Dark Matter: Latest result from the LHC & outlook

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Medium Linked in

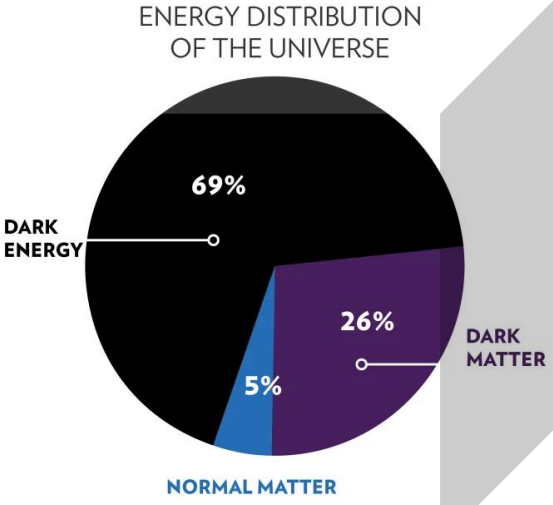
2nd November 2022

Overview

- ❏ Why Dark Matter Matters
- ❏ Dark Matter Properties
- ❏ Colliders & CMS experiment
- ❏ Looking for Dark Matter at CMS
  - ❏ Structuring an analysis
  - ❏ **Latest** result
- ❏ Towards Run 3

Dark Matter Matters

Dark Matter

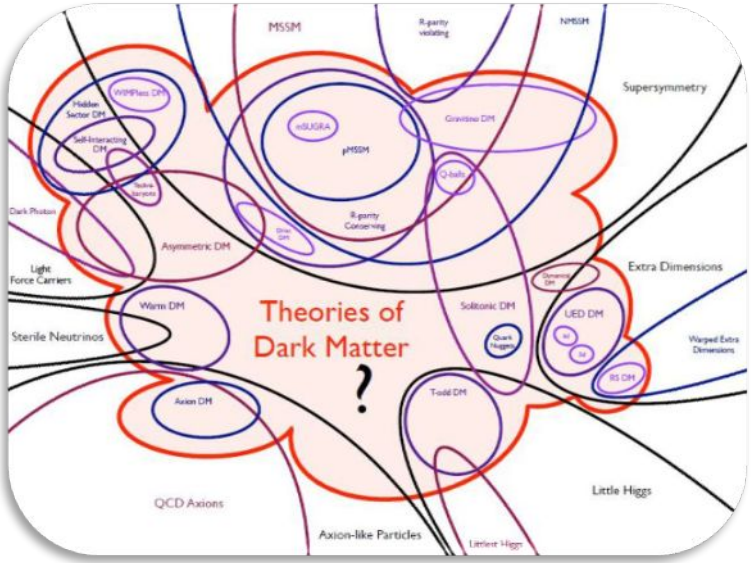


Dark matter comprises most matter in our universe and is one of the biggest unanswered puzzles in physics.

Responsible for the evolution of structure in the universe - **no dark matter, no galaxies, no life.**

Dark Matter allows astronomers to observe phenomena occurring out of reach of current telescopes.

Dark Matter Properties



- From observation we can infer that its;
  - Electrically neutral
  - Does not emit / absorb light
  - Weakly interacting with regular matter
  - Stable
  - Extremely abundant in our universe
- Many theories exists;
  - Axions (additional Field suppressing strong cp violation)
  - Sterile neutrinos (right-handed analogue of active neutrino)
- Most Popular?
  - Weakly interacting massive particles (WIMPs)
    - As predicted by Supersymmetry 😇

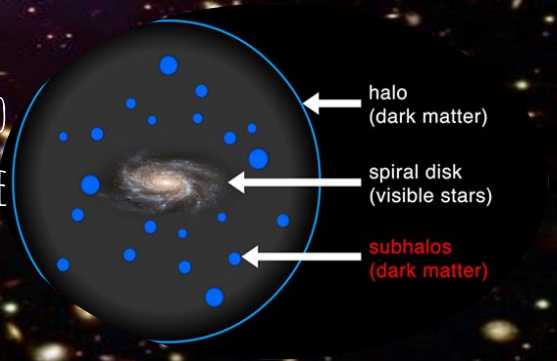
Evidence for Dark Matter

The Bullet Cluster was formed in the most energetic event in known universe.

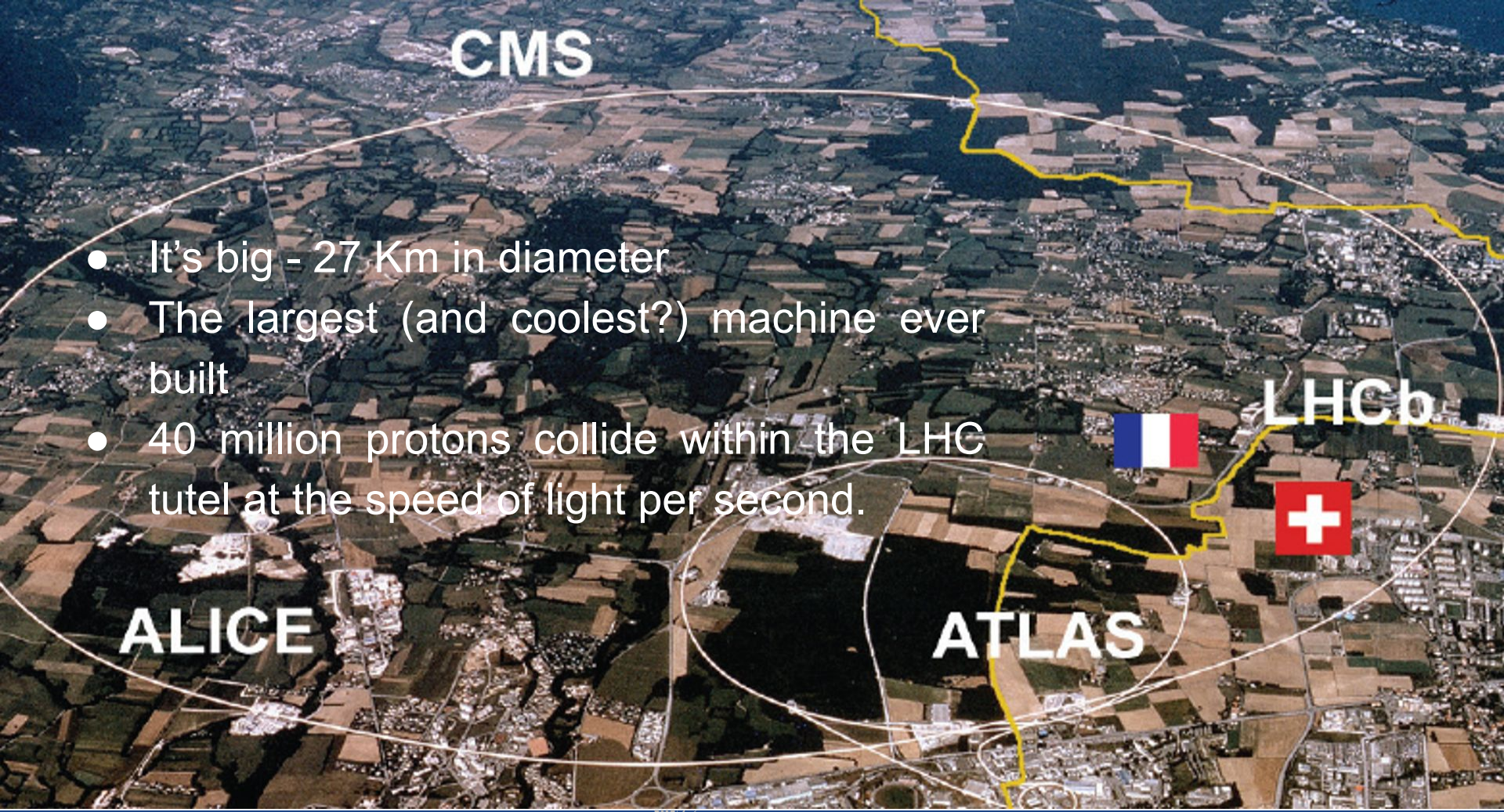
The mass of this cluster as determined by gravitational lensing (distortion of light by massive objects) is not fully accounted for by the visible (pink) distribution.

In fact, most mass in the cluster is the blue (dark) distribution.

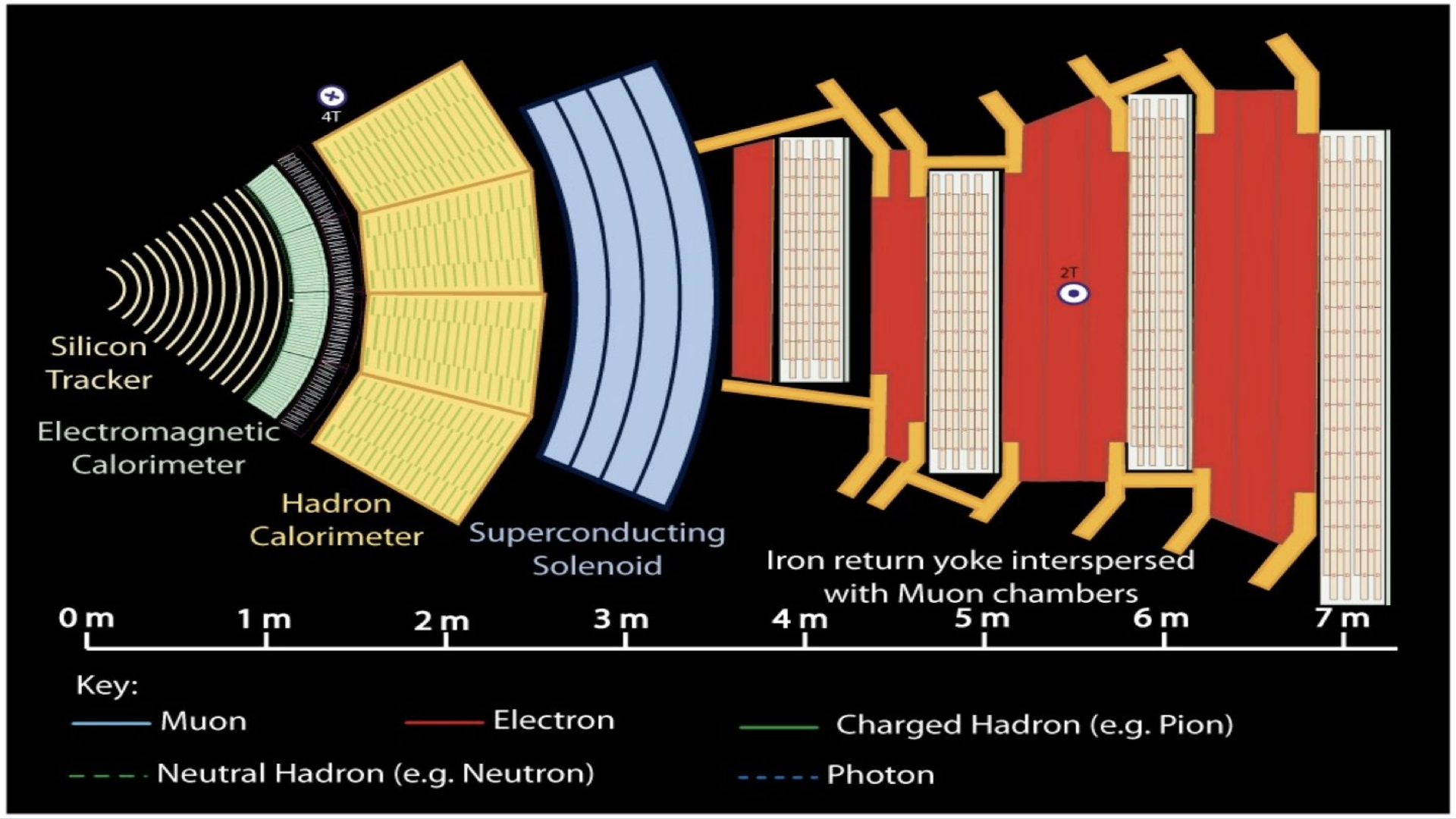
Dark Matter is hypothesised to occupy halos around visible matter.



Large Hadron Collider (LHC) & CMS experiment



- It’s big - 27 Km in diameter
- The largest (and coolest?) machine ever built
- 40 million protons collide within the LHC tutel at the speed of light per second.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2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
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1 m
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3 m
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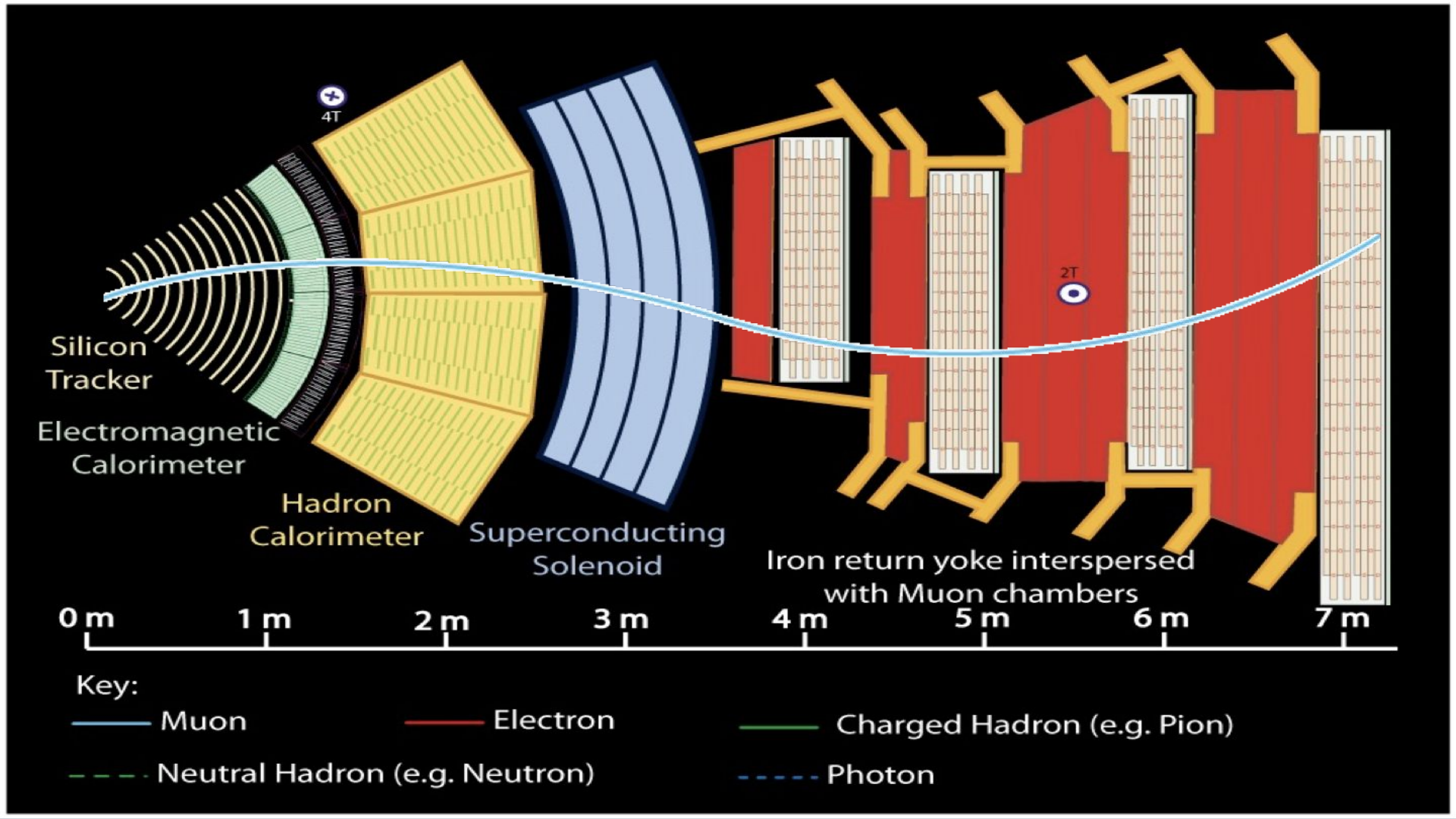
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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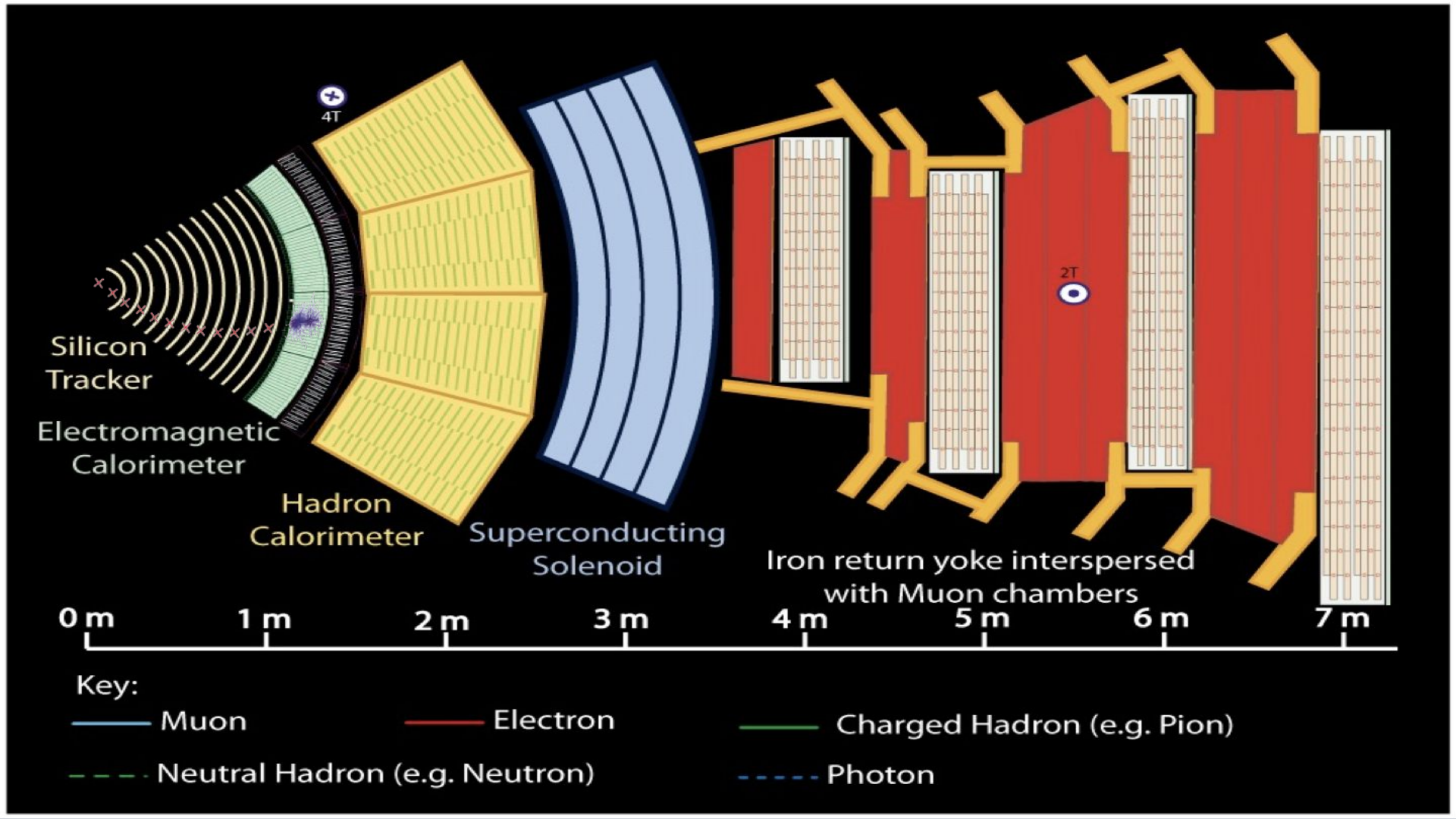
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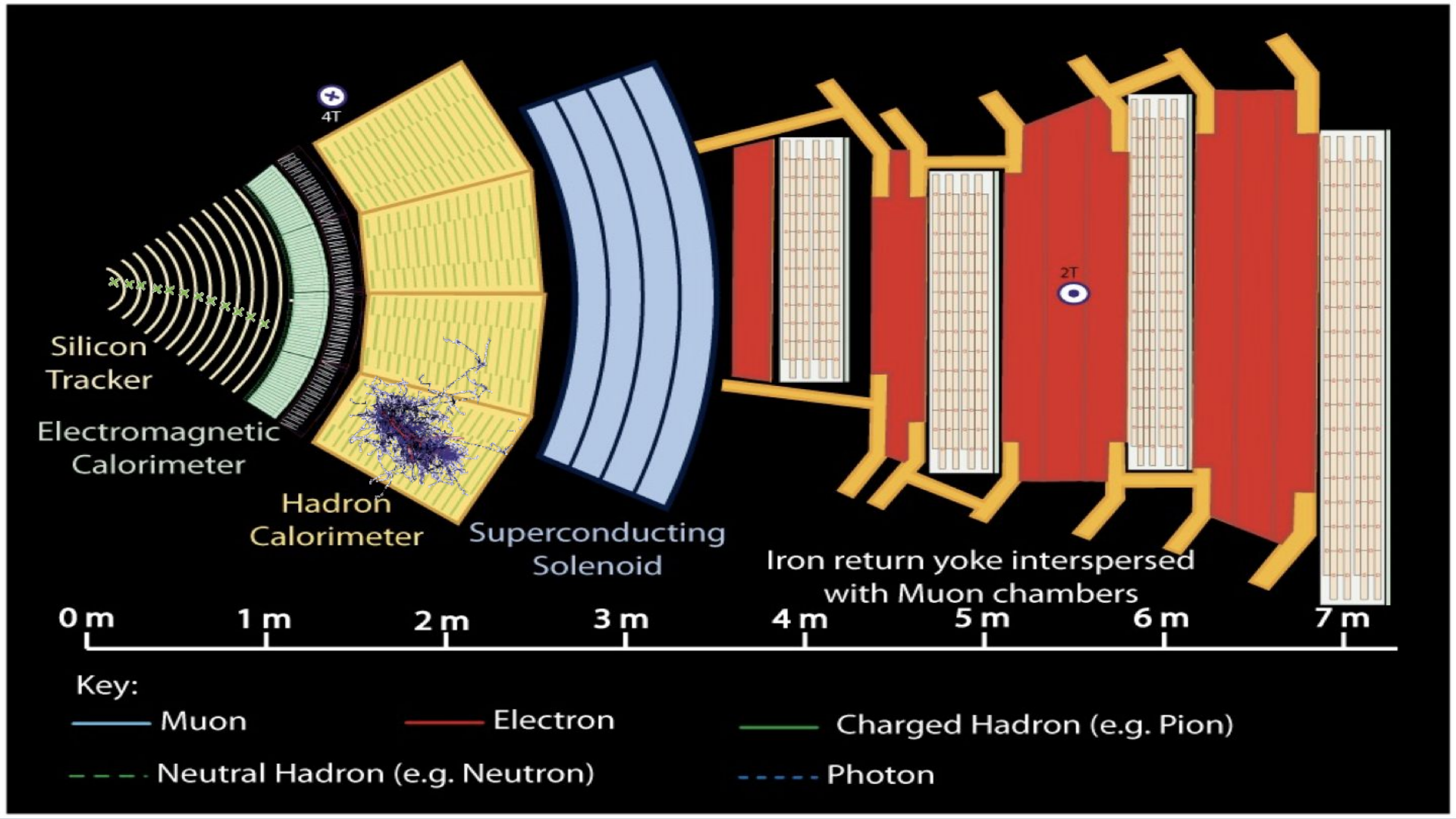
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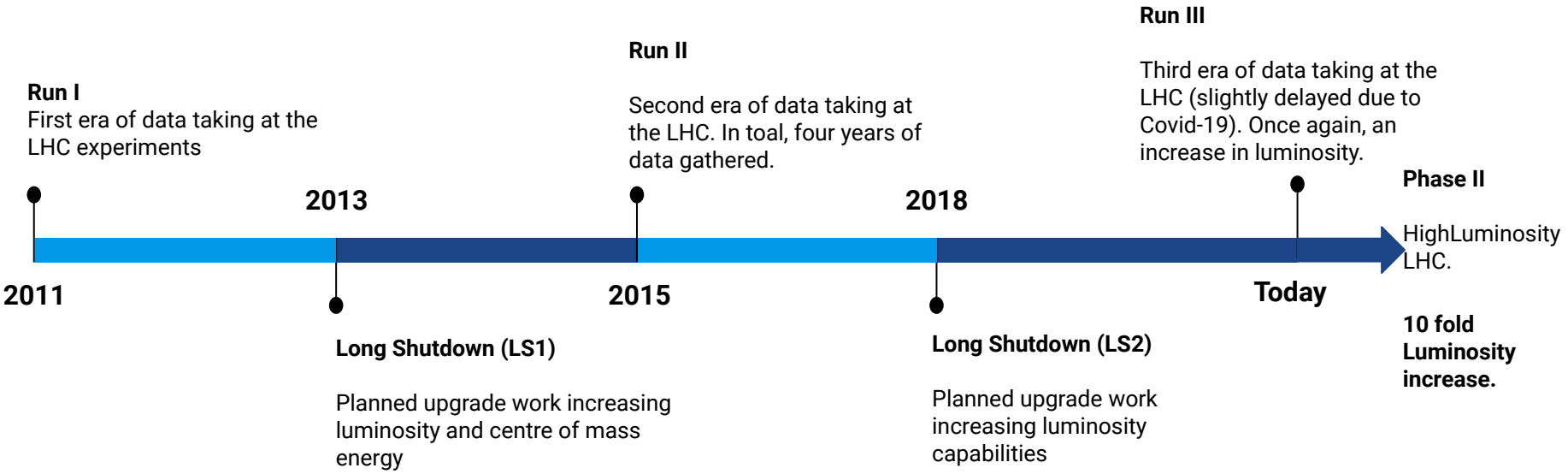
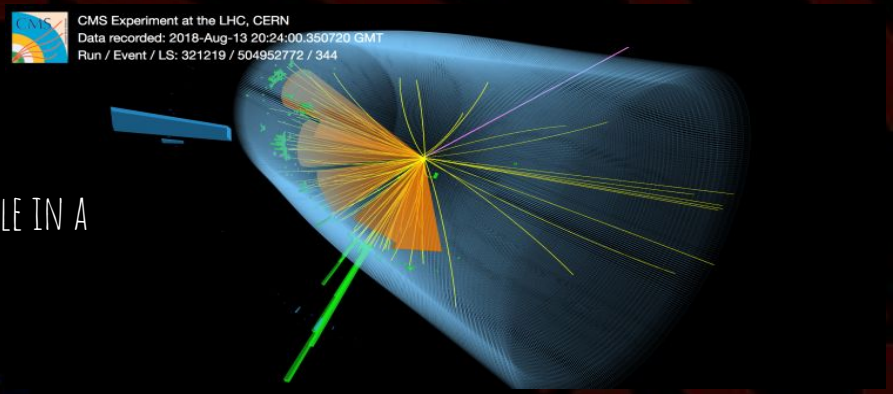
CMS Experiment at the LHC, CERN
Data recorded: 2015-May-05 09:05:27.863456 GMT
Run / Event / LS: 248484 / 355552567 / 50

LHC timeline



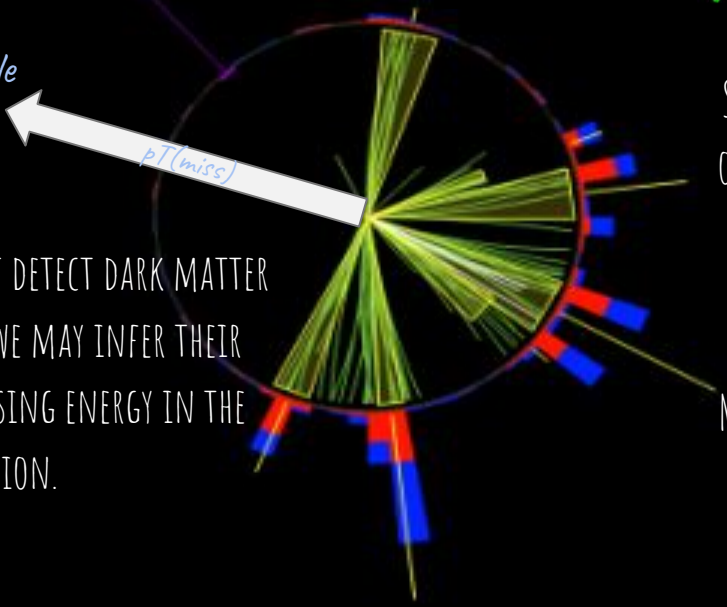
WIMP searches @ CMS

WIMPs @ CMS



Very rare processes (needle in a haystack search)

Missing transverse energy (the invisible WIMP particle produced in collision)



Since WIMPs only interact weakly, our detection techniques from the previous slide are hopeless!

Even though we can't detect dark matter particles directly, we may infer their existence from missing energy in the collision.

Momentum must be balanced (**initial transverse momenta = 0**).

WIMPs @ CMS II

1. Define a signal signature

   Simplified Dark Matter Model (DMsimp)

   -Standard model decay to Dark Matter via (scalar / vector) mediator

   - Higgs as a portal to Dark Matter

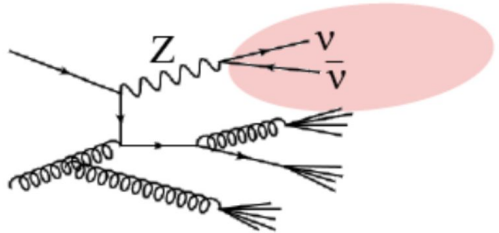
   - Higgs couples proportionally to mass, making it a viable portal to DM

   - Invisible Higgs decays prohibited in the SM

2. Identify irreducible background (almost identical signatures)

Signal

Background



CMS: Latest Result

HIG-21-007

For the first time considers ttH and VH Higgs production mechanisms and combines all Higgs production modes for the **most sensitive H→invisible measurement ever made.**

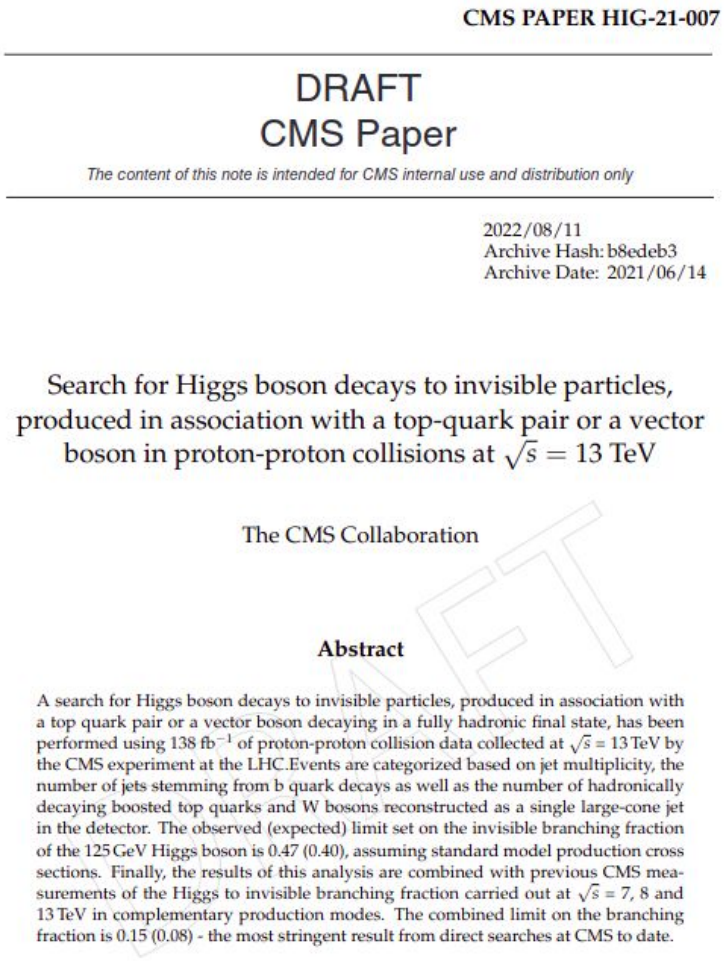
✅ Public result

Authors:

- David Anthony
- Olivier Davignon
- Henning Flaecher
- **Maciej Glowacki**
- Robert White
- Imperial College London, Boston University, École polytechnique collaborators

Conference: Higgs Hunting, Paris, 12-14 September 2022

Journal: EPJC



CMS PAPER HIG-21-007

DRAFT
CMS Paper

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2022/08/11
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Archive Date: 2021/06/14

Search for Higgs boson decays to invisible particles, produced in association with a top-quark pair or a vector boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

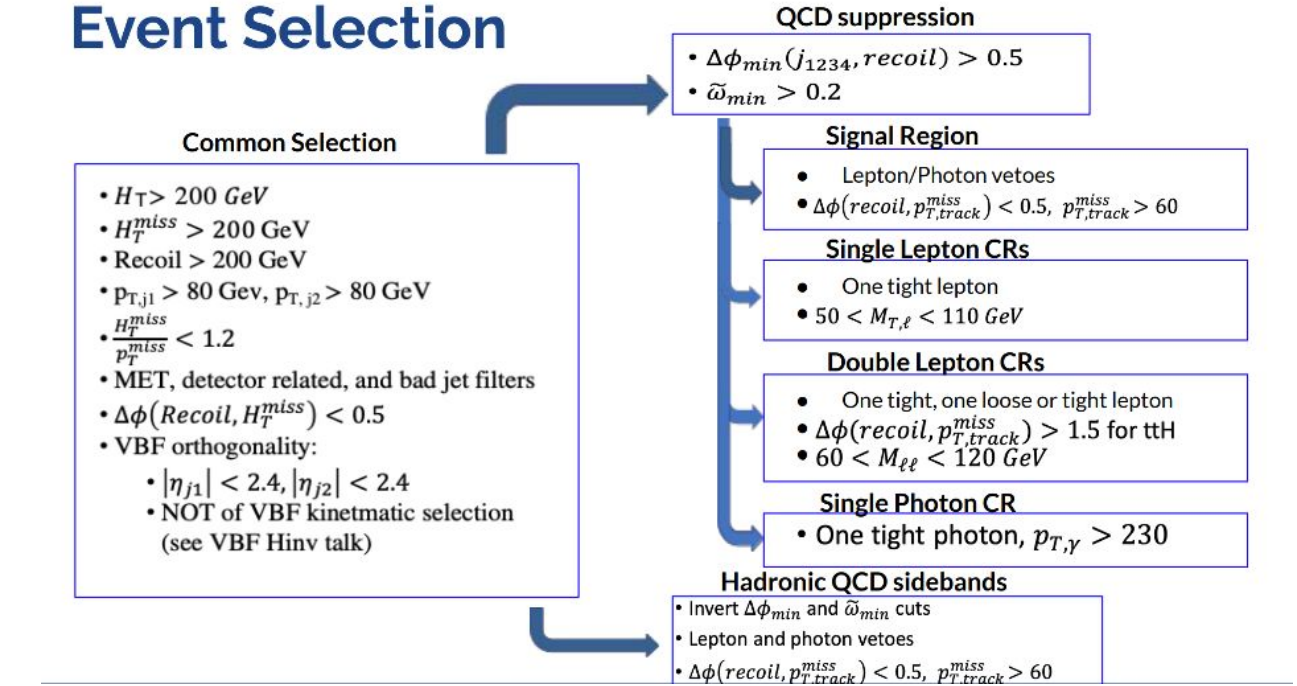
The CMS Collaboration

Abstract

A search for Higgs boson decays to invisible particles, produced in association with a top quark pair or a vector boson decaying in a fully hadronic final state, has been performed using 138 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC.Events are categorized based on jet multiplicity, the number of jets stemming from b quark decays as well as the number of hadronically decaying boosted top quarks and W bosons reconstructed as a single large-cone jet in the detector. The observed (expected) limit set on the invisible branching fraction of the 125 GeV Higgs boson is 0.47 (0.40), assuming standard model production cross sections. Finally, the results of this analysis are combined with previous CMS measurements of the Higgs to invisible branching fraction carried out at $\sqrt{s} = 7$, 8 and 13 TeV in complementary production modes. The combined limit on the branching fraction is 0.15 (0.08) - the most stringent result from direct searches at CMS to date.

Event selection

MapReduce style operations

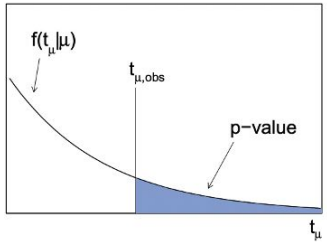


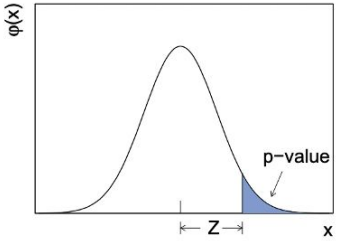
Statistical Inference

- Number of data entries = $\mu\, s + b$
  - We want to infer the μ parameter
  - Estimating parameters -- > maximum likelihood
  - From the likelihood we can build a test statistic:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \theta_\mu)}{\mathcal{L}(\mu, \theta)}$$

- The purpose of the test statistic is to compress our data into something which we can test our hypothesis against
  - Null hypothesis: background only ($\mu = 0$)
  - Alternative hypothesis: background + signal ($\mu > 0$





- By integrating the test-statistic we can find the p-value
- $p = \int_{q\ obs}^{\infty} f(q|0)dq$
- The p-value then quantifies the level of disagreement between the null and alternative hypotheses, it's the probability of obtaining a number of events at least as extreme as the one observed under the null hypothesis.

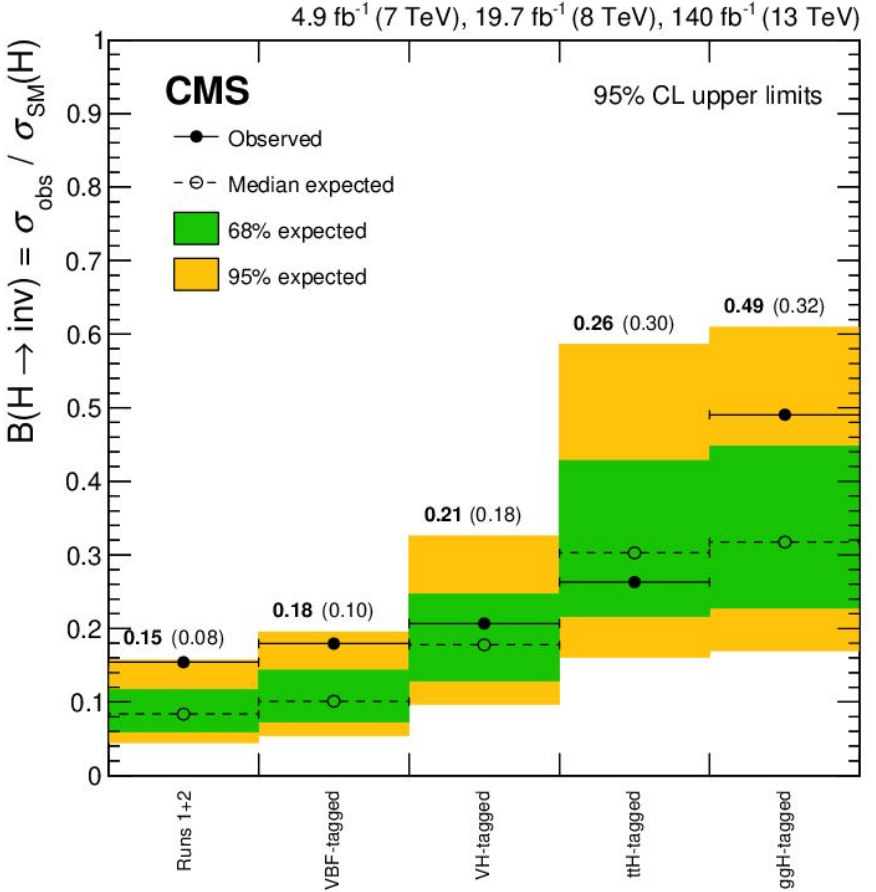
Run 2 Results

Sensitivity breakdown by production mode

- Run 1+2 result of **15%** (8%), driven by VBF channel.
- Run 1 (and 2015) have little effect on overall picture
  - Run 1 and Run 2015 contributions are as follows:

Analysis Tag	Production Mode	Integrated Luminosity (fb^{-1})		
		7 TeV	8 TeV	13 TeV (Run 2)
VBF-tagged	VBF	-	19.2	139.9
	Z(ll)H	4.9	19.7	139.9
VH-tagged	Z(bb)H	-	18.9	137.6
	V(jj)H	-	19.7	139.9
ttH-tagged	ttH	-	-	137.6
qqH-tagged	MonoJet	-	19.7	139.9

- 2σ excess from null hypothesis.
  - 3σ level needed for *evidence*



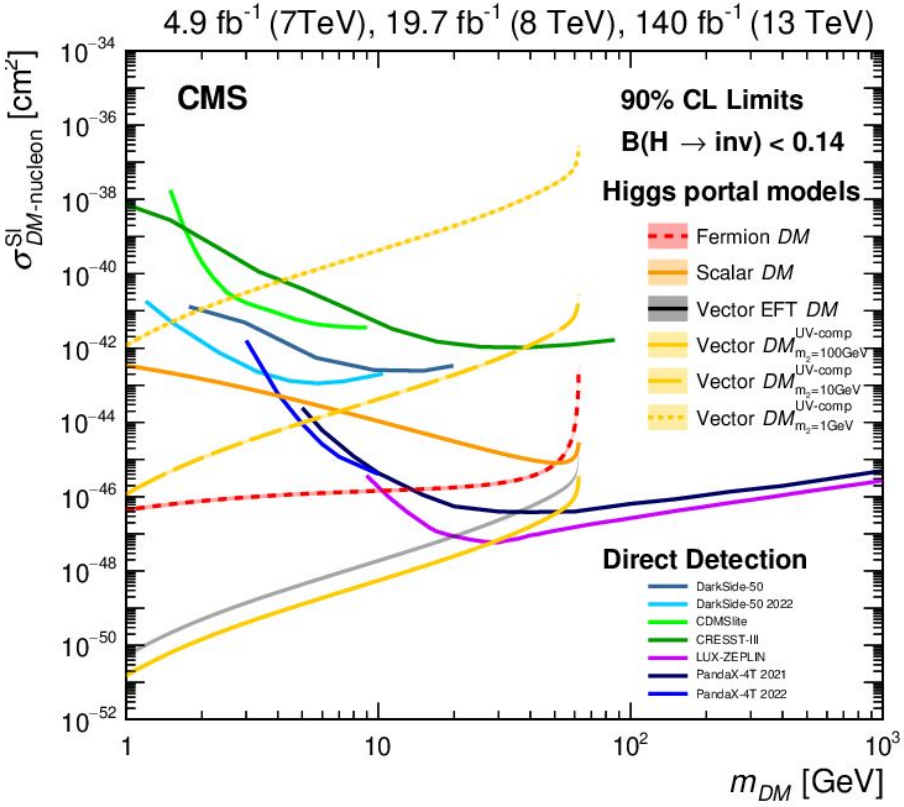
Interpretation in Higgs Portal Model

Interpretation of Hinv limit in the wider landscape of Dark Matter Searchers (DM-nucleon scattering)

- A large number of new direct detection results recently published (LZ, Panda-4X, DarkSide-50…)

- H->DM DM interpretation **gives most stringent limit at the low Dark Matter mass regime (yellow, orange and red curves)**

- Model dependence on nature of DM candidate



TOWARDS RUN 3

Higgs → invisible in Run 3

Building blocks

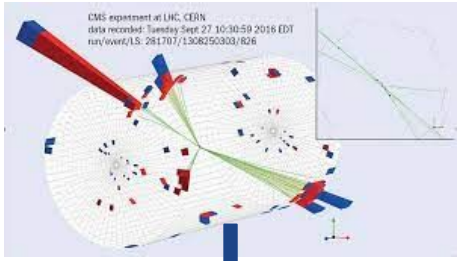
- Increased Centre of Mass energy
- Increased Luminosity for Run 3 which will compliment data collected during Run 1 + 2.
- Improved efficiency in data acquisition targeting events with missing transverse energy.
- Improved identification and reconstruction algorithms:
  - Deep Jet (Flavour tagging)
  - Deep Jet (Boosted tagging)
  - Deep Tau

CMS welcoming Run 3 events back in June 🥳

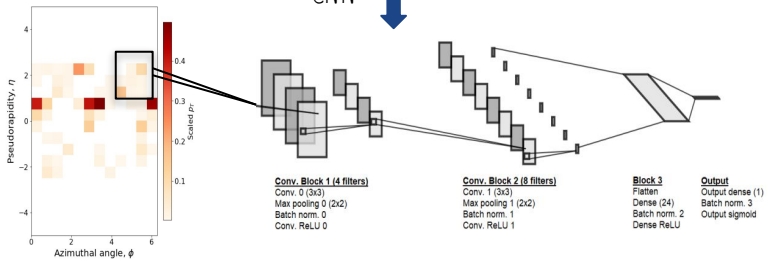
Signal enhancement with Deep Learning

- Train deep learning algorithm to discriminate signal from background events.
- Re-define signal region in terms of classifier probability distribution for improved sensitivity.
- Many approaches currently under consideration;

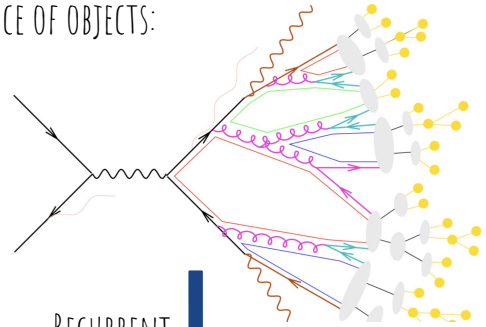
Represent as image:



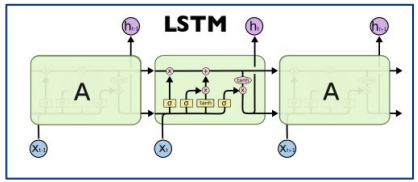
CNN



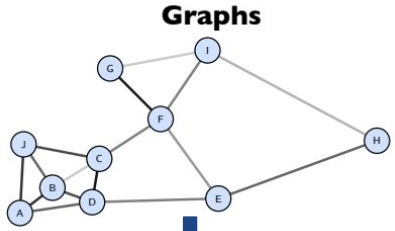
Sequence of objects:



Recurrent (LSTM)

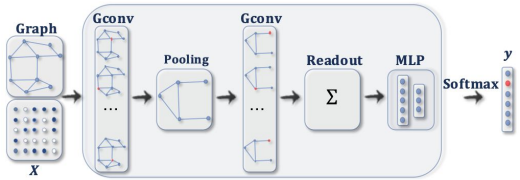


Represent as Graph:



GNN (ParticleNet)

Edge conv



Wrap-up

- Dark Matter Searches @ CMS:
  - Simplified Dark Matter models are accessible to LHC detectors in the form of WIMP search.
  - Proportional to mass coupling makes the Higgs Boson the perfect candidate as a portal to Dark Matter.
  - For the first time ever, all Higgs Boson production modes have been combined for the most precise Dark Matter Measurement ever made!
    - Probability of Higgs to DM decays: 8% expected, 15% observed → 2σ excess (5σ needed to claim discovery, 3σ considered evidence).
  - Run 3 has commenced. More events, optimised search.

Official party line? Run 3 Hit or Bust!

Reach me at:
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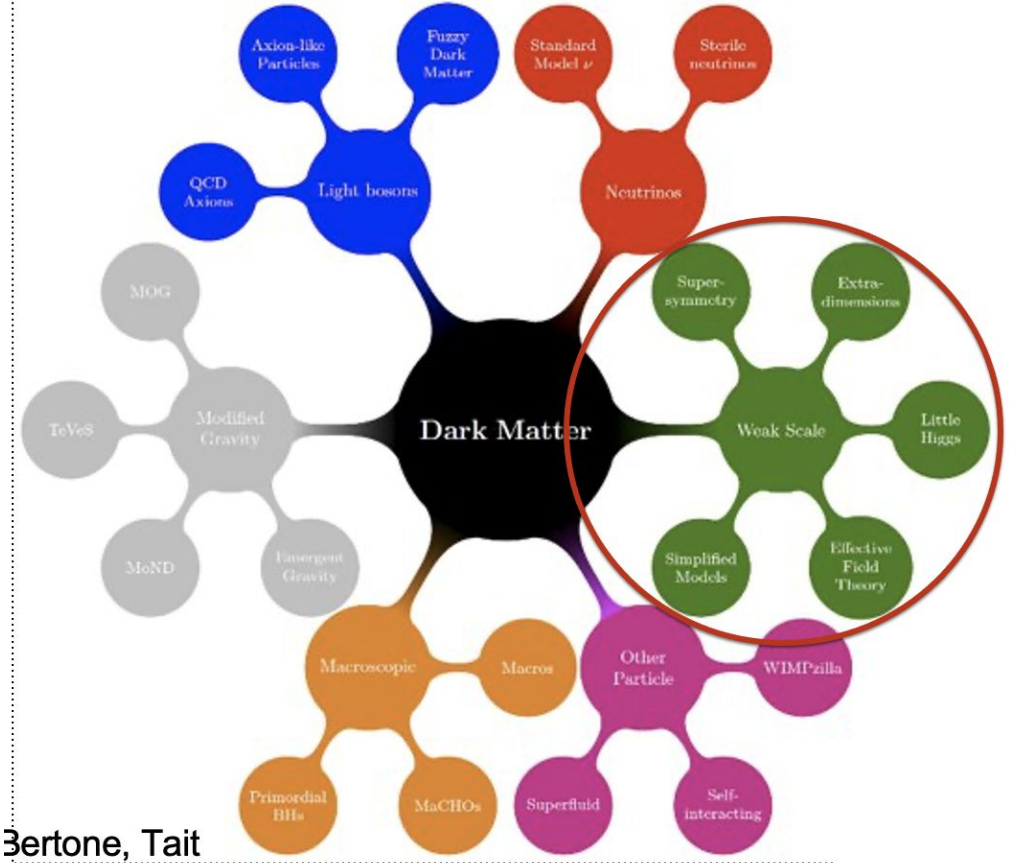
CERN

University of BRISTOL

Back Up



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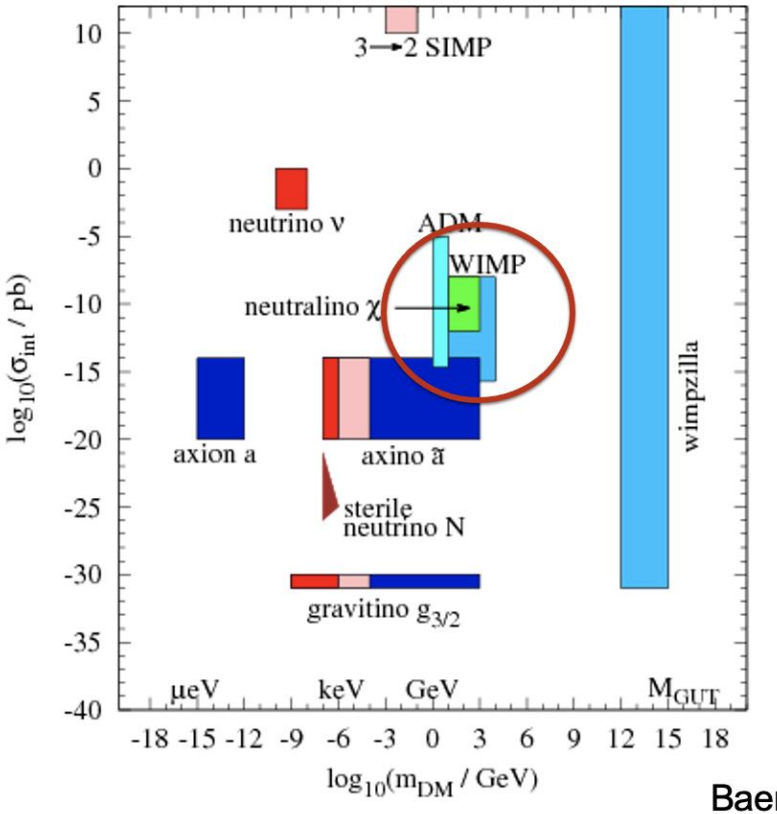
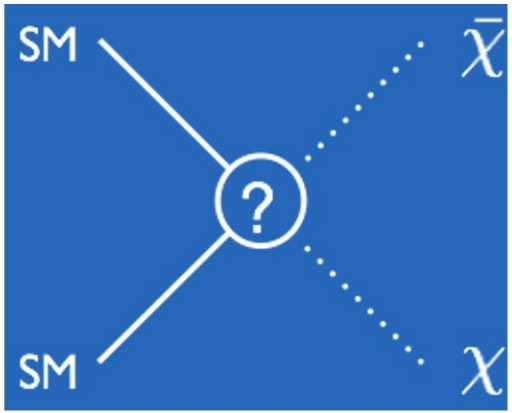


Baer

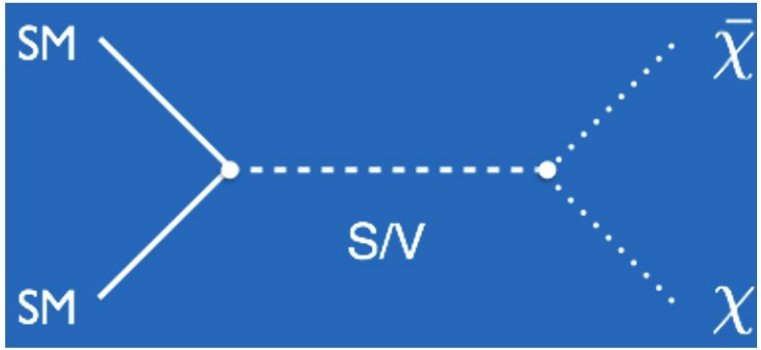
- Start with minimal assumptions
  - Effective Field Theories



- Described in terms of Lorentz structure, DM mass and cut-off scale

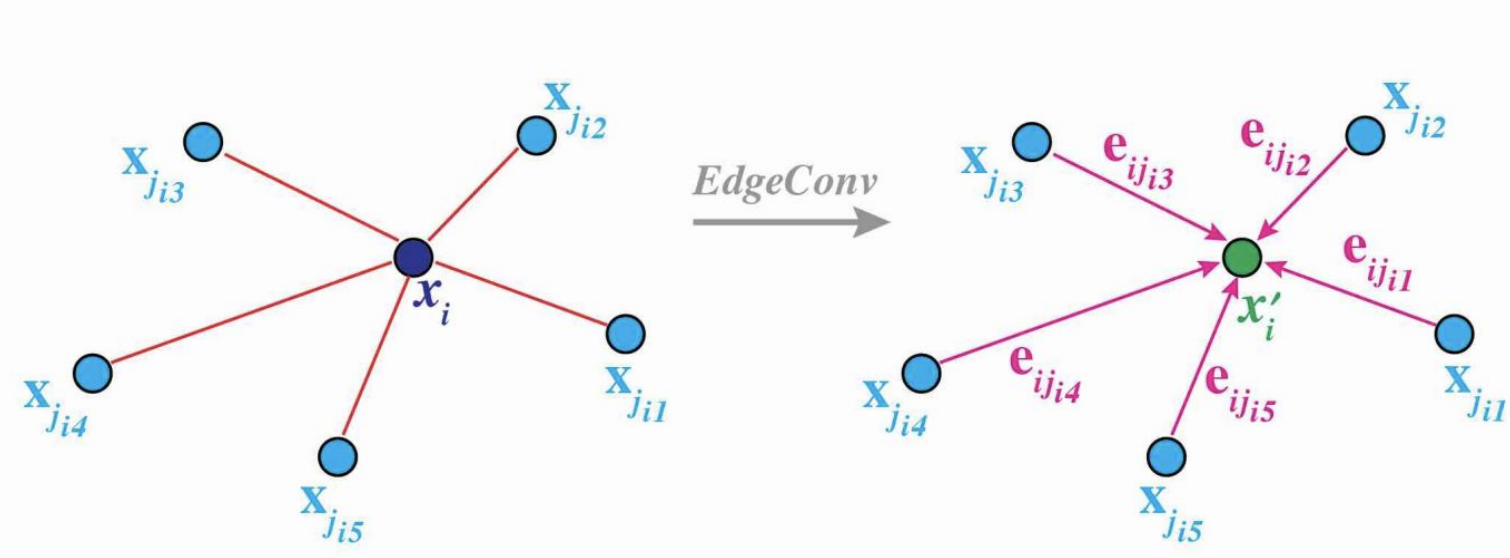
- Need to be careful at LHC @ 13 TeV
- EFT only valid if $Q^2 << M$

- Simplified models
  - Resolve the interaction



- Come with different assumptions for interactions/mediators

- scalar ($\psi\psi$)
- pseudo scalar ($\psi\gamma^5\psi$)
- vector $\psi\gamma^\mu\psi$,
- axial-vector ($\psi\gamma^\mu\gamma^5\psi$)

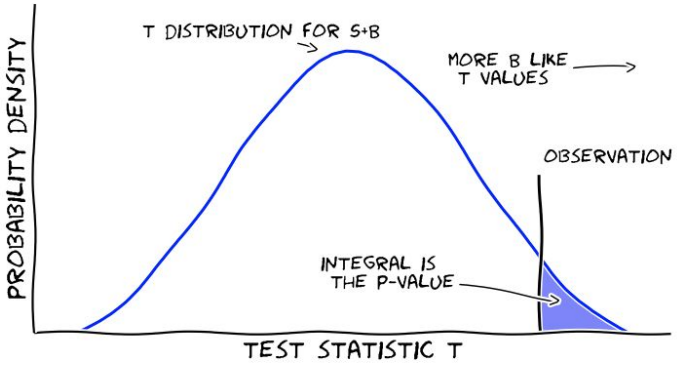


Cluster (KNN) and convolve along edges to extract features

$$\boldsymbol{x}'_i = \square_{j=1}^{k} \boldsymbol{h}_{\boldsymbol{\Theta}}(\boldsymbol{x}_i, \boldsymbol{x}_{i_j}),$$

Procedure

1. Pick a test statistic $T \in \mathcal{R}$
2. Determine T distribution under null hypothesis (S+B)
3. Compute the test statistic for the observed measurement, T_{obs}
4. Integrate the distribution from T_{obs} to the more "B only" like end $\rightarrow$ the "p-value" or "CL_{S+B}"



Reject S+B at 5% if:

$CL_{S+B} < 0.05$