Certainties and Uncertainties in Collider Searches for Dark Matter

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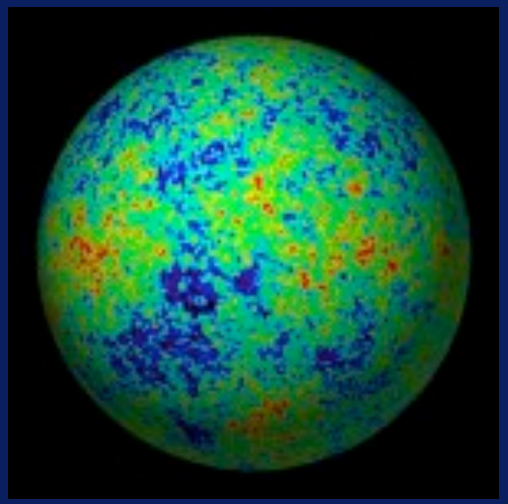
Dark Matter in Collision
UC Davis
April 13 2012

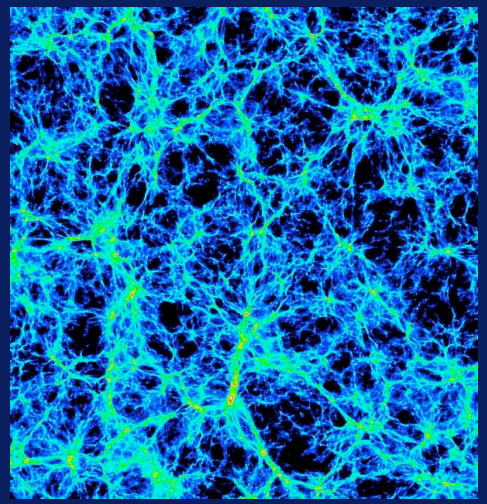
Outline

- Certainties
- Uncertainties
  - PDFs
  - Backgrounds
  - Signals / Observables
- Strategies

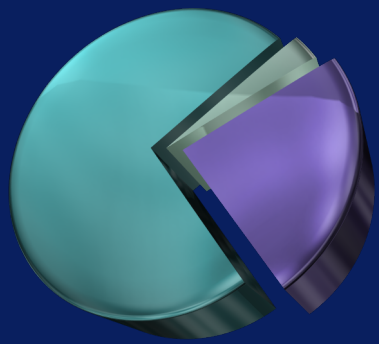
Certainties

Dark Matter





- Certainty: Dark Matter exists.



- Ordinary Matter
- Dark Matter
- Dark Energy

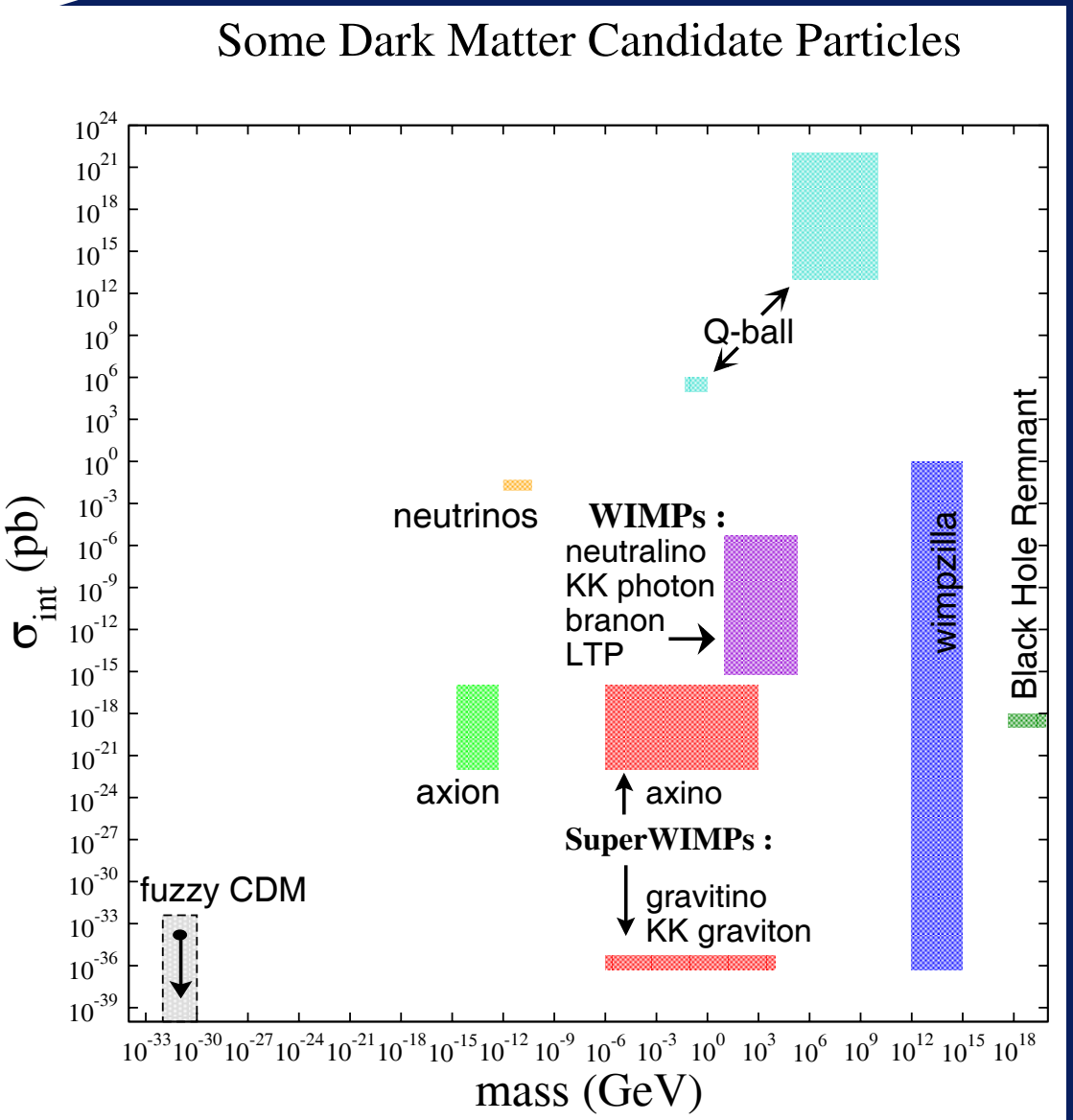
Dark Matter

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

- Certainty: Dark Matter exists.
- And it's cool.

$59.99 for 20 servings
Available in Blue Raspberry, Fruit Punch, and Grape flavors.

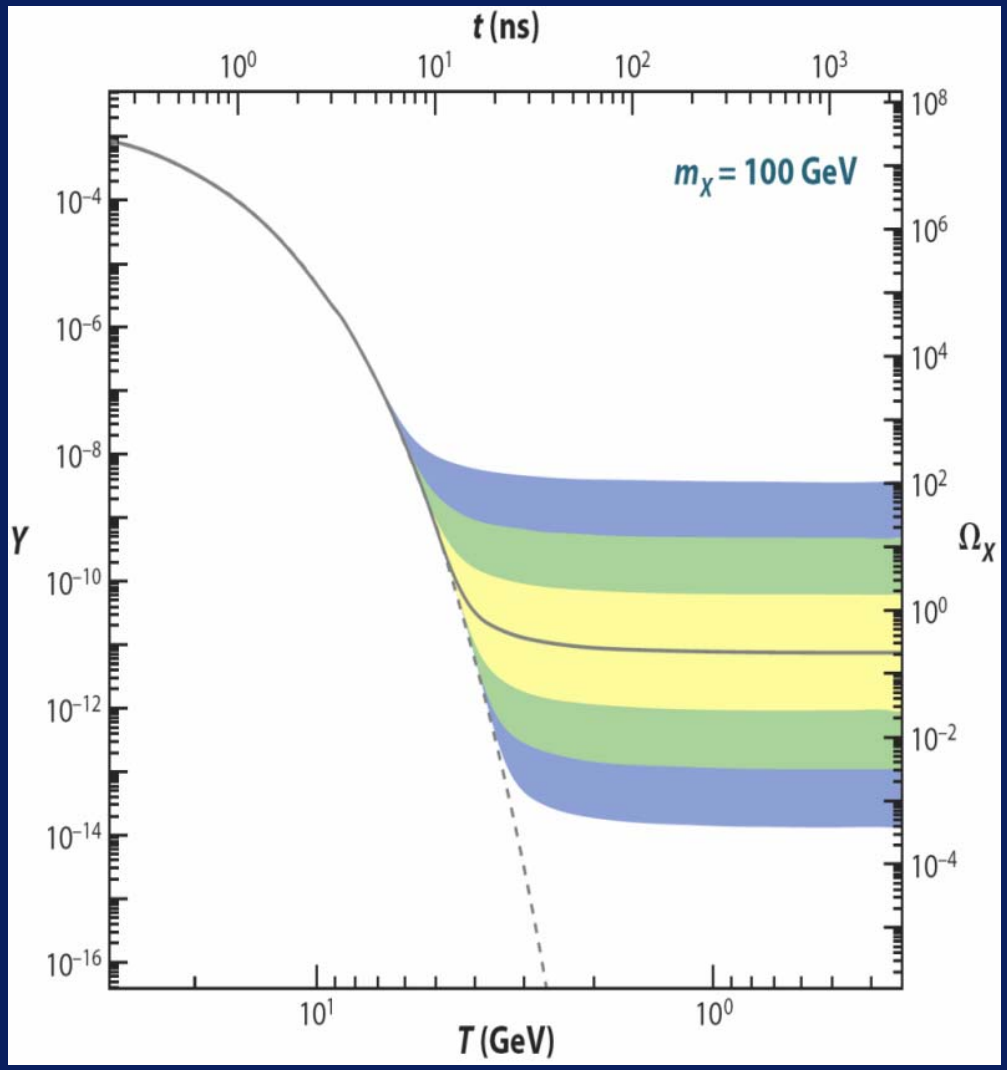
Dark Matter



- Certainty: Dark Matter exists.
- ...And it's cool.
- ...And we have lots of ideas but no certainty about what it is.

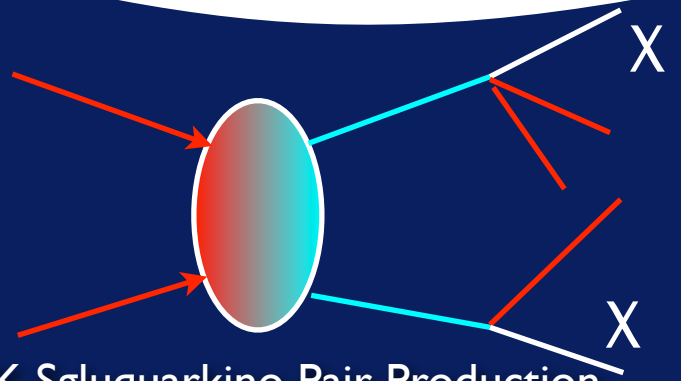
WIMP / Relic Density

- If DM is a thermal relic WIMP, it couples to SM particles with some reasonable strength, and can be produced at colliders in some channel we're looking for.
  - Quarks/gluons/top/bottom
  - Leptons
  - Photons/W/Z/Higgs bosons
- All of these couplings would show up in some kind of search which will be done.
- The question is how heavy the WIMP is what the backgrounds are.

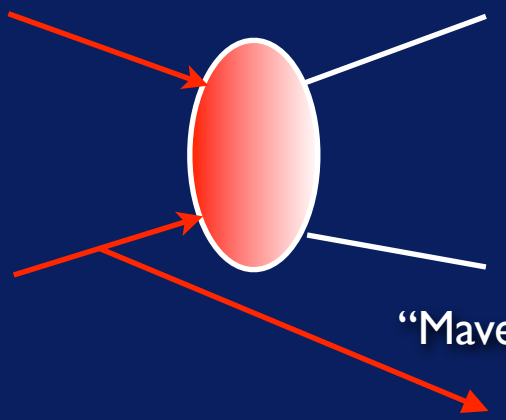


Production at Colliders

- If WIMPs interact with quarks and gluons, meaning our direct detection experiments are relevant, we can also produce them at hadron colliders.
- For specific UV theories we're interested in (like SUSY), we can study them directly.
  - Simplified Models can help keep things more generic. (e.g. for putting limits or making initial discoveries).
  - Eventually we will need a more detailed description of some kind.
- Effective theories are particularly useful when the WIMP is the only relevant new particle.



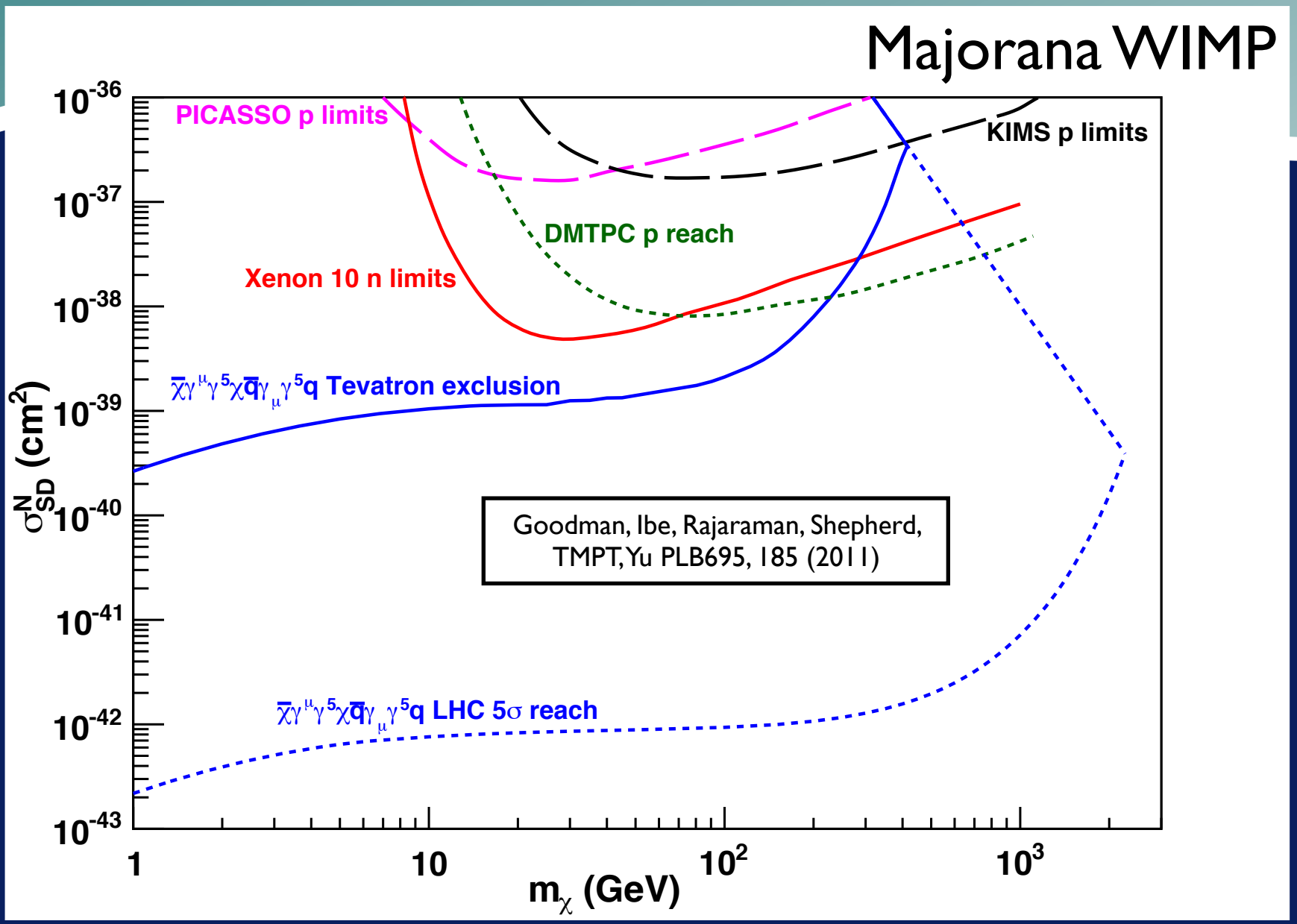
"KK Sgluquarkino Pair Production Followed by Decay into WIMPs"



"Maverick Production"

Feng, Su, Takayama PRL hep-ph/0503117; Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037

...to Direct Detection

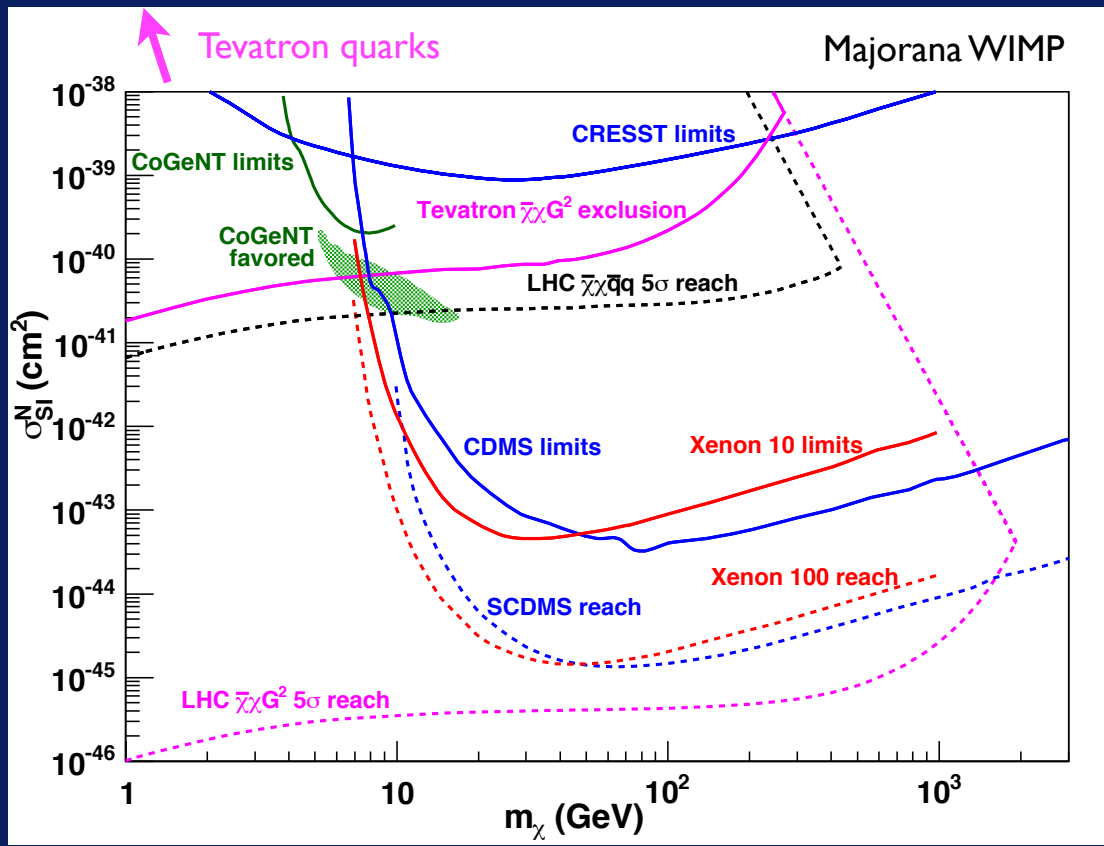


Roni showed us similar results from Bai, Fox, Harnik...

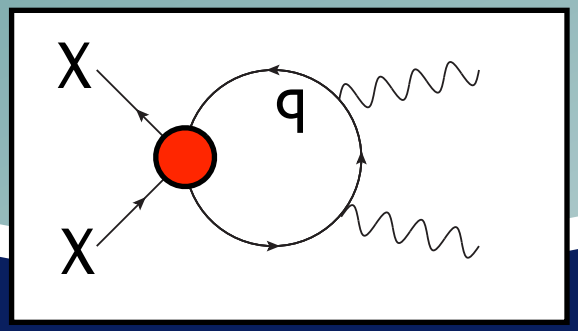
Colliders and Mavericks

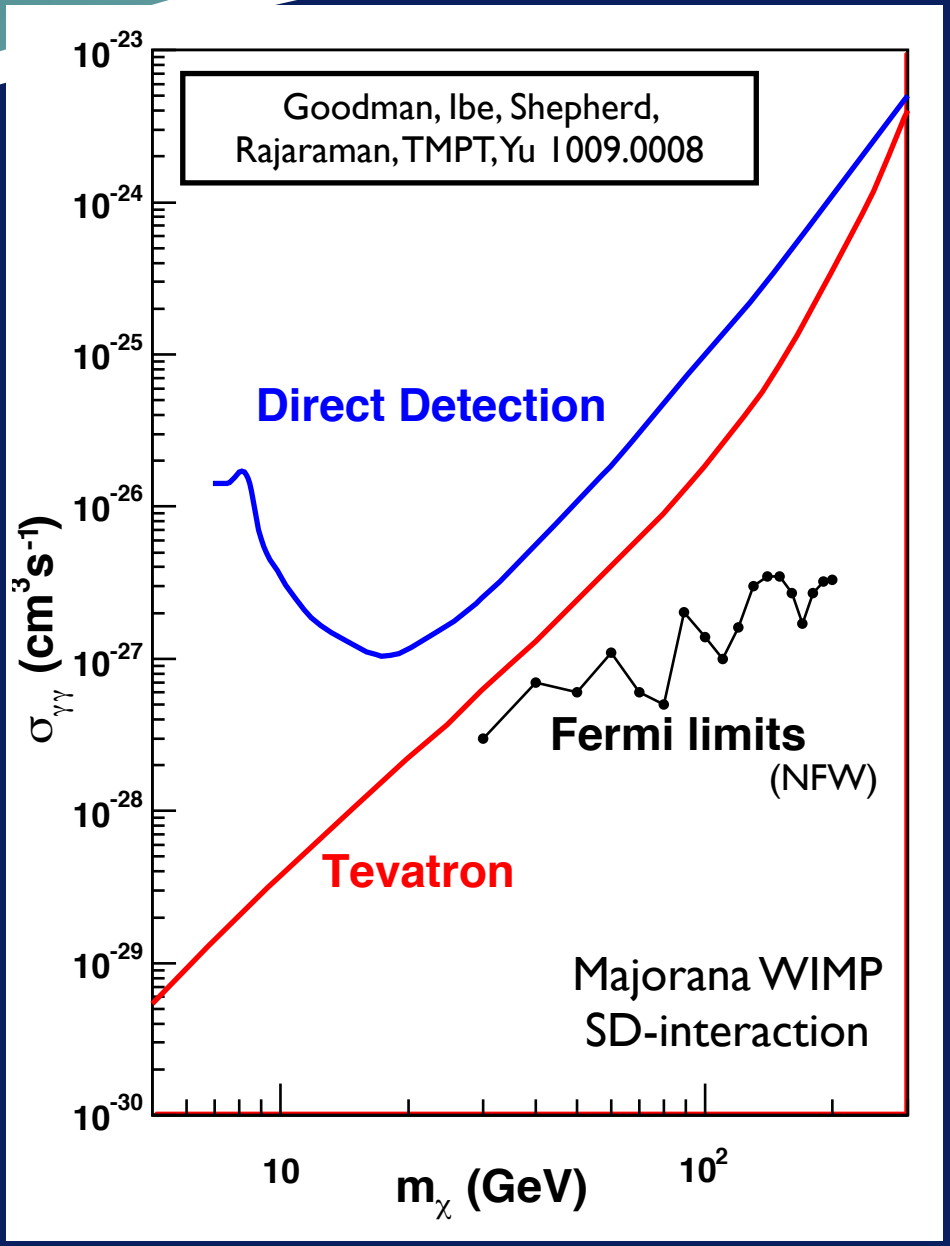
- Colliders are an interesting (orthogonal) take on WIMP-parton interactions.
  - High energy collisions see the nucleon incoherently.
- We can get information about (a linear combination of) individual partons, with no possibility of destructive interference.
- In principle, signals at multiple collision energies or even the distributions of MET/HT give *some* information about which partons are most important.

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu PLB 695, 185 (2011)



Implications...



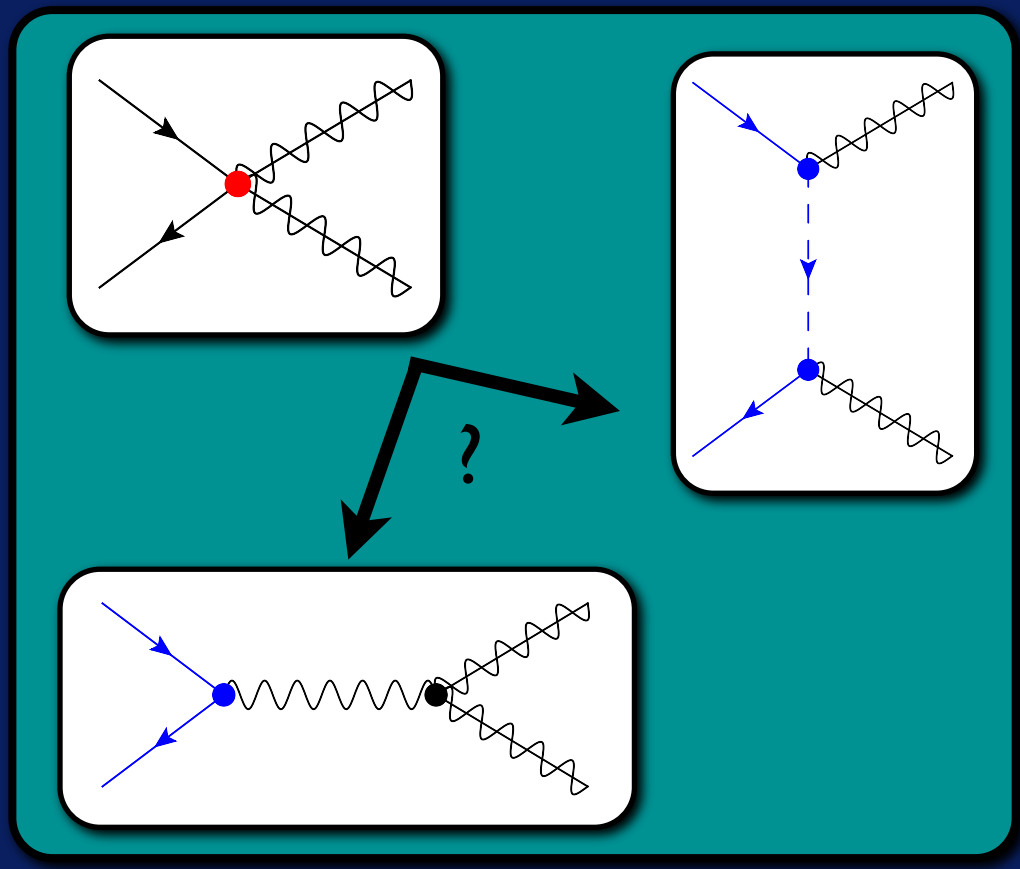


- With some more assumptions, an effective theory can have an impact on indirect detection as well.
- For example, operators map into gamma ray line features, and can be bounded using Fermi data.
  - (This particular operator contributes UV-finitely at 1-loop).
- Colliders continue to cover the low mass region in a way that is difficult for other kinds of experiments to reach.

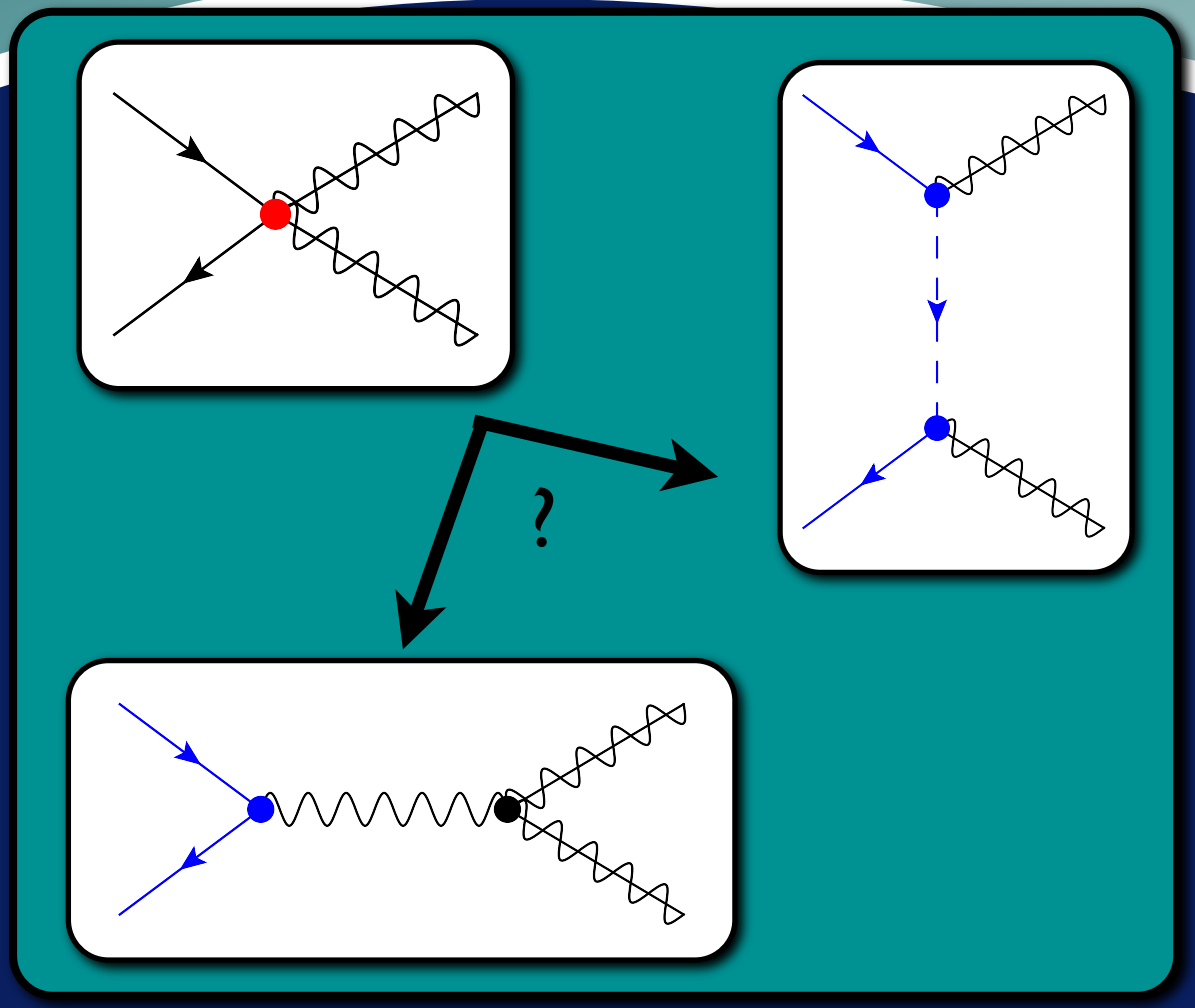
Uncertainties

How Effective a Theory?

- How good is the EFT approximation?
- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \text{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in SUSY-like theories, problematic for quirky WIMPs or maybe co-annihilators.
- Colliders: $Q^2 \sim p_T^2$
  - Bounds are generically too conservative for colored mediators.
  - Too stringent for light neutral mediators.



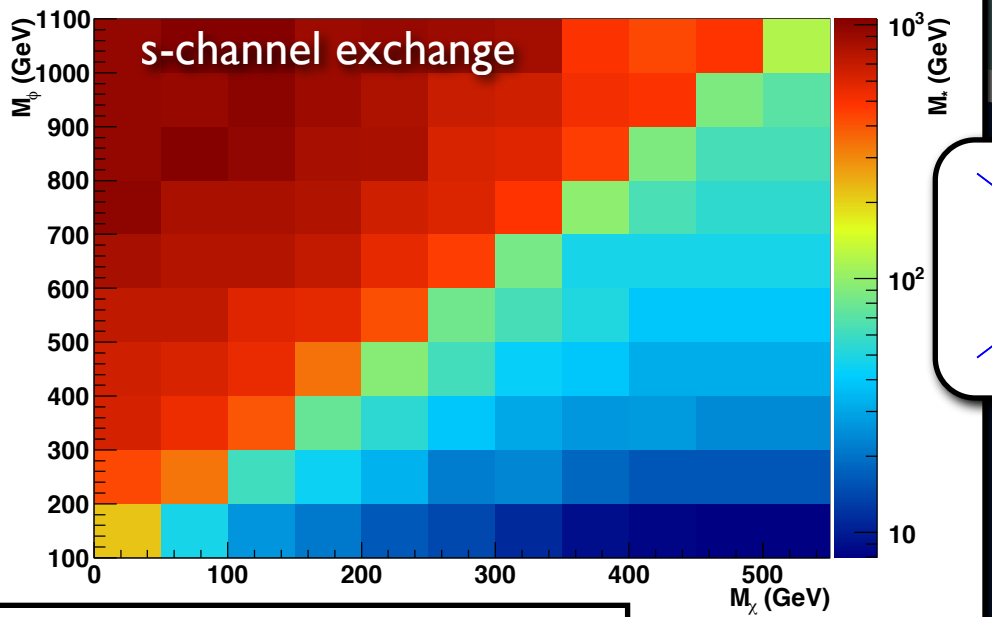
How Effective a Theory?



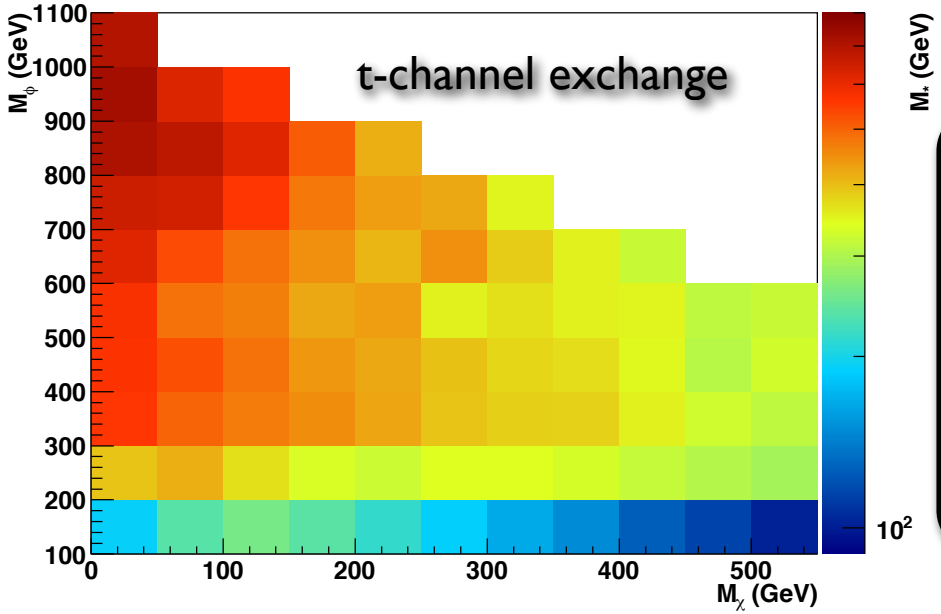
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

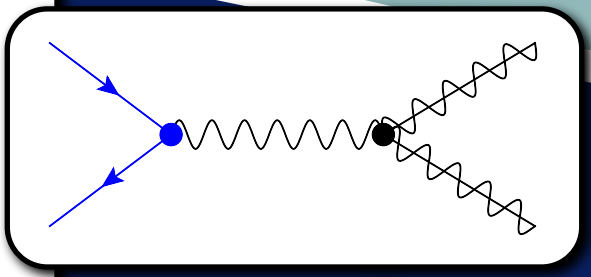
"s-channel" mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

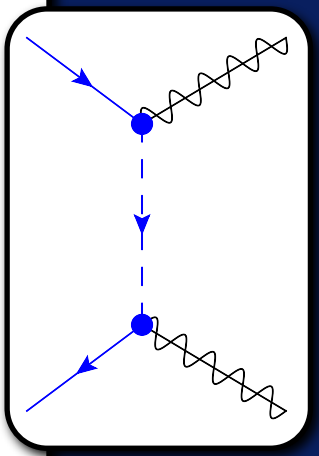
How Effective a Theory?



Goodman, Shepherd 1111.2359

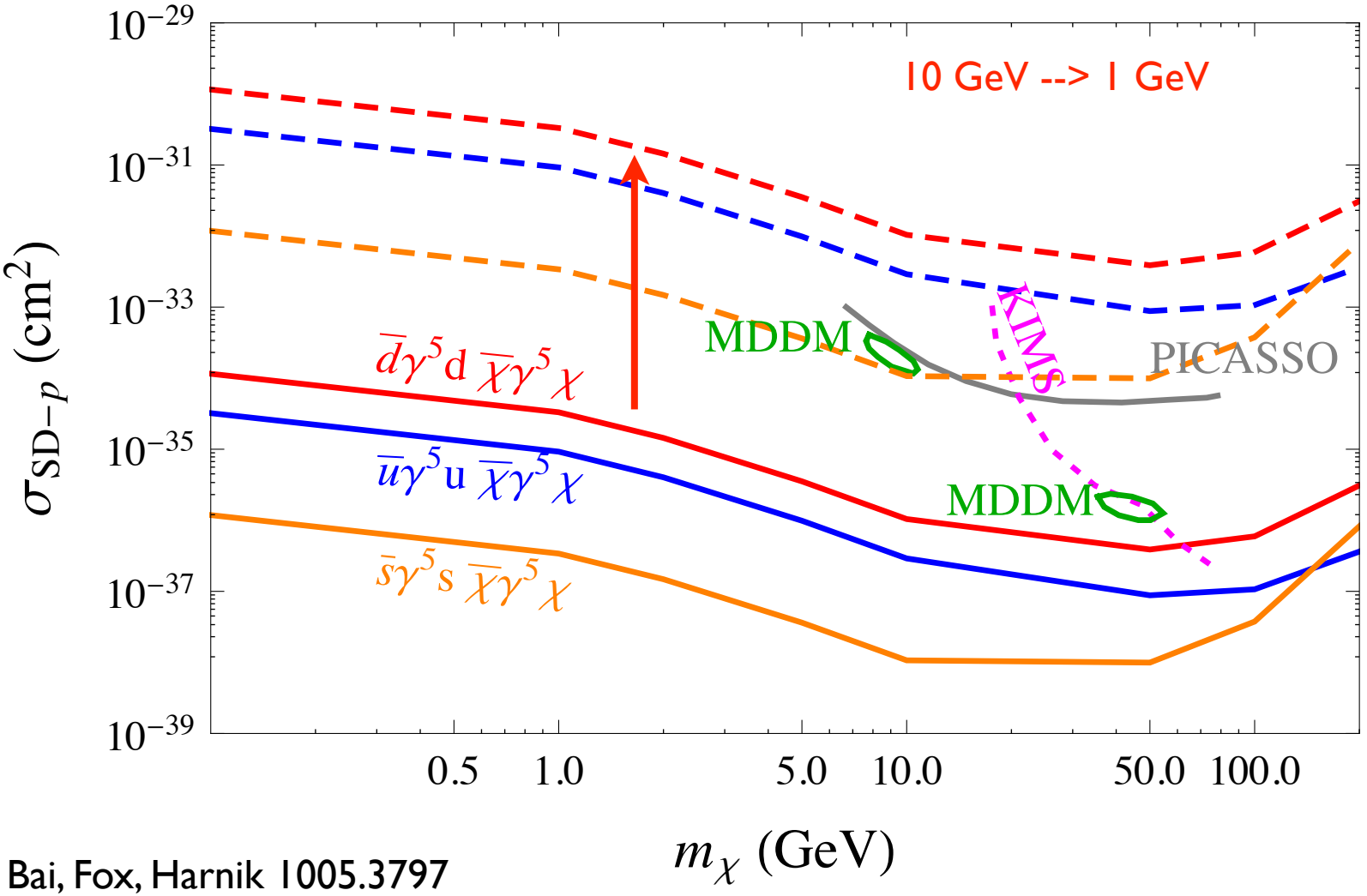






- When the effective theory breaks down (see Maxim, Roni, and Ian for discussions), technically we need a different theory.
- Simple UV-completions can help us understand how much it matters and whether other searches can cover these regions of parameter space.
- Ultimately, we can think of the EFT as a corner of the parameter space of a simplified model.

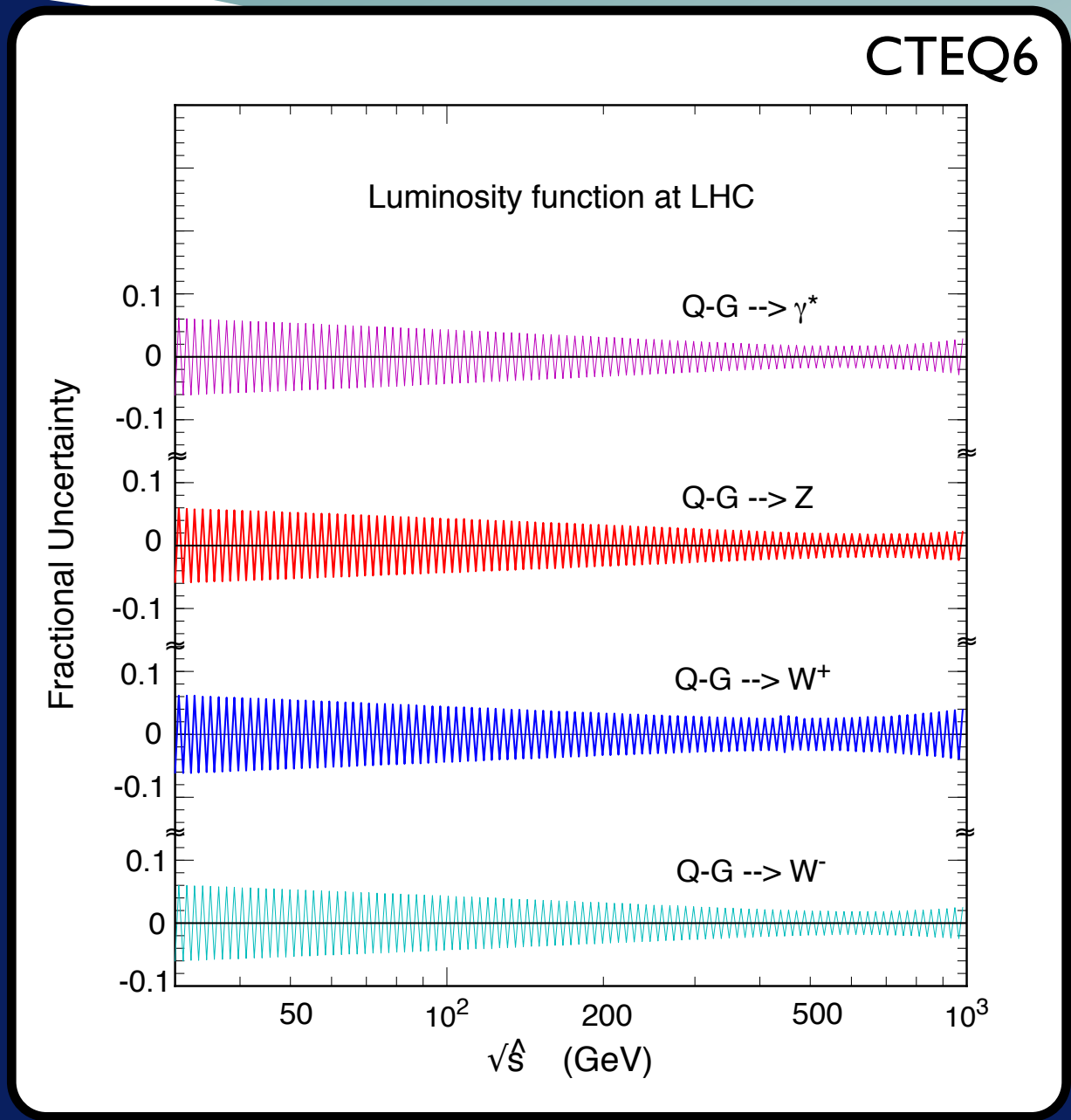
How Effective a Theory?



Bai, Fox, Harnik 1005.3797

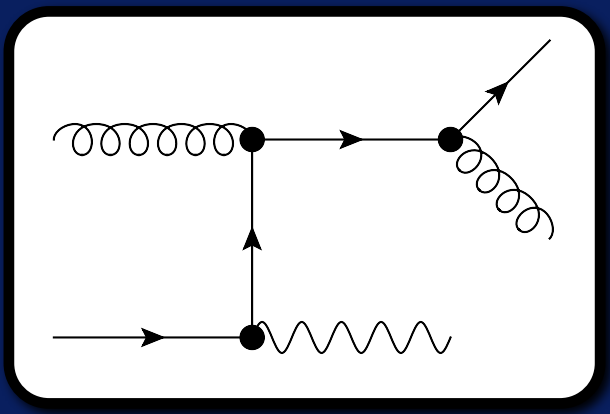
The usual suspects...

- PDFs
  - The bane of existence at a hadron collider.
  - Not "so" bad here.
- Quoted errors on the integrated PDF are less than about 10%
- Central values between, for example, CTEQ and MSTW typically differ by more than the quoted errors. (PDF fitting is a black art!).



Higher Orders

- (Irreducible) Backgrounds are coming under control at NLO due to heroic efforts.
- Simple searches need things like Z + jet, which exist at NLO.
- Huge progress! For example, Z + 2 jets:



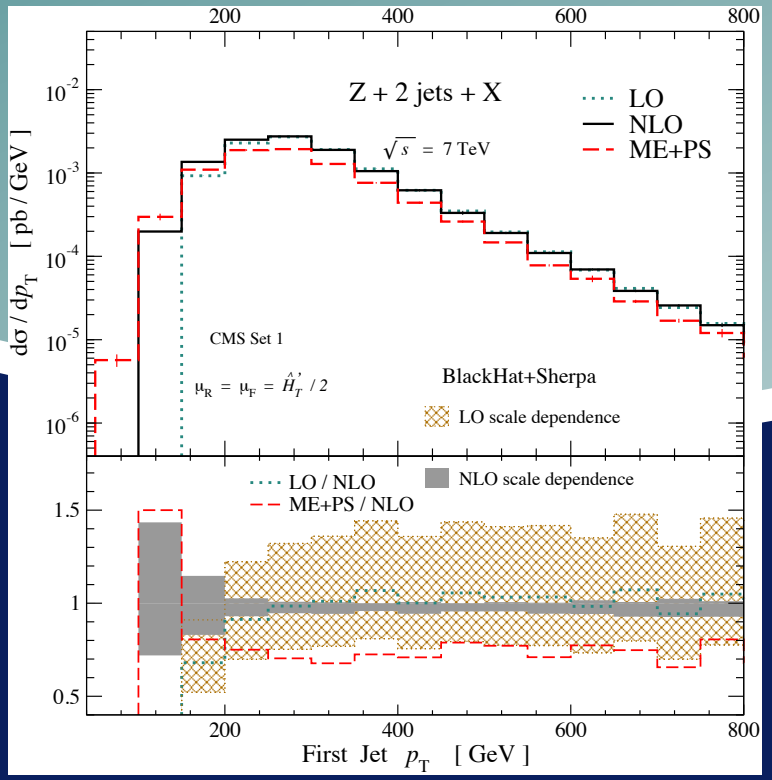
"Set One" Cuts

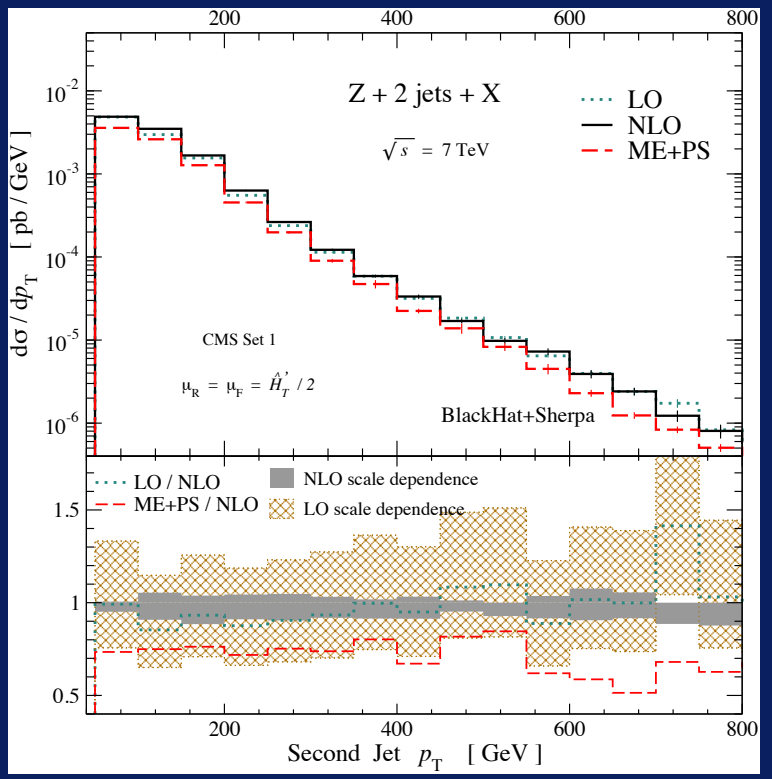
$HT^{>50} > 300$ GeV

$MET^{>30} > 250$ GeV

Bern, Diana, Dixon, Febres Cordero, Hoche, Ita, Kosower, Maitre, Ozeren arXiv:1106.1423

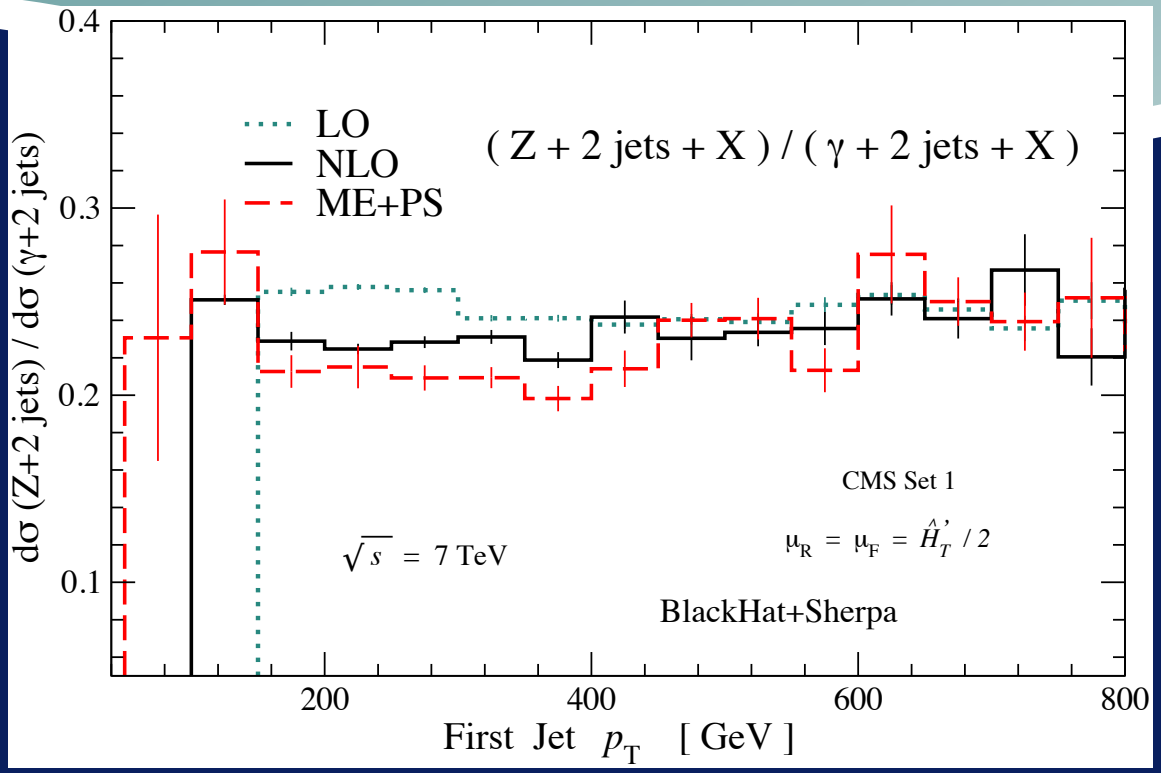
- Lance promises Z + 4 jets is on the way.





Data-Improved

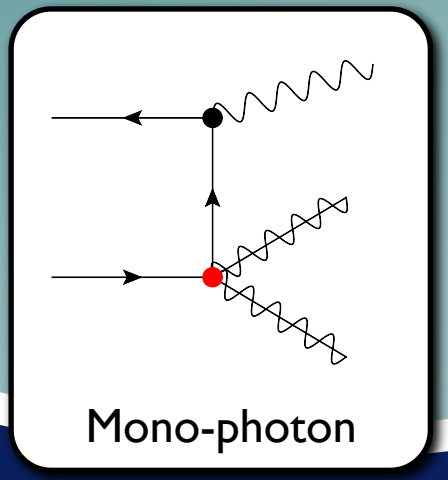
- One can imagine using γ + 2 jets as a control to data-improve the background.
- This is not entirely straightforward, one needs isolation criteria (e.g. Frixione) to define the photon.
- That still requires theoretical control over the ratio to implement reliably.
- One could also look at Z->μμ + 2 jets, which has a smaller branching ratio, but not hopelessly so.



Bern, Diana, Dixon, Febres Cordero, Hoche, Ita, Kosower, Maitre, Ozeren arXiv:1106.1423

Ultimately, it may be more effective at higher luminosities to just transition to mono-photon or mono-Z searches.

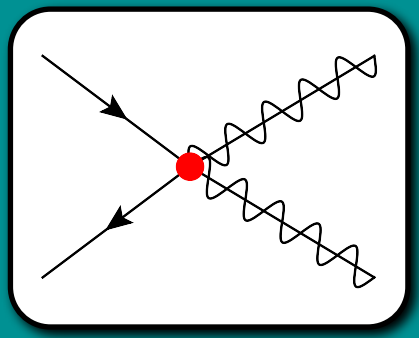
Maverick Signal
(Monojet)



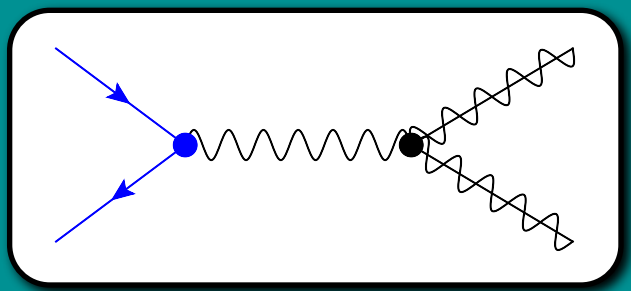
- No NLO calculation for DM.
  - The "mono-photon" signal recently appeared at NLO.

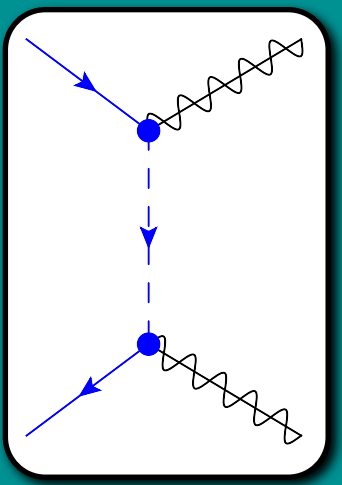
Wang, Li, Shao, Zhang arXiv:1107.2048

- For monojets, higher orders can distinguish operators that would otherwise Fierz into each other.
  - NLO reshuffles the sensitivity to UV physics.
- Let's look at the background and come back to the signal.

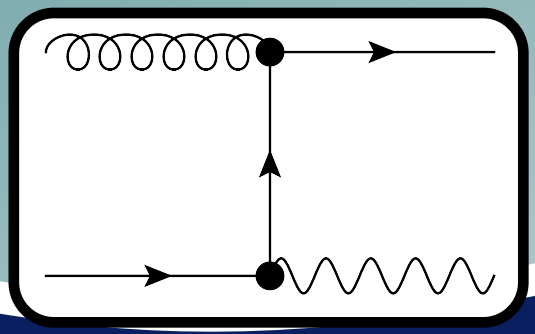


$$\bar{q}\gamma_\mu q\ \bar{\chi}\gamma^\mu\chi \quad \overset{\text{Fierz}}{\Longleftrightarrow} \quad \bar{q}\chi\ \bar{\chi}q$$





Monojet Background



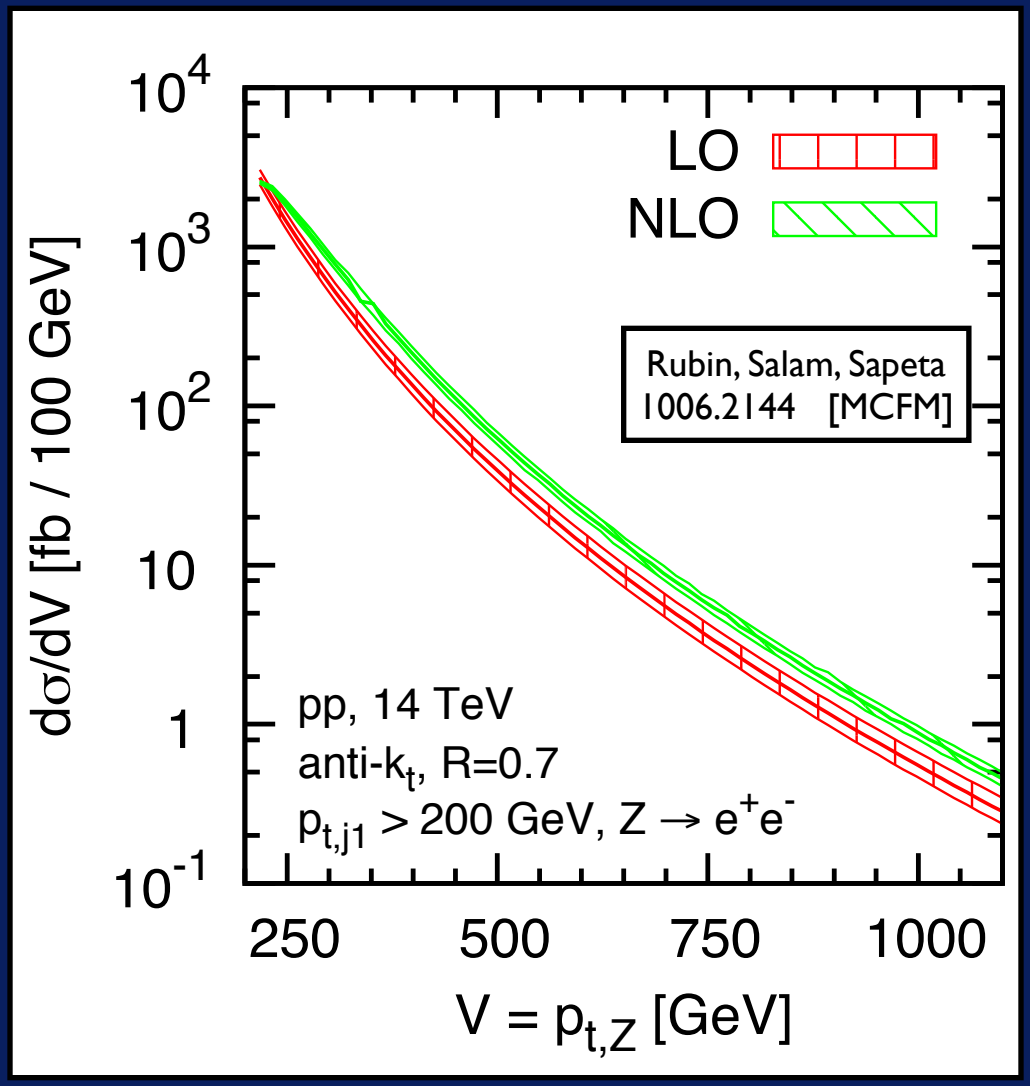
- The primary background is Z + jet.
- This one has actually been known for much longer...

Giele, Glover, Kosower
NPB hep-ph/9302225

- Recent study by Rubin, Salam, Sapeta (arXiv:1006.2144), running MCFM.

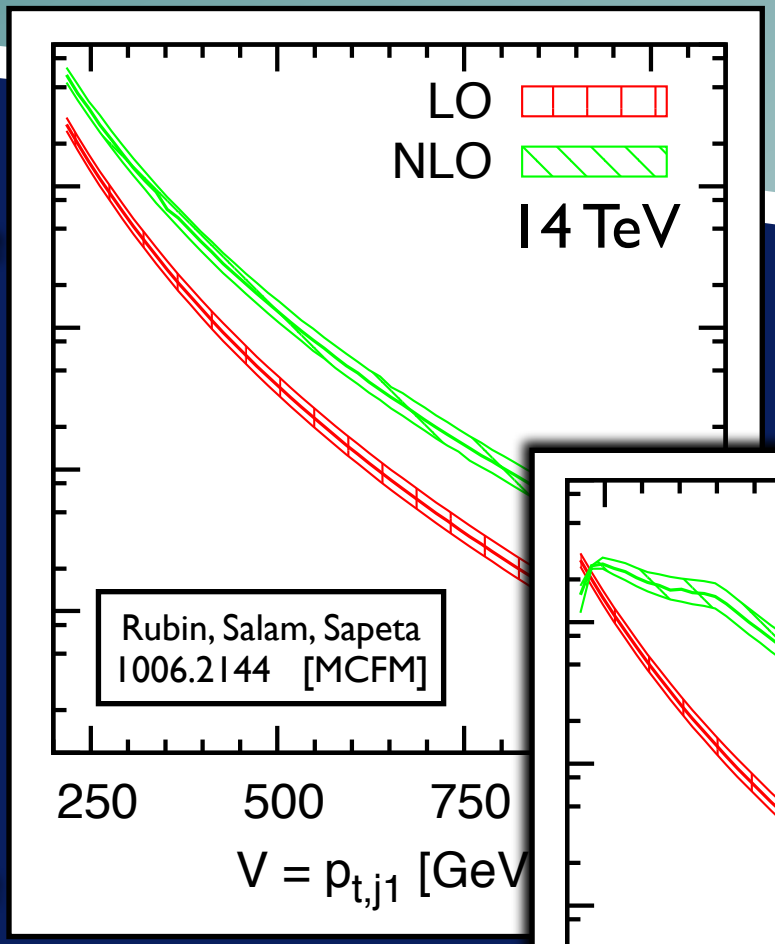
Campbell, Ellis

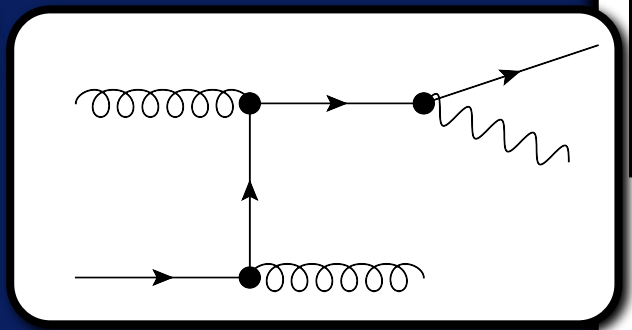
- Results differential in the Z PT (MET) look reasonable, k-factors on the order of 1.5 and not too strongly dependent on PT.

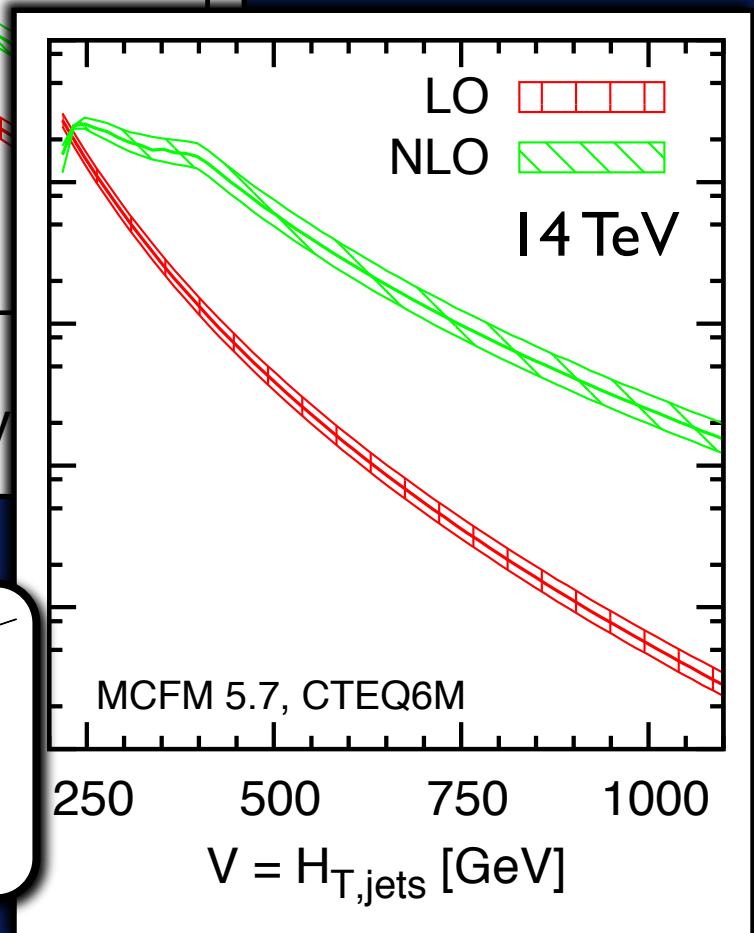


More Distributions

- Plotted versus the PT of the leading jet, the k-factor is a much more alarming factor of ~5 at large PT.
- (How is the LO defined?)
- Plotted versus HT, it gets closer to a factor of 100.
- Salam et al identify the large corrections as arising at NLO from configurations where the Z is "radiated" from a jet whose PT is much greater than the Z mass.

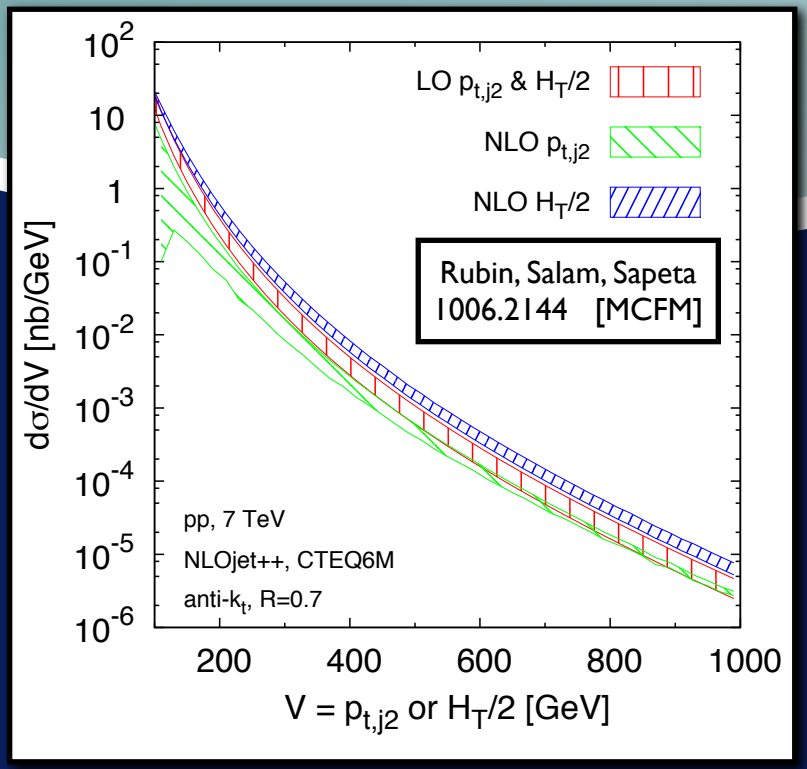






Monojet Backgrounds

- The same enhancements for soft/collinear Z emission are present in Z + 2 jets, but already at Leading Order.
- Essentially, the problem with Z + jet at NLO is that it only has Z + 2 jets at LO.
  - Matched calculations should provide improved predictions.
  - Data-driven background methods are invaluable: measurements such as γ + jets or Z->μμ + jets provide sanity checks.
  - Not just to extrapolate from control to signal region, but for actual "signal" kinematic regions.



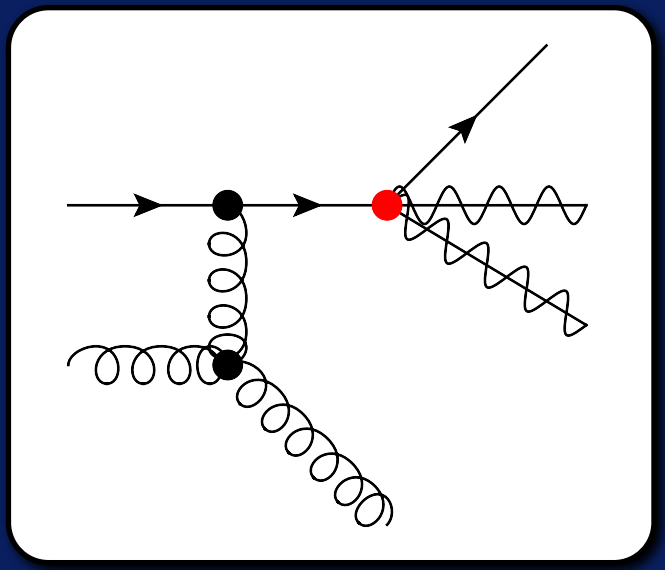
In practice, a monojet search will have vetoes on additional jets and an acollinearity cut.

Both of these will help reduce the impact of the ~collinear Z effects.

(But jet vetoes should make you nervous, too...)

How about the Signal?

- The signal can potentially enjoy the same kind of soft/collinear enhancement (if DM is light).
- A large k-factor would be nice, except that unlike the background, we can't use control measurements to figure it out precisely.
  - It would be good to have the NLO at hand to at least do some sanity checks.
  - And that would be the first step in bringing the tools up to the same level of sophistication as the background.
- If we can't normalize the signal, we can't reliably map the bound (discovery) into the direct detection parameter space (etc).



This issue is inherent in any search using monojets that involves light states-- such as ADD gravitons.

N-Jettiness?

- We may be able to profit from some of the strategies currently being explored in other small jet-number processes.
- For example, "n-jettiness" has been proposed to resum logs in Higgs production and provide more stable jet vetoes.

$$\tau_N \equiv \frac{2}{Q^2} \sum_k \min \{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, ..., q_N \cdot p_k\}$$

q_i: N massless jet 4-momenta
q_a,q_b: "Beam jets"

τ_N -> 0: There are N perfectly massless jets aligned with the q_i.
τ_N -> 1: There are additional hard emissions.

- If the "mono" part of the DM search is buying us something, that could be a way to go. (Given the FNAL razor analysis, not clear it is).
- It's probably not going to help much with approximately collinear Z emissions.

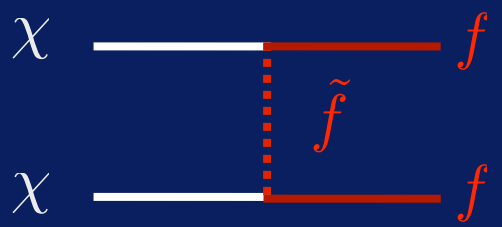
Outlook

- Colliders are an important piece of covering dark matter parameter space.
  - Particularly useful for very light WIMPs, for interactions which are suppressed when WIMPs are non-relativistic, or if there are colored particles which like to decay into dark matter.
- Searches are useful either to make colored particles which decay into WIMPs, or to produce WIMPs directly when mediators are heavy.
  - Like any search, there are uncertainties associated with the inputs: PDFs, cross sections, etc, and some observables are more robust than others.
    - In the case of monojet searches, better understanding of the signal and perhaps observables like N-jettiness could be helpful.
  - Ok, so let's make some dark matter. Anyone see what the beams are doing this afternoon....?

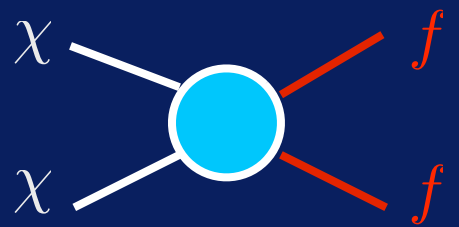
Bonus Material

Example EFT: Majorana WIMP

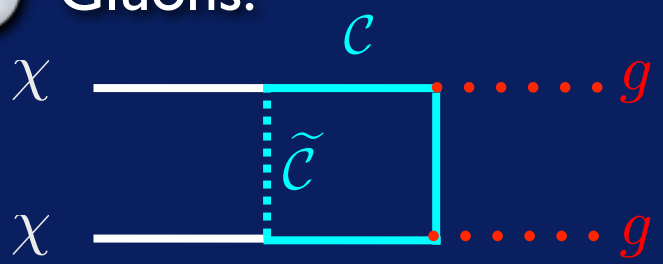
- Here are pictures for how a Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



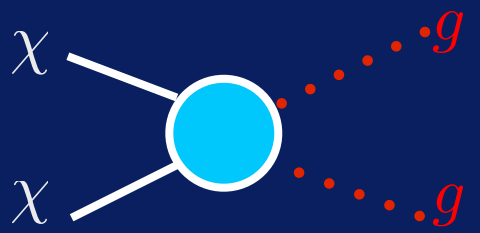
$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



  - Gluons:

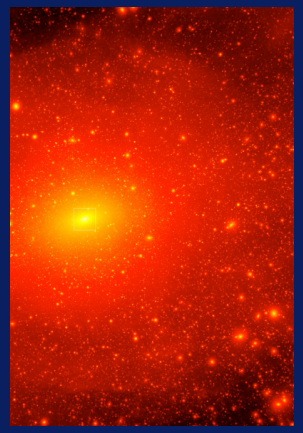


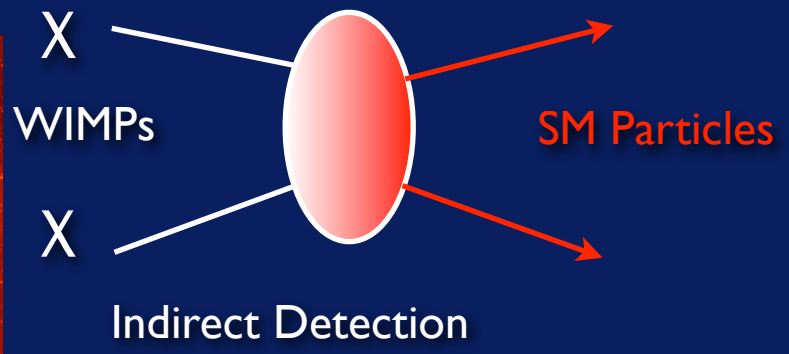
$$\sim \alpha_S \frac{g^2}{M_c M_{\tilde{c}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



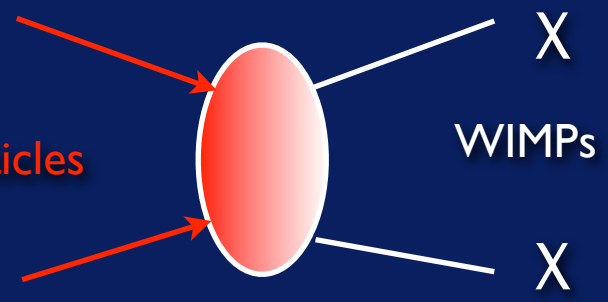
  - Each requires new states with masses heavier than the WIMP.

WIMP Searches

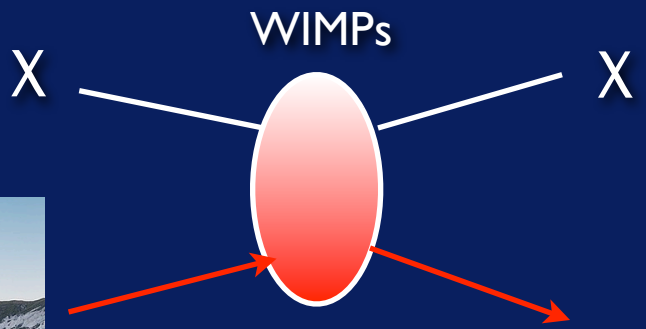




Indirect Detection



Collider Searches



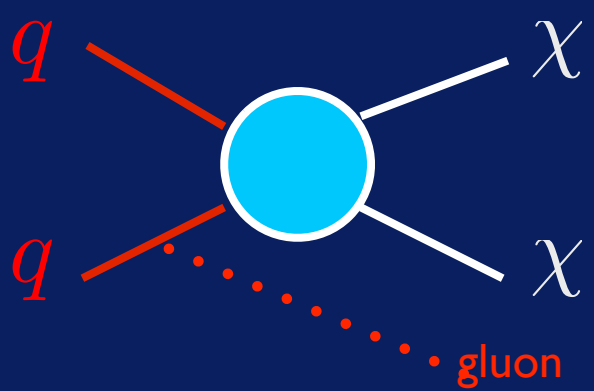
Direct Detection

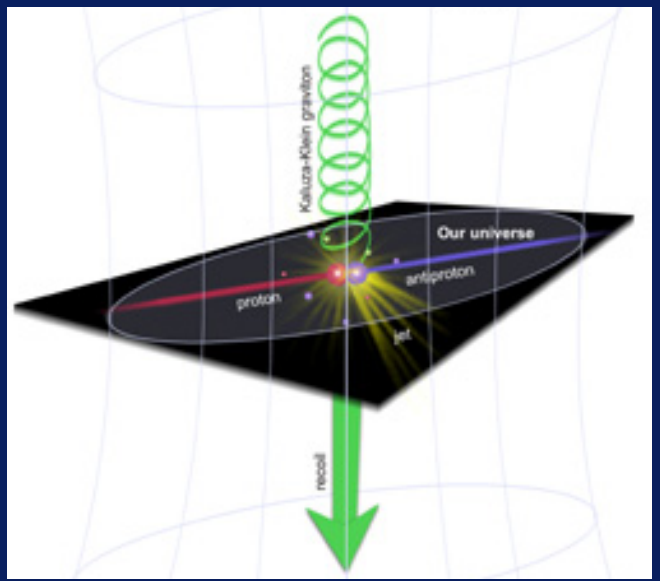
- WIMPs interacting with SM particles allow indirect searches for annihilation products, direct scattering searches, and production at colliders.

CDF Search

- The Collider Detector at Fermilab has already performed a search for our signature.
- They were not actually searching for dark matter, but for a kind of theory with large extra dimensions.
- In this theory, gravity becomes strong at the TeV scale and high energy collisions produce gravitons which escape into the extra dimension.

CDF, 0807.3132





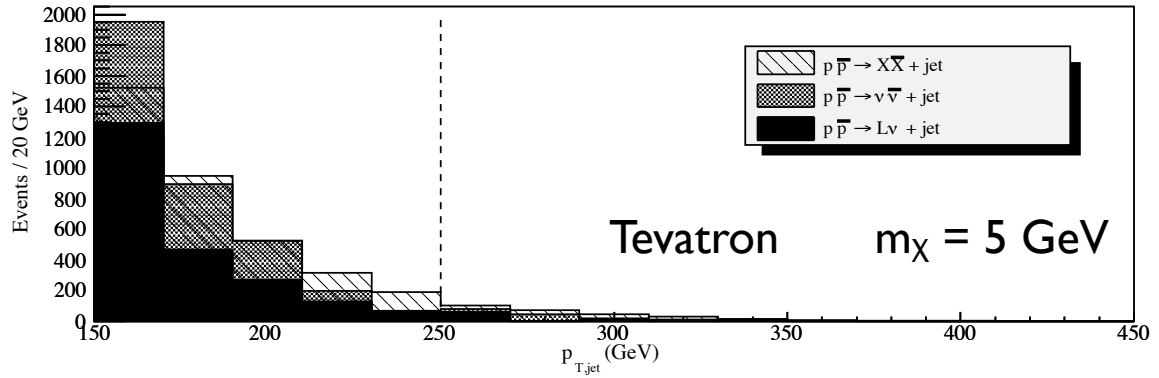
- Having escaped our four dimensional world, the gravitons look like missing energy.
- I'll reinterpret their results to learn something about WIMPs!

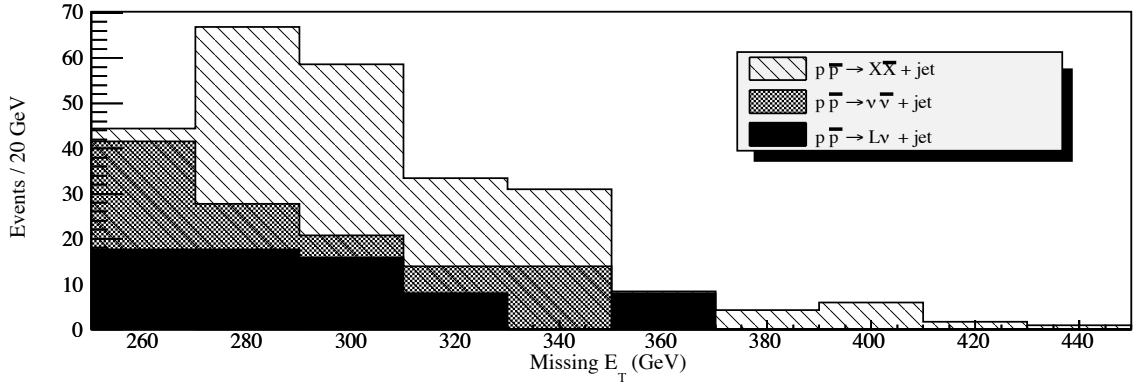
Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

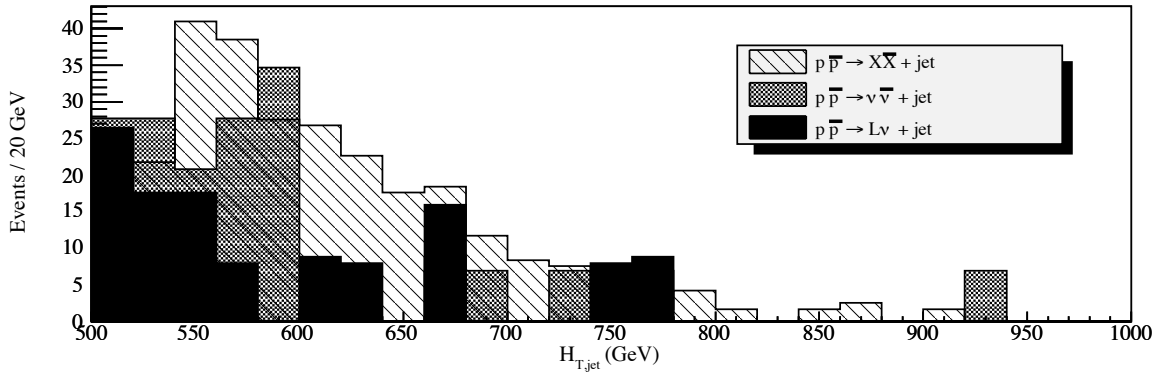
Signal and Background

Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

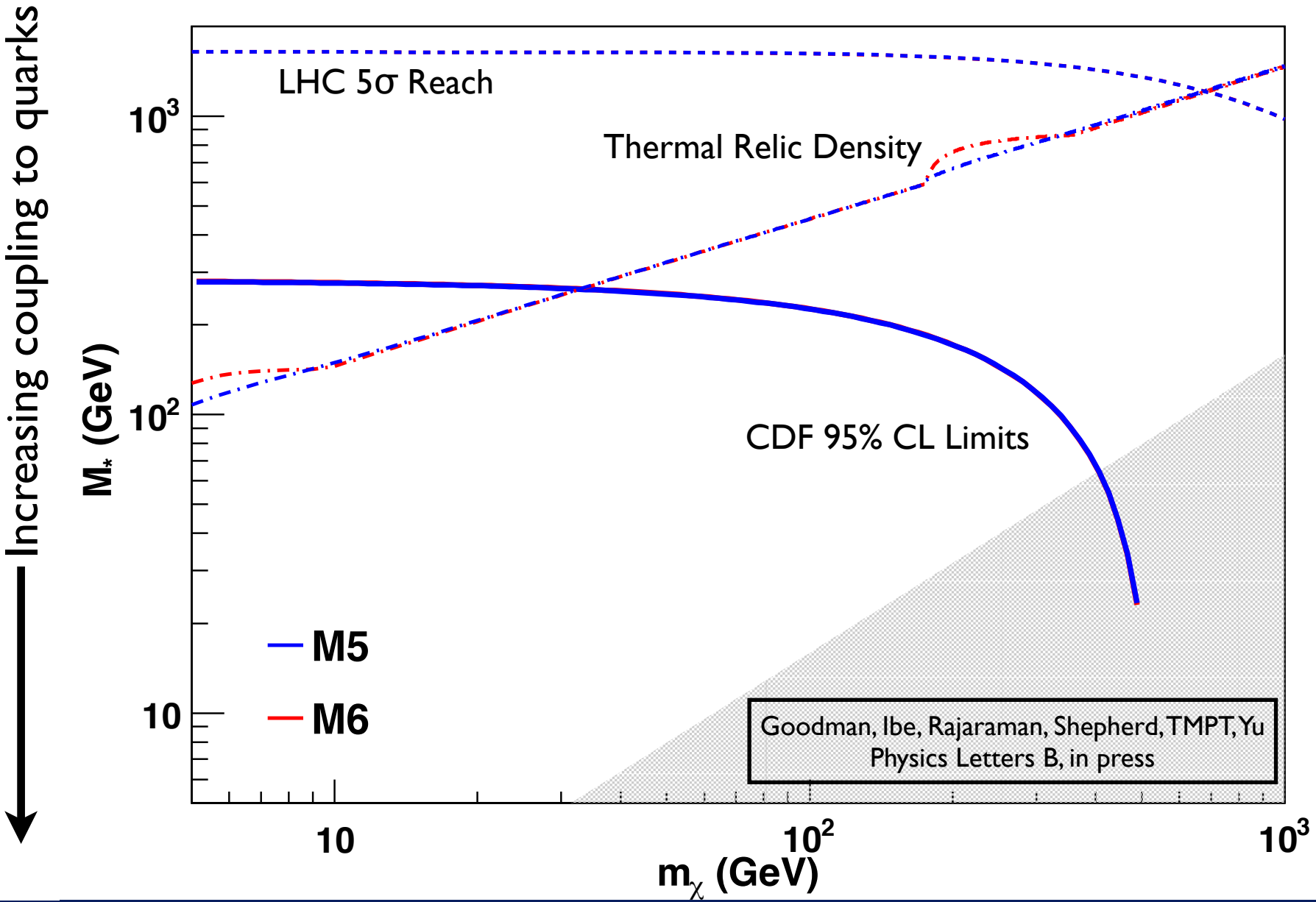
- The WIMP signal results in events containing higher average missing energy than the Standard Model background processes.
- Based on our projections, a CDF group is currently performing the more optimized search we suggested.
- Until that is ready, we rely on the existing CDF search for large extra dimensions.

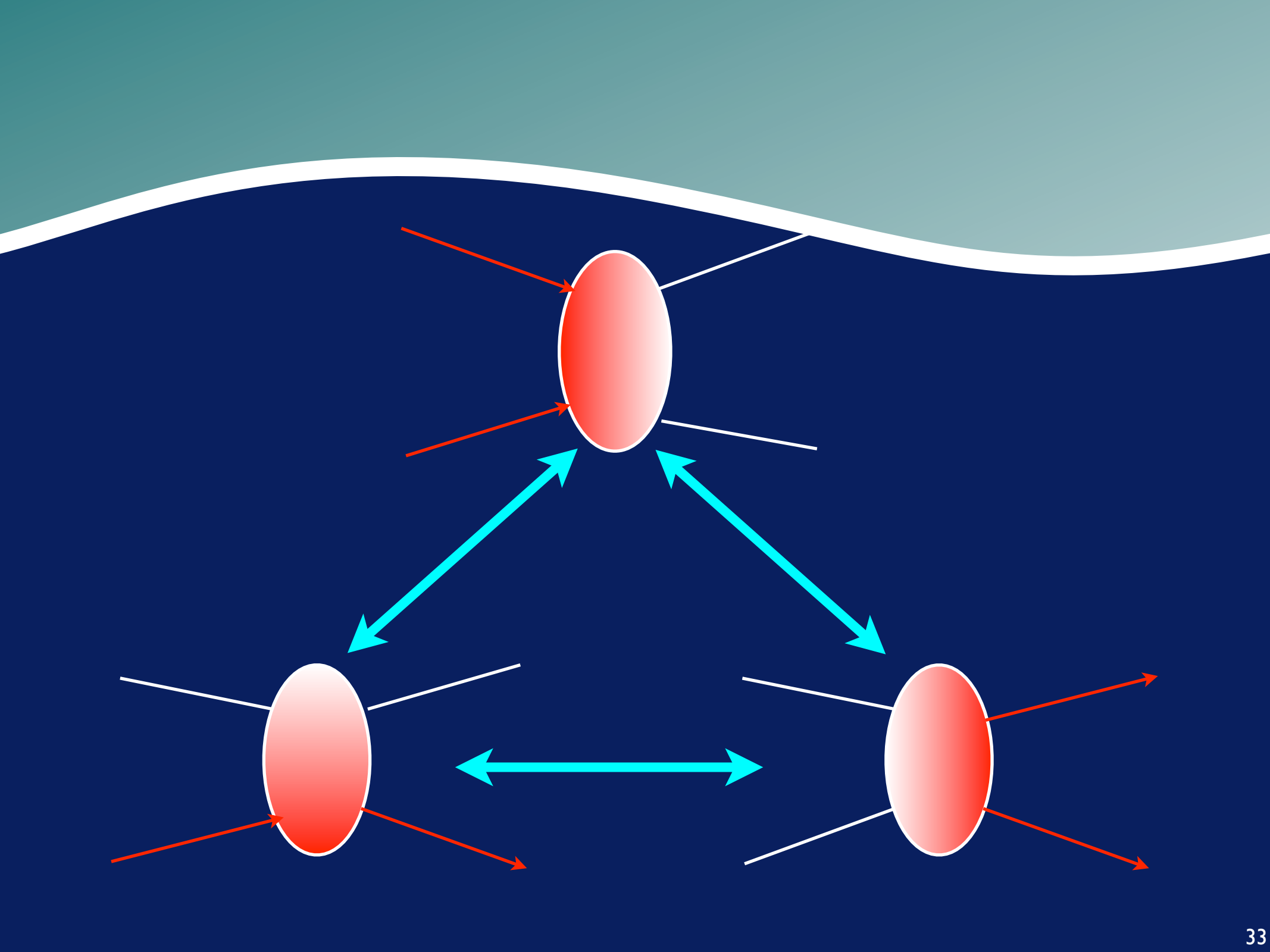


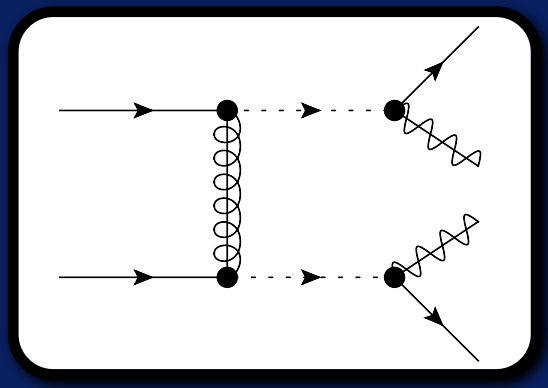
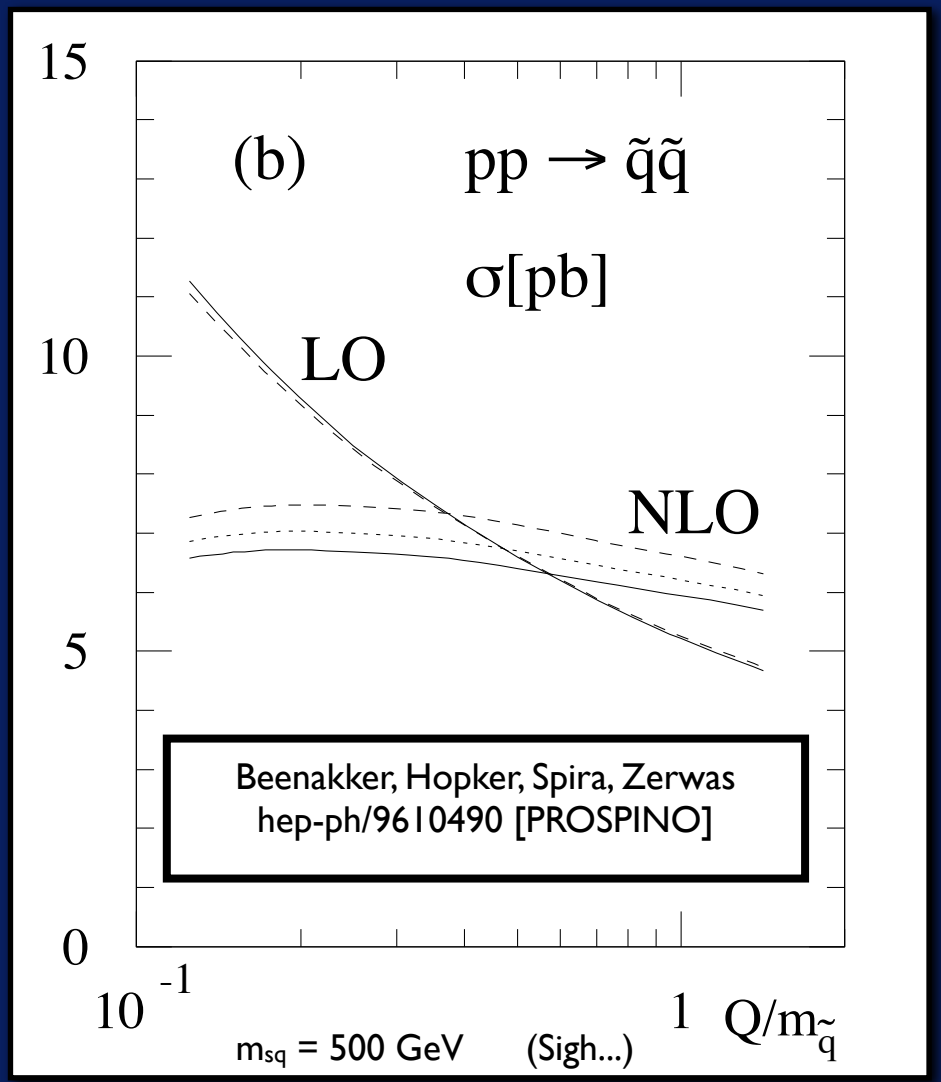




Example of Limits/Sensitivity





Higher Order QCD

- Higher order calculations for SUSY signals have existed for some time.
- E.g. Squark Pair Production
  - MET + 2 jets
- NLO shows much more stability with respect to renormalization/ factorization scales.
- Corrections are relevant, but look "reasonable".