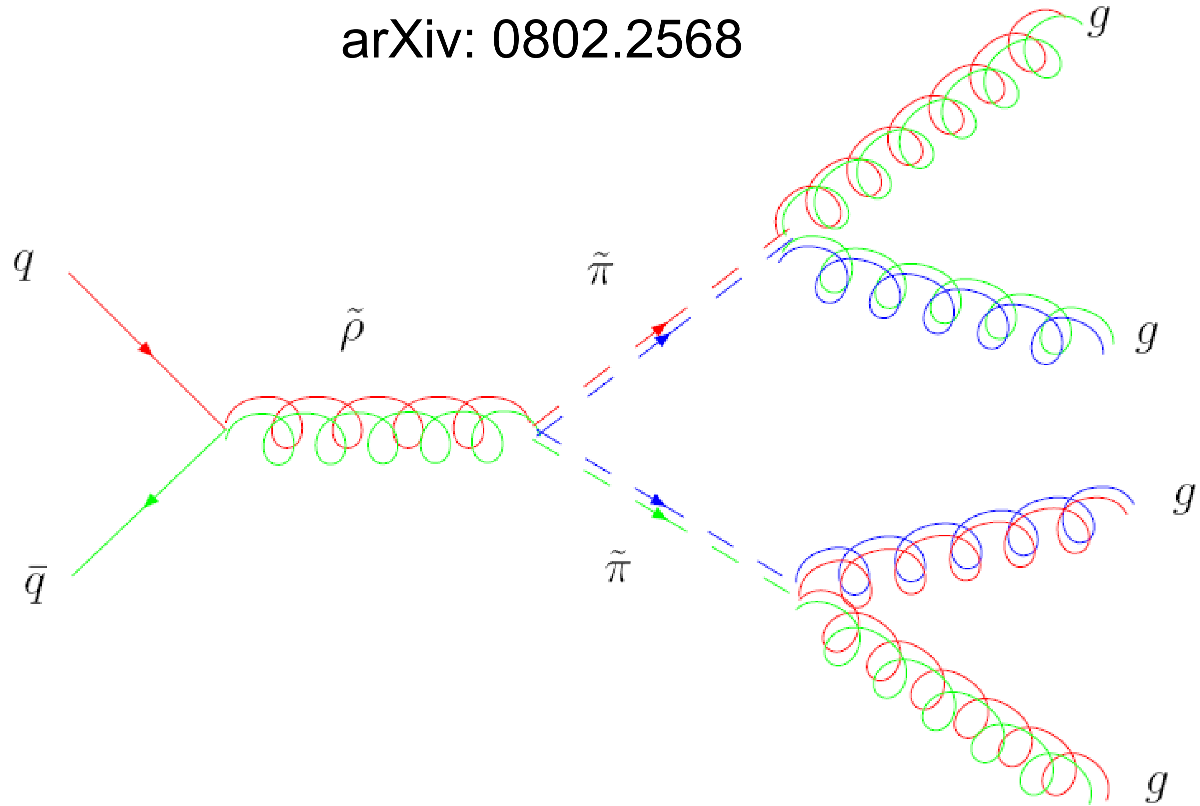
Colored Resonances at the Tevatron: Phenomenology and Discovery

arXiv: 0802.2568



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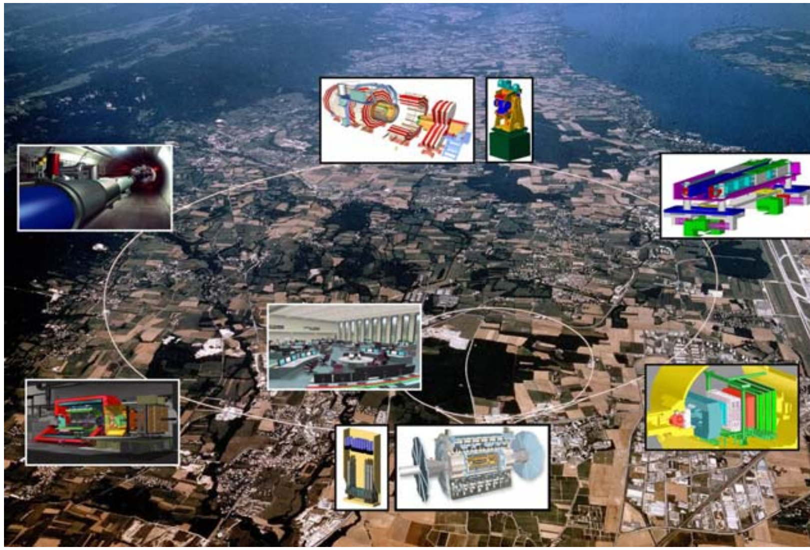
work done with Takemichi Okui and Raman Sundrum

Outline

- Introduction: Why colorons are interesting
- A minimal model:
  - Description: qualitative
  - Phenomenology: quantitative
- Constraints
- Looking for a colorful needle in a haystack
- Outlook and Conclusions

INTRODUCTION
THE AGE OF COLOR



- The 90's and 00's:

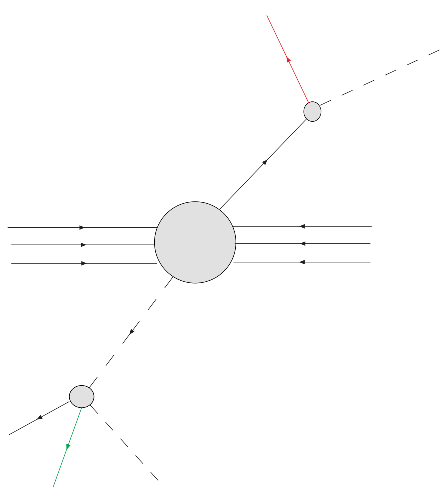
  The Tevatron Age
  - Run I: E_{CM}=1.8 TeV
  - Run II: E_{CM}=1.96 TeV
- The 10's (and 20's?):

  The LHC Age: E_{CM}=14 TeV
- Our greatest strength is the production of new colored states.
- Our greatest weakness is the production of *old* colored states.
- Discovery strategy for most BSM models lie in distinctive signatures:
  - leptons
  - heavy flavors
  - missing energy

INTRODUCTION
WHAT DREAMS MAY COME (TRUE)

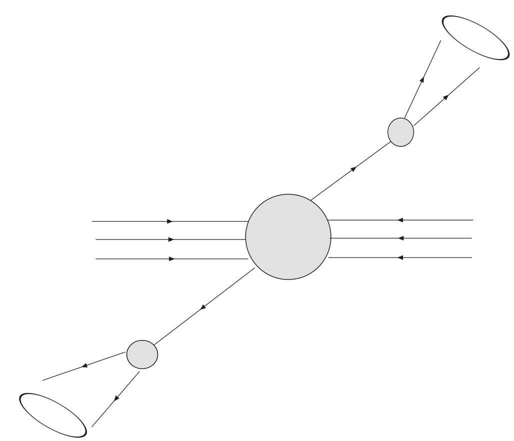
Solutions to the hierarchy problem:

- New states carry EW quantum numbers
- Highly constrained by precision data
- Must be heavy, small cross section (usually 2→2). Background reasonable
- Many search strategies devised

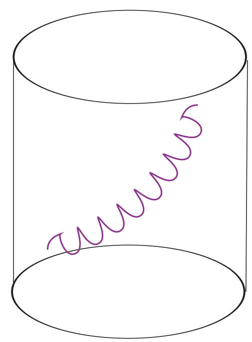
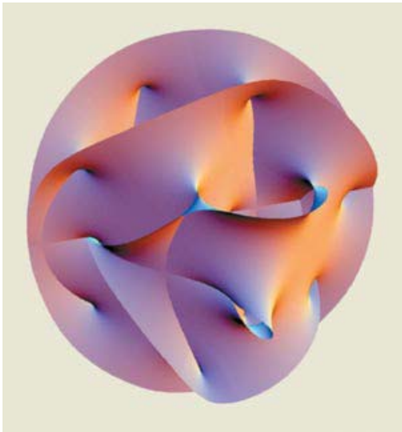


Incidentals: ("Who ordered this?")

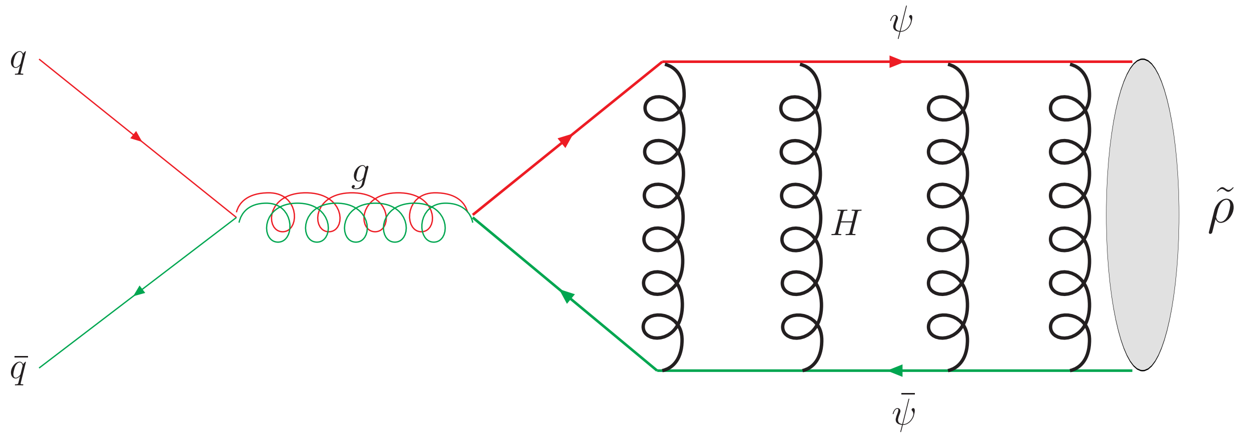
- New states can be EW singlets
- Then color is our best (only) bet
- Need large signal to beat large background (2→1 ideal)
- Search strategies based on kinematic signatures



INTRODUCTION
A BRIEF HISTORY OF COLORONS

KK Gluons 	TeV Gravity 
$SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_c$ Topcolor	V_8 non-minimal TC

INTRODUCTION
A MORE GENERAL MOTIVATION



- This should be familiar from $e^+e^- \to \rho$
- Also known as γ/ρ mixing
- *Resonant* production, large cross section

INTRODUCTION DIFFICULTIES

- Colorons proposed before in order to explain high-p_T excess.
- Coming from $q\bar{q}$ the coloron can decay back to dijets.
- O(1) BF into dijets has been excluded in the sub-TeV regime.
- O(1) coupling to $t\bar{t}$ excluded by top production measurements.
- $\tilde{\rho} \rightarrow \tilde{\pi}\tilde{\pi}$ is *allowed*.

INTRODUCTION
MAIN STATEMENTS

- The coloron is a generic object that can arise in many BSM scenarios, motivated or incidental.
- One should keep an open mind in devising search strategies.
- A light coloron can be consistent with existing bounds if it carries no EW charge and is flavor blind.
- It can be detected at the Tevatron in multijets.
- The LHC will have lessened sensitivity to such a state.

A MINIMAL MODEL QUALITATIVE DESCRIPITION

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}H_{\mu\nu}H^{\mu\nu}$$

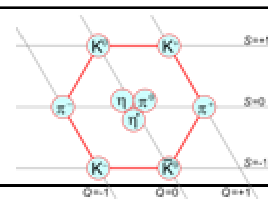
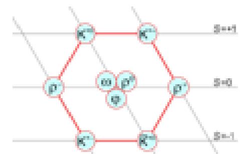
Ingredients:

- New colored fermions (EW singlets)
- Confining gauge interactions (“Hypercolor”)

Consequences:

- QCD gauges unbroken flavor symmetry
- For G_{HC}=SU(3) with massless hyperquarks, we can use QCD as an analog computer.
- Renormalizable, possible separation of scales from EWB or flavor physics

A DICTIONARY

	QCD	HYPERCOLOR
Gauge	$SU(3)_c$	$SU(3)_{HC}$
Flavor (unbroken)	SU(3): broken by quark masses, U(1) gauged	$SU(3)_c$ No quark masses All gauged
Scale	1 GeV	~500 GeV
Goldstones		$\tilde{\pi}$
Vectors		$\tilde{\rho}$

DICTIONARY, cont`d

	QCD	HYPERCOLOR
Kinetic	$\overline{e} i \not{D} e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$	$\overline{q} i \widetilde{\not{D}} q - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$
Mixing/ Production	$-\frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{m_\rho^2}{2}\rho_\mu\rho^\mu + \frac{\varepsilon}{2}\rho_{\mu\nu}F^{\mu\nu}$	$-\frac{1}{4}\tilde{\rho}^a_{\mu\nu}\tilde{\rho}^{a\mu\nu} + \frac{m_{\tilde{\rho}}^2}{2}\tilde{\rho}^a_\mu\tilde{\rho}^{a\mu} + \frac{\tilde{\varepsilon}}{2}\tilde{\rho}^a_{\mu\nu}G^{a\mu\nu}$
Strong sector Decay	$-i g_{\rho\pi\pi}\rho^\mu(\pi^- \overleftrightarrow{D}_\mu \pi^+)$	$-g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} f^{abc} \tilde{\rho}^a_\mu \tilde{\pi}^b \partial^\mu \tilde{\pi}^c$
Goldstones Decay	$-\frac{e^2 \epsilon^{\mu\nu\rho\sigma}}{32\pi^2 f_\pi}\pi^0 F_{\mu\nu}F_{\rho\sigma}$	$-\frac{3 g_3^2 \epsilon^{\mu\nu\rho\sigma}}{16\pi^2 f_{\tilde{\pi}}} \mathrm{tr}\left[\tilde{\pi} G_{\mu\nu} G_{\rho\sigma}\right]$

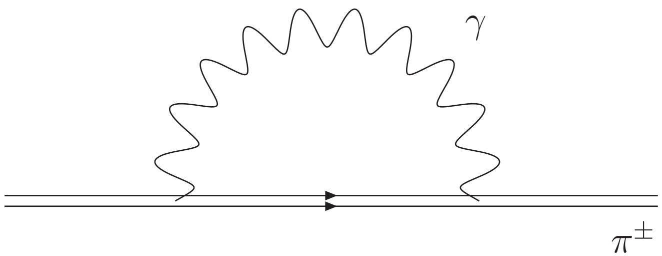
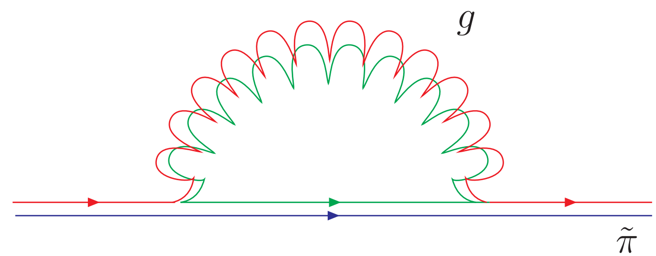
MOVING ON UP - I

QCD	HYPERCOLOR
$\Lambda_{\rm QCD} \sim m_\rho$	$\Lambda_{\rm HC} \sim m_{\tilde\rho}$
$f_\pi \simeq 92\,{\rm MeV}$	$f_{\tilde\pi} \simeq 92\,{\rm GeV}\,\frac{m_{\tilde\rho}}{10^3 m_\rho}$
$g_{\rho\pi\pi} \simeq 6$ ($\Gamma_{\rho\to\pi\pi} = 149\,{\rm MeV}$)	$g_{\tilde\rho\tilde\pi\tilde\pi} = g_{\rho\pi\pi}$ ($f^{abc}\rho^a_\mu \pi^b \partial^\mu \pi^c = i\rho^\mu(\pi^- \overleftrightarrow{\partial}_\mu \pi^+) + \cdots$) determines $\Gamma_{\tilde\rho\to\tilde\pi\tilde\pi}$

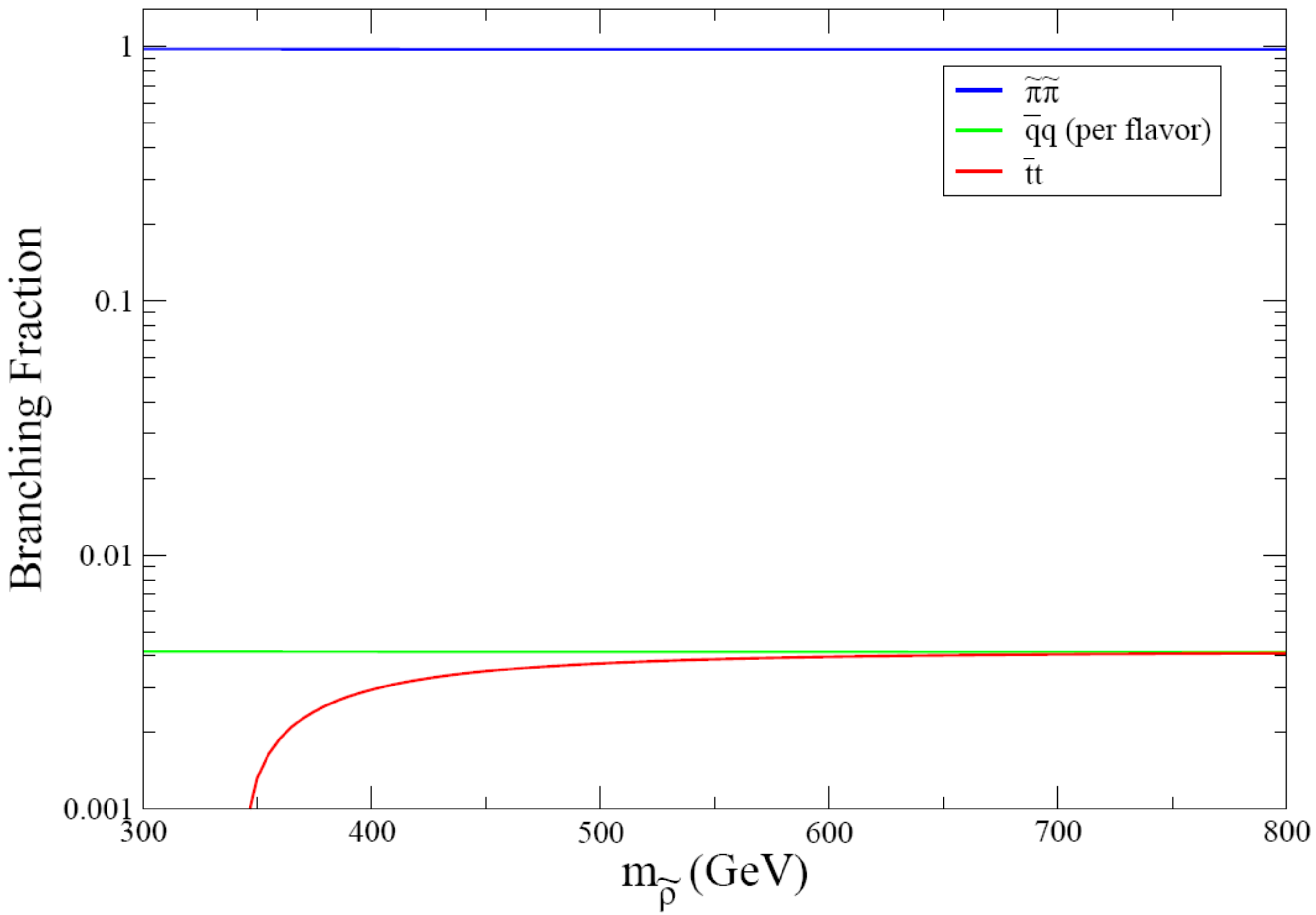
MOVING ON UP - II

QCD	HYPERCOLOR
$-e\varepsilon\rho_\mu\overline{e}\gamma^\mu e$ $\varepsilon \simeq 0.06$ $(\Gamma_{\rho\to e^+e^-} = 7.04\ \mathrm{keV})$	$-g_3\tilde{\varepsilon}\,\tilde{\rho}^a_\mu\,\overline{q}\gamma^\mu T^a q$ $\tilde{\varepsilon} = \frac{g_3}{e}\varepsilon \simeq 0.2$ σ_{prod} fixed $\Gamma_{\tilde{\rho}\to q\bar{q}}/\Gamma_{\tilde{\rho}\to\tilde{\pi}\tilde{\pi}}$ fixed by $\tilde{\varepsilon}/g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}}$

MOVING ON UP - III

QCD	HYPERCOLOR
	
$c\, m_\rho^2\, f_\pi^2\, \mathrm{Tr}\left[\Sigma^\dagger Q \Sigma Q\right] \longrightarrow$	$c\, m_{\tilde{\rho}}^2\, f_{\tilde{\pi}}^2 \sum_a \mathrm{Tr}\left[\tilde{\Sigma}^\dagger T^a \tilde{\Sigma} T^a\right] \longrightarrow$
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\frac{m_{\tilde{\pi}}^2}{m_{\tilde{\rho}}^2} = 3\, \frac{g_3^2}{e^2}\, \frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{m_\rho^2}$
	$m_{\tilde{\pi}} \simeq 0.3 m_{\tilde{\rho}}$

Coloron Decay

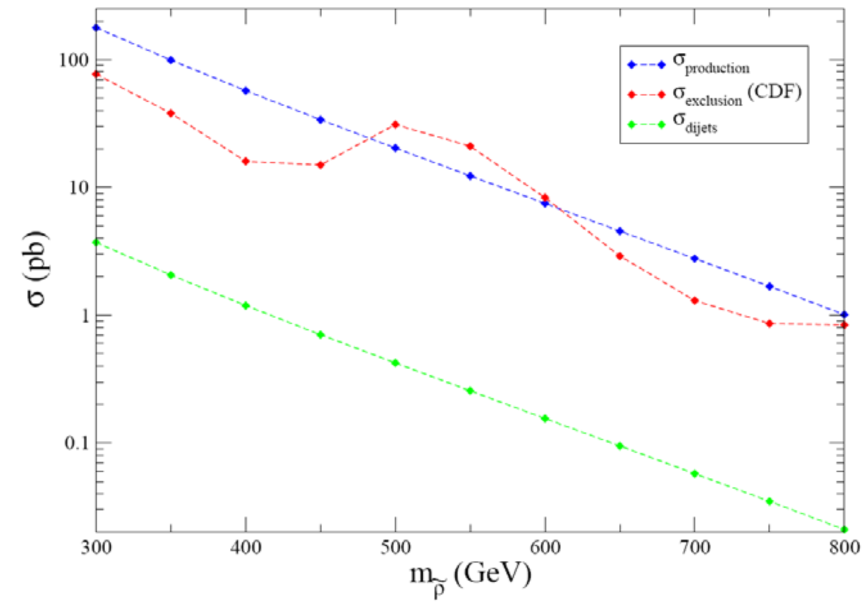


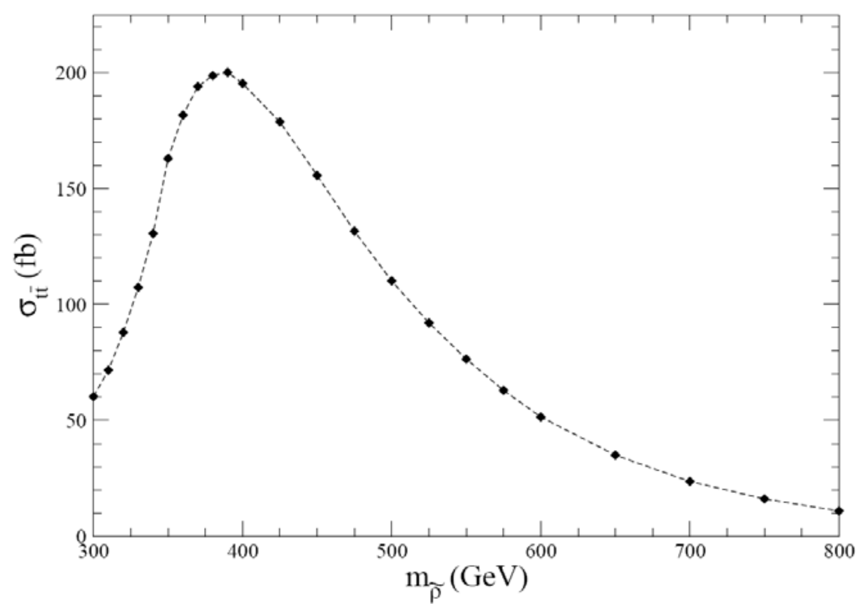
Constraints on $\tilde{\rho}$

- Dijet resonance searches
- $t\bar{t}$ production
- Multi-jet studies

  Run I (105 pb^{-1})

  Severe cuts
- Global searches





Constraints on $\tilde{\pi}$

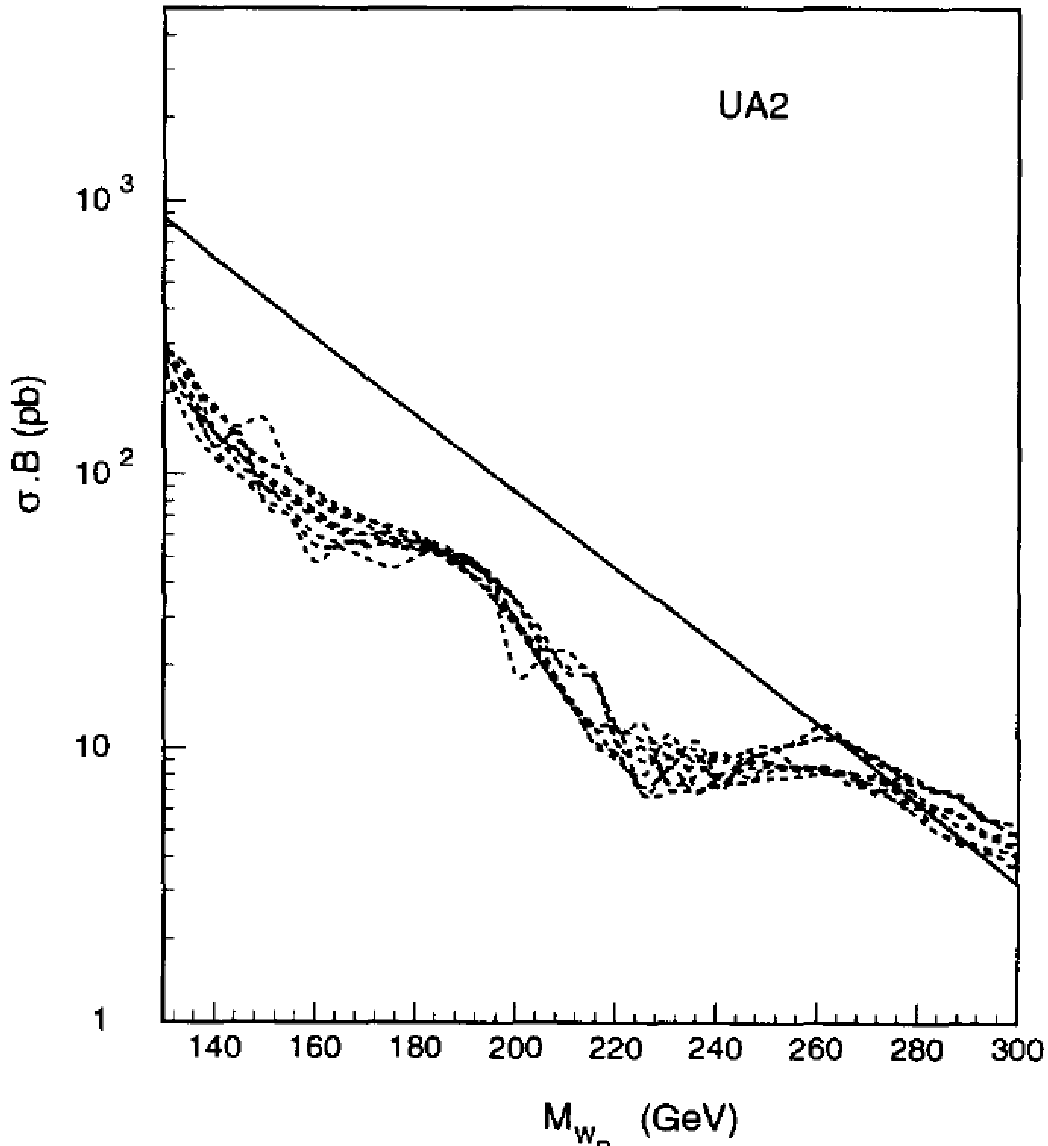
- $gg \to \tilde{\pi}$ is loop suppressed
  - $Sp\bar{p}S$:

    $\sigma(p\bar{p} \to \tilde{\pi}) \simeq 21\,\mathrm{pb}$

    for $m_{\tilde{\pi}} = 100\,\mathrm{GeV}$
  - Tevatron Run I:

    $\sigma(p\bar{p} \to \tilde{\pi}) \simeq 4.8\,\mathrm{pb}$

    for $m_{\tilde{\pi}} = 250\,\mathrm{GeV}$
- Pair production
- How light?



Other Sources of Constraints

- LEP direct searches
- Precision Electroweak $\frac{m_{\tilde{\rho}}}{\tilde{\varepsilon}} \geq 450\ \mathrm{GeV}$
- FCNC
- Compositeness
- Other states: Lightest Hyper-Baryon

  Stable if $\mathrm{U}(1)_{\mathrm{HB}}$ is exact

  Same quantum numbers as a gluino

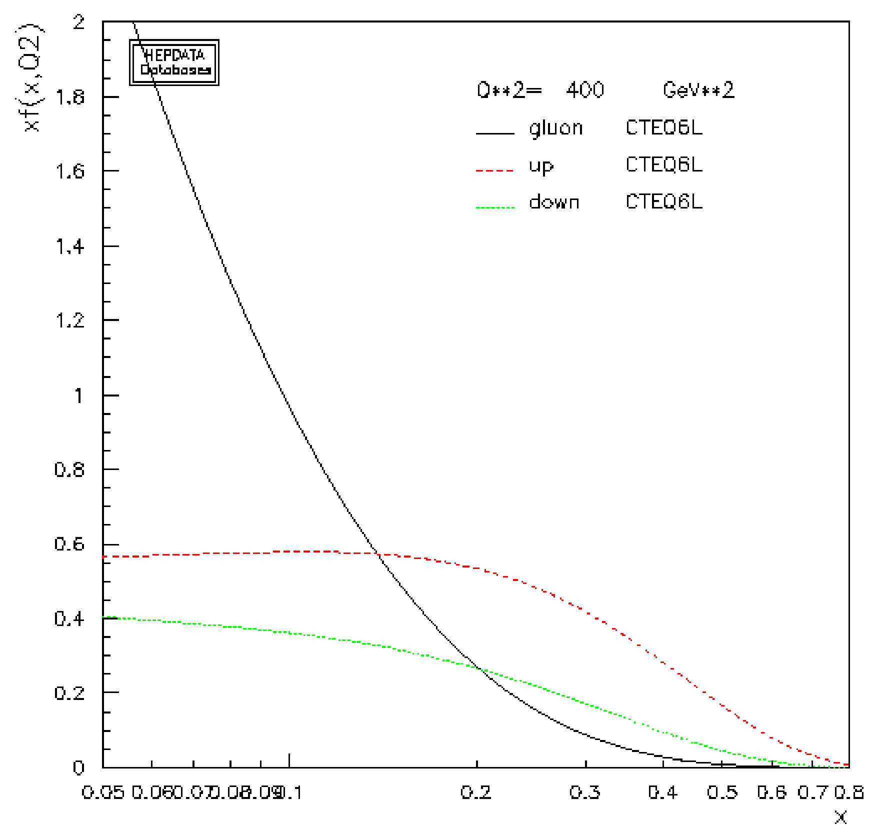
  Straightforward to break $\mathrm{U}(1)_{\mathrm{HB}}$

Search Strategy

- Signal $\tilde{\rho} \longrightarrow \tilde{\pi}\tilde{\pi} \longrightarrow gggg$
  Background: QCD 4j
- Effect of PDF's
- Margin of error
- Two benchmarks:

$$m_{\tilde{\rho}} = 350 \text{ GeV and } m_{\tilde{\pi}} = 100 \text{ GeV}$$
$$m_{\tilde{\rho}} = 600 \text{ GeV and } m_{\tilde{\pi}} = 180 \text{ GeV}$$

- Emulate triggers
  leading jet p_T ¤ 120GeV



Case I : Lighter Coloron

- Event generation:

  parton level: MadEvent
  shower/hadronization: Pythia
  detector simulation: PGS
  cone jets: $\Delta R=0.7$

- Use different p_T hierarchy in signal vs. background

  Cut: Four jets with p_T ¤ 40GeV

- Signal: $1fb^{-1}$, 3.6 pb after cuts

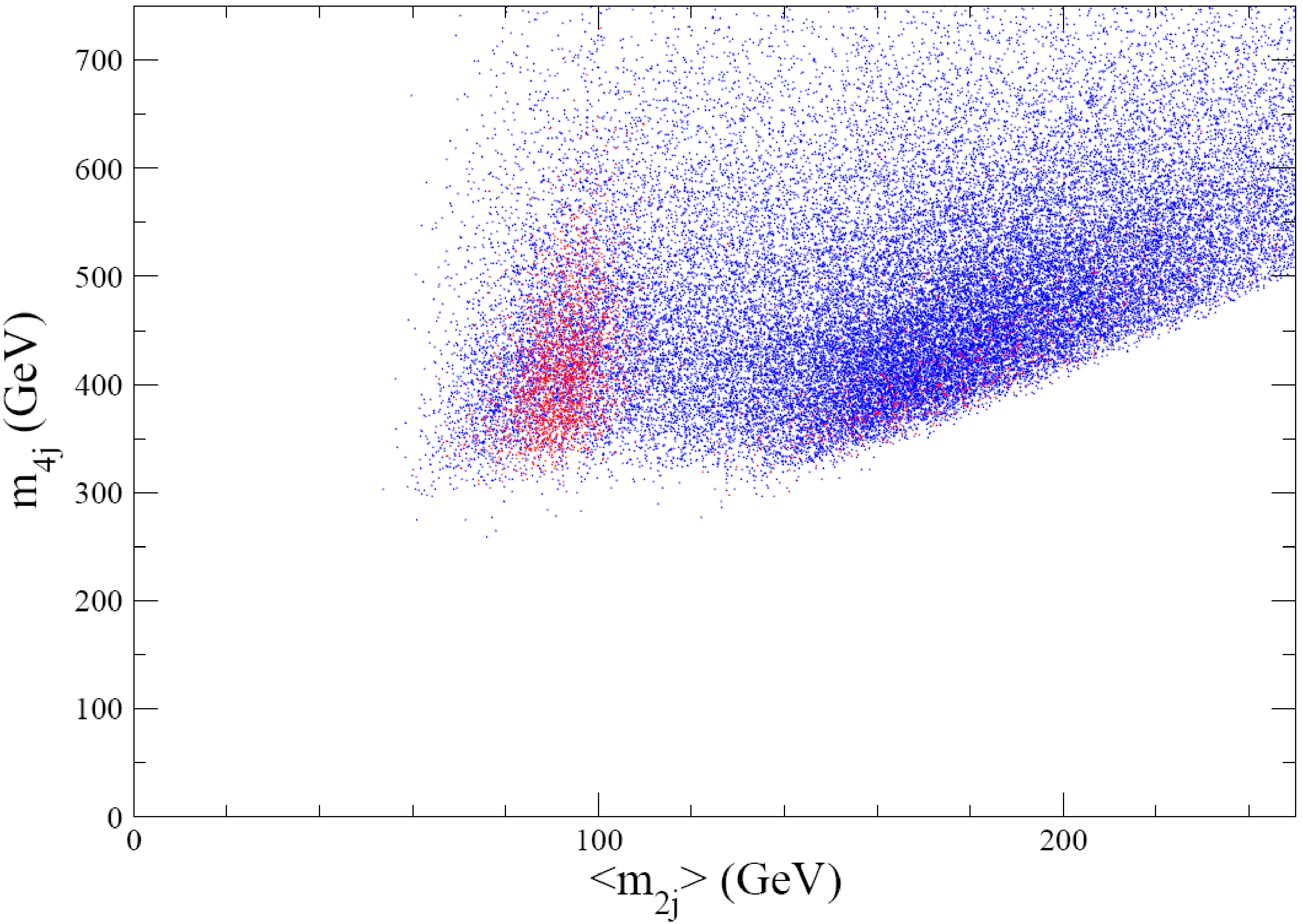
  Background: $2fb^{-1}$, 66 pb after cuts

- Pairing:

  signal: 2.7 pb after cuts
  background: 21 pb after cuts

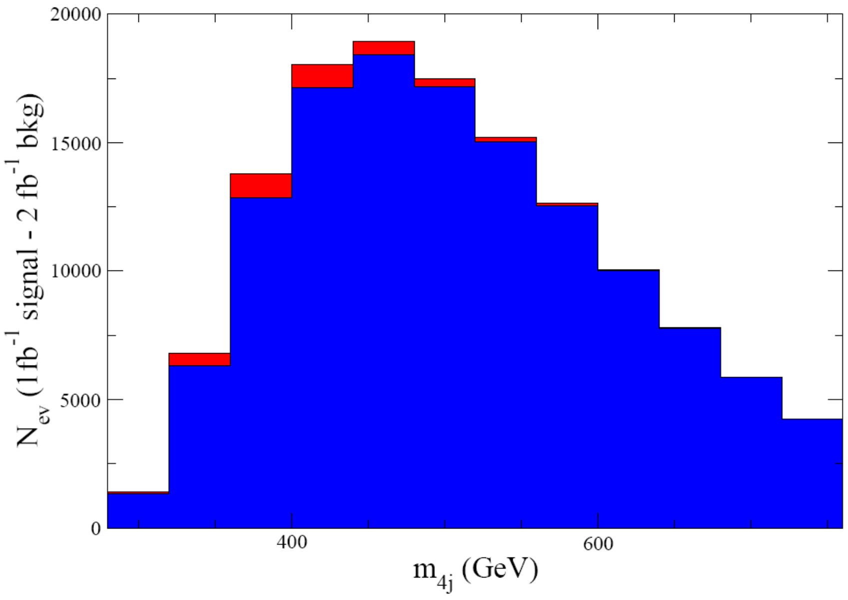
- Significance estimate $$\chi^2 = \sum_{bins} \left(\frac{n_s}{\sqrt{n_b}} \right)^2$$

The Result: Significance of Excess is 32.3σ



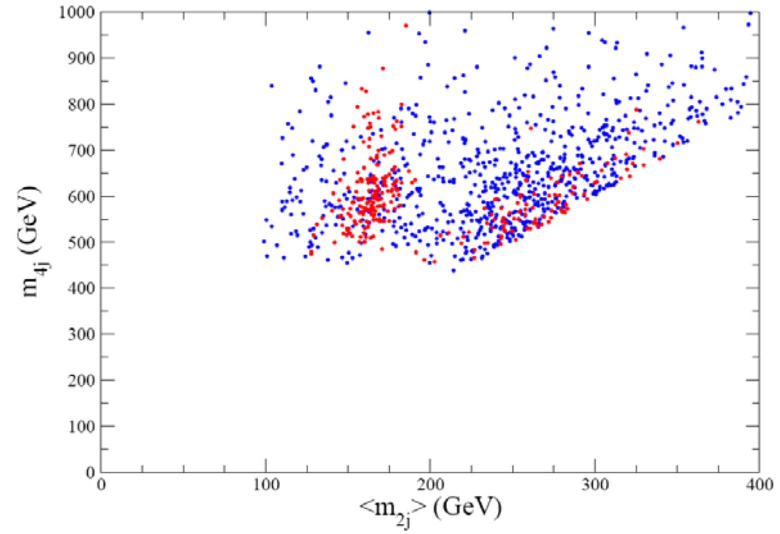
Model Independent Search

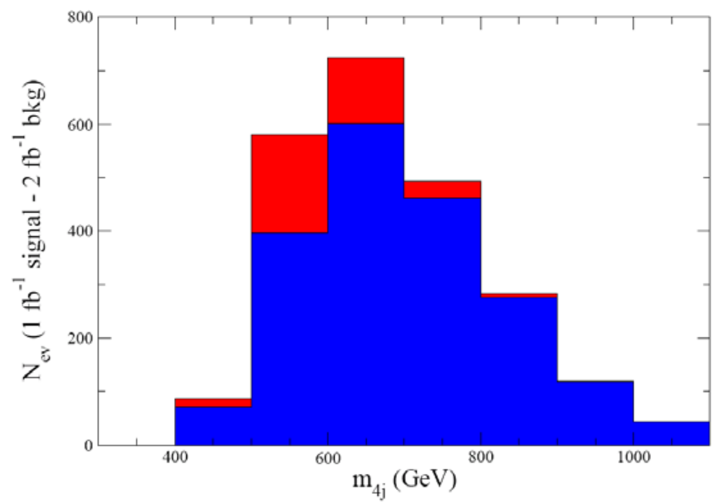
- Without pairing: Sensitive to alternative models but smaller significance
- Signal in the lower bins $S/\sqrt{B}$ is 13.4σ (8.3σ for bins above 400 GeV)
- Caveats: Cannot impose harder cuts without losing signal



Case II : Heavier Coloron

- Light coloron discoverable despite low trigger efficiency, larger background
- Now we can impose harder cuts (4 jets with p_T ¤ 90GeV)
- Signal: $1fb^{-1}$, 0.36 pb
  Background: $2fb^{-1}$, 0.99 pb
  (after cuts)
- Pairing:
  signal: 0.27 pb
  background: 0.38 pb
- Significance: 17.2σ
- 10.8σ for less model-dependent search, excess shape is more reliable than before.





OUTLOOK AND CONCLUSIONS

- Colorons are generic physics objects appearing in various contexts.
- Model with QCD analog experimentally allowed for masses as light as few hundred GeV.
- Search strategy in multijet channel at the Tevatron looks promising for a range of parameters.
- Prospects for the LHC:
  - pp machine: PDF's for signal vs. background
  - higher luminosity and trigger thresholds
  - other states in the model
- Variations of the model:
  - direct couplings to quarks
  - less minimal flavor structure
  - LHC regime: better prospects than minimal model
  - additional states: heavy colored fermions

BACKUP SLIDES

S EEKING

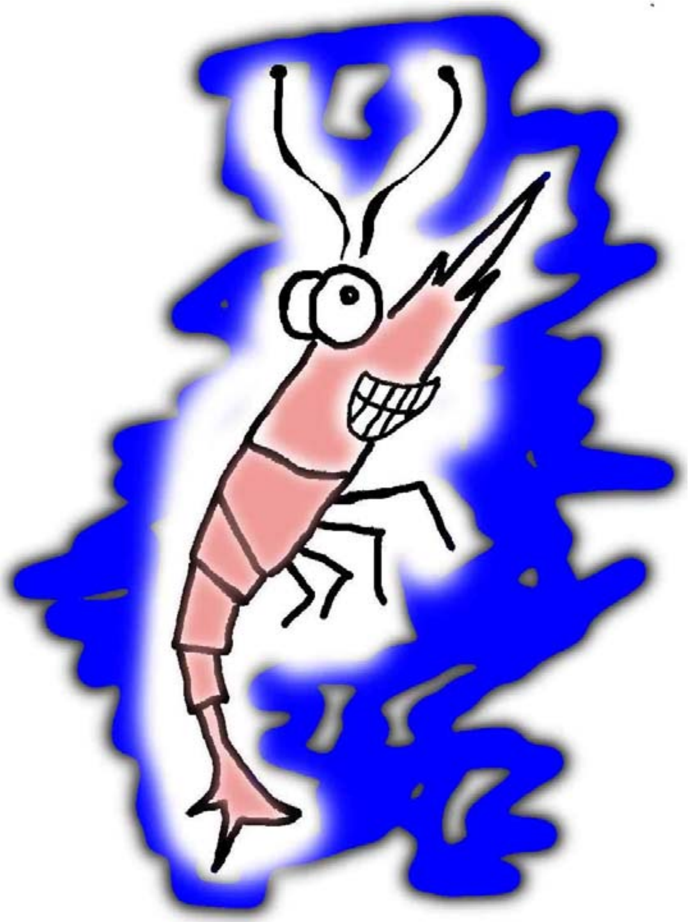
H ADRONIC

R ESONANCES

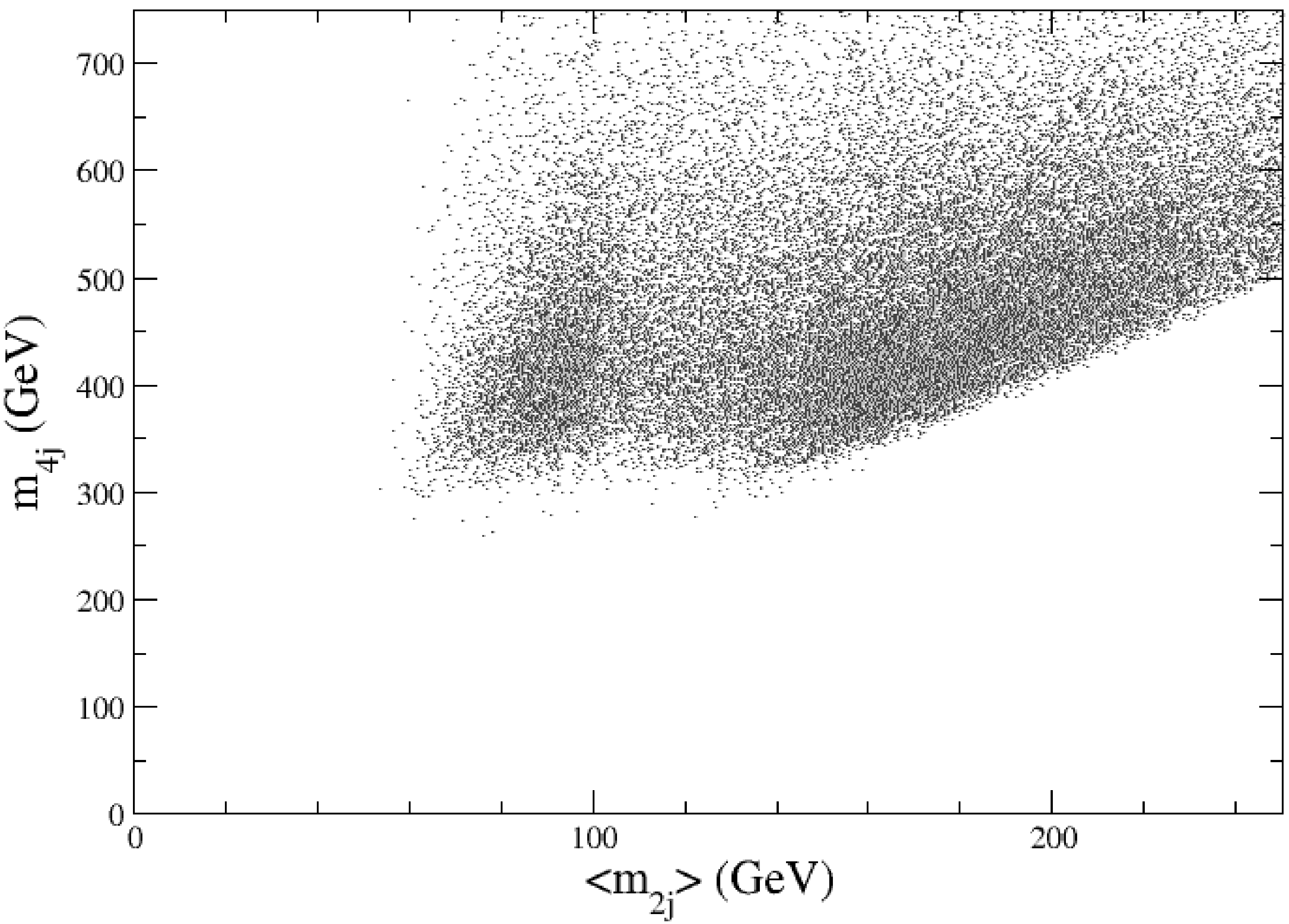
I N

M ULTIJET

P EAKS



Search Plot Without Coloring
Lighter Coloron



Search Plot Without Coloring
Heavier Coloron