Certainties and Uncertainties in Collider Searches for Dark Matter

Tim M.P. Tait

University of California, Irvine

DMUH11, CERN

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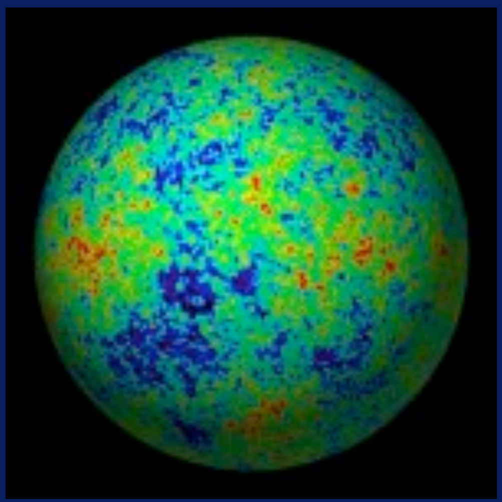
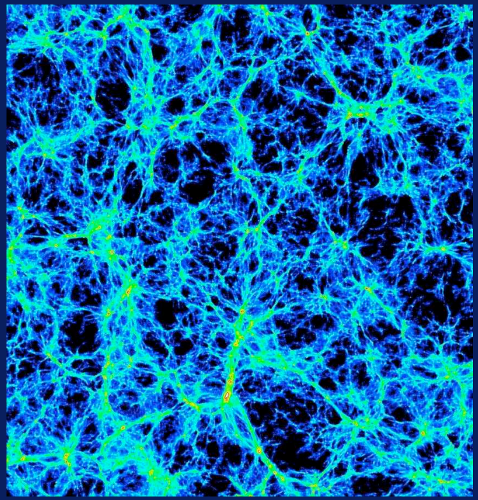
Outline

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

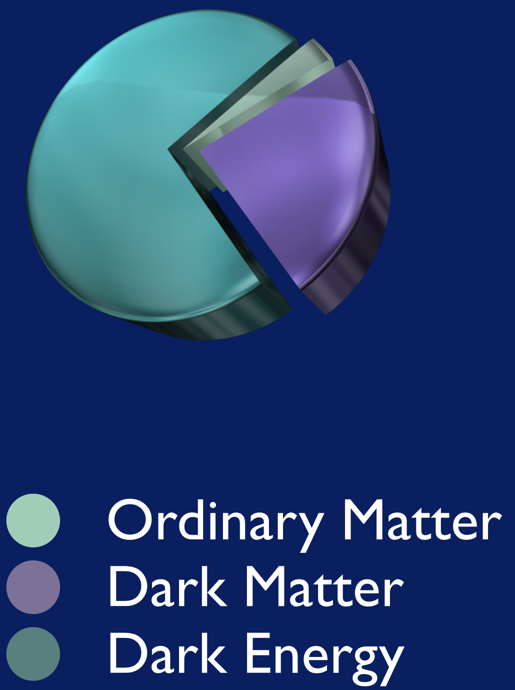
Certainties

Dark Matter





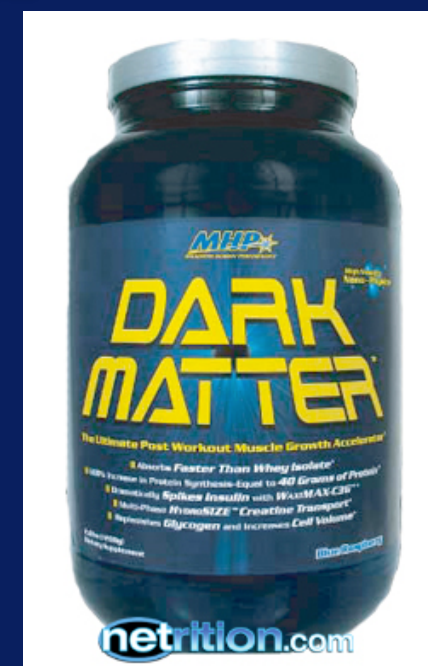
- Certainty: Dark Matter exists.



Dark Matter

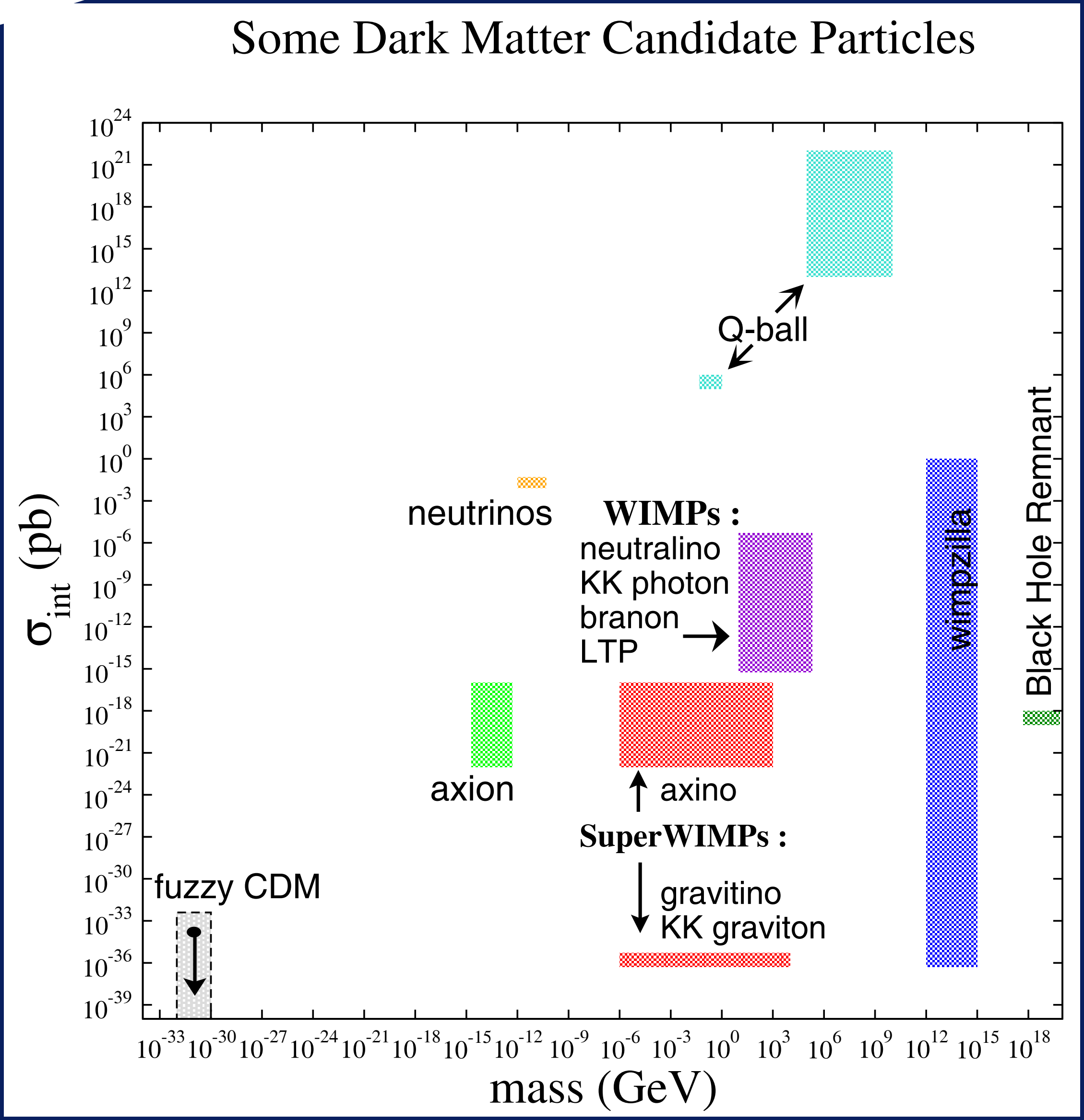
"Cold Dark Matter: An Exploded View" by Cornelia Parker

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



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

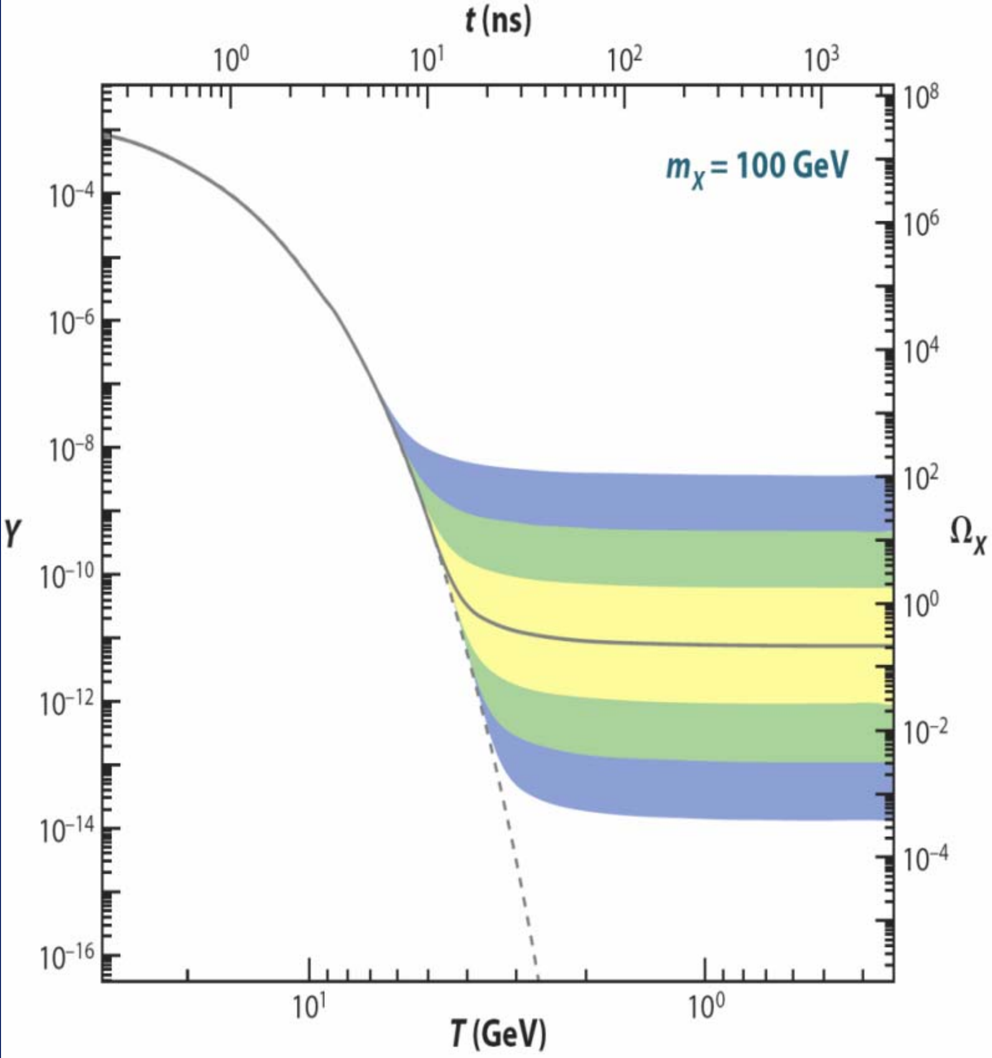
Dark Matter



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

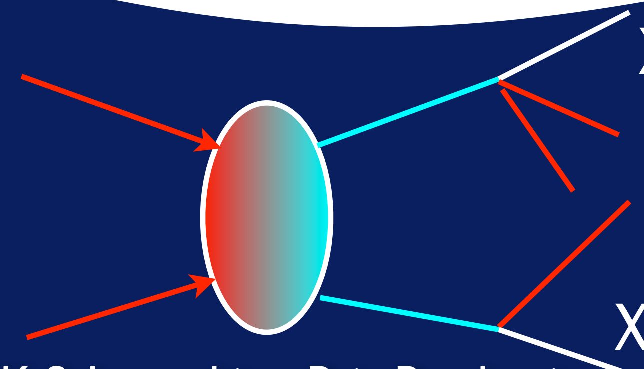
WIMP / Relic Density

- 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.

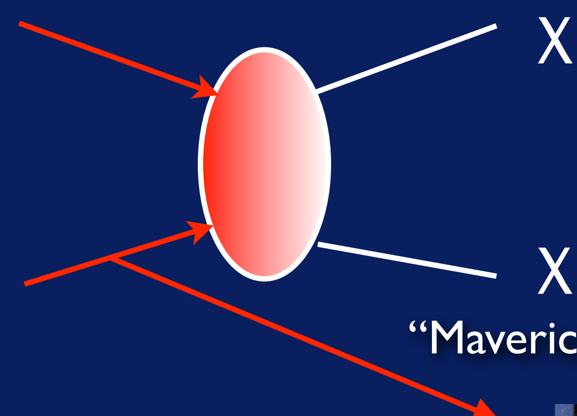


Production at Colliders

- 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.



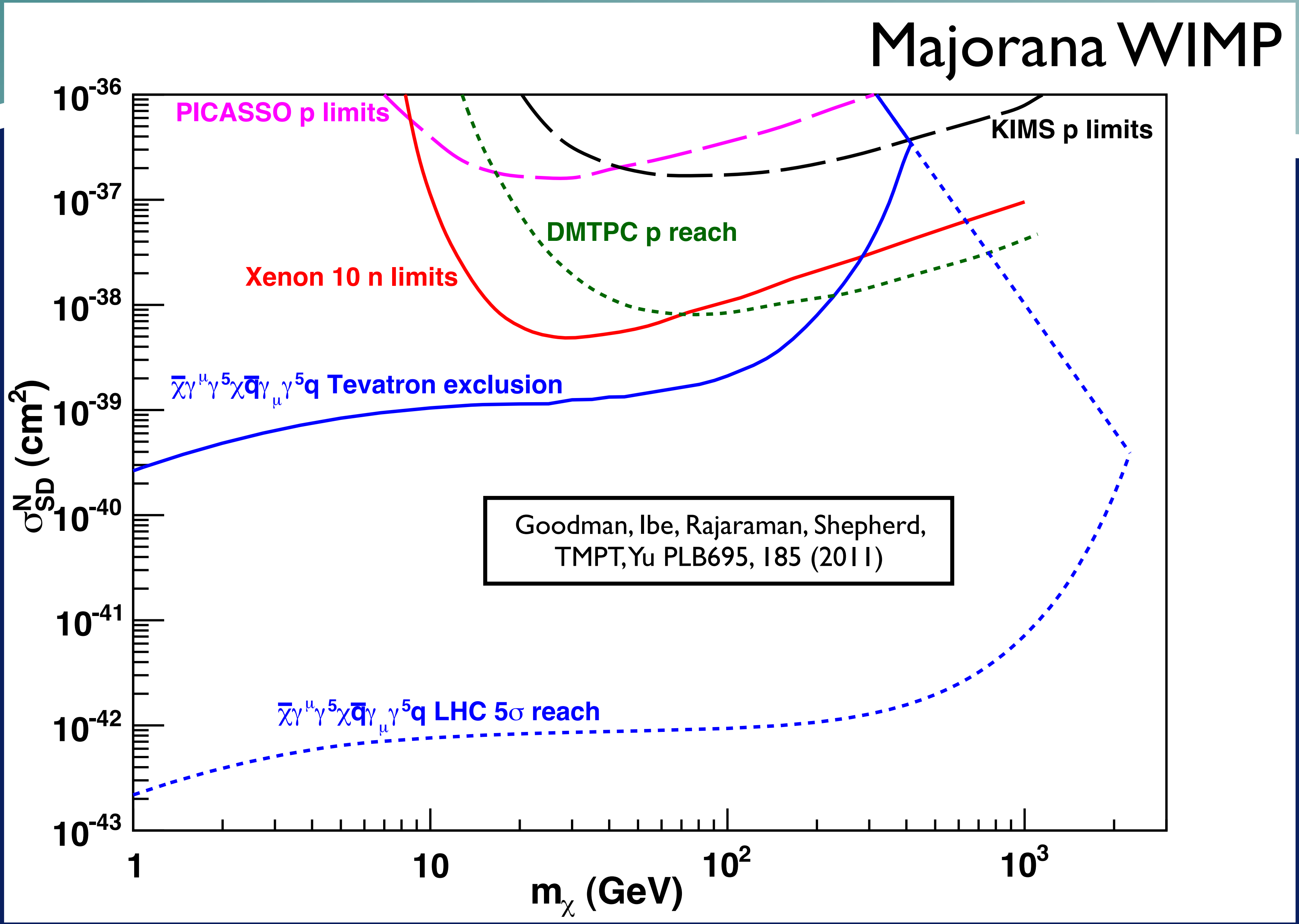
"KK Sgluquarkino Pair Production Followed by Decay into WIMPs"



"Maverick Production"

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

...to Direct Detection

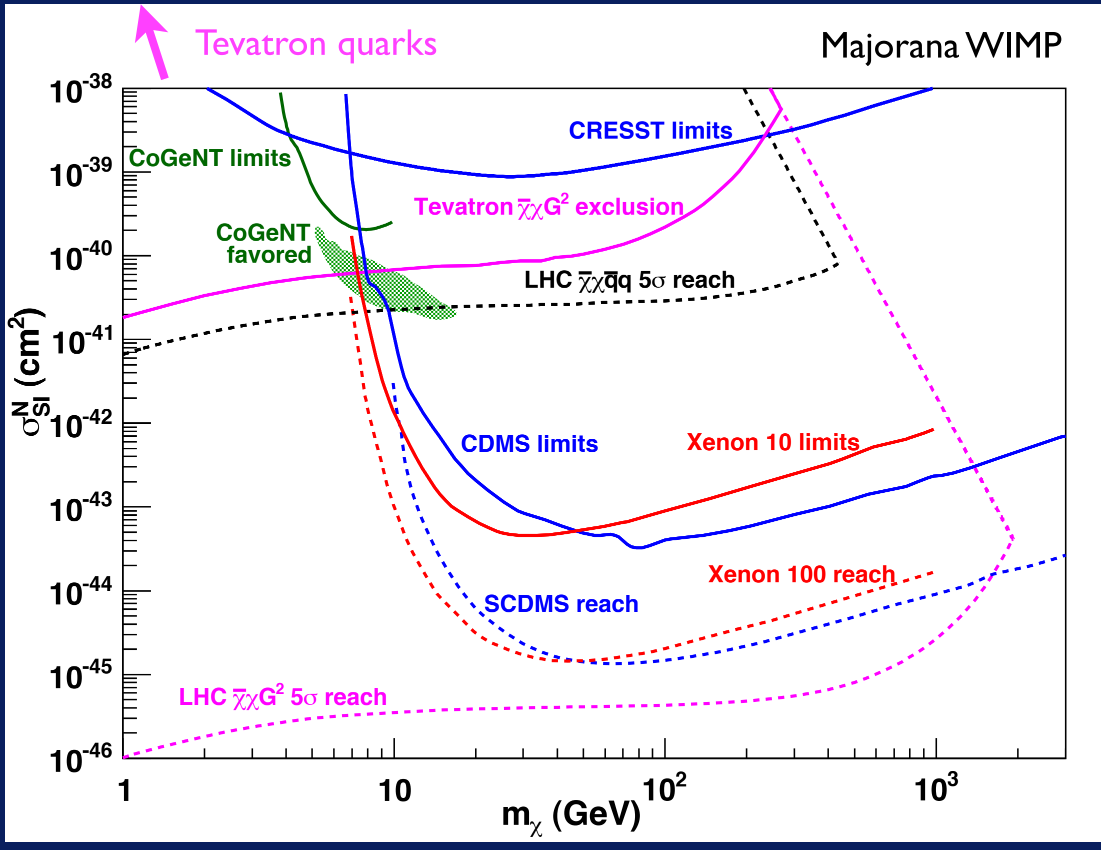


Similar results from Bai, Fox, Harnik...

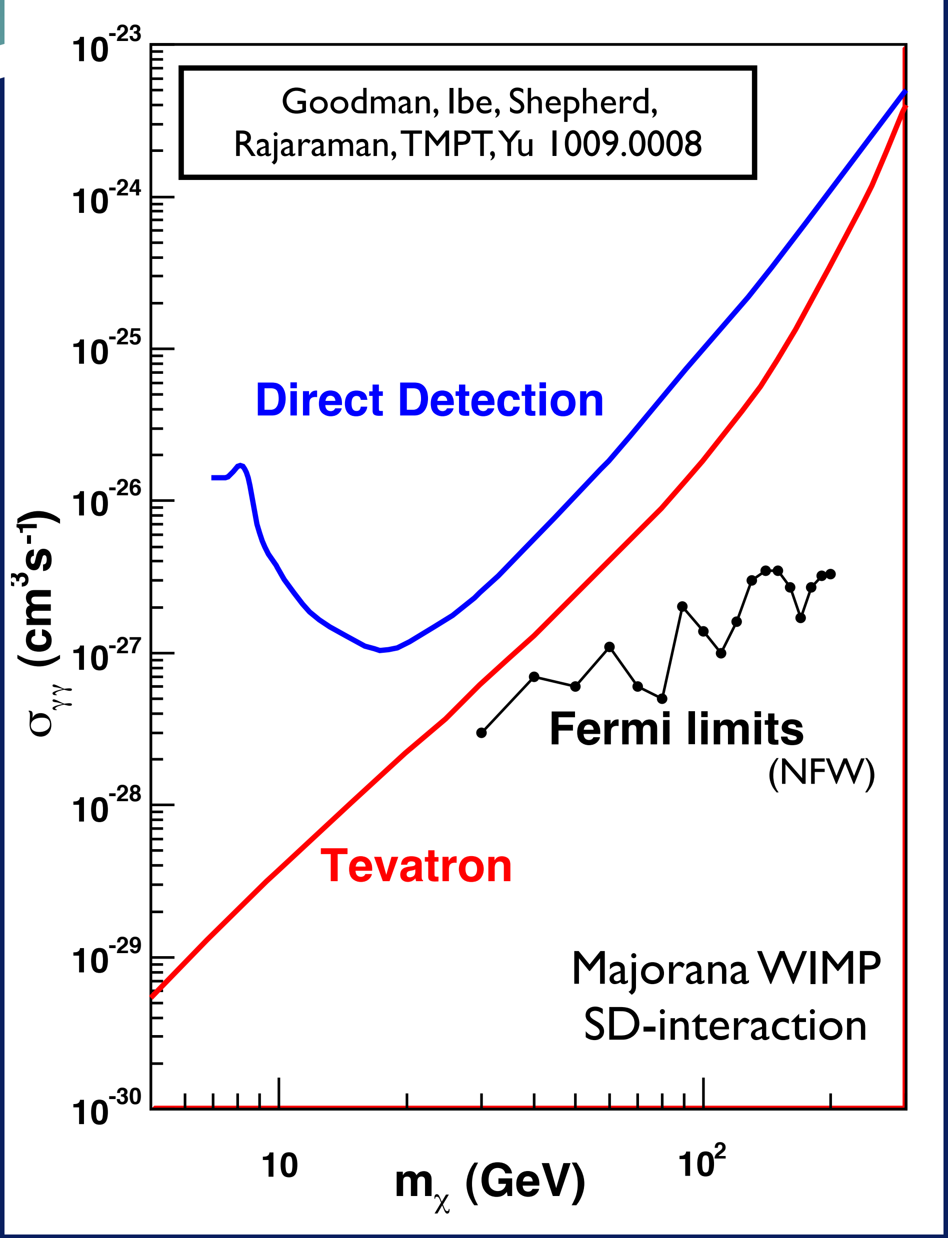
Colliders and Mavericks

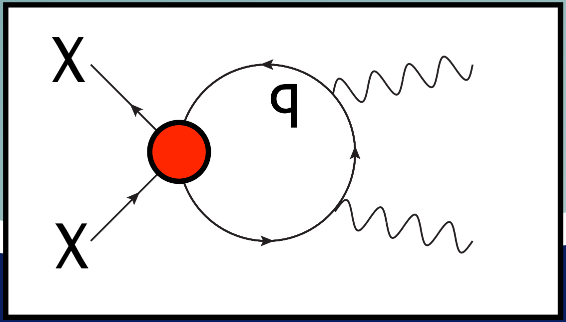
- Colliders are an interesting (orthogonal) take on WIMP-parton interactions.
  - High energy collisions see the nucleon incoherently.
- We can get information about (a linear combination of) individual partons, with no possibility of destructive interference.
- In principle, signals at multiple collision 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...

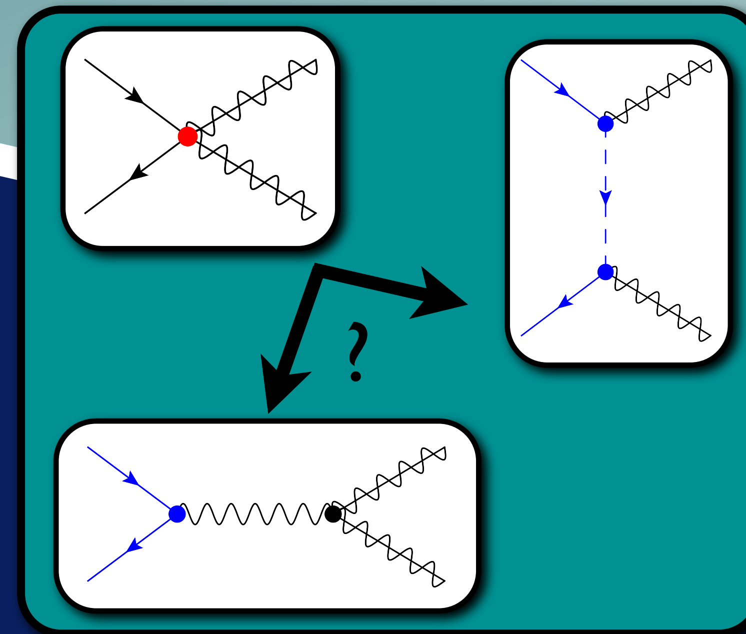




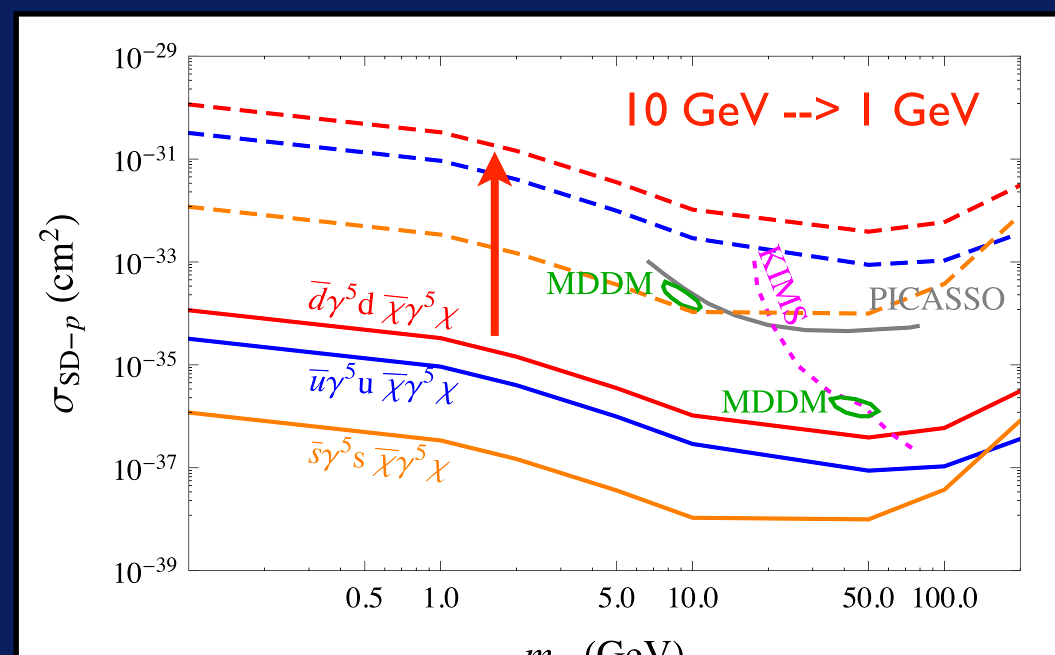
- With some more assumptions, an effective theory can have an impact on indirect detection as well.
- For example, operators map into gamma ray line features, and can be bounded using Fermi data.
  - (This particular operator contributes UV-finitely at 1-loop).
- Colliders continue to cover the low mass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

Uncertainties

How Effective a Theory?



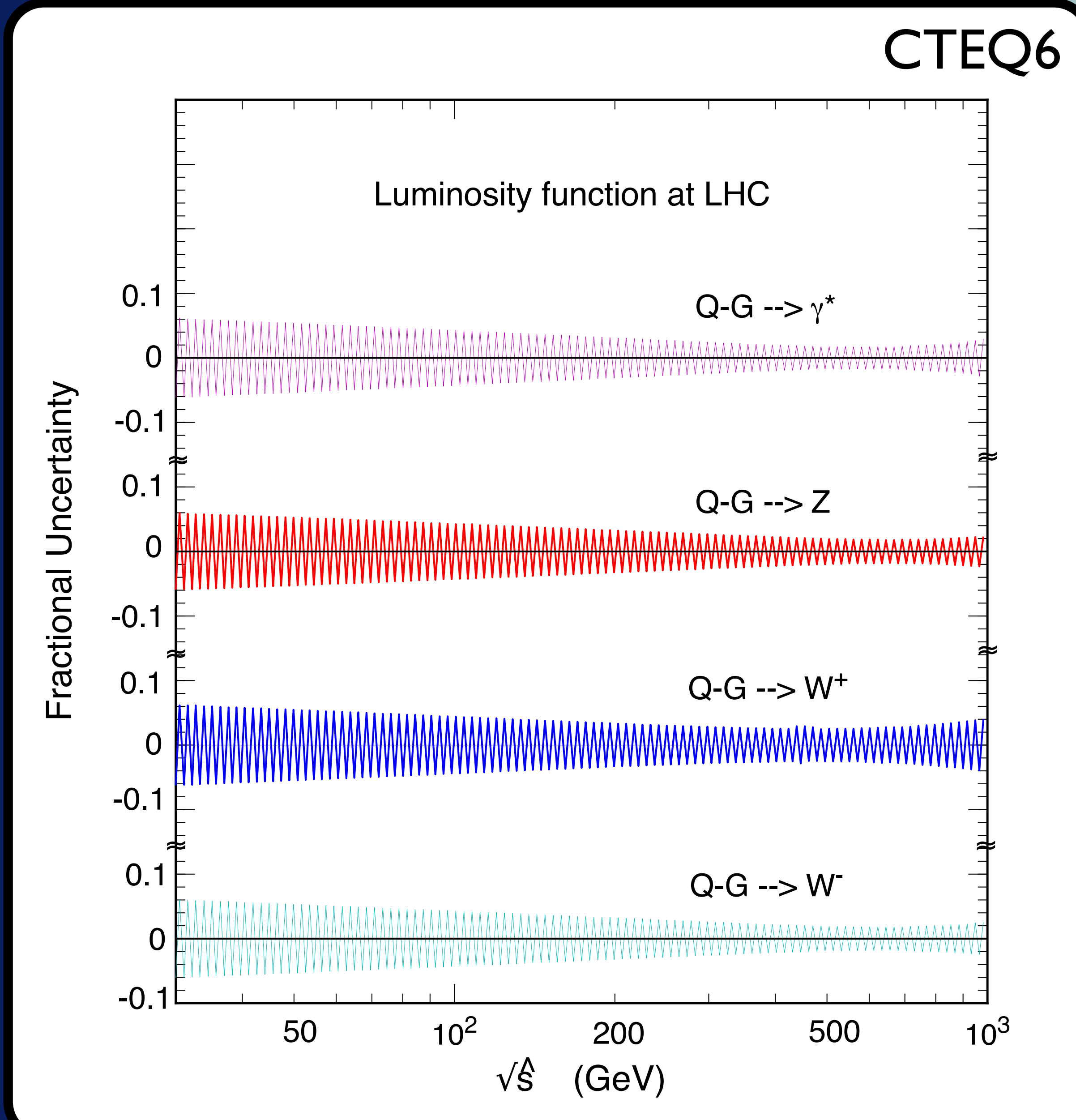
- One thing that is uncertain ahead of time is how good the EFT approximation is.
- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \text{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in SUSY-like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



Bai, Fox, Harnik 1005.3797

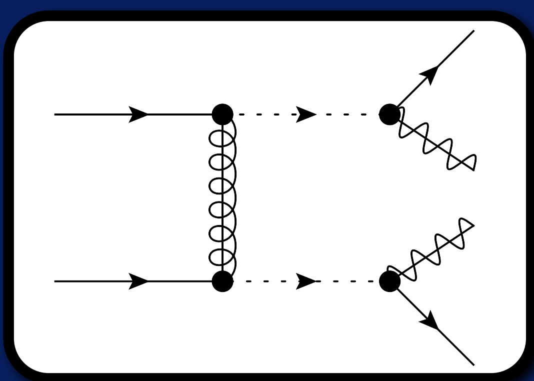
The usual suspects...

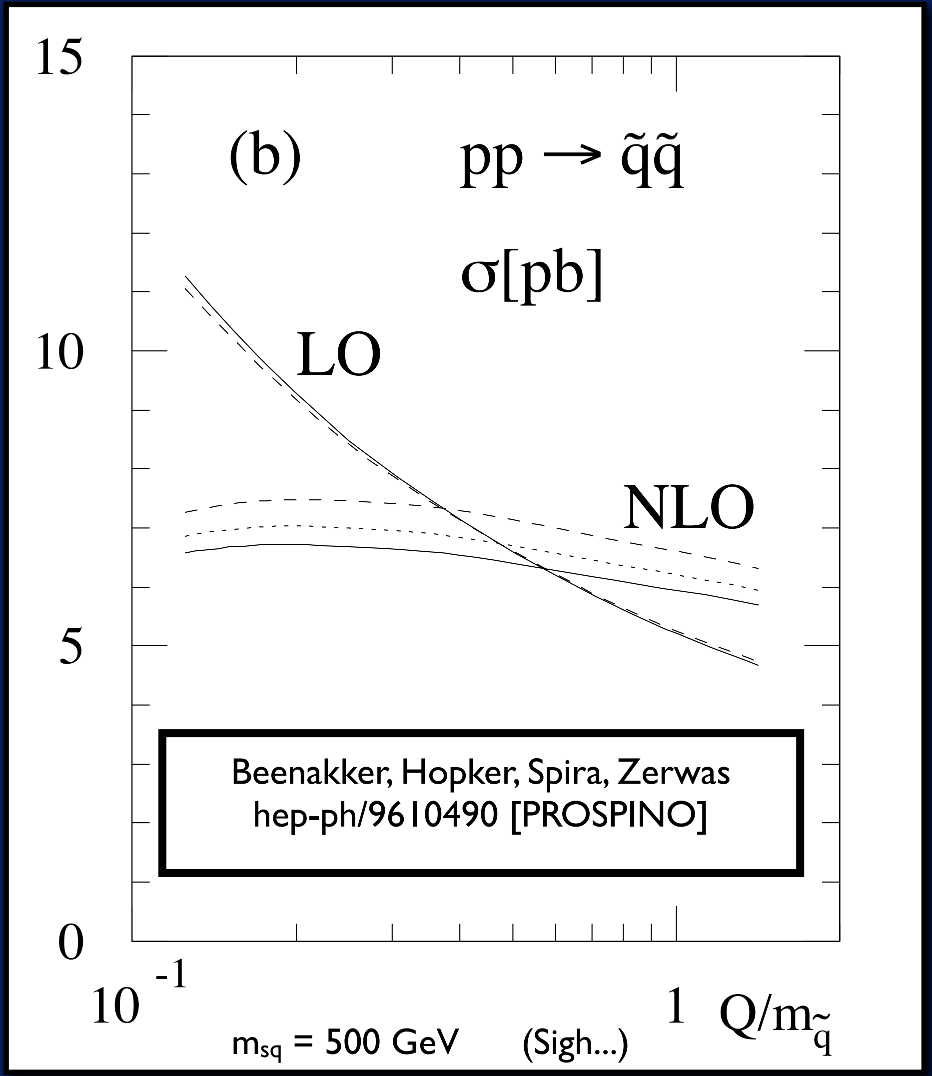
- PDFs
  - The bane of existence at a hadron collider.
  - Not "so" bad here.
- Quoted errors on the integrated PDF are less than about 10%
- Central values between, for example, CTEQ and MSTW typically differ by more than the quoted errors. (But not by a huge amount).



Higher Order QCD

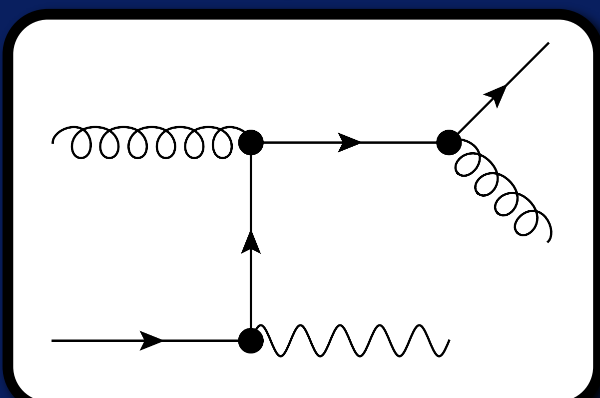
- Higher order calculations for SUSY signals have existed for some time.
- E.g. Squark Pair Production
  - MET + 2 jets
- NLO shows much more stability with respect to renormalization/ factorization scales.
- Corrections are relevant, but look “reasonable”.





Higher Orders

- (Irreducible) Backgrounds are coming under control at NLO due to heroic efforts.
- For example, for the squark pair production (and decay) of the previous slide, we need Z + 2 jets.

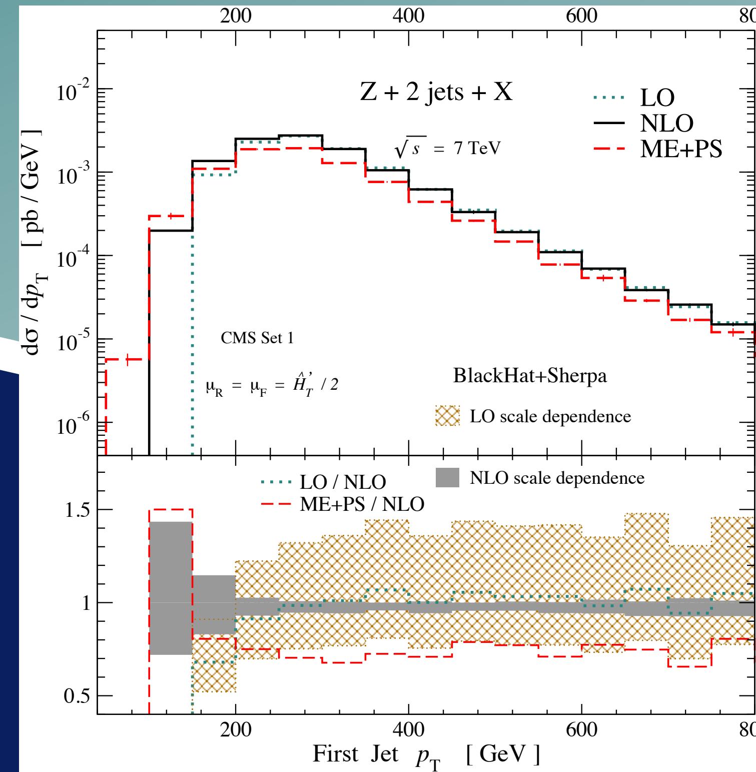


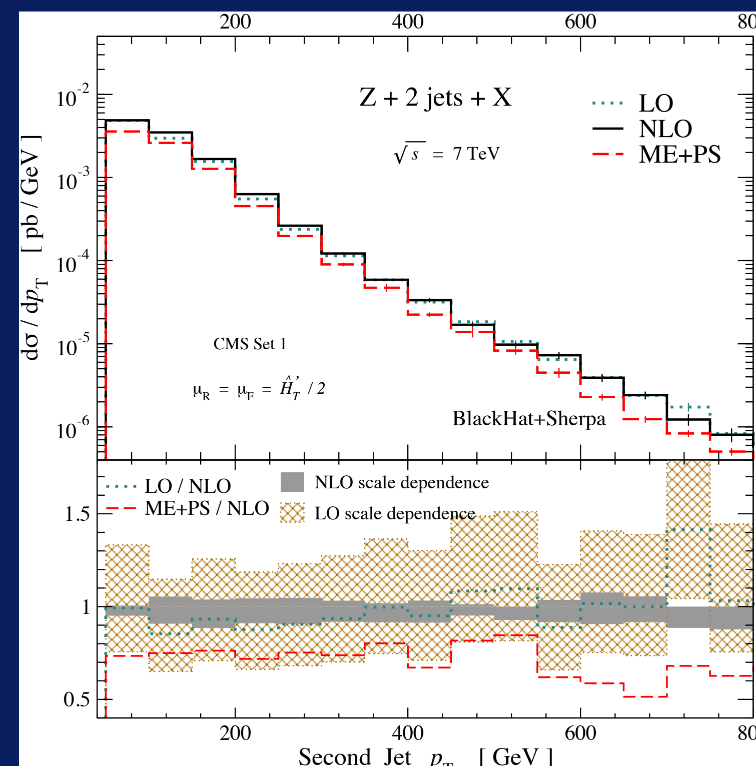
"Set One" Cuts

$HT^{>50}$ > 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.

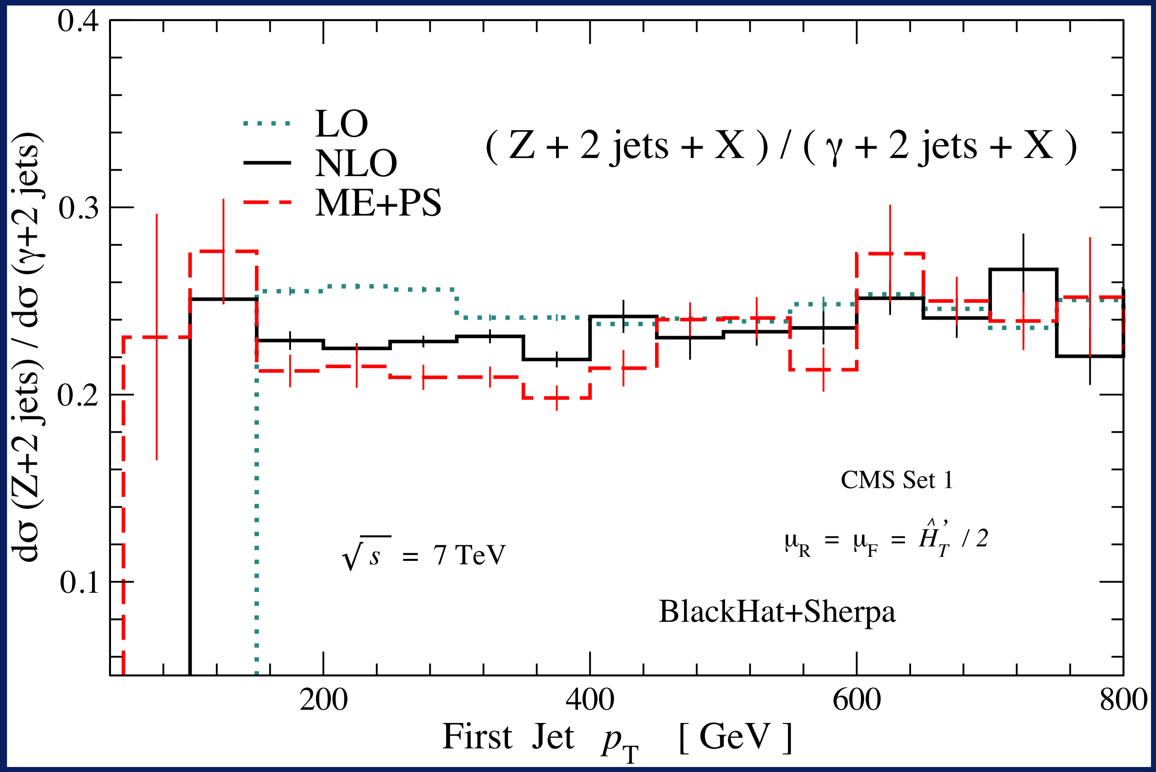




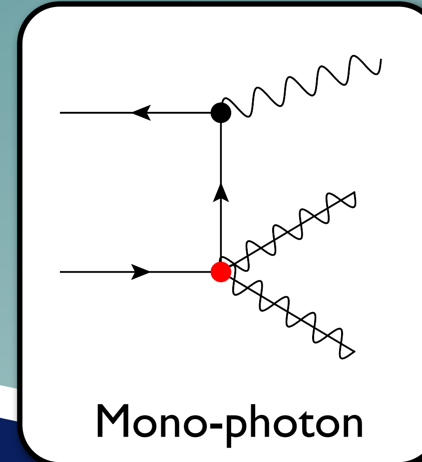
Data-Improved

- 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



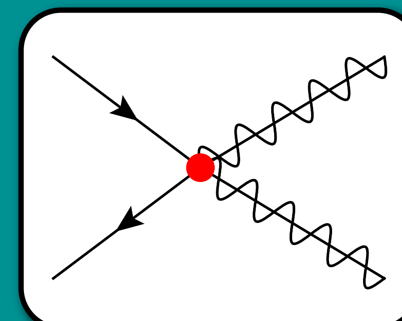
Maverick Signal
(Monojet)



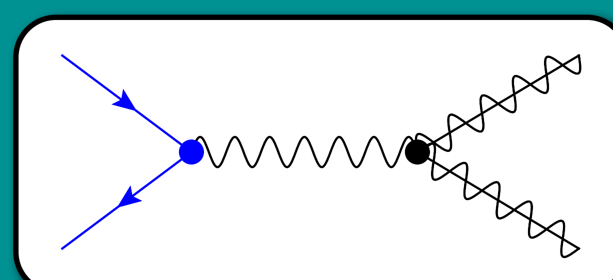
- No NLO calculation for DM.
  - The "mono-photon" signal recently appeared at NLO.

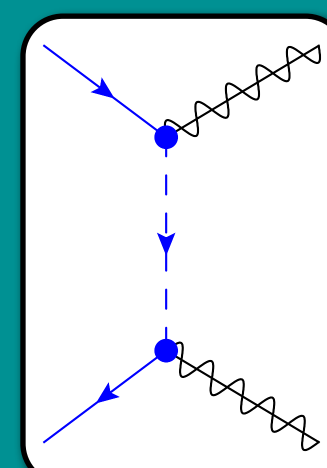
Wang, Li, Shao, Zhang arXiv:1107.2048

- 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.

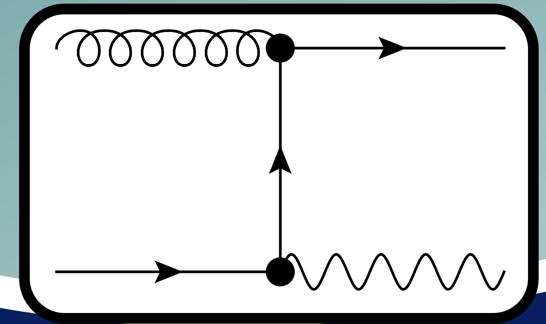


$$\bar{q}\gamma_\mu q \ \bar{\chi}\gamma^\mu \chi \quad \overset{\text{Fierz}}{\Longleftrightarrow} \quad \bar{q}\chi \ \bar{\chi}q$$





Monojet Background



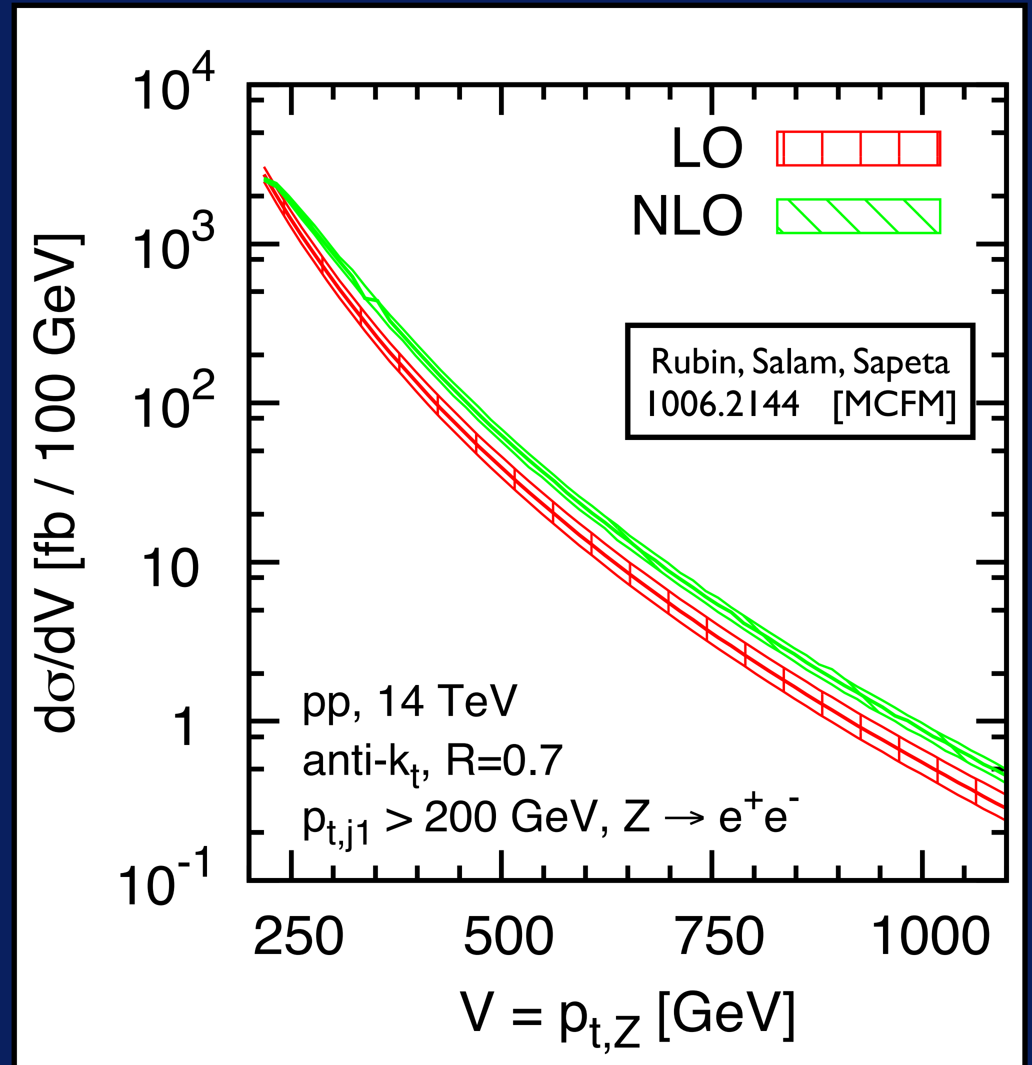
- The primary background is Z + jet.
- This one has actually been known for much longer...

Giele, Glover, Kosower
NPB hep-ph/9302225

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

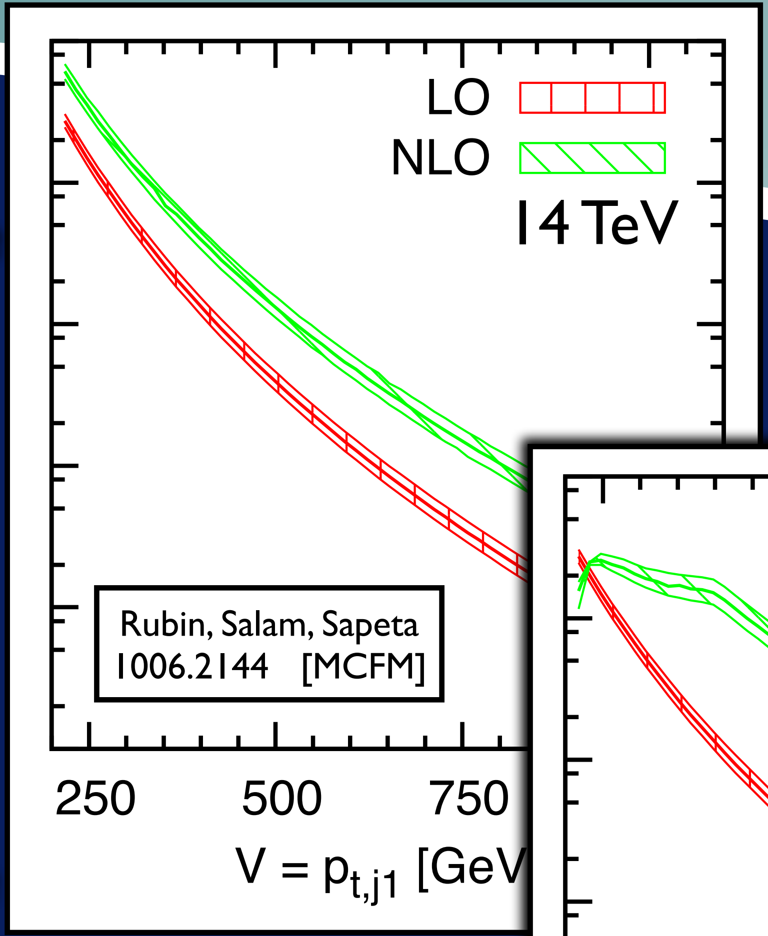
Campbell, Ellis

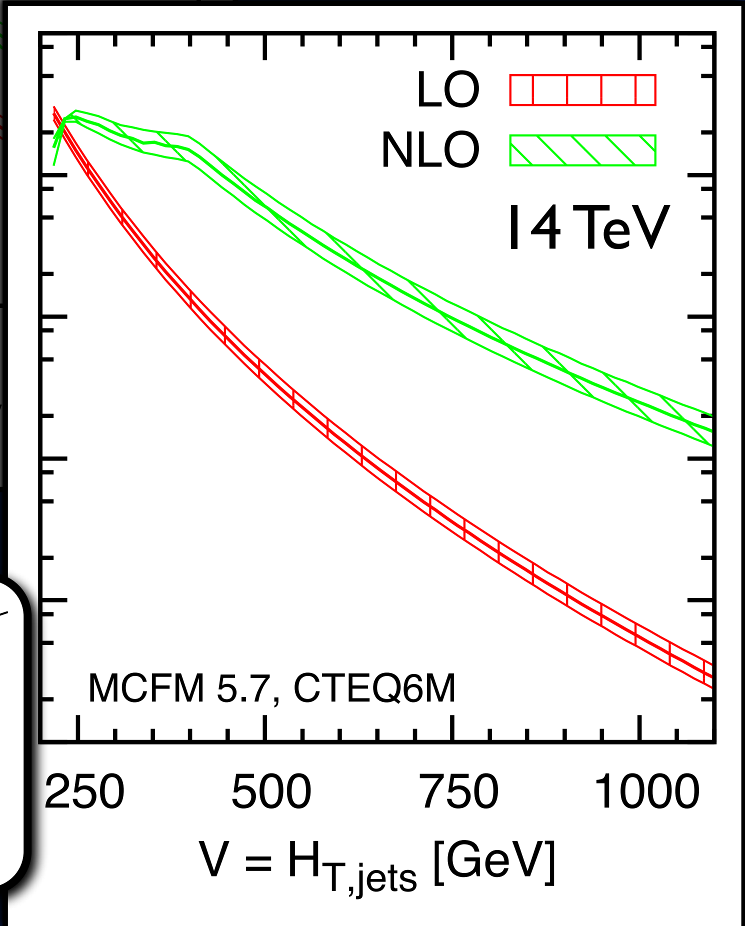
- Results differential in the Z PT (MET) look reasonable, k-factors on the order of 1.5 and not too strongly dependent on PT.

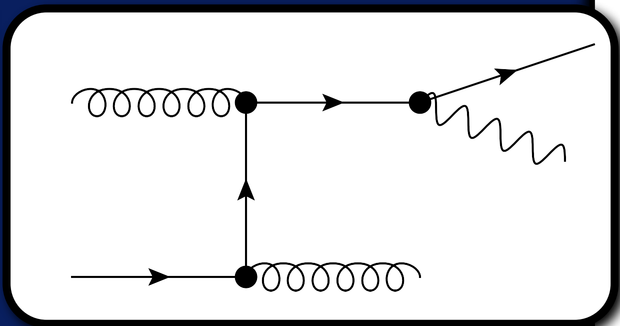


More Distributions

- 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.

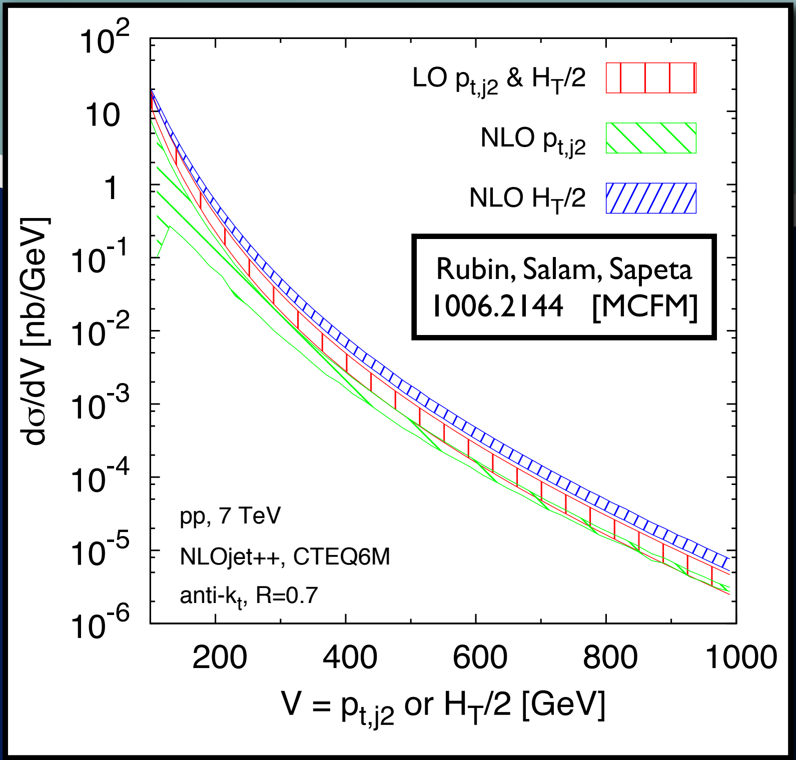






Monojet Backgrounds

- 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.



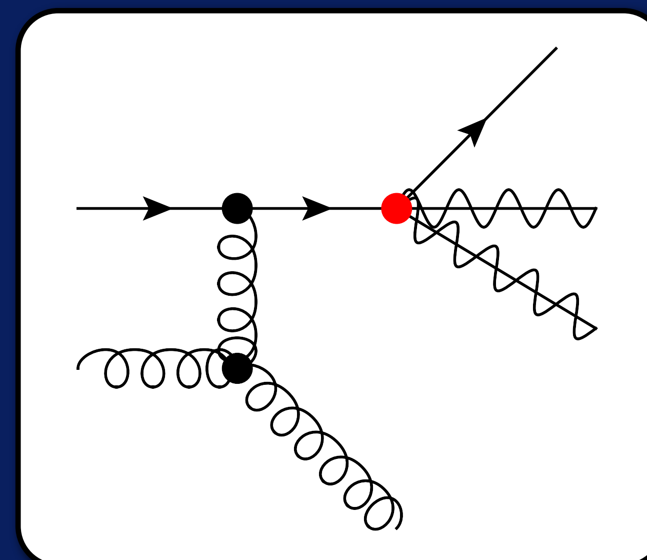
In practice, a monojet search will have vetoes on additional jets and an acollinearity cut.

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.
- It's probably not going to help much with approximately collinear Z emissions.

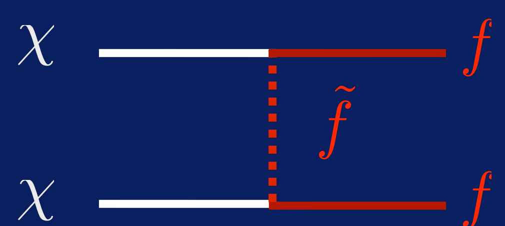
Outlook

- 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....?

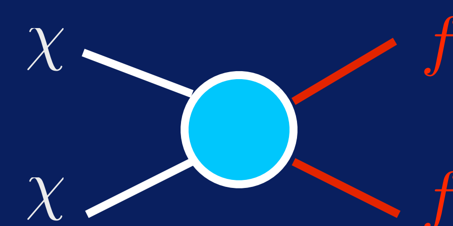
Bonus Material

Example EFT: Majorana WIMP

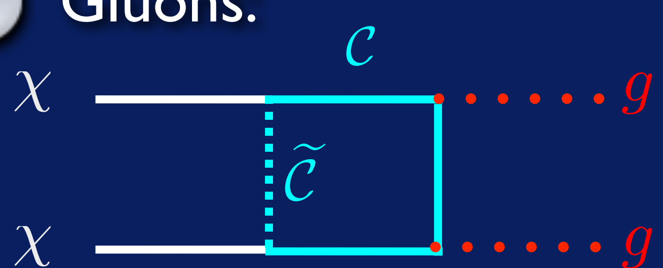
- Here are pictures for how a Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



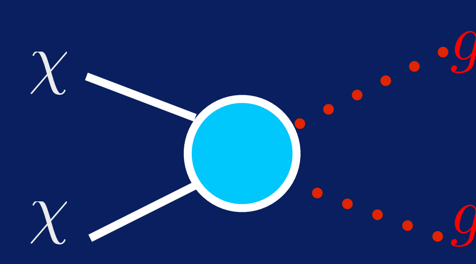
$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



  - Gluons:

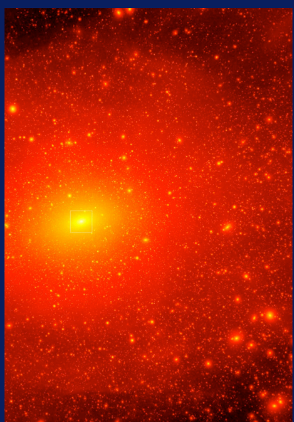


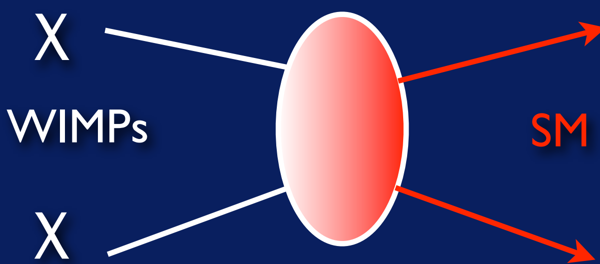
$$\sim \alpha_S \frac{g^2}{M_{\mathcal{C}} M_{\tilde{\mathcal{C}}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



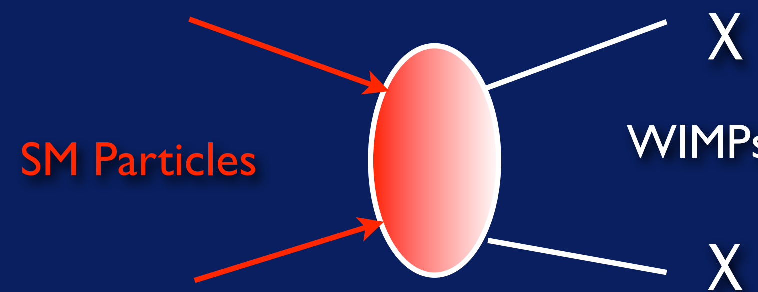
  - Each requires new states with masses heavier than the WIMP.

WIMP Searches

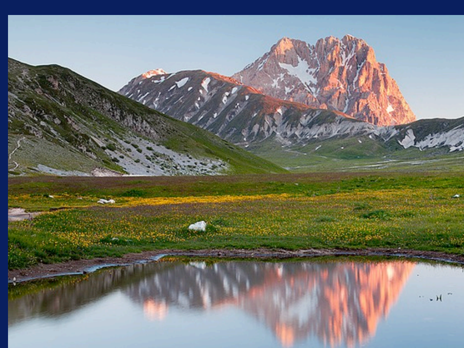


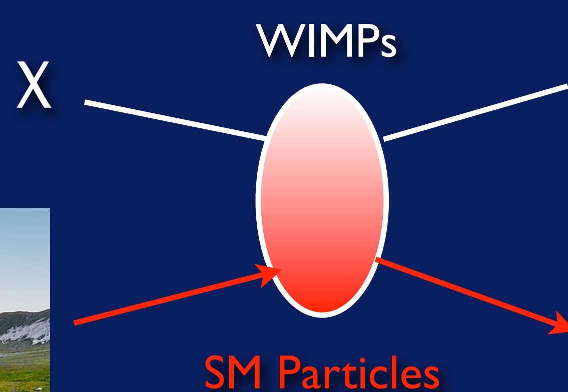


Indirect Detection



Collider Searches



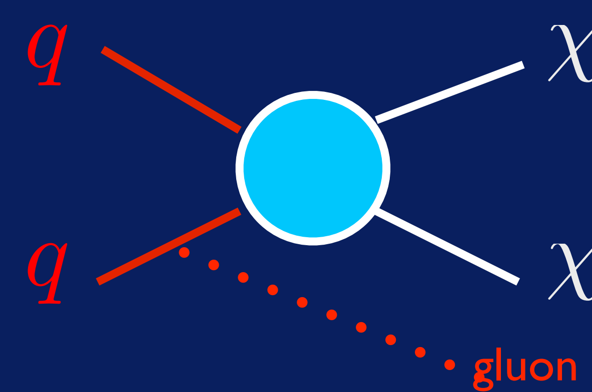


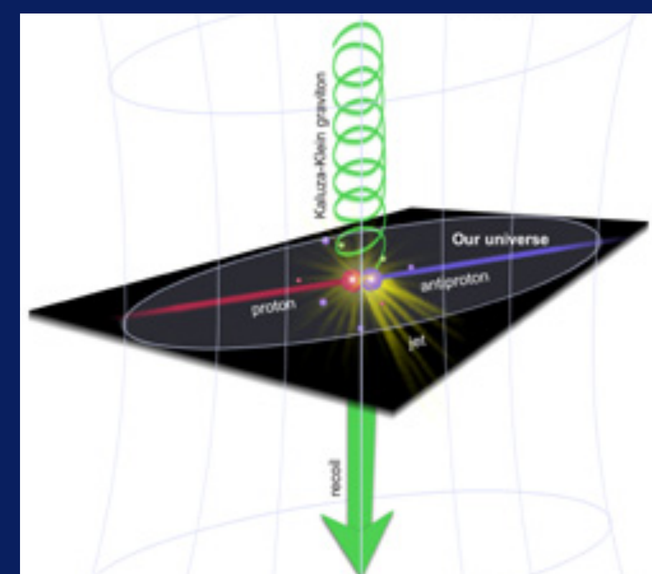
Direct Detection

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





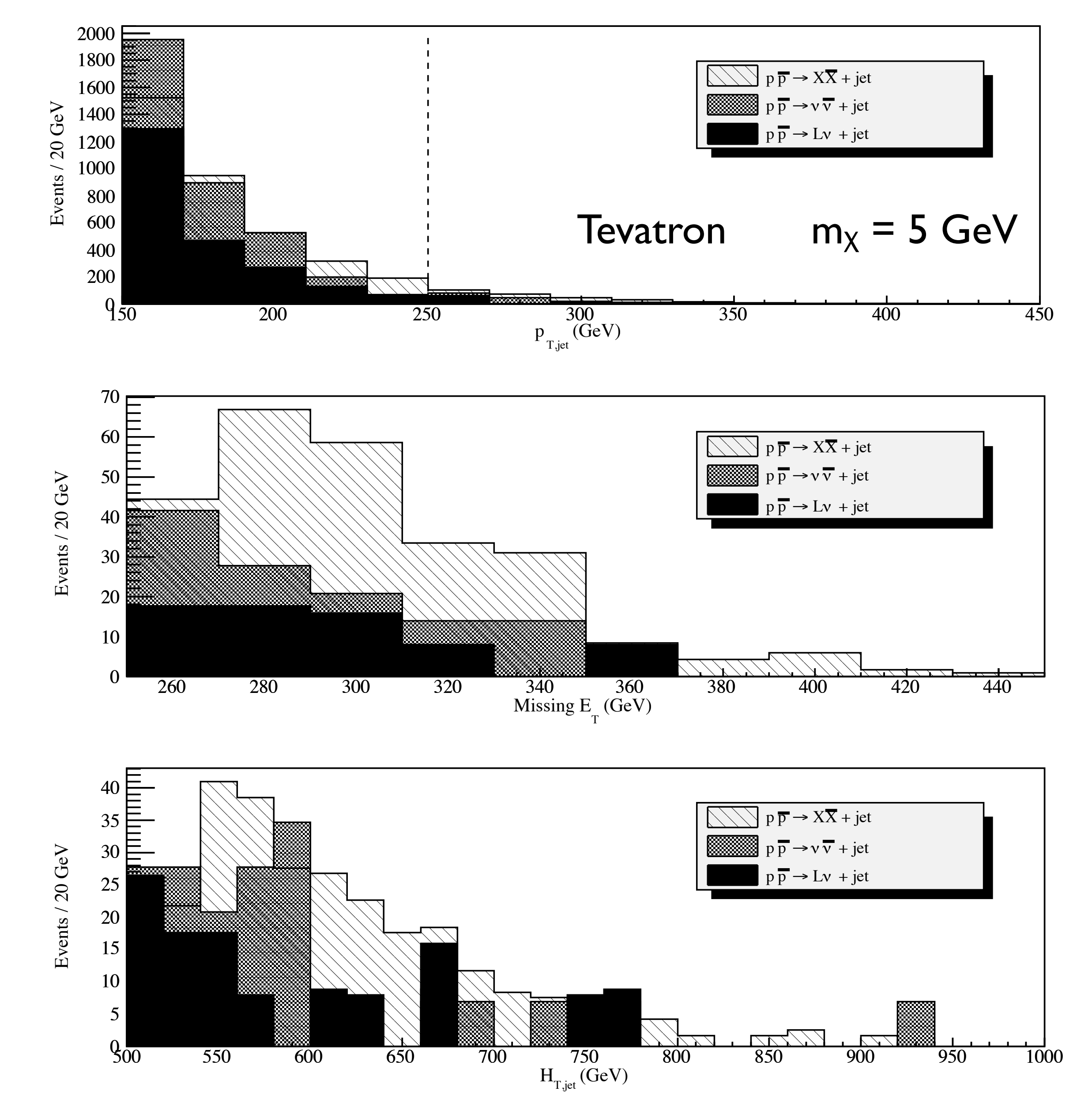
CDF, 0807.3132

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