Early LHC Prospects for Exotic Physics

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West Coast LHC @ UCSC
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Outline

- Resources
- Comparing LHC0.5 with Tevatron
- Resonances
- Fourth Generation Quarks

Resources

- I agreed to speak about what early LHC running can tell us about some exotic physics scenarios.
  - I'm not really an expert on this subject.
  - I'll do my best.
  - I welcome input from the audience as we go to improve the talk!
- Some resources I have found useful:
  - Baur, Ligetti, Schmaltz, Thaler, Walker, "Supermodels", 0909.5213.
  - Alwall, Feng, Kumar, Su, "Dark Matter Motivated Searches for an Exotic 4th Generation Quarks in Tevatron and Early LHC data", 1002.3366.
  - Berger, Cao, Chen, Shaughnessy, Zheng, "Color Sextet Scalars at the Early LHC", 1005.2622.

New Physics -- Early?!

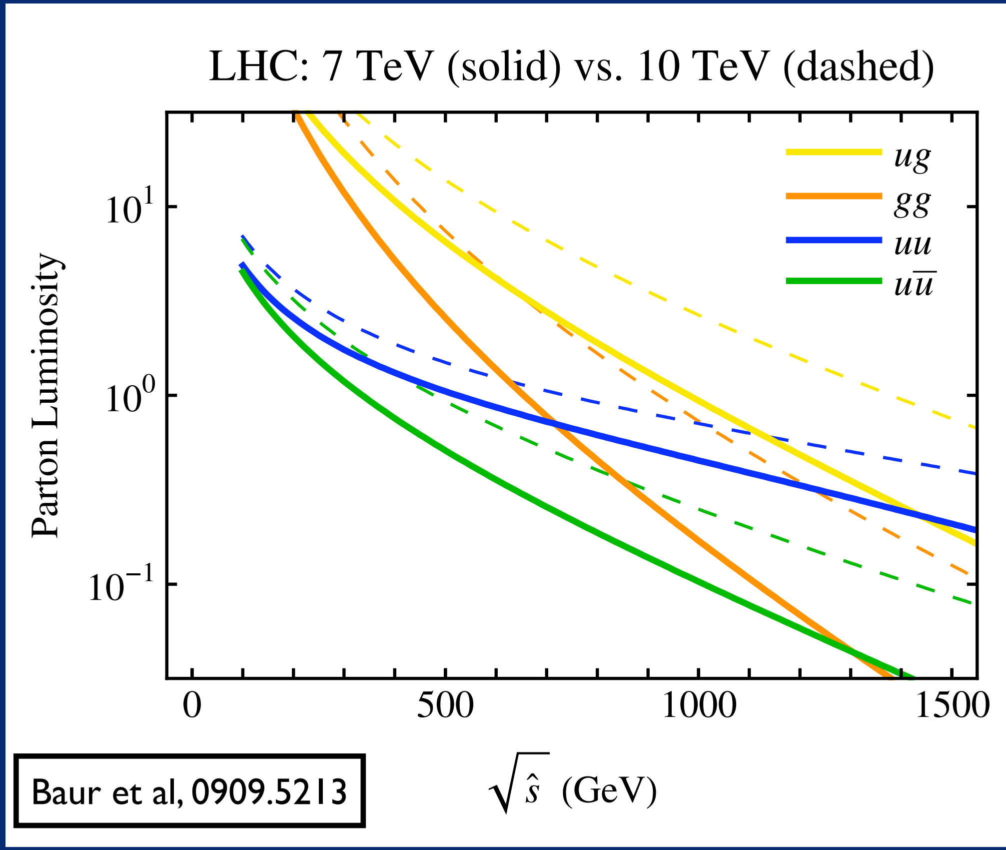
Searching for new physics with small amounts of data is fun, challenging, and gives us something to do while we collect enough anti-matter to terrorize the vatican.

For the purposes of this talk, "early" mostly refers to 7 TeV pp collisions with about 1 fb^{-1} of collected data.

The challenge in identifying such signals is to find examples which are not already ruled out by precision data, LEP II, or the Tevatron.

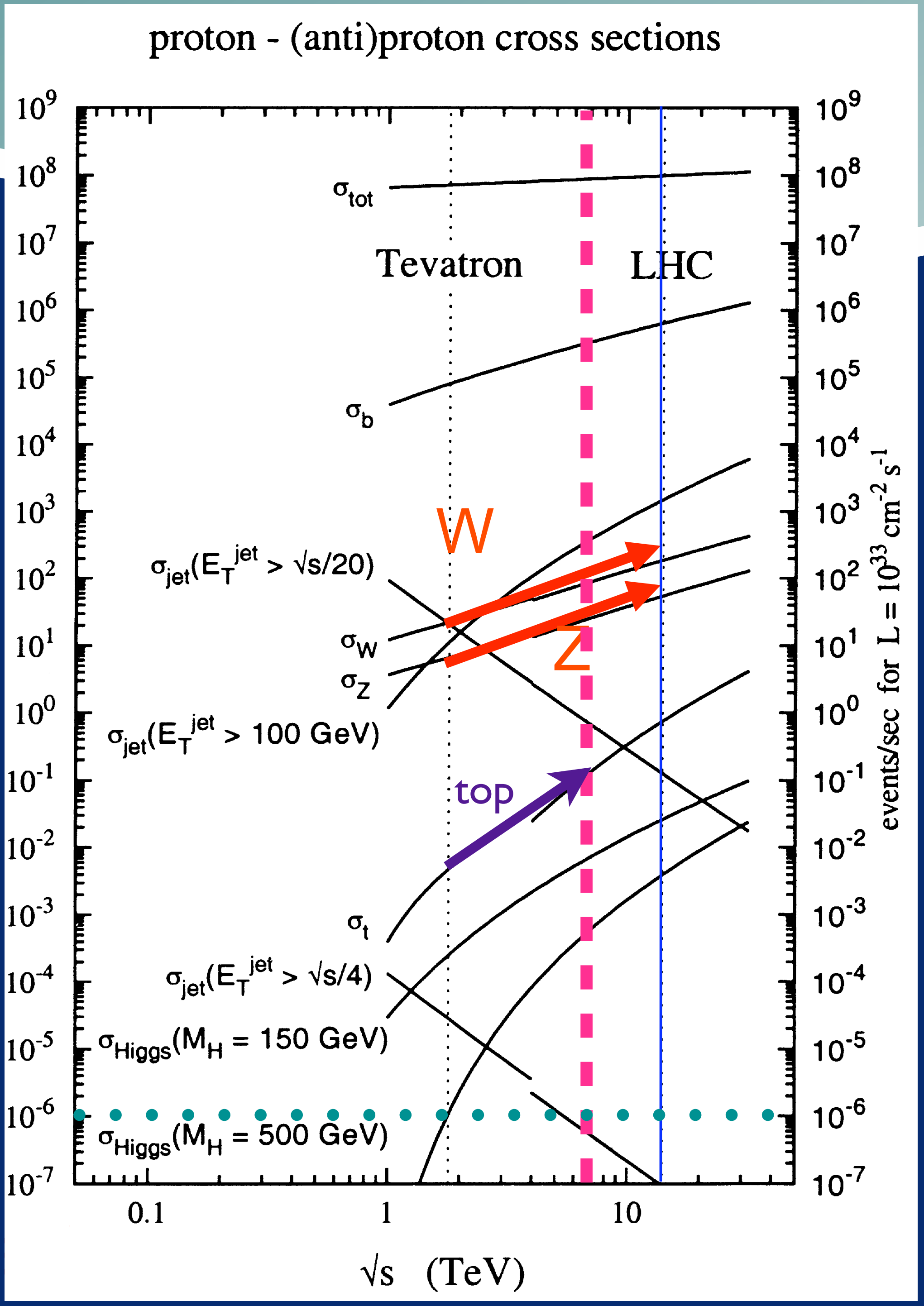
Seven vs Ten (vs Fourteen)

- At lower energies, signals involving high energy physics are smaller.
- Rare, low background processes almost always lose compared to 10 or 14 TeV.
- Unless the reaction itself grows with energy, most cases are controlled by the parton flux.
- Often backgrounds are smaller too -- particularly those driven by a gg initial state like top pair production.
- Electroweak processes sometimes gain ground compared to top backgrounds!



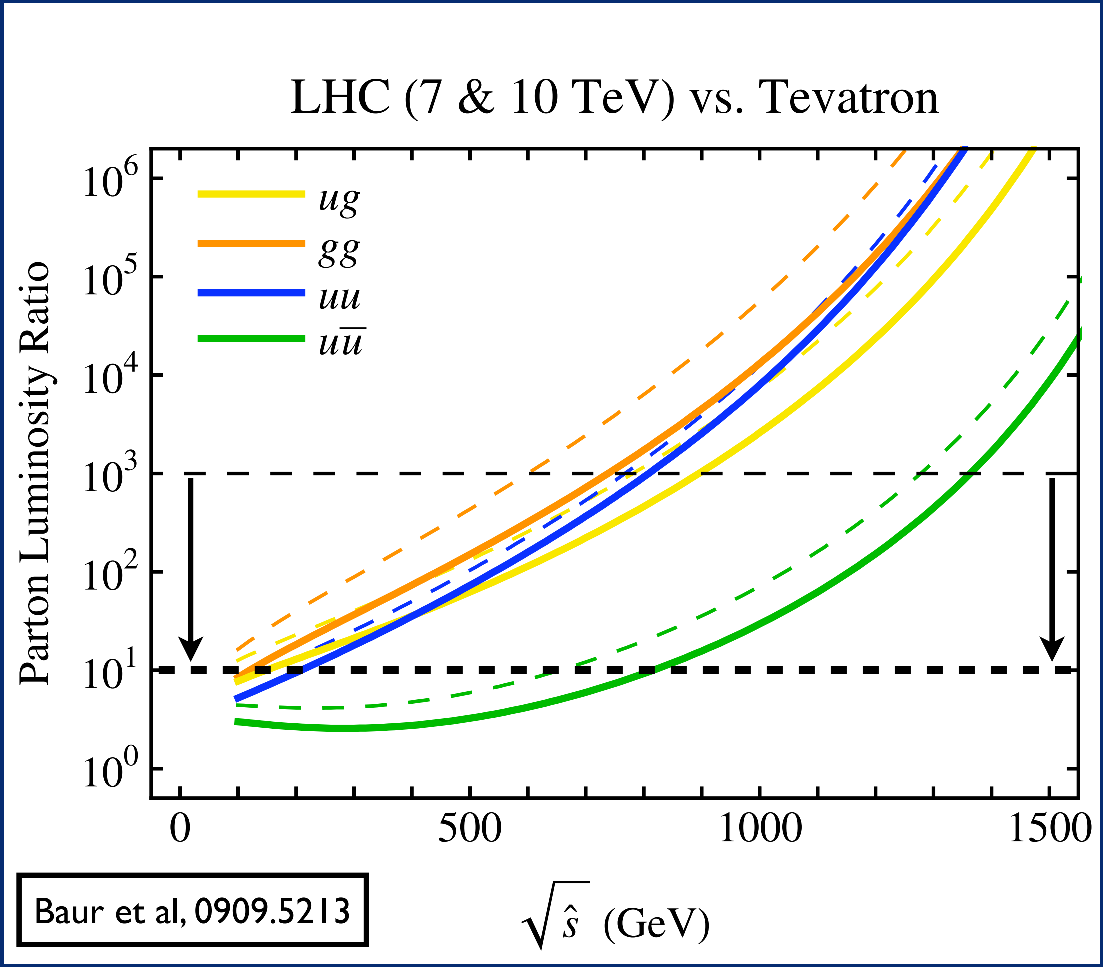
Cross Sections

- Luminosities of order fb^{-1} still include many interesting SM processes: (as Ian has told us...)
  - Electroweak bosons
  - Top quarks
- Some interesting search processes:
  - Higgs (probably not SM)
  - Super-partners (light ones, Andre Lessa will tell us about them after lunch...)



Seven versus Tevatron

- Compared to the "Supermodel" analysis (which remains an interesting survey of 10 pb^{-1}), collecting 1 fb^{-1} actually helps quite a bit compared to the Tevatron with 10 fb^{-1}.
- For example, for a Z'-like resonance (which feeds off of the q qbar initial state), a 7 TeV LHC rapidly begins to win over Tevatron for masses around 1 TeV.
- Pair production from a gg initial state becomes more sensitive even for low masses.



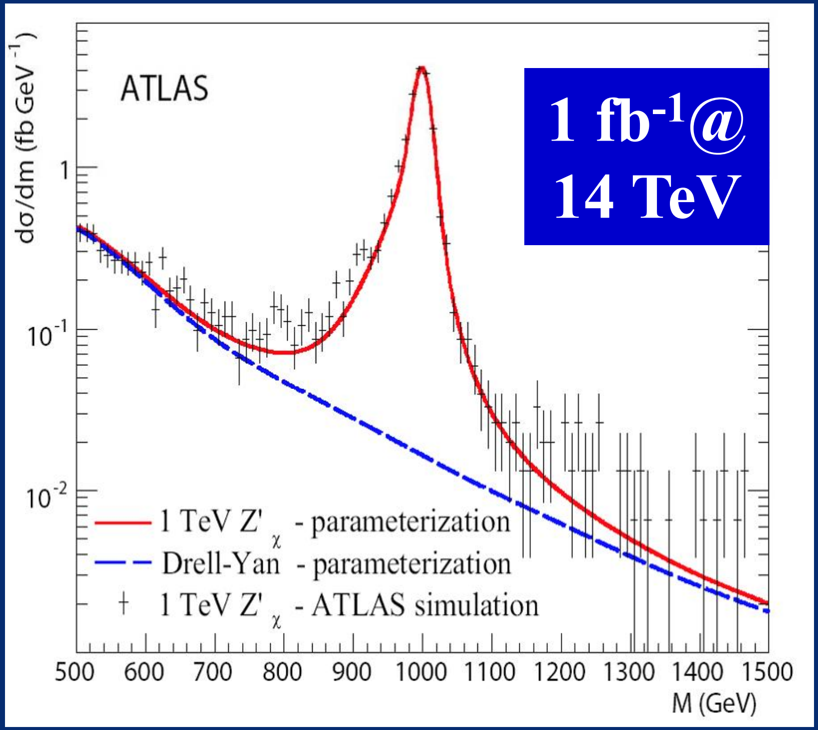
Solid: 7 TeV LHC compared to Tevatron
Dashed: 10 TeV LHC compared to Tevatron

New Physics at the Early LHC

- So where does the LHC have a shot at an early discovery?
- Some properties of the new physics would help a lot:
  - High cross sections combined with large masses to take us beyond the Tevatron reach.
  - Strong energy dependence of the signal, to give us more increase in signal than parton luminosities alone would infer.
  - Low backgrounds and striking morphologies never hurt...
- In the remaining time, I'll look at a few examples:
  - Resonances
  - Pair production through the strong force

Z's

- For the purposes of this talk, a Z' is anything that is produced from a q qbar initial state and produces a lepton resonance.
- Z's occur in GUT models, top/technicolor theories of EWSB, little Higgs models, in effective theory descriptions of extra dimensions, WIMPonium, ...
- The Tevatron cannot get much past 1 TeV masses because the parton luminosity just gives out too fast.
- The dominant backgrounds have the same initial states -- so signal and background scale similarly with energy.



Some kinds of Z's

- There are many many many different kinds of Z's.
- Four sets of model lines are defined by continuous parameter x.
- The famous E_6 Z's can be realized for specific values of x.

Hewett, Rizzo
Phys Rept 183, 193 (1989)

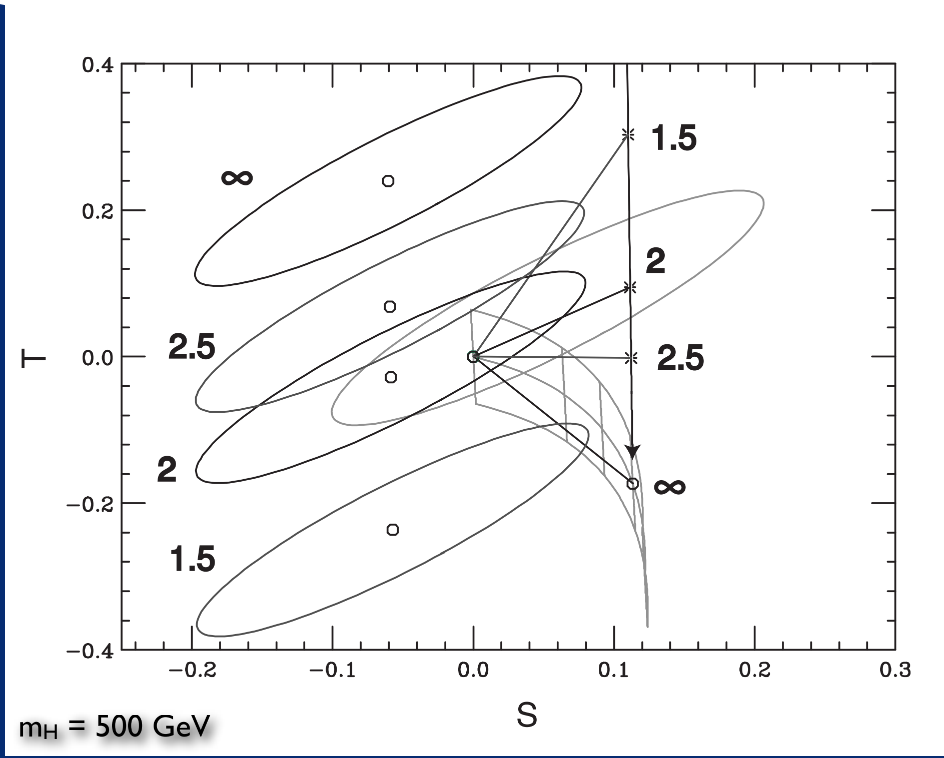
Carena, Daleo, Dobrescu, TT '04	B-*x*L	Q+*x*u	10+*x*5	d-*x*u
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	+x/3	-1/3	-x/3
d_R	+1/3	(2-x)/3	-x/3	+1/3
$l_L=(e_L,\nu_L)$	-x	-1	+x/3	(x-1)/3
e_R	-x	-(2+x)/3	-1/3	+x/3

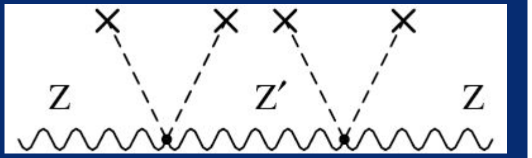
These Z's are anomaly free provided one adds pairs of leptons which are vector-like under the SM gauge symmetries with appropriate charges.

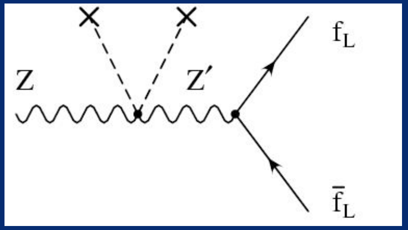
Precision data and Z's

Peskin & Wells
hep-ph/0101342

- Precision data is often highly constraining for theories containing Z's:
  - Flavor observables are highly restrictive for new flavor-changing neutral currents. Couplings must be approximately flavor-diagonal.
  - A Z' which mixes with the Z would affect Z pole measurements:
    - Mixing could be the result of the Higgs being charged under the Z'.
    - For the right Z', this could shift to a larger preferred m_H!



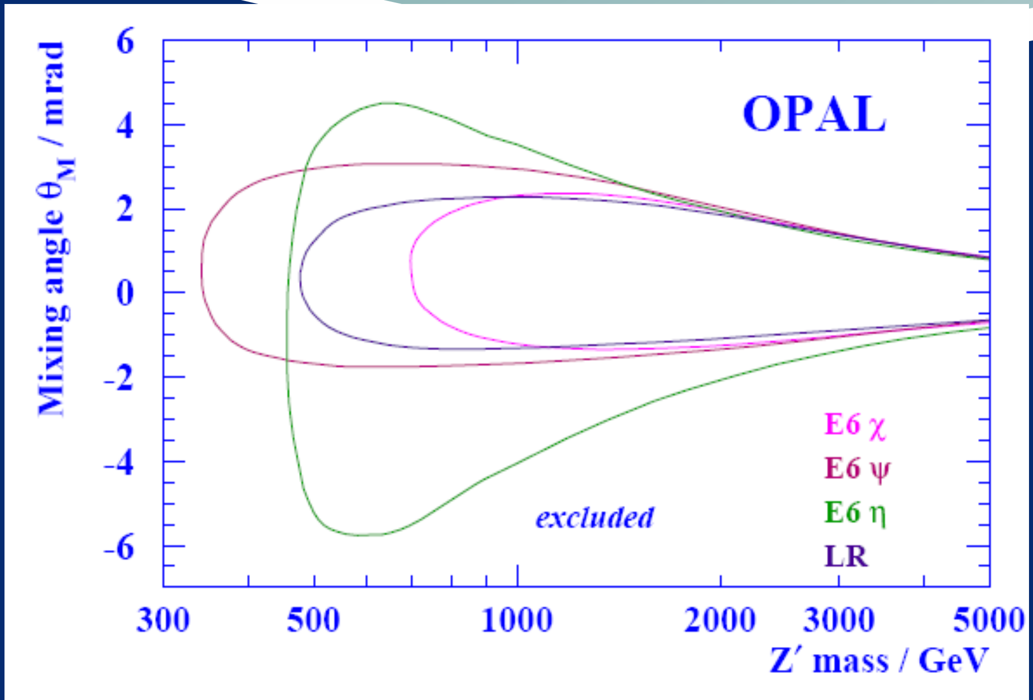




See also: Chanowitz 0903.2497

Z - Z' Mixing

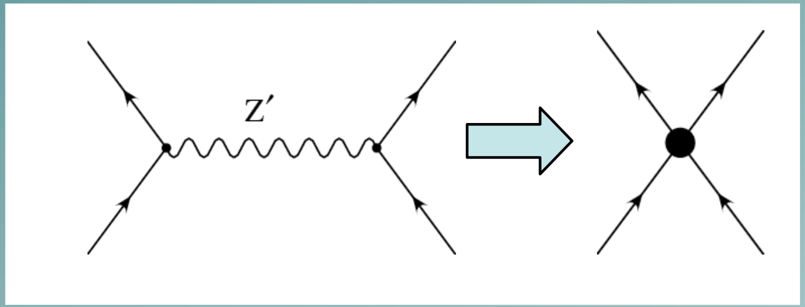
- LEP data clearly does not want a Z' mixing by a large amount with Z.
- Typical constraints are ~10^{-3} rad.
  - This requires the SM Higgs to have something like $z_H < 10^{-3}$
  - A two Higgs doublet model offers more flexibility if the two doublets have different charges.
    - Tan β ~ 10 provides enough suppression.
    - Otherwise we can play the two charges against one another.



$$|\epsilon| \simeq \frac{g_z}{g}\left(\frac{\cos\theta_w}{M_{Z'}^2/M_Z^2 - 1}\right)\frac{|z_{H_1} + z_{H_2}\tan^2\beta|}{1+\tan^2\beta}$$

Hewett, Rizzo
Phys Rept 183, 193 (1989)

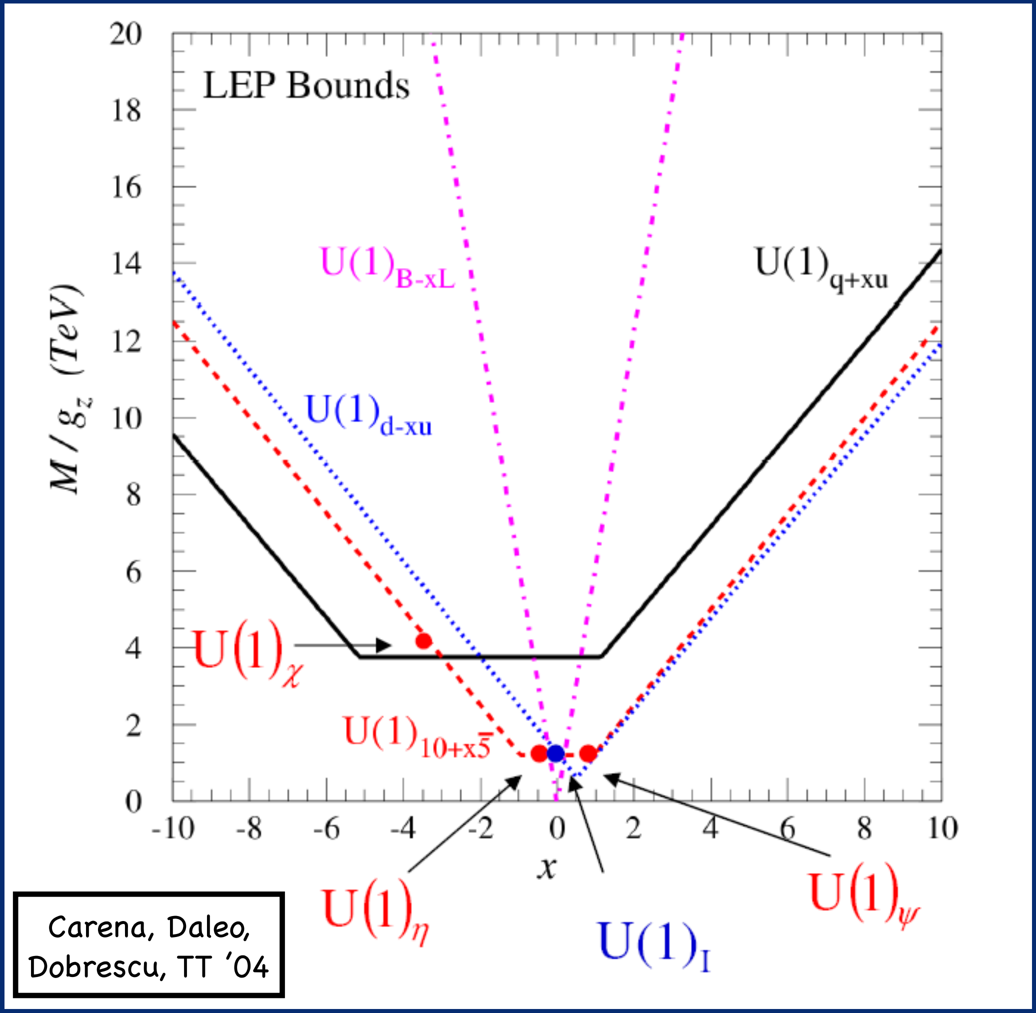
LEP II and Z's



- A Z' which survives the Z-pole measurements may still be constrained by LEP-II. Since we assume our Z' has some couplings to leptons, it can appear as a contact interaction in e+e- --> f fbar.
- Such a contact interaction, at leading order, constrains the scale of the Z' symmetry-breaking.

$$\frac{g^2}{M_Z'^2} \rightarrow \frac{1}{u^2}$$

- Z's can remain kinematically within reach of colliders provided they are weakly coupled enough that their masses are within reach.



Tevatron Constraints on Z's

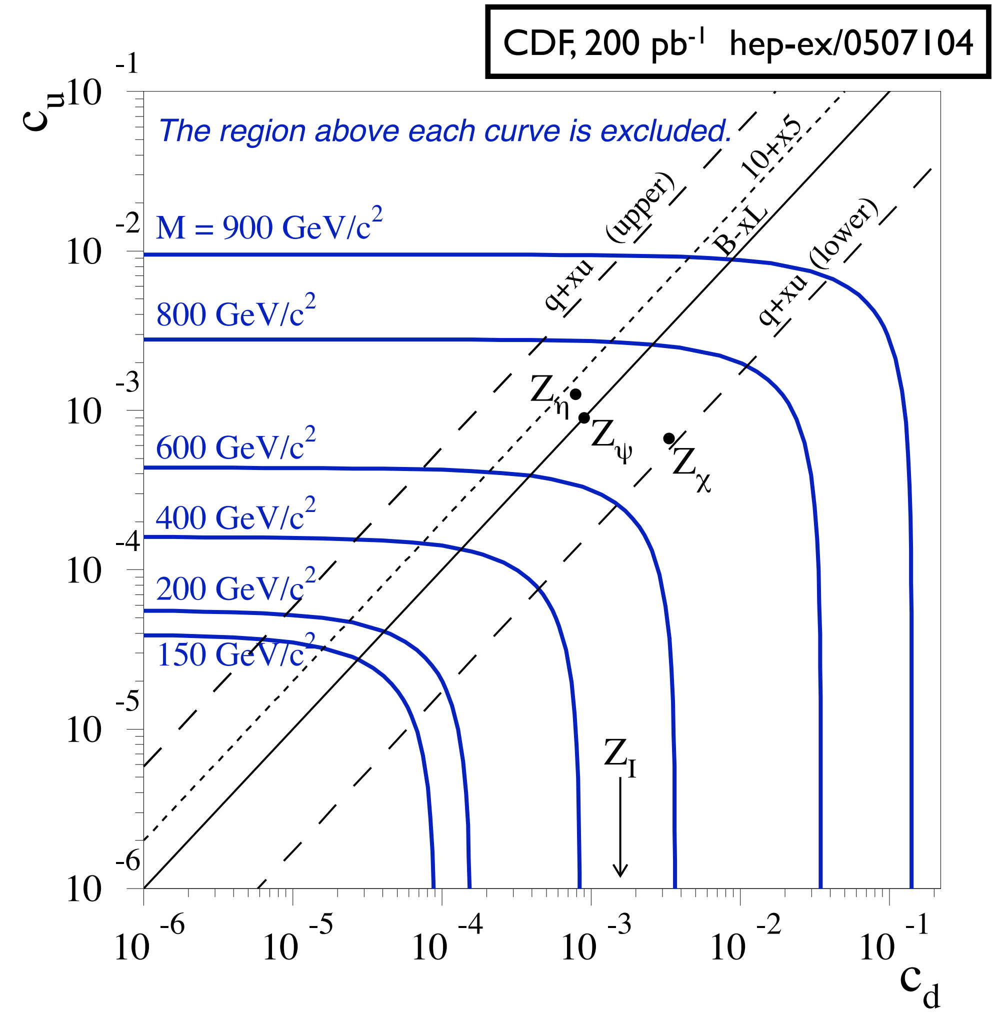
- We can parameterize the Z' cross section at a hadron collider in terms of parameters c_u and c_d: Carena, Daleo, Dobrescu, TT '04

$$\sigma(p\bar{p} \to Z' \to \ell^+\ell^-) = \frac{\pi}{48s}\left[c_u w_u + c_d w_d\right]$$

$$c_u \equiv g^2(z_q^2 + z_u^2) BR(Z' \to \ell^+\ell^-)$$

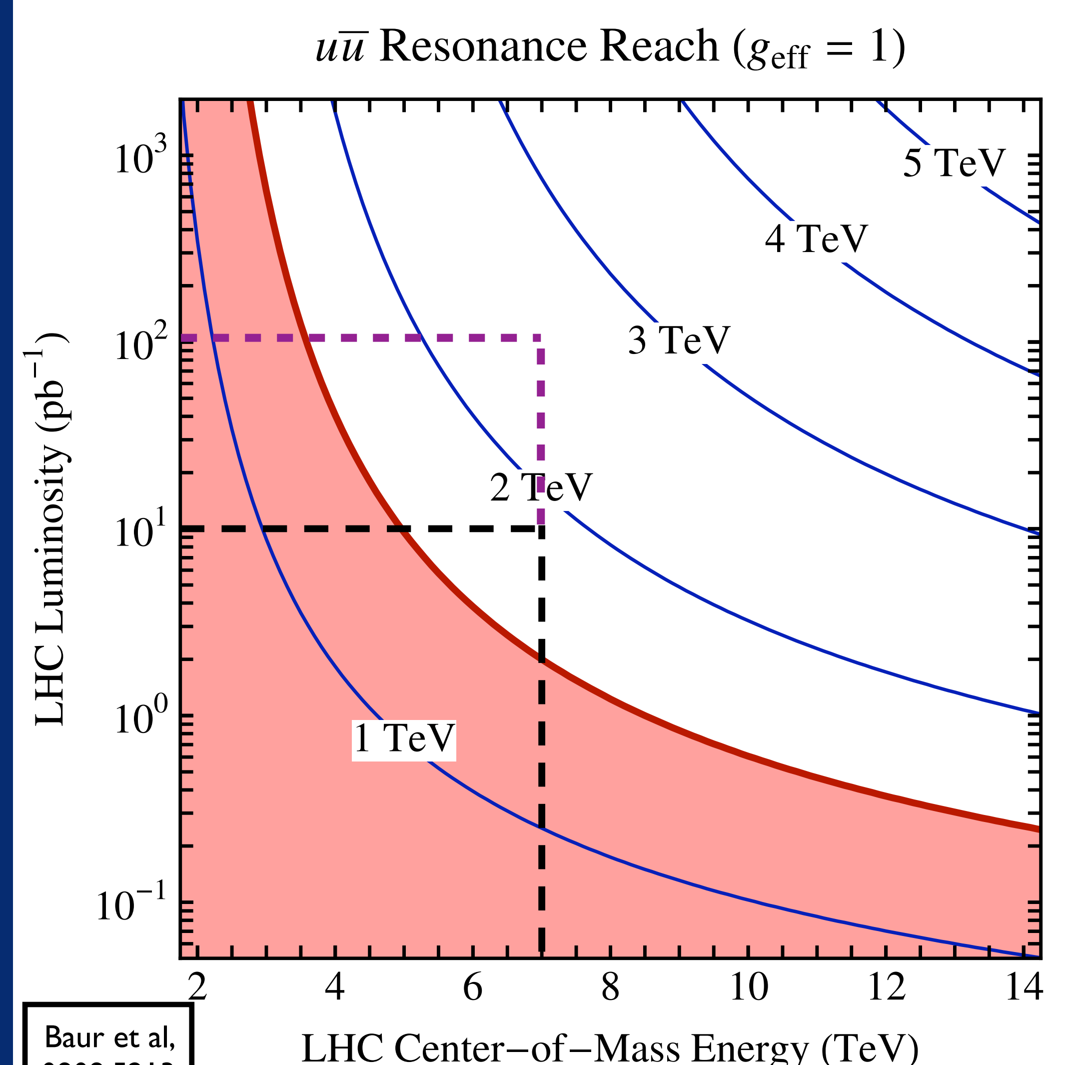
$$c_d \equiv g^2(z_q^2 + z_d^2) BR(Z' \to \ell^+\ell^-)$$

- The PDFs are hidden in the w's, which capture up to NLO in QCD.
- Based on the limits, one sees that for a ~ 900 GeV Z', universal couplings on the order of ~ 1/4 or so are allowed.



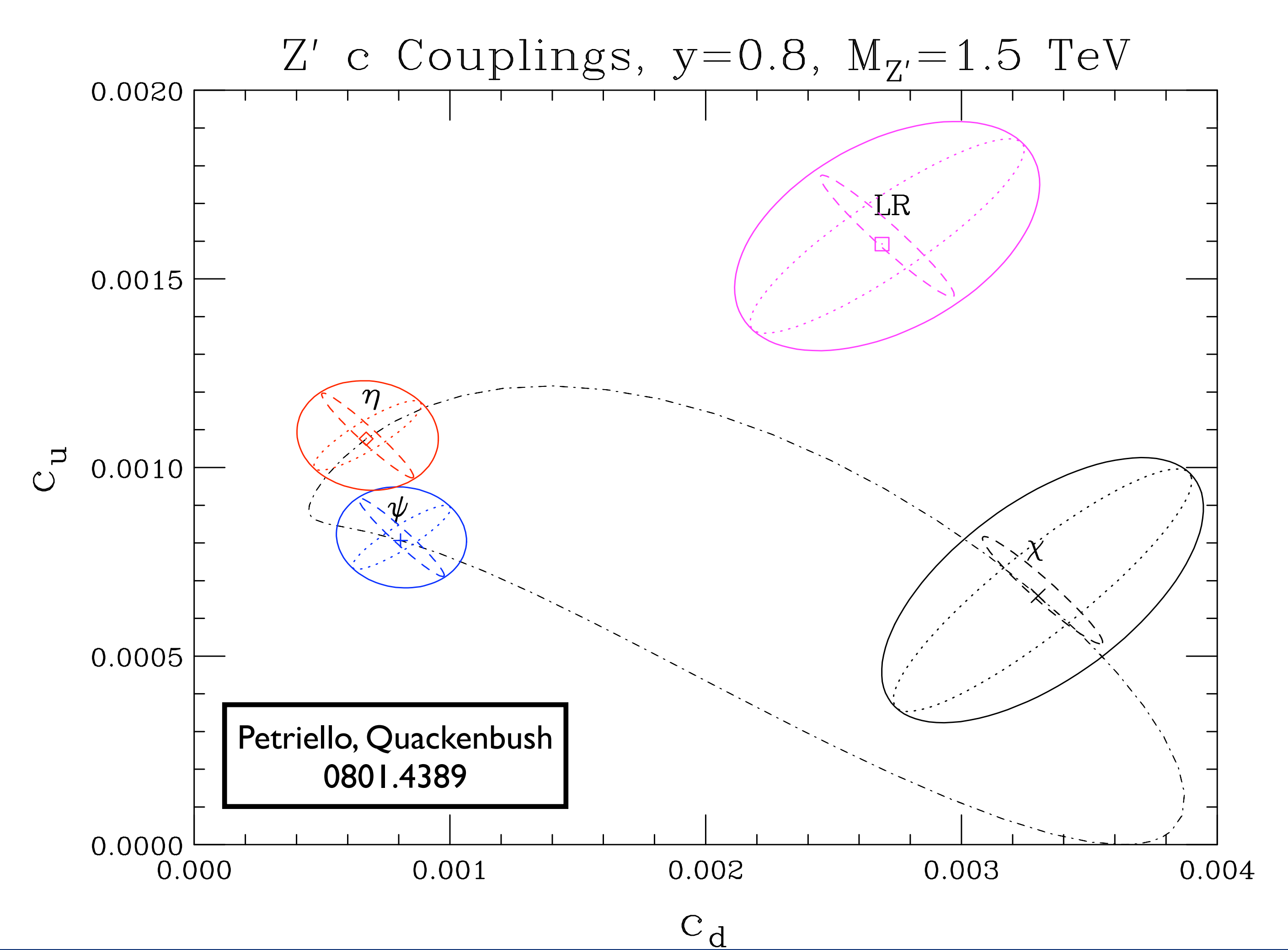
LHC Z' Prospects

- The supermodel study contains estimates of Z' reaches (defined as: 10 events or more) for 7 TeV.
- To put together the constraints, I increase the luminosity to 1 fb^{-1}.
- To handle the LEP-II constraints I dial down the couplings by a factor of 3-4. (So σ by about 10).
- The result is that I think I find reasonable Z' models for which the early LHC can expect to see Z's with masses ~ 2.5 TeV -- well beyond the Tevatron reach!



Baur et al,
0909.5213

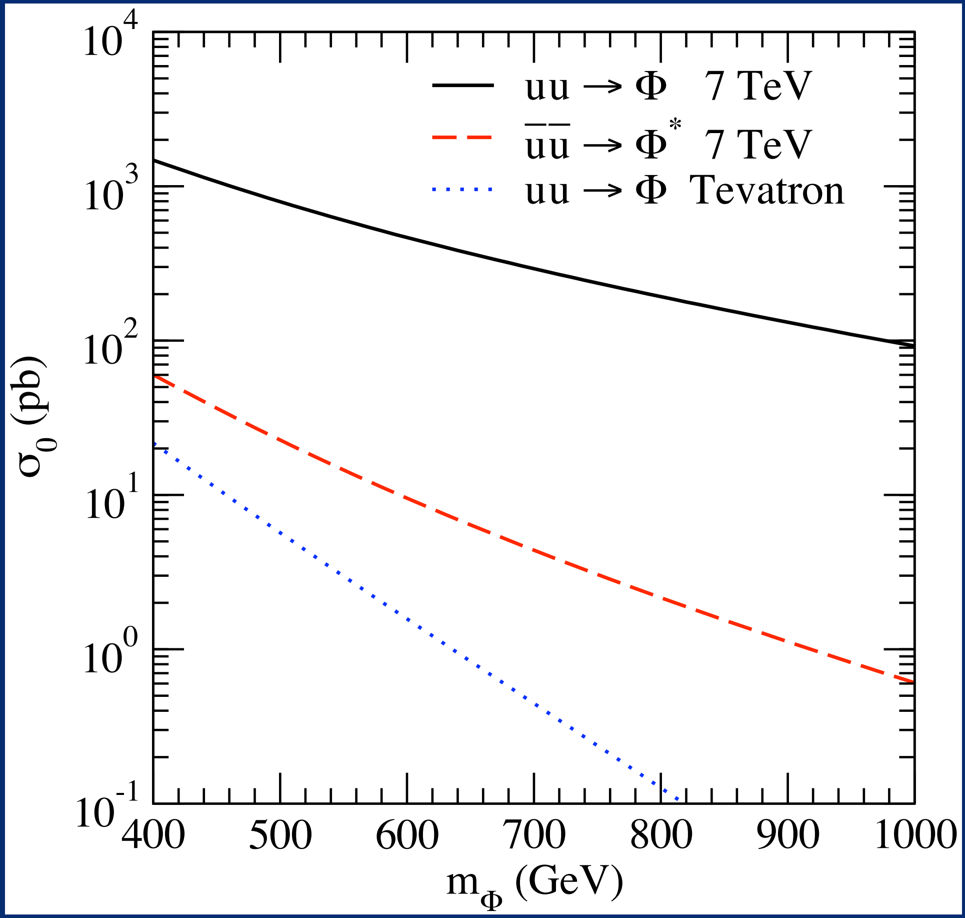
Eventually Measurements...



- With 14 TeV and 100 fb-1, we go beyond discovery and into measurement. (West coast theory meeting, 201x?)
- Rapidity distributions and asymmetries break the c_u - c_d degeneracies and allow one to disentangle left and right lepton charges as well.

Exotic Resonances

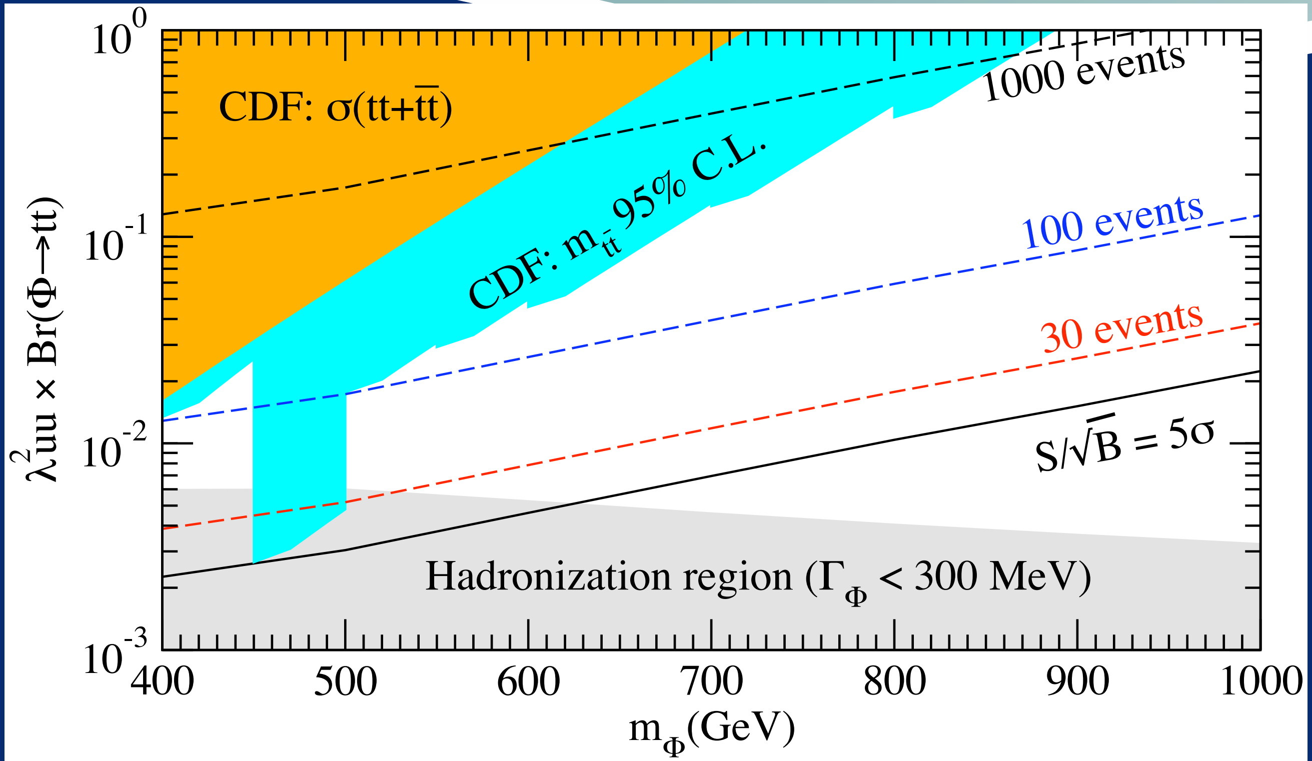
- A more exotic resonance may result in better discovery prospects. For example, a color sextet scalar particle (6, 1, 4/3) can be produced as a resonance in uu parton collisions. Tailor-made for the LHC!
- Such objects have been invoked in the t-channel to explain the top FB asymmetry at CDF. Shu, TT, Wang 0911.3237
- If they have large enough diagonal couplings, they can be produced in uu collisions and result in the unusual tt resonance.



Berger, Cao, Chen, Shaughnessy, Zheng 1005.2622

Bounds and Prospects

- Bounds from the CDF search for tt (+ tt) pairs restricts the parameter space in the plane of m_Φ and coupling^2 x BR.
- Resonance searches (which are in the leptons + jets channel and thus not sensitive to the wonky charges) provide additional constraints.
- For the 7 TeV LHC, regions not ruled out by Tevatron may lead up to 1000 events. Masses up to a few TeV may be discovered using like-sign $\mu^+\mu^+$ events.



Backgrounds Considered:

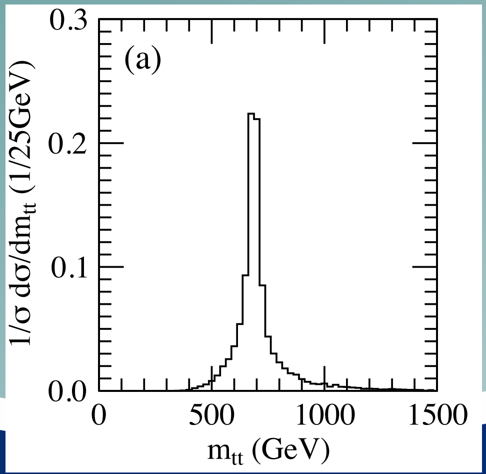
WWW
WWjj
t tbar
ZWW

→ like-sign muons

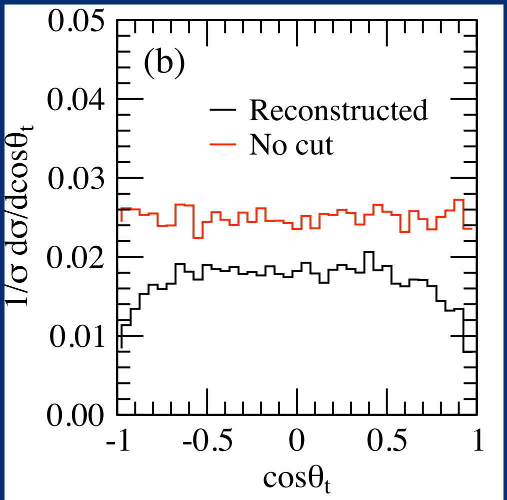
Berger, Cao, Chen, Shaughnessy, Zheng
1005.2622

1 fb^{-1} background: 12 SM events expected.

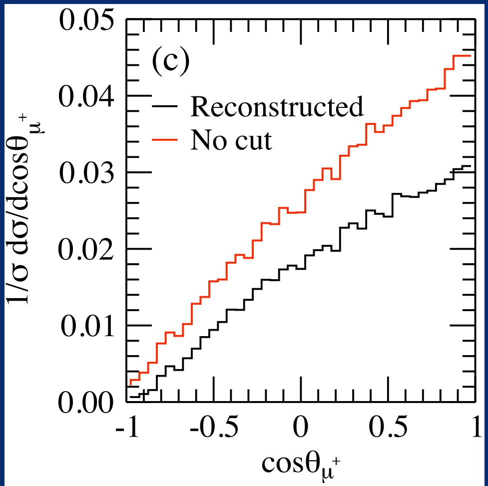
Reconstruction



- Using MT2, the invariant mass of the tt system can be reconstructed, revealing the resonance and measuring its mass.
- MT2 reconstructs the top four vectors. The angle of the tops in the CoM frame is flat in cos θ, characterizing the resonance as scalar.



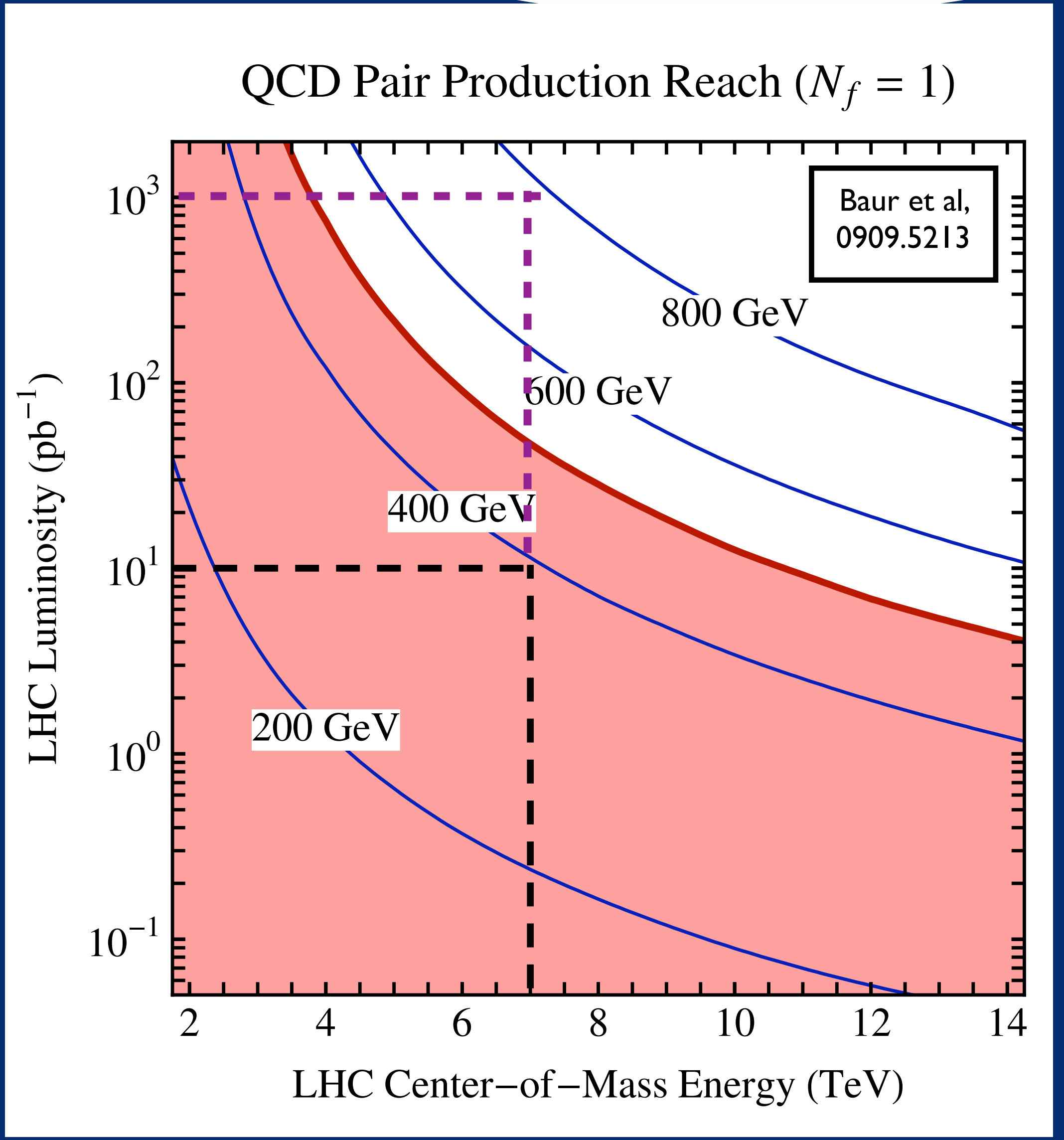
- The left-handed weak interaction implies that the tops analyze their own polarizations when decaying. The right-handed tops produce a characteristic angle between the charged lepton and the top boost in the top rest frame.



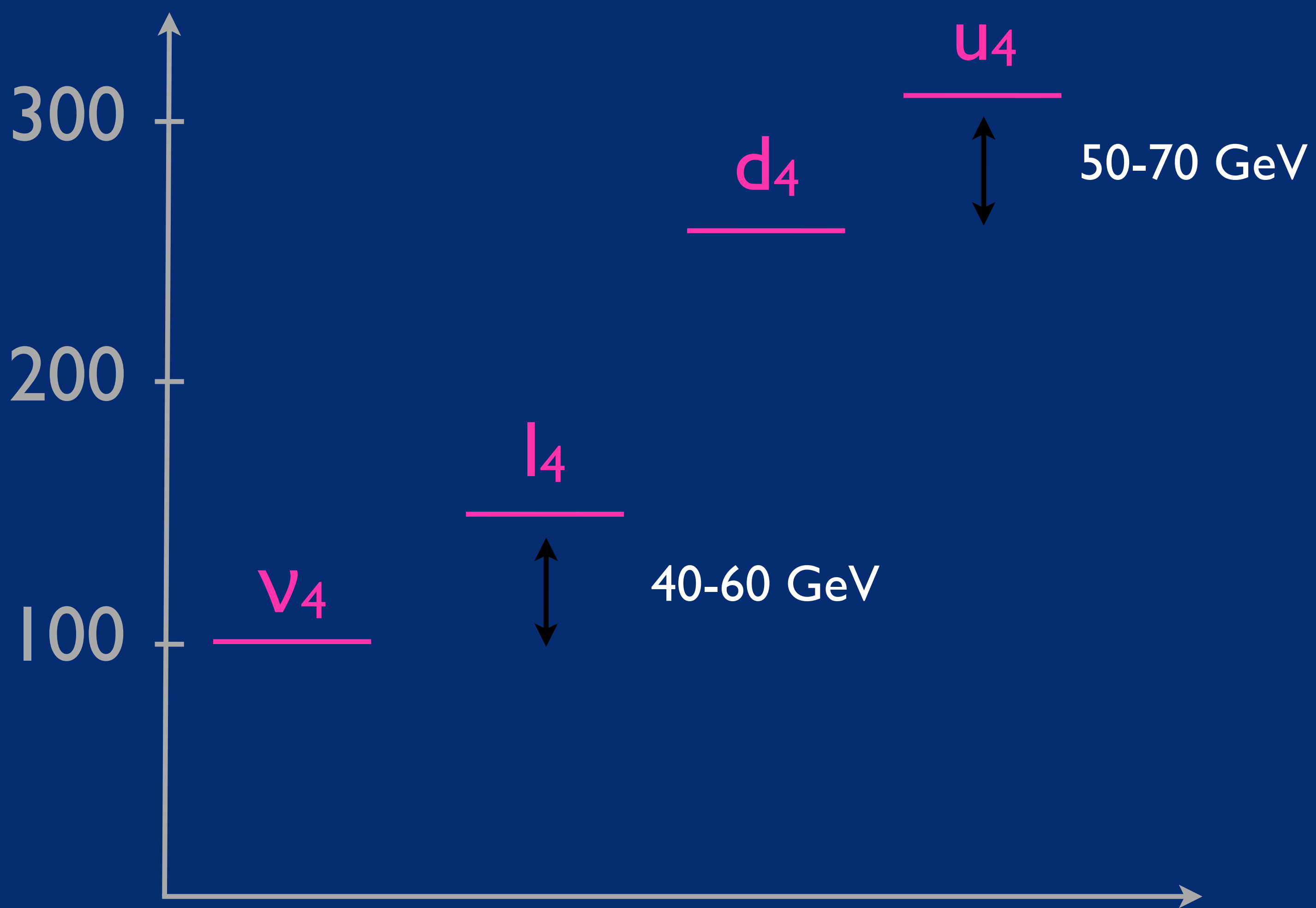
Berger, Cao, Chen, Shaughnessy, Zheng
1005.2622

Pair Production

- Colored states may be pair-produced and can feed off of gg as well as quark-anti-quark initial states with large production cross sections.
- The "10 event test" reaches masses close to 800 GeV. Actual reaches will depend on backgrounds.
- For low background signatures, such as perhaps objects which hadronize into CHAMPs, we will get well beyond the Tevatron limits.



Chiral Quarks

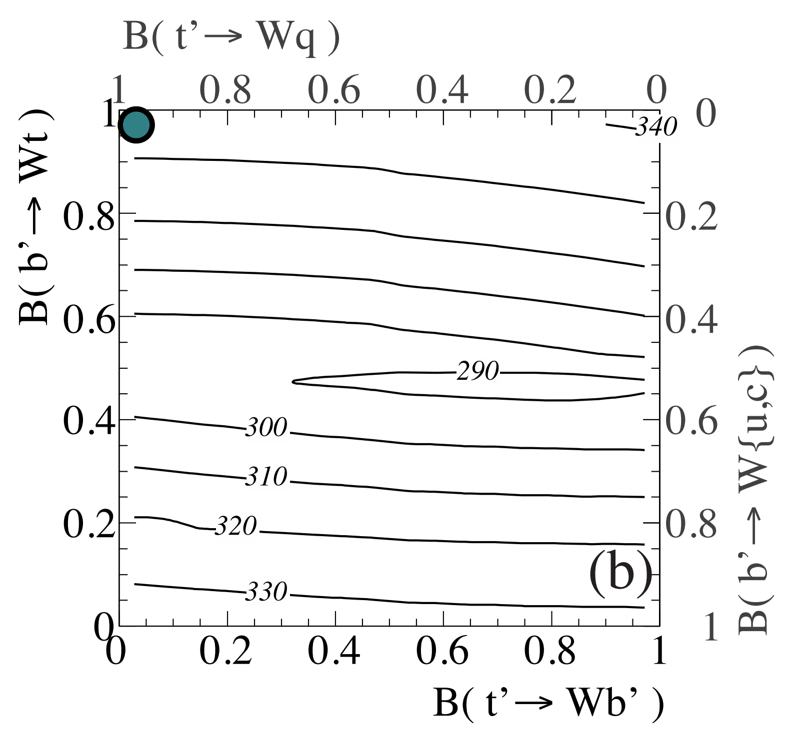


- One of the simplest extensions of the SM is another chiral generation. Since we have no idea why there are three, why not four?
- Precision EW and flavor observables can work provided there is sufficiently small mixing between the fourth generation and the other three.

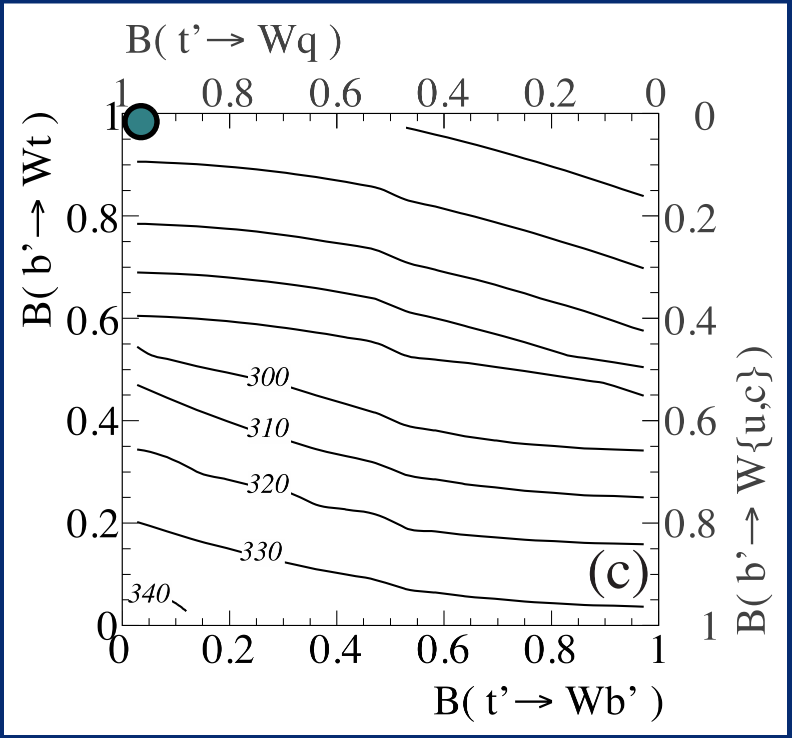
He, Polonsky, Su hep-ph/0102144
Kribs, Plehn, Spannowsky, TT 0706.3718
Langacker, Erler 1003.3211
Chanowitz 0904.3570
Eberhardt, Lenz, Rohrwild 1005.3505

Tevatron Limits

mt' = mb' + 100 GeV



- There are two CDF searches relevant for chiral quarks:
  - $\bar{t}'t' \to (W \to \ell\nu)q(W \to q\bar{q})q$
  - $\bar{b}'b' \to W t W \bar{t} \to \ell^{\pm}\ell^{\pm}\ldots$
- Putting these together, one can place combined limits on a t' and b', which in a chiral model will always come together.
- Robust limits of order 300 GeV result from the Tevatron.



Contours of b' mass

Flacco, Whiteson, TT, Bar-Shalom 1005.1077

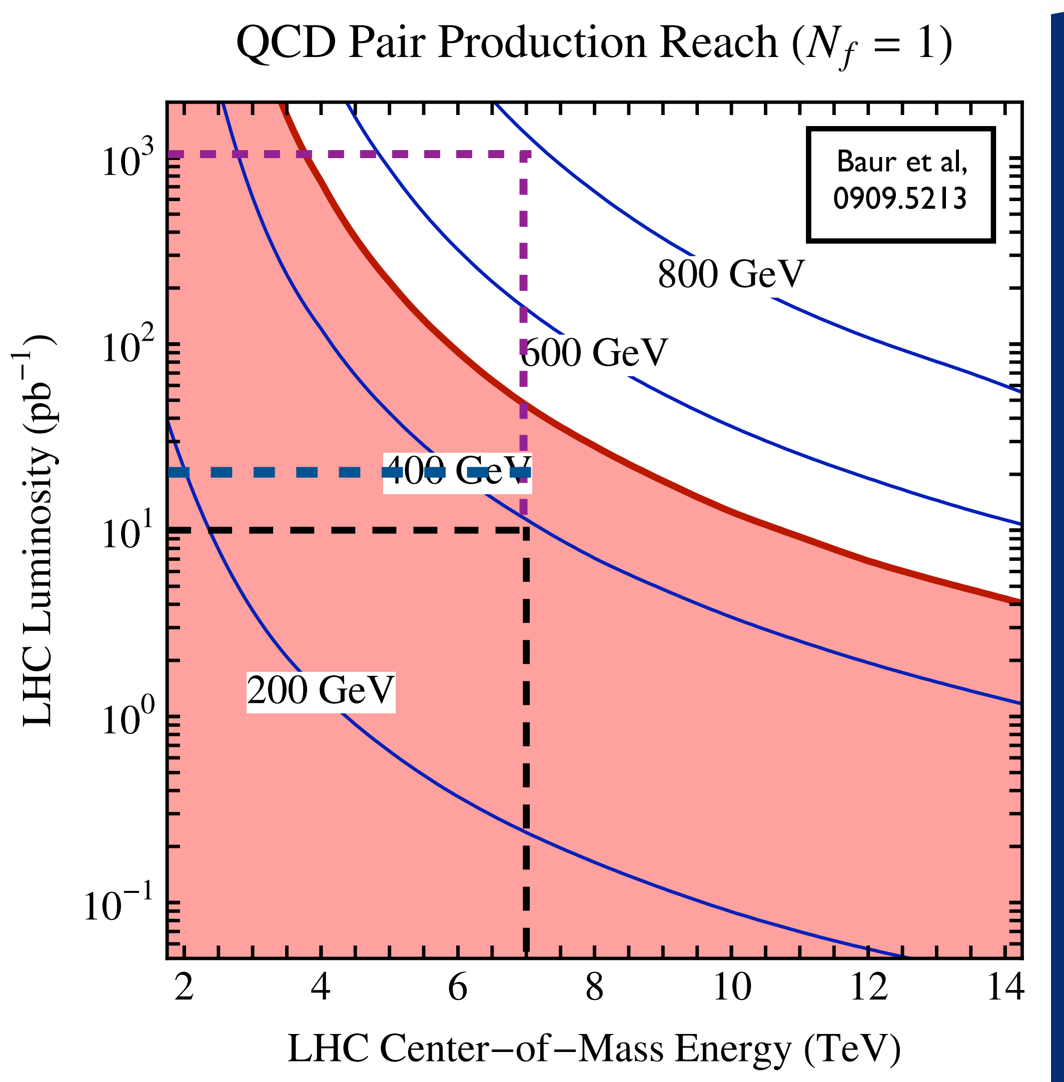
mt' = mb' + 50 GeV

Prospects for Chiral Quarks

- I wasn't able to find a plot for pair production of colored quarks at 7 TeV. However, let's do some simple estimates:
  - The diquark analysis had a background of 12 events.
  - For 5σ discovery, we need about 17 like-sign muon signal events.
- Pairs of t's with the decay t' -> b' -> t produce 6 Ws total., three of each charge.
  - The BR for 2+ like-sign muons from 3 W^+s is 3.4%.
  - I only took + sign, since that is what the diquark paper did.
  - They did not impose any invariant mass cuts on the resonance.
- So before the W BRs, we need ~500 events, or with 1 fb^{-1}, we need $\sigma \sim 0.5$ pb.

Naive Chiral Quark Prospects

- Tevatron limits (~3.5 fb^{-1}) for:
  - BR(t' --> b' W) ~ 1
  - BR(b'-->t W) ~ 1
- Are mb' up to ~340 GeV. The two studies assumed mt' was mb' + 50 or 100 GeV.
  - There's not much room here for the LHC to add to Tevatron numbers.
- However, it is close enough that a dedicated analysis could probably do *something*.



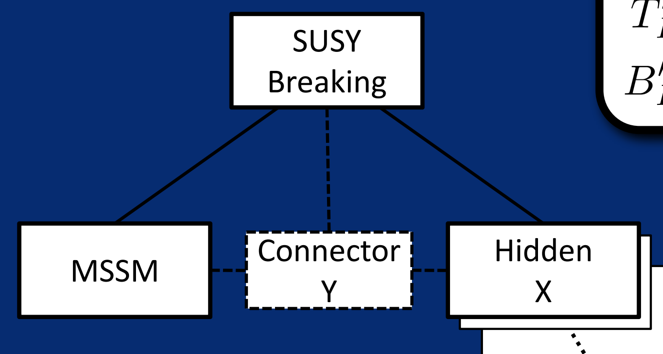
Exotic Quarks for WIMPless DM

- A WIMPless dark matter model has scalar WIMPs X which interact with the SM quarks through a "connector" mirror generation.
- The "WIMPless miracle" insures the relic density works out by keeping the mass / coupling ratio fixed to be approximately weak.
- This setup can reconcile the DAMA/CoGeNT light WIMP interpretations with other experiments. (Xenon100...?)

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

$$V = \lambda \left[X \bar{Q}'_L q_L + X \bar{B}'_R b_R + X \bar{T}'_R t_R \right]$$

$$\begin{array}{lcl} Q'_L & : & (3, 2, \frac{1}{6}) \\ T'_R & : & (3, 1, \frac{2}{3}) \\ B'_R & : & (3, 1, -\frac{1}{3}) \end{array} .$$



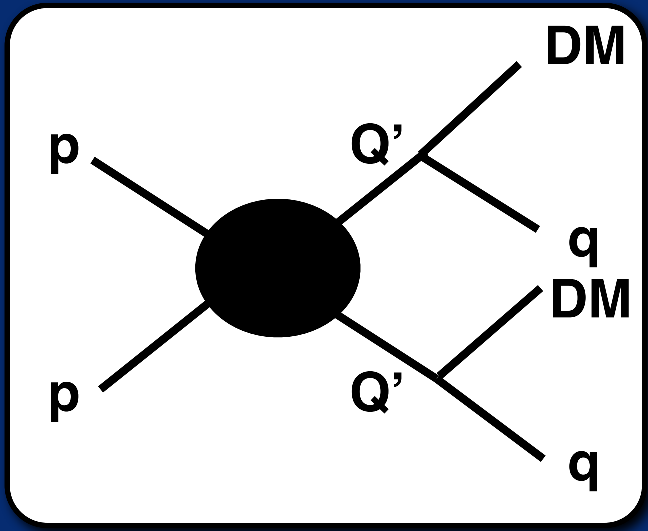
Virtually the same setup invoked to gauge B and L: Dulaney, Perez, Wise 1005.0617

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \rightarrow \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Feng, Tu, Yu, CAP 0810:043,2008

Tevatron Limits

- The connector quarks are colored, and can be pair-produced at colliders.
- Once produced, they decay into ordinary quarks (t or b) and the light WIMP.
- In 1002.3366, Alwall, Feng, Kumar, and Su considered Tevatron bounds and early LHC prospects.
- They considered existing searches, which they evaluated for their particular WIMPless model.



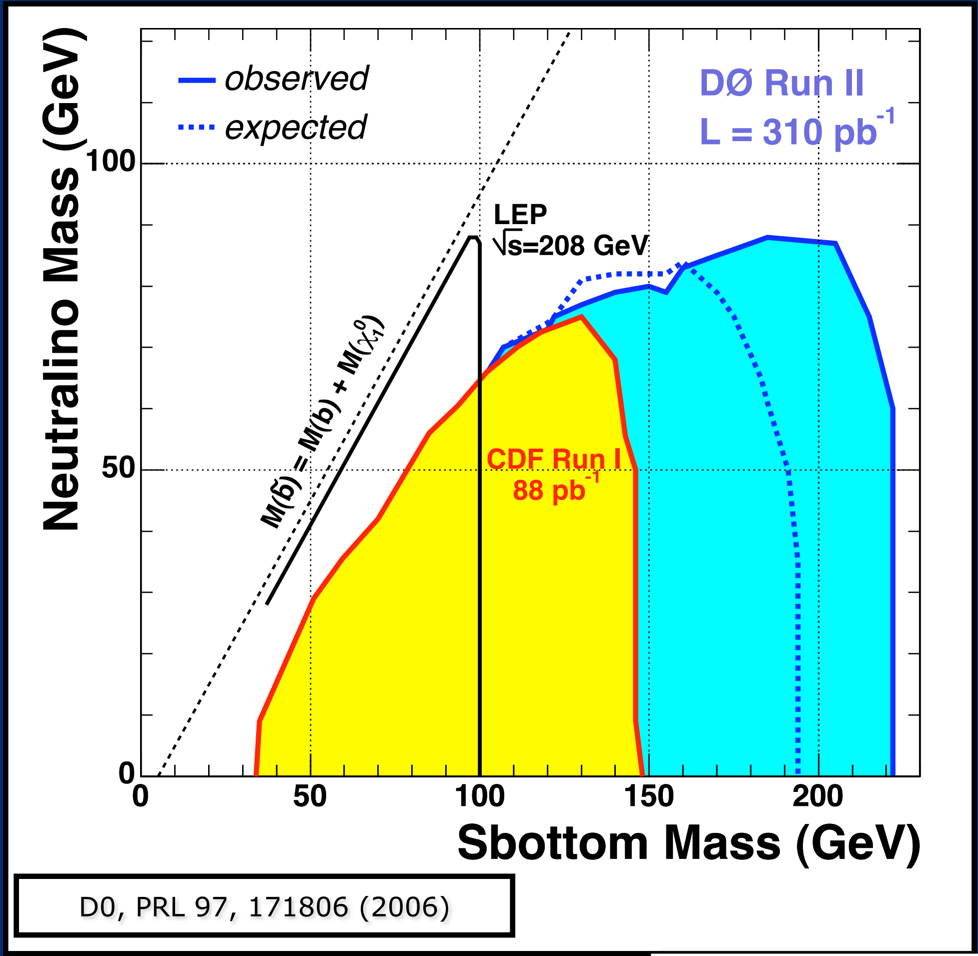
Collider Signatures:

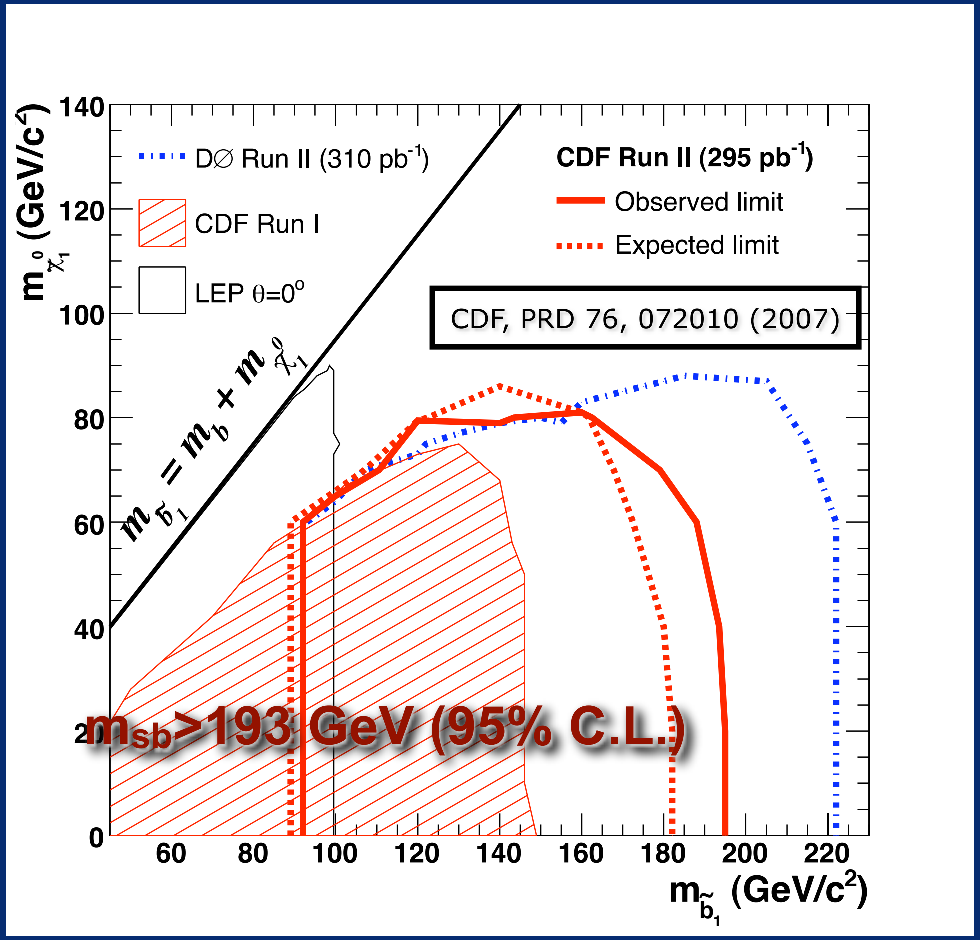
B'B' --> bXbX
T'T' --> tXtX

Alwall, Feng, Kumar, Su 1002.3366

Sbottom Searches

B'B'→bbXX is similar to sbottom pair production with sbottom -> bottom neutralino.

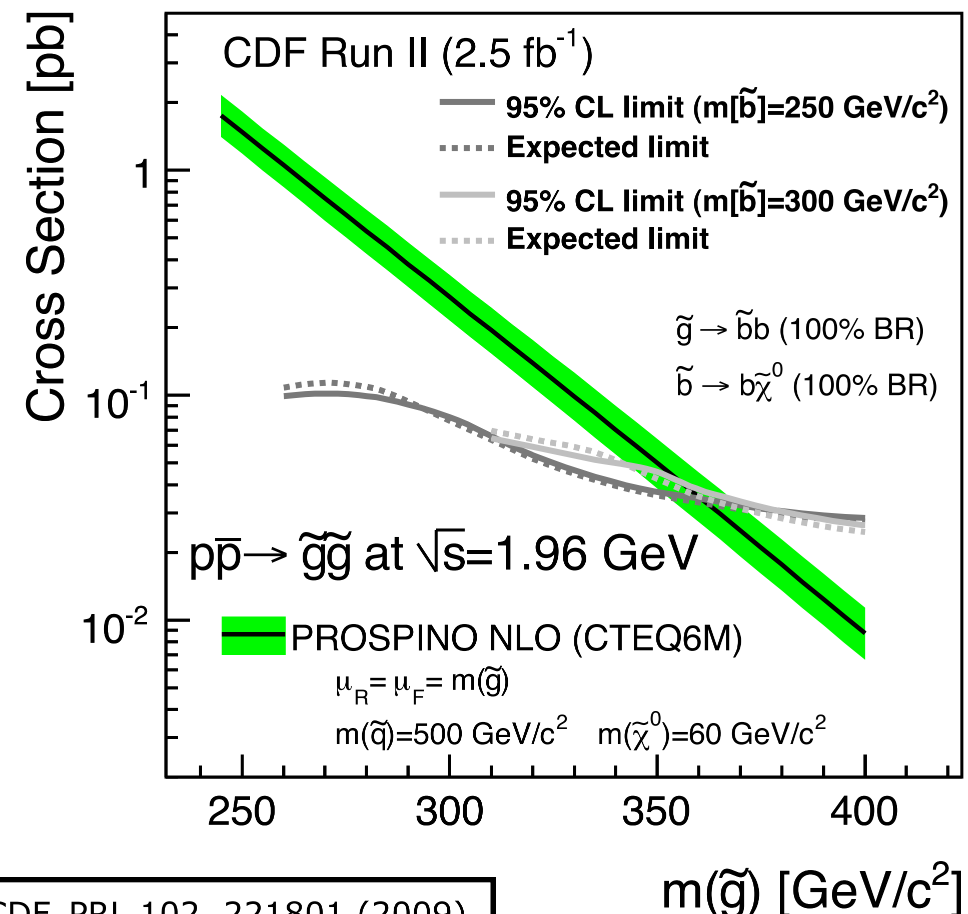




Alwall et al translate these into mB' > 330 GeV

Gluino Searches

- There is also a higher luminosity CDF search for gluinos which decay via sbottoms into 2 hard b-jets and missing energy.
- The CDF search is sufficiently inclusive that the B'B' signal can pass the cuts.
- Alwall et al translate these bounds into mB' > 370 GeV.



CDF, PRL 102, 221801 (2009).

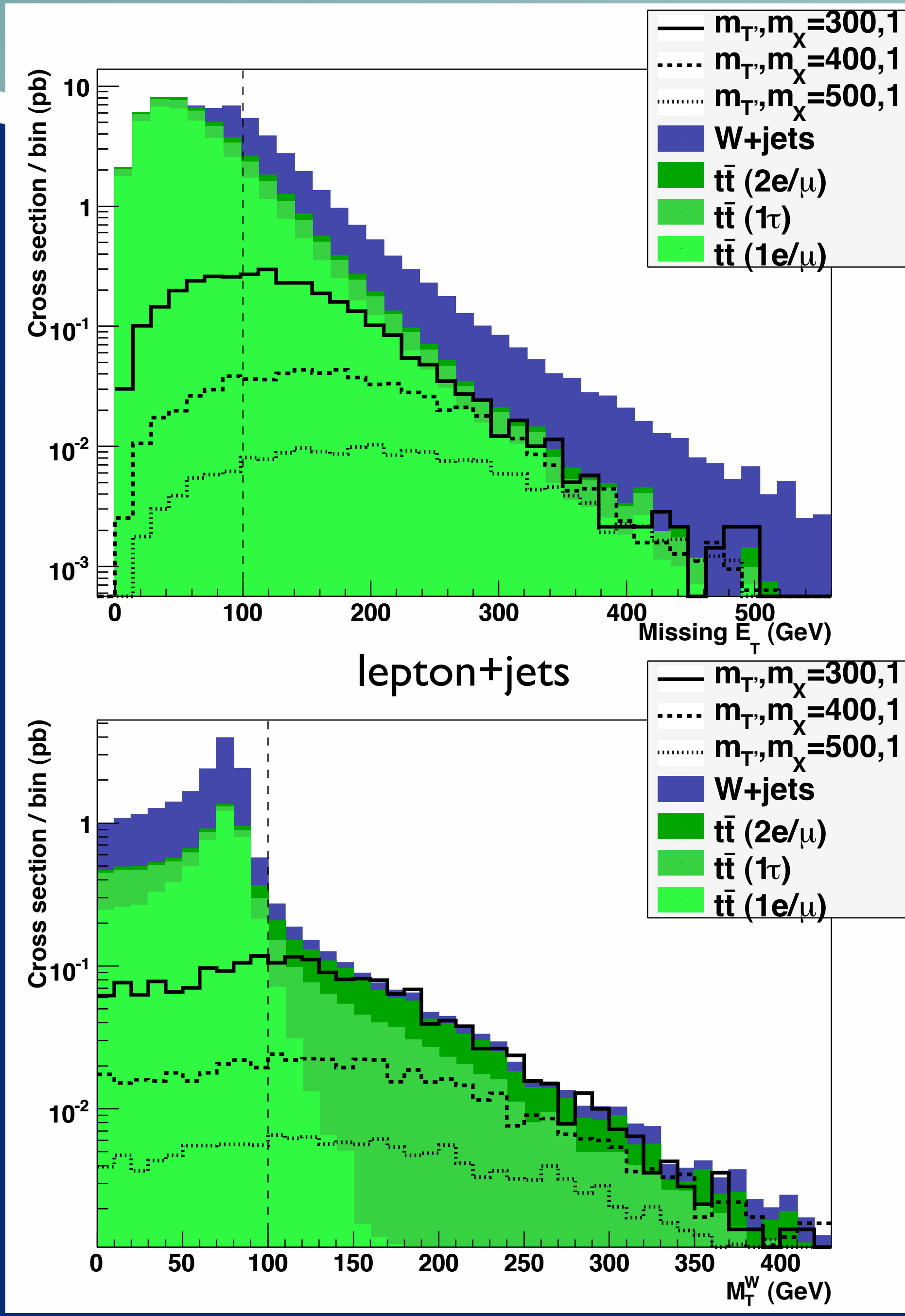
Early LHC Prospects

Alwall, Feng, Kumar, Su 1002.3366

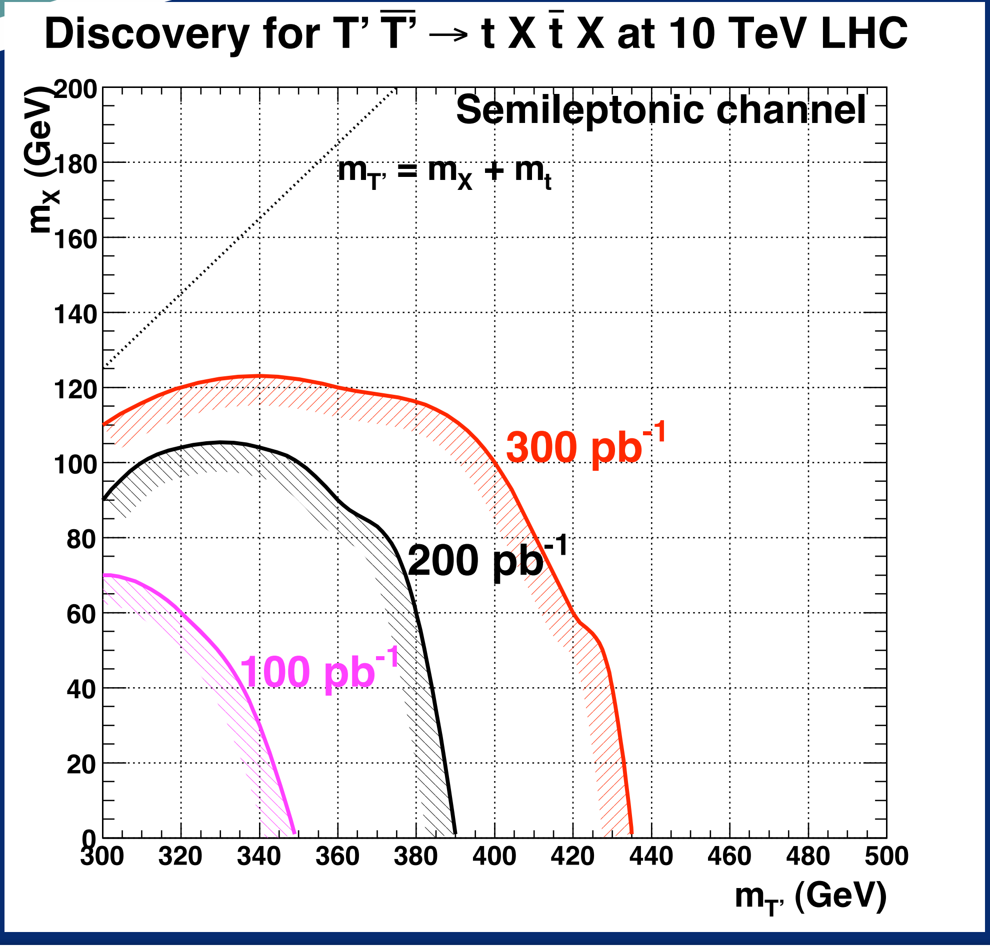
- Early LHC in this case means 10 TeV and ~300 pb-1.

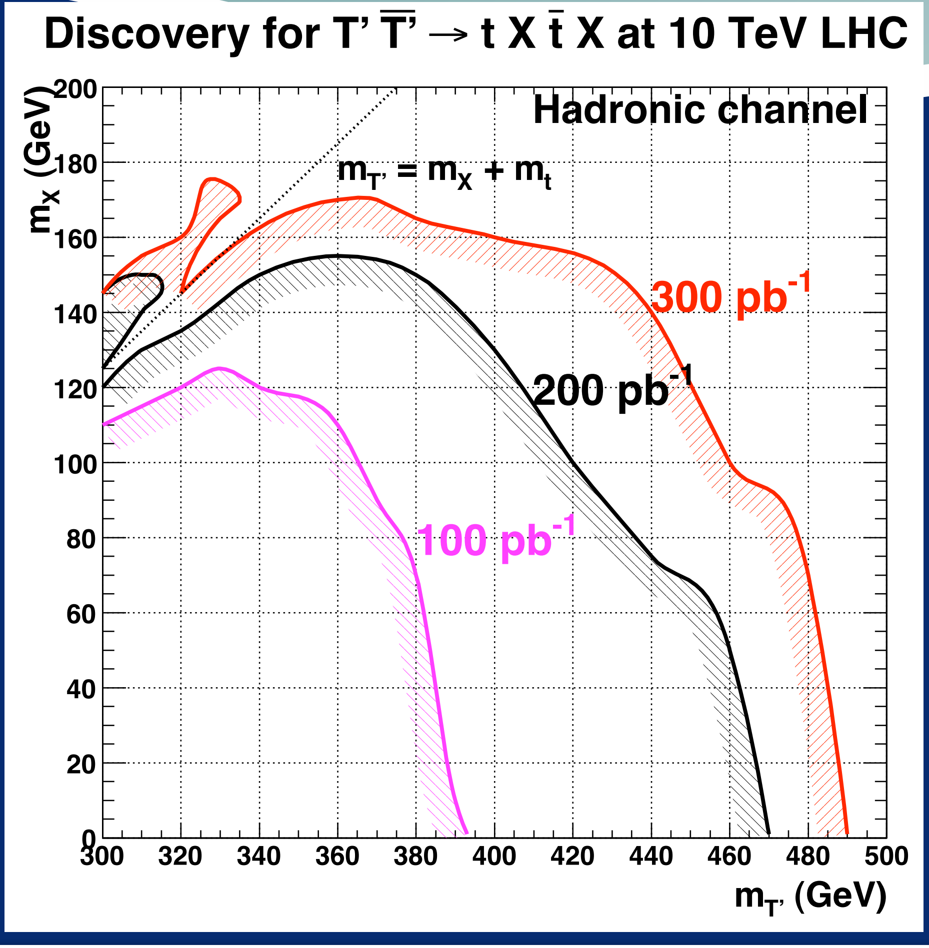
$$T'\bar{T}' \to t^{(*)}X\bar{t}^{(*)}X \to bW^+X\bar{b}W^-X$$

- T' pair production produces top pairs and missing energy.
  - Both all-hadronic and lepton+jets top (pair) decays are considered.
  - The dominant background is t tbar itself. Stiff cuts on the missing transverse energy help a lot in extracting the signal.



3σ LHC Reach



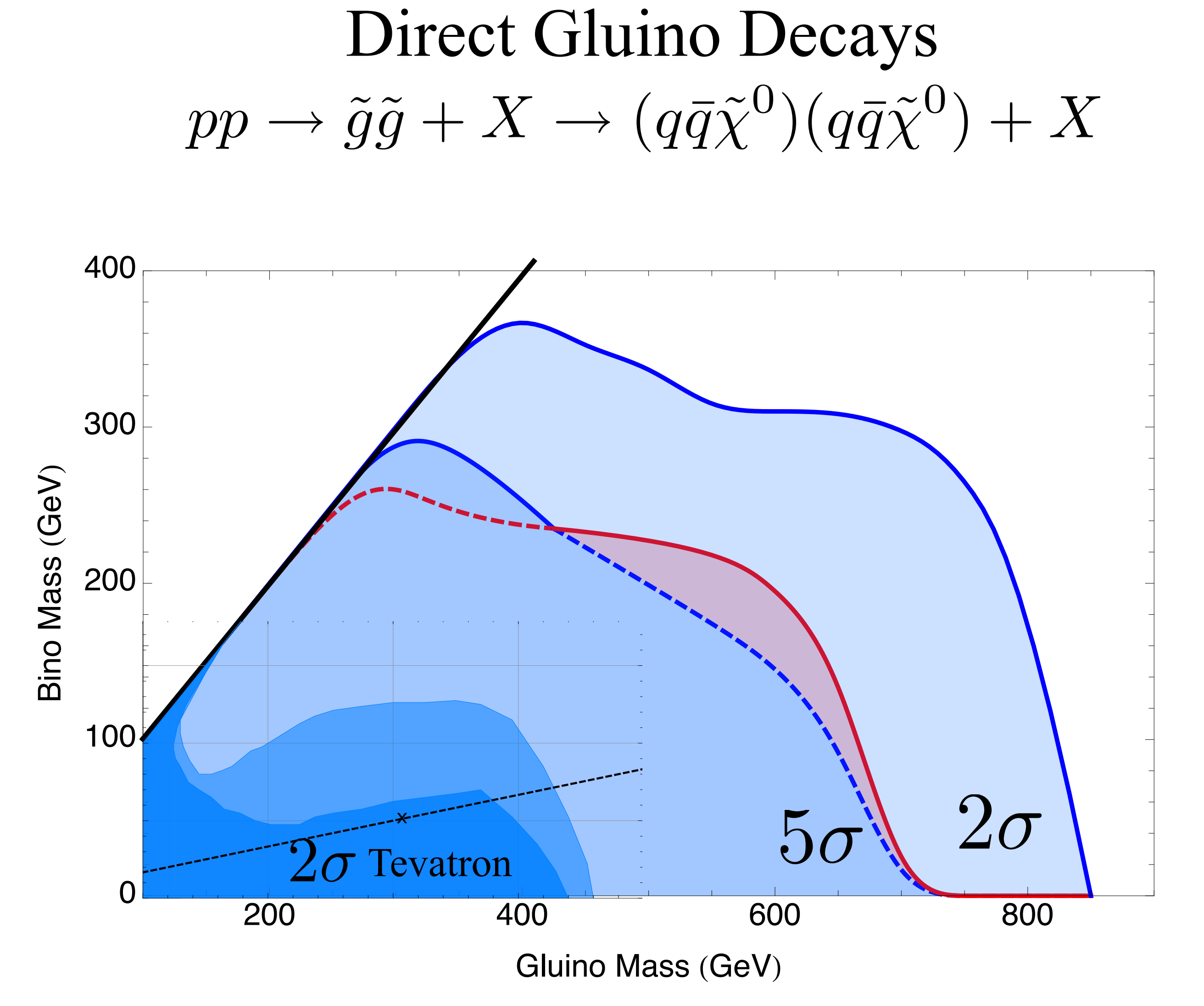


From a talk at GGI by S. Su: For LHC @7TeV, *same reach for 3 x Luminosity.*

Some window for an early observation even post Tevatron.

Jets + Missing Energy

- For large color charged objects (gluinos!) decaying into jets and missing energy, there is reach at 7 TeV!
- The reach depends sensitively on the parent mass (which controls the over-all rate) and the mass splitting with the neutral state (controls the missing energy).



Izaguirre, Wacker, to appear soon

Thanks Jay!

Outlook

- There is still much to do to make the most of the 7 TeV LHC run. Most studies still only exist for 14 TeV. The lower energy studies tend to focus on 10 TeV.
- Some work has been done on 7 TeV, and I expect this to continue. It would be great to gather the 7 TeV material -- I am sure there is quite a bit of which I am just unaware exists.
- There *are* prospects for BSM physics at 7 TeV and 1 fb^{-1}:
  - Z's
  - Diquark resonances
  - Pairs of colored particles -- at least for some masses!
- We have to get (a little) lucky, but nature could easily surprise us!

Bonus Material

Bonus Material

In the likely event that I have some extra time, I thought to tell you about some other LHC-related from UCI:

“Model-independent Collider Limits on Majorana WIMPs”

Beltran, Hooper, Kolb, Krusberg, TT, 1002.4137

Goodman, Ibe, Rajaraman, Shepherd, TT, Yu, 1005.1286

Model-independent Limits on Majorana WIMPs using EFTs

- I'll focus on the case in which the (Majorana) WIMP is the only accessible new physics to a given experiment -- A "Maverick" particle.
- WIMPs interact with SM through higher dimensional operators.
- For both colliders and direct detection, the most relevant operators are the ones which connect WIMPs to quarks or gluons.
- This limits the leading operators of interest to the set of 10 which preserve Lorentz and gauge invariance. (Others can be Fierz'd into this form).
- We assume MFV; leading terms in vector operators are universal and scalar operators are proportional to quark masses.

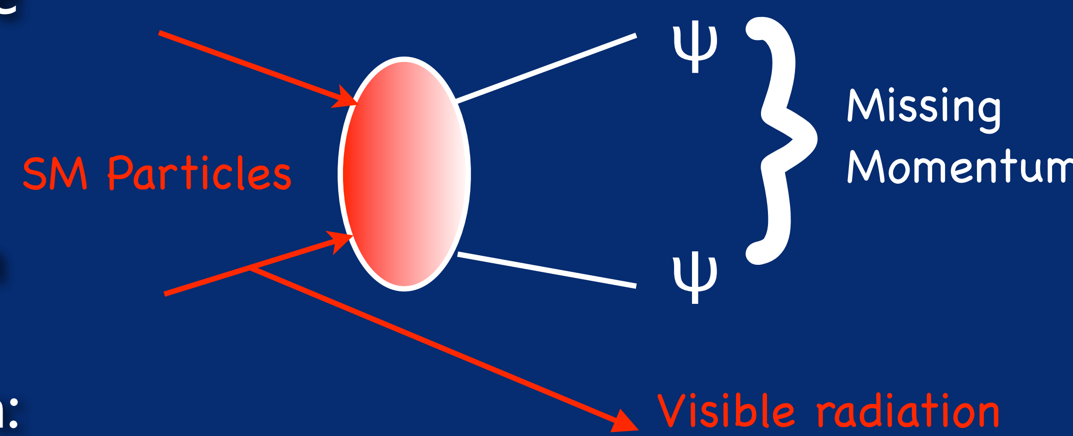
Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$\sum_q [\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

$$[\bar{\chi}\Gamma^\chi\chi]\,G_{\mu\nu}G^{\mu\nu}$$

Jets + Missing Energy

- The collider signature is one or more hard jets recoiling against the WIMPs -- "Nothing" as far as a collider detector is concerned.
- To place bounds, we compare with a CDF monojet search which was aimed at ADD graviton production:
  - Leading jet PT > 80 GeV
  - Missing ET > 80 GeV
  - 2nd jet allowed PT < 30 GeV
  - Veto more jets PT > 20 GeV
  - Veto isolated leptons with PT > 10 GeV.

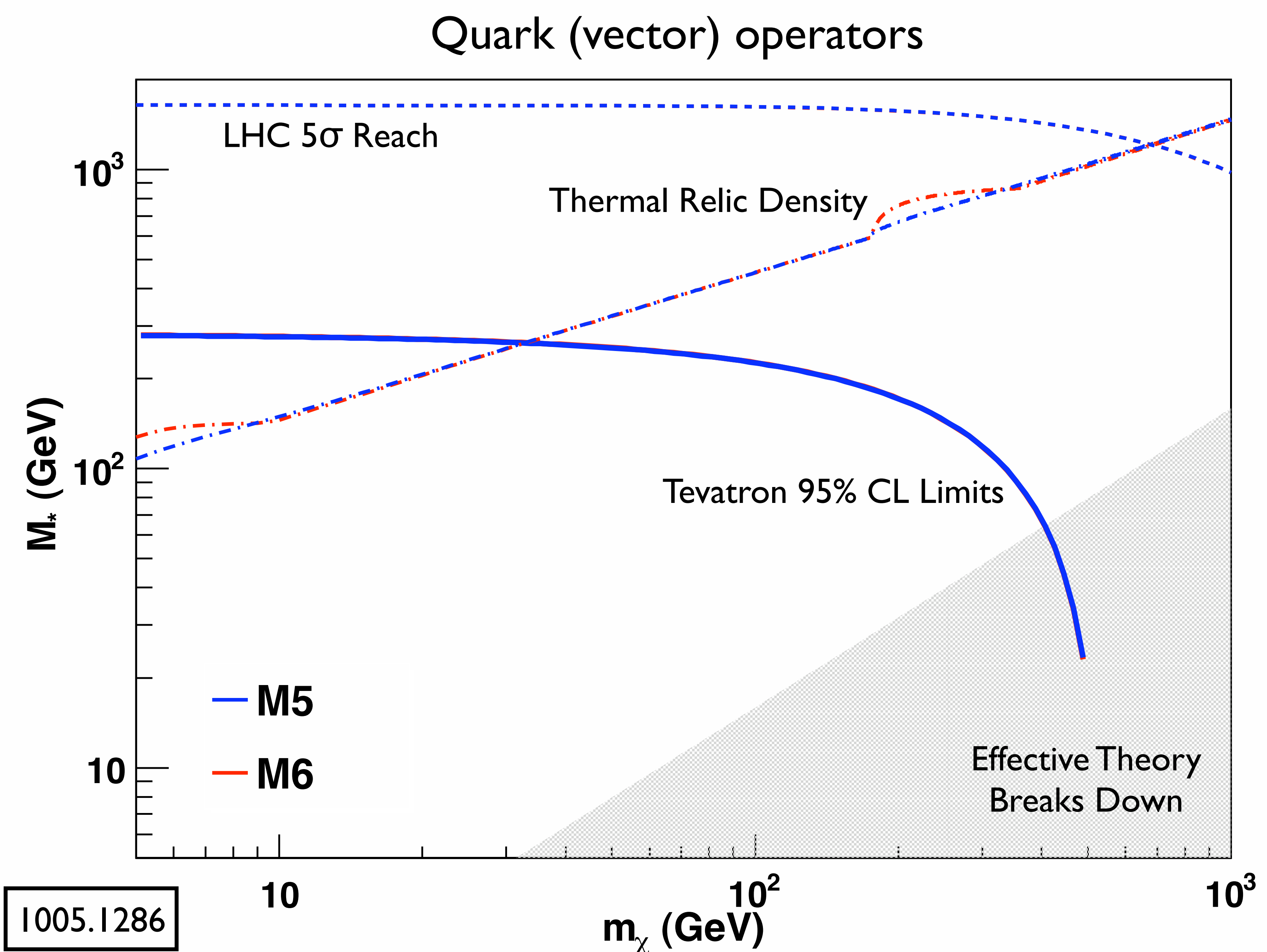


Based on 1 fb^{-1}, CDF constrains new physics (after cuts) $\sigma < 0.6$ pb.

CDF, 0807.3132
http://www-cdf.fnal.gov/physics/exotica/r2a/20070322.mono_jet/public/ykk.html

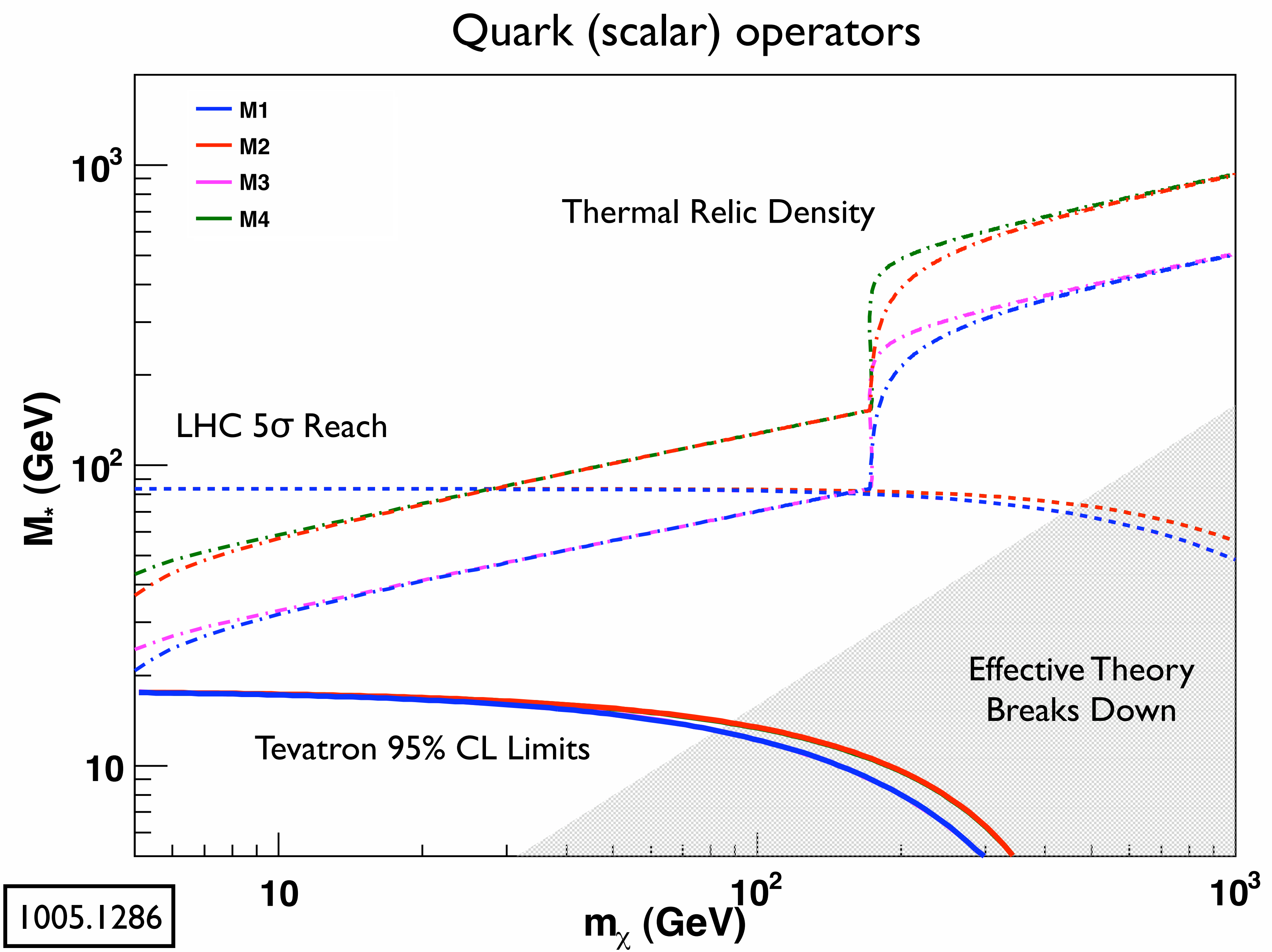
Limits/Sensitivity

LHC bounds for 14 TeV, 100 fb^{-1}, Sorry...



1005.1286

Limits/Sensitivity



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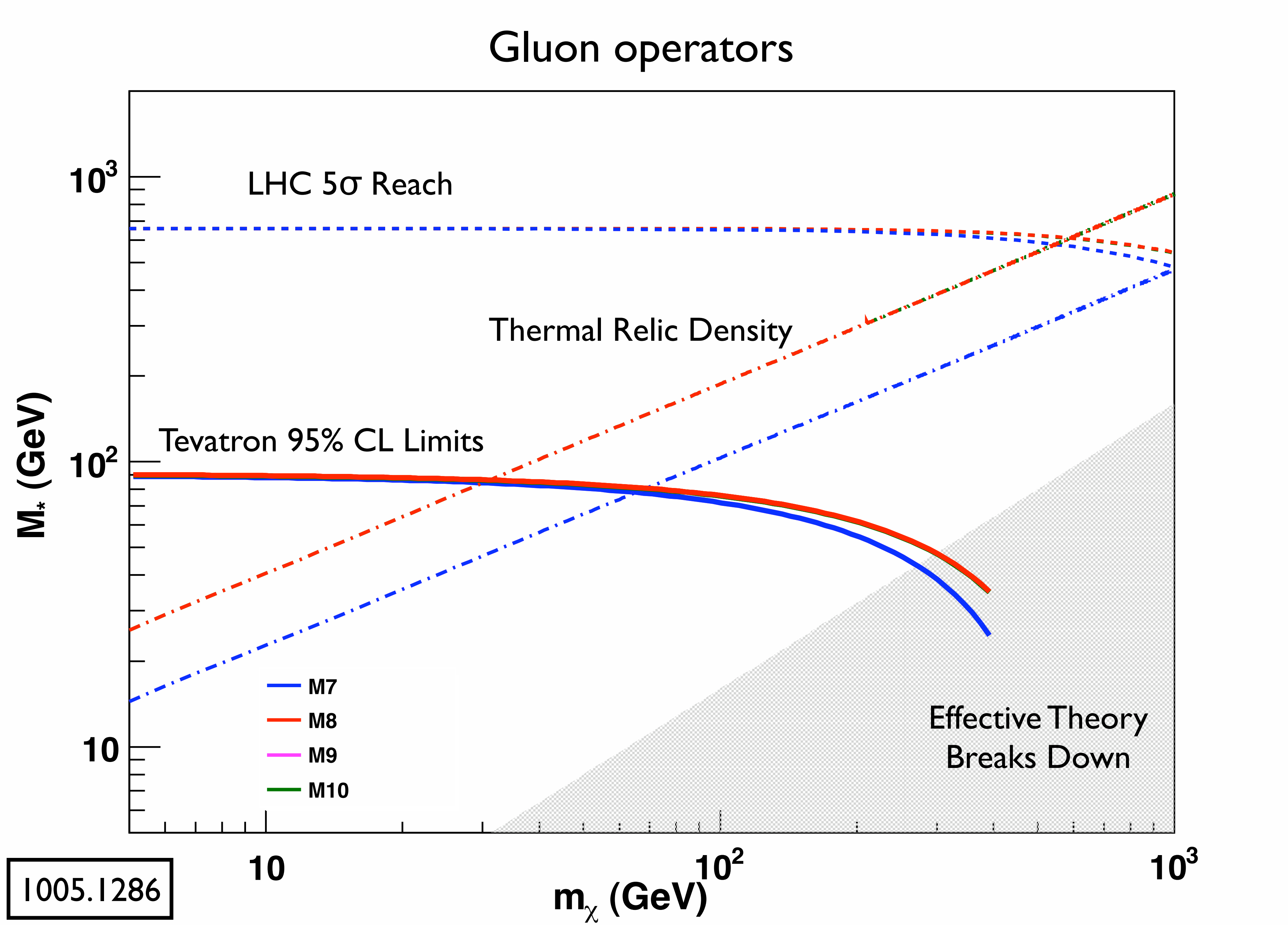
Limits / Sensitivity



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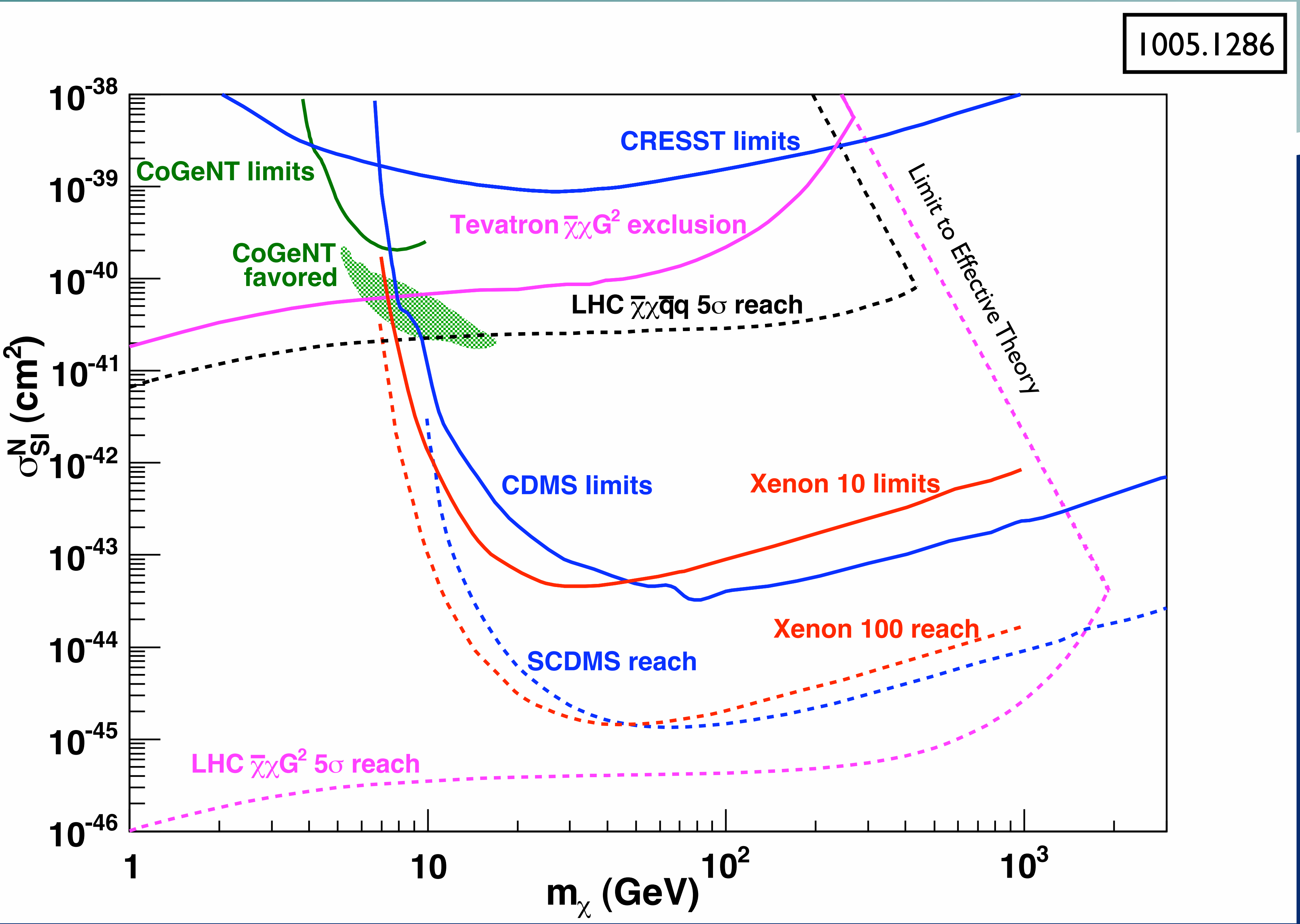
Direct Detection

- Our operators can also be translated into direct detection experiments.
- Only three operators contribute to non-relativistic WIMP scattering with a heavy nucleus.
  - Two operators potentially contribute to spin-independent scattering.
  - One operator potentially contributes to spin-dependent scattering.
- We follow the usual procedure and quote WIMP-nucleon cross sections. In terms of M_* we have:

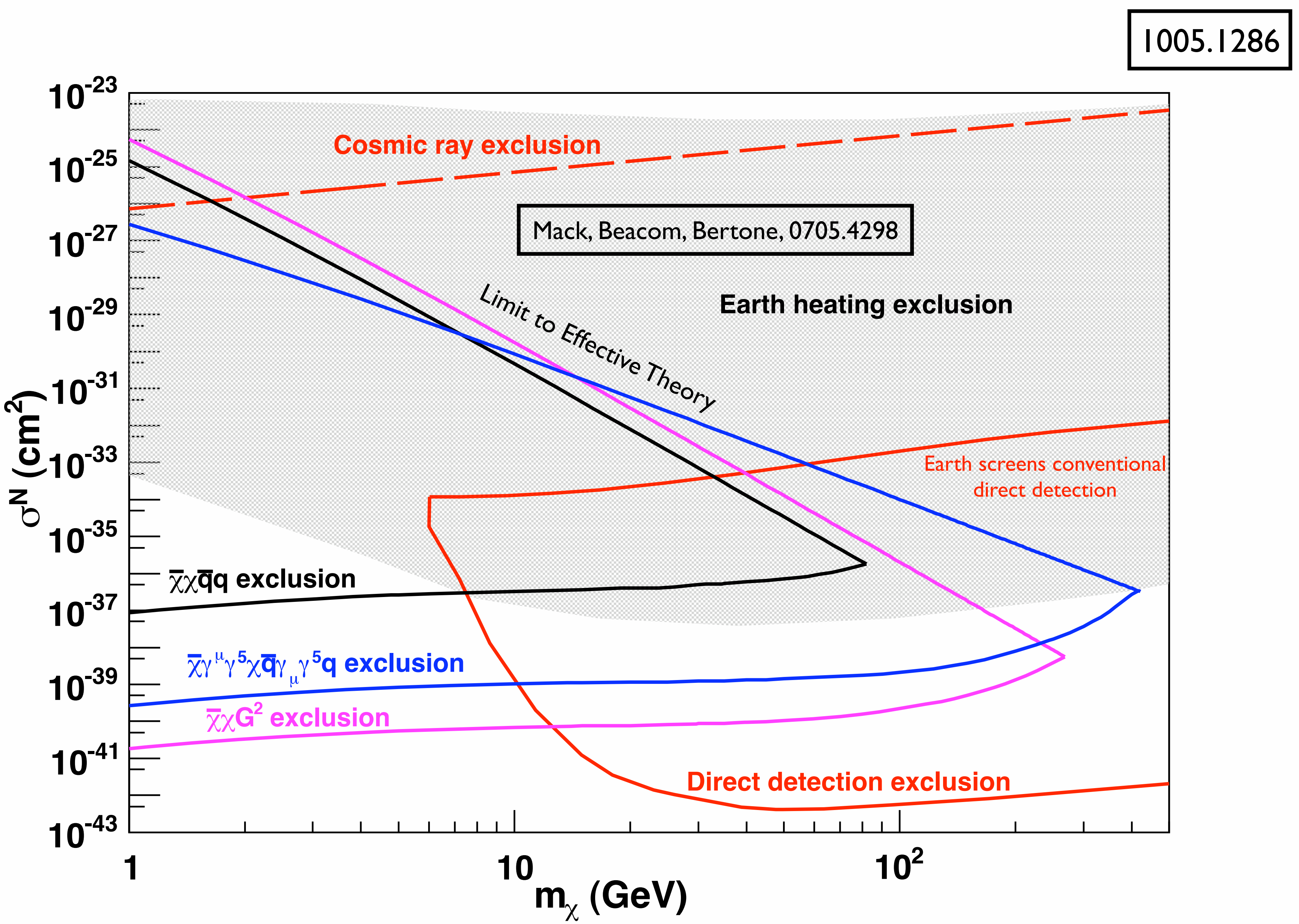
$$\sigma^N_{SI;M1} = \frac{4\mu_\chi^2}{\pi}\left(0.082\ \mathrm{GeV}^2\right)\left(\frac{1}{2M_*^3}\right)^2 \qquad \sigma^N_{SD;M6} = \frac{16\mu_\chi^2}{\pi}\left(0.015\right)\left(\frac{1}{2M_*^2}\right)^2$$

$$\sigma^N_{SI;M7} = \frac{4\mu_\chi^2}{\pi}\left(5.0\ \mathrm{GeV}^2\right)\left(\frac{1}{8M_*^3}\right)^2$$

Spin-independent

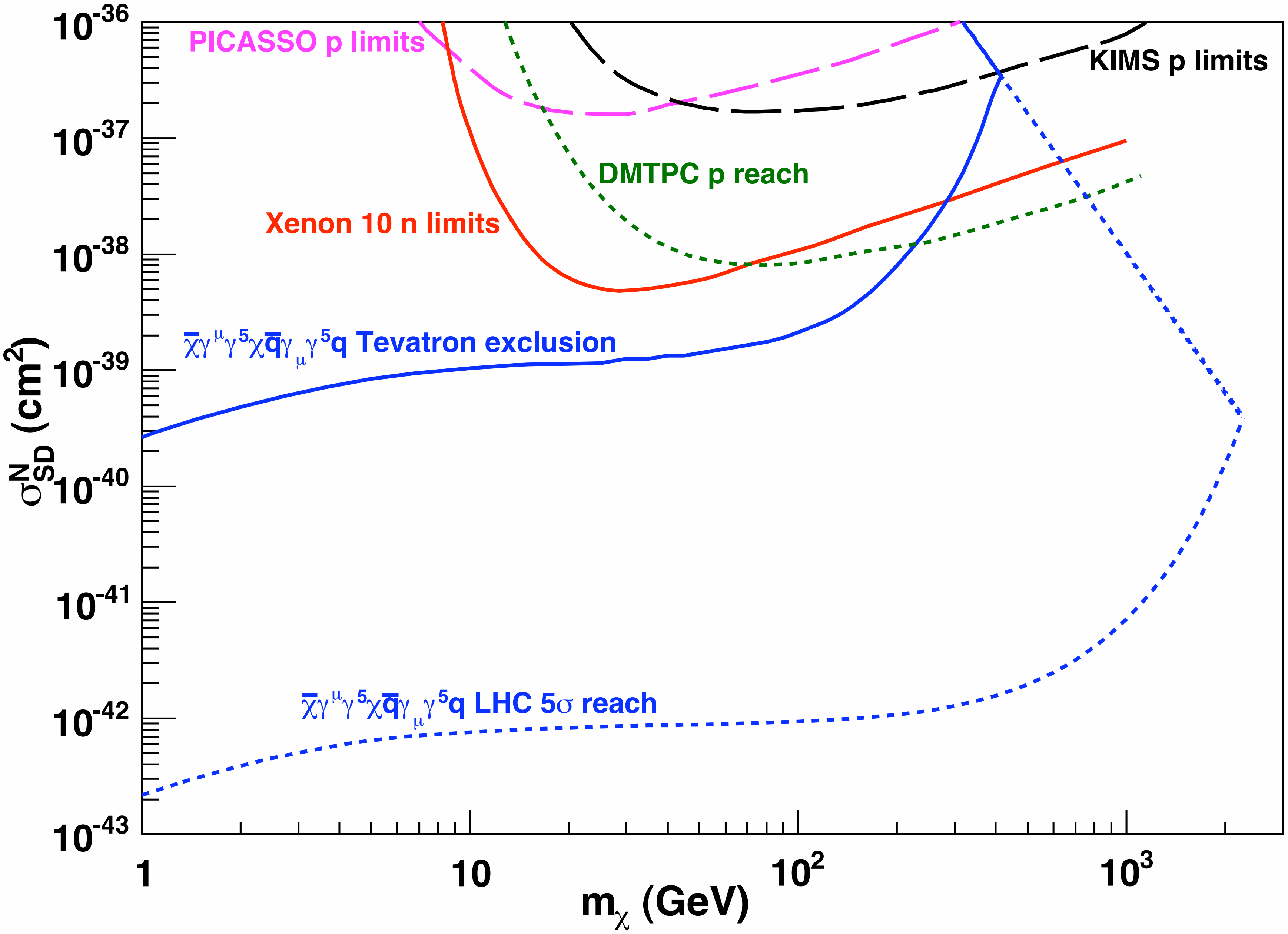


From WIMPs to SIMPs...



Spin-dependent

1005.1286

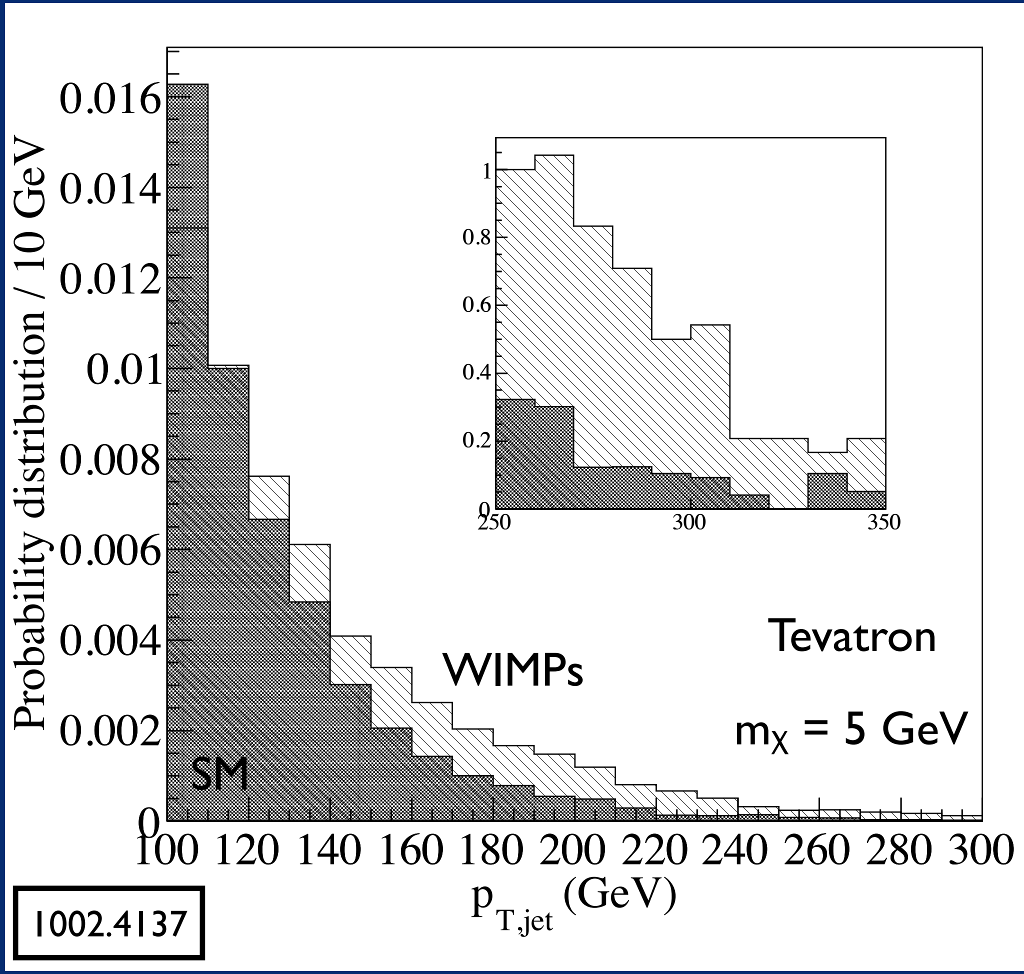


Comparison with CDF Study

- In 1002.4137 we were able to reproduce the backgrounds CDF found based on its own Monte Carlo simulations (improved with data):
  - The dominant background is Z + jets with the Z decaying into neutrinos.
    - Efficiencies from Monte Carlo, matched to Z + jet with Z decaying into leptons data (correcting for the branching ratios).
  - Next in importance is W + jets (where the charged lepton from the W decay gets lost).
    - Veto isolated ($\Delta R > 0.4$) leptons with PT > 10 GeV.
  - "QCD" background from mismeasured jets was negligible.
  - Theory uncertainties in background rates ~ %; (N)NLO rates available and LO rates are driven by quark PDFs.

Signal and Background

- At the parton level, there is a clear difference between the kinematics of the WIMP events compared with the SM backgrounds.
- The WIMPs are produced by higher dimensional operators, which grow with energy compared to the softer SM background processes.
- The harder spectrum is reflected in the PT of the associated jet(s), which must balance the WIMPs.

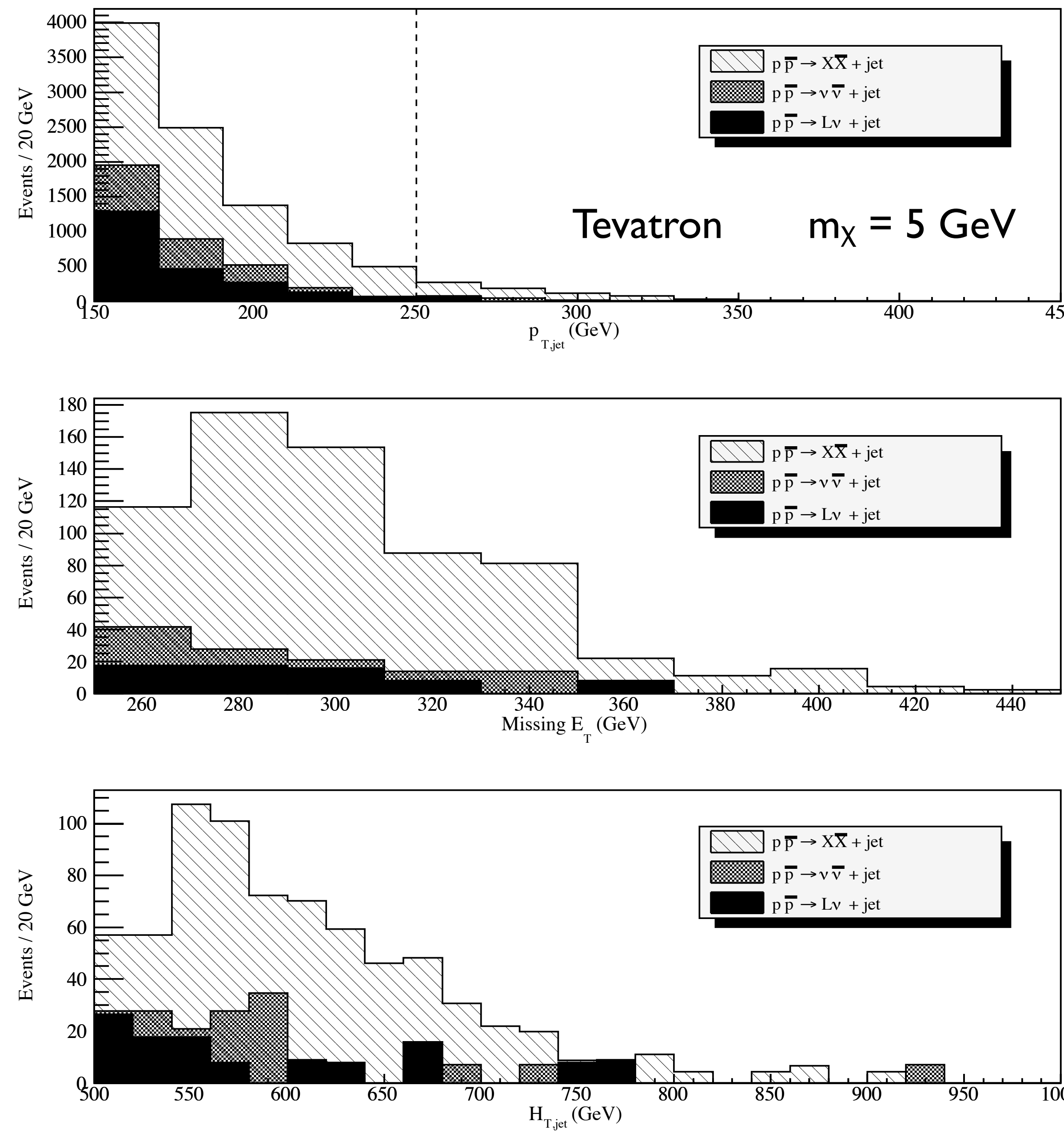


$$[\bar{\chi}\gamma^{\mu}\gamma_5\chi]\,[\bar{q}\gamma_{\mu}\gamma_5 q]$$

Beyond the Parton Level

1002.4137

- These differences survive parton showering and hadronization (simulated by PYTHIA) and detector response (simulated by PGS in its default Tevatron detector model).
- Our detailed study suggests that one can probably optimize a search and do better than the CDF monojet search aimed at Large Extra Dimensions.



LHC

- To estimate the LHC sensitivity we rely on the ATLAS search for jets + missing energy:

  Vacavant, Hinchliffe, J Phys G 27, 1839 (2001)

  - Missing ET > 500 GeV
- Vetoing extra jets is counter-productive at the LHC.
- Since we are interested in the eventual reach of the LHC, we assume 14 TeV and 100 fb^{-1}.
- It would be interesting to see what the LHC can say for 7 TeV and ~ 1 fb^{-1} -- it is probably non-trivial!

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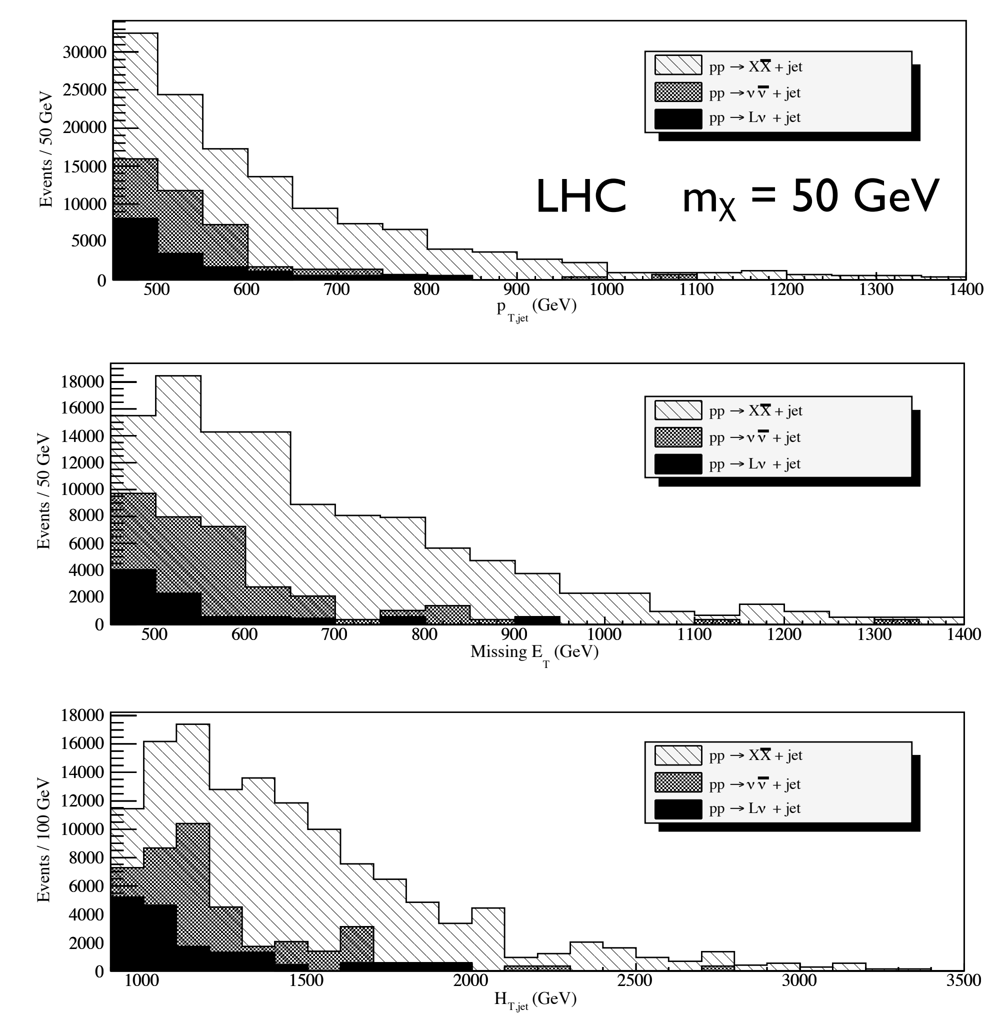
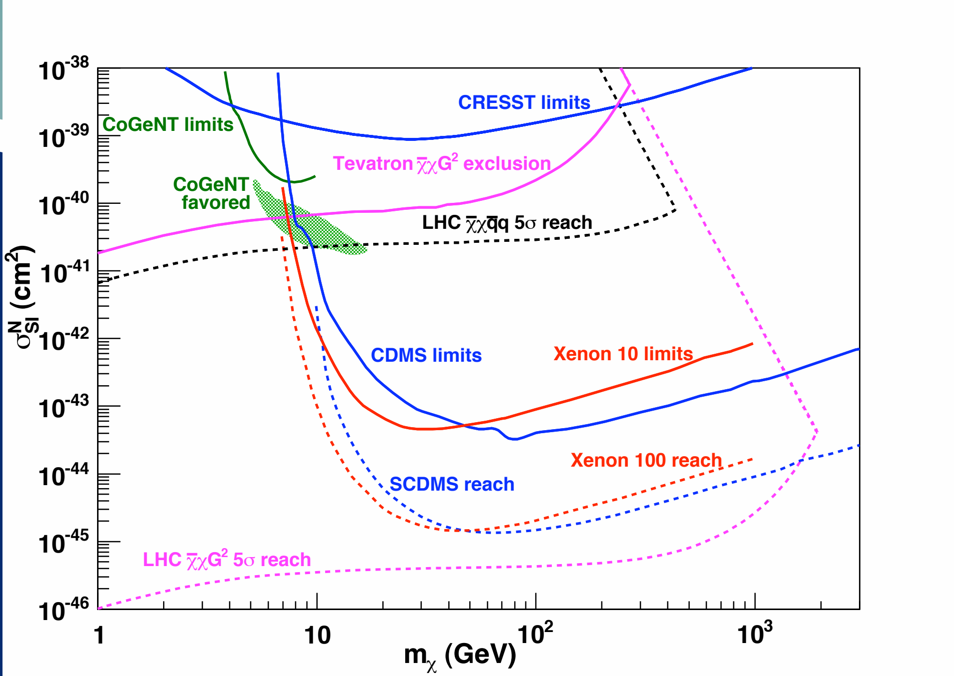
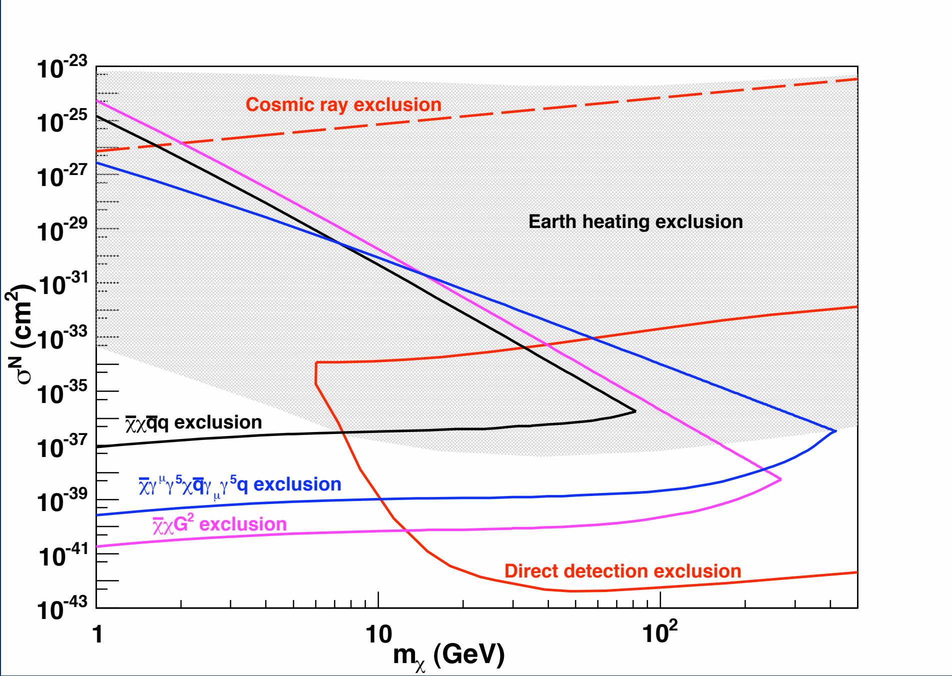


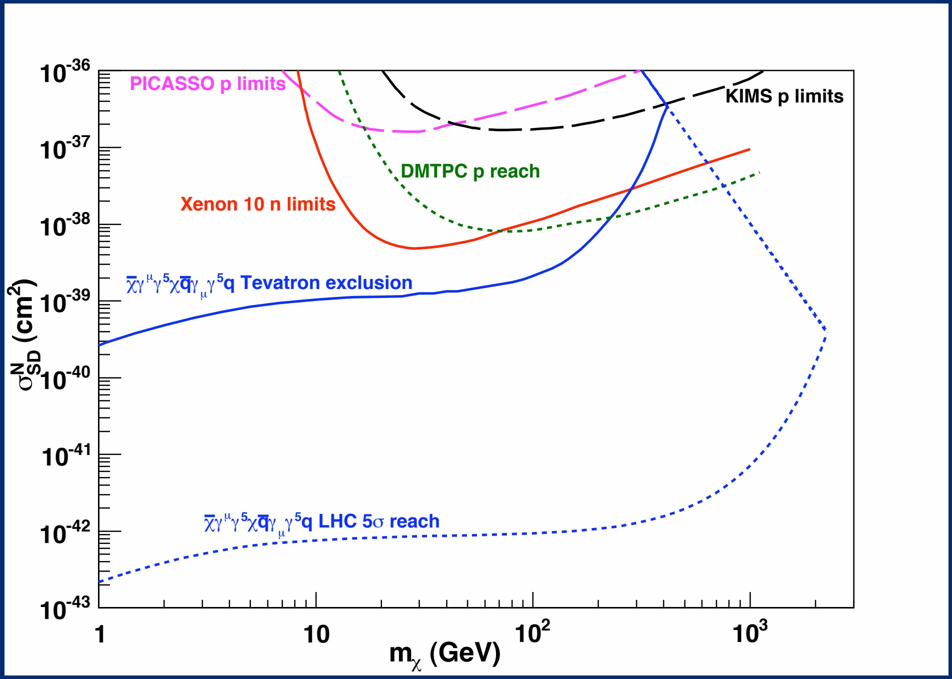
Collider/Direct Synergy

- For operators leading to spin-independent scattering, colliders and direct searches show a lot of complementarity.
  - Colliders win at low WIMP masses and for gluon interactions.
  - Direct detection can reach much lower cross sections for quark-scattering at ~100 GeV masses.
  - Tevatron already says something about the DAMA/CoGeNT low mass region; LHC will say a lot.
  - Not shown: Xenon100 low mass analysis.





- Colliders already do an excellent job for spin-dependent scattering WIMPs.
  - Tevatron limits are better than existing or near future direct limits, except at large masses.
- Generally, colliders easily handle even higher dimensional operators with more momentum dependence, because colliders are not energy limited except for large masses.



Outlook -- Collider DM

- Effective field theories can be used to study WIMP interactions, and provide a common language for direct, indirect, and collider searches.
- Colliders can provide interesting bounds on WIMPs. In this specific case, we have looked at theories where bounds don't originate from production of some exotic colored particle which decays into WIMPs.
  - Where this assumption does not hold, bounds could get stronger or weaker, depending on how one UV-completes the operator description.
- Already, Tevatron puts interesting constraints on spin-dependent interactions which are stronger than direct searches.
- LHC has a large degree of complimentarity with spin-independent searches.
- Together, direct, indirect, and collider searches offer a more complete picture of dark matter interactions with the Standard Model!