Dark Matter: Particle Searches

Tim M.P. Tait

University of California, Irvine

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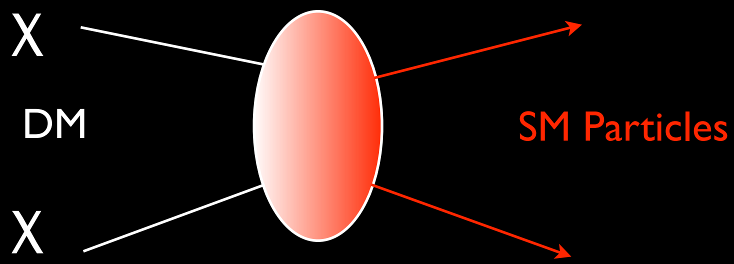
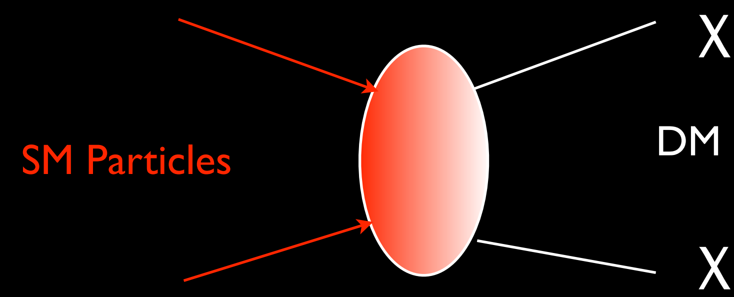
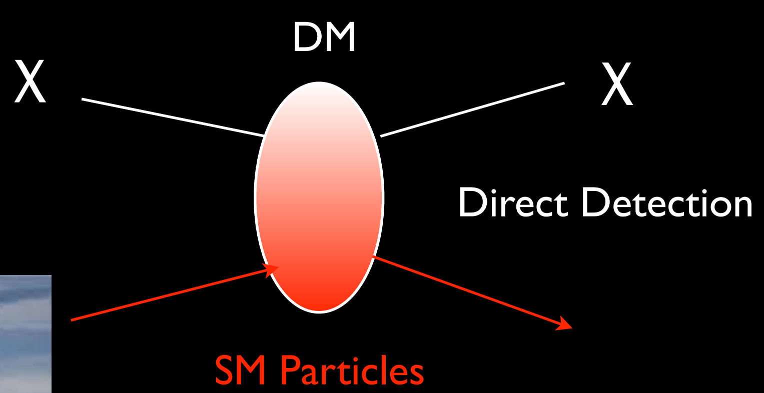
Outline of Lecture II



Indirect Detection

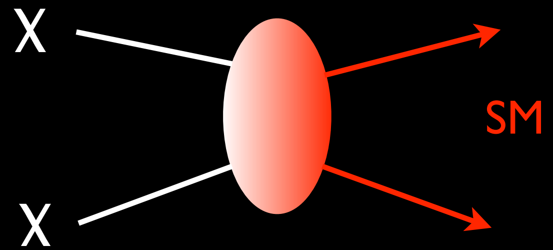


Collider Searches

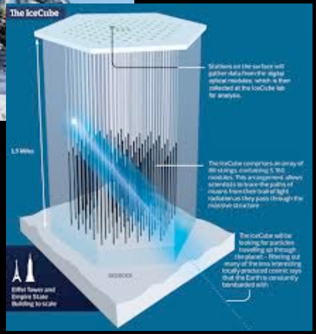


Indirect Detection of Dark Matter

Indirect Detection



- Indirect detection tries to see dark matter annihilating.
- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.
- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.
- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them could be noticeable.



Indirect Detection

- The rate of production is described by a cross section which depends on the WIMP model, and the density of WIMPs along the line of sight, squared.

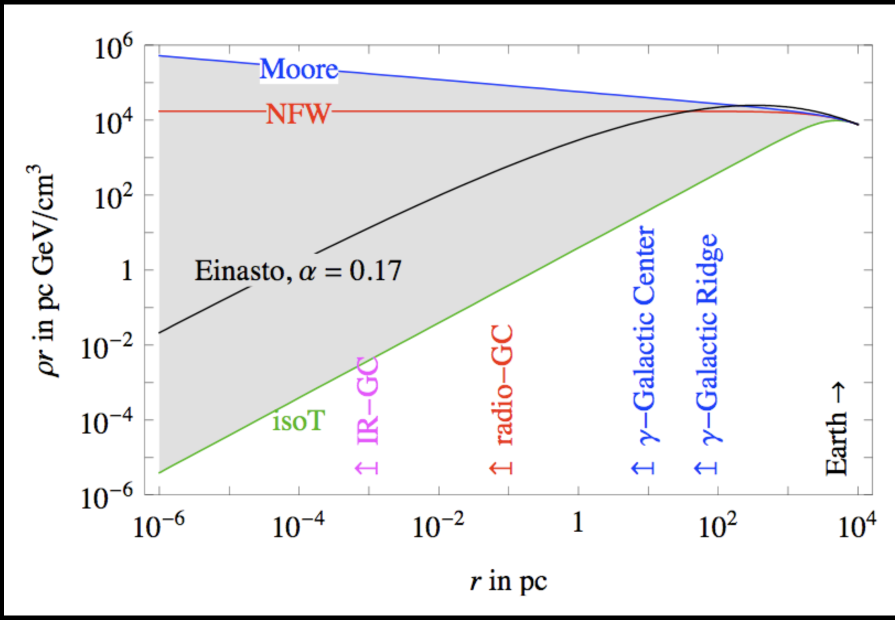
Microphysics

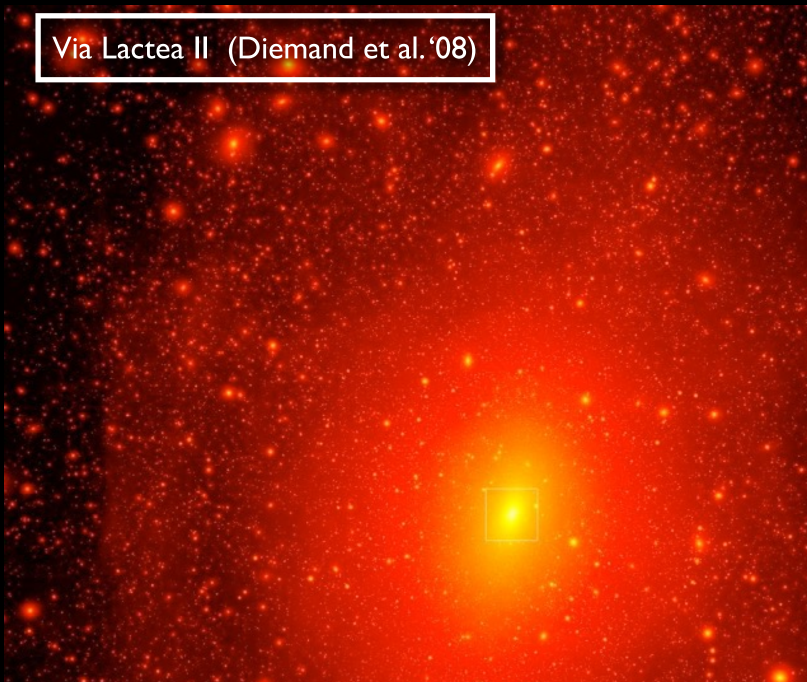
Distance along line of sight

DM density

$$\frac{dN}{dE} = \frac{d\langle\sigma v\rangle}{dE}\int dl\;\rho^2_{DM}(l)$$

- Simulations of the dark matter density provide clues as to where to look. The center of the galaxy has the largest concentrations of dark matter (but also the most ferocious backgrounds). There are also dwarf galaxies and perhaps dark sub-haloes.





Gamma Rays

- I'll focus on gamma rays:
    - Gamma rays do not get highly scattered over galactic distances, so they generally point back to their source.
        - Unlike charged particles, which get scattered by galactic magnetic fields, we can ask if gamma rays come from regions of the sky where we expect dark matter, and what the backgrounds in that region are expected to look like.
    - Gamma rays are produced from almost any SM final states, and offer some hope of reconstructing the primary annihilation products.
    - The Fermi/GLAST satellite is rapidly increasing our understanding of the gamma ray sky in the energy range from a few MeV to 100's of GeV!

Continuum Gammas

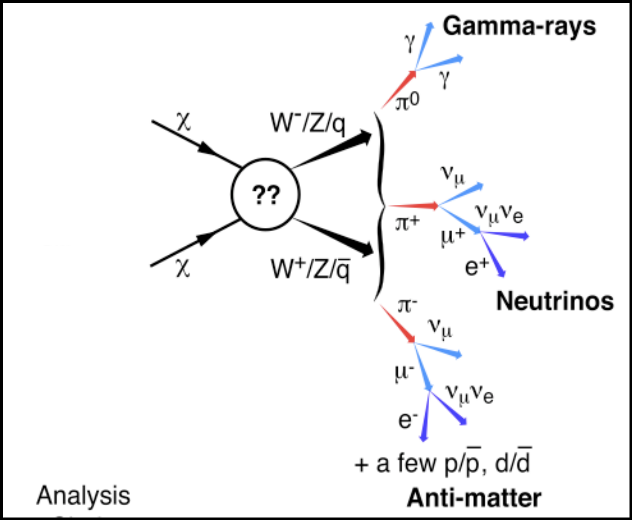
- Since WIMPs are neutral, they don't couple directly to photons. The rates into photons can be expressed as a convolution of the rates into other particles with the rate for those particles to produce gammas.

$$\frac{d\langle\sigma v\rangle}{dE_\gamma} = \sum_F \frac{d\langle\sigma v(\chi\chi \to F)\rangle}{dE_F} \, f_{\gamma/F}\left(\frac{E_\gamma}{E_F}\right)$$

Sum over perturbative final states F

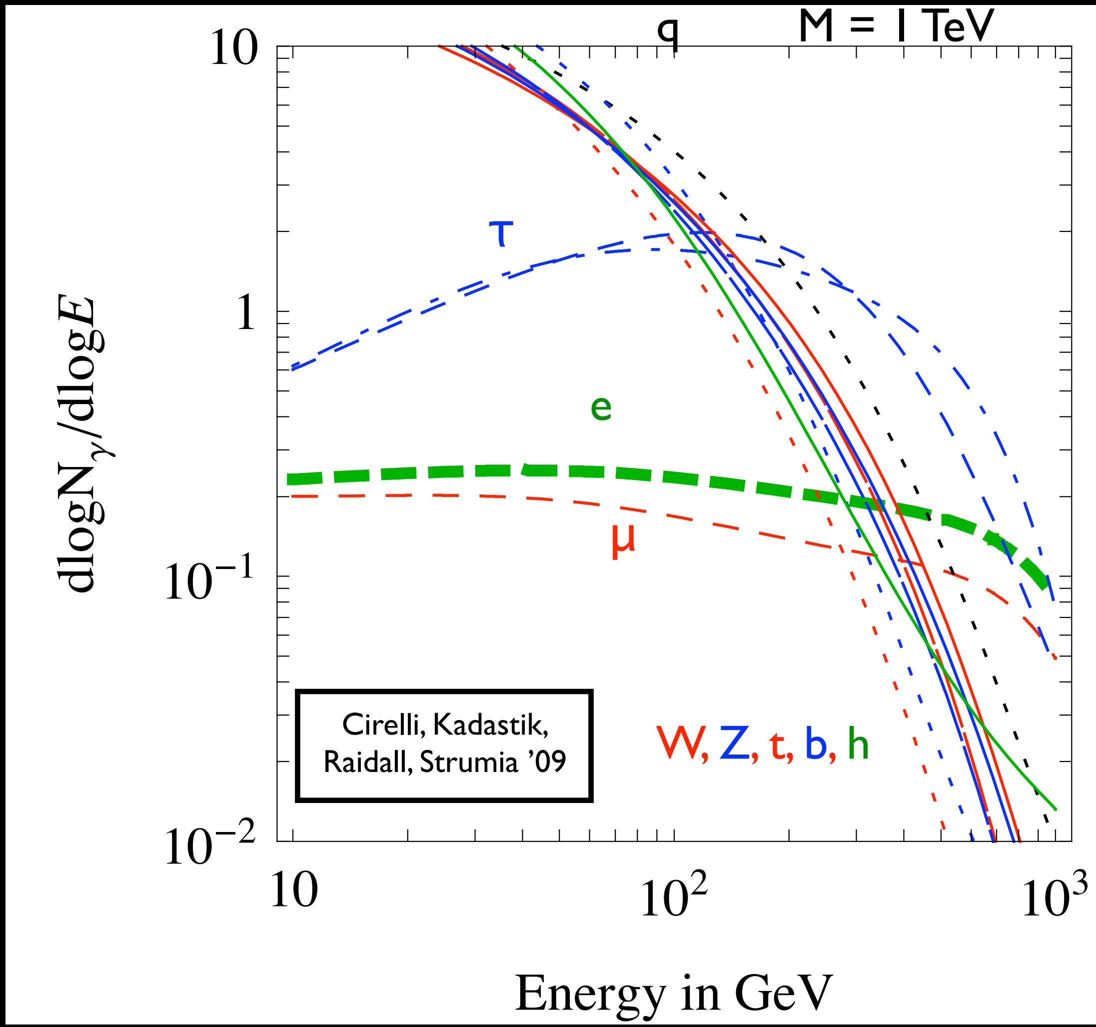
Gamma yield from final state F

- The final E_γ are complicated and smeared out:
  - Some gammas are produced as radiation from charged final states.
  - Hadronic final states undergo corrections from parton showering.
  - Heavy particles share energy among many final state decay products.



$f_{\gamma/F}$ (E_γ/E_F)

- WIMPs which annihilate into pairs of leptons produce a relatively hard spectrum of gammas from FSR. (e's and μ's are even somewhat harder than τ's).
- Annihilation into quarks ultimately produces π^0s which decay into pairs of γs.
- Heavy particles (W, Z, h, t, b) produce a mix, ending up looking much like hadronic final states.
- The mapping from final state to signal is computed from a showering Monte Carlo, like Pythia; parameterized forms exist in micro-omegas or the PPPC4DM.



Challenges

- While the signals for WIMPs annihilating into gamma rays can have large rates, observing a signal is challenging.
- Backgrounds (especially from the galactic center) are complicated, coming from many different kinds of objects, and the spectrum and distribution of these objects are not always well understood.
- The WIMP signal has a cut-off at the mass of the WIMP, but, especially without knowing which final states the compromise the primary annihilations, the shape of the signal, and the prominence of the cut-off is difficult to know.
- Most of the experimental searches currently focus on a bb final state, motivated by supersymmetry.

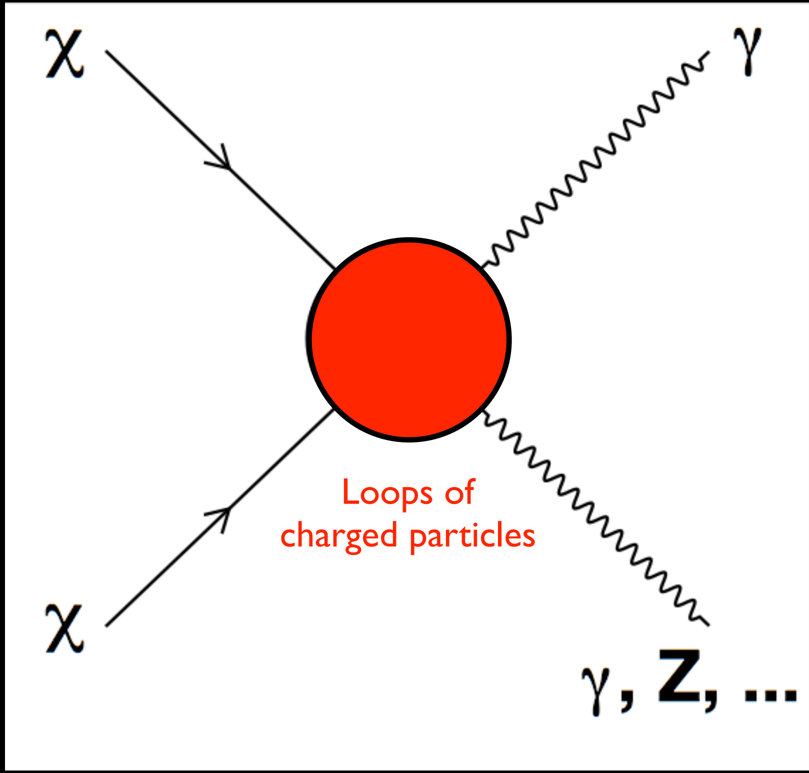
Gamma Ray Lines

- The spectrum of gamma rays may also contain spectral lines. They occur when WIMPs produce gammas in a two-body final state.

- Since WIMPs are thought to be highly non-relativistic in the galaxy, energy conservation predicts the energy of the photon in the reaction $\chi\chi \rightarrow \gamma X$ to be:

$$E_\gamma = M_\chi \left(1 - \frac{M_X^2}{4M_\chi^2}\right)$$

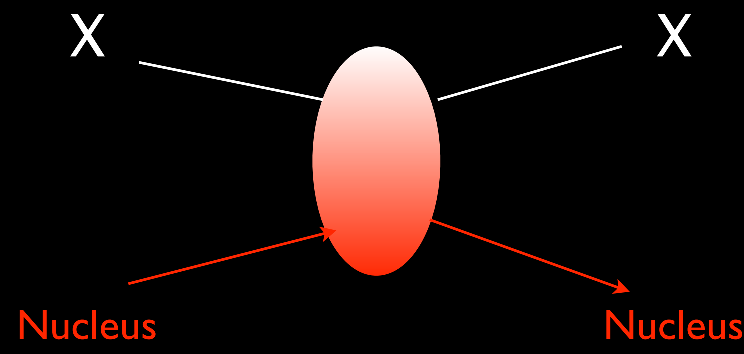
- This is a feature that conventional astrophysics has great difficulty producing, perhaps compensating for a loop level rate.

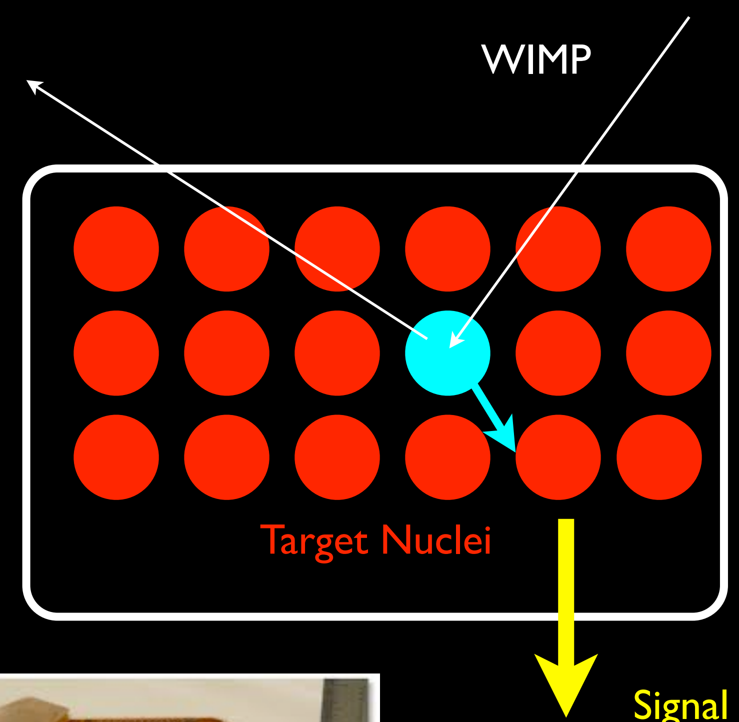


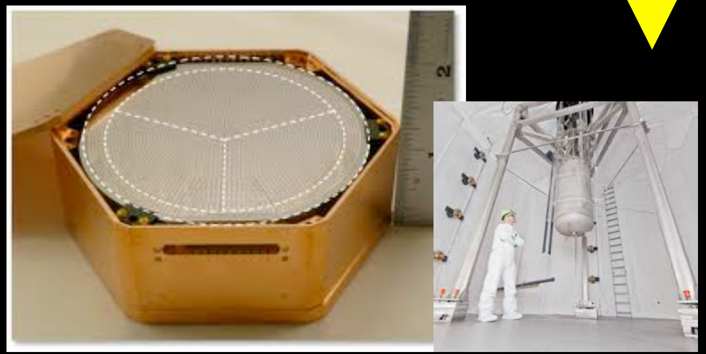
Direct Detection of Dark Matter

Direct Detection

- Before looking at direct detection of neutralinos, let’s review some basic features of the searches.
- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.
- Direct detection looks for the dark matter in our galaxy’s halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- In the non-relativistic (v -> 0) limit, the DM-nucleon interaction can either be a constant (Spin-Independent scattering) or the dot product of their spins (Spin-Dependent scattering).







Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

DM density

Nuclear Physics

$$\frac{dN}{dE} = \sigma_0 \, \frac{\rho}{m} \int dv \, f(v) \, F(E)$$

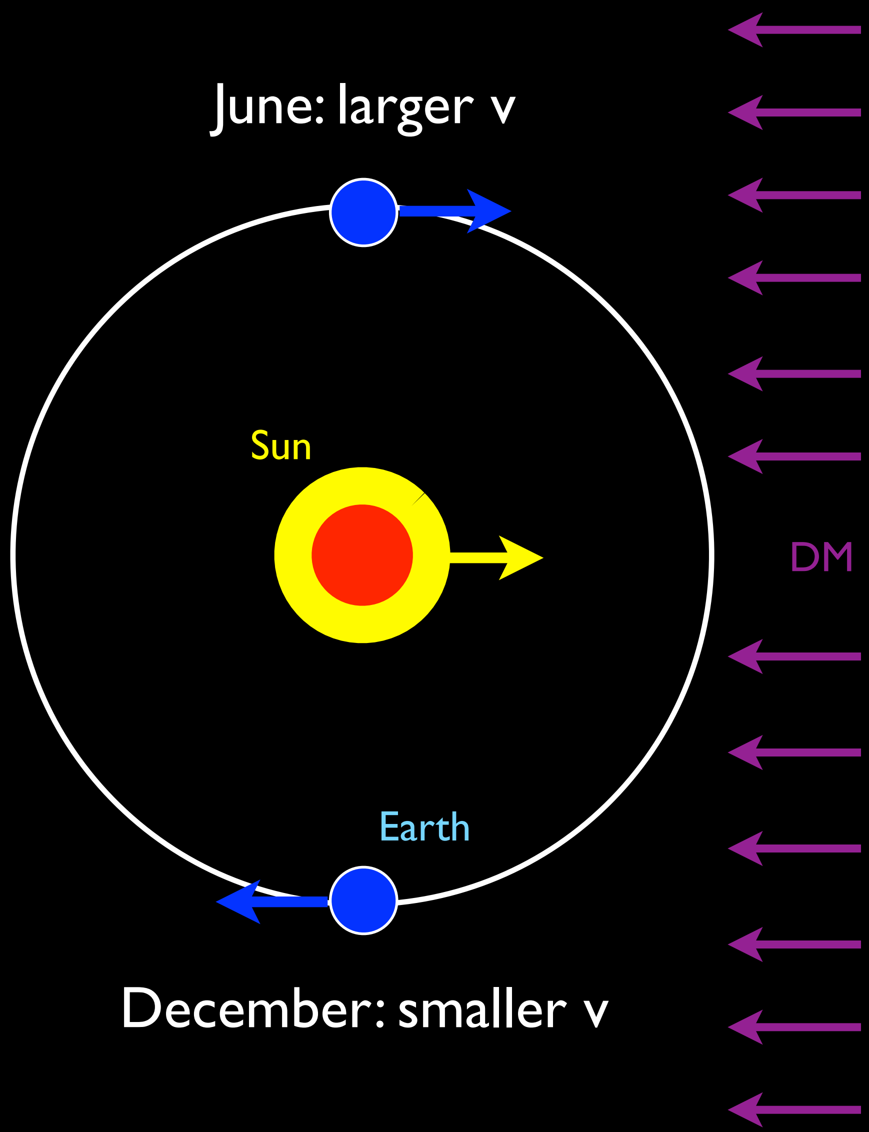
Particle Physics

DM velocity distribution

- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.

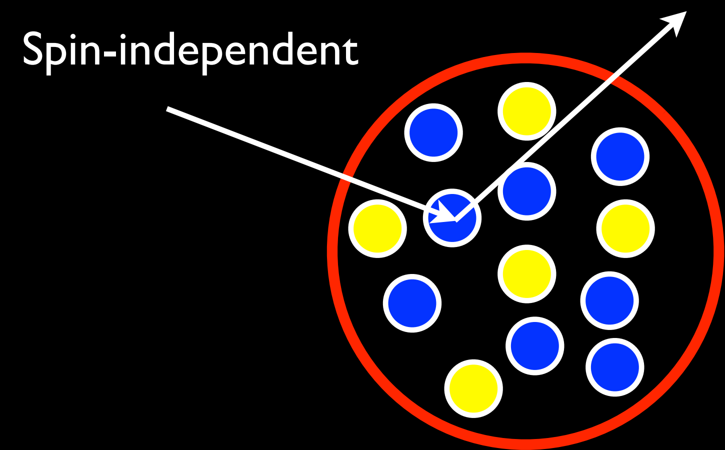
- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

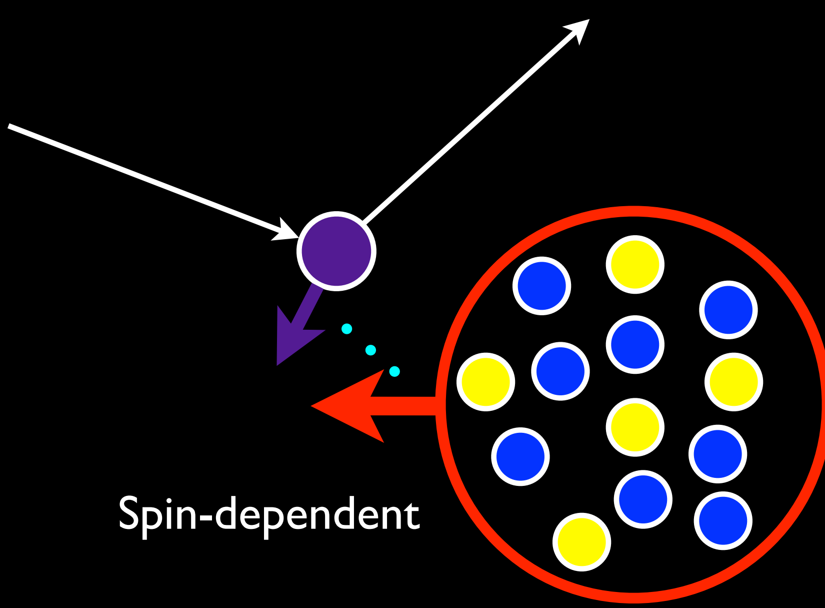
- An interesting handle on the signal is an expected annual modulation.



From Quarks to Nuclei

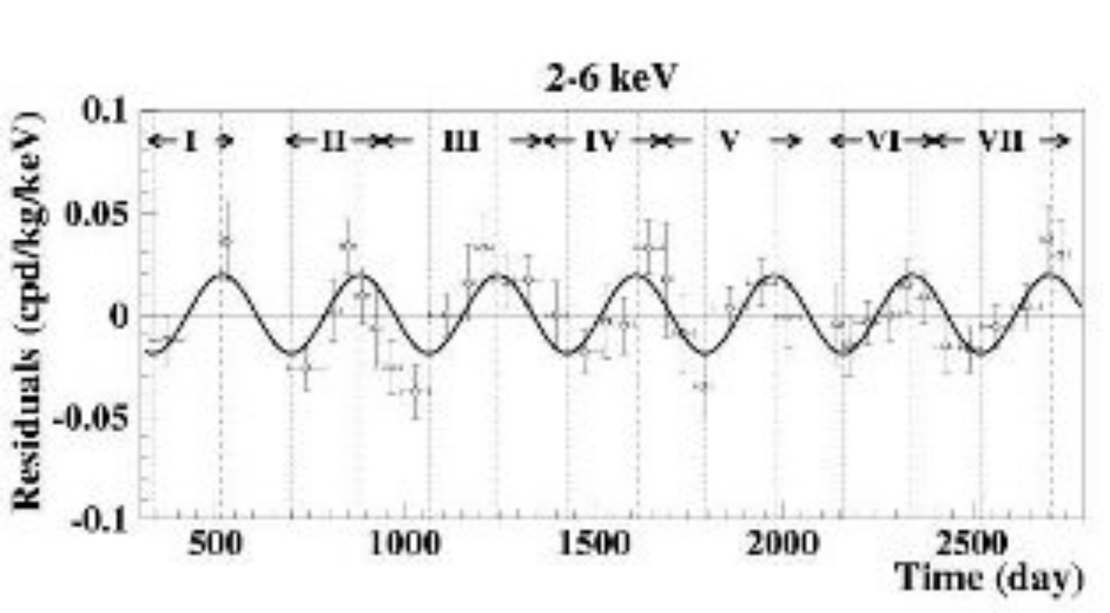
- In a particle theory, we usually know how the dark matter interacts with quarks and gluons.
- However, in direct detection, the momentum transfer is so tiny that the dark matter does not see the individual quarks and gluons, but just the entire nucleus.
- The SI interaction is thus enhanced by the total number of protons or neutrons (or both), and is larger for heavier nuclei with larger atomic number.
- The SD interaction is larger for nuclei with larger spin.
- Connecting the scattering rate with a nucleus to quarks/gluons requires hadronic matrix elements and nuclear form factors (these are largely taken from experiments).

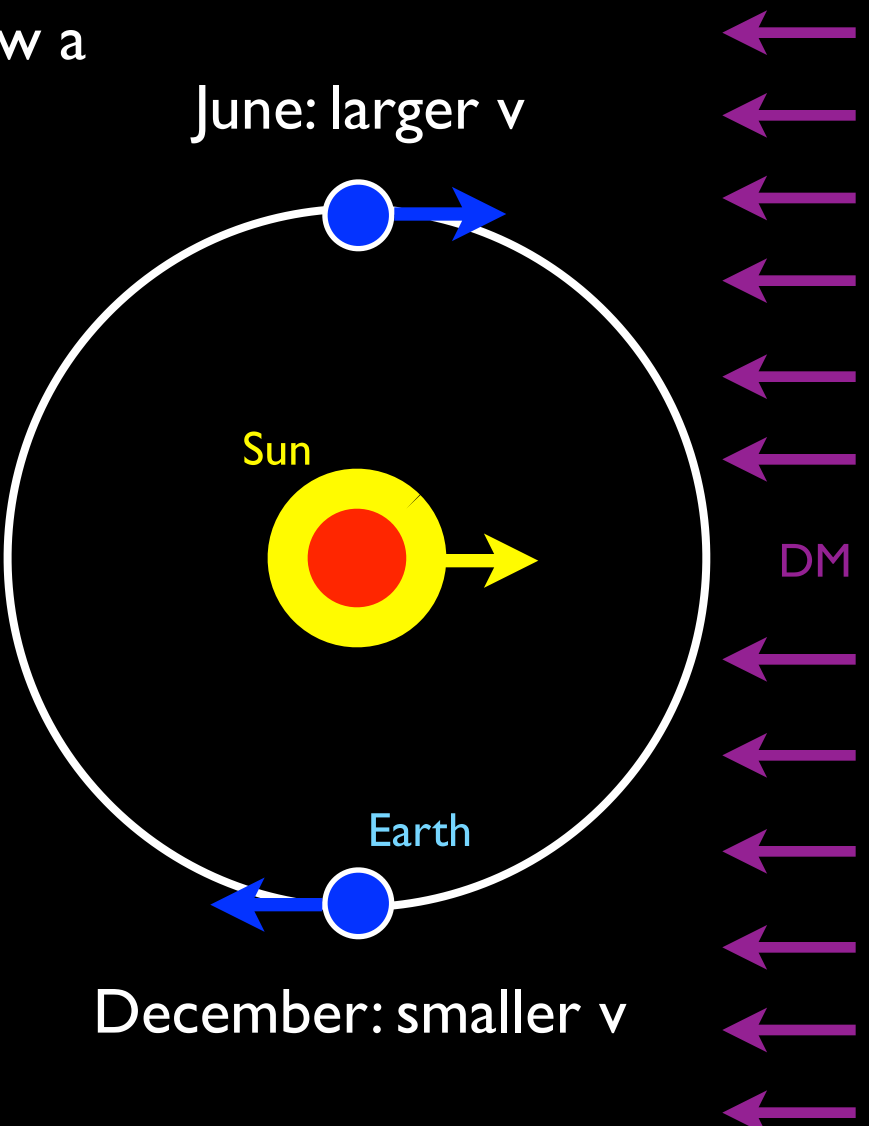




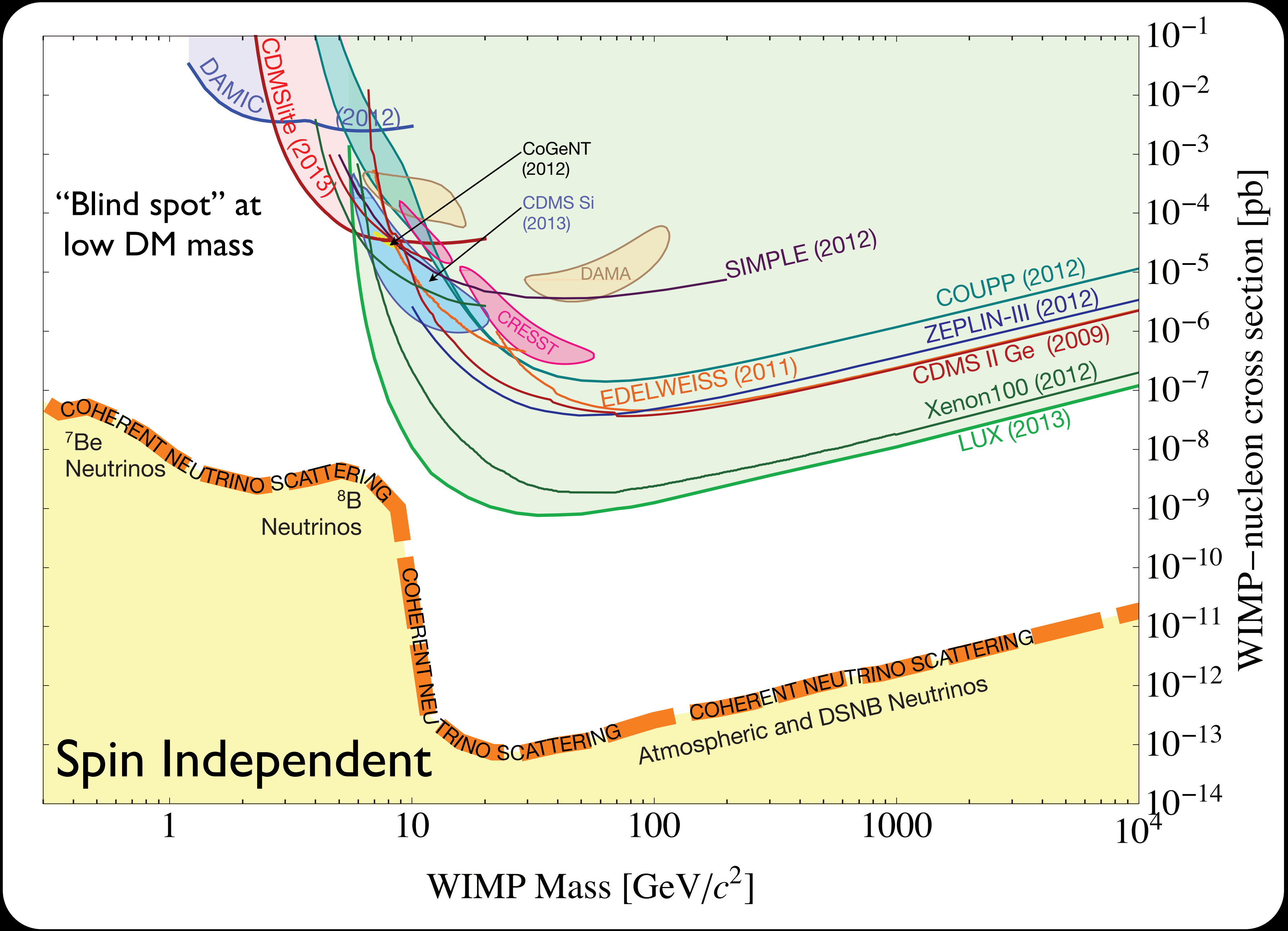
DAMA / Libra

- DAMA/Libra looks for this annual variation in scattering from an NaI target.
- Data collected over more than a decade show a significant (~9σ) annual modulation of a few percent with a maximum in June.
- The signal is in tension with other experiments, but we still don't know how to explain it.





Direct Detection



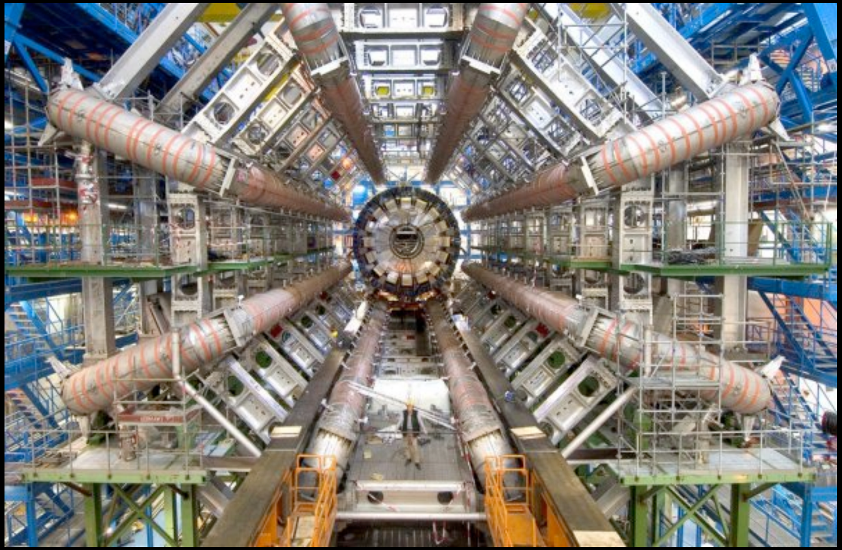
Neutrino "Floor"

Billard, Figueroa-Feliciano, Strigari 1307.5458

Dark Matter at Colliders

Collider Production

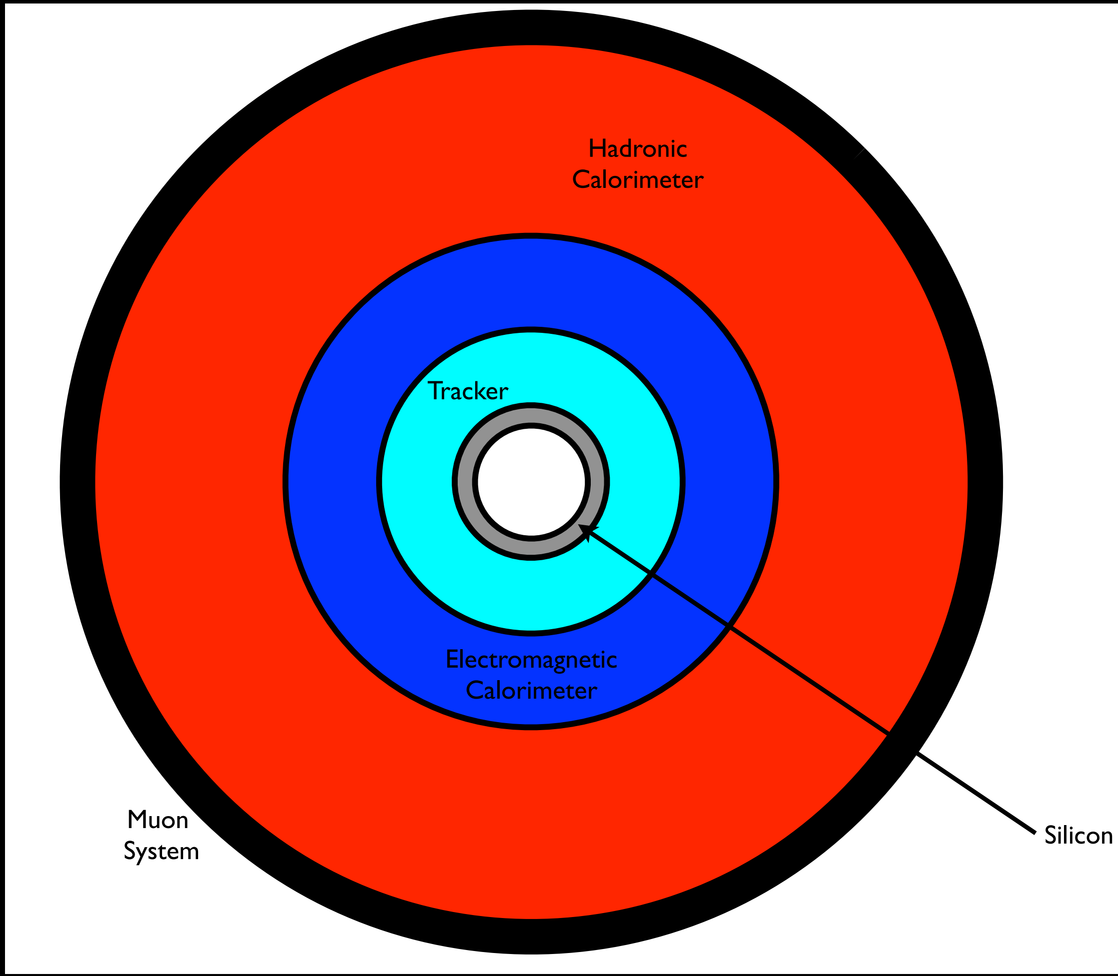
- If dark matter couples to quarks or gluons, we should also be able to produce them at high energy colliders.
- To make the most of collider searches, we need to understand:
  - How collider searches map on to our favorite theories of dark matter.
  - It would also be nice to know what they tell us about dark matter's properties more generally.
  - E.g. How colliders fit in with the other kinds of searches for dark matter.



A Cartoon LHC Detector

(For a more sophisticated discussion, see Jon's lectures!)

- A typical collider detector is composed of different layers designed to identify different particles and measure their momenta.
- They all follow a similar plan:
    - An inner layer of silicon detectors is used to detect particles which travel some distance from the interaction before decaying.
    - An EM tracker measures the path of charged particles.
    - Two calorimeters "stop" electrons +photons and hadrons.
    - A muon system at the outer radius measures the momenta of muons.



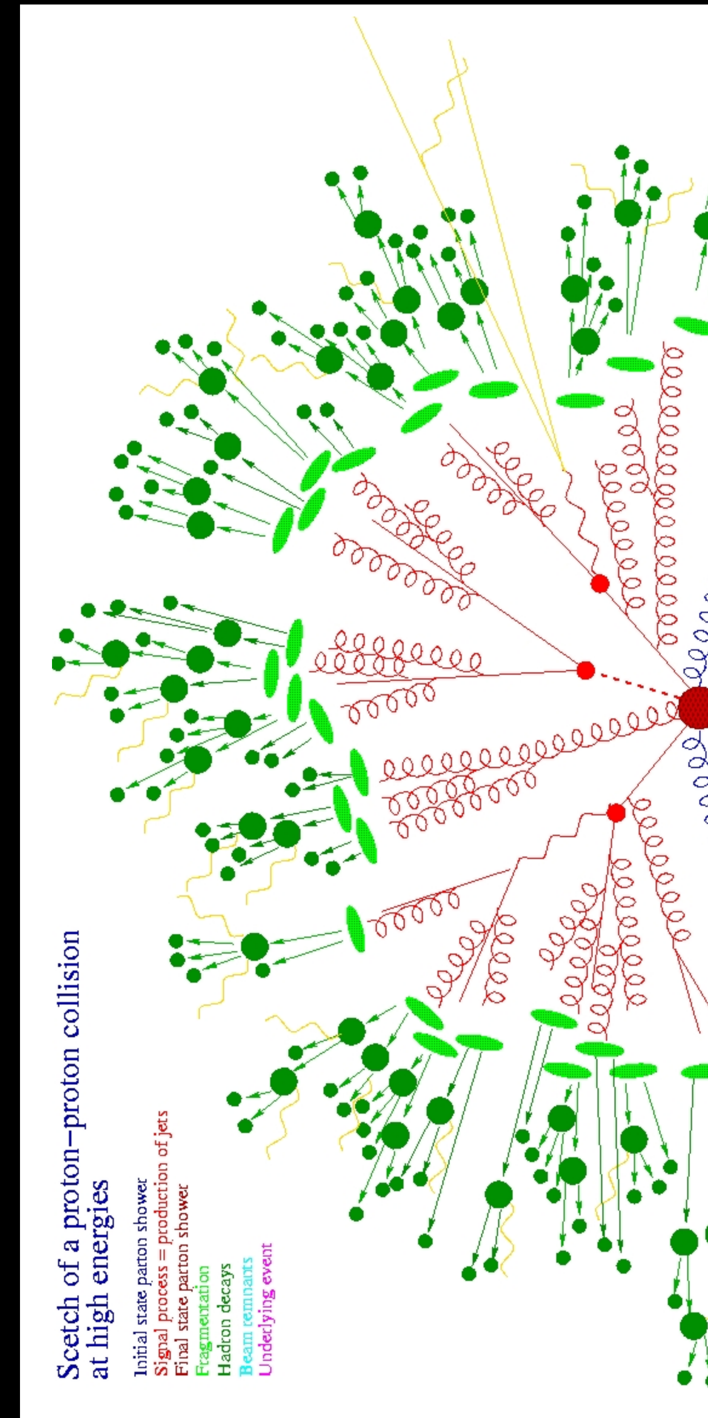
Magnetic fields bend charged particles, providing another measure of their momentum.

Photons & Leptons

- Electrons
  - Electrons leave a track in the Silicon and tracker and deposit essentially all of their energy in the the EM calorimeter.
- Photons
  - Photons (being neutral) leave no tracks, but deposit their energy in the EM calorimeter.
- Muons
  - Muons (being charged) leave tracks, but because of their large mass do not easily lose energy through radiation. They typically make it through the EM and hadronic calorimeters and deposit their energy in the muon system.
- Neutrinos
  - Neutrinos to zeroth order do not interact with a collider detector at all.

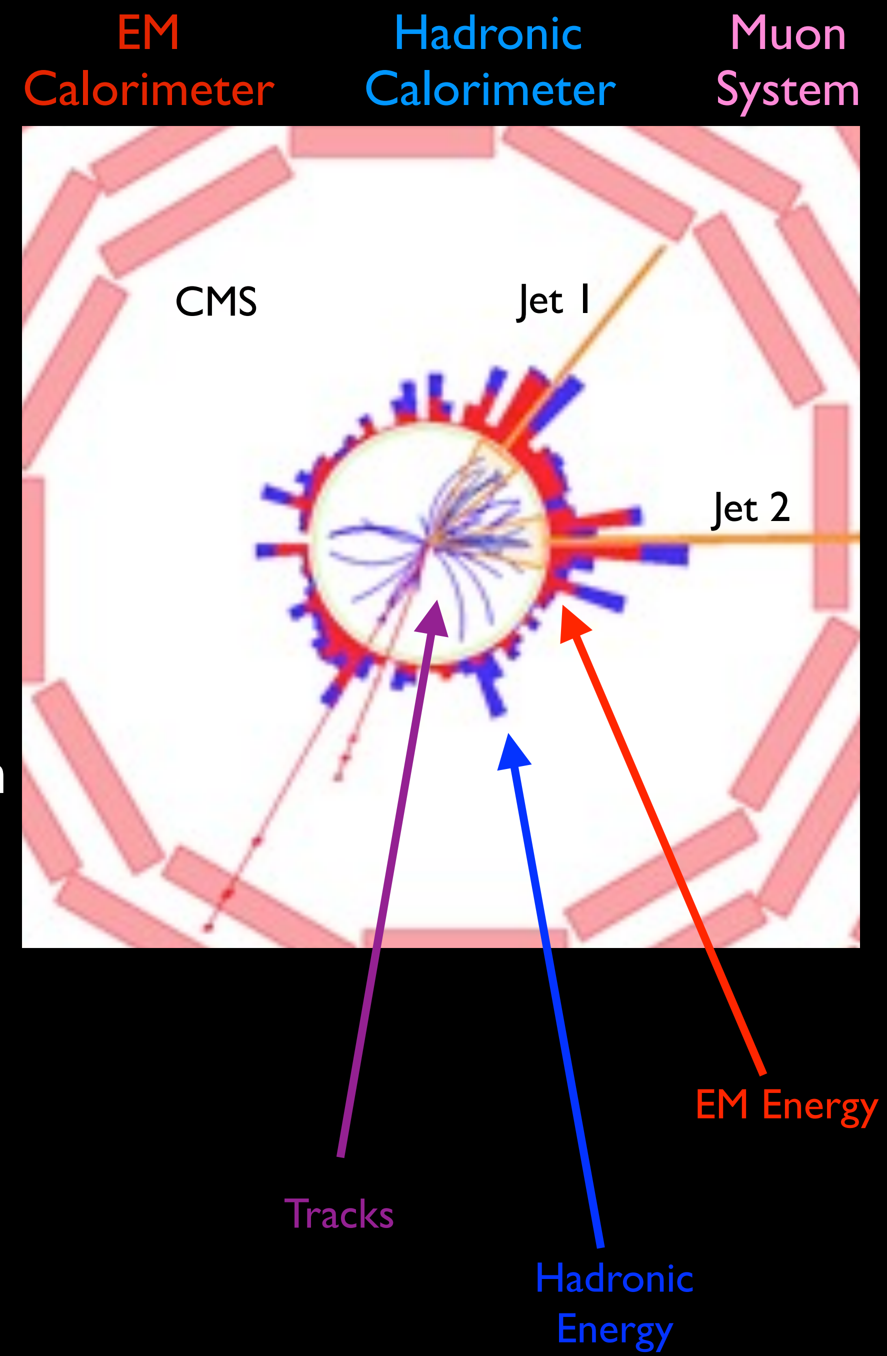
Jets

- A quark or gluon produced in a collision will evolve into a jet:
  - First, there is a large probability to radiate more quarks and/or gluons in almost the same direction (collinear) as the original one. This process is called "fragmentation".
  - Finally, the strong force neutralizes the color of each quark or gluon, producing a number of hadrons ("hadronization").
- As a result, an energetic quark or gluon typically results in a cluster of hadrons moving in approximately the same direction. This is called a jet.



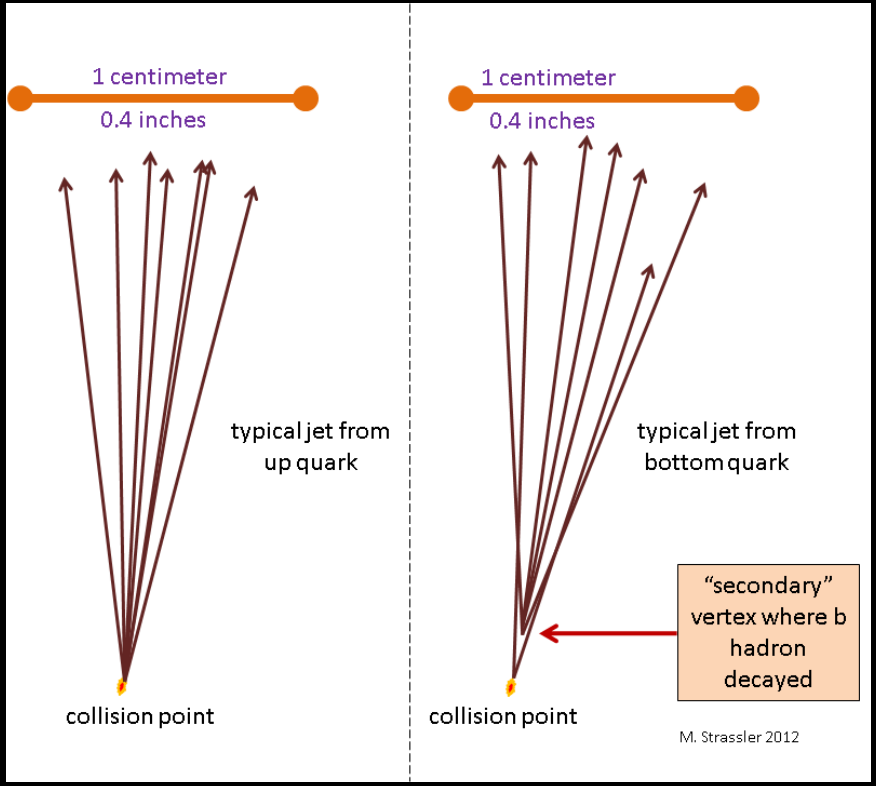
Jets

- A jet typically contains several hadrons, including both charged and neutral objects.
  - The charged hadrons leave tracks in the tracker and silicon.
  - They also deposit energy in the EM calorimeter.
  - Neutral pions decay very quickly into photons, which also register as energy in the EM calorimeter.
  - Particles which make it to the hadronic calorimeter are slowed down and their energies measured.
  - So jets look like a cluster of activity in the tracker, EM & hadronic calorimeter.



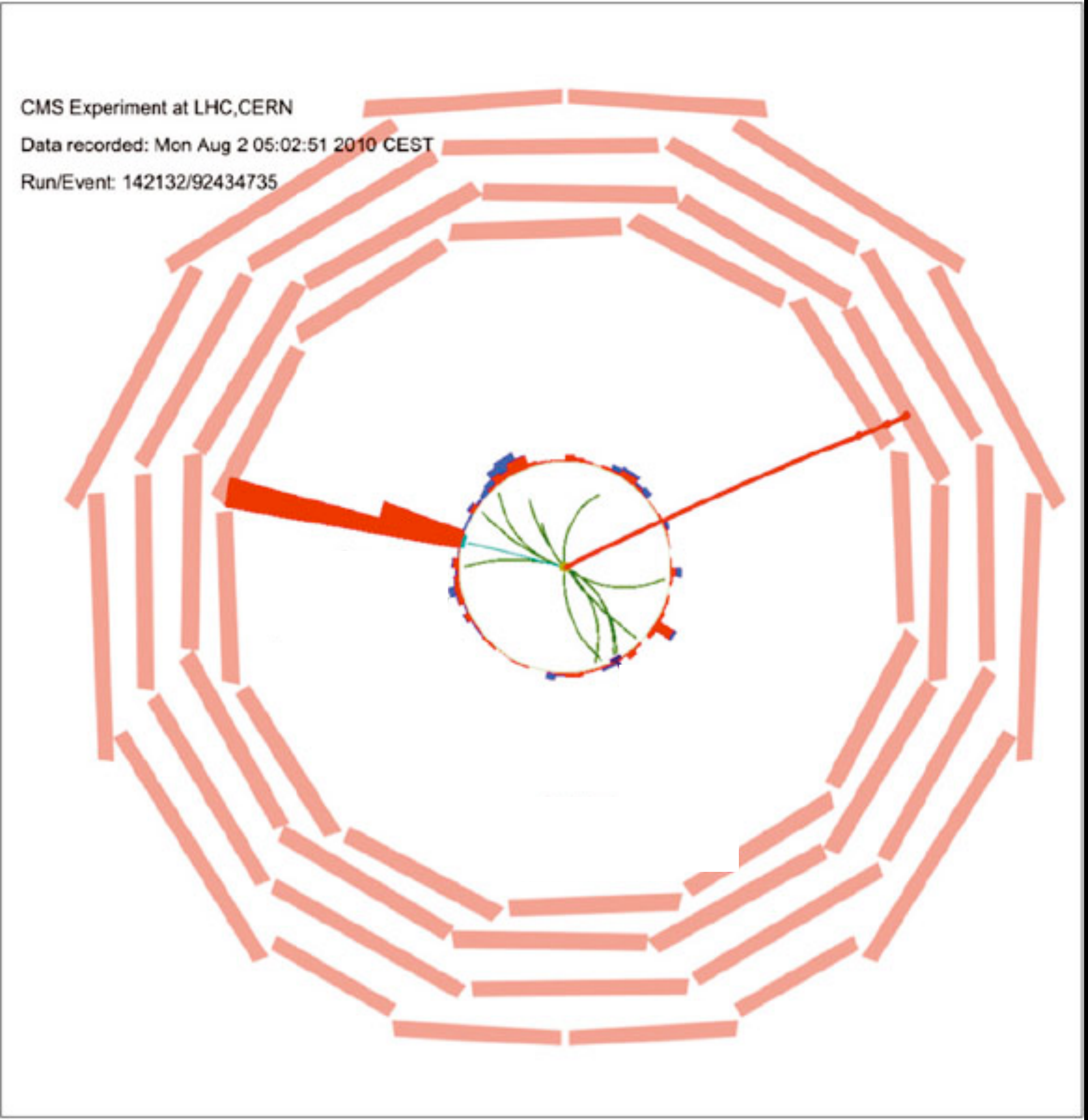
B-Jets

- B-quarks are much the same as other quarks.
- The big difference is that they live a long time, because they have small interactions with the W and charm quark.
- As a result, they travel a finite distance of about ~ mm scale as hadrons before they decay.
- The silicon detector is able to see this finite distance, and thus can tag the bottom hadron decay from its displaced vertex.
- Otherwise, they story of fragmentation and hadronization is the same, resulting in a jet of hadrons in the detector layers (tracking and EM & hadronic calorimeters).



(Graphic courtesy of Matt Strassler)

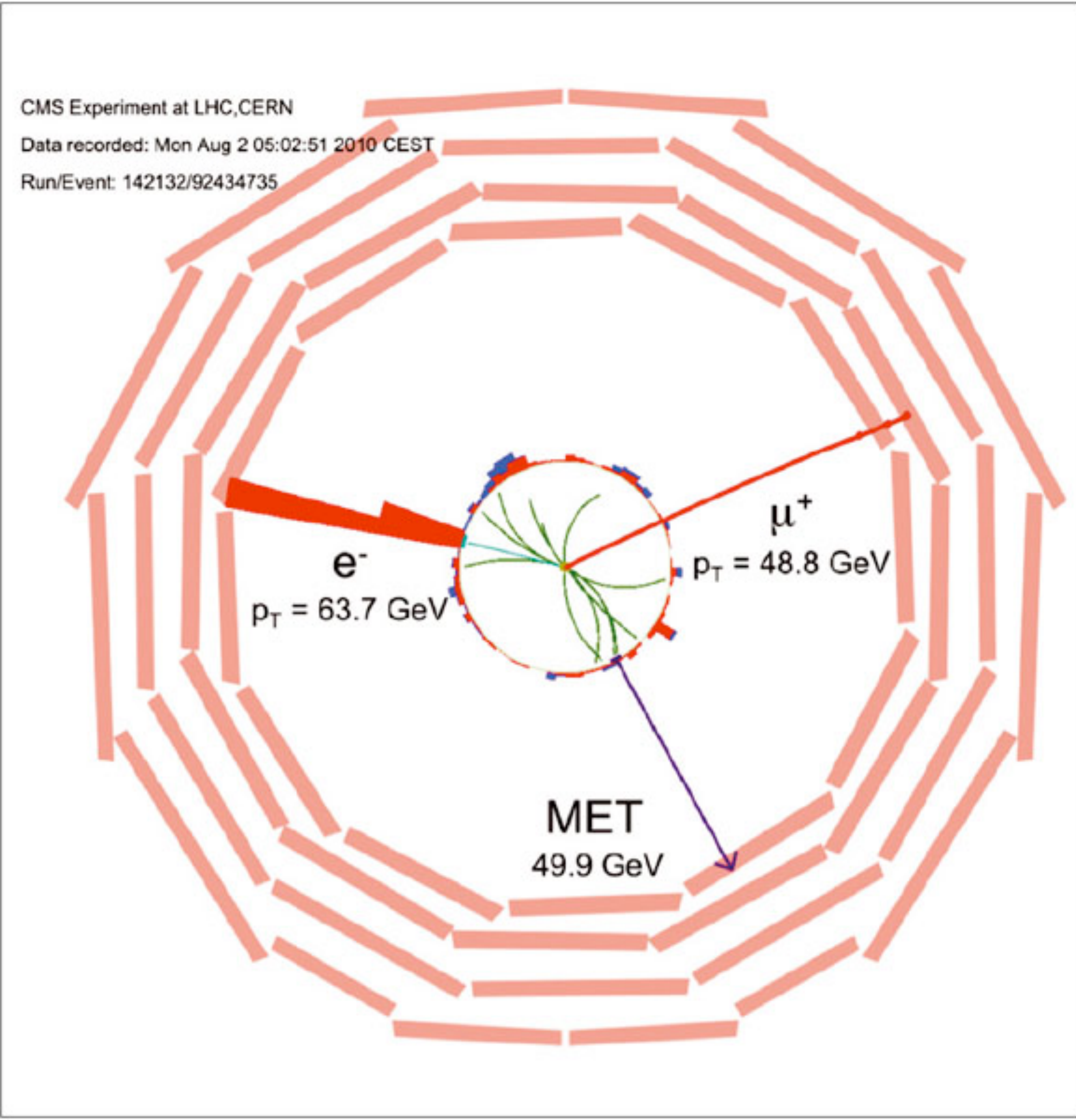
Let’s analyze some events…



EM Calorimeter

Hadronic Calorimeter

Muon System

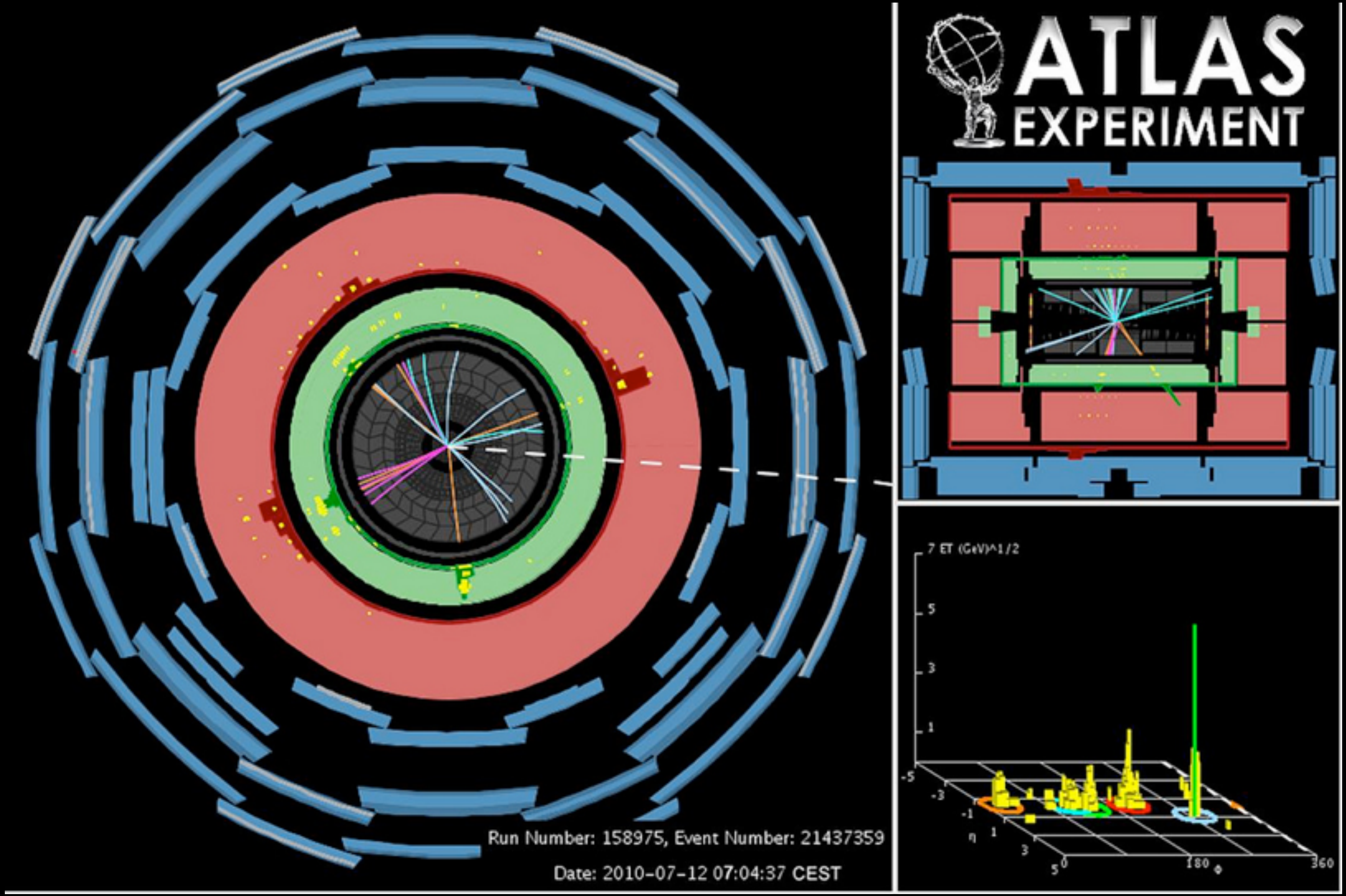


EM Calorimeter

Hadronic Calorimeter

Muon System

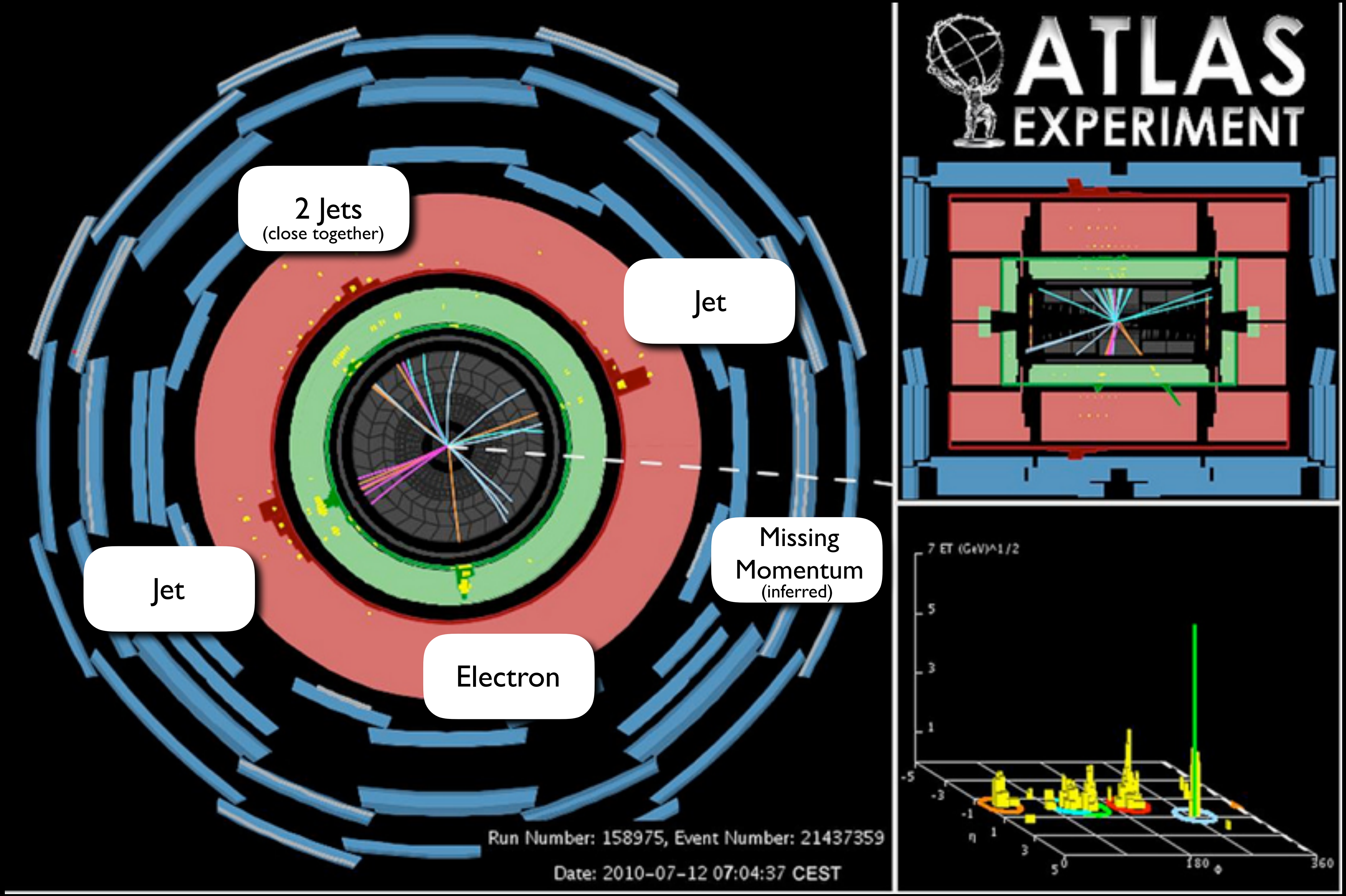
(This event was probably a W^+W^- pair which decayed into $e^-\nu$ and $\mu^+\nu$.)



EM
Calorimeter

Hadronic
Calorimeter

Muon
System

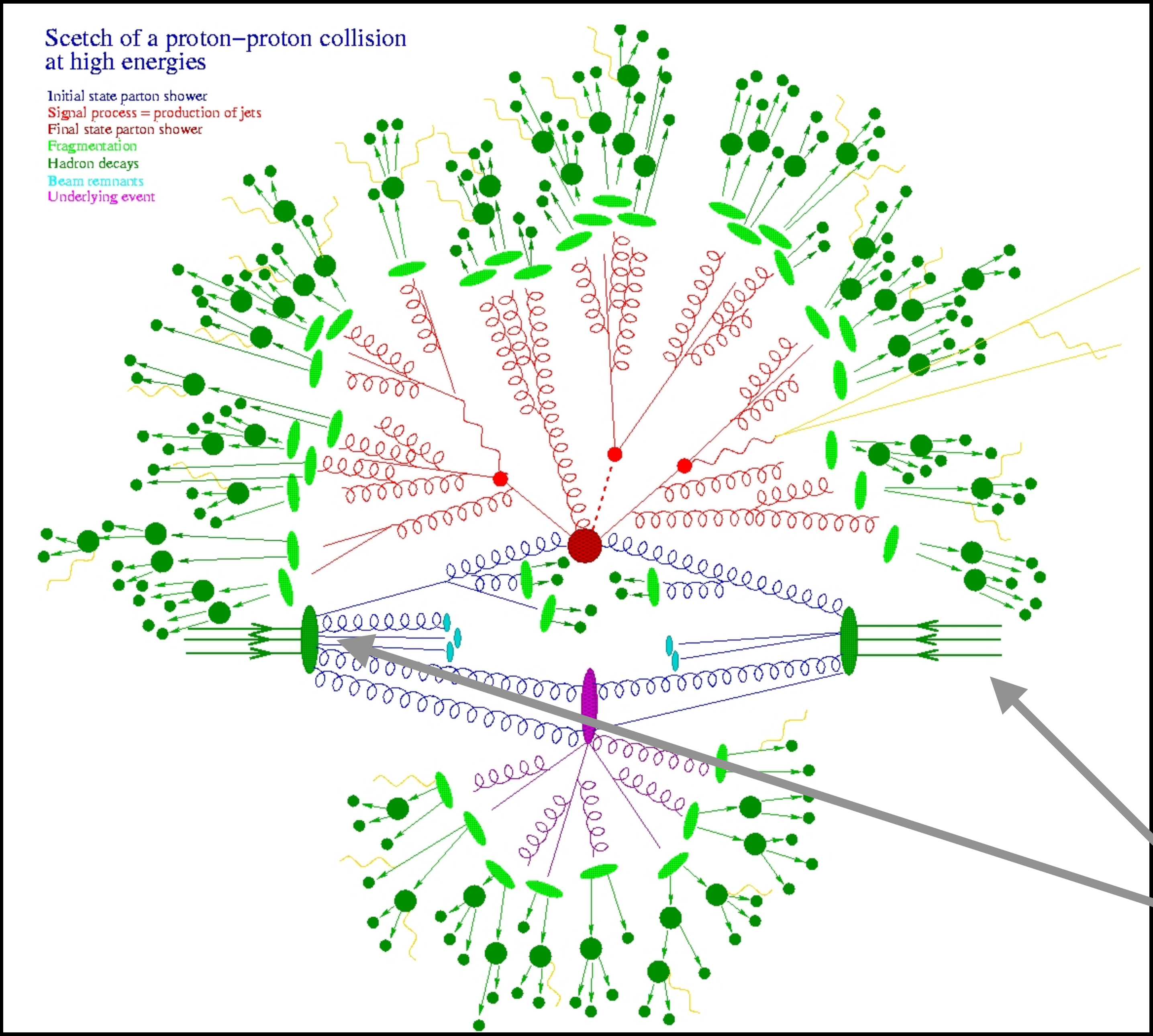


EM
Calorimeter

Hadronic
Calorimeter

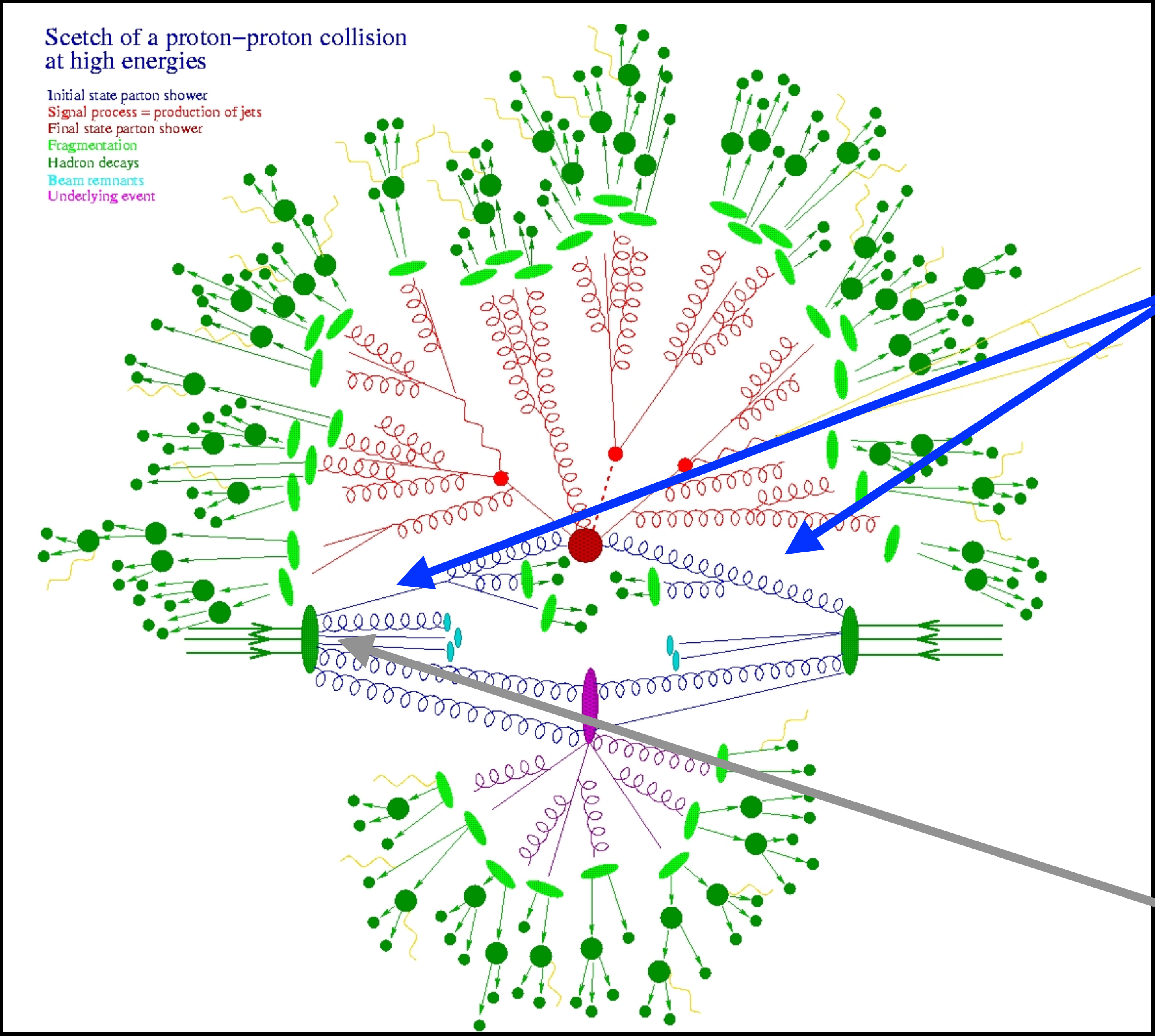
Muon
System

Anatomy of a Collision



Protons come in as color singlets.

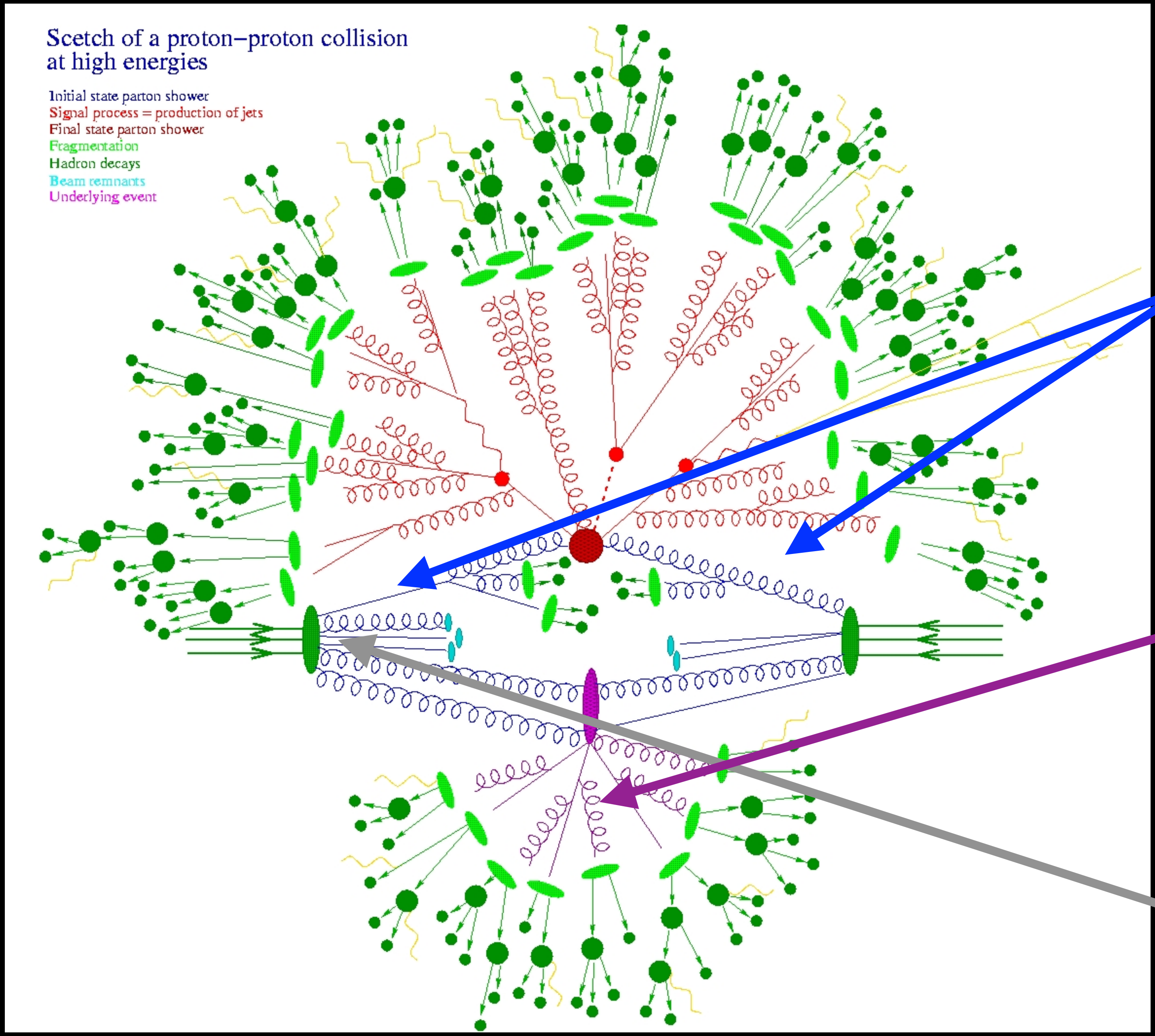
Anatomy of a Collision



Energetic partons participate in the hard scattering (controlled by PDFs).

Protons come in as color singlets.

Anatomy of a Collision

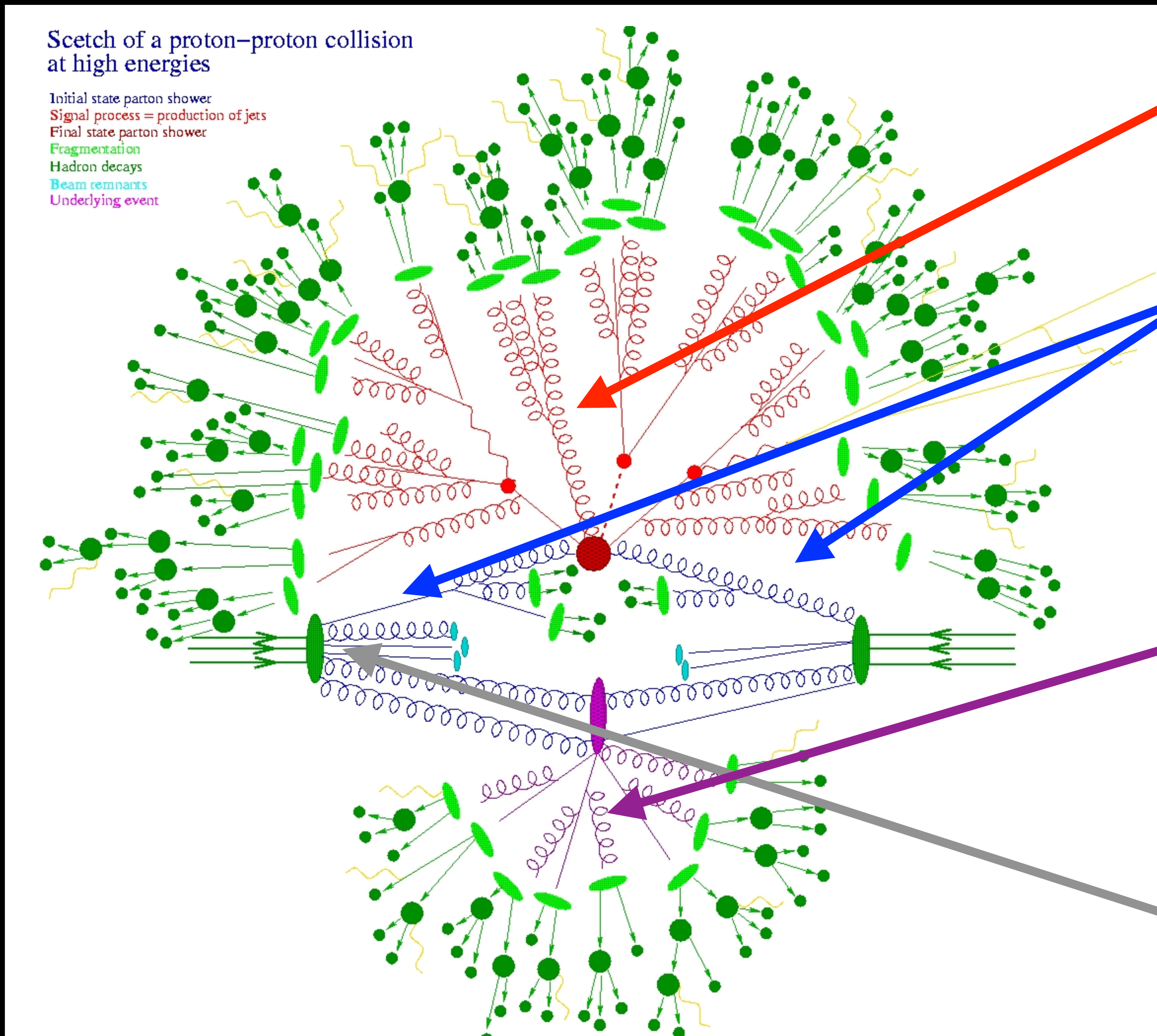


Energetic partons participate in the hard scattering (controlled by PDFs).

Proton remnants leave behind hadronic debris.

Protons come in as color singlets.

Anatomy of a Collision



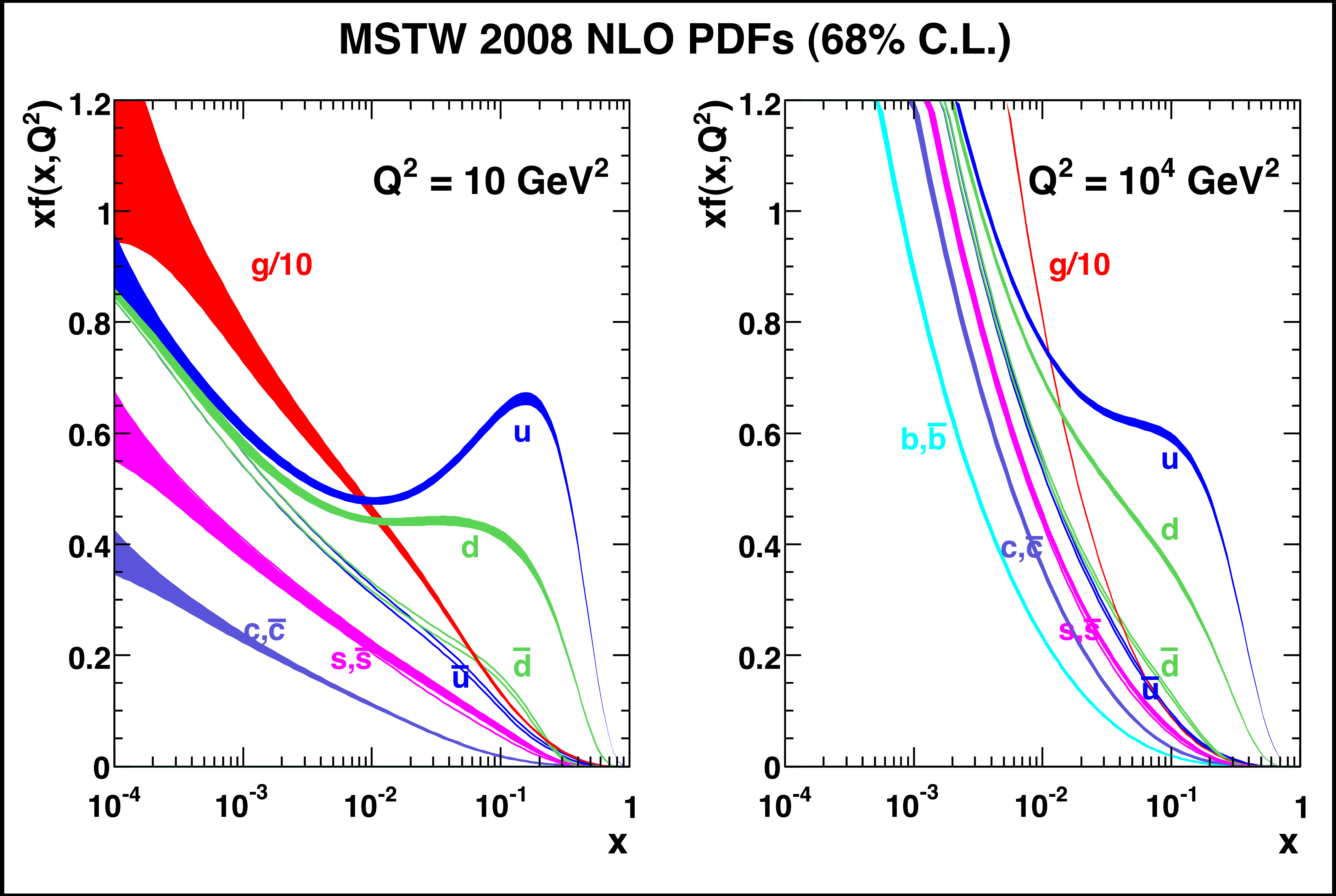
Outgoing partons fragment and hadronize into jets.

Energetic partons participate in the hard scattering (controlled by PDFs).

Proton remnants leave behind hadronic debris.

Protons come in as color singlets.

Parton Distribution Functions



Note they have plotted x*f(x) and the gluons are divided by 10.

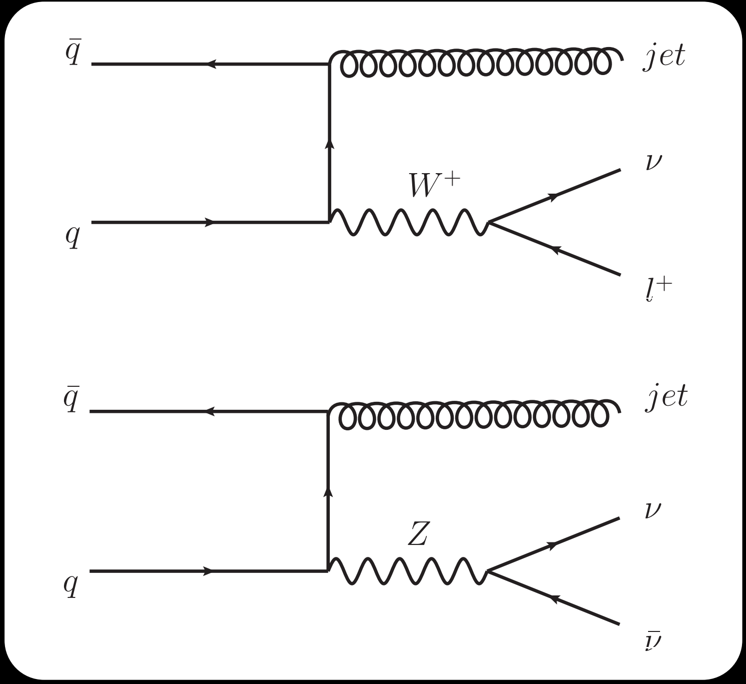
Missing Energy Signals

- Missing transverse energy (really: transverse momentum) signals are a big part of the new physics menu at colliders, largely because of the potential connection to dark matter.
- They are challenging, because to infer that momentum is missing, one needs to accurately measure *everything* visible!
- "To measure nothing you have to understand everything".
- Colliders have the disadvantage that they aren't looking for the ambient dark matter around us.
  - They could easily discover a form of missing momentum that has nothing to do with DM.
  - Limits are more robust.

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

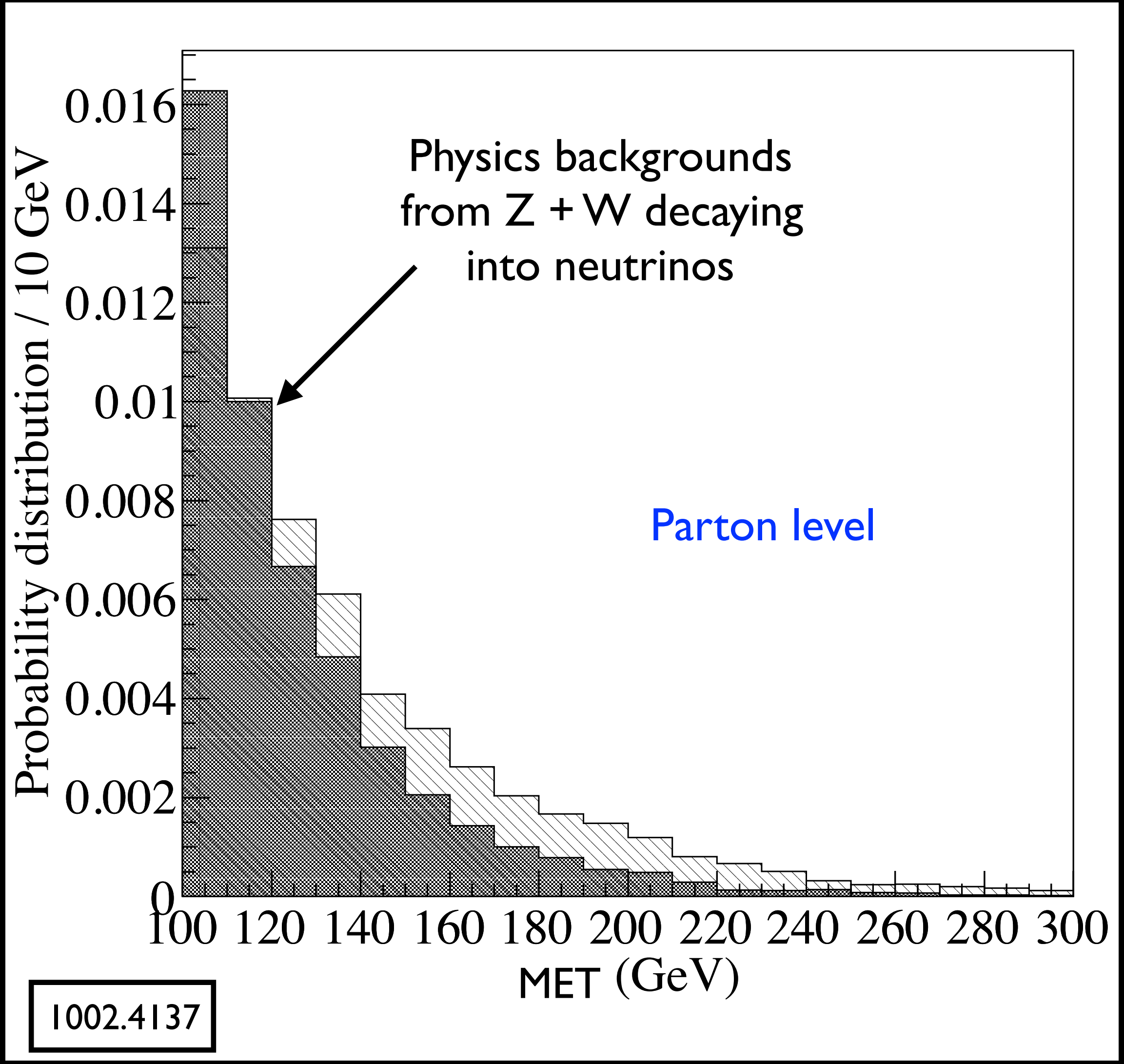
Backgrounds

- There are important backgrounds to searches for missing momentum.
- Neutrinos also appear as a momentum imbalance in the detector.
  - The Z boson decays ~20% into νν.
  - W bosons decay into l^+ ν. If the detector misses the l^+, this just looks like missing momentum.
  - τ lepton decays also produce neutrinos.
- If jet energies are mis-measured a little bit, this is a fake source of missing momentum. (This is usually called the “QCD background”).

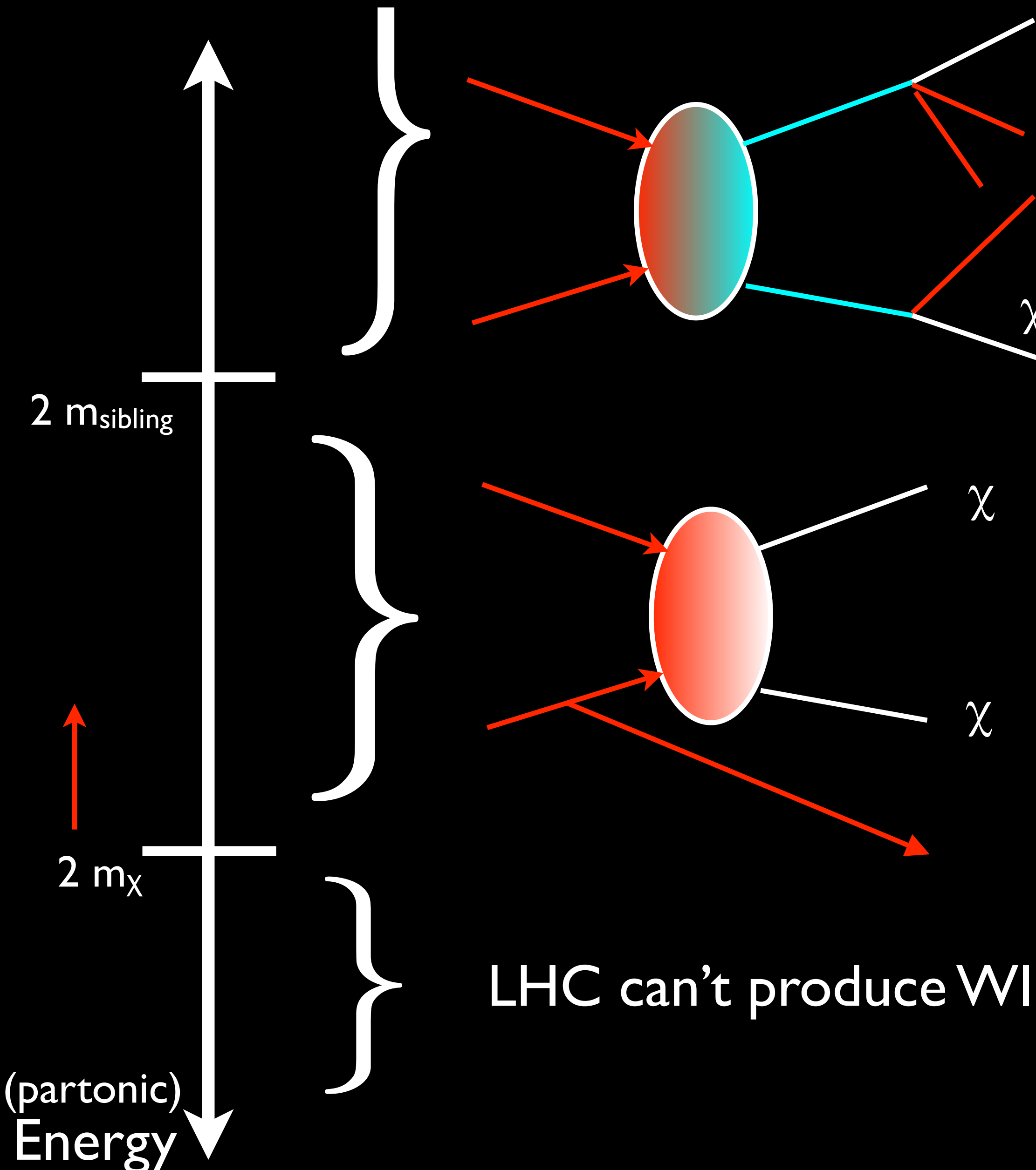


Physics Background

- The QCD background depends a lot on the detector performance and usually can't be predicted — it must be measured.
- The neutrino backgrounds result in missing momentum which falls sharply above the masses of the W and Z bosons at ~ 100 GeV.
- Typical analyses ask for some amount of MET plus other interesting objects (jets, leptons, photons) in the event.
- Something must be there in addition to the MET to trigger on!



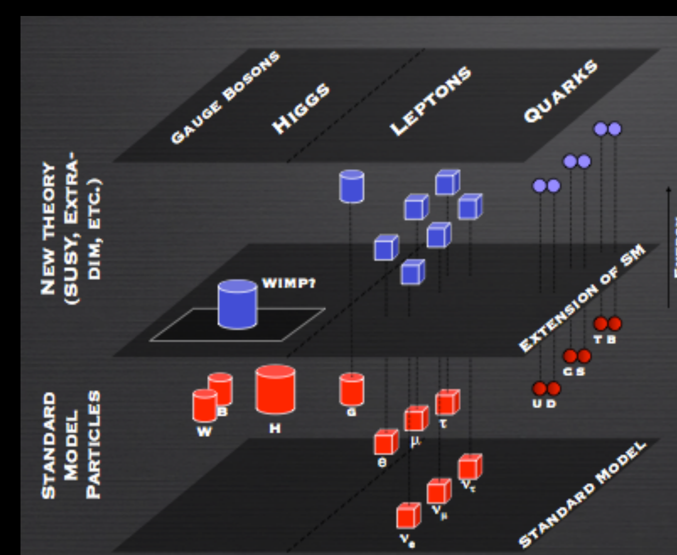
LHC WIMP Production



LHC can produce WIMP siblings, which decay into WIMPs and other SM particles.

LHC can directly produce WIMP pairs.

LHC can't produce WIMPs.



Recap: Searches for DM

- Particle physics offers many interesting opportunities to learn about the particle properties of dark matter.
- Indirect detection tries to observe dark matter annihilating around us.
  - This technique is trying to see the dark matter where it is the most dense, and can help us map out its distribution (eventually).
  - Many final states lead to interesting signals in gamma rays, anti-matter, and/or neutrinos.
  - The big challenge is the astrophysical backgrounds, which are largely poorly known.
- Direct detection tries to see dark matter scattering with detectors on the Earth.
  - Current experiments are mostly sensitive to coupling to quarks or gluons.
  - Very sensitive devices currently have close to zero background and thus make rapid progress in constraining the parameter space.
  - Eventually, they will become sensitive to neutrino scattering, which will make detecting dark matter much more challenging.

Recap: Searches for DM

- Collider production tries to produce dark matter at high energy accelerators.
  - The control over the initial state and understanding of the Standard Model processes gives a lot of control over backgrounds.
  - Collisions at an accelerator with fixed energy can only produce dark matter if it is light enough.
  - The challenge will be establishing that a discovery is really the dark matter around us, and not some other kind of new physics, like a particle which looks like missing energy or some new physics in high energy neutrino scattering.
- Together, all of these particle physics searches provide complementary information!