UC SANTA CRUZ

CERN

PARTY CALL PHYSICS

Likelihoods and Classifiers

Dr. Giordon Stark

Lund Seminar

September 15th, 2022

giordonstark.com

ATLAS EXPERIMENT

Run: 300800

Event: 2418777995

2016-06-04 03:47:03

if you can read this, you're too close

About Me

- B.S Caltech 2012 (LIGO)
  - Brownian Thermal Noise
- Working on ATLAS since 2014
- PhD UChicago 2018 (ATLAS)
  - Search for new (hadronic) physics and instrumentation upgrades
- Currently postdoc at SCIPP, UC Santa Cruz since 2018
  - Large-scale physics analysis combinations, software development, and instrumentation upgrades
- Lots of outreach/teaching/DEI experience (bootcamps, workshops, committees)

Overview of Today

The long road to making physics accessible

(and how rocky it has been at times)

- The Standard Model… and **beyond**!
- The Large Hadron Collider, **ATLAS**, and you
- Searching for signs of **new physics**
- Experimentalist introduction to **statistics and hypothesis testing**
- **Accessibility** in physics education
- What does the **future** have in store for us?

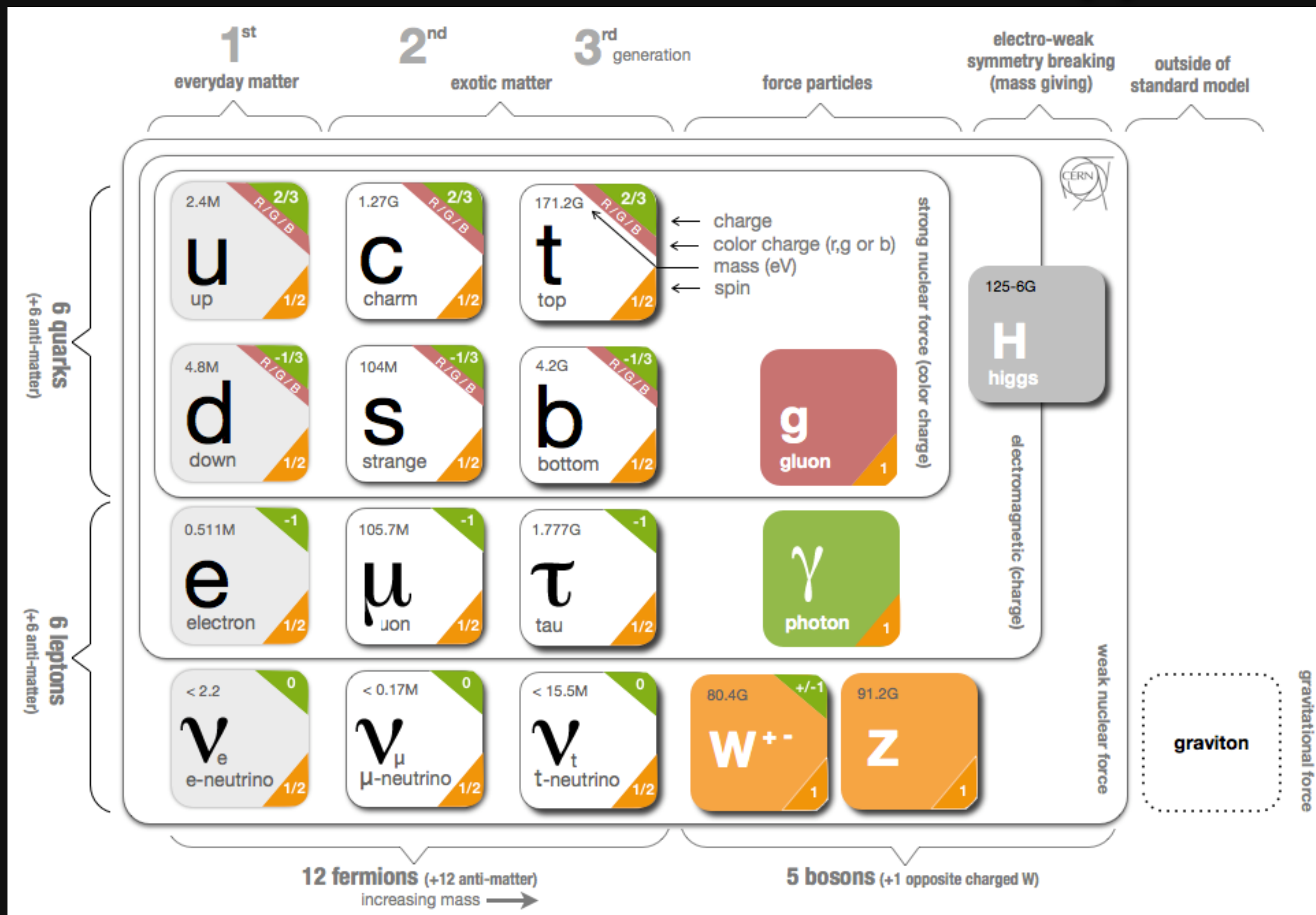
⌛ **Let's get started**

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

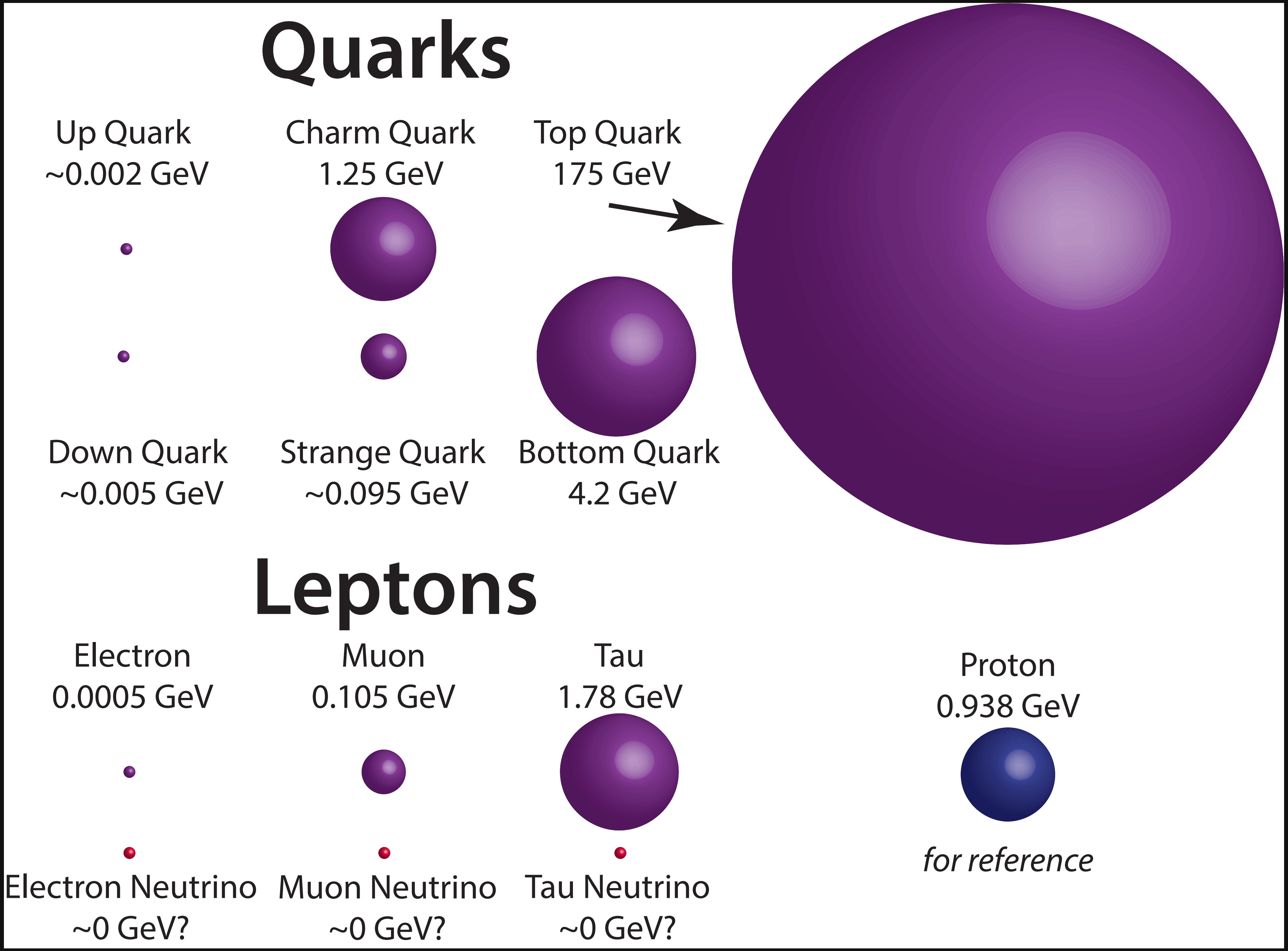
The Standard Model (I)



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

5 bosons
(4 force-carriers)
integer spins

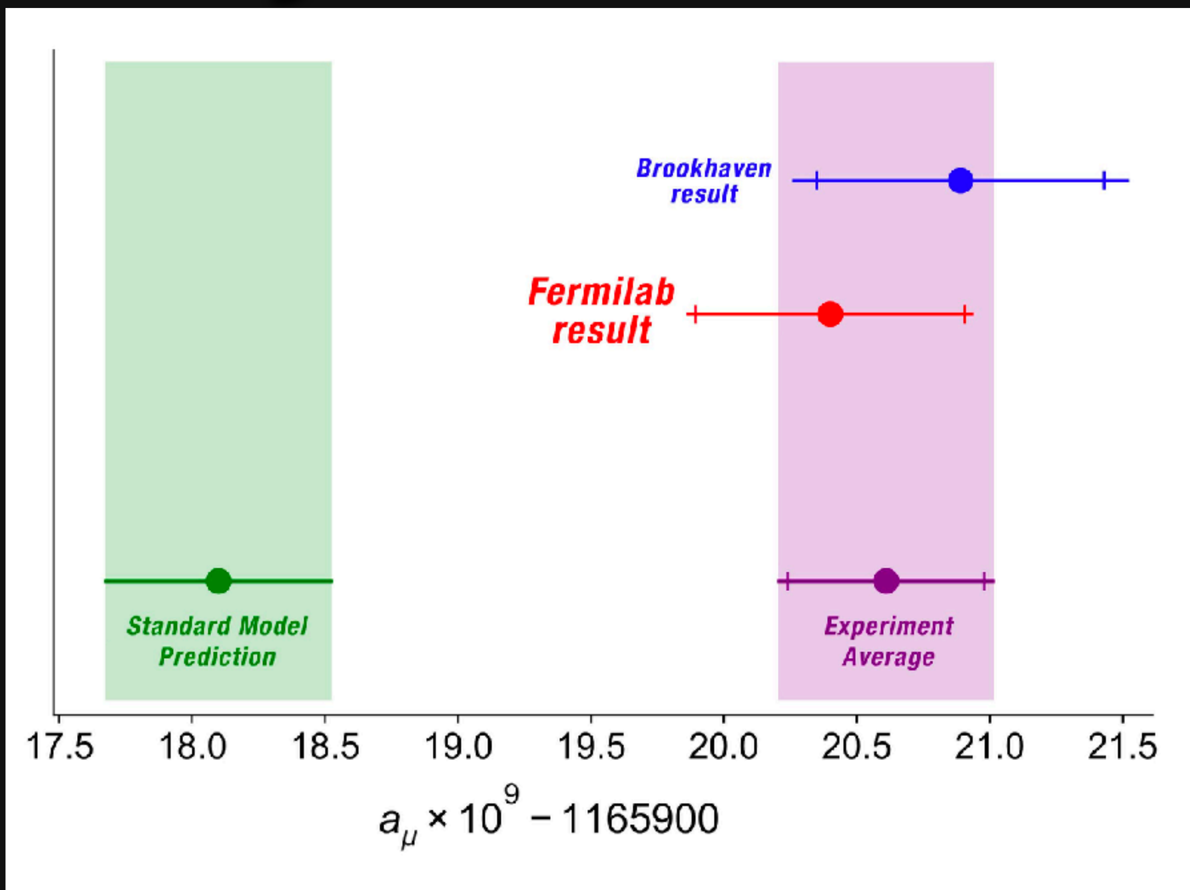
The Standard Model (II)



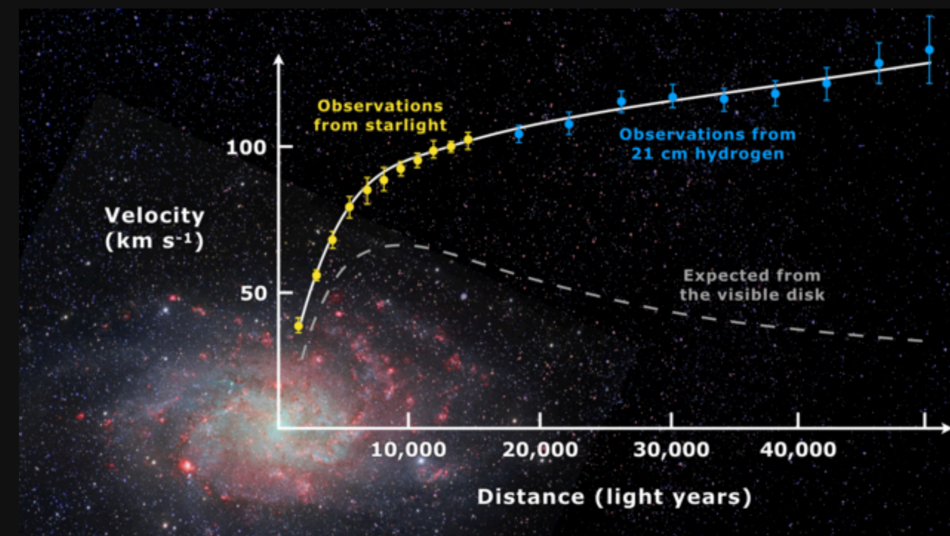
Volume proportional to the mass

https://en.wikipedia.org/wiki/Galaxy_rotation_curve

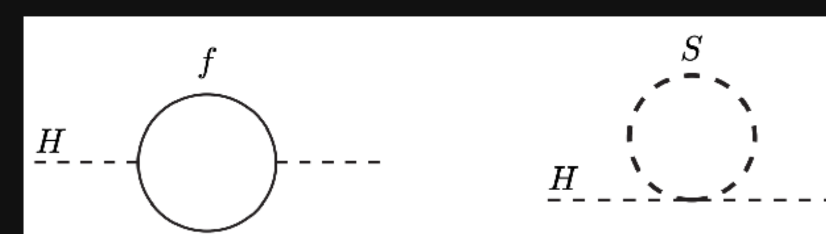
Beyond the Standard Model

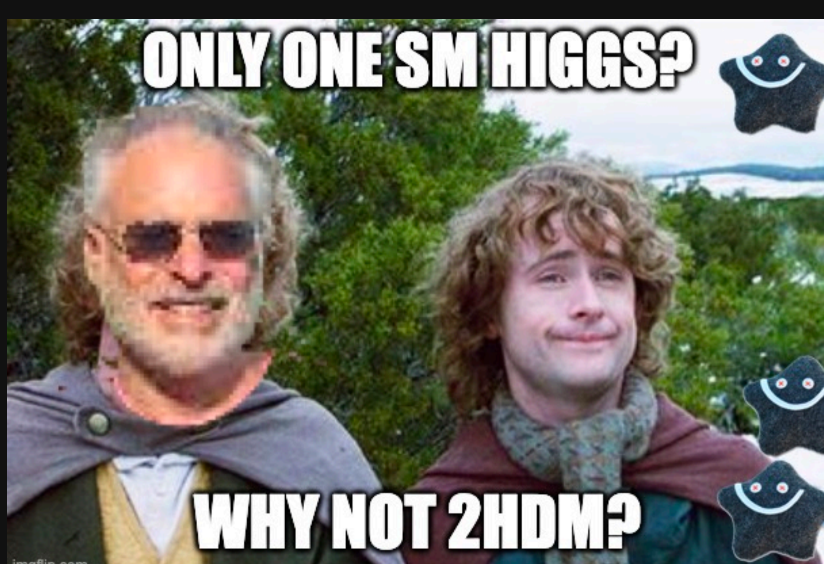


anomalous magnetic dipole moment of muon

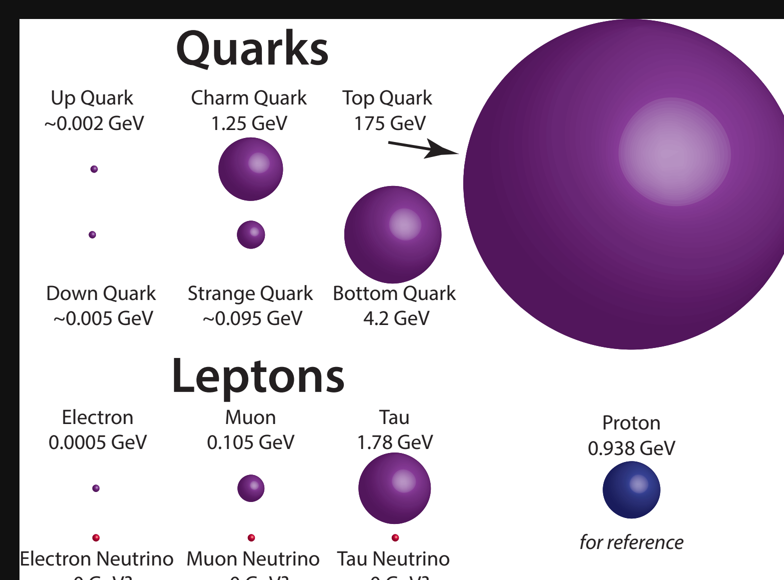


Cold Dark Matter candidates?





Flavour anomalies?



Hierarchy Problem

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)

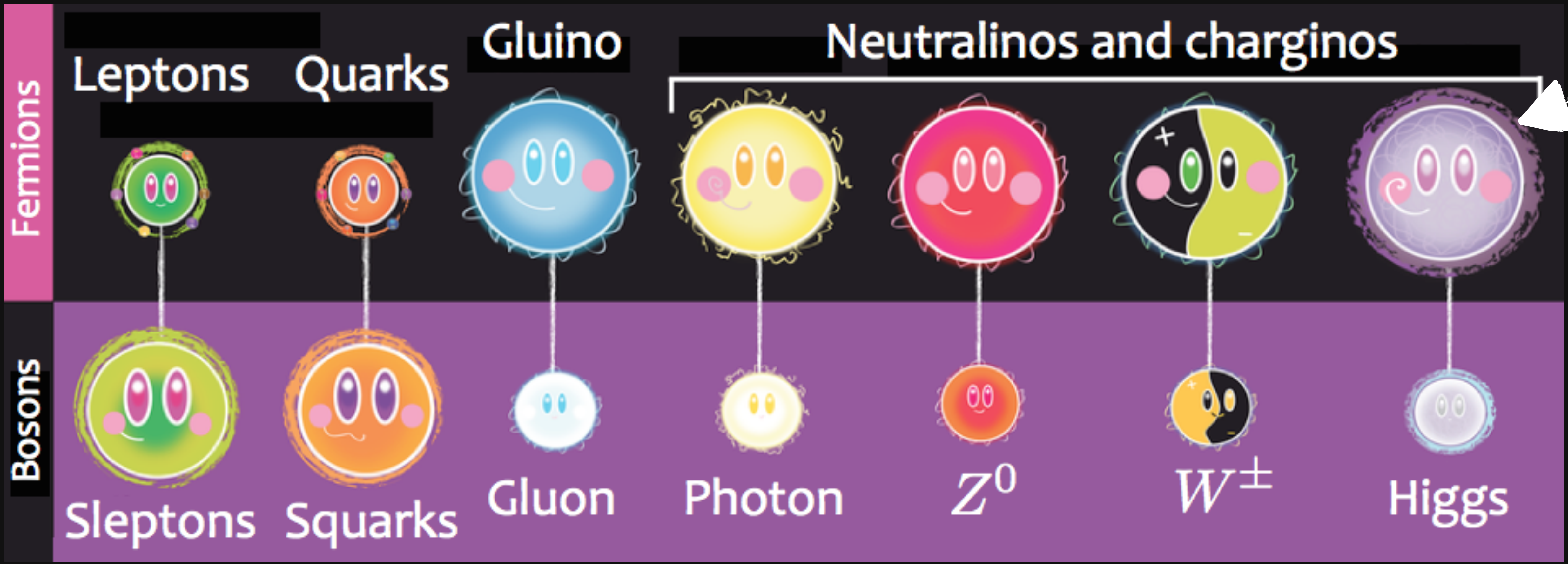
Supersymmetry (SUSY) is a framework with good theoretical motivations in which theorists can study BSM physics

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

What is supersymmetry?

small = Standard Model
large = Beyond the SM

Higgsinos

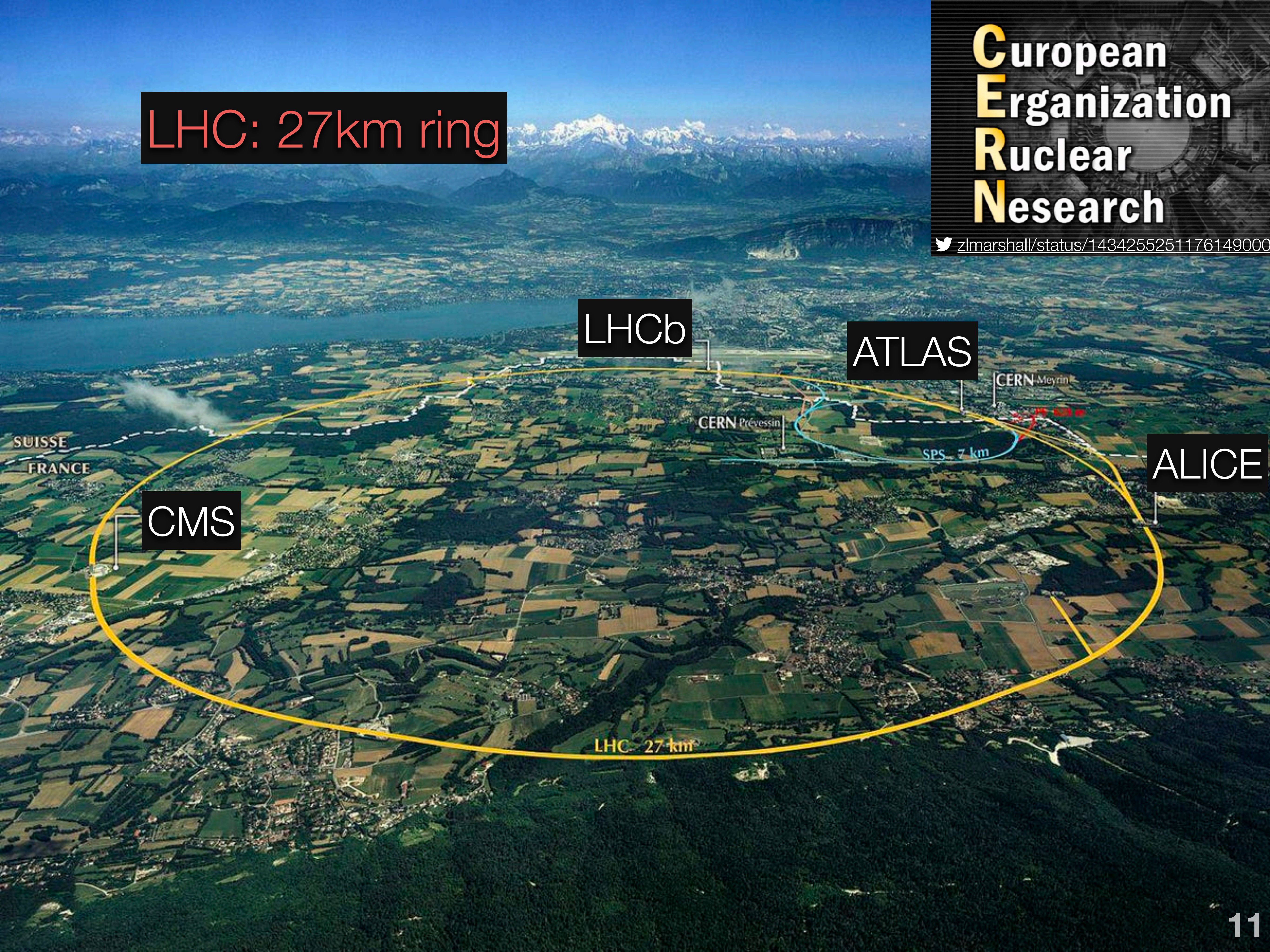


A particle physics tango between fermions and bosons

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


LHC: 27km ring
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
SUISSE
FRANCE
LHC 27 km
Curopean
Erganization
Ruclear
Nesearch
zlmarshall/status/1434255251176149000

LHC *ATLAS*

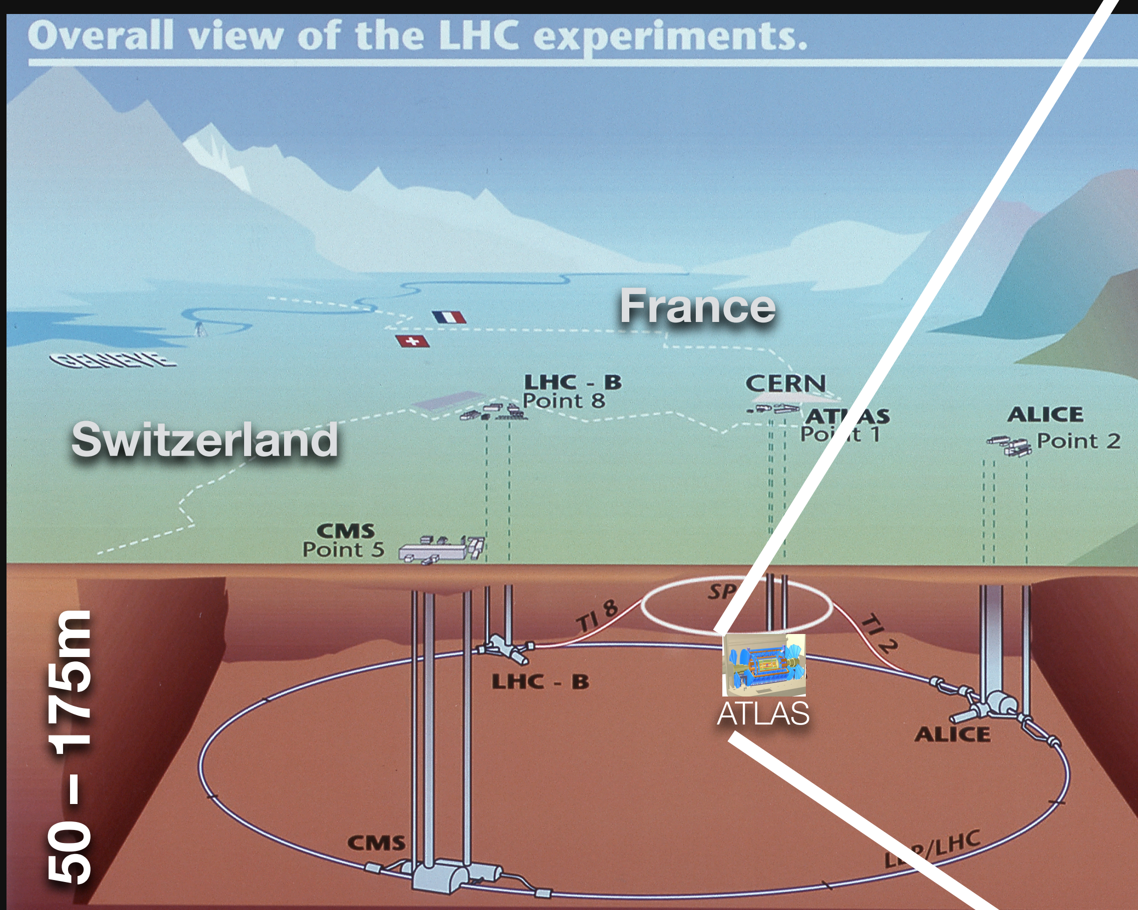
A collider and a detector

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

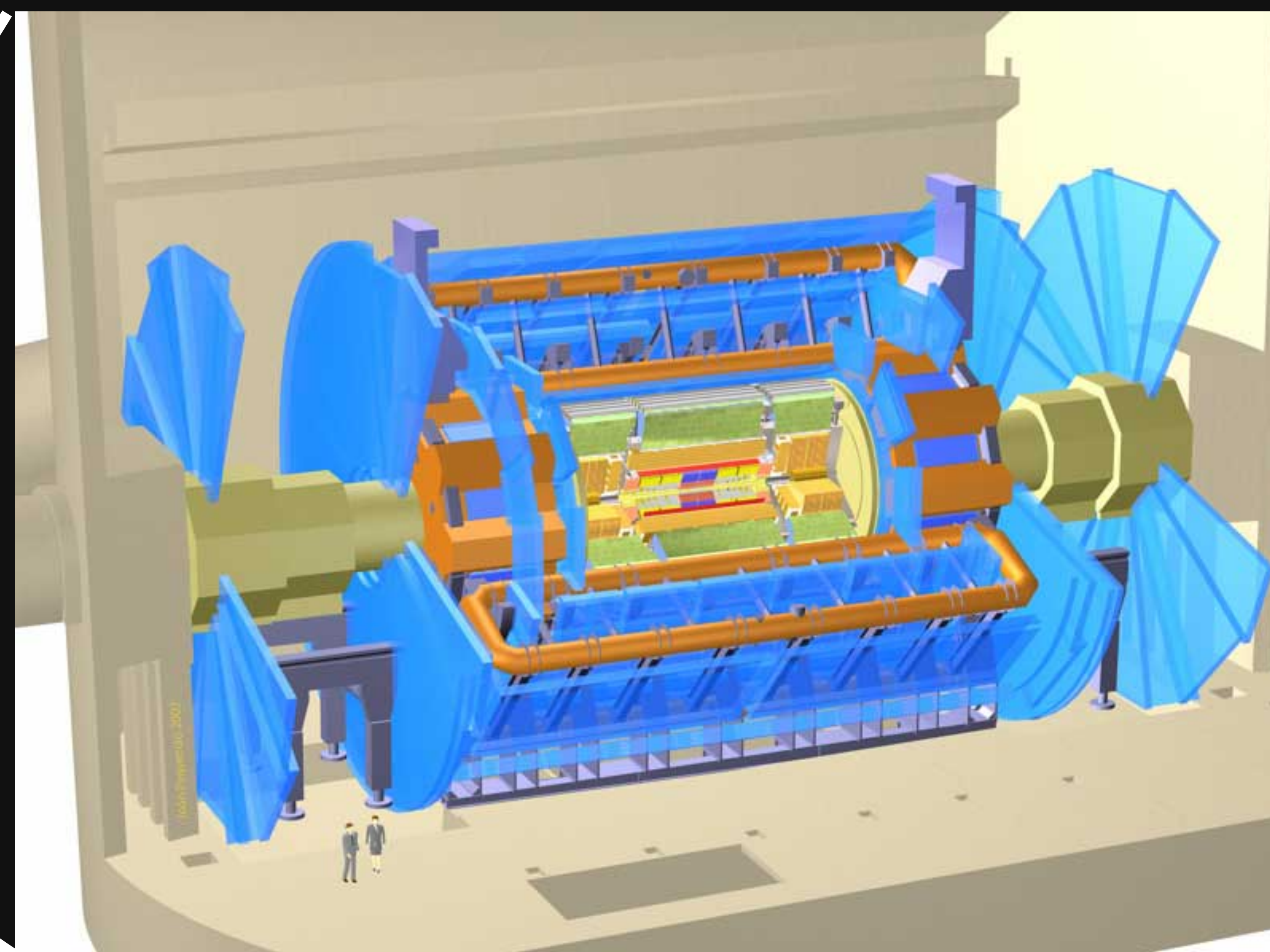
Four points along the ring at which the proton-proton beams cross

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

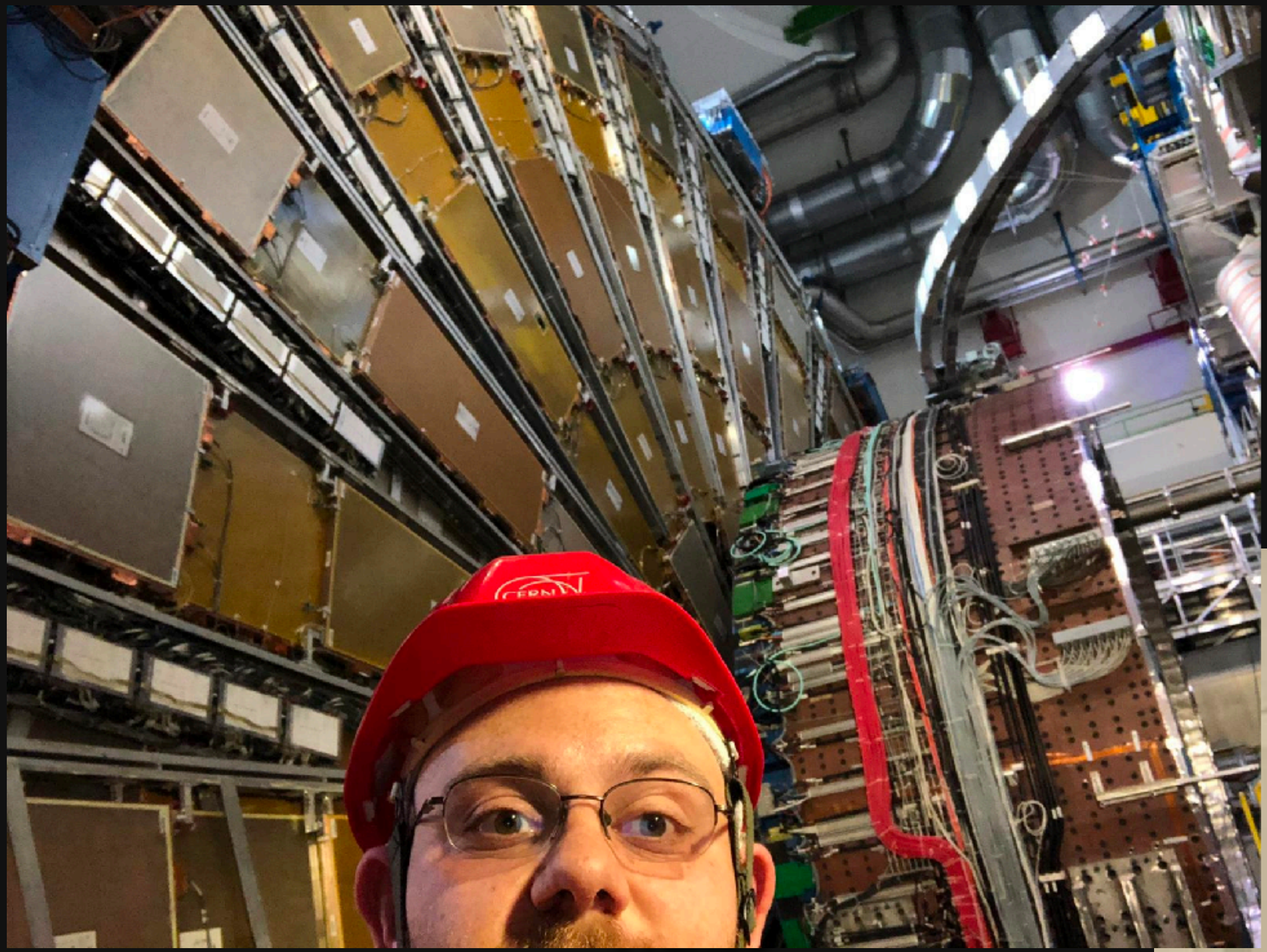
Located at collision Point 1

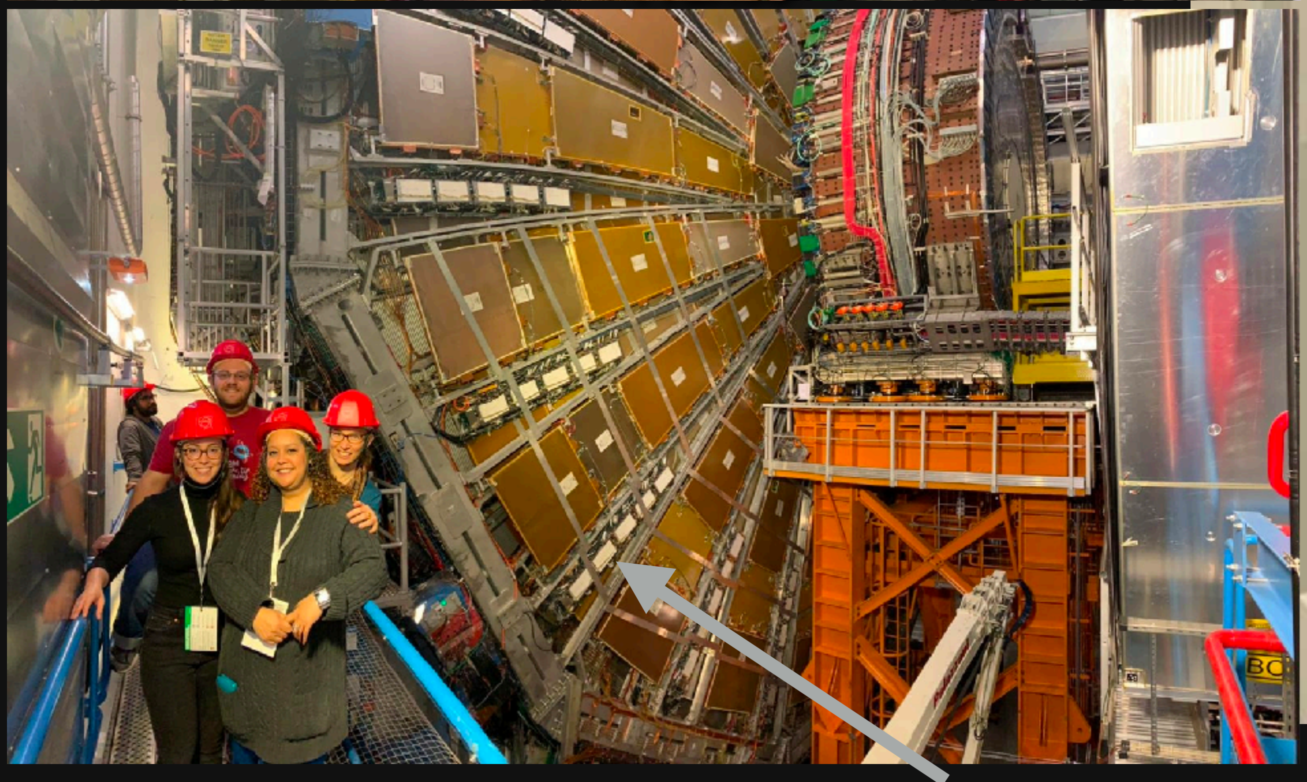


Stable rock at that depth



LHC



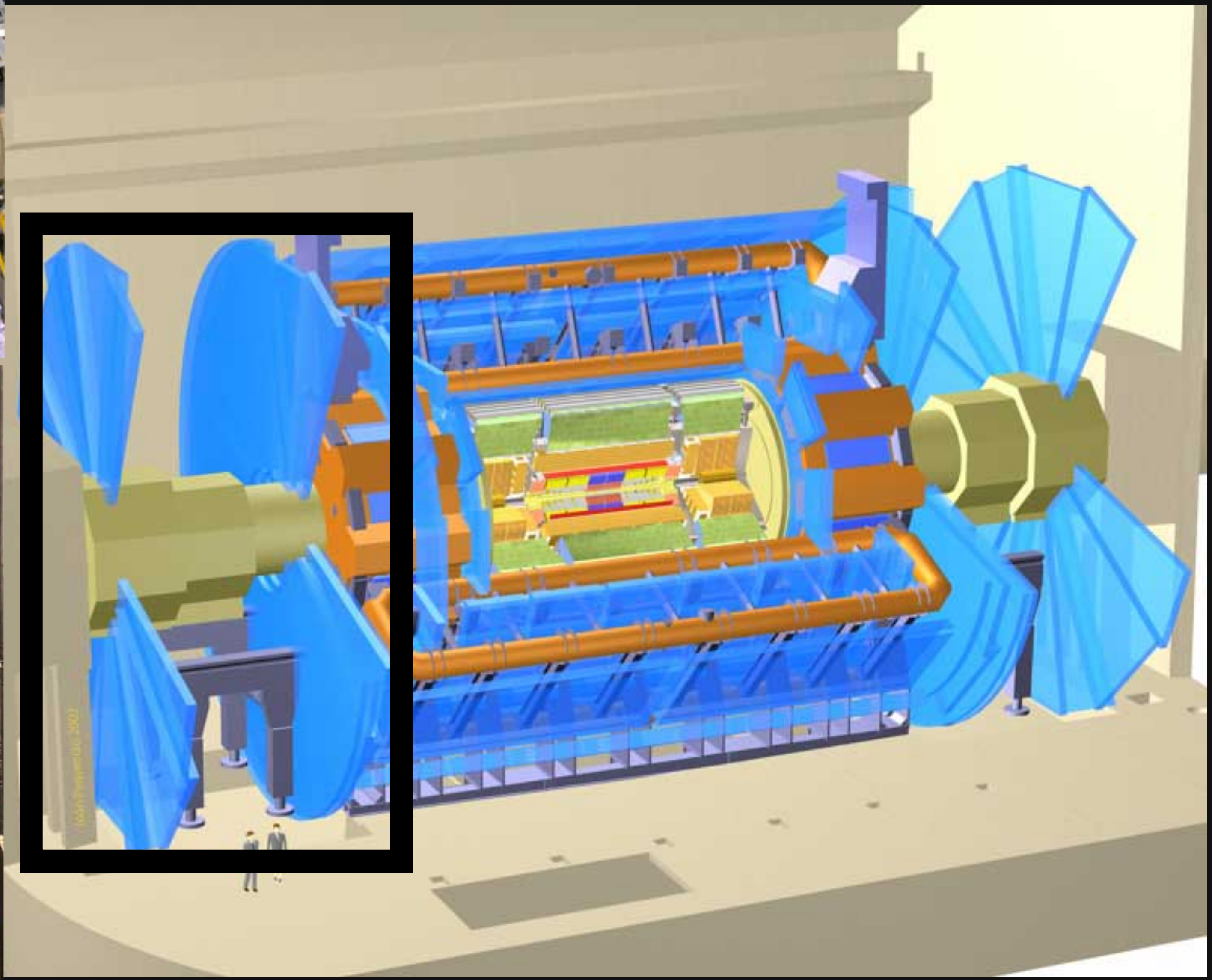


ATLAS

a detector

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

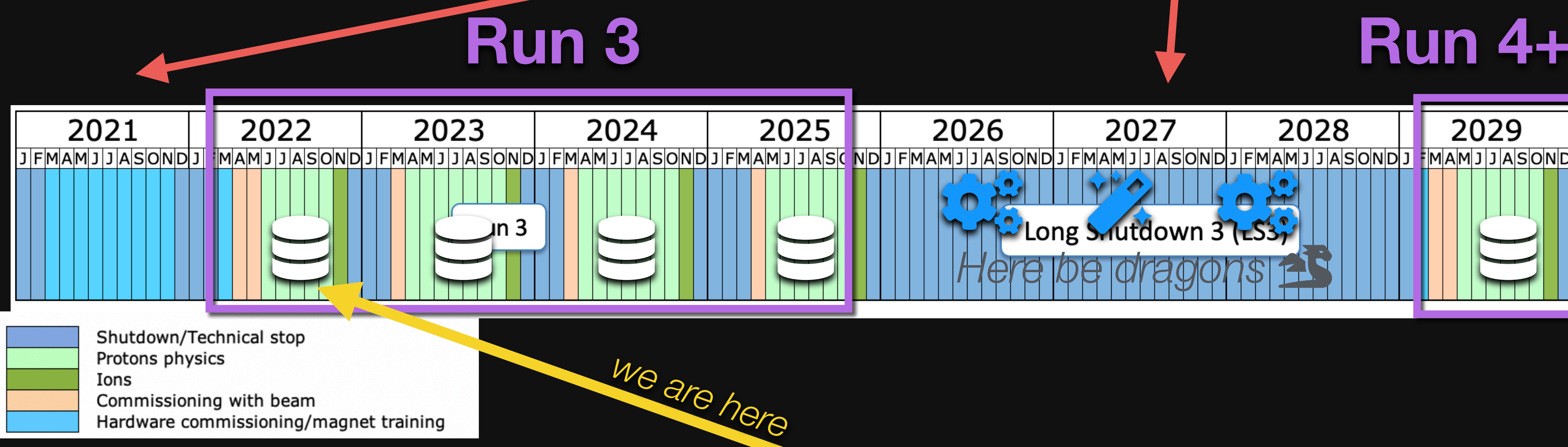
Located at collision Point 1



https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm
https://atlas.cern/Updates/Press-Statement/Run3-first-collisions

LHC Schedule

No data collection



Experiments recently started up, **Run 3 data** July 5th 2022!

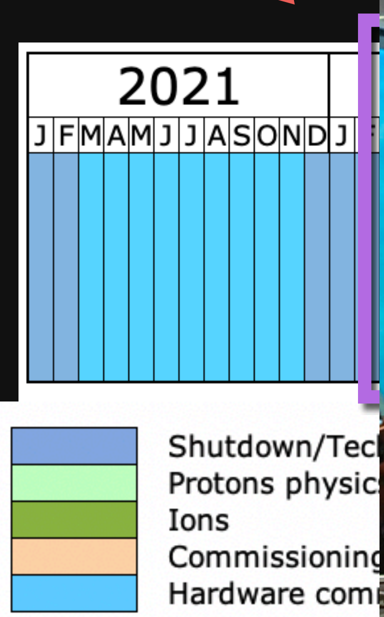
- Focus on doing more with what we have
  - clever techniques to find new physics (SUSY?) in existing data
  - **global fits and large scale combinations to determine future directions**
- **Finalized calibrations** on physics objects (electrons, muons, jets, photons) and pushed **object definitions to lower energies**

https://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm
https://atlas.cern/Updates/Press-Statement/Run3-first-collisions

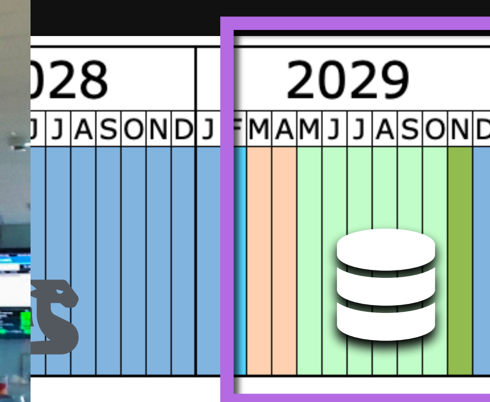
No data collection

LHC Schedule

Run 4+



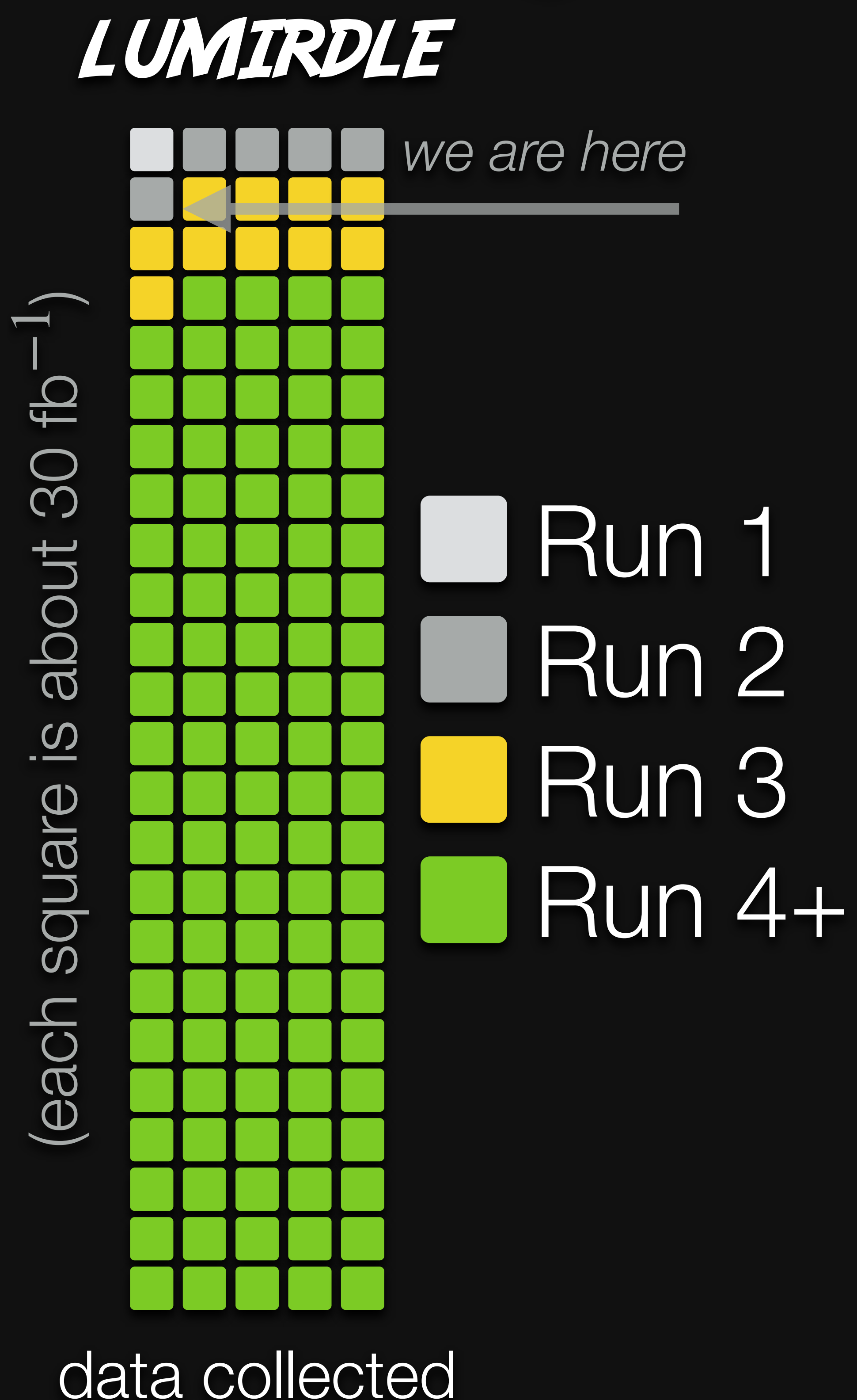
https://www.youtube.com/watch?v=06kFq1QF5-s



Ex 022!

- Focus o
  - cleve
- **glob ections**
- **Finalized calibrations** on physics objects (electrons, muons, jets, photons) and pushed **object definitions to lower energies**

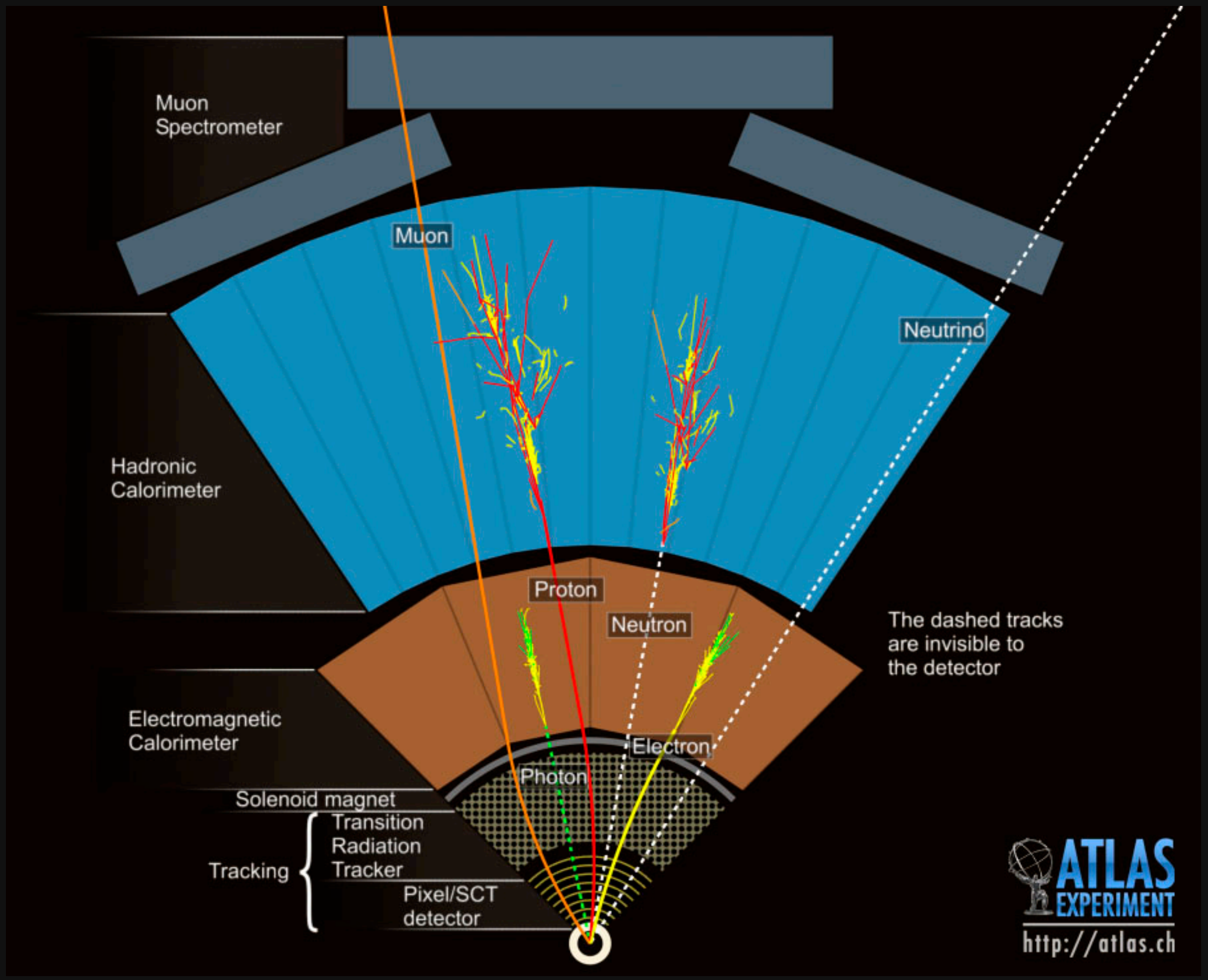
The Large Hadron Collider

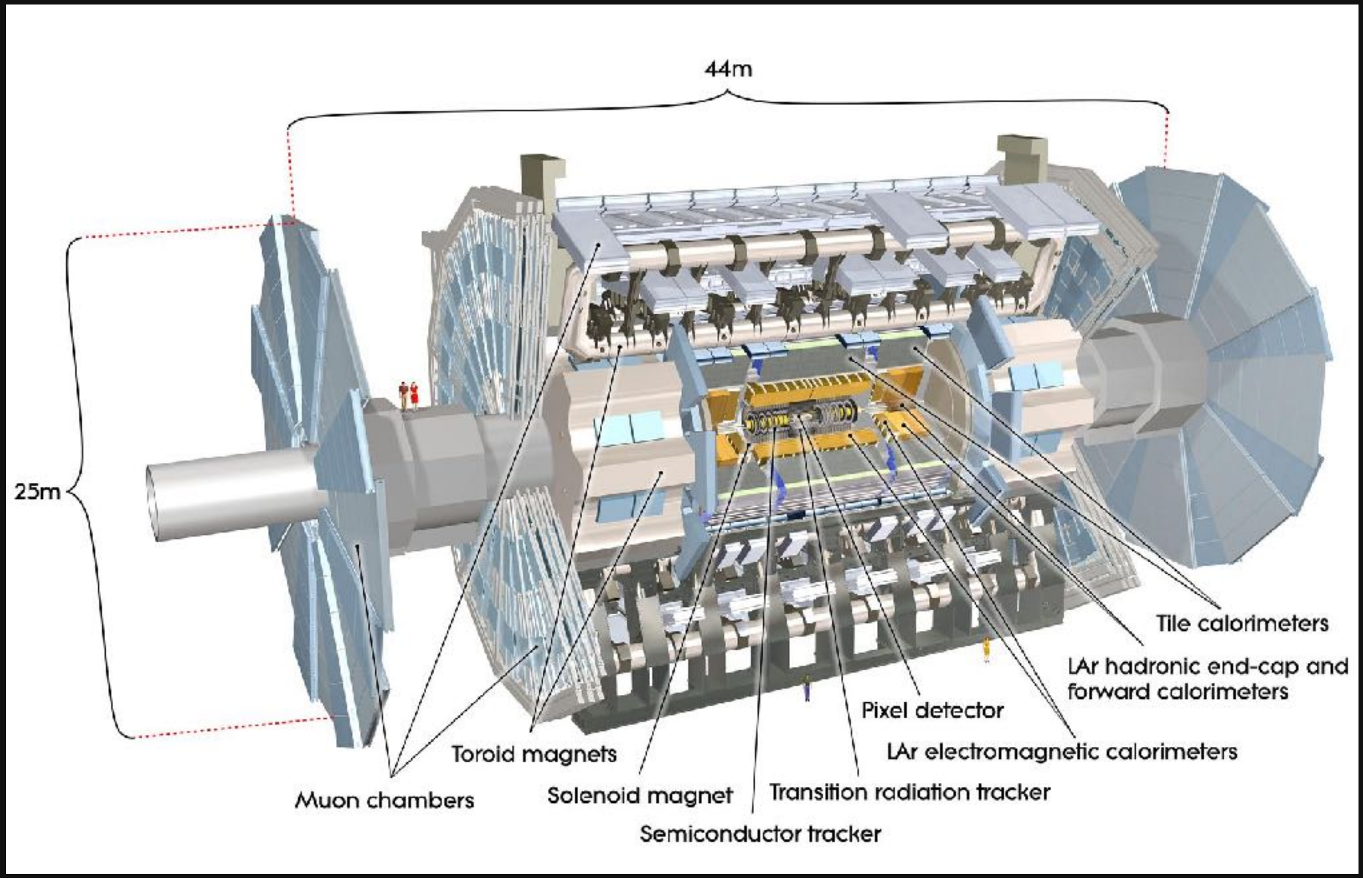


- **20 more years** of (HL-)LHC physics
- In 2015-2018: collected 5x more data than in the dataset where we discovered the Higgs
  - 40 million collisions per second (one every **25 ns**)
  - 90 petabytes/year of data

The ATLAS Detector

4 main subsystems: inner detector, muon spectrometer, calorimetery, and trigger

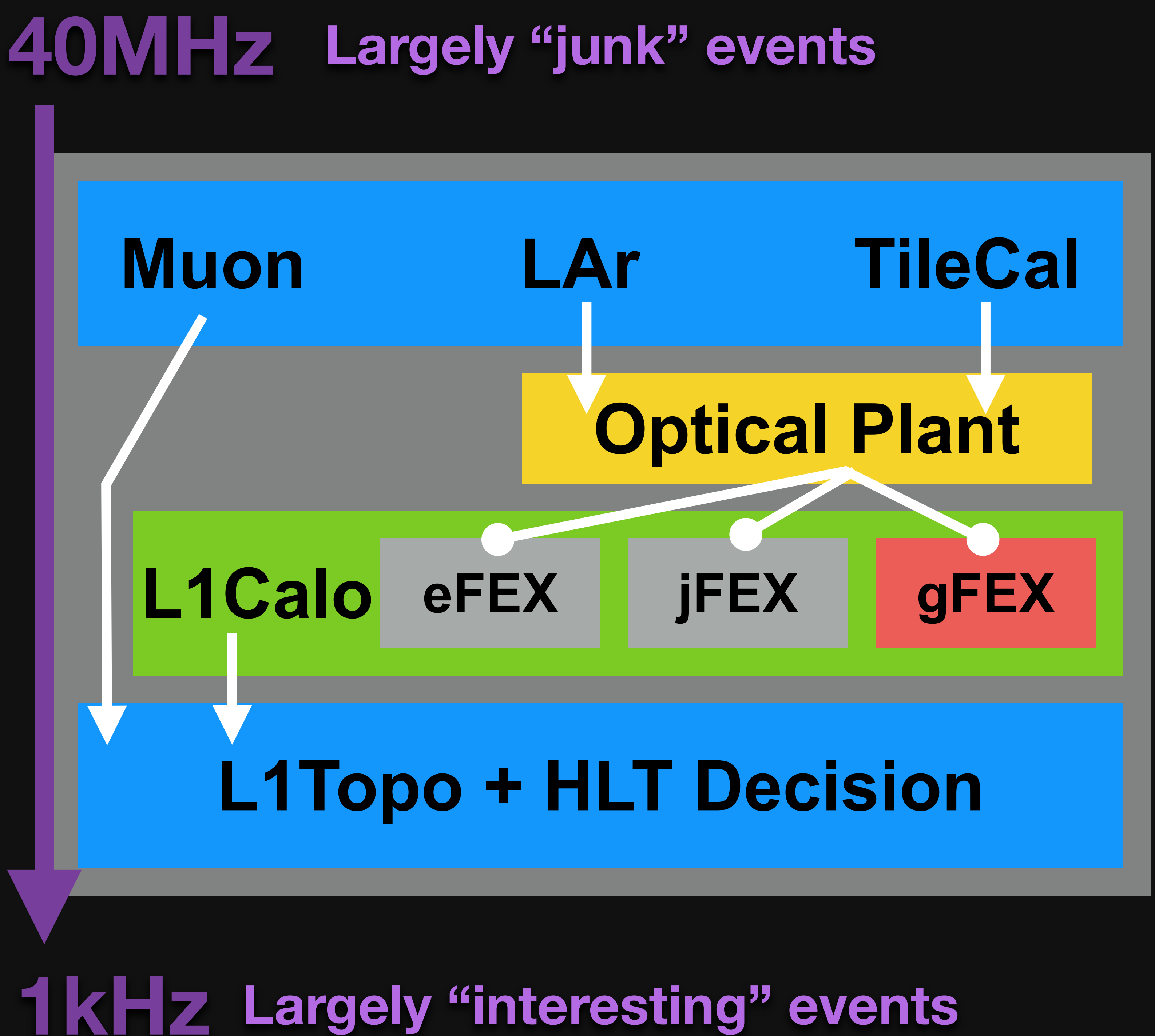




A single complex detector compromising many subsystems. Over 100 million electronic channels and **3000km of cables**!

⚠ One event/bunch-crossing has many simultaneous proton-proton collisions

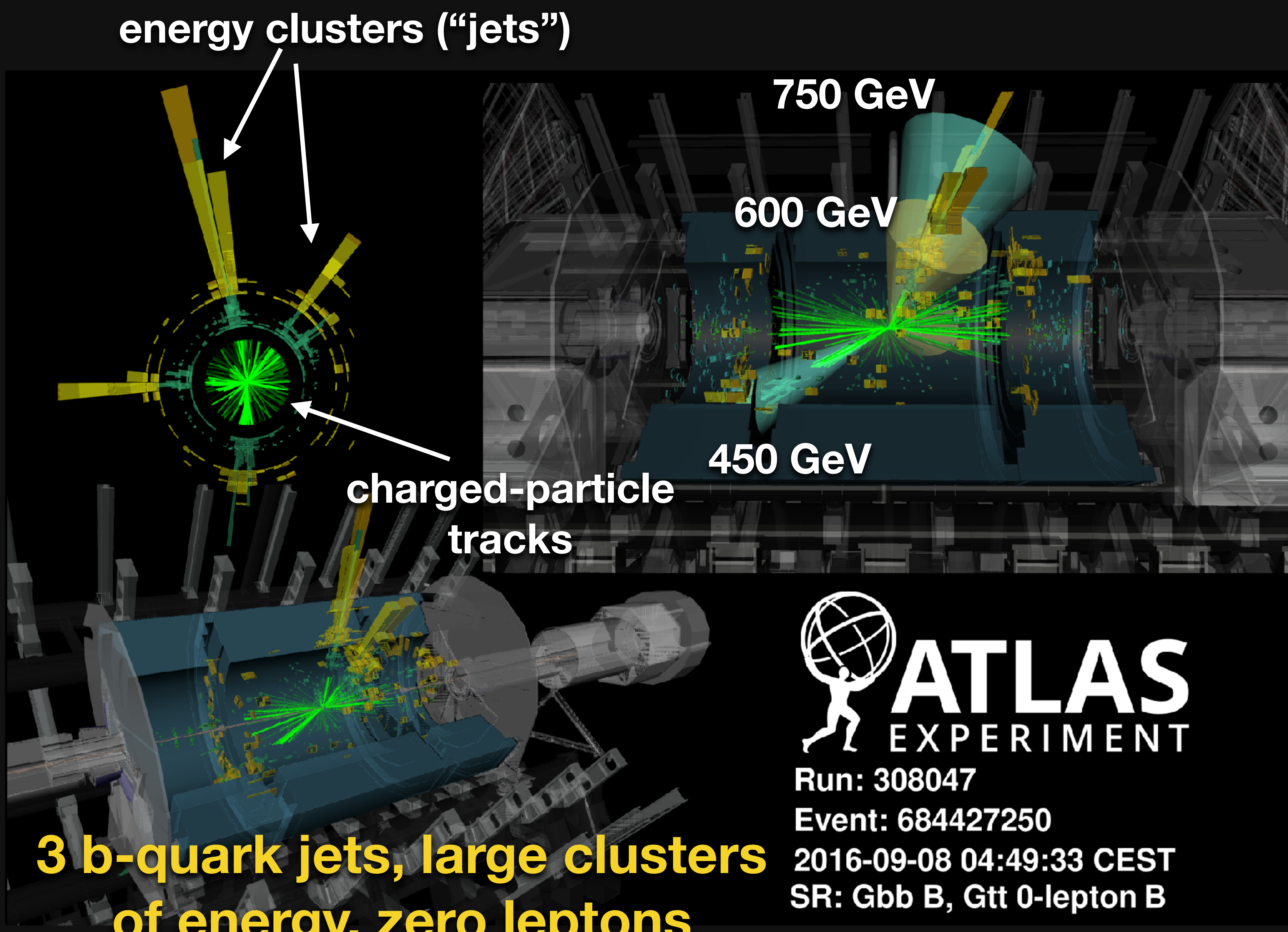
Calorimetry and Trigger



- The trigger system uses data from the calorimeters
- Bunches of protons collide 40 million times per second
  - Can only save ~1000 events per second 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

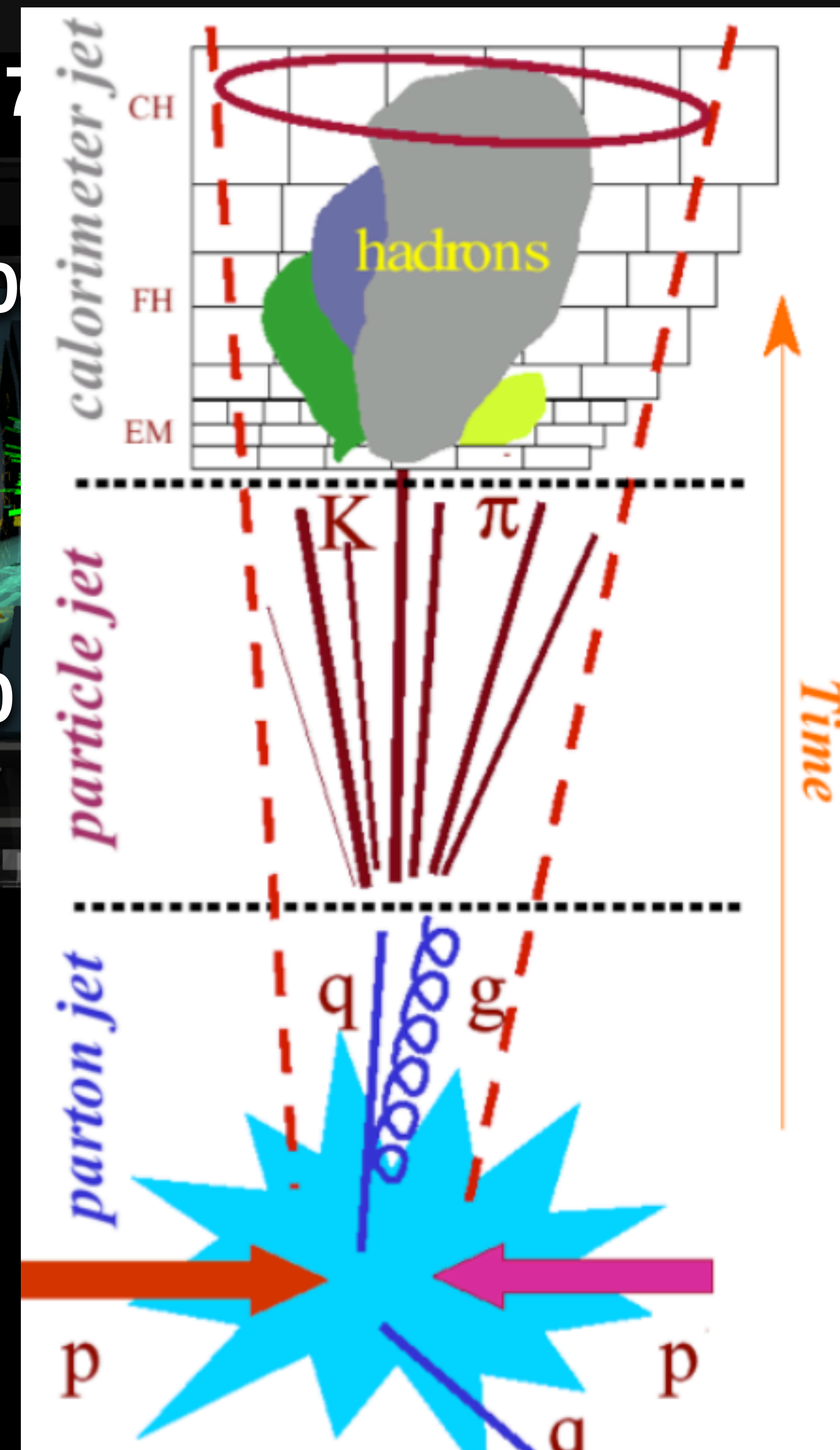
? Make a selection to **keep** or **throw away** data forever

A fully reconstructed event



A fully reconstructed event

energy clusters ("jets")

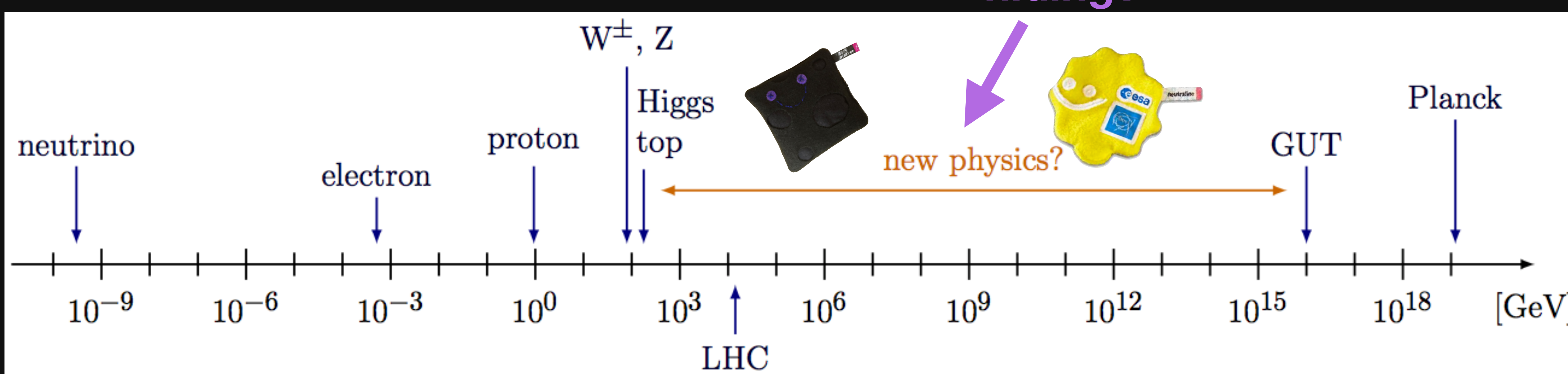


David Miller (2011)

3 b-quark jets, large clusters of energy, zero leptons

Searching for SUSY

Where is SUSY hiding?

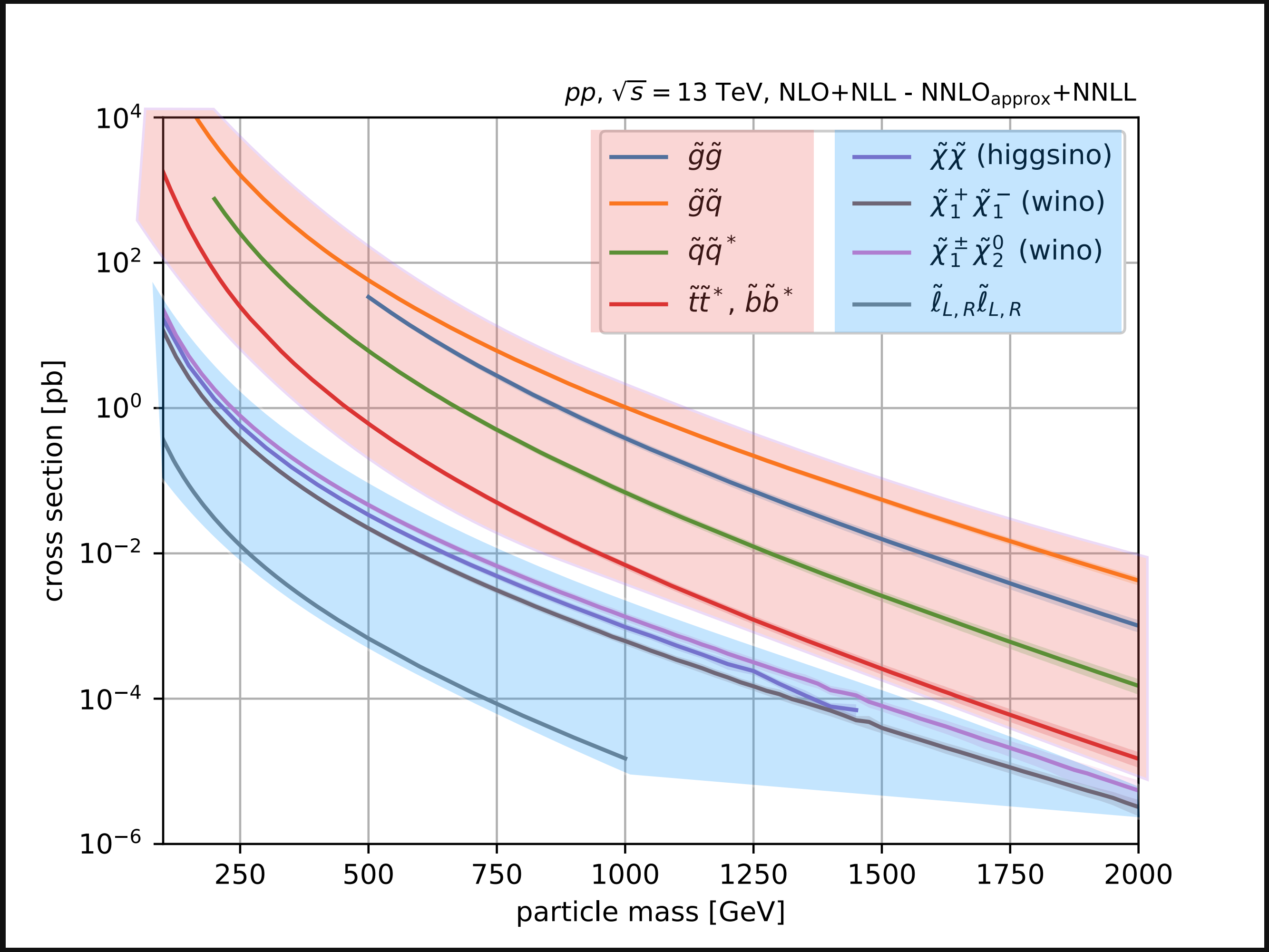


"SUSY is just around the corner."
— Carlos Wagner

❗ "Naturalness" motivates light gluinos and stops

Maybe gluinos/squarks?

- LHC at 13 TeV well-motivated to search for SUSY (*some searches are possible for the first time!*)
- **Gluinos and squarks**, with large color coupling, have highest cross-section in SUSY
- **Electroweak-produced** sparticles are subdominant



Search for strongly-produced sparticles!

(electroweak states may be first detected if high mass limits on strong production)

https://arxiv.org/abs/1605.01416
https://arxiv.org/abs/1711.01901

What does SUSY look like?

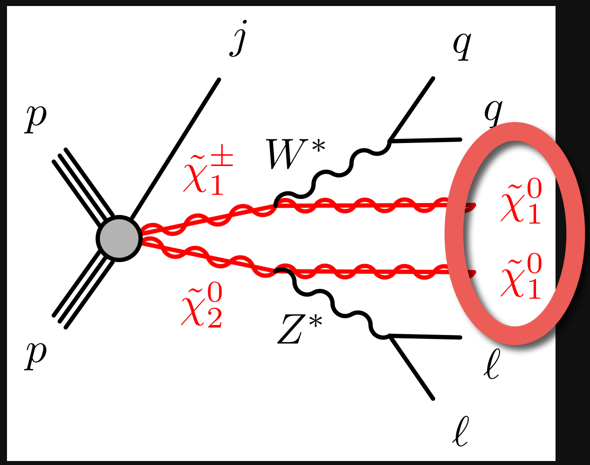
Lots of kinematics! Grouped into three categories:

https://arxiv.org/abs/1605.01416
https://arxiv.org/abs/1711.01901

What does SUSY look like?

Lots of kinematics! Grouped into three categories:

- **Missing momentum-type**: sensitive to the properties of the invisible states
  - **how many neutralinos in the event? (*RPC: LSP escapes detection*)**

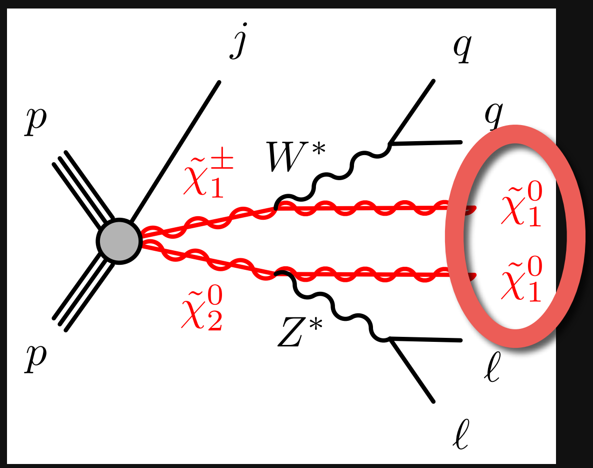


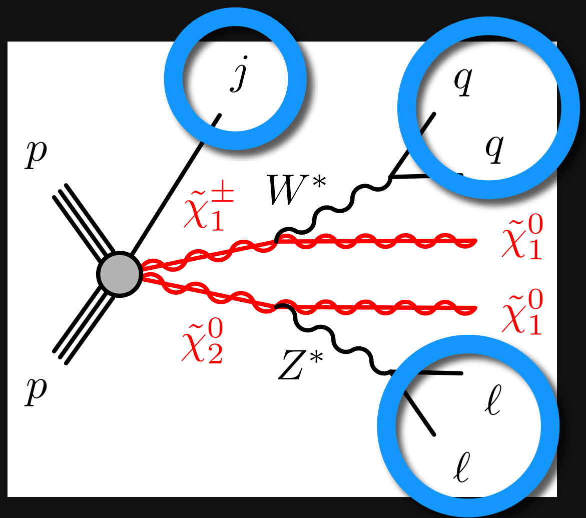
https://arxiv.org/abs/1605.01416
https://arxiv.org/abs/1711.01901

What does SUSY look like?

Lots of kinematics! Grouped into three categories:

- **Missing momentum-type**: sensitive to the properties of the invisible states
  - ? **how many neutralinos in the event? (*RPC: LSP escapes detection*)**
- **Energy scale-type**: sensitive to the overall energy scale of the event
  - ? **how much energy in the event? (*SUSY can reach high mass scales*)**



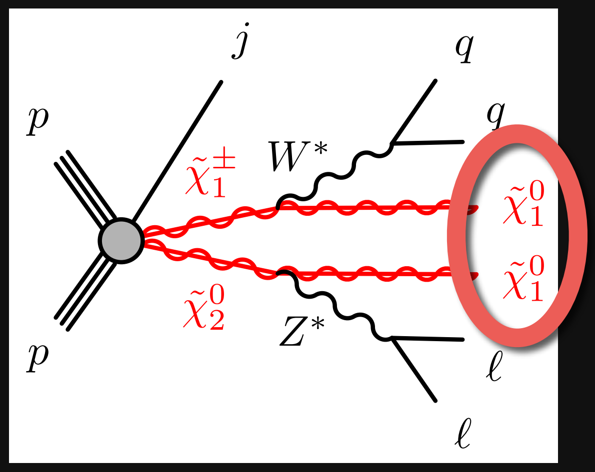


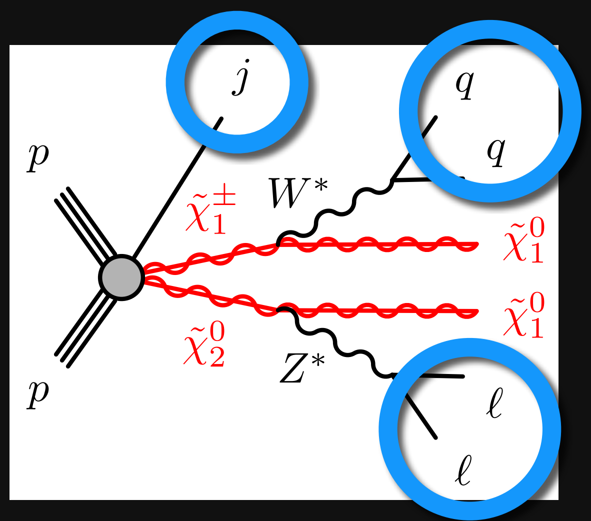
https://arxiv.org/abs/1605.01416
https://arxiv.org/abs/1711.01901

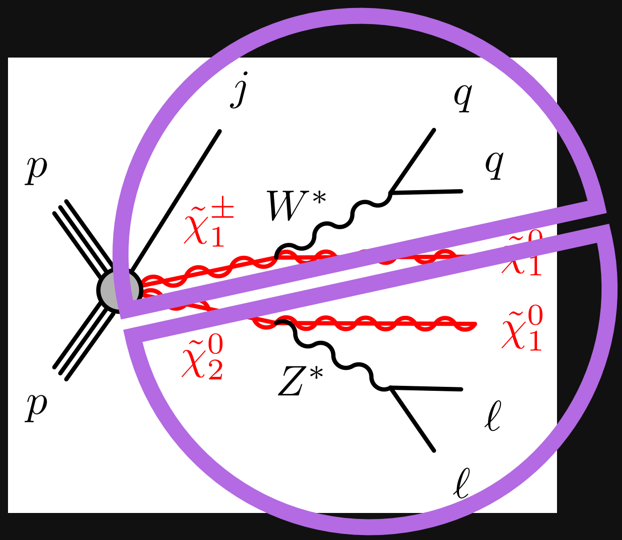
What does SUSY look like?

Lots of kinematics! Grouped into three categories:

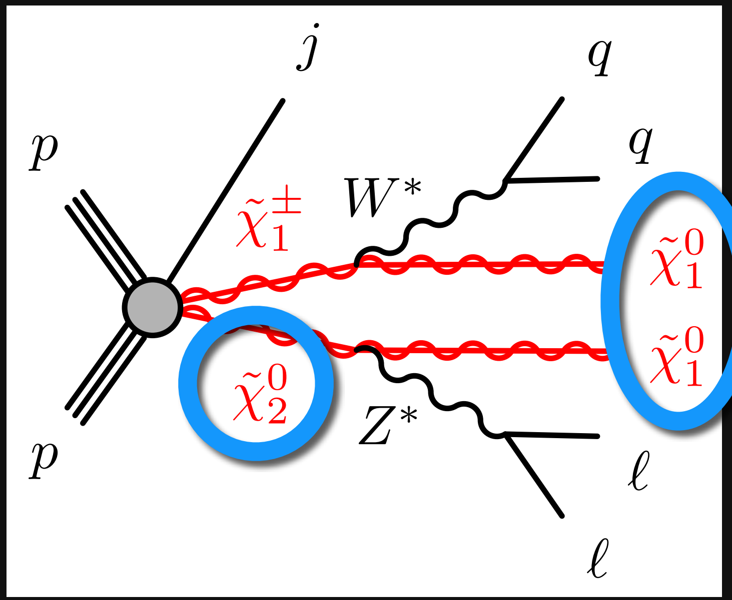
- **Missing momentum-type**: sensitive to the properties of the invisible states
  - **how many neutralinos in the event? (*RPC: LSP escapes detection*)**
- **Energy scale-type**: sensitive to the overall energy scale of the event
  - **how much energy in the event? (*SUSY can reach high mass scales*)**
- **Energy structure-type**: sensitive to the structure of the visible energy
  - **how is the energy of the decay partitioned across the final state visible/invisible objects? *(e.g. decay angle between LSP and jets)***







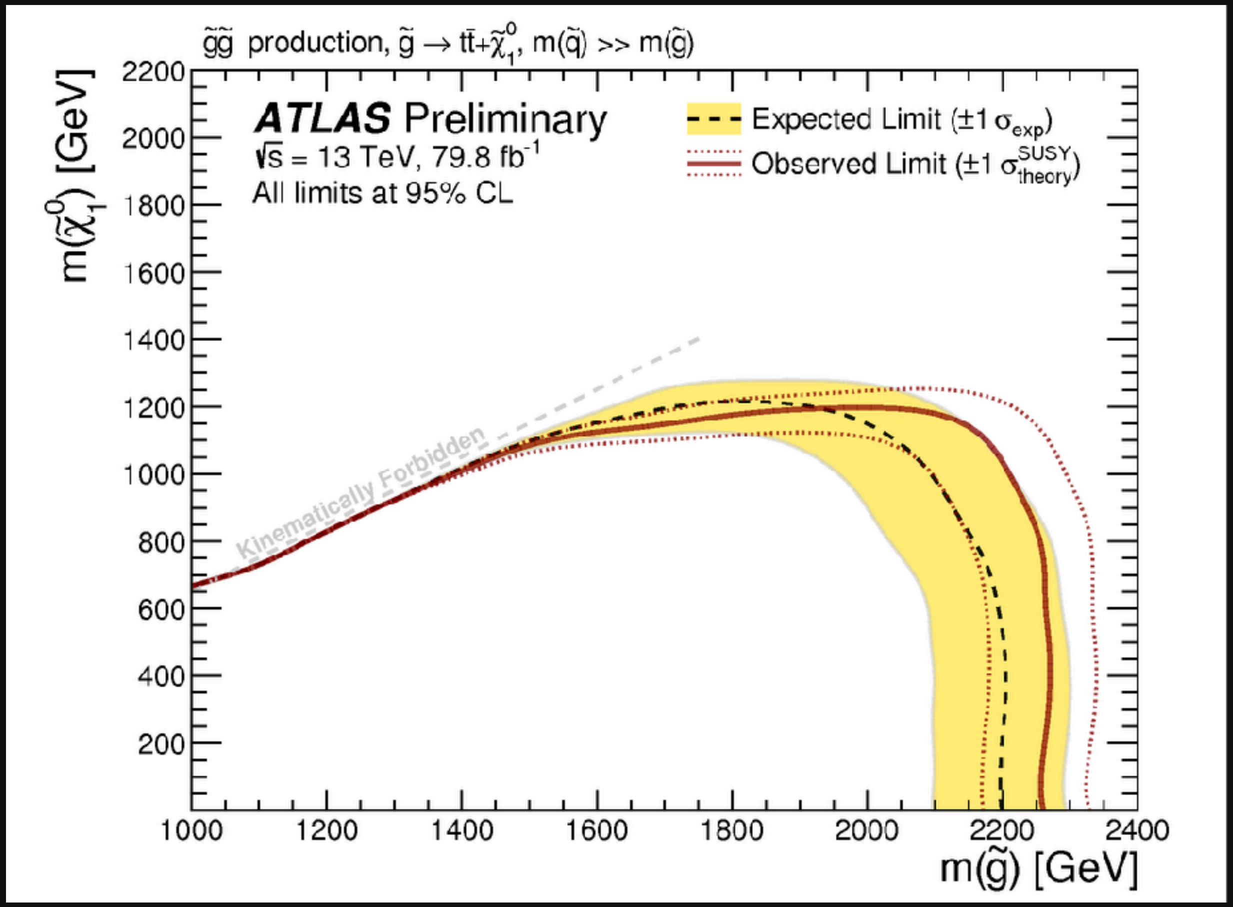
Interpreting Results



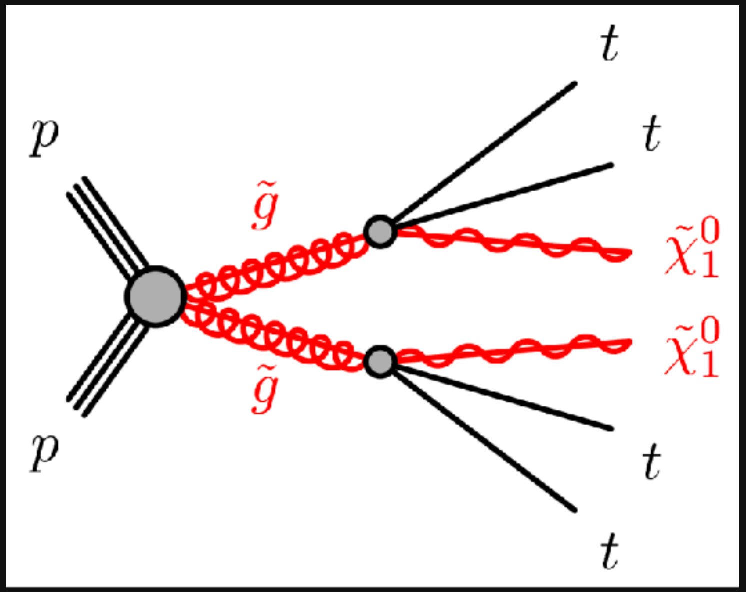
https://arxiv.org/abs/1605.09318
https://arxiv.org/abs/1711.01901

2018

(My thesis analysis)



Limit on gluino mass ~2.20 TeV @ 95% CL



gluino-mediated stop pair production

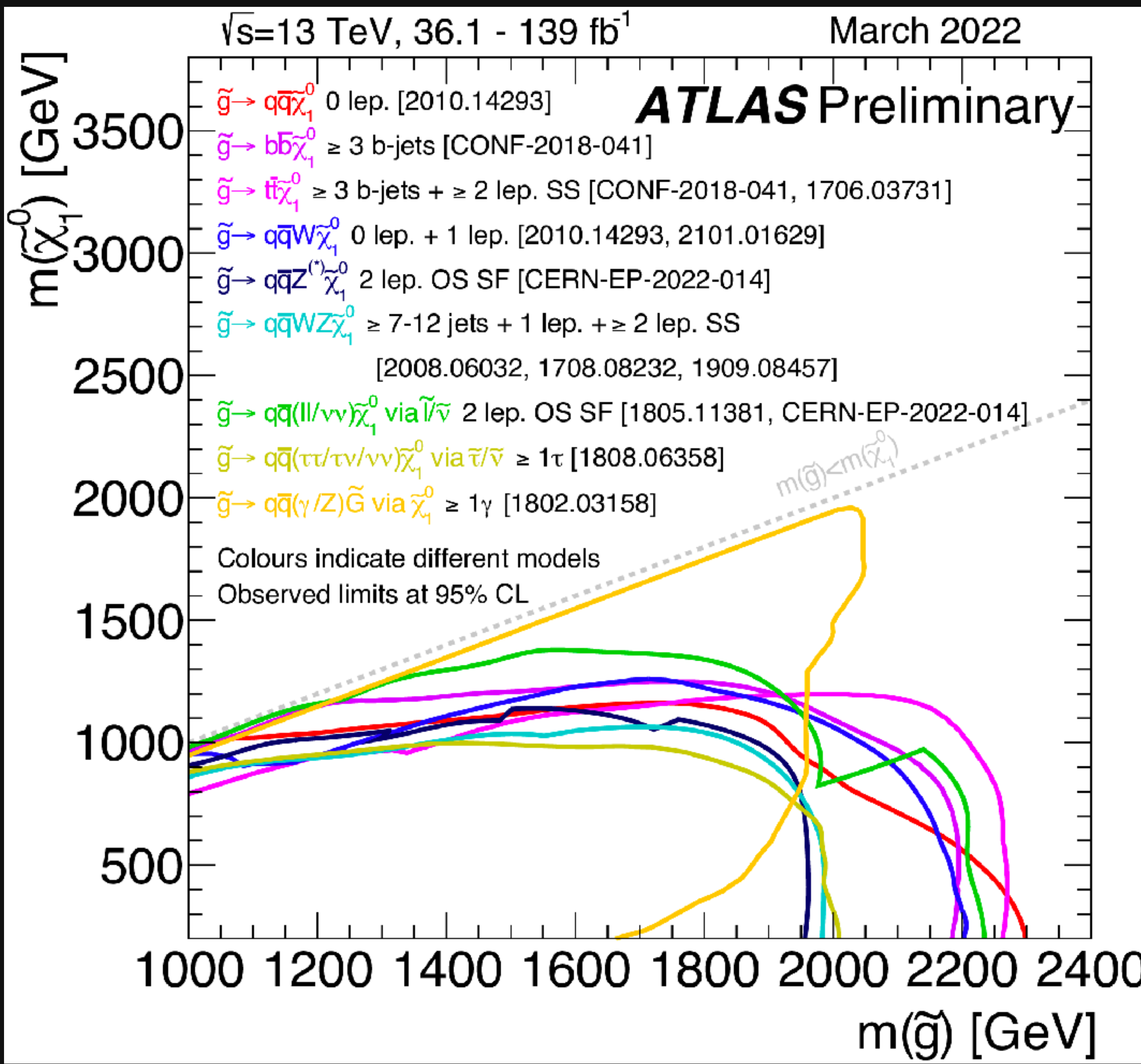
- No SUSY found here. (but I finished my PhD!)

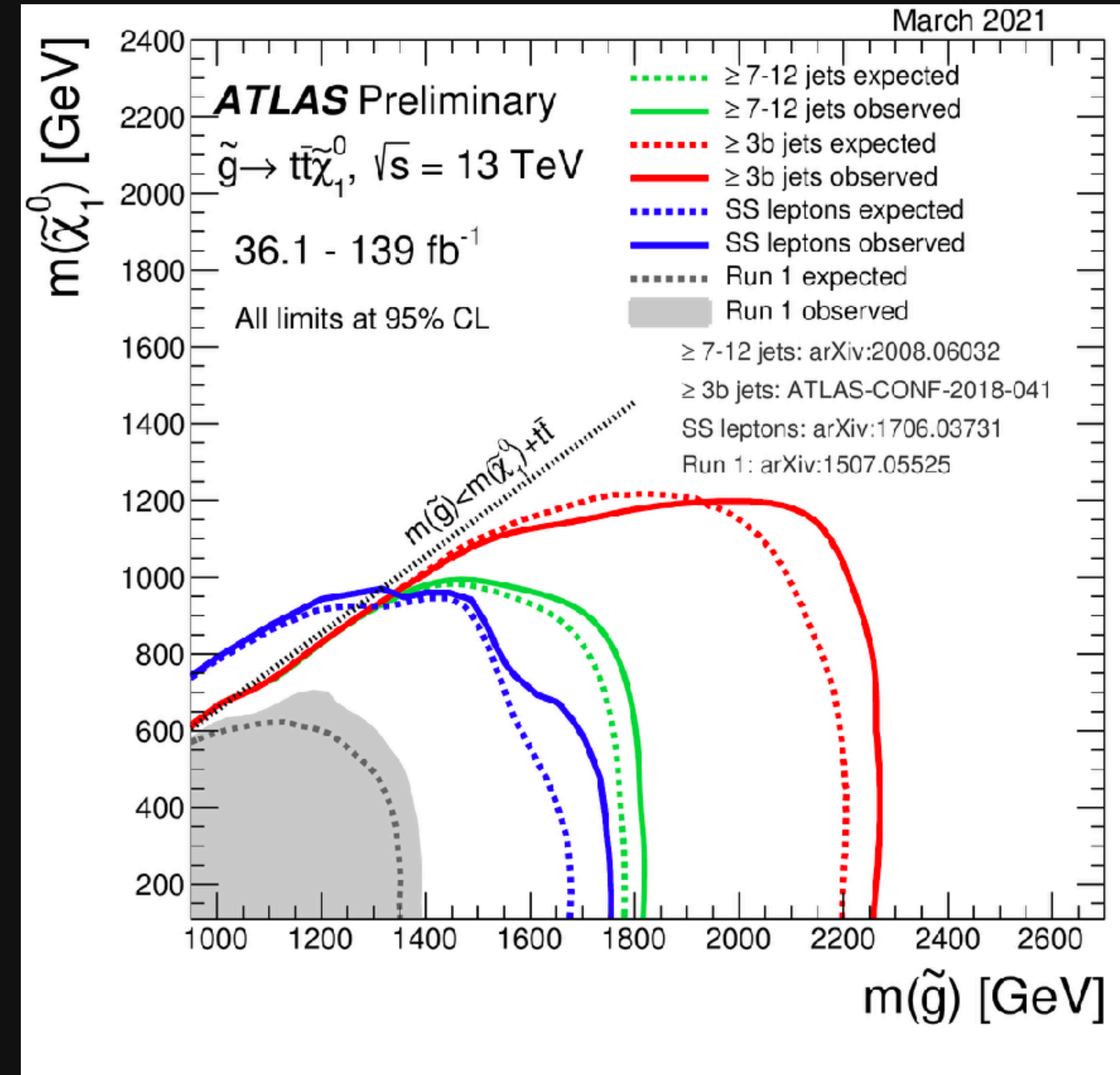
Search for strongly-produced sparticles!

ATL-PHYS-PUB-2022-013

2022

And so far…





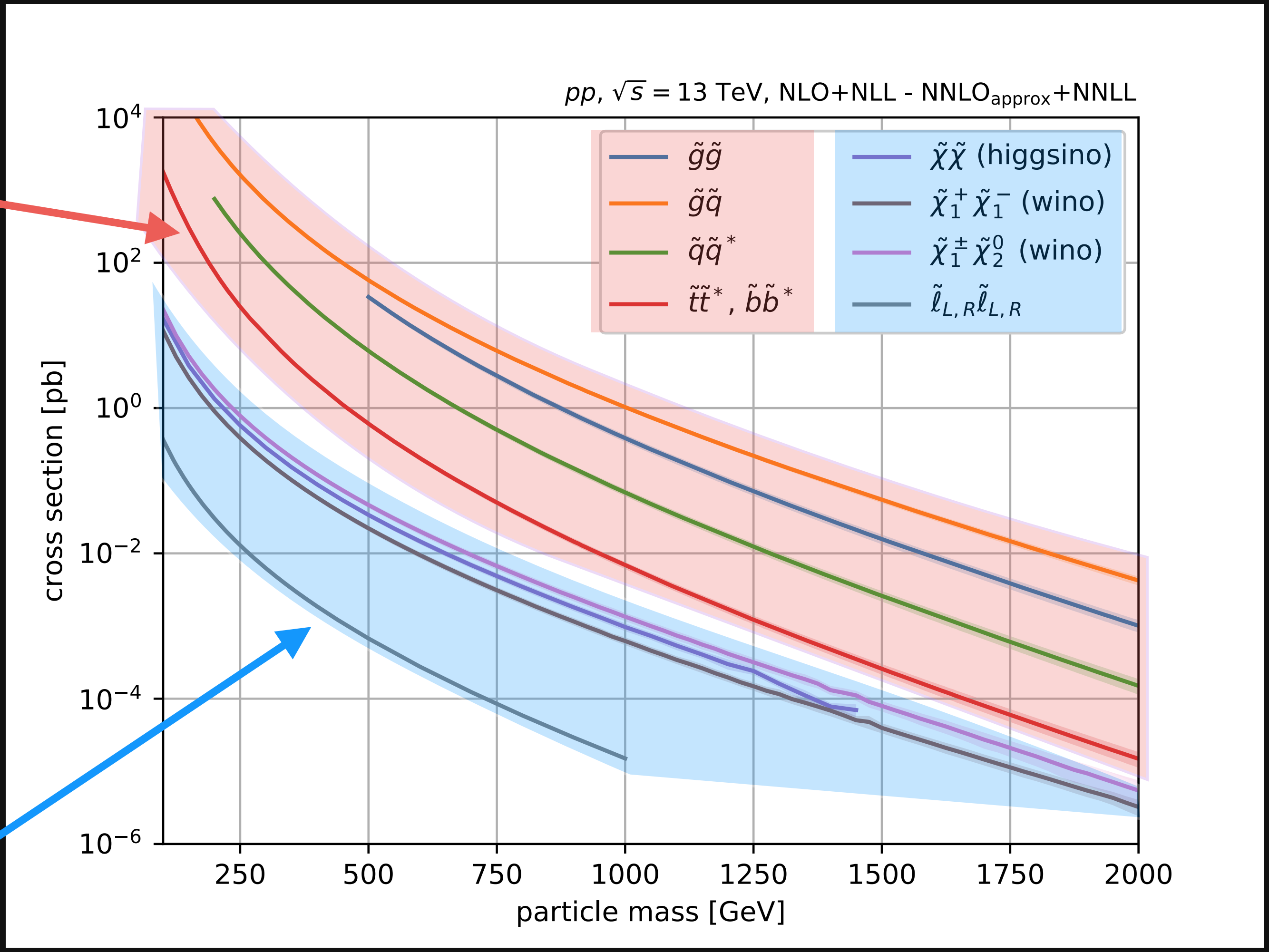
- No SUSY found here.
- Not really “light” anymore!
- Maybe we should look **somewhere** else!

each contour represents different interpretations of a SUSY model

Search for ~~strongly-produced~~ electroweakly-produced sparticles?

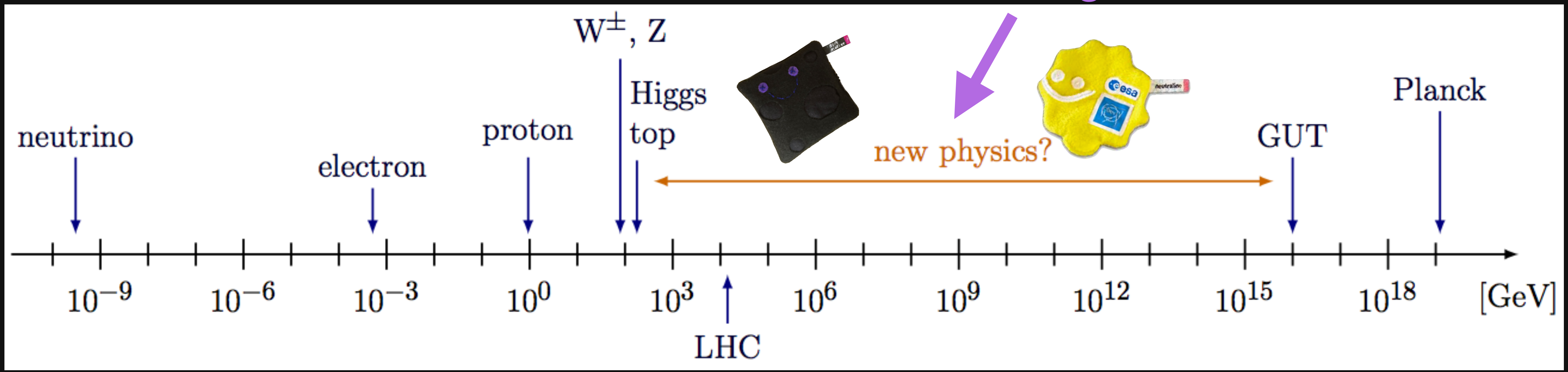
Questions so far

- Reaching the **energy limits** of our current machine searching for SUSY produced through strong interactions
- Bigger dataset → start hunting **rarer processes** to produce SUSY through electroweak interactions



Searching for EWK SUSY

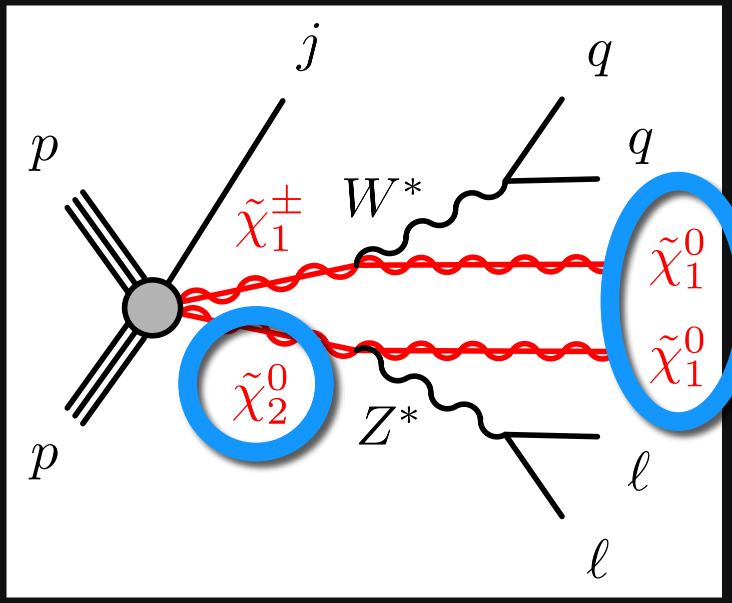
Where is SUSY hiding?

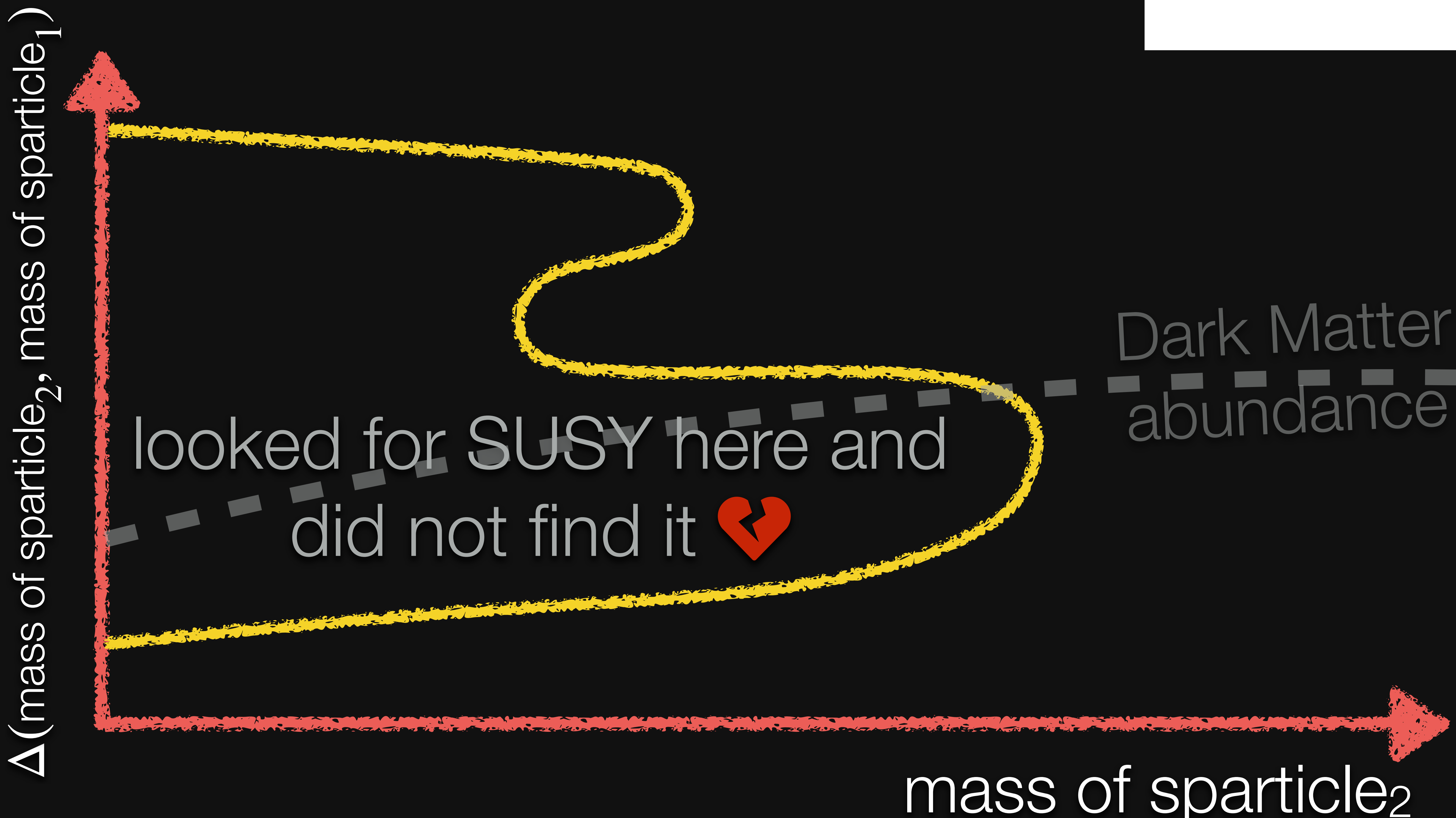


"SUSY is just around another corner."

— Giordon Stark

Interpreting Δm

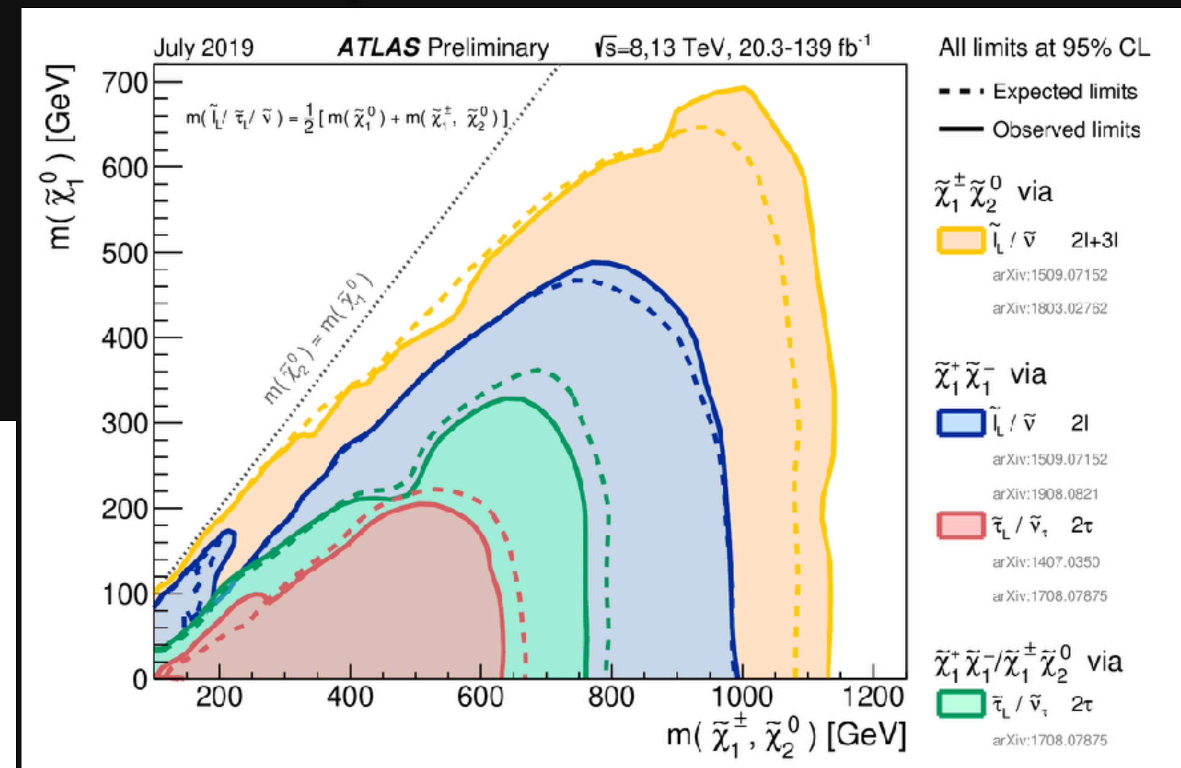




ATL-PHYS-PUB-2022-013

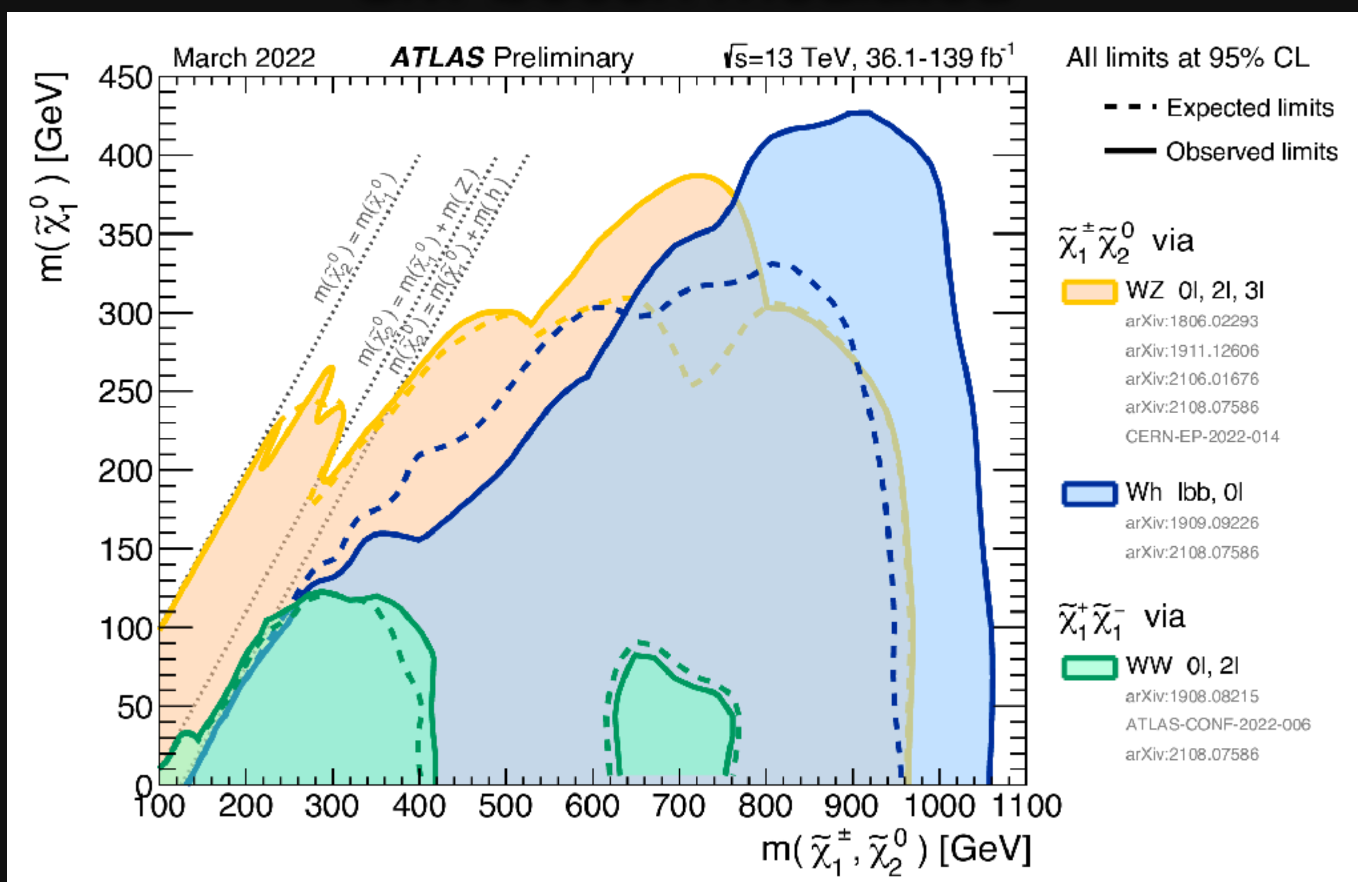
And so far…

lepton mediated



SM-boson mediated

$m(\tilde{\chi}_1^0)$



$m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0)$

- No SUSY found here.
- Maybe we should **combine** results!

each contour represents different interpretations of a SUSY model

What is our best understanding of the universe?

Questions so far

- ~~"Naturalness" isn't that well-motivated here, so perhaps SUSY is possibly electroweakly-produced?~~
  - 🔍 Keep searching using (upcoming) Run 3+ data
- How do we make sure that our analysis results are still **interpretable** with new phenomenology today?
- How do we **combine** different analysis results to constrain the allowed SUSY models?

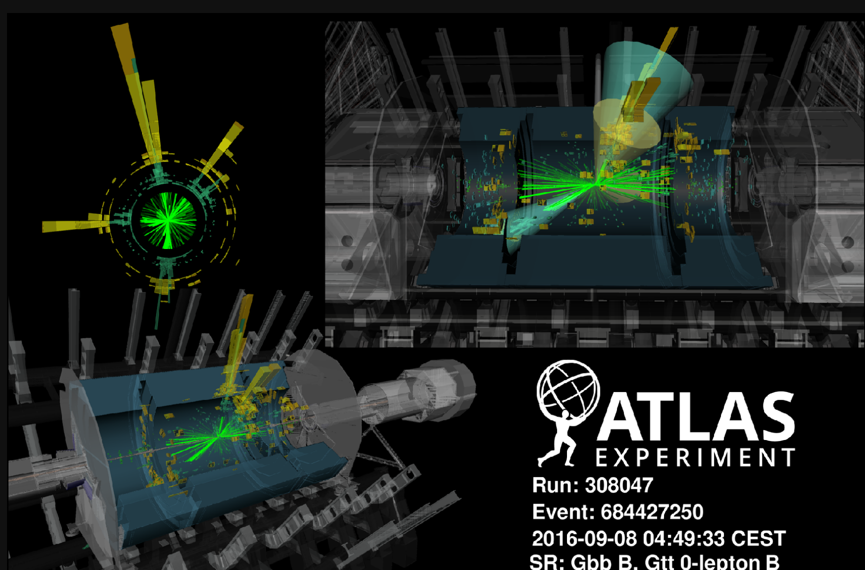
Statistical Techniques

How do experimentalists count?

"Do you know why they call me the Count? Because I love to count! Ah-hah-hah!" — The Count (of Sesame Street)

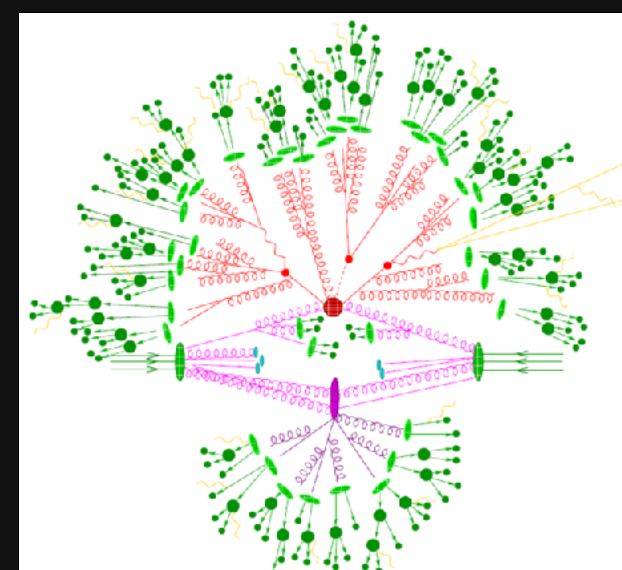
The Big Picture

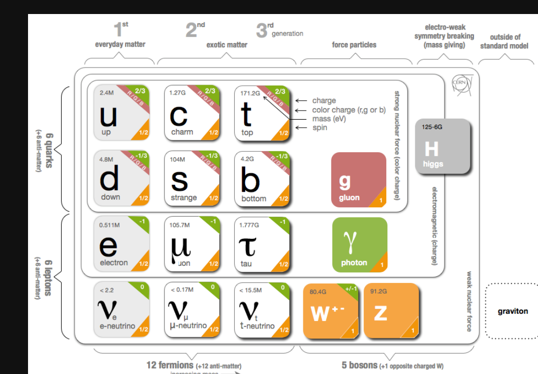
observations

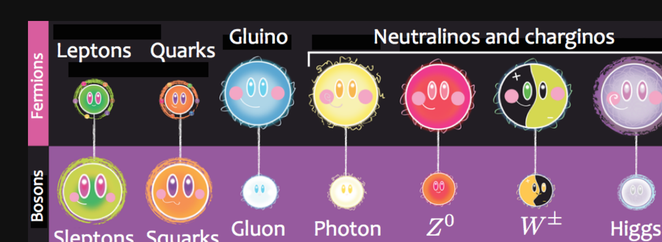


$p(\text{data} = \text{observed})$

model
(SM + SUSY)







$p(\text{theory})$

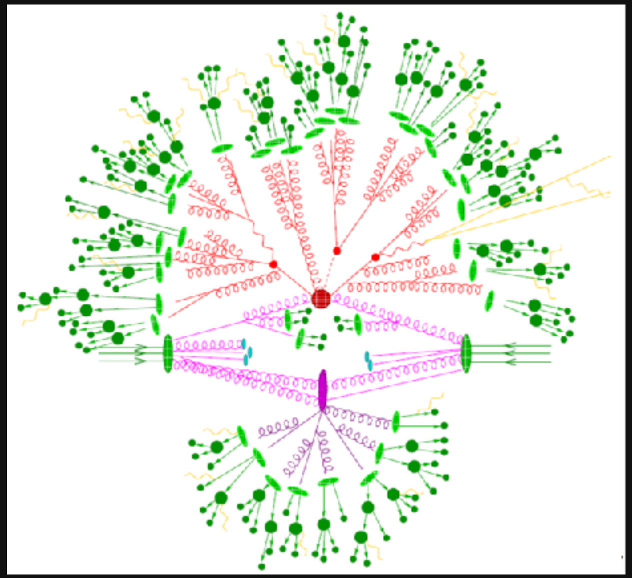
❗ **A likelihood function** encodes everything we know about the **detector**, the **theory**, and the **data**

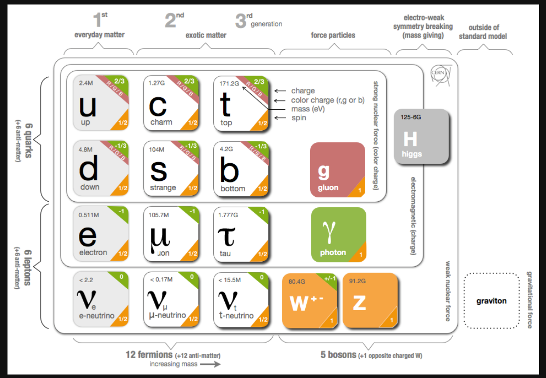
How good is our theory?

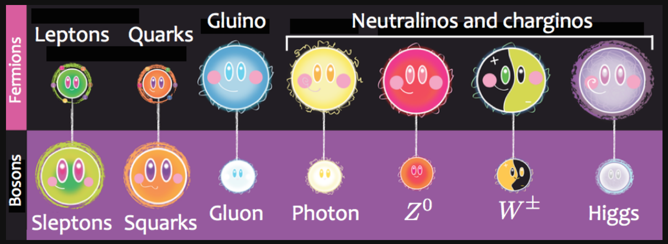
The Big Picture (I)

- Rely on our best **understanding of the theory**
  - Standard Model / Beyond the Standard Model (e.g. QED, QCD, MSSM)
  - Matrix Elements
  - Parton Distribution Functions
  - Finite Order in Perturbative Calculations (e.g. NLO, NNLO, etc…)
  - Parton Showering and Hadronization
- … and best **simulation of our detector**
  - Material Interactions
  - In-time and out-of-time pile-up
  - Calorimeter efficiency
  - Tracking efficiency
  - Magnetic field mapping
  - Beamspot origin
  - etc…

model
(SM + SUSY)





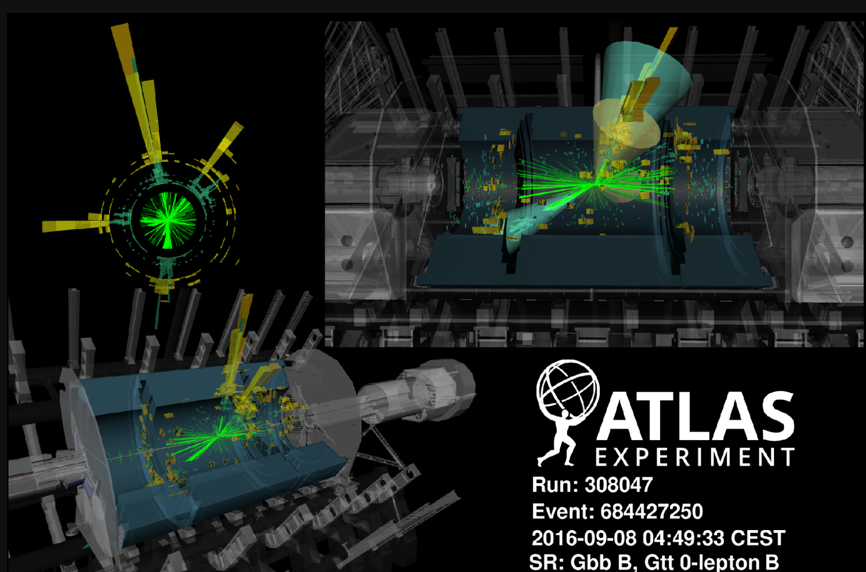


$p(\text{theory})$

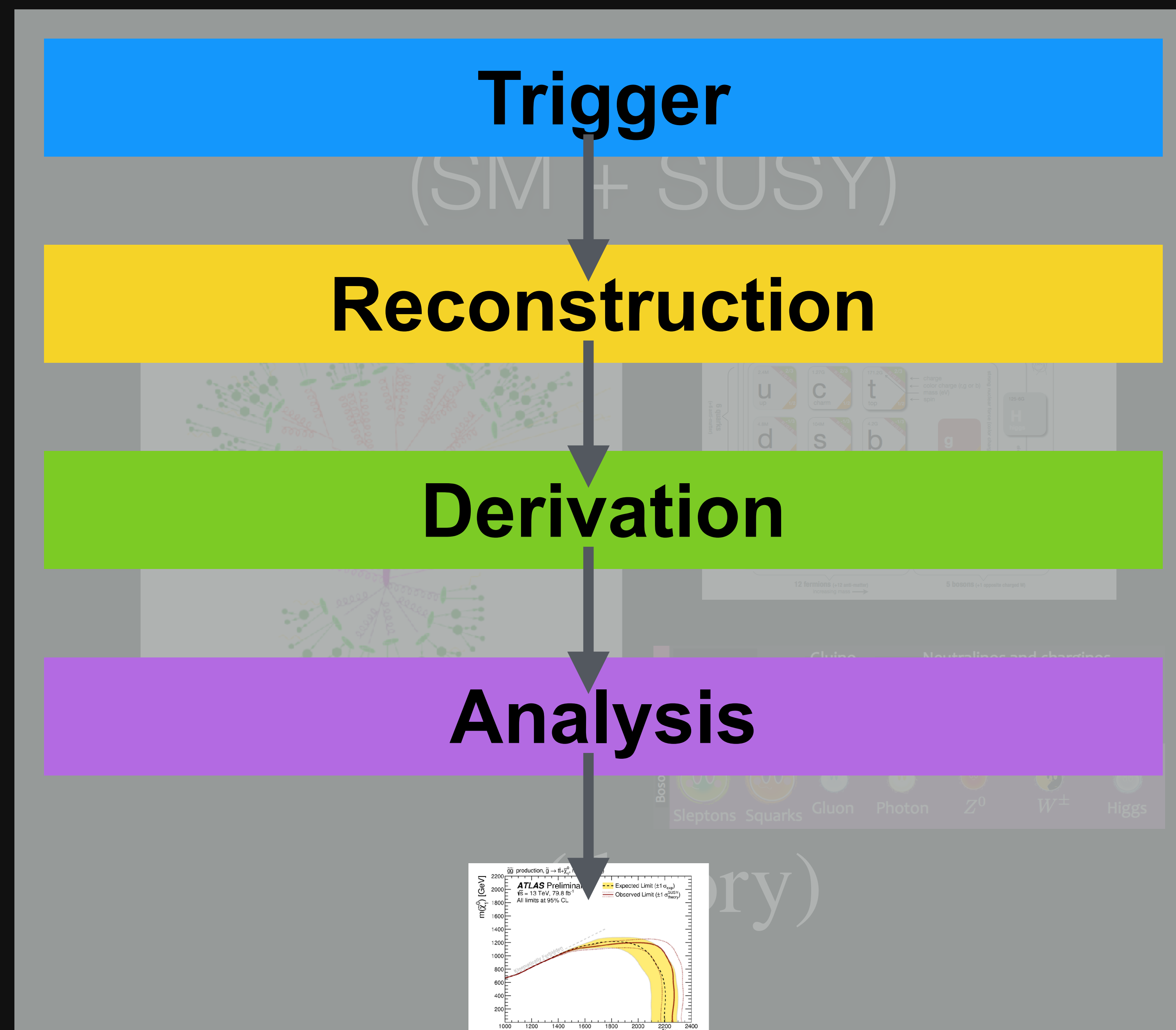
How good is our modeling?

The Big Picture (II)

observations



$p(\text{data} = \text{observed})$



arXiv:1207.7214
Phys. Rev. D 101, 052005

What is a statistical model?

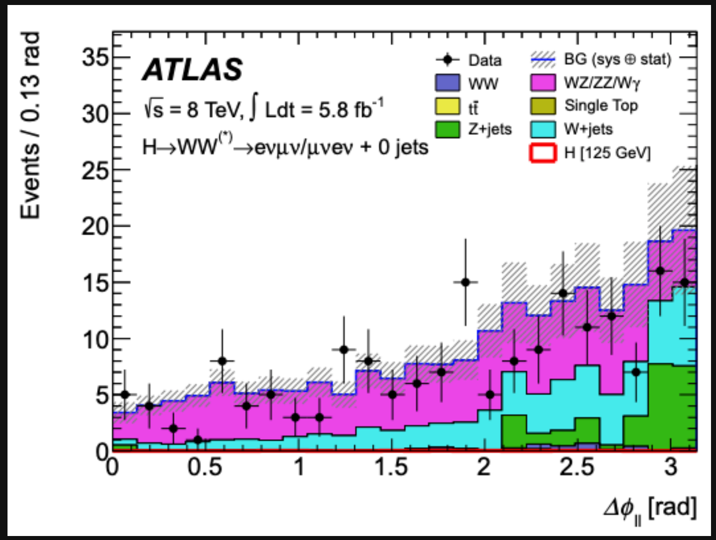
$$p(\text{data}\,|\,\text{theory})$$

- In a perfect world, we know the model.
- However, due to uncertainties and the high-dimensional phase-space, most analyses will only approximate the model, using a statistical model

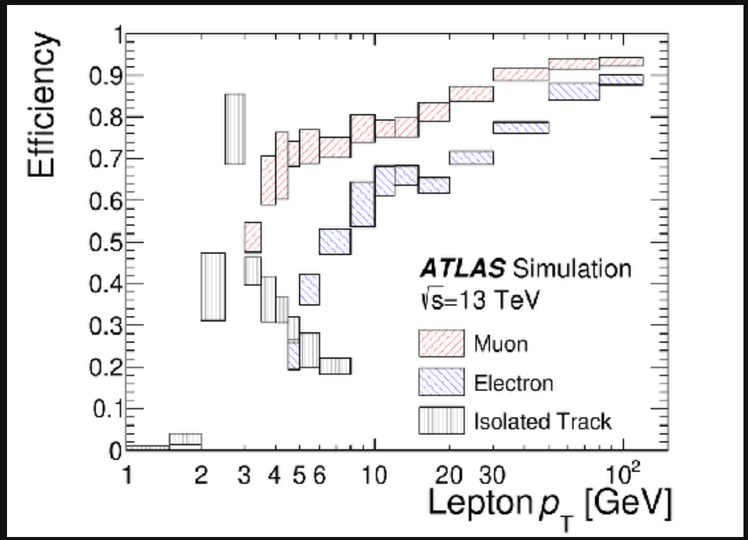
$$p_{\text{approx}} \equiv \hat{p}(q(x)\,|\,\text{theory})$$

- Make this more tractable by sampling from the true model and constructing an approximate likelihood

a projection of n-dimensional physics into one kinematic variable



how well can our ATLAS detector identify low p_T leptons?



A probability distribution function

arXiv:1207.7214
Phys. Rev. D 101, 052005

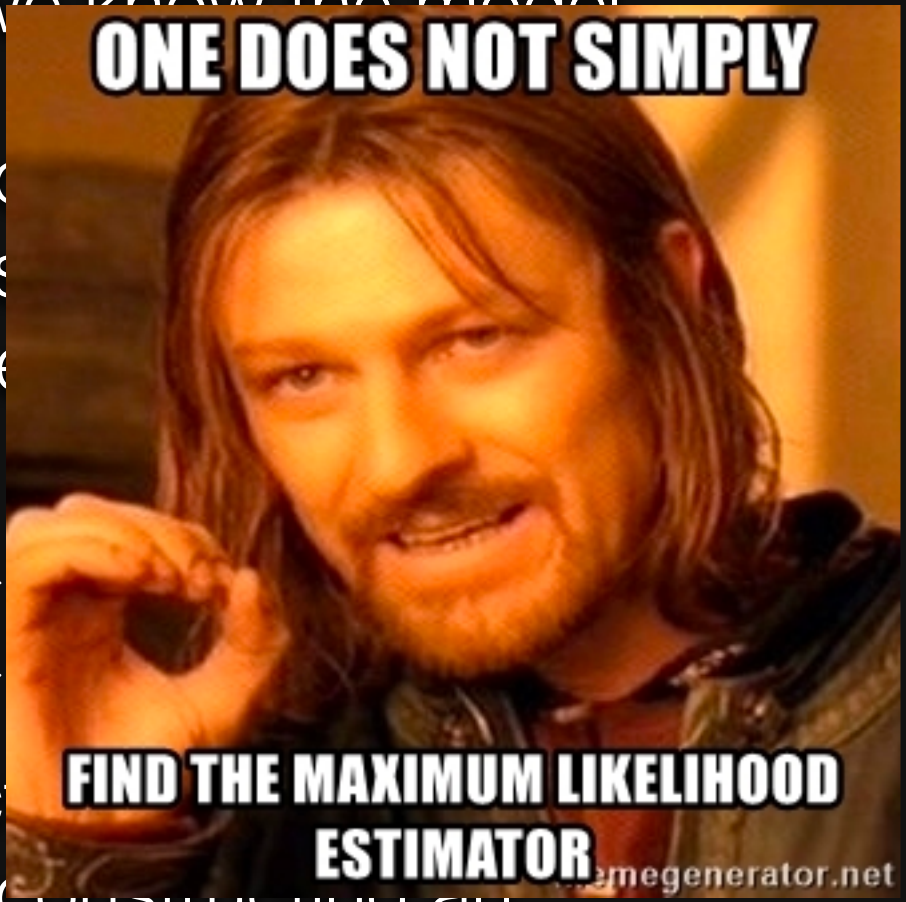
What is a statistical model?

$$p(\text{data}\,|\,\text{theory})$$

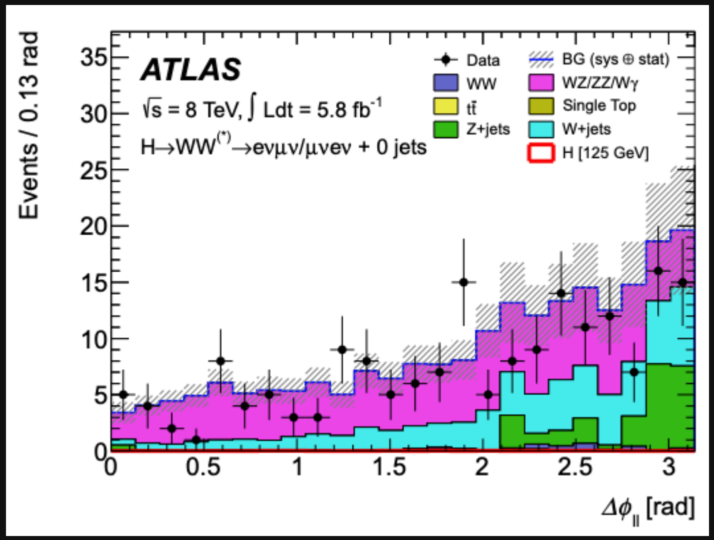
- In a perfect world, w
- However, due to unc dimensional phase-s will only approximate statistical model

$$p_{\text{approx}} \equiv \hat{p}($$

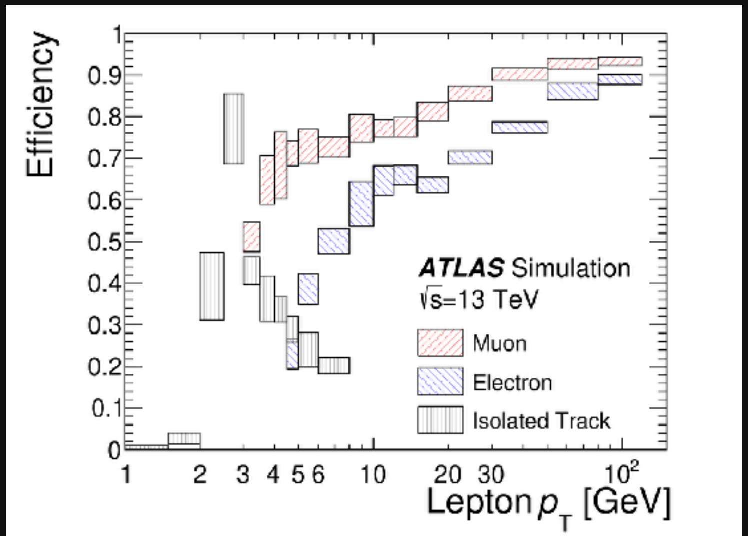
- Make this more trac the true model and c approximate likelihood



a projection of n-dimensional physics into one kinematic variable



how well can our ATLAS detector identify low p_{T} leptons?



A probability distribution function

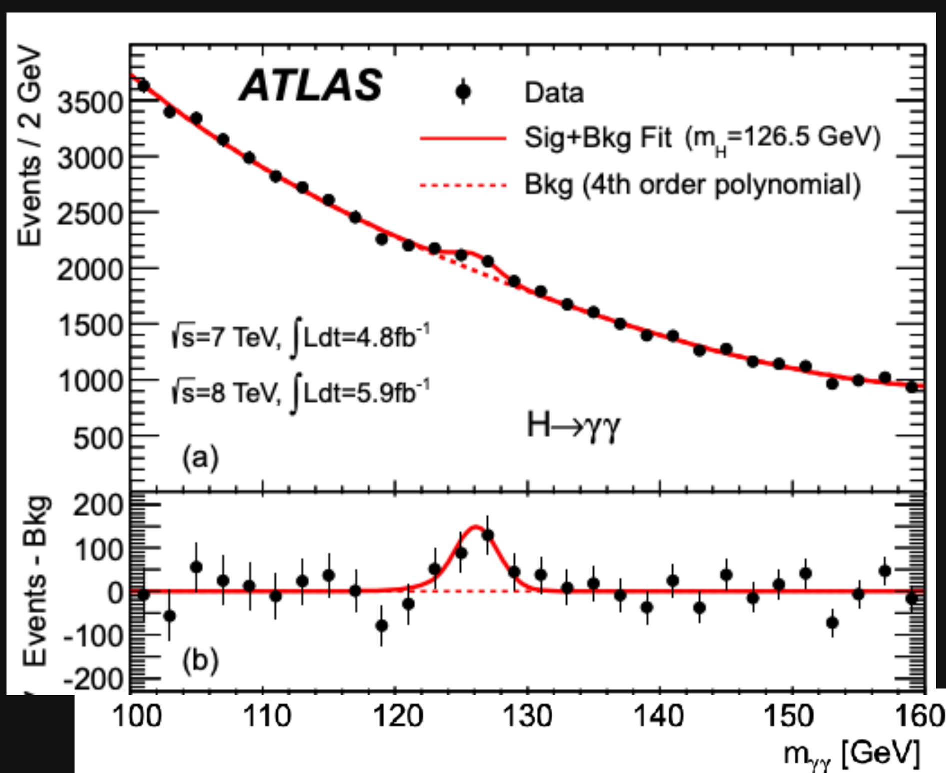
arXiv:1207.7214
Cowan (Statistical Data Analysis)
James (Statistical Methods in Experimental Physics)

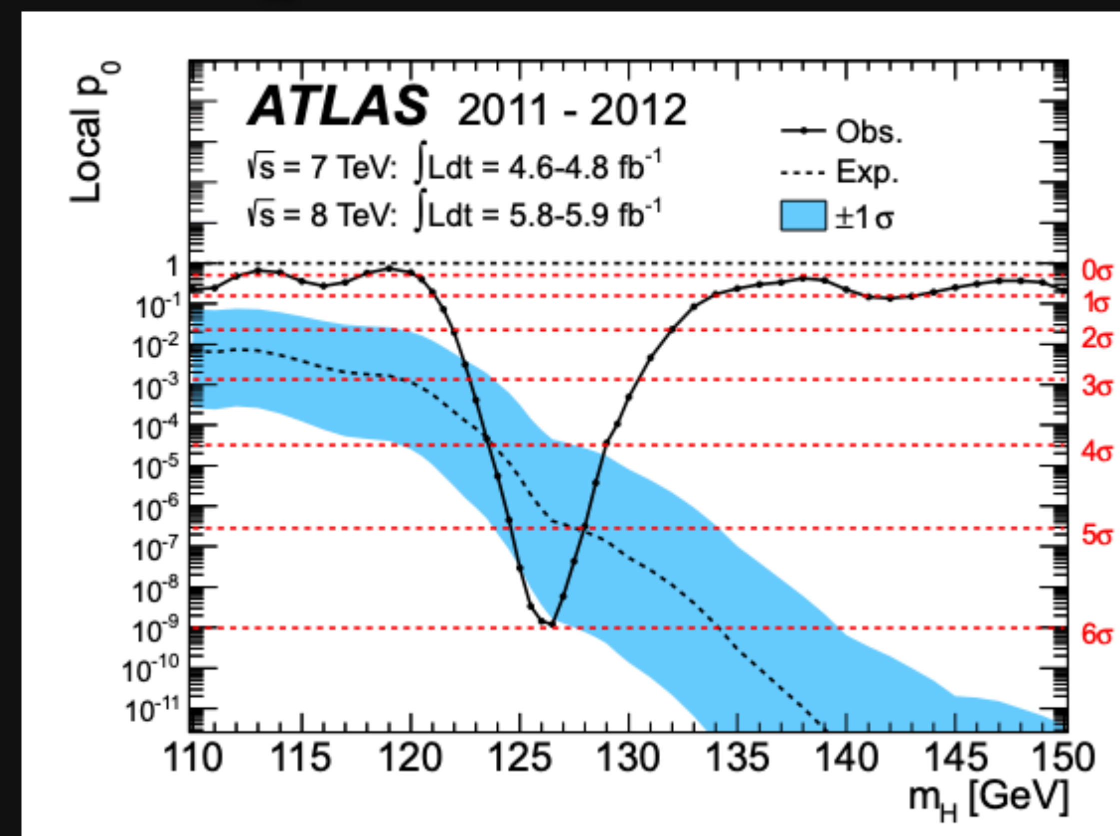
What is a statistical model?

$\hat{p}(\text{data}\,|\,\text{theory})$

Higgs discovery p-value $< 10^{-7}$

$m_h = 125.7 \pm 0.7$ GeV





- **Two statistical models in orange**
  - one representing "background" [SM, excluding Higgs]
  - one representing "signal+background" [SM, including Higgs mechanism]
- Using observations (black data points) and a statistical model, **inferences** include:
  - p-values
  - confidence intervals
  - limits
  - expected yields
  - data/MC comparisons, etc…

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	-
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	-
$W +$ jets	15 ± 7	2 ± 1	-
Total Background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

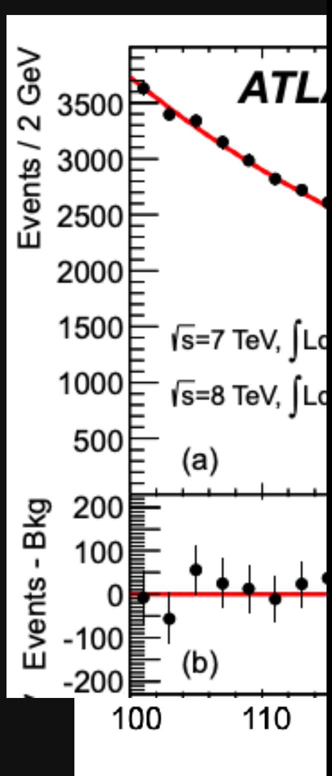
arXiv:1207.7214
[Cowan (Statistical Data Analysis)]()
[James (Statistical Methods in Experimental Physics)]()

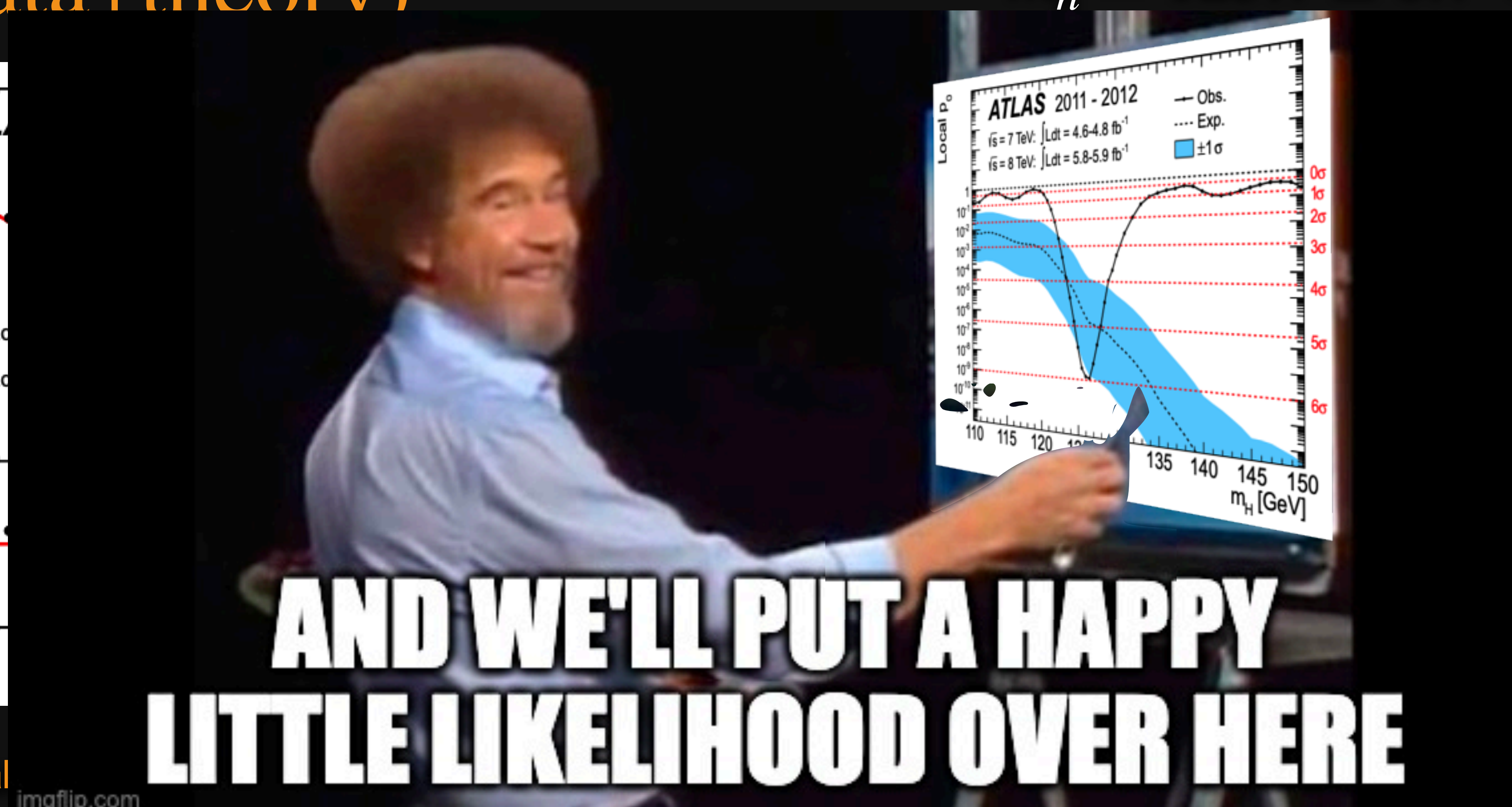
What is a statistical model?

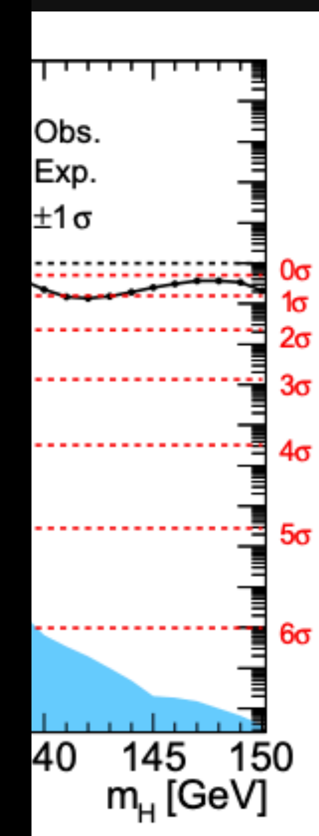
Higgs discovery p-value $< 10^{-7}$

$m_h = 125.7 \pm 0.7$ GeV

$\hat{p}(\text{data} \mid \text{theory})$







- **Two statistical**
  - one representing "background" [SM, excluding Higgs]
  - one representing "signal+background" [SM, including Higgs mechanism]

inferences include:

- p-values
- confidence intervals
- limits
- expected yields
- data/MC comparisons, etc…

	[illegible]	1-jet	2-jet
Signal	[illegible]	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	-
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	-
$W +$ jets	15 ± 7	2 ± 1	-
Total Background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

https://indico.cern.ch/event/100458/

12 years ago…

he was also at this workshop

Jason Nielsen
SCIPP director

The situation 10 years ago...

CENTER FOR COSMOLOGY AND PARTICLE PHYSICS

Origins I: The First "Statistics in HEP" conference

WORKSHOP ON CONFIDENCE LIMITS

CERN, Geneva, Switzerland
17–18 January 2000

CERN 2000–005

Massimo Corradi

Does everybody agree on this statement, to publish likelihoods?

Louis Lyons

Any disagreement? Carried unanimously. That's actually quite an achievement for this Workshop.

...[Fred James wants to be able to calculate coverage, Don Groom wants to able to calculate goodness of fit]...

Cousins

I thought the point of unanimity was that publishing the likelihood function was a *necessary* condition, not a sufficient condition.

But a practical problem remained: *How* to communicate multi-D likelihood?

http://indico.cern.ch/conferenceDisplay.py?confId=100458

⚠ ATLAS reminded everyone that we all agreed in 2000 to publish likelihoods!

https://indico.cern.ch/event/100458/

he was also at this workshop

Jason Nielsen
SCIPP director

⚠ ATLAS reminded everyone that we all agreed in 2000 to publish likelihoods!

So we (3) did it…

THE MAIN DEVELOPERS

G. Stark

M. Feickert

L. Heinrich

pyhf
differentiable
Likelihoods

New open release streamlines interactions with theoretical physicists

The ATLAS Collaboration has released the first open likelihoods from an LHC experiment.

12th December 2019 | By Katarina Anthony

Explore ATLAS open likelihoods on the HEPData platform. (Original image: Ahmet Anil Sen/Behance)

https://atlas.cern/updates/news/new-open-likelihoods

Courtesy of CERN

ATLAS releases 'full orchestra' of analysis instruments

01/14/21 | By Stephanie Melchor

The ATLAS collaboration has begun to publish likelihood functions, information that will allow researchers to better understand and use their experiment's data in future analyses.

Meyrin, Switzerland, sits serenely near the Swiss-French border, surrounded by green fields and the beautiful Rhône river. But a hundred

https://www.symmetrymagazine.org/article/atlas-releases-full-orchestra-of-analysis-instruments

ATLAS-CONF-2019-011 JHEP12(2019)060 ATL-PHYS-PUB-2019-029

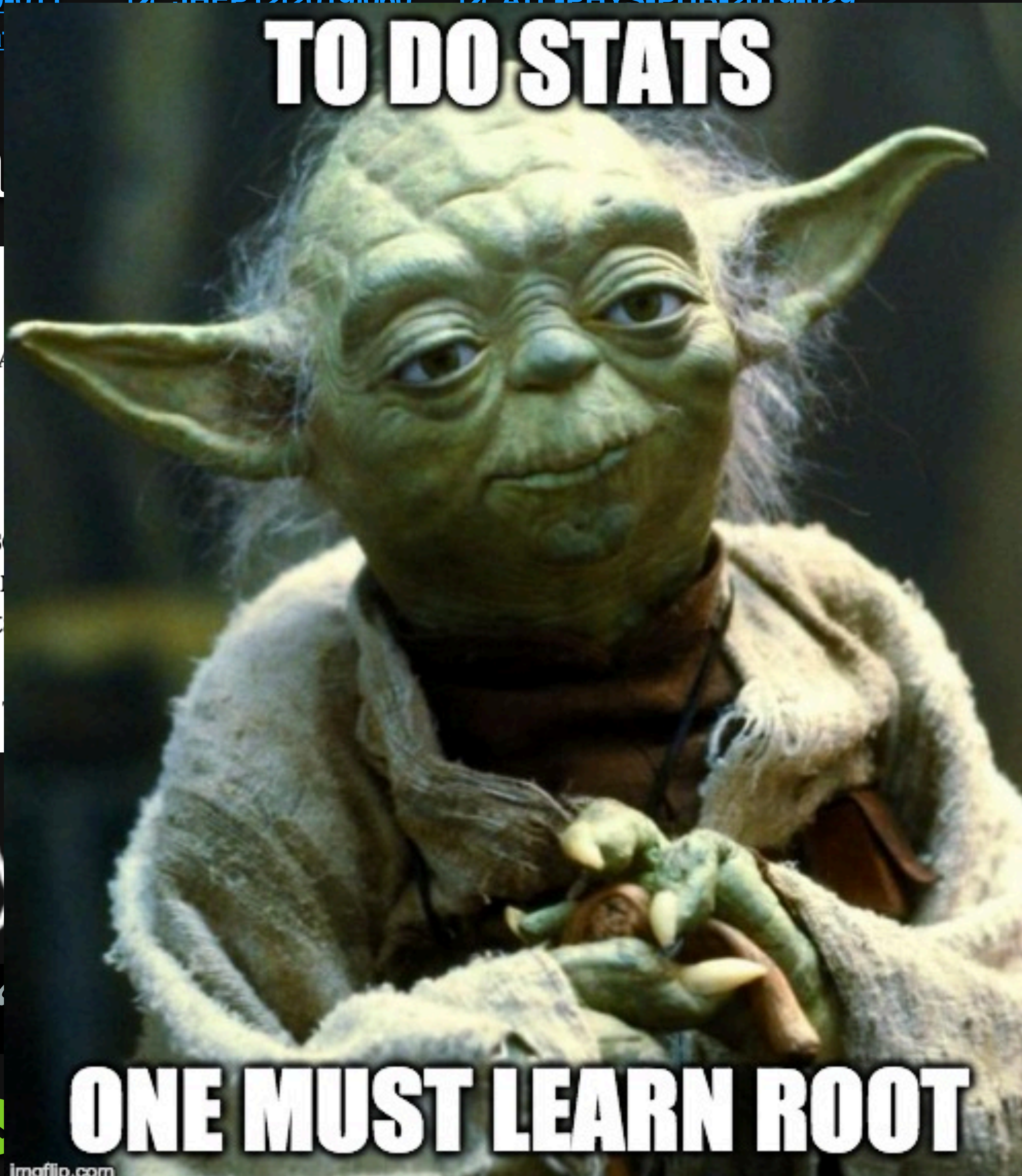
https://www.hepda

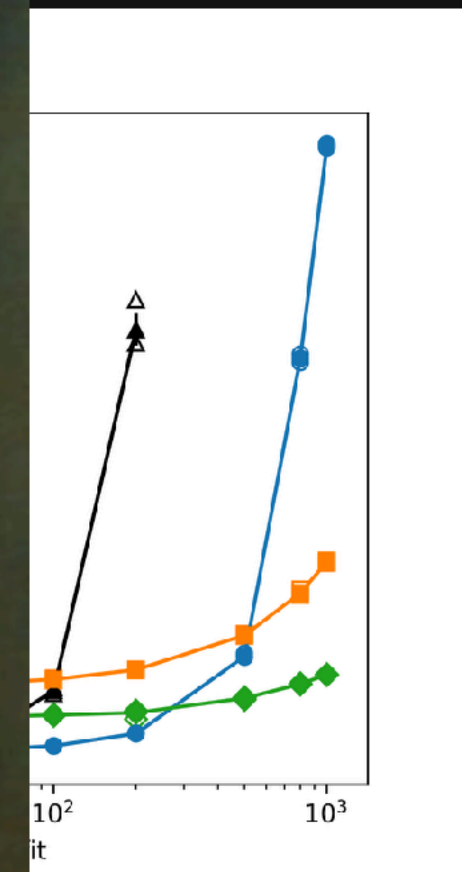
Seria

unch binder

ATLAS EXPERIMENT

Reproducing s
ATLAS experi
st





Py

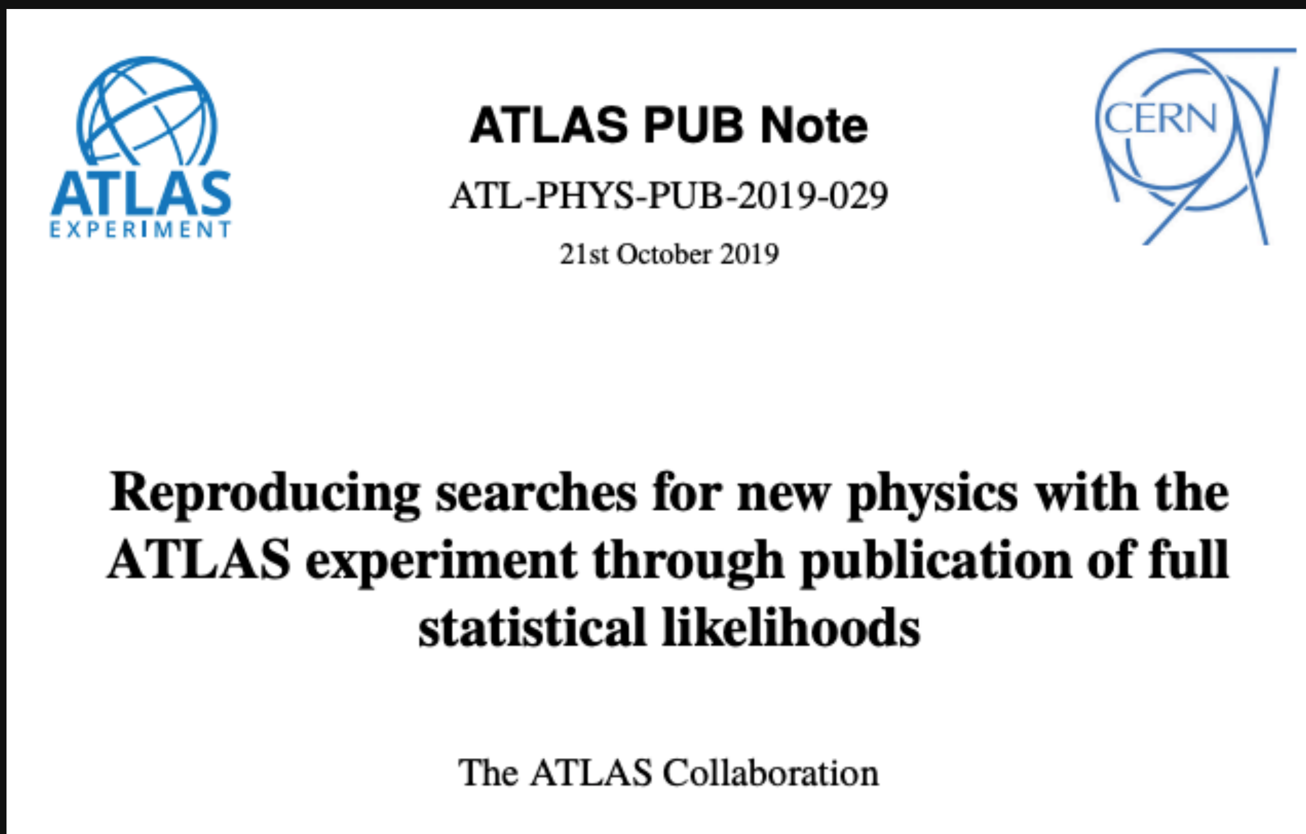
“ ”

e

ATLAS-CONF-2019-011 JHEP12(2019)060 ATL-PHYS-PUB-2019-029
https://www.hepdata.net/record/ins1748602

Serialized and Published!

launch binder


ATLAS EXPERIMENT

ATLAS PUB Note

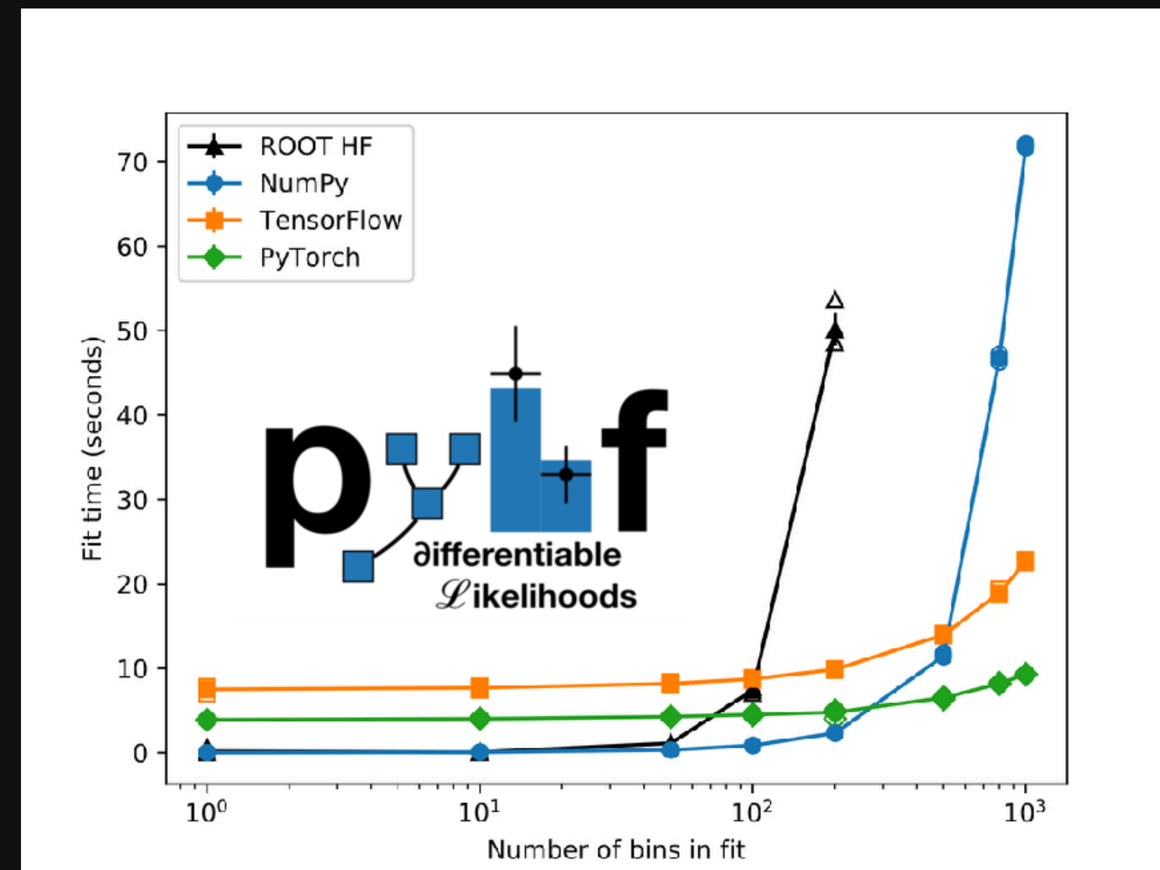
ATL-PHYS-PUB-2019-029

21st October 2019

CERN

Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods

The ATLAS Collaboration



PyTorch TensorFlow NumPy

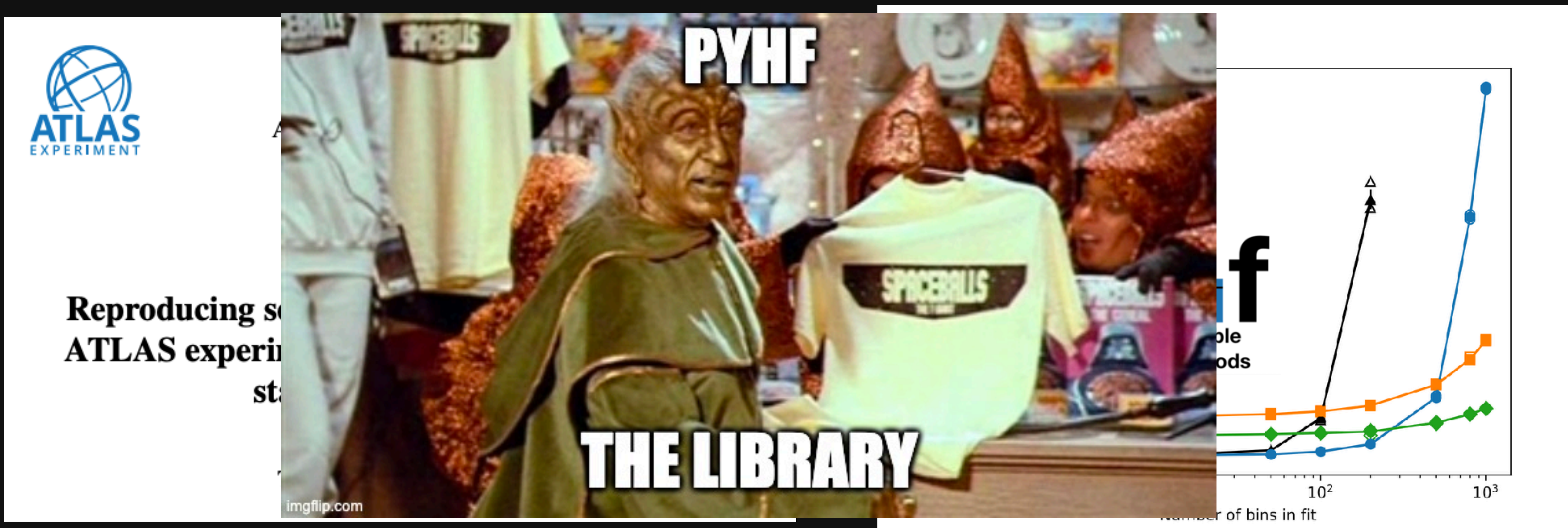
"python -m pip install pyhf"

orders-of-magnitude faster inference

ATLAS-CONF-2019-011   JHEP12(2019)060   ATL-PHYS-PUB-2019-029
https://www.hepdata.net/record/ins1748602

Serialized and Published!

launch binder



PyTorch TensorFlow NumPy

```
"python -m pip install pyhf"
```

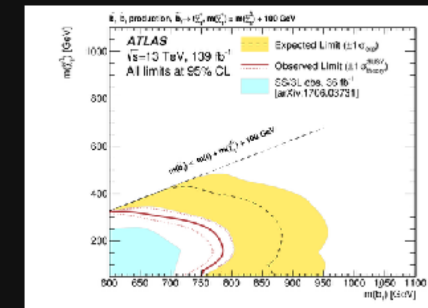
orders-of-magnitude faster inference

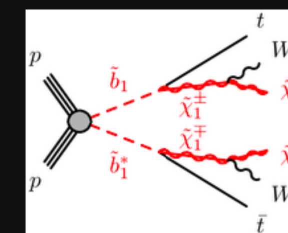
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

More public l'lhoods!

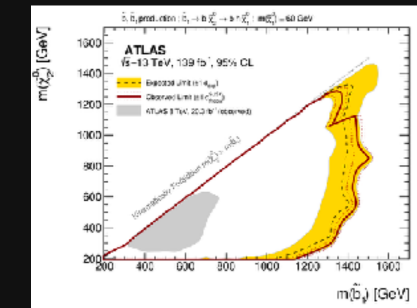
(since 2021!)

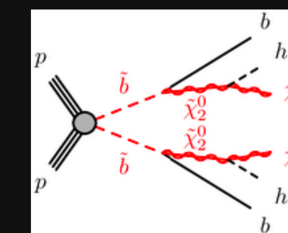
SUSY-2018-09



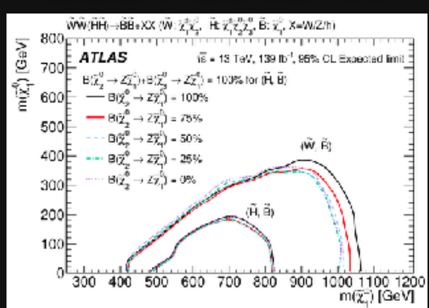


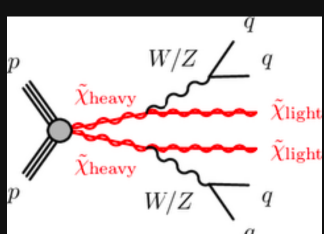
SUSY-2018-31



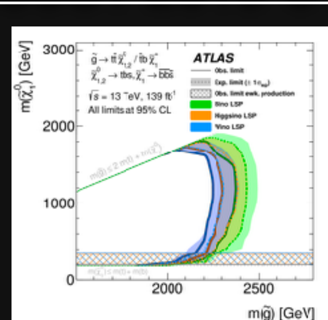


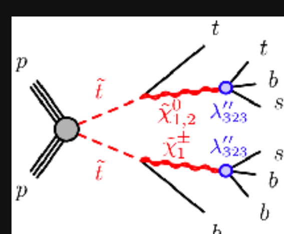
SUSY-2018-41



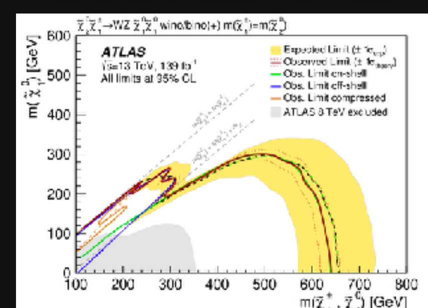


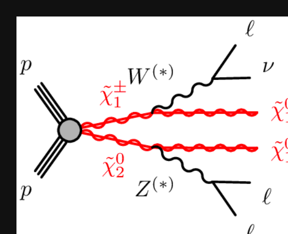
SUSY-2019-04



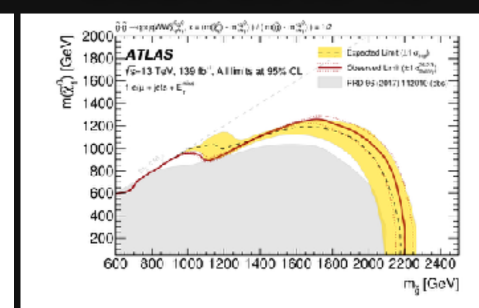


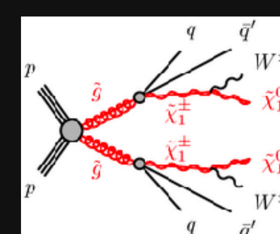
SUSY-2019-09



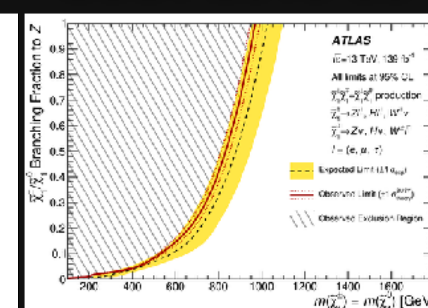


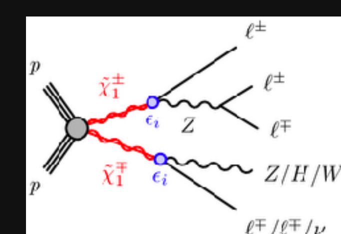
SUSY-2018-10



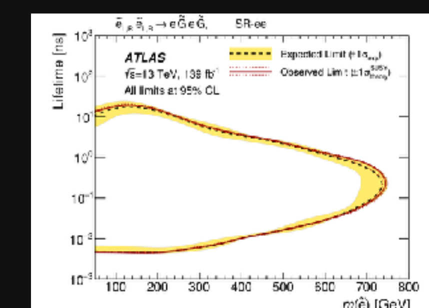


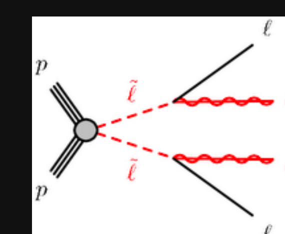
SUSY-2018-36



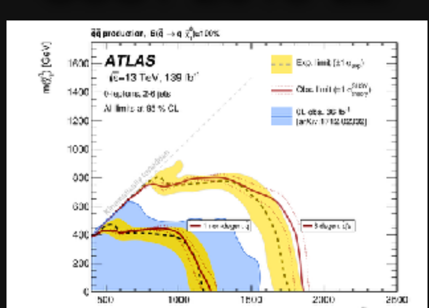


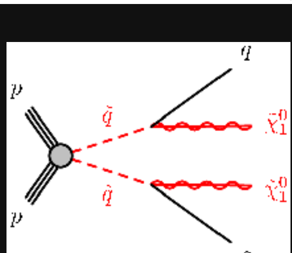
SUSY-2018-14



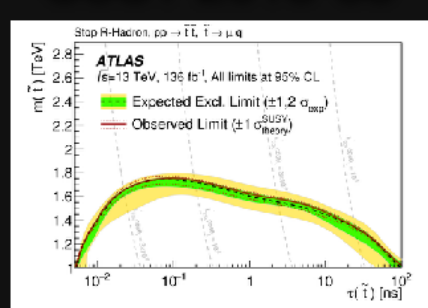


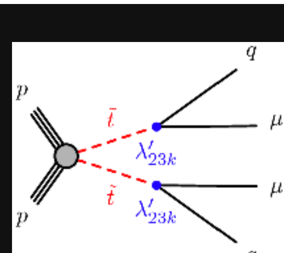
SUSY-2018-22



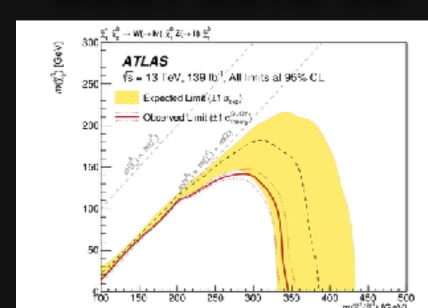


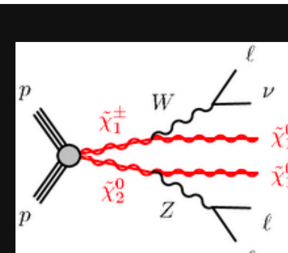
SUSY-2018-33



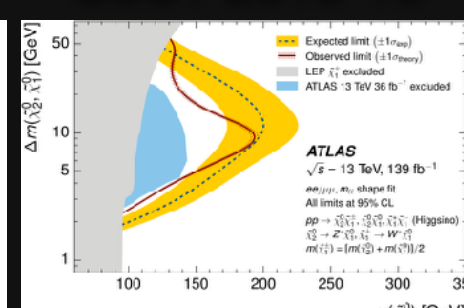


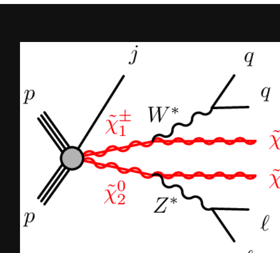
SUSY-2018-06



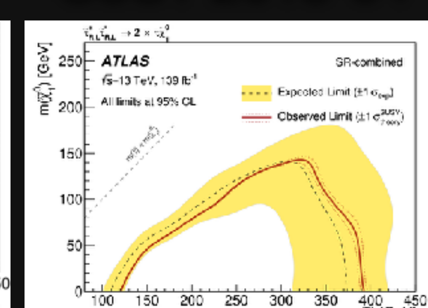


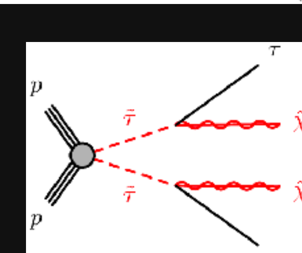
SUSY-2018-16



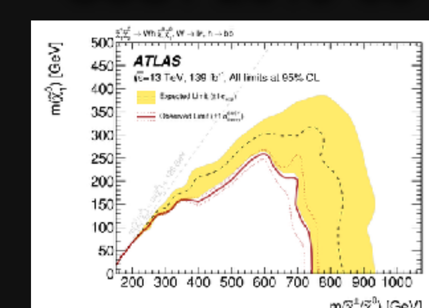


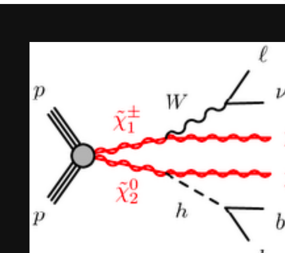
SUSY-2018-04





SUSY-2019-08



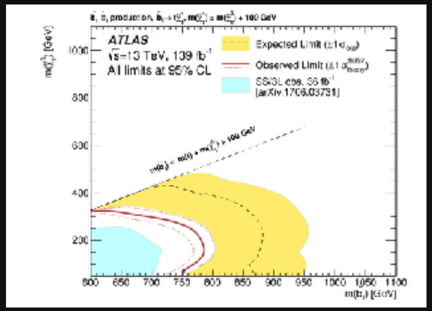


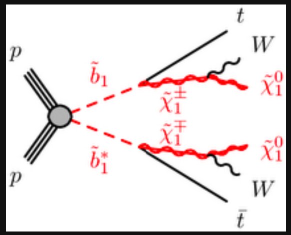
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

More public l'lhoods!

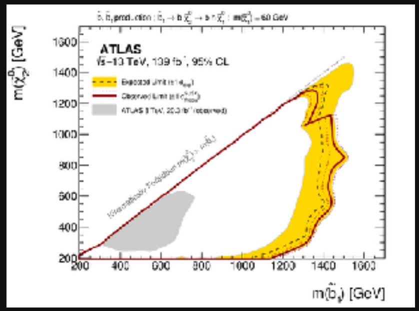
(since 2021!)

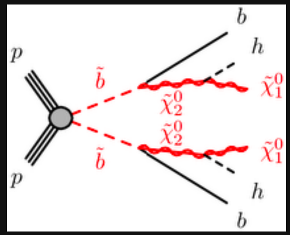
SUSY-2018-09



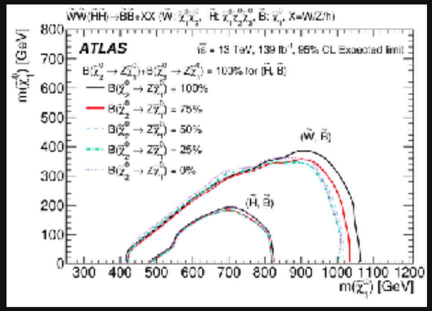


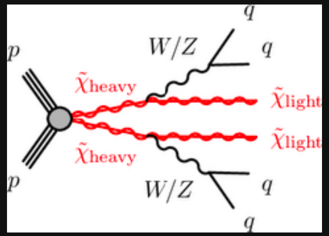
SUSY-2018-31



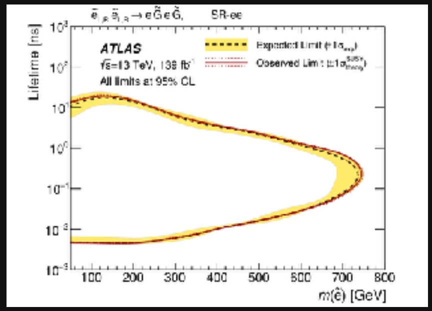


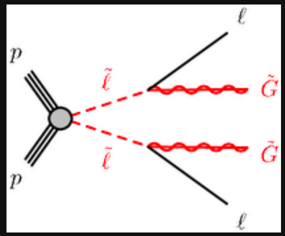
SUSY-2018-41



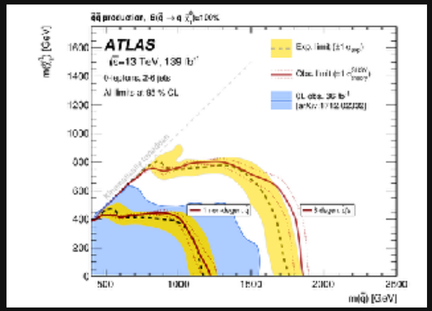


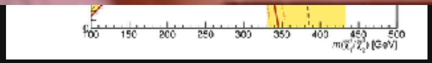
SUSY-2018-14

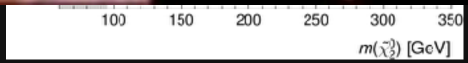


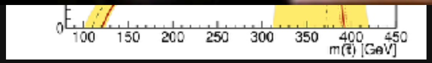


SUSY-2018-22

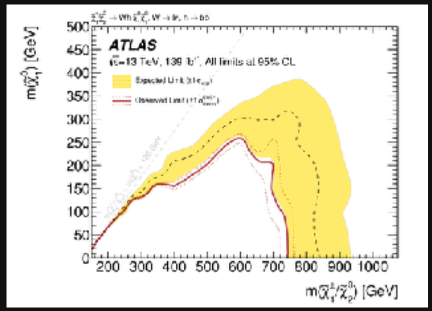


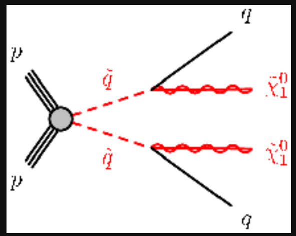


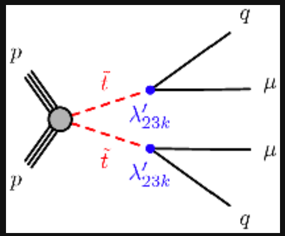


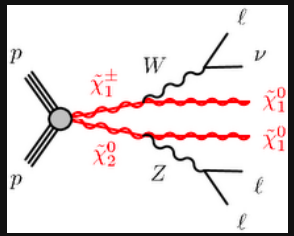


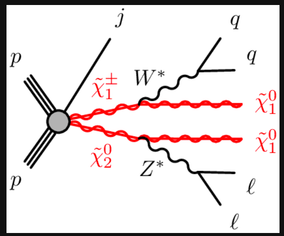
SUSY-2019-08

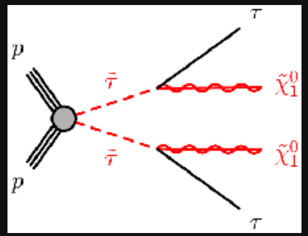


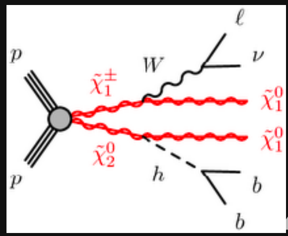












❗ Builds on top of my work with pyhf

Integration into theory tools

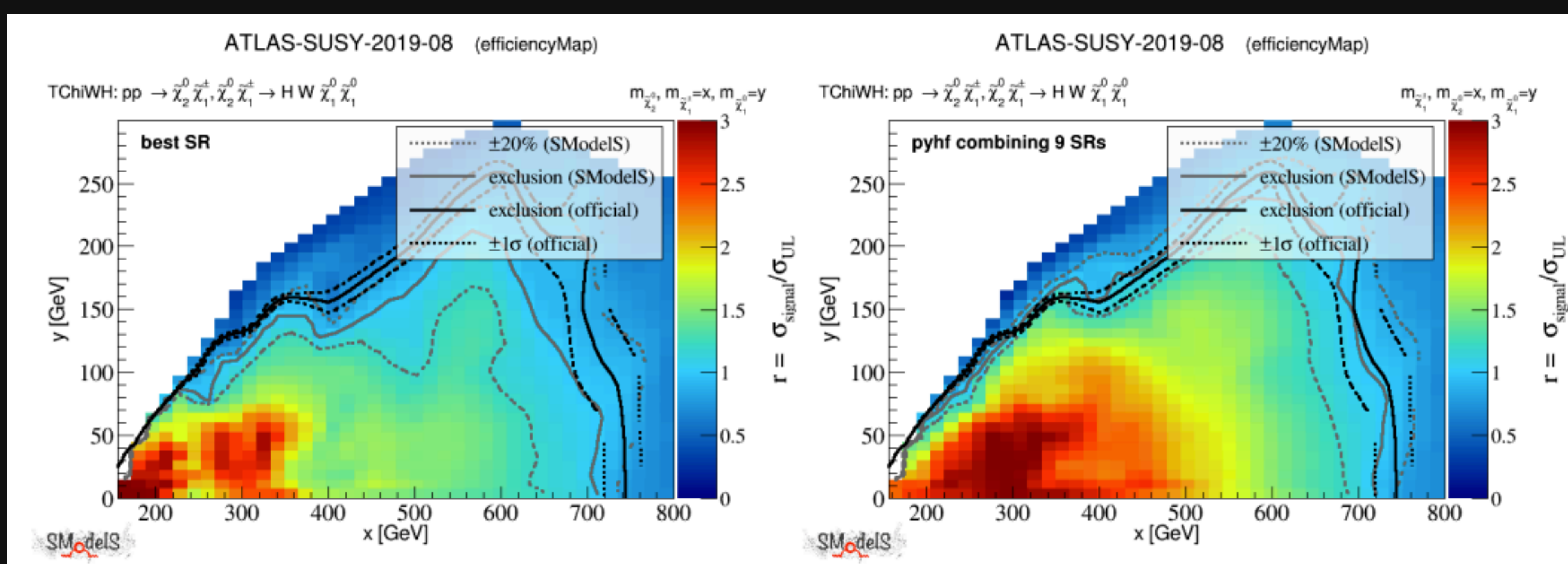
“if you build it, they will come”

[arXiv:2009.01809](https://arxiv.org/abs/2009.01809)

A SModelS interface for pyhf likelihoods

Gaël Alguero[a], Sabine Kraml[a], Wolfgang Waltenberger[b,c]

[a] *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France*
[b] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfer Gasse 18, 1050 Wien, Austria*
[c] *University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Wien, Austria*



https://scikit-hep.org/pyhf/citations.html

…and other experiments

LHC QCD

arXiv:2012.09120

How to discover QCD Instantons at the LHC[1]

Simone Amoroso[a] Deepak Kar[b] Matthias Schott[2c]

[a] DESY, Hemburg, Germany
[b] University of Witwatersrand, South Africa
[c] Johannes Gutenberg-University, Mainz, Germany

E-mail: matthias.schott@cern.ch

FCC

Sensitivity of Future Hadron Colliders to Leptoquark Pair Production in the Di-Muon Di-Jets Channel

B. C. Allanach[1], Tyler Corbett[2], Maeve Madigan[a,1]

[1] DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom
[2] The Niels Bohr International Academy, Blegdamsvej 17, University of Copenhagen, DK-2100 Copenhagen, Denmark

arXiv:1911.04455

EIC

arXiv:2102.06176

Charged Lepton Flavor Violation at the EIC

Vincenzo Cirigliano, Kaori Fuyuto, Christopher Lee, Emanuele Mereghetti, and Bin Yan

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.
E-mail: cirigliano@lanl.gov, kfuyuto@lanl.gov, clee@lanl.gov, emereghetti@lanl.gov, binyan@lanl.gov

ATLAS

Search for new phenomena in events with two opposite-charge leptons, jets and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

arXiv:2102.01444

Belle II

SEARCH FOR $B^+ \to K^+ \nu\bar{\nu}$ DECAYS WITH AN INCLUSIVE TAGGING METHOD AT THE BELLE II EXPERIMENT

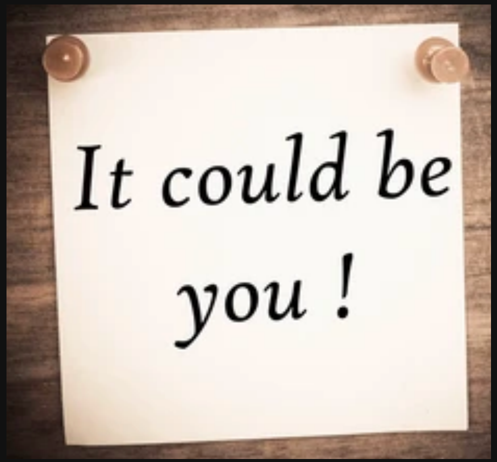
arXiv:2103.12504

On the single leptoquark solutions to the B-physics anomalies

Andrei Angelescu,[1,*] Damir Bečirević,[2,†] Darius A. Faroughy,[3,‡] Florentin Jaffredo,[2,§] and Olcyr Sumensari[2,¶]

arXiv:2105.05754

ALICE



μ-collider

Hunting wino and higgsino dark matter at the muon collider with disappearing tracks

Rodolfo Capdevilla,[a,b] Federico Meloni,[c] Rosa Simoniello,[d] Jose Zurita[e]

arXiv:2102.11292

Theory/experiment adoption across the field

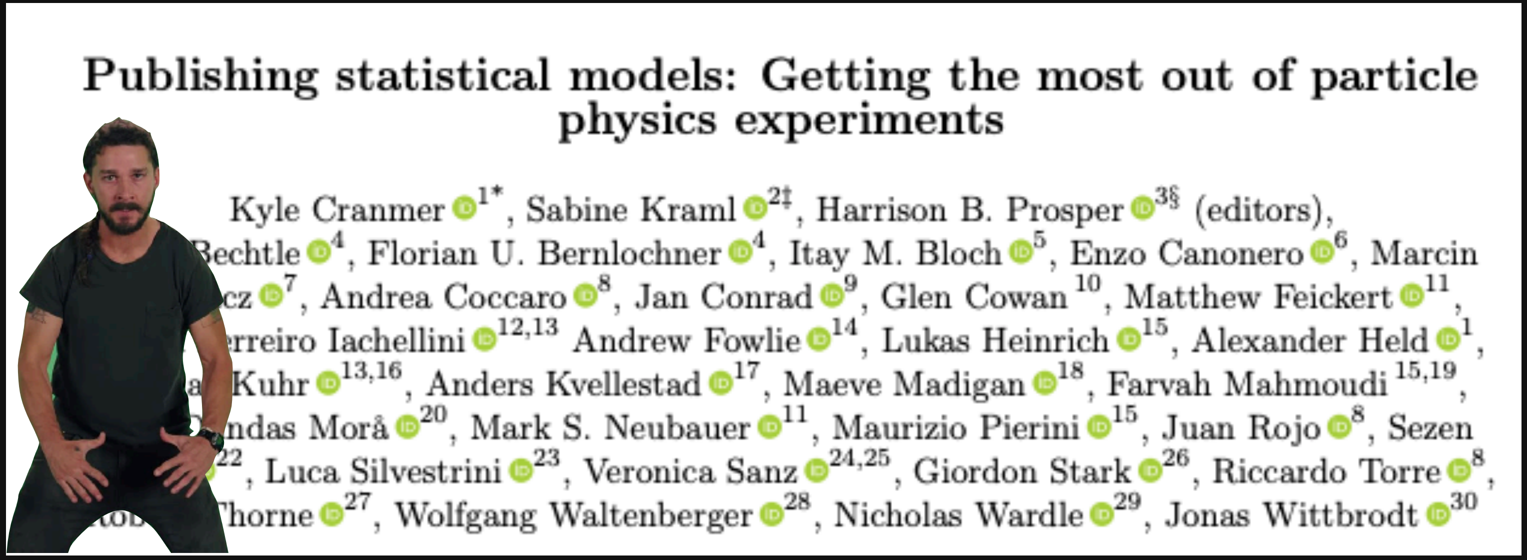
[arXiv:2109.04981](https://arxiv.org/abs/2109.04981)

! HEP-wide call to action!

Published Models (I)

- With a new JSON format, user-friendly tools, and increasing experimental support — key inference results can be reproduced in minutes — for physics including
  - Parton distribution functions
  - Higgs boson measurements at the LHC
  - Searches for new particles at the LHC
  - Searches for dark matter
  - Heavy flavor physics
  - World averages
  - Global fits

[arXiv:2109.04981](https://arxiv.org/abs/2109.04981)



Publishing statistical models: Getting the most out of particle physics experiments

Kyle Cranmer[1*], Sabine Kraml[2‡], Harrison B. Prosper[3§] (editors),
Bechtle[4], Florian U. Bernlochner[4], Itay M. Bloch[5], Enzo Canonero[6], Marcin
cz[7], Andrea Coccaro[8], Jan Conrad[9], Glen Cowan[10], Matthew Feickert[11],
rreiro Iachellini[12,13] Andrew Fowlie[14], Lukas Heinrich[15], Alexander Held[1],
Kuhr[13,16], Anders Kvellestad[17], Maeve Madigan[18], Farvah Mahmoudi[15,19],
ndas Morå[20], Mark S. Neubauer[11], Maurizio Pierini[15], Juan Rojo[8], Sezen
[22], Luca Silvestrini[23], Veronica Sanz[24,25], Giordon Stark[26], Riccardo Torre[8],
Thorne[27], Wolfgang Waltenberger[28], Nicholas Wardle[29], Jonas Wittbrodt[30]

Applications of Likelihoods

Hold your breath. Make a wish. Count to three.
Come with me. And you'll be. In a world of…

"Pure imagination." — Willy Wonka

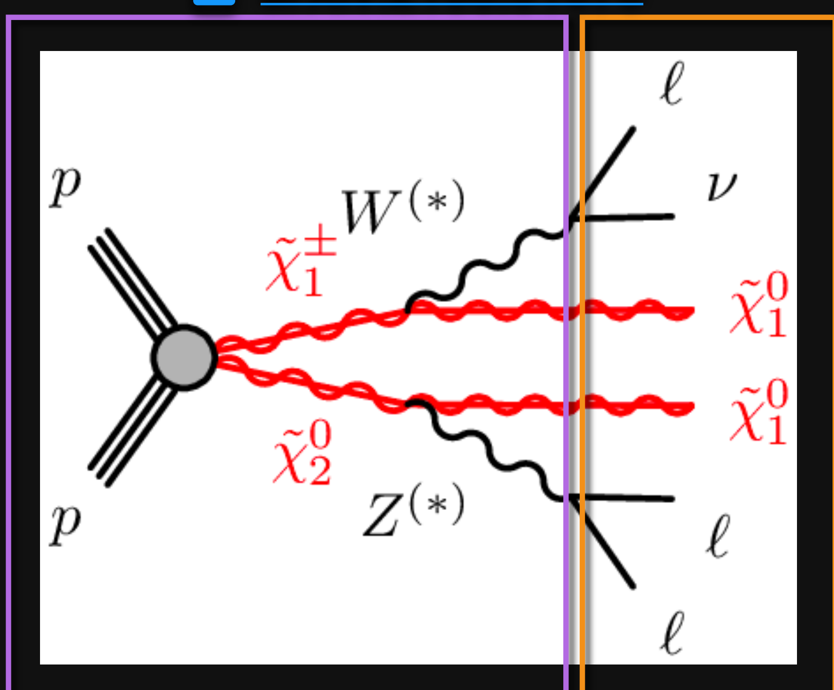
arXiv:1911.12606 ATLAS-CONF-2020-015 arXiv:2106.01676 ATL-PHYS-PUB-2021-019
atlas.cern/updates/briefing/new-higgsino-limits

E.G.: Stat. Combination (I)

- Multiple analyses with different **signatures** can still target the same **model**
  - See Zach Marshall's talk on differences between signature and model: https://indico.cern.ch/event/1023573/contributions/4400586/

ATLAS-CONF-2020-015
arXiv:2106.01676

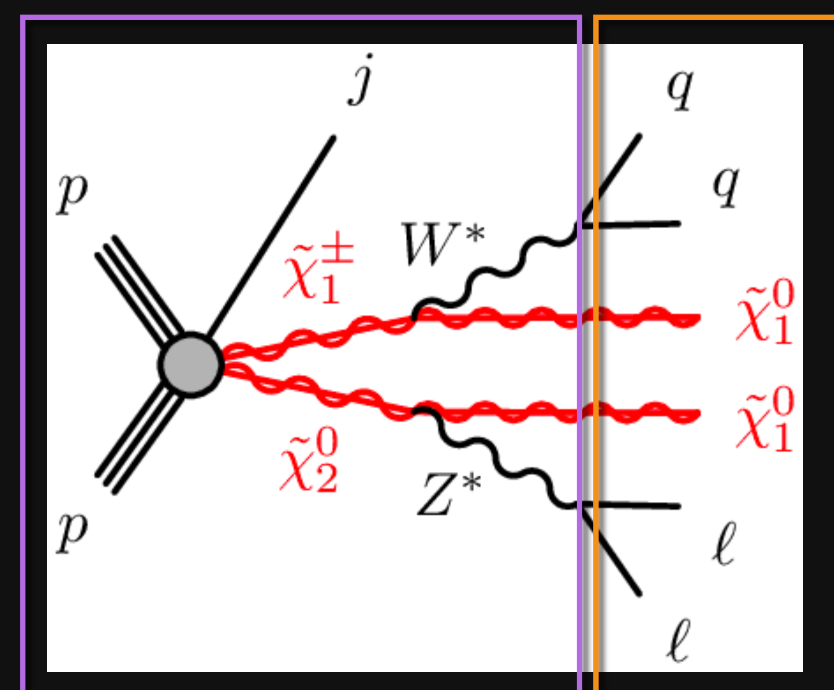
3L



off-shell: $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \in [5,90]$ GeV
on-shell: $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \geq 90$ GeV
signature: $3\ell + 0j + E_T^{miss}$

arXiv:1911.12606

soft 2L



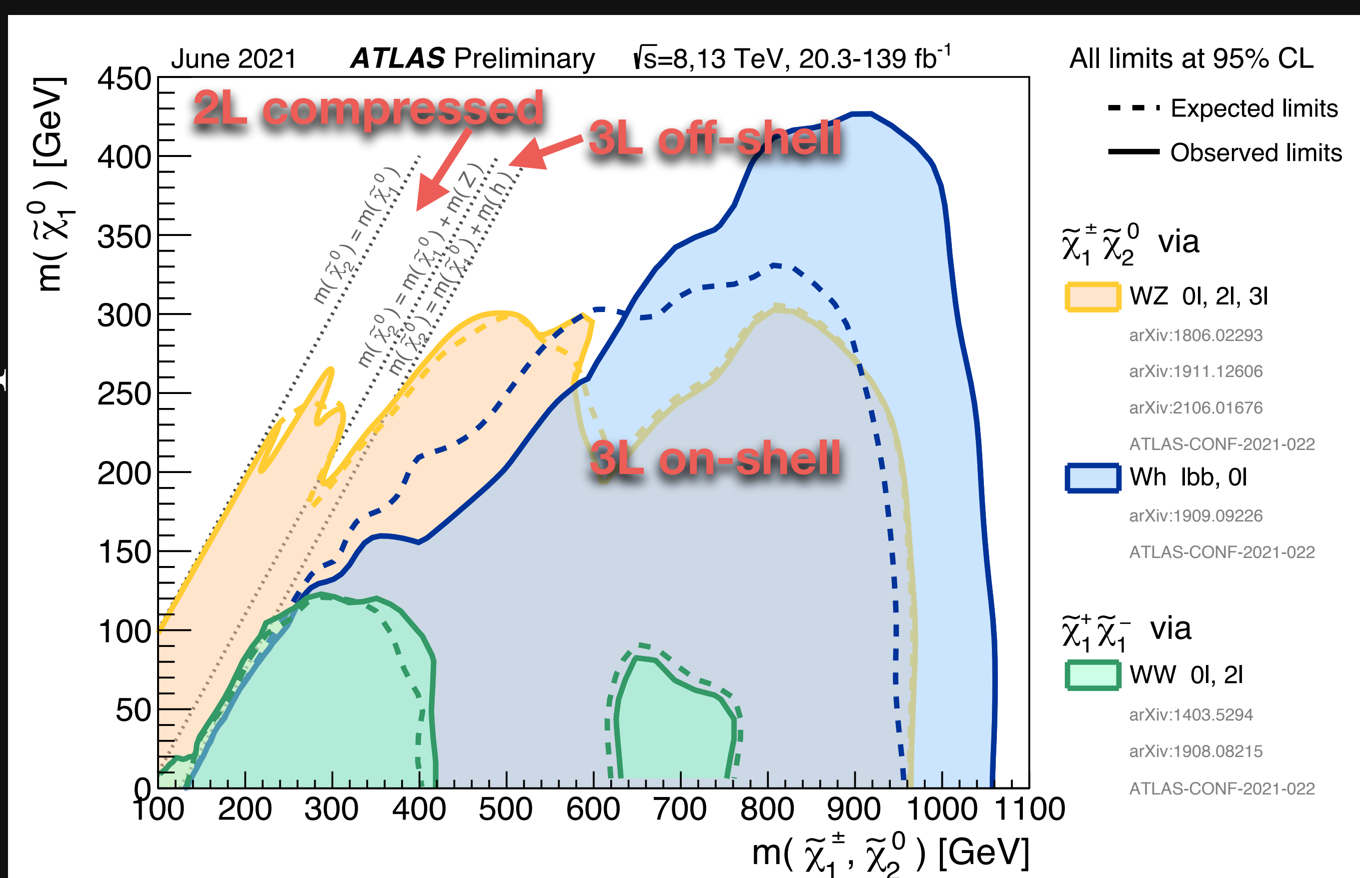
soft 2L: $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \in [1,60]$ GeV
signature: $2\ell + 3j + E_T^{miss}$

arXiv:1911.12606 ATLAS-CONF-2020-015 arXiv:2106.01676 ATL-PHYS-PUB-2021-019
atlas.cern/updates/briefing/new-higgsino-limits

E.G.: Stat. Combination (II)

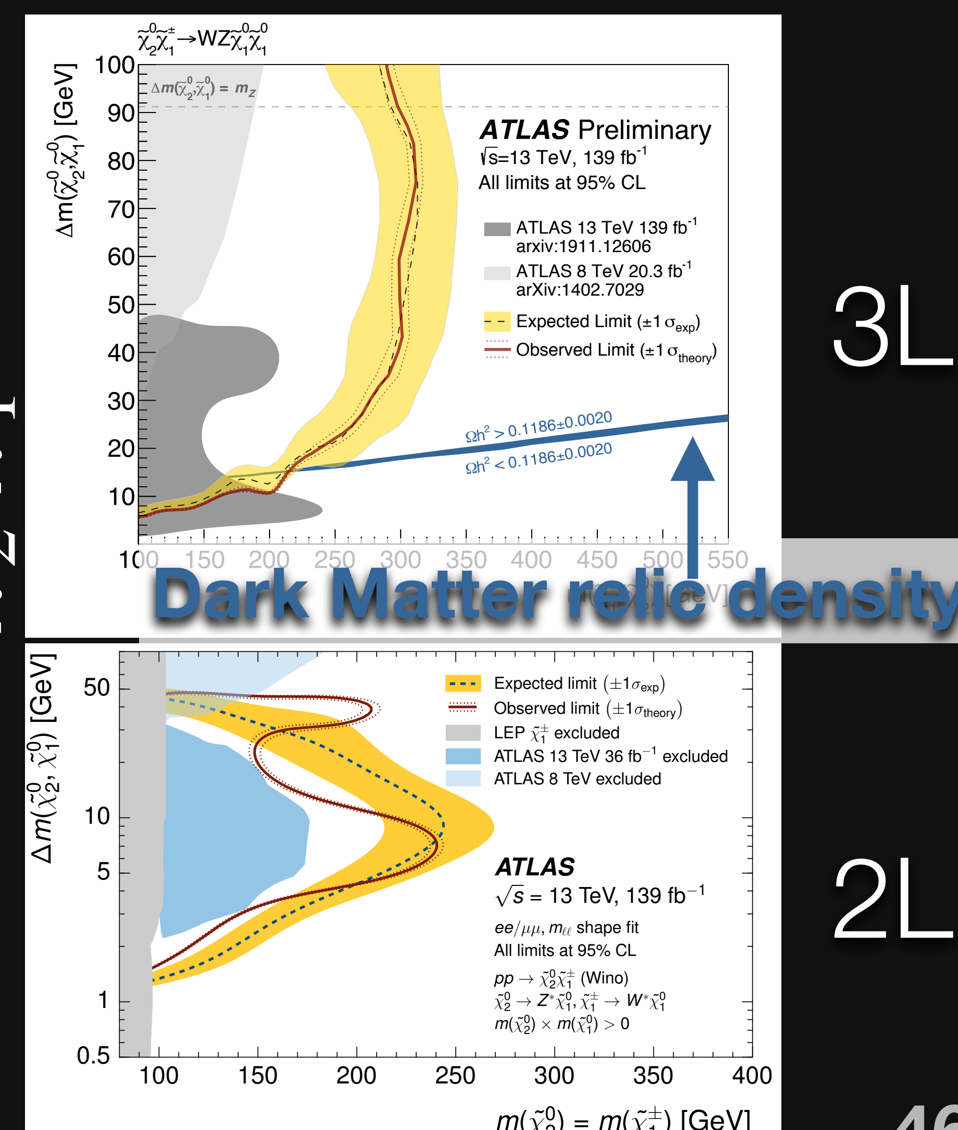
- Goal: **combine multiple searches** to paint a tapestry of our sensitivity to Higgsino/Wino-Bino models (production) which decay to on-shell/off-shell Standard Model bosons (W/Z)

$m(\tilde{\chi}_1^0)$



$m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0)$

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

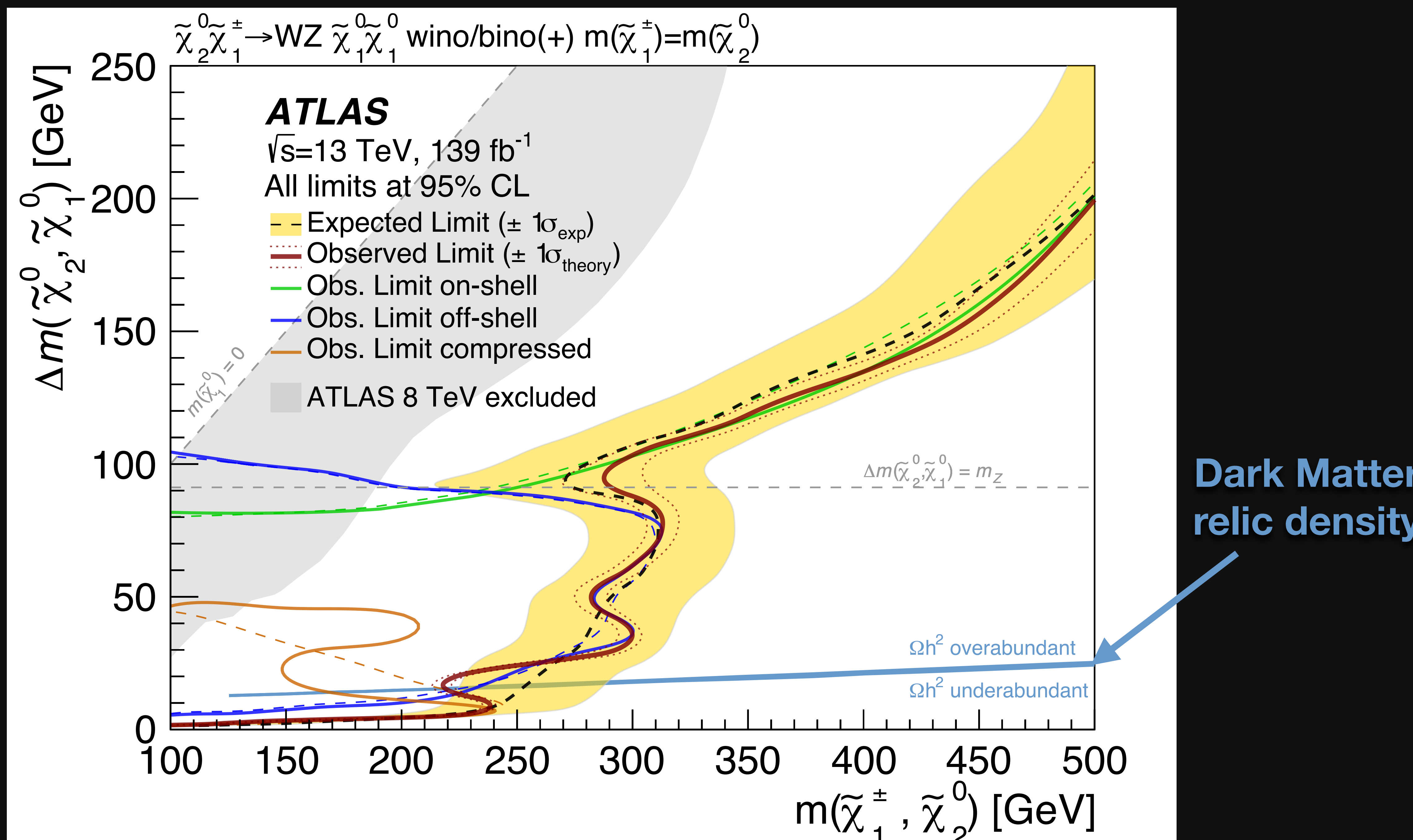


3L

2L

arXiv:1911.12606 ATLAS-CONF-2020-015 arXiv:2106.01676 ATL-PHYS-PUB-2021-019
atlas.cern/updates/briefing/new-higgsino-limits

E.G.: Stat. Combination (III)

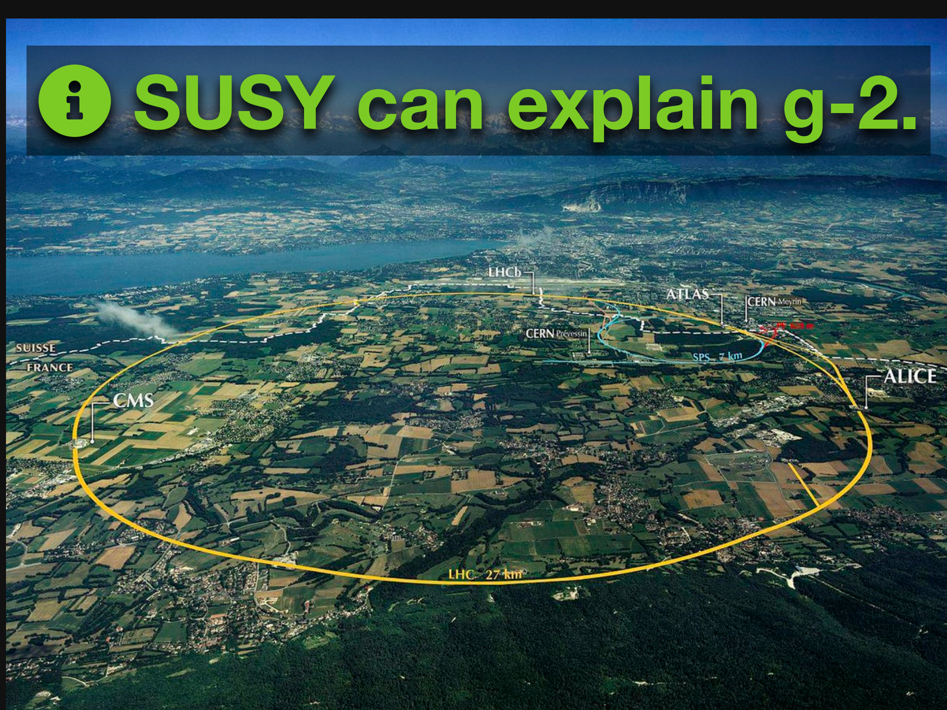


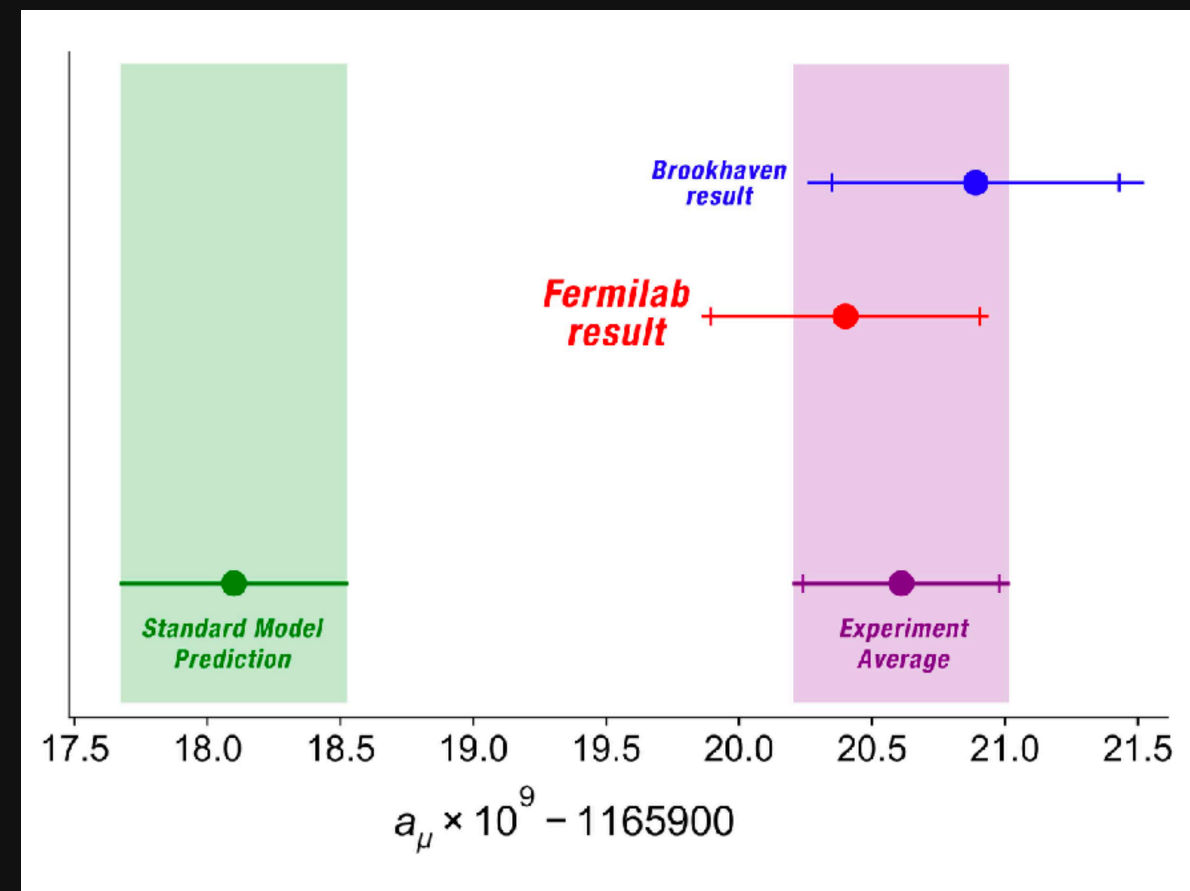
Not possible without my work on pyhf and reproducibility

ATL-PHYS-PUB-2021-019 arXiv:1403.5294 arXiv:1908.08215 arXiv:1911.12606
10.1103/PhysRevLett.126.141801

Example: global fit (g-2) (I)

combine!



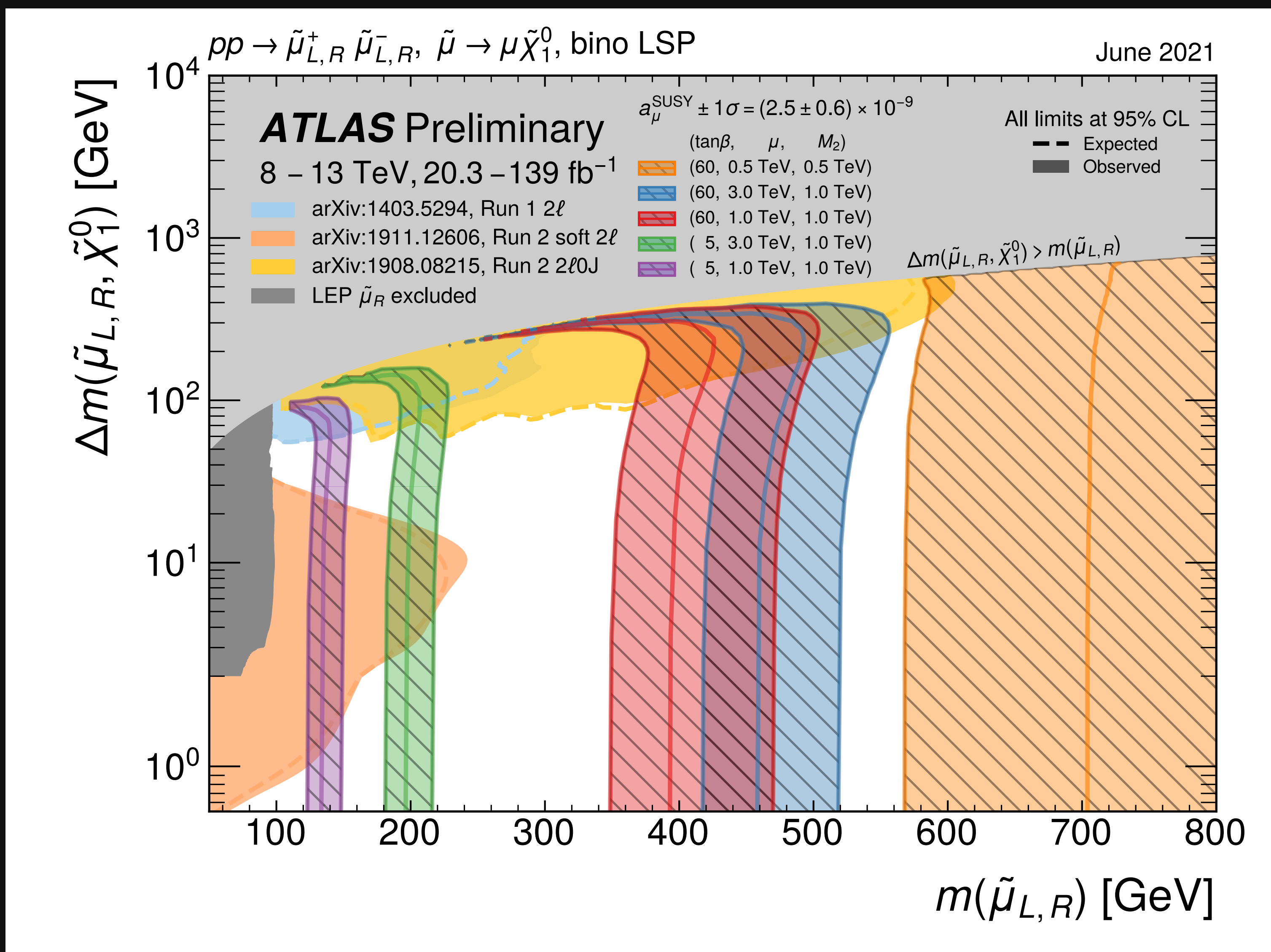


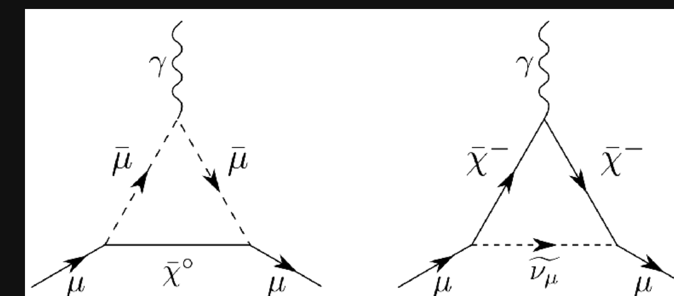
April 27th, 2021

Can we use experimental measurements of g-2 to inform our ATLAS physics program?

ATL-PHYS-PUB-2021-019 arXiv:1403.5294 arXiv:1908.08215 arXiv:1911.12606
10.1103/PhysRevLett.126.141801

Example: global fit (g-2) (II)





$\tilde{\mu}^{\pm}/\tilde{\chi}^0$ or $\tilde{\chi}^{\pm}/\tilde{\nu}_\mu$

- Compute exclusion limits in the $(\tilde{\mu}, \tilde{\chi}^0_1)$ mass plane for different analyses that are sensitive to the smuon model with muon/bino-like $\tilde{\chi}^0_1$ signature
- Hatched bands are compatible with the observed g-2 anomaly measured by Fermilab and BNL experiments to $\pm 1\sigma$, for a variety of pMSSM parameters

center line = combined g-2 measurement
hatching = $\pm 1\sigma$ uncertainty on experimental measurement

Light smuon/light neutralino needed!

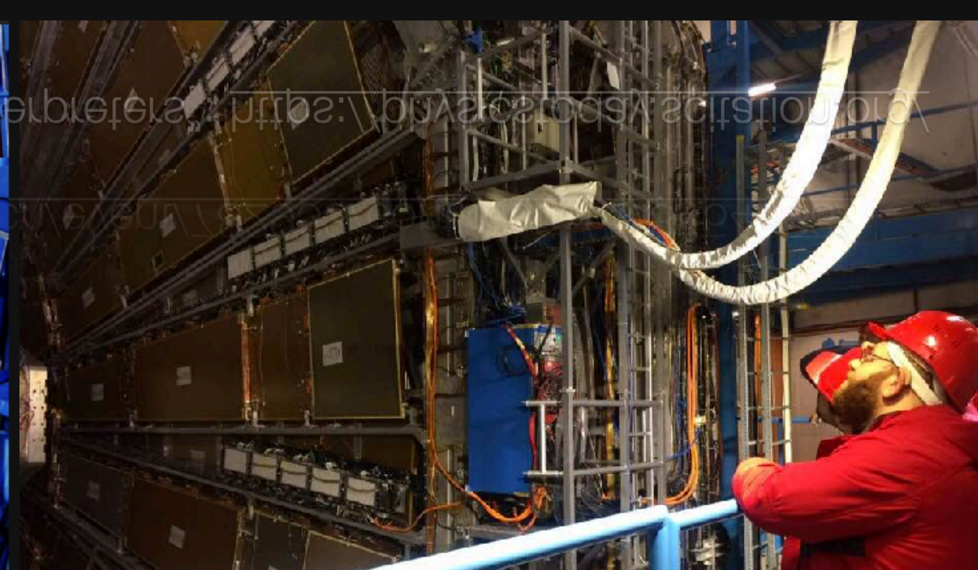
Outreach

Making physics more approachable

"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

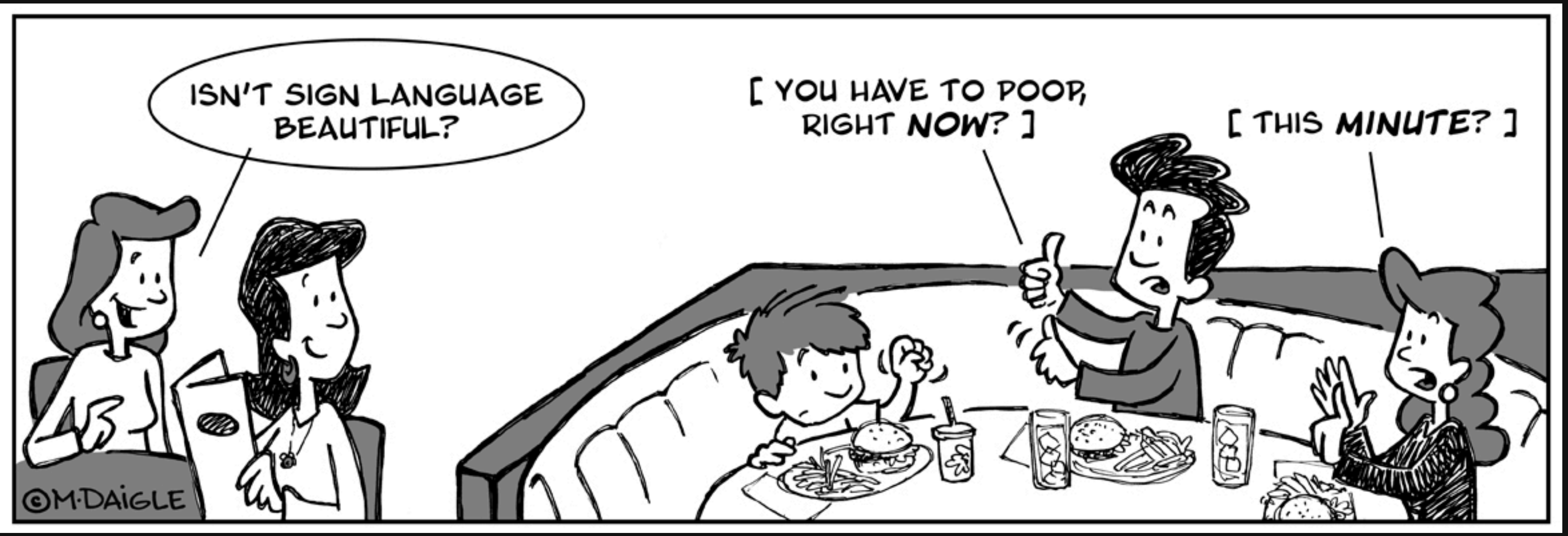
Outreach

- Exhibit in ASL at the CERN museum (Microcosm): https://www.youtube.com/watch?v=BaGjAruqFec
- My life as a Particle Physicist (in ASL): https://www.youtube.com/watch?v=3sESUT1UO6E
- Fermilab Publication: “A Matter of Interpretation”: https://www.symmetrymagazine.org/article/a-matter-of-interpretation-asl-physics
- "PARTY CALL PHYSICS”: Presentation during American Physical Society meeting about physics and accessibility: https://indico.cern.ch/event/782953/contributions/3454898/
- Physics Today: “Deaf Scientists thrive with interpreters”: https://physicstoday.scitation.org/do/10.1063/PT.6.4.20210723a/full/



Signed Language

Making physics more accessible



https://www.lifeprint.com/asl101/pages-layout/grammar.htm

Sign Language

70+ million people in the world **use sign language**

- Different from **country to country**
  - ASL, LSF, DGS, LIS, NZSL, Auslan, BSL, etc…
- Different **Grammar**
  - English (Subject-Object-Verb) vs ASL (Time-Subject-Verb-Object)
  - EXAMPLE: “The boy threw the ball.” vs “BALL, BOY THROW” / “BOY THROW BALL”
  - TOPICALIZATION: “She gave me money.” vs “MONEY? she-GIVE-me”
- Each sign is composed of **five parameters**. Altering one parameter changes the entire meaning
  - Handshape (HS), Palm Orientation (PO), Location, Movement, and Facial Expressions (NMS)
  - EXAMPLE: cool/apple/Bronx/ask/need/must/manage/scar/etc…

Phonology and Parameters

- Elementary particles are the **building blocks of matter**.
- The five parameters are the **building blocks of signs**.

- **Matter** is made up of **elementary particles**
  - **proton**: up, up, down
  - **neutron**: up, down, down

- **Signs** are built up using **parameters**
  - **mother**: HS5, PO-left, chin
  - **father**: HS5, PO-left, forehead

https://aslcore.org/

WELCOME TO **ASLCORE!**

Examples

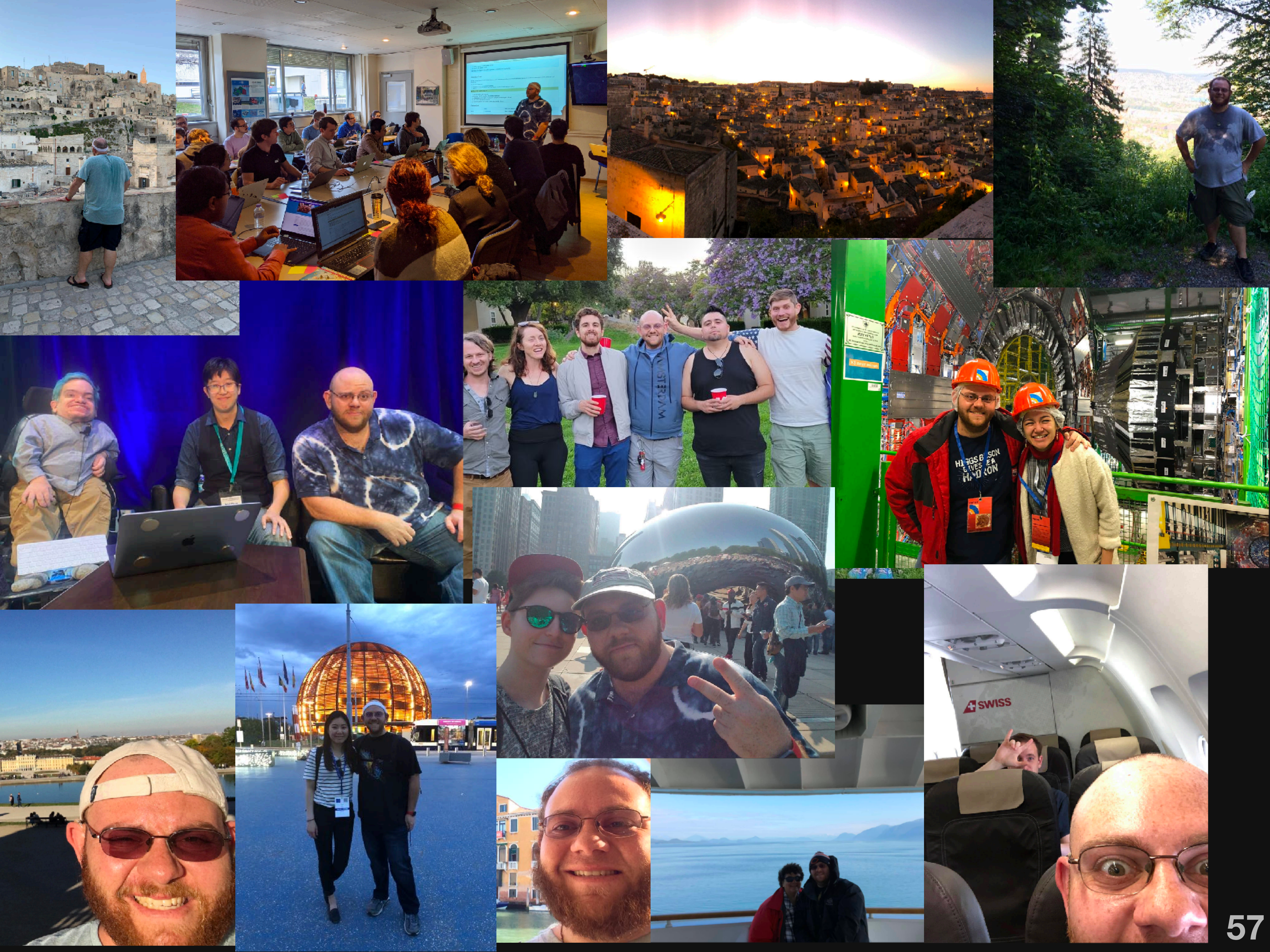
- **PARTICLES**: Closed small C, champagne flick multiple
- **STANDARD MODEL**: NDH O PO side, DH 4 GRID-TABLE
- **RADIATE/RADIATION**: 2H A HS TOGETHER to 5 wiggle outwards
- **ENERGY**: bent-L, shake
- **LUMINOSITY**: NDH B PO up, DH AND HS open-twist to 5 HS (make sure DH palm always touch)
- **COLLISION** (Quantum Physics): Moving FLAT O to Open-Hand 5 twist (make sure back of hands are touching at the end of the sign)

https://aslcore.org/

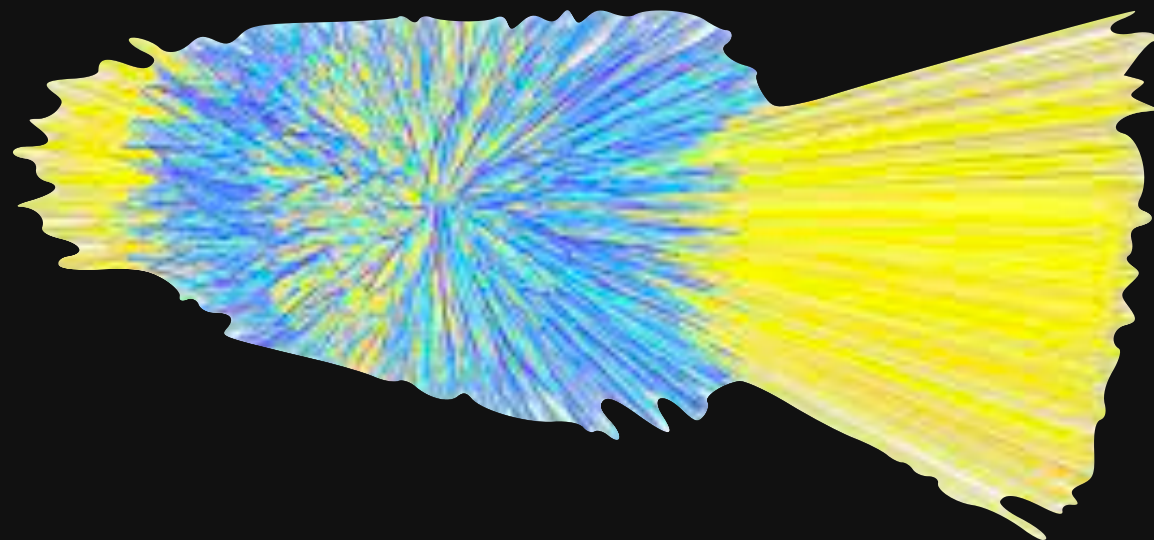
Expansion Example

- What are atoms? Atoms are atomic particles that have many properties and are composed of three different subatomic particles: electrons, protons, and neutrons. The electrons form the atom’s “cloudy” atmosphere. At the center of an atom is the nucleus where all the protons and neutrons live. Are protons and neutrons elementary particles? Nope, they can be broke up into even smaller particles. For example, the proton is made of three quarks: up, up, down.

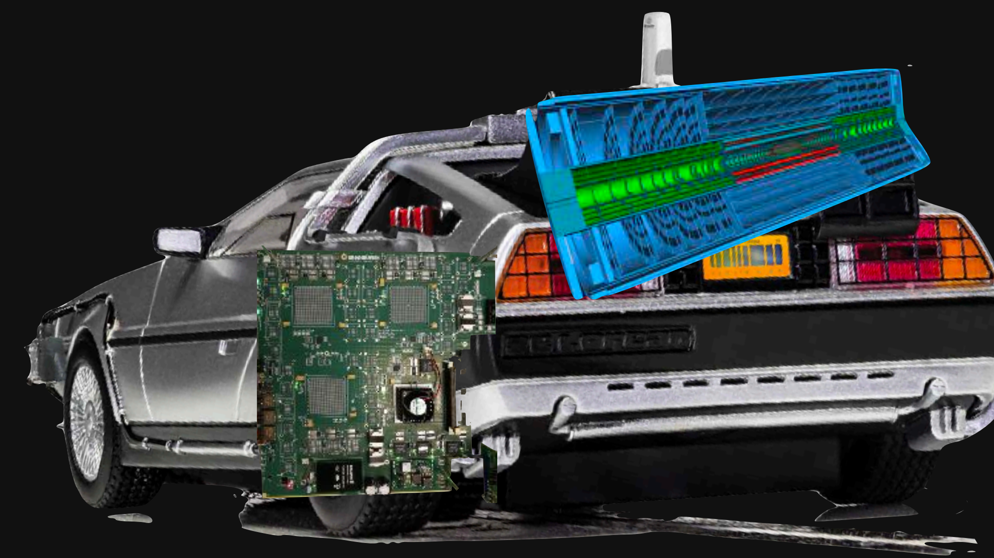
Key features: “cinematic ASL”


SWISS

High-Luminosity LHC



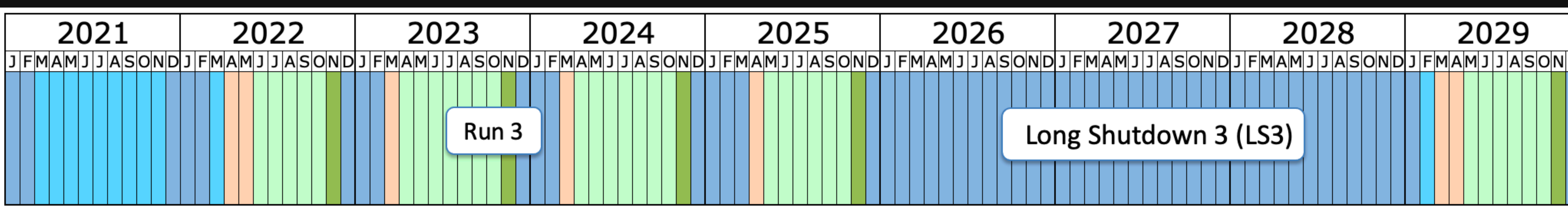
ATLAS



ITk Flux Capacitor

Looking Forward

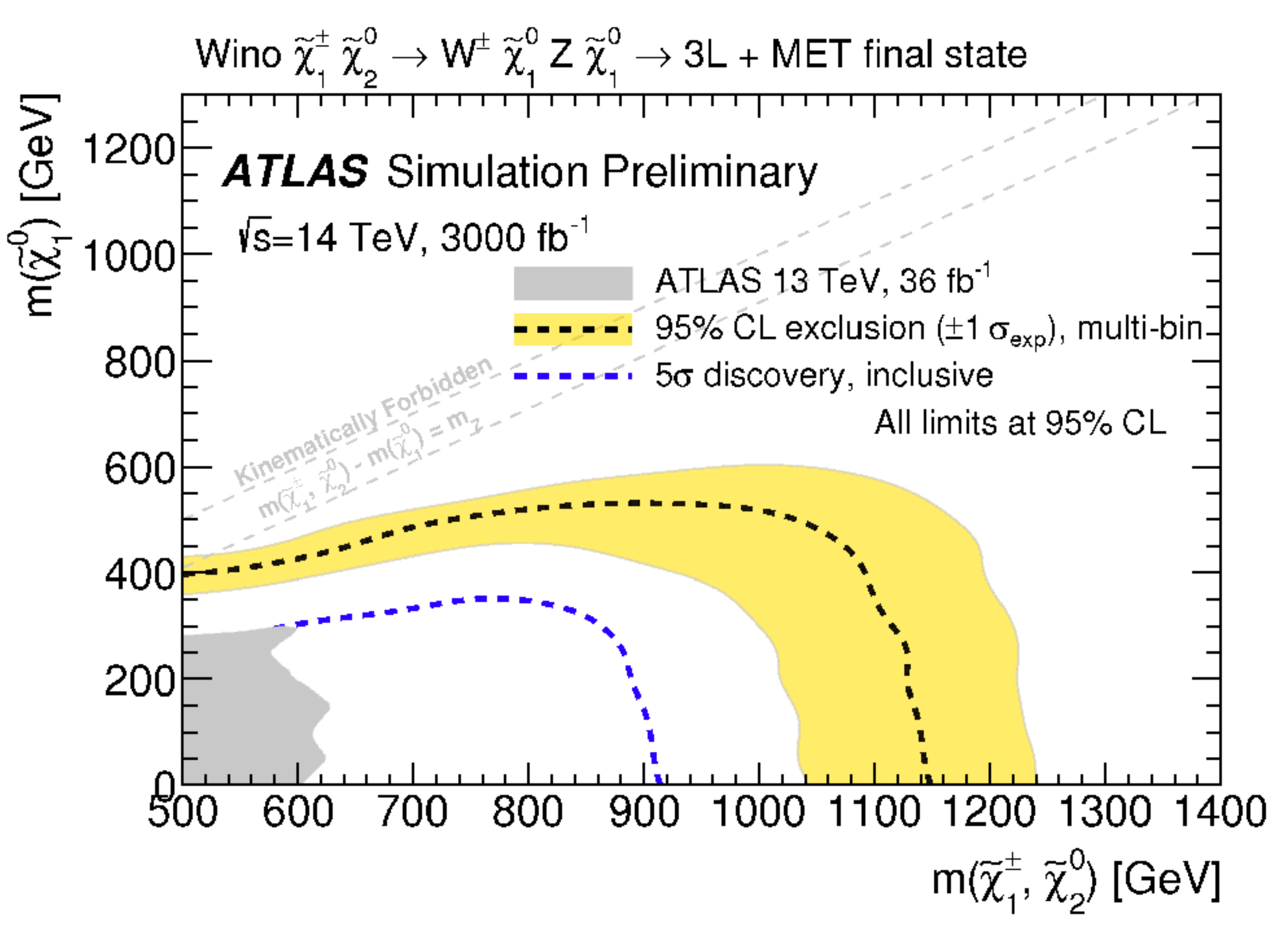
Instrumentation Upgrades to continue the success of the LHC physics program

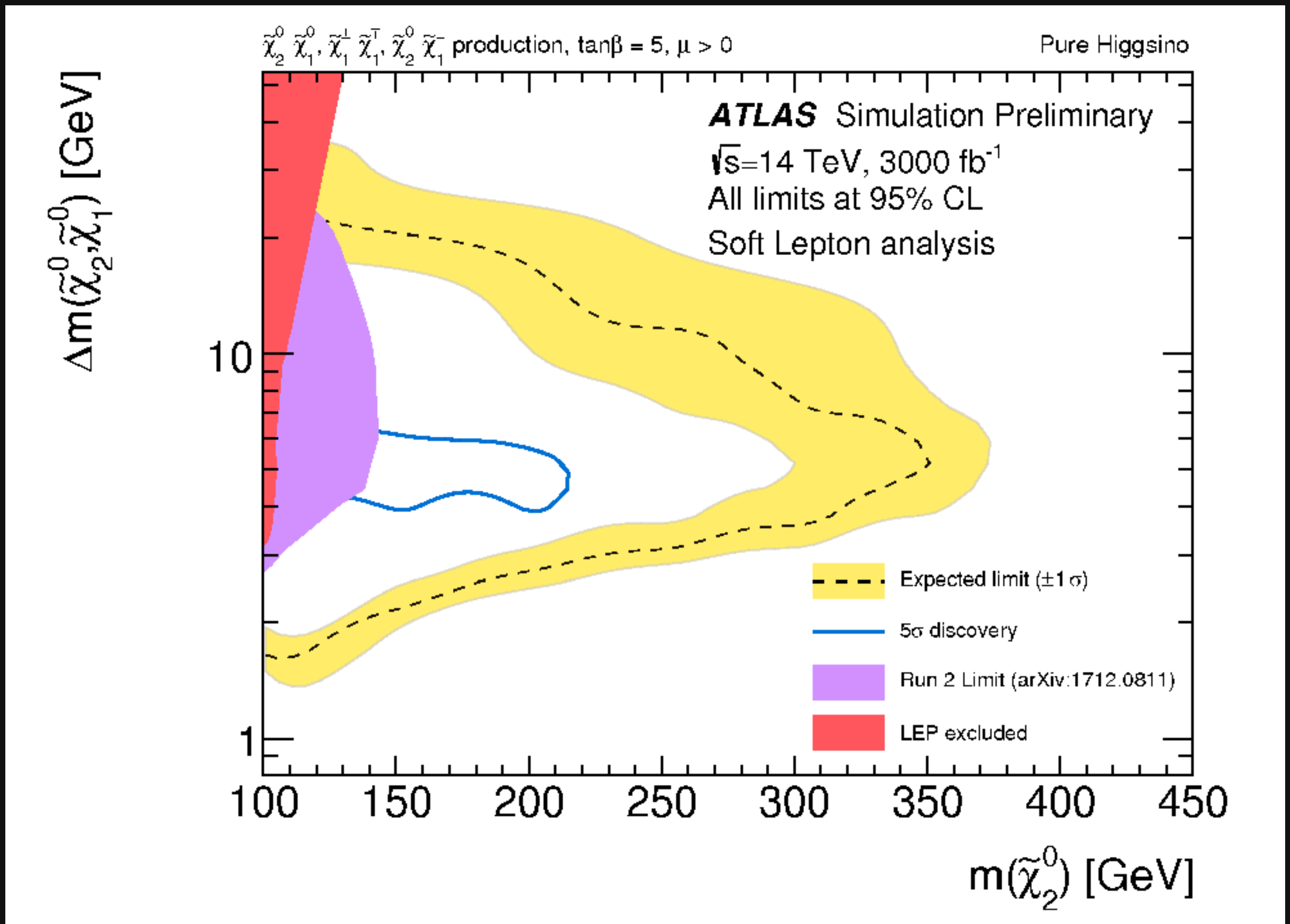


"Roads? Where we're going, we don't need roads." — Doc Brown

[ATL-PHYS-PUB-2018-048]

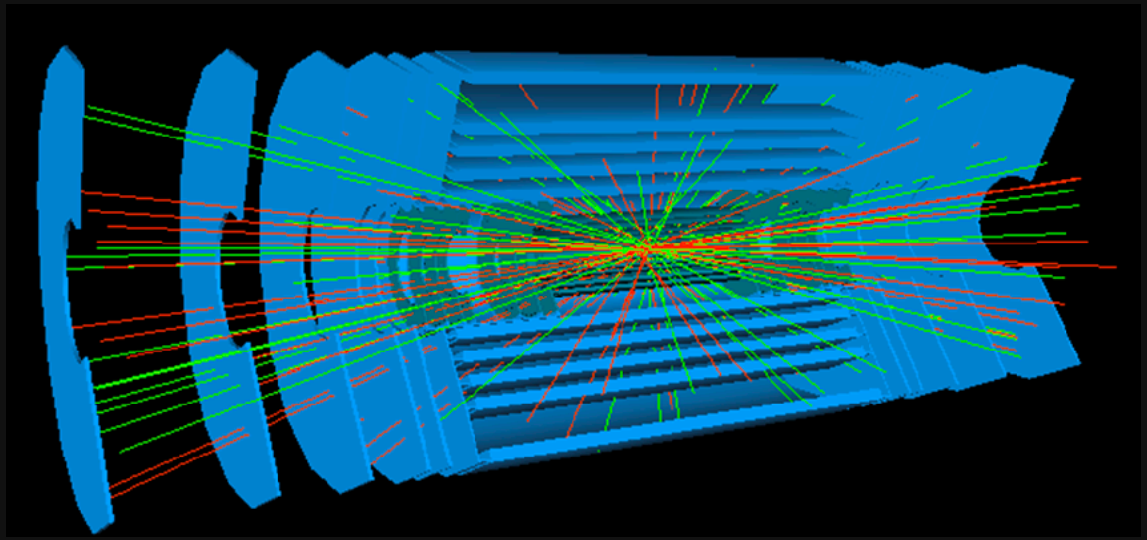
The Future of SUSY



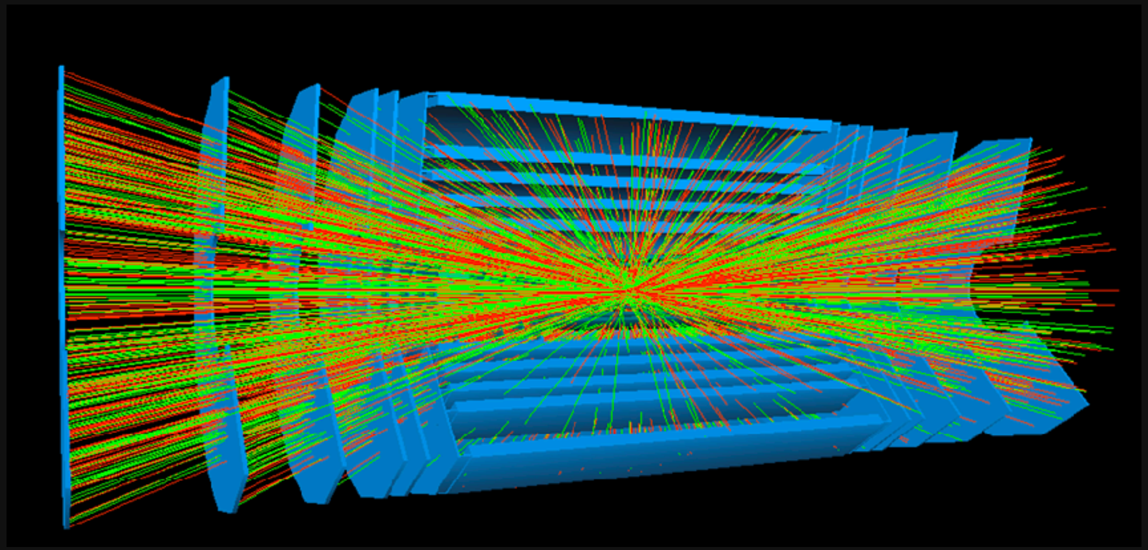


How do we get there?

The High-Luminosity LHC



$\langle \mu \rangle \approx 20$

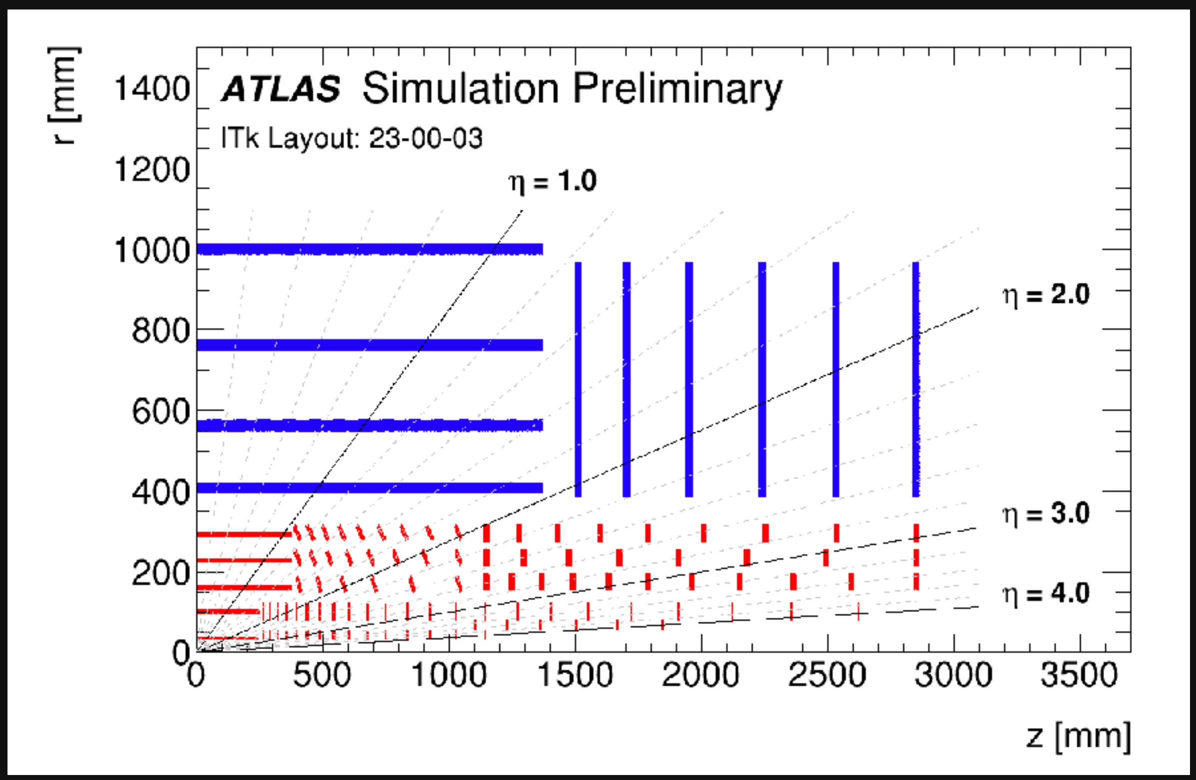


$\langle \mu \rangle \approx 200$

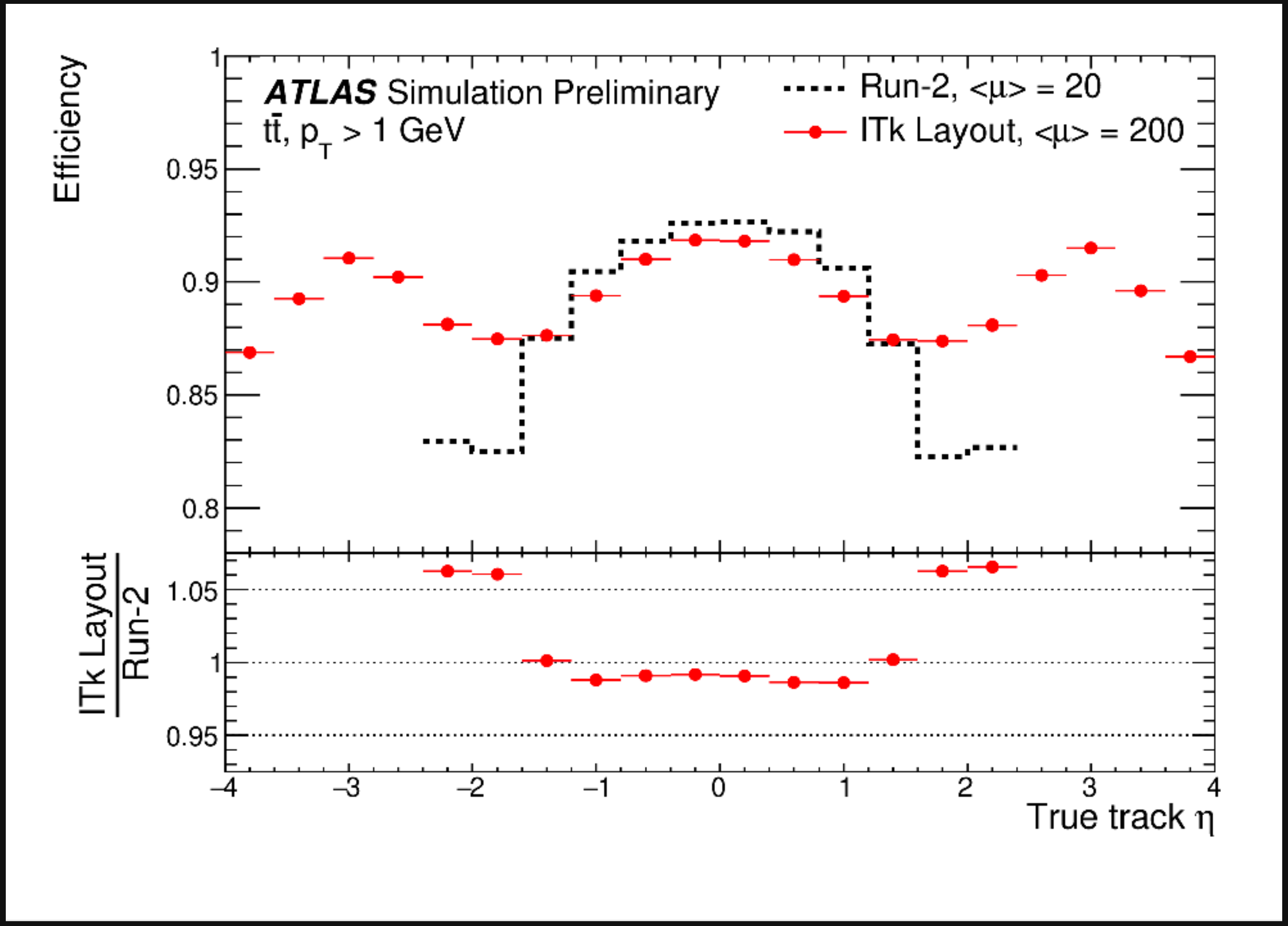
- Starting 2029, expect **200 simultaneous collisions**
- Requires high-throughput hardware, an **efficient trigger system**, and **radiation-tolerant tracking instrumentation** to survive

ATL-PHYS-PUB-2019-014 ATL-PHYS-PUB-2021-040

Inner TracKer (ITk)



schematic of layout



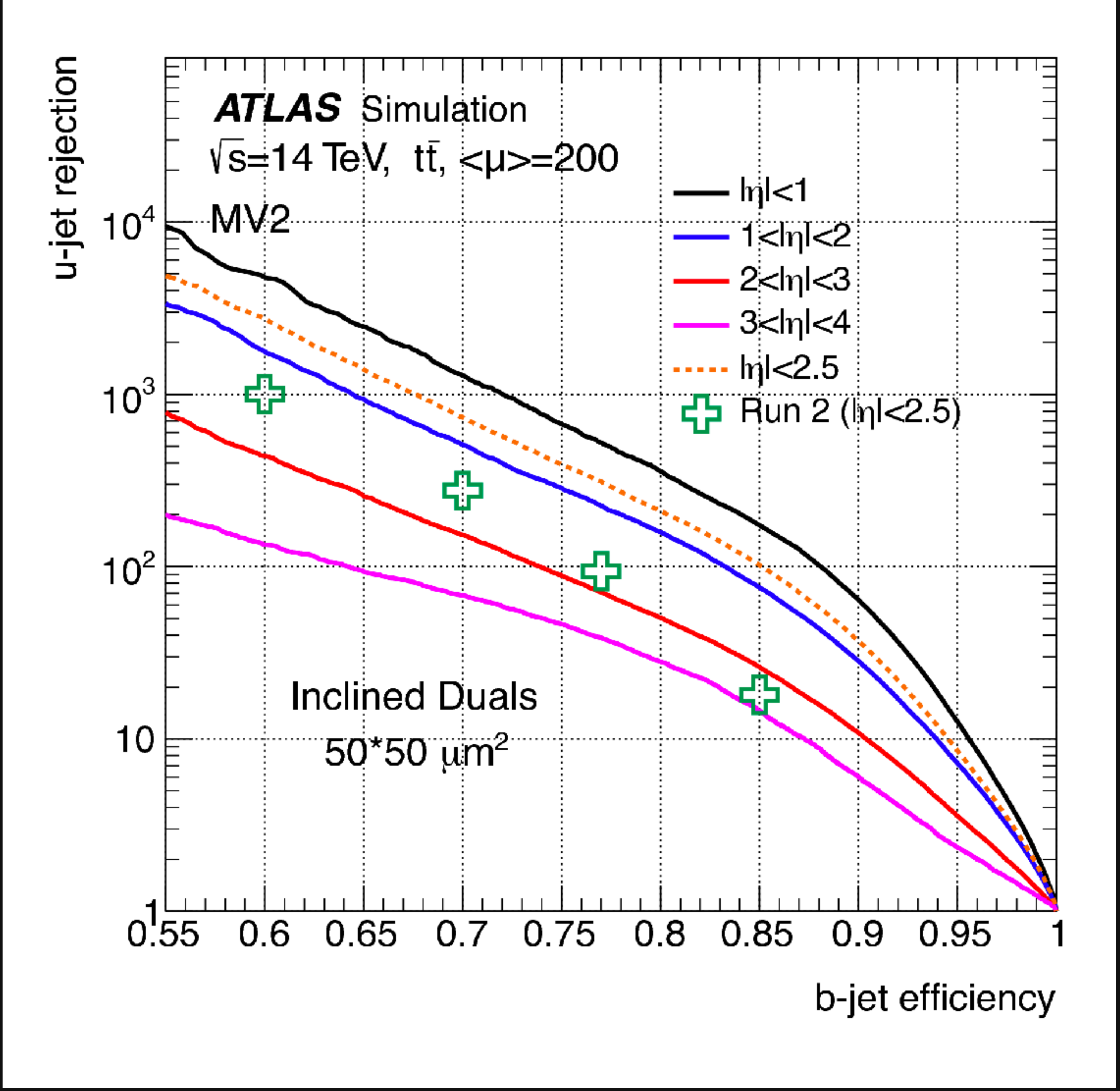
track reconstruction efficiency for $t\bar{t}$ events

- After Run 3 (2026), **completely replace** the inner detector of the ATLAS experiment
- We need **efficient tracking** with **excellent vertex resolution**

ATL-PHYS-PUB-2019-005

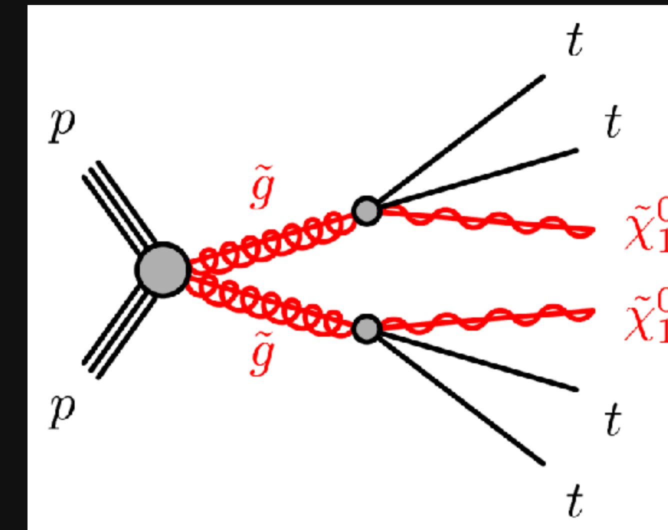
Tracking Upgrades

- Requires improved tracking hardware to at least **maintain** these efficiencies, and **survive** the harsh environment
- "How well can we identify *b*-quark jets?"

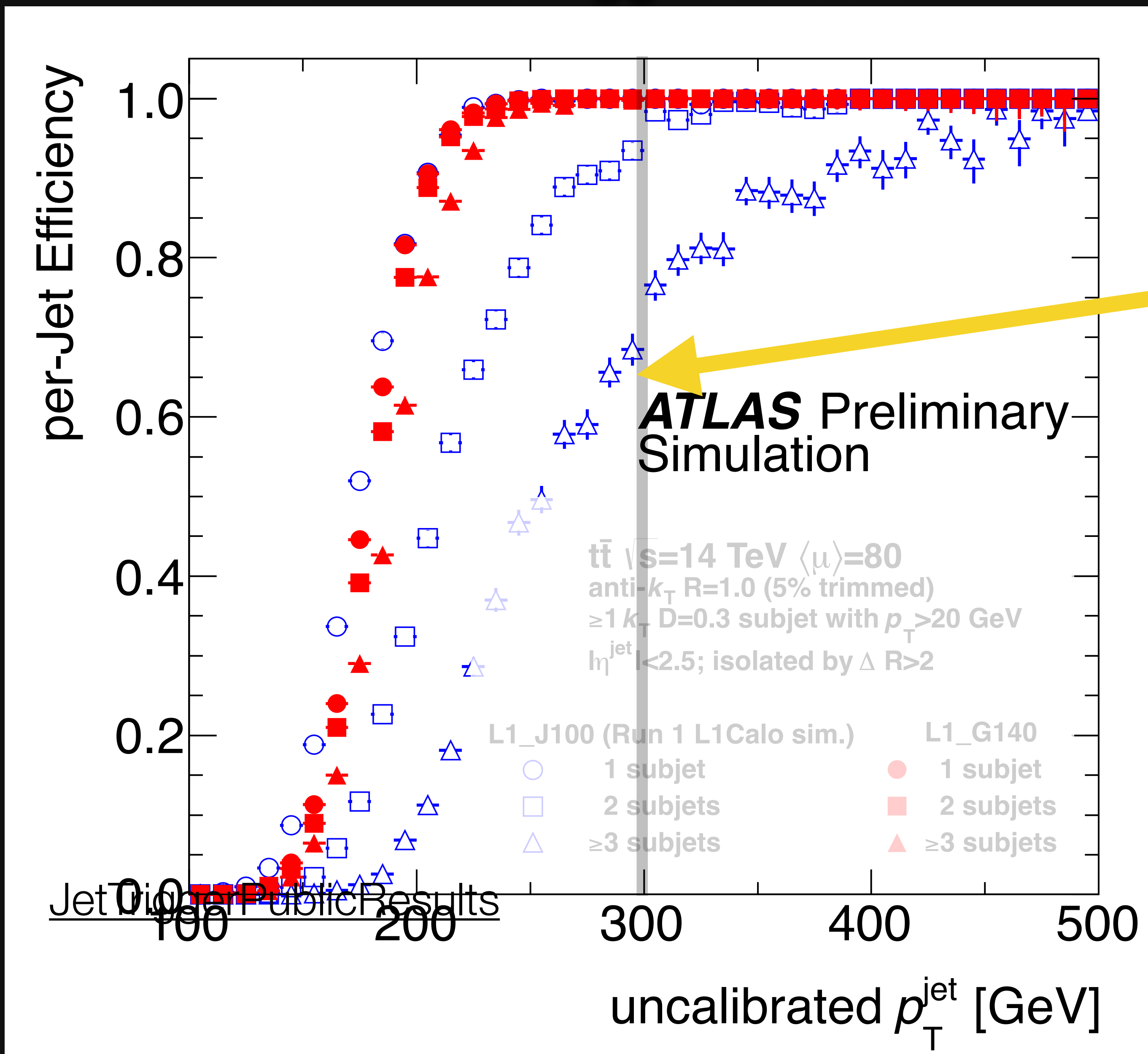


JetTriggerPublicResults

Trigger Upgrades



Blue=Current Trigger @ 100 GeV



Red=gFEX Trigger @ 140 GeV

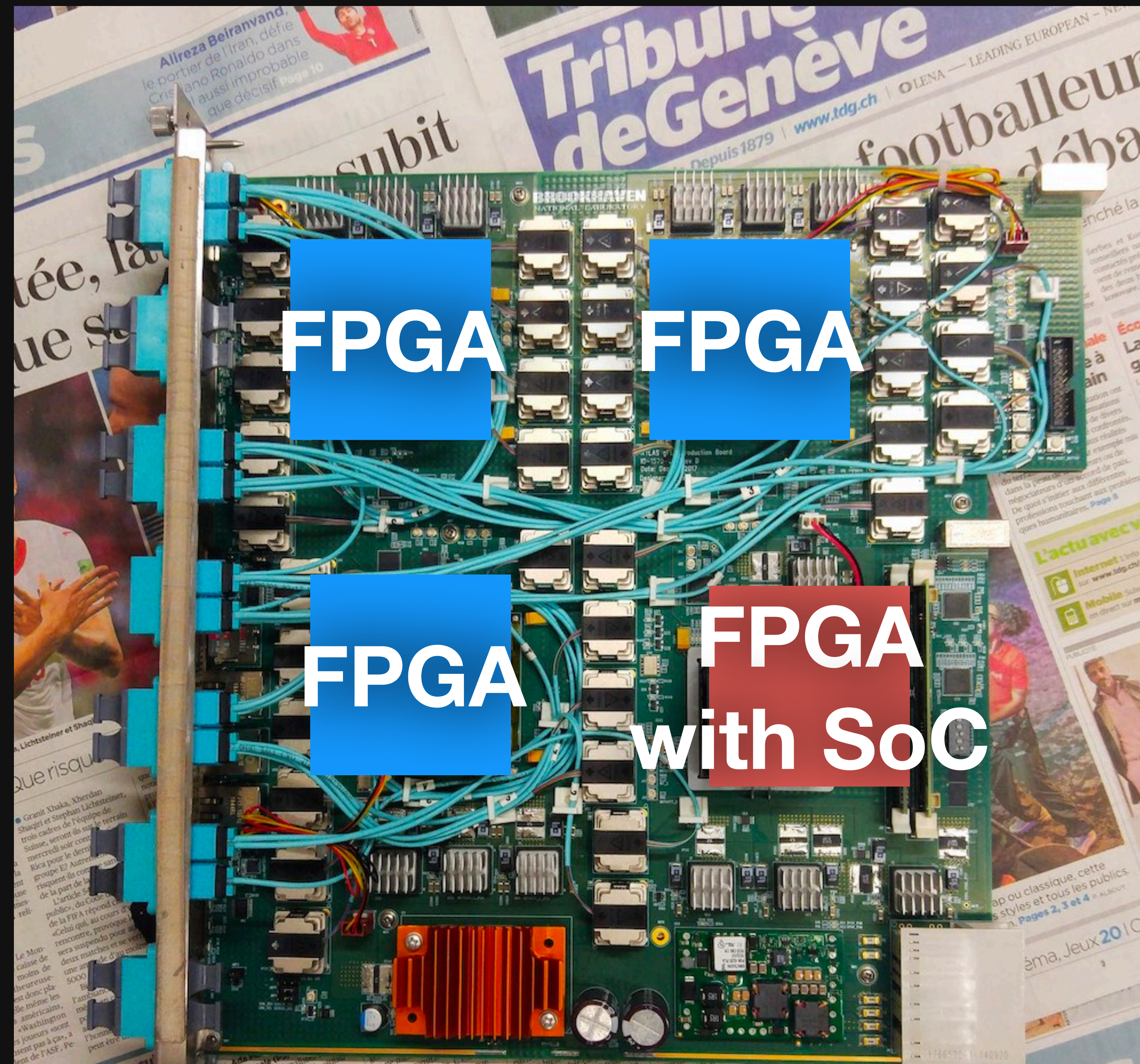
a top quark at 300 GeV

- 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 (and MET)!**

gFEX Board (commissioning!)

- Must process everything in 5 bunch crossings - 125 nanoseconds!
- **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**
- Started in 2014 and now installed and commissioning since October 2021!



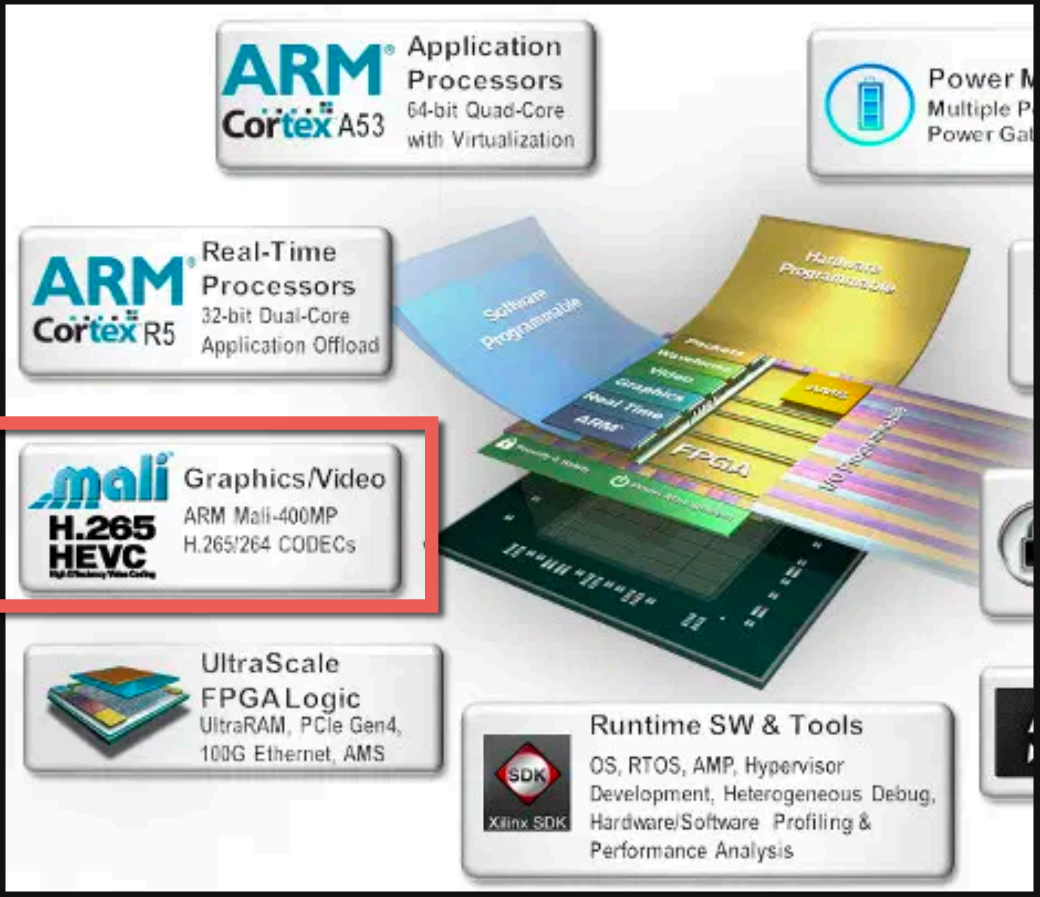
! full calorimeter information on a single board

[arXiv: 2103.05579](https://arxiv.org/abs/2103.05579) [arXiv: 2104.06622](https://arxiv.org/abs/2104.06622) [arXiv:1804.06913](https://arxiv.org/abs/1804.06913)

Trigger Thoughts

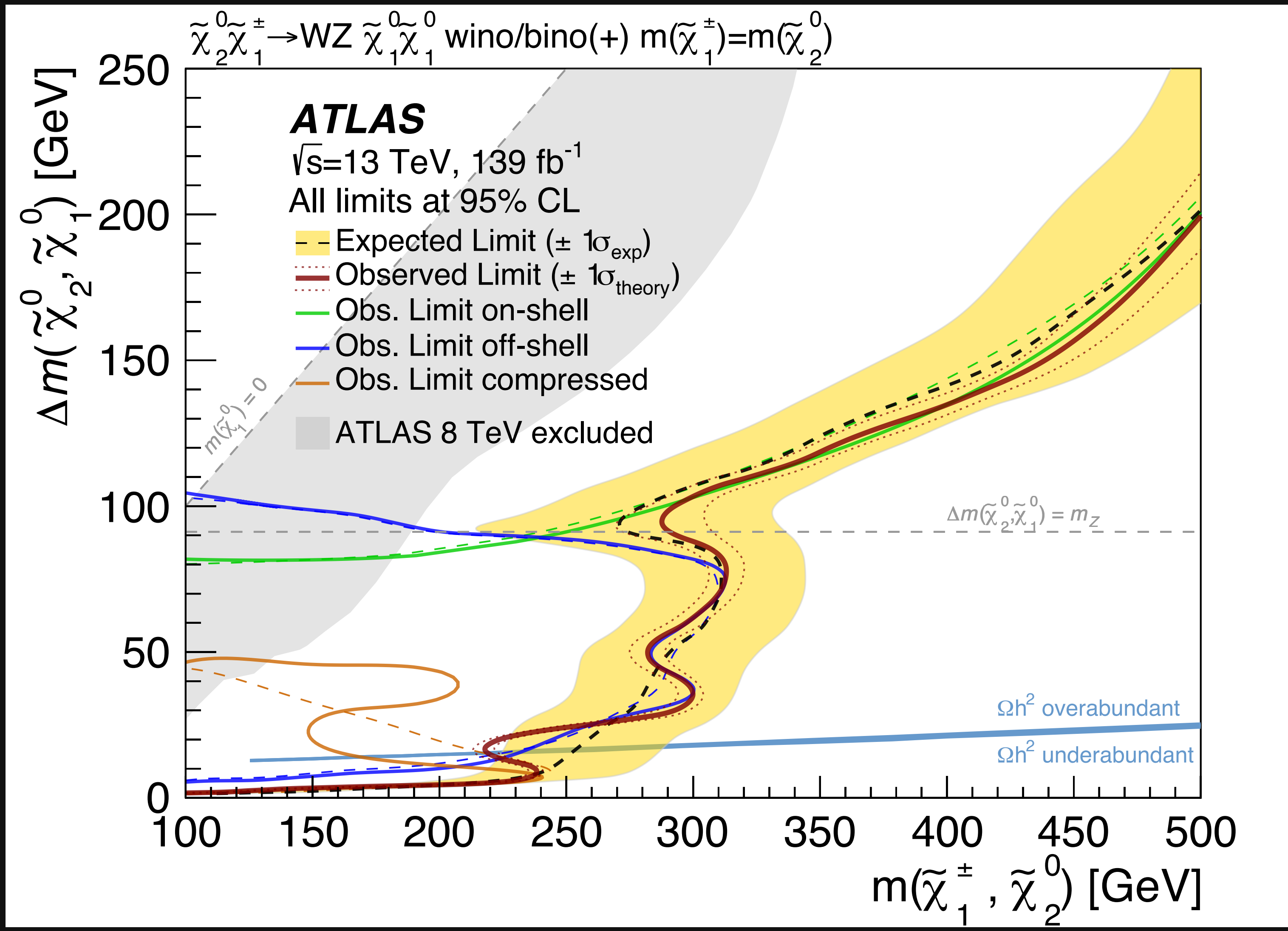
- gFEX is using bleeding-edge technology (UltraScale+ MPSoC with ARM Mali-400 MP2 GPU)
- **What can we do with GPUs** in the trigger/detector?
  - Exploit tracking algorithms? Vertexing?
  - More global object reconstruction?
  - Parallelize algorithms?
- Could **information from the ITk readout chips** be used in the trigger?
  - Requires low latency (bandwidth-limited?)
  - Possibly reduce front-end electronics in the detector

Research in this area could be exploited not only for HL-LHC, but other experiments such as μ-collider, EIC, FCC, DUNE, etc…



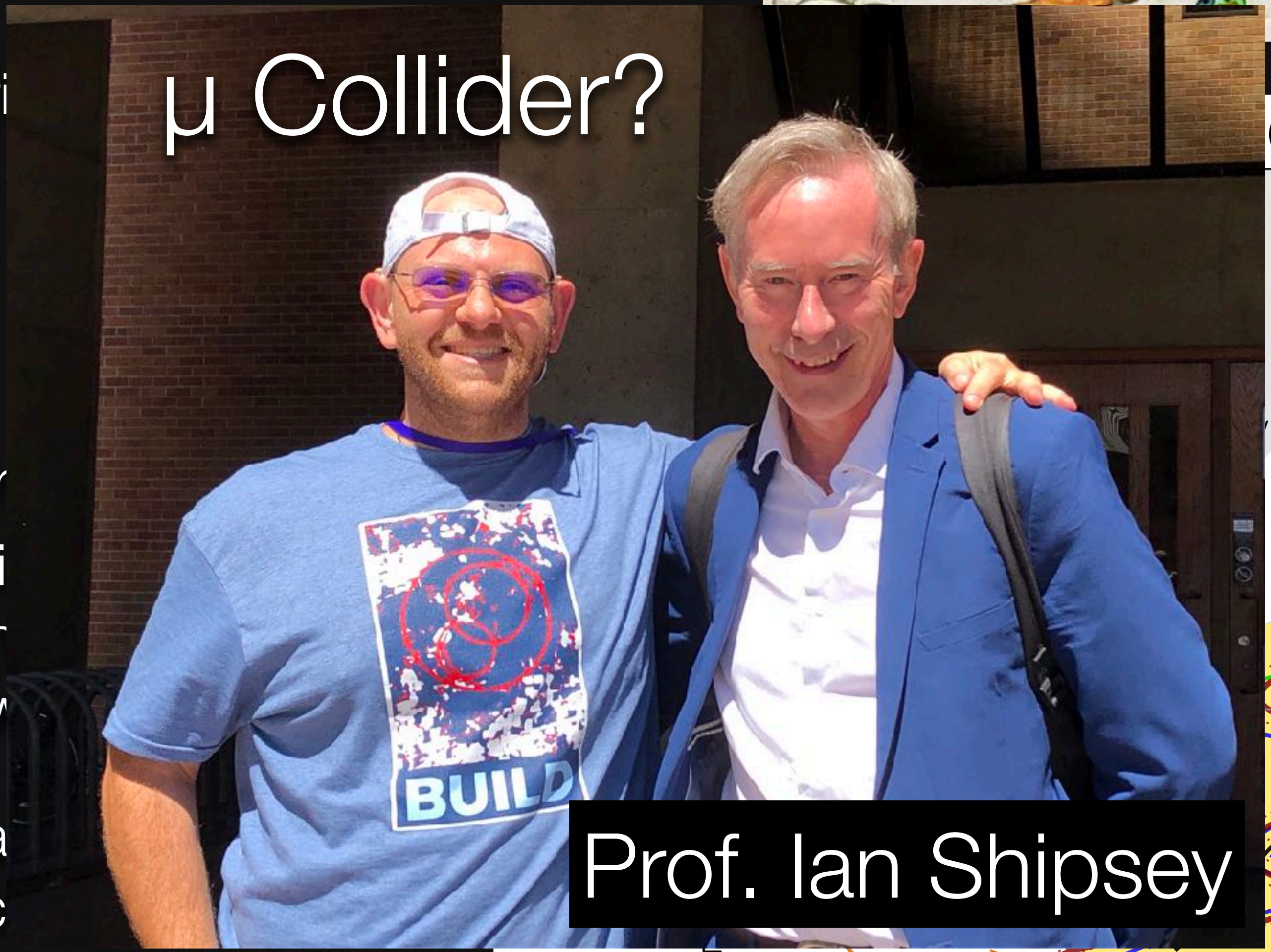
Conclusion

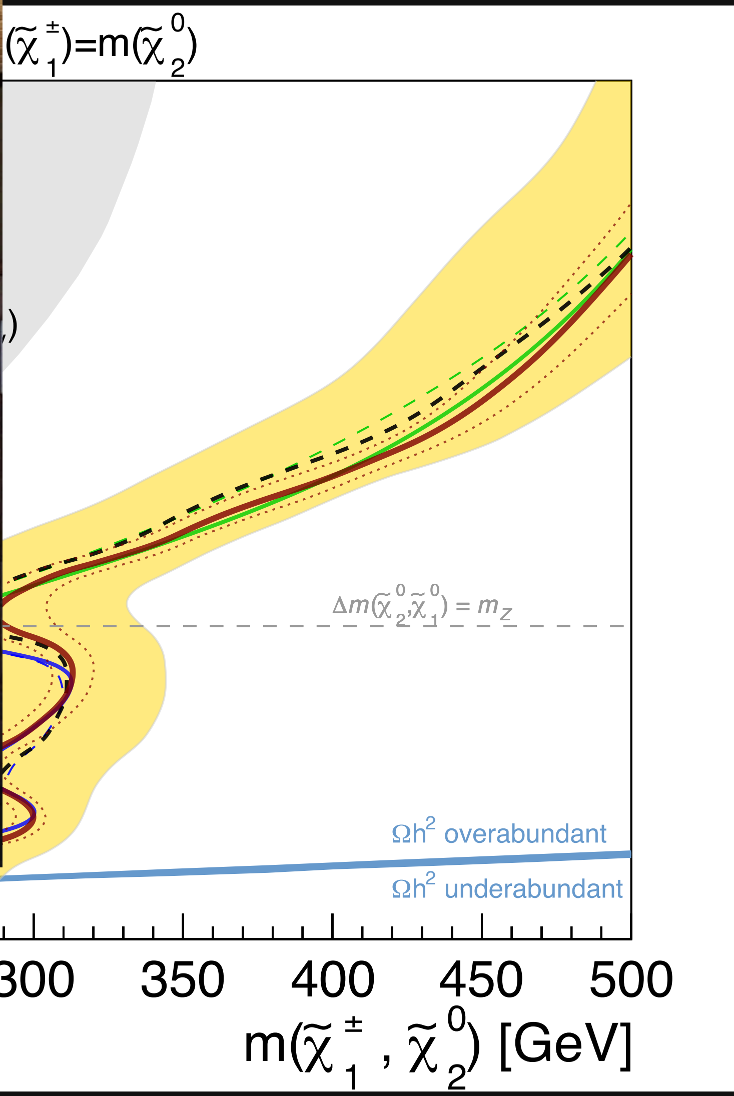
- What will the future bring?
  - Run 3 is now!
  - Run 4+ in 2029
  - Other colliders?
- A rich physics and hardware program
  - Lots of opportunities for students to work on instrumentation, data analysis, and software development
- Continue to improve accessibility through preservation/reproducibility as well as teaching/promoting inclusive practices
- Identify uncovered areas and find new rocks to look under for SUSY



Conclusion

- What will the future bri
  - Run 3 is now!
  - Run 4+ in 2029
  - Other colliders?
- A rich physics and har
  - Lots of opportuniti work on instrumer analysis, and softv
- Continue to improve a preservation/reproduc teaching/promoting inclusive practices
- Identify uncovered areas and find new rocks to look under for SUSY





https://snowmass21.org/ http://seattlesnowmass2021.net/

Seattle Snowmass — July 25th, 2022

https://snowmass21.org/ http://seattlesnowmass2021.net/

Seattle Snowmass — July 25th, 2022