Discovering Colorons at the LHC

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Discovering Colorons at the LHC

Dicus, Kao, Nandi, Sayre (2010) and Sayre, Dicus, Kao, Nandi (2011)

- A model with colorons and hyper-pions
- The production cross sections
- The Physics Background
- Discovery Potential at the LHC
- Conclusions

A Model with Colorons and Hyper-Pions

Dicus, Dutta, and Nandi (1995); Dobrescu, Kong, Mahbubani (2008);

Kilic, Okui, and Sundrum (2008), Kilic, Schumann and Son (2009)

- In this model, we assume that there exists a new strong force (hypercolor, HC) which becomes confining at a higher energy than the strong QCD force: $SU(N)_{HC} \times SU(3)_C \times SU(2) \times U(1)$.
- Hyper-quarks will form spin-1 bound states that are hypercolor singlets but carry QCD color quantum numbers (octet). These hyper-gluons are the colorons.
- Analogous to the chiral symmetry breaking, this model will also produce relatively light scalars (hyper-pions) as pseudo-Goldstone bosons.

The Effective Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} \; = \; & -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}i\not{D}q - \frac{1}{4}\tilde{\rho}^a_{\mu\nu}\tilde{\rho}^{a\mu\nu} + \frac{M^2_{\tilde{\rho}}}{2}\tilde{\rho}^a_\mu\tilde{\rho}^{a\mu} \\
- \; & g_3\epsilon\tilde{\rho}^a_\mu\bar{q}\gamma^\mu T^a q + \frac{1}{2}(D_\mu\tilde{\pi})^a(D^\mu\tilde{\pi})^a - M_{\tilde{\pi}}{}^2\tilde{\pi}^a\tilde{\pi}^a \\
- \; & ig_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} f^{abc}\tilde{\rho}^{a\mu}(\tilde{\pi}^b D_\mu\tilde{\pi}^c) - \frac{3{g_3}^2\epsilon^{\mu\nu\rho\sigma}}{16\pi^2 f_{\tilde{\pi}}}\mathrm{Tr}[\tilde{\pi}G_{\mu\nu}G_{\rho\sigma}] \\
+ \; & i\chi g_3\,\mathrm{Tr}[G_{\mu\nu}[\tilde{\rho}^\mu,\tilde{\rho}^\nu]]\,.
\end{aligned}
$$

- *$N_{\text{HC}} = 3$ for simplicity.* a **is a color index.**
- $G_{\mu\nu}$ and q are gluon and quark fields.
- *D_μ is the SM covariant derivative and g_3 the coupling constant of QCD.*

Relevant Parameters

By analogy with the phenomenology of SM mesons,

- *the $\tilde{\rho}q\bar{q}$ coupling* $\epsilon \simeq 0.2$,
- *the strongly induced $\tilde{\rho}\tilde{\pi}\tilde{\pi}$ coupling* $g_{\tilde{\rho}\tilde{\pi}\tilde{\pi}} \simeq 6$,
- **the $\tilde{\pi}$ decay constant** $f_{\tilde{\pi}} \simeq f_{\pi} \times \frac{M_{\tilde{\rho}}}{M_{\rho}}$,
- *and the mass relation* $M_{\tilde{\pi}} \simeq 0.3 \times M_{\tilde{\rho}}$.
- $\Gamma_{\tilde{\rho}} \simeq 0.19 \times M_{\tilde{\rho}}$, and $\Gamma_{\tilde{\pi}} \simeq 0.12\alpha_s^2 \times M_{\tilde{\pi}}$.

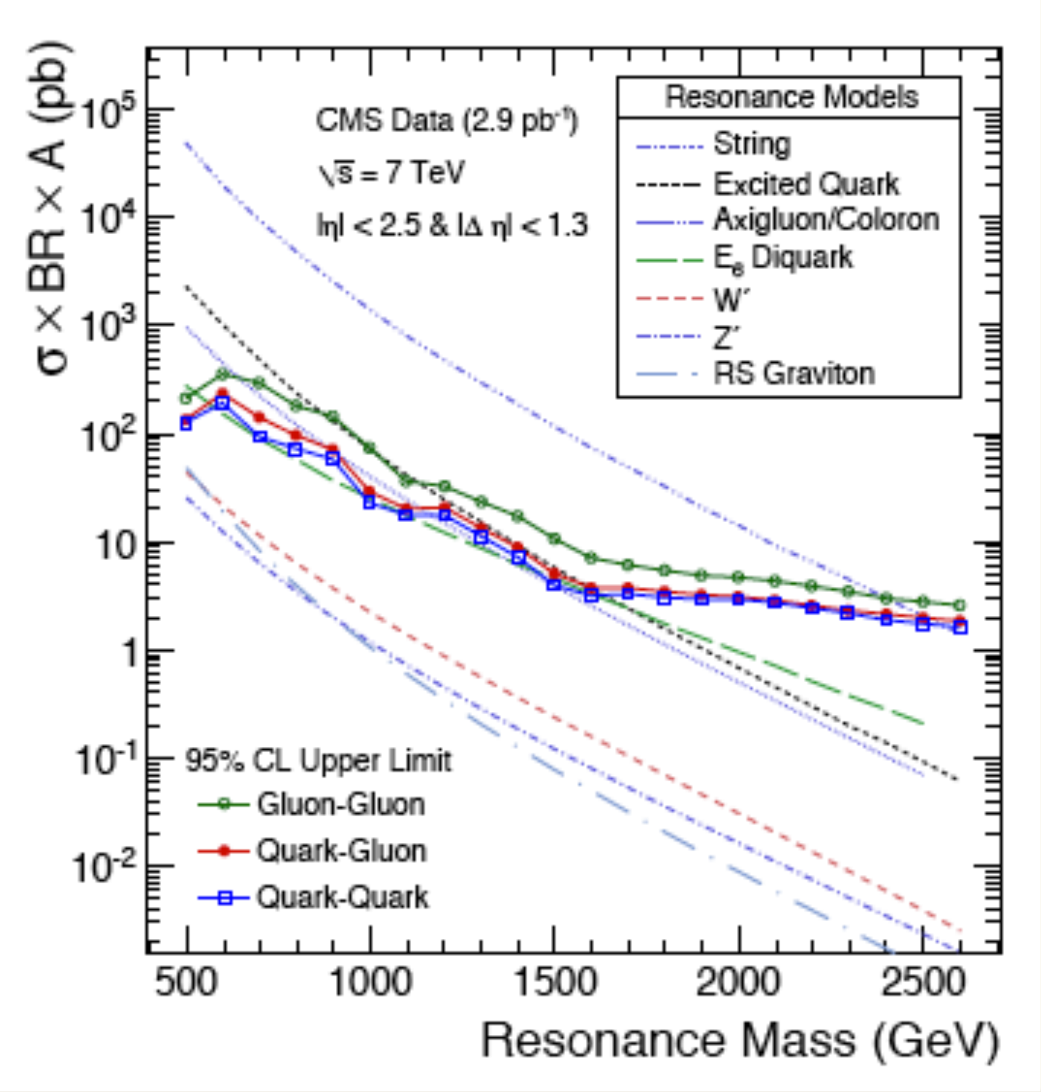
Constraints from CDF and CMS Data

CDF Collaboration (2008); CMS Collaboration (2010)

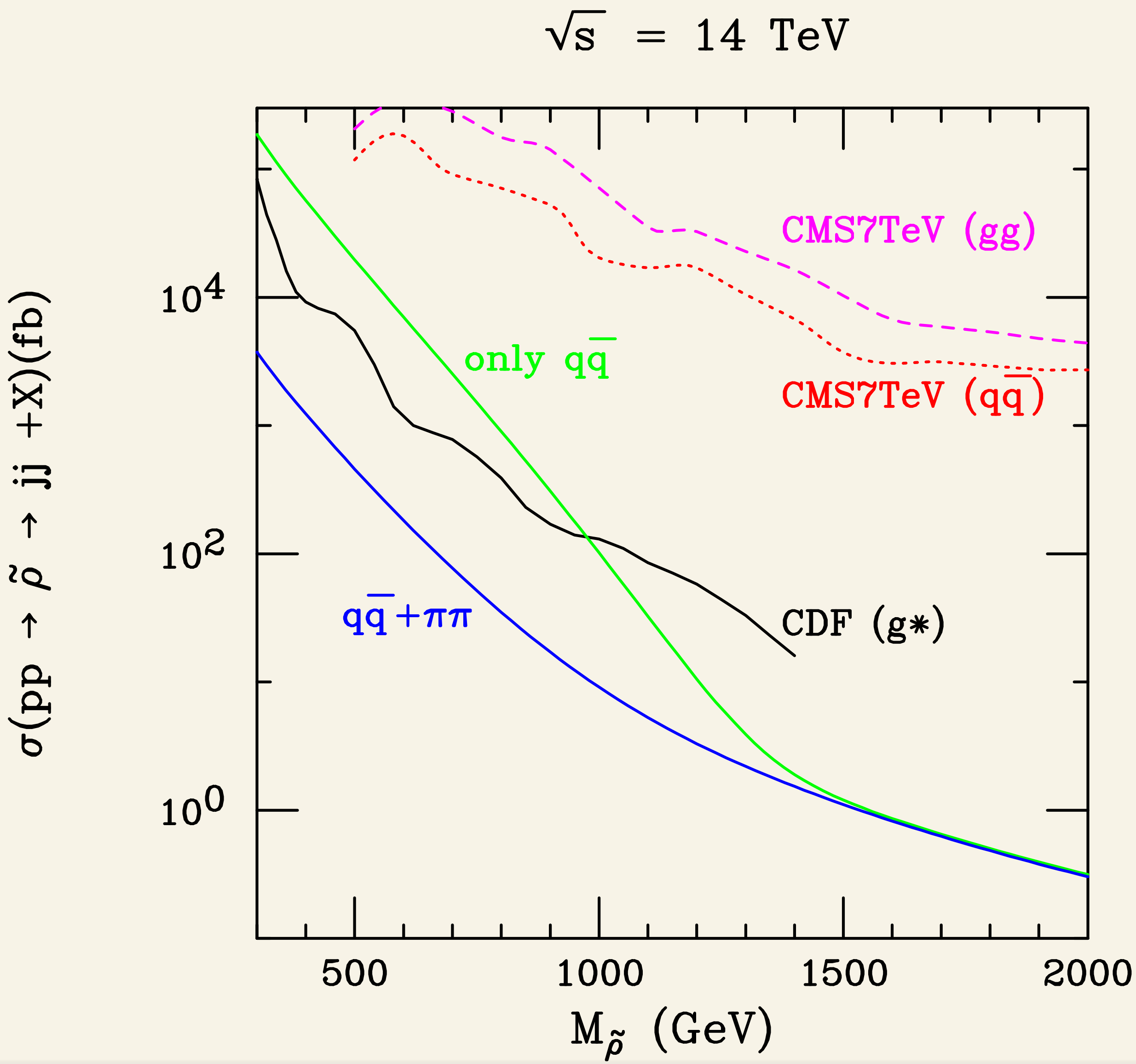
- Electroweak precision data provide important constraints on electroweak models beyond the SM.
- New strong interactions can still be consistent LEP and Tevatron Data.
- In this model, the hyper-pions couple sufficiently weakly to gluons.
- The hyper-rhos have only a small branching fraction to decay into two quarks or two gluons.

CMS Limits with 7 TeV

CMS Collaboration (2010)



CMS and CDF Limits



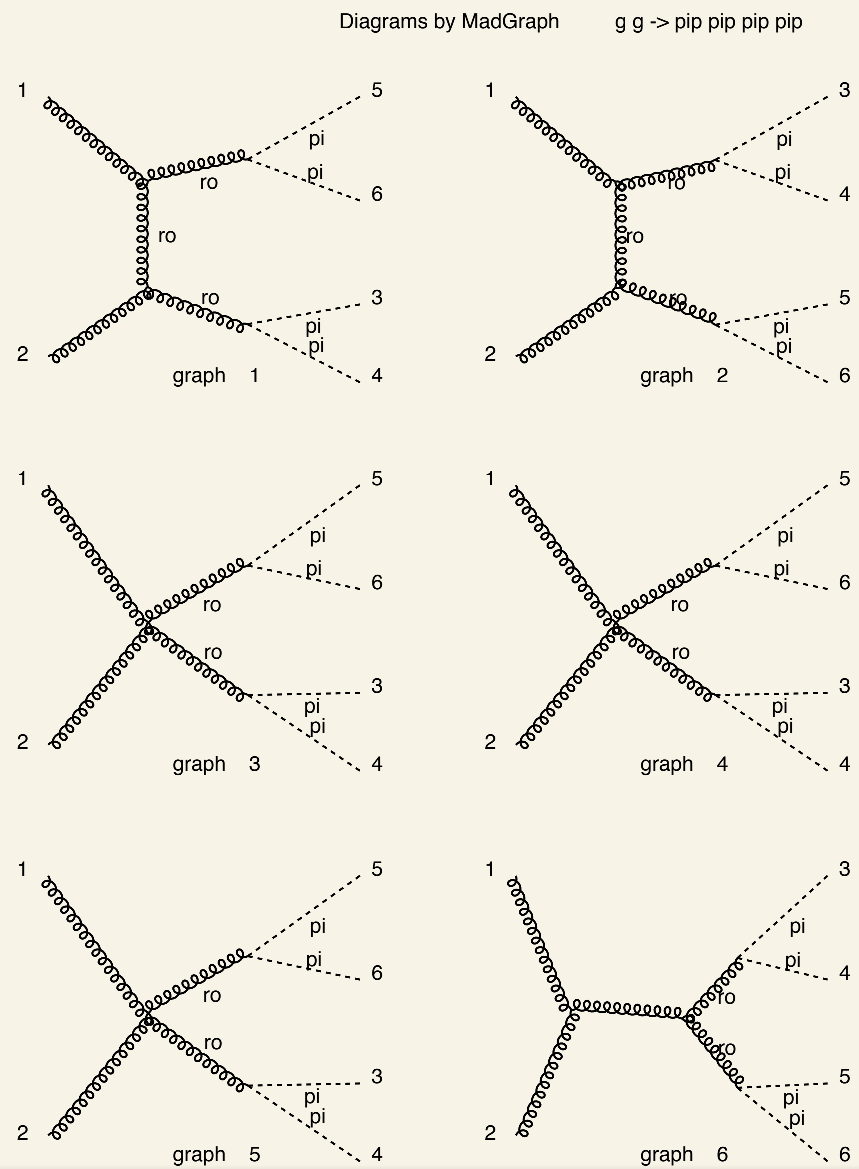
Production Cross Section

- In this model, the coloron decays predominantly into a pair of hyper-pions, which then each decay into a pair of gluons.
- Thus the dominant signal for resonant coloron production is a 4-jet decay chain.
- A new model has been added in MadGraph with new interactions and new particles to generate matrix elements squared for all processes.

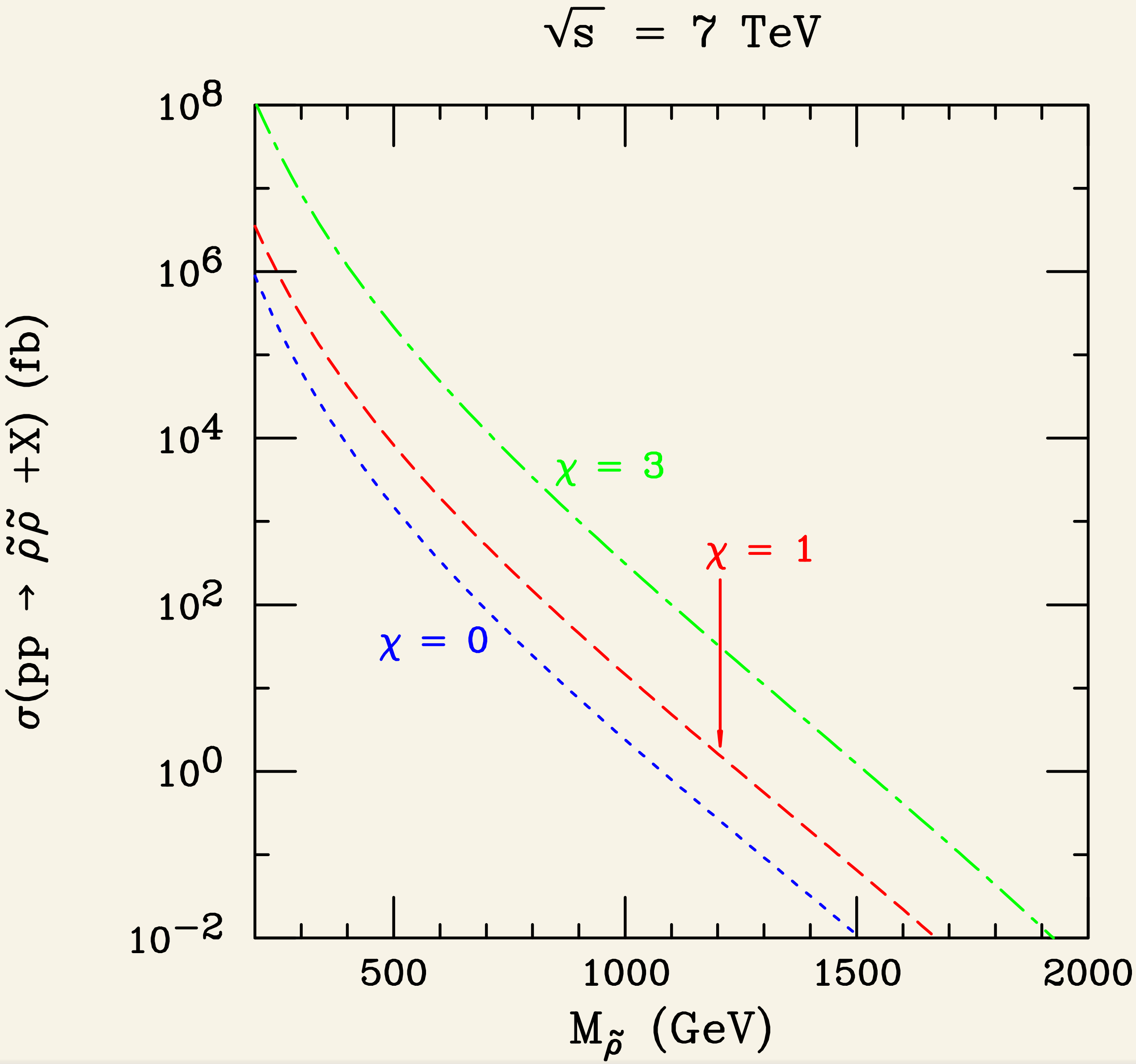
Production of Coloron Pairs

- Signal: $pp \to \tilde{\rho}\tilde{\rho} \to 4\tilde{\pi} \to 8g + X$
- Cross sections of signal evaluated with analytical formulas are in good agreement with results from MadGraph.
- Dominant Physics Background: $pp \longrightarrow 8g + X$ calculated with COMIX using Berends-Giele recursion relations, and checked with MadGraph for $gg \longrightarrow 4g$

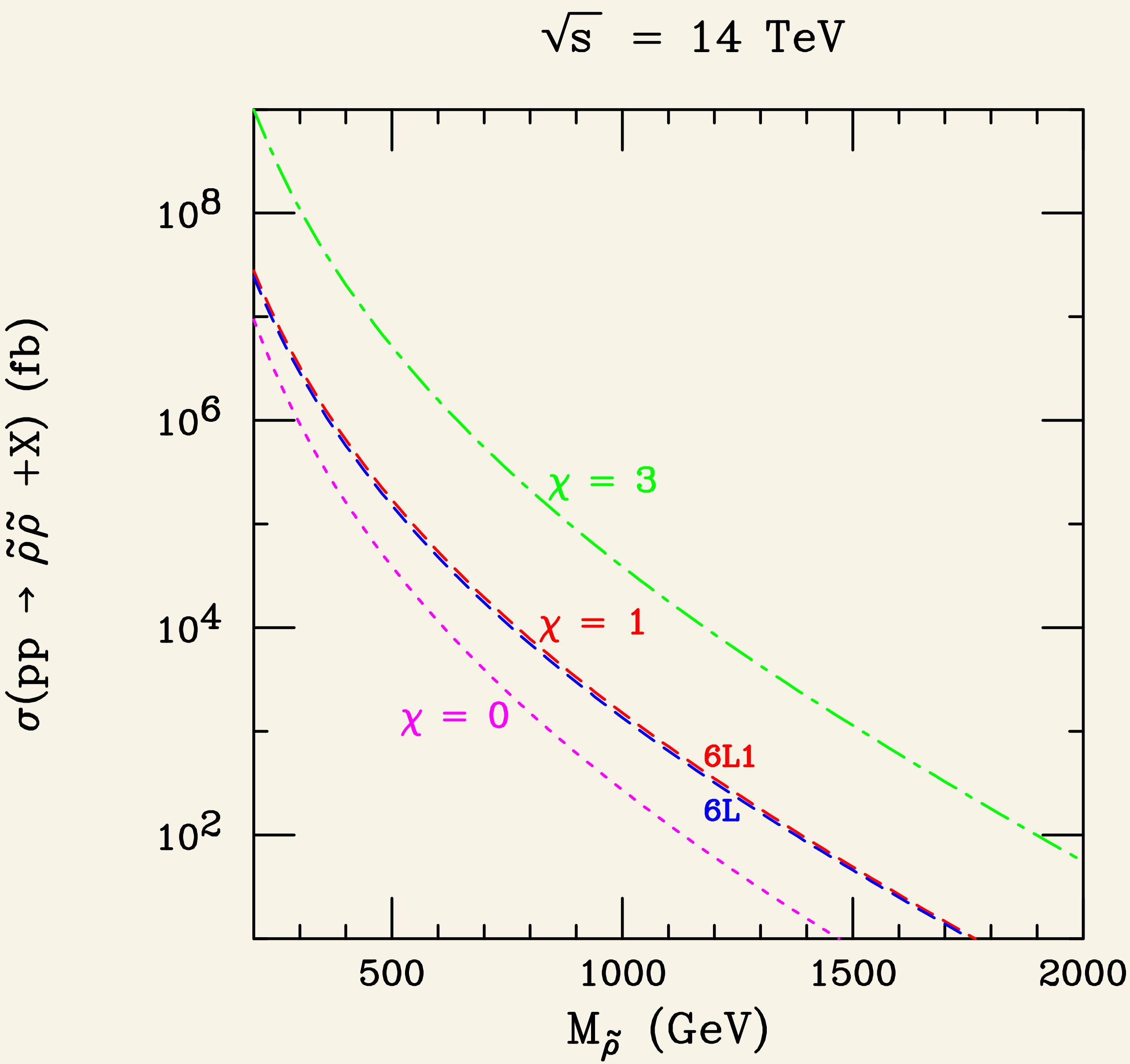
$$gg \rightarrow \tilde{\rho}\tilde{\rho} \rightarrow 4\tilde{\pi} + X$$



$$pp \rightarrow \tilde{\rho}\tilde{\rho} + X$$



$$pp \to \tilde{\rho}\tilde{\rho} + X$$



Effect of χ and Unitarity, $Y = \chi - 1$

$$
\begin{aligned}
\sum_{\text{pol}} |T|^2 &= \frac{Y^2(1-z^2)^2}{(1-\beta^2 z^2)^2}\frac{E^4}{M_{\tilde{\rho}}^4}\left[12 - 12Y + (5+z^2)Y^2\right] \\
&+ \frac{Y^2(1-z^2)}{(1-\beta^2 z^2)^2}\frac{E^2}{M_{\tilde{\rho}}^2}\left[16(1+3z^2) - 2(11+18z^2)Y + (5+9z^2+3z^4)Y^2\right] \\
&+ \frac{1}{(1-\beta^2 z^2)^2}\Bigg[8\left(16 + 3\frac{M_{\tilde{\rho}}^4}{E^4}\right) - 256Y + (160+16z^2+36z^4)Y^2 \\
&\qquad -(32+22z^2+24z^4)Y^3 + (2+5z^2+4z^4+2z^6)Y^4\Bigg] \\
&+ \frac{1}{1-\beta^2 z^2}\left[-6\left(16 + 4\frac{M_{\tilde{\rho}}^2}{E^2} + \frac{M_{\tilde{\rho}}^4}{E^4}\right) + 140Y - (58+24z^2)Y^2 + 3(1+4z^2)Y^3 - z^4Y^4\right] \\
&+ 28 + 6\frac{M_{\tilde{\rho}}^2}{E^2} - 3(1-\beta^2 z^2) - 16Y + 4Y^2 \qquad (4)
\end{aligned}
$$

where E is the gluon energy, z is the cosine of the scattering angle, $\beta^2 = 1 - M_{\tilde{\rho}}^2/E^2$,

The Physics Background

We compute the cross section of the dominant eight jet physics background with the matrix-element generator COMIX interfaced with the event generator SHERPA.

- The backgrounds included are, in the order of importance, $gq \to 7g1q, gg \to 8g, qq \to 6g2q$, and $gq \to 5g3q$.
- MadGraph employs Feynman diagrams. It can calculate matrix elements with at most 5 outgoing gluons from gluon fusion.
- We require that in each event, there should be eight jets with lower limits on their transverse momenta of $p_T(j_1, \cdots, j_8) \geq 250, 200, 160, 120, 80, 60, 40, 20$ GeV , a pseudo-rapidity for each jet of $|\eta(j)| < 2.5$, and angular separation for each pair of jets of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$.

Recursion Relations in QCD

Duhr, Hoche and Maltoni (2006)

- Berends and Giele [1988]
- Twistor: Witten [2004]
- Cachazo, Svrcek and Witten (CSW) [2004]
- Britto, Cachazo and Feng (BCF)[2005]

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.2	7.19	11.9	59.1	27.8	30.6
$7g$	58.5	23.7	73.6	646	146	195
$8g$	276	82.1	597	8690	919	1890
$9g$	1450	270	5900	127000	6310	29700
$10g$	7960	864	64000	-	48900	-

Discovery Potential at the Early LHC

We define the signal to be observable if the lower limit on the signal plus background is larger than the corresponding upper limit on the background, namely,

$$L(\sigma_s + \sigma_b) - N\sqrt{L(\sigma_s + \sigma_b)} > L\sigma_b + N\sqrt{L\sigma_b}$$

which corresponds to

$$\sigma_s > \frac{N^2}{L}\left[1 + 2\sqrt{L\sigma_b}/N\right] .$$

We take $N = 2.5$, which corresponds to a 5σ threshold in the limit $\sigma_s << \sigma_b$.

We employ a Poisson distribution for $N_B < 16$ and require that the probability for the background to fluctuate to this level is less than 2.85×10^{-7}.

Relative Mass Cuts

We have considered two types of mass cuts: (i) relative mass cuts and (ii) fixed mass cuts.

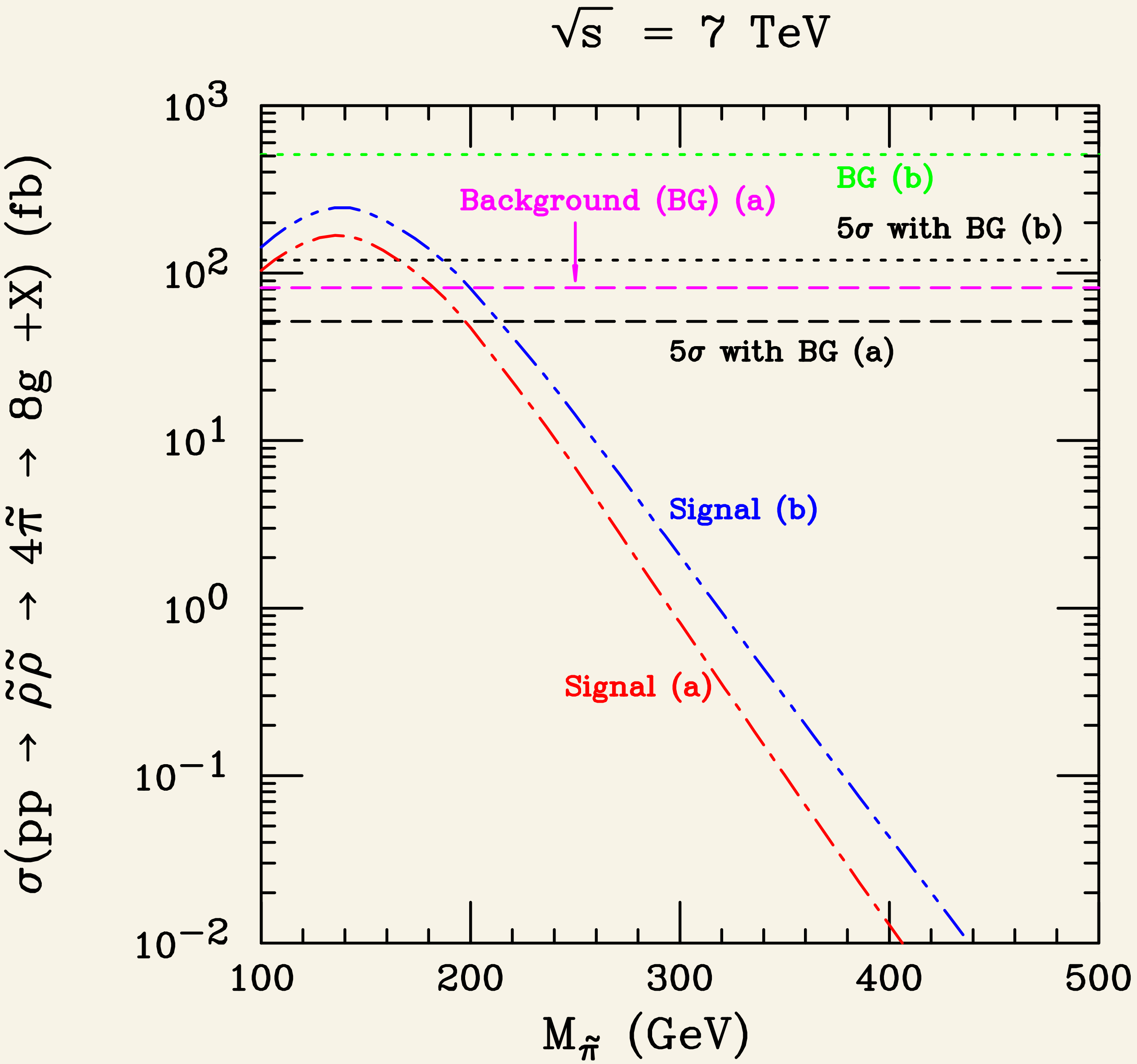
The relative mass cut requires that in each event there must be 8 jets, which can be arranged into 4 pairs of jets that have invariant mass within ΔM_{2j} of one another, and there must be distinct pairs of 4 jets that have invariant mass within ΔM_{4j} of each other.

We have chosen

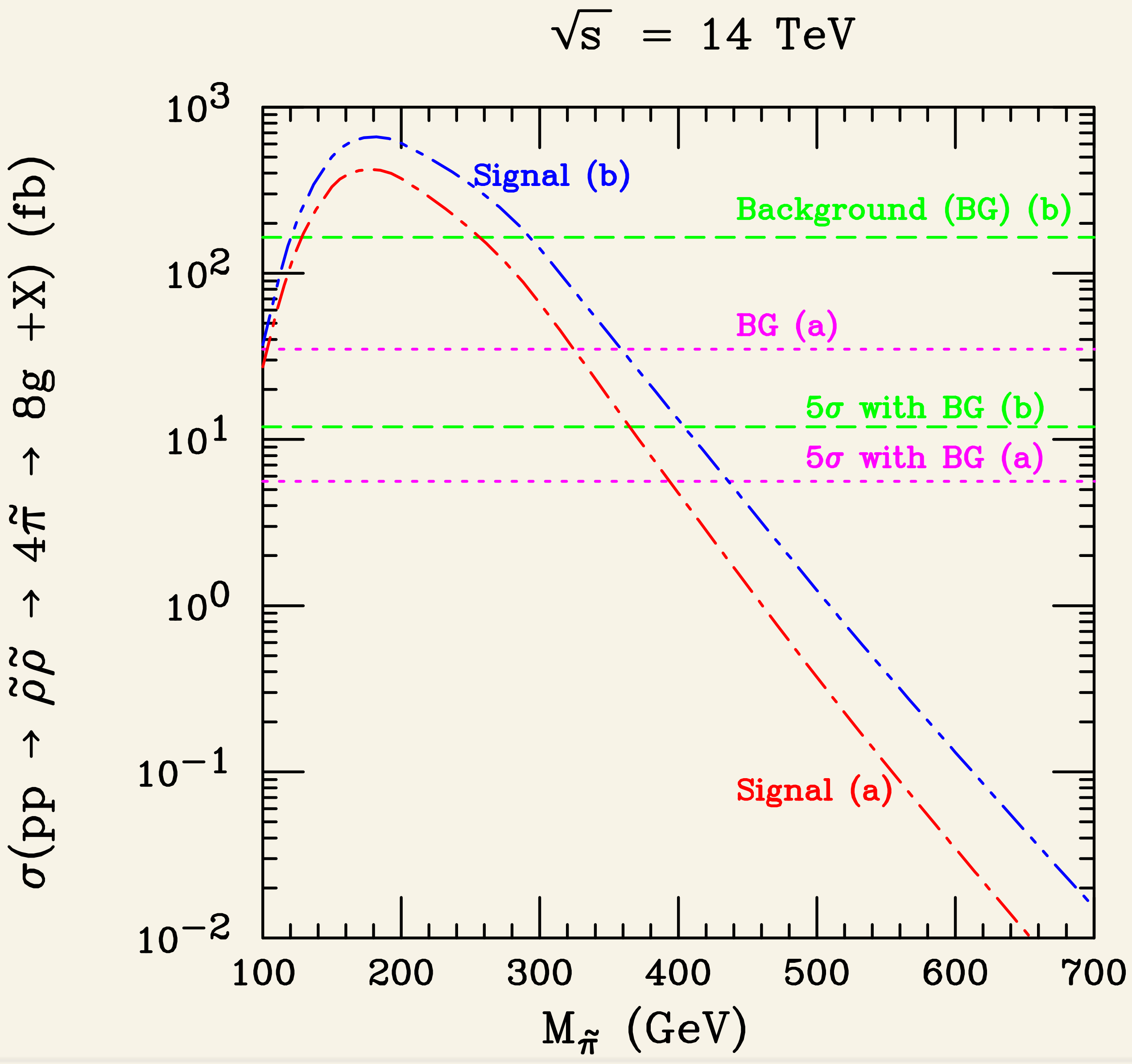
(a) $\Delta M_{2j} \leq 30$ GeV and $\Delta M_{4j} \leq 60$ GeV or

(b) $\Delta M_{2j} \leq 50$ GeV and $\Delta M_{4j} \leq 100$ GeV.

Relative Mass Cuts



Relative Mass Cuts



Fixed Mass Cuts

The fixed mass cut requires that in each event, there must be 8 jets with 4 pairs of jets that have invariant mass within $\pm\Delta M_{2j}$ centered at $M_{\tilde{\pi}}$, and there must be two groups of 4 jets that have invariant mass within a $\pm\Delta M_{4j}$ centered at $M_{\tilde{\rho}}$.

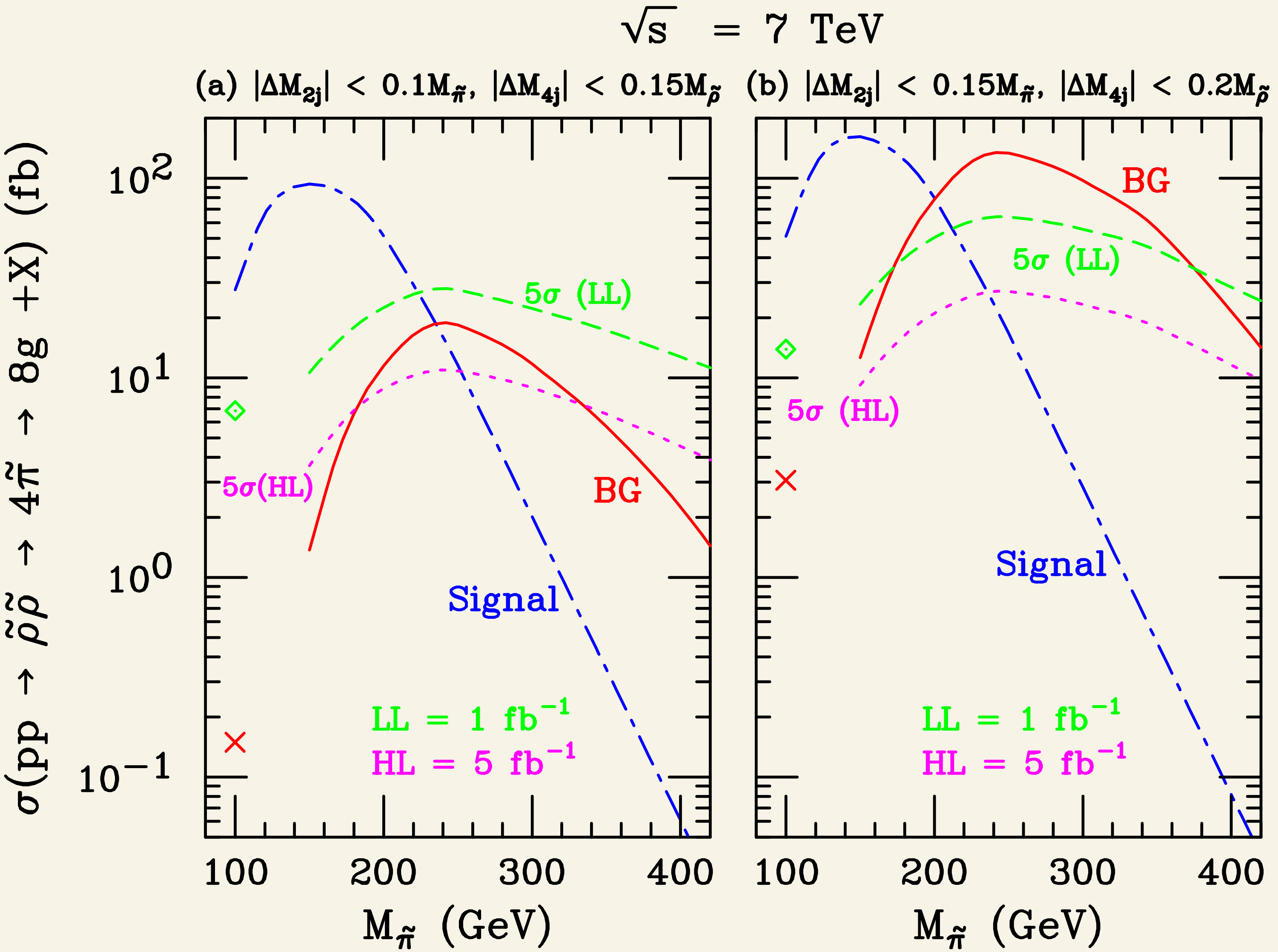
We have chosen

(a) $|M_{2j} - M_{\tilde{\pi}}| \leq 0.10 M_{\tilde{\pi}}$ and $|M_{4j} - M_{\tilde{\rho}}| \leq 0.15 M_{\tilde{\rho}}$ or

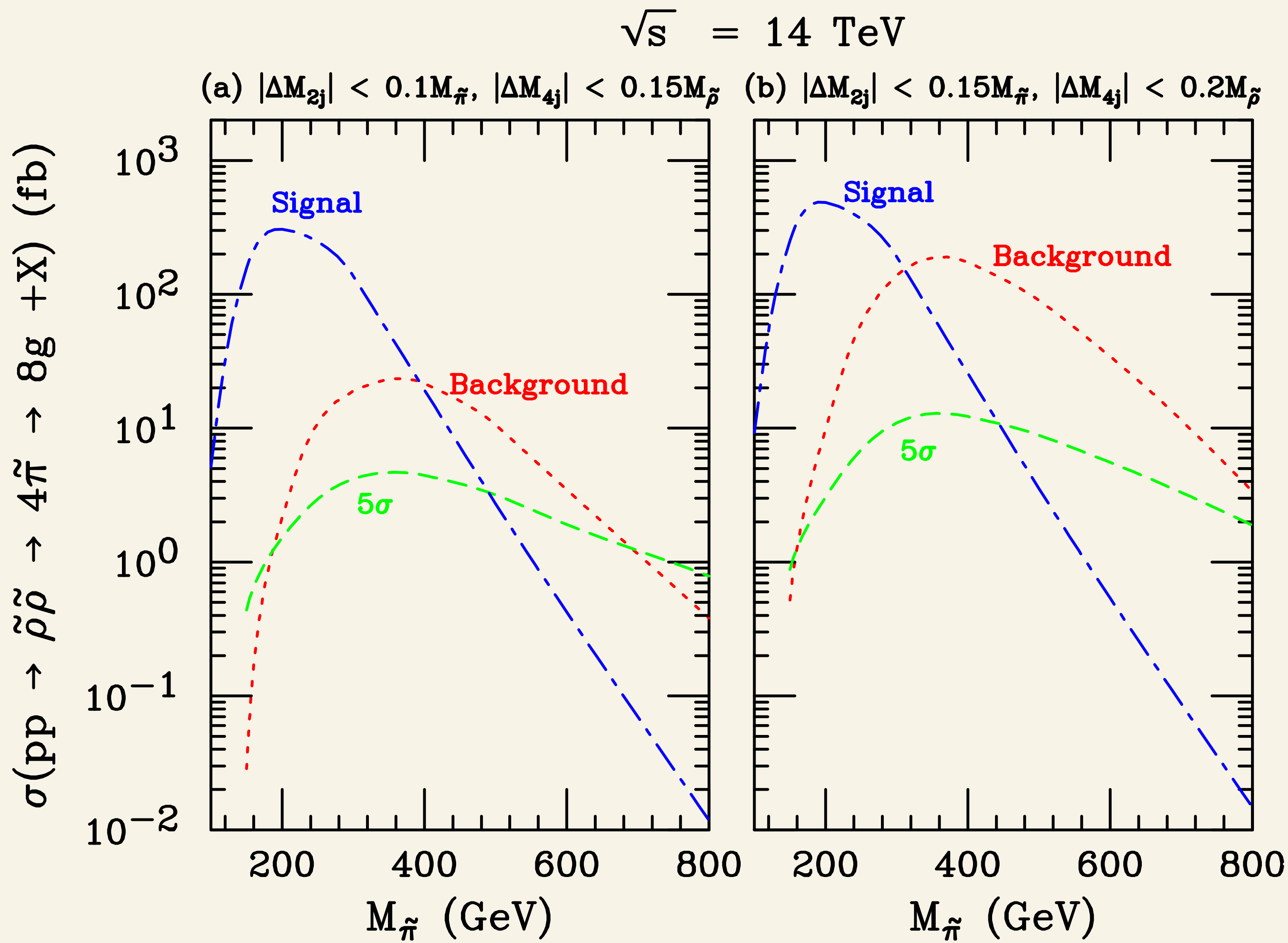
(b) $|M_{2j} - M_{\tilde{\pi}}| \leq 0.15 M_{\tilde{\pi}}$ and $|M_{4j} - M_{\tilde{\rho}}| \leq 0.20 M_{\tilde{\rho}}$.

The fixed mass cut has more power to discriminate against background.

Fixed Mass Cuts



Fixed Mass Cuts



Conclusions

Colorons and hyper-pions can be produced abundantly at the LHC with a center of mass energy $\sqrt{s} = 7$ TeV or $\sqrt{s} = 14$ TeV.

- With $\sqrt{s} = 7$ TeV, the LHC experiments will be able to discover colorons for hyper-pion mass (coloron mass) as large as $M_{\tilde{\pi}} \lesssim 220$ GeV ($M_{\tilde{\rho}} \lesssim 733$ GeV) for $L = 1\ \mathrm{fb}^{-1}$ or $M_{\tilde{\pi}} \lesssim 265$ GeV ($M_{\tilde{\rho}} \lesssim 883$ GeV) for $L = 10\ \mathrm{fb}^{-1}$.
- With $\sqrt{s} = 14$ TeV, the LHC experiments will be able to discover colorons for $M_{\tilde{\pi}}$ or $M_{\tilde{\rho}}$ as large as $M_{\tilde{\pi}} \lesssim 455$ GeV ($M_{\tilde{\rho}} \lesssim 1515$ GeV) for $L = 10\ \mathrm{fb}^{-1}$ or $M_{\tilde{\pi}} \lesssim 535$ GeV ($M_{\tilde{\rho}} \lesssim 1780$ GeV) for $L = 100\ \mathrm{fb}^{-1}$.
- Naturally, our estimates are subject to higher-order corrections which may be substantial in the case of the background. However, a factor of two increase in the background would only degrade our discovery limit by ~ 20 GeV.