Prospects for LHC and HL-LHC Physics

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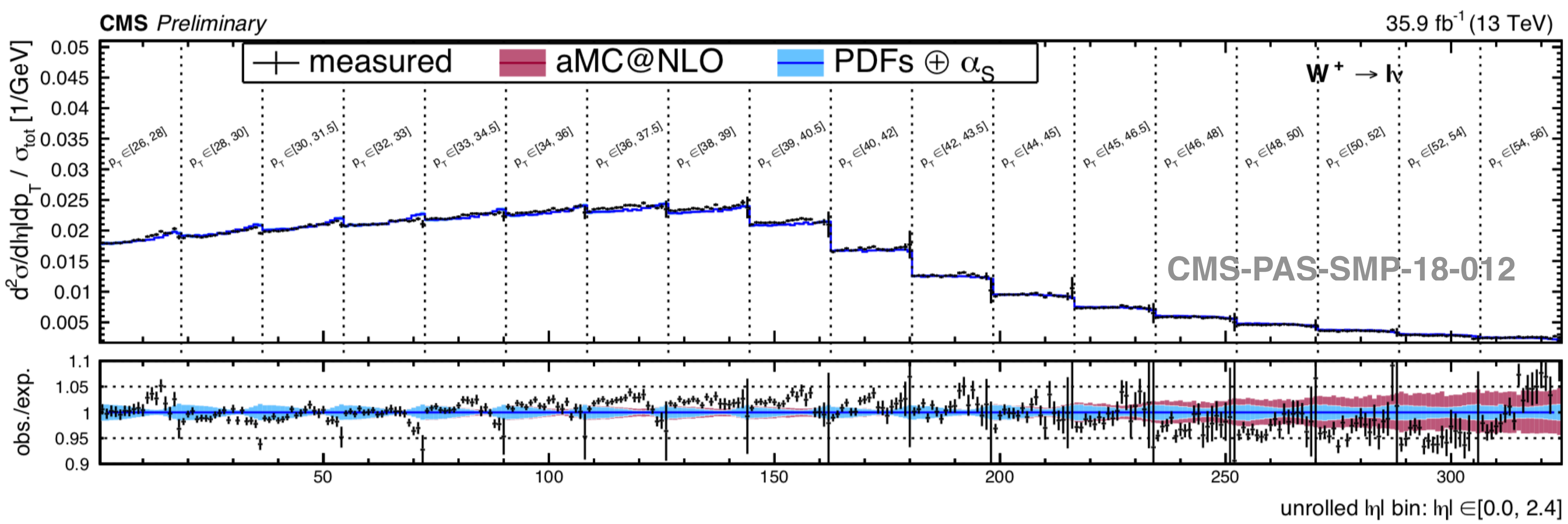
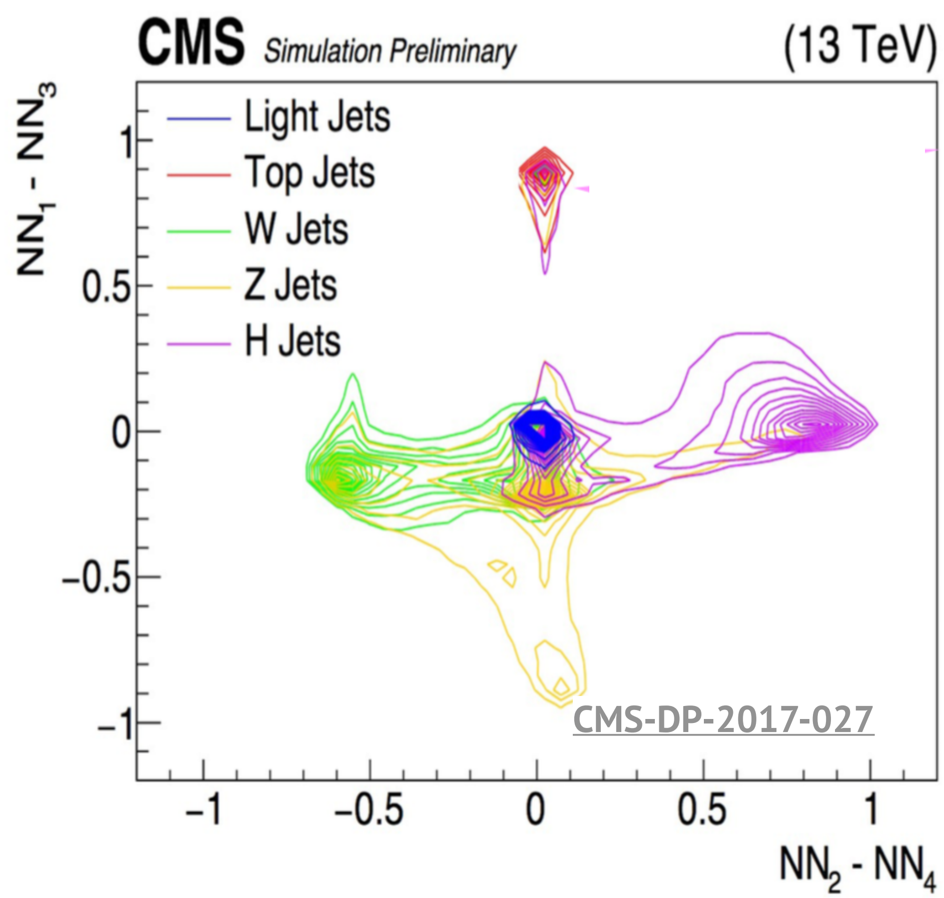
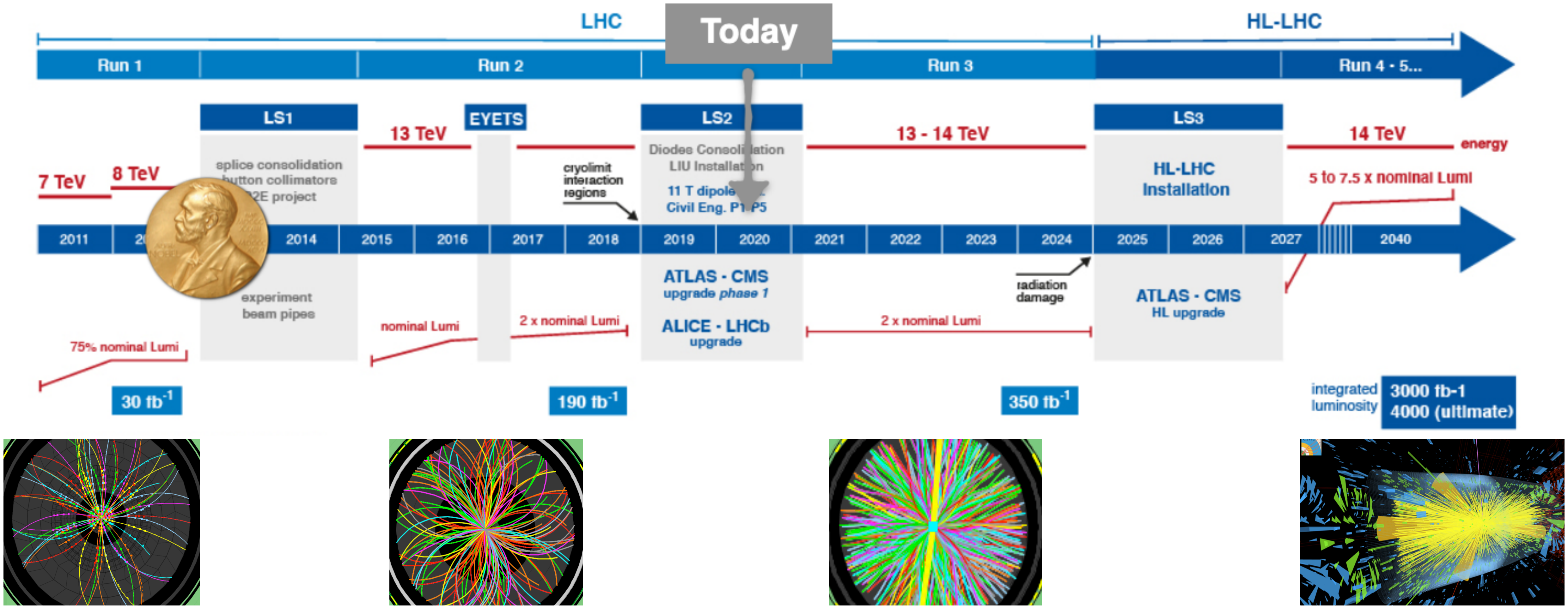
A FEW WORDS OF INTRODUCTION

- **Monumental advances in the characterization of the SM and searches for BSM by the LHC experiments**
  - over 2000 journal publications
- **Unparalleled progress in statistical analysis of data, including but not limited to usage of AI/ML for object reconstruction and signal-to-background separation**
- **Breakthrough in detector and trigger technologies as well as in computing**





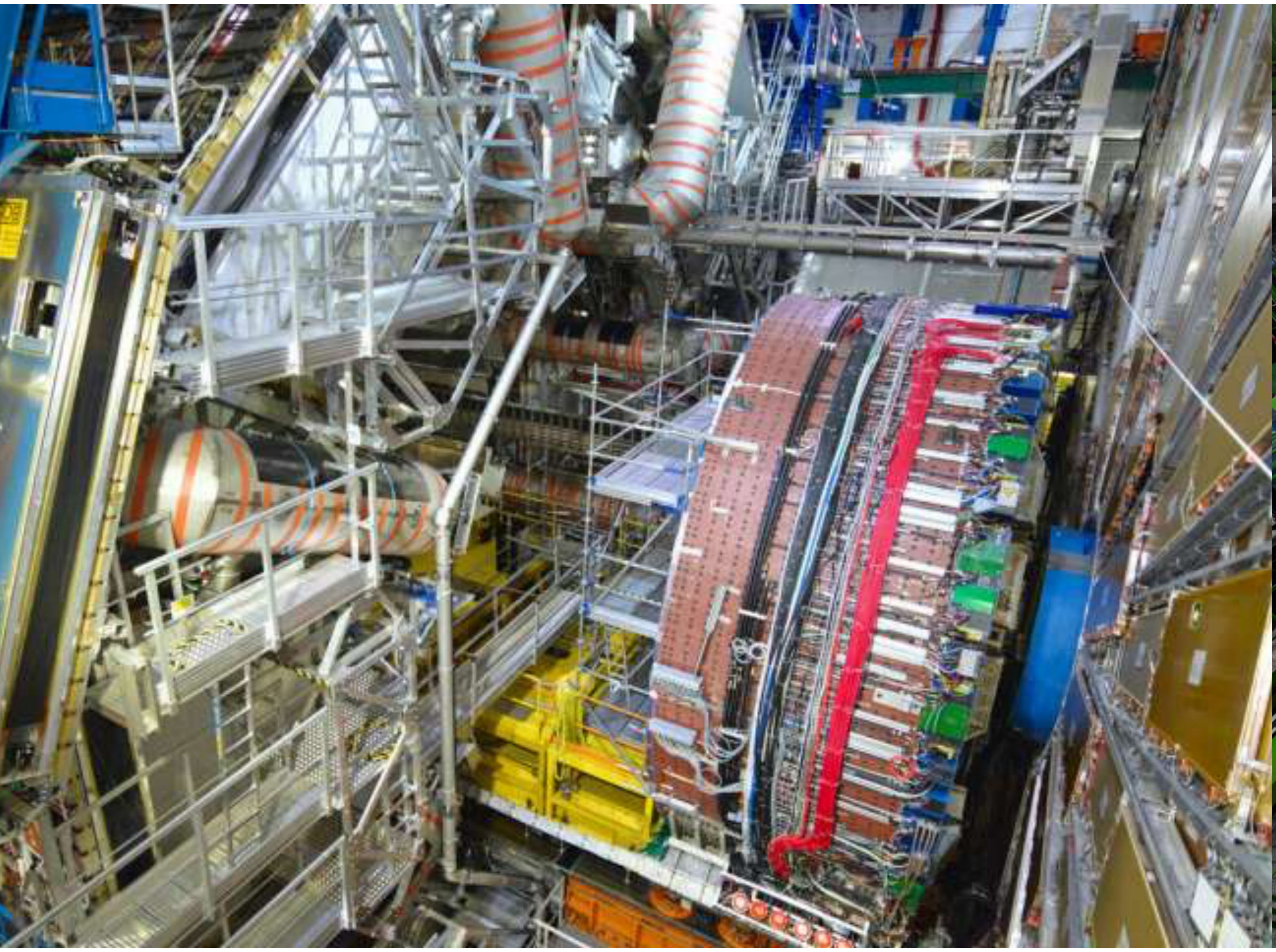
THE FUTURE

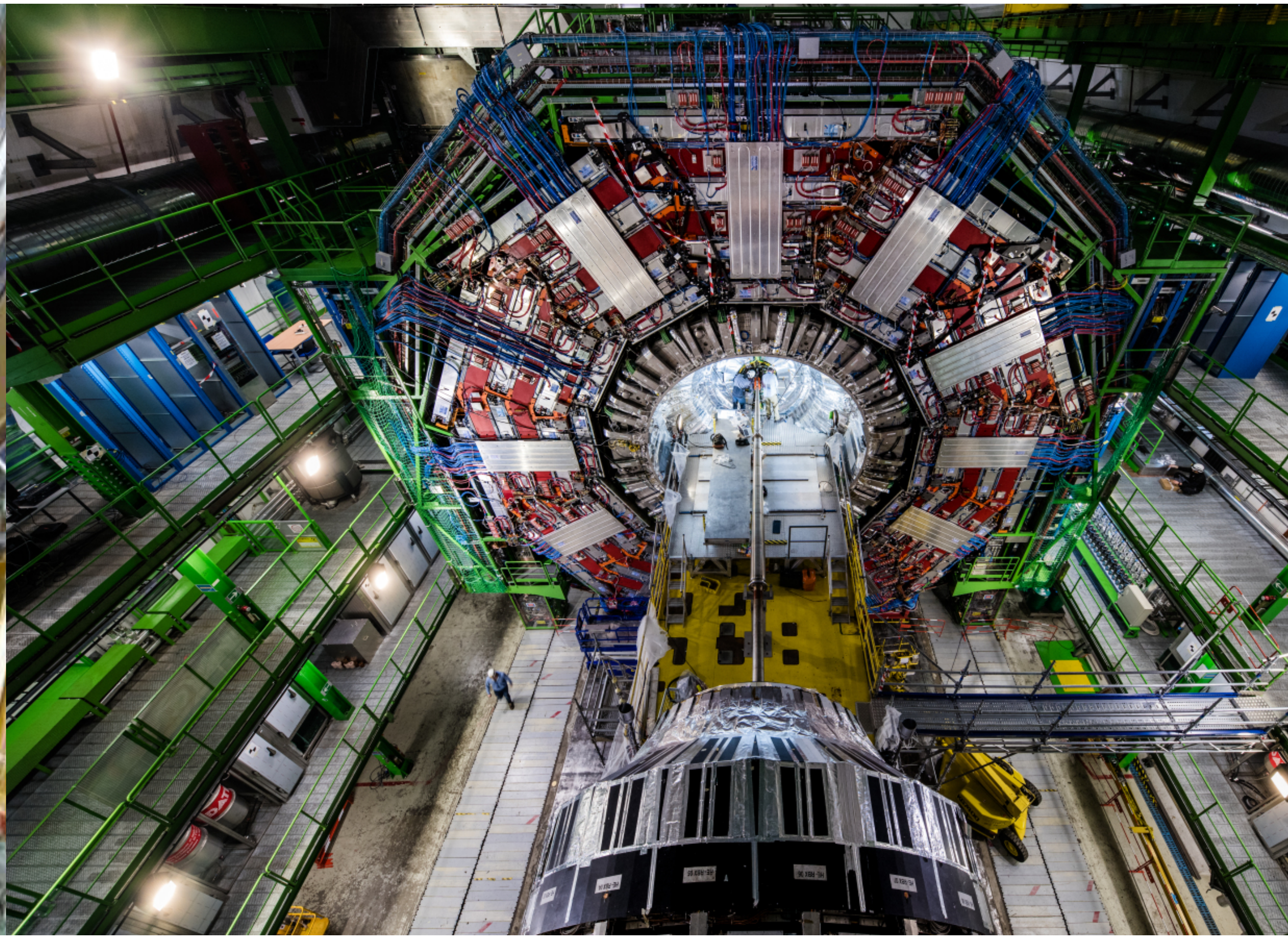


- **Decision on center of mass-energy (13 vs 14 TeV) expected at the end of the long shutdown 2**
- **Increase of pile up (PU) up to 60-70 in Run 3 and up to 200 at HL-LHC**
- **ATLAS and CMS experiments being upgraded to perform efficiently at higher instantaneous luminosities and to provide new capabilities**

OUTLINE OF THE PRESENTATION

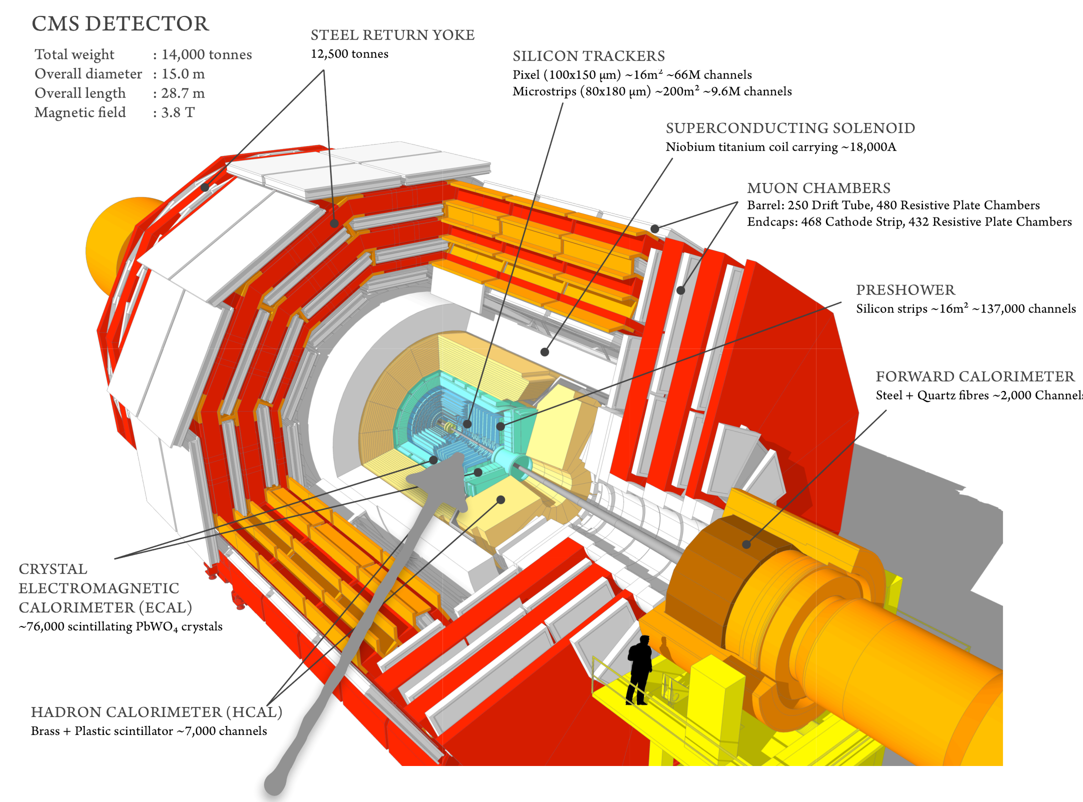
- New opportunities offered by the upgraded CMS and ATLAS detectors
- Prospects for LHC Run 3
- Preparation for the HL-LHC and exploration of the HL-LHC dataset
- Conclusions

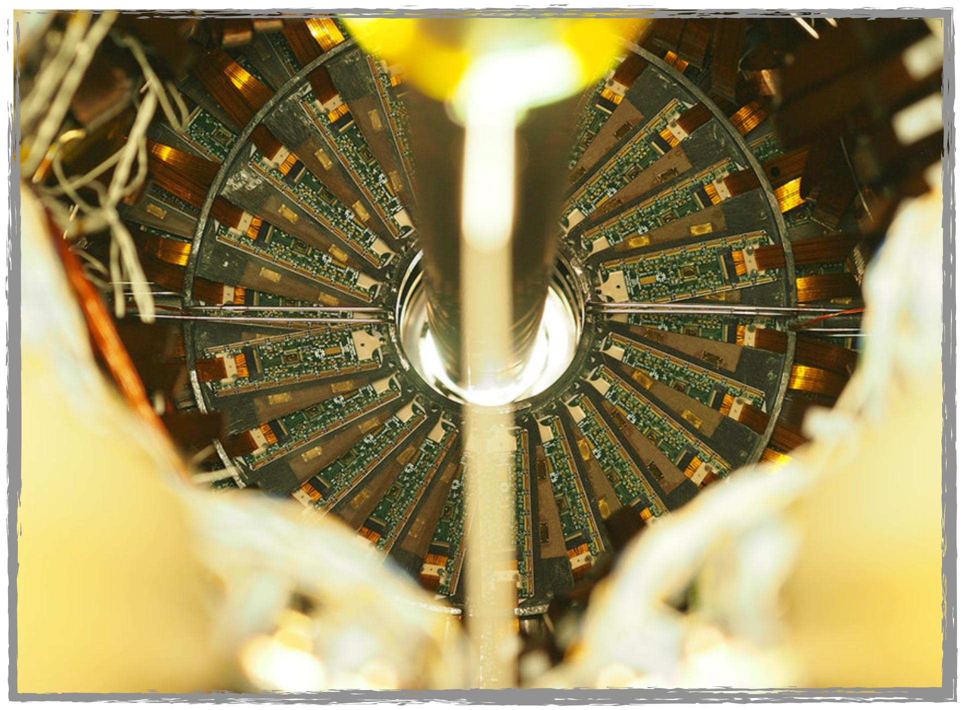




CMS: (STAGED) PHASE 1 UPGRADE

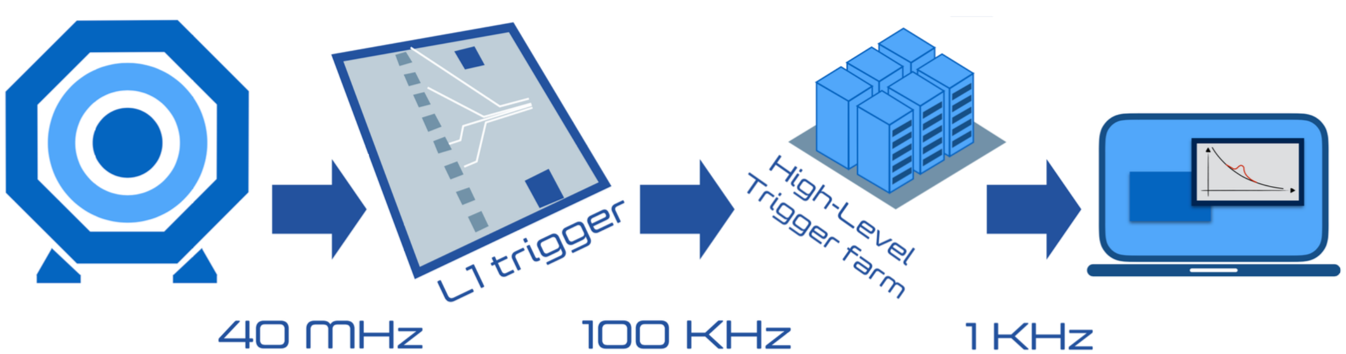
- **New Pixel detector**
  - Additional layer
  - New fully digital readout ASIC with deeper buffers
  - Less material
- **New front-end for hadronic calorimeter (HCAL)**
  - Silicon photomultipliers in place of photodetectors
  - Increase of granularity of the energy measurement
- **New muon system technology to detect muons at 10 deg**
- **Upgrade of the L1 trigger with state-of-the-art electronics (FPGAs) and high-bandwidth optical transmission**
  - Use of the additional calorimeter and muon information

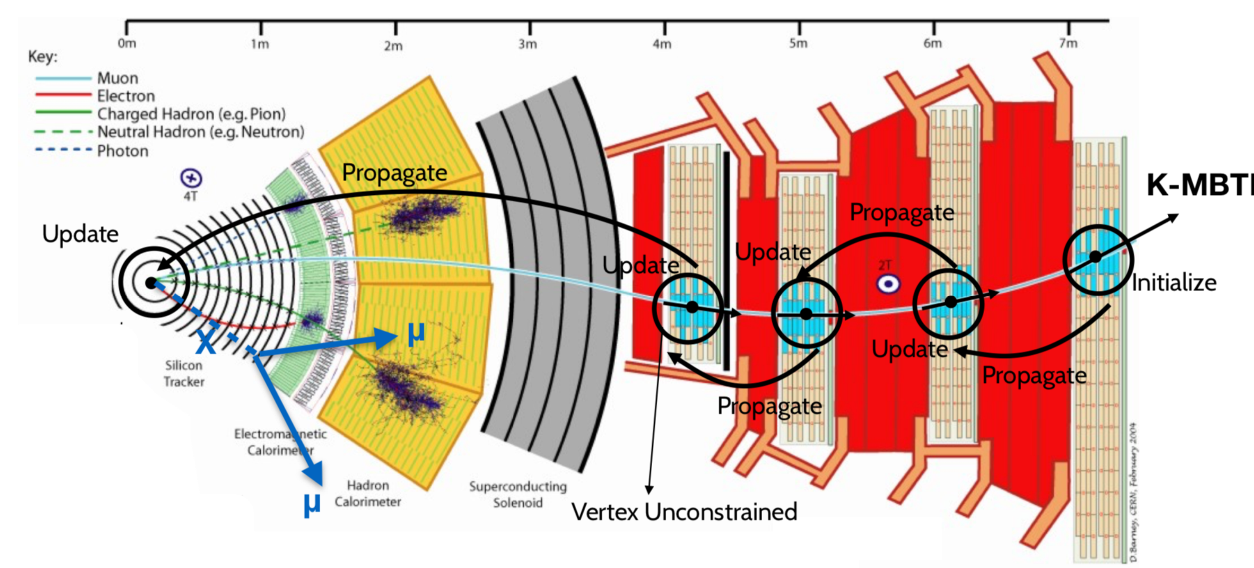




PROFITING FROM PHASE 1 UPGRADE

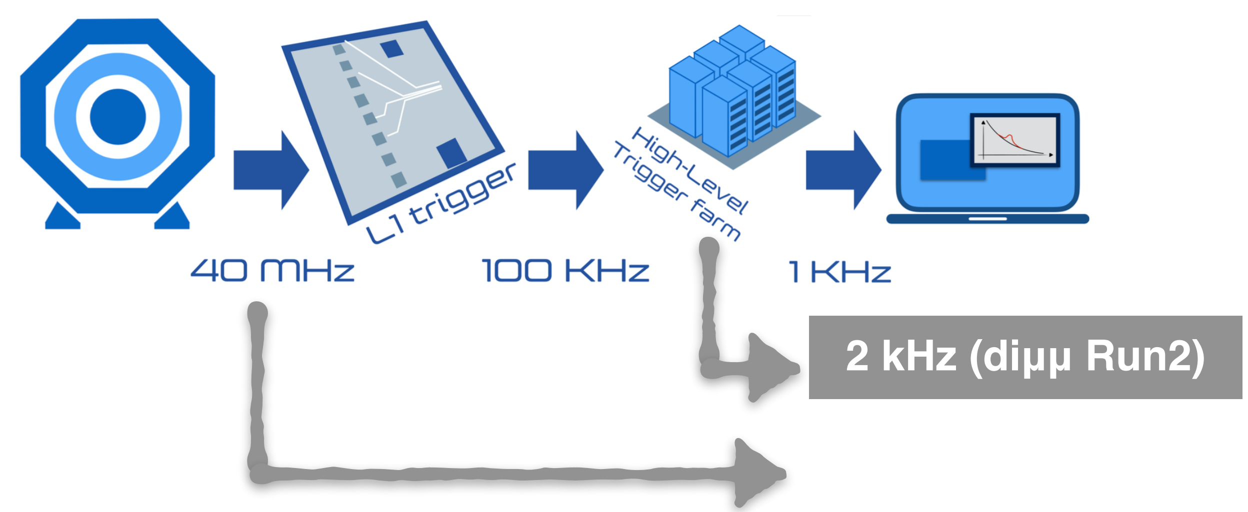
- **The upgraded L1 trigger as key to searches for challenging signatures at Run 3**
  - Delayed jets identified using HCAL depth segmentation and timing information
  - Displaced muons in the barrel region reconstructed thanks to new Kalman filter algorithm
  - Displaced muons in the forward region reconstructed using a neural network implementation of forward muon tracking
  - Event signatures (e.g. VBF production) reconstructed by topological algorithms
- **Heterogeneous online reconstruction to boost capabilities of high level trigger and thus to increase significantly coverage of new signatures (*e.g.* displaced taus)**
  - Today, achieved 24% offload of reconstruction on GPUs

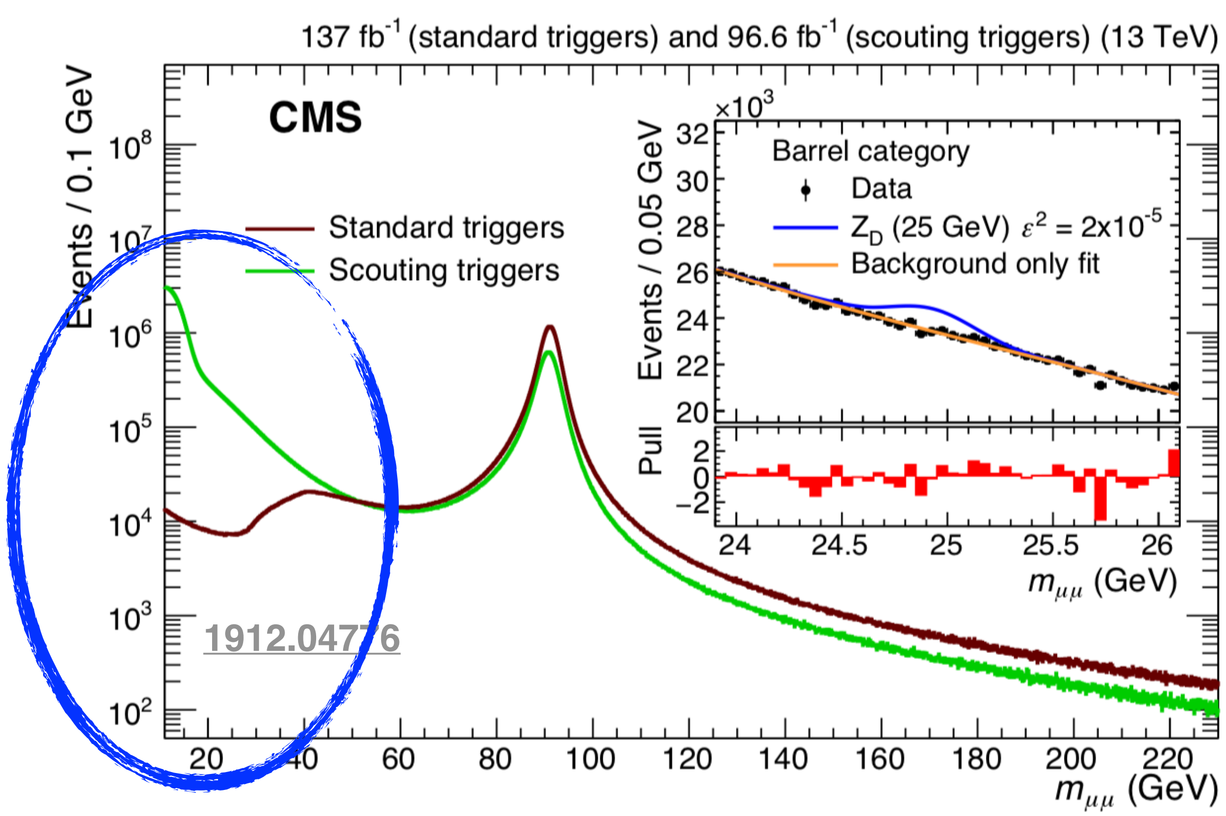




RECORDING MORE EVENTS: SCOUTING

- “Scouting” at High Level Trigger
  - Read out L1 triggered events
  - Store offline only information from HLT processing, event size reduced by 100
  - x10 more events
- New algorithms based on particle flow objects and L1 seeds for displaced particles

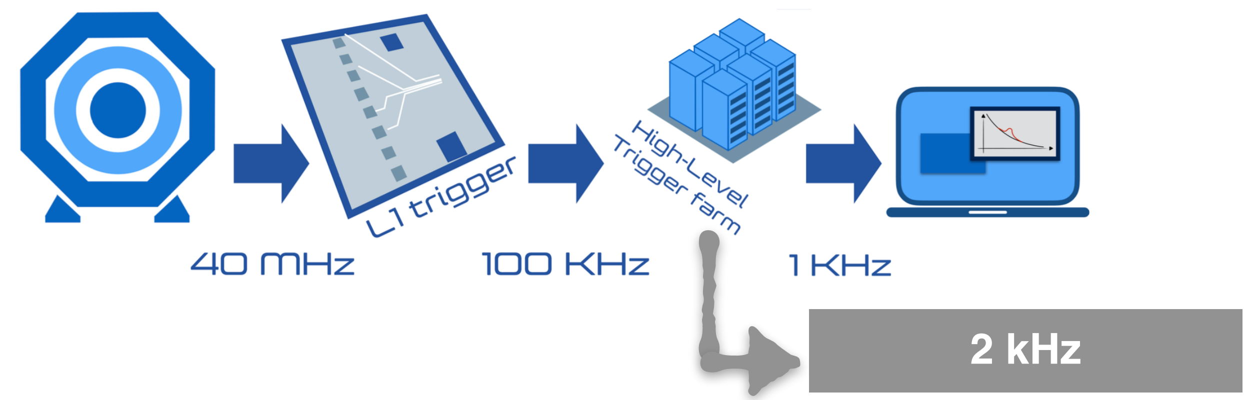


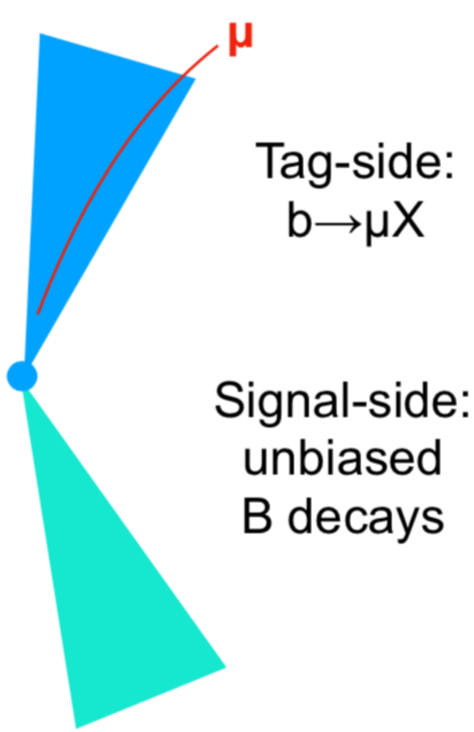


- **Scouting at 40 MHz with Deep Learning**
  - Read out at the full bunch crossing rate
  - Independent of the L1 trigger
  - Semi real-time analysis of the L1 trigger objects
    - neural network determination of muon parameters
    - jets, photons/electrons, global variables

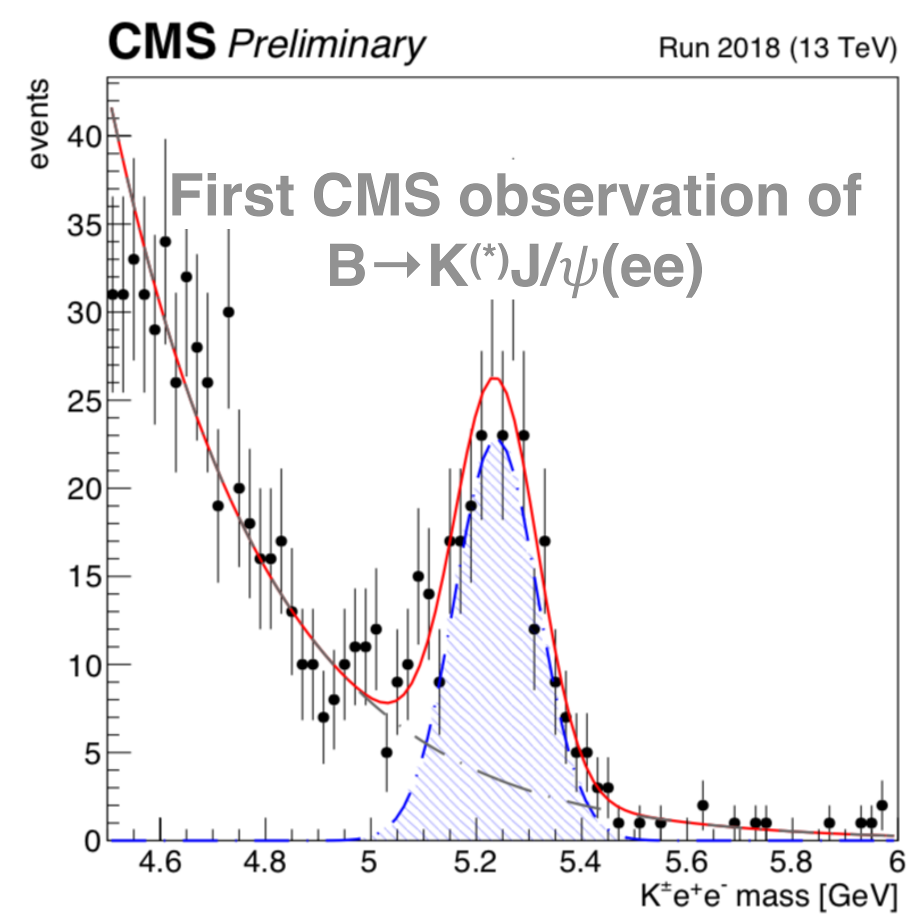
RECORDING MORE EVENTS: PARKING

- **Storing more events for the B physics program**
  - typically allocated ~15% of 1 kHz rate
- **"B-parking" strategy**
  - Raw data to tape, offline reconstruction during no data taking





- **Events triggered on b→μX decays, with signal side being unbiased**
  - Sensitive to events with very low p_T SM particles, including electrons
- **Promising dataset collected so far (10B events)**
- **Challenging in Run 3 but ideas are emerging**



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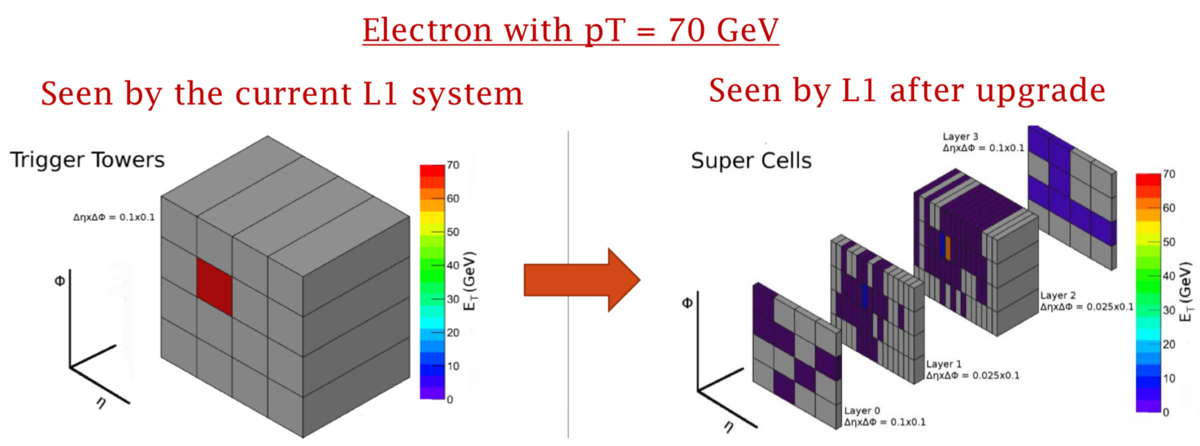
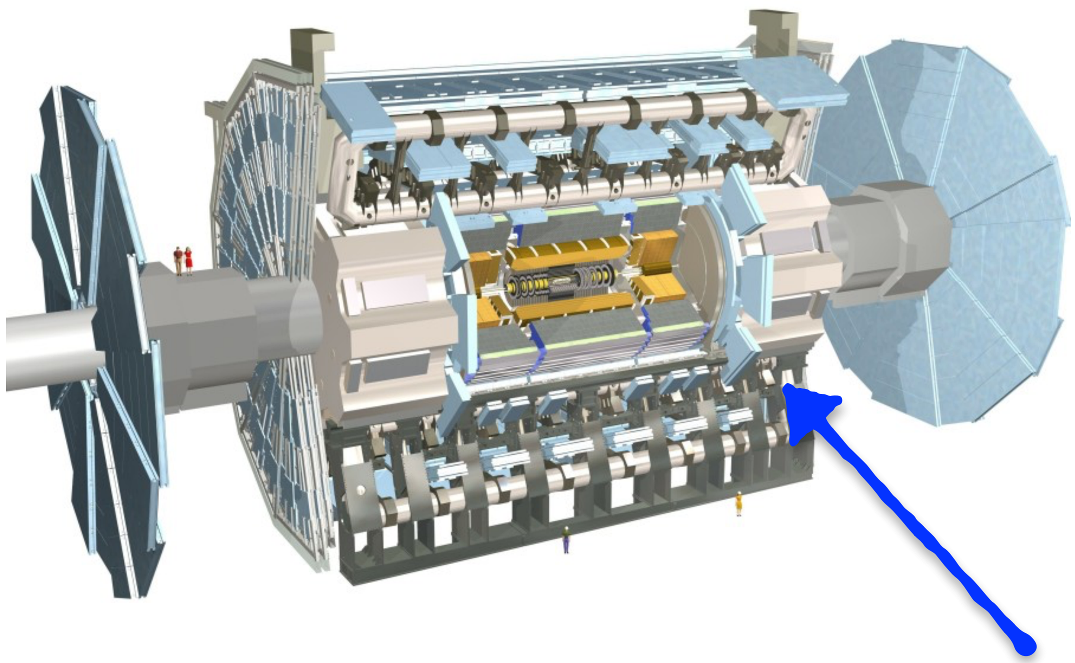
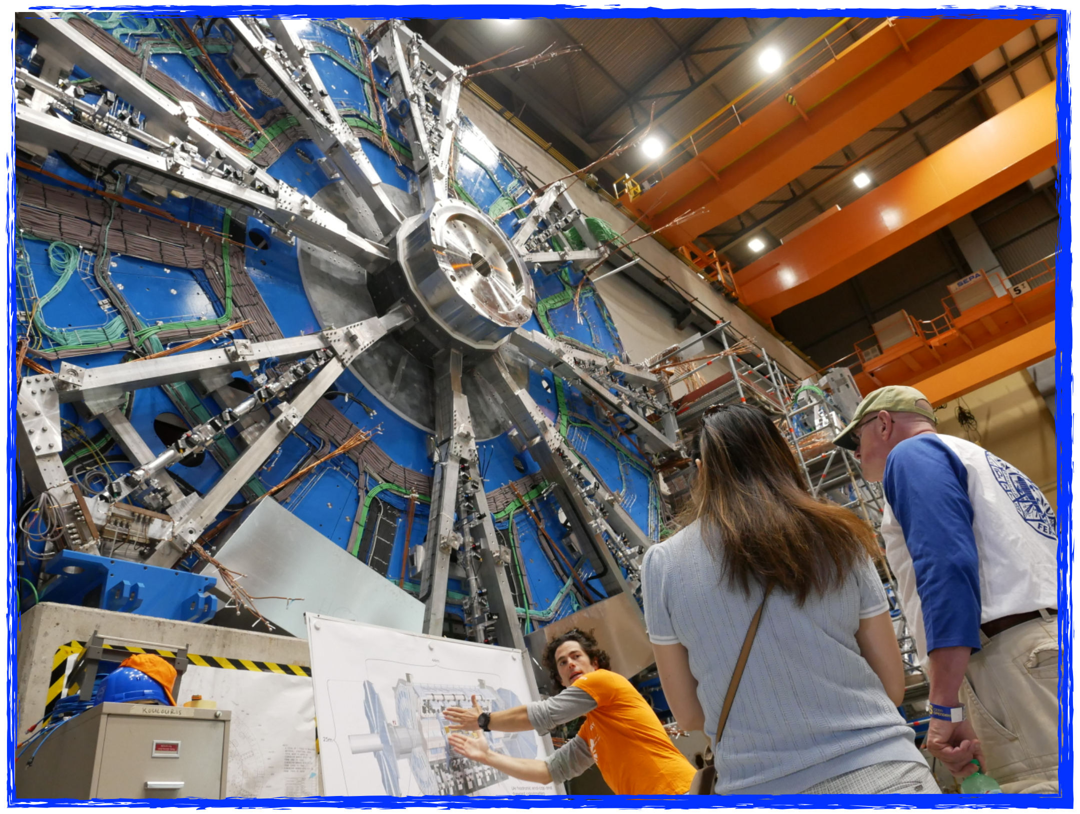
ATLAS: PHASE 1 UPGRADE

- **New front-end for Liquid Argon Calorimeter**
  - Increase of granularity of the energy measurement

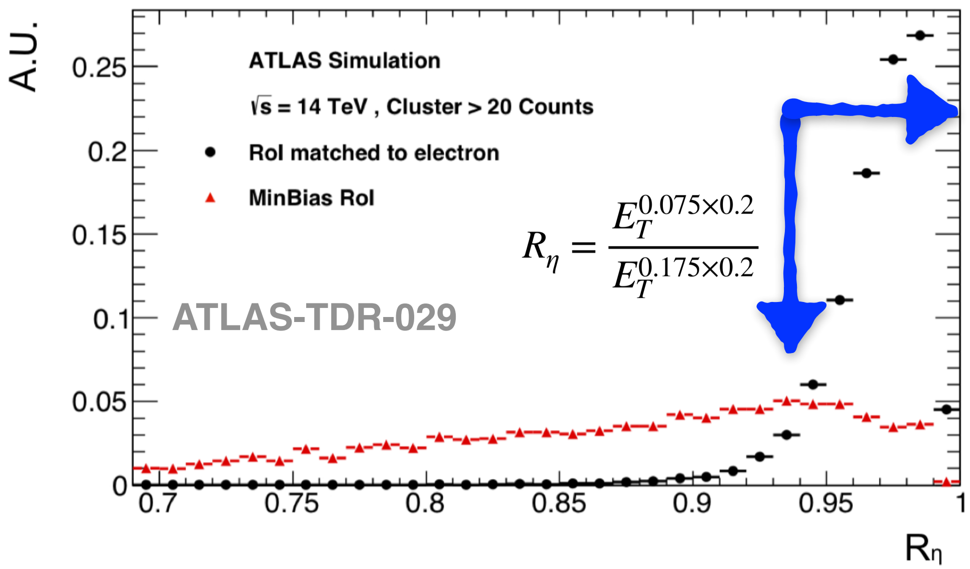


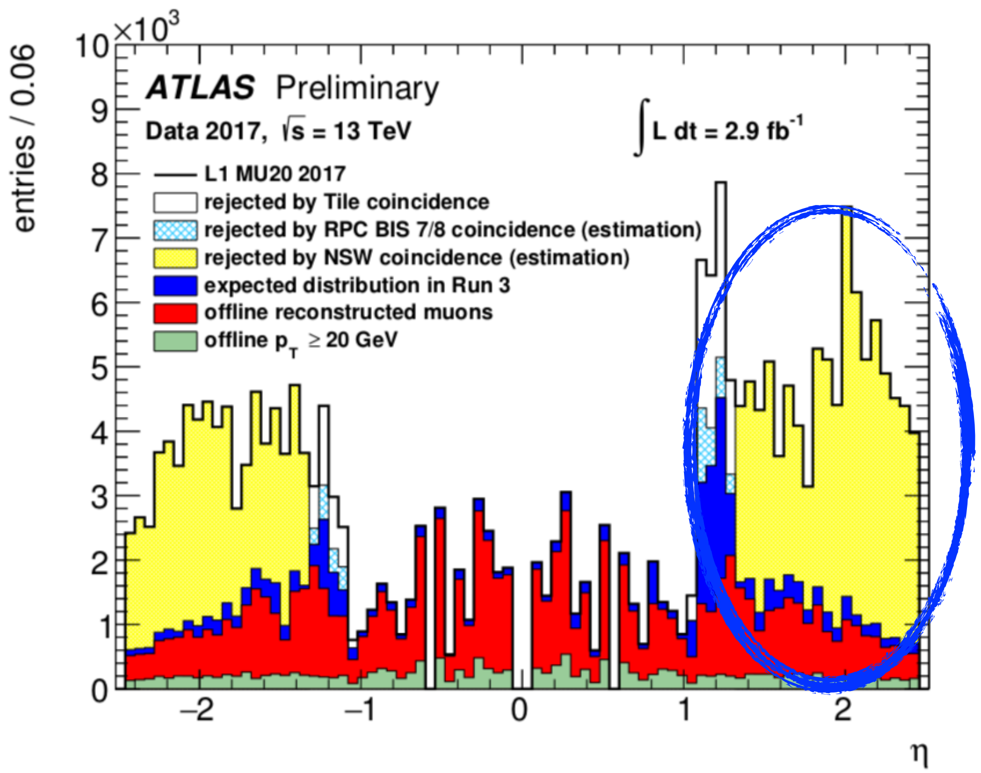
- **New Small Wheel (NSW) + BIS78**
  - Replacement of the inner muon station in the endcap regions of the detector
- **Upgrade of Trigger and DAQ**
  - Use of finer calorimeter segmentation
  - Improved muon trigger information from NSW
  - Topological information and feature extractions

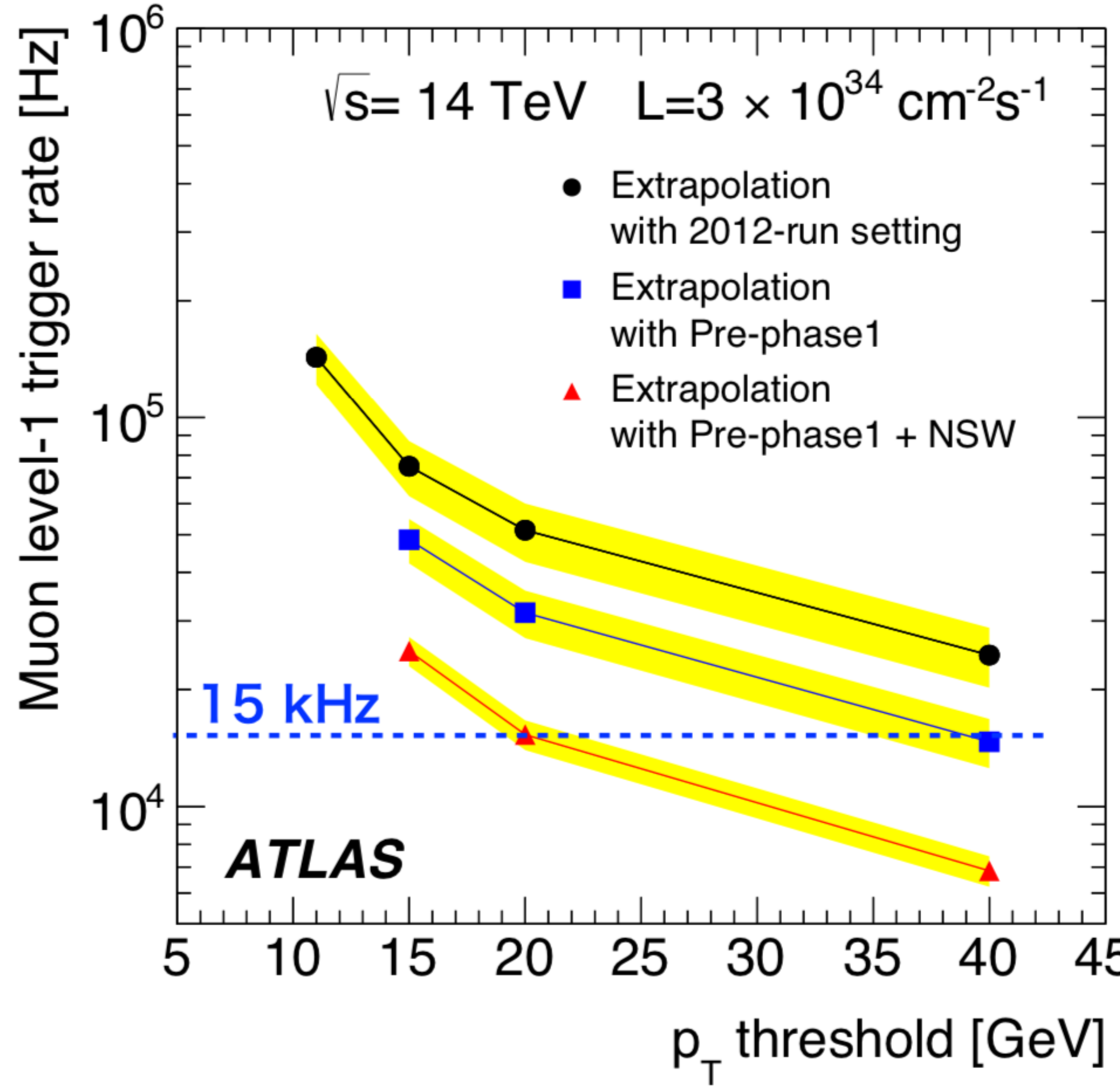




NEW CAPABILITIES OF ATLAS IN RUN3







ATLAS-TDR-020

- **Phase 1 upgrade enabling ATLAS to maintain low trigger thresholds and thus to collect an excellent sample of pp collision events at the EWK scale**

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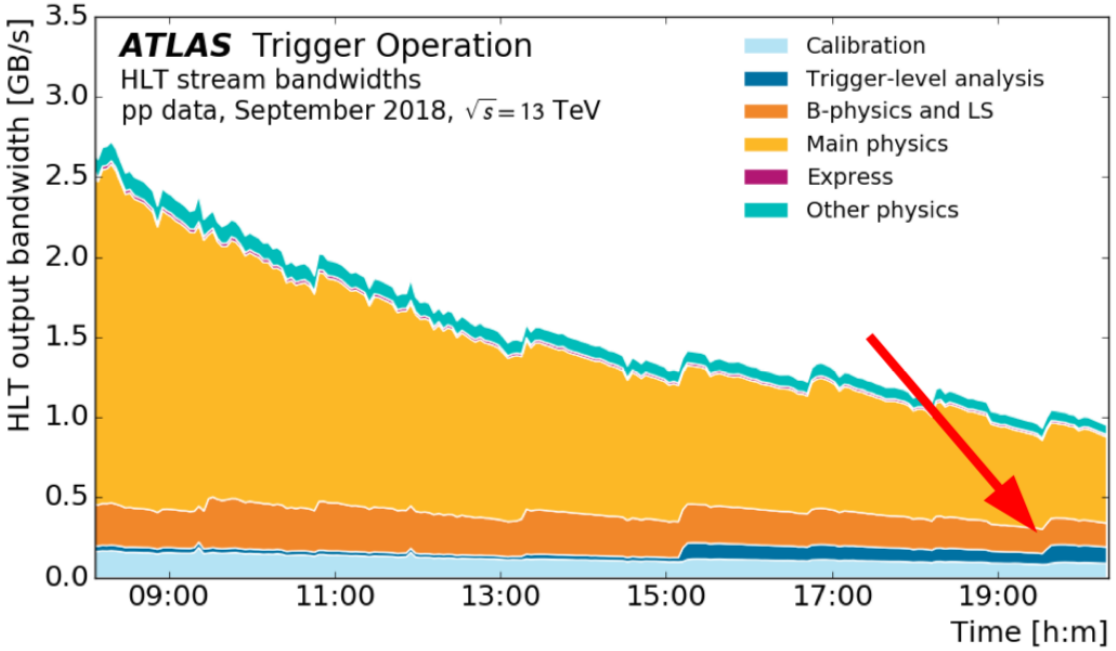
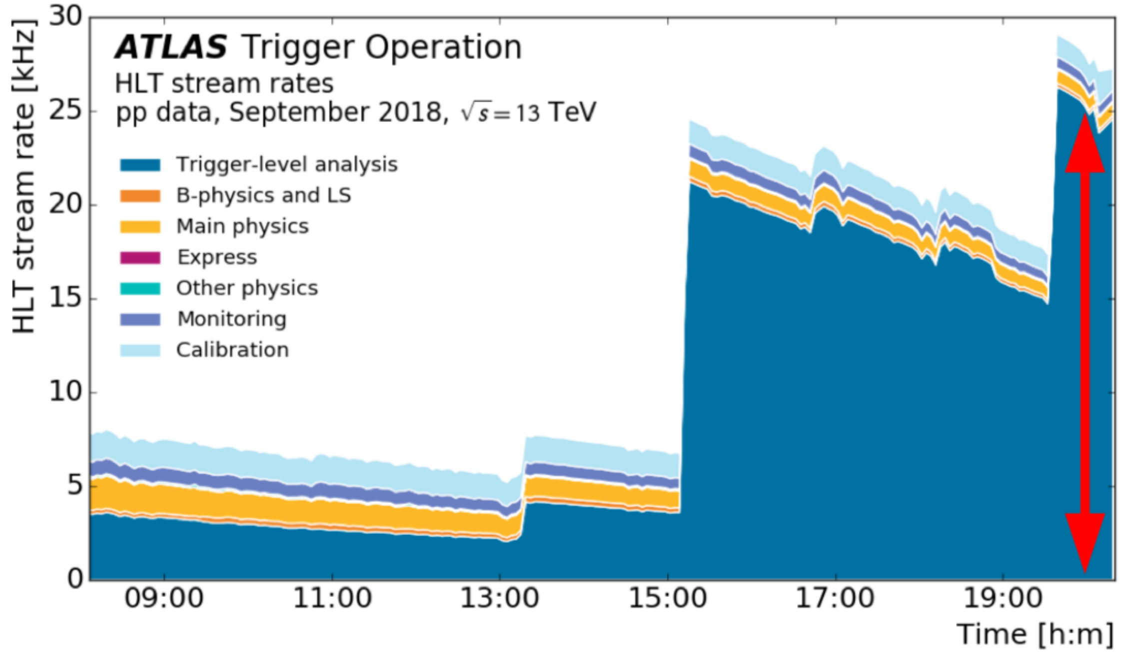
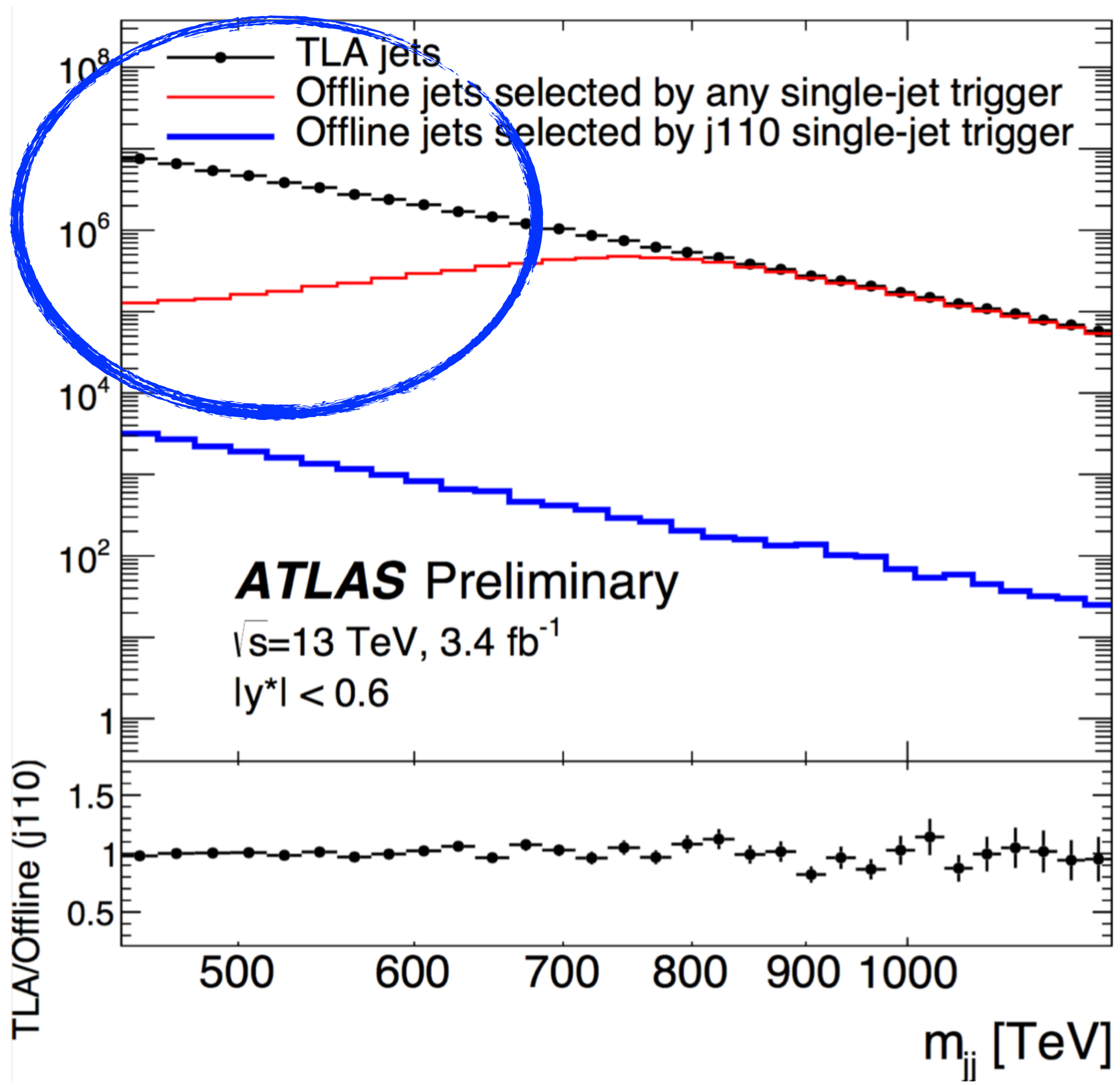
EXTENDING SENSITIVITY TO LOW MASS

- "Trigger level analysis" implemented during Run 2
  - enabled at low luminosity, peak rate of ~ 30 kHz, event size of few kB







PREAMBLE

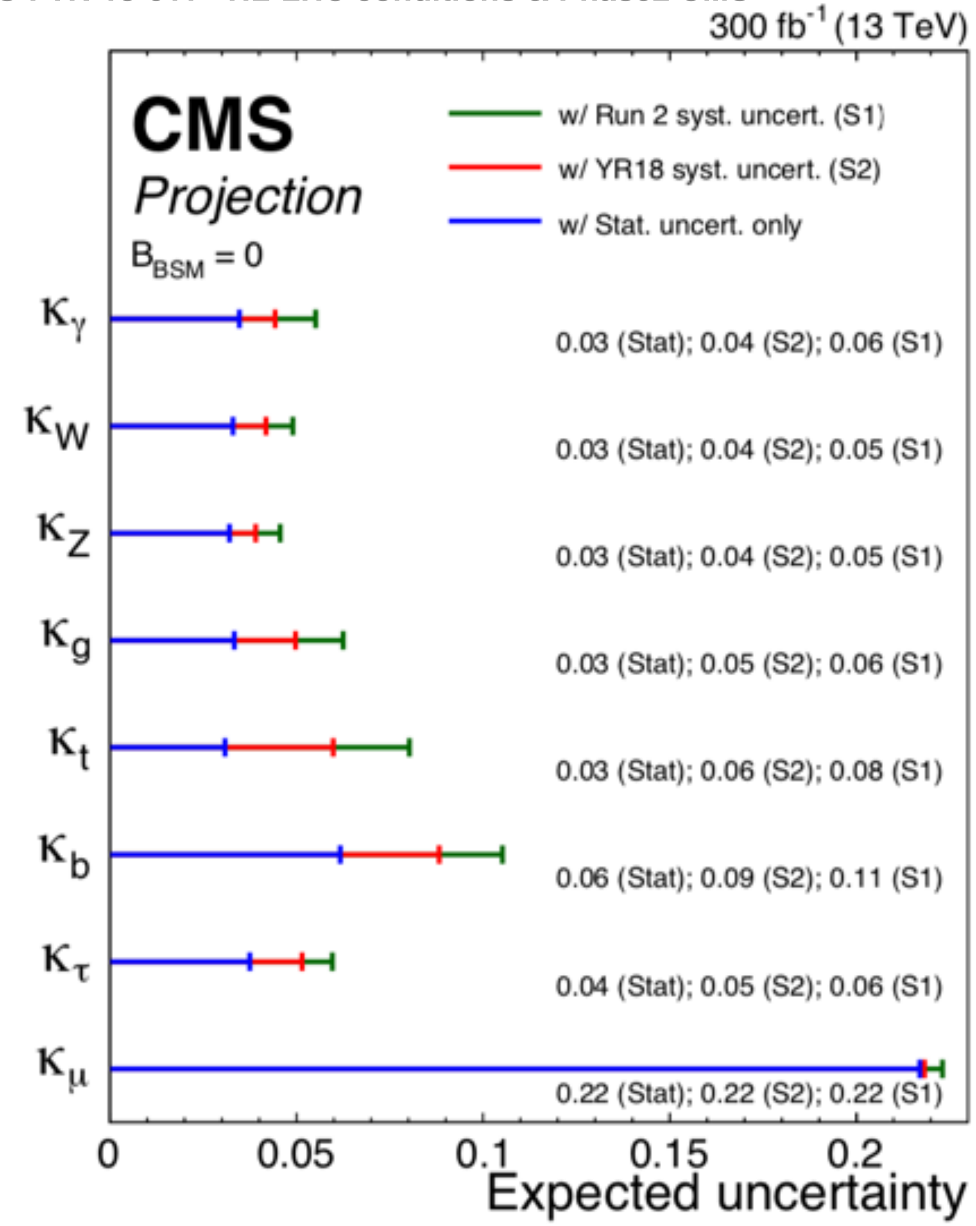
- **Run 3 will allow to perfect the classic program of measurements and searches we have developed so far, while opening up new avenues for discovery**
- **A lot of novel ideas being developed by the ATLAS and CMS collaborations**
  - mainly internal results for now
  - a few directions mentioned today

HIGGS PHYSICS

- **Progressing from the discovery machine to the Higgs factory**
- **Increase of precision for statistically limited measurements (*e.g.* selected couplings and differential cross-sections)**
  - Observation of rare modes (*e.g.* H→μμ)
- **Reduction of systematic uncertainties on high statistics ones *e.g.* mass in H→γγ mode**
- **Improvement of signal-to-background separation via ML and better triggers expected at Run 3**
  - Machine-learning based global triggers
  - Parking and scouting/TLA techniques
- **If center of mass-energy increased to 14 TeV, order of 10% gain in cross-sections**
  - ggH (13%), VBF (13%), VH (10%), ttH (20%)
  - HH (18%)

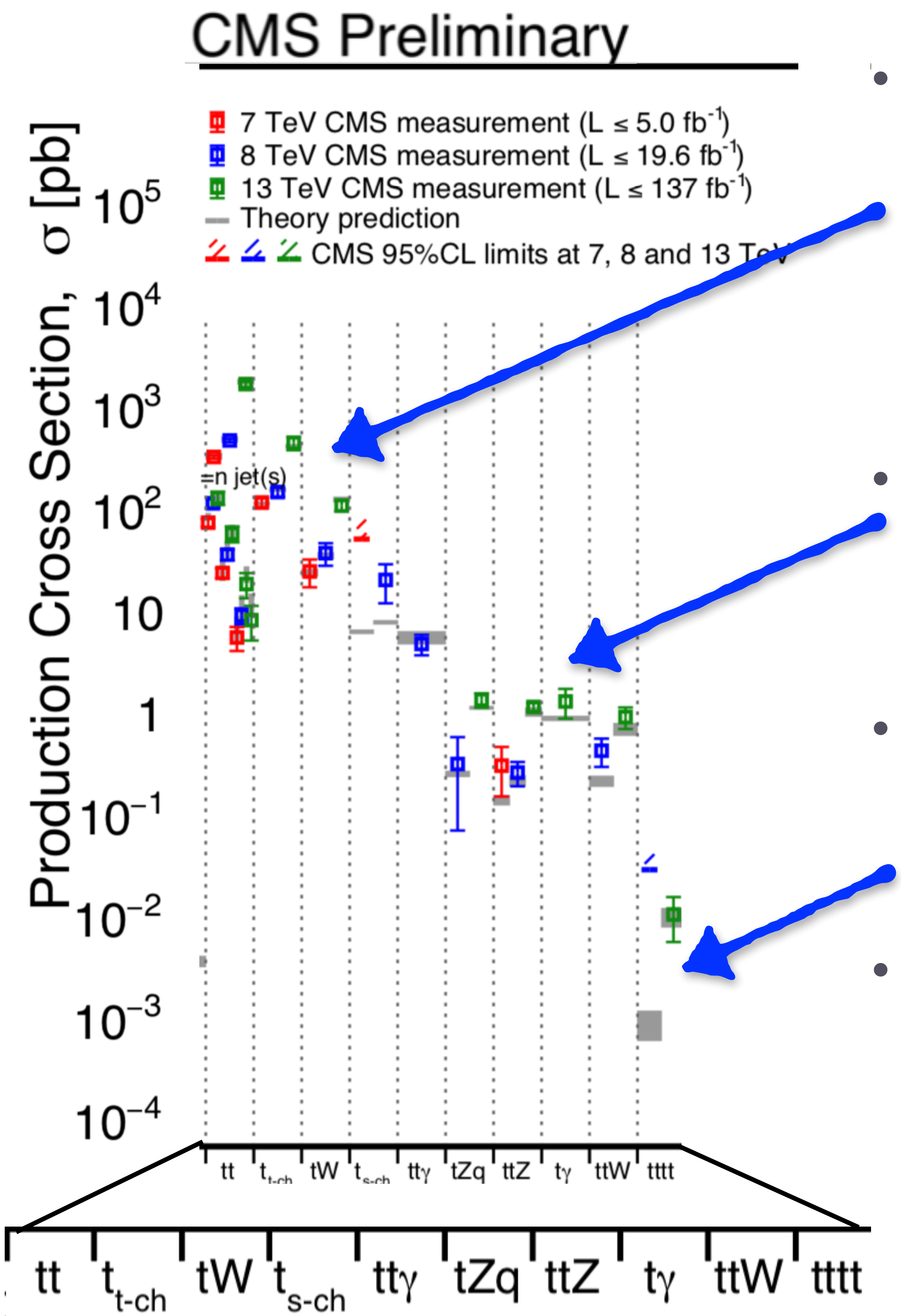
$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$

CMS-FTR-18-011 - HL-LHC conditions & Phase2 CMS



Improvements
> 2x w.r.t Run2 (36/fb)

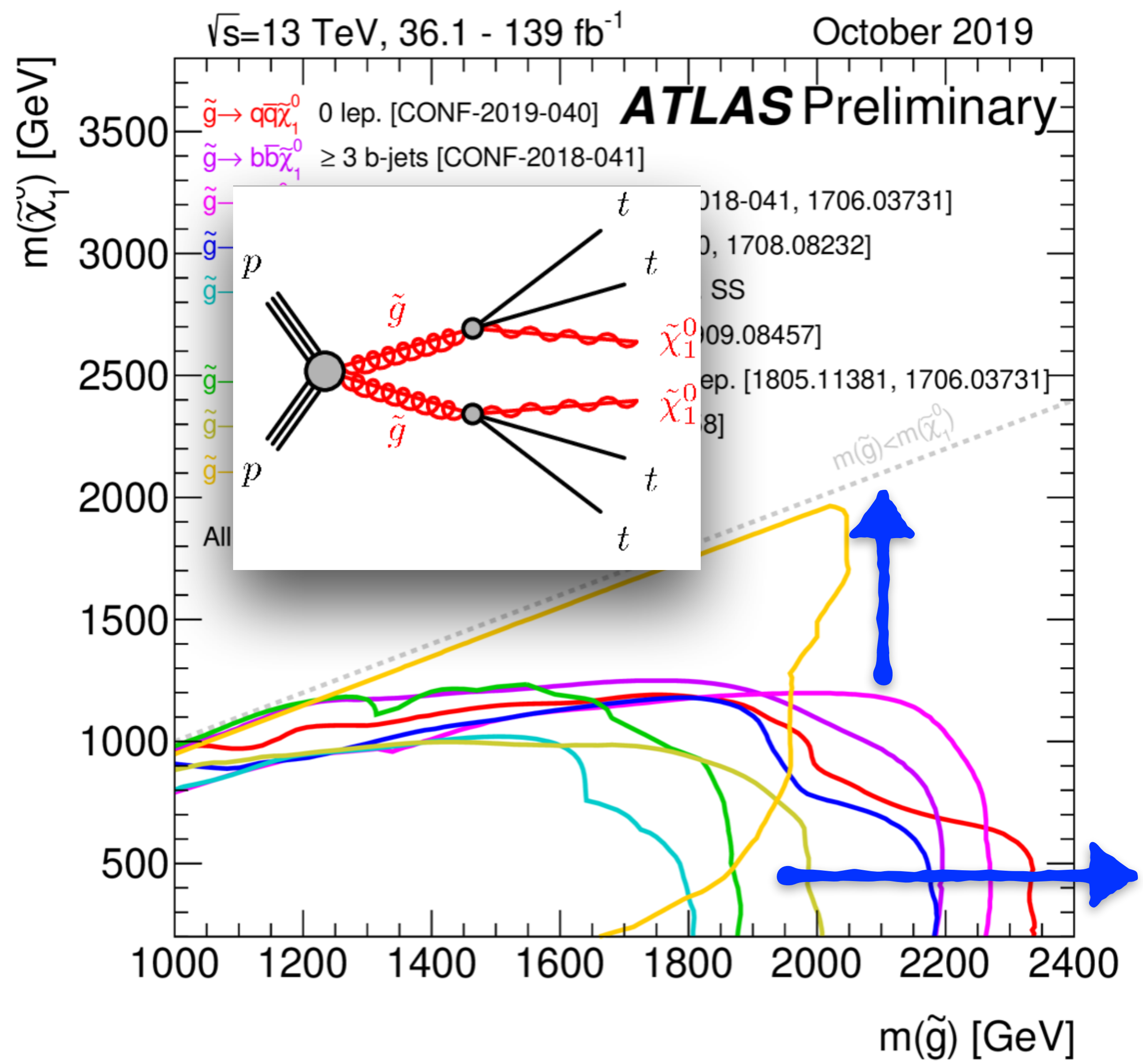
TOP PHYSICS



- Extensive program of top physics at Run 3
- High cross section processes entering high precision regime with expected reduction of systematic uncertainties
  - *e.g.* inclusive and differential cross-section of tt, measurement of top mass and width, W helicity,…
- Former rare processes becoming systematically dominated
  - e.*g.* ttV and tZq
- Exploration of the “fb frontier”
  - very rare processes approaching observation (*e.g.* production of 4 top)
- Significant increase of cross sections at 14 TeV, between 10% (s-channel single t) and 30% (4 top)
  - boost of sensitivity to very rare phenomena *e.g.* ttWW (~14 fb)

SUPERSYMMETRY (1)

- **Sensitivity to high mass models (hitting the "σ-wall") boosted by aggressive use of advanced identification algorithms (like sub-structures for top tagging) and machine learning**
  - **Further gain at 14 TeV center of mass energy with cross-sections increasing by 1.3-2.0 for TeV scale sparticles**
- **Upgraded detectors enabling extension of the search to unexplored regions of phase space**



- **Searches for compressed scenarios as key components of Run 3 program**
- **"Compressed' regions of strong sector could be probed by lowering thresholds on trigger objects (jets, total hadronic energy) using parking and scouting/TLA**

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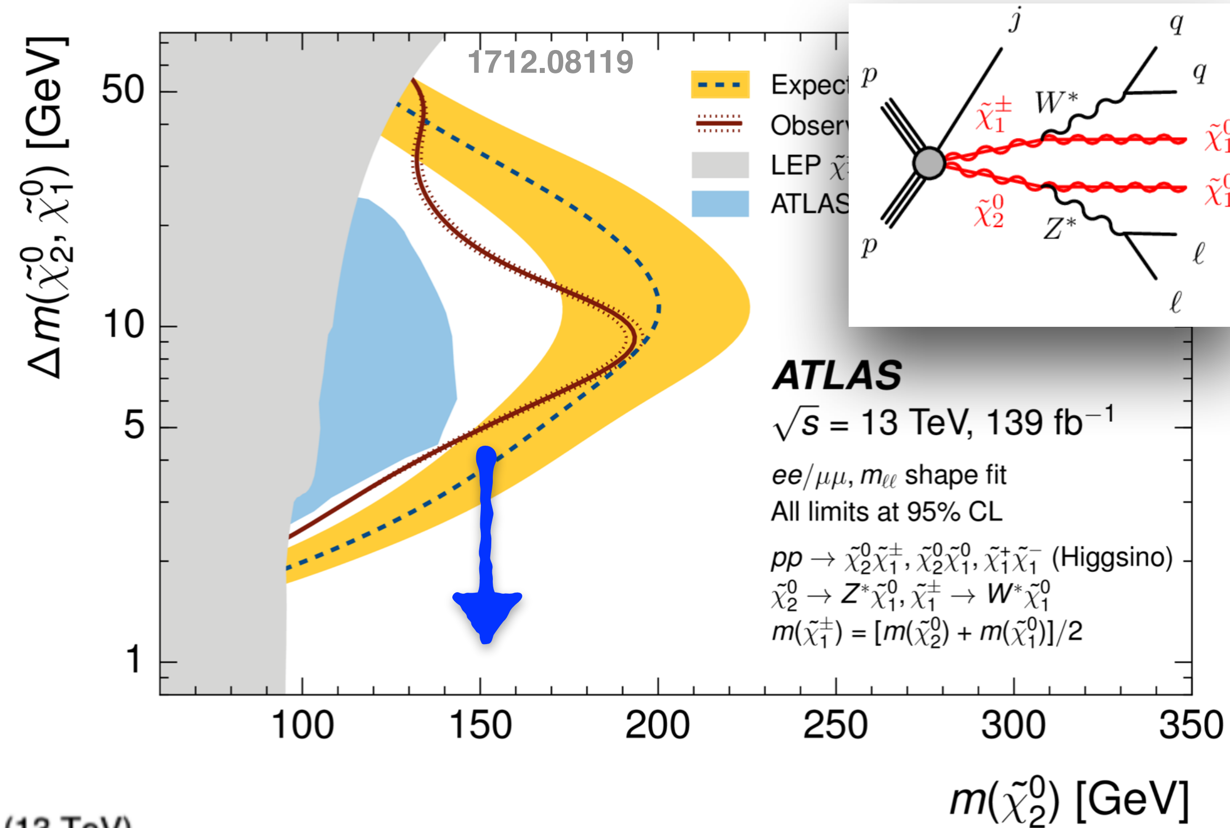
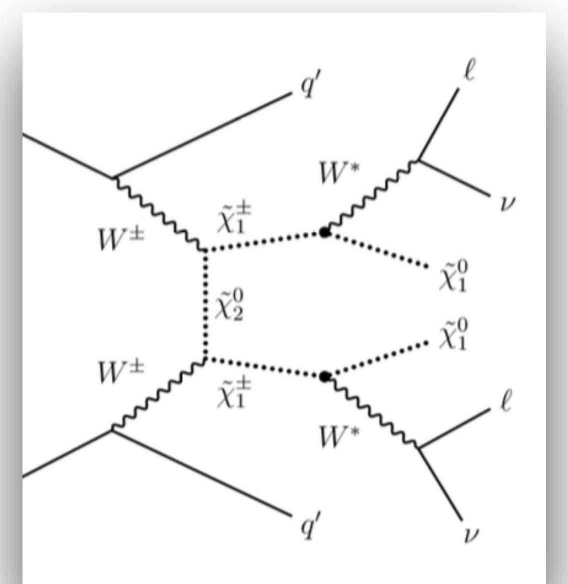
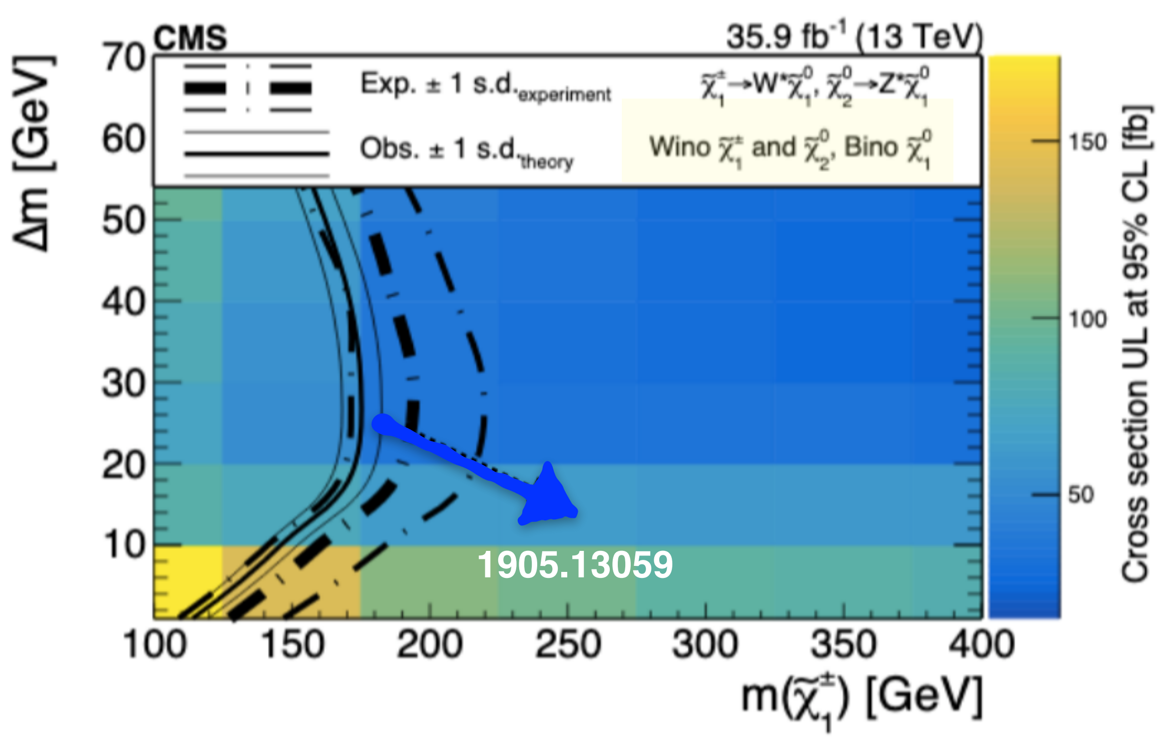
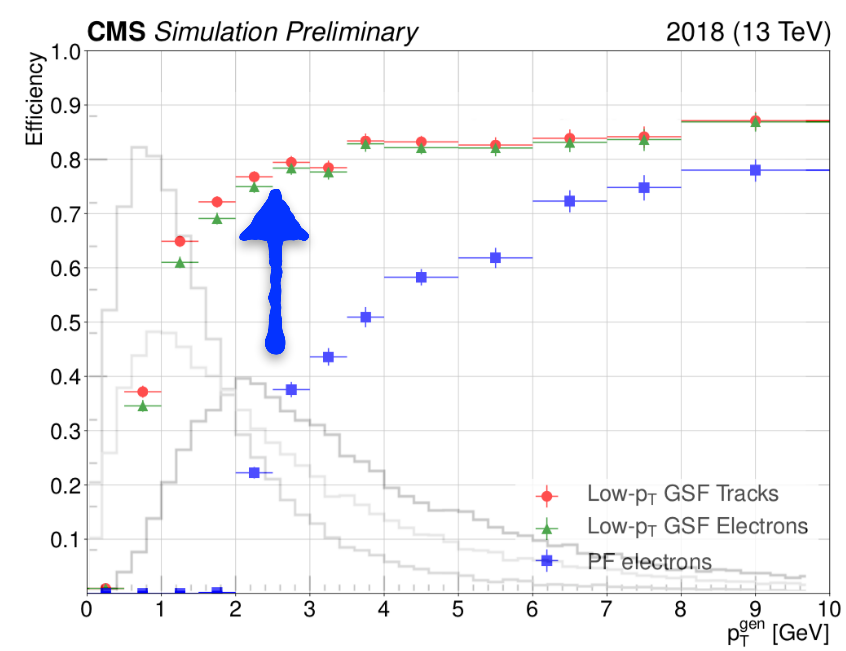
SUPERSYMMETRY (2)

- **Compressed scenarios predicted in highly motivated models with low mass higgsinos**
- **Aim at extending sensitivity**
  - More efficient trigger selection of events including VBF production
  - Use of very low p_T lepton
  - Refine techniques to tag disappearing, displaced, soft and displaced tracks



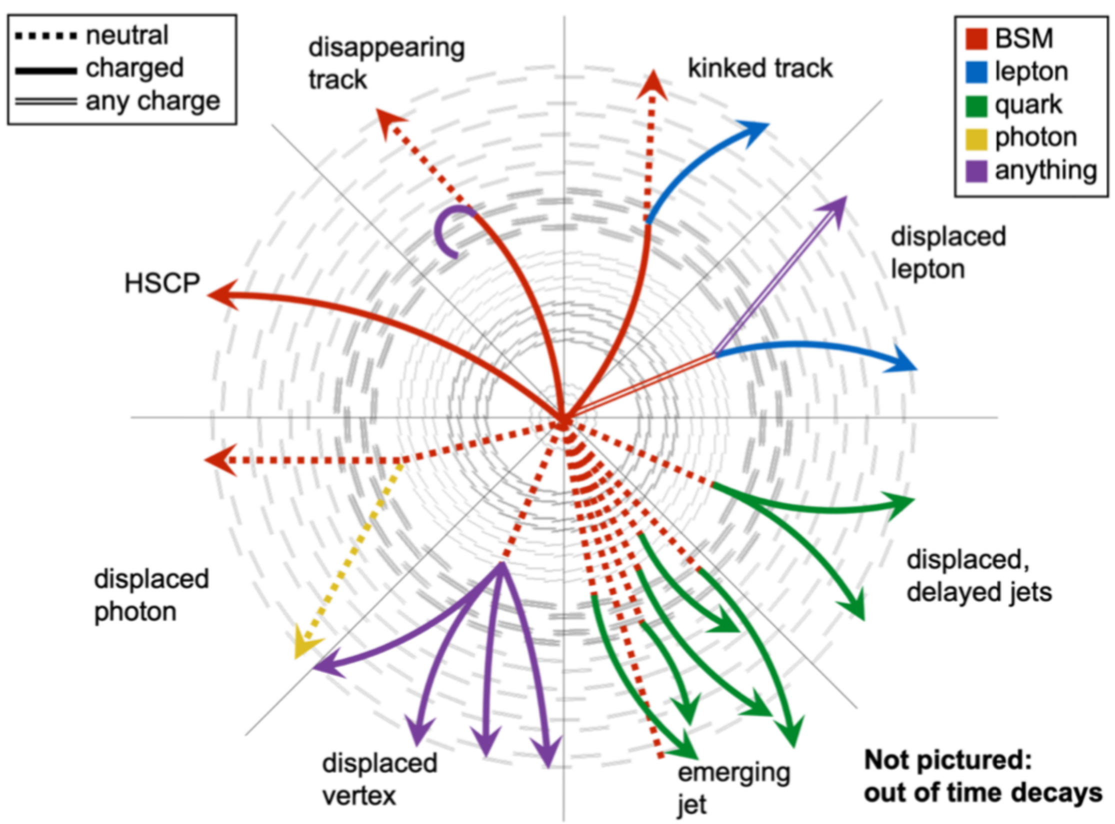


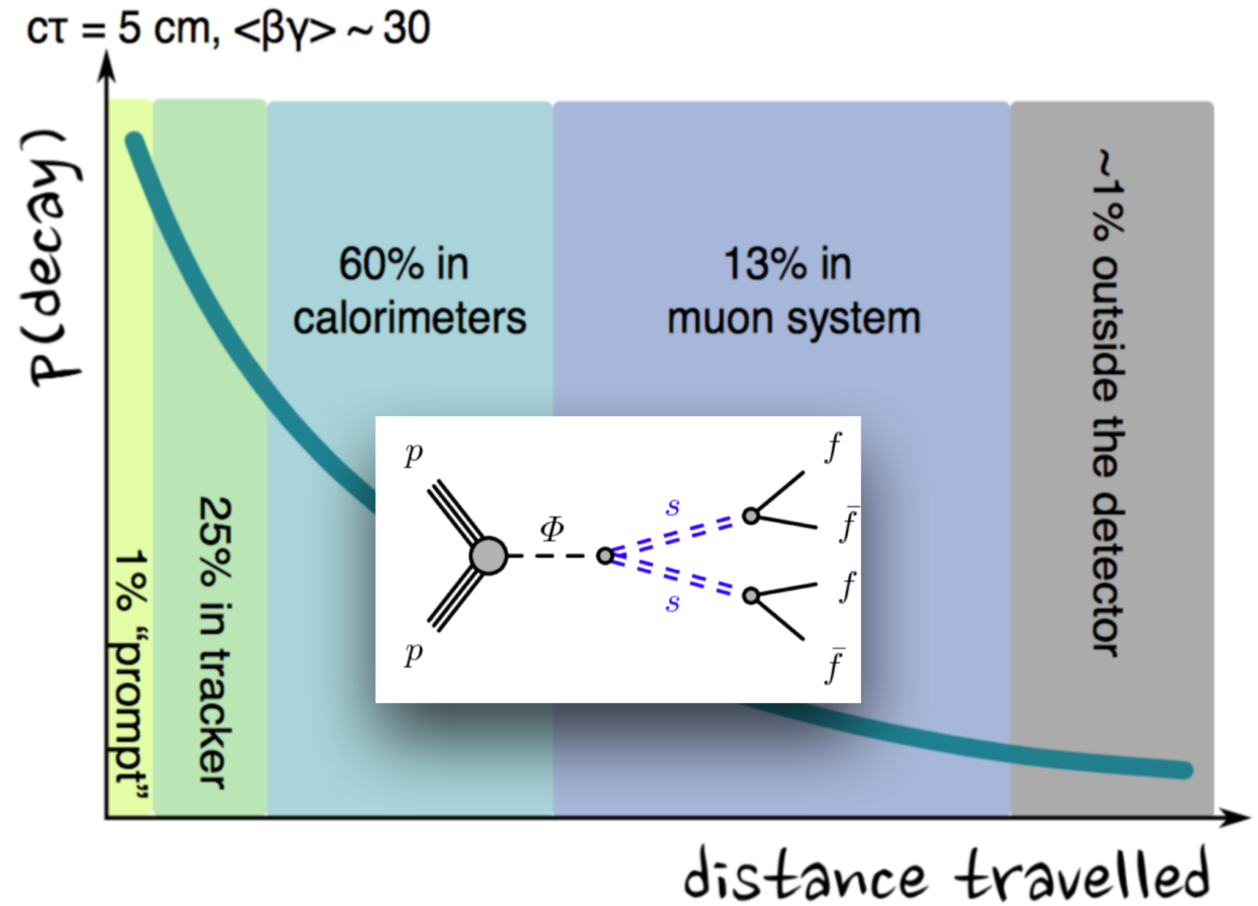




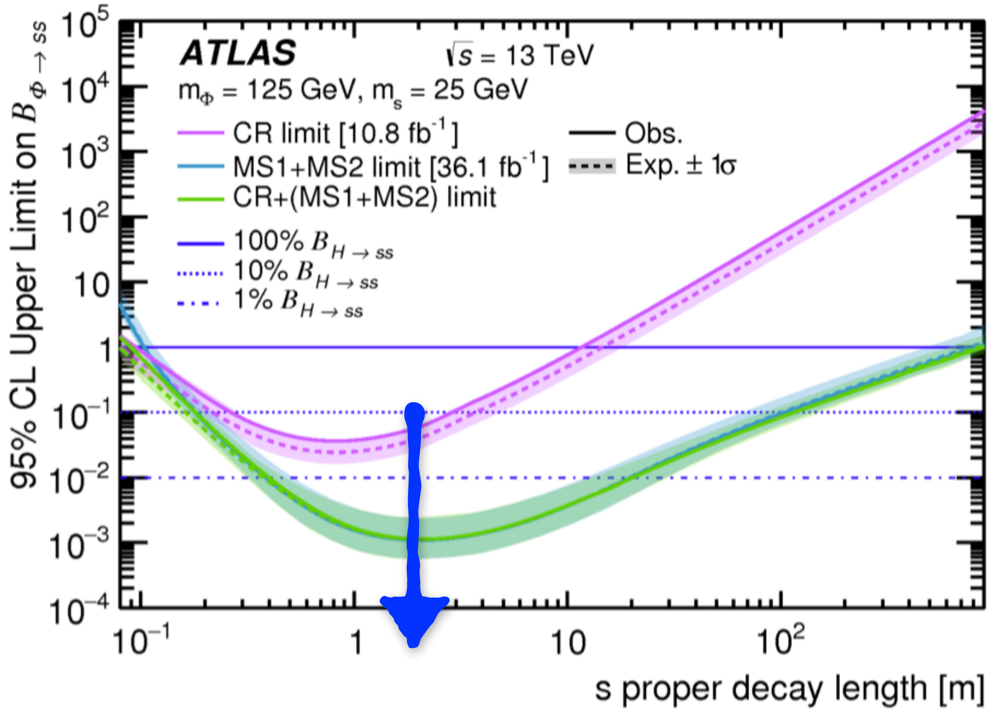
LONG LIVED PARTICLES (1)

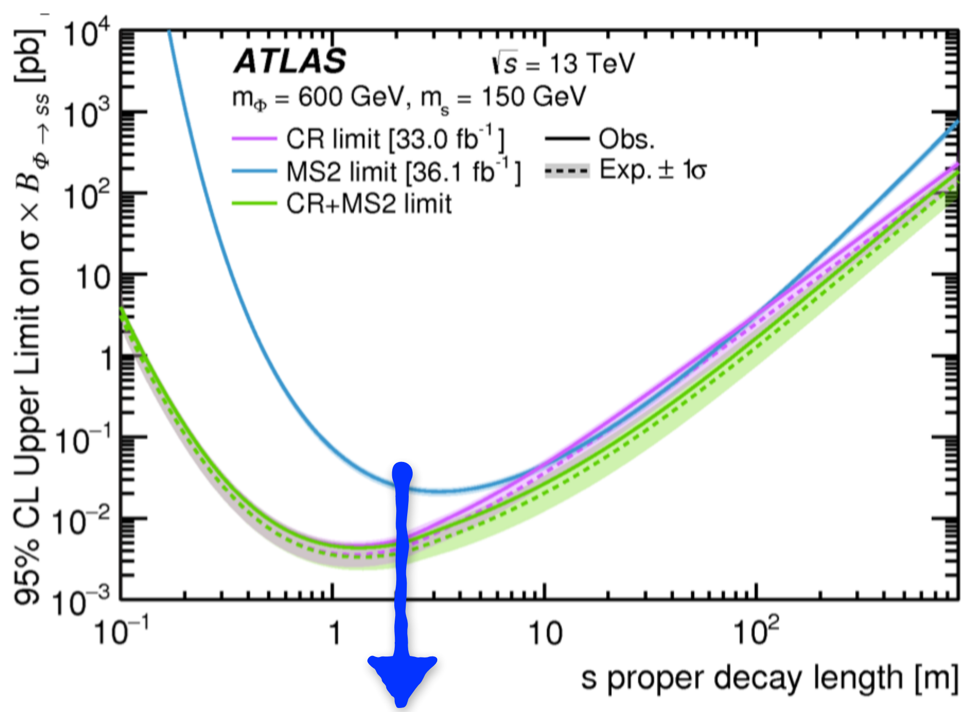
- **Paradigm shift, extending well established searches for prompt BSM to searches for long lived particles**
  - Neutral or charged particles decaying at a macroscopic distance from the interaction point
  - Rich landscape of signatures that may have not been selected by triggers in Run 2 requiring dedicated and innovative reconstruction techniques
- **Model independent approach focusing on generic signatures in each subsystem**





LONG LIVED PARTICLES (2)





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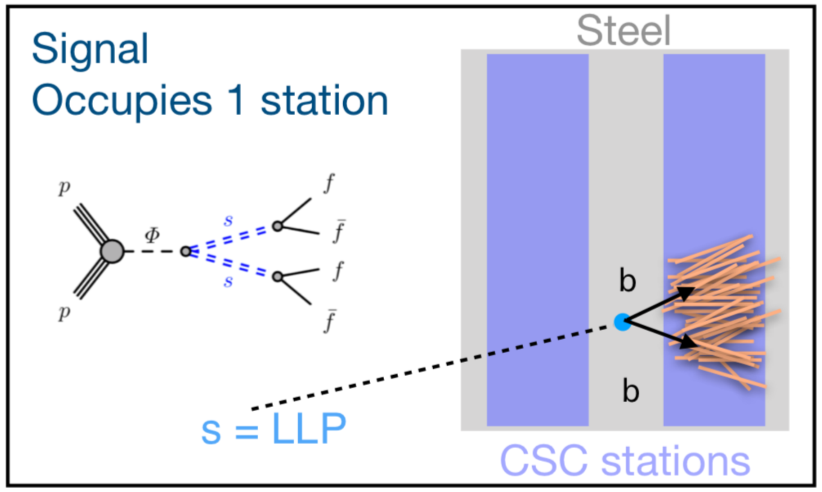
- **Benefitting from the ATLAS Phase 1 upgrades**
  - Use of high ratio of energy deposited in hadronic calorimeter to energy deposited in the electromagnetic calorimeter
  - Use of cluster of muon candidates resulting from charged hadrons
  - and muon narrow scan, displaced (MS-only) muon, stopped particles (empty bunch crossings)
- **In addition, CMS exploiting**
  - shower's timing in hadronic calorimeter at L1
  - showers initiated muon chambers at L1



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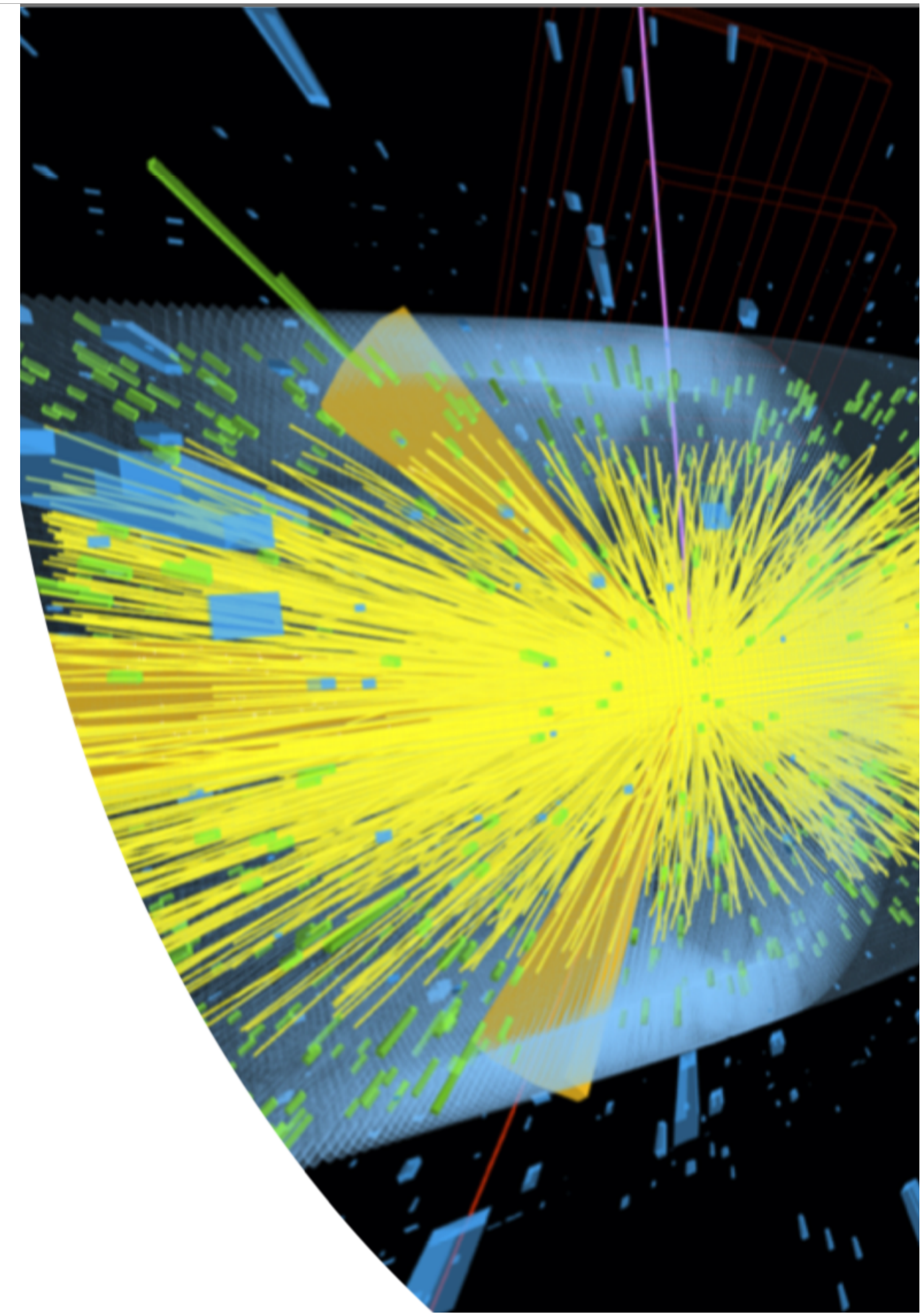
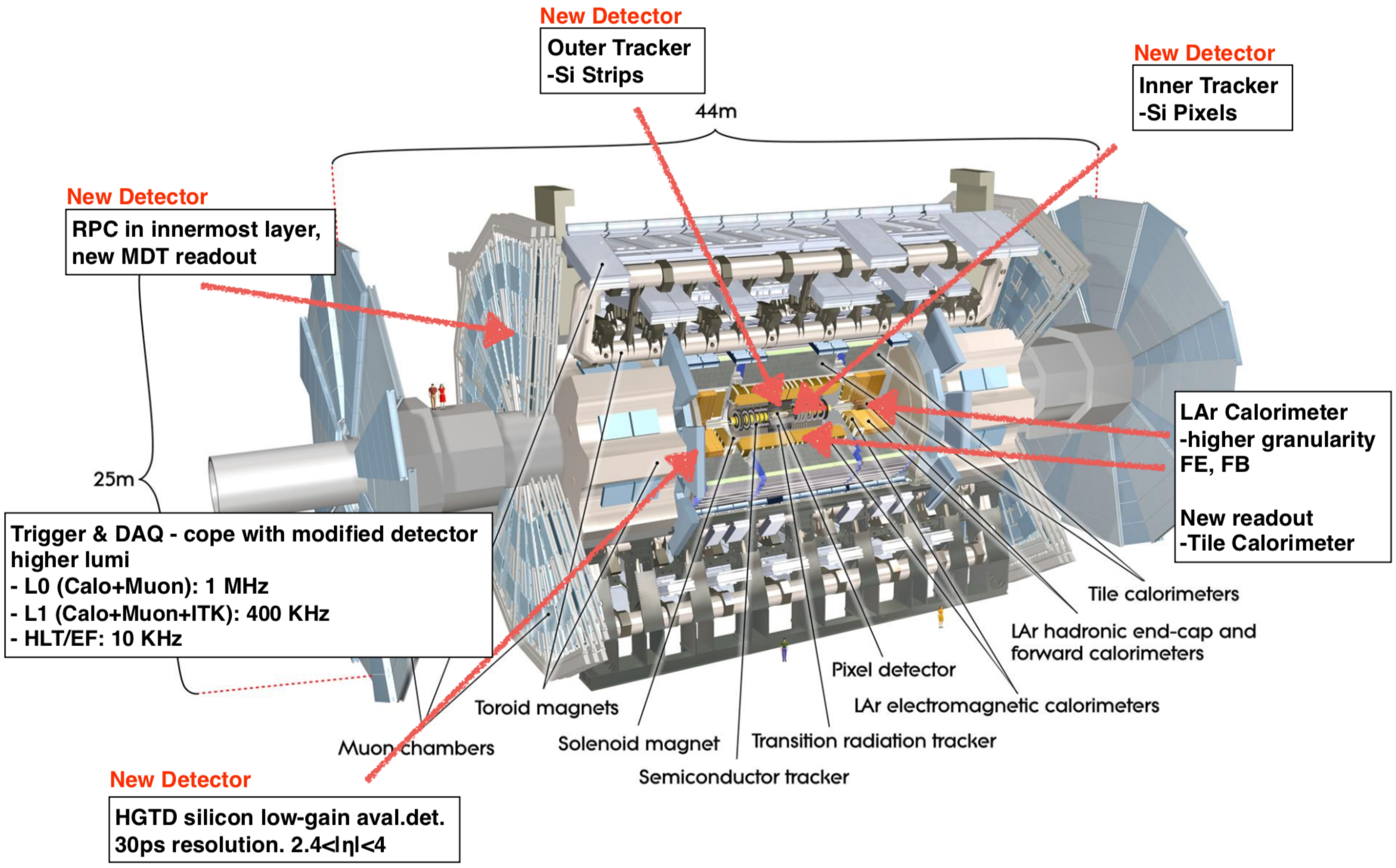
HL-LHC: THE OPPORTUNITY AND THE CHALLENGE

- **3000/fb, the ultimate pp dataset for the incoming decades**
- **Comprehensive program in almost all areas of hadron collider physics**
  - Precision measurement of the QCD, EWK and Top sectors in the SM
  - Searches for rare SM processes
  - Precise characterization of the Higgs boson
  - Flavor physics
  - Search for Beyond the SM, including long lived particles and dark matter
  - Forward physics ….
- **The technology challenge:**
  - pile up to 200 and ~10k tracks / event
  - x10 higher radiation levels



NEW CHAPTER FOR THE ATLAS EXPERIMENT

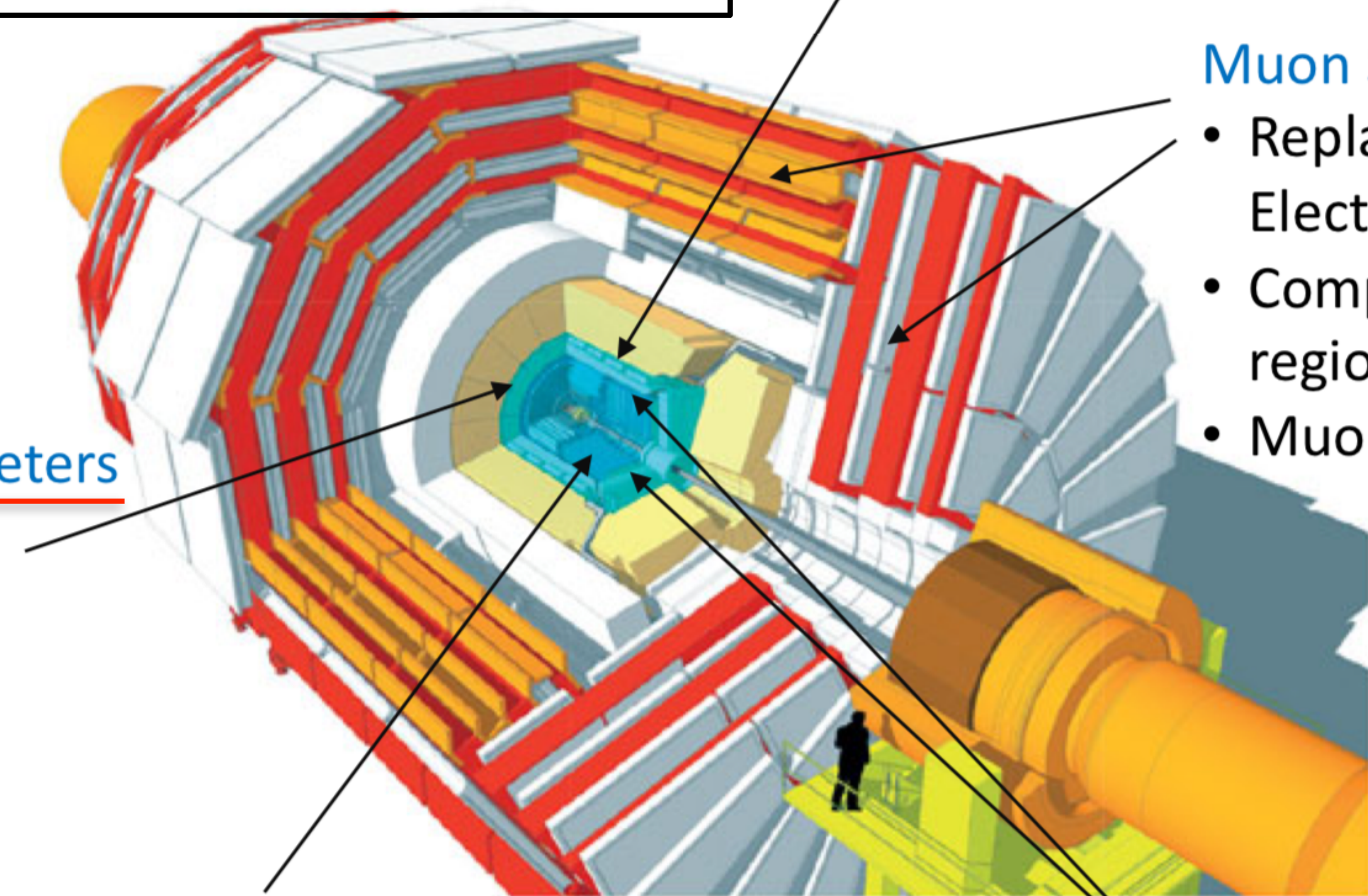


NEW CHAPTER FOR THE CMS EXPERIMENT

Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region $1.5<\eta<2.4$
- Muon tagging $2.4<\eta<3$



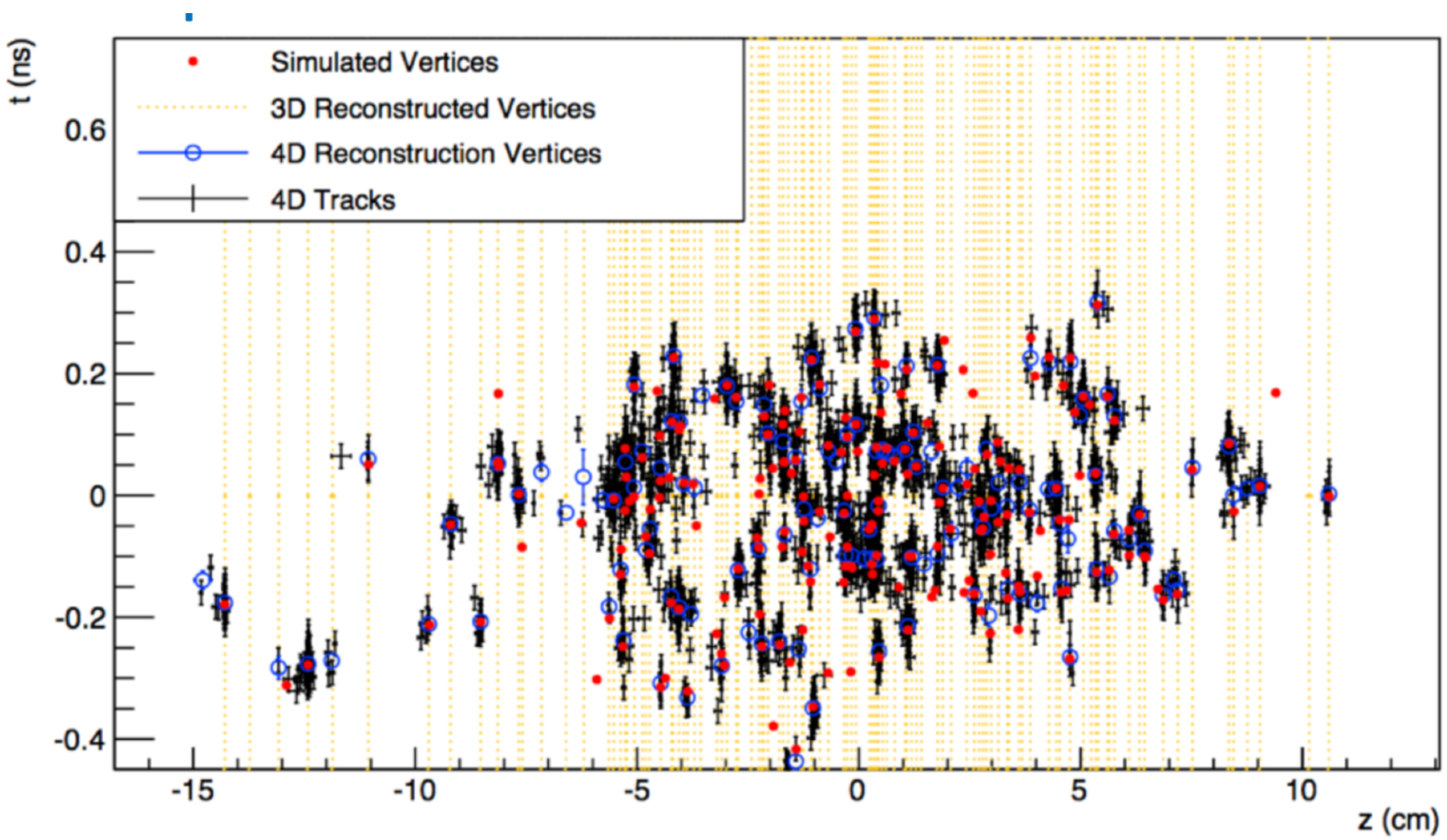
New Endcap Calorimeters
- Rad. Tolerant
- High granularity
- 3D capable

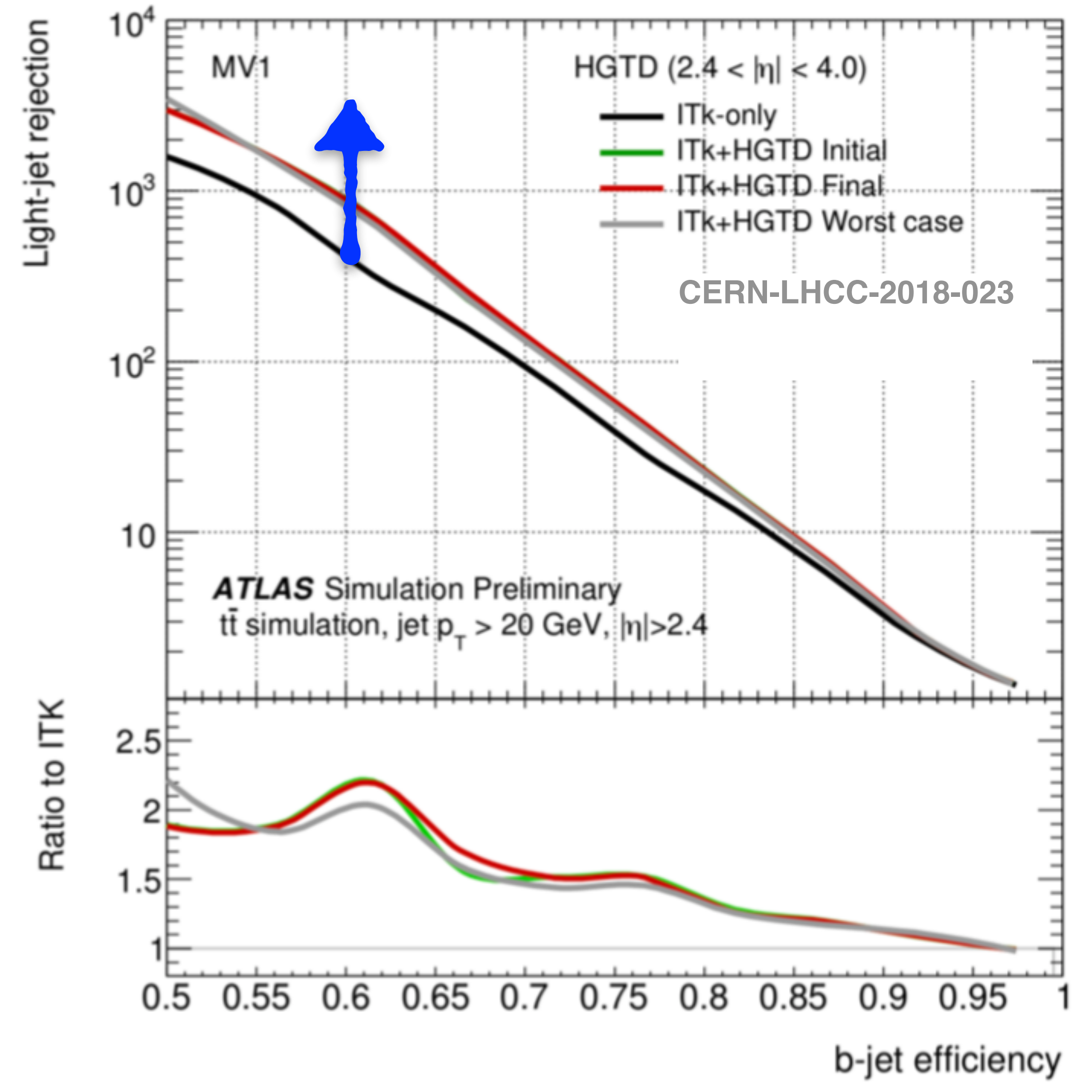
New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $\eta=4$

MIP Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

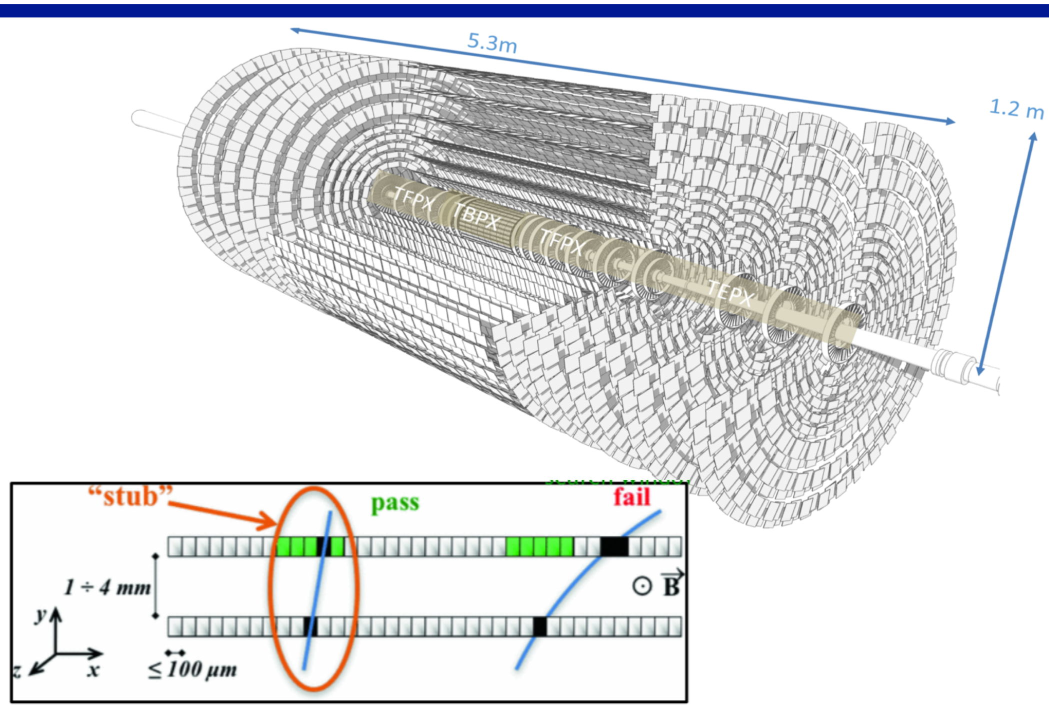
SELECTED HIGHLIGHT: TIMING IN ATLAS AND CMS

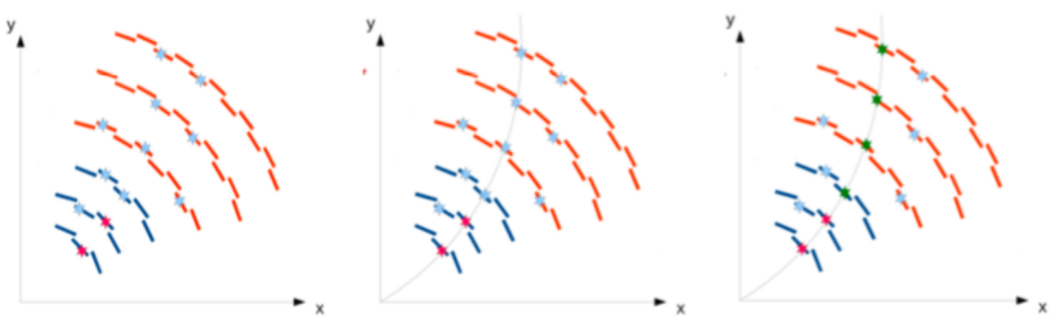
- **Breakthrough technologies enabling a leap forward in experimental techniques at hadron colliders**
  - *e.g.* precision timing as a key to discriminate pileup against hard collisions (recreating Run 2 conditions) and extend tagging capabilities

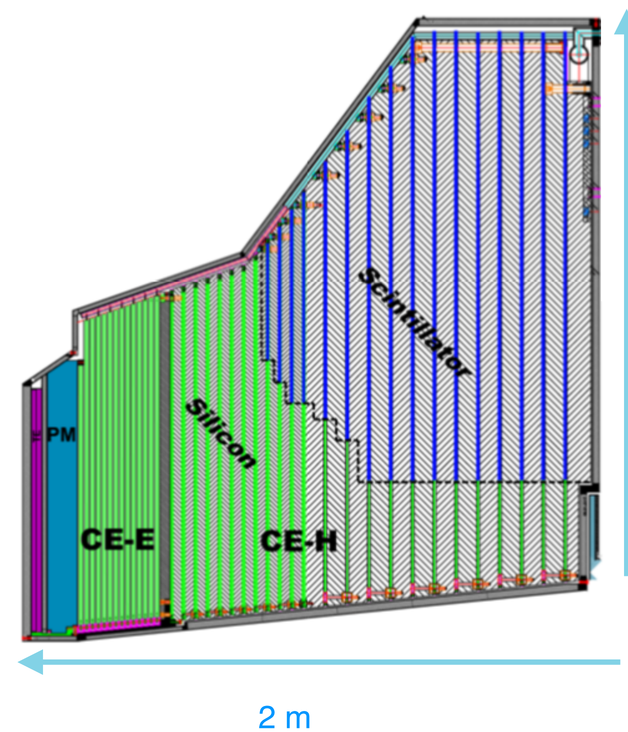


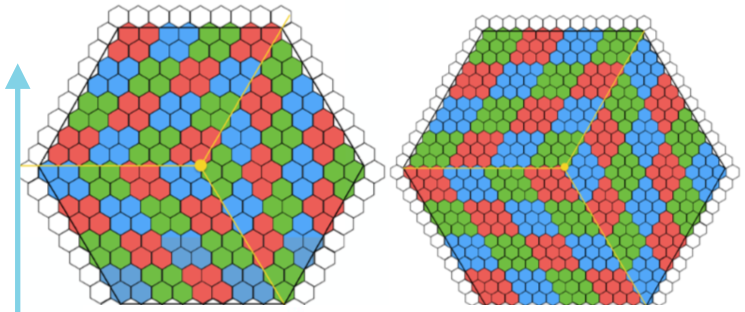


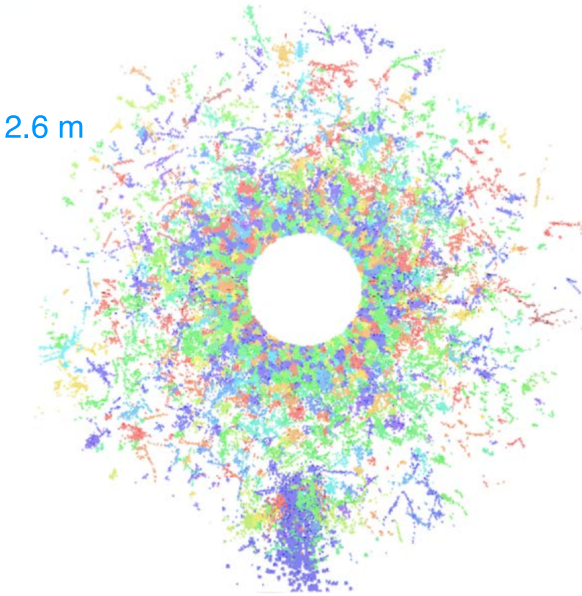
SELECTED HIGHLIGHT: TRACKING AND IMAGING











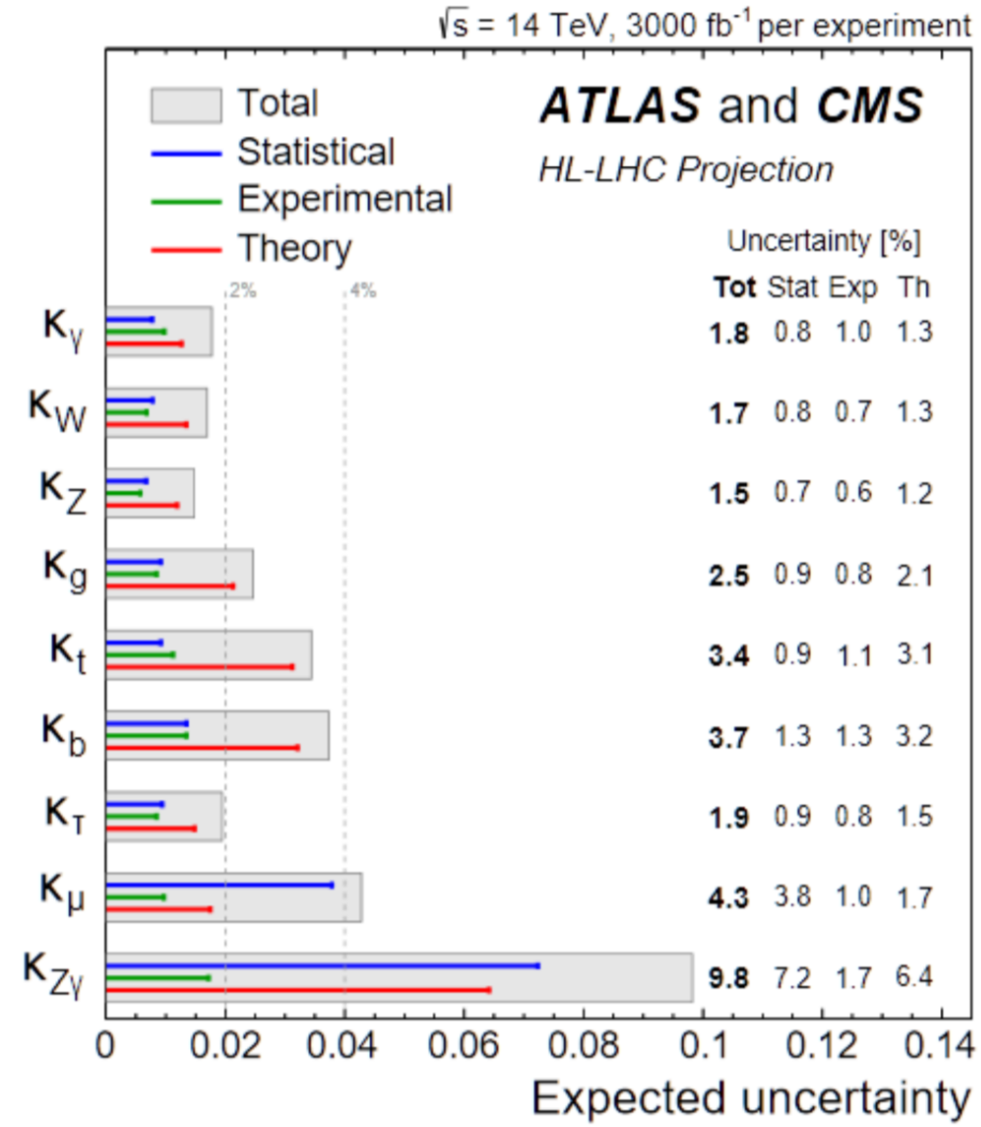
- **Tracking at 40 MHz for the first time in hadron collider**
  - Outer tracker modules capable of measuring track momentum and sending high pT tracks to the L1 track trigger
- **Imaging of showers in the forward region**
  - HGCAL proving 4D shower information with excellent spatial resolution (6M channels) and timing resolution (order of 50 ps)

CHARACTERIZATION OF THE HIGGS BOSON

1902.00134

- One of the primary science goals of the HL-LHC
- All main production mechanisms measured at 5% level or better
- Rare modes (H→μμ, H→Zγ) becoming accessible
  - Hcc still challenging (6xSM) but may benefit from new experimental techniques! ATL-PHYS-PUB-2018-016
- Approaching observation of HH to probe Higgs self coupling
  - $0.52 \leq \kappa_\lambda \leq 1.5$ at 68%

1902.00134	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



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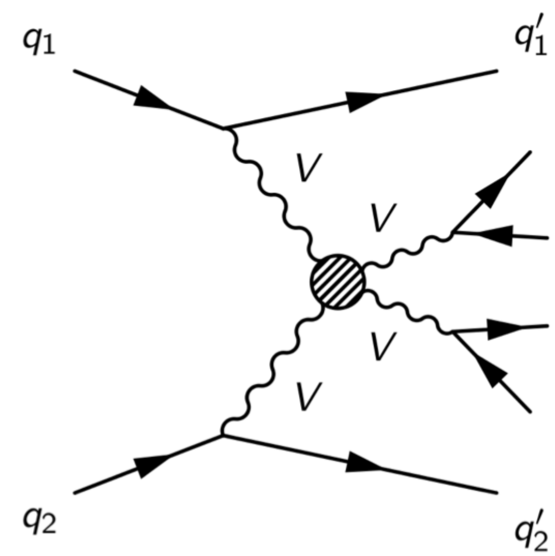
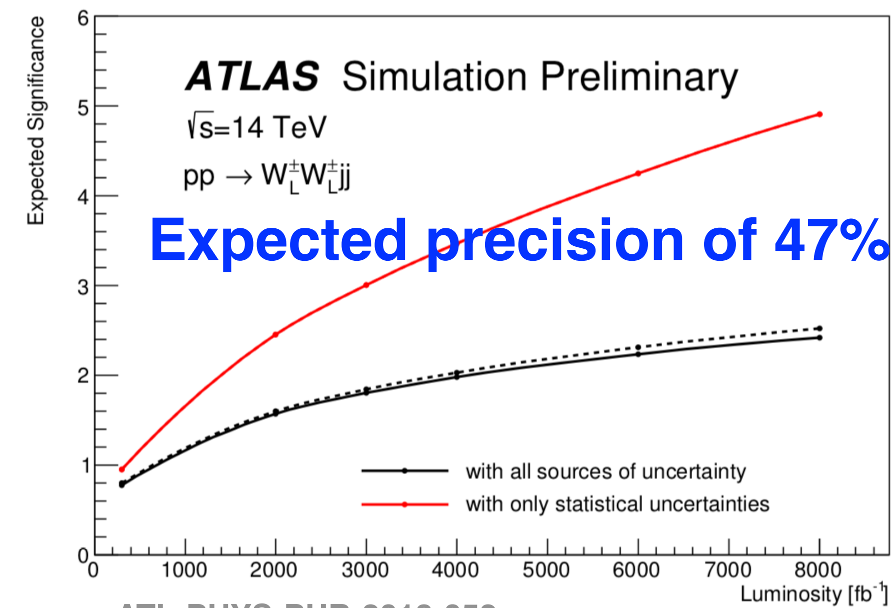
STUDY OF THE EWK AND TOP SECTORS

- **Observation of the vector boson scattering as key to continue probing the EWKSB**
  - **$V_L V_L \rightarrow V_L V_L$ diverges if no Higgs boson**
  - **Run2, EWK WWjj σ measured at 20% (observed), EWK WZjj at 30% (evidence)**





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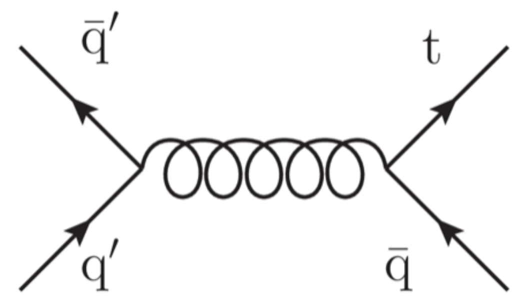
- **Search Flavour-changing neutral current (FCNC) decays entering the 10^{-5} regime**



	-1σ	Expected	+1σ
$\mathcal{B}(t \rightarrow uZ)$	3.3×10^{-5}	4.6×10^{-5}	6.5×10^{-5}
$\mathcal{B}(t \rightarrow cZ)$	3.9×10^{-5}	5.5×10^{-5}	7.7×10^{-5}

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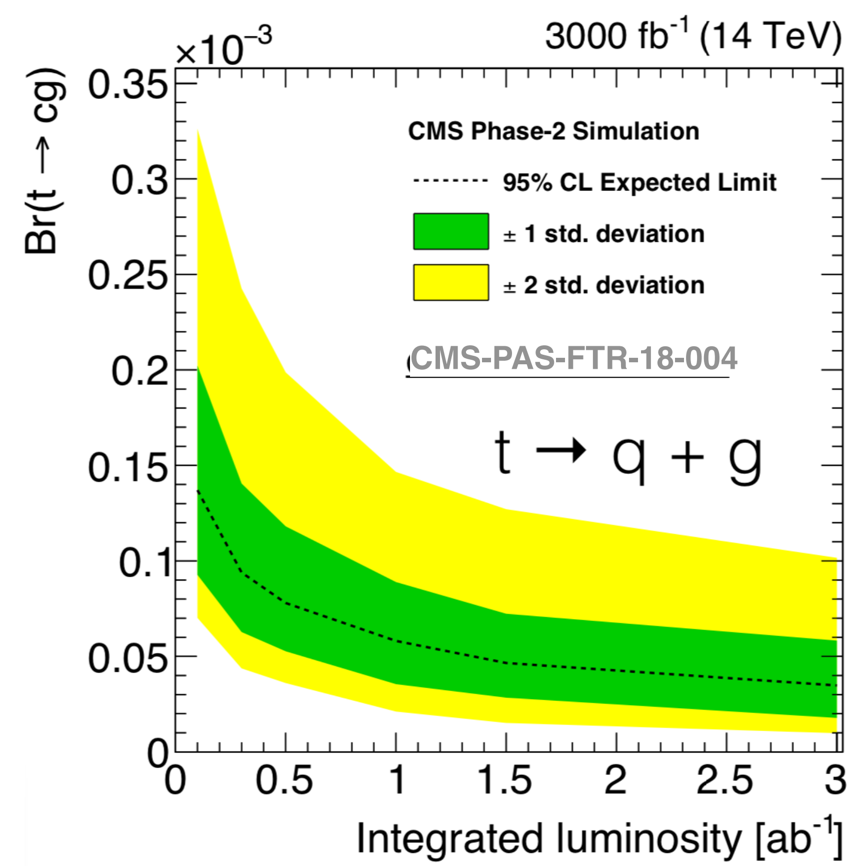
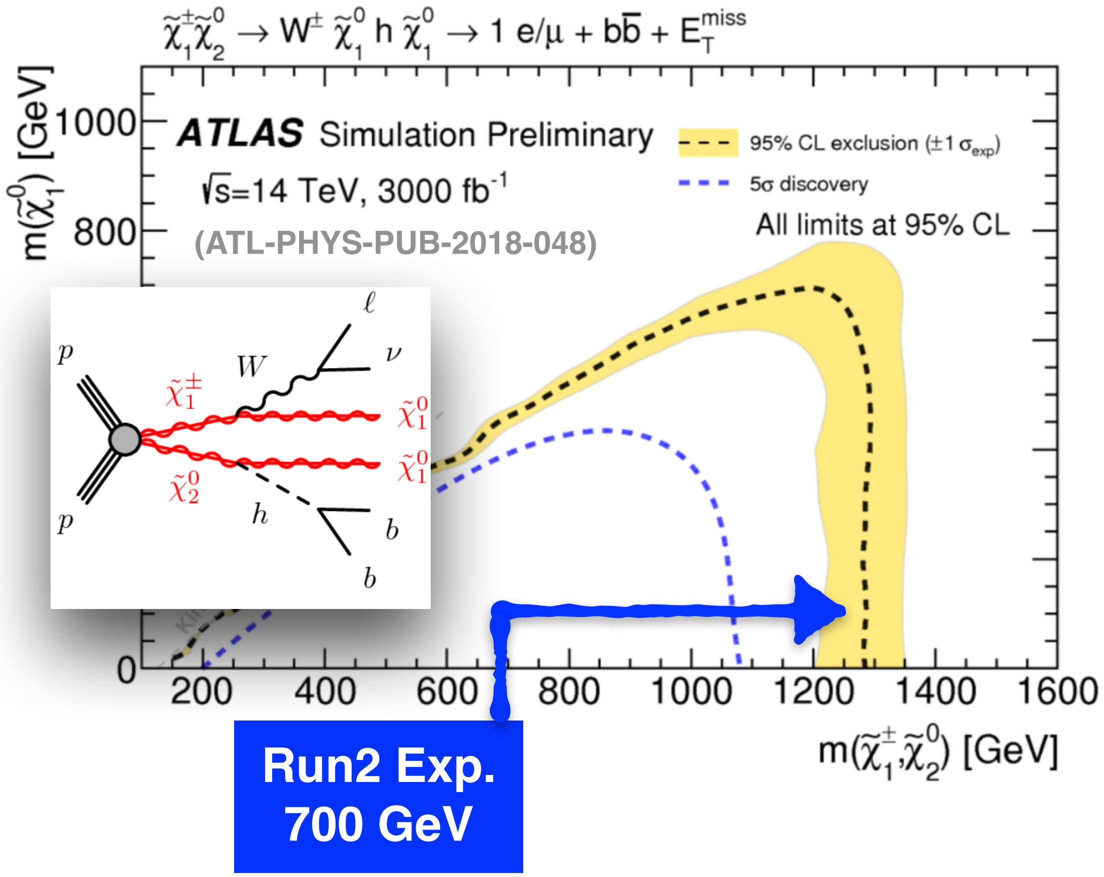
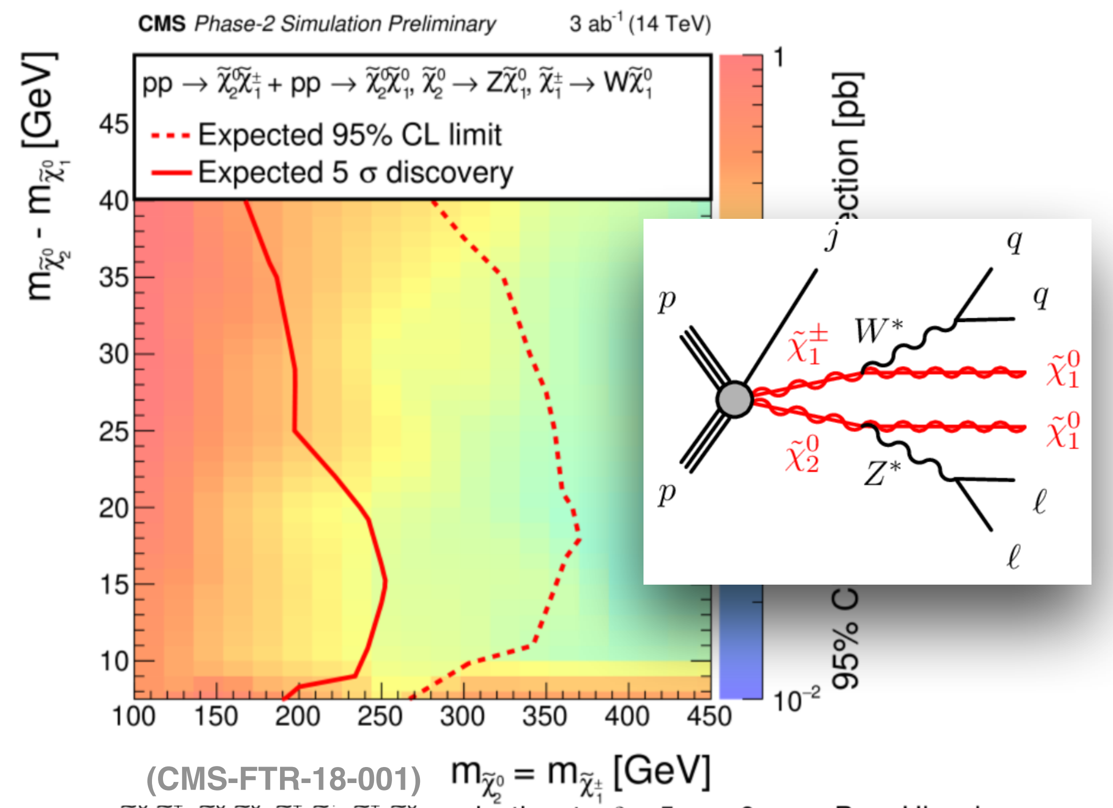
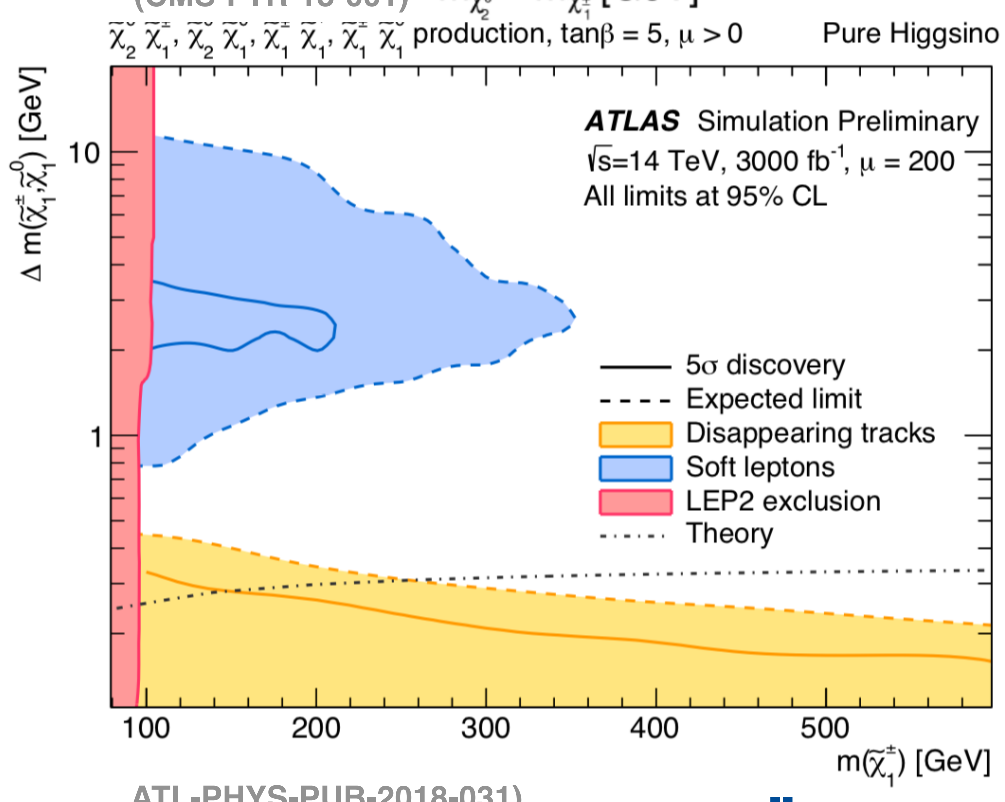


SEARCHES FOR SUSY

- **Classic searches for strongly produced SUSY becoming systematics limited**
  - except for compressed models, stealth SUSY,…
- **Focus at HL-LHC on searches for EWK-ly produced SUSY**
  - small cross sections, huge gain from HL-LHC
  - limit on staus from 400 to 800 GeV

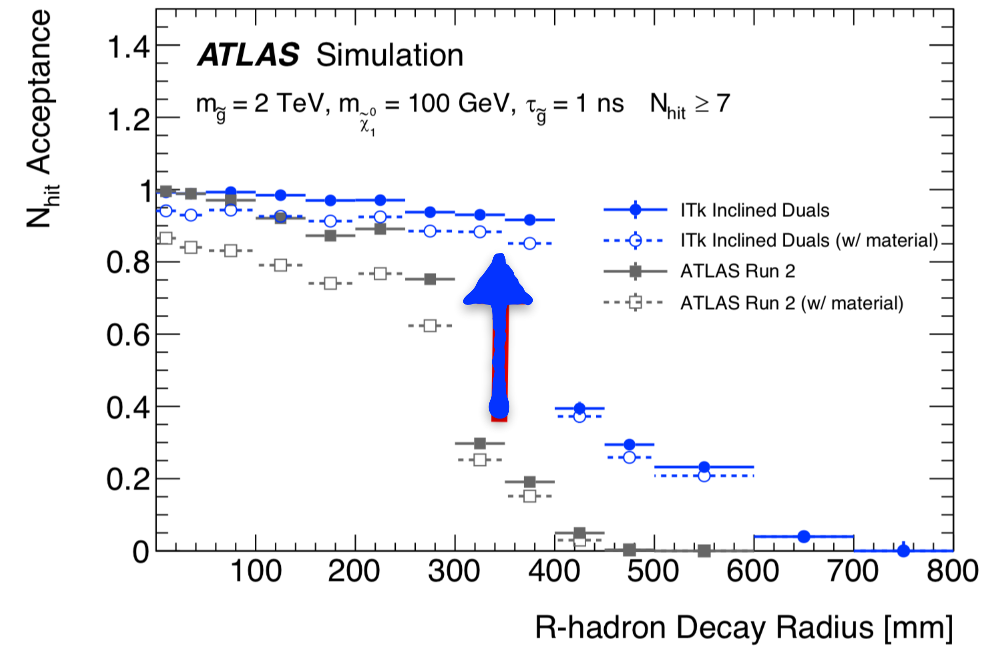


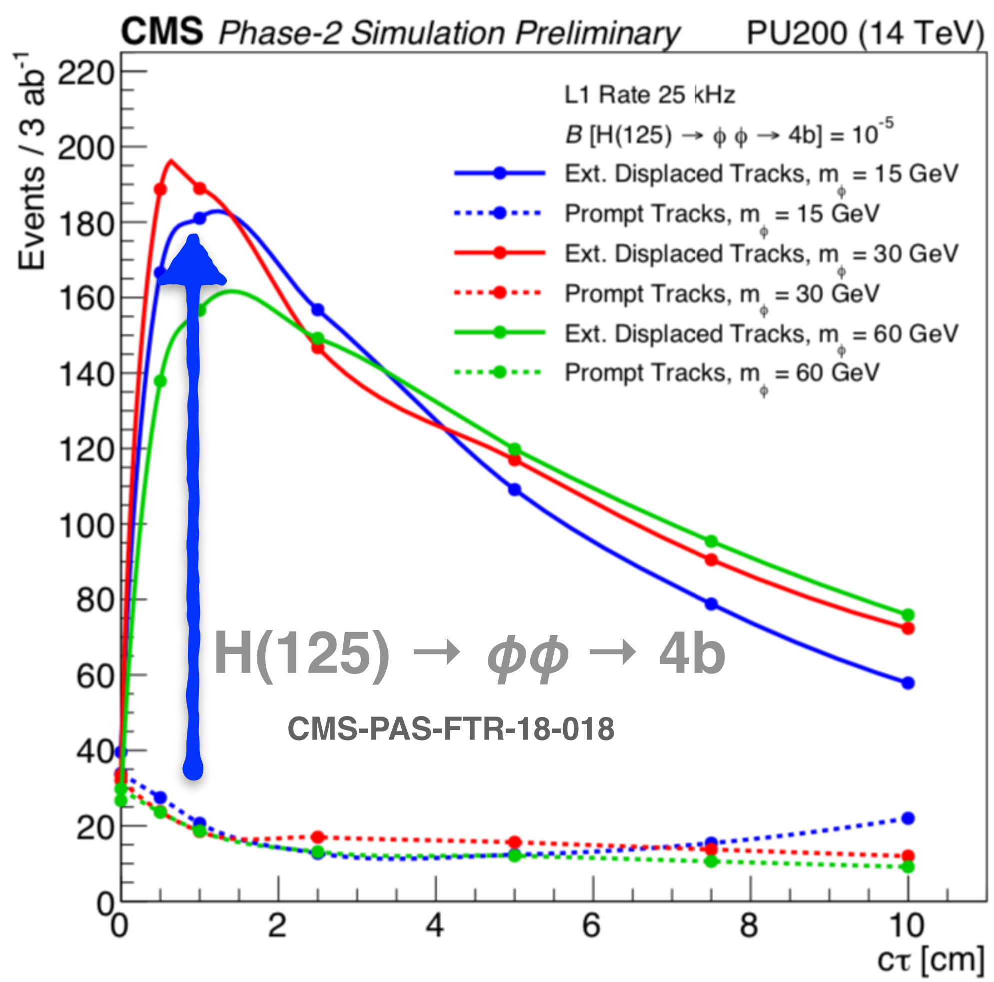


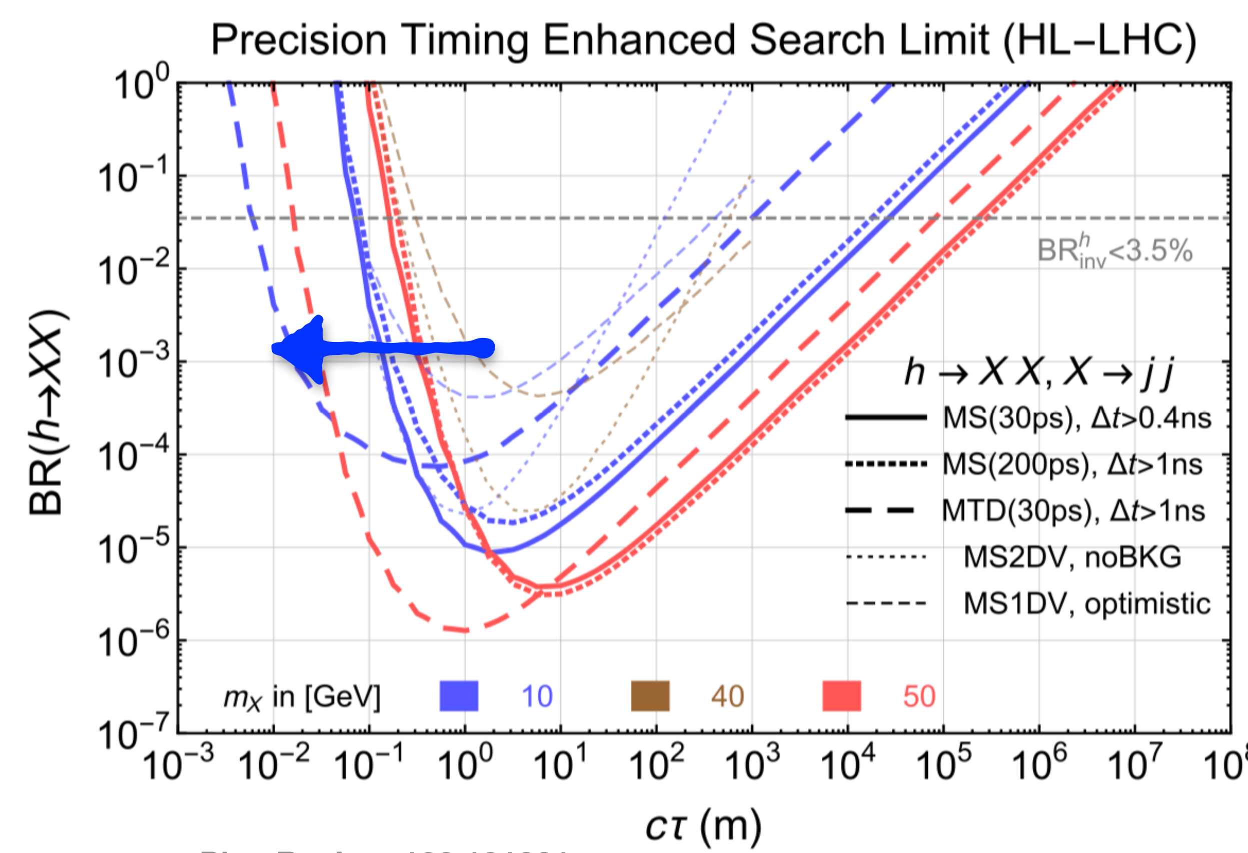


SEARCHES FOR LONG LIVED PARTICLES

- **Background free search benefiting greatly from innovative detectors**
  - larger acceptance triggering on displaced candidates, timing information
- **Leap forward in sensitivity to uncharted territory**







PhysRevLett.122.131801

CONCLUSIONS

- **The LHC and the HL-LHC will provide an unprecedented dataset of pp collisions for the decades to come**
  - **95% of the data yet to be collected!**
- **Both the ATLAS and the CMS detectors (and experiments) are being upgraded with state of the art technologies to cope with the harsh operational conditions and to offer new capabilities**
  - ***including* tracking at 40MHz, timing information, detection of displaced particles, machine learning for online and offline reconstruction**

The LHC & HL-LHC are both

discovery and the precision machine of the future

RESULTS AND NEW IDEAS FROM ATLAS AND CMS

1. **Tatiana Lyubushkina: ATLAS results on quarkonia and heavy flavour production (including exotics)**
2. **Manuel Alvarez Estevez: Jet and Photon Measurements using the ATLAS detector**
3. **Ann-kathrin Perrevoort: ATLAS measurements of CP violation and rare decays processes with beauty mesons**
4. **Silvano Tosi Recent ttbar and single top inclusive and differential cross sections results in CMS**
5. **Agostino De Iorio Recent top quark properties in CMS**
6. **Julian Kempster: Measurement of top-quark properties with the ATLAS detector at the LHC**
7. **Zhi Zheng: Measurement of rare top-quark production processes with the ATLAS detector**
8. **Clara Ramon Alvarez Rare top quark production in CMS: ttZ, ttW, ttgamma, tZ, tgamma, and tttt production**
9. **Louie Corpe: Measurements of inclusive multi-boson production at ATLAS**
10. **Victor Solvyev: Precision measurements of W and Z boson production at ATLAS**
11. **Jing Chen: Recent observation and measurements of vector-boson fusion and scattering with ATLAS**
12. **Nadezada Proklova: Studies of rare production and decay processes of the Higgs boson at the ATLAS experiment**
13. **Kunlin Ran: Combined Higgs boson measurements at the ATLAS experiment**
14. **Eleonora Rossi: Constraining the Higgs boson self-coupling in a combined measurement of single and double Higgs boson channels at the ATLAS experiment**
15. **Verena Maria Walbrecht: Measurements of Higgs boson properties in the final state with four leptons at the ATLAS experiment**
16. **Weitao Wang: Studies of Higgs boson properties in decays to two b-quarks at the ATLAS experiment**
17. **Siew Yan Hoh: Recent Higgs boson measurements in the WW final state using CMS data**
18. **Aashaq Shah Searches for scalar sector extensions of the standard model via $H \rightarrow ZA \rightarrow llbb$ process at CMS**

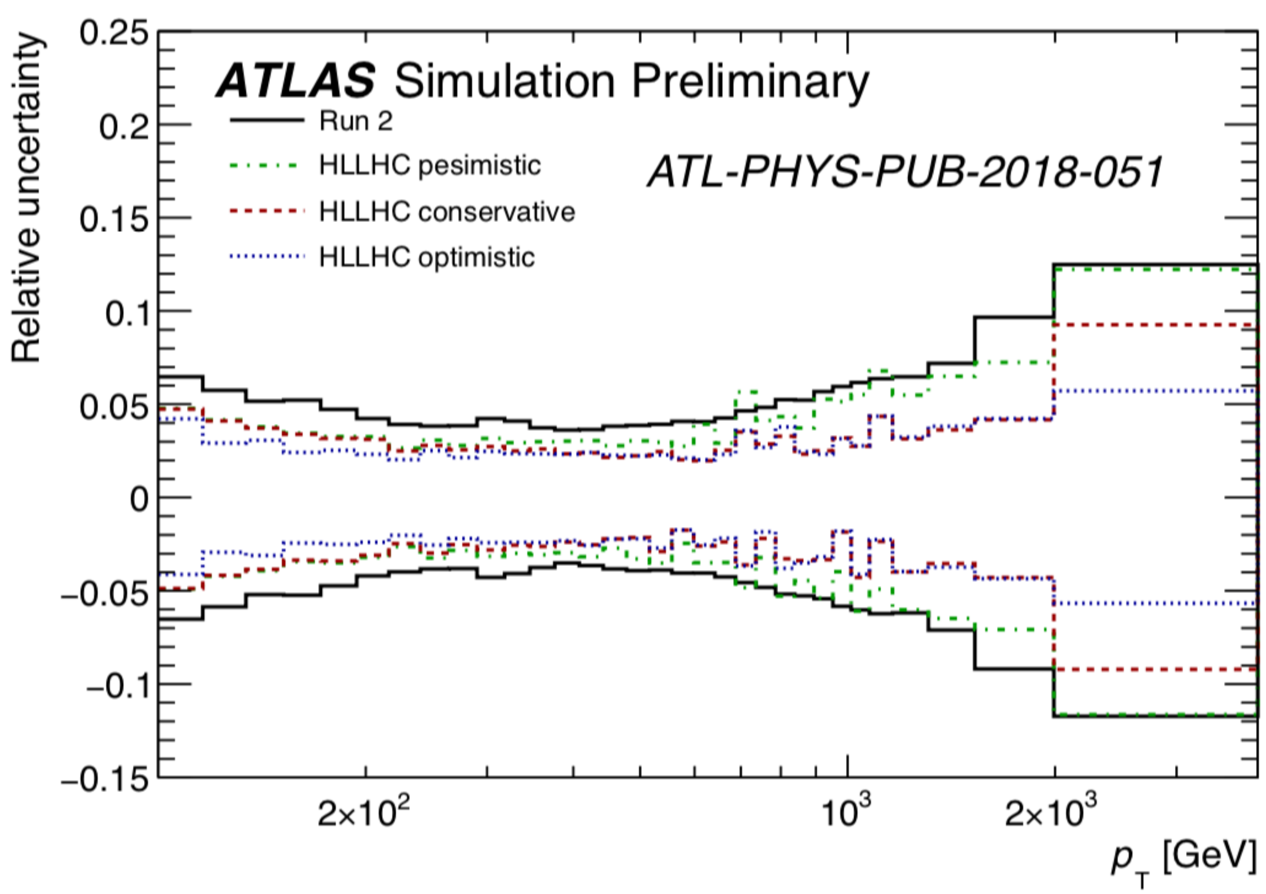
RESULTS AND NEW IDEAS FROM ATLAS AND CMS

19. Andrea Trapote Fernandez Searching for pair production of top squarks at the CMS
20. Marco Valente: Searches for strong production of supersymmetric particles with the ATLAS detector
21. James William Dolen Search for heavy BSM particles coupling to third generation quarks at CMS
22. Angira Rastogi Search for new phenomena in leptonic final states at CMS
23. Damiano Vannicola: Beyond exclusive leptonic resonances with the ATLAS detector
24. Binbin Dong: Searches for resonances in hadronic final states with the ATLAS detector
25. Alexander Emerman: Diboson resonances
26. Simranjit Singh Chhibra Search for dark matter at CMS
27. Swagata Mukherjee Search for dark sector at CMS
28. Julian Wollrath: Dark Matter searches with the ATLAS Detector
29. Sven Dildick Search for long-lived signatures at CMS and Run-3/HL-LHC developments
30. Malgorzata Kazana Search for unconventional signatures at CMS
31. Brian Francis Full Run 2 Results for Disappearing Tracks at CMS

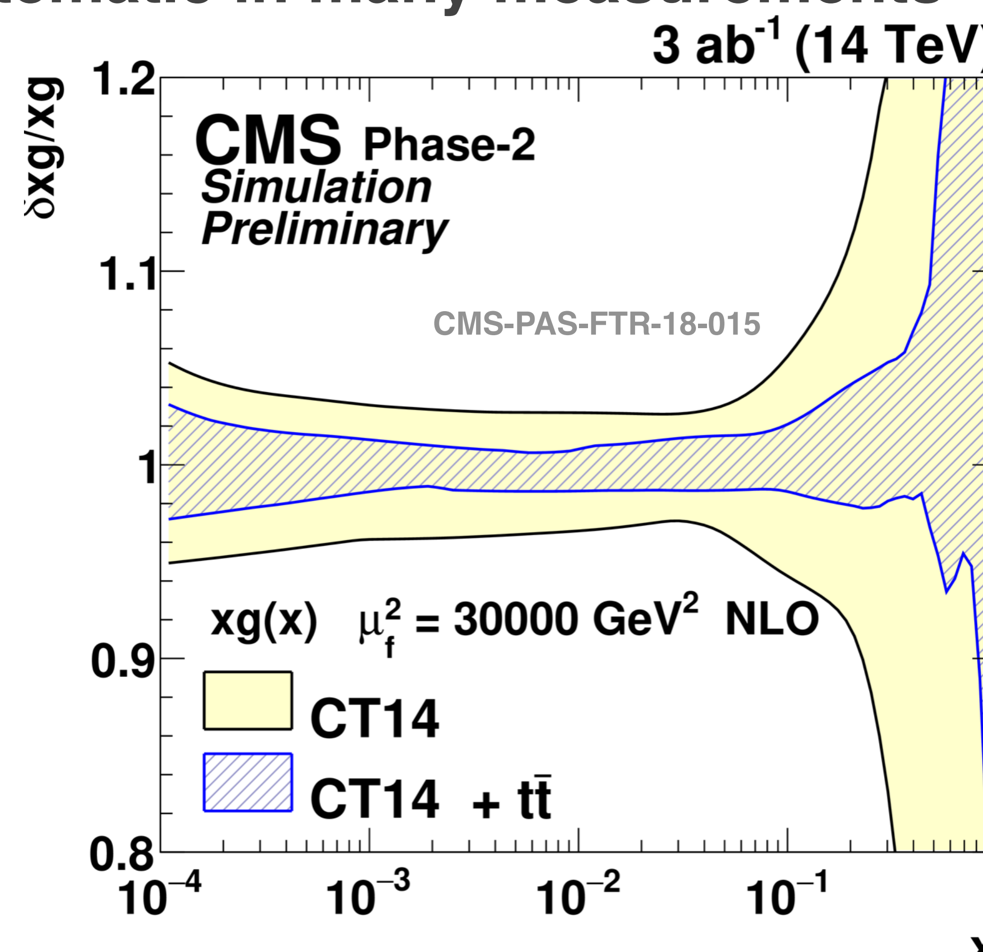
ADDITIONAL MATERIAL

PRECISION FRONTIER

- **Significant reduction of statistical and systematic uncertainties**
  - **New generation of precision parton distribution sets including HL-LHC data**
  - **Improved measurement of luminosity**
- **Theory uncertainties becoming the leading systematic in many measurements**



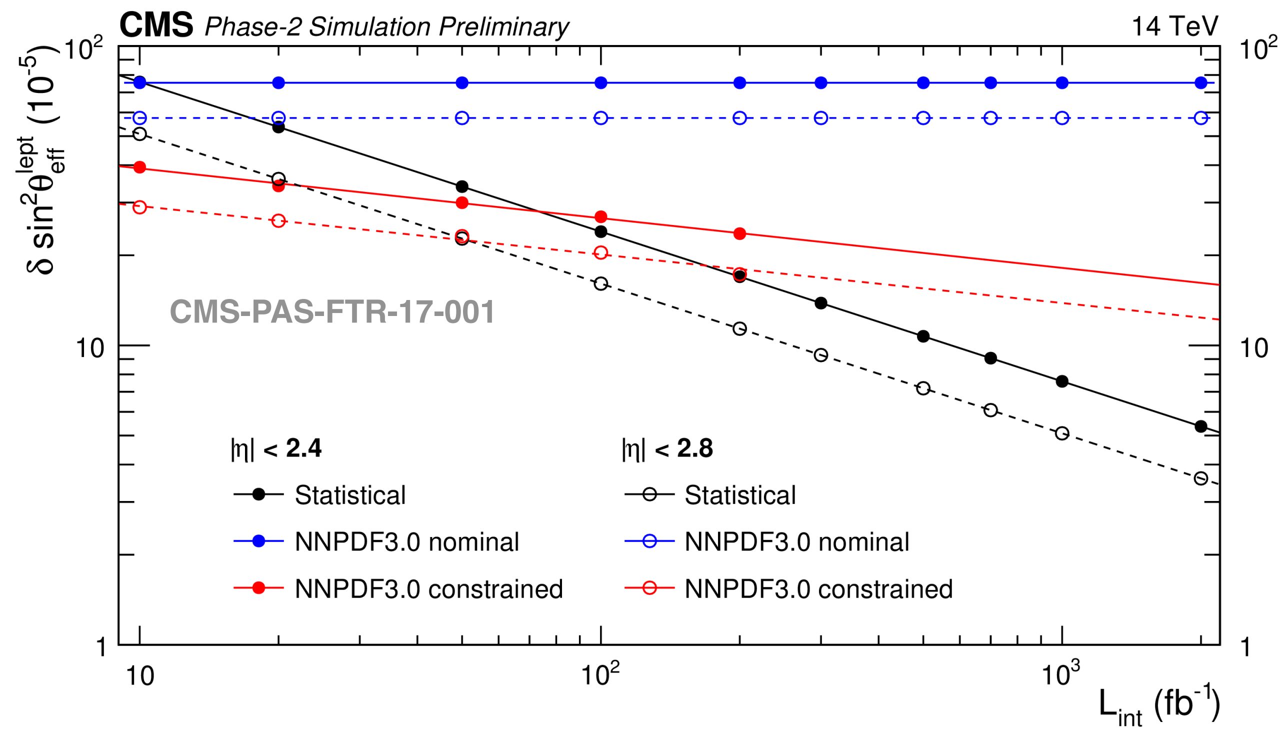
10% up to 4 TeV (while up to 2 TeV with 7/8 TeV data)

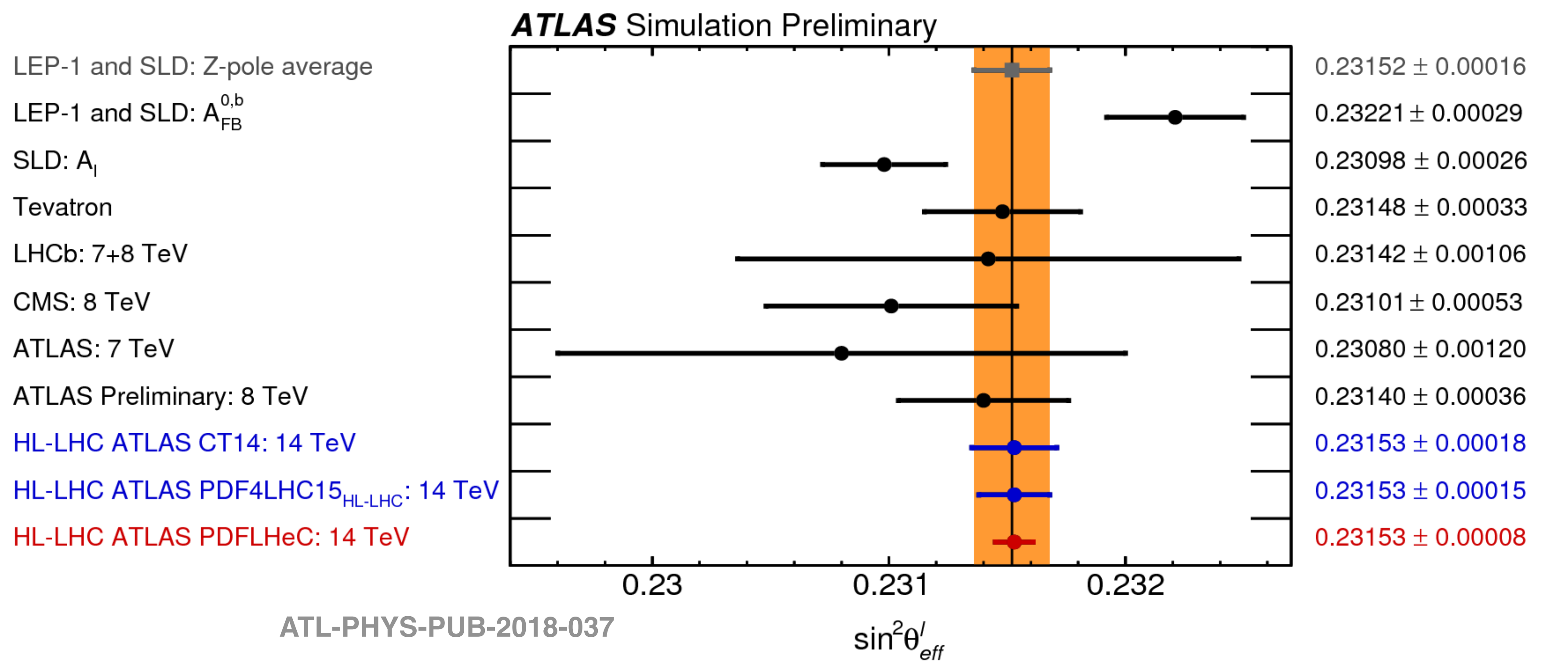


unprecedented sample of top quarks at high p_T

(ULTIMATE) PRECISION FRONTIER

- **Better knowledge of PDF and increased acceptance in forward region leading to significant improvement e.g. of the weak mixing angle measurements**
  - matching LEP precision





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