Colored Resonances at Tevatron:

Phenomenology and Discovery Potential in Multi-jets

Can Kilic, Takemichi Okui, and Raman Sundrum

(JHU) (JHU&UMD) (JHU)

ArXiv:0802.2568

Outline

A color-octet spin-1 resonance (= "coloron")

* theoretically simple and plausible
* phenomenologically interesting

$\Rightarrow$ Worth investigating in isolation $(\sim Z')$

* Naturally evade all bounds even for $m < \text{TeV}$ $(\neq Z')$

* Discoverable at the Tevatron!

Outline

A color-octet spin-1 resonance (= “coloron”)

* theoretically simple and plausible
* phenomenologically interesting

$\Rightarrow$ Worth investigating in isolation $(\sim Z')$

* Naturally evade all bounds even for $m <$ TeV $(\neq Z')$

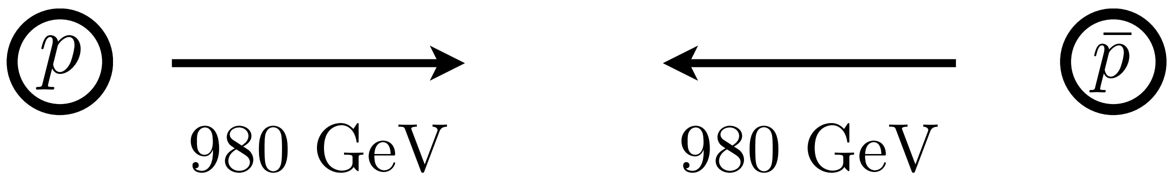
* Discoverable at the Tevatron!

* *Harder* at the LHC!

Energy Frontier in Fundamental Physics

Tevatron

Currently Running



Large Hadron Collider (LHC)

Coming (Very) Soon!

These are *hadron* colliders.

c/w

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

  Good for exploring electroweak physics.

- HERA $(e\text{-}p)$

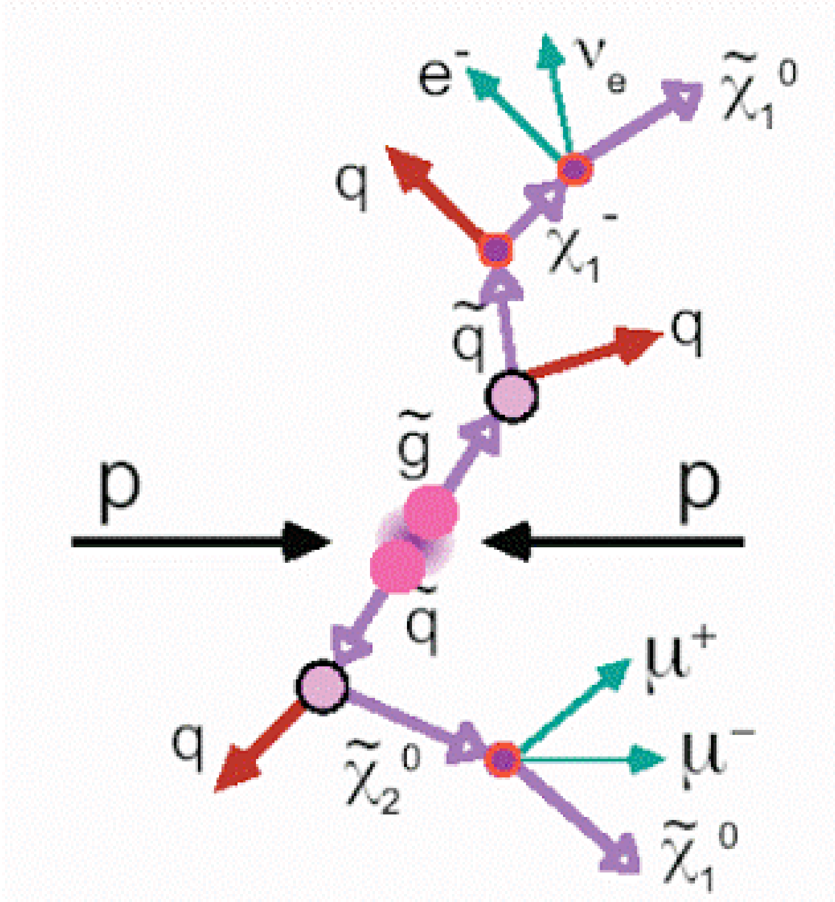
  Parton distributions.

  Lepto-quarks.

- *Hadron machines*

  Best for producing colored particles.
  But studying them tends to be hard due to QCD background.

So, we usually look for *distinctive final states*:



Typical SUSY cascade

photons

leptons

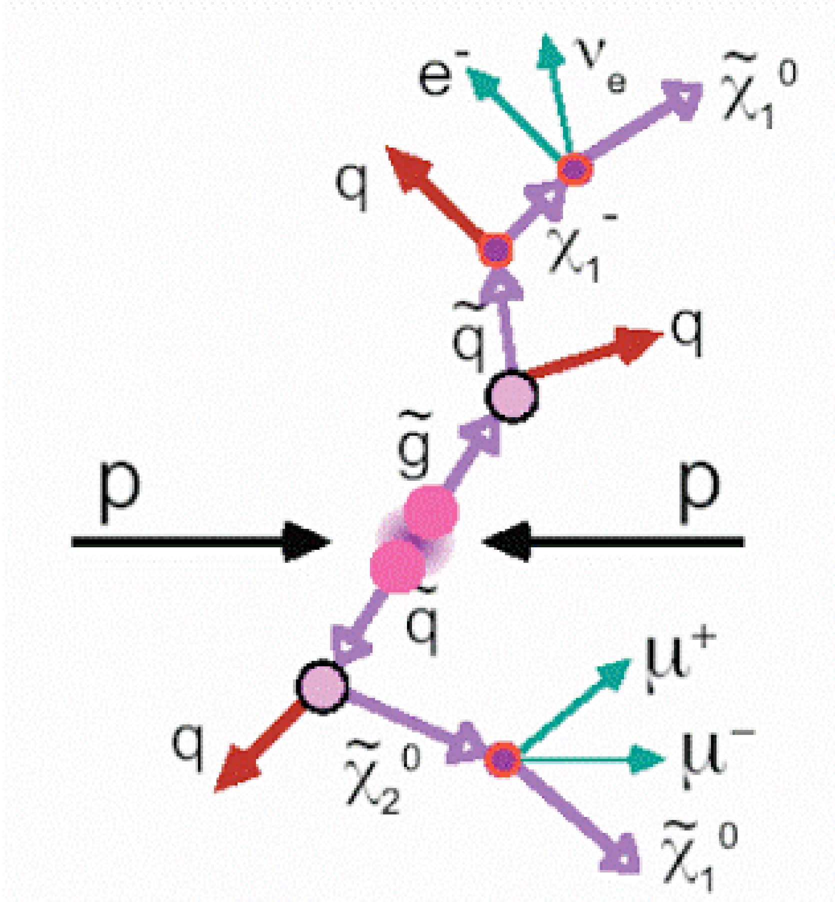
missing $\vec{p}_T$

displaced vertices

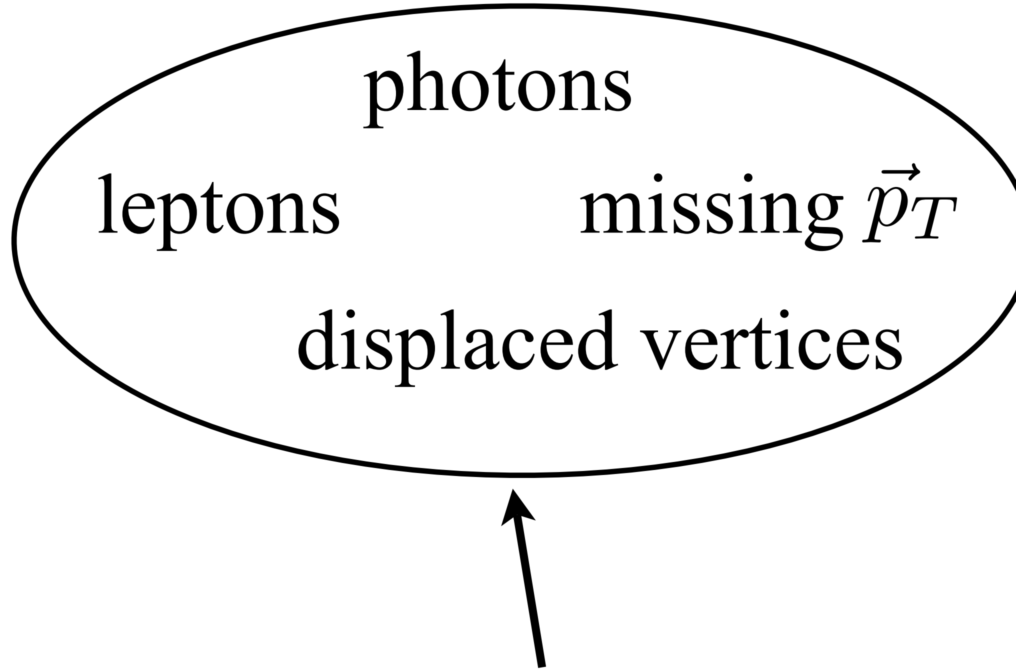
electroweak physics, heavy flavors.

—— *tend to be highly constrained...*

So, we usually look for *distinctive final states*:



Typical SUSY cascade

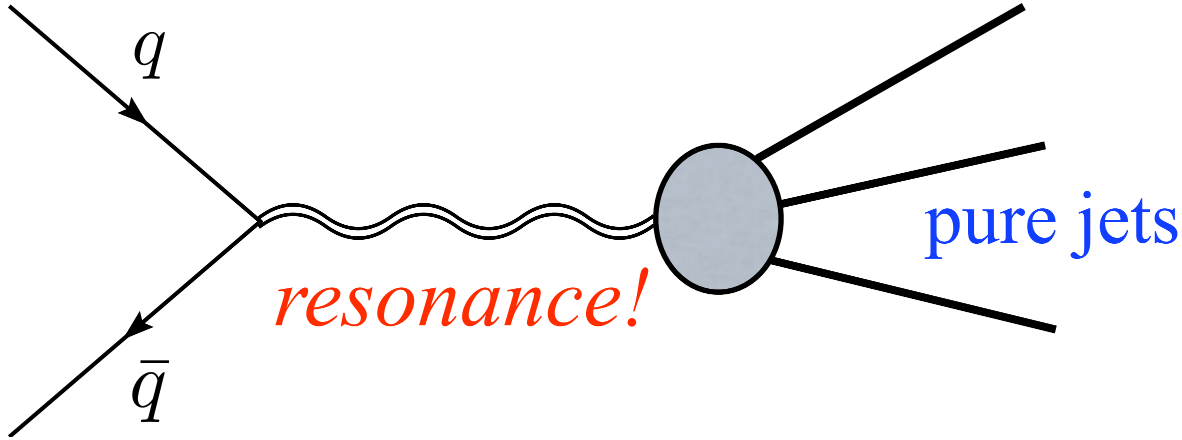


electroweak physics, heavy flavors.

— *tend to be highly constrained...*

Any other way for new colored stuff to be "detectable"?

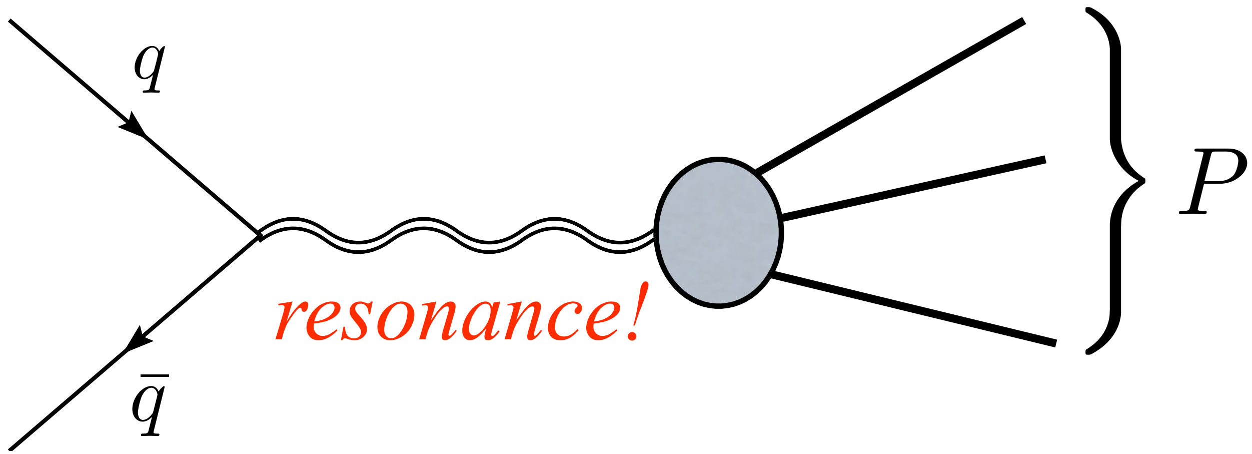
Certainly!



- ***HUGE*** production cross section!

c/w *pair* production of, e.g., SUSY particles

Certainly!

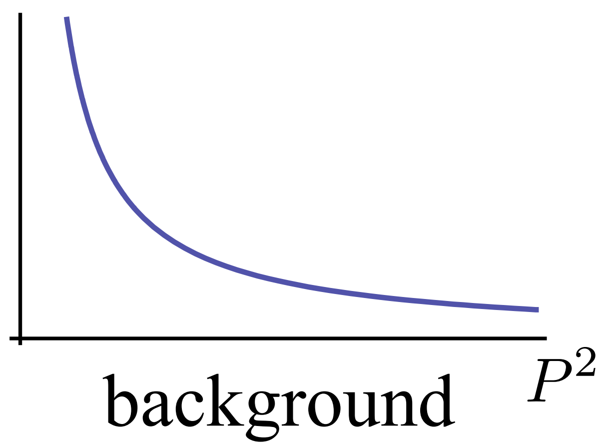


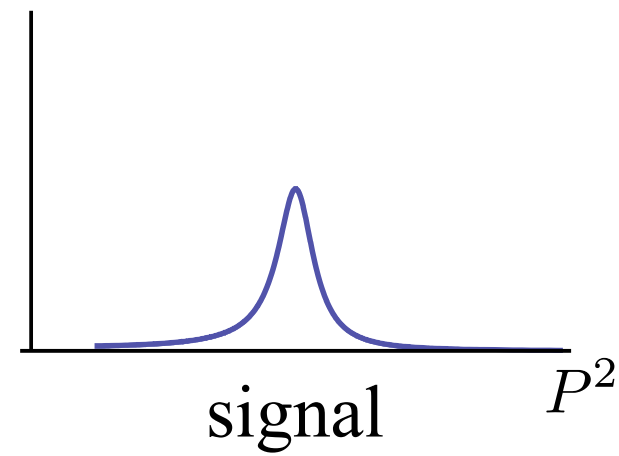
- ***HUGE*** production cross section!

  c/w *pair* production of, e.g., SUSY particles

- Distinct *shape* in distribution

  vs distinct final *states*



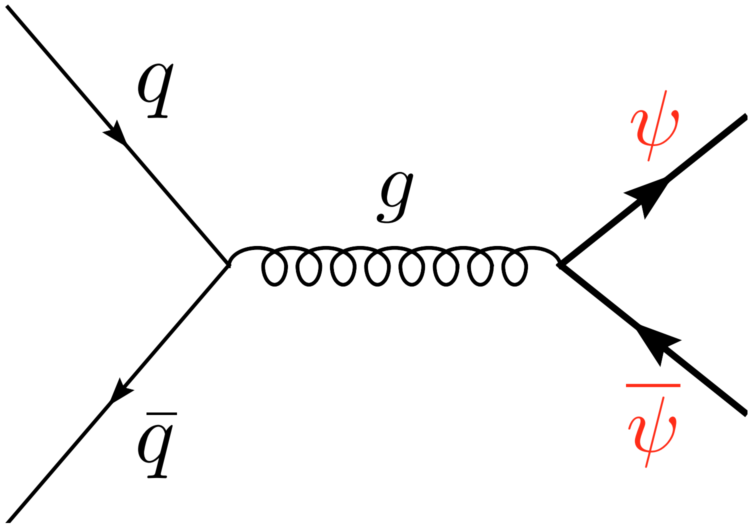


Maybe possible to pick out!

Such a resonance can appear *in two easy steps!*

Step 1: Suppose there's *a new particle with color.*

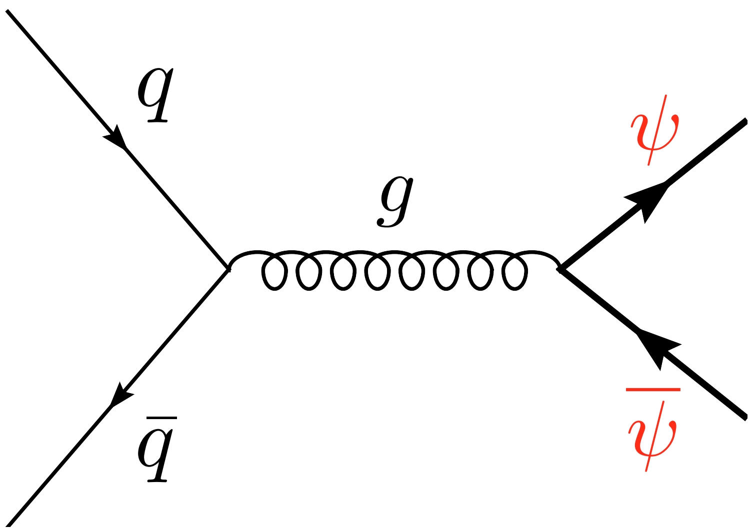
Then, at hadron colliders, we'll get



Such a resonance can appear *in two easy steps!*

Step 1: Suppose there's *a new particle with color.*

Then, at hadron colliders, we'll get



Why haven't we seen ψ?

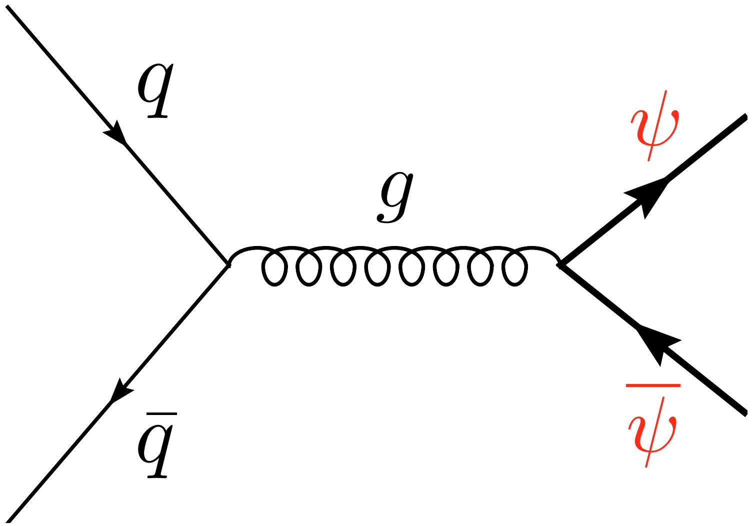
(A) Because it's heavy.

(B) Because it's *confined by a new force!*

Such a resonance can appear *in two easy steps!*

Step 1: Suppose there's *a new particle with color.*

Then, at hadron colliders, we'll get



Why haven't we seen ψ?

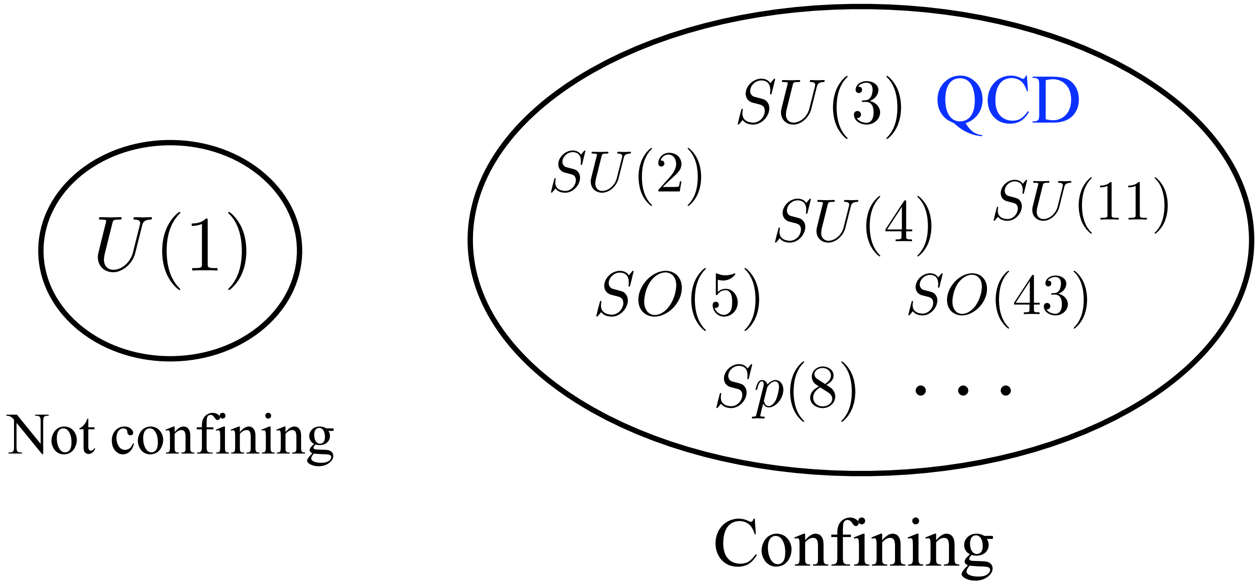
(A) Because it's heavy.

✓ (B) Because it's *confined by a new force!*

Is confinement something special?

Not at all!

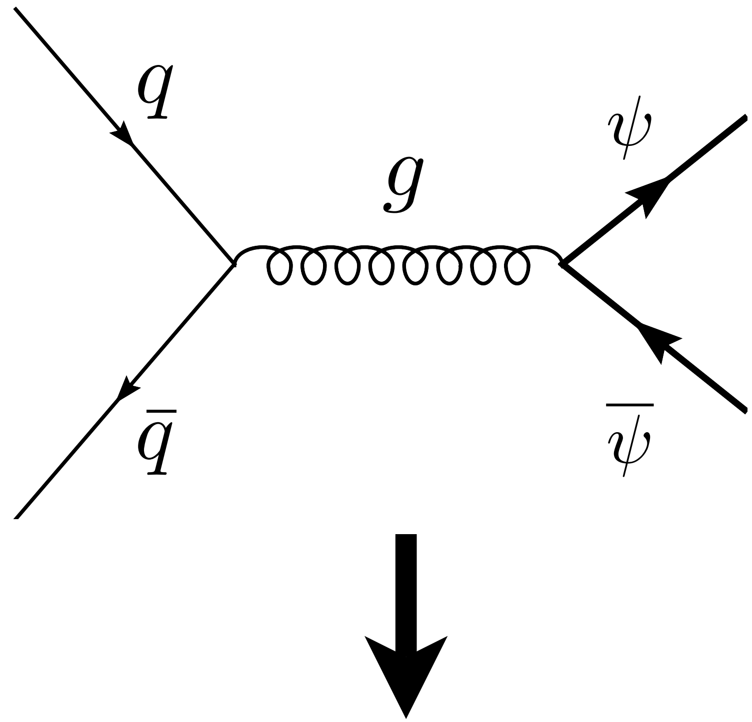
In “gauge theory space”,

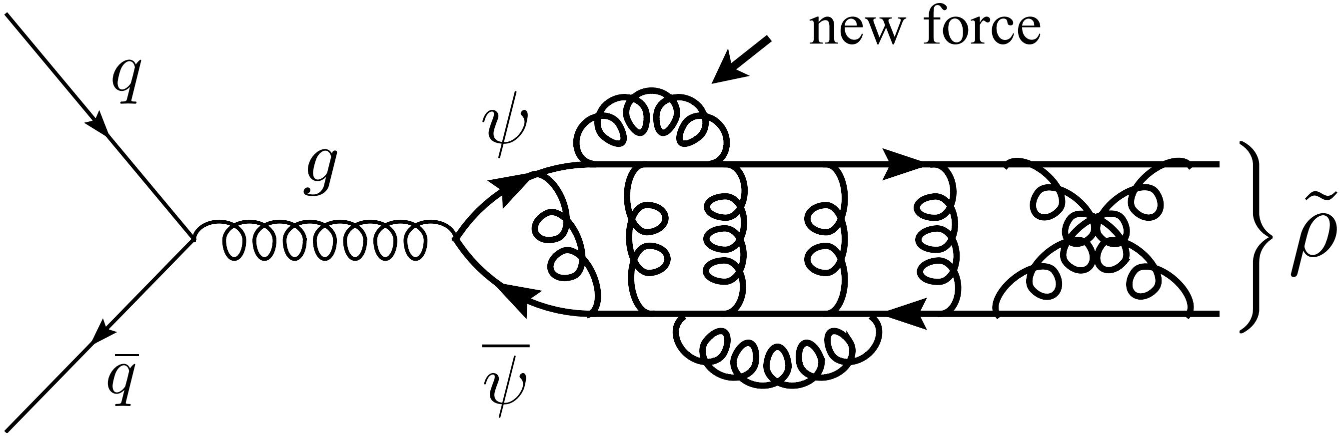


Confinement prevails!

Step 2: Suppose ψ also feels *a new confining force.*

Then,

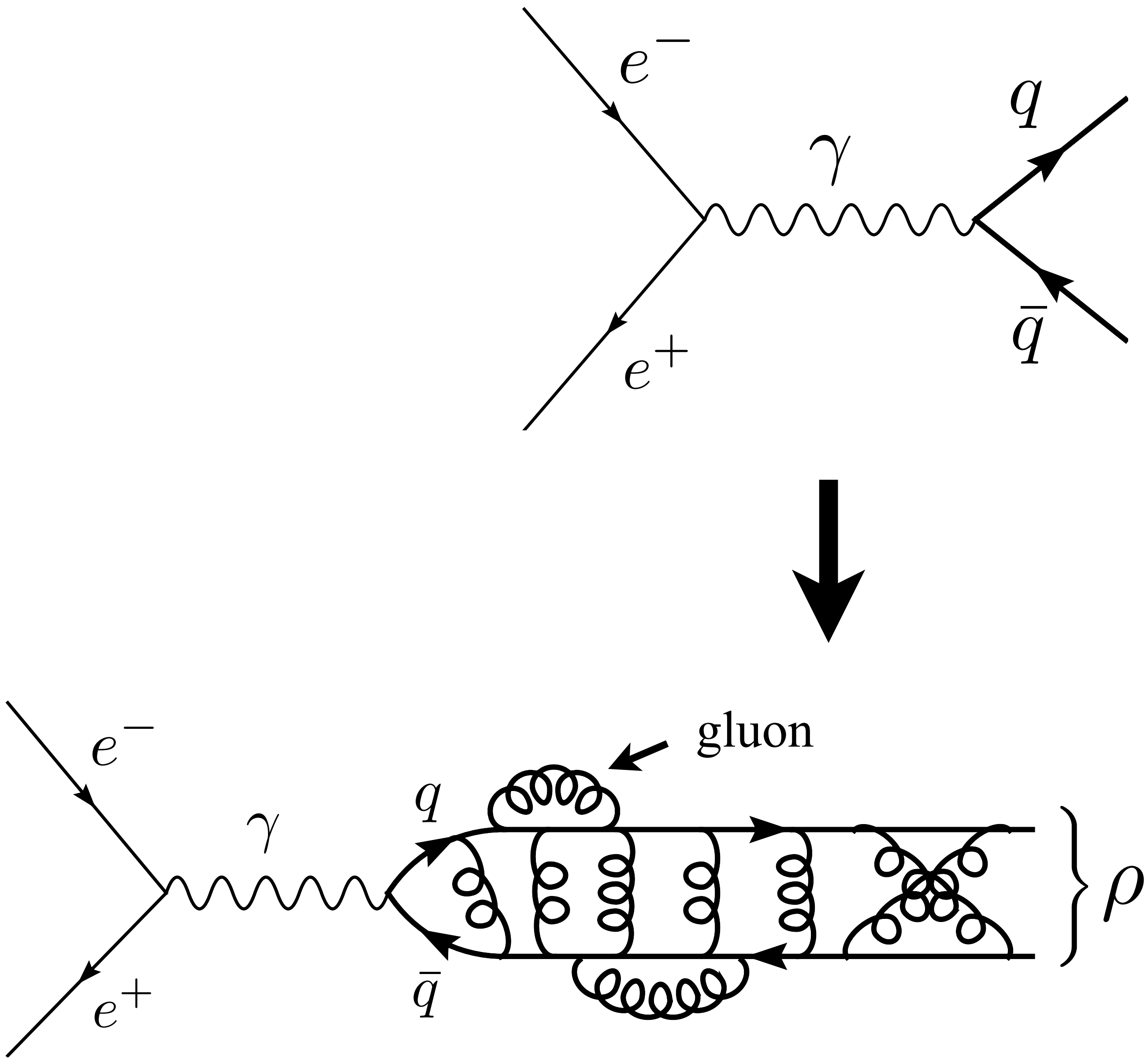




a spin-1 color-octet bound state!

"coloron"

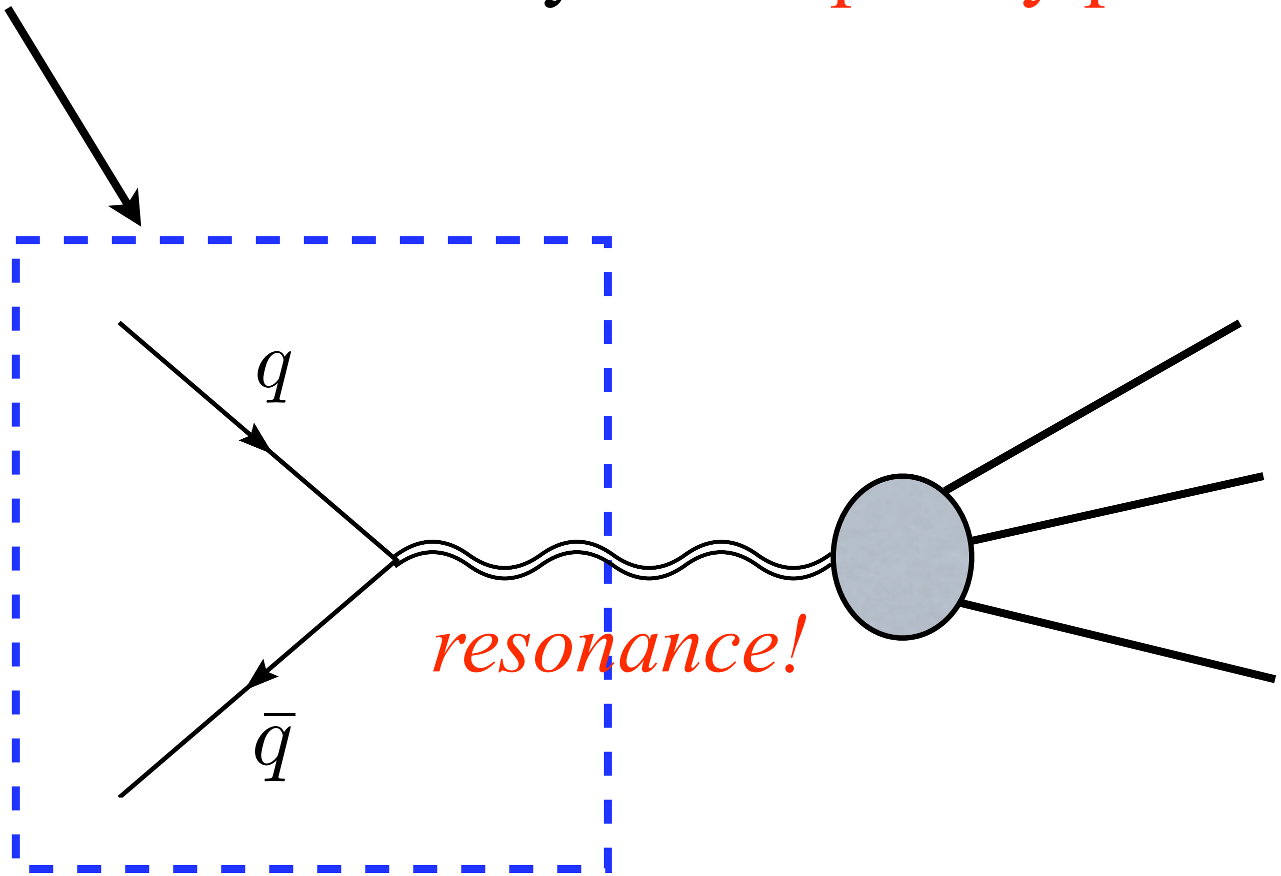
Note that nature has already done this trick once!



a spin-1 bound state

"rho meson"

So, this half of the story is completely plausible!



(*Any* new confining force)
+ (*Any* new light colored particle that feels the new force)
= *A coloron!*

Indeed, many well-motivated models *contain* colorons!

* Non-minimal technicolor

"coloron" = ρ_{T_8}, V_8

* Top-color models

Coined the term "coloron"

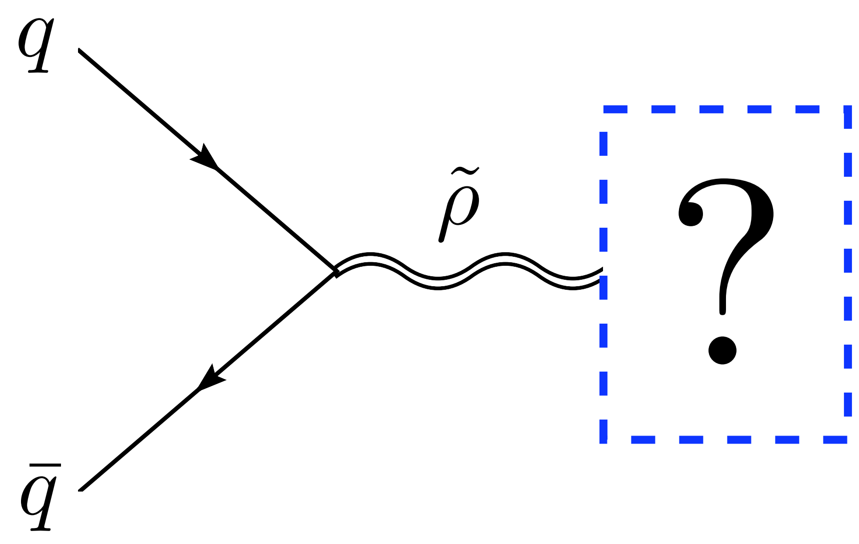
* Extra-dimensional models

"coloron" = Kaluza-Klein excitation

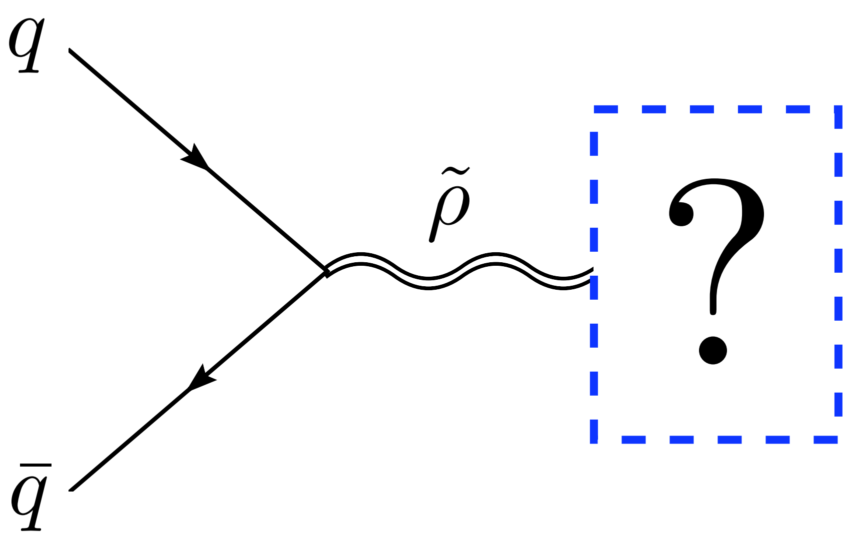
* TeV scale quantum gravity

"coloron" = string excitation

What about the other half?

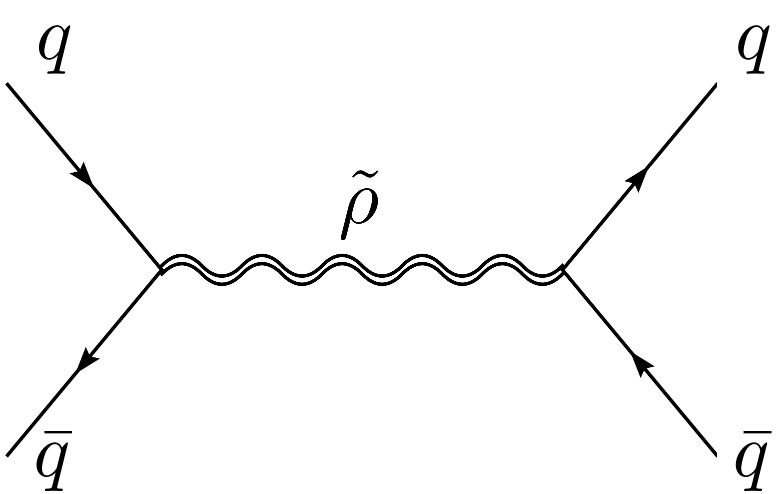


What about the other half?



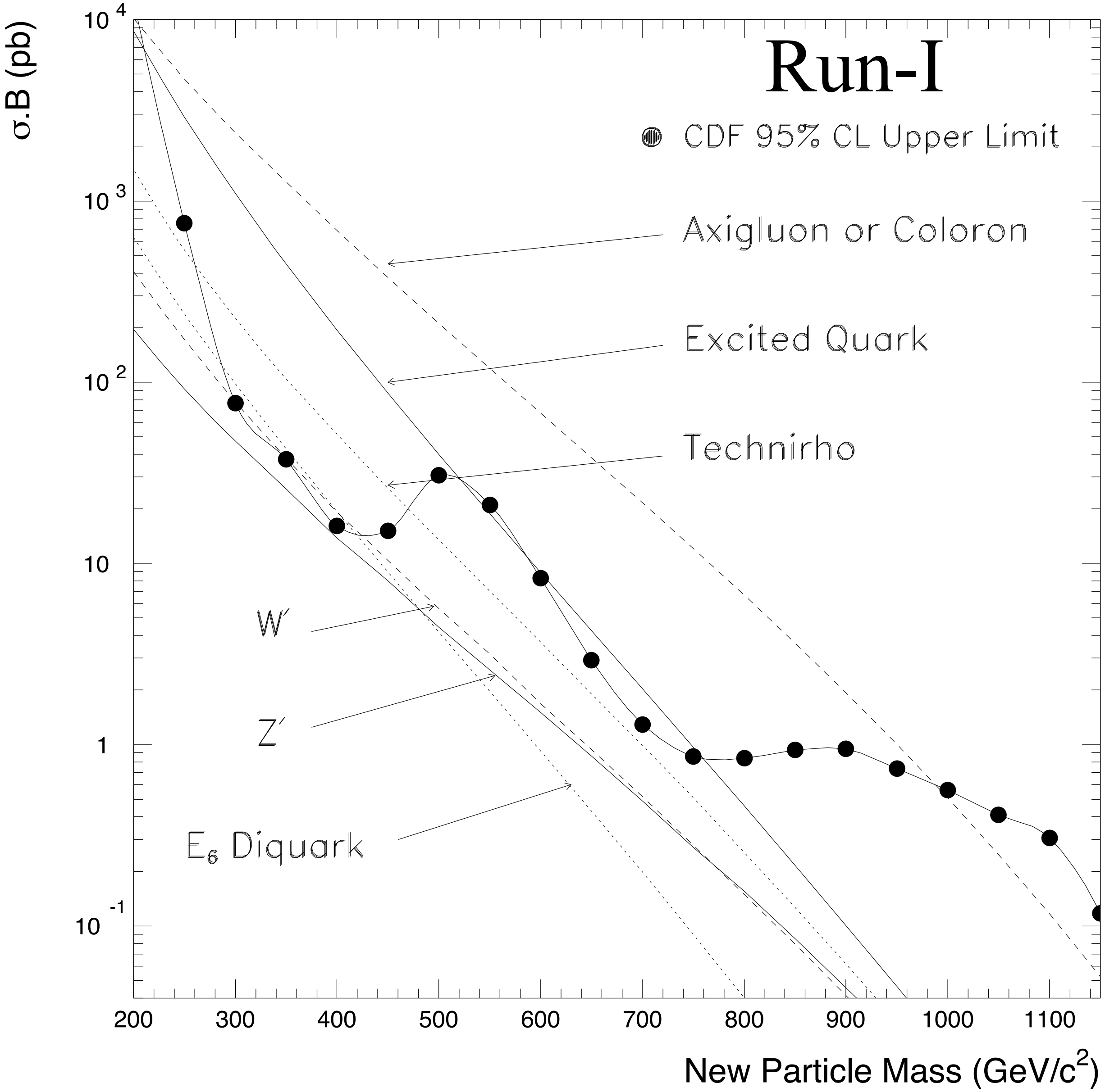
IF $\tilde{\rho}$ is the *lightest* bound state, then

a dijet

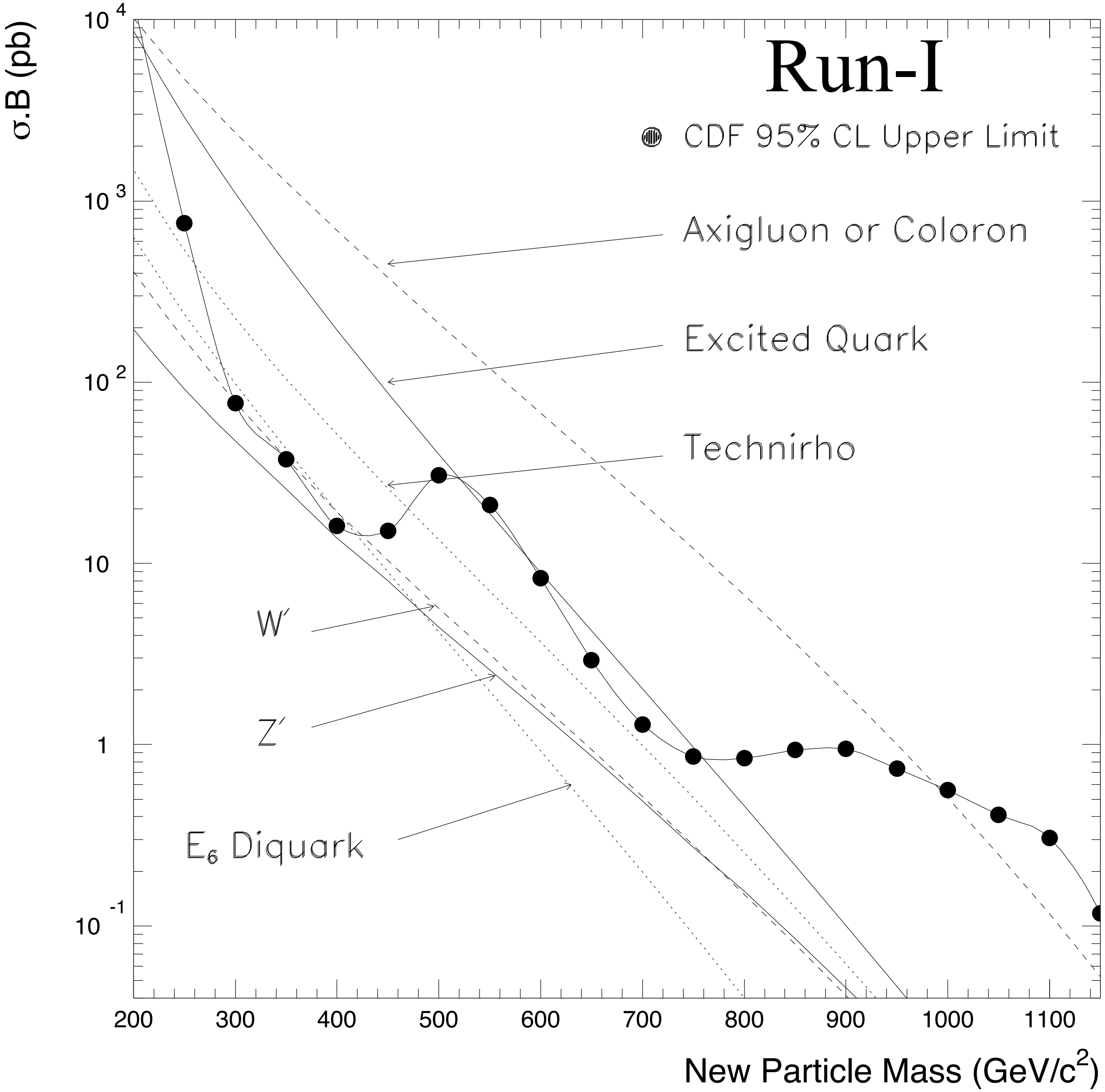


is the only possibility.

Then, there is a *severe* bound:



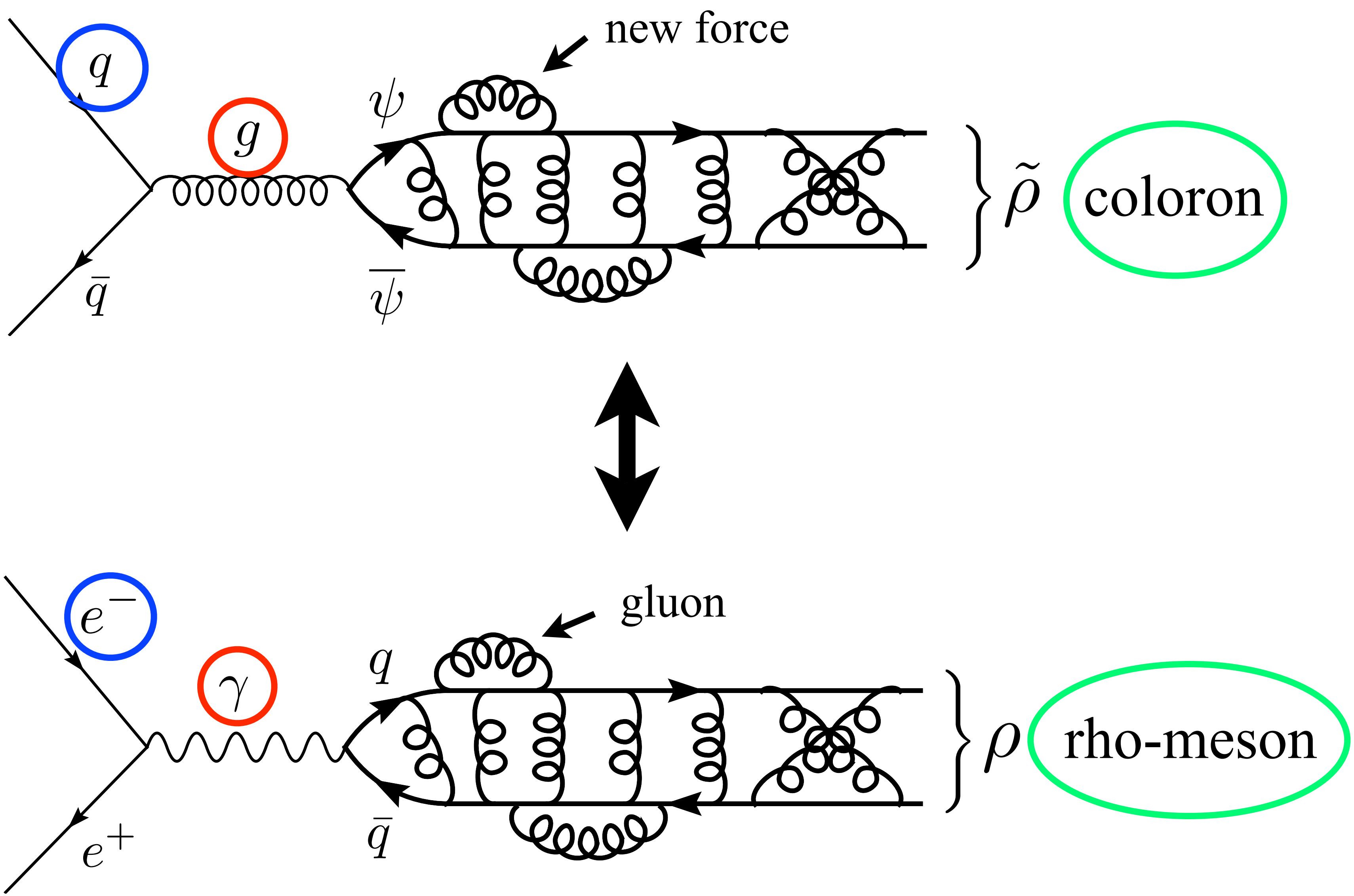
Then, there is a *severe* bound:



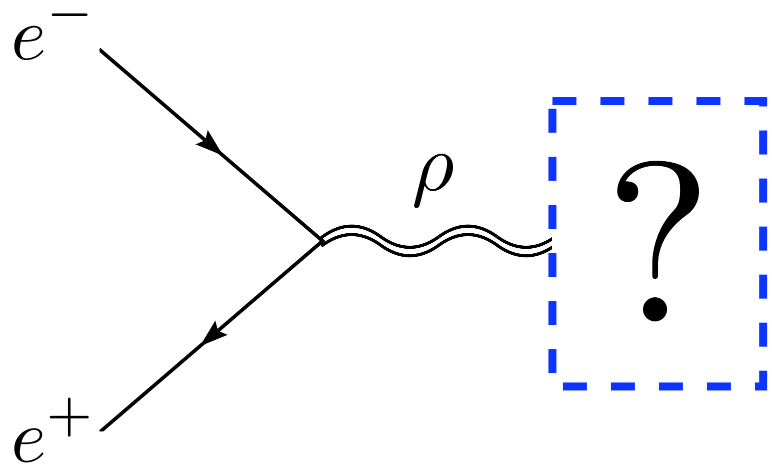
But, does $\tilde{\rho}$ *have to* be the lightest?

Not at all!

Recall the “dictionary”:

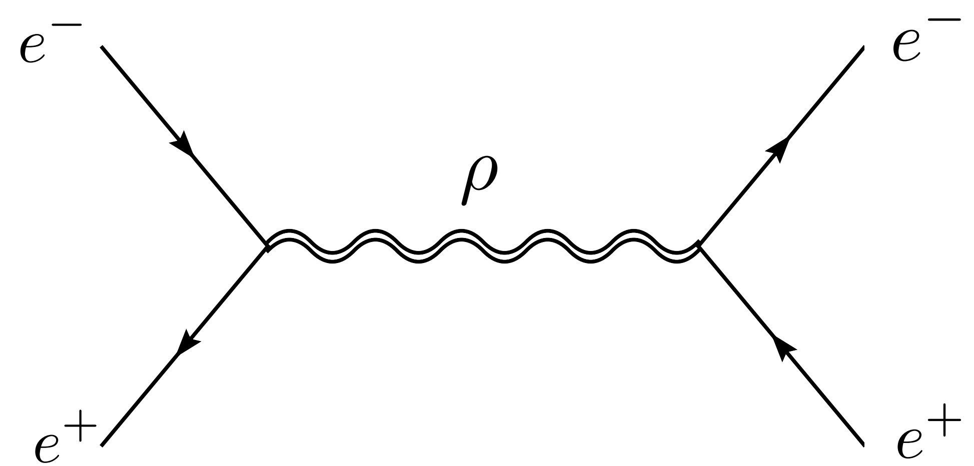


So, the analogous QCD question would be



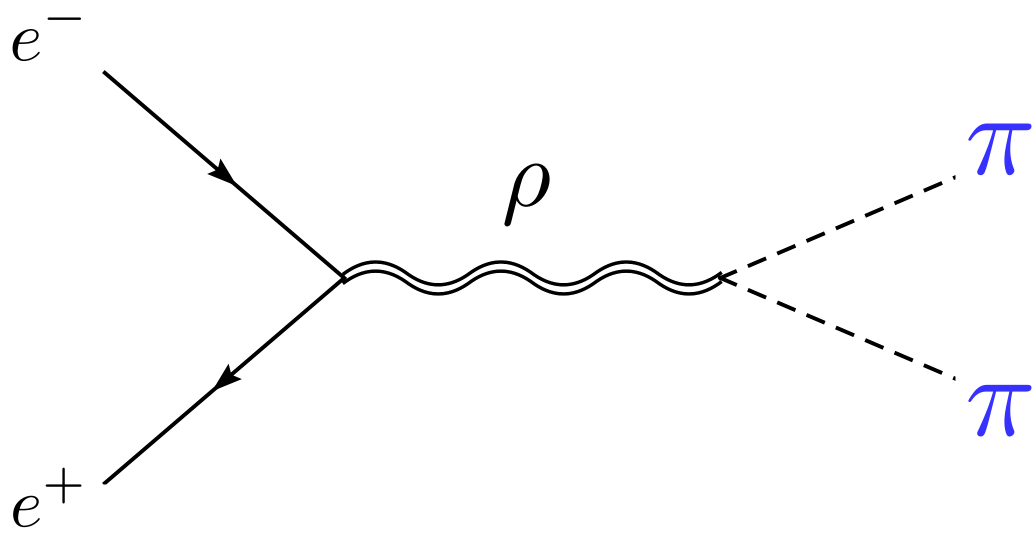
← *"What is this half?"*

The analog of the dijet would be

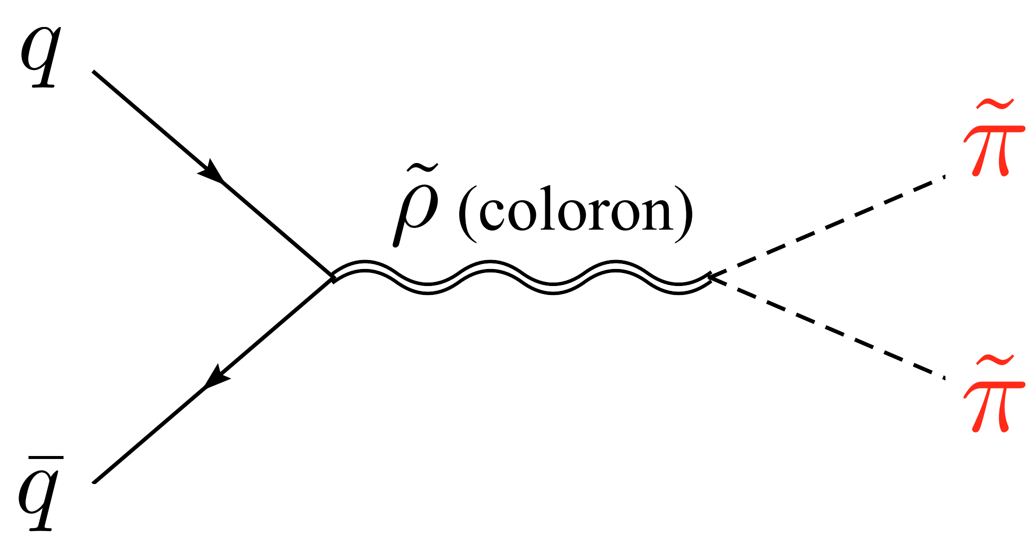


But $\mathrm{Br}(\rho \to e^+e^-) \sim 10^{-5}$!

Instead, the dominant ($\approx 100\,\%$) mode in QCD is



So, by analogy, we expect

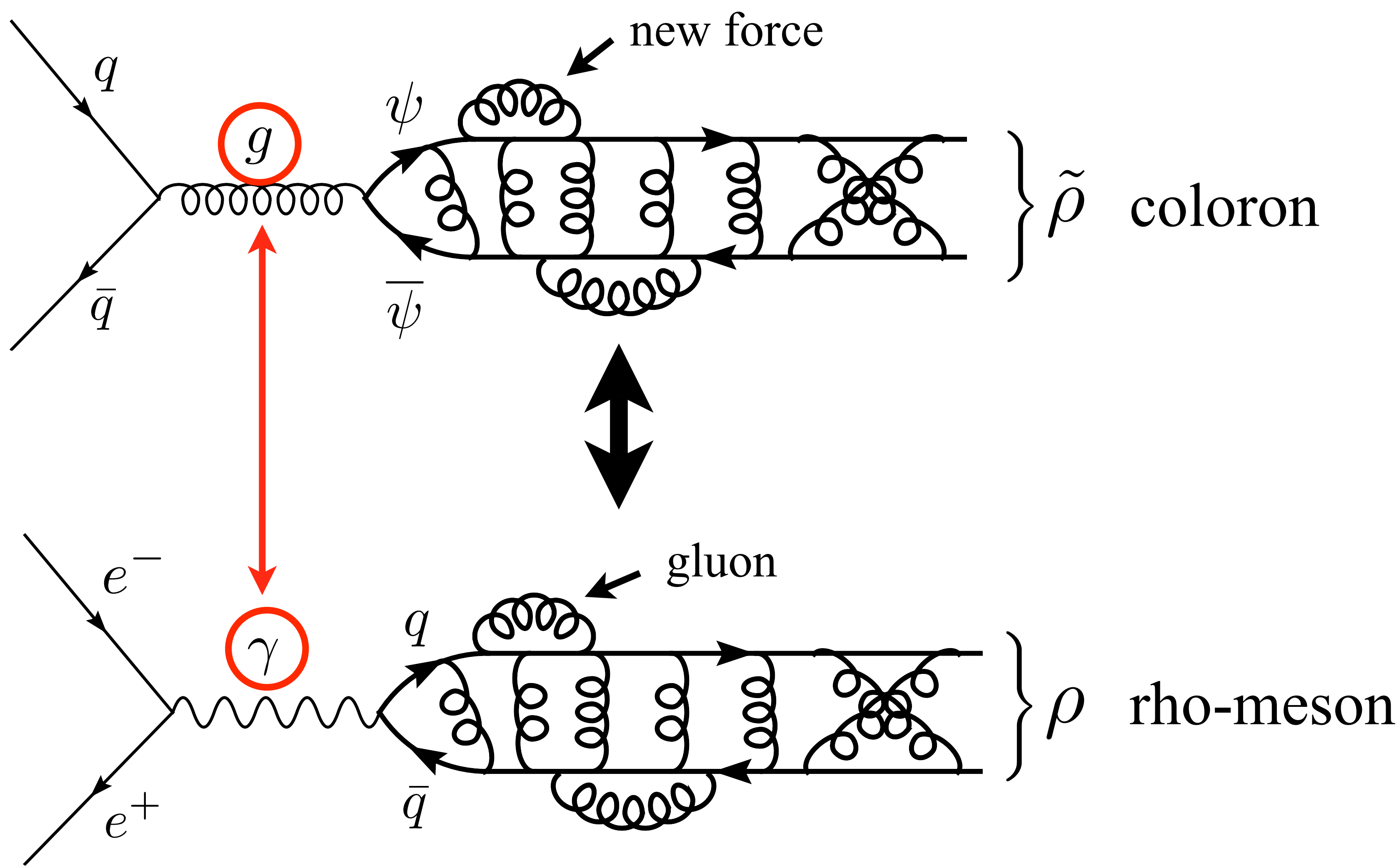


dominates!

How should $\tilde{\pi}$ decay?

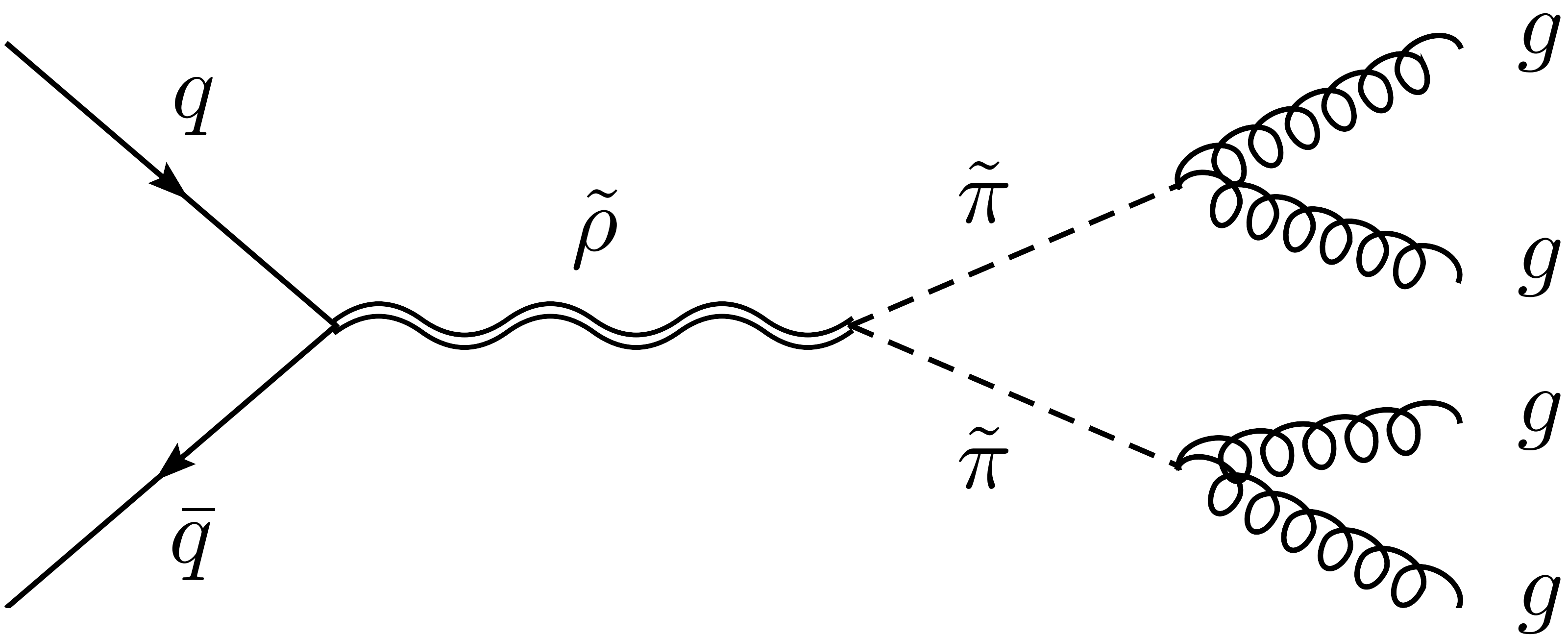
In QCD, we know $\pi \longrightarrow \gamma\gamma$ dominates.

Let's look up the dictionary!



So, we expect $\tilde{\pi} \to gg$ dominates!

*Therefore, **this is our main process:***



A colored resonance in a pure four-jet!

Dijets are sub-dominant!

Thus, our *scenario* has been fixed.

Let's choose a specific *model* for detailed study.

A good model must

* represent the scenario,
* be quantitatively under control.

Thus, our *scenario* has been fixed.

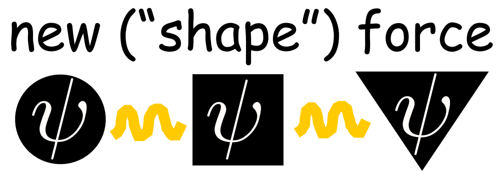
Let's choose a specific *model* for detailed study.

A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose ψ = spin 1/2, and

(QCD)



(Our model)

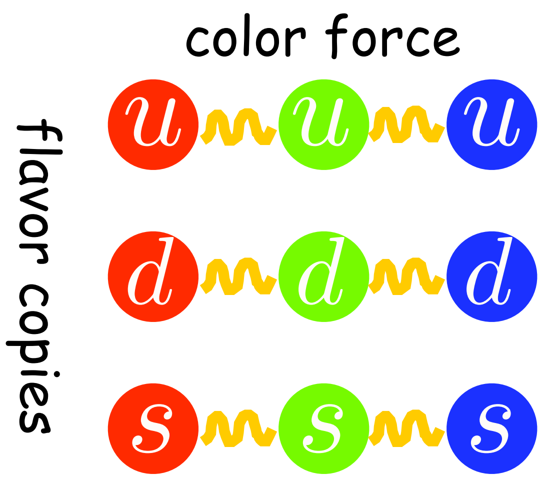
Thus, our *scenario* has been fixed.

Let's choose a specific *model* for detailed study.

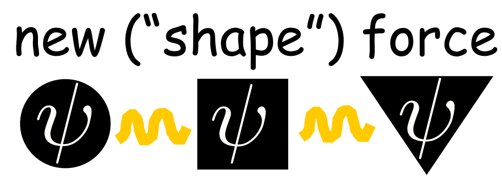
A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose $\psi =$ spin 1/2, and



(QCD)



(Our model)

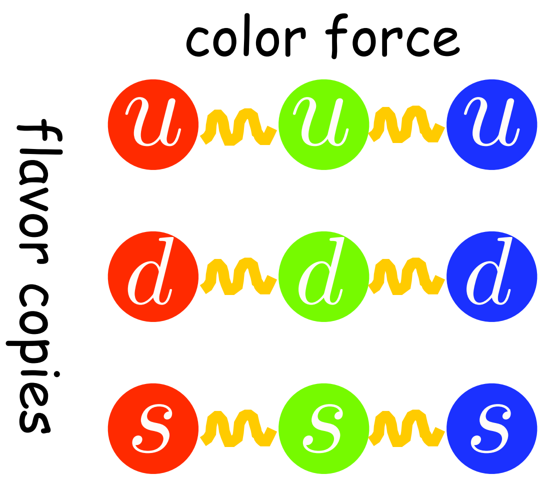
Thus, our *scenario* has been fixed.

Let’s choose a specific *model* for detailed study.

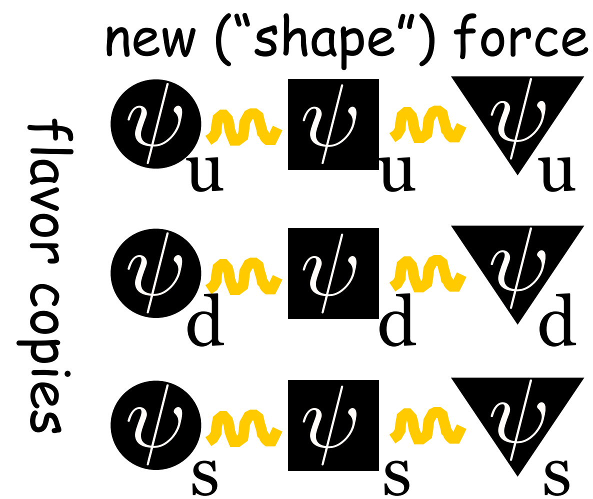
A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose ψ = spin 1/2, and



(QCD)



(Our model)

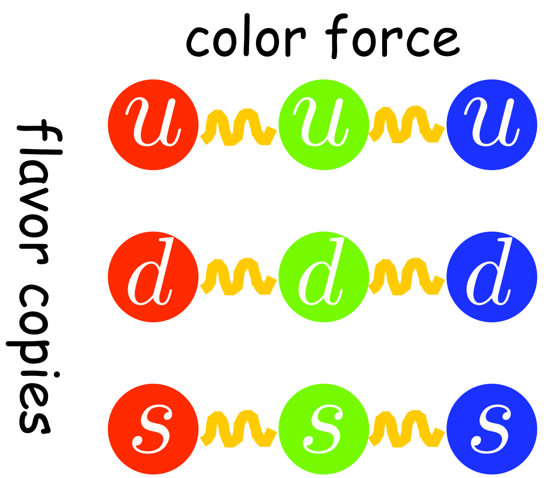
Thus, our *scenario* has been fixed.

Let's choose a specific *model* for detailed study.

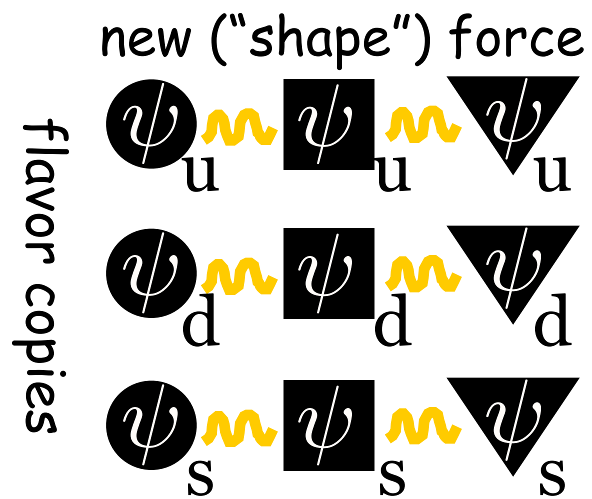
A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose ψ = spin 1/2, and



(QCD)



(Our model)

Where is the color?

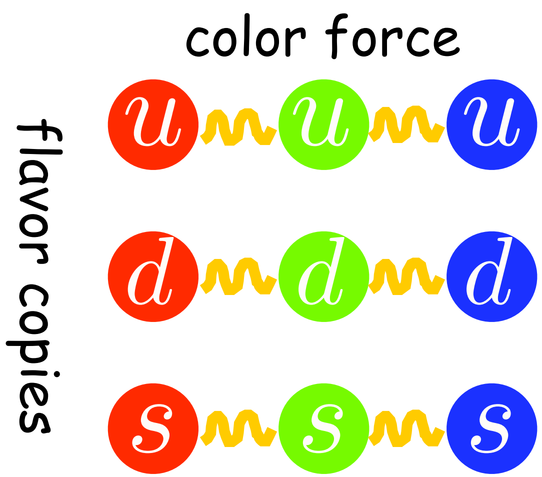
Thus, our *scenario* has been fixed.

Let's choose a specific *model* for detailed study.

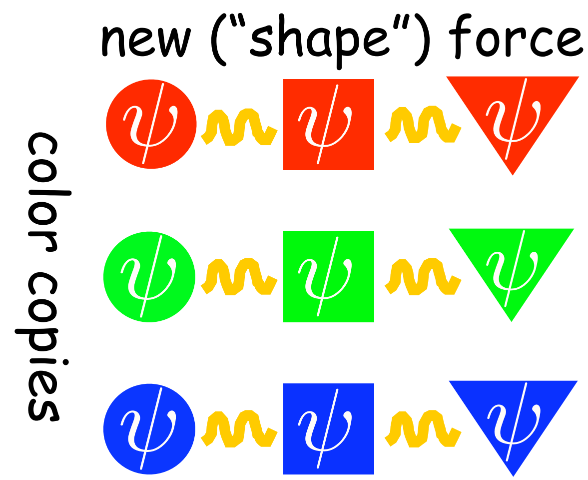
A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose ψ = spin 1/2, and



(QCD)



(Our model)

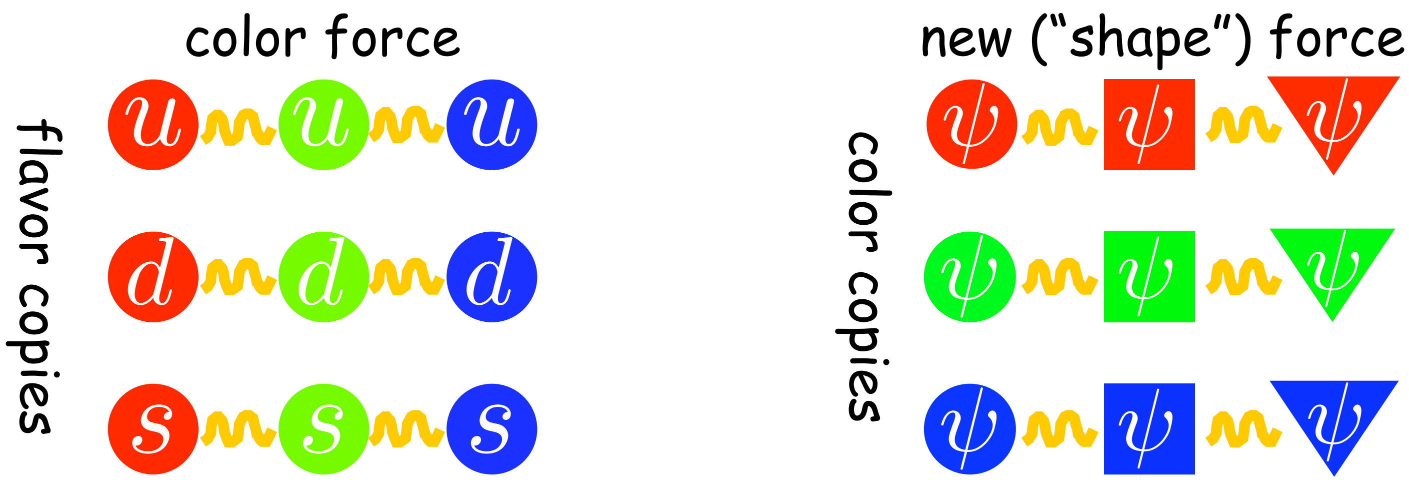
Thus, our *scenario* has been fixed.

Let's choose a specific *model* for detailed study.

A good model must

* represent the scenario,
* be quantitatively under control.

So, we choose ψ = spin 1/2, and



(QCD) (Our model)

QCD as an "analog computer"!

Let's analog-compute parameters!

First, change the overall scale

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

Then,

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

(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

Let's analog-compute parameters!

First, change the overall scale

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

Then,

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

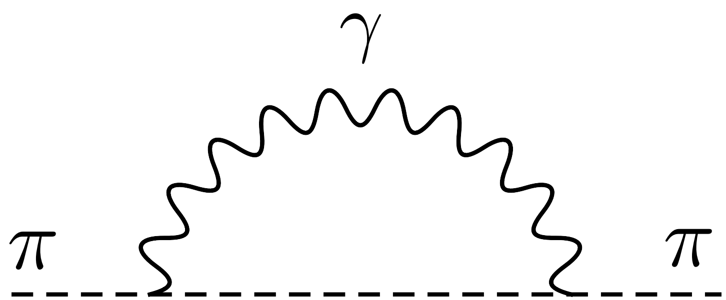
(b) $\Gamma_{\rho\to e^+e^-} \quad \Longrightarrow \quad \tilde{\rho}$-$q$-$\bar{q}$ coupling

(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,

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



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

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

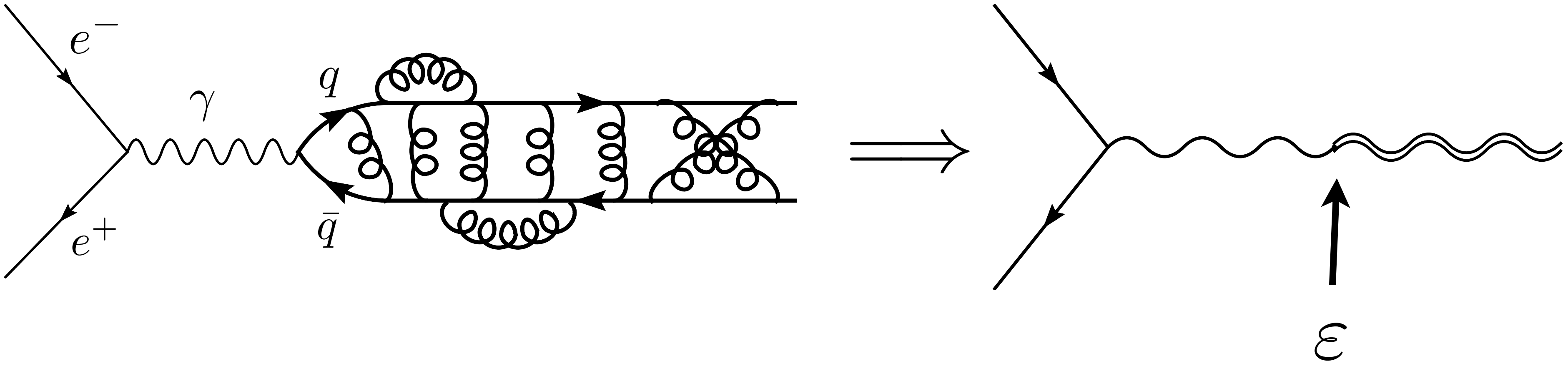
(Nature's solution to "hierarchy problem"!)

So, in our model,

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

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

(b) Recall in QCD,



where

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

This translates to

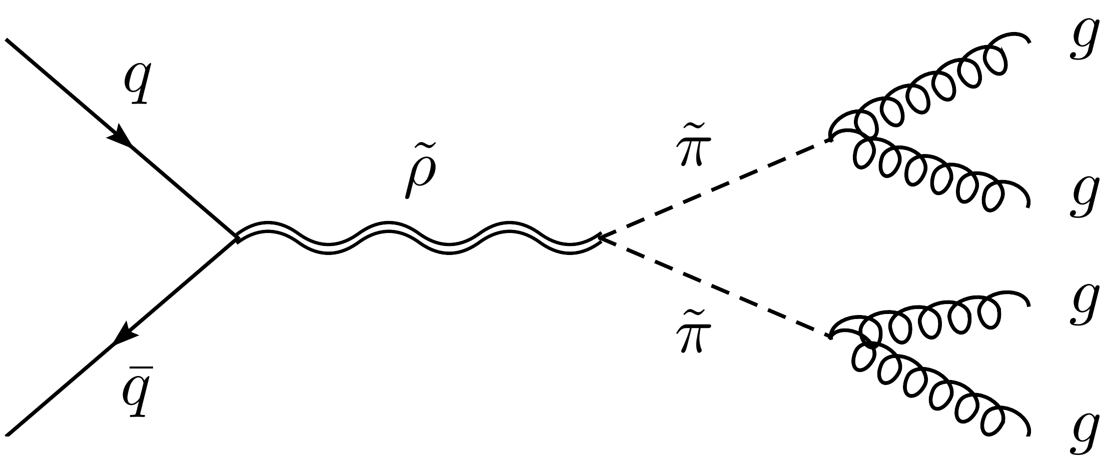
$$\tilde{\varepsilon} = \frac{g_3}{e} \varepsilon \simeq 0.2$$

Summary of the *Representative* Model

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

new fermion (3 colors & 3 shapes) → $\bar{\psi} i \not{D} \psi$

$SU(3)_{\rm shape}$ → $H_{\mu\nu} H^{\mu\nu}$



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

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

- Renormalizable (= "isolatable" from other new physics)
- Can extrapolate relevant parameters from QCD.
- *Only one parameter* $m_{\tilde{\rho}}$ to vary. $(m_{\tilde{\pi}} \simeq 0.3\, m_{\tilde{\rho}},\ g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} \simeq 6, \cdots)$

Constraints on the Representative Model

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

No Constraints on the Representative Model

This simple model of coloron escapes all existing bounds!

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

No Constraints on the Representative Model

This simple model of coloron escapes all existing bounds!

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

No Constraints on the Representative Model

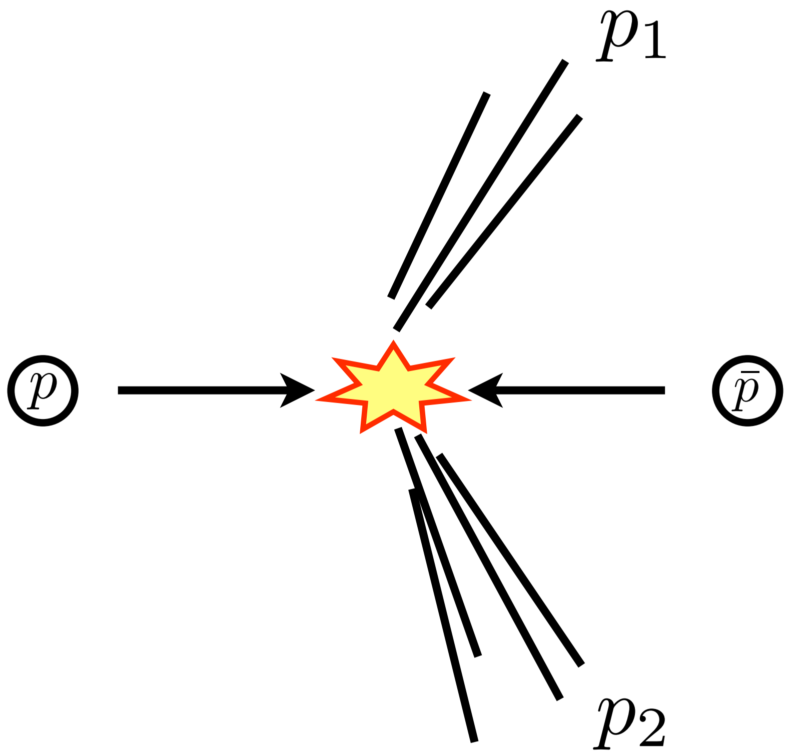
This simple model of coloron escapes all existing bounds!

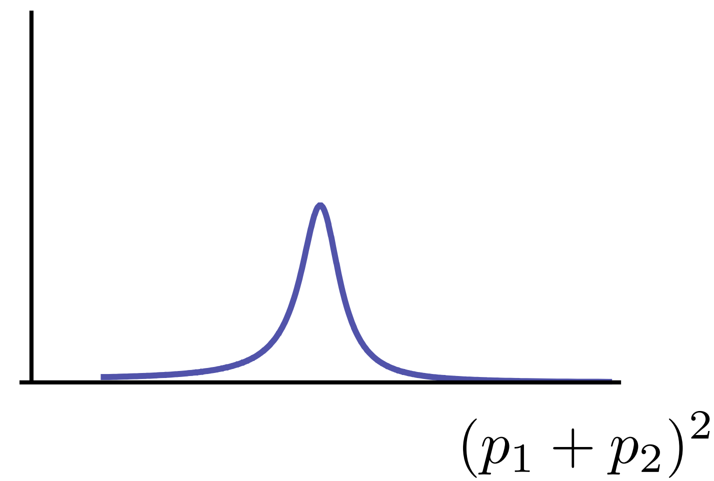
- ✓ Electroweak precision, flavor constraints
- ✓ Multi-jet studies
- ✓ QCD pair production of $\tilde{\pi}$
- ✓ Long-lived "gluino" search

(A) Resonance searches in di-jets

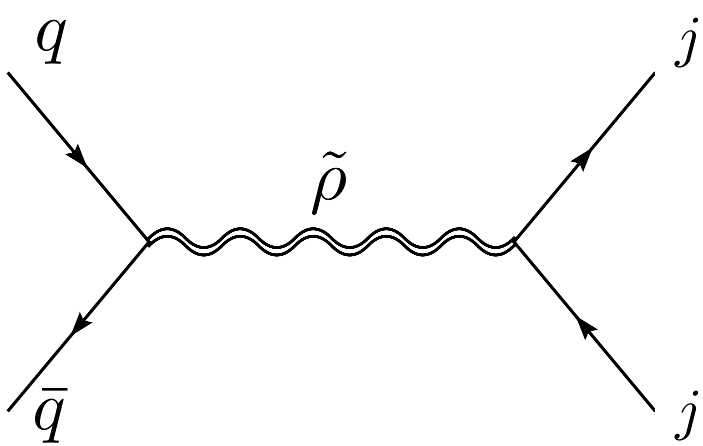
(B) Resonance searches in t-$\bar{t}$ pairs

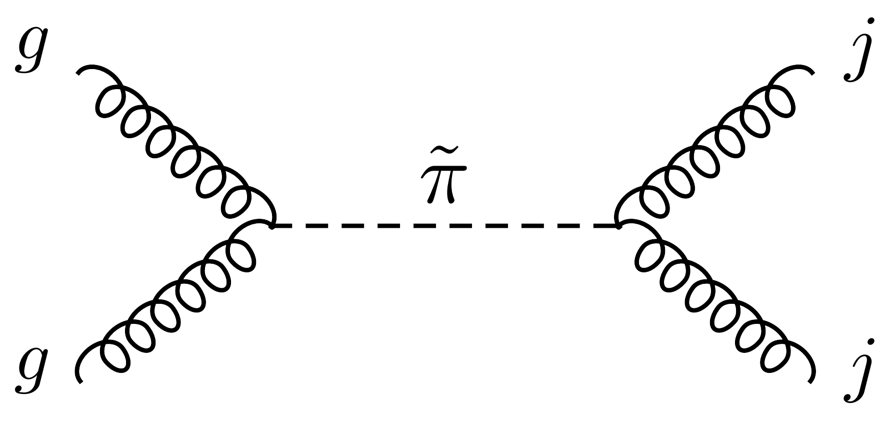
(A) Resonance searches in di-jets



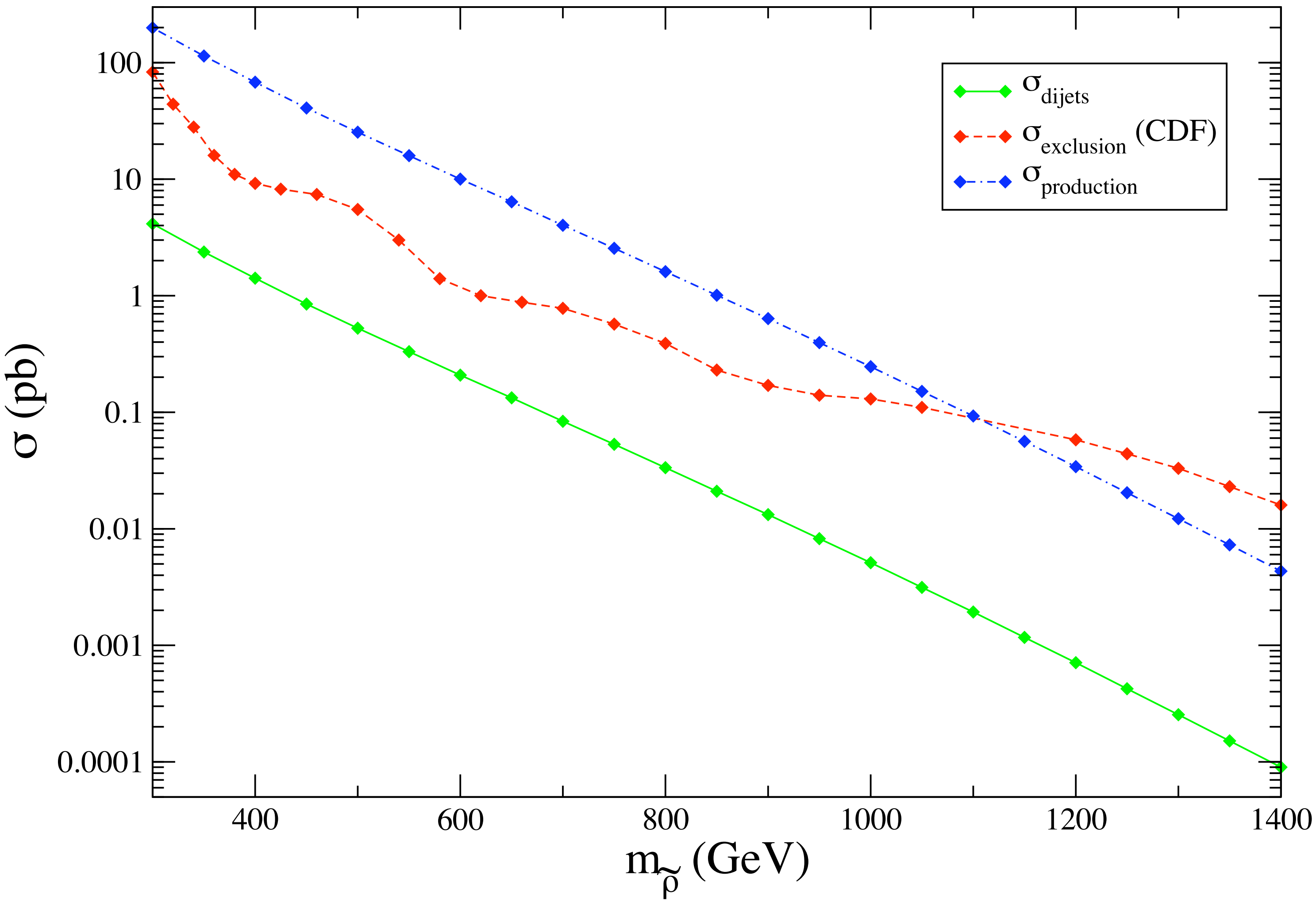


Potentially constrains



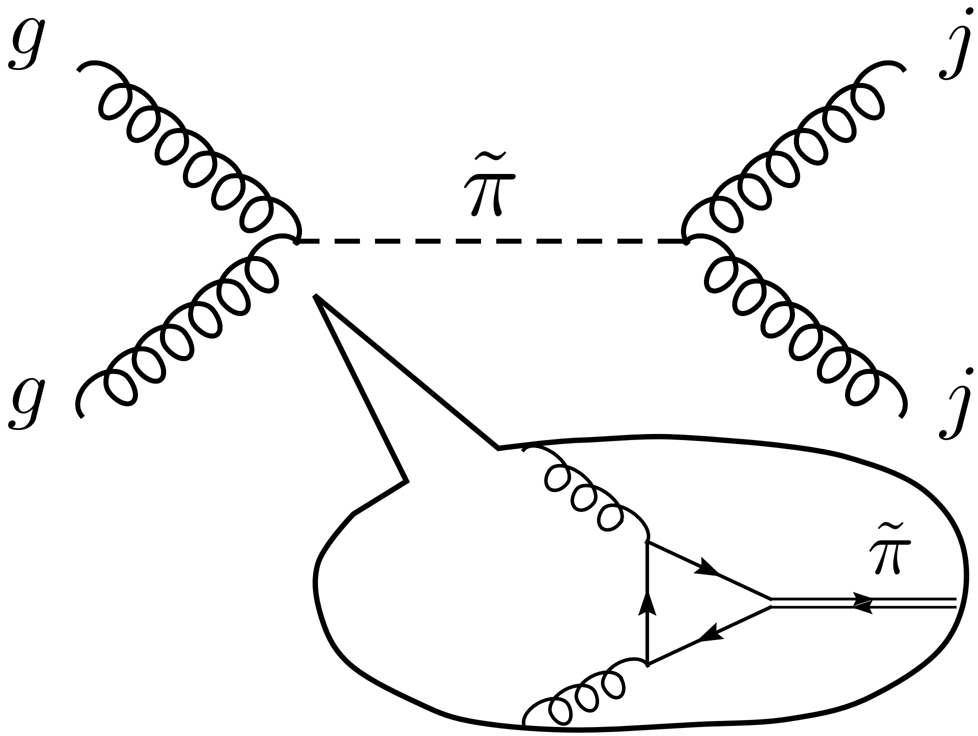


Tevatron Run-II

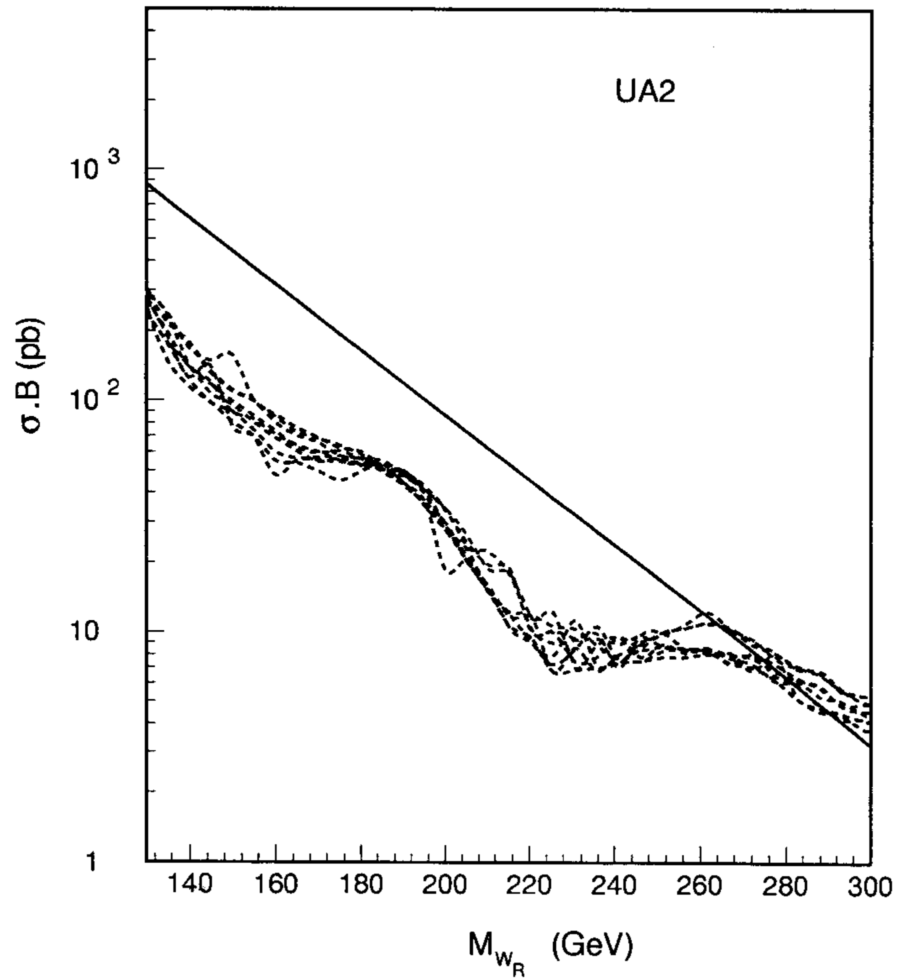


- Dominance of $\tilde{\rho} \rightarrow \tilde{\pi}\tilde{\pi}$ crucial!
- Our “scenario” robust!

Resonant $\tilde{\pi}$ production



suppressed by $1/16\pi^2$



$\sigma(p\bar{p} \to \tilde{\pi}) \simeq 10$ pb

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

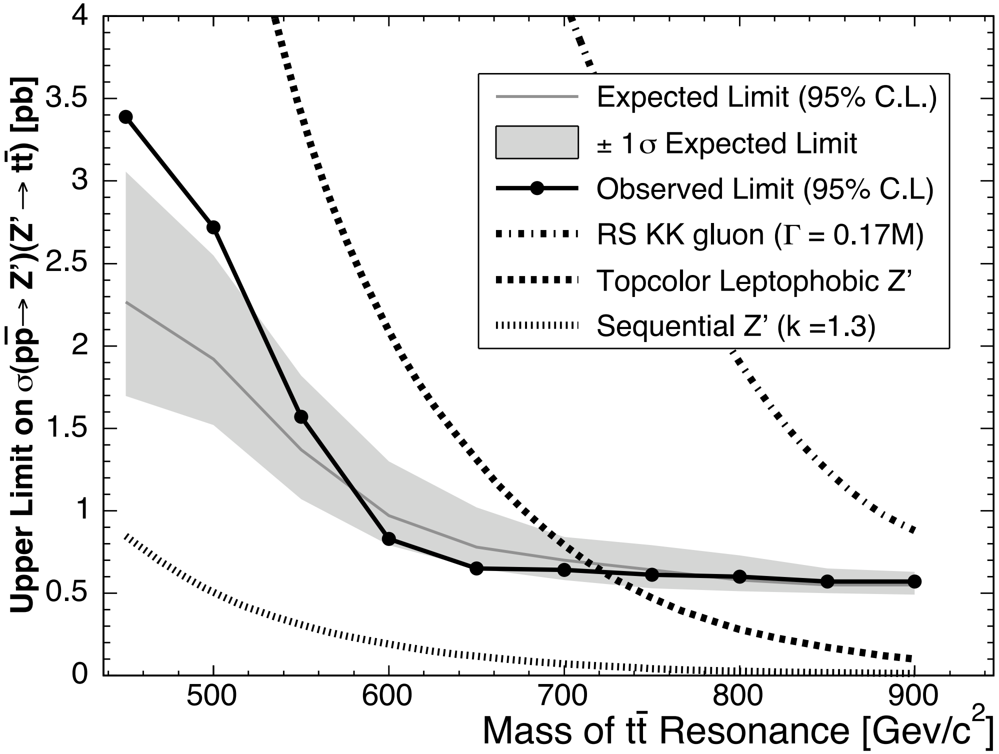
$\sqrt{s} = 630$ GeV

$\sigma(p\bar{p} \to \tilde{\pi}) \simeq 2.4$ pb

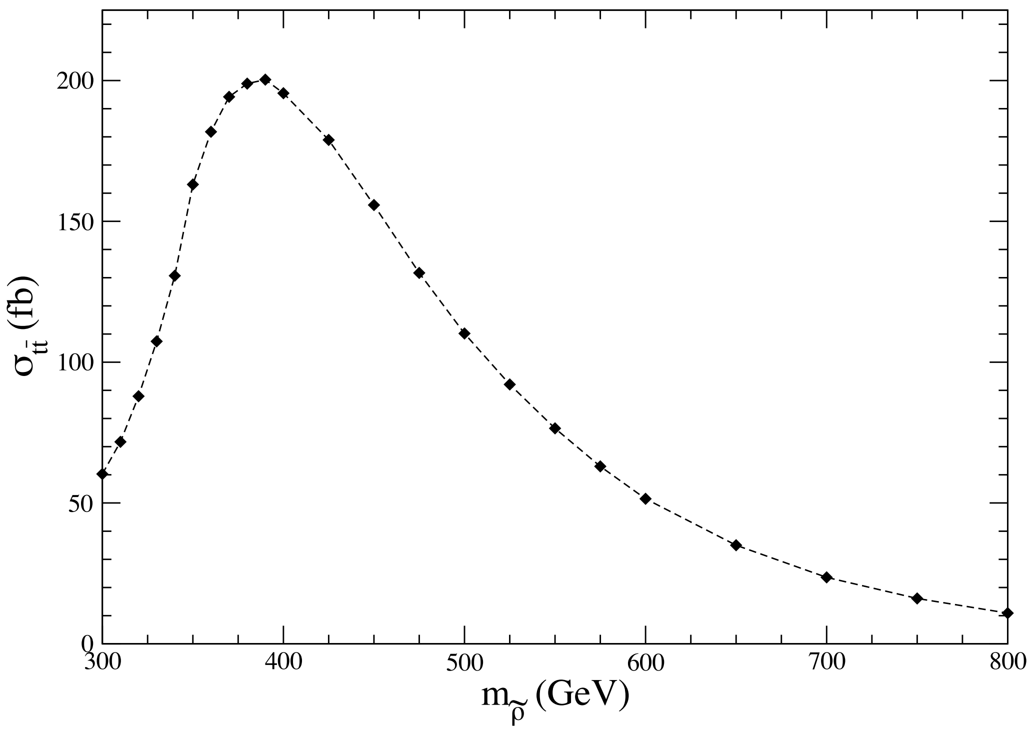
for $m_{\tilde{\pi}} = 250$ GeV

$\sqrt{s} = 1.8$ TeV

(B) Resonance searches in t-$\bar{t}$ pairs



[CDF 2008]

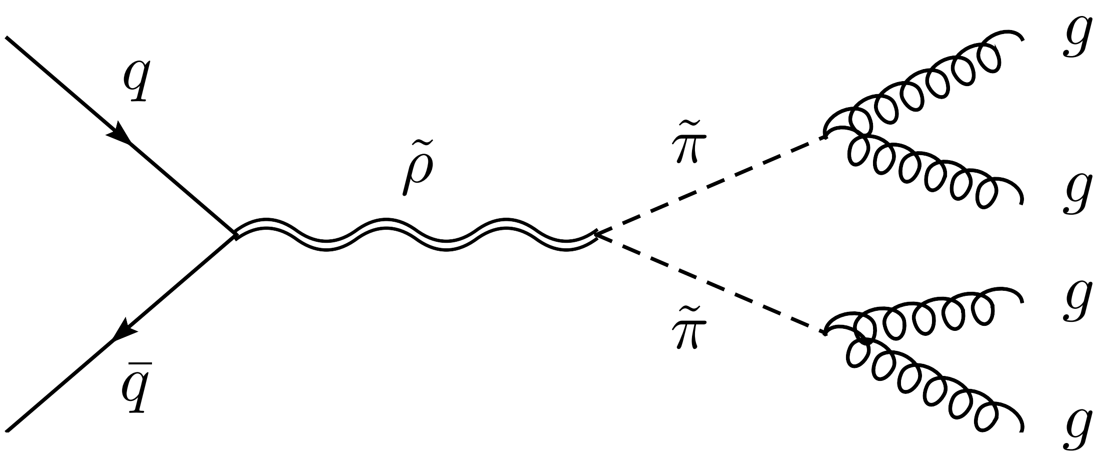


Way below the bound!

Discovery Potential at Tevatron

Kinematical features:

Signal:



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

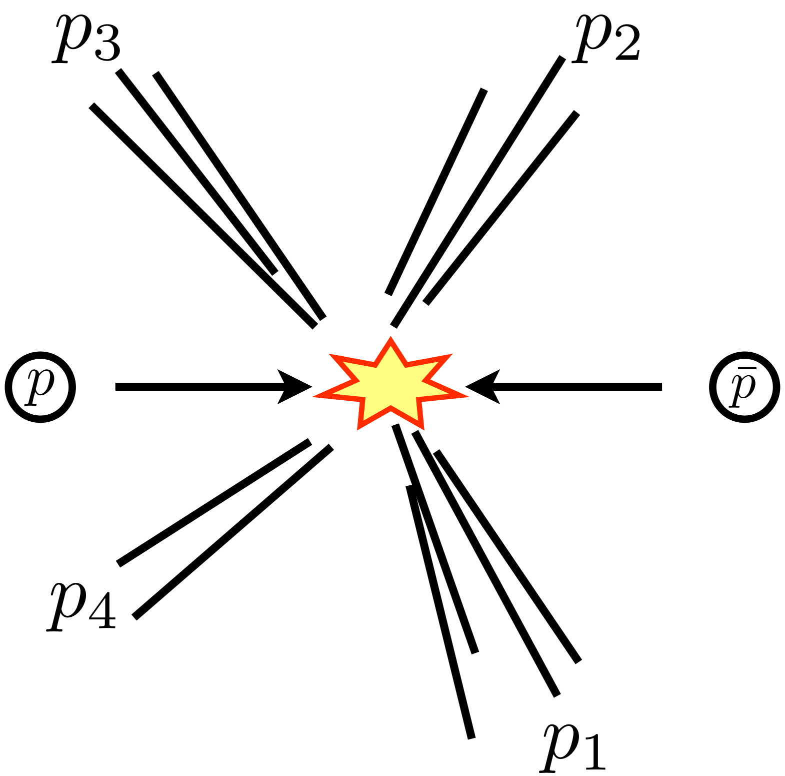
A pair of 2j resonances at $m_{\tilde{\pi}}$

Background: *No features.*

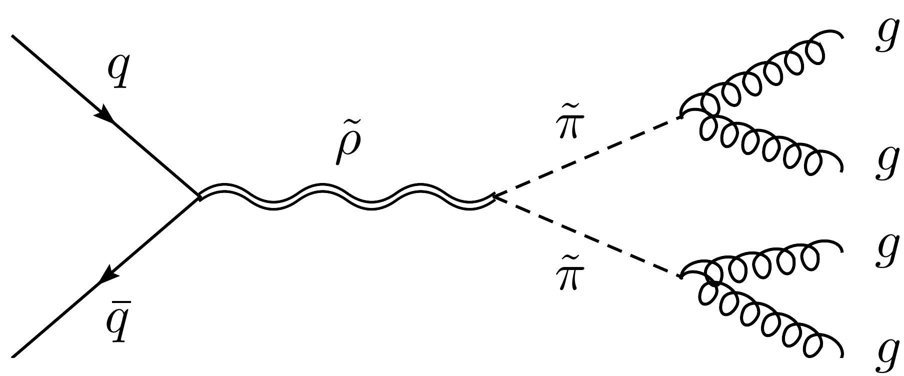
No scales.

g-g initiated.

Useful Observables



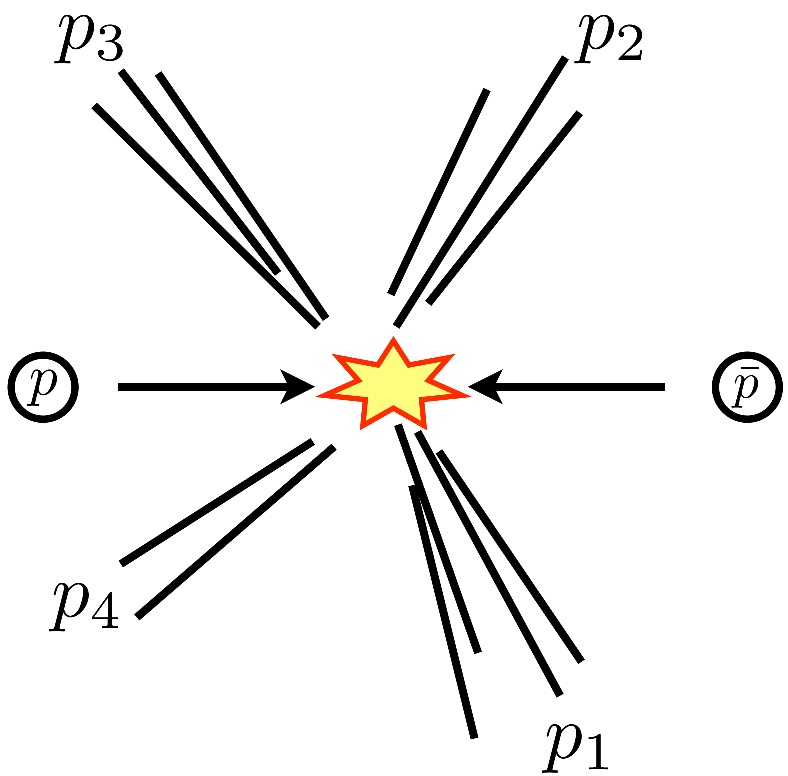
$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$



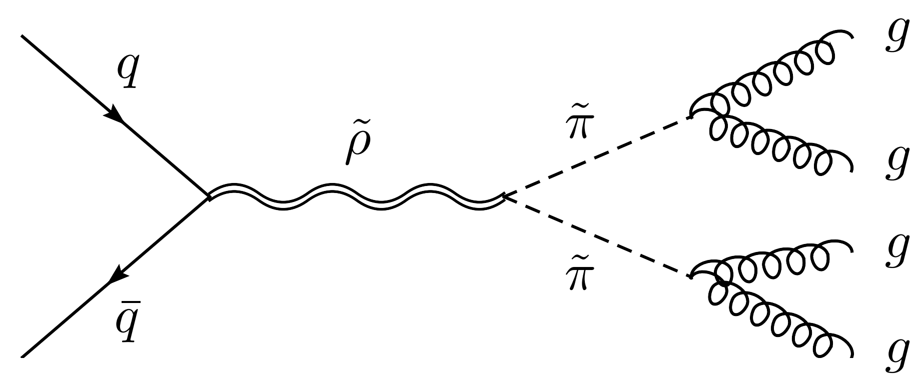
(1) To pick out the coloron,

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

Useful Observables



$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$



(1) To pick out the coloron,

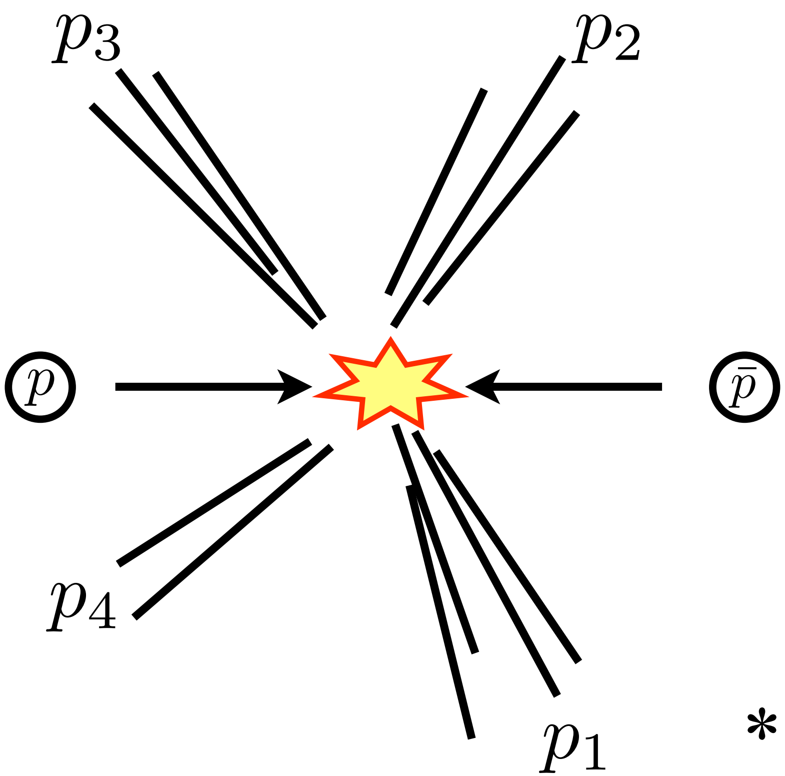
$$m_{4j}^2 \equiv (p_1 + p_2 + p_3 + p_4)^2$$

(2) To pick out the two scalars,

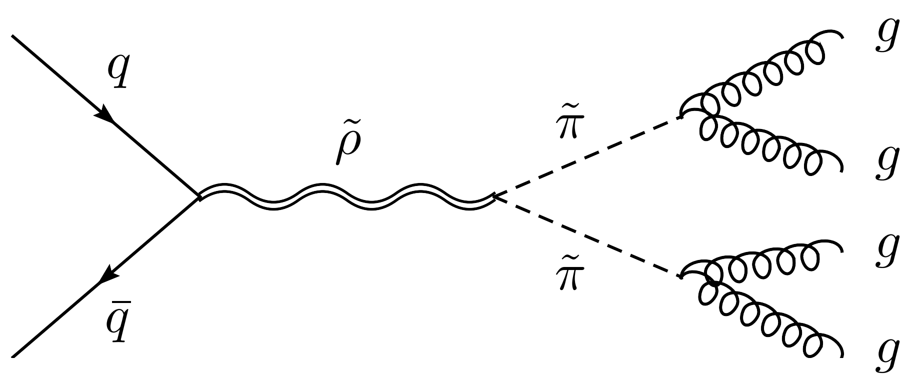
$$\langle m_{2j} \rangle \equiv (m_{ij} + m_{k\ell})/2 \quad \text{where} \quad |m_{ij} - m_{k\ell}| < 25 \text{ GeV}$$

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

Kinematical Tendencies



$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$



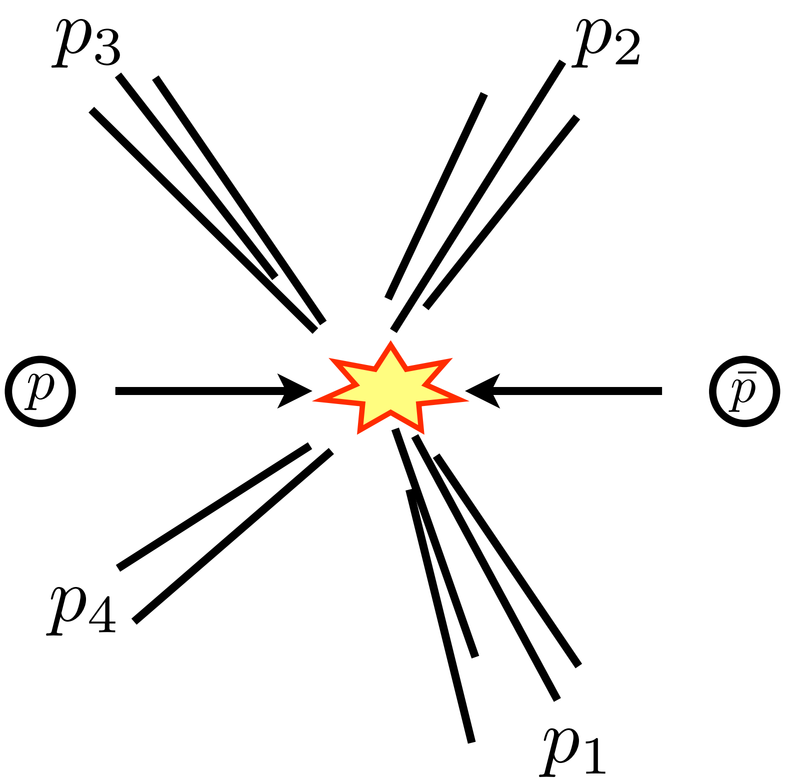
* The signal —*"democratic"*:

$$p_{T1} \sim p_{T2} \sim p_{T3} \sim p_{T4}$$

* QCD background — *"hierarchical"*:

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

Case study for **a light coloron**



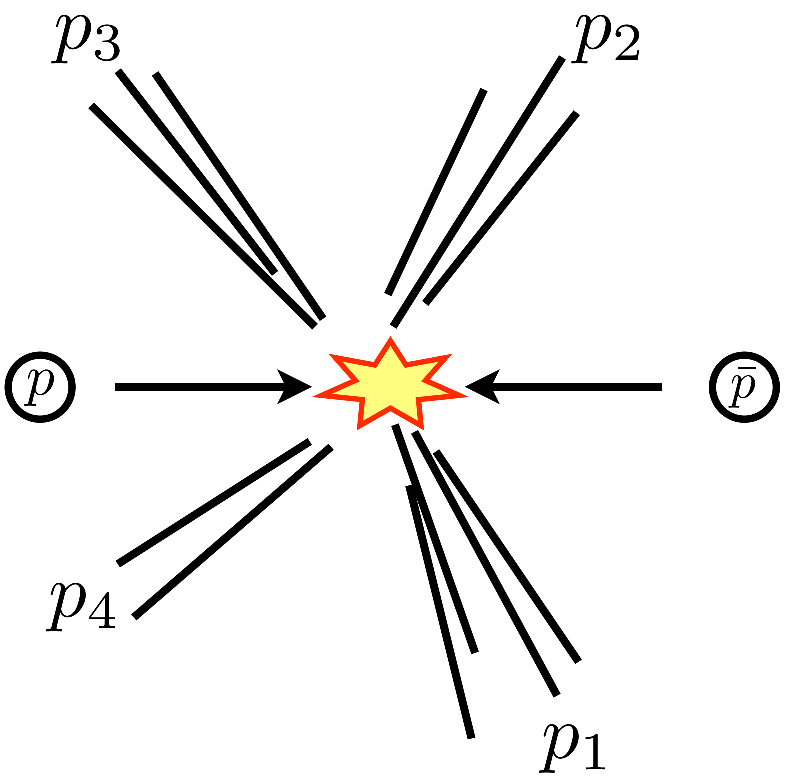
$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$

$m_{\tilde{\rho}} = 350$ GeV $(m_{\tilde{\pi}} = 100$ GeV$)$

* To pass the CDF single-jet trigger, (= 100 GeV)

$p_{T1} > 120$ GeV

Case study for **a light coloron**



$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$

$m_{\tilde{\rho}} = 350$ GeV $(m_{\tilde{\pi}} = 100$ GeV$)$

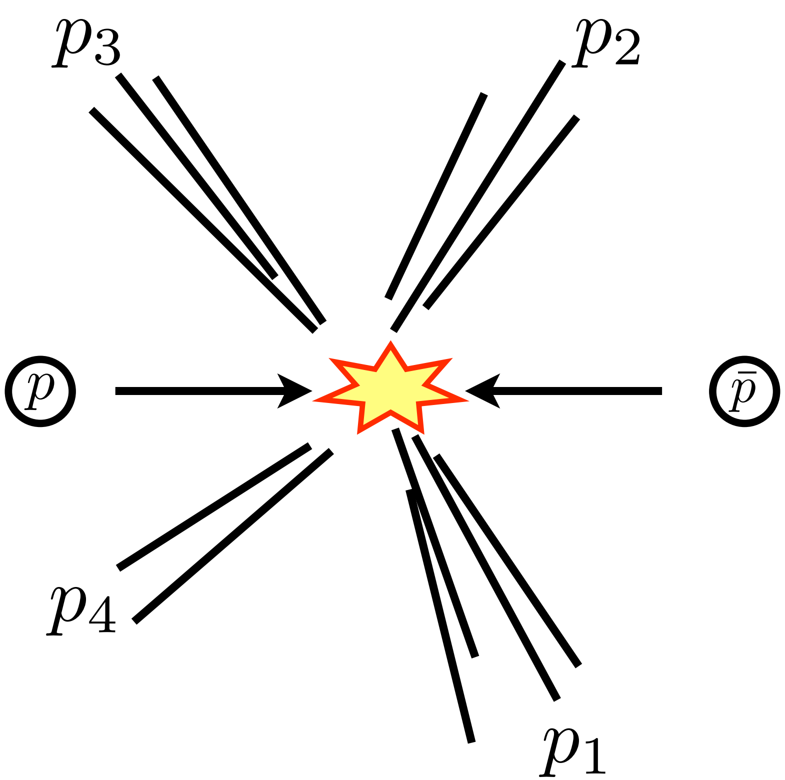
* To pass the CDF single-jet trigger,
(= 100 GeV)

$$p_{T1} > 120 \text{ GeV}$$

* To exploit "democratic vs hierarchical"

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

Case study for **a light coloron**



$(p_{T1} > p_{T2} > p_{T3} > p_{T4})$

$m_{\tilde{\rho}} = 350$ GeV $(m_{\tilde{\pi}} = 100$ GeV$)$

* To pass the CDF single-jet trigger, (= 100 GeV)

$$p_{T1} > 120 \text{ GeV}$$

* To exploit "democratic vs hierarchical"

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

* And recall that

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

Simulation Tools:

* Parton-level event generation

  MadGraph/MadEvent

* Parton showering & hadronization

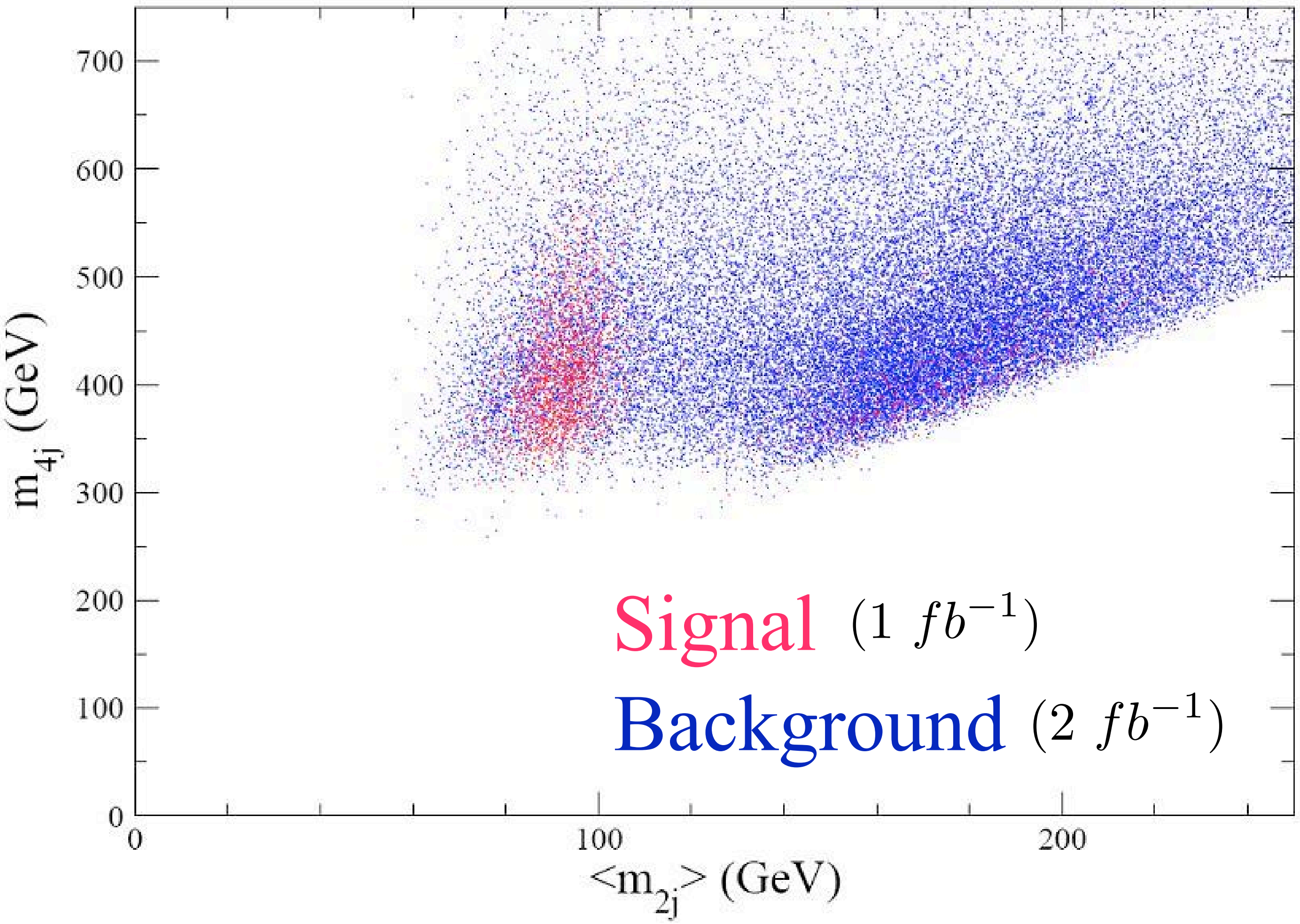
  Pythia

* Detector simulation

  PGS

  using standard CDF parameters w/ $\Delta R = 0.7$.

The Result for a **light coloron**



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

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

$\sigma_{p\bar{p}\to\tilde{\rho}} = 110$ pb

$p_{T1} > 120$ GeV

$p_{Ti} > 40$ GeV

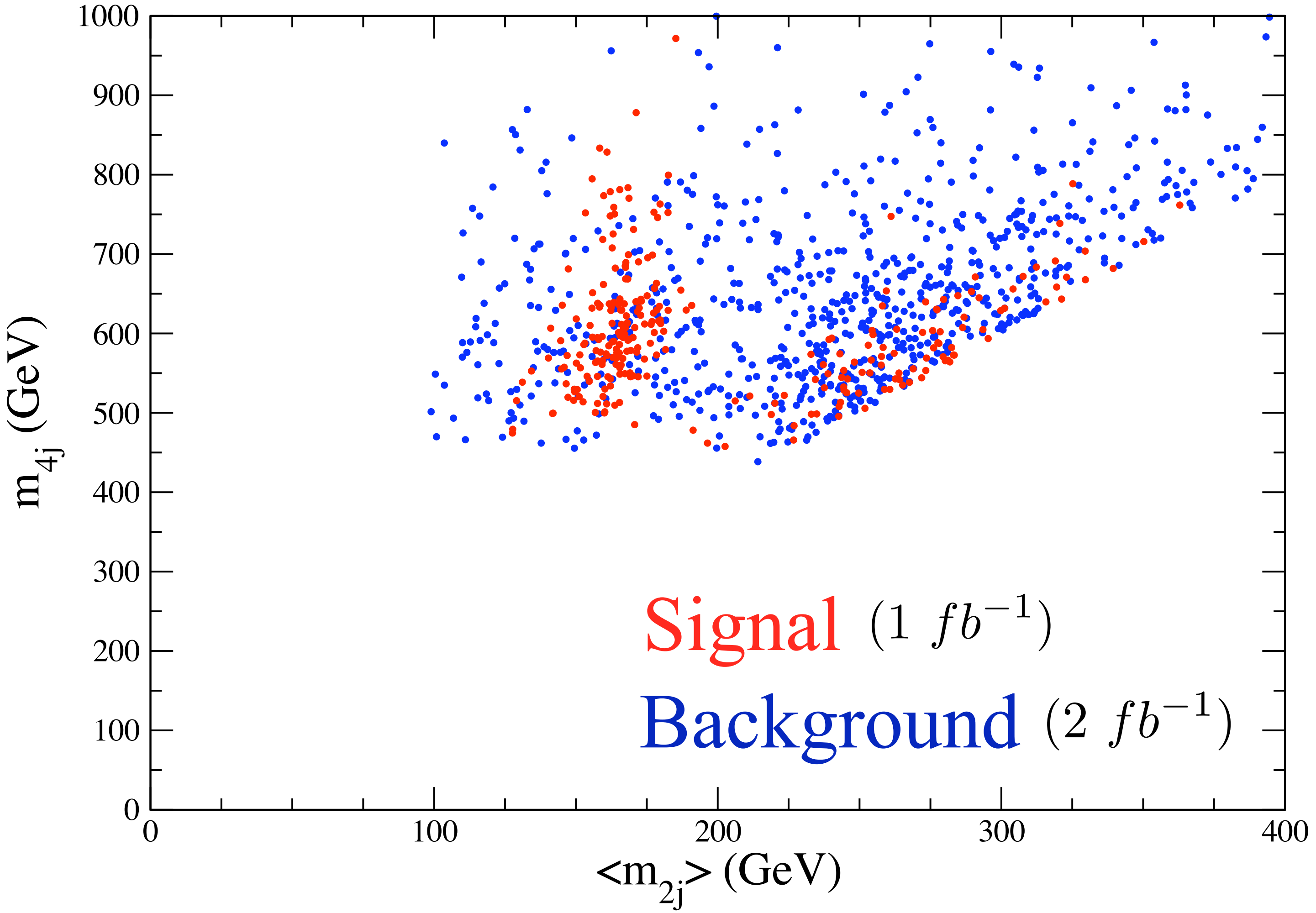
$|m_{ij} - m_{k\ell}| < 25$ GeV

Signal : 2.7 pb passing cuts

Background: 21 pb passing cuts

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

The Result for a **heavier coloron**



$m_{\tilde{\rho}} = 600$ GeV

$(m_{\tilde{\pi}} = 180$ GeV$)$

$\sigma_{p\bar{p}\to\tilde{\rho}} = 10$ pb

$p_{T1} > 120$ GeV

$p_{Ti} >$ 90 GeV

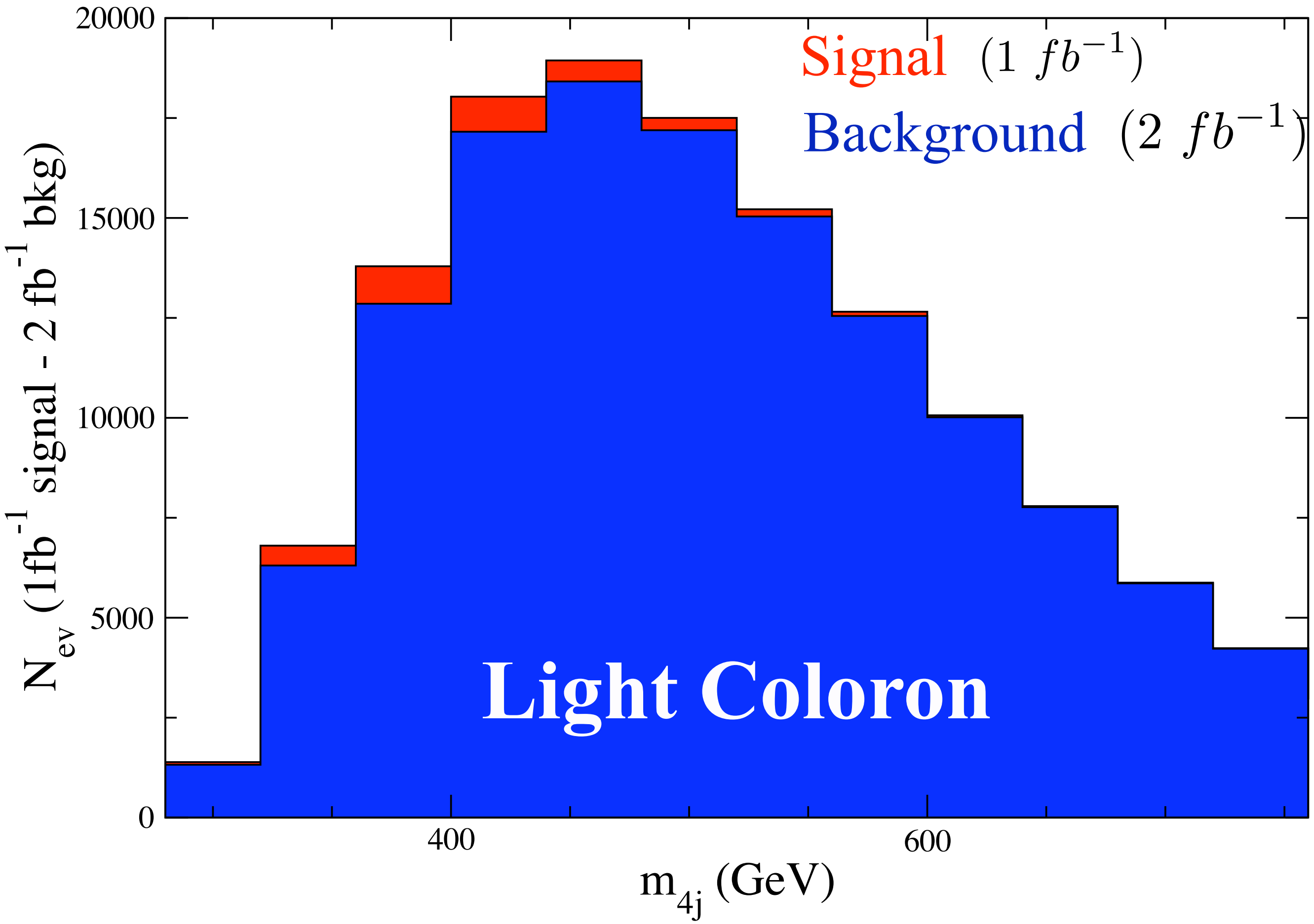
$|m_{ij} - m_{k\ell}| < 25$ GeV

Signal : 0.27 pb passing cuts

Background: 0.38 pb passing cuts

$$\sqrt{\sum_{\text{bins}} \left(\frac{S}{\sqrt{B}}\right)^2} = \mathbf{17\ !}$$

What if we don't pair up jets?



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

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

$$p_{T1} > 120 \text{ GeV}$$

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

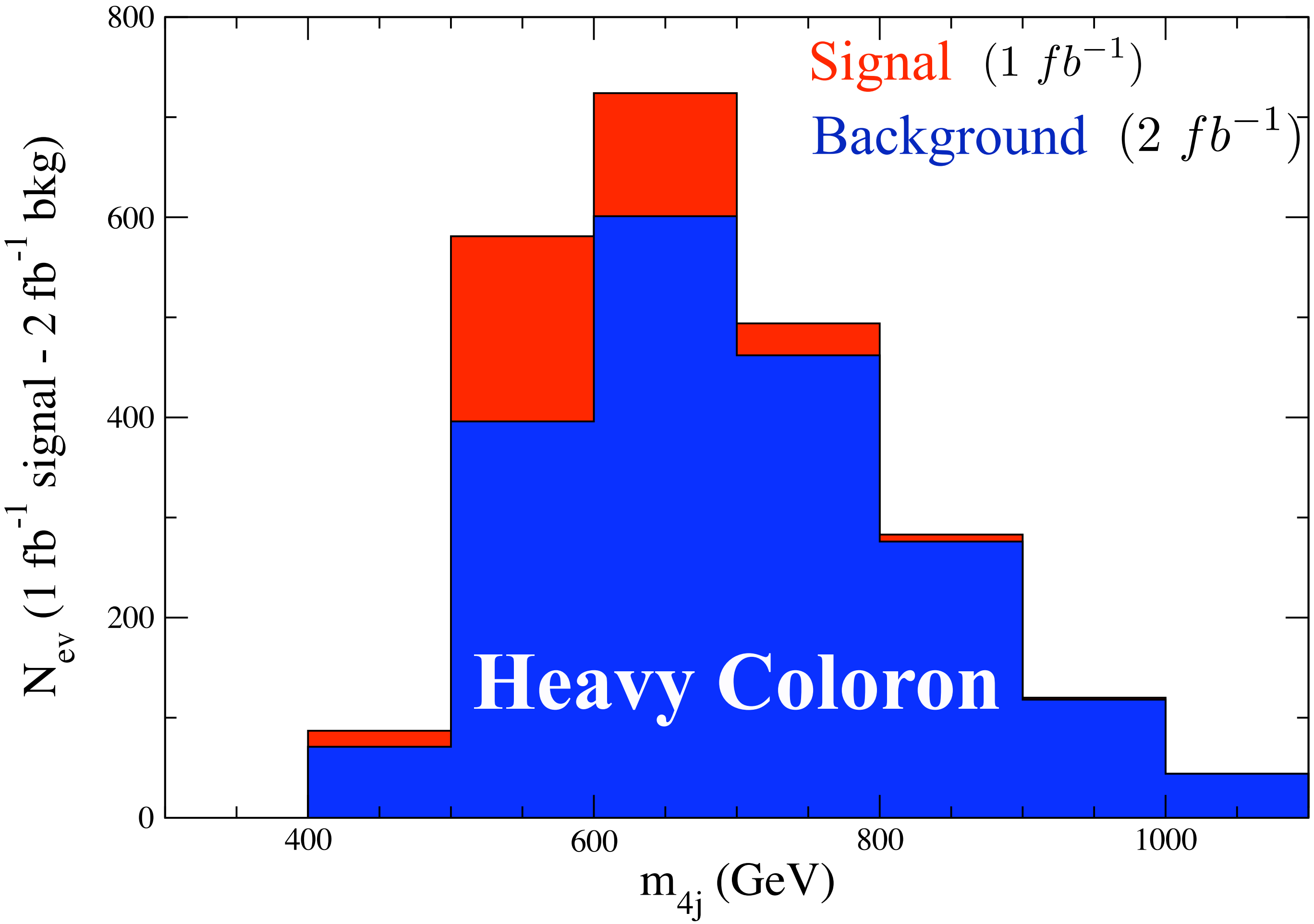
Signal : 3.6 pb passing cuts

Background: 66 pb passing cuts

$$\sqrt{\sum_{\text{bins}} \left(\frac{S}{\sqrt{B}}\right)^2} = 13,$$

BUT too suble to tell...

What if we don't pair up jets?



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

$$(m_{\tilde{\pi}} = 180 \text{ GeV})$$

$$p_{T1} > 120 \text{ GeV}$$

$$p_{Ti} > 90 \text{ GeV}$$

Much better!

Signal : 0.36 pb passing cuts

Background: 0.99 pb passing cuts

$$\sqrt{\sum_{\text{bins}} \left(\frac{S}{\sqrt{B}}\right)^2} = \mathbf{11\ !}$$

The LHC *won't* be good for $m_{\tilde{\rho}} \lesssim 1$ TeV !

* Bigger gluon p.d.f.

—— More background

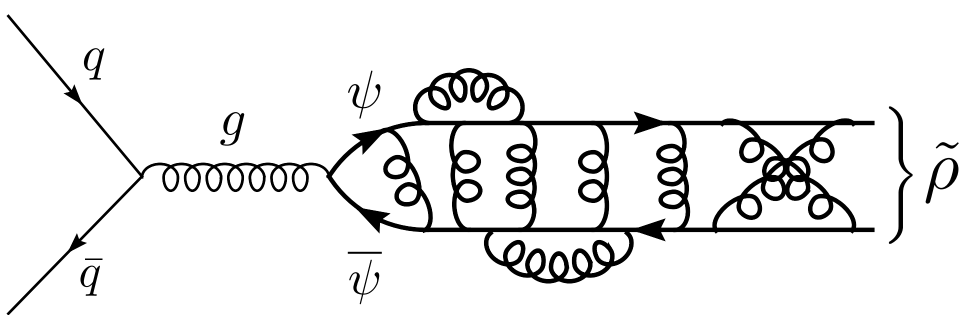
* p-p collider rather than p-$\bar{p}$

—— Less signal

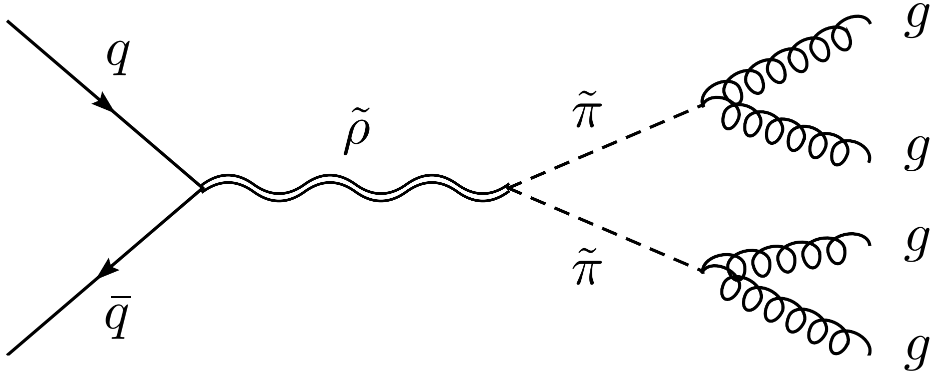
* Higher jet triggers

—— Even less signal

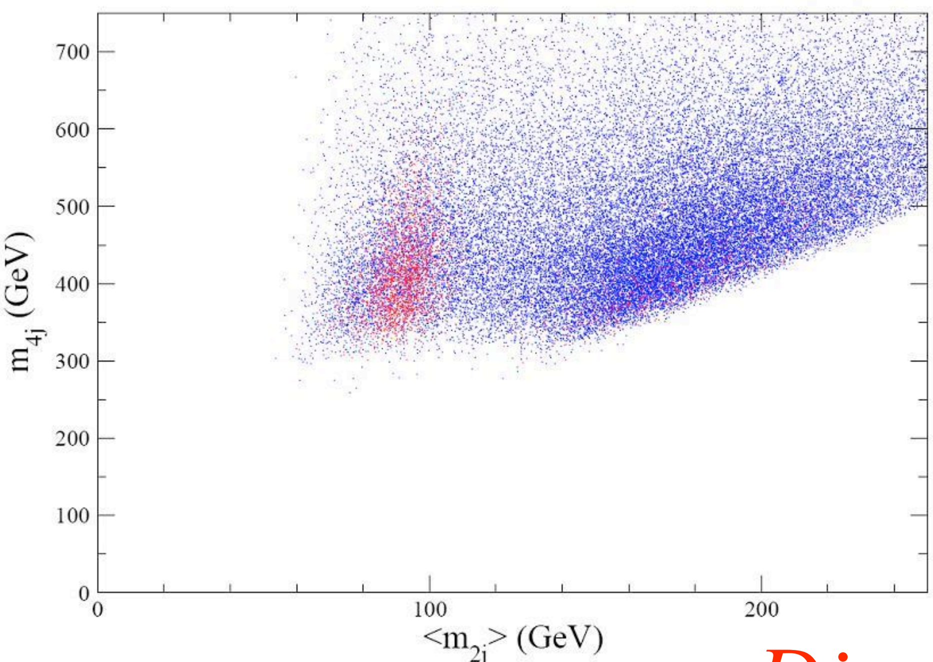
Conclusions

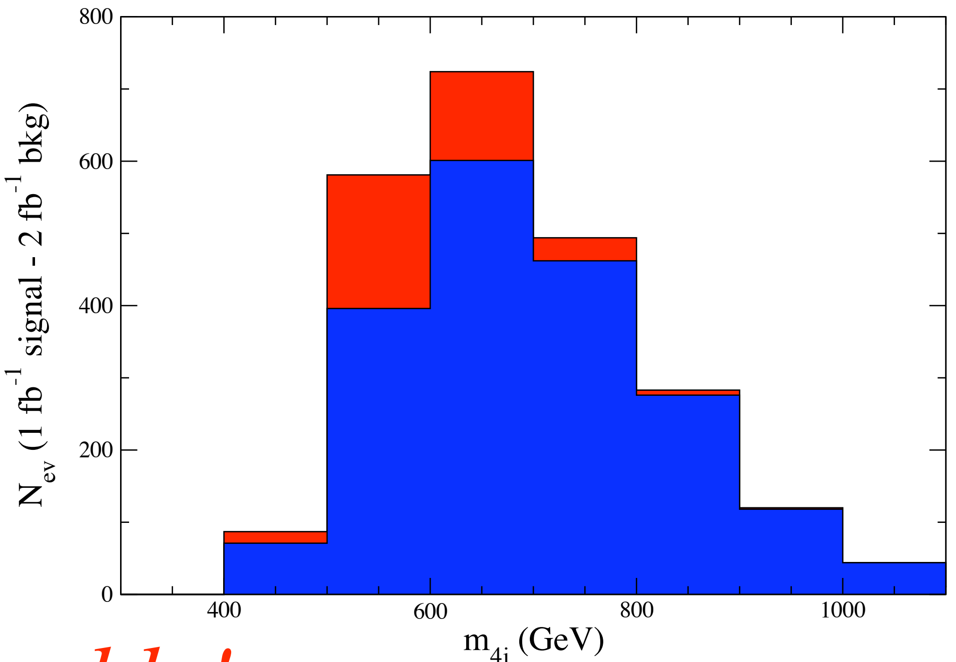


Theoretically robust & generic!



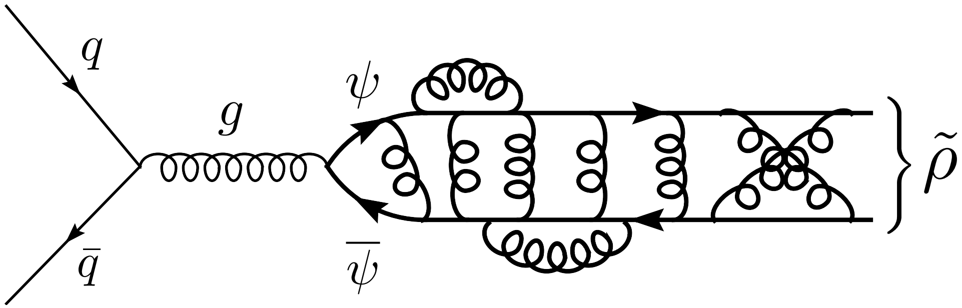
Naturally into multi-jets!

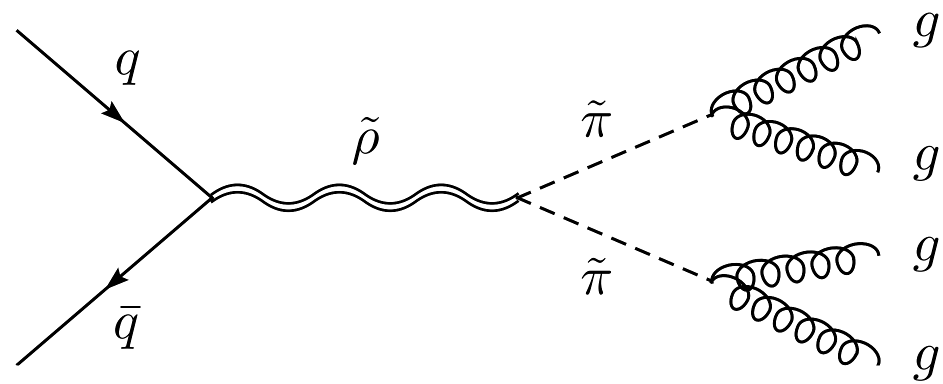




Discoverable!

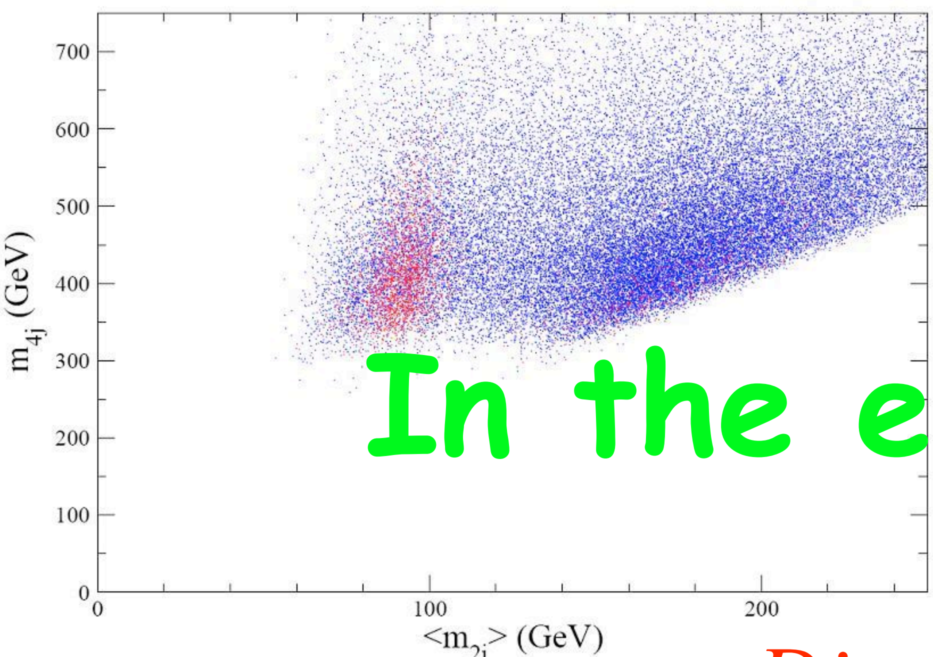
Conclusions

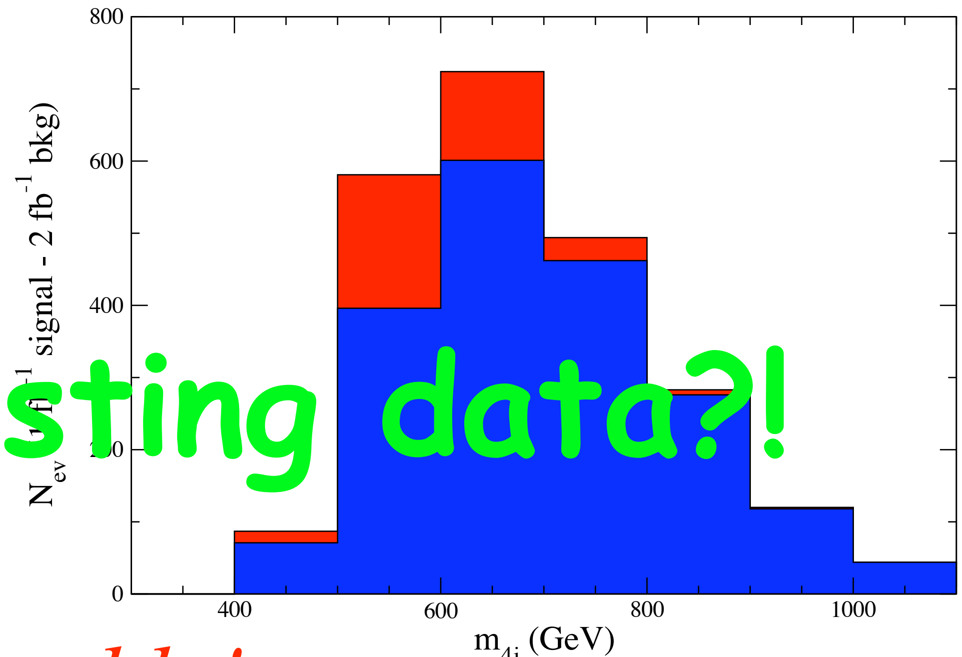




Theoretically robust & generic!

Naturally into multi-jets!

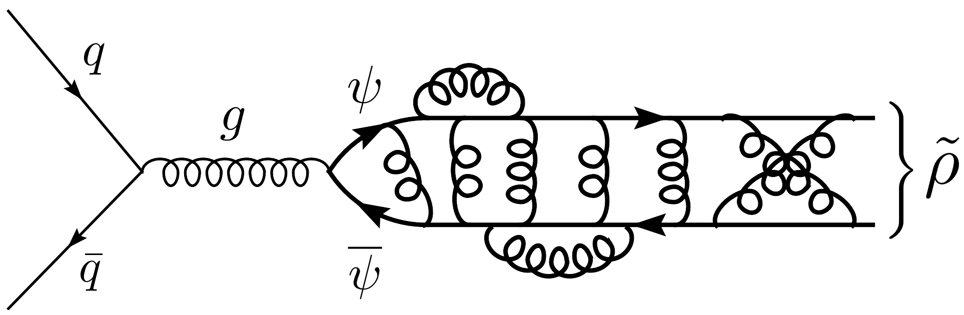




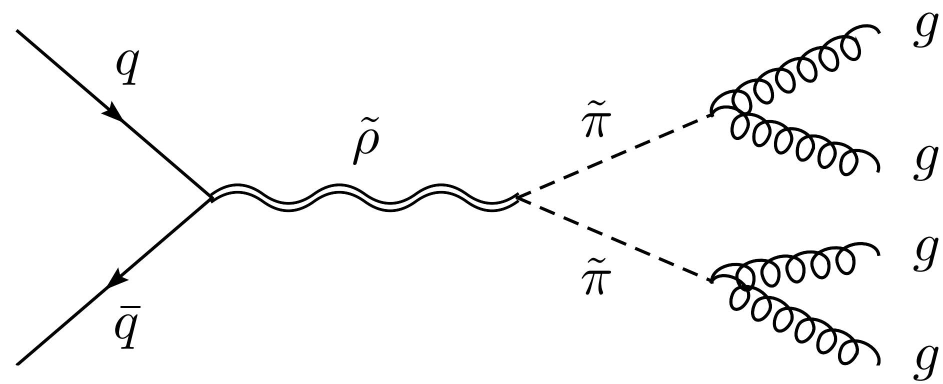
In the existing data?!

Discoverable!

Conclusions

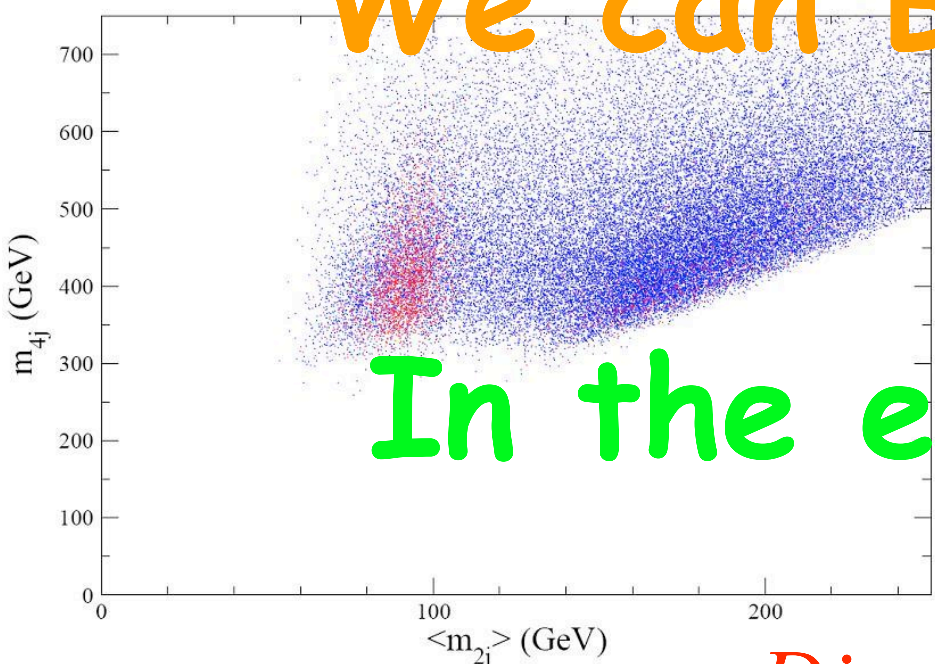


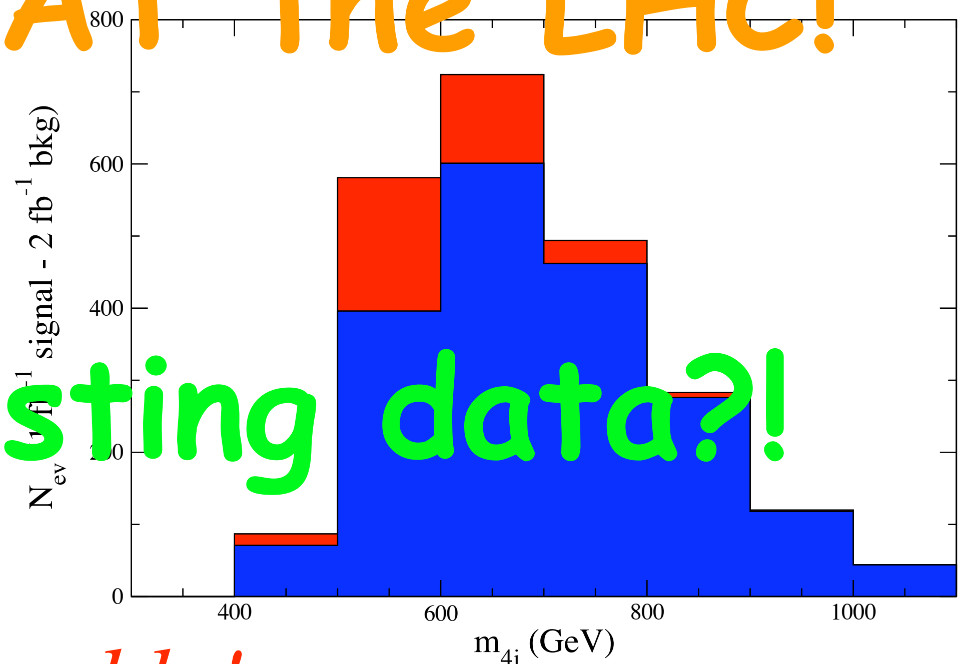
Theoretically robust & generic!



Naturally into multi-jets!

We can BEAT the LHC!





In the existing data?!

Discoverable!