STRONG DYNAMICS AT VLHC

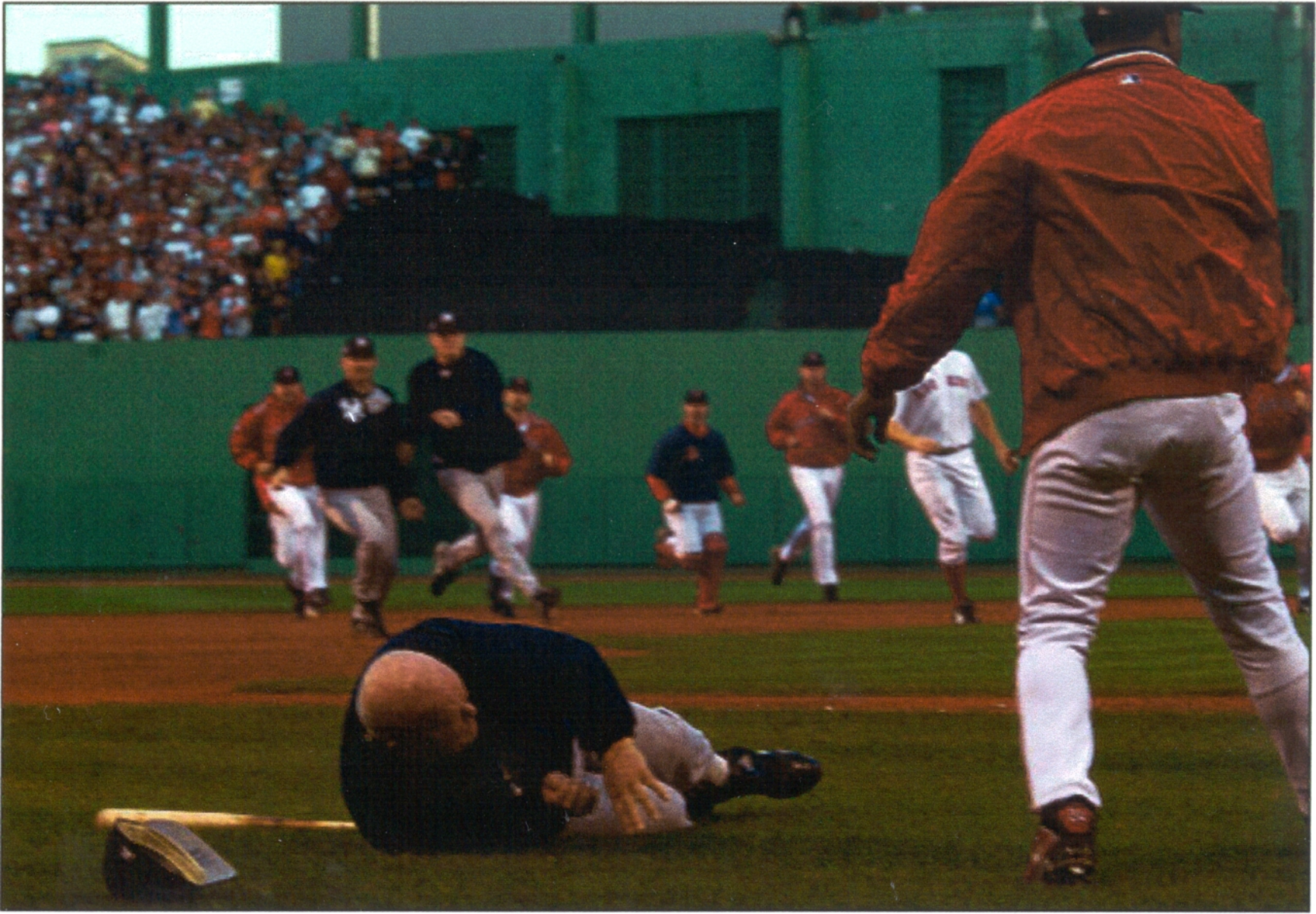
K. LANE, BOSTON UNIVERSITY — OCT. 16, 2003

- TC / ETC / TC2 OVERVIEW
  → WALKING TC → ~~FCNC~~ ; ~~PRECISION EW~~

- TC SIGNALS AT THE VLHC
  - A TOWER OF TECHNI-RHOS UP TO 100s TeV?
  - TC2 Z' AT 5-10 (OR MORE?) TeV

- THE LITTLE HIGGS
  - W', Z', t' AT $\lesssim$ 1-3 TeV
  - THE UV COMPLETION AT $\approx$ 10 TeV

- QUARK AND LEPTON SUBSTRUCTURE
  - PROBE UP TO $\Lambda \approx 100$ TeV!



TECHNICOLOR OVERVIEW

(WEINBERG; SUSSKIND 1979) **TC** = DYNAMICS OF $SU(2)\otimes U(1) \to U(1)_{EM}$ HIGGS MECHANISM WITHOUT ELEMENTARY HIGGS BOSONS.

TC INSPIRED BY QCD PRECEDENT:

MASSLESS QUARKS ACQUIRE DYNAMICAL "SOFT MASS" $m_Q \approx \Lambda_{QCD}$ — "SPONTANEOUSLY BREAKING" CHIRAL SYMMETRY, PRODUCING MASSLESS NAMBU-GOLDSTONE BOSONS $\pi, K, \eta, \ldots$ ($N_f^2 - 1$ NGB's)

"HARD MASS" **NOTE:** $(m_q) = (m_u, m_d, m_s, \ldots) \neq 0$ NEEDED FOR $M_\pi, M_K, M_\eta, \ldots \neq 0$

e.g. $$f_\pi^2 M_\pi^2 = (m_u + m_d)\langle 0|\bar{q}q|0\rangle$$

$$f_\pi = 93\,\text{MeV} = O(\Lambda_{QCD})$$

FOLLOWING THE QCD EXAMPLE:

- $F_\pi \equiv 2^{-1/4} G_F^{-1/2} = 246\ \text{GeV} = O(\Lambda_{TC})$

  INDUCED BY STRONG GAUGE DYNAMICS AT

  $\Lambda_{TC} = 0.1 - 1.0\ \text{TeV}$

- MASSLESS TECHNIFERMIONS (T)

  INTERACT STRONGLY AT SCALE Λ_{TC},

  ACQUIRE DYNAMICAL MASS $= O(\Lambda_{TC})$,

  PRODUCE MASSLESS TECHNIPIONS π_T.

- $T_L = \begin{pmatrix} T_U \\ T_D \end{pmatrix}_L$ & $SU(2)_{EW}$ DOUBLET

  T_{UR}, T_{DR} & $SU(2)_{EW}$ SINGLET

  $\Rightarrow$ $3\ \pi_T^{\pm,0}$ A.K.A. $W_L^\pm, Z_L^0$

  WITH $M_W^2 / M_Z^2 \cos^2\theta_W = 1$!!

- $N_D > 1$ TECHNIDOUBLETS $\Rightarrow$ $4N_D^2 - 4$ EXTRA π_T

  HOW DO THEY GET MASS??

EXTENDED TECHNICOLOR (ETC)

(DIMOPOULOS & SUSSKIND ; EICHTEN & K.L. 1979)

TC DOES NOT PROVIDE FOR "HARD MASSES"

- $m_q \neq 0$, $m_\ell \neq 0$.
- $m_T \neq 0$ — NEEDED FOR $M_{\pi_T} \neq 0$.

SOL'N: EMBED TC $\otimes$ COLOR $\otimes$ FLAVOR $\subset$ G_{ETC}

$$(N_{ETC}) = \begin{pmatrix} 1_{TC} \\ 2_{TC} \\ \vdots \\ N_{TC} \\ 1_{QCD} \\ 2_{QCD} \\ 3_{QCD} \\ 1_F \\ 2_F \\ \vdots \\ N_F \end{pmatrix}$$

BREAK $G_{ETC} \to G_{TC} \otimes G_{QCD} \otimes G_F$

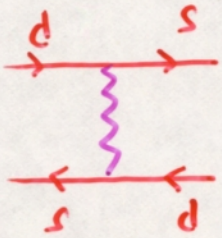
AT SOME HIGH ENERGY SCALE:

m_q (OR m_ℓ OR M_T) $\simeq$

$$\simeq \frac{g^2_{ETC}}{M^2_{ETC}} \langle 0 | \bar{T}_R T_L | 0 \rangle_{M_{ETC}}$$

BUT ... FCNC

e.g.



$$= \frac{g_{ETC}^2\, \theta_{sd}^2}{M_{ETC}^2}\, \bar{s}\gamma^\mu d\, \bar{s}\gamma_\mu d$$

$$\Rightarrow \quad \frac{M_{ETC}}{g_{ETC}\, \theta_{mix}} \gtrsim \underset{\Delta M_{K^0}}{10^3} - \underset{\epsilon_{K^0}}{10^4}\ \text{TeV}\,!$$

SCALING $\langle \bar{T}T \rangle_{METC}$ FROM QCD

$$\Rightarrow \quad m_q,\ m_\ell,\ m_T \sim \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \lesssim \text{FEW MeV}$$

$$M_{\pi_T} \sim \left[\frac{g_{ETC}^2/M_{ETC}^2\, \langle \bar{T}T\bar{T}T \rangle_{ETC}}{F_{\pi_T}^2} \right]^{1/2} \lesssim \text{FEW GeV}$$

CATASTROPHE !

WALKING TECHNICOLOR (WTC)

(Holdom 1981; Appelquist, et al. 1986; Yamawaki, et al. 1986; Akiba & Yanagida, 1986.)

TC DYNAMICS ($\langle \bar{T}T \rangle_{M_{ETC}}$, e.g.) MUST NOT BE SCALED NAIVELY FROM QCD.

(c.f. Tom's S-PARAMETER)

- PRECOCIOUS ASYMPTOTIC FREEDOM OF QCD

$$\Rightarrow \quad \langle \bar{T}T \rangle_{M_{ETC}} \approx \langle \bar{T}T \rangle_{\Lambda_{TC}} \simeq 4\pi F_{\pi_T}^3$$

- TC MUST APPROACH WEAK-COUPLING SLOWLY, i.e., WALK, NOT RUN:

$$\alpha_{TC}(M) \simeq \alpha_{TC}(\Lambda_{TC}) \quad \text{FOR } \Lambda_{TC} \lesssim M \lesssim M_{ETC}$$

$$\Rightarrow \quad \langle \bar{T}T \rangle_{M_{ETC}} \approx \frac{M_{ETC}}{\Lambda_{TC}} \langle \bar{T}T \rangle_{\Lambda_{TC}} \gg 4\pi F_{\pi_T}^3$$

$$\Rightarrow \quad m^{ETC}_{q,\ell,T} \lesssim \text{FEW GeV}$$

$$M_{\pi_T} \lesssim \text{FEW 100 GeV}$$

[N.B. WTC AND PRECISION EW TESTS.]

* WHAT MAKES α_{TC} WALK? *

NEED TO MAKE $\beta(\alpha_{TC}) \approx 0$.
(NEAR AN IR FIXED POINT, e.g. ??)

INVOKE

(1) MANY T-FERMIONS IN N OF $SU(N)_{TC}$
(APPELQUIST, et al. 1987-88)

OR (2) FEW T-FERMIONS IN HIGHER IR OF $SU(N)_{TC}$

OR (3) BOTH (E.E. & K.L., 1989; RAMONA & K.L. '91)
(B. BALAJI - 1996 -
- WON'T WORK BECAUSE OF $b \to s\gamma$.)

(1) → LOW-SCALE TC, ACCESSIBLE AT TEVATRON, LHC

(2) → HIGH-SCALE TC, ACCESSIBLE AT LHC (?), VLHC

TOPCOLOR-ASSISTED TECHNICOLOR

(TC2) (C. HILL, 1995)

$m_q^{ETC} \lesssim$ FEW GeV $\ll m_t = 175$ GeV

IF THERE'S AN ETC SCALE LOW ENOUGH (FEW TeV!!) TO GENERATE m_t

→ UNNATURAL FINE-TUNING OF g_{ETC}

→ TENDENCY FOR TROUBLE WITH $\rho = 1$.

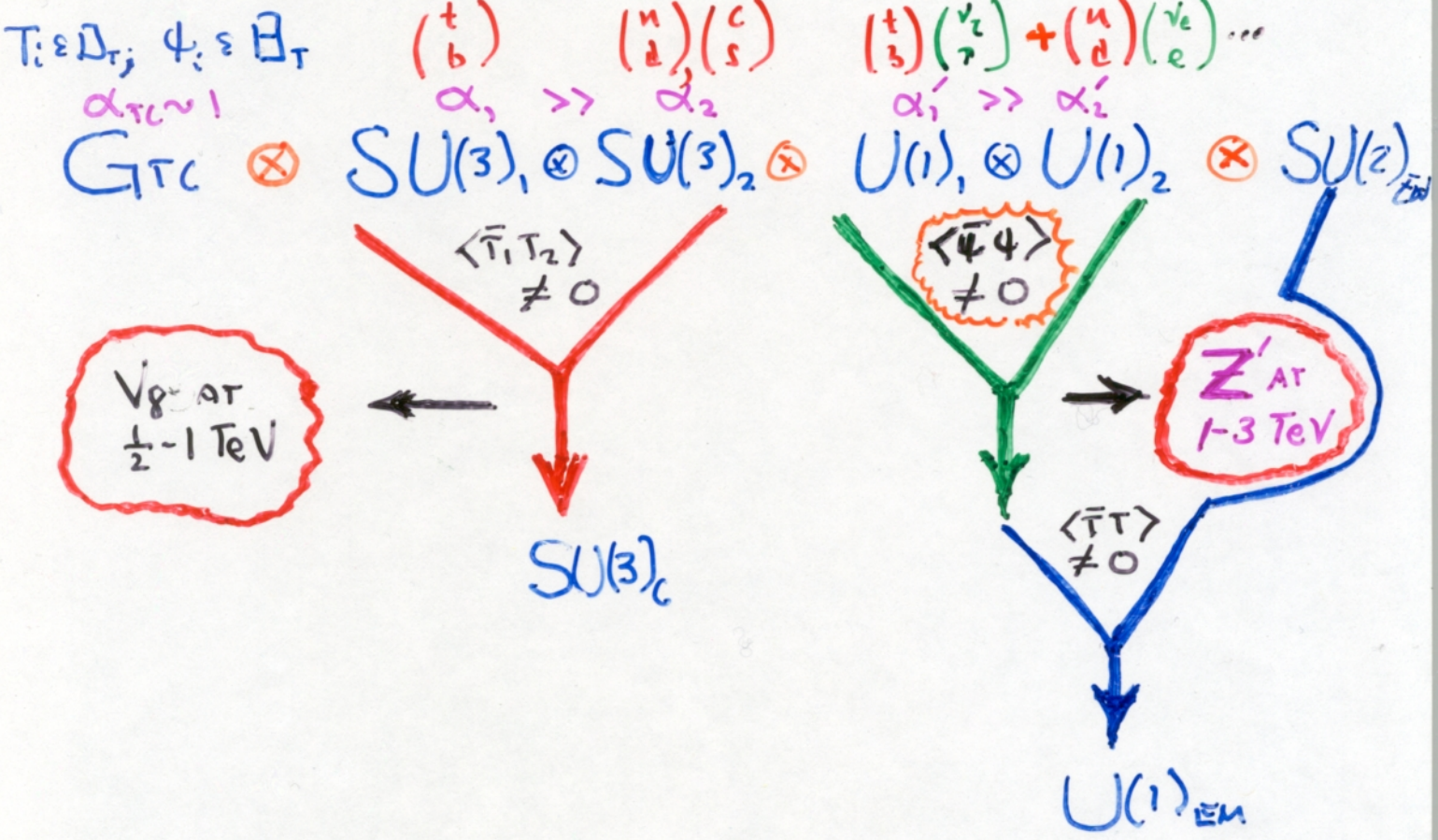
→ CONFLICT WITH $Z^0 \to b\bar{b}$

∴, INVOKE TOPCOLOR w/ $\Lambda_{top} \lesssim 1$ TeV TO GENERATE LARGE $\langle \bar{t}t \rangle$, m_t (NOT m_b!!)

* WEAK-ISOSPIN ; $b \to c + \bar{X}$; $B_d^0 - \bar{B}_d^0$ MIXING ; ...

⇝ MANY T-FERMIONS NEEDED TO GIVE ETC MASSES + MIXINGS TO QUARKS + LEPTONS .... FOR EXAMPLE:

"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.

TC Signals at the VLHC

• A tower of techni-vector mesons??

The s-channel of $\bar{f}f$ annihilation is controlled by vector + axial-vector spectral functions ρ_V + ρ_A. They satisfy Weinberg's SFSRs:

$$\int_0^\infty ds\,[\rho_V(s) - \rho_A(s)] = F_\pi^2$$

$$\int_0^\infty ds \cdot s\,[\rho_V(s) - \rho_A(s)] = 0$$

In QCD: $\rho_V^1 - \rho_A^1$ is dominated by $\rho(770)$ and $a_1(1260)$, and falls off like $1/s^3$ above a_1.

In WTC: $\rho_V - \rho_A$ falls off like $1/s^2$ up to $O(M_{ETC})$ — 100's of TeV!!

→ Dominance by single ρ_T + a_{1T} is impossible!

What holds $\rho_V - \rho_A$ up ??

• THE TC2 Z'

IF $m_t \simeq 175$ GeV IS DUE TO TC2,

$$M_{Z'} \gtrsim 5\text{-}10 \text{ TeV}$$

TO AVOID FCNC ($B_d^0 - \bar{B}_d^0$ MIXING, ETC.).

→ $M_{Z'}$ COMES FROM CONDENSATION OF HIGH-MASS ($\gtrsim 10$ TeV ?) FERMIONS ψ:

- $\psi \in$ HIGHER-DIM'AL REP'N OF $SU(N_{TC})$.
  (∴, $\langle \bar{\psi}\psi \rangle$ PRESERVES $SU(2) \otimes U(1)$)

OR ?

- ψ TRANSFORMS UNDER YET ANOTHER STRONG-INTERACTION GAUGE GROUP.

THE Z' LIKELY IS BROAD ($\Gamma_{Z'}/M_{Z'} \not\ll 1$),

BUT

$$\bar{q}q \rightarrow Z' \rightarrow \bar{\psi}\psi \quad (\rightarrow \text{WHAT ???})$$

IS THE WAY TO ACCESS ψ.

THE LITTLE HIGGS AND THE VLHC

(ARKANI-HAMED, et al...; HILL, et al.)

LITTLE HIGGS = LIGHT, COMPOSITE SCALAR φ WITH

$$M_\varphi \approx v_\varphi \lesssim 200 \text{ GeV}$$

$\ll$ SCALE Λ OF φ's CONSTITUENTS.

IN MODELS, $\Lambda \simeq 10$ TeV.

(COMPARE W/ TC: $M_{\text{"}\varphi\text{"}} \approx v_{\text{"}\varphi\text{"}} \approx \Lambda_{TC} \lesssim 1$ TeV)

φ IS KEPT LIGHT ($\ll \Lambda$) BY SYMMETRY —

DIVERGENT 1-LOOP SM CONTRIBUTIONS TO M_φ^2 — DUE TO W, Z, t — ARE CANCELLED BY SAME-STATISTICS PARTICLES — W', Z', t' — ALL AT $\lesssim$ 1-3 TeV. → LHC-LAND

WHAT ARE THE CONSTITUENTS OF φ?

→ NEW STRONG DYNAMICS AT $\Lambda \approx 10$ TeV.

BUT WHAT IS IT ??

NO COMPELLING MODEL OF THIS "UV COMPLETION"

YET ... STILL, THERE IS

EXCITING PHYSICS AT 10 TeV (+ UP)!

AND DON'T FORGET

QUARK & LEPTON SUBSTRUCTURE

(E.L.P., 1982 (!))

THE FIRST HINTS OF q, ℓ SUBSTRUCTURE WILL BE DEVIATIONS AT HIGH E_T + $\hat{s}$ OF SM CROSS SECTIONS FOR

JETS:

$$\mathcal{L}_{qq} = -\frac{4\pi}{2\Lambda^2} \sum_{\substack{\lambda_1,\lambda_2 \\ = L,R}} \eta_{\lambda_1\lambda_2} \bar{q}_{\lambda_1} \gamma^\mu q_{\lambda_1} \bar{q}_{\lambda_2} \gamma_\mu q_{\lambda_2} + \cdots$$

UP TO $\Lambda \overset{?}{\simeq} 100$ TeV AT $\sqrt{s} = 200$ TeV, $\int \mathcal{L} dt = 200\ fb^{-1}$

DREL-YAN:

$$\mathcal{L}_{q\ell} = -\frac{4\pi}{\Lambda^2} \sum_{\lambda_1,\lambda_2} \left\{ \bar{q}_{\lambda_1} \gamma^\mu q_{\lambda_1} \bar{\ell}_{\lambda_2} \gamma_\mu \ell_{\lambda_2} + \bar{u}_{\lambda_1} \gamma^\mu d_{\lambda_1} \bar{\ell}_{\lambda_2} \gamma_\mu \nu_{e\lambda_2} + \cdots \right\}$$

UP TO $\Lambda \overset{?}{\simeq} 75$ TeV

+ CHIRALITY INFORMATIONS FROM $\mu^+\mu^-$ + $\mu^\pm \nu_\mu$ ANGULAR DISTNS — DEPENDING ON $\Delta p_T / p_T$ AT 10-20 TeV.

BOB