LHCP Experimental ~~Summary~~ Highlights

Few selected highlights and perspectives

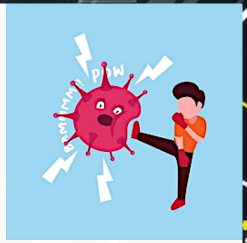
Andreas Hoecker (CERN)

LHCP, Everywhere, 30 May 2012

LHCP 2020

The Eighth Annual Conference on Large Hadron Collider Physics

This conference was …



- **Pioneering** — the first virtual of the large HEP conferences
- **Rich** — a showcase for first rate research under difficult circumstances
- **Important** — huge thanks to the organisers for bringing the community together

LHCP Experimental Highlights

Few selected highlights and perspectives

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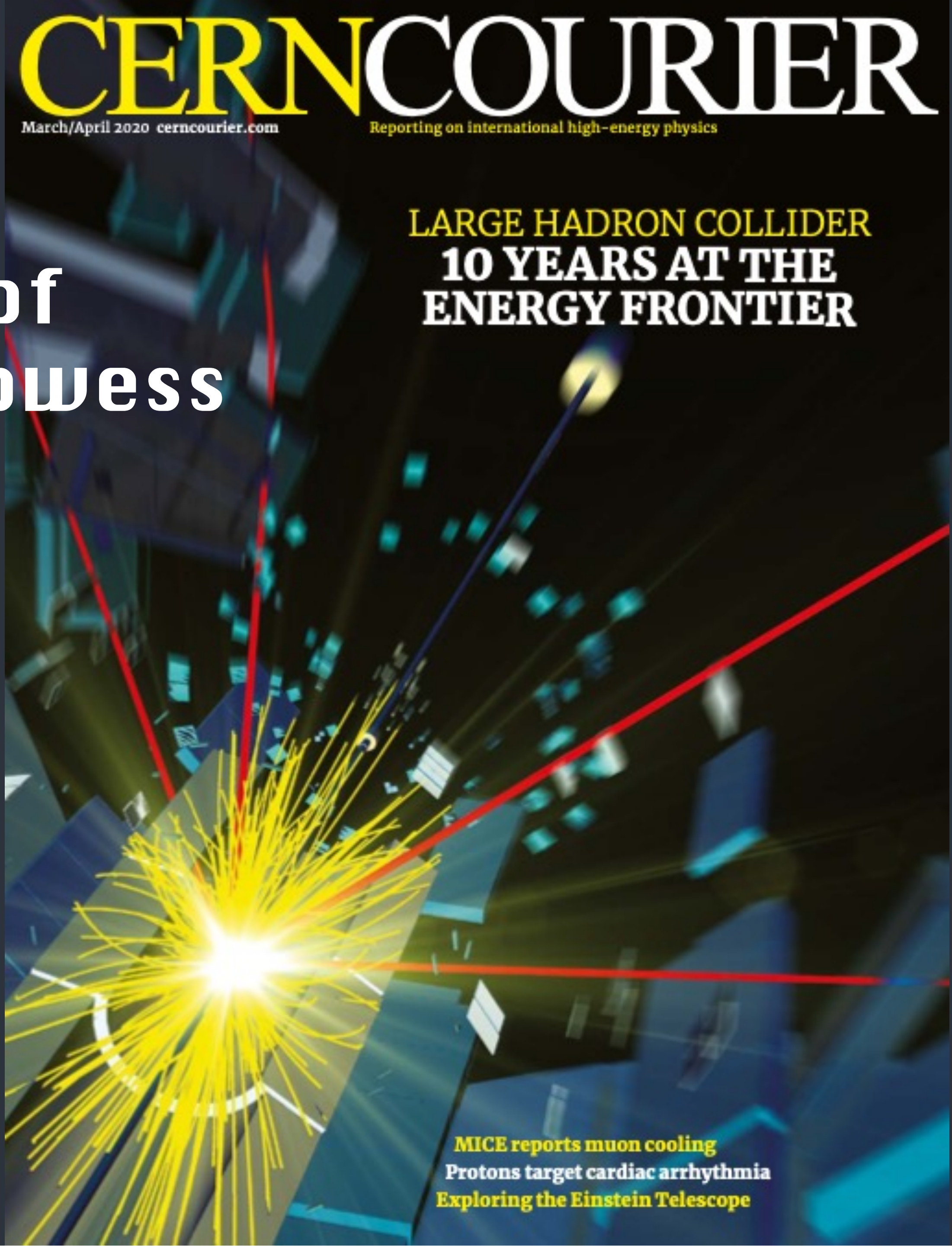
LHCP, Everywhere, 30 May 2012

Disclaimer: I apologise for not adding names on these slides. I have used so many talks/posters for the material presented here that I rather choose to **sincerely thank ALL speakers and poster presenters!**

We are celebrating 10 years of physics and technological prowess

- The Higgs boson exists
- There is — so far — no proof of physics beyond the SM up to the TeV scale
- Numerous discoveries within the SM were made involving rare processes, flavour, spectroscopy, high-density strong matter
- Accelerators, detectors, computing & analysis performed beyond expectations
- The LHC has prompted prodigious progress in particle theory

Michelangelo Mangano, CERN Courier March/April 2020



Remember

Google on 10 Sep 2008

INDEPENDENT

News > Science

Cern experiment: Machine switched on. No Big Bang. It works

The world watched and waited for the greatest experiment in history to begin. Impressive though it was, it was also a bit like booting up a sulky PC, says Andy McSmith who was at Cern

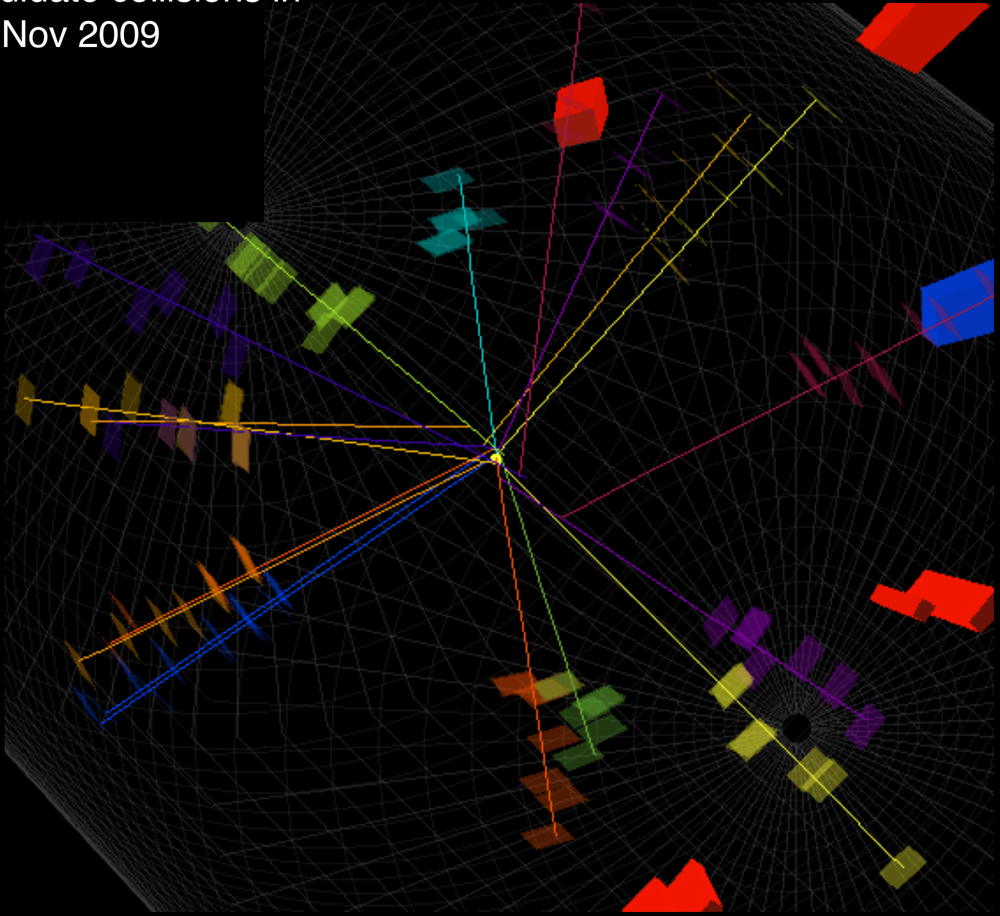
Thursday 11 September 2008 00:00 |

Remember

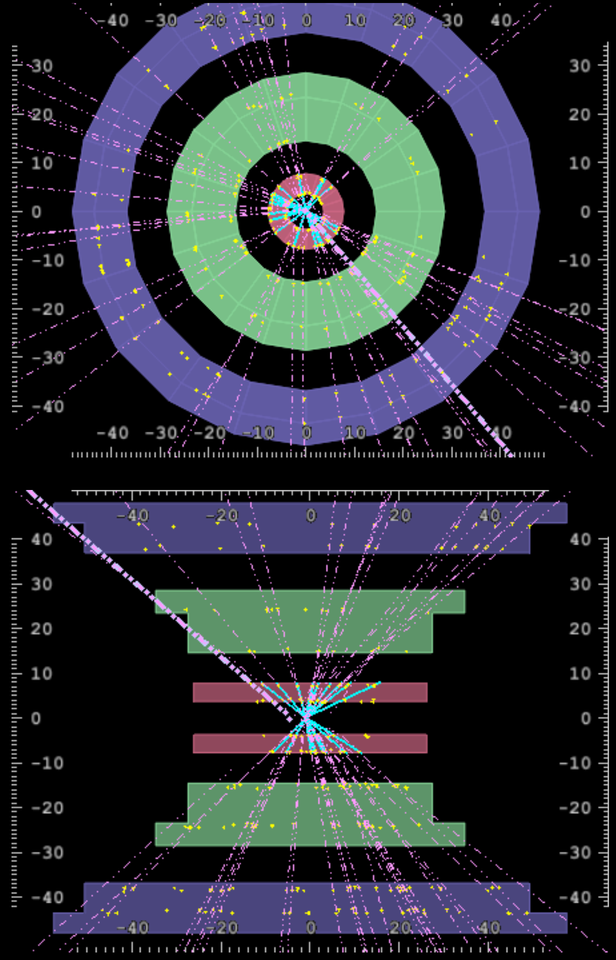
The First Year: 2009/10

$\sqrt{s}$ = 0.9, 7 TeV (35 pb^{-1})
2.76 TeV/NN (9 μb^{-1})

First candidate collisions in CMS 23 Nov 2009



High-multiplicity collision event seen in ALICE



Remember

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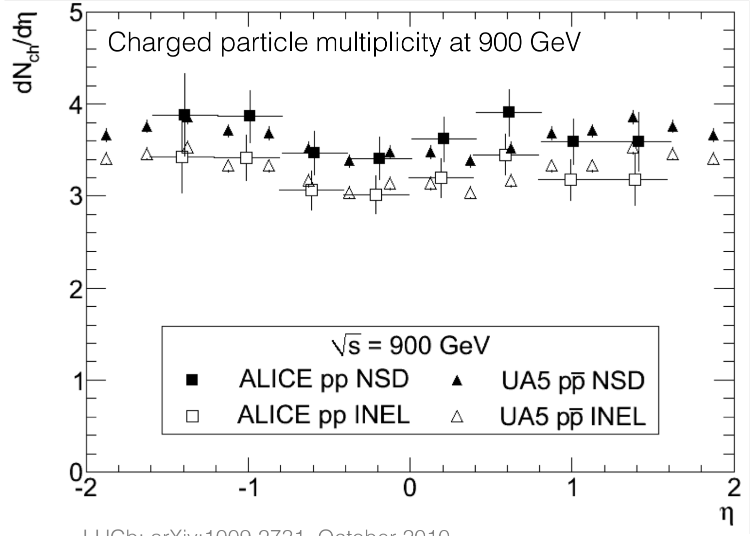
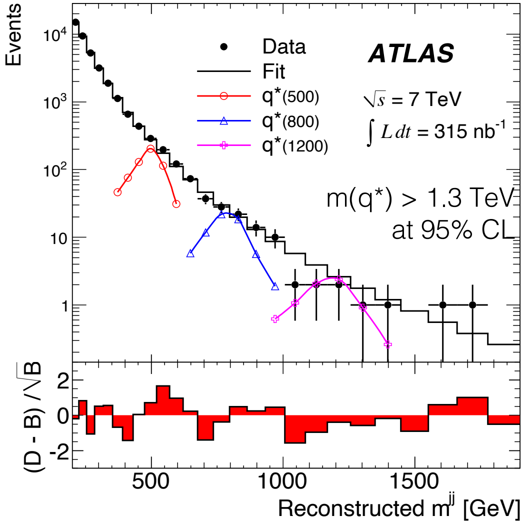
ALICE: arXiv:0911.5430, November 2009



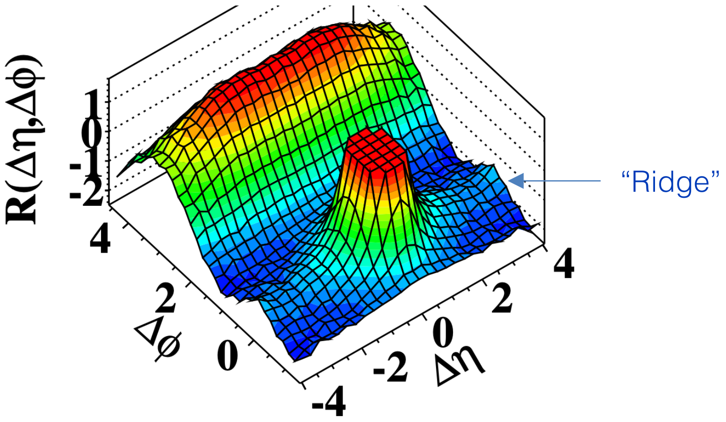
ATLAS: arXiv:2003.10866, August 2010



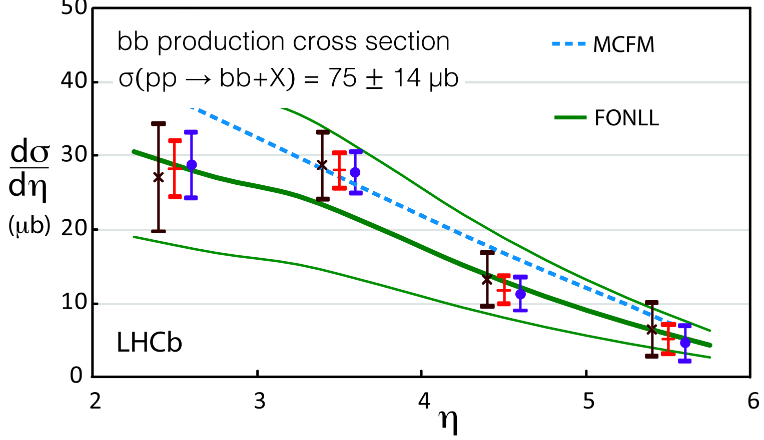
CMS: arXiv:1009.4122, September 2010

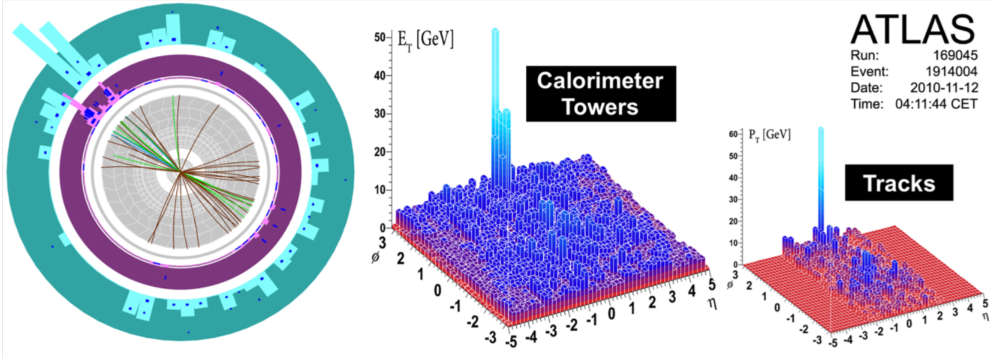
(d) CMS N ≥ 110, 1.0GeV/c<p$_T$<3.0GeV/c

Long-range correlations in pp



LHCb: arXiv:1009.2731, October 2010





ATLAS: arXiv:1011.6182, November 2010

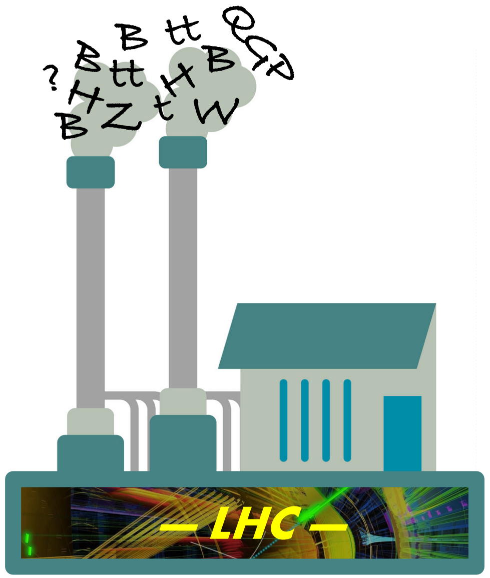
Jet quenching in PbPb collisions

LHC Run-2 (2015–2018)

$\sqrt{s}$ = 13 TeV (140 fb^{-1})
5 TeV/NN (2.3 nb^{-1})

Now — after an outstanding Run 2 — the LHC experiments have in their hands the richest hadron collision data sample ever recorded

Particle	Produced in 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	(115 million $t\bar{t}$)
Z boson	8 billion	($\to \ell\ell$, 270 million per flavour)
W boson	26 billion	($\to \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)



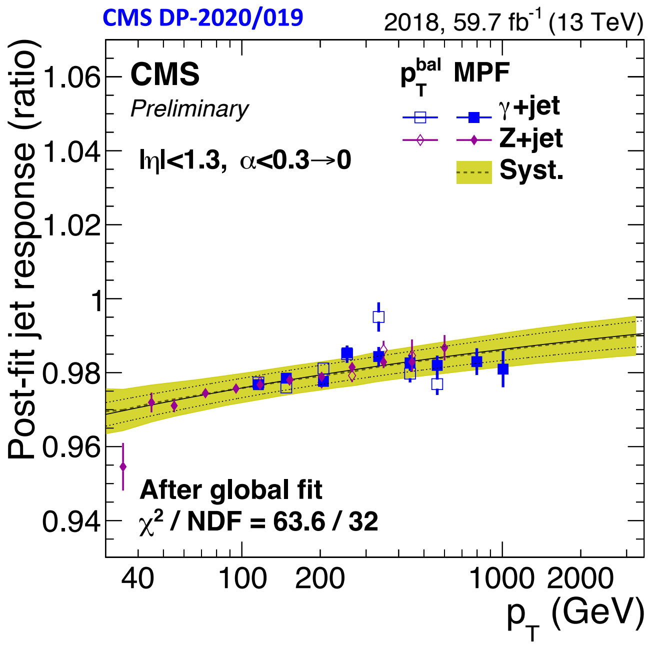
The LHC is an **everything** factory

Broad physics potential by probing with high-precision Higgs and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements

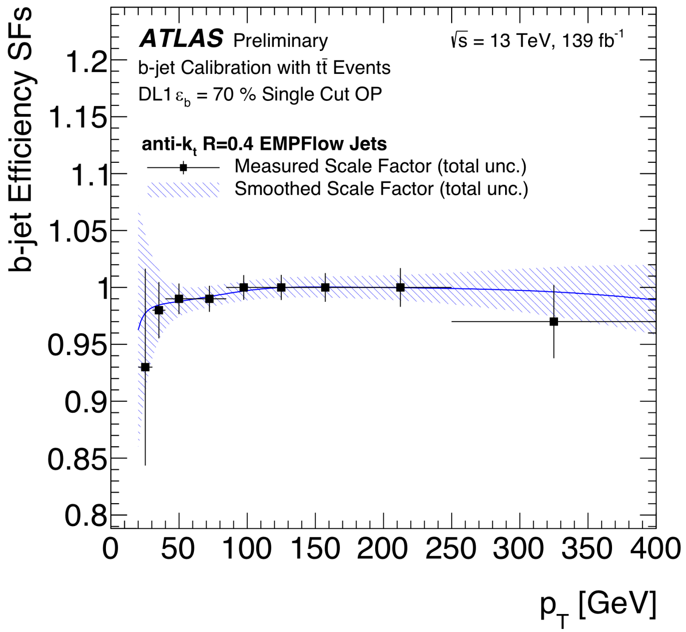
Precision calibration of data

The results presented this week rely on excellent detector and reconstruction performance, exploiting more and more low-level machine learning algorithms, but **most importantly on the meticulous calibration of the algorithms with data**

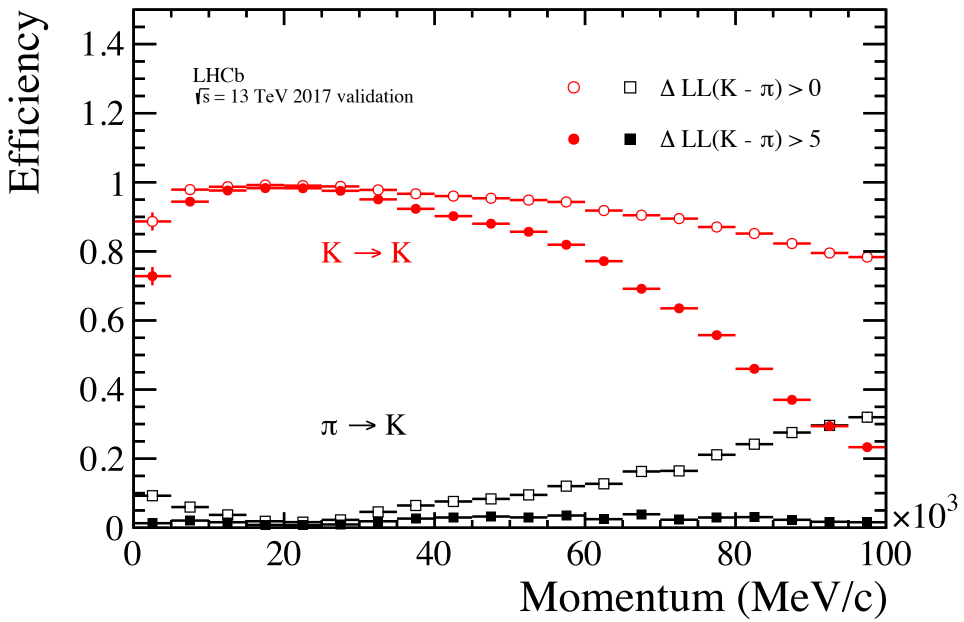
Jet energy scale calibration



b-jet tagging efficiency calibration

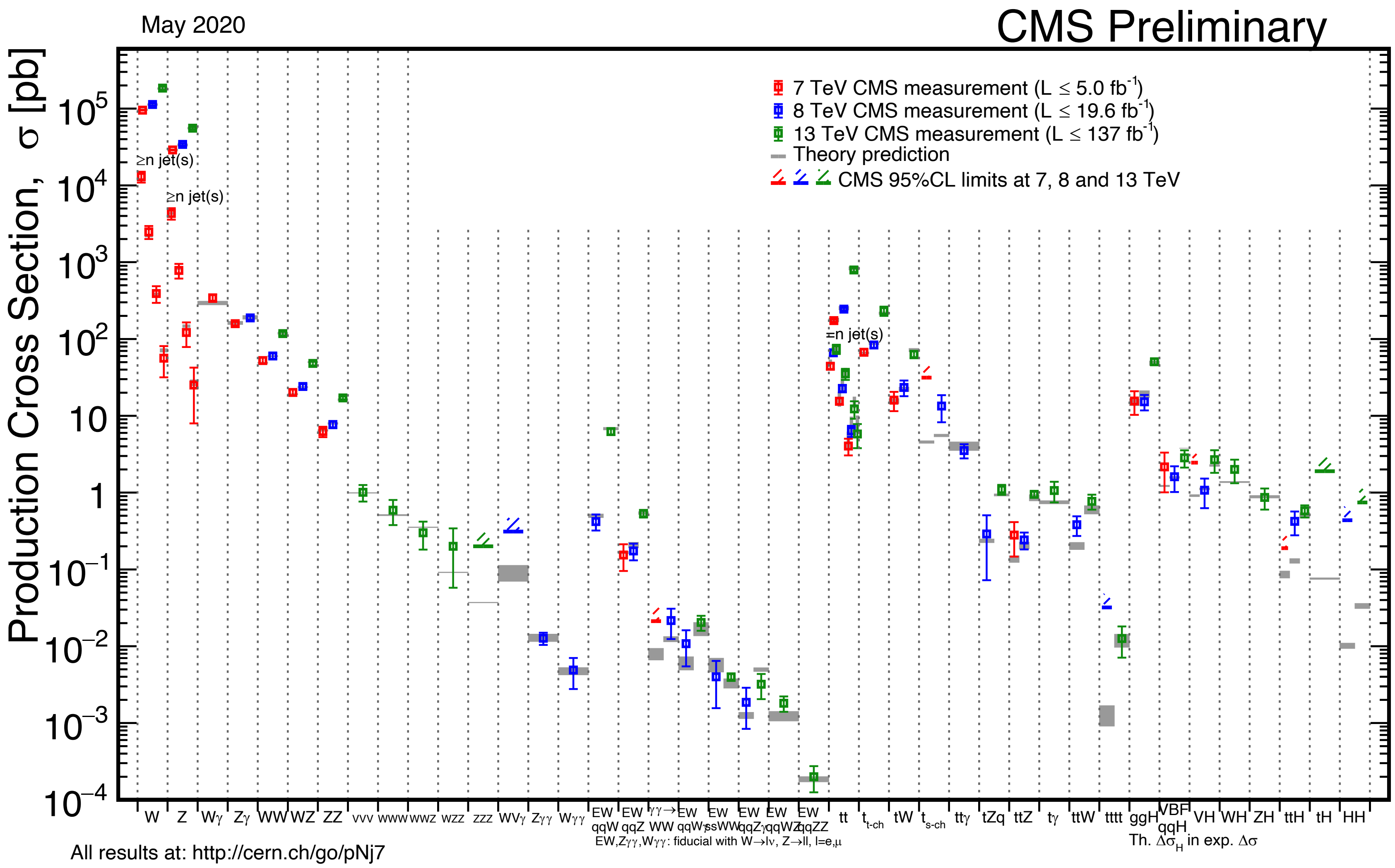


Kaon PID efficiency in LHCb



Crucial is also precise luminosity measurement: ~1.7% for ATLAS and CMS for all Run-2

Theory so far agrees with all measured cross sections — Across widely different processes

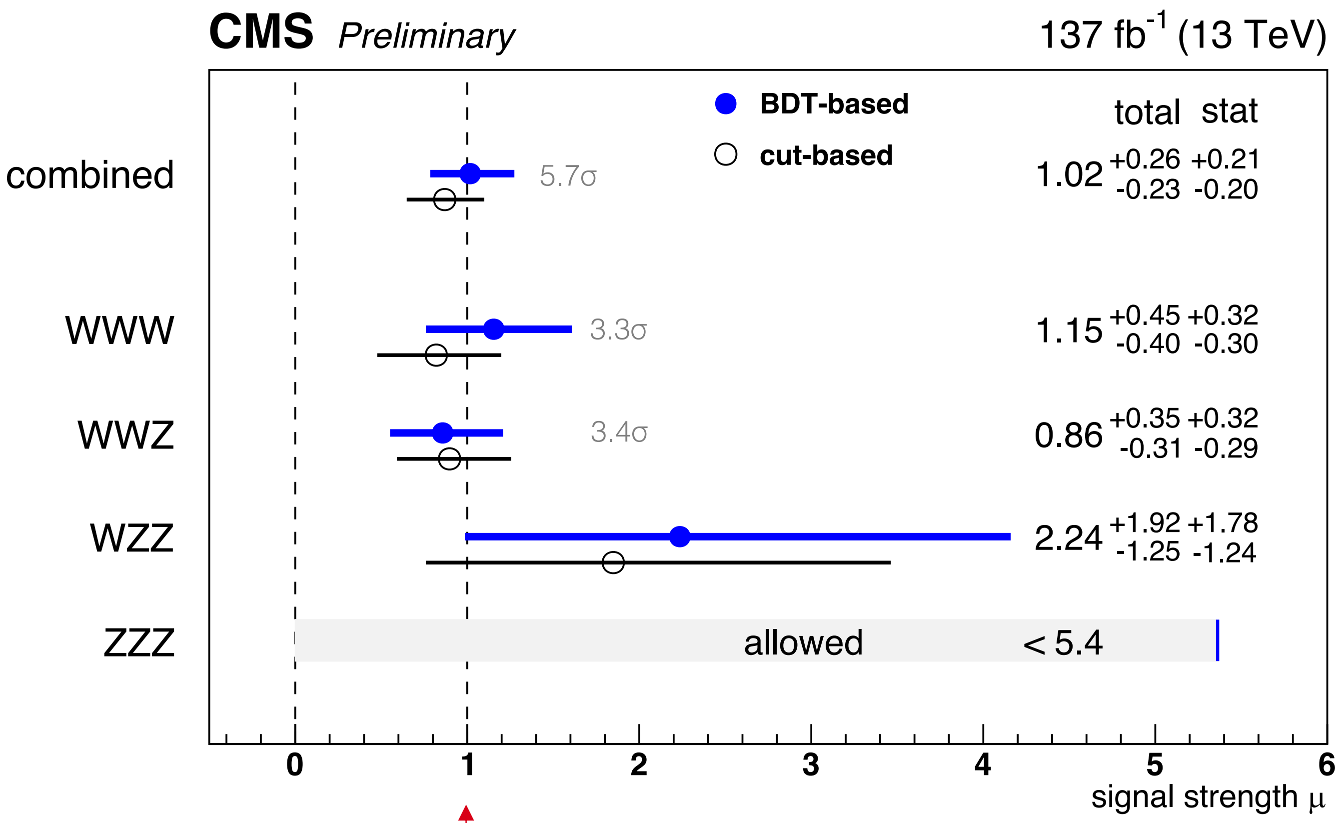


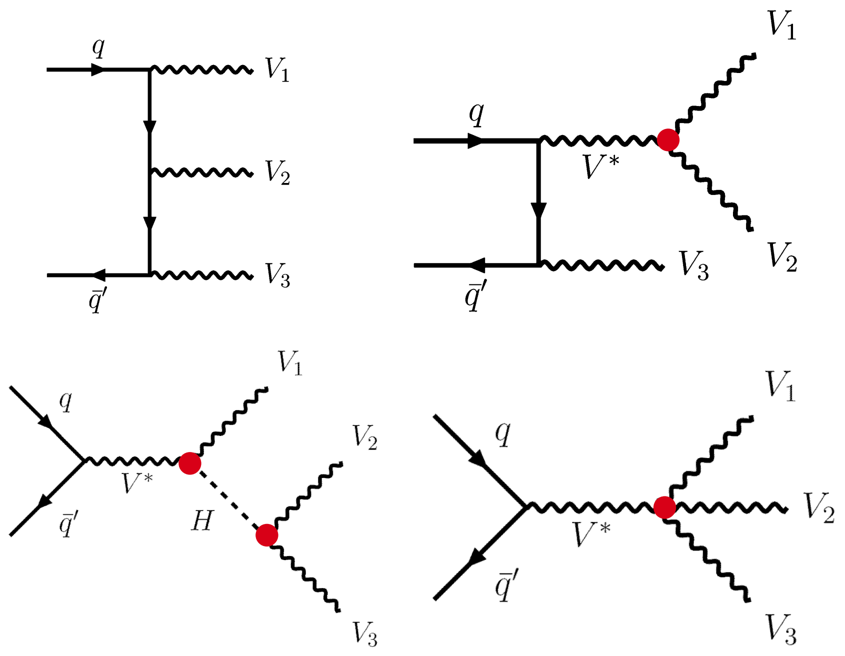
Harvest of cross section measurements confirms the predictive power of the Standard Model

Also huge progress on theoretical calculations (NNLO QCD revolution, NLO EW corrections, towards full DY NNLO QCD-EW)

Many more detailed fiducial and differential cross section measurements

ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles

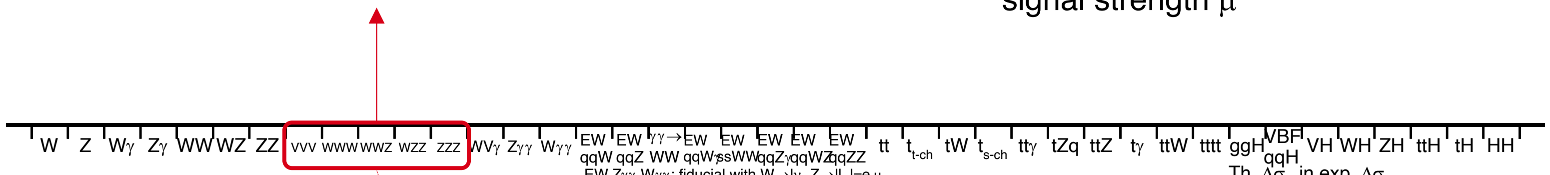




CMS observes massive triboson production

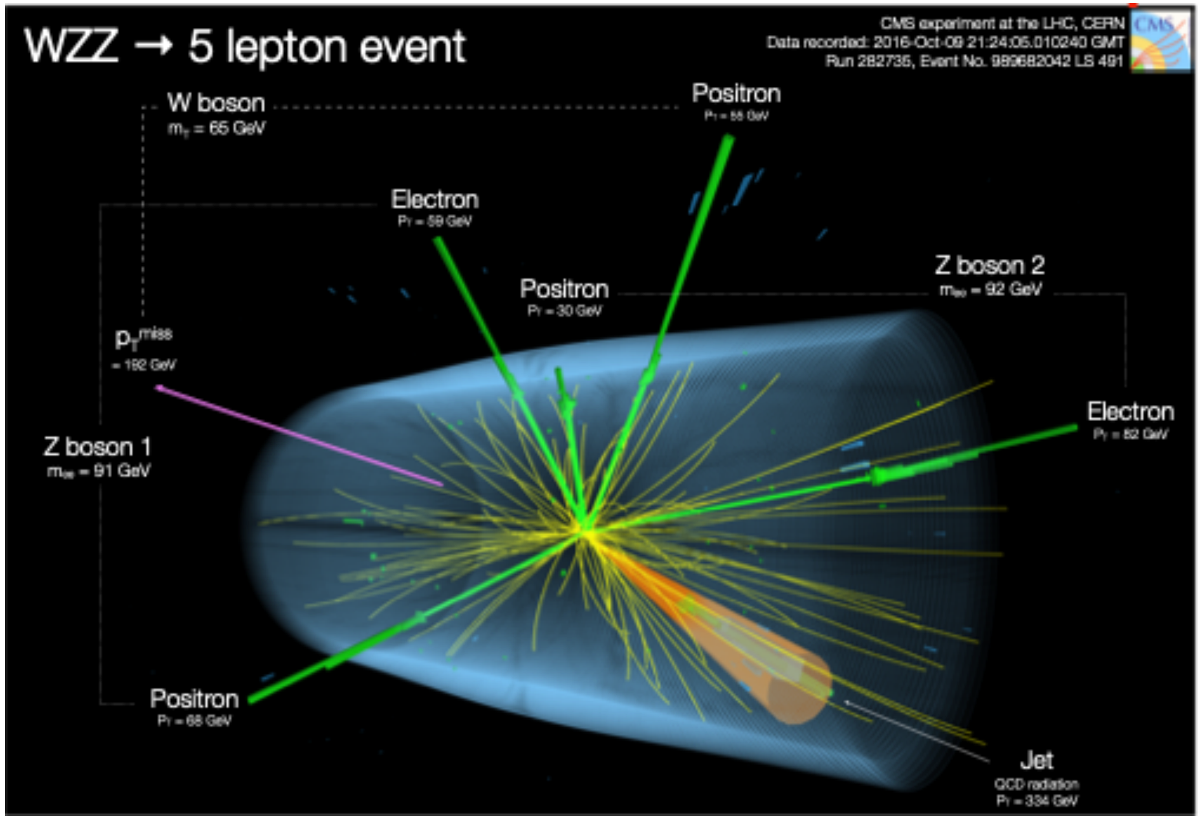
Involves (among others) quartic gauge coupling vertex

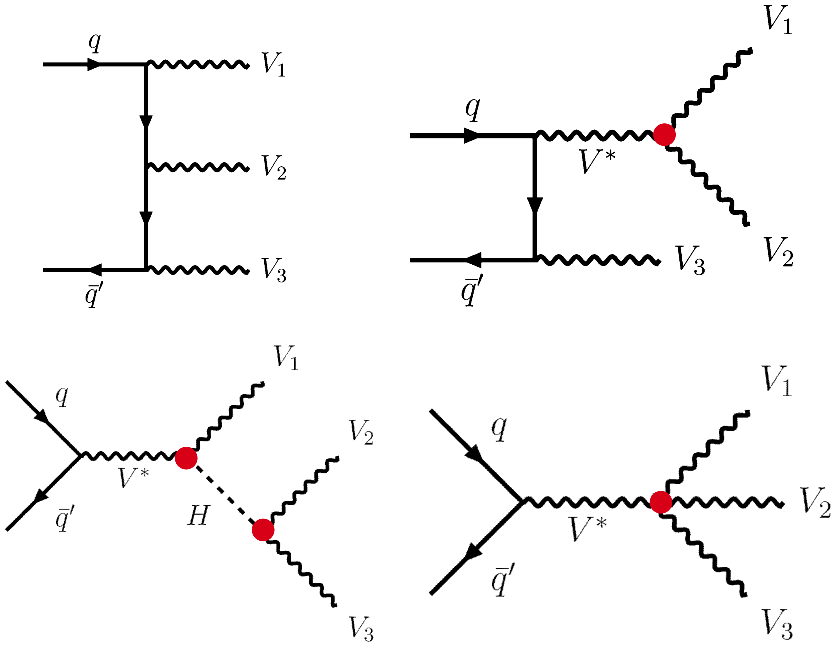
CMS PAS SMP-19-014



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

ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles





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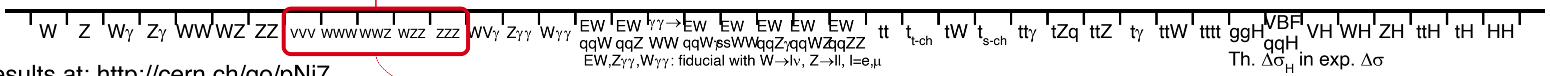

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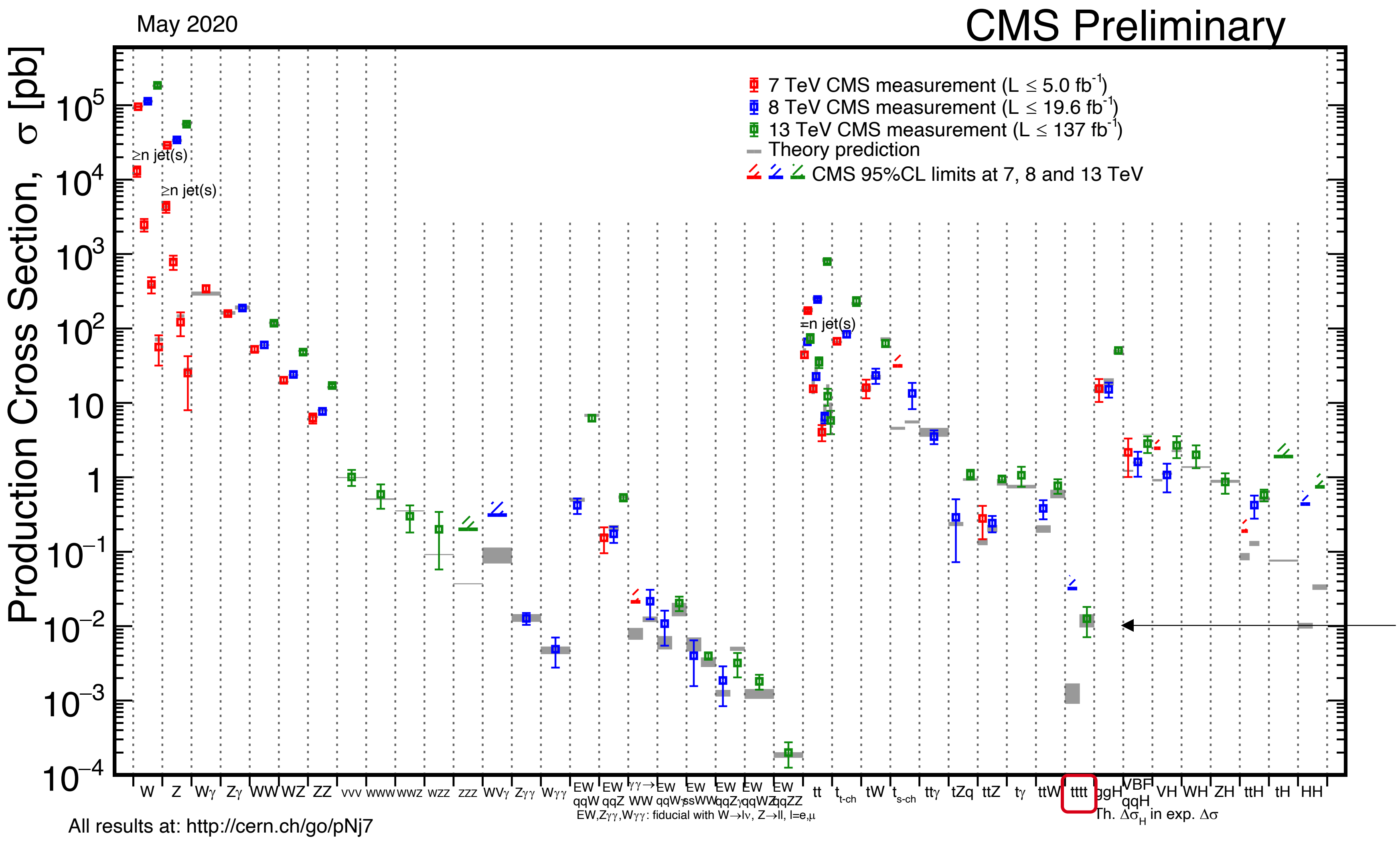
ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles



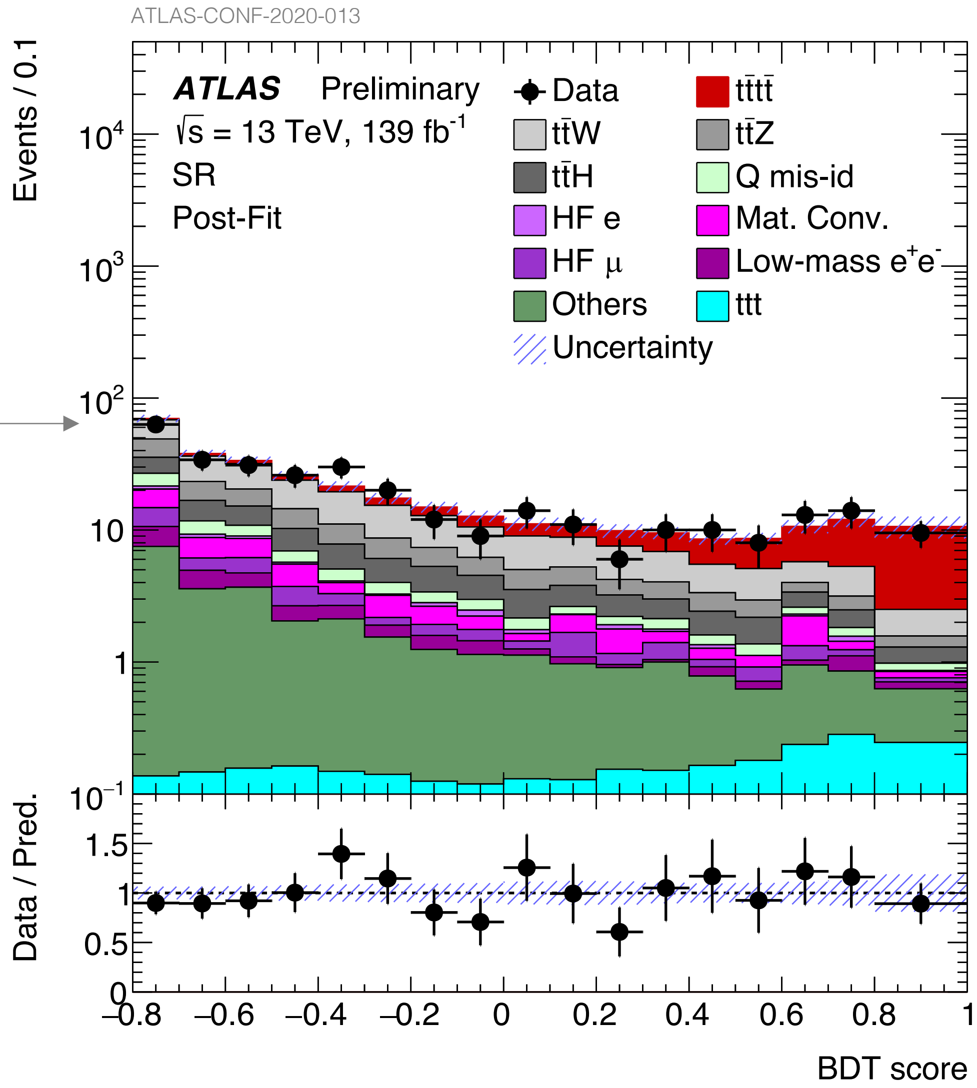
Somewhere here at 12 fb we expect 4-top production, a spectacularly massive state of almost 700 GeV

ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles

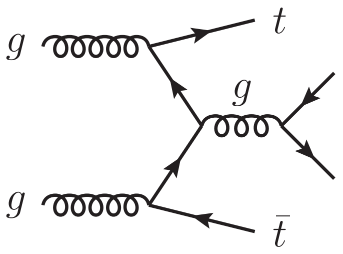
Large ttW contribution:
1.6 ± 0.3 times SM

(consistent with excess seen in ATLAS ttH-multilepton analysis)

For triboson and 4-top measurements with many leptons and jets as well as MET, good physics modelling and control of fake leptons crucial: among the big analysis challenges for the coming years!



ATLAS finds strong evidence for 4-top production

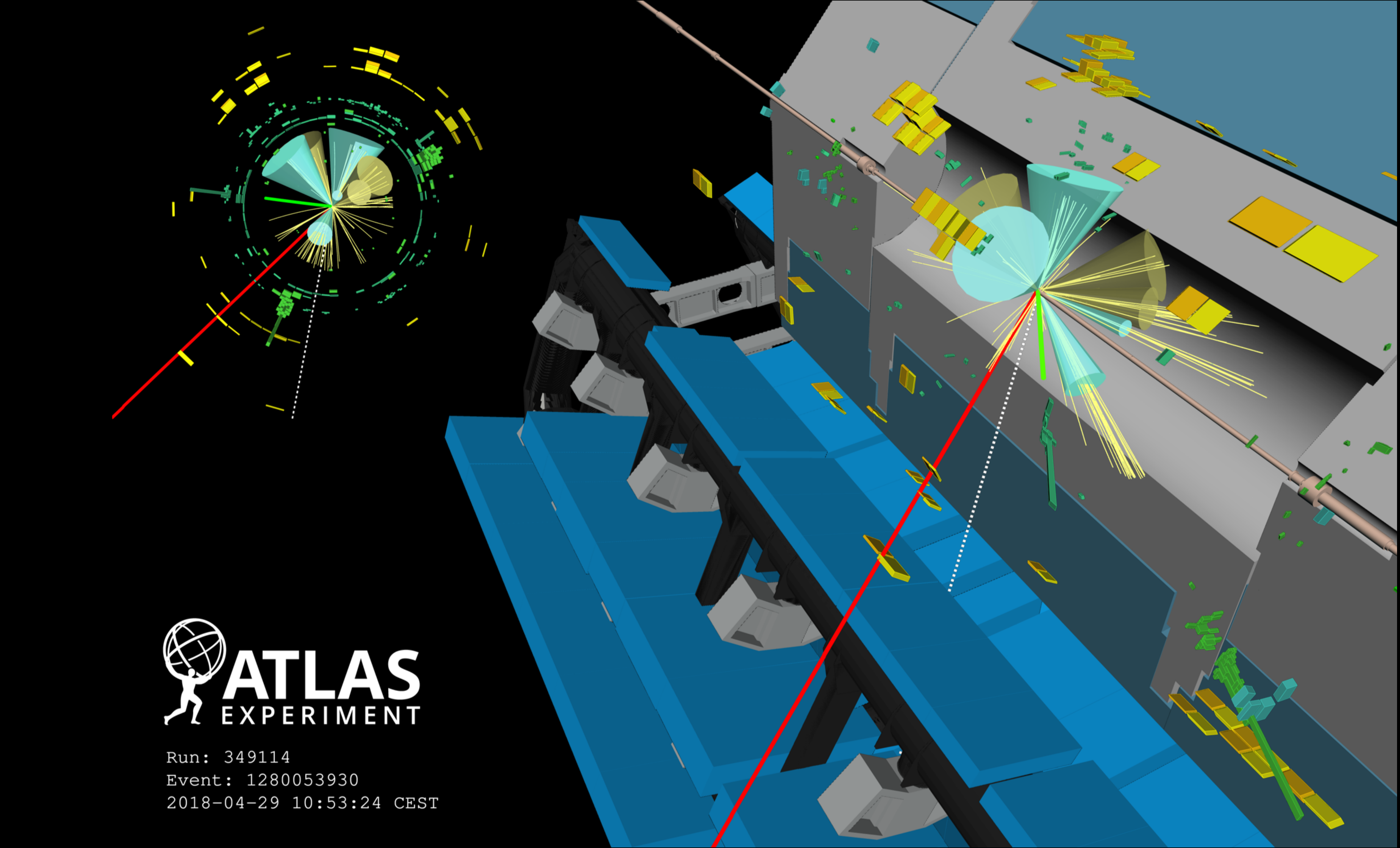


+ other QCD and EW graphs

Fitted 4-top signal

$\sigma(tttt) = 24^{+7}_{-6}$ fb

Obs. (exp) significance: 4.4σ (2.4σ)


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

Hadron colliders enable high-precision — See W & top mass, $\sin^2\theta_W$, W, Z, top cross sections, flavour, etc.

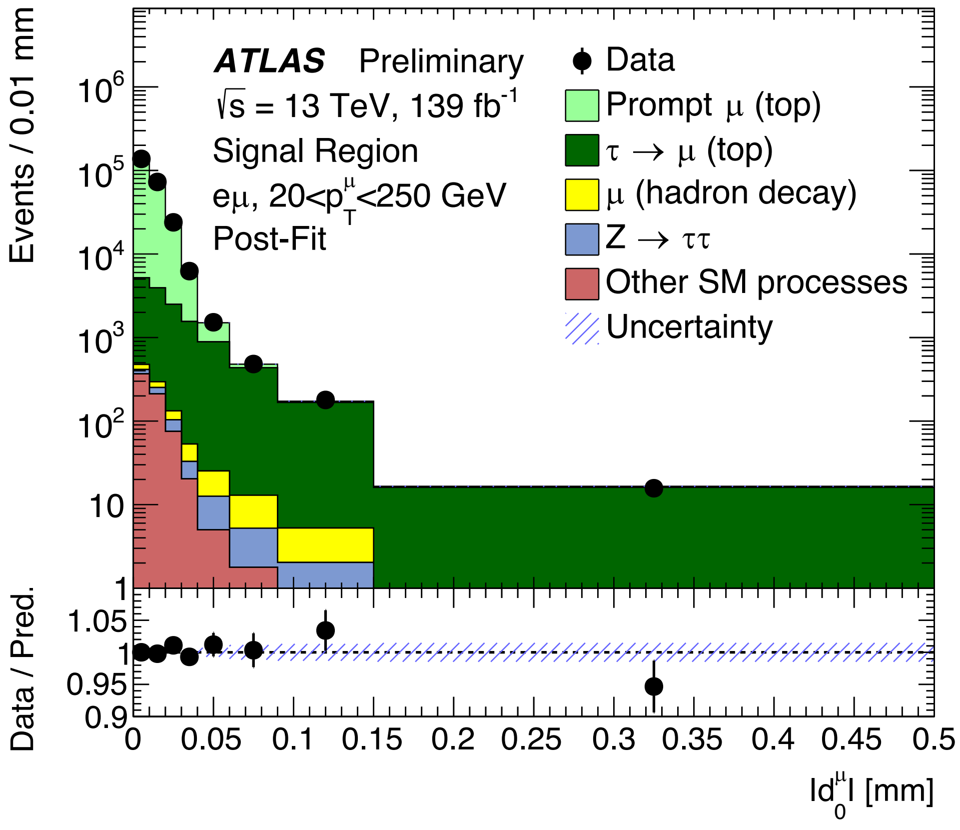
Longstanding 2.7σ LEP puzzle of R = B(W → τν)/B(W → μν) = 1.070 ± 0.026

— Driven (a.o.) by high B(W → τν) and low B(W → μν) measurements from L3 (R[L3] = 1.19 ± 0.05)

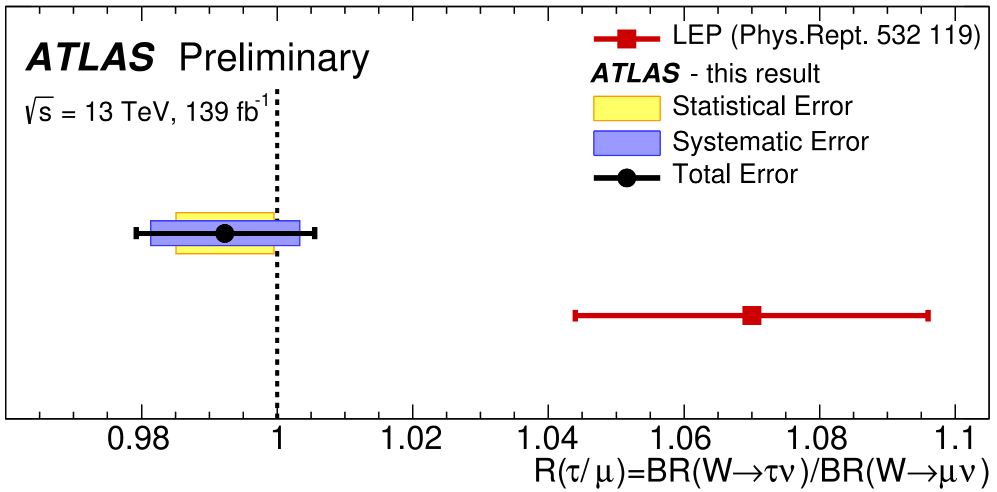
HOT TOPIC

In view of B-decay tensions

ATLAS used top-pair events as clean probe for W's to measure the ratio of prompt to softer delayed muons from tau decays



ATLAS-CONF-2020-014



Result 0.992 ± 0.013 is twice more precise than LEP and in agreement with lepton universality

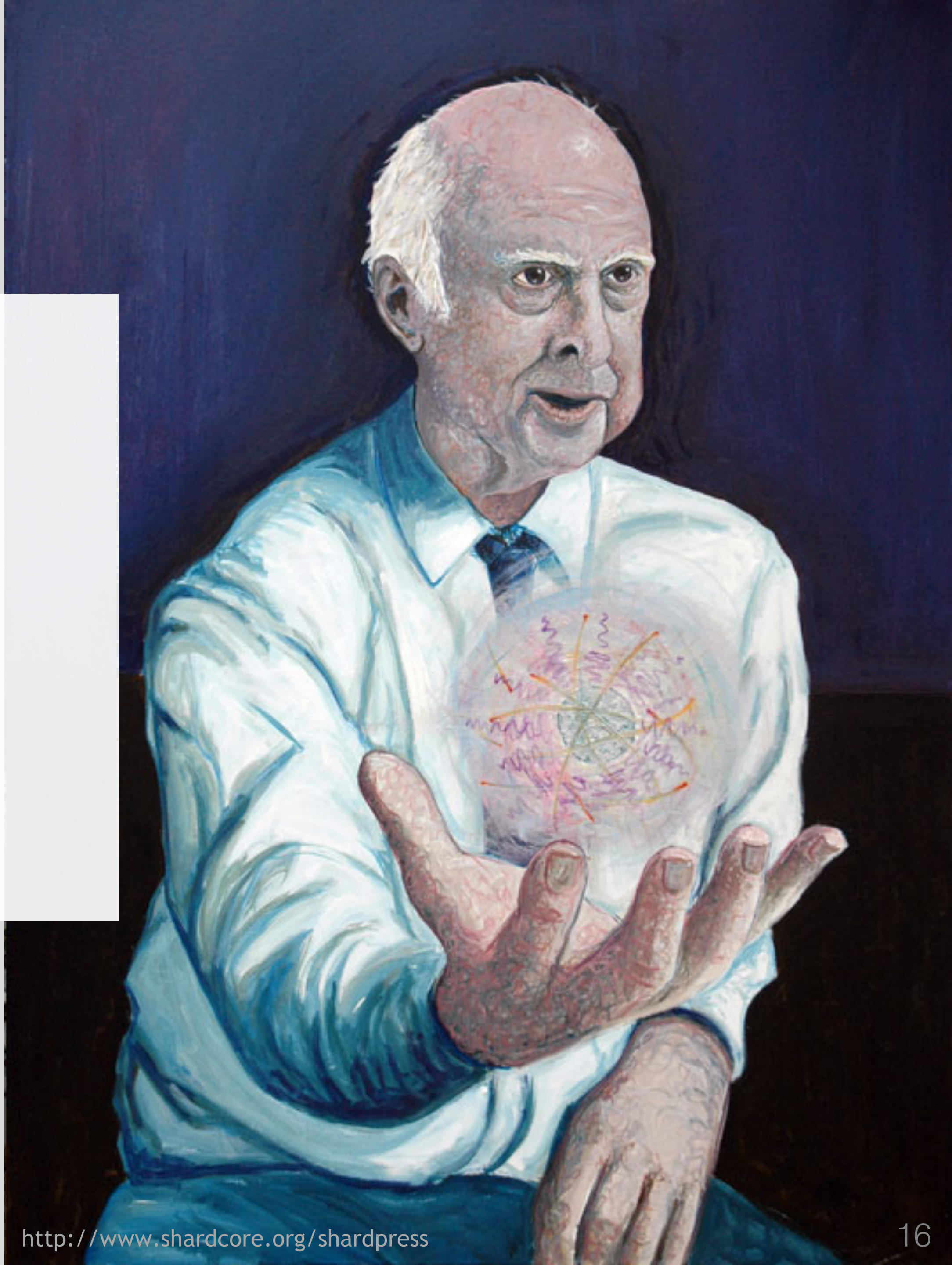
… as are LEP τ_τ, τ → μνν, τ → eνν measurements within 0.14% precision (but at lower energy, off-shell W)

The Higgs boson

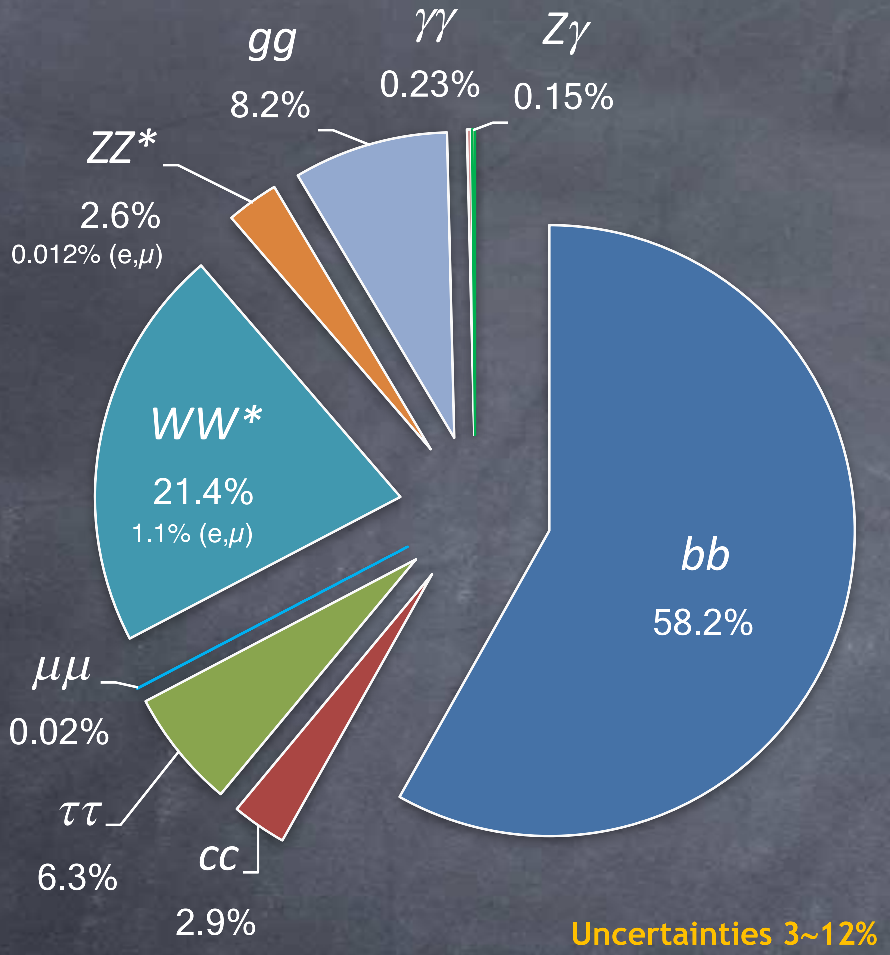
The LHC’s magnum opus

Discovery allows to access new sector of SM Lagrangian:

- Yukawa couplings
- Gauge–scalar boson interactions
- Higgs potential (incl. self coupling)



http://www.shardcore.org/shardpress



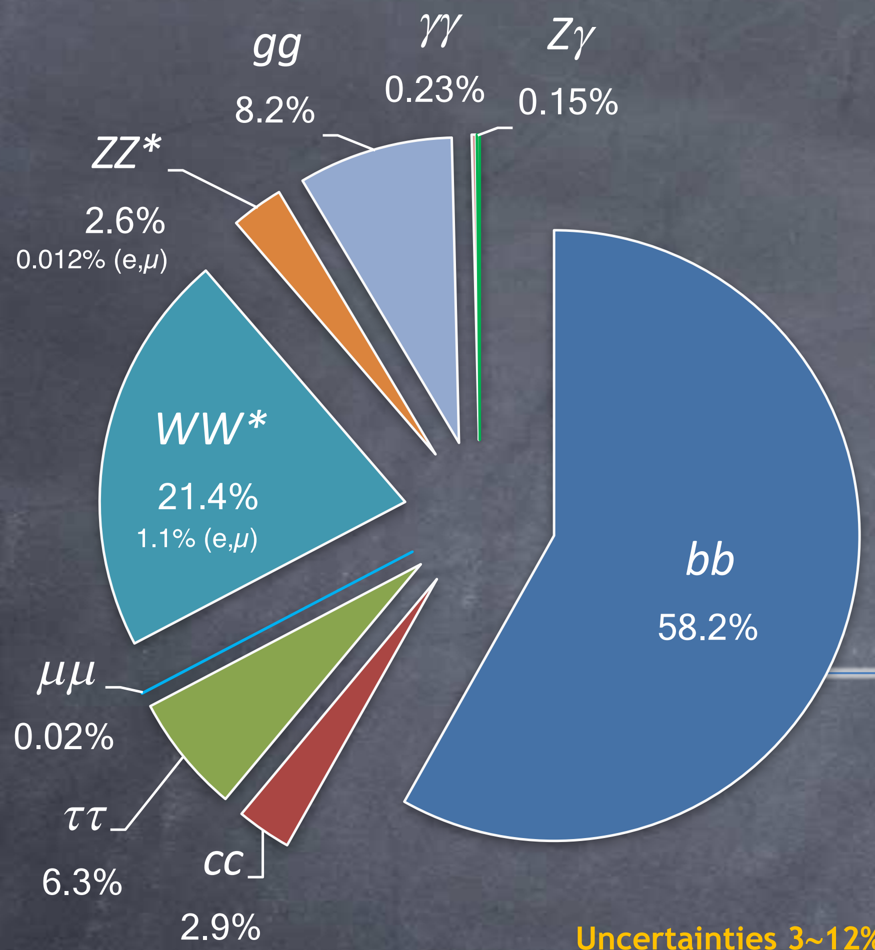
Run 2 provided proof & measurements of Higgs couplings to 3rd generation fermions, with results on full Run-2 dataset being released

Also progress on probing Higgs dynamics, rare decays, CP violation, dark matter

$y_{ij}\, \psi_{i,L}\, \phi\, \psi_{j,R}$

Yukawa force between elementary particles: new form of interaction — not a gauge force, non-universal, driving the fate of the universe

Just think what happens had the electron the mass of a muon (answer here: R. Cahn, Rev. Mod. Phys. 68, 951)



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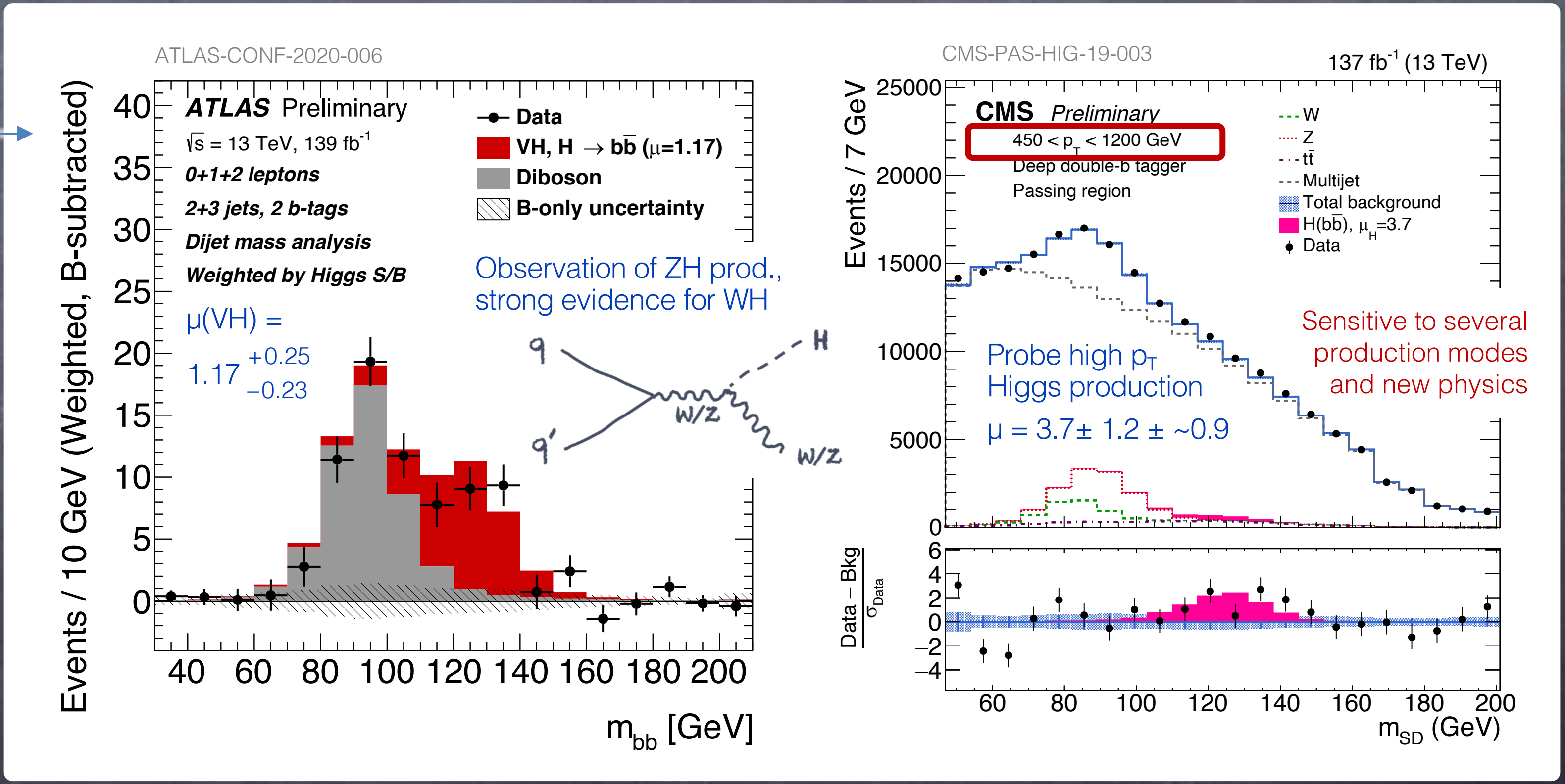
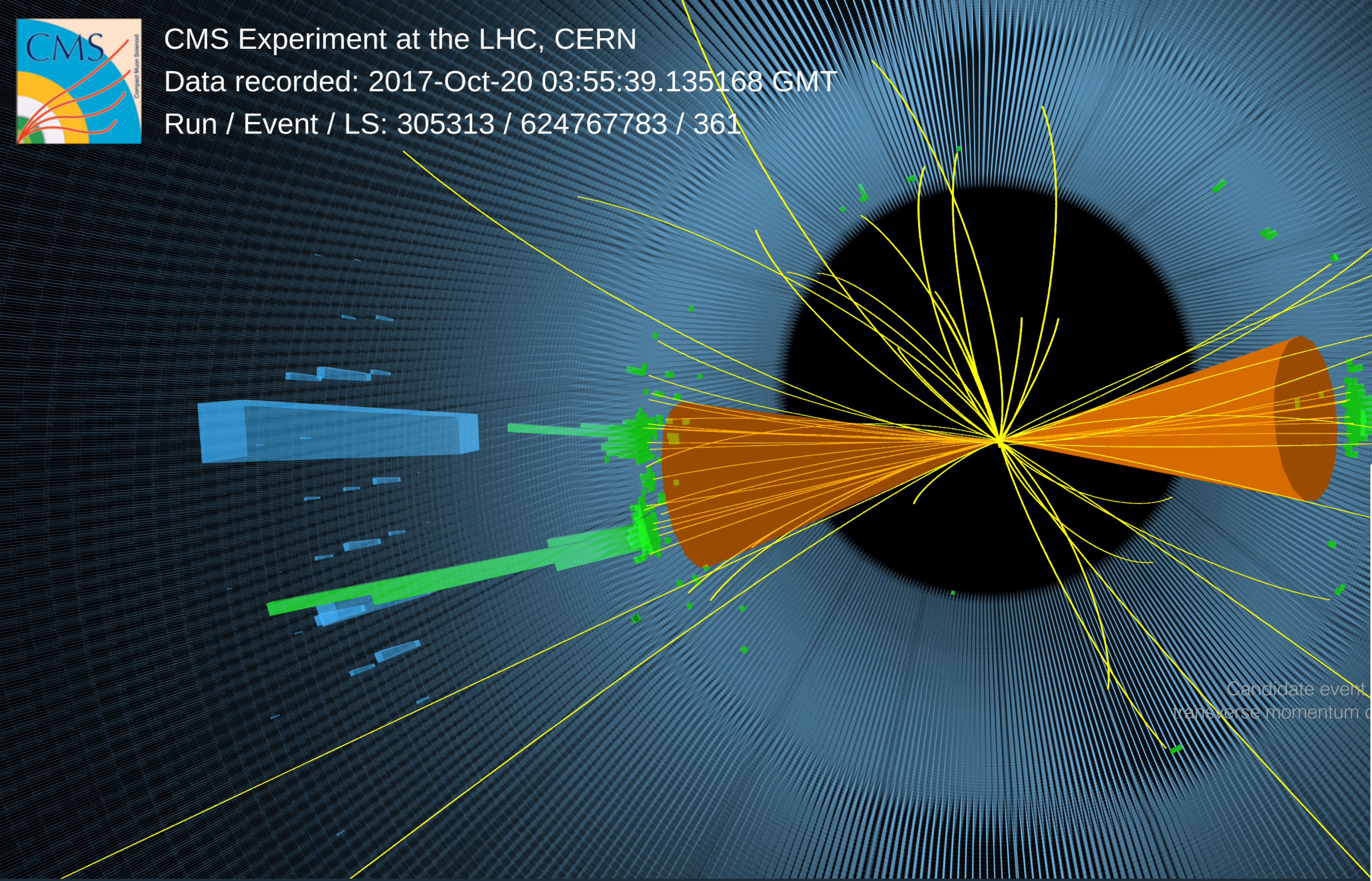
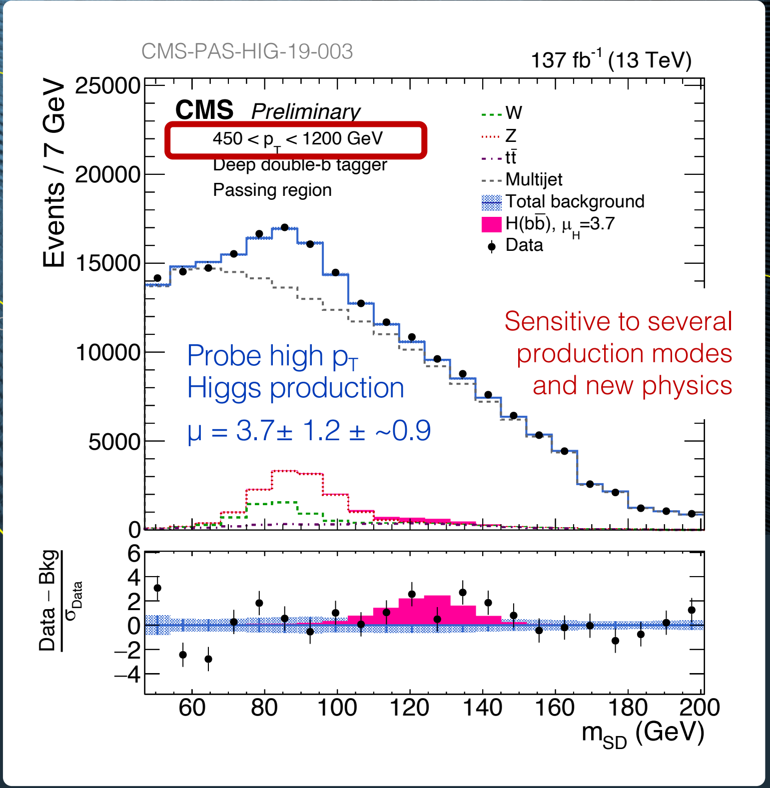
Uncertainties 3~12%





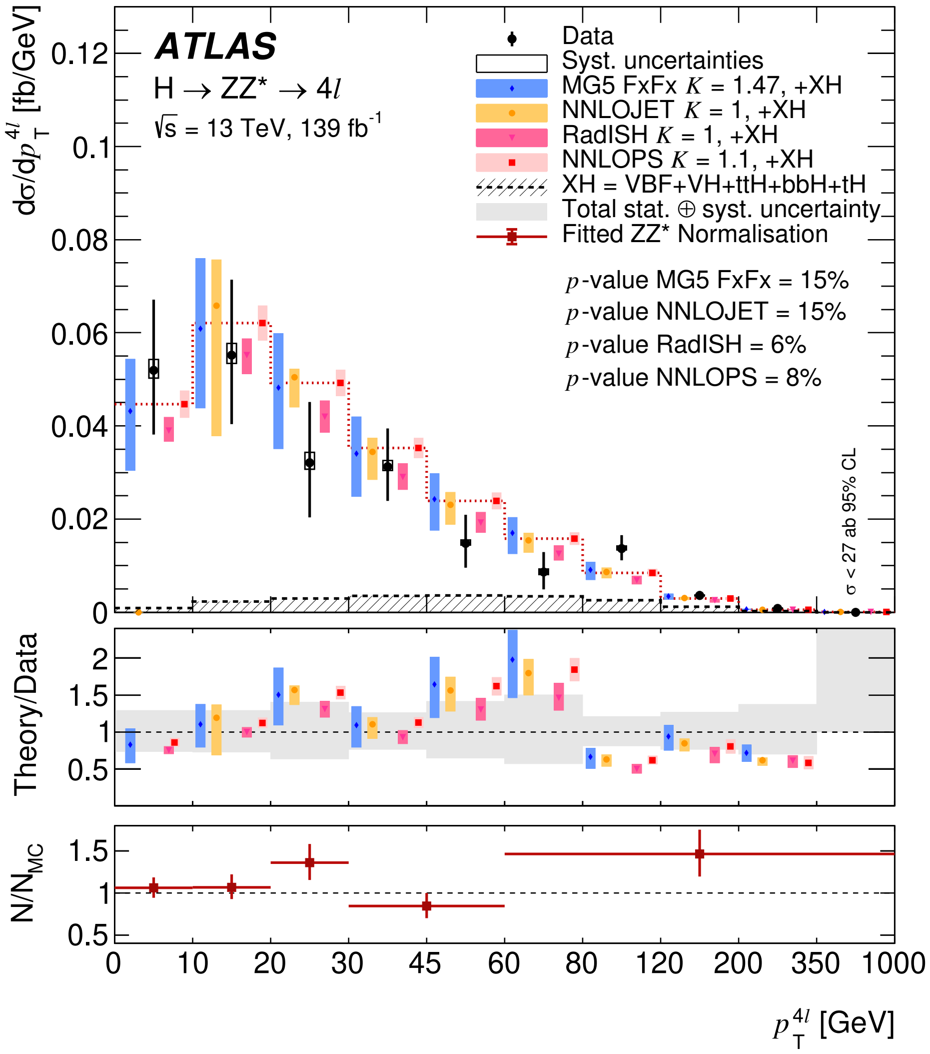


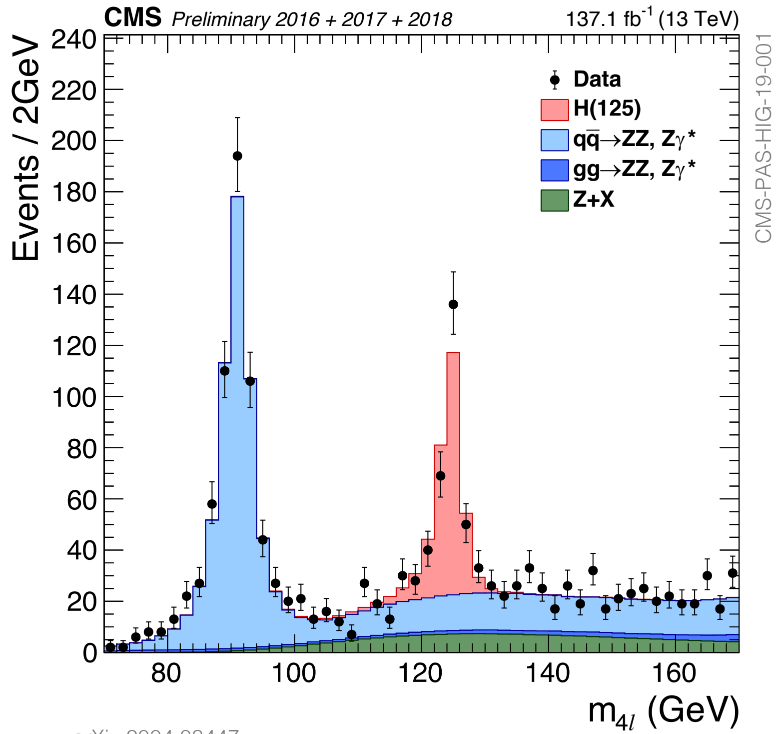
Striking example of the **power of our detectors**, also exploited in many high-mass searches: analysis of jet substructure by combining precise vertexing, tracking and calorimeter information measured in a dense environment

Probing Higgs properties in four-lepton channel

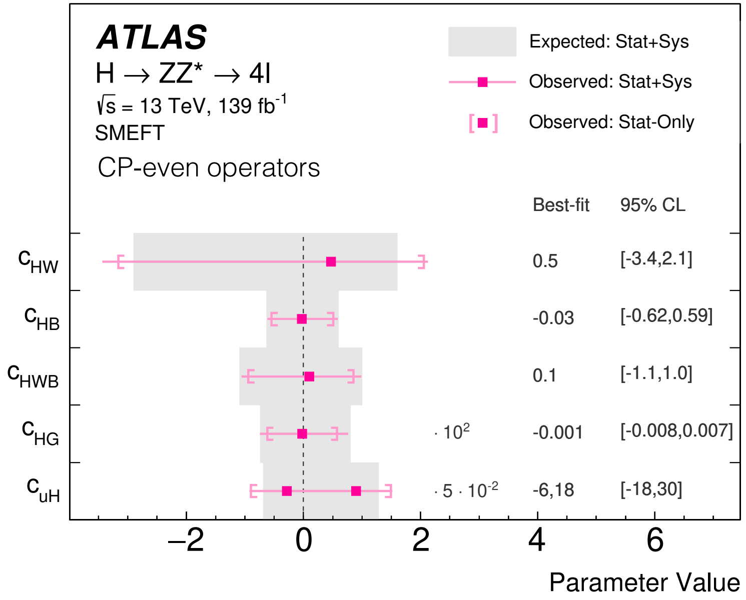
ATLAS and CMS move towards predefined less model-dependent fiducial cross-section (STXS) measurements and effective field theory interpretations

arXiv:2004.03969





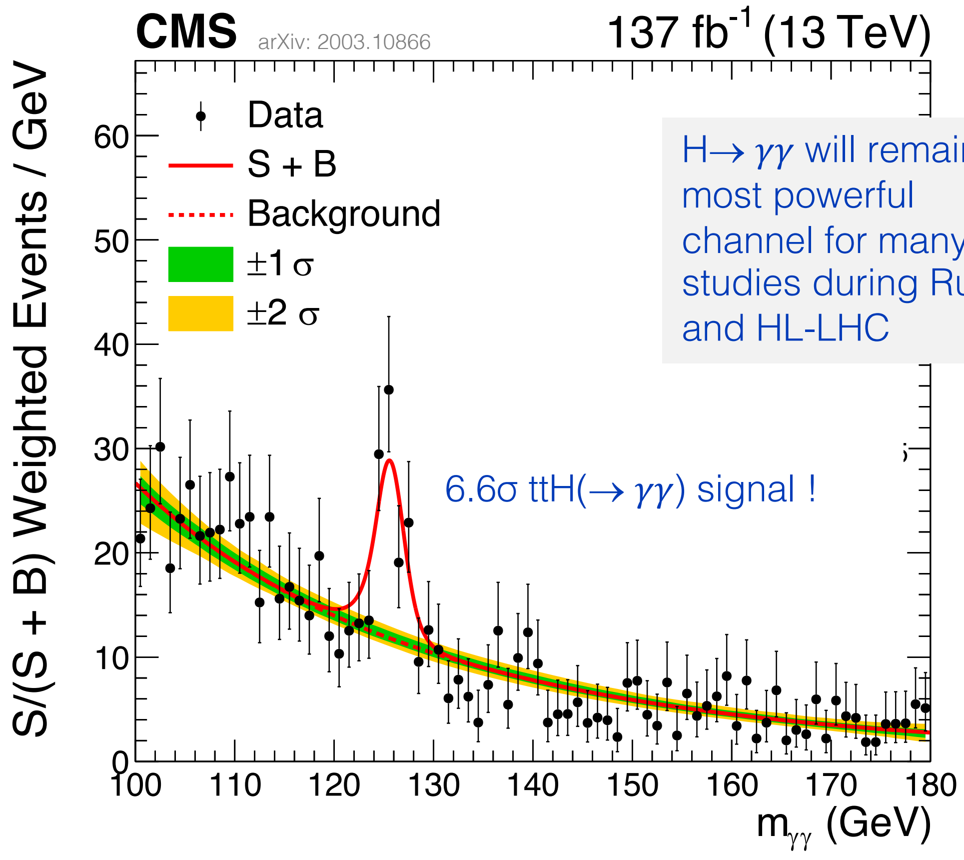
arXiv:2004.03447



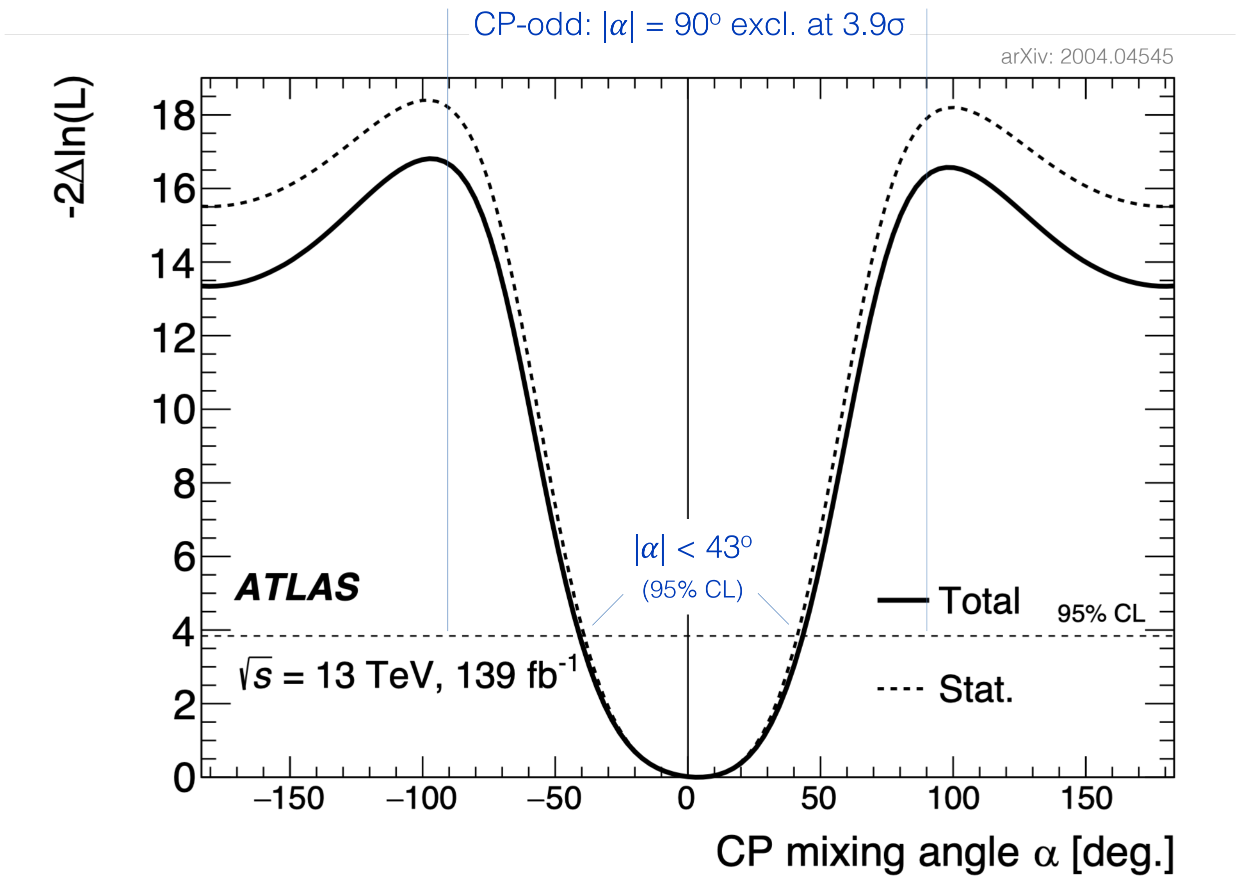
ATLAS & CMS explore ever rarer processes — $J^{CP}(H) = 0^{++}$ established, but CP-odd admixture possible

Matter–antimatter asymmetry of universe remains a mystery. SM far insufficient, lepton sector ("baryogenesis via leptogenesis") offers elegant but speculative solution → must look further

CMS & ATLAS looked for CP-odd contribution (α) in Higgs–top coupling using ttH($\to \gamma\gamma$)



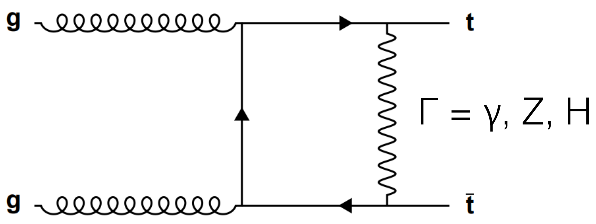
H→ $\gamma\gamma$ will remain most powerful channel for many studies during Run-3 and HL-LHC

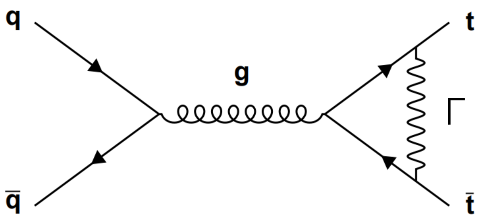


Top Yukawa coupling

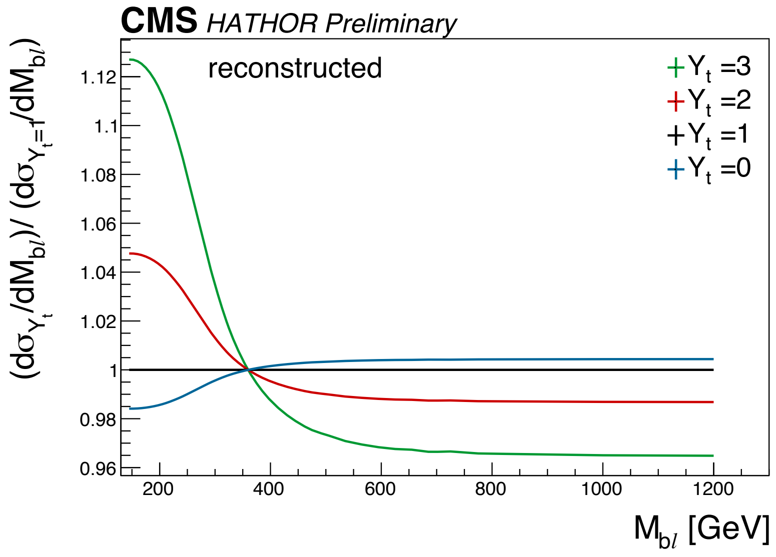
Combined fit of Higgs couplings constrains κ_t coupling modifier to 11%, ttH alone to about 15%

New CMS study indirectly determines $Y_t = \kappa_t$ from top-pair kinematics in the dilepton final state sensitive to virtual Higgs boson exchange (part of EW corrections)

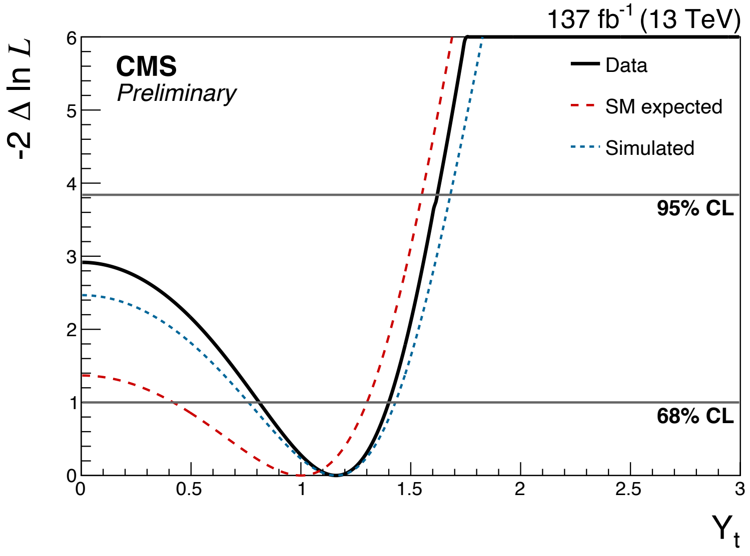




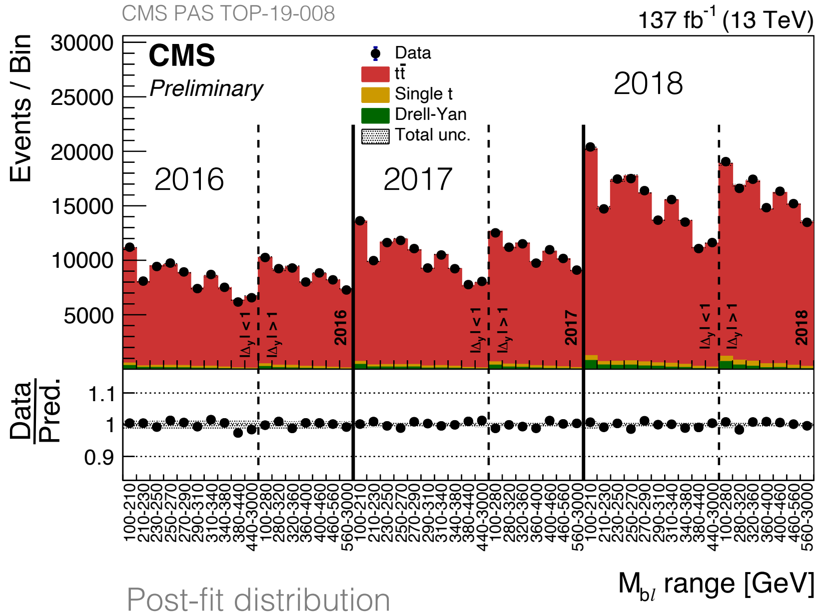
Result: $Y_t = 1.16\ ^{+0.24}_{-0.35}$ (dominated by systematic effects from EW corr. and FSR)



Simulation of M_{bl} spectrum versus Y_t

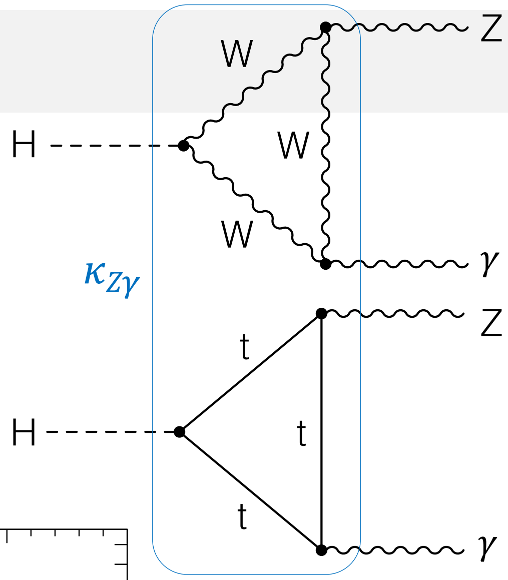


Fit result



Post-fit distribution

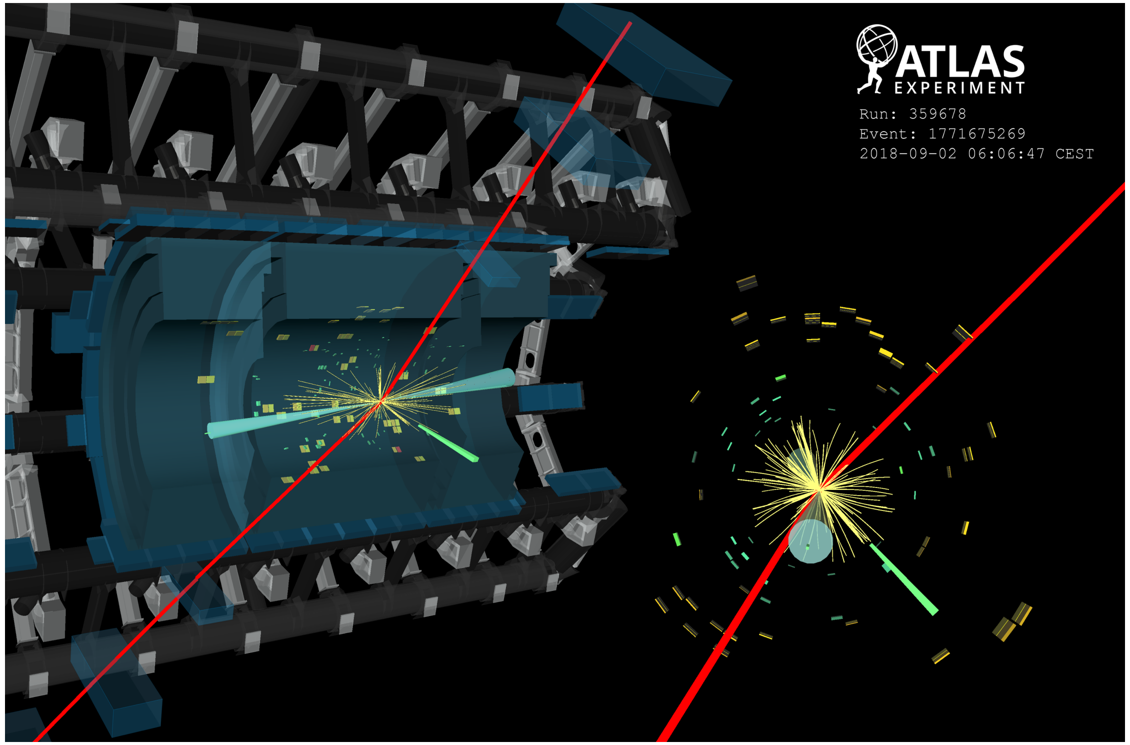
Rare Higgs decays — Sensitivity to 2nd generation fermion couplings and new physics



Tightly linked to detector momentum & energy resolution capabilities

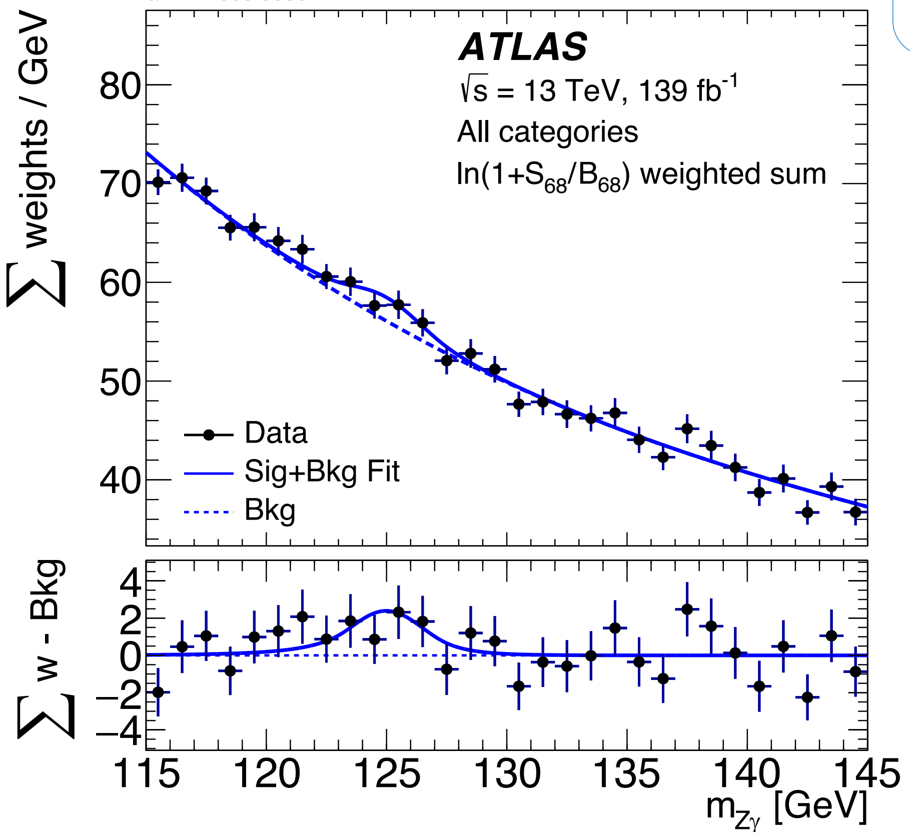
New ATLAS result on H → Zγ: $\mu = 2.0^{+1.0}_{-0.9}$ (2.2σ)

HL-LHC studies: σ(μ) ~ 20% for ATLAS & CMS combined (6 ab^{-1})



H → Z(→ μμ) + γ candidate event

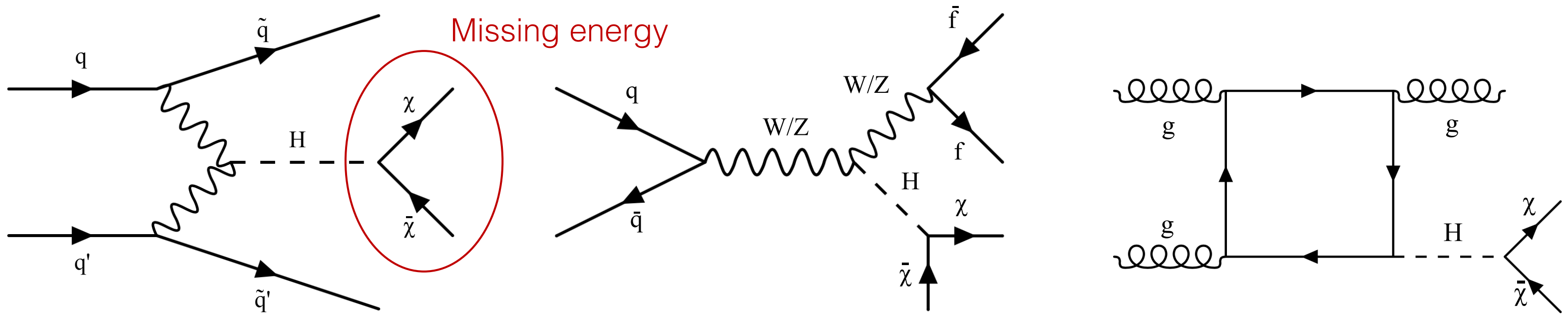
arXiv: 2005.05382



Higgs as probe of Dark Matter — DM massive, could (should?) couple to Higgs boson

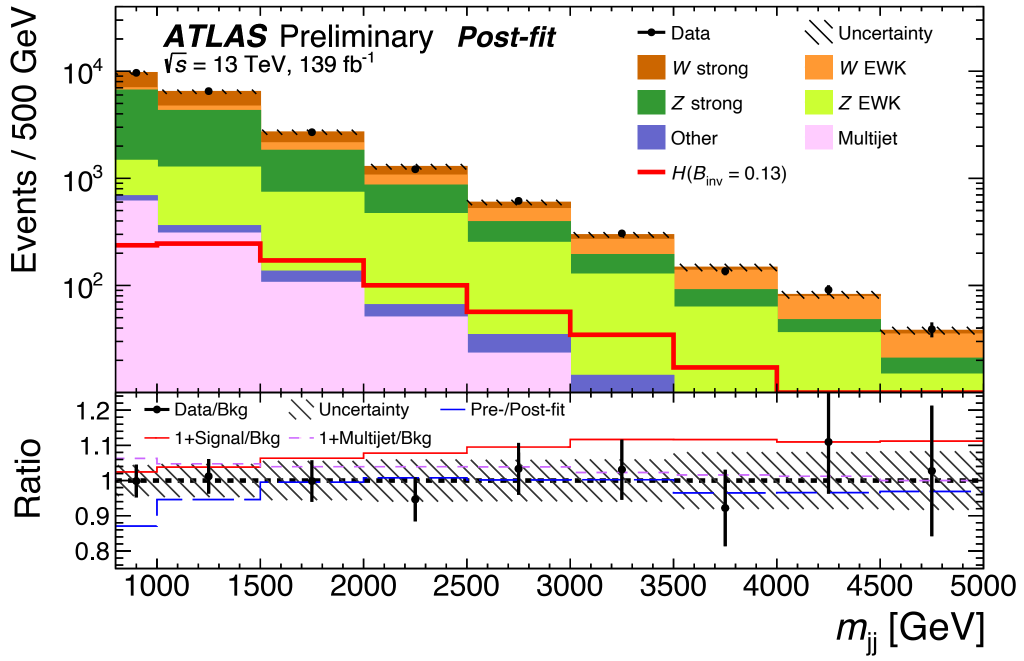
$\Omega_B \sim \Omega_{DM}$ may suggest other than gravity interaction

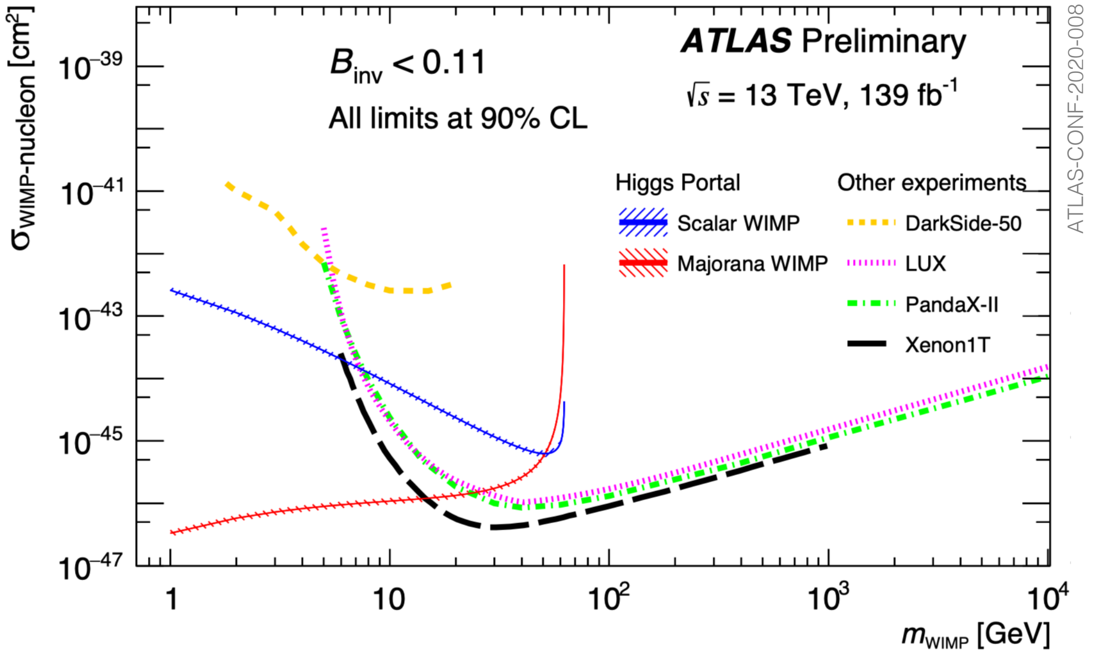
Invisible Higgs decays can be probed by associated production (VBF, VH, …)



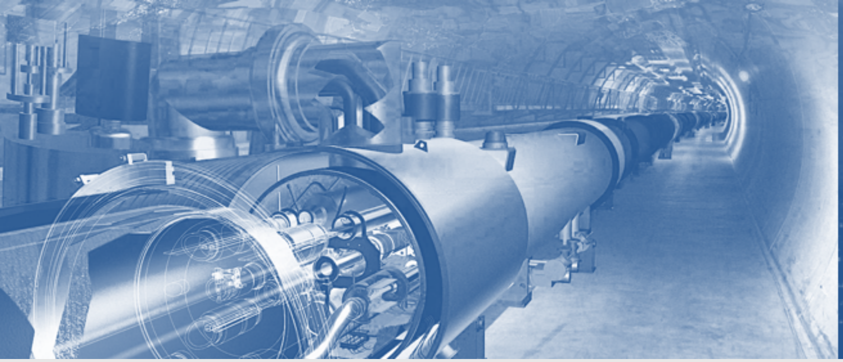
Sensitivity to WIMP mass < m_H / 2, complementary to direct dark matter searches

B(H → invisible) < 0.13 at 95% CL

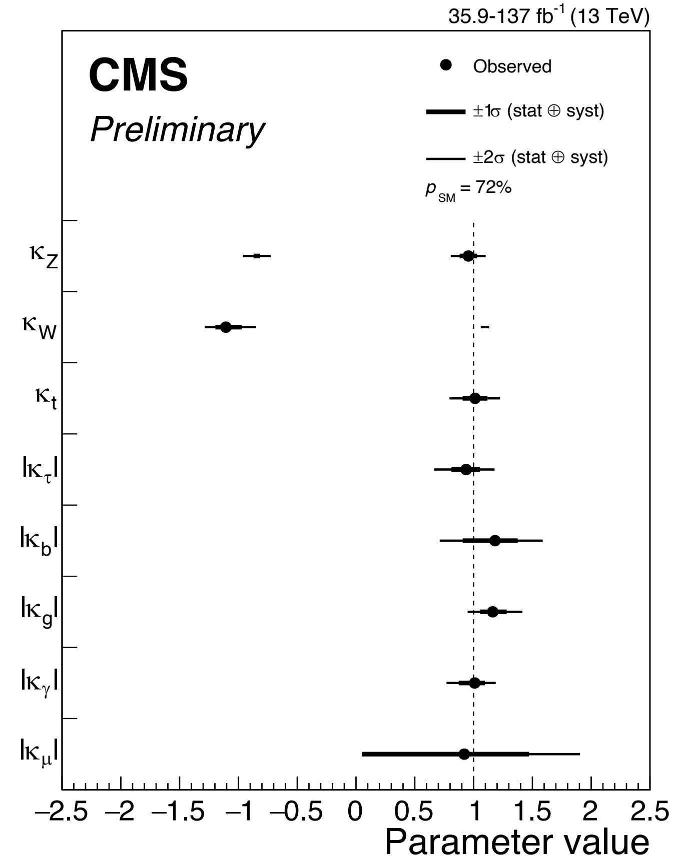


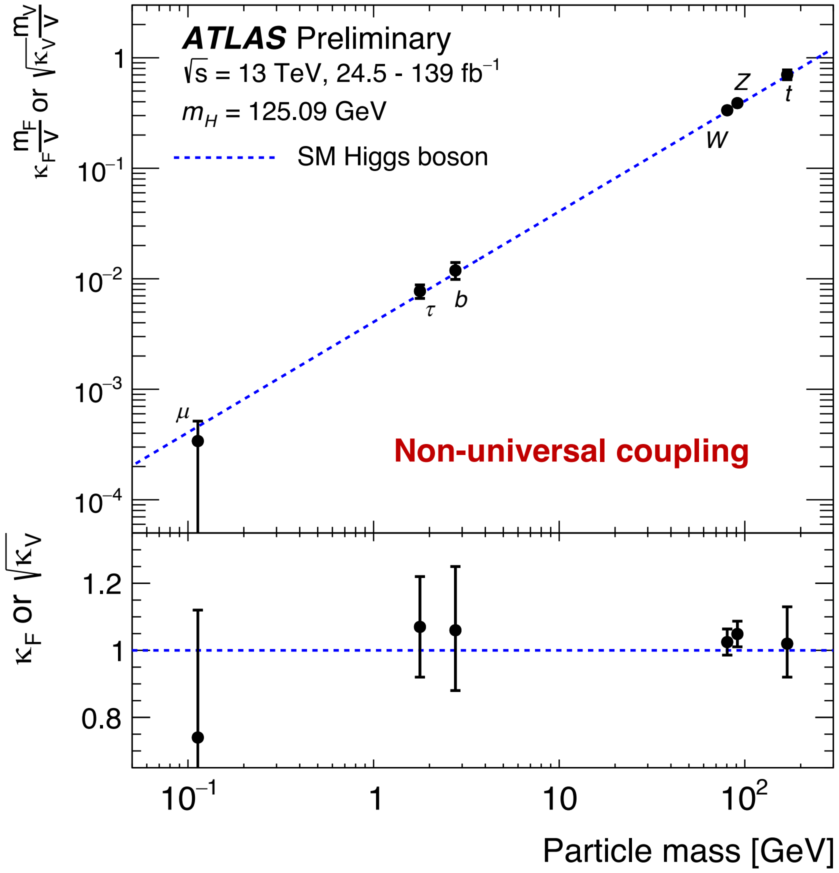


Precision obtained depends crucially on control of $Z \to \nu\nu$ and $W \to \ell\nu$ backgrounds (theory input and very large MC statistics needed)



The Brout-Englert-Higgs mechanism is real !





The scalar sector is directly connected with profound questions: naturalness, vacuum stability & energy, flavour

The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades

And the Higgs boson does more …

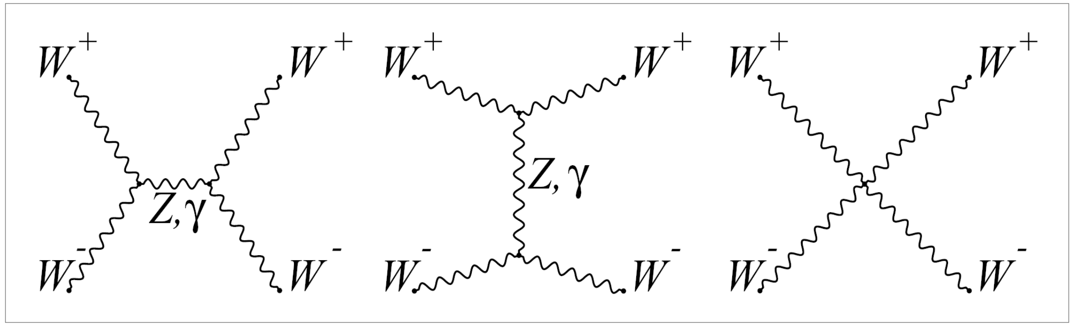
Higgs boson moderates high-energy longitudinal vector boson scattering

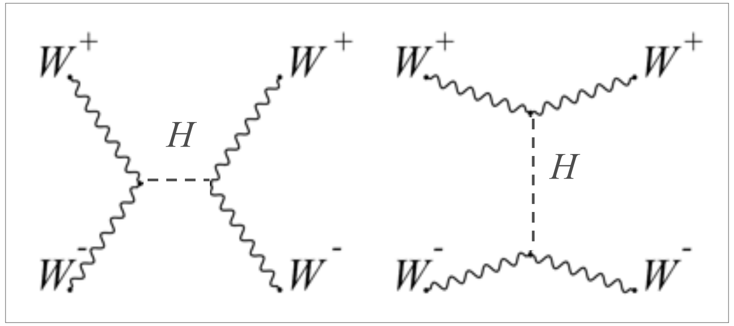
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

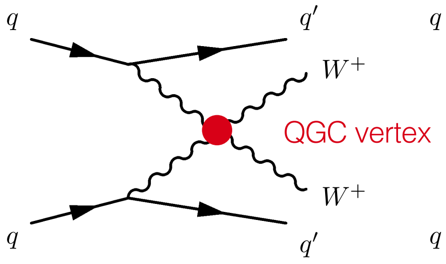
$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$



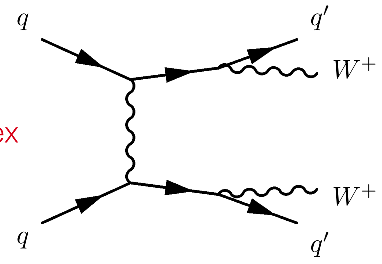


m_H must not be too large (which is fulfilled)

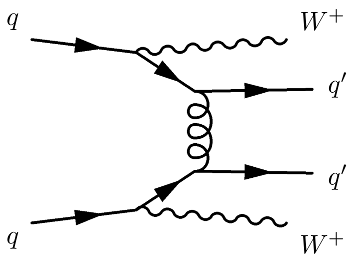
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

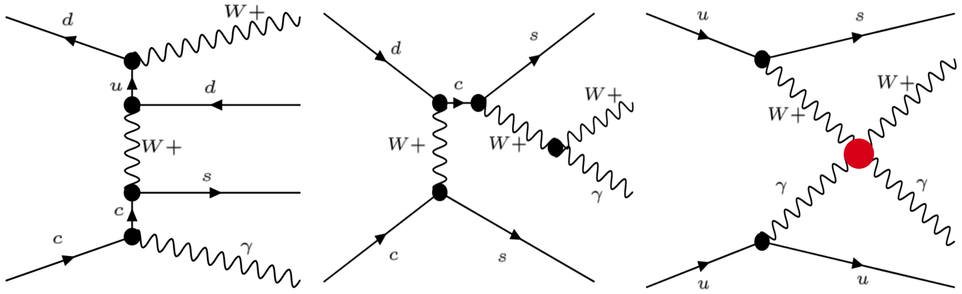
Look for EW production (and VBS) at high dijet mass

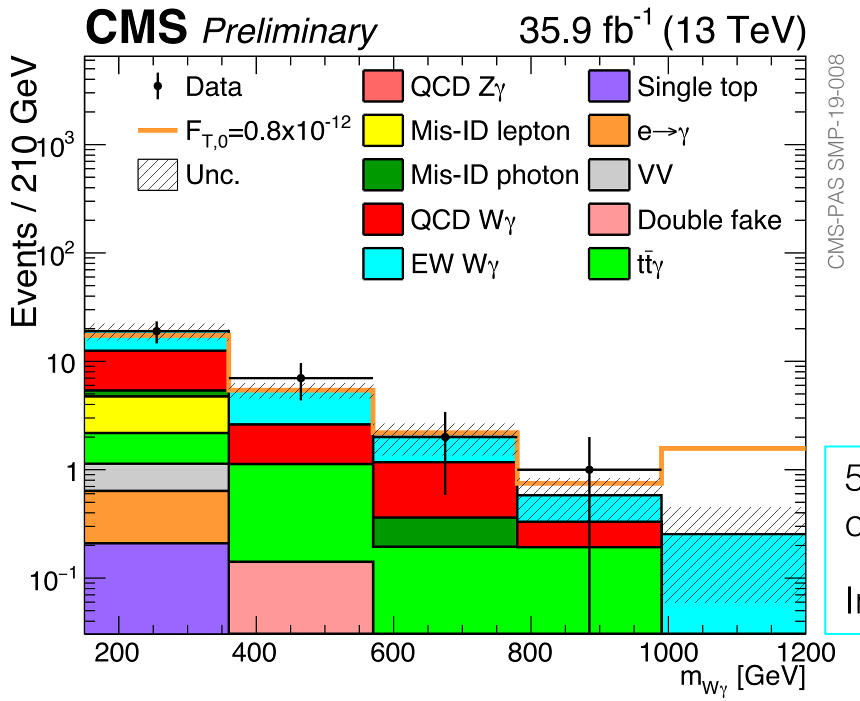
Observation of EW production during Run 2:

- **WW+jj** (CMS, 2017, ATLAS 2019)
- **WZ+jj**, **ZZ+jj** (ATLAS 2018, 2019)

New electroweak production results on Wγjj and ZZjj from CMS

Electroweak Wγjj processes:

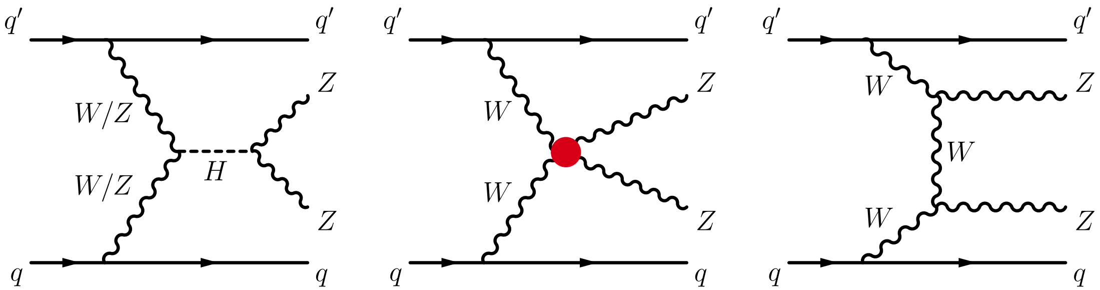


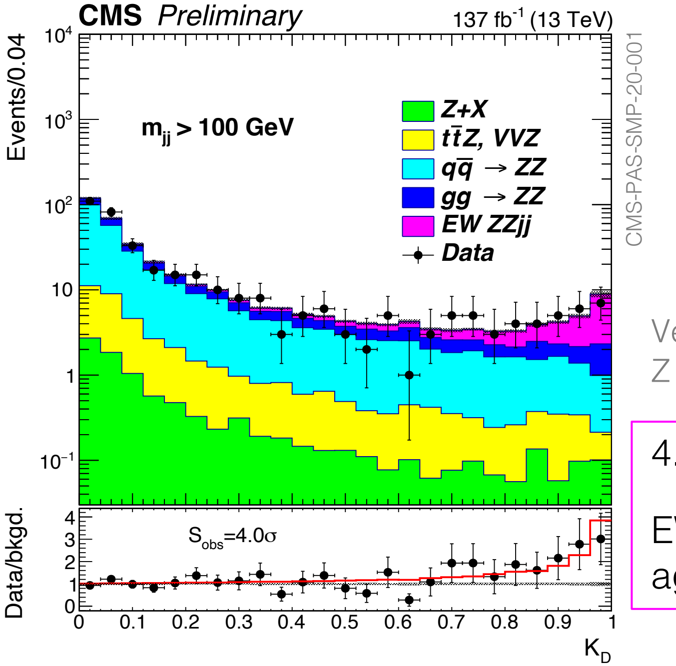


5.8σ (4.8σ exp.) after combining with 8 TeV

In agreement with SM

Electroweak ZZjj processes:





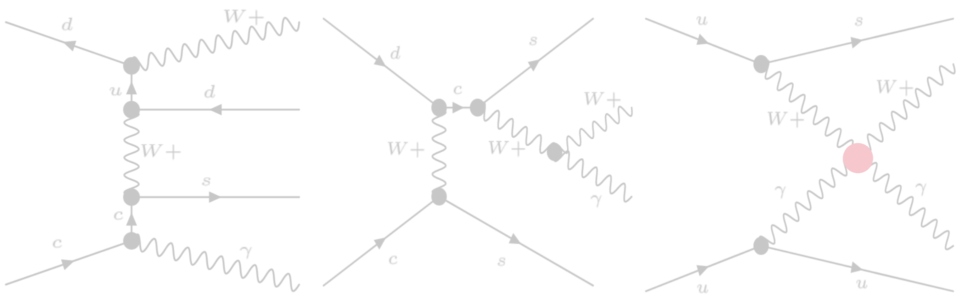
Very rare but clean mode using Z decays to charged leptons

4.0σ (3.5σ exp.)

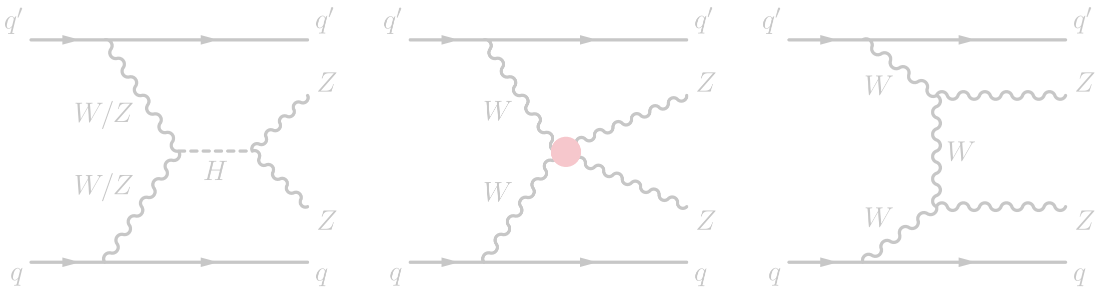
EW and EW+QCD in agreement with SM

New electroweak production results on Wγjj and ZZjj from CMS

Electroweak Wγjj processes:



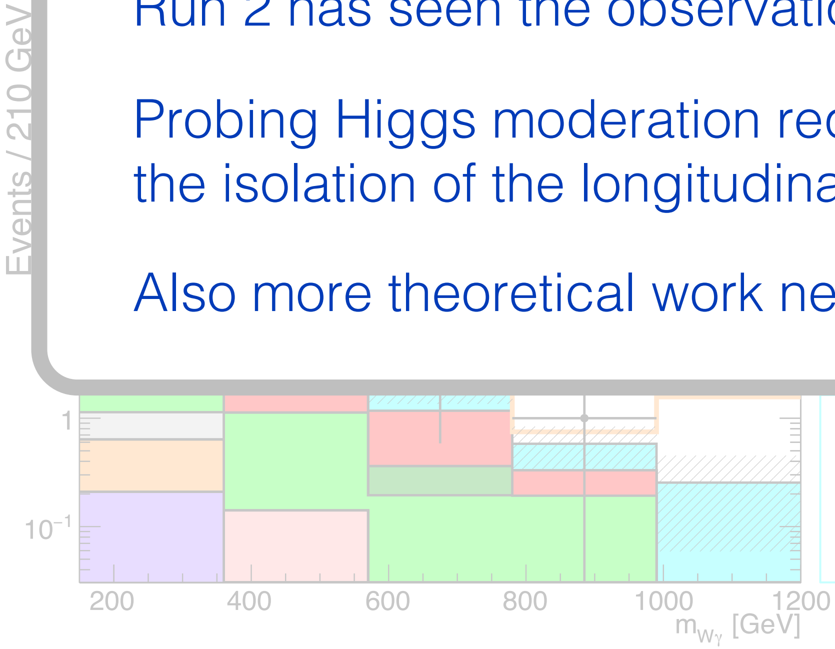
Electroweak ZZjj processes:



Run 2 has seen the observation of electroweak qq → qqVV (and VVV) processes

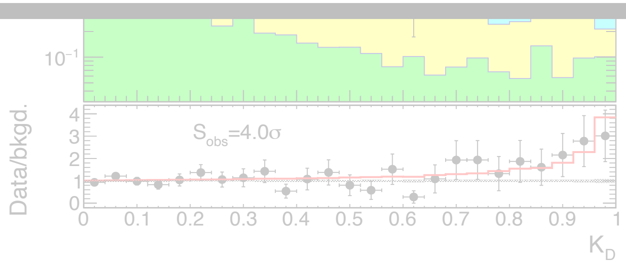
Probing Higgs moderation requires higher-mass studies (→ **Run 3**) and eventually the isolation of the longitudinally polarised components at large Δϕ(jj) → **HL-LHC**

Also more theoretical work needed for precise predictions of these complex processes



5.8σ (4.8σ exp.) after combining with 8 TeV

In agreement with SM



4.0σ (3.5σ exp.)

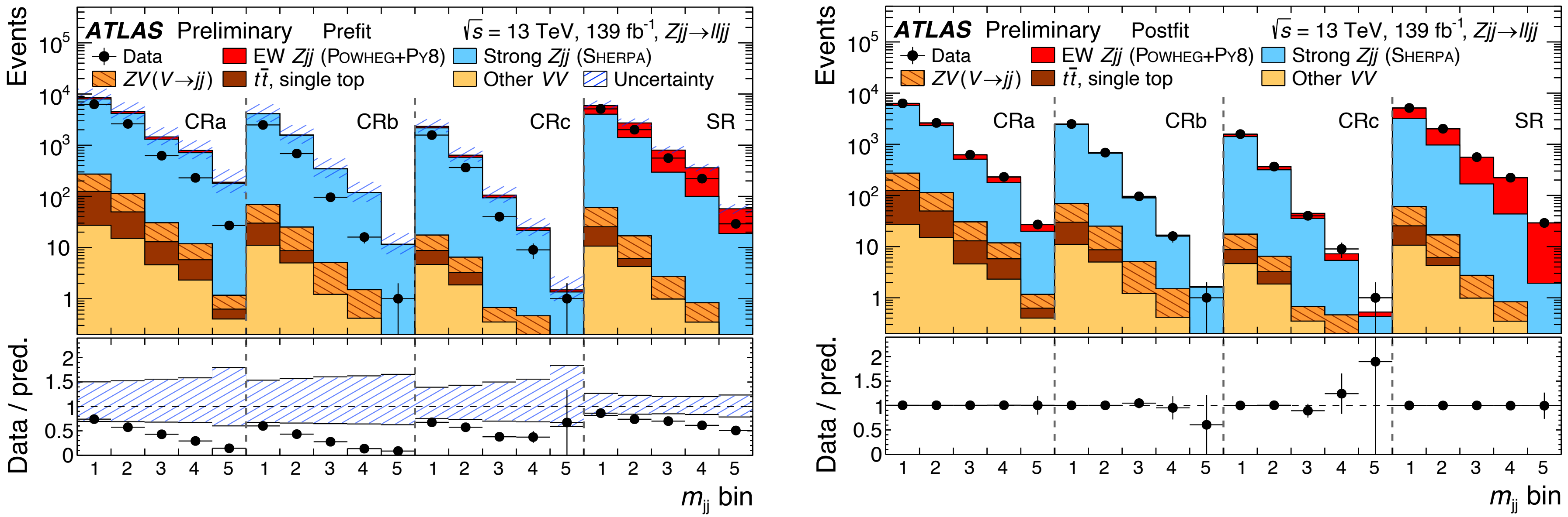
EW and EW+QCD in agreement with SM

New electroweak production results on Wγjj and ZZjj from CMS

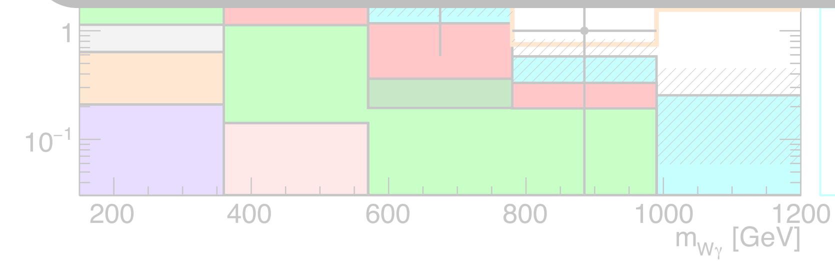
Electroweak Wγjj processes:

Electroweak ZZjj processes:

VBF + Z analysis, pre- and post-fit m(jj) background modelling [CERN-EP-2020-045]

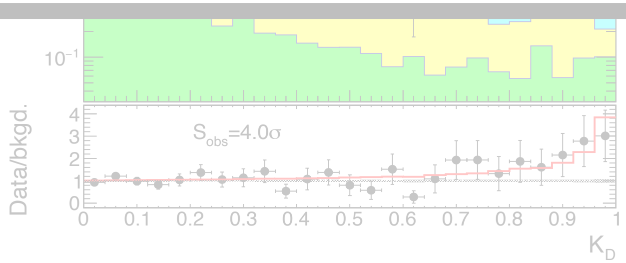


Also more theoretical work needed for precise predictions of these complex processes



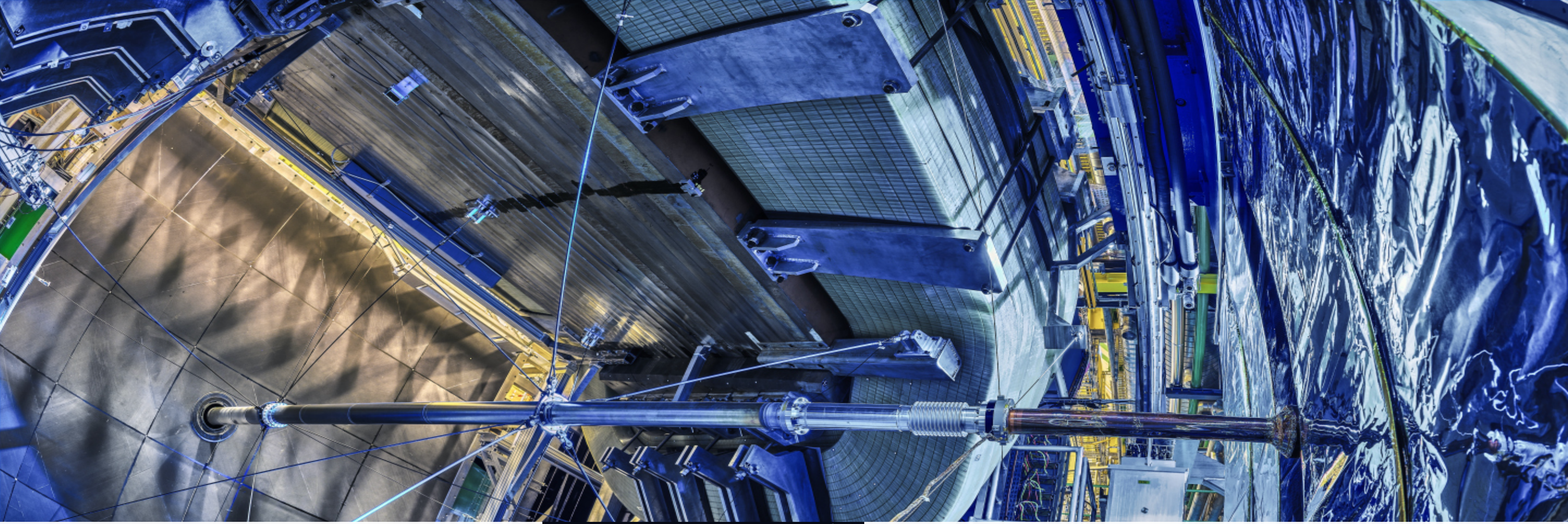
5.8σ (4.8σ exp.) after combining with 8 TeV

In agreement with SM

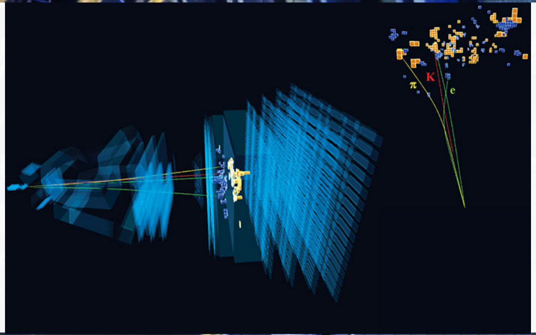


4.0σ (3.5σ exp.)

EW and EW+QCD in agreement with SM



Flavour physics & spectroscopy



Success of SM flavour structure is since long a source of discomfort for BSM physics, as are the anomalies a source of excitement

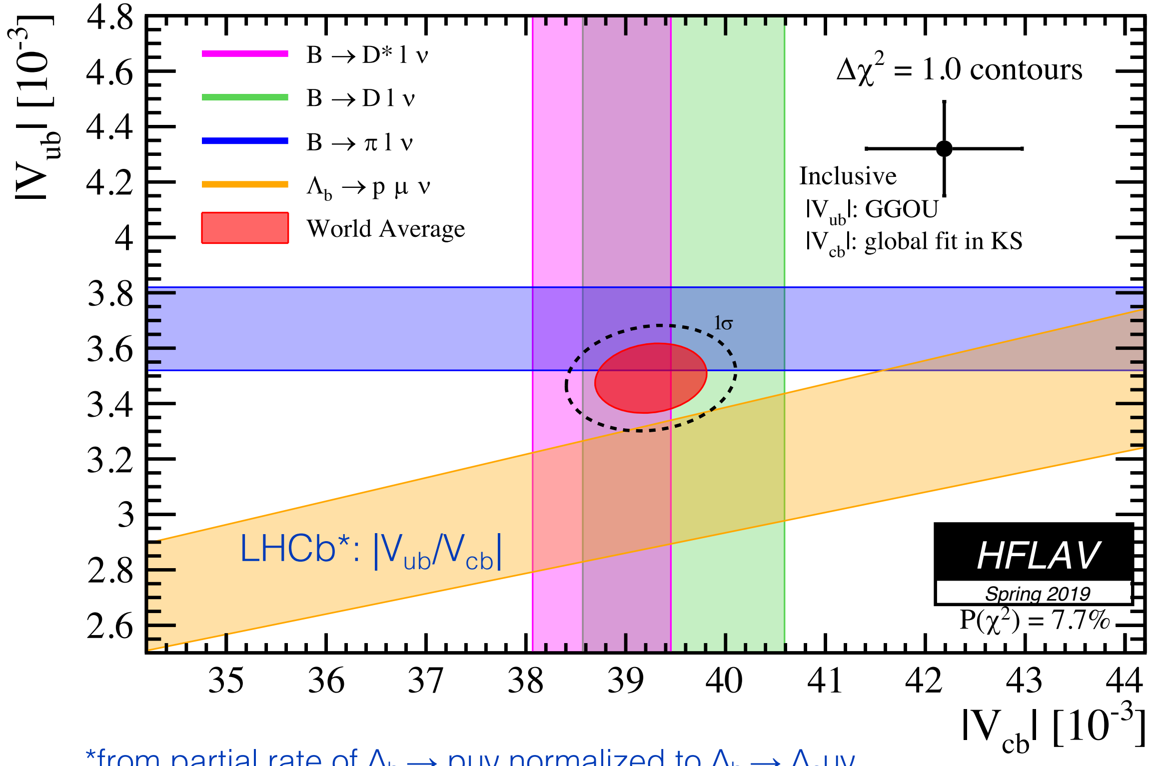
LHCb's dipole magnet at 2018 detector opening

CKM — LHCb is greatly contributing to CKM metrology, in particular through a large set of γ measurements

LHCb also seriously contributes to direct $|V_{cb}|$ and $|V_{ub}|$ determinations, where longstanding tensions between exclusive and inclusive results exist

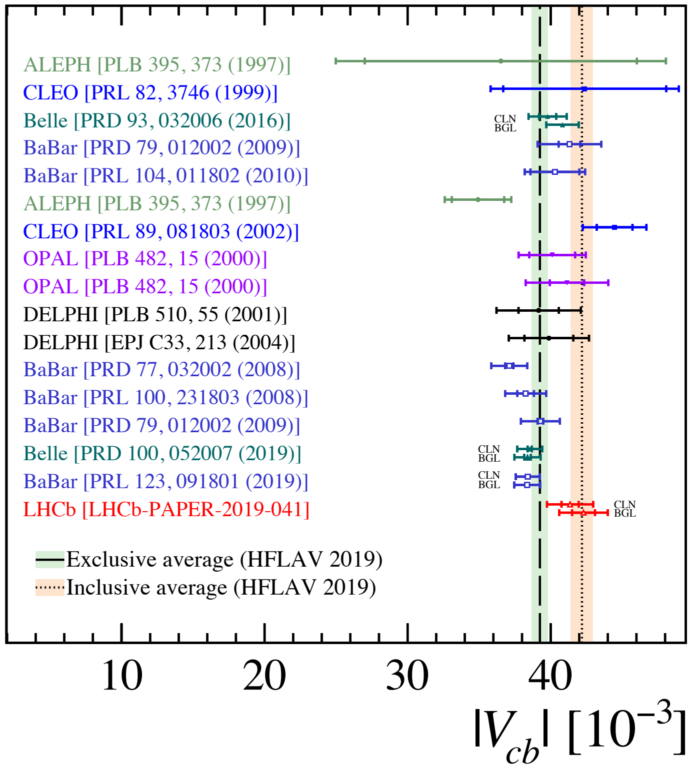
New $|V_{cb}|$ measurement from $B_s \to D_s^{(*)}\mu\nu$ decay rate vs recoil (novel approach to estimate recoil momentum)

HFLAV combination of exclusive results



*from partial rate of $\Lambda_b \to p\mu\nu$ normalized to $\Lambda_b \to \Lambda_c\mu\nu$,

LHCb arXiv:2001.03225



LHCb result consistent with incl. and excl. average

Dependence on theoretical form factor

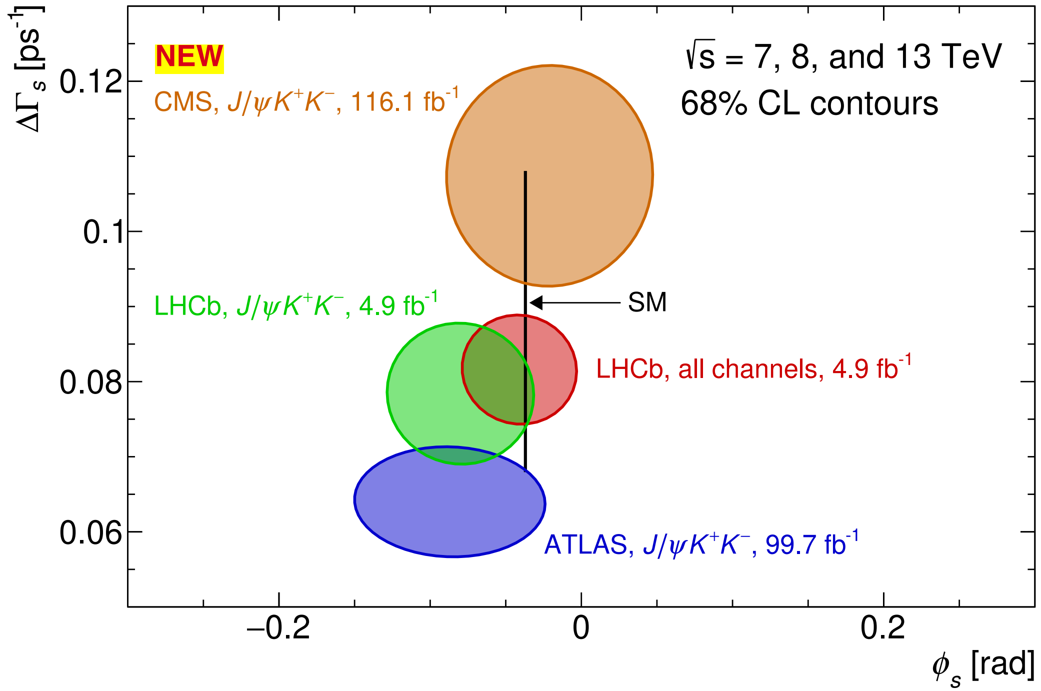
Also measured recoil shape

Time-dependent CP violation in B_s system and rare decays

Phase ϕ_s precisely predicted in SM — platin channel to look for new physics

New CMS result on 2017+2018 data (96 fb^{-1}) using 11 physics-par. fit (incl. direct CPV parameter $|\lambda|$ and Δm_s) and combination with Run-1 [CMS-PAS-BPH-20-001]

Tomas Jakoubek, *private communication*



Some tensions among parameters to be understood

Rare decays are powerful tools to look for new physics

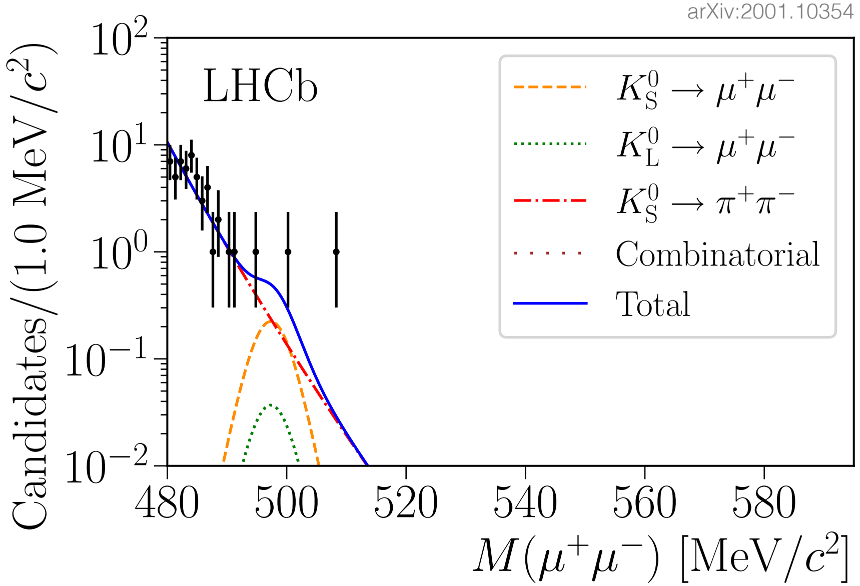
(loop amplitudes, small BSM contributions could be measurable)

New LHCb search for FCNC process $K_S^0 \to \mu\mu$ [arXiv:2001.10354]

SM BR: $(5.2 \pm 1.5) \times 10^{-12}$, uncertainty due to $K_S^0 \to \pi\pi \to \gamma\gamma \to \mu\mu$

[corresponding K_L^0 decay already measured in agreement with SM: 6.8×10^{-9}]

arXiv:2001.10354



Use BDT against material interactions and random combinations

Result: $B(K_S^0 \to \mu\mu) < 2.1\times10^{-10}$ combined 2011 and 2012 data

Status of anomalies

Status of flavour anomalies:

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}$$

Possible new physics in charged current in tree diagram

Tension reduced after 2019 Belle result [1904.08794]
in agreement with SM

Remaining tension (HFLAV): 3.1σ
Corresponding $R_{J/\psi|\tau/\mu}$ ~2σ above SM [LHCb: 1711.05623]

$$R_{K^{(*)}} = \frac{B(B \to K^{(*)}\mu\mu)}{B(B \to K^{(*)}ee)} \overset{[SM]}{\cong} 1$$

Experiments measure double ratio involving J/ψ

R_K: LHCb most precise, Run-2 ~SM,
combination with Run-1: 2.5σ < SM

R_{K^*}: LHCb (most precise) low (2.3~2.5σ) at low q^2

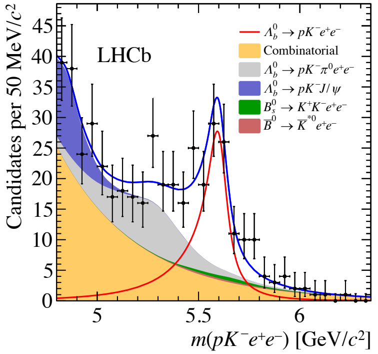
New results by LHCb:

$$R_{pK} = \frac{B(\Lambda_b^0 \to pK^-\mu\mu)}{B(\Lambda_b^0 \to pK^-ee)} \overset{[SM]}{\cong} 1$$

LHCb measures double ratios to J/ψ

Result: $\boldsymbol{R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05}$
in agreement with SM (but also lower)

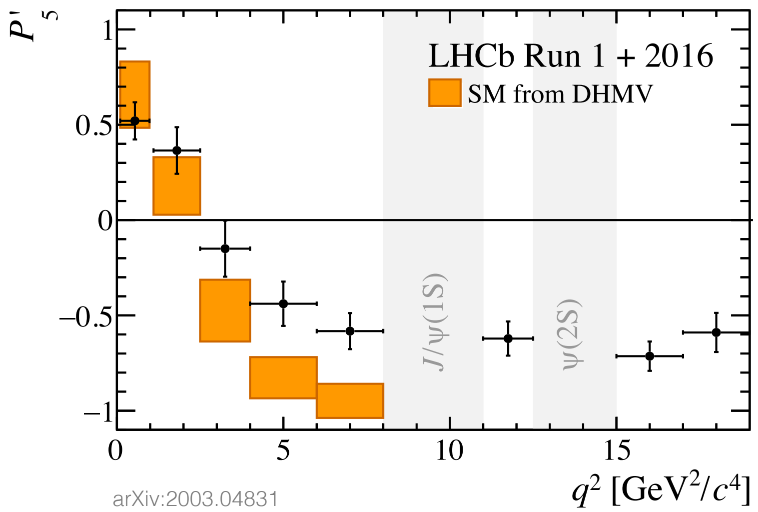
arXiv:1912.08139



Observation > 7σ

$B \to K^*\mu\mu$ angular analysis

New result from LHCb with 4.7 fb^{-1} (Run 1 + 2016 data)



arXiv:2003.04831

Full fit to all angular observables

Global fit by LHCb to SM model varying Re(C_9) only gives 3.3σ discrepancy

Status of anomalies

Status of flavour anomalies:

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}$$

Possible new physics in charged current in tree diagram

R

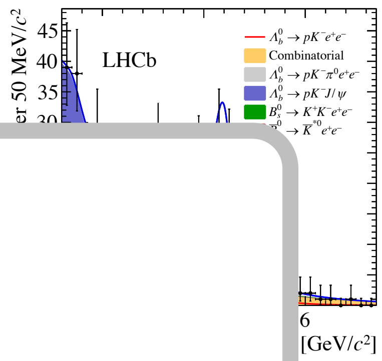
R_K: LHCb most precise, Run-2 ~SM, combination with Run-1: 2.5σ < SM

R_{K^*}: LHCb (most precise) low (2.3~2.3σ) at low q^2

New results by LHCb:

$$R_{pK} = \frac{B(\Lambda_b^0 \to pK^-\mu\mu)}{B(\Lambda_b^0 \to pK^-ee)} \overset{[SM]}{\cong} 1$$

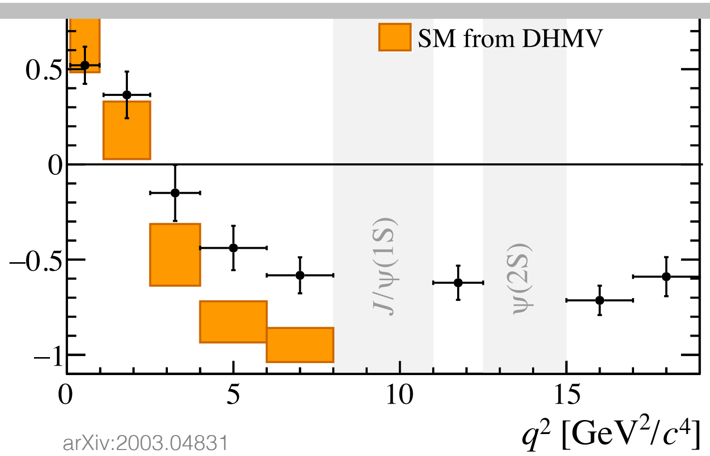
arXiv:1912.08139



7σ

Only one firm conclusion here:

More data needed



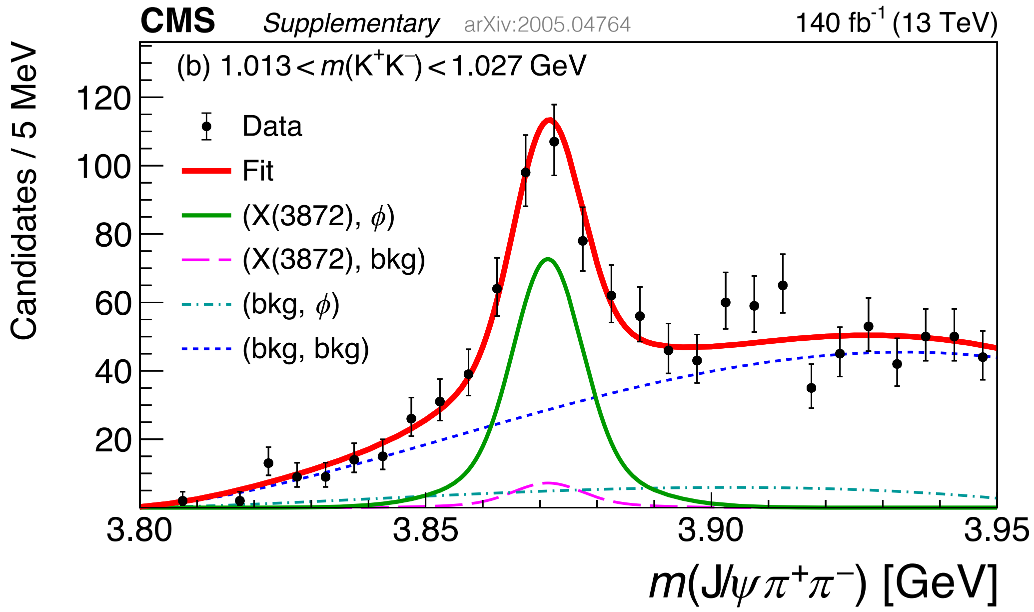
arXiv:2003.04831

gular observables

Global fit by LHCb to SM model varying Re(C_9) only gives 3.3σ discrepancy

New decays and states!

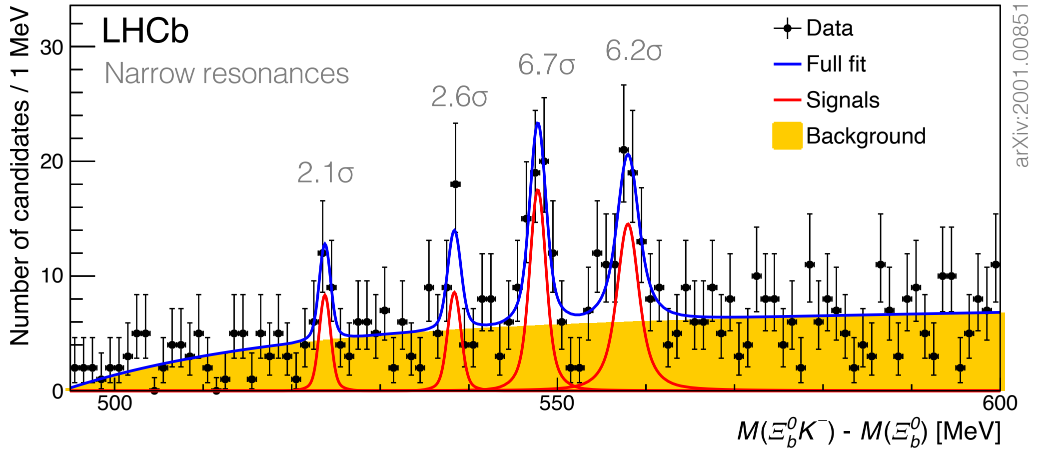
Observation of $B_S^0 \to X(3872)(\to J/\psi\pi\pi)\phi$ decay



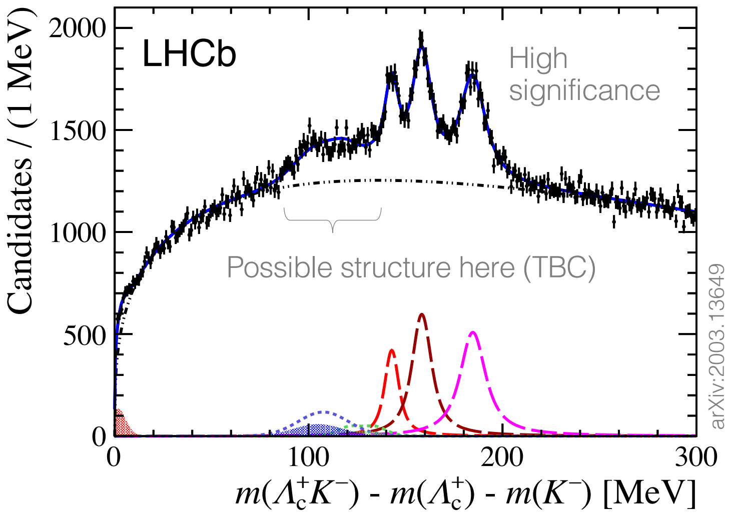
BR consistent with $B_d^0 \to X(3872)K^0$, but 1/2 of $B^+ \to X(3872)K^+$
This differs from $\psi(2S)$ for which B_s^0/B^+ ratio is 0.87

Observation of excited $\Omega_b^-(ssb)$ states in decay to $\Xi_b^0(usb)K$-

Ω_b^- (6.0 GeV) discovered by CDF in 2009, $\Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\pi^-$

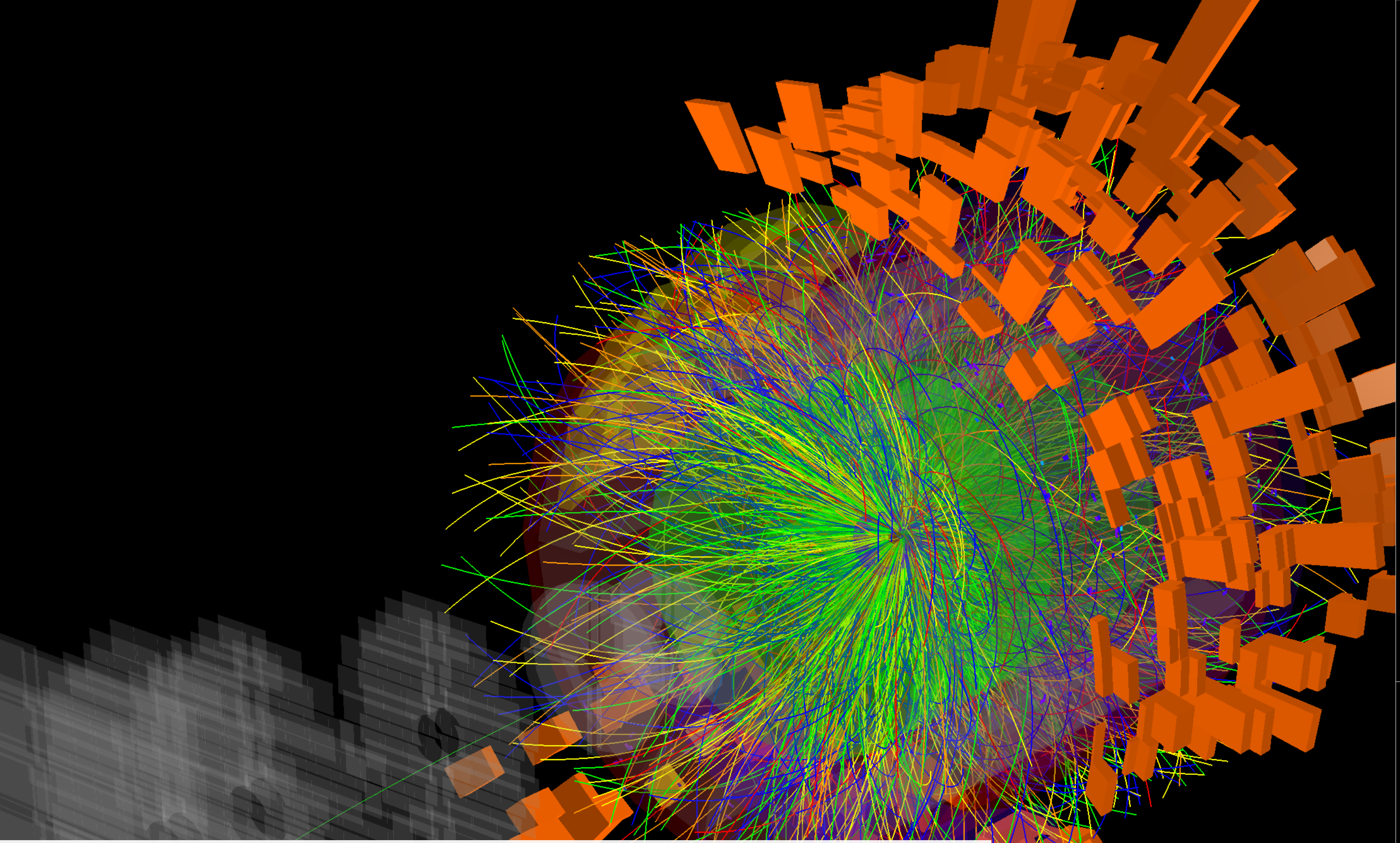


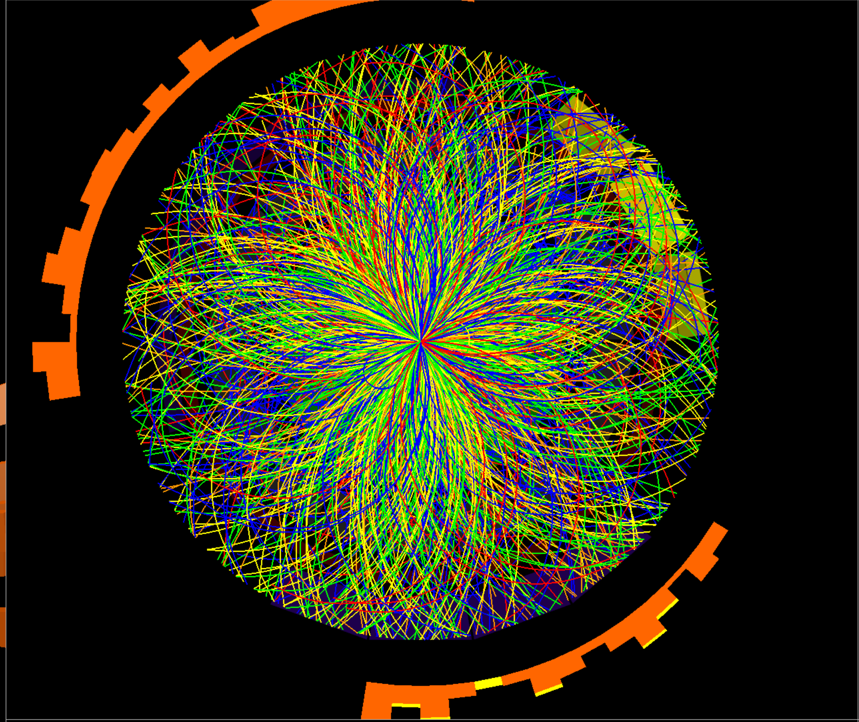
Qualitatively similar $\Omega_b^- \to \Xi_b^0 K$- spectrum as for $\Omega_c^0 \to \Xi_c^+ K$-
Consistent with expectation from $L=1$ excitations of ground state

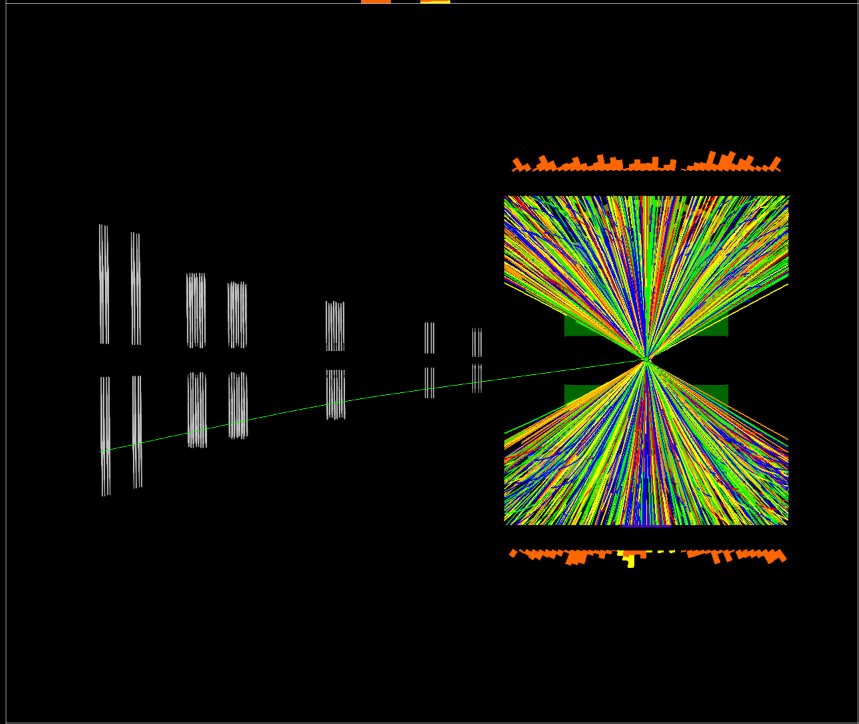


Observation of excited $\Xi_c^0(dsc)$ states in decay to $\Lambda_c^+(udc)(\to pK^-\pi^+)K$-

ALICE







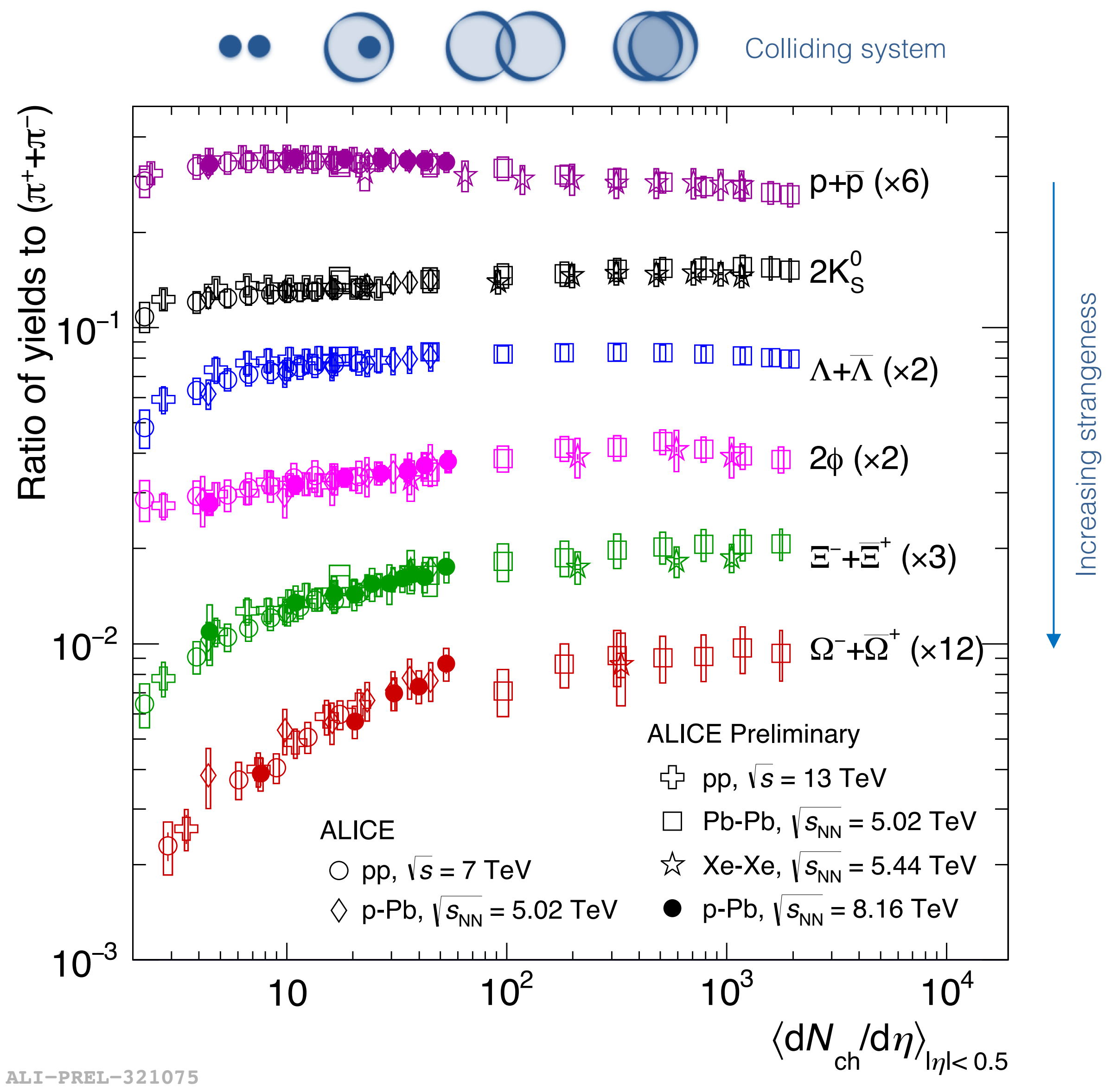
Heavy Ion Physics

High-density strong Matter

… and physics of strong electromagnetic fields !

Run:297624
Timestamp:2018-12-02 15:55:16(UTC)
Colliding system:Pb-Pb
Energy:5.02 TeV

Understanding of Heavy Ion collisions has hugely evolved since start of LHC

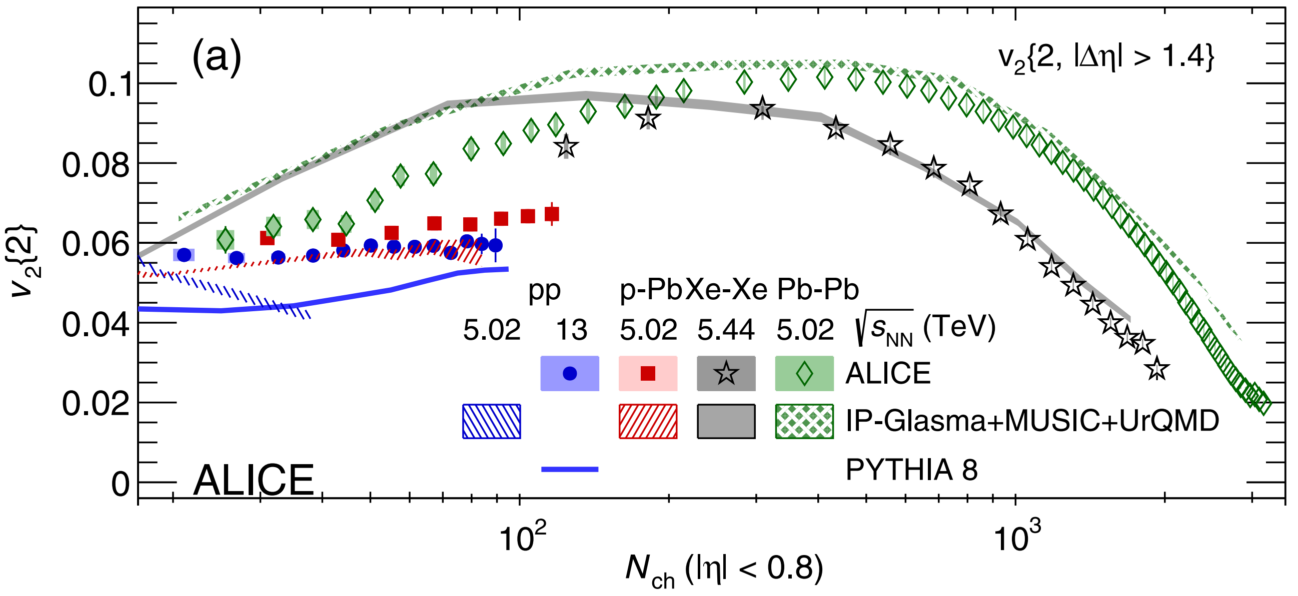


Seminal plot from ALICE with rich physics

- Hadron / pion ratio smoothly evolves across multiplicity reaching thermal values in Pb-Pb
- Rise of strangeness (the stranger the steeper)
- No $\sqrt{s}$ dependence
- Low multiplicity pp data described by Pythia (but remains constant towards higher N_{ch})
- Increase of ratio could indicate thermal production of strangeness independent of size of system
- High-multiplicity pp ~ same hadro-chemistry as fully thermalized system
- Is it possible to understand behavior of large systems from parton (re-)scattering in small systems?
- Theoretical models allow quantitative description

Understanding of Heavy Ion collisions has hugely evolved since start of LHC

ALICE PRL 123, 142301 (2019)



True collectivity (flow) in small systems established: revealed by applying techniques from heavy ion physics to pp (and p-Pb)

Theoretical analysis of precise Pb-Pb flow data shows that shear viscosity of QGP is 10 × lower than for any other form of matter → almost perfect fluid [S. Bass et al, Nature Phys 15, 1113 (2019)]

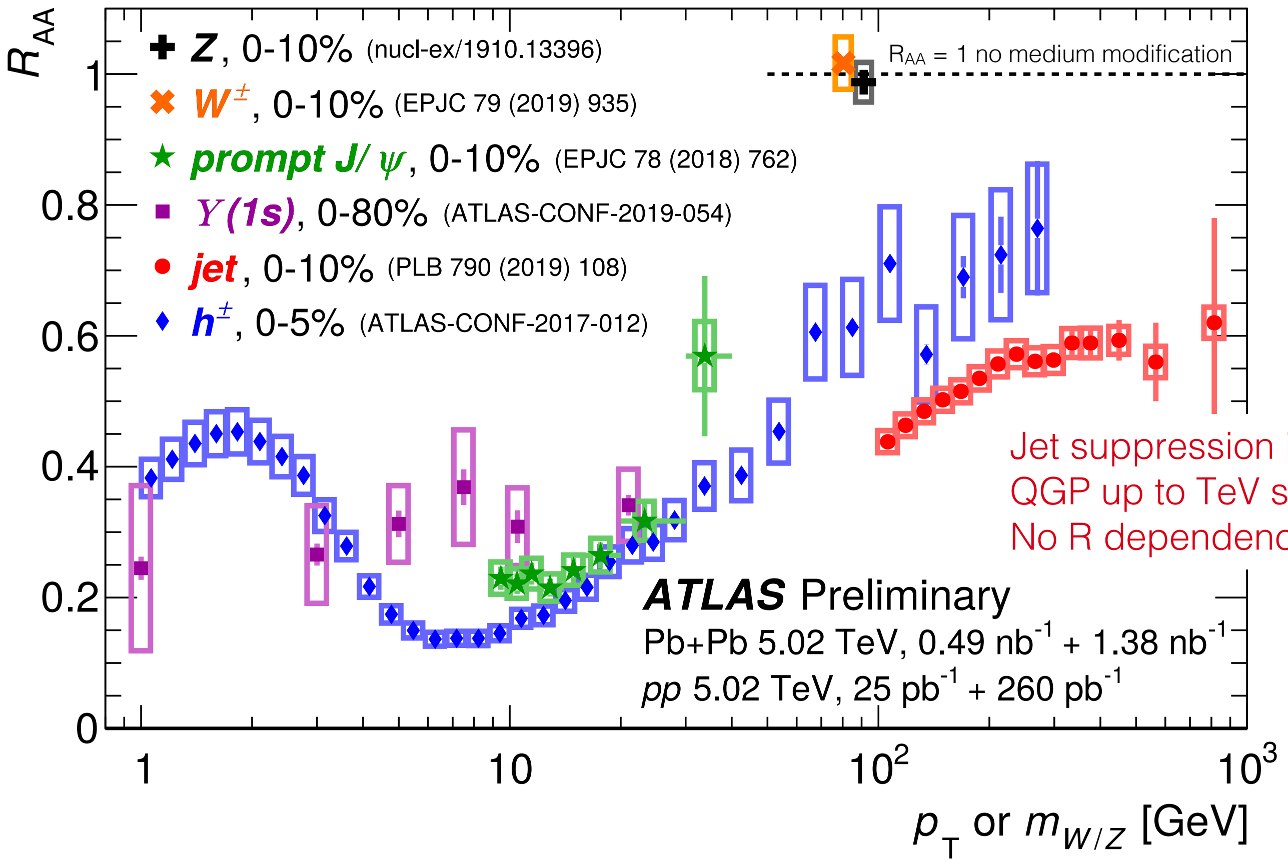
ALI-PREL-321075

Hard probes — Suppression of strongly interacting probes in Pb-Pb collisions uniformly observed

Colourless probes not suppressed

→ Useful as reference and for measurement of nuclear PDFs

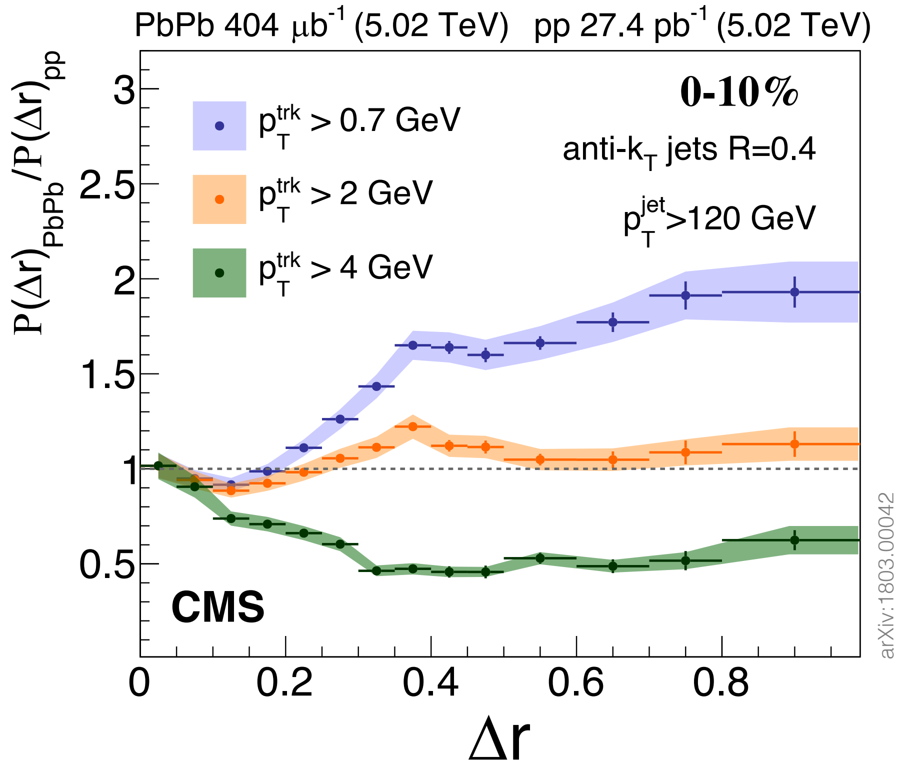
R_{AA} = Pb-Pb cross section / scaled pp cross section



But what *is* jet quenching?

→ Redistribution of energy to large angles from the jet axis observed in Pb-Pb

→ Energy goes out of the cone

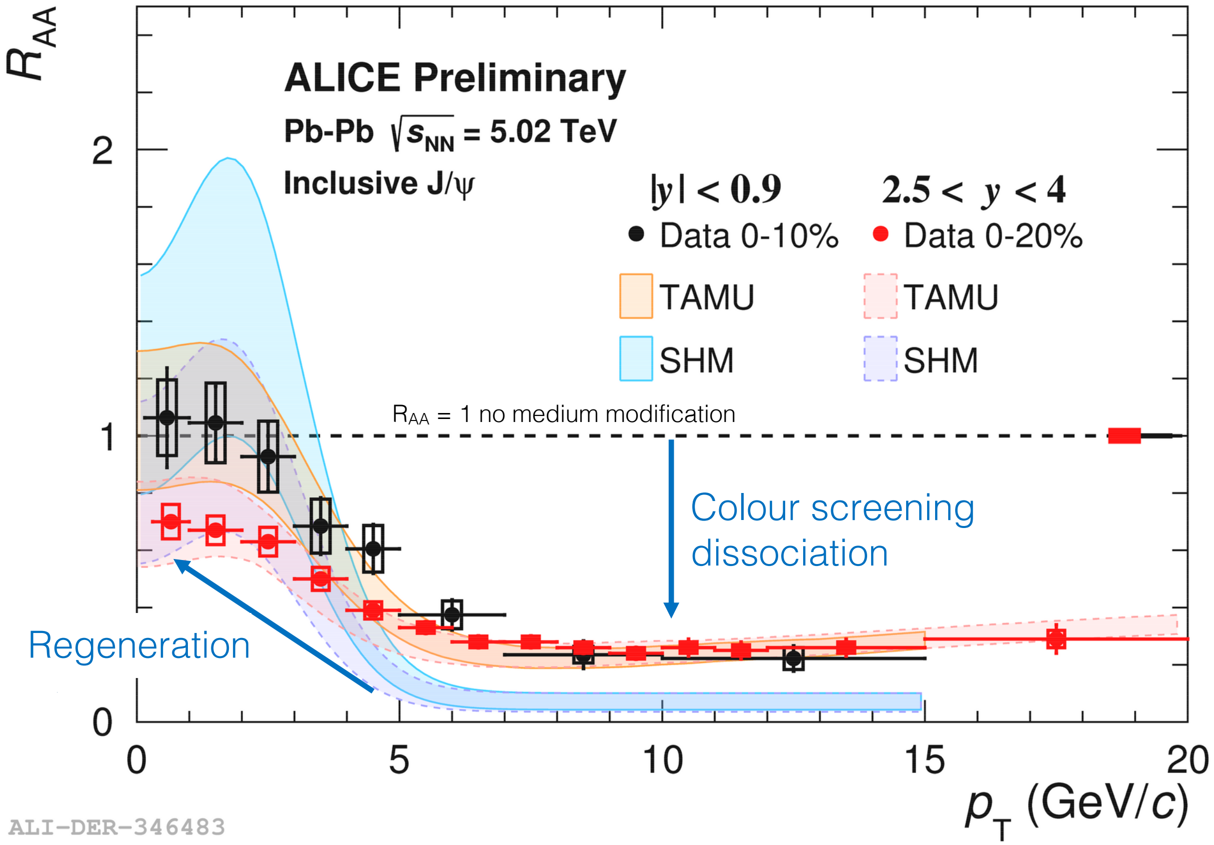


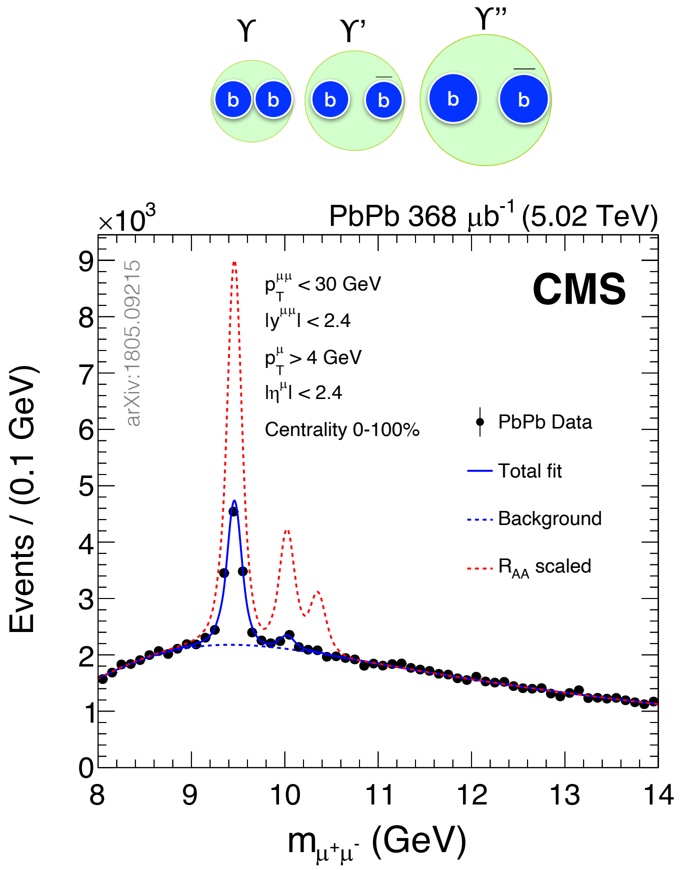
Quarkonia — Suppression versus recombination in deconfined medium (QGP)

Colour screening at high temperature dissociates ("melts") quarkonia in QGP

But, quarkonia also regenerated in QGP by re-combination of heavy $Q\bar{Q}$ pairs

Balanced effects at low p_T
Reproduced by theoretical models





Stronger suppression for loosely bound system

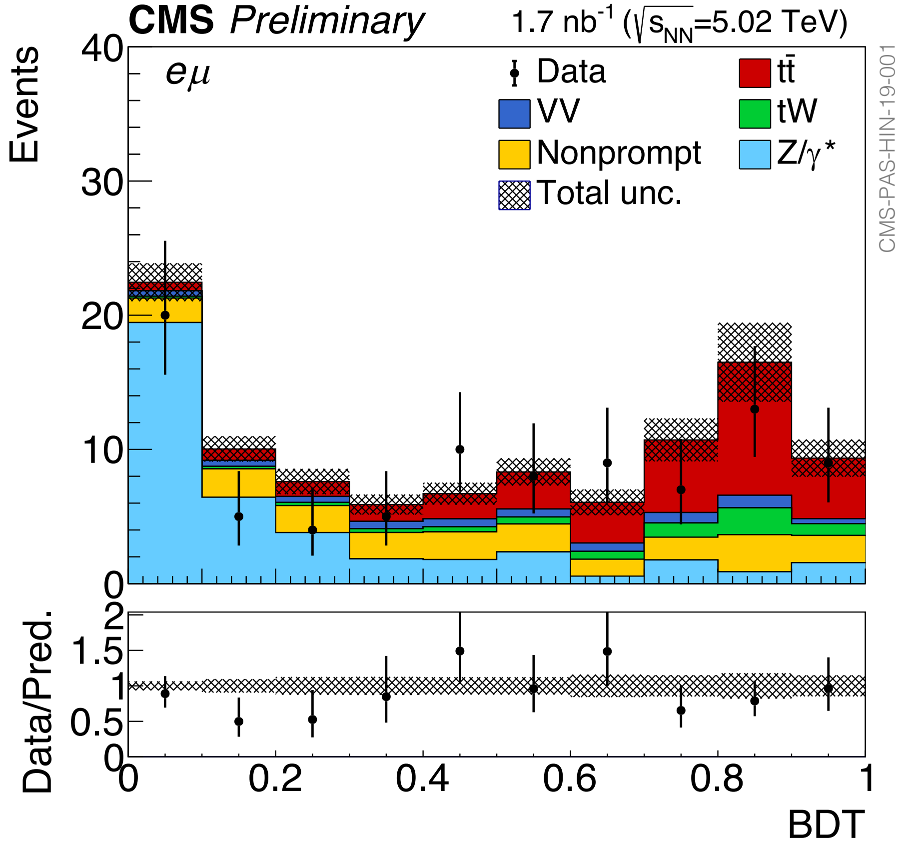
Bottomia less affected by recombination due to lower $b\bar{b}$ cross section

For open flavours, hierarchical energy loss gluons > charm > bottom (dead-cone effect + colour factor)

High data statistics allows to look for new probes

Top pair production in Pb-Pb collisions

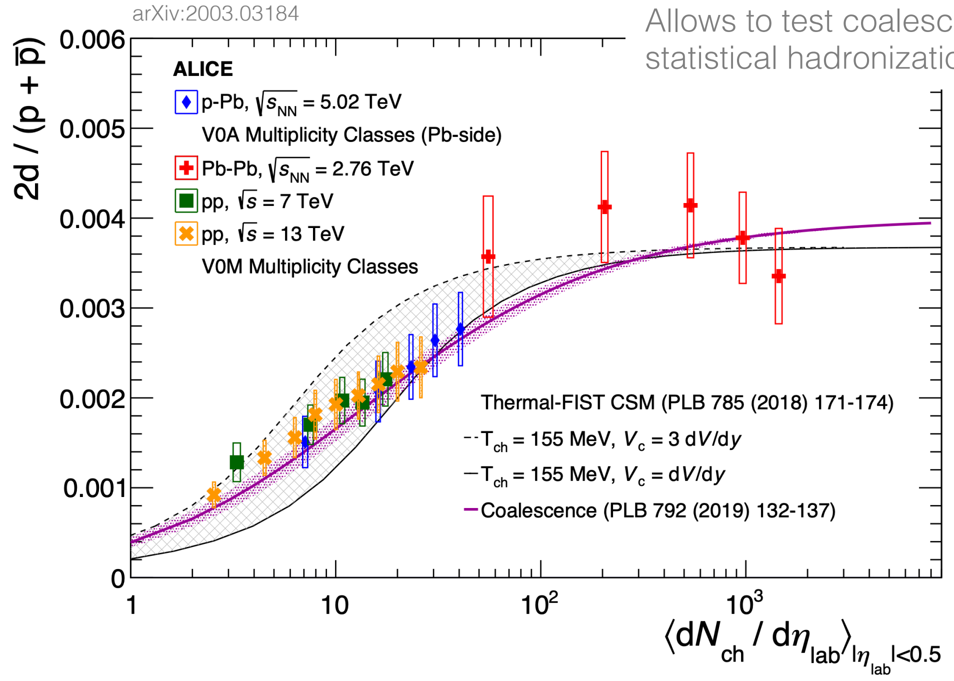
→ Decays before QGP creation, reconstructed m(tt) carries information on time structure of medium [arXiv:1711.03105]



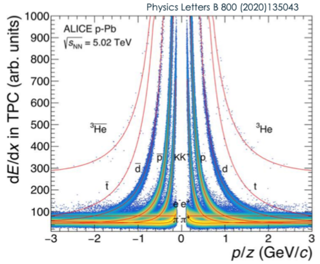
Significance: 4.0σ observed (6.0σ exp.) [w/ b-tag]

Light (anti)nuclei production and absorption

→ Ratio of (anti)deuteron, (anti)triton, (anti)^{3}He production to protons increases smoothly across colliding systems



Allows to test coalescence and statistical hadronization models



arXiv:2005.11122

Measurement of low-p_T $\bar{d}$ cross section in p-Pb

→ Novel method exploits detector as absorber. Measurement relevant for antinuclei production from cosmic rays

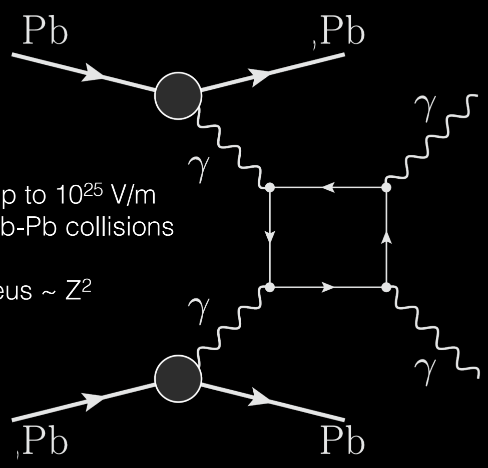
Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb-Pb collisions taken in 2018

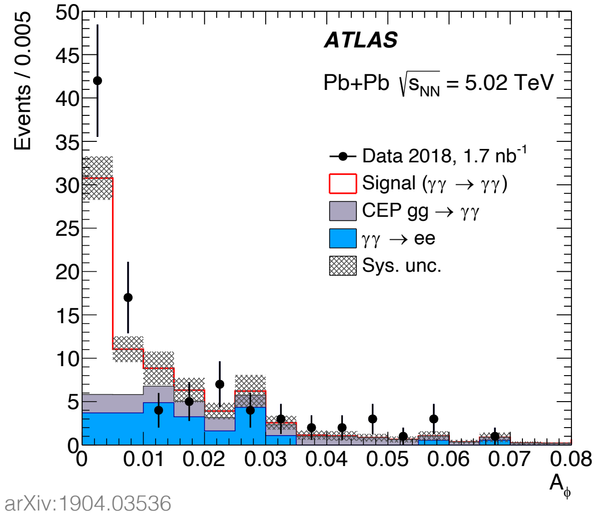
Look for low-energy back-to-back photon pair with no additional activity in detector

59 $\gamma\gamma \rightarrow \gamma\gamma$ events observed for 12 ± 3 expected background (8.2σ)

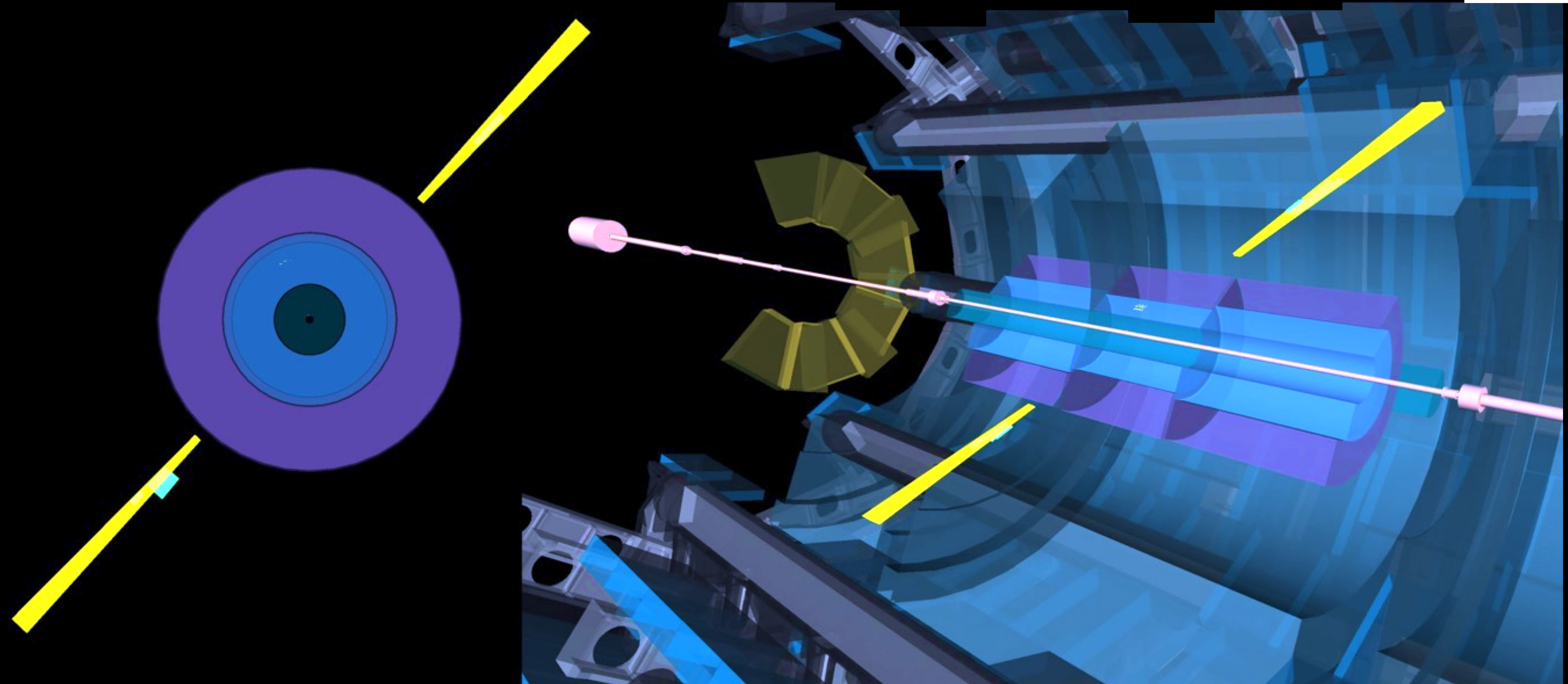
Field strength of up to 10^{25} V/m reached in UPC Pb-Pb collisions

Photon flux / nucleus ~ Z^2





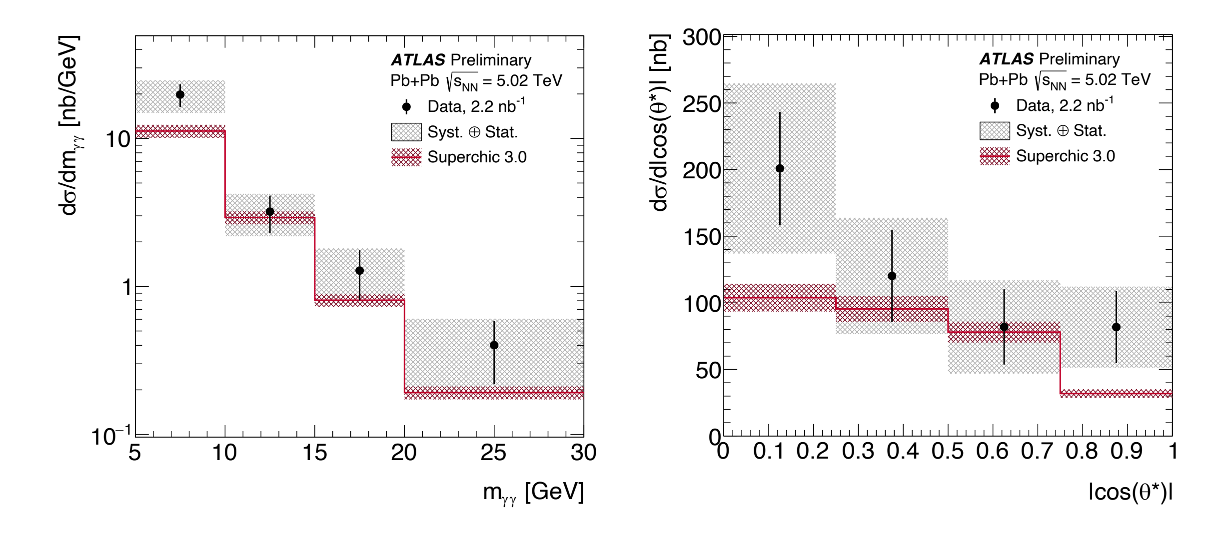
arXiv:1904.03536

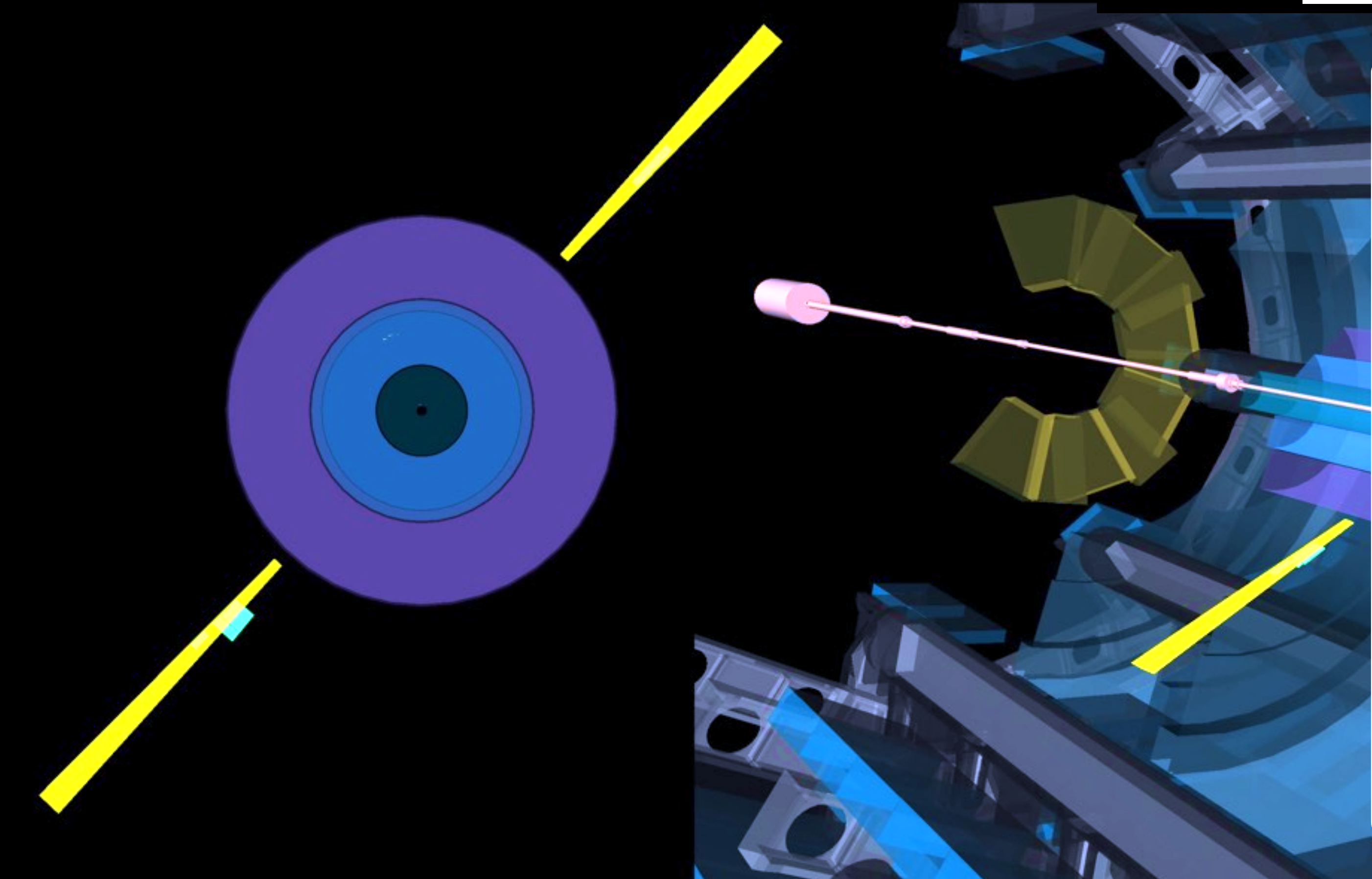


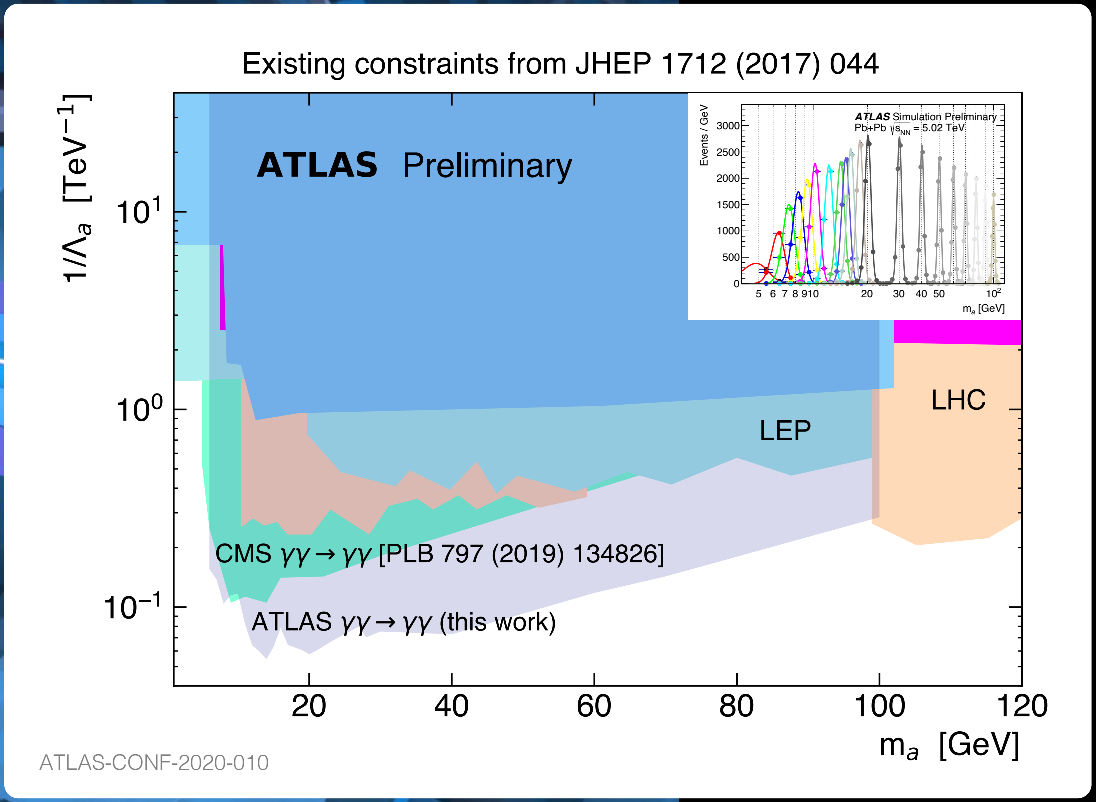
This opened the door to new studies and searches using the interaction of quasi-real photons in Pb-Pb collisions

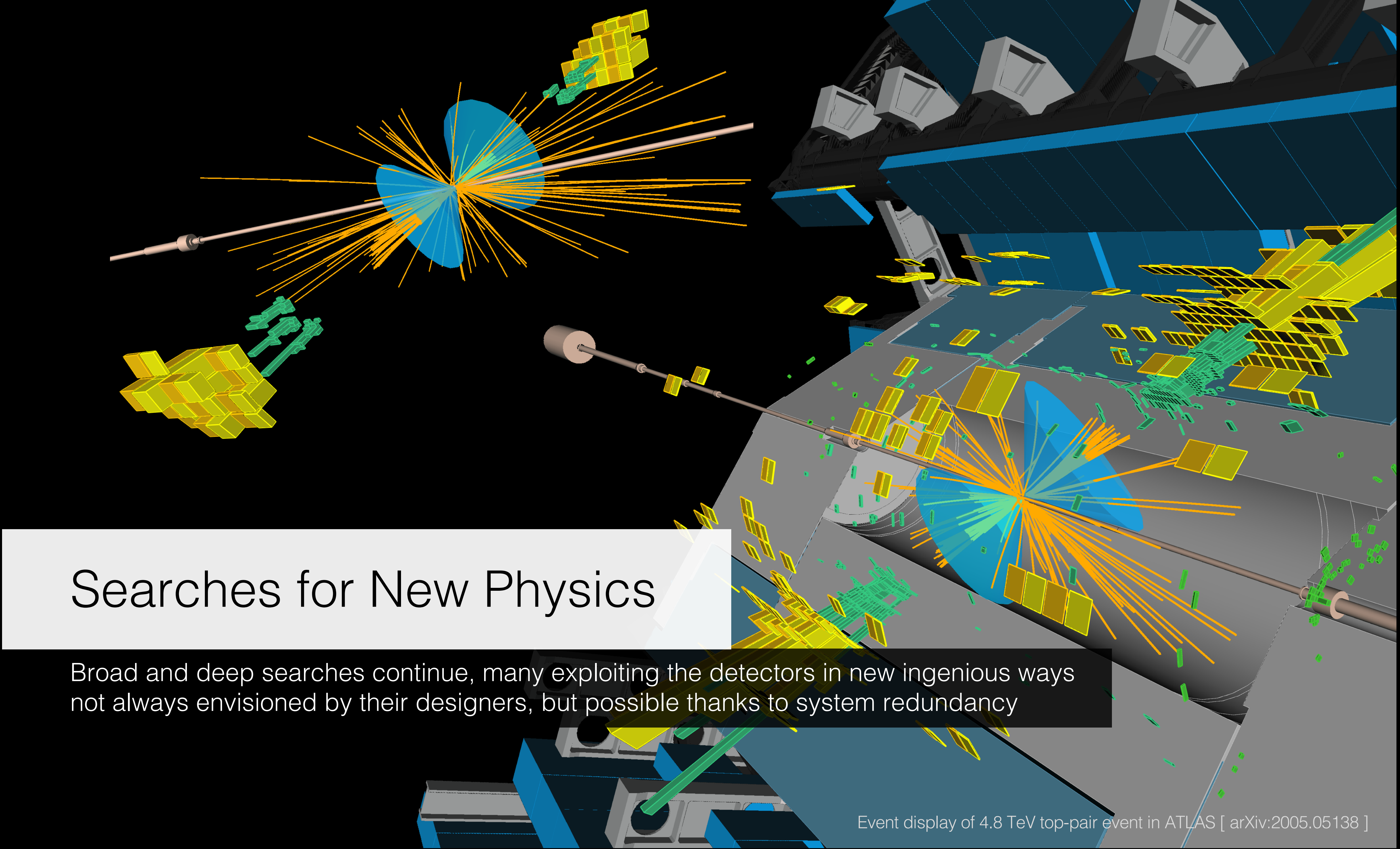
This week: measurement of light-by-light scattering in 5.02 TeV ultraperipheral Pb-Pb collisions taken in 2015 + 2018

Measurement of differential cross sections and constraints on ALP-photon coupling versus ALP mass









Searches for New Physics

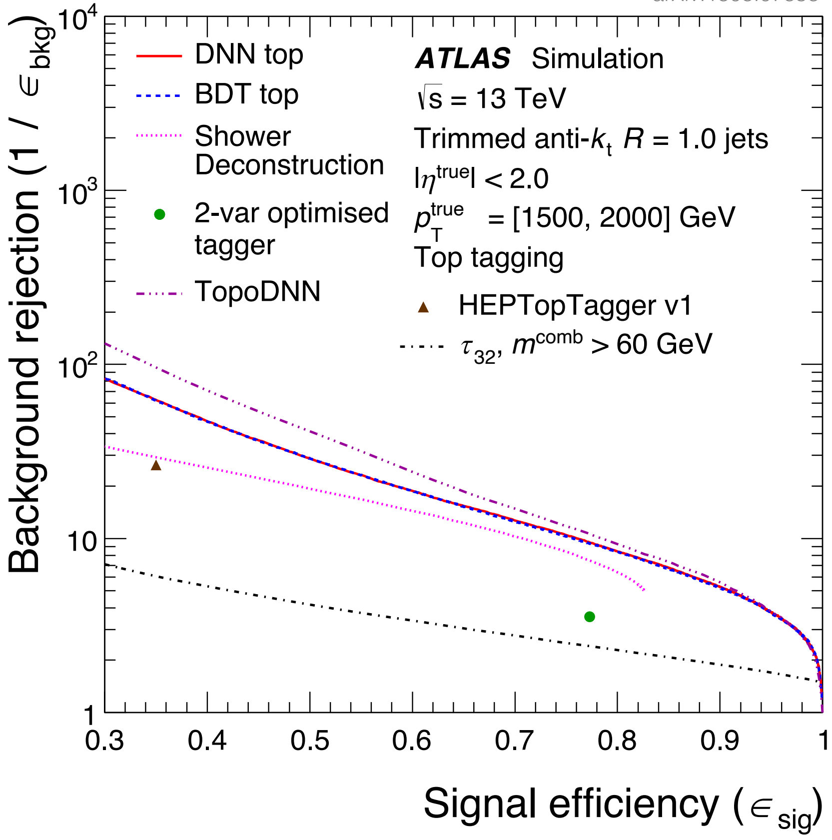
Broad and deep searches continue, many exploiting the detectors in new ingenious ways not always envisioned by their designers, but possible thanks to system redundancy

Event display of 4.8 TeV top-pair event in ATLAS [arXiv:2005.05138]

Searches for heavy resonances decaying via pairs of W, Z, H bosons or top quarks benefit from significantly improved boson and top tagging algorithms using machine learning

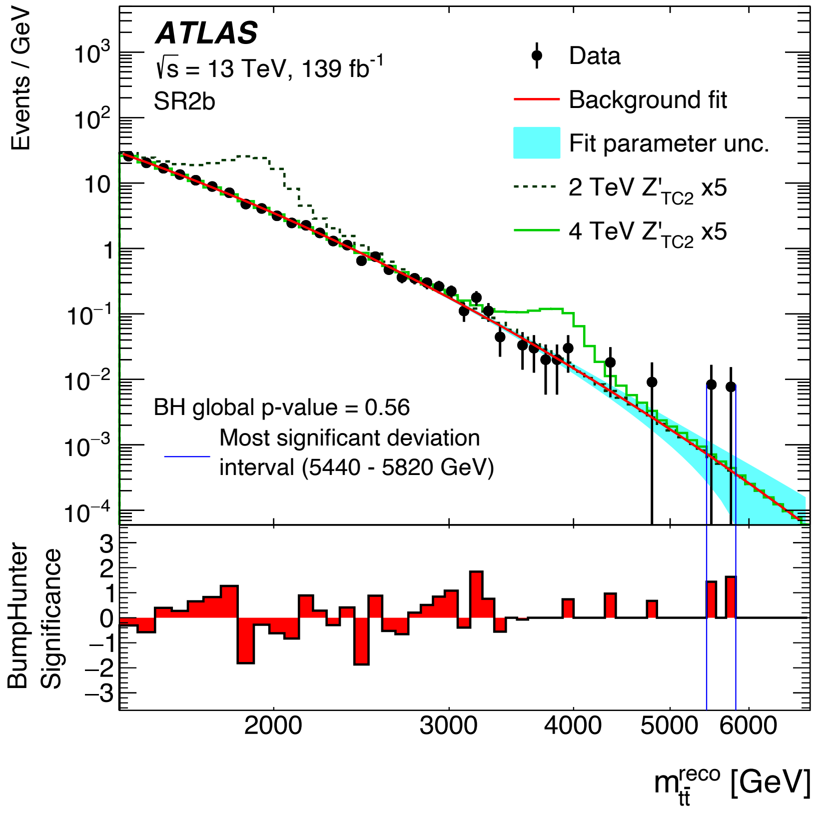
Backgrounds derived from data using smooth functions — requires faithful description

arXiv:1808.07858



tt resonance search

arXiv:2005.05138



b-tagging with variable-radius track-jet

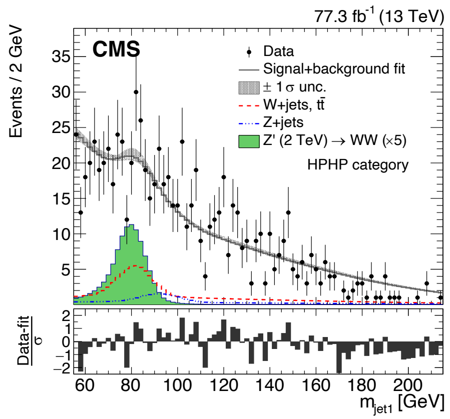
Large improvement over previous analysis

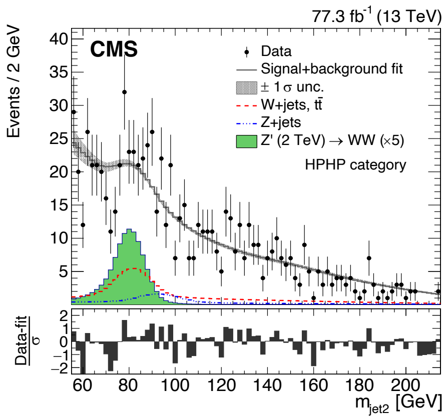
Limit: Z'_{TC2} (LO) > 4.0 TeV

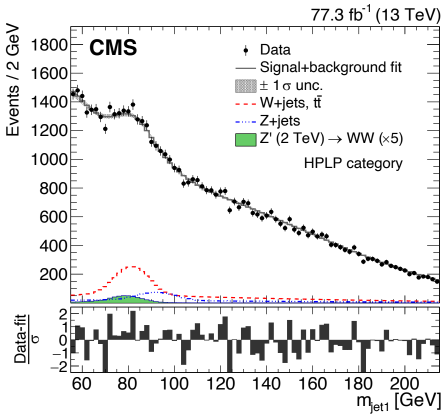
Searches for heavy resonances decaying via pairs of W, Z, H bosons or top quarks benefit from significantly improved boson and top tagging algorithms using machine learning

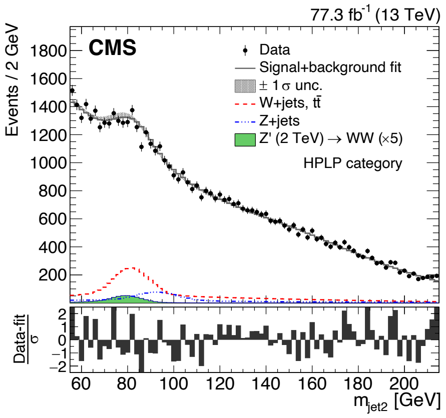
Backgrounds derived from data using smooth functions — requires faithful description

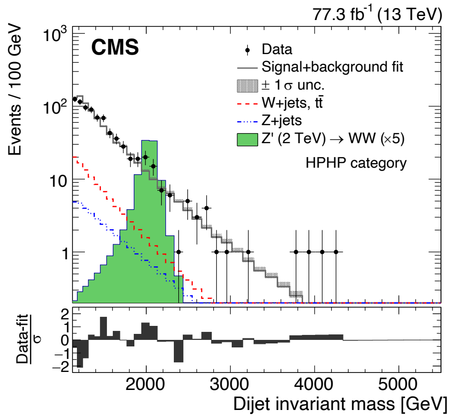
VV → qqqq resonance search







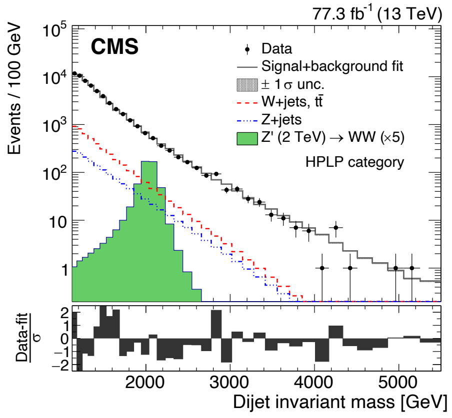




Novel method: 3D fit to the two large-R-jet masses & dijet mass → up to 30% better sensitivity

High — Low
Purity category

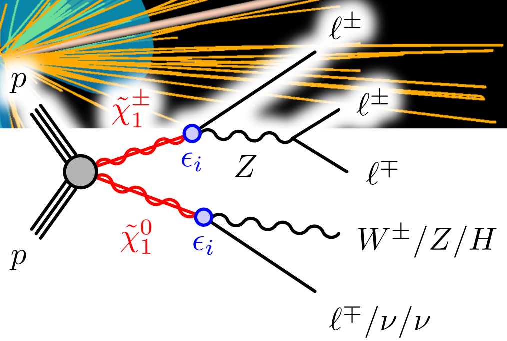
Limit HVT_B W'(Z') > 3.8 (3.5) TeV



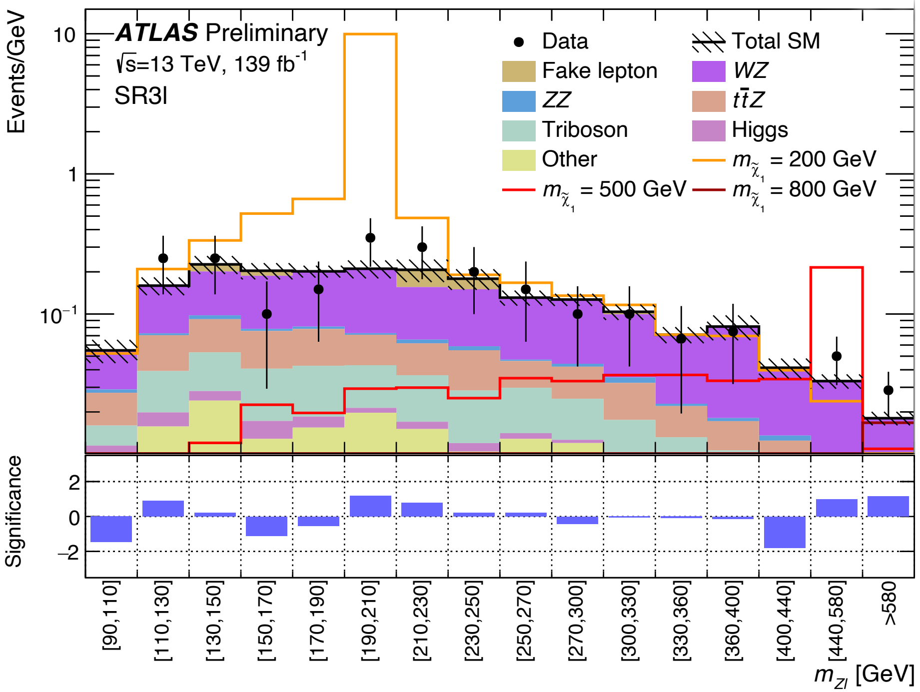
arXiv:1906.05977

Searches for Supersymmetry are significantly improving sensitivity in difficult areas of compressed spectra, and deepen quest for R-parity violating scenarios

Look for Z+lepton (3ℓ) resonance:

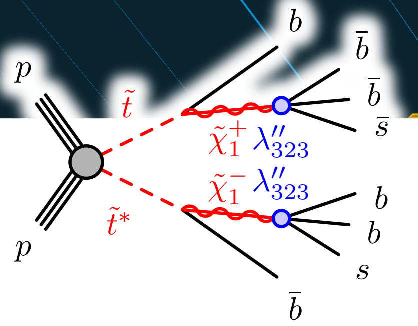


ATLAS-COONF-2020-009

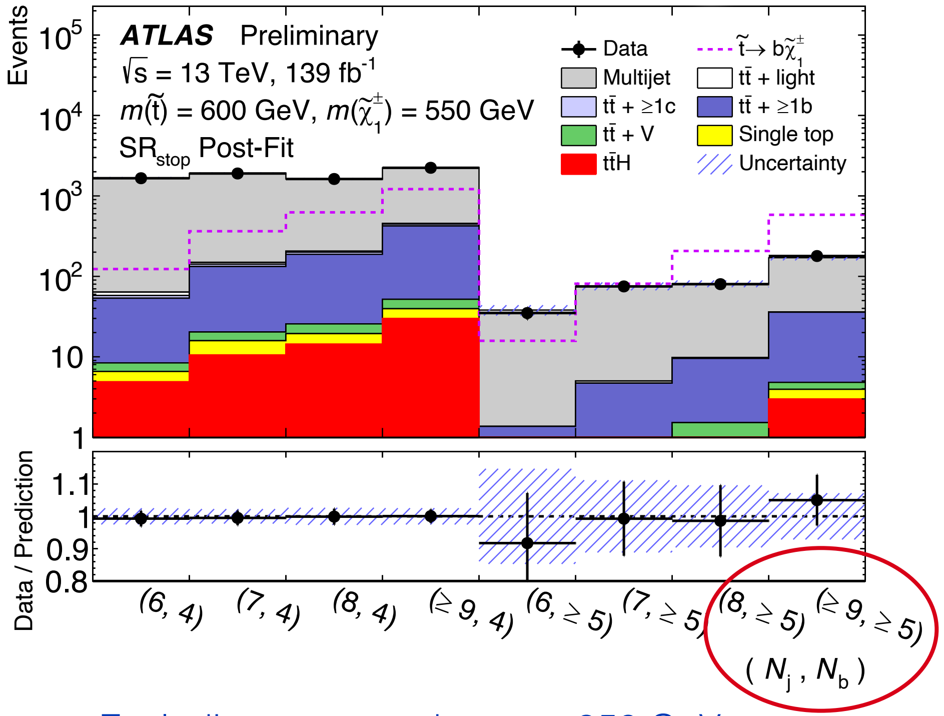


Excluding charginos up to 1 TeV

Look for many jets & b-jets, no leptons:

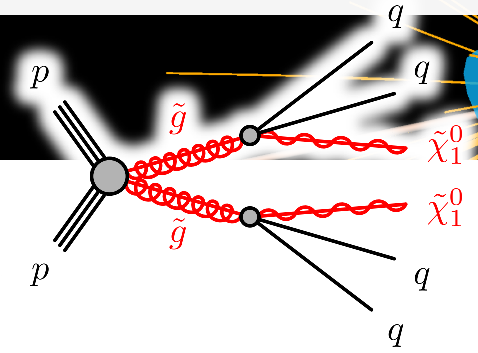


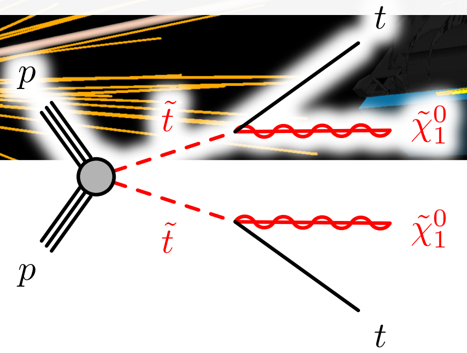
ATLAS-COONF-2020-016

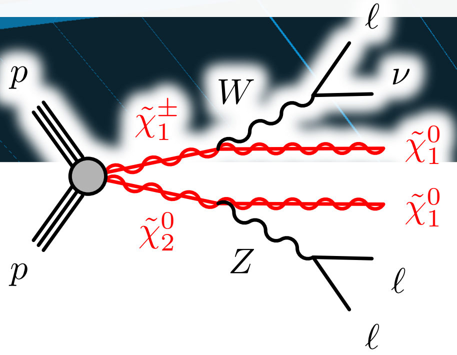


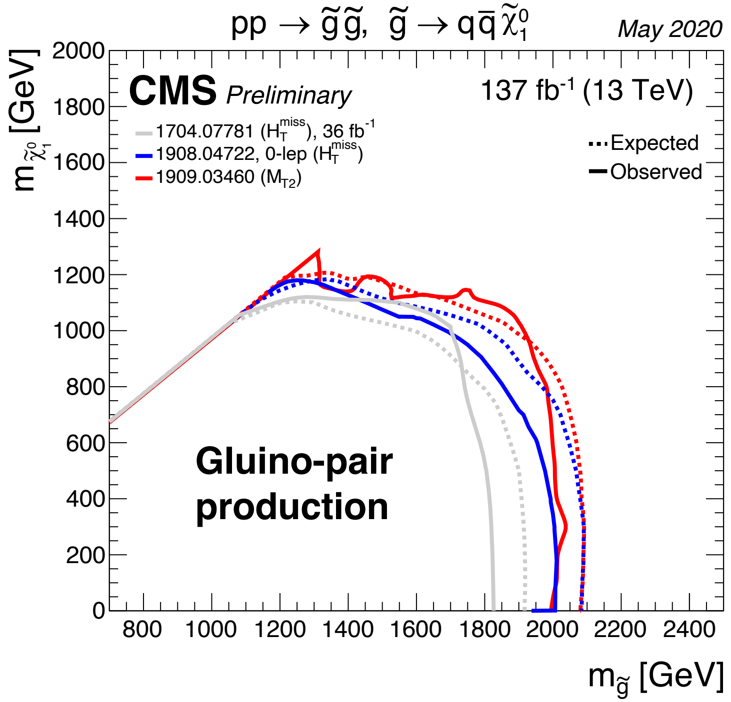
Excluding top squarks up to 950 GeV

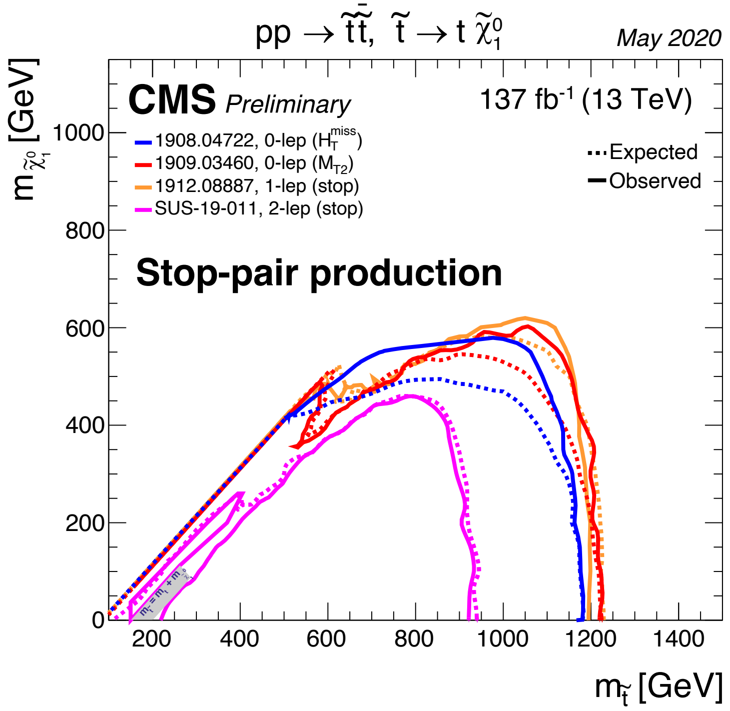
Searches for Supersymmetry state-of-the-art sensitivity and limits for gluino, top squark and electroweak pair production

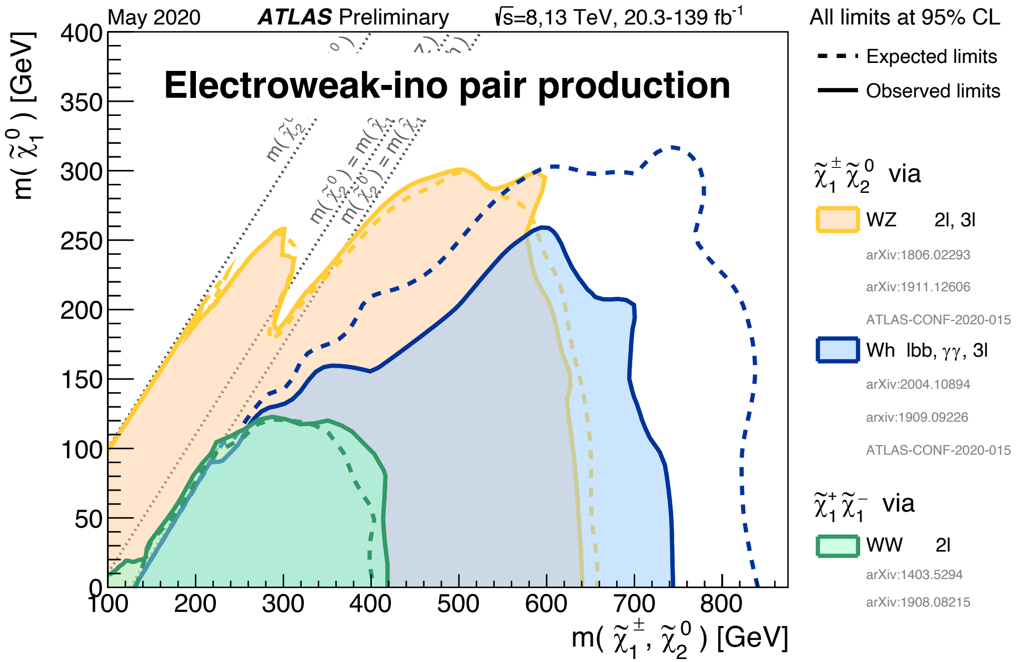








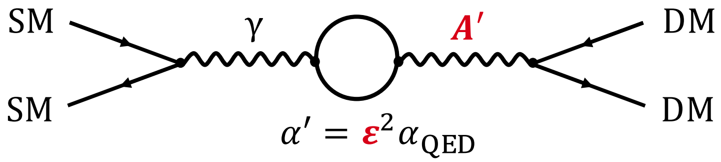


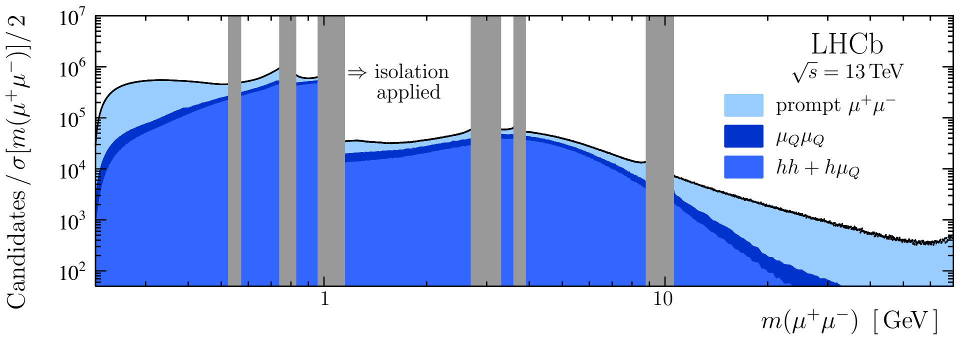


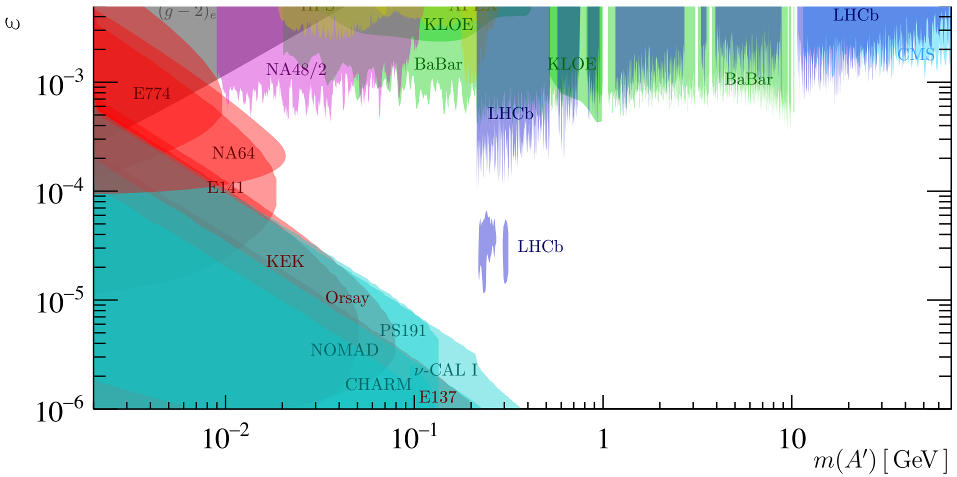
Dark sector and long-lived particle searches

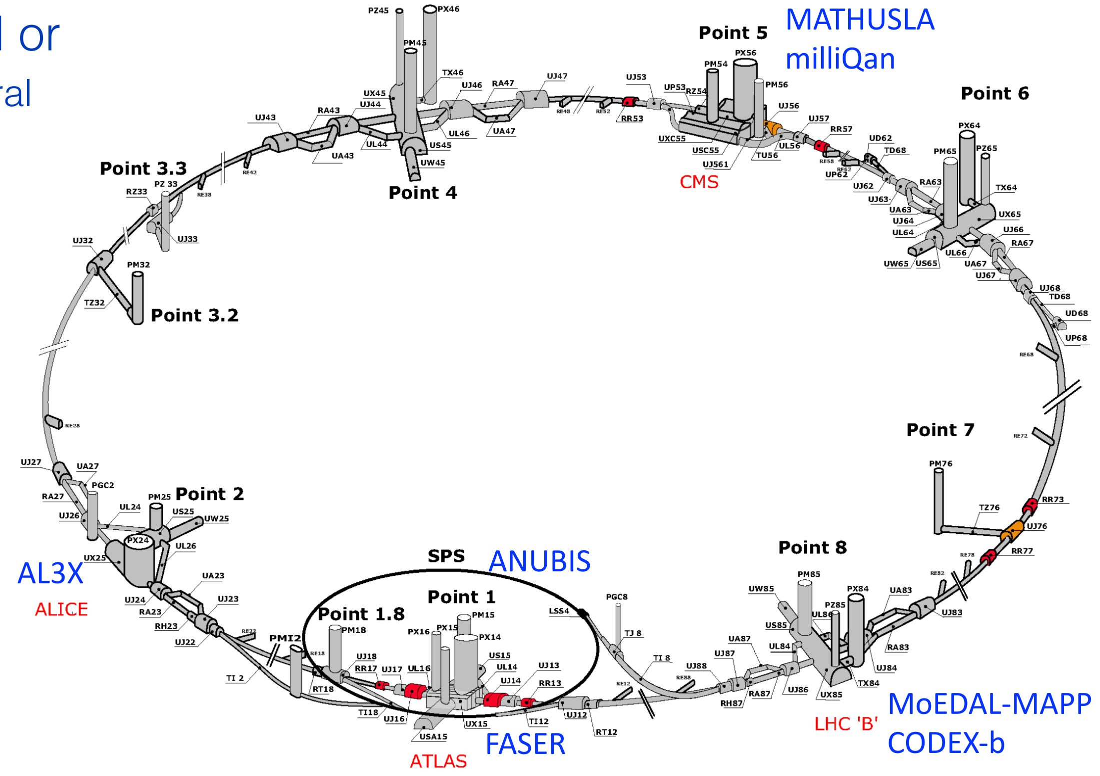
Number of new experiments around LHC and SPS proposed or approved to look for long-lived neutral particles (eg, heavy neutral leptons ("sterile neutrinos"), dark photons, dark scalars, axion-like particles)

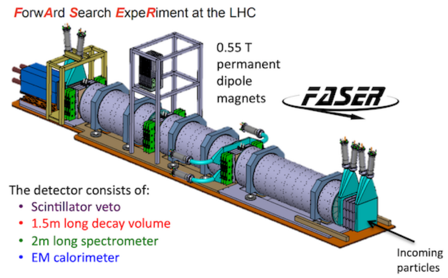
One possibility: dark photon (A') portal









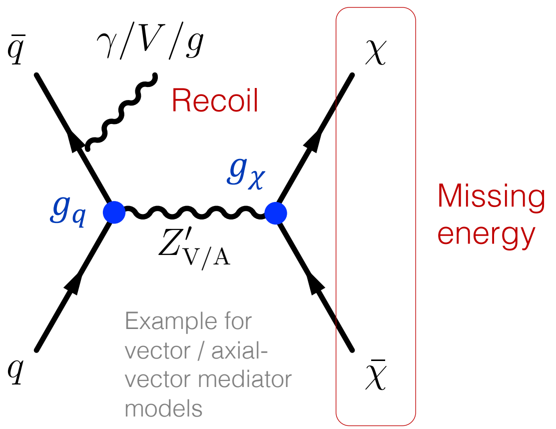


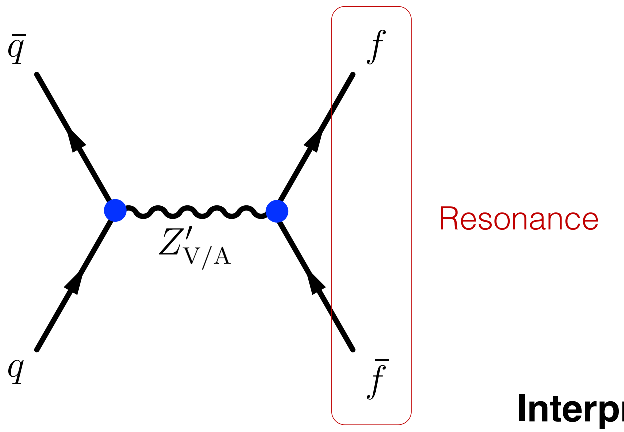
Recent LHCb search for prompt and long-lived A' → μμ (5.5 fb^{-1})

arXiv:1910.06926

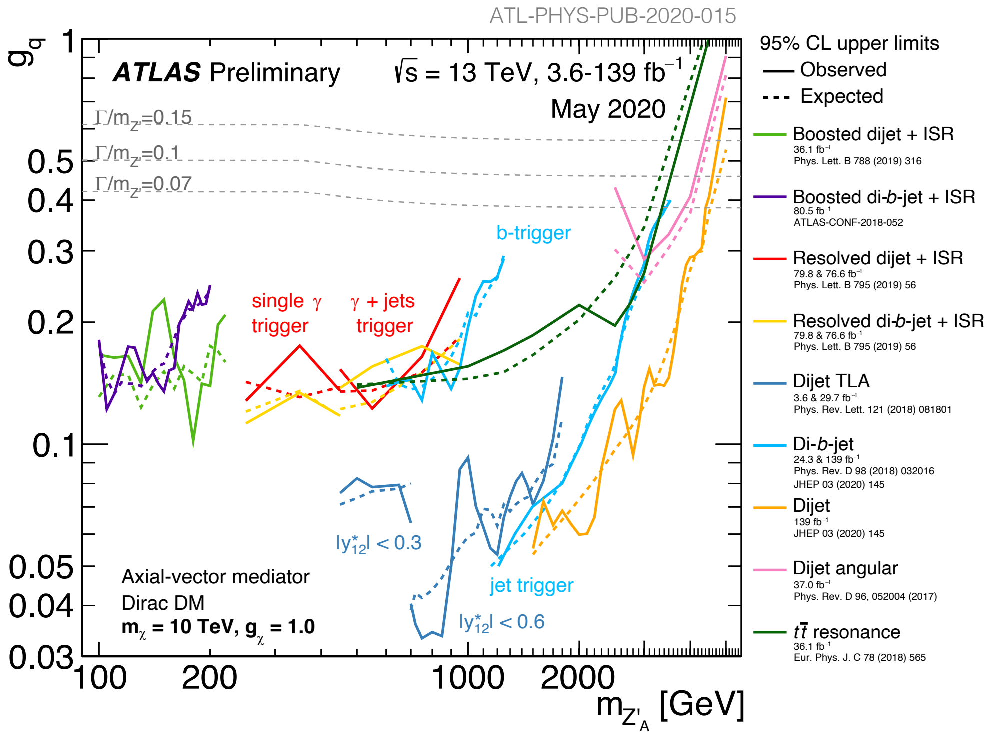
Dark matter searches at the LHC — Direct through recoil (incl. SUSY), indirect through mediator

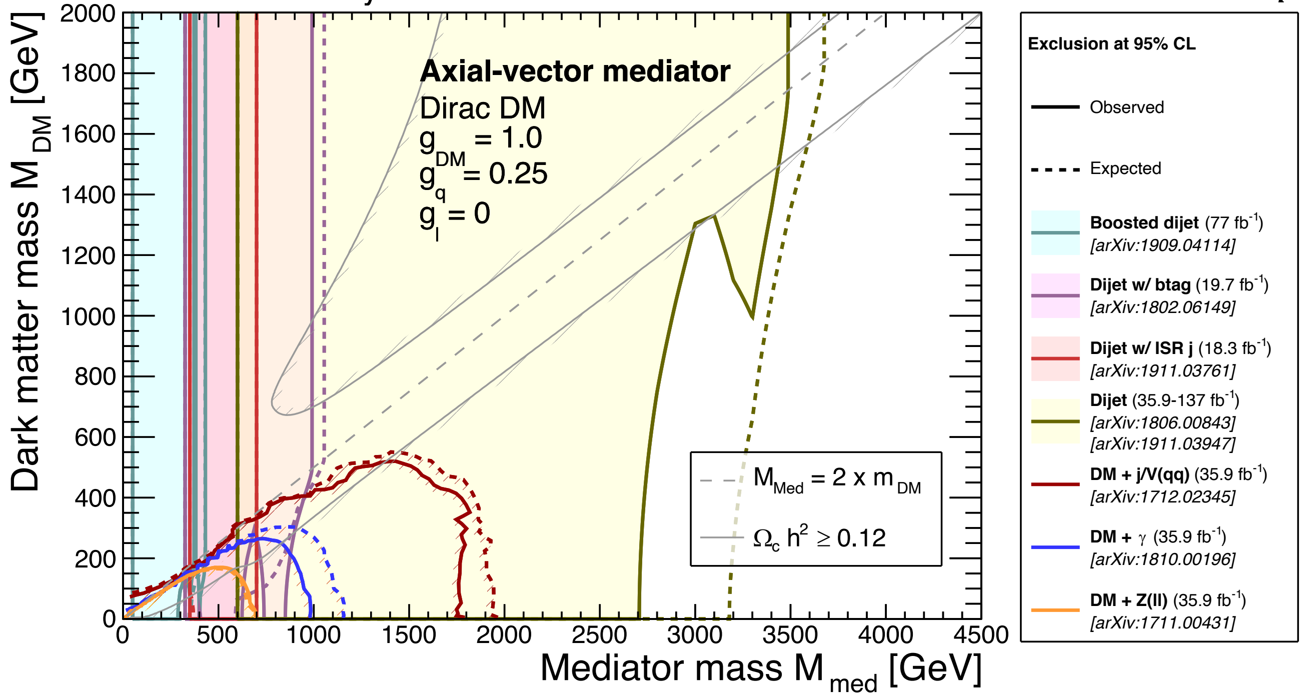
If produced at the LHC, DM interactions will be mediated by particles that can also be directly searched for — complementarity



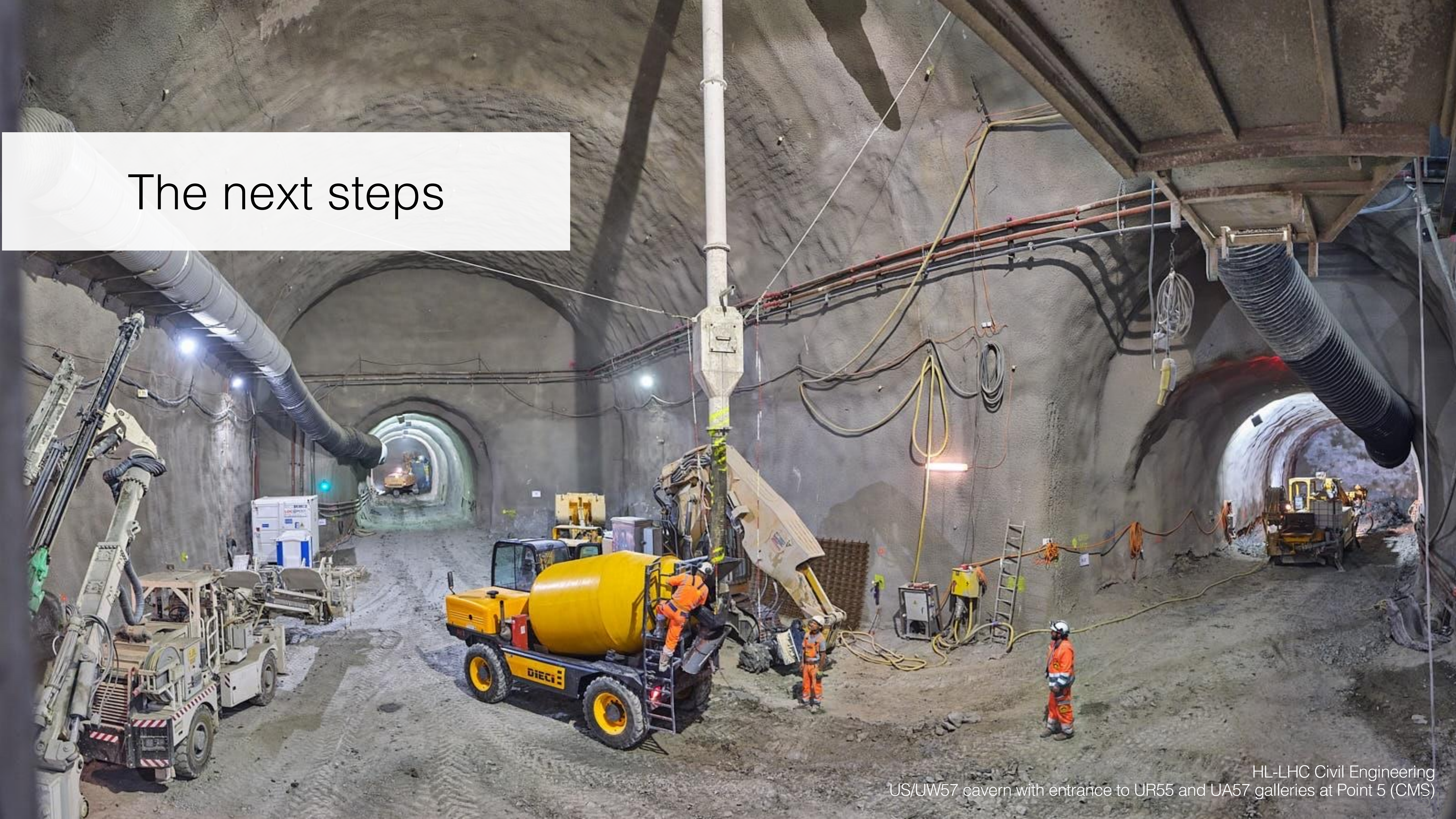


Interpretation depends strongly on values of g_q, g_χ





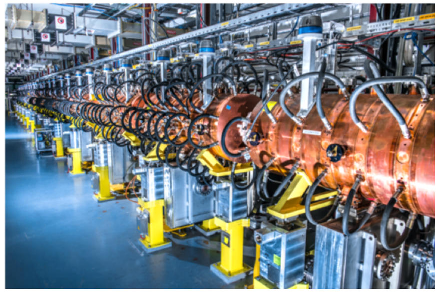
The next steps

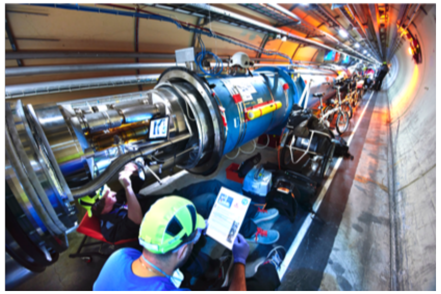


HL-LHC Civil Engineering
US/UW57 cavern with entrance to UR55 and UA57 galleries at Point 5 (CMS)

Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

Accelerators


New Linac 4


Inspecting & cleaning a diode enclosure

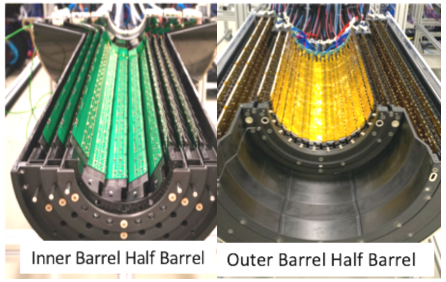
LHC Injector Upgrade (LIU): Linac 4, PSB, SPS
For improved beam brightness and reliability

LHC: consolidation of interconnections & diode boxes

Two 11 T dipoles at P7 to make room for collimator
Unclear whether will be installed

Civil engineering for HL-LHC

ALICE

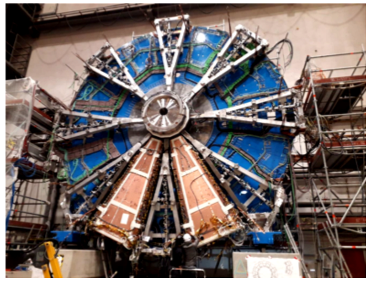


Main theme: trigger-less readout
50-100 times min bias, 50 kHz readout (was 1 kHz)

New Pixel Inner (ITS2) and Fwd muon tracker (MFT) — 13B pixels
Pioneers monolithic MAPS (CMOS) technology

GEM-based TPC readout + Fast Interaction Trigger, new Online-Offline computing system, …

ATLAS



Main theme: refine trigger selection
In view of Run-3 and the HL-LHC

LAr upgrade for better L1Calo granularity
Exploited by more powerful L1 trigger boards

Muon New Small Wheel (NSW), …
Improved fake muon rejection at trigger level

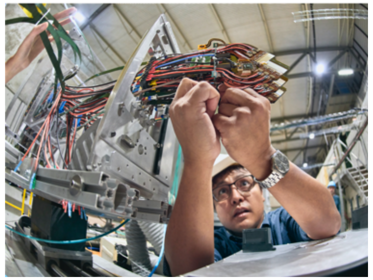
CMS

Many upgrades already during Run-2
New Pixel, DCDC, L1 trigger, PPS, HCAL elec.

Finalise this work during LS2
Plus for HL-LHC: new beampipe, civil eng., muon electronics & GEMs, beam & Fwd systems

Additional consolidation tasks

LHCb



Main theme: 5 times luminosity and pileup
Maintain performance of detector — update ~all systems
- New tracking detectors: pixel, strips, outer (SciFi)
- New RICH optical system and photo detectors

40 MHz all-software trigger (current HW: 1.1 MHz)
New RICH, calorimeter, muon readout (L0 trigger removal)
HLT1 (first level) reconstruction on GPUs
Surface data centre for event filter and building

Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

Accelerators

LHC Injector Upgrade (LIU): Linac 4, PSB, SPS
For improved beam brightness and reliability

LHC: consolidation of interconnections & diode boxes

Two 11 T dipoles at P7 to make room for collimator
Unclear whether will be installed

Civil engineering for HL-LHC

ALICE

Run 3 will be a game changer for ALICE (×50 of Run 1+2) and LHCb (×5)

For ATLAS and CMS, the LS2 upgrades prepare for the game changing HL-LHC

Trigger, new Online-Offline computing system, …

CMS

Many upgrades already during Run-2
New Pixel, DCDC, L1 trigger, PPS, HCAL elec.

Finalise this work during LS2
Plus for HL-LHC: new beampipe, civil eng., muon electronics & GEMs, beam & Fwd systems

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HLT1 (first level) reconstruction on GPUs
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Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

We have heard this week that much of this work is affected by the necessary COVID-19 measures. In addition to the restrictions at CERN, the international experiments depend on the situation at production sites and travel of experts

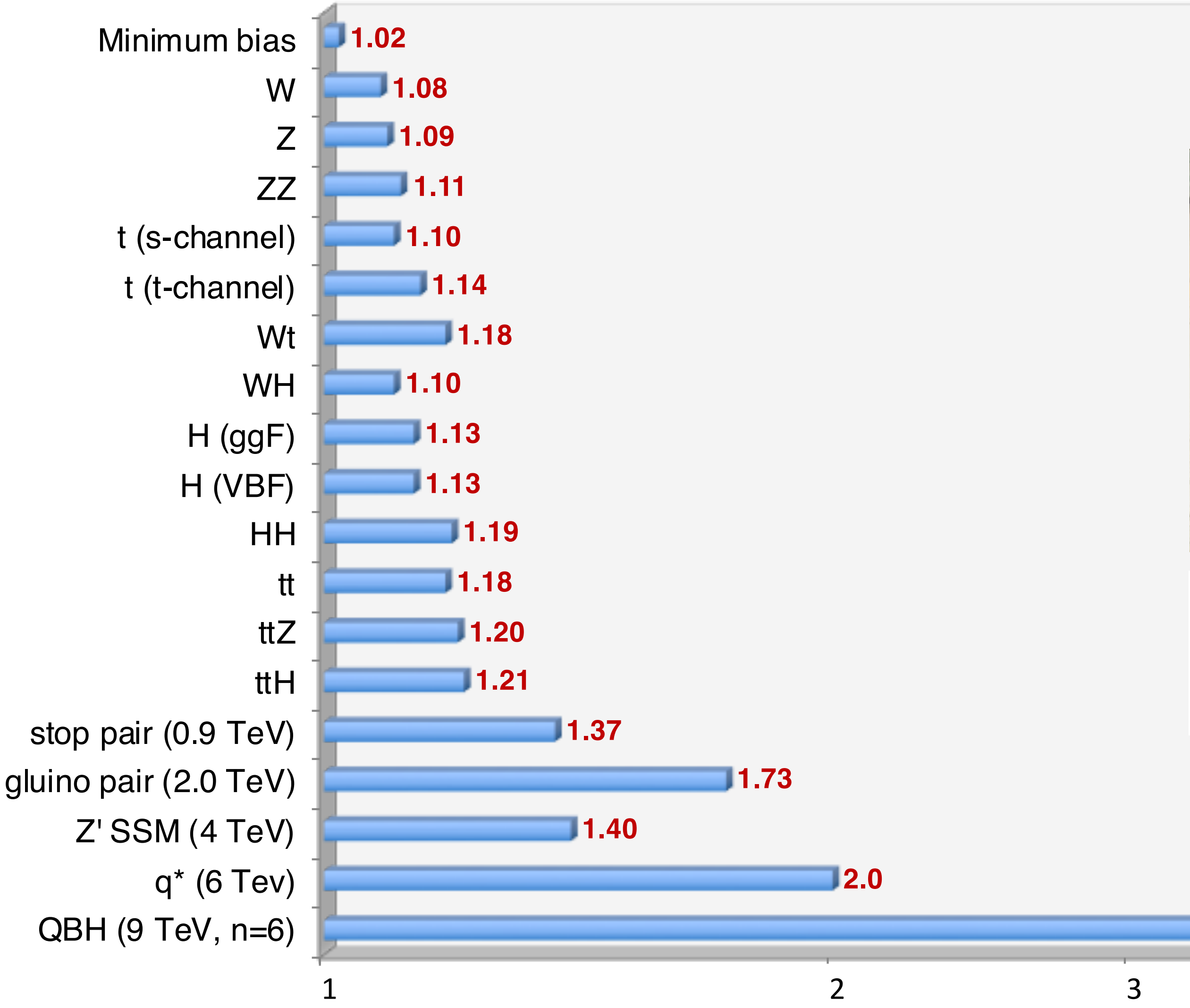
There will be delays. Reassessment of schedule performed over the summer

As soon as possible experts restarted urgent work wearing their protective equipment and keeping distance

Photos shown by Matt Charles (LHCb) and Miguel Jimenez (LHC & Injectors)

14 TeV proton–proton centre-of-mass energy is better !

14 TeV / 13 TeV inclusive pp cross-section ratio

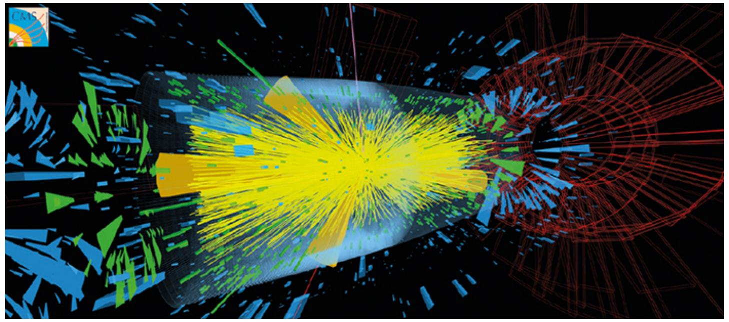


Miguel Jimenez confirmed on Monday that the additional time needed by the experiments due to COVID-19 will be used for magnet training

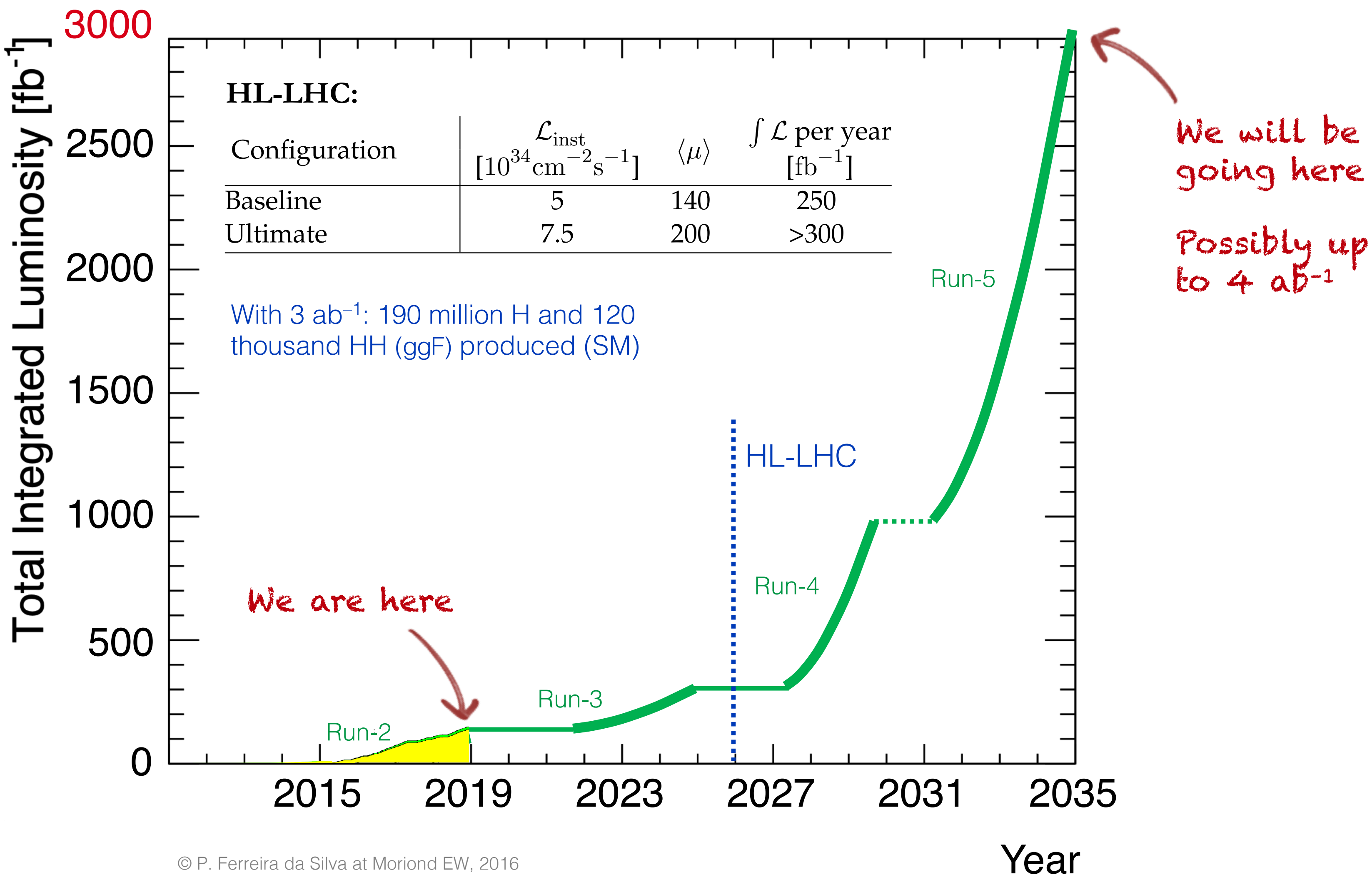
HL-LHC: monumental upgrades of LHC, ATLAS & CMS, proposals by ALICE & LHCb

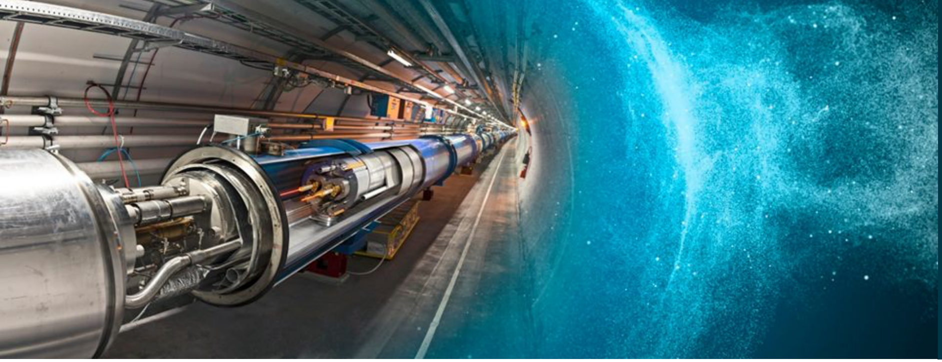
ATLAS & CMS Phase-II upgrades entering construction phase

No time to summarise the many innovating and challenging projects here



Simulated VBF Higgs event with 200 pileup interactions in CMS

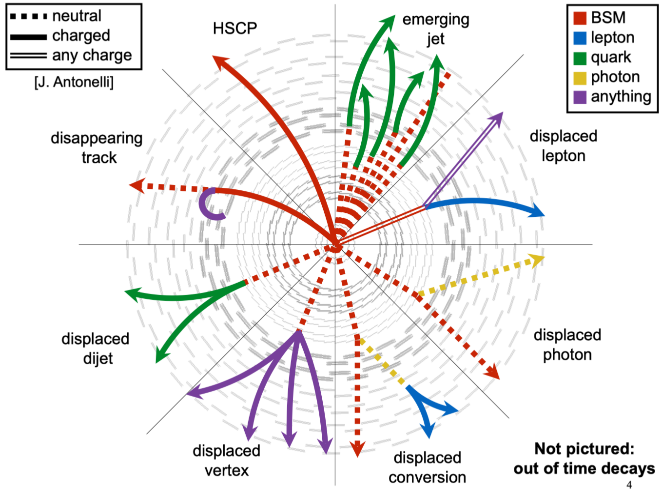


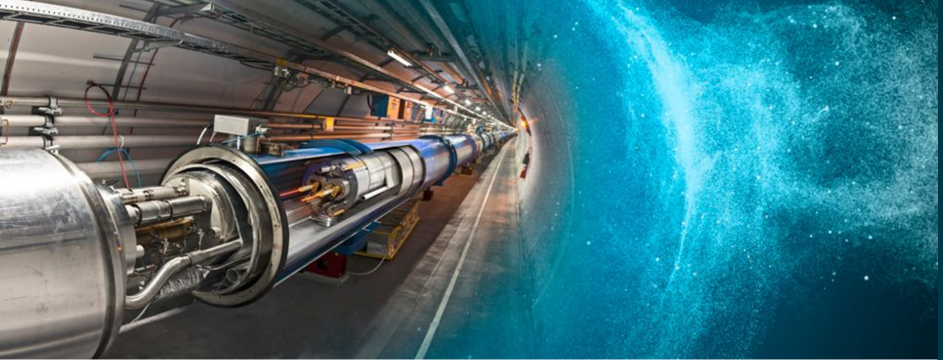


Before concluding…

Among the many things I did not discuss

- Many, many, many other beautiful results (among these, the suit of new and ingenious long-lived particle searches, an utterly creative field as we heard today)
- Further progress on theoretical calculations and modelling is critical for exploiting the physics of Run-3 and the HL-LHC
- SMEFT, SMEFT, SMEFT: theorists and experimentalists are moving to a global and coherent BSM interpretation framework of measurements and searches — this is an excellent development
- The importance of outreach for particle physics: go and speak to policy makers, your colleagues at universities and labs, and the public about this exciting and important science!





Conclusions

A decade after the start, the LHC and its experiments have exceeded all performance promises and transformed particle physics

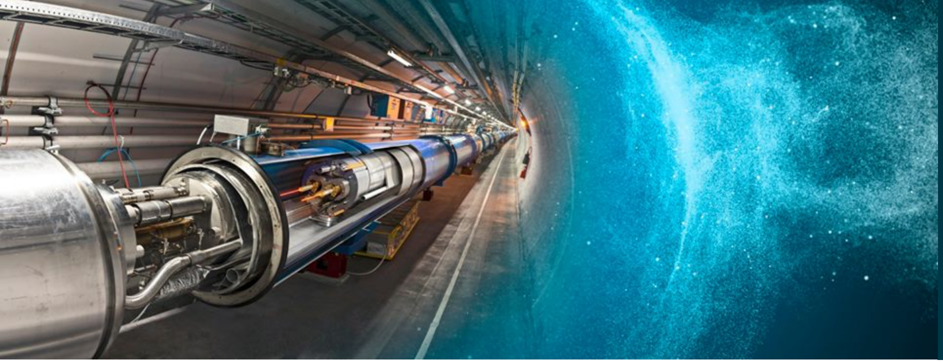
We have discovered many new tools to approach the big questions:

- Nature of dark matter and energy
- Hierarchy of scales and stability of the scalar sector
- Matter-antimatter asymmetry in Universe
- Strong CP problem

to which — unfortunately — direct experimental probes are yet elusive

But there is *huge* progress on ”answerable questions” through measurement (G. Salam, LHCP 2018)

We live in data-driven times, experiment must guide us to the next stage. The LHC and its experiments represent the flagship of particle physics at the energy frontier for the decade to come



Conclusions

A decade after the start, the LHC and its experiments have exceeded all performance promises

The unprecedented COVID-19 crisis hits our societies hard with human suffering and huge societal as well as economic challenges

In this situation, we are extremely grateful to Giovanni, Roberto and all the LHCP 2020 Organisers as well as CERN for allowing this important conference with many fascinating talks and posters to happen

to which — unfortunately — direct experimental probes are yet elusive

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