Colored Resonances at Tevatron:

Phenomenology and Discovery Potential in Multi-jets

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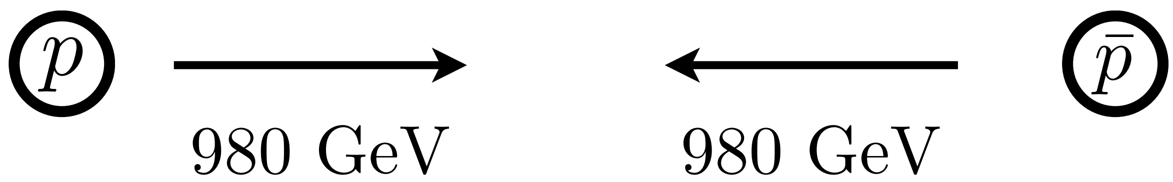
ArXiv:0802.2568

with C. Kilic and R. Sundrum

Energy Frontier in Particle Physics

Tevatron currently running



Large Hadron Collider (LHC)

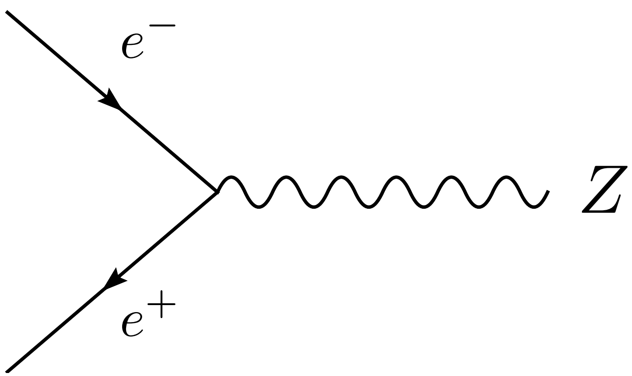
Coming Very Soon!

These are *hadron* colliders, while

LEP $(e^+\text{-}e^-)$ HERA $(e\text{-}p)$

- $e^+\text{-}e^-$ machines

  Good for exploring electroweak physics



- $e\text{-}p$ machines

  Parton distributions

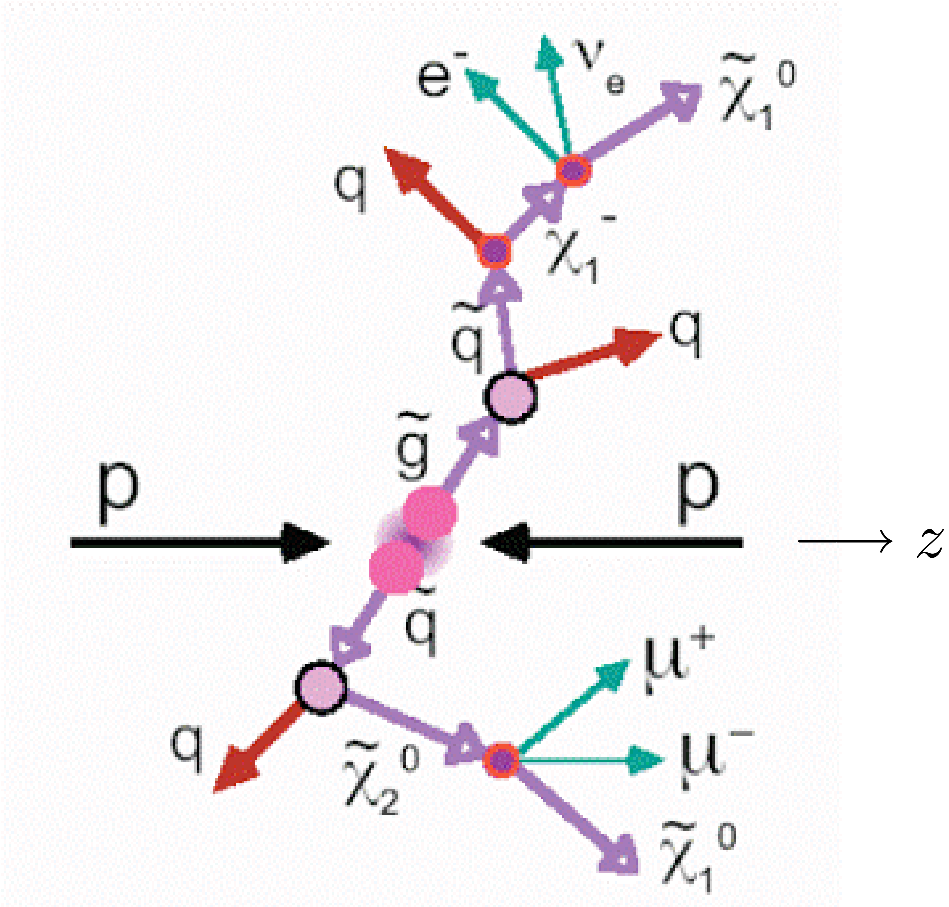
  Lepto-quarks

- Hadron machines

  Good for *producing* colored stuff,

  but *not* good for *studying* colored stuff...

So, we usually hope for distinctive final *objects*:

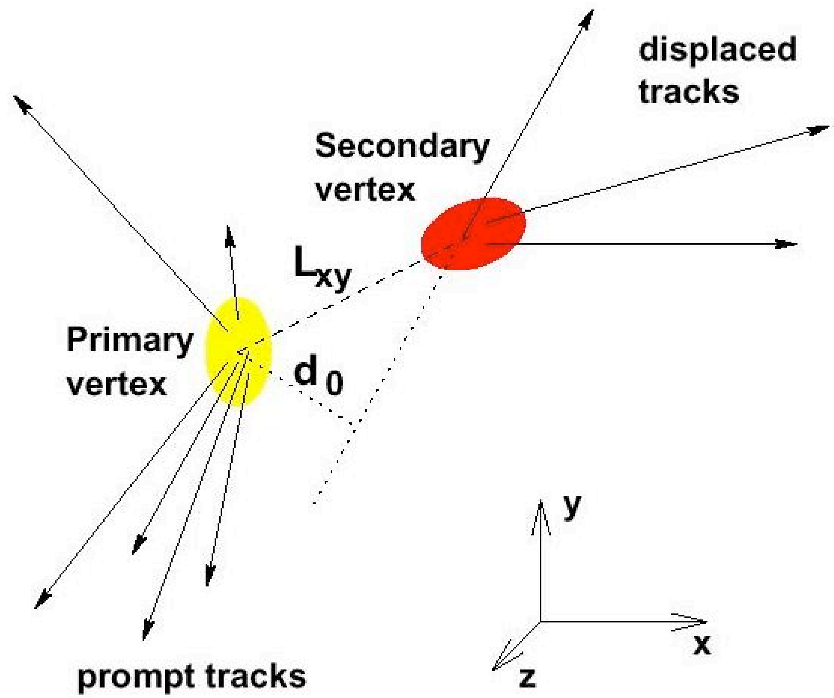


Typical SUSY cascade

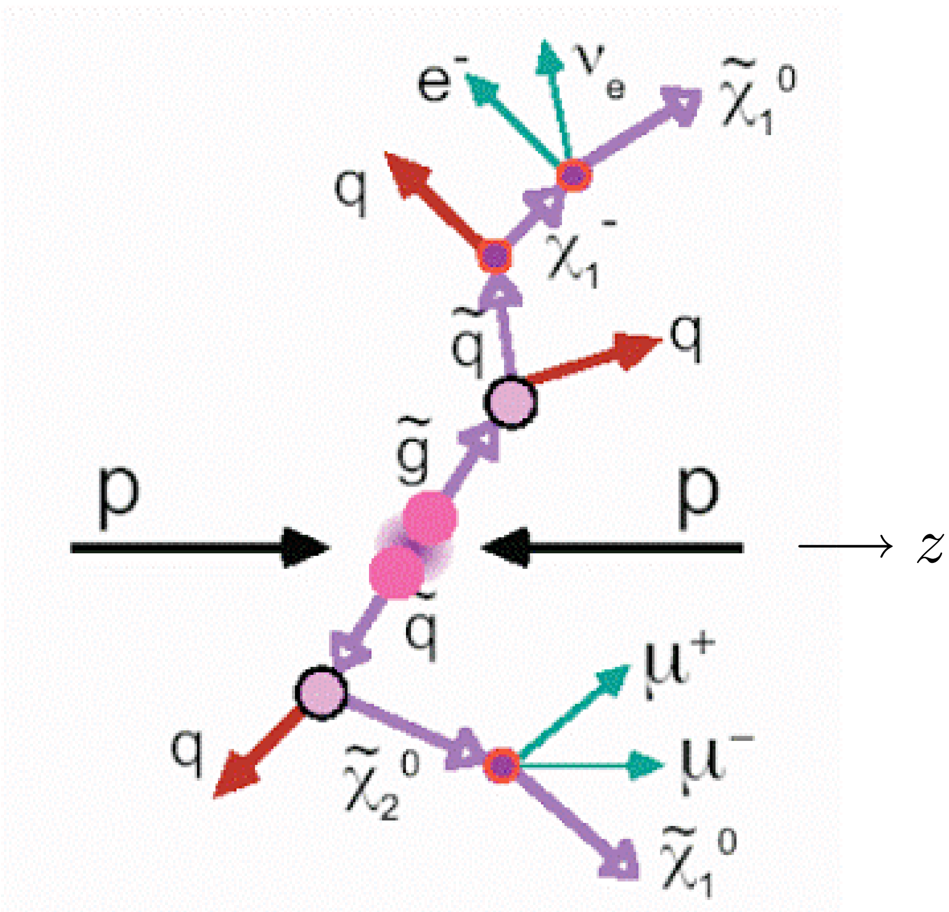
leptons, photons,

missing $p_T \equiv \sqrt{p_x^2 + p_y^2}$

displaced vertices



So, we usually hope for distinctive final *objects*:



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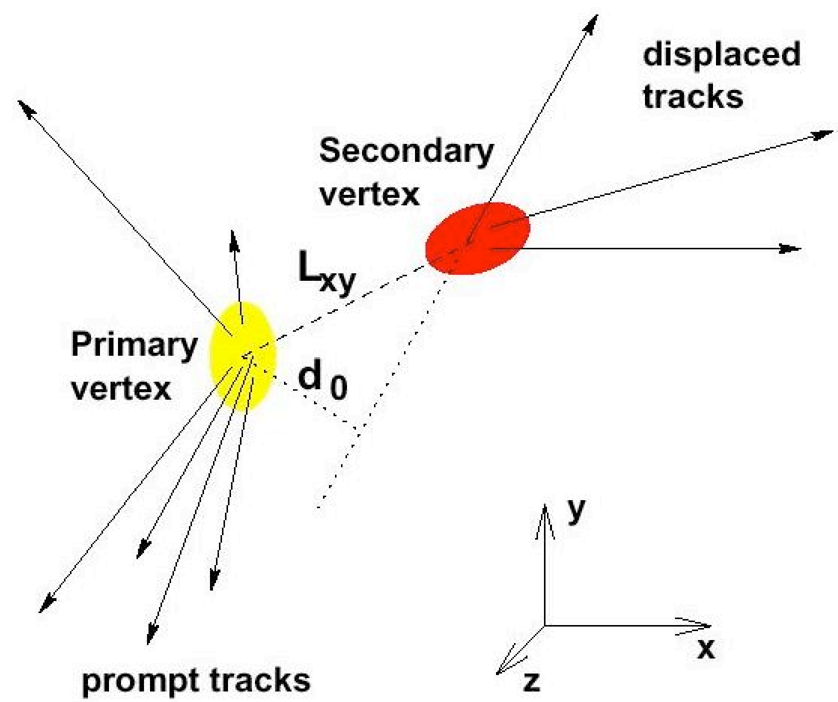
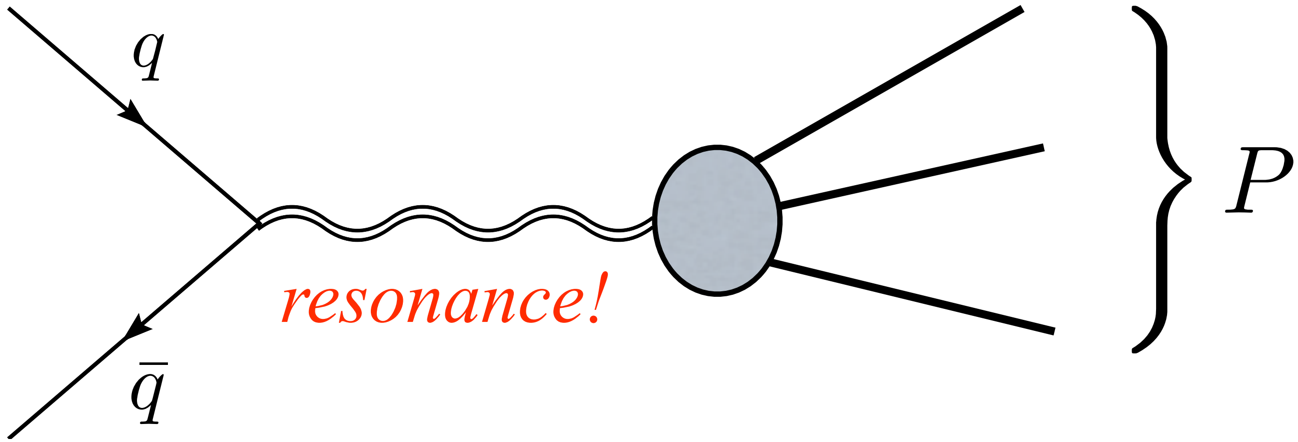


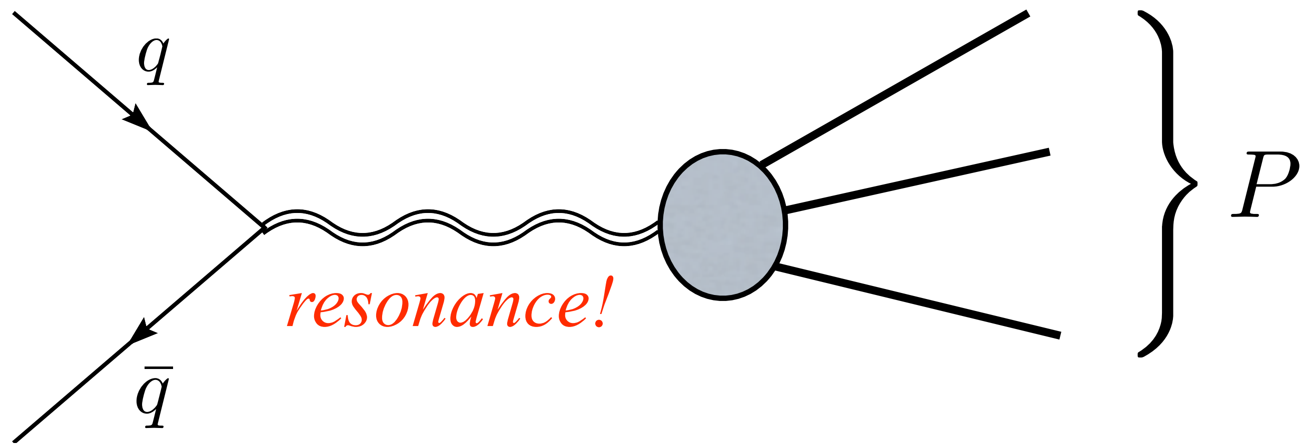
Is it hopeless w/o distinctive objects?

Not necessarily! Here's an alternative:

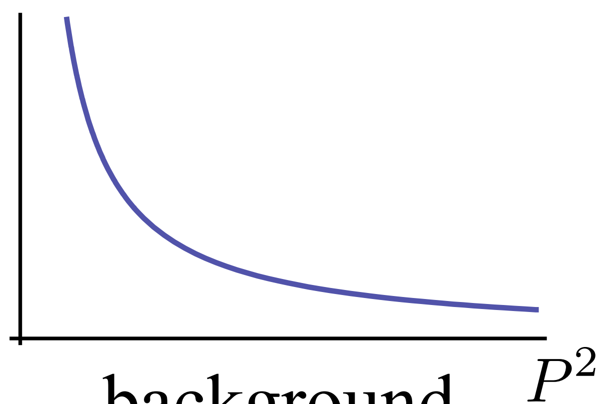


- ***HUGE*** production cross section! vs typical QCD pair-production cross section

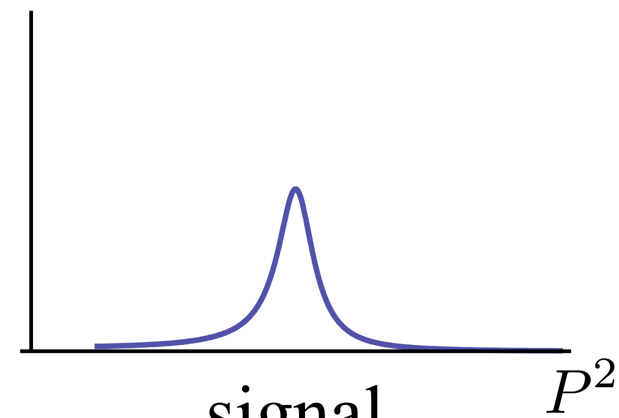
Not necessarily! Here's an alternative:



- ***HUGE*** production cross section! vs typical QCD pair-production cross section
- Distinct *shape* in distribution
  vs distinctive objects



background



signal

Maybe possible to pick out!

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It takes no theorists' effort to have such a thing.

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

↑

a new confining force

"hyper-color"

It takes no theorists' effort to have such a thing.

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

a new fermion

colored & hyper-colored

"hyper-quarks"

a new confining force

"hyper-color"

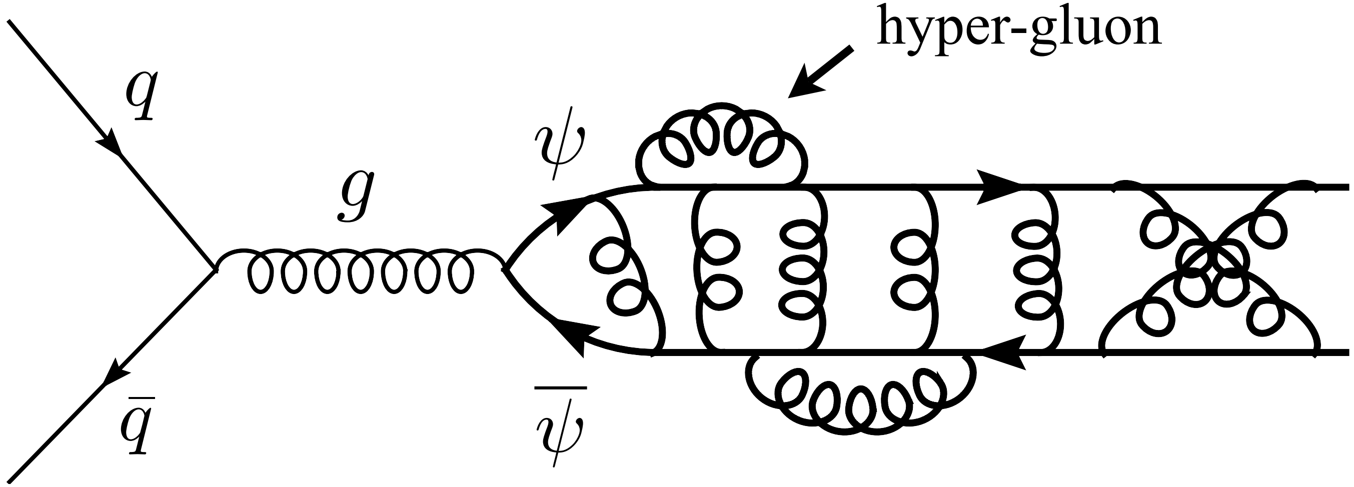
That's it!

Very simple!

Can easily be a part of a bigger model. (Like Z'.)

(e.g. KK gluon, top color, non-minimal technicolor, ...)

Now, this must happen:

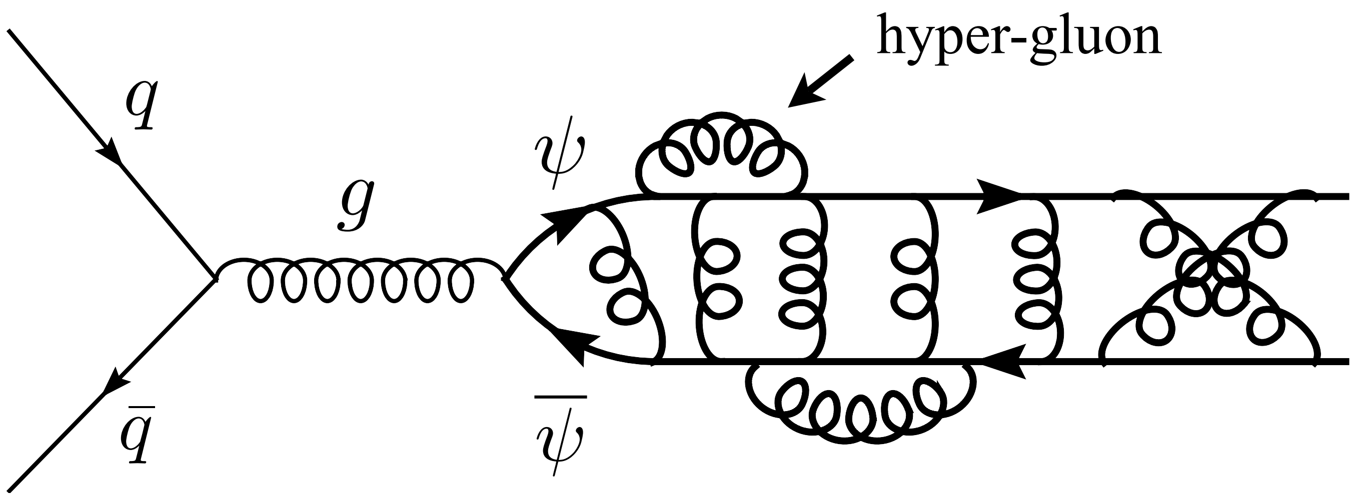


"coloron" $\tilde{\rho}$

spin-1

color octet

Now, this must happen:

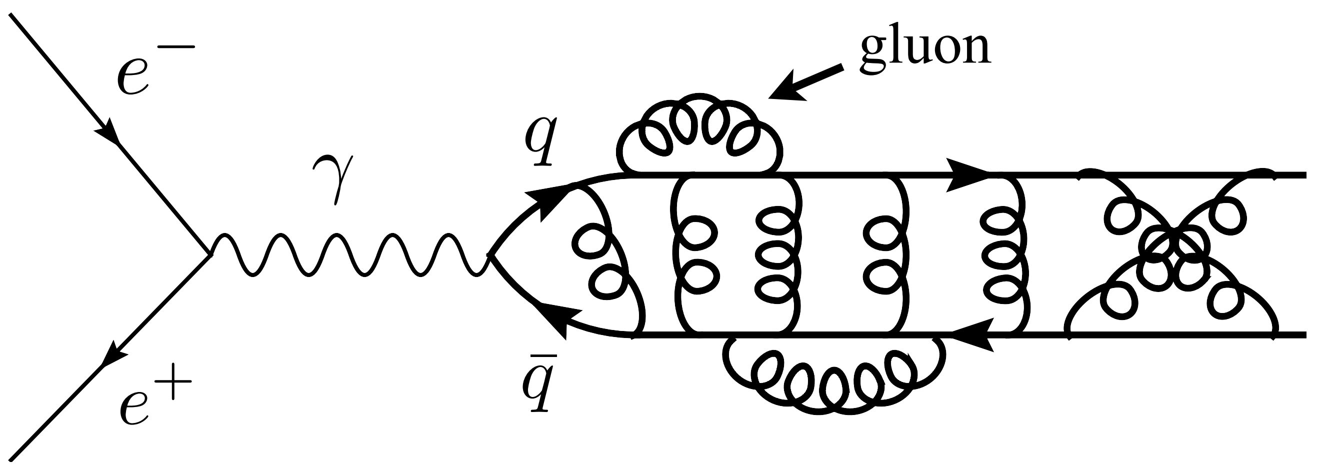


"coloron" $\tilde{\rho}$

spin-1

color octet

Nature has already done this trick once:



ρ meson

spin-1

electrically neutral

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What is the coloron mass scale?

Hyper-sector has $\begin{cases} \text{no connection to electroweak sector} \\ \text{no connection to flavor physics} \end{cases}$

$\Longrightarrow$ Not constrained by EW precision or flavor physics data!

$\Longrightarrow$ Coloron can be light, *within Tevatron reach!*

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$\Longrightarrow$ Coloron can be light, *within Tevatron reach!*

(vs typical story:

New phys "tagged" by EW processes, heavy flavor, etc.

$\Longrightarrow$ Constrained by EW precision, flavor phys.

$\Longrightarrow$ New physics must be heavy or "well hidden"

$\Longrightarrow$ Out of Tevatron reach. Wait for LHC...)

Summary so far

* A coloron (spin-1 color-octets) can appear quite naturally in physics beyond the standard model

* Colorons are resonantly produced at hadron colliders

* Coloron can be very light, within the Tevatron reach

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* A coloron (spin-1 color-octets) can appear quite naturally in physics beyond the standard model

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Outline for the rest

(1) A representative model of coloron

(2) Constraints on the representative model

(3) Discovery Potential at the Tevatron

A Representative Model

Microscopic Lagrangian:

with three hyper-colors

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

A Representative Model

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

Can use QCD as an "analog computer"!

QCD	Hyper-sector
$SU(3)_{\rm col}$	$SU(3)_{\rm hyp\text{-}col}$
quarks	hyper-quarks
$SU(3)_{\rm iso}$	$SU(3)_{\rm iso}$

[Neglect (hyper-)quark masses & weak interactions]

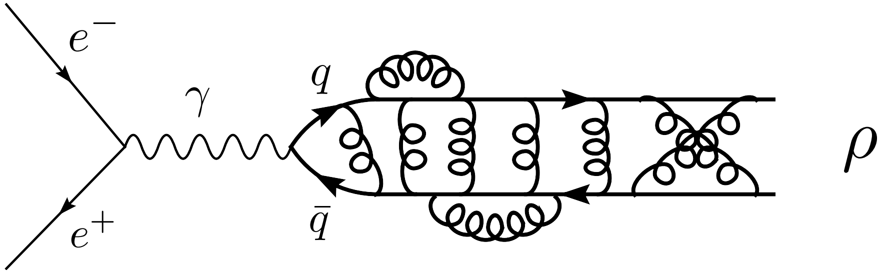
Recall in QCD,

$$SU(3)_{\rm iso} \supset \text{ 8 charges acting on } \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

One linear combination is electric charge:

$$Q = T^3 + T^8/\sqrt{3} = \begin{pmatrix} 2/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 0 & -1/3 \end{pmatrix}$$

which couples to photon:



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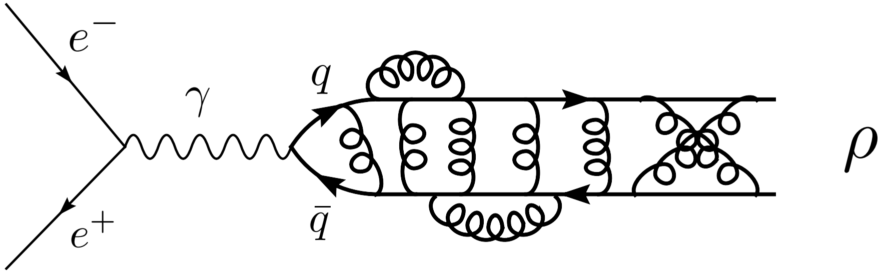
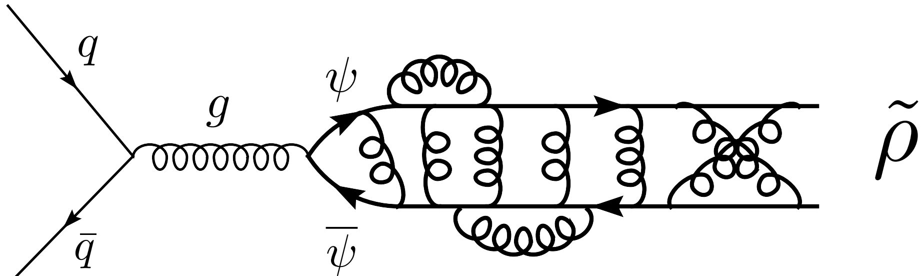


In our scenario,

we couple *all* $SU(3)_{\text{iso}}$ currents to gluons.

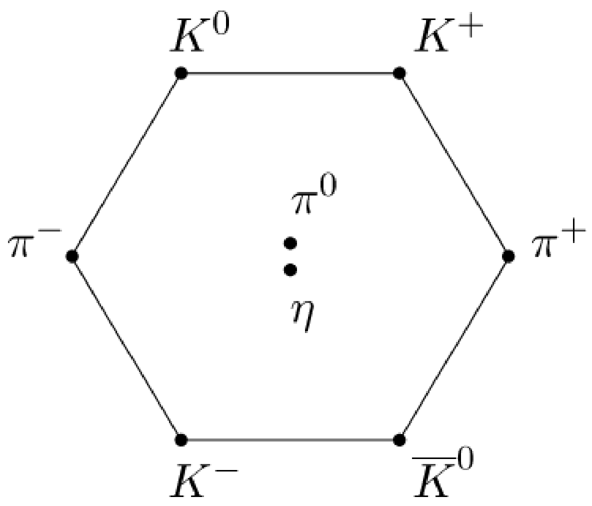
$$SU(3)_{\text{iso}} = SU(3)_{\text{col}}$$



So we have

QCD	Hyper-sector
$SU(3)_{\rm col}$	$SU(3)_{\rm hyp\text{-}col}$
quarks	hyper-quarks
$SU(3)_{\rm iso}$	$SU(3)_{\rm iso}$
$\mathrm{QED} \subset SU(3)_{\rm iso}$	$\mathrm{QCD} = SU(3)_{\rm iso}$
photon	gluon
ρ meson	coloron $\tilde{\rho}$
$e^+e^- \to \rho$	$q\bar{q} \to \tilde{\rho}$

How does a coloron decay?

QCD	Hyper-sector
 $SU(3)_{\rm iso}$ octet	A "*hyper-pion*" $\tilde{\pi}$ in $SU(3)_{\rm col}$ octet!
$\rho \longrightarrow \pi\pi$ nearly 100%	$\tilde{\rho} \longrightarrow \tilde{\pi}\tilde{\pi}$ nearly 100%

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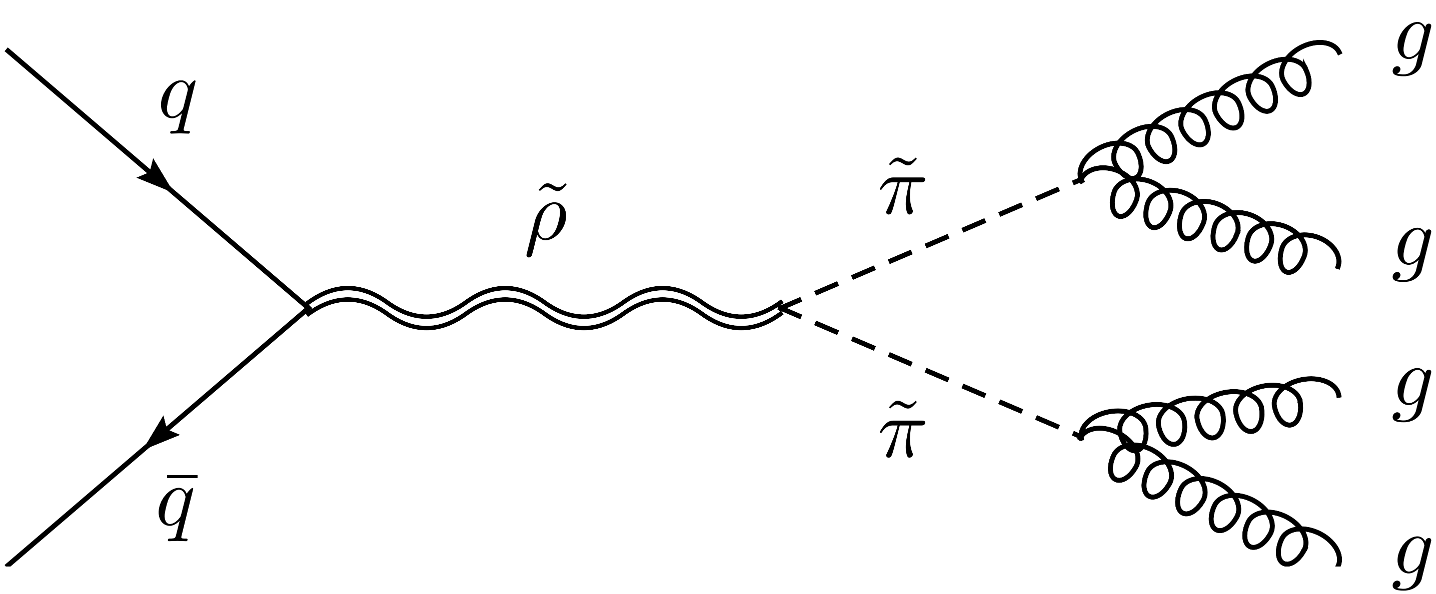
How does a $\tilde{\pi}$ decay?

QCD	Hyper-sector
$\pi \longrightarrow \gamma\gamma$	$\tilde{\pi} \longrightarrow gg$
nearly 100%	nearly 100%

How does a $\tilde{\pi}$ decay?

QCD	Hyper-sector
$\pi \longrightarrow \gamma\gamma$	$\tilde{\pi} \longrightarrow gg$
nearly 100%	nearly 100%

Therefore, this is the dominant process:



Let's analog-compute parameters!

First, change the overall scale

$$m_\rho \longrightarrow m_{\tilde{\rho}}$$

Then,

(a) $m_{\pi^\pm}^2 - m_{\pi^0}^2 \quad \Longrightarrow \quad m_{\tilde{\pi}}^2$

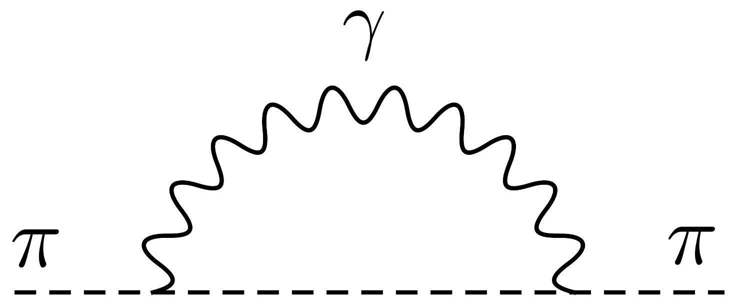
(b) $\Gamma_{\rho\to e^+e^-} \quad \Longrightarrow \quad \tilde{\rho}$-$q$-$\bar{q}$ coupling

(c) $\Gamma_{\rho\to\pi\pi} \quad \Longrightarrow \quad \tilde{\rho}$-$\tilde{\pi}$-$\tilde{\pi}$ coupling

(d) $\Gamma_{\pi\to\gamma\gamma} \quad \Longrightarrow \quad \tilde{\pi}$-$g$-$g$ coupling

(a) Recall in QCD,

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim$$



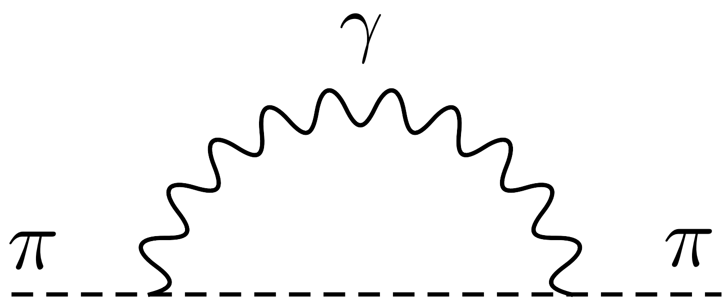
$$\sim \frac{e^2}{16\pi^2}\Lambda^2$$

$$(\Lambda \sim m_\rho)$$

(Nature's solution to "hierarchy problem"!)

(a) Recall in QCD,

$$m^2_{\pi^\pm} - m^2_{\pi^0} \sim$$



$$\sim \frac{e^2}{16\pi^2}\Lambda^2$$

$$(\Lambda \sim m_\rho)$$

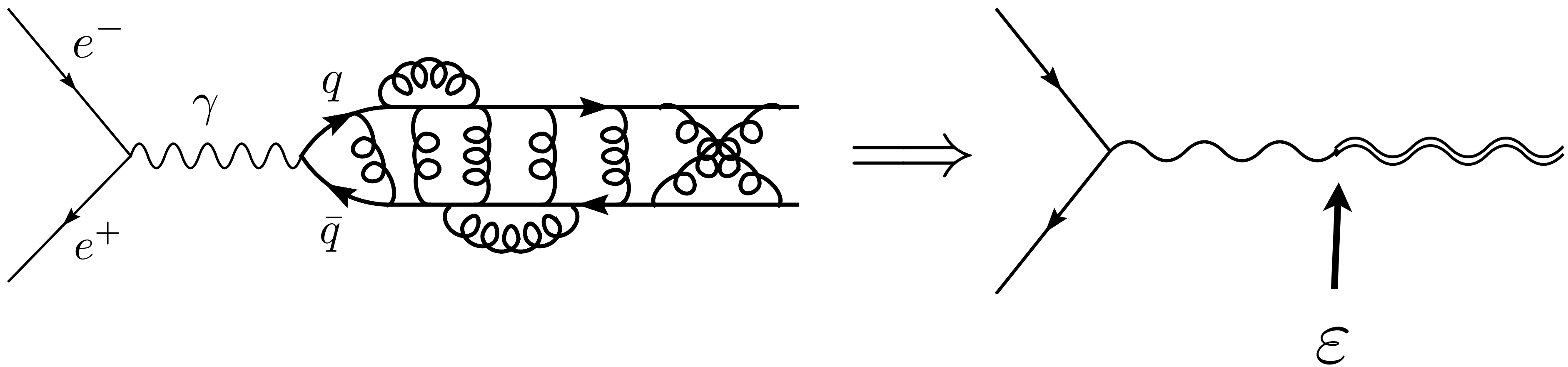
(Nature's solution to "hierarchy problem"!)

So, in our model,

$$m^2_{\tilde{\pi}} \sim \frac{3g_3^2}{16\pi^2} m^2_{\tilde{\rho}}$$

Chiral perturbation theory $\Longrightarrow$ $m_{\tilde{\pi}} \simeq 0.3 m_{\tilde{\rho}}$

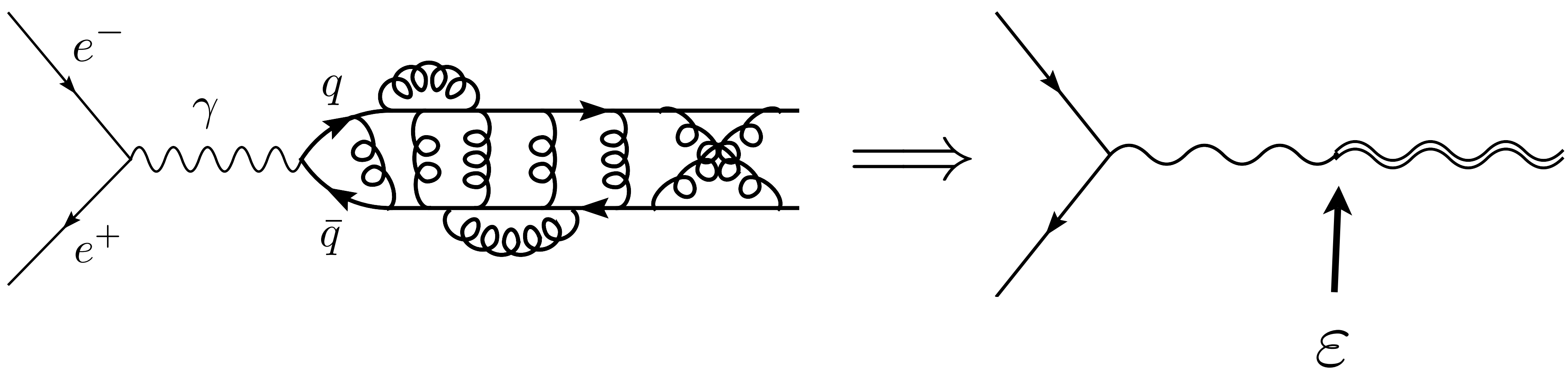
(b) Recall in QCD,



where

$$\Gamma_{\rho\to e^+e^-} \quad \Longrightarrow \quad \varepsilon \simeq 0.06$$

(b) Recall in QCD,



where

$$\Gamma_{\rho\to e^+e^-} \quad \Longrightarrow \quad \varepsilon \simeq 0.06$$

This translates to

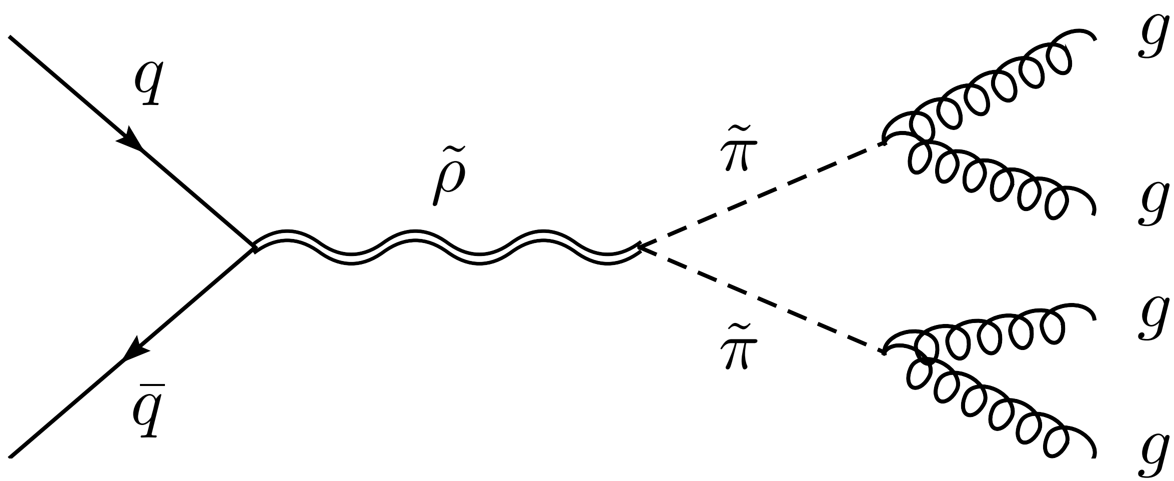
$$\tilde{\varepsilon} = \frac{g_3}{e}\varepsilon \simeq 0.2$$

Summary of the Representative Model

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

$SU(3)_{\text{hyp-col}}$

A hyper-quark (3 colors & 3 hyper-colors)



$\tilde{\rho} \cdots$ spin-1, color-octet

$\tilde{\pi} \cdots$ spin-0, color-octet

- Simplest model of coloron!
- Can extrapolate relevant parameters from QCD.
- Only one parameter $m_{\tilde{\rho}}$ to vary.

Constraints on the Representative Model

- Resonance searches in di-jets
- Resonance searches in t-$\bar{t}$ pairs
- Pair production of $\tilde{\pi}$
- Multi-jet studies
- Electroweak precision, flavor constraints
- Long-lived gluino search

No Constraints on the Representative Model

This simplest model of coloron escapes all existing bounds!

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- Resonance searches in t-$\bar{t}$ pairs
- Pair production of $\tilde{\pi}$
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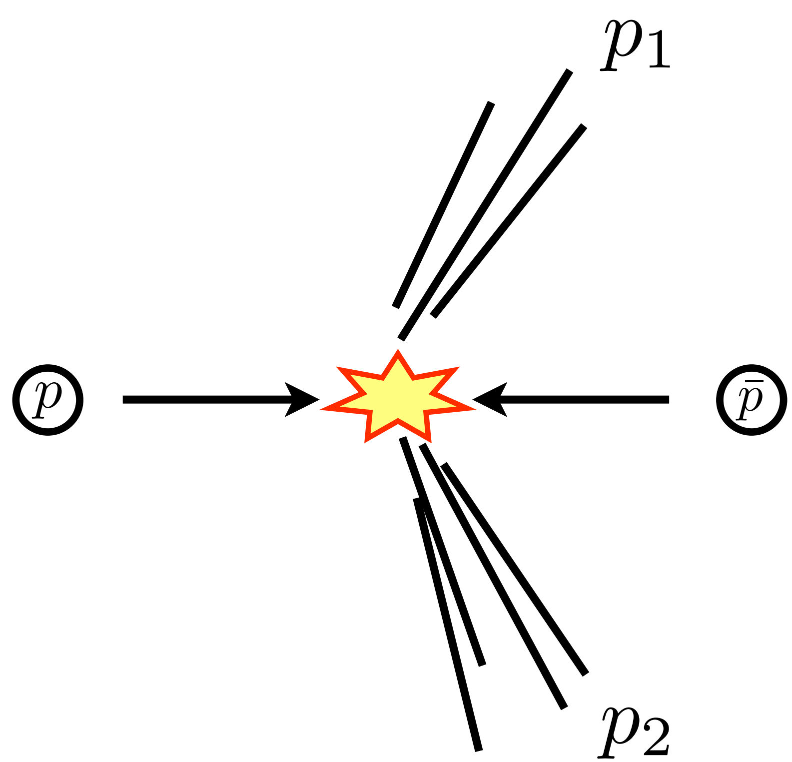
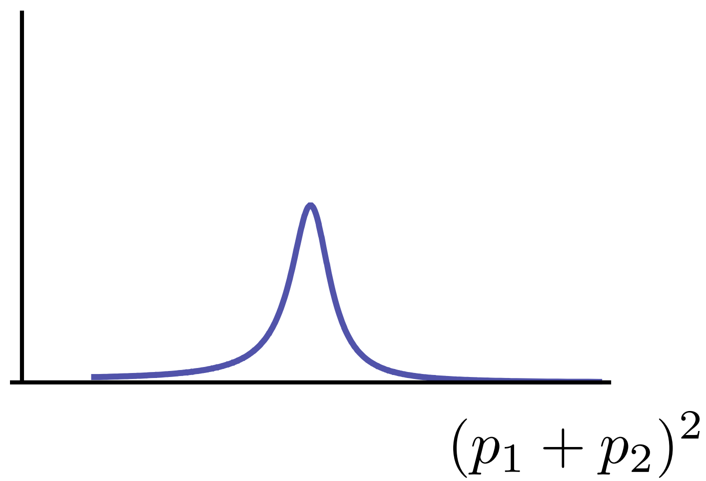
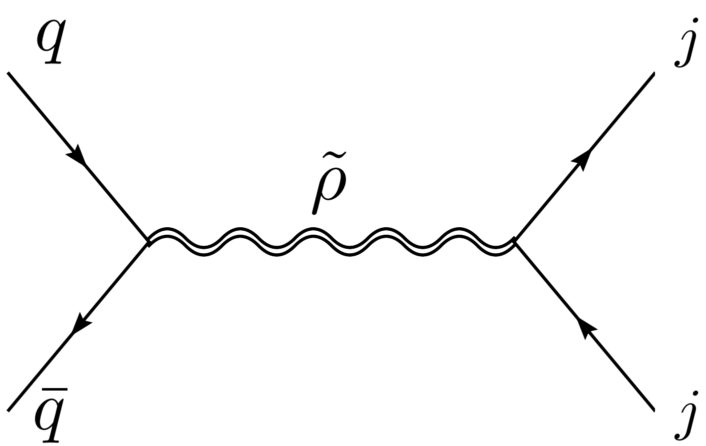
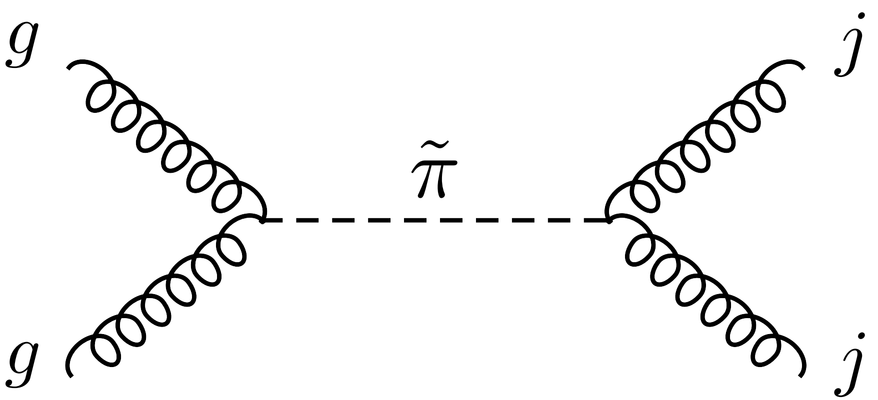
Resonance searches in di-jets



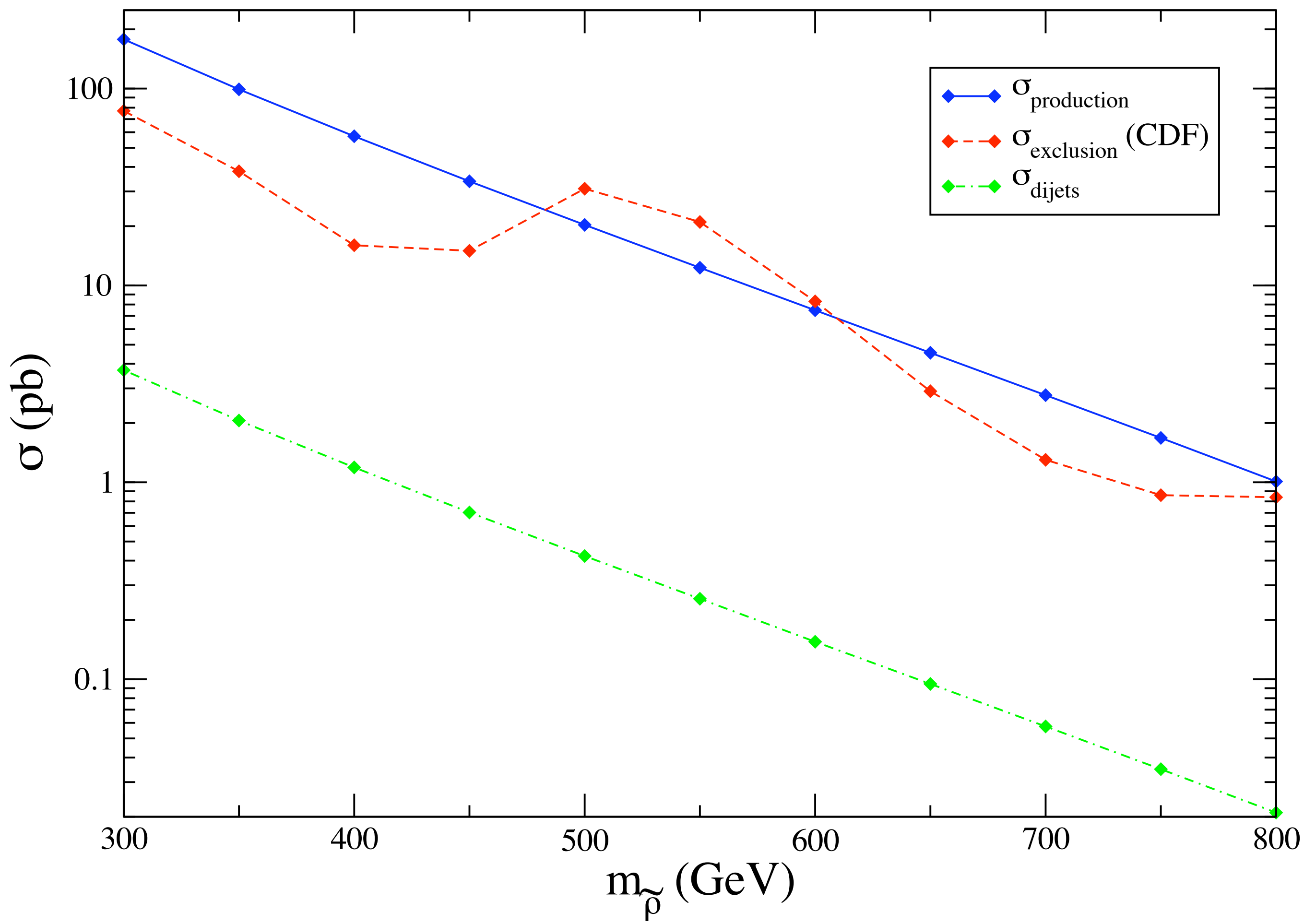


Potentially constrains



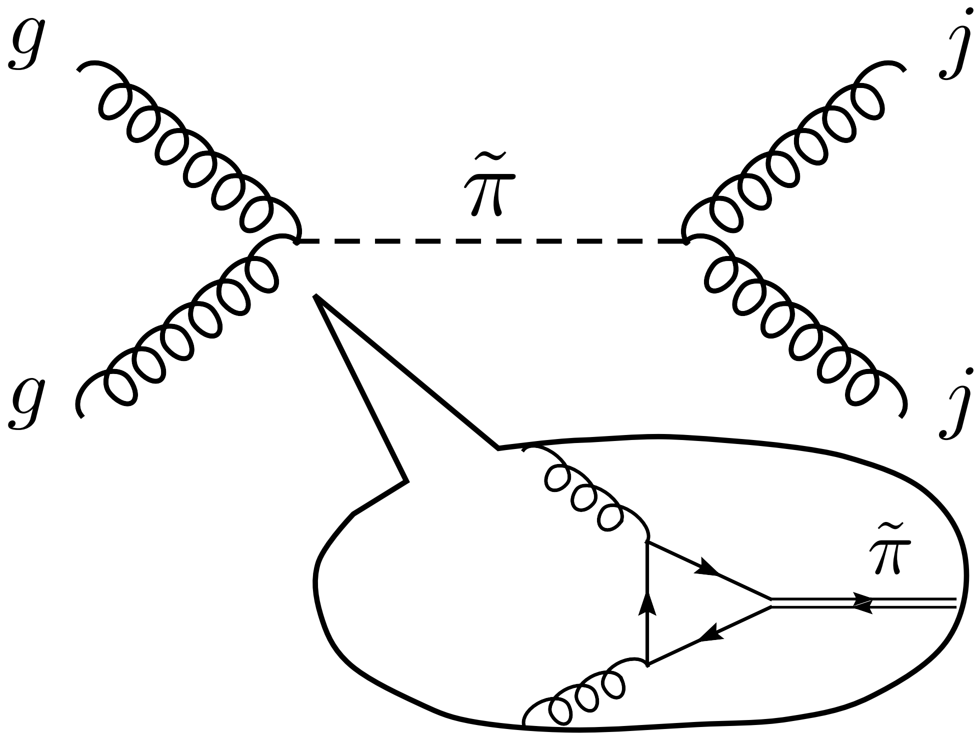


Tevatron Run-I

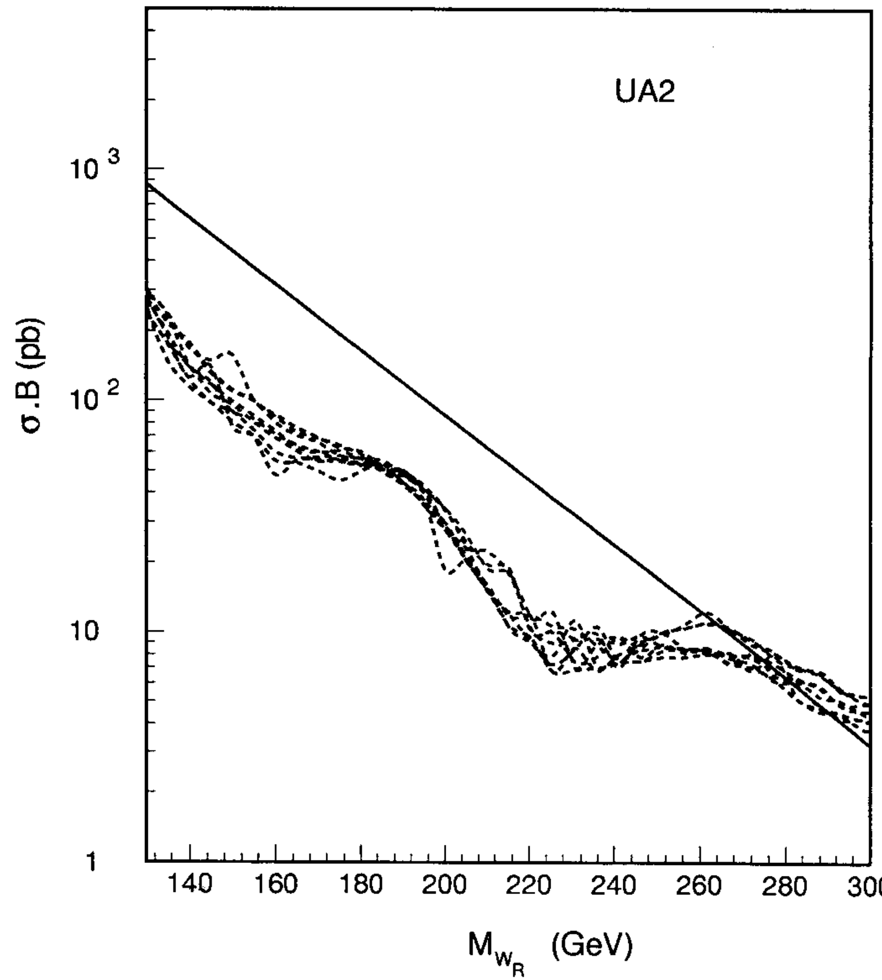


- Dominance of $\tilde{\rho} \to \tilde{\pi}\tilde{\pi}$ crucial!
- Our “scenario” robust!

Resonant $\tilde{\pi}$ production



suppressed by $1/16\pi^2$



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

for $m_{\tilde{\pi}} = 100\,\text{GeV}$

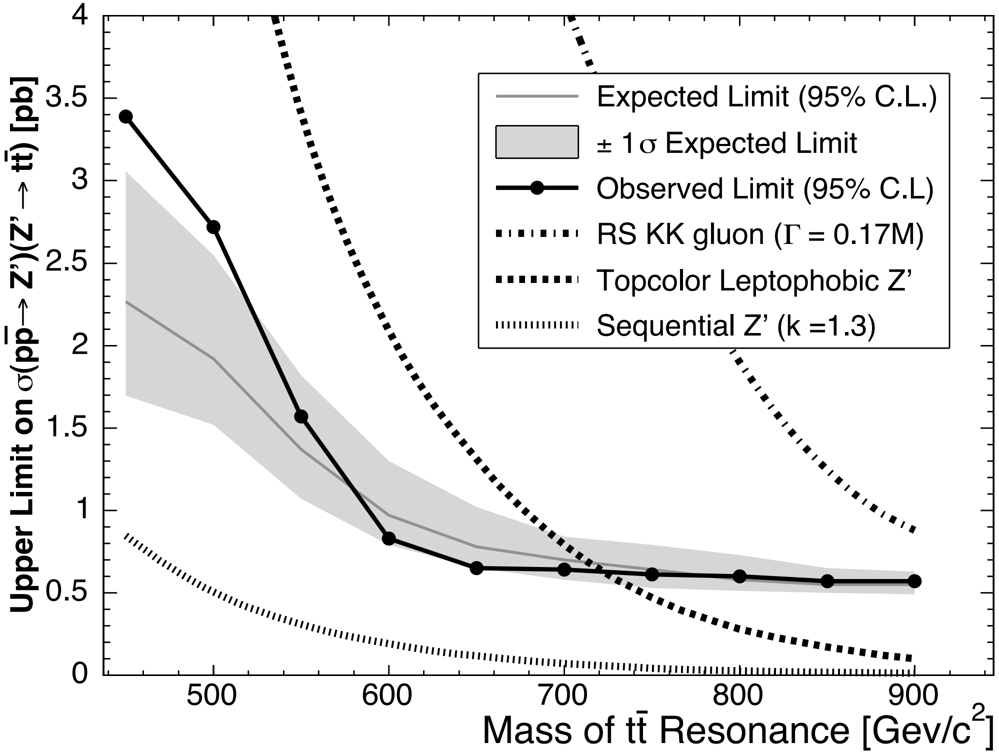
$\sqrt{s} = 630\ \text{GeV}$

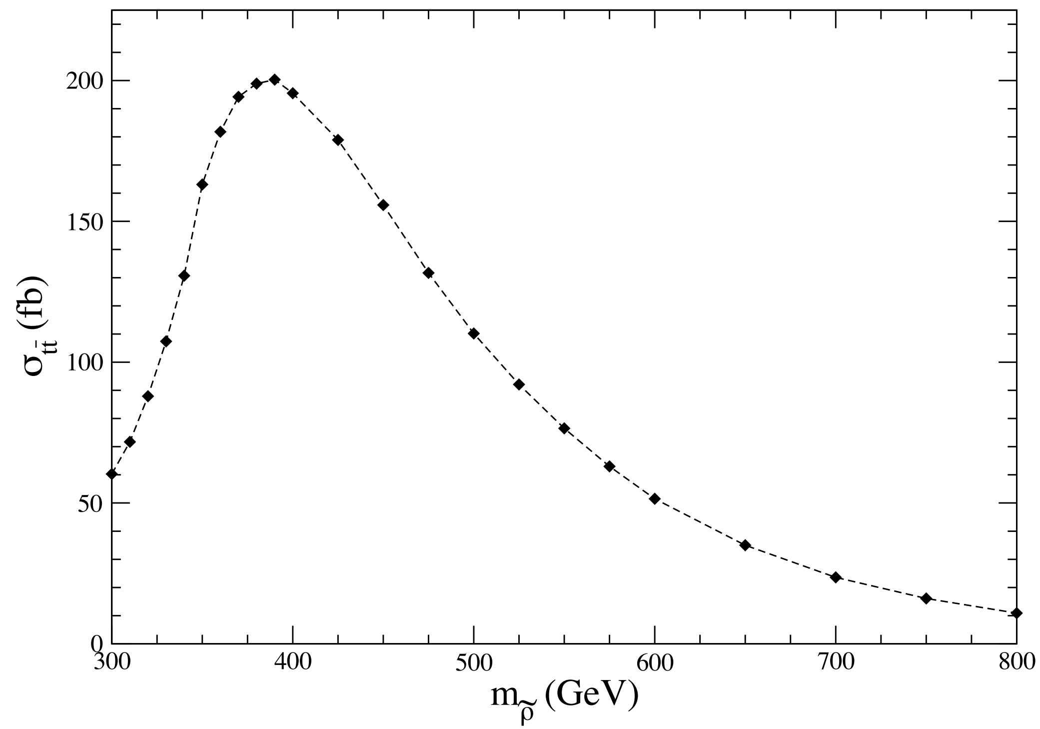
$\sigma(p\bar{p} \to \tilde{\pi}) \simeq 4.8\,\text{pb}$

for $m_{\tilde{\pi}} = 250\,\text{GeV}$

$\sqrt{s} = 1.8\ \text{TeV}$

Resonance searches in t-$\bar{t}$ pairs





Way below the bound!

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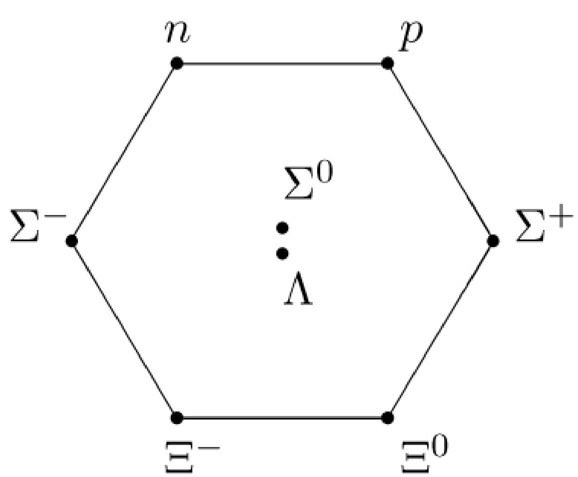
Long-lived "hyper-baryons"

Accidental $U(1)_{\text{hyp-B}}$ at renormalizable level.

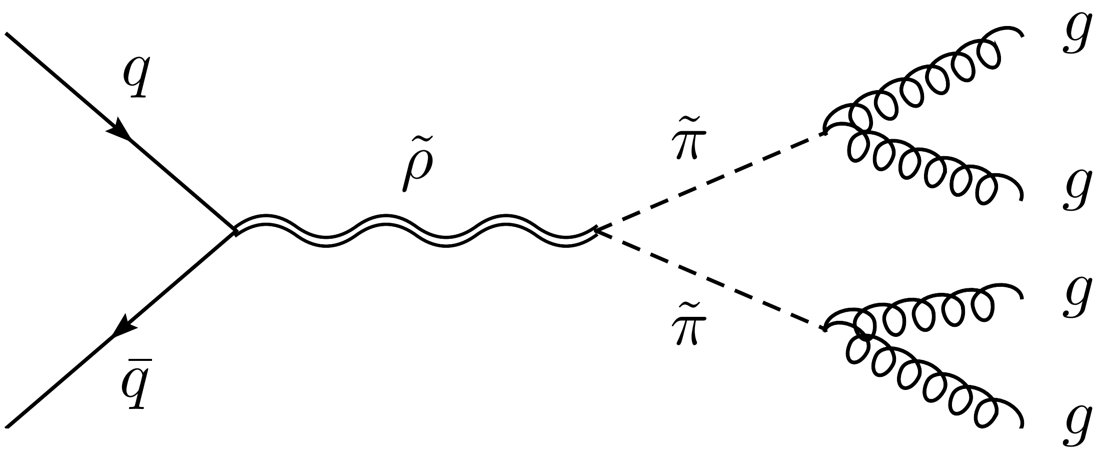
$\Longrightarrow$ Lightest hyper-baryon naturally long-lived!

QCD	Hyper-sector
 An $SU(3)_{\text{iso}}$ octet	A color-octet fermion i.e. a "gluino"!

Long-lived gluino searches $\Longrightarrow$ $m_{\tilde{g}} \gtrsim 100$ GeV

Discovery Potential at Tevatron

Signal:



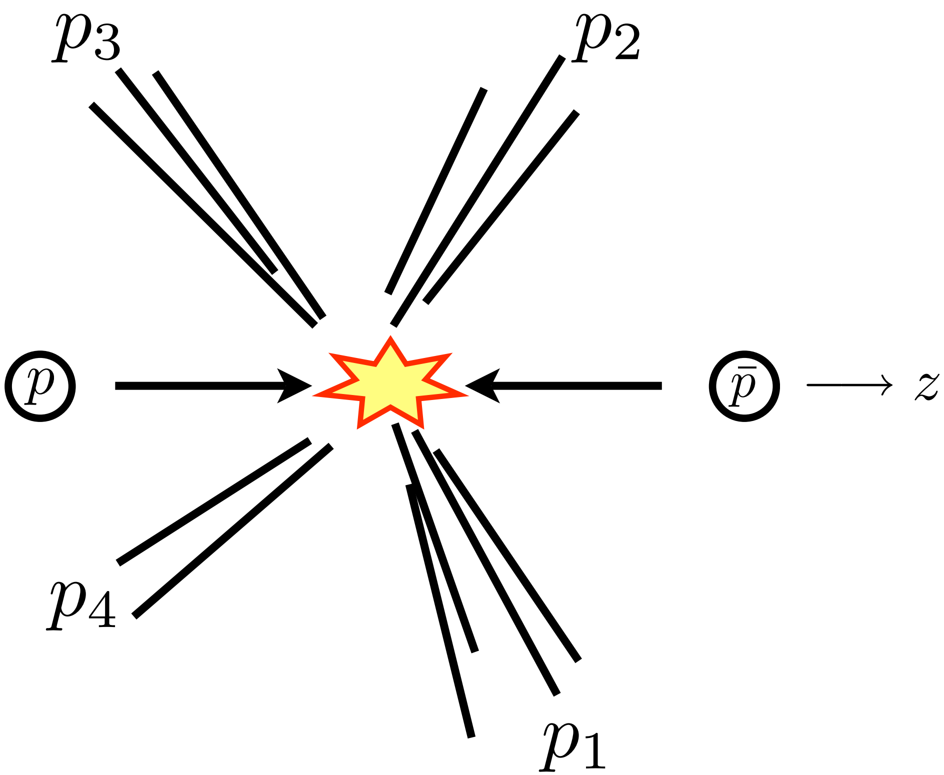
A resonance in 4j at $m_{\tilde{\rho}}$

A pair of 2j resonances at $m_{\tilde{\pi}}$

Background: *No features.*

No scales.

Case study for $m_{\tilde{\rho}} = 350\ \text{GeV}$ $m_{\tilde{\pi}} = 100\ \text{GeV}$



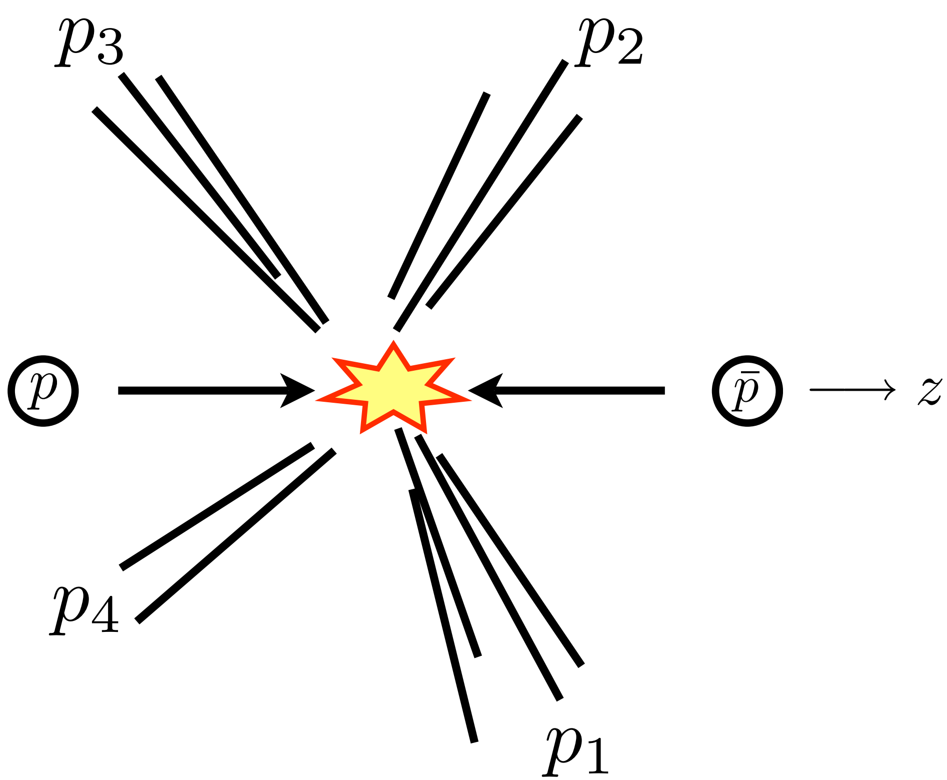
* For events to be written on tape,

$\text{Max}\{p_{T1}, p_{T2}, p_{T3}, p_{T4}\} > 120\ \text{GeV}$

$\left(p_T \equiv \sqrt{p_x^2 + p_y^2}\right)$

(CDF single-jet trigger = 100 GeV)

Case study for $m_{\tilde{\rho}} = 350\ \text{GeV}$ $m_{\tilde{\pi}} = 100\ \text{GeV}$



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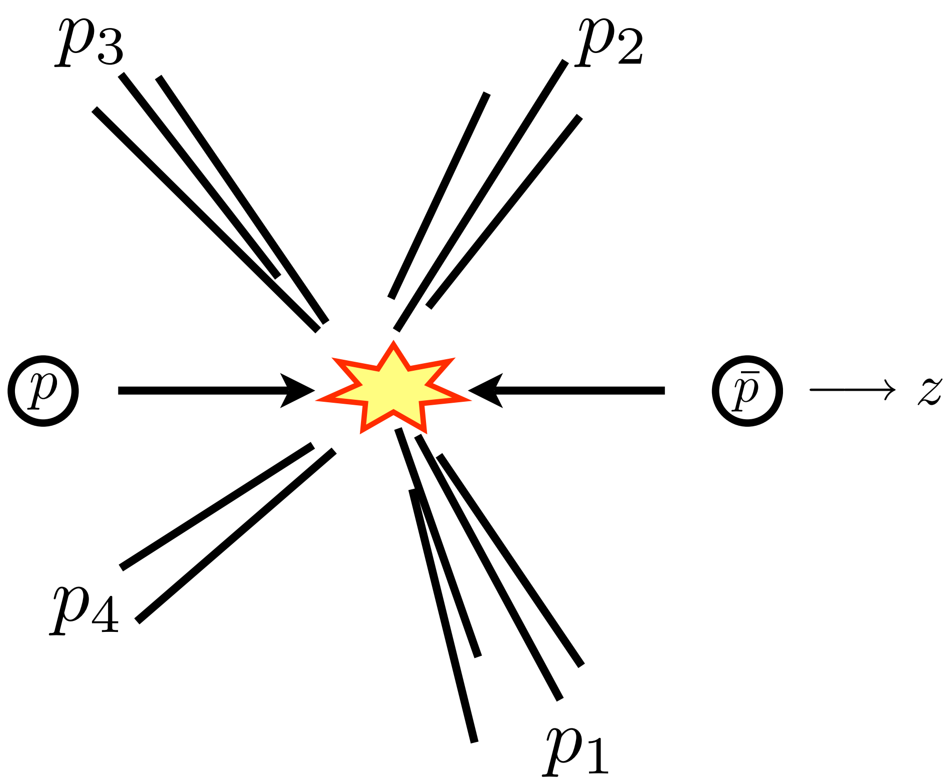
(CDF single-jet trigger = 100 GeV)

* p_{Ti} of background tend to be hierarchical, so

$p_{Ti} > 40\ \text{GeV}$ for *all* jets

Case study for $m_{\tilde{\rho}} = 350$ GeV $m_{\tilde{\pi}} = 100$ GeV



* For events to be written on tape,

$$\mathrm{Max}\{p_{T1}, p_{T2}, p_{T3}, p_{T4}\} \;>\; 120 \text{ GeV}$$

$$\left(p_T \equiv \sqrt{p_x^2 + p_y^2}\right)$$

(CDF single-jet trigger $= 100$ GeV)

* p_{Ti} of background tend to be hierarchical, so

$$p_{Ti} > 40 \text{ GeV} \quad \text{for } \textit{all} \text{ jets}$$

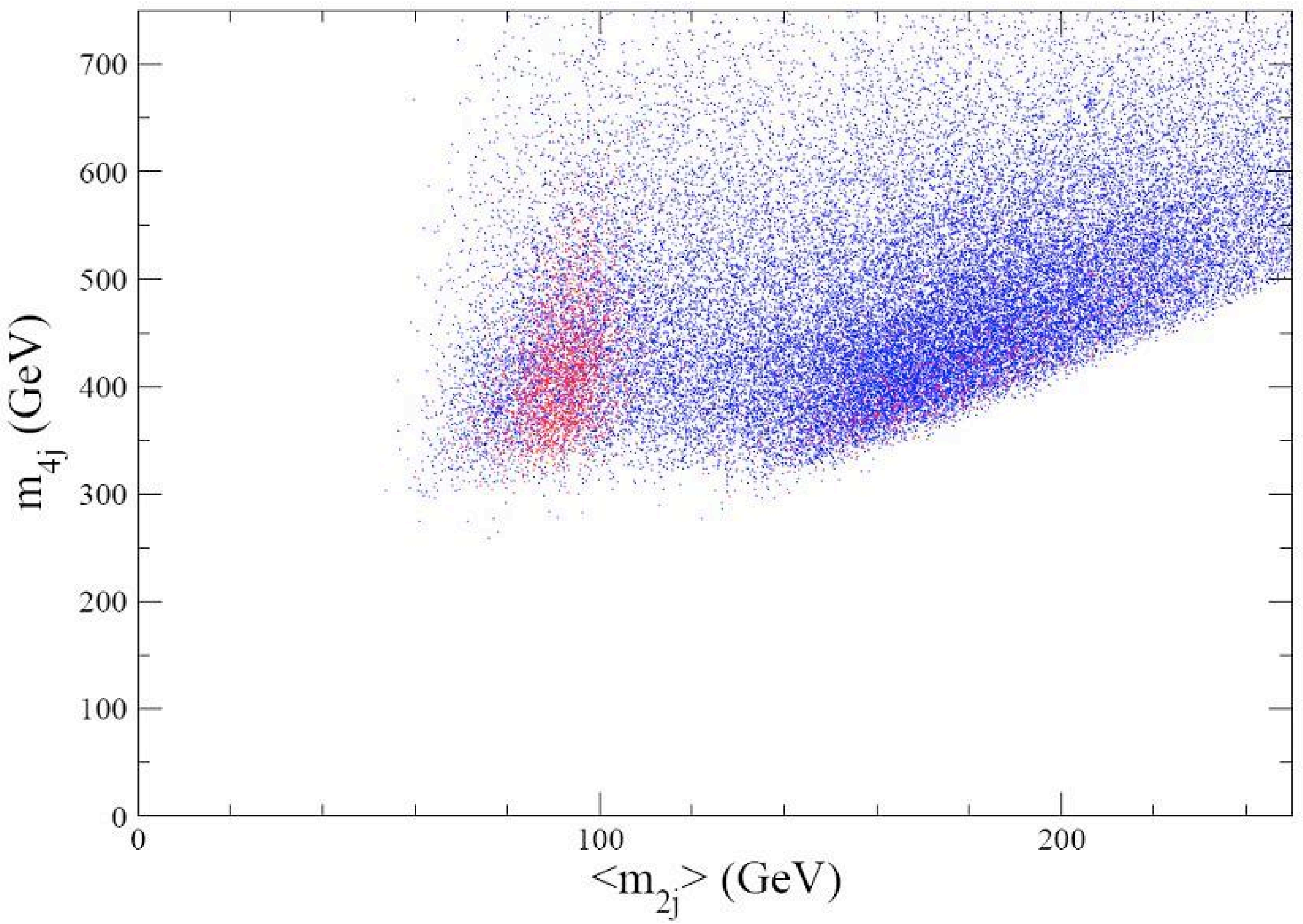
Observables to pick out signal features:

$$m_{4j}^2 \equiv (p_1 + p_2 + p_3 + p_4)^2$$

$$\langle m_{2j} \rangle \equiv (m_{ij} + m_{k\ell})/2 \qquad |m_{ij} - m_{k\ell}| < 25 \text{ GeV}$$

$$\left(m_{ij}^2 \equiv (p_i + p_j)^2\right)$$

The Results



Signal $(1\ fb^{-1})$

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

$m_{\tilde{\rho}} = 350$ GeV

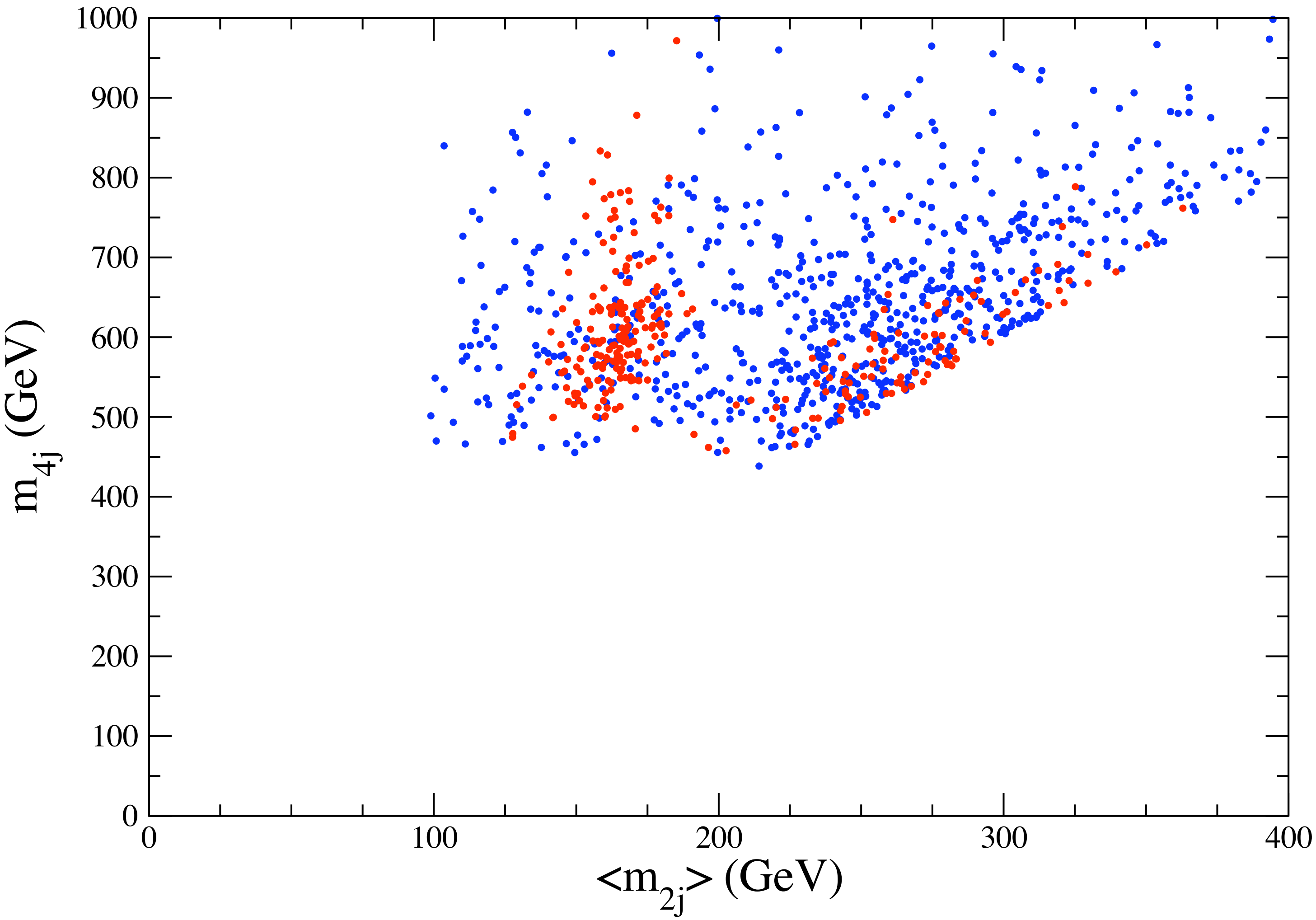
$m_{\tilde{\pi}} = 100$ GeV

Signal : 2.7 pb passing cuts

Background: 21 pb passing cuts

$S/\sqrt{B} = 32$!

The Results



Signal $(1\ fb^{-1})$

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

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

Signal : 0.27 pb passing cuts

Background: 0.38 pb passing cuts

$$S/\sqrt{B} = 17 \text{ !}$$

Conclusions

* Colorons can easily appear beyond the SM

* Colorons naturally decay to four jets via two intermediate scalars

* The coloron can be as light as a few hundred GeV

* A simple set of cuts can reveal colorons with high signal significance at Tevatron, possibly in existing data!

* At the LHC, such light colorons are difficult to find due to much larger background and higher triggers