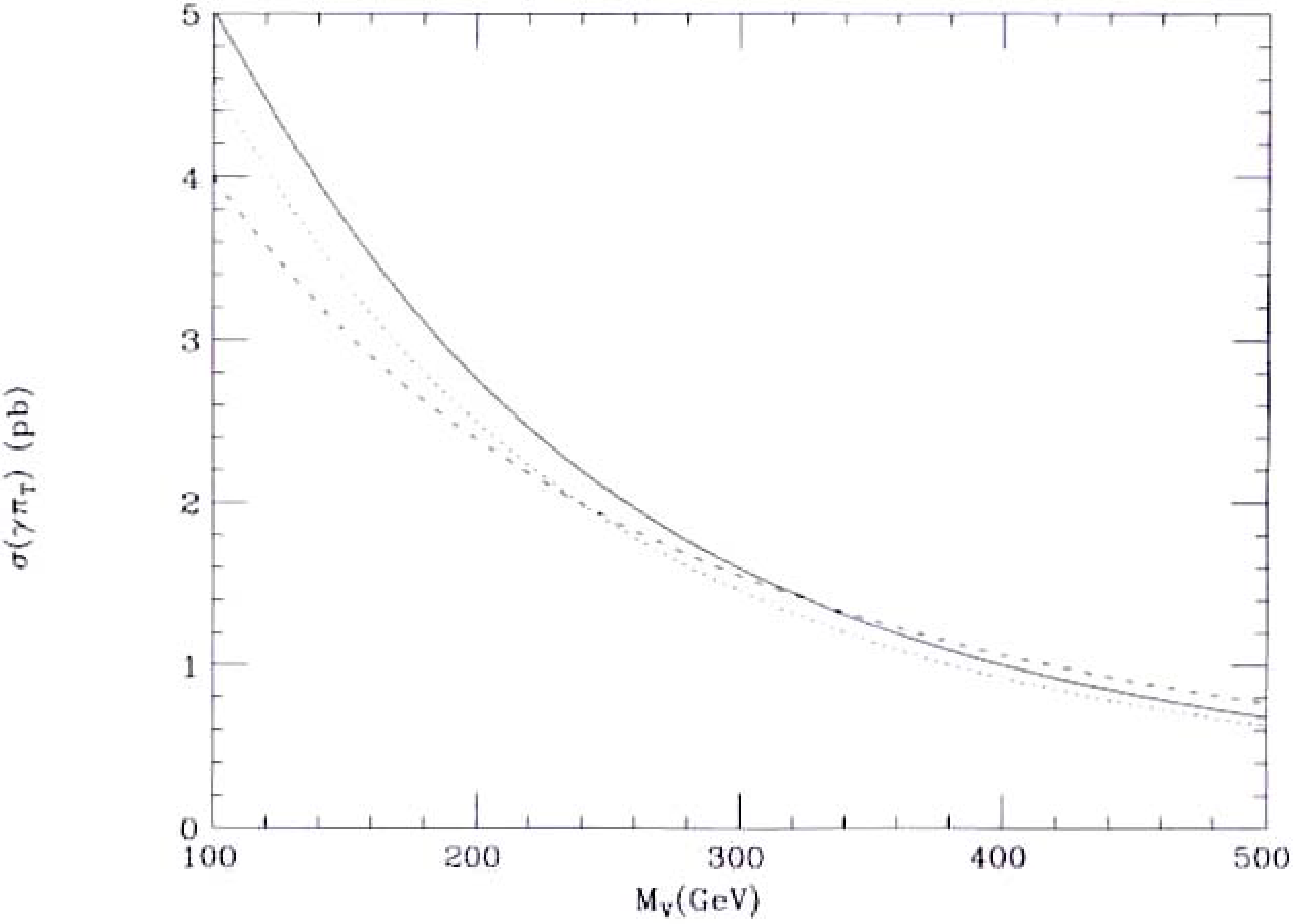
$$\Gamma(\rho_T) \sim 1\,\mathrm{GeV}, \quad \Gamma(\omega_T) \sim 0.1\,\mathrm{GeV}$$

V_T Decay Mode	$V(V_T \to G\pi_T) \times M_V/e$	$A(V_T \to G\pi_T) \times M_A/e$
$\omega_T \to \gamma\pi_T^0$	$\cos\chi$	0
$\to \gamma\pi_T^{0\prime}$	$(Q_U + Q_D)\,\cos\chi'$	0
$\to Z^0\pi_T^0$	$\cos\chi \cot 2\theta_W$	0
$\to Z^0\pi_T^{0\prime}$	$-(Q_U + Q_D)\,\cos\chi' \tan\theta_W$	0
$\to W^\pm\pi_T^\mp$	$\cos\chi/(2\sin\theta_W)$	0
$\rho_T^0 \to \gamma\pi_T^0$	$(Q_U + Q_D)\,\cos\chi$	0
$\to \gamma\pi_T^{0\prime}$	$\cos\chi'$	0
$\to Z^0\pi_T^0$	$-(Q_U + Q_D)\,\cos\chi \tan\theta_W$	0
$\to Z^0\pi_T^{0\prime}$	$\cos\chi'\ \cot 2\theta_W$	0
$\to W^\pm\pi_T^\mp$	0	$-\cos\chi/(2\sin\theta_W)$
$\rho_T^\pm \to \gamma\pi_T^\pm$	$(Q_U + Q_D)\,\cos\chi$	0
$\to Z^0\pi_T^\pm$	$-(Q_U + Q_D)\,\cos\chi \tan\theta_W$	$\cos\chi\,/\,\sin 2\theta_W$
$\to W^\pm\pi_T^0$	0	$\cos\chi/(2\sin\theta_W)$
$\to W^\pm\pi_T^{0\prime}$	$\cos\chi'/(2\sin\theta_W)$	0

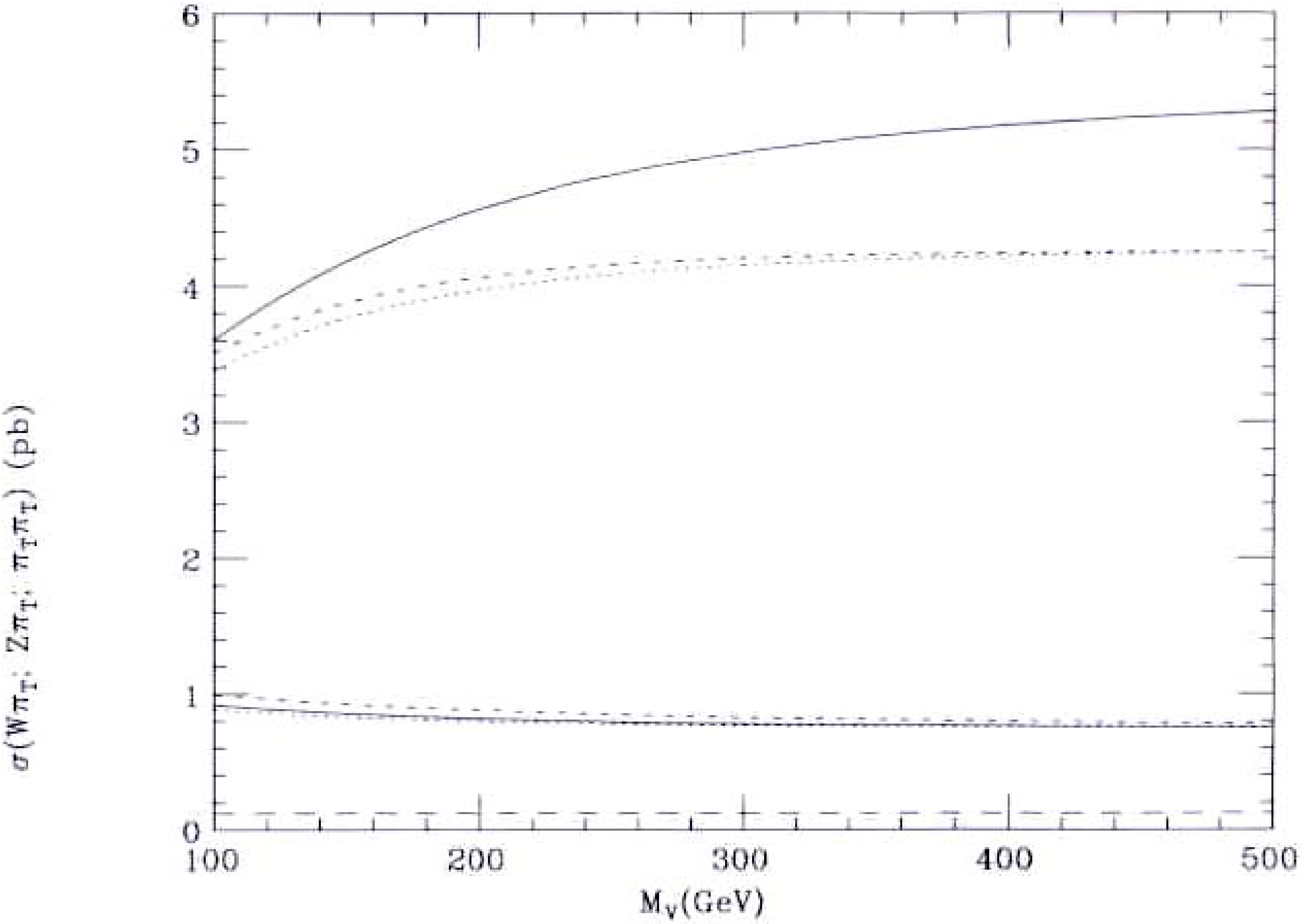
Relative vector and axial vector amplitudes for $V_T \to G\pi_T$ for $V_T = \rho_T, \omega_T$ and G a <u>*transverse*</u> electroweak boson, $\gamma, Z^0, W^\pm$. Decay rates are suppressed by $1/M_{V,A}^2$ where $M_{V,A} = \mathcal{O}(\Lambda_{TC})$ are TC mass parameters.



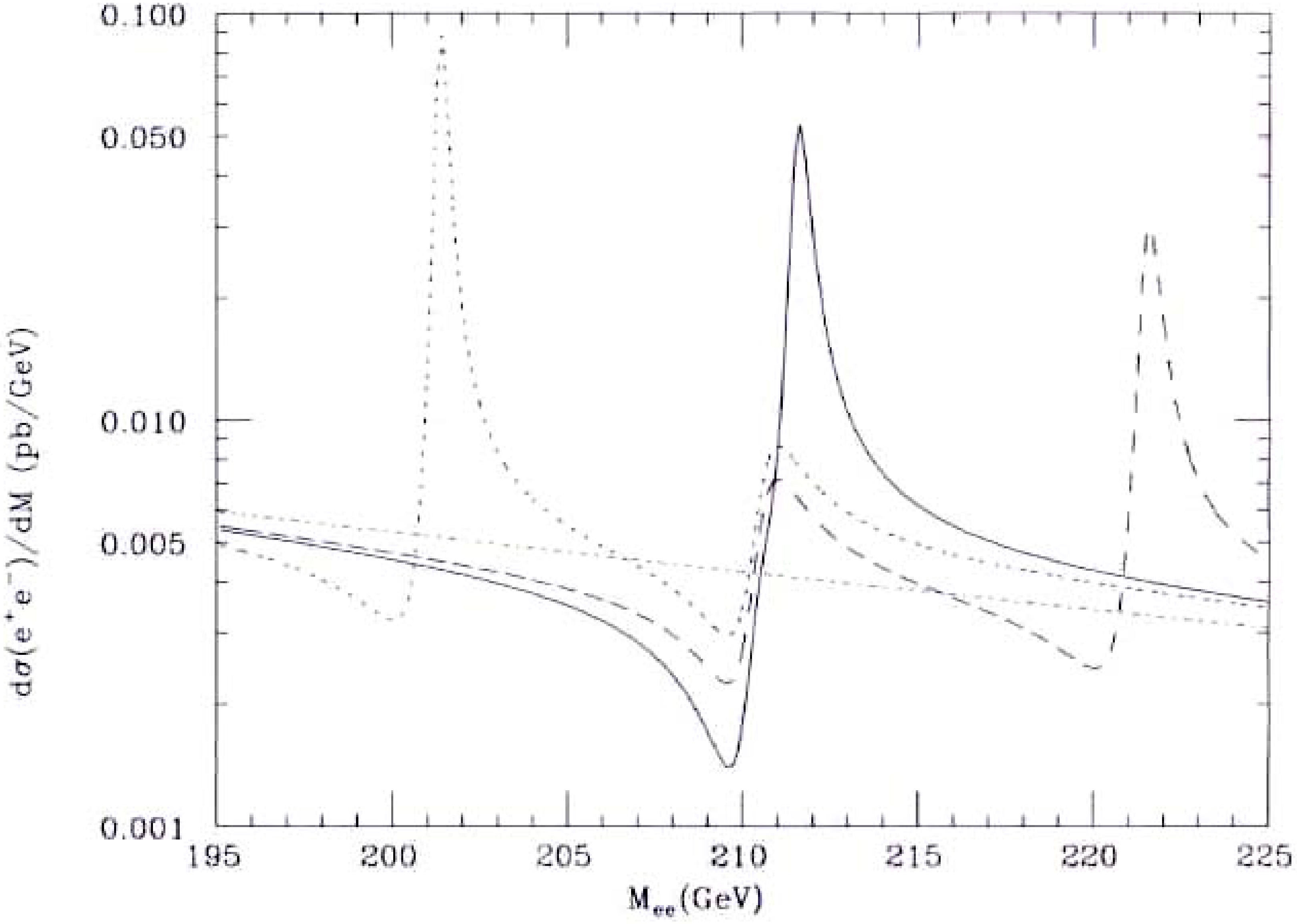
1.00
0.50
0.10
0.05
$\gamma(V_T)$ (GeV)
100
200
300
400
500
M_V(GeV)



5
4
3
2
1
0
100
200
300
400
500
$\sigma(\gamma\pi_T)$ (pb)
M_V(GeV)



$\sigma(W\pi_T;\ Z\pi_T;\ \pi_T\pi_T)$ (pb)
M_V(GeV)
0
1
2
3
4
5
6
100
200
300
400
500



0.100
0.050
0.010
0.005
0.001
195
200
205
210
215
220
225
M_{ee}(GeV)
$d\sigma(e^+e^-)/dM$ (pb/GeV)

Parameter	Default Value
N_{TC}	4
$\sin\chi$	$\frac{1}{3}$
$\sin\chi'$	$\frac{1}{3}$
Q_U	$\frac{4}{3}$
$Q_D = Q_U - 1$	$\frac{1}{3}$
C_b	1
C_c	1
C_τ	1
C_t	m_b/m_t
C_{π_T}	$\frac{4}{3}$
$\lvert\epsilon_{\rho\omega}\rvert$	0.05
$F_T = F_\pi \sin\chi$	82 GeV
$M_{\rho_T^\pm}$	210 GeV
$M_{\rho_T^0}$	210 GeV
M_{ω_T}	210 GeV
$M_{\pi_T^\pm}$	110 GeV
$M_{\pi_T^0}$	110 GeV
$M_{\pi_T^{0\prime}}$	110 GeV
M_V	200 GeV
M_A	200 GeV

Table 2: Default values for parameters in the Technicolor Straw Man Model.

III. TCSM PLOTS

1. $\Gamma(V_T)$ for default parameters and Tevatron Run II.
2. $\sigma(V_T \to \gamma\pi_T)$ for default parameters.
3. $\sigma(V_T \to W\pi_T,\ Z\pi_T,\ \pi_T\pi_T)$ for default parameters.
4. $\sigma(V_T \to e^+e^-)$ for default parameters.

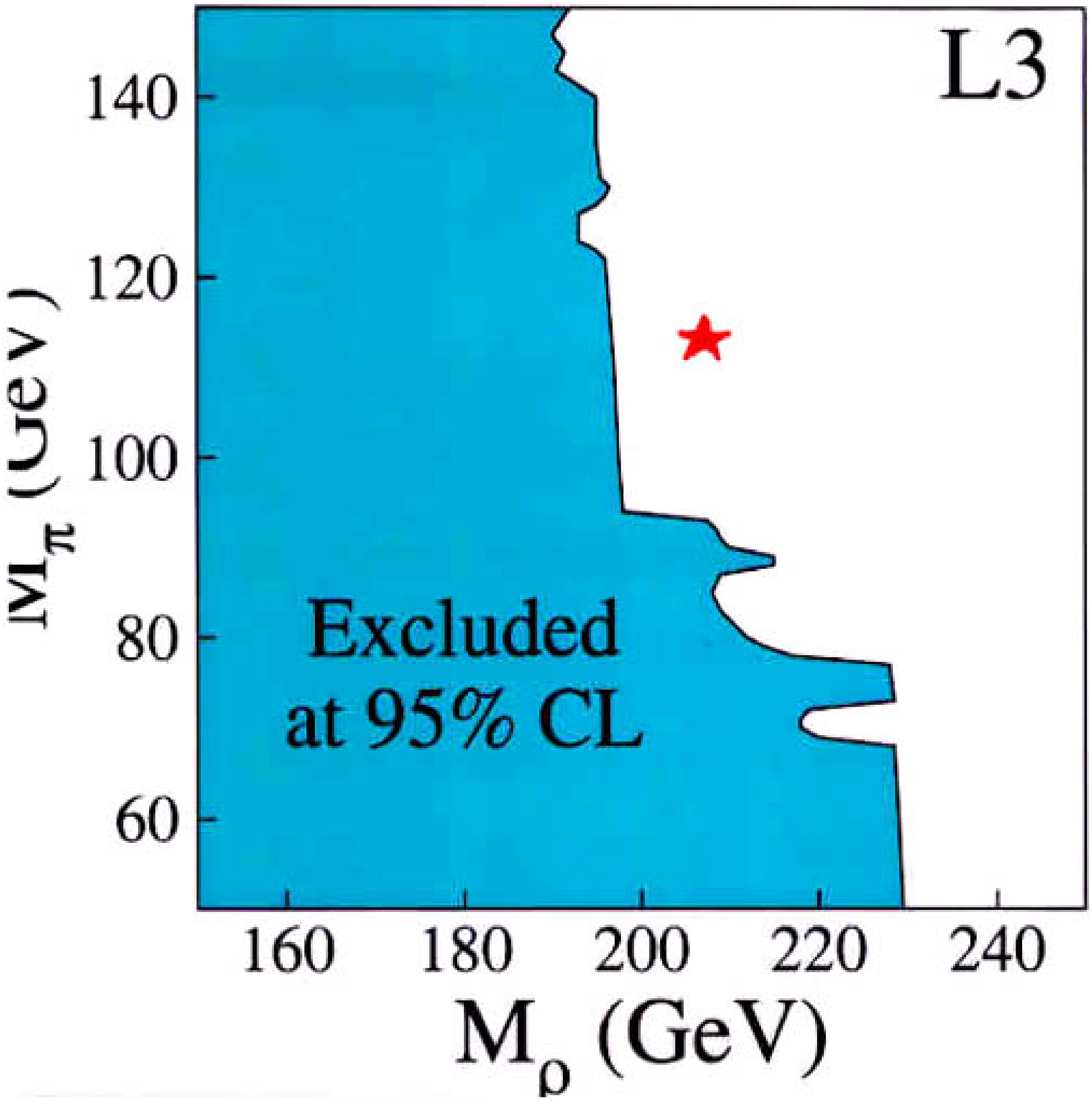
IV. EXPERIMENTAL SEARCH PLOTS

1. L3 exclusion plot (assumptions and critique).
2. DELPHI exclusion plot (assumptions and critique).
3. CDF $\rho_T \to W\pi_T \to \ell^\pm \nu_\ell b$ jet data.
4. CDF $\rho_T \to W\pi_T$ exclusion plot (assumptions).
5. CDF $\rho_T \to W\pi_T$ Run II exclusion plot (assumptions).
6. CDF $\rho_T, \omega_T \to \gamma\pi_T \to \gamma b$ jet data.
6. CDF $\rho_T, \omega_T \to \gamma\pi_T$ exclusion plot (assumptions).
8. DØ $\rho_T, \omega_T \to e^+e^-$ exclusion plot (assumptions).
9. DØ $\rho_T, \omega_T \to e^+e^-$ Run II exclusion plot.
10. ATLAS $\rho_T \to W\pi_T \to \ell^\pm \nu_\ell b$ jet "data" (assumptions).

V. COLOR–NONSINGLET TCSM

1. Searches to date: use existing transparency.
2. CDF $\rho_{T8} \to \pi_{\bar{L}Q}\pi_{\bar{Q}L} \to \tau^+\tau^- jj$ exclusion plot.
3. CDF $\rho_{T8} \to \pi_{\bar{L}Q}\pi_{\bar{Q}L} \to \tau^+\tau^- jj$ RUN II exclusion plot.
4. CDF $\rho_{T8} \to jj$ exclusion plot.
5. Technifermions $T_1 = (U_1, D_1)$ and $T_2 = (U_2, D_2)$.
6. Four ρ_{T8} and V_8 mix with g
7. Mrenna's plots for Run II (preliminary!

L3 NOTE 2428 / EPS-HEP 99



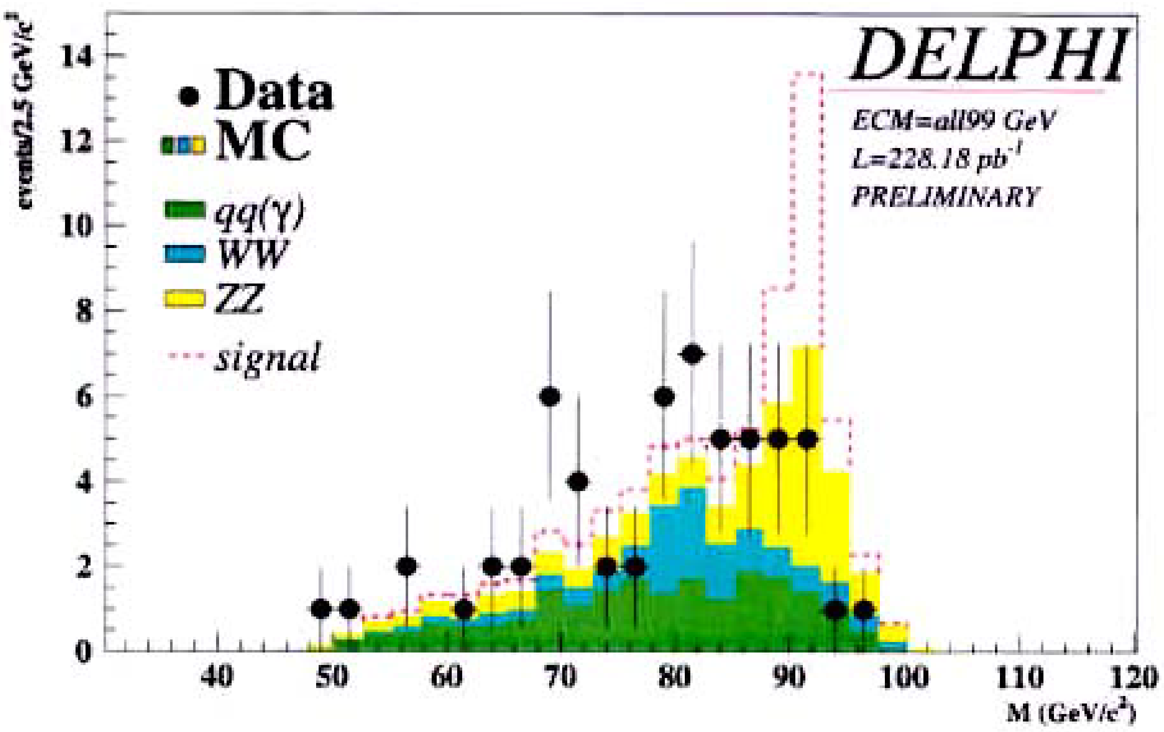


Figure 4: Mass distributions at the end of the analysis. Normalisation of the technicolor signal with $M_{\pi_T} = 89$ GeV/c^2 (dashed histogram) is arbitrary.

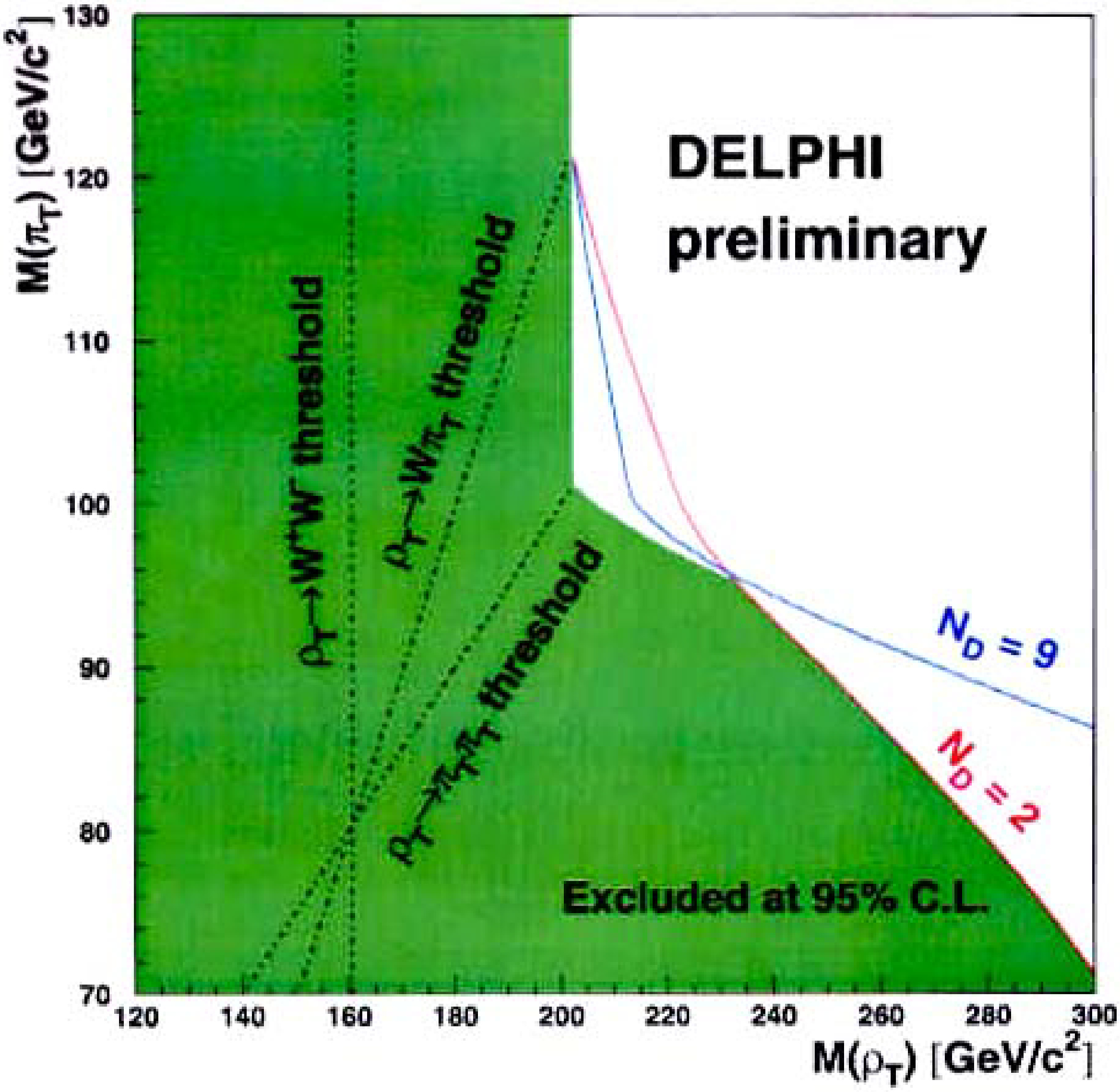
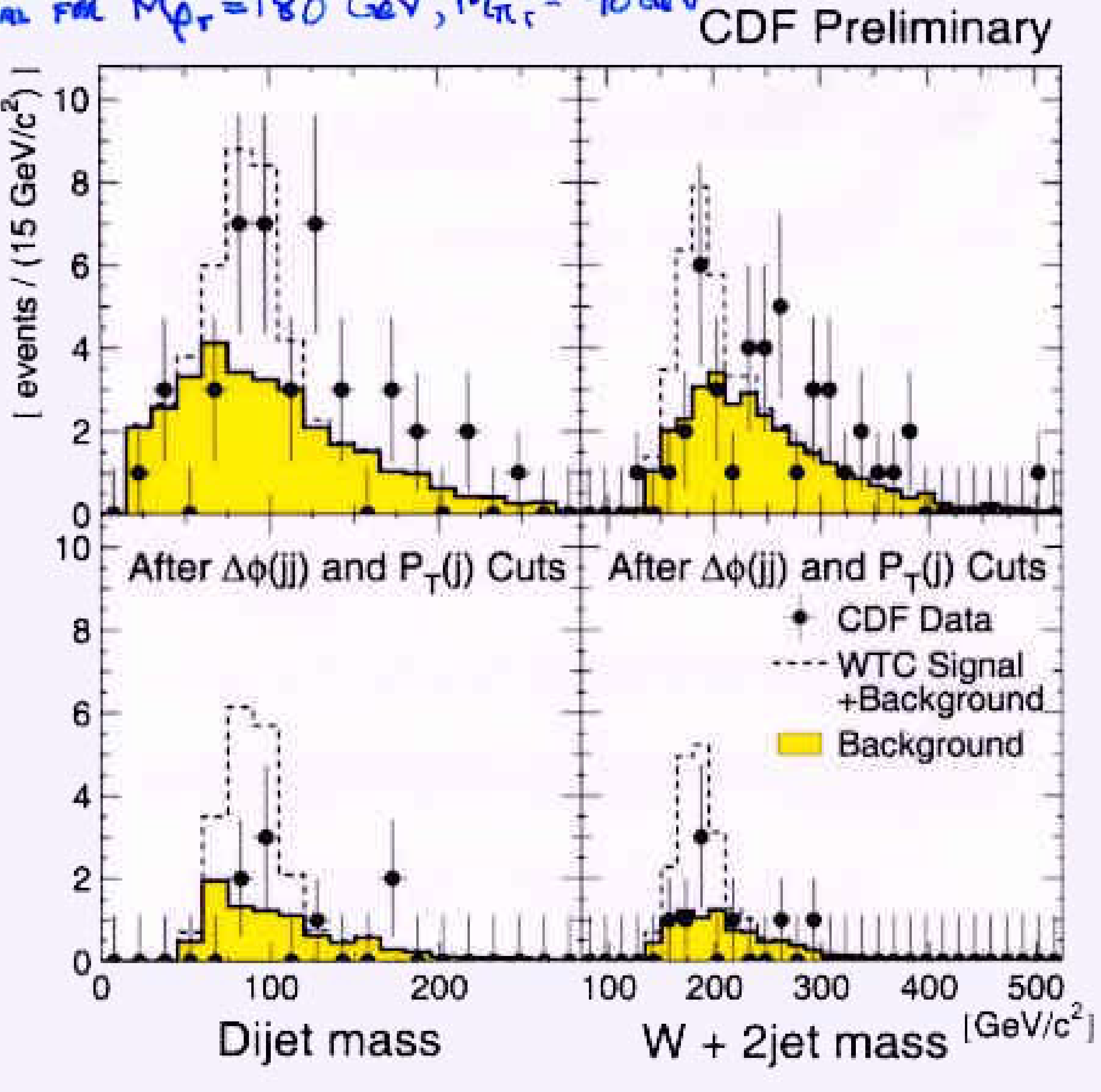


Figure 5: The region in $(M_{\rho_T} - M_{\pi_T})$ plane (filled area) excluded at 95% C.L. for any value of W_L - π_T mixing.

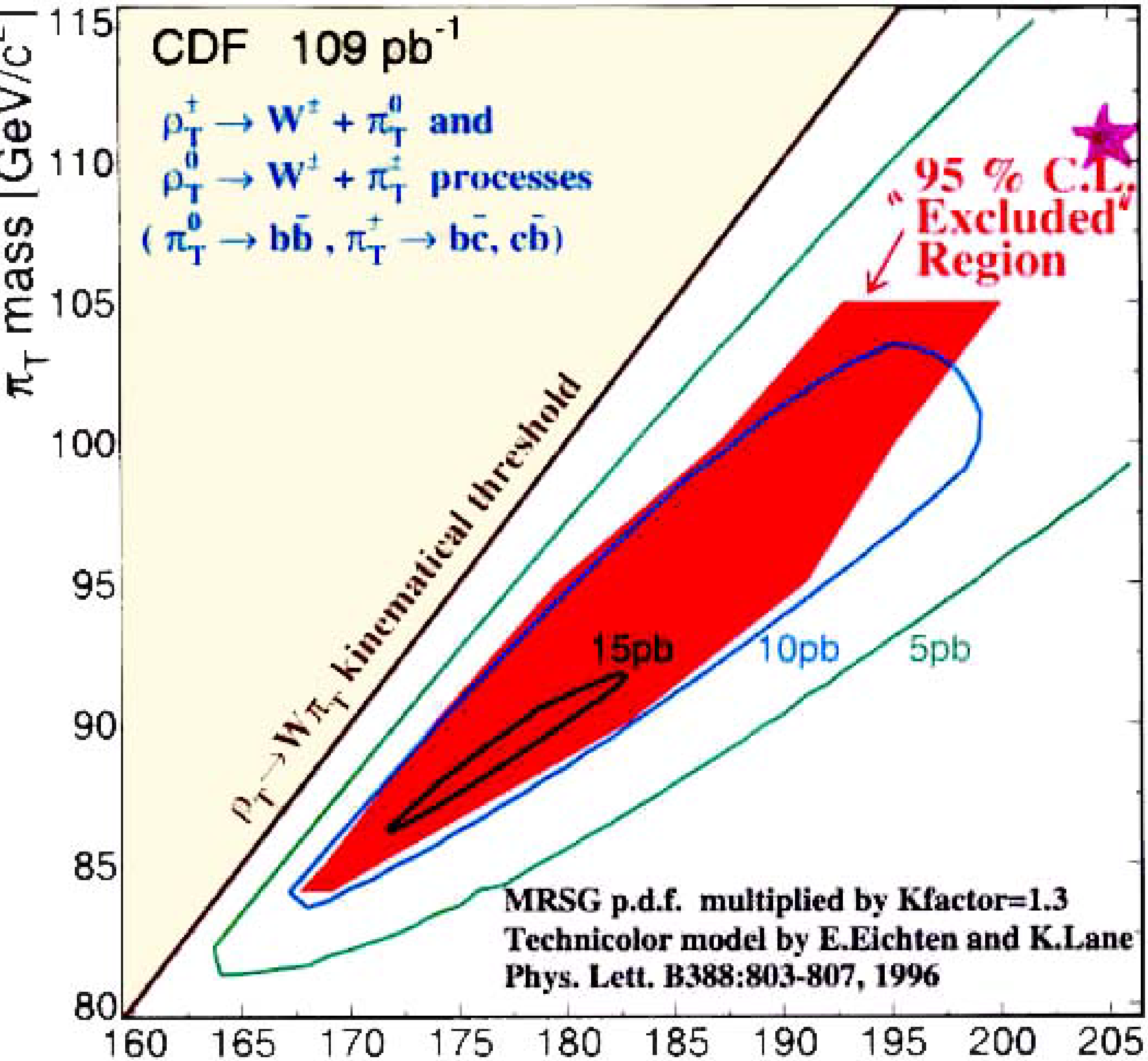
CDF SEARCH FOR $\rho_T \rightarrow W_T^{\pm} \pi_T \rightarrow \ell^{\pm} \nu_\ell b j$

PRL 84, 1110 (2000)

"WTC Signal" for $M_{\rho_T} = 180$ GeV, $M_{\pi_T} = 90$ GeV



PRL 84, 1110 (2000)



Technicolor RUN2 Prospects   Mar. 14, 2000 Takanobu Handa
Apr. 20, 2000 Revised for PYTHIAv6.139

The result is from PYTHIAv6.115 for RUN1.
PYTHIAv6.139 for RUN2.

N_TC = 4
Q_U Q_D+1 = 1(for RUN1), 4/3(for RUN2)
M_V=M_A= 100,200,400GeV(three plots)
Sin\chi = 1/3

Analysis mode:
Wpi0 -> lepton + neutrino + bbbar and
Wpi+- -> lepton + neutrino + bcbar

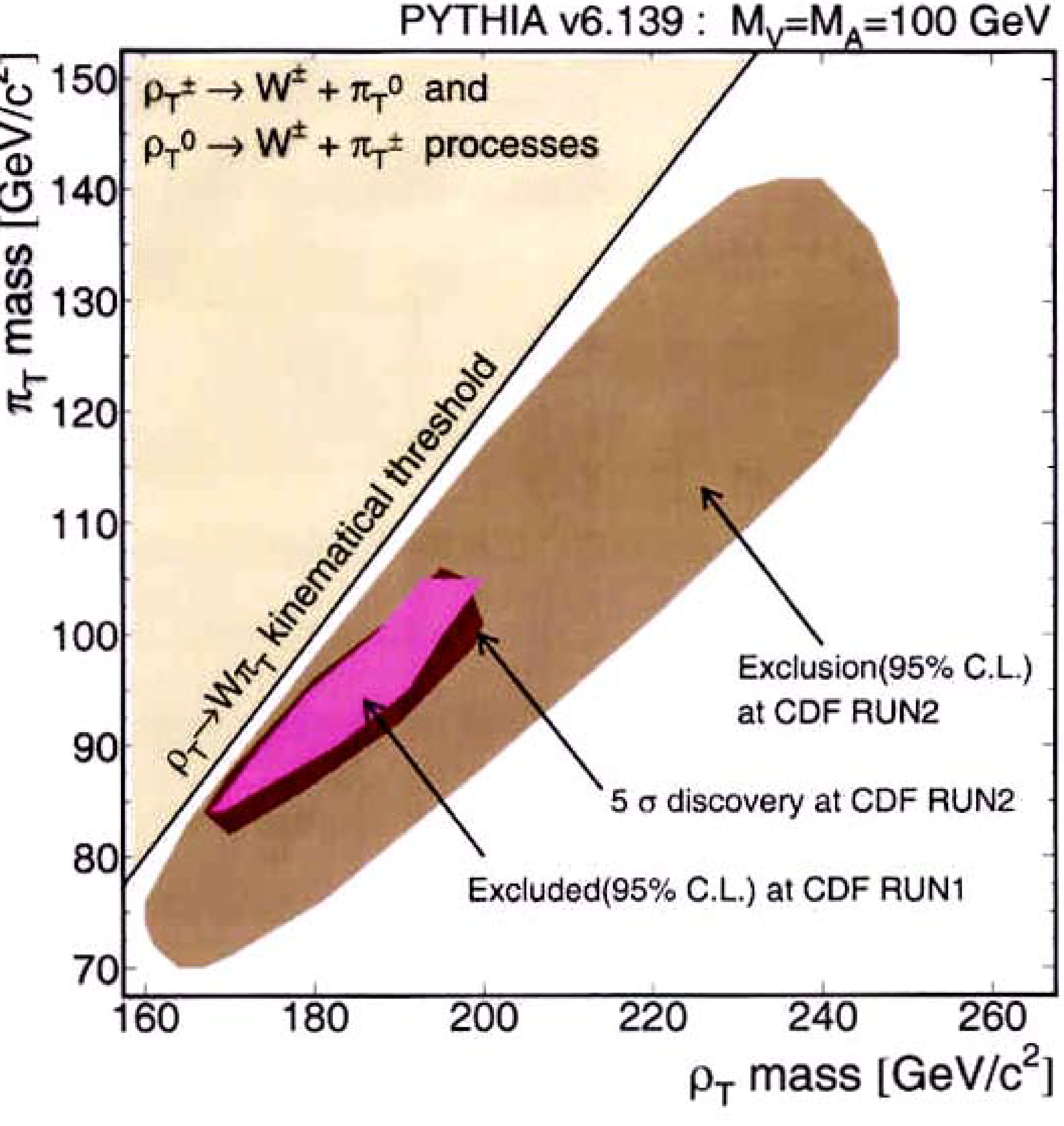
Major selection requirements:[Same method as our published PRL]
* High Pt lepton (e or mu) E_T > 20 GeV
* Missing Transverse Energy > 20 GeV
* At least two jets E_T > 15 GeV
* At least one secondary vertex b-tag
* Two jets Topology cuts (delta phi, Pt(jj system)), depending on the masses.
* Mass window cuts (+- 3 sigma on M(jj) and M(Wjj)).

RUN2 Assumptions :
TC signal efficiency is twice compared to Run1.
(from improved lepton ID and b-tag efficiency)
Background efficiency is also twice. (conservative estimation).
Efficiency is same for any mass combination.
sqrt(s) = 1.8TeV -> 2.0TeV

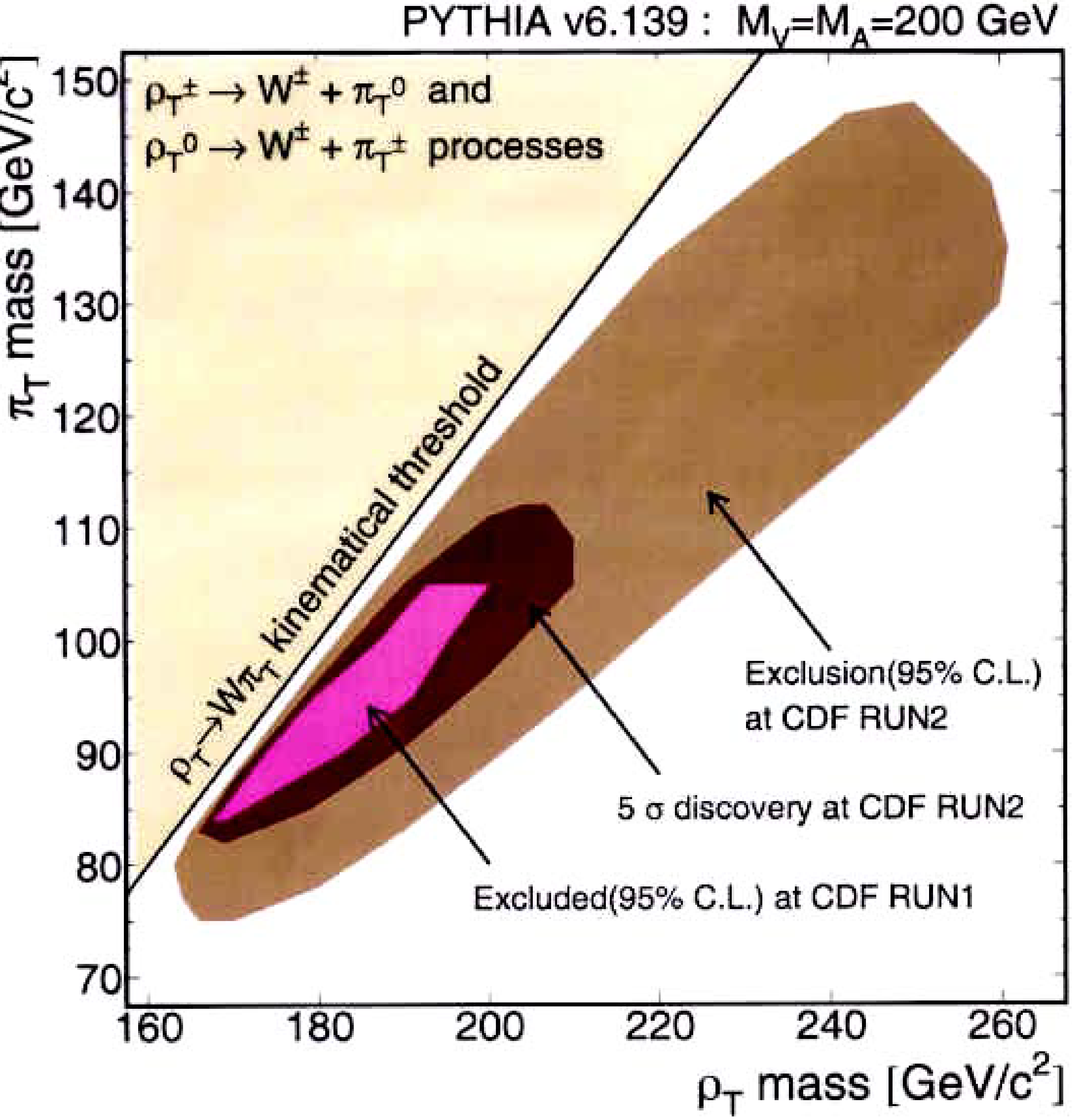
		[RUN1 result]	[RUN2 prospect]
PYTHIA version	:	v6.115	v6.139
sqrt(s)	:	1.8TeV	2.0TeV
Integrated Luminosity	:	109 pb-1	2 fb-1
Signal Efficiency	:	0.69%	1.38%
Expected number of Background	:	5.7 +- 0.8	209 +- 29
Systematic uncertainty	:	26%	26%

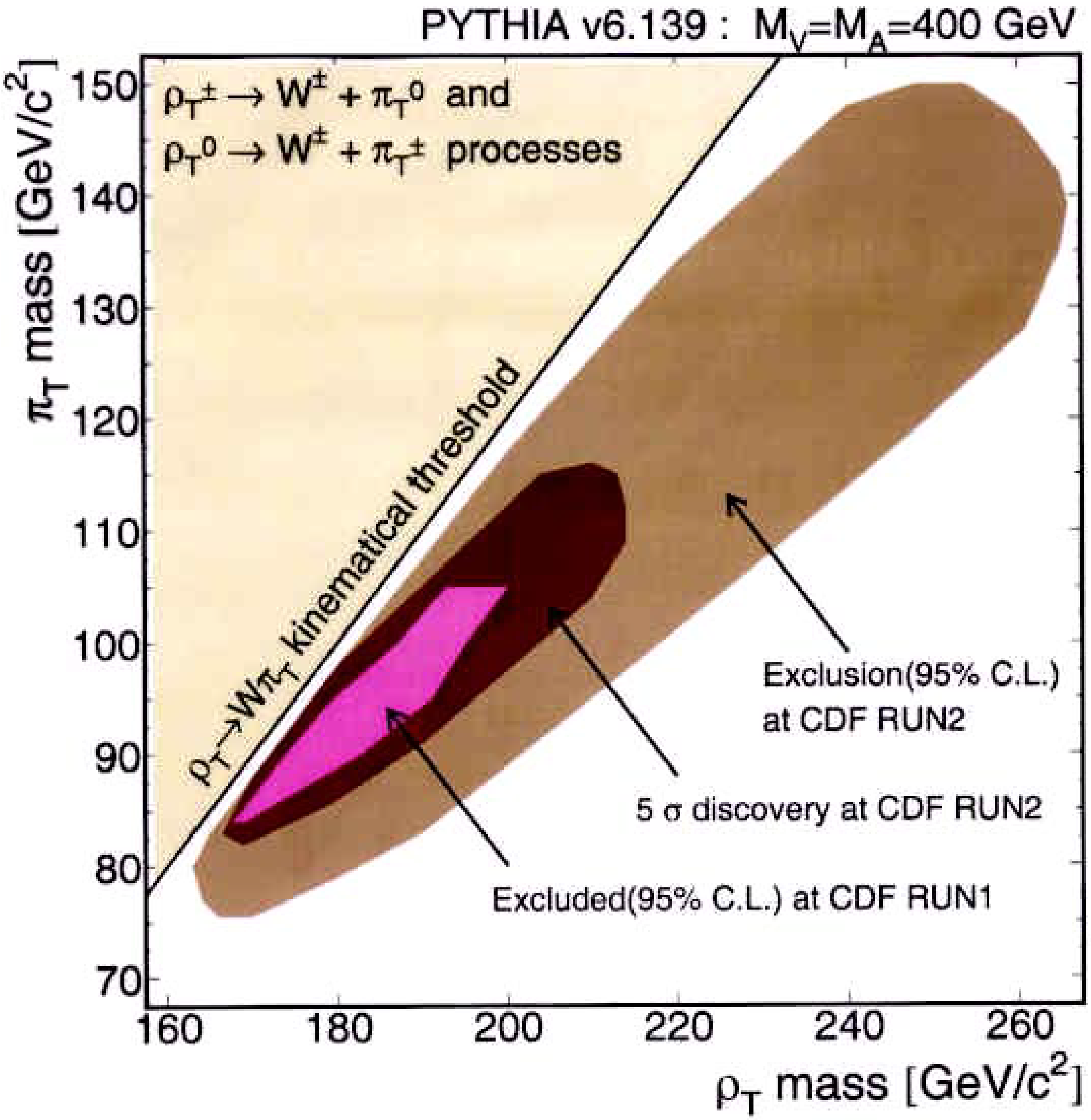
--- Statistical Calculation Results ---		[RUN1]	[RUN2]
#events (95% C.L. upper limit if the data is same number of the background expected)	:	8.0	76
		[sigma(pp-->rho_T->W+pi_T)*BR(pi_T->bb,bc)]	
Cross section upper limit	:	11 pb (90,180GeV)	2.8 pb
5 sigma discovery	:	28 pb	7.0 pb

Comment: I think a double b-tag method would improve the
signal to background ratio.



PYTHIA v6.139 : M_V=M_A=100 GeV
$\rho_T^\pm \to W^\pm + \pi_T^0$ and
$\rho_T^0 \to W^\pm + \pi_T^\pm$ processes
$\rho_T \to W\pi_T$ kinematical threshold
Exclusion(95% C.L.)
at CDF RUN2
5 σ discovery at CDF RUN2
Excluded(95% C.L.) at CDF RUN1
π_T mass [GeV/c^2]
ρ_T mass [GeV/c^2]
150
140
130
120
110
100
90
80
70
160
180
200
220
240
260

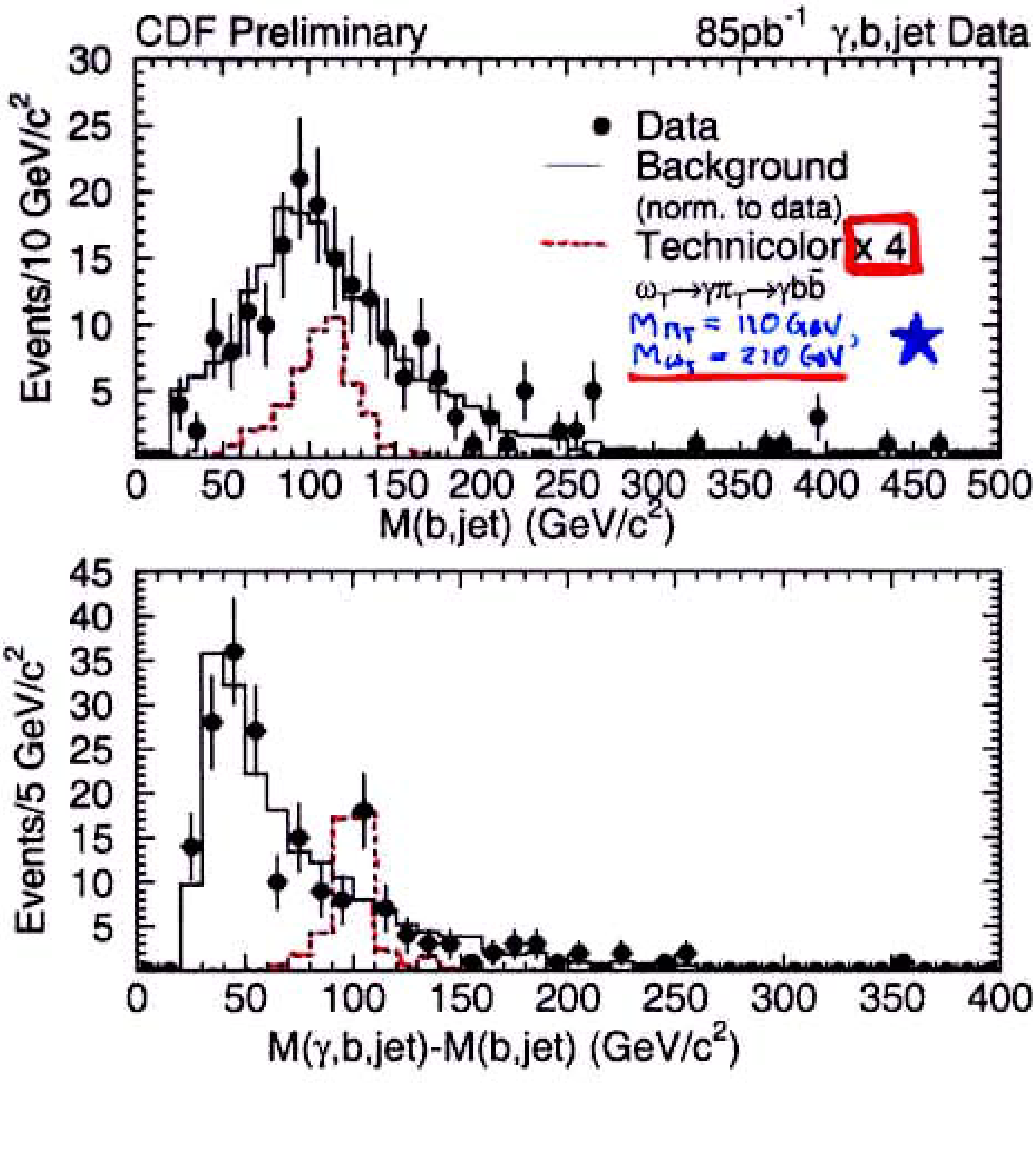

PYTHIA v6.139 : M_V=M_A=200 GeV
$\rho_T^\pm \to W^\pm + \pi_T^0$ and
$\rho_T^0 \to W^\pm + \pi_T^\pm$ processes
$\rho_T \to W\pi_T$ kinematical threshold
Exclusion(95% C.L.)
at CDF RUN2
5 σ discovery at CDF RUN2
Excluded(95% C.L.) at CDF RUN1
π_T mass [GeV/c^2]
150
140
130
120
110
100
90
80
70
160
180
200
220
240
260
ρ_T mass [GeV/c^2]



PYTHIA v6.139 : M_V=M_A=400 GeV
ρ_T^± → W^± + π_T^0 and
ρ_T^0 → W^± + π_T^± processes
ρ_T → Wπ_T kinematical threshold
Exclusion(95% C.L.)
at CDF RUN2
5 σ discovery at CDF RUN2
Excluded(95% C.L.) at CDF RUN1
π_T mass [GeV/c^2]
ρ_T mass [GeV/c^2]
150
140
130
120
110
100
90
80
70
160
180
200
220
240
260

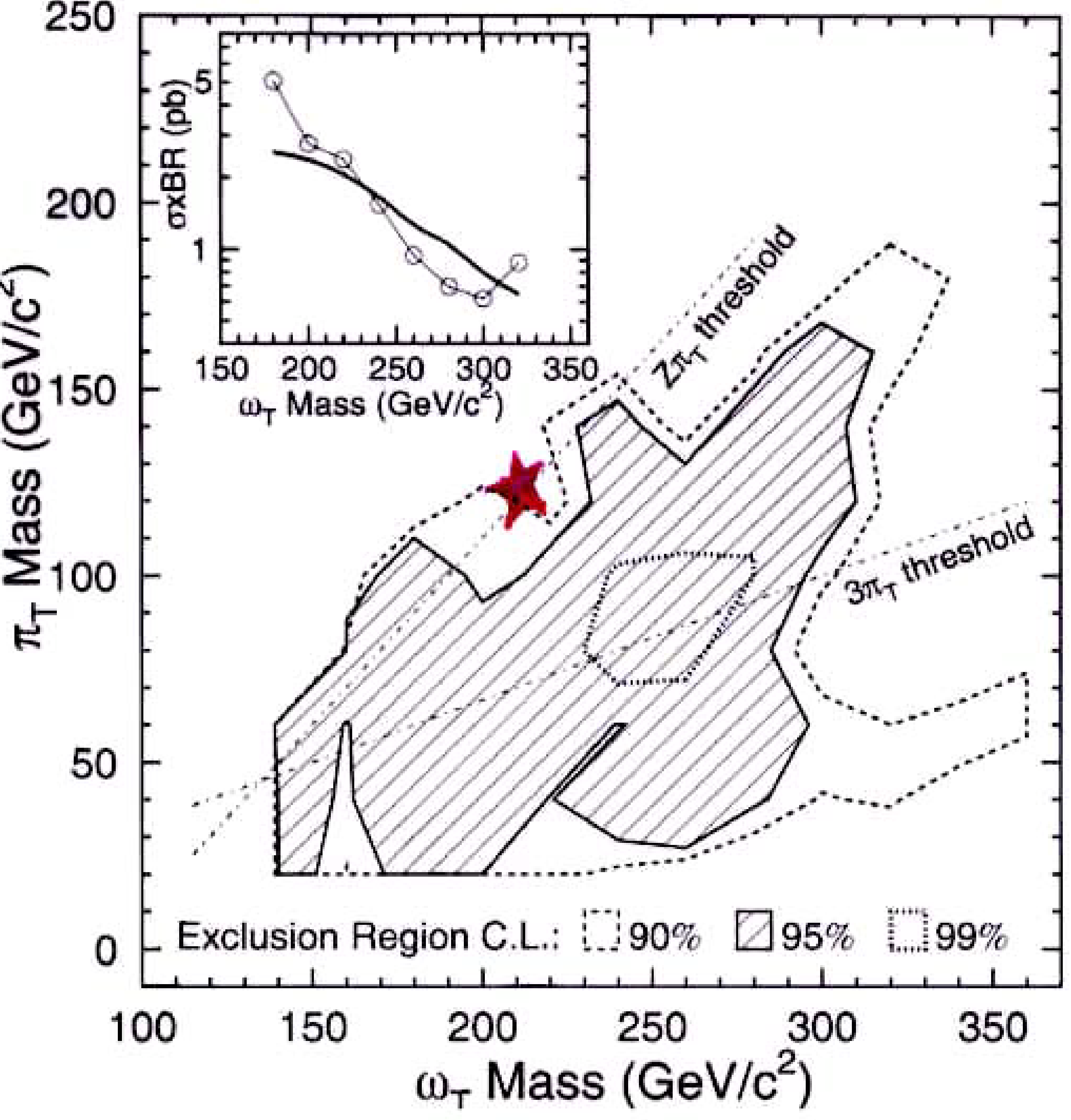
CDF – PRL 83, 3124 (1999)

Technicolor: $\omega_T \to \gamma\pi_T \to \gamma b\bar{b}$



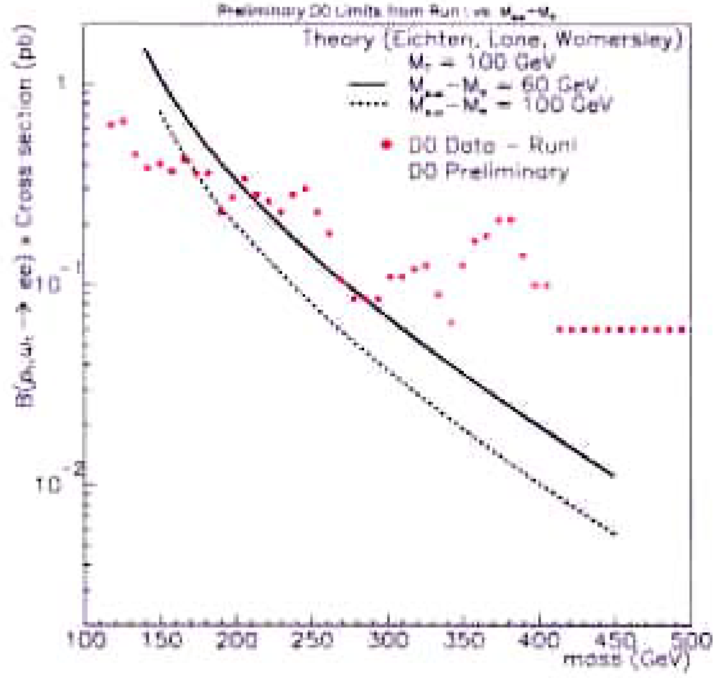
11

CDF – PRL 83, 3124 (1999)

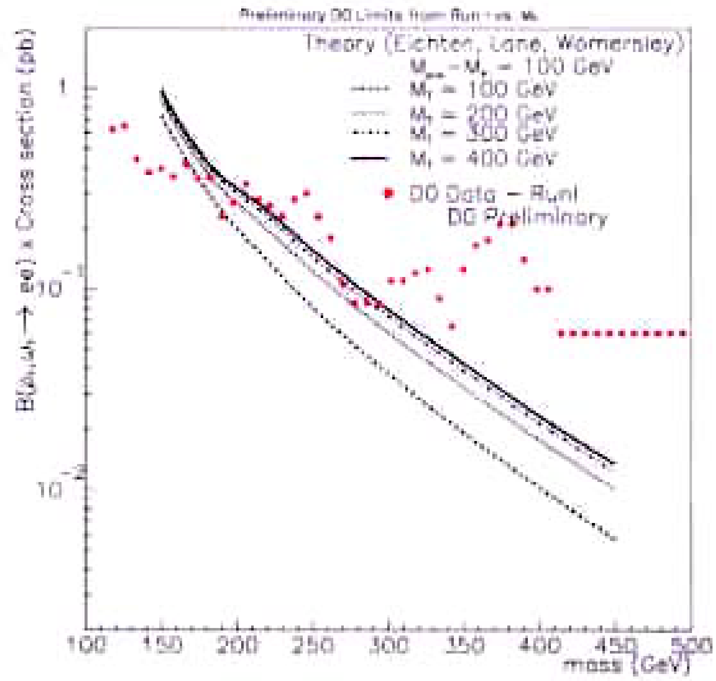


Limits on Cross Section for $\rho_T, \omega_T \to e^+e^-$

DØ Preliminary

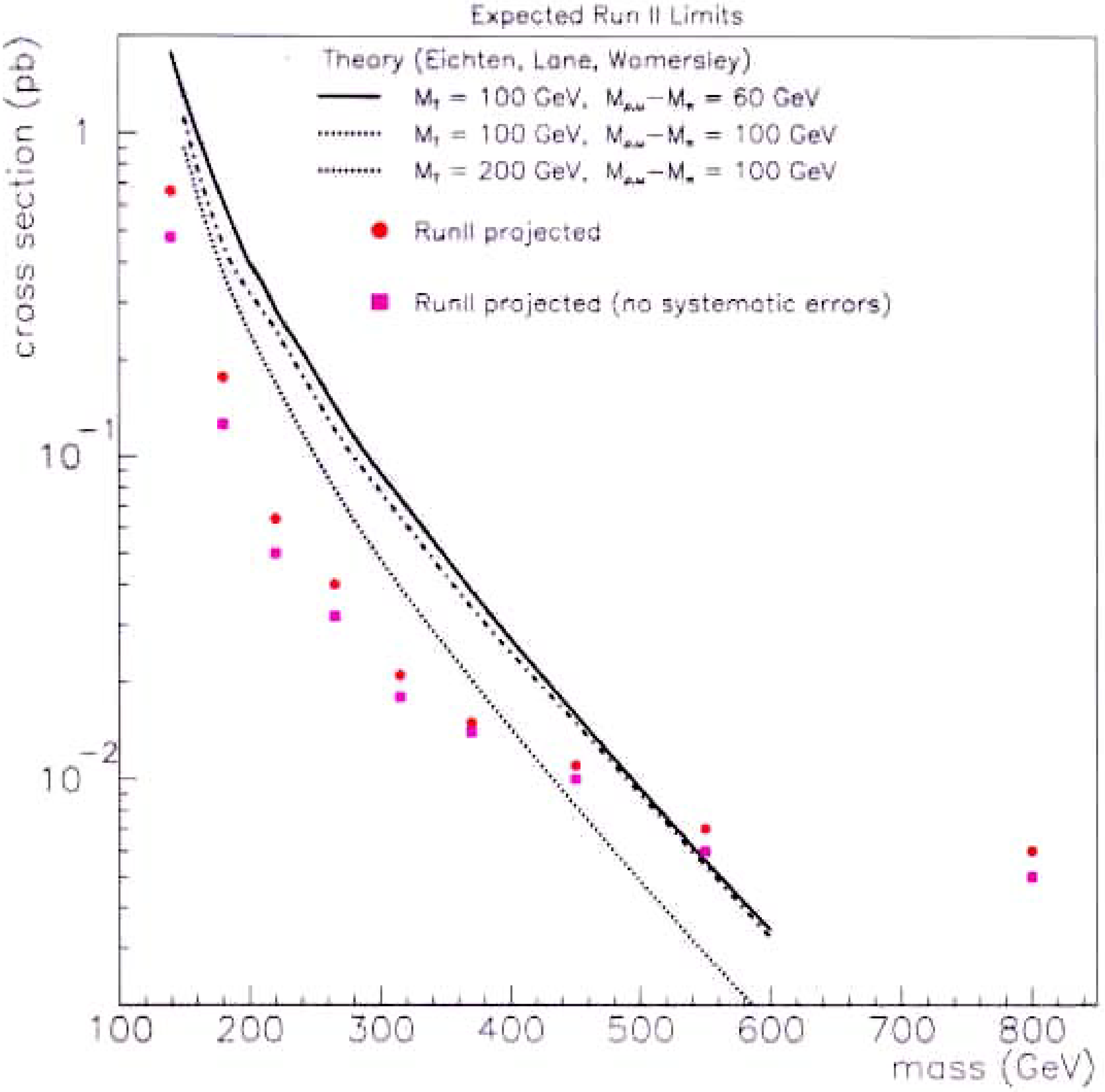


Rule out ρ_T, ω_T with masses below 200 GeV,
IF $M(\rho_T, \omega_T) - M(\pi_T) < M(W)$



Rule out ρ_T, ω_T with masses below 200 GeV,
IF $M_{V/A} > 200$ GeV

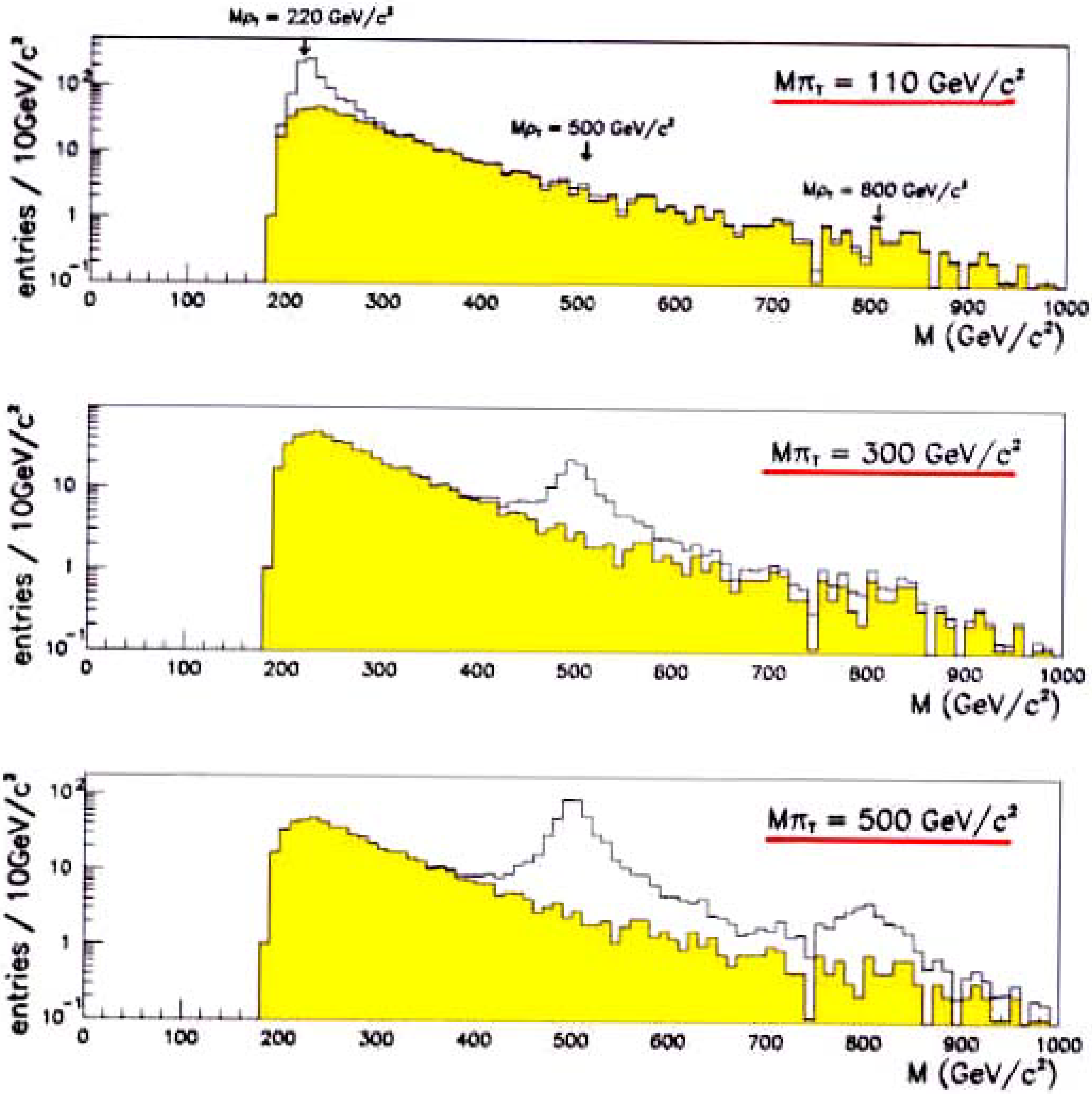
DØ - Sensitivity for RunII



ATLAS @LHC (DETECTOR & PHYSICS TDR)

SEARCH FOR TCSM

$$\rho_T \to W^{\pm}\pi_T \to \ell^{\pm}\nu b j$$



The Color-Nonsinglet Sector

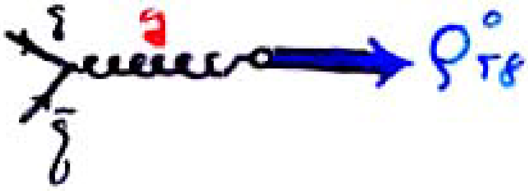
Searches so far concentrate on pre-TC2 signals:

Technipions: π_{T8} w/ $I = 0, 1$ $\in \underline{8}$

$\pi_{L\bar{Q}}$ w/ $I = 0, 1$ $\in \underline{3}, \bar{\underline{3}}$

$\hookrightarrow \tau\bar{t}, \tau\bar{b}, \nu\bar{t}, \nu\bar{b}$, etc. etc.

Technirho: ρ_{T8} w/ $I = 0, 1$

Isoscalar ρ^0_{T8} in 

$\rho_{T8} \longrightarrow \pi_{T8}\pi_{T8}$; $\pi_{L\bar{Q}}\,\pi_{Q\bar{L}}$

<u>if</u> kinematically allowed

More (?) likely, $M_{\rho_{T8}} < 2M_{\pi_T}$

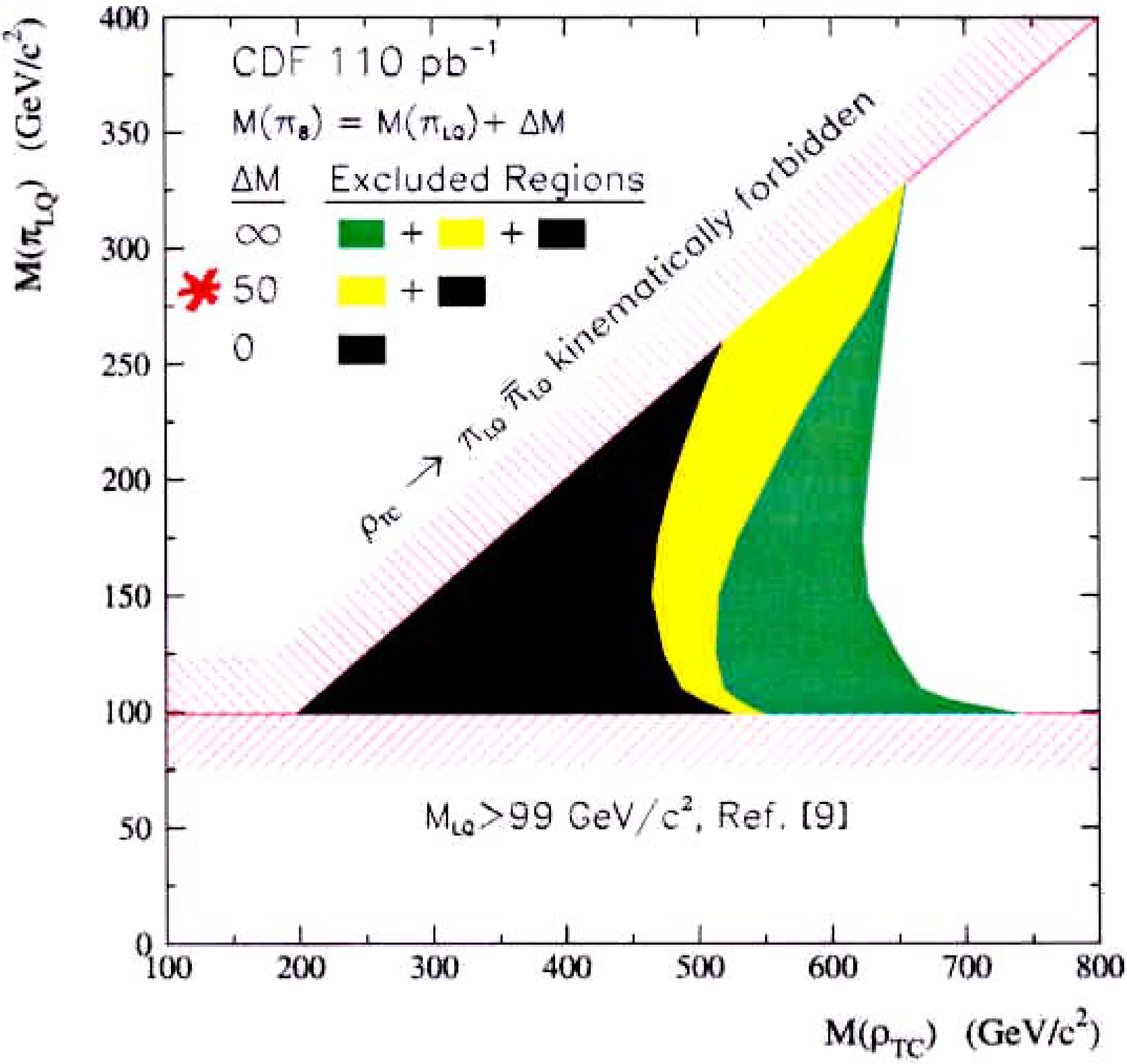
➡ $\rho_{T8} \to \bar{q}q, gg$ dijets

$\longrightarrow g\,\pi_{T8}$, $g\,\pi_{T1}$

$\hookrightarrow$? $\bar{b}b$? $\hookleftarrow$

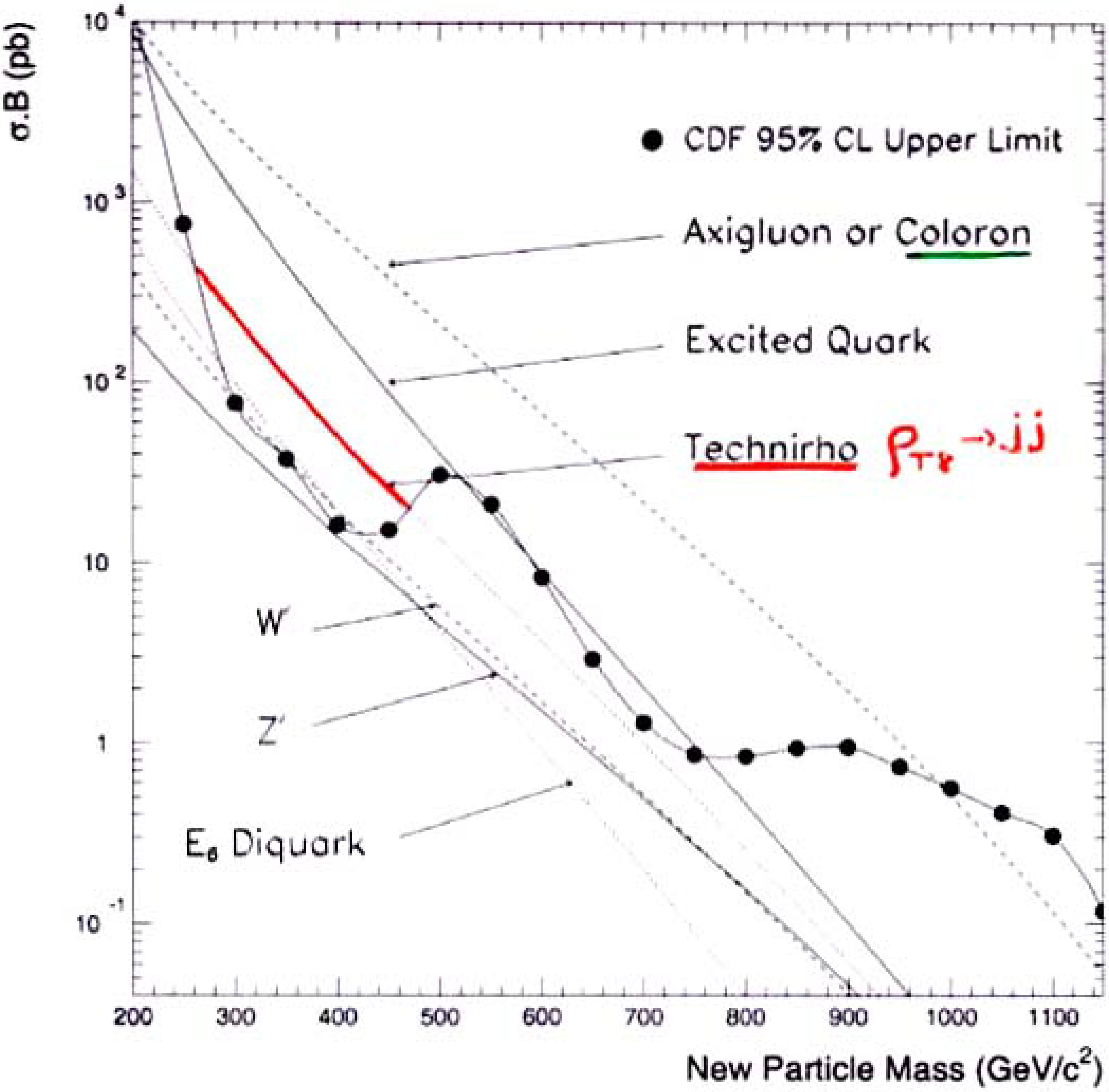
CDF SEARCH FOR $\rho_{T8} \to \pi_{L\bar{Q}} \pi_{\bar{L}Q}$ $\hookrightarrow \tau^- \tau^+ jj$

PRL 82, 3206 (1999)



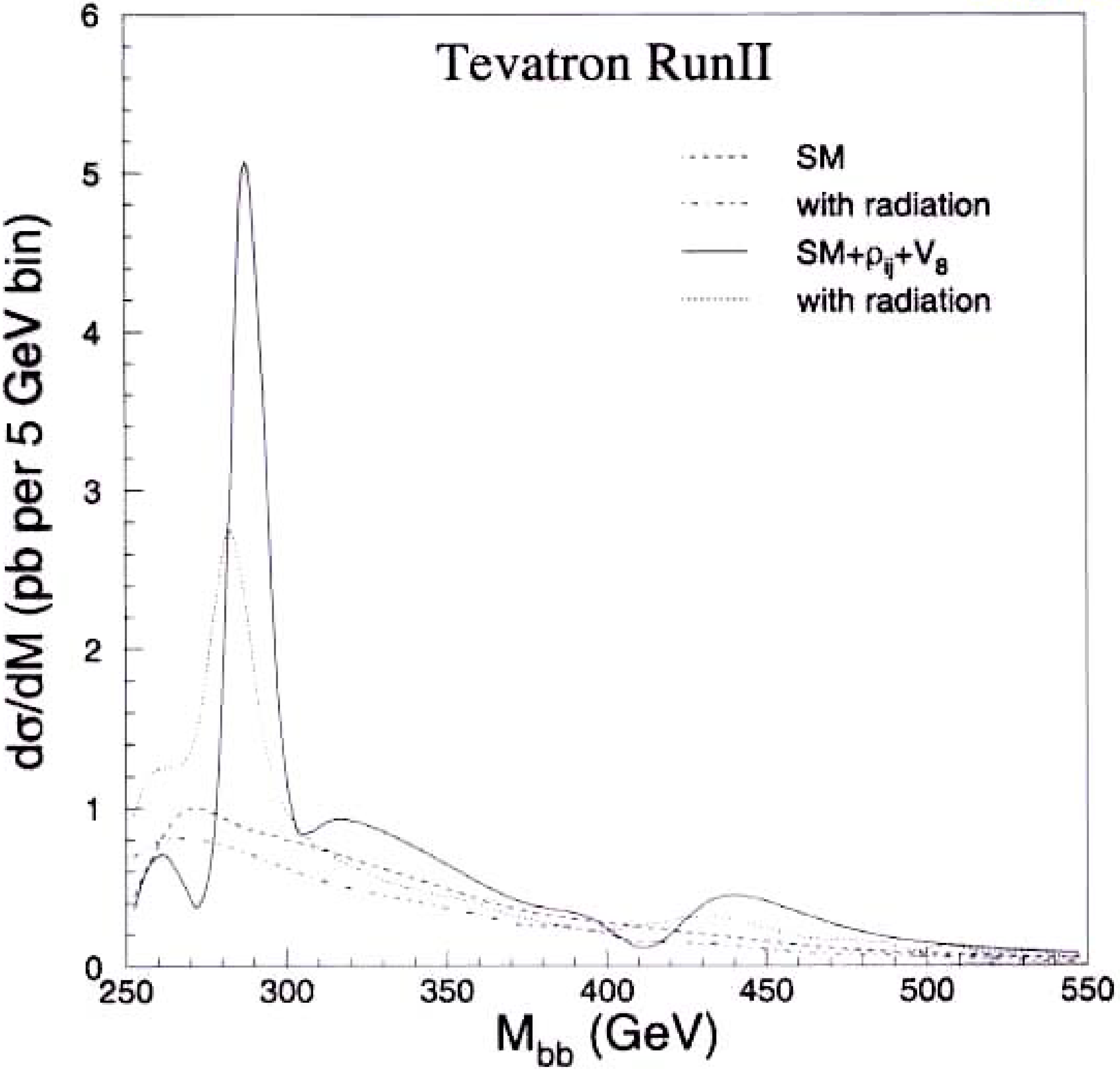
CDF SEARCH FOR $\rho_{T8}, V_8, \ldots \to jj$

PR **D55**, R5263 (1997)



PRELIMINARY!

TC2 assisted Strawman TC - S. Mrenna + K.L.



PRELIMINARY!

TC2 assisted Strawman TC – S. Mrenna & K.L.