Recent results from LHC experiments

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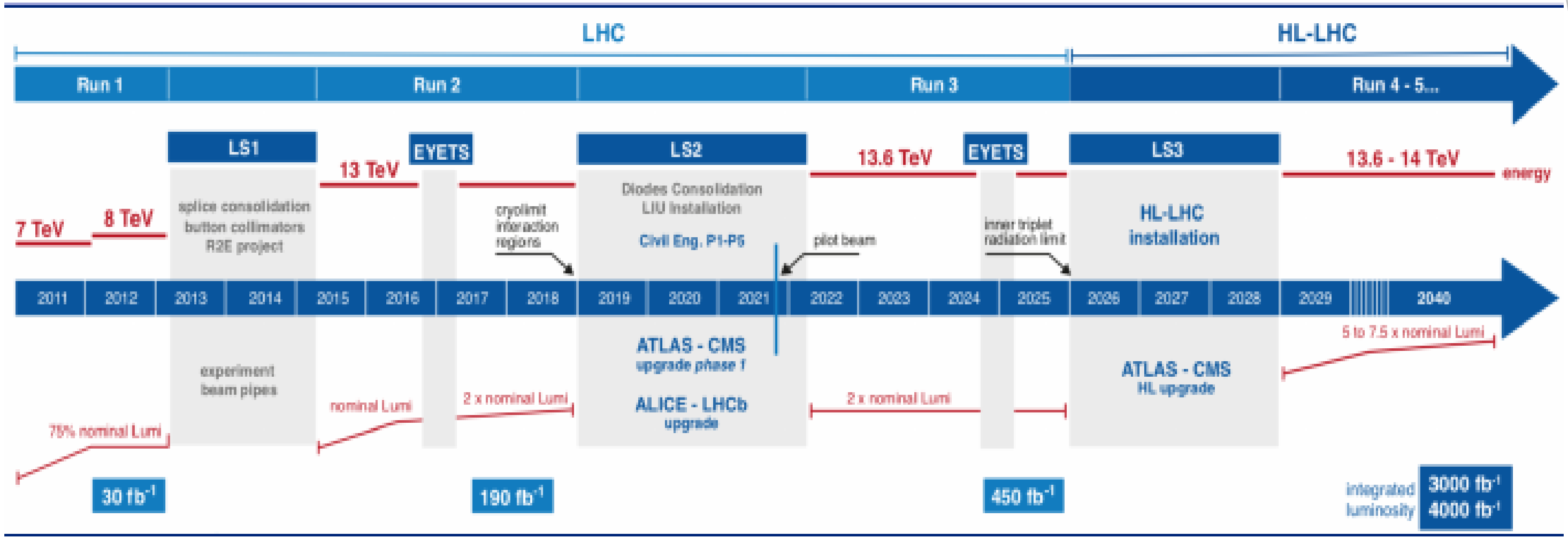
NIC KI - IHEP

LHC: status and plans



Run 3 6.8 TeV
ATLAS, CMS target 250 /fb
LHCb 25-30 /fb
ALICE 200/pb pp, 7/nb Pb-Pb

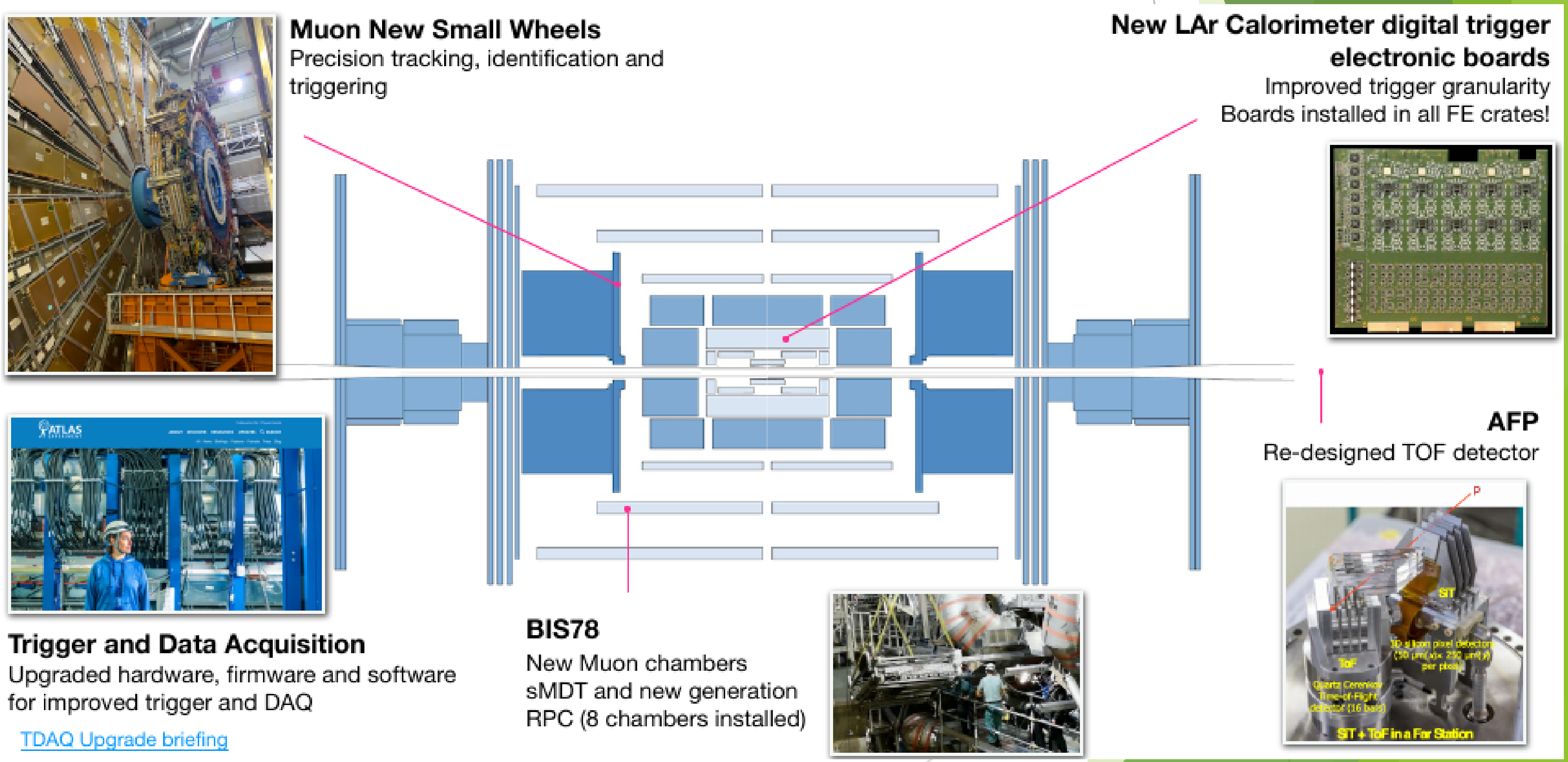
Run 4 (H_LHC) High pileup up to ‹μ›=140-200, high particle multiplicity, plan ~3/ab

ATLAS Upgrade Phase 1

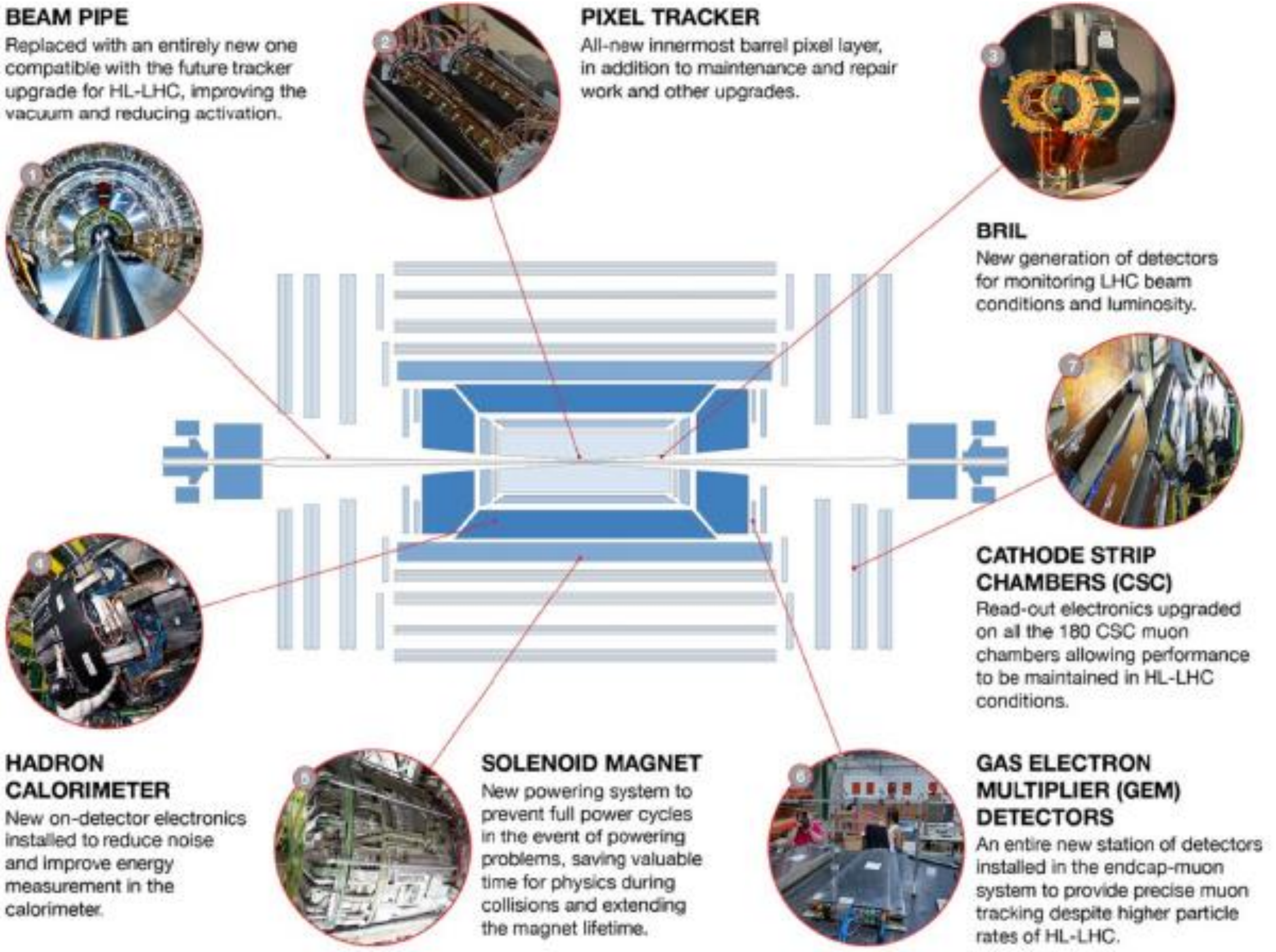
New Small Wheel muon detector: replacement of previous end-cap CSC based detector with a sTGC+MicroMega

BIS78-RPC muon detector: new RPCs in the barrel to improve the rejection rate of the L1 trigger in the barrel-endcap transition region

LAr front-end: new electronics with higher granularity for improved performances of the detector and of the Level-1 Calorimeter electromagnetic trigger



CMS Upgrade Phase 1



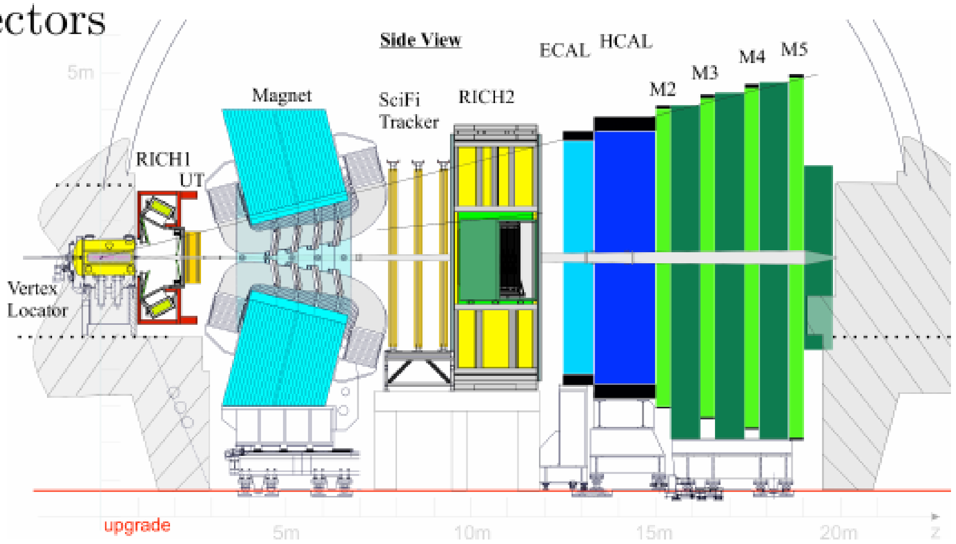
LHCb Upgrade Phase 1

- Major upgrade of all sub-detectors

  $\rightarrow \mathscr{L}_{\text{peak}} = 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

  pile-up ≈ 5

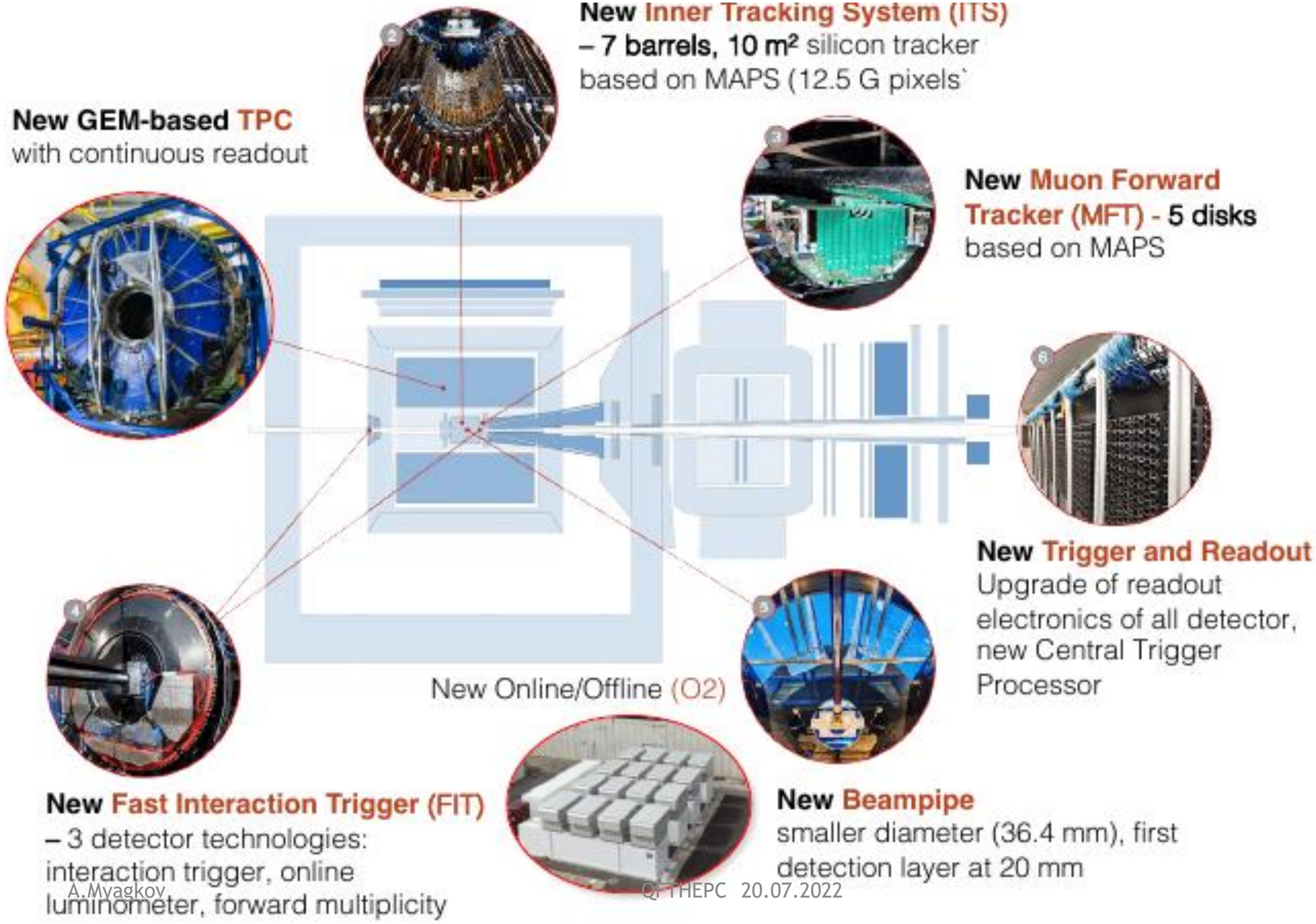
  $\rightarrow$ fully software trigger for 40MHz readout



- New pixel-detector **VELO**
- New **RICH** mechanics, optics, photodetectors
- New Silicon strip upstream tracker **UT** (installation at end of year)
- New **SciFi** tracker
- New electronics for **MUON** and **CALO**
- New luminometer **PLUME**

Installed for operations in Run 3

ALICE   Upgrade Phase 1



ALICE 2 Upgrade

→ Tracking precision ×3
→ Pb-Pb rate ×50

Papers in hep-ph with ML,NN etc in title

2012	2013	2014	2015	2016	2017	2018	2019	2020	21
11	14	17	35	55	110	221	373	520	697

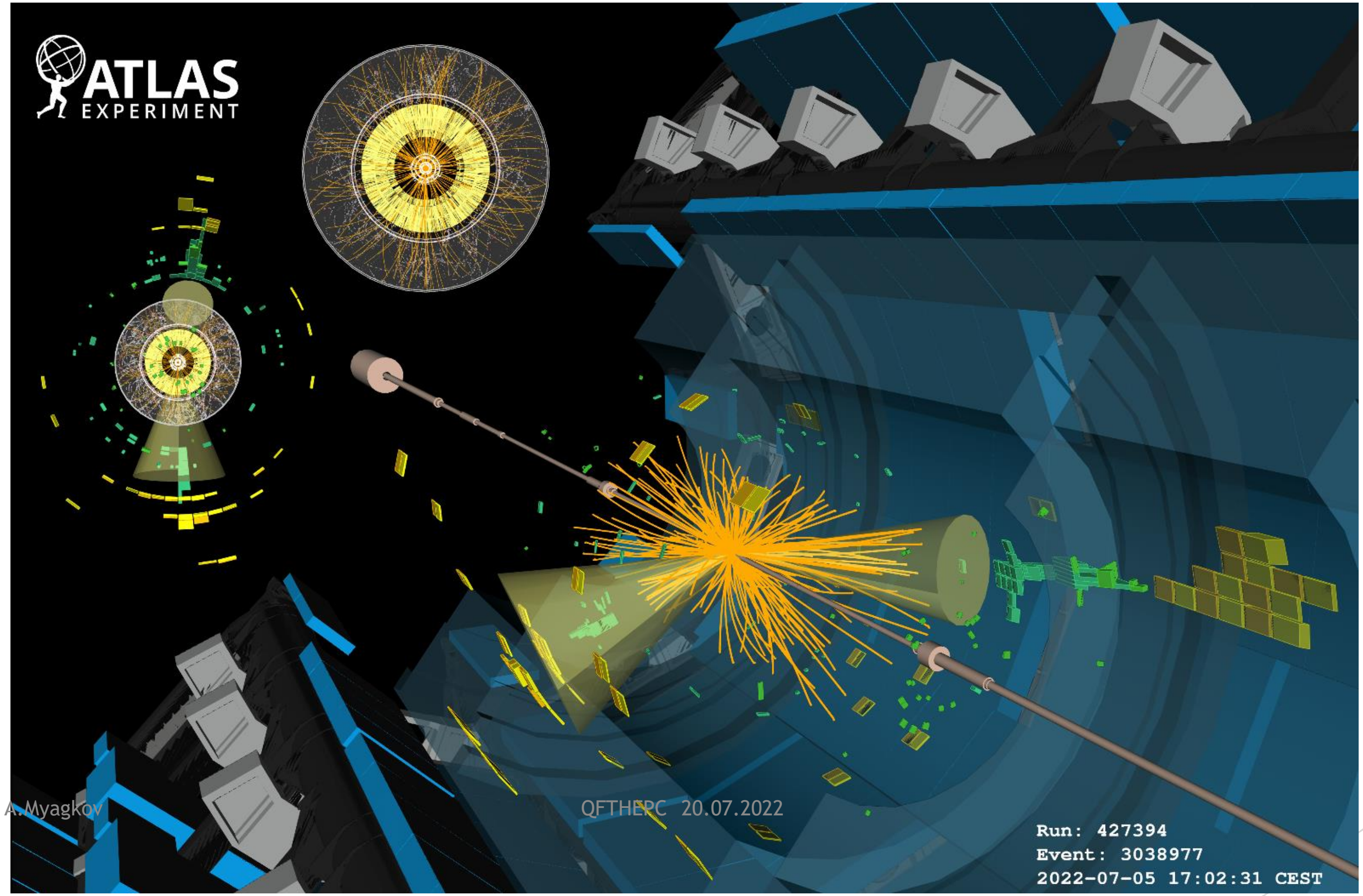
In inspire: f t machine learning or t neural network or t deep learning

TensorFlow 2015

Scikit-lean 2014

Review in Nature (2018) Machine learning at the energy and intensity frontiers of particle physics,

First events Run 3



Main part of materials were taken from these conferences

since 1966
Rencontres de Moriond

ICHEP 2022
BOLOGNA

ICHEP 2022
XLI
International Conference
on High Energy Physics
Bologna (Italy)

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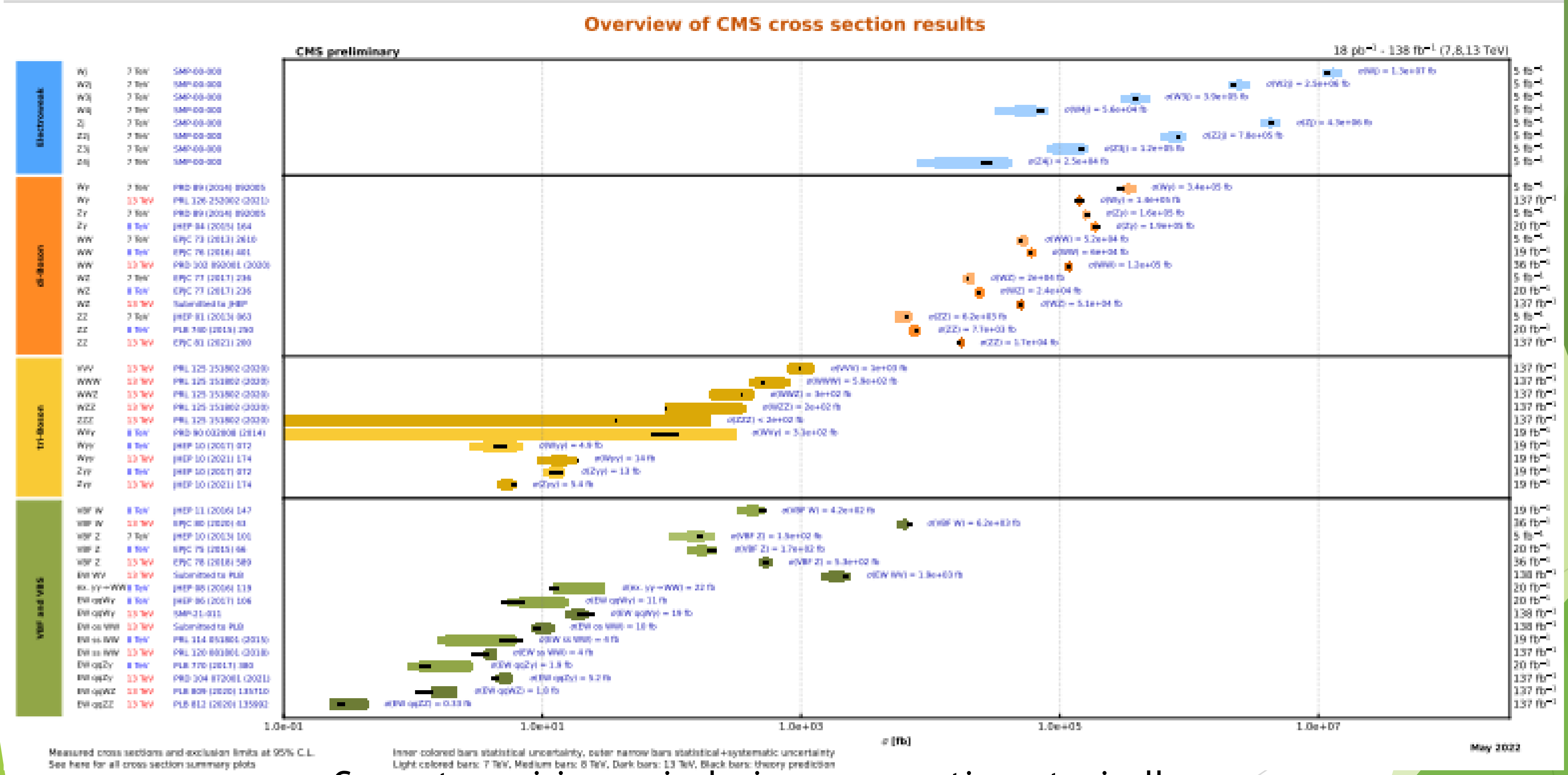
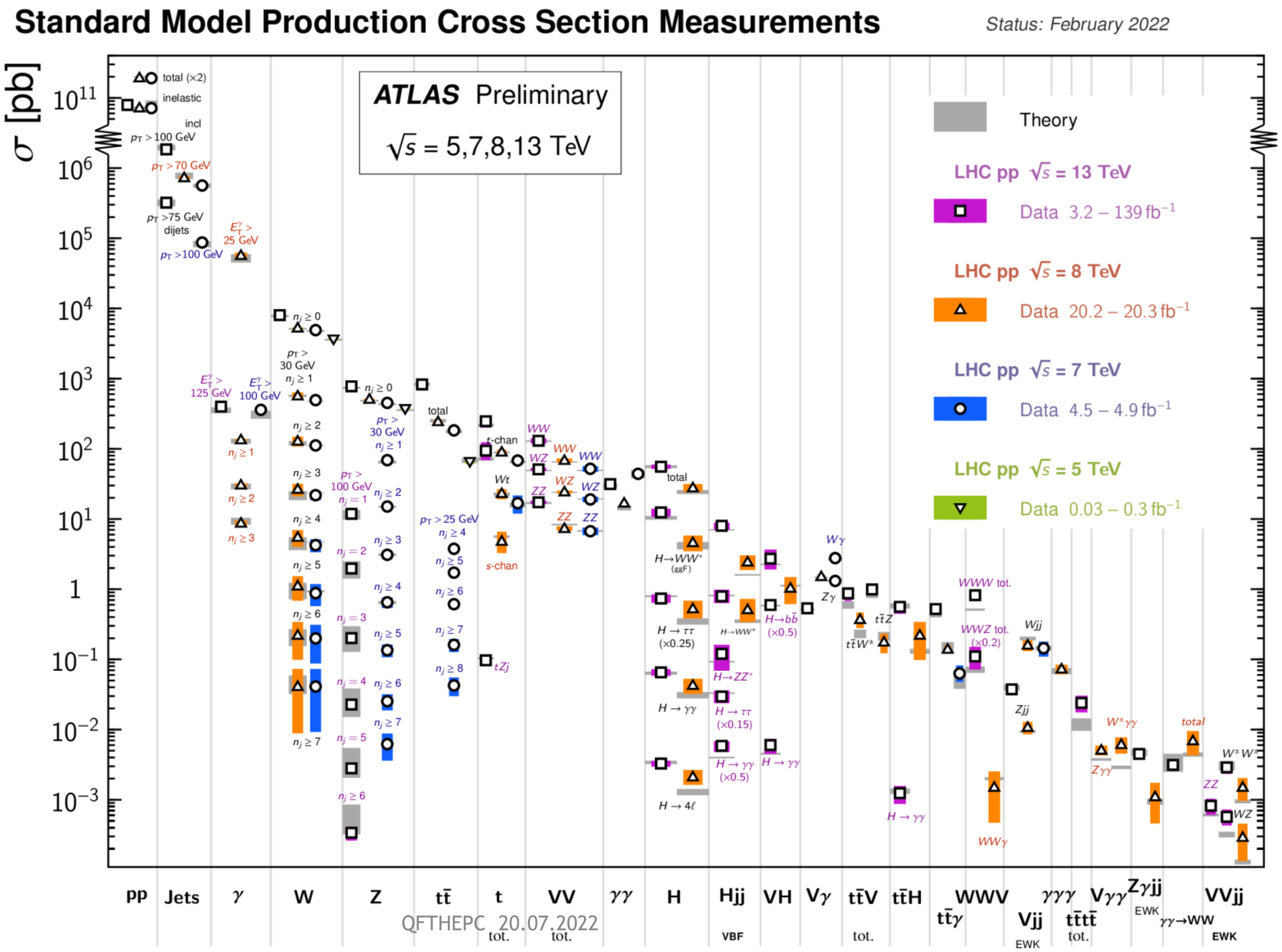
13 07 2022

Main SM processes and X-sec

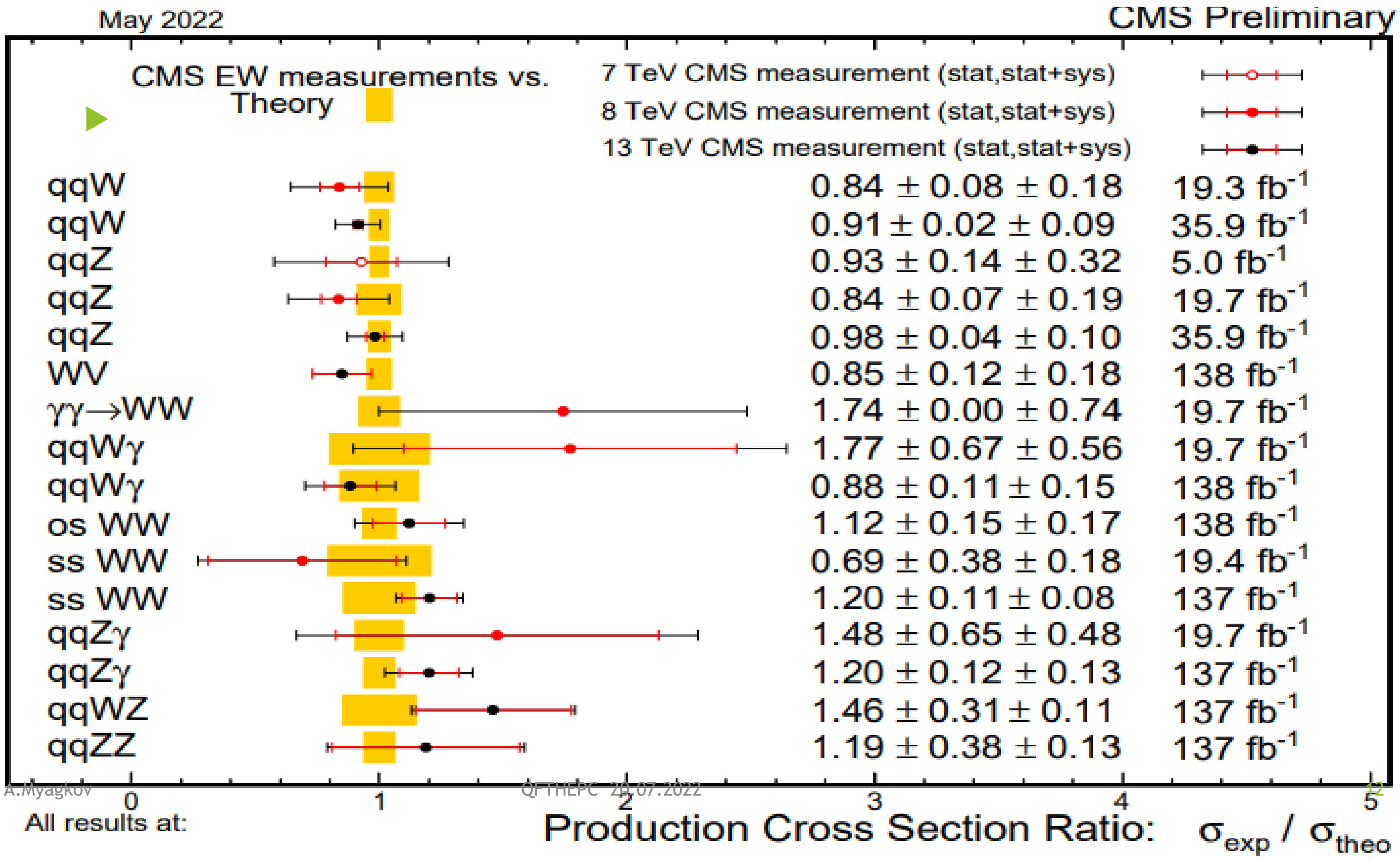


Current precision on inclusive cross-sections: typically few percent over almost 14 orders of magnitude!

Main SM processes and measured X-sec



Measured X-sec vs theory



ATLAS first observation of production *WWW*

arXiv:2201.13045v1

Measurements of triboson production are a direct test of SM gauge boson self-interactions, deviations would hint at NP

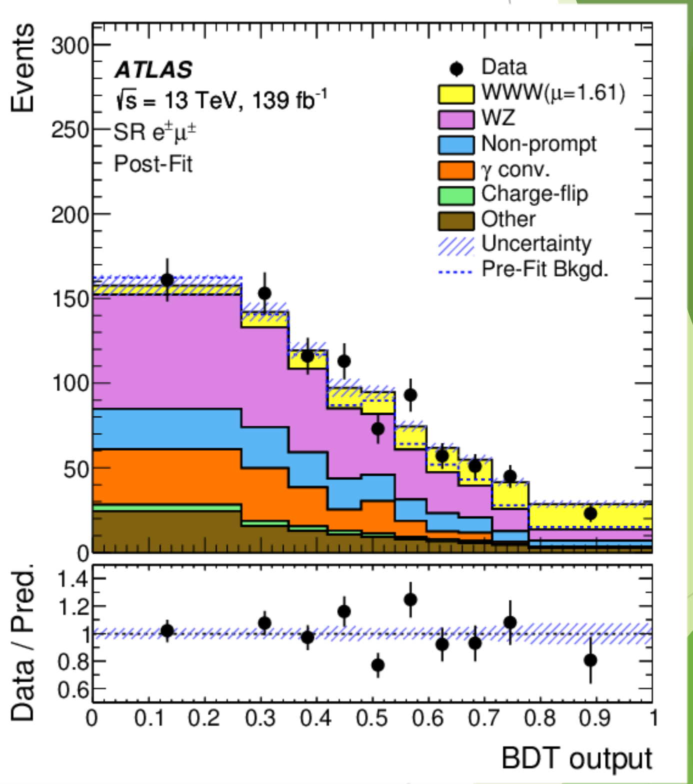
•Triboson states are among the least-understood SM processes given the small production cross sections

• WWW production looked for by ATLAS in 2l (SS) and 3l states

Observed for first time with a significance of 8.0 σ (5.4 expected)

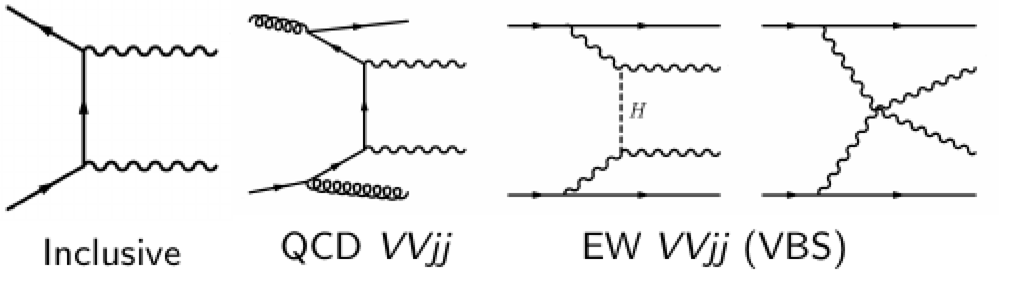
σ WWW(incl) = 820 ± 100(stat) ± 80(syst) fb

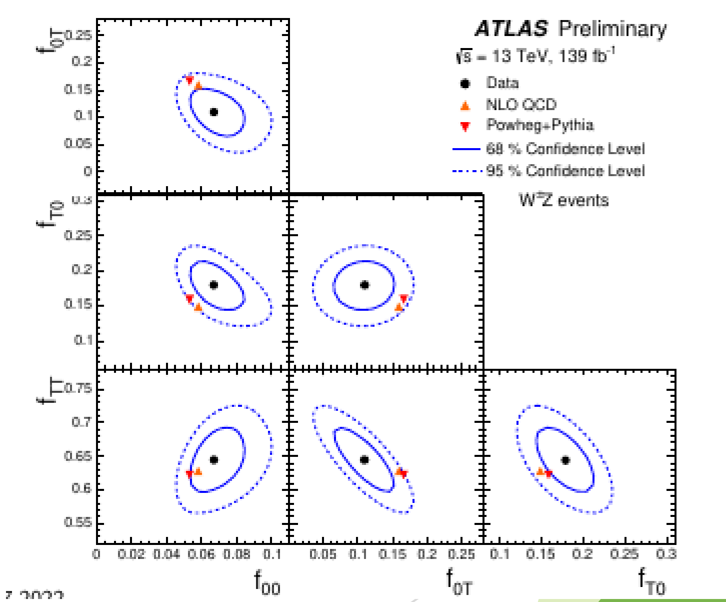
compatible with SM at 2.6 σ (SM: 511 ± 18 fb)



WZ (lvll) polarisation
ATLAS-CONF-2022-053, arXiv:2110.11231 (CMS)

- Electroweak VVjj production can proceed in transverse (T) or longitudinal (0) polarisation states
- Longitudinal (00) component intertwined with Higgs mechanism VBS unitarization: long term goal
- Probes for the HL-LHC
- currently measurements focus on polarisation or VBS
- New: first measurement of joint polarisation states in inclusive WZ production by ATLAS using DNN
- reconstruction techniques – observation of double-longitudinal component with > 7σ



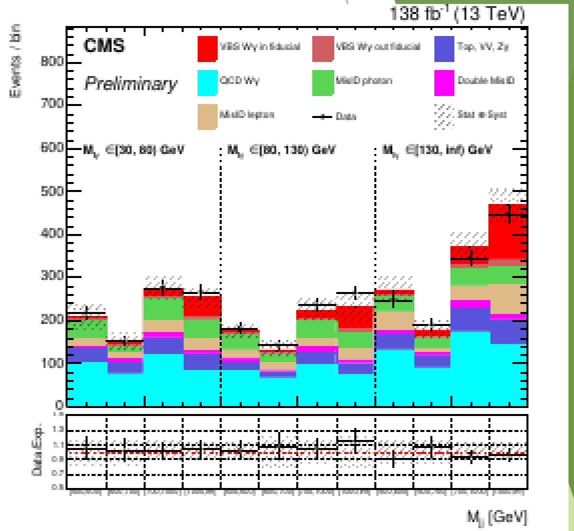


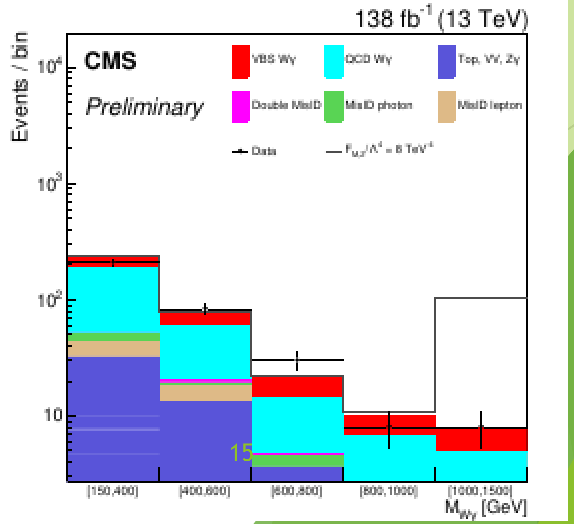
Measured joint helicity fractions f00, f0T, fT0 and fTT of the W and Z bosons in W±Z events, compared to NLO QCD fixed-order predictions

VBS Measurements - W (lν)γ   CMS-PAS-SMP-21-011

- Vector boson fusion and vector boson scattering are direct probes
- of boson interactions, both in Standard Model and beyond
- EW Wγjj signal observed with a significance

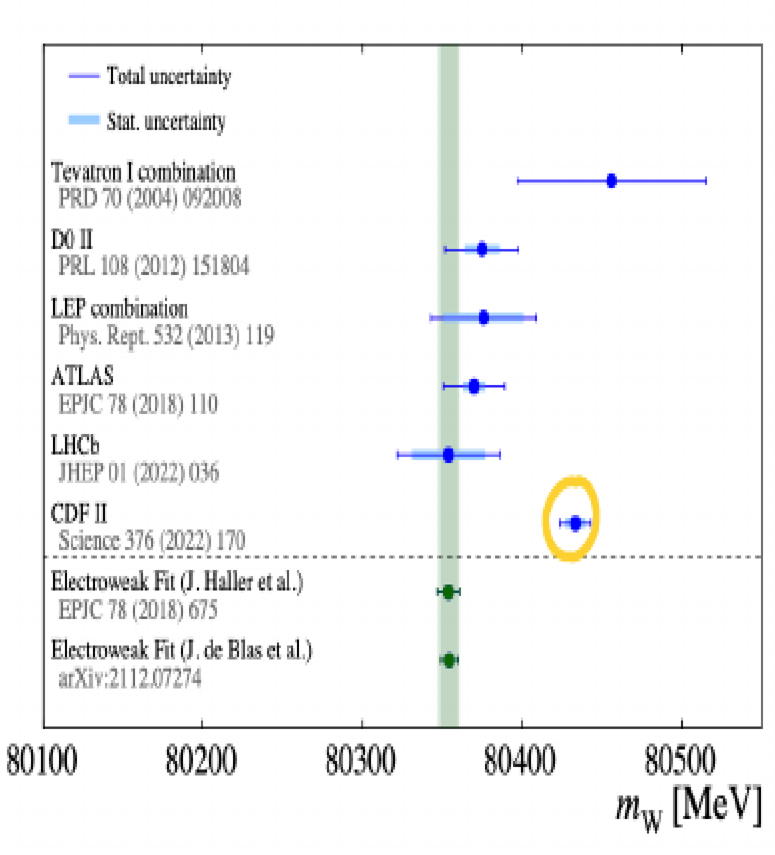
  6.0 (6.8 exp)
- cross section for the electroweak Wγjj production in a restricted region is 19.2±4.0 fb





W mass @ LHCb

- Measurement based on shape of p_T distribution of muons from W decay
- Simultaneous fit of q/p_T of muons from W and of φ^* of $Z \to \mu\mu$
- $m_W = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 9_{PDF}$ MeV
- Important because LHCb probes an acceptance region complementary to that of ATLAS/CMS

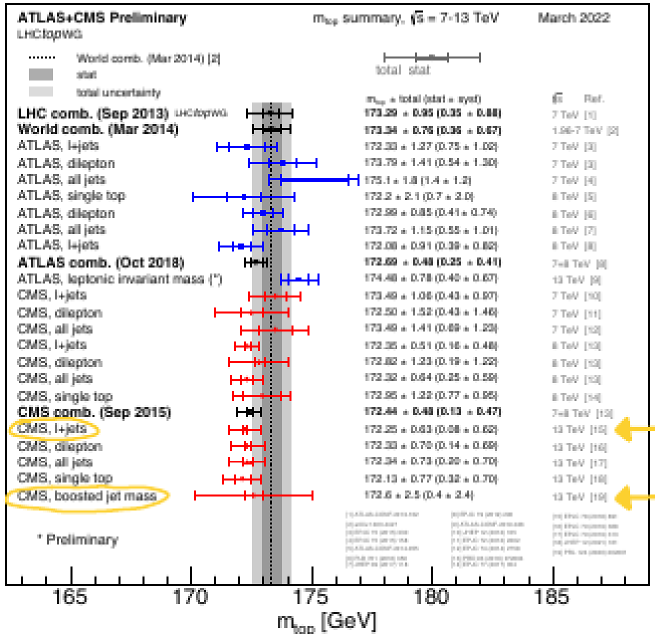


- **Still waiting for CMS result!**

The top mass

Direct mass measurements

- Measure m_t^{MC} from reconstructed decay products
- Very high exp. precision : ~0.5 GeV
- Uncertainty in relation to theoretically well-defined mass $\mathcal{O}$(0.1-1) GeV



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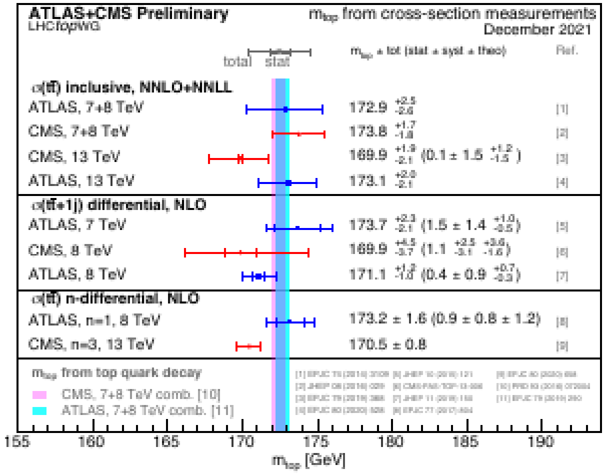
Indirect mass measurements

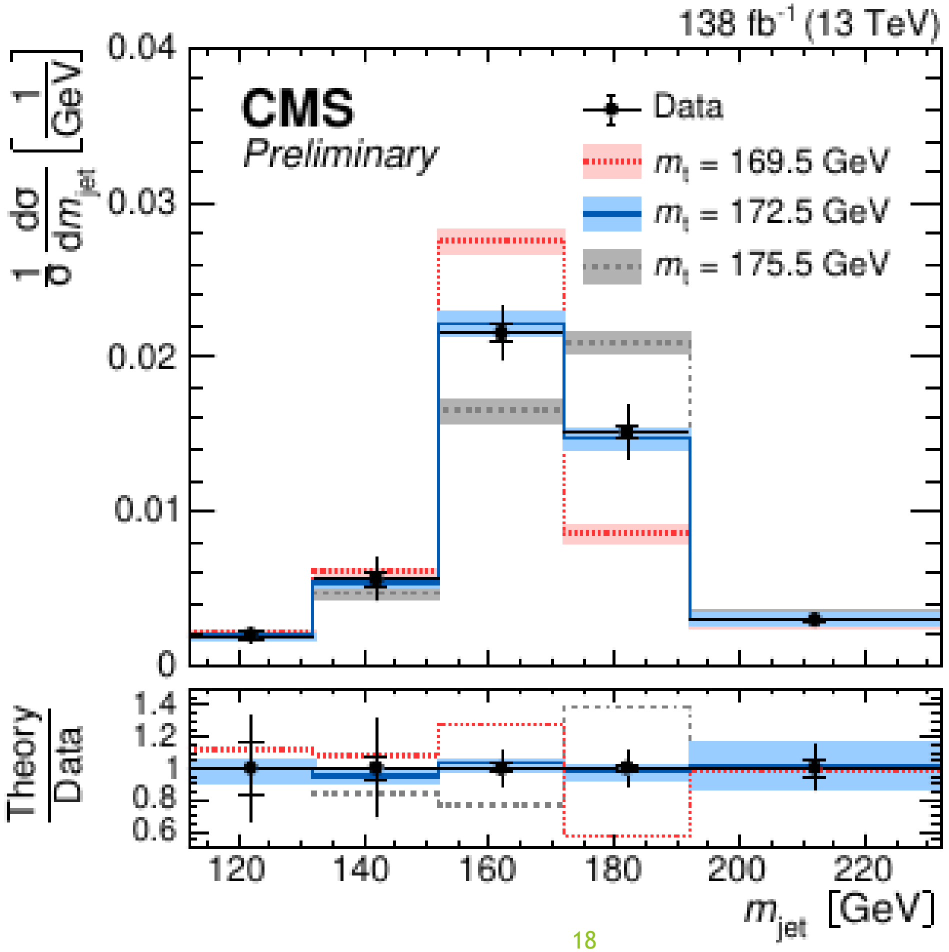
- Extract m_t in well defined renormalisation scheme (pole, $\overline{\mathrm{MS}}$)
- Measures cross section, either inclusive or differential, corrected for detector effects, and compare to analytical calculations.
- Unfolding of detector/hadronization effects typically yields bigger uncertainty : 1-2 GeV



Top quark mass (CMS)

- Direct measurement with 5D fit constraining jet uncertainty from W peak m_t=171.77 ± 0.38 GeV
- Measurement from tt+jet cross section
- m_t^pole=172.94± 1.37 GeV
- Measurement of mass distribution and
- m in hadronic decay to boosted jets
- m_t = 172.76 ± 0.81 GeV

- Boosted jets (tt¯l+jets) | 2016-2018 data



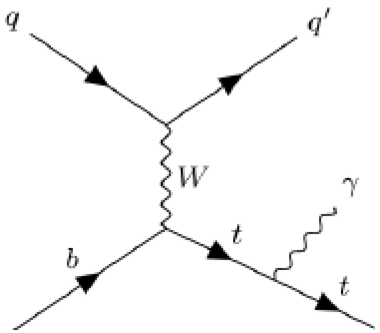
Rare single top production ATLAS-CONF-2022-013 ATLAS-CONF-2022-031

- Rare single top process observation
- Tqγ Single-top quark and a photon of all single-top processes
- Powerful probe of top-EW coupling

(and constraints on new physics)

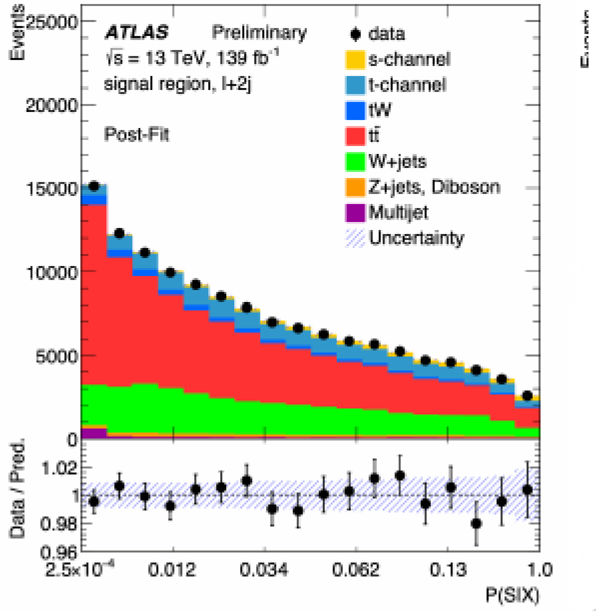
- semileptonic top-quark decays ($t \to l\nu b$)
- The observed (expected) significance

of the tqγ signal is 9.1σ (6.7σ)



S-channel single top production

Lowest cross-section measurement



3.3σ Observed (3.9 σ expected)

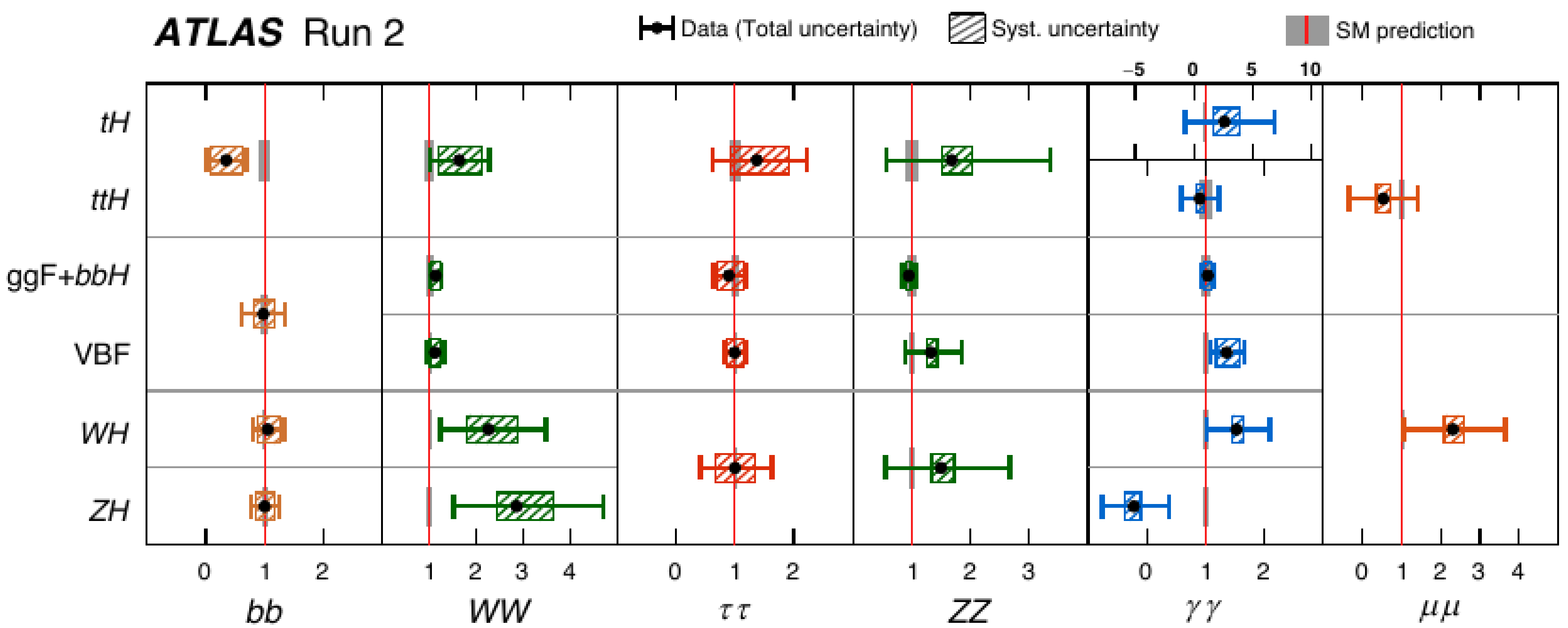
Higgs boson

Monday 4 Jul 2022, CERN

2207.00043 A portrait of the Higgs boson by the CMS experiment ten years after the discovery

2207.00092 A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Coupling in productions and decays



For decay BR:

- H→WW, ττ, ZZ, γγ now all at precisions between 10% and 12%
- H→bb observed with 7.0σ (7.7σ)
- H→ μμ with significances of 2.0σ (1.7σ) and Zγ with 2.3σ (1.1σ)

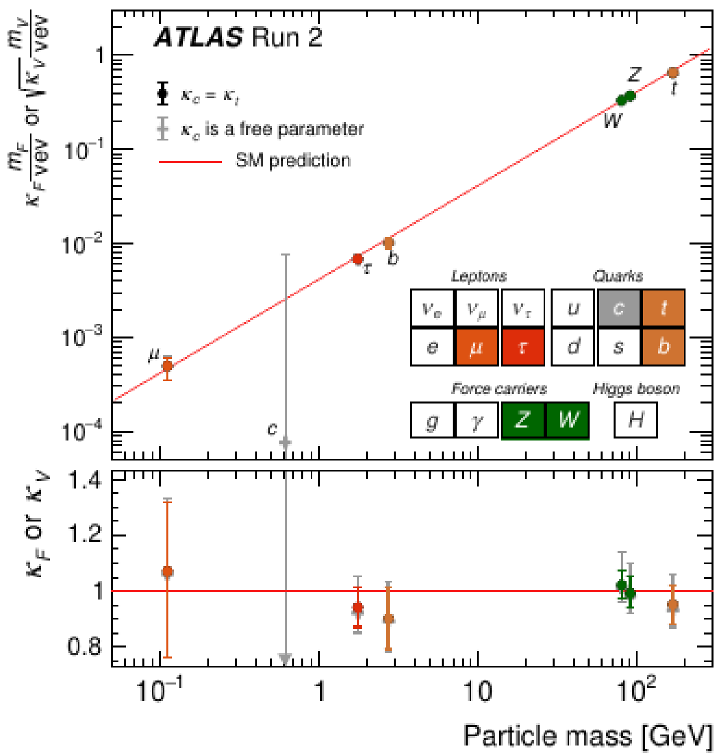
Higgs couplings and H->cc (CMS)

DeepJet: charm tagger for AK4 jets
Charm jet properties are in-between udsg and b-jets
DNN multiclasifier is used to tag the AK4 jets: DeepJet
Efficiencies of the Working Point (for jet with highest charm-tag score):
 42% c-jet eff
 15% b-jet mistag rate
 4% light jet mistag rate

CMS has released two H→cc analysis with full Run-2 dataset

- ggH(cc):
  - Exploring H+jet topology with boosted large-cone jets
  - Limit set at 45xSM
- VH(cc)
  - Using two complementary approaches to fully explore the VH(H→cc) decay topology (AK4/AK15 jets).
  - Limit set at 14xSM; 1.1<|kc|<5.5 (95%CL interval)

 Most stringent limit to date



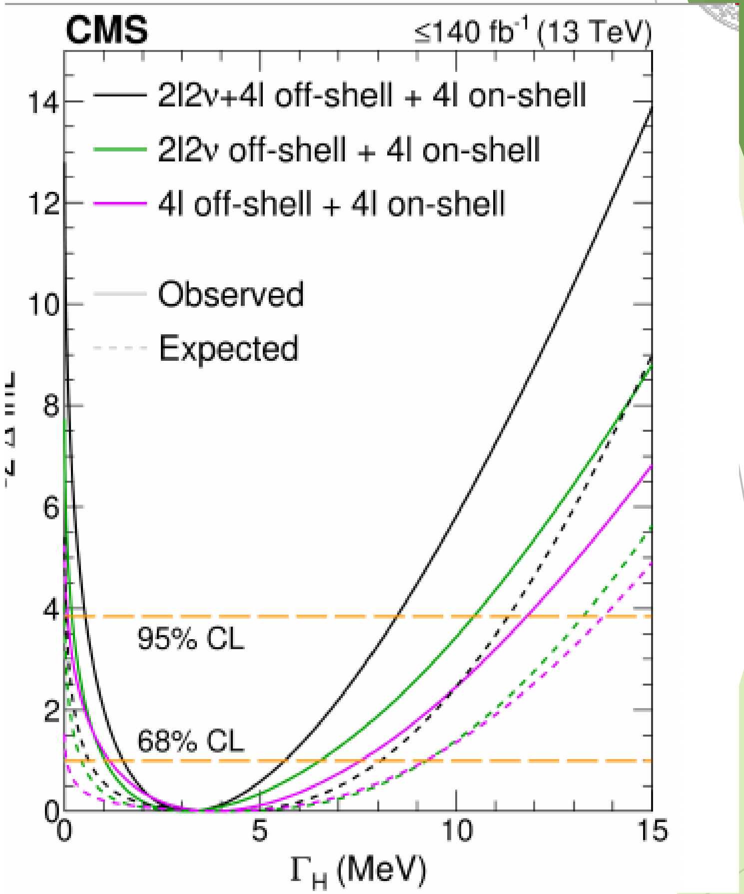
Mass range probed covers 3 orders of magnitude !

Higgs Boson Width

- Expected width: Γ= 4.1 MeV
- Direct limit: ΓH < 1.1 GeV
- $\sigma = \int \frac{1}{(s-m^2)-(\Gamma_H m_H)^2} g_i^2 g_f^2$

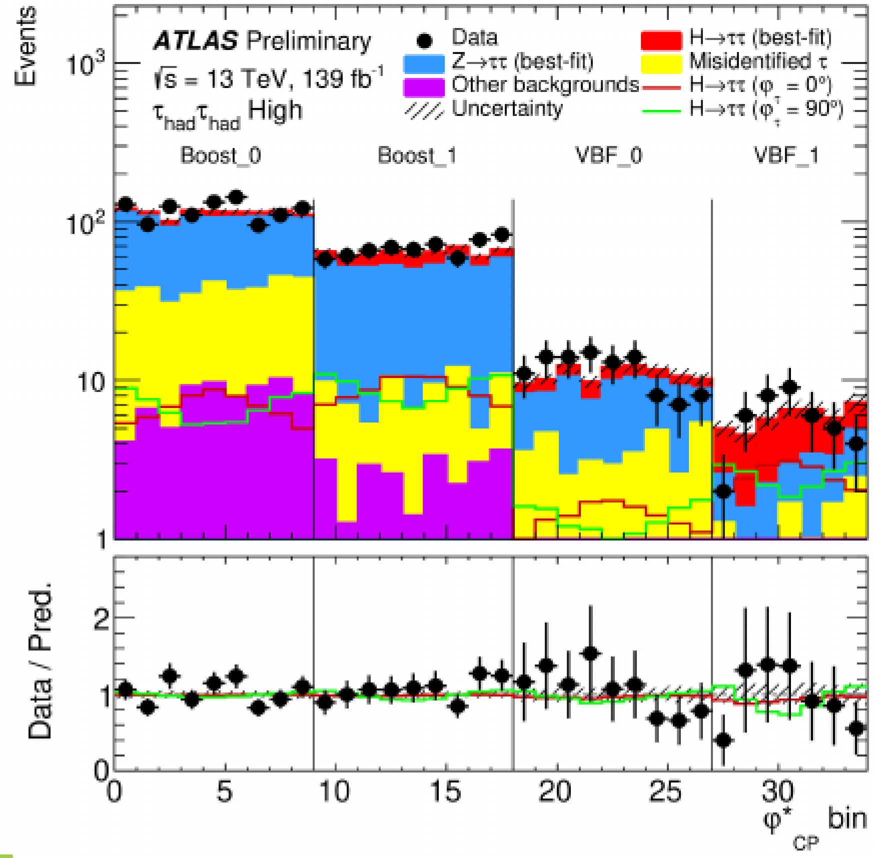
Off-shell data 2l2ν, on-shell 4l

- 117 multidimensional distributions were used in the fit
- $H\ H \rightarrow ZZ(*) \rightarrow 4\ell\ 2\ell 2\nu$
- From a combined measurement of on-shell and
- off-shell production CMS finds
- evidence for off-shell Higgs production, scenario with no
- off-shell production is excluded with 3.6 σ
- Γ_H = $3.2^{+2.4}_{-1.7}$ MeV [arXiv:2202.06923]



CP properties Higgs boson

- ATLAS-CONF-2022-032
- H → τ+ τ- (at least one decay hadronically)
- CP-sensitive angular distribution was measured

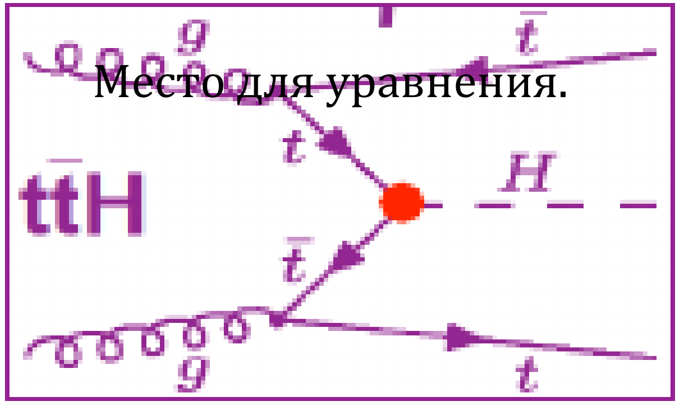


Pure CP odd (φ τ = ± 90∘) disfavoured at 3.4σ

CMS-PAS-HIG-21-006

CP structure Yukava interaction between Higgs and one or two tops was measured

Fractionally CP-odd contribution not observed

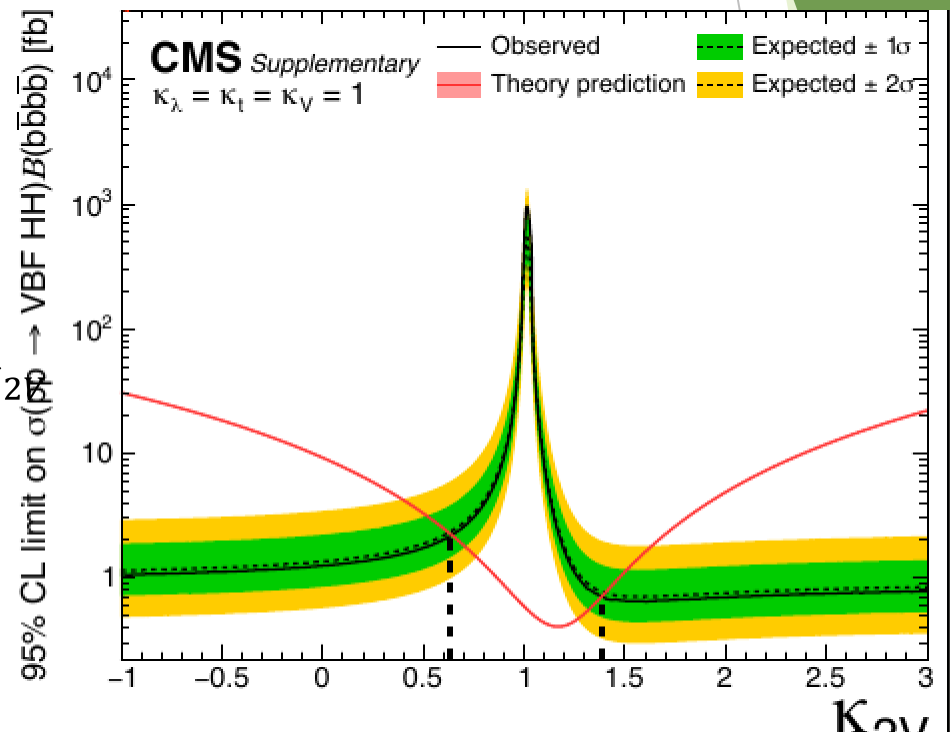


Pure CP-odd coupling excluded at 3.7 σ

Search for Higgs boson pair production (CMS)

The trilinear self-couplings of the Higgs boson can
Be extracted in the process of pair production.
Search was done for the ggF and VBF mechanisms.
HH -> bbττ and HH → bbbb
BRSM(HH → bbbb) = 33% -> ~1400 events in 138 /fb

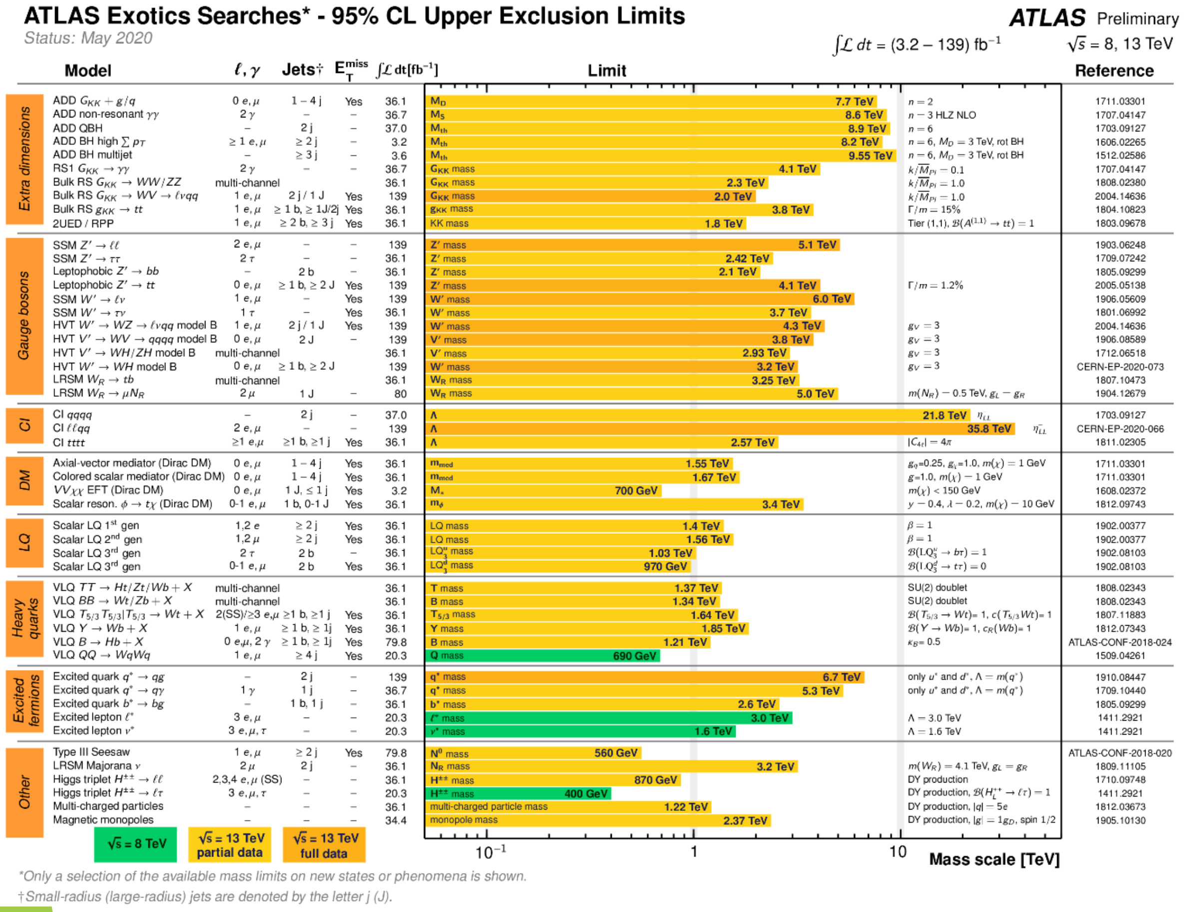
Limits on coupling modifiers k_λ for HHH (ggF) and for k_{2V} for VVHH (ggF and VBS)

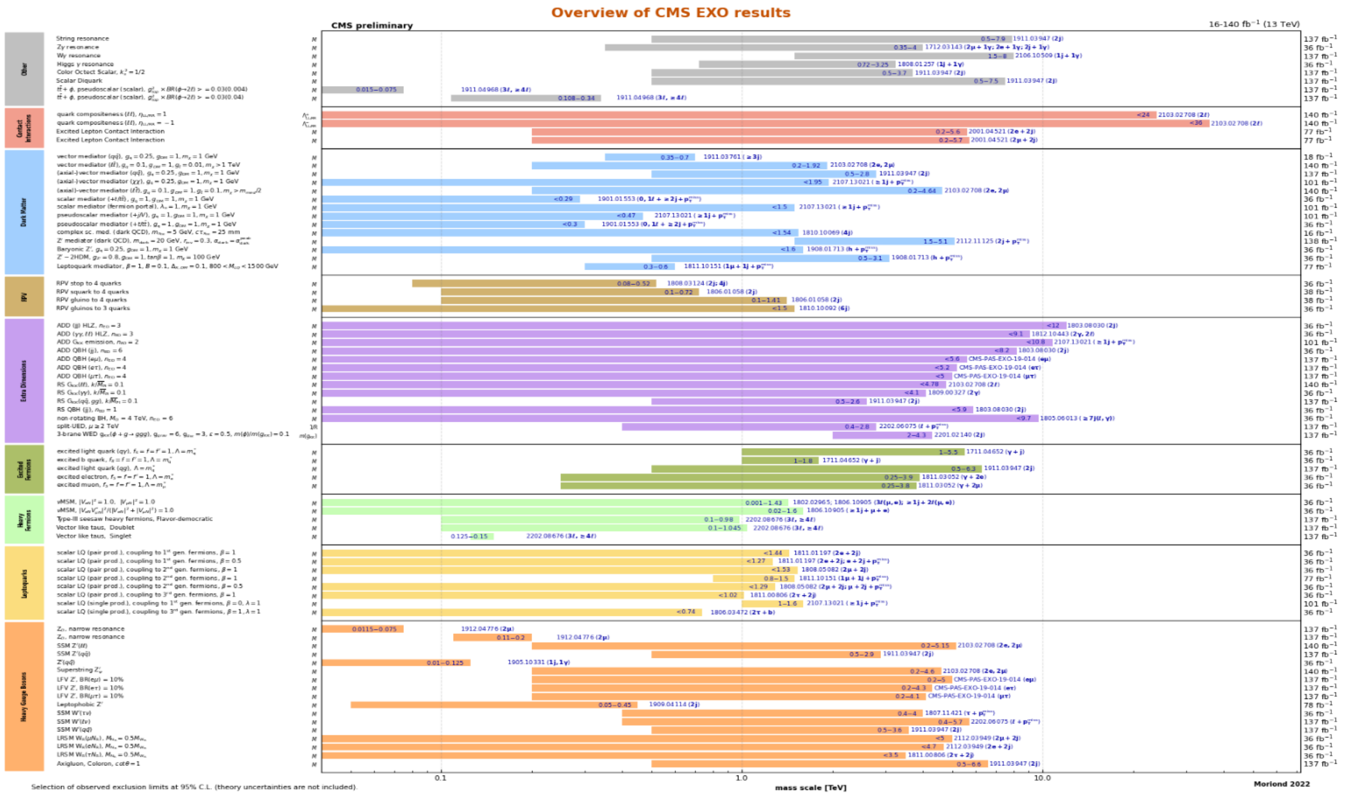


$0.62 < \kappa_{2V} < 1.41$

$(0.66 < \kappa_{2V} < 1.37)$ @ 95% CL

Heavy Resonance Searches

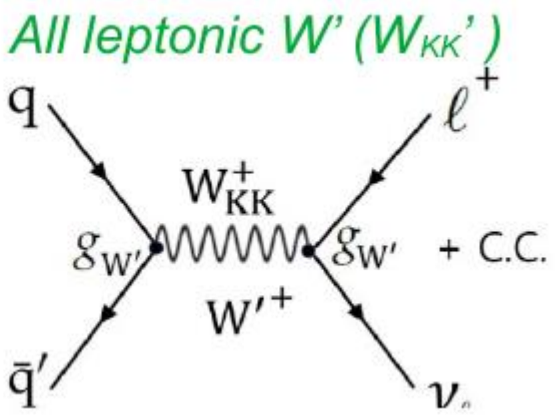


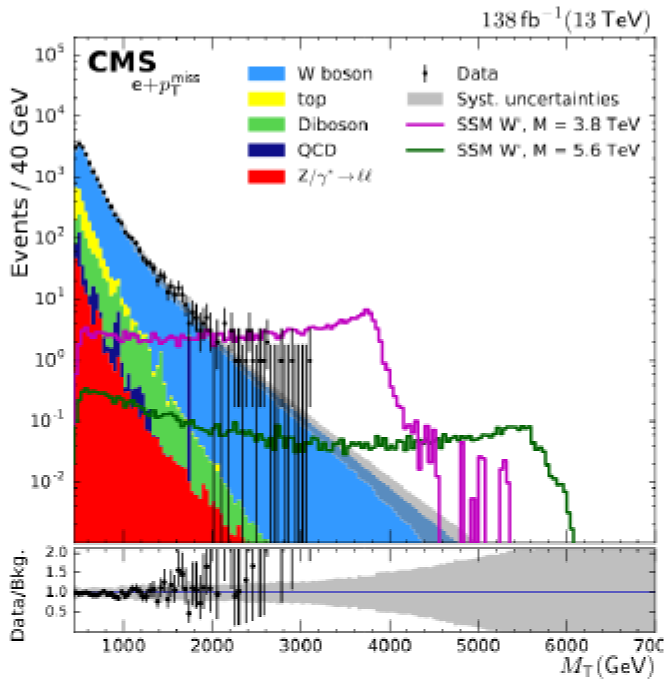


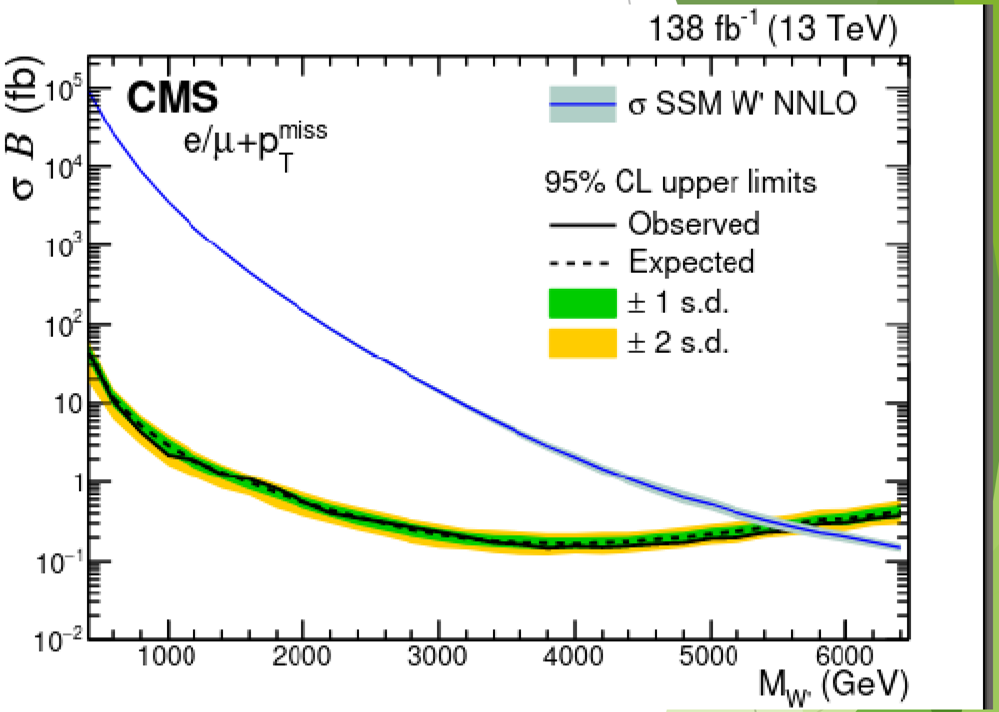
Heavy-resonance searches

- ~100 decay channels studied for various models that predict certain production rate (extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks etc)
- \- Commonly excluded masses ~ **0.4 – 12 TeV**

Searches for W' heavy bosons







CMS arXiv:2202.06075

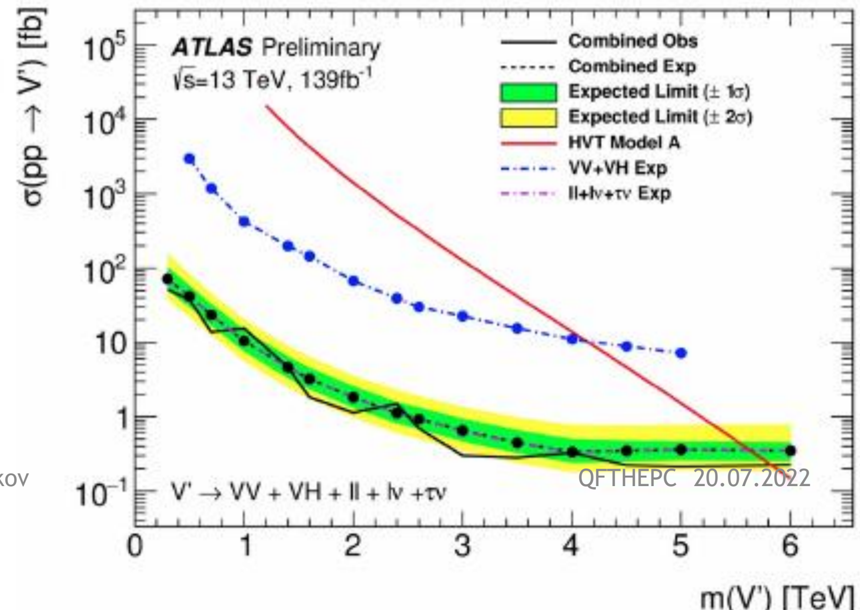
use transverse mass (m T) calculated from charged lepton and the missing transverse momenta

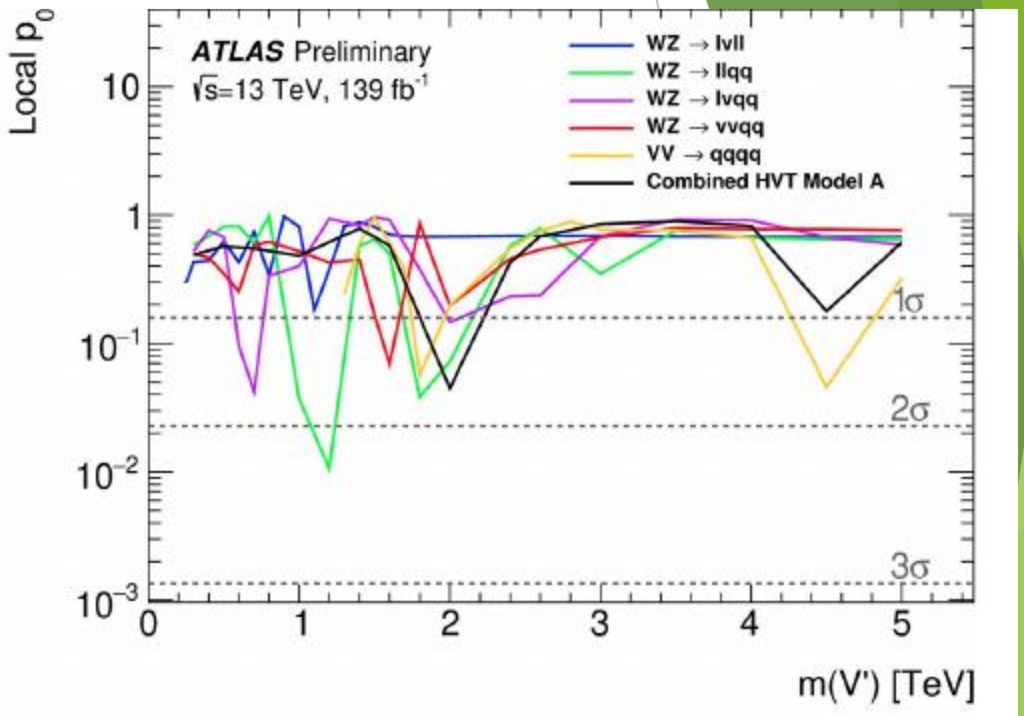
LHC data exclude M(W'): < 5.7 TeV

Combination of searches for heavy resonances

- ATLAS-CONF-2022-028
- Uses 16 (orthogonal) ATLAS publications during 2018 - 2022
- Combine bosonic decay modes qqqq, vvqq, lvqq, llqq, lvll, qqbb, vvbb, lvbb
- Results are interpreted in terms in the context of Spin-1 Heavy Vector Triplet (I
-

Weakly coupled HVT-A coupling

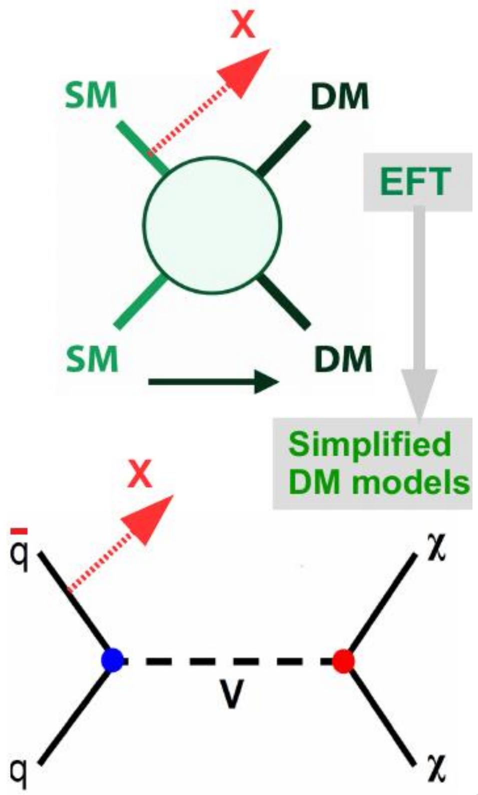




Typical example of p-value scan over the HVT pole masses up to 5 TeV

Searches for Dark Matter (DM) at the LHC

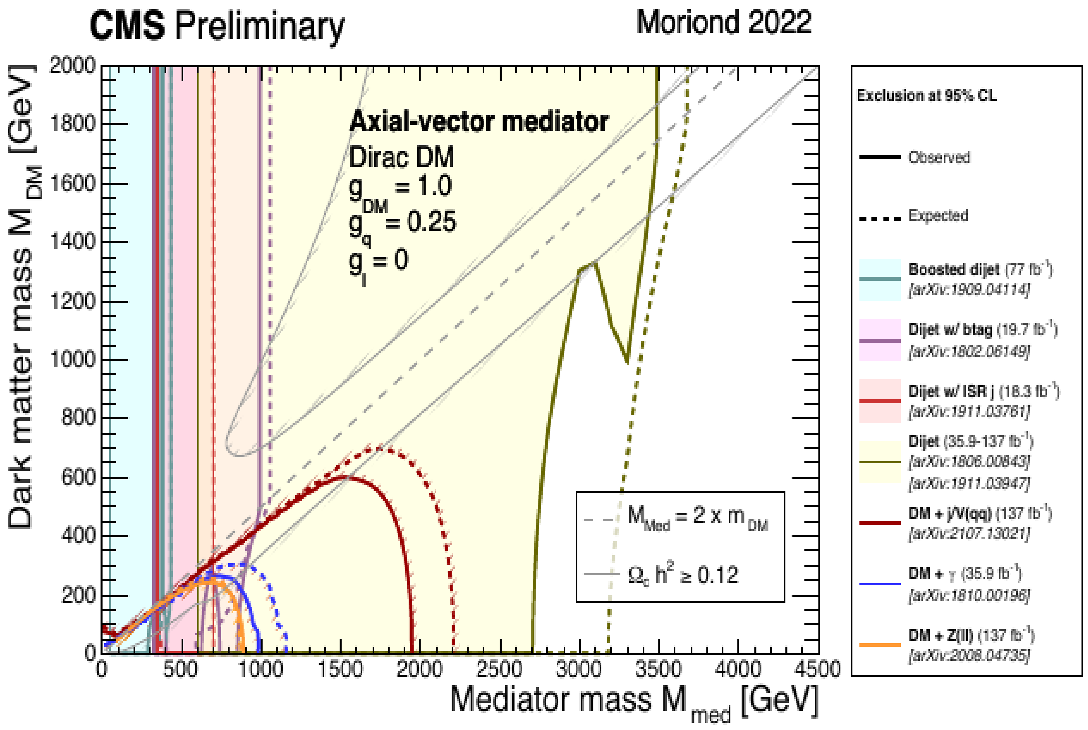
LHC collides pp under well-controlled conditions
SM particles can radiate other SM particles “X” (via ISR)
Undetected DM → imbalance in transverse momentum

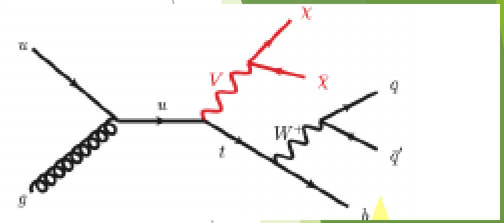


Adopt simplified DM model with a “mediator” V
gq (gDM) – mediator coupling to quarks (DM)
mmed (mDM) – mass of mediator (DM)
ATLAS & CMS: gq=0.25 (S=1), gq=1 (S=0), gDM =1
Γ=minimum width formula

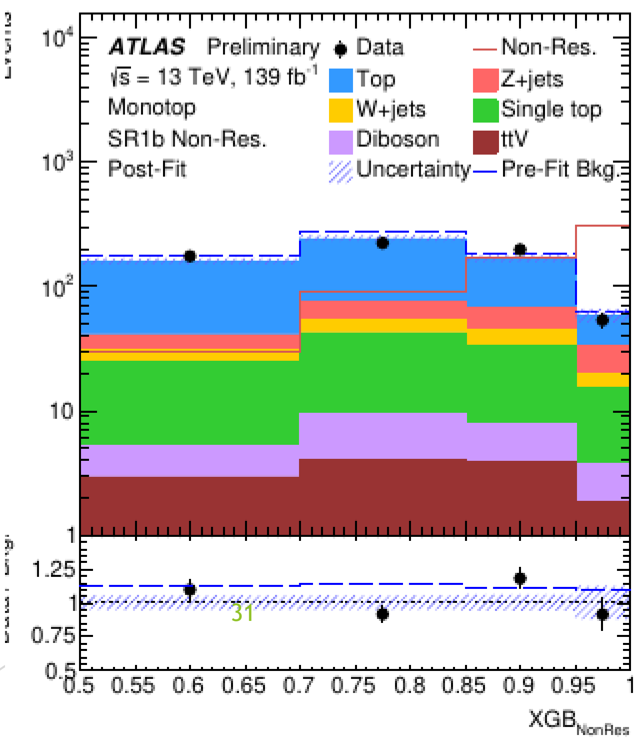
Dark Matter

Searches for mono-top production
fully hadronic final state
mass reach for V mediator ~ 2.5 TeV
probe also non-resonant model

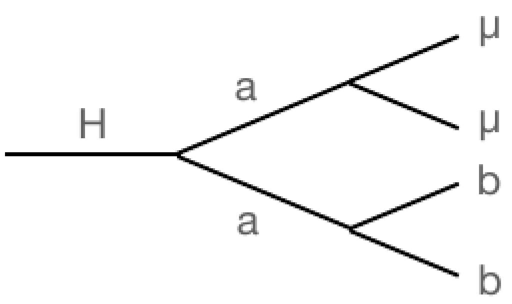


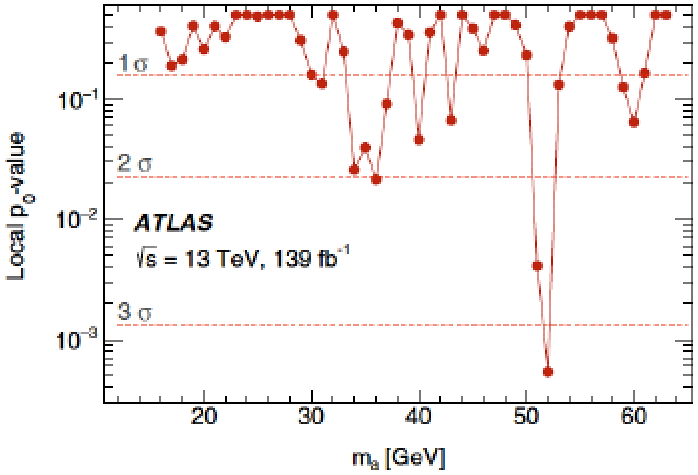


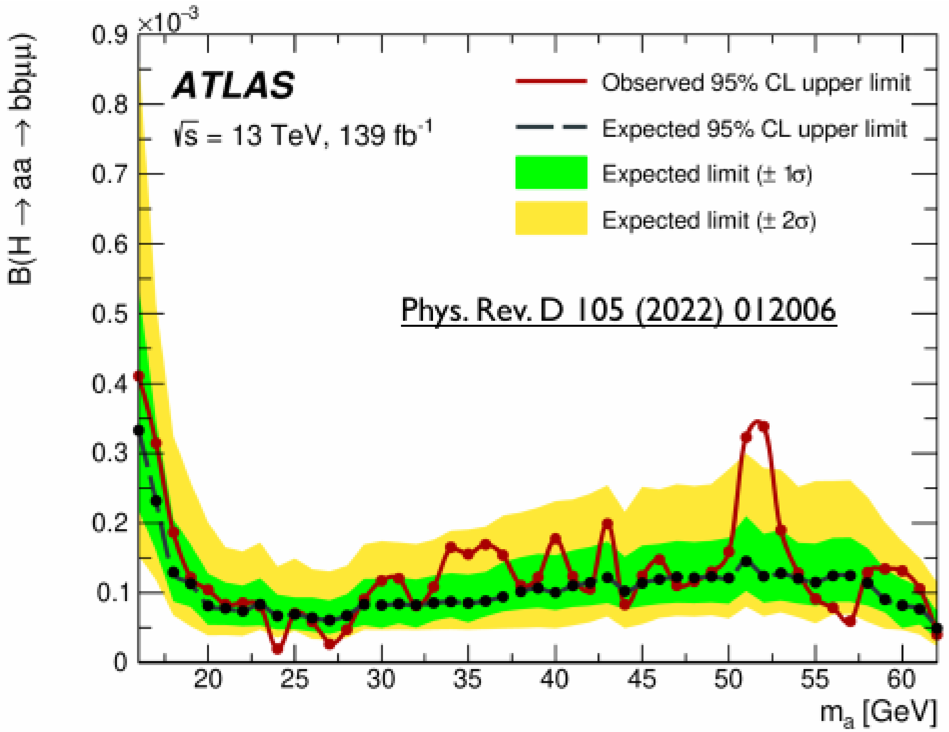
ATLAS-CONF-2022-036



Exotic Higgs: nMSSM







Long-lived Particles

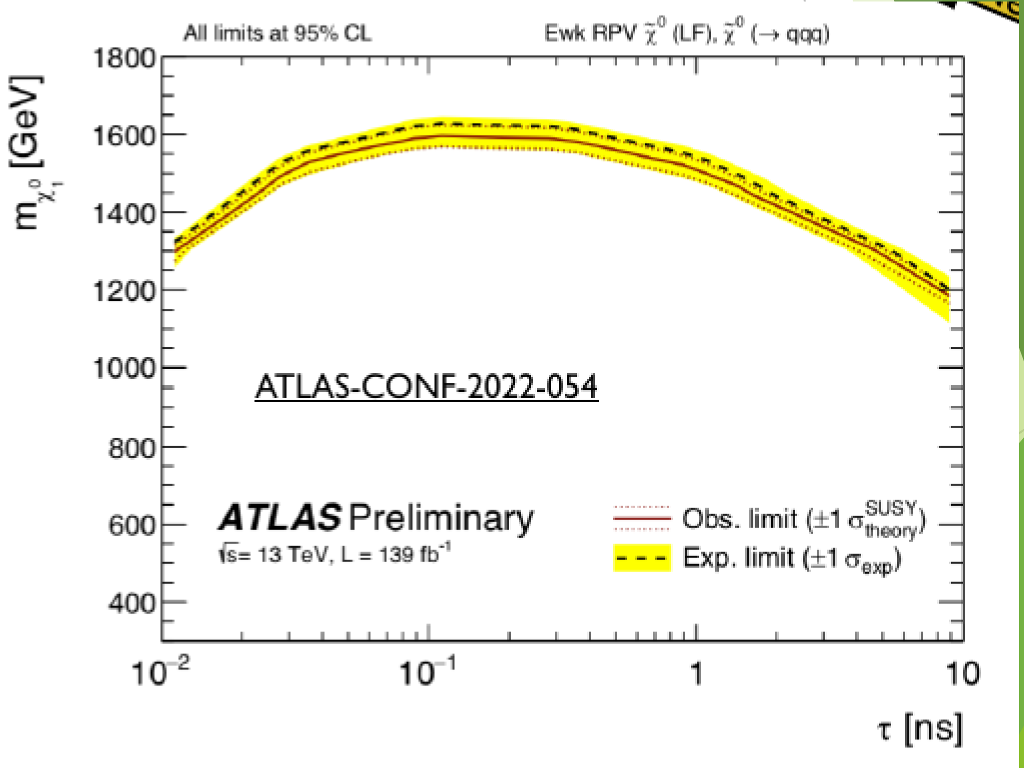
- LLPs arise in models of SUSY (compressed spectra or weakly-coupled RPV),
- Hidden Valleys, QCD axions, dark matter, dark portal particles, heavy neutral
- leptons...Very popular experimental topic in the last years!

- LLPs at LHC:
- - displaced vertices
- - long time-of-flight
- - unusual energy deposits

- Large radius tracking ATL-PHYS-PUB-2017-014

- ATLAS: search for displaced vertices

plus jets signatures

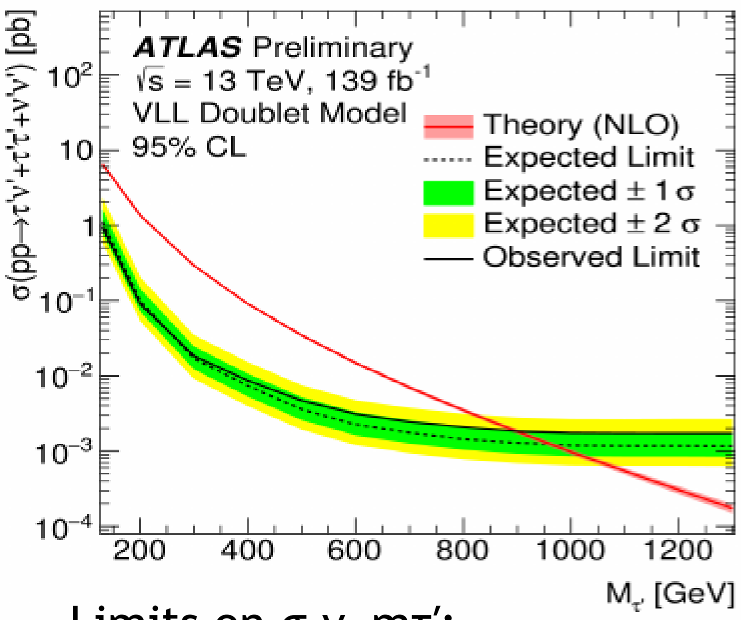


Vector-like Quarks and Leptons

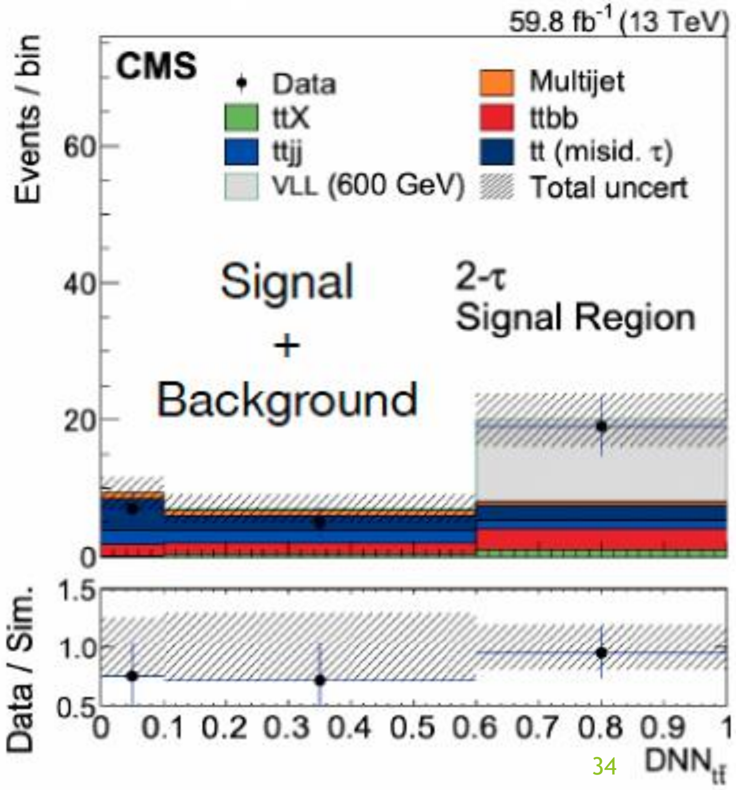
- Higgs- good agreement with SM: Hard to accommodate new particle masses.

• Vector-like fermions: Dirac masses— decouple from EWK scale at large mass.• Motivated by string theory or extra dimensions.

Additional motivation from recent B flavor anomalies. Relevant: Searches for 3rd gen L!



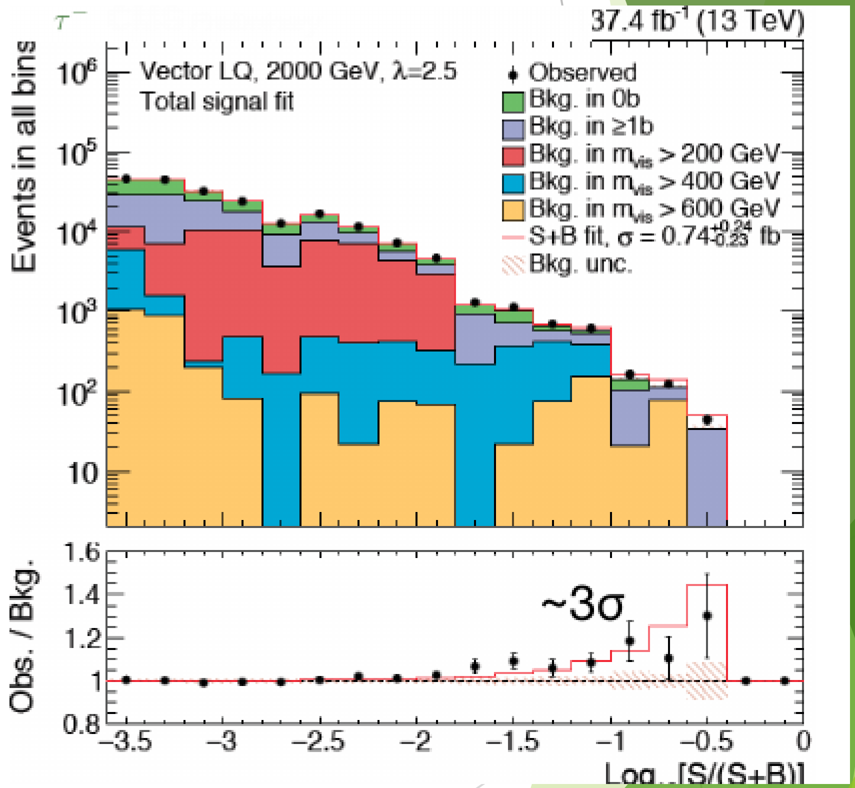
Limits on σ v. mτ':
967 GeV (exp) / 898 GeV (obs)



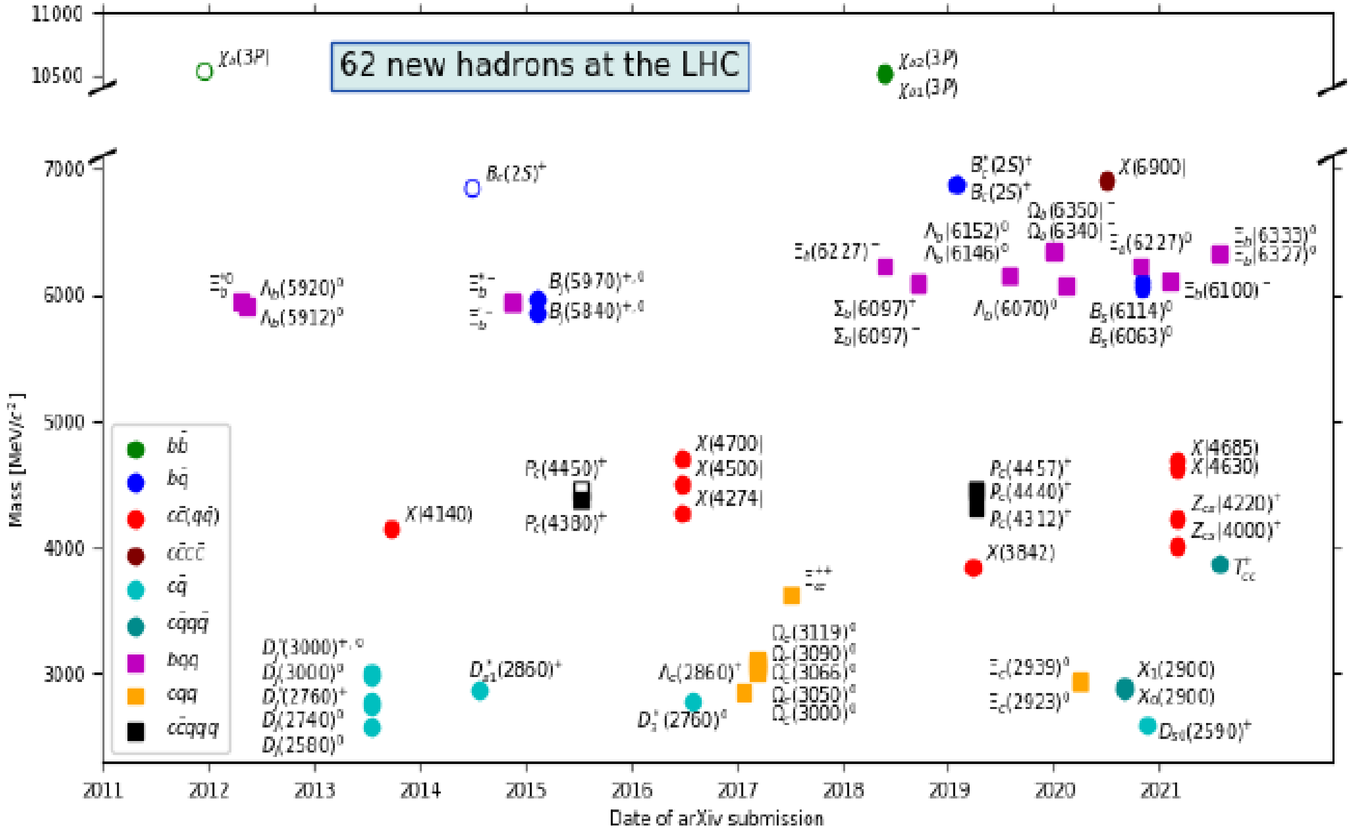
CMS: new search for combined b-tau LQ production

- CMS-PAS-EXO-19-016
- Events with τ leptons and at least 1 b-jet selected
- Targeting the single and pair production of LQ
- limits on scalar and vector LQ with varied couplings

- slight excess (~3σ) in categories
- compatible with the H→ττ
- Result driven by non-res categories



LHCb

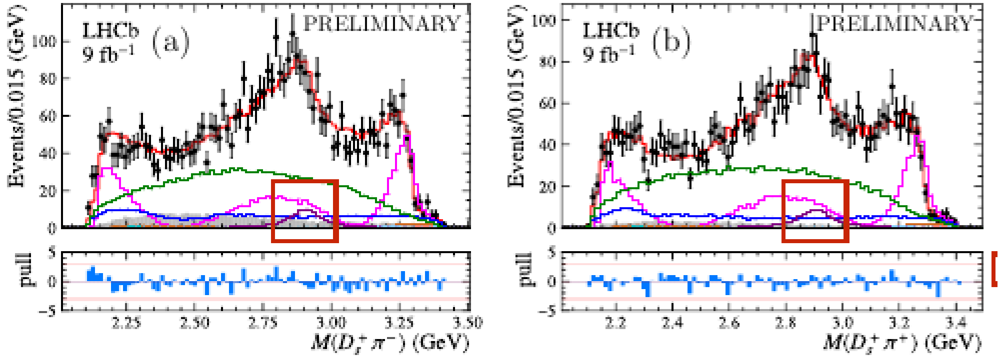


New hadrons that are discovered by the LHC experiments

LHCb report the observation of new exotic states T_{cc}^{+} (3875) a
)

New tetra- and pentaquark states (LHCb)

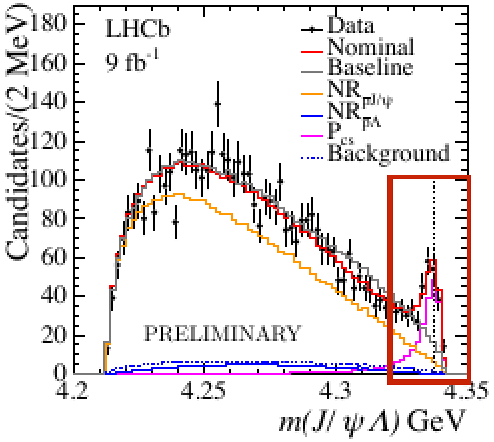
Isospin pair of doubly charged and neutral tetraquarks:



Narrow peak in the mass spectrum $D^0 D^0\pi+$
State consistent with ccud
Very narrow state, slightly below $D^{*}+D^0$
arXiv:2109.01038
arXiv:2109.01056

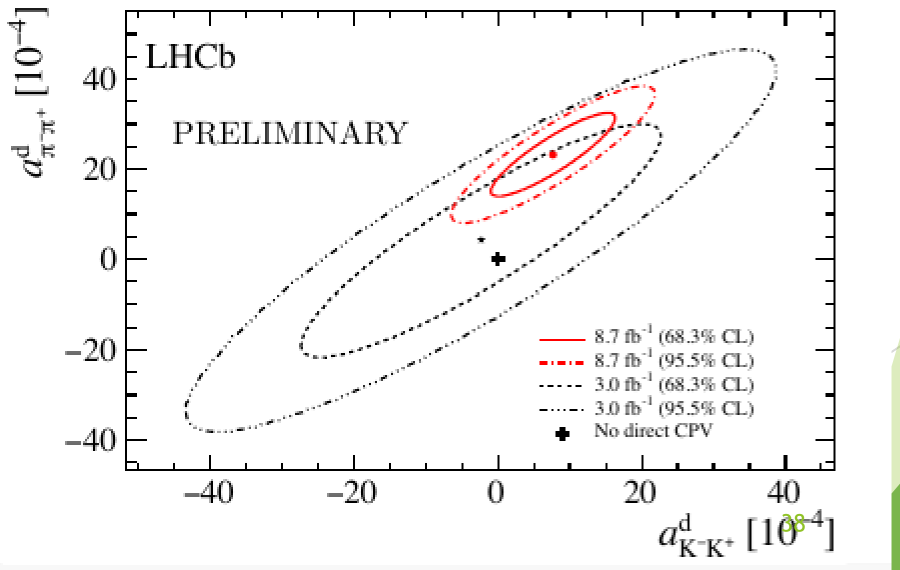
Double heavy spectroscopy is now a fact in the LHC physics program!

First $P_{\psi s}^{\Lambda}$(4438) strange pentaquark
LHCb-PAPER-2022-031 (in preparation)



+ First charm CPV in single channel

- CPV in charm small in the standard model –> sensitive to new physics
- CPVin charm observed in time – integrated difference of CP asymmetries
- $\Delta A\,CP = A\,CP(K+K-) - A\,CP(\pi+\pi-) = (-15.4 \pm 2.9) \times 10^{-4}$
- New measurement of A CP(K-K+)=[6.8+-5.4(stat)+-1.6(syst)] 10^-4
- 3.8σ evidence for direct CP violation



Lepton Flavor Universality in the SM

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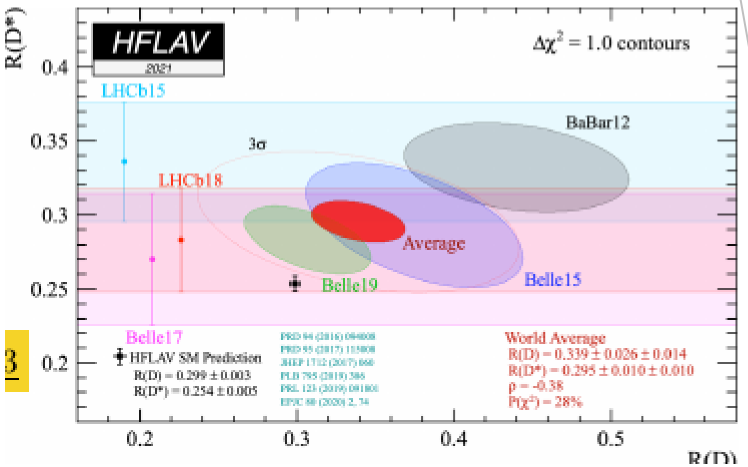
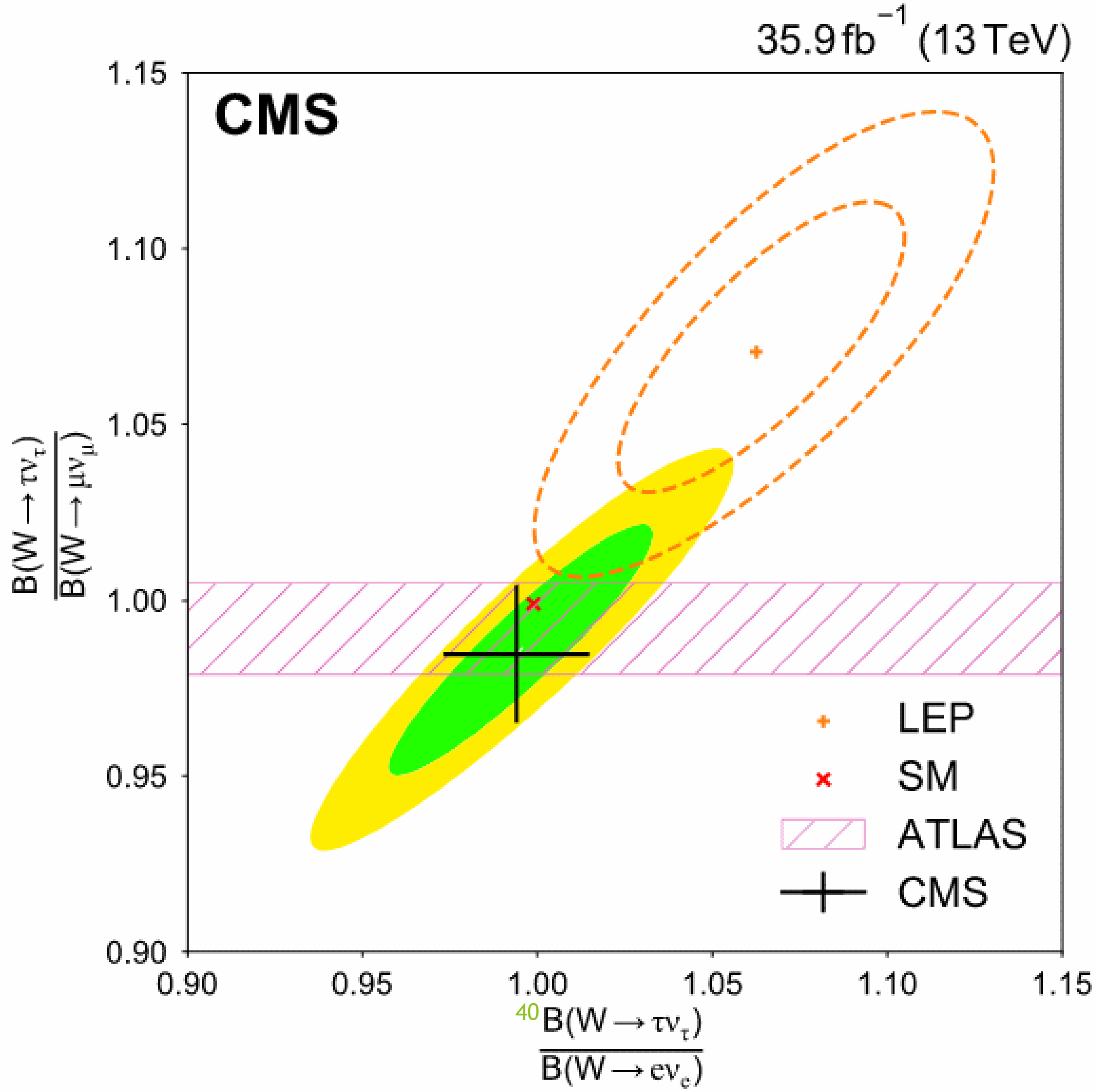
- In the Standard Model couplings of leptons to W,Z,γ are independent of flavor by axiom



- Some SM extensions include particles that can cause LFU violation (e.g. LQ, Z')
- Experimental investigation of LFU has been pioneered at LEP $(W \to l{+}\nu)$ and at the Bfactories $(R(D*))$[PRL 109, 101802] showed hints of a tension with the SM

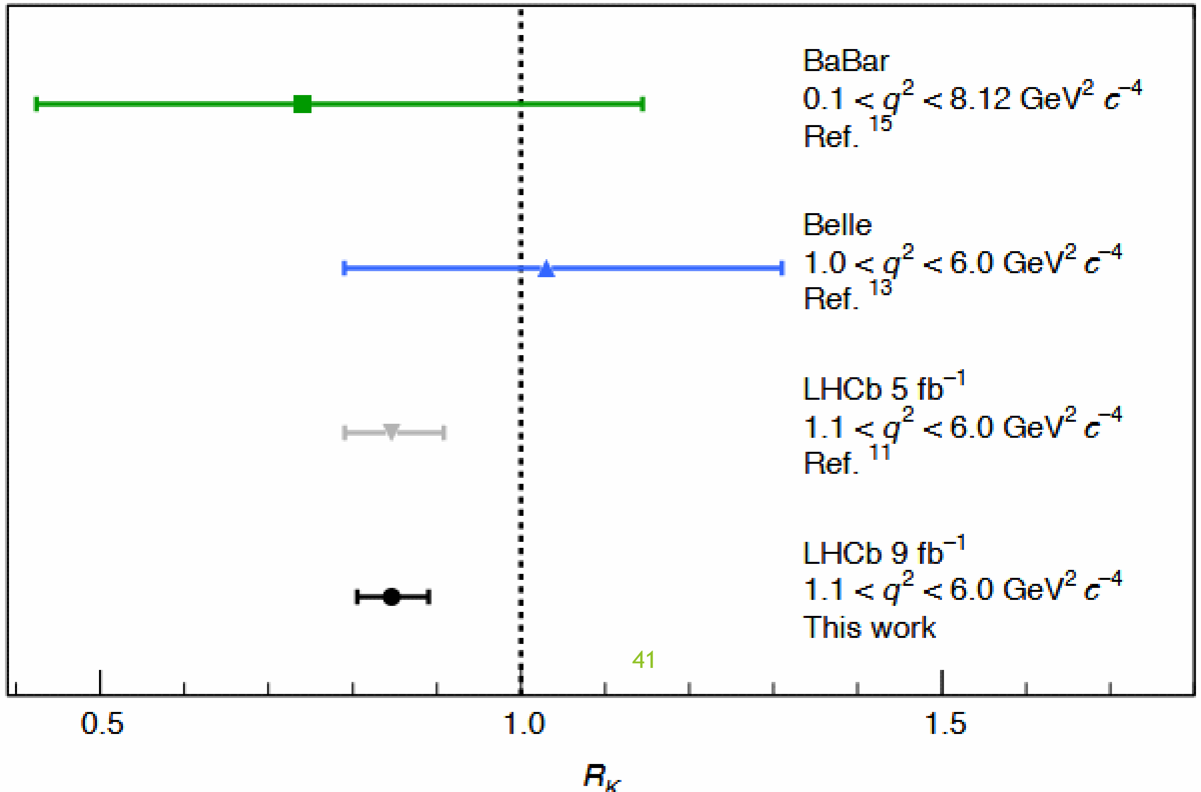
CMS test of LFU in in W boson decay PHYSICAL REVIEW D 105,) 072008 (2022)

A binned maximum likelihood estimate of the W boson branching fractions is performed simultaneously in each event category. The measured branching fractions of the W boson decaying into electron, muon, and tau lepton final statesare(10.83±0.10)%,(10.94±0.08)%, and(10.77±0.21)%, consistent with lepton flavor universality for the weak interaction.



LFU in $b \to sll$

- $b \to sll$ are FCNC, forbidden at tree level and therefore very rare
- LHCb has investigated $RK+$, $RK*0$, RpK, $RK**+$, RK
- Coherent set of b->sll tensions



QCD evolution via photon studies @ALICE

Prompt direct photons produced in initial hard-parton scatterings,

prior to the formation of the QGP

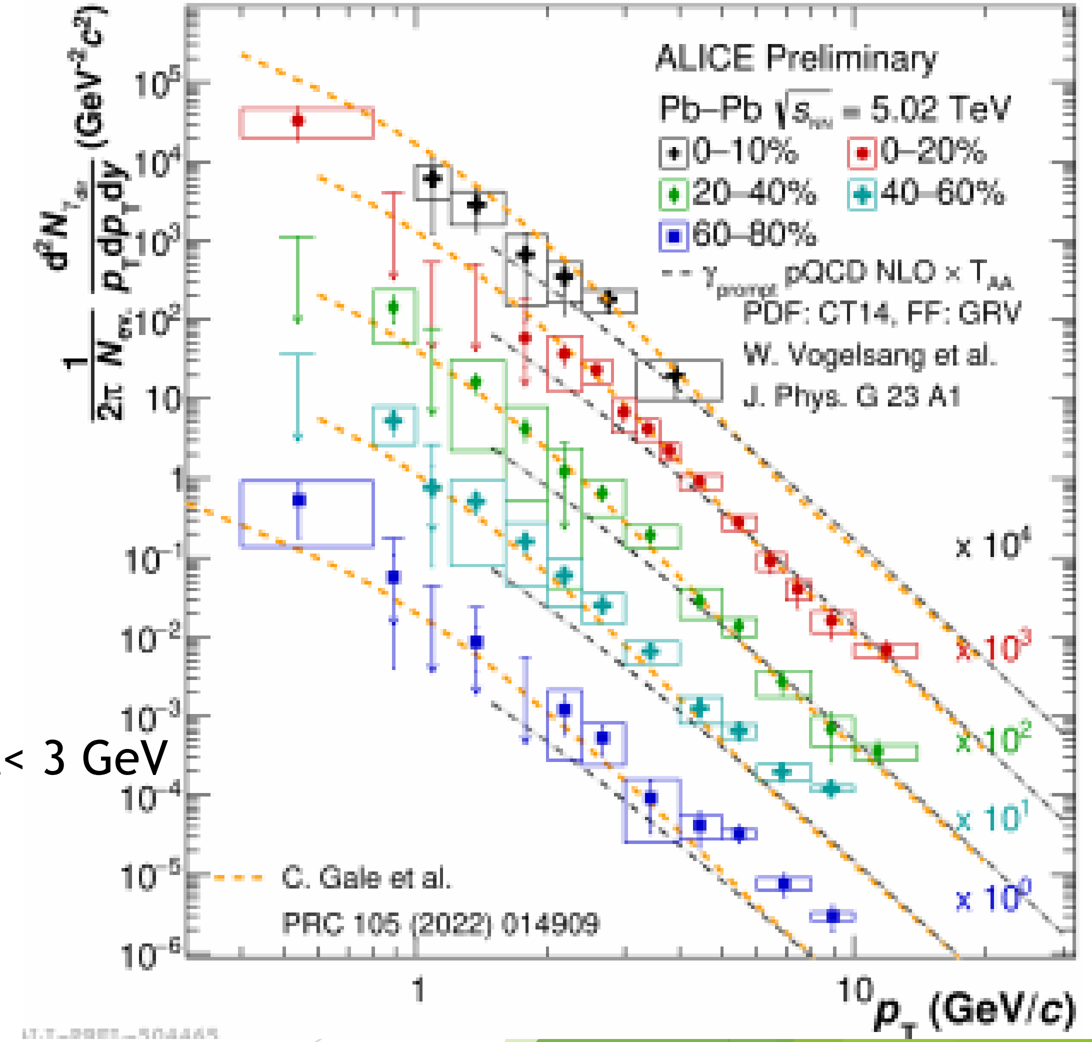
Thermal photons from QGP phase

Thermal photons from hadron gas

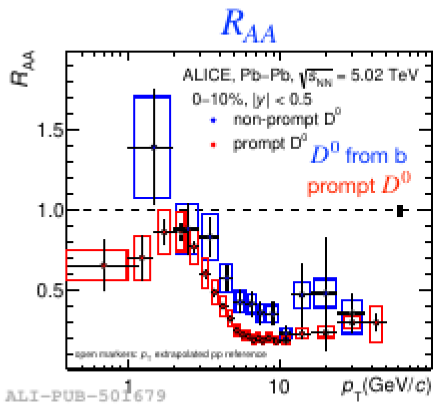
Thermal photons excellent probe for QGP temperature

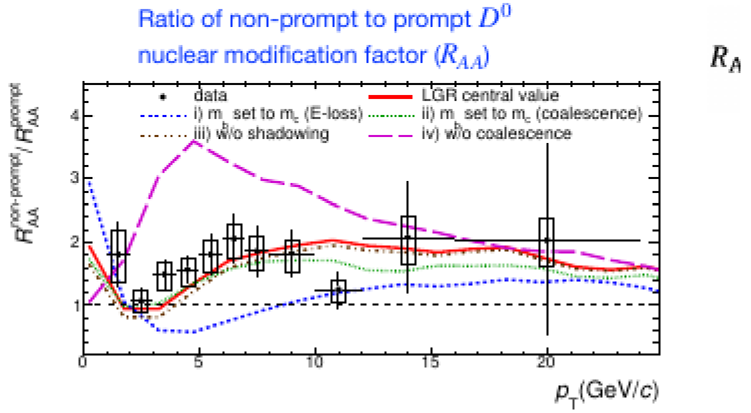
Extract effective temperature from slope of exponential photon

Photon spectrum well described by calculations that include
Prompt photons from hard scattering and thermal photons.
These calculations suggest a dominance of thermal photons at Pt< 3 GeV



Energy loss of charm and beauty quarks in the QGP@ALICE





[Nature 605, 440 (2022)]

Beauty R AA measured down to p T = 1GeV
ALI−PUB−501659
for the rst time ; large suppression for p T > 5GeV

Data well described by models that include collisional and radiative energy loss and quark recombination, in addition to
fragmentation as a hadronization mechanism

Anomaly Detection

- This is a unique time in history: we have no solid prediction of what might come next (unlike W/Z, top, Higgs). Robin Erbacher

- New approach: anomaly detection via
- • bump hunting (a la $H \rightarrow \gamma\gamma$) with background from data
- • unsupervised networks (autoencoders, adversarial nets, …)
- • weakly or semi-supervised networks

Conclusion

- Run3 is started 5 of July, ATLAS and CMS plan to add 250/fb to data
- Very broad spectrum of the tasks.
- Several hints give a hope.
- This is a great time to search for surprises!