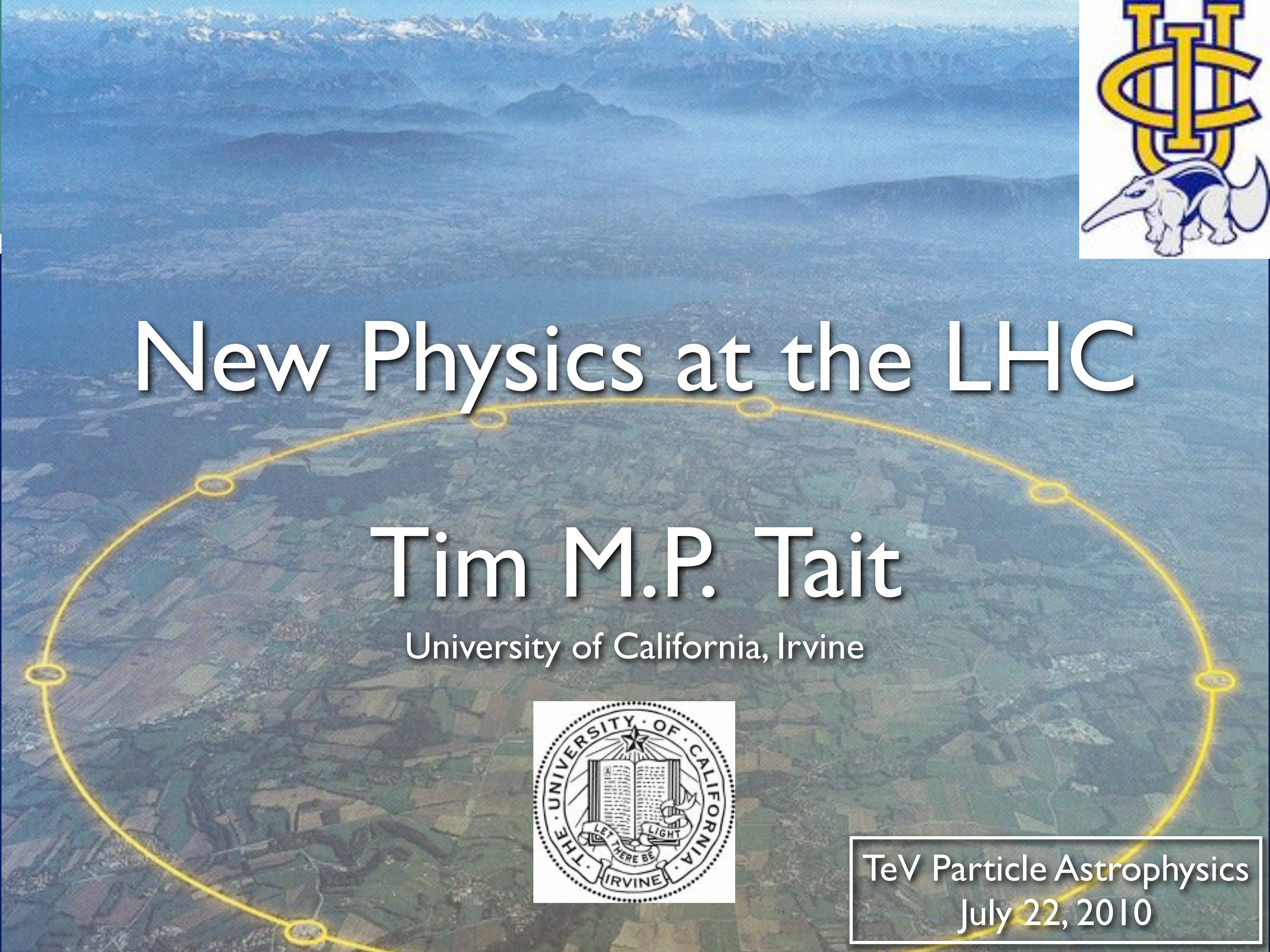


New Physics at the LHC

Tim M.P. Tait

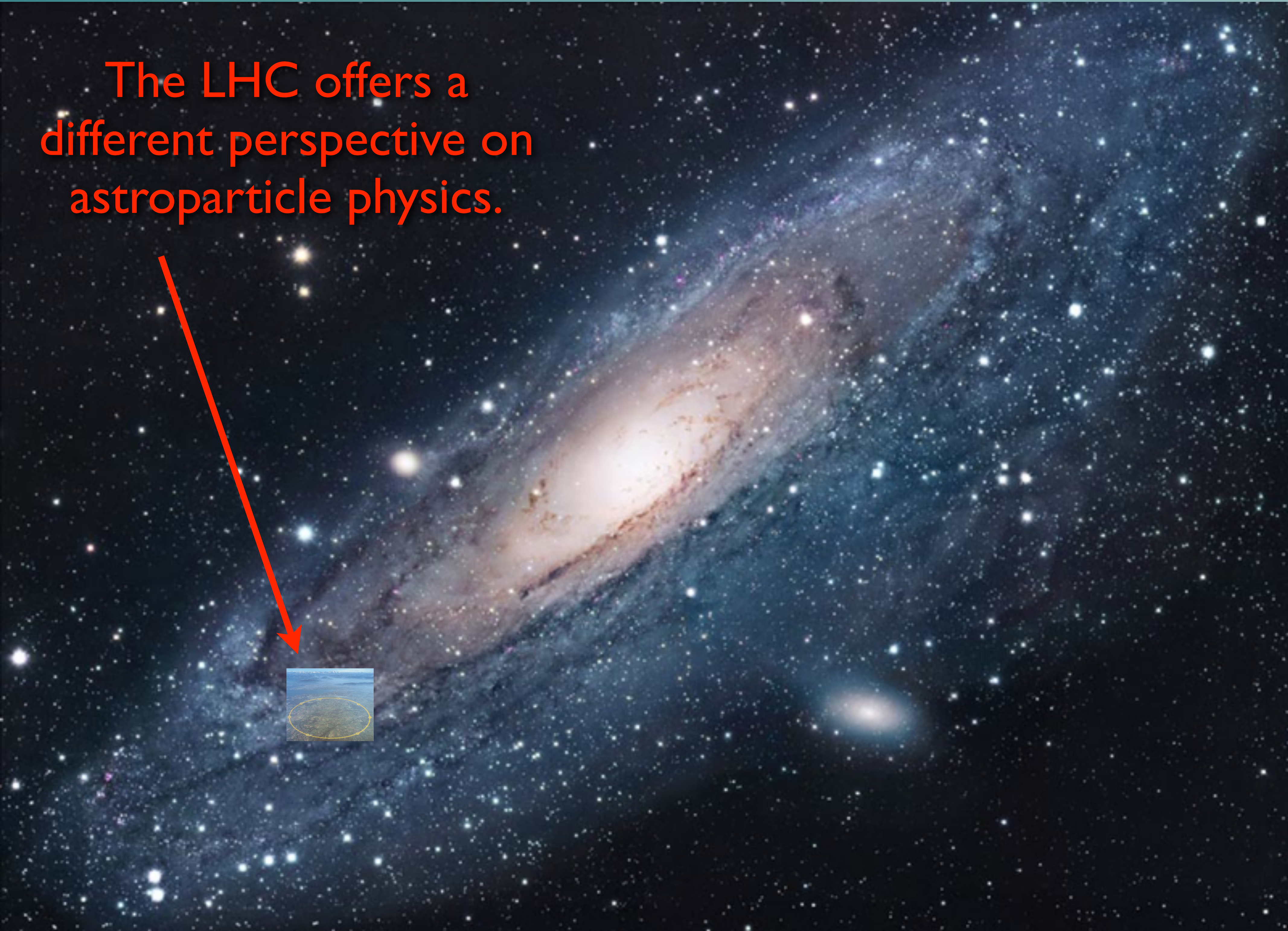
University of California, Irvine

TeV Particle Astrophysics
July 22, 2010

Disclaimer

- New Physics at the LHC is worthy of an entire conference. There is no way to do it justice in 35 + 5 minutes!
- My discussion will thus be incomplete, and I will try to focus on things that are of particular interest to TeV Particle Astrophysics.
- Apologies if I miss your favorite theories or signatures. I'd be happy to answer questions about them or discuss them afterwards as best I am able.

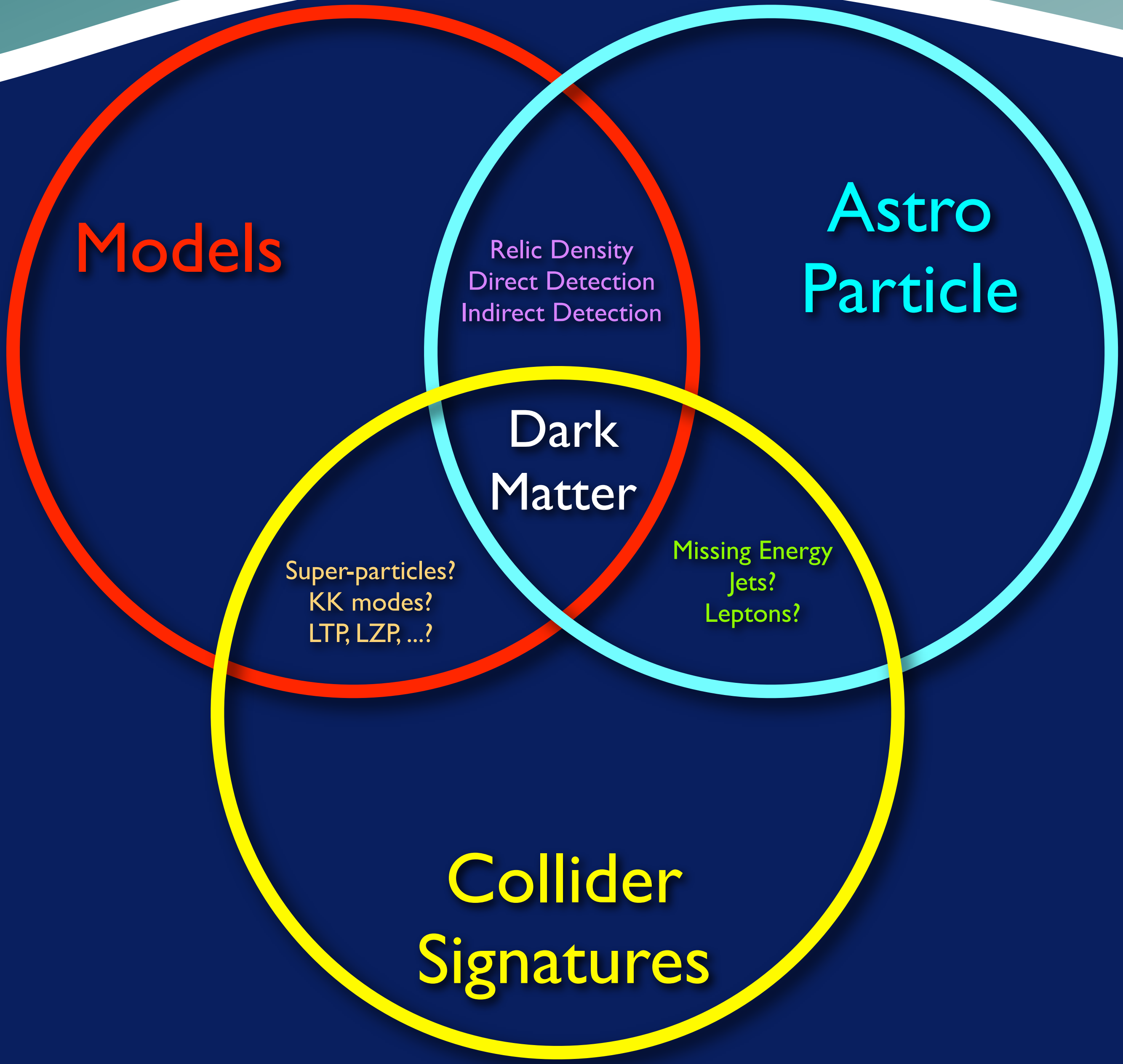
- I won't be covering the exciting current developments at the LHC. Andy Lankford will be showing us many of those results next.
  - This talk is a partial "roadmap" to possible LHC discoveries.



The LHC offers a different perspective on astroparticle physics.

...hopefully not this one...

Collider - Astro Synergy



Models

Astro
Particle

Relic Density
Direct Detection
Indirect Detection

Dark
Matter

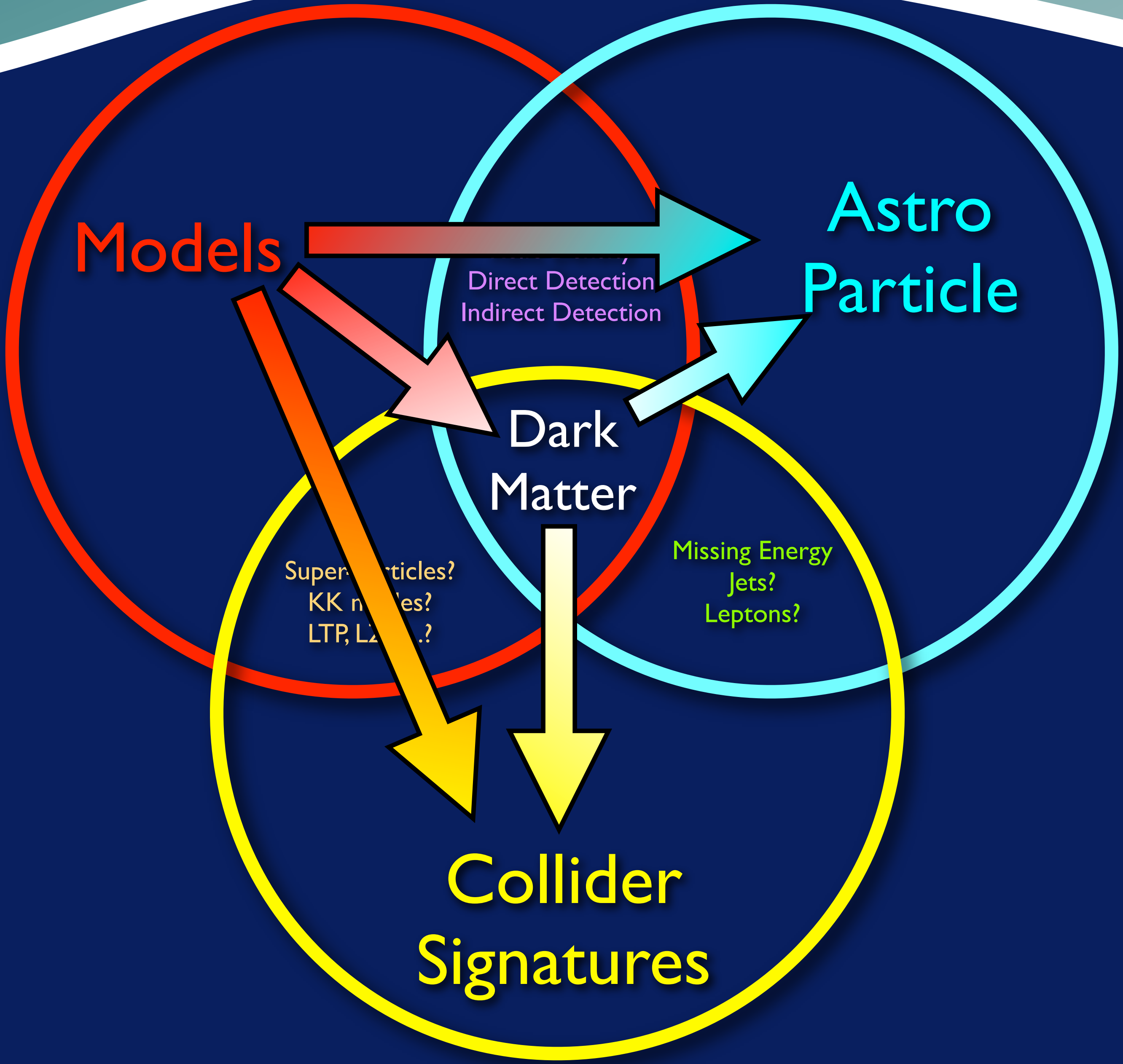
Super-particles?
KK modes?
LTP, LZP, ...?

Missing Energy
Jets?
Leptons?

Collider
Signatures

Dark Matter
as an Example

Historically Model-Driven



Models

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Direct Detection
Indirect Detection

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Super- rticles?
KK n es?
LTP, LZ .?

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Collider
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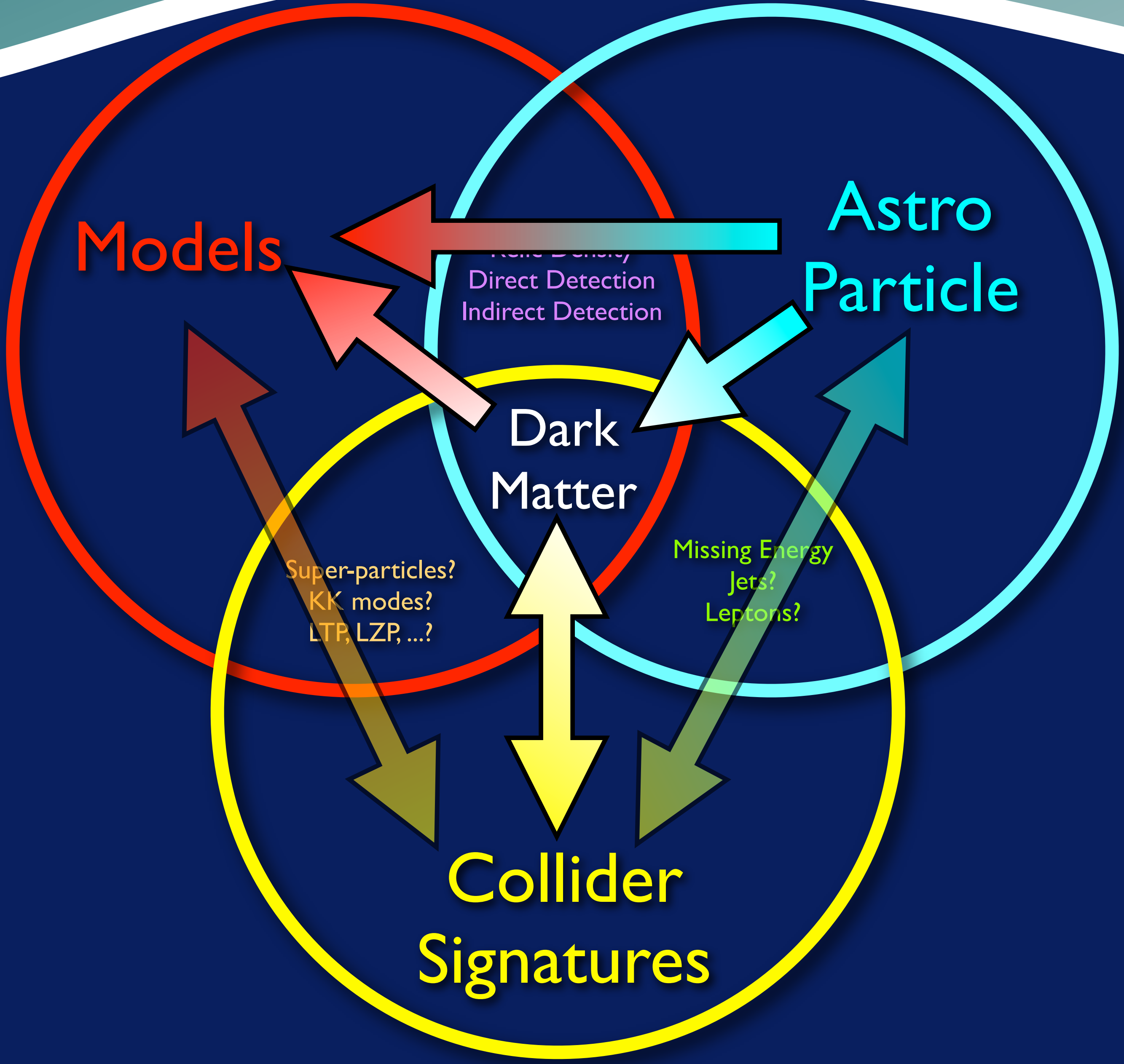
… but times are changing…



Models

Astro Particle

Relic Density
Direct Detection
Indirect Detection

Dark Matter

Super-particles?
KK modes?
LTP, LZP, …?

Missing Energy
Jets?
Leptons?

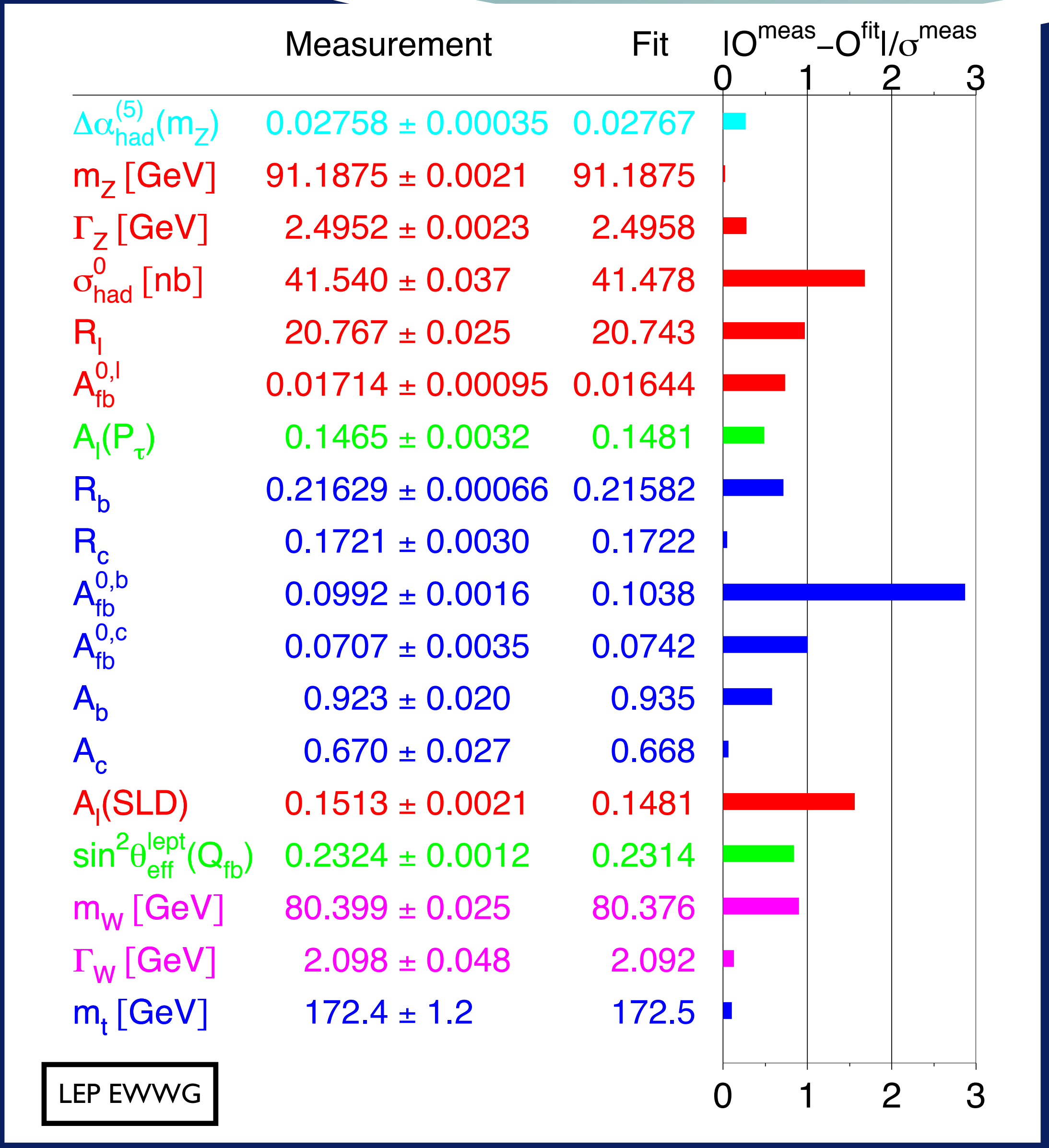
Collider Signatures

Models:

Problems with the Standard Model

The Standard Model works...

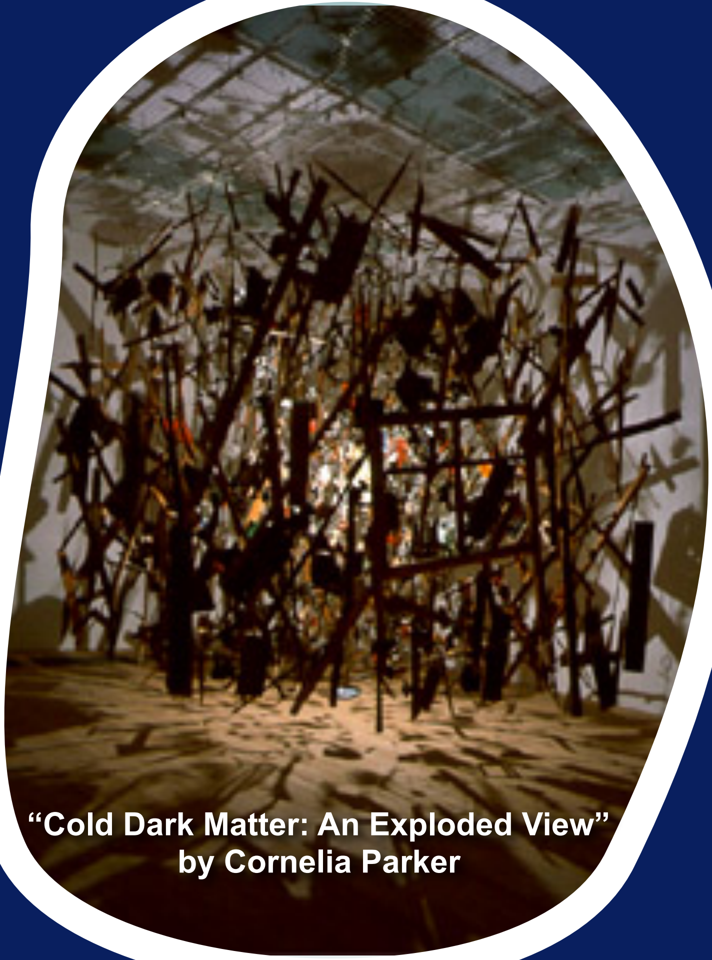
- Before talking about its faults, it needs to be said that the Standard Model **works**.
- In a global fit to data, a huge number of observables agree with predictions, some at the per mil level.
- Much of the precision inputs come from low energy measurements and physics at the Z pole from LEP/SLD.
- Important contributions (m_t, m_W, and α_S) from the Tevatron.



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4958
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01644
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21582
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.376
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	172.4 ± 1.2	172.5

The SM is missing...

- An experimental verification of the mechanism of Electroweak symmetry breaking.
  - An explanation for the Planck-Weak hierarchy...?
- A particle to play the role of dark matter.
  - Thermal relic? WIMP? ...?
- A dynamical explanation for the matter-anti-matter asymmetry of the Universe.
- Understanding of quark and neutrino masses and mixing angles (flavor).
- Unification of forces?
- A quantum formulation of Gravity.
  - String theory? M-theory?



"Cold Dark Matter: An Exploded View" by Cornelia Parker

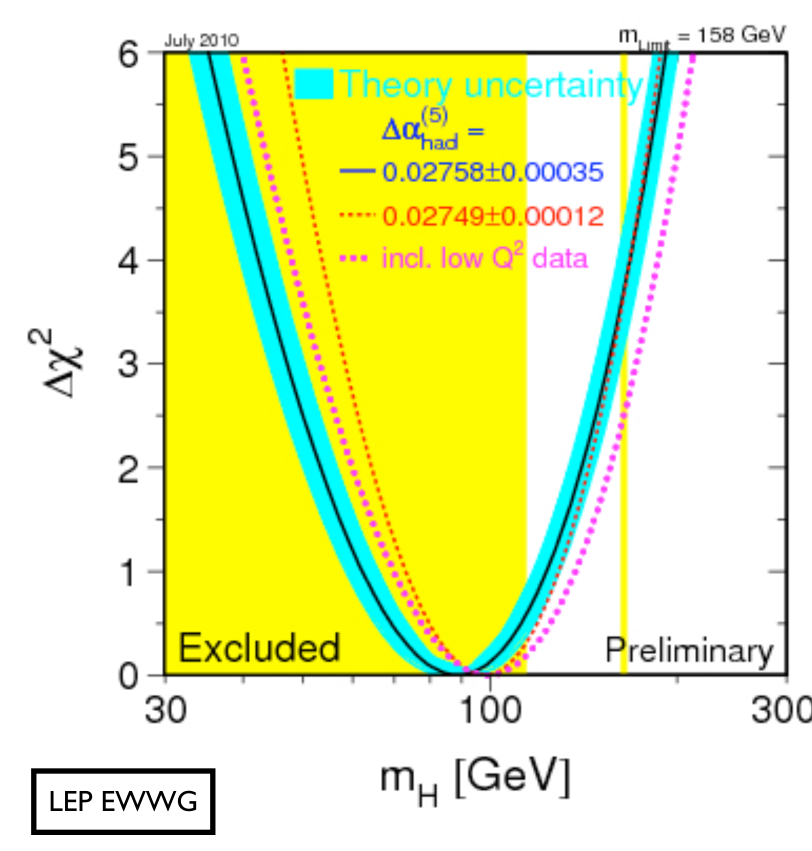
The SM is missing...

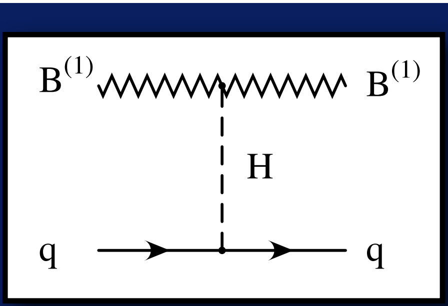
LHC Prospects:

The SM is missing...	LHC Prospects:
An experimental verification of the mechanism of Electroweak symmetry breaking. An explanation for the Planck-Weak hierarchy...?	Pretty sure thing.
A particle to play the role of dark matter. Thermal relic? WIMP? ...?	Good prospects.
A dynamical explanation for the matter-anti-matter asymmetry of the Universe.	There’s hope.
Understanding of quark and neutrino masses and mixing angles (flavor). Unification of forces?	If we’re lucky.
A quantum formulation of Gravity. String theory? M-theory?	If we’re REALLY lucky...

The SM Higgs

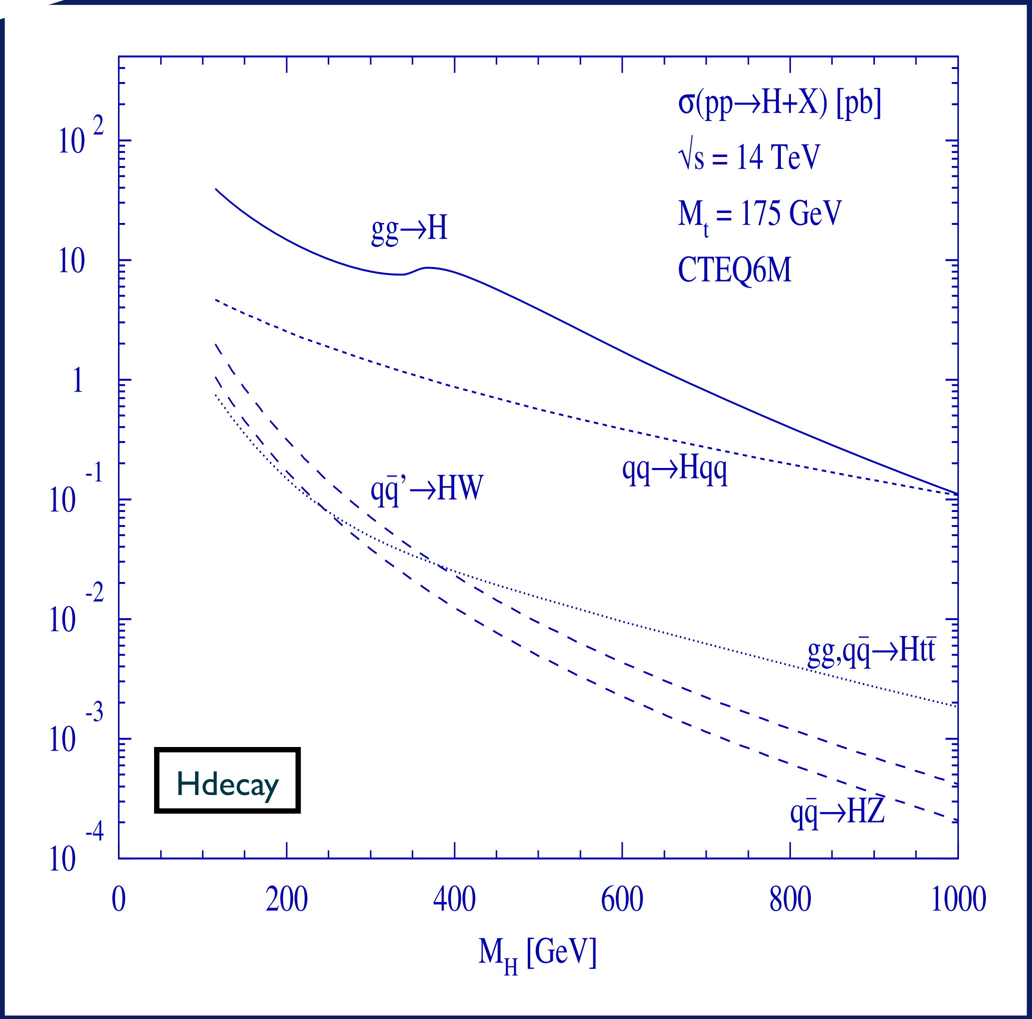
- Electroweak Symmetry-Breaking and the Higgs boson
  - A primary mission of the LHC is to verify the SM picture of EWSB.
  - The good EW fit to precision data does not rule out surprises. New physics can substantially affect the fit to the Higgs mass, so even discovering an ordinary Higgs heavier than about 200 GeV would tell us there is more to look for.
  - A Higgs can be an important messenger between WIMPs and the SM, and thus important to understand, e.g. predictions for direct detection rates.

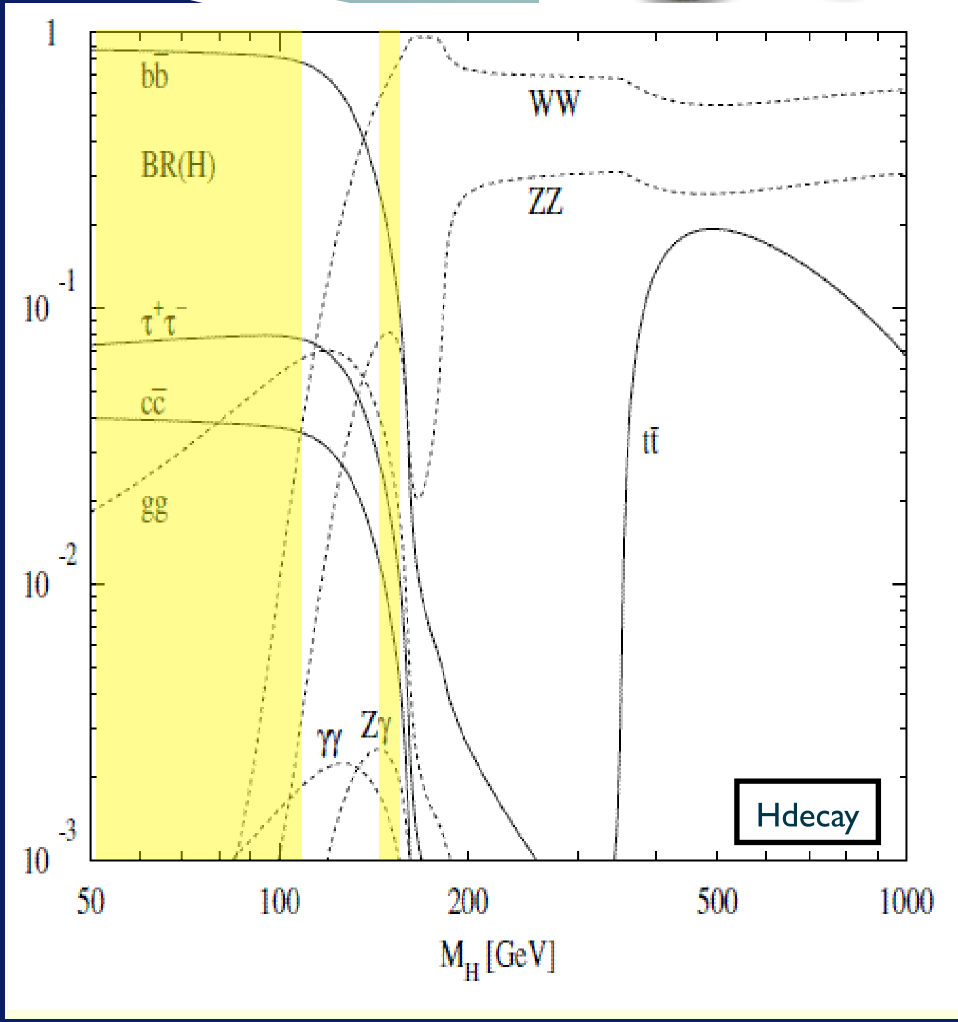




Standard Model Higgs

$9.75 + shipping

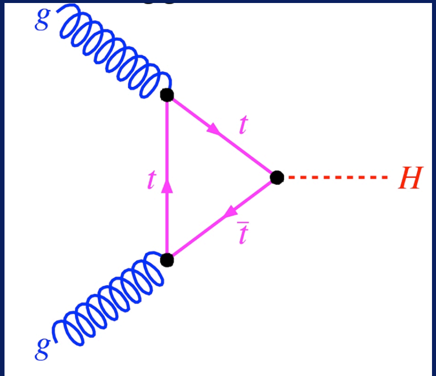


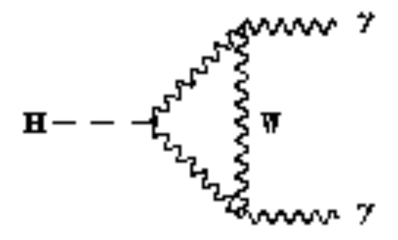


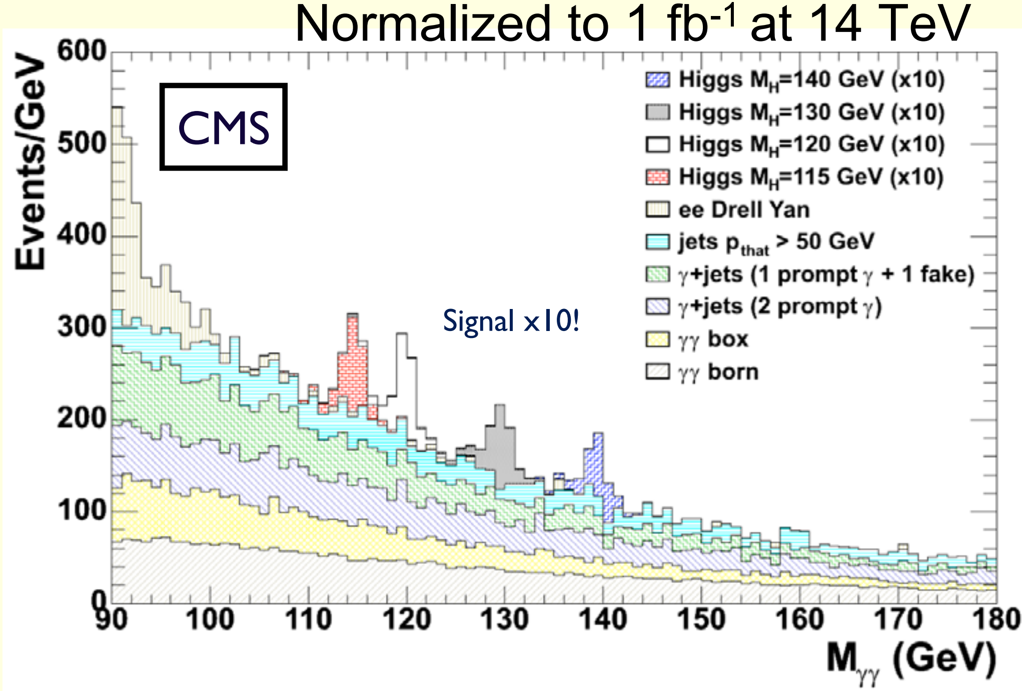
- The Higgs mass (quartic) is the only SM parameter we don’t know. Thus, the SM makes very definite predictions for the properties of the Higgs.

The Low Mass Higgs

- A low mass Higgs decays primarily to bb. At the LHC, this decay mode is probably swamped with backgrounds. (Though with a lot of data it could be accessible using sub-jet analyses).
- The primary window for the LHC comes from production through gluon fusion followed by the rare decay H -> γγ.
- This is still a subtle channel, because of the very low BR into photons. $L > 10\ \text{fb}^{-1}$ needed for discovery...
- Can also look for H->ττ.



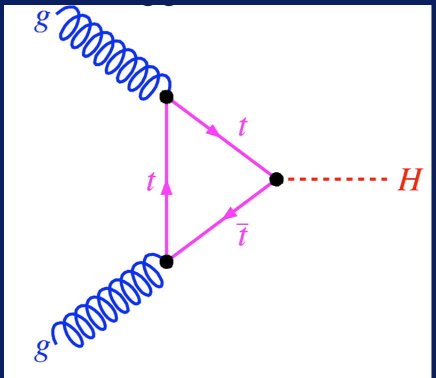


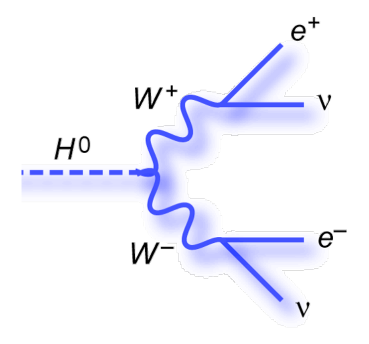

Normalized to 1 fb^{-1} at 14 TeV

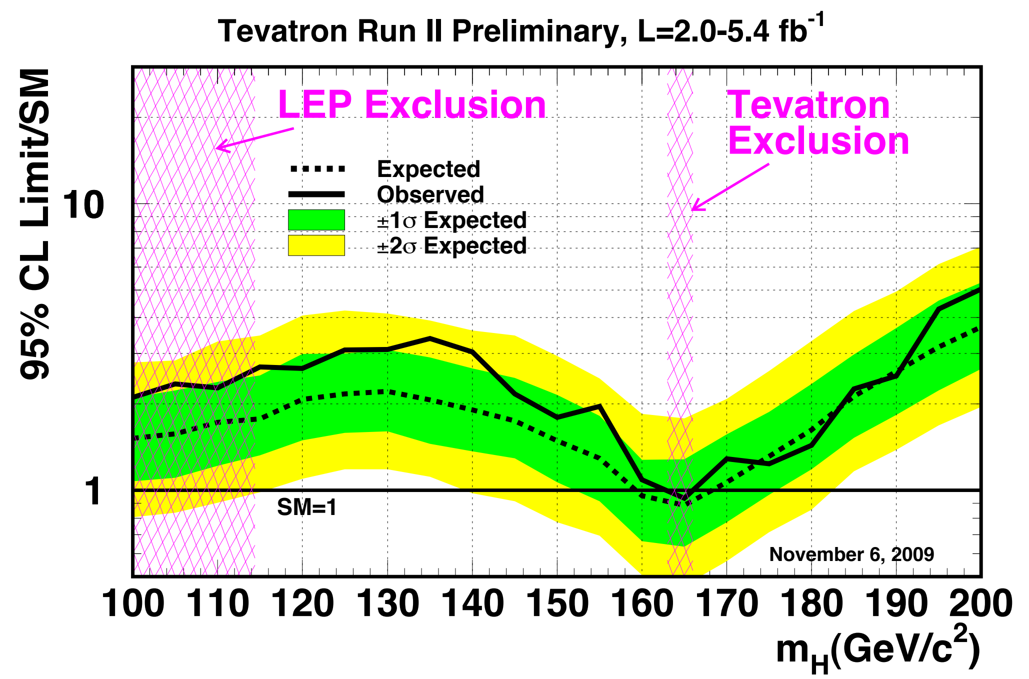
Signal x10!

The Heavy Higgs

- A heavy Higgs is paradoxically more easy to see. It has a slightly lower cross section, but much more vivid decays into WW and ZZ, which produce hard leptons.
- Since the decay is spectacular, we can afford to use the large gg production rate.
- In fact, the Tevatron experiments can rule out a Higgs mass in a narrow window around 165 GeV using the WW channel.

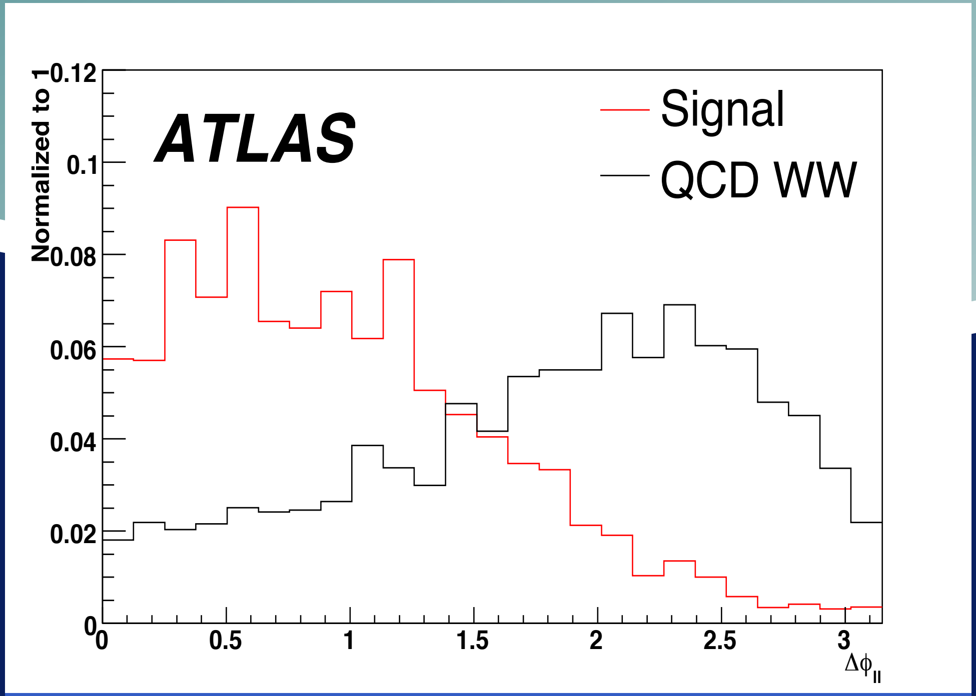




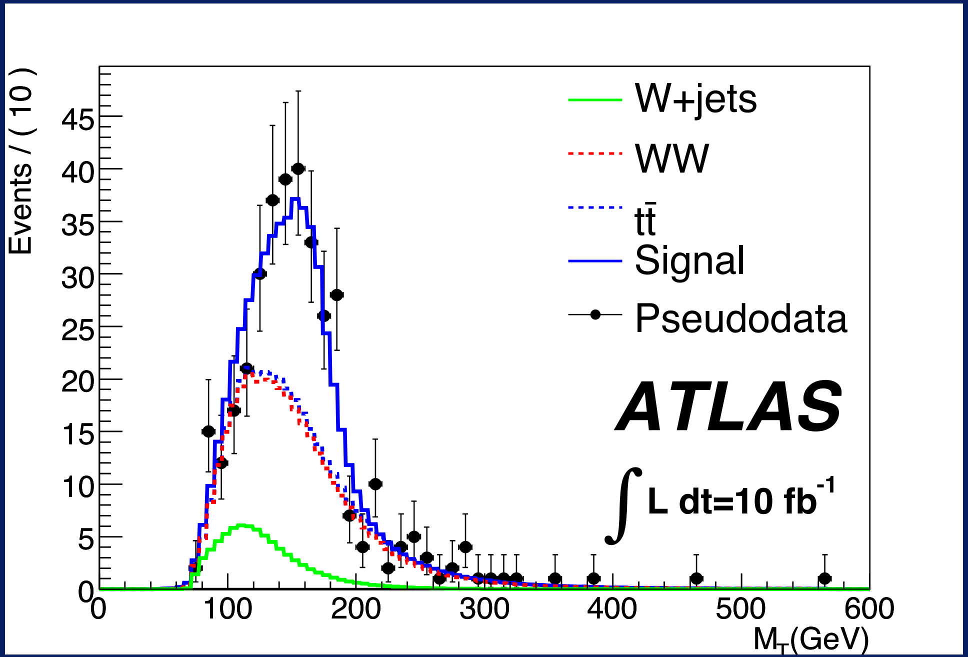


Heavy Higgs

- A heavy Higgs decaying into WWs (which themselves decay into leptons) provides a few handles to help discriminate the signal from the background.
- The azimuthal angle between the two leptons tends to be smaller, because of the spin correlation enforced by the spin zero Higgs.
- The Higgs mass itself is hard to reconstruct because of the two missing neutrinos. The "transverse mass" is broad, but correlates with the Higgs mass.

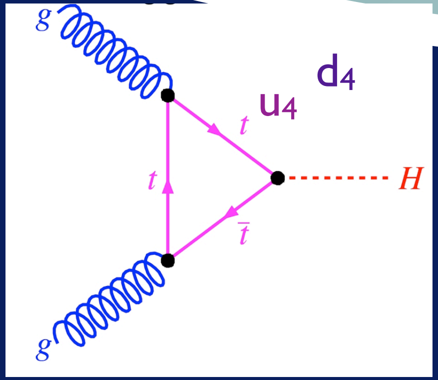


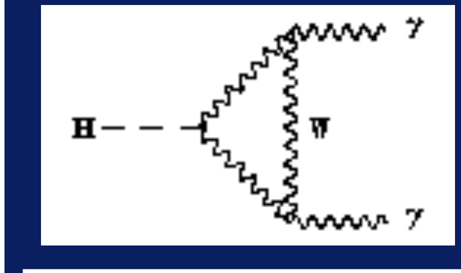
m_H = 170 GeV



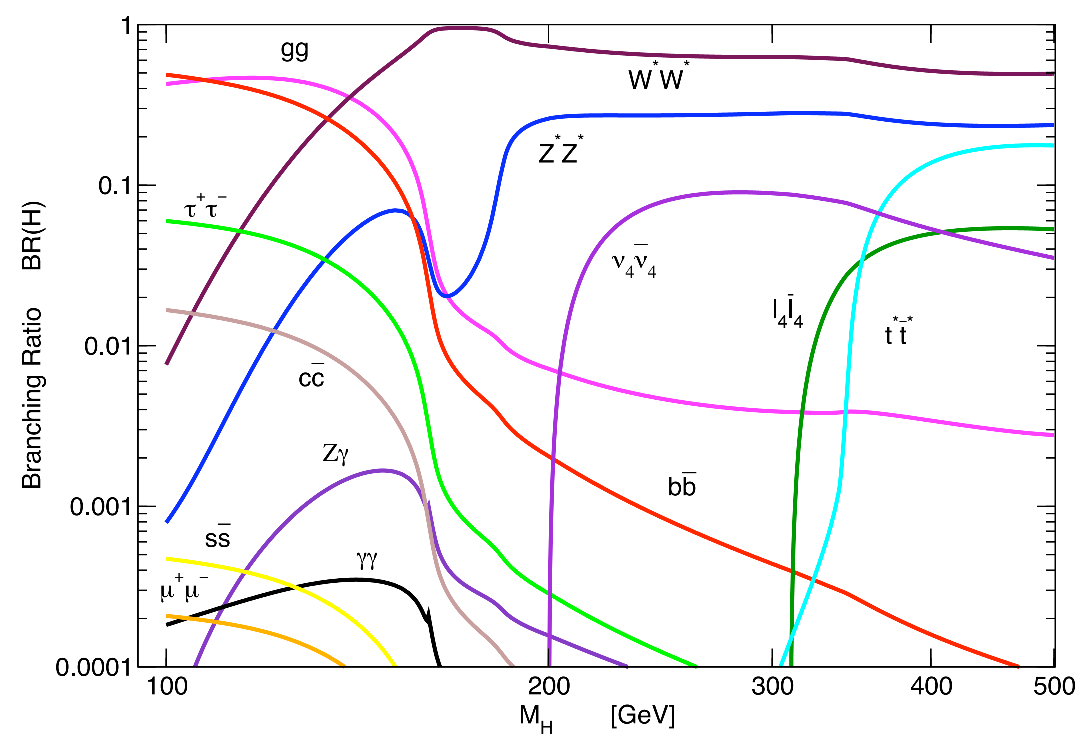
Higgs Properties: 4th Generation Higgs

- It’s interesting that key searches for the Higgs rely on couplings induced through loop-induced processes.
- Exotic particles can also run in the loops, and thus easily affect the sizes of the couplings.
  - One very simple example is a chiral fourth generation of quarks, which can modify the coupling to gg and γγ.
  - In the limit of large u_4 and d_4 masses, this increases the effective coupling to gg by about a factor of 3.

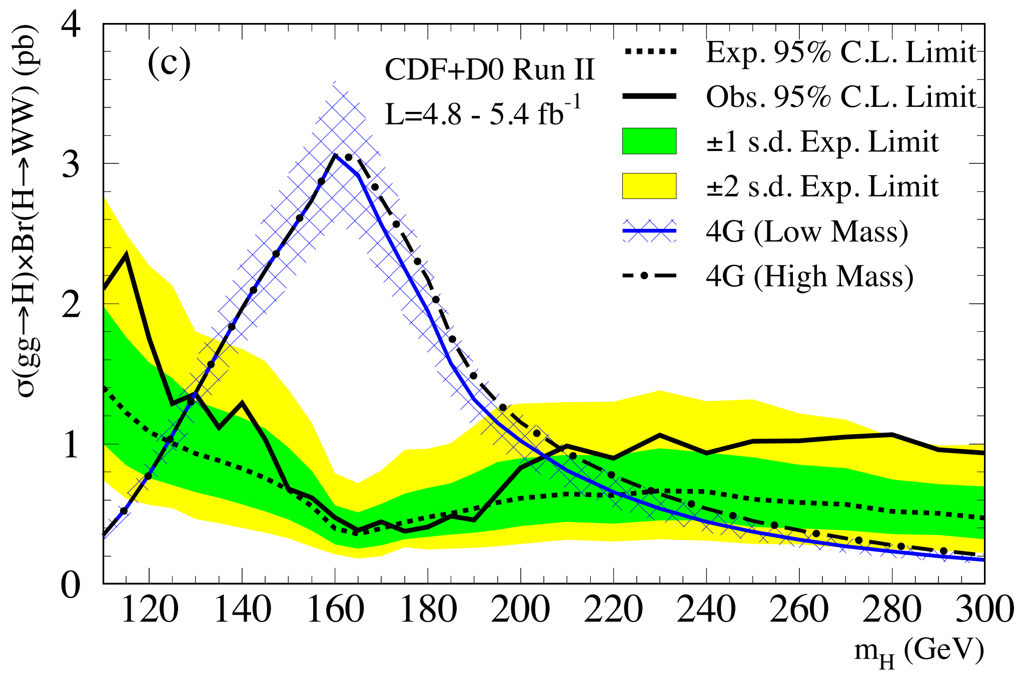




Kribs, Plehn, Spannowsky, TT ’07

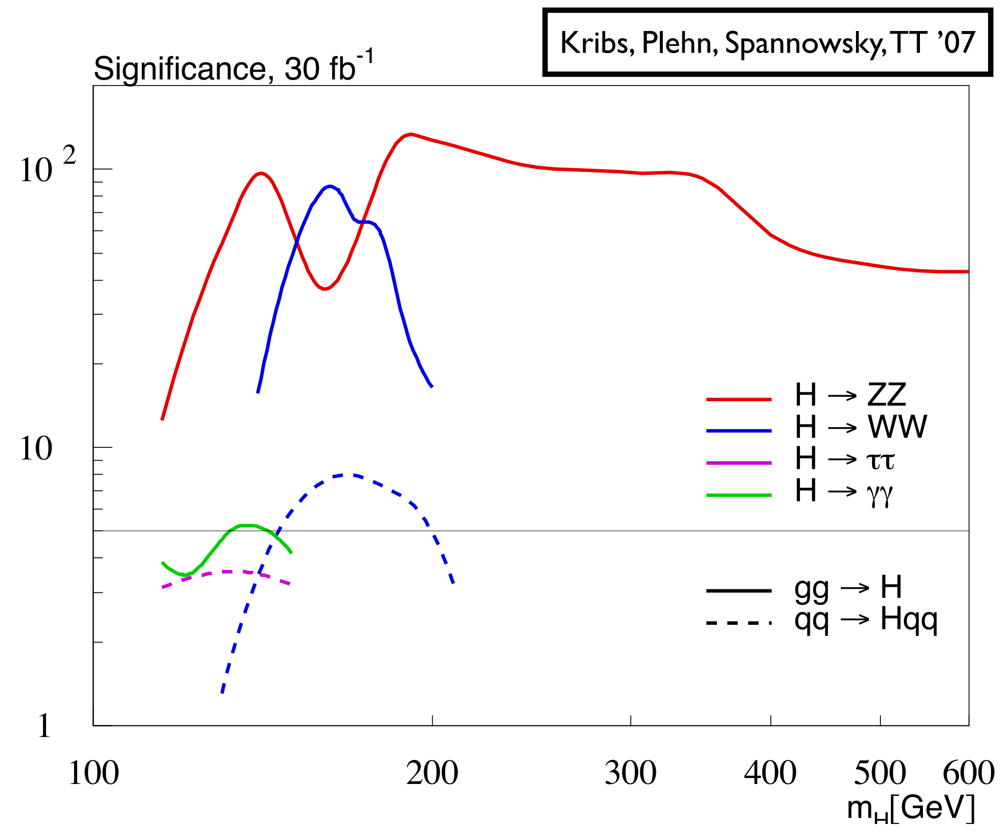


A 4th Generation Higgs



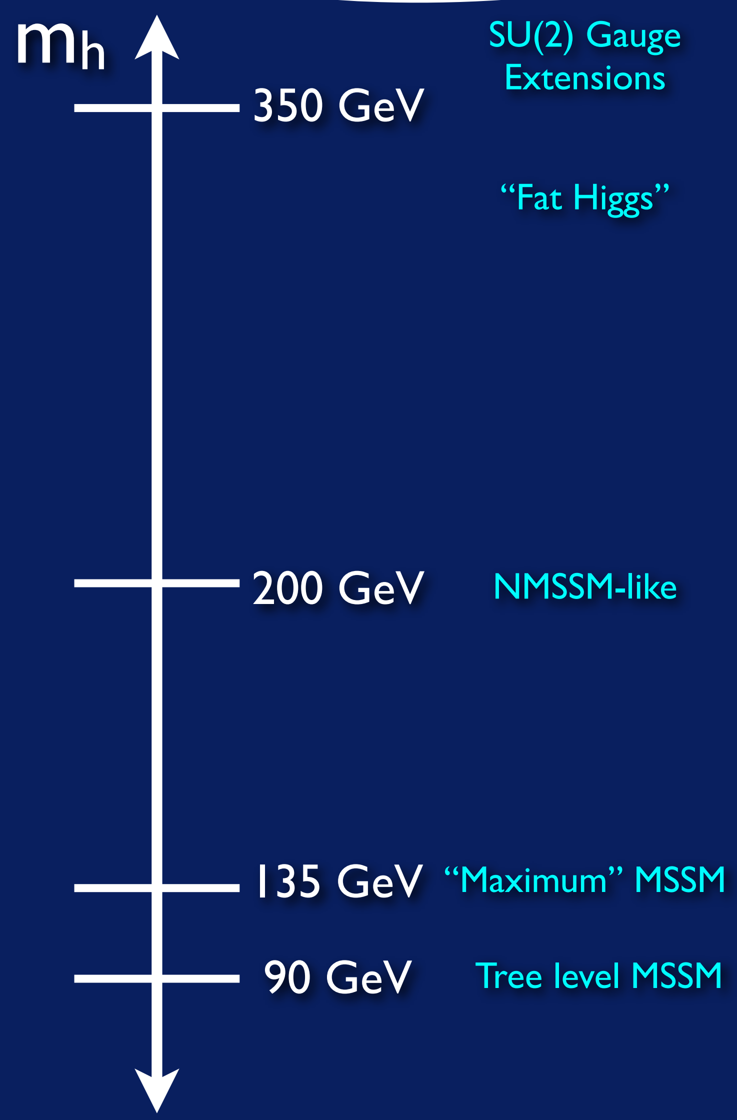
Ultimately, though we lose many channels, the gg -> H is so enhanced that even for low masses where the branching ratio would be small, we can use h -> ZZ -> 4 l's.

These modifications make life harder for low m_H but easier at high m_H.


Kribs, Plehn, Spannowsky, TT '07

A SUSY Higgs

- In supersymmetry, the Higgs comes along with a fermion super-partner. To cancel its gauge anomalies we need to include another doublet.
- After electroweak symmetry-breaking, there are 5 physical Higgs bosons: h^0, H^0, A^0, $H^\pm$.
- The lighter CP even Higgs, h^0 generally has roughly SM-like properties.
- In the minimal model, the lighter Higgs is predicted to have a mass less than roughly 135 GeV. Less minimal models relax this bound.
- A heavy Higgs + SUSY would tell us a lot!



m_h

SU(2) Gauge Extensions

350 GeV

“Fat Higgs”

200 GeV NMSSM-like

135 GeV “Maximum” MSSM

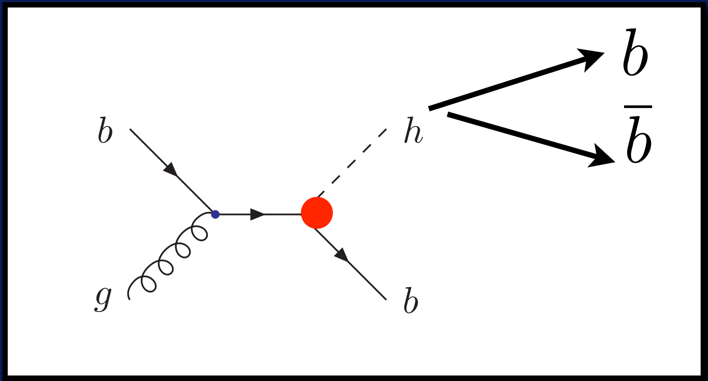
90 GeV Tree level MSSM

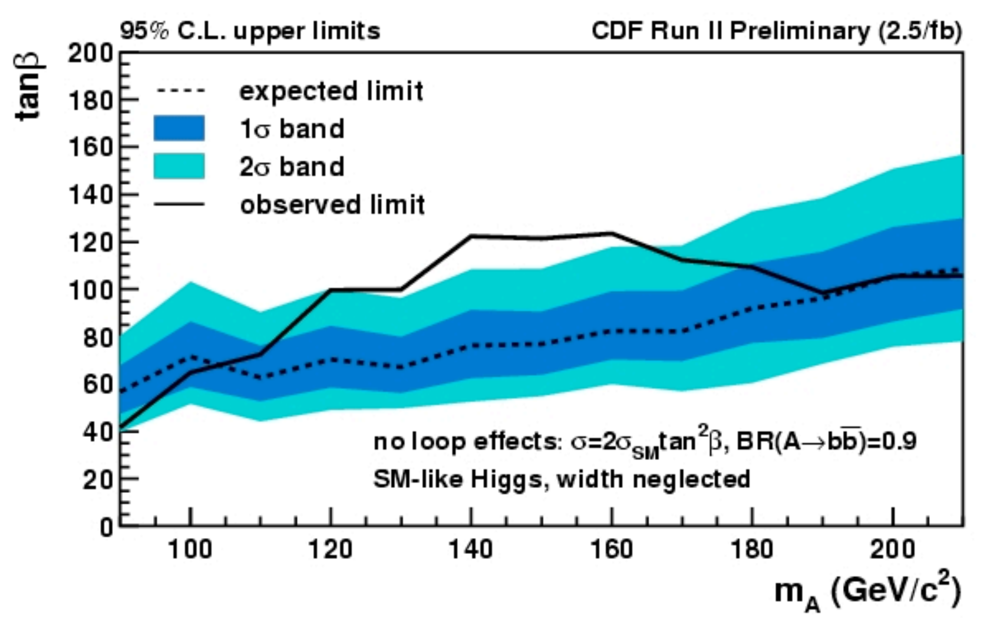
SUSY Higgses

- The simple fact of two Higgses leads to much richer spectrum of phenomena.
- The two doublets share the VEV, with the Z mass determined by the sum in quadrature:

$$v_1 = v \sin\beta \qquad v_2 = v \cos\beta$$

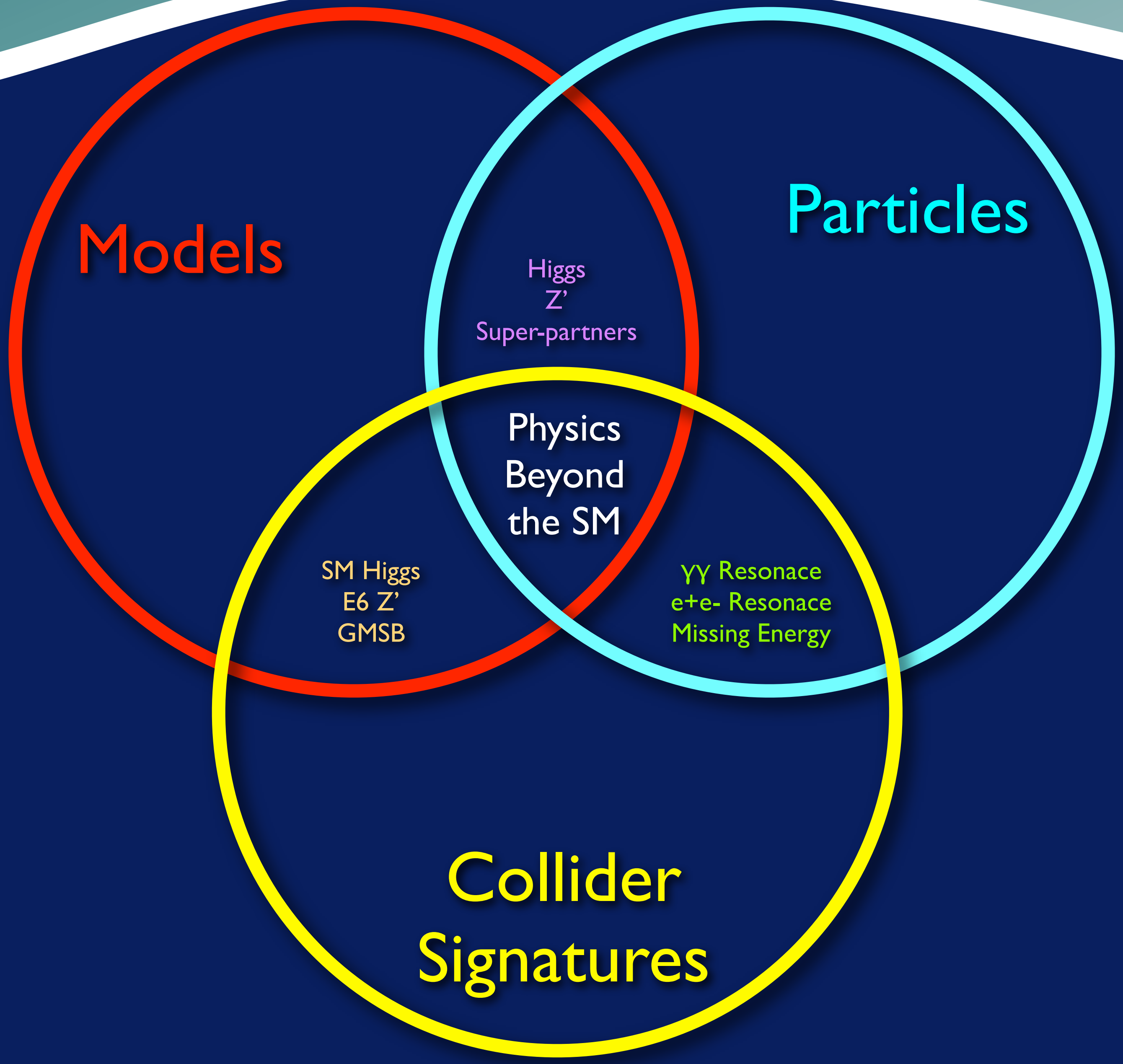
- In the MSSM, one of the doublets couples to down-type quarks and charged leptons, and the other to up-type quarks.
- Couplings to fermions are modified by the angle β. Large tan β enhances couplings to down-type quarks.
- The channel where bottom quarks fuse into a Higgs can dominate for large tan β, providing unique signatures different from the SM Higgs.





New(er) Particles

Models, Particles, Phenomena



Models

Particles

Collider Signatures

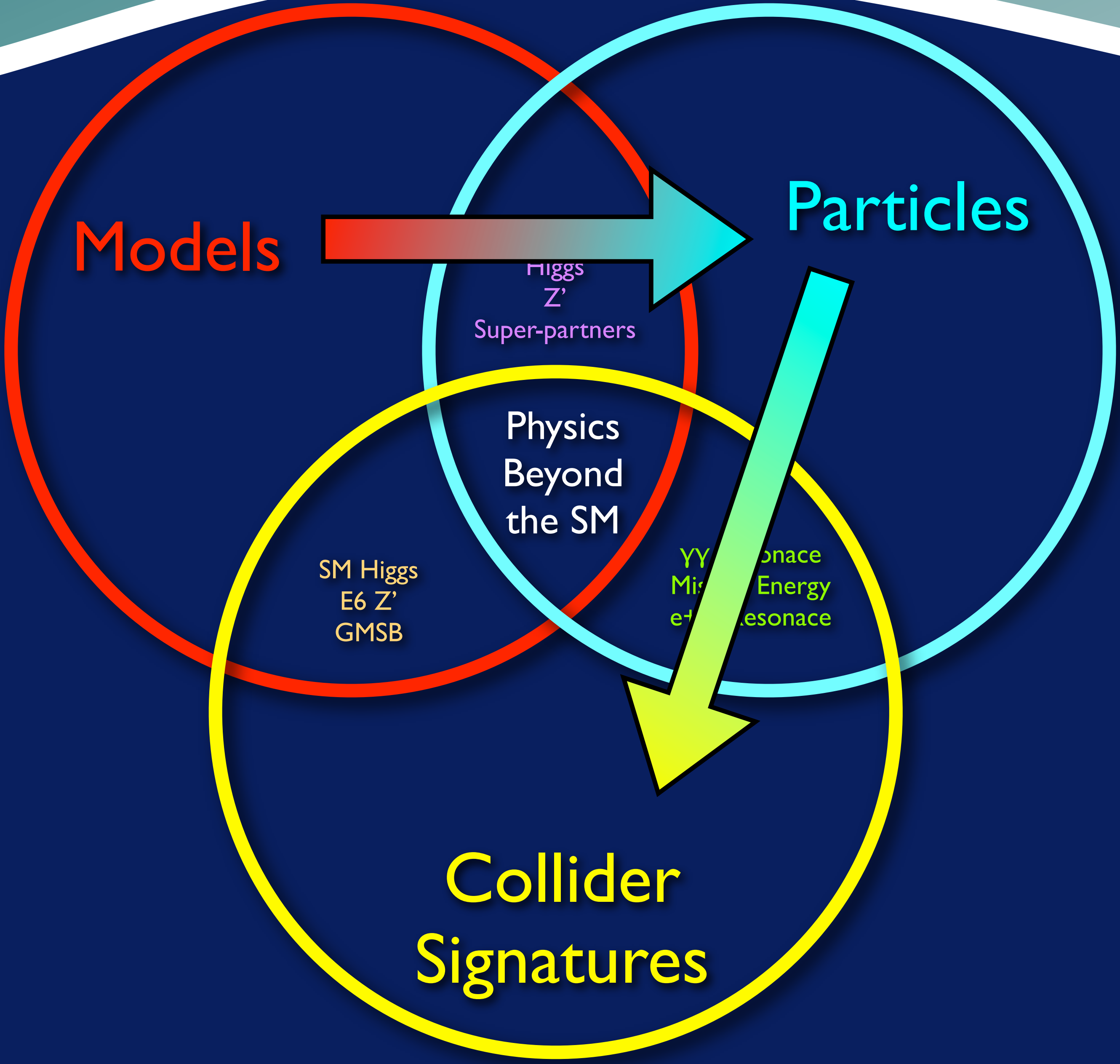
Higgs
Z'
Super-partners

Physics Beyond the SM

SM Higgs
E6 Z'
GMSB

γγ Resonace
e+e- Resonace
Missing Energy

Lots of practice going one way...



Models

Particles

Higgs
Z'
Super-partners

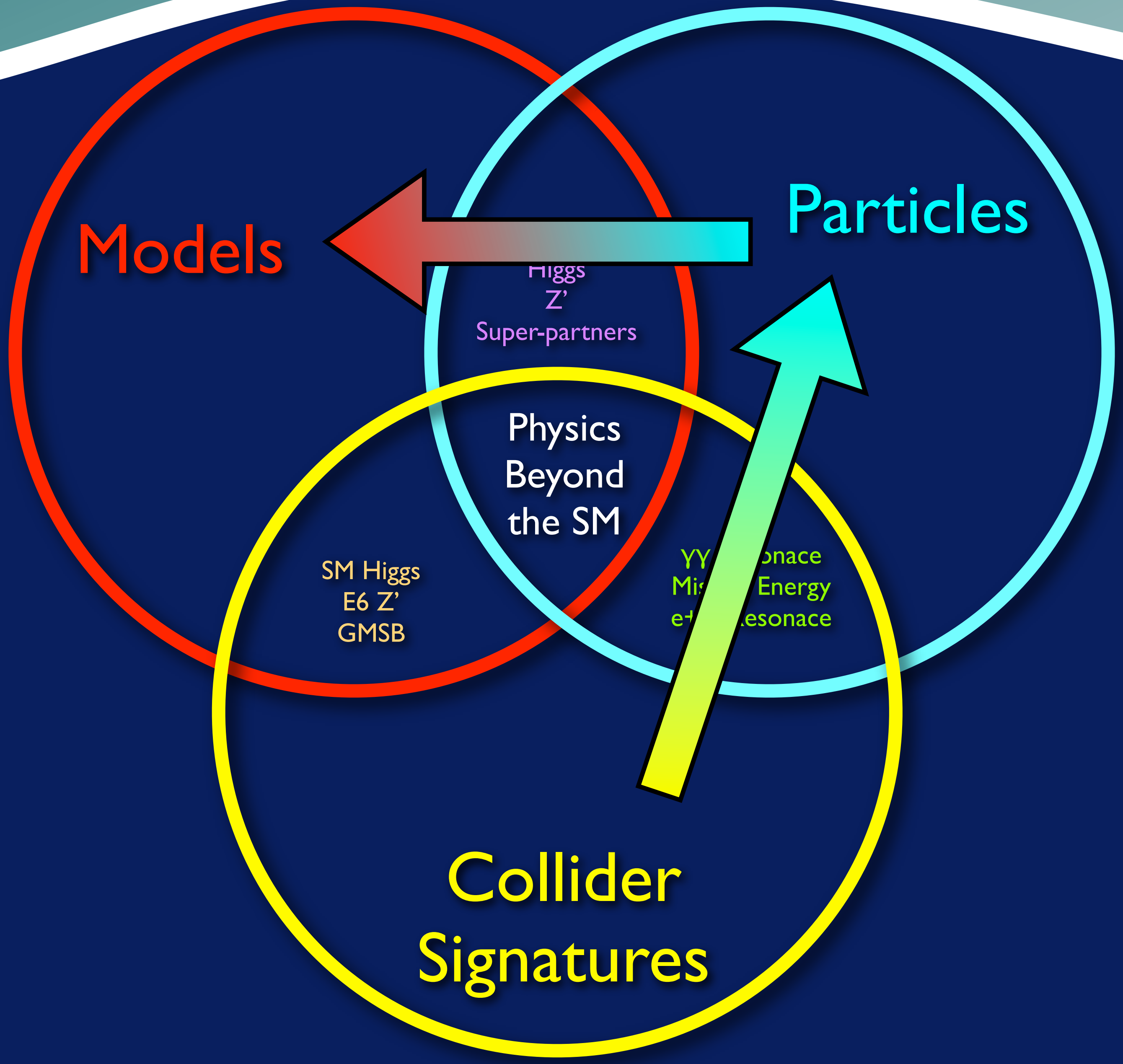
Physics
Beyond
the SM

SM Higgs
E6 Z'
GMSB

γγ onace
Mis Energy
e+ esonace

Collider
Signatures

...still need more practice with the other...



Models

Particles

Higgs
Z'
Super-partners

Physics
Beyond
the SM

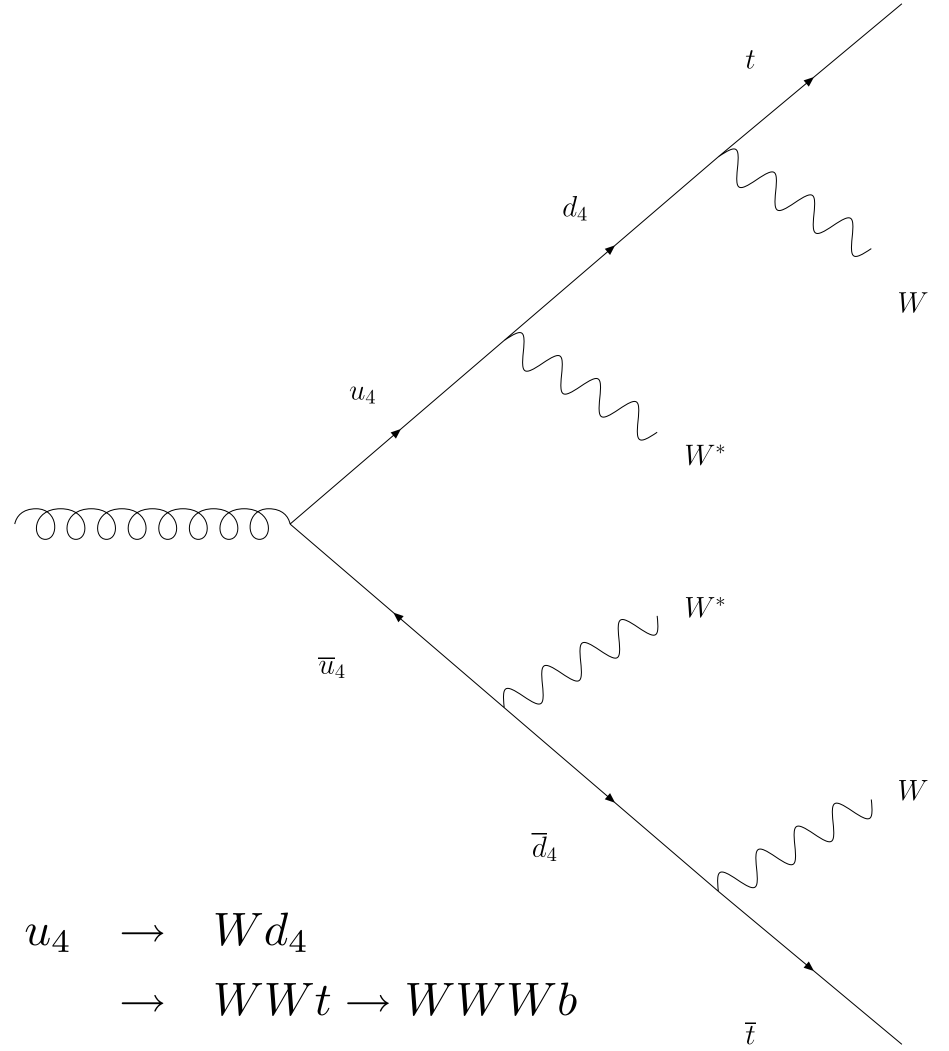
SM Higgs
E6 Z'
GMSB

γγ onace
Mis Energy
e+ esonace

Collider
Signatures

Fourth Generation

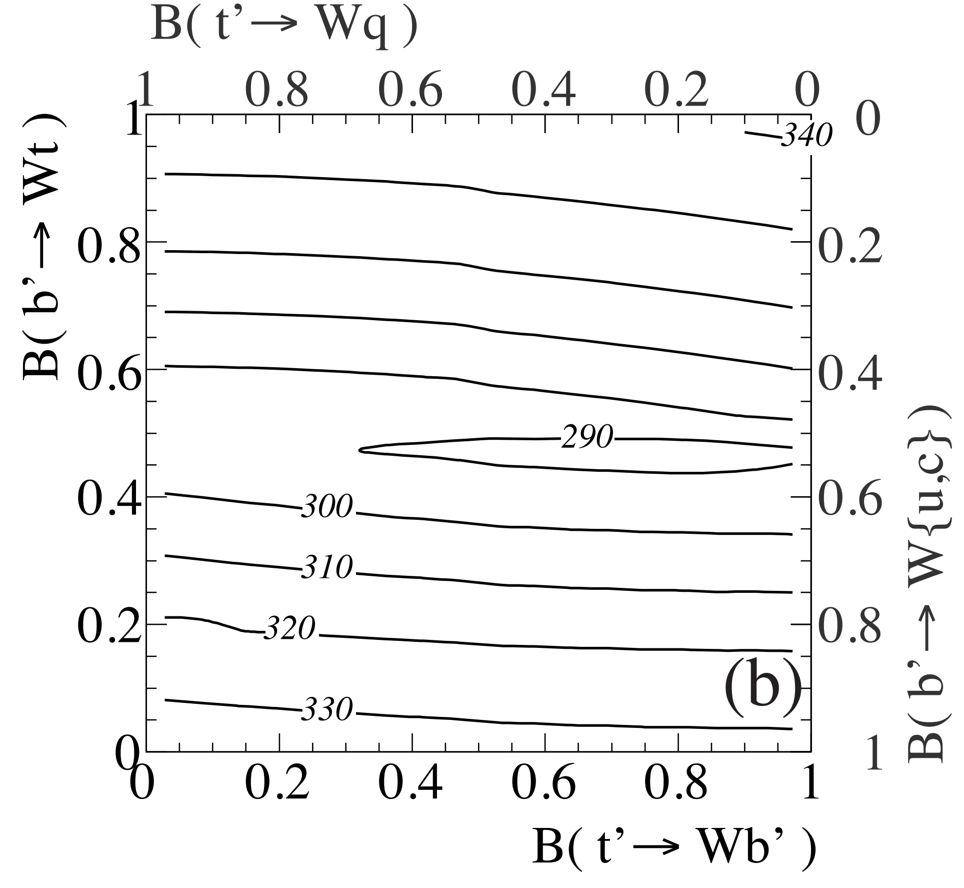
- In addition to the effects on Higgs properties, fourth generation quarks are interesting to look for in their own right.
- Fourth generation quarks can decay through W's into lighter quarks.
- The most likely decays are into third generation quarks (limits on 3-4 mixing are the least constrained).
- Pair production of u_4 can lead to final states with six W's and two bottom quarks -- a spectacular signal the SM has difficulty producing.



$$\begin{aligned} u_4 &\rightarrow W d_4 \\ &\rightarrow W W t \rightarrow W W W b \end{aligned}$$

Fourth Generation

- Tevatron searches exist for t's and b's produced in pairs.
  - t't' -> (W-> lν)q (W->qq)q
    - No b-tags; $m_{t'}$ reconstruction
  - b'b' -> WWtt -> WWWWbb -> same-sign leptons.
    - No mass reconstruction
- Combined limits depend on the branching ratios of t' and b'. Robust limits are $m_{b'}$ > about 300 GeV.
- This is physics that the LHC at 7 TeV can improve with ~ 1 fb^{-1}.

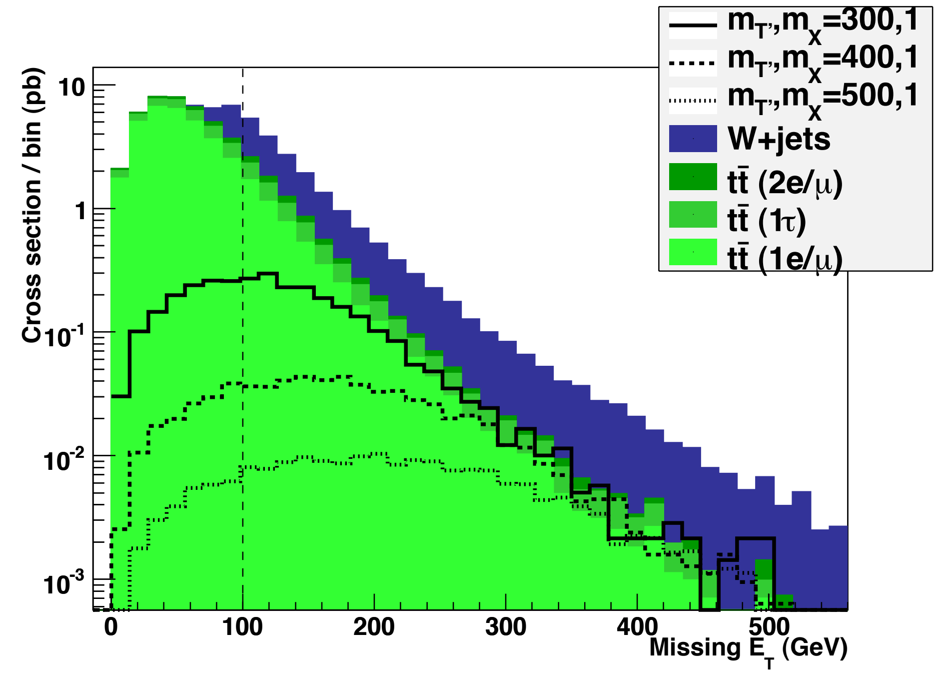


$m_{t'} = m_{b'} + 100$ GeV

Flacco, Whiteson, TT, Bar-Shalom, arXiv:1005.1077

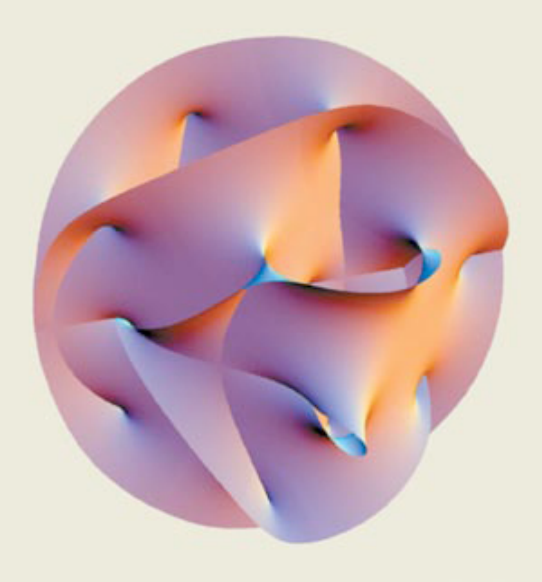
A Dark Fourth Generation?

- A fourth generation could even have something to do with dark matter.
- Jason Kumar told us about a model of “WIMPless” dark matter in the parallel sessions.
- The fourth generation acts like the bridge between the dark matter and ordinary quarks.
- It decays into dark matter and a third generation quark, leading to unusual signals.
- For example T’T’ -> ttXX.



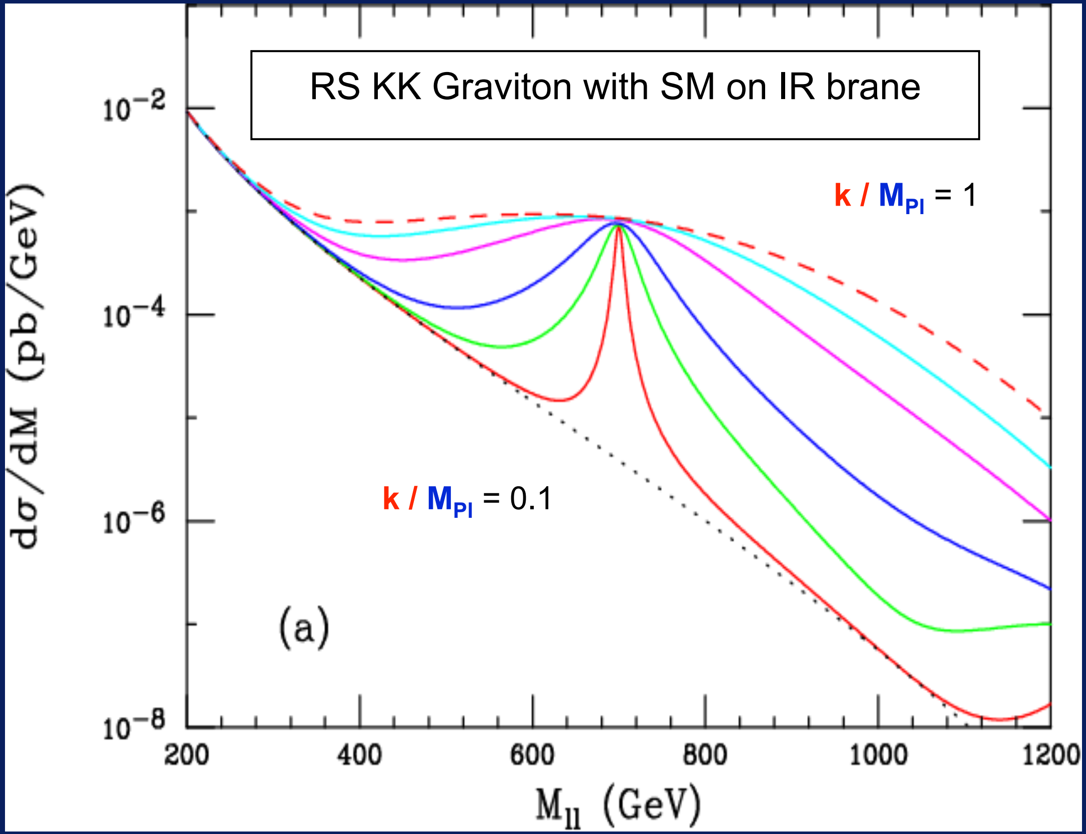
Feng and Kumar, PRL 101, 231301 (2008)
Alwall, Feng, Kumar, Su, 1002.3366

Kaluza Klein Modes



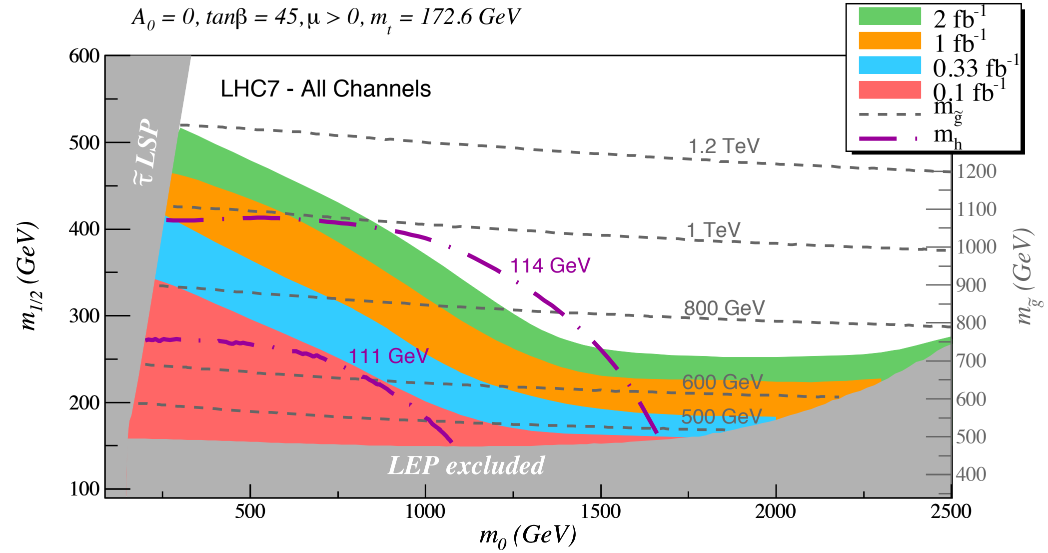
- If there are additional compact dimensions, any field that propagates into them will have KK modes -- higher mass copies.
- The spectrum and couplings of the heavy states depend on how the space is folded up.
  - Number of dimensions
  - Topology
  - Which quantum fields are functions of them
- Many, many variations abound...

Davoudiasl, Hewett, Rizzo, PRD63, 075004 (2001)

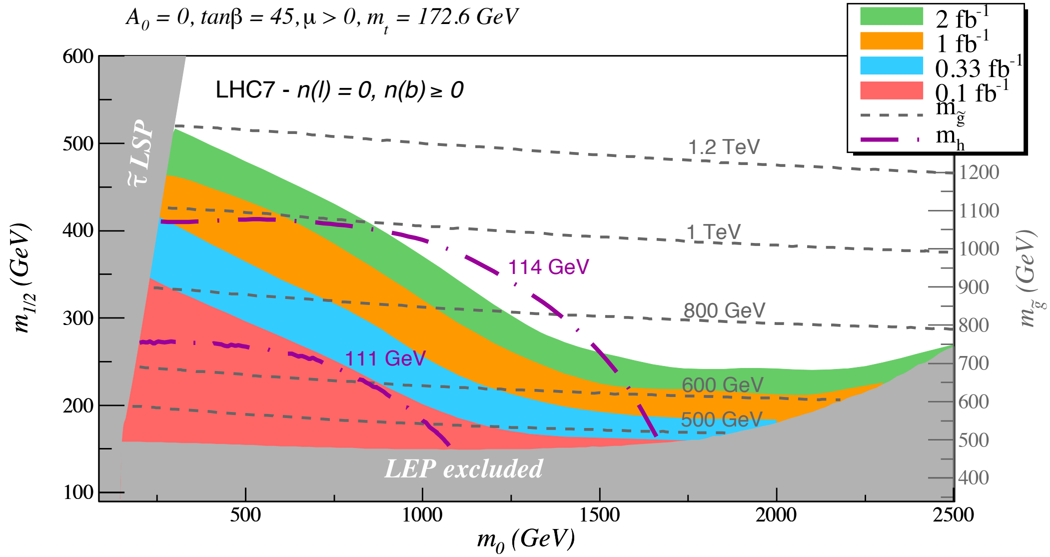


Super-particles

- When colored super-partners can be produced, they can decay into jets (and sometimes leptons) and neutralinos, producing jets + missing energy signatures.
- A complicated soup of production and decay modes contribute to a given signature.
- A recent study examines mSUGRA (common scalar masses, fermion masses, and A terms at the GUT scale) with the 7 TeV LHC and 1 fb^{-1}.
- Even without missing energy signals, LHC can discover SUSY!



Baer, Barger, Lessa, Tata 1004.3594



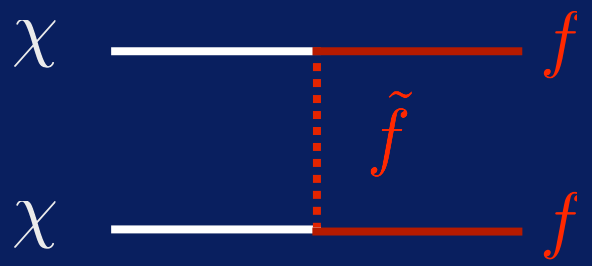
More details from Genevieve
in the parallel sessions this afternoon!

WIMPs

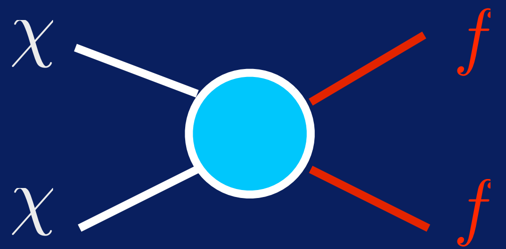
- Production of super-partners highlights one of the important connections between new LHC physics and particle astrophysics: if WIMPs do indeed couple to colored SM particles, we can produce them at colliders.
- In SUSY, the way this works is to produced colored squarks and gluinos, which then decay into neutralinos. The details depend on the zoo of SUSY particles (with their detailed spins and masses).
- One question we can ask is what happens when the colored super-partners are a little too heavy for the LHC to produce them?
- Colored super-partners still appear virtually in processes, even if they are not produced on-shell. Since the WIMP needs to be somewhat lighter anyway, we can imagine a situation in which the colored states are negligibly produced at a collider, whereas the WIMP remains accessible...

Effective Theory

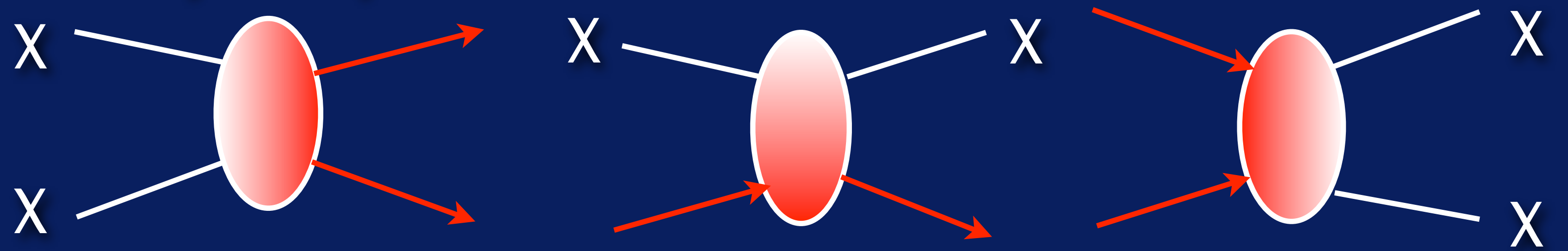
- We don’t want to get too attached to the details of a given WIMP model. We use effective field theory to capture the physics of WIMP interacting with the Standard Model.



$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



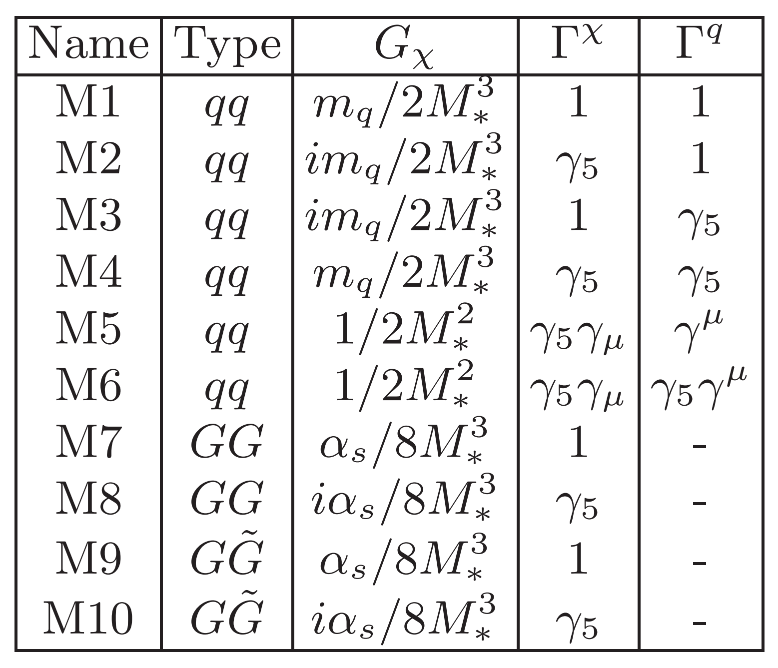
- This provides a language which can describe direct, indirect, and collider production of WIMPs.
- The EFT works well for experiments whose energies are small compared to the masses of any new particle other than the WIMP -- a “Maverick” WIMP.



Operators

Similar Approaches:
Beltran, Hooper, Kolb, Krusberg PRD80, 043509 '09
Cao, Chen, Li, Zhang 0912.4511
Beltran, Hooper, Kolb, TT, Krusberg 1002.4137
Bai, Fox, Harnik 1005.3797

- For both colliders and direct detection, the most relevant operators are the ones which connect WIMPs to quarks or gluons.
- I'll focus on the case of a Majorana WIMP. We have results for Dirac and scalar WIMPs too.
- The EFT contains the set of 10 leading operators which preserve Lorentz and gauge invariance. (Others can be Fierz'd into this form).
- We assume minimal flavor violation; 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	-

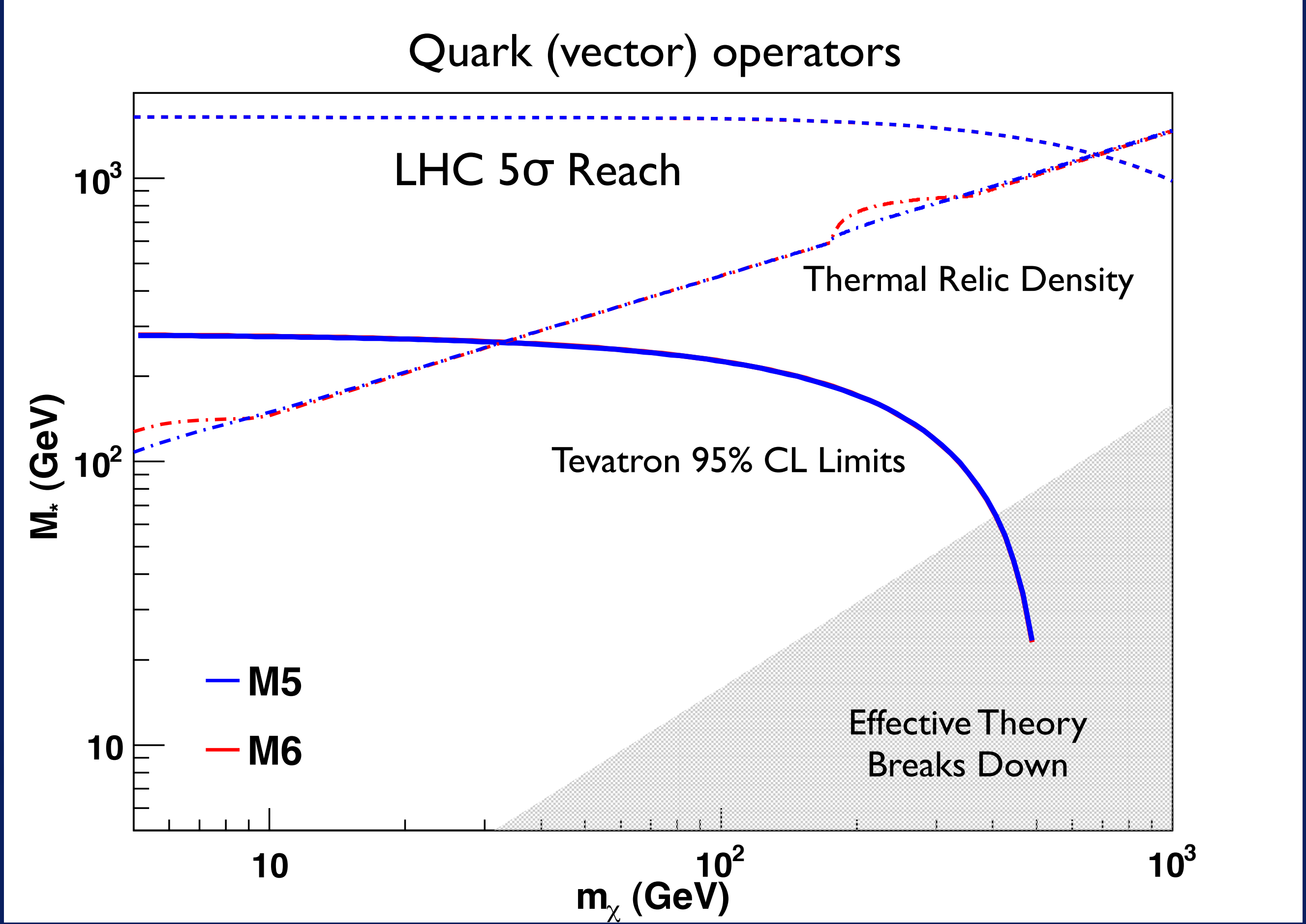
$$\sum_q \left[\bar{q}\Gamma^q q\right]\left[\bar{\chi}\Gamma^\chi \chi\right]$$

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

Limits/Sensitivity

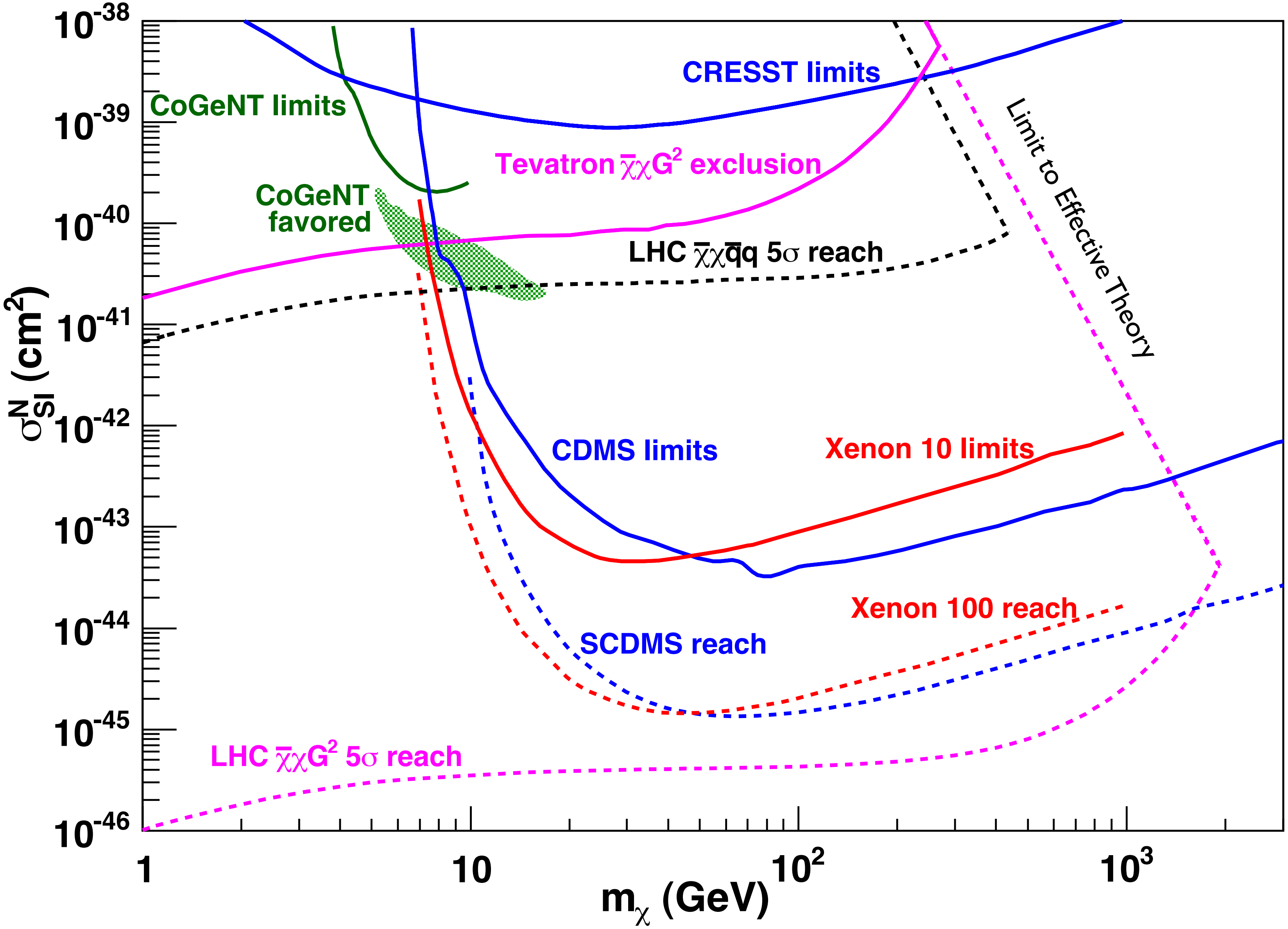
- Our primary interest is how colliders can put bounds or discover how WIMPs interact with quarks or gluons.
- We compare with a CDF search [0807.3132] for monojets (designed for large extra dimensions) and a proposed LHC search [hep-ex/0005033] to get bounds from Tevatron null results and LHC discovery prospects.
- The EFT also predicts the thermal relic density and direct detection rates, allowing us to compare them to the collider picture.

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



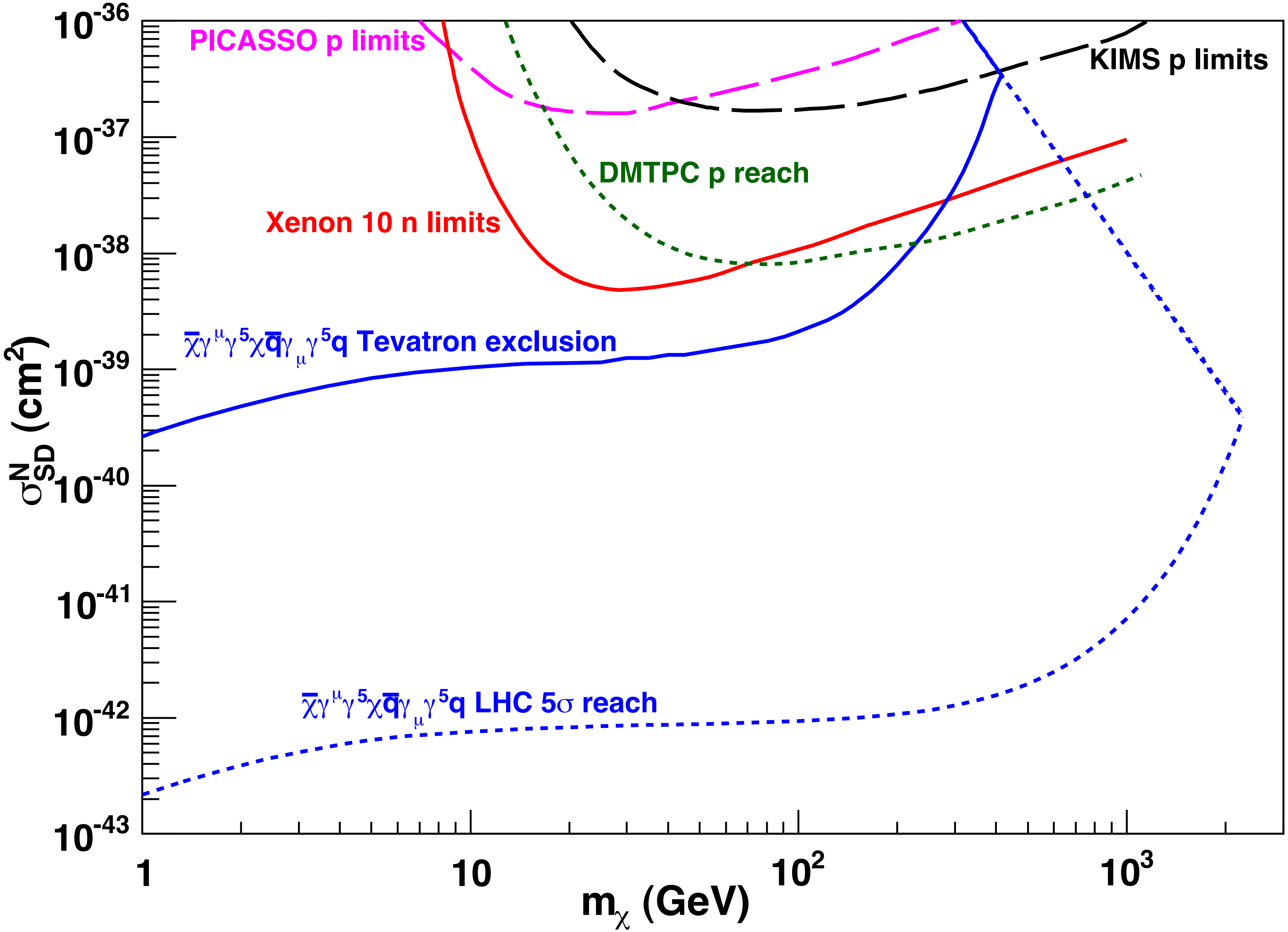
Spin-independent

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



Spin-dependent

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



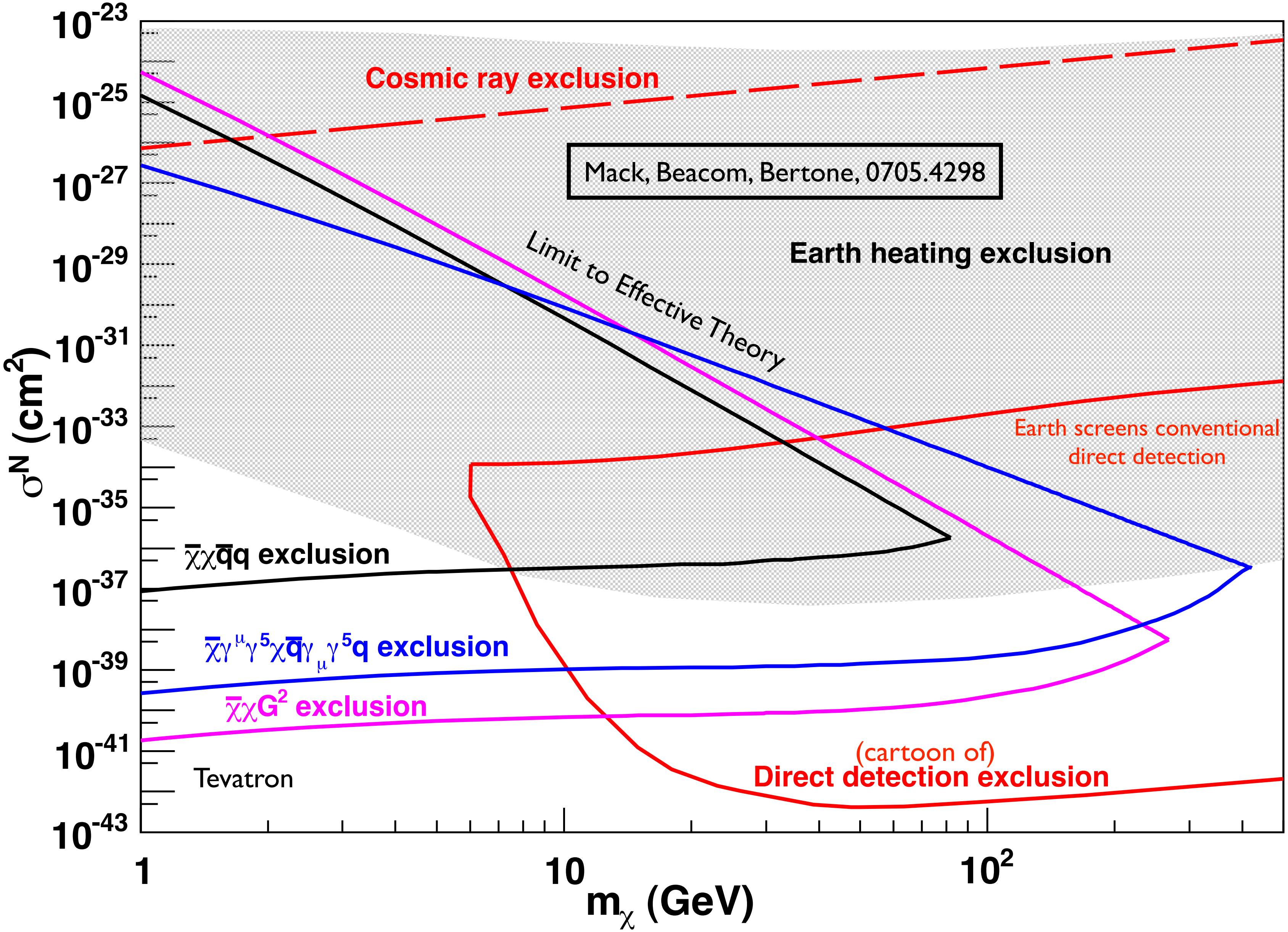
Outlook

- The LHC is online! It promises an unparalleled look at the TeV scale.
  - We expect it should in the very least reveal the mechanism of electroweak symmetry-breaking, and some properties of the Higgs (if there is one!).
    - A fourth generation or supersymmetry could affect the properties of the Higgs in interesting, noticeable ways.
    - Knowledge of Higgs properties can help shape our understanding of dark matter, for example as an input to direct detection.
  - If we are lucky, we could get hints for supersymmetry, extra dimensions, a fourth generation, or ....???
- Colliders can provide interesting information about WIMPs, complementary information to direct & indirect detection experiments.

Bonus Material

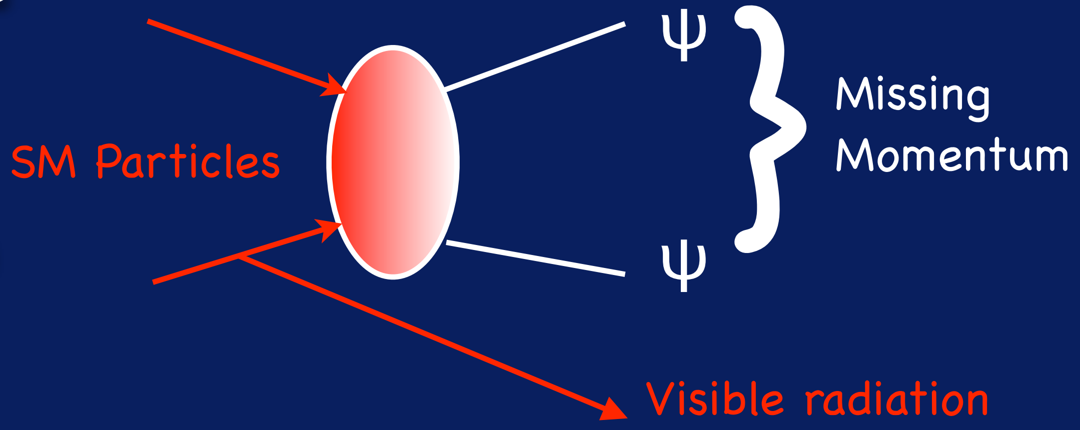
From WIMPs to SIMPs...

1005.1286



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 for ADD KK 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.

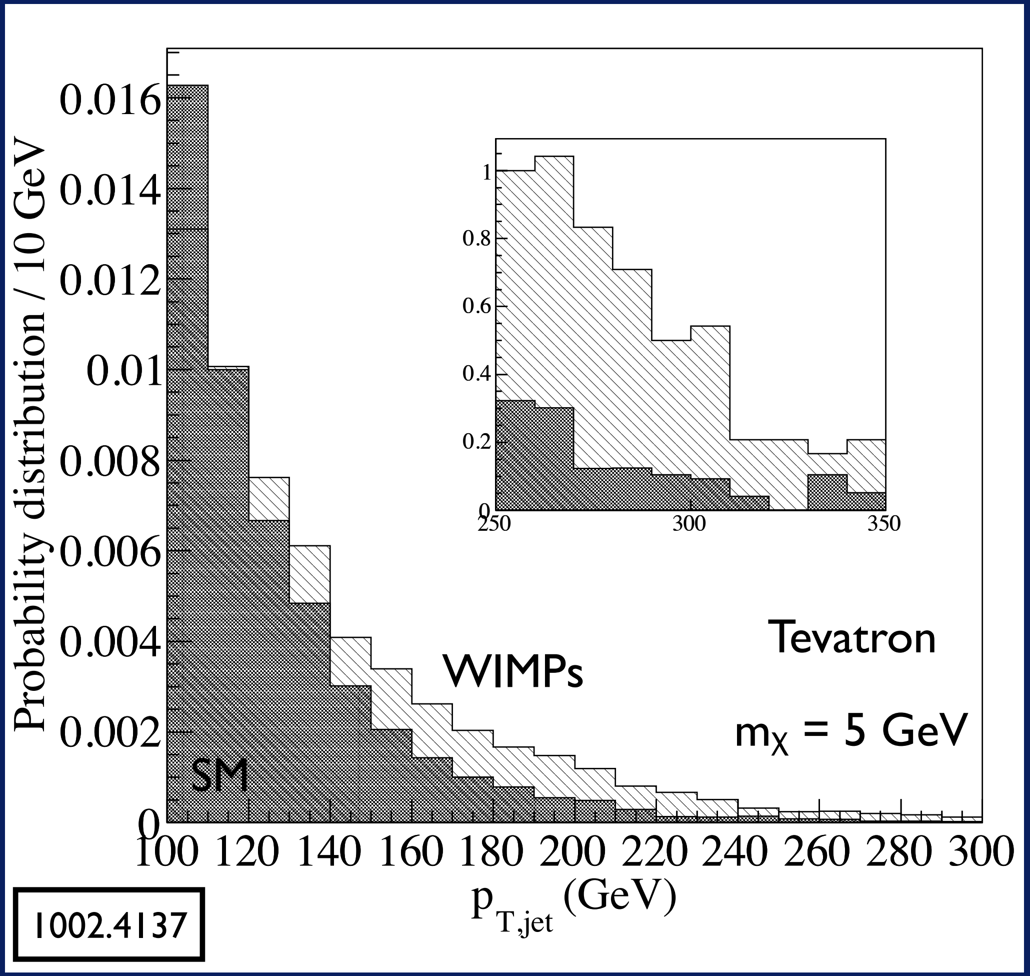
CDF, 0807.3132
http://www-cdf.fnal.gov/physics/exotica/r2a/20070322.mono_jet/public/ykk.html

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 (ΔR > 0.4) leptons with PT > 10 GeV.
  - The "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.



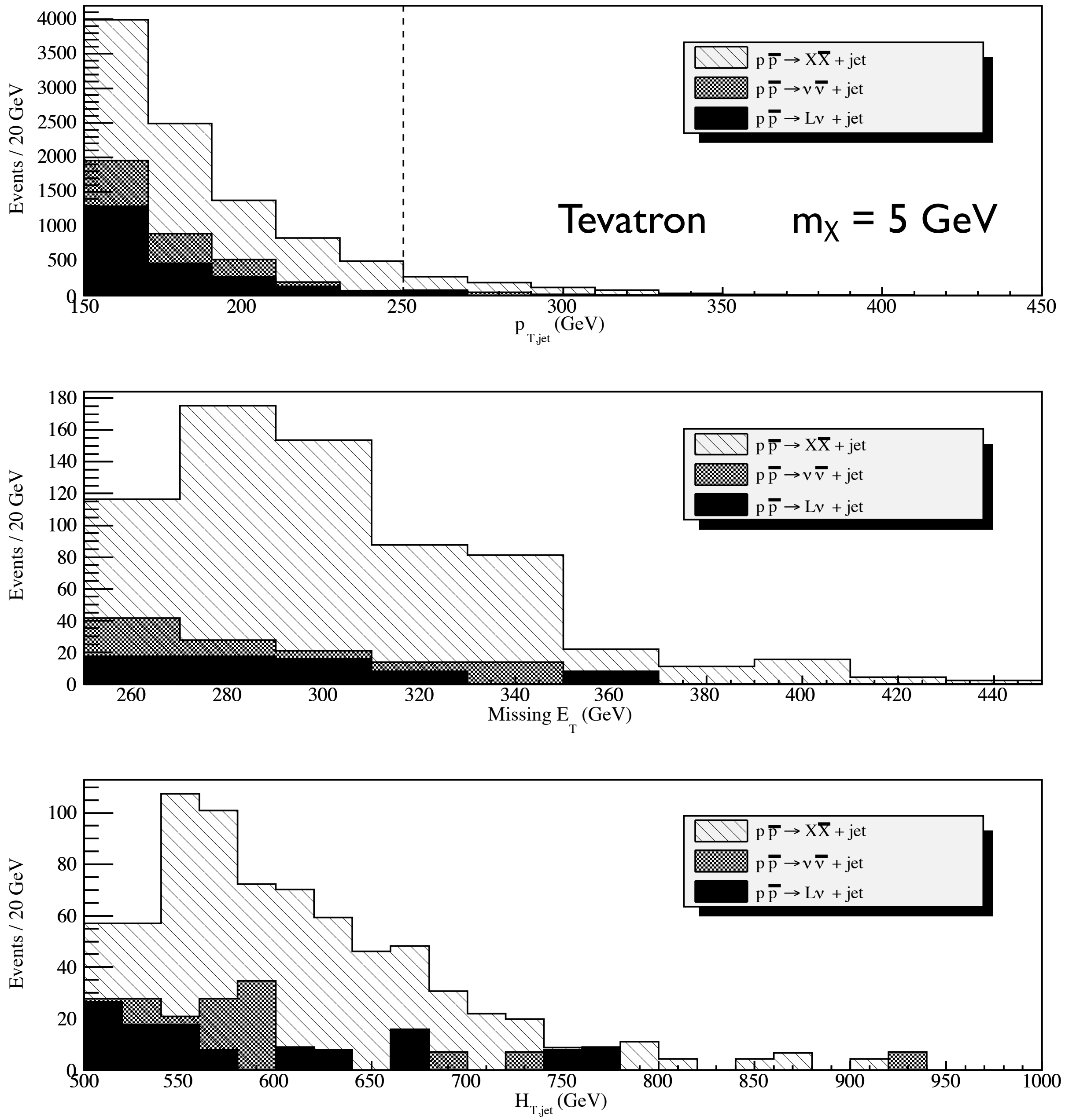
1002.4137

M6: $[\bar{\chi}\gamma^{\mu}\gamma_5\chi]\,[\bar{q}\gamma_{\mu}\gamma_5 q]$

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.



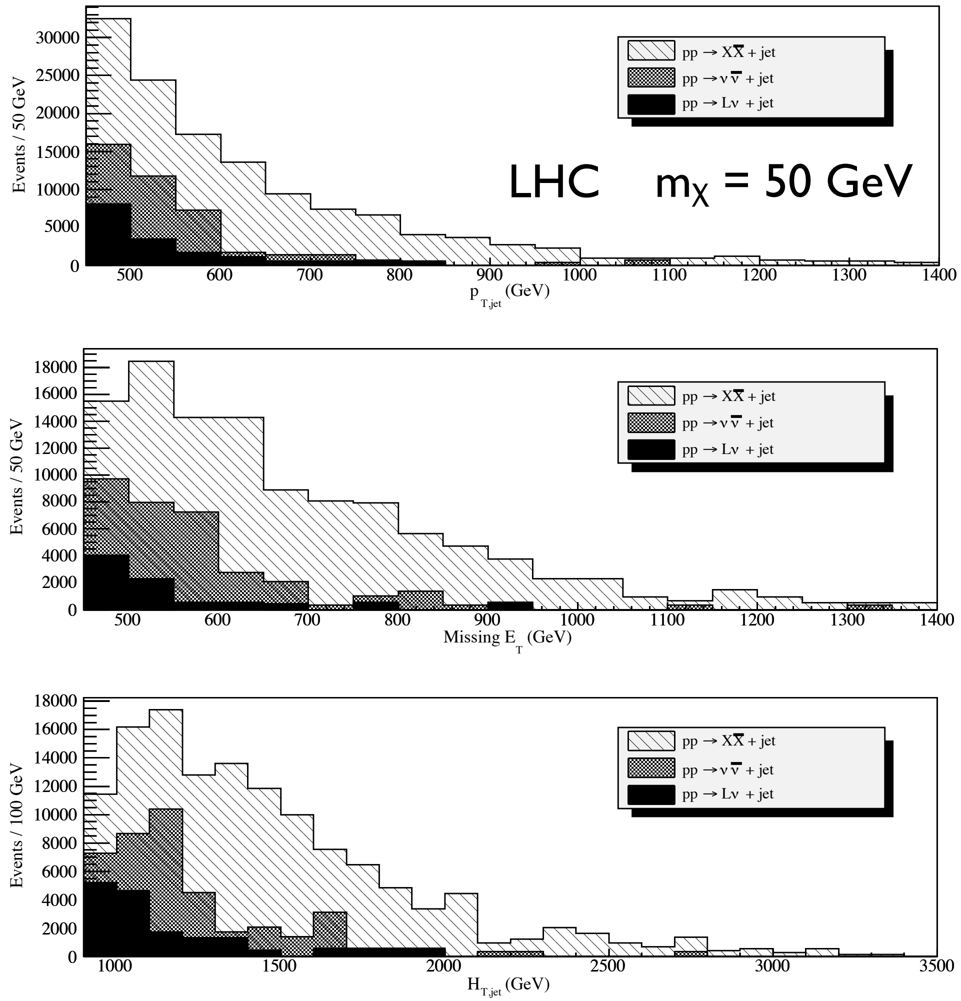
LHC

1002.4137

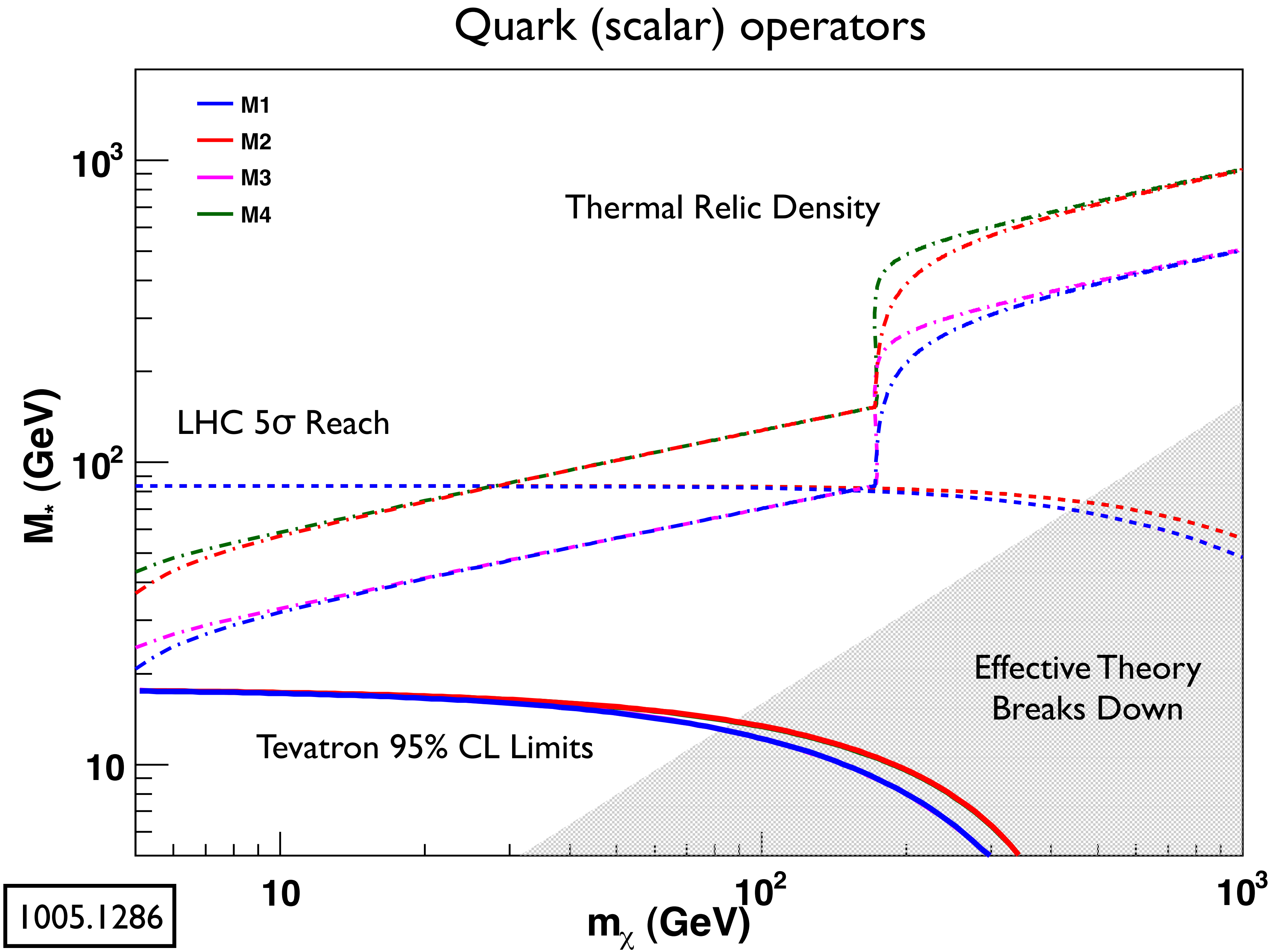
- To estimate the LHC sensitivity we rely on the ATLAS search for jets + missing energy:

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!

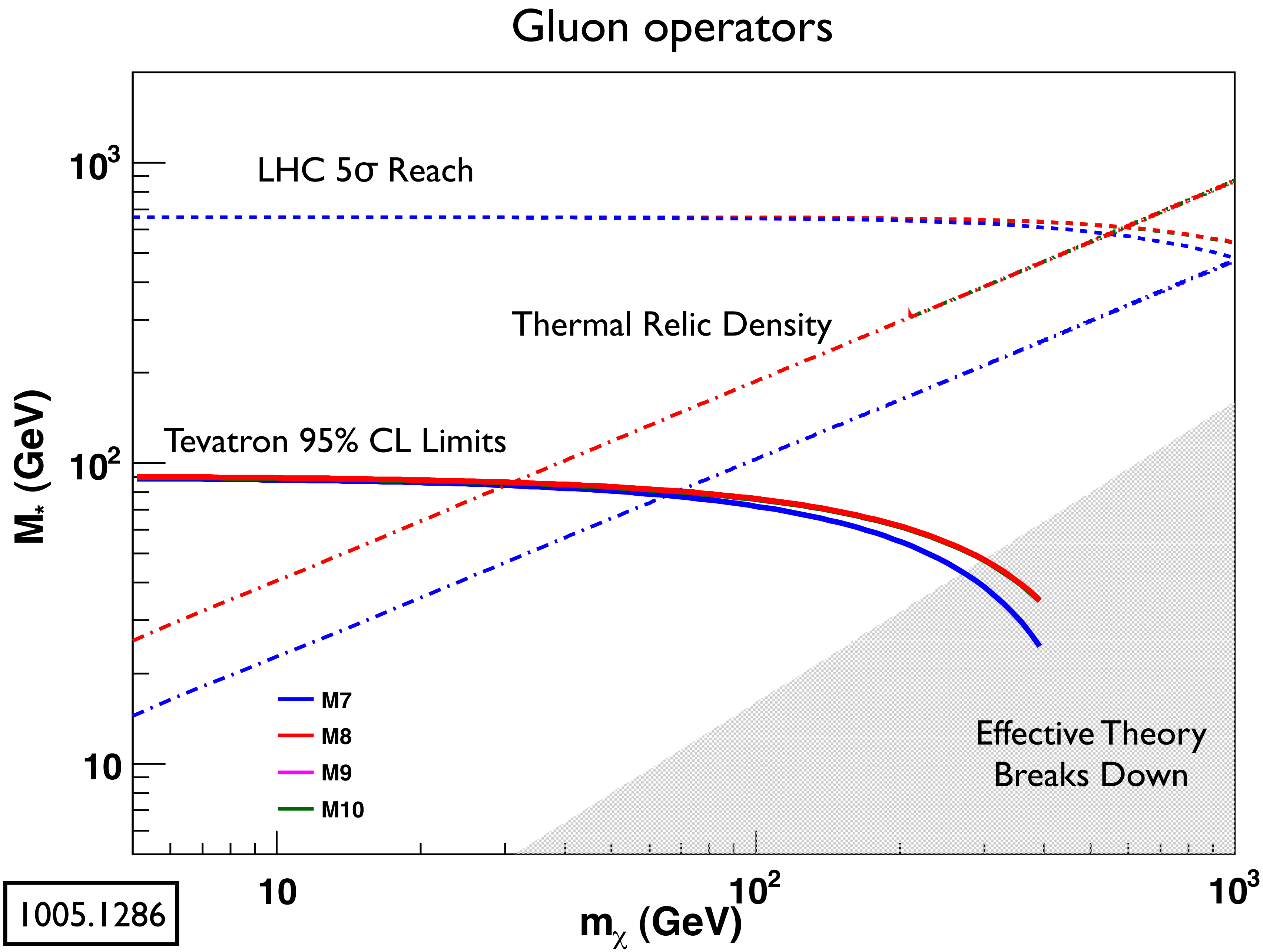


Limits/Sensitivity



1005.1286

Limits / Sensitivity



1005.1286

Direct Detection

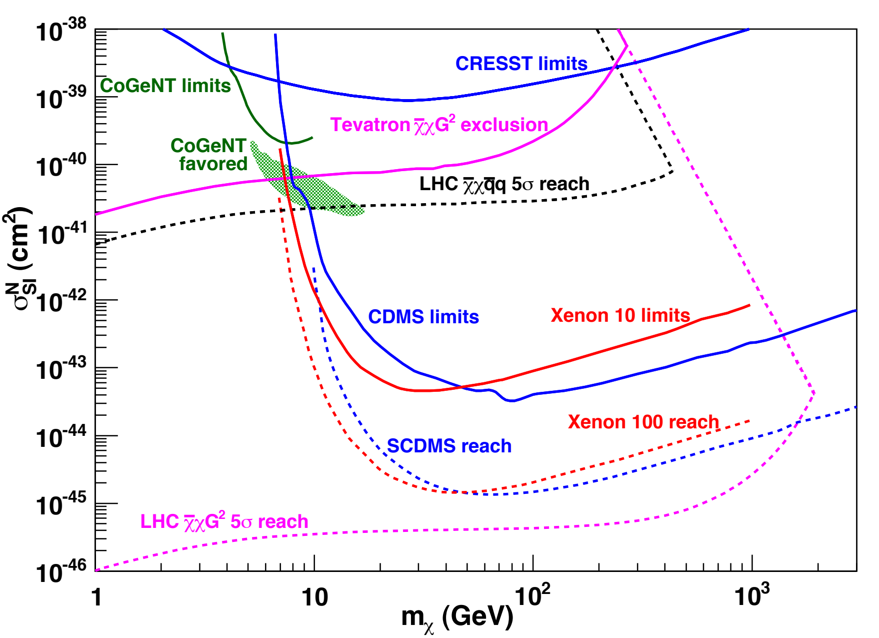
- Our operators can also be translated into direct detection experiments.
- Only three operators contribute to non-relativistic Majorana WIMP scattering with a heavy nucleus.
  - Two operators potentially contribute to spin-independent scattering.
  - One operator potentially contributes to spin-dependent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

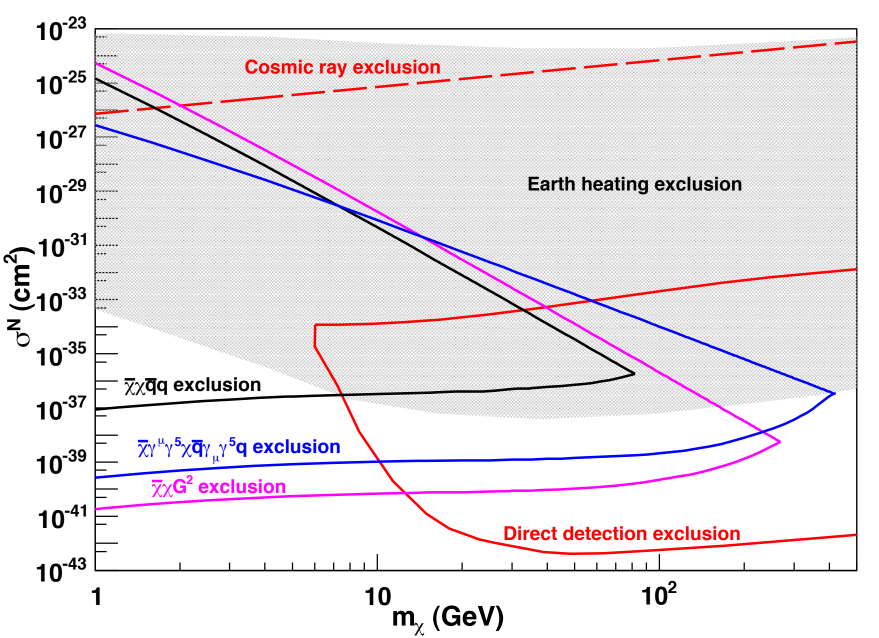
$$\sigma^N_{SI;M1} = \frac{4\mu_\chi^2}{\pi}\left(0.082\ \mathrm{GeV}^2\right)\left(\frac{1}{2M_*^3}\right)^2 \qquad \sigma^N_{SD;M6} = \frac{16\mu_\chi^2}{\pi}\left(0.015\right)\left(\frac{1}{2M_*^2}\right)^2$$

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

Collider/Direct Synergy

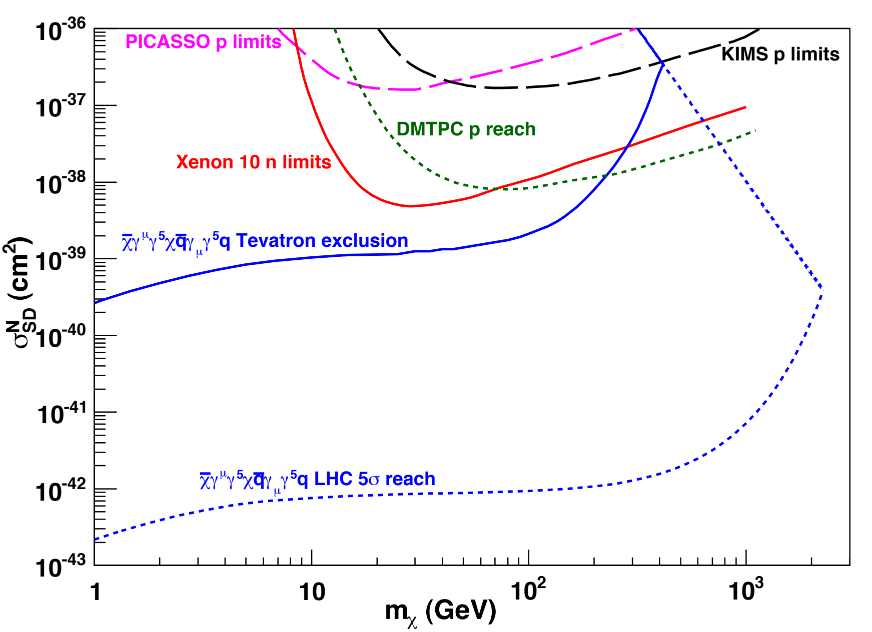
- Spin-independent scattering, colliders and direct searches show a lot of complementarity.
  - Colliders win at low WIMP masses and for gluon interactions.
  - Direct detection can reach much lower cross sections for quark-scattering at ~100 GeV masses.
  - Tevatron already says something about the DAMA/CoGeNT low mass region; LHC will say a lot.
  - Also note: Xenon100 low mass analysis. (which I guess Elena will show us tomorrow).





Spin-dependent

- 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.
- Such as have been invoked to explain DAMA versus other experiments -- “momentum-dependent dark matter”, but note the presence of light states!



Chang, Pierce, Weiner, 0908.3192

Outlook

- 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 complementarity with spin-independent searches.
- Together, direct, indirect, and collider searches offer a more complete picture of dark matter interactions with the Standard Model!

Bonus Material