Vanderbilt QuarkNet Workshop 2021

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June 21st, 2021

Vanderbilt University

Overview

- Introduction
- Particle Physics & The Standard Model
- Dark Matter (DM)
- SuperSymmetry (SUSY)
- Compressed Mass Spectra & Co-annihilation scenarios.

Theory

- Compact Muon Solenoid (CMS) Experiment and the Large Hadron Collider (LHC)
- How to search for new physics at the LHC
- Probing SUSY at the LHC
- Vector boson fusion (VBF) interactions.

Experiment

- Conclusion and Future Outlook
- Data Analysis:
  - ⤷ Trigger studies
  - ⤷ Signal Optimization
  - ⤷ Background (BG) Estimation
  - ⤷ VBF Jet Studies

Time permitting, discussion of analysis techniques

Introduction

- I am a 4th year graduate student and Ph.D. candidate in the Vanderbilt High Energy Physics group.
- My research looks for new physics beyond the standard model (to be covered shortly).
- I hold B.S. degrees in both electrical engineering & physics.
- My first true interest in physics started my sophomore year when before class a professor briefly explained his research to is in understandable terms.

Timeline:

Gee, I wish I was studying Physics instead

TEXAS A&M UNIVERSITY

2015, B.S.
Electrical Engineering

→

S. Kanetzky Engineering, LLC.

2015-2017,
Work in industry

→

TEXAS STATE UNIVERSITY 1899

2017- 2018, B.S.
Physics

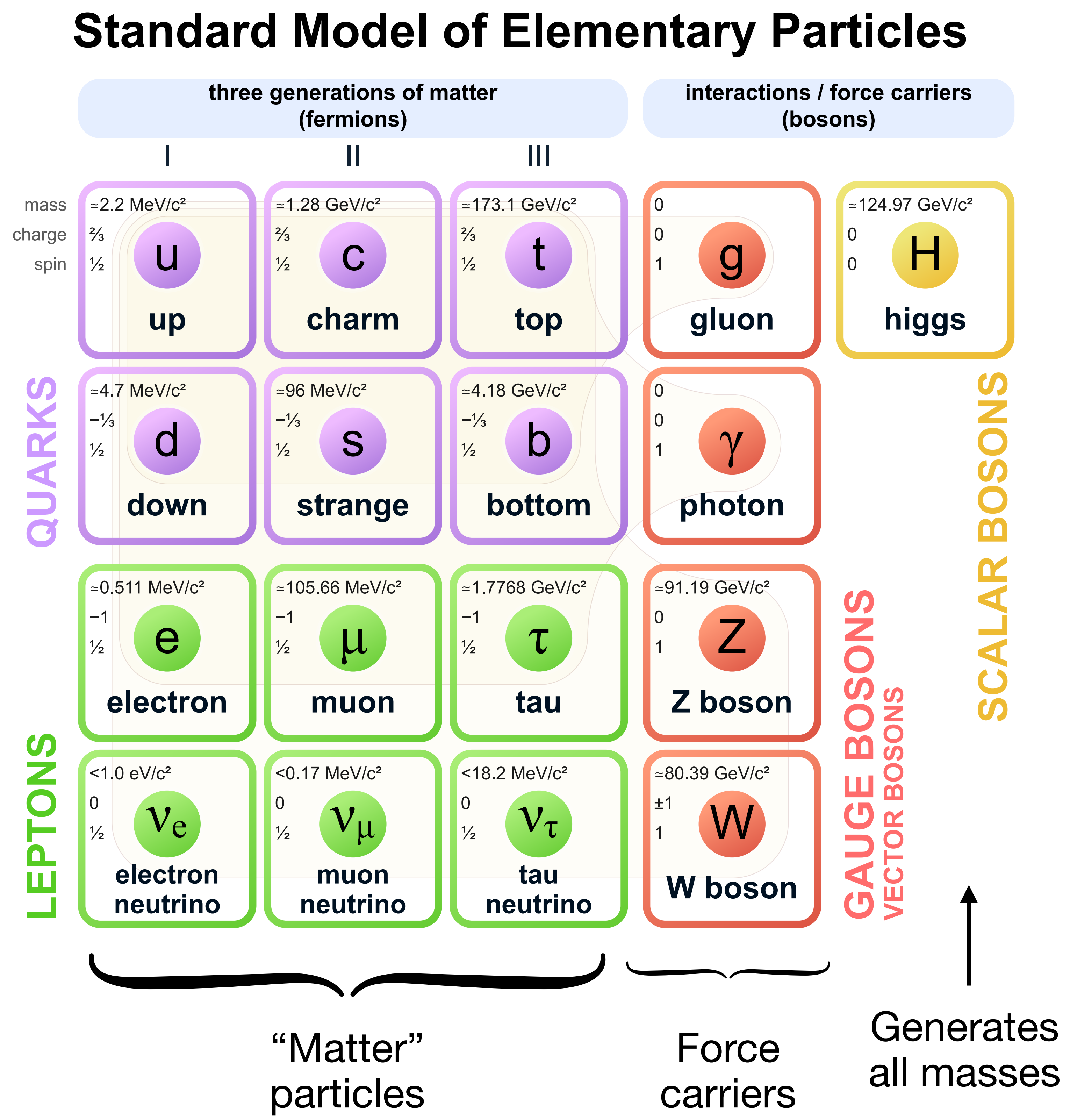
→

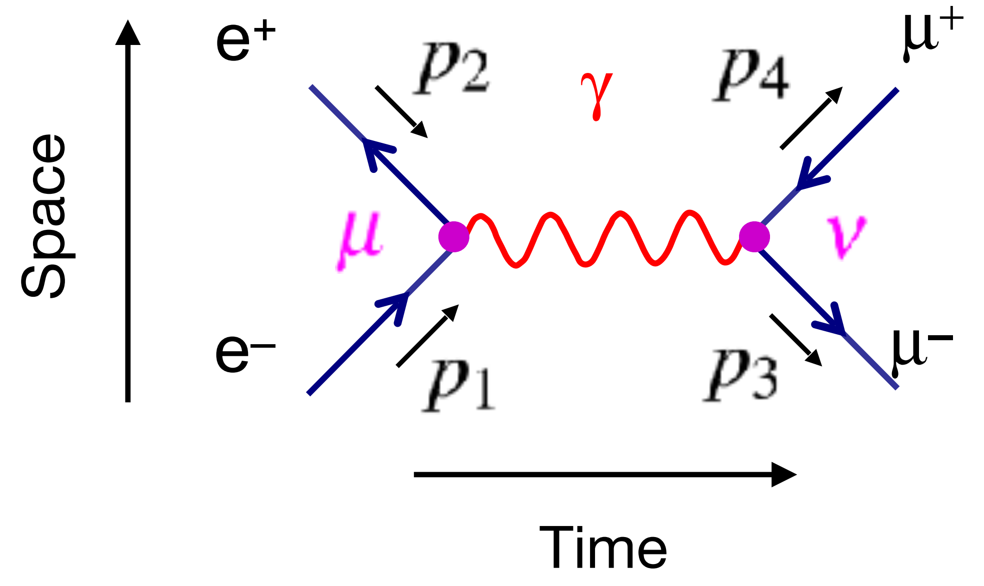
VANDERBILT UNIVERSITY

2018 - Current, Ph.D.
Physics

The Standard Model of Particle Physics

- The Standard Model (SM) represents our current understanding of particle physics.
- Completed in the mid 1970's, the SM predicted the existence of and many qualities of:
  - ↳ $W^{\pm}$ & Z^0 bosons (1983, CERN)
  - ↳ Top quark (1995, Fermilab)
  - ↳ Tau neutrino (2000, Fermilab)
  - ↳ Higgs boson (2012, CERN)
- The SM provides the theoretical foundation for what we expect to see at collider experiments. Interactions can be expressed in terms of Feynman diagrams***:





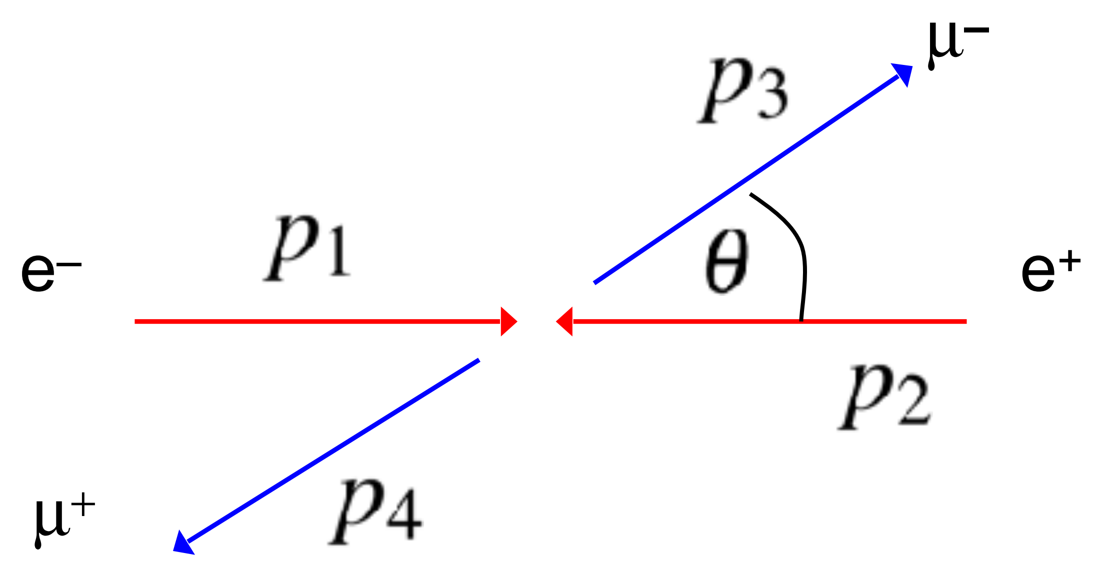
$$: \quad -iM = [\bar{v}(p_2)ie\gamma^{\mu}u(p_1)]\frac{-ig_{\mu\nu}}{q^2}[\bar{u}(p_3)ie\gamma^{\nu}v(p_4)]$$

↑ Matrix element

***(Okay to be thought of pictorially, but remember these actually represent parts of integrals)

Feynman Diagrams & Calculations

- Say we have an electron positron collider, we want to know how many muon pairs we expect to detect:



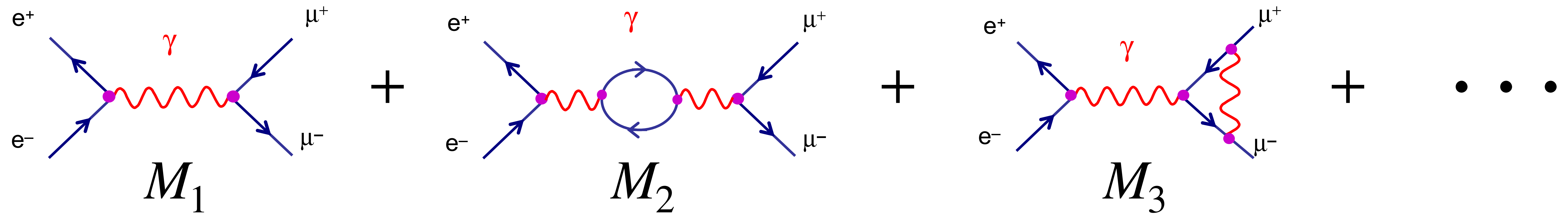
$$N = \sigma \times L$$

Number of muons we detect in the experiment (assuming perfect reconstruction)

Cross section, calculated theoretically using Feynman diagrams

Luminosity of the experiment, essentially how many $e^+ e^-$ pairs we collide

- Draw out all Feynman diagrams that contribute to cross section (beware, there are infinitely many!):



- Final result (ignoring summation over polarizations):

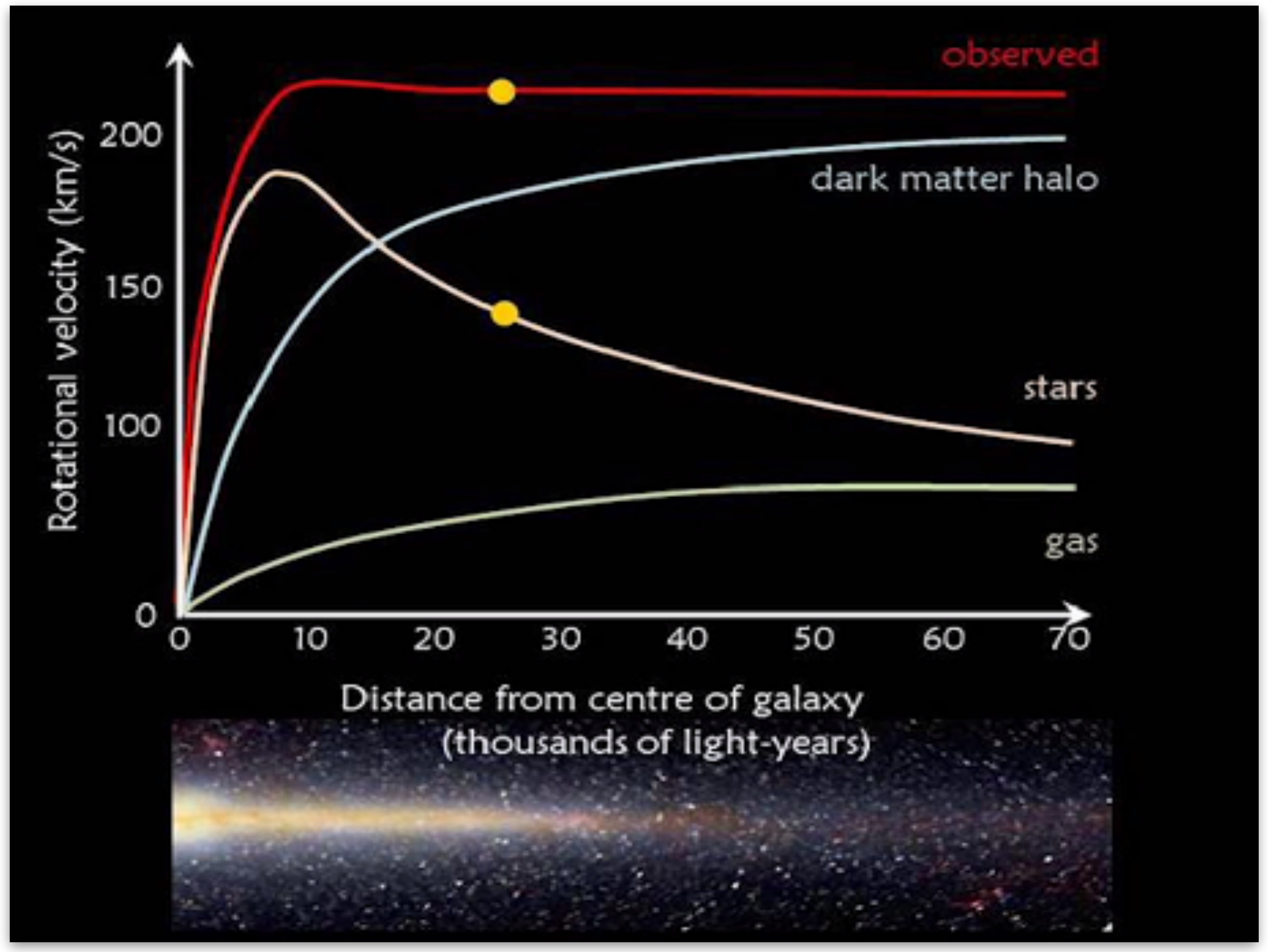
$$\sigma = \int \frac{\alpha^2}{64\pi^2(E_1+E_2)^2}\frac{|p_3|}{|p_1|}(M_1^* + M_2^* + M_3^* + \ldots^*)(M_1 + M_2 + M_3 + \ldots)\sin\theta d\theta d\phi$$

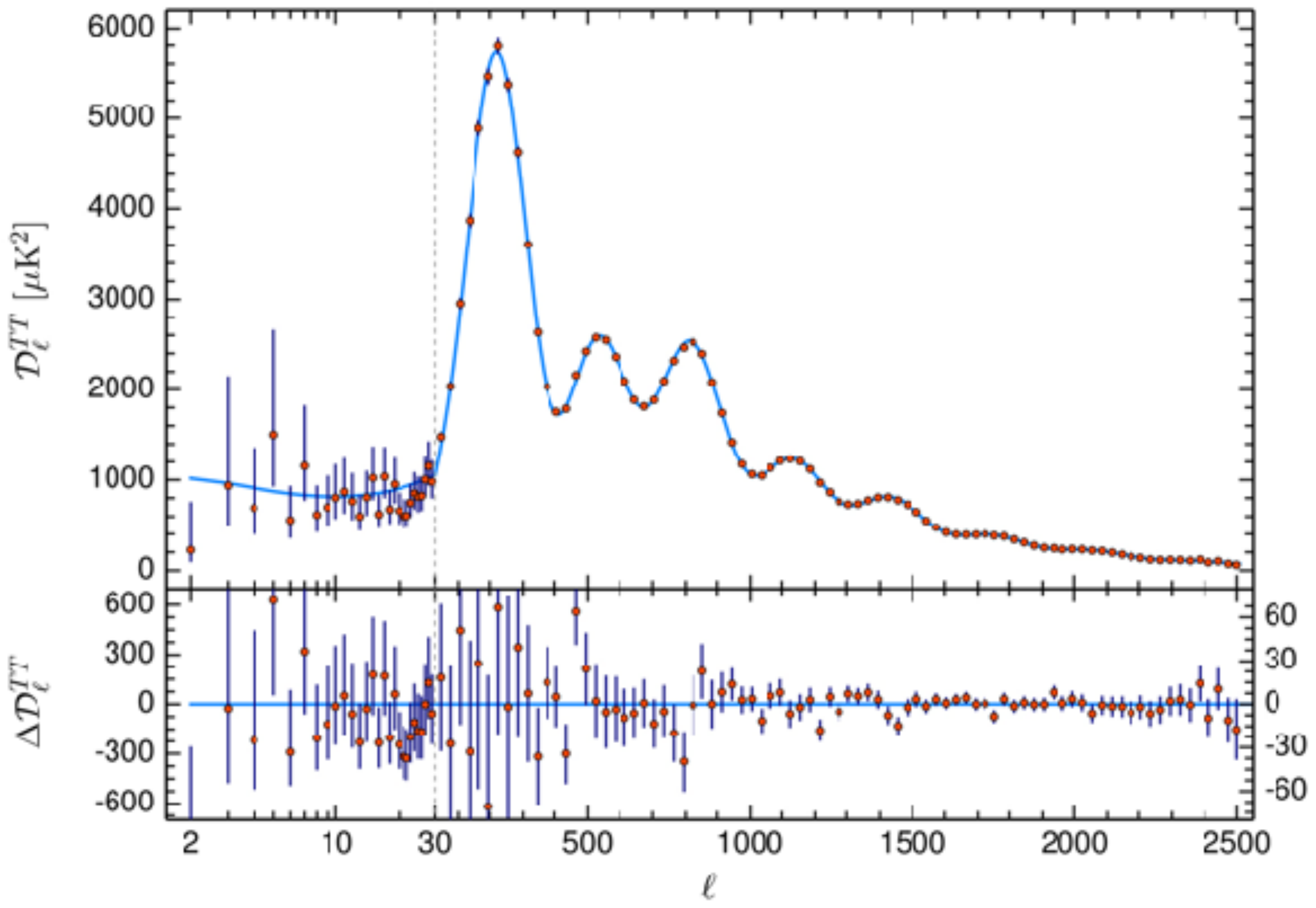
Dark Matter

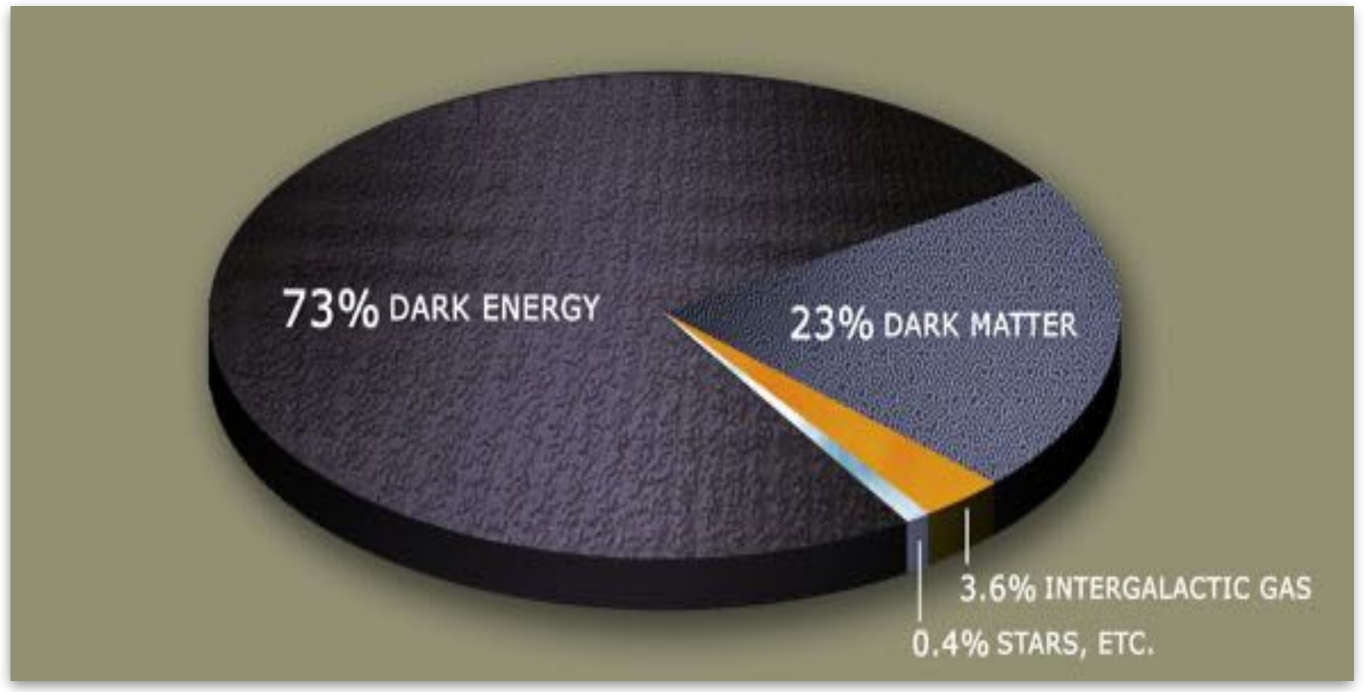
- The rotational velocity per distance of an object goes as:

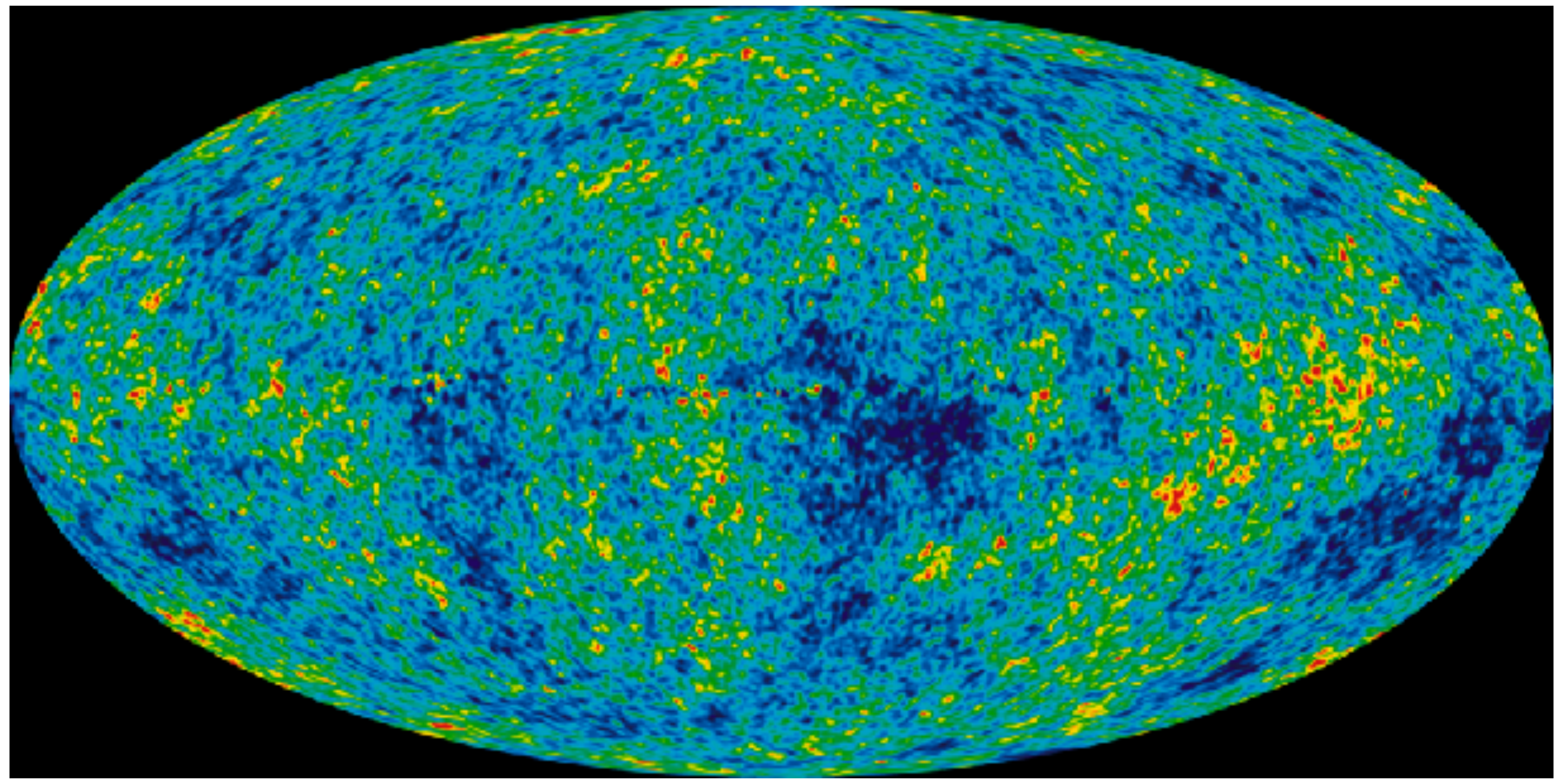
$$G\frac{Mm}{r^2} = \frac{mv^2}{r} \rightarrow v(r) = \sqrt{\frac{GM}{r}}$$

- When observing actual galaxy velocity curves however, the visible matter does not follow the trend, implying invisible mass!
- Strongest current day evidence comes from surveys of the cosmic microwave background. This looks at pressure waves in the very early universe to determine early universe composition.
- Our research group is very interested in dark matter! We primarily perform searches for theories which can postulate a “dark matter candidate particle”.





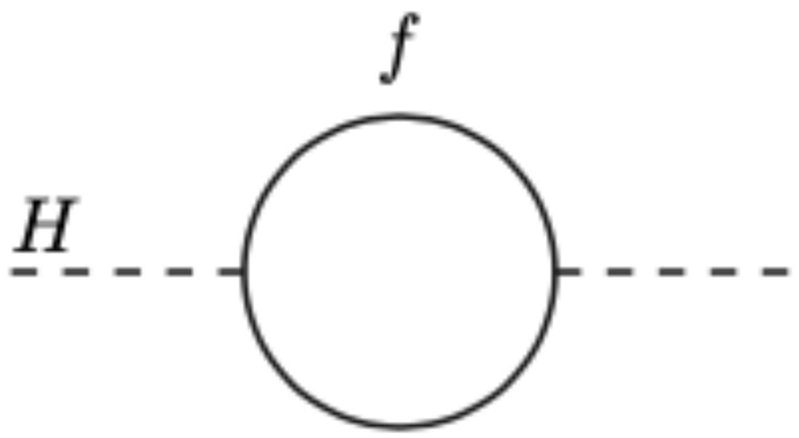




SuperSymmetry (SUSY)

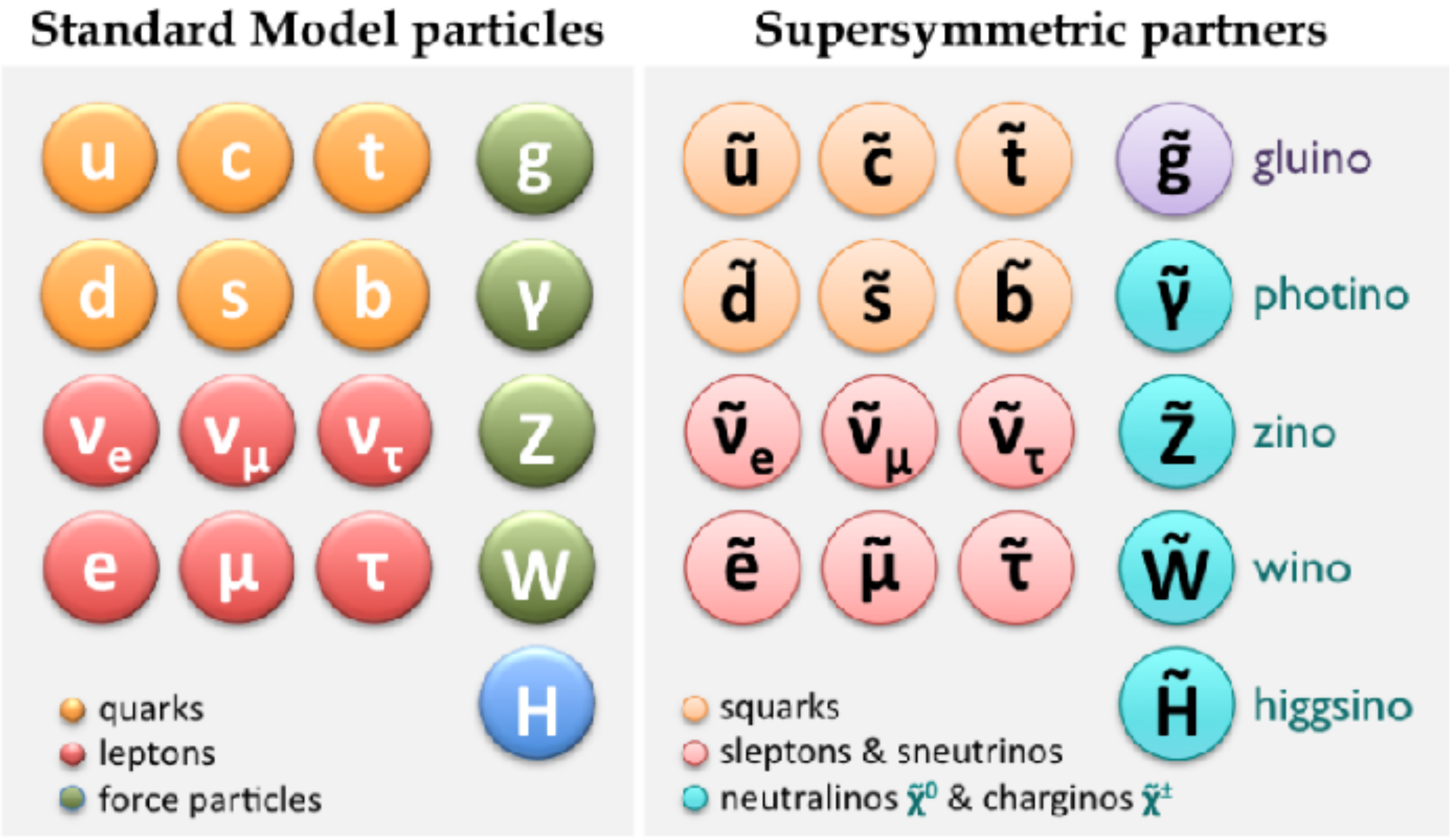
- The SM is a very good theoretical model, however there are problems!
- We know the Higgs field generates the masses of all particles. As a result, its own mass ($m_H = 125$ GeV) should receive quantum corrections and be much much bigger:

Direct Higgs coupling:



Indirect Higgs coupling:

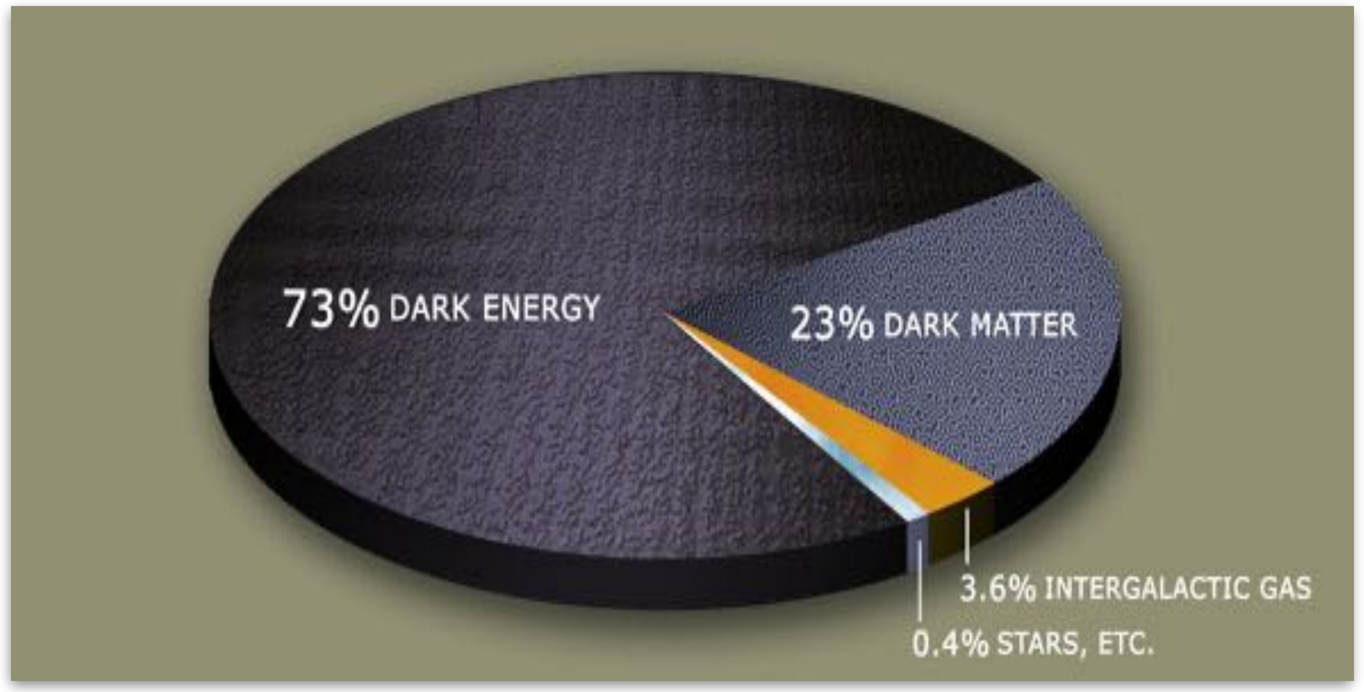
- Either any new physics must not interact with the SM at all, or there must be some way to cancel these quantum corrects. In comes SuperSymmetry (SUSY):



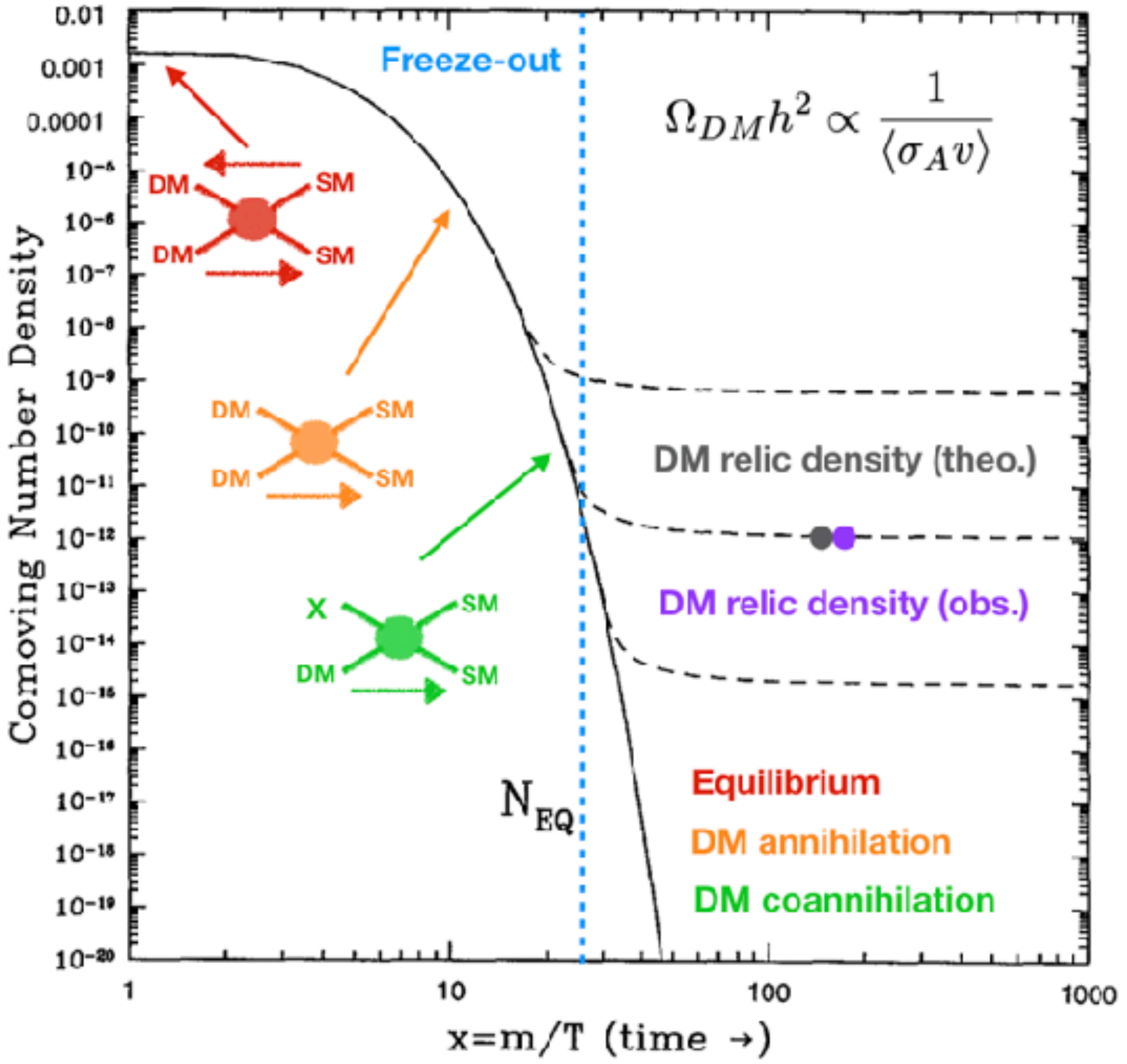
- SUSY predicts a new fundamental symmetry between all particles. The result is that the quantum corrections cancel exactly, leaving the Higgs boson a “natural” mass.
- Even better though, SUSY offers a **dark matter candidate particle**!!
- The photino, zino, wino, and higgsino “mix” to form new particles, the lightest of which is massive, stable, and weakly interacting (exactly what we expect DM to be)

Dark Matter & the Evolution of the Universe

- Current evidence suggests Dark matter (DM) constitutes 85% of the matter content of the universe (23% of the energy content).
- For thermal Big Bang Cosmological models, DM is created in thermal equilibrium with SM matter, permitting the interaction $DM + DM \rightleftarrows SM + SM$
- As the universe expands and cools, DM annihilation begins per $DM + DM \rightleftarrows SM + SM$.
- Eventually, DM becomes too diffuse to interact, leaving behind the "DM relic density" (freeze-out).
- When searching for DM, the DM relic density offers a benchmark test for identifying new particles as being the canonical DM particle (does it predict the experimentally observed value?).
- DM relic density depends on the cross section (σ) of the DM annihilation interaction. For scenarios that predict an overabundance, a "co-annihilation" (CA) partner is required for experimental consistency.



Energy contents of the universe.



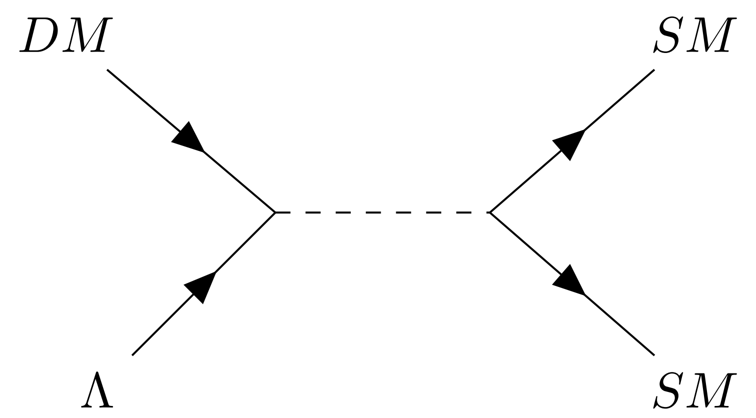
Dark matter density over the evolution of the universe.

CA Partners & Compressed Mass Spectrum Scenarios

- For scenarios in which the DM is primarily bino, meaning the mass and flavor eigenstates are very close ($\tilde{\chi}_1^0 \approx \tilde{B}$), an overabundance of DM is predicted (DM does not reduce quickly enough).

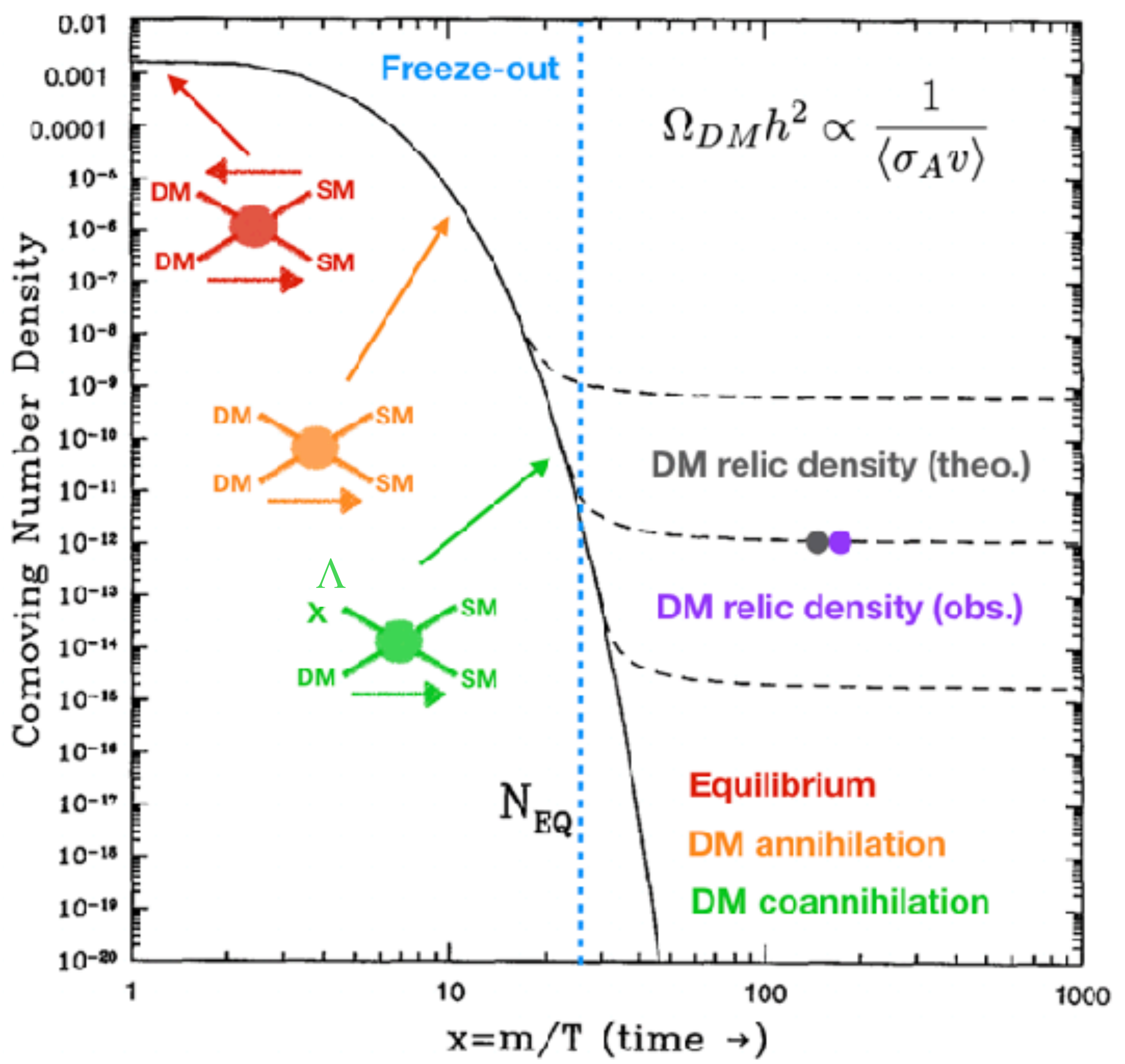
- To remedy this, a CA partner (Λ) is introduced in order to increase the cross section ($\sigma_{eff} = \sigma_{DM} + \sigma_{\Lambda}$):

- The cross section of such an interaction is exponentially dependent on the mass gap (Δm) between DM & Λ:



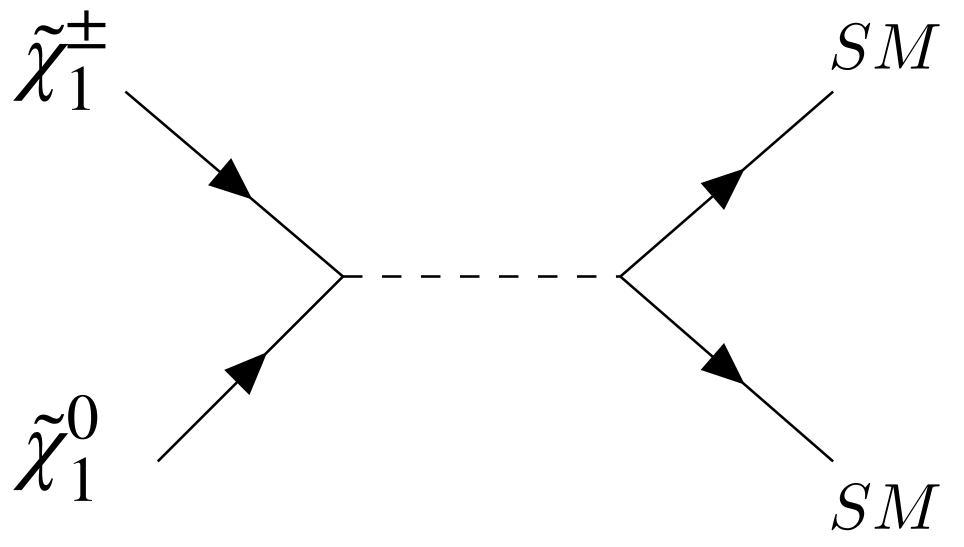
$$\sigma_{\Lambda} \propto e^{-\frac{\Delta m}{T}}$$

$$\Delta m \equiv m_{\Lambda} - m_{DM}$$

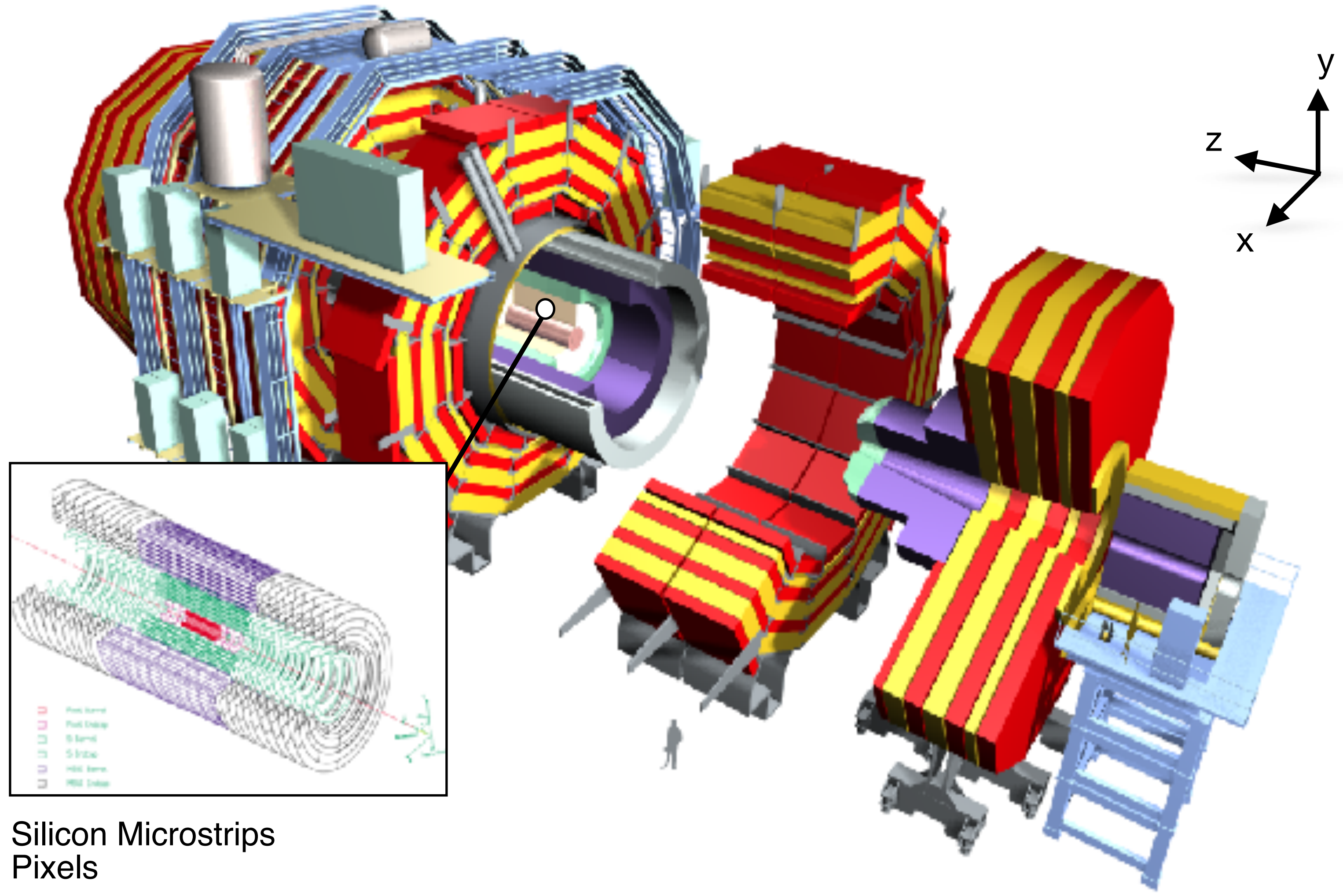


- For scenarios in which Δm is small, this interaction sufficiently reduces the DM relic density. These scenarios are referred to as "compressed mass spectrum".

- These cosmologically motivated compressed mass spectrum scenarios can be experimentally difficult to probe. This analysis assumes such a scenario where the CA partner of the $\tilde{\chi}_1^0$ is the $\tilde{\chi}_1^{\pm}$.



Ariel view of the Large Hadron Collider.



3D Rendering of CMS.

- The Large Hadron Collider (LHC) is (primarily) a proton-proton collider located at CERN, operating at $\sqrt{S} = 13$ TeV.
- The LHC consists of 2 all purpose detectors (CMS & ATLAS), 5 smaller detectors (ALICE, LHCb, TOTEM, MoEDAL, LHCf).
- CMS consists of 4 detector layers + a 4T superconducting solenoid magnet:
  - Inner tracker (Pixel & Silicon Strip Tracker):

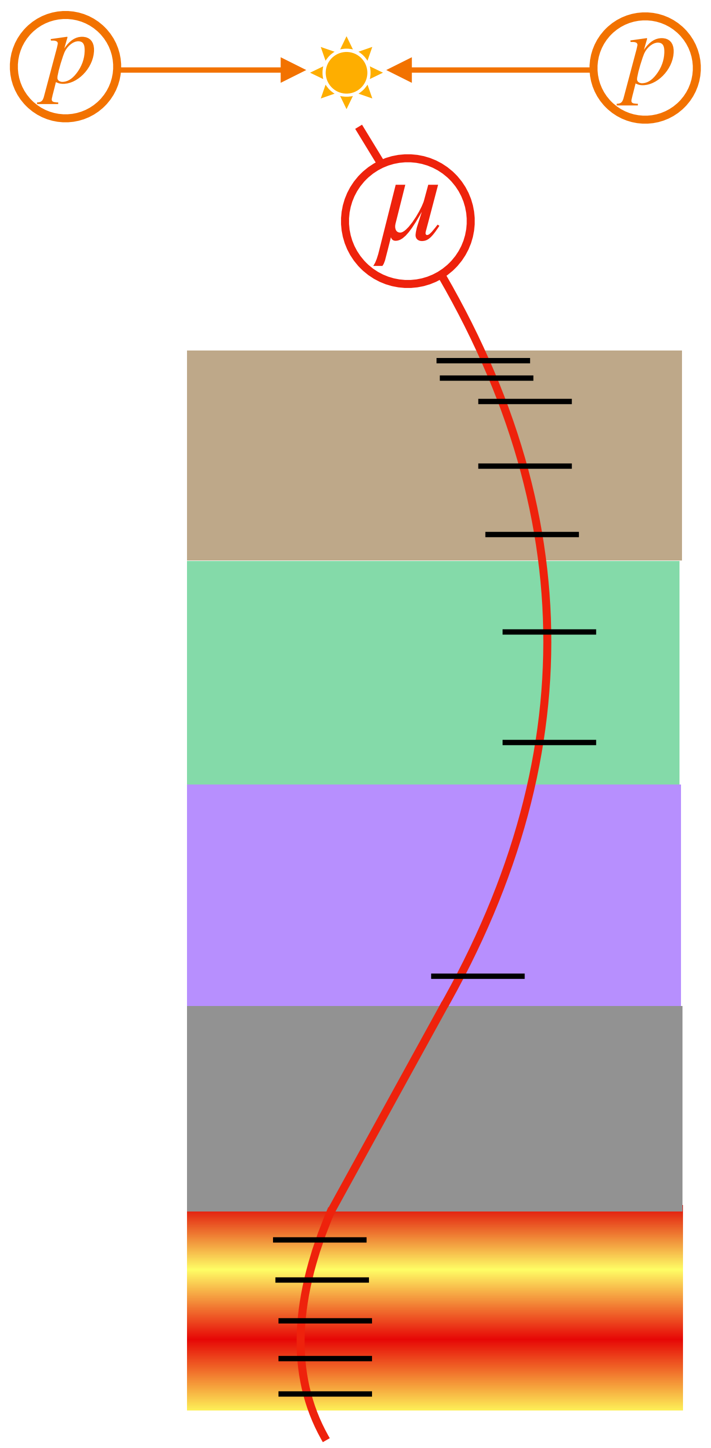
    Tracks trajectories of charged particles, essential for reconstructing paths & measuring momentum.
  - Electromagnetic calorimeter (ECAL):

    Measures energy of electrons, positrons, and photons.
  - Hadronic calorimeter (HCAL):

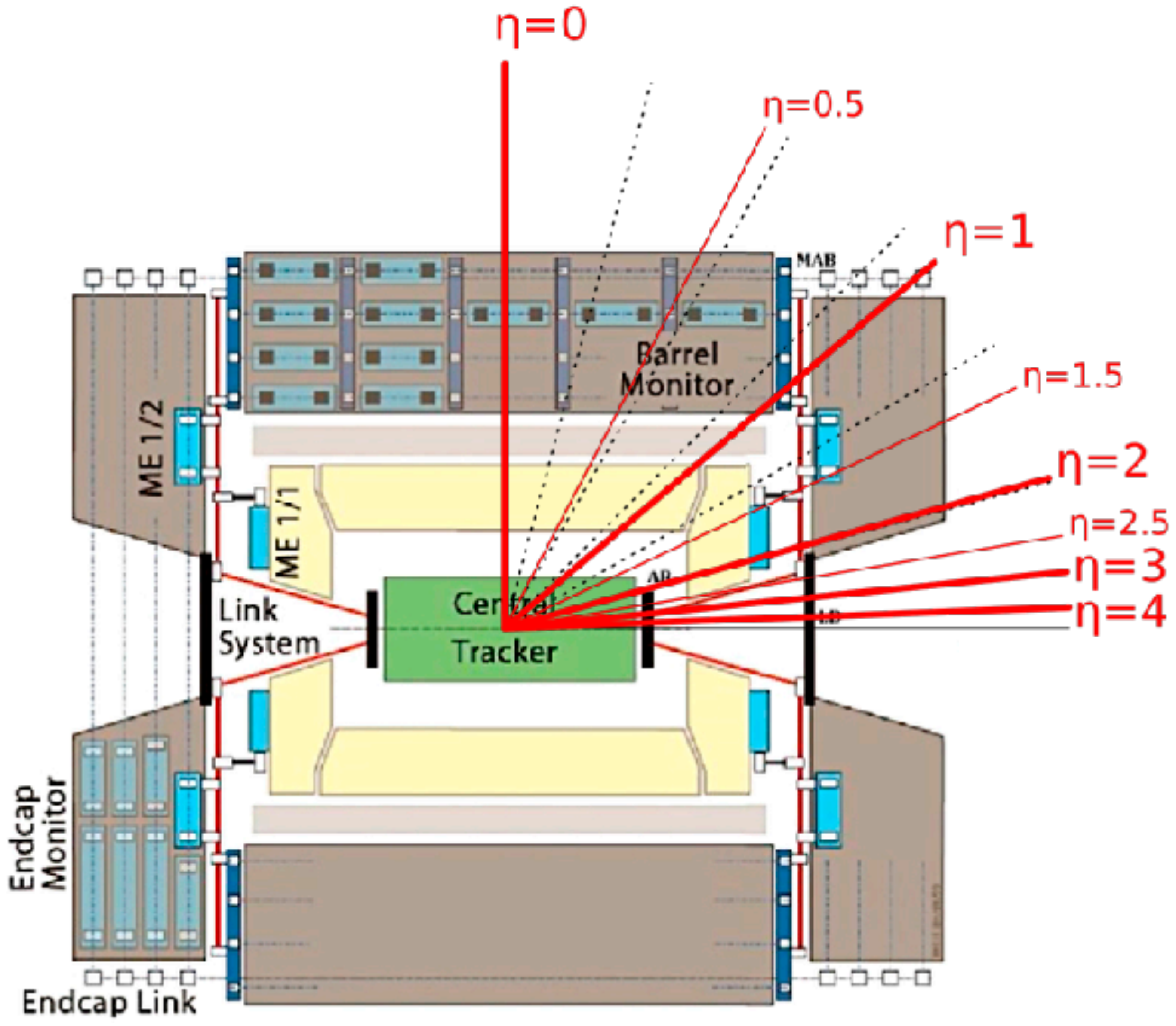
    Measures energy of hadronic material (protons, neutrons, pions, etc.)
  - 4T solenoid magnet:

    Bends charged particles to measure p, $r = \frac{p}{qB}$
  - Muon Chamber:

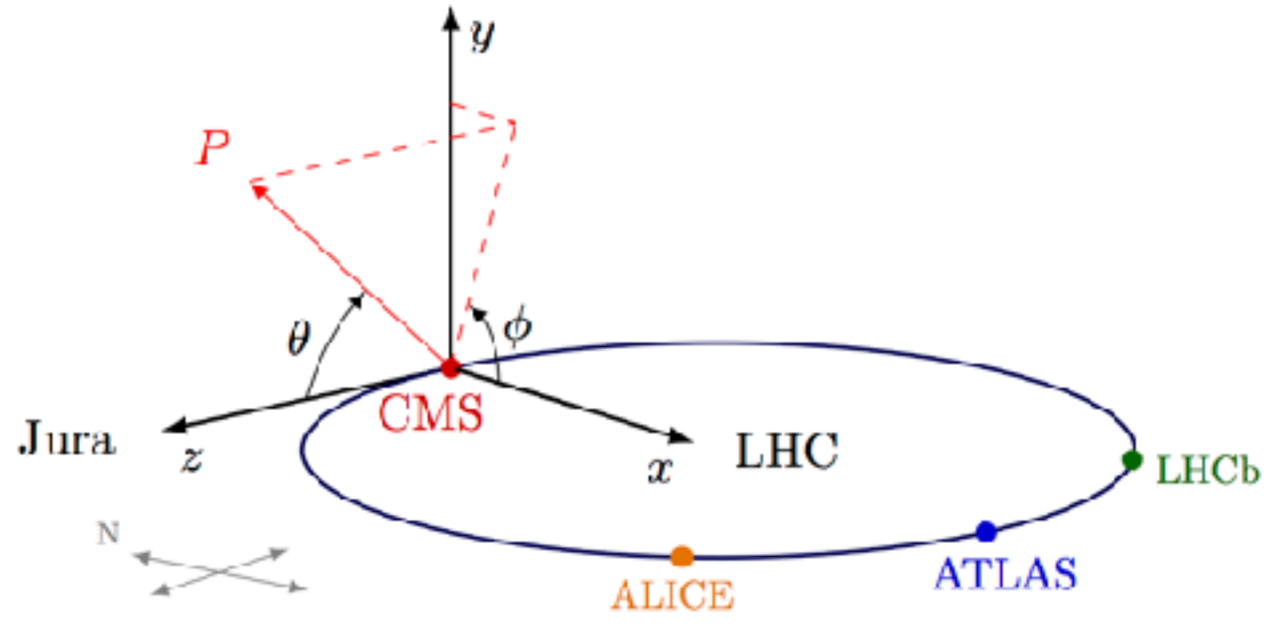
    Tracks muons, aids in muon particle identification.



CMS Coordinates

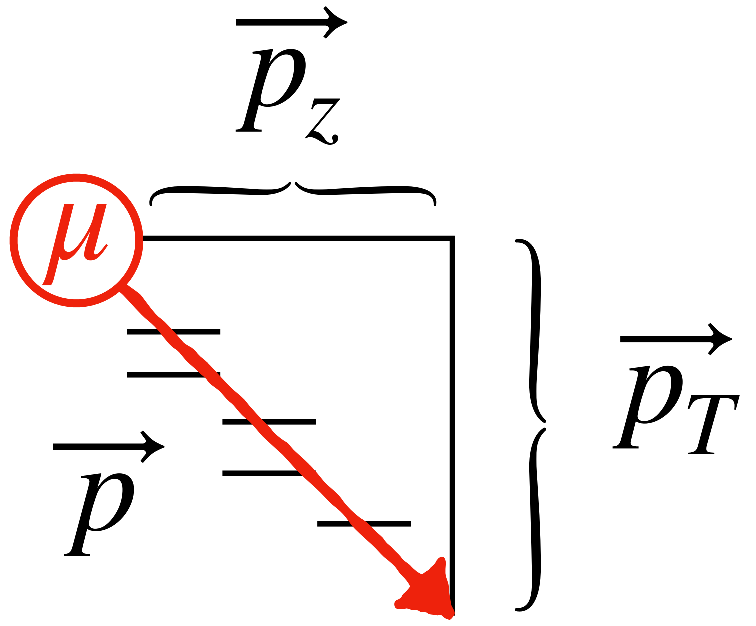


Profile view of CMS showing η values.



CMS coordinates in cartesian & polar form.

- The CMS detector can be defined in cartesian or polar coordinates (as shown below).
- In order to work in Lorentz invariant coordinates, the ‘pseudorapidity’ (η) is defined as: $\eta = -\ln[\tan\theta/2]$
- The “transverse plane” is then defined as $\eta = 0$. It is common to work with vector components only in the transverse direction.



- $|\eta|$ coverage for detector layers:
  - Inner tracker (Pixel & Silicon strip tracker) < 2.5
  - Electromagnetic calorimeter (ECAL) < 3.0
  - Hadronic calorimeter (HCAL) < 5.0
  - Muon Chamber < 2.4
- Phase II upgrades will extend the Inner tracker out to $\eta = 4$.

How to Search for New Physics at CMS

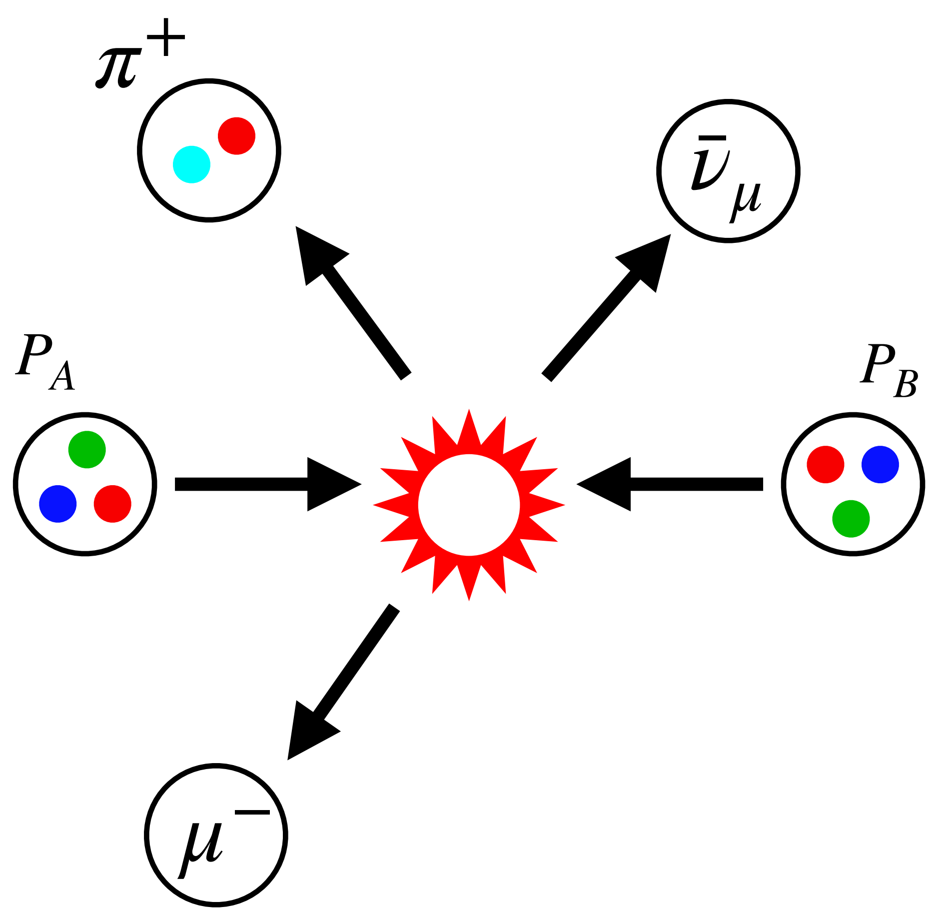
- Protons are collided in well defined momentum states. The total incoming momentum is zero (subject to a Parton Distribution Function), therefore outgoing momentum is zero, per conservation of momentum.
- CMS records tracks of charged particles, and deposits of energy in calorimeters. Not all particles interact with the detector (e.g. neutrinos, dark matter).
- We can infer undetected particles using "missing momentum":

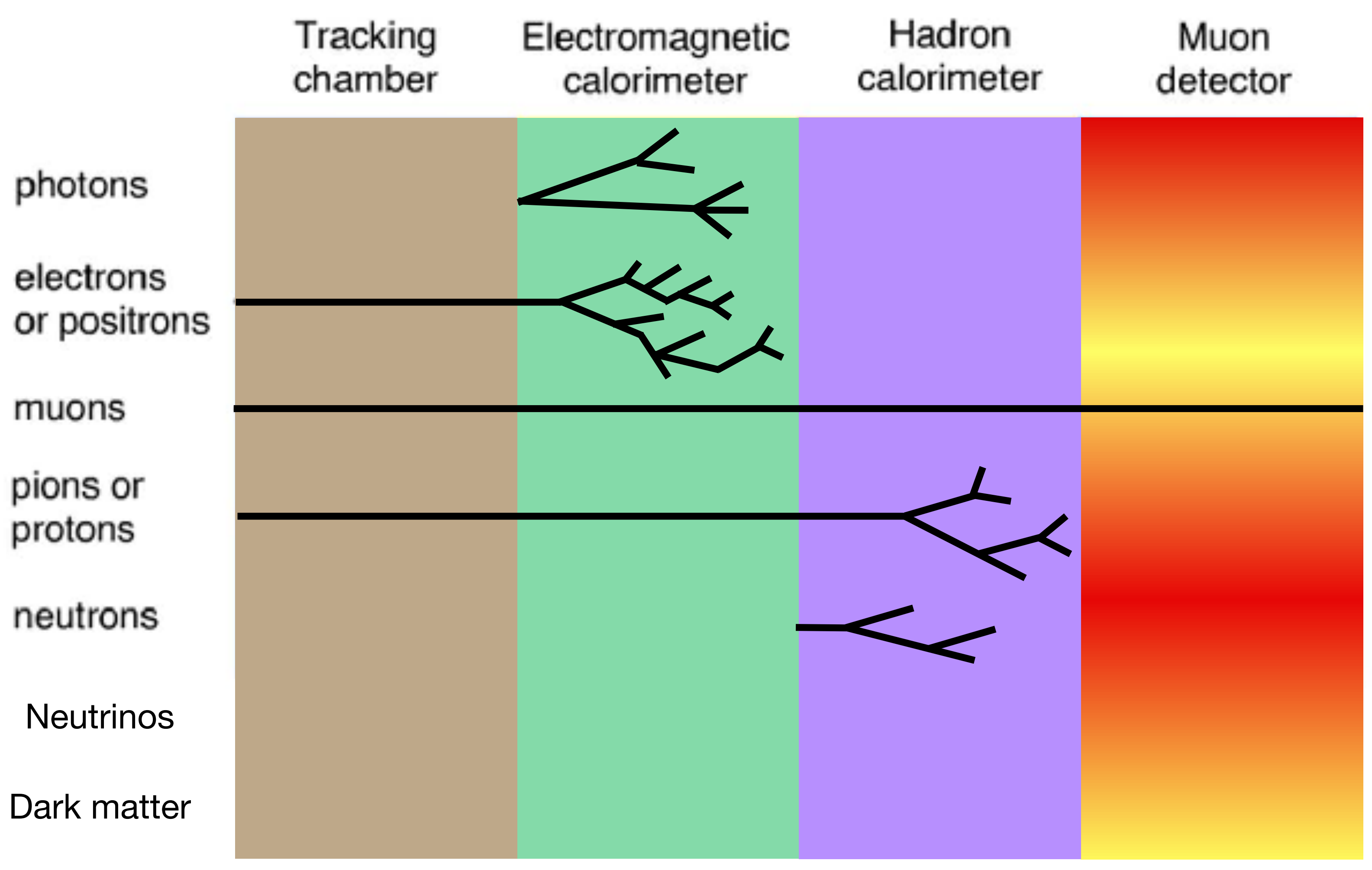
$$\sum \vec{p}_{(Total)} = \sum \vec{p}_{(visible)} + \sum \vec{p}_{(invisible)} = 0$$

- We can then define two common search quantities (working along the transverse plane offers the best resolution):

$$\vec{p}_T^{\,miss} = -\sum \vec{p}_{(T,visible)} \qquad E_T^{miss} = \left|\sum \vec{p}_{(T,visible)}\right|$$

- CMS records 4×10^7 proton bunch crossings every second, many containing multiple interactions (Pile-up). To reduce this number, triggers are employed to signal an event should be permanently recorded. These triggers reduce the data rate to $\approx 1\,kHz$.

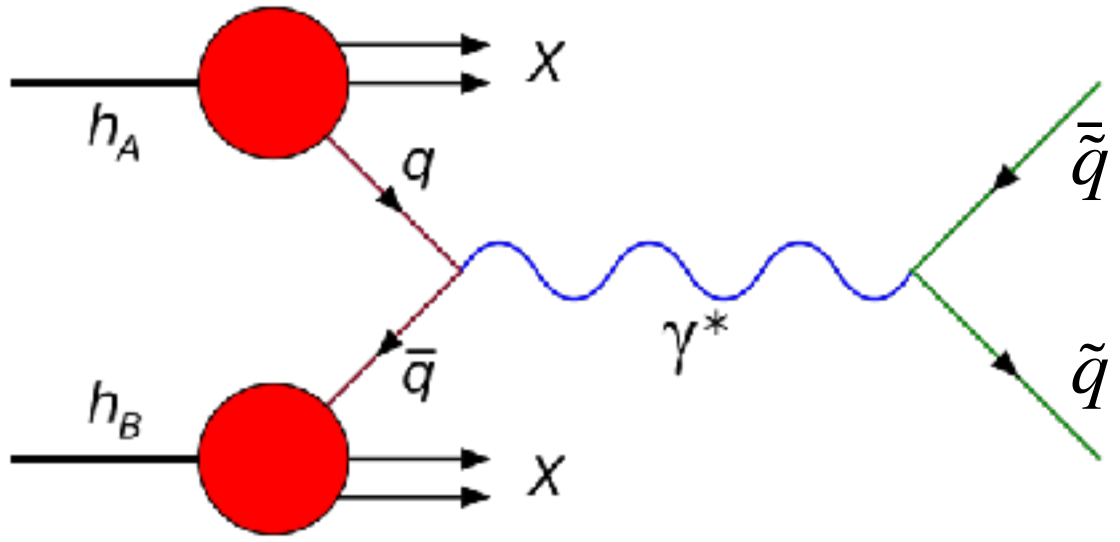




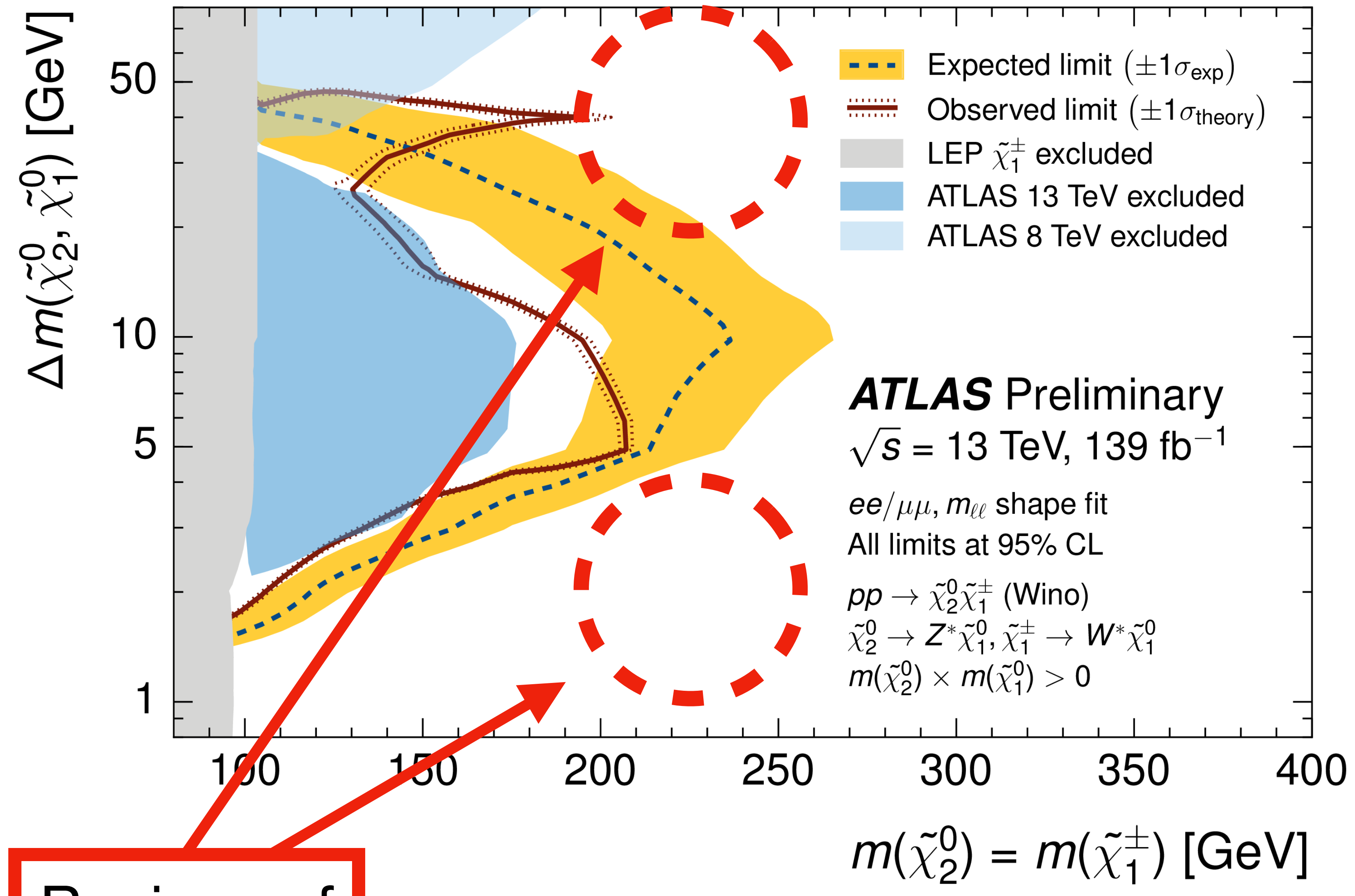
Particle interactions with specific detector layers.

Probing SUSY at the LHC

- Traditional SUSY searches at the LHC have relied on Drell-Yan (DY) sparticle production and cascade decays. These have excluded strongly coupled gluinos and 1st and 2nd generation squarks for masses up to ~2 TeV.
- Electroweakino searches have also primarily relied on DY production ($q\bar{q}' \to W^* \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$). The mass ranges for these particles however are much less constrained. Searches for $\tilde{\chi}_1^{\pm}$ have been ruled out for masses up to 650 GeV, for massless $\tilde{\chi}_1^0$ (i.e. large mass gap).



Feynman diagram of Drell-Yan squark production.



Regions of Interest

ATLAS excluded regions plot.

Vector Boson Fusion (VBF)

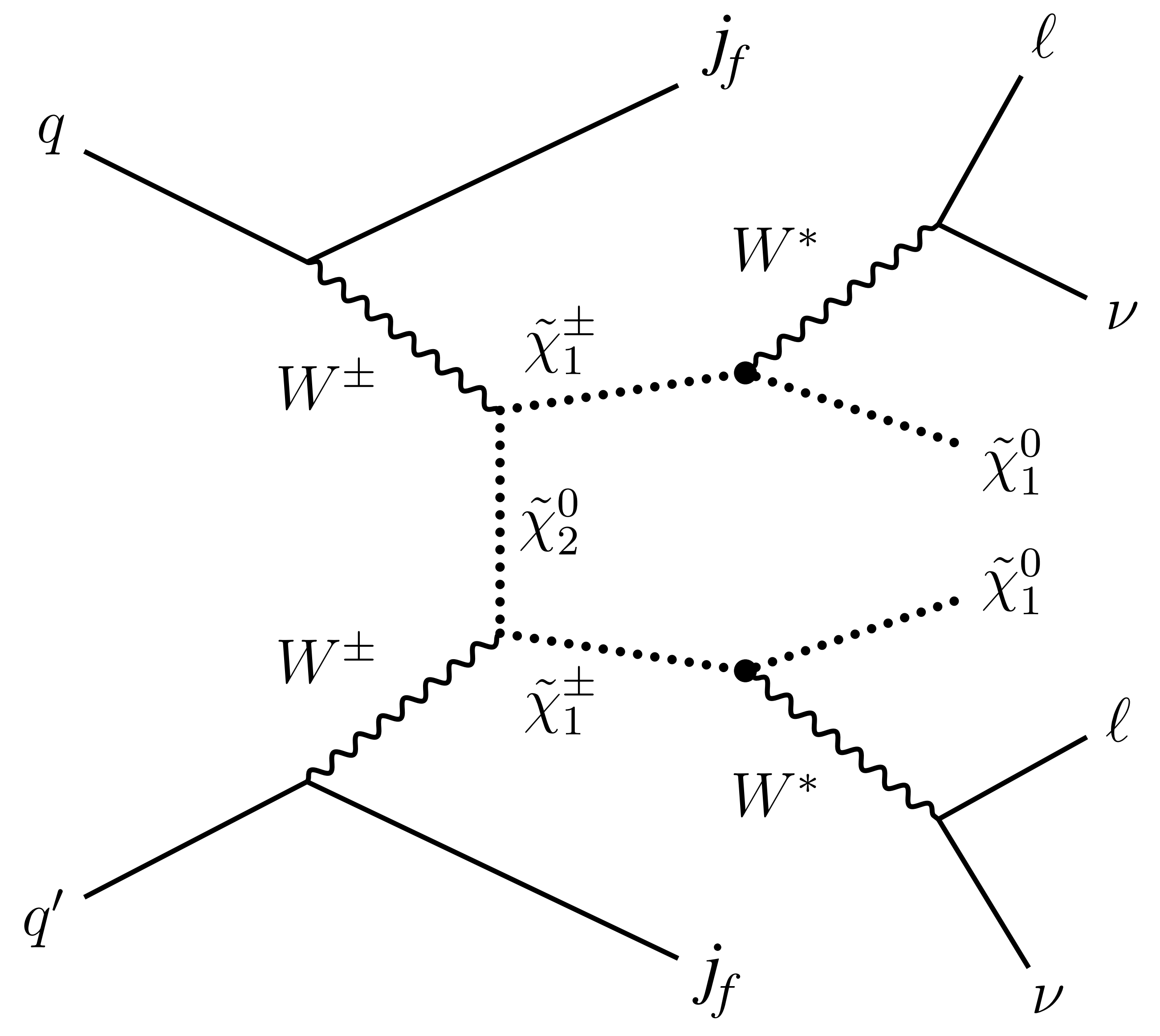
- Vector boson fusion (VBF) is a rare production mechanism, which provides a novel approach to probing compressed mass spectrum scenarios.

- VBF occurs when partons radiate weak vector bosons. These bosons “fuse”, producing a recoil effect which aids in the detection of E_T^{miss} and identification of soft decay products.

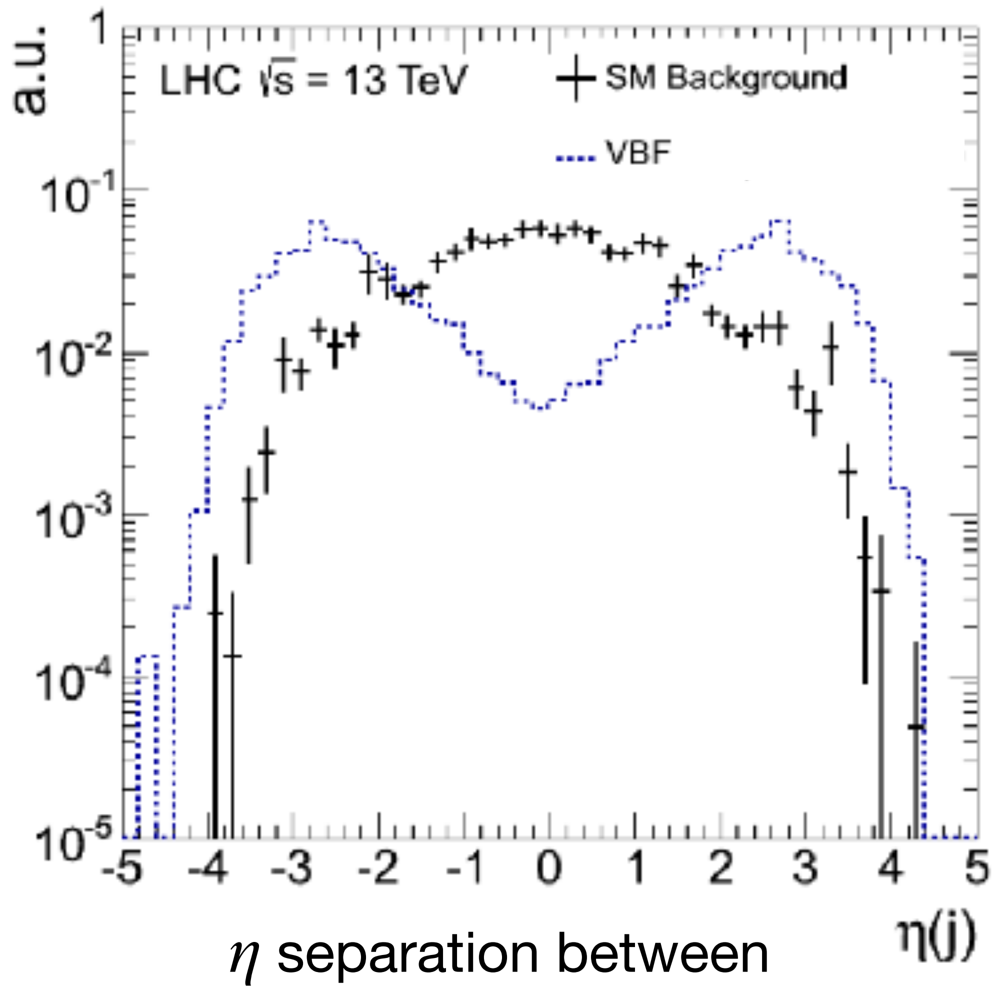
- VBF is characterized by two high-p_T jets, occurring in opposite hemispheres of the detector, with a large invariant dijet mass (m_{jj}) and large gap in pseudorapidity ($\Delta\eta > 5$).

- These unique interaction characteristics effectively suppress other SM background processes, which will produce decay products primarily along the transverse plane.

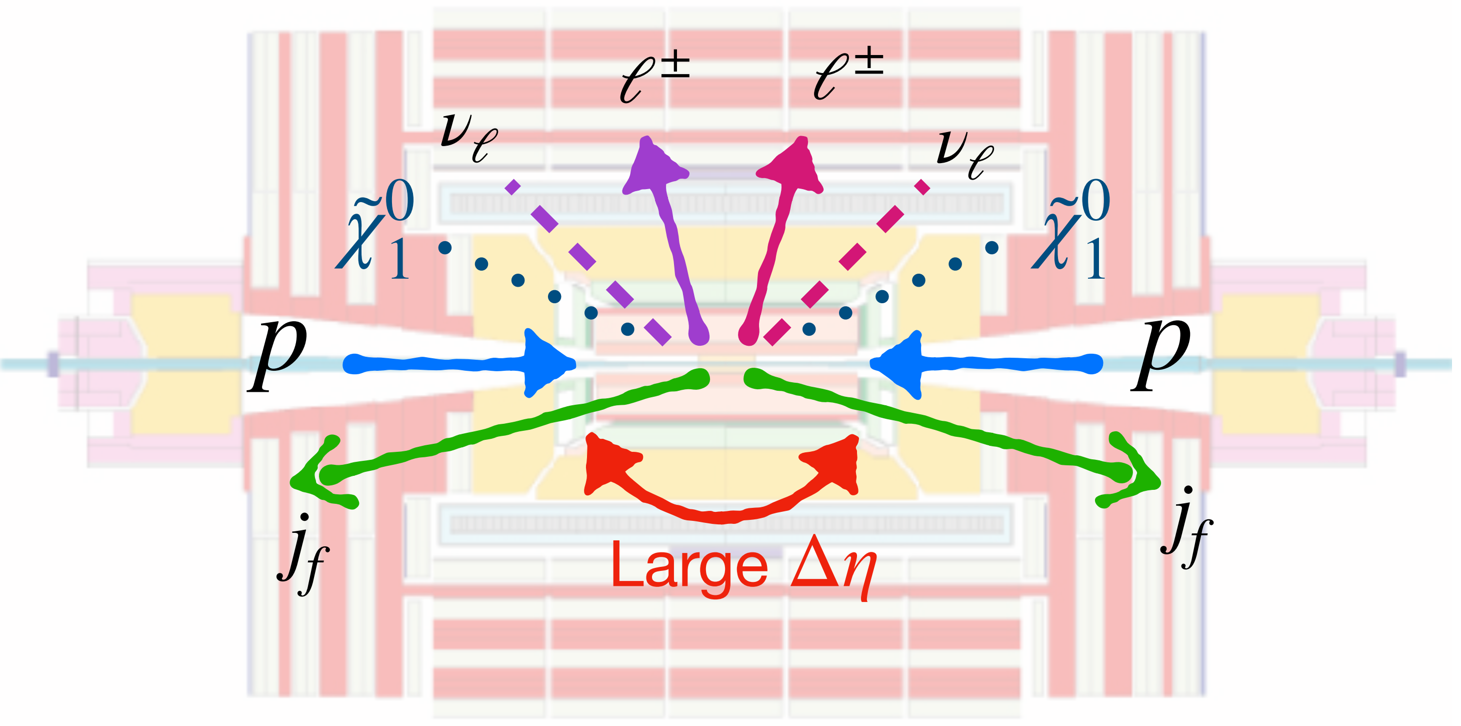
- The combination of the recoil effect from the heavy jets, with the SM BG suppression that allows for probing of small mass gap scenarios.



A VBF SUSY interaction resulting in 2 forward jets, 2 leptons, and E_T^{miss}.



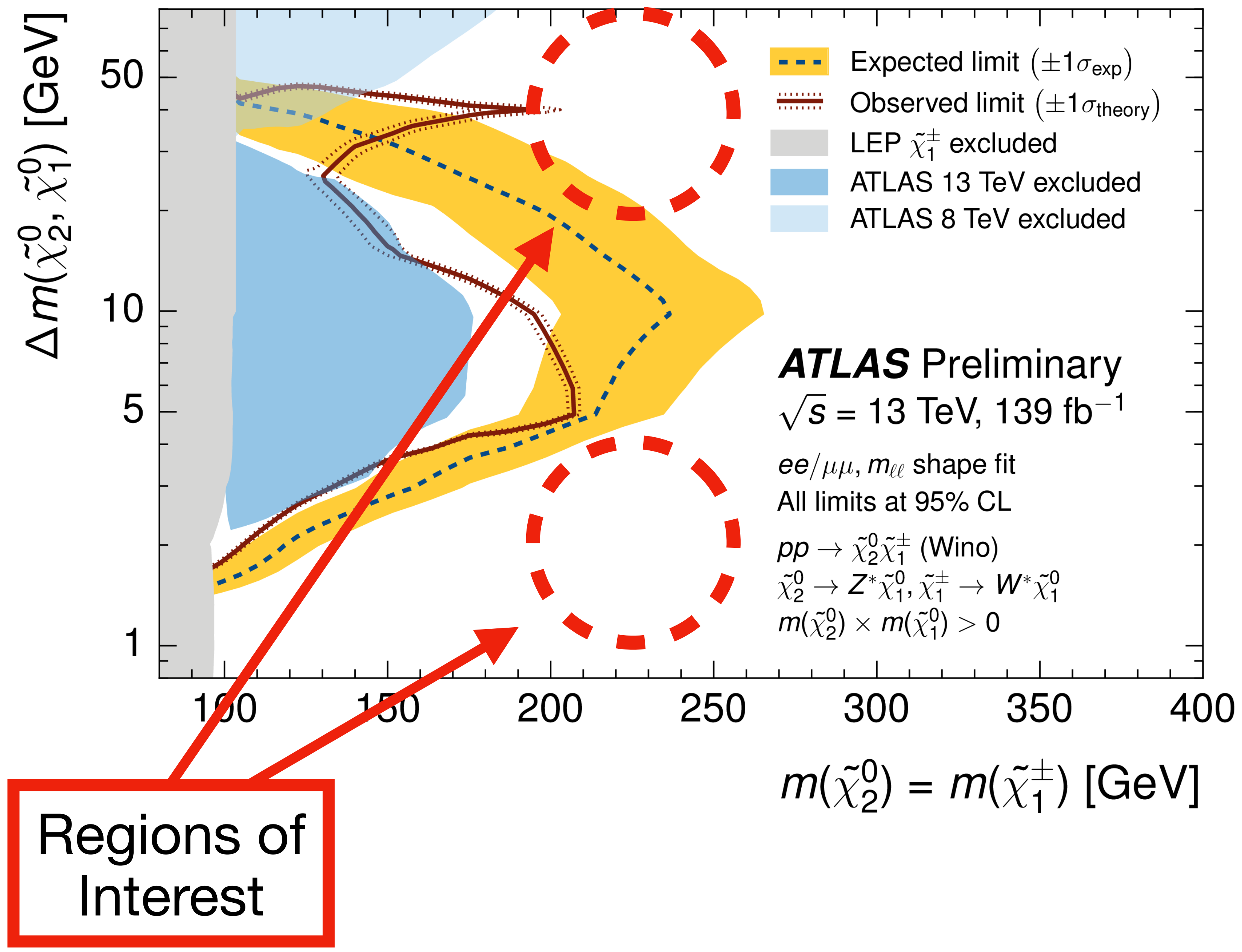
η separation between VBF & SM backgrounds.



A visualization of a VBF interaction, as seen in the detector.

Conclusion

- The standard model of particle physics represents one of the most accurate theories of physics ever created. It has predicted the existence of numerous particles which were eventually discovered, however there are known problems with the model.
- Dark matter is a mysterious substance we can infer gravitationally but currently have no firm understanding of what it might consist of.
- Supersymmetry postulates a symmetry which doubles the total number of particles in the universe and can solve multiple problems in modern physics.
- The Large Hadron Collider is a particle detector that searches for signs of new physics, including SUSY. To date, no new physics has been found outside the standard model, but searches are ongoing.
- Our group uses Vector Boson Fusion to search areas of phase space that are traditionally hard to probe. This will help us determine if SUSY is a correct theory, or just a fruitless endeavor.



Thank you! Questions?

Data Analysis & Research Objectives

Research Objectives:

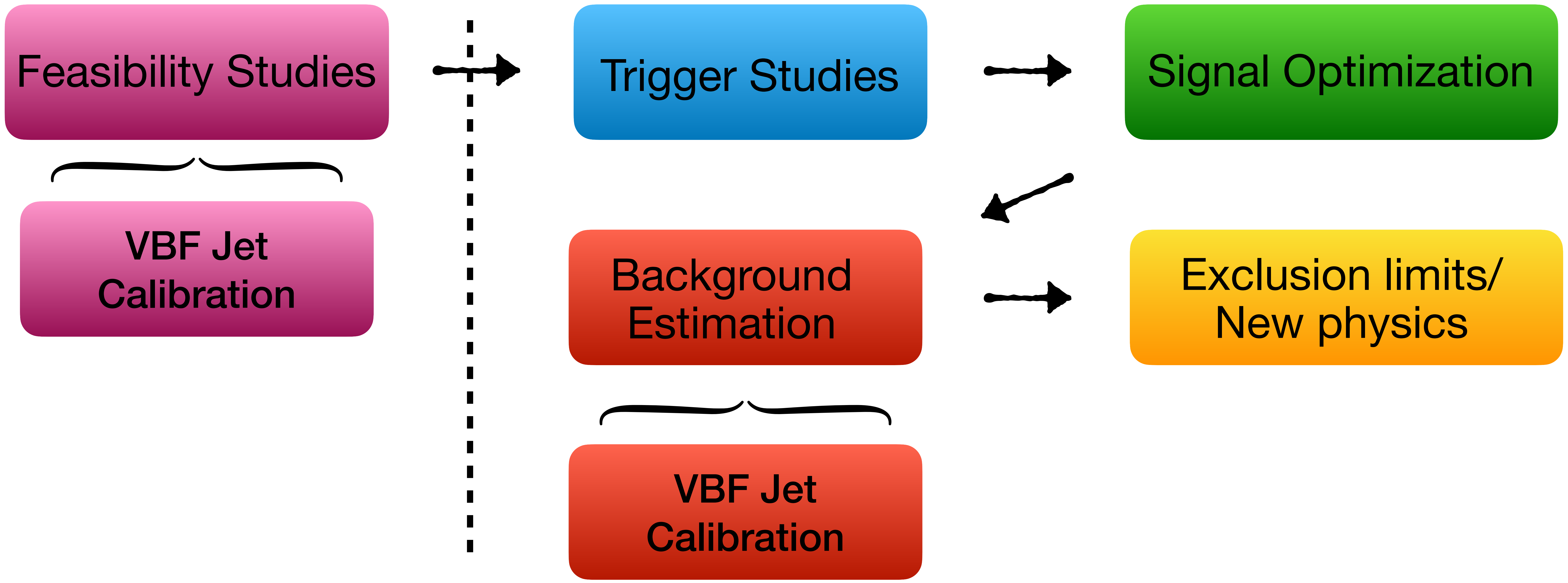
Data Analysis

Trigger Studies

Signal Optimization

Background (BG) Estimation

Calibrating VBF Jets



Data Analysis: Trigger Studies

- Triggers are "filters" that allow for reducing the 40 MHz interaction rate to ~1 kHz.

- All triggers have an associated efficiency curve (as shown to the right).

- Trigger efficiency affects signal significance:

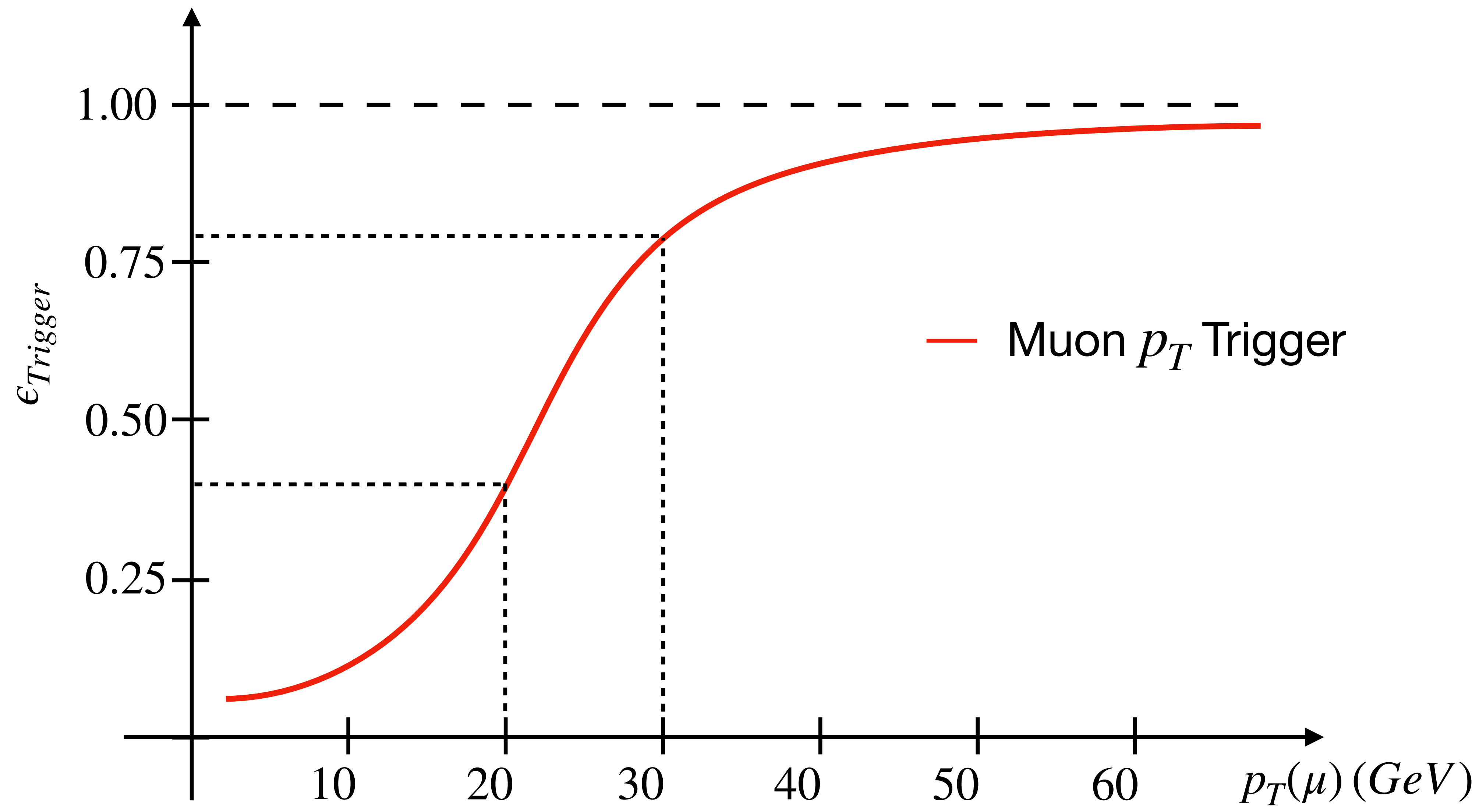
$$N_{events} = \sigma \times \mathscr{L} \times \epsilon_{cuts},$$

σ - Cross section
$\mathscr{L}$ - Luminosity
ϵ_{cuts} - Efficiency of applied cuts

$$\epsilon_{cuts} = \epsilon_{kinematic\_cuts} \times \epsilon_{particle\_ID} \times \boxed{\epsilon_{triggers}} \times \epsilon_{other}$$

- As trigger efficiency increases, systematic uncertainty decreases. More stringent cuts however reduce statistics.

- Trigger efficiency is particularly important when looking for "soft" leptons, which might have low corresponding trigger efficiencies.



Trigger Efficiency Curve for $p_T(\mu)$

$$\epsilon_{Cut} = \frac{N_{Cut\_applied}}{N_{Cut\_not\_applied}}$$

Triggers to be studied:
$p_T(\mu),\ E_T^{miss},\ VBF$

Data Analysis: Signal Optimization

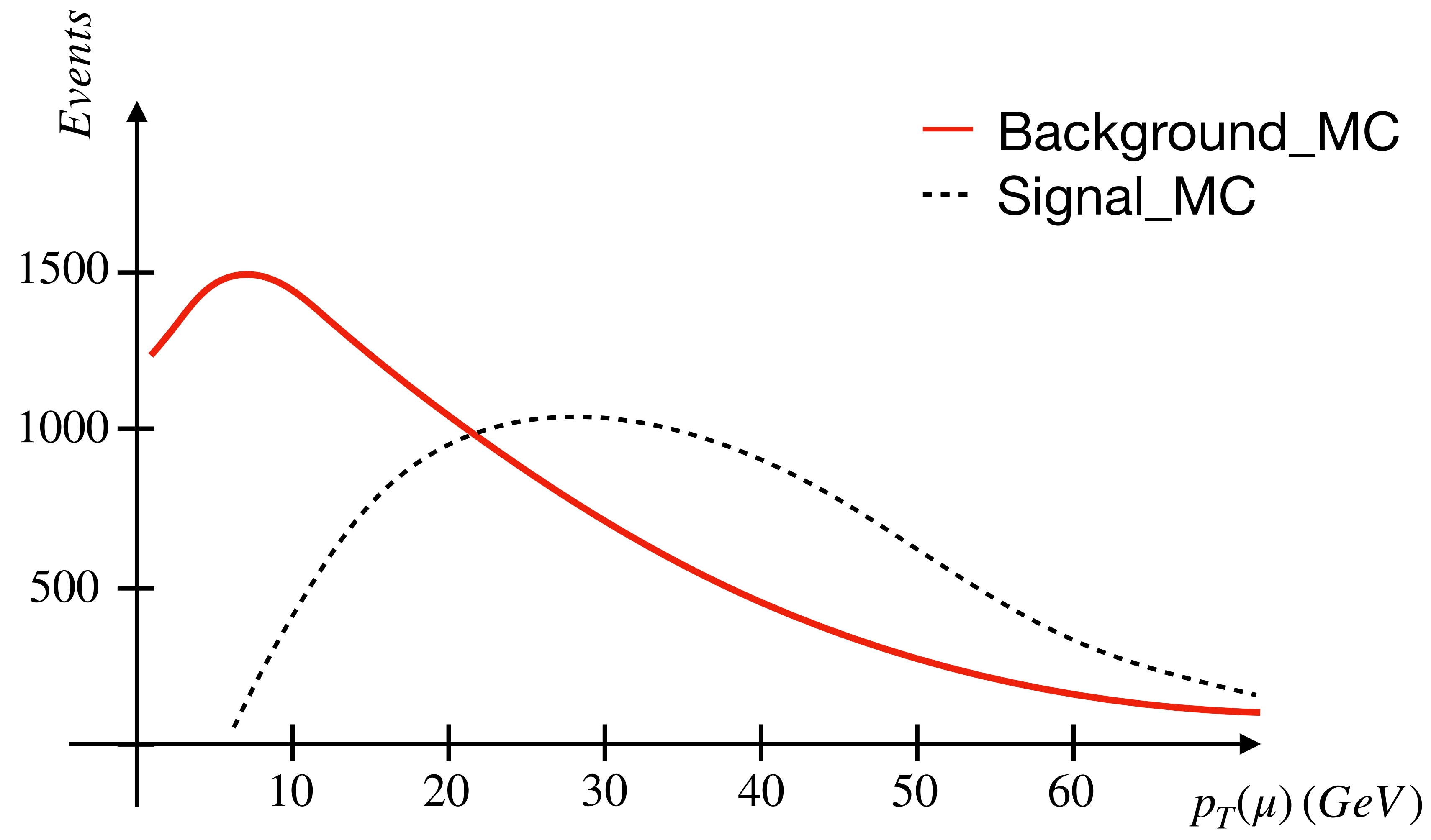
- In order to maximize discovery potential, it is imperative to find search regions in which the signal to noise ratio is optimized.
- It is not sufficient to simply look for large differences between signal and background, as this might also reduce signal events.
- This is an iterative process in which ‘Selection cuts' are applied to MC, and signal significance calculated.
- Cuts to optimized include $p_T(\ell)$, E_T^{miss}, and VBF kinematics

$$\frac{signal}{noise} = \frac{S}{\sqrt{S + B + (x \cdot (S+B))^2}}$$

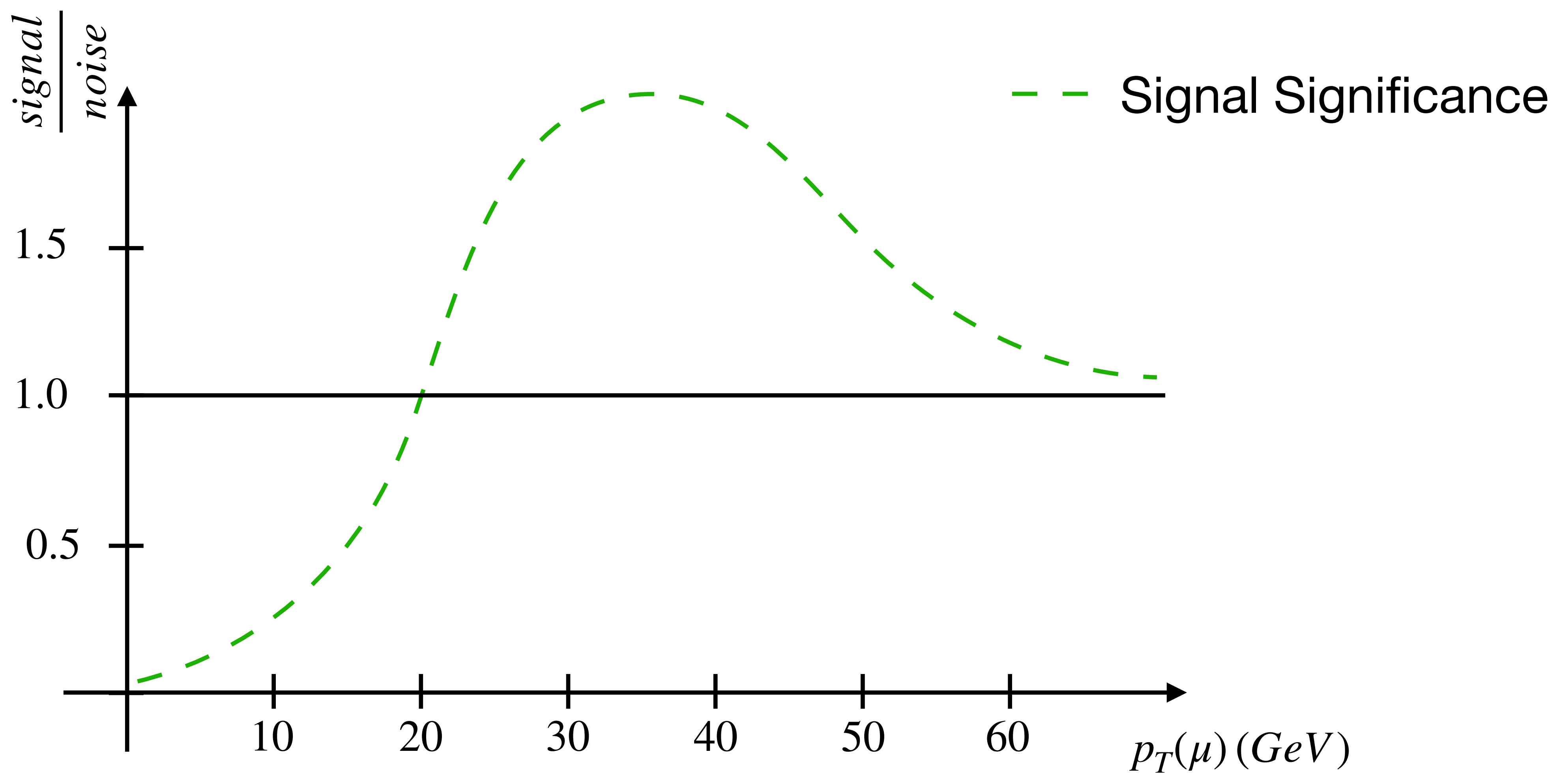
S - Signal yield

B - Background yield

x - Systematic uncertainty



BG vs Signal Yield (MC) for $p_T(\mu)$

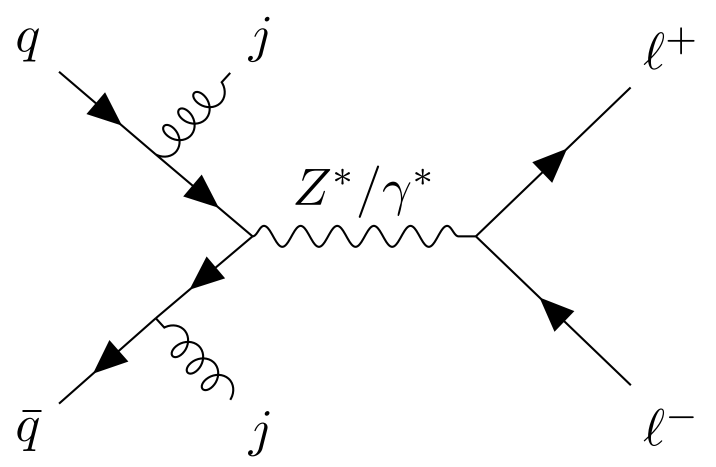


Signal Significance for $p_T(\mu)$

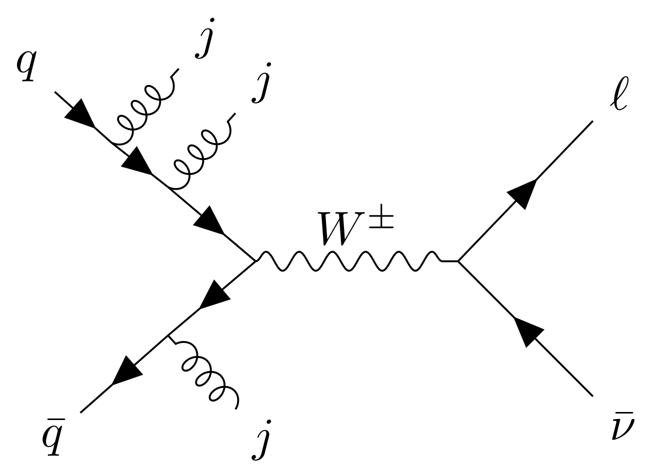
Data Analysis: Background Estimation

- Many SM processes can produce the same final state as the signal process. These are referred to as “backgrounds”.
- “New physics” looks like excess of events in data compared to simulation (Monte Carlo, MC), therefore correctly estimating backgrounds is imperative.
- To reduce potential biasing, it is recommended not to “look” at the kinematic region defined as the “signal region” (SR).
- Control regions (CR), which are search regions orthogonal (not overlapping) to the SR are therefore defined, where data & MC can be compared.
- To ensure agreement between MC and data, scale factors (SF) are used to re-weight MC events:

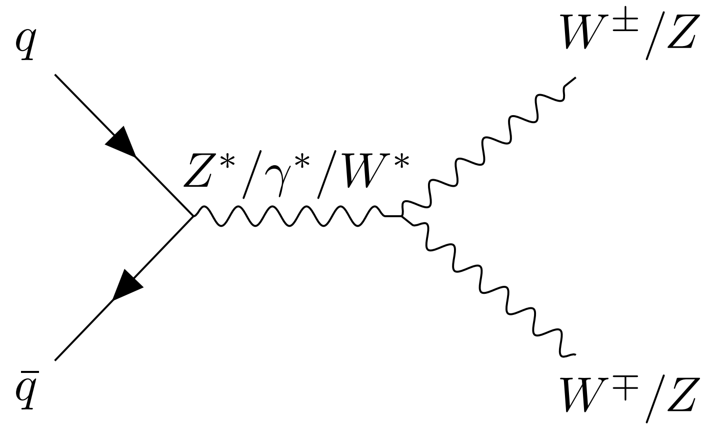
$$SF_{CR} = \frac{N_{data} - \sum N_{non-process,MC}}{N_{process,MC}}, \quad N_{Data} = SF_{CR} \times N_{MC}$$



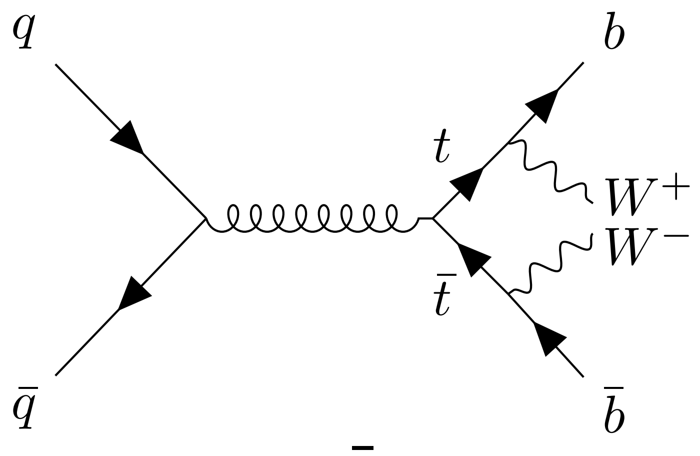
Z+Jets



W+Jets



Diboson



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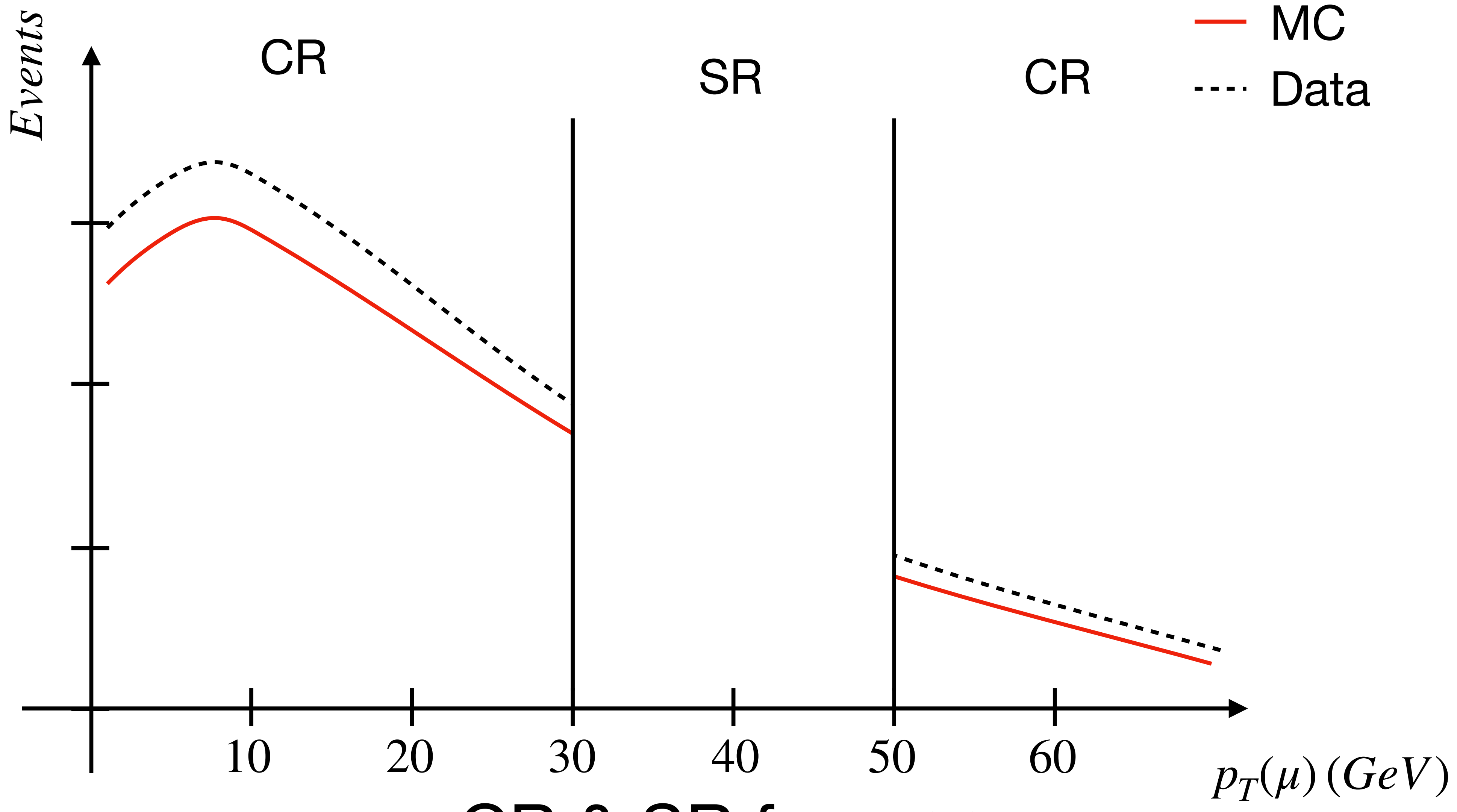

CR & SR for $p_T(\mu)$