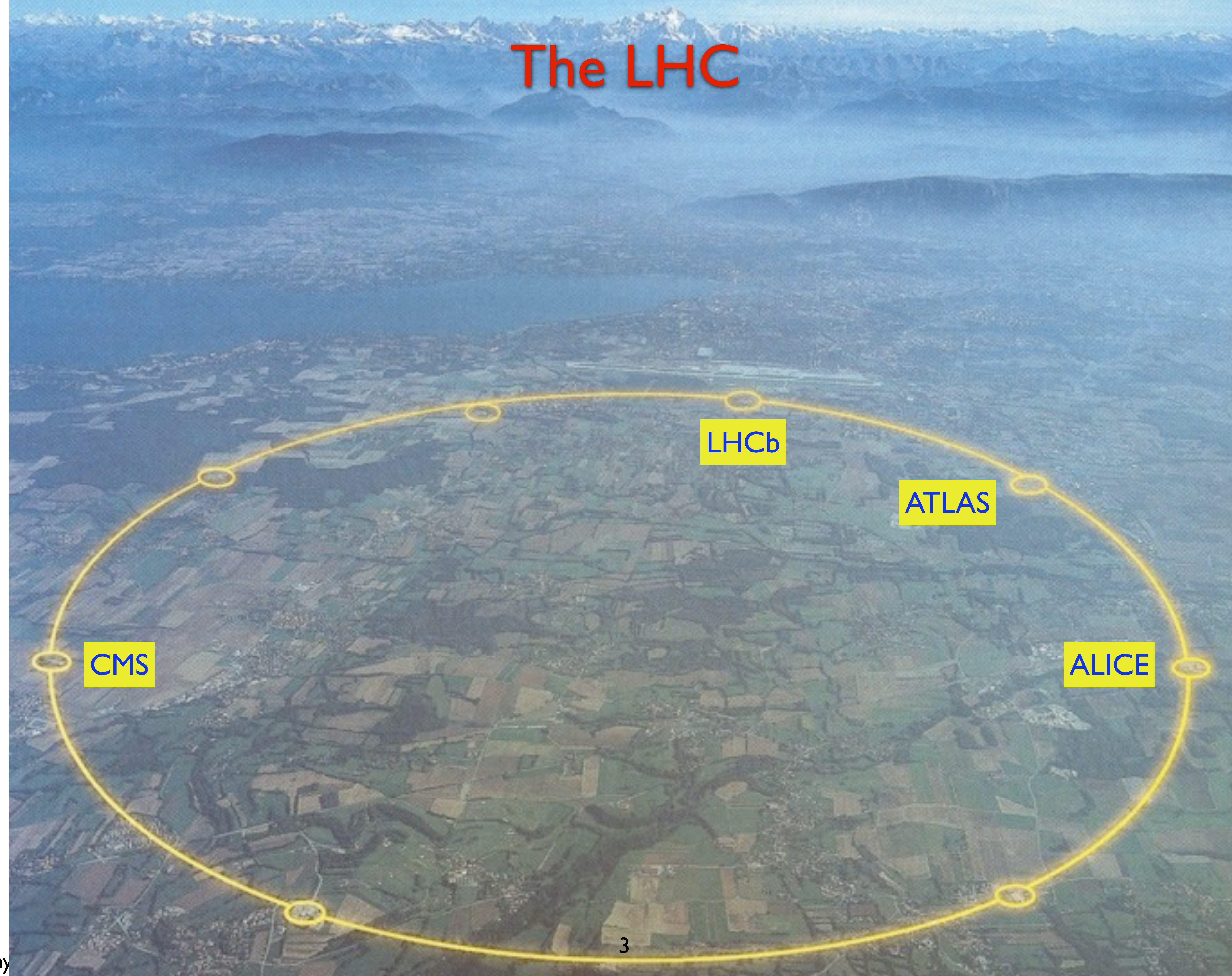
Physics Harvest at the Large Hadron Collider

Frank Filthaut
Radboud University Nijmegen & Nikhef

- The LHC: challenges & operation
- Probing deconfinement
- Challenging the Standard Model

LHC

The LHC



The LHC

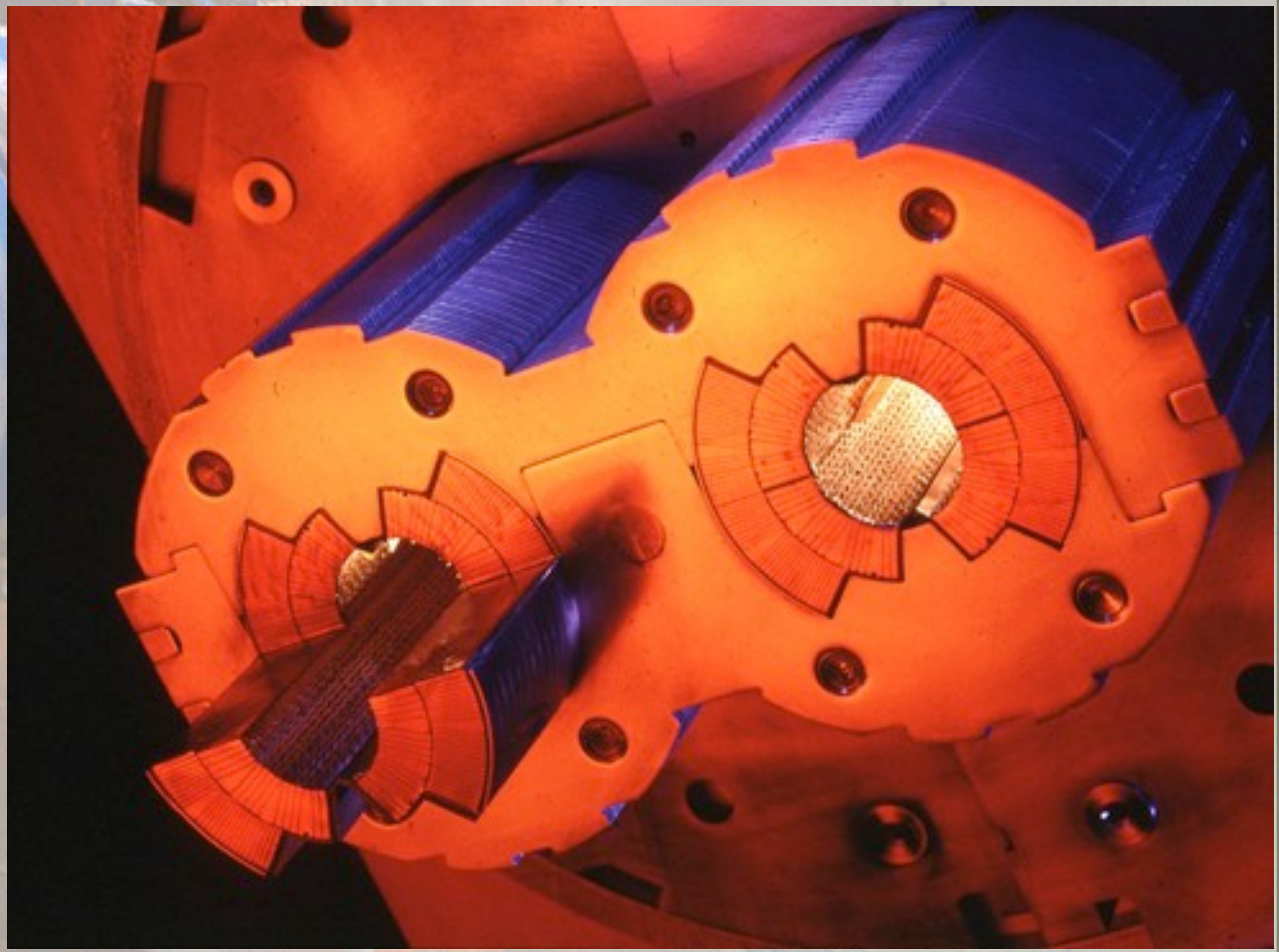
27 km circumference

proton-proton collisions at E_{CM} = 8 TeV (last year)

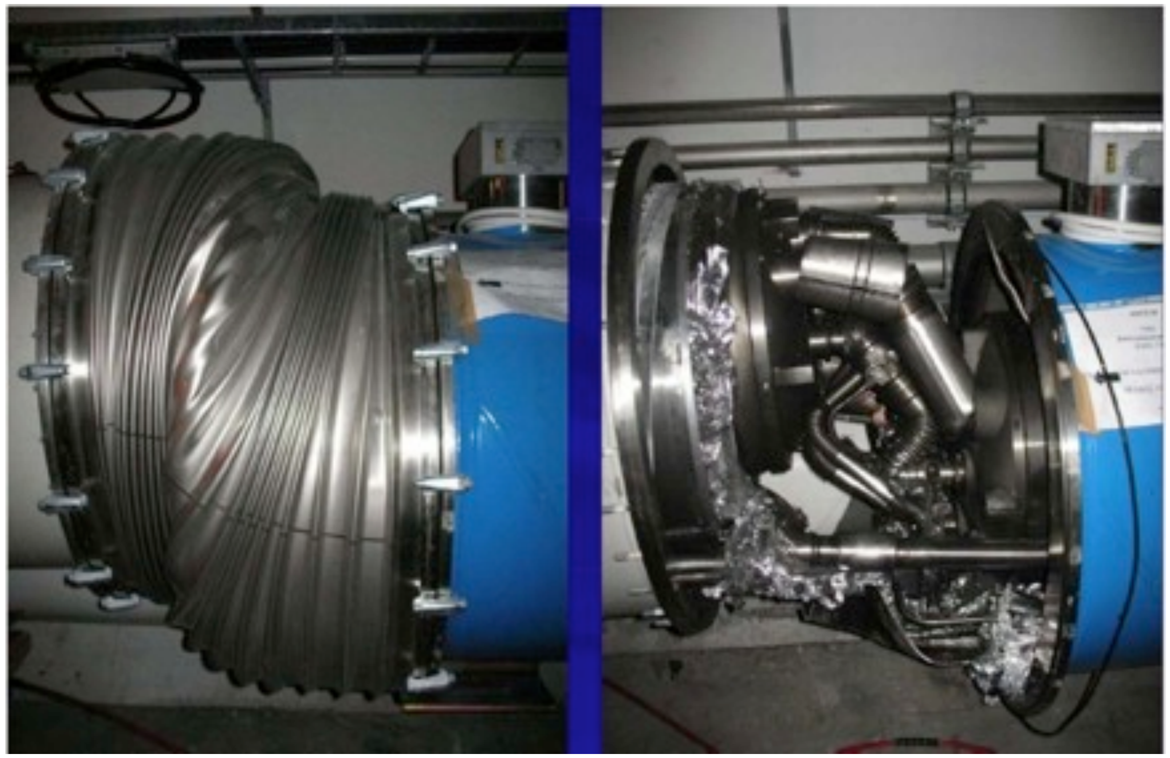
- up to 8.3 T B-field to provide bending power
- superconducting, T = 1.9 K (superfluid He)
- twin aperture: protons going around in both directions!
- collisions every 50 ns

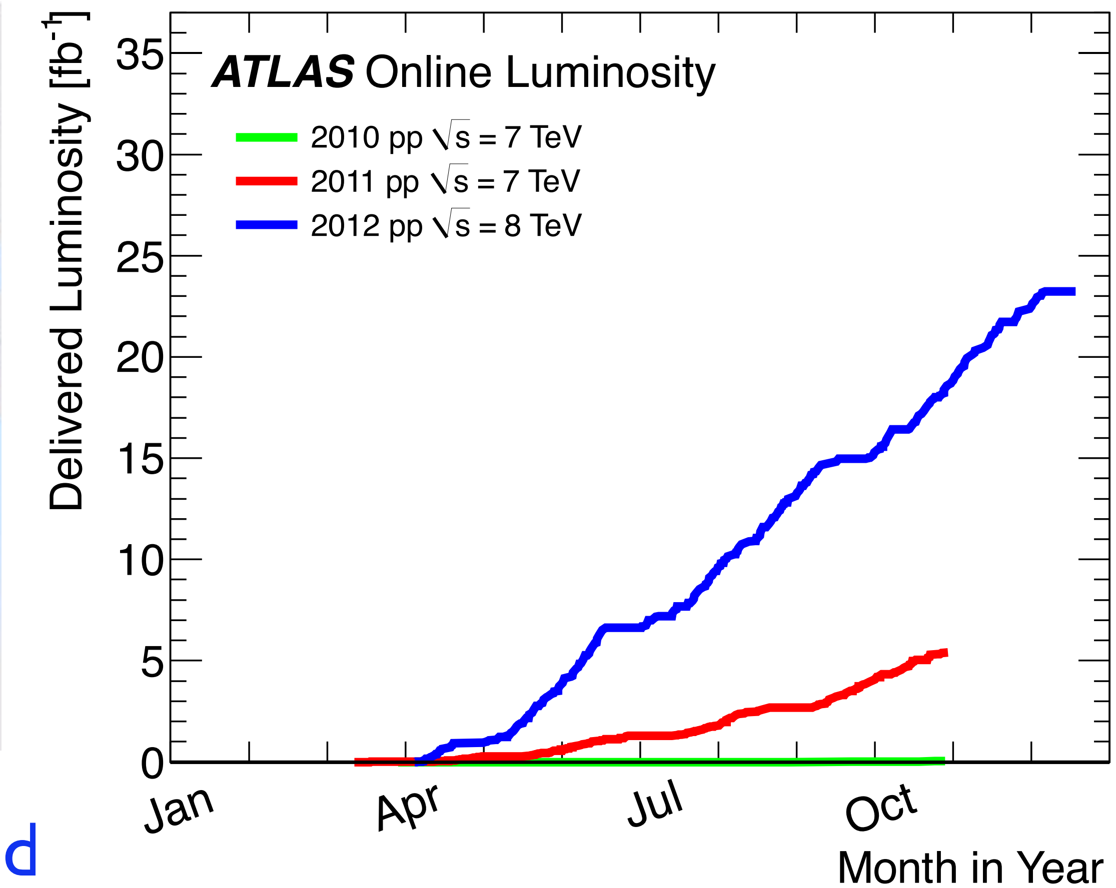
Required intensity implies enormous power

- and corresponding protection, etc.
- 2 × ~ 1300 bunches × 10^{11} protons / bunch: stored energy O(100 MJ)



The LHC : a Success Story!



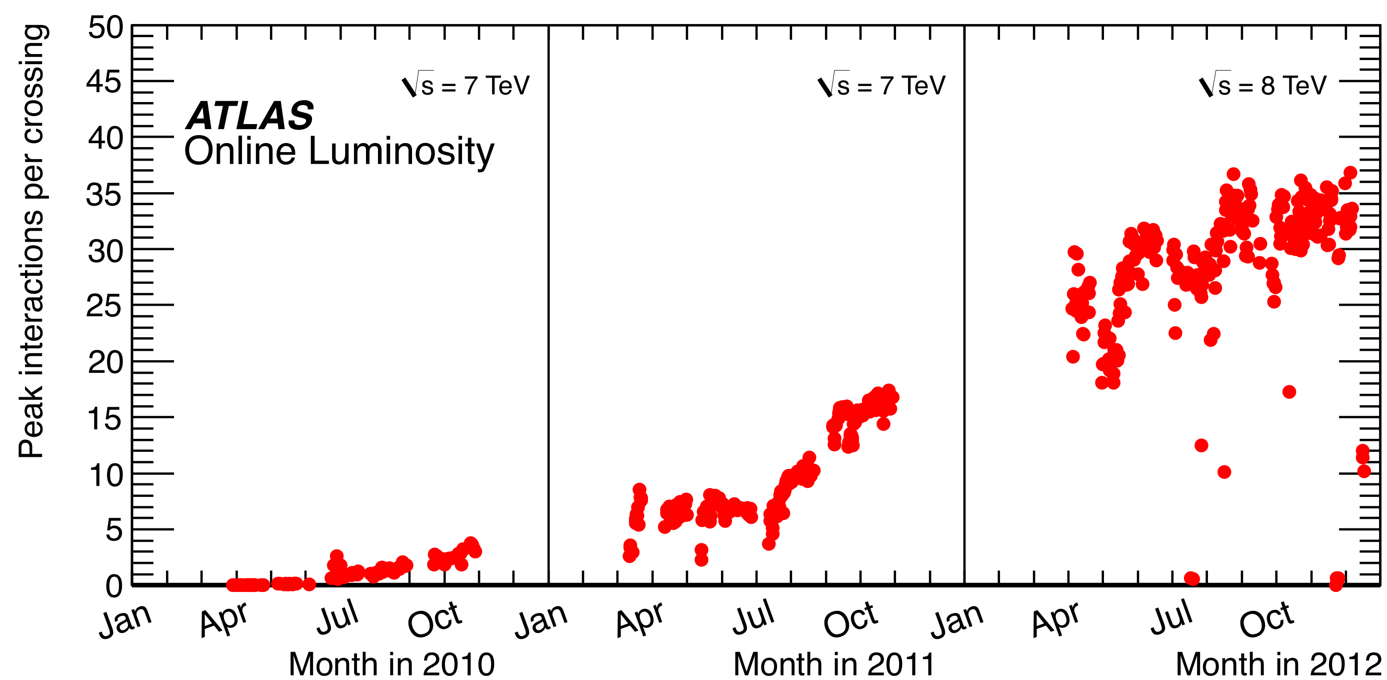


LHC expectations for 2011 exceeded by a factor 5

- even if at $\sqrt{s}$ = 7 TeV

2012 integrated luminosity exceeded that at end of 2011 by another factor 5

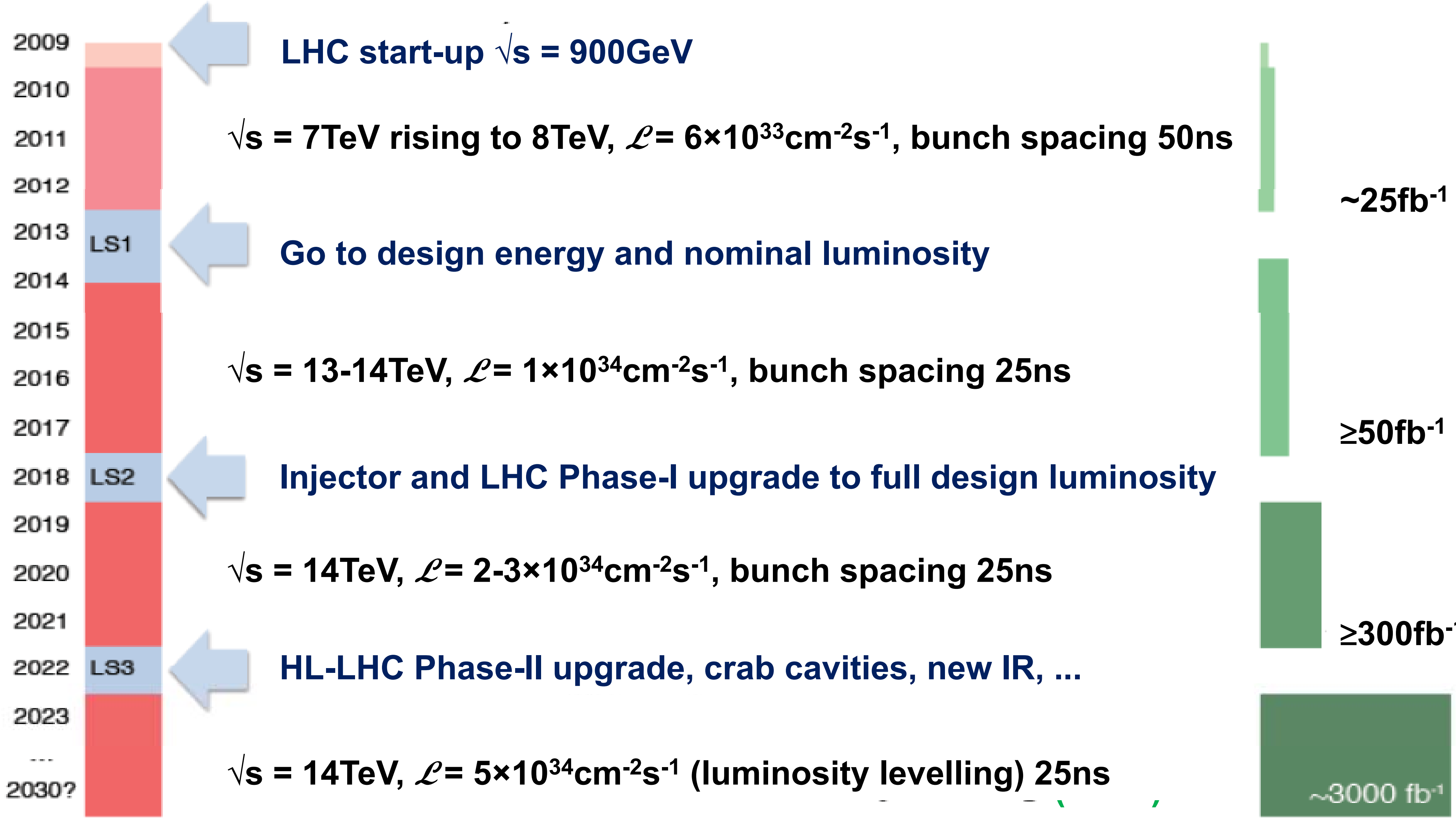
- at $\sqrt{s}$ = 8 TeV



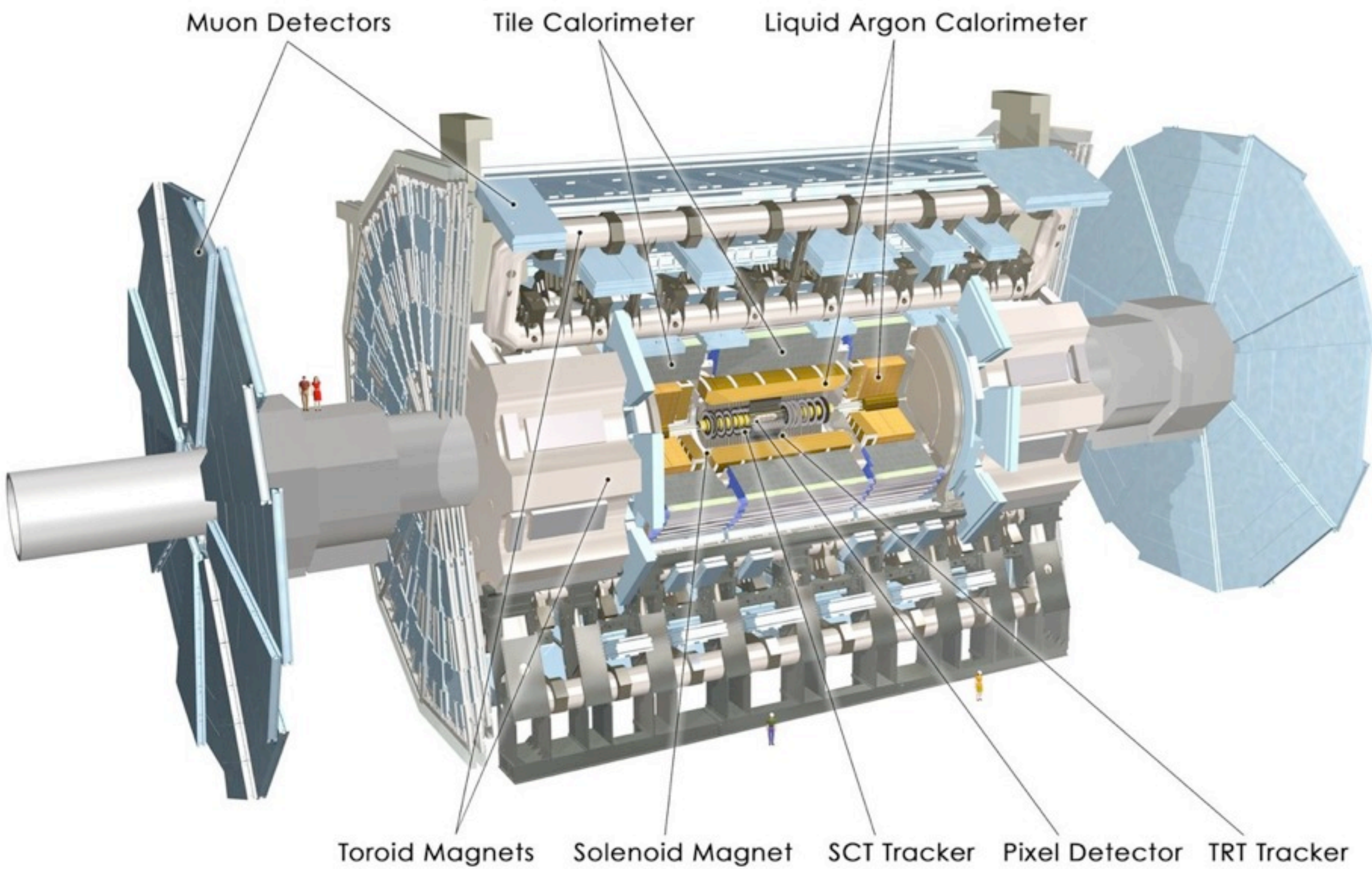
increased pile-up: up to 35 interactions / crossing

LHC Timeline

"Run 1" just finished: work in progress towards energy upgrade



The ATLAS Detector



Particle Detection in ATLAS

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In addition to individually observable particles:

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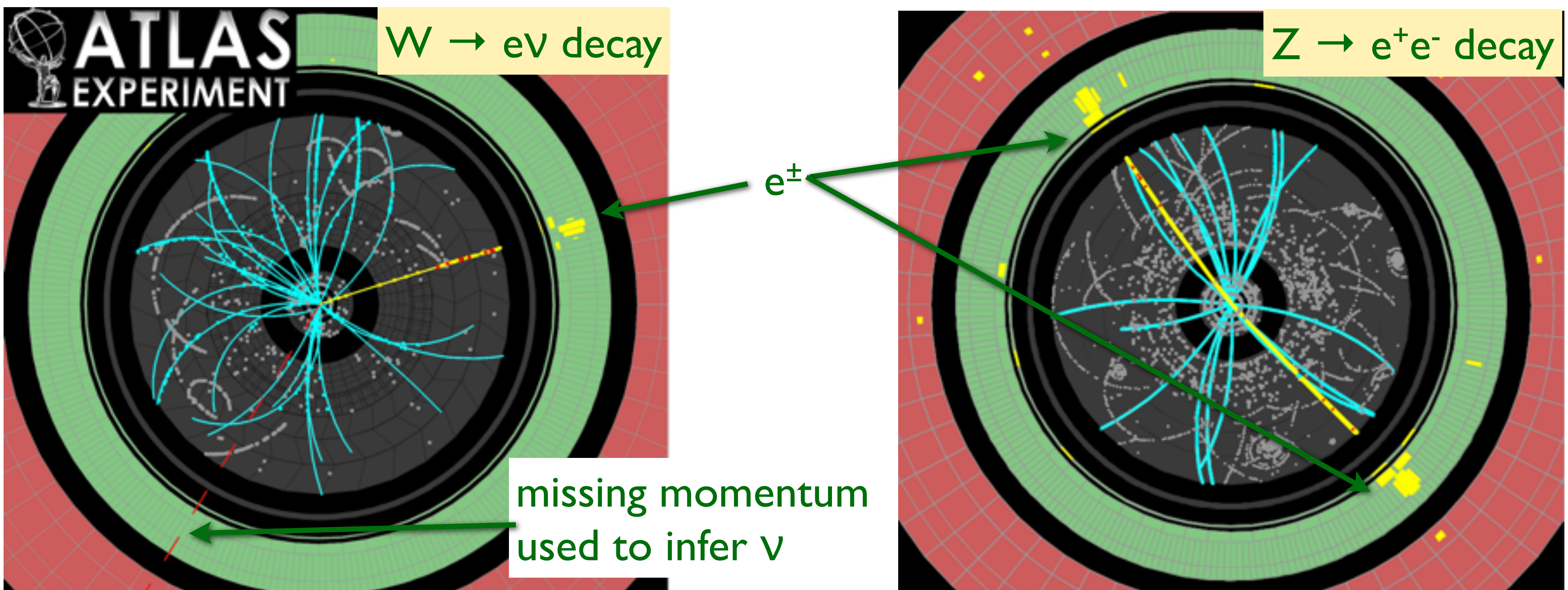

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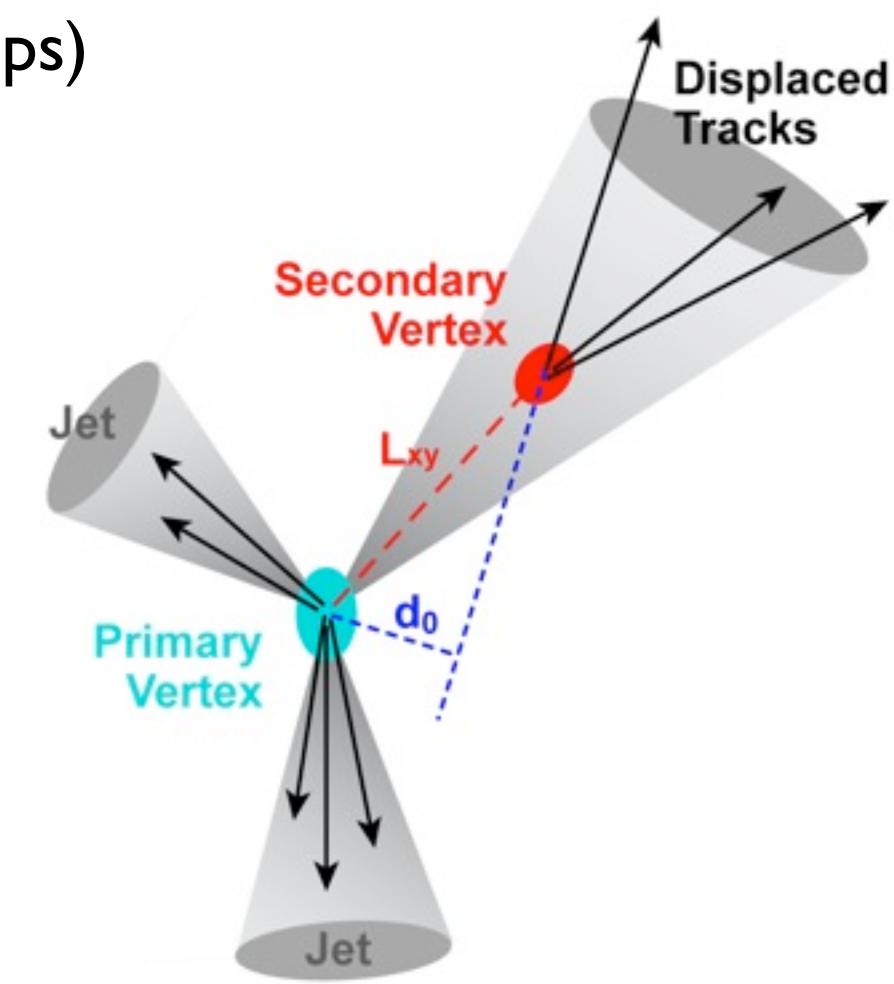

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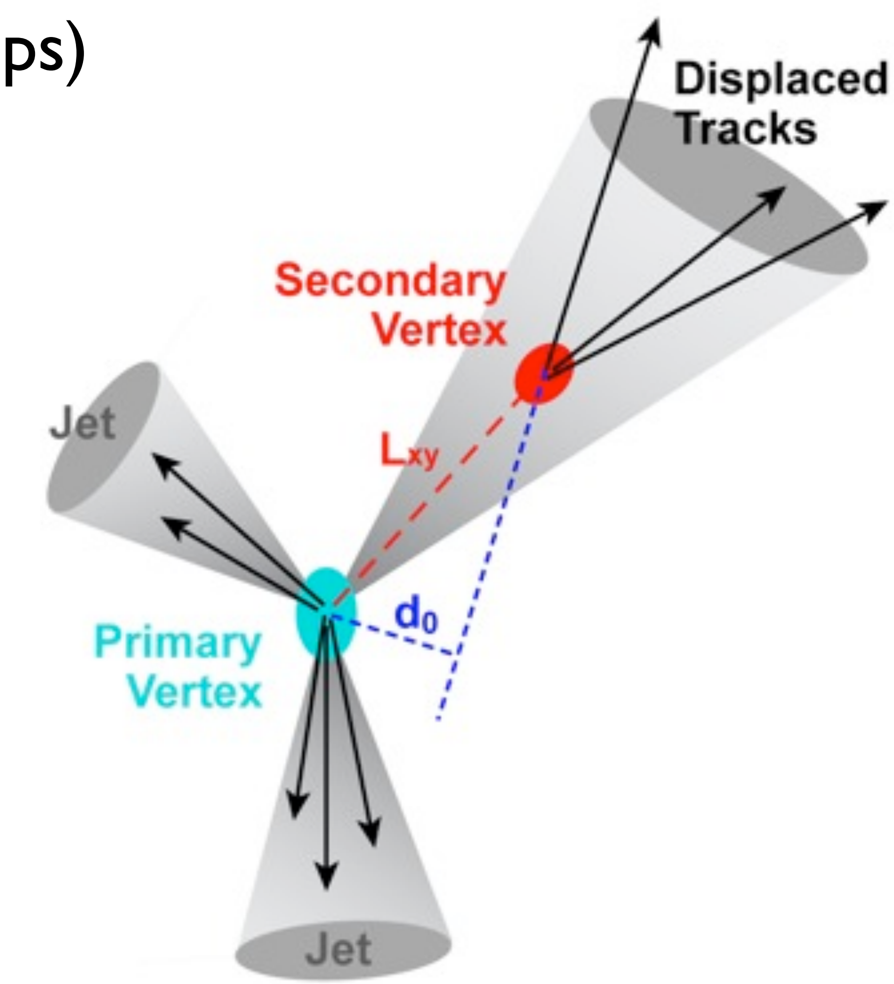
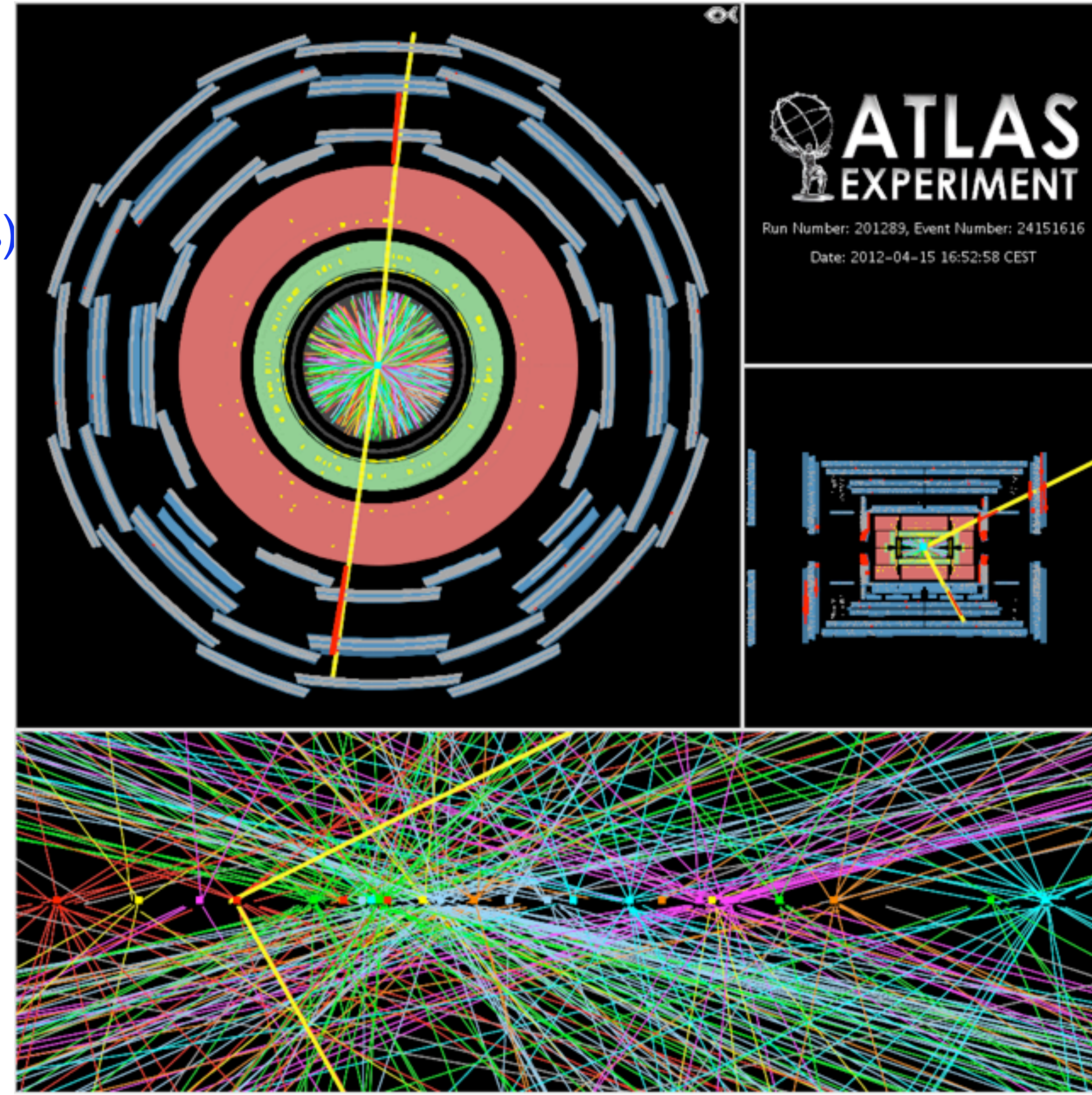


Analyzing 2012 ATLAS Data

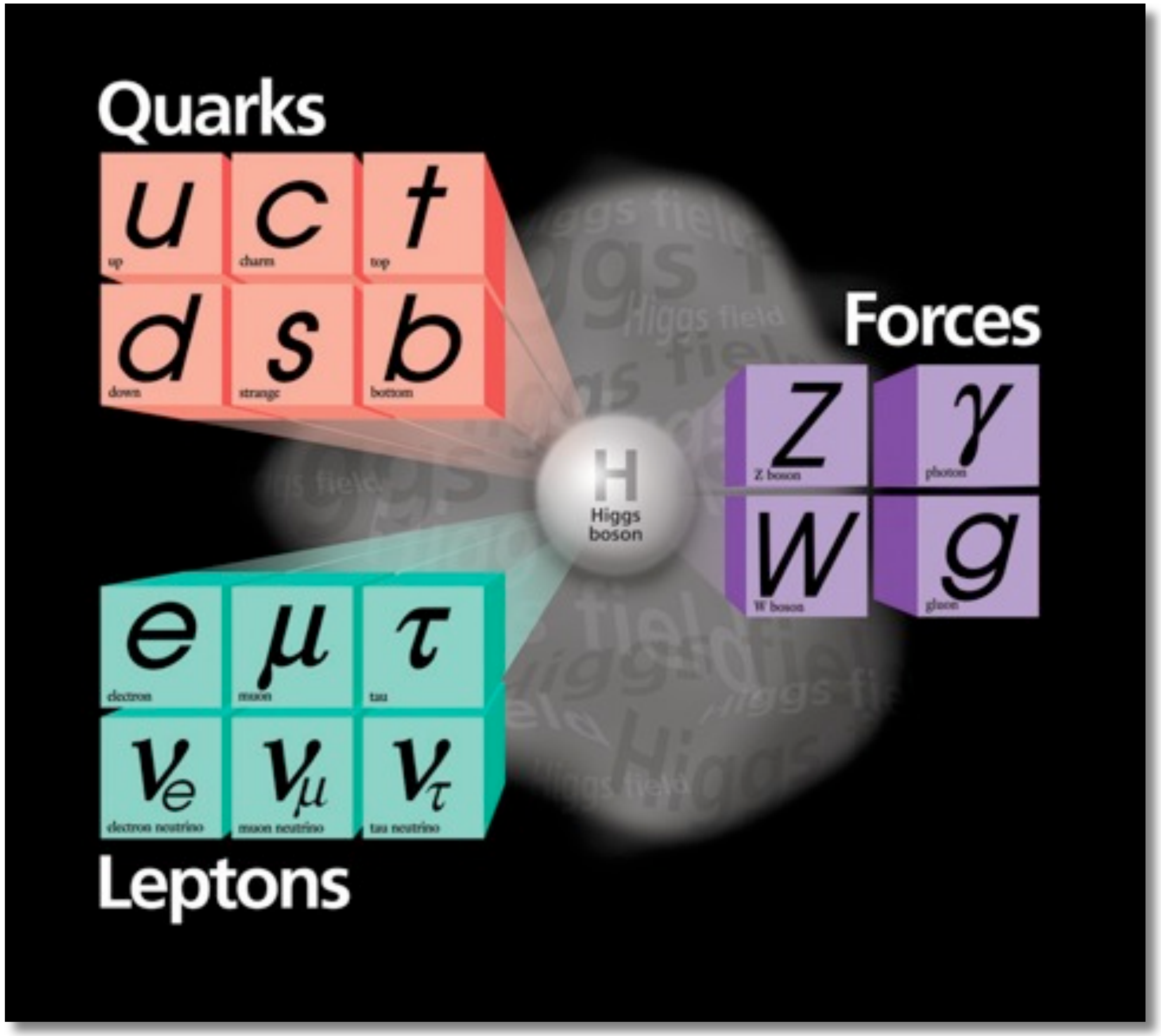
$Z \rightarrow \mu^+\mu^-$ interaction with 25 reconstructed primary vertices (additional interactions)

- challenge to select only the interesting interaction!



Particle Summary

In the Standard Model...



Notes:

1. gravity cannot be described by the Standard Model
2. the Higgs boson was not discovered until last year

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detectable as
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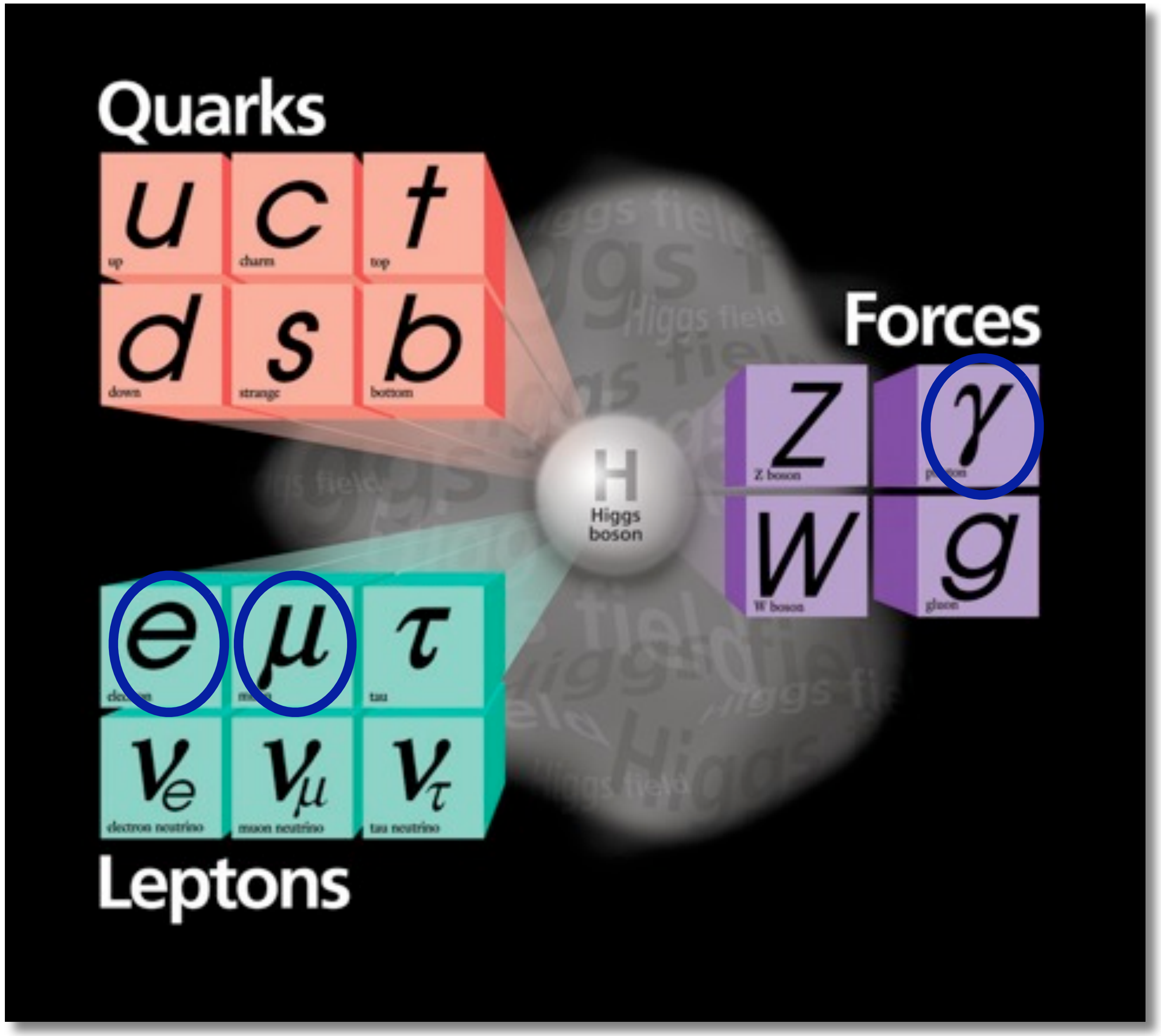

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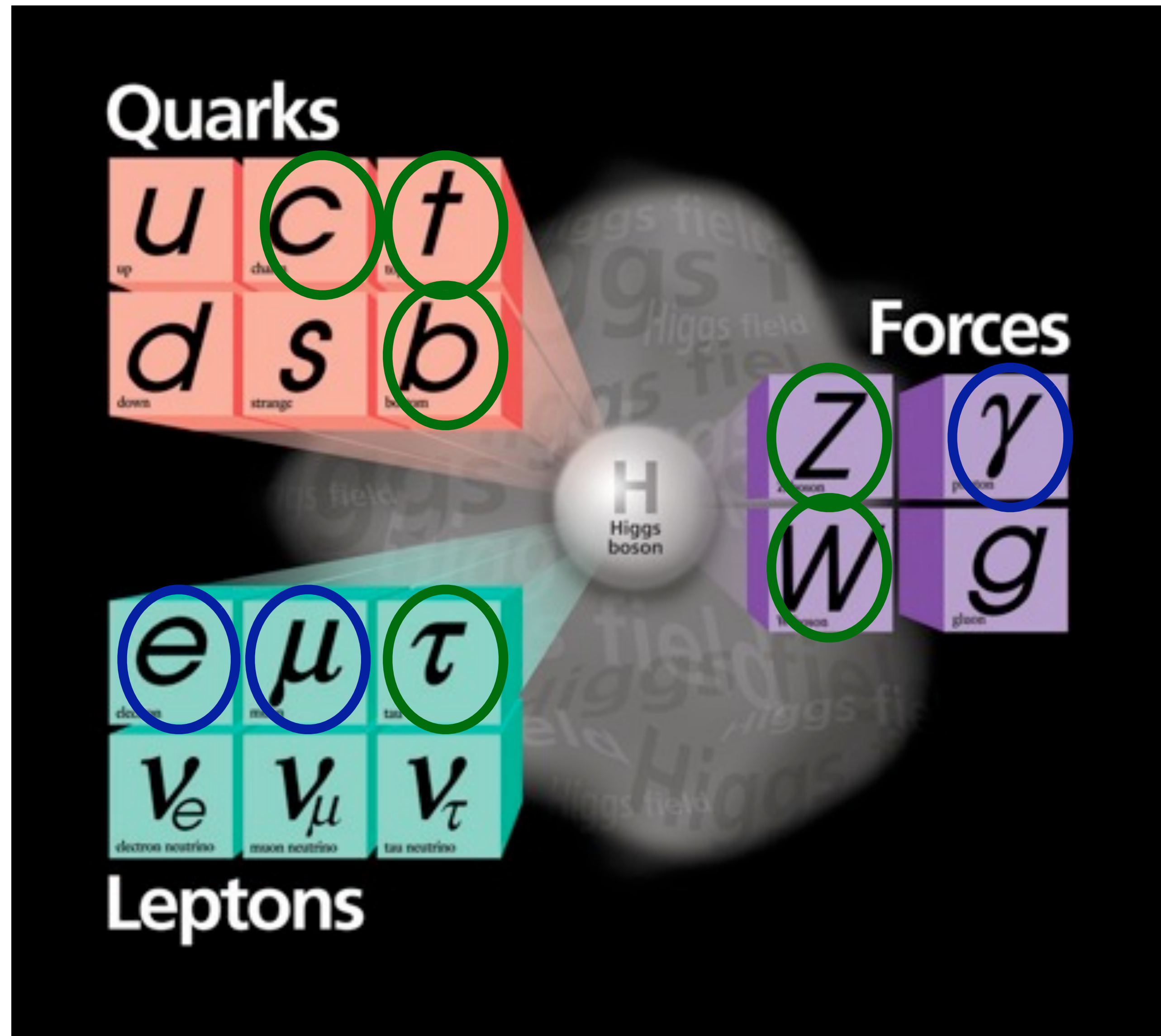
detectable through decay



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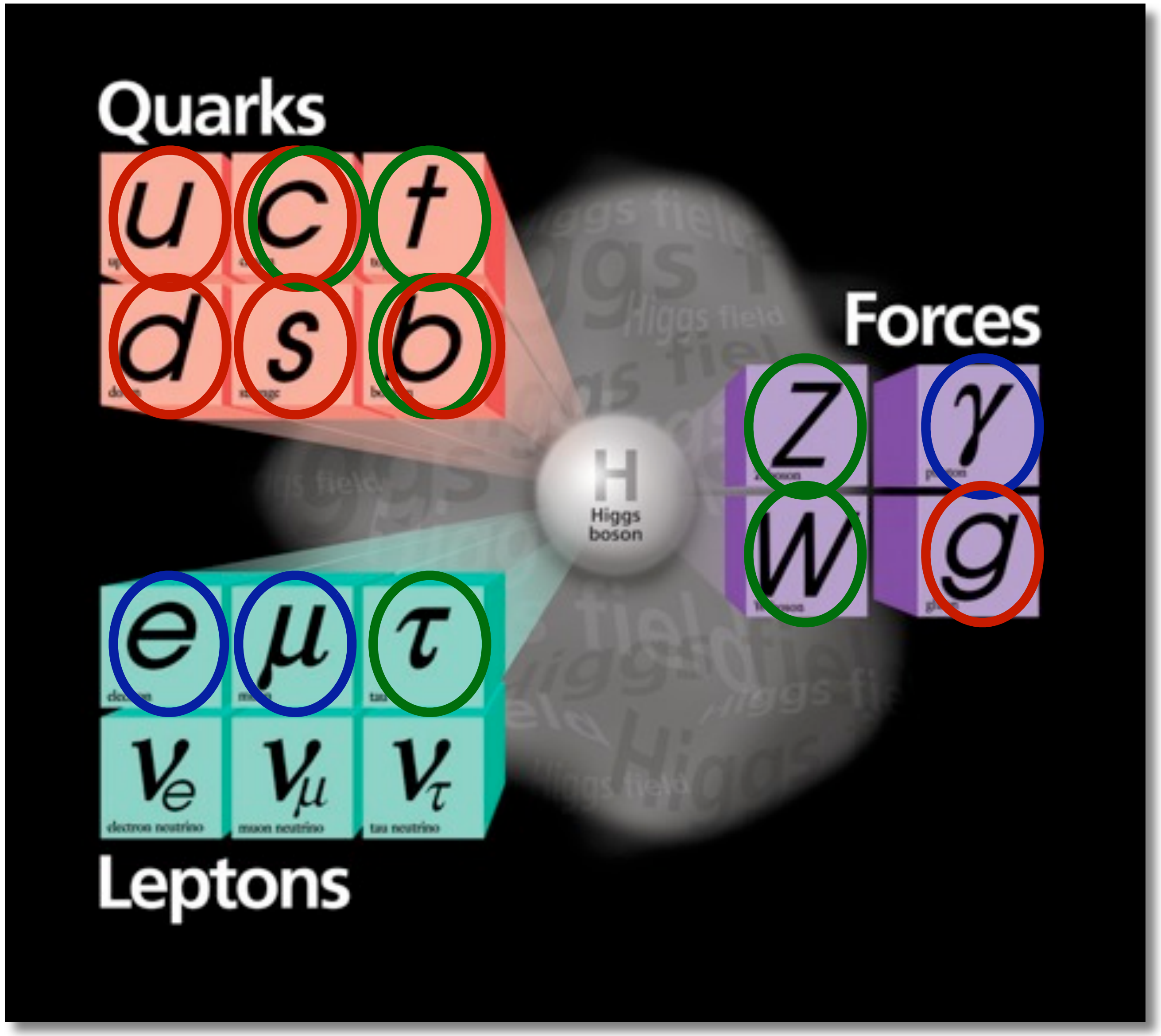

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(masses in GeV)

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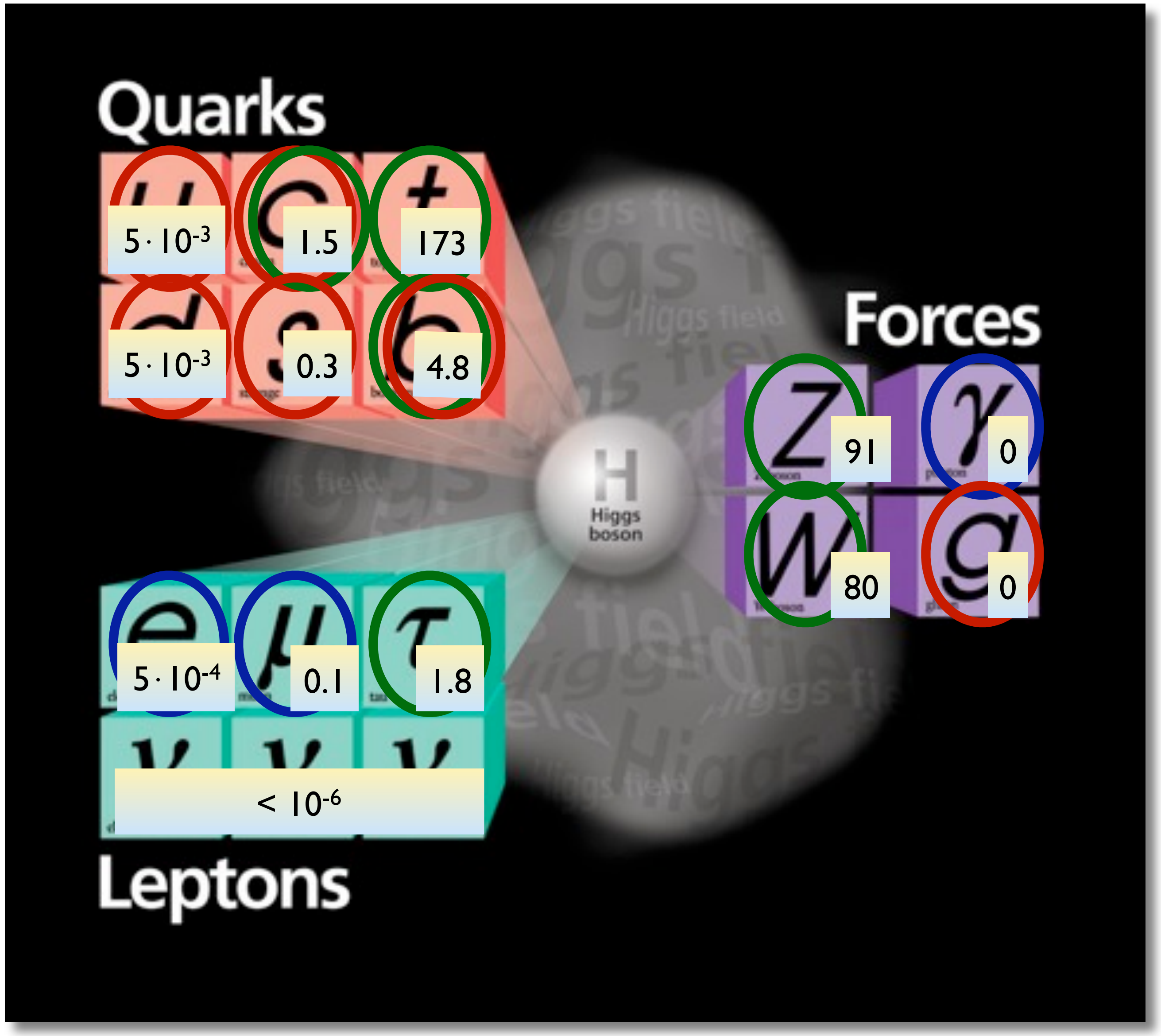

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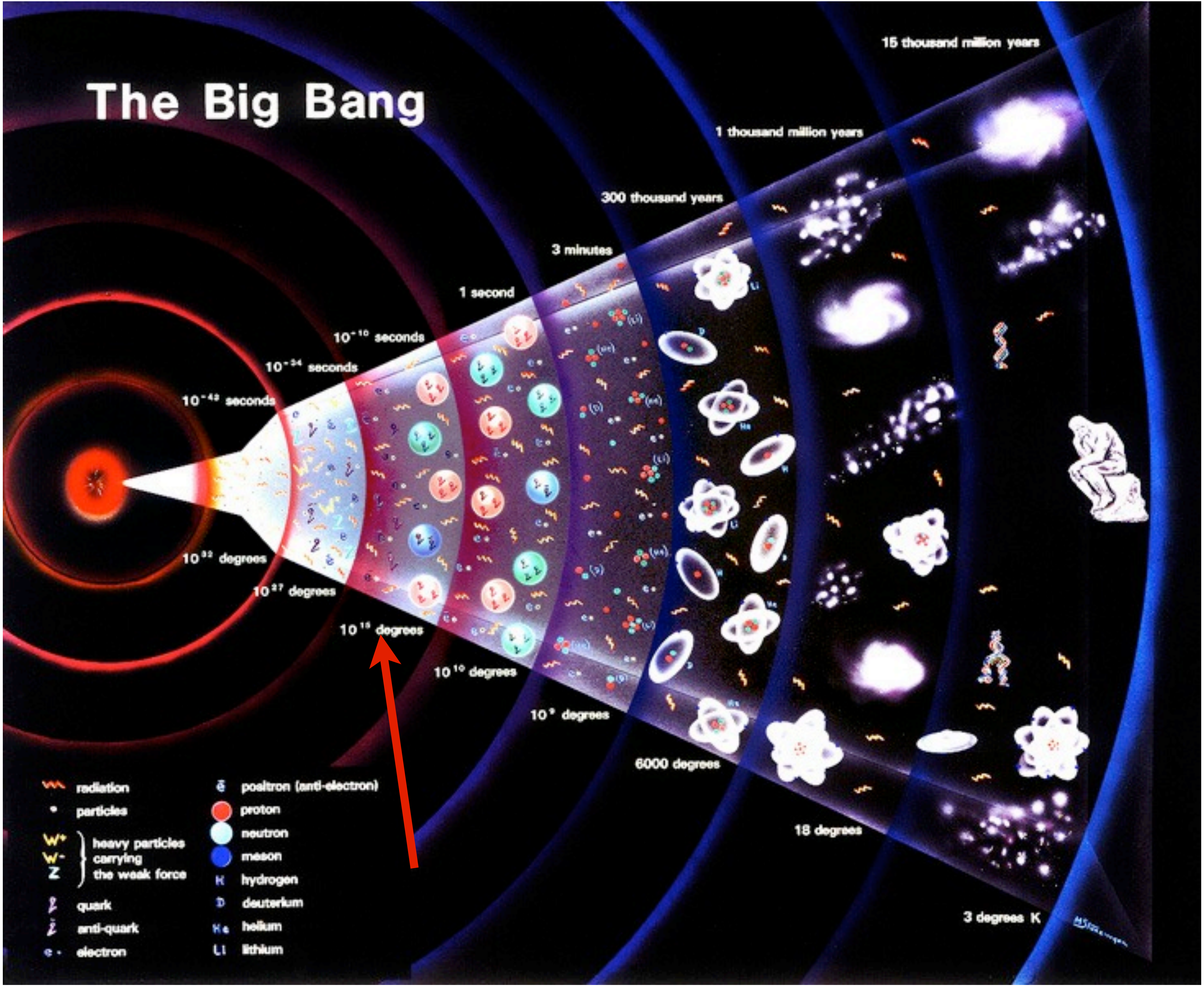
Probing Deconfinement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1 thousand million years
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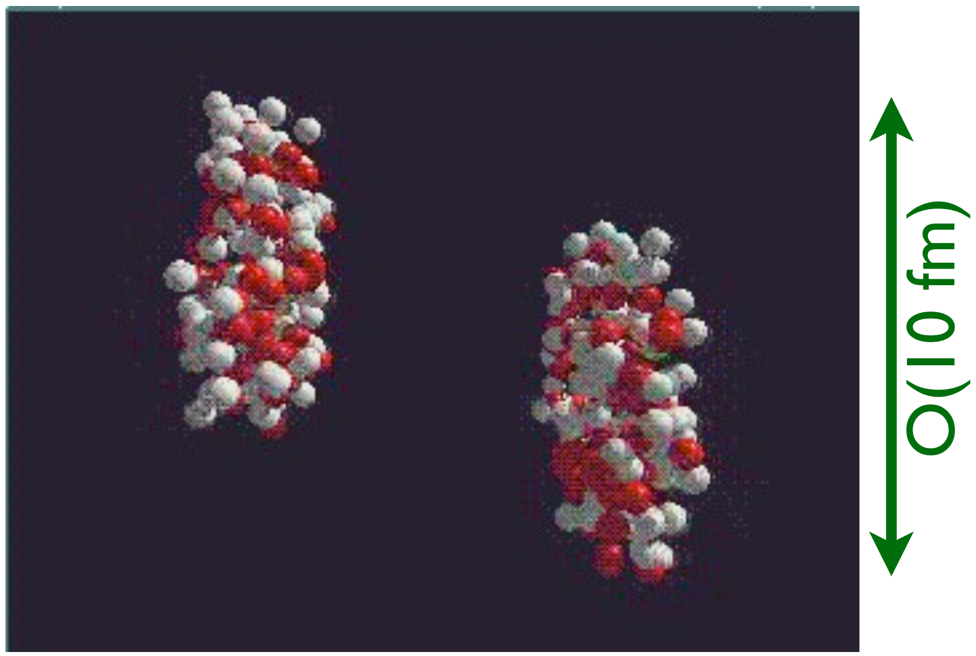
3 minutes
1 second
10^-10 seconds
10^-34 seconds
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Heavy Ion Collisions

The LHC can also be used to accelerate heavy ions (Pb, Z=82, A=208)!

- following earlier experiments at RHIC (Brookhaven): Au (Z=79, A=197)

Such collisions are qualitatively different from proton-proton collisions!



- possible to create a quark-gluon plasma (different state of matter)

First evidence for creation of a QGP from RHIC; unequivocal signals expected from the LHC

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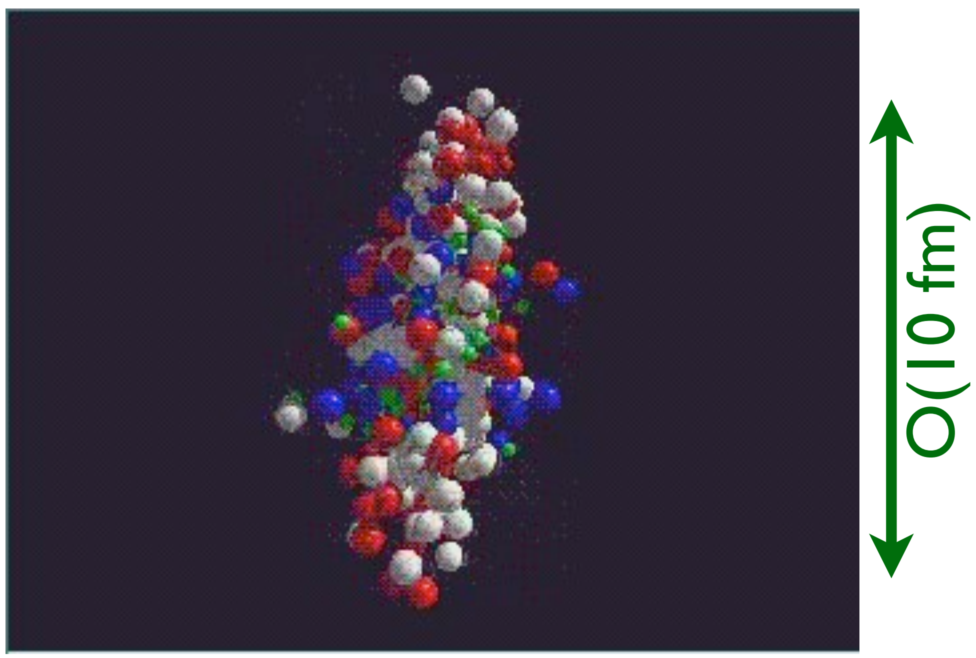

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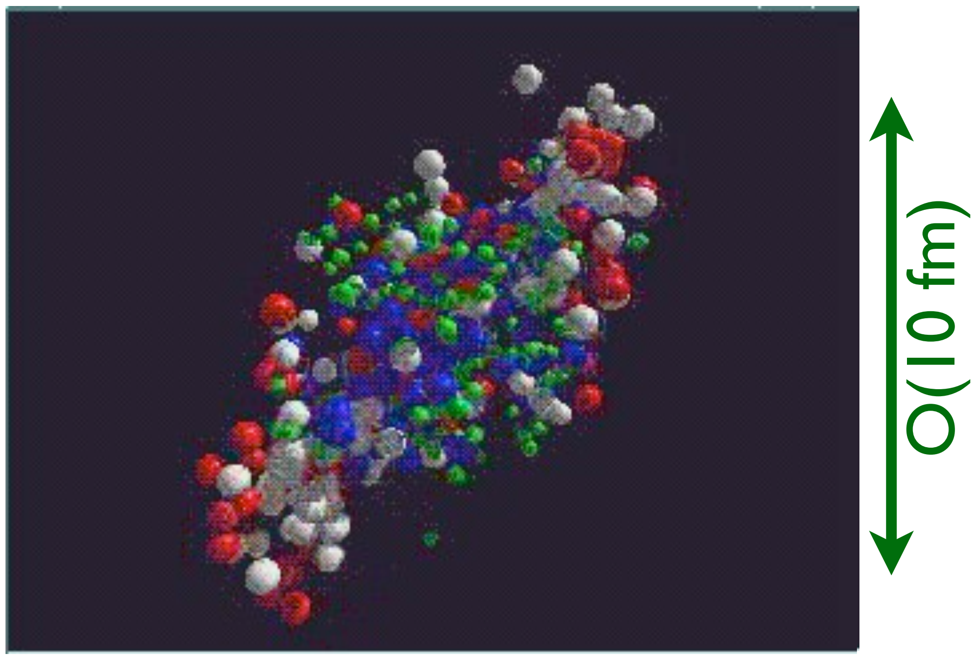

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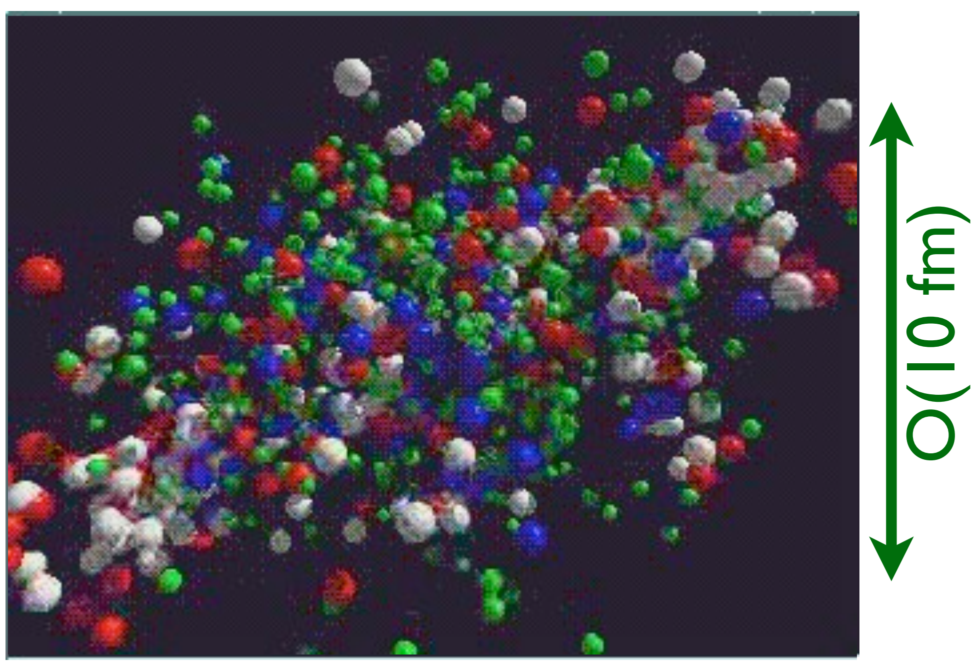

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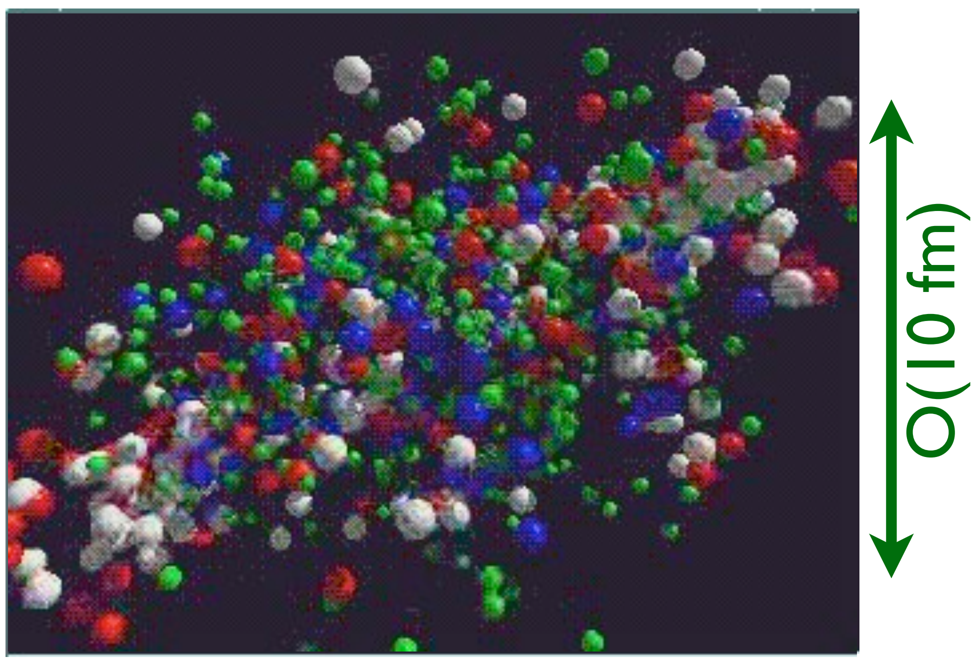

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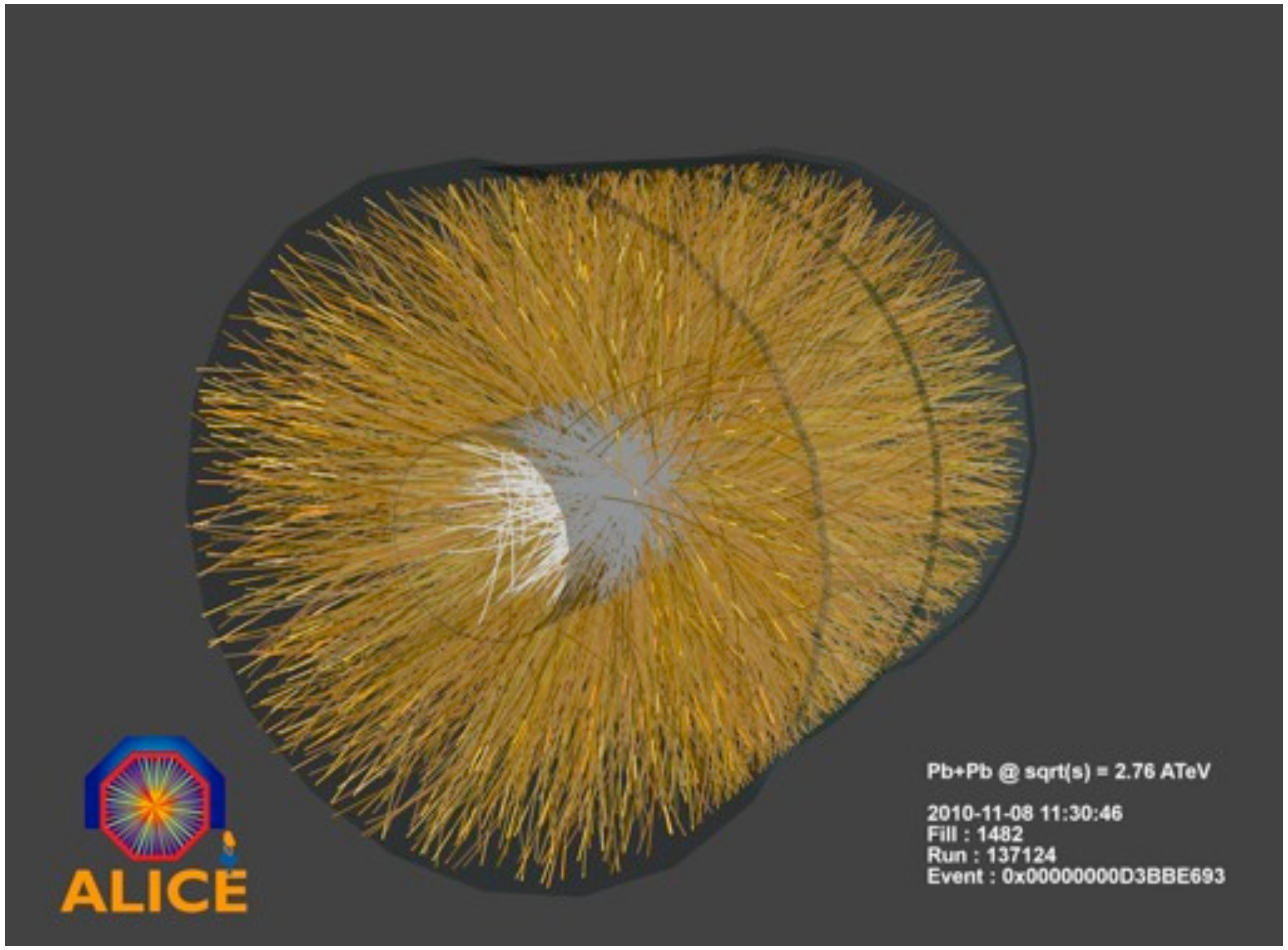

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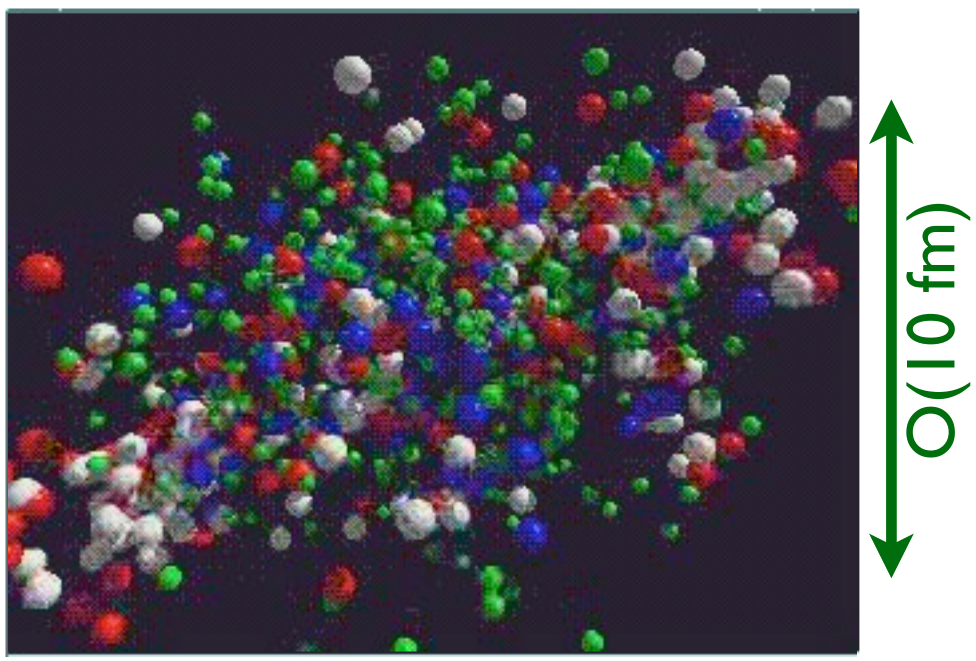

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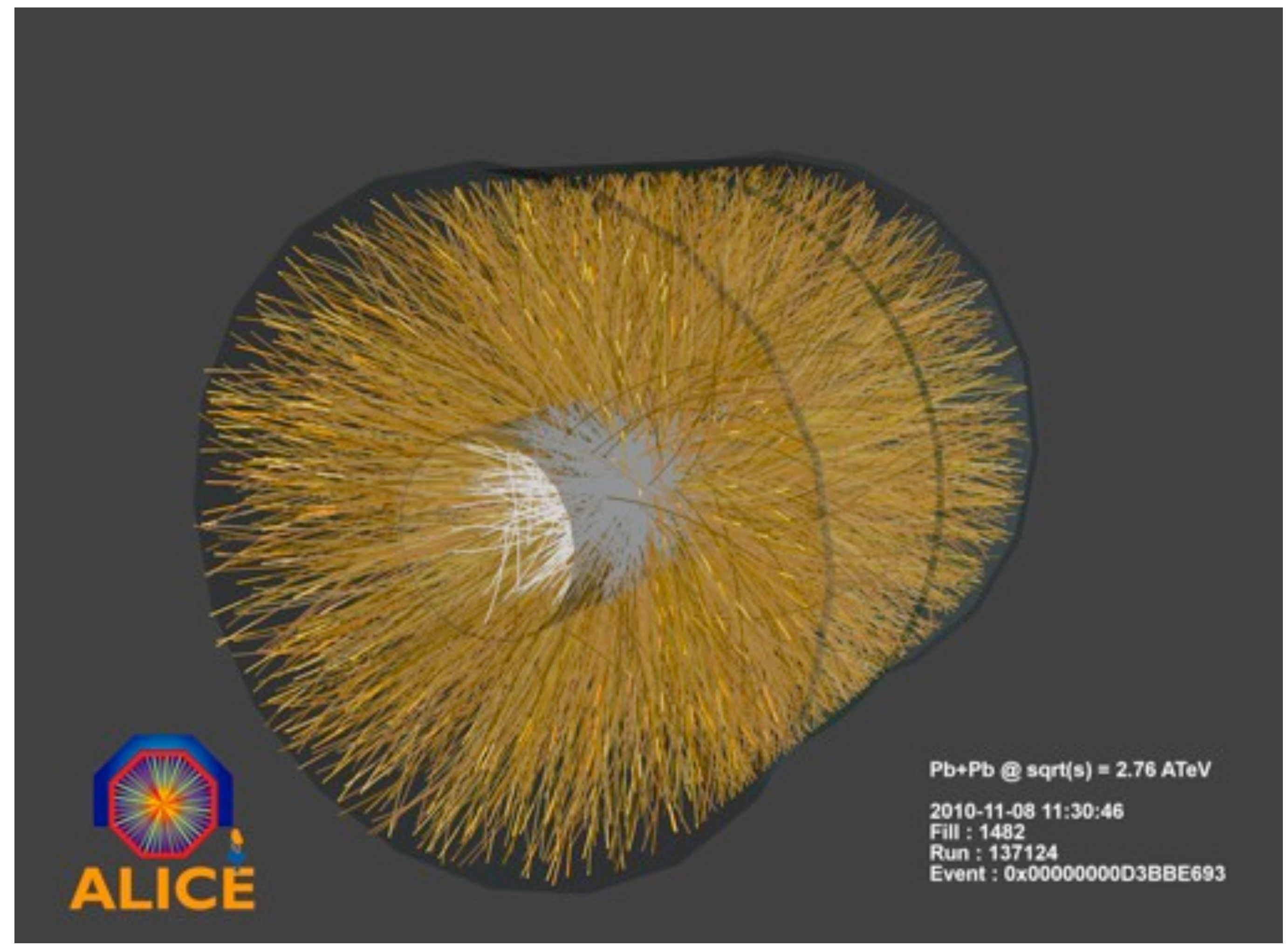

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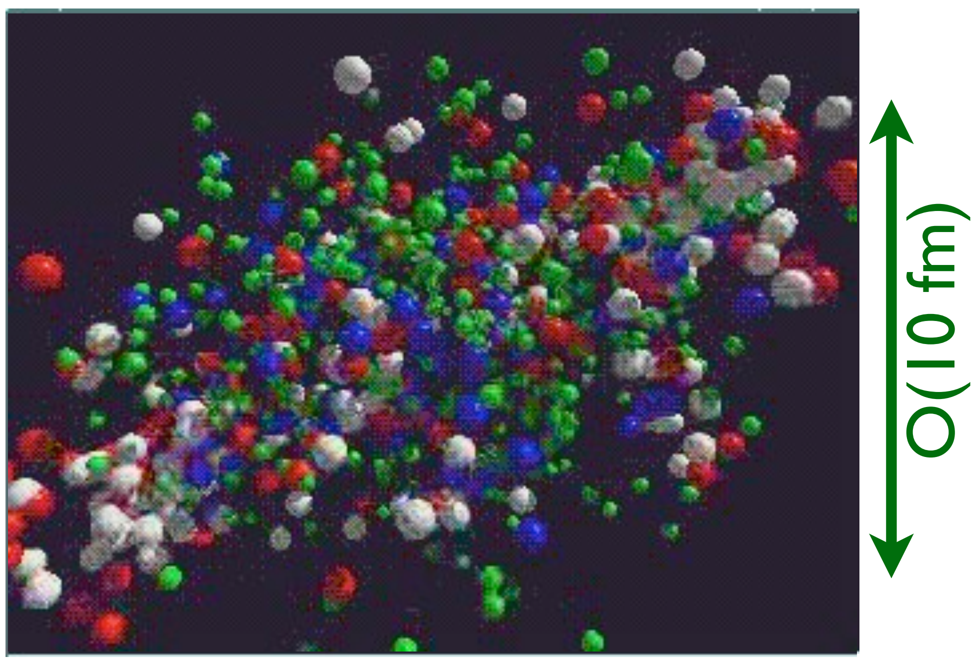

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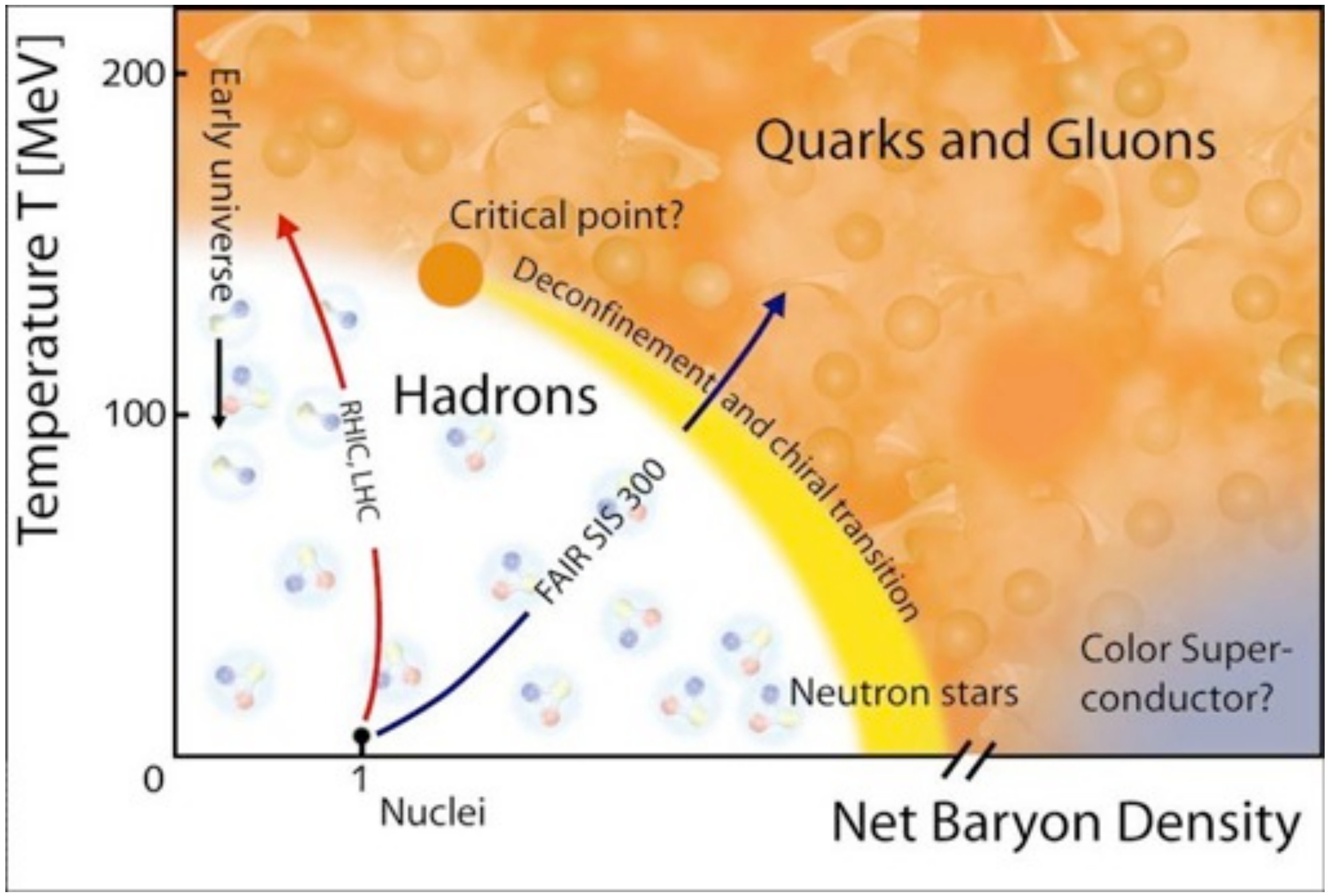

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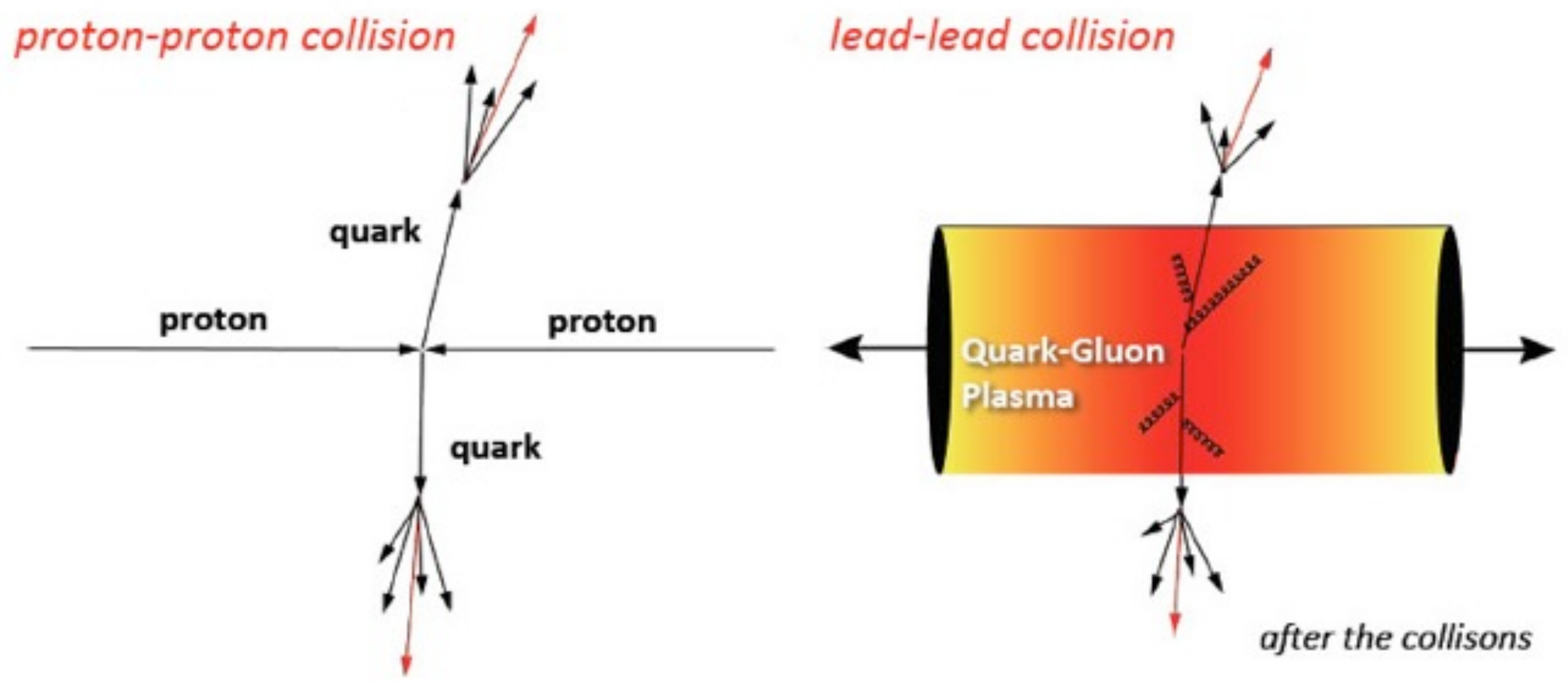
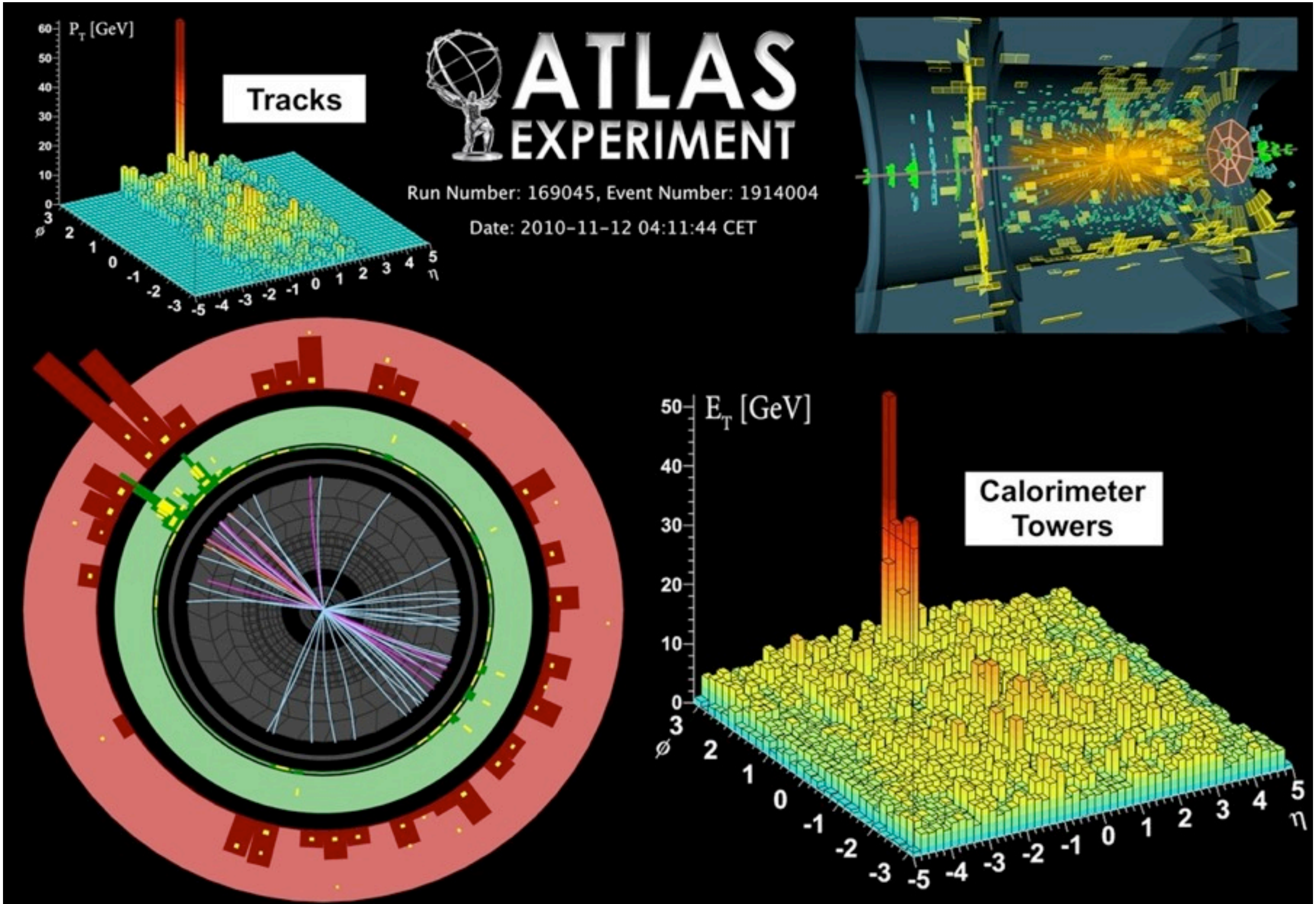
Heavy-Ion Physics Programme

Study particle physics processes and how they are affected by the presence of a quark-gluon plasma. Many probes:

- charged particle flow
- production of particles containing heavy (b, c) quarks
- production of quarkonia ($c\bar{c}$, $b\bar{b}$ bound states)
- production of jets



Jet Quenching & J/ψ Suppression



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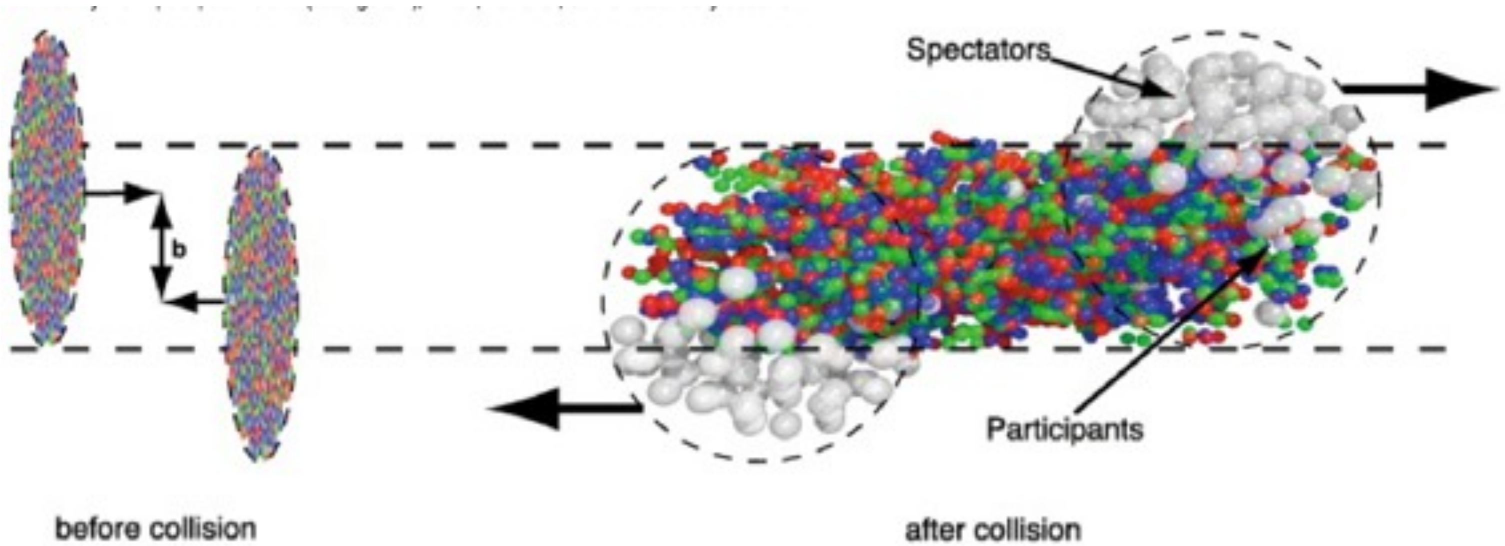
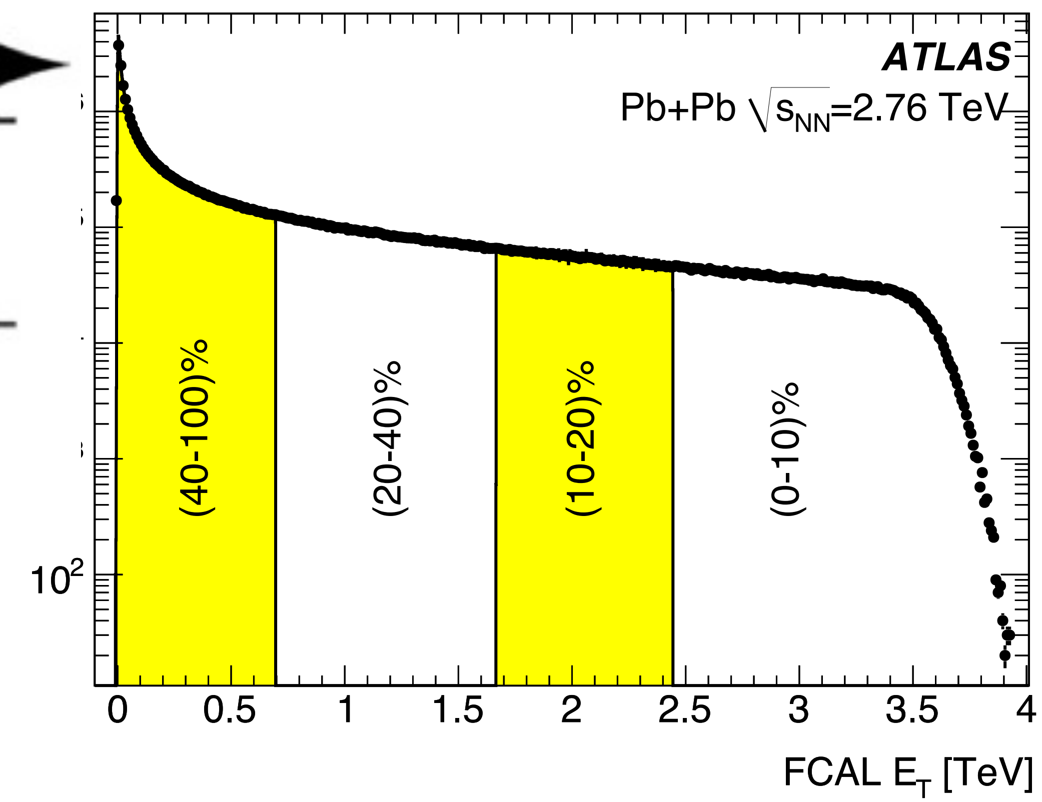
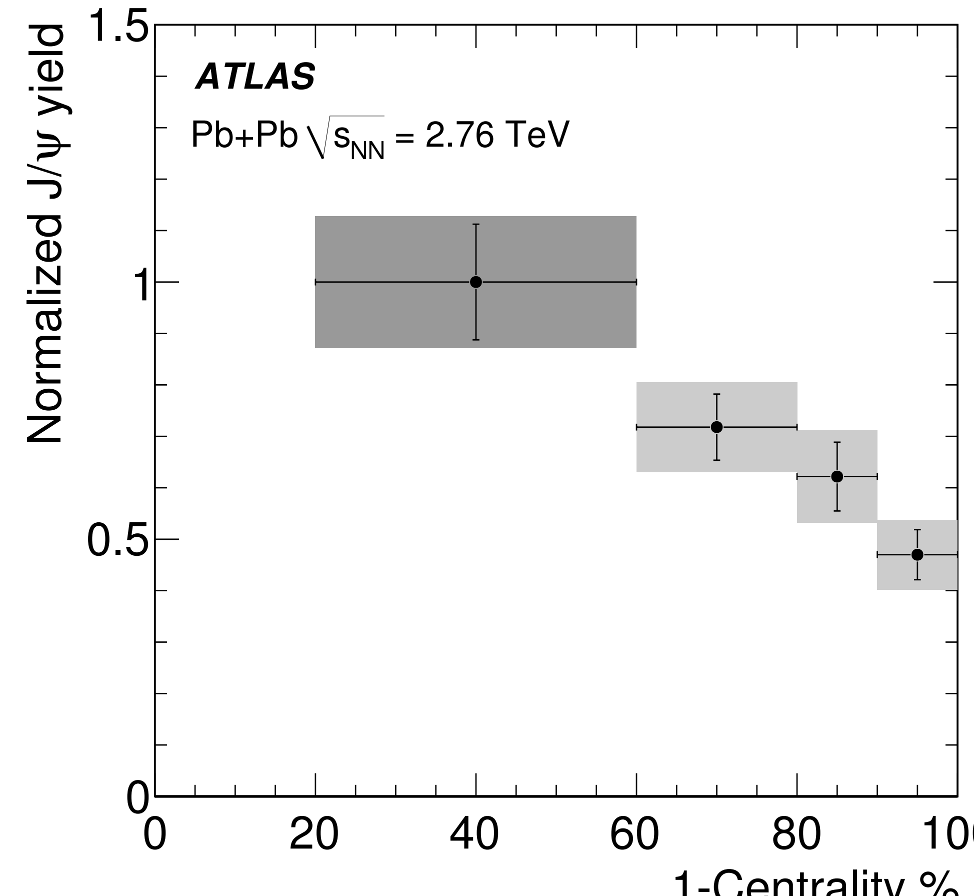


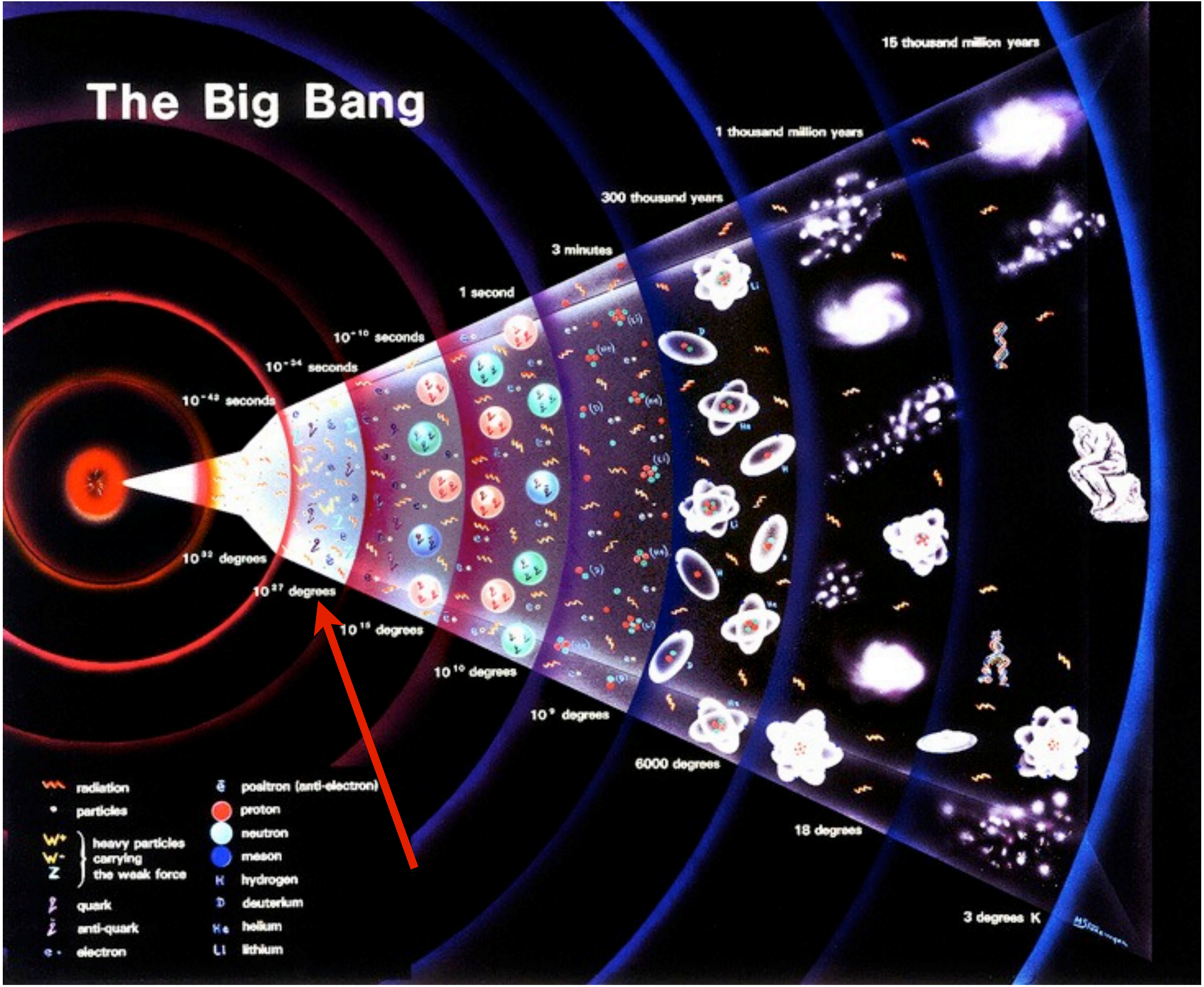


J/ψ particles ($c\bar{c}$ bound states) live long enough ($\tau \sim 10^{-20}$ s) to interact with the QGP: lower number of J/ψ $\rightarrow \mu^+\mu^-$ decays observed for central collisions than expected

- effect not observed for $Z \rightarrow \mu^+\mu^-$ decays (Z does not interact strongly and has $\tau \sim 10^{-25}$ s)



Challenging the Standard Model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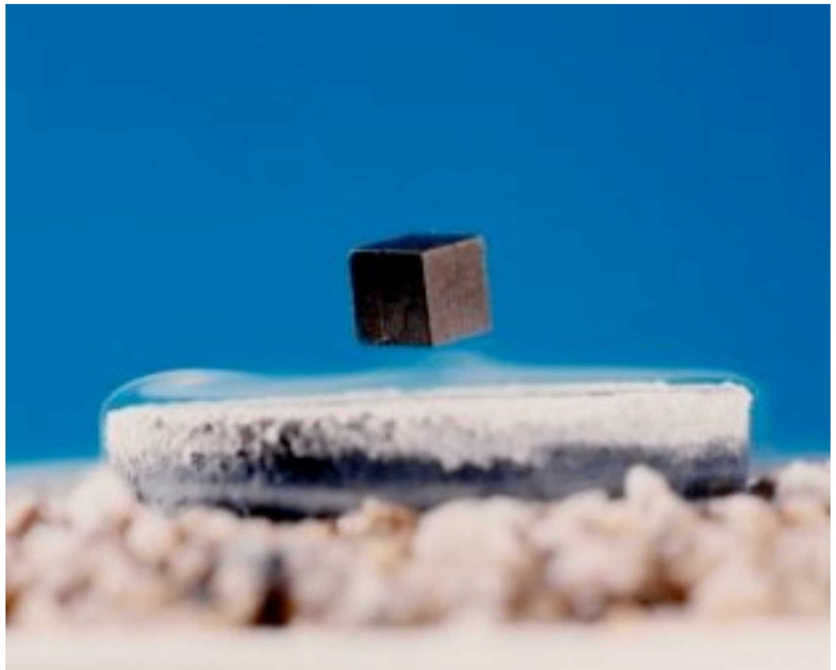
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e- electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

The Higgs Mechanism



Meißner effect: massive photons in a superconductor

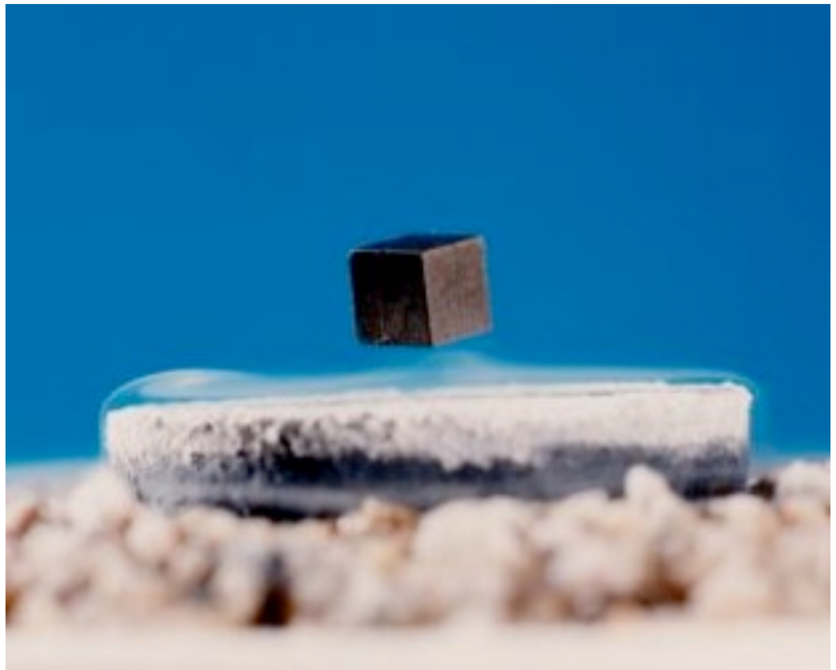
The Higgs mechanism does the same for elementary particles but without the need for a medium (superconductor)

The Higgs Mechanism

The Standard Model: a quantum field theory built on the concept of gauge theories, with spin-1 bosons mediating the electromagnetic, strong, and weak interactions

- "internal" symmetries transforming between particle types, leaving physical laws invariant
- the gauge principle works to extreme accuracy for QED: g_e, g_μ
- problem: under normal circumstances this works only for massless gauge bosons ➠ in stark contrast to M_W = 80.4 GeV, M_Z = 90.1 GeV

The Higgs mechanism allows for massive W and Z bosons without breaking the Standard Model's symmetries explicitly



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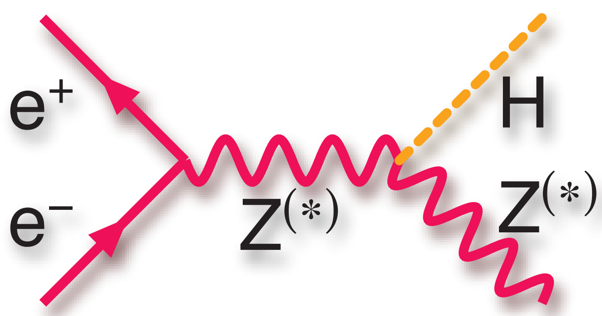
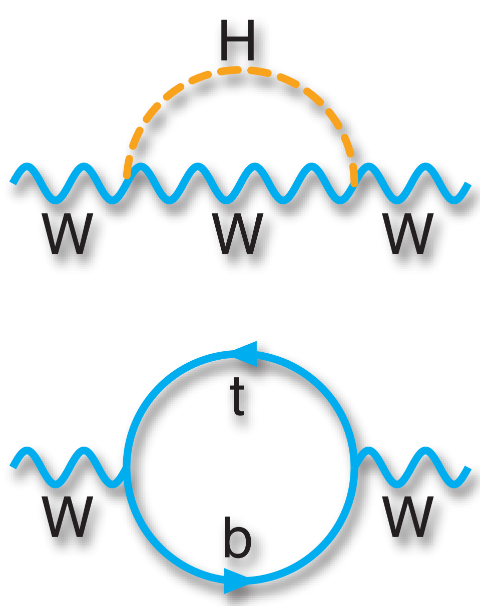
Previous Searches & Indirect Evidence

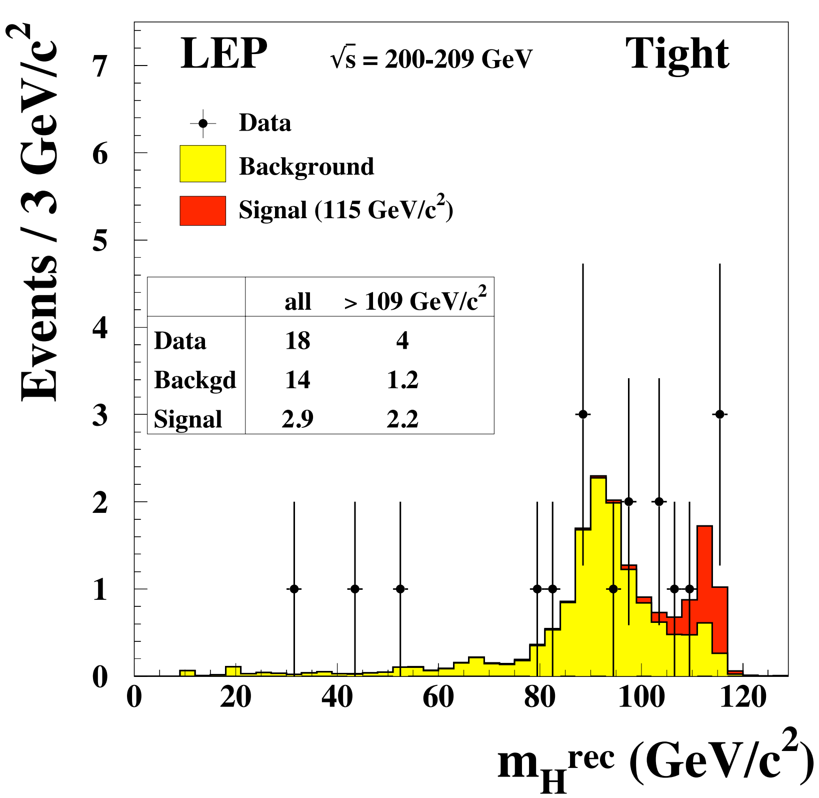
The mass of the Higgs boson is a priori a free parameter; however, given its mass all other properties are known

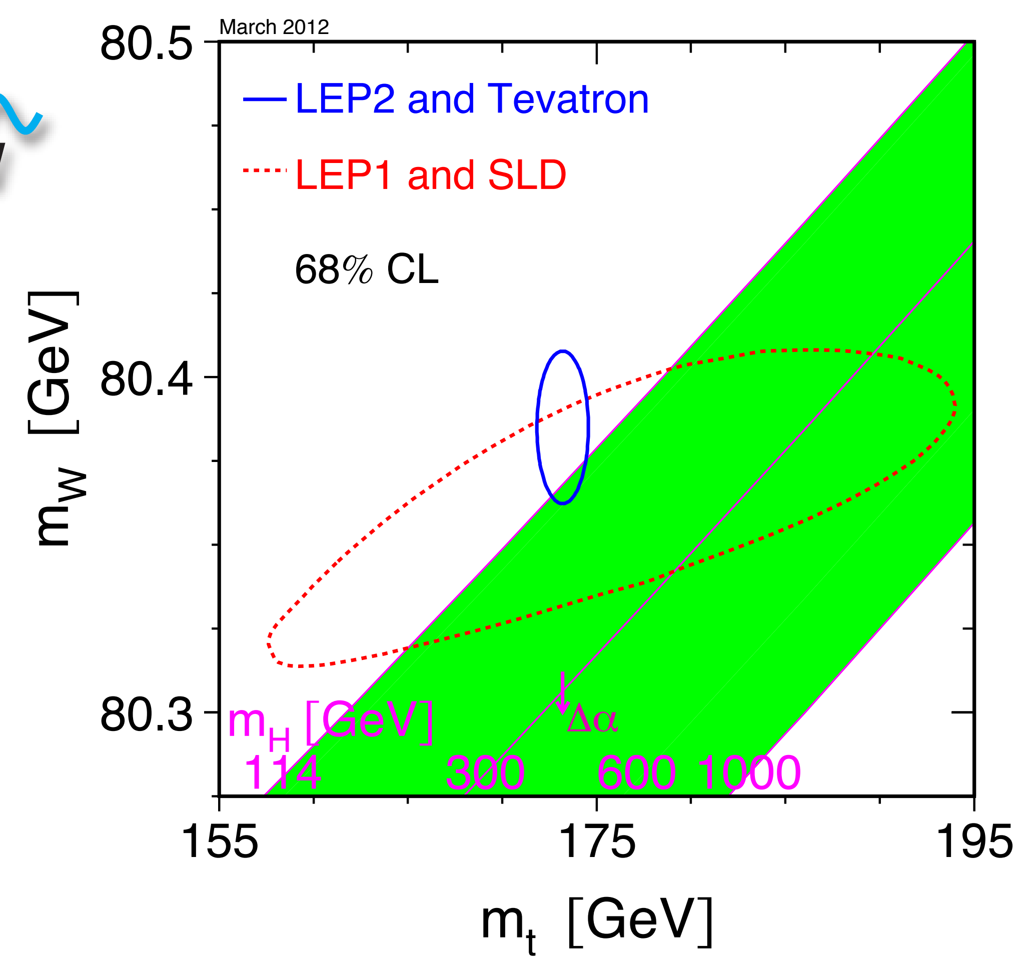
- notably: coupling to other particles proportional to these particles' masses
- targeted searches possible!





Radiative corrections to mW depend on m_H; comparison with experiment indicates a preference for a "light" Higgs boson

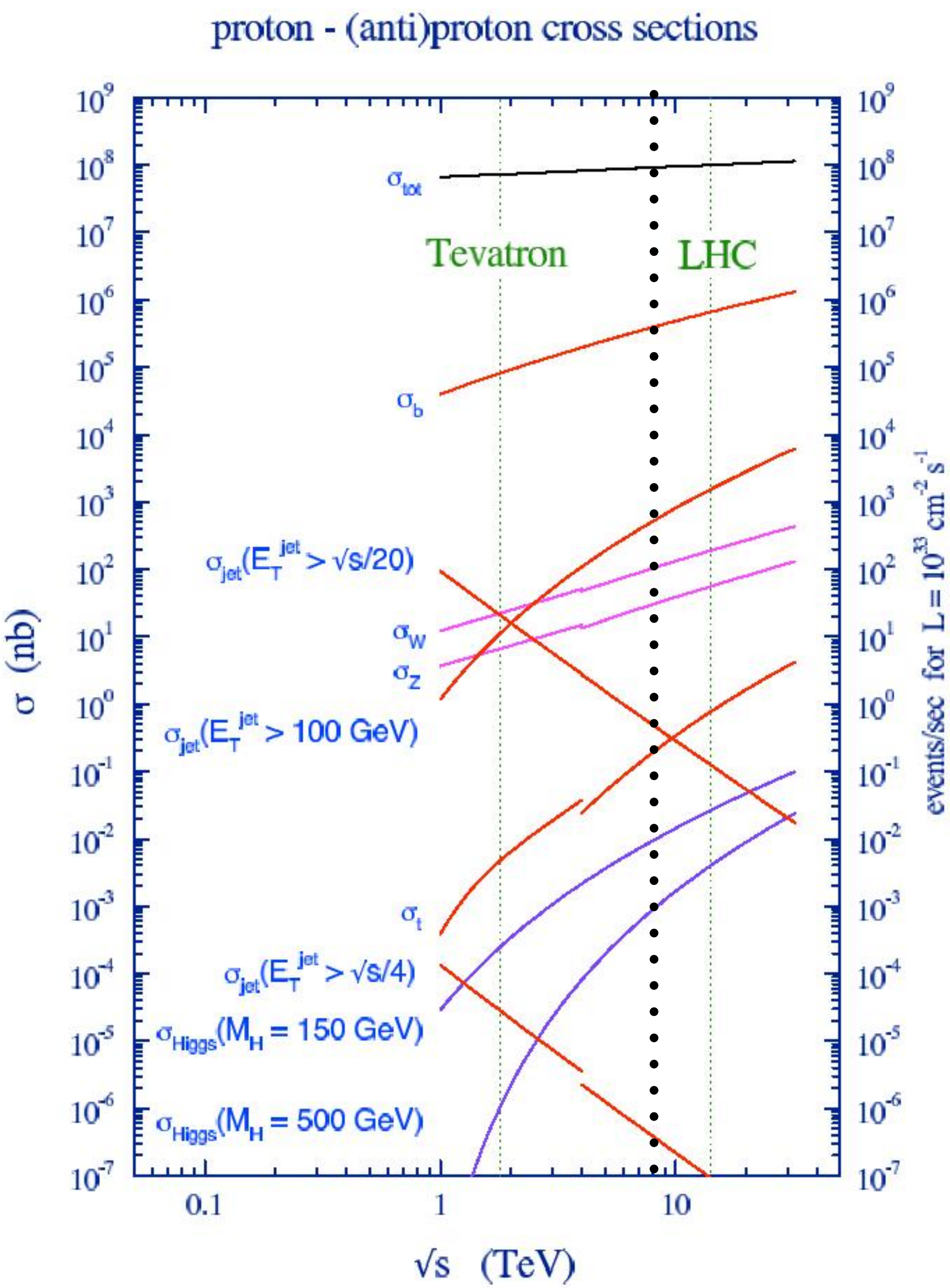




Excluded m_H < 114.4 GeV

Higgs Boson Discovery Channels

Many possible production and decay modes! Here, focus on channels relevant in the most "interesting" mass range



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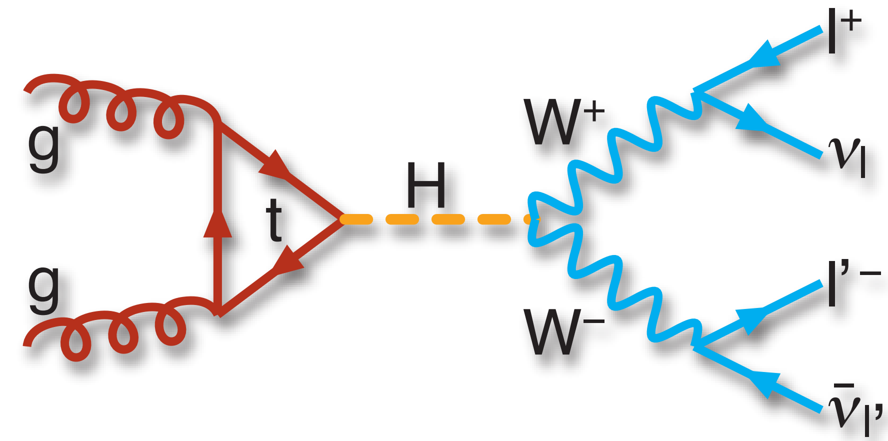
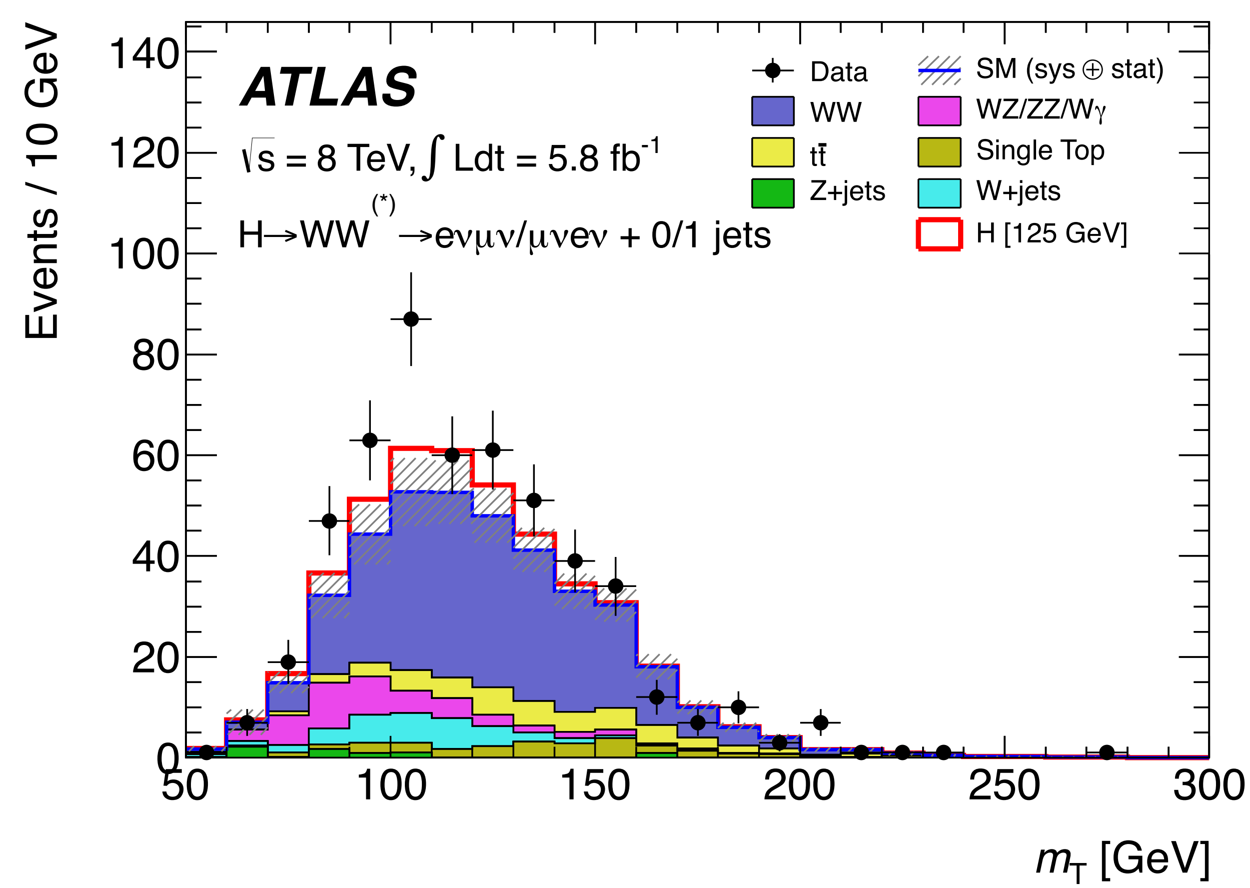


- $H \to WW^{(*)} \to l\nu l\nu$: relatively large event rate but cannot reconstruct mass of event candidates due to escaping neutrinos
  - rely on shapes of kinematic variables
  - also substantial backgrounds



- $H \to ZZ^{(*)} \to l^+l^- l'^+l'^-$: precise mass reconstruction, very rare but very pure

- $H \to \gamma\gamma$: precise mass reconstruction, modest rate but large background

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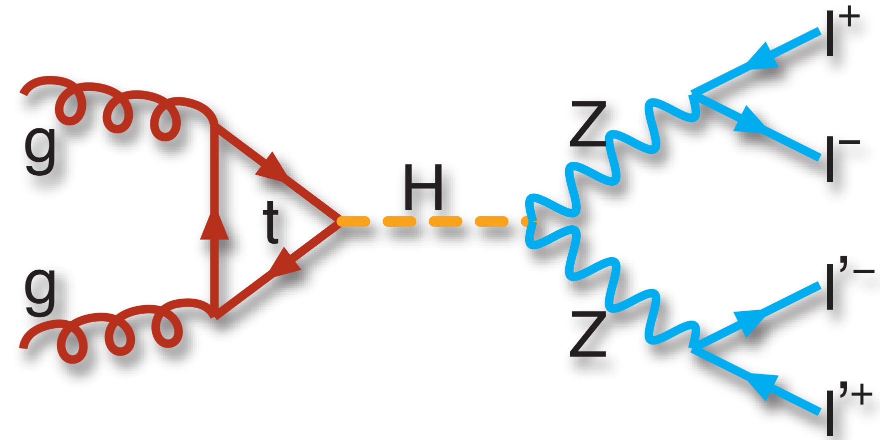

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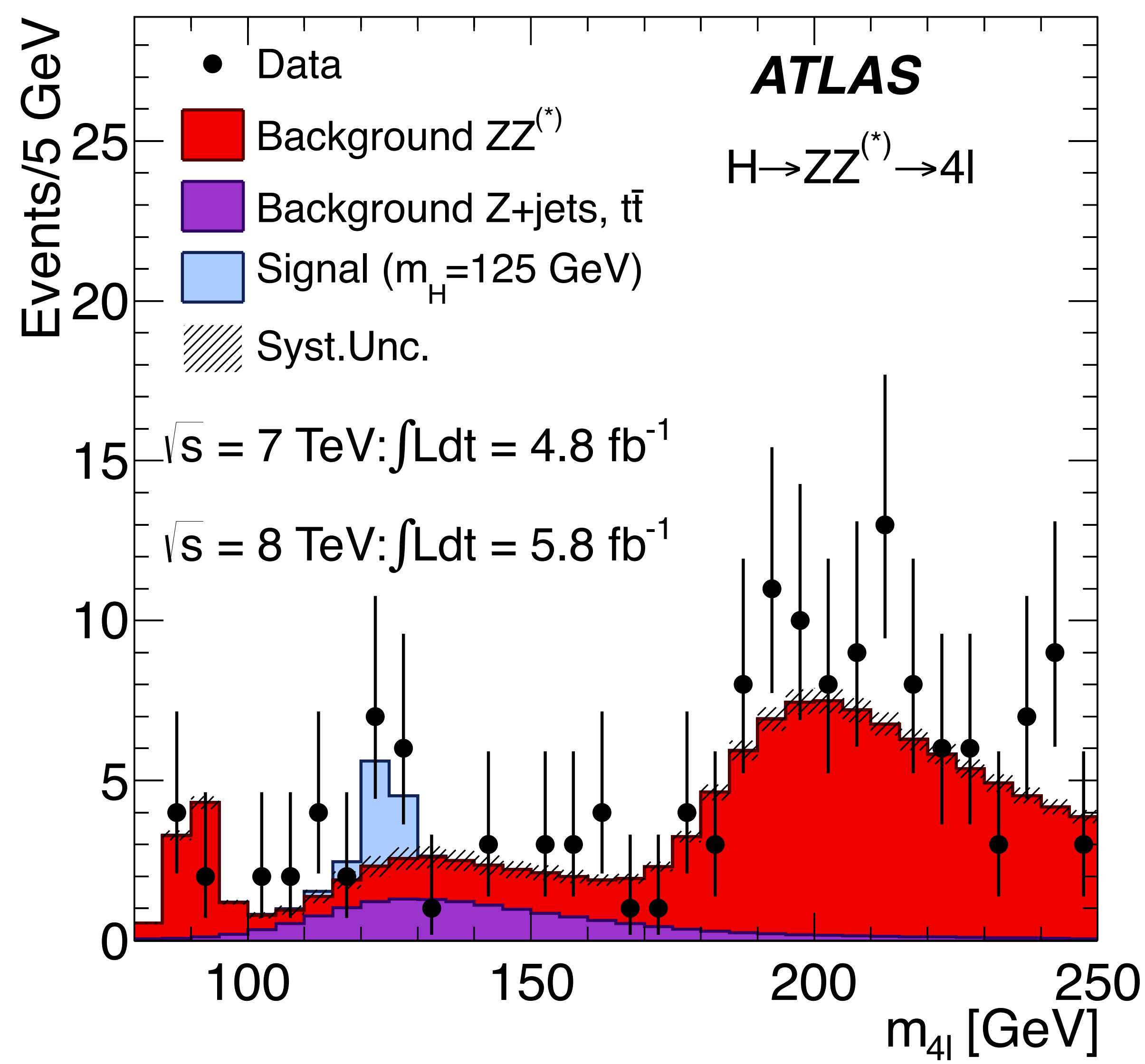

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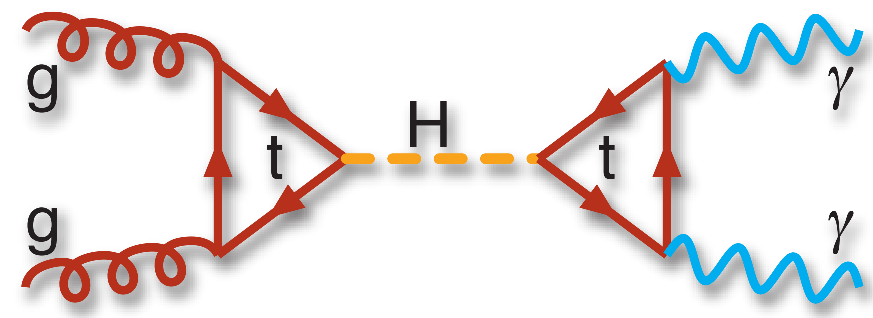

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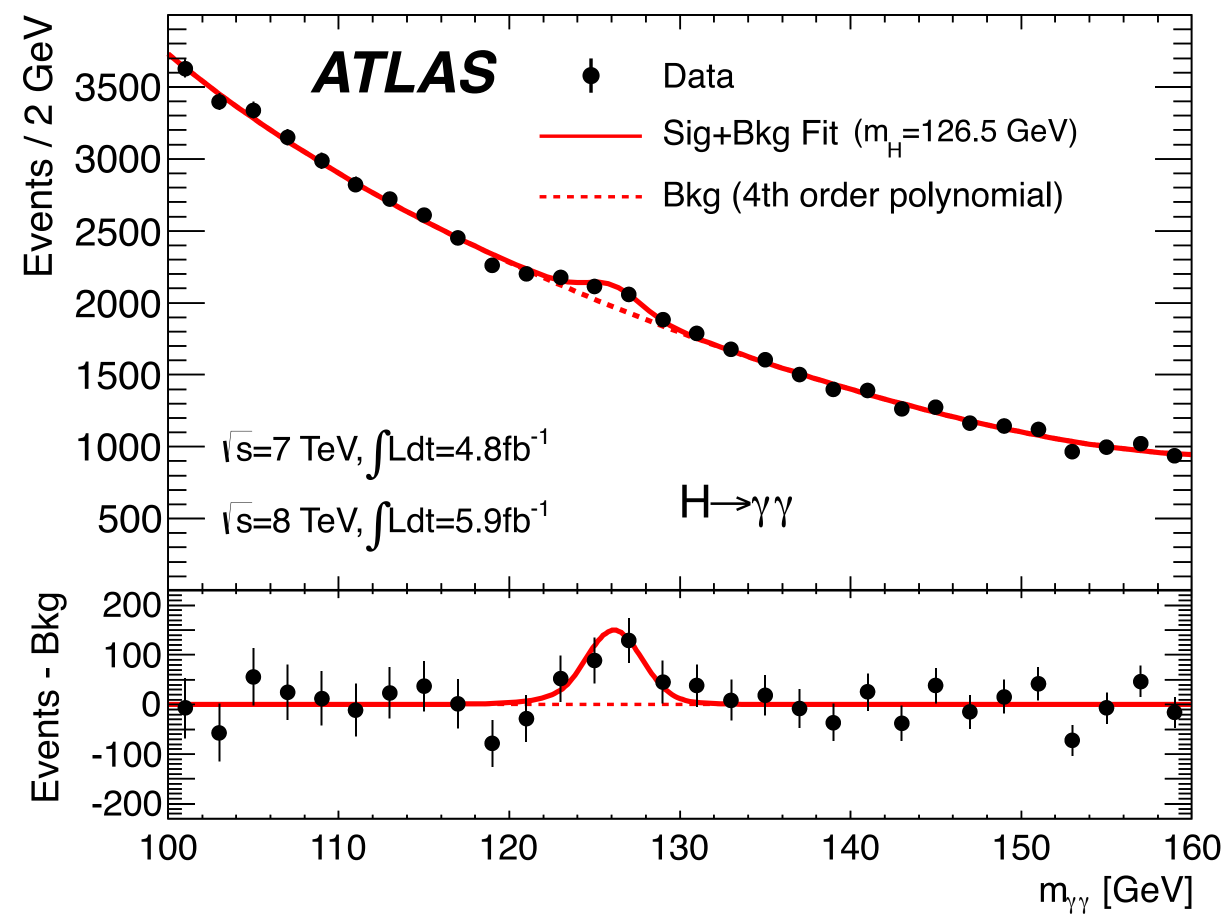
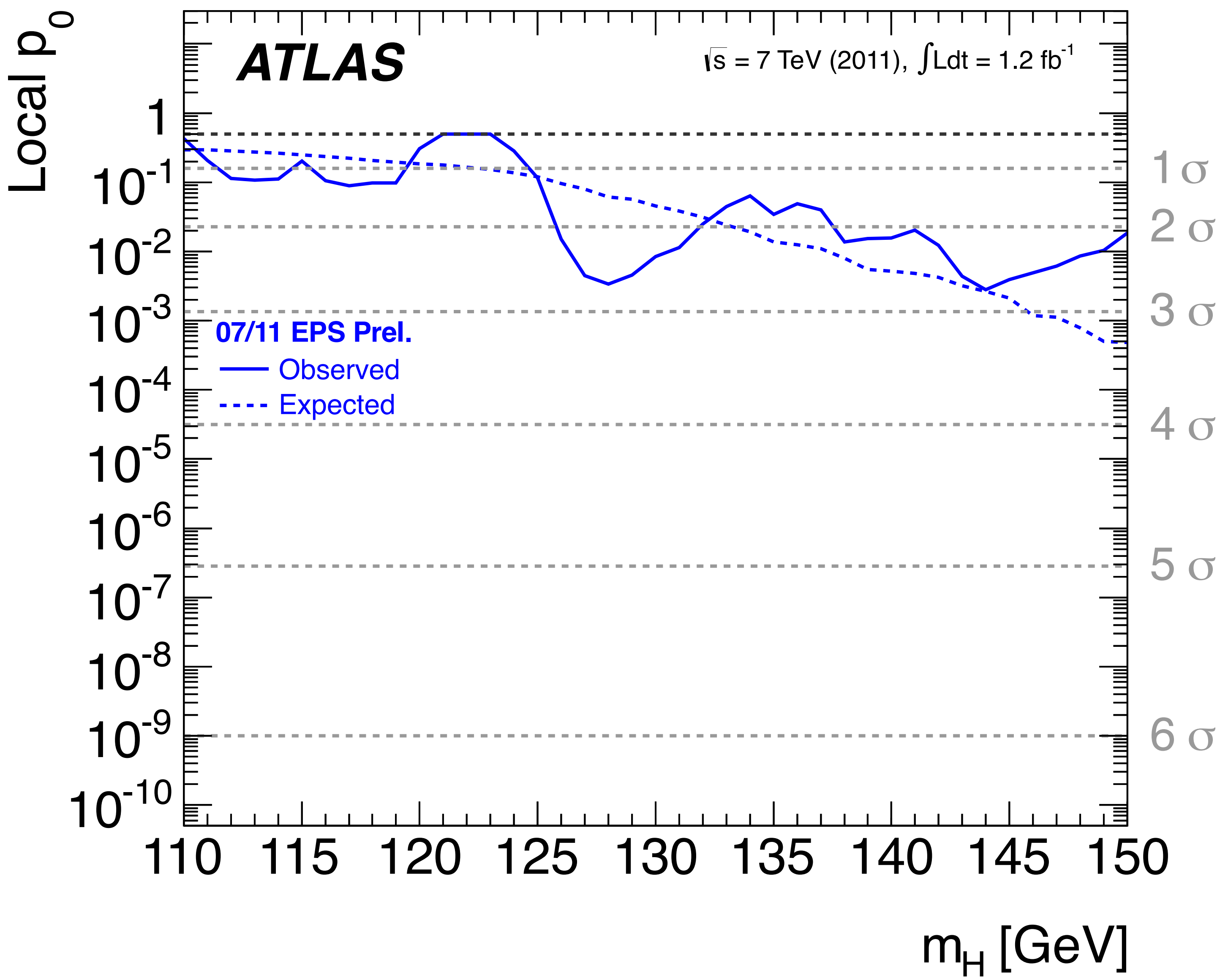


Chronology of a Discovery



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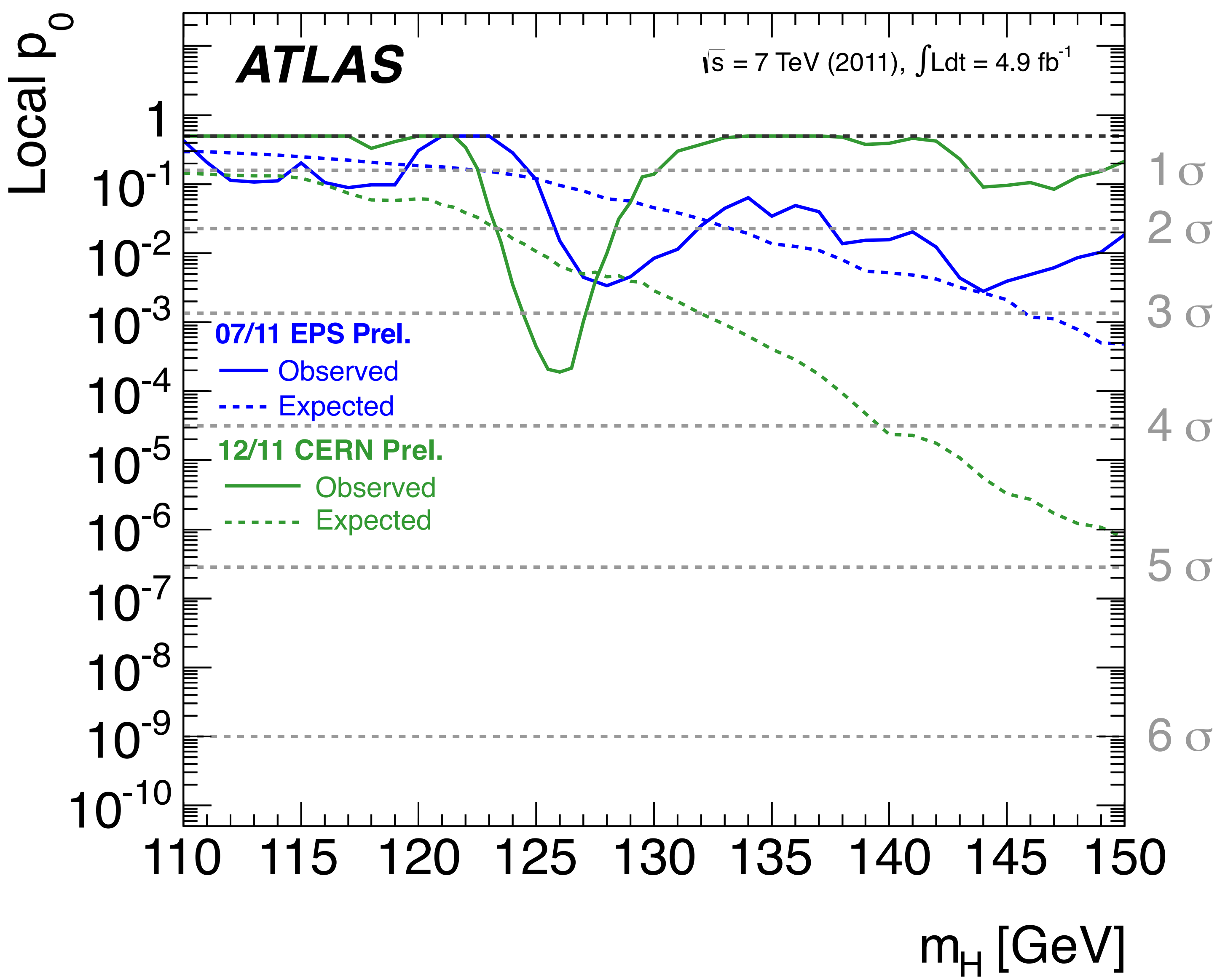

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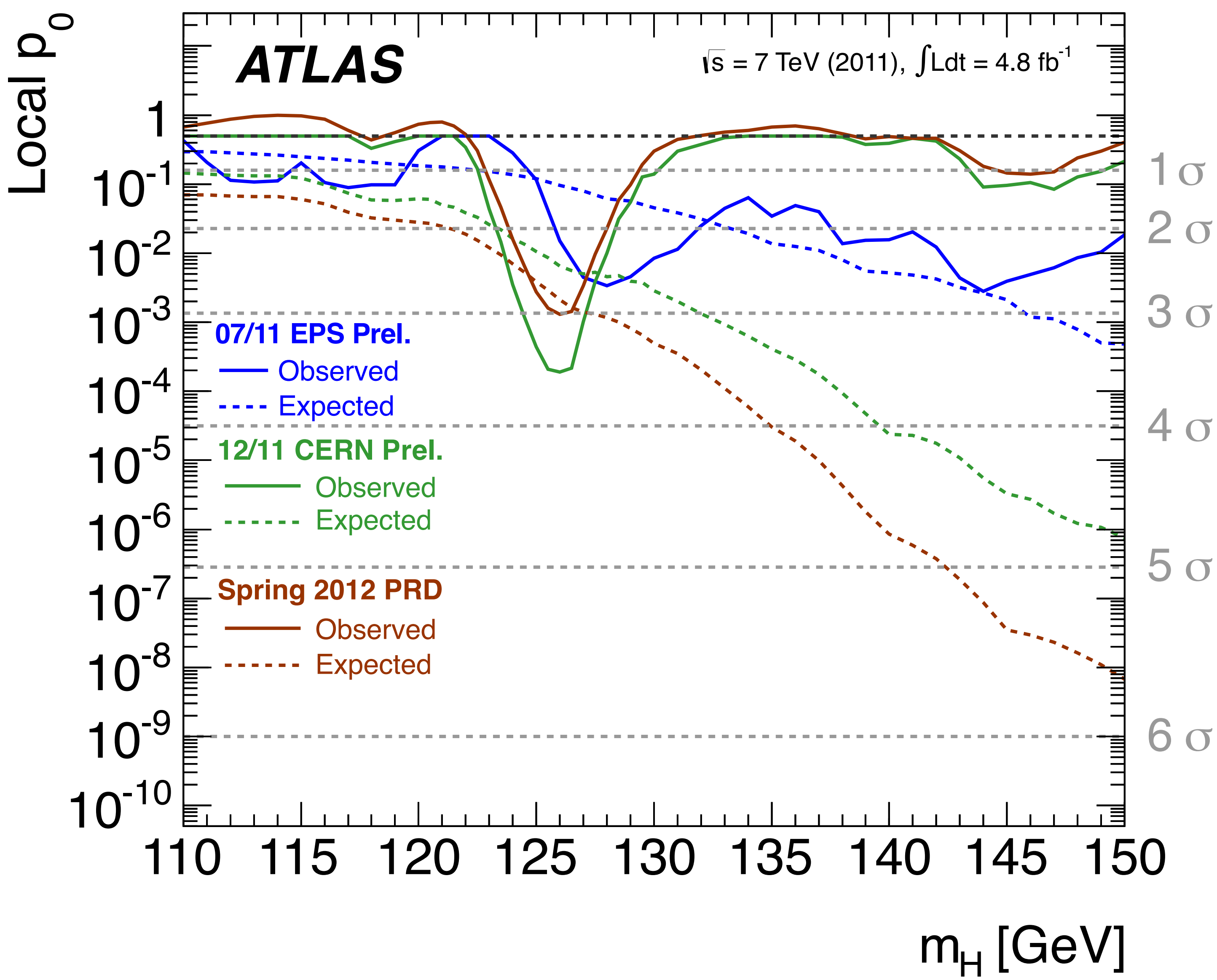
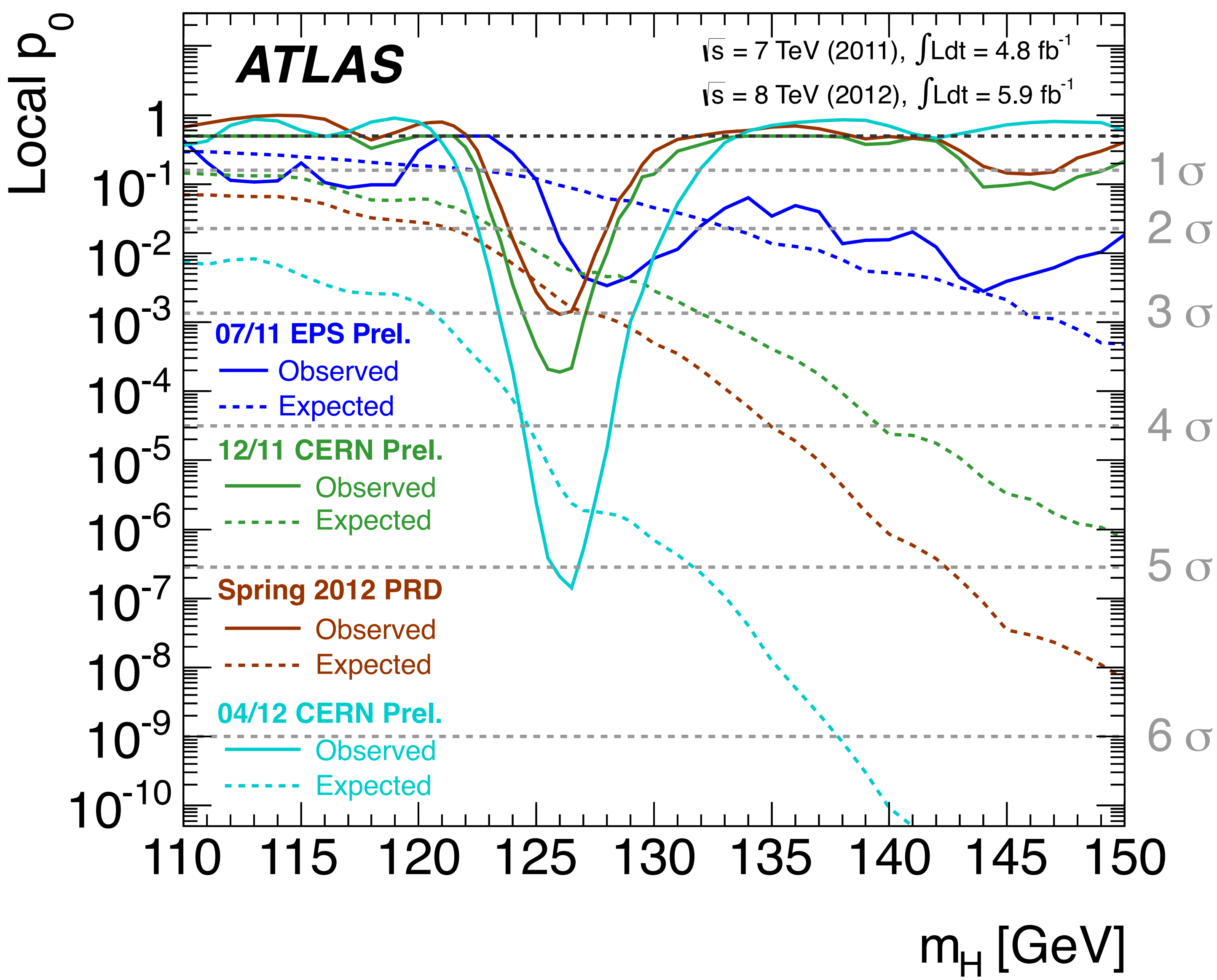


Chronology of a Discovery



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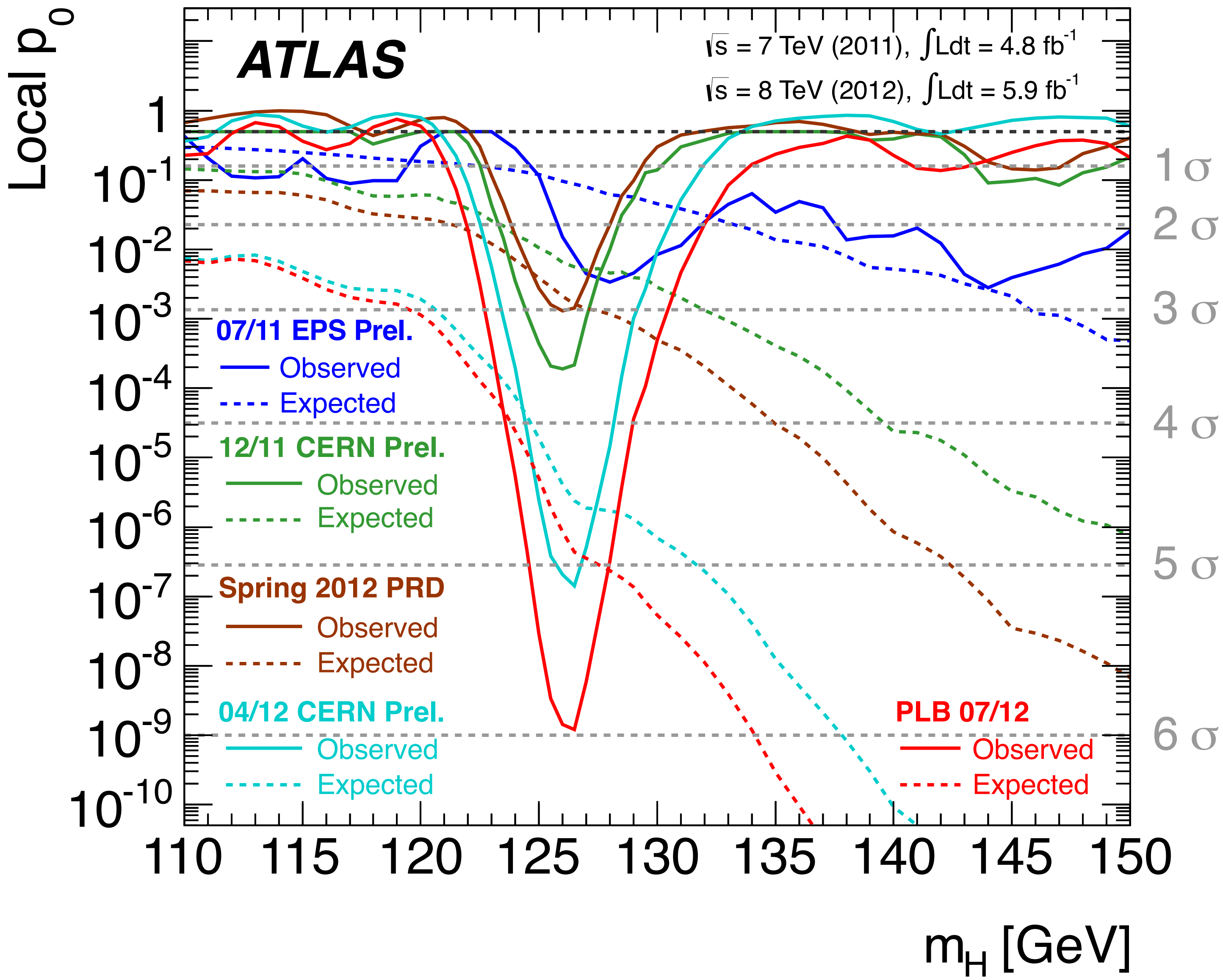
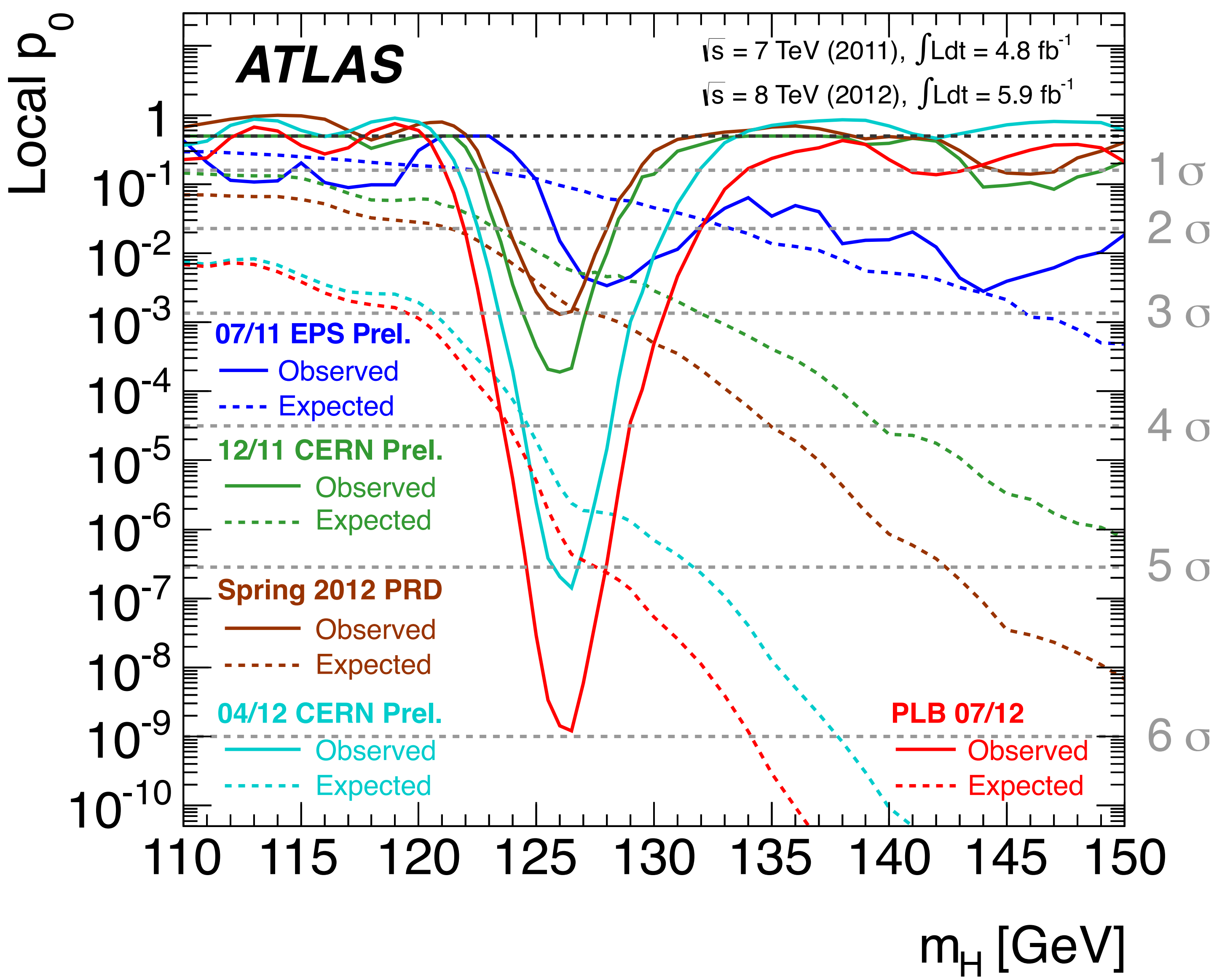
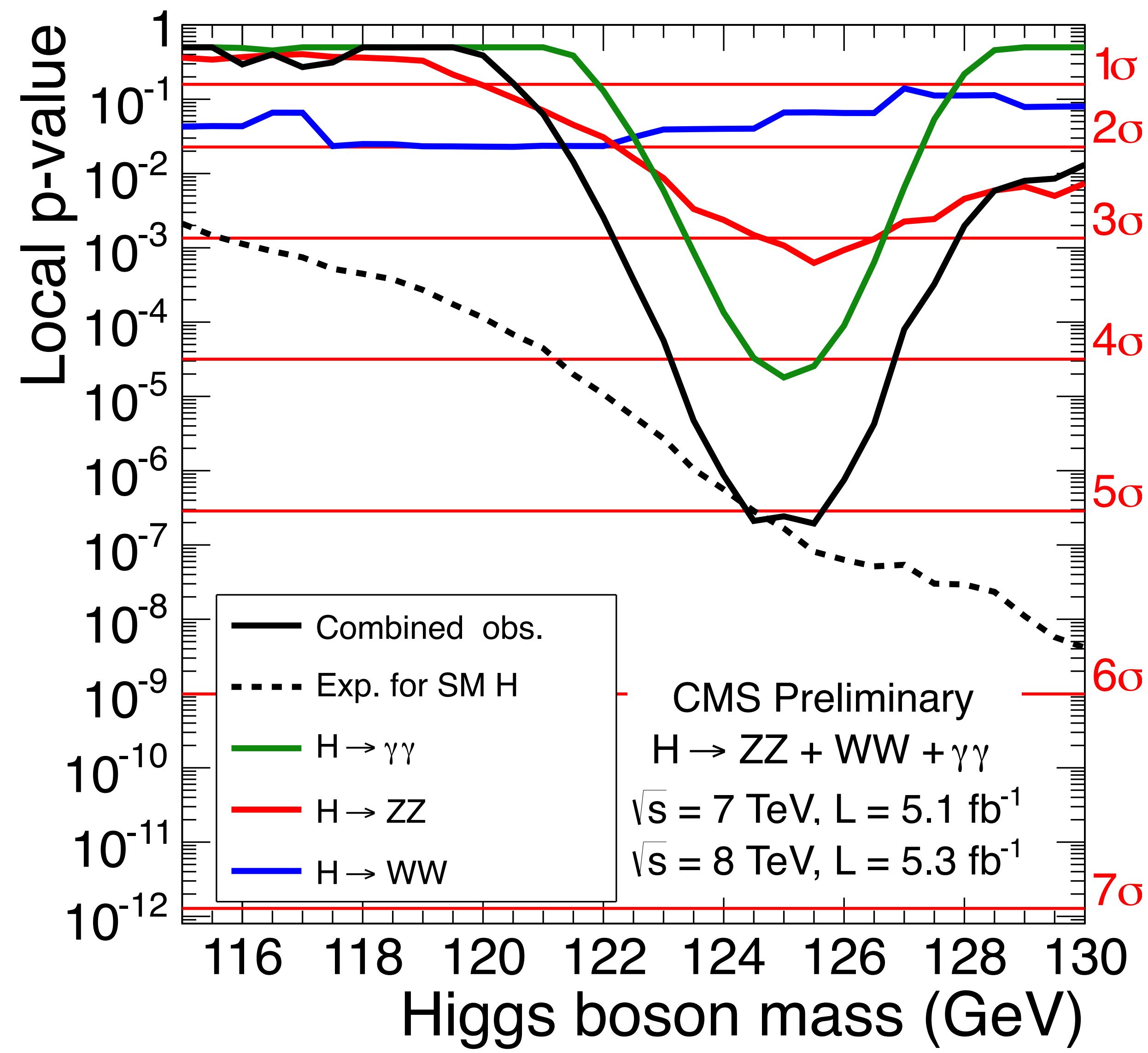


Chronology of a Discovery





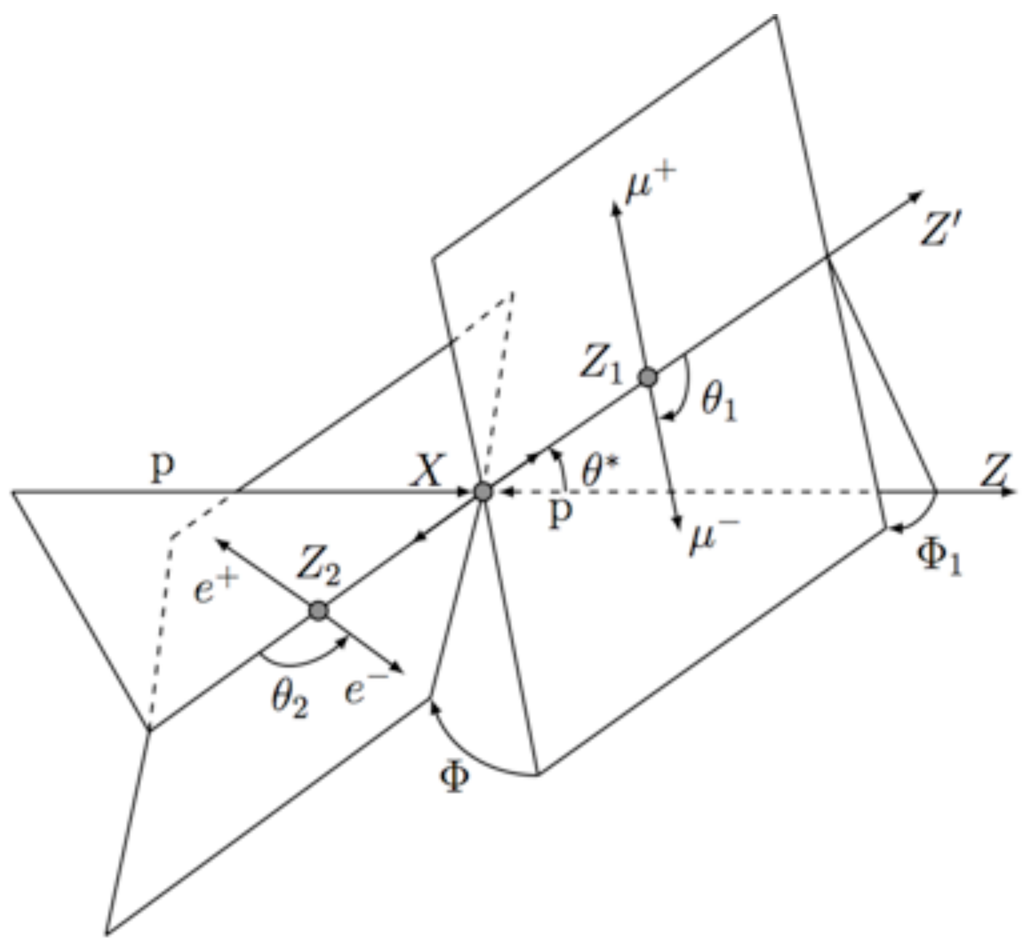
What did we Discover? I. Spin & Parity

Discovered a new particle with $m_H \approx 126$ GeV

- boson: decay to ZZ, WW, γγ
- spin ≠ 1: Landau-Yang theorem would forbid decay to γγ
  - even if there could be a conspiracy: > 1 new particle

Since the discovery, further studies (with more H →ZZ data) have established that indeed the data are most compatible with J=0 and positive intrinsic parity

- representativ > 84% CL



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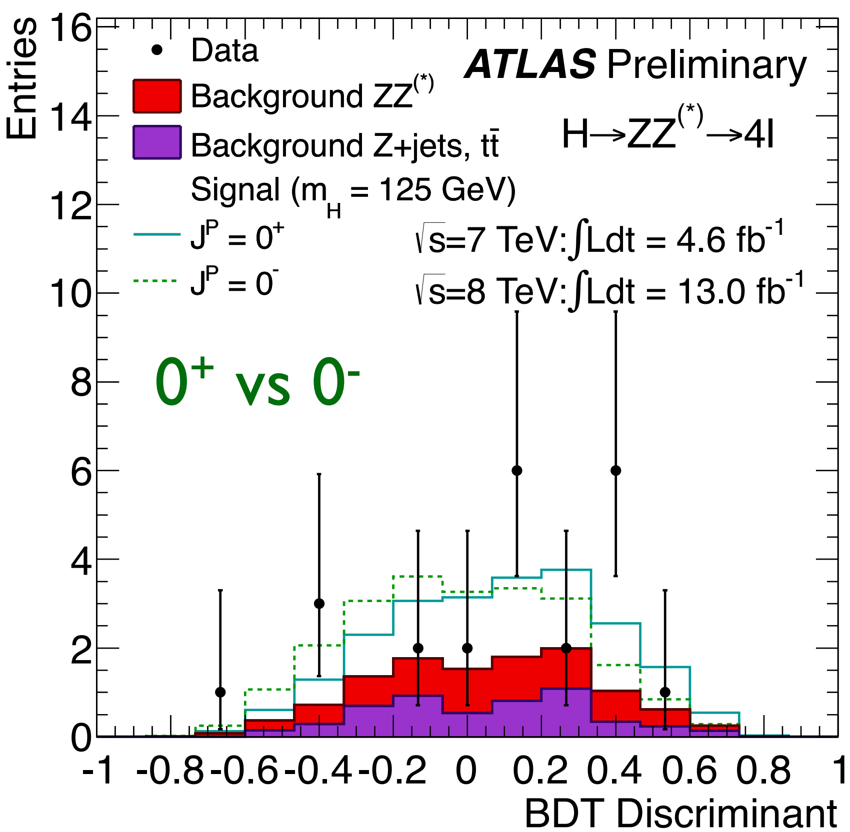

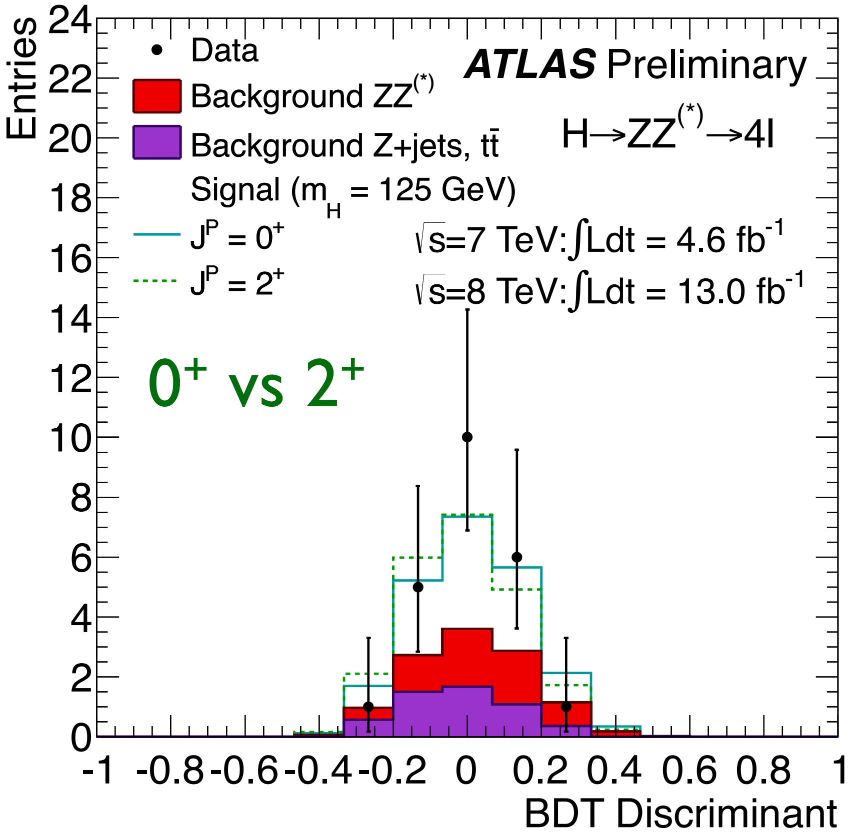

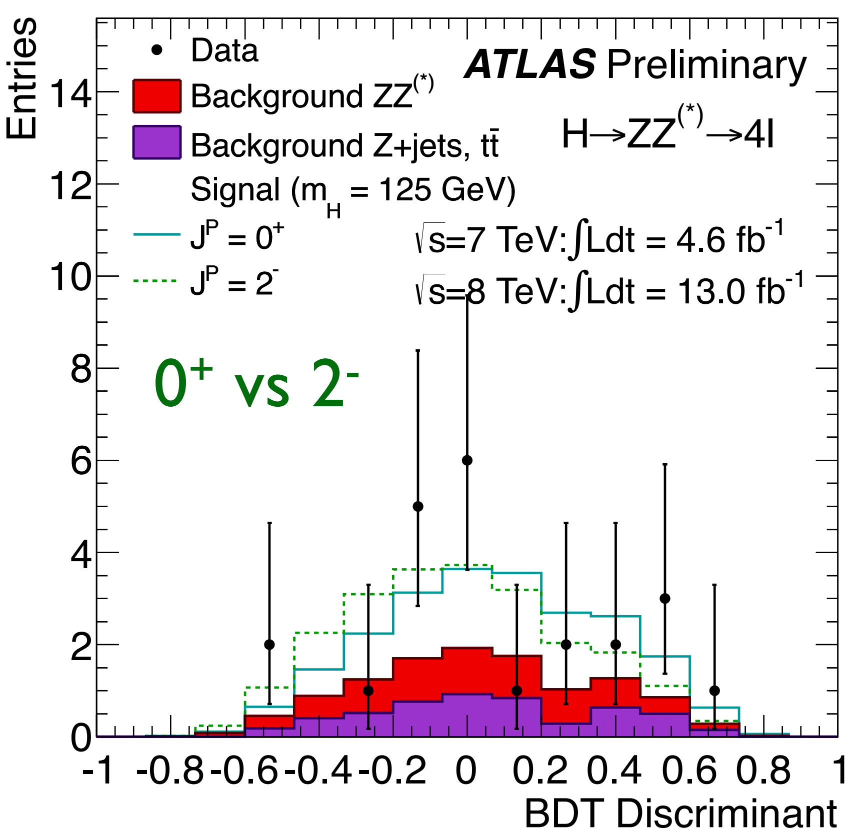

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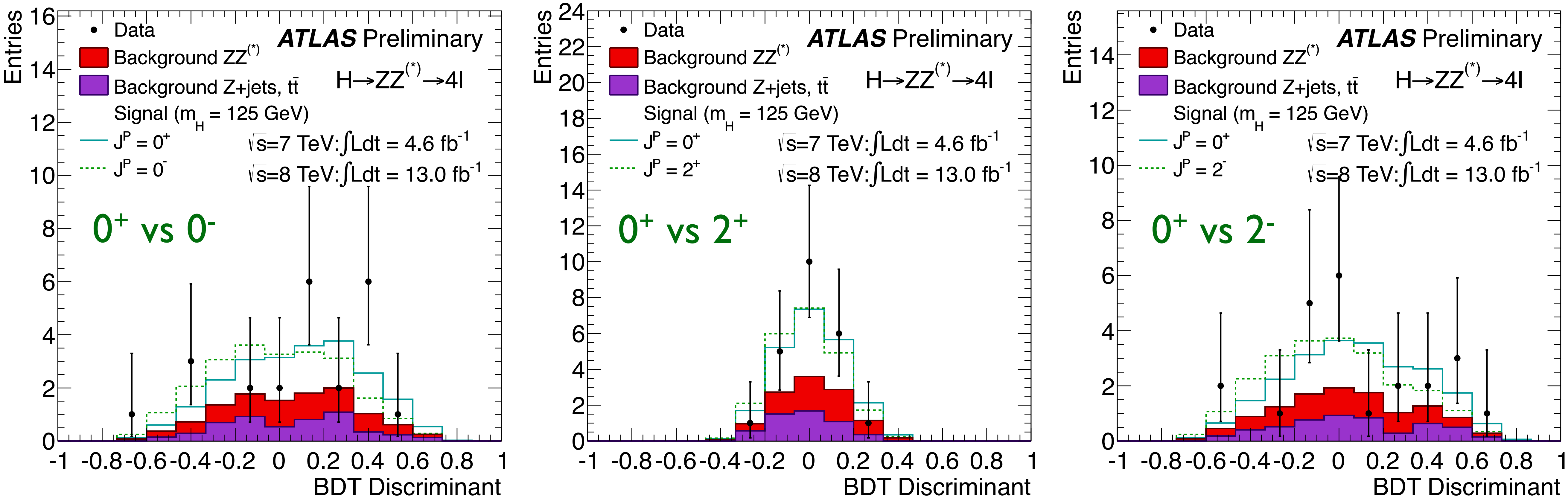

Digression: Supersymmetry

The Standard Model, despite its spectacular successes, is believed by many to be incomplete!

- it does not describe gravity
- m_H is not "stable" against radiative corrections ➠ low m_H requires fine-tuning
- it does not provide a candidate particle to explain dark matter

Bullet cluster: two colliding galaxies
Luminous matter interacts and stays behind
while dark matter continues largely undisturbed

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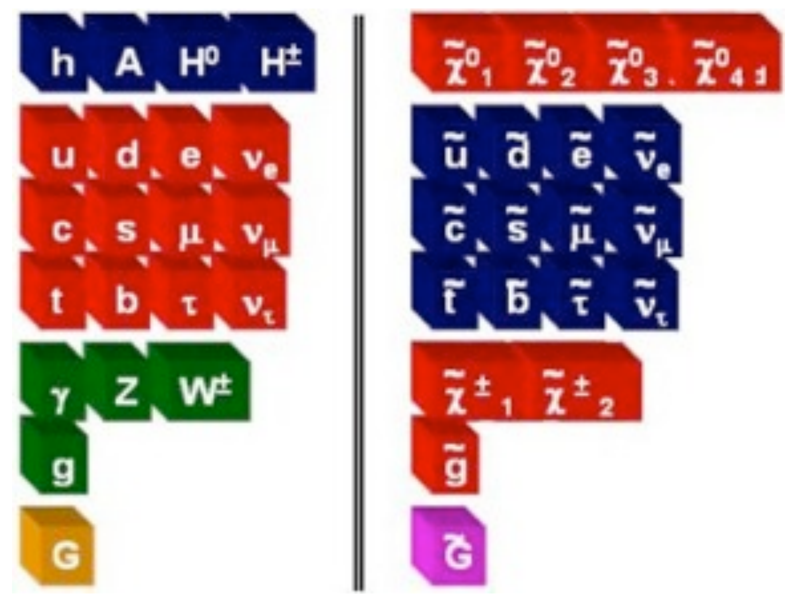


Supersymmetry (SUSY) does (potentially) have these features!

- internal symmetry doubling particle content, relating fermions to bosons
- must again be a (spontaneously) broken symmetry, otherwise $m_{fermion} = m_{boson}$
  - foremost extension of the Standard Model, searched for for decades

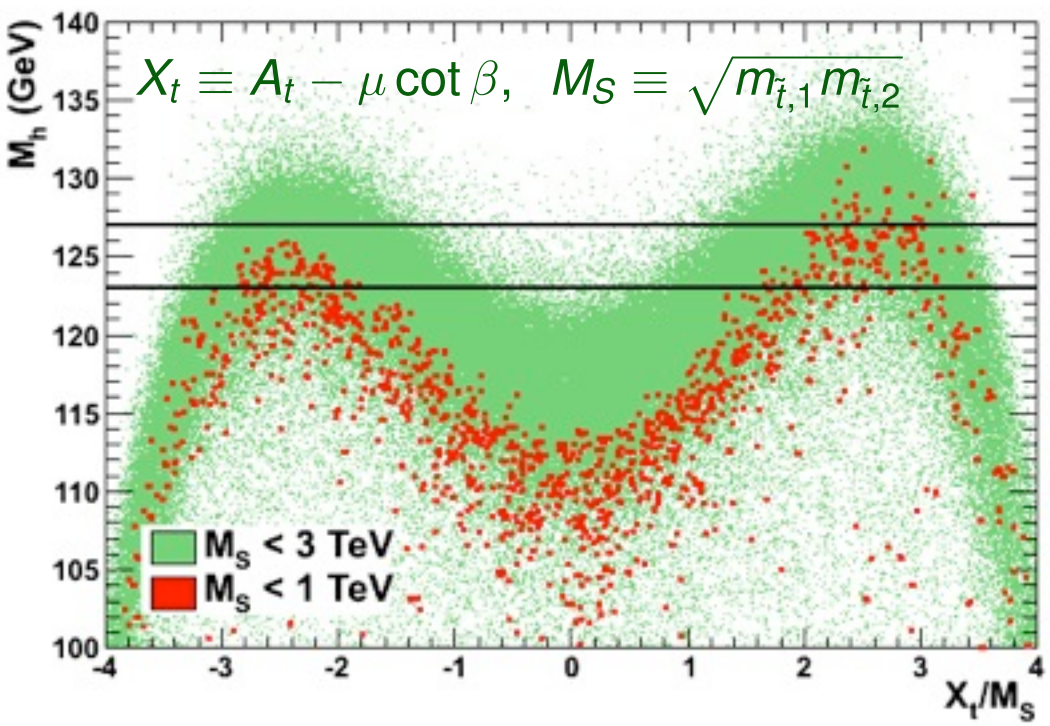
What did we Discover? 2. Mass

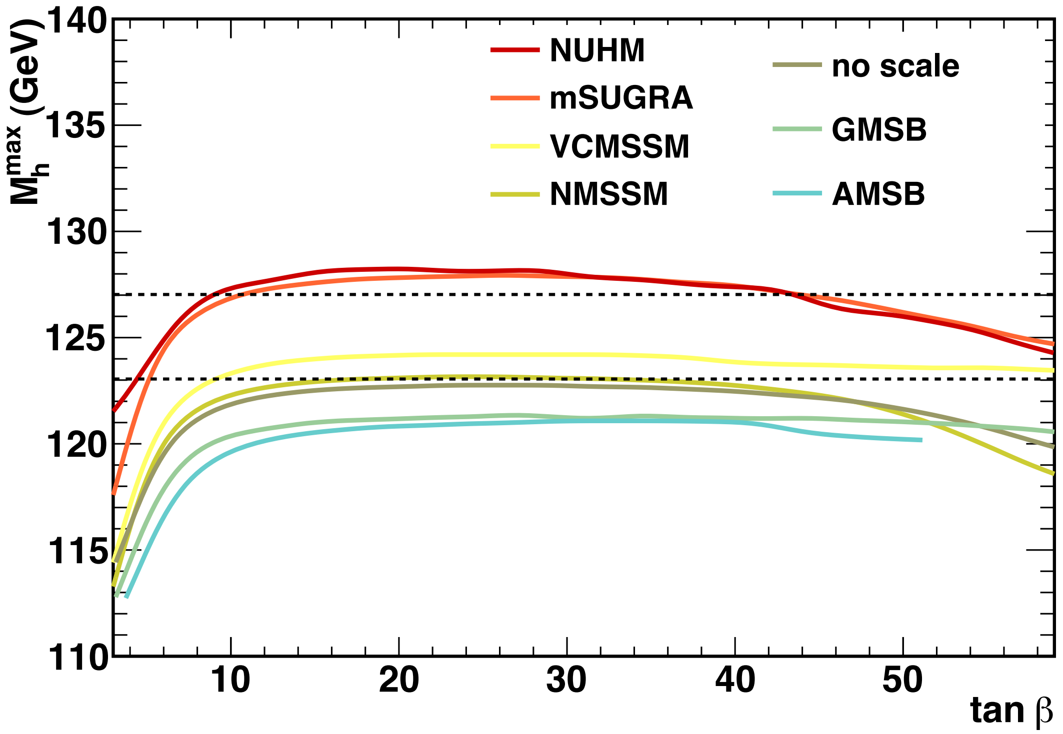
In the MSSM (generic "low-energy" parametrisation),

$m_h \approx m_Z |\cos 2\beta|$ + radiative corrections

- significant dependence on SUSY breaking scenario

Arbey et al. ('12)





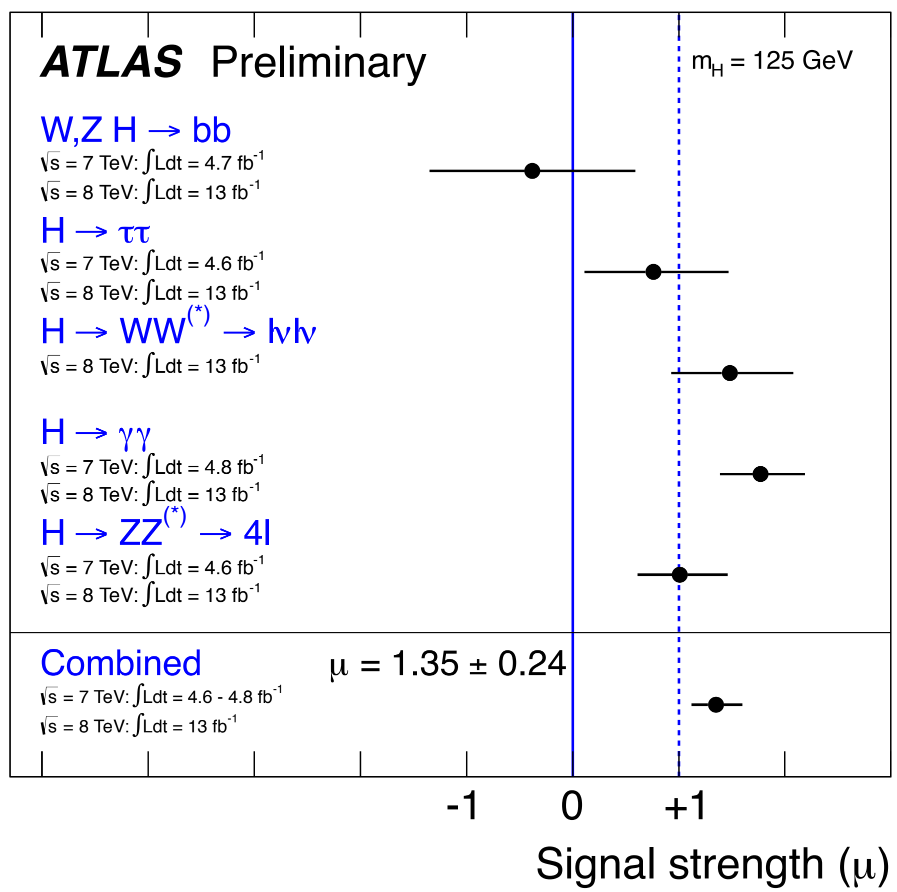
- rule out multiple SUSY breaking mechanisms, more exotic scenarios being considered
  - e.g. split SUSY: heavy scalars, m(fermions) ~ M_Z; heavy SUSY

The mass relations change when going beyond the MSSM...

What did we Discover? 3. Couplings

In various extensions of the Standard Model, the coupling of the Higgs boson to other particles is modified

- use full suite of measurements to test these couplings!
- “signal strength” measurements sensitive to couplings in both production and decay
  - now looking also at specific production modes, not just decay modes



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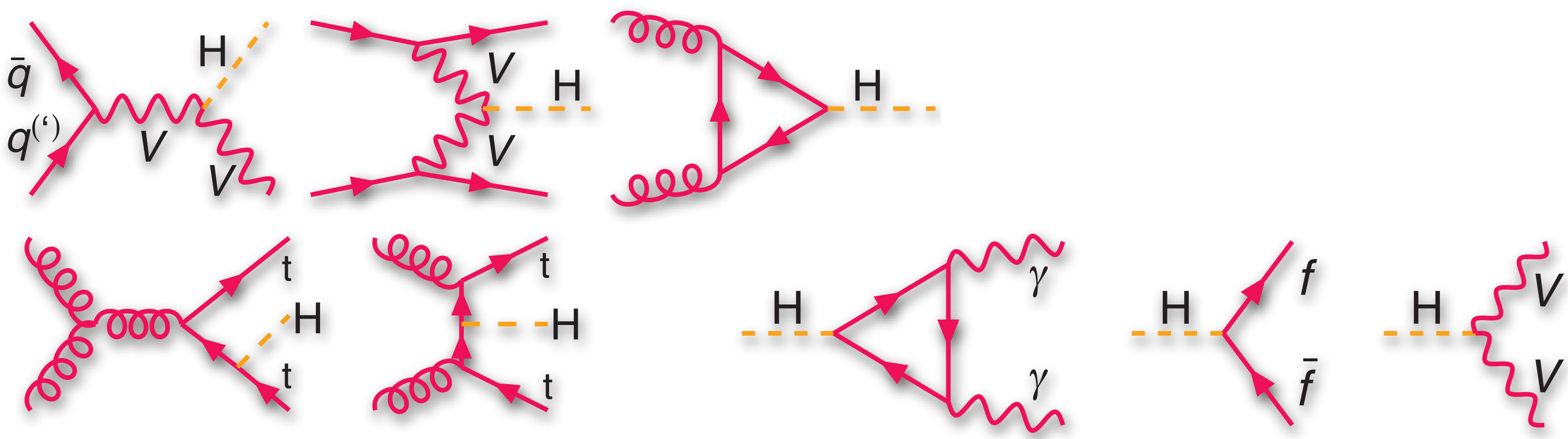

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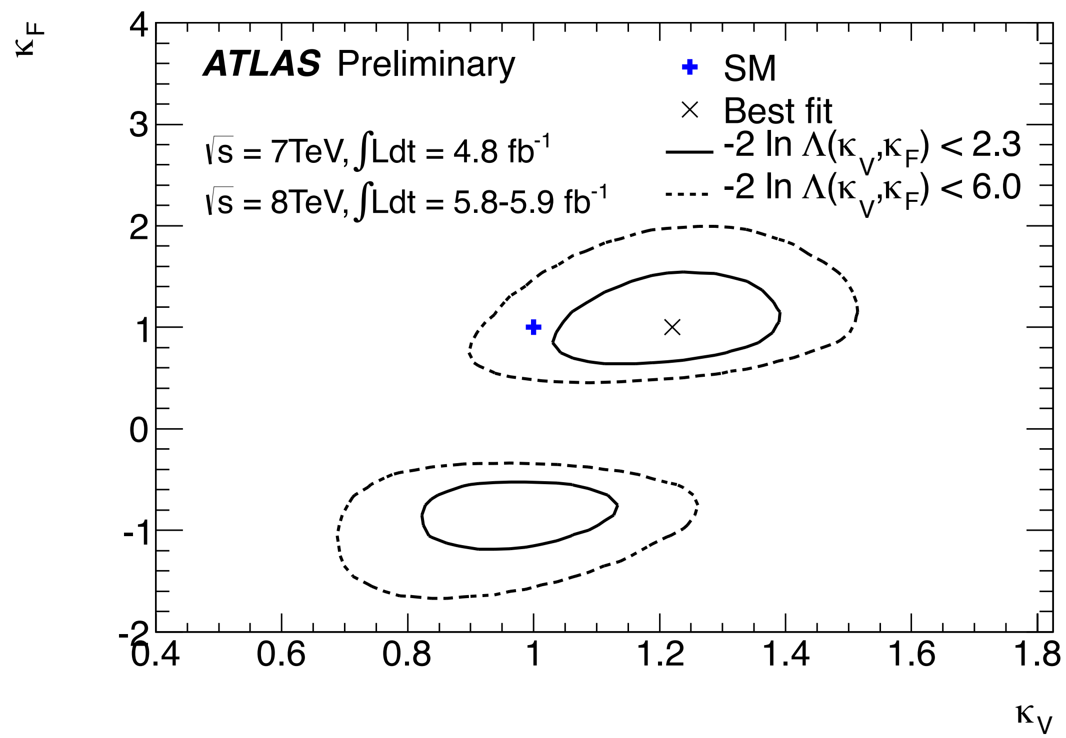

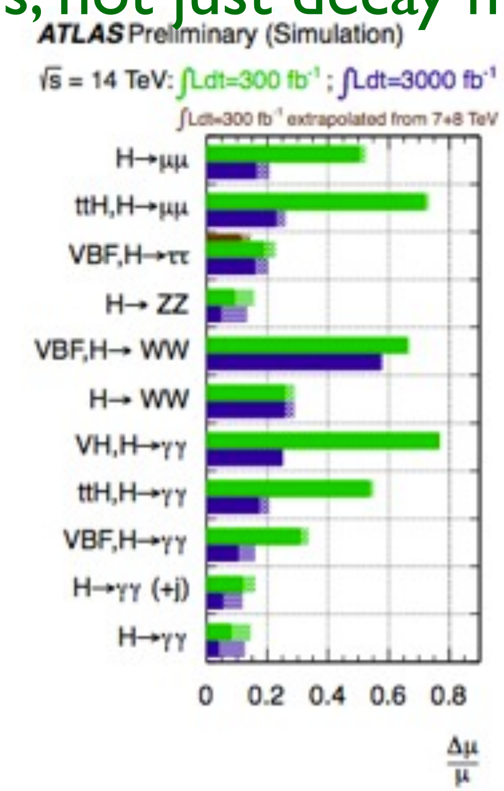

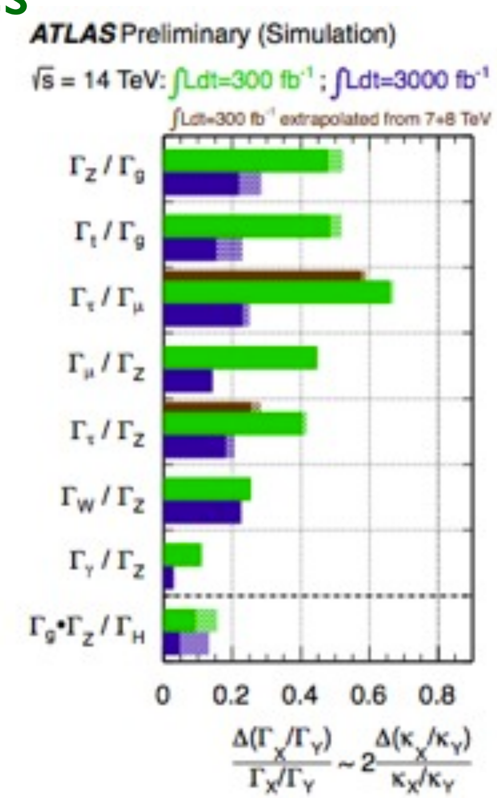

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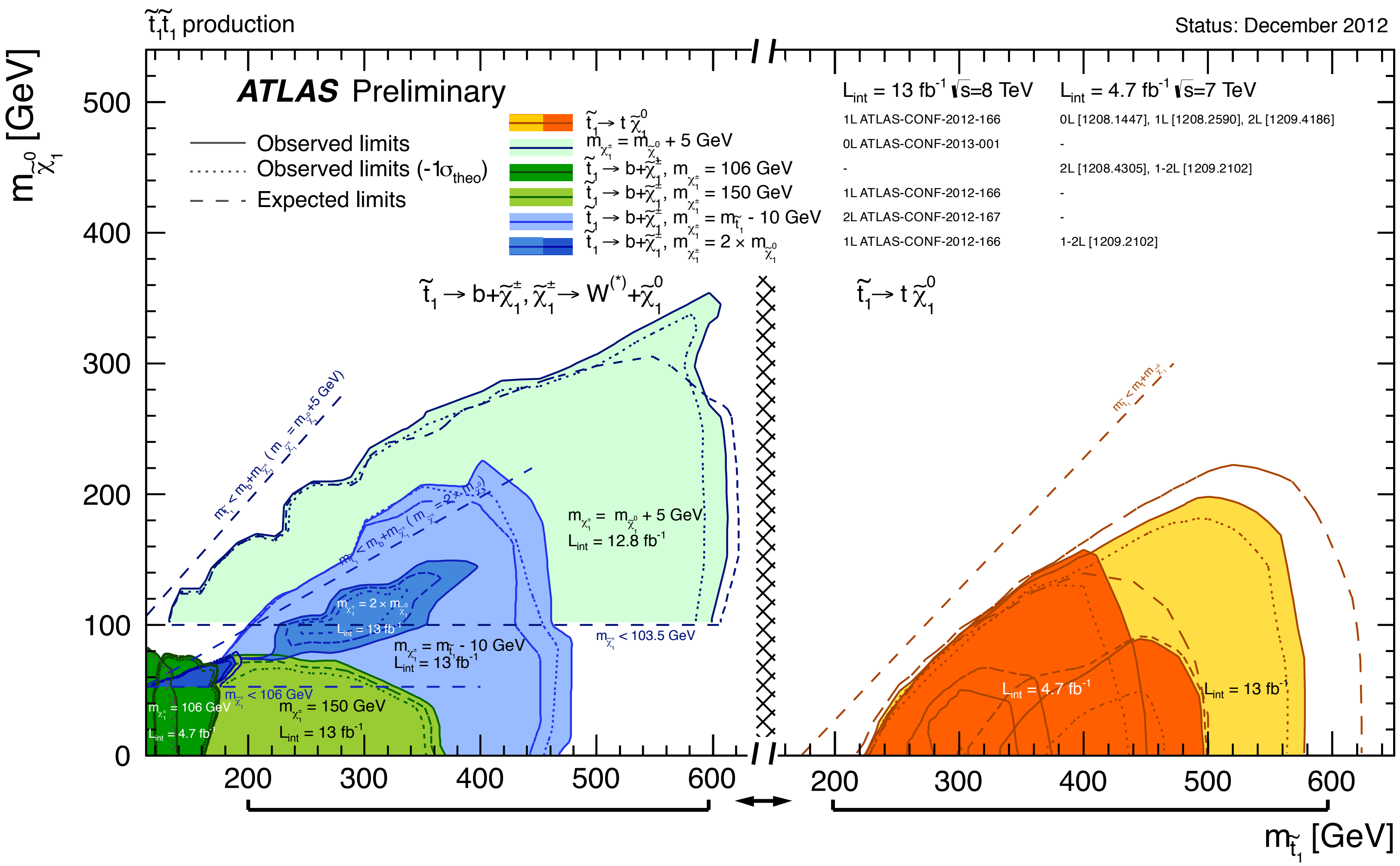
Meanwhile...

Supersymmetry has not been found yet in direct searches



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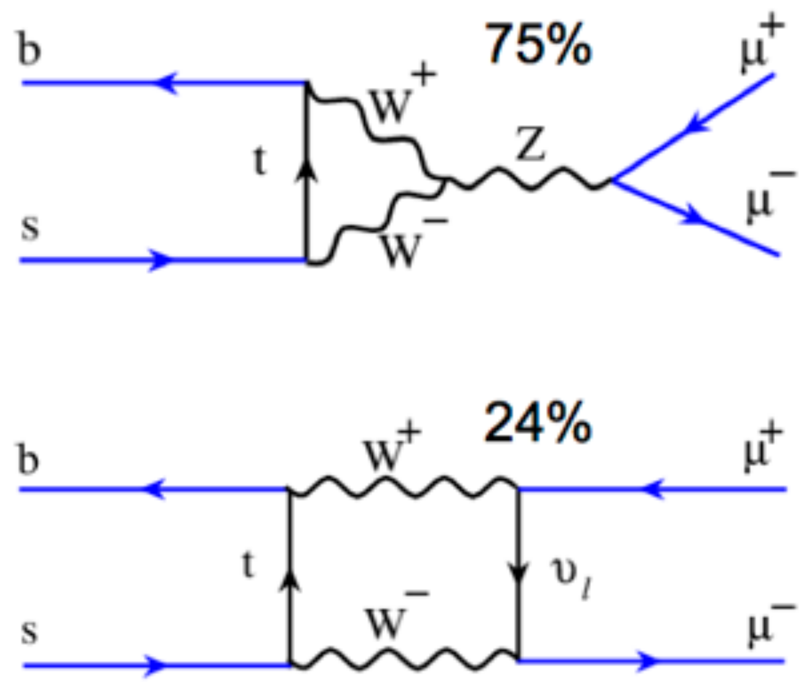
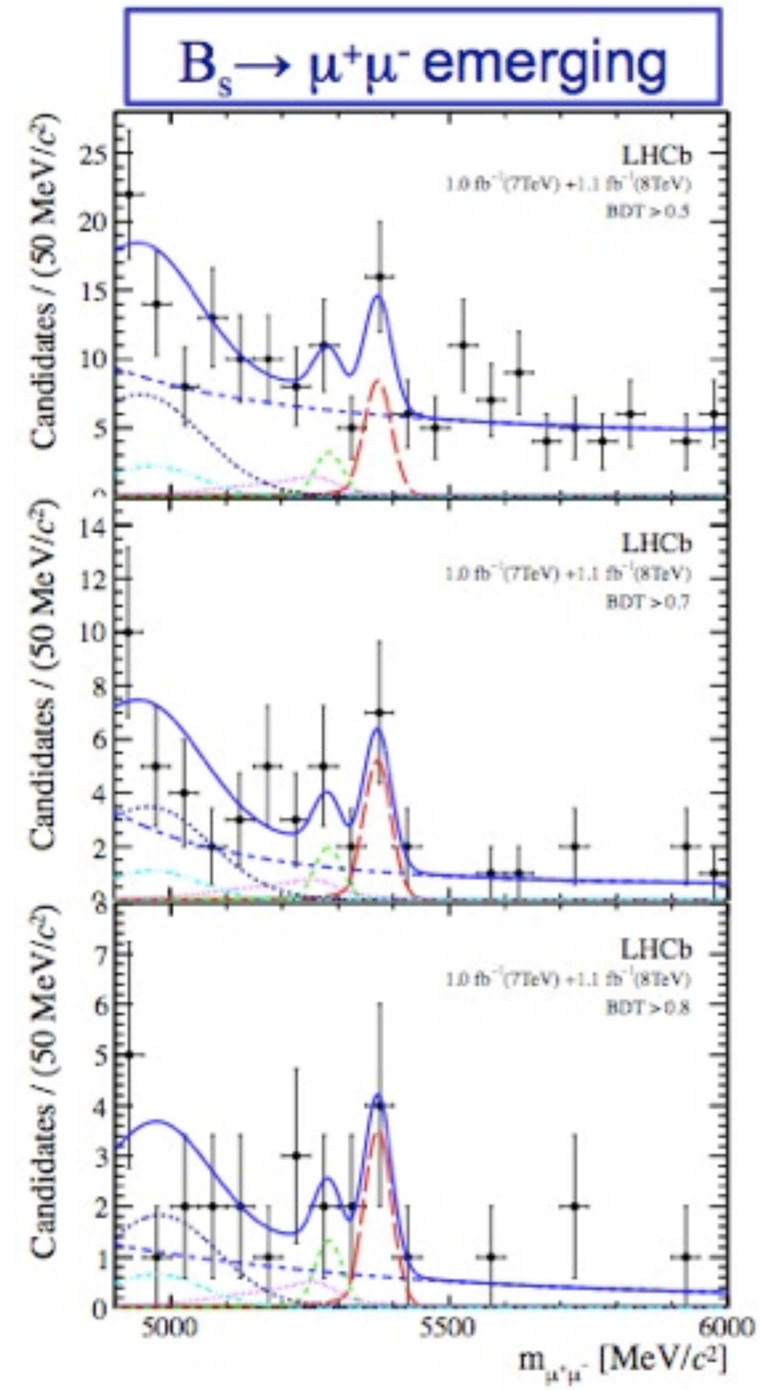
Nor is there any evidence for its contributions in other sensitive processes

- notably B_s decays (LHCb discovery): branching fraction ~ $3 \cdot 10^{-9}$, very sensitive to non-SM contributions





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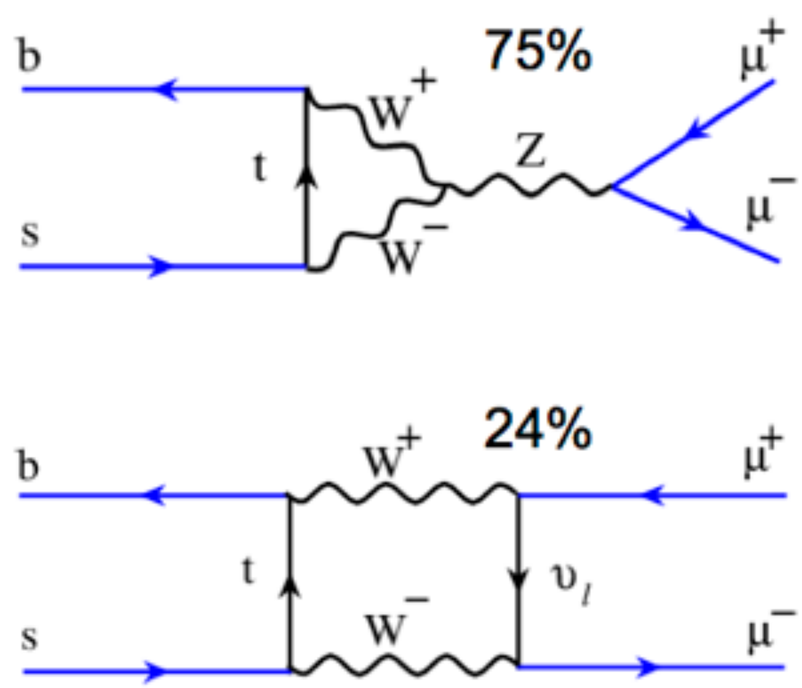

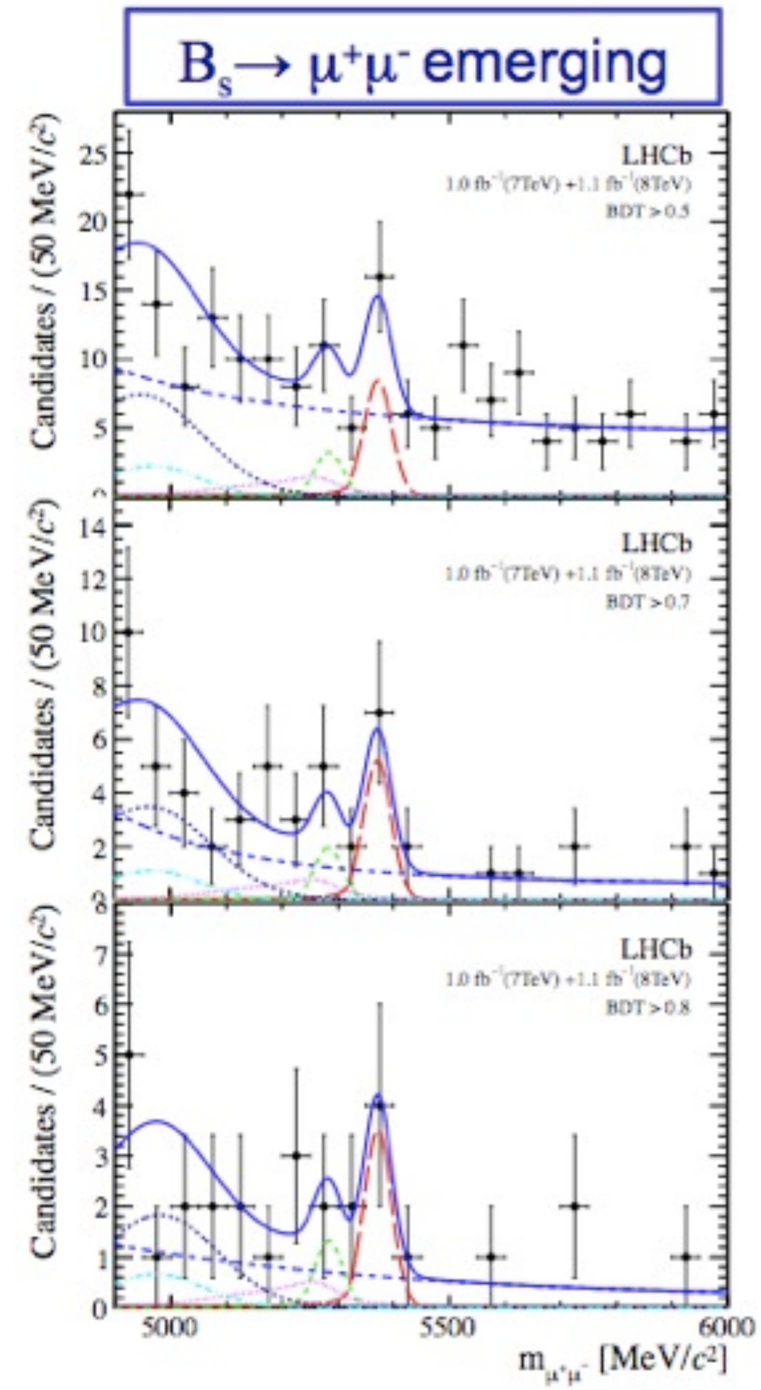

Many "generic" supersymmetric models excluded

- focus is now on heavier particles and/or specific couplings

Conclusions

The Large Hadron Collider, in its first 3 years, has delivered roughly the integrated luminosity projected (long) in advance

- albeit with quite a different time profile than expected!

The data from this first run have led to new qualitatively new insights in particle physics as it dominated the (very) early stages of the universe

With the further energy and luminosity increases to come, we expect yet a deeper understanding

- and hope for surprises!