Physics with ATLAS at the High-Luminosity LHC

New Directions in Accelerator-Based Experiments

Maximilian Swiatlowski

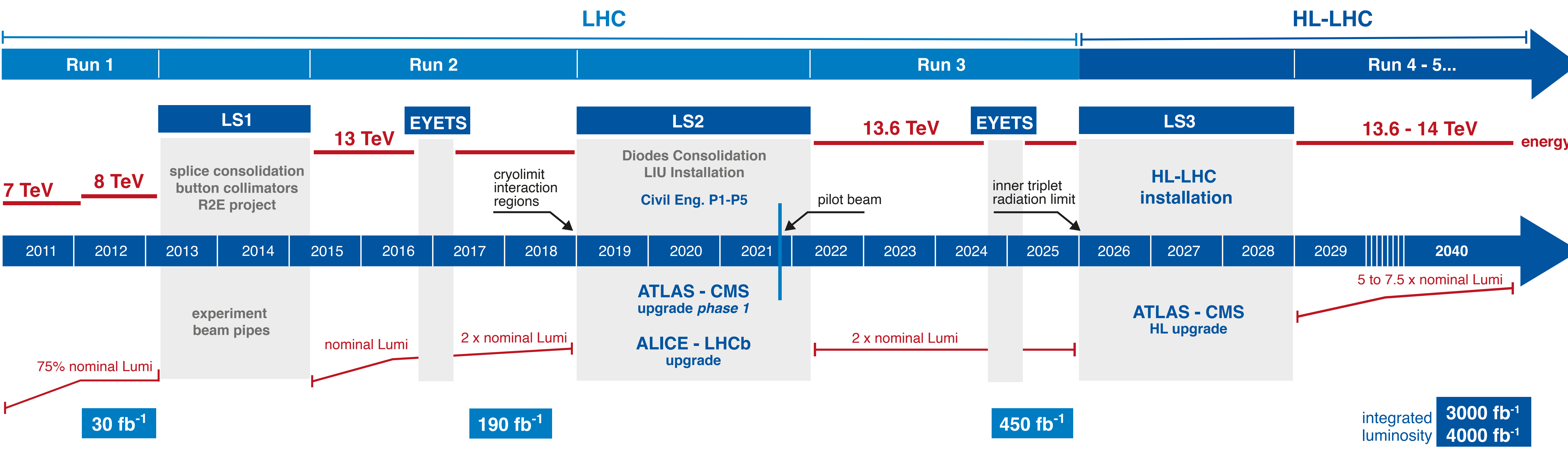
TRIUMF

The LHC Today

- The Large Hadron Collider is a 27 km long accelerator on the French/Swiss border
- Collides protons at 13 TeV: upgrade to 13.6 TeV this year for Run3
- Two large general purpose experiments, but I will focus on ATLAS

The HL-LHC, ~Tomorrow

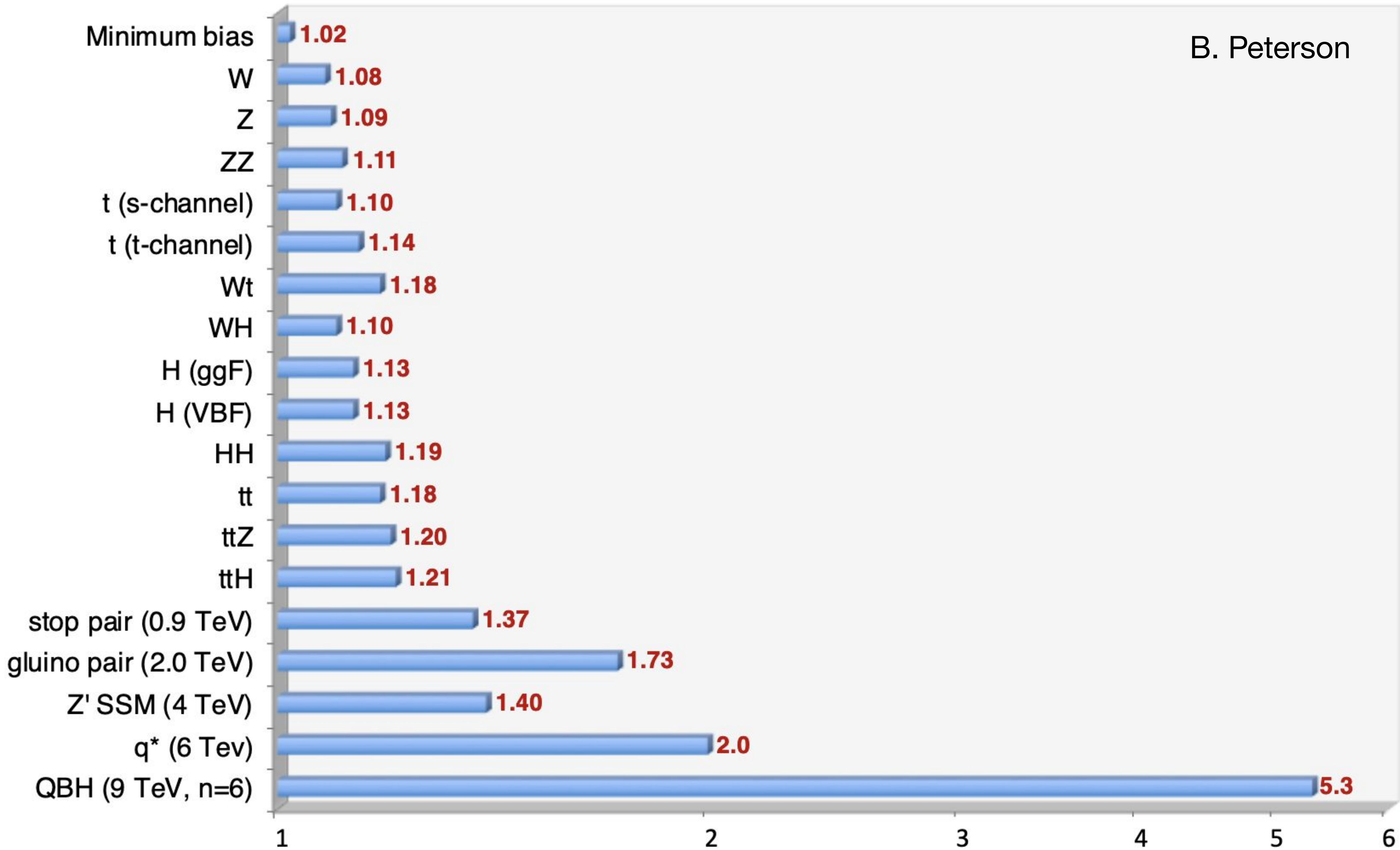
LHC / HL-LHC Plan



The HL-LHC will be installed 2026-2028, and run in 2029-2035(++)

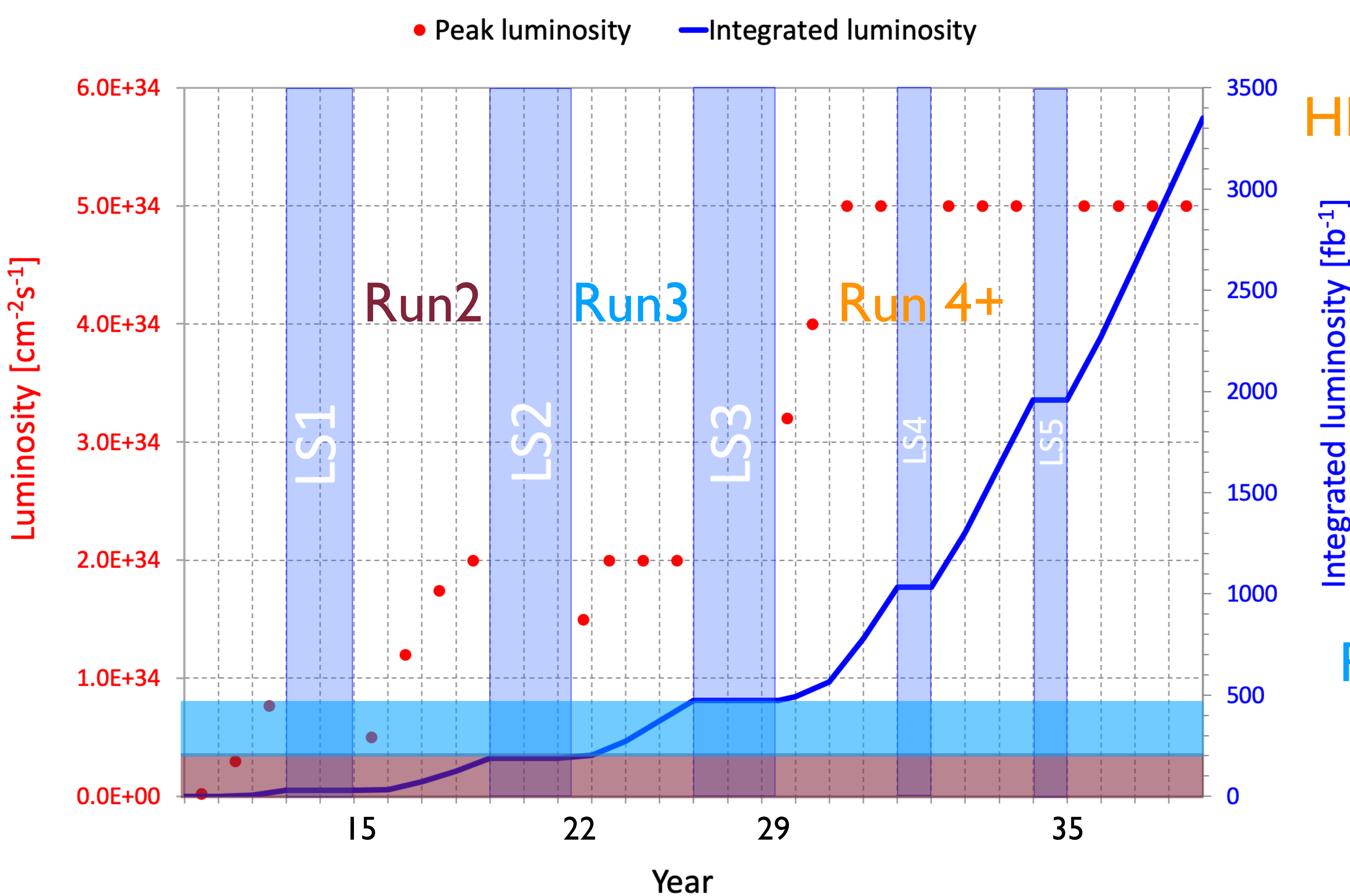
Increase energy to **14 TeV**,
and instantaneous luminosity to **5-7x10^{34} cm^{-2}s^{-1}**

Rising Energy



Increase in energy may seem small, but can have a big impact on important physics processes!

Datasets



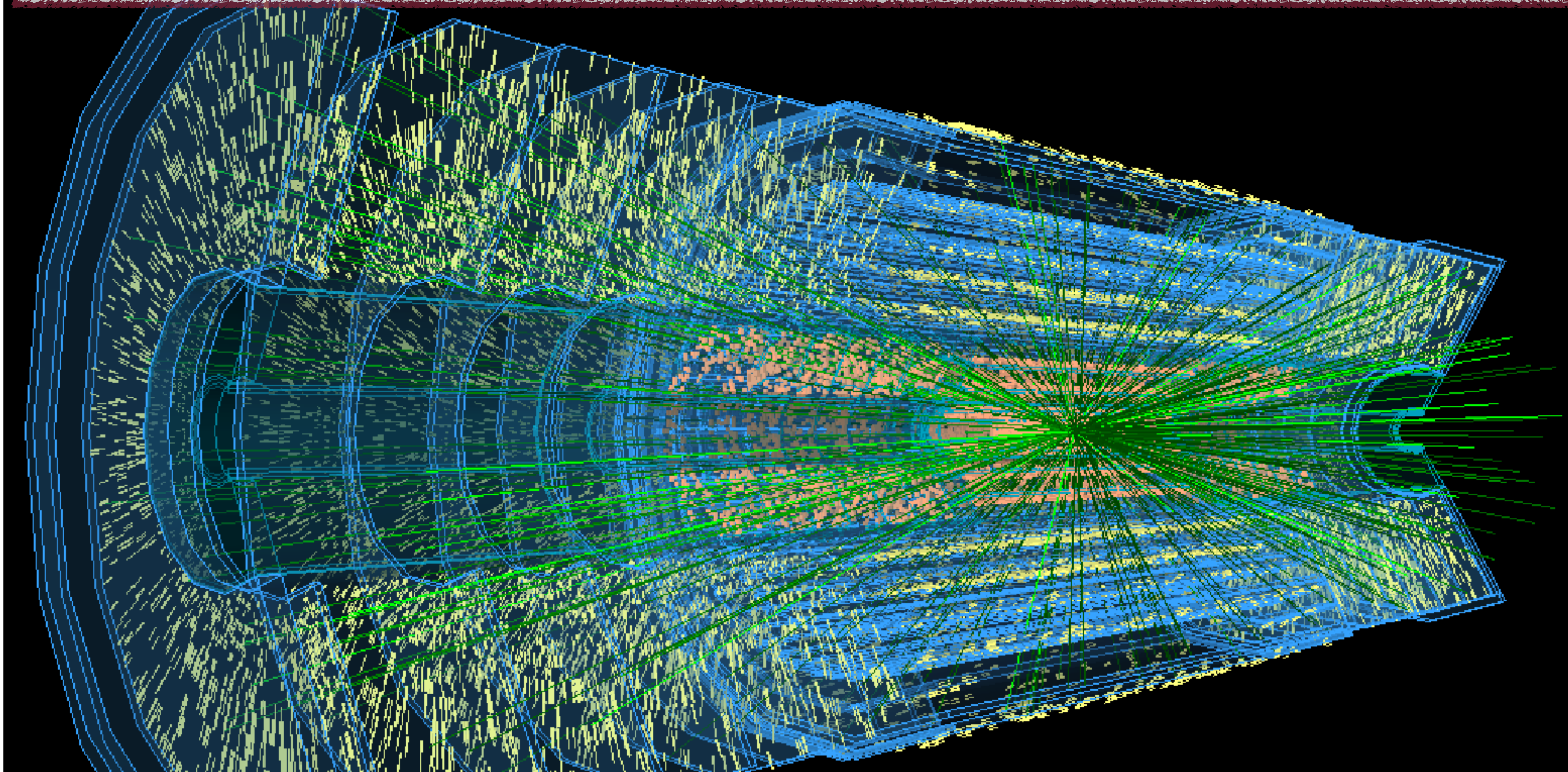
HL-LHC data

Run3: 10% of total

Run2: 5% of total

The Price of Rate: Pileup

To enable increased luminosity, collisions need to be more frequent



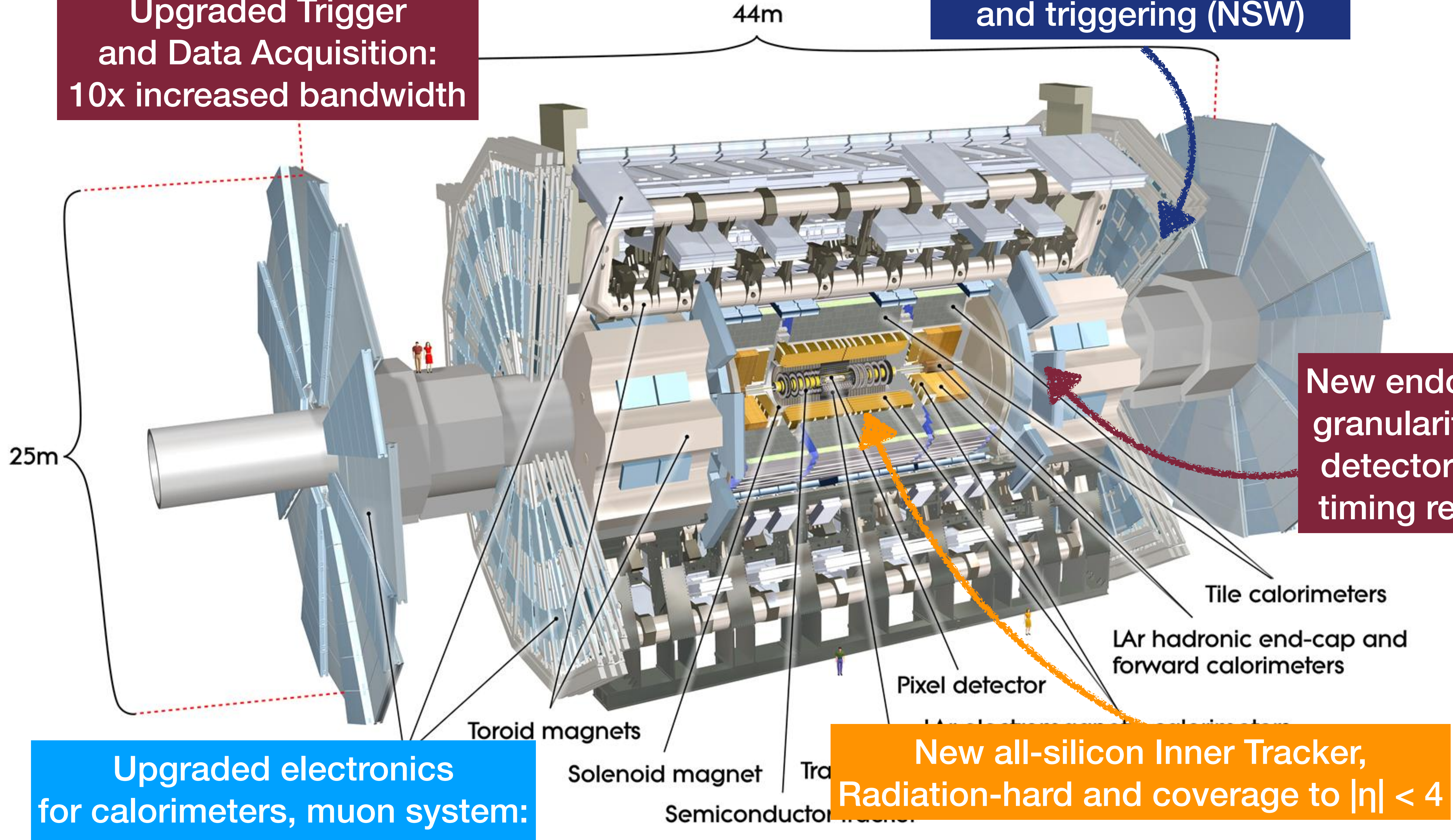
Bunch spacing fixed at 25 ns
Only option: increase **pileup**

Expect **200 collisions** per crossing! Compare to ~50 today

Upgrades

Upgraded Trigger and Data Acquisition: 10x increased bandwidth

Improved muon coverage and triggering (NSW)



New endcap high-granularity timing detector: ~20 ps timing resolution

New all-silicon Inner Tracker, Radiation-hard and coverage to |η| < 4

Upgraded electronics for calorimeters, muon system: greater precision, speed

Preparing for the Future

- European Strategy Update
- Canadian Long Range Planning
- Snowmass Community Planning Exercise
- The HL-LHC plays a critical role in all of these exercises
  - Important to understand how this device interplays with others!

How We Do Projections

- We don't have the HL-LHC data in hand, but we have a pretty good idea of what we'll be able to do with it

- Typically, **start existing Run 2 analyses**, and adjust for new conditions

  - **Increase cross-sections** (due to energy), **larger datasets** (~20-80x larger), **projected detector performance** (pileup)

  - **Experimental and theory uncertainties** are key: usually present a few scenarios

    - Baselines assume reductions in both: $1/\sqrt{L}$ for experimental, and half for theoretical. Ambitious, but achievable.

- **These projections may significantly undersell what we can do!**

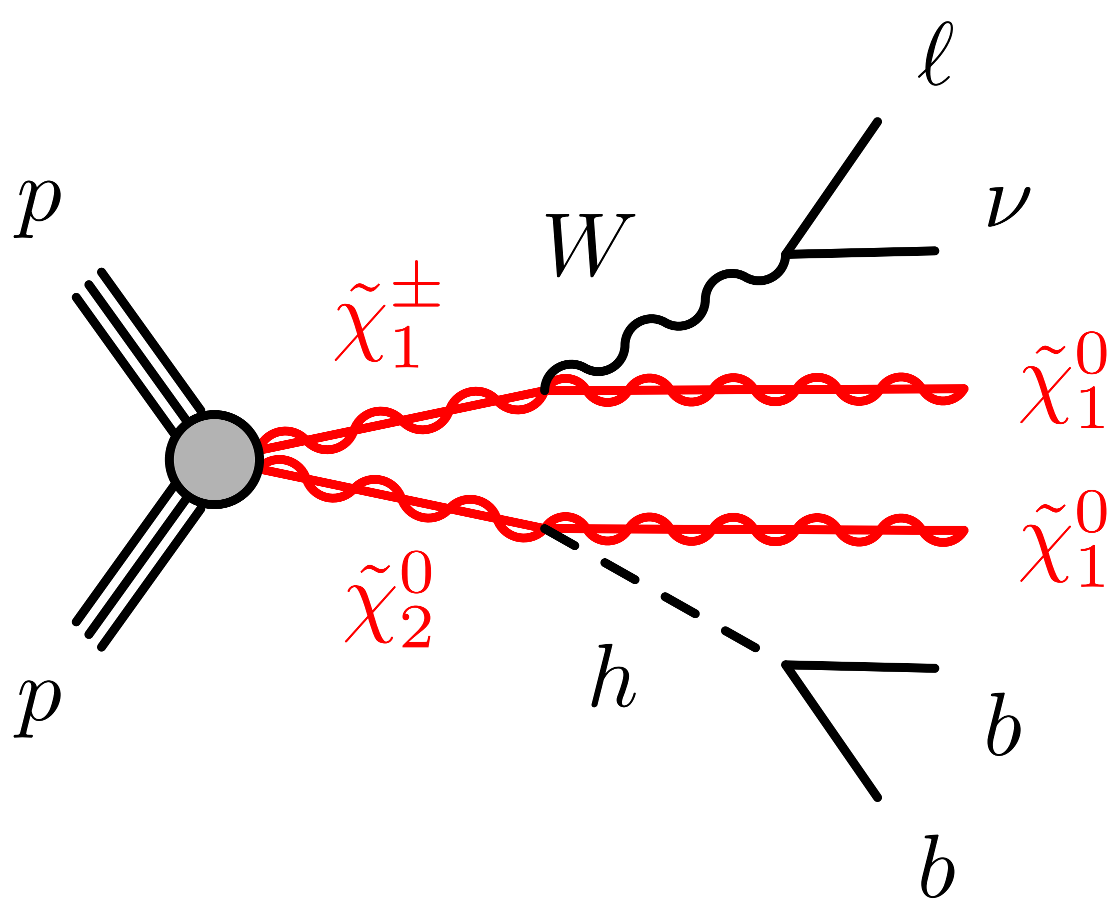
  - Analysis improvements often significantly outpace luminosity

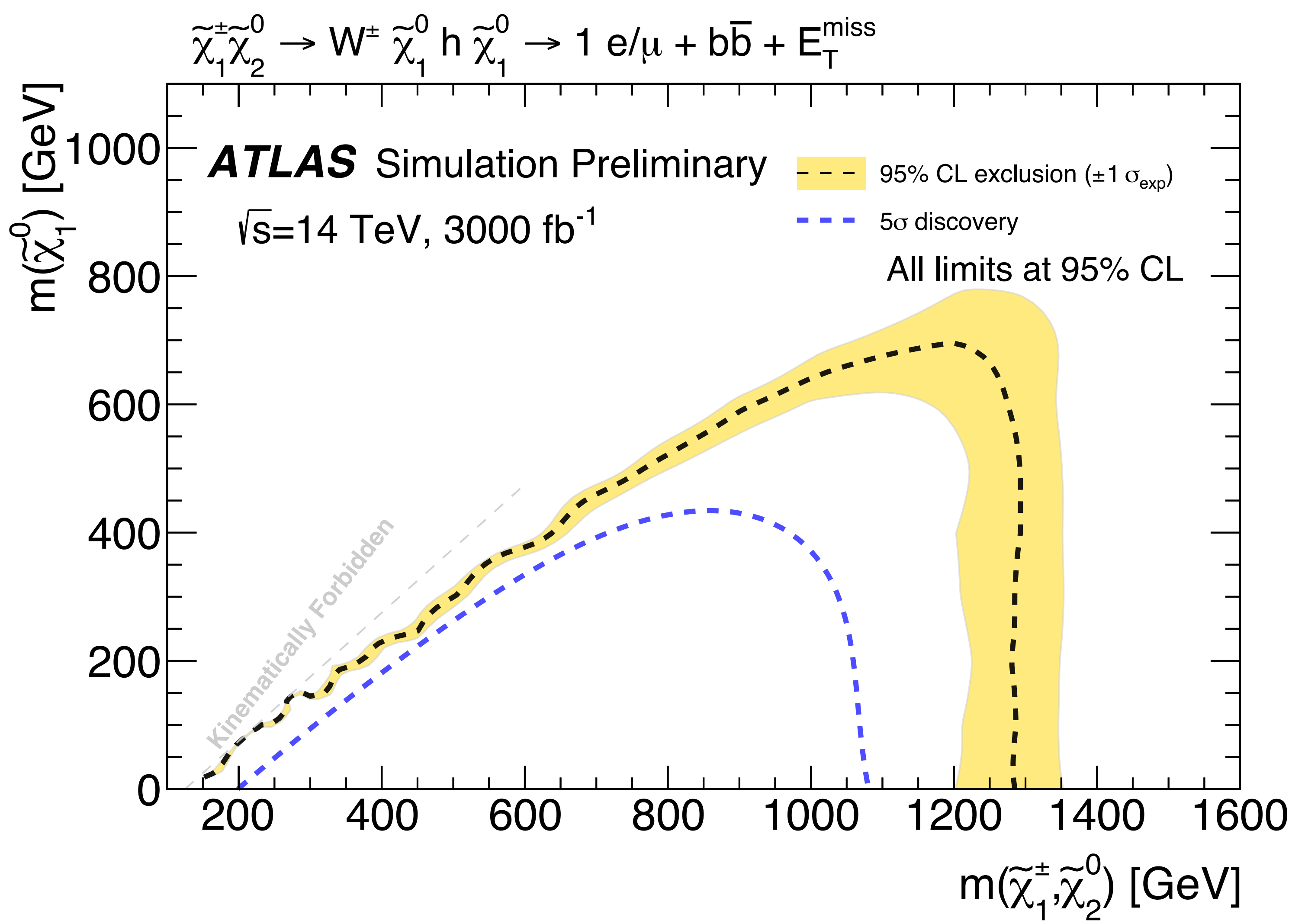
Direct Searches for New Physics

Electroweak SUSY

ATL-PHYS-PUB-2018-048

Run 2 physics program did not discovery SUSY: could signal be hiding in the low cross-section electroweak sector?



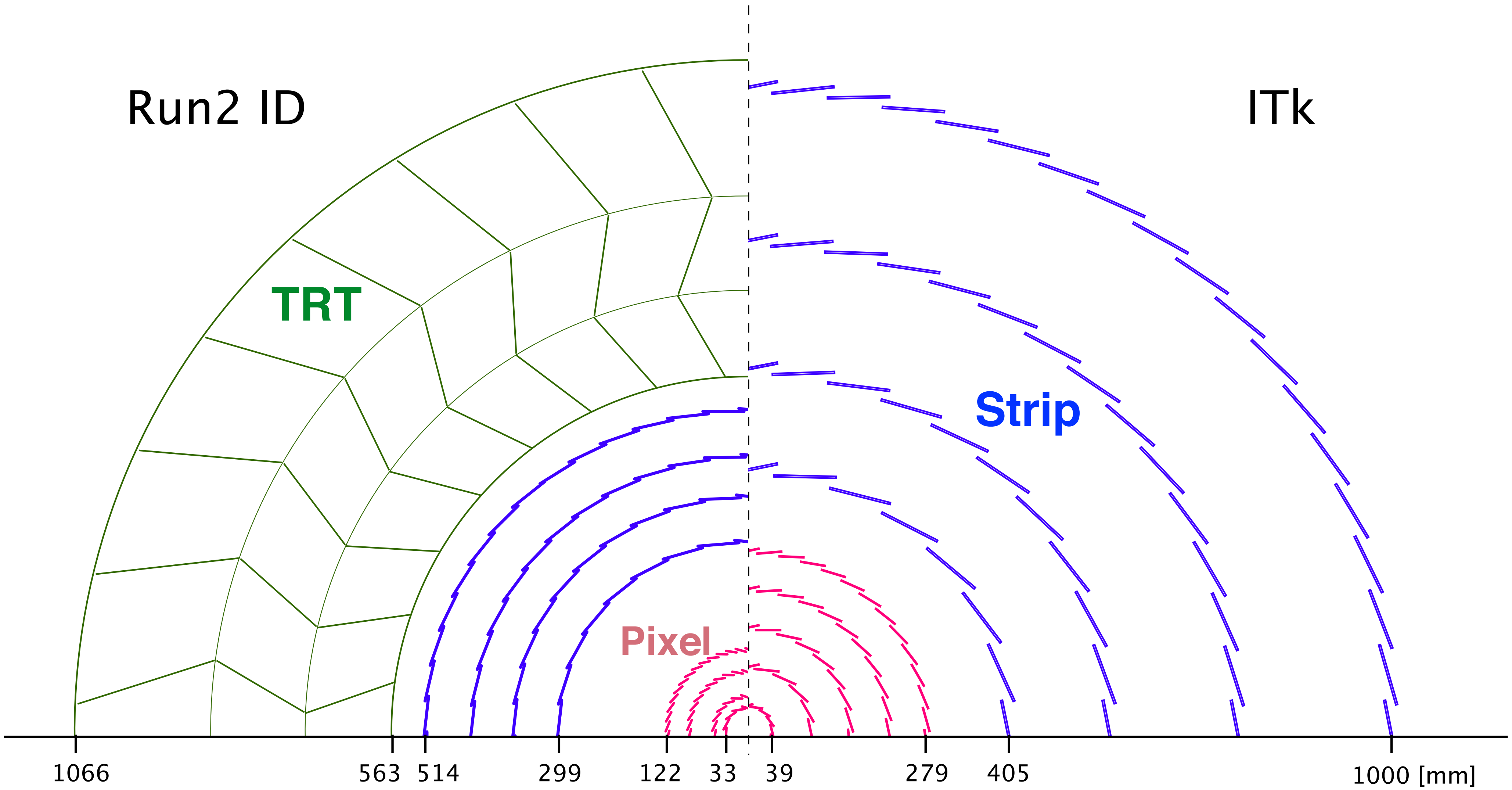


Wide range of models studied: many sensitive to TeV scale

ATL-PHYS-PUB-2018-033

Long Lived Particles

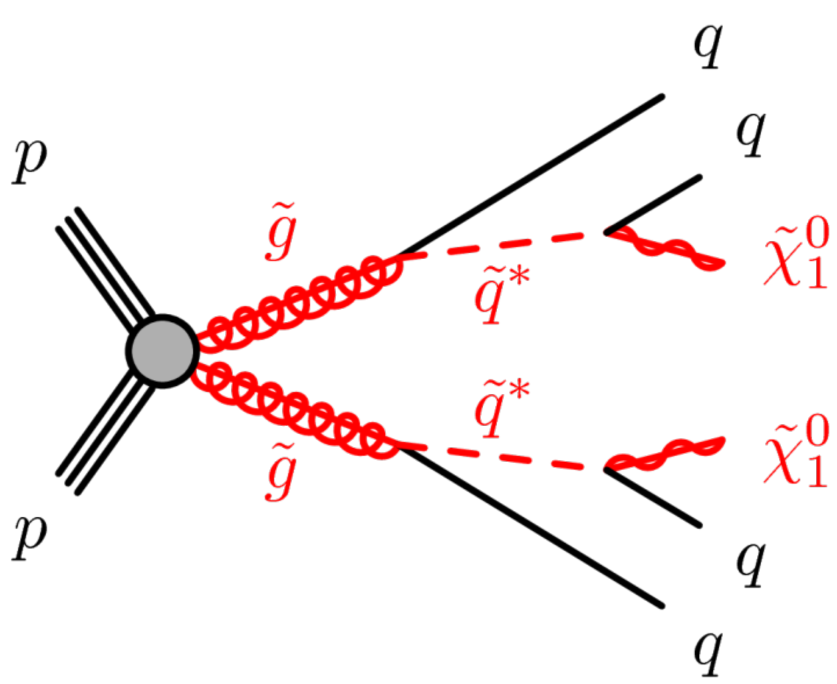
Run 2 physics program did not discovery SUSY: could difficult to measure signatures from “long lived” particles be the answer?

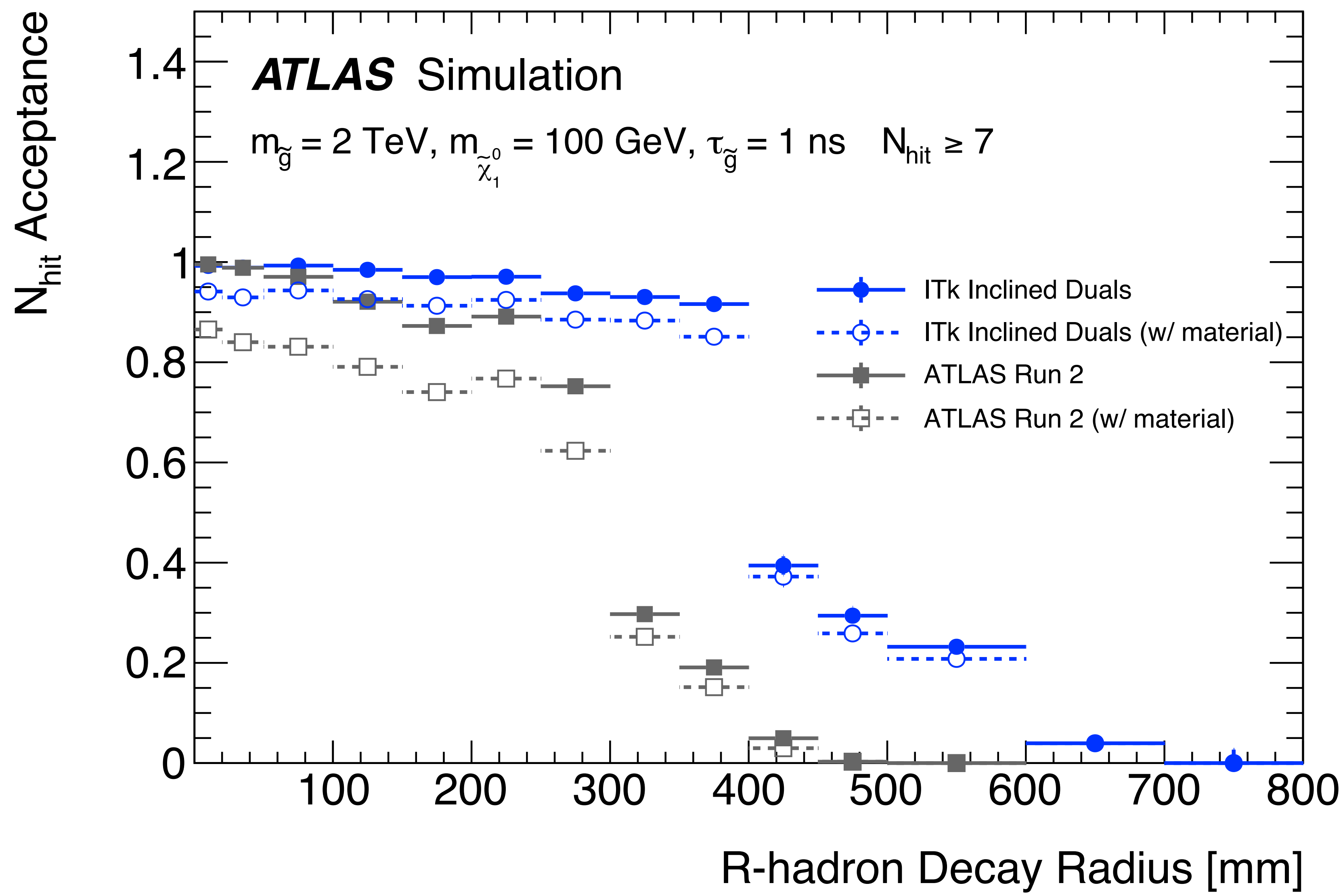


Many searches depend critically on detector design and layout: upgrades provide new opportunity for discovery

LLP Sensitivity

ATL-PHYS-PUB-2018-033





Significantly larger pixel and strip radii enable large increase in acceptance for long-lived particles!

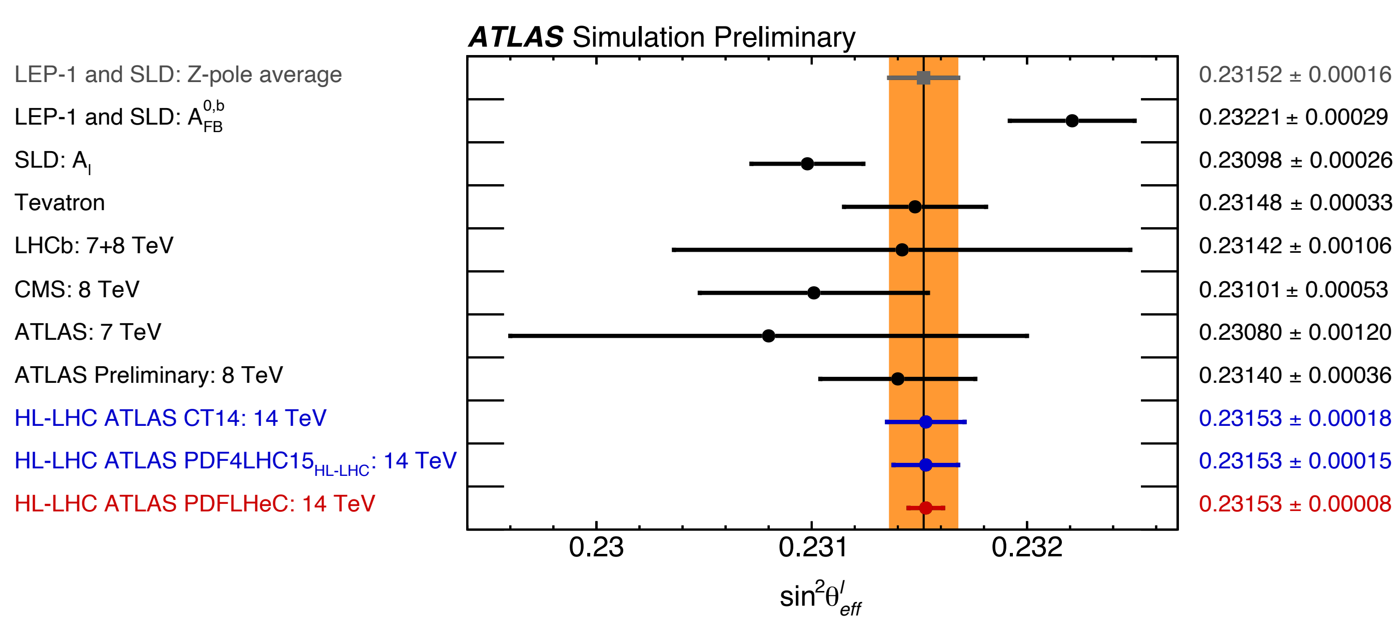
Precision Measurements of the Standard Model

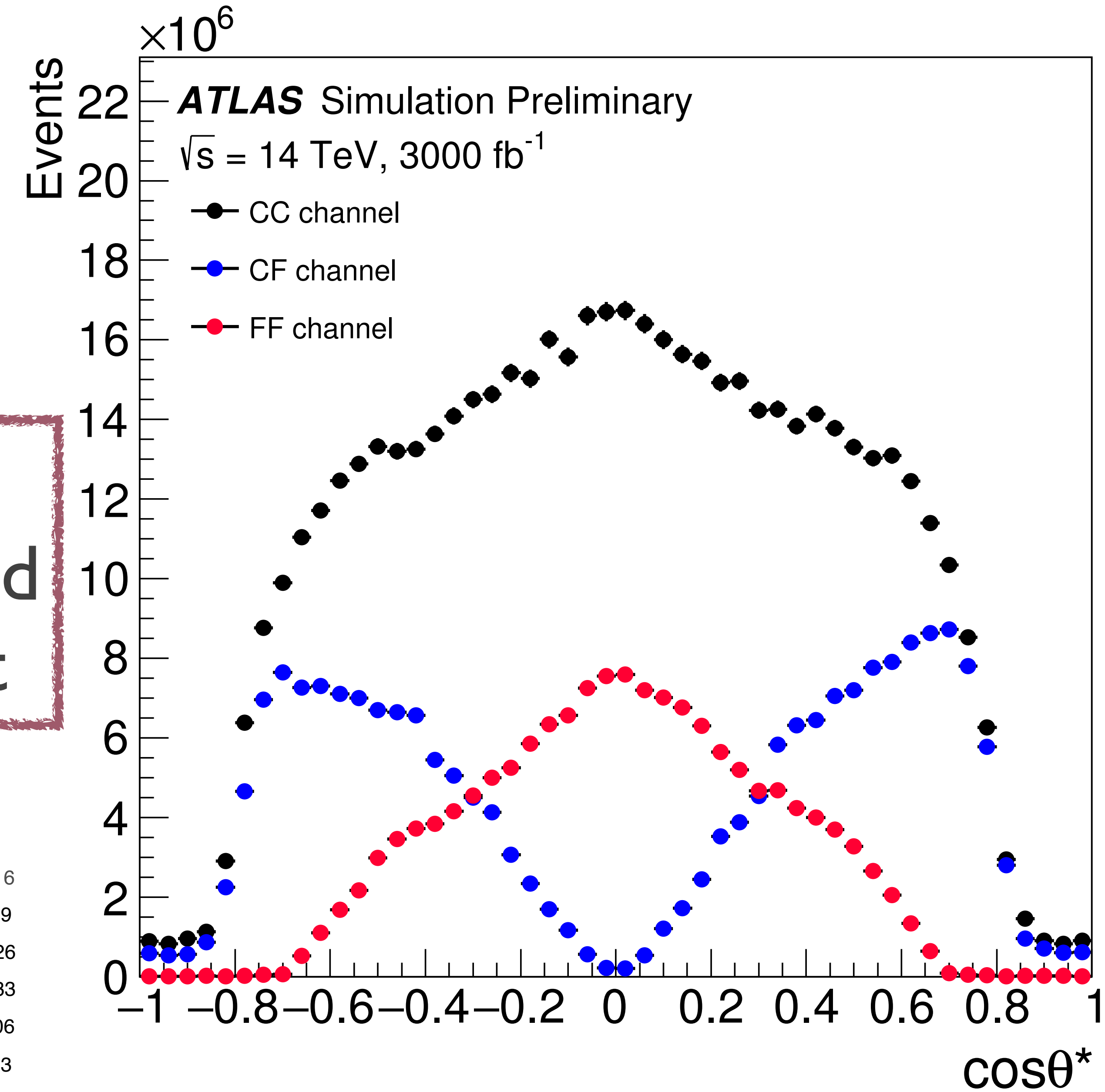
Weak Mixing Angle

ATL-PHYS-PUB-2018-037

The weak mixing angle, $\sin^2\theta_W$, is a fundamental measurement of the consistency of the SM

HL-LHC measurement exploits increased tracker acceptance, improved PDF measurements, and large dataset





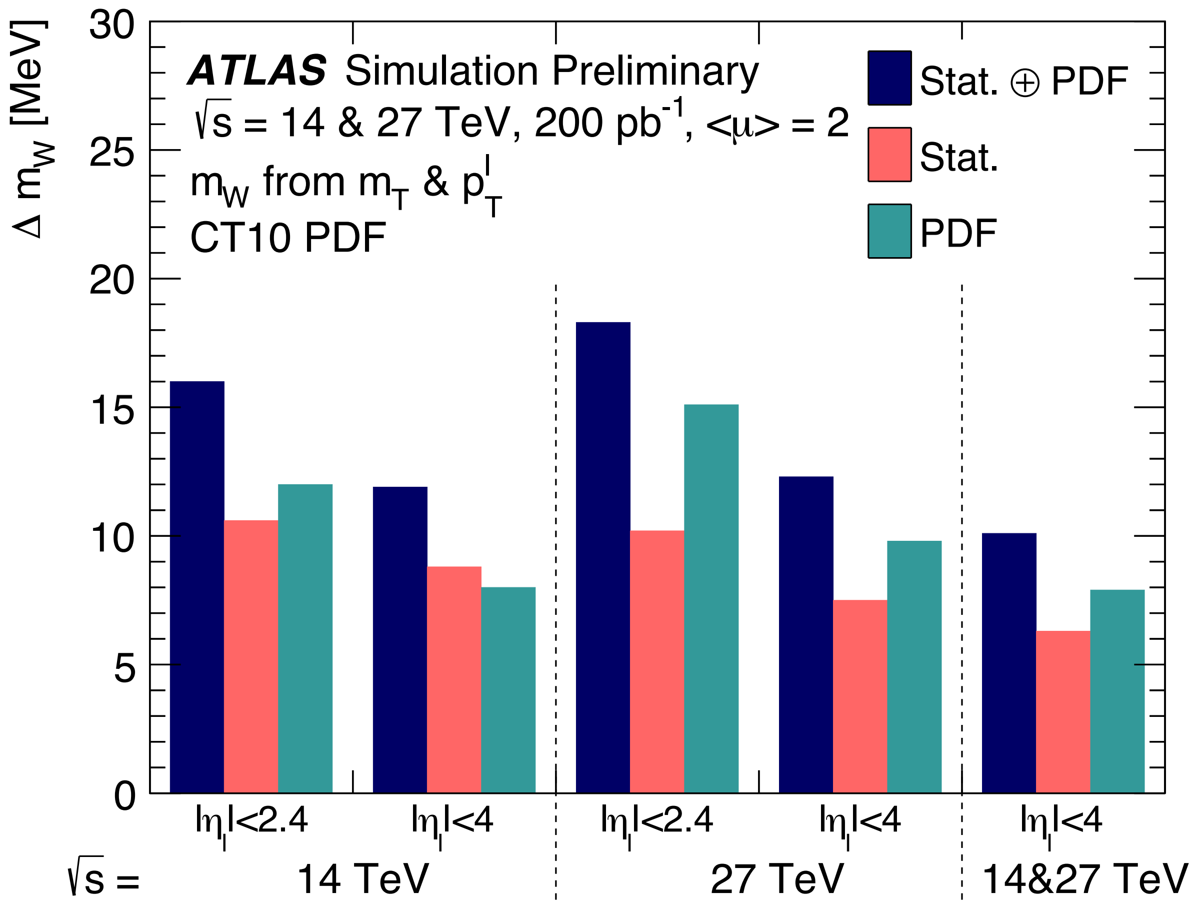
Potential for world's best measurement!

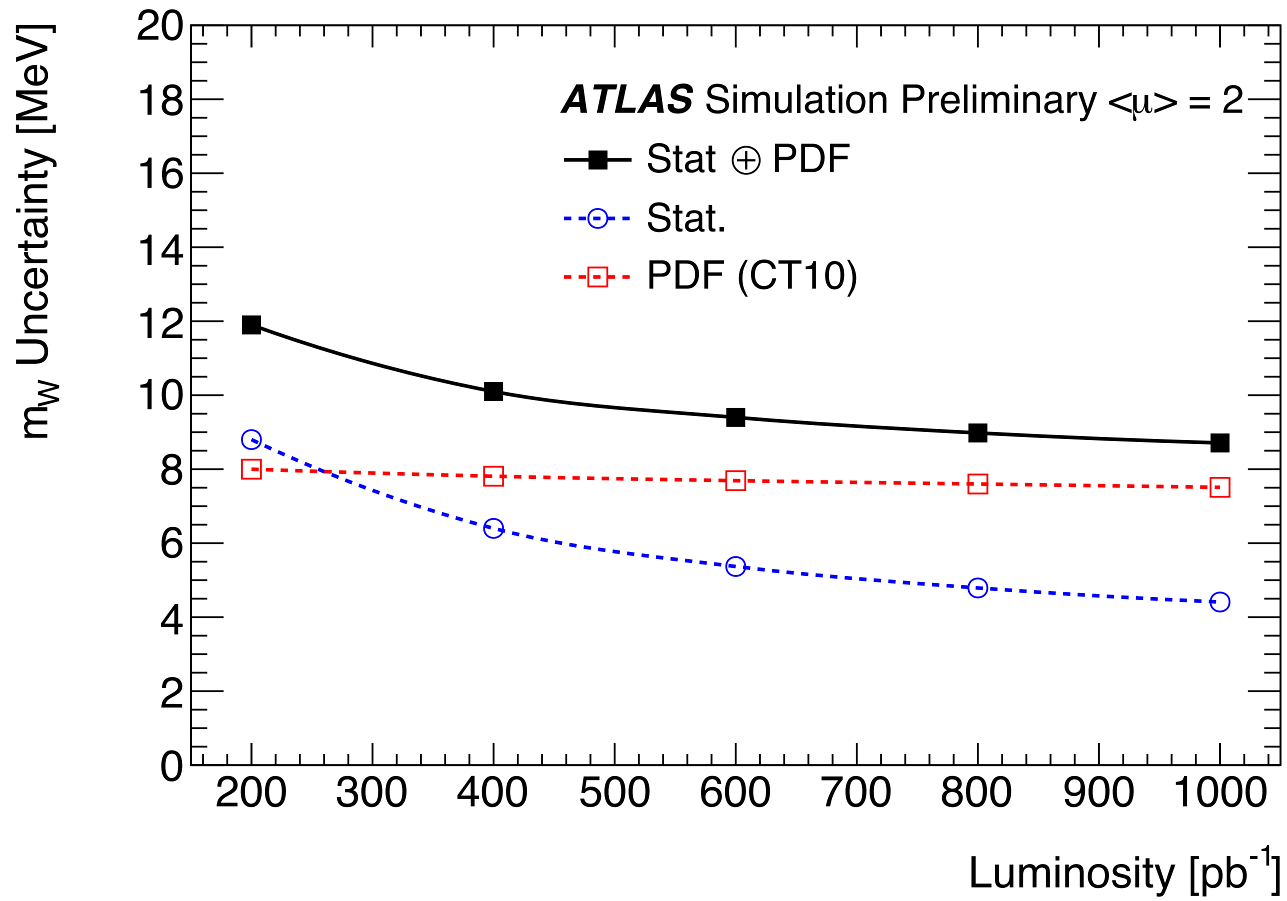
W Boson Mass

W boson mass is of great interest, especially given latest CDF results

HL-LHC measurement would exploit upgraded tracker acceptance, improved PDF, larger dataset

Special low-pileup dataset could lead to ~9 MeV precision: best cross-check of CDF result?





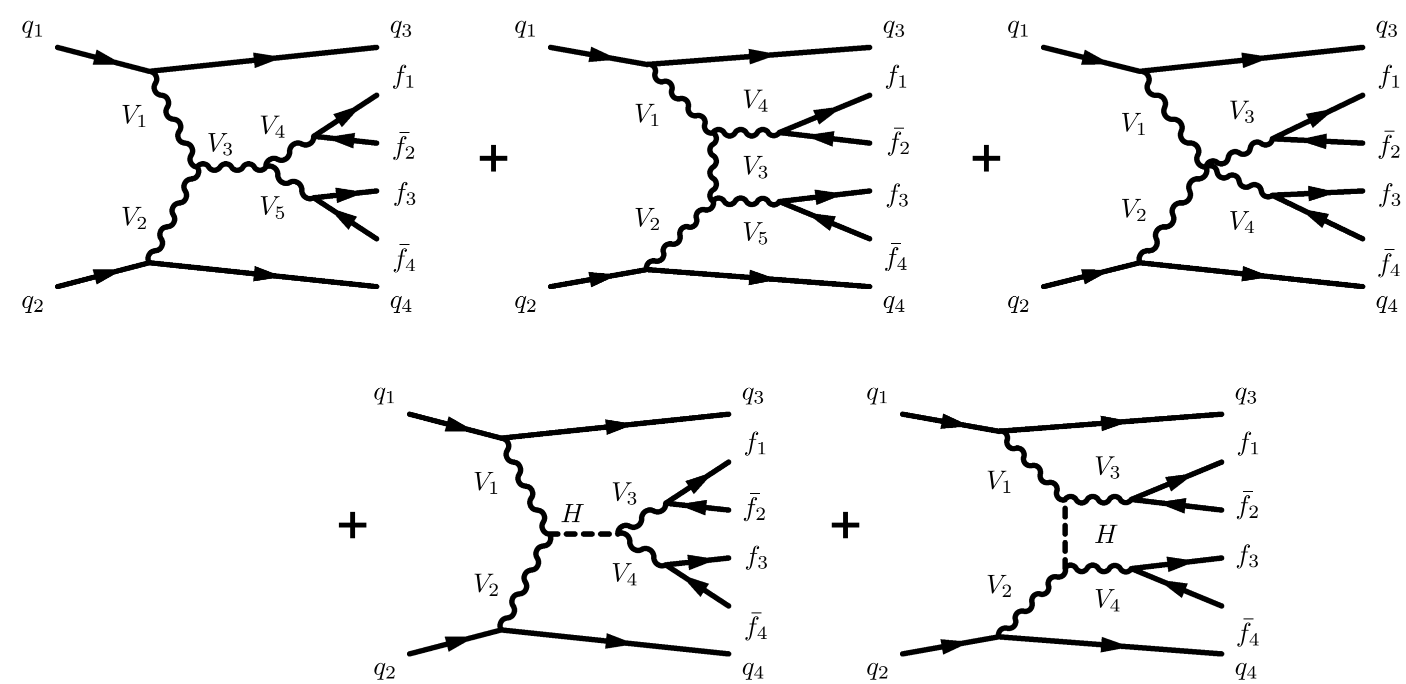
Vector Boson Scattering

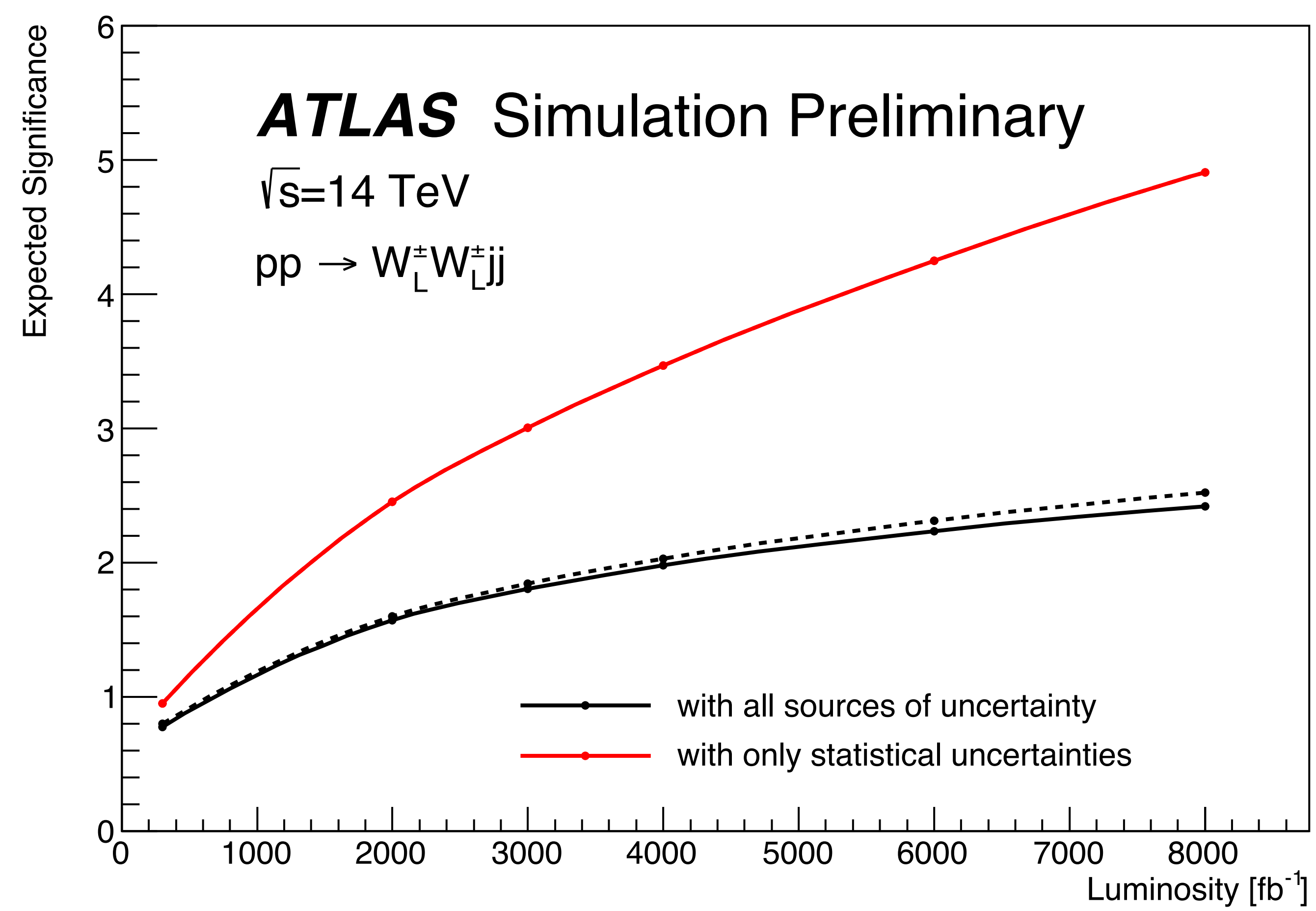
ATL-PHYS-PUB-2018-052

Vector boson scattering critical to our understanding of the Higgs: $V_L V_L$ diverges without the Higgs boson!

VV scattering observed in Run 2 with > 5σ: goal now is to extract longitudinal component of the process

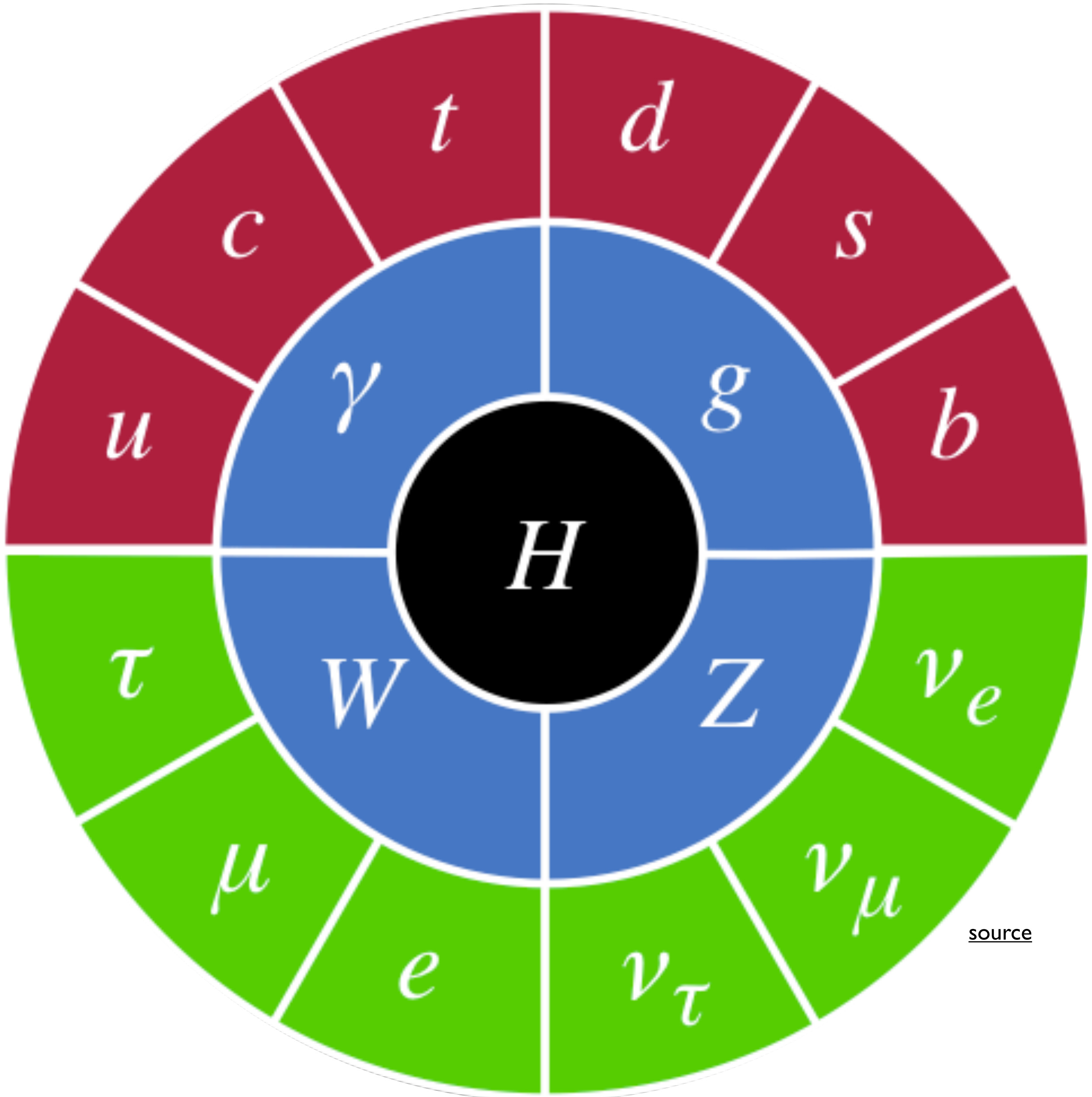
Challenging to observe: systematic and analysis improvements needed for evidence





The Higgs Boson

Why Higgs?



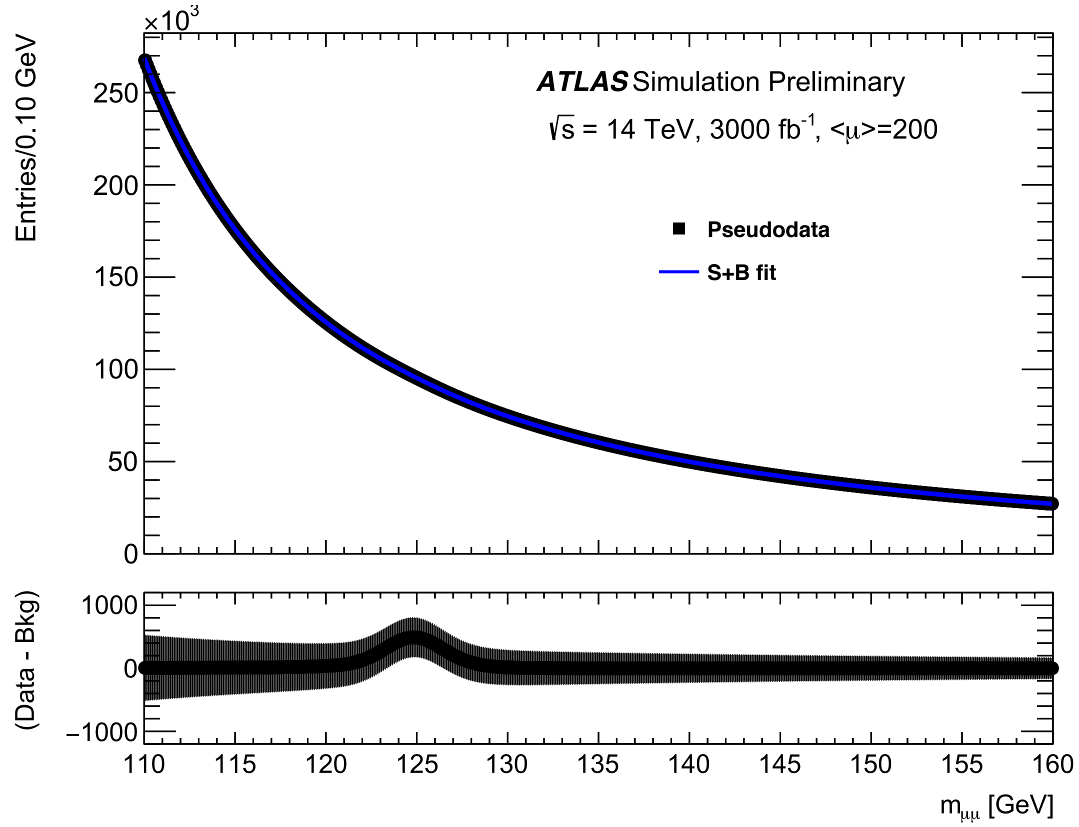
source

- The Higgs is the **center of the Standard Model**: related to all the particles, so critically important to understand
- The Higgs is the **newest particle**: we know the least about it
- The Higgs is **incredibly rich**: many different ways to study it

Rare Higgs Processes

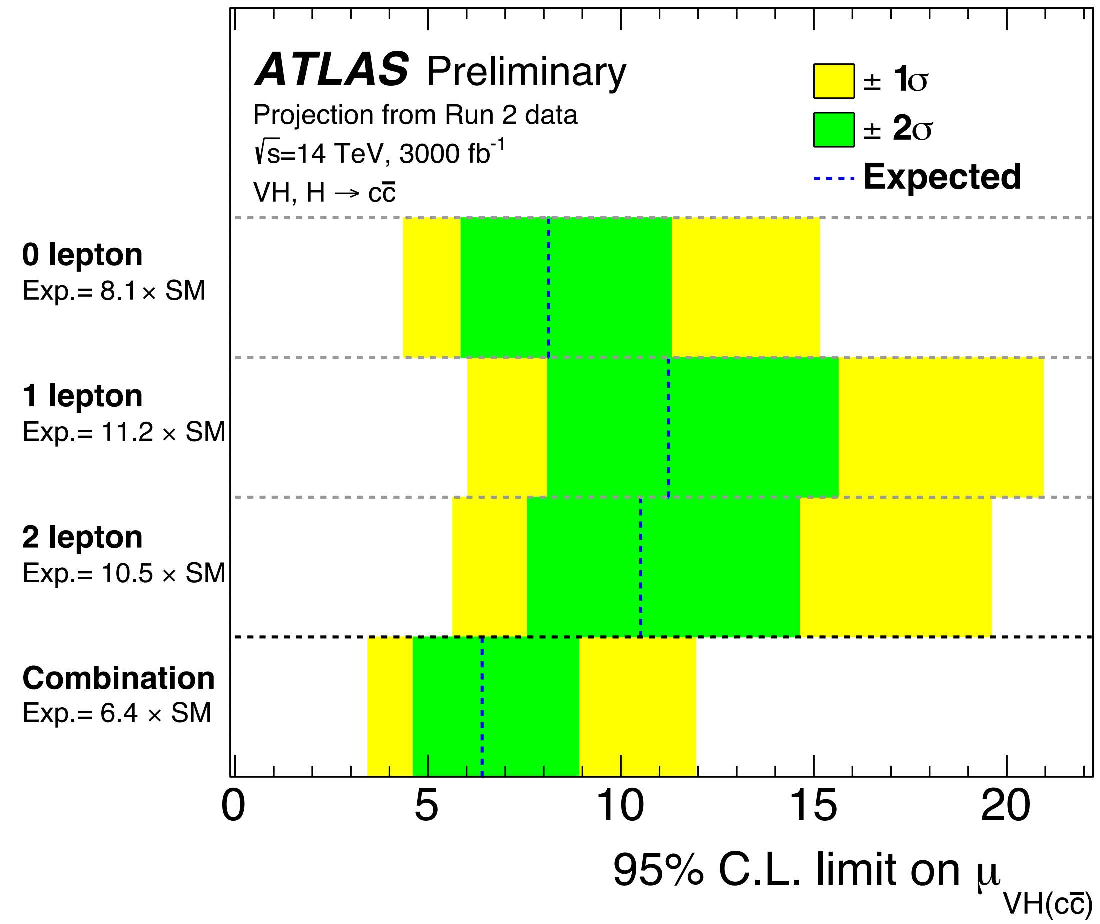
ATL-PHYS-PUB-2018-006
ATL-PHYS-PUB-2021-039

Even rare Higgs decays become measurable at the HL-LHC



Scoping Scenario	$\langle\mu\rangle$	Overall significance	$\Delta\mu$ w/ syst. errors	$\Delta\mu$ w/o syst. errors
reference	200	9.5	±0.13	±0.12
middle	200	9.4	±0.14	±0.12
low	200	9.2	±0.14	±0.13

$H \to \mu^+\mu^-$ observable at >9σ!



Expected $H \to c\bar{c}$ sensitivity at ~6x SM: improvements in charm tagging and analysis can improve this further

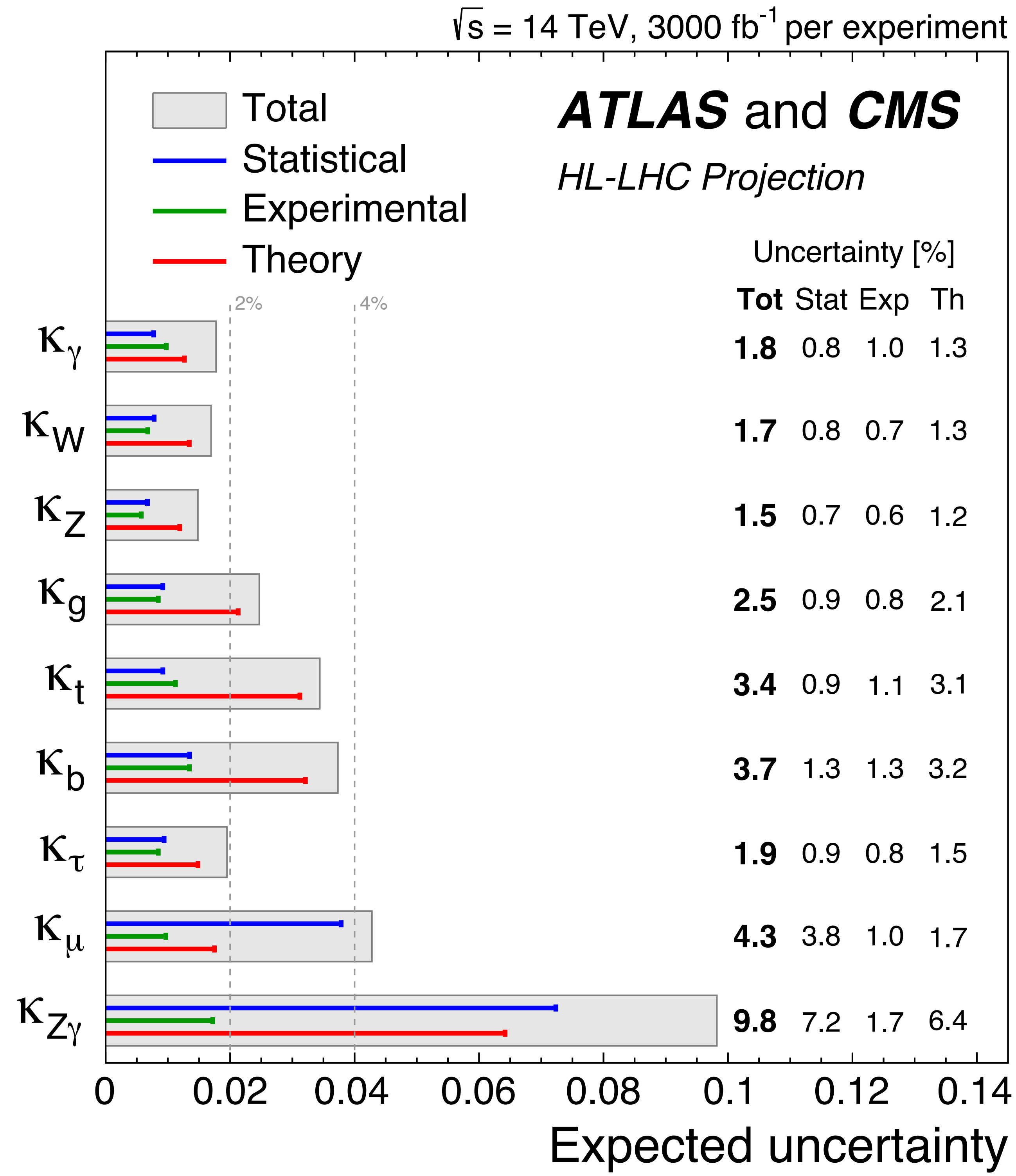
Higgs Precision

ATL-PHYS-PUB-2019-006

Huge number of detailed analyses summarized here in one plot: expected uncertainty on Higgs couplings to particles

Some couplings ($\kappa_\gamma, \kappa_V, \kappa_\tau$) measurable to <2%!

Many of these measurements expected to be complementary to Higgs Factories (especially rarer decays)

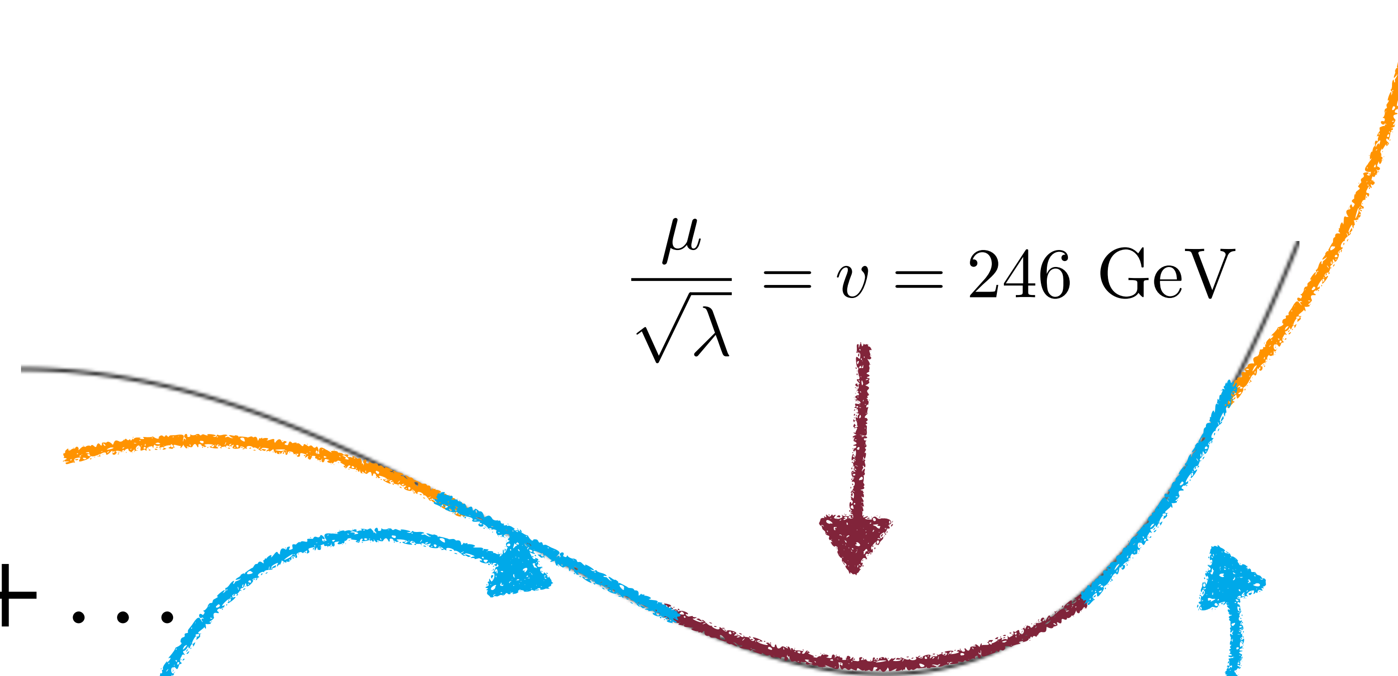


Understanding EWSB

The SM Higgs potential is:

$$V(\phi) = -\mu\phi^2 + \lambda\phi^4$$

We live in the minimum:



$$V(\phi) = V_0 + \lambda\nu^2 h^2 + \lambda\nu h^3 + \ldots$$

$$V(\phi) = V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_h^2}{2\nu^2}\nu h^3$$

$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2} \quad \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

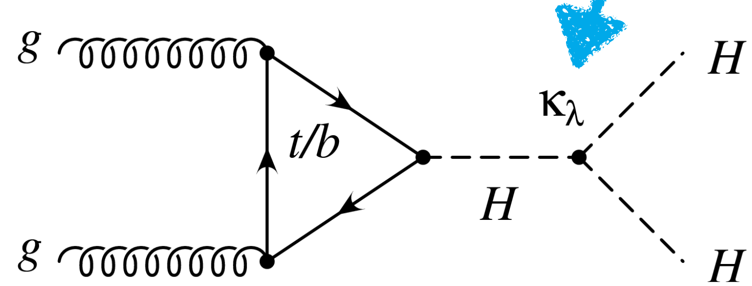
In the SM, $\kappa_\lambda = 1$: but we haven't measured it!

But what if we see something completely different? Could be hints of new physics, related to baryogenesis or vacuum stability!

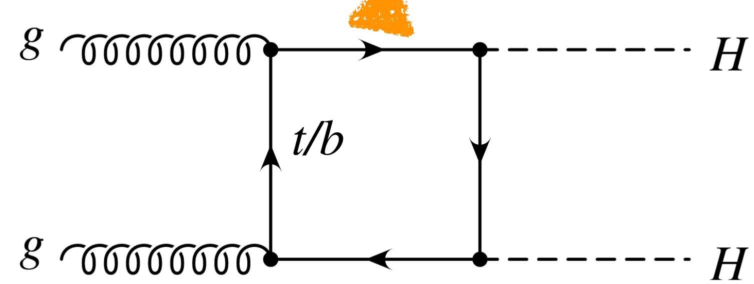
Higgs Pairs

Two diagrams produce HH at the LHC…

One diagram involves κ_λ: What we want to measure



The other is just proportional to κ_t: already well understood

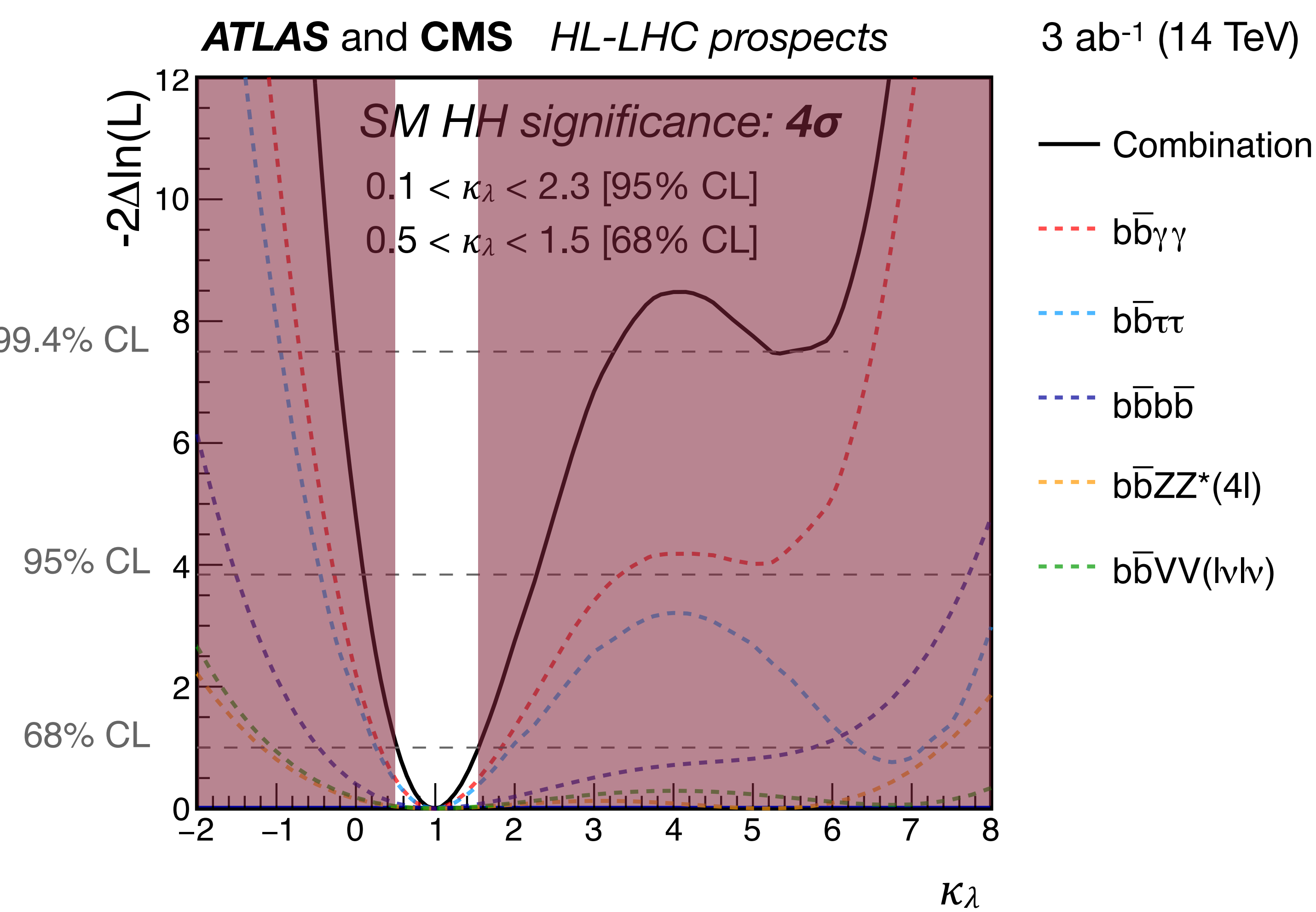


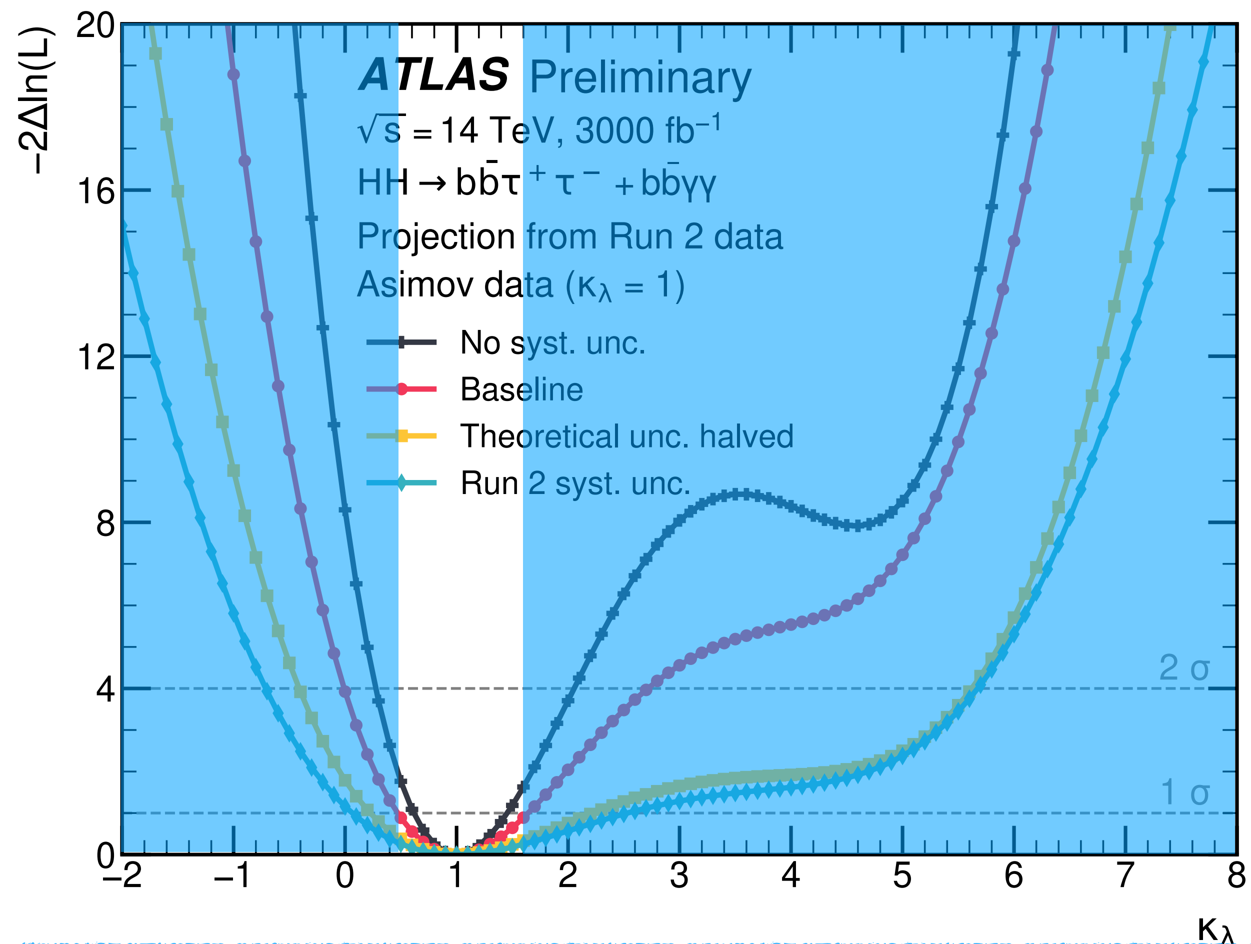
Destructive interference makes HH difficult to observe! But differential observables can help measure κ_λ

More in Colm's talk later today

Self Coupling Projections

ATL-PHYS-PUB-2022-005
ATL-PHYS-PUB-2019-006





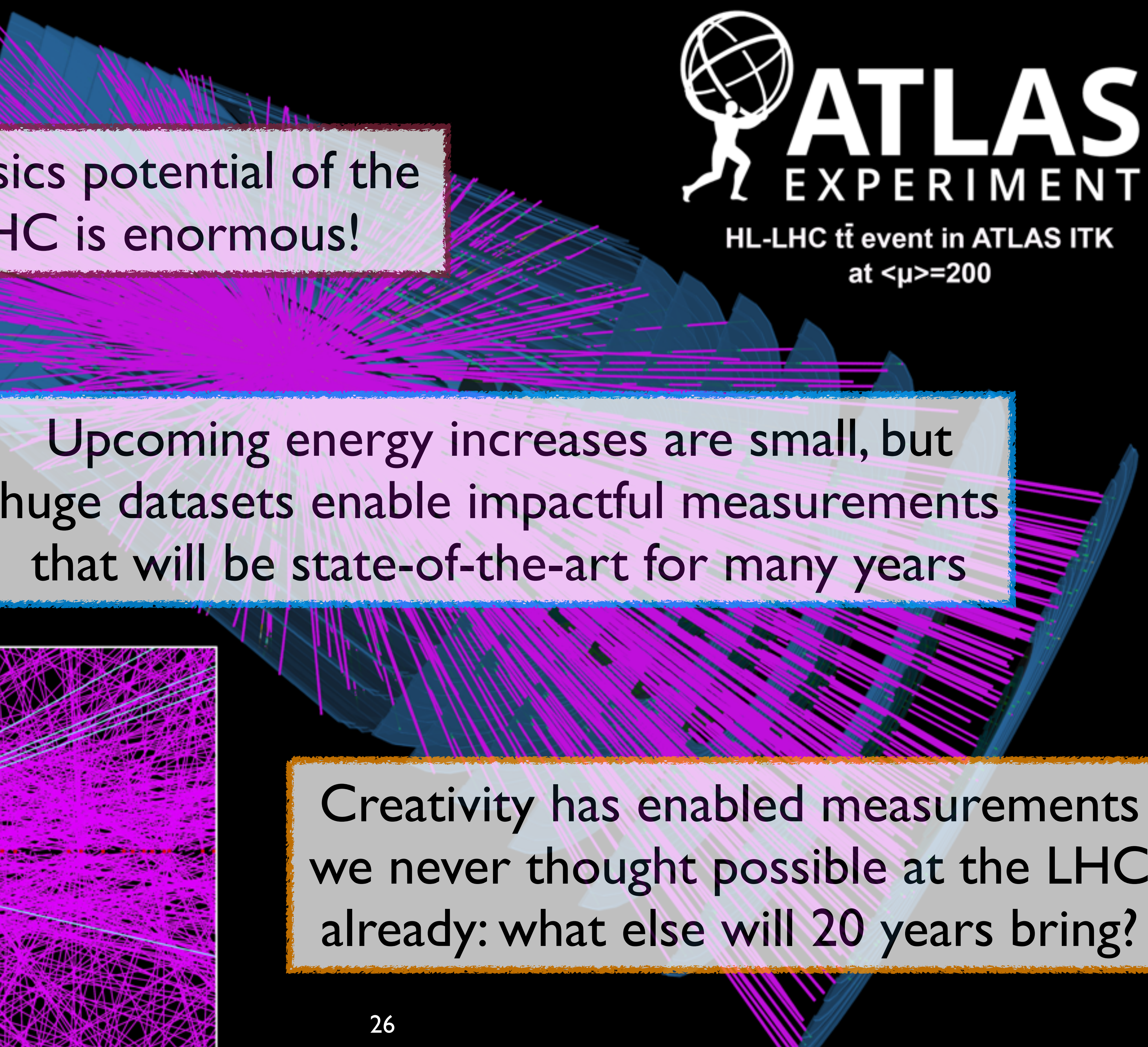
Combination of all ATLAS+CMS measurements: $0.5 < \kappa_\lambda < 1.5$ at 1σ

Updated ATLAS-only measurement, just two channels: ATLAS alone reaches $0.5 < \kappa_\lambda < 1.5$ at 1σ!

High hopes for even more significant improvements in the future

Conclusions

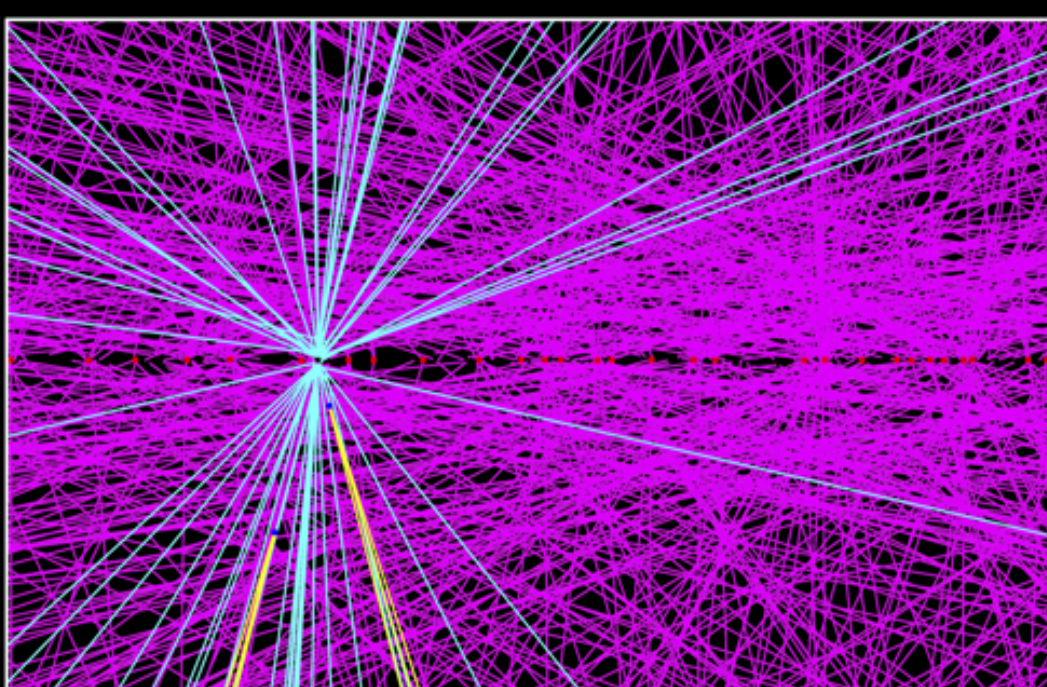
Conclusions



HL-LHC $t\bar{t}$ event in ATLAS ITK at $\langle\mu\rangle=200$

The physics potential of the HL-LHC is enormous!

Upcoming energy increases are small, but huge datasets enable impactful measurements that will be state-of-the-art for many years



Creativity has enabled measurements we never thought possible at the LHC already: what else will 20 years bring?

Thank you!