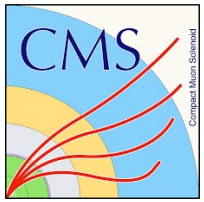


Lomonosov 2021
ATLAS and CMS Highlights

Paul Jackson (University of Adelaide),
on behalf of the ATLAS and CMS collaborations

August 22nd, 2021

LHC physics program

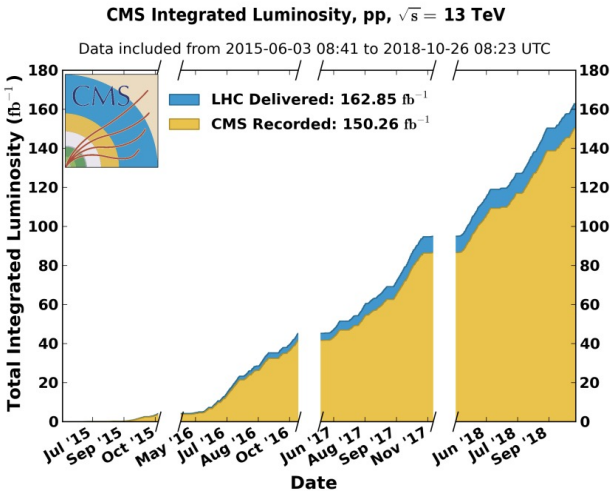
- Physics@LHC is most ambitious and farthest reaching HEP program ever
- **Huge dataset with well understood detector performance** allows
  - Precision measurements
    - Determine fundamental parameters, probe higher-order QCD and EW effects
  - Access to rare processes (e.g. production of WWW or $t\bar{t}t\bar{t}$)
    - Probe poorly or untested corners of SM
  - Broad search program at TeV scale and beyond (high energy frontier) & feeble interactions (low coupling frontier)
    - Directly address compelling issues: naturalness, dark matter, flavor puzzles, etc.
  - Study of new states of matter —> quark-gluon plasma

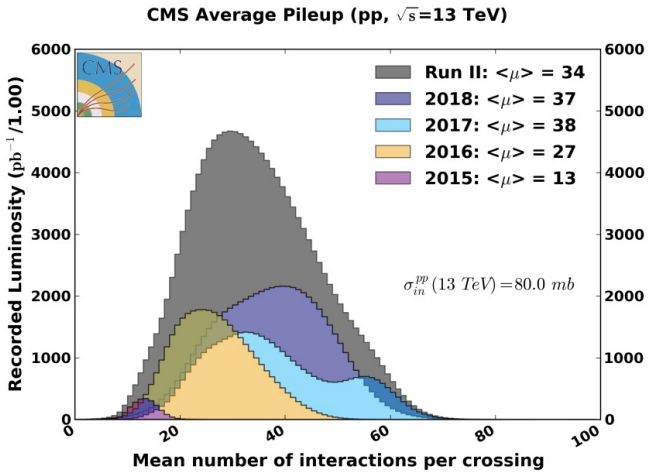
$$\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\bar{\psi}\not{D}\psi + \psi_i\, y_{ij}\,\psi_j\,\phi + \mathrm{hc} + |\,D_\mu\phi\,|^2 - V(\phi)$$

See dedicated ATLAS and CMS talks throughout the conference for more details

LHC data

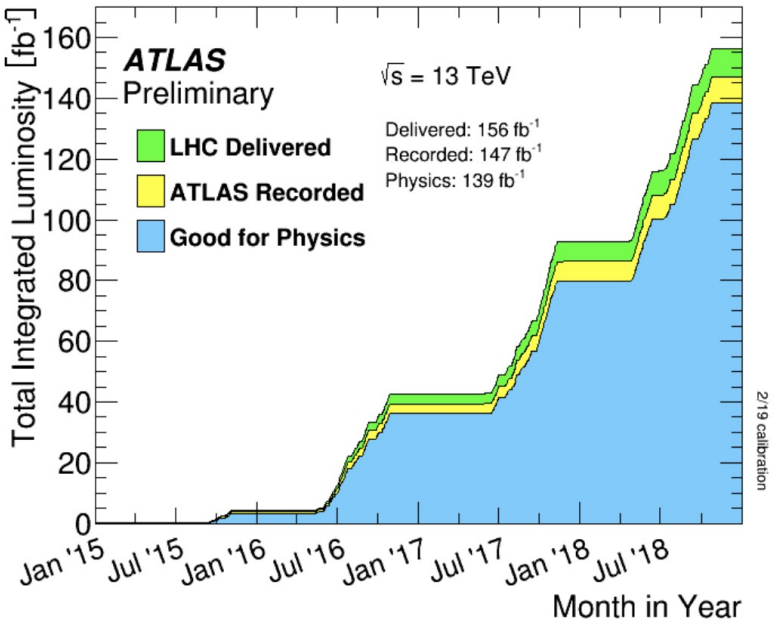
- **Extremely successful Run 2**
  —> dataset is a goldmine for physics





139 fb^{-1} @ √s = 13 TeV

Run 2



Many thanks to the LHC team for the excellent data they provided to us in Run 1 and Run 2 and for their commitment in view of Run 3

Run 2 Breakthroughs

- Higgs
  - Observation of all main production mechanisms
  - Observation of Yukawa interactions w/ 3rd generation fermions
  - Constraints on Higgs self-interaction via HH cross section
  - Evidence for H→ $\mu\mu$ and H→ $ll\gamma$

ggF VH
VBF ttH

$\begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} \nu \\ \tau \end{pmatrix}$

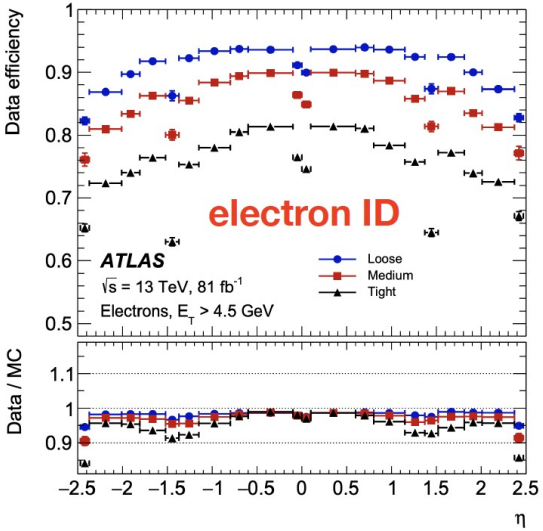
- Rare processes
  - Observation of weak boson scattering modes (incl. $W^{\pm}W^{\pm}$)
  - Observation of ttW, ttZ and tZq
  - Evidence for tttt production
- Searches
  - Excluded a wide range of BSM parameter space with a broad search program
    - SUSY and resonances: gluino, squark, stop and Z' exclusions* up to m= 2.3, 2.0, 1.3 and 5.0 TeV respectively
    - Dark matter constraints, incl. H → invisible <~10%
    - Experimentally challenging signatures such as compressed spectra, displaced vertices, long-lived particles and unconventional signatures

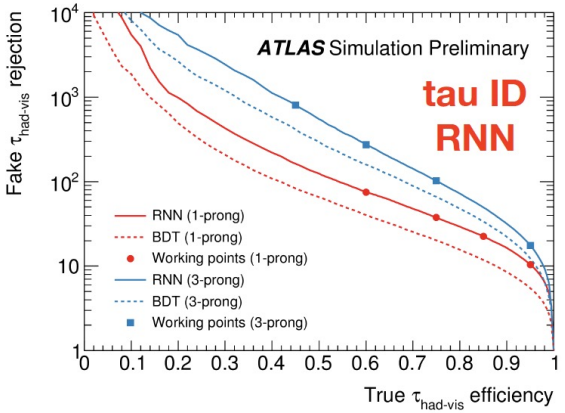
* all limits given in this talk are at 95% confidence level

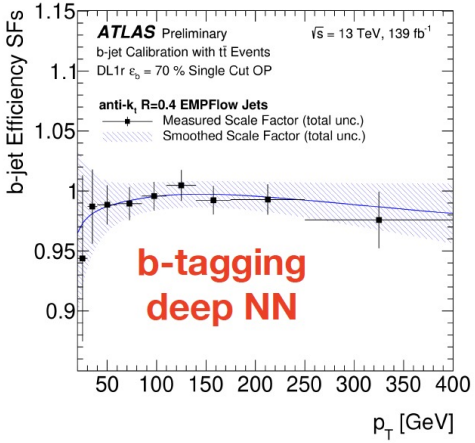
Detector performance

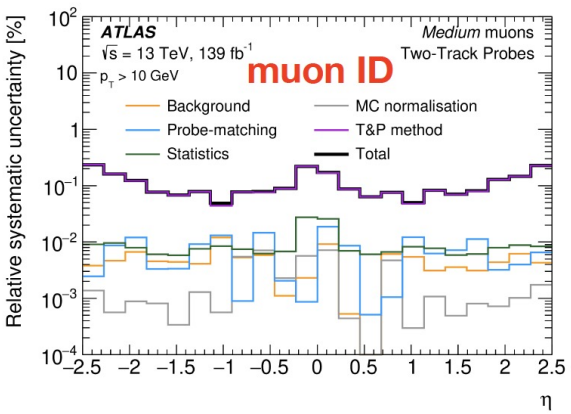
Results from Run 2 only possible thanks to excellent understanding of detector performance, and development of reconstruction and identification algorithms

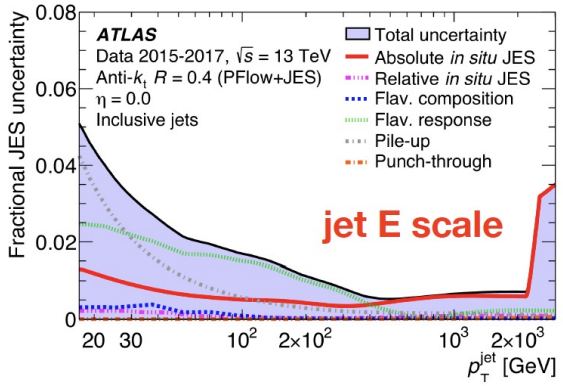
- High level of precision achieved & excellent modeling with simulation









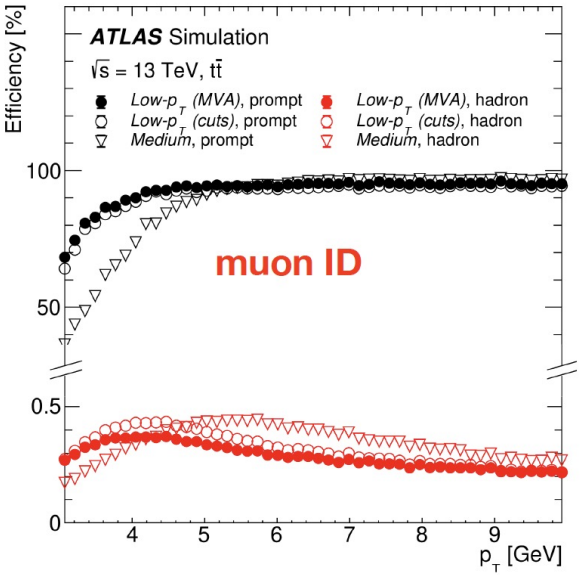


Very highly efficient object reconstruction.
Percent-level (or better) understanding of this performance in data.

Detector performance

- Charm-hadron tagging
- Deep NN for $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction
- Single-particle calorimeter response in $W^{\pm} \to \tau^{\pm}\nu \to \pi^{\pm}\nu$
- Lepton identification at very low p_T (down to 3.0 GeV for μ)

arXiv:2012.00578



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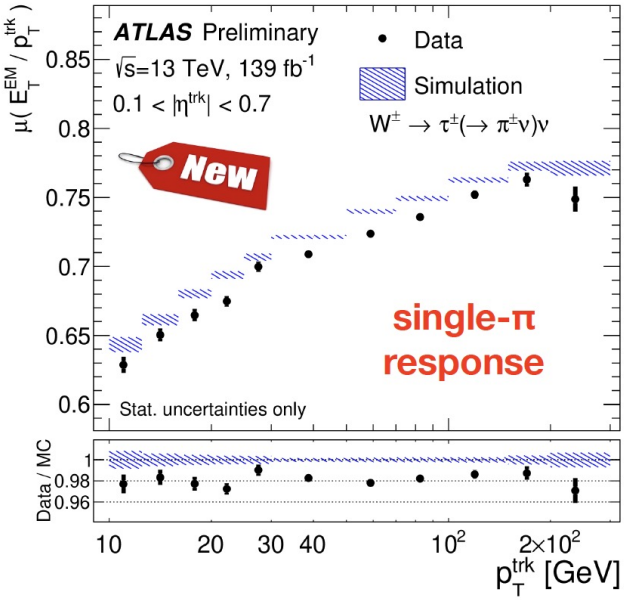
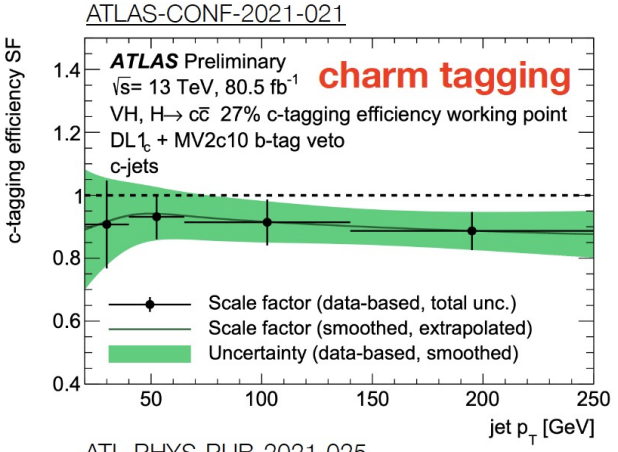
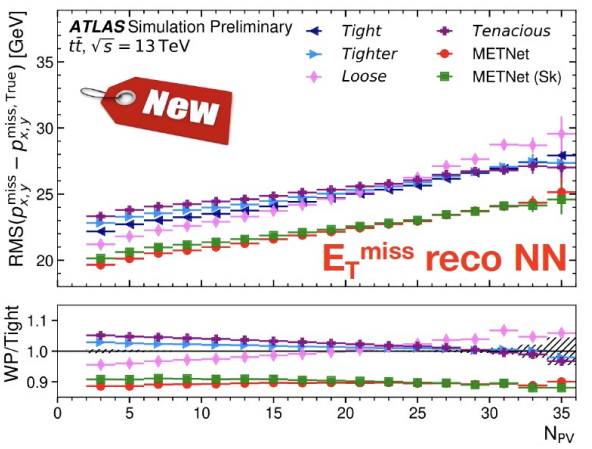


ATLAS-CONF-2021-021



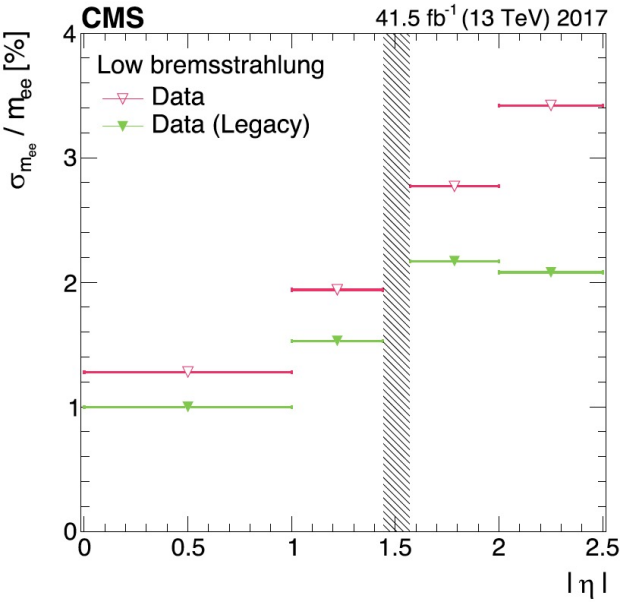
ATL-PHYS-PUB-2021-025



E/γ reconstruction and muon trigger

JINST 16 (2021) P05014

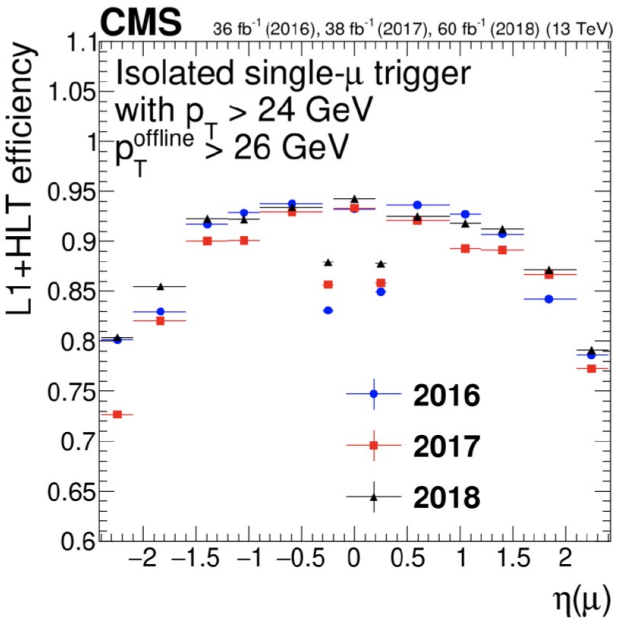
Comparison of Z mass resolution
Before and after final calibration
Included in Legacy Run 2 rereco

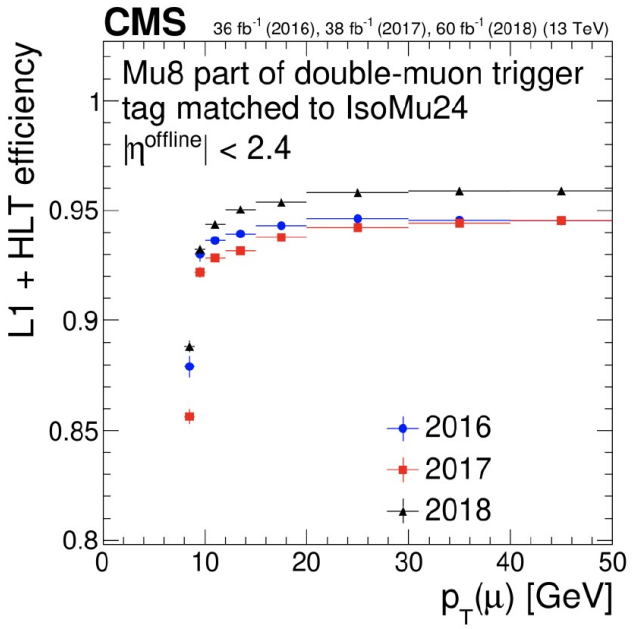


16 (2021) P07001

Performance of the CMS muon trigger system
in proton-proton collisions √s = 13 TeV

Extensive measurements of Run 2 L1 and HLT trigger performance



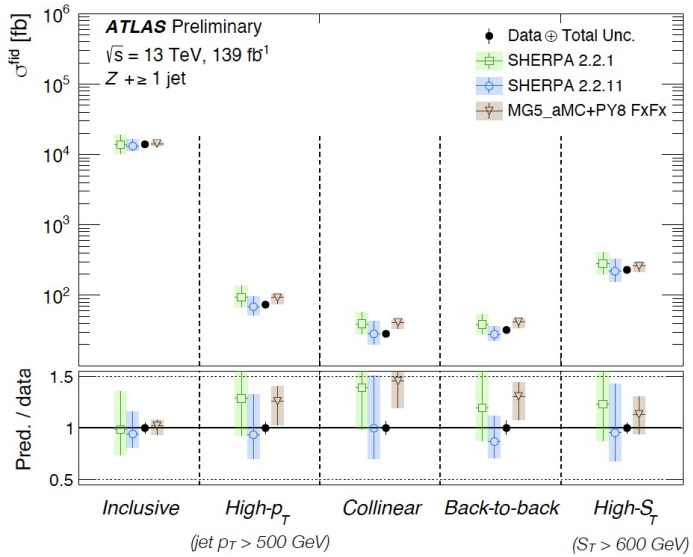


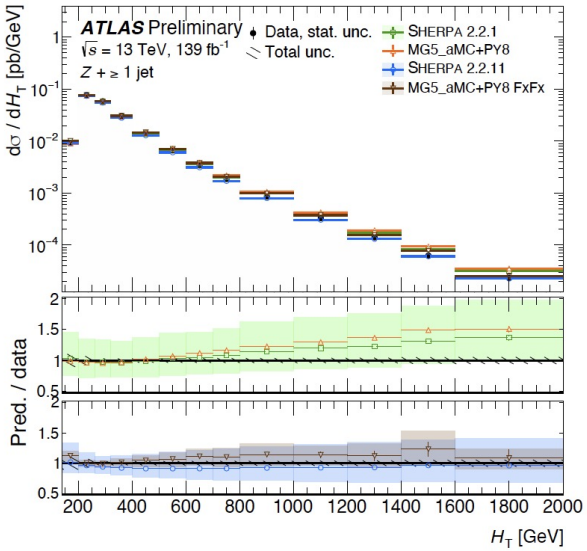
Very highly efficient object reconstruction.
Percent-level (or better) understanding of this performance in data.

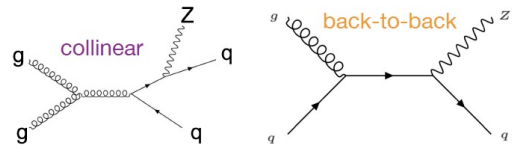
Z-boson + jets production

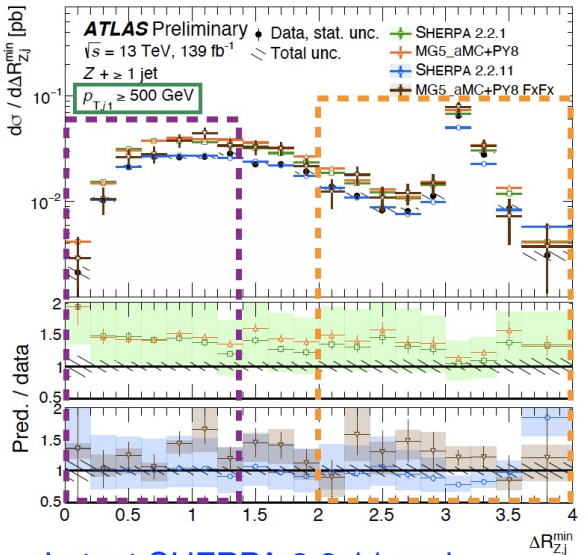
- Run 2: ~8 x 10^9 Z bosons produced
- Test SM in events w/ $Z(\rightarrow ee, \mu\mu)$ and ≥ 1 jet with $p_T > 100$ GeV
  - SM predictions w/ event generators up to NLO QCD + NLO EW
  - Measure cross section in more extreme phase space: collinear vs. back-to-back jet emission, high jet p_T or high sum p_T

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





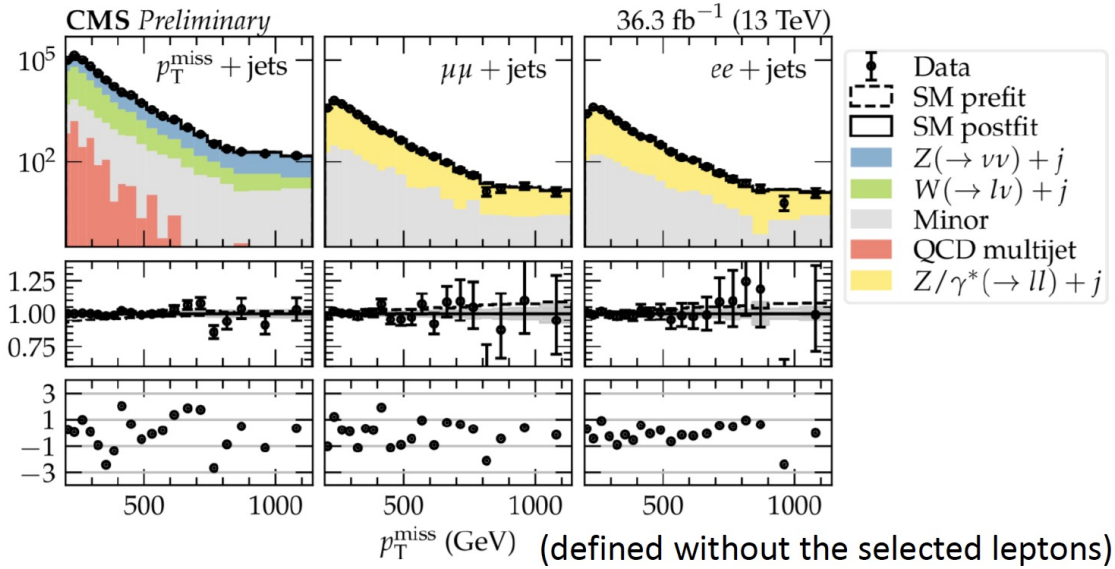




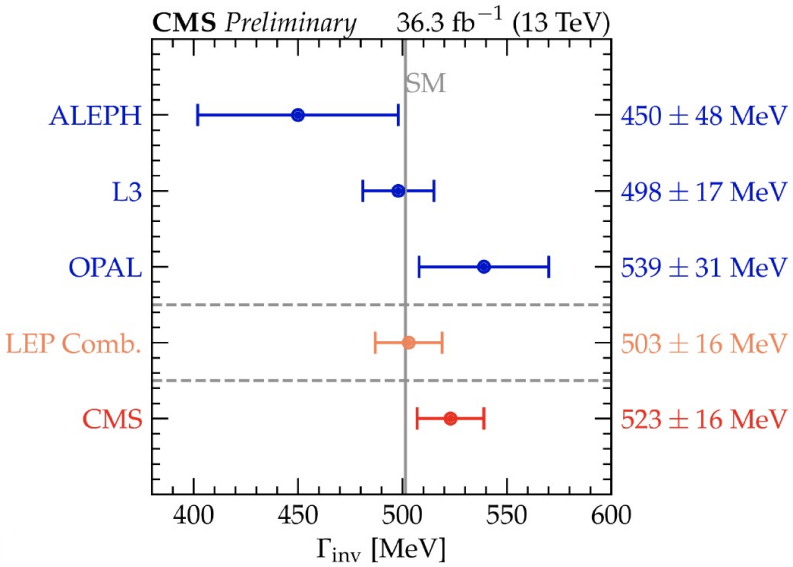
- Latest SHERPA 2.2.11 and MG5_aMC + Py8 (FxFx) provide improved modeling esp. in collinear region and at high p_T

Z invisible width

Ratio of $\Gamma_{\nu\nu}/\Gamma_{ll}$ from a simultaneous fit of $Z \to \nu\nu, Z \to \mu\mu, Z \to ee$ enriched categories



(defined without the selected leptons)

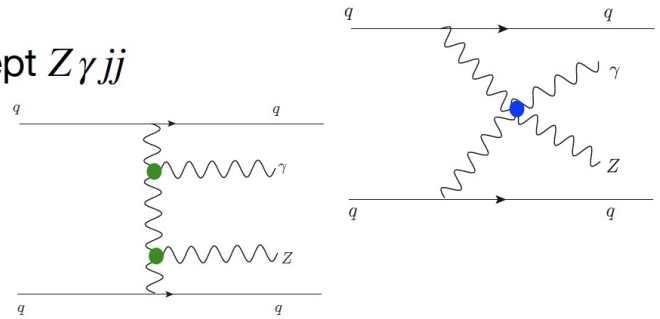


- $\Gamma_{inv} = 523 \pm 3$ (stat) ± 16 (syst) MeV
- Single most precise direct measurement of the Z invisible width Γ_{inv}, competitive with the combined direct LEP result

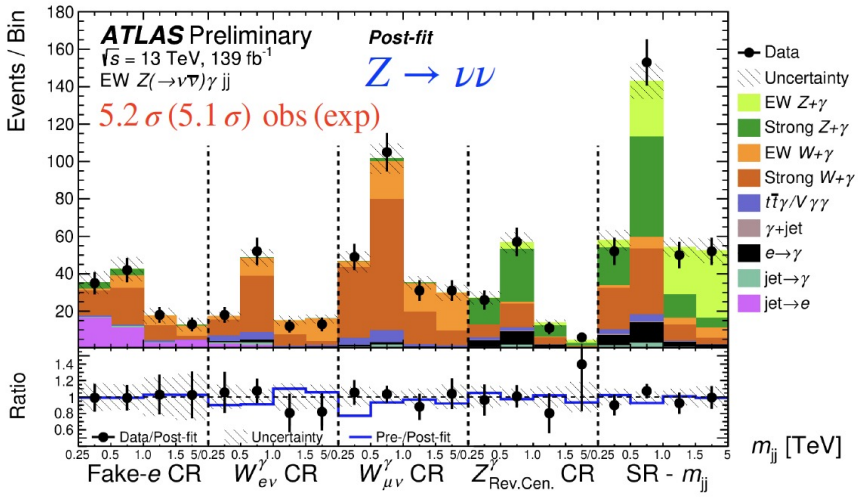
Vector-boson Scattering

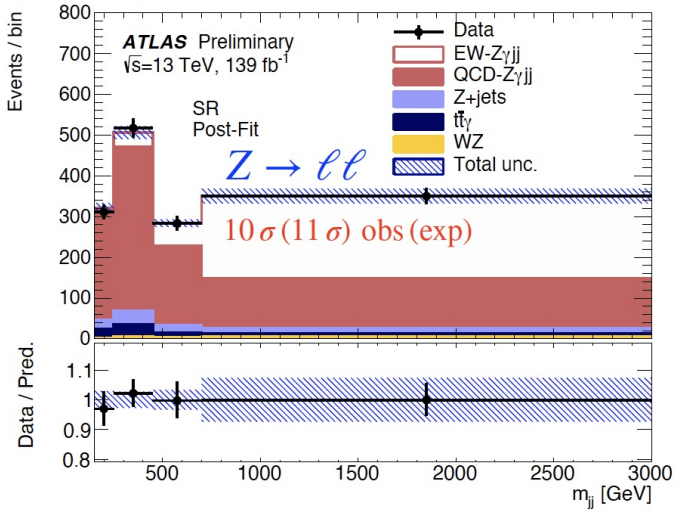
- Key test of EW symmetry
  —> **vector boson self-interactions**
  —> cubic and quartic couplings; previously observed - $VVjj$, except $Z\gamma jj$
- Events characterized by jets with large mass and rapidity gap
- Signal strength for $Z\gamma jj$ EW production (rel. to LO prediction)
  - $Z \to \nu\nu$: $\mu_{\mathrm{EW}} = 1.03 \pm 0.16\,(\mathrm{stat}) \pm 0.19\,(\mathrm{syst})$
  - $Z \to \ell\ell$: $\mu_{\mathrm{EW}} = 0.95 \pm 0.08\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})$

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



most precise with 13% cross-section uncert.





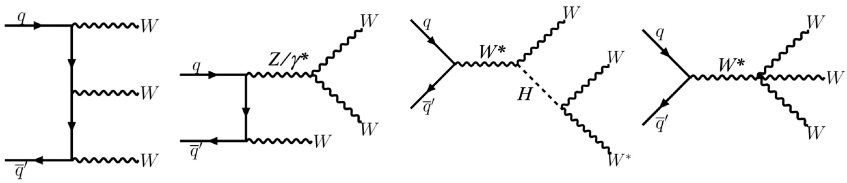
[CERN-EP-2021-137]

[ATLAS_CONF_2021-038]

WWW Production

- Rare process providing access to **W/Z self-interactions**
  —> cubic and quartic couplings

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

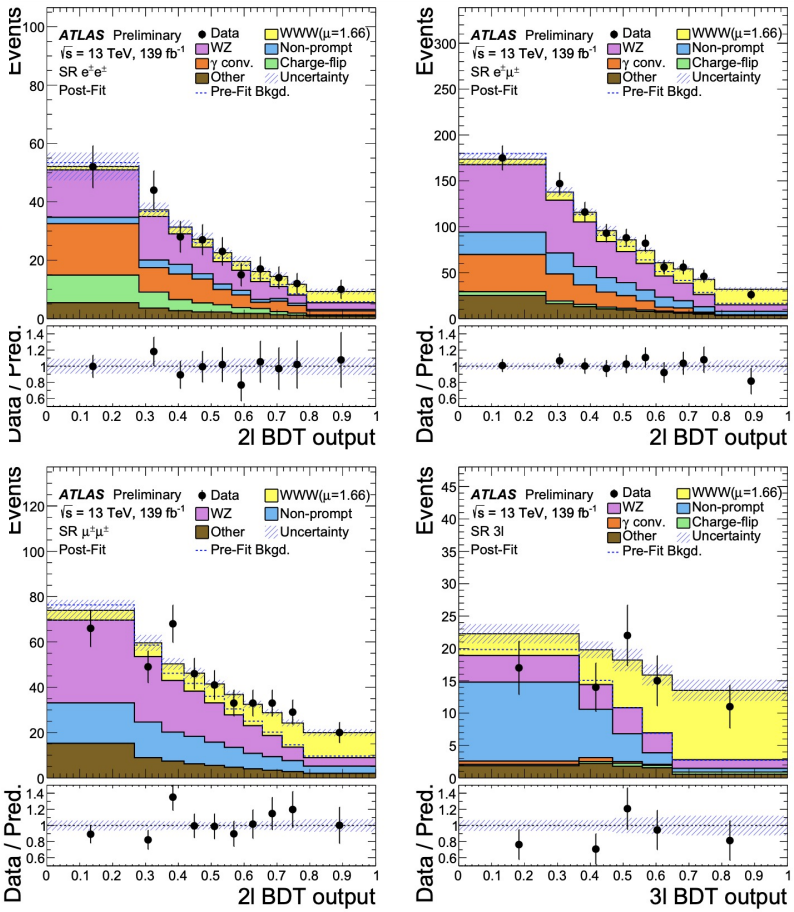


- Channels: $W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\nu\,\ell^{\pm}\nu\,qq'$ with $\ell = e, \mu$
  $\to \ell^{\pm}\nu\,\ell^{\pm}\nu\,\ell^{\mp}\nu$
- Main bkg: $WZ \to \ell\nu\,\ell\ell$ estimated w/ control regions
- Signal extracted w/ BDTs for 2ℓ and 3ℓ channels
- **First *WWW* observation** with
  significance of $8.2\,\sigma\,(5.4\,\sigma)$ obs (exp)

$$\sigma(pp \to W^{\pm}W^{\pm}W^{\mp}) = 850 \pm 100\,(\mathrm{stat}) \pm 80\,(\mathrm{syst})\,\mathrm{fb}$$

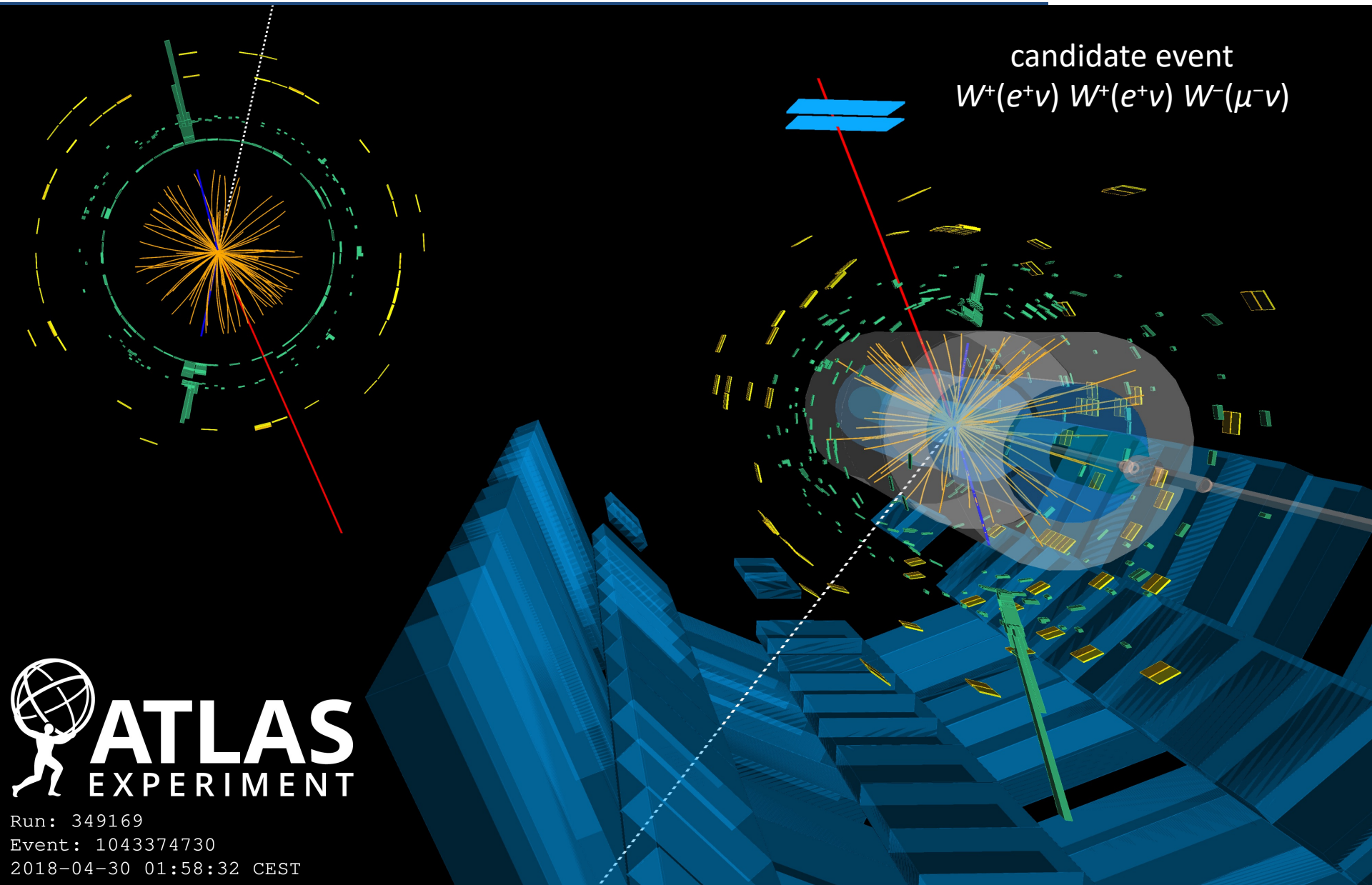
signal strength : 1.66 ± 0.28

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



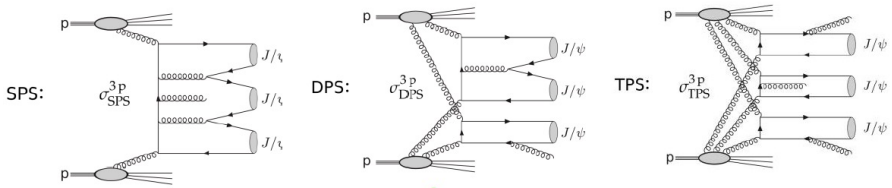
[ATLAS_CONF_2021-039]

WWW Production



Triple J/ψ production

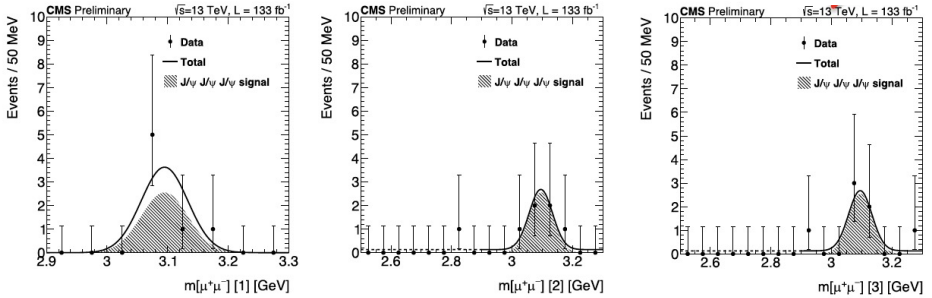
- Contributions to the production from single (SPS), double- (DPS), and triple- (TPS) parton scattering:



3 prompt J/ψ

CMS-PAS-BPH-21-004

Three J/ψ candidates in each event ordered by p_T



- Fiducial cross section:

$\sigma(pp \to J/\psi\, J/\psi\, J/\psi\, X) = 272^{+141}_{-104}(stat) \pm 27\ (syst)$ fb

First observation of triple J/ψ production with >5 σ significance

- Production is expected to be dominated by DPS and TPS contributions, the DPS associated effective cross section parameter is:

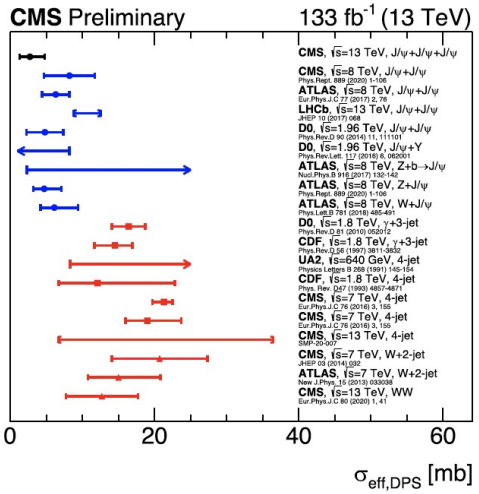
$\sigma_{Eff,DPS} = 2.7^{+1.4}_{-1.0}(exp)^{+1.5}_{-1.0}(theo)$ mb

where $\sigma_{Eff,DPS}$ is an effective interaction area:

$$\sigma_{DPS}^{pp\to\psi_1\,\psi_2+X} = \left(\frac{m}{2}\right) \frac{\sigma_{SPS}^{pp\to\psi_1+X}\ \sigma_{SPS}^{pp\to\psi_2+X}}{\sigma_{eff,DPS}}$$

- **Candidate channel for first observation of TPS**

Measured $\sigma_{Eff,DPS}$ compared to the same measurement in other processes

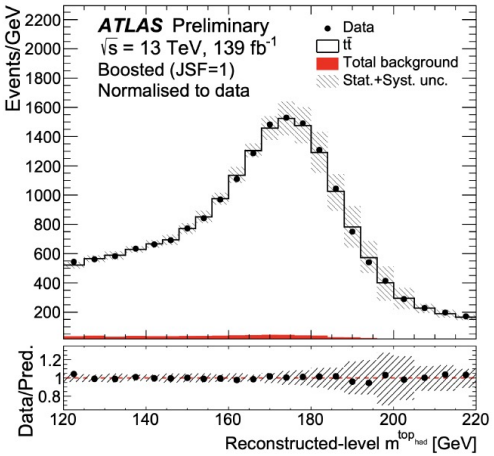


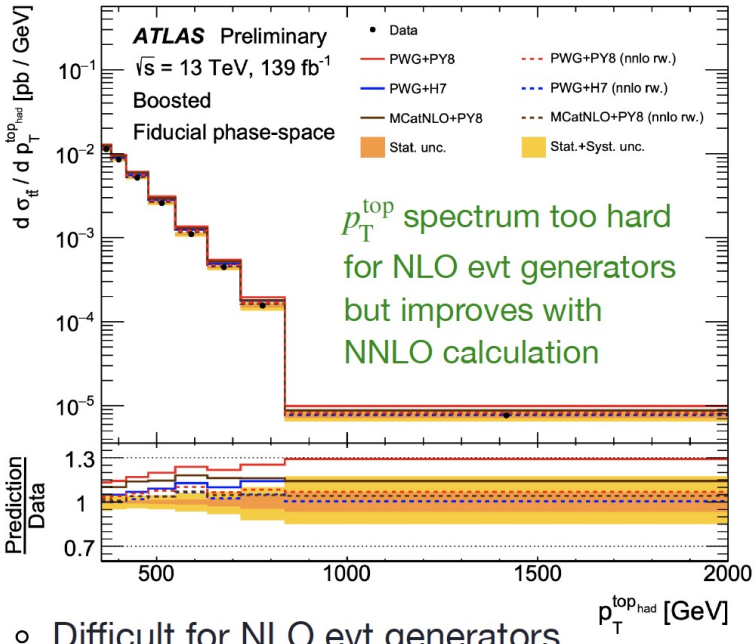
Top

top-quark production

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

- Run 2: ~1.2 x 10^8 $t\bar{t}$ produced
- Test SM at high $p_{\mathrm{T}}^{\mathrm{top}}$, where deviations expected from BSM, measure both $t\bar{t}$ system and radiation
  - SM predictions at NNLO QCD + NLO EW
- l+jets channel: $t\bar{t} \rightarrow Wb\,Wb \rightarrow \ell\nu b\, qq'b$
  - Reconstruct hadronic top as reclustered R=1.0 anti-kt jet w/ p_{T} > 355 GeV, |η|<2.0, and mass ∈ 120-220 GeV
  - Reduce jet energy scale uncertainties by using mass of reconstructed hadronic top
    —> jet energy scale factor
    —> ~30% reduction in $\sigma_{\mathrm{syst}}^{\mathrm{tot}}$
  - Differential cross sections provided for 16 variables
    (8 for the first time for boosted top quarks)





- Difficult for NLO evt generators to model additional radiation
- Constraints placed on EFT operators $\mathcal{O}_{tG}$ and $\mathcal{O}_{tq}^{(8)}$

CP violation in semileptonic ttbar

- Measure asymmetry of 4 T-odd observables which if CPT is conserved are also odd under CP transformation

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p'}_b \cdot (\vec{p'}_\ell \times \vec{p'}_{j_1})$$

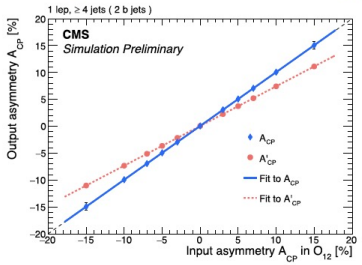
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$

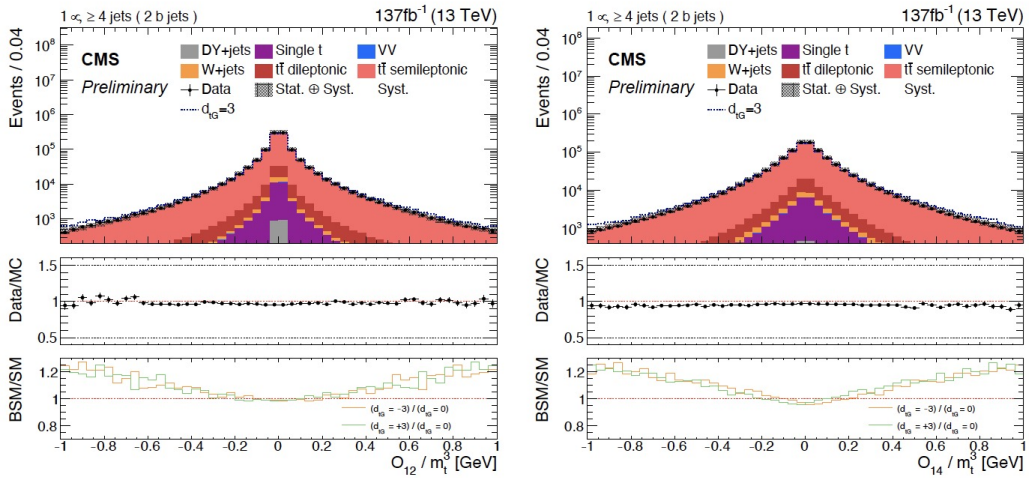
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}, i = 3, 6, 12, 14$$

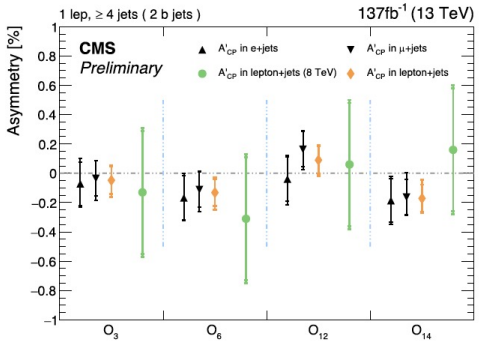
Measured asymmetries A'_{CP} are affected by dilution effects
Due for example to the mis-assignment of the quark/antiquark



CMS-PAS-TOP-20-005



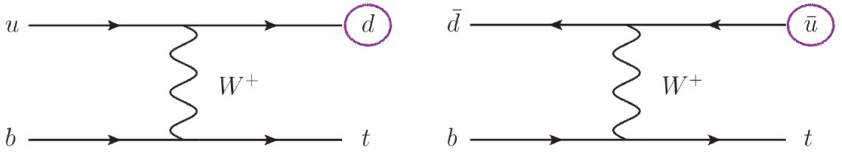
Raw asymmetries



All measures asymmetries consistent with 0 indicating no CPV

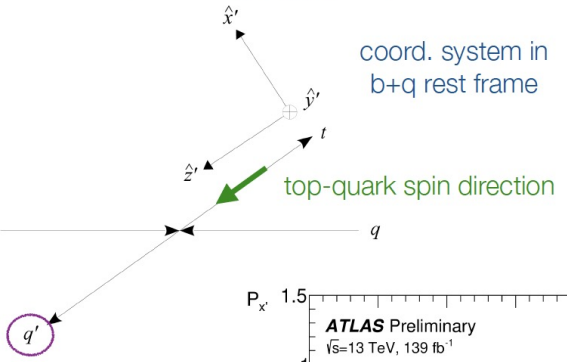
Single top-quark polarization

- t-channel dominates single top-quark production

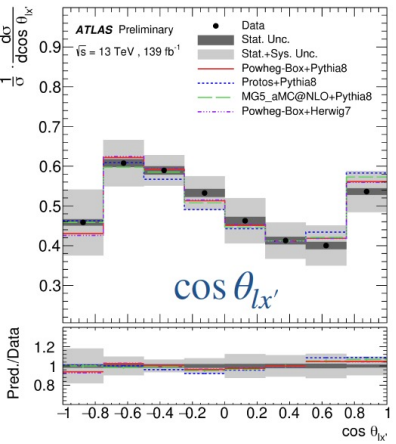


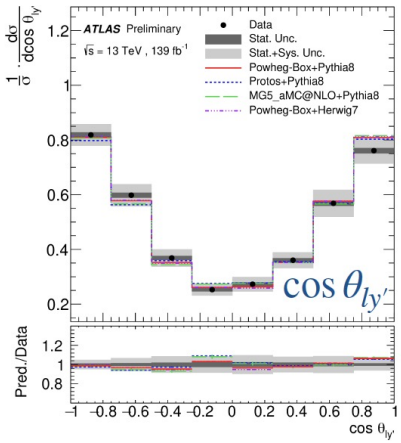
spectator quark q'

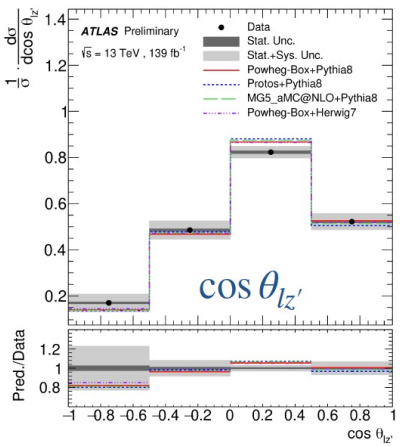
$$\mathscr{L}_{\mathrm{SM}} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\bar{\psi}\not{D}\psi + \psi_i\, y_{ij}\, \psi_j\, \phi + \mathrm{hc} + |D_\mu \phi|^2 - V(\phi)$$

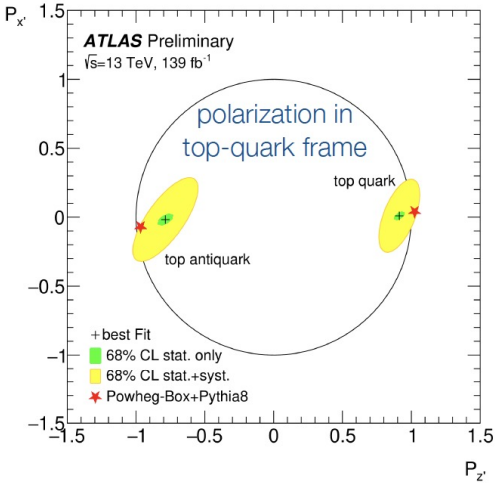


- High polarization expected from V-A structure of CC weak interaction + test BSM impact on tWb vertex
- First measurement of polarization vector in 3-D via angular distributions of lepton (e or μ) from $t \to b\ell\nu$ decay









- Constraints placed on Re and Im parts of EFT operator $\mathcal{O}_{tW}$

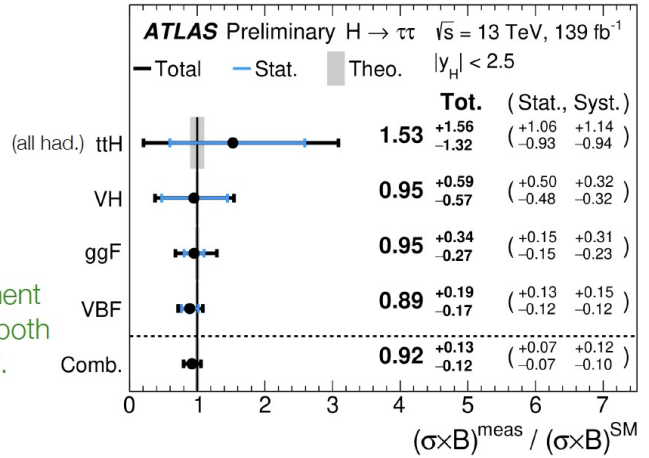
Higgs

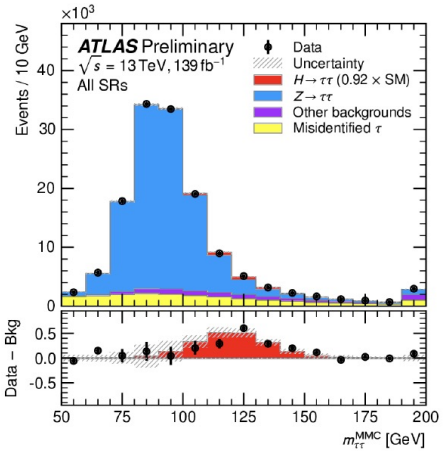
Higgs Couplings to τ leptons

- Run 2: ~8 x 10^6 Higgs bosons produced
- $\mathcal{B}(H \to \tau\tau) = 6.3\,\%$ —> test **Yukawa interactions with leptons**
- Expt. challenge: 2-4 neutrinos in final state, poor mass resolution
- Multiple BDTs used to suppress $Z \to \tau\tau$ and $t\bar{t}$ background, and categorize event purity for each production mechanism
- Dominant $Z \to \tau\tau$ background from MC, controlled with $Z \to \ell\ell$ data via kinematic embedding procedure

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

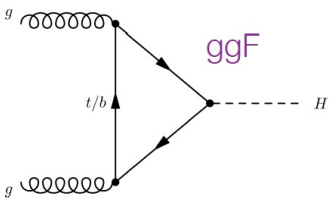
factor of 2.5 improvement over 36 fb^{-1} analysis in both stat and syst uncert.

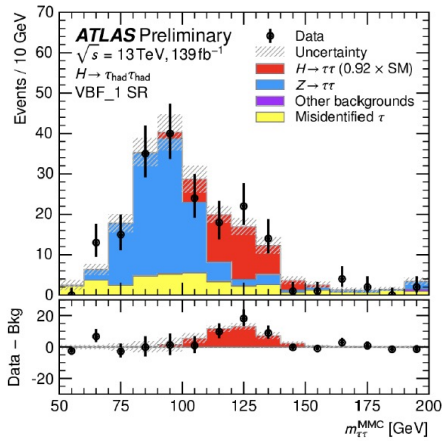




- ggF significance

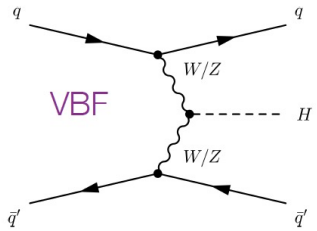
$3.9\,\sigma\,(4.6\,\sigma)$ obs (exp)





- VBF significance

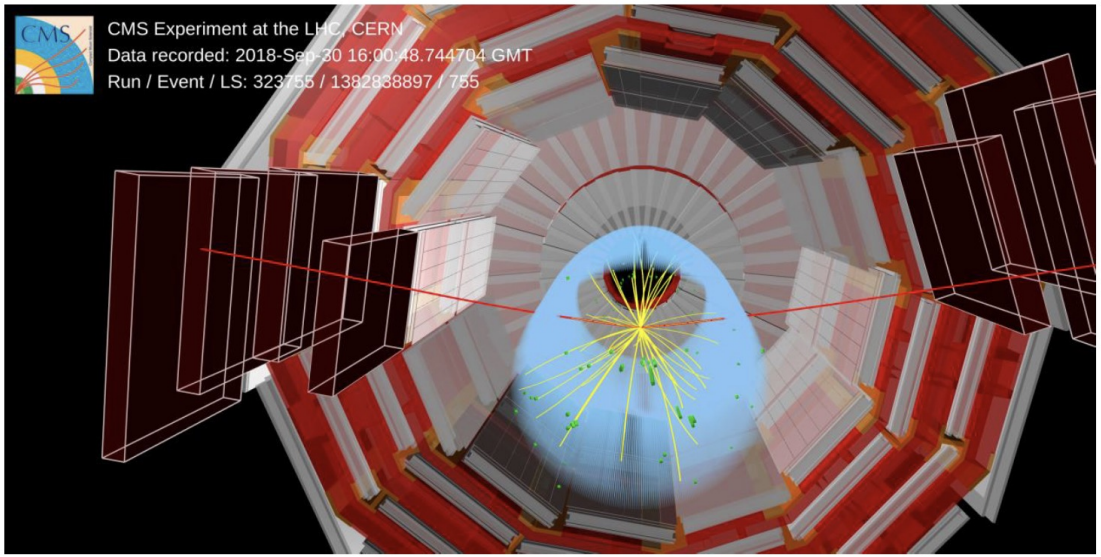
$5.3\,\sigma\,(6.2\,\sigma)$ obs (exp)

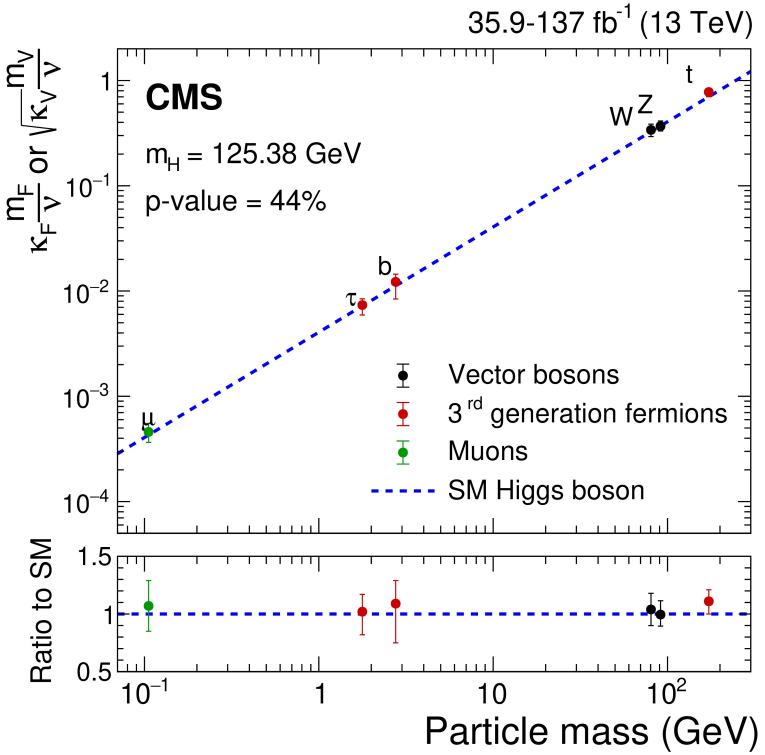


ATLAS_CONF_2021-044

Evidence for $H \rightarrow \mu^+\mu^-$

H → $\mu\mu$ candidate in gluon fusion channel
Mass = 125.46 ± 1.13 GeV





- Signal strength, relative to the SM prediction $\mu = 1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$
- **Obs. (exp.) significance 3.0σ (2.5σ)**

CMS-HIG-19-006
ATLAS-HIGG-2019-14

Higgs to 2nd generation quarks

- Test of **Yukawa interactions w/ 2nd generation fermions**: evidence for leptons only
- **Search for H—> cc** in associated $V(\ell\ell, \ell\nu, \nu\nu)\,H$ production
- Dedicated charm tagging
- Results:

$VW(\rightarrow cq)$ with $3.8\,\sigma\,(4.6\,\sigma)$ obs (exp)

$VZ(\rightarrow cc)$ with $2.6\,\sigma\,(2.2\,\sigma)$ obs (exp)

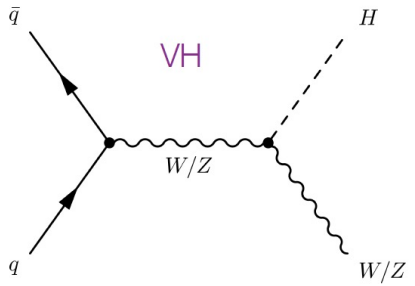
$VH(\rightarrow cc) < 26\,(31)\,\sigma_{\mathrm{SM}}$ obs (exp)

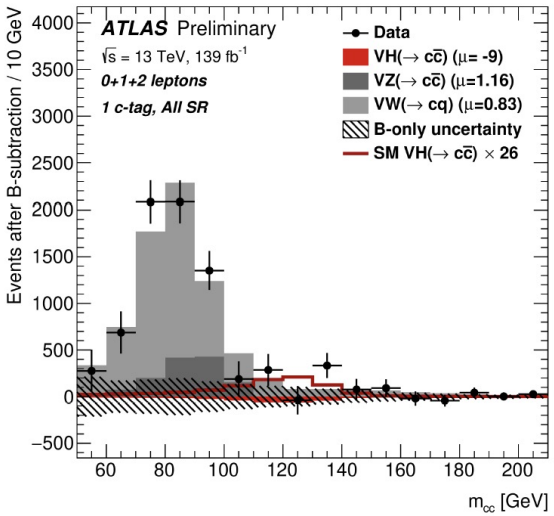
- Charm Yukawa modifier

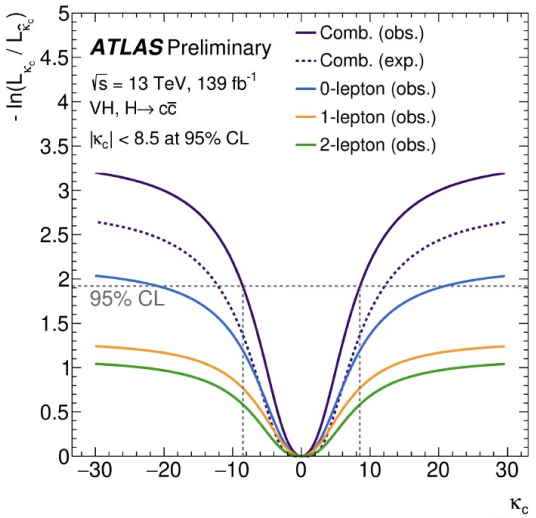
$|\kappa_c| < 8.5\,(12.4)$ obs (exp)

first direct constraint

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

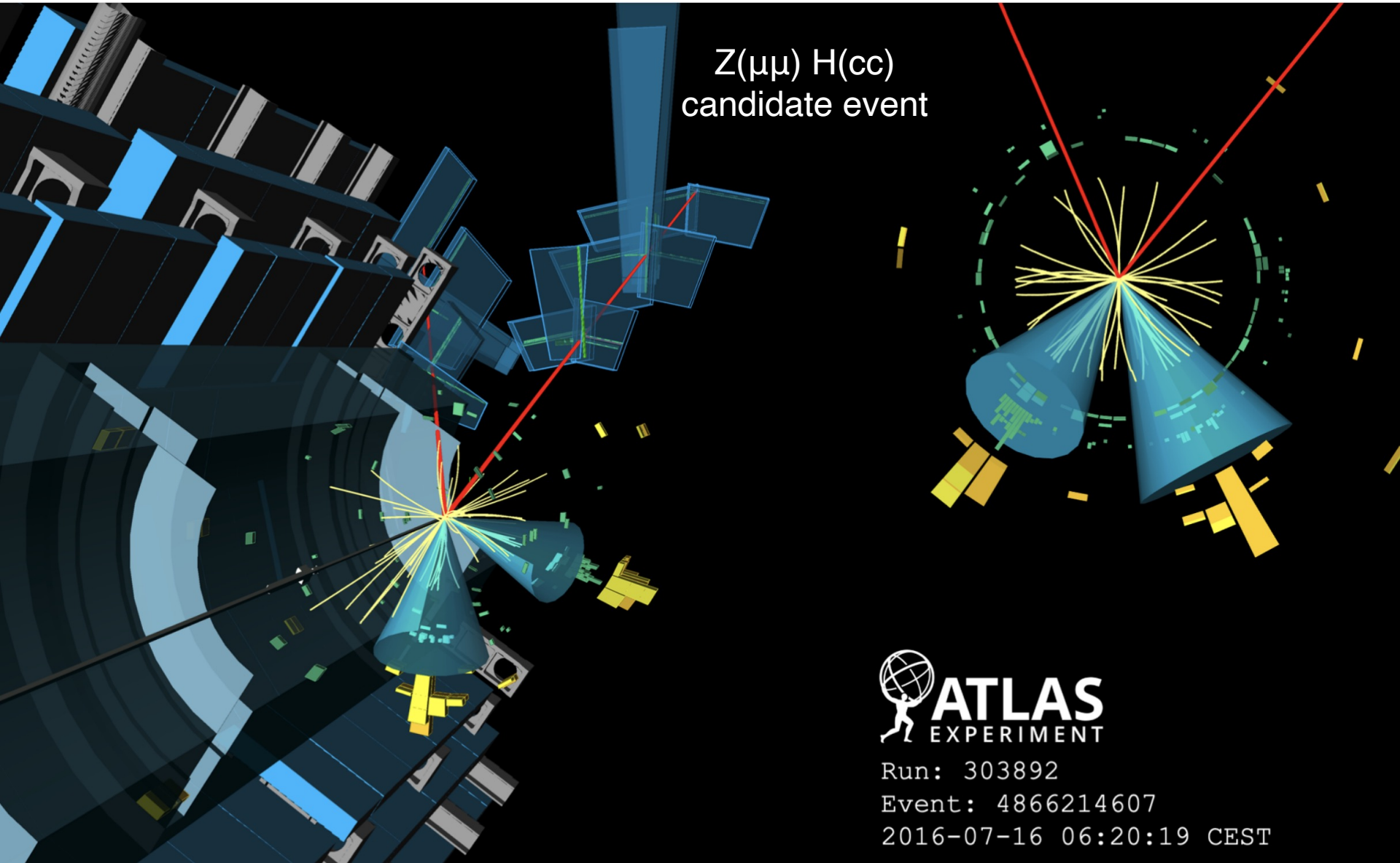






ATLAS-CONF-2021-021
CMS-HIG-18-031

Higgs to 2nd generation



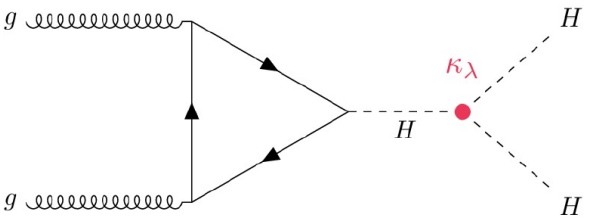
Di-Higgs production

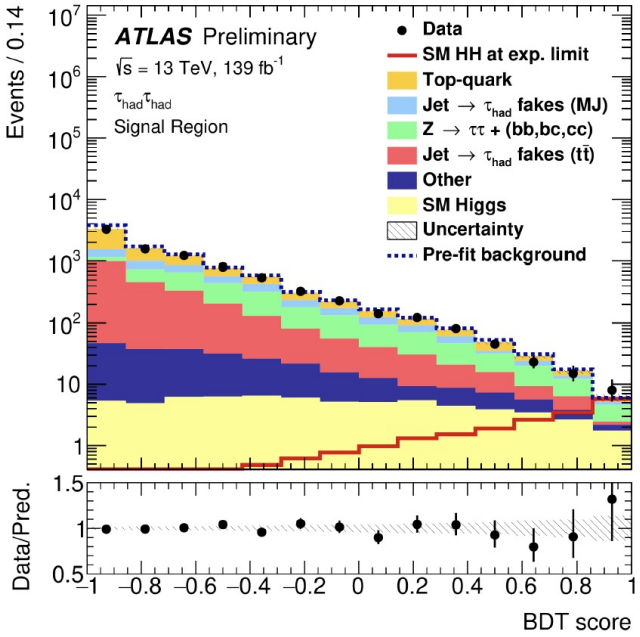
- **Direct access to Higgs potential**
  - Last part of SM needing direct test
  - Small HH XS (ggF 31 fb @NNLO)
- HH —> bbbb (33%), bbττ (7.3%), bbγγ (0.3%)
- **HH —> bbττ channel**
  - Trigger: single lepton, lepton+τ_{had}, single τ_{had}, di-τ_{had}
  - MVAs (BDT and NN) used for signal vs. bkg
  - Z($\ell\ell$)+heavy flavor CR
  - multiple fake-tau CRs
  - most sensitive channel to non-resonant HH

$$\sigma_{HH}/\sigma_{HH}^{SM} < 4.7\ (3.9)\ \text{obs (exp)}$$

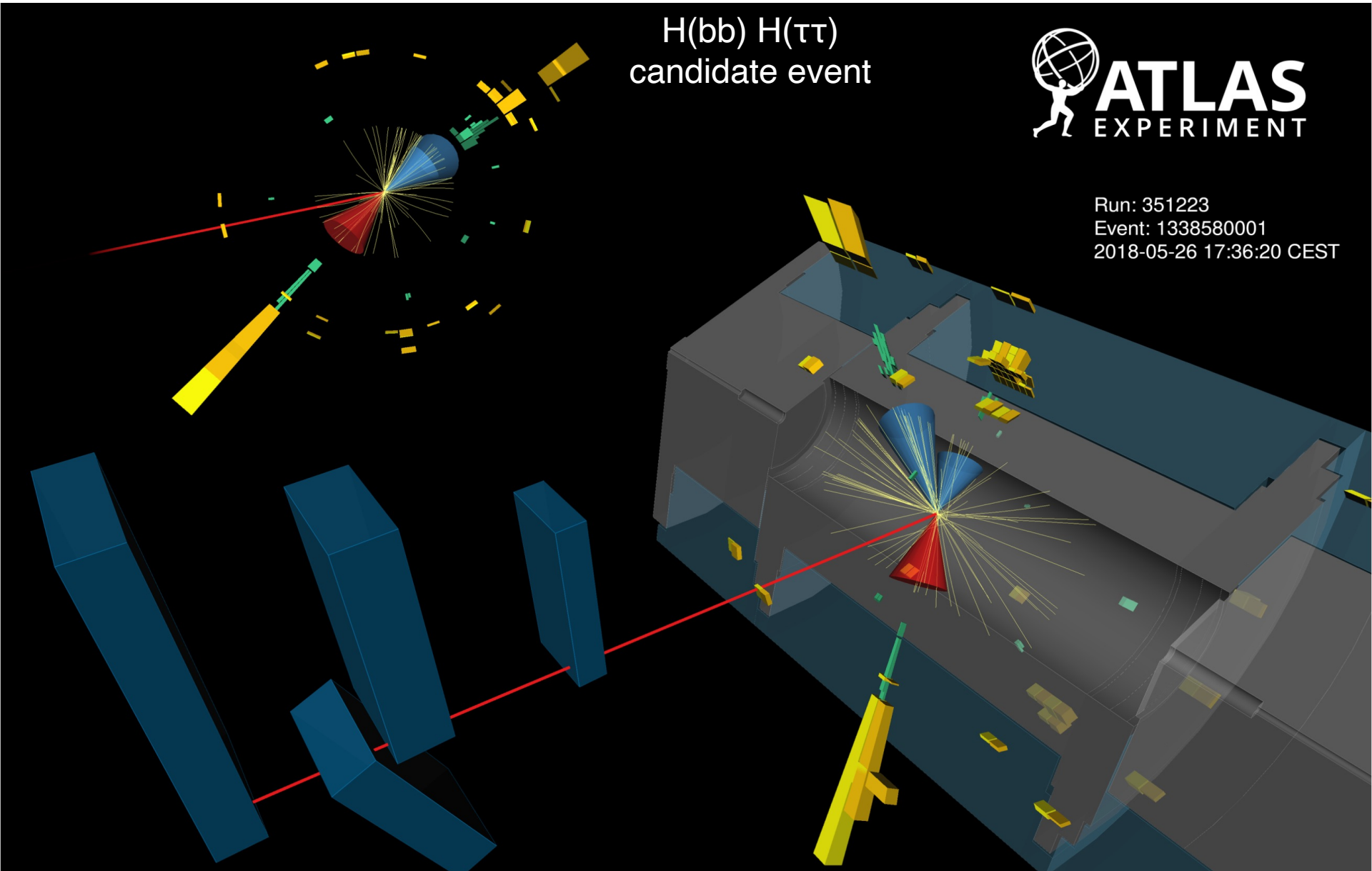
factor of 4 improvement over 36 fb^{-1} analysis

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





Di-Higgs production

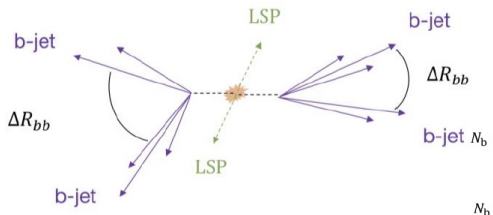


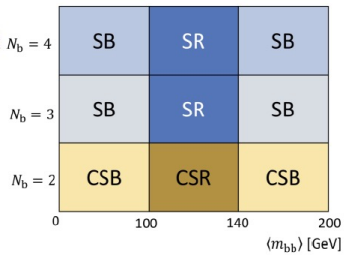
SEARCHES

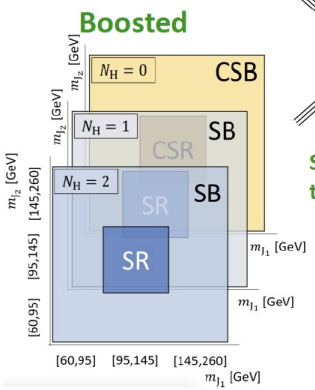
SUSY $HH \rightarrow 4b$

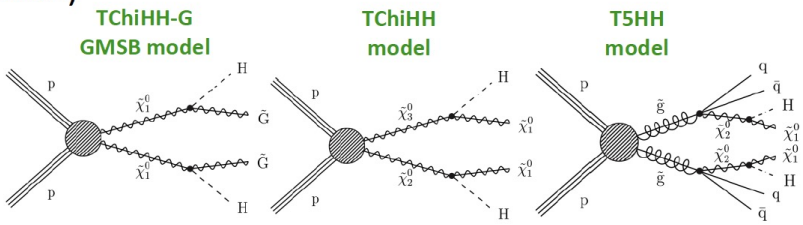
- Search carried out for boosted ($\Delta R_{bb} < 0.8$) and resolved ($\Delta R_{bb} > 0.4$) Higgs to bb (exclusive search enforced by giving priority to the resolved search)
- Search results are interpreted using simplified SUSY models

CMS-PAS-SUS-20-004

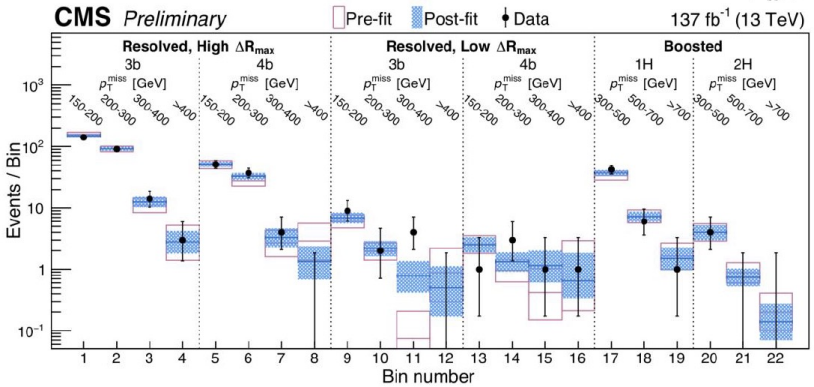








Several intermediate gluinos, charginos and neutralinos may contribute to the final state

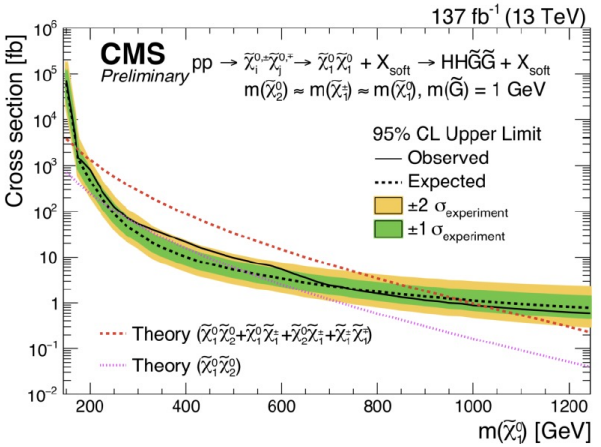


Small excess in one single bin (1.9σ global)

Excluded at 95%C.L.:

- TChiHH-G:
  $175 < m_{\tilde{\chi}_1^0} < 1025$ GeV
- T5HH:
  $m_{\tilde{g}} < 2330$ GeV

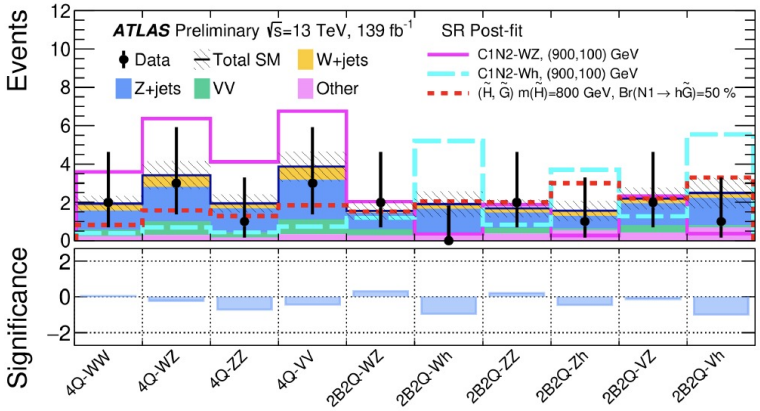
Exclusion limit in the GMSB model



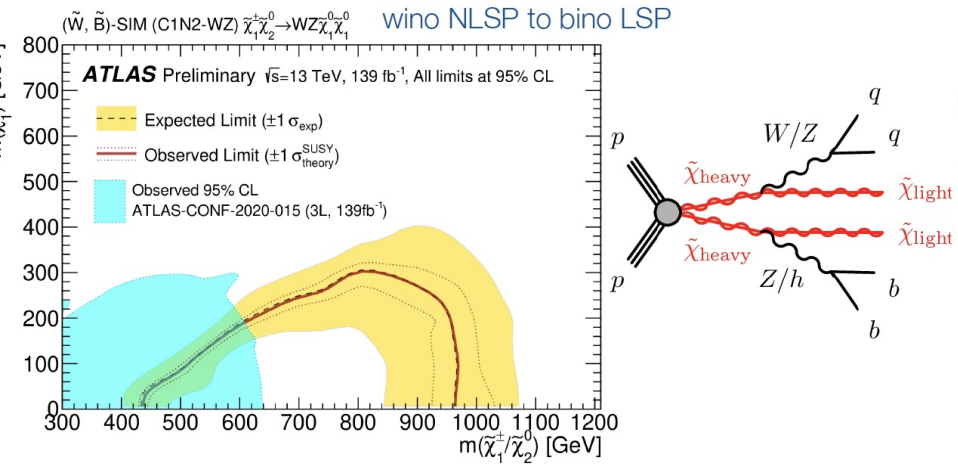
SUSY Electroweak

- **Electroweakinos** with mass ~0.1—1 TeV well motivated:
  - Neutralino LSP as dark matter, naturalness problem, muon g-2 anomaly
- Target mass splitting between NLSP and LSP > 400 GeV
- *First SUSY EW search* with fully hadronic final state using large-R jets tagged as W/Z or H jets
- Strongest limits at high electroweakino mass

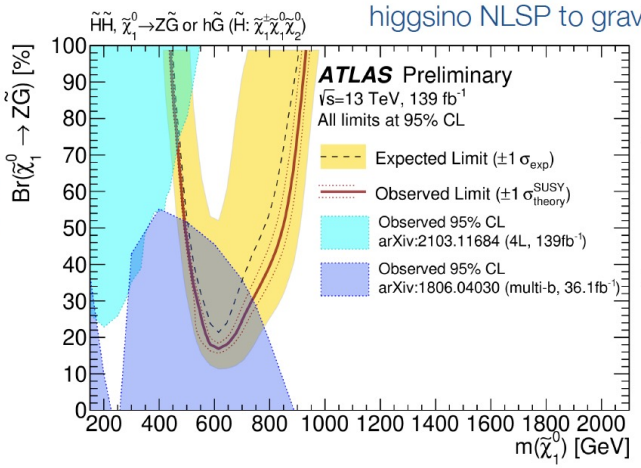
$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{SUSY}$

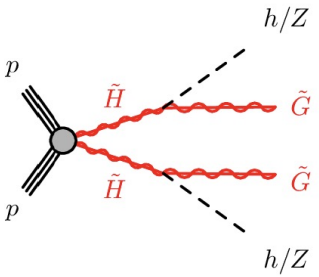


wino NLSP to bino LSP



higgsino NLSP to gravitino LSP





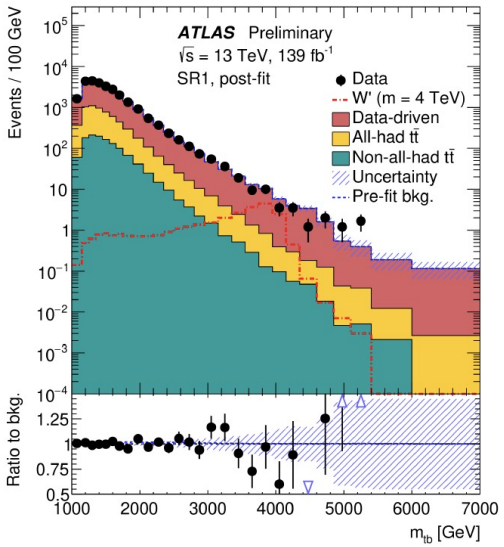
arXiV:2108.07586
SUSY-2018-41

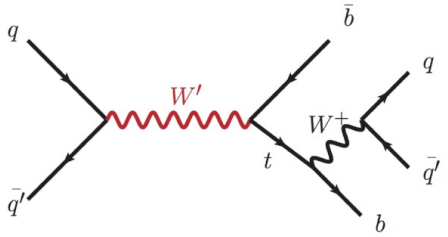
Heavy Particle Search

- Motivated by hierarchy problem —> new physics at TeV scale

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{BSM}}$$

- **Heavy gauge boson** with right-handed couplings
  - Top-tagged large-R jet + b-tagged small-R jet
  - Deep NN top tagger using jet substructure
  - Discriminant: m_{tb}

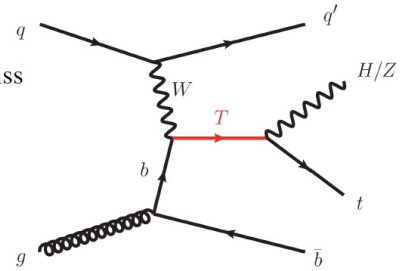


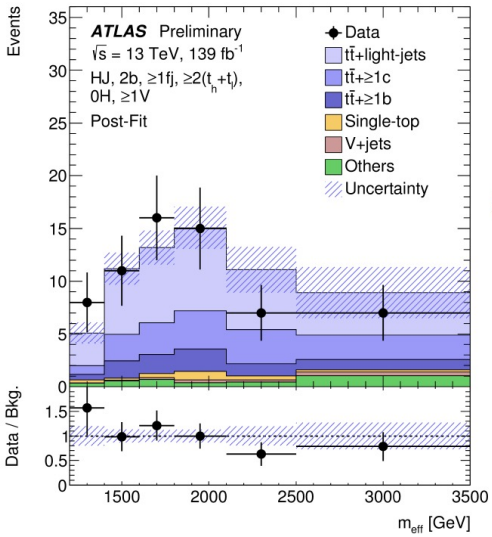


$m(W'_R) > 4.4\ \mathrm{TeV}\ (4.1\ \mathrm{TeV})$
obs (exp)

lower limit improves upon best previous limit by 1 TeV

- **Vector-like top quark** (single production)
  - e/μ + Z/H-tagged large-R jet + small-R jets (some b-tagged)
  - Discr.: $m_{\mathrm{eff}} = \sum_i p_{T_i} + E_T^{\mathrm{miss}}$





$m(T) > 1.8\ \mathrm{TeV}\ (1.5\ \mathrm{TeV})$
obs (exp)
for coupling $\kappa \geq 0.5$

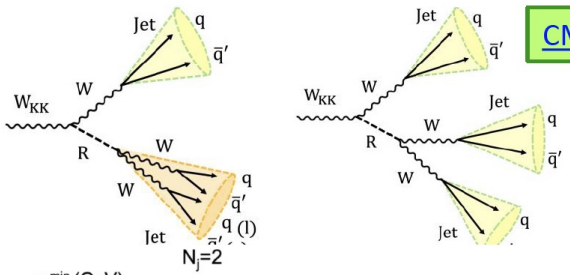
ATLAS-CONF-2021-043

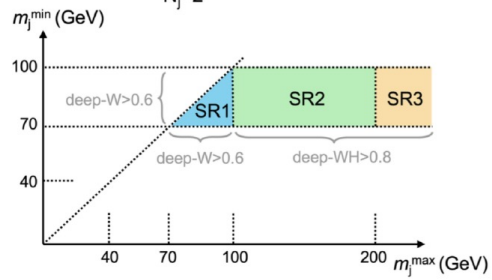
ATLAS-CONF-2021-040

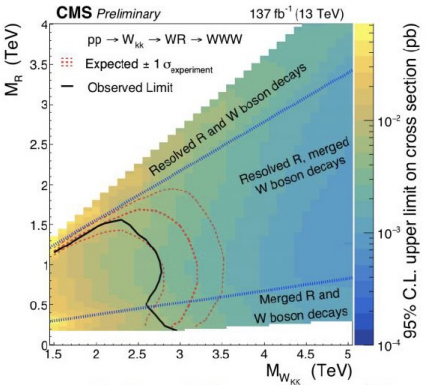
Triboson resonance

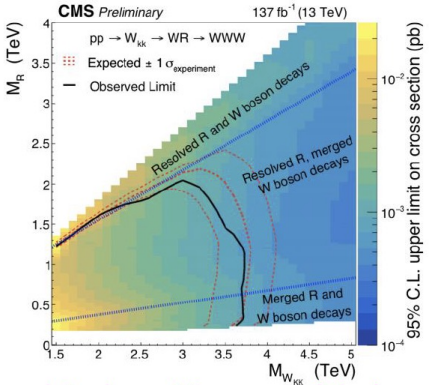
- Search for decays via a scalar radion R
  - X→WR→WWW,
- The radion can decay into 1 or 2 reconstructed large radius jets
- Results are combined with the complementary search in the l + jets finals state CMS-PAS-B2G-20-001

CMS-PAS-B2G-21-002

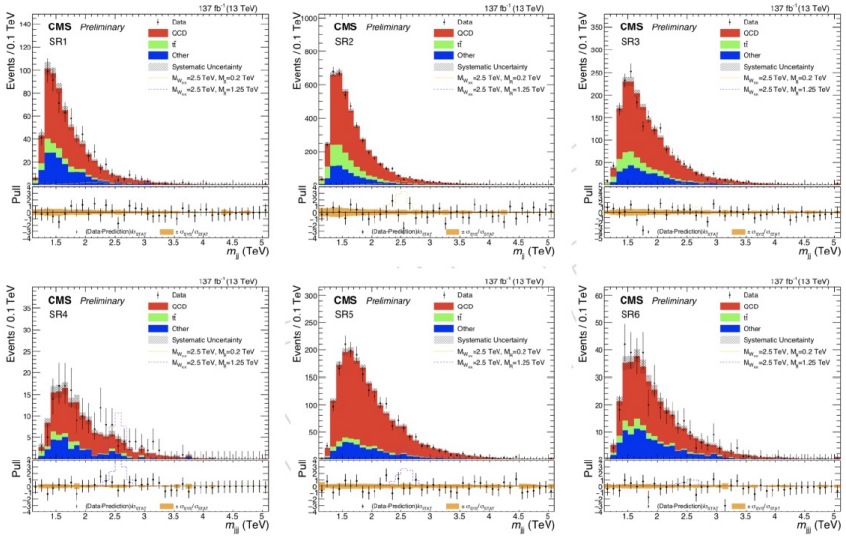






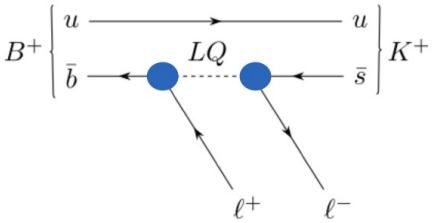


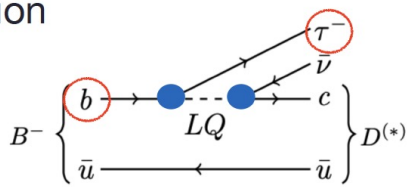
Resonance mass spectrum in the 6 categories



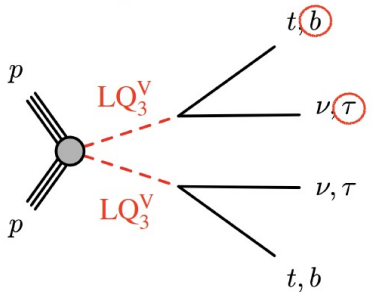
Flavour Anomalies

- Recent results from B decays indicate deviations from lepton-flavor universality
  - $R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$ and $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$ (with $\ell = e, \mu$) both disagree w/ SM at ~3σ
  - Vector leptoquarks a potential explanation

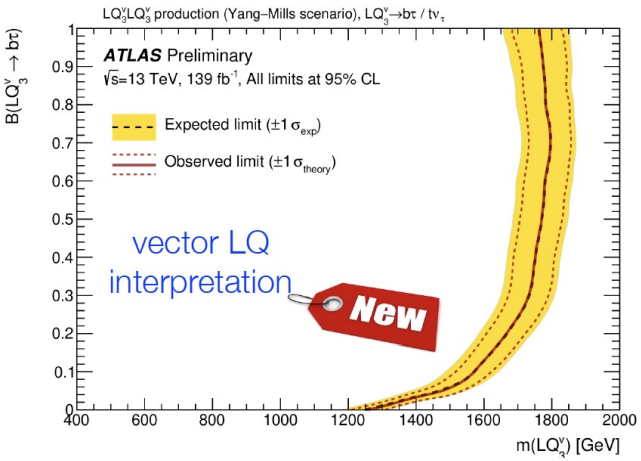




- **Search for LQ pair production*** (other relevant searches not covered here)
  - Trigger on $E_{\mathrm{T}}^{\mathrm{miss}}$ + require offline $E_{\mathrm{T}}^{\mathrm{miss}} > 280$ GeV, 1 τ_{had}, ≥ 2 b-tagged jets
  - Main bkg: $t\bar{t}$ and single top from CRs
  - $m(\mathrm{LQ}_3^{\mathrm{V}}) > 1.8$ TeV for $\mathcal{B}(\mathrm{LQ}_3^{\mathrm{V}} \to b\tau) \sim 0.5$
  - Addresses $R(D^{(*)})$ anomaly at ~expected scale



ATLAS-CONF-2021-008



* search also targeting SUSY stop to stau production

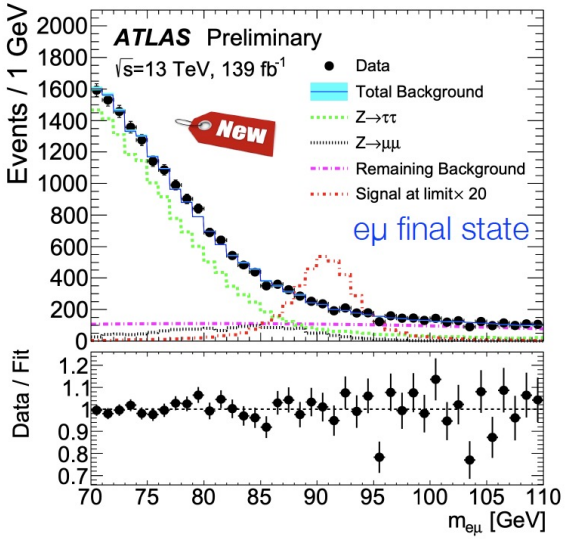
LQ Summary plots

SUSY-2019-18

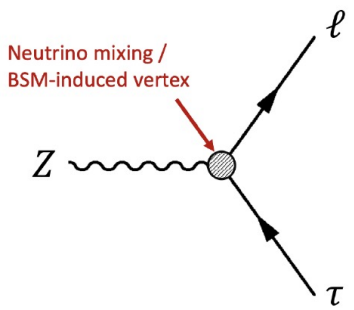
Lepton Flavour Violation

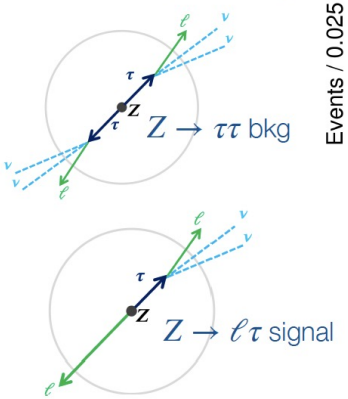
$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$

- Run 2: ~8 x 10^9 Z bosons produced
- Lepton flavor violation only observed in neutrino oscillations, ~negligible for $\ell^{\pm}$ in SM
- Z —> e μ search based on $m_{\ell\ell'}$ w/ reduced uncert. normalizing to Z—>ee, μμ
- Z —> e τ, μ τ search w/ NNs to suppress $Z \to \tau\tau$, $t\bar{t}$, VV & $W \to \ell\nu$ + jets bkg

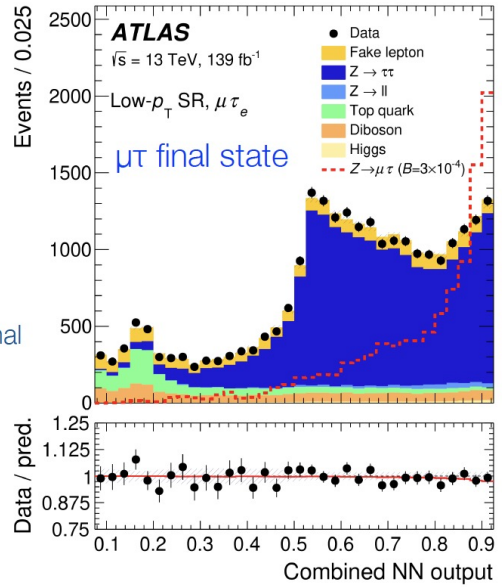


- LEP limits surpassed by factors of 5 ($Z \to e\mu$) and 2 ($Z \to e\tau, \mu\tau$)





Upper limits at 95% CL	ATLAS	LEP
B(Z —> e μ)	0.34 × 10^{-6}	1.7 × 10^{-6} (OPAL)
B(Z —> e τ)	5.0 × 10^{-6}	9.8 × 10^{-6} (OPAL)
B(Z —> μ τ)	6.5 × 10^{-6}	12 × 10^{-6} (DELPHI)

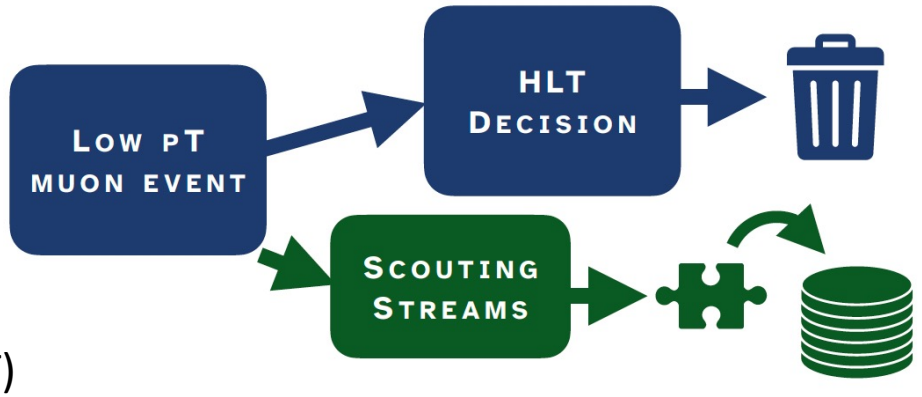


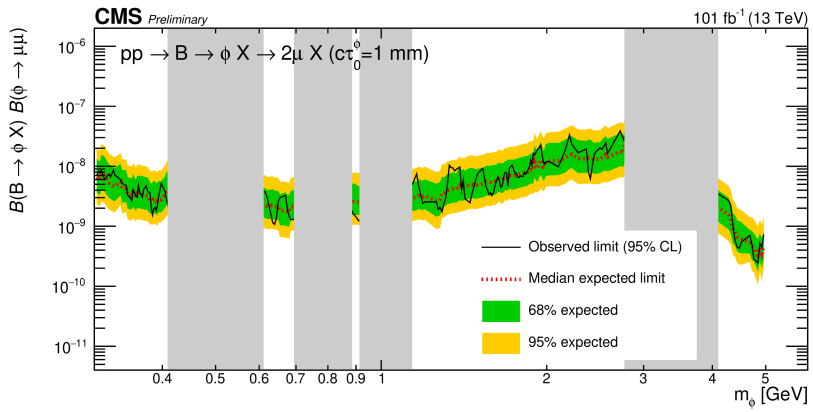
[ATLAS-CONF-2021-042](#)
[EXOT-2020-28](#)
[EXOT-2018-36](#)

Low Mass Long-Lived Particles

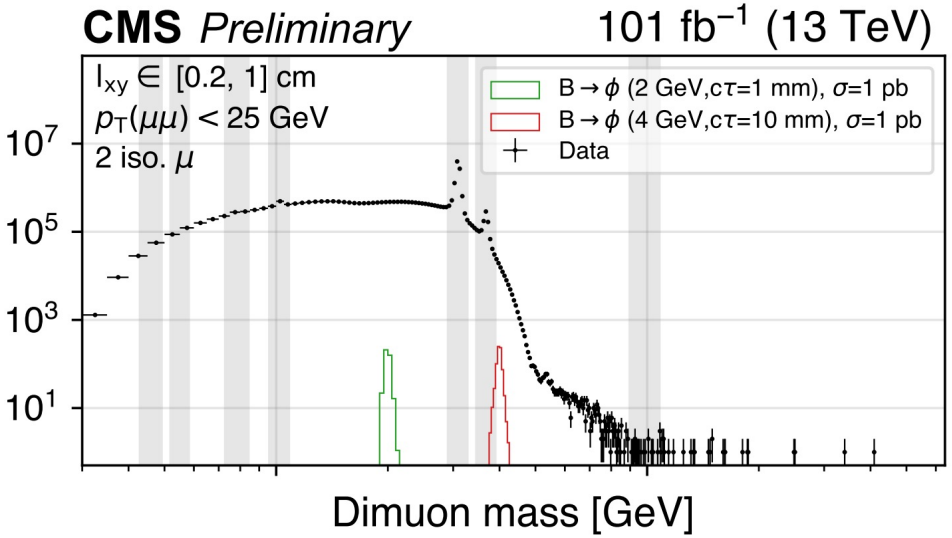
[CMS Displaced Di-Muons w/ Data Scouting]

- Lower trigger thresholds by recording reduced information
- Record O(kHz), low threshold, unprescaled, by throwing away information
- Gives low muon pT sensitivity (>3 GeV @HLT)
- Gives sensitivity to $m_{\mu\mu}$~300 MeV
- Veto regions of SM resonances

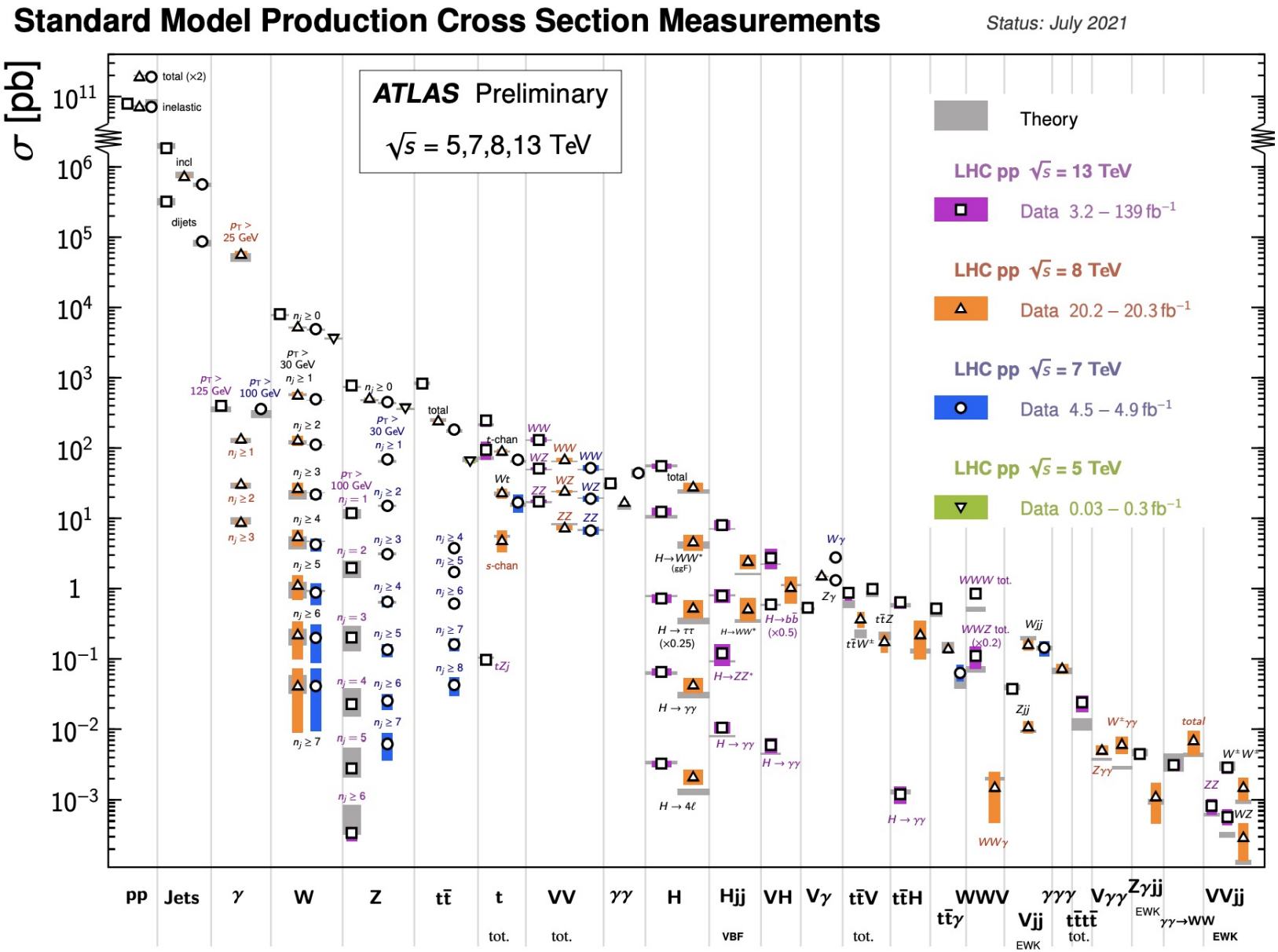




Example exclusion plot for one value of $c\tau$

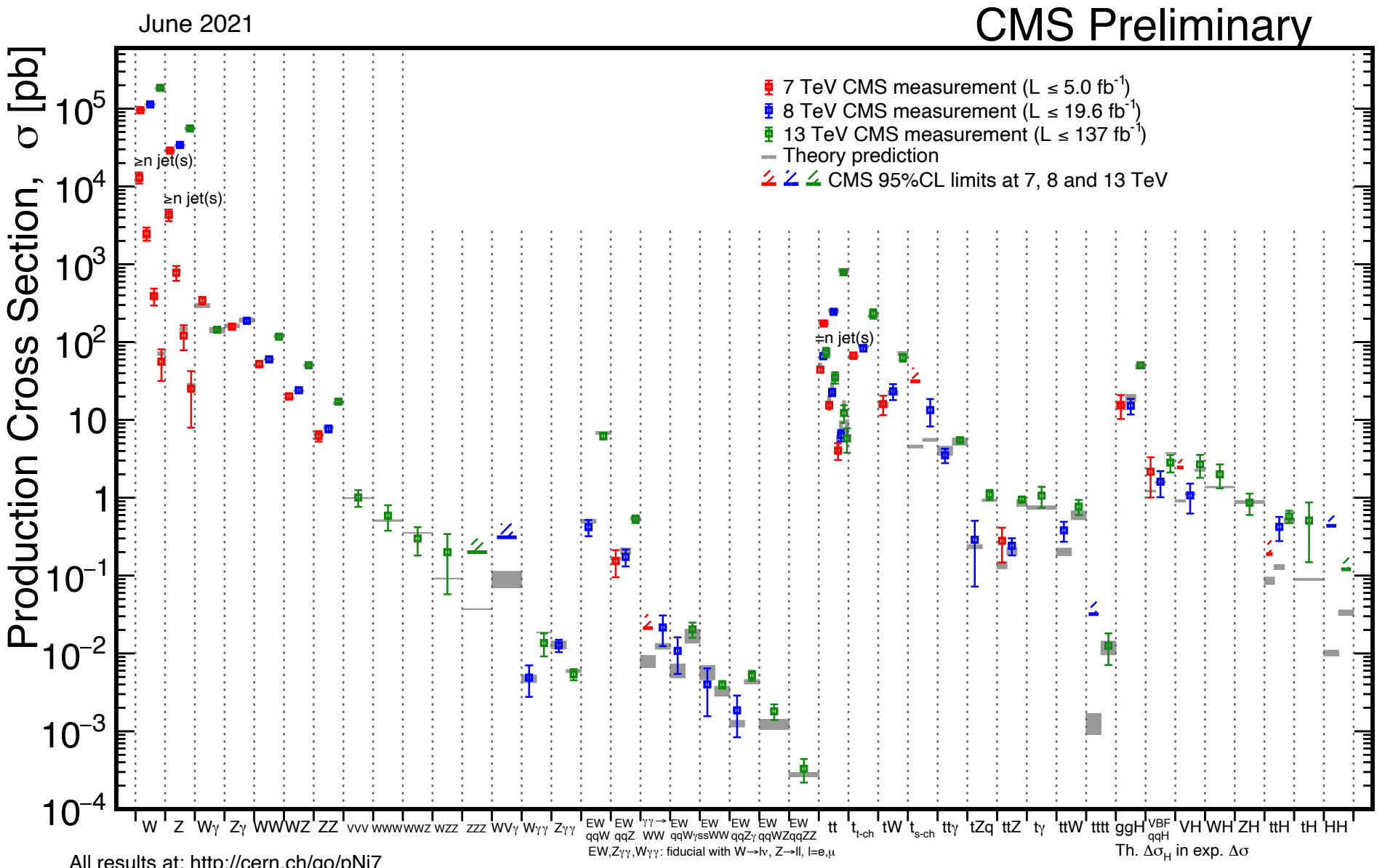


Standard Model Summary



THE UNIVERSITY of ADELAIDE

Standard Model Summary



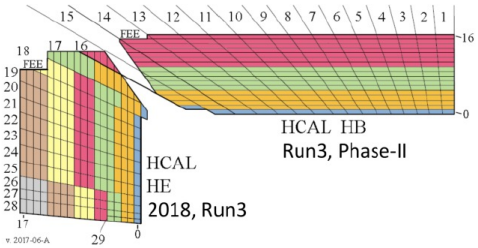
All results at: http://cern.ch/go/pNj7

LS2 Activities

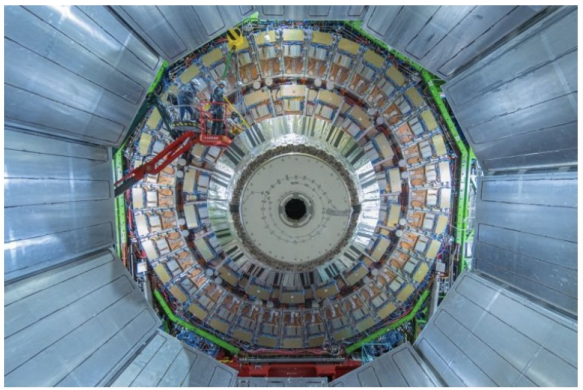
- Run 2 ended in 2018 and Run 3 will take place from 2022 to 2024 at CM energy between 13 and 14 TeV
  - Pilot Beam Test Oct. 21, start of Run-3 2022 (stable beams expected in May)
  - expected to more than double the integrated luminosity of Run 2
- 2019-2021, long shutdown between Run and Run 3 (LS2)

Highlights of activities during LS2
Mostly done, detector ready to close

HCAL readout upgrade

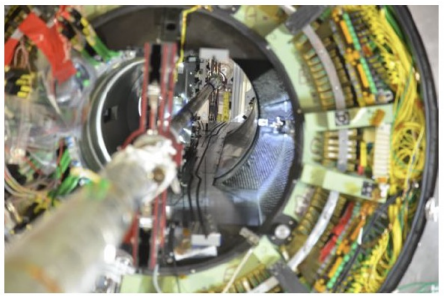


GEM detector first station (GE1/1) (first Phase II upgrade) installed during the COVID pandemic



New beam pipe installed

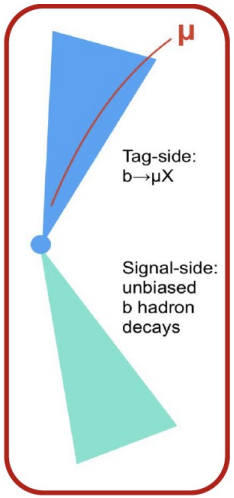
New Barrel Pixel layer 1 installed



- **Cosmic Running started 2 weeks ago with the complete detector to get ready for the Pilot Test beam in October**

Ready for Run3

- B-parking
  - Low pT displaced triggers save a sample of unbiased B-hadrons
  - Enables several LFV analyses
  - Studying how to further optimise trigger for Run3
- Scouting
  - Aim to run particle flow at higher rate, possibly with additional L1 triggers (on GPUs or pixel tracks)
- Long-lived particle improvements
  - L1 trigger to improve displaced signature efficiency
  - HLT developments also ongoing

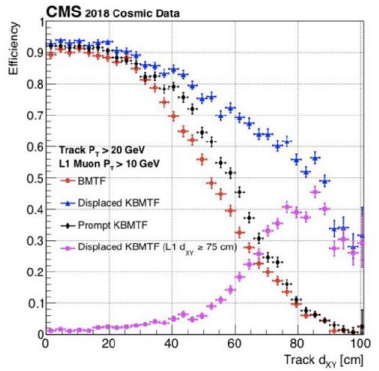


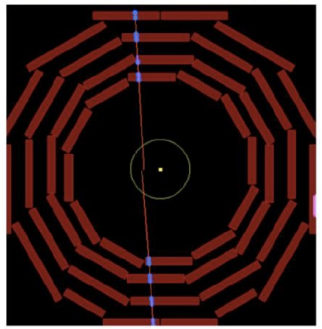
Collected billions of unbiased B decays
12 billion events total

Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B_d^0	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
Events for R_K and R_{K^*} analyses			
$B^0 \to K^* \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}

Kalman filter at L1

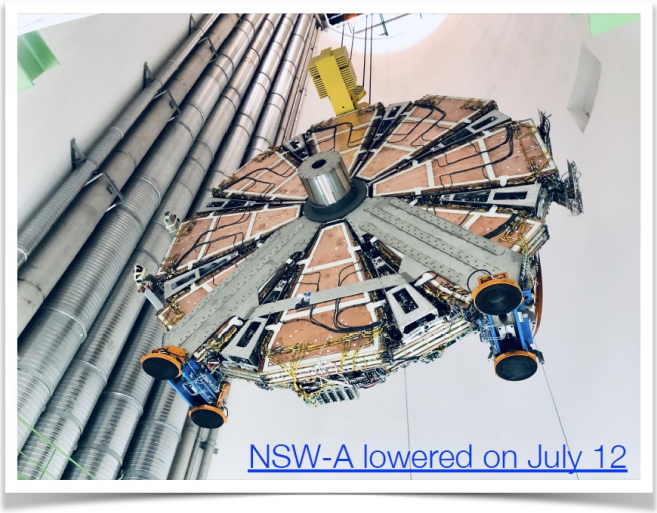
tested in parallel in 2018 and commissioned with cosmic rays



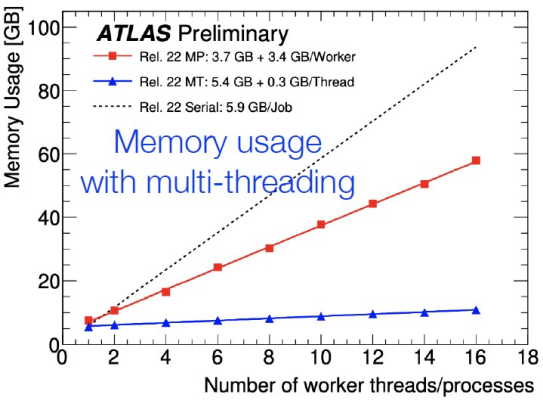


Run 3 Preparation

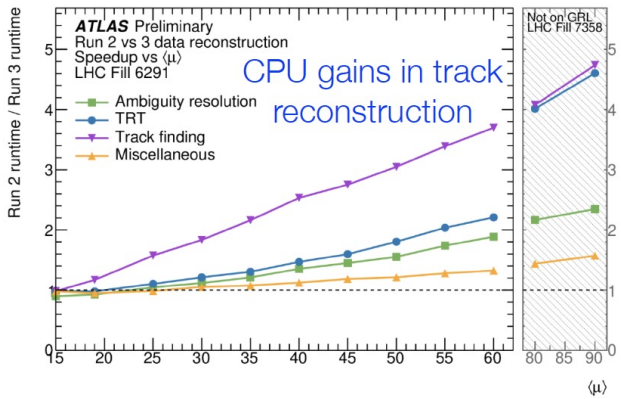
- Preparations ongoing w/ maintenance and multiple improvements to trigger, detector, and computing systems, as well as software
- **New for Run 3:**
  - L1Calo, L1Muon, and L1Topo trigger
  - Increased availability of tracking at HLT
  - New Small Wheel (NSW) for the muon spectrometer
  - AFP with time-of-flight
  - Increased performance of software algorithms


NSW-A lowered on July 12

ATL-SOFT-PUB-2021-002



ATL-PHYS-PUB-2021-012




electron trigger feature extraction

Summary

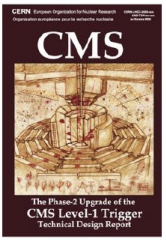
- An enormous body of work in recent times from ATLAS and CMS
- Results presented herein include final states with all SM particles!
- Preparations for Run 3 are ramping up as we prepare > 13 TeV!

- All ATLAS Physics Analysis Public Results appear at
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018
- All CMS Physics Analysis Summaries appear at:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/CMS/index.html

- ATLAS Physics Briefings at
  - https://atlas.cern/updates/briefing
- CMS Physics Briefings at:
  - https://cms.cern/tags/physics-briefing

Backup

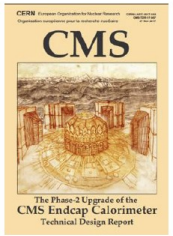
CMS: Upgrade plans



L1-Trigger HLT/DAQ

https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2283193

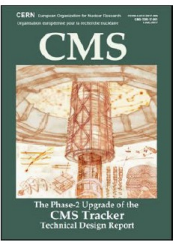
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



Calorimeter Endcap

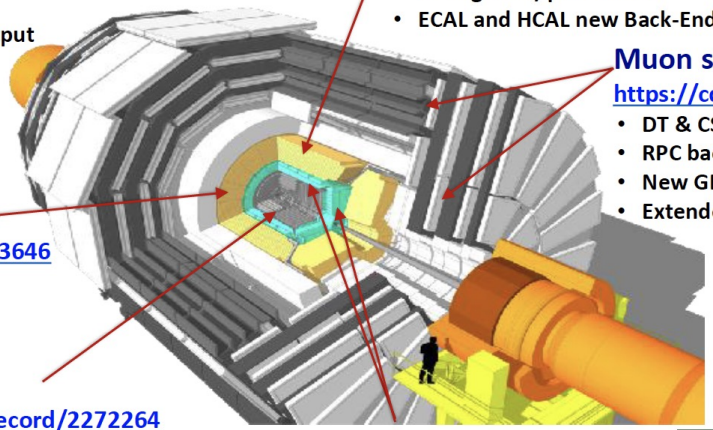
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Tracker https://cds.cern.ch/record/2272264

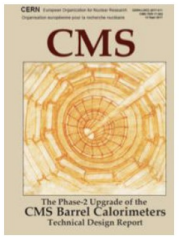
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



Barrel Calorimeters

https://cds.cern.ch/record/2283187

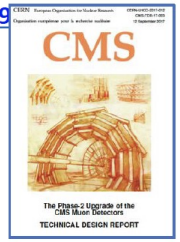
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

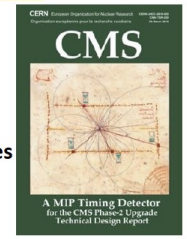


MIP Timing Detector

https://cds.cern.ch/record/2667167

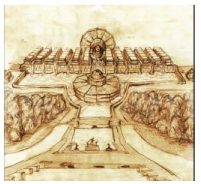
Precision timing with:

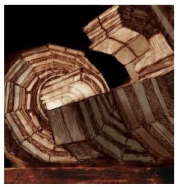
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



All shown Technical Design Reports approved by the LHC Committee.
Two currently under scrutiny:

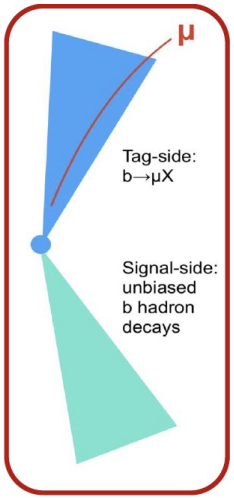
DAQ/HLT **BRIL**





Ready for Run3

- B-parking
  - in 2018 we used low p_T displaced triggers to save a sample of unbiased B hadron decays recoiling wrt the triggered muon
    - Parked trigger rate ~2kHz was reconstructed after the end of the run
  - **Enables several analyses on LFU violation** currently in progress
    - Expect first approved results soon
  - **Studying how to further optimize the trigger in Run 3**
- Scouting
  - Analysis based on a reduced data format and on the online reconstruction in the HLT farm (do not save the full event data)
  - In Run 2 all analyses based about 5 kHz (~1 kHz of Particle Flow scouting)
  - **For Run 3 aim at running PF on higher rate, possible adding additional L1 triggers (use GPUs and pixel tracks)**
- LLP improvements
  - **Ongoing developments in the L1 trigger** area with the aim to increase efficiency for displaced signatures
    - Increase efficiency for displaced muons
    - Extend muon triggers to hadronic showers
    - Out of time ECAL and HCAL at L1
    - Using HCAL depth information
  - **HLT developments also ongoing**



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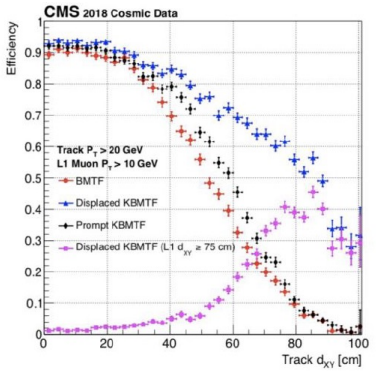
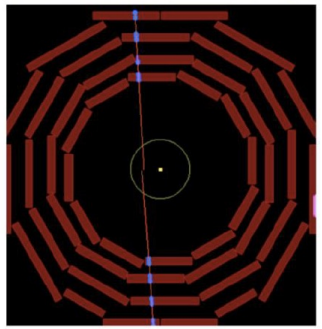
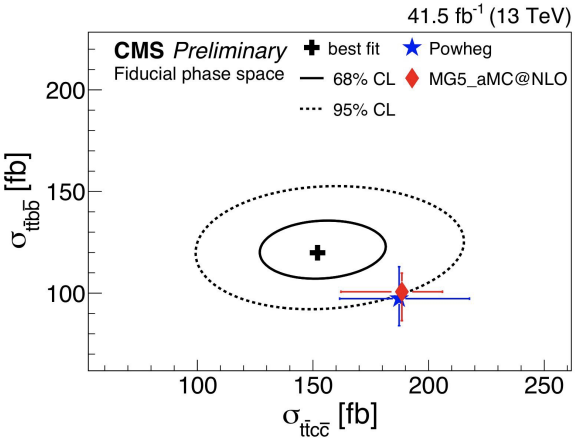
tested in parallel in 2018 and commissioned with cosmic rays



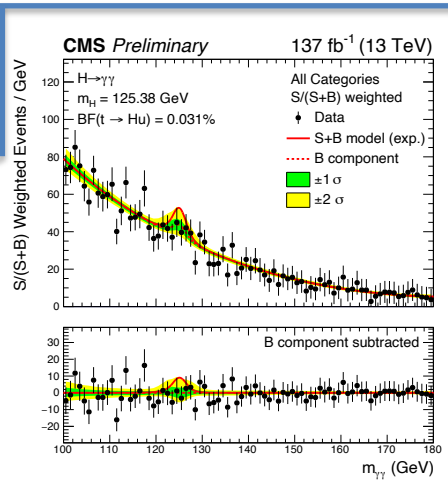


CMS

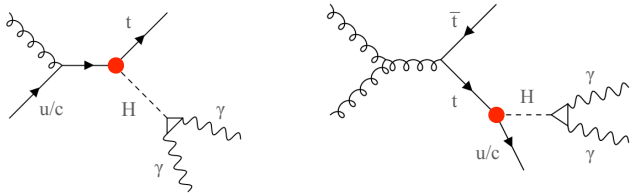


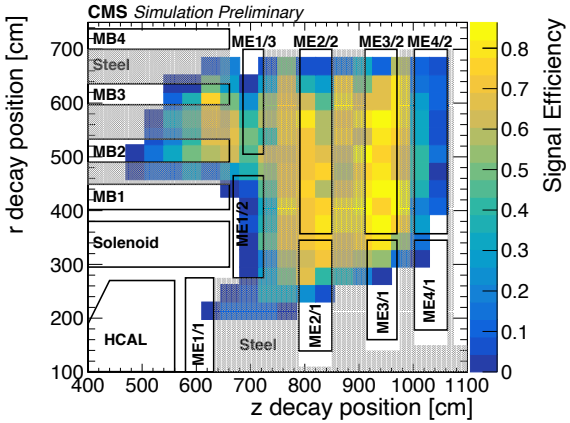
tt+bb production now exceeding theoretical knowledge! – Important background in study of top-Higgs Yukawa coupling

Also tt+cc with 19% precision – key role of c-tagging for current and future analyses



FCNC top decays: t->Hu and t->Hc are expected to be $O(10^{-17})$ and $O(10^{-15})$in SM. Clear NP if we observe them.

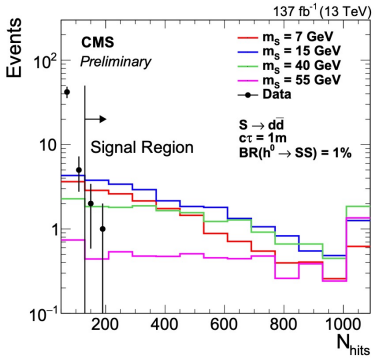


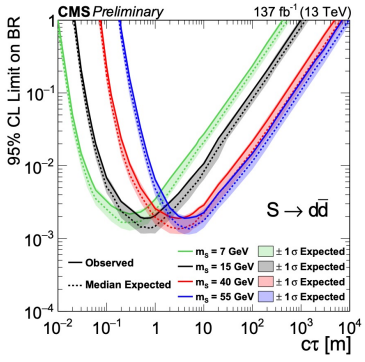


Search for Long-lived Particles Decaying in the CMS Endcap Muon System

[CMS-PAS-EXO-20-015]

Displaced decay in muon endcap produces hadronic shower (w/ ~1k CSC hits!) in low BG environment

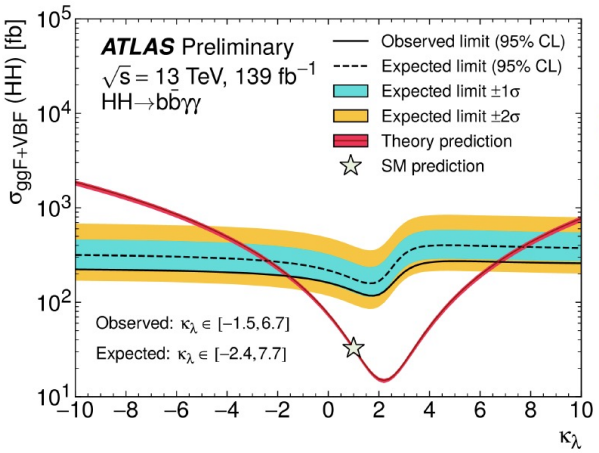




Di-Higgs production

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

- **HH —> bbγγ**



$\sigma_{HH}/\sigma_{HH}^{SM} < 4.1\ (5.5)$ obs (exp)

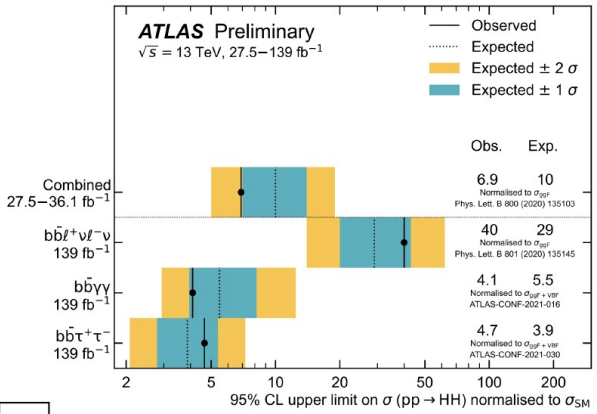
factor of 5 improvement over 36 fb^{-1} analysis

self-coupling modifier κ_λ

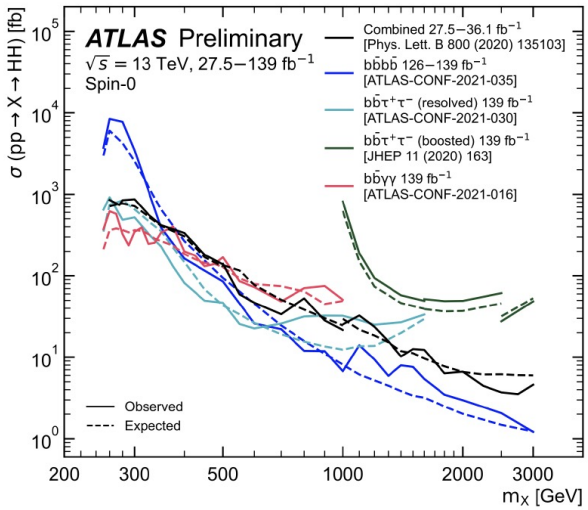
$\lambda_{HH}/\lambda_{HH}^{SM} \in [-1.5,6.7]$

(exp $[-2.4,7.7]$)

strongest constraint



- **Search for HH resonances** New
  - HH —> bbbb, bbττ, bbγγ
  - HH —> bbbb with both resolved and merged topologies
    - Data-driven bkg
    - Dominates for m(X) > 700 GeV



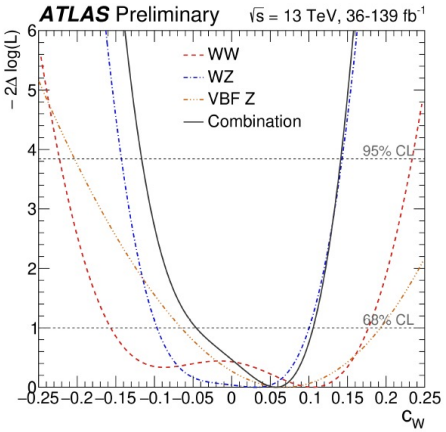
ATLAS-CONF-2021-035
ATLAS-CONF-2021-016

Effective Field Theory

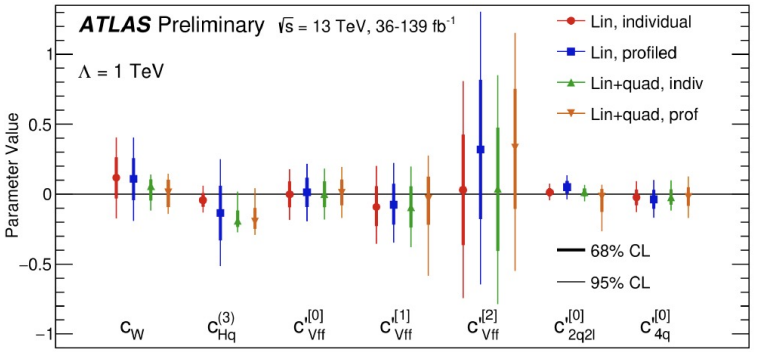
- **EFT**: allows to systematically study impact of wide range of measts. on BSM physics at higher E

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

- Study here is a step toward global EFT fits
- **Input**: 1 differential cross-section measst. for each of WW, WZ, 4-lepton (Z/ZZ*/ZZ), and VBF Z analyses
- **Output**: constrain operators affecting W/Z self-couplings, W/Z couplings to fermions, 4-fermion couplings



- 15 eigenvectors constrained individually or in combination ("profiled")
- coefficients of all 15 eigenvectors consistent with SM within 2σ



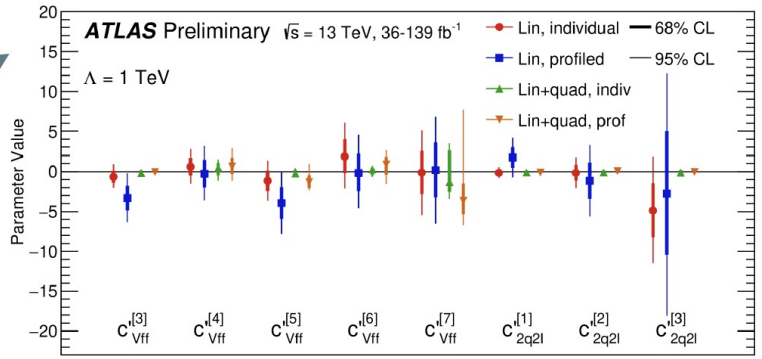
$c'^{[0]}_{\text{Vff}} \approx 0.81c_{\text{HWB}} + 0.38c_{\text{HD}} + 0.13c^{(1)}_{\text{Hl}} + 0.37c^{(3)}_{\text{Hl}} - 0.14c^{(1)}_{\text{ll}} + 0.12c^{(1)}_{\text{Hq}}$

$c'^{[1]}_{\text{Vff}} \approx 0.73c^{(1)}_{\text{Hl}} - 0.28c^{(3)}_{\text{Hl}} - 0.48c_{\text{He}} + 0.38c^{(1)}_{\text{ll}} + 0.13c^{(1)}_{\text{Hq}}$

$c'^{[2]}_{\text{Vff}} \approx 0.37c_{\text{HWB}} + 0.17c_{\text{HD}} - 0.31c^{(1)}_{\text{Hl}} - 0.53c^{(3)}_{\text{Hl}} + 0.25c_{\text{He}} + 0.59c^{(1)}_{\text{ll}} - 0.21c^{(1)}_{\text{Hq}}$

$c'^{[0]}_{\text{2q2l}} \approx -0.37c^{(1)}_{\text{lq}} + 0.89c^{(3)}_{\text{lq}} - 0.11c_{\text{lu}} - 0.21c_{\text{eu}} - 0.13c_{\text{qe}}$

$c'^{[0]}_{\text{4q}} \approx 0.11c^{(11)}_{\text{qq}} + 0.22c^{(18)}_{\text{qq}} + 0.95c^{(31)}_{\text{qq}} - 0.2c^{(38)}_{\text{qq}}$



$c'^{[3]}_{\text{Vff}} \approx -0.19c^{(1)}_{\text{Hl}} - 0.14c^{(3)}_{\text{Hl}} + 0.86c^{(1)}_{\text{Hq}} + 0.41c_{\text{Hu}} - 0.17c_{\text{Hd}}$

$c'^{[4]}_{\text{Vff}} \approx -0.35c_{\text{HWB}} + 0.49c_{\text{HD}} + 0.26c^{(1)}_{\text{Hl}} + 0.35c^{(3)}_{\text{Hl}} + 0.51c_{\text{He}} + 0.38c^{(1)}_{\text{ll}} + 0.18c^{(1)}_{\text{Hq}}$

$c'^{[5]}_{\text{Vff}} \approx 0.25c_{\text{HD}} + 0.33c^{(1)}_{\text{Hl}} - 0.22c^{(3)}_{\text{Hl}} + 0.18c_{\text{He}} - 0.35c^{(1)}_{\text{ll}} - 0.3c^{(1)}_{\text{Hq}} + 0.71c_{\text{Hu}} - 0.16c_{\text{Hd}}$

$c'^{[6]}_{\text{Vff}} \approx -0.22c^{(1)}_{\text{Hl}} + 0.52c^{(3)}_{\text{Hl}} - 0.39c_{\text{He}} + 0.44c^{(1)}_{\text{ll}} - 0.22c^{(1)}_{\text{Hq}} + 0.52c_{\text{Hu}}$

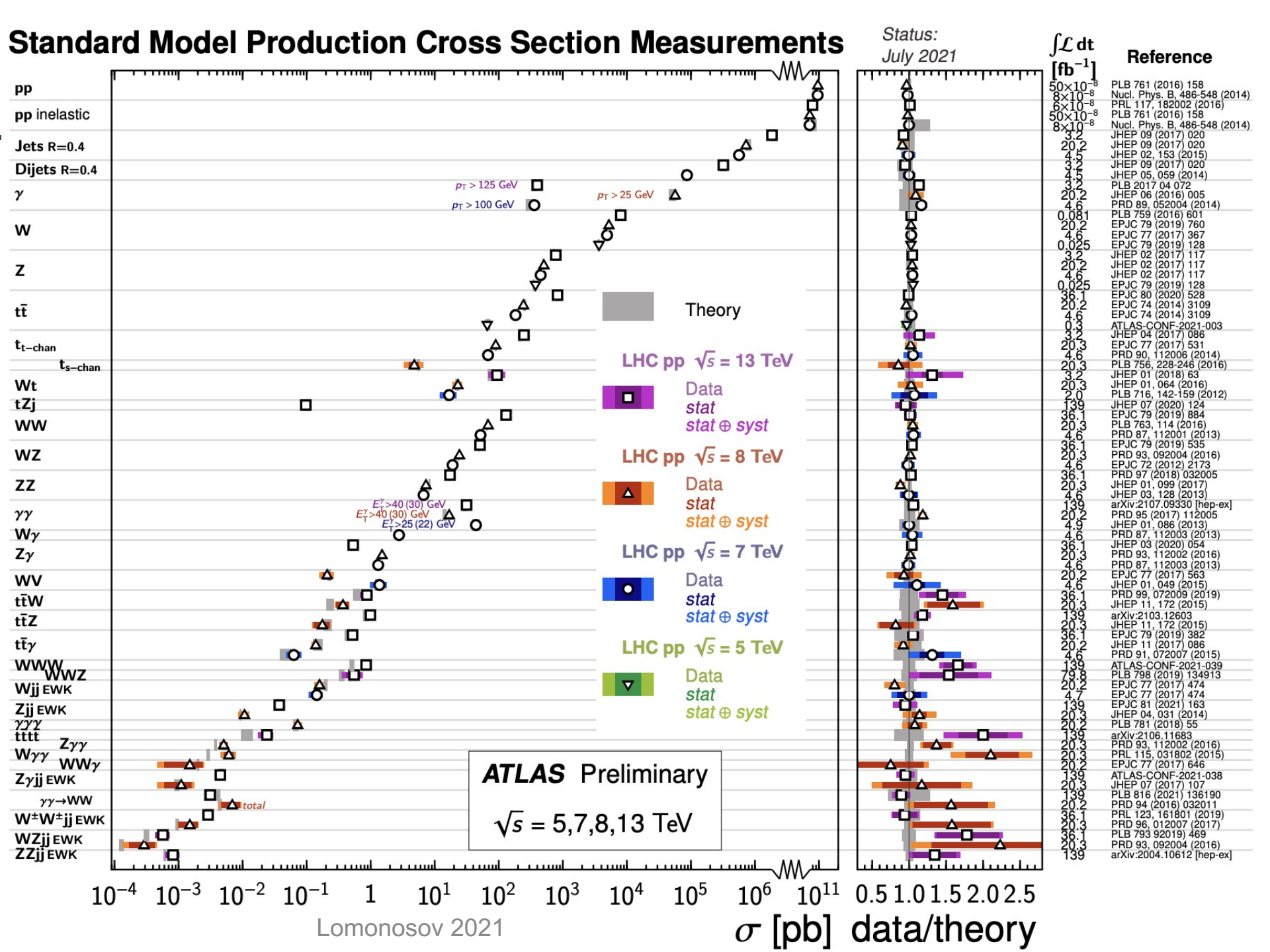
$c'^{[7]}_{\text{Vff}} \approx -0.28c_{\text{HWB}} + 0.71c_{\text{HD}} - 0.31c^{(1)}_{\text{Hl}} - 0.21c^{(3)}_{\text{Hl}} - 0.5c_{\text{He}} - 0.14c^{(1)}_{\text{ll}}$

$c'^{[1]}_{\text{2q2l}} \approx 0.56c^{(1)}_{\text{lq}} + 0.44c^{(3)}_{\text{lq}} + 0.61c_{\text{eu}} - 0.1c_{\text{ed}} + 0.34c_{\text{qe}}$

$c'^{[2]}_{\text{2q2l}} \approx 0.68c^{(1)}_{\text{lq}} + 0.15c^{(3)}_{\text{lq}} + 0.33c_{\text{lu}} - 0.51c_{\text{eu}} + 0.13c_{\text{ed}} - 0.37c_{\text{qe}}$

$c'^{[3]}_{\text{2q2l}} \approx -0.27c^{(1)}_{\text{lq}} + 0.79c_{\text{lu}} - 0.39c_{\text{ld}} + 0.26c_{\text{eu}} - 0.22c_{\text{ed}} - 0.16c_{\text{qe}}$

Topic	Reference	Topic	Reference
Bc —> J/psi Ds(*)	ATLAS-CONF-2021-046	LFV Z —> eμ	ATLAS-CONF-2021-042
b-quark fragment. in B^+ —> J/ψ K^+	CERN-EP-2021-123	eμ charge asymmetry	ATLAS-CONF-2021-045
collinear Z + jets	ATLAS-CONF-2021-033	dark matter in Z(ll) + ETmiss	ATLAS-CONF-2021-029
diphoton cross section	arXiv:2107.09330	dark matter combination 2HDM+a	ATLAS-CONF-2021-036
EFT analysis of WW, WZ, ZZ, VBF Z	ATL-PHYS-PUB-2021-022	SUSY in photon + jets + ETmiss	ATLAS-CONF-2021-028
VBS Z(ll) + γ	ATLAS-CONF-2021-038	W' —> tb (all hadronic)	ATLAS-CONF-2021-043
VBS Z(νν) + γ	CERN-EP-2021-137	W/Z γ resonances	ATLAS-CONF-2021-041
WWW	ATLAS-CONF-2021-039	VLQ single production in Ht/Zt	ATLAS-CONF-2021-040
H —> ττ couplings	ATLAS-CONF-2021-044	HH —> bb ττ	ATLAS-CONF-2021-030
boosted top cross section	ATLAS-CONF-2021-031	HH —> bb bb	ATLAS-CONF-2021-035
top mass w/ boosted top	ATL-PHYS-PUB-2021-034	H —> XX/XZ —> 4l	ATLAS-CONF-2021-034
E/p from W—>τν	CERN-EP-2021-147	t —> bH+(cb)	ATLAS-CONF-2021-037
ETmiss performance with NN	ATL-PHYS-PUB-2021-025	LLP in muon spectrometer	ATLAS-CONF-2021-032


Standard Model Production Cross Section Measurements
Status: July 2021
∫L dt [fb⁻¹]
Reference
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t t−chan
t s−chan
Wt
tZj
WW
WZ
ZZ
γγ
Wγ
Zγ
WV
tt̄W
tt̄Z
tt̄γ
WWW
WWZ
Wjj EWK
Zjj EWK
γγγ
tttt
Zγγ
Wγγ
WWγ
Zγjj EWK
γγ→WW
W±W±jj EWK
WZjj EWK
ZZjj EWK
pT > 125 GeV
pT > 100 GeV
pT > 25 GeV
Eγ T>40 (30) GeV
Eγ T>40 (30) GeV
Eγ T>25 (22) GeV
total
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
√s = 5,7,8,13 TeV
10−4 10−3 10−2 10−1 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory
Lomonosov 2021