UK HEP Forum 2021: From Laboratories to the Universe and Back

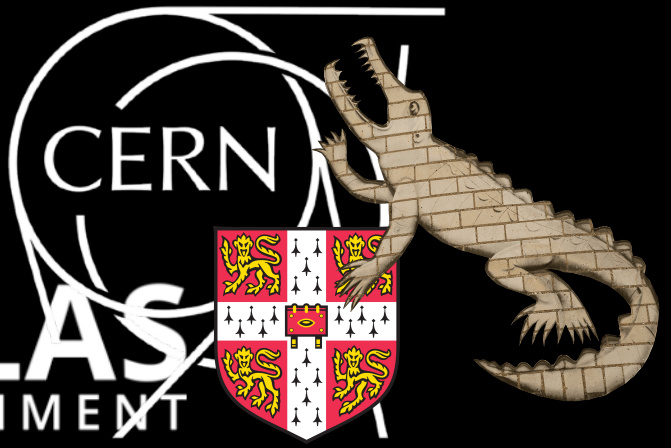
# ATLAS: Physics prospects in (early) Run 3

OLEG BRANDT

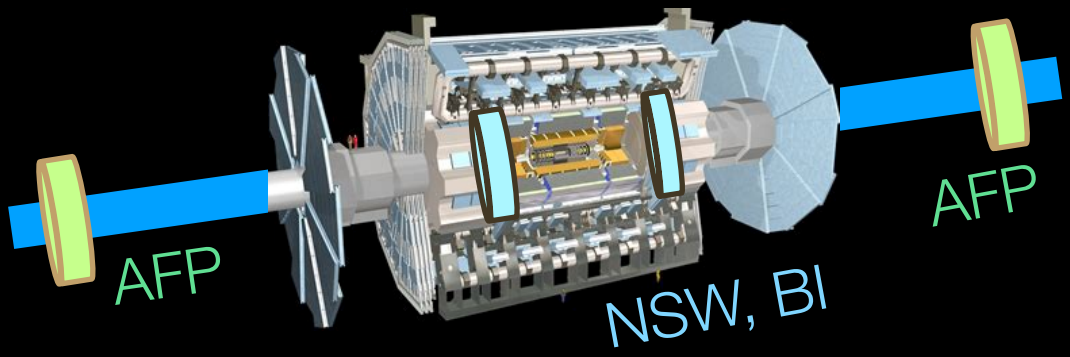
24/11/2021

UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT



# ATLAS DETECTOR MAJOR UPGRADES FOR RUN 3



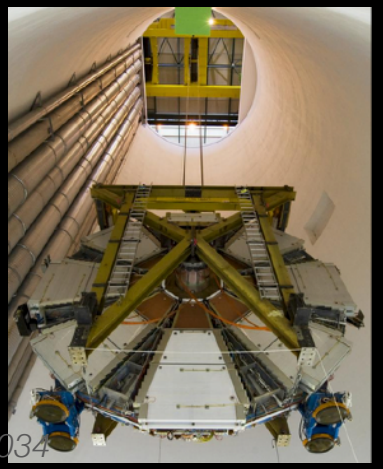

*UK leadership*

AFP: ATLAS Forward Proton detector

- Scheduled to run throughout data taking (only 15 fb-1 / 140 fb-1 in Run 2)
- Important feature: Time of Flight (ToF)

NSW: New Small Wheel

- New muon detector in $|\eta| > 1.05$ based on Micromegas and small Thin Gap Chambers
- Excellent spatial + time resolution
- Mitigate pile-up and reduce fake muons

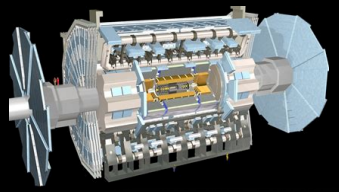
*ATL-COM-MUON-2014-034*

BI: Barrel Inner layer muon system upgrade

- Inner barrel layer extension of muon spectrometer based on Resistive Plate Chambers + small Muon Drift Tubes
- Excellent time resolution
- Improve muon trigger efficiency in the intermediate region

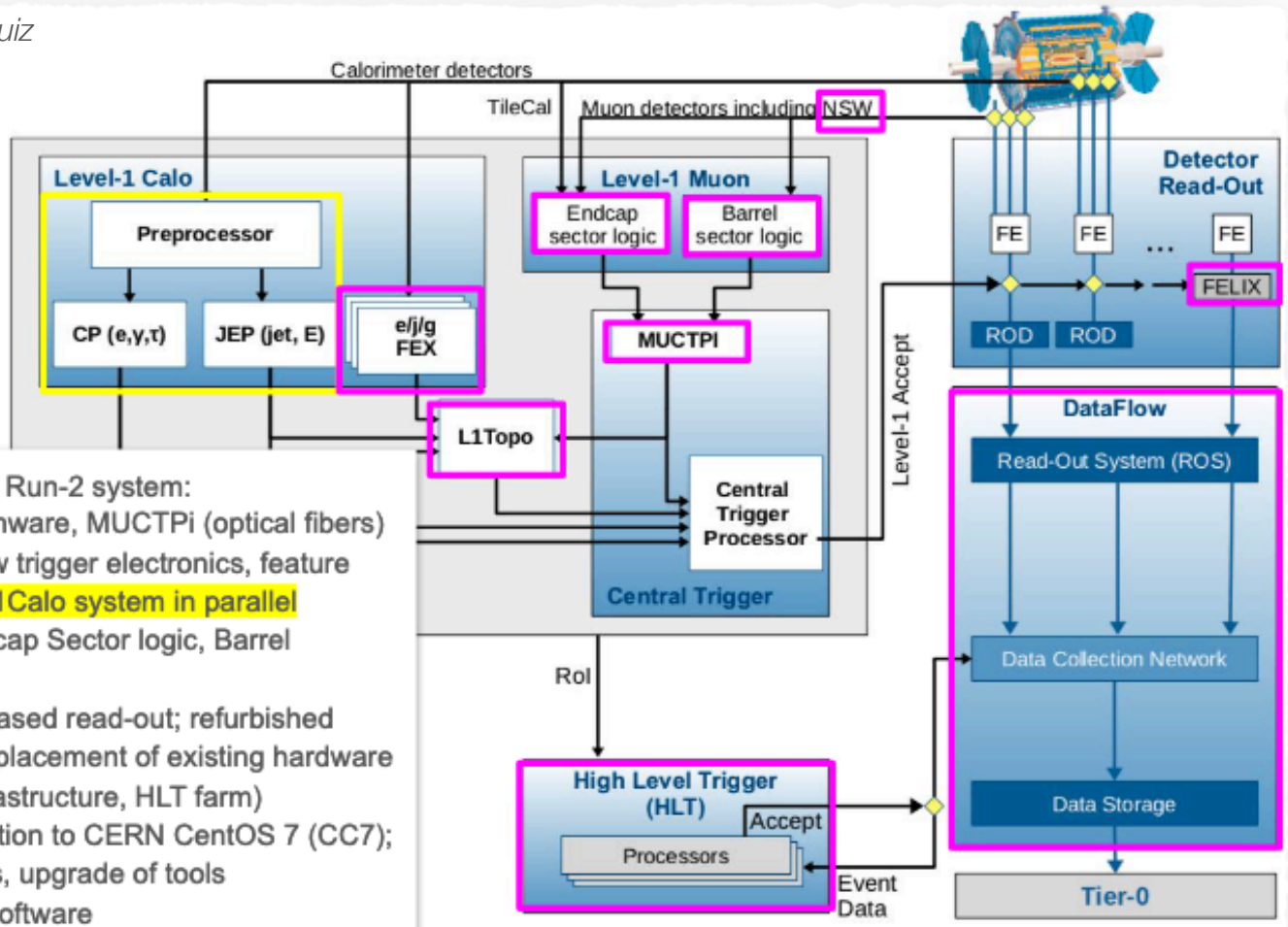
# ATLAS DAQ + TRIGGER UPGRADES FOR RUN 3

~ COMPLETE REPLACEMENT



**DAQ** **L1** **HLT** **Tier 0**

*Courtesy: C. Bernius, A. Ruiz*

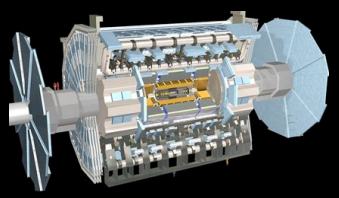



Many changes compared to Run-2 system:

- L1 Central: CTP firmware, MUCTPi (optical fibers)
- L1Calo/L1Topo: new trigger electronics, feature extractors; Run-2 L1Calo system in parallel
- L1Muon/NSW: Endcap Sector logic, Barrel MUCTP interface
- DAQ: New FELIX-based read-out; refurbished read-out system; replacement of existing hardware (networks, core infrastructure, HLT farm)
- Software: OS migration to CERN CentOS 7 (CC7); new TDAQ releases, upgrade of tools
- HLT: new HLT MT software

# ATLAS DAQ + Trigger upgrades for Run 3

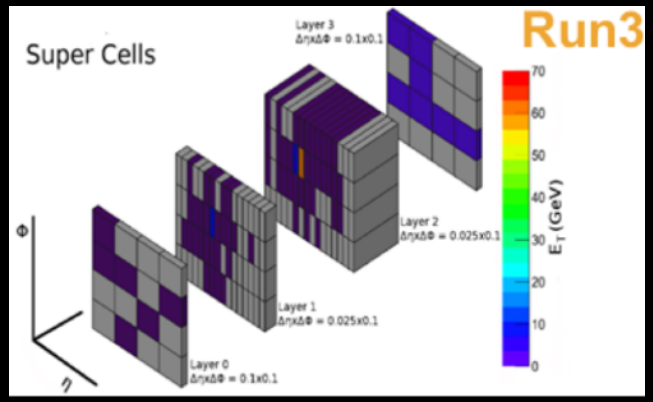
~ COMPLETE REPLACEMENT



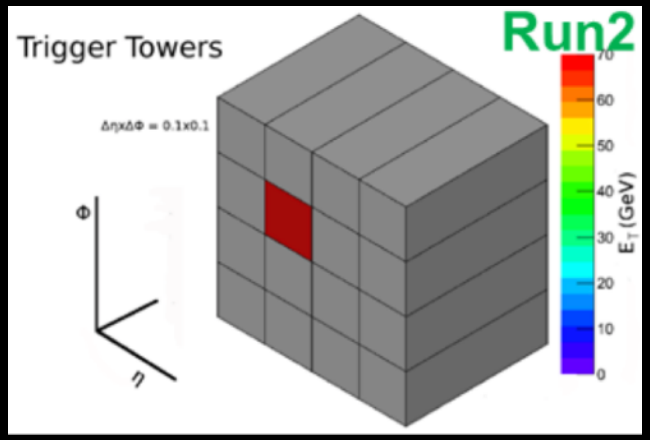
**DAQ** | **L1** → **HLT** → **Tier 0**

## L1Calo (level 1 calo trigger)

- Trigger readout fully digitised + finer granularity ("super cell")
- Improved $e/\gamma$, $\tau$, jet, $E_T^{miss}$ with new hardware
- Large-R jet reconstruct'n
- UK: eFEX (electron feature extractor)+ROD (readout driver), leadership

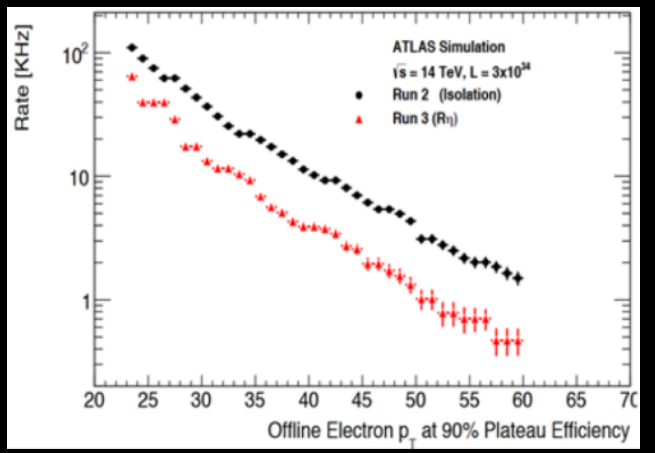



*ATLAS-TDR-022*




*ATLAS-TDR-022*

10x higher granularity!




*ATLAS-TDR-023*

## L1Muon (not shown)

- 6 →15 $p_T$ thresholds
- Charge information

## HLT (High Level Trigger) & Data AQuisition (DAQ)

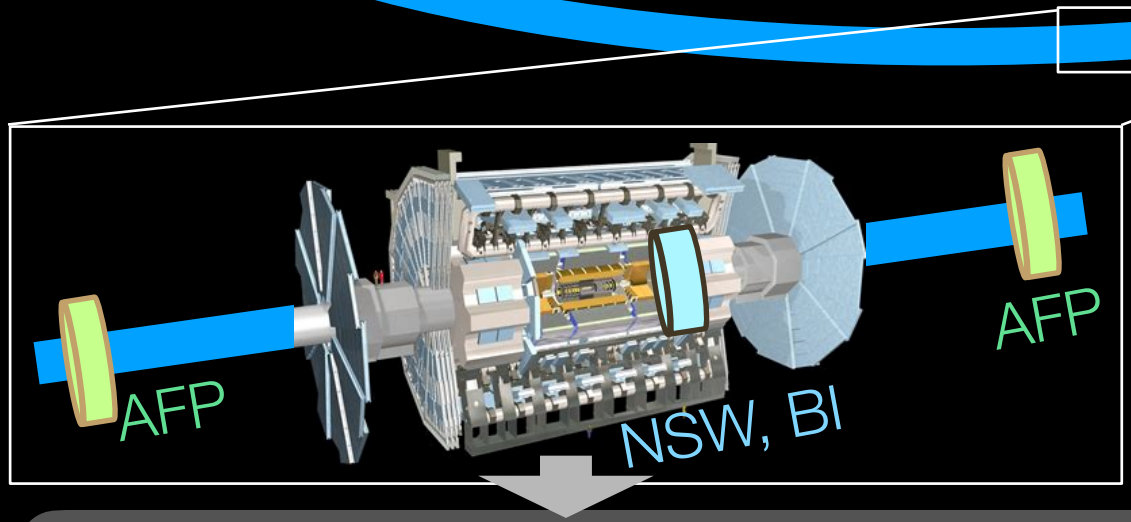
- Similarly dramatic improvements!
- Not shown (→ backup)

# LHC Run 3: 2022 - 2025

**pp:** $\sqrt{s} = 13.6$ TeV, $\mathscr{L} \approx 160$ fb$^{-1}$

**PbPb:** $\sqrt{s_{NN}} = 5.5$ TeV, $\mathscr{L} \approx 6$ nb$^{-1}$

**Special runs:** low-$\mu$, high $\beta^*$, O-O, p-O, p-He




Potentially 2x more PbPb, pp data in 2021 using AFP + time of flight!

**DAQ** **L1** eFEX* … ROD* → **HLT** New tracking +trigger → **Tier 0** Trigger Level Analysis, delayed reconstruct'n

Major UK involvement

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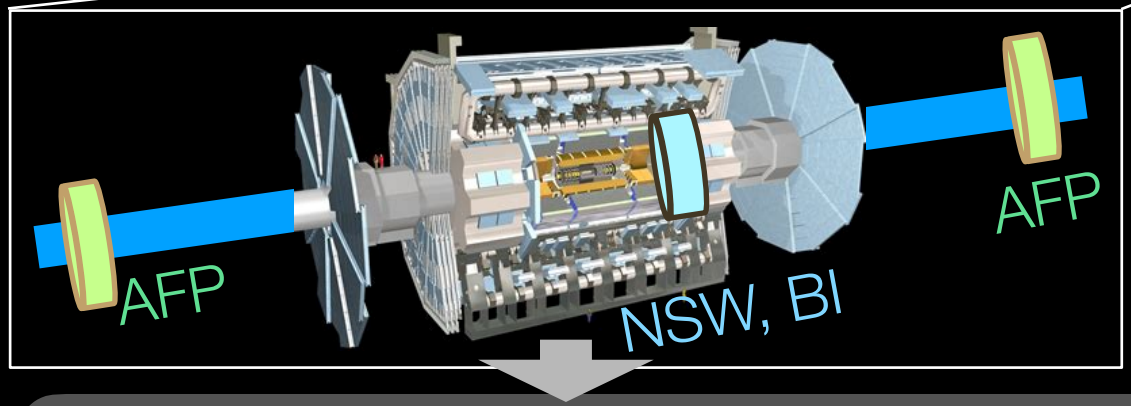


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**DAQ** | **L1** eFEX* … ROD* | **HLT** New tracking +trigger | **Tier 0** Trigger Level Analysis, delayed reconstruct'n

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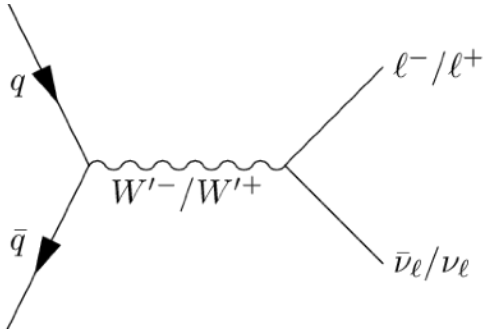
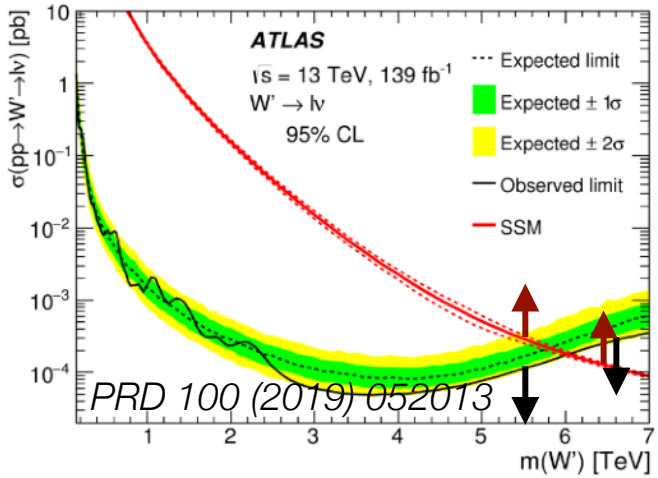
# Increase in $\sqrt{s} = 13 \rightarrow 13.6$ TeV

- Substantial increase in sensitivity to BSM physics at mass scales > 5 TeV:
  - W' / Z':



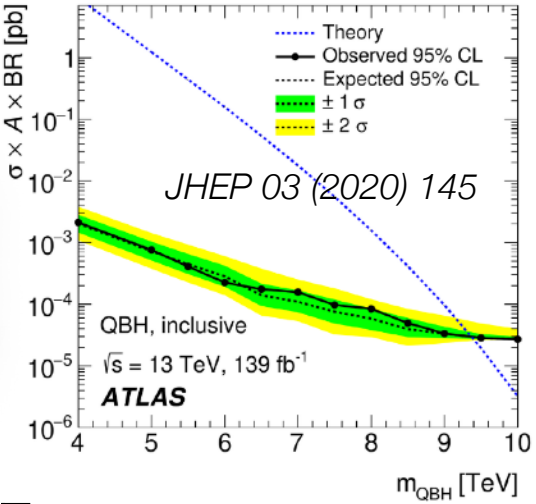



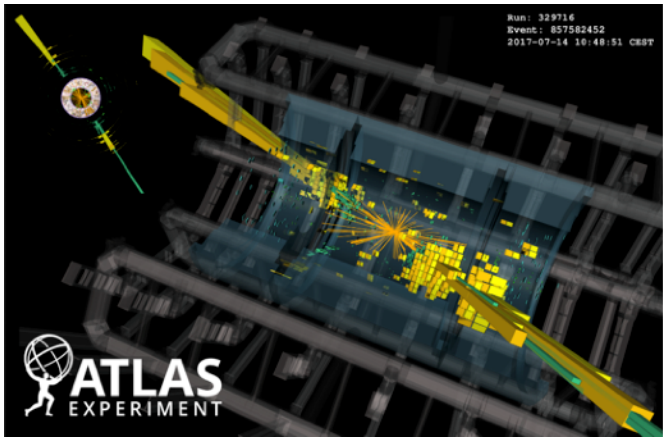

Potential limit improvement by ~1 TeV…

*ATL-PHYS-PUB-2018-044*

  - Quantum black holes:

For $m_{\text{QBH}} = 9.5$ TeV:
$\sigma_{\text{QBH}}$ increases by ~ 250%!

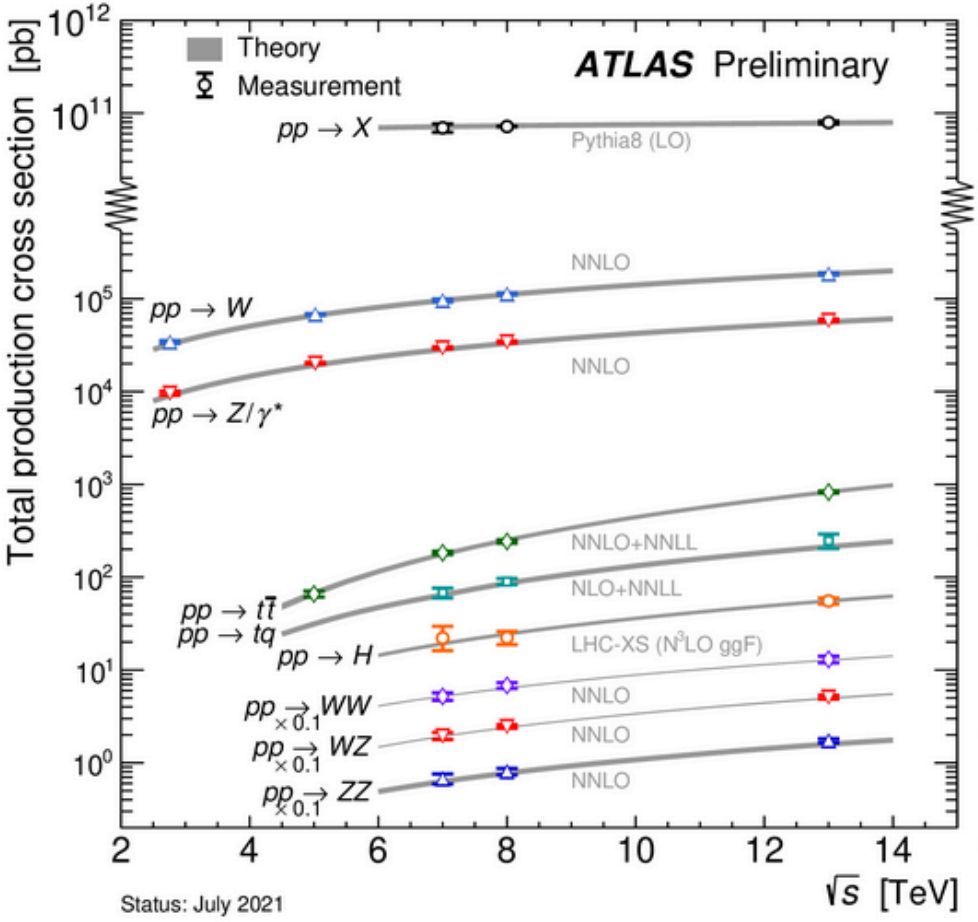



- [Moderate benefits from $\sqrt{s}$ increase for most analyses]
  - Example: stop with $m_{\tilde{t}} = 1.5$ TeV → $\sigma_{\tilde{t}\tilde{t}}$ increases by 30%

# Increase in $\sqrt{s} = 13 \rightarrow 13.6$ TeV

- Additional data point for cross section measurements:




$pp \rightarrow X$
7 TeV, 20 $\mu b^{-1}$, Nat. Commun. 2 (2011) 463
8 TeV, 500 $\mu b^{-1}$, PLB 761 (2016) 158
13 TeV, 60 $\mu b^{-1}$, PRL 117 182002 (2016)

$pp \rightarrow W$ $pp \rightarrow Z/\gamma^*$
2.76 TeV, 4 $pb^{-1}$, EPJC 79 (2019) 901
5 TeV, 25 $pb^{-1}$, EPJC 79 (2019) 128
7 TeV, 4.6 $fb^{-1}$, EPJC 77 (2017) 367
8 TeV, 20.2 $fb^{-1}$, JHEP 02, 117 (2017) (for $Z$)
8 TeV, 20.2 $fb^{-1}$, EPJC 79 (2019) 760 (for $W$)
13 TeV, 81 $pb^{-1}$, PLB 759 (2016) 601 (for $W$)
13 TeV, 3.2 $fb^{-1}$, JHEP 02, 117 (2017) (for $Z$)

$pp \rightarrow t\bar{t}$
5 TeV, 257 $pb^{-1}$, ATLAS-CONF-2021-003
7 TeV, 4.6 $fb^{-1}$, EPJC 74 (2014) 3109
8 TeV, 20.3 $fb^{-1}$, EPJC 74 (2014) 3109
13 TeV, 3.2 $fb^{-1}$, EPJC 80 (2020) 528

$pp \rightarrow tq$
7 TeV, 4.6 $fb^{-1}$, PRD 90, 112006 (2014)
8 TeV, 20.3 $fb^{-1}$, EPJC 77 (2017) 531
13 TeV, 3.2 $fb^{-1}$, JHEP 1704 (2017) 086

$pp \rightarrow H$
7 TeV, 4.5 $fb^{-1}$, EPJC 76 (2016) 6
8 TeV, 20.3 $fb^{-1}$, EPJC 76 (2016) 6
13 TeV, 139.0 $fb^{-1}$, ATLAS-CONF-2019-032

$pp \rightarrow$
7 TeV, 4.6 fb
8 TeV, 20.3
13 TeV, 36.1

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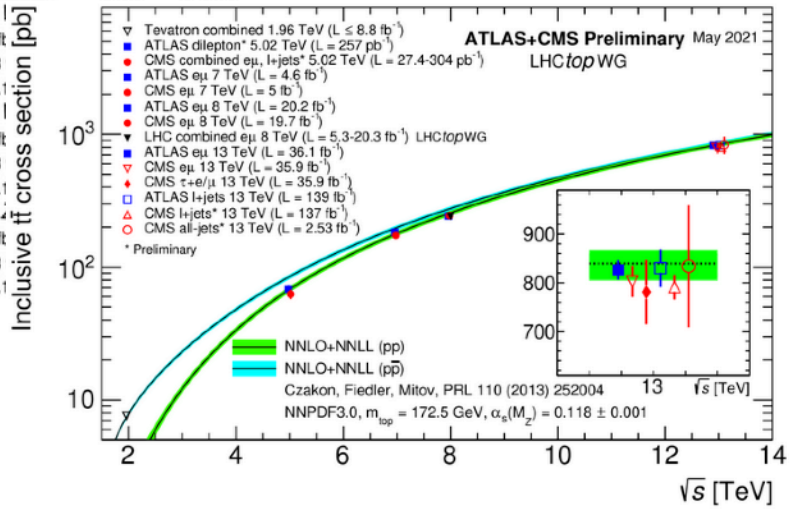

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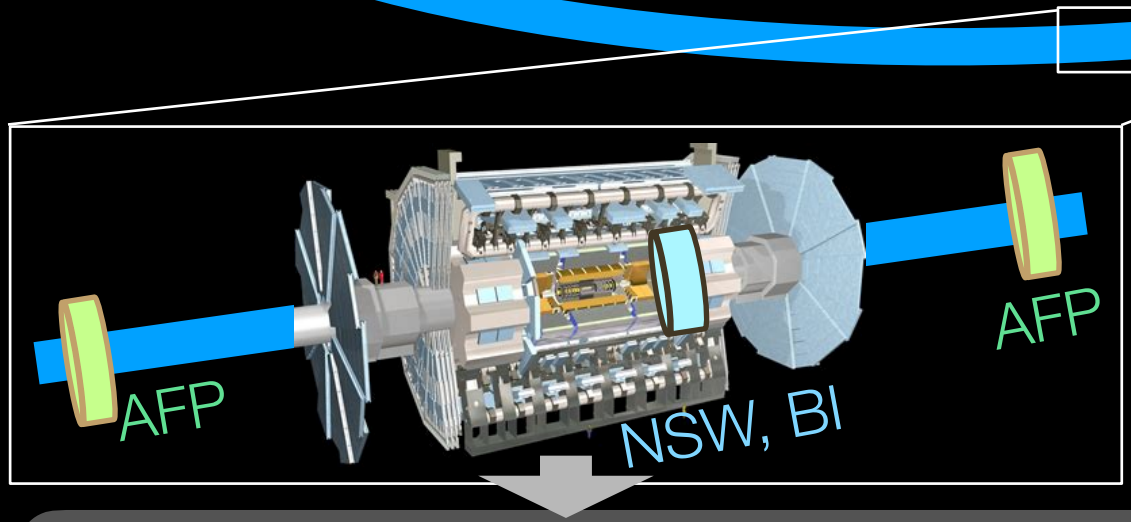


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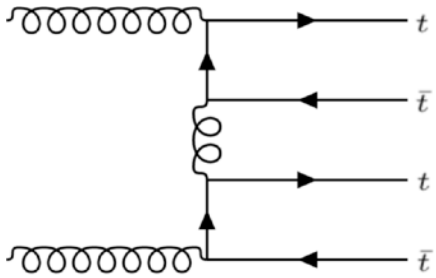
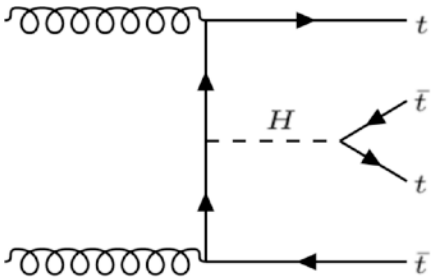
**DAQ** | **L1** eFEX* … ROD* | **HLT** New tracking +trigger | **Tier 0** Trigger Level Analysis, delayed reconstruct'n

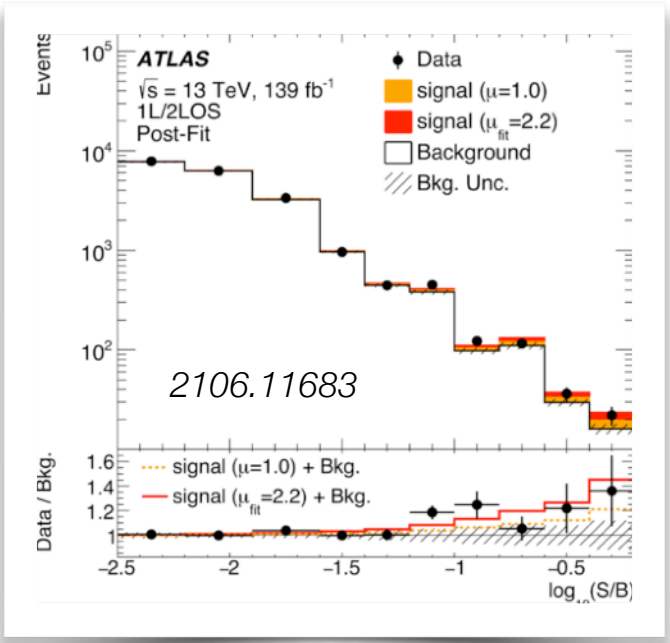
Major UK involvement

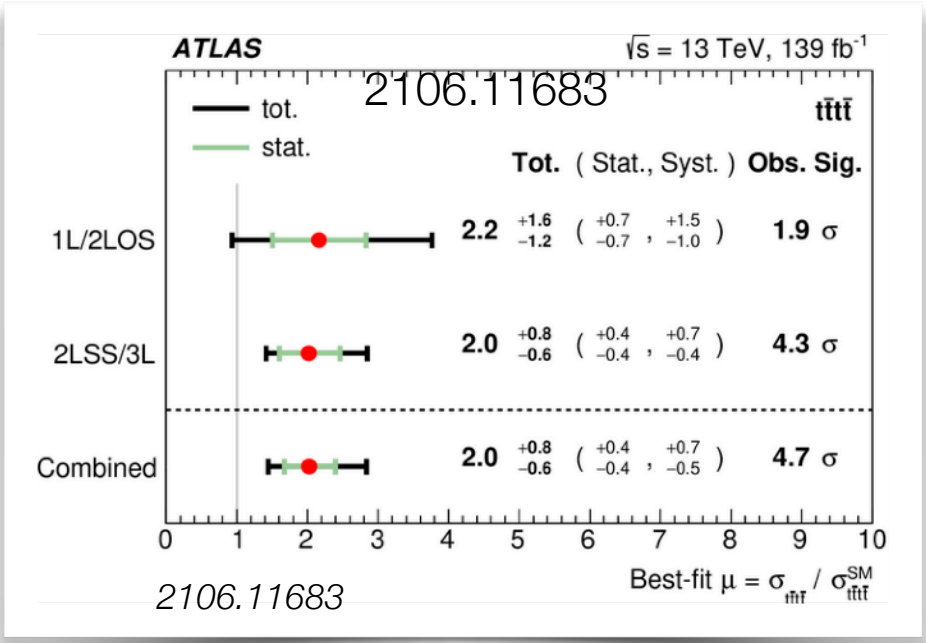
# Increased integrated luminosity $\mathscr{L}$

- Searches very close to observation / evidence threshold
- Example:
  - 4-top production
    - Currently very close to observation ($4.7\sigma$)



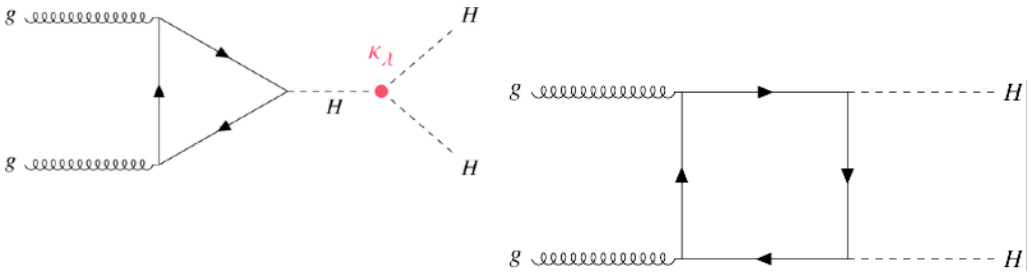



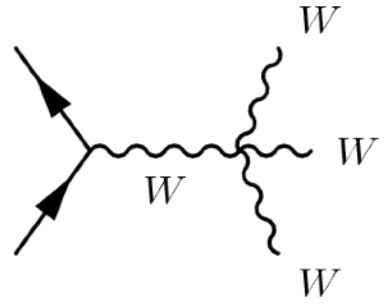



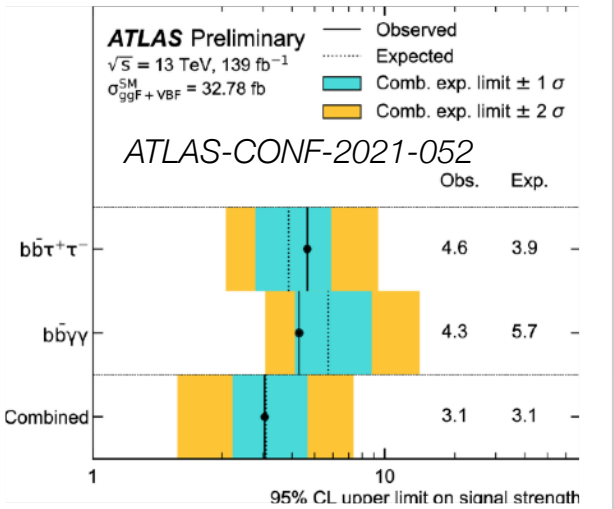
# Probing rare processes

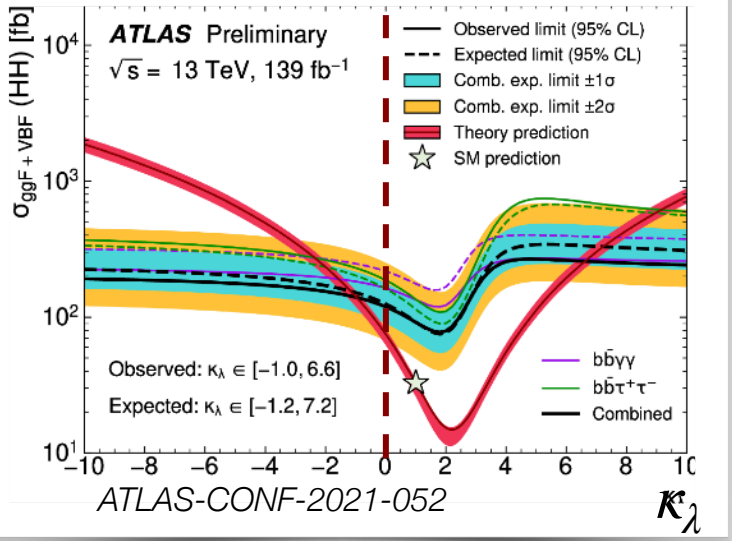
## Di-Higgs production

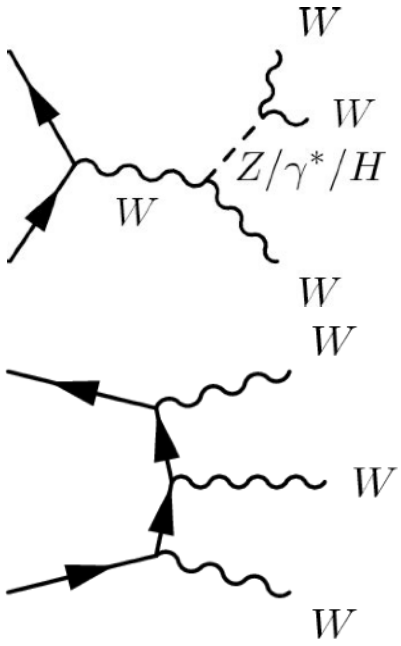



## Triboson production



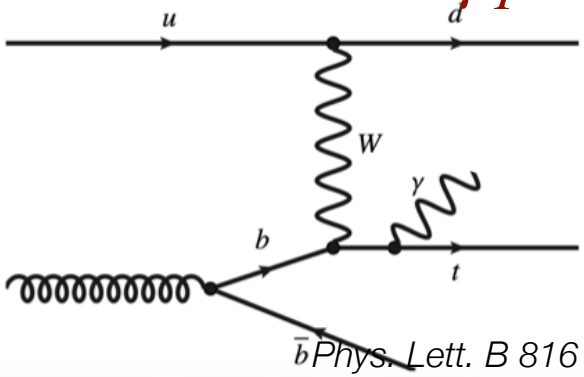



Differential measurements of rare processes + new phase space

## Processes with $t\gamma q$

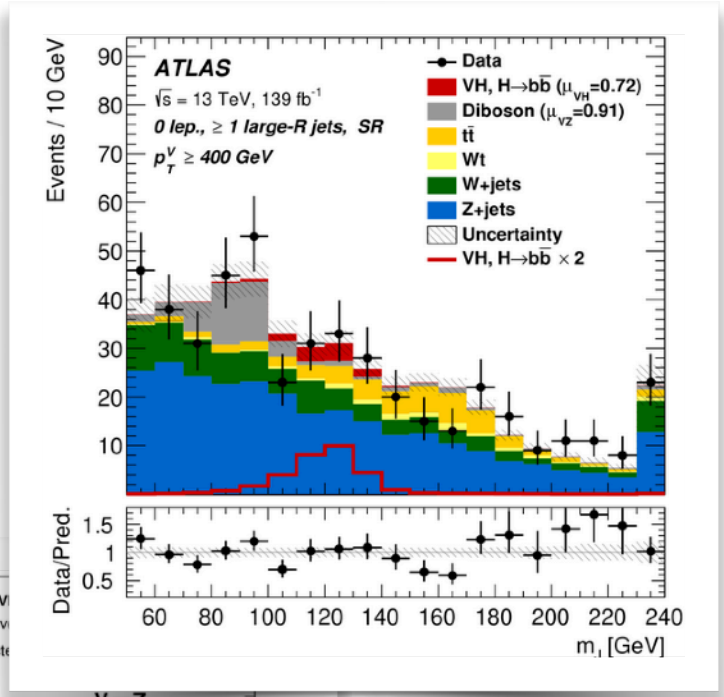


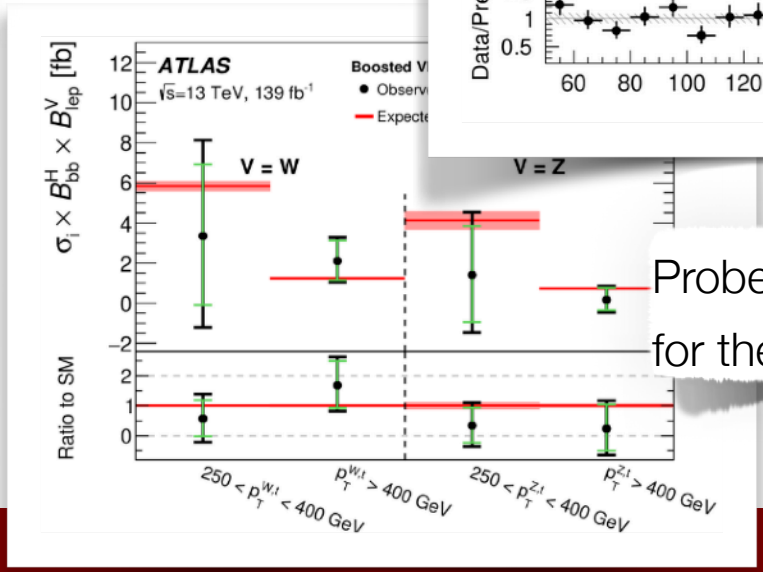

*Phys. Lett. B 816 (2021) 136204*

Differential measurement of $t\gamma q$ logical next step after observation

EW EFT operators
*2107.13917*

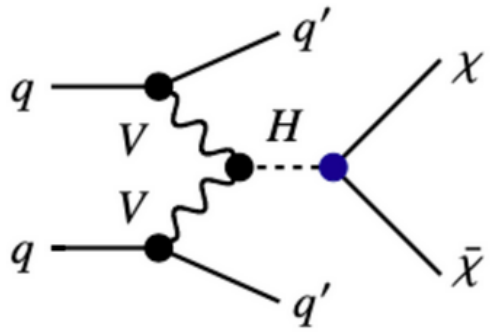
## Boosted Higgs bosons



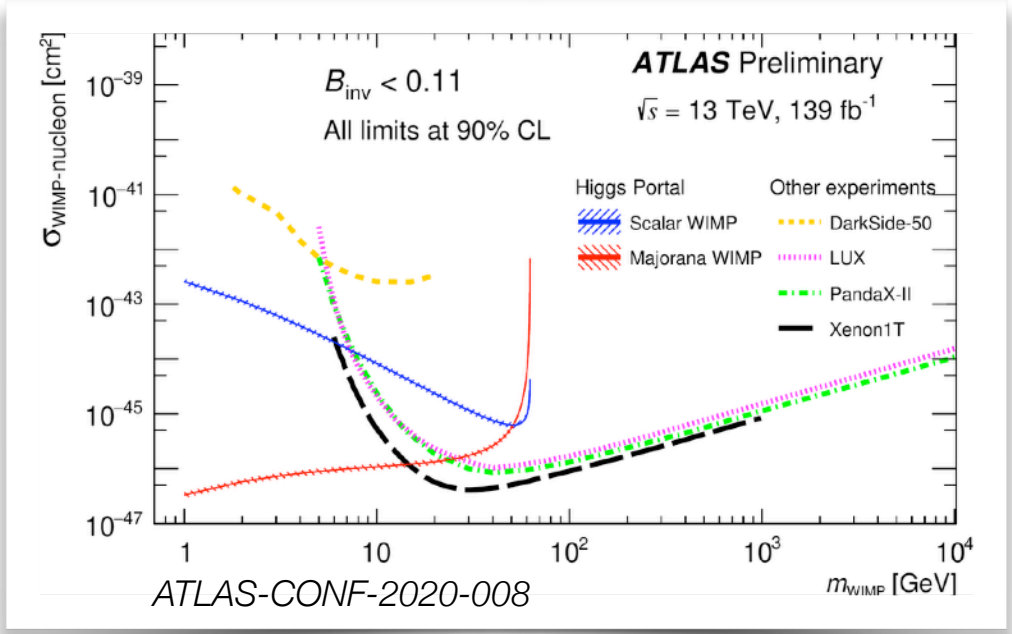




Probe $p_T^{\text{Higgs}} > 1$ TeV for the first time!

Flagship search for DM via Higgs-portal statistically limited!




| Source | Δ [%] |
|---|---|
| Jet energy scale | 1.8 |
| Jet energy resolution | 5.5 |
| Lepton | 4.6 |
| Other | 1.9 |
| Multijet | 7.0 |
| $V$+jets theory | 1.6 |
| Signal theory | 1.0 |
| MC stats. | 7.9 |
| Data stats. | 17.3 |



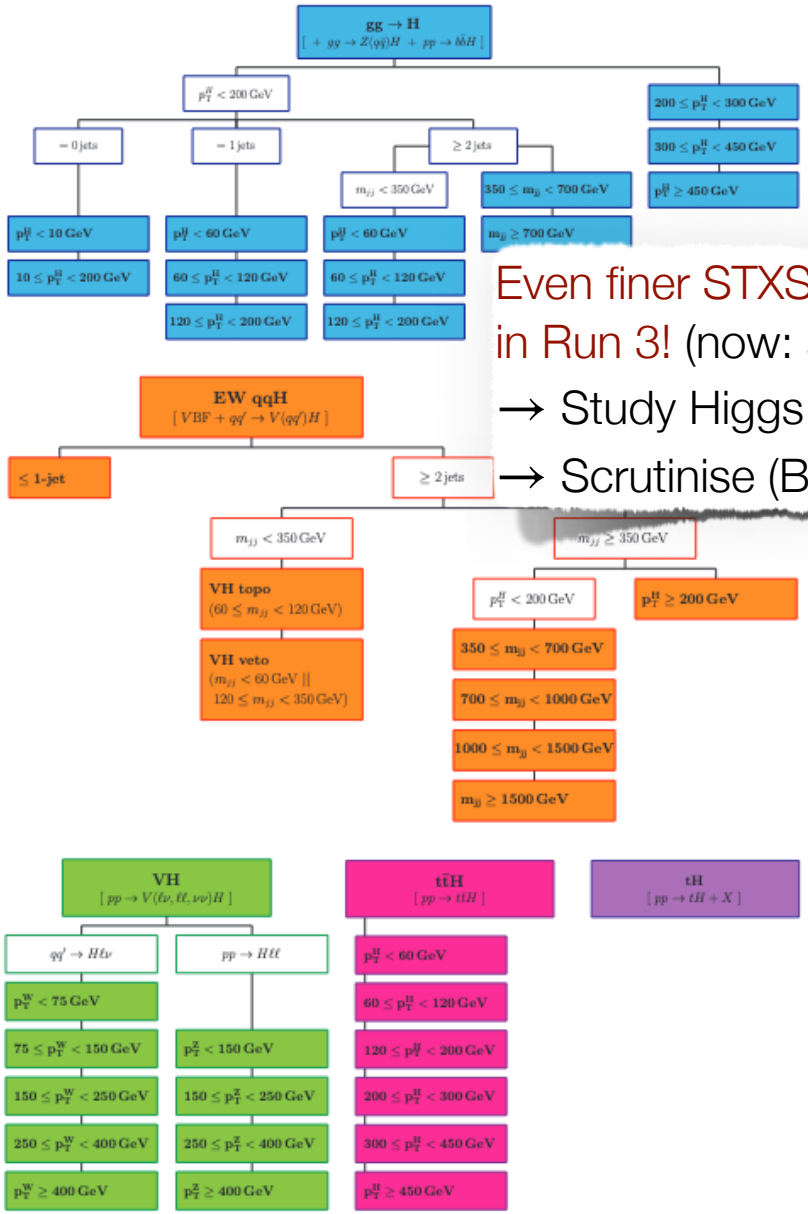

Limit: $BR(H \to \text{inv}) < 0.11\ (0.11^{+0.04}_{-0.03})$

Note: current results stat limited…

Pushing below $BR(H \to \text{inv}) < 0.1$ is really exciting…

Many searches for DM models with extended Higgs sectors limited!

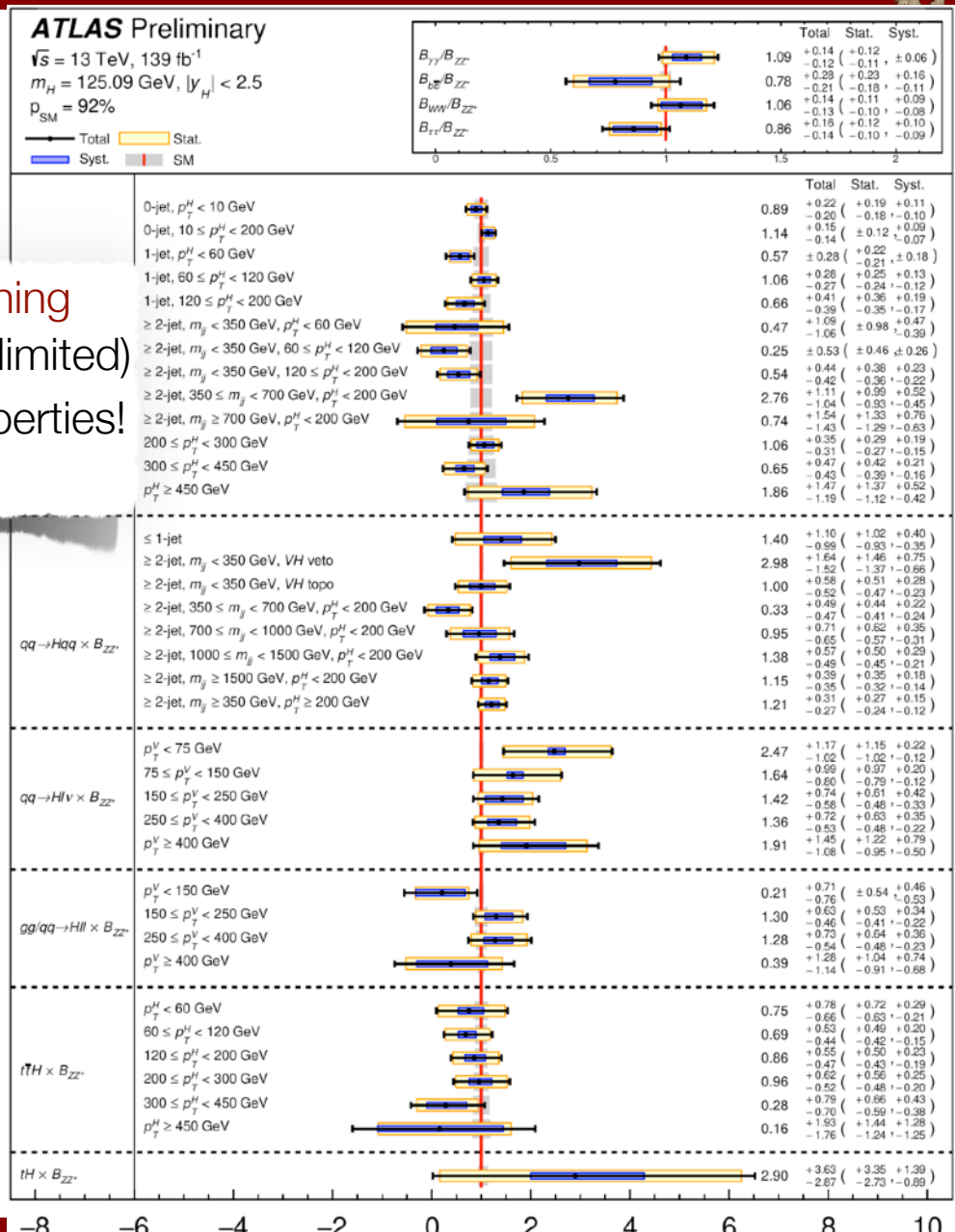
# Increased integrated luminosity $\mathscr{L}$




Even finer STXS binning in Run 3! (now: stat limited)

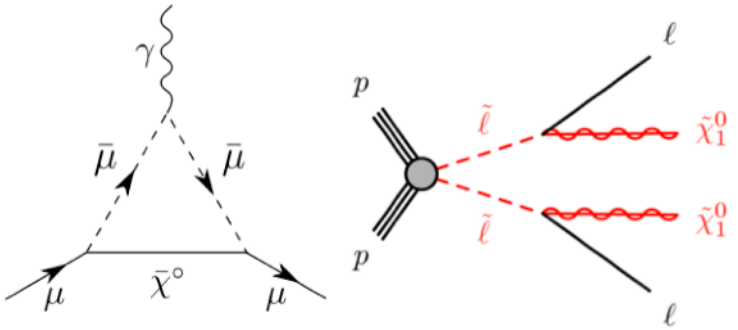
→ Study Higgs properties!

→ Scrutinise (B)SM!

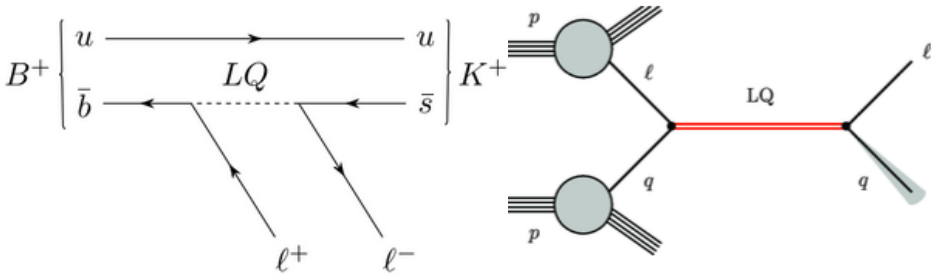


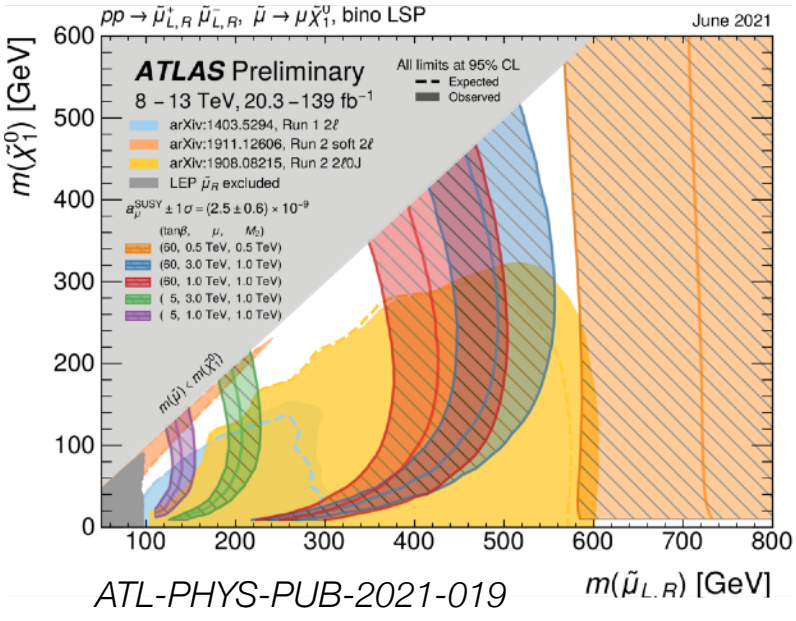

ATLAS-CONF-2021-053

## Connection to $g_\mu - 2$ anomalies?

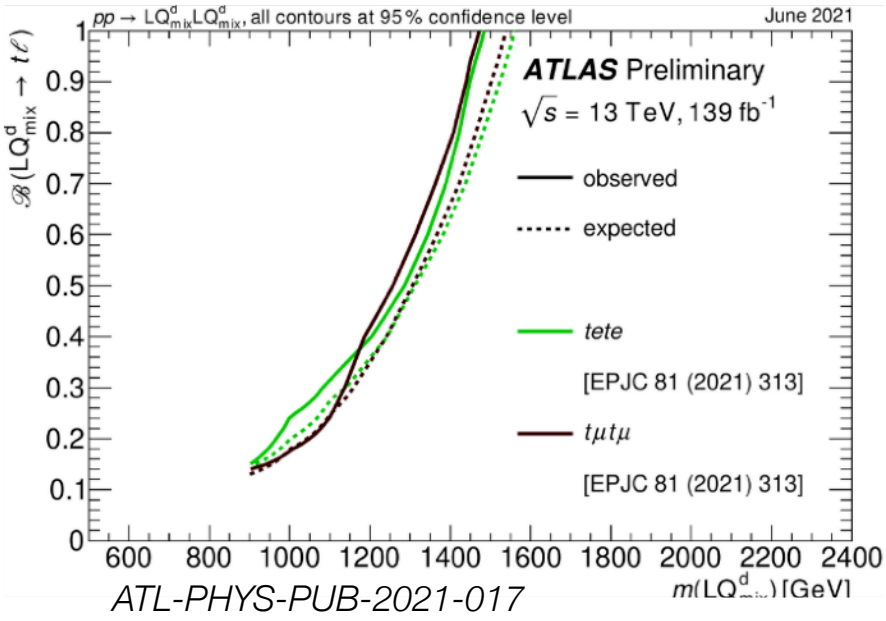



## Connection to $R_K^{(*)}$ anomalies?




ATL-PHYS-PUB-2021-019




ATL-PHYS-PUB-2021-017

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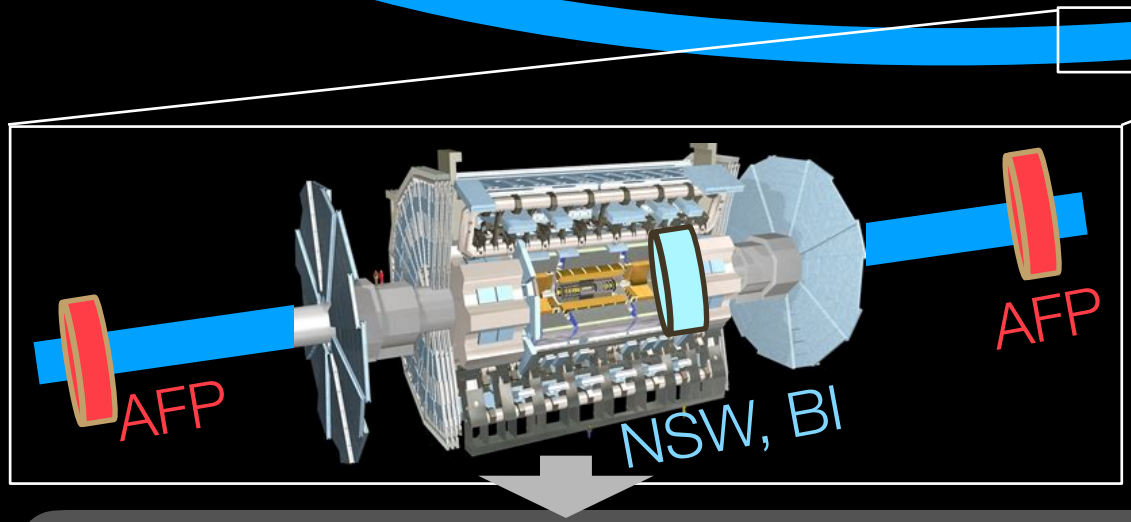



Potentially 2x more PbPb, pp data in 2021 using AFP + time of flight!

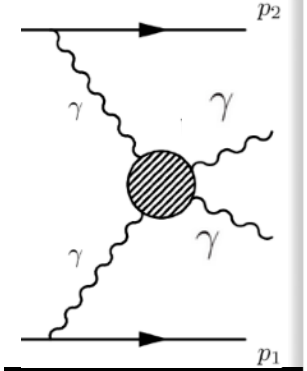
**DAQ** | **L1** eFEX* … ROD* | **HLT** New tracking +trigger | **Tier 0** Trigger Level Analysis, delayed reconstruct'n

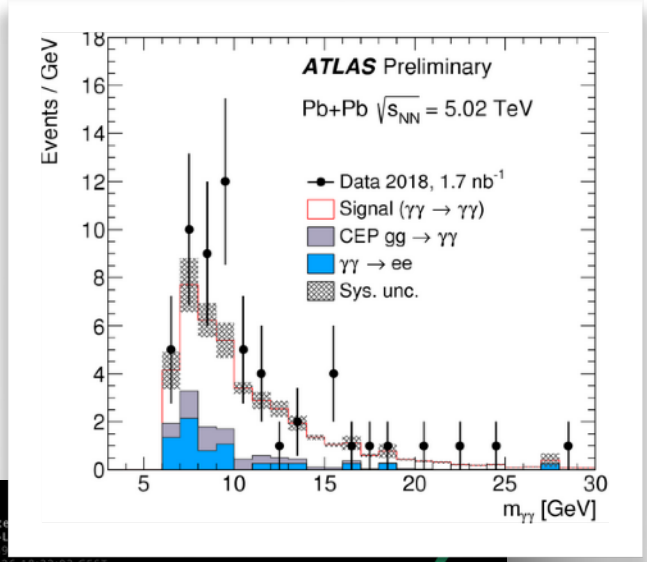
Major UK involvement

# Pb-Pb and pp collisions with AFP

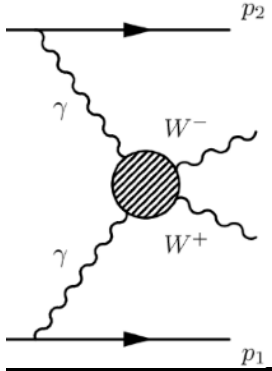
- In Run 2 only 15 fb$^{-1}$ pp recorded with AFP → expect doubling in 2022 alone!
  - similar improvement for PbPb running!
- Use AFP time of flight to tag $\gamma\gamma$ fusion!

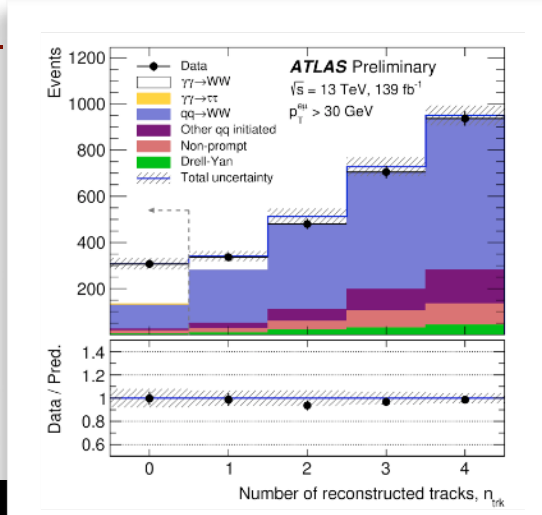
$\gamma\gamma \to \gamma\gamma$

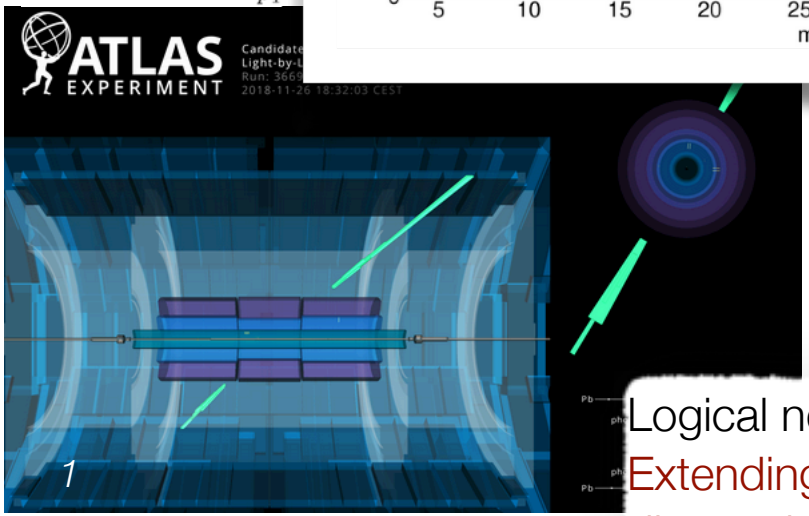


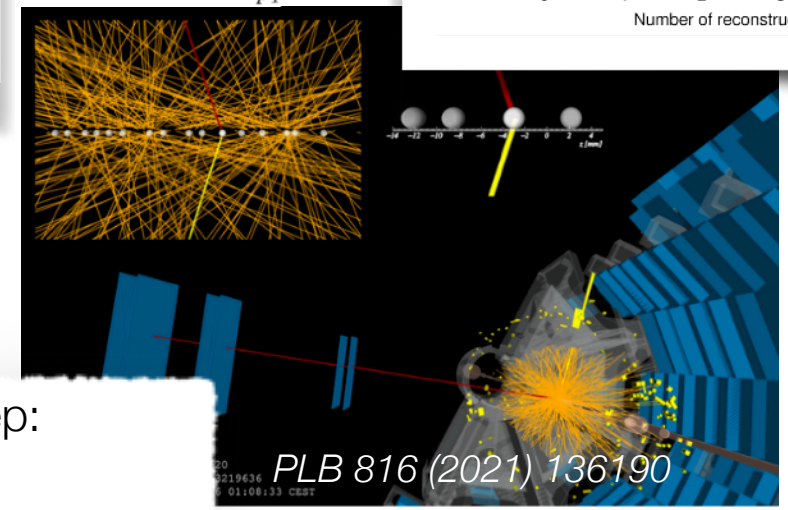




$\gamma\gamma \to W^+W^-$



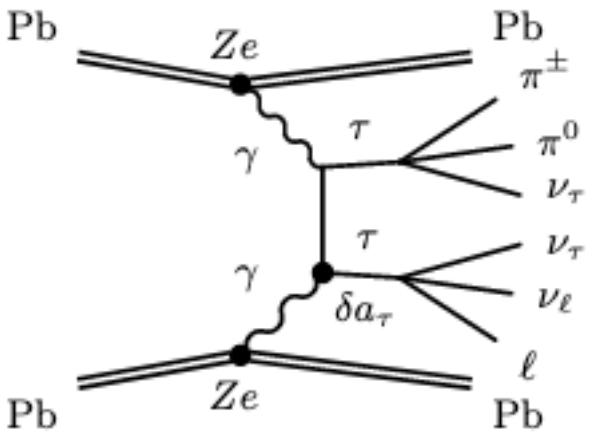



Logical next step:
Extending / first differential measurements!

PLB 816 (2021) 136190

$$\gamma\gamma \to \tau^+\tau^-$$



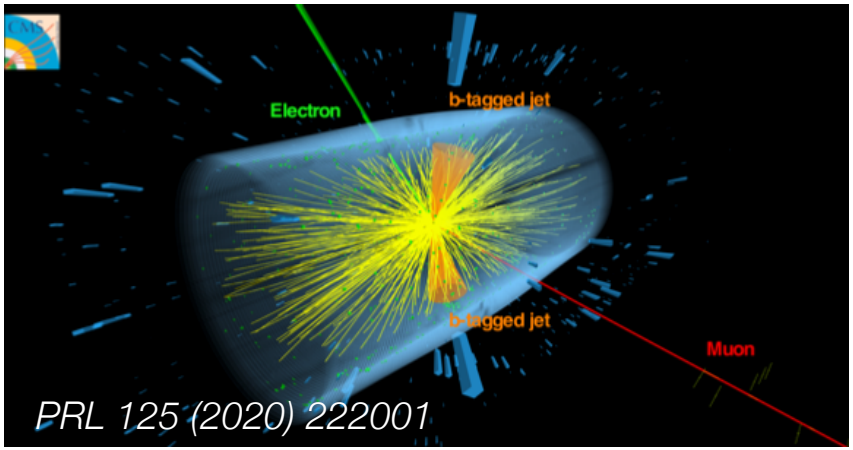

*PRD 102 (2020) 113008*

Could use polarised $\tau$ to measure $g_\tau - 2$?

Surpass BSM sensitivity of $g_\mu - 2$: $m_\tau \gg m_\mu$

Top quarks as a probe of temporal evolution of quark-gluon plasma in heavy ion collisions

Idea: *PRL 120 (2018) 232301*



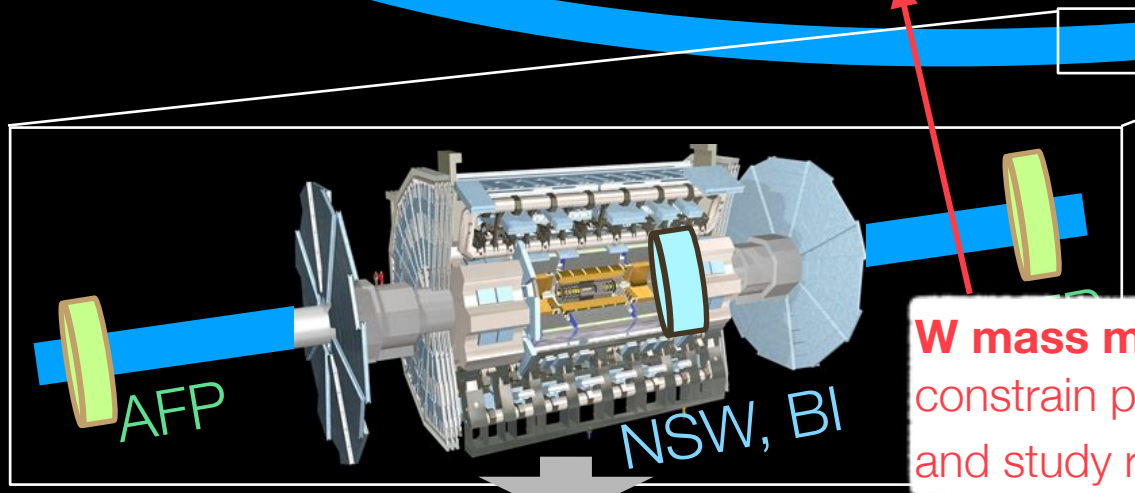

*PRL 125 (2020) 222001*

# LHC Run 3: 2022 - 2025

**pp:** $\sqrt{s} = 13.6$ TeV, $\mathscr{L} \approx 160$ fb$^{-1}$

**PbPb:** $\sqrt{s_{NN}} = 5.5$ TeV, $\mathscr{L} \approx 6$ nb$^{-1}$

**Special runs:** low-$\mu$, high $\beta^*$, O-O, p-O, p-He




**Cosmic ray shower models:**
constrain high $Q^2$ contributions

**W mass measurement:**
constrain pile-up contribution
and study recoil using low-$\mu$ data

**DAQ** **L1** eFEX* … ROD* → **HLT** New tracking +trigger → **Tier 0** Trigger Level Analysis, delayed reconstruct'n

Major UK involvement

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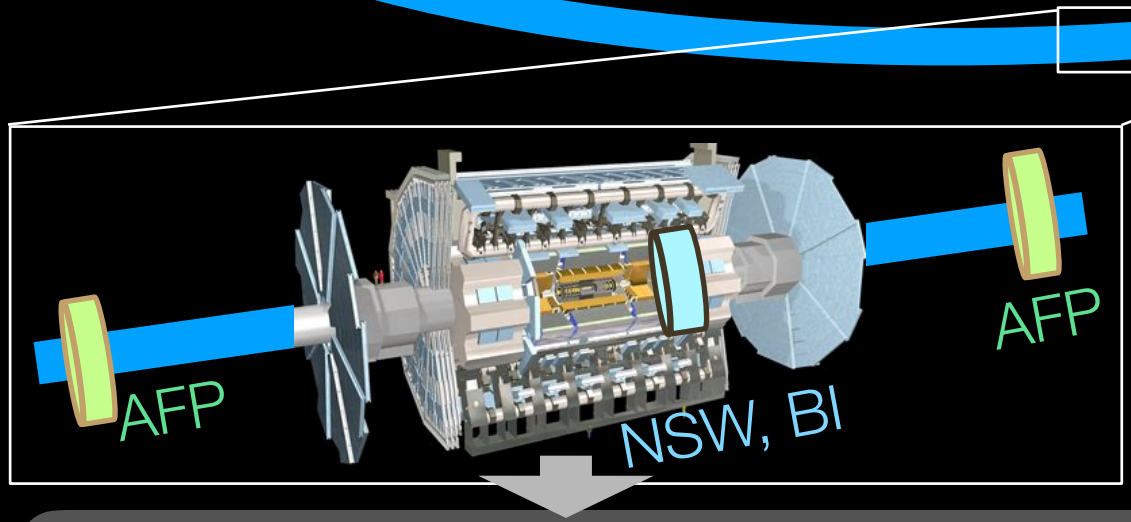


Potentially 2x more PbPb, pp data in 2021 using AFP + time of flight!

**DAQ**

**L1** eFEX* … ROD*

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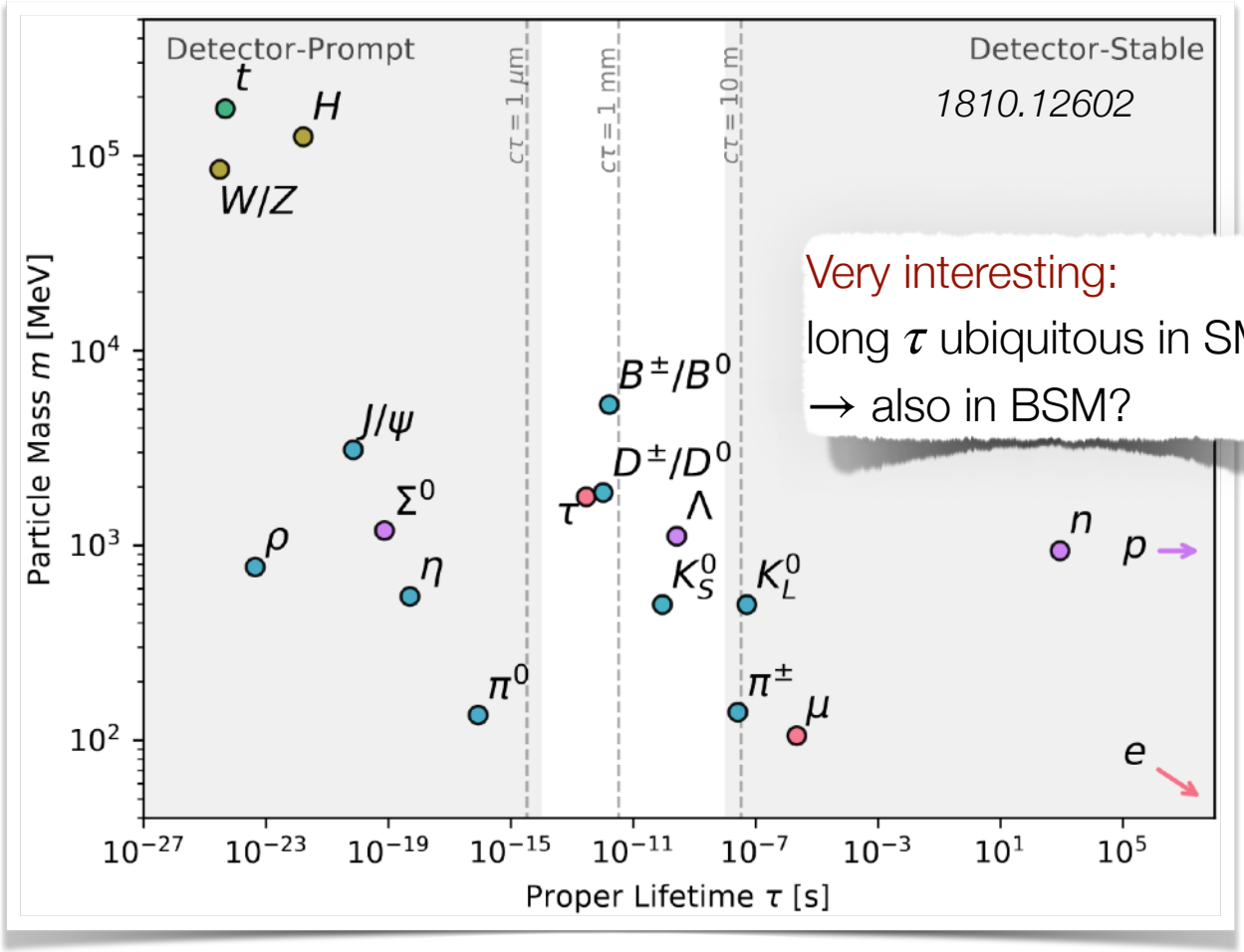
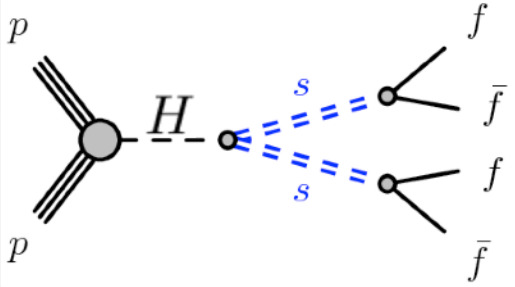
- Unprecedented opportunities for displaced signatures of long-lived particles!
  - [Detectors+triggers originally purpose-built for prompt physics]



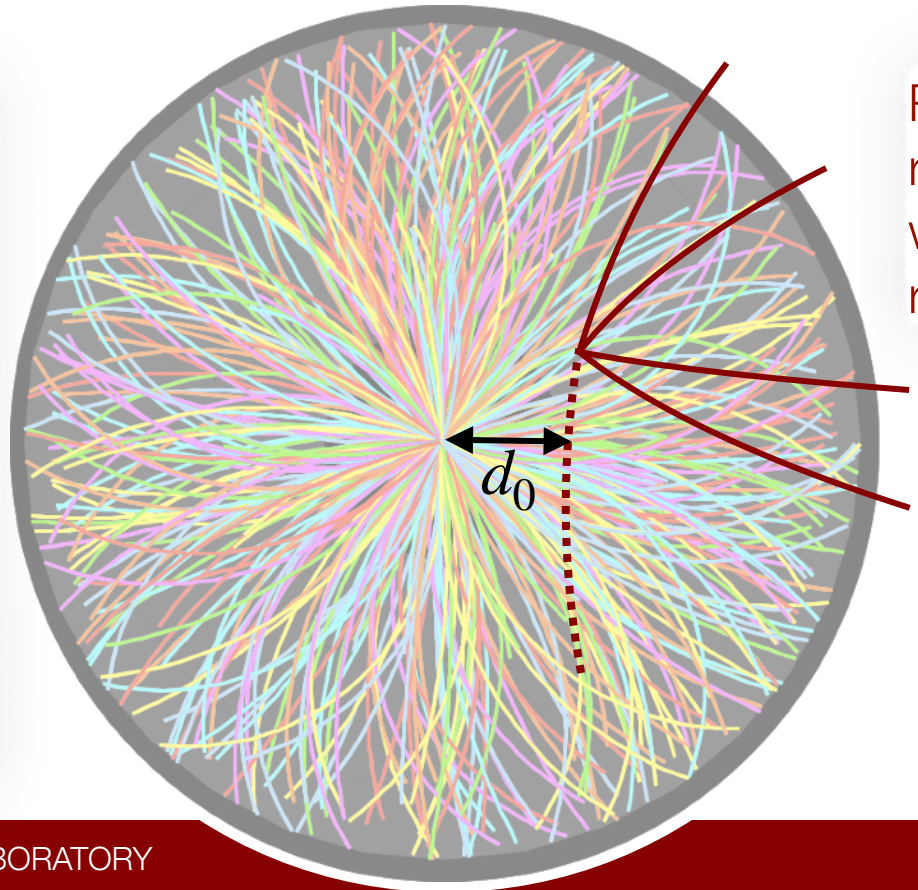
# Improvements due to new trigger system

- Unprecedented opportunities for displaced signatures of long-lived particles!
  - [Detectors+triggers originally purpose-built for prompt physics]
- Major improvements on software side of high-level trigger (and reco):
  - Multi-threading
  - Improved large-radius tracking (LRT) in regions identified by L1 trigger:
    - Reconstruct tracks with large transverse impact parameter $d_0 < 30$ cm

Trigger on displaced $s \to f\bar{f}$ decays directly




(Run 2: trigger on associated objects, e.g., $Z \to \ell^+\ell^-$ in $ZH$)




Reconstruct red tracks with large radius tracking!

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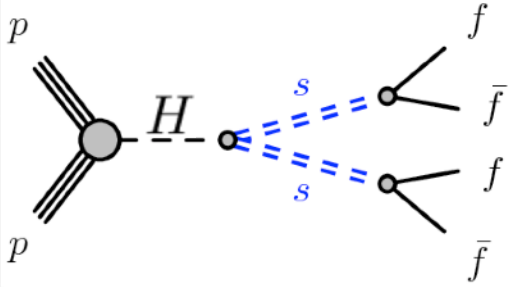


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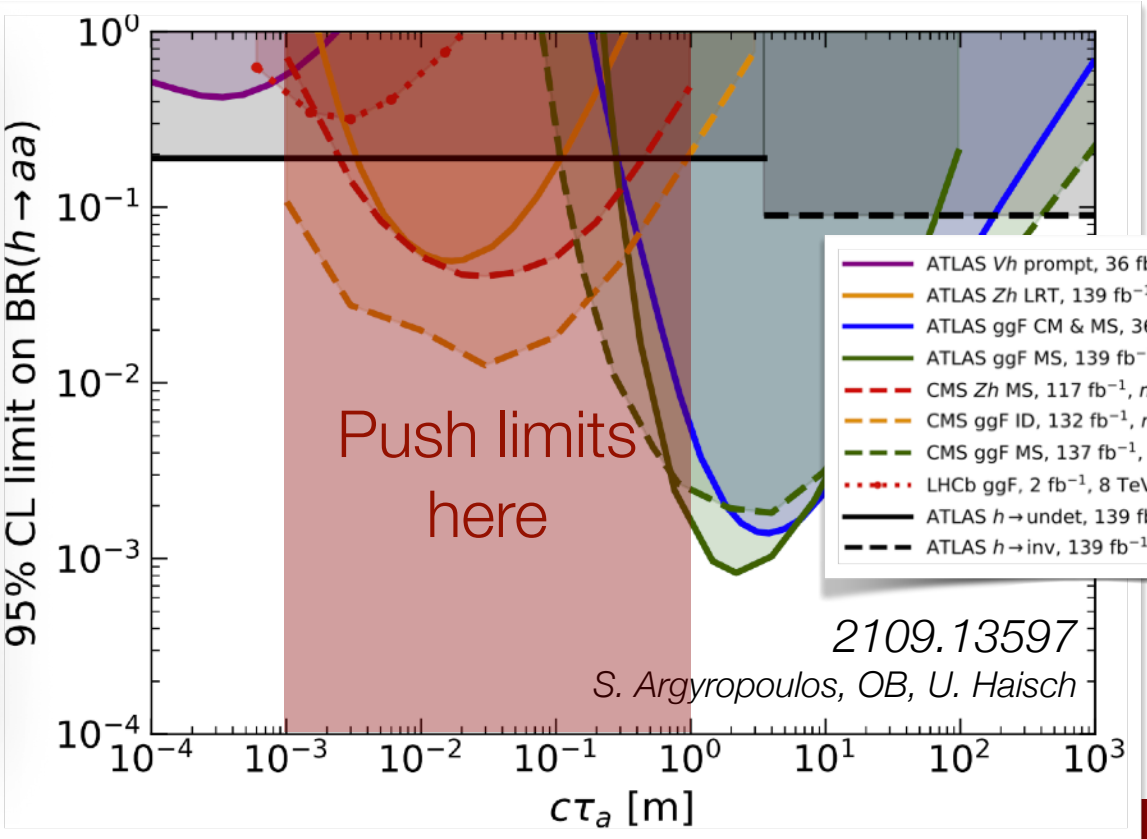

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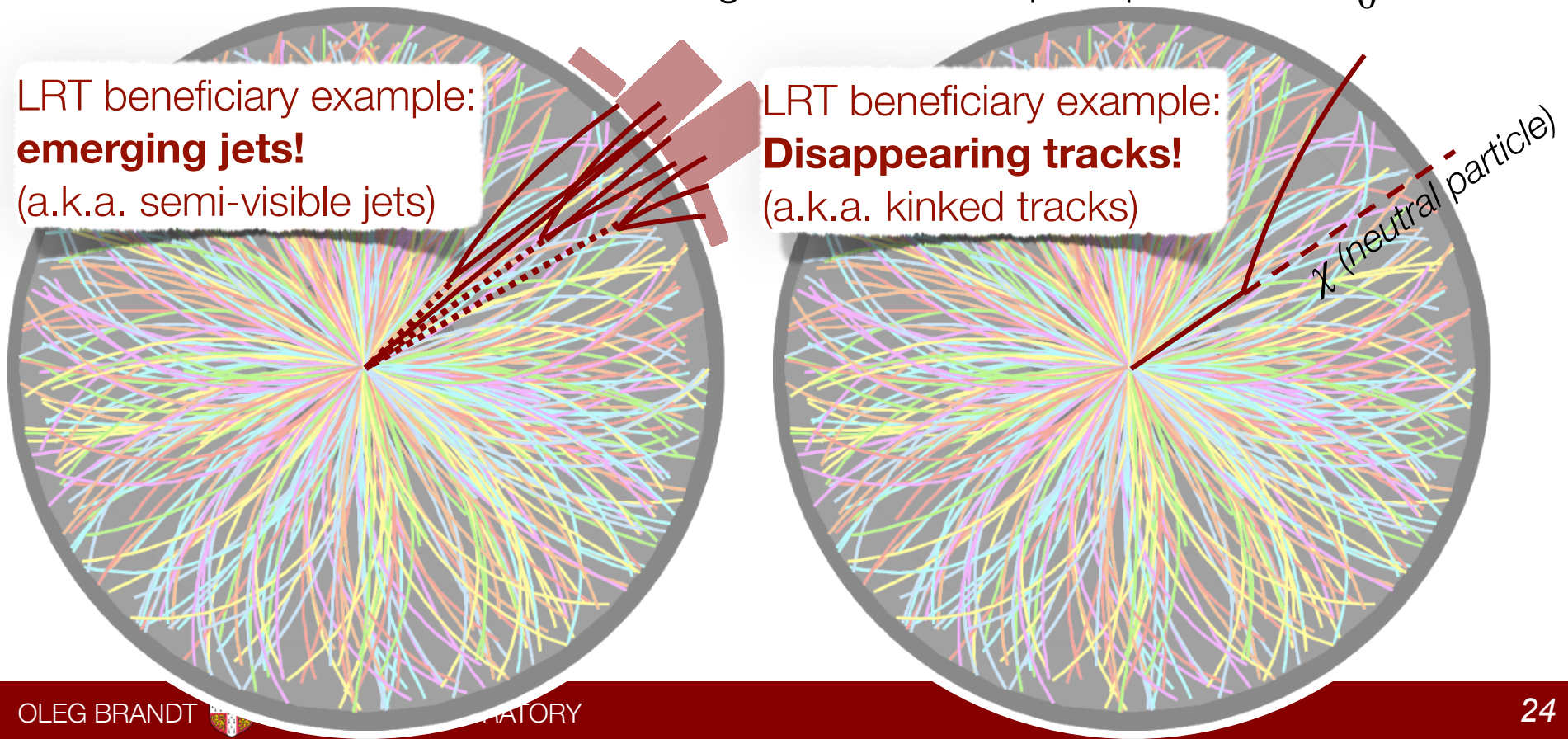

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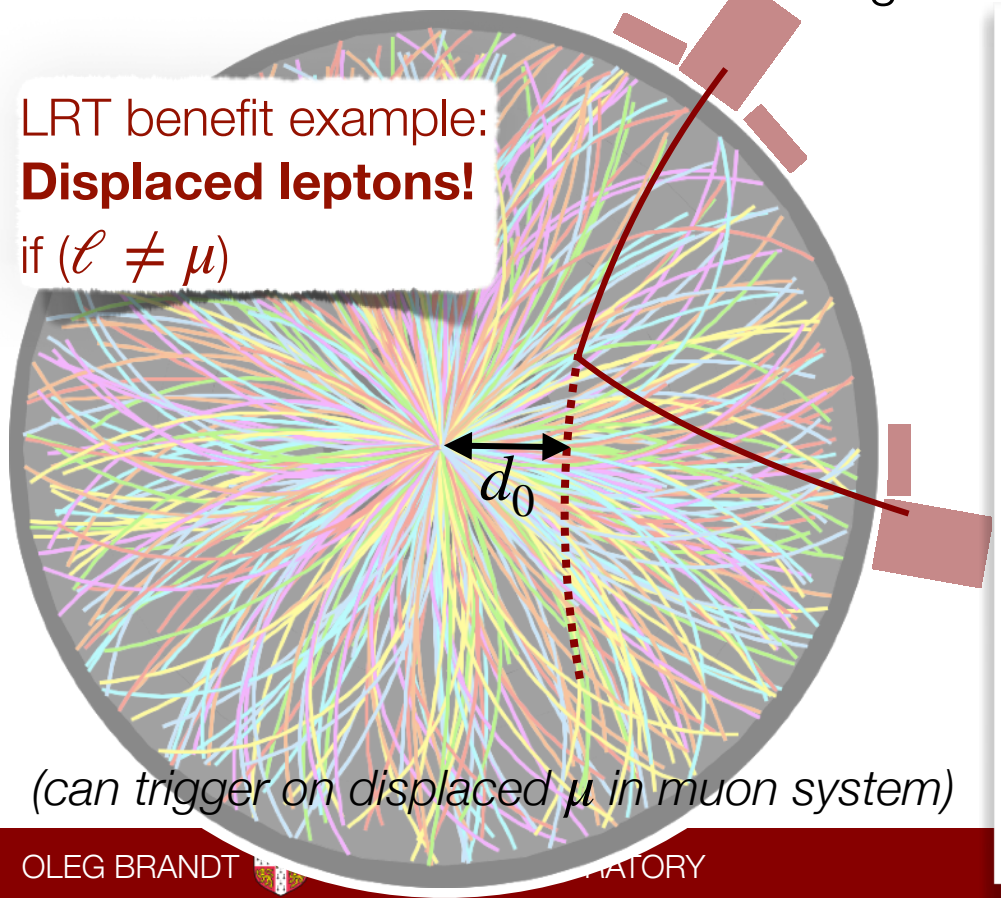
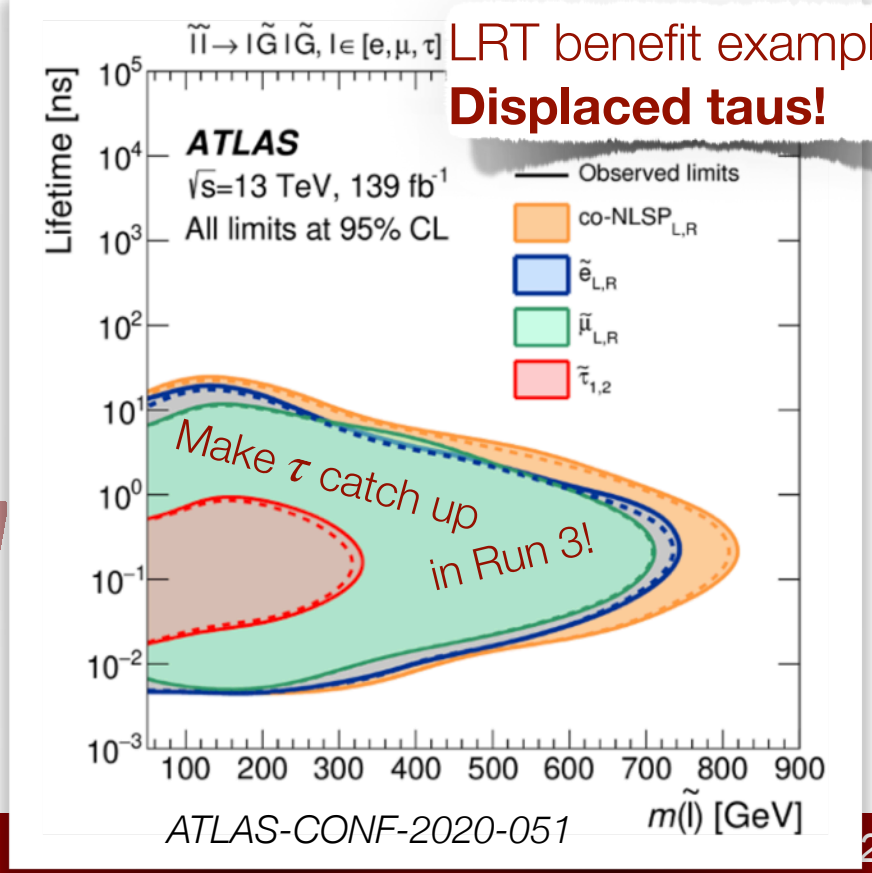



*(can trigger on displaced μ in muon system)*



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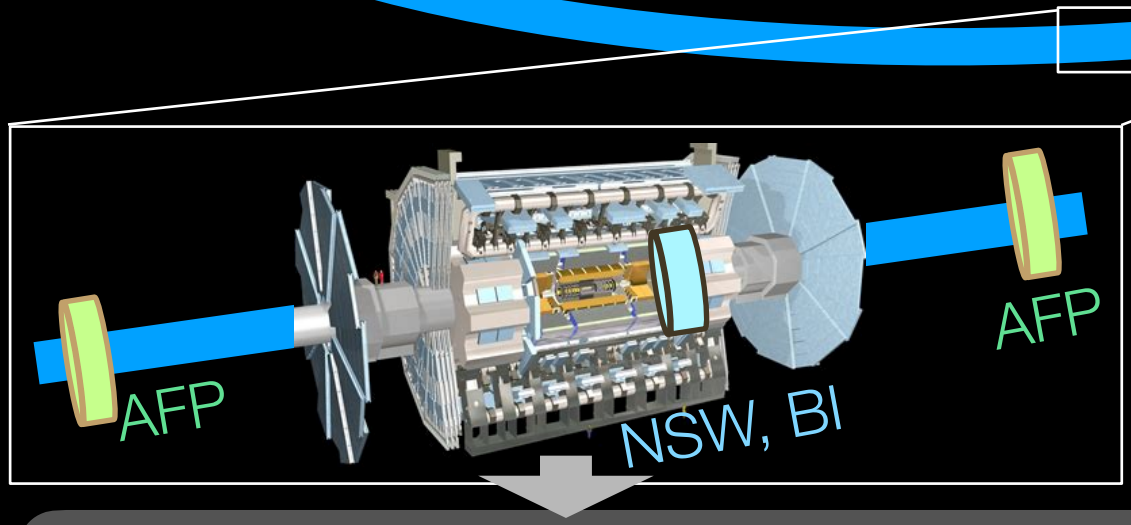


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Major UK involvement

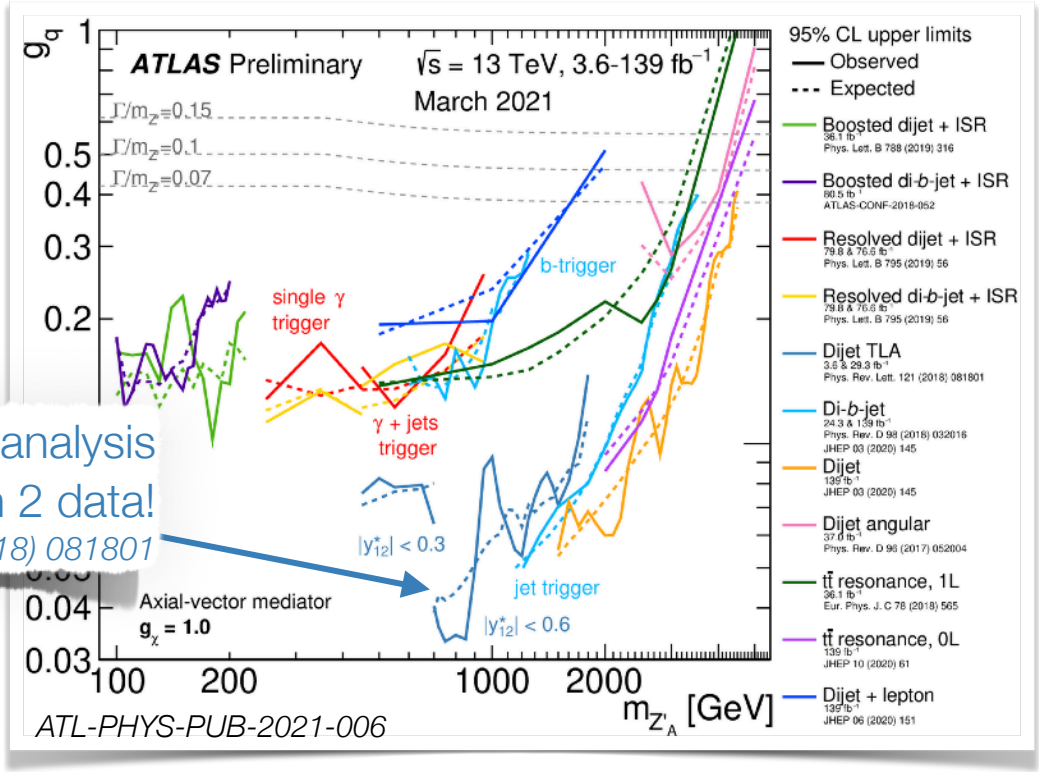
# Trigger-level analysis and other opportunities

- New opportunities due to more flexible high-level trigger:
  - Partial event building → useful for calibrations at low $p_T$
  - Delayed reconstruction → avoid ~1.5 kHz limit for prompt reconstruction
    - Use in-between LHC fills and technical stops
      (also end of fill, but probably not due to $\mathscr{L}$ levelling)
- Expand very successful trigger-level analysis (TLA) analyses from Run 2!

Logical next step, after completing Run 2 analysis:

- rinse & repeat with Run 3 data
  → unprecedented sensitivity!

Best limits from TLA analysis using only 1/4 of Run 2 data!
*PRL 121 (2018) 081801*



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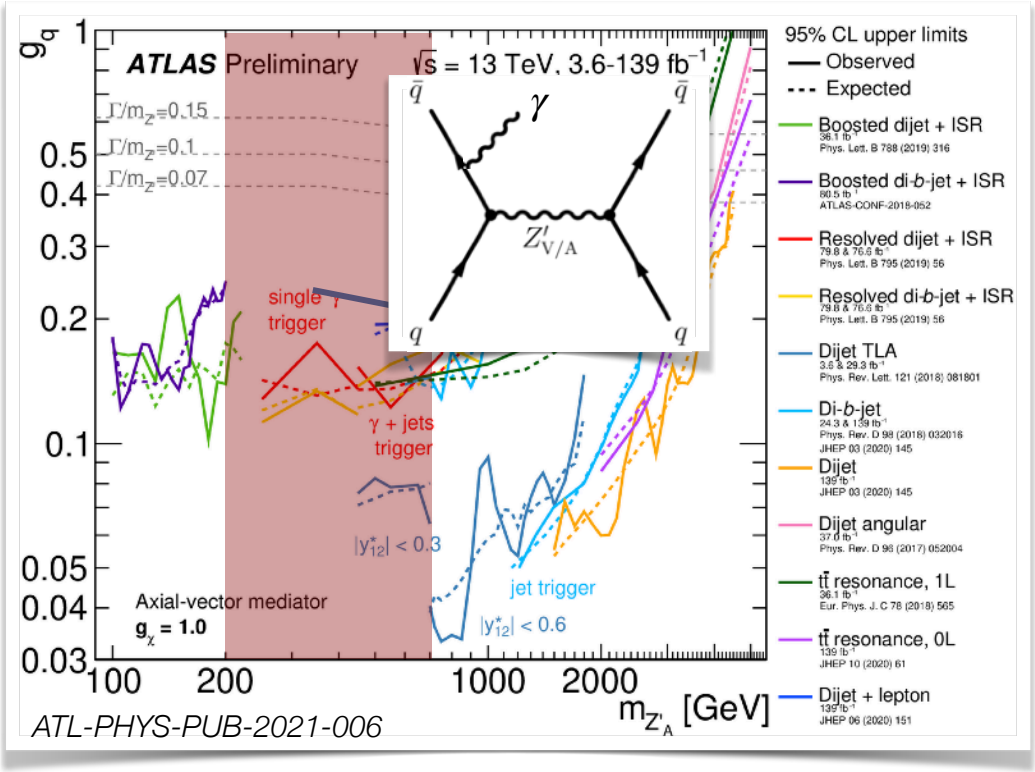
  → Example: $\mathrm{ISR}(\gamma) + q\bar{q}$



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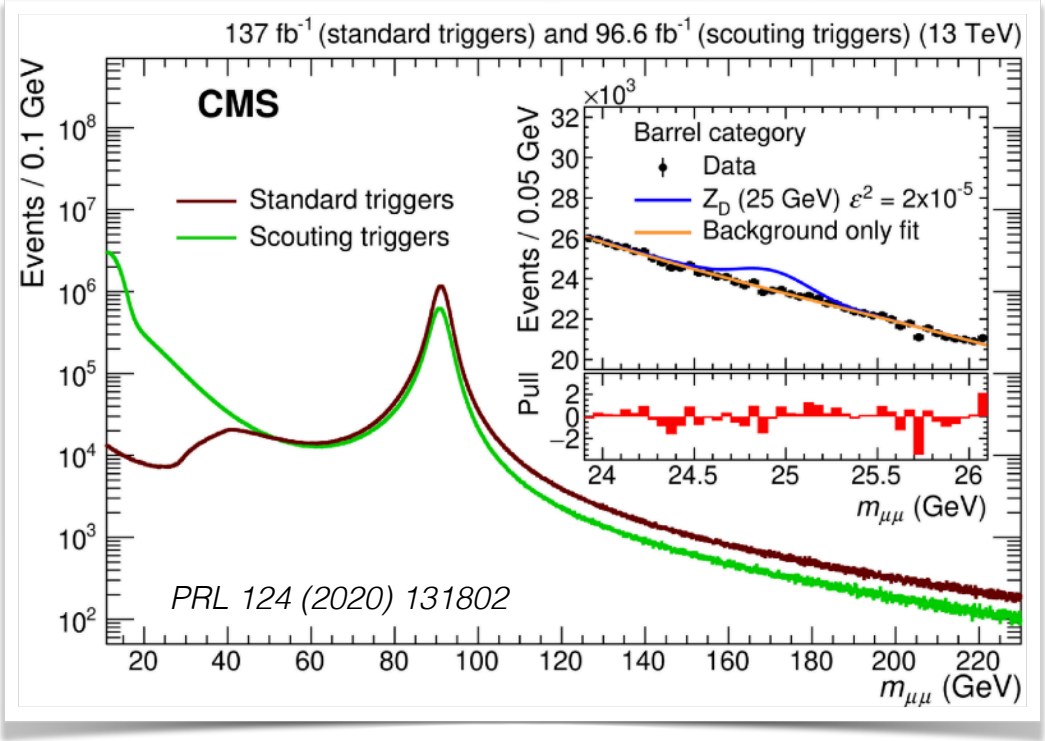
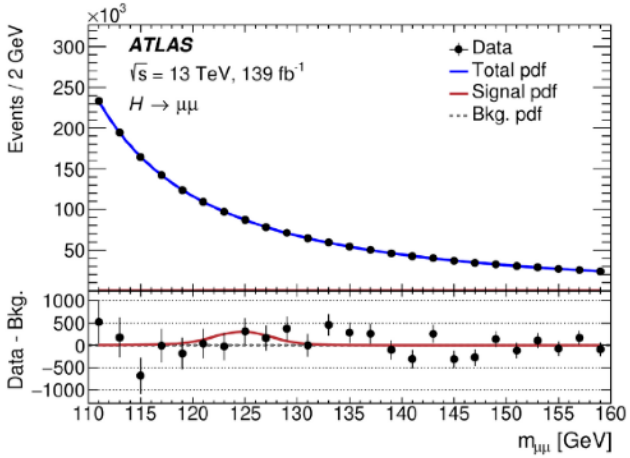
  → Example: $\mathrm{ISR}(\gamma) + q\bar{q}$
- Completely different final states
  → Example: $\mu^+\mu^-$ with $m_{\mu\mu} > 10$

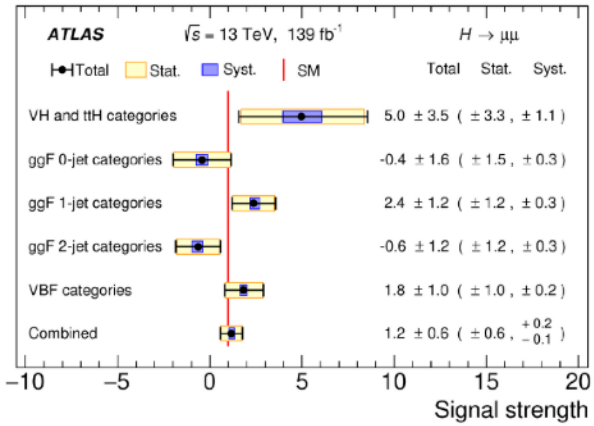


# Thank you!

- Probing rare processes

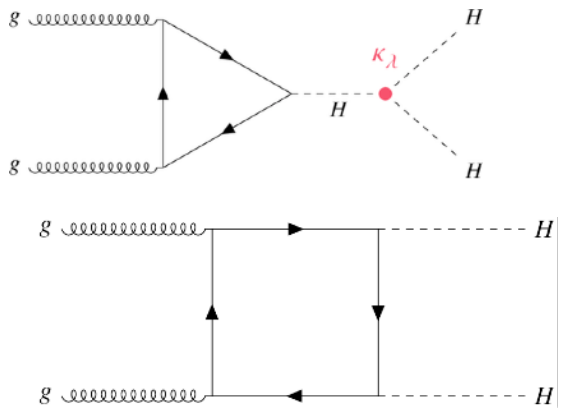
$H \to \mu^+\mu^-$



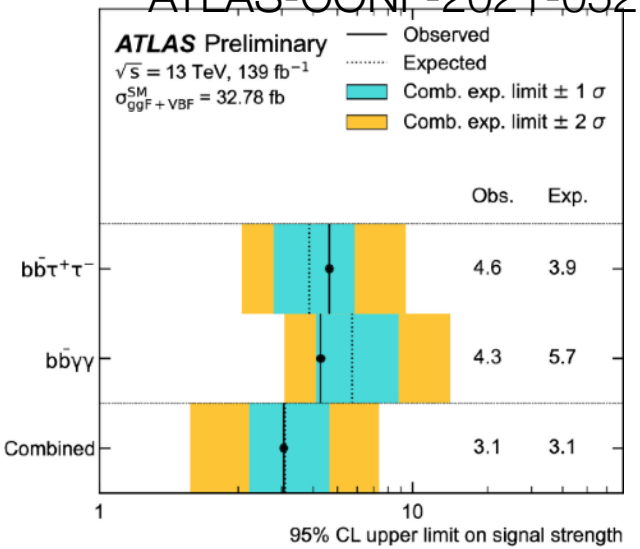




Phys. Lett. B 812 (2021) 135980

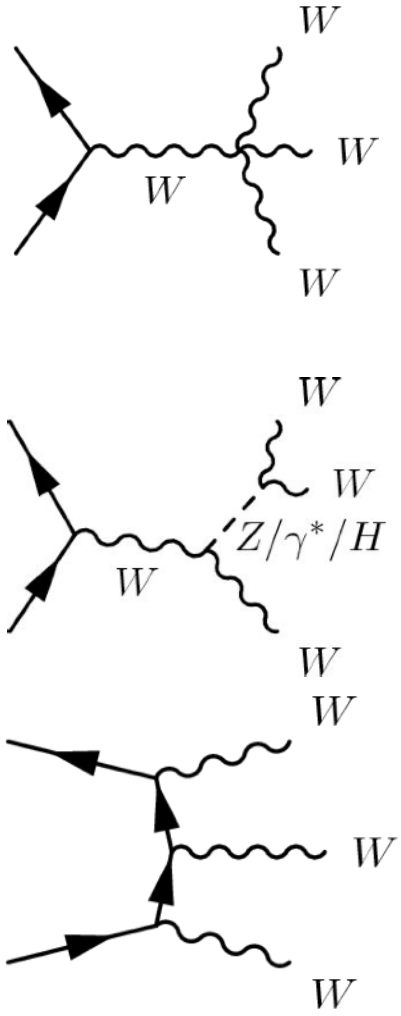
Di-Higgs production




ATLAS-CONF-2021-052

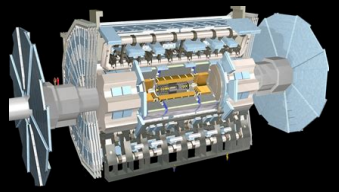



Triboson production

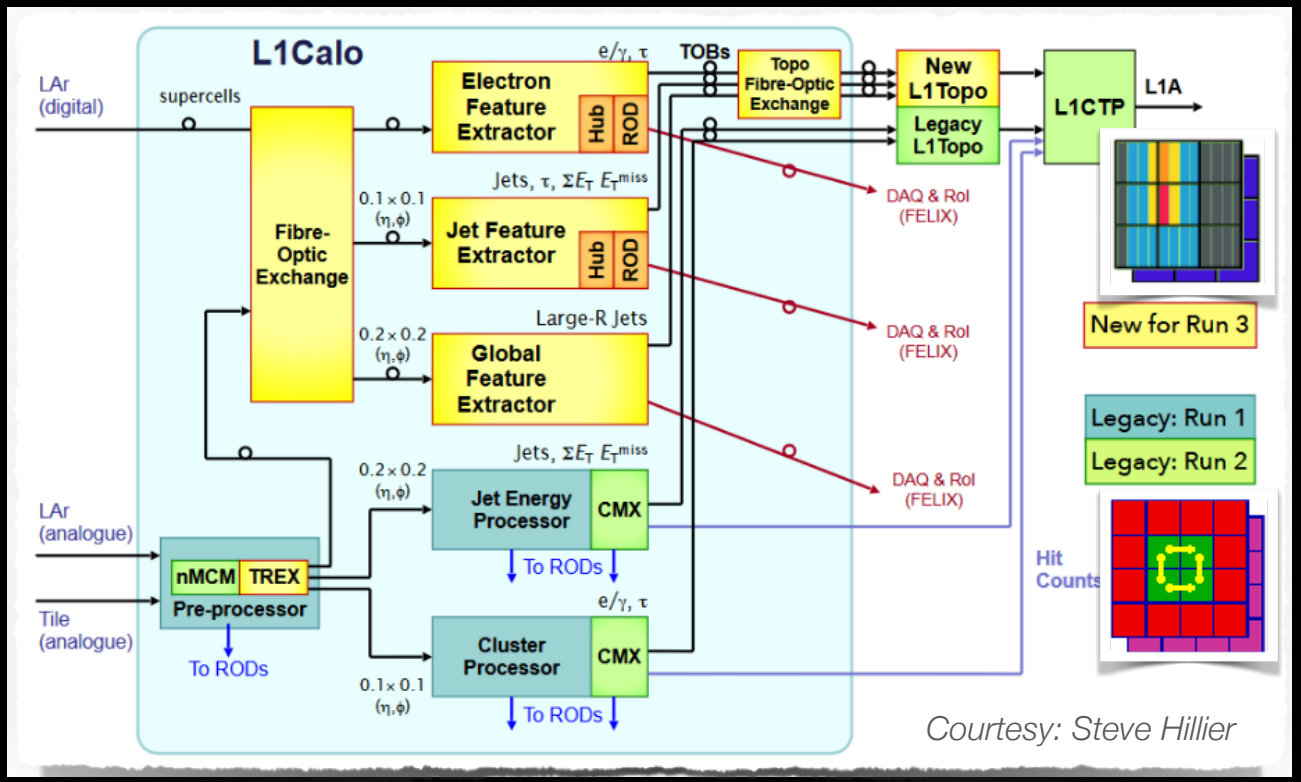


# ATLAS DAQ + TRIGGER UPGRADES FOR RUN 3

~ COMPLETE REPLACEMENT



**DAQ** | **L1** | **HLT** | **Tier 0**




L1Calo (level 1 calo trigger)

- Trigger readout fully digitised + finer granularity ("super cell")
- Improved $e/\gamma$, $\tau$, jet, $E_T^{miss}$ with new hardware
- Large-R jet reconstruct'n
- UK: eFEX (electron feature extractor)+ROD (readout driver), leadership

L1Muon (not shown)

- 6 →15 $p_T$ thresholds
- Charge information

# ATLAS DAQ + TRIGGER UPGRADES FOR RUN 3

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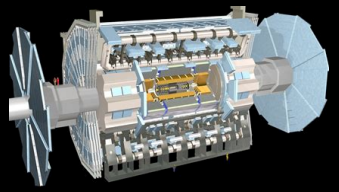

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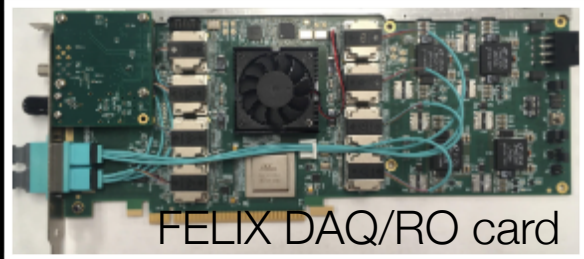
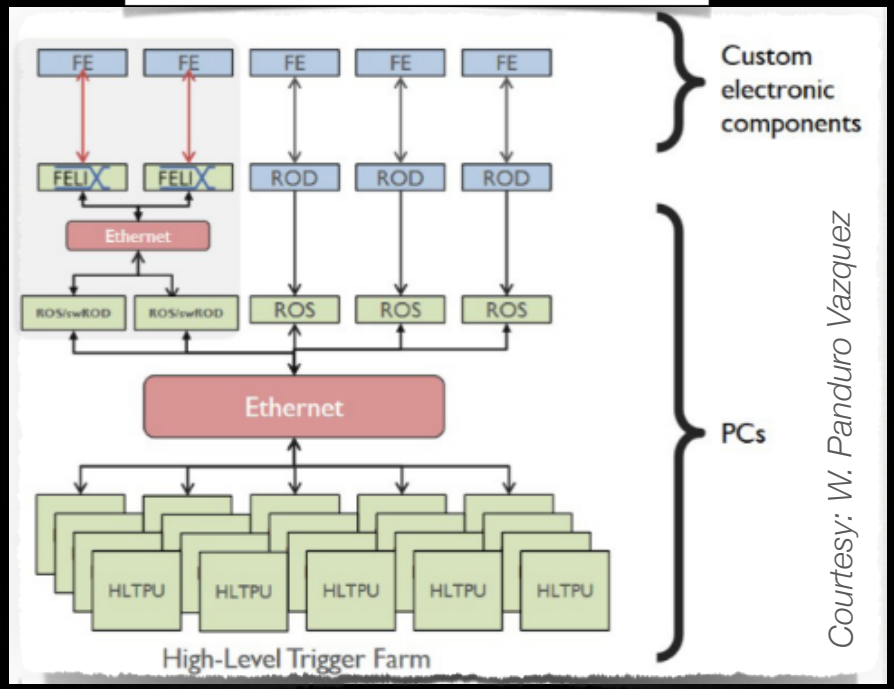


FELIX DAQ/RO card




DAQ (Data AQuisition)

- New readout paths (+ legacy system):
  - FELIX: PCI cards in dedicated servers
  - Software Read Out Driver (ROD) on servers → interface to HLT
- More bandwidth + stability
- UK: coordination

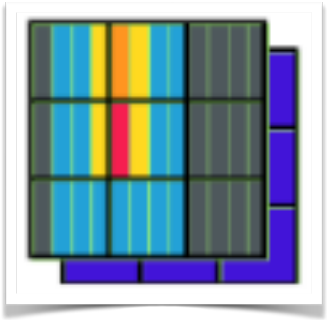
HLT (High Level Trigger)

- Computing farm with $\mathcal{O}(10^5)$ cores
- Multithreading implemented
- Full-scan tracking of L1 trigger subset
- large-radius tracking (high impact parameter tracks) of L1 trigger subset
- UK: leading contributions on all fronts

# Improvements due to new trigger system

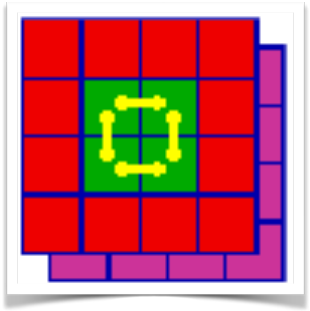
- Generally: new trigger more sophisticated, more full reconstruction-like
  → sharper trigger efficiency turn-on
  → lower trigger thresholds for same bandwidth!
- Example L1 Calo (similarly striking improvements for L1Muon):

Now: "super-cells"



EM22 Medium:
$p_T^e > 22$ GeV
medium isolation

Before: 2 x 2 $\Delta\eta = 0.1$ cells



EM22 VHI:
$p_T^e > 22$ GeV
very high isolation

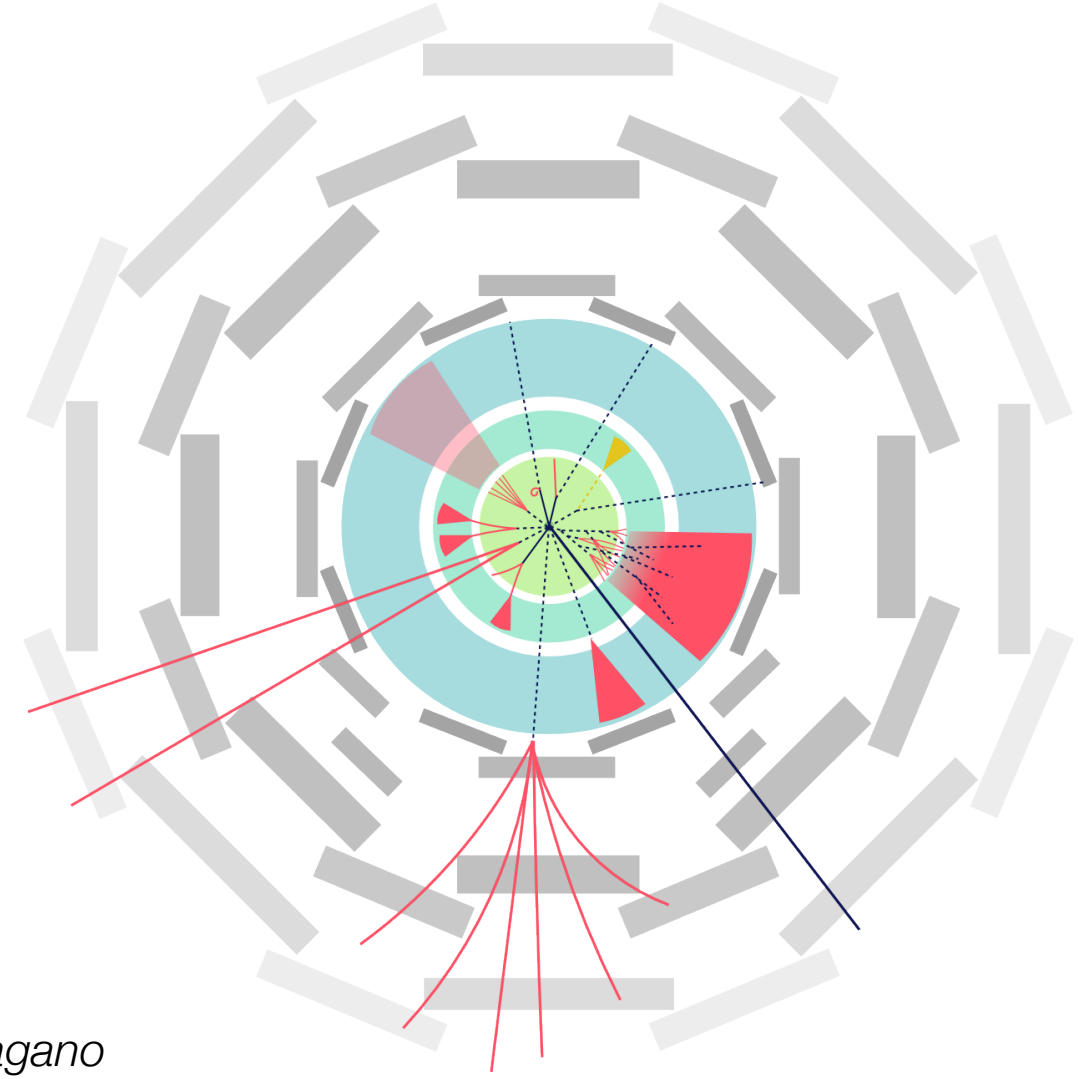
Significant benefit for all analyses using $e$ or $\gamma$!

Performance: efficiency now up to 10% higher for similar bandwidth:
$\varepsilon_{\text{trig}} \gtrsim 98\,\%$ at $p_T^e = 35$ GeV vs. $\varepsilon_{\text{trig}} \approx 90\,\%$ with legacy system

- Improvements for large-R jets
- Similar performance for small-R jets and $E_T^{miss}$

More rate improvements by combining with improved, more versatile L1Topo!

# LLP Signatures



*Slide courtesy K. Nagano*

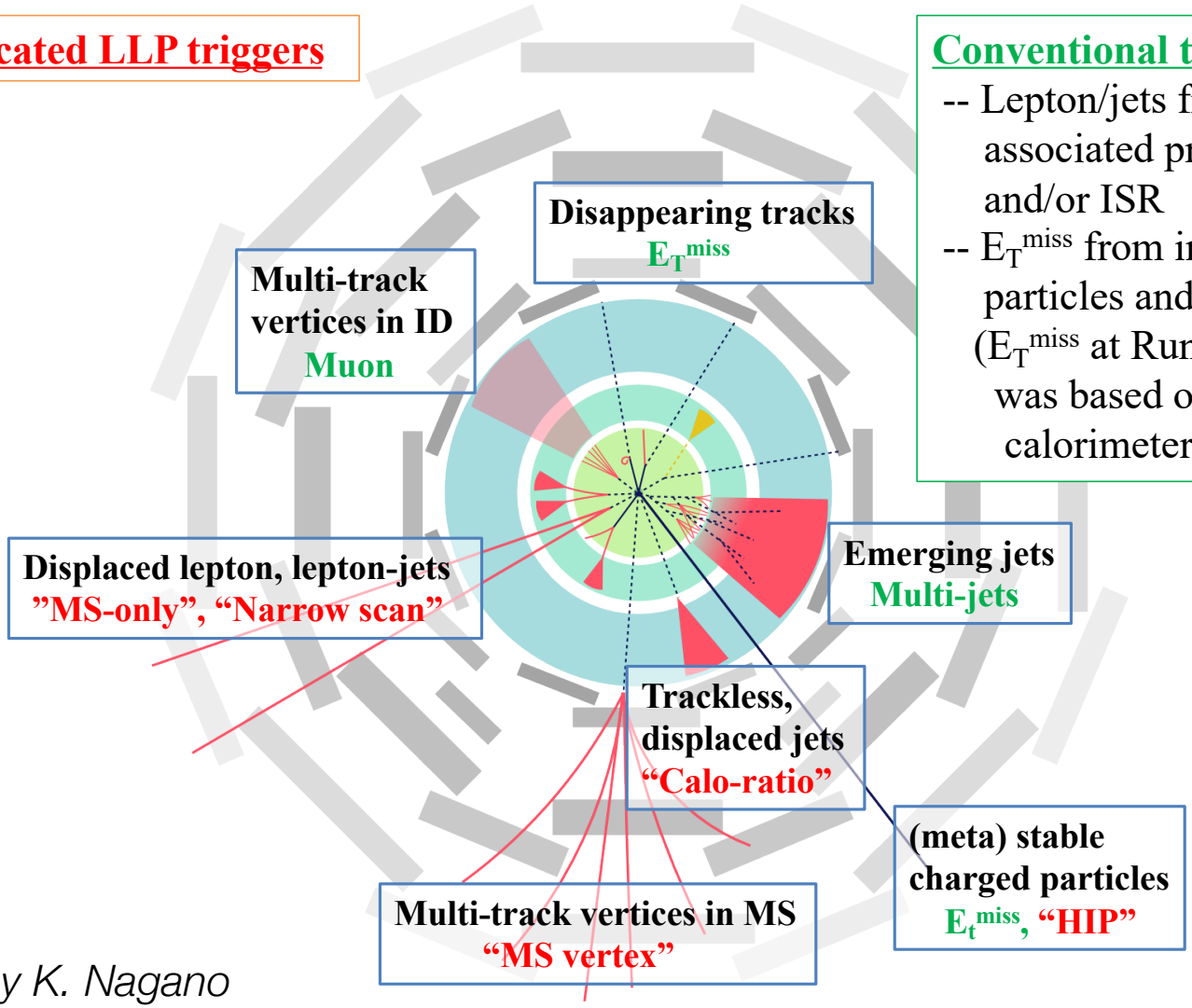
# LLP Signatures and Run-2 Triggers

**Dedicated LLP triggers**

**Conventional triggers**

-- Lepton/jets from associated production and/or ISR

-- $E_T^{miss}$ from invisible particles and/or muon ($E_T^{miss}$ at Run-2 trigger was based on calorimeter-only)




*Slide courtesy K. Nagano*

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