Recent LHC Results

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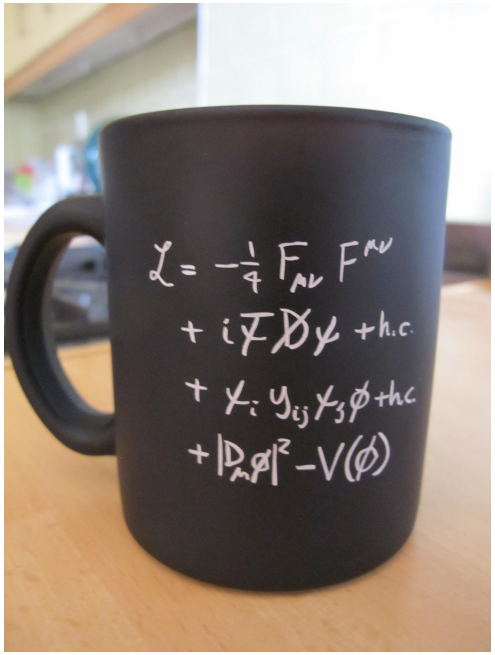
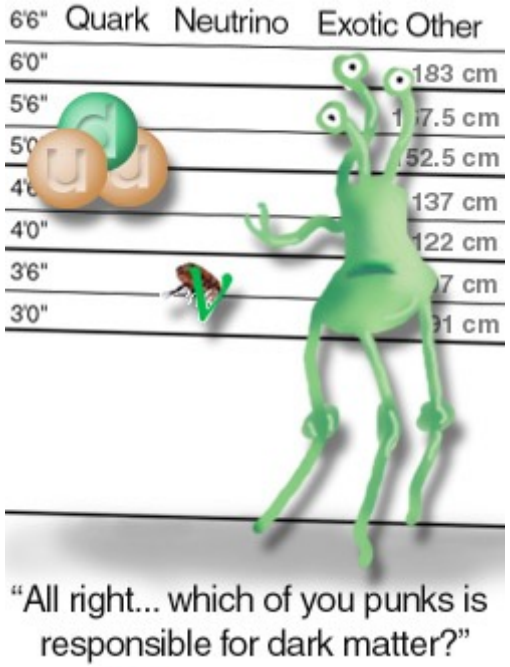
(for the ATLAS, CMS and LHCb Collaborations)

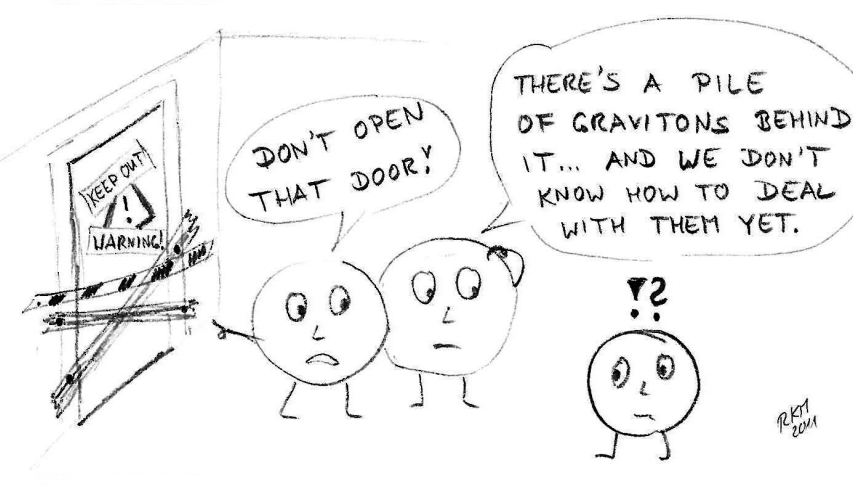
May 25th, 2021

PHENO 2021

Goals of experimental particle physics







Achieved by…

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

SM as a tool for discovery

- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space ➔ innovate!

Explore new frontiers: Go beyond the SM

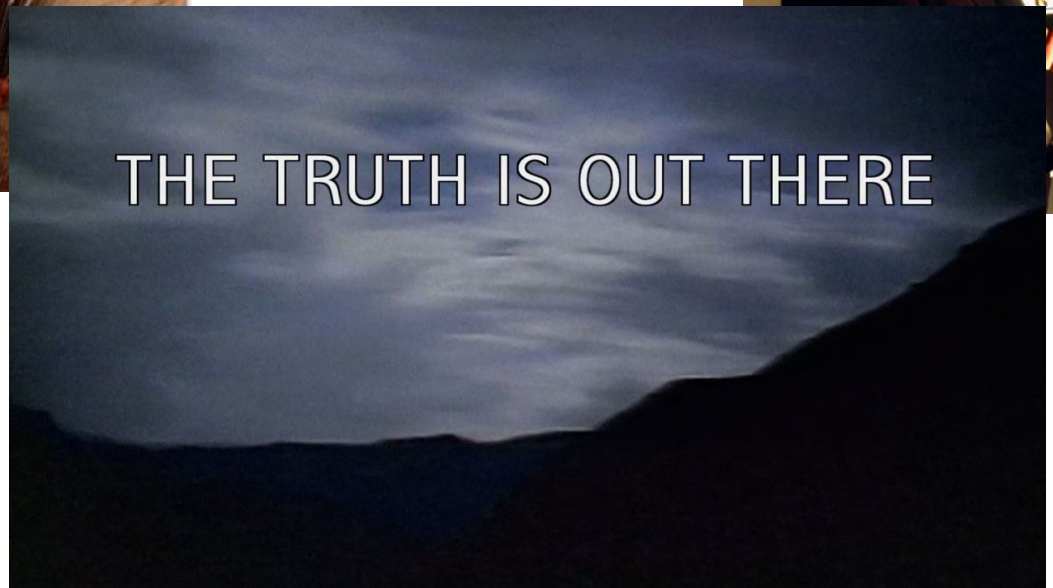
Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

Achieved by…

Good collaboration between theorists and experimentalists!

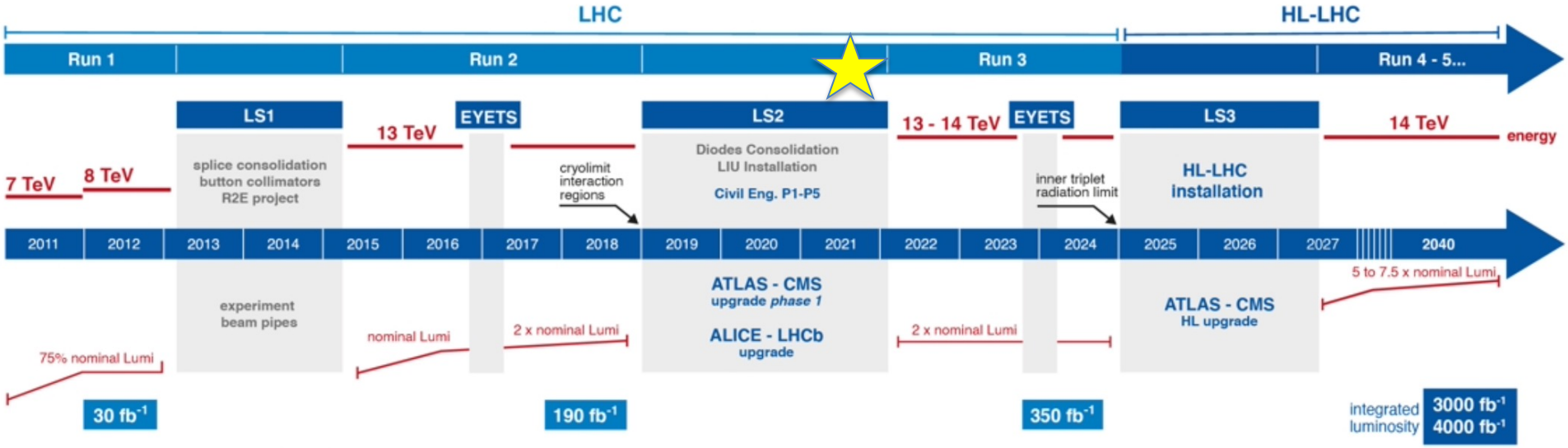
Theorist: comes up with (sometimes crazy) idea

Experimentalist: debunks theory



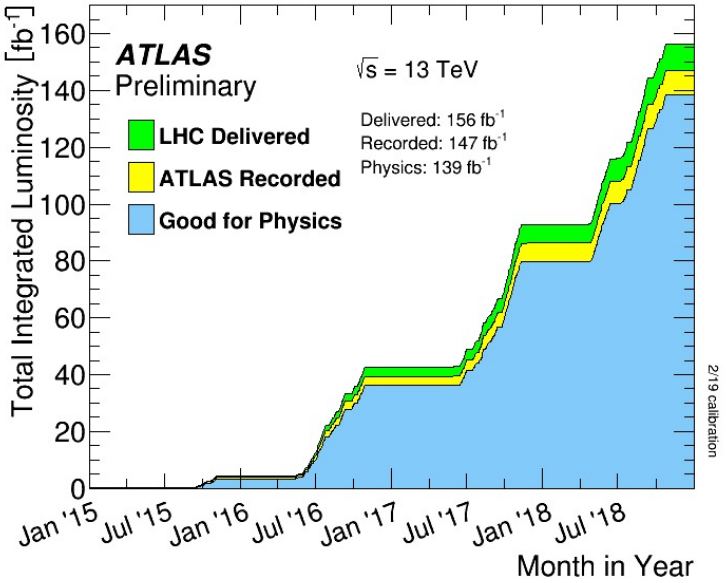
Inspired by P. Q. Hung @ Moriond EWK

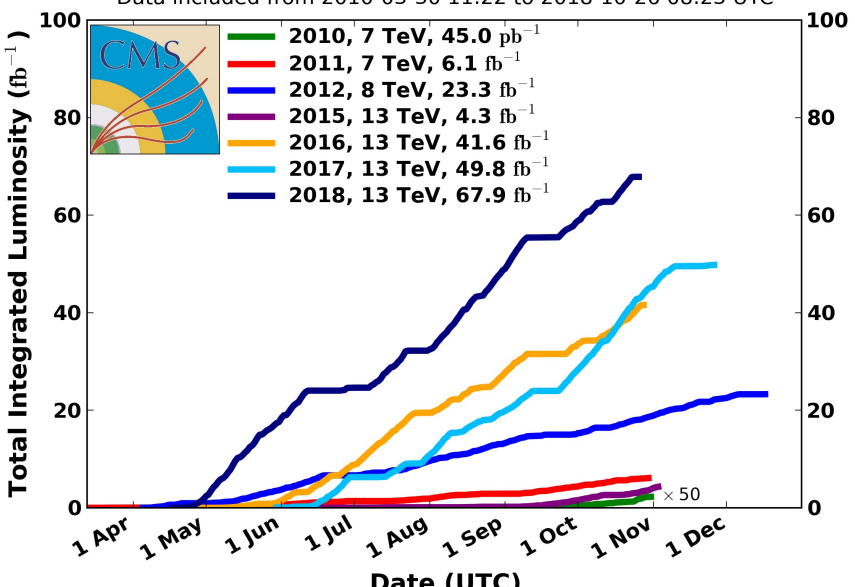
LHC/HL-LHC Program



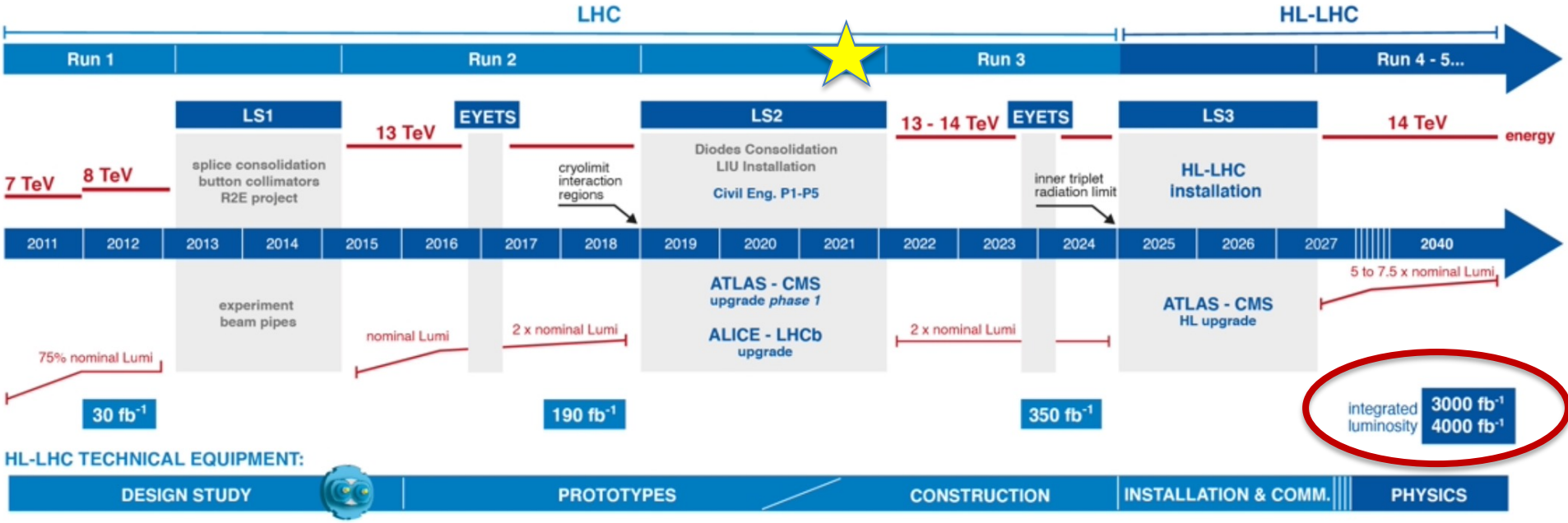
HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS



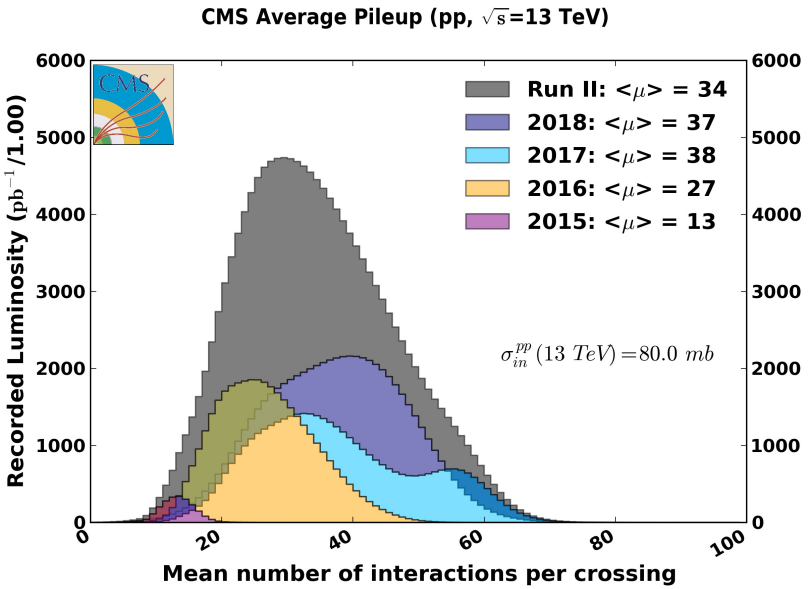


LHC/HL-LHC Program

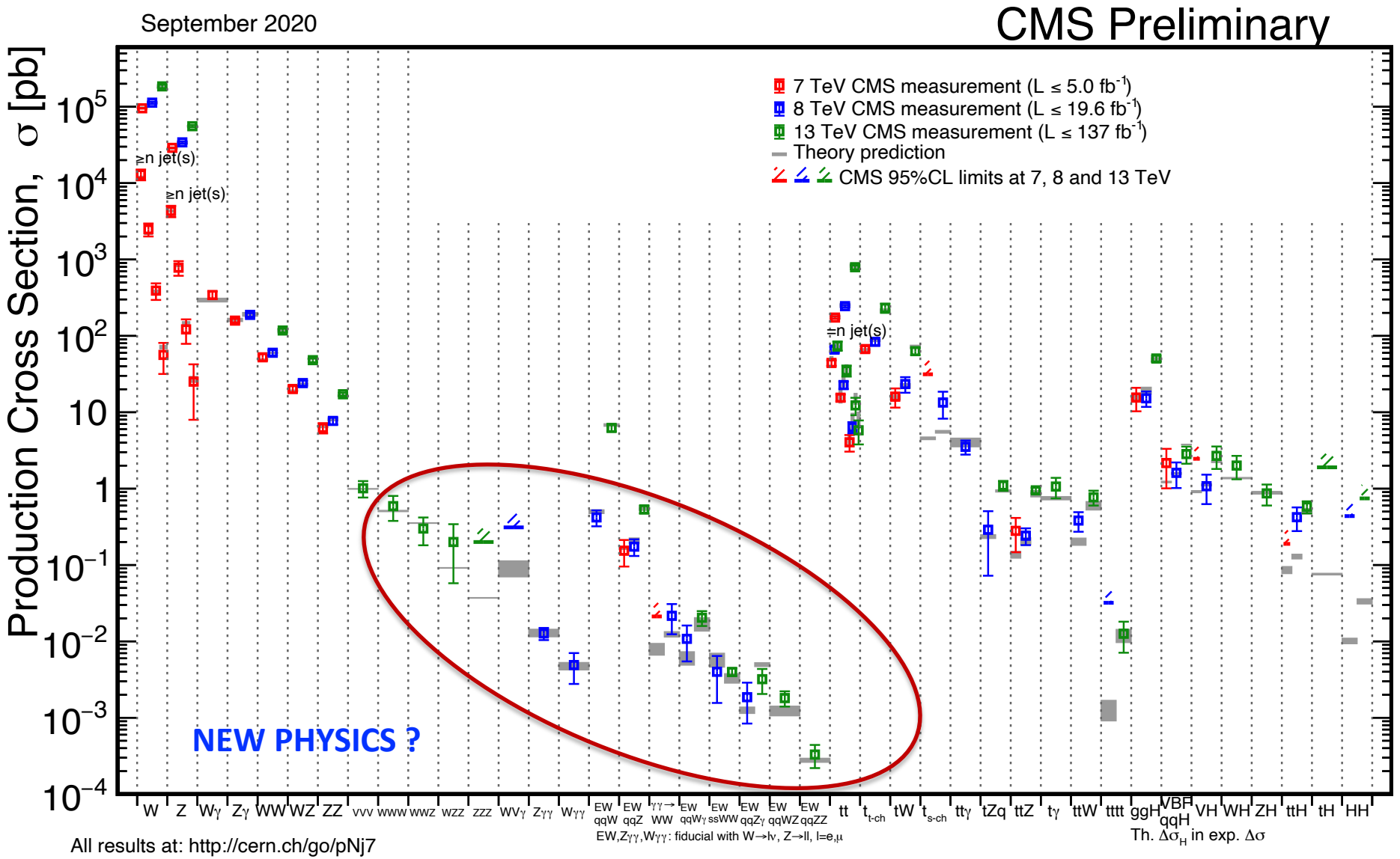


Excellent performance by LHC and the experiments: ~140 fb^{-1} good for analysis during Run 2 (ATLAS/CMS)

But 95% of the total LHC data still to come (and be studied)!



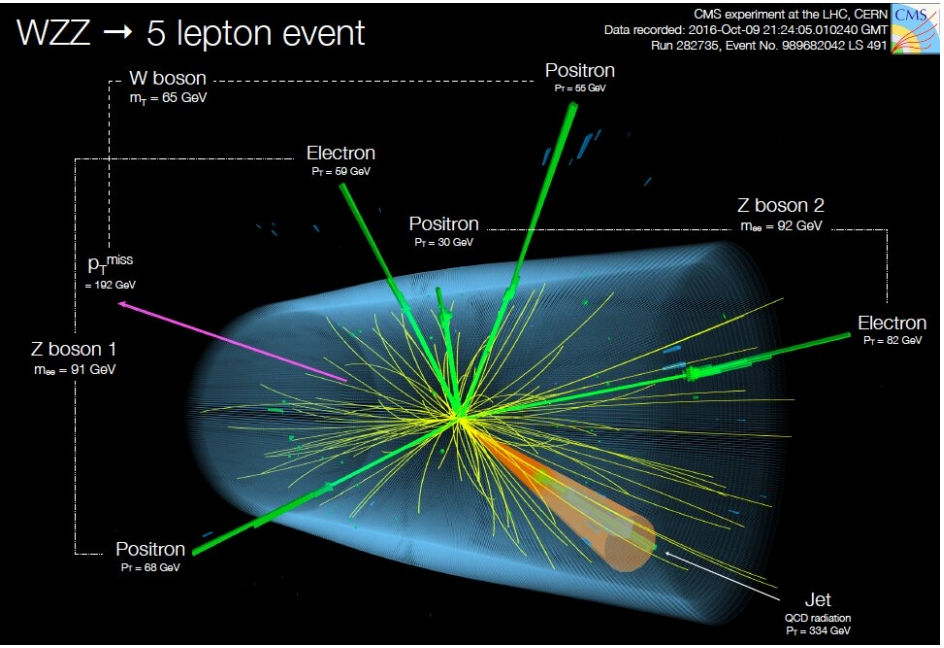
Standard Model reigns supreme

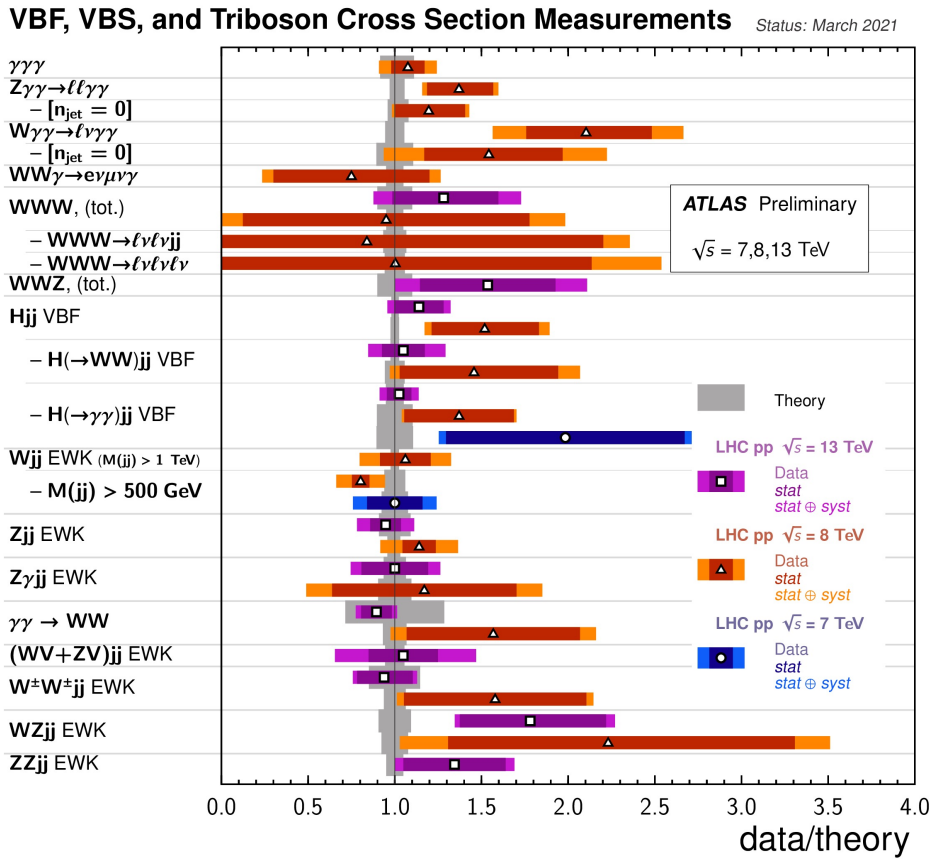


All results at: http://cern.ch/go/pNj7

Precision measurements of rare processes

- Large datasets allow us to test the SM in complementary ways
  - multi-differential cross-section measurements
  - First-time sensitivity to rare multi- boson final states and production mechanisms





Still room for surprises!

Becoming sensitive to NNLO corrections

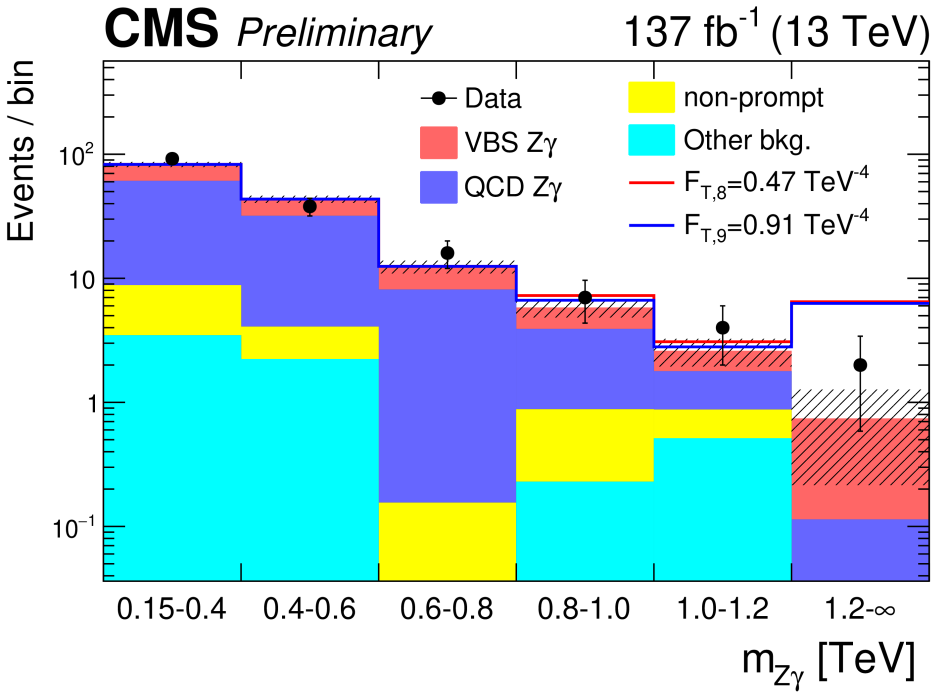
Quartic gauge couplings known exactly in SM and sensitive to new physics

Precision measurements and BSM constraints

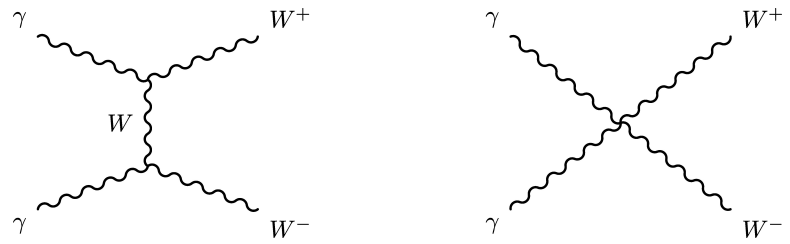
EWK production of Zγ + 2 jets

- Measurements of fiducial and diff. cross-sections
- Constraints on anomalous gauge couplings

CMS-PAS-SMP-20-016



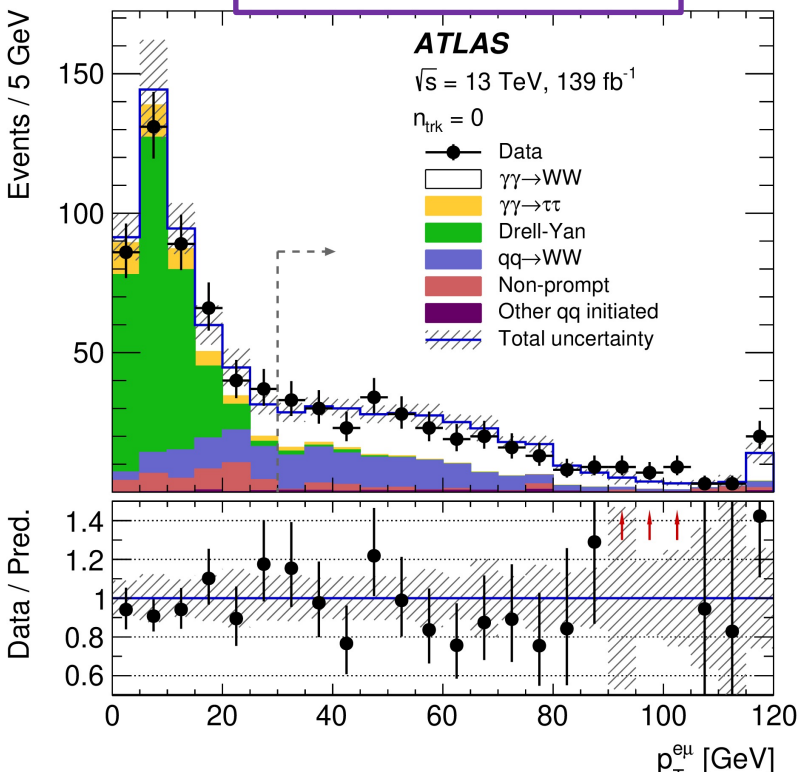
Photon-induced WW production



$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

Observed significance > 5σ

arXiv: 2010.04019



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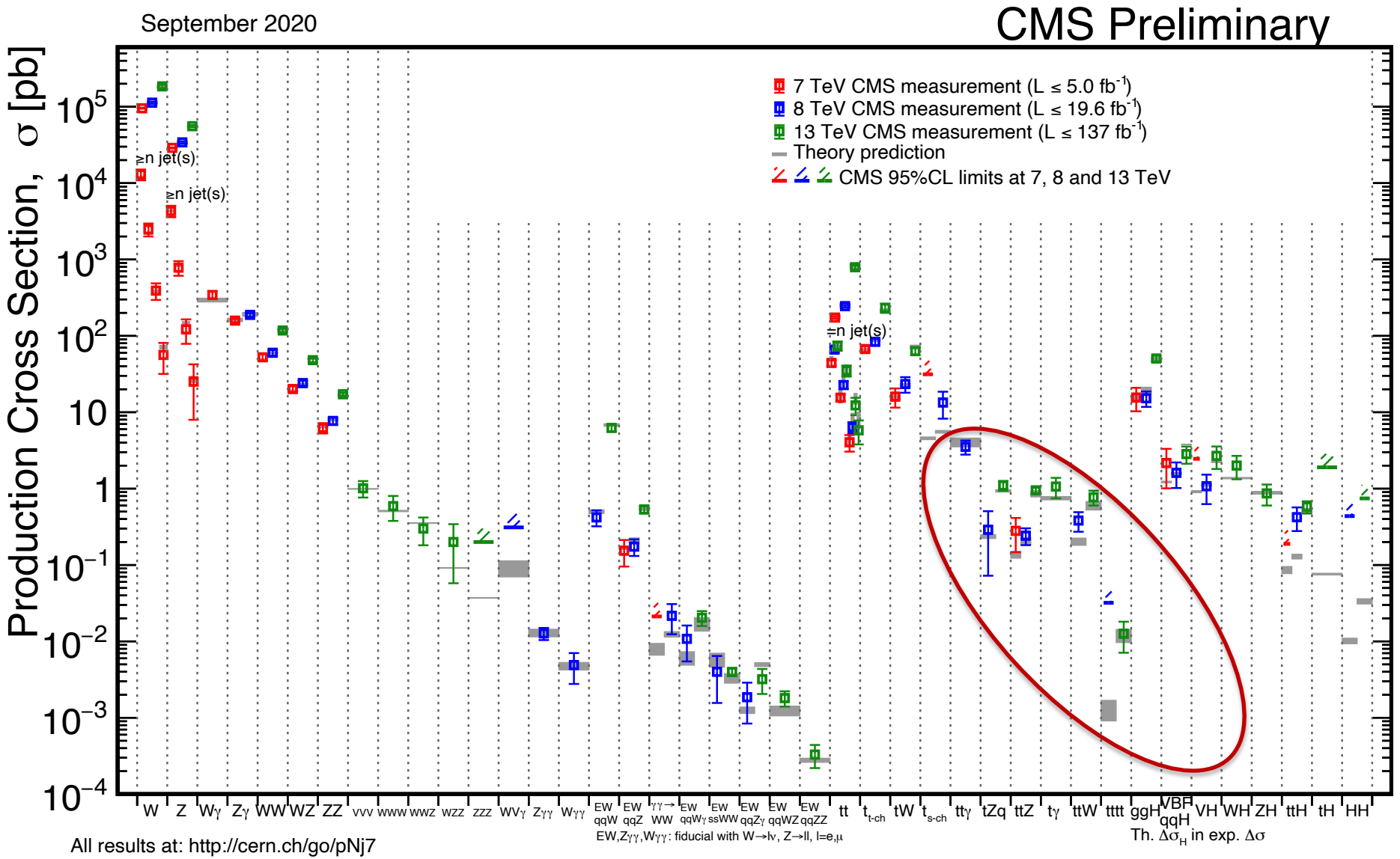
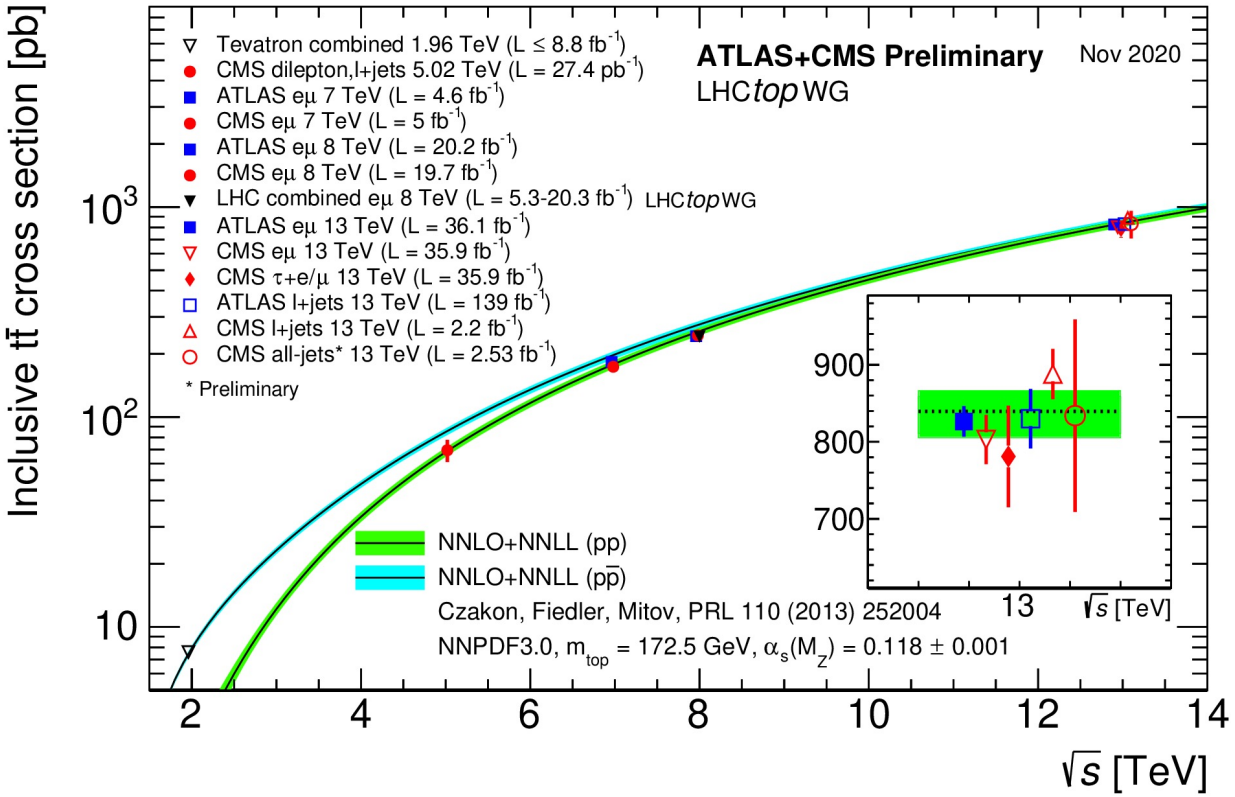


Precision Top Quark Physics

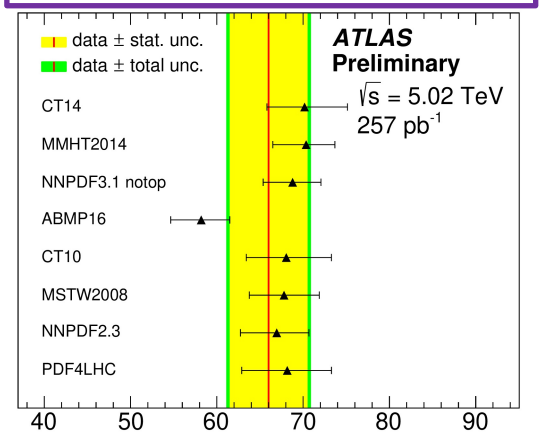
Over ~25 years since its discovery, the top quark is still one of the hottest topics…

LHC: a top quark factory!

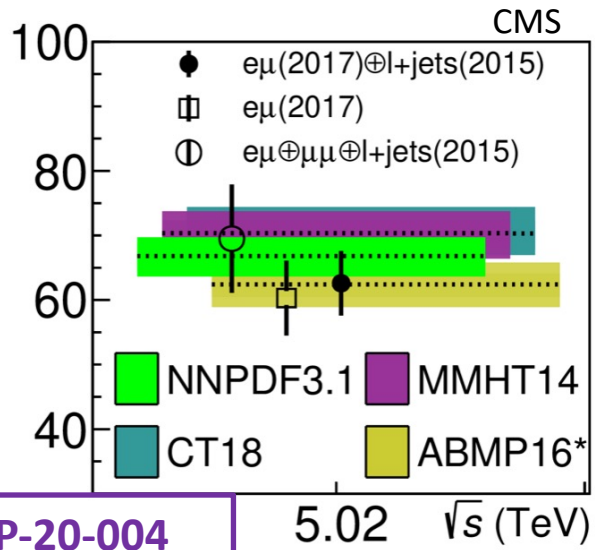


Inclusive cross section well understood; agrees with NNLO predictions

ATLAS-CONF-2021-003

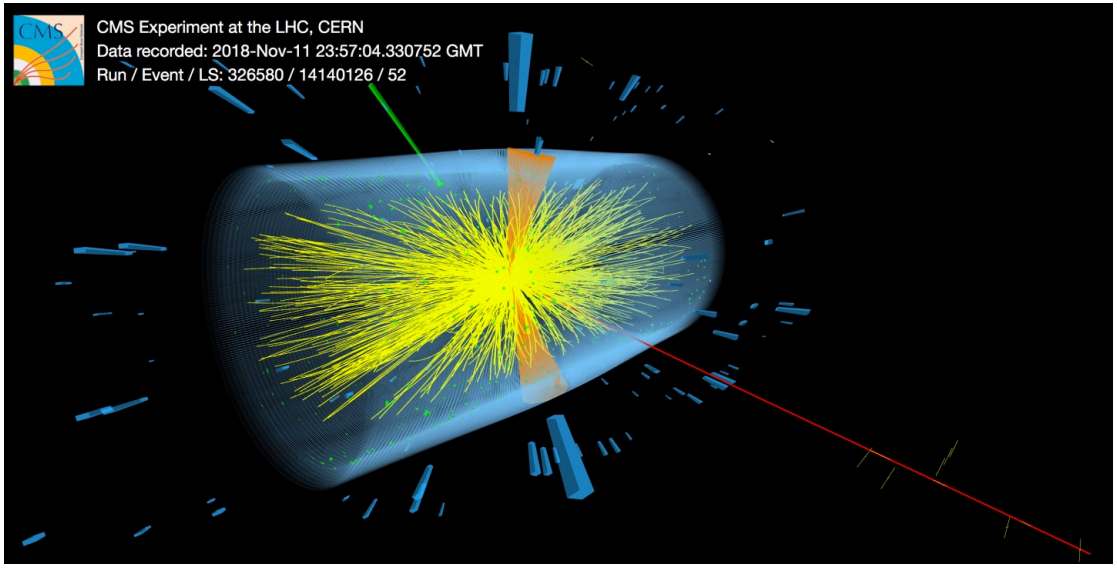


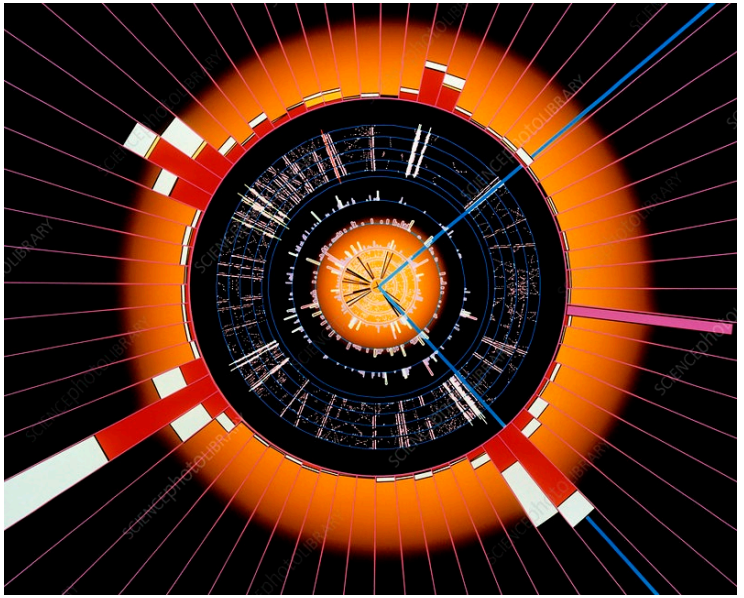
~7.5% uncertainty

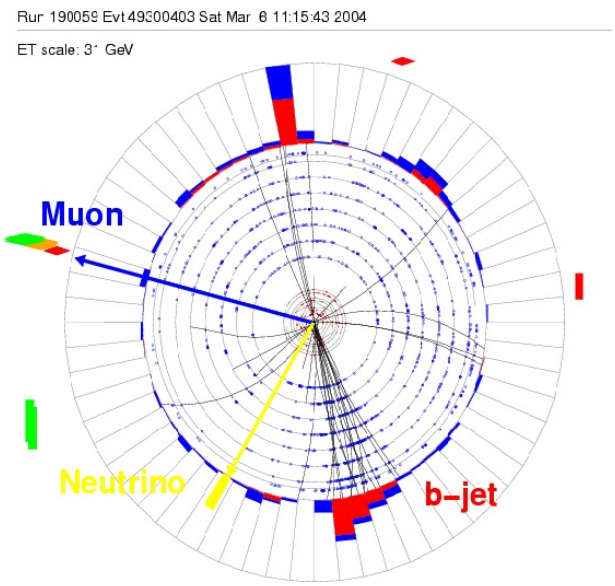


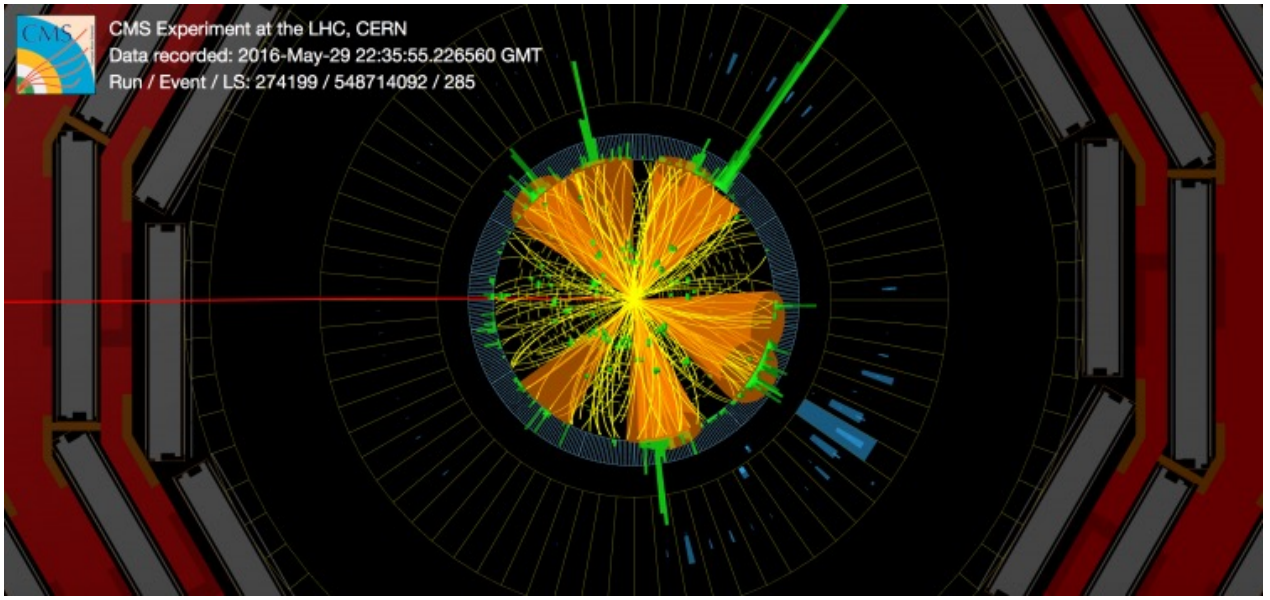
CMS-PAS-TOP-20-004

Top evolution



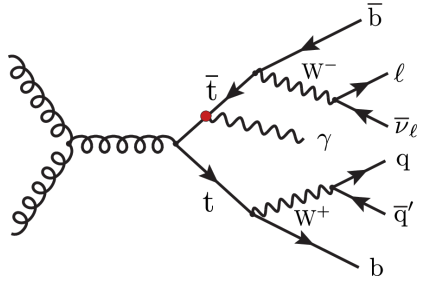


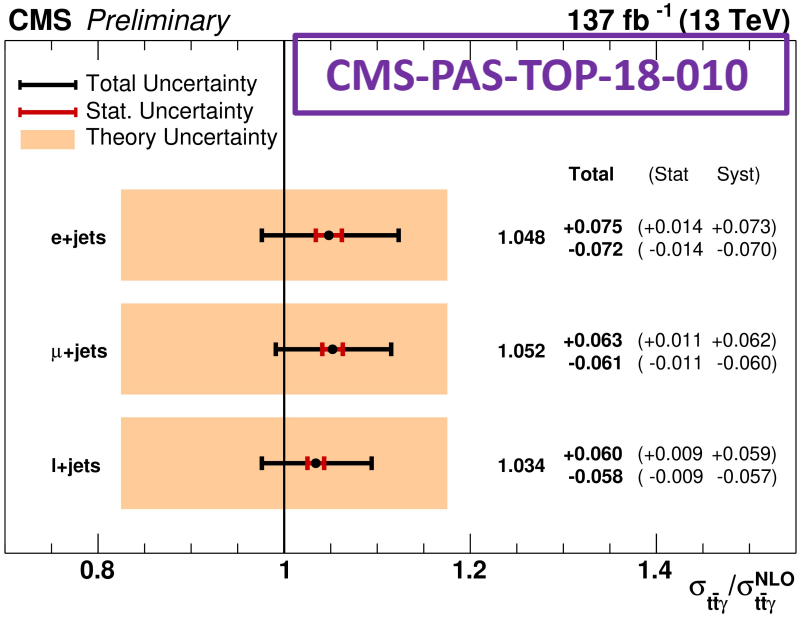




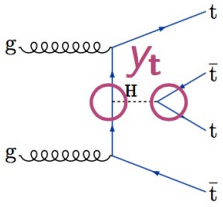
Rare top

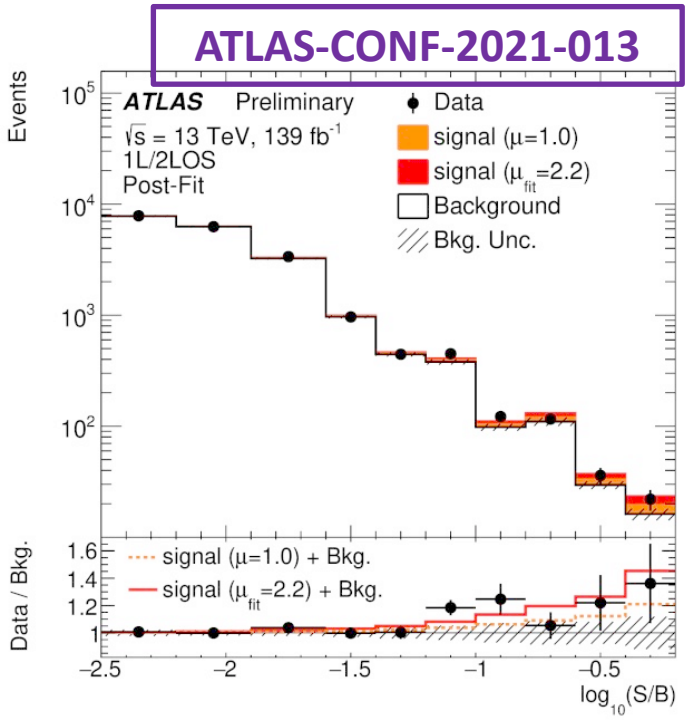
- Anomalous top quark couplings predicted in many BSM models
- Exploit ttγ and interpret results within the context of SMEFT





- tttt: unobserved very rare process (σ_{tttt} = 12 +-2.4 fb)
  - Sensitive to top yukawa coupling and BSM effects





Evidence for 4-top prod @ ATLAS: obs. (exp.): 4.7 (2.6) σ

CMS: obs. (exp.): 2.6 (2.7) σ

Outlook for SMP and TOP measurements: Run 3

- Lots of ground to cover in Run 3
  - Aim for ultimate precision in measurements (inclusive & differential)
  - Revise analysis strategies and techniques to constrain systematics better
  - Work on improving calibrations for objects
  - Increase usage of jet substructure techniques for boosted topologies
- Critical to ensure best possible modelling of SM processes
  - Strengthen link with theory/pheno/generator experts
  - Work on Monte Carlo generator development and implementation
  - Physics studies (ISR/FSR, hadronization...)
- Work on well-understood & comprehensive recipes for systematic uncertainties
- Work on new and improved trigger strategies for keeping thresholds low, explore parking…

Higgs Physics

"Greetings Earth-people. We have been monitoring your progress. Now that you have discovered the Higg's boson you are qualified to join the Federation of Advanced Civilisations."

Following its discovery, significant effort has been put into characterizing the properties of the Higgs Boson

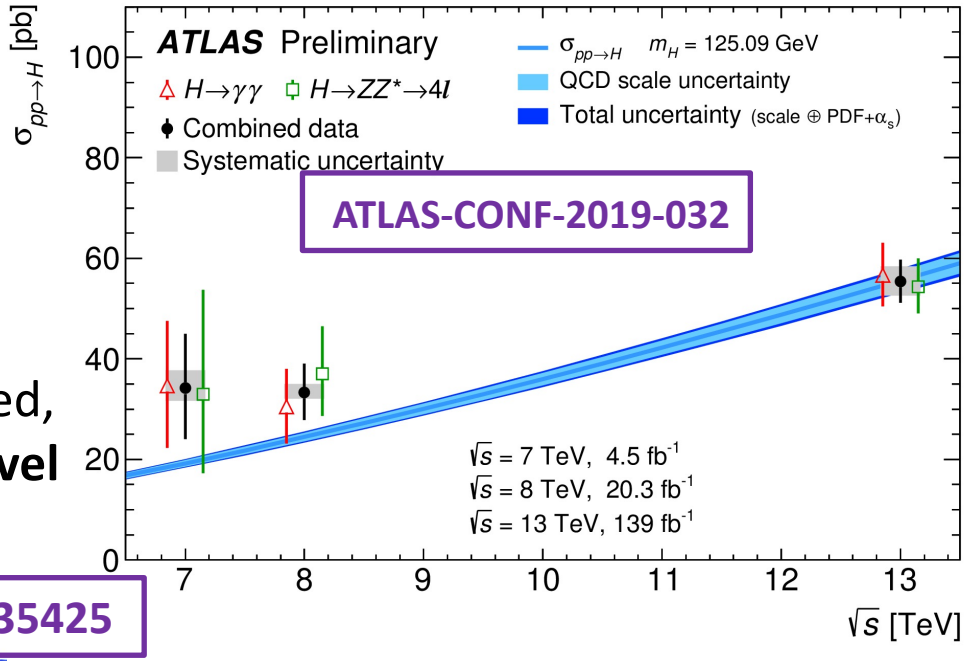
Higgs Highlights

PLB 805 (2020) 135425

- In the 8+ years since its discovery there has been significant progress in the Higgs sector:
  - Firmly established $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb decays and diff. prod. modes
  - Tau-Higgs, bottom-Higgs and top-Higgs Yukawa couplings
  - mass measurement w/ 1 per-mille precision 125.38 ± 0.14 GeV CMS
  - Quantum #s consistent with $J^{PC} = 0^{++}$

Fiducial and differential cross section measurements comparing data to state-of-the-art calculations

Already, with the Run 2 dataset analyzed, the **experimental precision is at the level of the theoretical precision**



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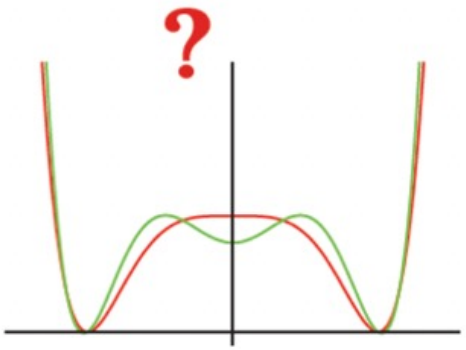
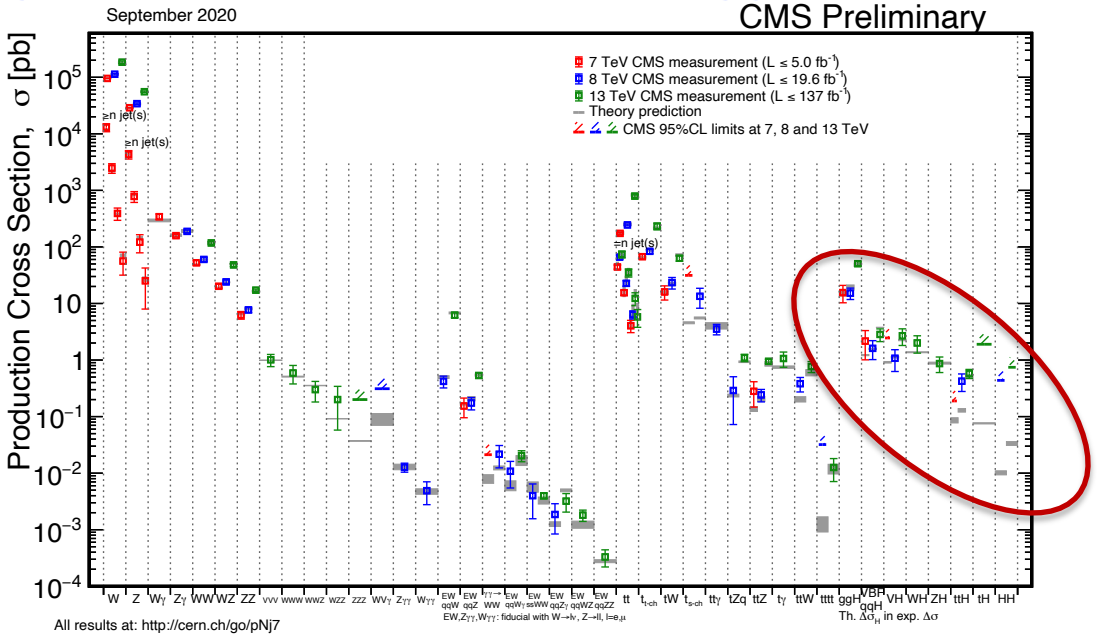
$\sigma/\sigma_{SM} = 1.06 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$ ATLAS

Higgs Physics: Open Questions

- Why is the Higgs so light ? Is m_H stabilized by ~TeV scale new physics or is it fine-tuned ?
- Is the Higgs elementary or composite?
- Higgs couplings to charm (e.g. h->ccbar, h → J/Ψ+γ)
- Higgs coupling to muons ?
- Are there exotic Higgs decays ?
- Is it a Higgs or the Higgs ? Are there additional Higgs bosons ?

…





2^{nd} generation – the next frontier

- Goal: establish Higgs couplings to 2^{nd} generation fermions w/ H → μμ
  - CMS: **obs. (exp.): 3.0 (2.5) σ**
  - ATLAS: **obs. (exp.): 2.0 (1.7) σ**

BR ($H \to \mu\mu$) ~ 2.2 x 10^{-4} : small but enhanced in some BSM scenarios

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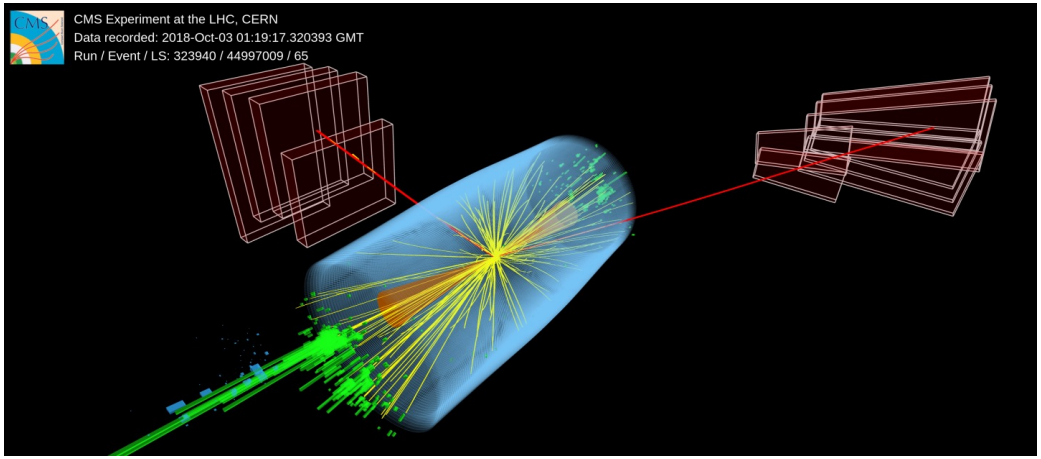
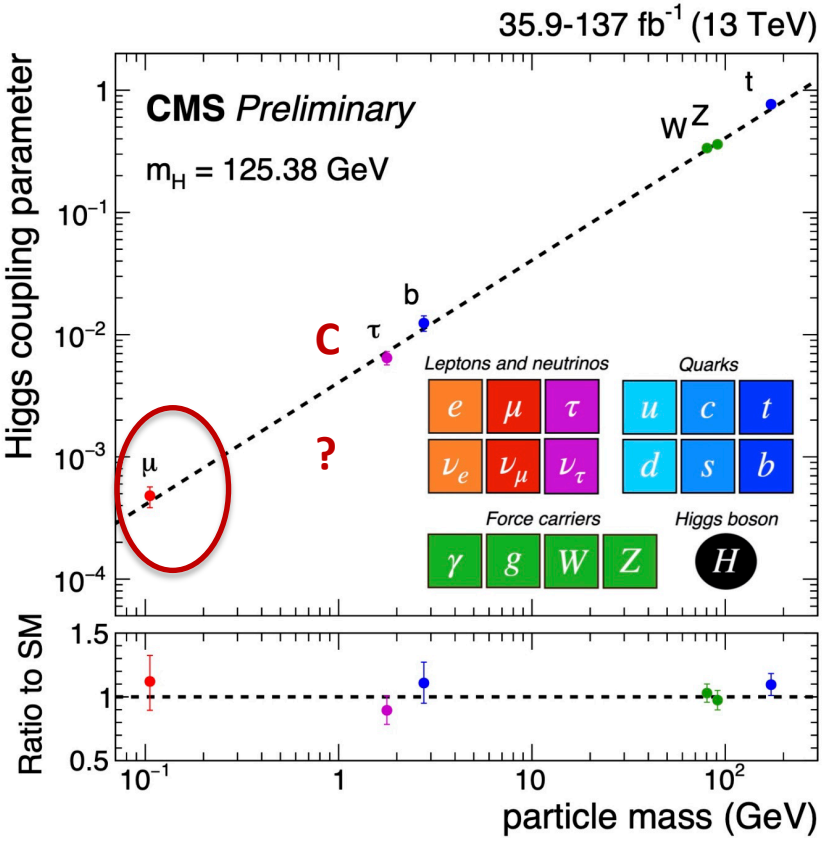
PLB 812 (2021) 135980





- Next target: utilize advances in charm tagging to tackle (V)H-> cc

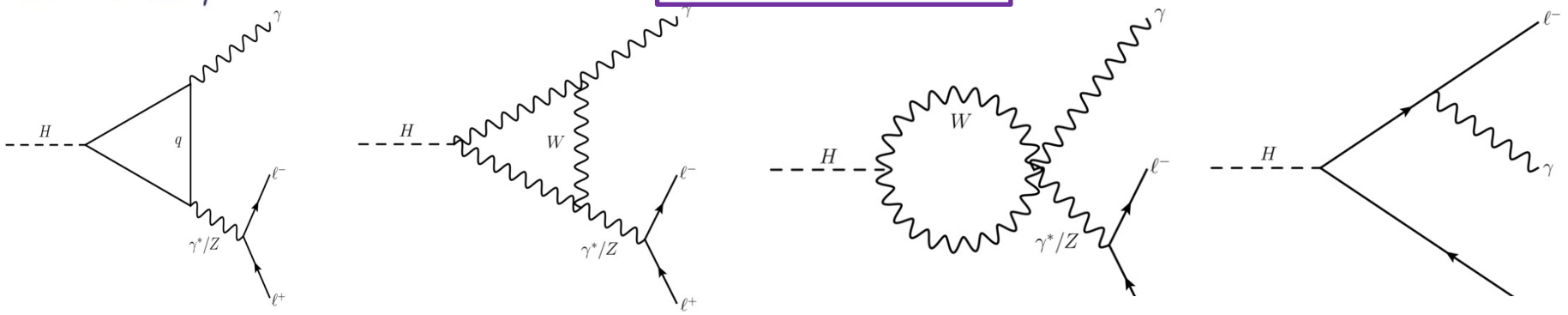
Evidence for H->μμ prod @ CMS

$$\mu = 1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$$

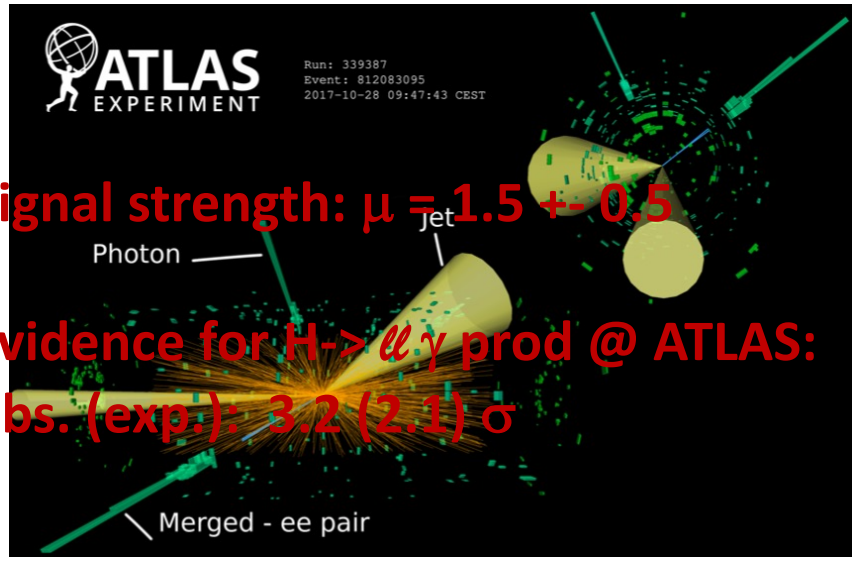
Rare Higgs decays

$H \to \ell\ell\gamma$

arXiv:2103.10322

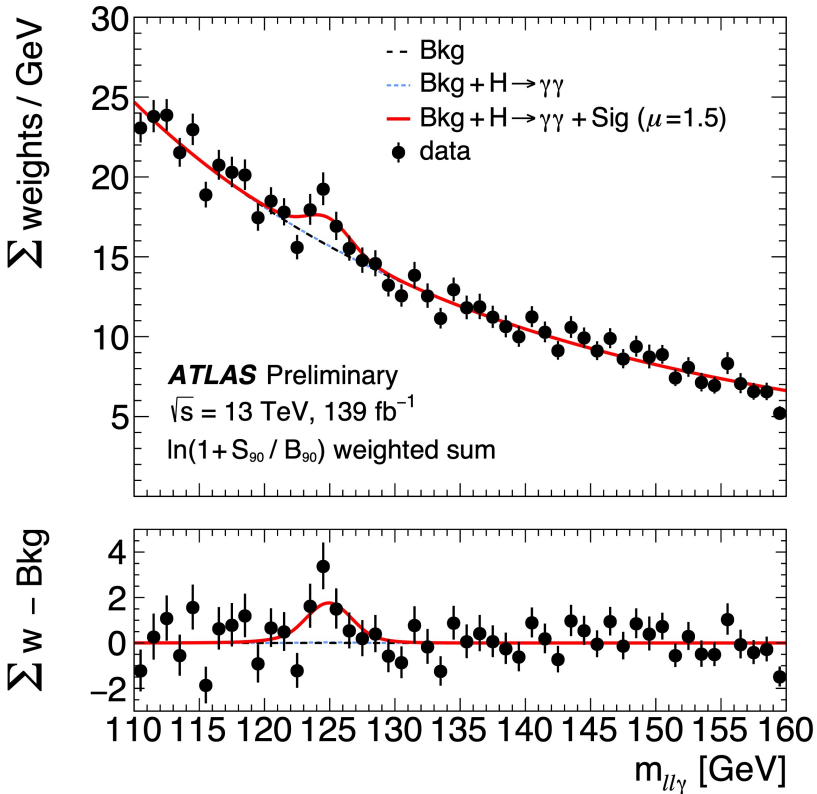


- Probes possible exotic couplings,
- Would probe CP nature of the Higgs
- Analysis considers m(ll) < 30 GeV;



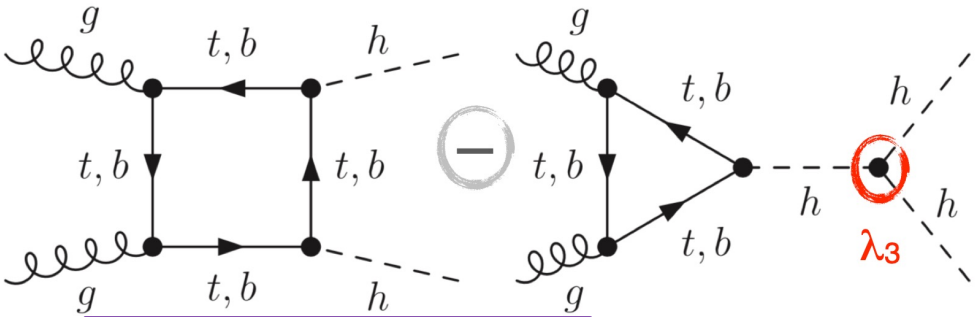
Signal strength: μ = 1.5 +- 0.5

Evidence for H->ℓℓγ prod @ ATLAS: obs. (exp.): 3.2 (2.1) σ



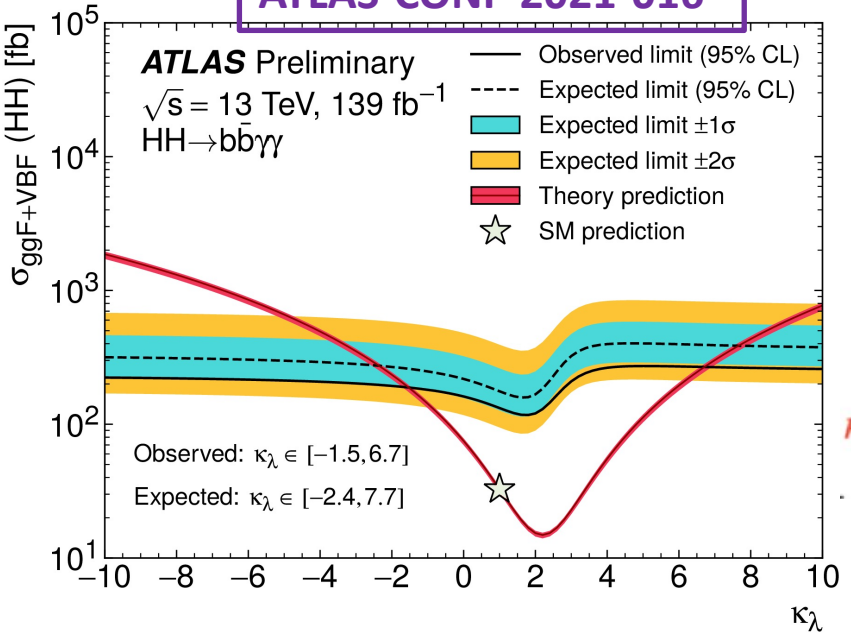
HH production

- Di-Higgs production directly probes the structure of the Higgs potential
- Gluon-gluon fusion process dominates, small cross-section due to negative interference between the two diagrams



Much progress being made; Sensitivity to SM Higgs self-coupling needs HL-LHC

ATLAS-CONF-2021-016



$$\kappa_\lambda \equiv \frac{\lambda}{\lambda^{SM}}$$

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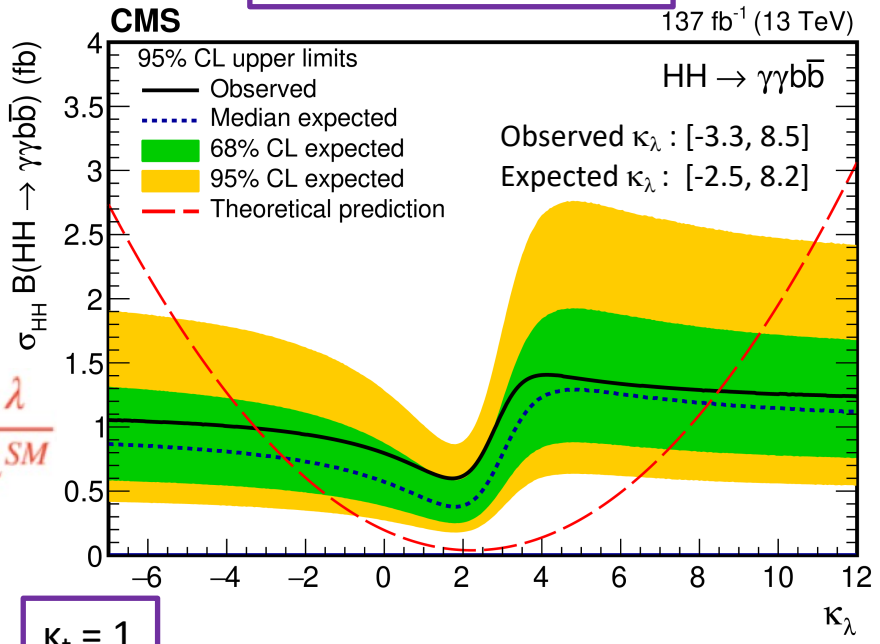


$\kappa_t = 1$

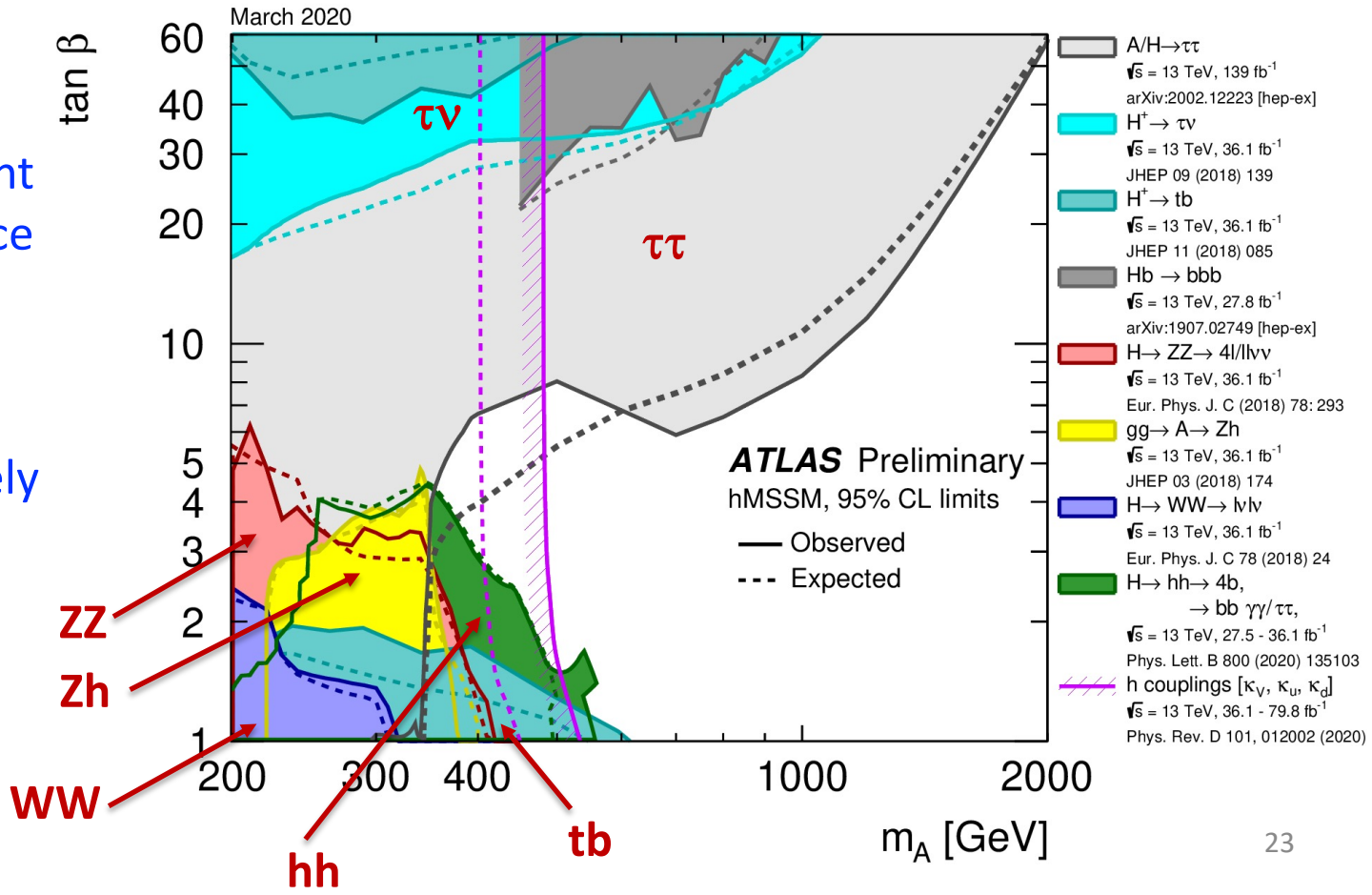
BSM Physics in the Higgs Sector

Various searches are performed for exotic Higgs bosons: MSSM and 2 Higgs Doublet Models (HDM) and beyond

- Direct searches as well as combinations of Higgs coupling measurements used to exclude large regions of parameter space

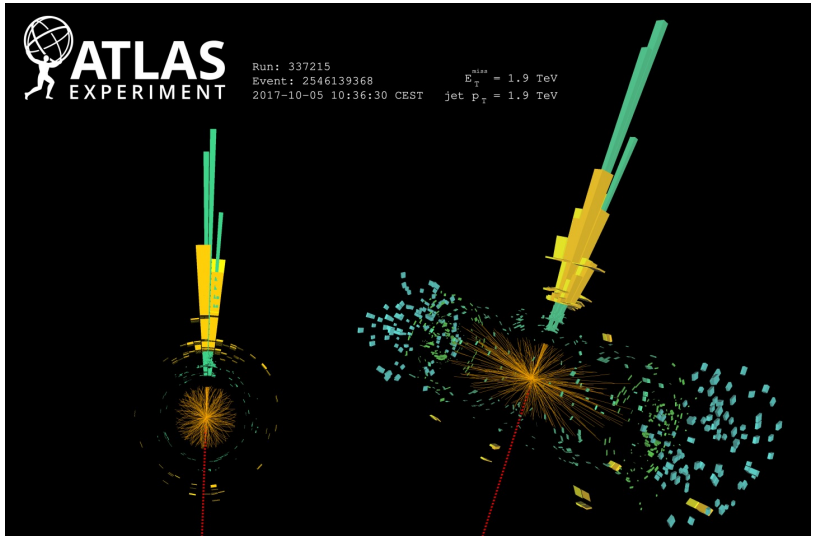
Substantial amount of parameter space (and masses) left;

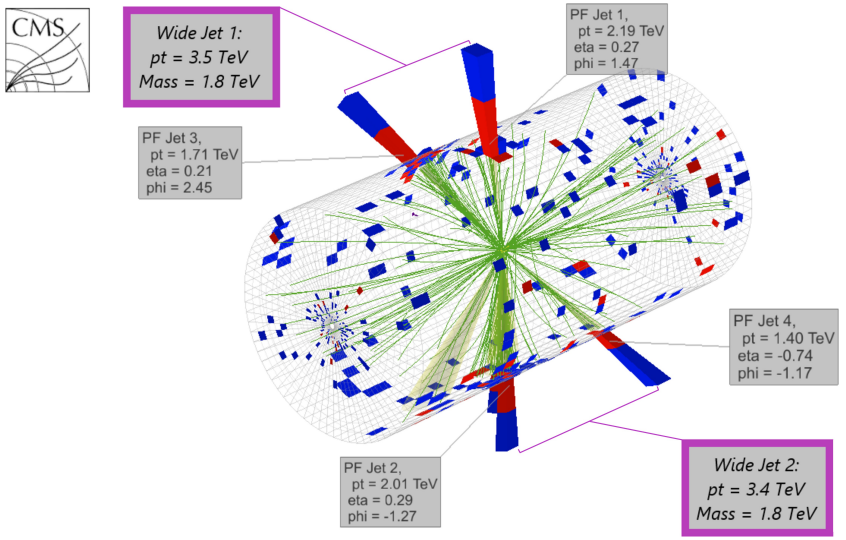
Improve searches to access extremely difficult region of intermediate tan beta and high masses.

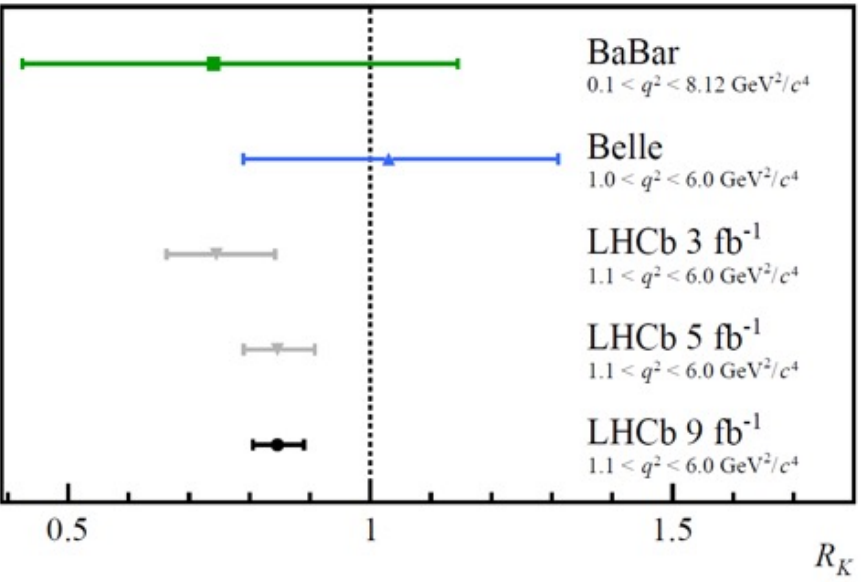


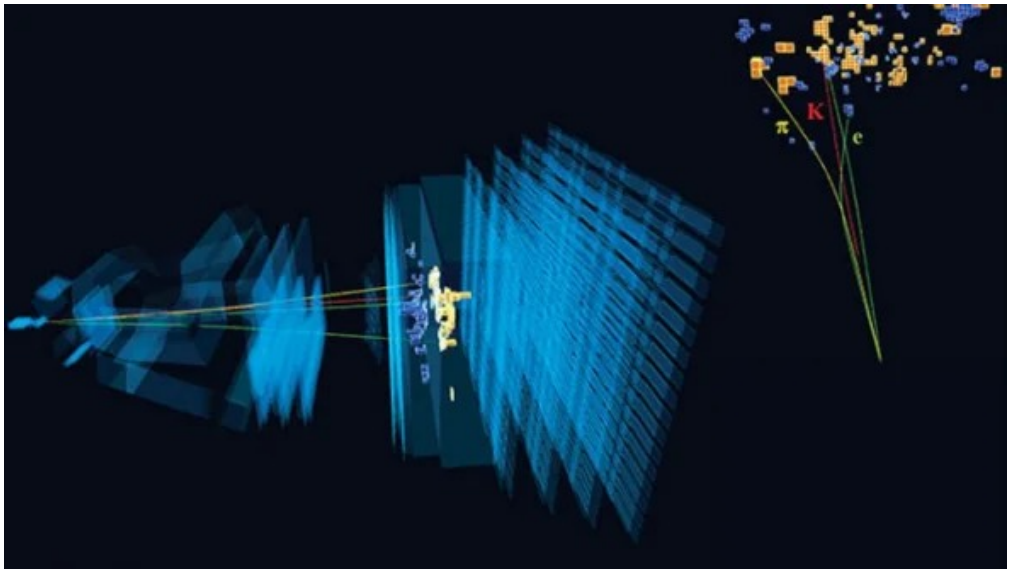
Explore the Unknown:

new particles, interactions and physical principles

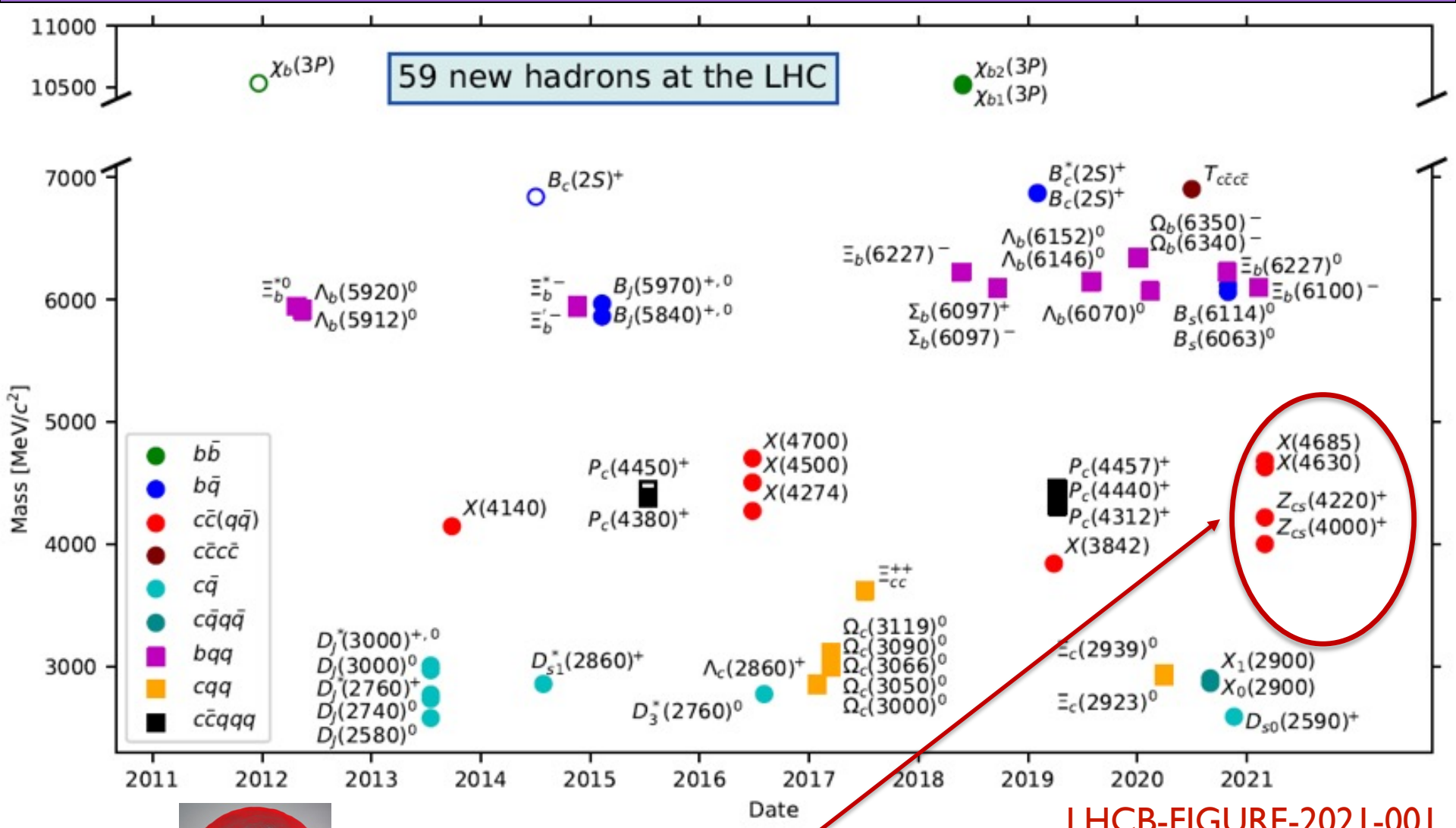




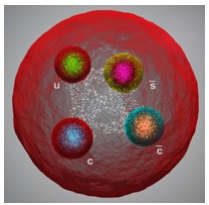




Large Hadron Discovery Factory



LHCB-FIGURE-2021-001

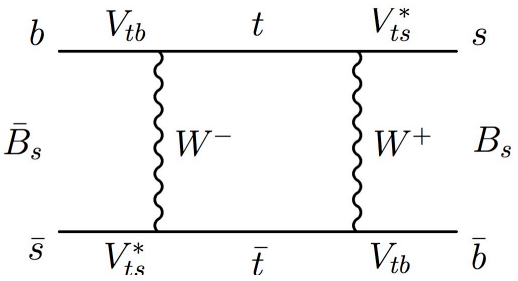


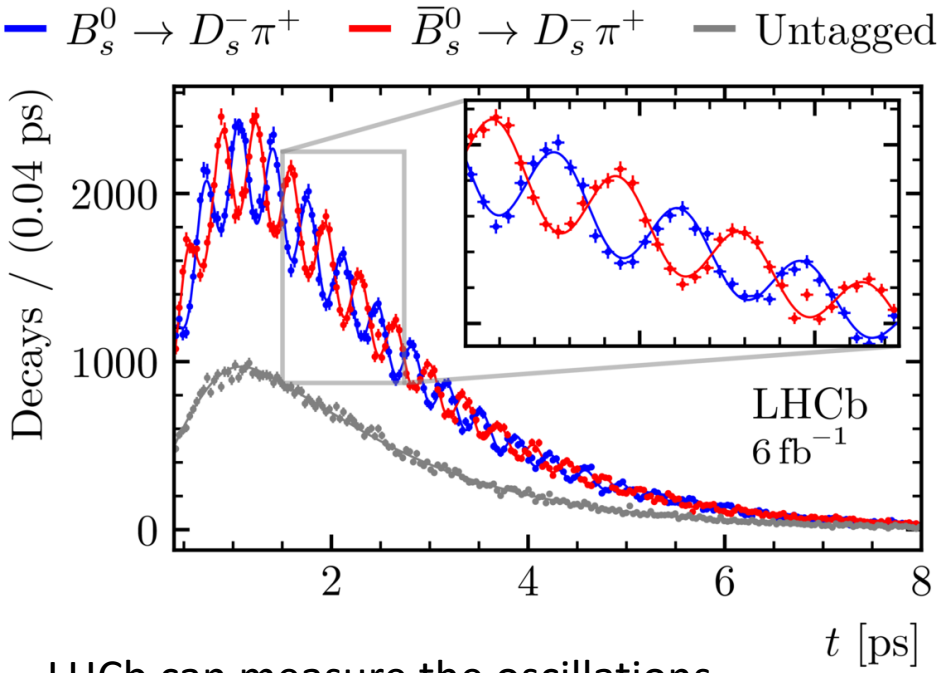
Most recent discoveries at LHCb

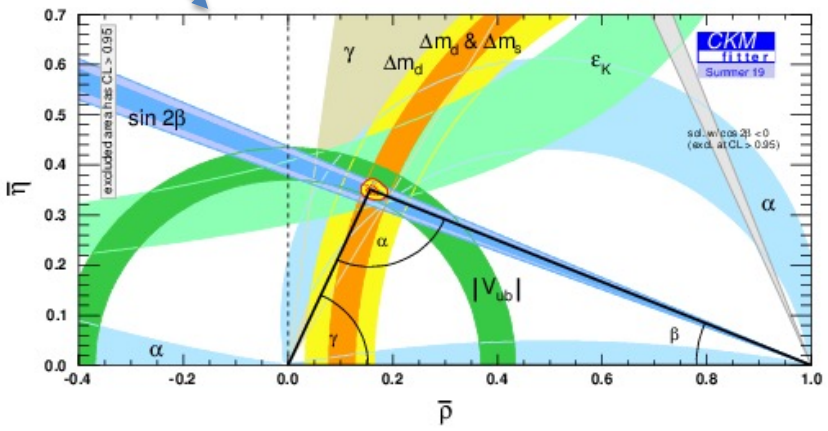
LHCb: arXiv:2103.01803

B_s oscillations

- B_s oscillations are very fast, 3 trillion times per sec
- Measurement helps (over)constrain unitarity triangle



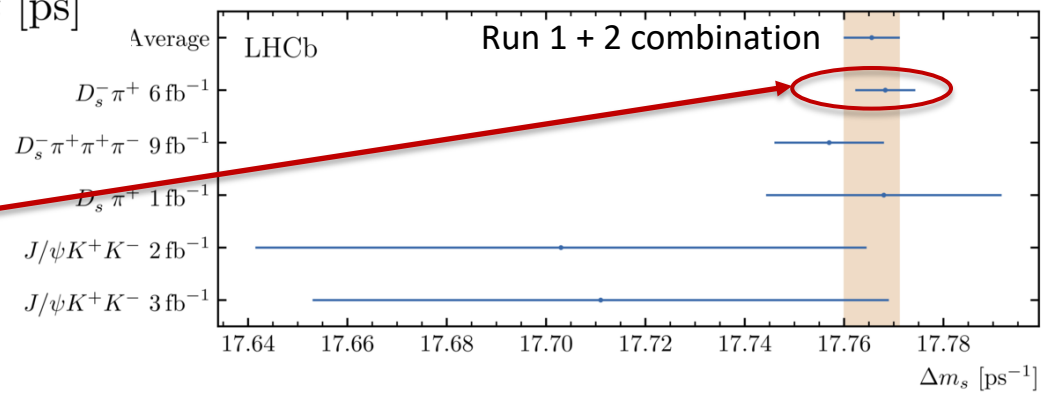




$\Delta m_s = 17.7656 \pm 0.0057$ ps^{-1}

LHCb can measure the oscillations thanks to its excellent time resolution

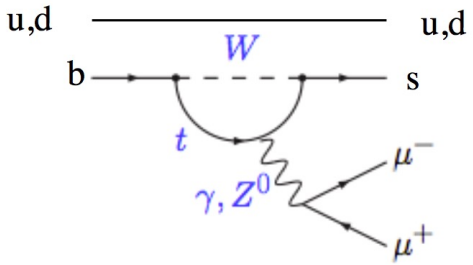
Factor of 2 improvement over previous result!



LHCb: arXiv:2104.04421

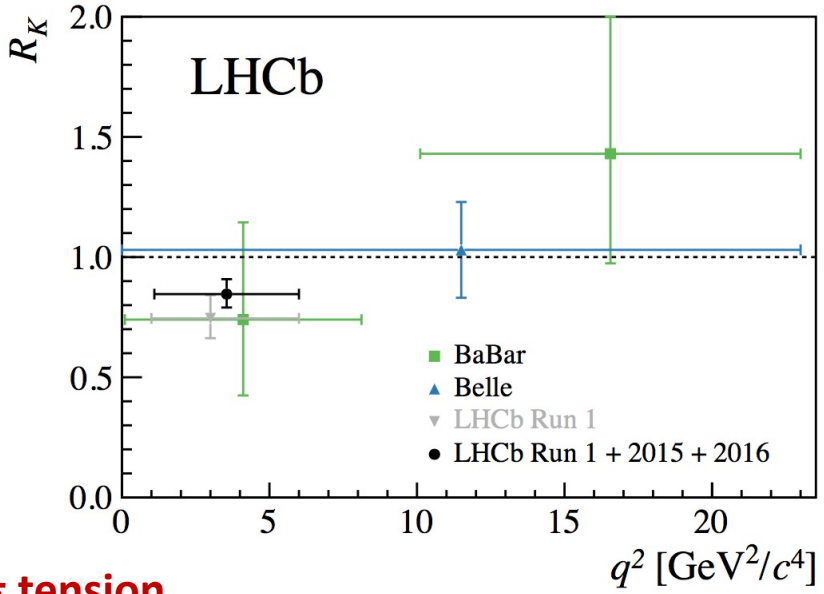
Flavor anomalies

muons / electrons [b → s]

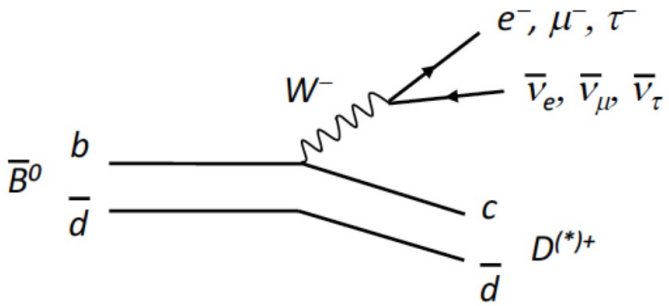


$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

Analogously: R_{K^*}

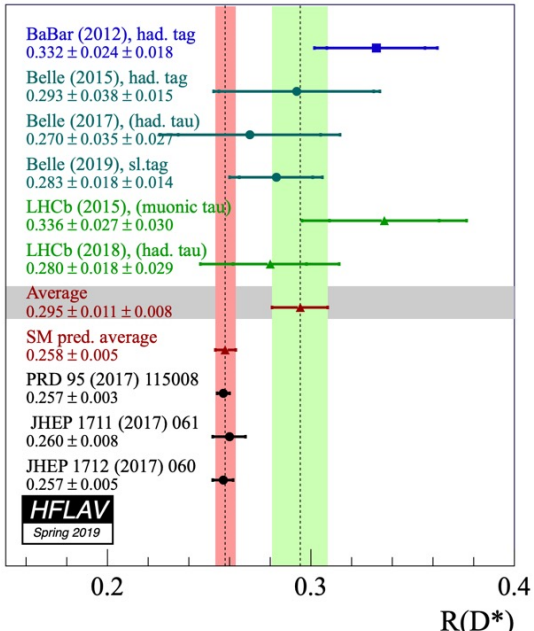


2.5 σ tension

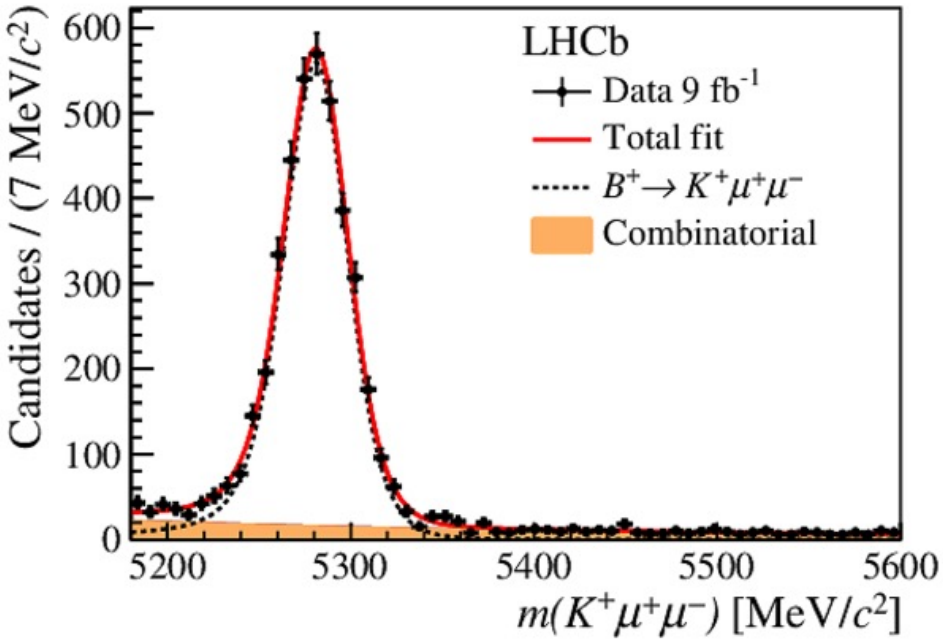


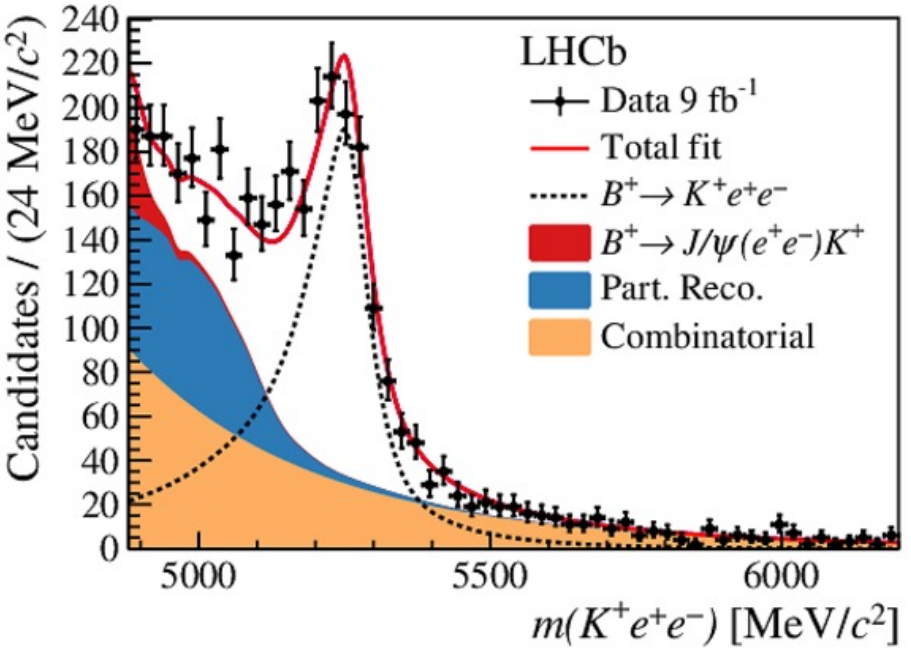
$$R_{D^*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

$R(D^*)_{SM} = 0.252 \pm 0.003$ [PRD85(2012)094025]



Lepton Flavor Universality Violation



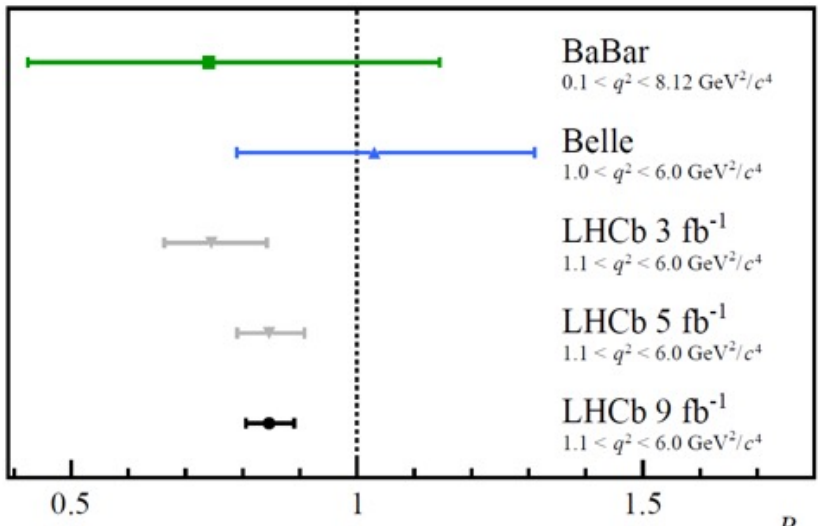


LHCb: arXiv:2103.11769

Use J/ψ decays to calibrate;
$r_{J/\psi}$ known to be LFU within 0.4%

$$R_K = 0.846^{+0.042}_{-0.039}\ (\text{stat.})\ ^{+0.013}_{-0.012}\ (\text{syst.})$$

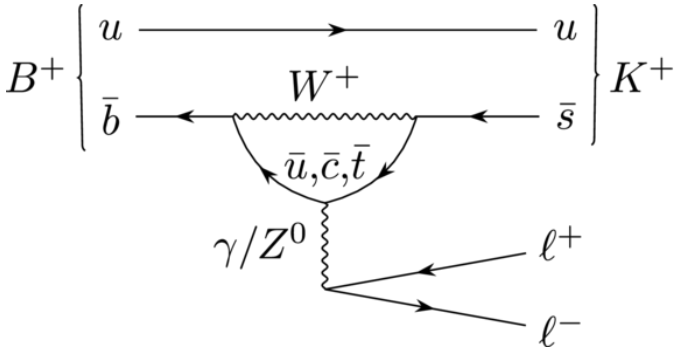
First Evidence for LFU violation at 3.1 σ

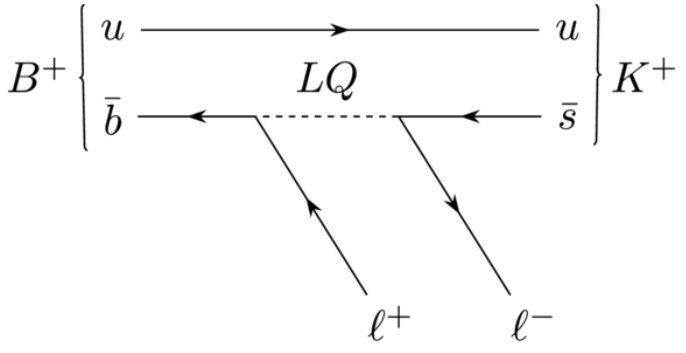


Searches for leptoquarks

Renewed interest in leptoquark searches, particularly 2nd & 3rd generation

SM



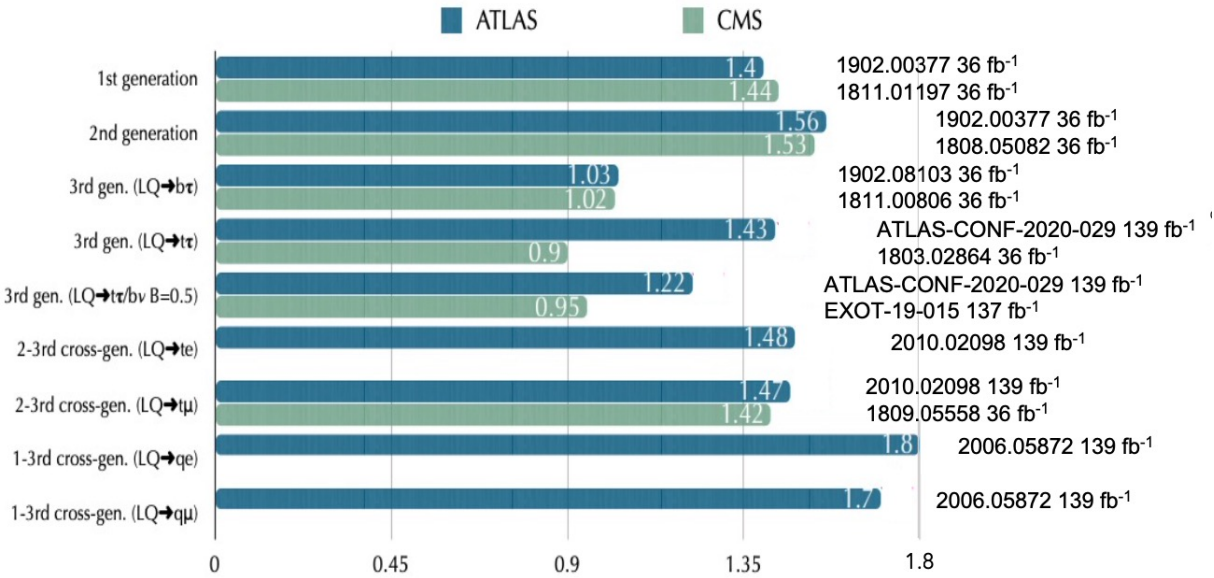


BSM

Many channels starting to push sensitivity above the TeV scale, favored by B physics anomalies

Warrants investigation of new/more complicated final states or model phase space (e.g. bigger couplings/widths)

Searches adding and using 2017+2018 data in progress



summary of observed lower limits on scalar LQ mass (TeV)

Moriond 2021 summary

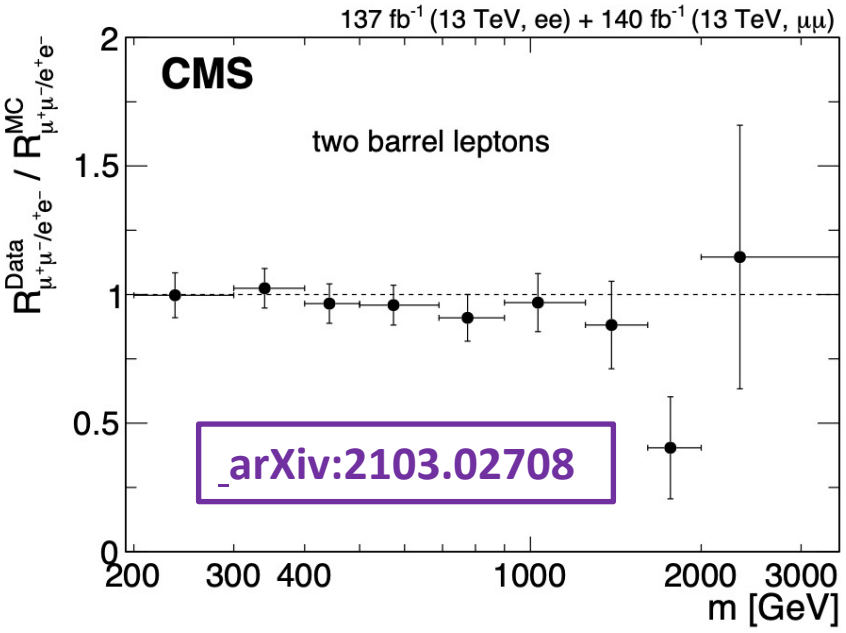
30

Exploring lepton flavor anomalies

Lepton universality is tested at TeV scale by comparing the ee & μμ mass spectra!

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$

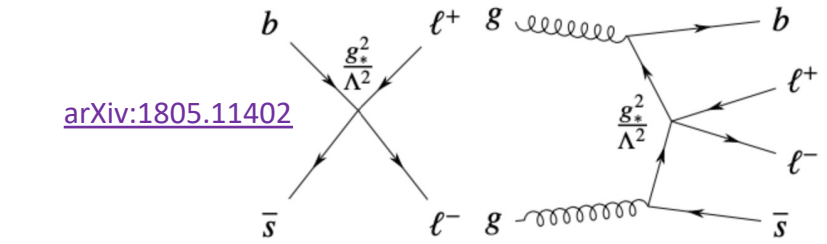
LFU ➔ ratio is unity

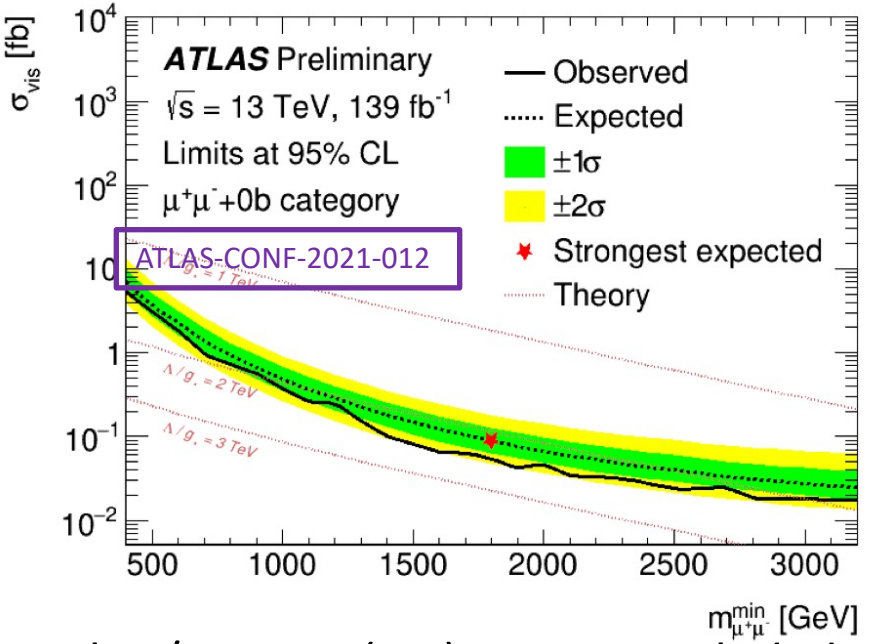


Good agreement with this expectation observed up to 1.5 TeV.

Contact interaction b/w (*b*, *s*) quarks & 2 leptons, inspired by *B*-meson anomalies.

arXiv:1805.11402

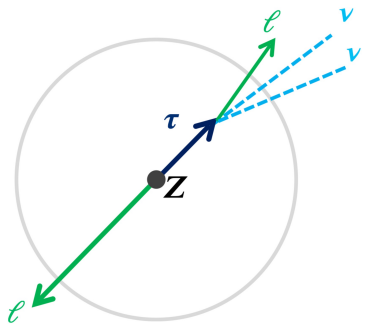




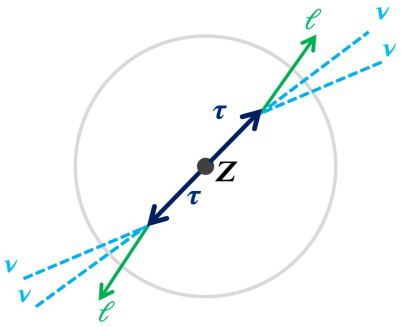
CI with Λ/g∗ < 2.0 (2.4) TeV are excluded for e (μ), far from the value favored by *B*-meson decay anomalies (30 TeV).

Exploring Lepton Flavor Violating decays

LFV decays of the Z boson



LFV signal



Bkg

ATLAS-CONF-2021-017

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarised τ [10]	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ [10]	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ [10]	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarised τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarised τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

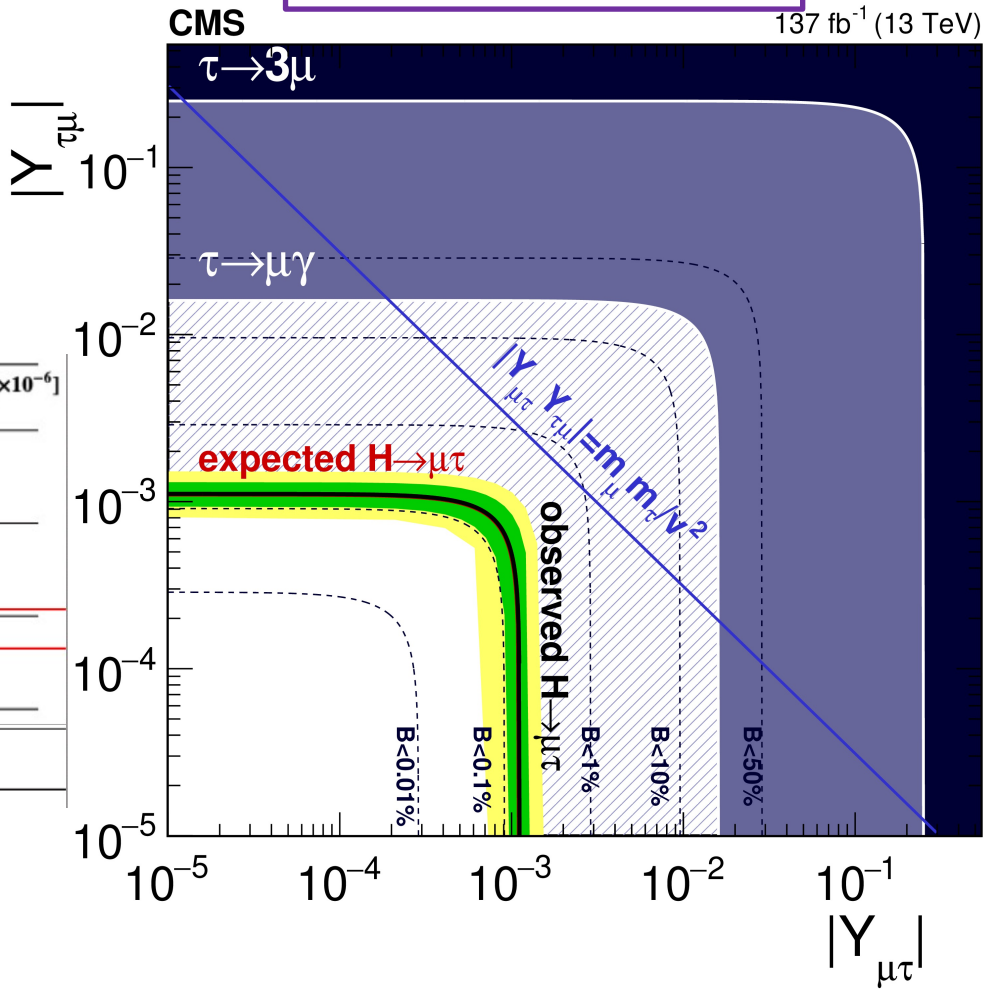
Limits are factor of 2 better than LEP

arXiv:2010.02566

LFV decays of the Higgs

Search for $h \to e\tau$ and $h \to \mu\tau$

CMS-PAS-HIG-20-009

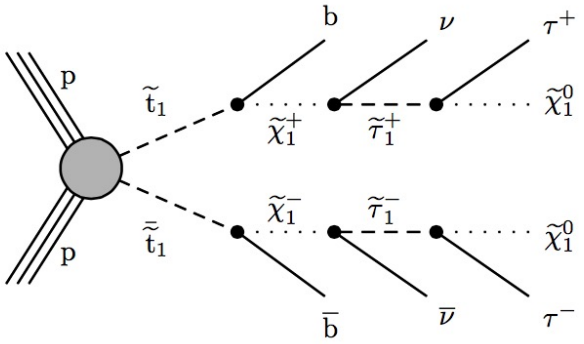


Direct search strategies

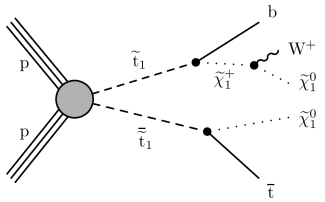
Rich and diverse search landscape

- Big inclusive searches complemented by dedicated searches that target gaps in coverage
- Incorporate machine learning for Higgs, b, charm, top tagging
- Improve lepton reconstruction/ID for low p_T leptons; improve analysis techniques

Longer decay chains



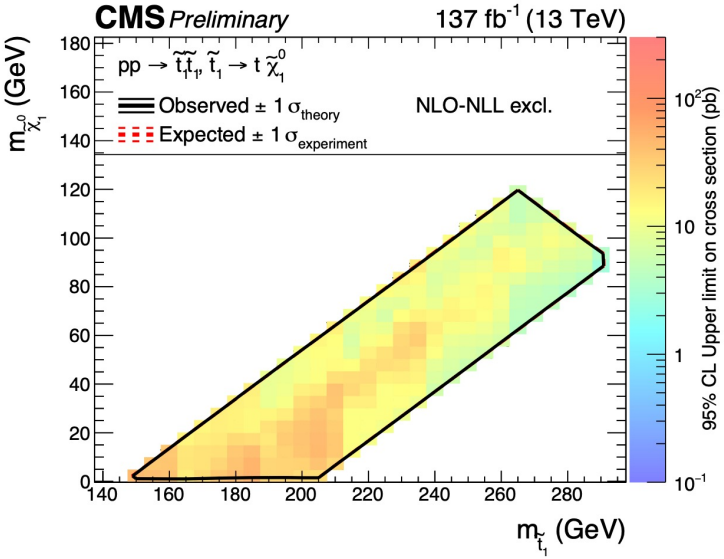
e.g. consider taus in stop decay chains (traditional searches veto taus or don't focus on them



Challenging topologies

$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_t$

CMS-PAS-SUS-20-002

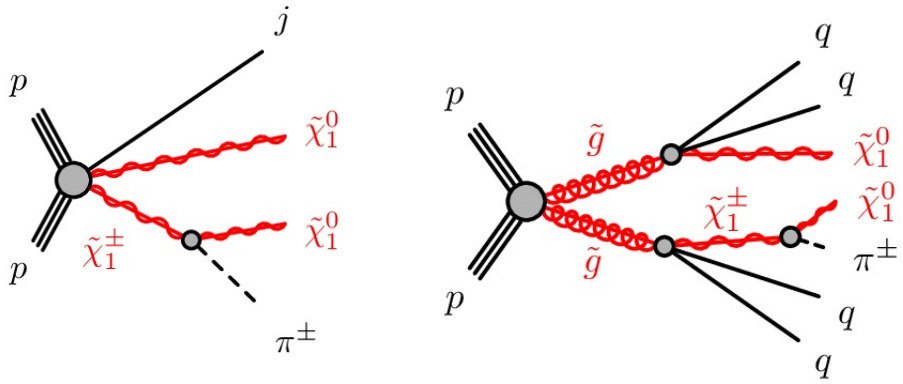


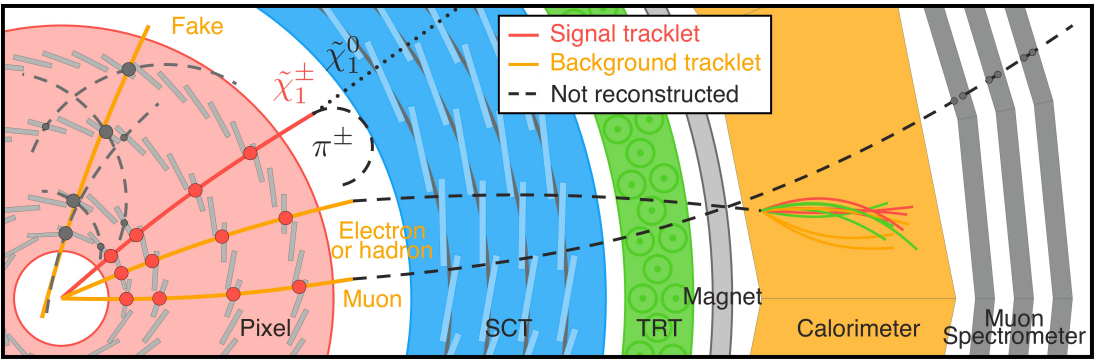
A lot of ground covered in Run 2; more luminosity awaits in Run 3

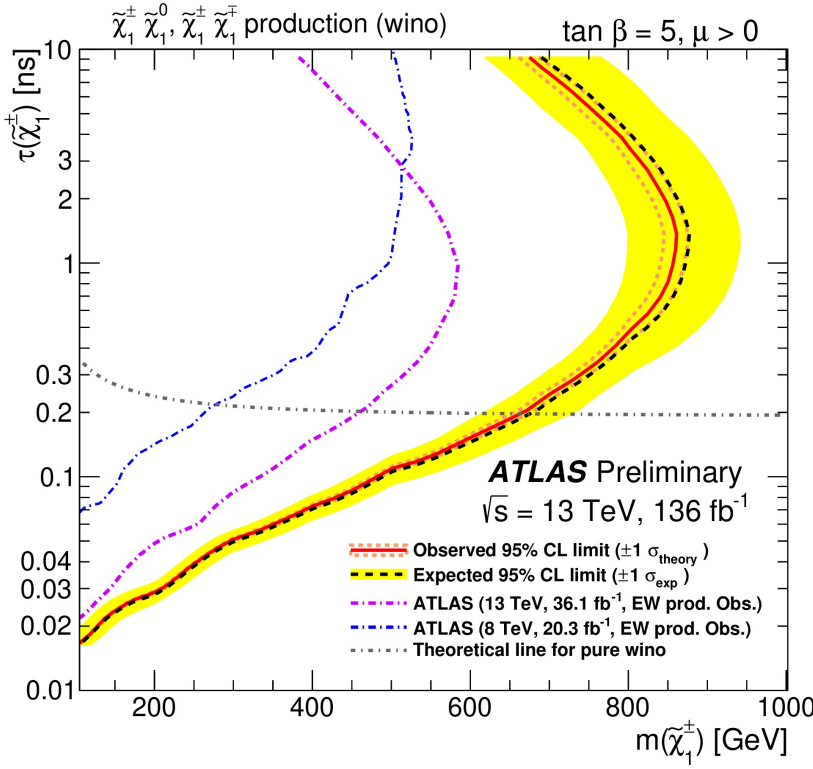
SUSY Searches @ LHC

Many new searches targeting strong and electroweak production

- Unconventional analyses
- Target EWK production of long-lived charginos and neutralinos, and the strong production of gluinos decaying promptly to long-lived chargino



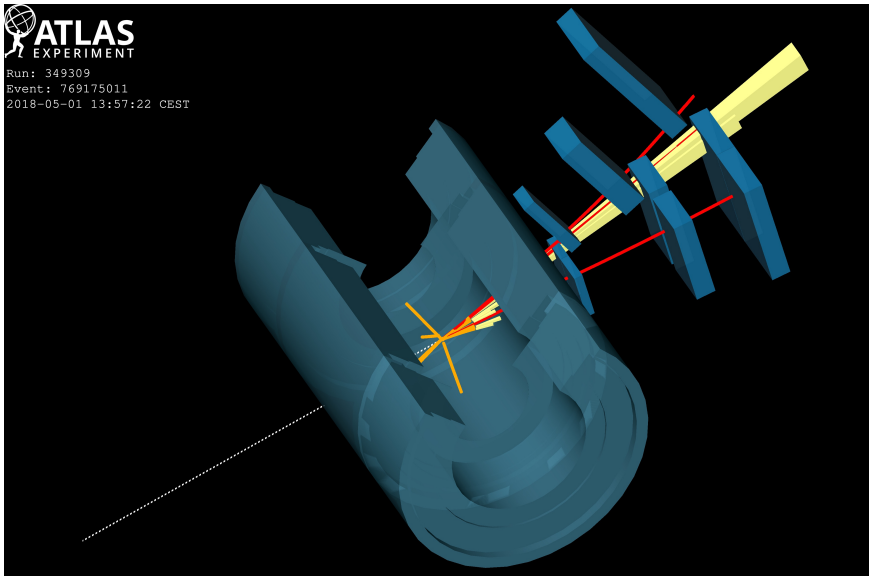




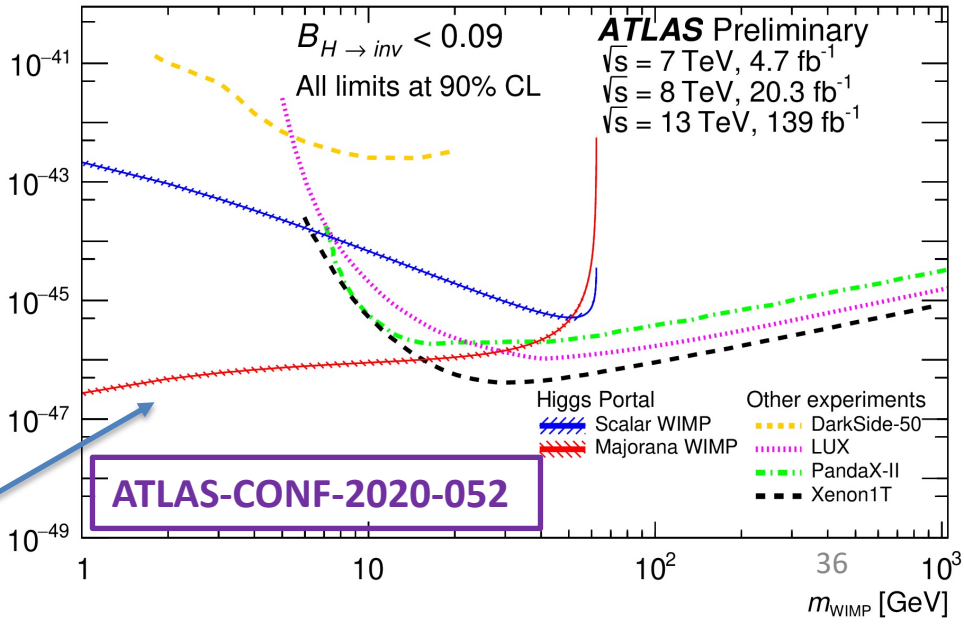
ATLAS-CONF-2021-015

Dark Matter Searches @ LHC

- Dark Matter (DM) searches @ LHC remain a thriving field of research
- A large number of mono-X searches have been performed by ATLAS and CMS, already probing a large part of the parameter space
- No “low-hanging fruit” but significant progress in exploring a variety of final states
  - incl. searches where Higgs acts as a mediator to DM
- LHC searches complementary to direct searches, improved sensitivity to low DM masses

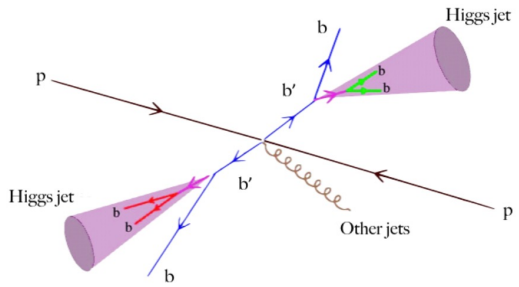


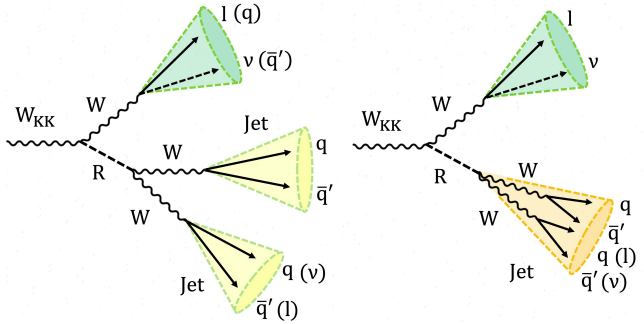
ATLAS-CONF-2021-006

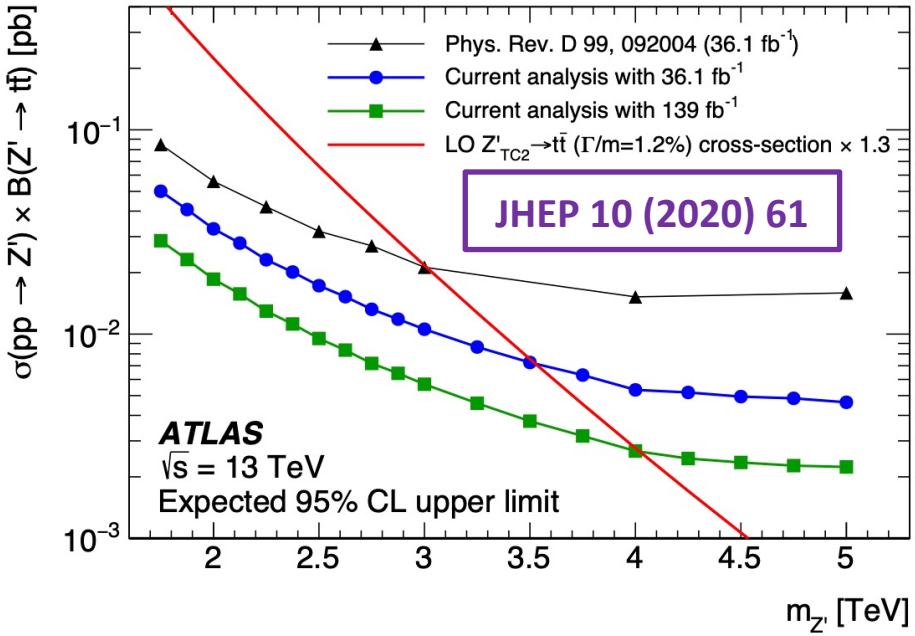


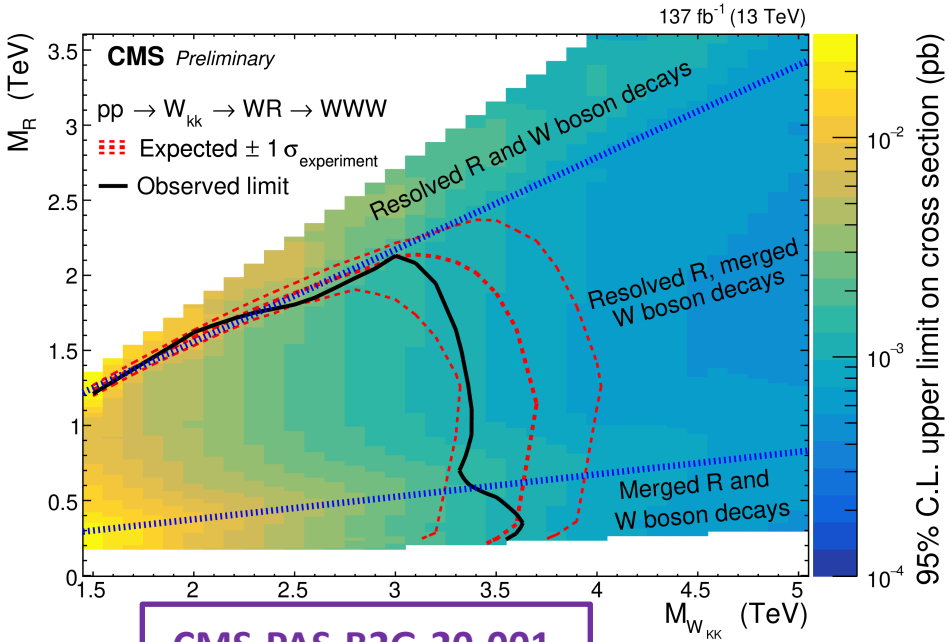
Boosting searches @ LHC

- Substructure techniques (for jets, b-tagging) + better reco + ML are being used for maximizing sensitivity to boosted topologies, large mass range
  - Includes using the Higgs as a discovery tool ("Higgs-tagging")







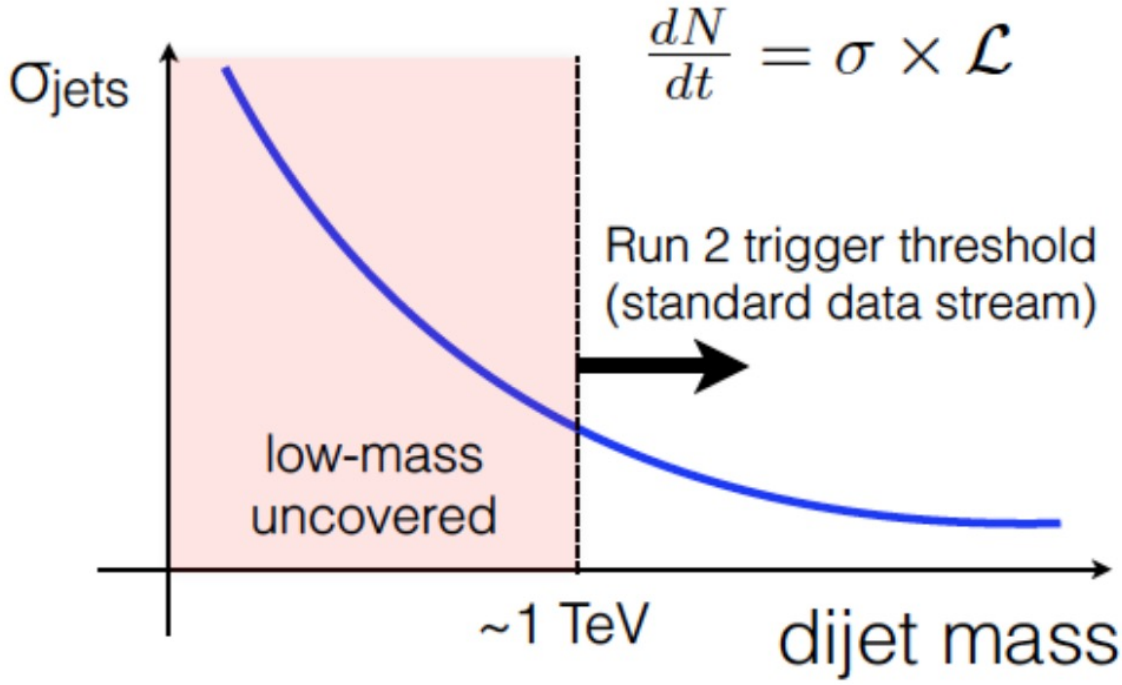


Challenging topologies

Important to cover the full mass range in BSM searches

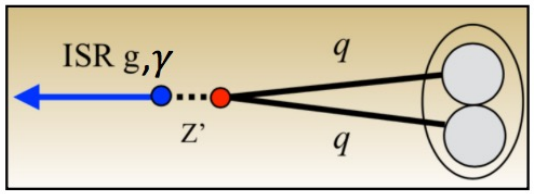
Experimental challenges:

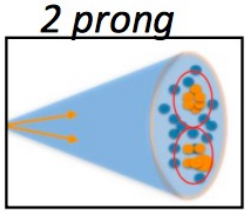
- large (di-jet) cross section at hadron colliders at low-mass
- limited resources to process and store data
- trigger thresholds raise with increasing inst. luminosity

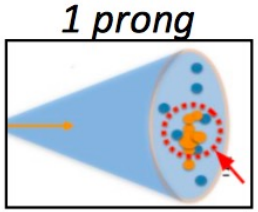


Dijet Resonance Searches

"scouting" [CMS] & "trigger-level analysis" [ATLAS] probe low masses;





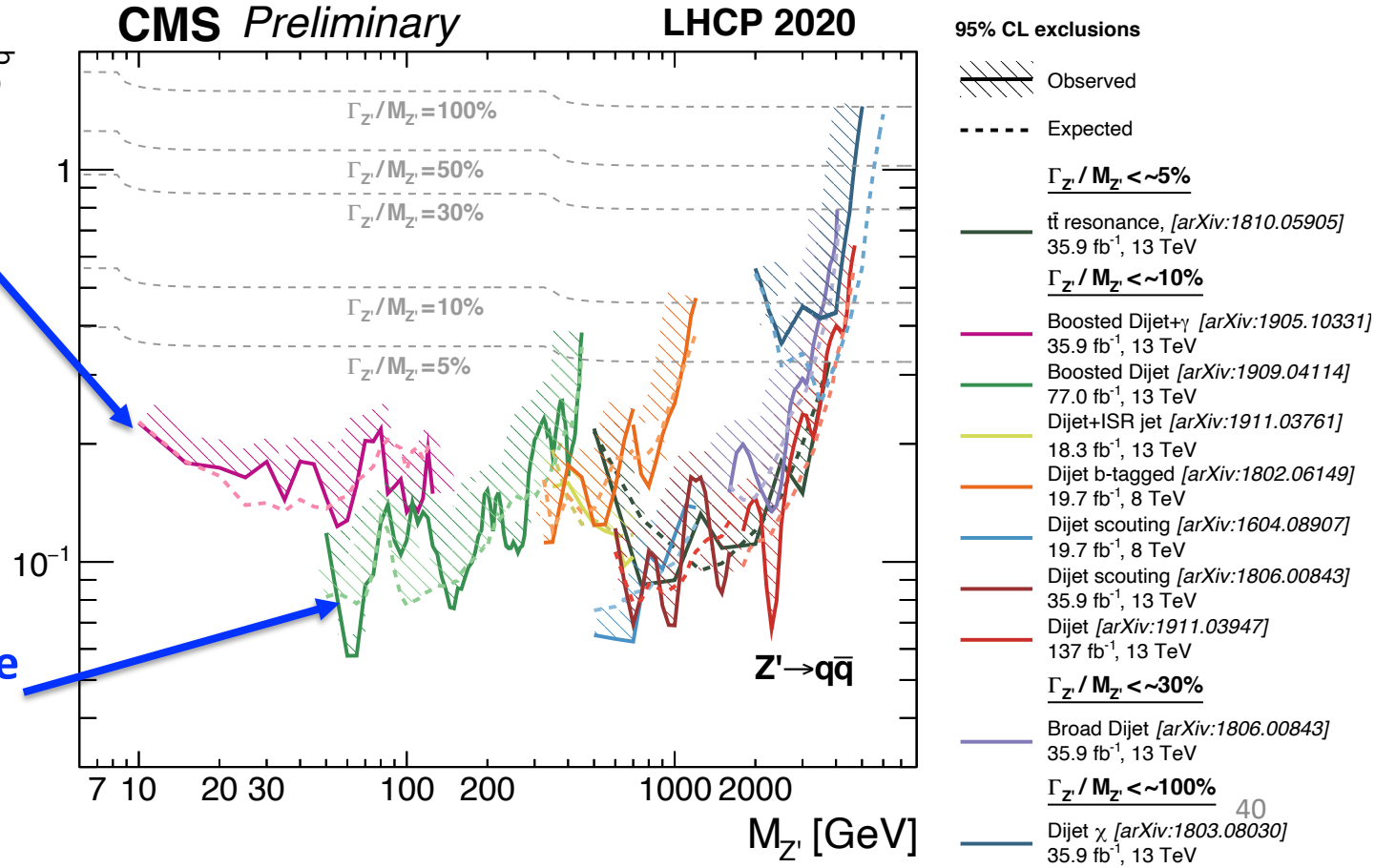


Use boosted techniques for event reco.

ISR photon tag @ HLT

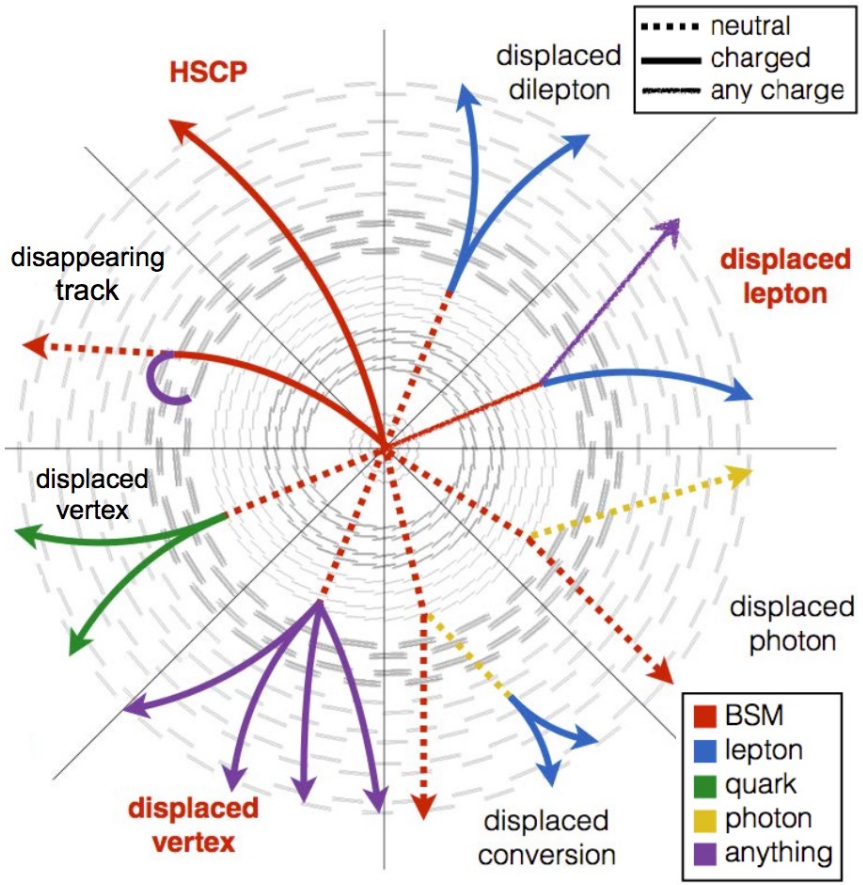
Constraints down to 10 GeV for the first time at a hadron collider!

Jet substructure trigger @ HLT



Long-lived particle searches

Long-lived and other exotic particles with striking signatures predicted by many BSM models



Credits: J. Antonelli

Searches need to often overcome challenges in trigger, reconstruction, & background estimation

Excellent detector understanding is absolutely critical

Taking advantage of several topologies currently

HL-LHC upgrades will provide improved sensitivity

CMS LLP Results

ATLAS LLP Results

Summary & Outlook

- The ~11 years of LHC operation has been one amazing ride!
  - Discovery of the Higgs boson
    - Now using the Higgs as a tool for discovery
  - Huge amounts of BSM parameter space ruled out
  - At the same time, innovative strategies for triggering, data-taking and analysis are providing access to previously unexplored territory!
  - Tantalizing hints of new physics in the flavor sector

- An exciting time to develop and implement new ideas
  - Go in directions where no one has gone before!

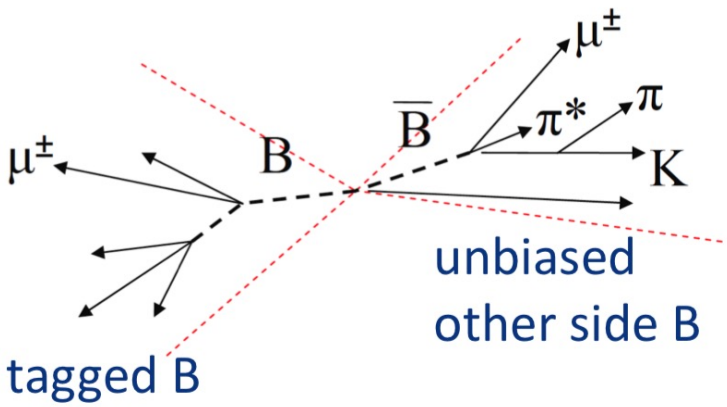
- **95% of the total LHC data still to come (and be studied)!**


CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-28 06:09:43.129280 GMT
Run / Event / LS: 257645 / 1610888538 / 1073
I WANT TO BELIEVE

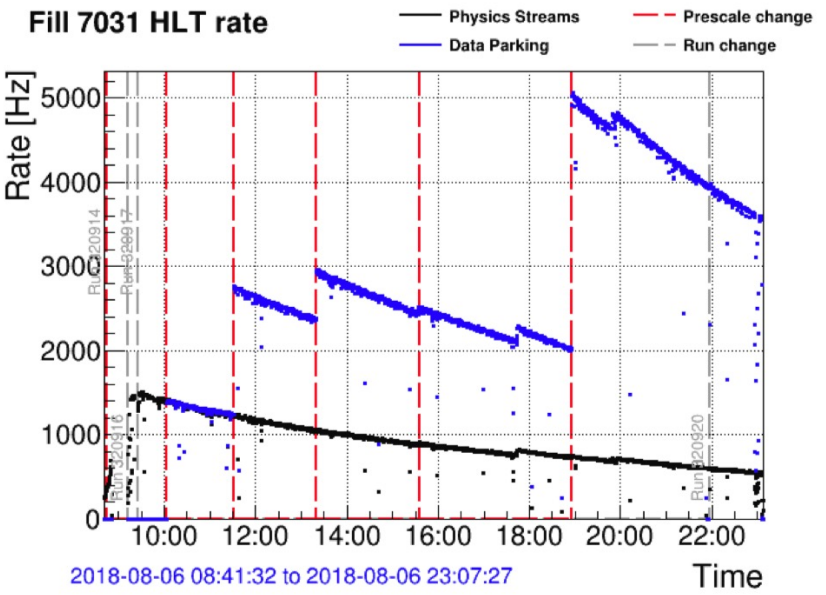
Additional Material

Data parking and B physics

- During Run 2, CMS stored a large unbiased B hadron sample by tagging on the “opposite-side” B
  - 12 B events recorded
  - Up to 6 kHz additional rate to tape



- Data was “parked” (→ no prompt reconstruction) and processing delayed to times of lower load on the computing system



- Potential resource for investigating B flavor anomalies and searches for other exotic phenomena

Analyses ongoing – stay tuned!