New Strong Dynamics at the TeV Scale:
from multi-jet resonances at the Tevatron

to di-CHAMP resonances at the LHC

Takemichi Okui
(Johns Hopkins U & U of Maryland)

Based on C. Kilic, T.O, R. Sundrum, JHEP 0807:038, 2008
The worry...

The SM
Beautifully tested
No signs of new physics

Rich new physics?
tension! ⇔
The worry...

The SM

Beautifully tested
No signs of new physics

Rich new physics?

Encouraging “history”

“SM” @ $E < 100$ MeV

$E$ [MeV]

100

Beautifully tested
No signs of new physics

0.5
$e$

γ

0
The worry...

The SM

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Rich new physics?

Encouraging "history"

"SM" @ $E < 100$ MeV

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$E$ [MeV]

1000

100

0.5

0

$e$

$\gamma$

$\rho$

$K^\pm$

$\pi^0$

$\mu$

$\nu$

$\alpha$

DRAMATIC

new physics!!

(Vectorlike confinement)

T. OKUI (JHU&UMD)
If Nature repeats itself at TeV...

- QED-QCD system -

leptons → E&M → quarks (vectorlike) → color force

- Vectorlike Confinement at TeV -

SM fermions → SM gauge int. → new fermions (vectorlike) → hyper-color force
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leptons E&M quarks (vectorlike) 4-fermion op. color force

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“Gauge Mediation”
Safe from flavor constraints
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hyper-color force

Can have mass w/o EWSB
Safe from EW precision constraints

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SM fermions  SM gauge int.  new fermions (vectorlike)

hyper-color force

Confinement

Rich phenomenology

"Gauge Mediation"

Safe from flavor constraints

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If Nature repeats itself at TeV...

- QED-QCD system -

Let stable particles decay

4-fermion op.

leptons

E&M

quarks (vectorlike)

color force

“Gauge Mediation”

Safe from flavor constraints

SM fermions

SM gauge int.

new fermions (vectorlike)

4-fermion op.

hyper-color force

Confinement

Rich phenomenology

Can have mass w/o EWSB

Safe from EW precision constraints

Simple and plausible (yet pheno rich) possibility at TeV!

T. OKUI (JHU&UMD)
The Signature Process

\[ \rho \rightarrow e^+e^- \sim 10^{-5} \]

\[ \rho \rightarrow \pi\pi \sim 10^{-5} \]
The Signature Process

\[
\frac{\rho \rightarrow e^+e^-}{\rho \rightarrow \pi\pi} \sim 10^{-5}
\]

\[
\frac{\rho \rightarrow \pi\pi}{\rho \rightarrow e^+e^-} \sim 100 \%
\]

\[
\text{Br}(\rho \rightarrow f\bar{f}) < 1\%
\]

How does \( \tilde{\pi} \) decay?
Two fates for $\tilde{\pi}$: Life can be short or long!

$\pi^0$ short-lived! ($c\tau \sim 10$ nm)
Two fates for $\tilde{\pi}$: Life can be short or long!

Same species:

$\pi^0$ short-lived! ($c\tau \sim 10$ nm)

Different species:

$\tilde{\pi}_{\text{short}}$ short ($c\tau \sim 10$ nm)

Decays promptly!

$\pi^0$, $\bar{q}$, $q$, $\gamma$, $W$, $Z$, $g$

$\psi$, $\bar{\psi}$, $\gamma$, $W$, $Z$, $g$
Two fates for $\tilde{\pi}$: Life can be short or long!

$\pi^0$ short-lived! $(c\tau \sim 10 \text{ nm})$

$\pi^0$ short lived

Decays promptly!

$\pi^+$ long-lived! $(c\tau \sim 10 \text{ m})$

Need nonrenormalizable int. to change species
Two fates for $\tilde{\pi}$: Life can be short or long!

- Same species
  - $\pi^0$ short-lived! ($c\tau \sim 10\text{ nm}$)
  - $\tilde{\pi}_{\text{short}}$
  - Decays promptly!

- Different species
  - $\pi^+$ long-lived! ($c\tau \sim 10\text{ m}$)
  - $\tilde{\pi}_{\text{long}}$
  - Need nonrenormalizable int. to change species

$\gamma, W, Z, g$

$\tilde{\pi}$ long-lived in $\tilde{\text{SM}}$, species changing 4-fermion int.
Two fates for $\tilde{\pi}$: Life can be short or long!

$\pi^0$ short-lived! ($c\tau \sim 10 \text{ nm}$)

$\pi^0$ long-lived! ($c\tau \sim 10 \text{ m}$)

Need nonrenormalizable int. to change species

Absence of excessive flavor violations

$\Rightarrow$ Stable in collider times scale!
Summary of Phenomenology

* Charged massive stable particles (CHAMPs)
* Colored massive stable particles (R-hadrons)
* (Displaced) leptoquarks, di-quarks, di-leptons
* Multi-W, Z, photon production
* Multi-jet resonances
* SUSY-like scalar spectra
* Dark matter
* Grand unification
Summary of Phenomenology

- **A** *Charged massive stable particles (CHAMPs) @LHC*
  - Colored massive stable particles (R-hadrons)
  - (Displaced) leptoquarks, di-quarks, di-leptons
  - Multi-W, Z, photon production

- **B** *Multi-jet resonances @Tevatron*
  - SUSY-like scalar spectra
  - Dark matter
  - Grand unification

- New confining force
- $\bar{q}q$, $\gamma, W, Z, g$
- $\psi$, $\psi'$
- $\tilde{\pi}_{\text{long}}$, $\tilde{\pi}_{\text{short}}$
- Stable!
Scenario A (LHC)

2 species: $\psi, \chi$  No QCD int. (Say, EW doublet and singlet)

$\tilde{\pi}_{\text{short}} = \psi, \chi$

Four $W, Z, \gamma$'s from a $\tilde{\pi}_{\text{short}}$ pair!

$\tilde{\pi}_{\text{long}} = \psi, \chi$

Charged, massive & stable!

("CHAMP")

Existence very robust!

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Scenario A (LHC)

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A CHAMP = a highly ionized, penetrating track

Spectacular collider signal!

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Scenario A (LHC)

2 species: $\psi, \chi$  No QCD int. (Say, EW doublet and singlet)

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("CHAMP")

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A CHAMP = a highly ionized, penetrating track

Spectacular collider signal!

Resonant CHAMP pair production!
Can we see the parent $\tilde{\rho}$ resonance?

[fb/100 GeV]

@LHC

CHAMPs from "Drell-Yan"

$E_{\text{champ1}} + E_{\text{champ2}}$ (in c.m. frame)

$\Psi_{\text{long}}$

$\tilde{\pi}$

$\gamma, W, Z$

$\Psi$

$P$

$\bar{q}$

$P$

$q$

$\tilde{\rho}$

$\rho$

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Can we see the parent \( \tilde{\rho} \) resonance?

@LHC

“Di-CHAMP” resonance!

CHAMPs from “Drell-Yan”

\[ E_{\text{champ}1} + E_{\text{champ}2} \text{ (in c.m. frame)} \]

\( m_\rho = 2.5 \text{ TeV} \)

\( m_\rho = 4.0 \text{ TeV} \)
Can we see the parent \( \tilde{\rho} \) resonance?

@LHC

CHAMPS from "Drell-Yan"

Cross-section

\[ E_{\text{champ1}} + E_{\text{champ2}} \text{ (in c.m. frame)} \]

Angular distribution shows spin-1 nature
Scenario B (Tevatron)

Only one species: $\psi$ w/ no electroweak int. Only QCD int.

$\tilde{\pi}_{\text{short}} = \psi$

No $\tilde{\pi}_{\text{long}}$
Scenario B (Tevatron)

Only one species: $\psi$ w/ no electroweak int. Only QCD int.

$\tilde{\pi}_{\text{short}} = \psi$

No $\tilde{\pi}_{\text{long}}$

Kinematical features:

Event rate

$\tilde{\rho}$

$E_a + E_b + E_c + E_d$

(in c.m. frame)

Event rate

$\tilde{\pi}$

$E_a + E_b$

(in a-b c.m. frame)

Event rate

$\tilde{\pi}$

$E_c + E_d$

(in c-d c.m. frame)
Scenario B (Tevatron)

Only one species: $\psi$ w/ no electroweak int. Only QCD int.

$\tilde{\pi}_{\text{short}} = \psi$

No $\tilde{\pi}_{\text{long}}$

Kinematical features:

Event rate

$\tilde{\rho}$

$E_a + E_b + E_c + E_d$

(in c.m. frame)

Event rate

$\tilde{\pi}$

at the same mass

$E_a + E_b$

(in a-b c.m. frame)

Event rate

$E_c + E_d$

(in c-d c.m. frame)
Useful observables and cuts

\[ p_T \equiv |\vec{p}_{\perp \text{beam}}| \]

\[ m_{4j} \equiv E_1 + E_2 + E_3 + E_4 \quad \text{(in c.m. frame)} \]

(1) To pick out the \( \tilde{\rho} \)
Useful observables and cuts

(1) To pick out the $\tilde{\rho}$

$$m_{4j} \equiv E_1 + E_2 + E_3 + E_4 \quad \text{(in c.m. frame)}$$

(2) To pick out the two $\tilde{\pi}$'s

(i) choose 2 pairs $ij$ and $kl$
(ii) calculate

$$m_{ij} \equiv E_i + E_j \quad \text{(in i-j c.m. frame)}$$

and similarly $m_{kl}$

(iii) minimize $\Delta m \equiv |m_{ij} - m_{kl}|$

(iv) keep event only if

$$\Delta m < 25 \text{ GeV}$$

(v) take average

$$\langle m_{2j} \rangle \equiv (m_{ij} + m_{kl}) / 2$$
Useful observables and cuts

(1) To pick out the $\tilde{\rho}$

$$m_{4j} \equiv E_1 + E_2 + E_3 + E_4 \quad (\text{in c.m. frame})$$

(2) To pick out the two $\tilde{\pi}'$s

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$$\langle m_{2j} \rangle \equiv (m_{ij} + m_{kl}) / 2$$

(3) Signal: $p_{T1} \sim p_{T2} \sim p_{T3} \sim p_{T4}$

Backgrounds: $p_{T1} \gg p_{T2} \gg p_{T3} \gg p_{T4}$

so keep event only if $p_{Ti} > p_{\text{cutoff}}$ for all 4 jets

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Discovery potential for: $m_{\tilde{\rho}} = 350$ GeV

\[ (m_{\tilde{\pi}} = 100 \text{ GeV}) \]

$p_{Ti} > p_{\text{cutoff}} = 40$ GeV

$\text{Min} \ |m_{ij} - m_{kl}| < 25$ GeV

$p_{T1} > 120$ GeV

(CDF single-jet trigger: $p_{T1} > 100$ GeV)

Signal: \( (1 \text{ fb}^{-1}) \quad \sigma_{p\bar{p} \rightarrow \tilde{\rho}} = 110 \text{ pb} \quad (\text{pb} = 10^{-36} \text{ cm}^2) \)

Background: \( (2 \text{ fb}^{-1}) \)

Signal: 2.7 pb passing selection criteria

Background: 21 pb passing criteria

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Discovery potential for: $m_{\tilde{\rho}} = 350$ GeV  
($m_{\tilde{\pi}} = 100$ GeV)

$p_{T1} > p_{\text{cutoff}} = 40$ GeV

Min $|m_{ij} - m_{kl}| < 25$ GeV

$p_{T1} > 120$ GeV

(CDF single-jet trigger: $p_{T1} > 100$ GeV)

Signal (1 fb$^{-1}$) $\sigma_{pp\rightarrow\tilde{\rho}} = 110$ pb  
(pb = $10^{-36}$ cm$^2$)

Signal: 2.7 pb passing selection criteria

Background (2 fb$^{-1}$)

Background: 21 pb passing criteria

$\sqrt{\sum_{\text{bins}} \left( \frac{S}{\sqrt{B}} \right)^2} = 32$ !

Discoverable in existing Tevatron data!

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Conclusions

A broad class of simple extensions of the SM:

4-fermion op.

SM fermions  SM forces  new fermions (vector-like)  new confining force

4-fermion op.

leptons  EM force  quarks (vector-like)  color force

* can robustly evade all existing precision constraints
* can lead to extremely rich collider phenomenology

e.g.  Multi-jets resonances

Di-CHAMP resonances

In existing Tevatron data!!