Higgs Boson, Dark Matter and New Physics:

Progress and Prospects in Particle Physics at the LHC

Graduate Open House 2024

Duke ATLAS Group

Particle Physics at Duke

- ATLAS experiment at the LHC
  - 4 faculty; Arce, Goshaw (emeritus), Kotwal, Kruse
  - 2 postdocs
  - Typically 6 PhD students (2 graduating this year)
- Neutrino Physics
  - 3 faculty (Barbeau, Walter and Scholberg)
  - 2 postdocs
  - 2 students
- New Cosmology group (Scolnic, Troxel and Walter)

Recent Postdoc and Students

Postdoc Bodhitha Jayatilaka receiving
Fermilab's Tollestrup Award, 2012
(now a senior scientist at Fermilab)

Chris
Pollard
(now a professor
at Warwick U.)

Ben Cerio
(now a data scientist)

Recent Postdoc and Students

Kate Pachal
(now a scientist at TRIUMF)

Shu Li
(now a professor at Jiao Tong University in Shanghai)

Sourav Sen
(now a data scientist)

Current Postdoc

Neza Ribaric – obtained PhD from ATLAS

+ 5 undergraduate students working on ATLAS research projects

Conceptual Problem in Quantum Field Theory – 50 years ago

- In spite of its success, a self-consistent quantum mechanical theory of matter and forces had a huge missing link – the theory required all fundamental particles to have exactly zero mass

- The non-zero electron mass could not be understood – and yet the electron mass defines the size of the atom and physical and chemical properties of all substances

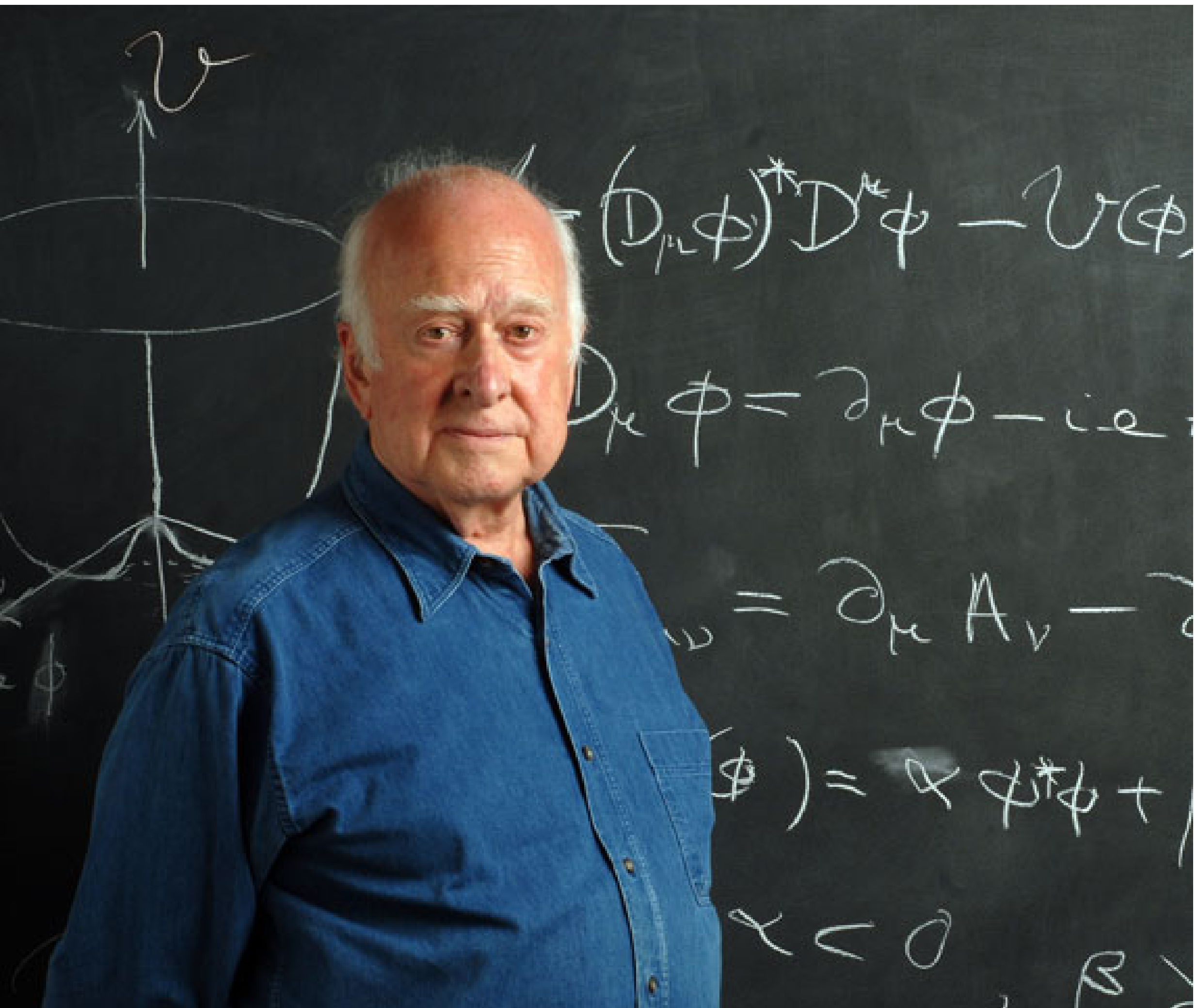
Knowledge from the LHC

- Why do fundamental particles have mass?
  - the Higgs hypothesis

- The mystery of Dark Matter –
  - Could Dark Matter particles be produced at the LHC?

- Why is there more matter than anti-matter in the universe?

The Higgs Boson



Peter Higgs

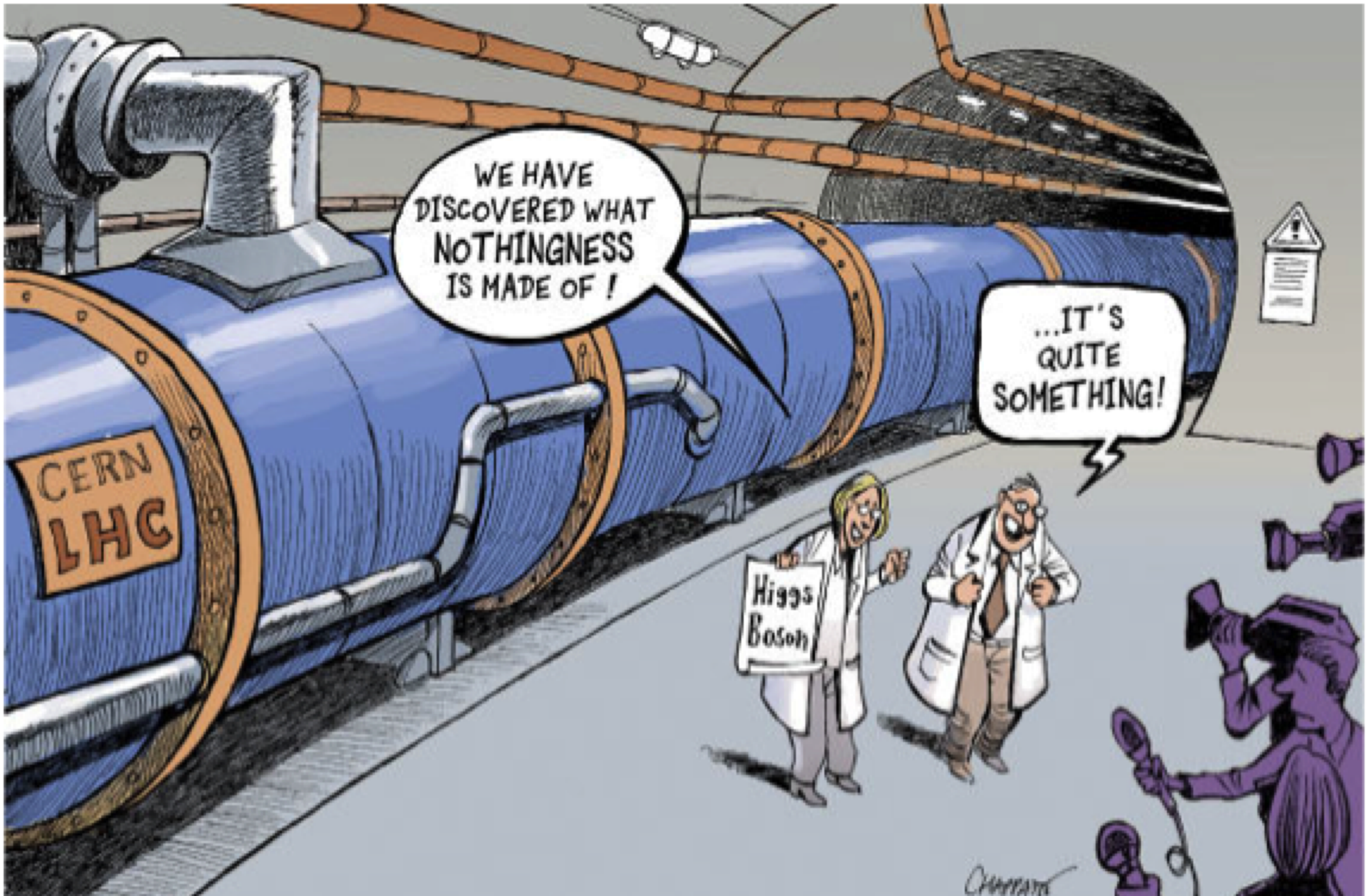
Satyendra Nath Bose in 1920's

Solution to the Problem of Fundamental Particle Masses

- Fill all of space with “Higgs” field

- W boson propagating through “empty space” actually propagating though Higgs field

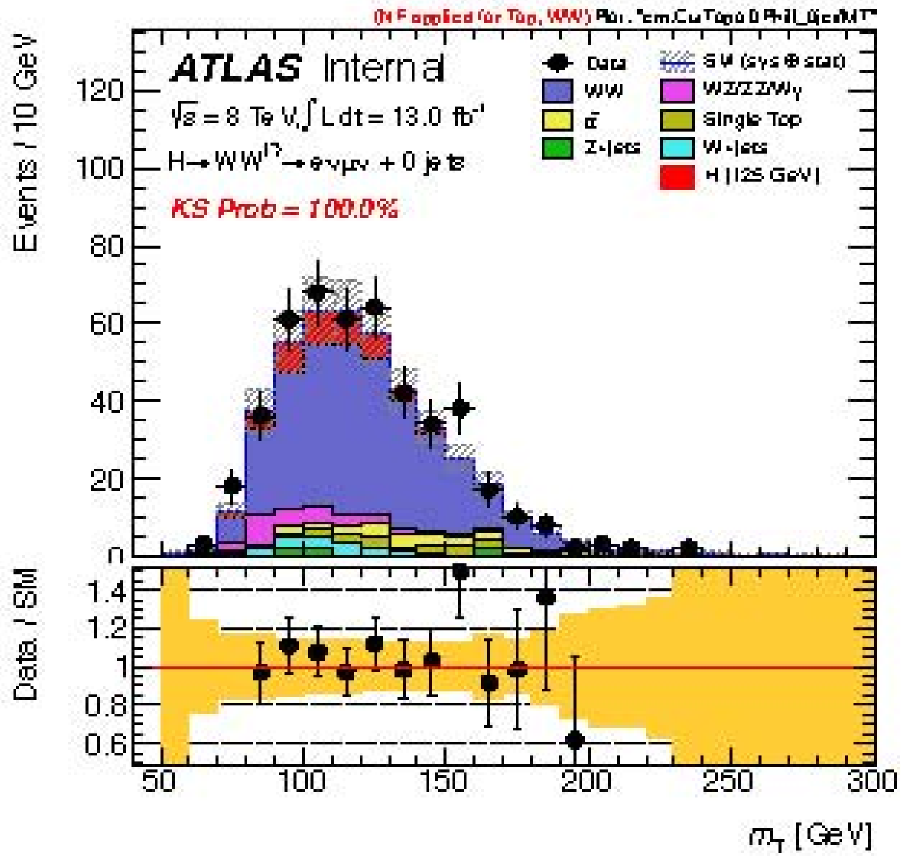
- Interaction of particles with Higgs field slows them down => imparting the property of mass

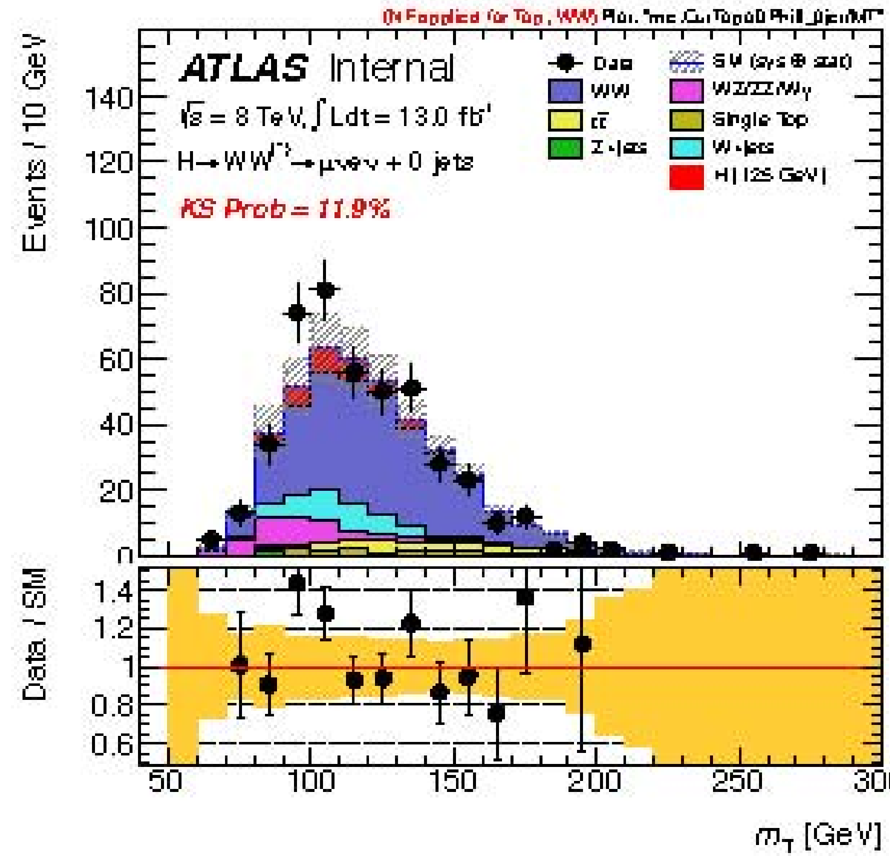

WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson
CHAPPATTE

Higgs Discovery Implications

- Provide an understanding of all masses of fundamental particles
- Revolutionizes our understanding of empty space <=> filled with Higgs
- Further studies of the properties of the Higgs will be of tremendous importance

Ben Cerio's Ph.D. Thesis Topic: H->WW



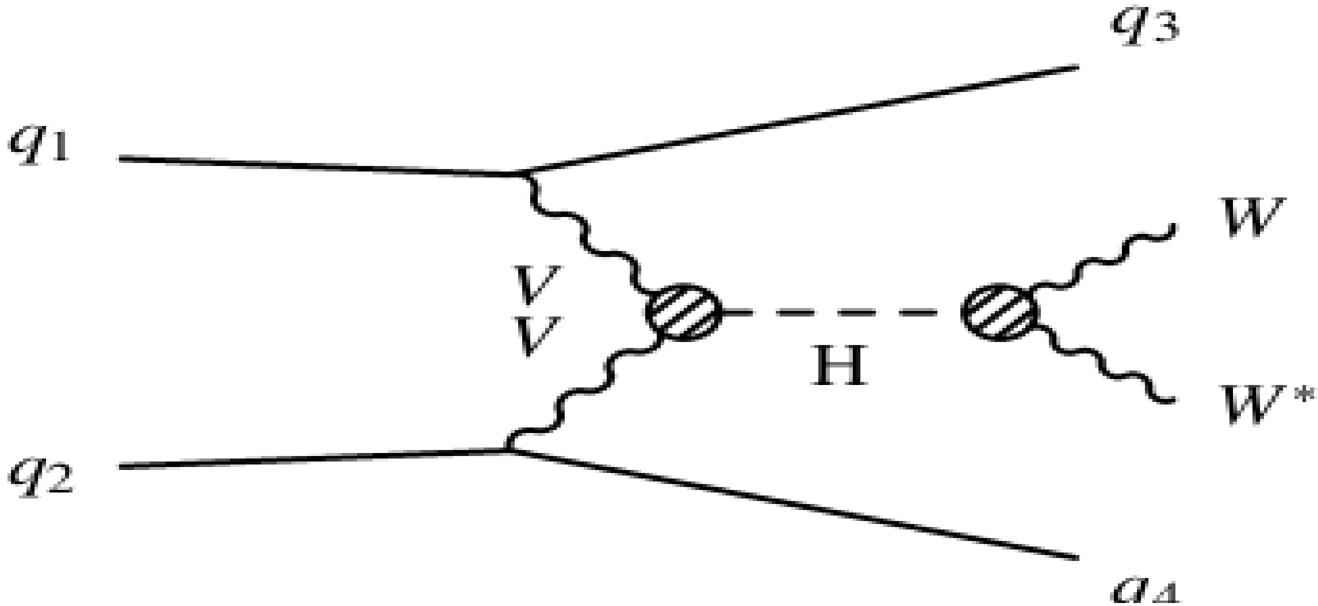


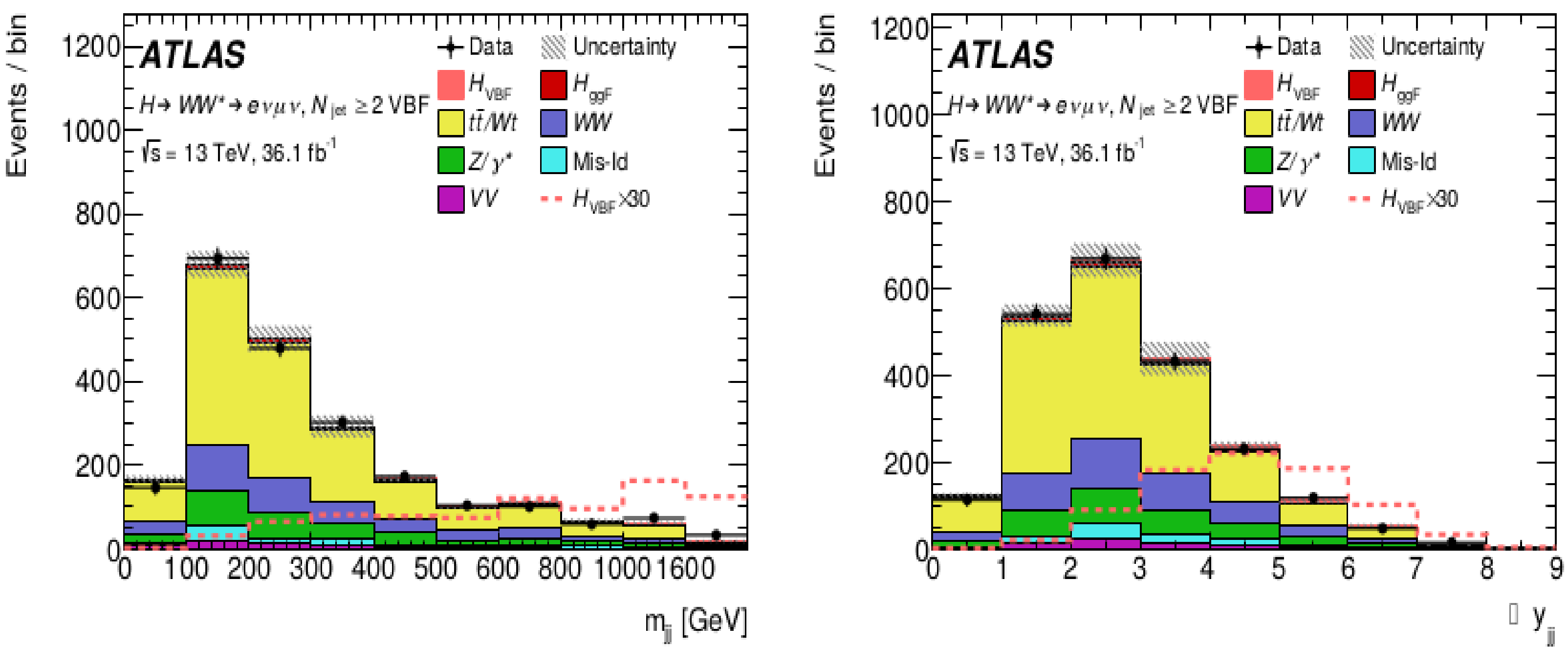
Ben worked on the determination of the Higgs boson's intrinsic spin and on detecting Higgs production via vector boson fusion: VV -> H -> WW

Published 3.1 sigma "Evidence"

Sourav Sen's PhD thesis => 5 sigma "Discovery"

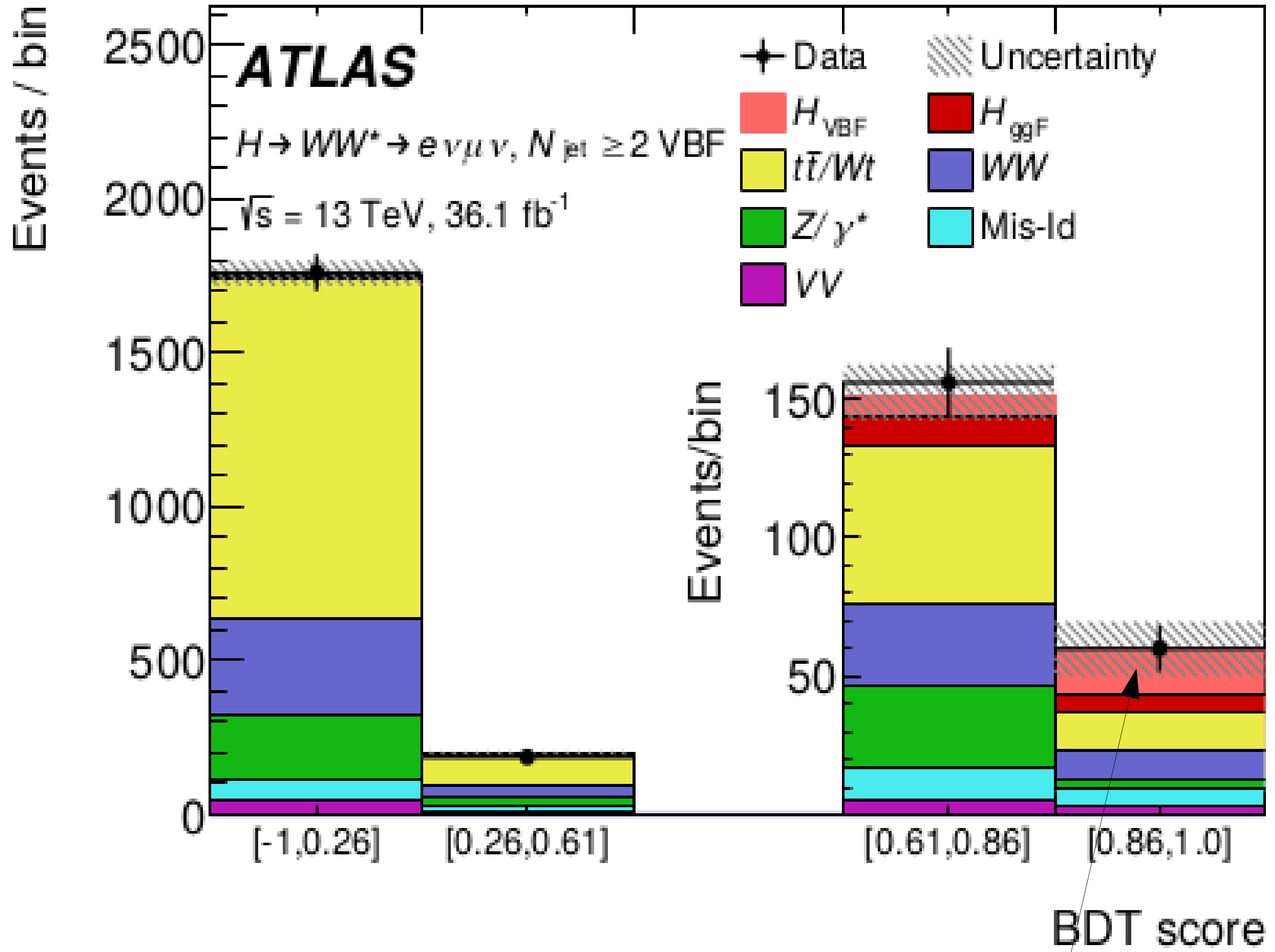
Sourav Sen's Ph.D. Thesis Topic: WW->H->WW





(a)
(b)

Sourav Sen’s Ph.D. Thesis Topic: WW->H->WW



Sourav Sen's PhD thesis => 5 sigma “Discovery”

But still open questions remain…

- The Higgs is a completely new kind of “stuff”, never before seen in nature
- It is *NOT* matter
- It is *NOT* a force
- it has condensed everywhere, even in empty space in the entire Universe
- We have no proven theory of this condensation process

Why aren't we satisfied?

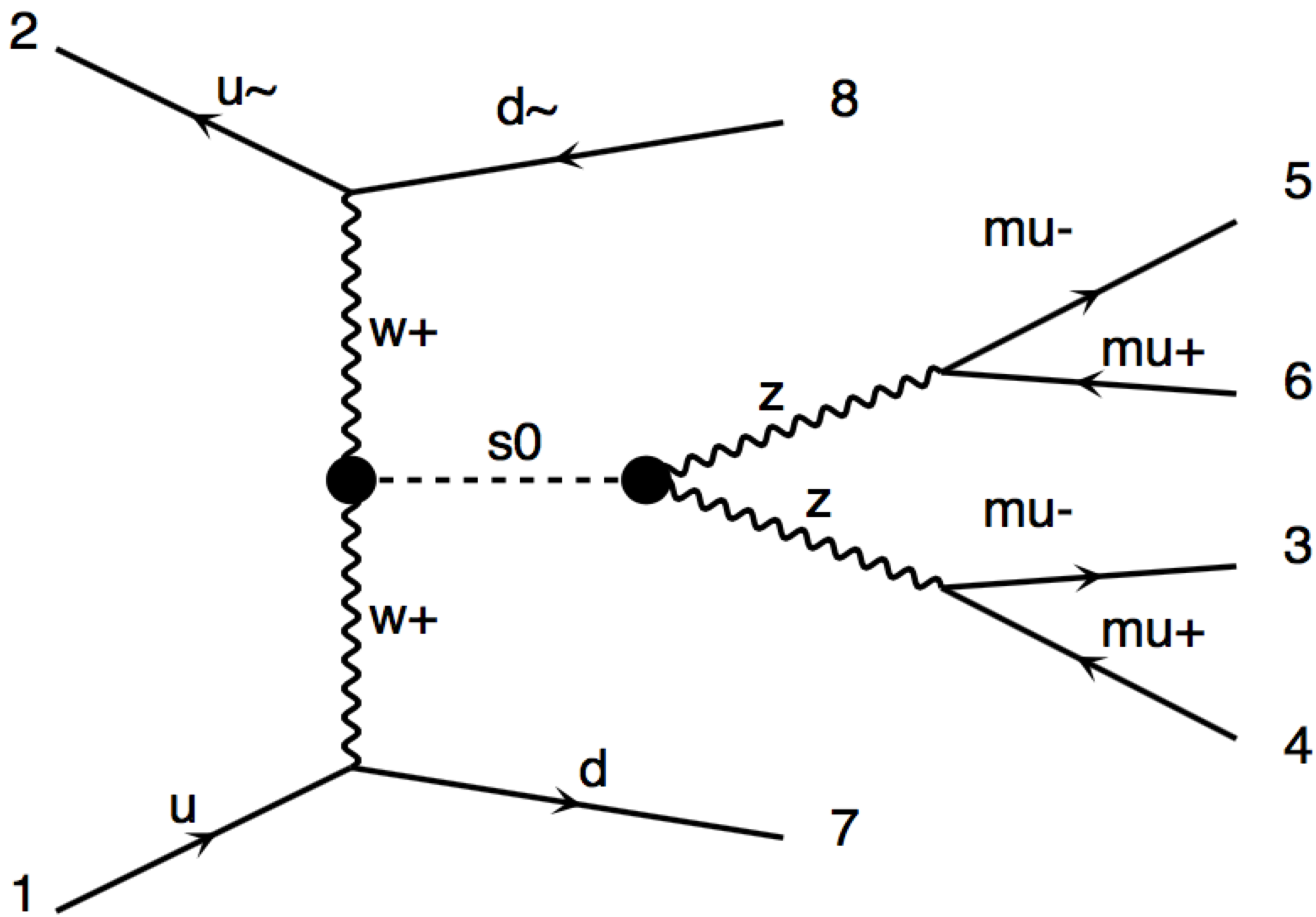
- Why does the Higgs field condense all over space ?
  - We understand other condensation phenomena at the microscopic level…condensation of gases to liquids and solids for example
- We need a similar, dynamical explanation for condensation of the Higgs field
- Additional ingredients and new physics principles are required to explain this condensation process..
  - The confirmed theory of fundamental particles and forces – "the Standard Model of Particle Physics', CANNOT explain this condensation process

Composite Higgs Hypothesis

- Theories postulate new states of matter (fermions) that bind together to form the Higgs boson
  - These ideas gaining popularity since the other popular hypothesis – supersymmetry - has not been discovered yet
  - Analogous to Bardeen, Cooper, Schrieffer theory of superconductivity (formation of a condensed bound state of fermions)

- Such “Higgs constituents” are expected to manifest other, heavier bound states
  - May only be detectable via their vector boson and Higgs interactions

Search for Composite Higgs Sector Resonances

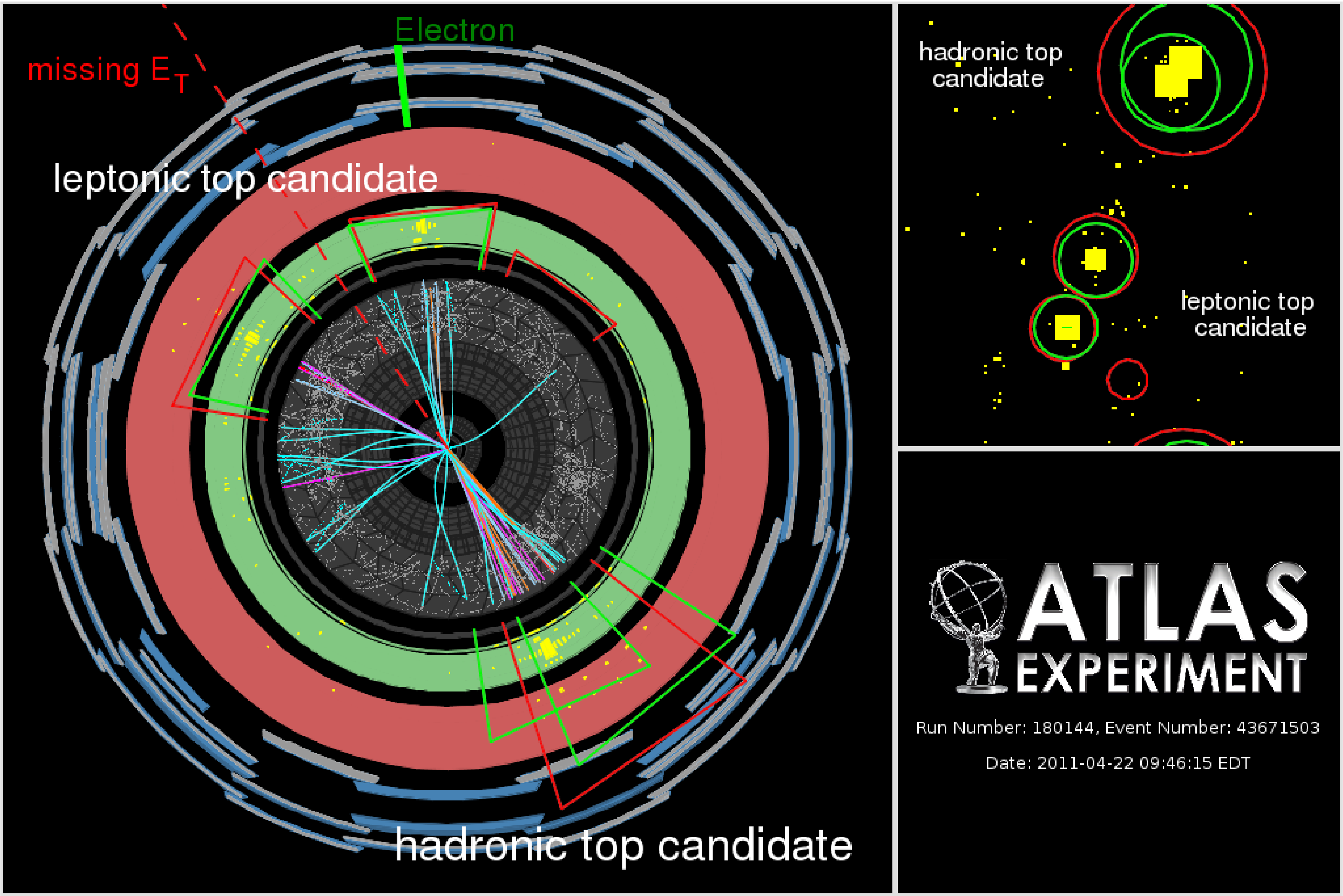


New analyses ramping up in ATLAS experiment :
VV -> new composite resonances
Will use 10x more data than previously available

Why is the top quark so heavy?

- Top quark is very heavy => very large coupling to Higgs
  - If Higgs boson is composite, top quark may also contain the same constituents
- Collisions involving top quarks in the initial and/or final states will reveal their composite nature
- Completed study: top quarks in final state
- Ongoing and future studies: top quarks in both initial and final states

Chris Pollard's PhD Thesis:
search for heavy particles decaying to top quark pairs



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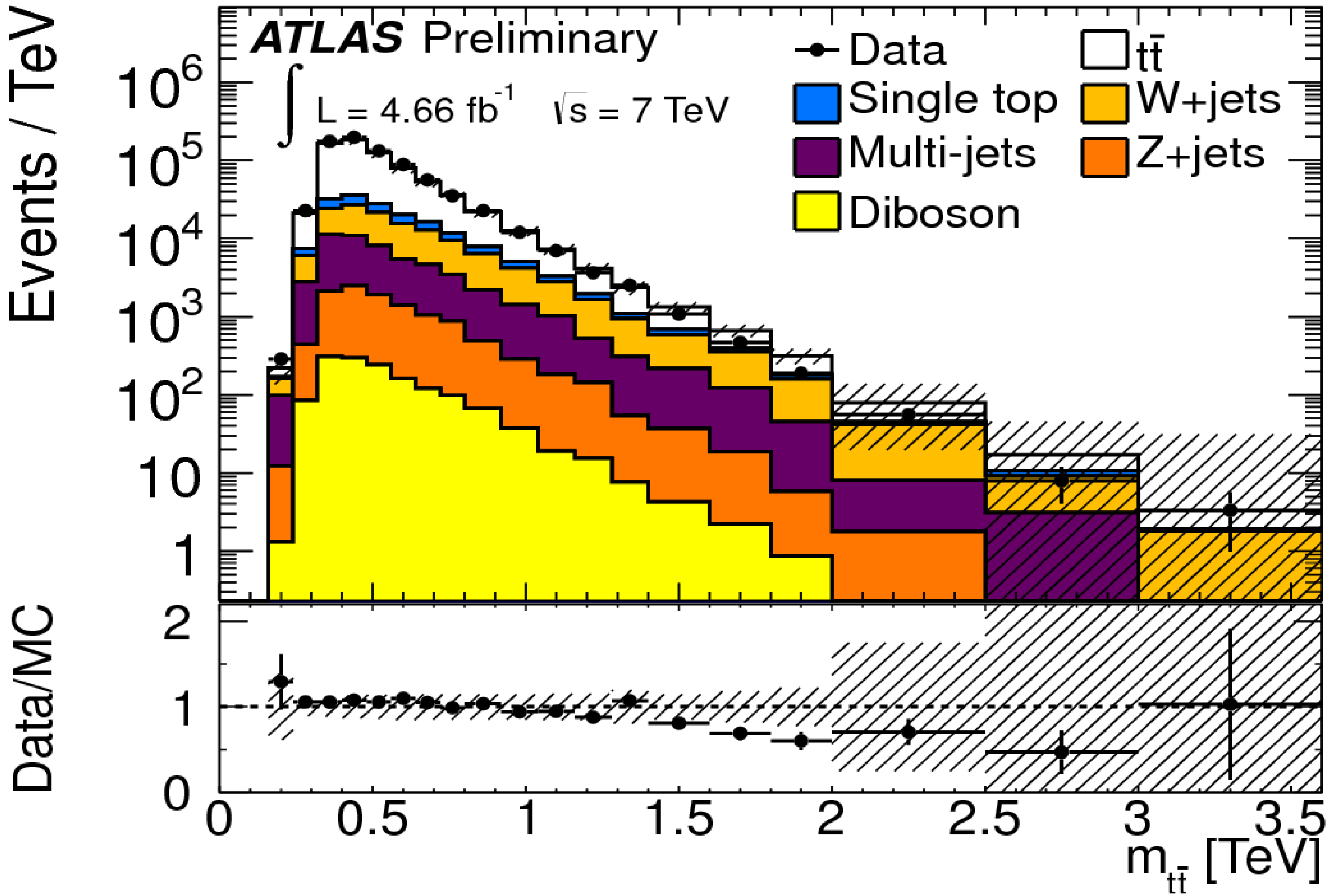


Composite top signature: heavy composite resonance
→ top quark pair + dark matter particles

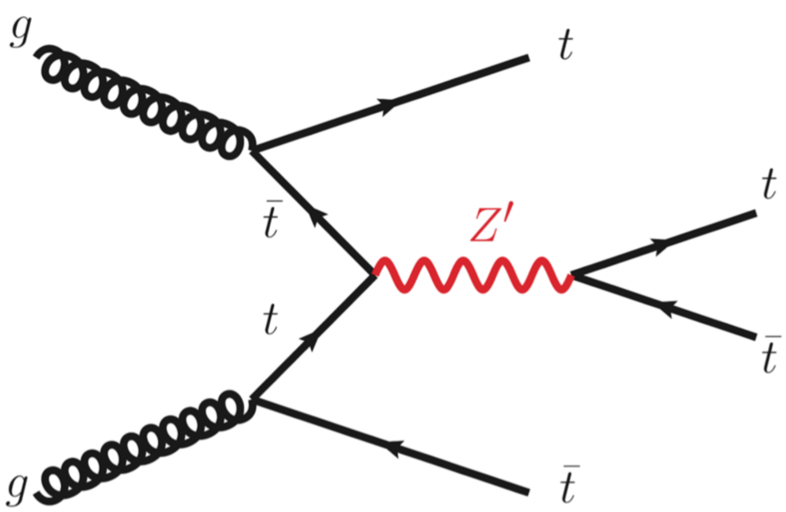
Search for BSM 4 tops
Status report

Elise Le Boulicaut (Duke) on behalf of the analysis team
(*Nedaa-Alexandra Asbah*, William Barbe, Samuel Calvet, James Ferrando, Ashutosh Kotwal, Kate Pachal, Chris Pollard, Sourav Sen, *Loïc Valéry*, Alicia Wongel)

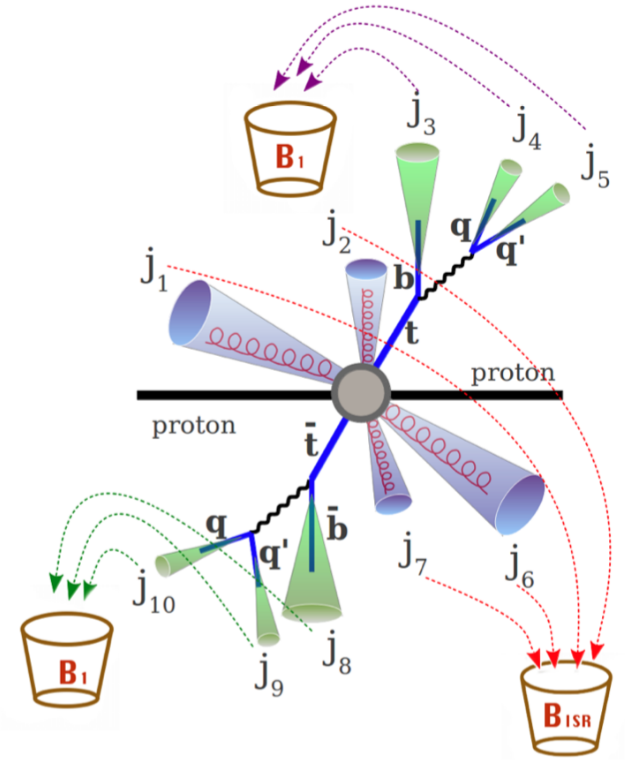
HQT meeting 09/09/2019

Motivation

- Search for truly top-philic resonance (couples preferentially to top quarks)
  - ➢ Predicted by multiple BSM theories, as discussed in this paper
- Not accessible in usual $t\bar{t}$ resonance searches because production is suppressed
- Uniquely accessible through associated production with $t\bar{t}$ pair → 4 tops
- Input for DM combination/summary papers



- **Goal**: reconstruct tops by sorting small-R jets into different groups ("buckets")
- **Original design** (see this paper for example) :
  - $t\bar{t} \rightarrow$ all hadronic
  - jets with $p_T \in (100\ GeV, 400\ GeV)$
- **Current plan**: use to resolve spectator tops → improve selection of resonance tops
- **Discriminating power**: signal has 2 spectator tops, but not the dominating background

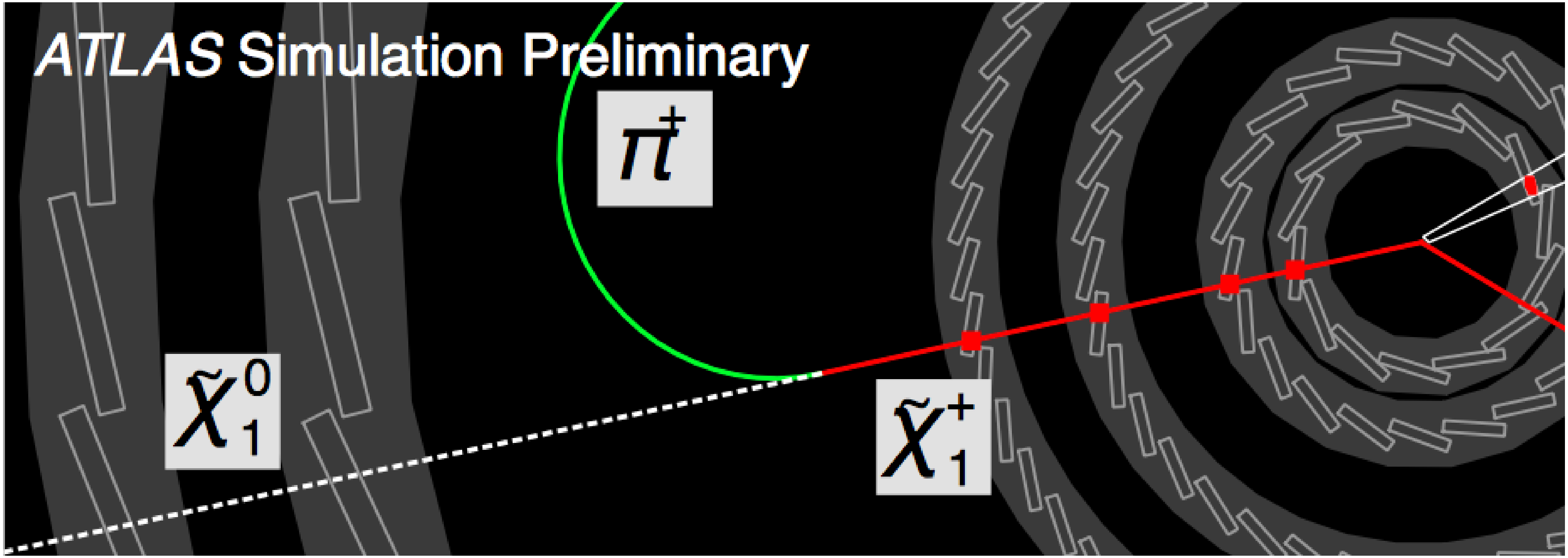


⇨ Initial tests on all-hadronic $t\bar{t}$ resulted in maximum efficiency of ~ 73% (both tops correctly reconstructed)

Great opportunities for applying advanced machine learning techniques !

The Mystery of
Dark Matter

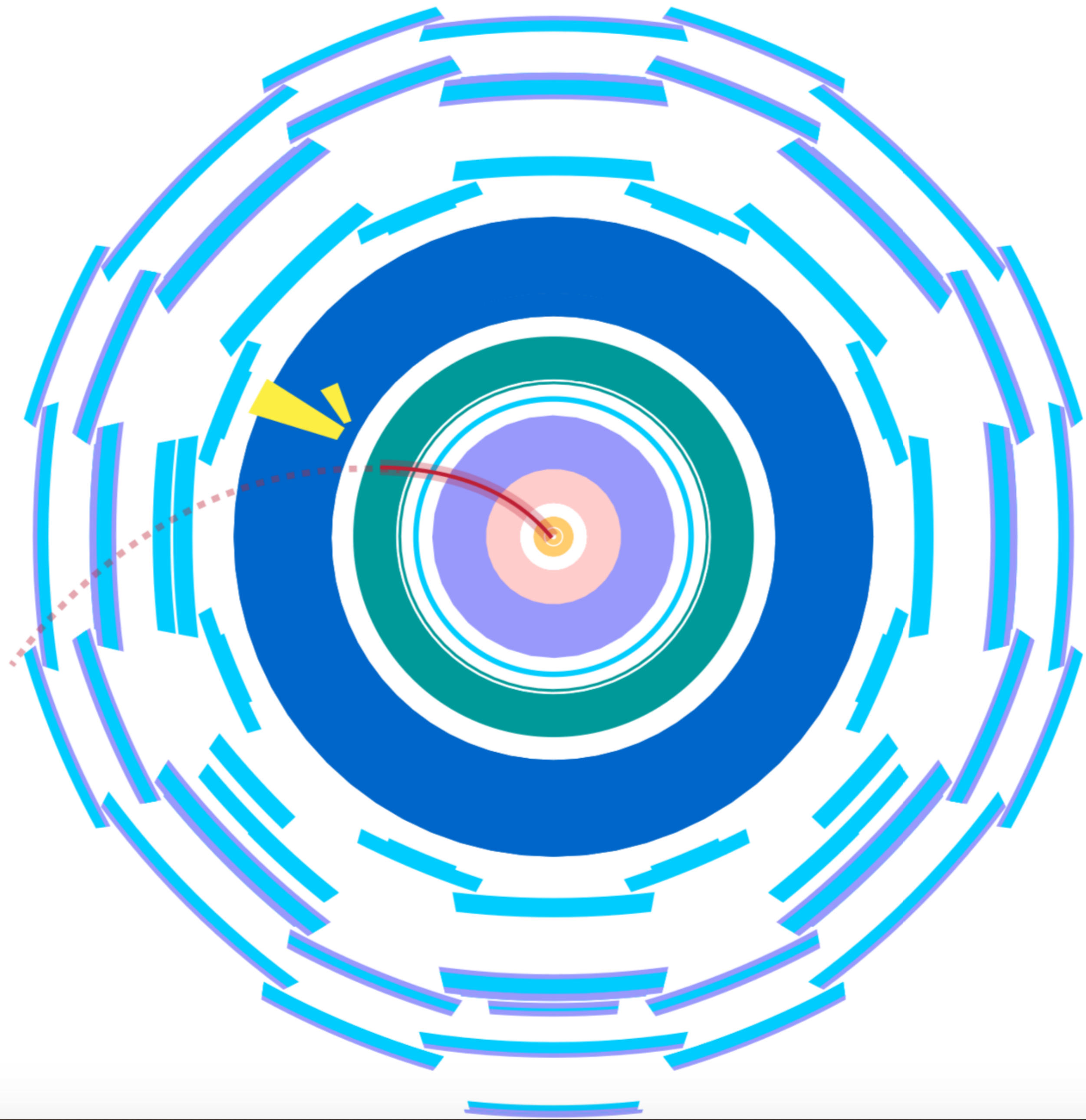
Dark Matter Progenitor Production



Explains why DM and visible matter have similar amounts in the Universe

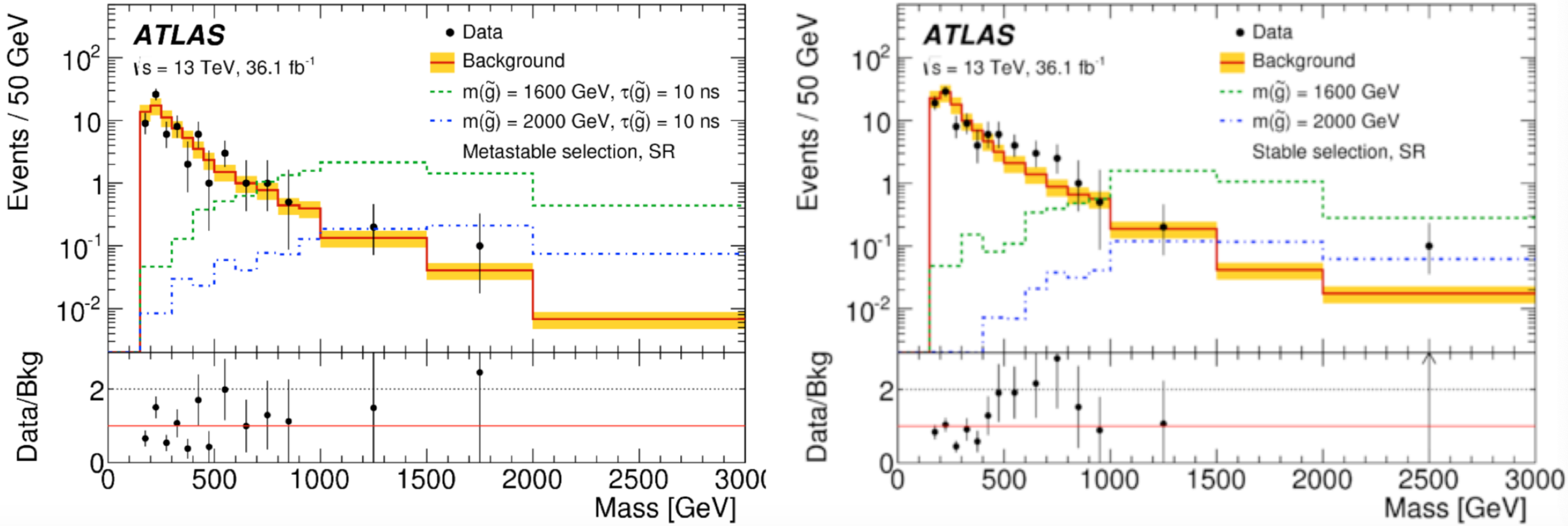
Large ionization

- Sensitivity
  - charged heavy particle, lifetime > 1 ns
- Signature
  - high p_T track with large dE/dx signature in tracker



Metastable charged heavy particles: ATLAS

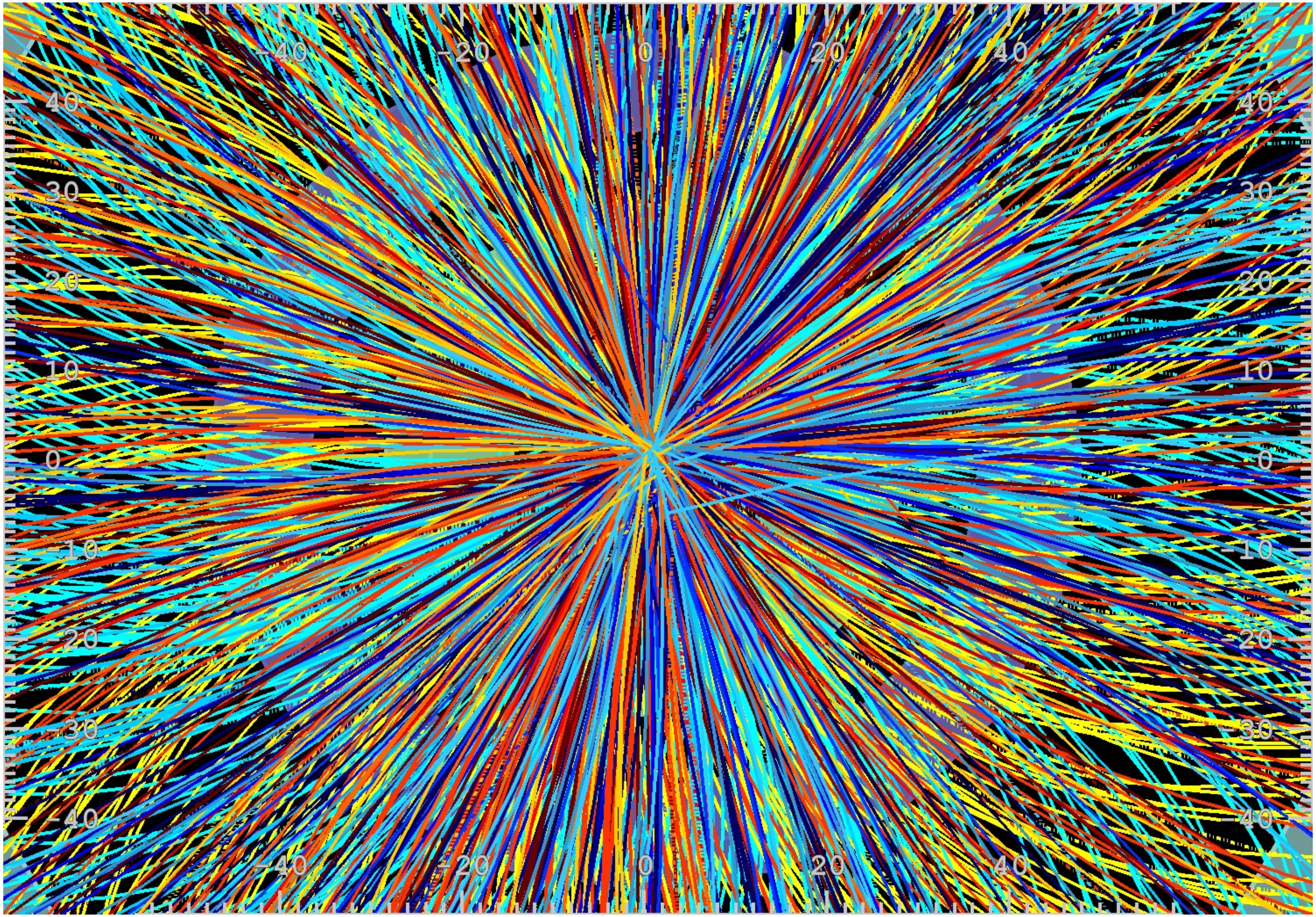
- Results
  - 2.4σ local excess in stable region, pre-defined mass window 500 - 5000 GeV
  - For gluino R-hadrons with lifetimes of 1.0 ns above, masses excluded from 1290 to 2060 GeV



Previous analysis by Duke postdoc Kate Pachal, Ann Wang (Harvard student)

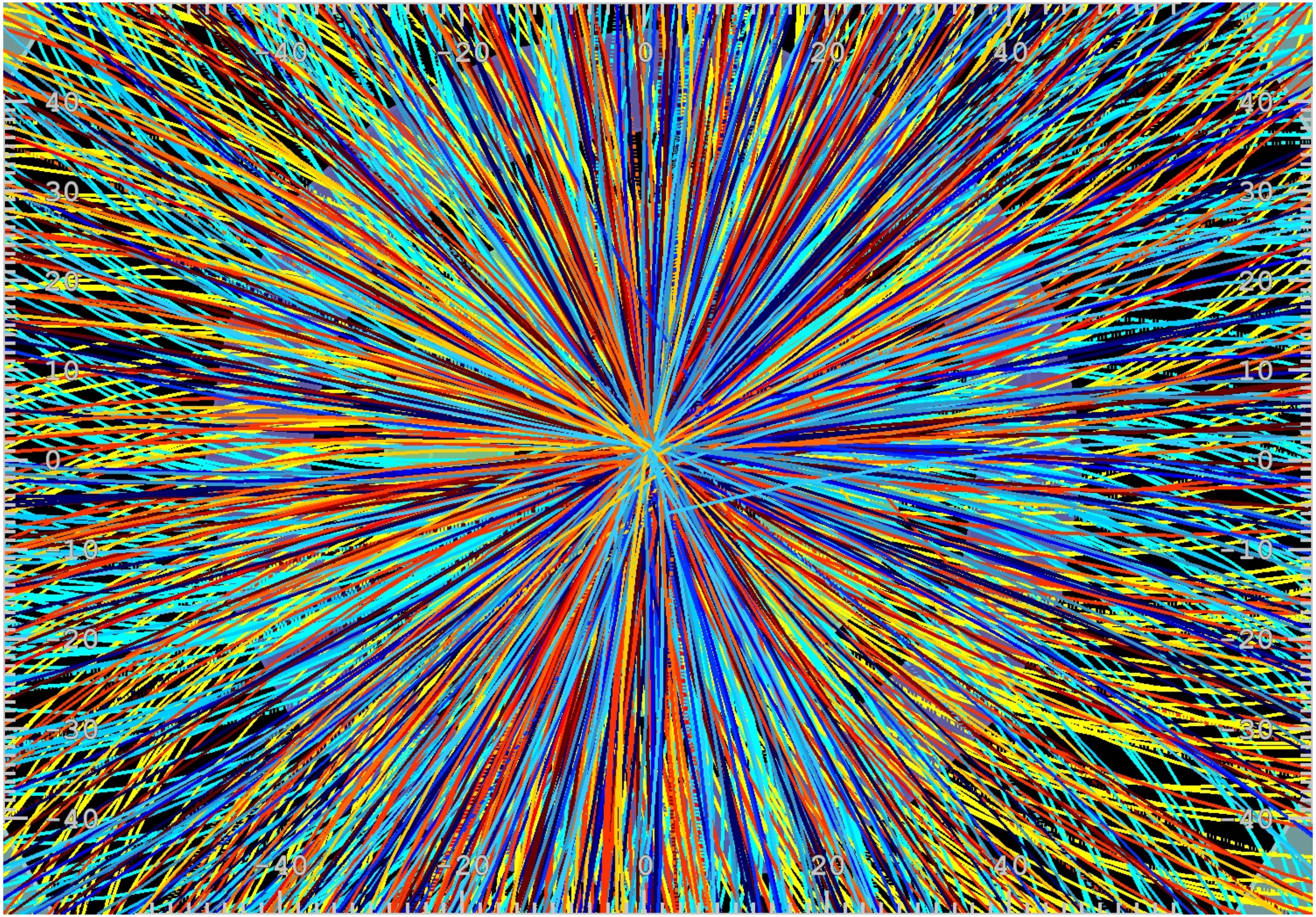
10x larger dataset available for analysis – new opportunity !

New Techniques for Particle Tracking



- 200 proton-proton collisions per 25 ns, each collision producing 100 particles
- 240,000 point measurements every 25 ns in 12 layers of silicon sensors

New Techniques for Particle Tracking



- Developing fast pattern finding algorithms using GPUs
- Plan to implement algorithms on parallel-processing circuits

Prospects for Students

- Openings for new PhD students starting summer 2024

- Choice of topics made by students
  - Higgs physics
  - Top quark physics
  - Searches for new heavy particles and forces
  - Searches for Dark Matter

- Experimental work with tracking detectors (hardware, software, algorithms)

  - Development of new experimental techniques to enable discovery:
    - New triggering techniques
    - Improved algorithms for signal recognition and reconstruction

Summary

- LHC represents the research frontier for certain "big questions"
  - Higgs represents a new state of matter, with no fundamental explanation (yet)
  - Dark Matter has no explanation (other than gravitational detection)
  - Excess of matter over antimatter in the Universe, is not explainable
    - Could be related to Higgs and the heavy top quark
  - Development of new Machine Learning techniques necessary to search for rare signals