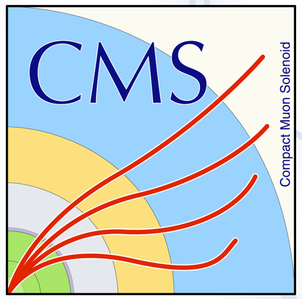
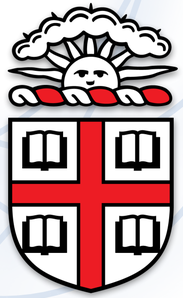
Outlook for experimental high-p_T LHC physics

Emanuele Usai
on behalf of the CMS and ATLAS Collaborations





BROWN

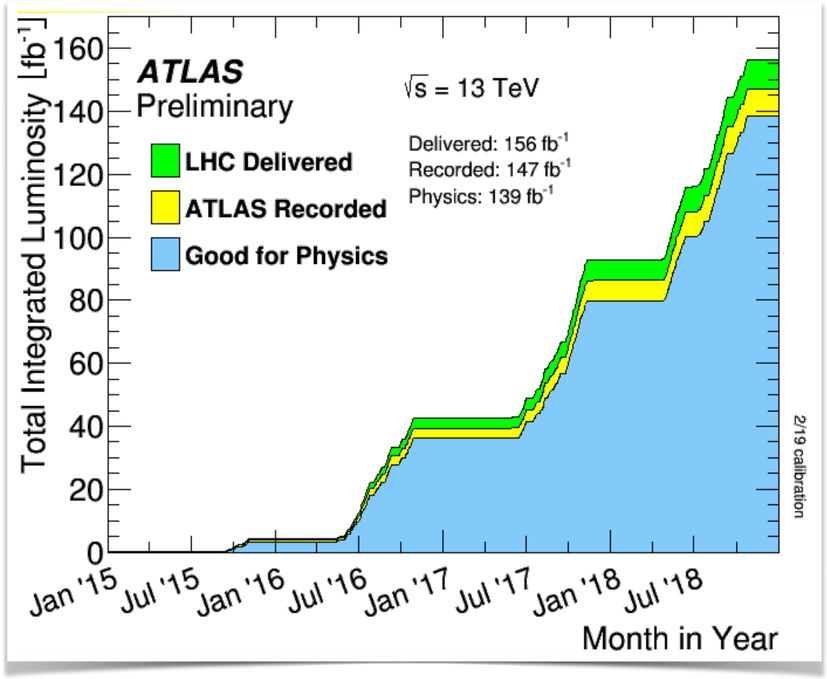
ATLAS EXPERIMENT

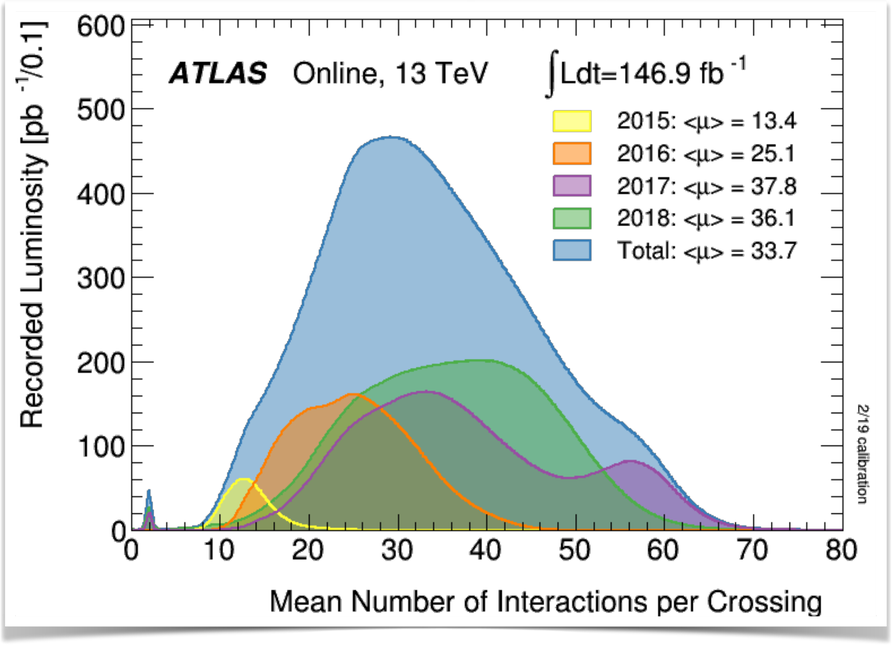
APS DPF 2021 — 14 July 2021

Overview

The Run2 dataset

- LHC ran at $\sqrt{s} = 13$ TeV from 2015-18
  - **147 fb^{-1} of pp data** recorded by ATLAS
  - 139 fb^{-1} good for physics analysis
- **High-pileup** data, $<\mu>$=33.7
- **Precise calibration** of physics objects
  - lepton efficiencies <1% e, ~0.1% μ
  - Jet energy scale ~1-3% for p_T>30 GeV
- Already **1000 ATLAS collision-data papers** with ~135 results on full run-2 dataset
  - New physics searches, SM measurements

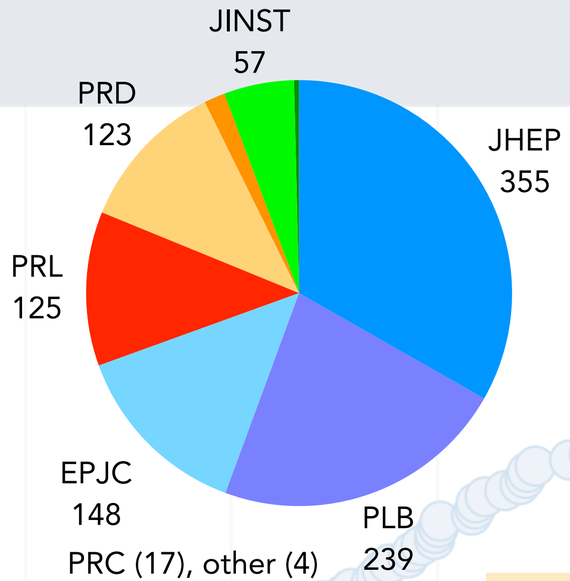


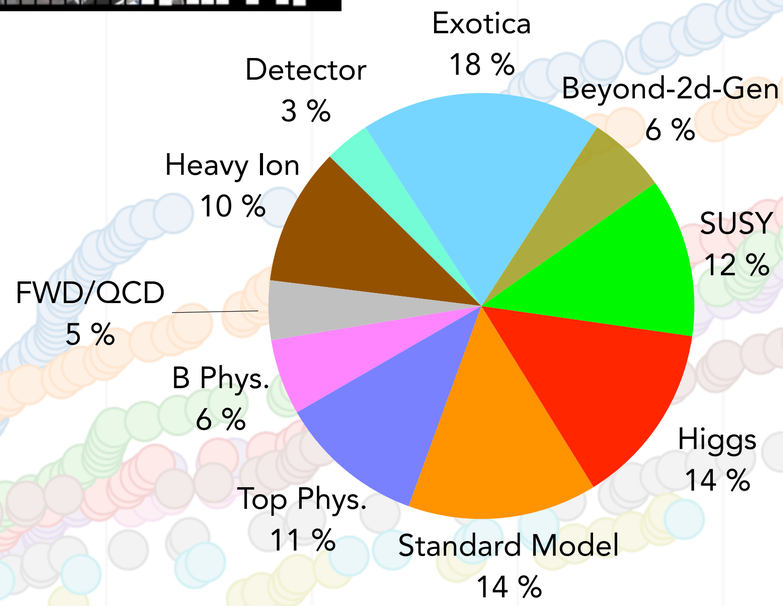


Publication statistics (CMS)

Phys. Briefing

On Nov. 24, 2020 CMS announced the **publication of its 1000th paper** in a peer-reviewed journal





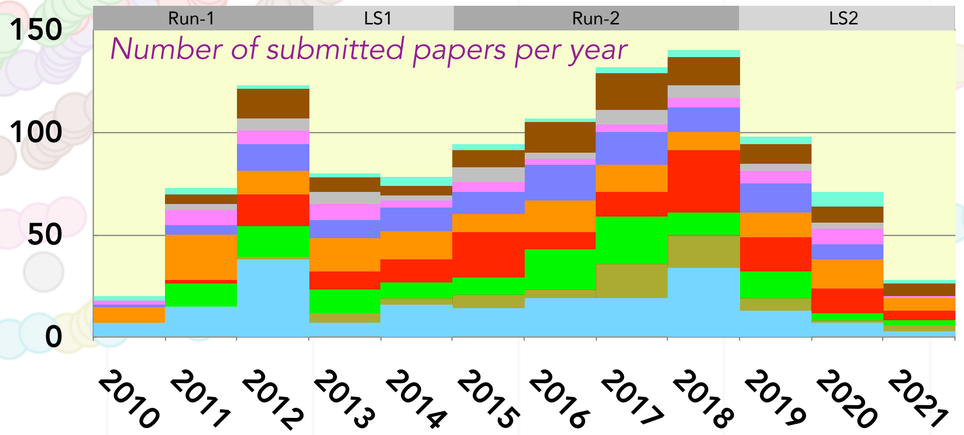
As of today

1077 CMS papers
- **1037** published

1068 papers based on **collision data**
- **1012** published
- 574 based on Run-1 data
- 469 based on Run-2 data

CMS with friends
- **ATLAS**: 5 (4 JHEP, 1 PRL)
- **LHCb**: 1 (Nature)
- **Totem**: 3 (1 JHEP, 2 EPJC)

CMS titles
- 527 "Search for"
- 39 "Observation"
- 18 "Evidence"
- 308 "Measurement"



Higgs physics

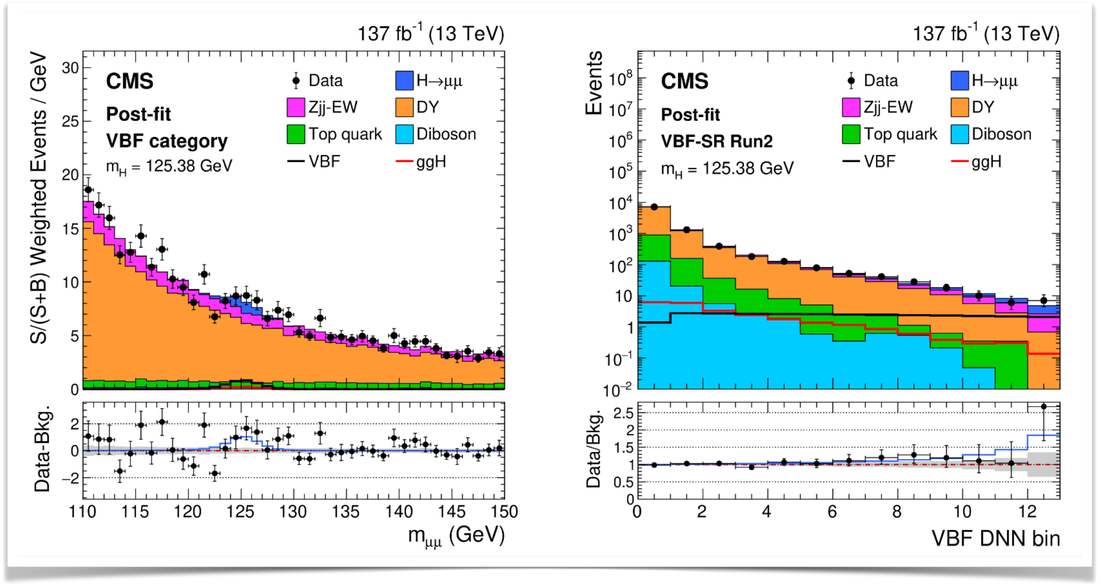
First evidence for $H \to \mu\mu$ (CMS)

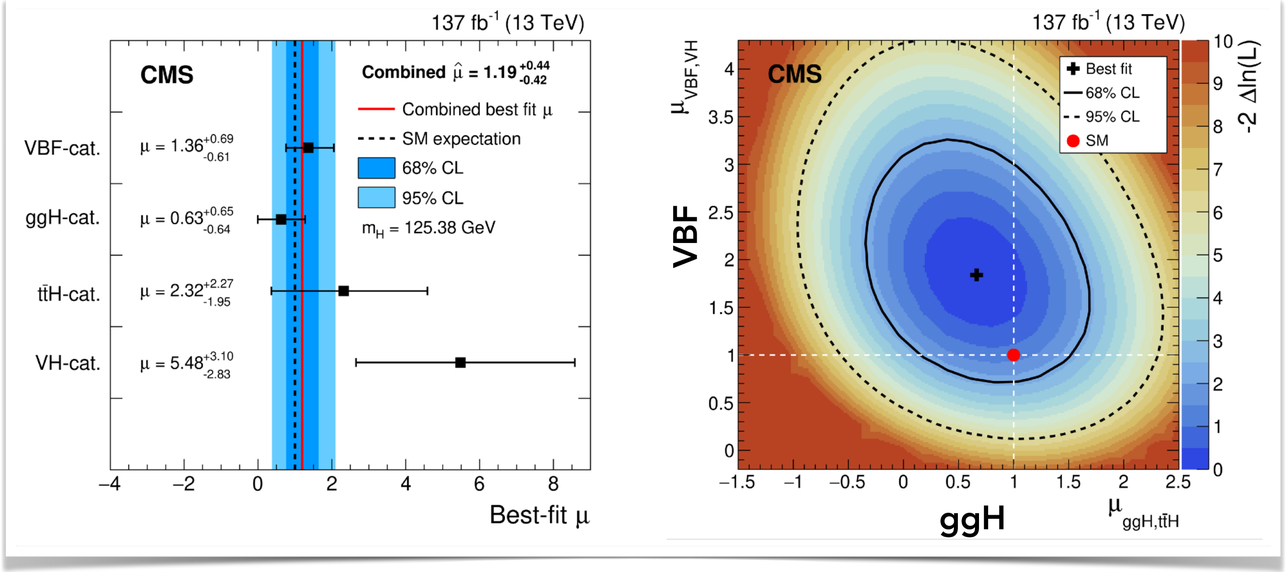
CMS-HIG-19-006
JHEP 01 (2021) 148

- Analysis in VBF category
  - makes use of advanced **machine learning** techniques
  - provides sensitivity similar to that in **ggH**
- Drell-Yan background considerably reduced by VBF topology requirement (two forward jets)
- Full Run2
- Combining with Run-1 (7 and 8 TeV) improves significance by 1%

$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$$

Obs. (exp.) significance: 3.0 (2.5) σ

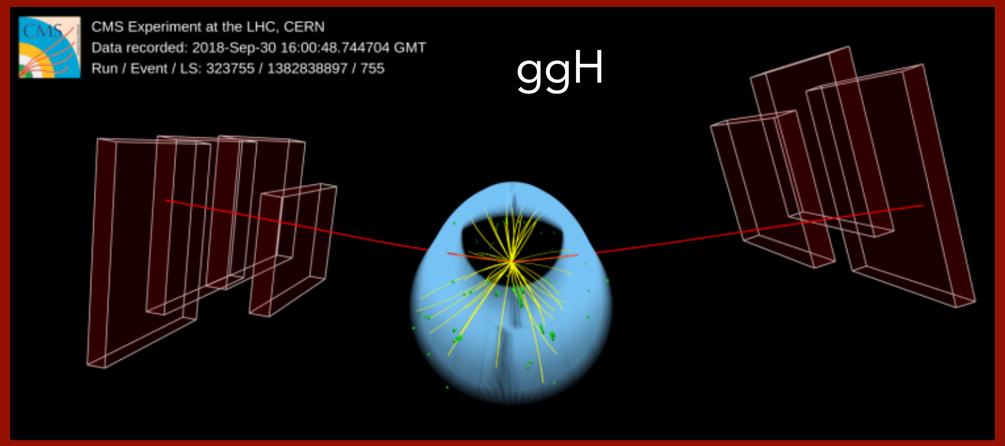


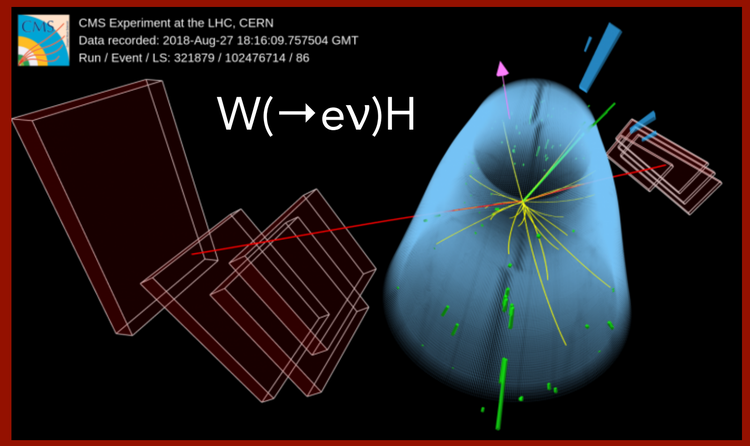


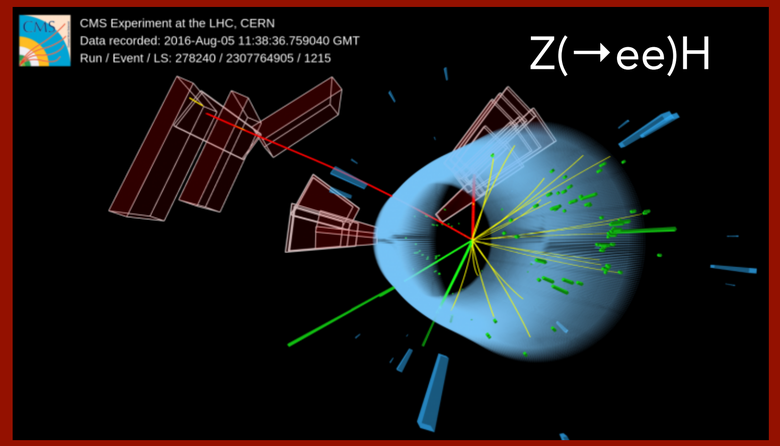
using $m_{\mathrm{H}} = 125.38$ GeV (best CMS result)

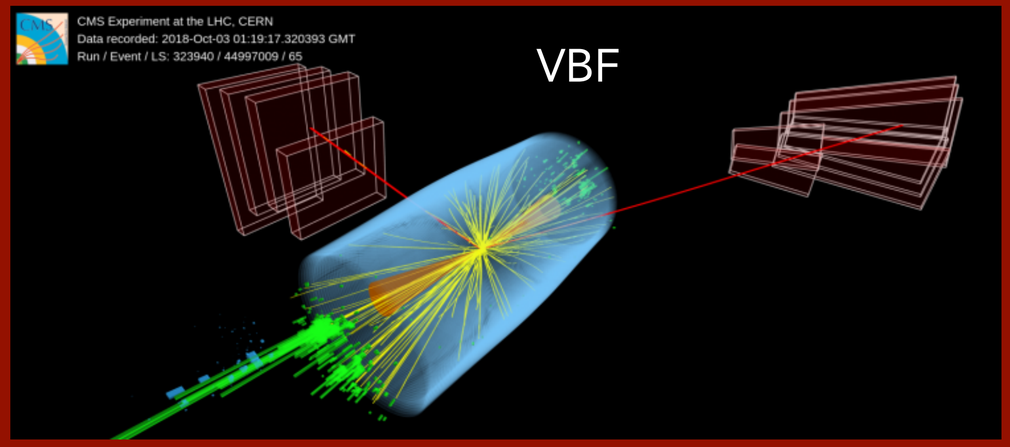
First evidence for H → $\mu\mu$ (CMS)

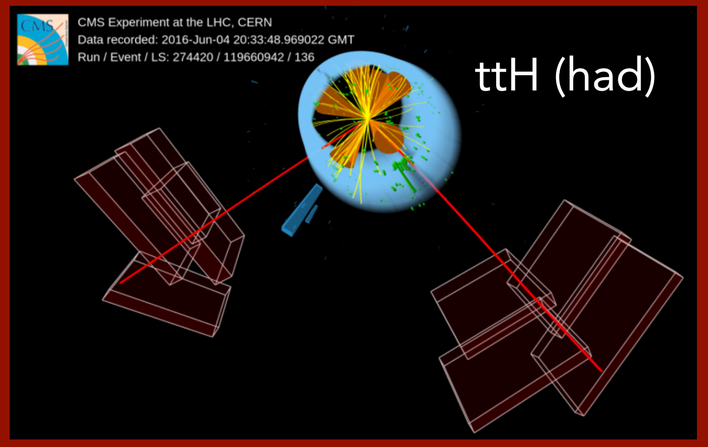
ggH, VBF, VH, and ttH exclusive production modes

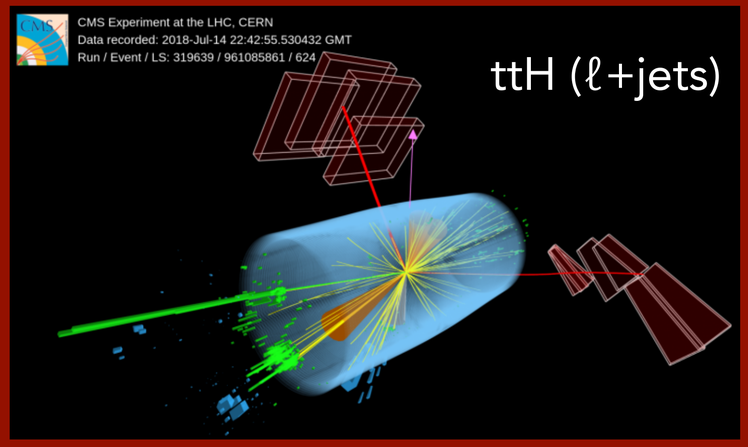












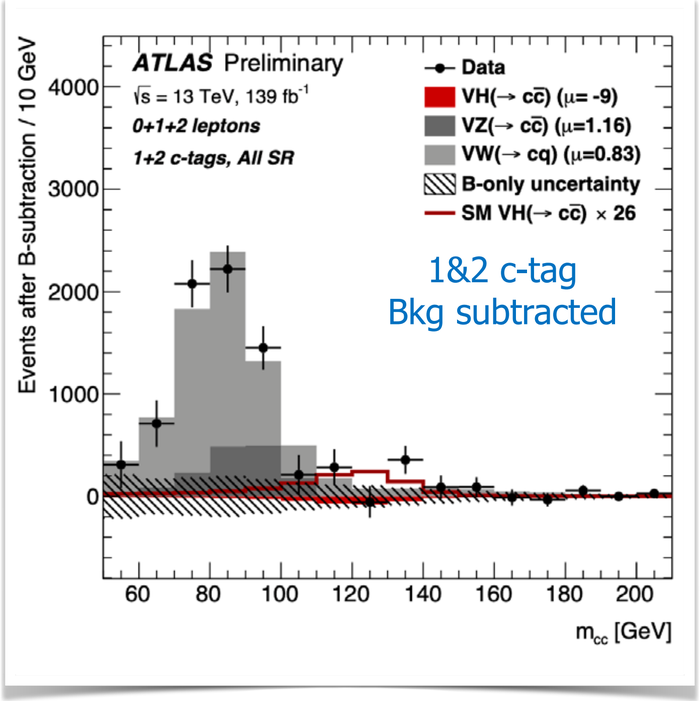
$VH \rightarrow c\bar{c}$ (ATLAS)

ATLAS-CONF-2021-021

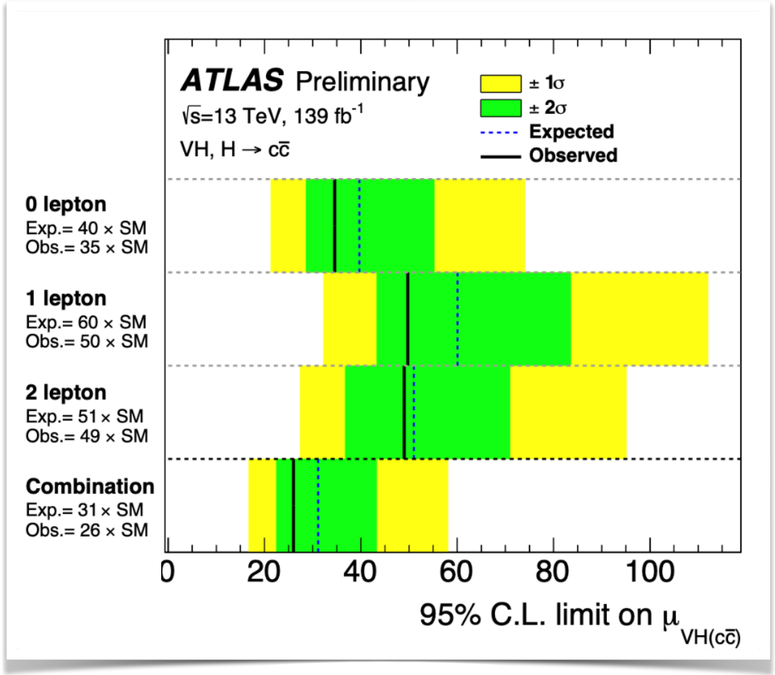
- Binned max-likelihood fit: $m_{c\bar{c}}$
- Kappa framework (Yukawa coupling modifier κ_c)
- Most stringent constraint to date

0, 1, 2, ℓ (ℓ = e, μ) + jets, VH($\rightarrow b\bar{b}$) veto
$ZH \rightarrow \nu\nu c\bar{c}$, $WH \rightarrow \ell\nu c\bar{c}$, $ZH \rightarrow \ell\ell c\bar{c}$

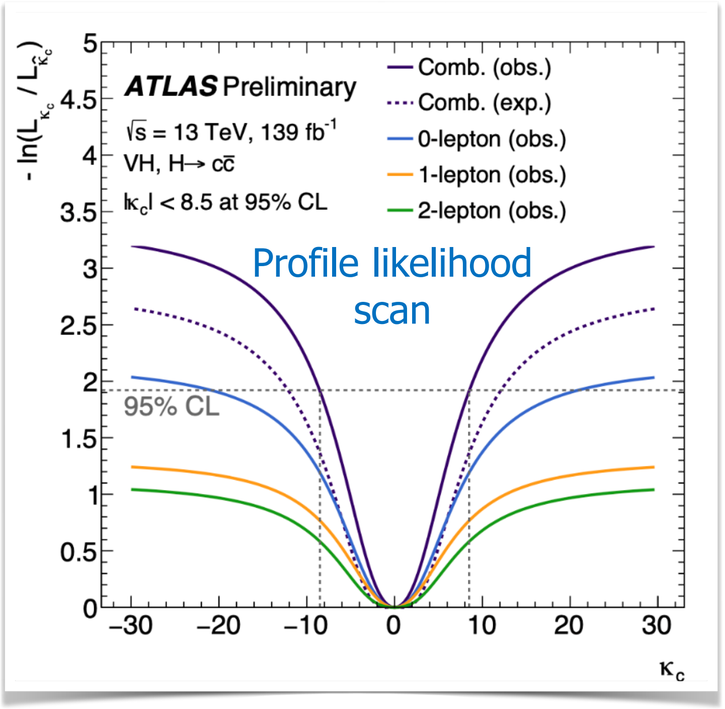
No VH($\rightarrow c\bar{c}$) excess observed



μ sig. strength {x $[\sigma \cdot Br]_{SM}$ } →26 (31) obs (exp)



$|\kappa_c|$<8.5 at 95% CL

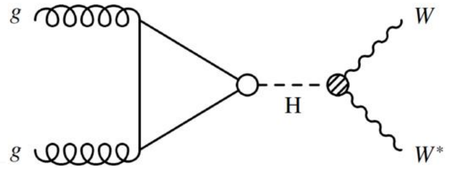


H → *WW** (ATLAS)

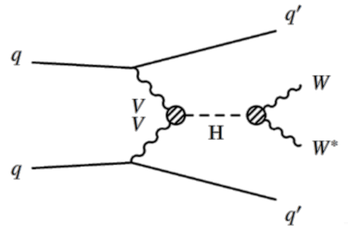
ATLAS-CONF-2021-014

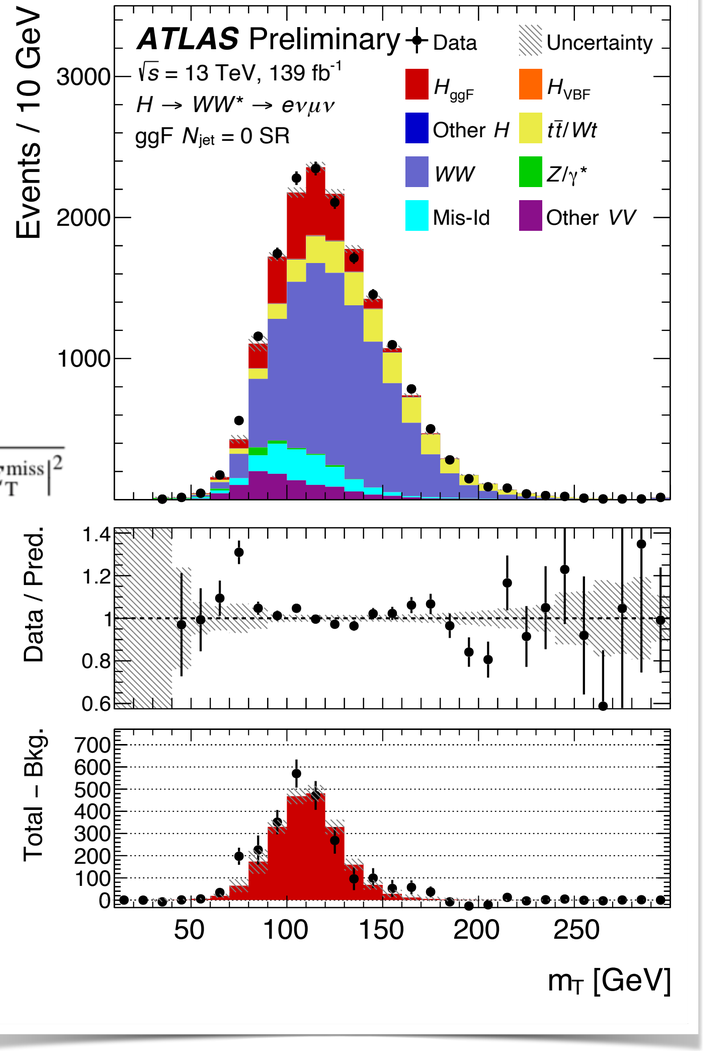
- High statistics H→WW*→$e\nu\mu\nu$ allows studies of different Higgs production modes
  - **ggF**: jets only from ISR
  - **VBF**: forward quark jets with large m_{jj} and large Δy
  - Backgrounds from continuum WW* production, top-pair
- Separate sample using N_{jet} and dedicated **deep NN** for VBF
  - Final discriminant for ggF: $m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$

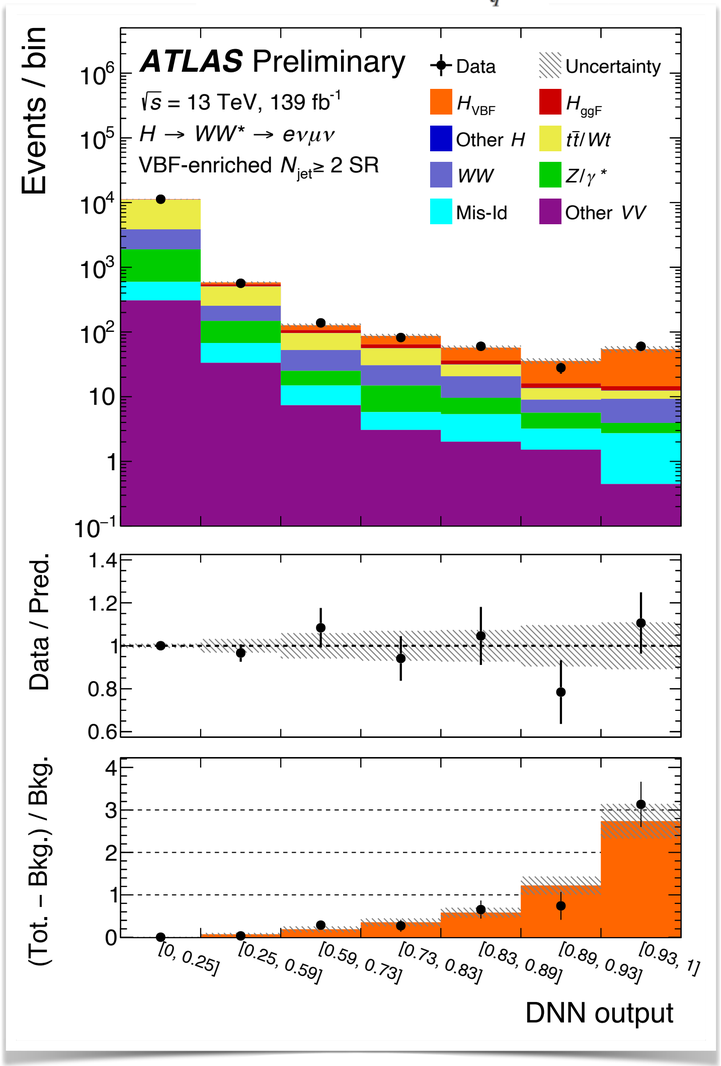
ggF

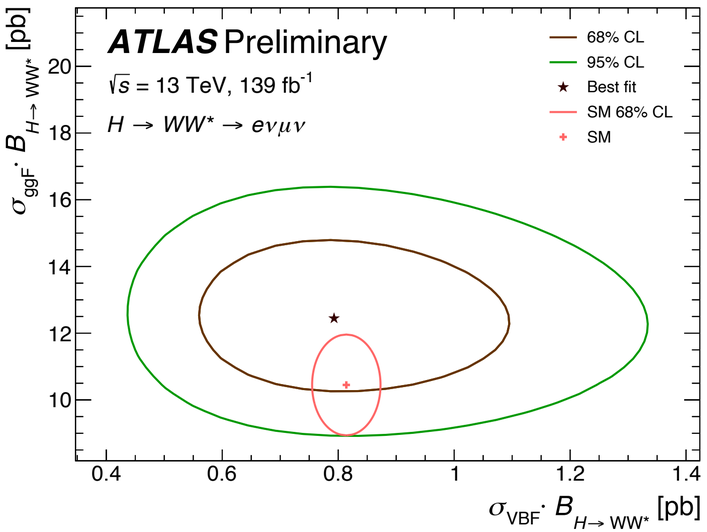


VBF





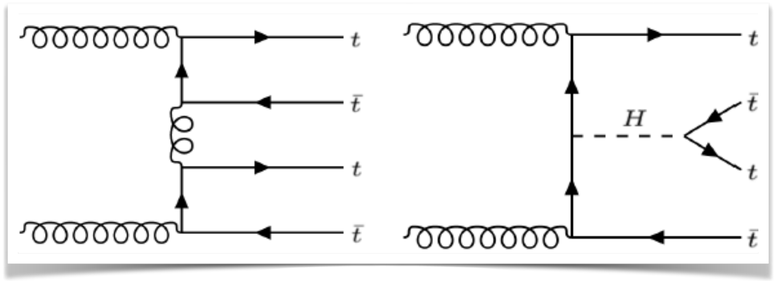


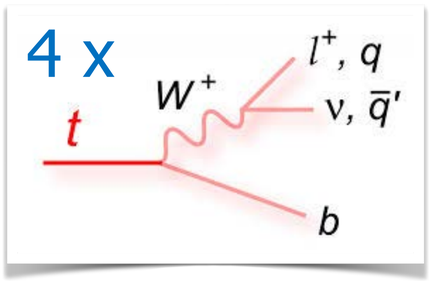


Top quark physics

Four top quark production (ATLAS)

ATLAS-CONF-2021-013 with Eur. Phys. J. C 80 (2020) 1085



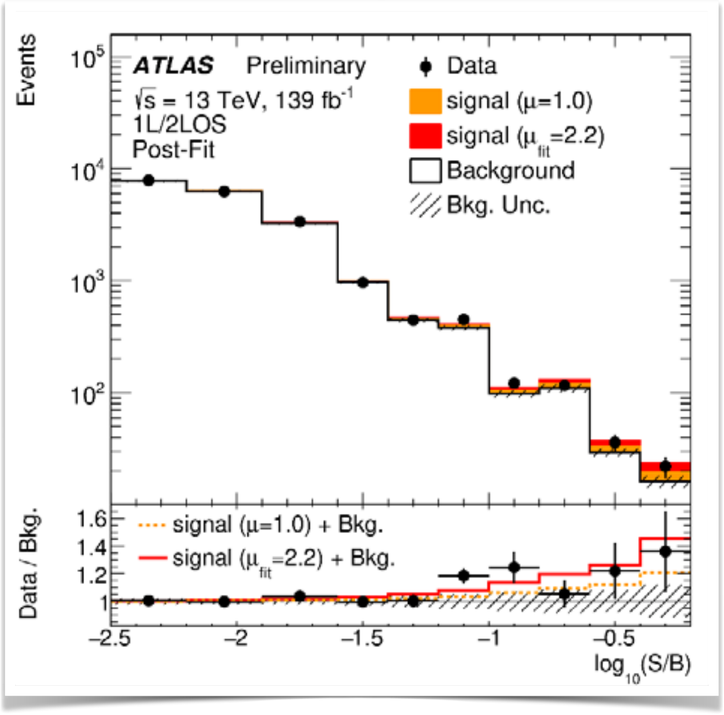


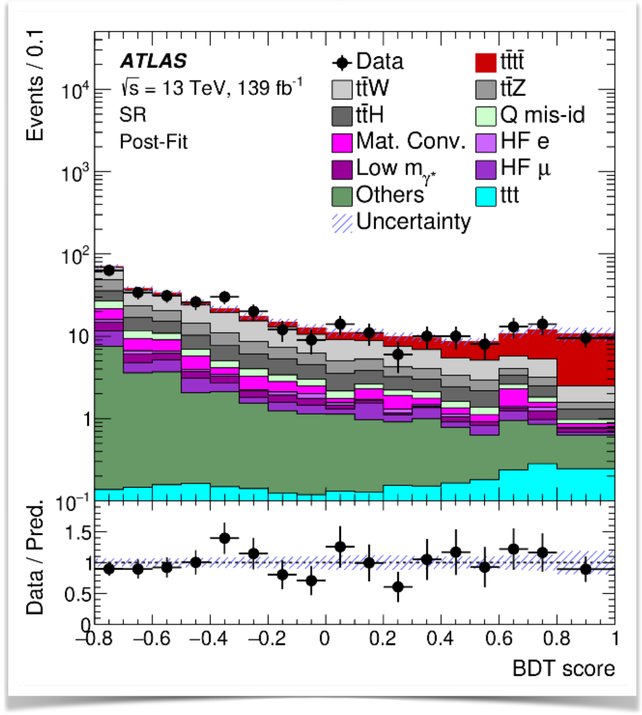
13 TeV, 139 fb^{-1}
$t\bar{t}t\bar{t}$ 1 ℓ / 2 ℓ OS (ℓ = e,μ)
[57% of $t\bar{t}t\bar{t}$ events]

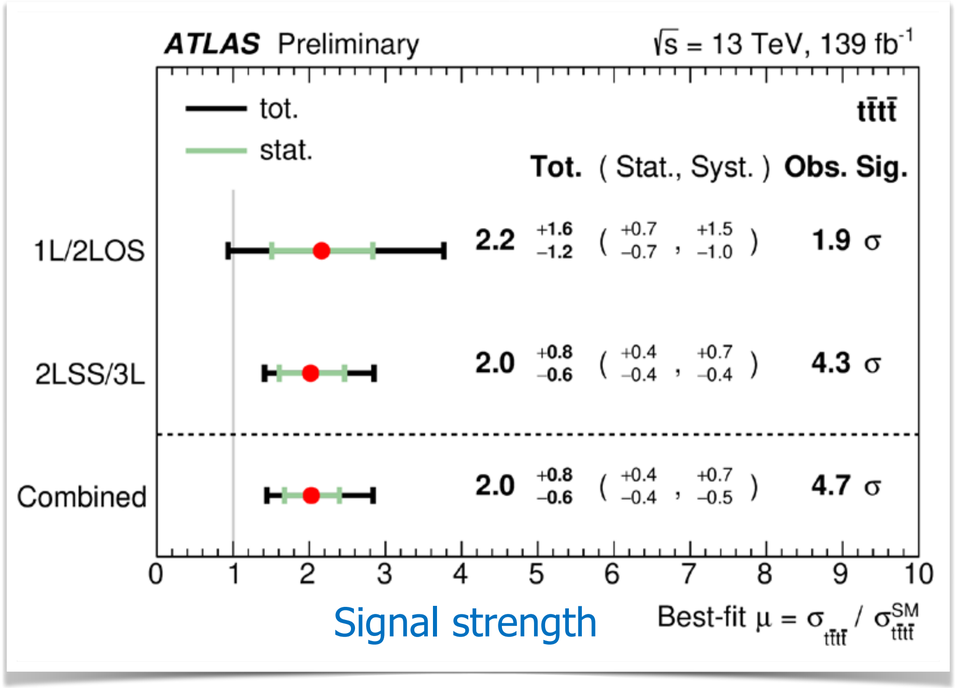
+

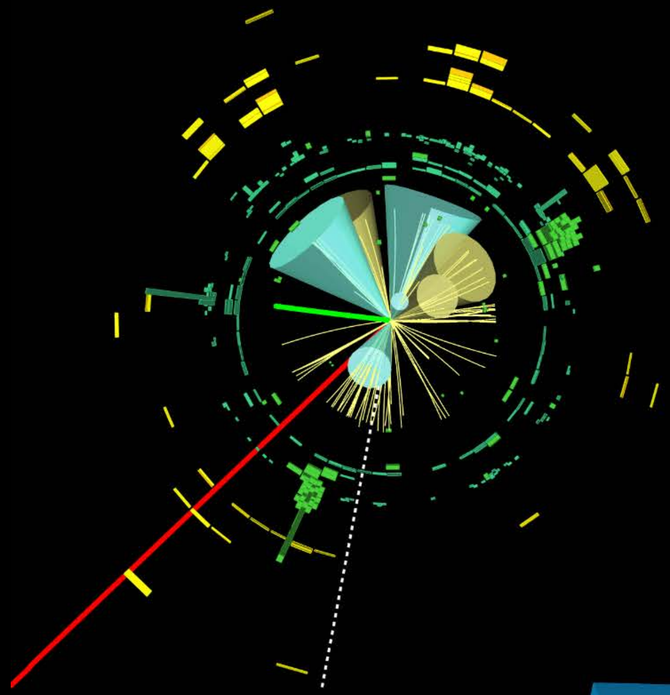
13 TeV, 139 fb^{-1}
$t\bar{t}t\bar{t}$ 2 ℓ SS / 3 ℓ (ℓ = e,μ)
[13% of $t\bar{t}t\bar{t}$ events]

- **Challenging $t\bar{t}$ modeling**
- Enhancements from pair production gluino & scalar gluons, 2HDM
- Prediction: $\sigma_{t\bar{t}t\bar{t}}$ = 12.0 ± 2.4 fb (NLO+EW)
- Result: $\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8(\text{stat}) \,^{+15}_{-13}$ (syst) , 1.9 obs. (1.0 exp.) σ
- **4.7 σ obs.** (2.6 σ exp.) above bkg-only hypothesis









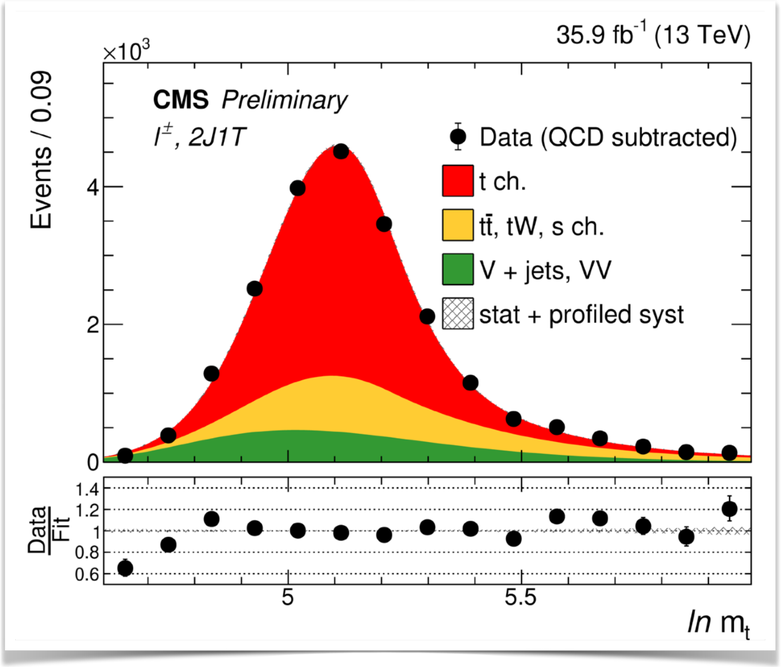
Candidate four-top-quark event

Leptons & (b-tagged) jets

ATLAS EXPERIMENT

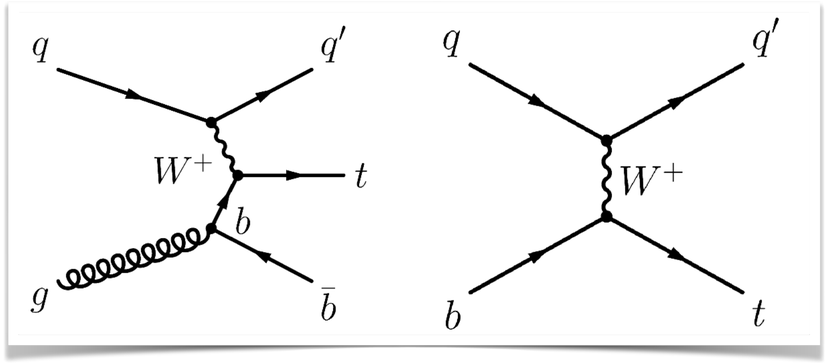
Run: 349114
Event: 1280053930
2018-04-29 10:53:24 CEST

Top mass from single top events (CMS)



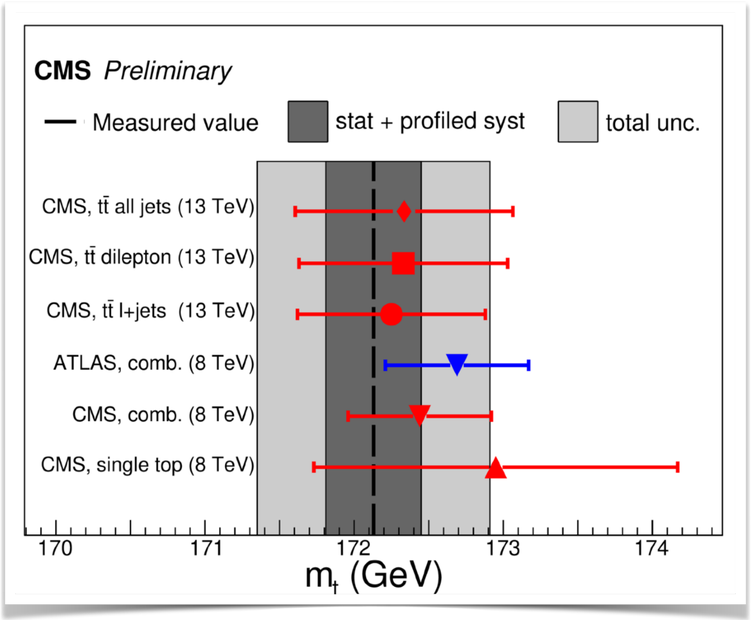
CMS-PAS-TOP-19-009

Fitted in top mass



t-channel single top production at LO in four- and five-flavor schemes

- Measurement based on **2016** data
- Selection requiring an isolated energetic lepton (muon or electron) and two jets
- One b-tagged jet is required
- The mass of the top quark is found to be be **172.13**$^{+0.76}_{-0.77}$ **GeV**
- the difference of masses of top quark and antiquark is measured to be **0.83**$^{+0.77}_{-1.01}$ **GeV**



the grey band is the new measurement

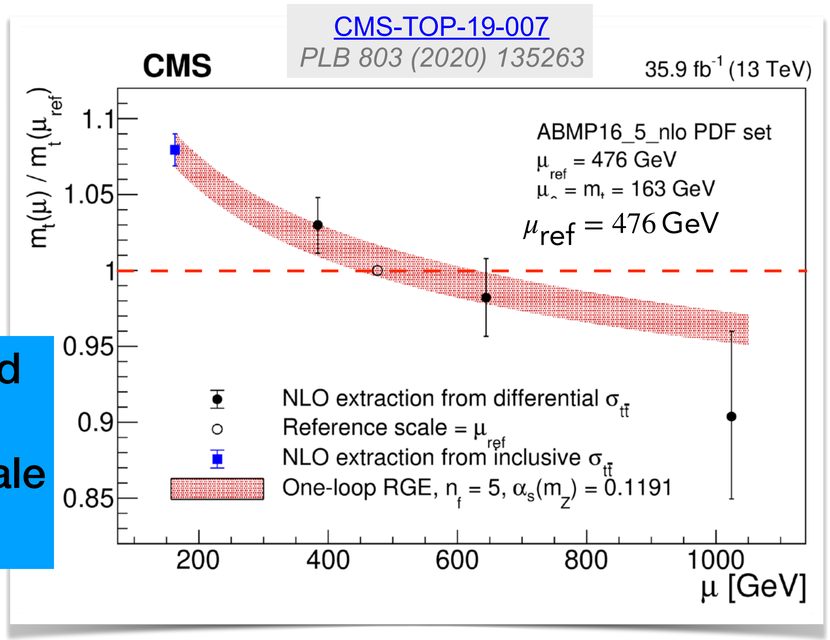
Measured m_t compared to previous measurement

Running of the Top-Quark mass (CMS)

"Pole" mass from multi-differential cross section measurements

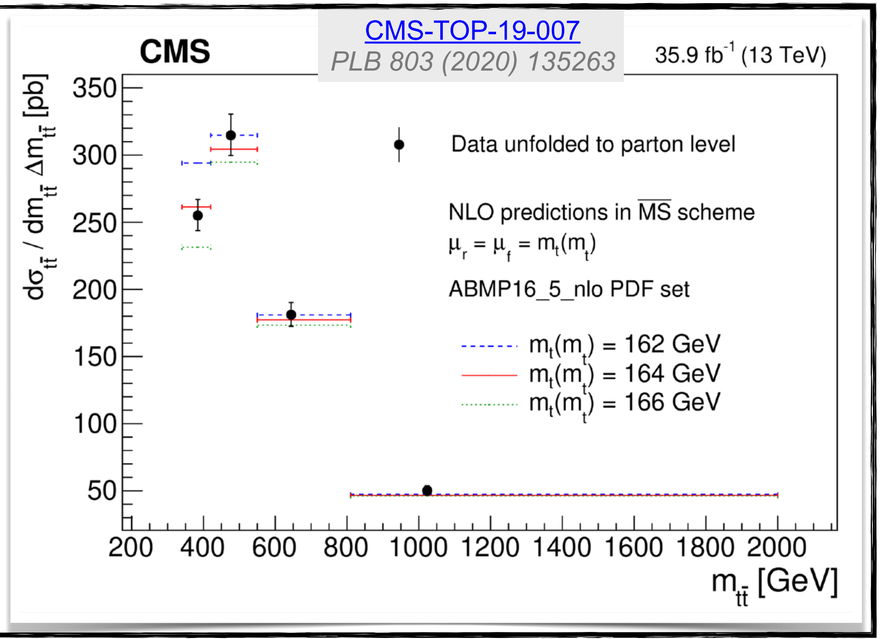
- in $e^{\pm}\mu^{\mp}$ final state
- as functions of mass and rapidity of the $t\bar{t}$ system, and jet multiplicity
- unfolded at parton level
- compared with NLO predictions in $\overline{MS}$ scheme
- m_t = **170.83 ± 0.72 GeV** CMS-TOP-18-004 *EPJC 80 (2020) 658*

uncertainty evolved from inclusive measurement at scale μ_0 = 163 GeV



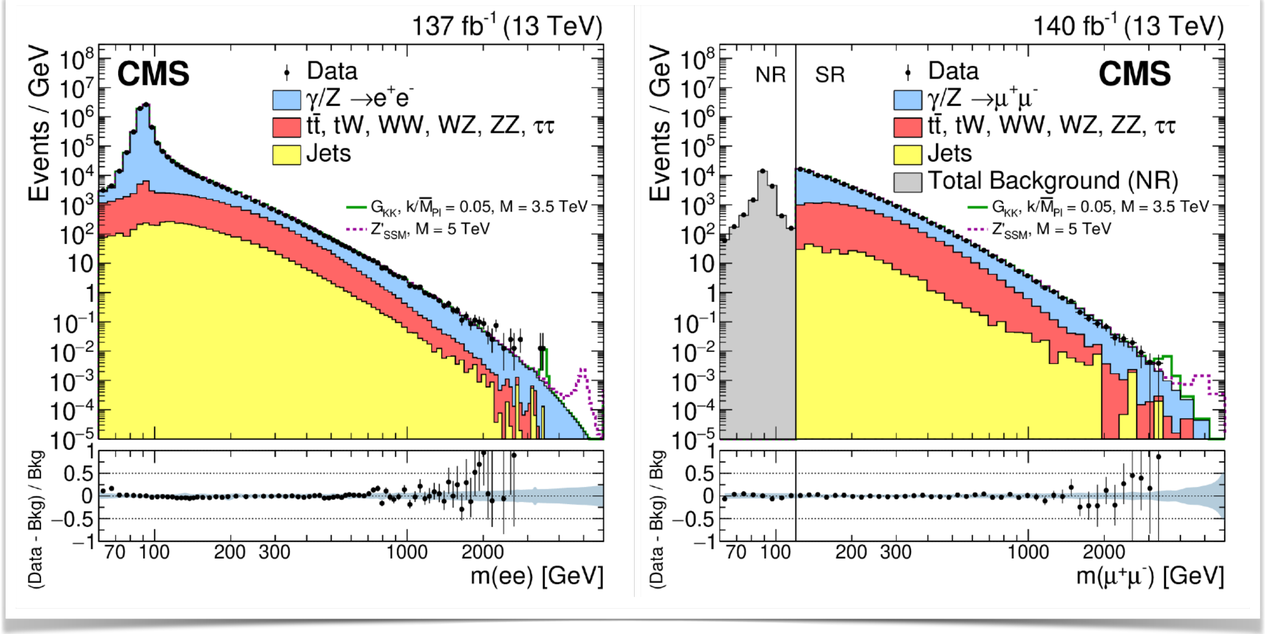
Evolution of the top quark mass from the differential cross section as a function of $m_{t\bar{t}}$

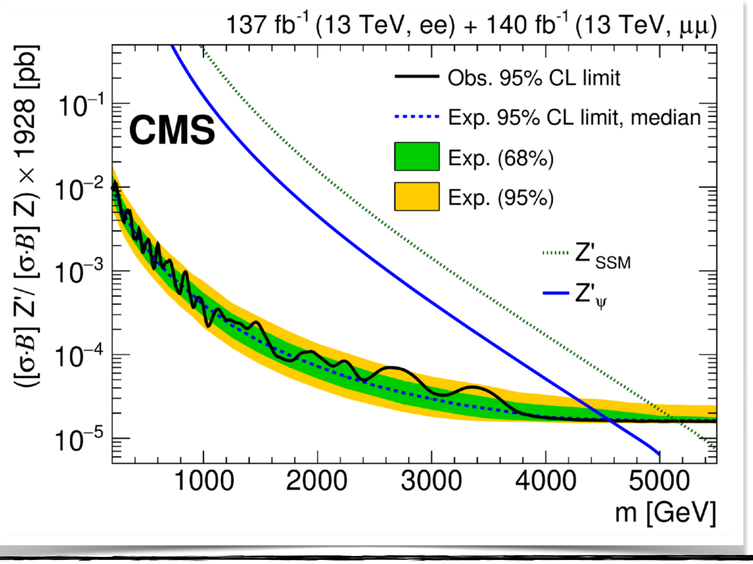
- Top-quark running mass probed up a scale of **order 1 TeV**
- compared to RGE prediction at one-loop precision ($n_f = 5$)
- scale dependance found consistent with predictions at the 1.1σ level
- no-running hypothesis **excluded** at the 95% CL



Searches for new physics

Heavy resonances in CMS



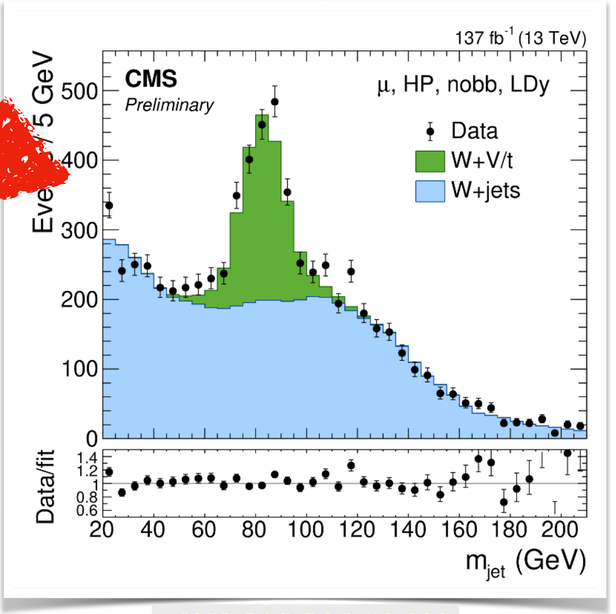


CMS-EXO-19-019
Submitted to JHEP

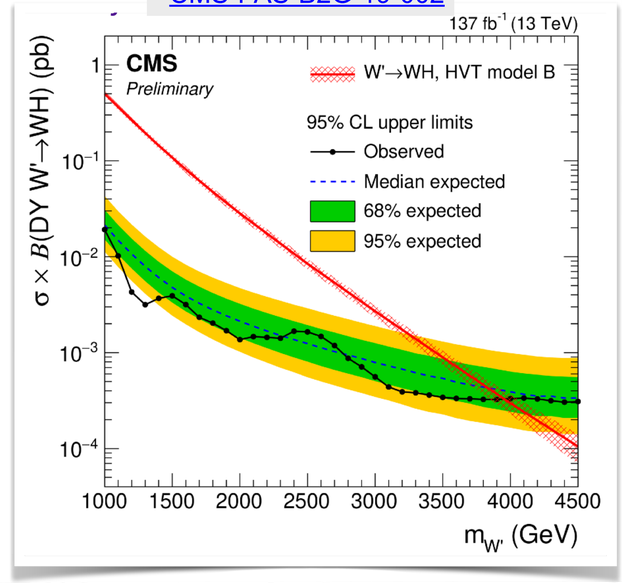
WW, WZ, WH in lepton + merged jet final state

Limits on cross section × BF translate into limits on resonance masses

depending on models new W' or Z' resonances with masses up to > 4 TeV are excluded



CMS-PAS-B2G-19-002

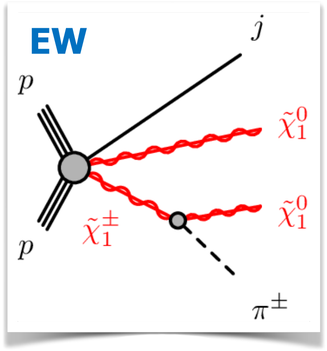


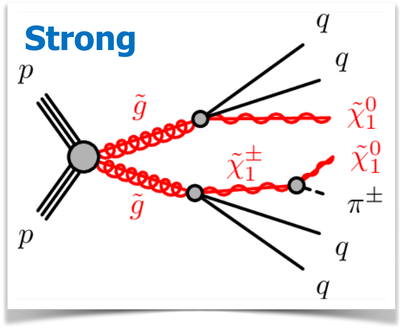
LLP in ATLAS

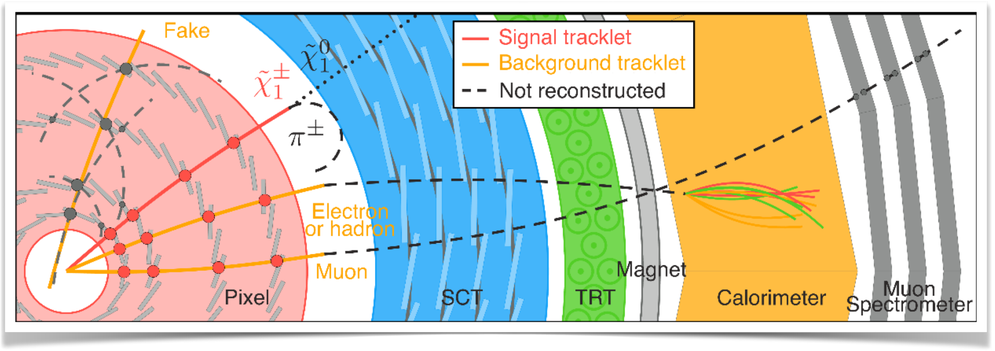
13 TeV, 136 fb^{-1}
$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + \pi^{\pm}$

ATL-PHYS-PUB-2021-019

- Signature
  - **Disappearing track** early in inner tracker: pixel tracklet + no calo activity
  - Significant $p_{T,miss}$
  - high-p_T jet(s)

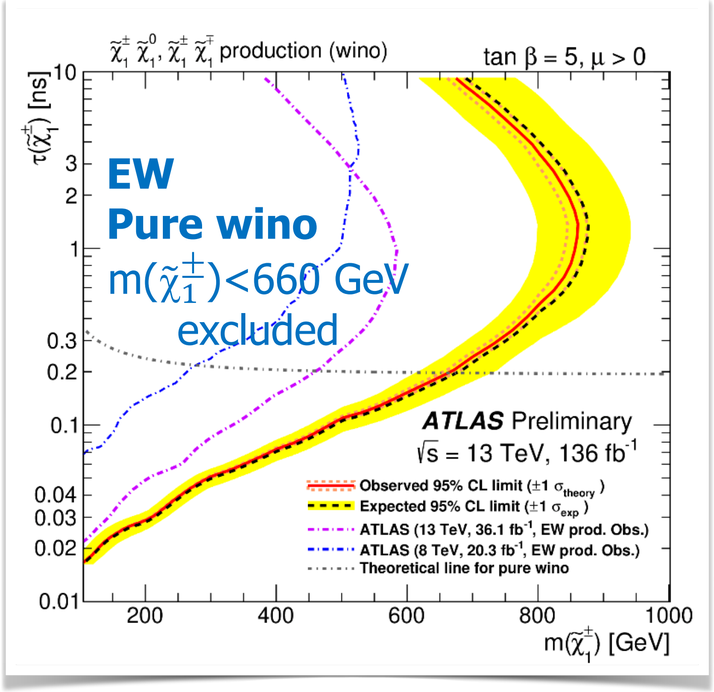


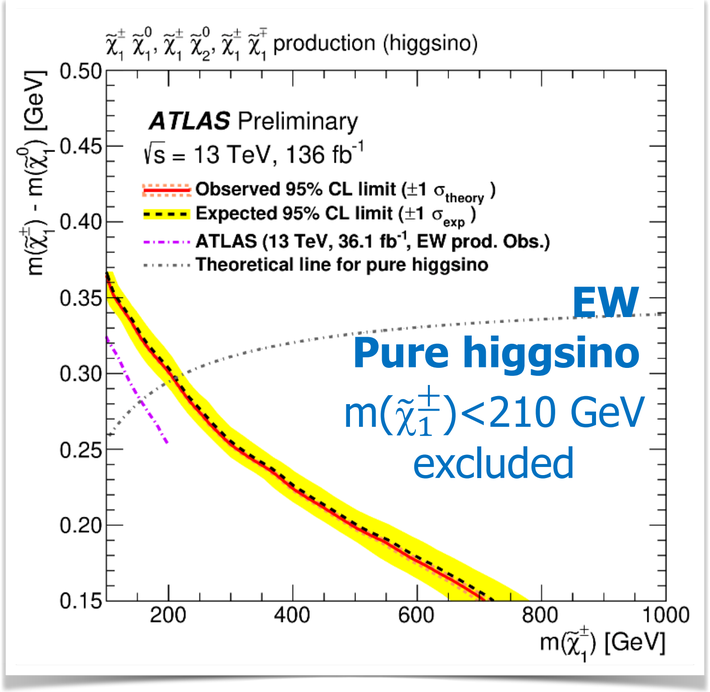


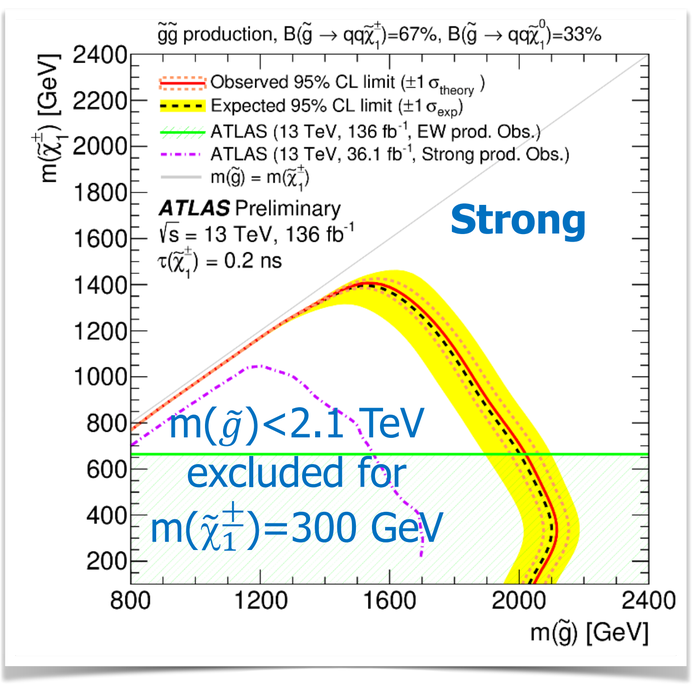


Chargino $\tilde{\chi}_1^{\pm}$ lives long enough to traverse multiple layers of Pixel detector before decaying

Two signal regions	
EW	**Strong**
3 evts (3.0 exp.)	1 evt (0.84 exp.)



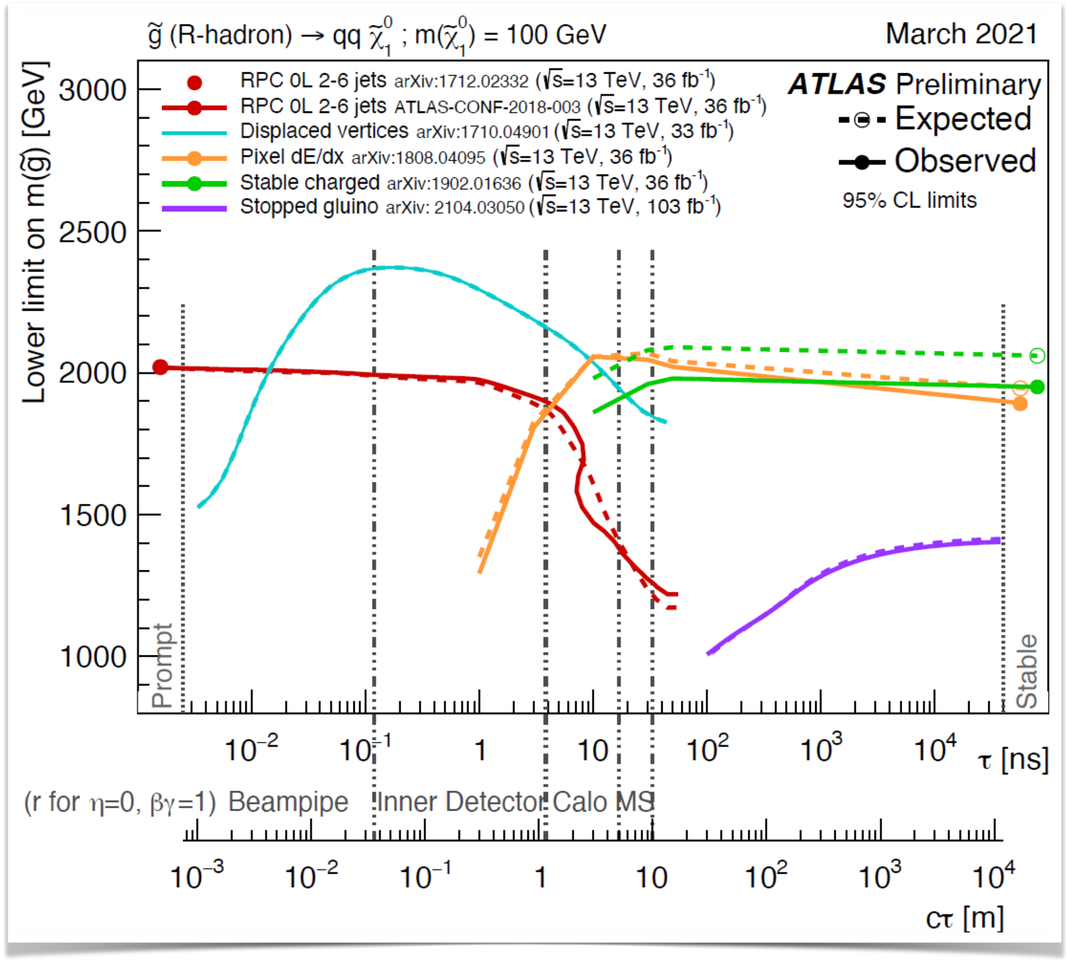




LLP program in ATLAS

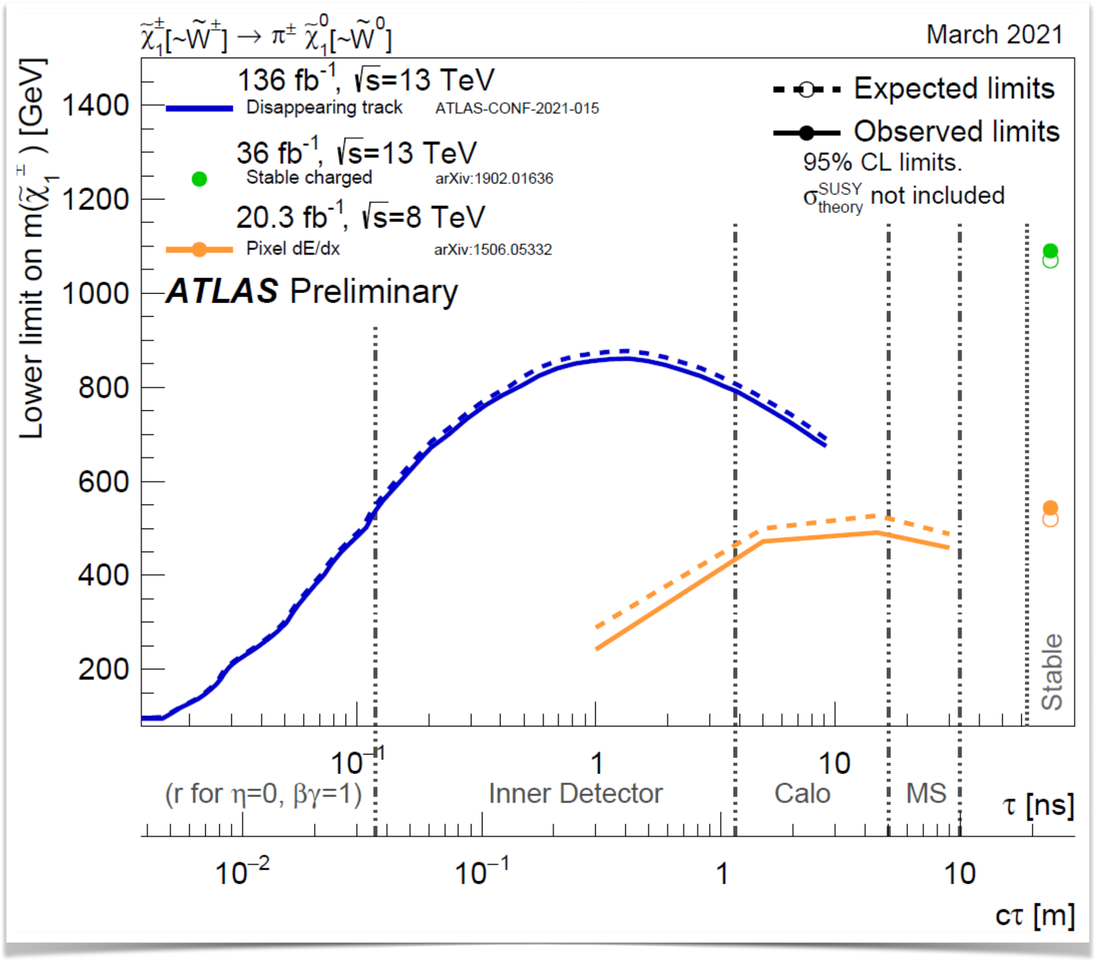
ATL-PHYS-PUB-2021-019

Constraints on gluino mass vs. lifetime



Gluino mass vs. lifetime for split-SUSY model with gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV.

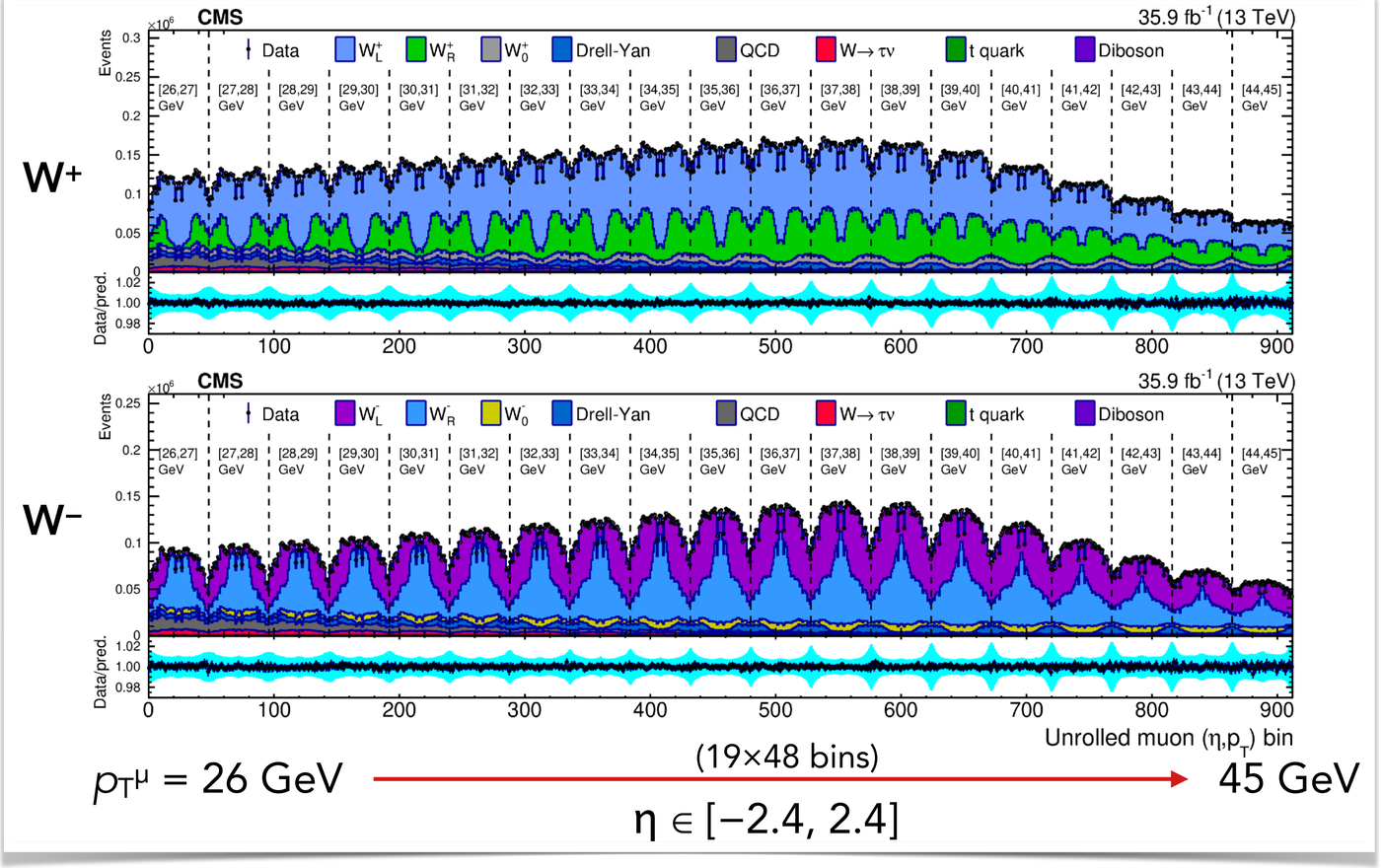
Constraints on chargino mass vs. lifetime

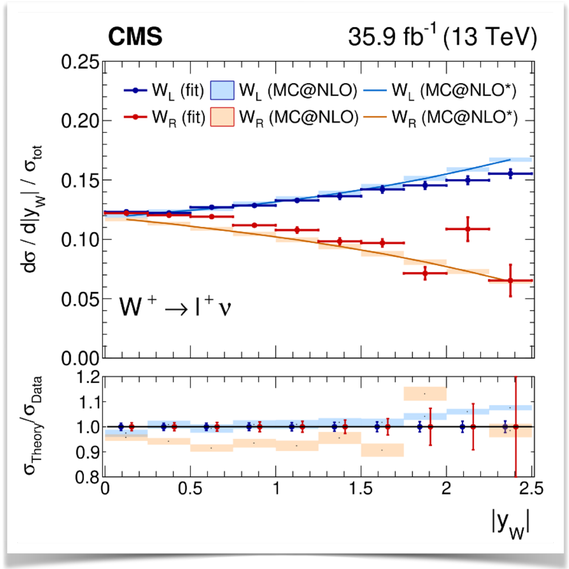


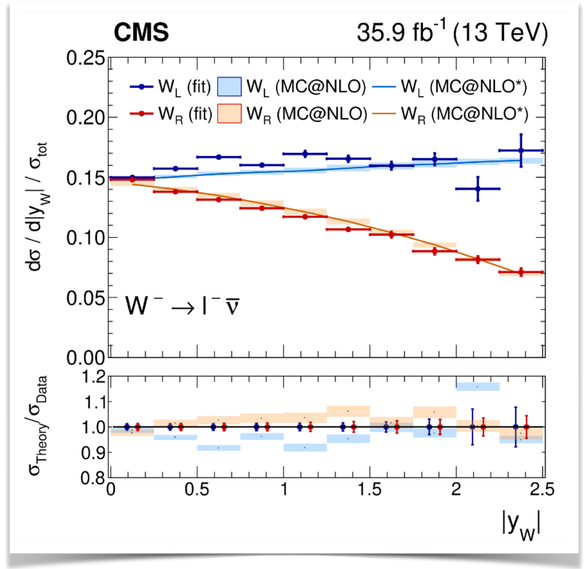
Chargino mass vs. lifetime for AMSB model with tan(β)=5, μ>0. Wino-like chargino is pair-produced and decays to wino-like neutralino and a very soft charged pion.

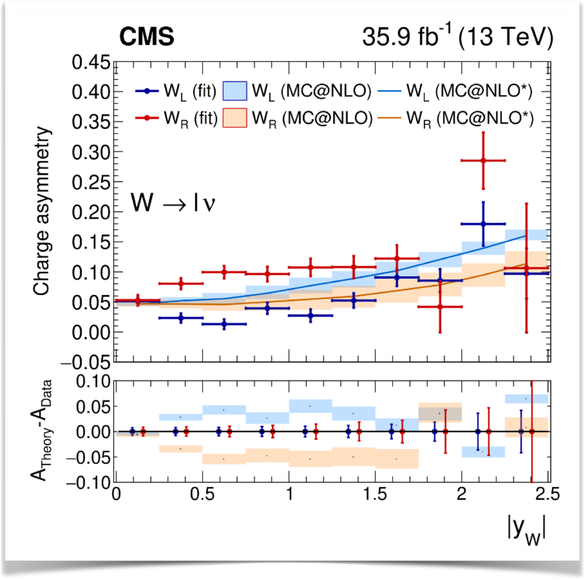
Standard Model

W helicity measurement in CMS









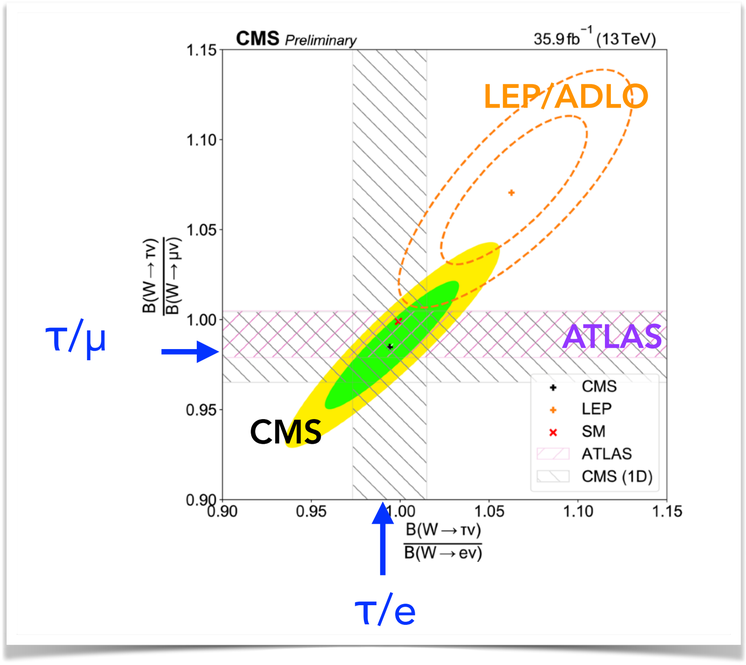
Template fit to extract differential cross-sections and charge asymmetries for the two helicity states

[CMS-SMP-18-012](#)
PRD 102 (2020) 092012

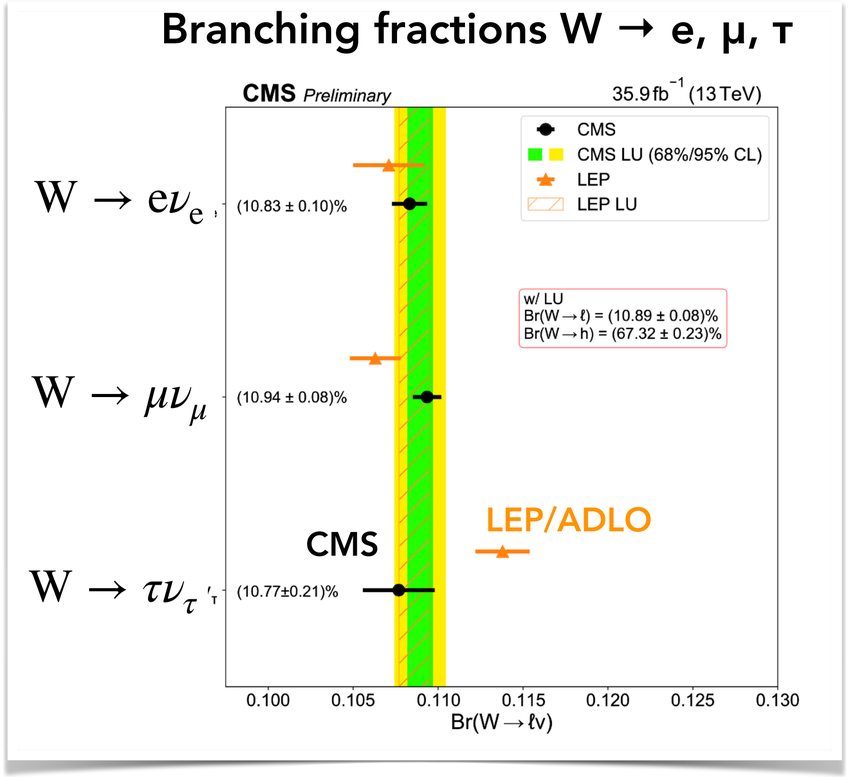
- Double-differential cross-sections in $p_{T,l}$ and η_l $(l = e, \mu)$ for W^+ and W^-
- constraints on PDFs
- **milestone** towards the W mass measurement

Test of lepton universality in W decays in CMS

- Using $t\bar{t}$ events in the dilepton channel, select relatively unbiased samples of on-shell Ws
  - **Trailing lepton** p_T used to discriminate between
  - prompt W → e/μ decays from W → τ → e/μ
  - decays in ee, $\mu\mu$, and $e\mu$ events



result consistent with SM and with recent ATLAS (most-precise) τ/μ result



CMS LU result is consistent with and improves on LEP/ADLO result

A long-standing LEP "tension" (>2.5σ) is gone

Run-2 2016, 35.9 fb^{-1}

CMS-PAS-SMP-18-011

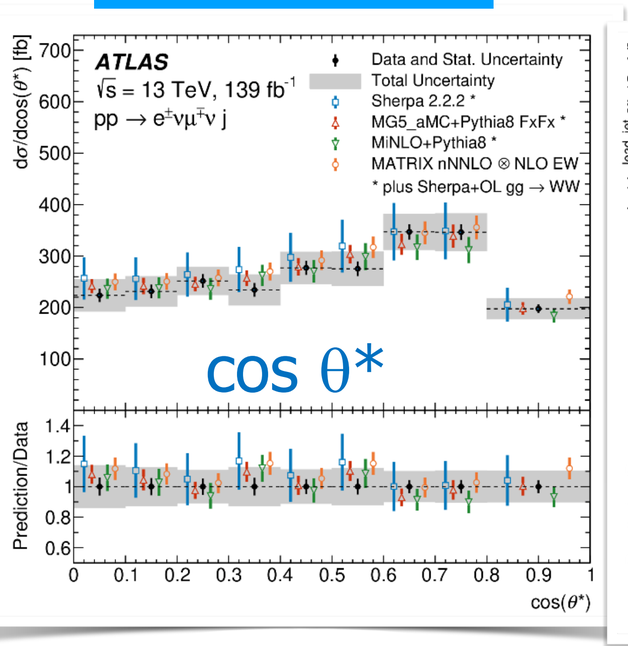
WW + ≥ 1 jet in ATLAS

arXiv:2103.10319

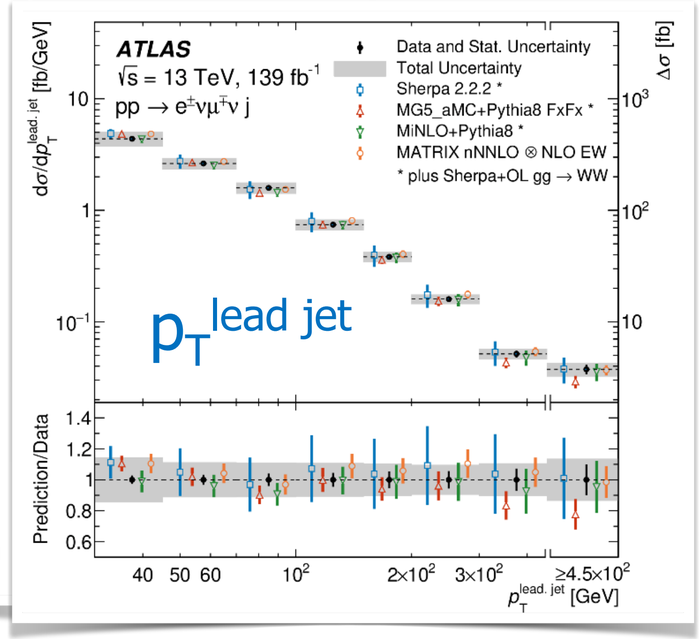
13 TeV, 139 fb^{-1}
$W^{\pm}W^{\mp}$ ($\rightarrow e^{\pm}\nu\mu^{\mp}\nu$) + ≥1 jet

- Differential cross section vs. variables that characterise W kinematics and jet production
- WW + ≥ 1 (hard) jet improves the sensitivity to searches for **anomalous triple gauge boson couplings**
- Challenging top background

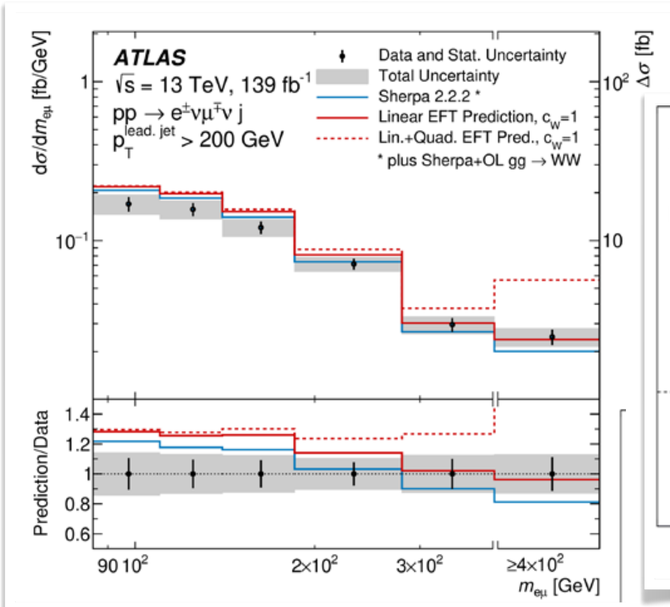
Sensitive to WW spin structure



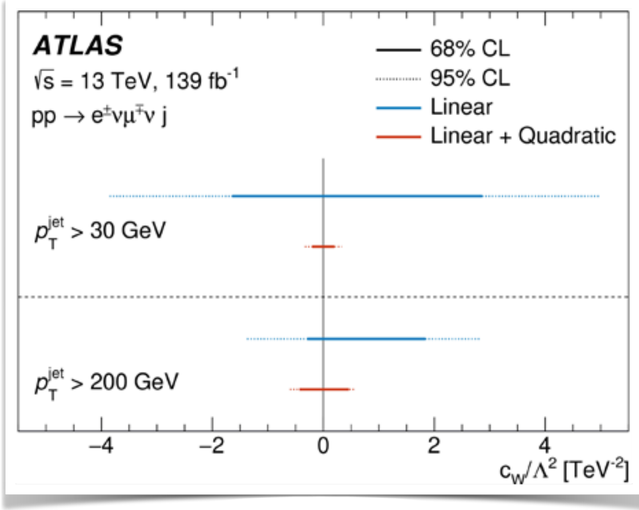
~10% systematics



meμ most sensitive



EFT: constraints on Wilson coefficient CW

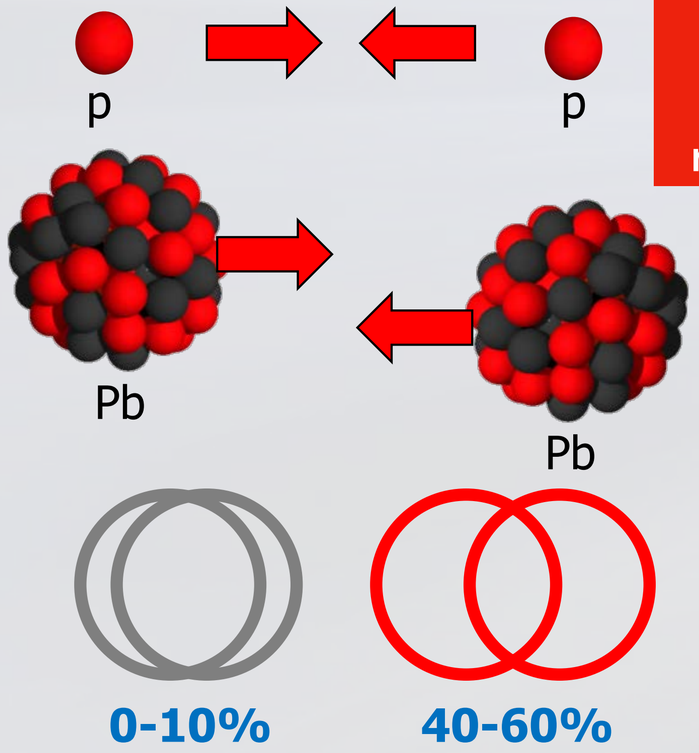


Heavy Ions

Heavy Ions in ATLAS

$$R_{AA} = \frac{N_{AA}/N_{evt}}{\langle T_{AA} \rangle \times \sigma^{pp}}$$

Modification to particle yields compared to pp scattering

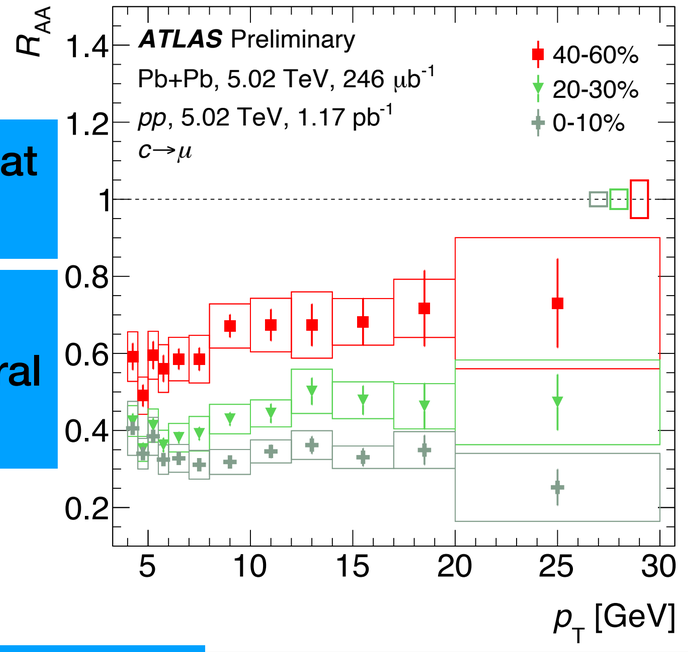


Centrality: overlap of colliding nuclei

Partons lose energy when traverse nuclear medium
Suppression of small-angle gluon radiation for massive quarks at low p_T

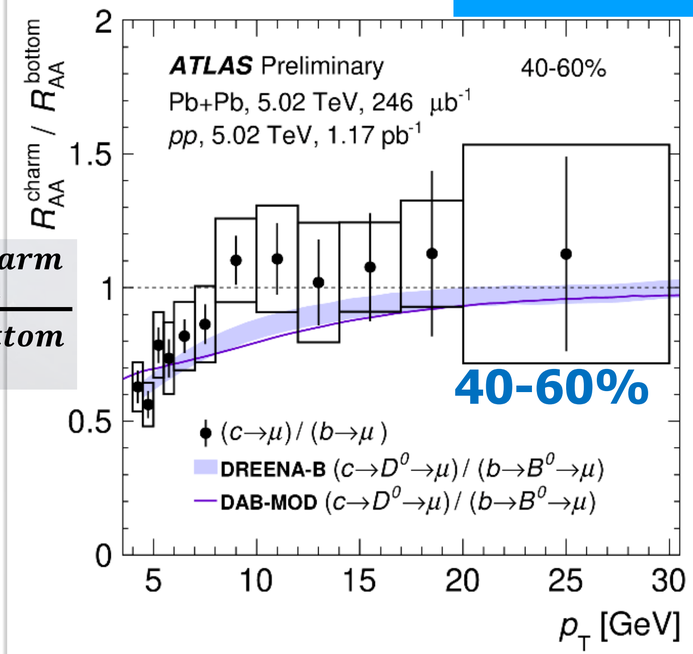
Stronger c→μ modification at low p_T

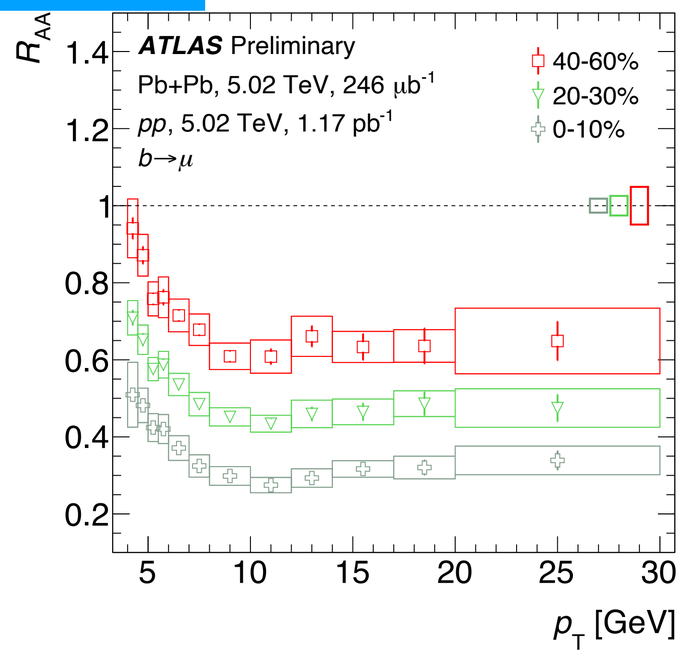
Suppression increases monotonically from peripheral to central collisions



ATLAS-CONF-2021-020

$$\frac{R_{AA}^{charm}}{R_{AA}^{bottom}}$$



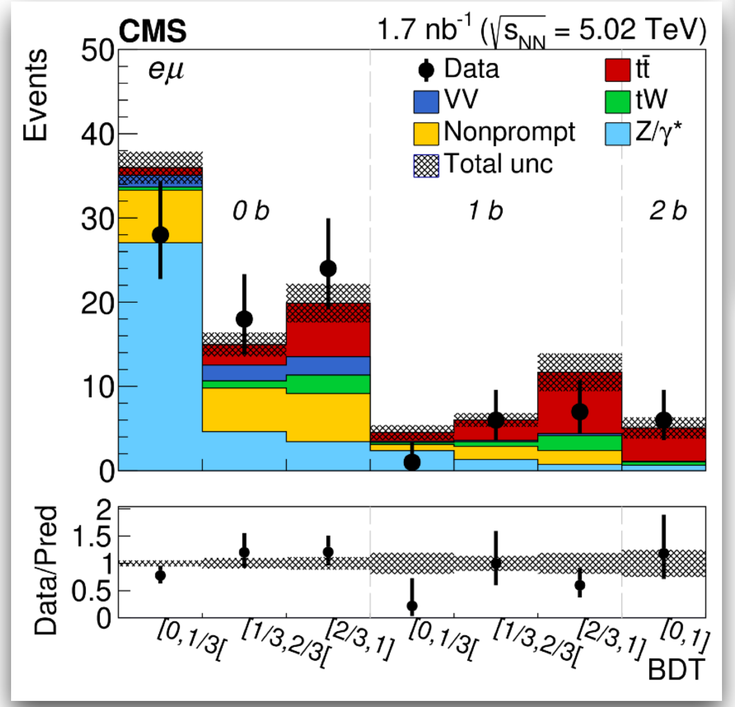


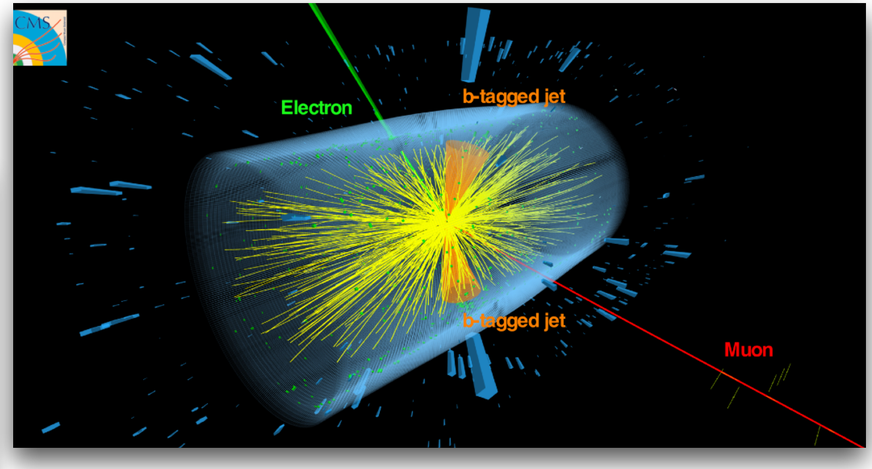
Heavy Ions in CMS

- Evidence for $t\bar{t}$ production
  - in the $e\mu$ channel
  - 4.0σ obs. (6.0σ exp.)
  - following a first observation in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

CMS-HIN-19-001
PRL 125 (2020) 222001

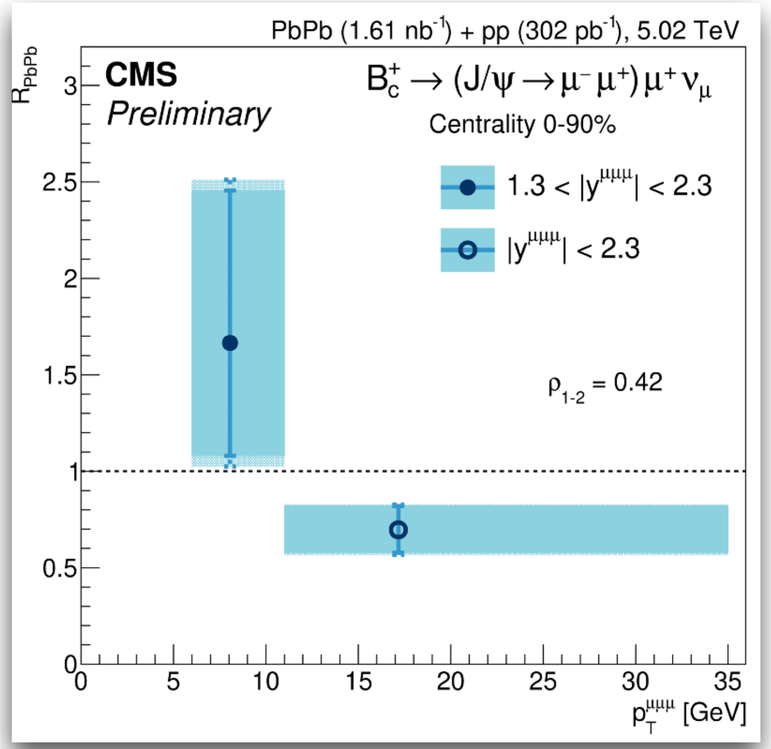
- Top quarks are thought to decay before QGP formation
  - **probes for nPDF** at high-x





- Observation of B_c meson production
  - in the decay channel $B_c \to J/\psi(\to\mu\mu)\mu\nu$ ($\gg 5\sigma$)
  - bridge between charm and charmonium
- rules out some (extreme) models of charm recombination
- will help disentangle the enhancement and **suppression mechanisms** at play in the evolution of heavy quarks through the QGP

CMS-PAS-HIN-20-004

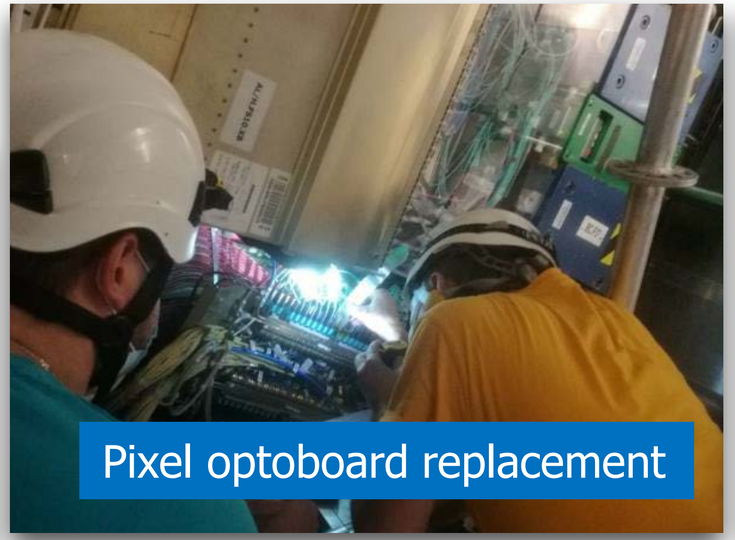


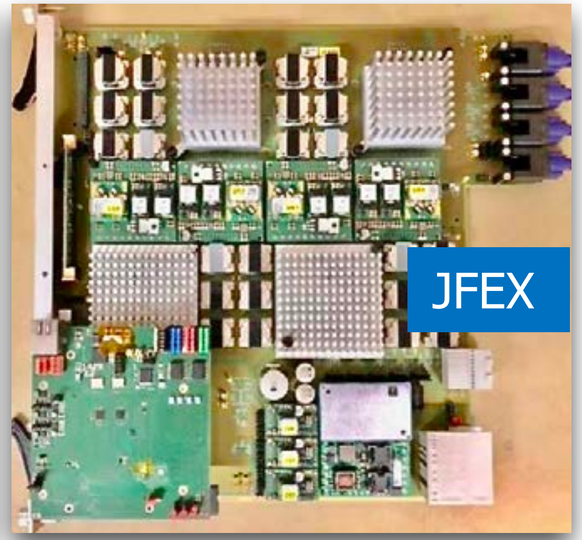
Run-2, $\sqrt{s_{NN}} = 5.02$ TeV, PbPb 1.7 nb^{-1} + pp 320 pb^{-1}

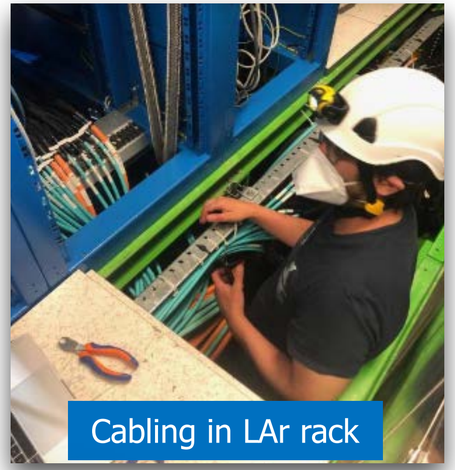
Long Shutdown activities

ATLAS

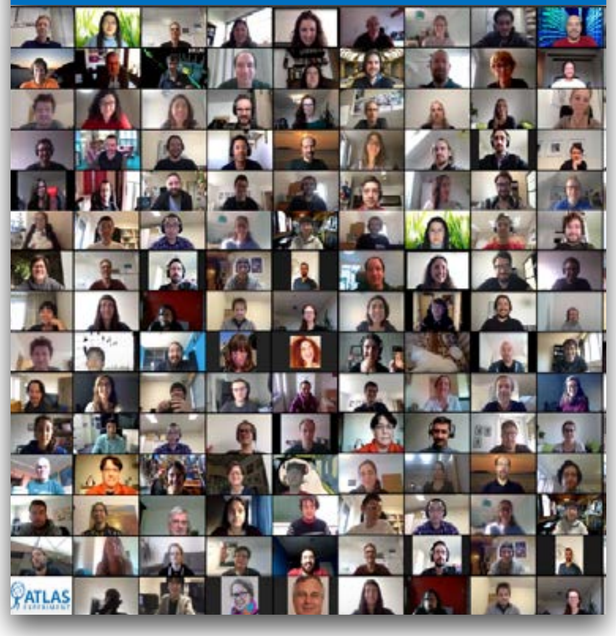

Muon New Small Wheels


Pixel optoboard replacement


JFEX


Cabling in LAr rack

Run-3 Trigger Workshop




Tile Calorimeter maintenance


Milestone Weeks in ATLAS Control Room


Installation Muon BIS78 chambers

FELIX

New LAr processing blade

CMS

LS2 = Long Shutdown 2 since 2019
Collisions to return mid 2022

Strip tracker
- kept cold to avoid reverse annealing
- currently warm during beam pipe bake-out

HCAL
- completion of Phase-I upgrades

Pixel detector
- replace first barrel layer
- replace all DCDC converters

Magnet
- at room temperature since mid 2020
- maintenance work: free wheel thyristor, cryo-cooling, power, pumps, etc.

Beam pipe
- new version Phase-II design

Muon system
- installation of GE1/1 chambers
- upgrade of CSC FEE to sustain HL-LHC trigger rates
- shielding against neutron background

CT-PPS
- upgrade of RP and moving system

BRIL
- BCM/PLT refit
- new T2 tracker

Civil engineering at P5
- prepare for Phase-II assembly and logistics

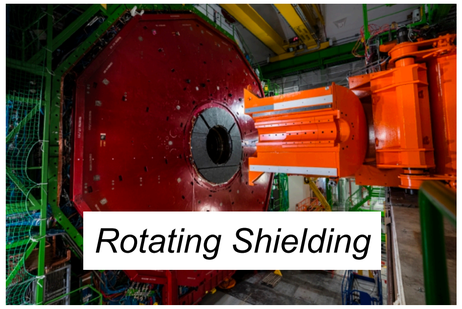
Work on HCAL Barrel (SiPM readout) completed in Oct. 2019

Muon critical path completed in Dec. 2020

Beam-pipe installation and bake-out completed in May 2021

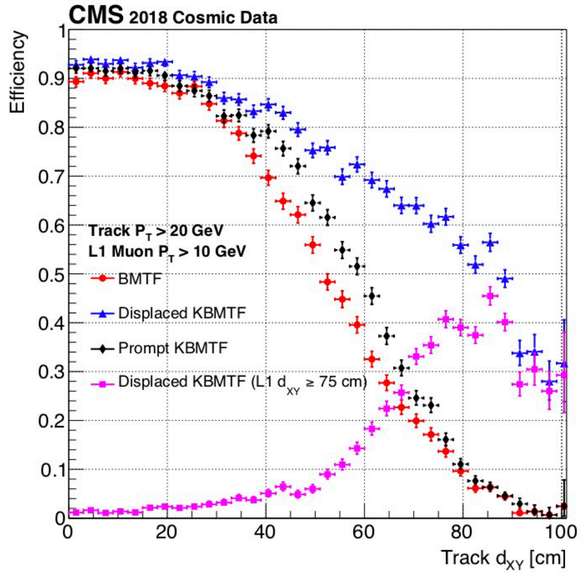
Remaining activities:
- pixel detector installation (starting June 22)
- yoke closing (starting July 19)
- magnet restart (3.8T) and tests
- comics runs at ~4T (CRAFT, 24/7)

After Pilot Beam Test
- Phase-II muon demonstrators
- new forward shielding

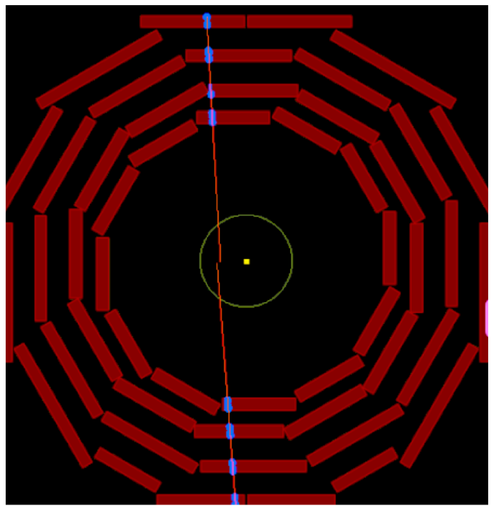


CMS

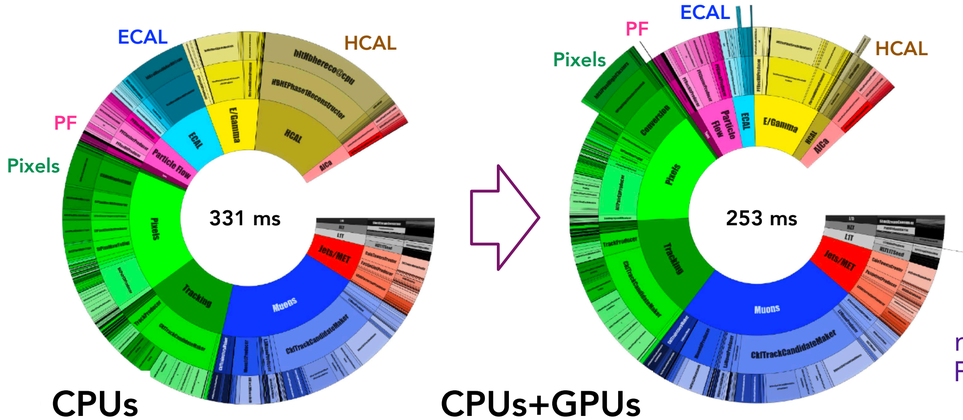
- **L1-Muon trigger**
  - Kalman track finding that provides better efficiency for displaced muons (without vertex constraint)
- **Computing and Offline software**
  - increased use of opportunistic computing (HPC: 10-15%)
  - 10% faster full simulation
  - improved fast simulation
  - development of event lighter data formats
- **GPUs in High-Level Trigger (HLT)**
  - A significant (and growing) fraction of the online reconstruction code is off-loaded from CPUs to GPUs
  - HCAL and ECAL local reconstruction and calibration
  - pixel tracking and electron seeding
  - some particle flow and jet algorithms
- **A significant improvement in speed (>30%) already**



tested in parallel in 2018 and commissioned with cosmic rays

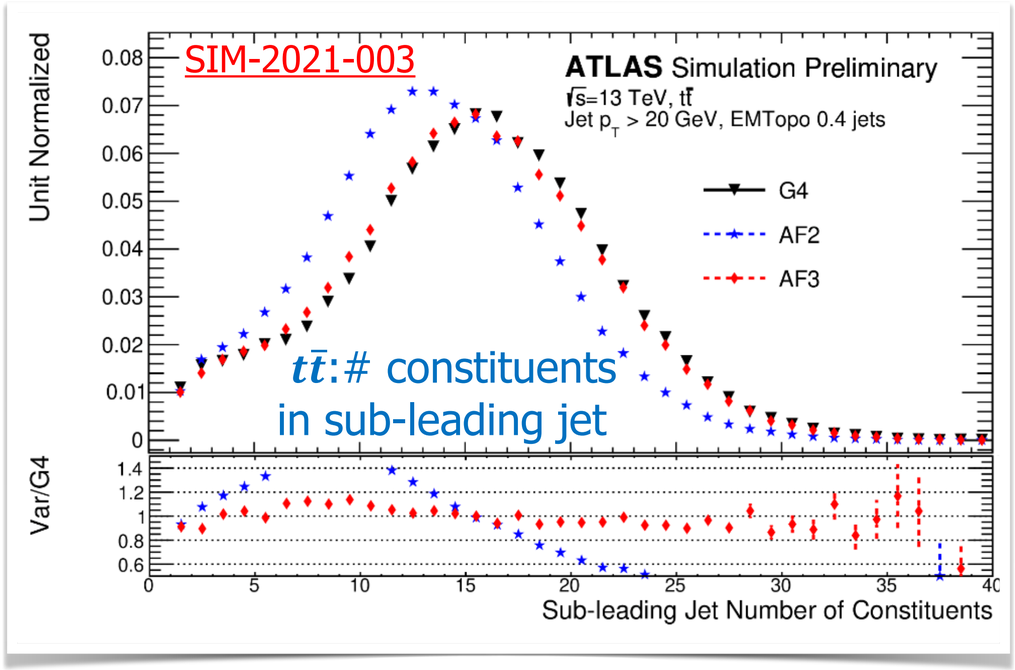


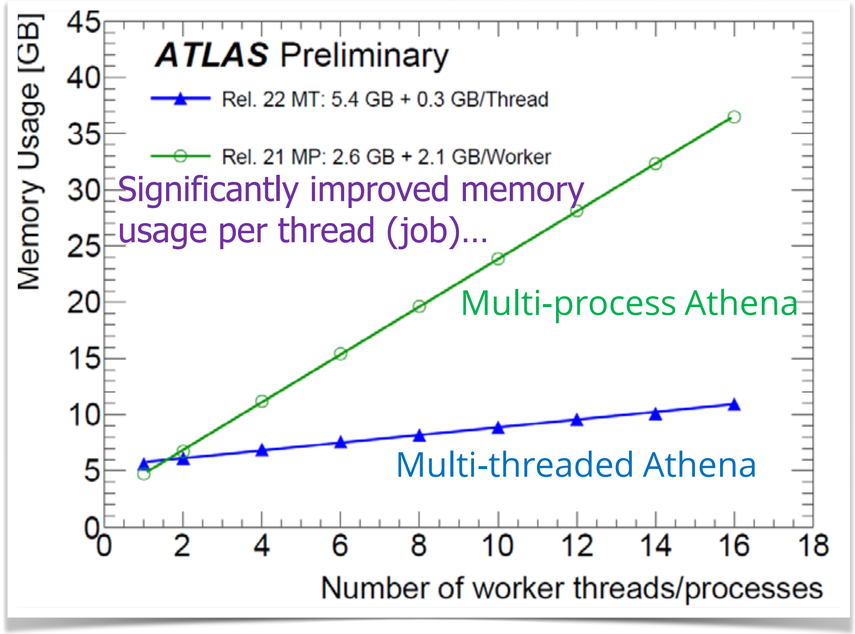
Heterogeneous online reconstruction



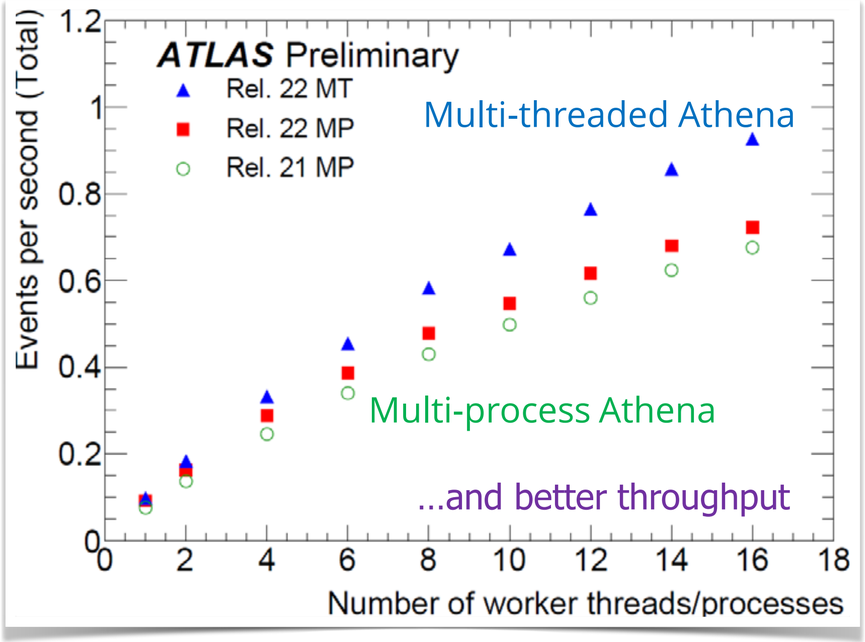
measured on PU 50 events

ATLAS

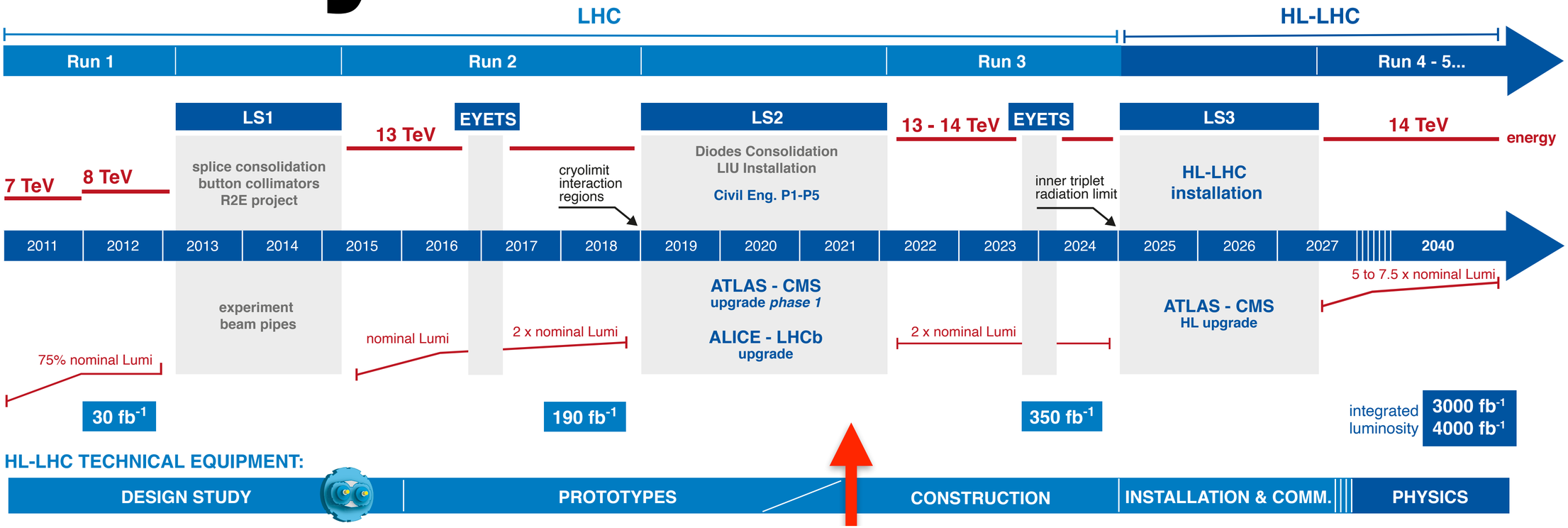




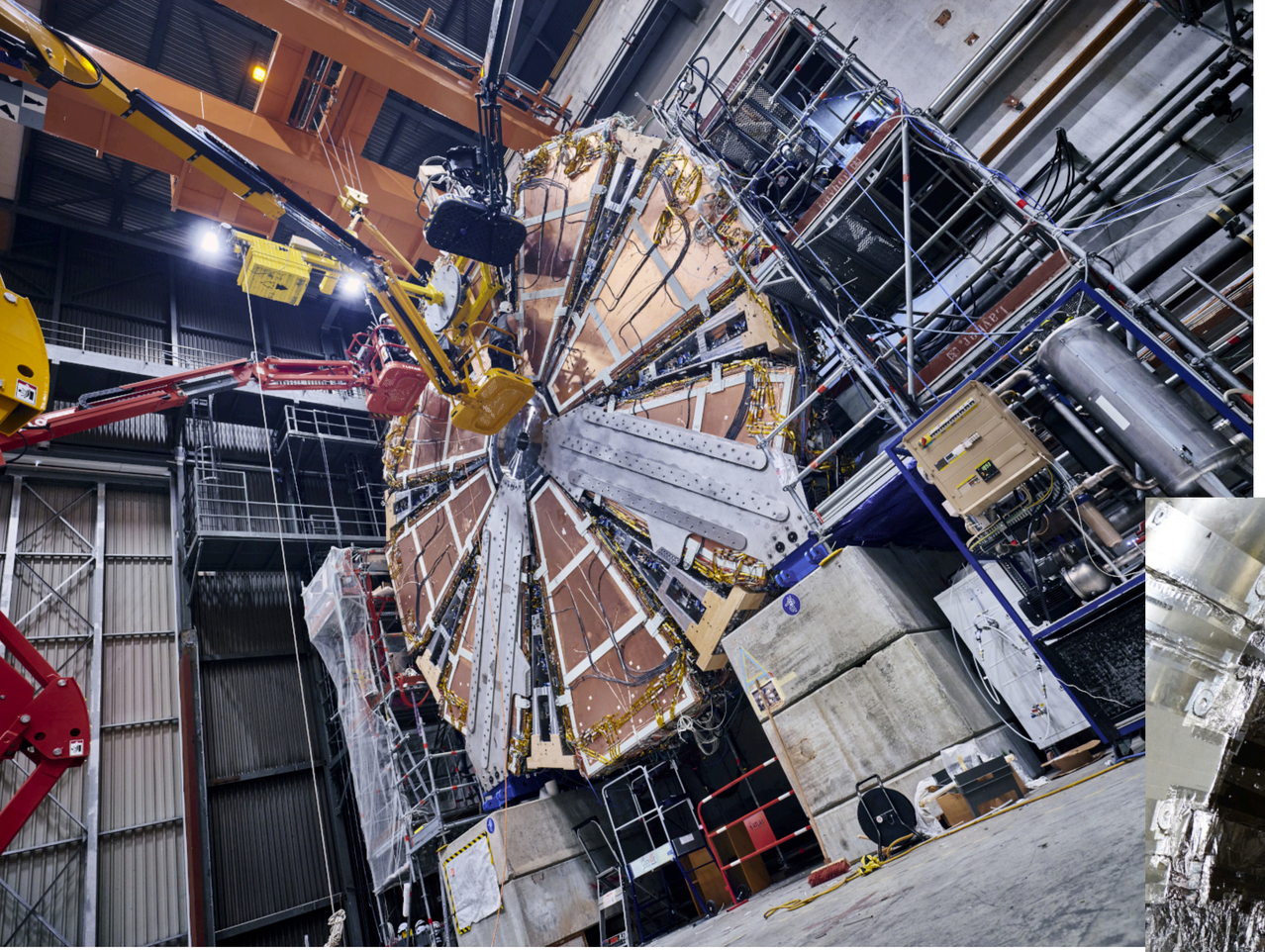
- **Take full advantage of the many detector improvements for Run 3**
  - Finer granularity of Liquid Argon calorimeter for Level-1 trigger
  - New “feature extractors” at Level-1 trigger to enable new event topologies
- **Huge effort preparing ATLAS for Run 3 data-taking and analyses**
  - (early) Run3+Run2 data combinations
  - single lightweight data format
  - Software migration to multi-thread-capable release
  - Finalisation trigger strategies, algorithms
  - New fast calo. simulation with significantly improved performance: AF3



Summary



- The last 18 months have not been an easy one for the entire world
- Despite the difficulties CMS and ATLAS were able to adapt and continue their program.
- LS2 activities are on track for a first pilot beam in October 2021
- CMS and ATLAS will be ready for Run3 in 2022 with new ideas to explore new phase spaces (see next talks!)
- The detector upgrade programs is continuing in full swing!



Thank you for

your attention

Backup