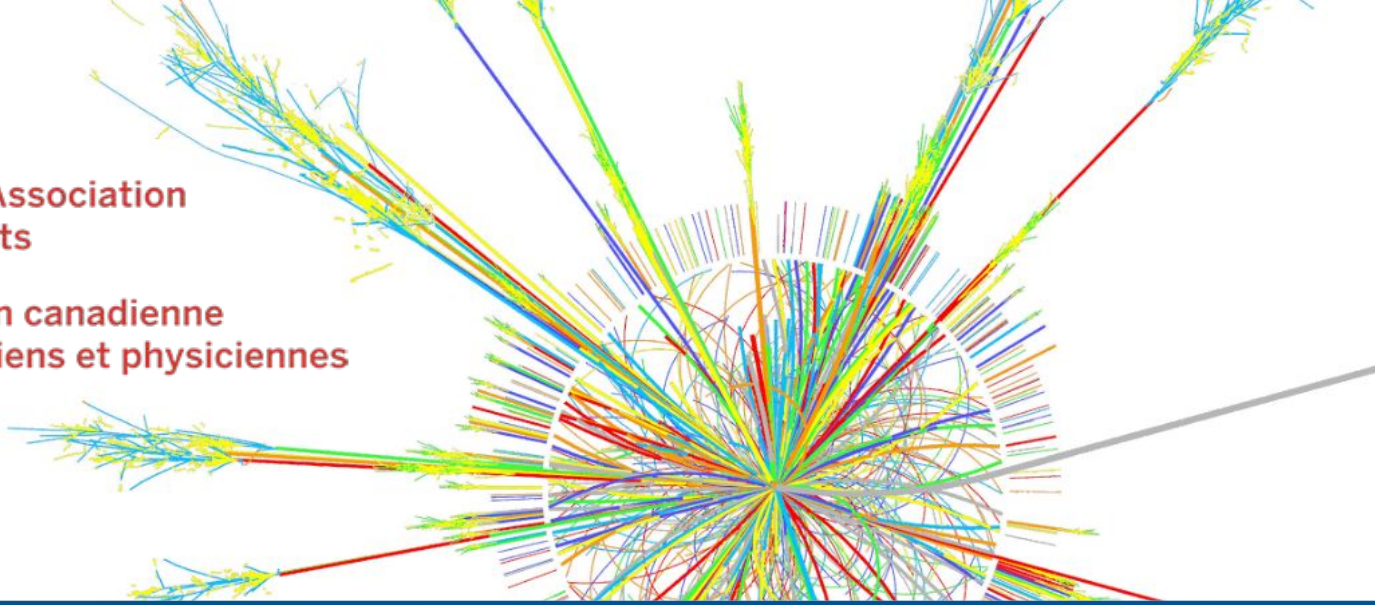


Canadian Association of Physicists

Association canadienne des physiciens et physiciennes

Highlights from the ATLAS Experiment

Ellis Kay - The University of Victoria

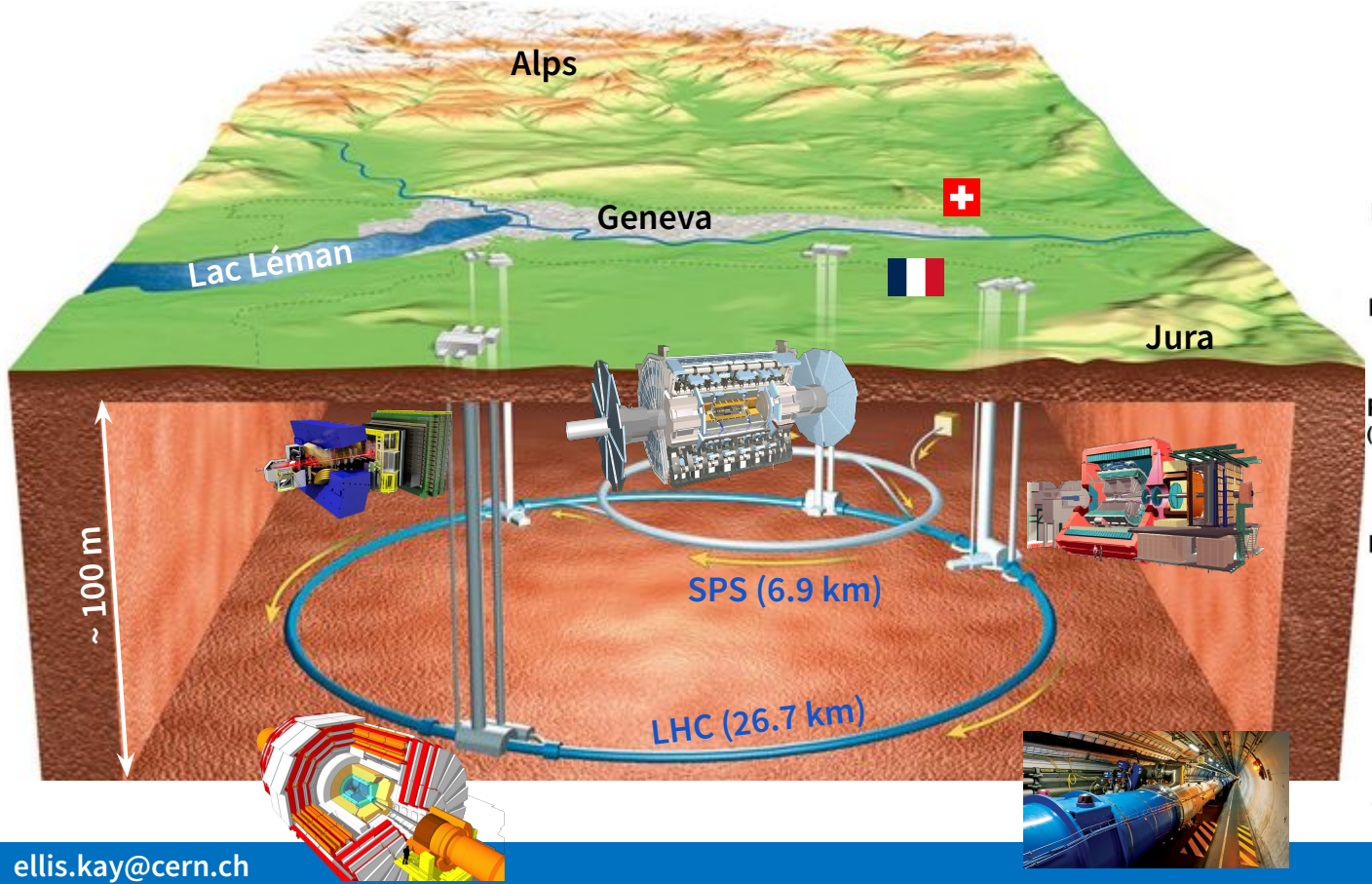
ATLAS EXPERIMENT

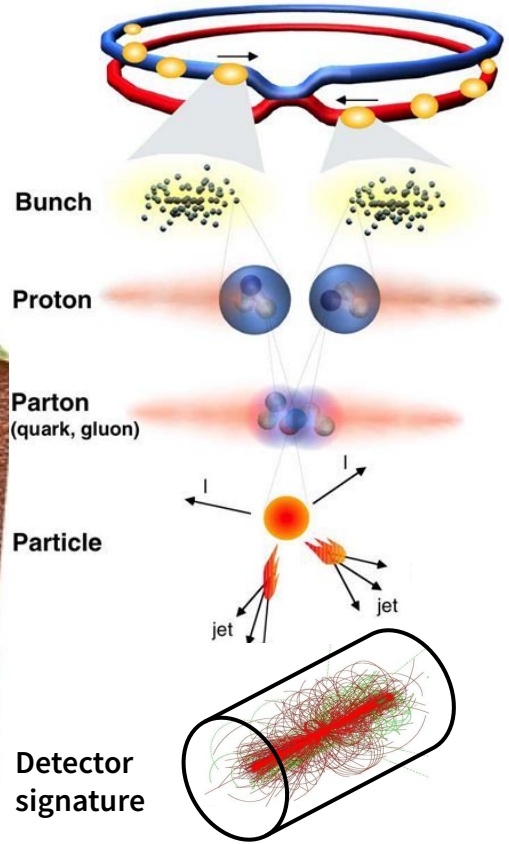
CERN

University of Victoria

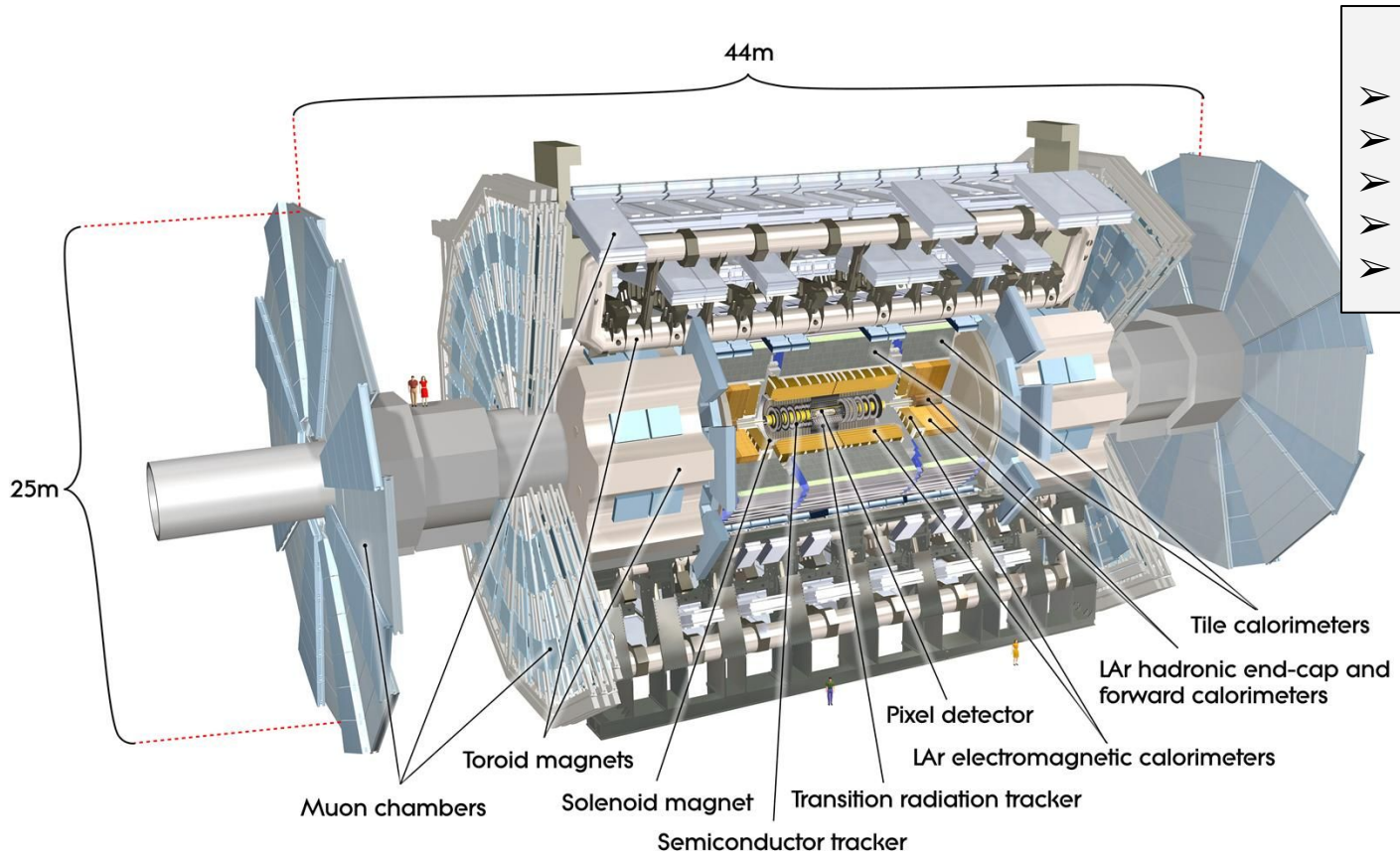
CAP 2022, Hamilton ON

The Large Hadron Collider





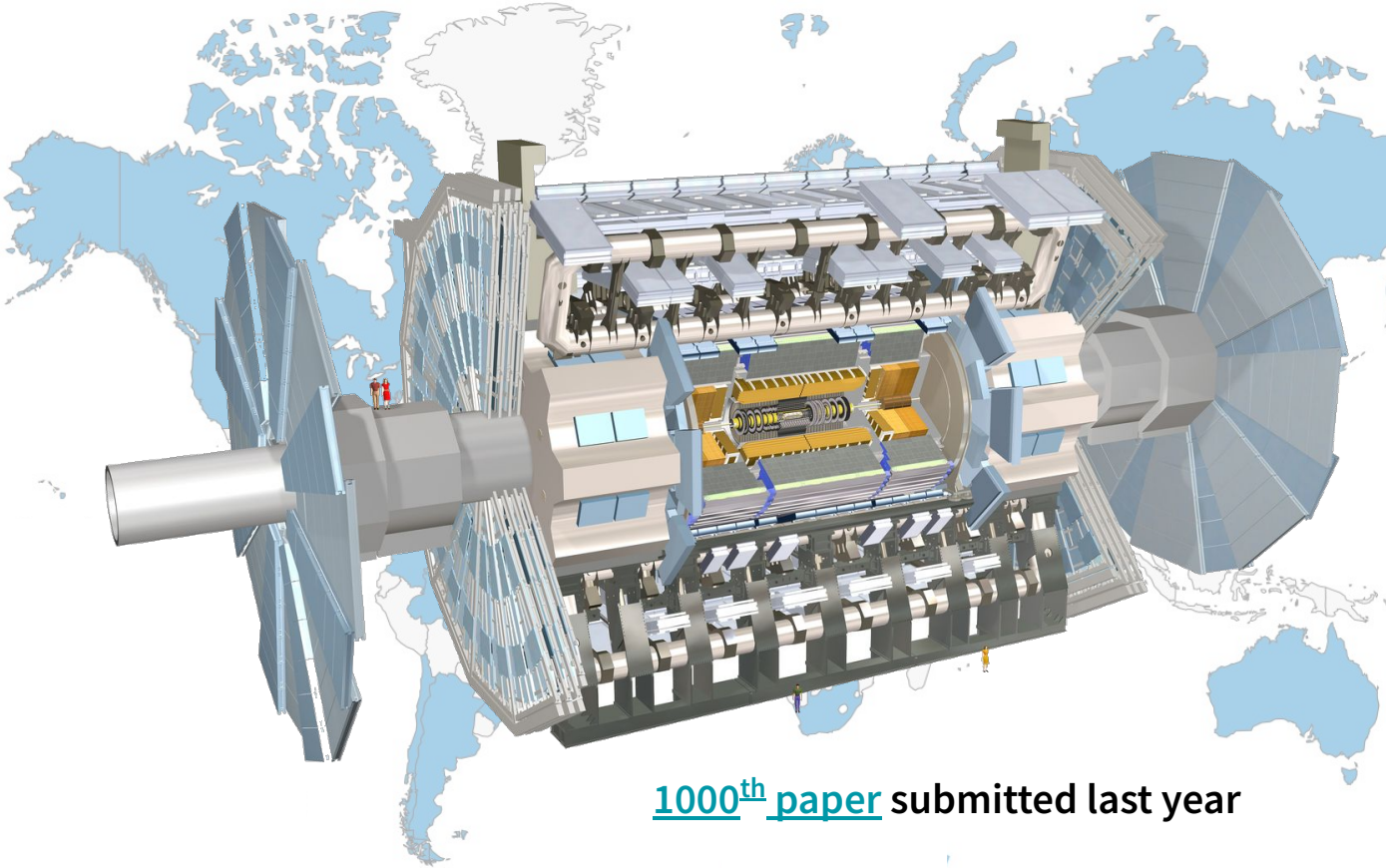
The ATLAS Experiment



Letter of Intent (1992)

- Hermetic jet & $E_{T,miss}$ calorimetry
- Excellent particle identification
- Excellent electron & photon resolution
- Standalone muon measurement
- Large acceptance

The ATLAS Collaboration



>5500 people from 245 institutes, including:

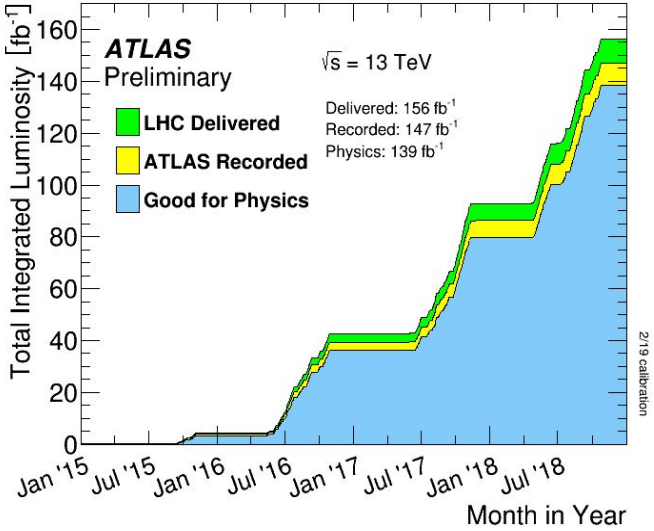
1000th paper submitted last year

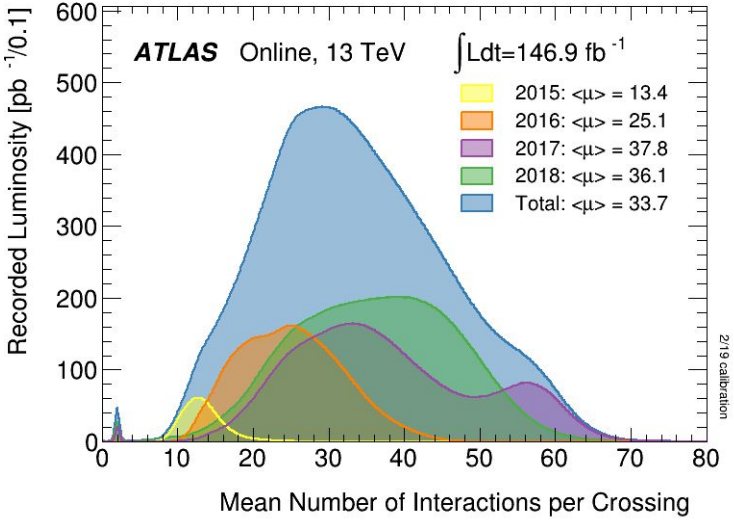
ATLAS Run-2 Data

A wealth of proton-proton collision data

Run-2 Luminosity Public Results

- Run-1: 2011-2012
  - $\sqrt{s}$ = 7-8 TeV
  - $\int \mathcal{L}$ = 25 fb^{-1}
- Run-2: 2015-2018
  - $\sqrt{s}$ = 13 TeV
  - $\int \mathcal{L}$ = 139 fb^{-1}





- Excellent detector performance, 95% of recorded run-2 data usable for physics

~140 papers from this dataset thus far

Too many to summarise here…

Will focus on a few recent results which exemplify the range of physics analyses

Physics with ATLAS

Precision measurements of the Standard Model (SM)

Observation of rare SM processes

Searches for new physics Beyond the Standard Model (BSM)

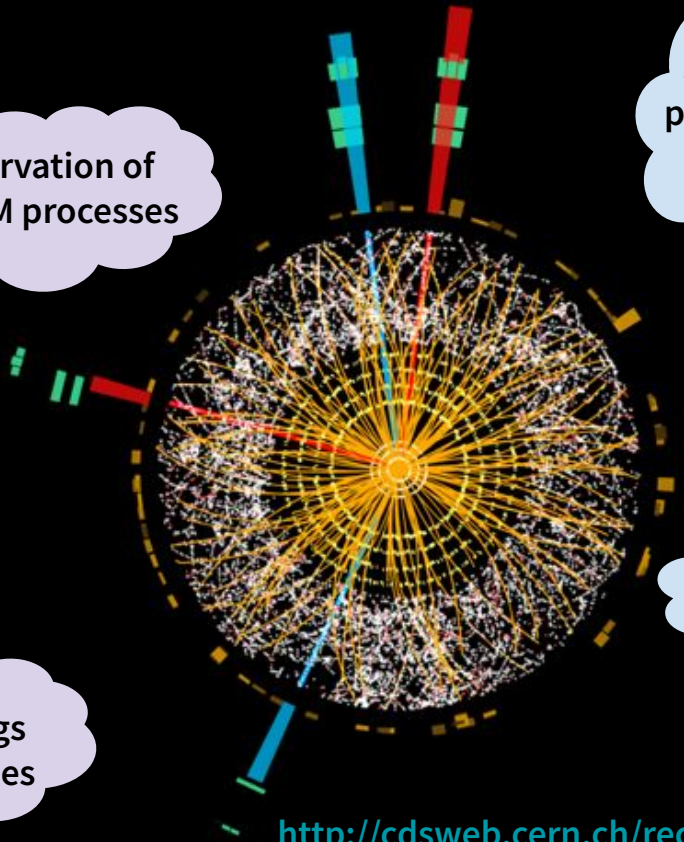
Searches for Supersymmetry (SUSY)

Studies of top quark properties

Searches for Dark Matter

Studies of Higgs Boson properties

Searches for exotic Higgs Boson decays

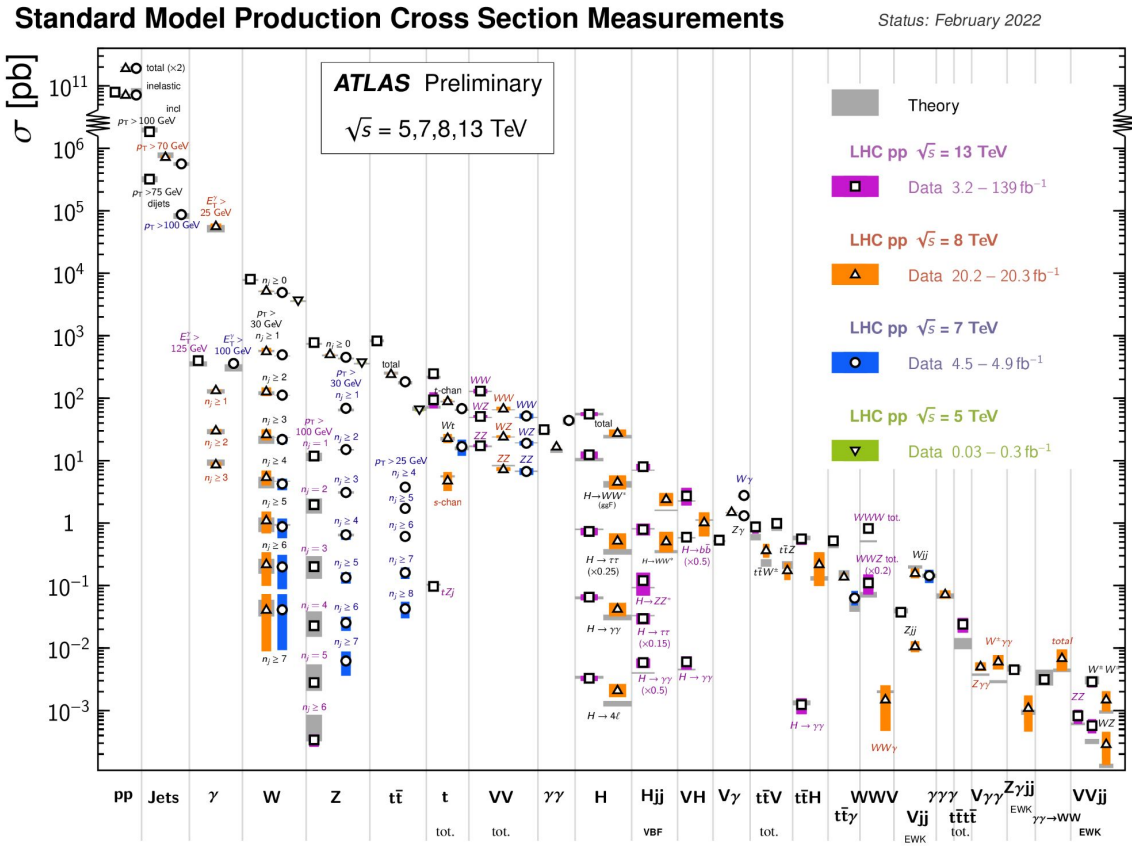


http://cdsweb.cern.ch/record/1459495

Testing the Standard Model

- Cross section measurements spanning many orders of magnitude

  Alexandre's talk Sahibjeet's talk
- Observations of rare SM processes with tiny cross-sections
- Measurements of top quark properties, which could be sensitive to new physics
- Confirm predictive power of the SM, plus improve understanding of backgrounds in searches for new physics

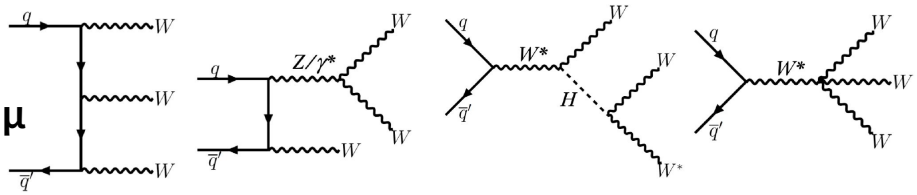


Observation of WWW Production

2201.13045 | Briefing

Direct probe of triple/quartic gauge couplings

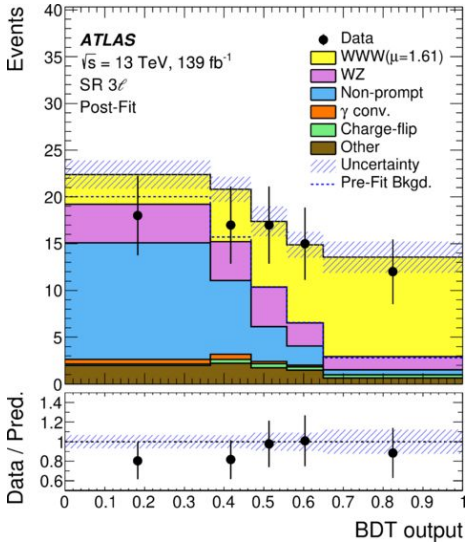
$$\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\not{D}\psi + \psi_i\, y_{ij}\,\psi_j\,\phi + \mathrm{hc} + |\,D_\mu\phi\,|^2 - V(\phi)$$

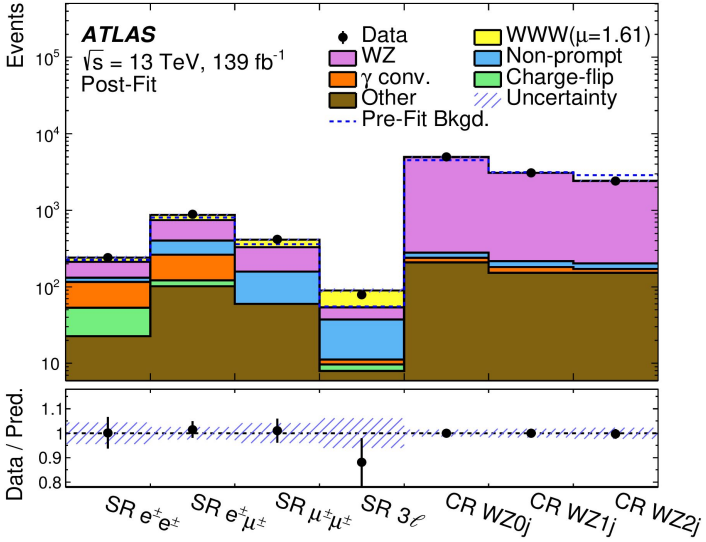


➟ Target $W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell^{\pm}\nu qq'$ / $\ell^{\pm}\nu\ell^{\pm}\nu\ell^{\mp}\nu$ where ℓ=e,μ

➟ Dominant background (WZ+jets) estimated with control regions

➟ Signal extracted using BDTs for 3ℓ & 2ℓ channels

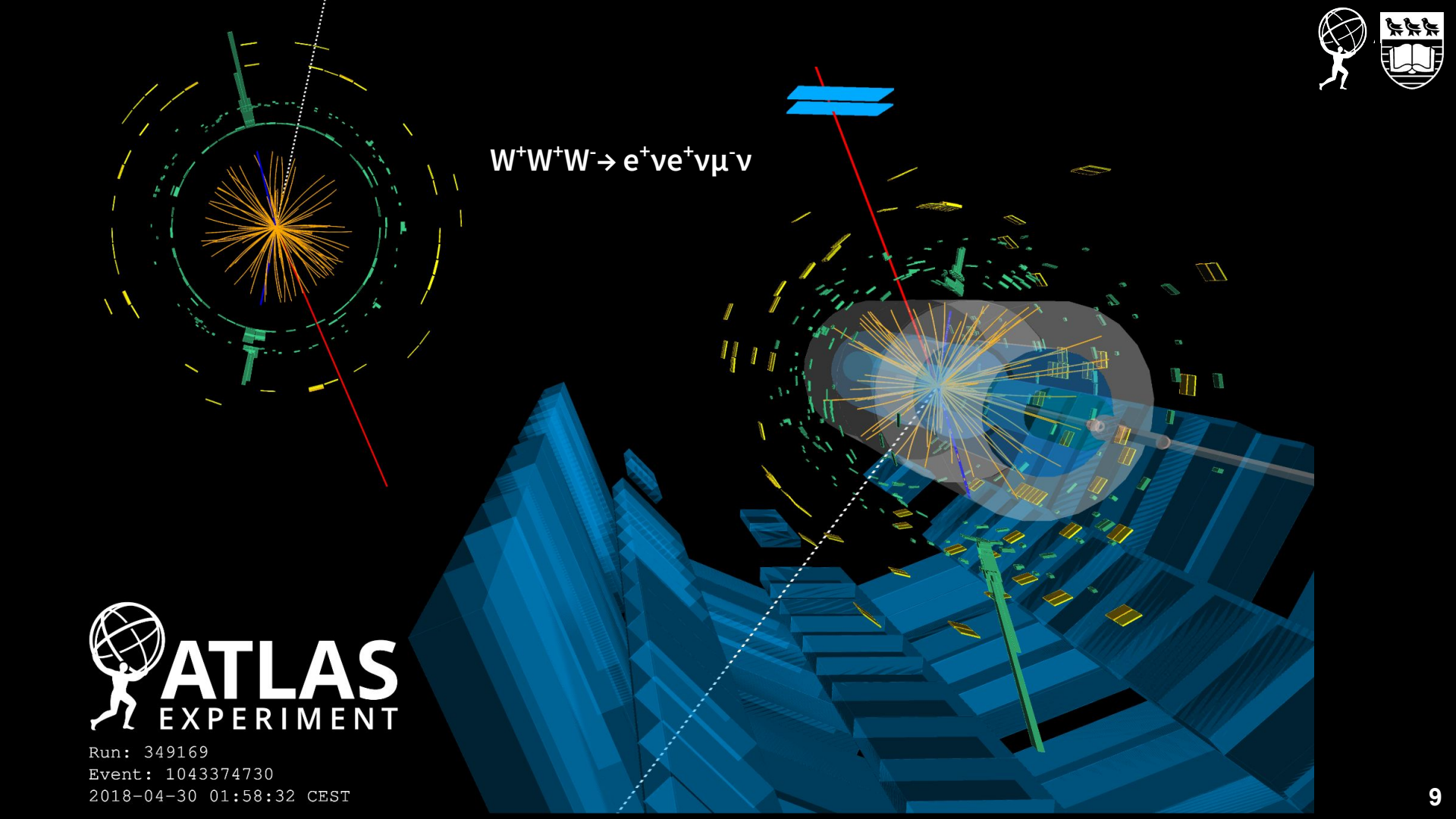




WWW production observed with 8.2σ (5.4σ) obs (exp)

σ(pp → $W^{\pm}W^{\pm}W^{\mp}$) = 850 ± 100 (stat) ± 80 (syst) fb

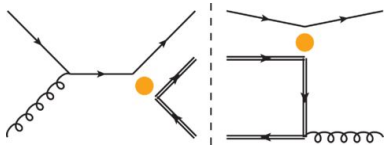
SM prediction for WWW+WH : 511 ± 42 fb @ NLO QCD


$W^+W^+W^- \rightarrow e^+\nu e^+\nu\mu^-\nu$
ATLAS
EXPERIMENT
Run: 349169
Event: 1043374730
2018-04-30 01:58:32 CEST

Top Energy Asymmetry

2110.05453 | Briefing

Probe matter/antimatter asymmetry



➟ Asymmetry in qg → $t\bar{t}$+jet events

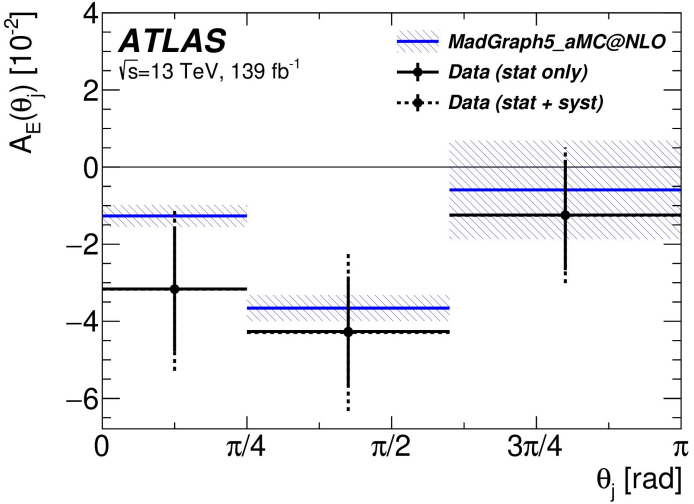
➥ Determine using energy difference as a function of jet angle

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0),$$

$$\Delta E = E_t - E_{\bar{t}}$$

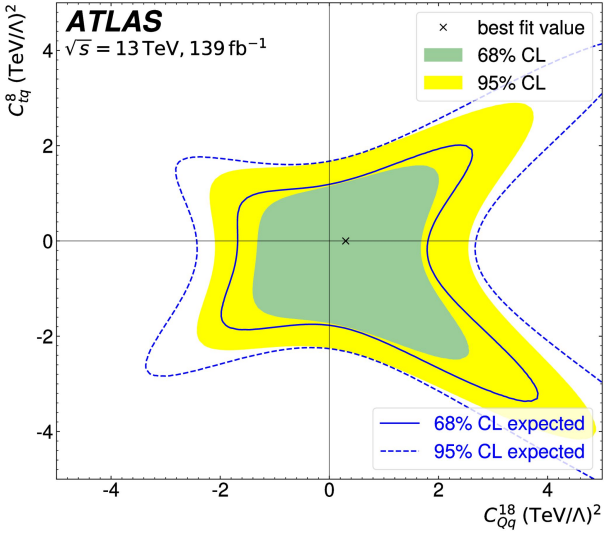
➟ Measure boosted ℓ+jets with hard additional jet, unfold at particle level



➟ No significant deviation from SM

➟ Sensitive to 4-quark EFT operators

➥ 2D limits on choice of 6 operators



Higgs Studies

$$\mathcal{L}_H = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$$

Couplings to EW gauge bosons

Higgs self-couplings

$\lambda = \frac{M_H}{v^2}$

Di-Higgs production

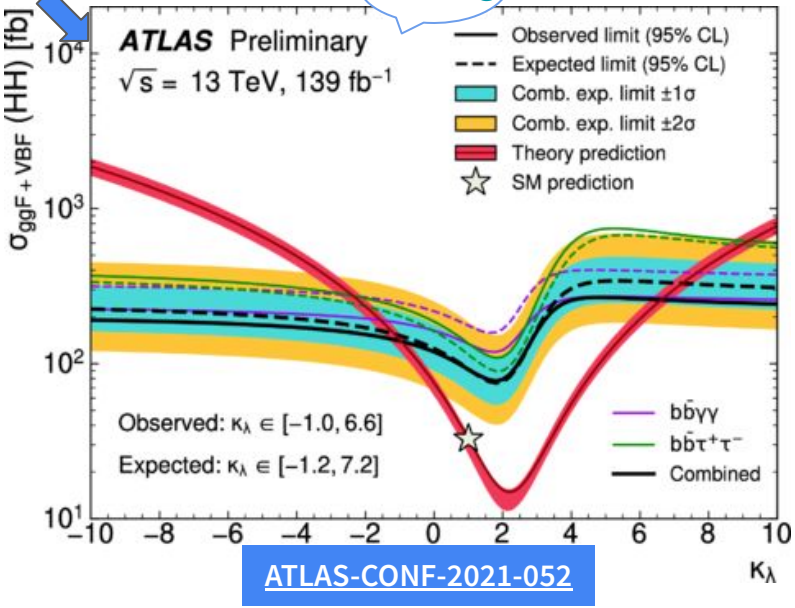
Couplings to fermions

Briefing

Colm's talk

Almost 8 million Higgs bosons produced at the LHC during Run-2!

- Higgs mass & decay width measurements
- Observations of rare Higgs decays
- Searches for new Higgs bosons and exotic Higgs decays



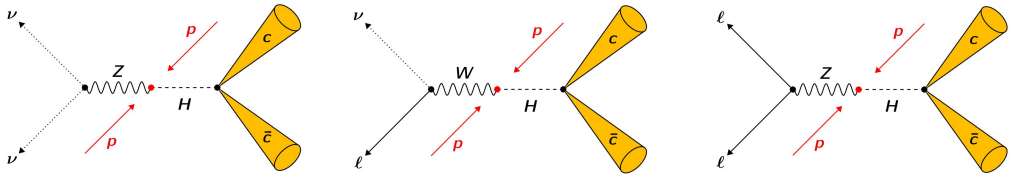
ATLAS-CONF-2021-052

2201.11428 Briefing

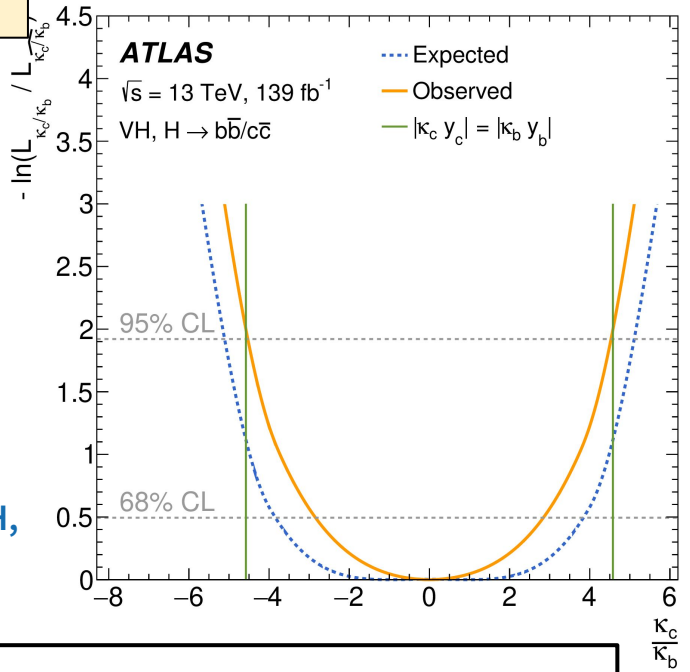
Probe Higgs-fermion Yukawa couplings, understand their hierarchy

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$

- Focus on VH production
  - Facilitate triggering, enhanced S/B w.r.t inclusive H→cc̄



- Use dedicated charm-tagging to identify signal jets
  - Tag with NN c-tagger AND veto with BDT b-tagger
  - Also b-tag veto for non-signal jets, ensuring orthogonality with VH, H → bb̄ analysis, allowing for combination of results
- Perform binned likelihood fit to m_{cc} in 16 SRs & 28 CRs
- Can interpret results in terms of couplings, based on κ framework (see 1, 2)
- Confirm weaker Higgs coupling to charm than bottom!



$|\kappa_c/\kappa_b| < 4.5\ (5.1)$ obs (exp) @ 95% CL

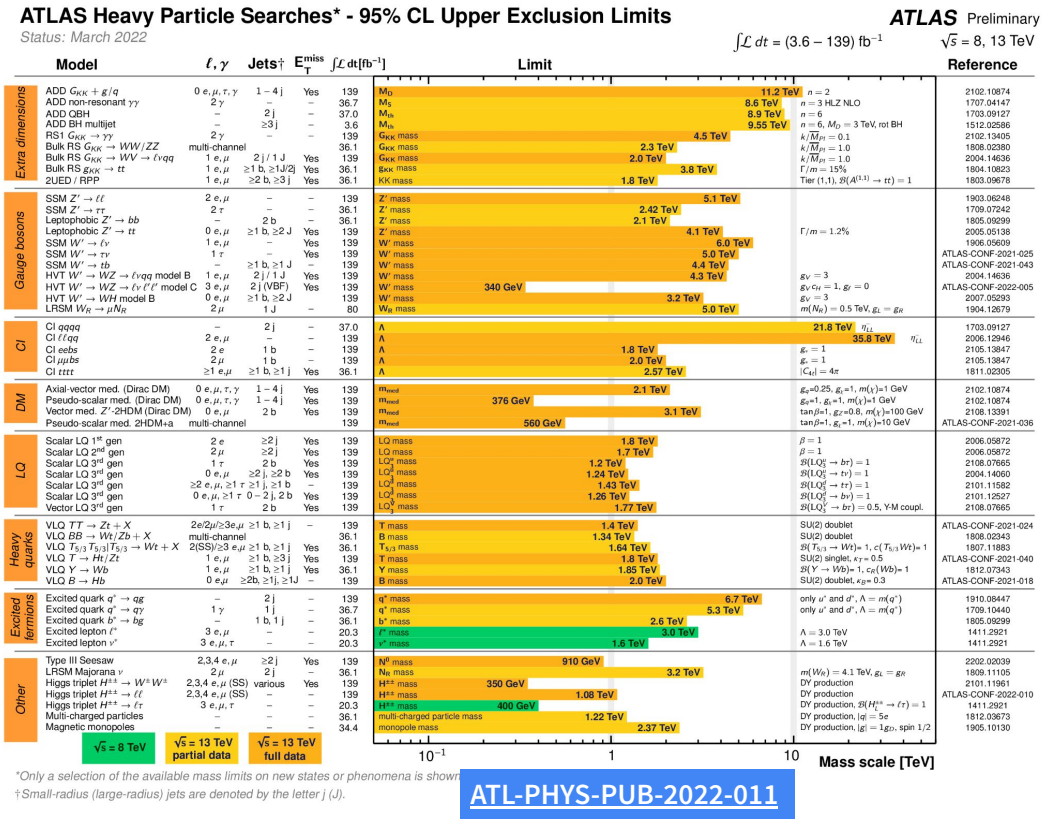
($m_b/m_c = 4.578 \pm 0.008$)

Searching Beyond the Standard Model

- New resonances, ‘bump hunting’
- Processes with large missing transverse energy
- Deviations from SM in angular distributions of final state particles
- Signatures of long-lived particles

Dominique’s talk

e.g. collider searches for Dark Matter (DM), SUSY searches..



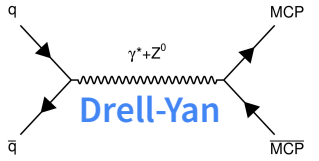
ATL-PHYS-PUB-2022-011

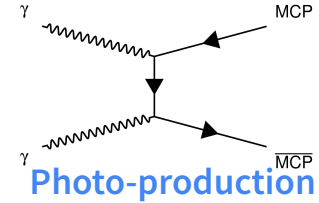
Search for Multi-charged Particles

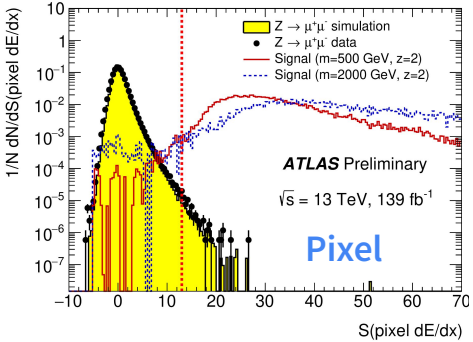
ATLAS-CONF-2022-034

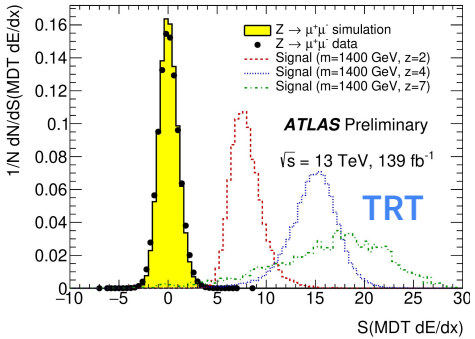
Look for BSM particles which may decay far from the primary vertex

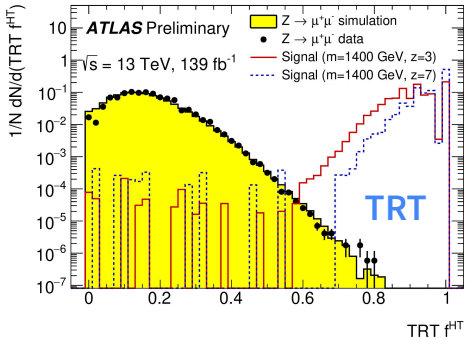
- Multi-Charged Particles (MCP) predicted by a plethora of models
  - Could explain some excesses observed in direct/indirect dark matter searches
- Muon-like high ionisation signals, measured in pixel, TRT & MDT detectors
  - $|q| = ze$ with $2 \leq z \leq 7$
- Single muon, missing energy & 'late muon' triggers used
  - Trigger on events with $p_T > 50$ GeV jet in the current bunch-crossing & $p_T > 10$ GeV muon in the next one
- No significant excess, set mass limits ranging from ~1 TeV (q=|2e|) - 1.6 TeV (q=|6e|)

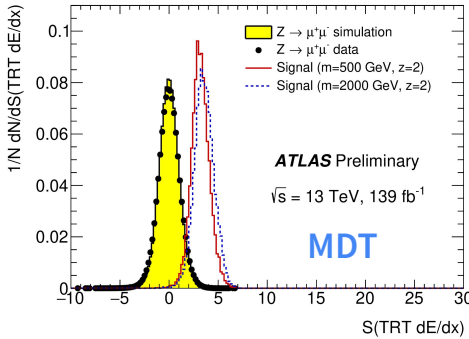




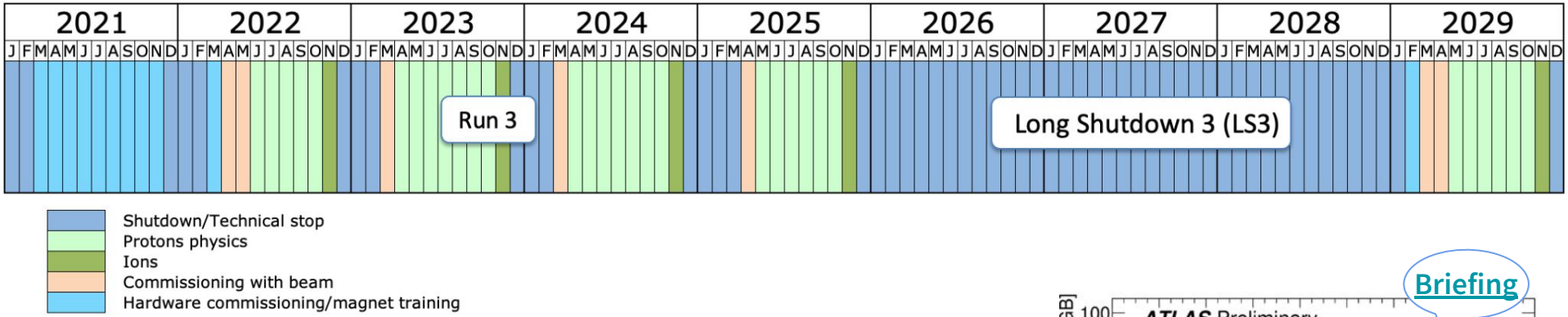






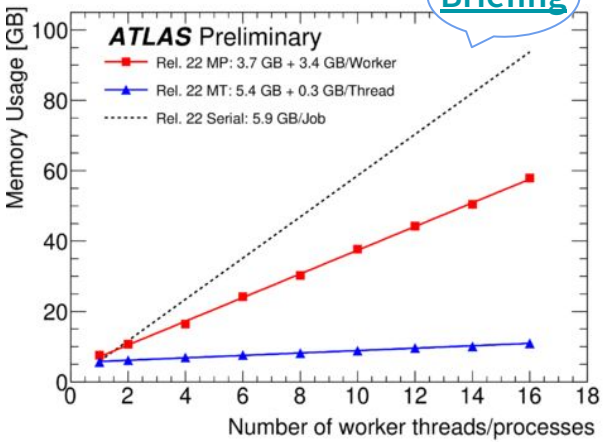


Long Shutdown 2 & Run-3



- Used the shutdown to make multiple improvements to detector, triggers, software, computing…
  - A longer shutdown than expected… restarting this year
  - Performed installation & commissioning of new hardware around COVID restrictions
  - Held remote ‘milestone weeks’ to simulate ATLAS control room in running conditions & train

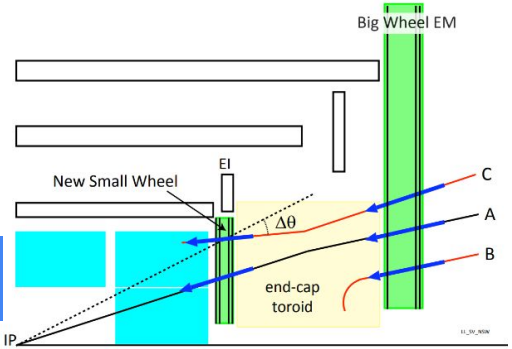
Briefing

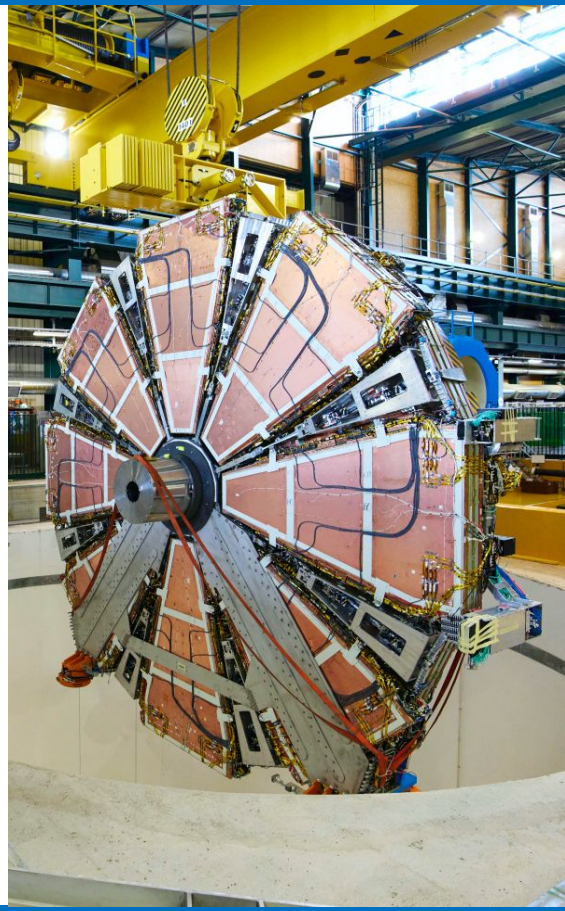


Phase-I Muon System Upgrade

- Replace existing small muon wheels with New Small Wheels (NSWs)
- Fast & precise muon tracking with micromegas & small-strip thin-gap chambers
  - Improve spatial resolution & granularity
  - 7x improvement in online fakes rejection & offline tracking in endcaps

ATLAS-TDR-020

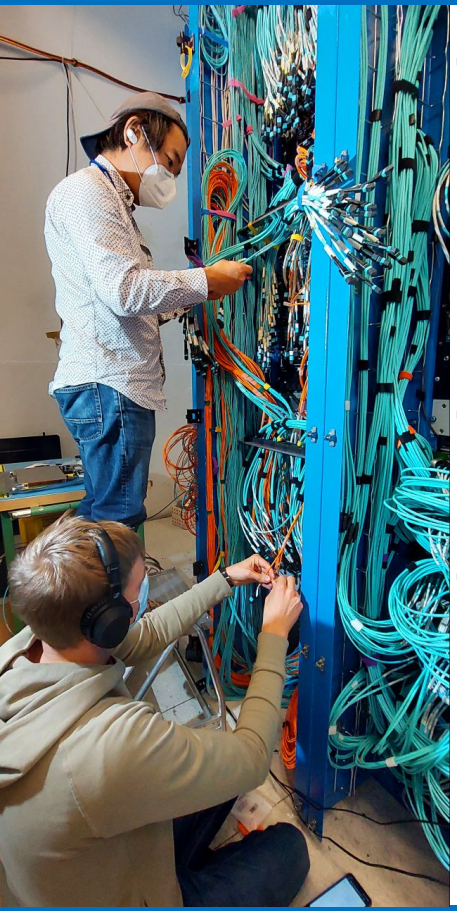




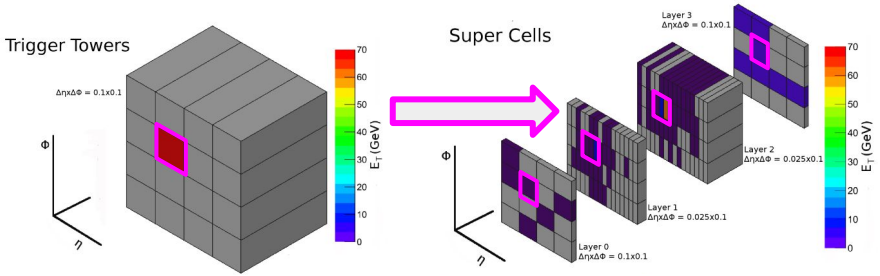
- Both A-side and C-side NSW have been installed in ATLAS

Constructed 25% of required sTGCs
Performed assembly, installation & commissioning at CERN

Phase-I Liquid Argon Calorimeter Upgrade



- Finer granularity information passed from the LAr calorimeter to L1 trigger



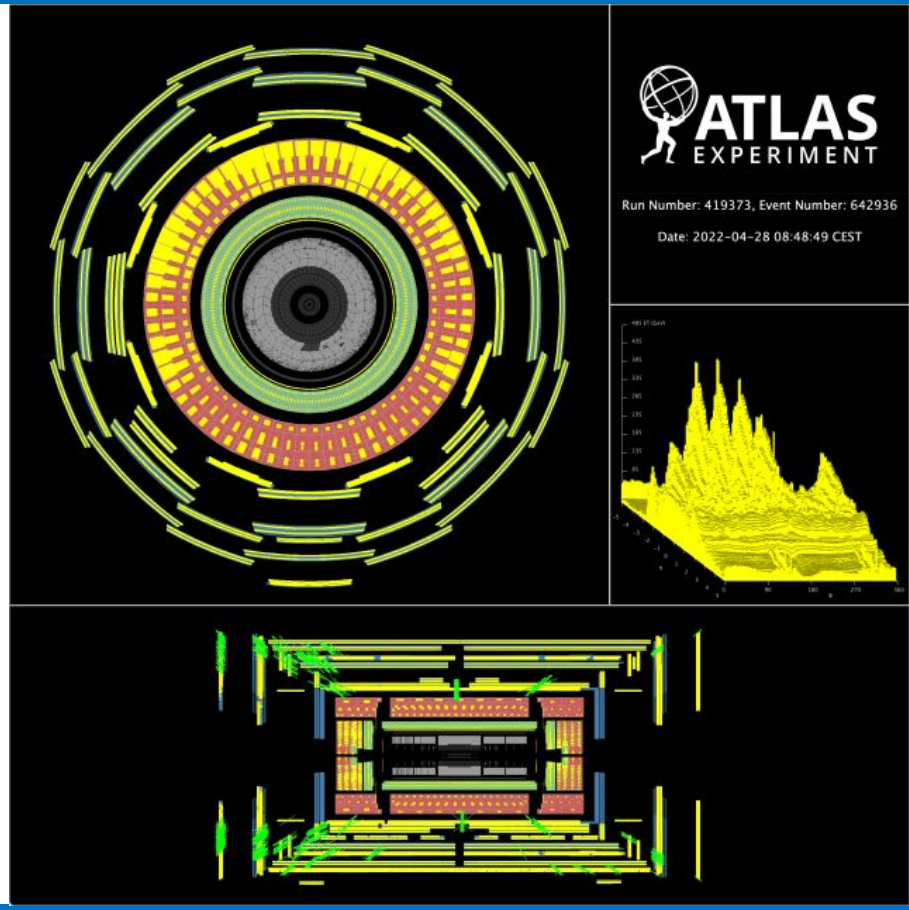
ATLAS-TDR-022

- Up to 10x granularity & provides shower shape information
  - Improved discrimination between electrons & jets
  - E_T threshold may be lowered by 7 GeV while maintaining current L1 trigger rate
- Requires upgraded front-end & back-end electronics
  - Installation completed during the long shutdown
  - Phase-I system is now used concurrently with the legacy system, undergoing commissioning as the ATLAS trigger upgrade continues

Design & construction of new front-end baseplanes
Financial contributions to new trigger digitiser boards
Commissioning of the new system

Beam Splashes

- Friday 22nd April marked the start of Run-3
- Need to recommission accelerator & safely ramp up beam energy/intensity
- Performed beam ‘splashes’
  - Single proton beam, hitting a collimator upstream of the detector
- Send splashes from one side at a time
  - Subsystems can perform timing studies, commission new upgrades
- Had first 13.6 TeV collisions on 31st May!



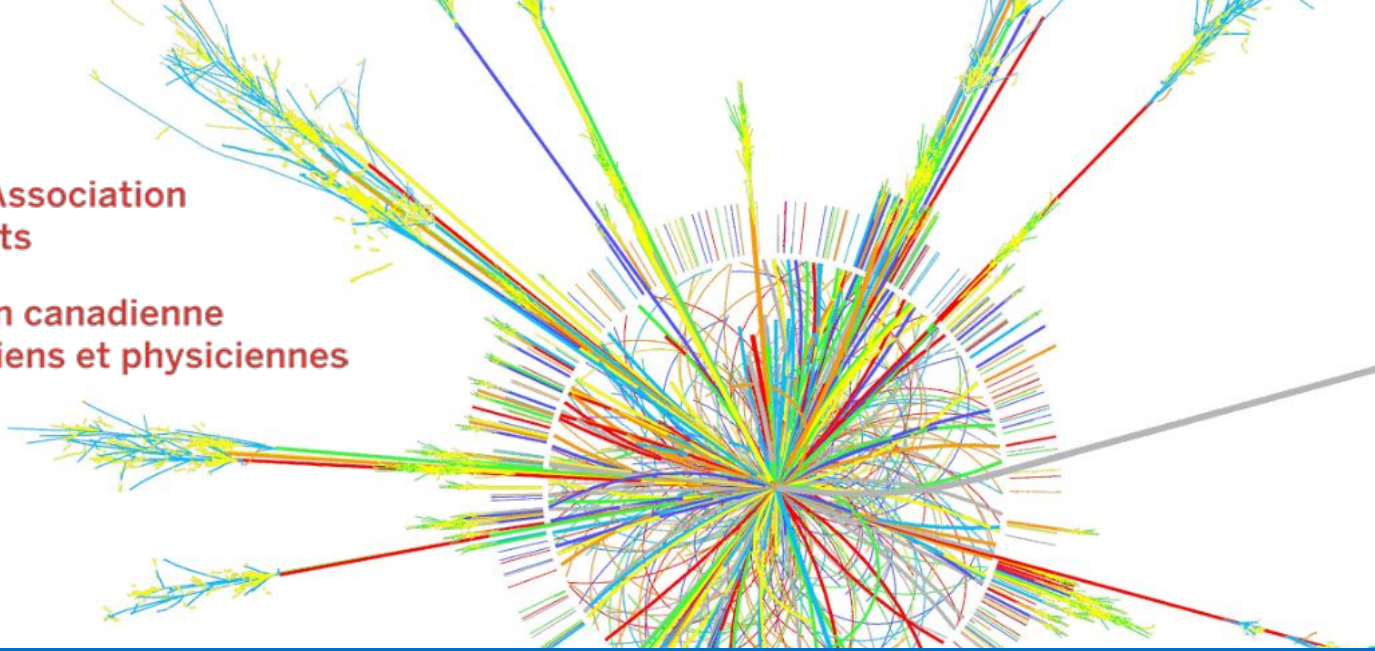
Conclusions & Outlook

- ATLAS has an extremely diverse physics programme, with >100 published Run-2 results so far
  - Only a handful of the latest results presented here
  - See the list of all public results on the AtlasPublic twiki, and catch up on latest news with ATLAS briefings

- Many of these analyses were completed during the long shutdown, during which time the phase-I upgrades were also installed
  - The collaboration were able to commission these upgrades & prepare experts & shifters, in spite of the challenges of international lockdowns
  - Now ready for Run-3 data, at higher luminosity & increased pile-up

- Run-3 has begun!
  - Beam 'splashes' and 900 GeV / 13.6 TeV pp collisions have now been observed in ATLAS, after the long break

- Phase-II upgrades, to be installed for the HL-LHC (2029)
  - See Maximilian's & Thomas' talks



Canadian Association
of Physicists

Association canadienne
des physiciens et physiciennes

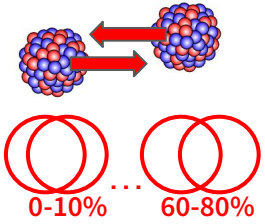
Backup

Heavy Ion Collision Studies

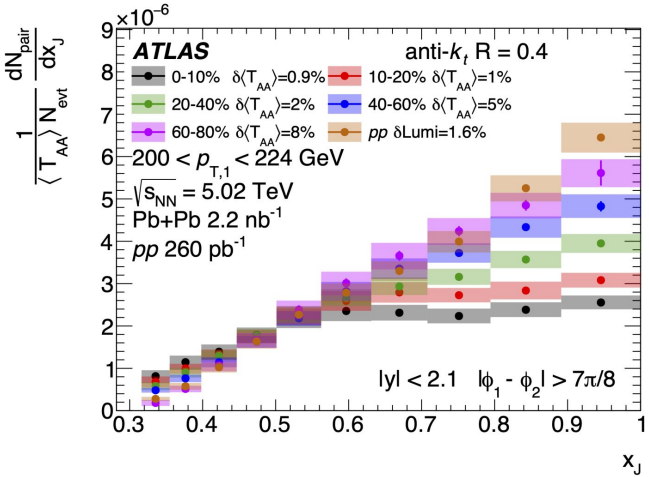
2205.00682 | Briefing

Probe the quark-gluon plasma

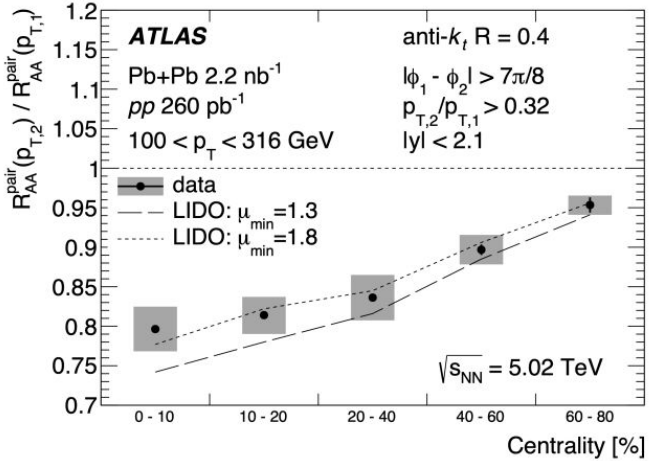
- Not just pp collisions from the LHC… also proton-lead, lead-lead and xenon-xenon
- Many studies arising from these collisions, e.g. jet suppression in Pb-Pb



- Particle yields modified compared to pp scattering $R_{AA} = \frac{1}{N_{evt}} \frac{dN_{jet}}{dp_T} \Big/ \left(\langle T_{AA} \rangle \frac{d\sigma_{pp}}{dp_T} \right)$
- Study rate of jets for a given centrality interval
- Measure 2D p_T distributions of leading dijet pair, unfold to extract $\frac{dN_{pair}}{dp_{T,1}dp_{T,2}}$, project across $p_{T,1}$ selections to extract $\frac{dN}{dx_J}$, where $x_J \equiv p_{T,2}/p_{T,1}$



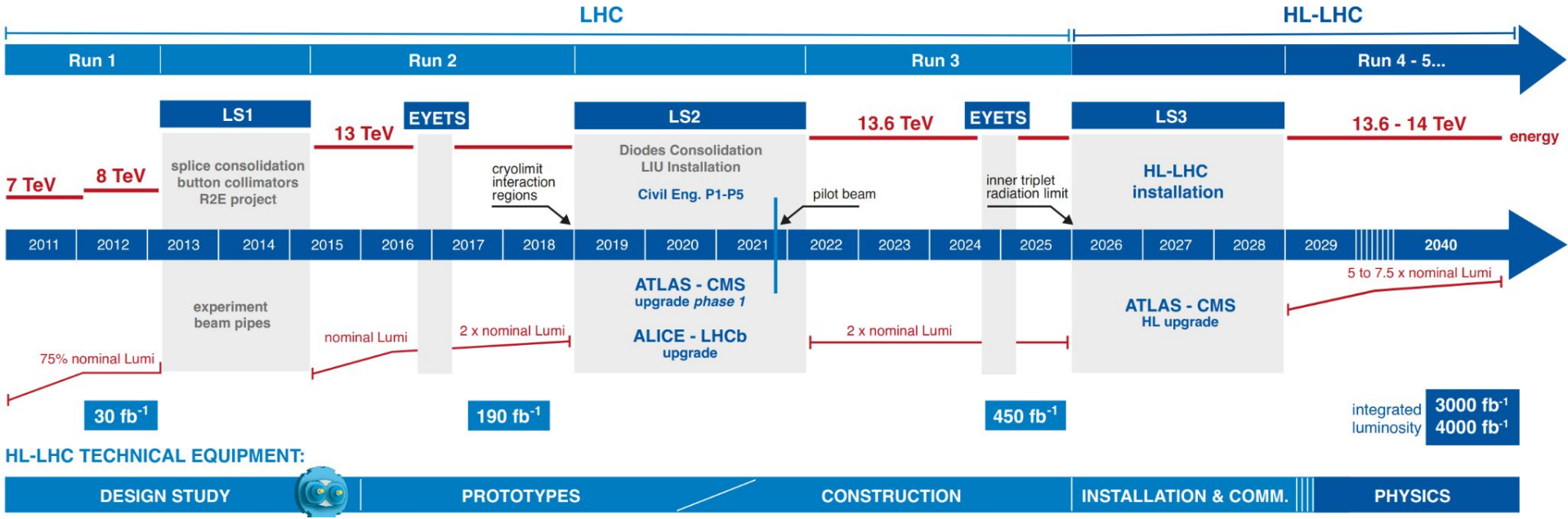
- Measure R_{AA}^{pair}, quantifying suppression of each jet in the dijet
- Observe 3σ suppression of subleading jets to leading jets in most peripheral collisions



LHC Schedule

https://hilumilhc.web.cern.ch/content/hl-lhc-project

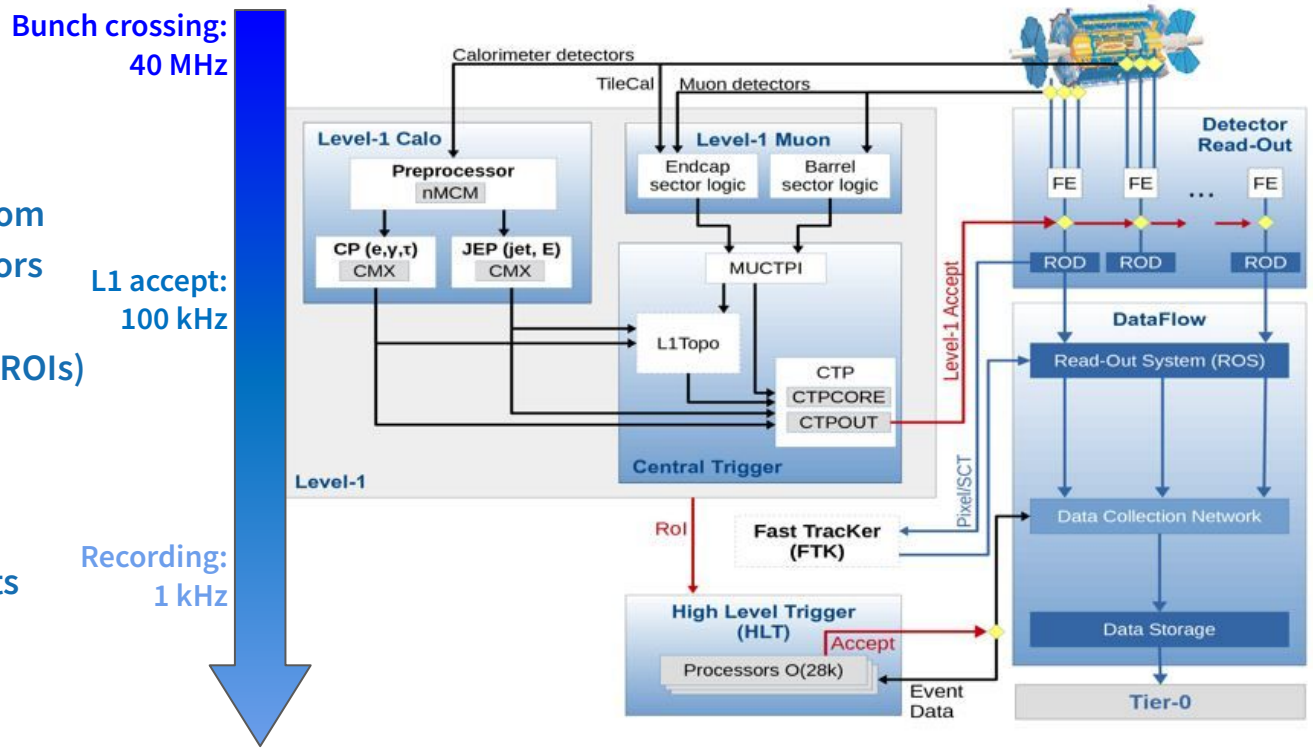
LHC / HL-LHC Plan



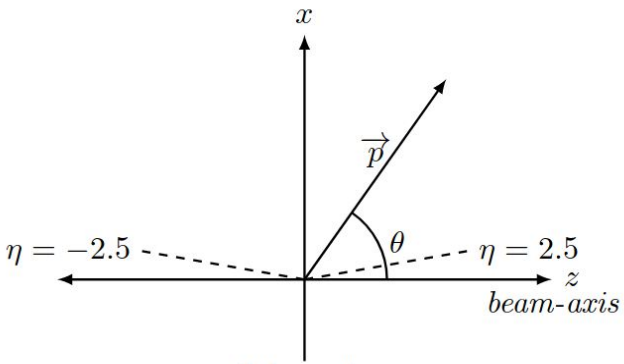
The ATLAS Trigger

2007.12539

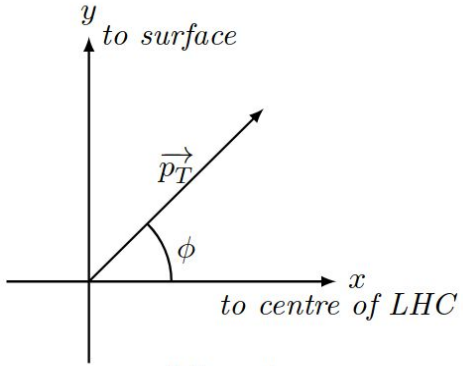
- Not all events observed by ATLAS contain interesting information…
  - Select events with trigger
- Level-1
  - Hardware based
  - Use subset of information from calorimeters & muon detectors
  - Decision made in < 2.5 μs
  - Defines Regions Of Interest (ROIs)
- High-Level Trigger (HLT)
  - Software based
  - Detailed analysis of L1 events in ROIs



LHC Coordinate System



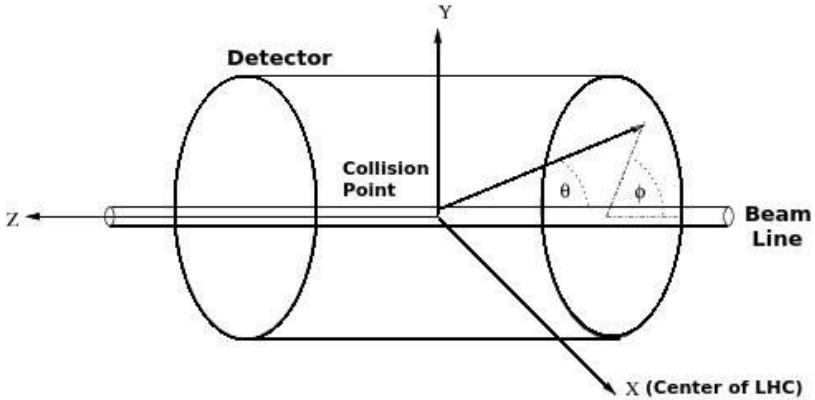
(a) xz-plane



(b) xy-plane

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Data Quality Efficiency

1911.04632

2018 Data Quality Efficiency [%]													
Dataset	Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger	
	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1	HLT
pp @ 13 TeV	99.78	99.77	100	99.67	100	99.80	99.72	99.98	99.98	100	99.58	99.99	99.99
pp @ 13 TeV ($\mu = 2$)	100	100	100	100	100	99.07	99.94	100	99.98	100	100	98.03	100
Pb-Pb @ 5.02 TeV	100	100	100	99.99	100	100	100	100	99.98	100	83.25	99.97	100

		Data Quality Efficiency [%]	Integrated Luminosity
pp @ 13 TeV	Good for Physics	97.46	58.5 fb^{-1}
pp @ 13 TeV ($\mu = 2$)		92.86	193 pb^{-1}
Pb-Pb @ 5.02 TeV		82.54	1.44 nb^{-1}

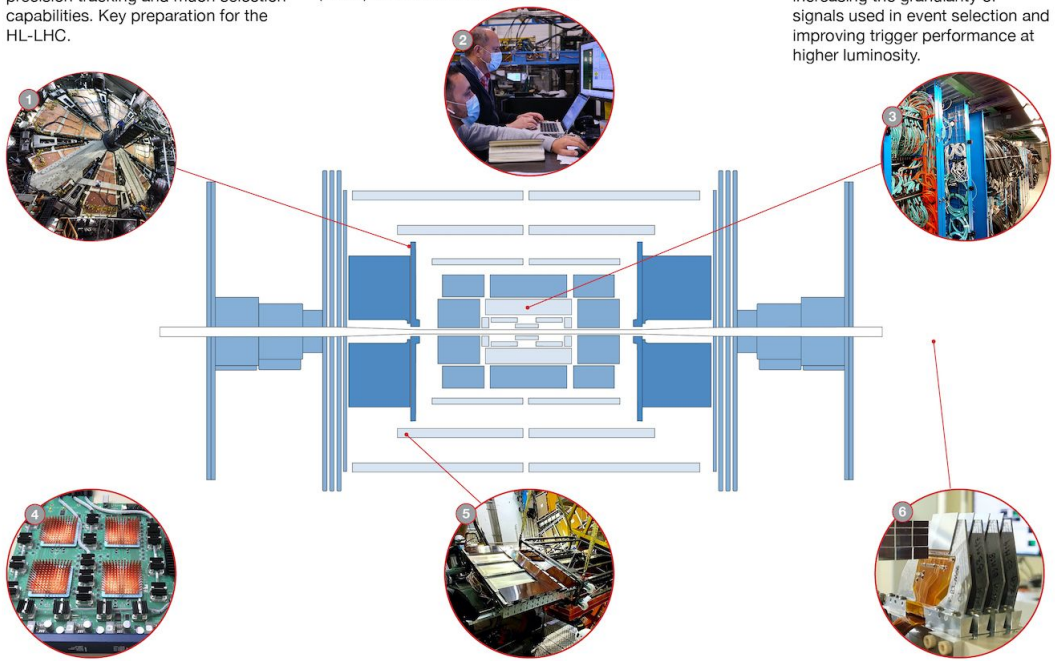
ATLAS LS2 Upgrades

https://home.cern/press/2022/ATLAS-upgrades-LS2

MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.



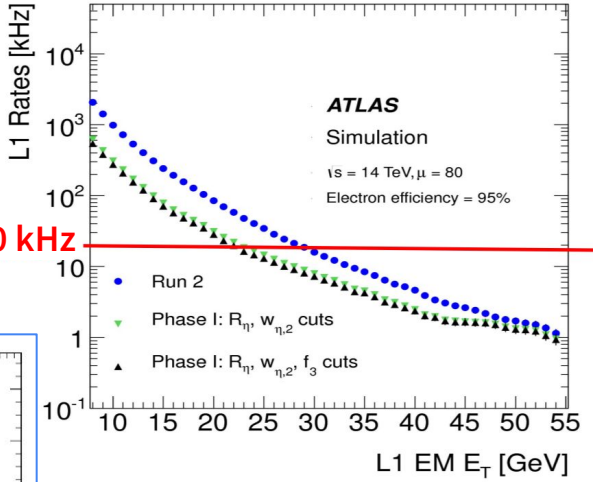
TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

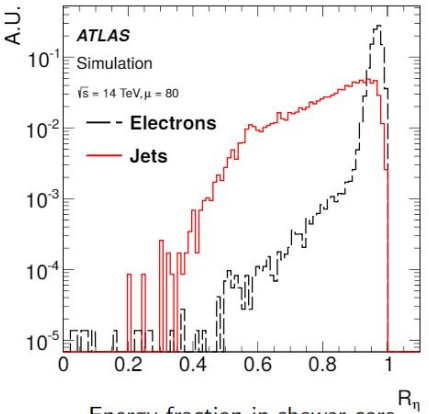
ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new "out-of-vacuum" solution.

Expected LAr Super Cell Performance

- Shower shape variables may be used to discriminate between jets and electrons at L1 trigger level
  - Improved jet background rejection for electron ID
- E_T threshold can be lowered by 7 GeV @ 20 kHz

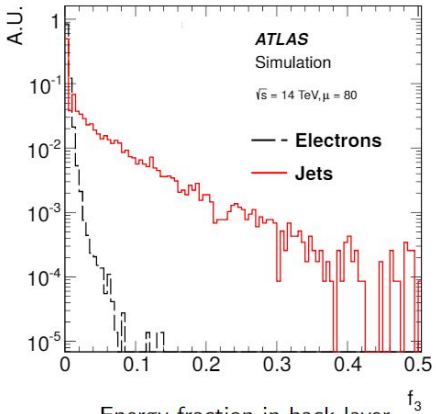


Shower shape variables



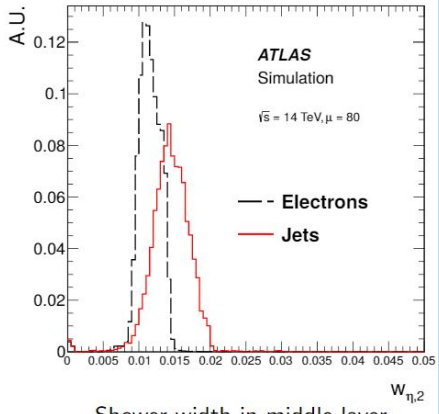
Energy fraction in shower core

$$R_\eta = \frac{E^{(2)}_{T,\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{T,\Delta\eta\times\Delta\phi=0.175\times0.2}}$$



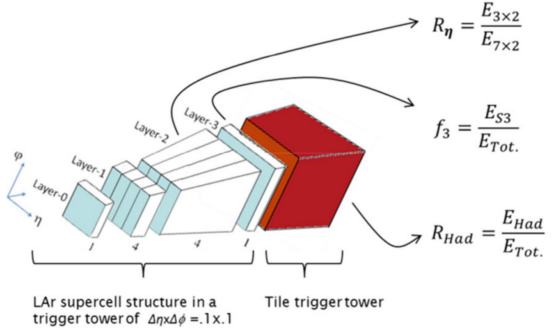
Energy fraction in back layer

$$f_3 = \frac{E^{(3)}_{T,\Delta\eta\times\Delta\phi=0.2\times0.2}}{E^{(1)}_{T,\Delta\eta\times\Delta\phi=0.075\times0.2} + E^{(2)}_{T,\Delta\eta\times\Delta\phi=0.075\times0.2} + E^{(3)}_{T,\Delta\eta\times\Delta\phi=0.2\times0.2}}$$



Shower width in middle layer

$$w_{\eta,2} = \sqrt{\frac{\Sigma\left(E^{(2)}_T\times\eta^2\right)_{\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{T,\Delta\eta\times\Delta\phi=0.075\times0.2}} - \left(\frac{\Sigma\left(E^{(2)}_T\times\eta\right)_{\Delta\eta\times\Delta\phi=0.075\times0.2}}{E^{(2)}_{T,\Delta\eta\times\Delta\phi=0.075\times0.2}}\right)^2}$$



Run-3 Detector Status

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

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	96.7%
SCT Silicon Strips	6.3 M	98.3%
TRT Transition Radiation Tracker	350 k	96.6%
LAr EM Calorimeter	170 k	100%
Tile Calorimeter	5200	99.2%
Hadronic End-Cap LAr Calorimeter	5600	99.9%
Forward LAr Calorimeter	3500	99.8%
LVL1 Calo Trigger	7160	99.9%
LVL1 Muon RPC Trigger	383 k	99.8%
LVL1 Muon TGC Trigger	312 k	100%
MDT Muon Drift Tubes	344 k	99.7%
MicroMegas NSW	2.1 M	98.0%
STGC NSW	358 k	99.2%
RPC Barrel Muon Chambers	383 k	87.7%
TGC End-Cap Muon Chambers	312 k	99.4%
ALFA	10 k	100%
AFP	430 k	100%
LUCID	2x16	100%
ZDC	2x20	100%