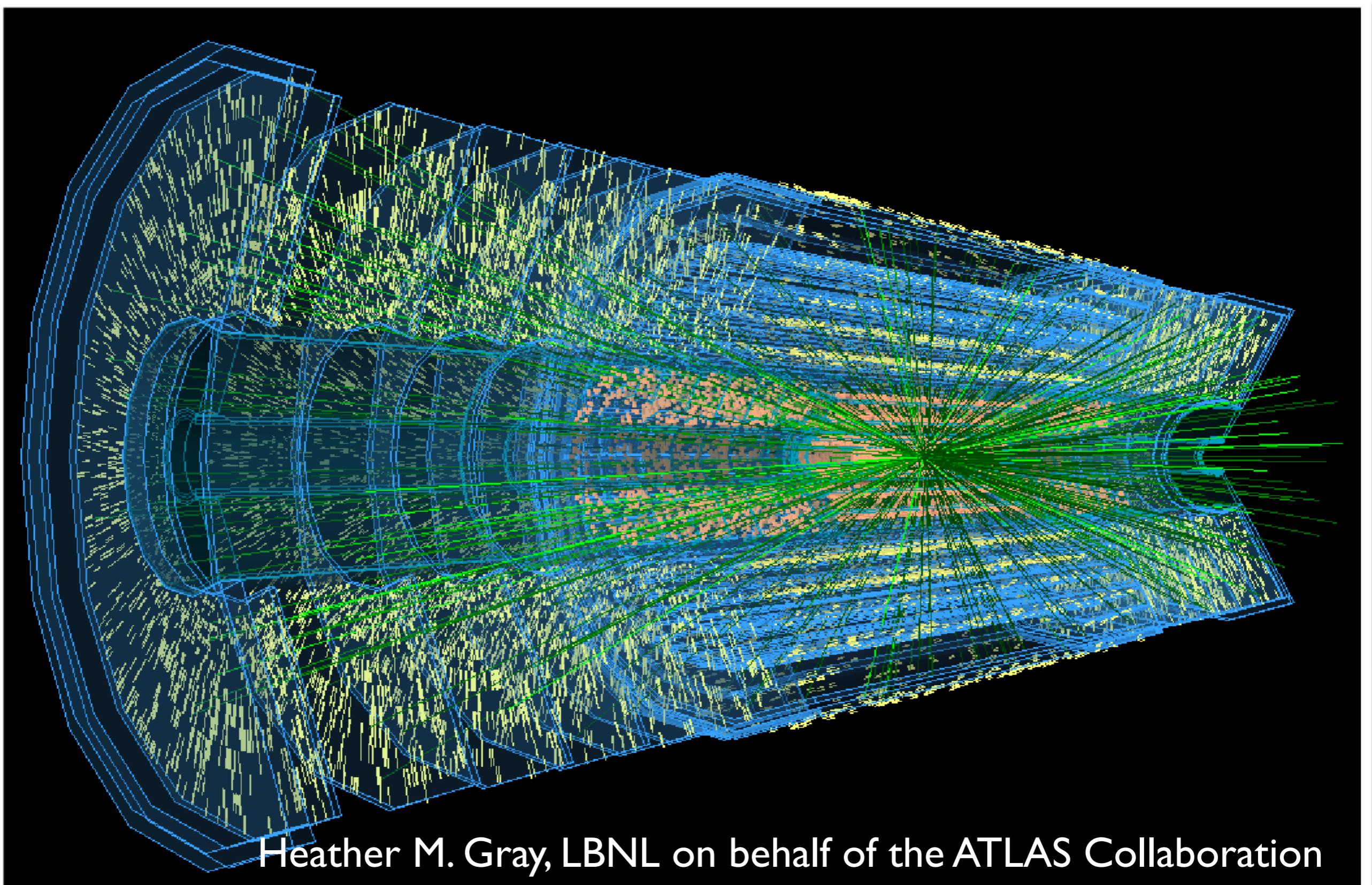


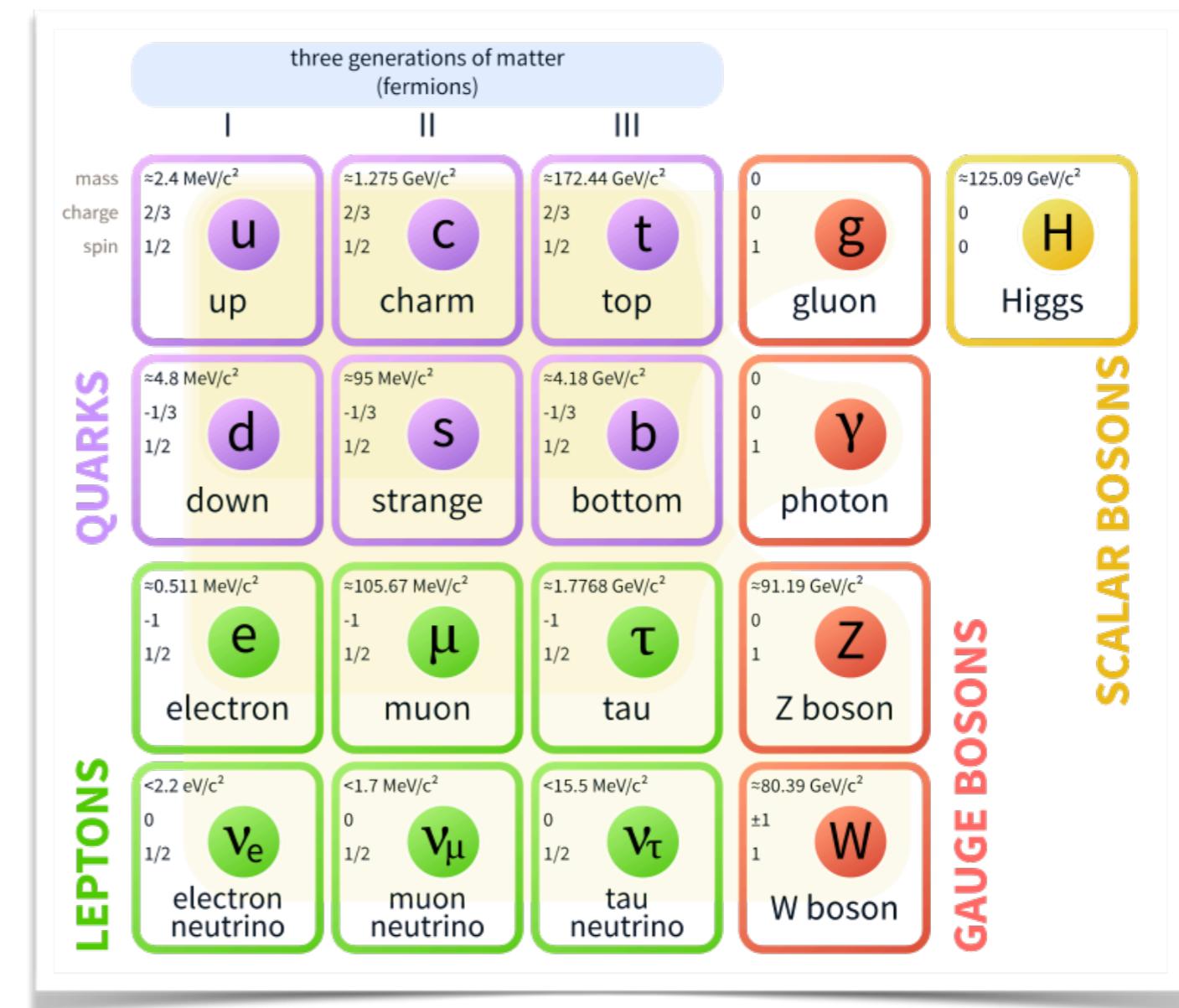
The ATLAS Physics challenge at the HL-LHC and early ideas about Quantum Computing



Heather M. Gray, LBNL on behalf of the ATLAS Collaboration

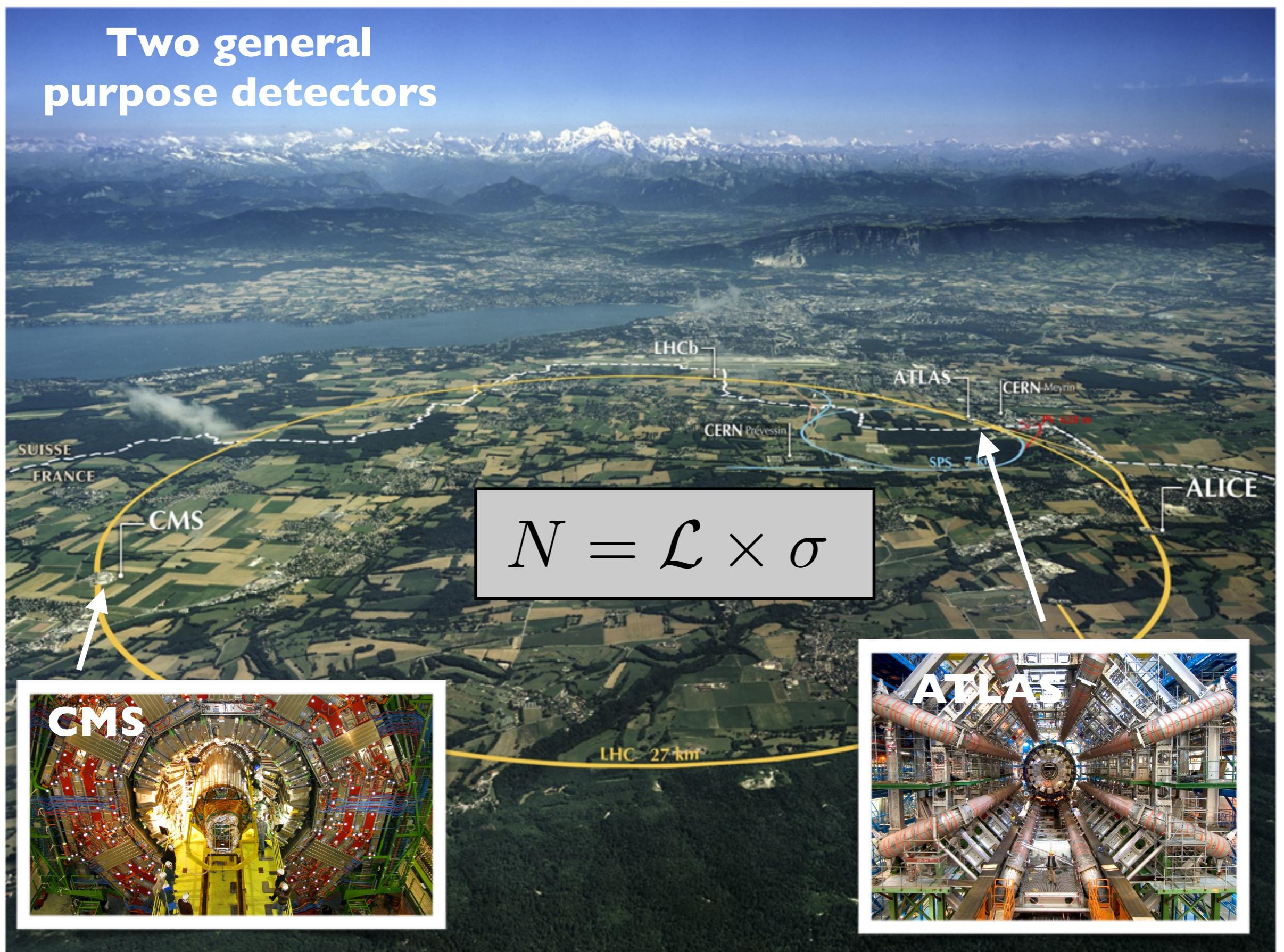
Particle Physics in one slide

- The central question of particle physics: what are **fundamental** constituents of matter and their **interactions**
- Current knowledge is encapsulated in the **Standard Model (SM)**
 - Consists of 24 elementary matter particles and 3 forces with a total of 19(+7) parameters
 - Remarkably **successful** in describing many experimental results, yet we know its **incomplete**
 - Dark matter
 - Baryon asymmetry
 - Neutrino mass



The Large Hadron Collider (LHC)

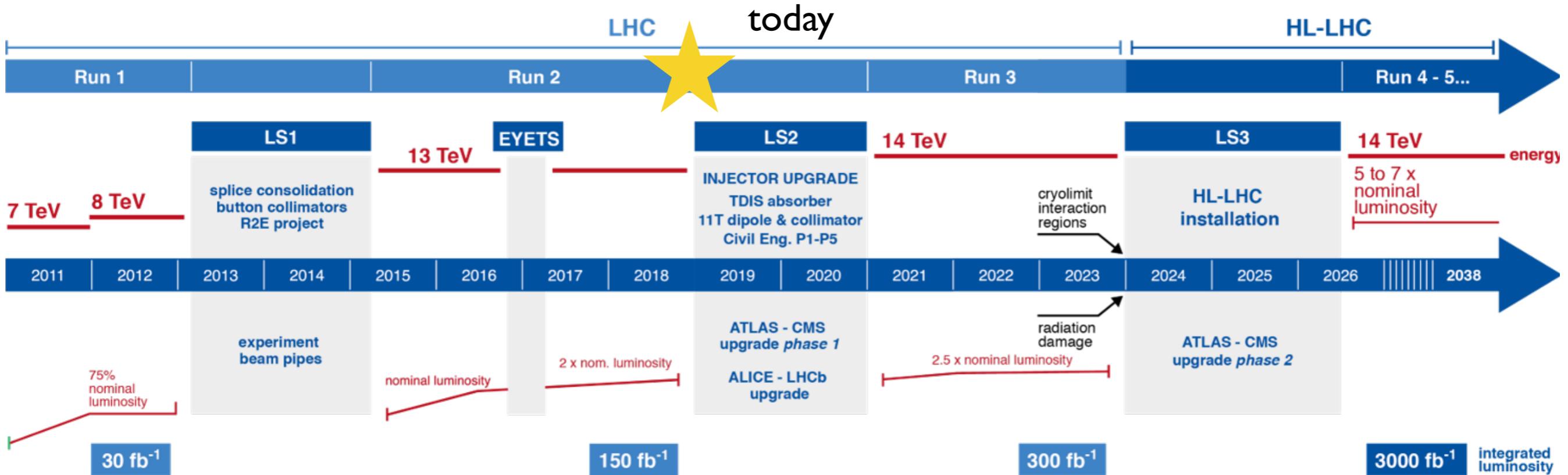
Two general purpose detectors



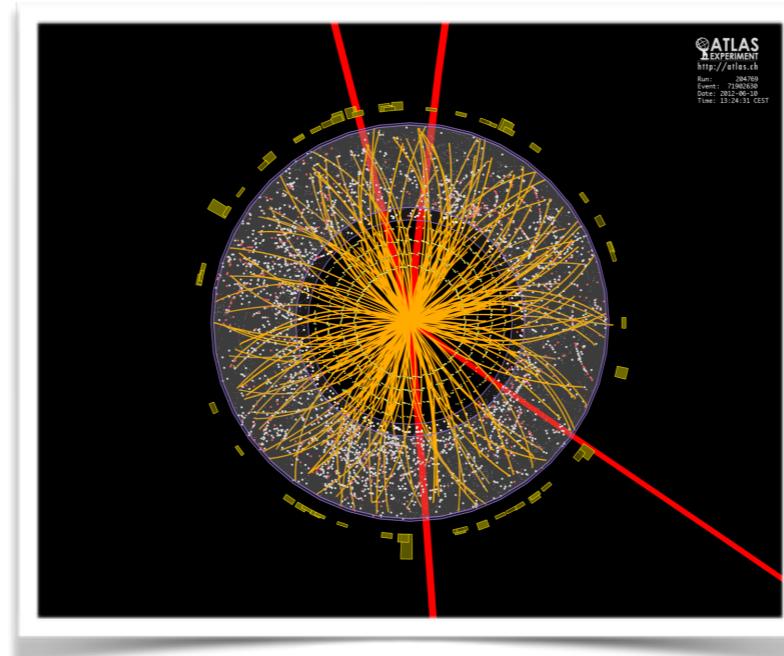
LHC / HL-LHC Plan



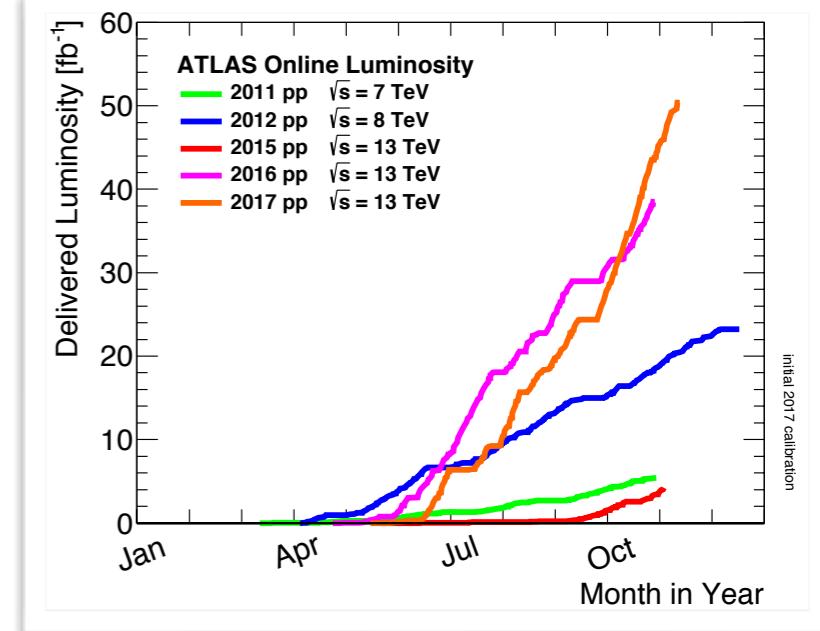
4



First beam in ATLAS
(2009)



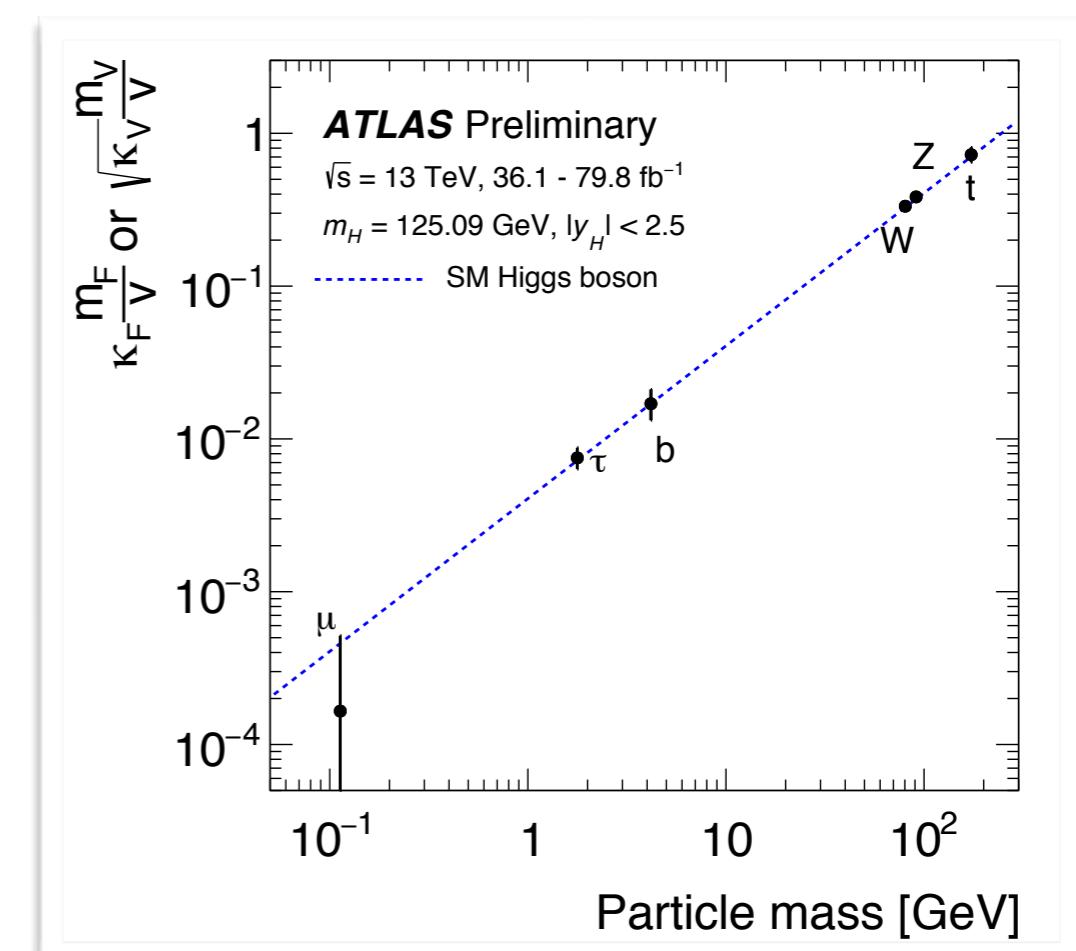
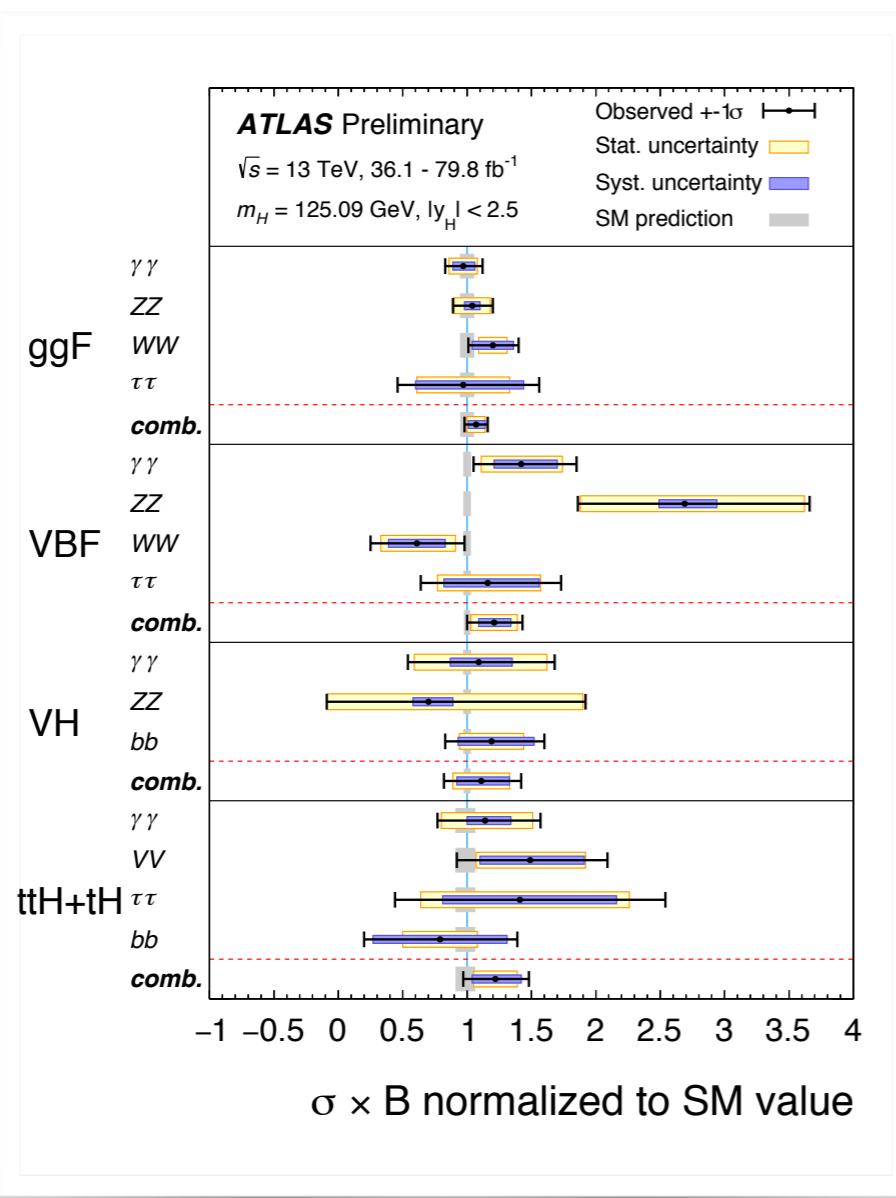
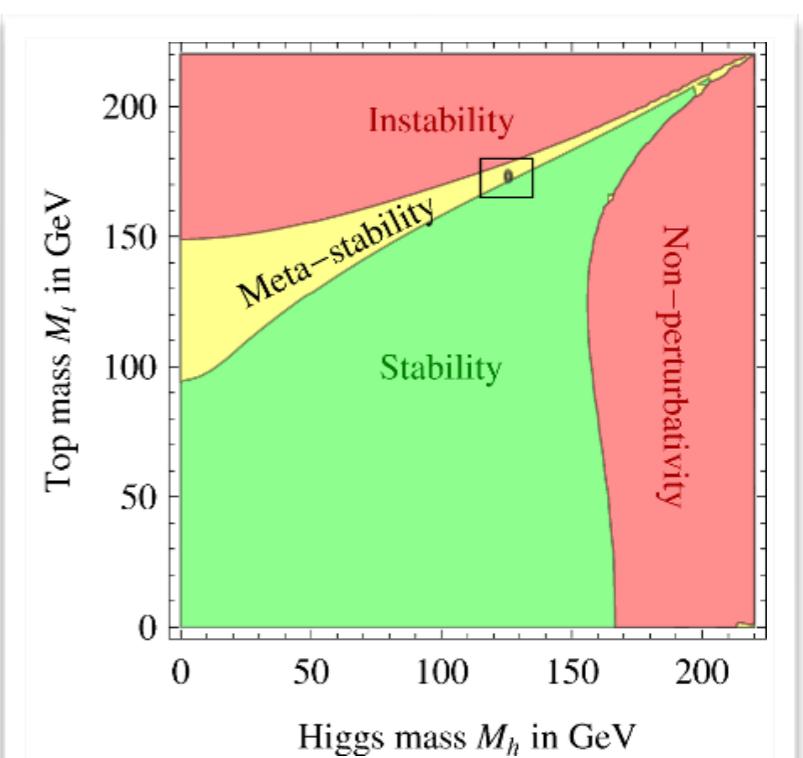
Higgs discovery
(2012)



Only ~5% of total expected data

Current Higgs Properties

- Mass: $124.97 \pm 0.24 (\pm 0.16)$ GeV
- Width: Indirect via off-shell < 14.4 (15.2) MeV
- Spin and parity $J^{PC} = 0^{++}$
- Couplings to other elementary particles



Probing supersymmetry to the TeV scale

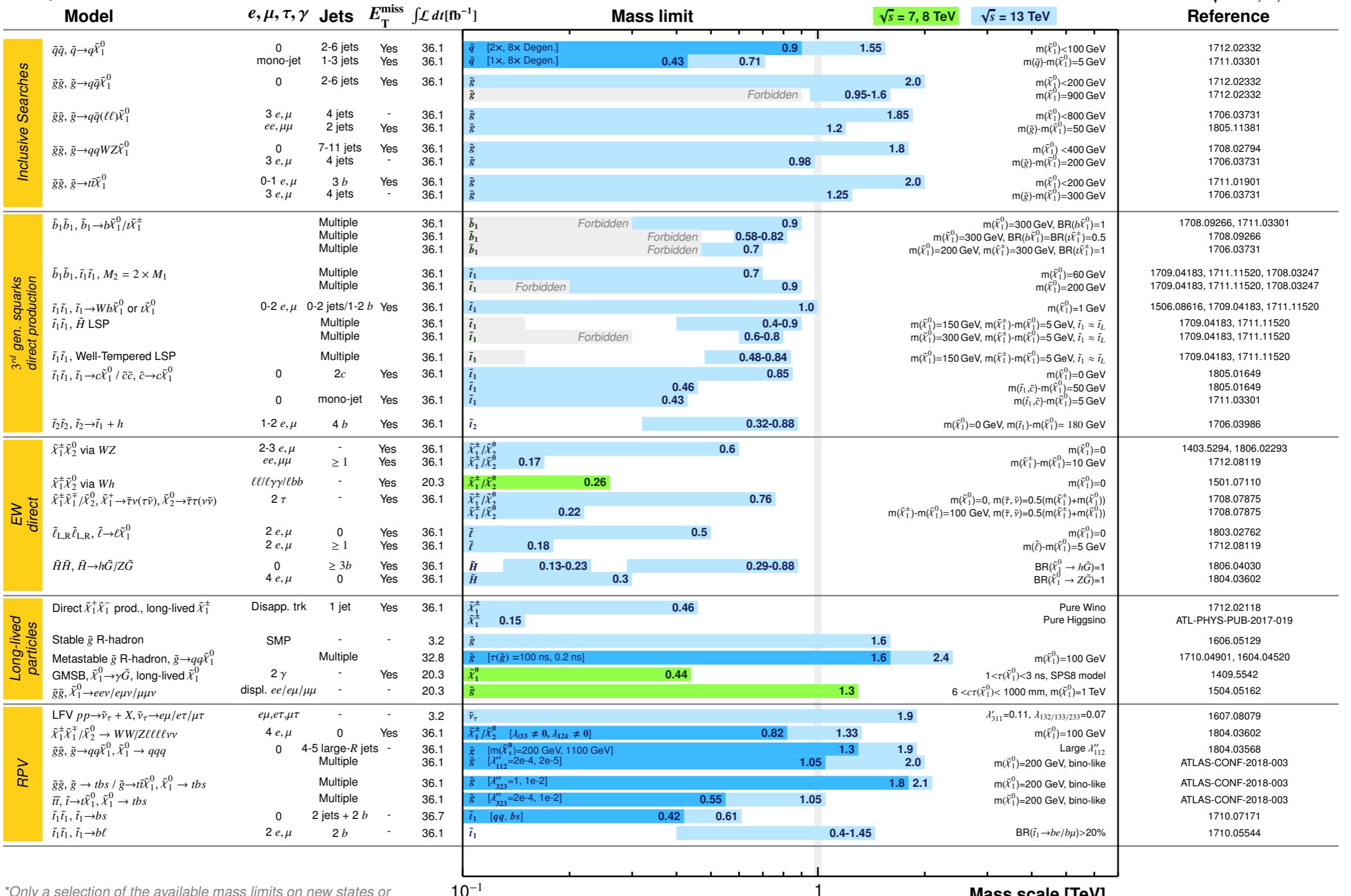
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Reference



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Searches for exotic particles to high mass

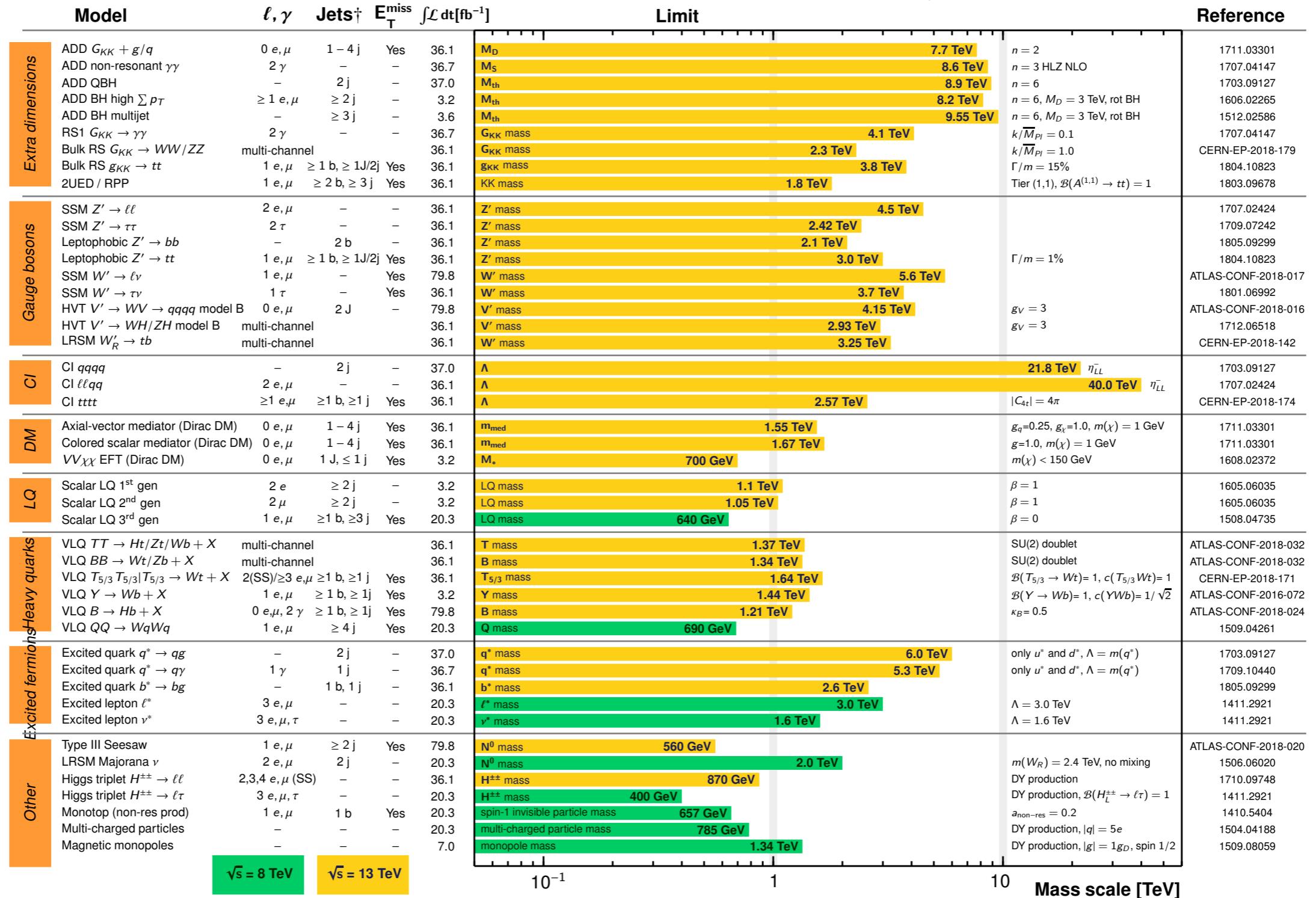
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$



$\sqrt{s} = 8$ TeV

$\sqrt{s} = 13$ TeV

10⁻¹

1

10

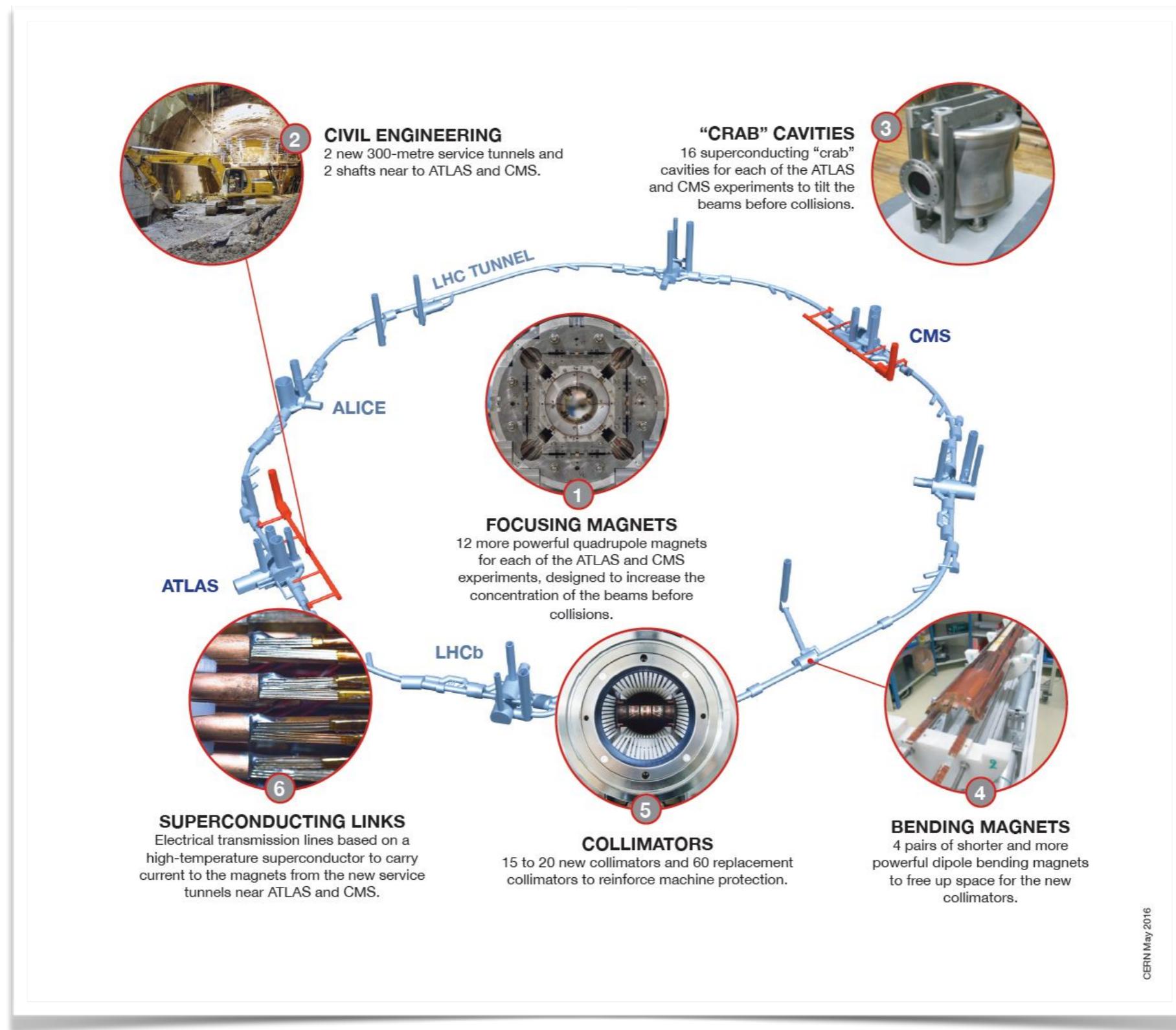
Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

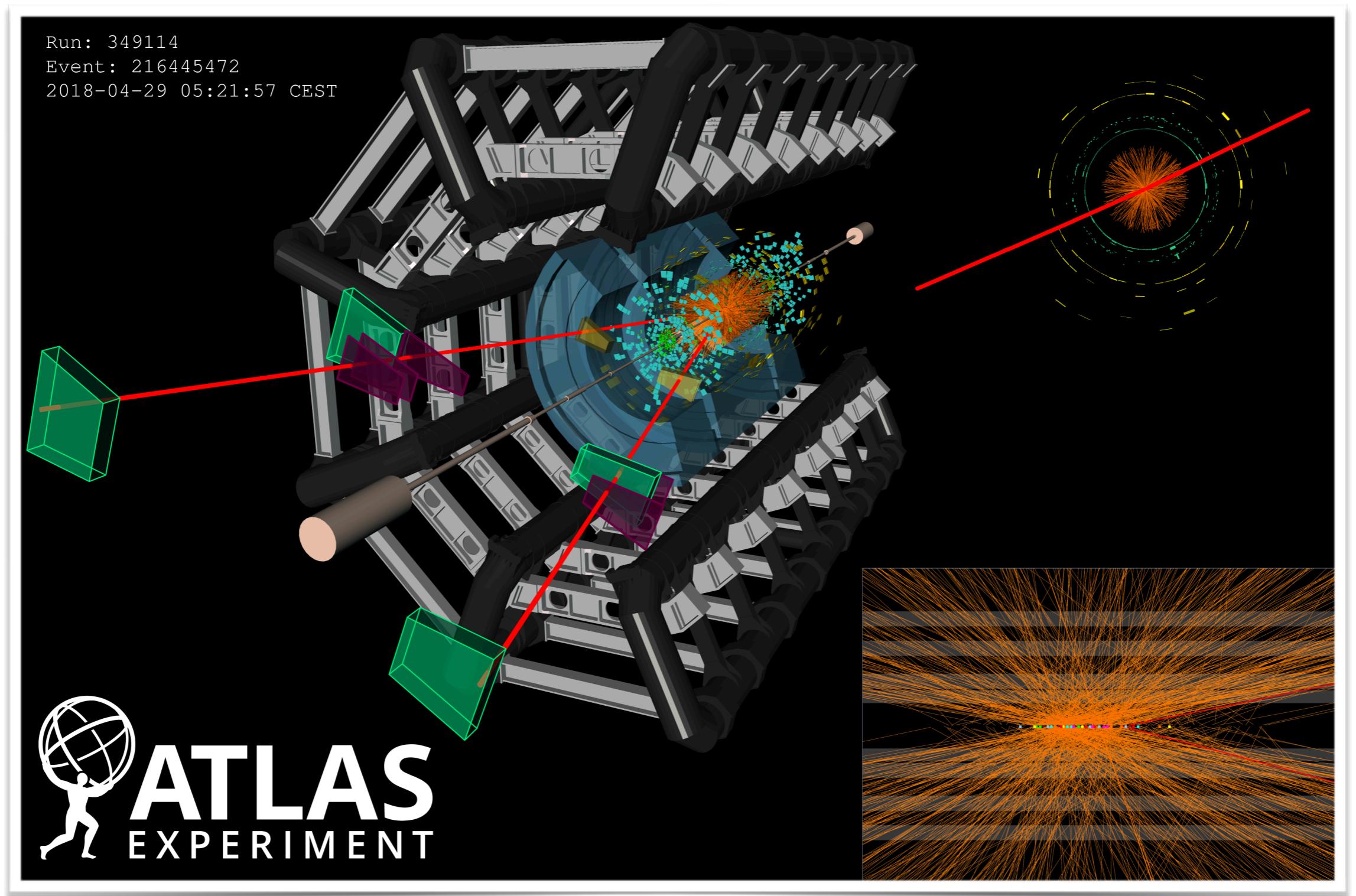
What's new at the HL-LHC?

- Upgraded accelerator: much more data!



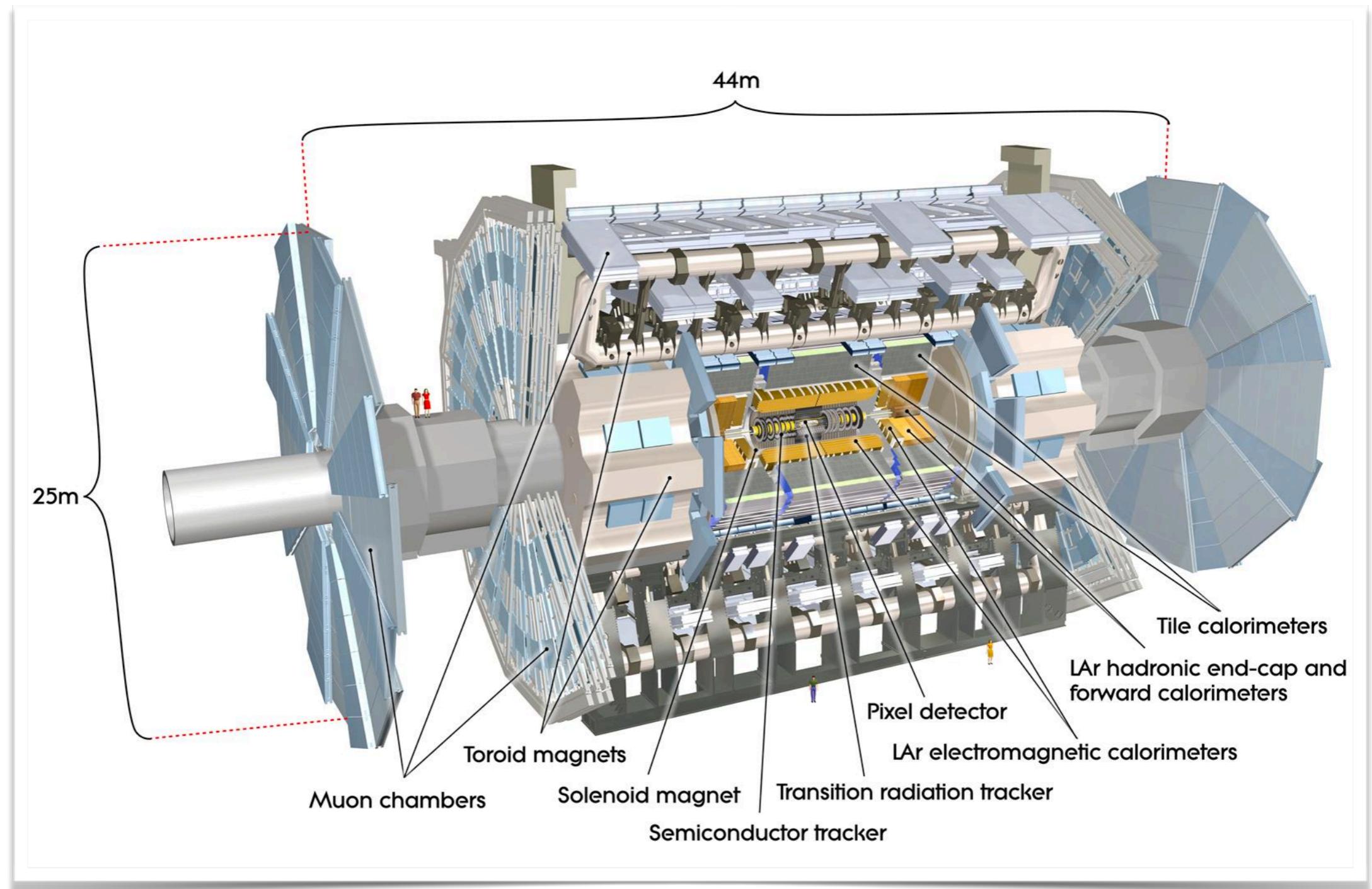
What's new at the HL-LHC?

- Upgraded accelerator: also many more interactions per bunch crossing



What's new at the HL-LHC?

Upgrades planned for almost all detectors



Why? Aka what physics will we do?

- Two key directions
 - What can we measure **more accurately**?
 - Precision measurements can be indirect probes for new physics at high energy scales
 - What **new processes** will we be able to reach that we can't measure now?
- A few examples
 - Higgs boson properties
 - Rare decays
 - Self-coupling
 - New physics
 - Search for even rarer phenomena
 - Small increase to higher mass scales

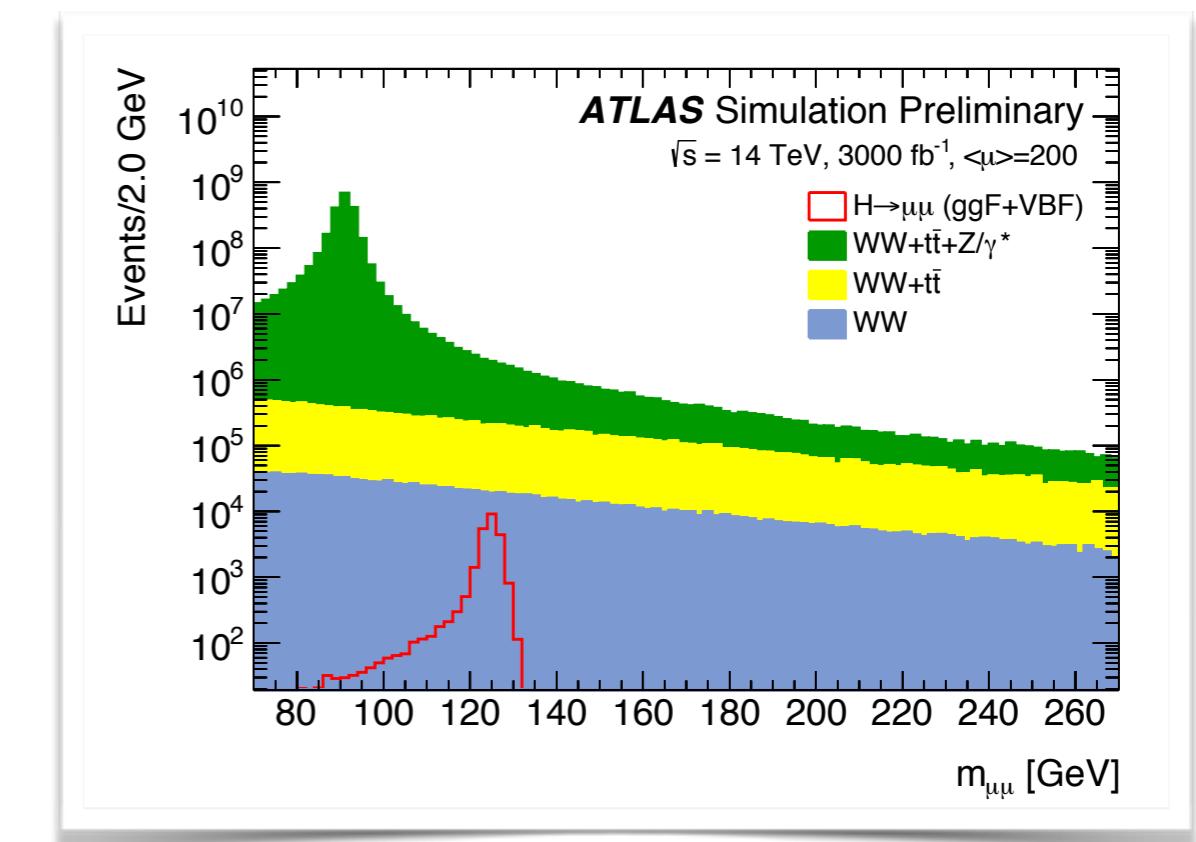
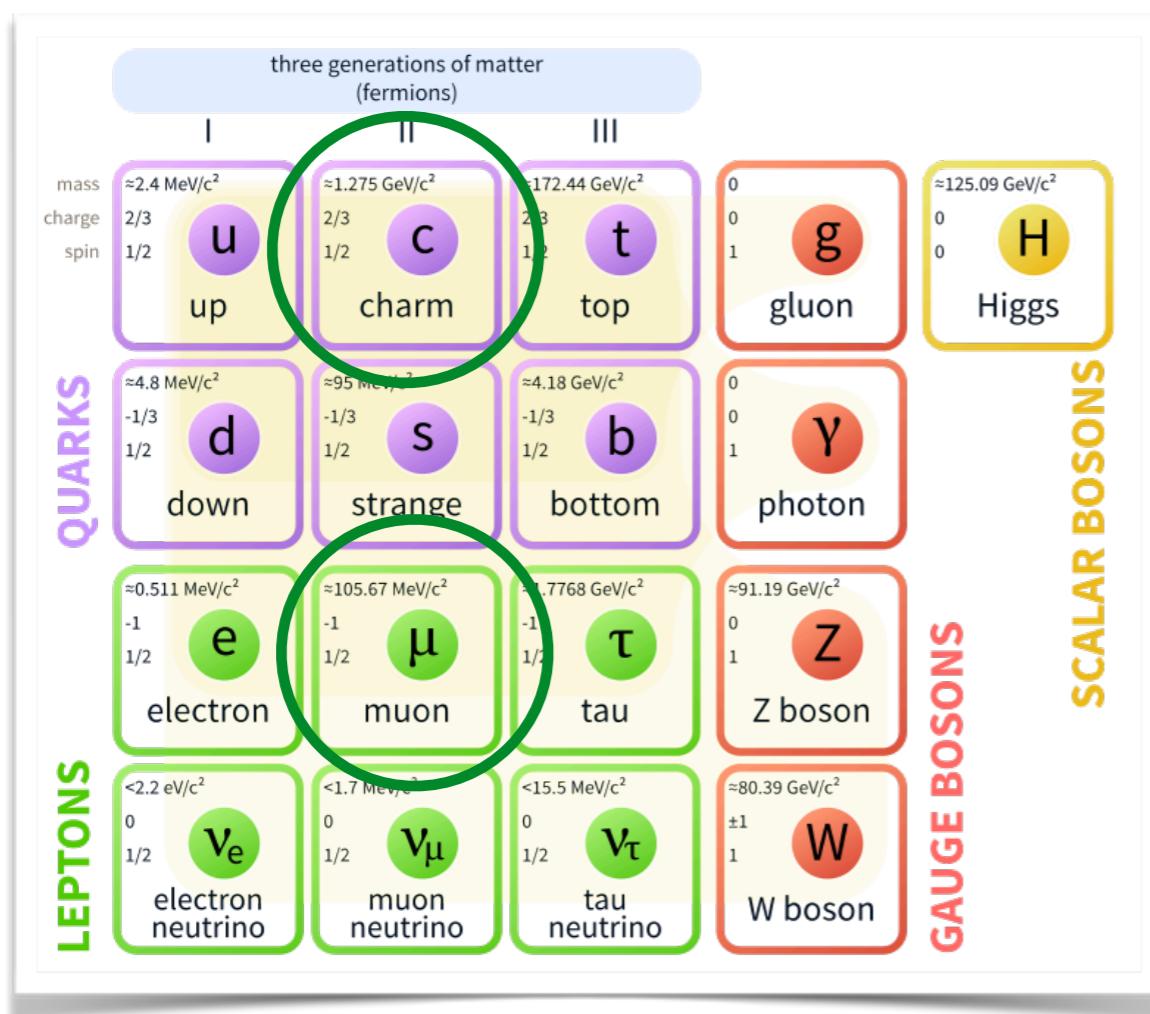
Caveat: Updates expected soon



European Strategy Update

Rare Higgs decays

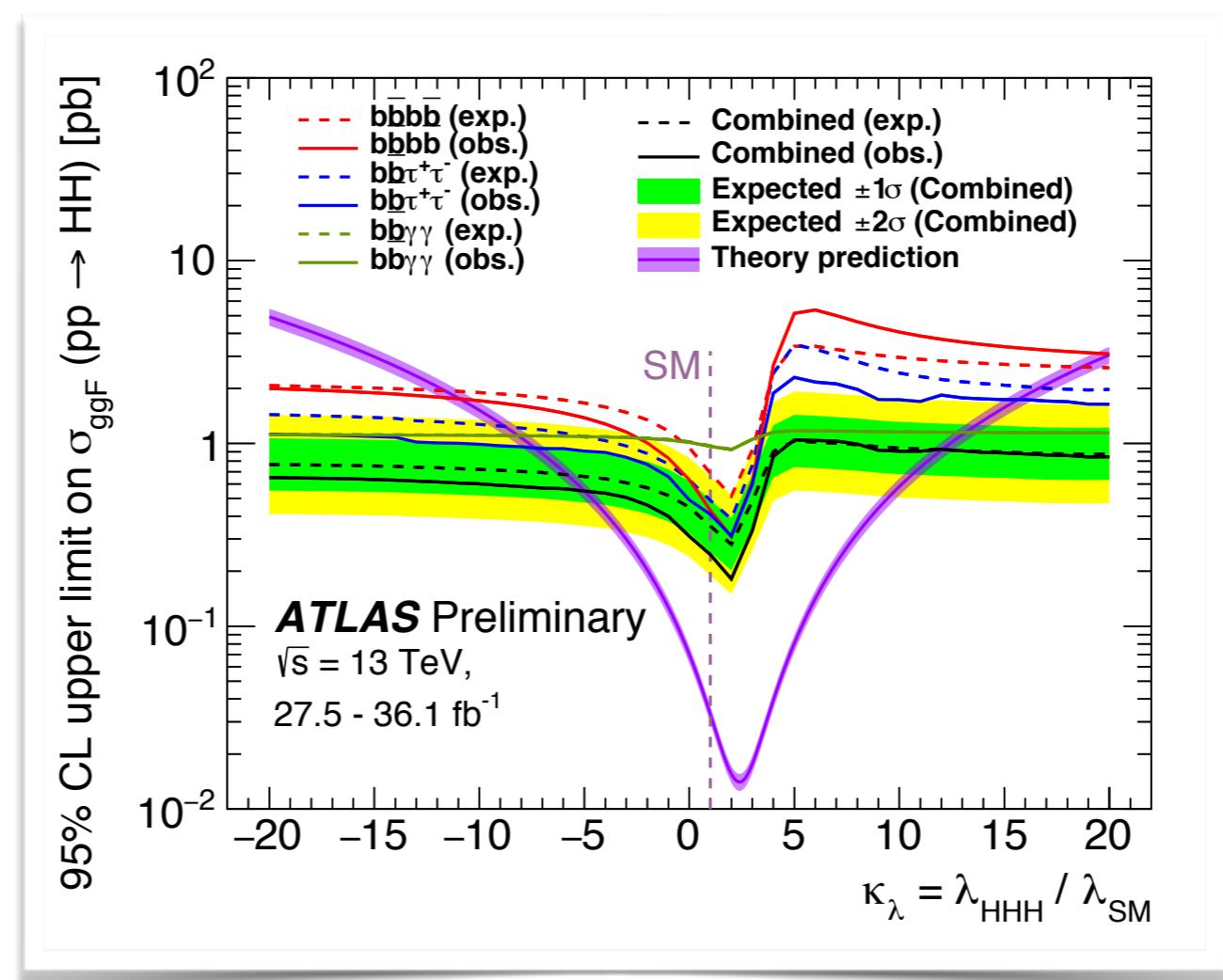
- So far we've only been able to directly probe the coupling of the Higgs to third generation fermions
- At HL-LHC, we would be able to study the coupling of the Higgs to muons to a precision of $\sim 15\%$
- Might also be able to probe the coupling to charm quarks



Double Higgs production

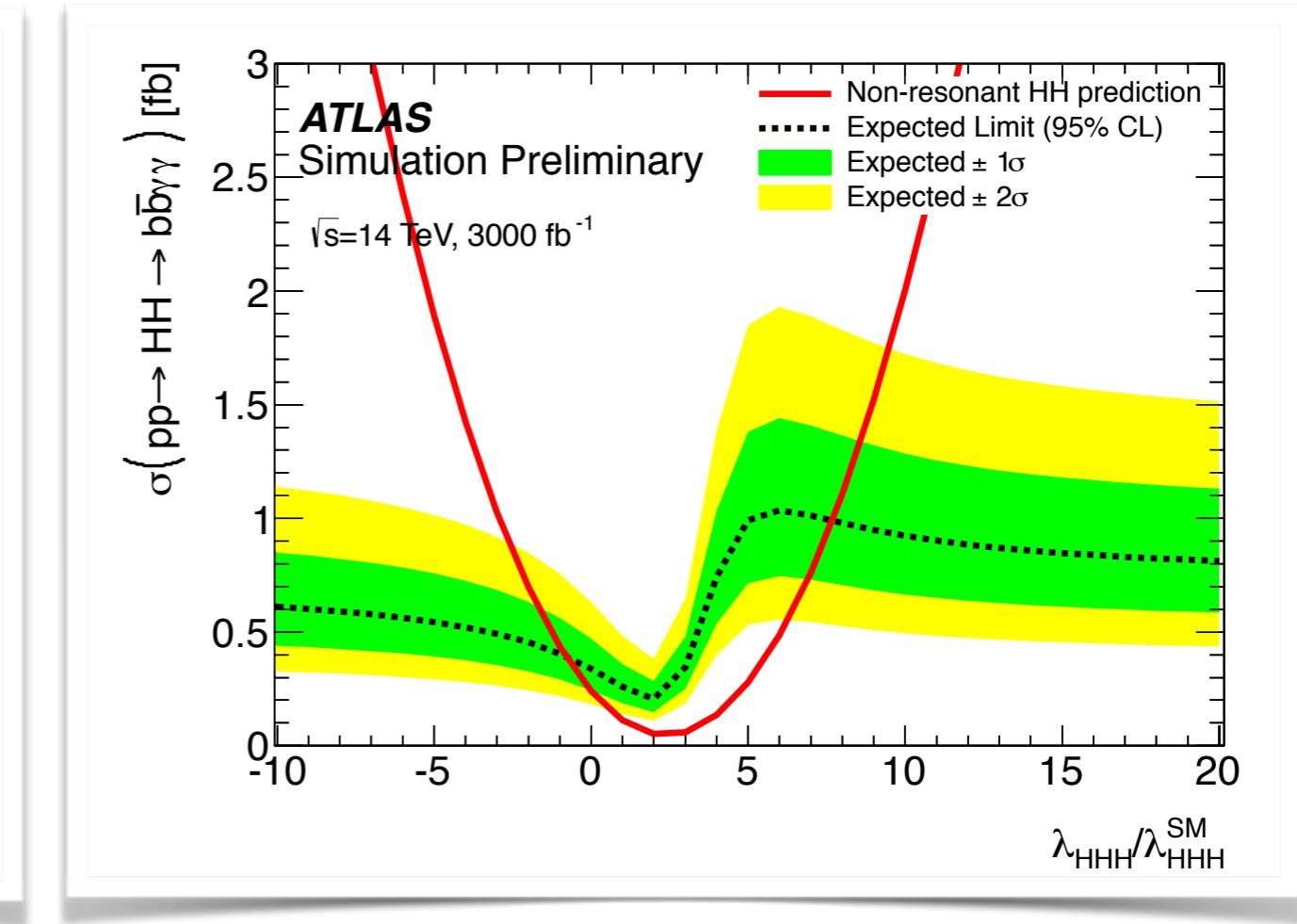
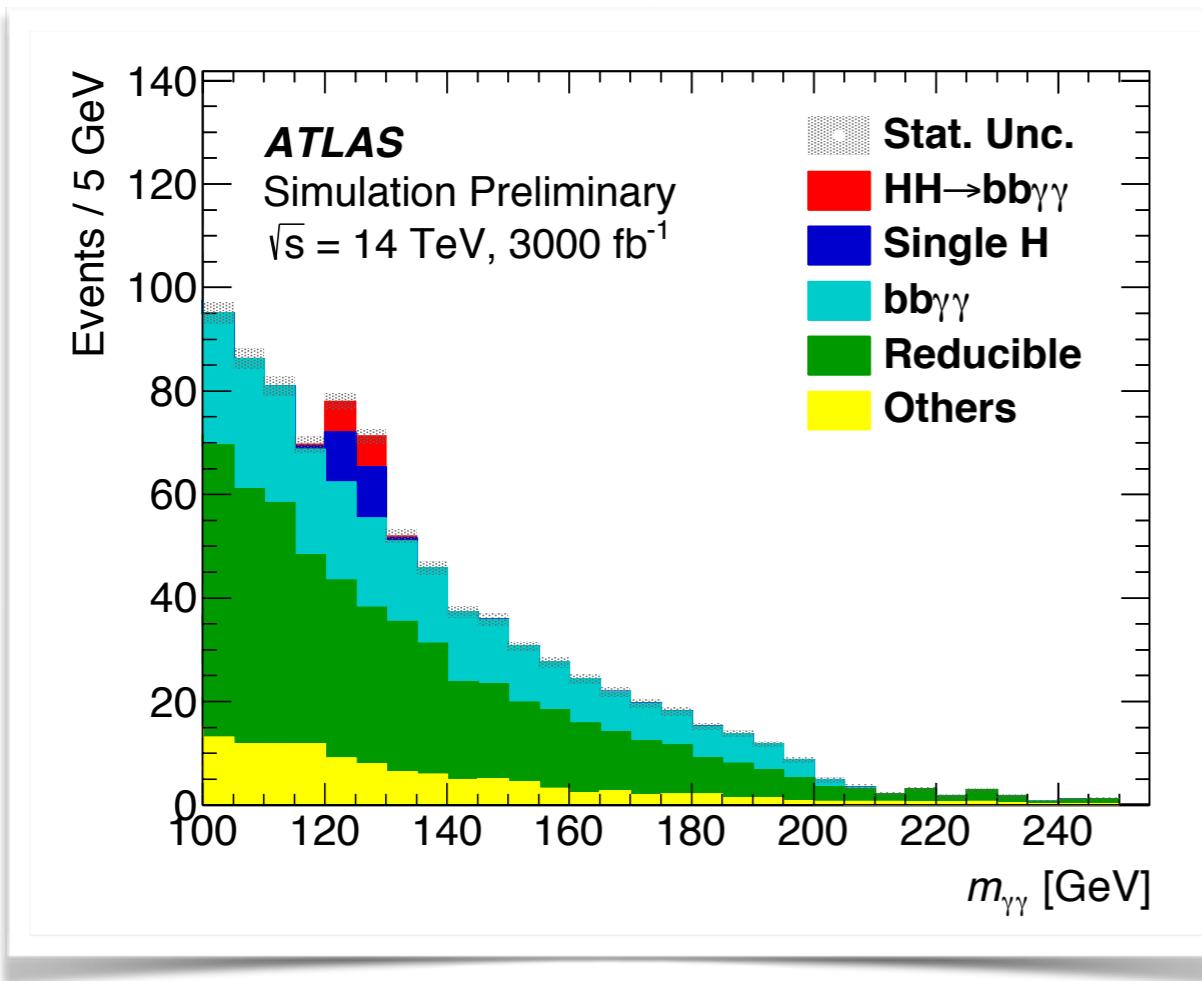
ATLAS-CONF-2018-043

- Key property of the Standard Model Higgs boson: it interacts with itself
- Main probe is via searches for pairs of Higgs bosons, but this process has a tiny cross-section
- Many possible channels: product of individual Higgs decay channels
- Current sensitivity is $O(10) \times \text{SM}$



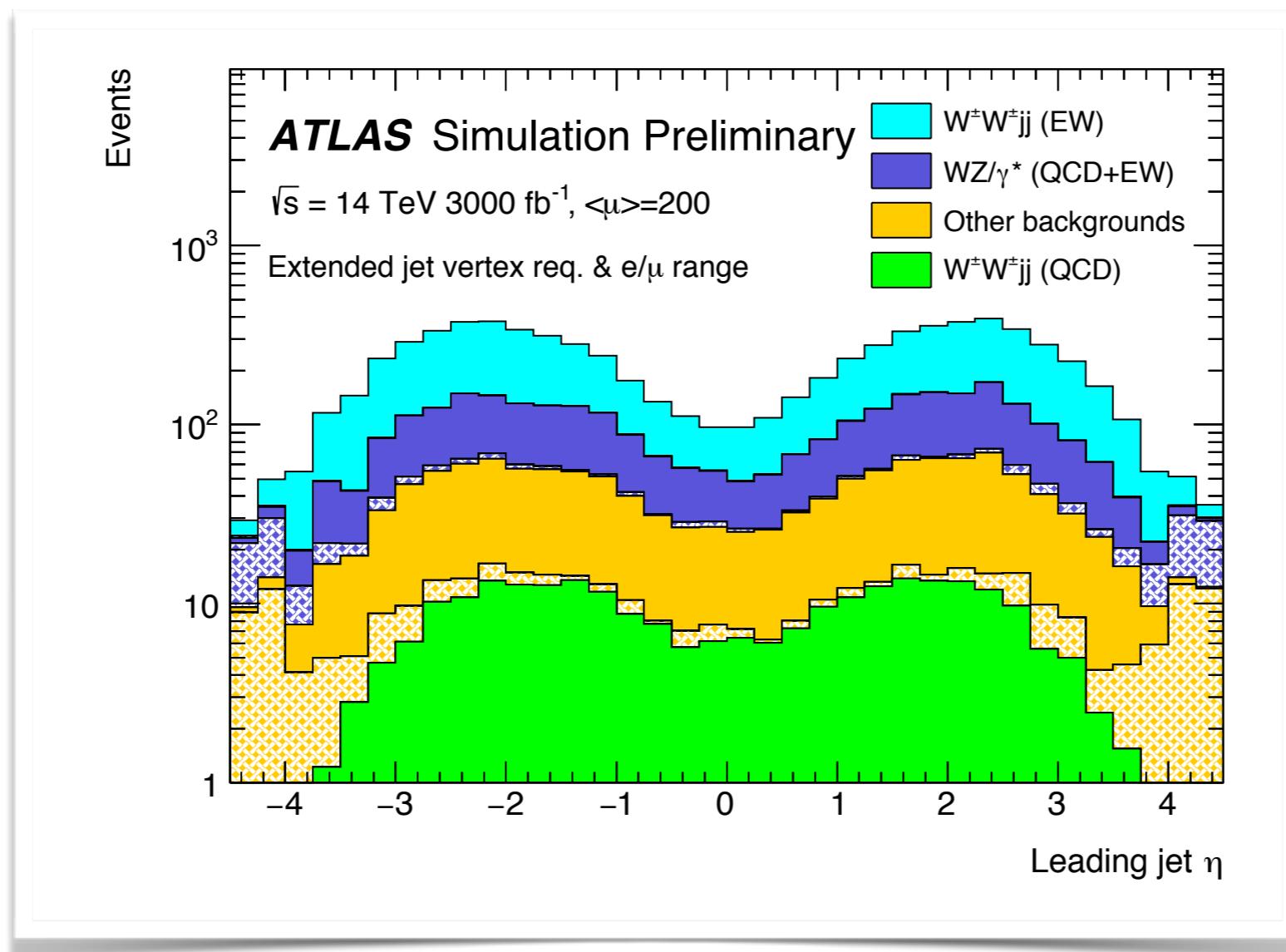
Example: $b\bar{b}\gamma\gamma$

- Search for events containing two Higgs bosons where one decays to photons and the other to b-quarks
- With a cut-based analysis, we'd expect to reach 1σ with the full HL-LHC dataset
- Will need to use as many channels as possible



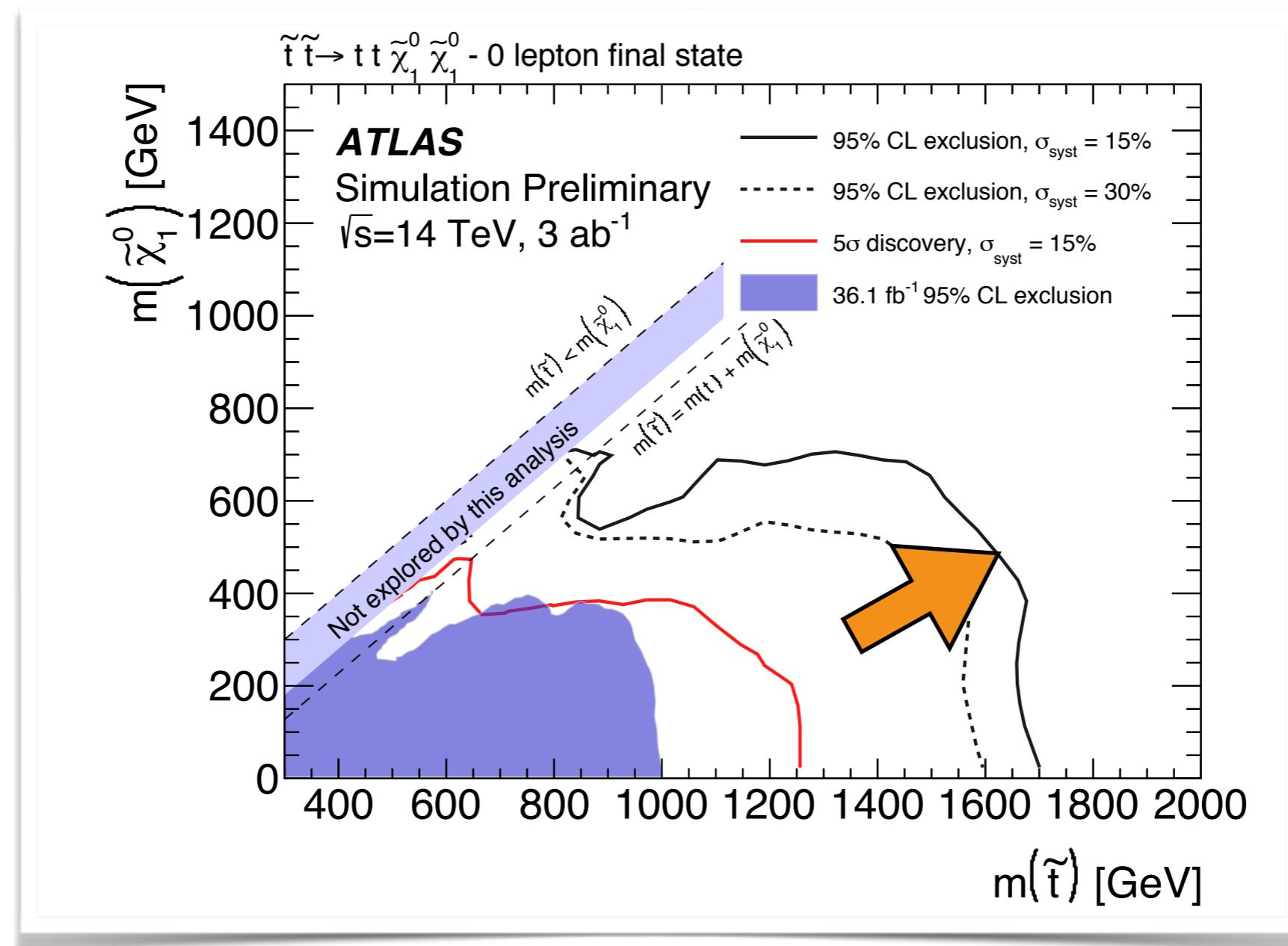
Vector boson scattering

- Vector boson scattering was a key element of the so-called “no lose” theorem for the LHC
- We have discovered the Higgs, but the measurement of same-charge WW provides an important probe of electroweak symmetry breaking
- Expect to reach a precision of ~4% by end of HL-LHC



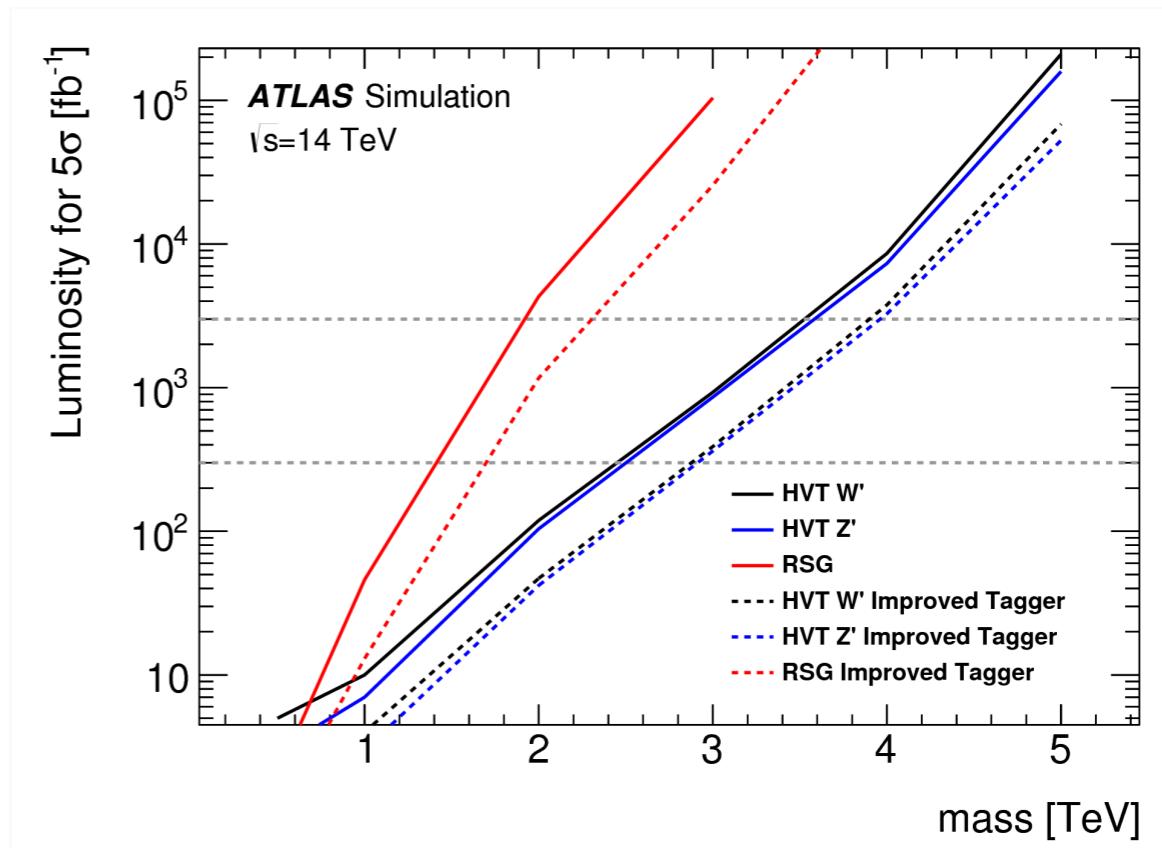
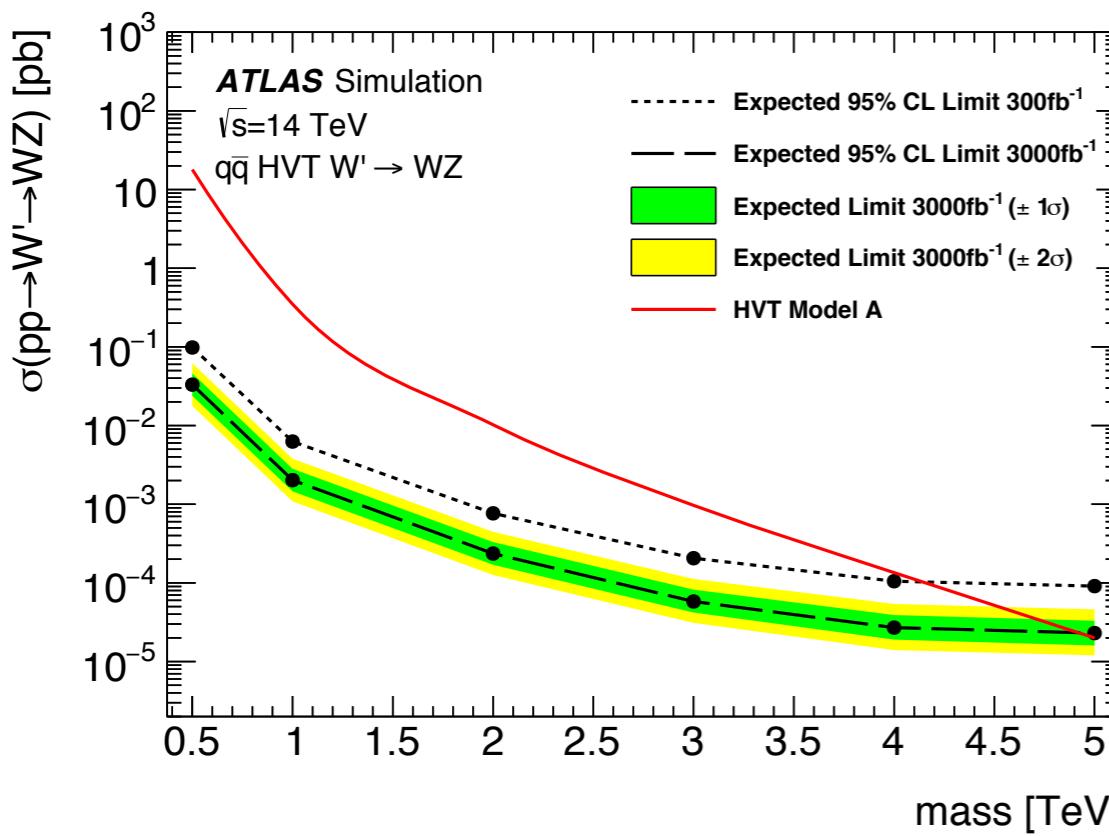
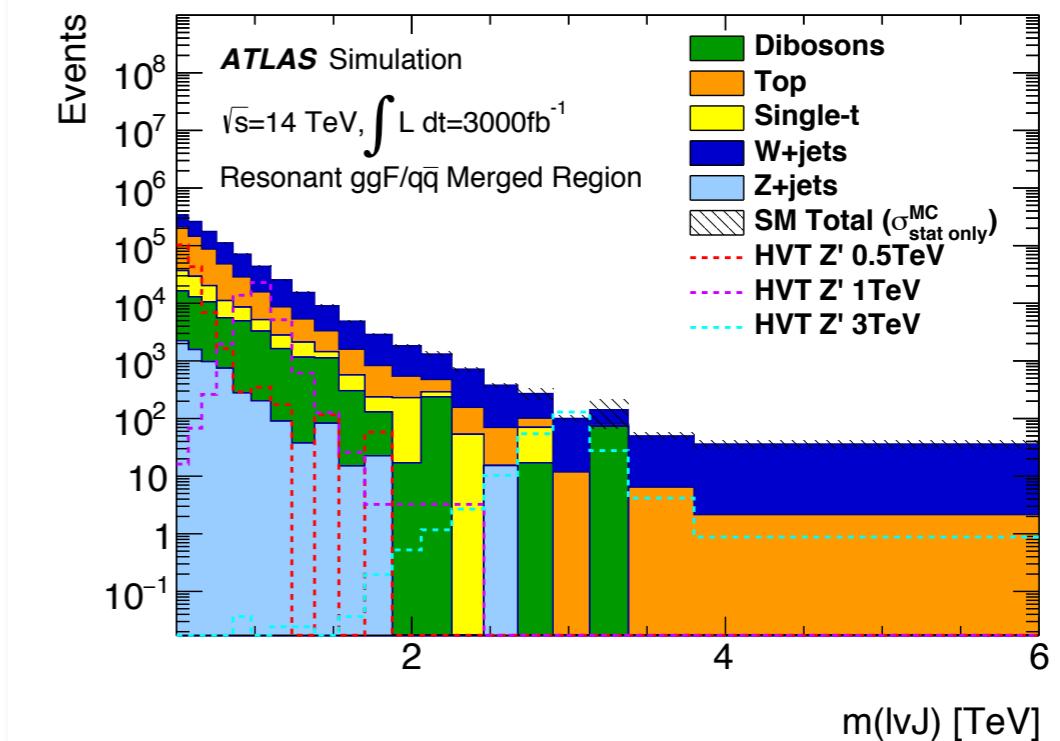
Example: Extending new physics searches to high mass

Search for the supersymmetric partner of the top quark using jets and MET



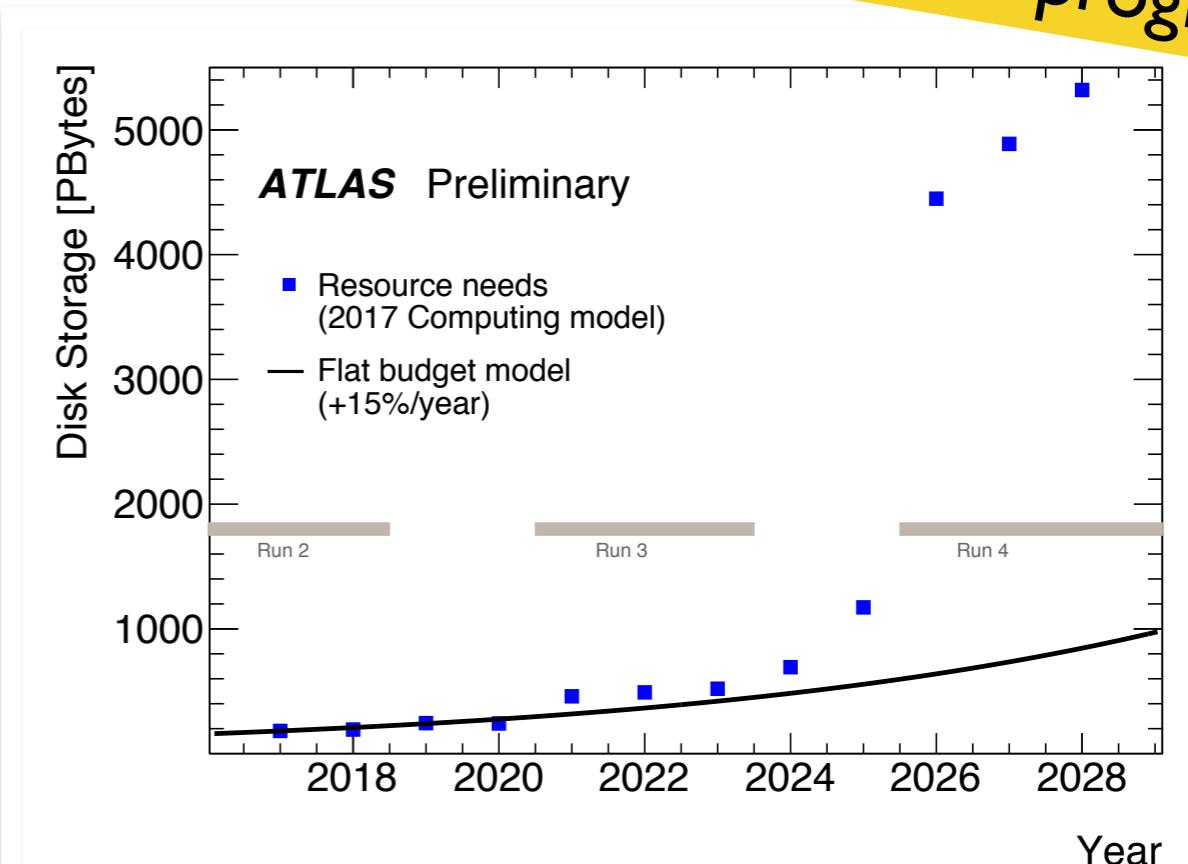
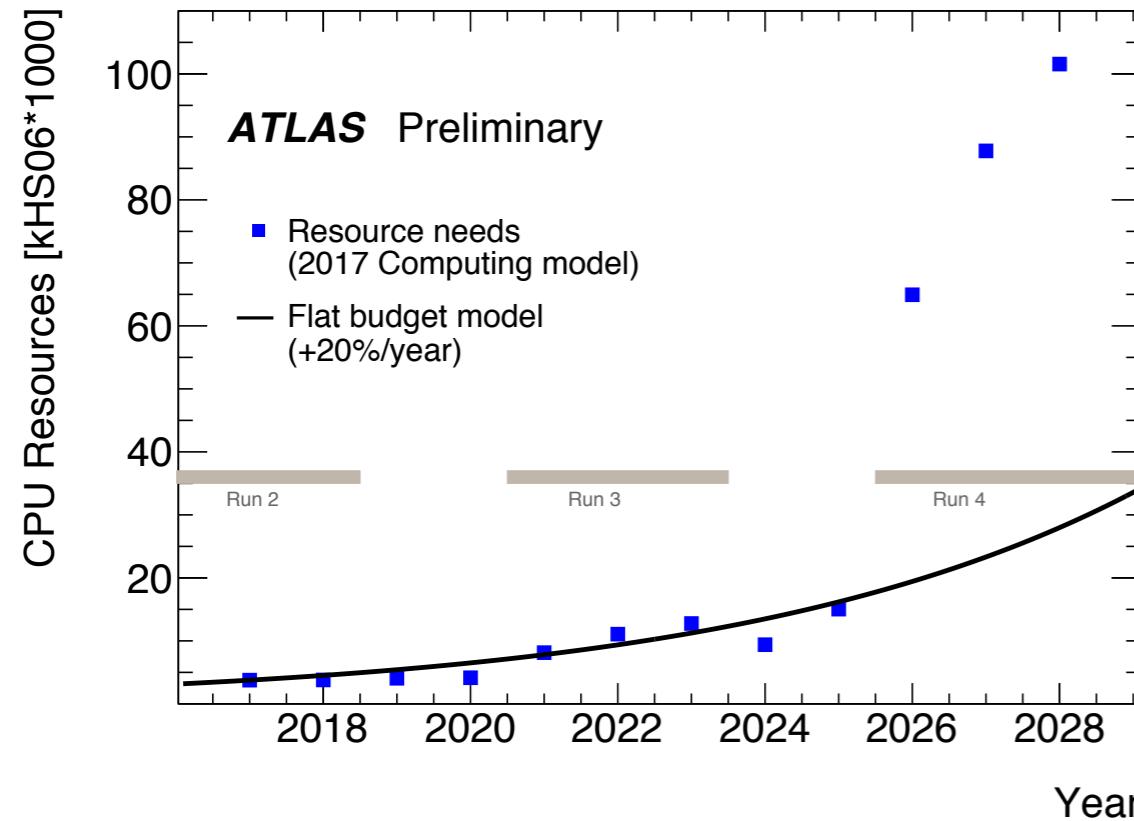
Example 2: Extending mass reach

- We can also use dibosons to look for new particles
 - e.g. $W' \rightarrow WZ$ or $Z' \rightarrow WW$
- Typically extend mass reach by ~ 1 TeV beyond LHC



Computing for HL-LHC

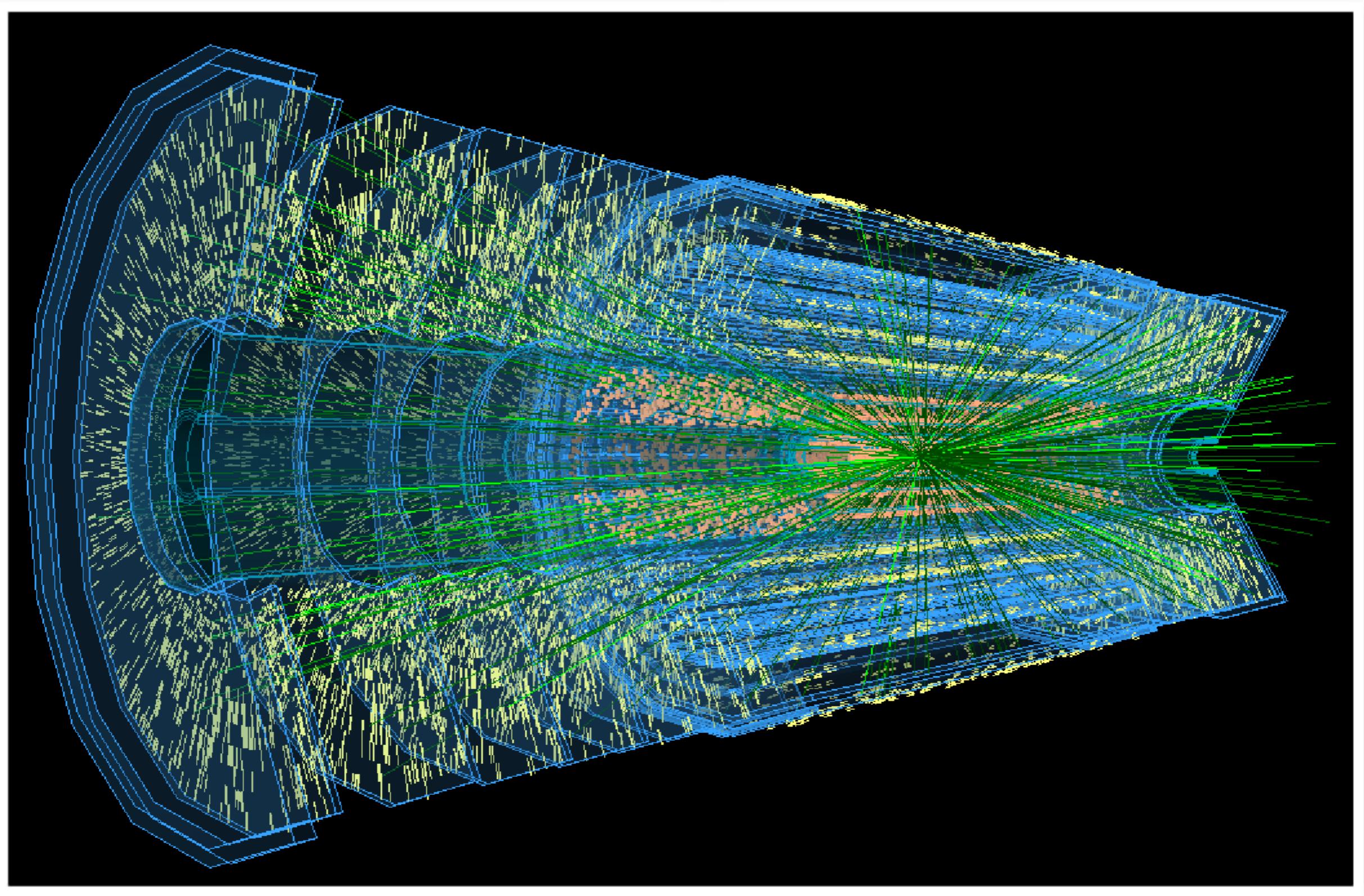
Update in progress



- The HL-LHC environment is expected to pose a **challenge** for computing
- Currently project 6x more CPU time needed to reconstruct events
 - Dominated by **track reconstruction** in the inner detector
- Also expect to need 10x more disk storage
- Major focus of current developments, see talk by T. Boccali for more details
 - More recently, explorations into whether quantum computing might play a role

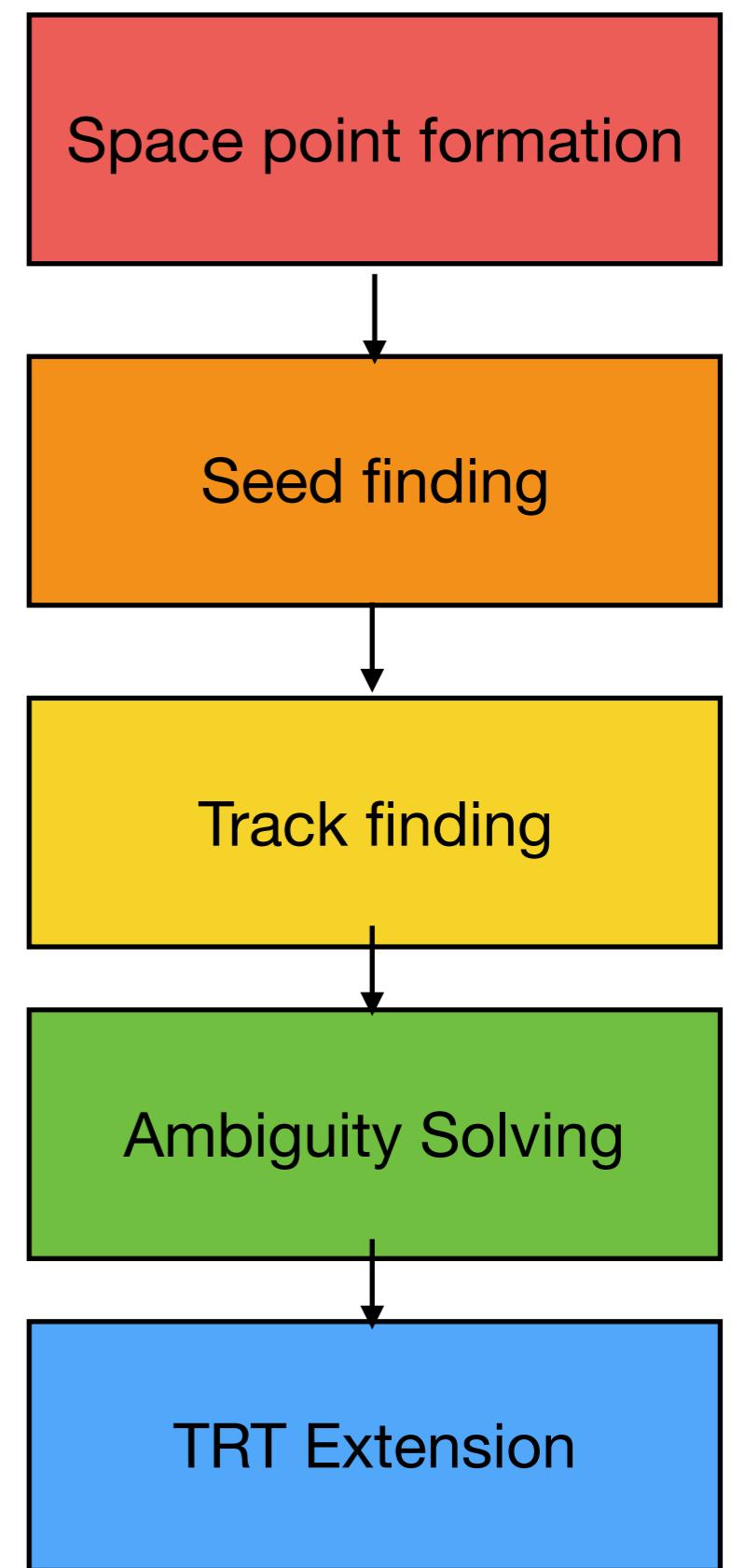
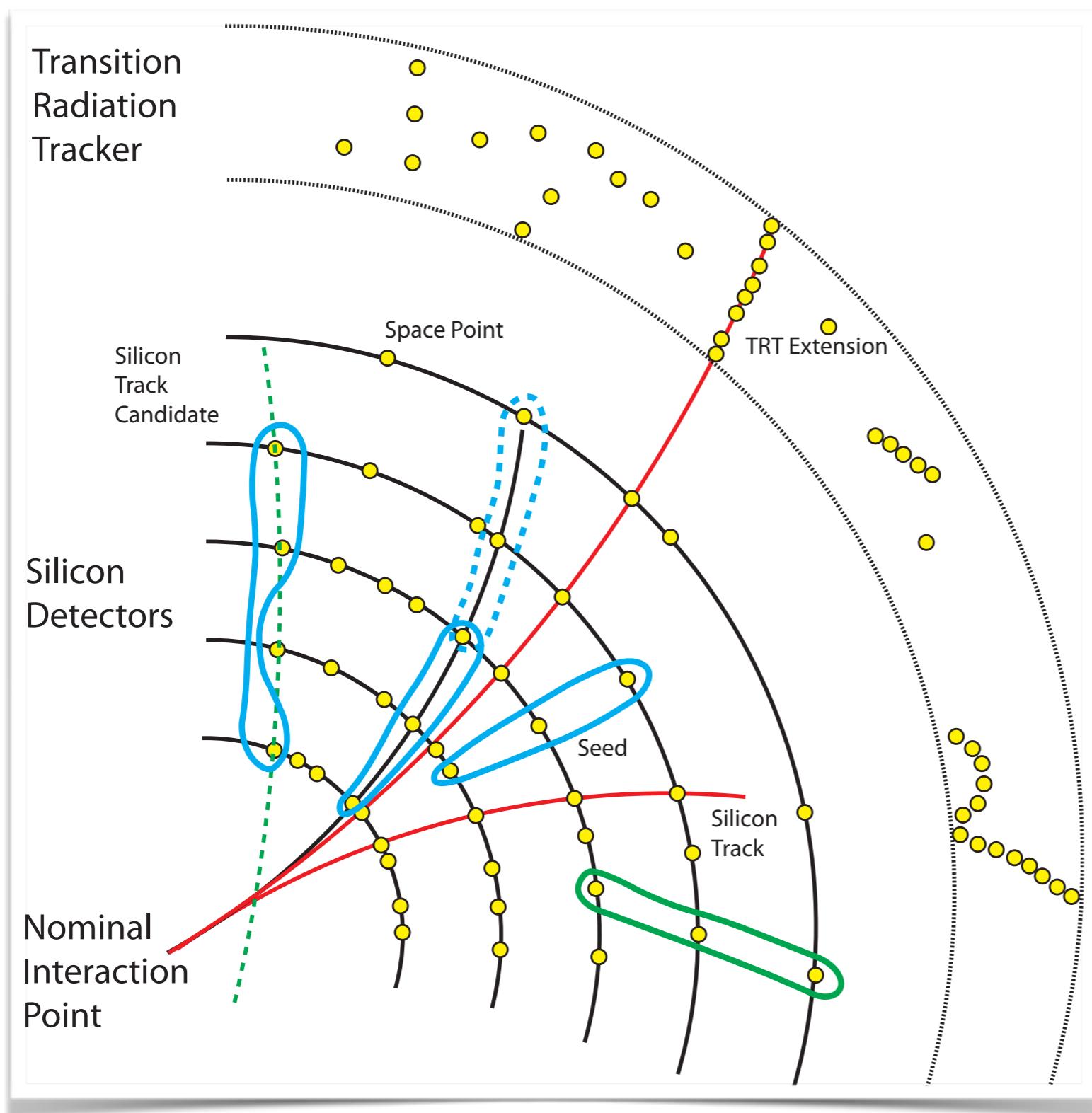
Simulated HL-LHC event in ATLAS

140 simultaneous proton-proton collisions



Track Reconstruction

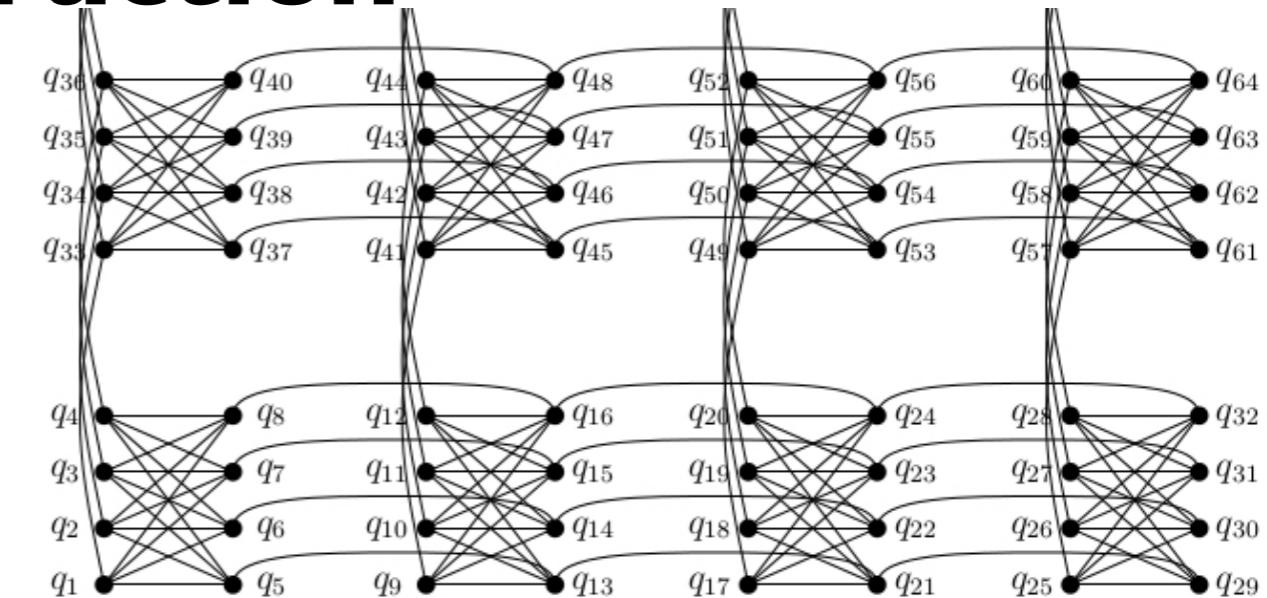
Multi-step iterative Kalman filter approach



QUBO for track reconstruction

A D-Wave QMI (Quantum Machine Instruction) minimises the hamiltonian O :

$$O(a; b; q) = \sum_{i=1}^N a_i q_i + \sum_i \sum_j b_{ij} q_i q_j$$



q_i = qubit i (“on” or “off”)

a_i = bias weight of a qubit,

b_{ij} = coupling between two qubits

⇒ equation of a *quadratic unconstrained binary optimization* (QUBO)

Idea: adaptation of [Fast track finding with neural networks, Stimpfl-Abele \(1990\)](#): replace Hopfield networks with QUBO

Use the dataset and efficiency scoring function developed in the context of the [trackml challenge](#)

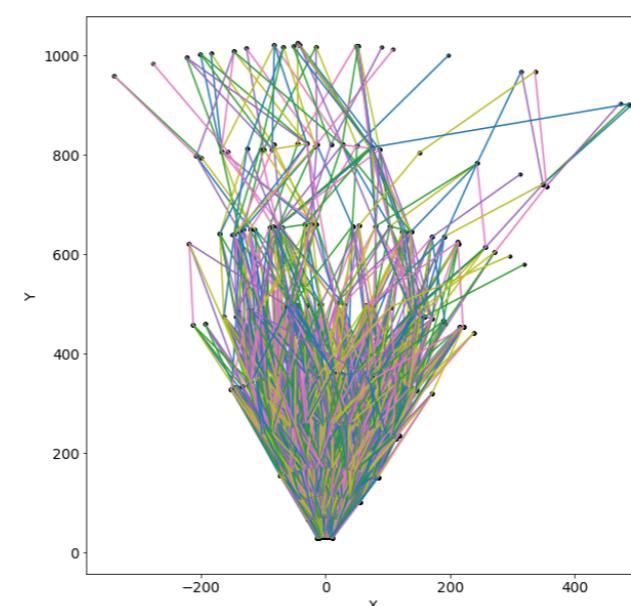
QUBO for track reconstruction

Currently testing implementation
on a subset of tracks with a cone
of $|\phi| < \pi/3$

In simulation, obtain 98.9%
efficiency for 100 tracks

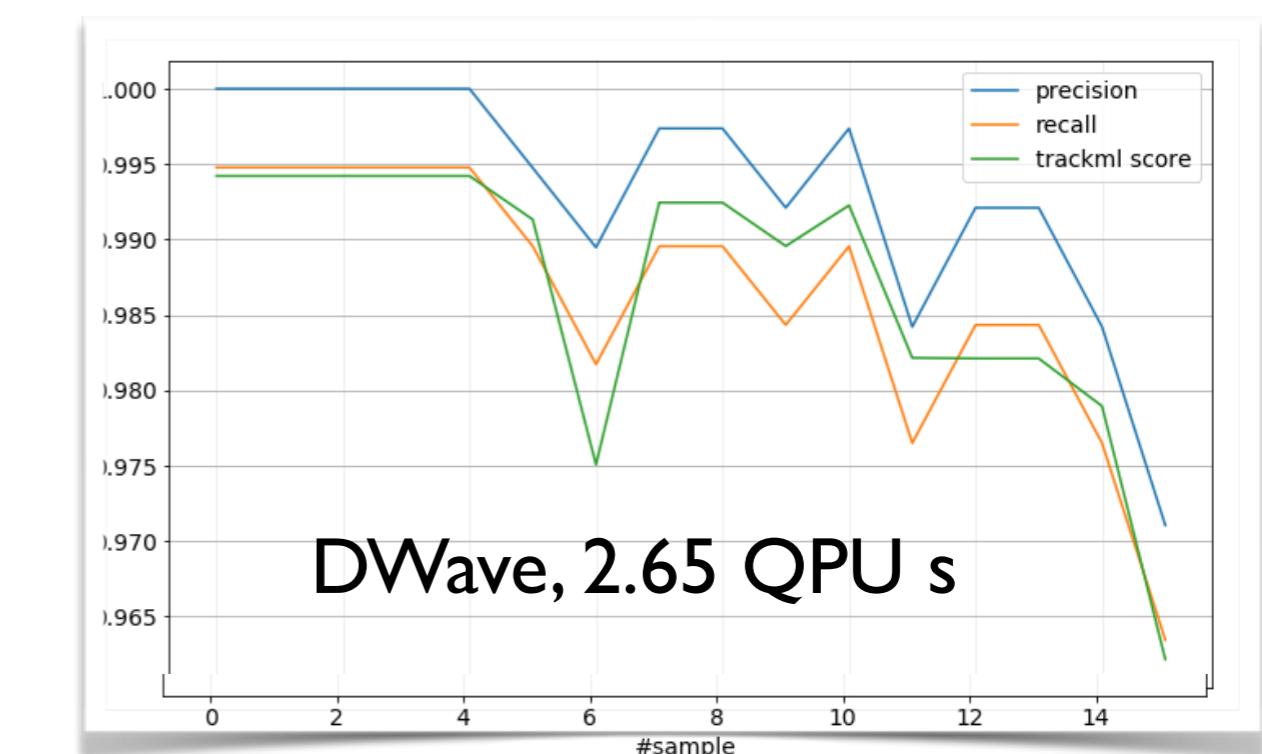
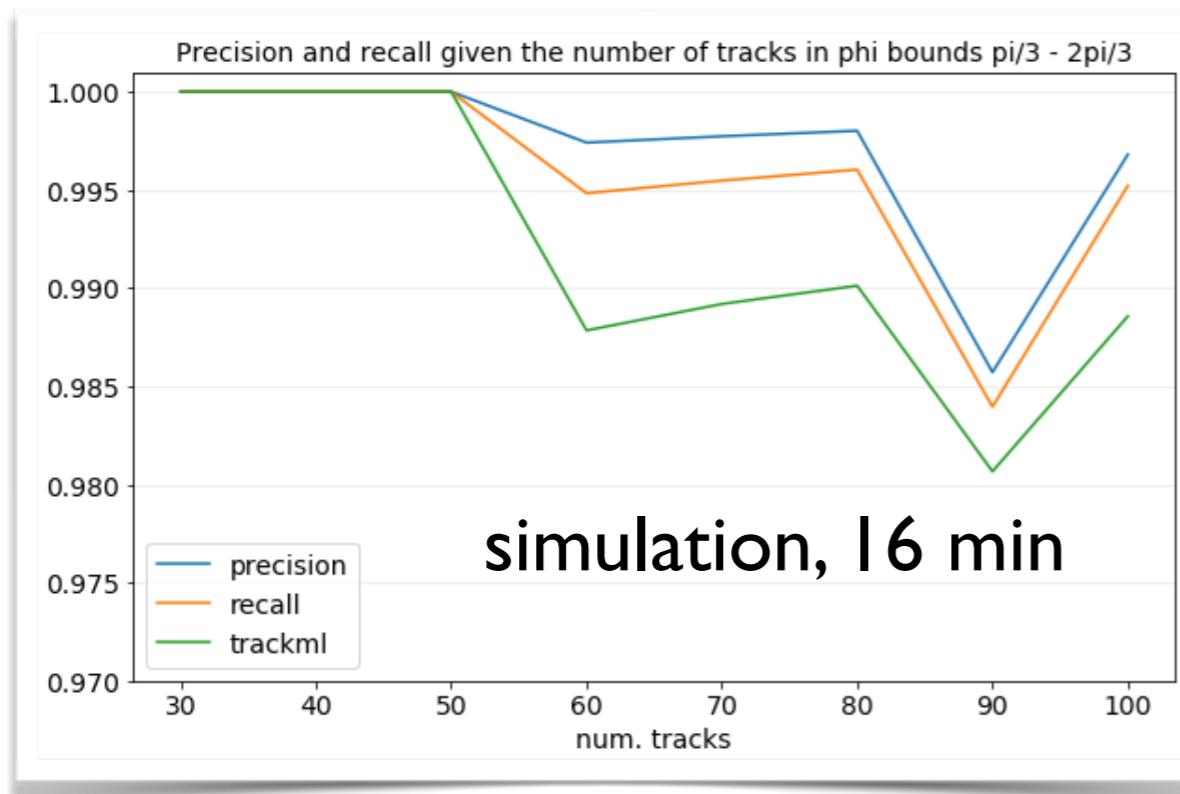
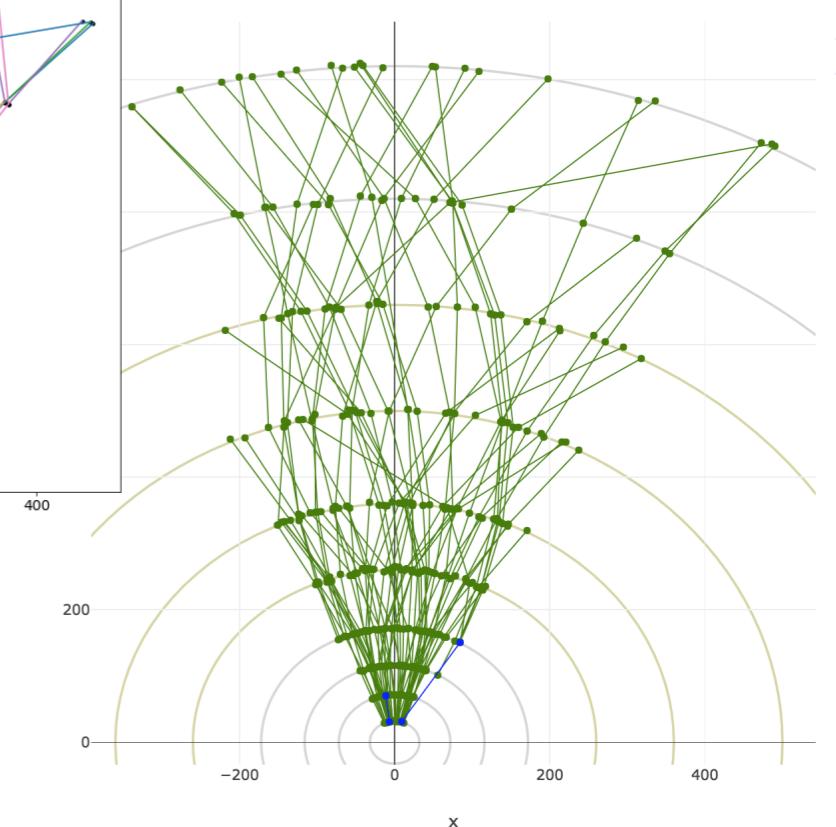
On DWave using qbsolv, obtain
99.42% for 60 tracks

Next step: extend to larger dataset



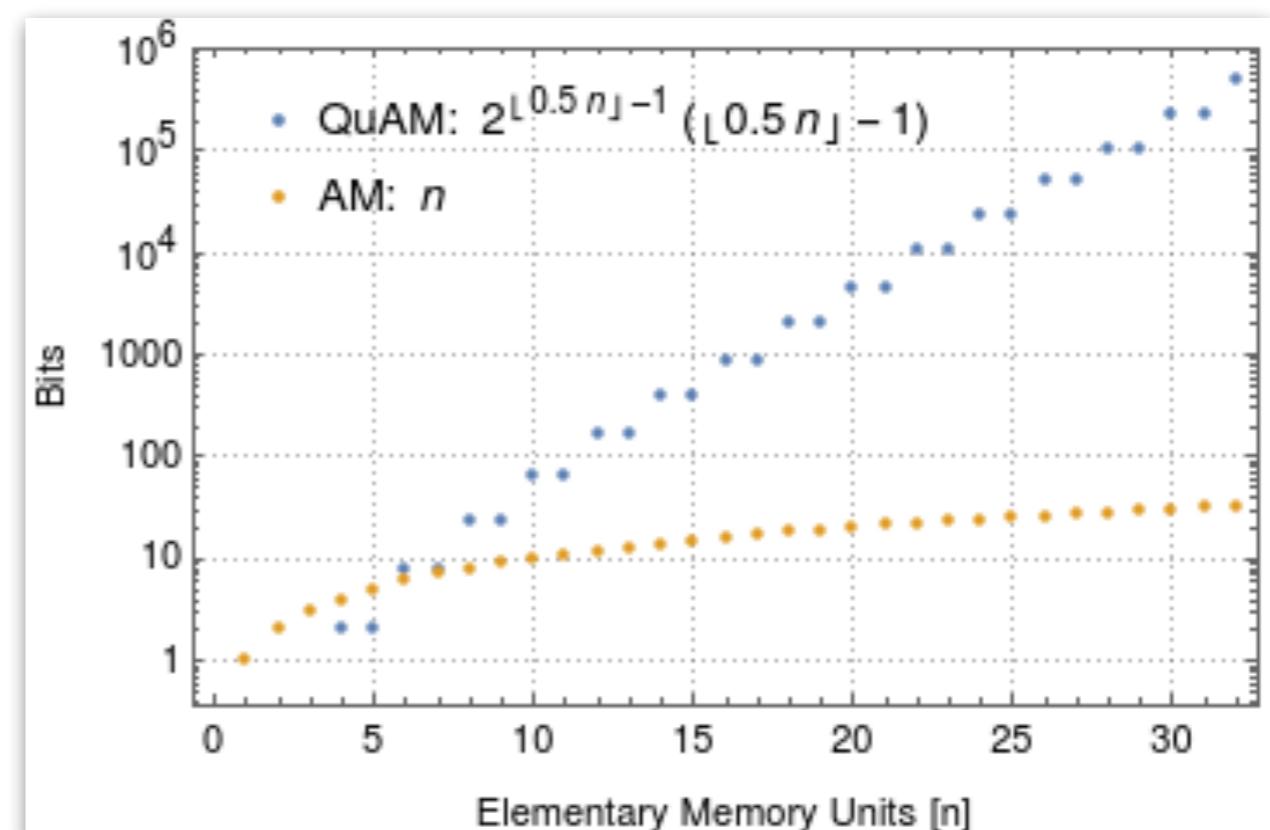
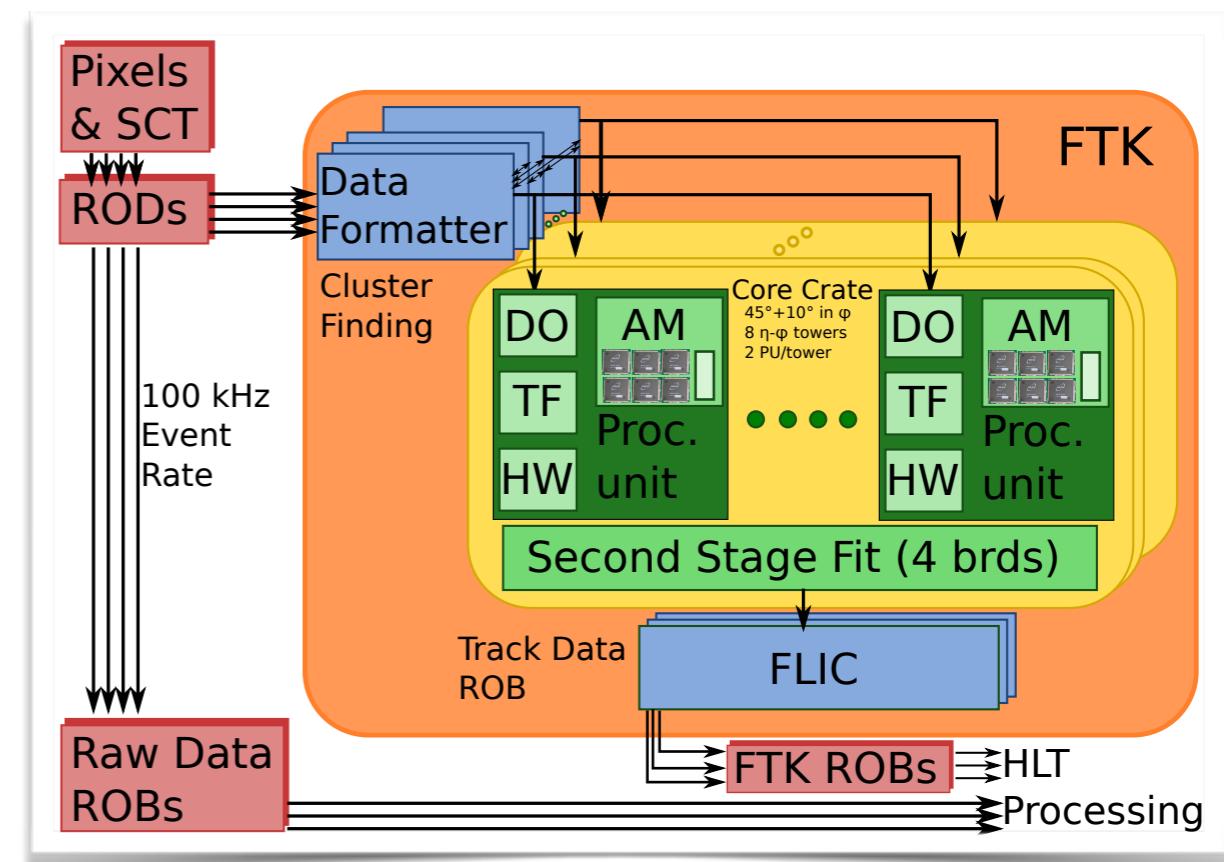
DWave

from 10952 input
doublets down to 380.



Quantum Associative Memory for Track Reconstruction

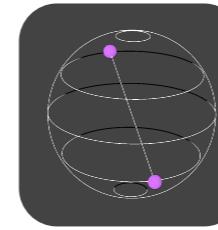
- ATLAS currently commissioning a new hardware-based track trigger, called the Fast Track Trigger (FTK)
- Pattern recognition engine: Associative Memory
- QuAM: A quantum variant of associative (a.k.a content-addressable) memory:
 - Exponential storage capacity (absolute)
 - Optimal QA for pattern recall
 - Implemented storage and retrieval quantum circuit generators on QISKit



QuAM on QISKit

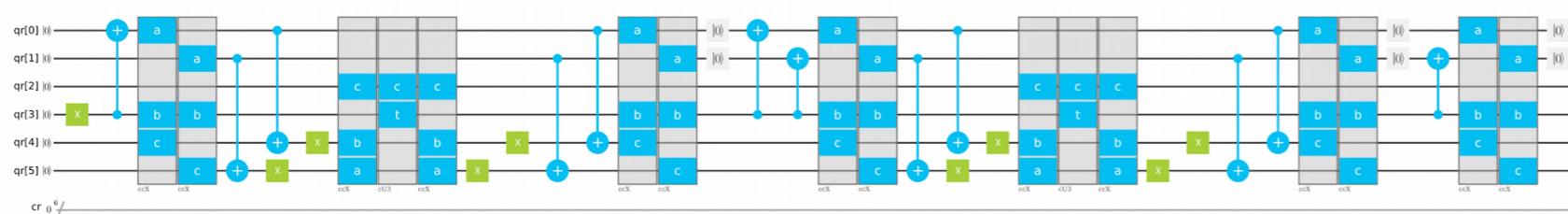
QISKit - Quantum Information Software Kit

An open source project comprising Python SDK, API and OpenQASM for implementing quantum algorithms on **IBM Quantum Experience (QE) hardware and simulators.**



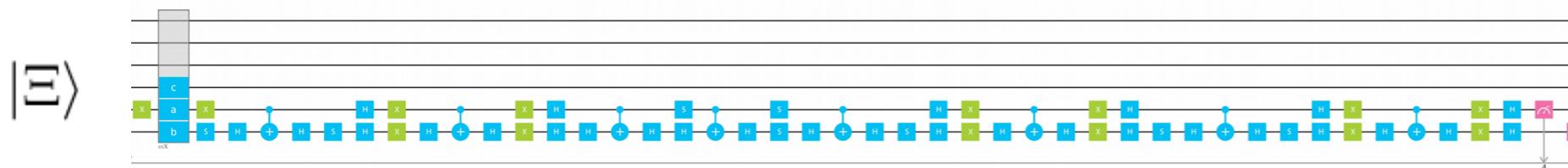
- ▶ QuAM storage circuit generator [implemented]

Ex.: complete circuit for encoding three 2-bit patterns



- ▶ QuAM retrieval circuit generator [implemented]

Ex.: complete circuit for retrieving one 2-bit pattern (1 iteration)



Ran on IBM Q Experience

Supported backends:

- ▶ **IBM QE cloud-based quantum chips**
[5Q Sparrow/Raven, 16Q Albatross, 20Q]
- ▶ **Local/remote simulators**
[with realistic noise models]

Storage QASM

```

1 OPENQASM 2.0;
2 include "qelib1.inc";
3 qreg qr[6];
4 creg cr[6];
5 x qr[3];
6 cx qr[3],qr[0];
7 cx qr[0],qr[3],qr[4];
8 cx qr[1],qr[3],qr[5];
9 cx qr[1],qr[5];
10 cx qr[0],qr[4];
11 x qr[5];
12 x qr[4];
13 cx qr[5],qr[4],qr[2];
14 cu3(1.23095941734077, 3.14159265358979, 3.14159265358979) qr[2],qr[3];
15 cx qr[5],qr[4],qr[2];
16 x qr[5];
17 x qr[4];
18 cx qr[1],qr[5];
19 cx qr[0],qr[4];
20 cx qr[0],qr[3],qr[4];
21 cx qr[1],qr[3],qr[5];
22 reset qr[0];
23 reset qr[1];
24 cx qr[3],qr[0];
25 cx qr[3],qr[1];

```

Snippet

Retrieval QASM

```

51 s qr[5];
52 h qr[5];
53 cx qr[4],qr[5];
54 h qr[5];
55 s qr[5];
56 h qr[4];
57 h qr[5];
58 x qr[4];
59 x qr[5];
60 h qr[5];
61 cx qr[4],qr[5];
62 h qr[5];
63 x qr[4];
64 x qr[5];
65 h qr[4];
66 h qr[5];
67 h qr[5];
68 cx qr[4],qr[5];
69 h qr[5];

```

Snippet

I. Shapoval et al, [hep-qpr](#)

Conclusion

- HL-LHC is coming soon!
- Major upgrade to accelerator and detectors which will enable an extensive and exciting physics program
 - Presented selected highlights here
- Fully exploiting this data is the topic of an extensive R&D program in software and computing
 - See, e.g. T. Boccali's talk for more details
- Too early to tell, but, perhaps quantum computing can play a role?
 - Showed some examples of preliminary research in pattern recognition on quantum computers
 - Other ideas will be covered in dedicated talks, e.g. machine learning

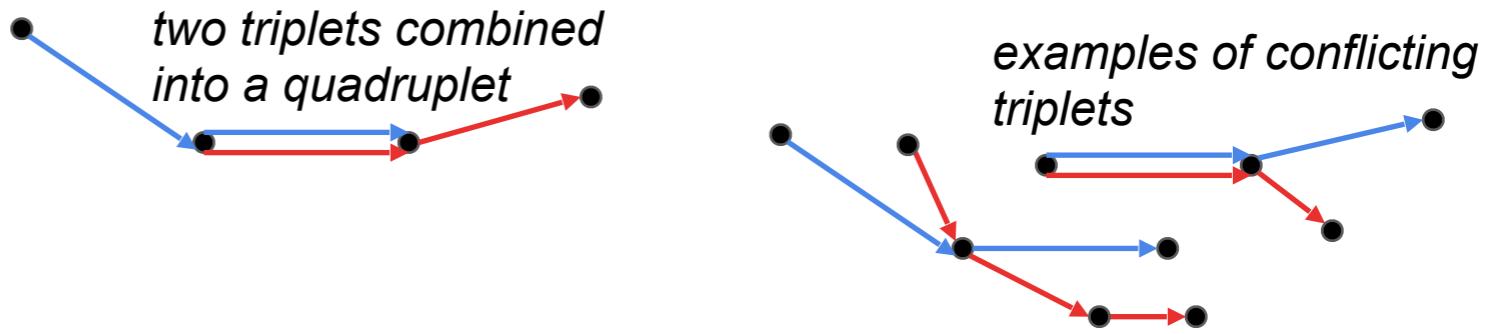
Back up

Algorithm

Input: seeds (doublets)

1. combine doublets into triplets, early cuts (R-Z angle, curvature, ...)
2. combine triplets into quadruplets, early cuts (Δ curvature, ...)
3. generate QUBO, qubits representing potential triplets:
 - a. qubit bias weight: negative constant (-0.01)
 - b. coupling based on
 - i. quadruplets: negative value depending on Δ curvature, R-Z angle, length
 - ii. conflicts: positive constant
4. sample QUBO (`qbsolv`)
5. assemble results

Output: final doublets



QuAM storage protocol

A quantum circuit implementing the iterative part of the storage protocol ¹.

$$1. |\psi_0^1\rangle = |p_1^1, \dots, p_d^1; 01; 0_1, \dots, 0_d\rangle$$

$$2. |\psi_1^i\rangle = \prod_{j=1}^d {}^{2c}\hat{X}_{p_j^i u_2 m_j} |\psi_0^i\rangle$$

$$3. |\psi_2^i\rangle = \prod_{j=1}^d {}^{1c}\hat{X}_{m_j} {}^{1c}\hat{X}_{p_j^i m_j} |\psi_1^i\rangle$$

$$4. |\psi_3^i\rangle = {}^{dc}\hat{X}_{m_1 \dots m_d u_1} |\psi_2^i\rangle$$

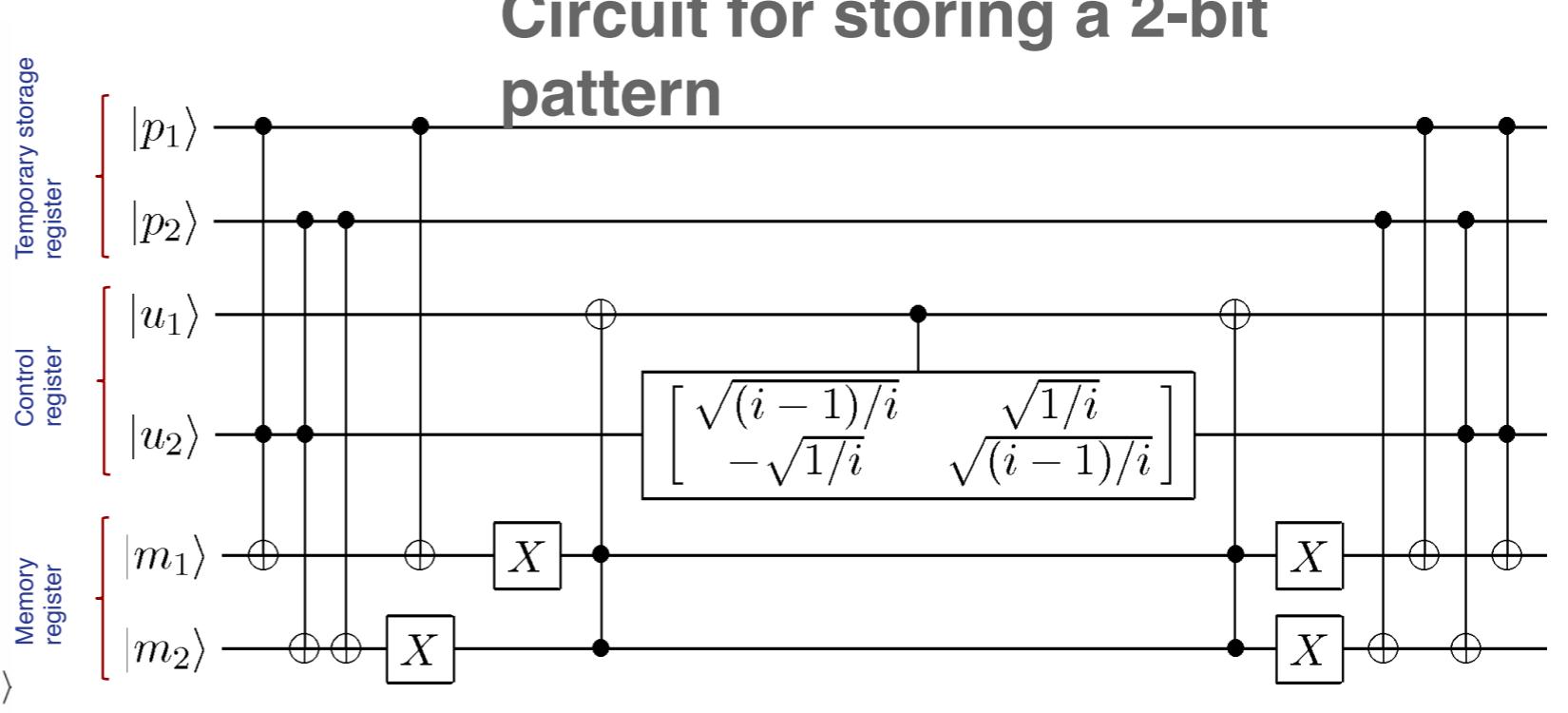
$$5. |\psi_4^i\rangle = {}^{1c}\hat{S}_{u_1 u_2}(p+1-i) |\psi_3^i\rangle$$

$$6. |\psi_5^i\rangle = {}^{dc}\hat{X}_{m_1 \dots m_d u_1} |\psi_4^i\rangle$$

$$7. |\psi_6^i\rangle = \prod_{j=d}^1 {}^{1c}\hat{X}_{p_j^i m_j} {}^{1c}\hat{X}_{m_j} |\psi_1^i\rangle$$

$$= \frac{1}{\sqrt{p}} \sum_{k=1}^i |p^i; 00; p^k\rangle + \sqrt{\frac{p-i}{p}} |p^i; 01; p^i\rangle$$

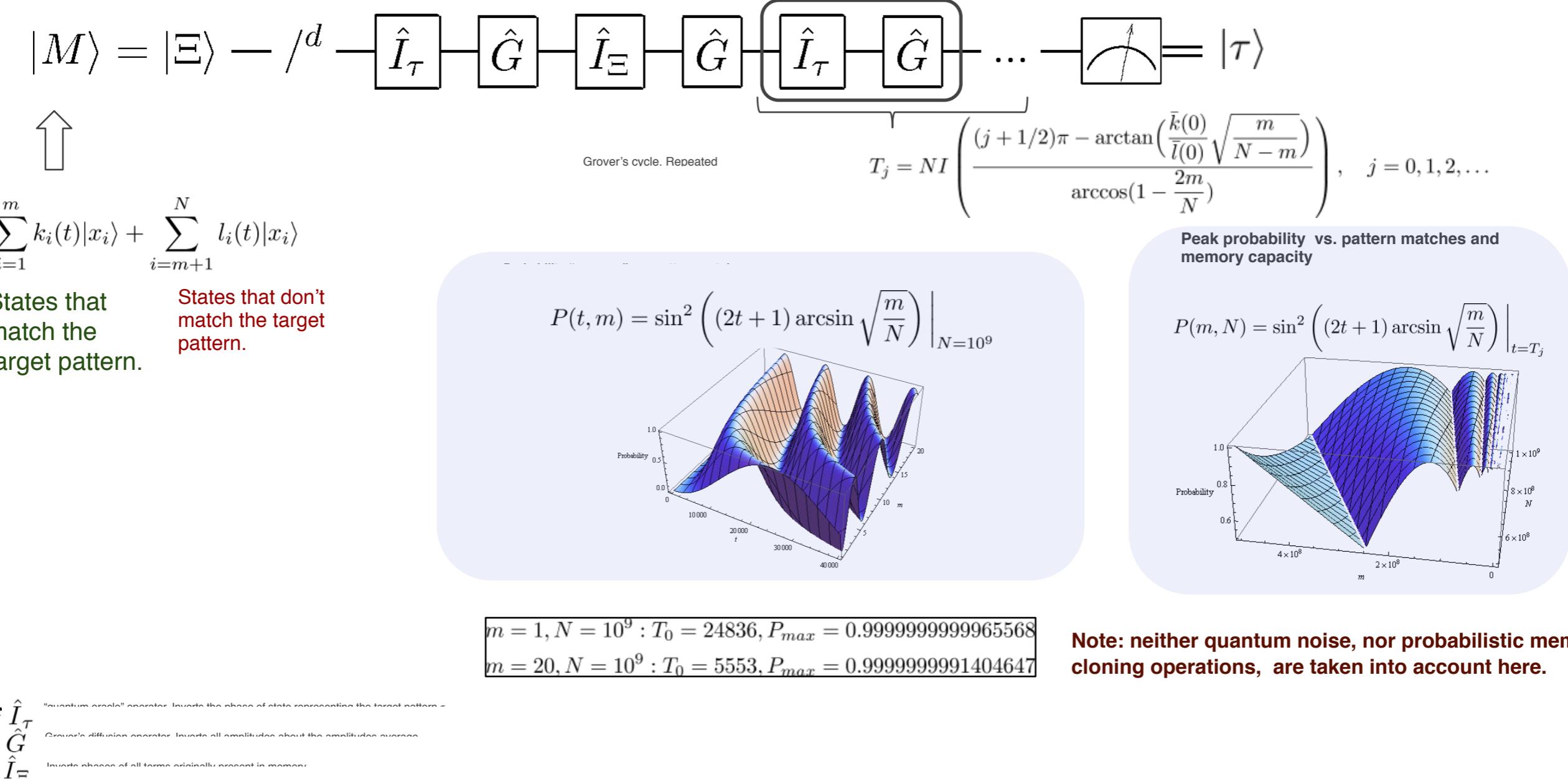
$$8. |\psi_7^i\rangle = \prod_{j=d}^1 {}^{2c}\hat{X}_{p_j^i u_2 m_j} |\psi_6^i\rangle$$



¹ C.A Trugenberger, Probabilistic Quantum Memories. Phys Rev. Lett. Vol 87, 6 (2001)

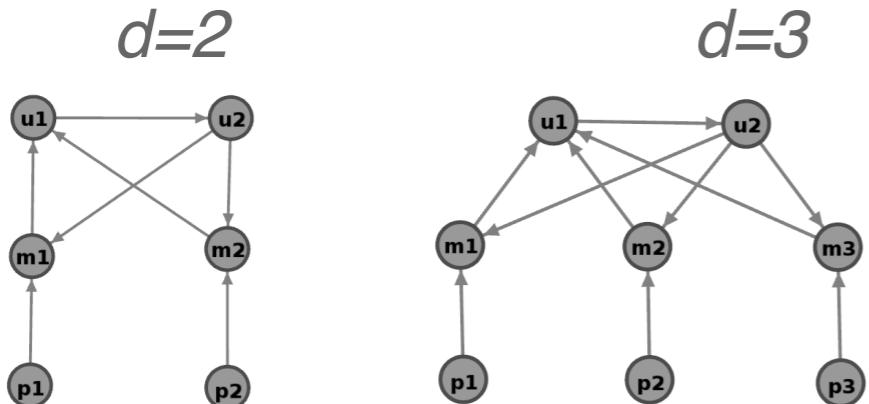
QuAM retrieval protocol

Generalized Grover's algorithm*

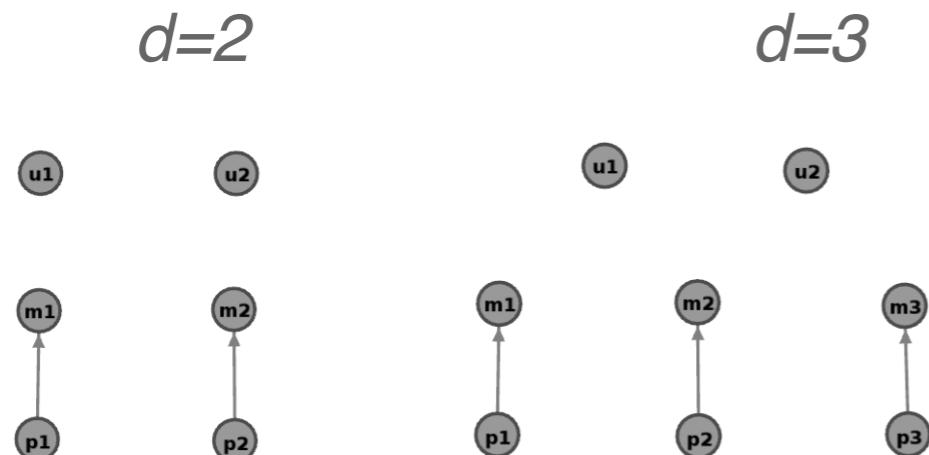


Topological complexity of QuAM¹

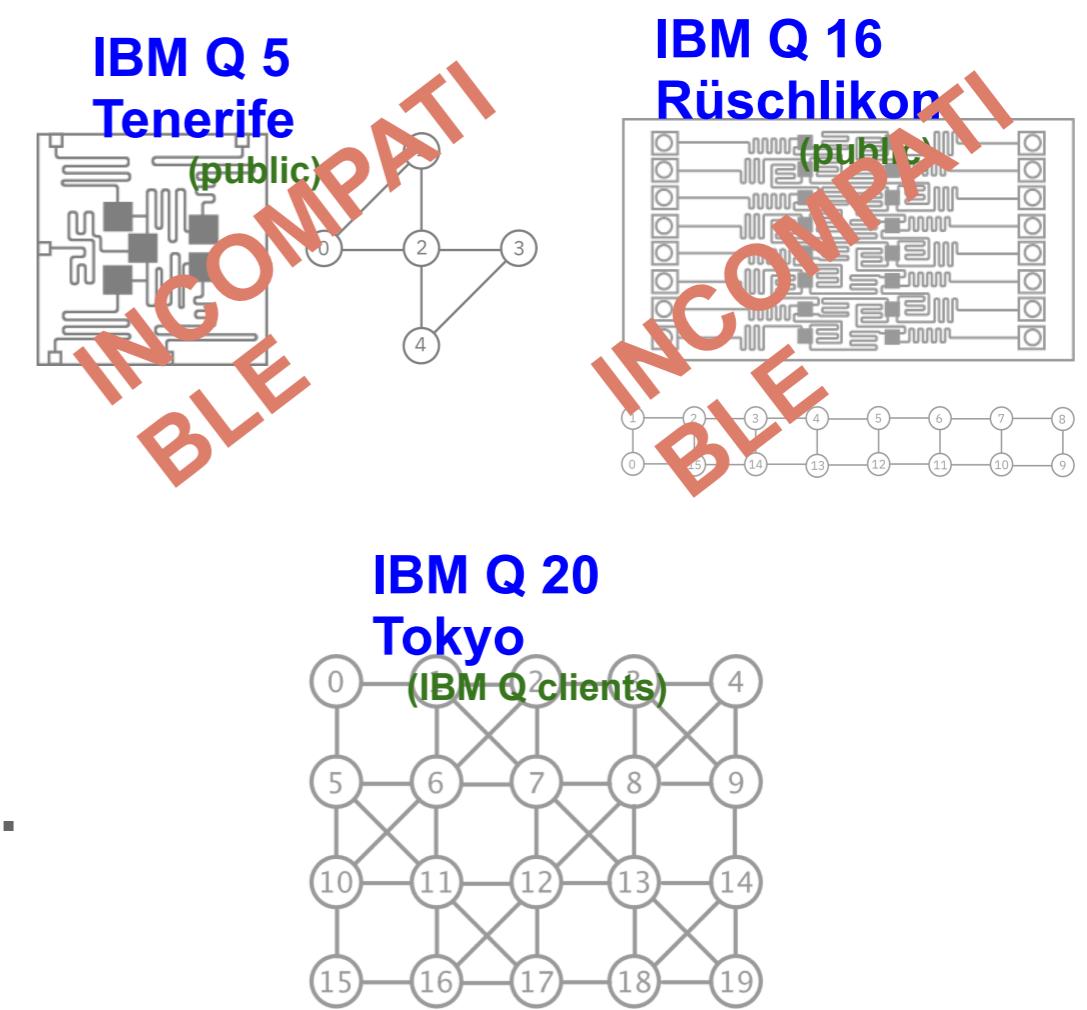
- ▶ Storage connectivity requirements



- ▶ Retrieval connectivity requirements



- IBM Q Experience QPUs

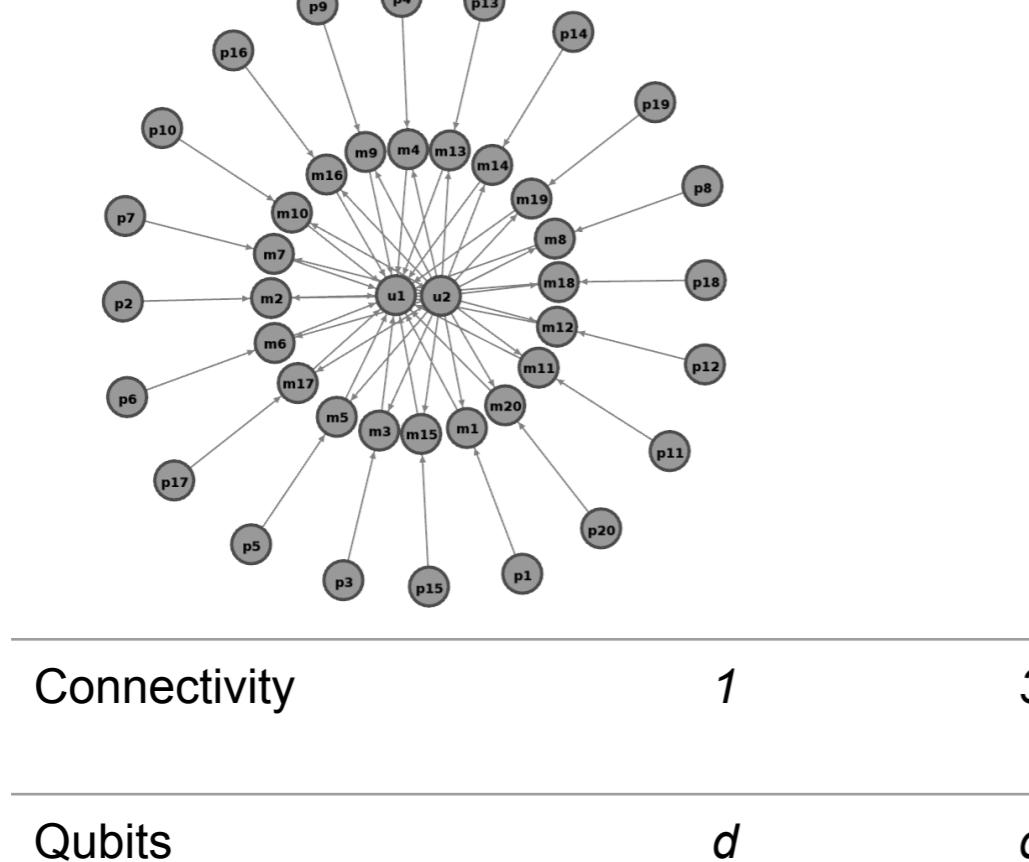


¹ $\{p\}$, $\{u\}$ and $\{m\}$ nodes represent qubits from temporary storage, control and memory registers.
 d - pattern length

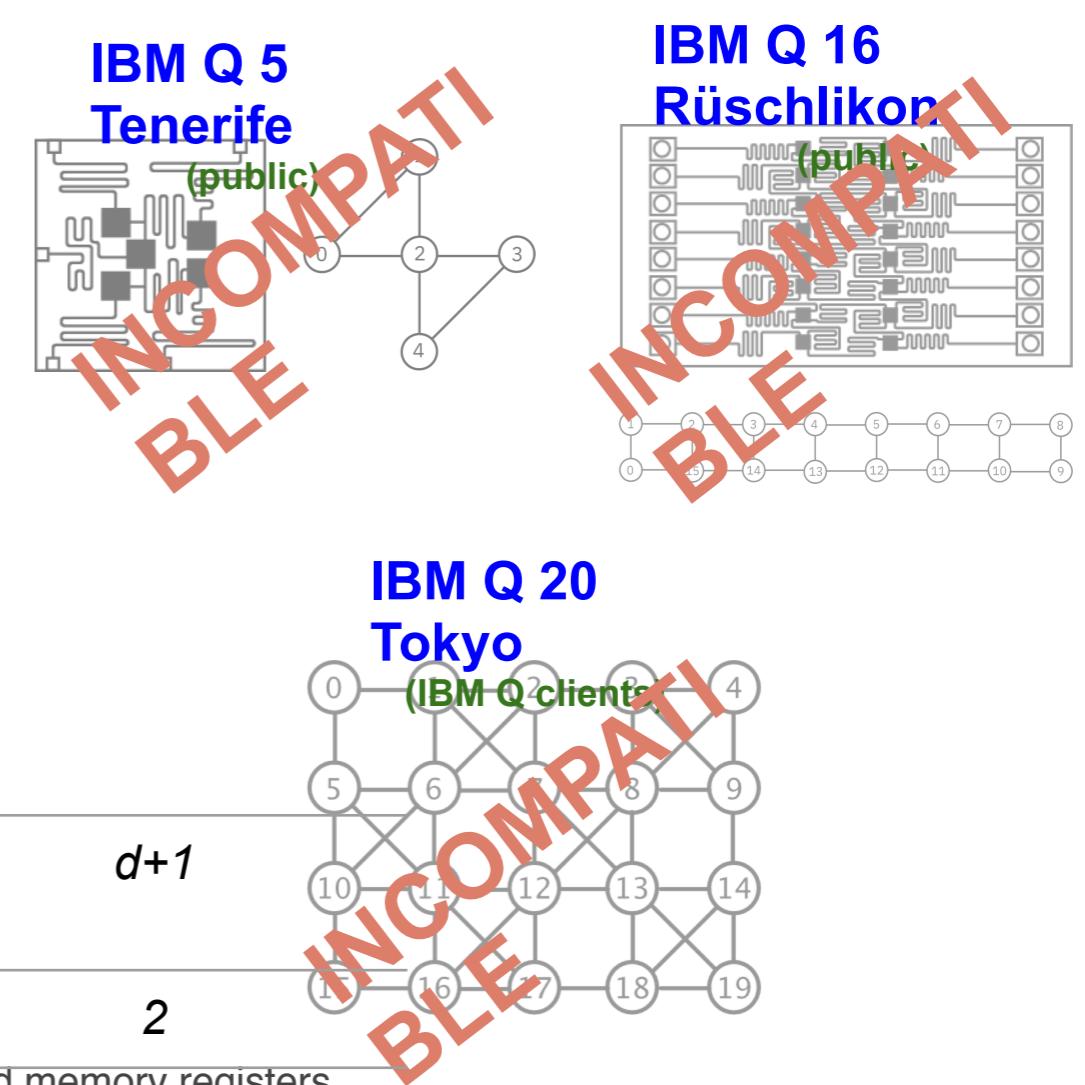
Topological complexity of QuAM¹

Aggregate QuAM requirements

$d=20$ (~ current pattern length in ATLAS)



¹ {p}, {u} and {m} nodes represent qubits from temporary storage, control and memory registers.
 d - pattern length



D-Wave execution (qbsolv)

trackml score of **99.42%** for 60 tracks
in a phi angle of $\pi/3$ rad.

