THE UNIVERSITY OF CHICAGO

ATLAS EXPERIMENT

CERN

The search for supersymmetry in hadronic final states using boosted object reconstruction

Ph.D. Thesis Defense

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April 26th, 2018
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ATLAS EXPERIMENT

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https://kratsg.github.io/thesis/

Overview of today's talk

- The Standard Model… and **beyond**!
- The Large Hadronic Collider, **ATLAS**, and you
- Jets and Lorentz-**boosted object reconstruction**
- Searching for **new physics** in busy hadronic final states
- **Instrumentation upgrades** for the next 20 years

The Standard Model

A study of particles and their interactions

"The story so far: In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move." — Douglas Adams

"Young man, if I could remember the names of these particles, I would have been a botanist." — Enrico Fermi

A (brief) history of nature

What	When	Who	Paper
Photon	1895	Wilhelm Röntgen	[16]
Electron	1897	J.J. Thomson	[17]
Proton	1919	Ernest Rutherford	[18]
Neutron	1932	James Chadwick	[19]
Muon	1937	Seh Neddermeyer, Carl Anderson	[20]
Electron neutrino	1956	Clyde Cowan, Frederick Reines	[21]
Muon neutrino	1962	BNL (AGS)	[22]
Up Quark Down Quark Strange Quark	1969	SLAC	[23,24]
Charm Quark	1974	SLAC and MIT	[25,26]
Tau	1975	SLAC-LBL	[27]
Bottom Quark	1977	Fermilab (E288)	[28]
Gluon	1979	DESY (PETRA)	[29]
W/Z Bosons	1983	CERN (UA1)	[30,31]
Top Quark	1995	Fermilab (D0, CDF)	[32,33]
Tau Neutrino	2000	Fermilab (DONUT)	[34]
Higgs Boson	2012	CERN LHC (ATLAS, CMS)	[2,35]

**dozens of other discovered particles not listed*

- More than a century since the **seed** was planted by the first particle discovery
- Highly collaborative and international
- July 4th, 2012 collaborations at LHC announce discovery of Higgs boson

The Standard Model (I)

- The Standard Model (SM) is a combination of two quantum field theories: Quantum Chromodynamics (QCD) and Quantum Electrodynamics (QED)

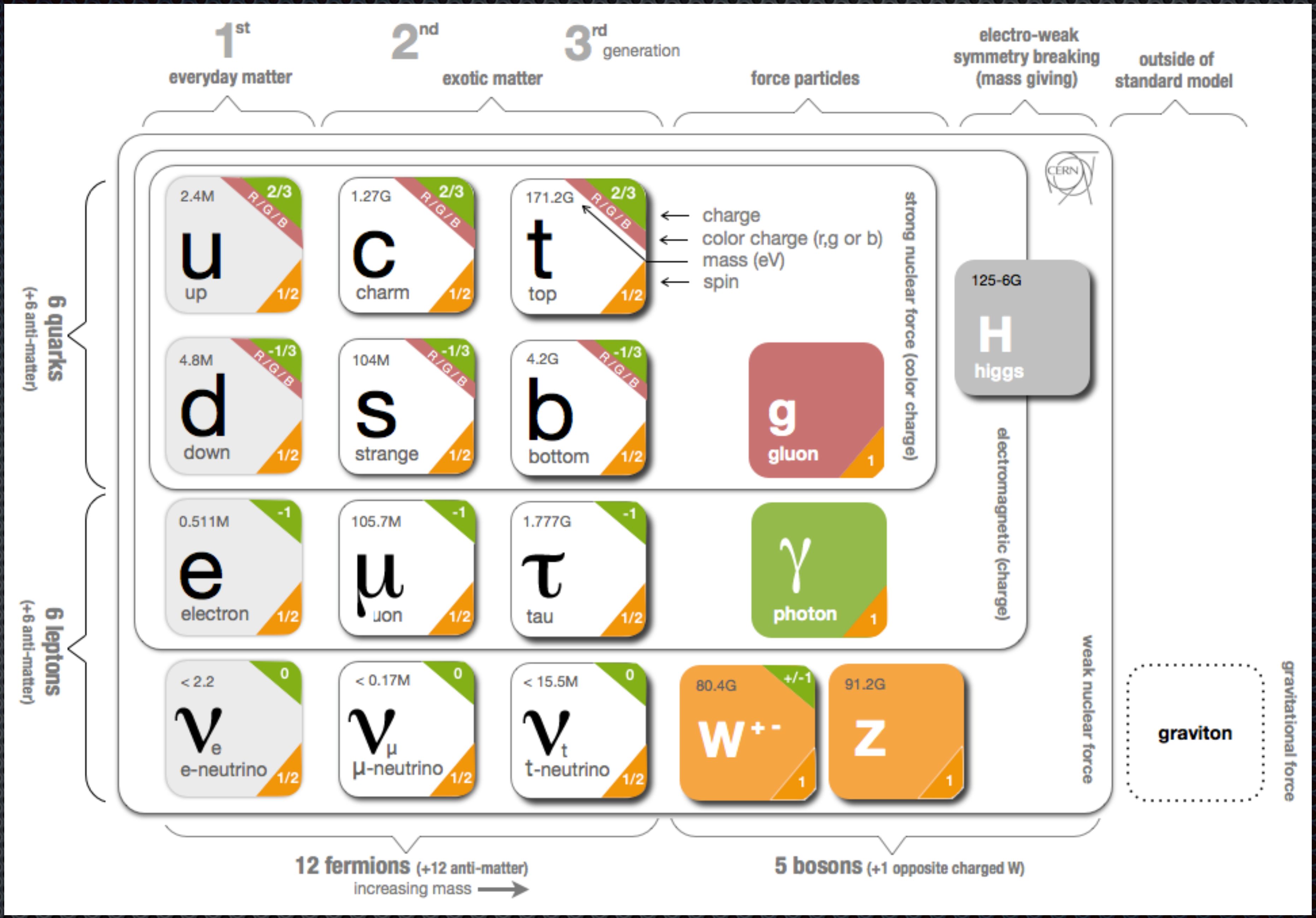
$$\boxed{SU_C(3) \otimes SU_L(2) \otimes U_Y(1)}$$

and three of the four interactions in nature: **strong**, **weak**, and **electromagnetic** [the fourth is gravity]

  - QCD describes the **strong interactions**, governed by **SU(3)** flavor symmetry [underlies the Eightfold way]
  - QED describes the **electromagnetic** and **weak** (electroweak) interactions, governed by **SU(2)**x**SU(1)**.

Property	Interaction			
	Gravitational	Weak	Electromagnetic	Strong
Acts On	Mass-Energy	Flavor	Electric Charge	Color Charge
Particles Experiencing	All	Quarks, Leptons	Charged	Quarks, Gluons
Particles Mediating	Graviton	W/Z bosons	Photons	Gluons
Strength at 10^{-18}m	10^{-41}	0.8	1	25

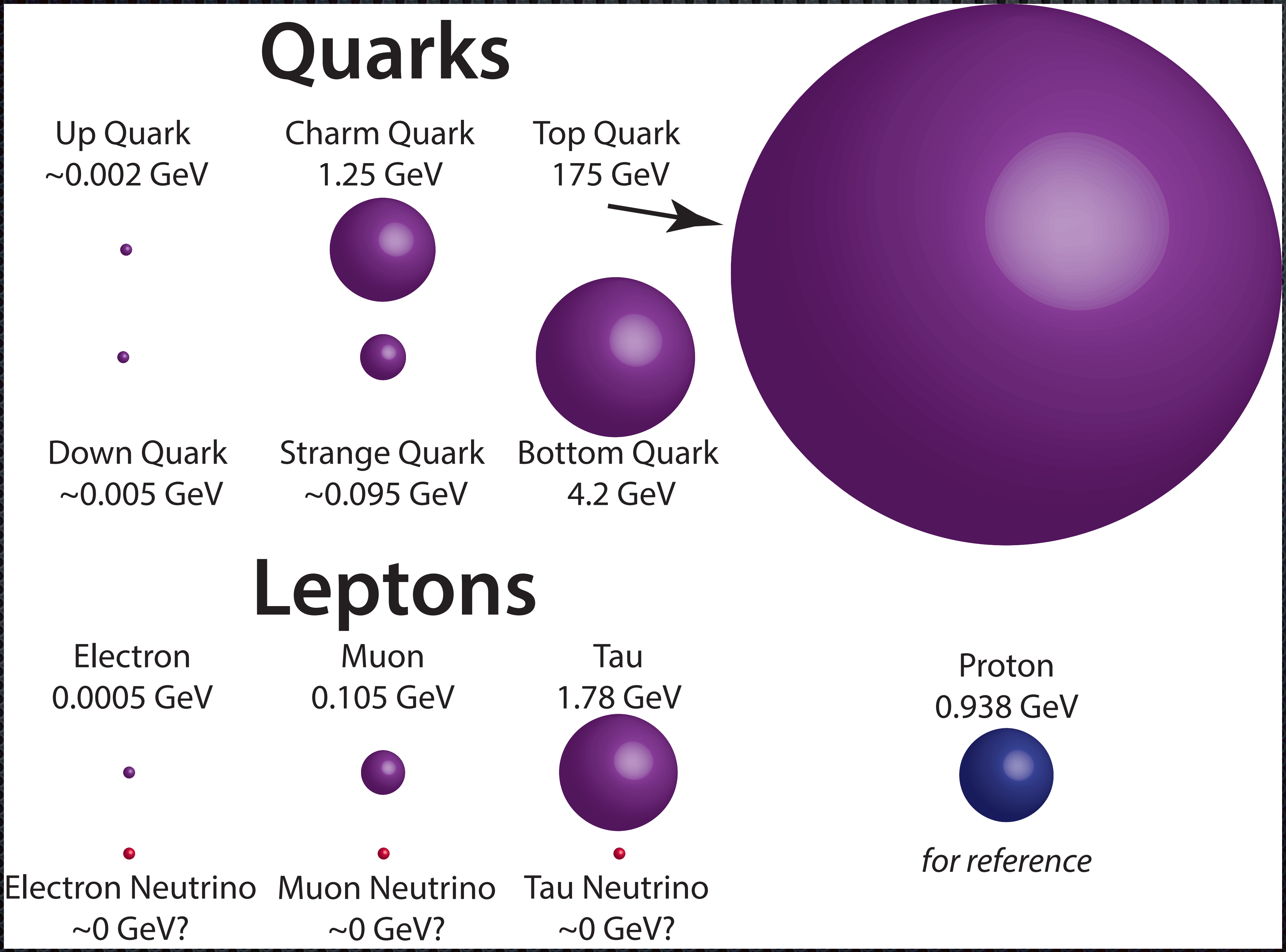
The Standard Model (II)



12 fermions
(6 leptons, 6 quarks)
1/2-spins

5 bosons
(4 force-carriers)
integer spins

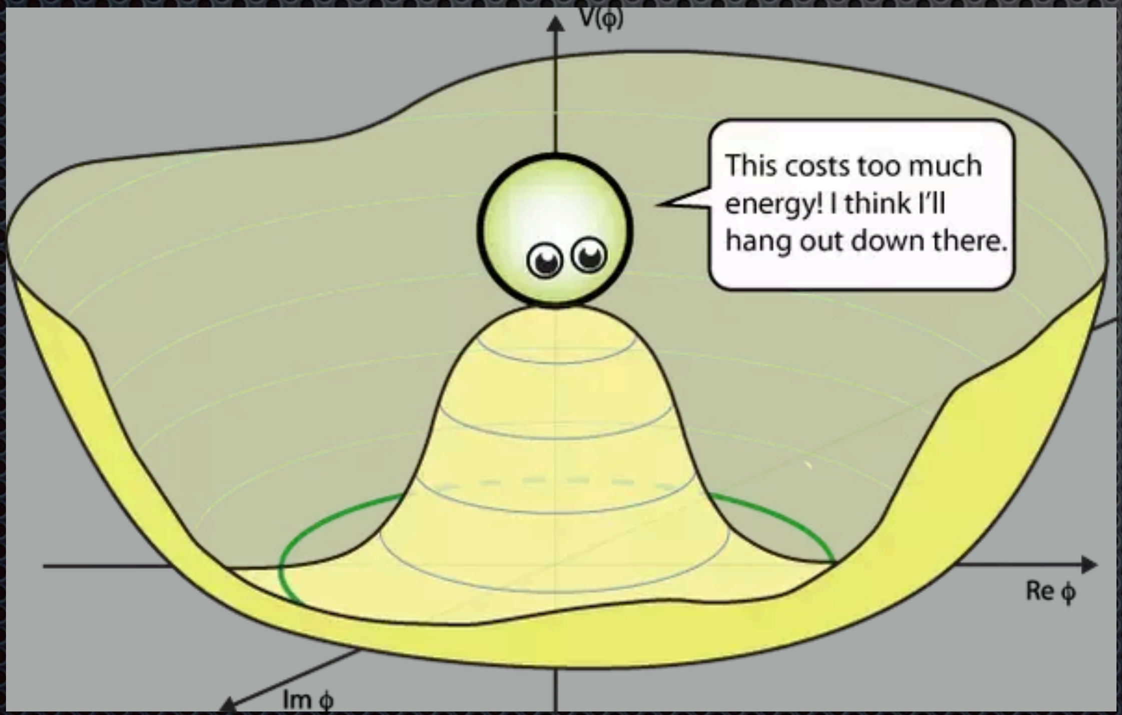
The Standard Model (III)



Volume proportional to the mass

The Higgs mechanism (I)

- All elementary particles are excited states of some particle field in the Standard Model
- Fields couple to other fields in the Standard Model Lagrangian
  - For example, the *b*-quark/anti-*b*-quark (*B*) couples to the Higgs field (*Φ*) with some coupling strength *g*
- This system has a **symmetry at the origin**, “nothing changes” when we rotate.



picture from Quantum Diaries

$$g\bar{B}B\phi$$

This is the Higgs potential, often called a “mexican hat”

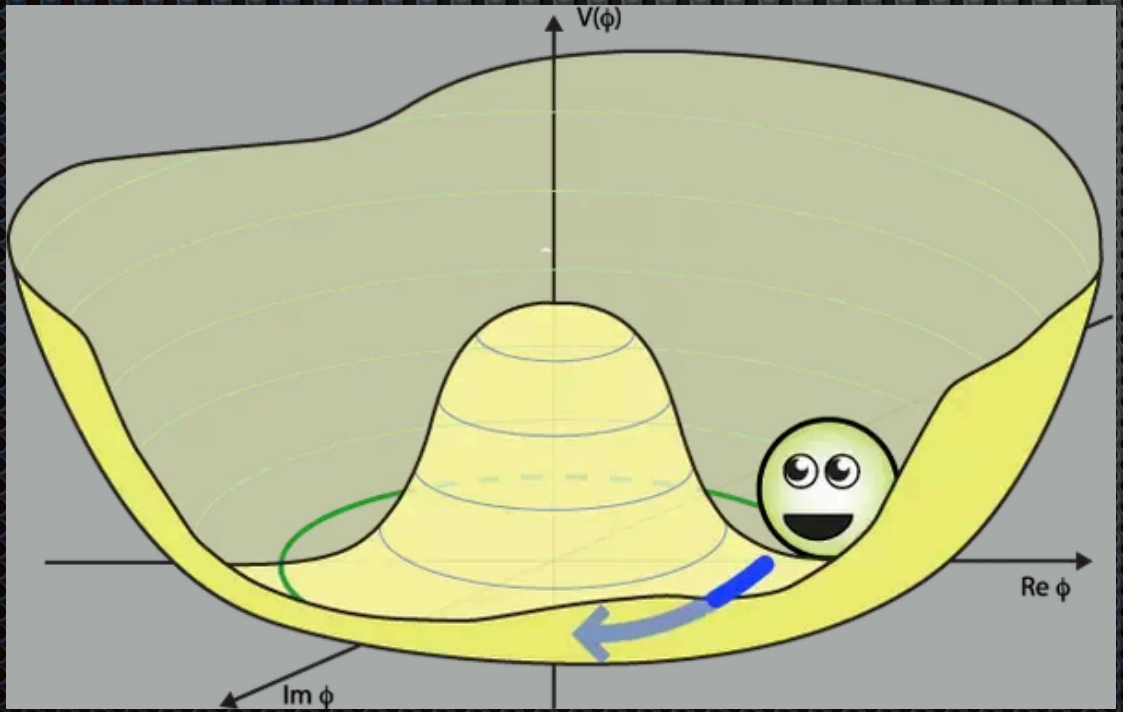
What happens when it rolls down?

This loss of symmetry is known as Spontaneous Symmetry Breaking (SSB)

The Higgs mechanism (II)

The loss of symmetry, triggered by the Higgs mechanism, gives particles mass!

- When the Higgs "rolled down" to a point of lower energy, it acquires a **vacuum expectation value (VEV)** — a value of the Higgs field — this is what **"gives mass"**
- The Higgs field (*Φ*) can be written in two components: the constant vev (*v*) and the dynamic Higgs boson



picture from Quantum Diaries

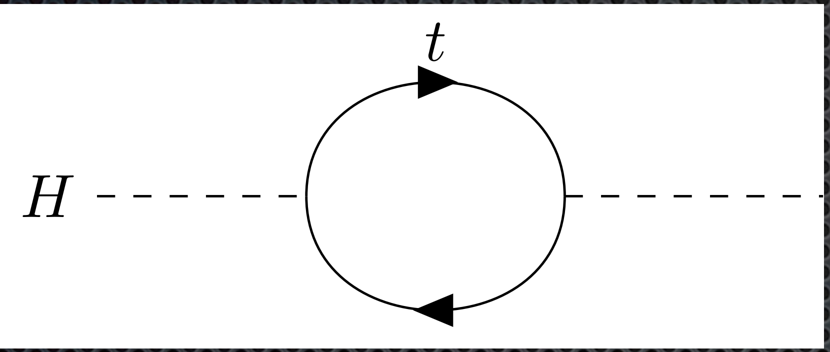
$$g\bar{B}B\phi \rightarrow g\bar{B}Bv + g\bar{B}BH$$

self-interacting term, we have mass = *gv*!

how *b*-quark interacts w/ Higgs

What about Higgs mass?

- The process of renormalizing a theory, such as Standard Model, up to some chosen energy scale incorporates "loop terms" which corrects properties of the theory
  - **What are the corrections to the Higgs mass m_0?**
- Standard Model: mass of particle is strength of Higgs field coupling (e.g. Yukawa interaction)
  - The top quark, with the largest mass, has the largest correction to the Higgs mass



$$\Delta m_H^2 = -\frac{|\lambda_t|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots$$

- If the Higgs boson is observed at the electroweak scale, 125 GeV, then the Higgs mass m_0 needs to be **finely-tuned** to almost-perfectly cancel out with the $(10^{19})^2$ correction!
  - This correction is proportional to the square of the cut-off scale — the Planck scale

This fine-tuning is certainly not natural

Beyond the Standard Model

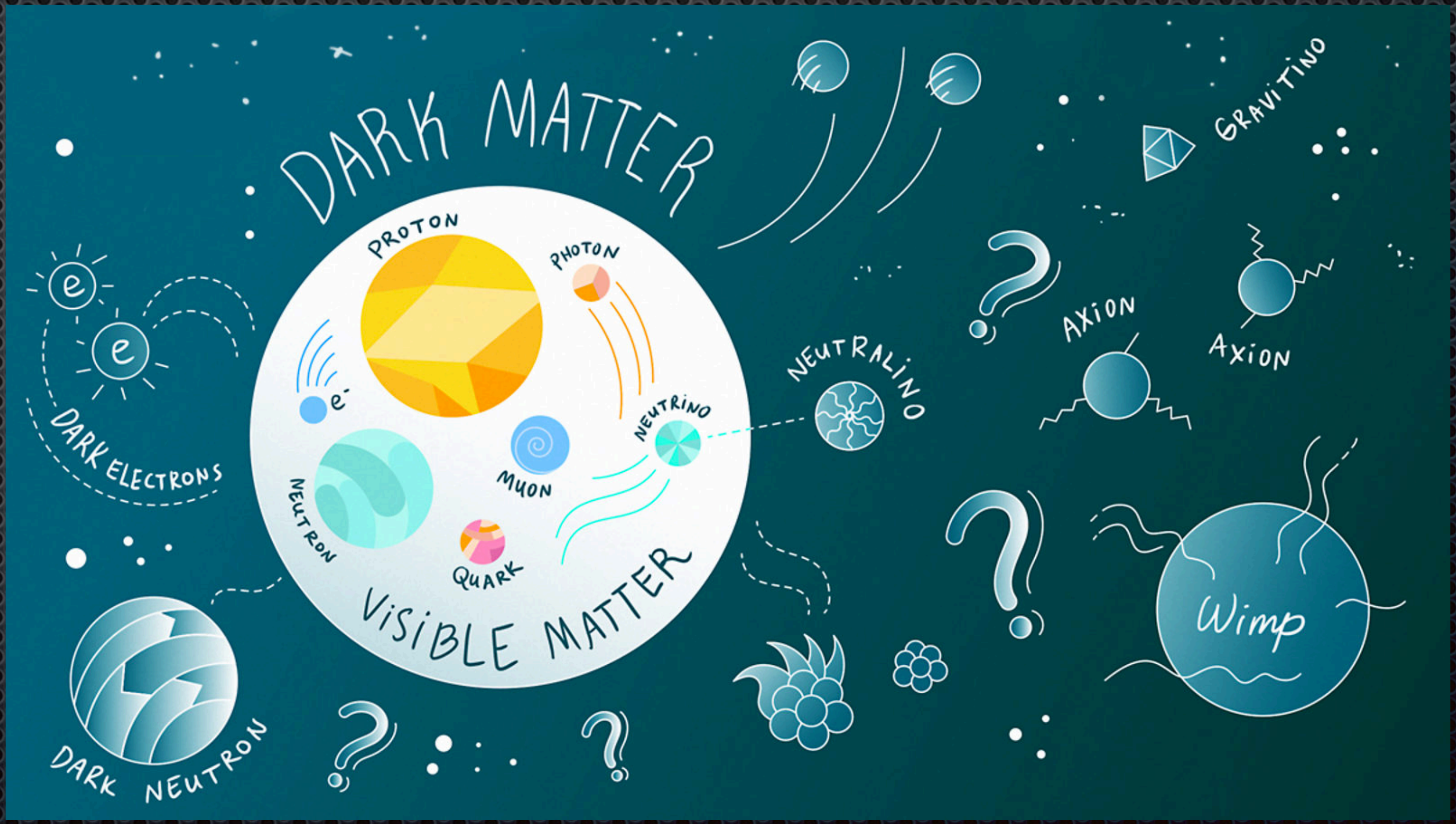
What *is* dark matter?

Where did all the antimatter go?

Why does the standard model look the way it does?

Why is the weak force so much stronger than gravity? (Hierarchy problem)

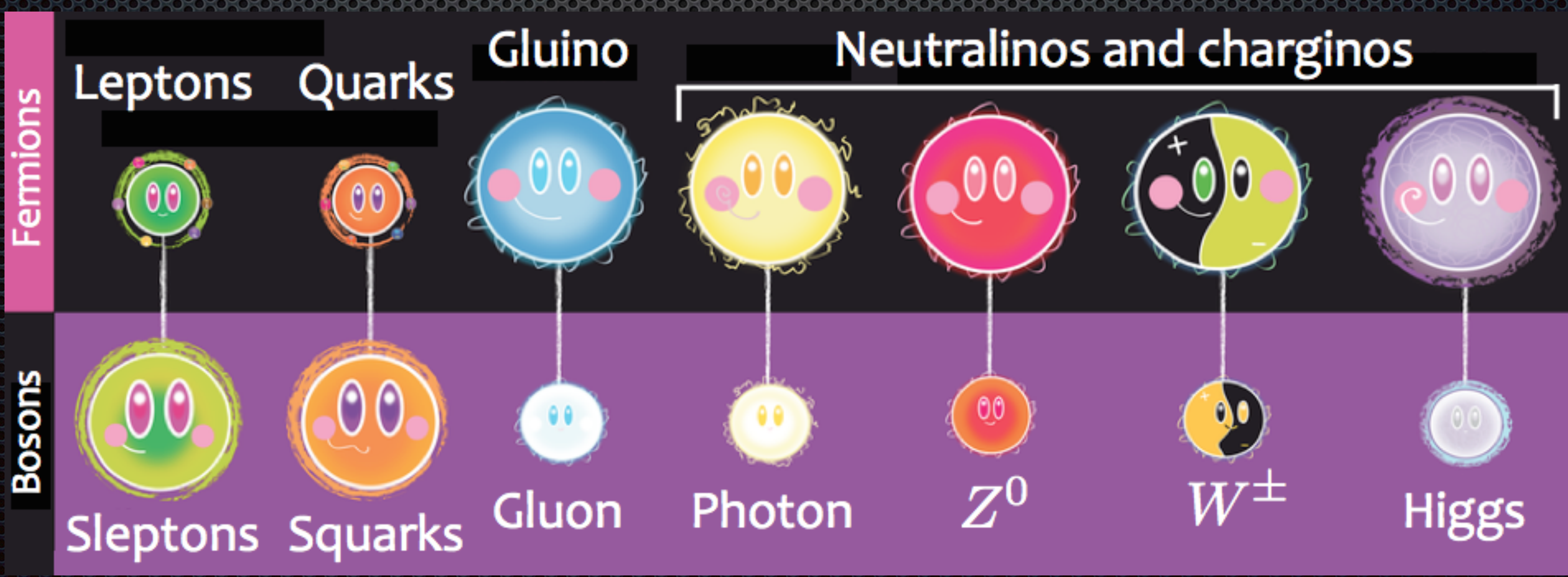
Supersymmetry (SUSY) is a framework with good theoretical motivations in which theorists can study BSM physics



Supersymmetry (SUSY) is a set of benchmark models to help experimentalists answer these questions!

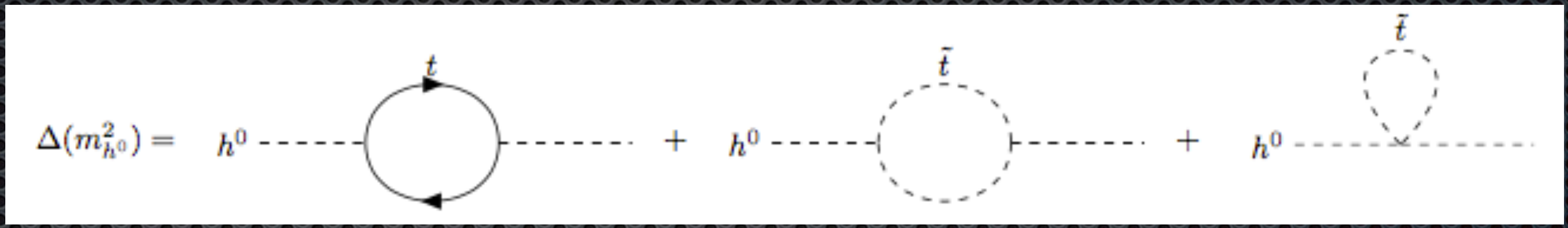
What is supersymmetry?

- **A set of theories** that predicts new boson (fermionic) partners for the fermions (bosons) of the Standard Model — each with spin differing by 1/2 unit
- When undergoing electroweak symmetry breaking, the higgsinos and electroweak gauginos mix
  - neutral higgsinos and neutral electroweak gauginos mix to form **neutralinos**
  - charged higgsinos and charged electroweak gauginos mix to form **charginos**



SUSY and naturalness

- 3rd generation fermions have large Yukawa couplings to the Higgs, treat the 1st and 2nd generation couplings as negligible in MSSM
- The stop squarks provide an equal and opposite contribution to the correction of the Higgs mass

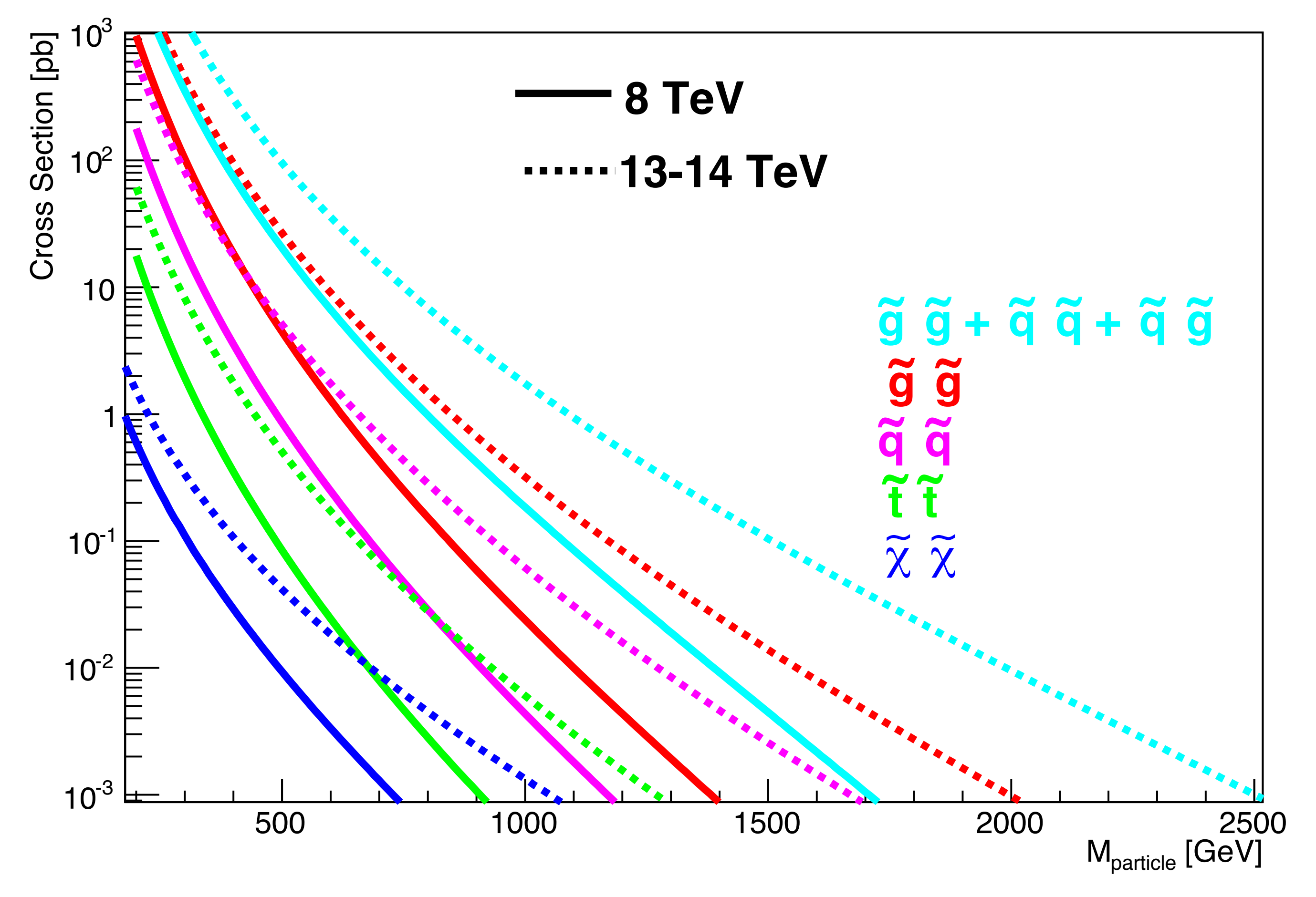


- To keep this **correction small**, a search for **light stops** is well motivated
  - Additionally, as gluinos couple to the stop squark, it pulls the mass up — a **light gluino** is well motivated

$$\Delta(m^2_{h^0}) = \frac{3}{4\pi^2}\cos^2\alpha\lambda_t^2 m_t^2\left[\ln(m_{\tilde{t}_1}m_{\tilde{t}_2}/m_t^2) + \Delta_{\text{threshold}}\right]$$

Searching for gluinos

- **Gluinos**, because of their strong color coupling, have the highest theoretical cross-section of the sparticles found at the LHC
  - The upgrade of LHC from 8 TeV to 13 TeV also provides an order of magnitude increase in the theoretical cross-section
- Theoretical cross-sections are shown for:
  - **total strong production**
  - **gluino production**
  - **total squark production**
  - **heavy squark**
  - **electroweak**



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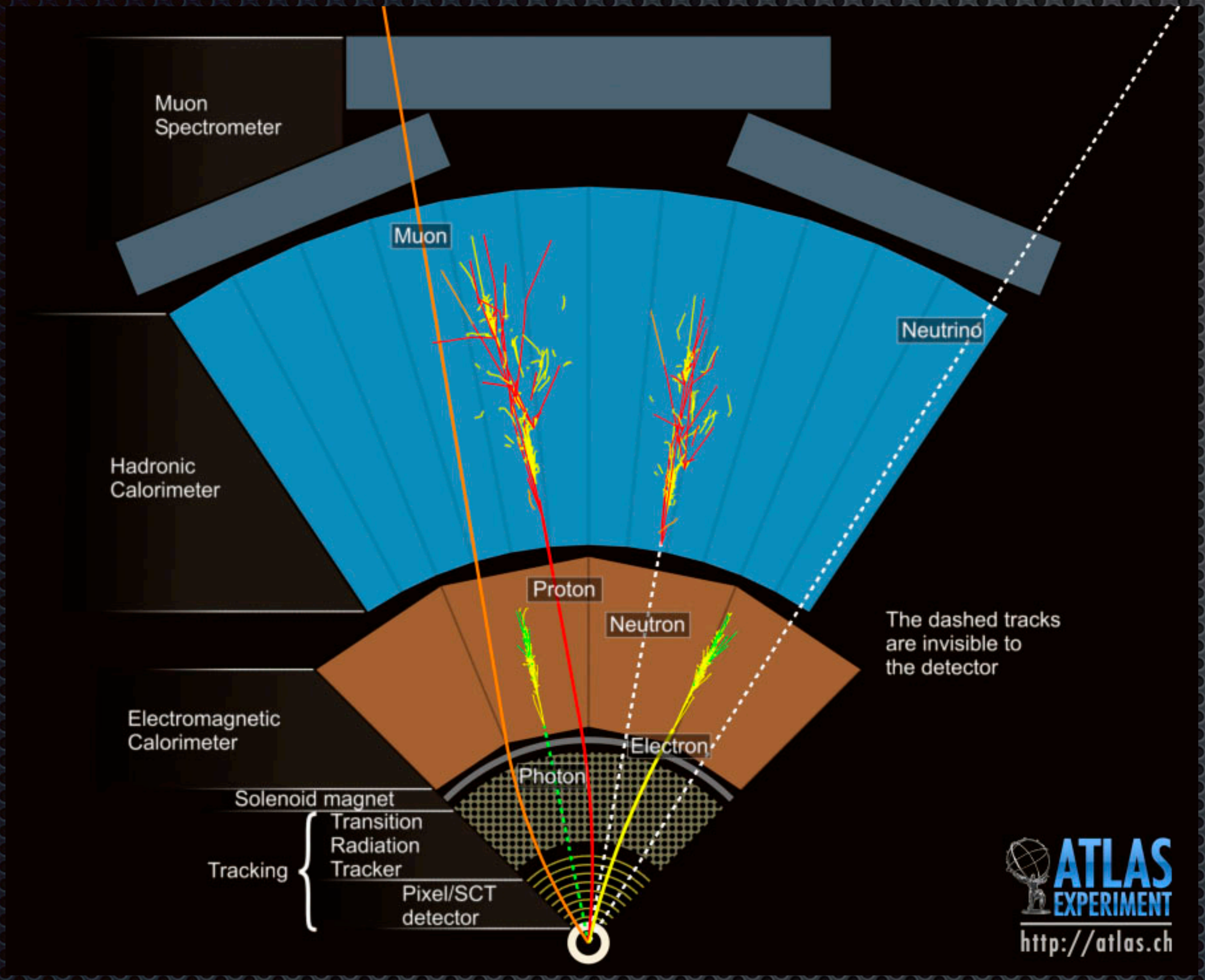
Let's search for gluinos, but how?

The ATLAS Detector

Taking pictures of proton-proton collisions

"The single most important component of a camera is the twelve inches behind it." — Ansel Adams

Detecting particles



- **Trackers**: use ionization to track charged particles
  - **Magnetic fields**: bend charged particles to measure momentum
- **Calorimeters**: use scintillation and ionization to measure particle energies

LHC *ATLAS*

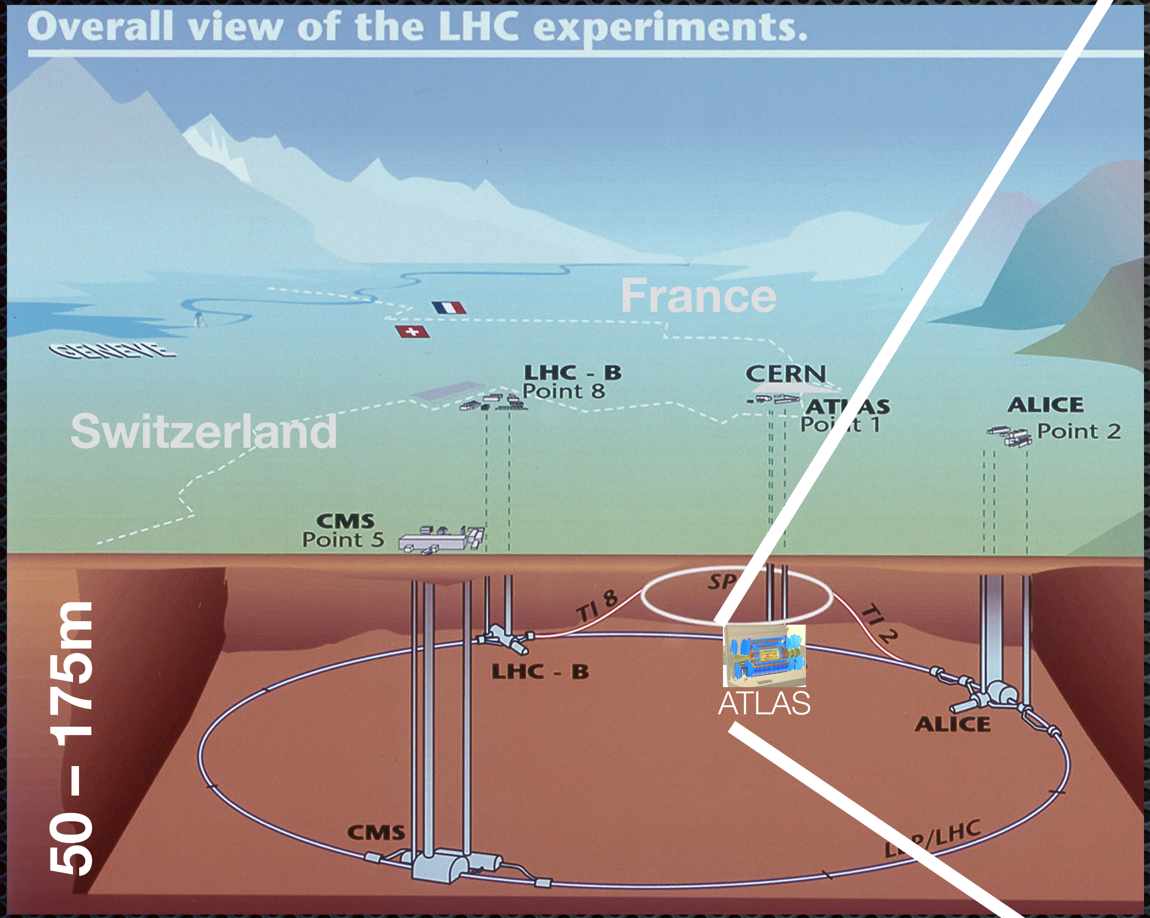
A collider and a detector

The **L**arge **H**adron **C**ollider is a massive, 27 km collider, operational since Sept. 2008

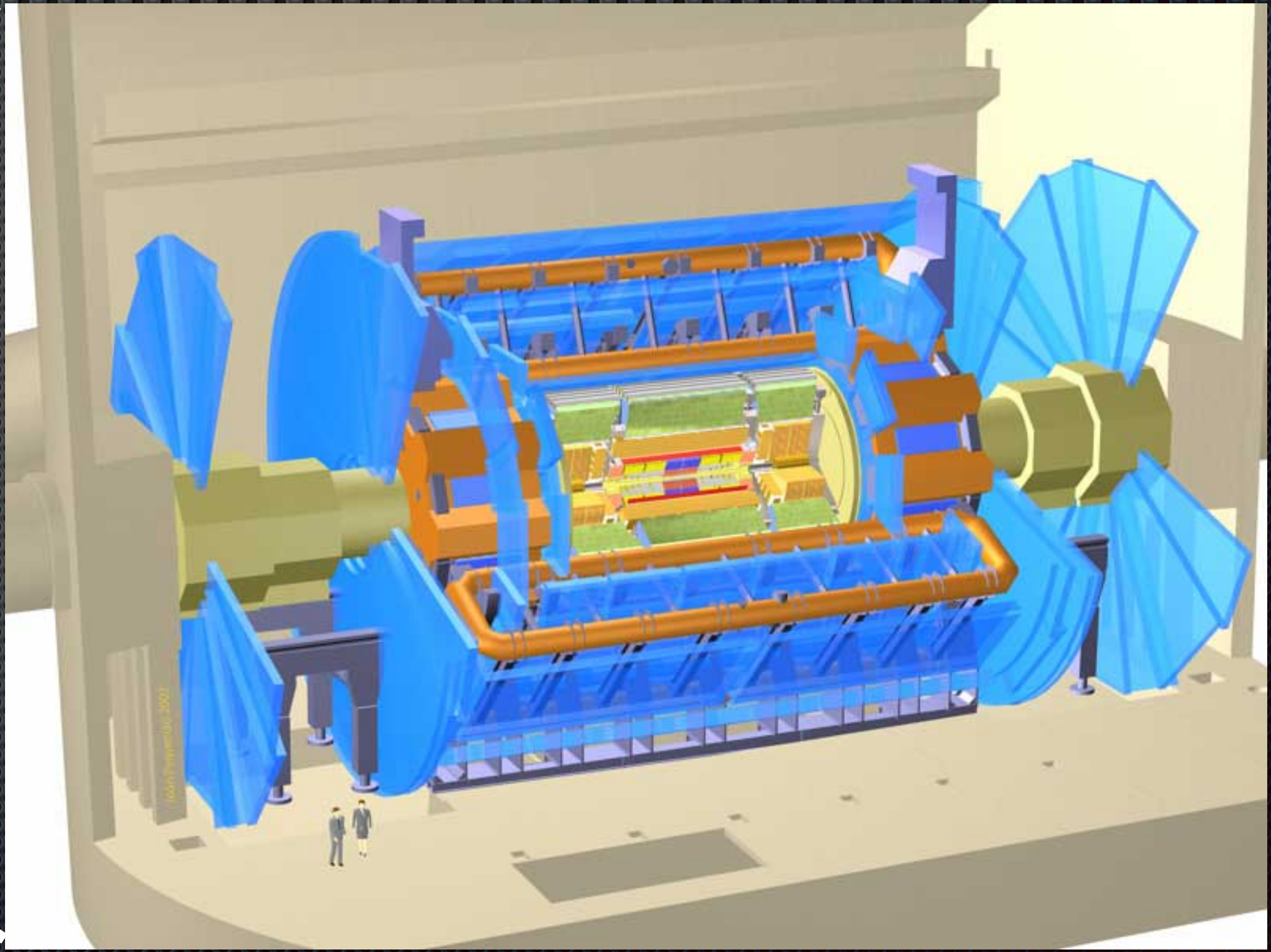
Four points along the ring at which the proton-proton beams cross

ATLAS is a large 7000 ton general purpose detector (46m x 25m)

Located at collision Point 1

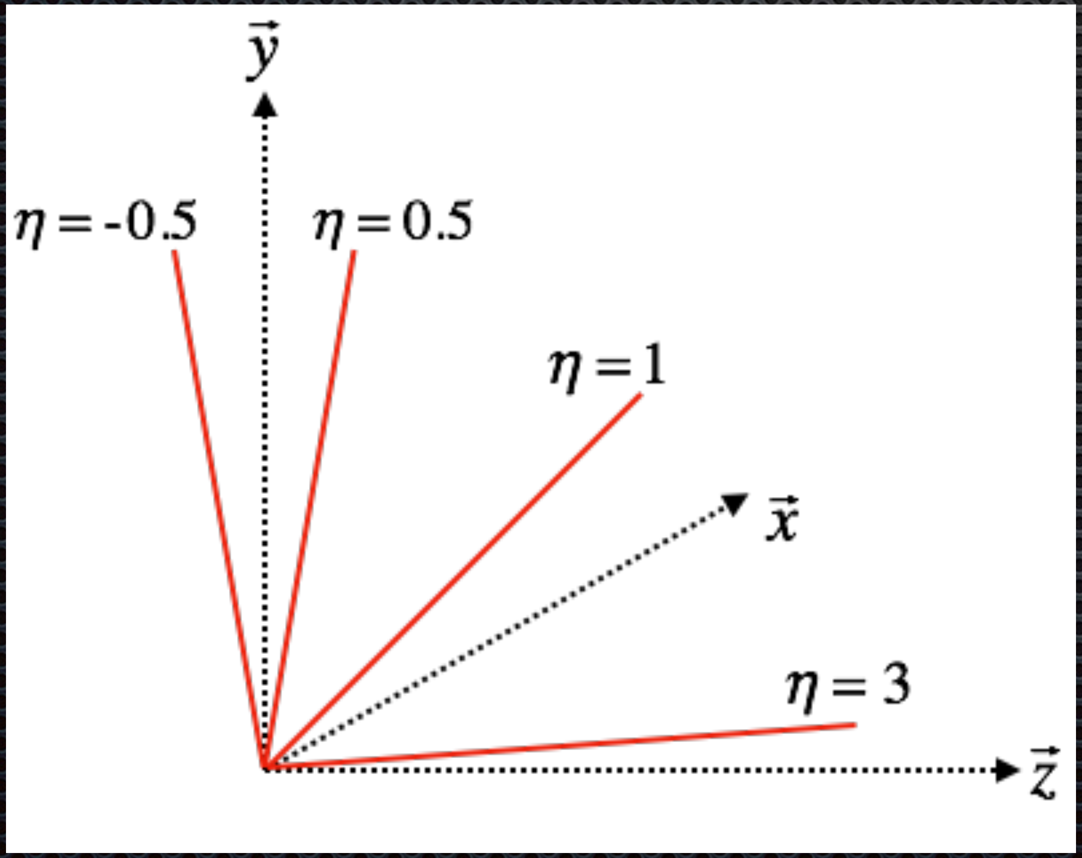


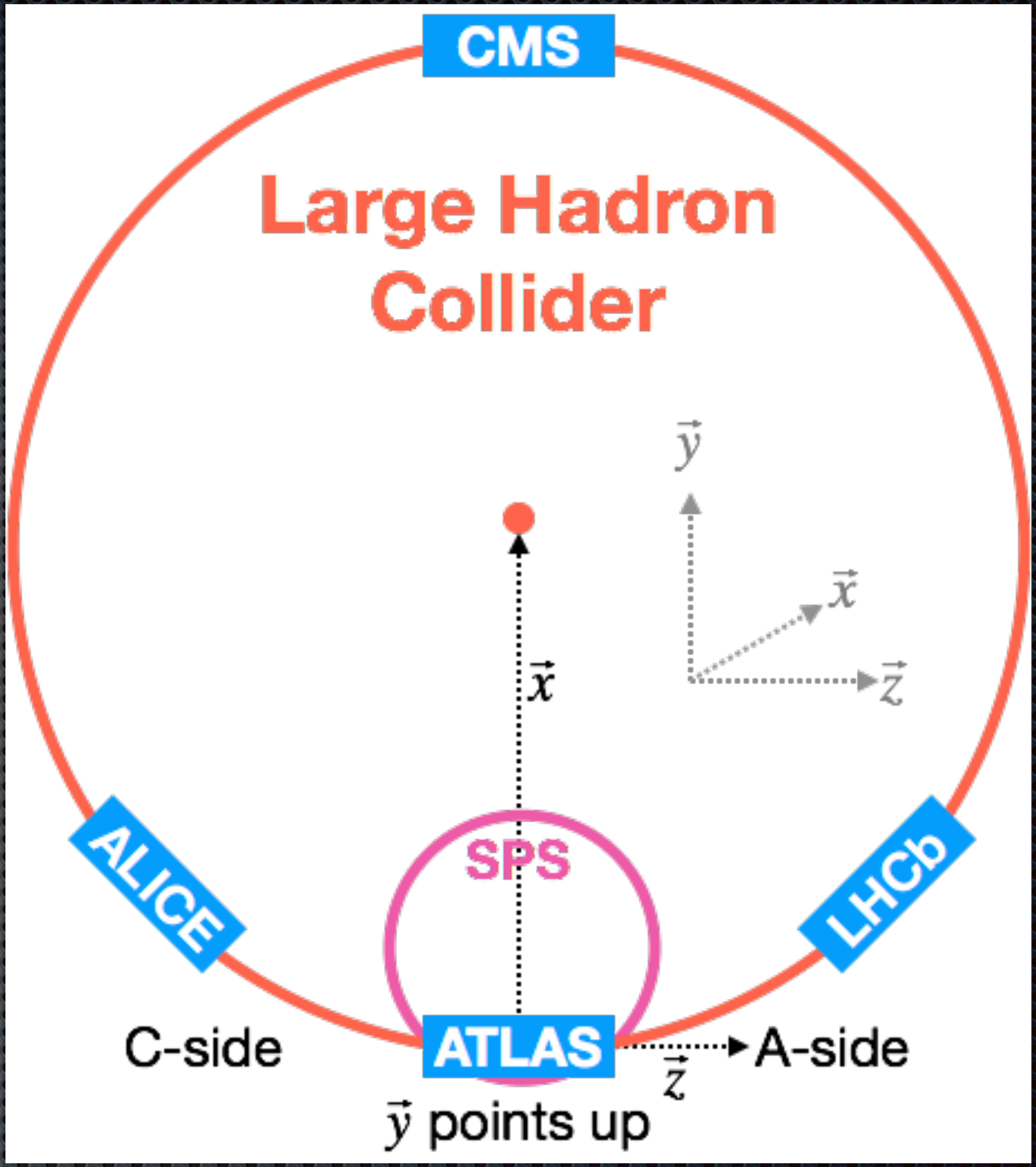
Stable rock at that depth



Geometry

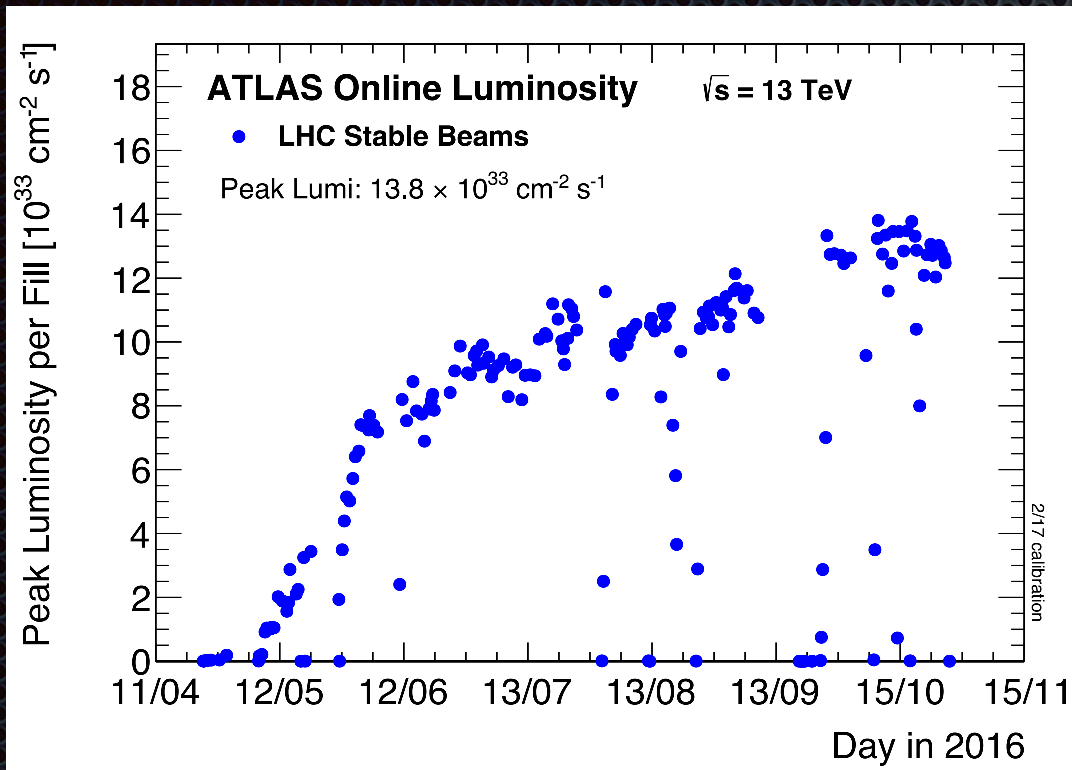
- A top-down cartoon of the LHC and the four experiments
  - **ATLAS** (Point 1)
  - **ALICE** (Point 2)
  - **CMS** (Point 5)
  - **LHCb** (Point 8)

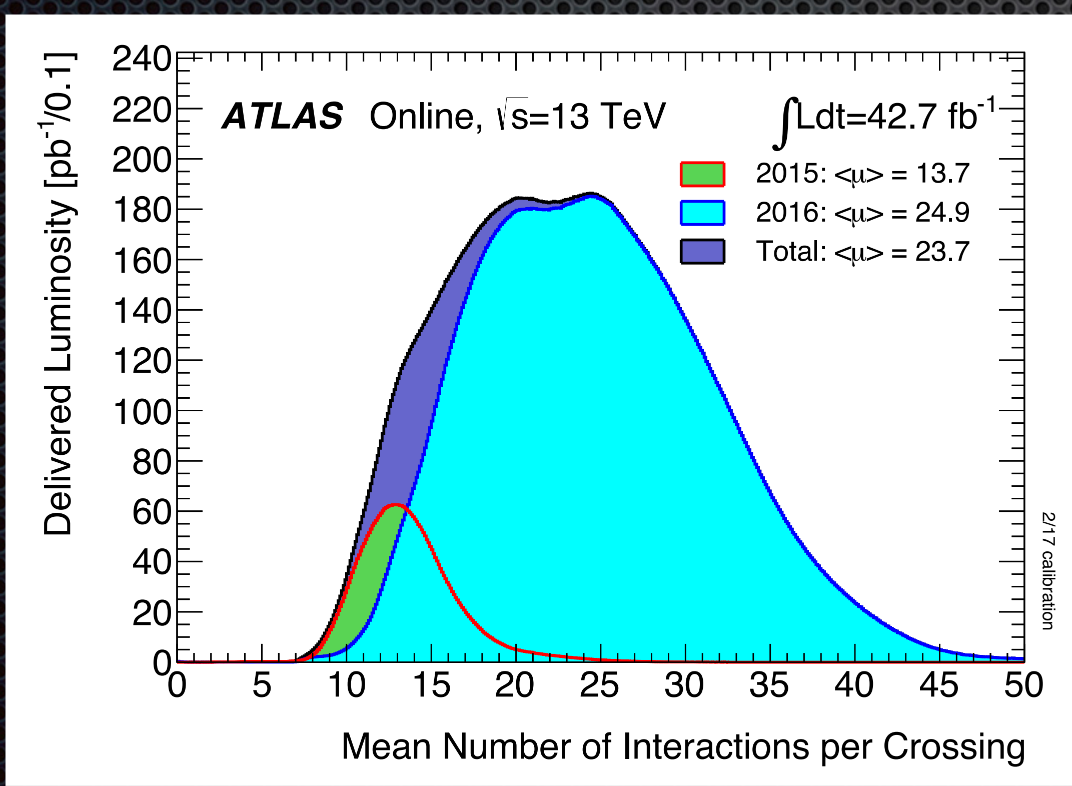




- ATLAS uses pseudorapidity (η) to describe the position of objects it measures inside the detector
- Often refer to energy in MeV or GeV (Giga/Mega — electronVolt)

The Large Hadron Collider





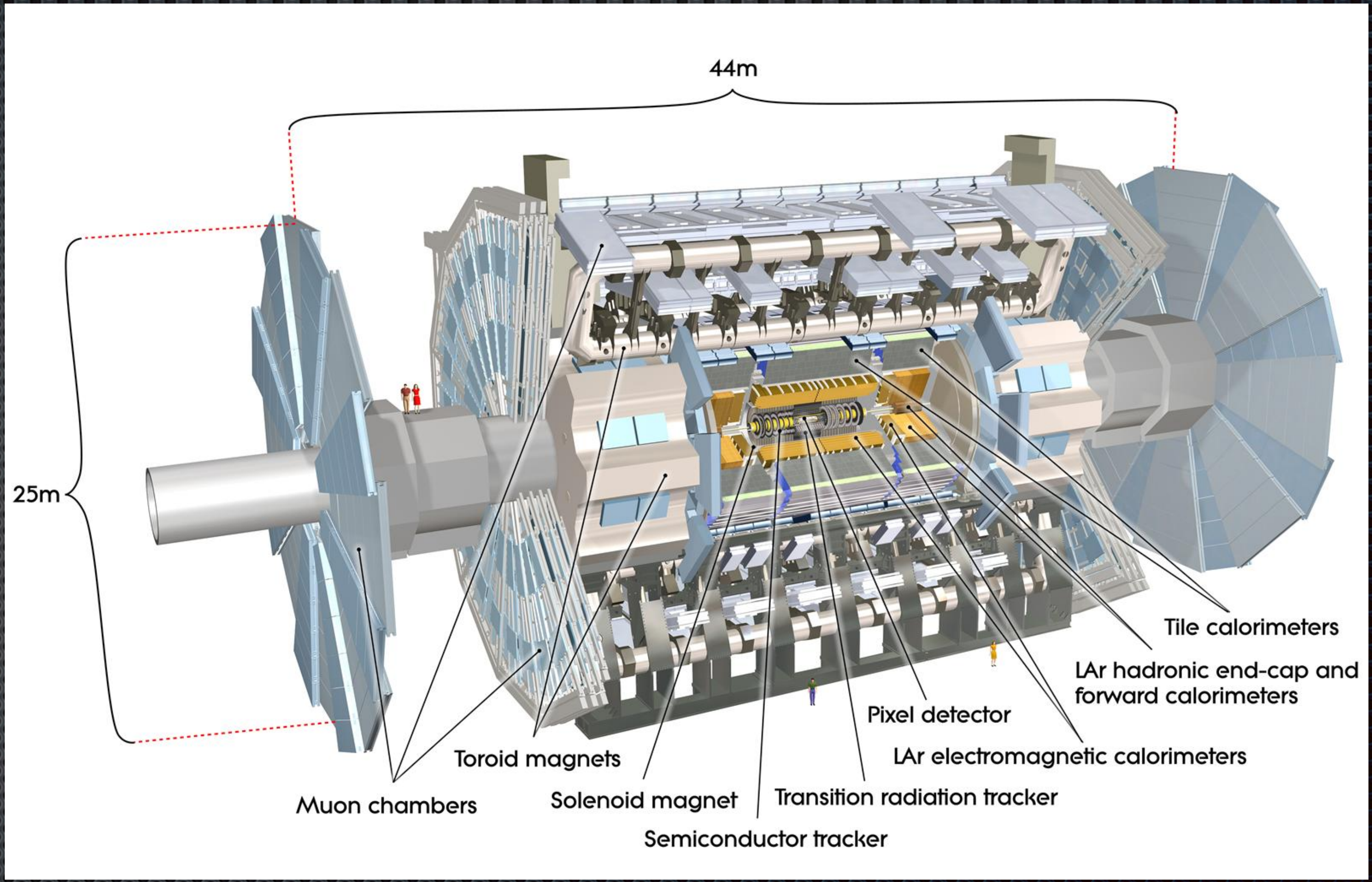
A proton-proton collider at 13 TeV center-of-mass energy

- For 2015-2016 operation:
  - Operating peak luminosity: 13.8 x 10^{33} cm^{-2} s^{-1}
  - Proton bunch spacing: **25 ns** — 40 million crossings per second
  - 2808 bunches colliding in ATLAS
  - **36.1 ifb of data delivered**
  - Up to 50 collisions per bunch crossing **(pileup!)** — billions of collisions per second!

The ATLAS Detector

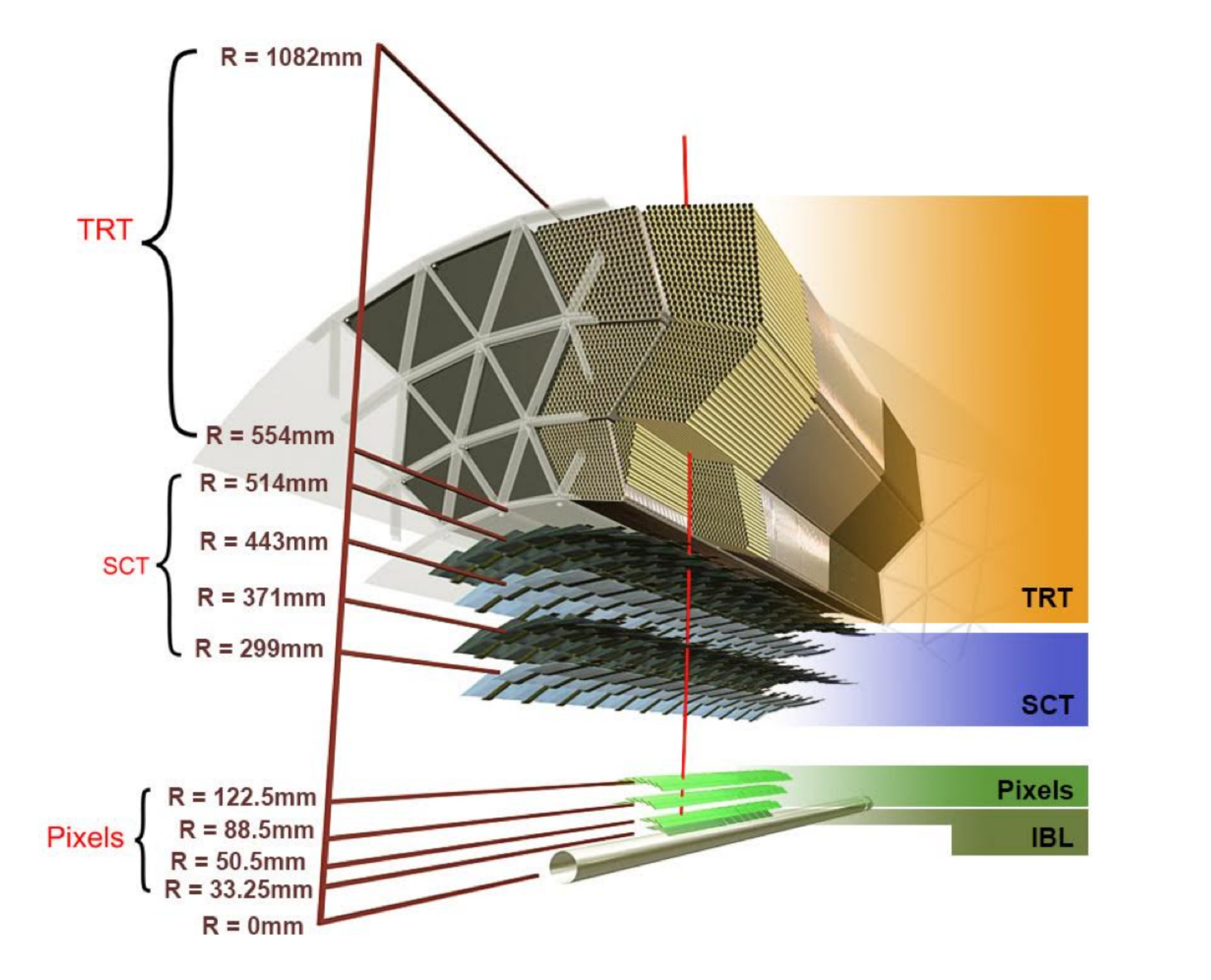
Four major subsystems

- Inner Detector
- Muon Spectrometer
- Calorimeters
- Trigger



A single complex detector compromised of many subsystems that total: 100 million electronic channels and 3000km of cables

Tracking — Inner Detector

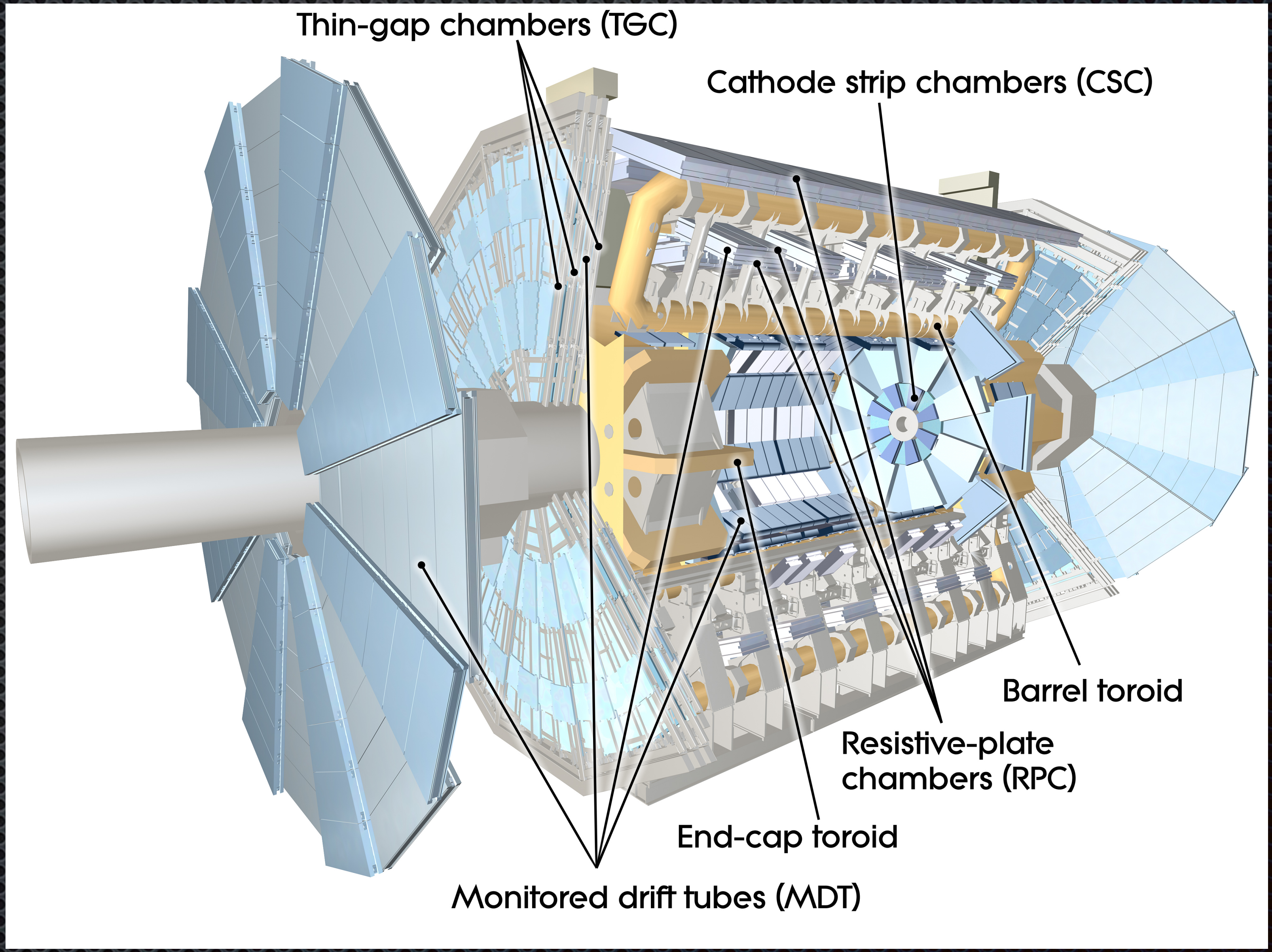


- Contained within a 2T solenoid magnet
- Four subsystems:
  - Insertable B-layer
  - Pixel Detector
  - Semiconductor Tracker
  - Transition Radiation Tracker
- Identifies charged particle tracks
- Reconstructs primary and secondary vertices

Coverage for $|\eta| < 2.5$

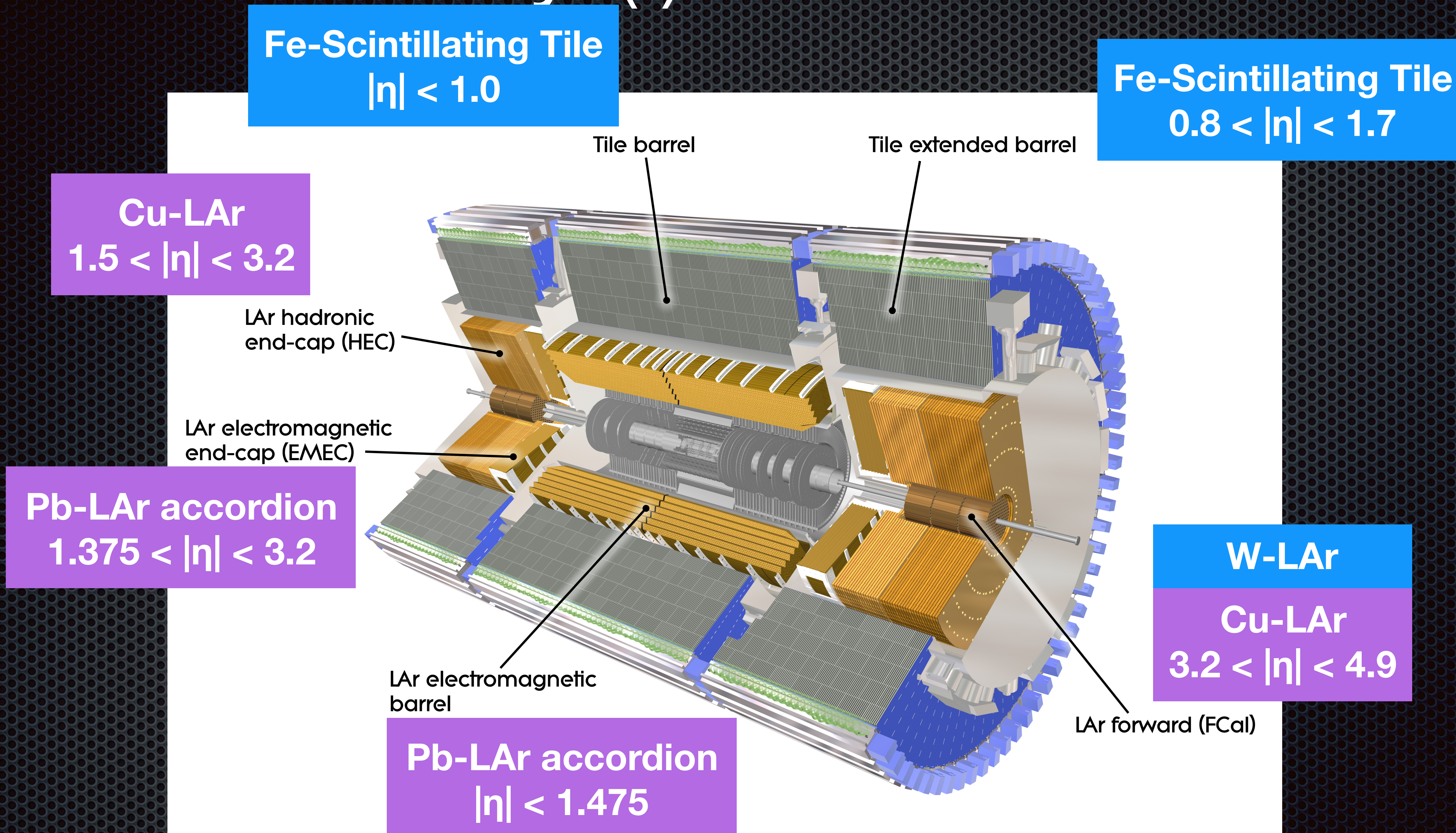
Tracking — Muon Spectrometer

- Uses large, superconducting 4T toroid magnets
- Four subsystems:
  - Monitored Drift Tubes
  - Cathode Strip Chambers
  - Resistive Plate Chambers
  - Thin-Gap Chambers
- Precision measurements of muons



Coverage for $|\eta| < 2.7$

Calorimetry (I)



- **hadronic** and **electromagnetic** sampling calorimeters
- Alternating layers of **dense “absorber” material** (Lead, Copper, Tungsten, Steel) to reduce particle energy and **“active” material** (Liquid-Argon, Plastic Scintillator) to provide detectable signal

Calorimetry (II)

- Approximately 180,000 read-out channels over the hadronic and electromagnetic sampling calorimeters
  - These are sent to the Level-1 Calorimeter Trigger system
- Full $|\eta| < 4.9$ coverage of the ATLAS detector with excellent energy resolution

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.4\%$$

constant

geometry, impact point

stochastic

calorimeter response

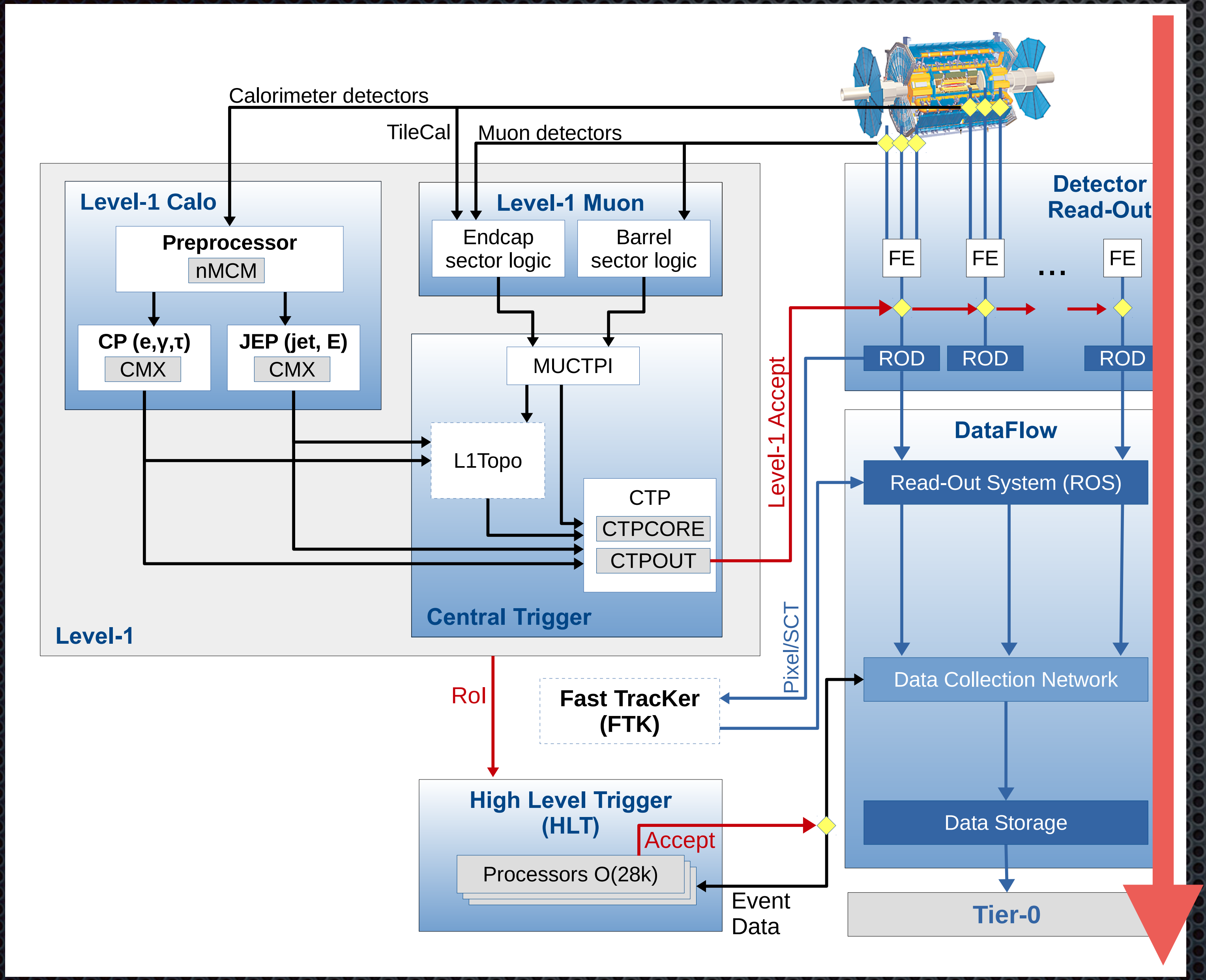
noise

electronic, readout

Will discuss planned upgrades later in this talk

Calorimetry and Trigger

Largely "junk" events **40MHz**



Largely "interesting" events **1kHz**

- The trigger system uses data from the calorimeters
- Bunches of protons collide every 25 ns (**40 MHz** rate)
  - Need to reduce this rate to **~1 kHz** for writing to disk
- **Goal**: retain efficiency of processes sought for in ATLAS
  - Need a lot of smart rejection
  - Need it fast and performant
  - Keep rates under control

Boosted object reconstruction

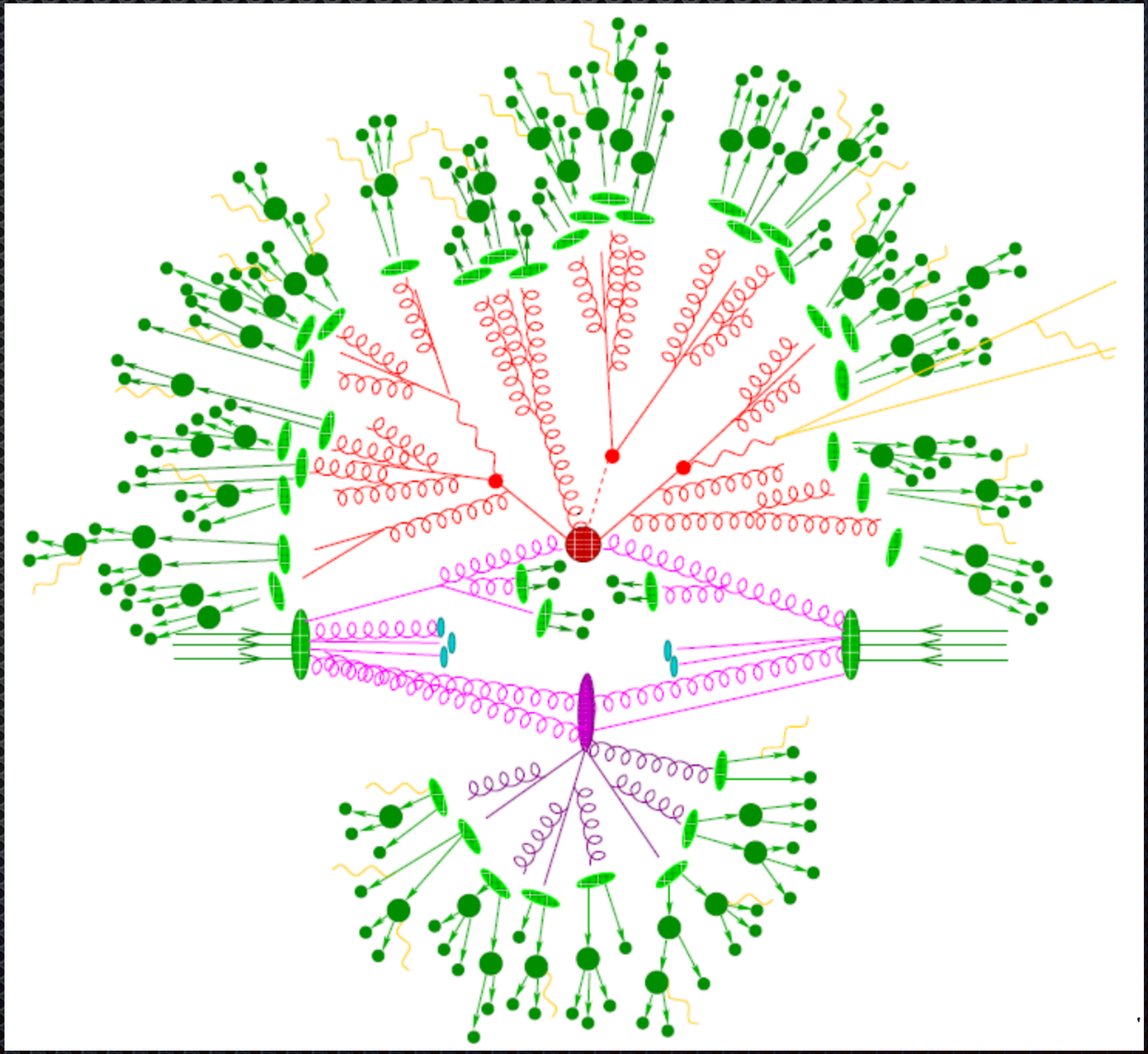
New techniques and understanding jet substructure

BOOST2017

An event in ATLAS

Marek Schönherr (YETI 2009)

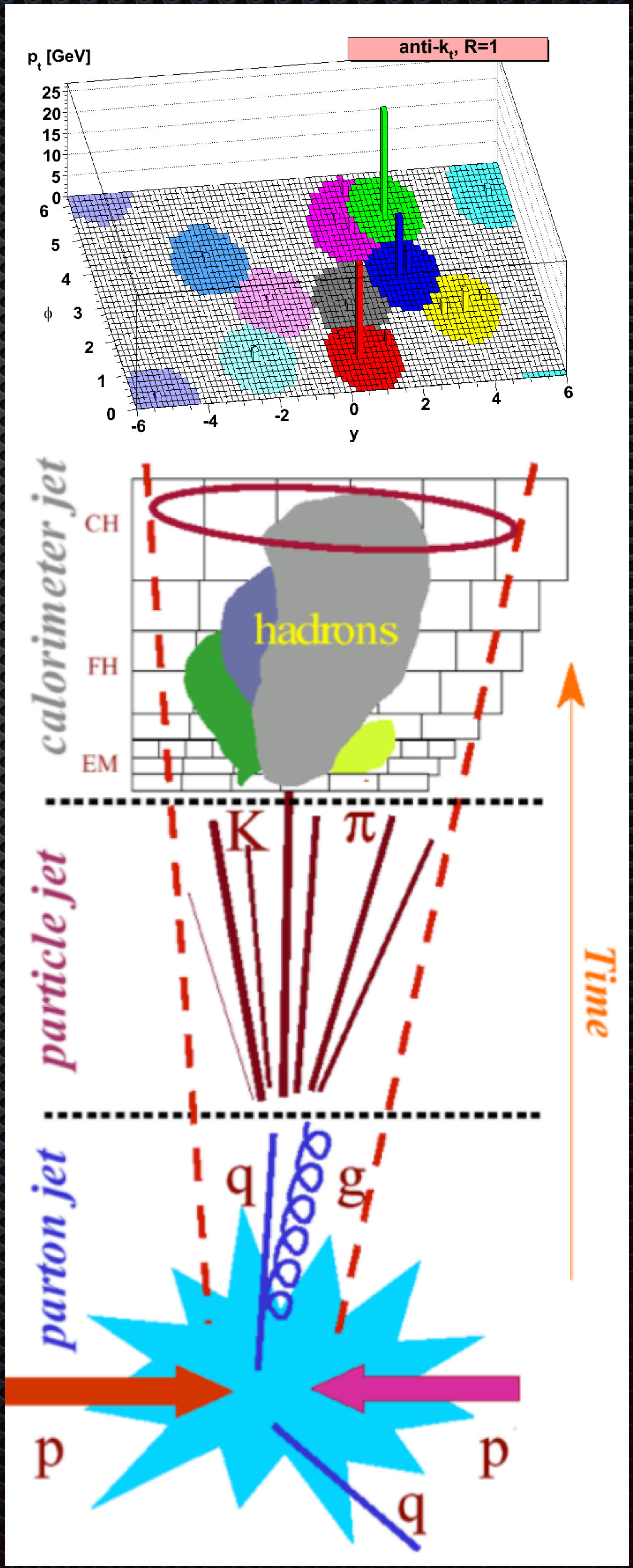
- Two protons enter, radiating gluons which form two groups of interactions described by QCD
  - **Hard Collision**: highest energy collision
  - **Secondary hard-scattering event**
  - **Parton Showers**: partons that radiate gluons that radiate quark pairs
  - **Hadronization (parton-to-hadron transition)**: at a low enough energy, color confinement takes over to form colorless hadrons
  - **Hadron decays**



How do we reconstruct the event?

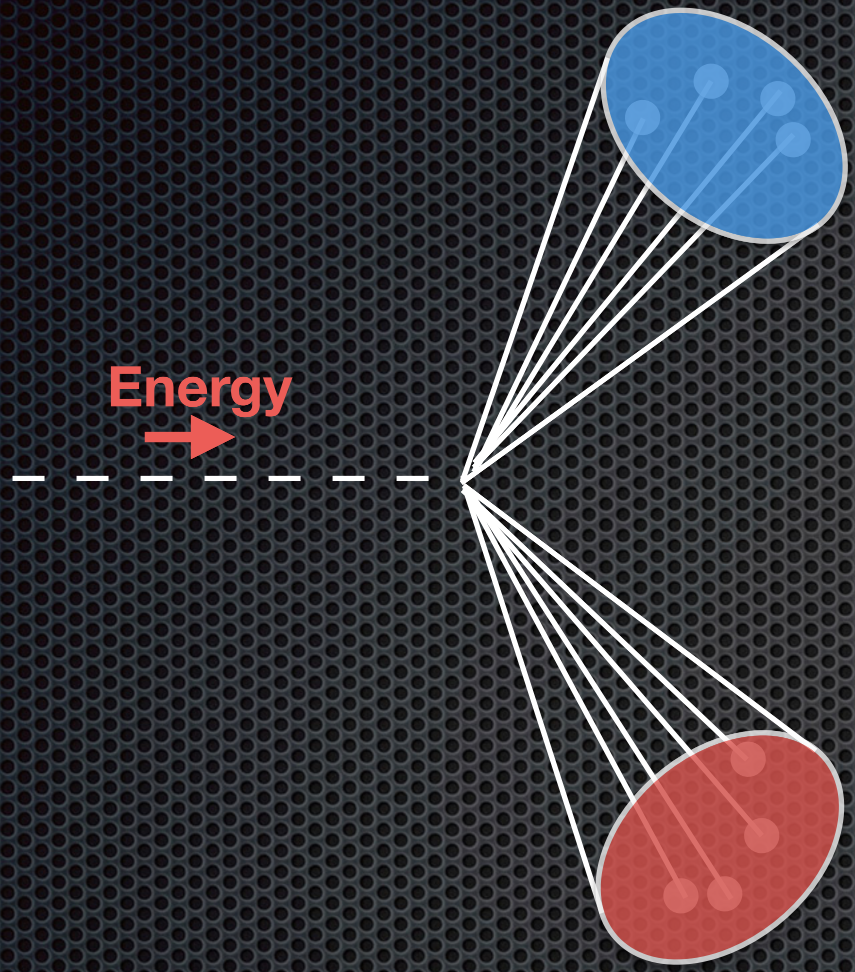
What's a jet?

- Proton-proton collision produces a **shower** of quarks and gluons which **hadronizes** due to confinement
- These hadrons deposit energy in calorimeters
  - Clusters of energy deposits form predictable patterns — underlying physics of the showering
  - Energy lost due to a variety of factors and needs to be compensated for (dead material, punch-through, out-of-cone, etc…)
- Jets are what we call the outputs of **clustering algorithms**
  - specify iterative procedures for which energy deposit to include in the jet or not



David Miller (2011)

What’s a boosted jet?



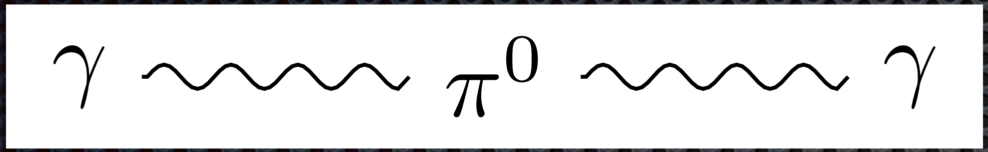
Particle decay at low Lorentz boost

Particle decay at high Lorentz boost

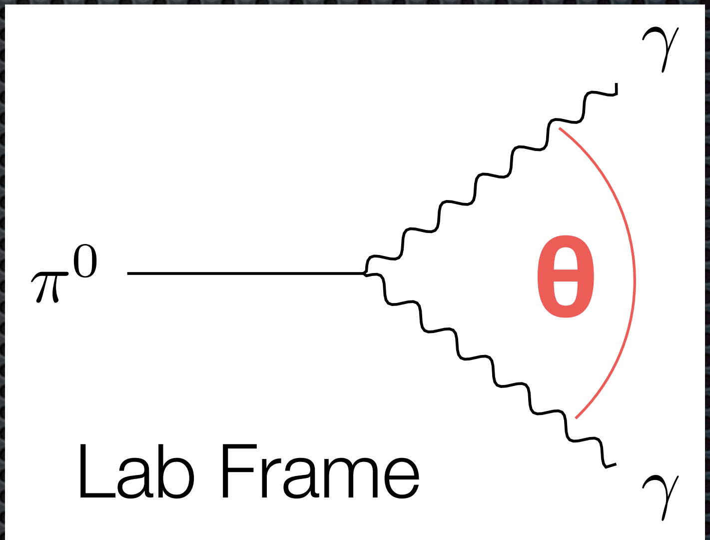
More (accidental) substructure!

How big is a boosted jet? (I)

Lorentz-boost



Rest Frame



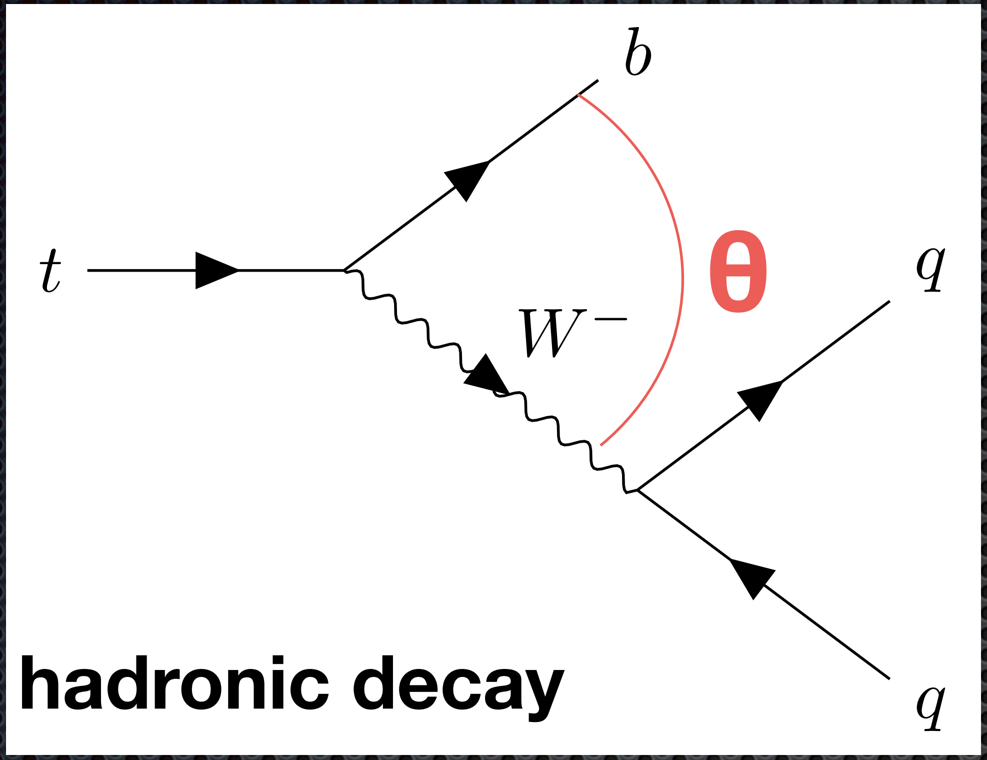
What is the angular separation between the decay products?

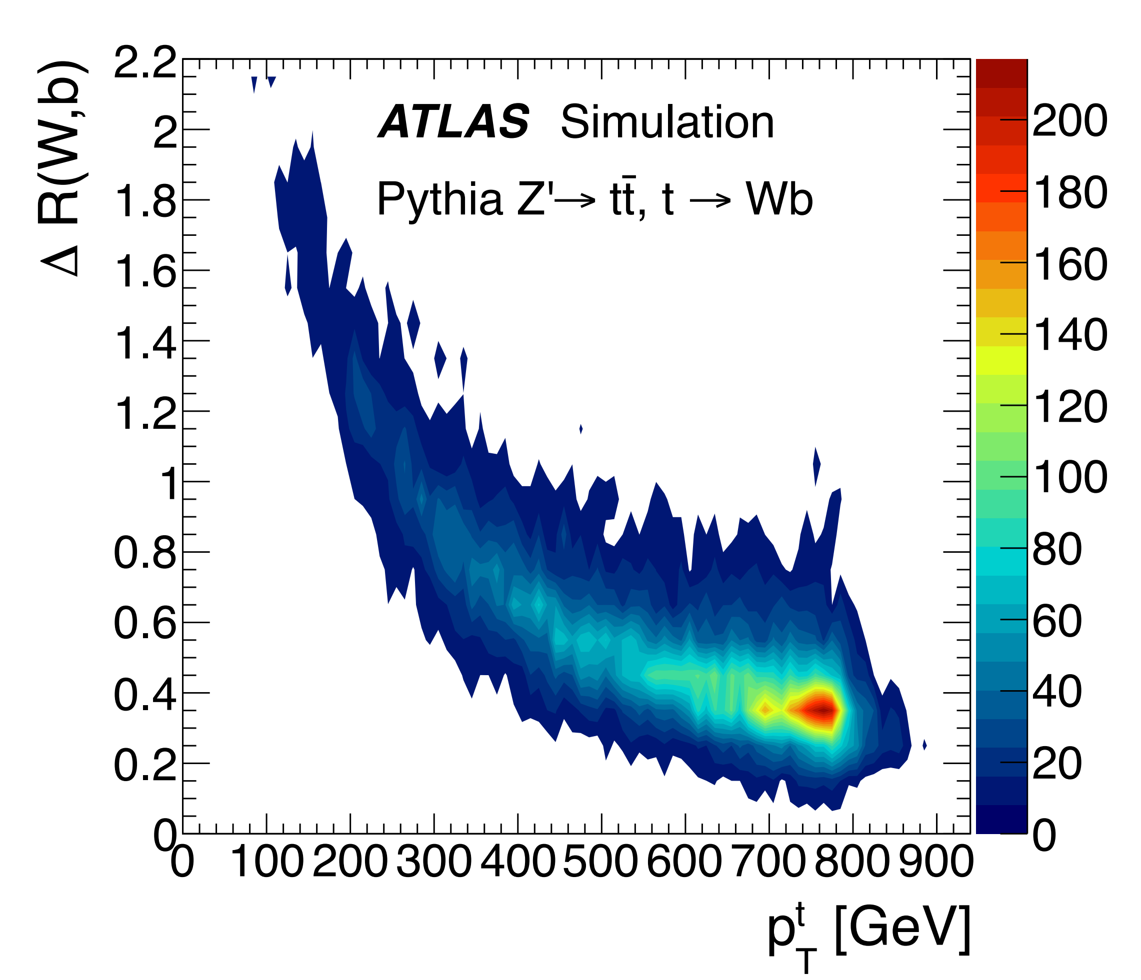
$$\cos\theta \approx 1 - \frac{1}{2}\theta^2 = 1 - \frac{2}{\gamma^2} \longrightarrow \Delta R \sim \frac{2m}{p_{\mathrm{T}}}$$

- The more massive the parent particle, the larger an area it decays over.
- The more boost the parent particle has, the smaller an area it decays over.

If the boost is large enough, can a large jet capture the entire decay?

How big is a boosted jet? (II)





1306.4945

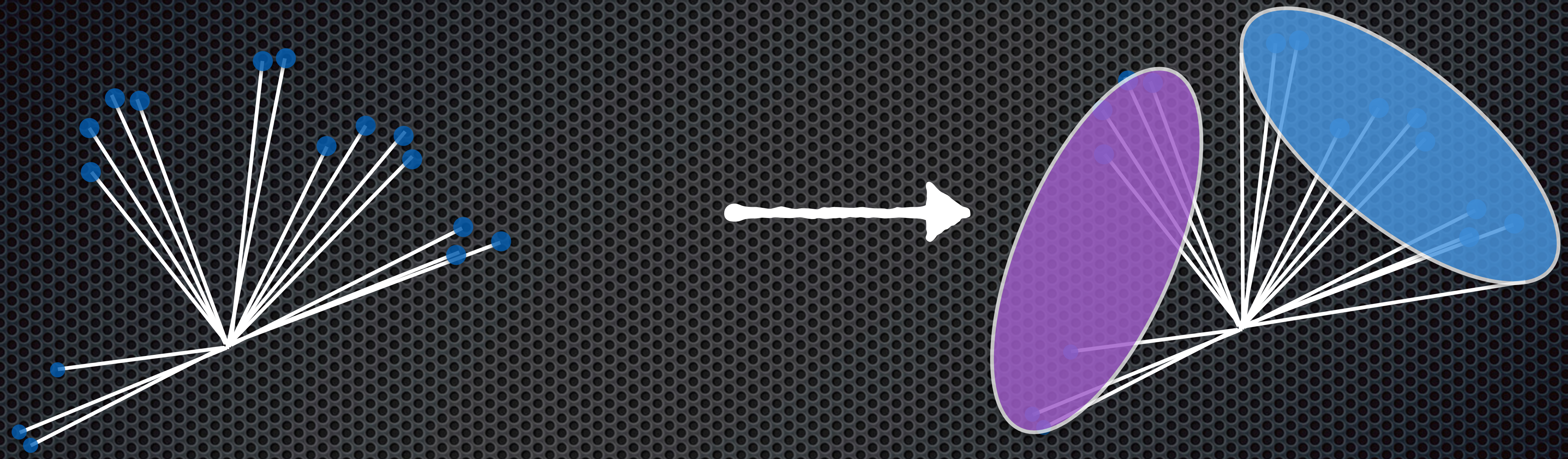
- The estimation of a jet size is modeled nicely in monte-carlo simulations of non-perturbative QCD for Z' to top-antitop

If the boost is large enough, can a large jet capture the entire decay?

YES!

Forming Large Jets (I)

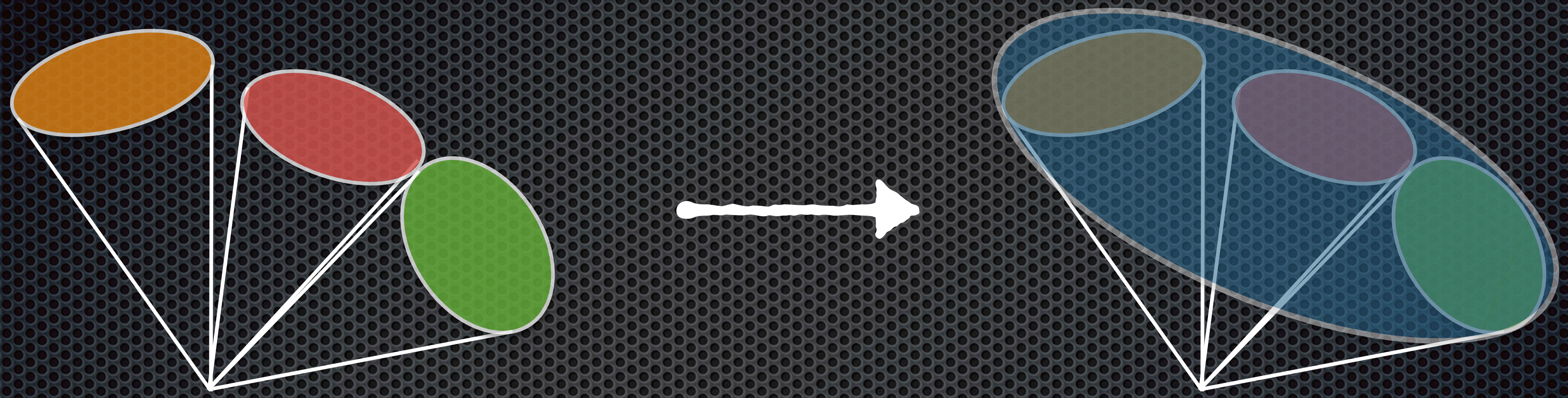
Larger jets can be formed from calorimeter clusters



- Apply same principles for reconstruction of smaller jets, to form large radius jets, (R=0.8, 1.0, 1.2, …)
- Formed from topoclusters and often **need grooming / pileup mitigation techniques, and large-R JES/JER calibrations**

Forming Large Jets (II)

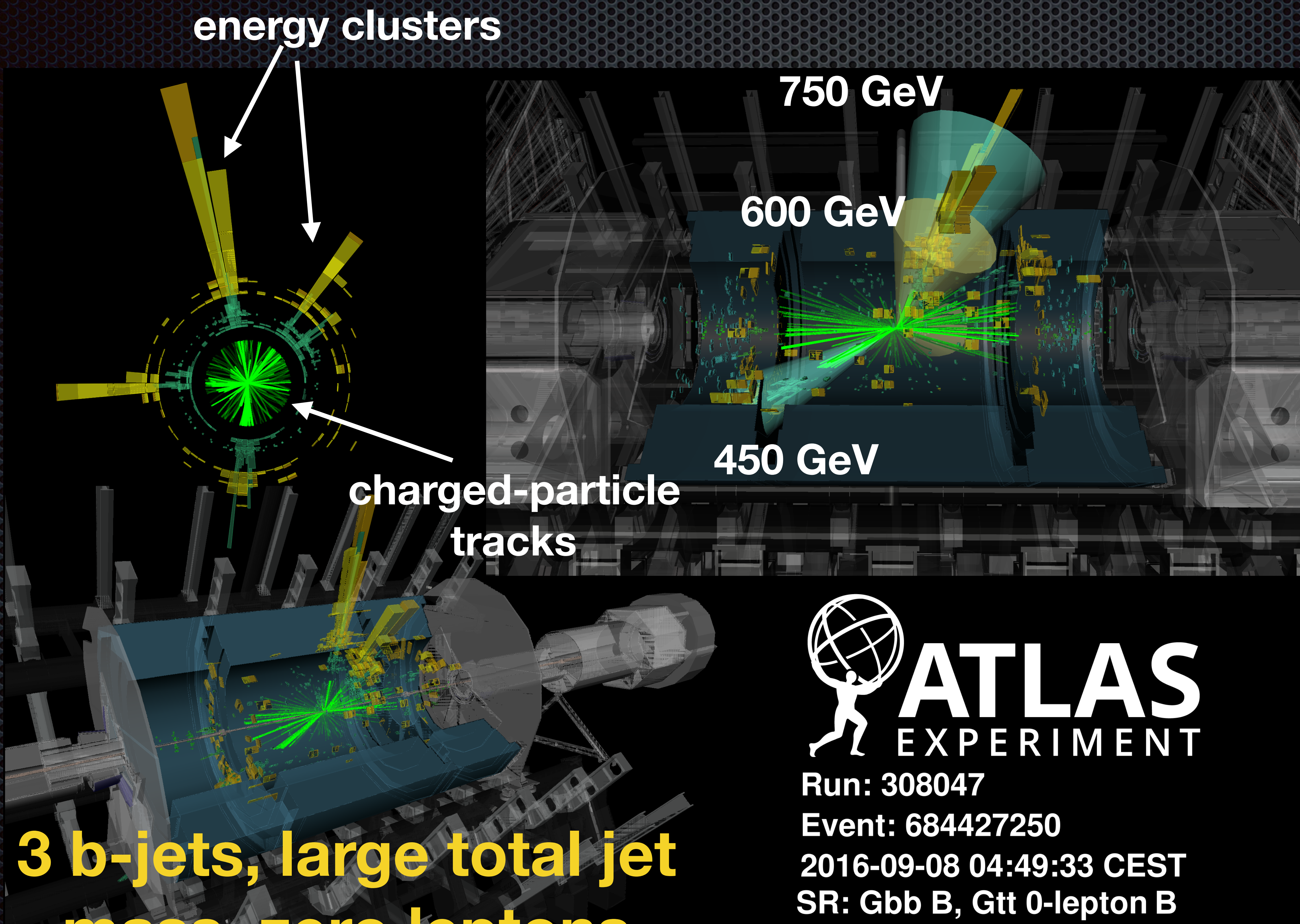
Larger jets can also be formed from smaller jets



This is known as **jet reclustering**

- Smaller jets are well-studied and better understood, reclustering from them takes advantage of this knowledge
- Large, reclustered jets can be used to calculate global quantities like a total jet mass, or the number of top quarks in an event

A fully reconstructed event



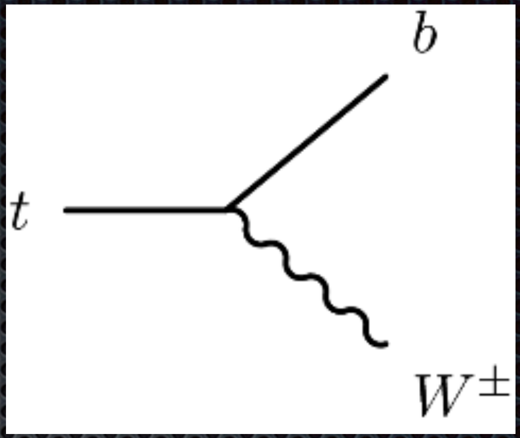
3 b-jets, large total jet mass, zero leptons

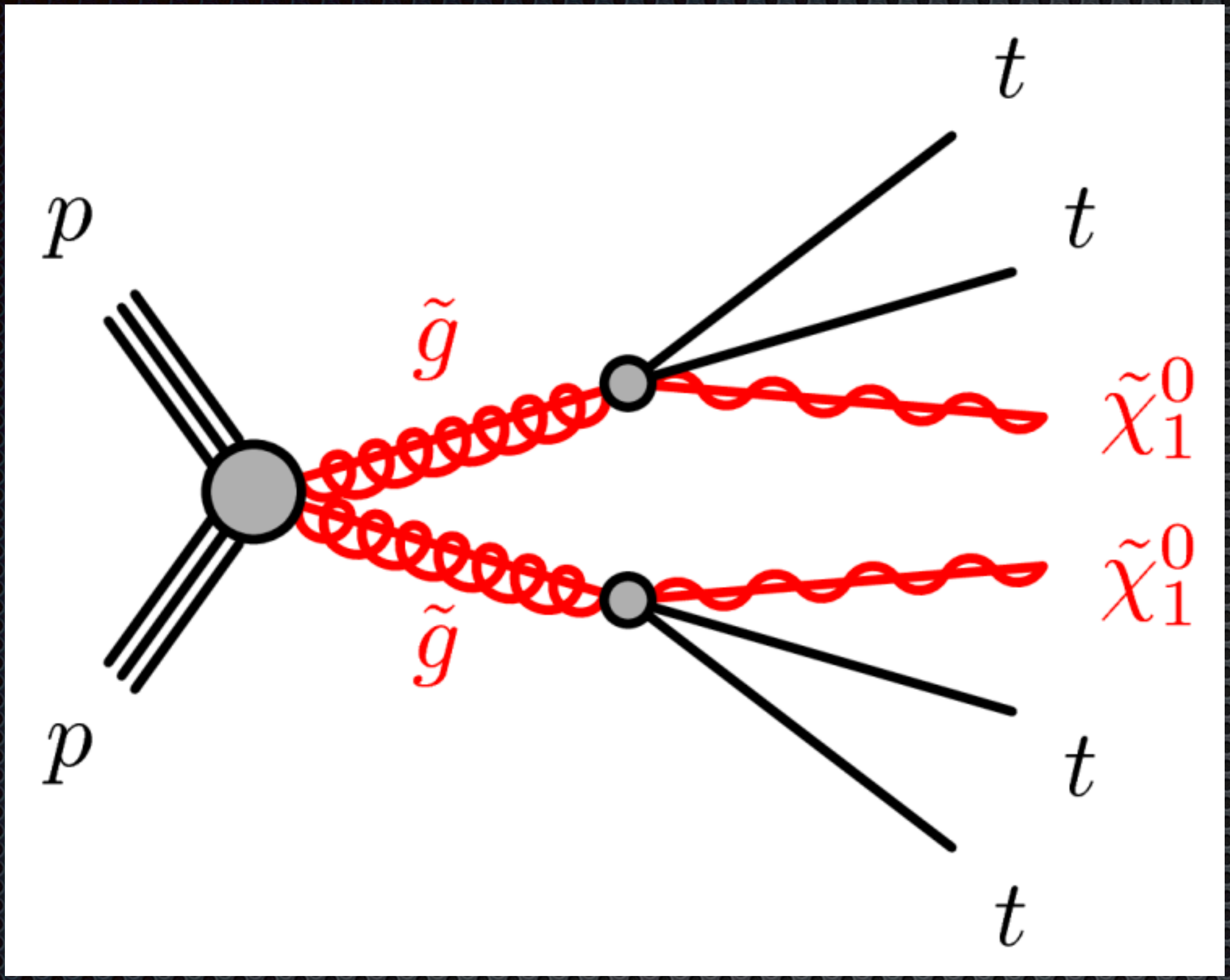
Searching for new physics

Pair production of gluinos decaying via stops

"SUSY is just around the corner." — Carlos Wagner

A simplified model





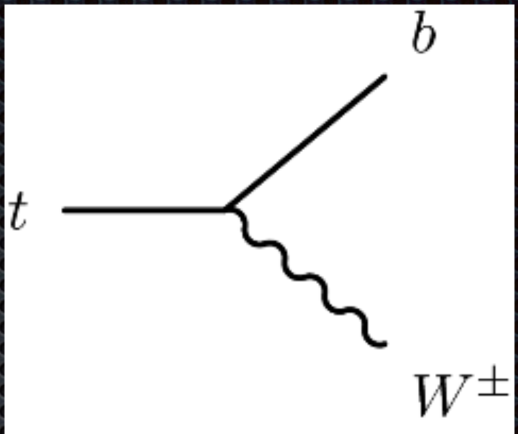
gluino-mediated stop pair production

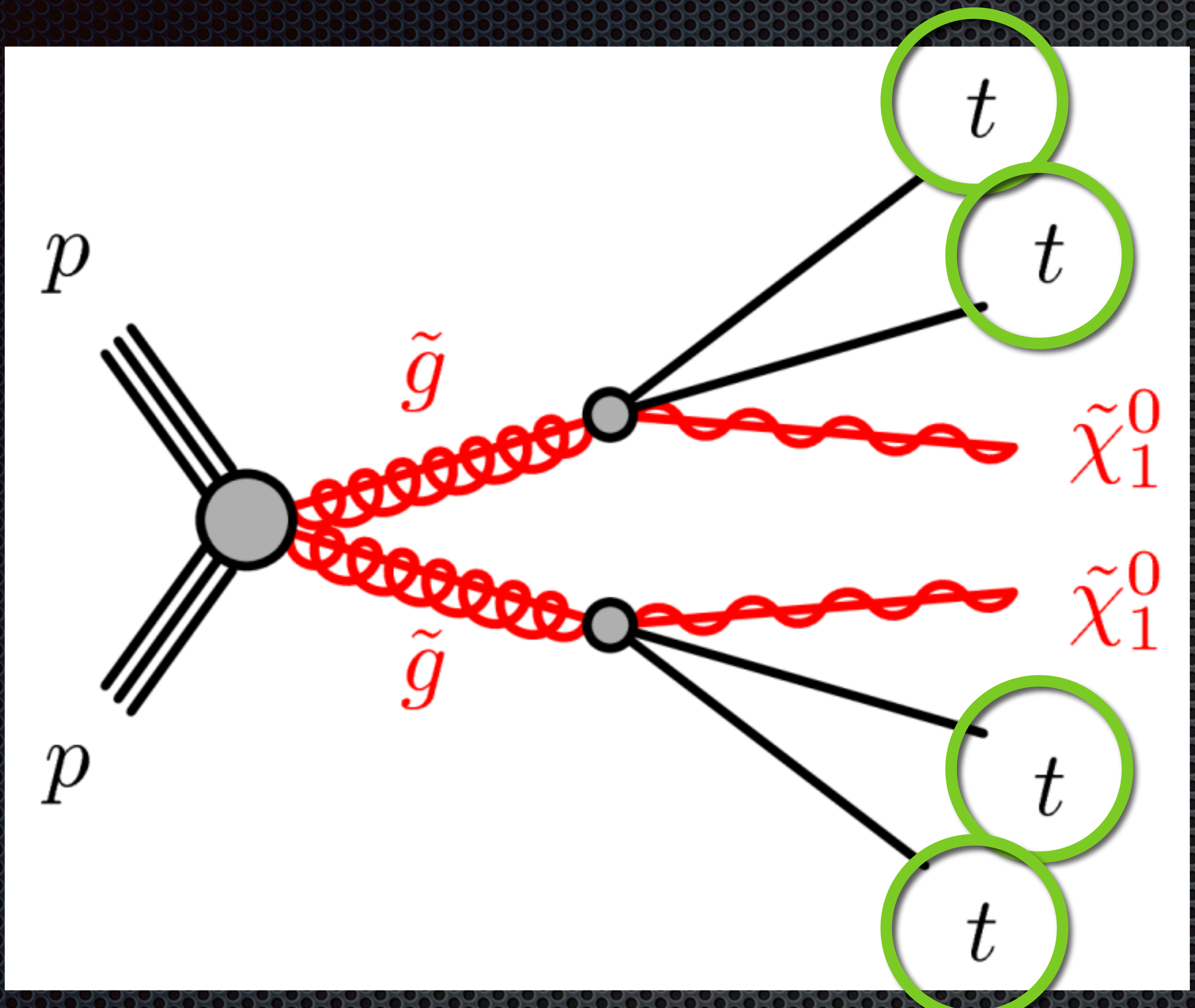
[2015 paper [1605.09318]]

- Gluinos, stops, and neutralinos motivated to be light by naturalness
- Branching ratios at each step are assumed to be 100% (**not realistic!**)
- Reinterpret the results of a search for this topology into different signal topologies
  - Help understand detector-based limits
  - Cover gaps in exploring the phase-space of new physics

[2016 paper [1711.01901]]

What do we look for?





gluino-mediated stop pair production

- Like many typical SUSY searches in ATLAS, a typical signature includes
  - large number of *b*-jets
  - high missing transverse energy (MET)
  - Lorentz-boosted W bosons and top quarks in certain regions of parameter space

4 top quarks in the final state!

[2015 paper [1605.09318]](#)

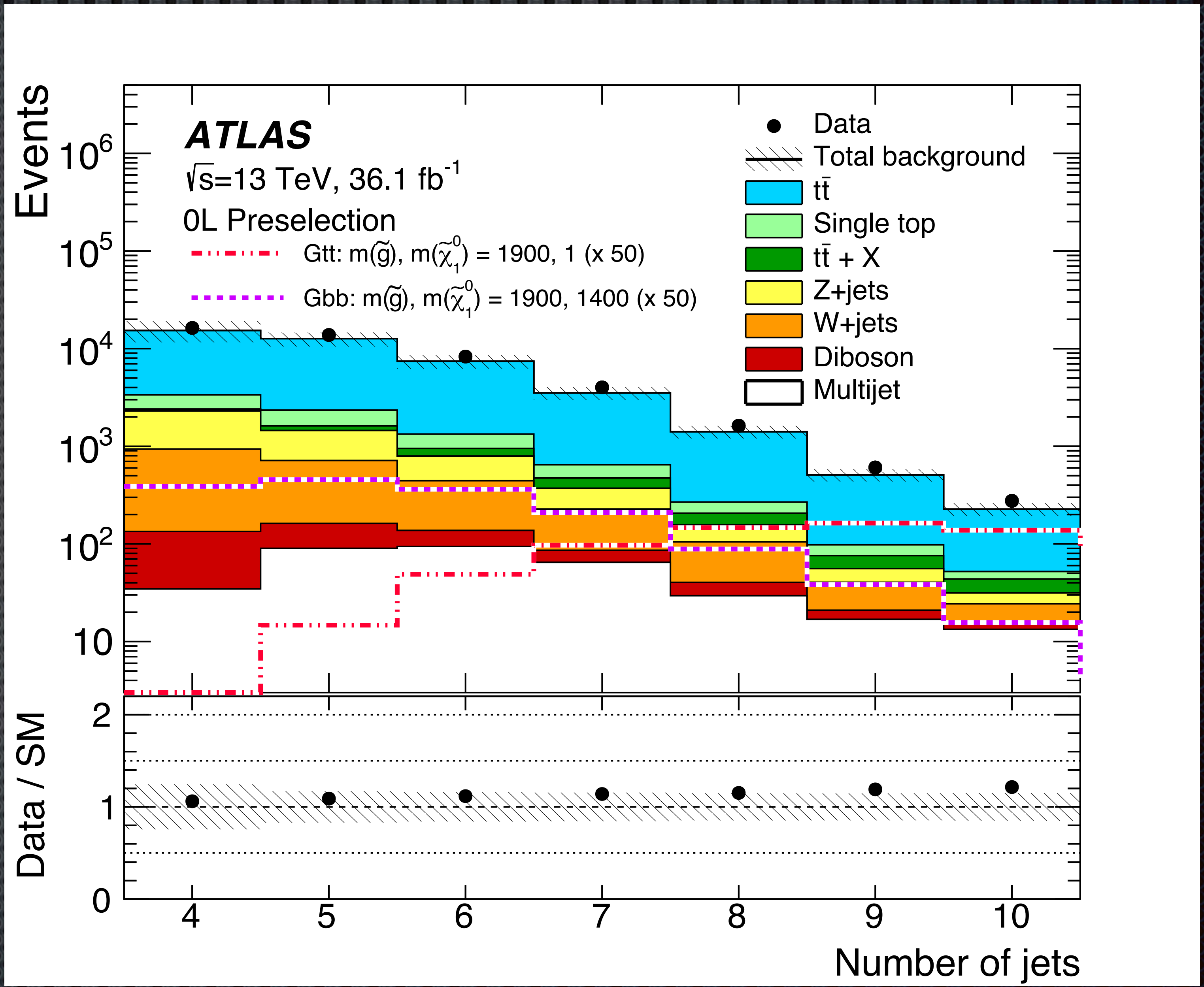
[2016 paper [1711.01901]](#)

Analysis pre-selection

- "standard" preselection
  - ≥ 4 signal jets
    - p_T > 30 GeV
    - $|\eta| < 2.8$
  - ≥ 2 *b*-tagged jets
    - 77% working point
    - $|\eta| < 2.5$
  - MET > 200 GeV

- **0L** means a **signal lepton veto (electron and muon)**

- **1L** means requiring **at least one signal lepton (electron or muon)**

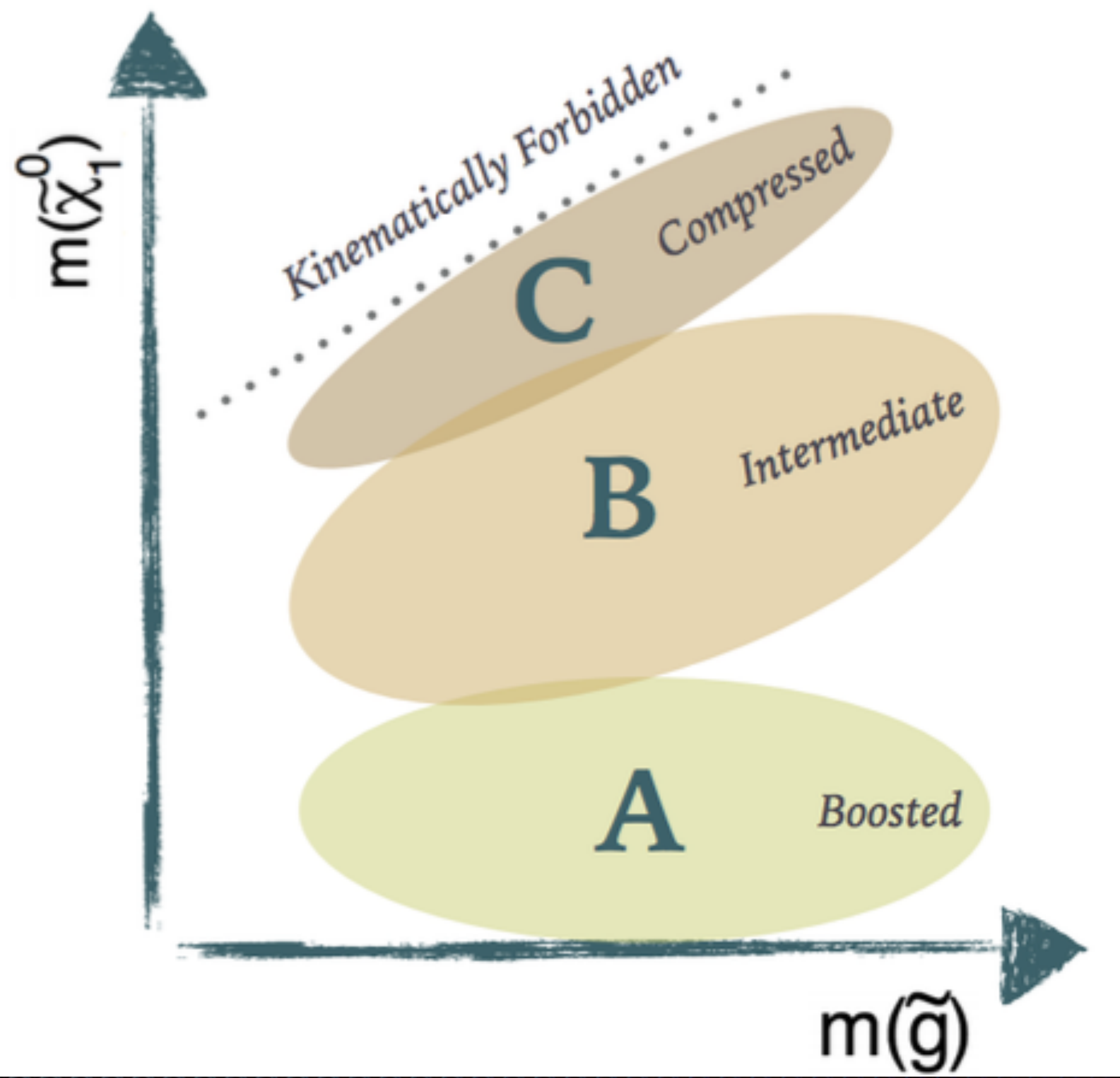


❗ Selections optimized for maximal SUSY discovery

maximize SUSY signal/SM background

Signal Region definition

- Define **three signal regions** sensitive to our SUSY model
  - Each region corresponds to the mass splitting between the gluino and neutralino
- Then define orthogonal **control regions** dominated by **semi-leptonic ttbar**
  - Likelihood fit using MC
  - Derive normalization factors by fitting to data
- Lastly, define orthogonal **validation regions**:
  - Verify that our control region derives normalization correctly
  - Check variable extrapolations between **signal** and **control**
- Open the box (unblind)!



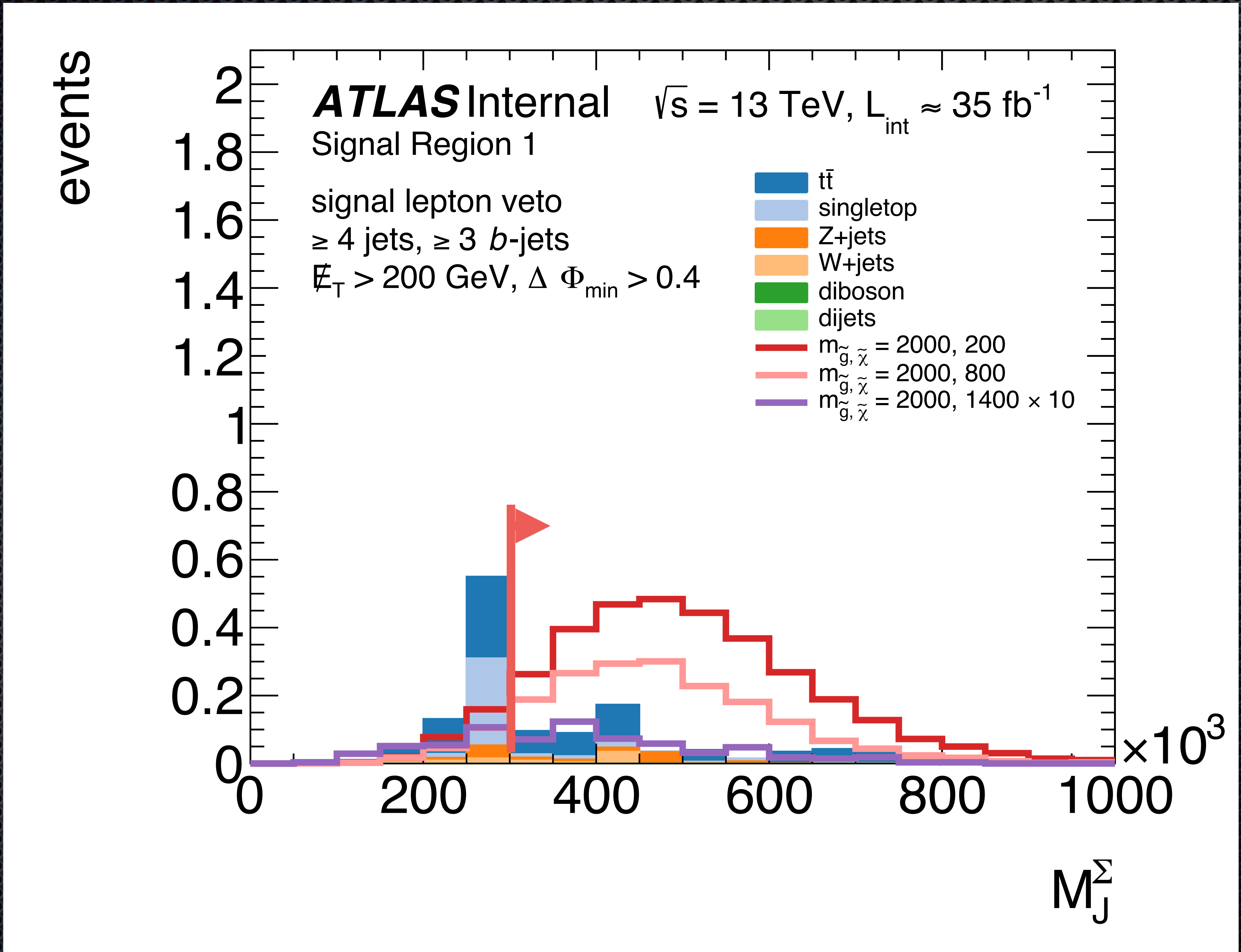
arxiv:1711.01901

	Variable	Signal	Control	Validation: 1L	Validation: 0L
Criteria common to all regions of the same type	$N^{\text{Signal Lepton}}$	$= 0$	$= 1$	$= 1$	$= 0$
	p_T^{jet}	> 30	> 30	> 30	> 30
	$\Delta\phi_{\min}^{4j}$	> 0.4	–	–	> 0.4
	m_T	–	< 150	< 150	–
Region A (Large mass splitting)	$m_{T,\min}^{b\text{-jets}}$	> 60	–	> 60	–
	$N^{b\text{-tag}}$	≥ 3	≥ 3	≥ 3	≥ 3
	N^{jet}	≥ 7	≥ 6	≥ 6	≥ 6
	E_T^{miss}	> 350	> 275	> 300	> 250
	$m_{\text{eff}}^{\text{incl}}$	> 2600	> 1800	> 1800	> 2000
	M_J^{Σ}	> 300	> 300	< 300	< 300
Region B (Moderate mass splitting)	$m_{T,\min}^{b\text{-jets}}$	> 120	–	> 80	–
	$N^{b\text{-tag}}$	≥ 3	≥ 3	≥ 3	≥ 3
	N^{jet}	≥ 7	≥ 6	≥ 6	≥ 6
	E_T^{miss}	> 500	> 400	> 450	> 450
	$m_{\text{eff}}^{\text{incl}}$	> 1800	> 1700	> 1400	> 1400
	M_J^{Σ}	> 200	> 200	< 200	< 200
Region C (Small mass splitting)	$m_{T,\min}^{b\text{-jets}}$	> 120	–	> 80	–
	$N^{b\text{-tag}}$	≥ 4	≥ 4	≥ 4	≥ 4
	N^{jet}	≥ 8	≥ 7	≥ 7	≥ 7
	E_T^{miss}	> 250	> 250	> 225	> 250
	$m_{\text{eff}}^{\text{incl}}$	> 1000	> 1000	> 850	> 1000
	M_J^{Σ}	> 100	> 100	< 100	< 100

0-lepton

- CRs require 1 lepton to be **orthogonal** to SRs, removes mTb
- MJSum decreases from 300 GeV in A to 100 GeV in C
  - The optimization showed that MJSum prefers to be tighter when there is a larger mass splitting between the gluino and neutralino

Understanding selections



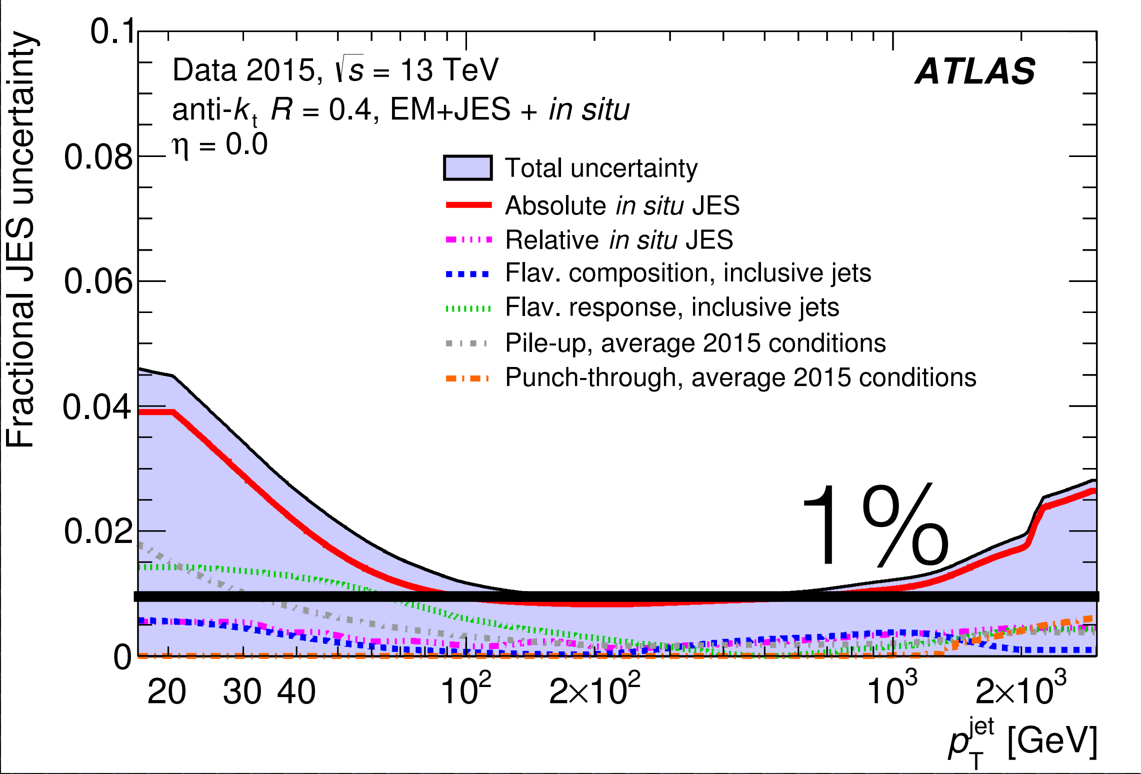
Apply all selections for a signal region, except for MJSum

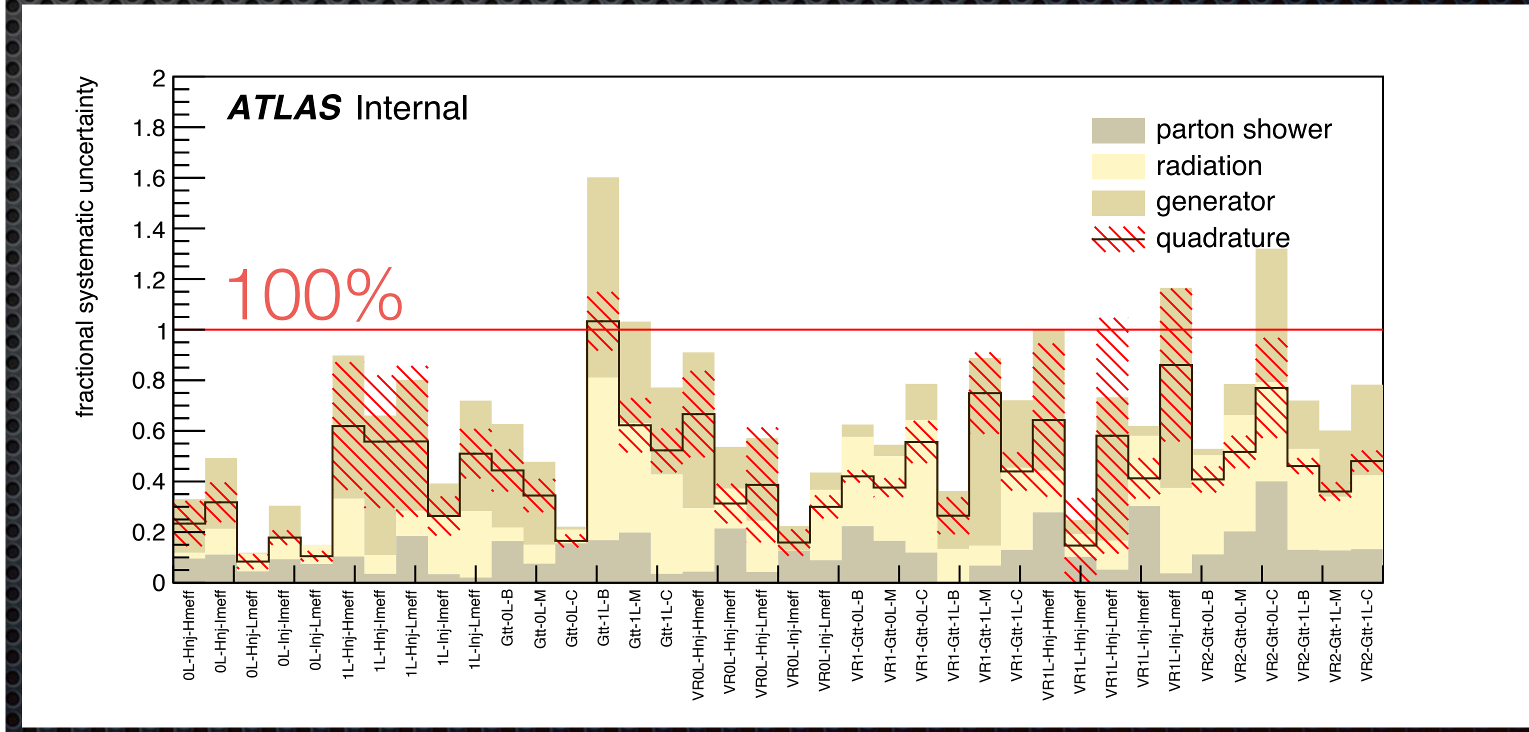
Statistical Fit Uncertainties

- Systematics on the objects — e.g. the measurement of a jet's momentum
- Statistical uncertainties — e.g. the normalization of ttbar in the control region to data
- Theory uncertainties — e.g. comparisons to alternatively-produced monte-carlo generators

Uncertainty of channel	SR
Total background expectation	36.23
Total statistical ($\sqrt{N_{\rm exp}}$)	± 6.02
Total background systematic	± 10.36 [28.59%]
ttbar normalization	± 9.60
theory systematics	± 9.12
jet energy scale	± 6.13

Gtt-0L-C

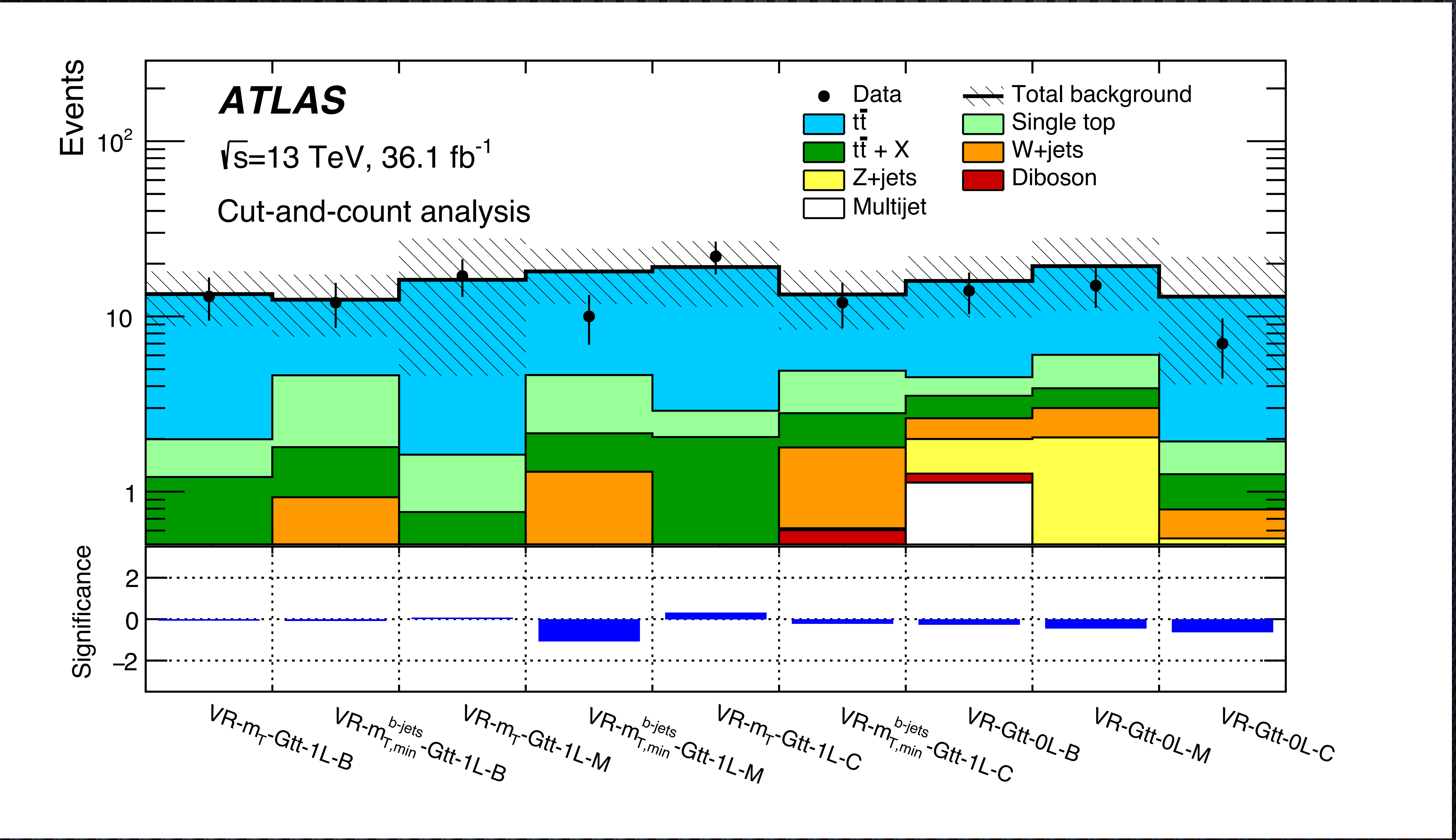




Jet Energy Scale

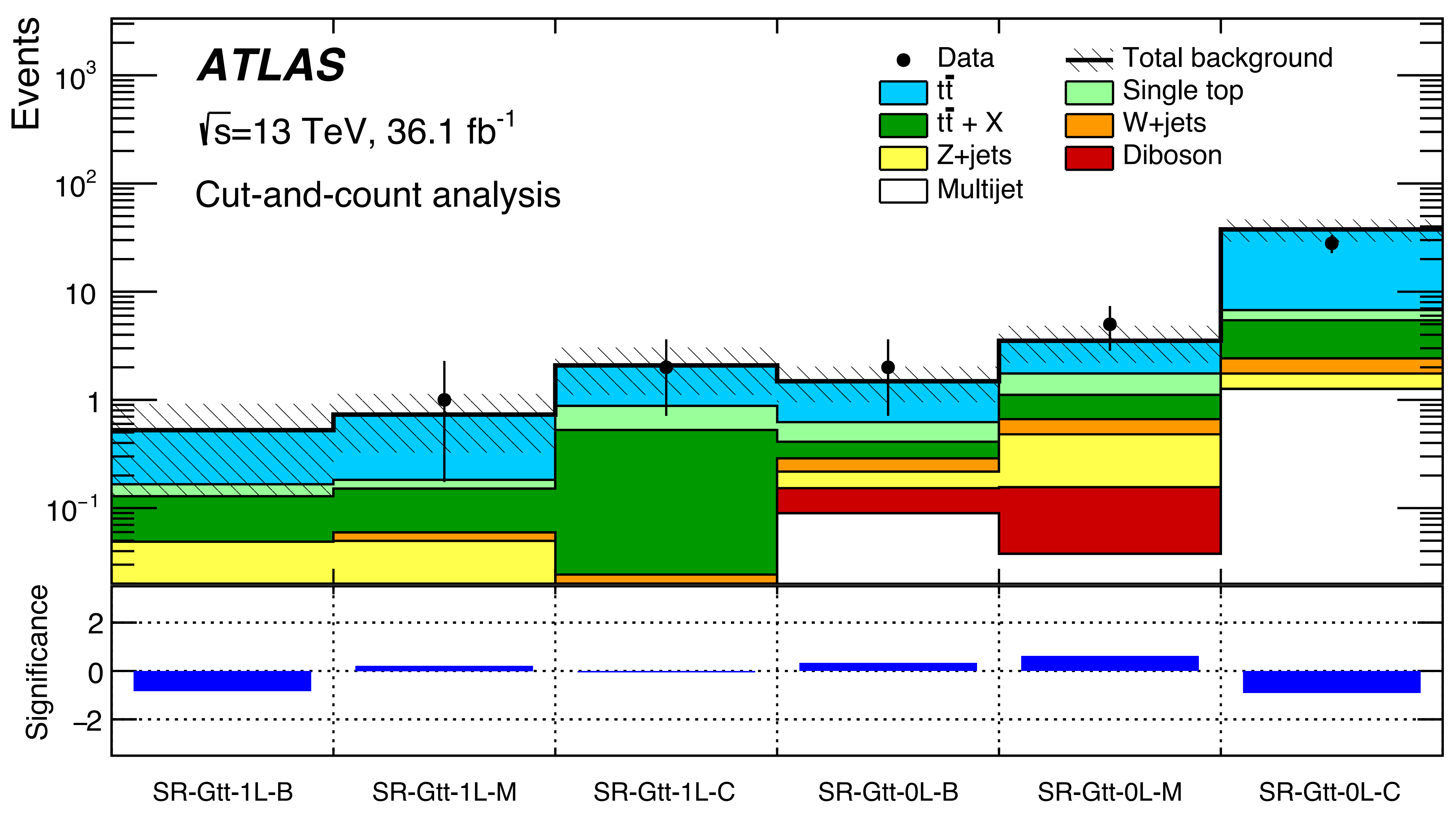
Theory

Validating our work



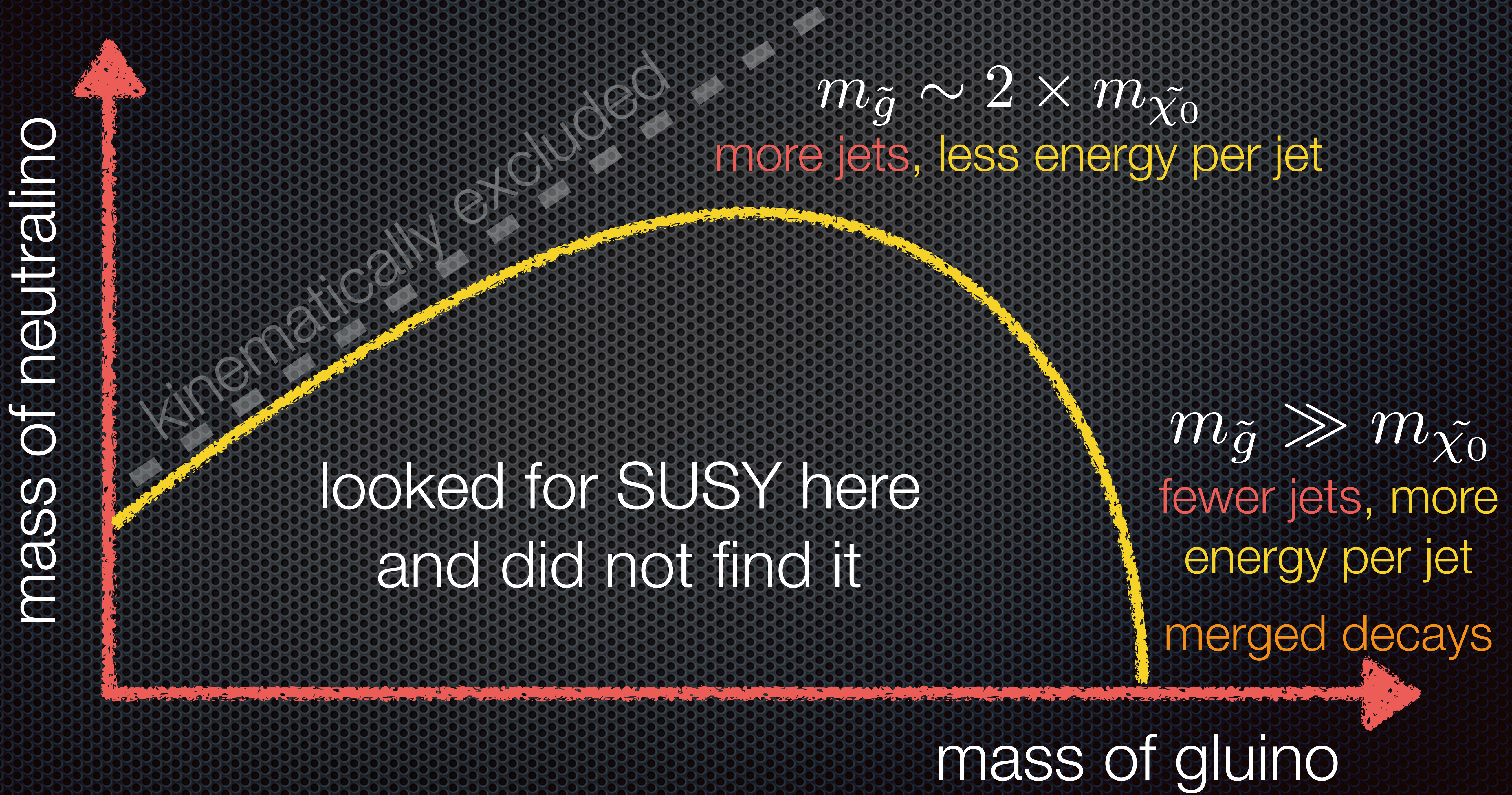
no significant mismodeling between observation and theory

Did we find SUSY?



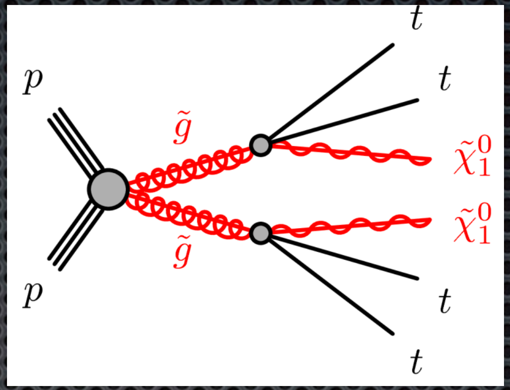
no large difference between observation and theory

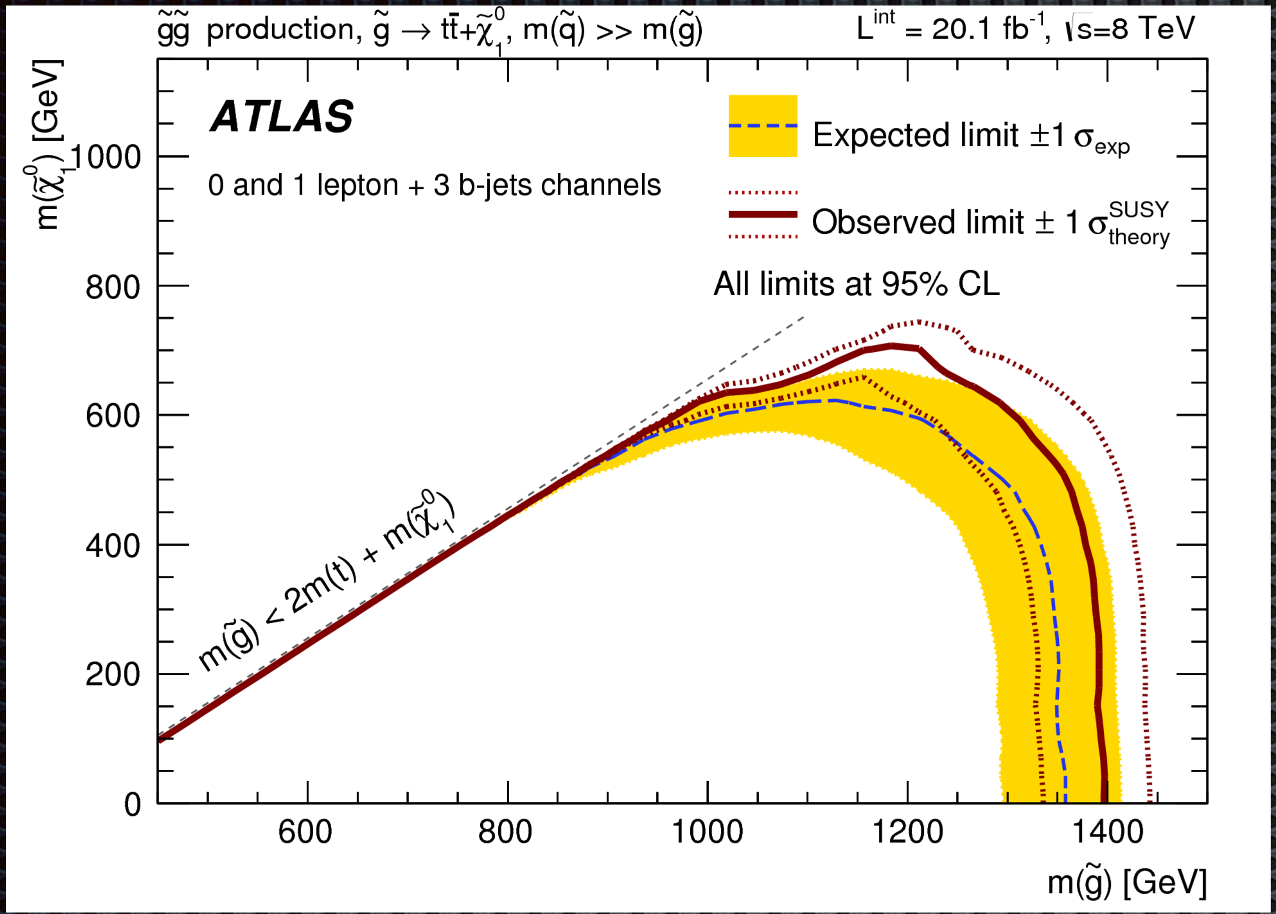
Parameterizing the model

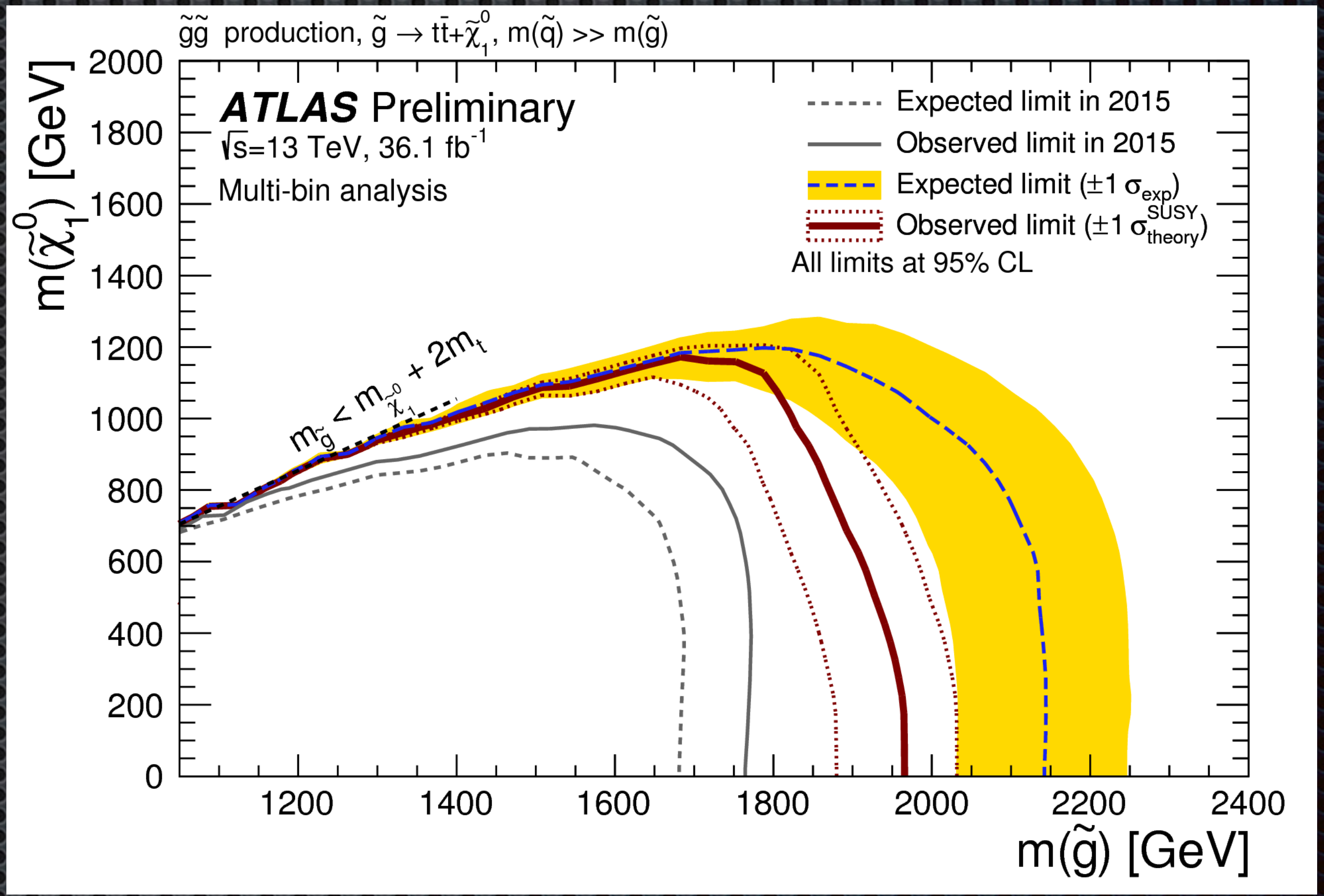


Set strong limits given no observed excess

Setting limits







[1407.0600]

2014 limits

[1711.01901]

2017 limits

Sensitivity increased from 1.4 TeV to 2.0 TeV

Instrumentation Upgrades

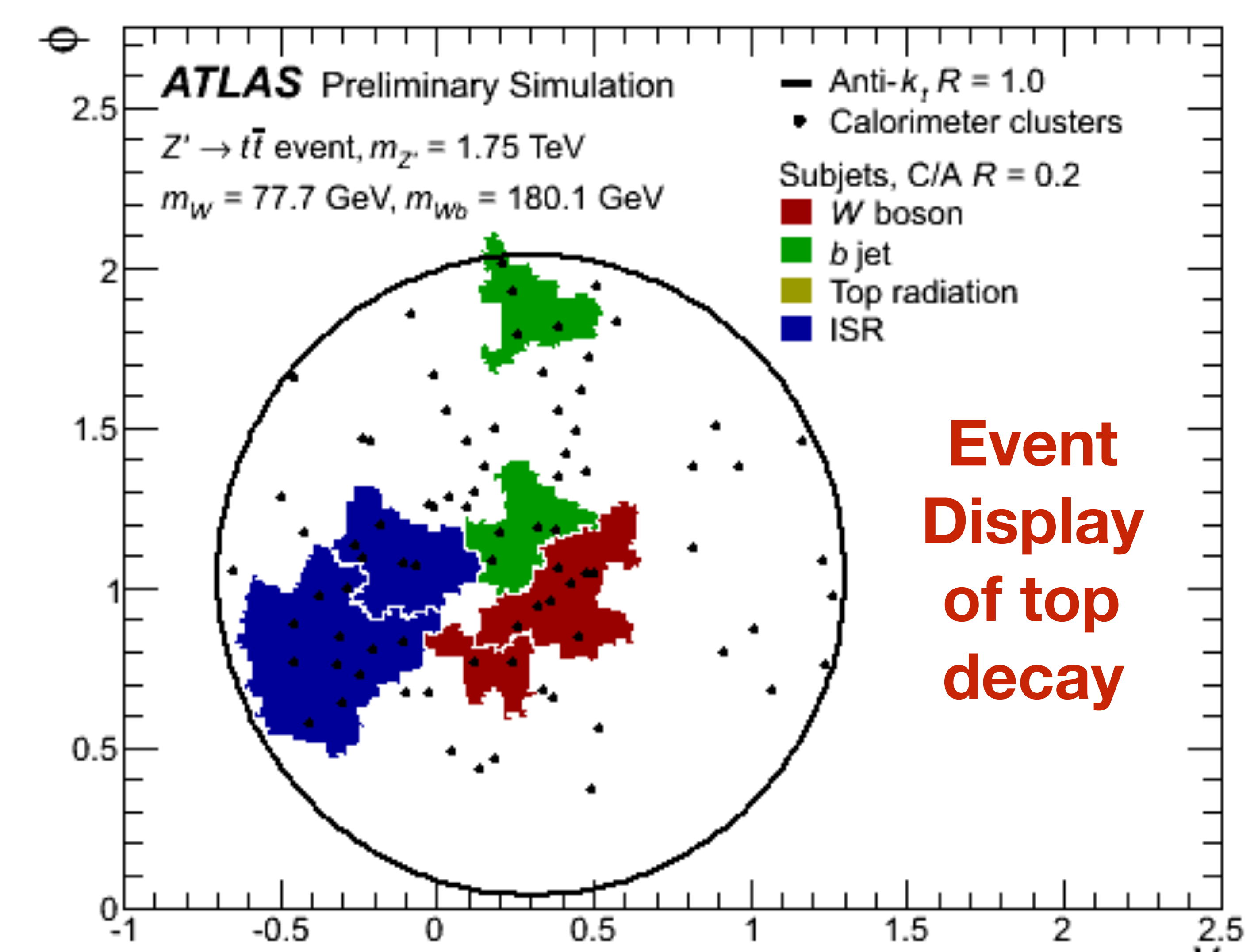
Maintaining the future of ATLAS physics for the next 20 years

"Places such as CERN become ever more important: places where people from around the world come together to show what can be achieved when people overcome their differences to work towards common goals that ultimately bring benefit to all of humanity.."

— Fabiola Gianotti

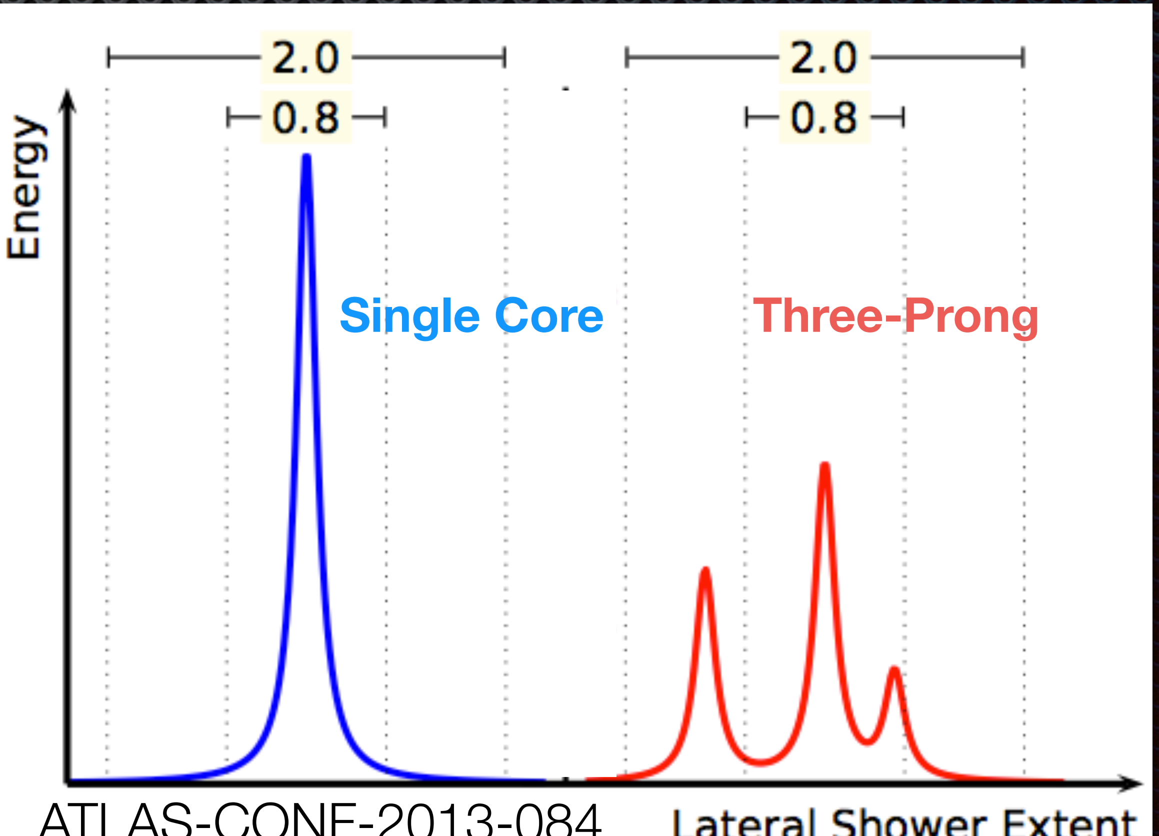
The Motivation

- High p_T Lorentz-boosted top quarks, W/Z/h bosons, and exotics are critical elements of the ATLAS physics program



ATLAS-CONF-2014-003

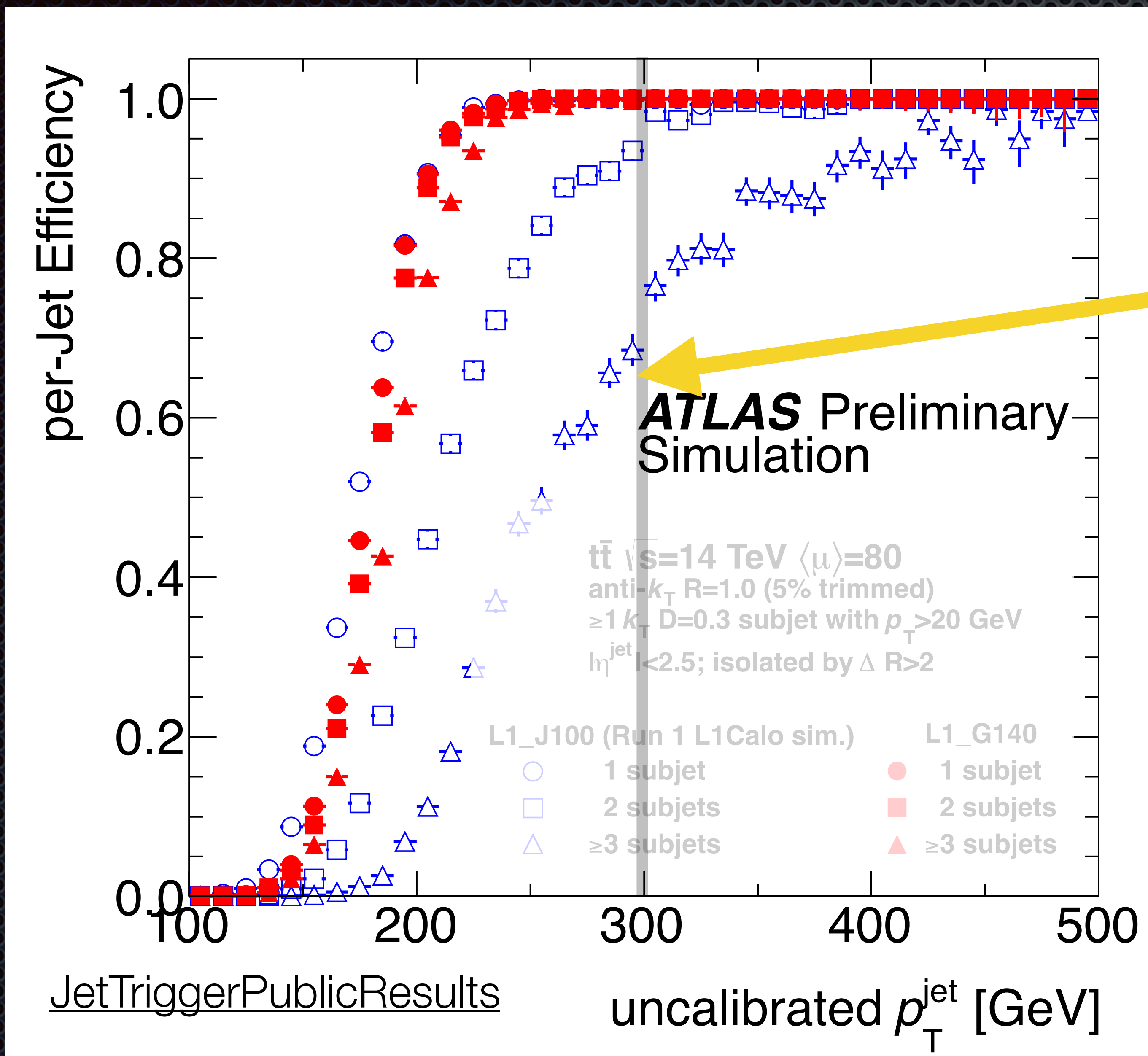
- Current trigger uses a **small window** to quickly scan an event
- If a jet with sufficient energy decays over a large area, **trigger will not fire**



ATLAS-CONF-2013-084

gFEX Trigger Performance

Blue=Current Trigger @ 100 GeV



Red=gFEX Trigger @ 140 GeV

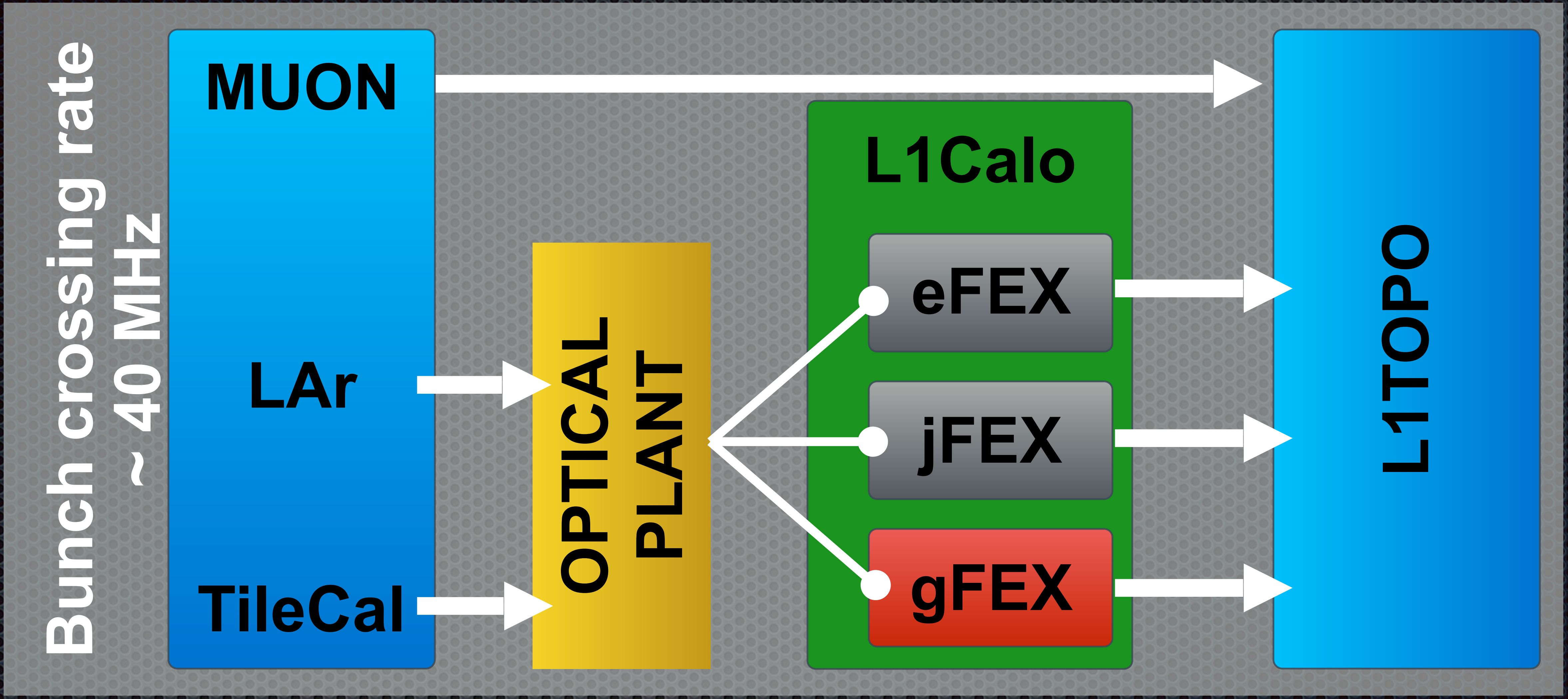
a top quark at 300 GeV

- Many analyses in ATLAS are sensitive to boosted objects with substructure
  - would like a trigger that does not cut them away
- gFEX maintains a flat trigger efficiency here

gFEX recovers trigger efficiency for jets with substructure!

global Feature Extraction

LHC Run 3 — a new feature extraction module

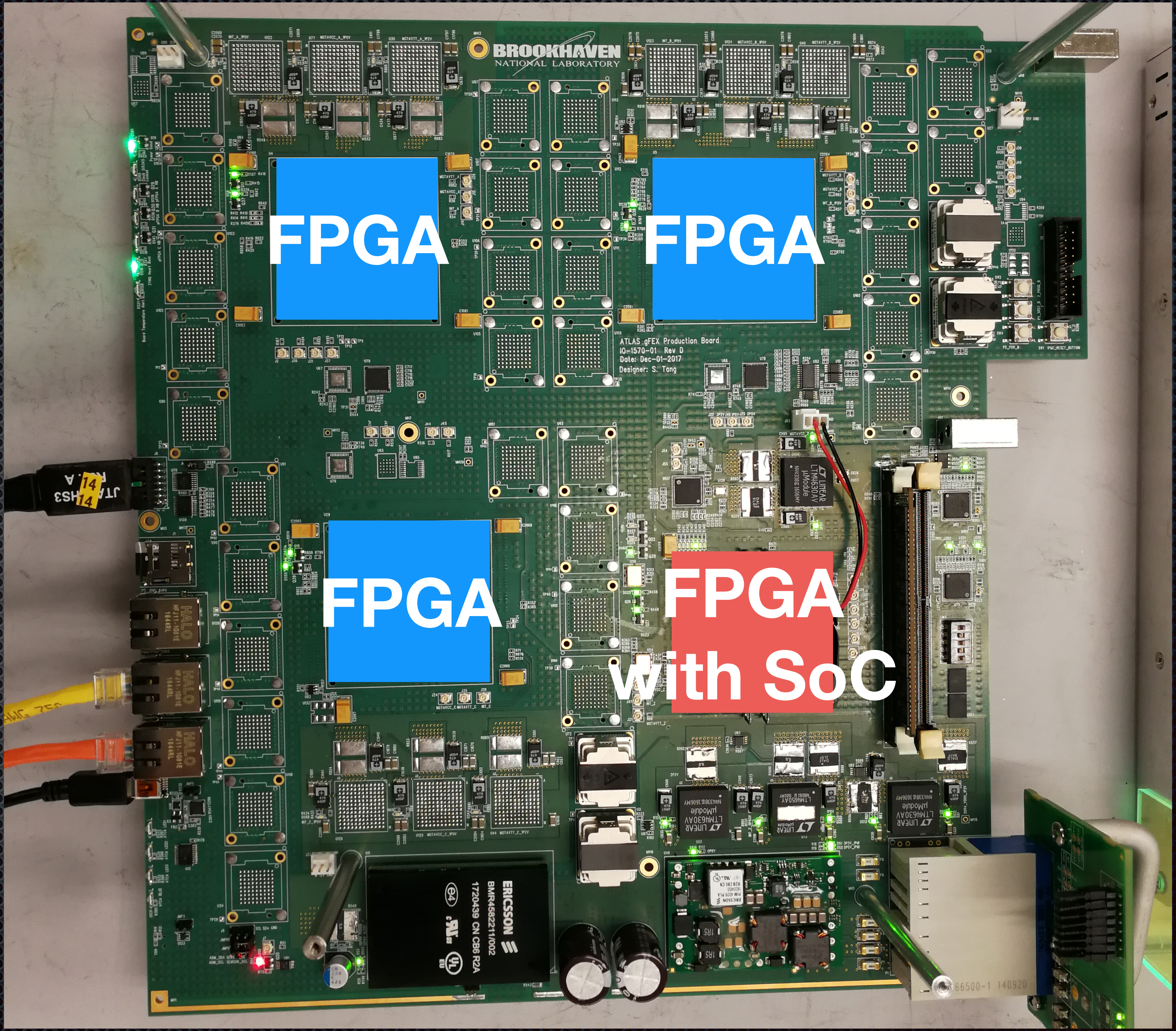


Our Solution: increase the RoI and processing speed, but some loss in angular resolution

- **algorithms run within 5 bunch crossings** (125 ns), not including data input/output
- L1Topo/HLT get info about **jets above a threshold and pileup calculation** for other triggers
- **full calorimeter information on a single board** enables calculation of global event quantities

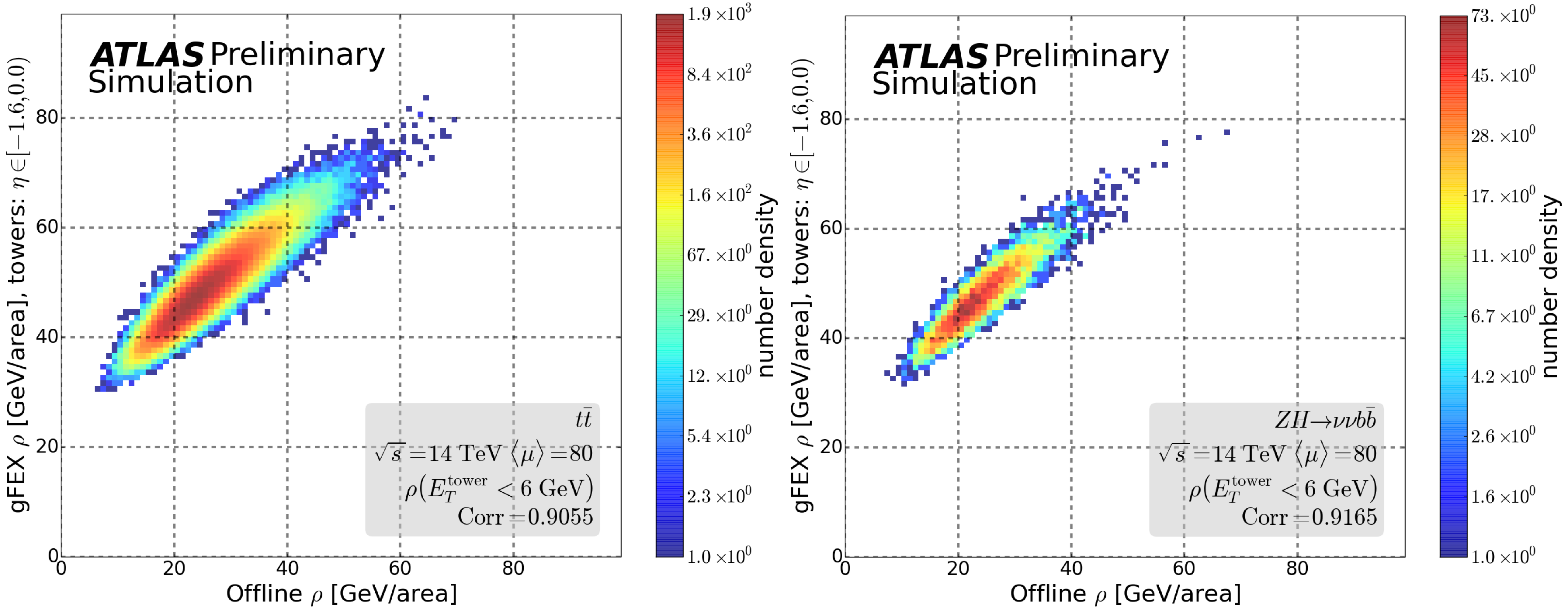
gFEX Prototype Board

- 3 processor FPGAs receiving calorimeter information and running algorithms
- An embedded System-on-Chip for slow control, monitoring, and slower but more advanced physics algorithms



Pile-up Energy Density (ρ) Calculations in the gFEX at the Level 1 Trigger

$t\bar{t}$ $\qquad\qquad$ $ZH \rightarrow \nu\nu b\bar{b}$



How does the online calculation of pile-up (ρ) match up to the offline calculation?

- Correlation between offline ρ and simplified online ρ using gFEX
- Online calculation independent of physics processes we're studying (it shouldn't and it doesn't).

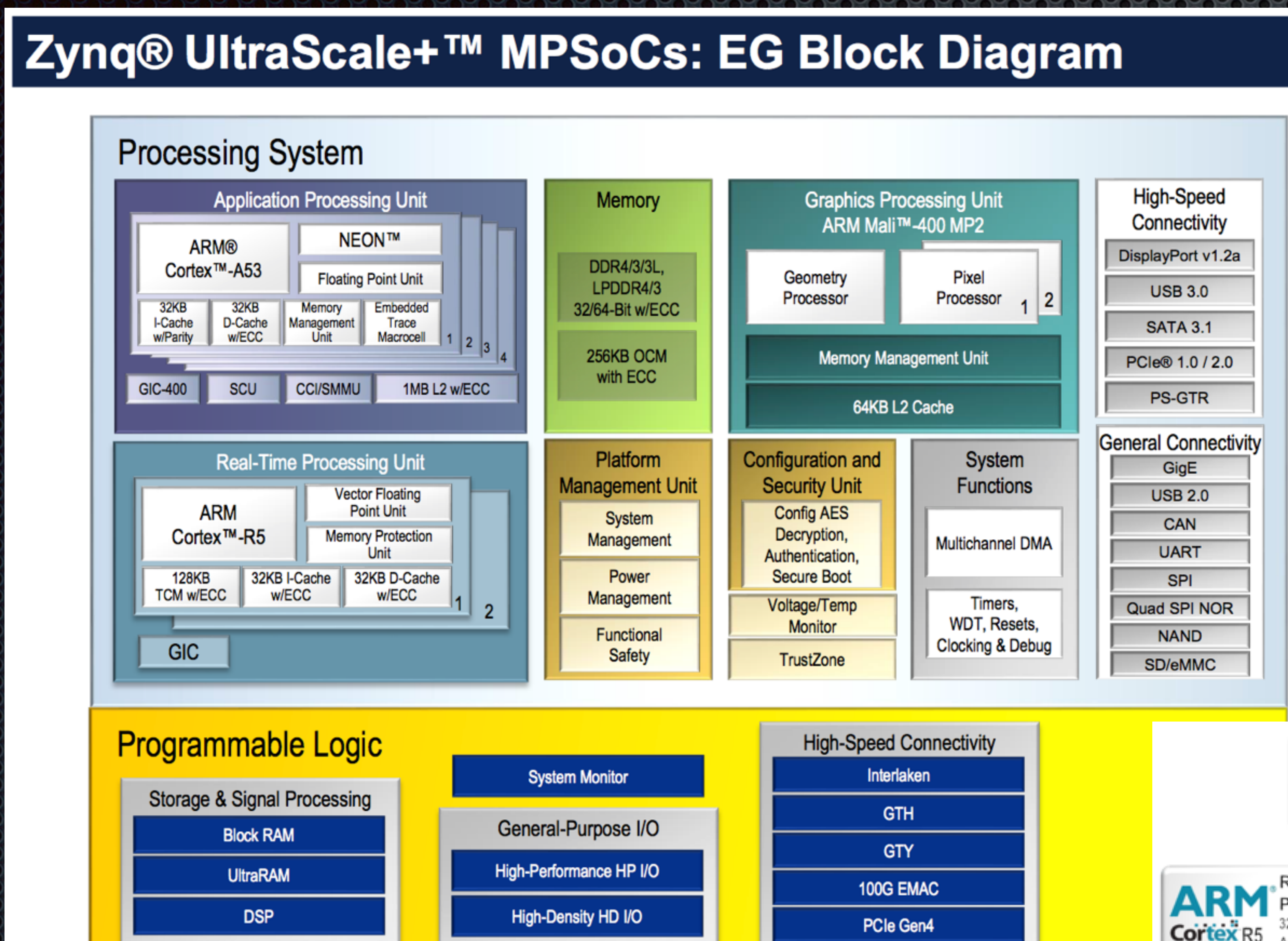
JetTriggerPublicResults

Slow-Control and Monitoring

- Custom OS designed with flexibility to run Python and other technologies for communications and control

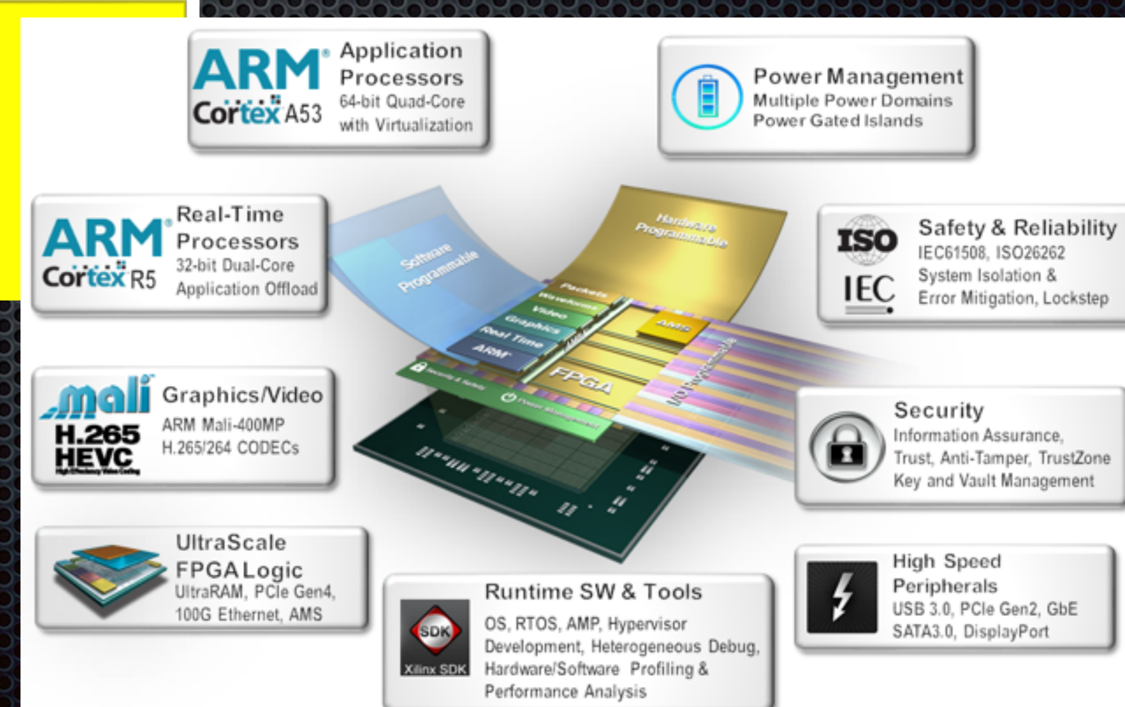
- Possibilities include memory-mapped access, TCP/IP streaming of monitoring data, and slow-control over HTTP with a web browser

Using bleeding-edge technology



The Zynq UltraScale+ MPSoC

- 4-core ARM Cortex-A53 APU
- 2-core Cortex-R5 RPU
- ARM Mali-400 MP2 GPU



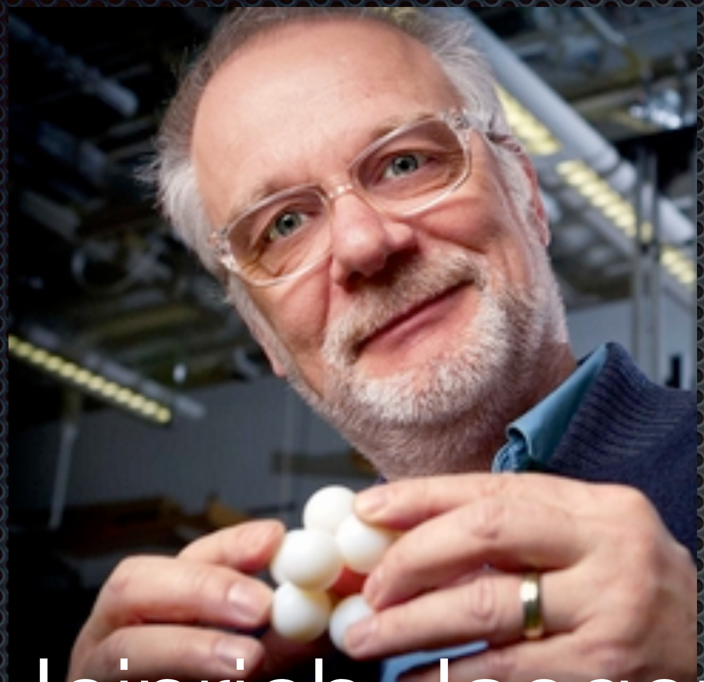
Want gFEX to be useful through to the next generation of physicists (~20 years)

Conclusion

- Instrumentation project fully underway to recover efficiency of objects with significant substructure
- Search for new physics in simplified supersymmetry models using reclustered jets sets strong lower limits on gluino masses


U.S. ATLAS
Outstanding Graduate Student Award
Giordon Stark
University of Chicago
CERN
CERN

Thanks to the committee!



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