New Physics with Multijets at the LHC

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New Physics with Multijets at the LHC

- Introduction and Challenges
- Discovering Higgs Bosons with Tri-bottom Quarks
  Kao, Sachithanandam, Sayre, and Wang, **arXiv:0908.1156**
- Flavor Changing Neutral Higgs Boson in Top Decays
  Kao, Cheng, Hou, and Sayre, **arXiv:1112.1707**
- Phenomenology of Colorons at the LHC
  Dicus, Kao, Nandi, and Sayre, **arXiv:1012.5694; arXiv:1105.3219**
- Conclusions

Introduction and Challenges

Backgrounds, Acceptance Cuts, and Reconstruction of Kinematics

- The Standard Model (SM) has been very successful in explaining almost all experimental data to date.
- Parton level calculations are in excellent agreement with experimental data for final states with leptons and photons but can be very different for final states with b's, tau's, and even light jets.
- How do we compare experimental data with theoretical predictions or expectations, especially when there are several b's, tau's and jets?
- How do we analyze experimental data to determine the 'correct' values of parameters?

Discovering Higgs Bosons with Tri-bottom Quarks

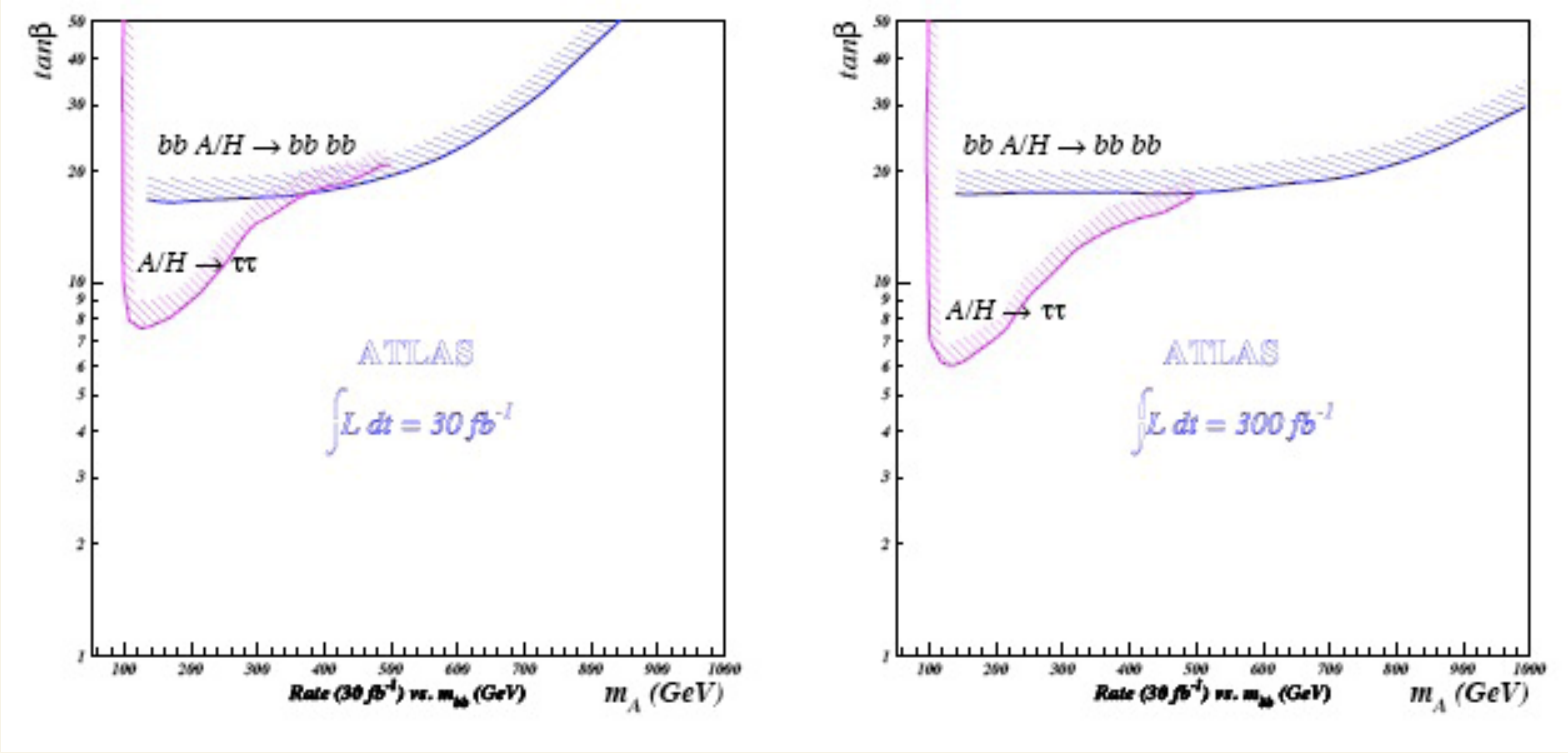
Kao, Sachithanandam, Sayre and Wang (2009)

- For a large value of tan(beta), the branching ratio of A^0 or H^0 to bb is approximately 89%.
- The inclusive channel of H to bb is overwhelmed by the QCD background.
- The associated channel of bbH to bbbb has two spectator b's such that 95% of the signal and background are removed by acceptance cuts.
- The associate channel of bH to bbb offers the best promise for Higgs search at hadron colliers.

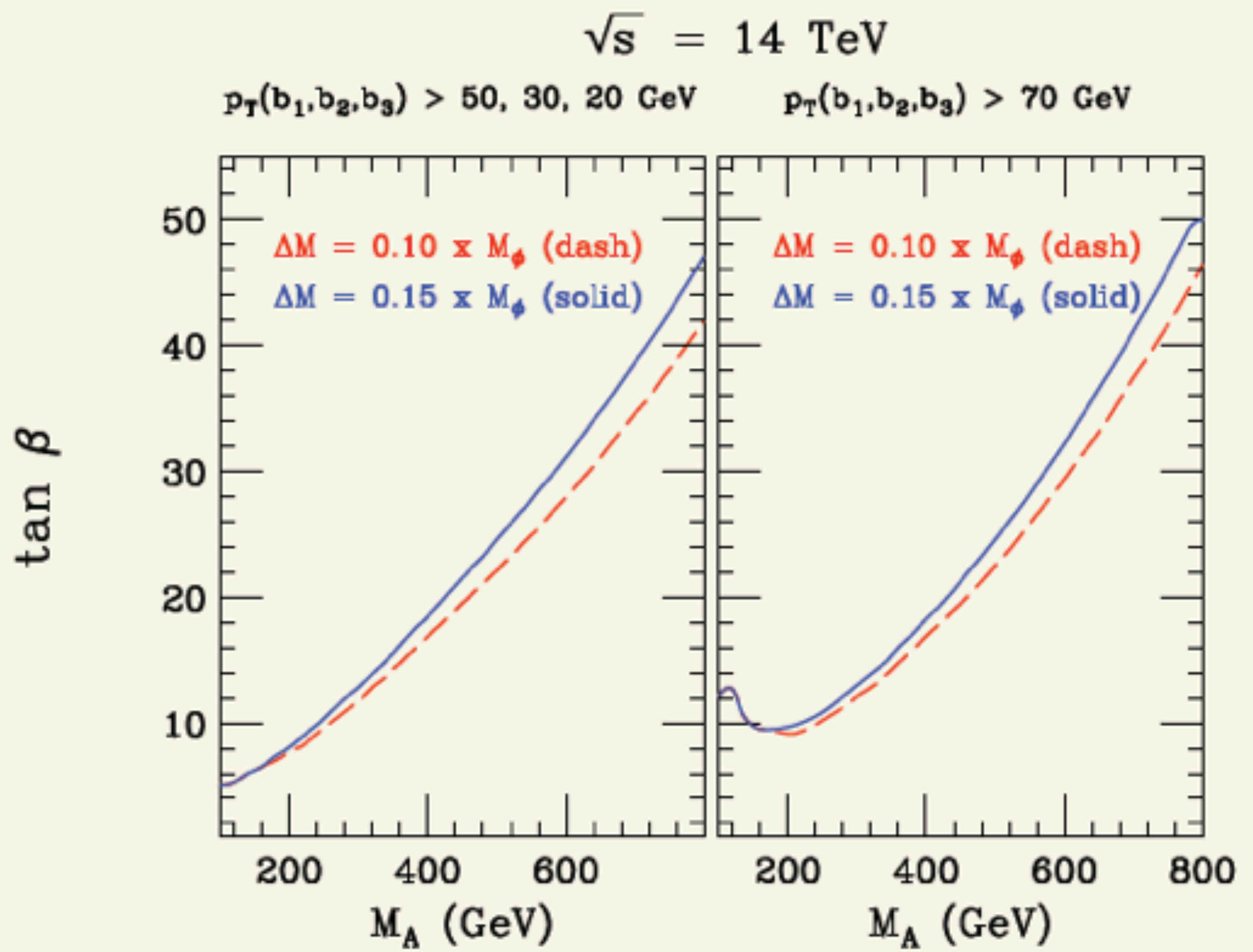
Associate Discovery Channel of bbH to bb bb

- Dai, Gunion and Vega (1994, 1996)
- Balazs, Diaz-Cruz, He, Tait and Yuan (1999)
- ATLAS TDR (1999), ATLAS Thesis (2002), ATLAS Report (arXiv:0901.0512/hep-ex, 2009)
- CMS TDR (2007)
- 3 jet trigger:
  $P_T > 70$ GeV (CMS) or $P_T > 75$ GeV (ATLAS)

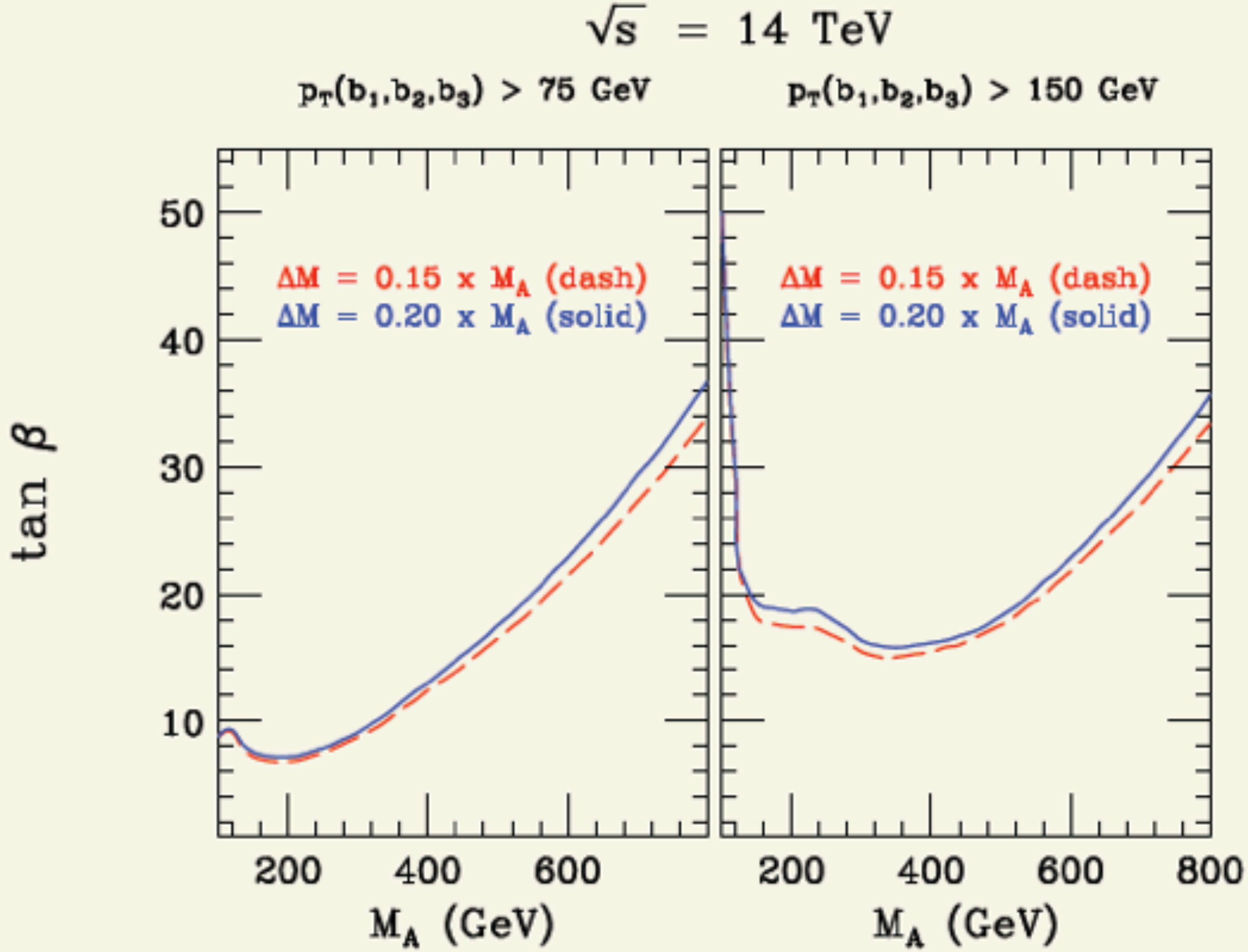
Discovery Potential at the ATLAS



Discovery Potential at the LHC with L = 30 fb^{-1}



Discovery Potential at the LHC with L = 300 fb^{-1}



Summary for the Tri-bottom Channel

- The tau pair discovery channel is the most promising mode to discover MSSM Higgs bosons up to 1 TeV at the LHC.
- The muon pair channel will provide an excellent opportunity to reconstruct Higgs boson mass with high precision.
- The bottom quark pair channel has large QCD background. With suitable cuts, the 3b final state will be promising at the LHC.
- In concert, this family of channels may provide an excellent window on the Yukawa sector of the MSSM or type II two-Higgs-doublet

Comparison with Results from MG_ME at the Parton Level for tan(b) = 10 with Basic Cuts: p_T > 50 GeV, |eta| < 2.5

M_A (GeV)		σ_{PM}(fb)	σ_{MGME}(fb)
150		1483	1528
200		1109	1102
250		663	653

Results with PYTHIA and PGS

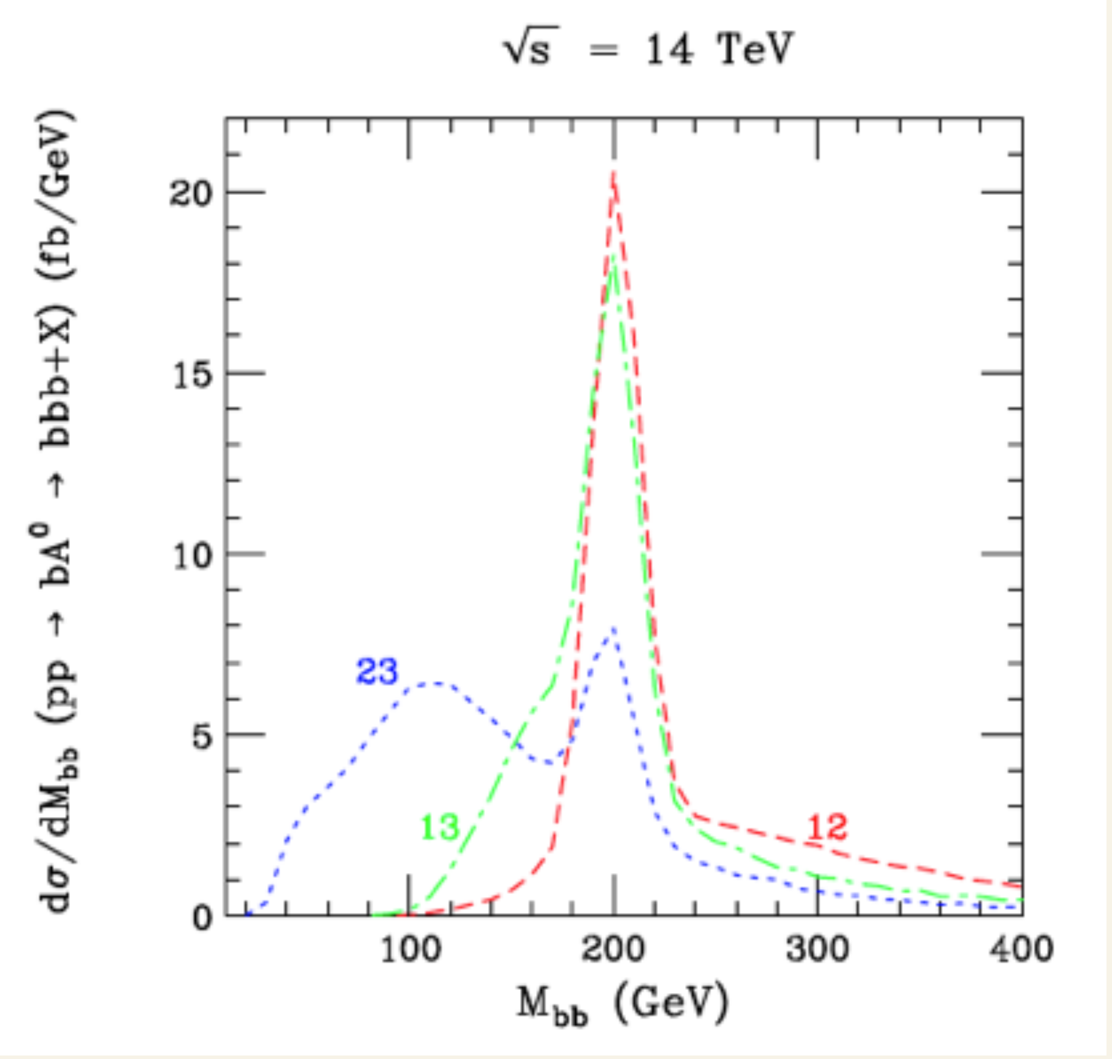
M_A (GeV)	σ_{PM}(fb)	σ_{MGME}(fb) (Delphes)	σ_{MGME}(fb) (PGS)
150	61.39		10.22
200	76.63	33.66	22.56
250	65.43		20.85

Results from PGS with eps(b) = 0.6

- ** Chain contains 40000 events
- 3 or more jets 37511
- less than 3-bs 29170
- 3 b-tags 8341
- PT/eta cuts 7652
- all cuts 588
- sigma = 22.56 fb

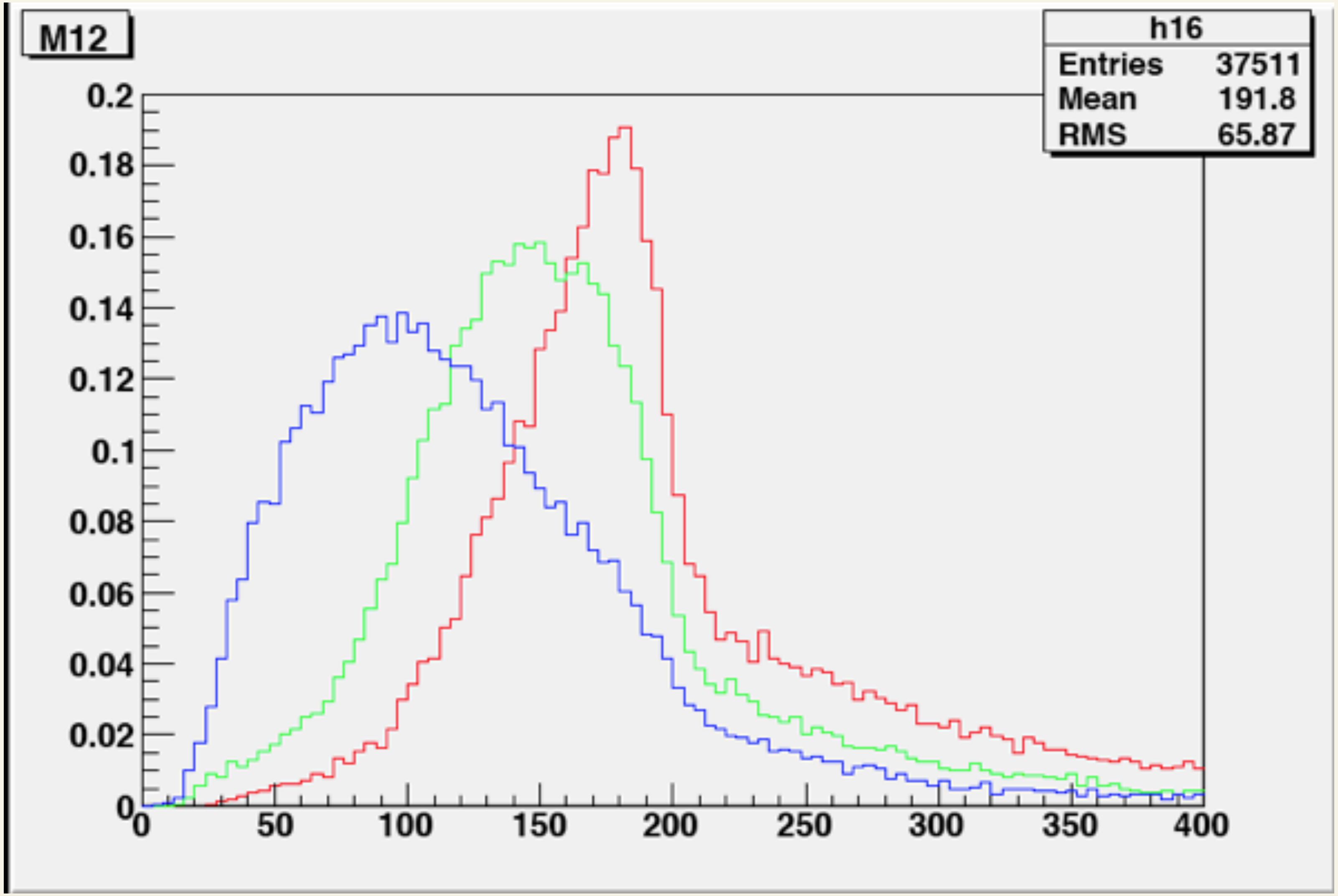
Invariant Mass Distribution

bA^0 to bbb at the Parton Level



Invariant Mass Distribution

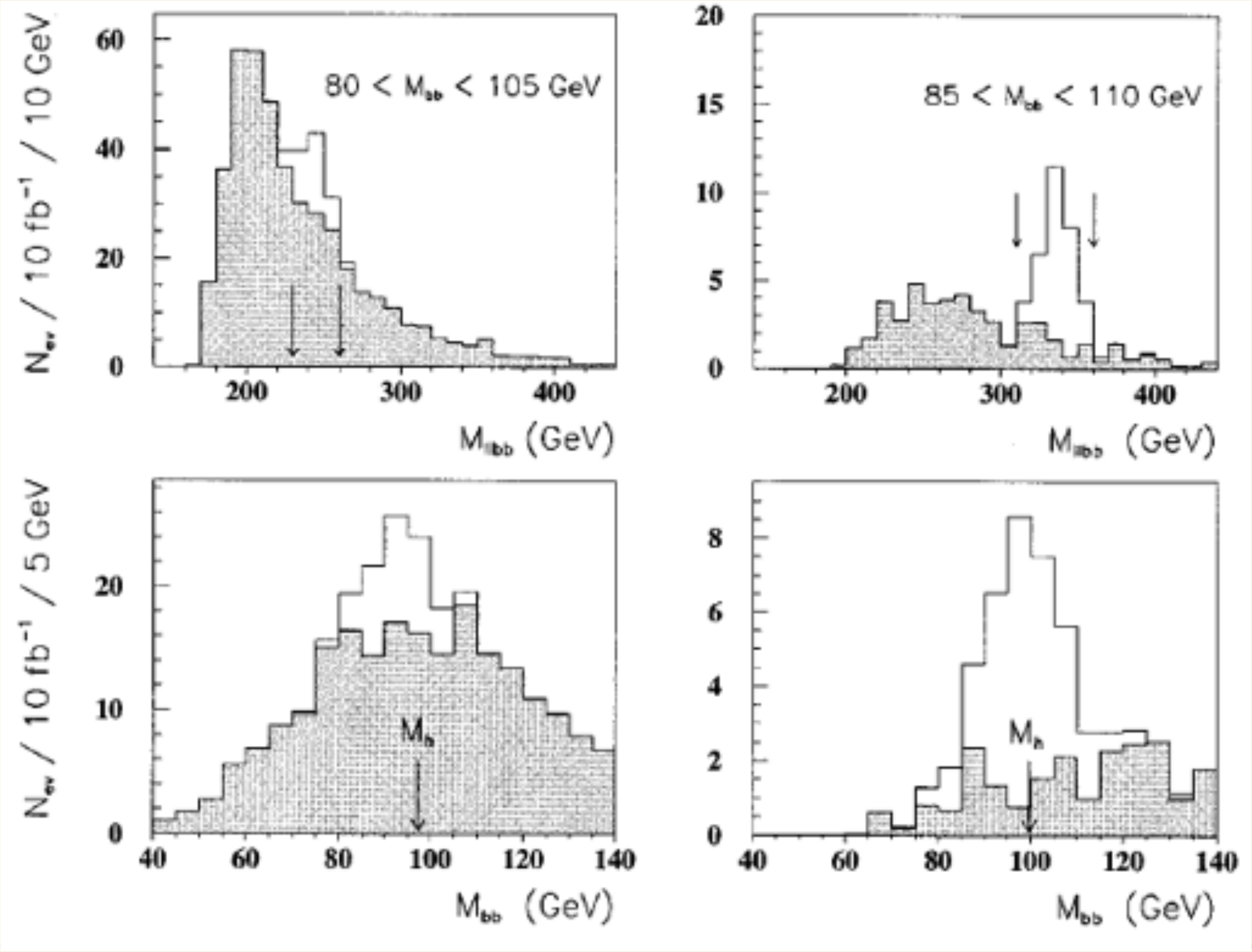
bA^0 to bbb with PYTHIA and PGS



Experimentalists are Pretty Clever

A^0 to Zh^0 to llbb with MA = 250 GeV or 345 GeV

Abdullin, Baer, Kao, Stepanov, and Tata (1996)



Flavor Changing Neutral Higgs Interactions in Top Decays

Kao, Cheng, Hou, and Sayre, **arXiv:1112.1707**

- Let us consider the following Lagrangian involving flavor changing neutral Higgs interactions with top and charm quarks:

  $$\mathcal{L} = -\lambda_{tc}\bar{t}cH^0 - i\lambda_{tc}\bar{t}\gamma_5 cA^0 + \mathrm{H.c.}$$

  where H^0 is a scalar and A^0 is a pseudoscalar.

FCNH Yukawa Coupling

- Let us consider the FCNH coupling of tcH to be the geometric mean of the Yukawa couplings of the quarks:

$$\lambda_{tc} = \frac{\sqrt{m_t m_c}}{v}$$

- In general, we will take it as a free parameter.

Top Decay Width

Hou (1991)

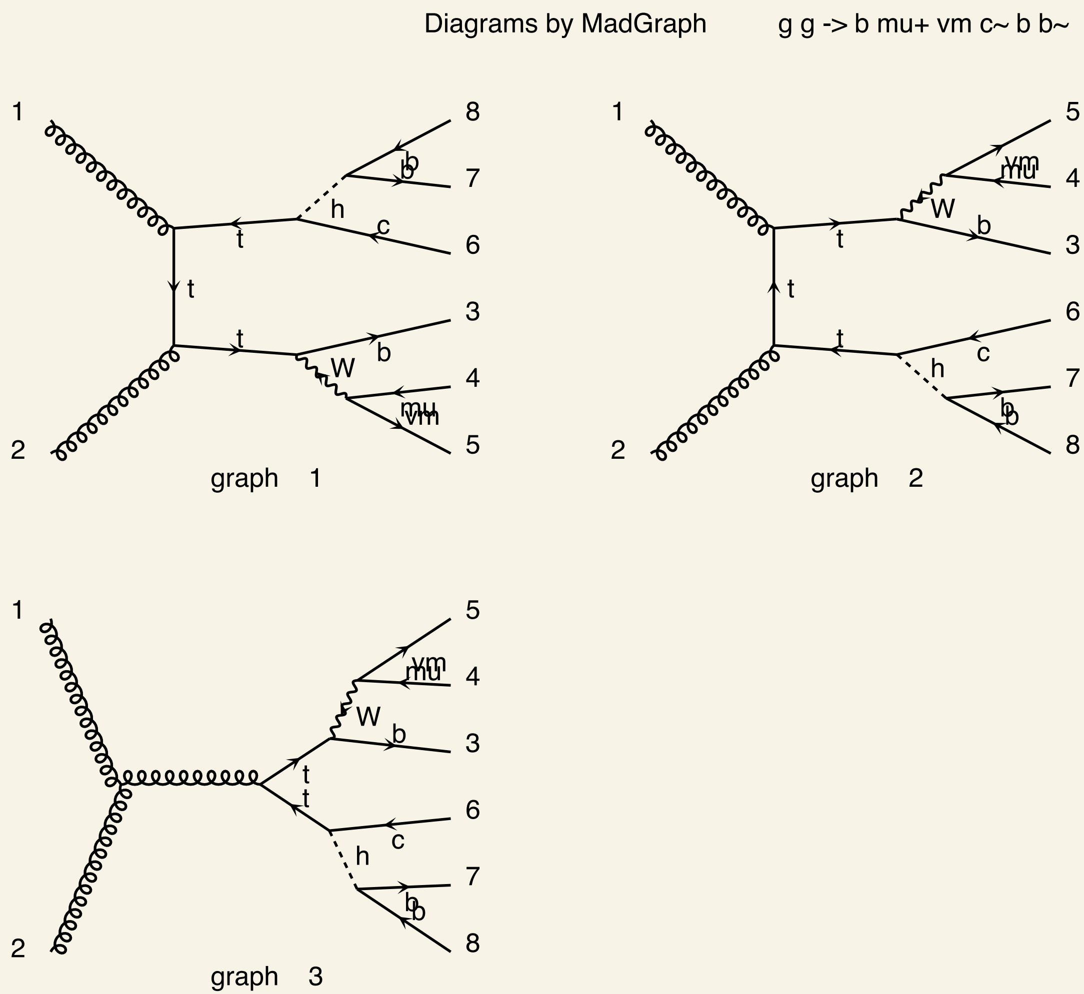
- The FCNH top decay with is

$$\Gamma(t \to c\phi^0) \quad = \quad \frac{|\lambda_{tc}|^2}{16\pi} \times (m_t) \times [(1 \pm \rho_c)^2 - \rho_\phi^2]$$
$$\times \sqrt{1 - (\rho_\phi + \rho_c)^2}\sqrt{1 - (\rho_\phi - \rho_c)^2}$$

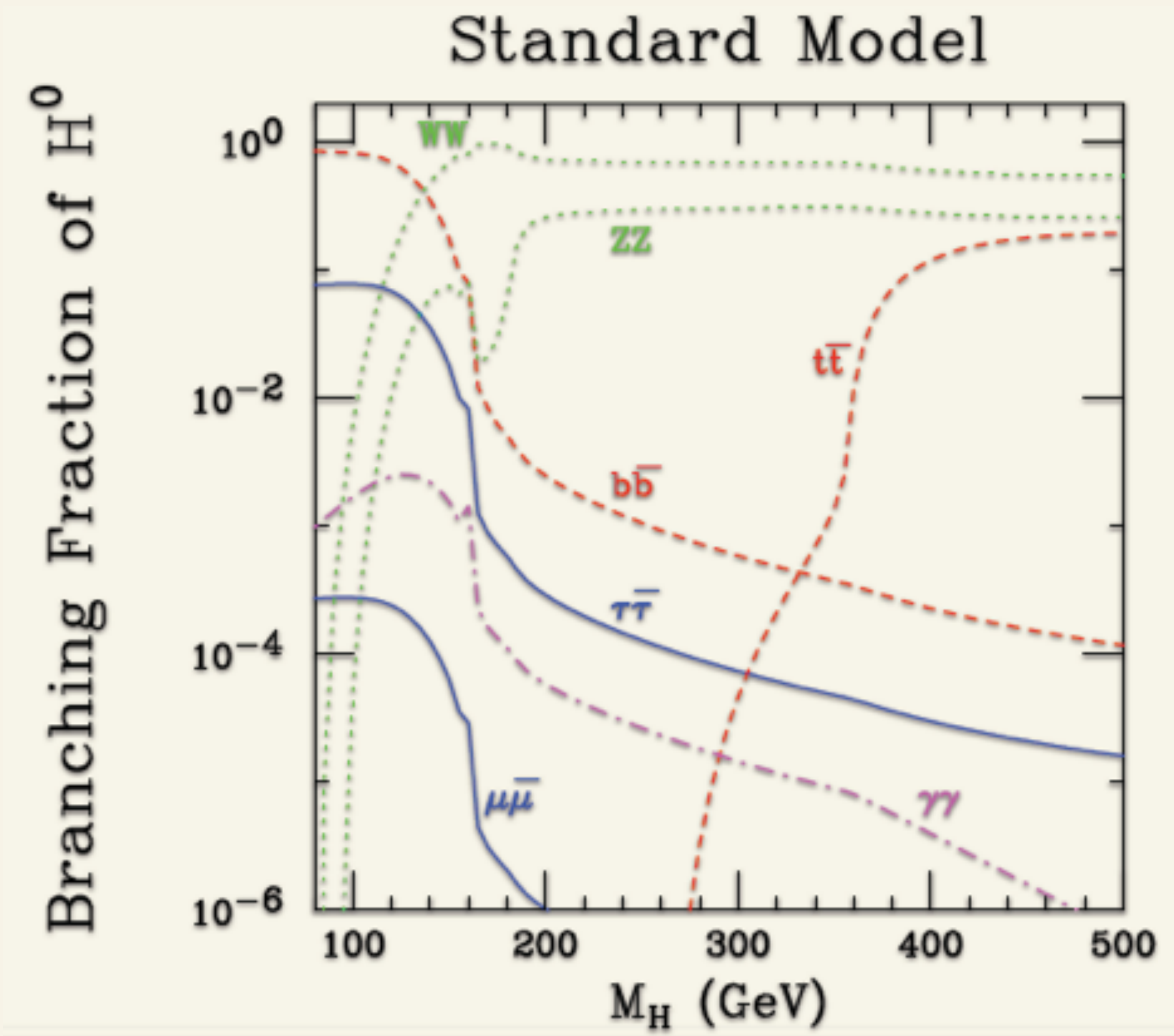
- The total width is

$$\Gamma_t = \Gamma(t \to bW) + \Gamma(t \to c\phi^0)$$

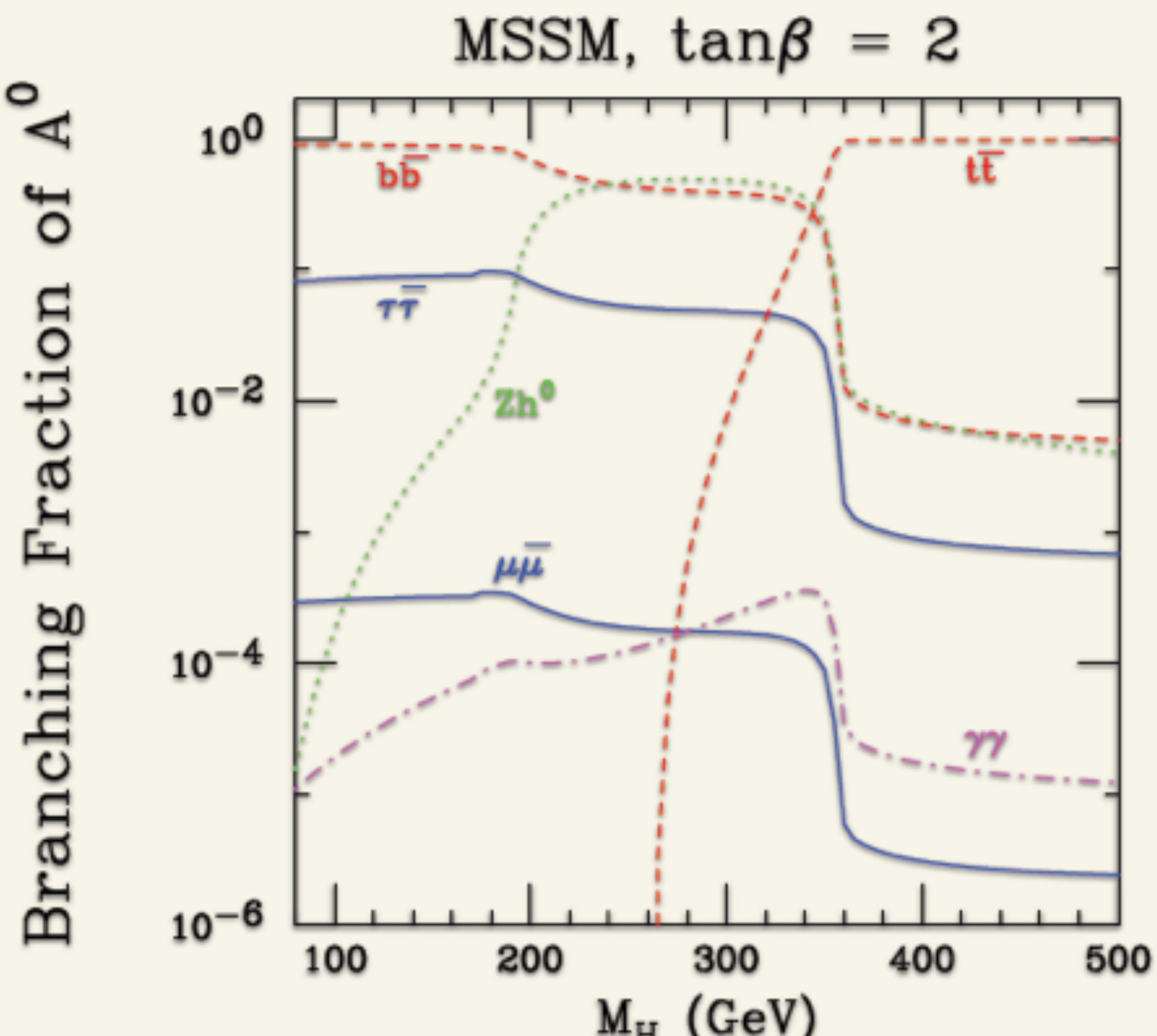
The FCNH Signal



Branching Fractions of the Higgs Boson



Branching Ratios of a Higgs Pseudoscalar

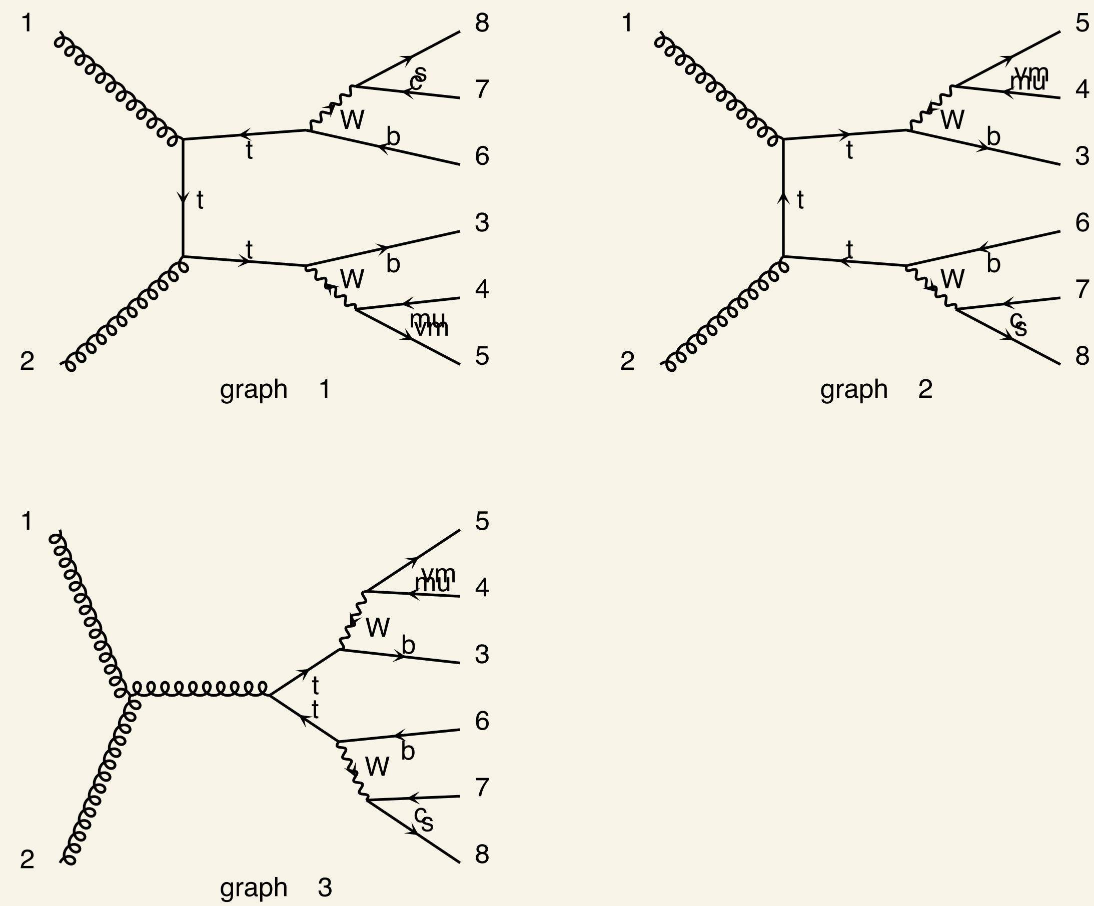


FCNH Signal Cross Section

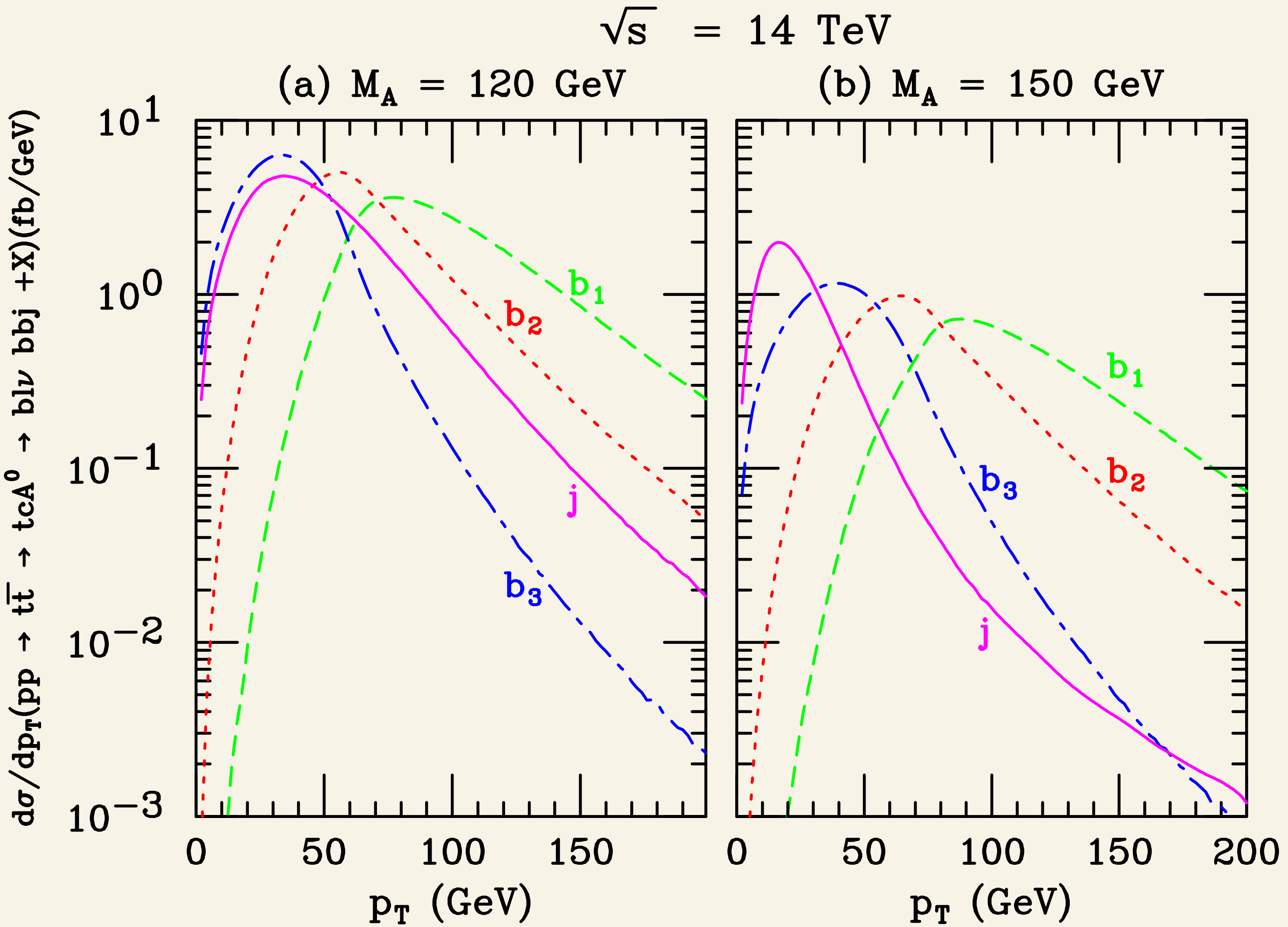
M_A	s(bmncbb)	B(t cH)	Gamma(H)	B(H bb)
120.0	0.440E+02	0.259E-02	0.351E-02	0.728E+00
140.0	0.820E+01	0.117E-02	0.428E-02	0.677E+00
150.0	0.268E+01	0.621E-03	0.473E-02	0.649E+00

Physics Background

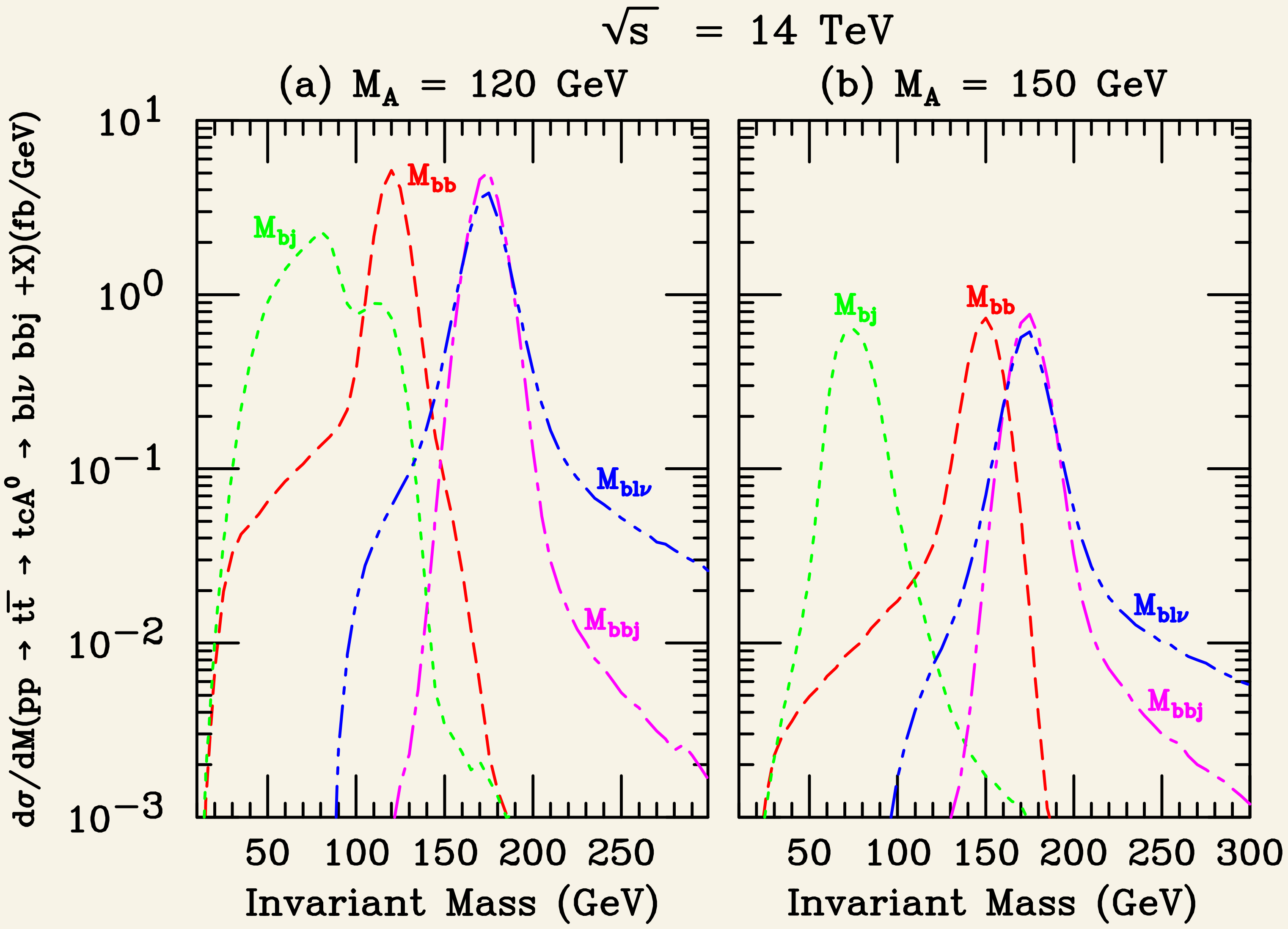
Diagrams by MadGraph g g -> b mu+ vm b~ c~ s



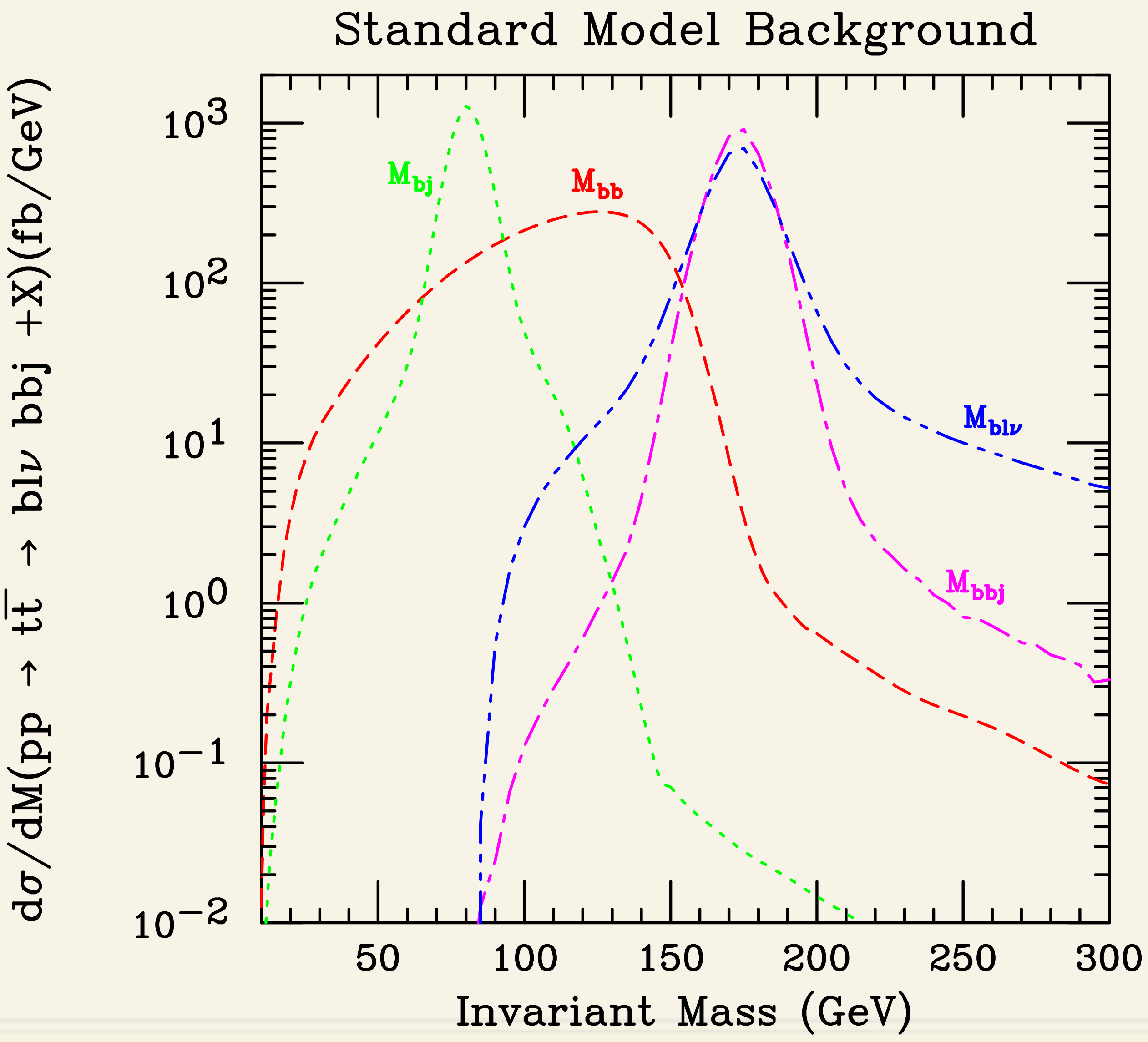
Transverse Momentum Distribution



Invariant Mass: FCNH Signal

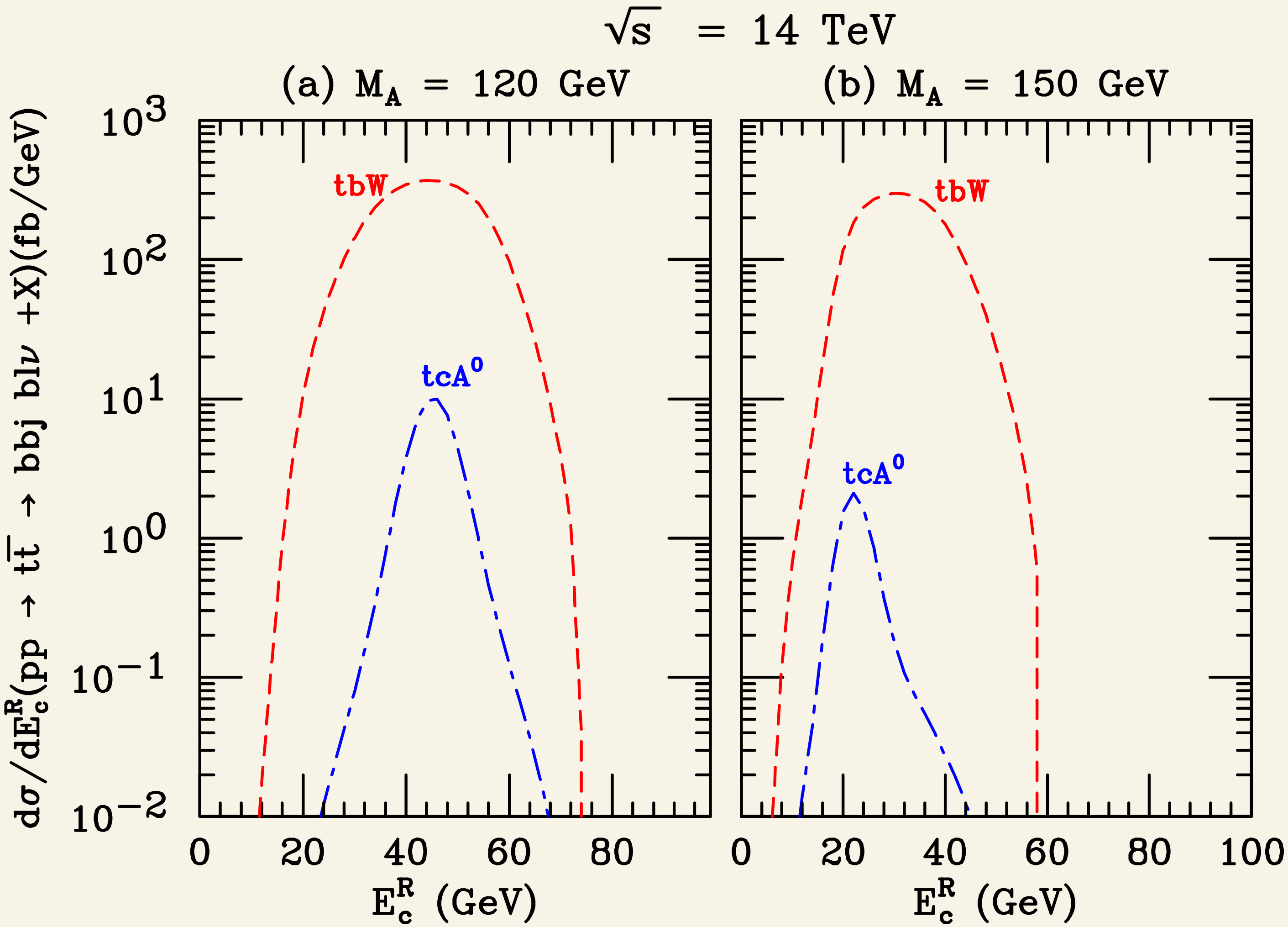


Invariant Mass: Physics Background

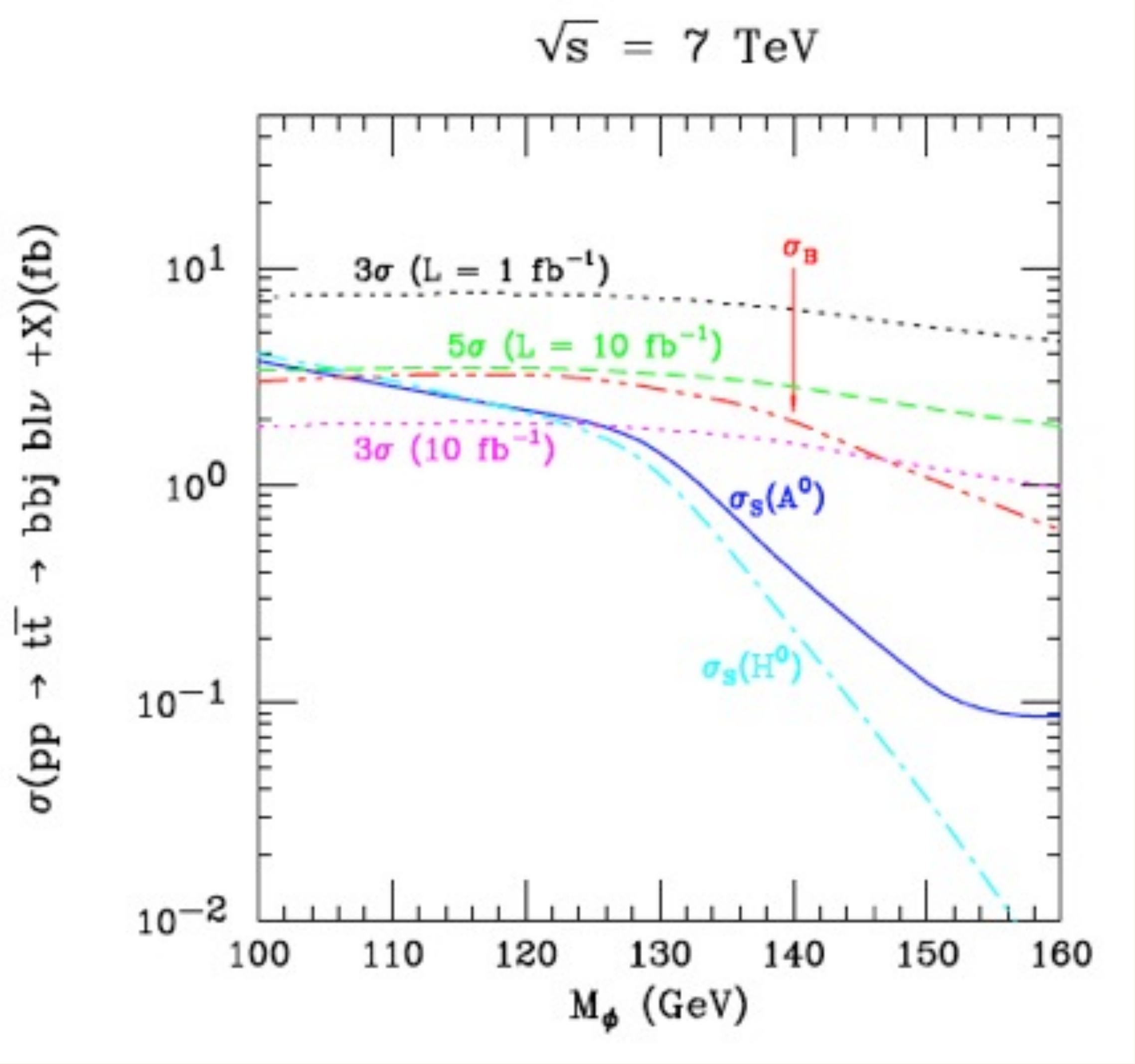


Reconstructed E_{charm}

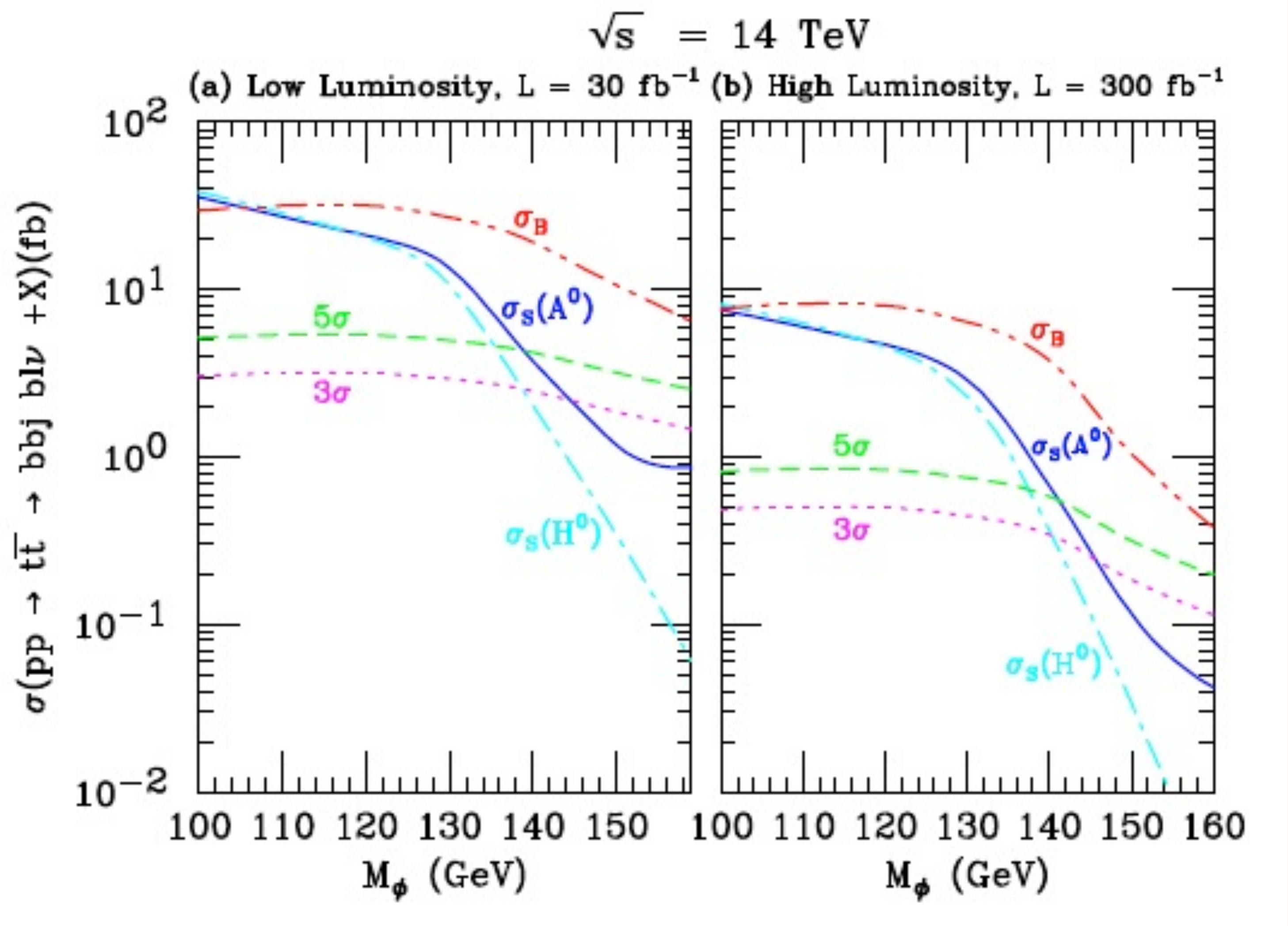
Han, Jiang, and Sher (2001)



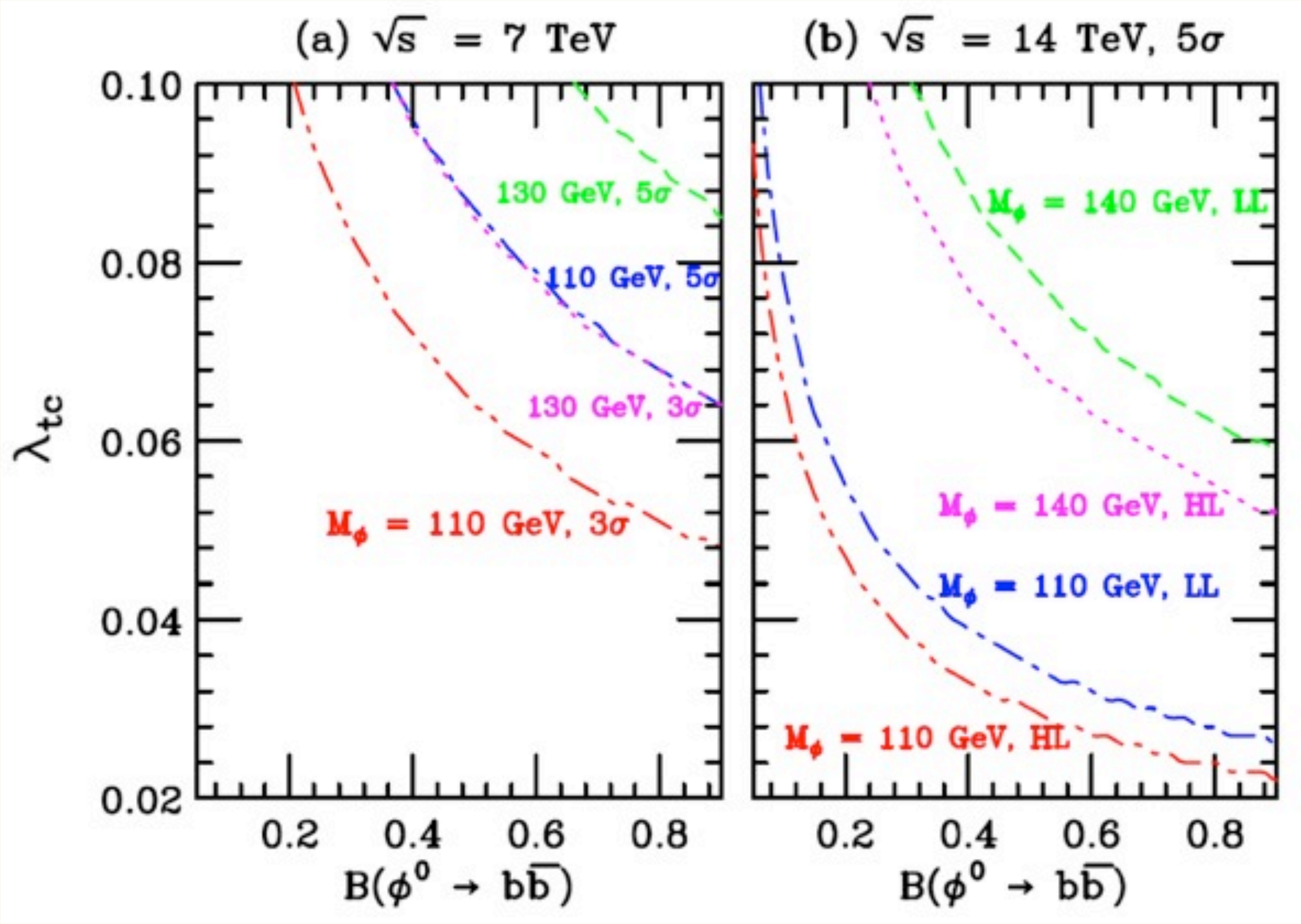
Signal versus Background



Signal versus Background



Discovery Contours



Comparison of Production Rates

Kao, Cheng, Hou, and Sayre (2011)

Aguilar-Saavedra and Branco (2000)

	Low Luminosity (10 fb^{-1})		High Luminosity (100 fb^{-1})	
	Before Cuts	Standard Cuts	Before Cuts	Standard Cuts
Signal	200 (267)	51.4 (98.2)	1630 (2150)	417 (797)
$t\bar{t}$	5491 (7186)	24.7 (33.2)	44540 (58230)	198 (270)
$Wbbjj$	58 (77)	0.22 (0.3)	476 (644)	1.7 (2.2)

Summary for FCNH Top Decay

- At the LHC, it is promising to detect FCNH top decays for $\text{lambda}_{tc} > 0.02$ and $M_H < 140$ GeV.
- For $M_H > 150$ GeV, most c-jets are removed by acceptance cuts.
- Higher luminosity can improve the discovery potential slightly.

Phenomenology of Colorons at the LHC

Dicus, Kao, Nandi, and Sayre, **arXiv:1012.5694; arXiv:1105.3219;** Dicus, Dutta, and Nandi (1995); Dobrescu, Kong, Mahbubani (2008); Kilic, Okui, and Sundrum (2008), Kilic, Schumann and Son (2009)

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

Hypercolor Comparison

SM	Hypercolor
$SU(3)_C$	$SU(N)_{HC}$
$SU(3)_L \times SU(3)_R$	$SU(3)_C \times SU(3)_{L+R}$
q	$\tilde{q}$
π, η, K	$\tilde{\pi}$
ρ, ω, K^*, ϕ	$\tilde{\rho}$
e^-,γ	q,g

The Effective Lagrangian

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

- $N_{\rm HC} = 3$ *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 $\Gamma_{\tilde{\pi}} \simeq 0.12\alpha_s^2 \times M_{\tilde{\pi}}$.

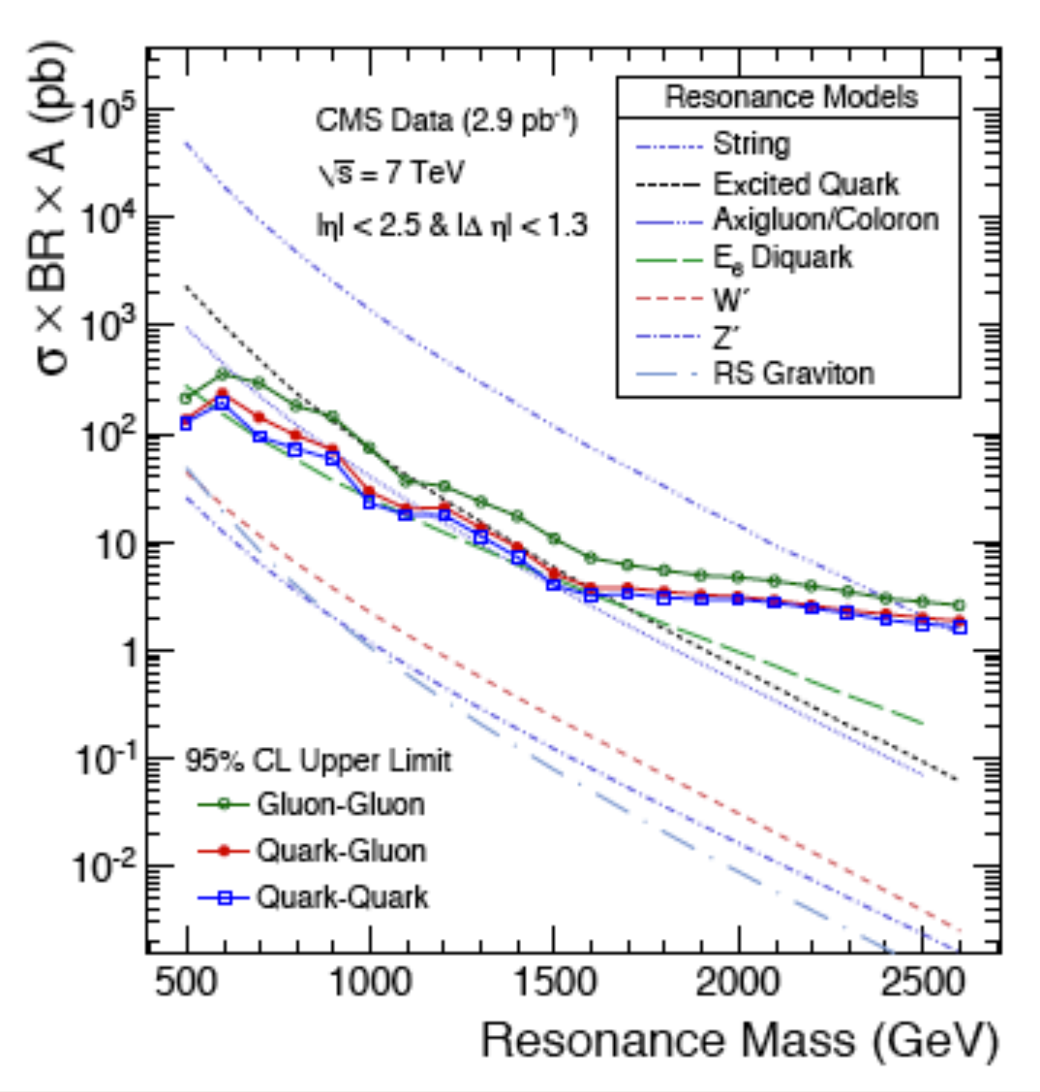
Constraints from CDF and CMS Data

CDF Collaboration (2008); CMS Collaboration (2010)

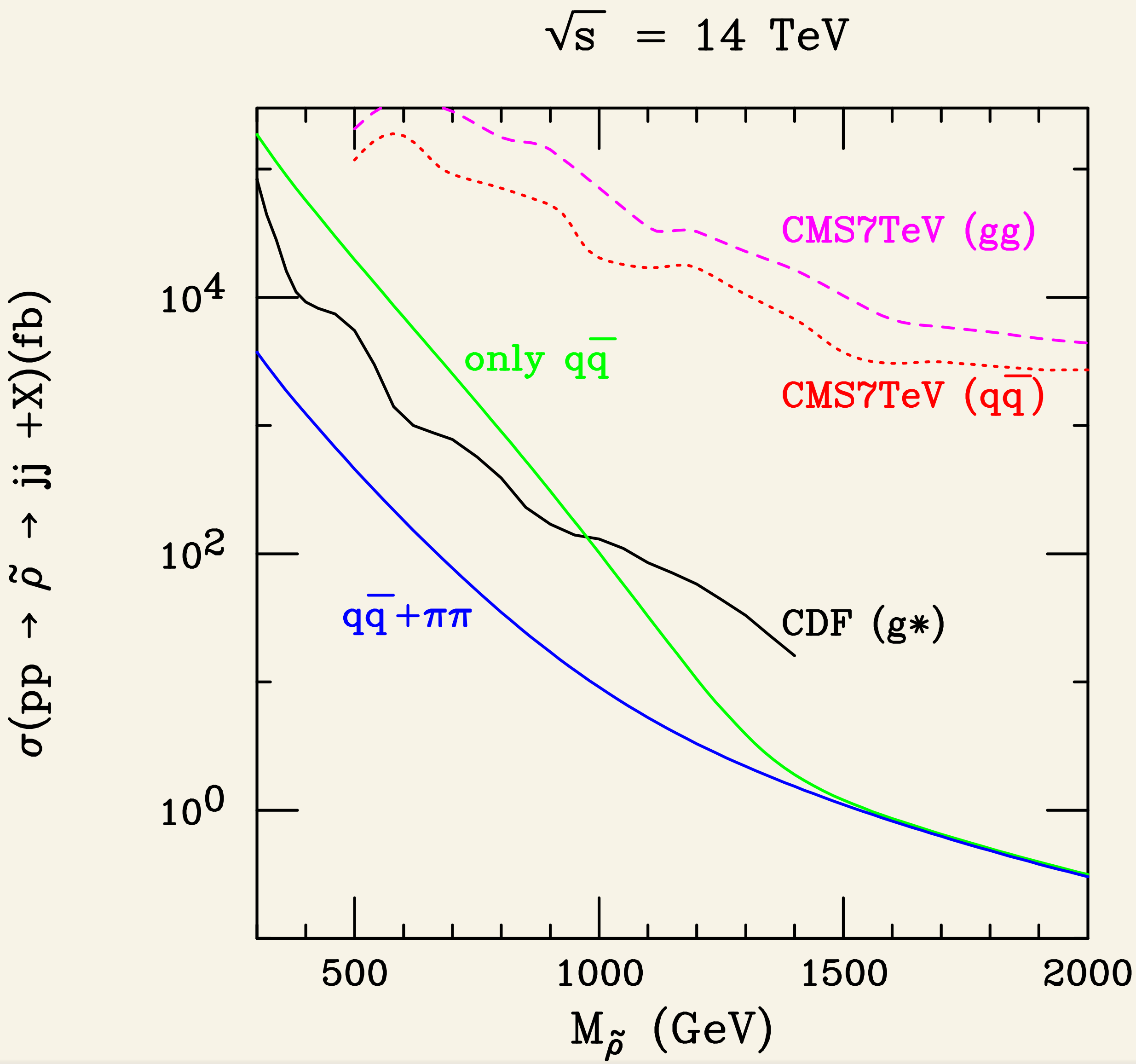
- Electroweak precision data provide important constraints on electroweak models beyond the SM.
- New strong interactions can still be consistent LEP and Tevatron Data.
- In this model, the hyper-pions couple sufficiently weakly to gluons.
- The hyper-rhos have only a small branching fraction to decay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

CMS Limits with 7 TeV

CMS Collaboration (2010)



CMS and CDF Limits



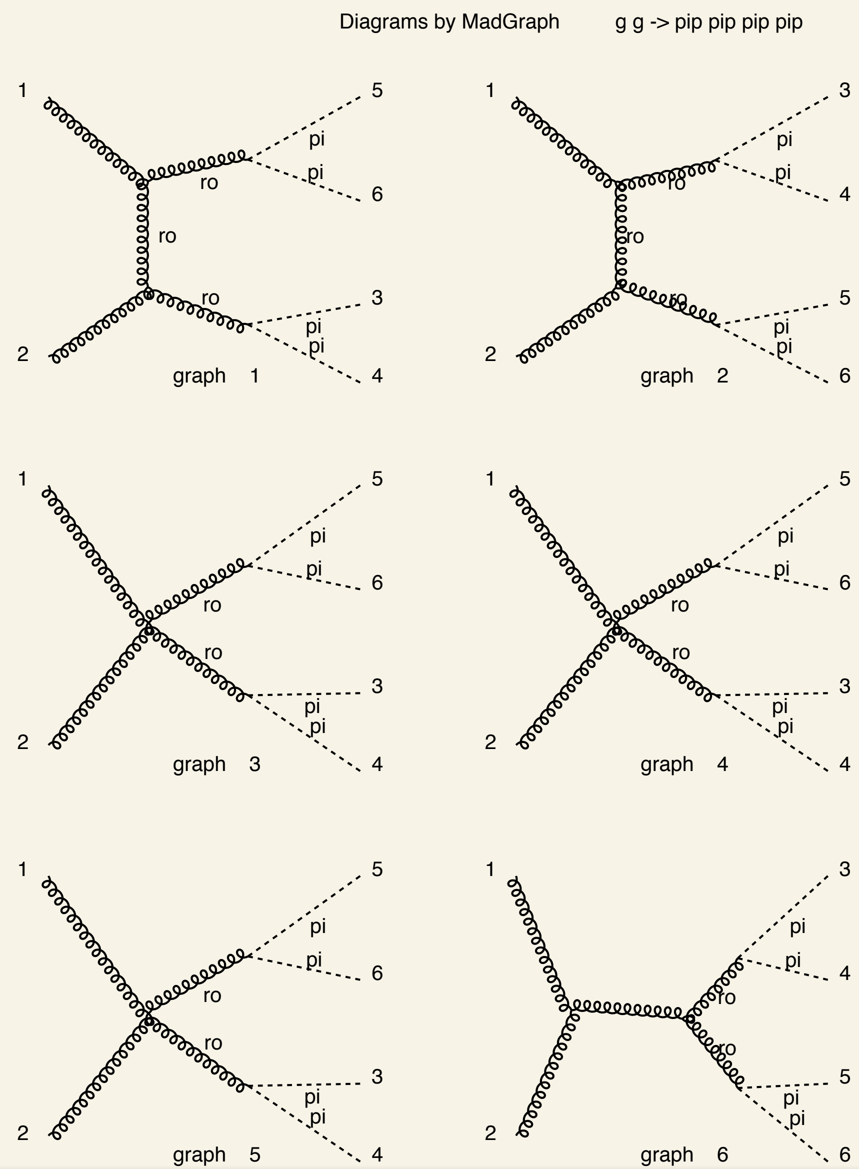
Production Cross Section

- 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.

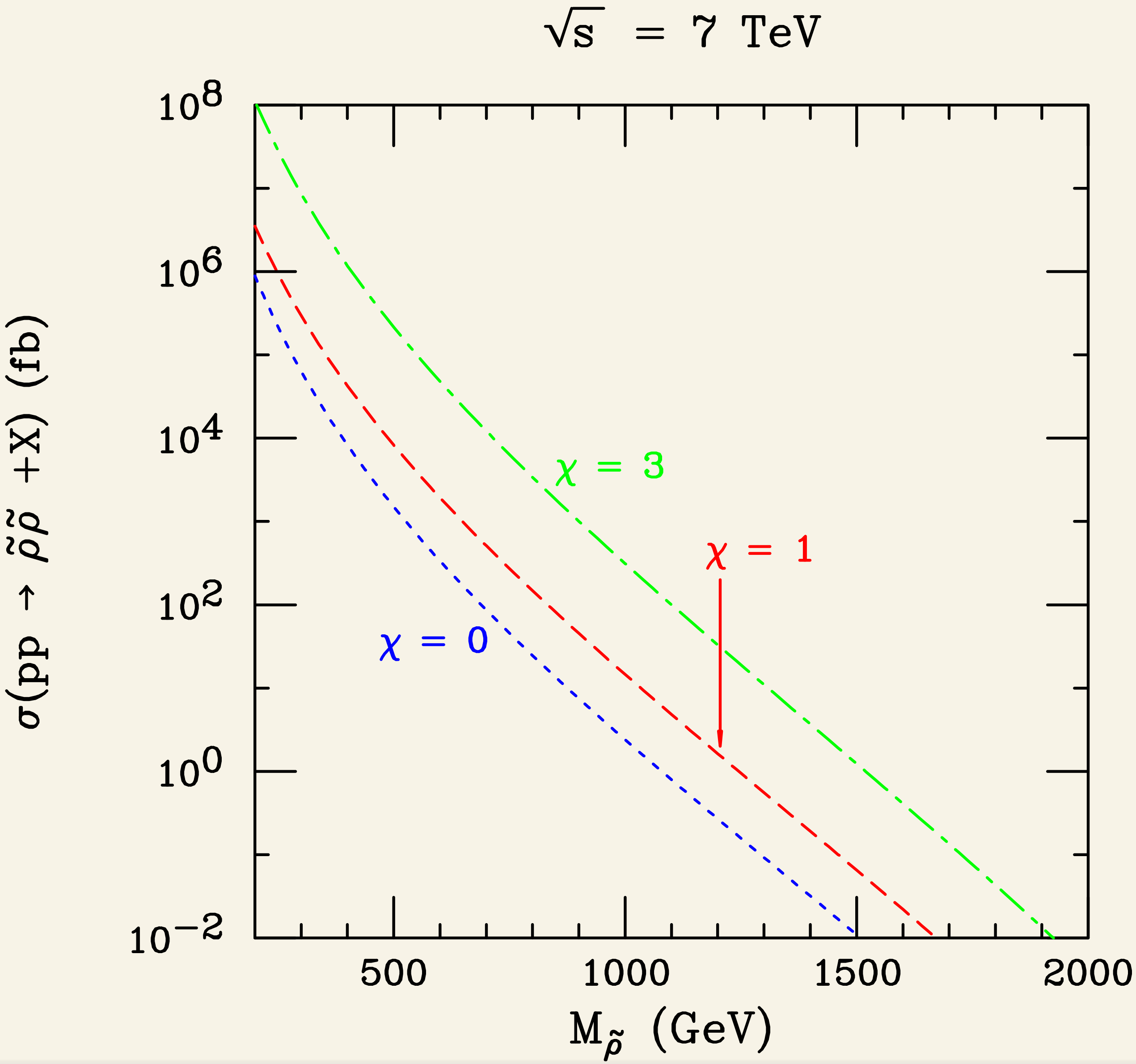
Production of Coloron Pairs

- 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 $gg \longrightarrow 4g$

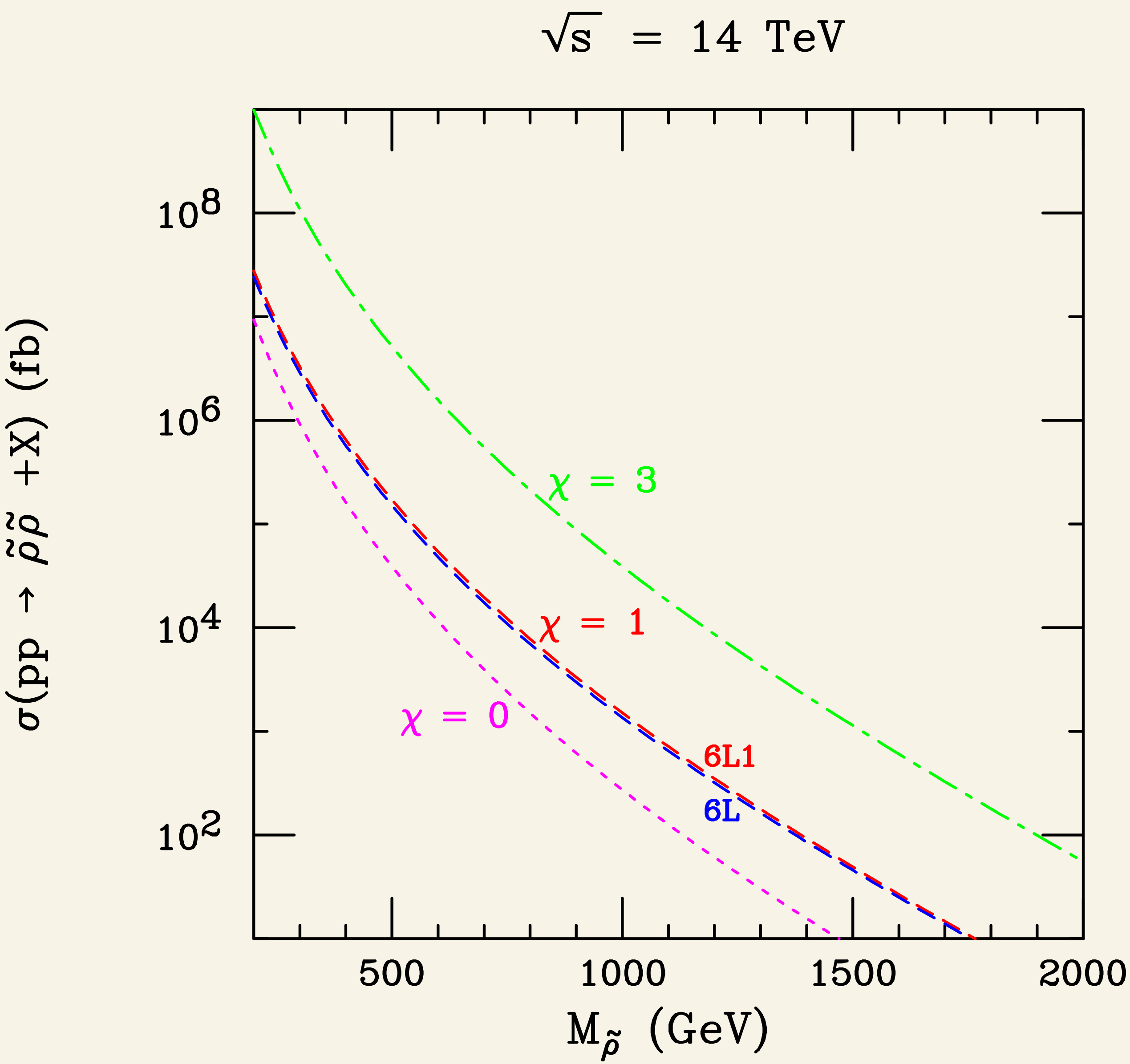
$$gg \to \tilde{\rho}\tilde{\rho} \to 4\tilde{\pi} + X$$



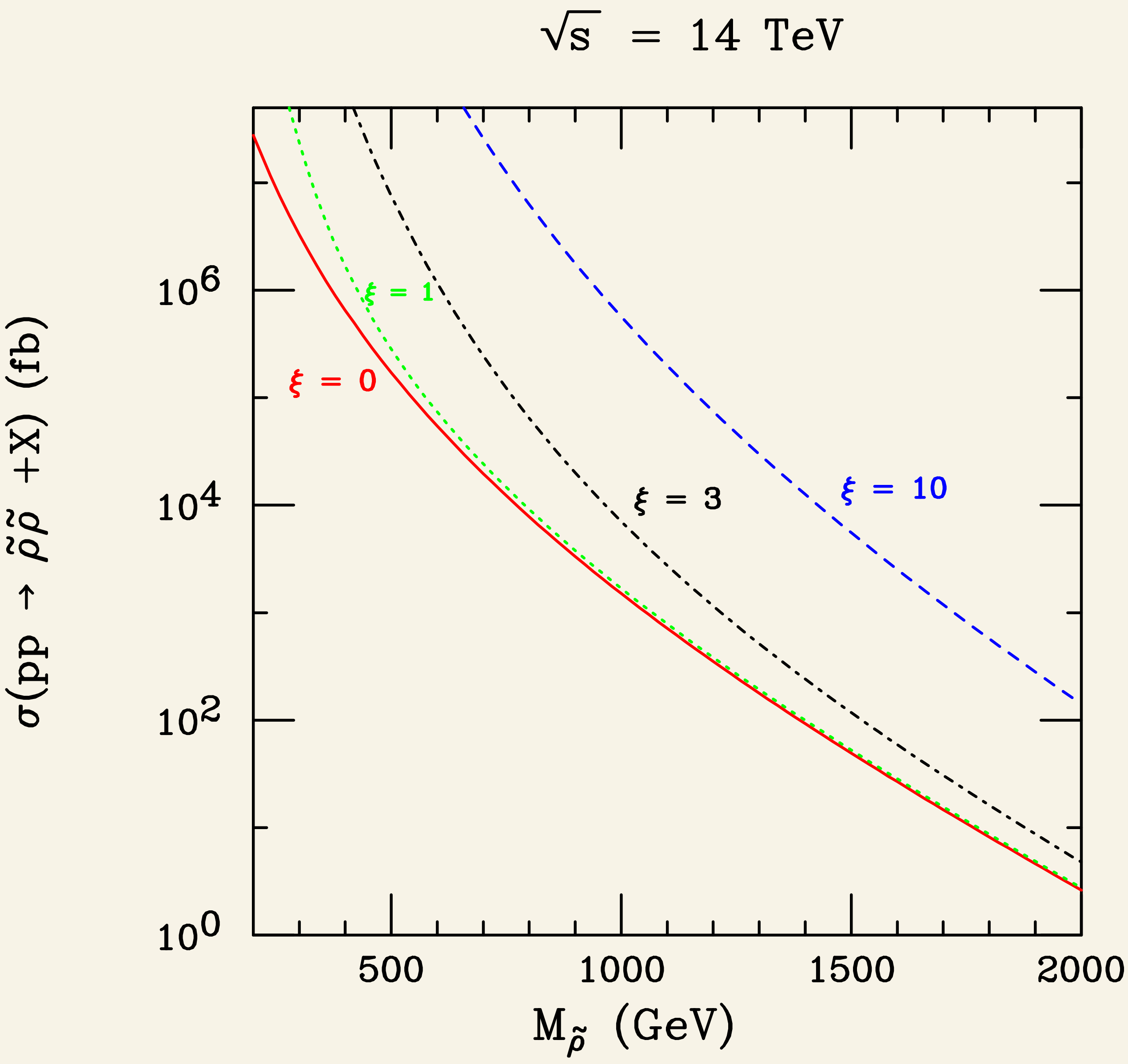
$pp \rightarrow \tilde{\rho}\tilde{\rho} + X$



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



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



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

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

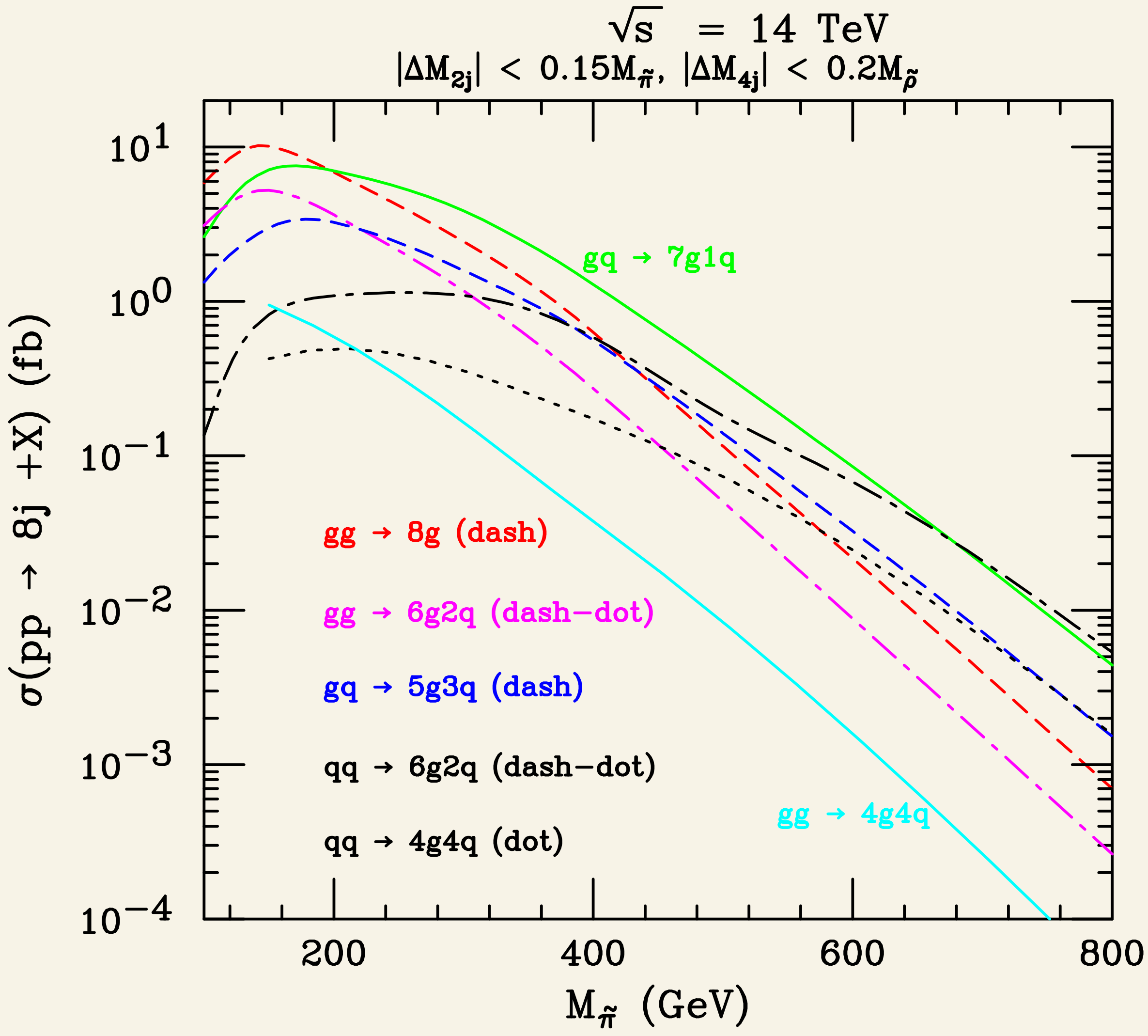
where E is the gluon energy, z is the cosine of the scattering angle, $\beta^2 = 1 - M_{\tilde{\rho}}^2/E^2$,

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 $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$.

Physics Background



Limitations of MadGraph

Skipping 7245 6999, There are 6999 graphs

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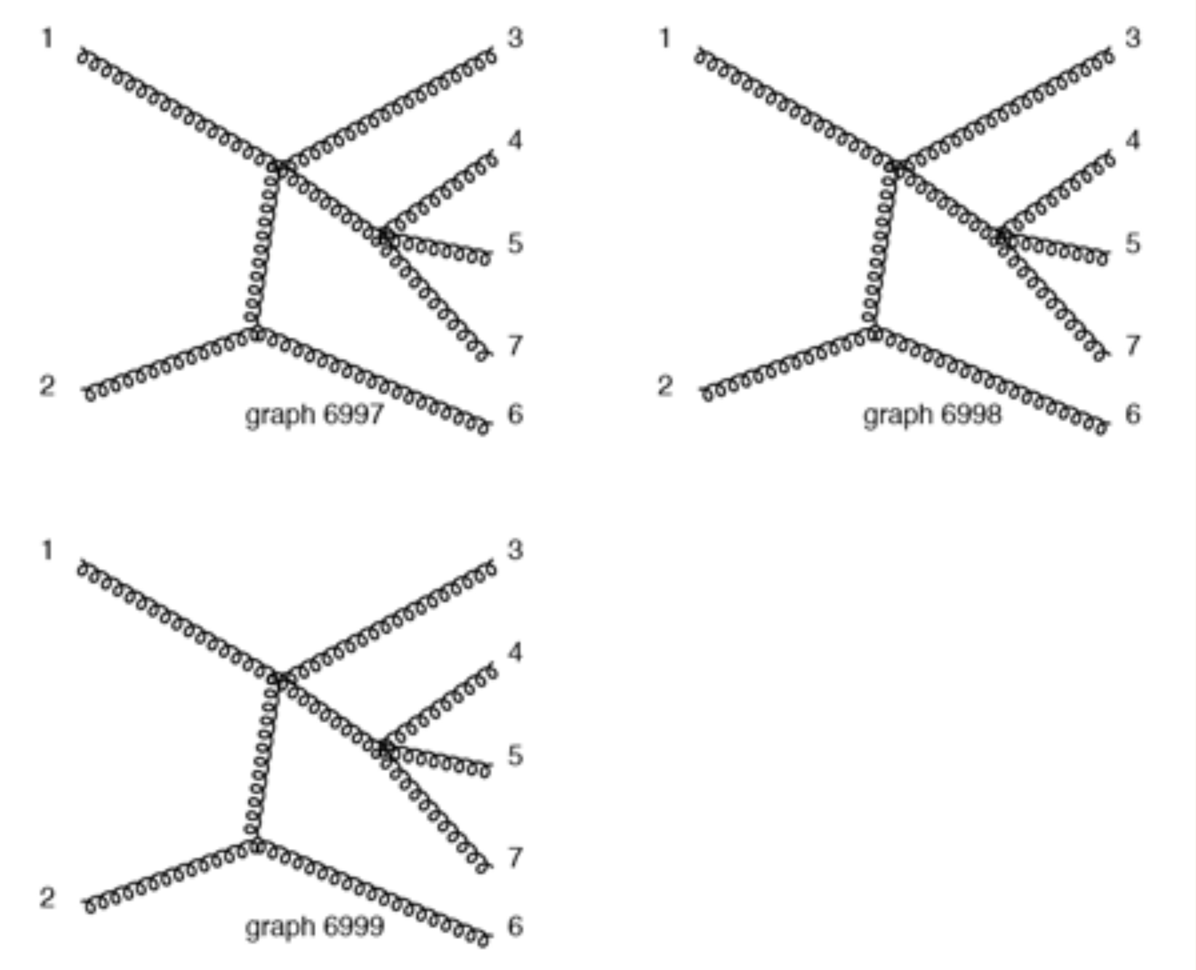


Recursion Relations in QCD

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.

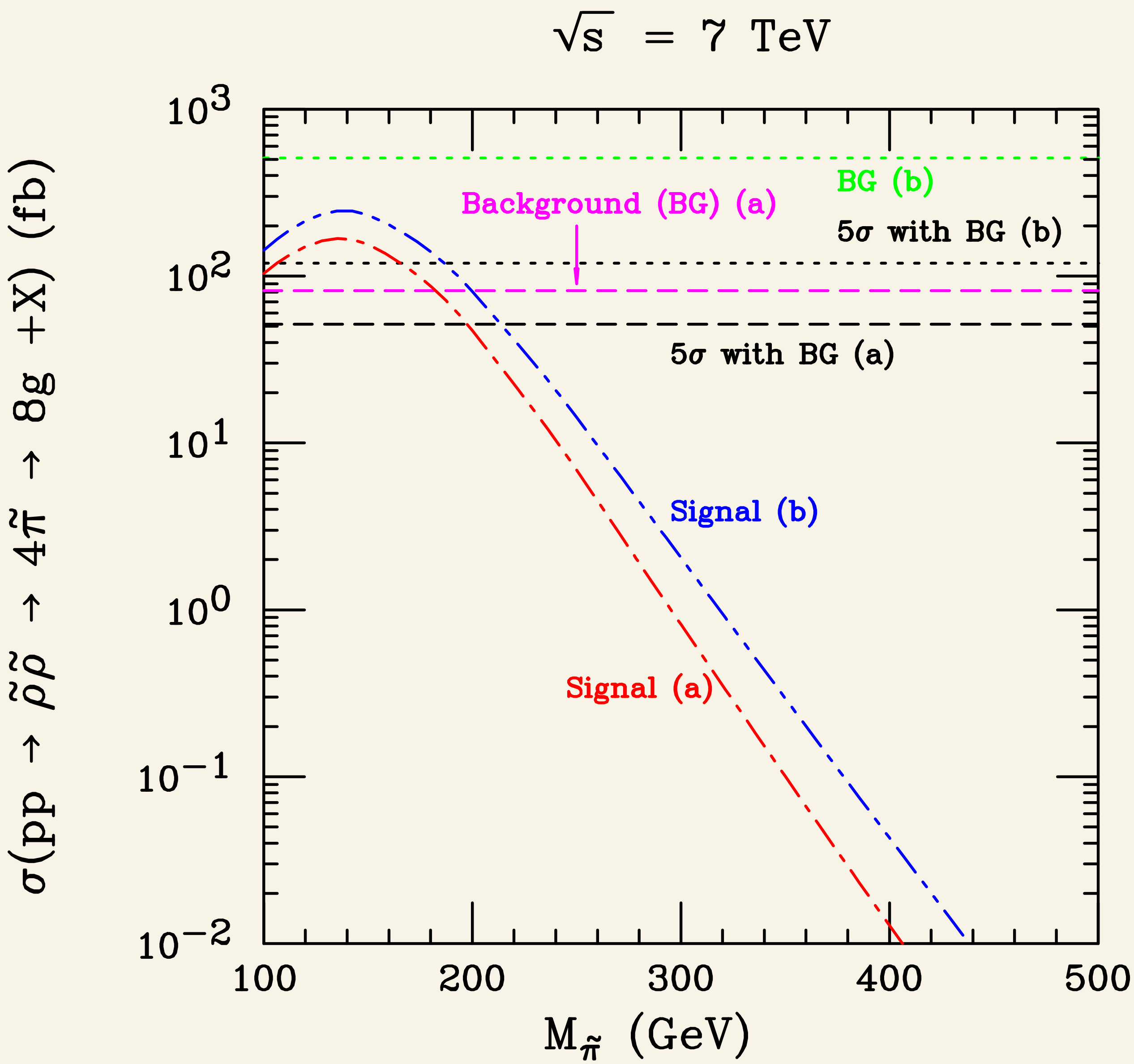
The relative mass cut requires that in each event there must be 8 jets, which can be arranged into 4 pairs of jets that have invariant mass within ΔM_{2j} of one another, and there must be distinct pairs of 4 jets that have invariant mass within ΔM_{4j} of each other.

We have chosen

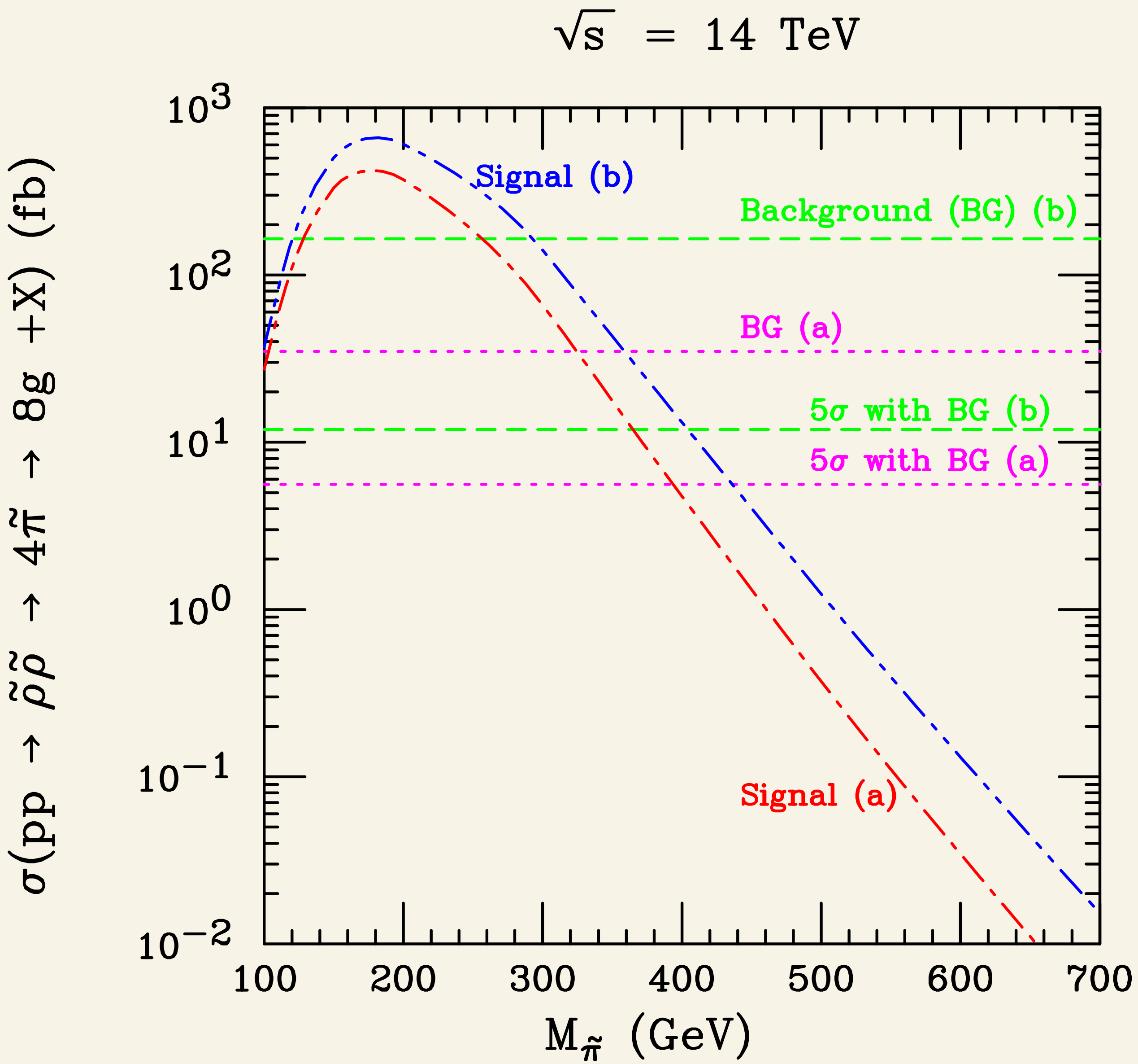
(a) $\Delta M_{2j} \leq 30$ GeV and $\Delta M_{4j} \leq 60$ GeV or

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

Relative Mass Cuts (7 TeV)



Relative Mass Cuts (14 TeV)



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 $M_{\tilde{\rho}}$.

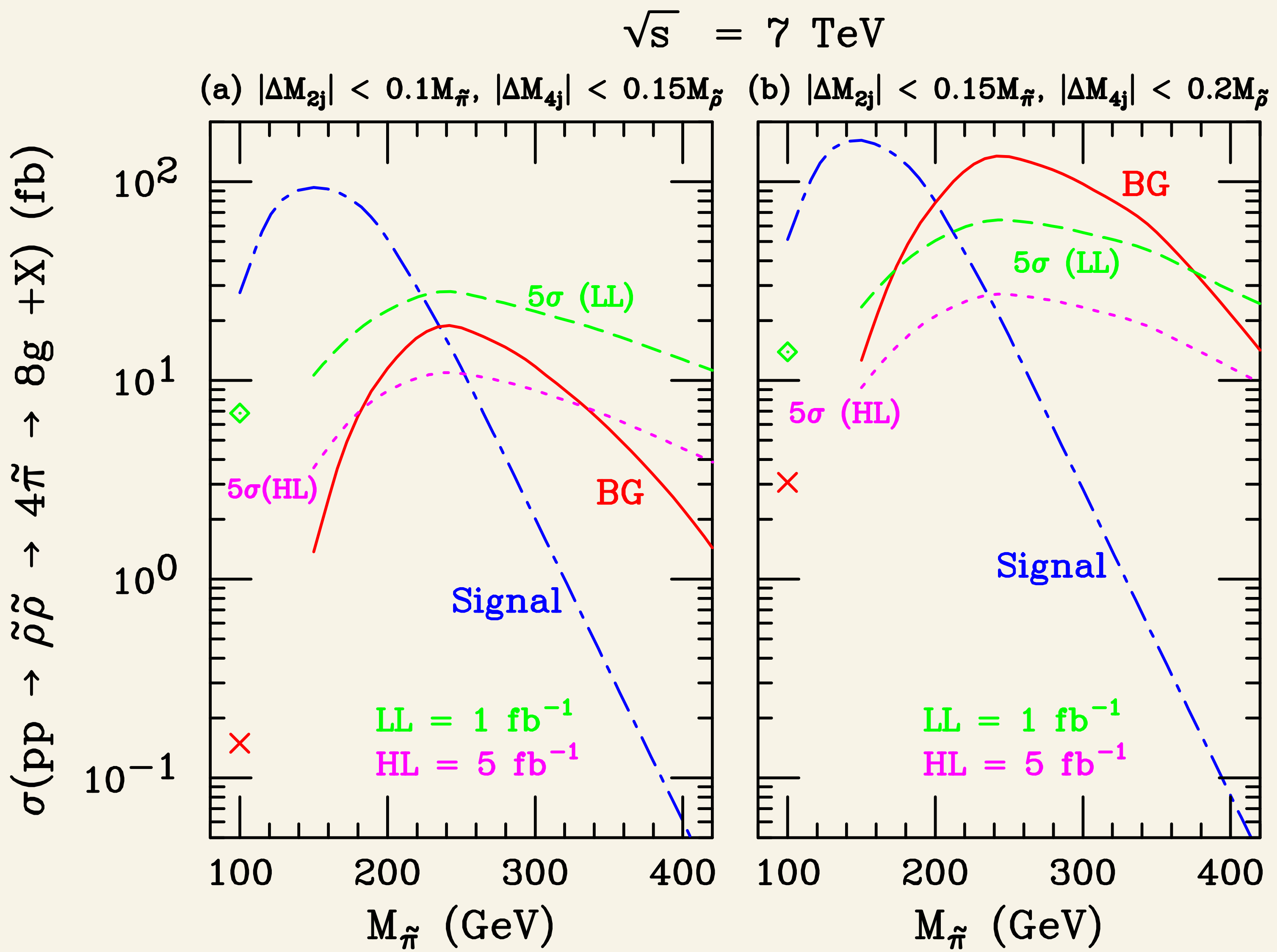
We have chosen

(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

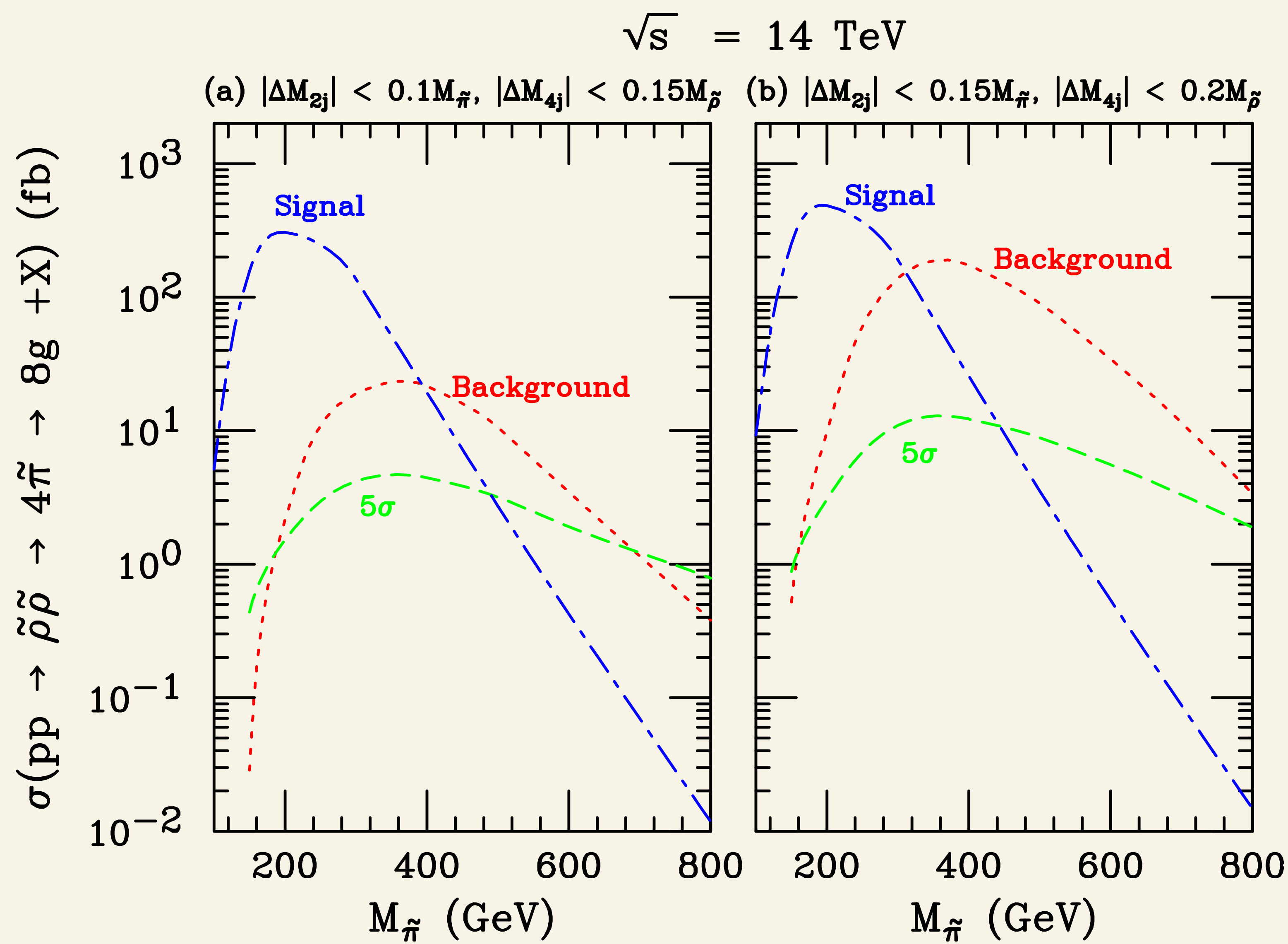
(b) $|M_{2j} - M_{\tilde{\pi}}| \leq 0.15 M_{\tilde{\pi}}$ and $|M_{4j} - M_{\tilde{\rho}}| \leq 0.20 M_{\tilde{\rho}}$.

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

Fixed Mass Cuts (7 TeV)



Fixed Mass Cuts (14 TeV)



Summary for Coloron Phenomenolgy

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 $L = 1$ fb^{-1} or $M_{\tilde{\pi}} \lesssim 265$ GeV ($M_{\tilde{\rho}} \lesssim 883$ GeV) for $L = 10$ 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 $L = 10$ fb^{-1} or $M_{\tilde{\pi}} \lesssim 535$ GeV ($M_{\tilde{\rho}} \lesssim 1780$ GeV) for $L = 100$ 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.