Experimental Highlights

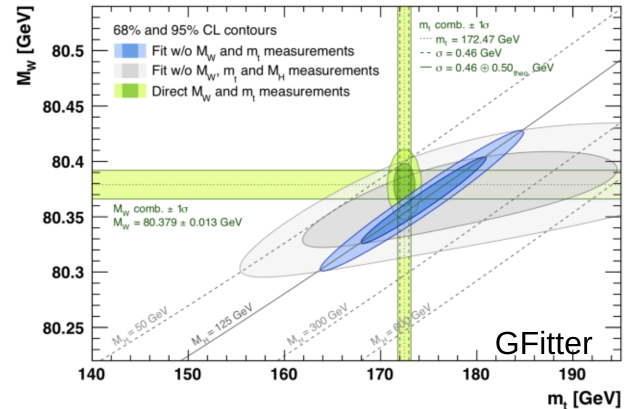
Richard Hawkings (CERN)

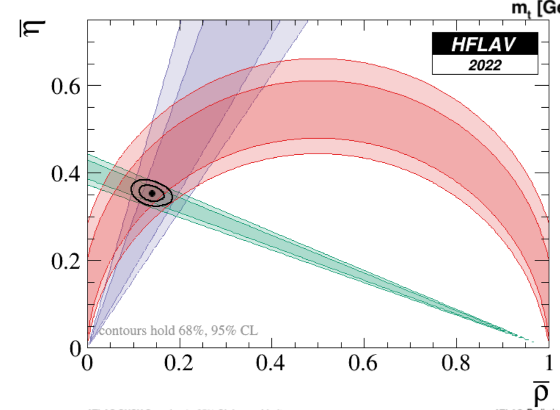
11th LHCP conference, Belgrade, Serbia, 26/5/2023

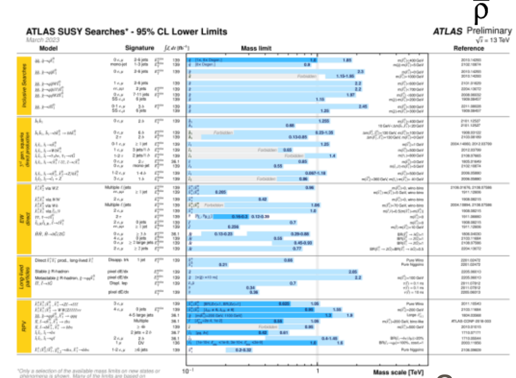
- An intense week of LHC physics
  - 42 plenary talks, 12 parallel tracks with multiple individual and joint sessions
    - Cannot summarise this in 30 minutes
- A personal selection of highlights ...
  - Trying to focus on most recent results
  - Apologies if your favourite topics are not included ☺

Where are we?

- 13 years since start of LHC data-taking
  - 11th LHCP conference, first in-person since 2019
- Achievements of the LHC/experiments to date
  - Exploration of a new energy regime
    - The Standard Model reigns supreme
  - Discovery of a / the(?) Higgs boson
    - A new precision measurement programme
  - Consistency of the CKM paradigm in flavour physics
  - Exploration of QCD in new environments
    - Pb+Pb, p+Pb, zoos of new hadrons
  - Many, many searches for new physics
    - A lot of models/parameter space ruled out
    - But new ideas / opportunities keep appearing
    - 3σ effects come and go (and come and go)
- Most results still coming from Run-2 data
  - 4.5 years after end of data-taking, a treasure trove that continues to be exploited





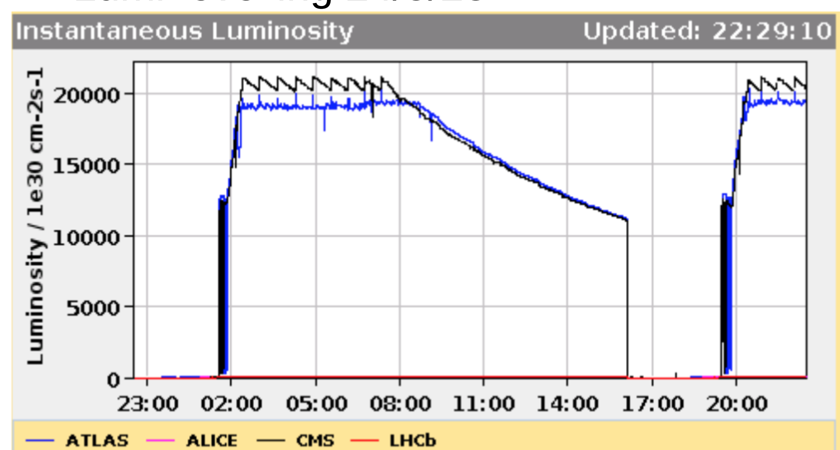


Where are we going?

- 4-year Run-3 started on 5th July 2022
  - Significant upgrades towards HL-LHC for both machine and detectors (esp. triggers)
  - Expect ~250 fb^{-1} for ATLAS/CMS, 25-30 fb^{-1} for LHCb and 7 nb^{-1} PbPb for ALICE
    - More than doubling the Run-2 dataset
    - Injector/LHC improvements (e.g. lumi-levelling)
    - New detector capabilities bring new possibilities
  - Starting to see first results from Run3 data ☺
- HL-LHC upgrade is coming (Run-4 ++)
  - Operation from 2029-2041, ~3 ab^{-1}
  - Major upgrades of ATLAS+CMS for Run-4
  - LHCb and ALICE scoping their phase2b upgrades for Run-5 (2035 onwards)
  - Challenges everywhere – data analysis, operations and construction of new detectors
    - All at the same time !

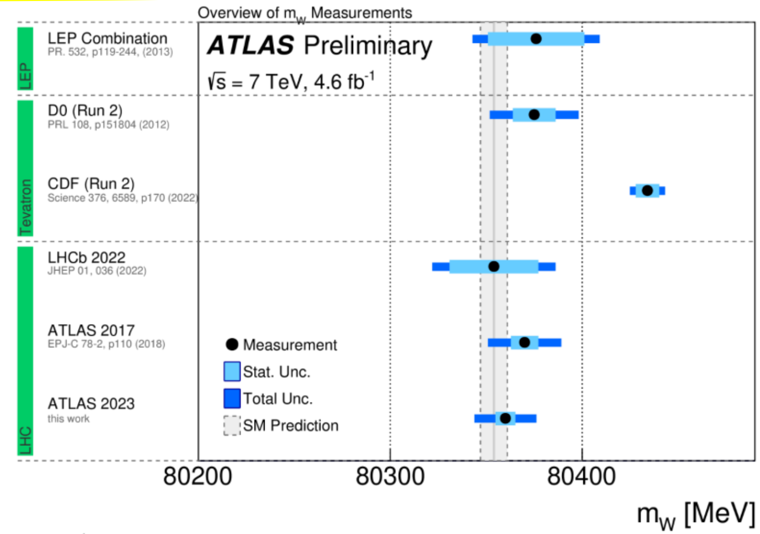

LHC control room 5/7/22

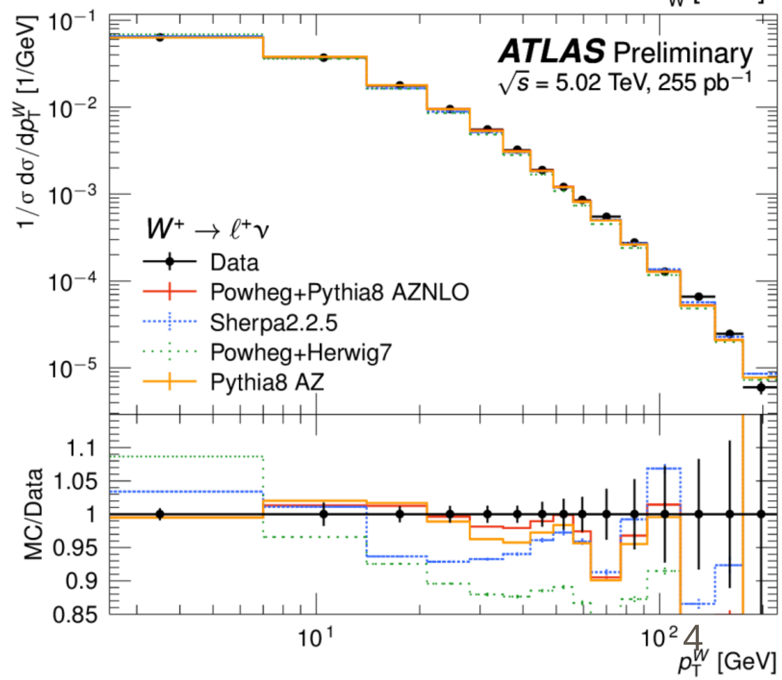
Lumi-levelling 24/5/23



Electroweak precision and the W mass

- Spectacular consistency of EW fit – indirect vs. direct measurements
  - LHC contributions to m_t, m_W, m_H, α_S, …
  - But latest CDF m_W strongly disagrees with other measurements and with SM
    - No convincing explanation so far
- Meanwhile, updated results from ATLAS
  - Reanalysis of 7 TeV data, updated PDFs
    - m_w=80.360±16 MeV
- New direct measurement of $p_T(W)$ with low pileup samples at $\sqrt{s}$=5 and 13 TeV
  - Reconstruction of $p_T(W)$ via hadronic recoil
  - Validation comparing recoil and $p_T(ll)$ in Z→ll
  - Pythia AZ MC (tuned to Z at 7 TeV) gives good description of $p_T(W)$ at 5 TeV at low $p_T(W)$
    - Validates modelling used in m_W measurement
- Eagerly awaiting a CMS result ...



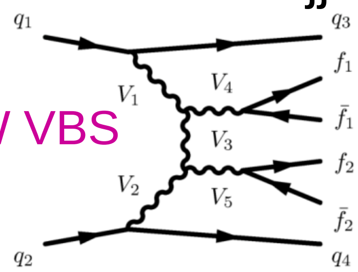


C. Mwewa. Q. Li

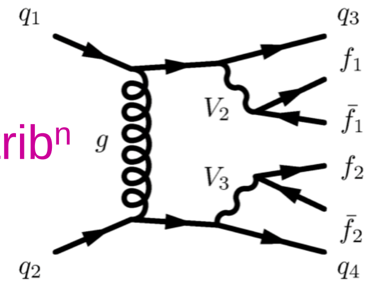
Vector boson scattering at high energy

- VV→VV with VVjj final states probes nature of electroweak symmetry breaking

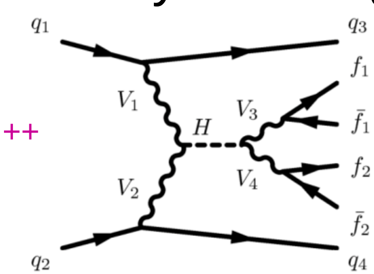
EW VBS



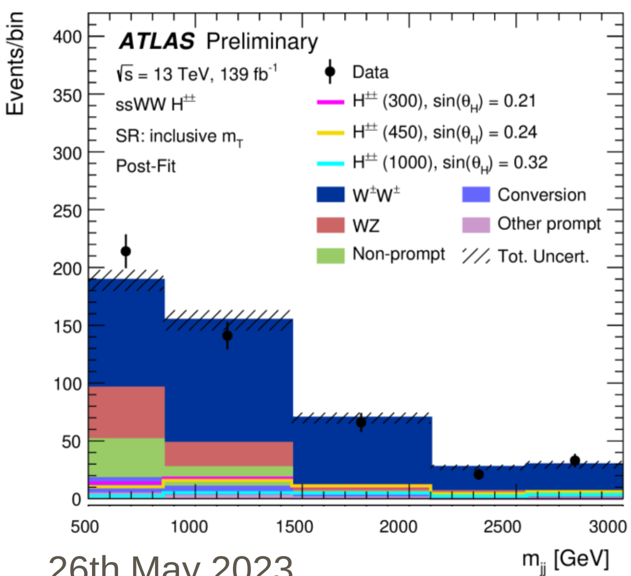
QCD contrib^n

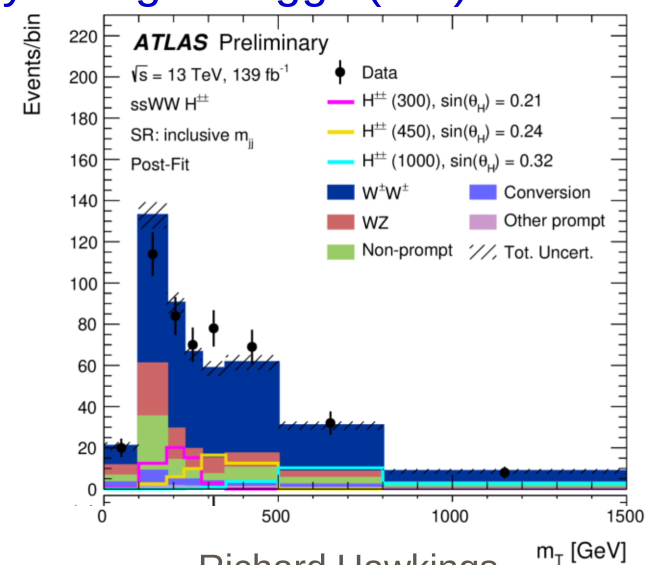


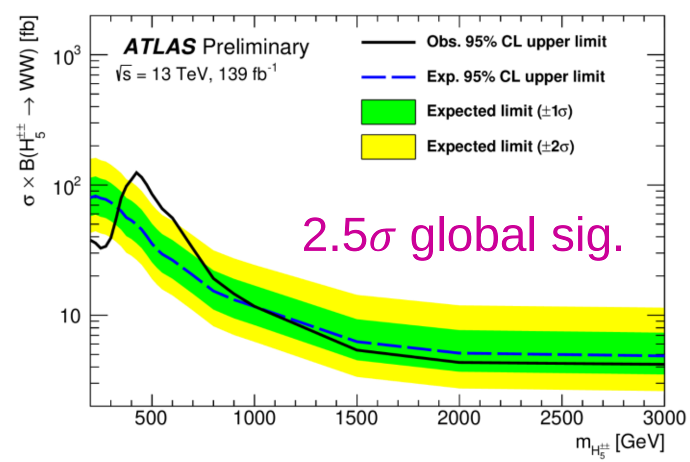
BSM H^{++}



  - Mature field with many inclusive and differential measurements, EFT limits
- New ATLAS measurement with same sign WW scattering
  - Largest relative contribution of EW to QCD; new fiducial measurements
  - Also sensitive to doubly-charged Higgs (H^{++}) – modest excess around 450 GeV



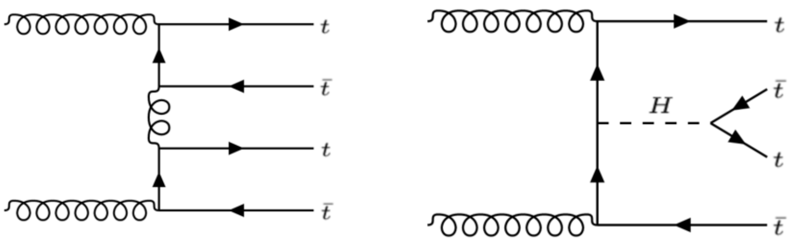




2.5σ global sig.

Rare processes with heavy objects – 4 tops

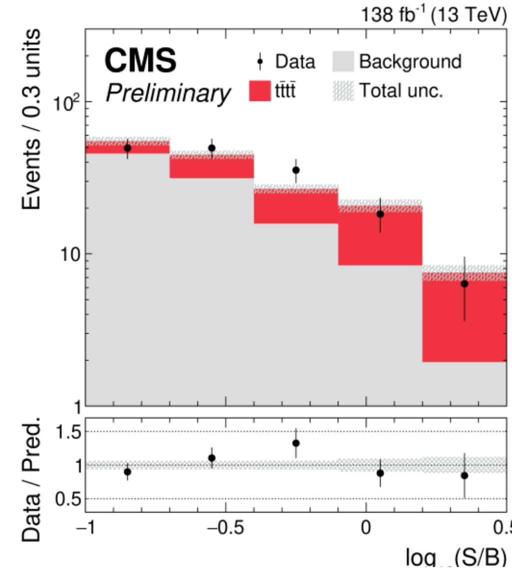
- 4 top quark production observed by ATLAS+CMS
  - Highest-threshold SM process, sensitive to top-Yukawa coupling and potential BSM (2HDM, SUSY…)

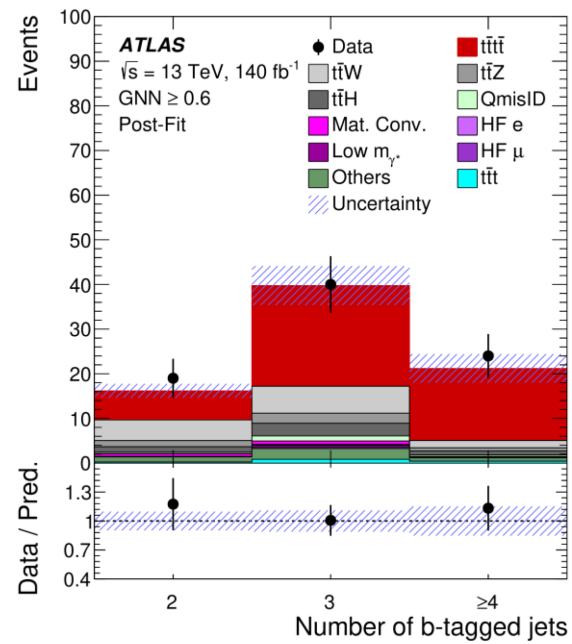


- 2nd generation full Run-2 analysis from both expts.
  - Focused on 2 same-sign leptons or 3+ leptons and large jet and b-jet multiplicity
  - Optimised selections, greater use of machine learning

	Obs	Exp	σ (fb)
ATLAS	6.1	4.3	$22.5^{+6.6}_{-5.5}$
CMS	5.6	4.9	$17.9^{+4.4}_{-4.0}$

- Slight upward fluctuation on SM σ=12.0±2.4 fb ..?

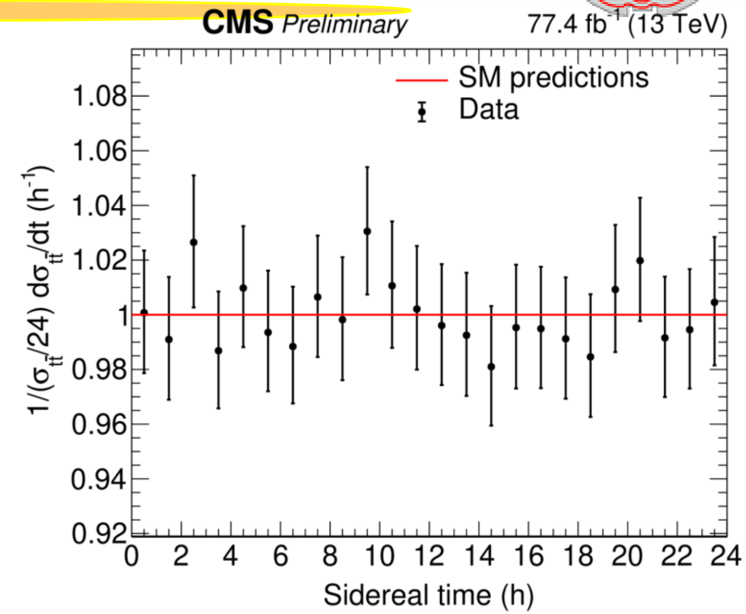


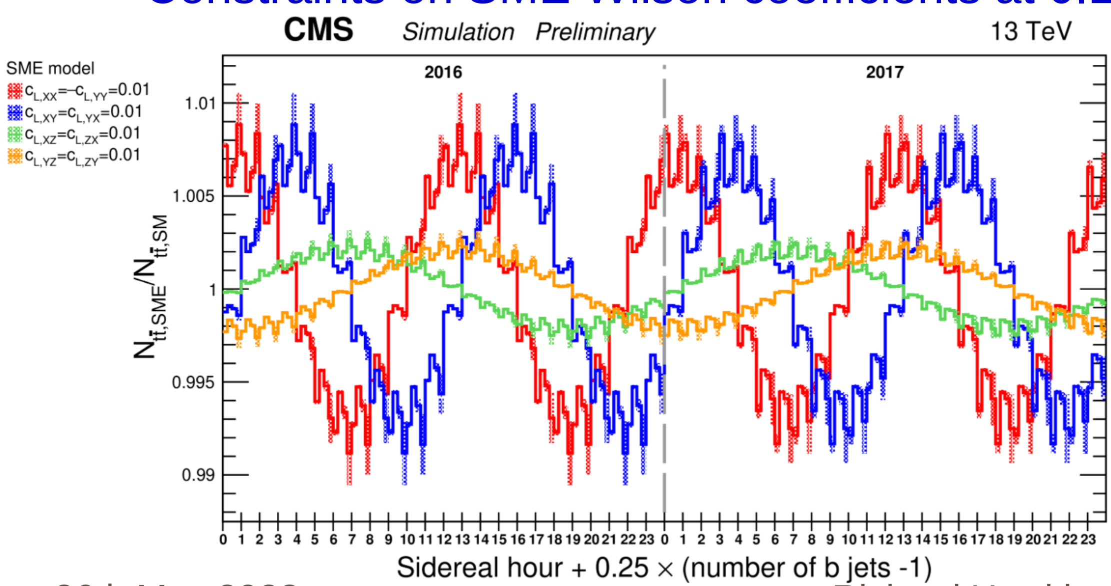


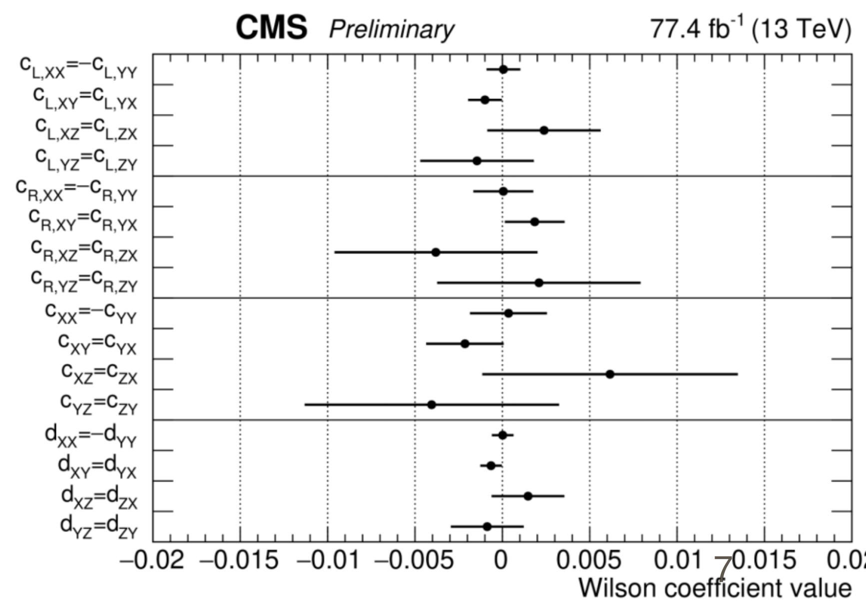
T. Stevenson, N.Chanon

Top quark physics – testing Lorentz invariance

- SMExtension adds Lorentz-violating operators
  - Lorentz violation at high scale in quantum gravity
  - Relatively unconstrained for quarks, ~10% top (D0)
- CMS measurement of top-pair cross-section as function of **sidereal time**, frame referenced to Sun
  - 24 sidereal hours ≈ 23h56m
  - Careful consideration of time-dependent systematics
- No evidence of variations seen at ~2% level
  - Constraints on SME Wilson coefficients at 0.1-1%







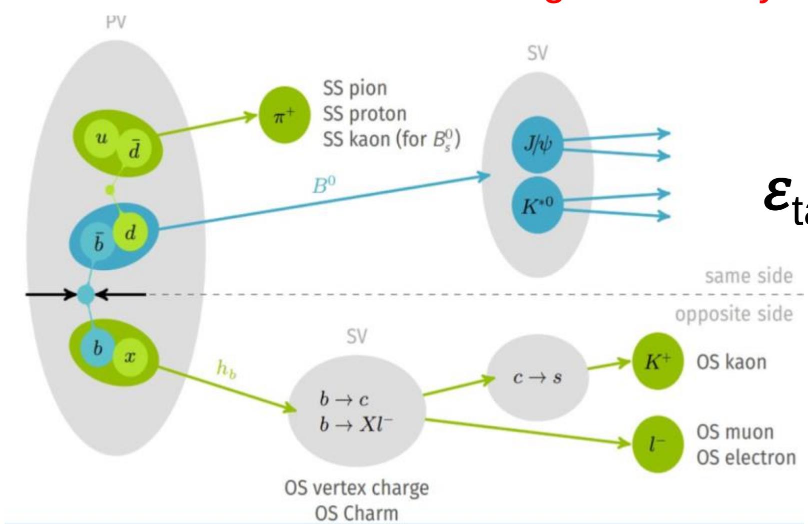
Y. Hou, L Hao

CKM measurements – sin2β

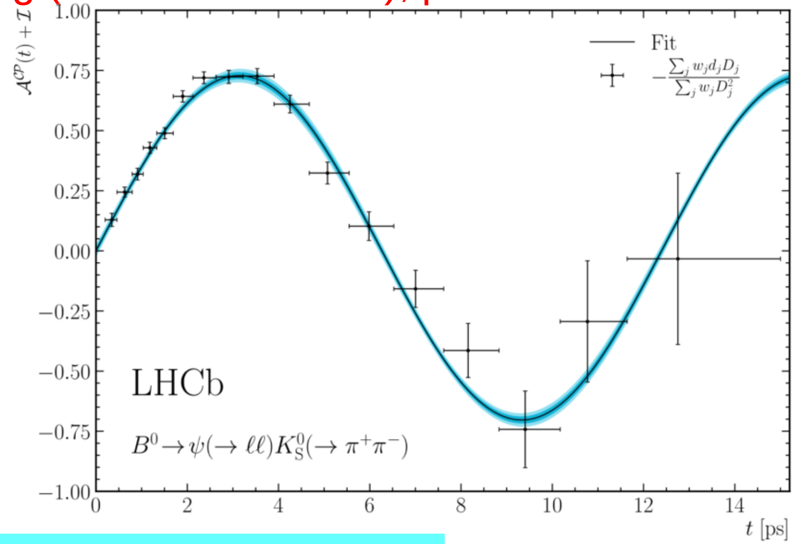
- New precision measurement of CKM angle β using full Run2 LHCb dataset
  - sin2β from time-dependent asymmetry of B^0/B^0bar$\to J/\psi K_s$ ($\to$μμ/ee $\pi^+\pi^-$)

$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

  - Flavour of B^0 at production tagged from both opposite- and same-sign info
    - Crucial to have high efficiency/small mistag (statistical dilution), precise calibration



ε_{tag}~4.7%



	S (≈sin2β)	C
LHCb Run2	0.716±0.013±0.008	0.012±0.012±0.003
Prev. comb (HFLAV)	0.699±0.017	-0.005±0.015

306k in $J/\psi(\to$μμ$)K_s$

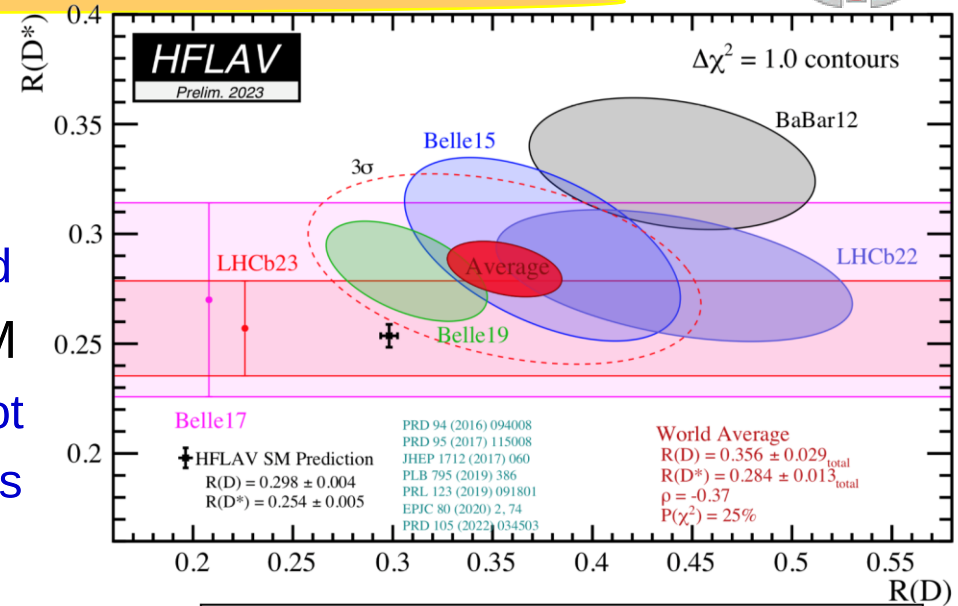
F. Reiss. R. Mohammed

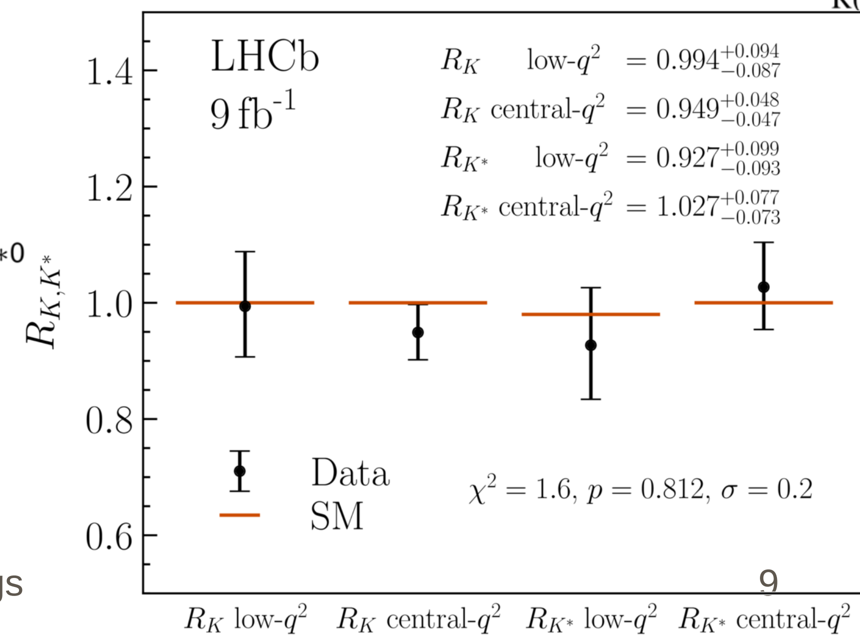
Lepton flavour violation (or not) in B decays

- Tree-level b→clν with l=τ / μ:
  - R(D) and R(D*) with hadronic/leptonic τ
  - Very challenging at hadron colliders due to missing ν, hadronic b/g, precise MC needed
- Recent LHCb analyses compatible with SM
  - World average now ‘only’ 3σ away in 2D plot
  - Awaiting full Run2 LHCb and Belle2 updates
- R(K/K*): Loop-level b→sll with ll=μμ / ee:
  - e and μ acceptance very different in LHCb, unique backgrounds only for electrons
  - Exploit normalisation via J/ψ

$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \times \frac{\mathcal{B}(B \to XJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to XJ/\psi(\to \mu^+\mu^-))}, X = K^+, K^{*0}$$

  - Cancellation of systematics, check r(Jψ)=1
  - Results now in agreement with unity ☺
- Other decay modes exploited, P_5’ persists...

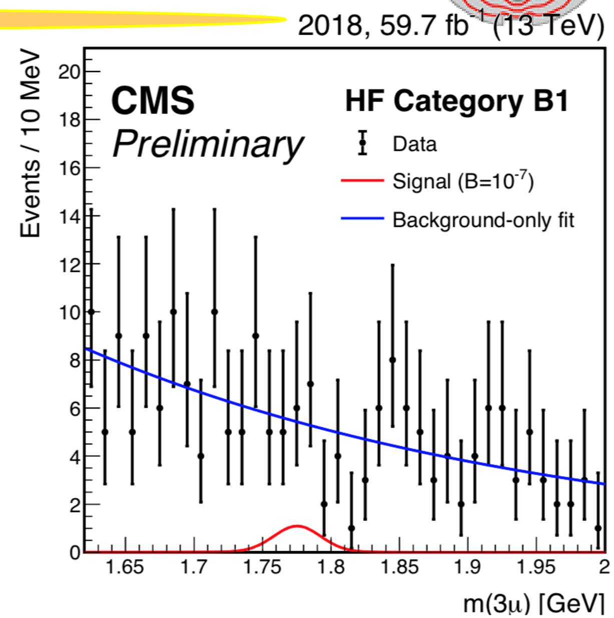


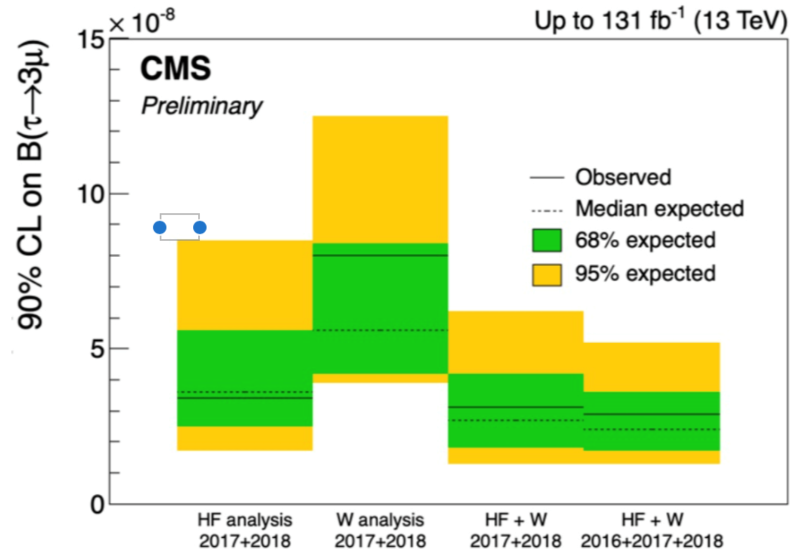


R. Jones, K. Ulmer

Lepton flavour violation in τ decays

- Search for LFV $\tau \rightarrow 3\mu$ decay in CMS 2017-18 data
  - τ from heavy flavour decays – low p_T, forward
    - Fit 3 low-p_T muons to common vertex
    - BDTs for fake muon rejection and event level S/B
    - Signal normalised to $D_s \rightarrow \phi(\rightarrow \mu^+\mu^-)\pi^+$ to minimise dependence on HF cross-sections and muon efi.
  - τ from W decays, higher p_T
    - Muons with pT>7, 1 1 GeV fit to common vertex
    - pT(3μ)>15 GeV, BDT to reduce background
  - In both cases, categorise based on 3μ mass resl^n
  - Sensitivity limited by L1 trigger for low-p_T muons
- Results combined with previous 2016 results
  - Limit Br($\tau \rightarrow 3\mu$)<2.9 10^{-8} at 90% CL
  - Approaching 2.1 10^{-8} limit set by Belle
  - New triggers for Run-3

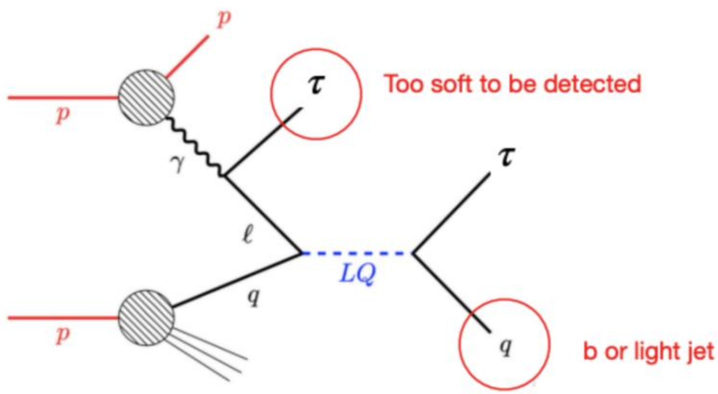




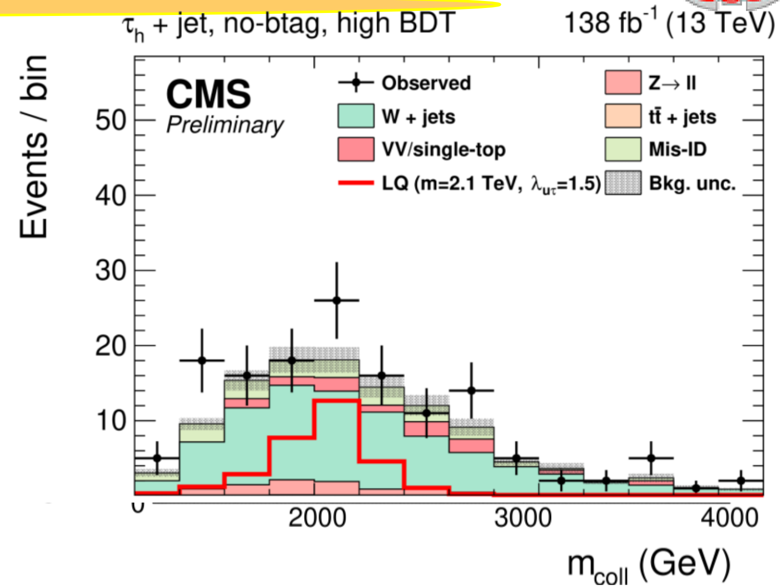
H. Saka, M. Kwok

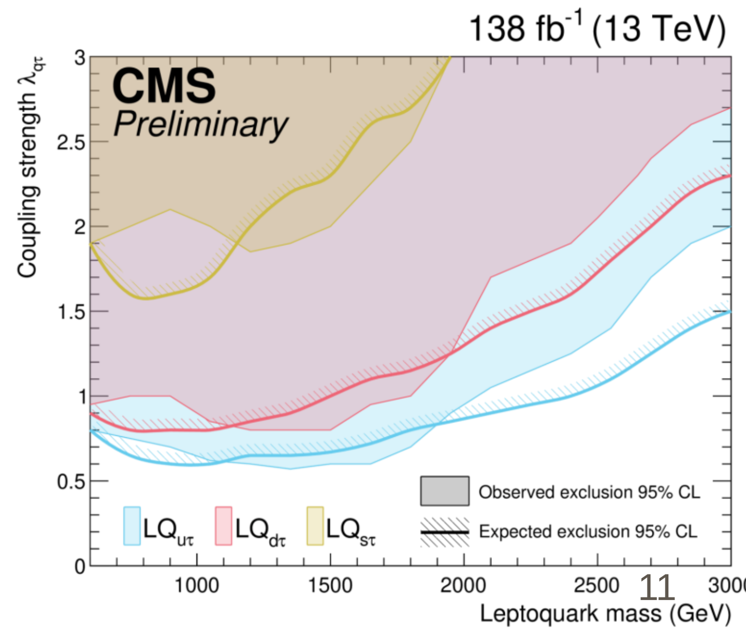
New technique in leptoquark searches

- CMS exploits leptonic content of the proton
  - Search for LQ coupling to τ+quark (uds, b)



- Final state: $\tau(\rightarrow\tau_{had}$, e, μ), (b) jet and p_T^{miss}
  - Unlike traditional single LQ, 2nd lepton is soft
    - Require p_T^{miss} to align with lepton direction
  - Main background from W+jets, exploit BDT
    - Use collinear mass m_{coll} as final discriminant
- Set direct limits on τ-light quark coupling $\Lambda_{q\tau}$
  - Competitive limits also set on Λ_{qb} at high m_{LQ}
  - Technique applicable to other lepton flavours

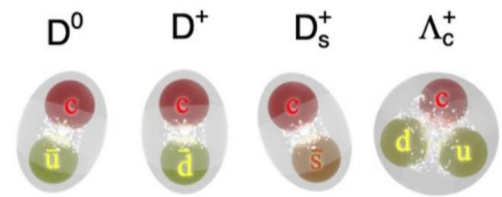


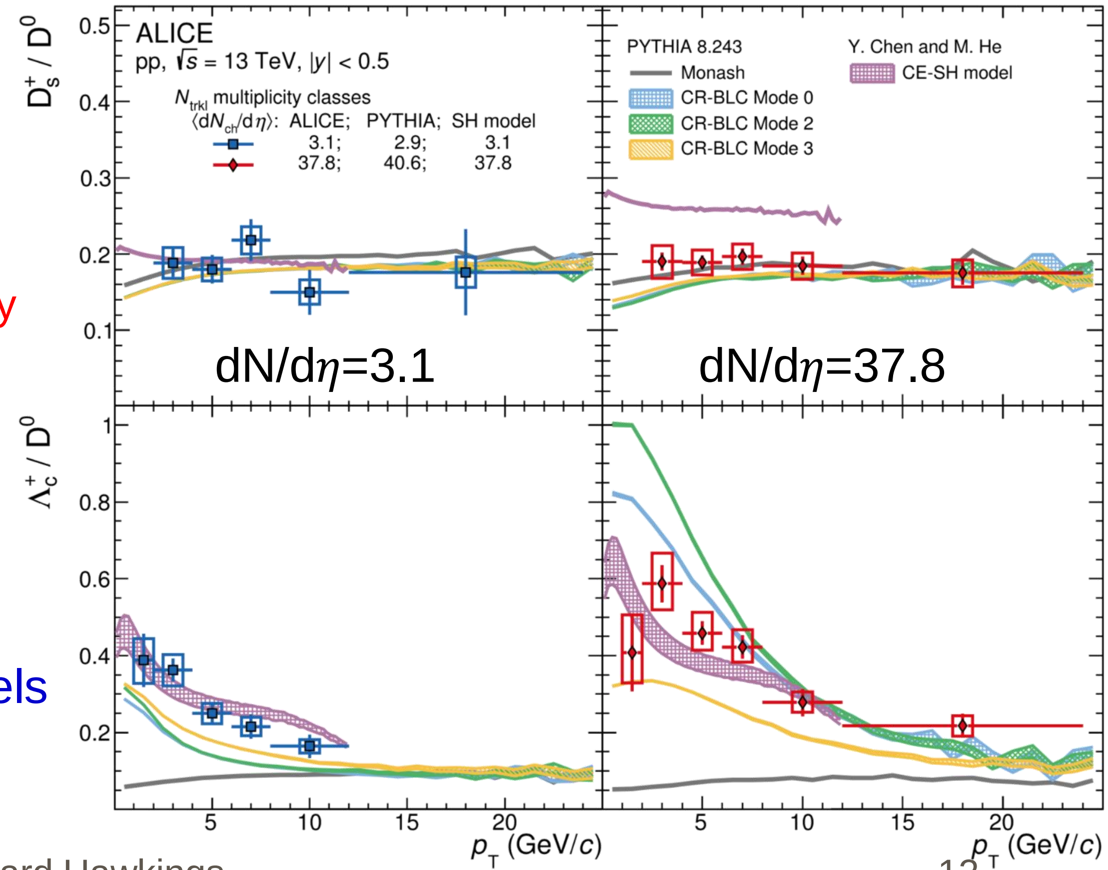


A. Bermudez Martinez

Heavy flavour production in pp collisions

- Study of charm hadron production at low and high multiplicity in 13 TeV pp
  - Do fragmentation functions measured in e^+e^- or ep also apply in pp?
  - Measurement of D_s/D^0 ratio
    - Constant with p_T, multiplicity
    - Compatible with e^+e^- and ep
  - Measurement of Λ_c/D^0 ratio
    - Strong decrease with p_T, and significant increase at high multiplicity
    - Breakdown of fragmentation universality
- Λ_c/D^0 not reproduced by PY Monash
  - But incorporating ‘beyond leading colour’ can reproduce trends in data
  - As can statistical hadronisation models
  - Also seen in K_s/Λ ratios
- Similar results from CMS (F. Catalano)





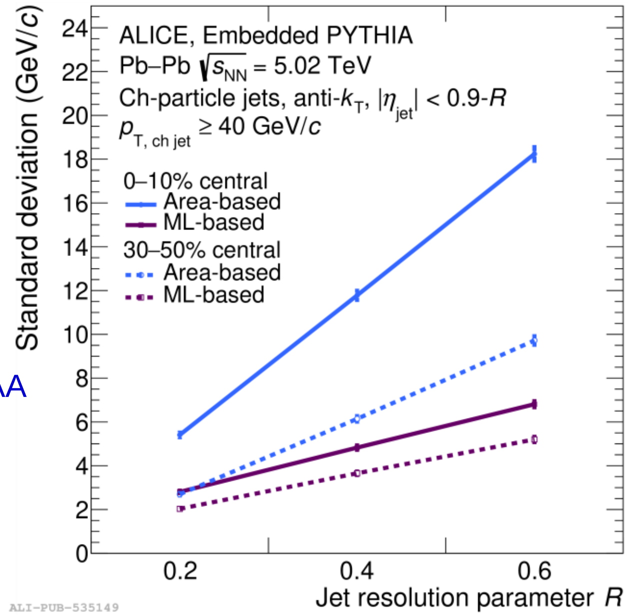
L. Cunqueiro

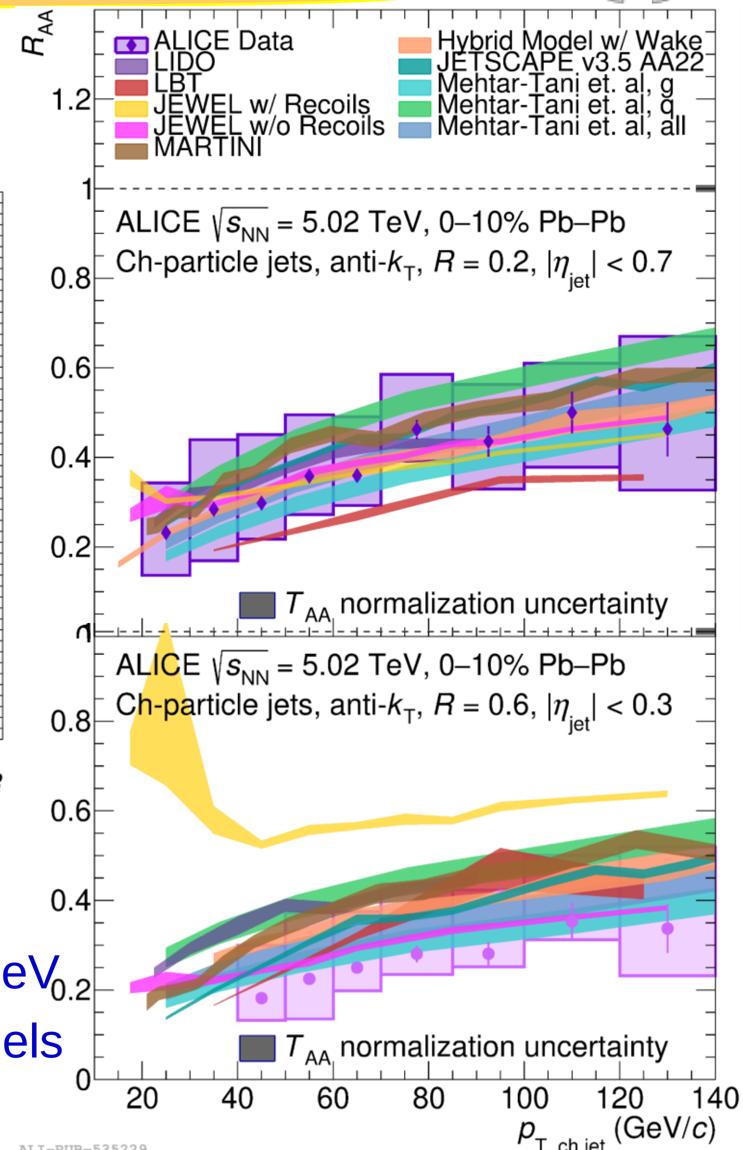
PbPb collisions - new directions in jet quenching

- Suppression and modification of jets by the QGP
  - Reduction of yields, modification of energy, shape

$$R_{AA} = \frac{d^2N^{AA}_{jets}/dp_T\,d\eta}{\langle T_{AA}\rangle\, d^2\sigma^{pp}_{jets}/dp_T\,d\eta}$$

Jet x-sec normalised to pp reference with nuclear factor T_{AA}



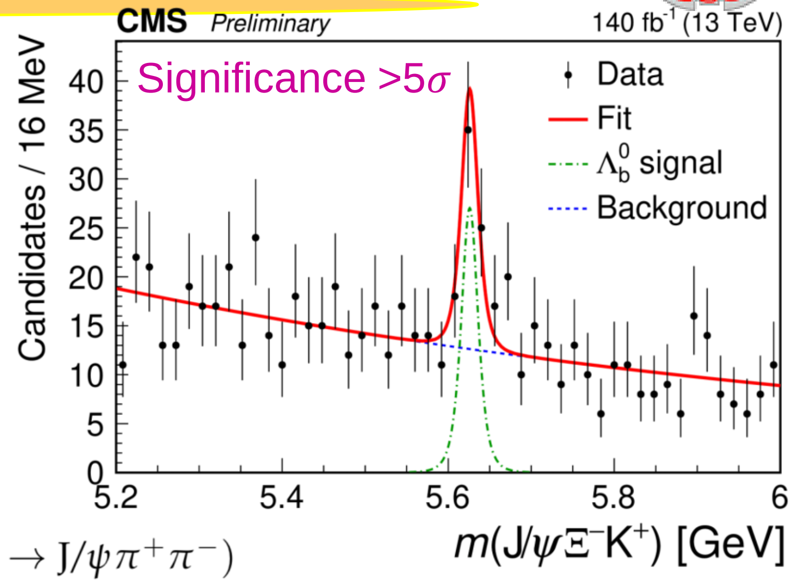


- New ALICE ML-based approach to jet recon^n
  - Reduces background from UE (model dep?)
  - Allows study of R_{AA} for R=0.6 jets down to p_T=40 GeV
  - Large-R jets more suppressed, reproduced by models
    - Also studied via jet axis differences

R. Jones

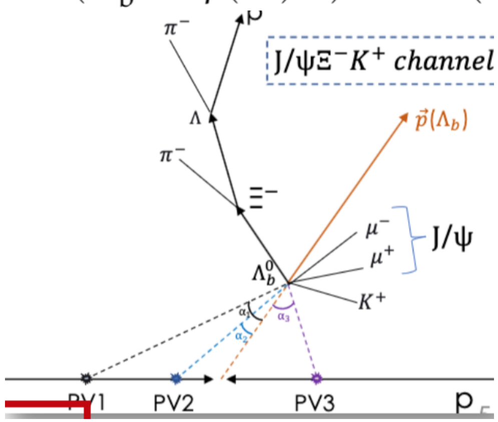
Hadron spectroscopy - more exotic states?

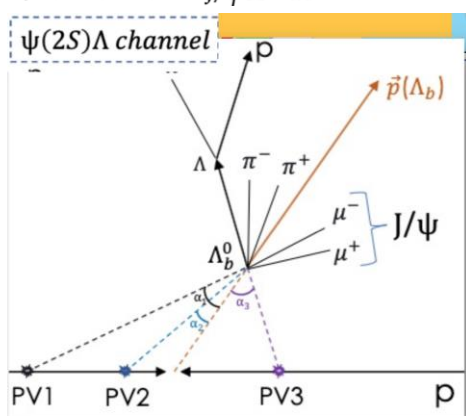
- 72 new hadrons discovered at LHC
  - Multibody B decays are a fruitful hunting ground for exotic states
    - E.g. structures in $\Lambda_b \rightarrow J/\psi$ p K^- seen by LHCb
- New CMS observation of $\Lambda_b \rightarrow J/\psi\, \Xi^- K^+$
  - Very complex topology with multiple secondary vertices
  - Normalisation via $\Lambda_b \rightarrow \psi(2S)\, \Lambda$

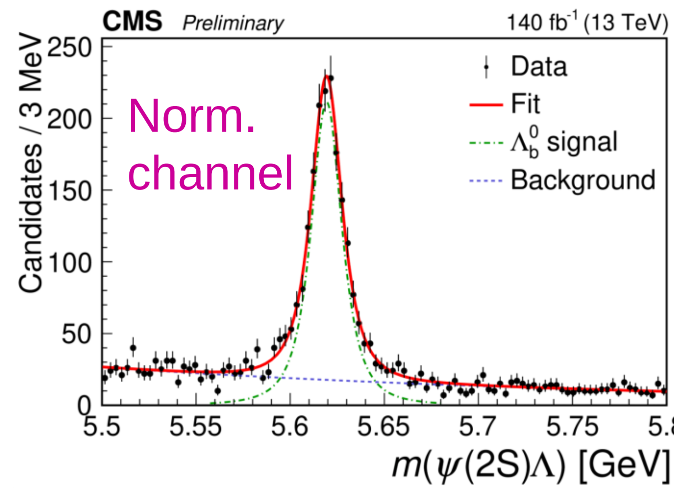


$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi\Xi^-K^+}} \times \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}$$

R=2.5±0.8±0.9%





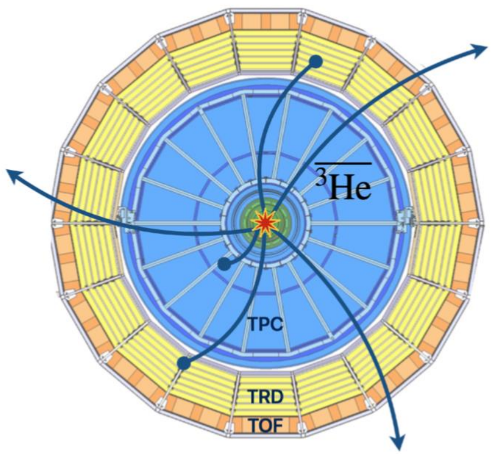


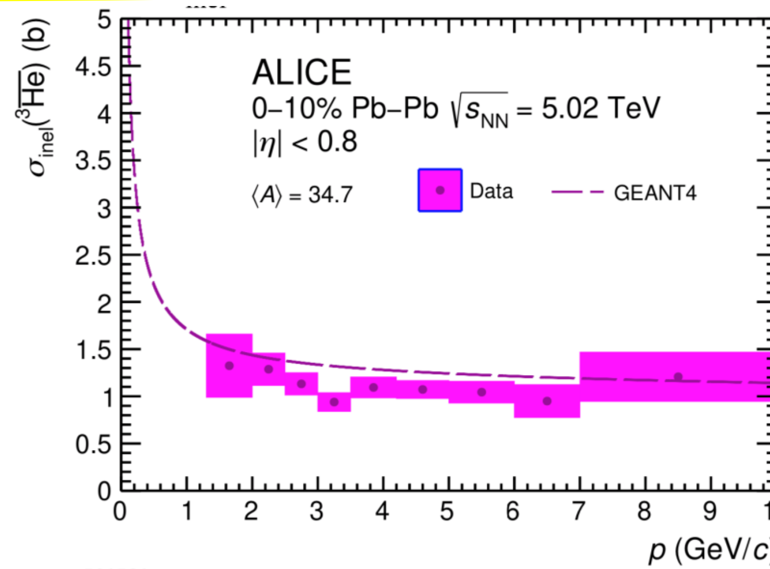
  - With more data, can look for doubly-strange hidden charm pentaquarks

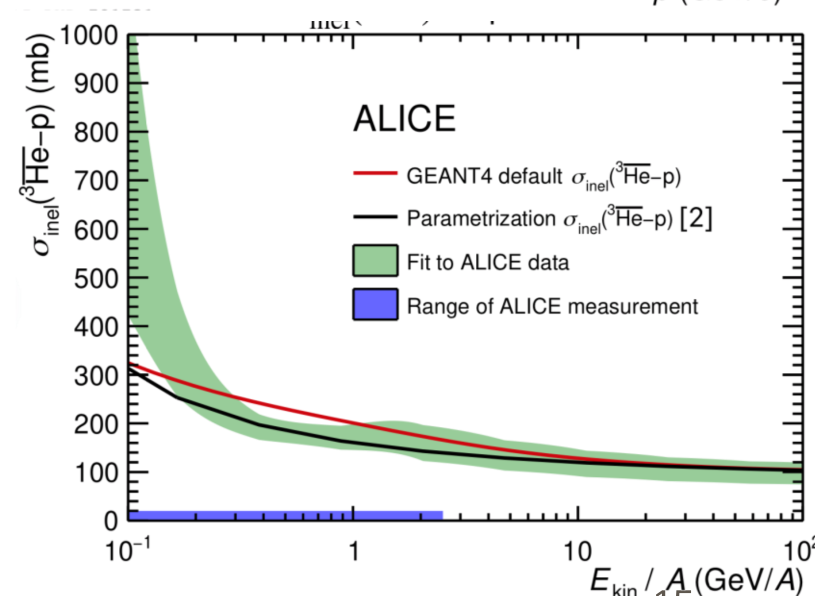
P. Larionov

Anti-nuclei cross-section measurement

- Interactions with detector usually a nuisance
  - ALICE used them to measure σ_{inel}(anti-^{3}He-p)
- Anti-^{3}He produced in central PbPb collisions
  - Study N^{TOF}/N^{TPC} ratio and compare to MC







  - Convert to σ_{inel} for p rather than ALICE material
    - Alternative method based on anti-^{3}He/^{3}He ratio, but requires assumption on σ_{inel}(^{3}He-ALICE)
- Input on transparency of galaxy to anti-^{3}He
  - Potential signature of dark matter annihilation

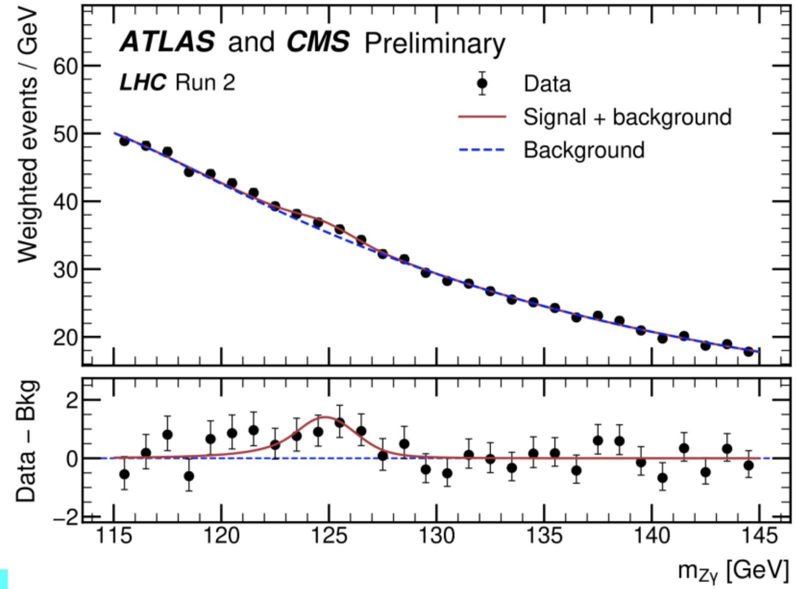
C. Arcangeletti

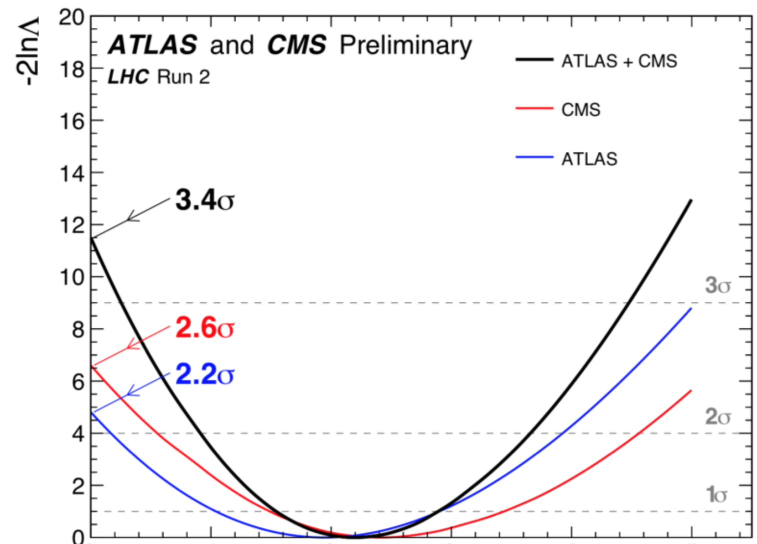
Evidence for a new Higgs decay

- Rare $H \to Z\gamma$ decay studied by ATLAS+CMS
  - BR in SM is ~$1.5\ 10^{-3}$, $\times$ 3% per $Z \to ll$ flavour
    - C.f $H \to \gamma\gamma$ discovery channel BR≈$2\ 10^{-3}$
  - BSM scenarios could lead to different BR
  - Analyses use a $Z \to ee/\mu\mu$ with m_{ll}>50 GeV + isolated photon, b/g from DY+γ, DY+jets
- Existing analyses have now been combined at the likelihood level

	Obs σ	Exp σ	Sig. strength μ
ATLAS	2.2	1.2	$2.0^{+1.0}_{-0.9}$
CMS	2.6	1.1	$2.4^{+1.0}_{-0.9}$
Combined	**3.4**	**1.6**	**2.2 ± 0.7**

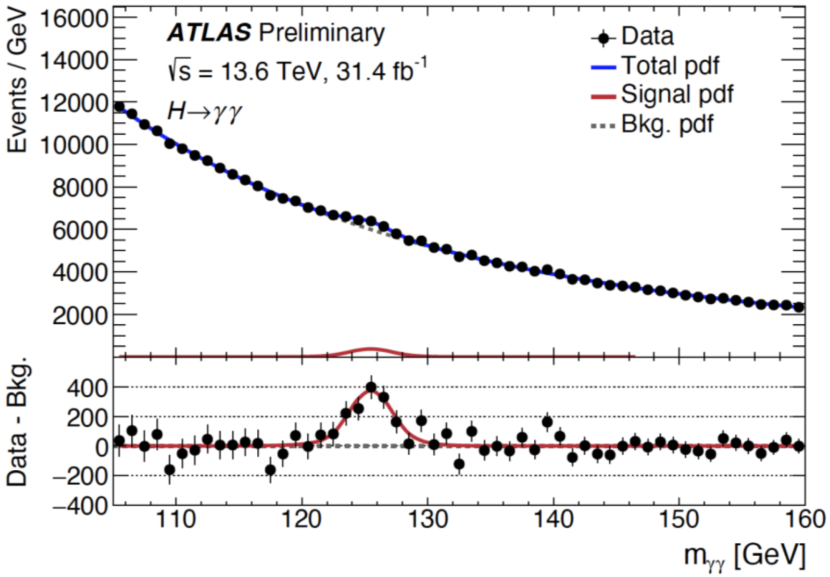
  - Combined BR is $(3.4 \pm 1.1)\ 10^{-3}$, 1.8σ higher but compatible with SM prediction
- Uncertainty is dominated by data statistics
  - Low-hanging fruit for Run-3 observation?

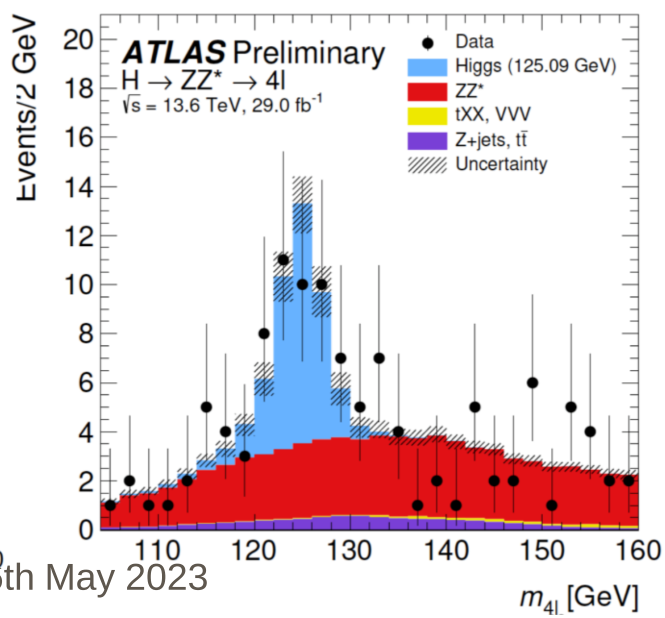




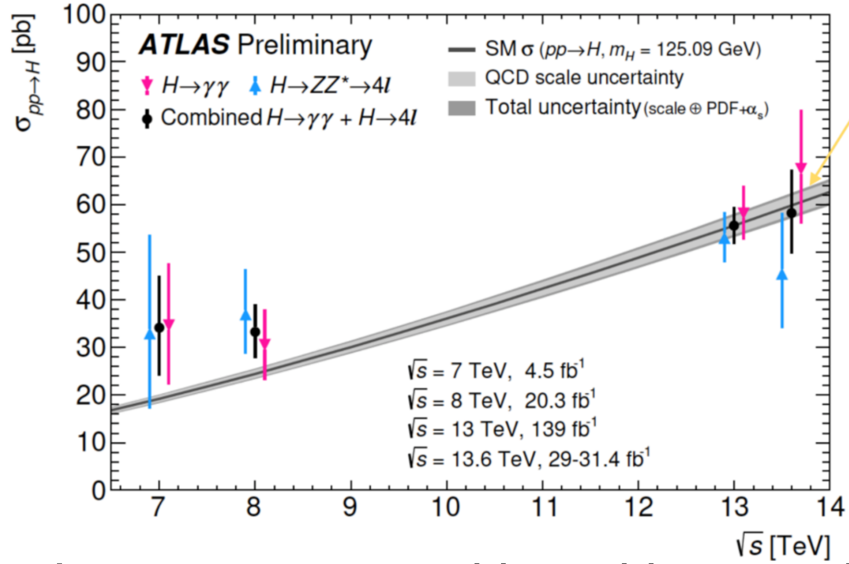
R. Di Nardo, C. Arcangeletti

Higgs at LHC Run-3





- ATLAS+CMS measured ttbar at 13.6 TeV
- Now ATLAS 'rediscovers' SM Higgs at Run-3
  - Requires understanding of e/μ/γ ID & scale
  - Simplified analyses without categorisation
    - Extrapolation of fiducial to total cross-section
  - Preliminary understanding of systematics

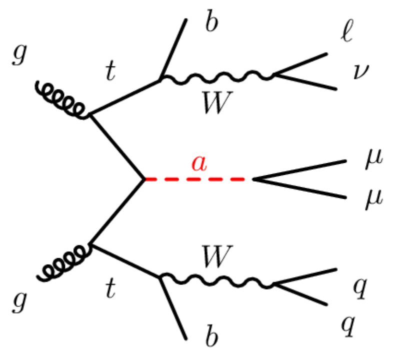


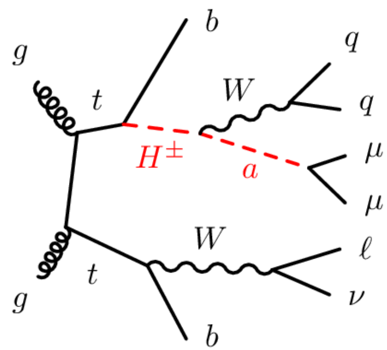
- Results not yet competitive with Run-1/2
  - But ... an essential step, fixing problems, training a new generation of analysers

N. Kyriacou, M. Chertok

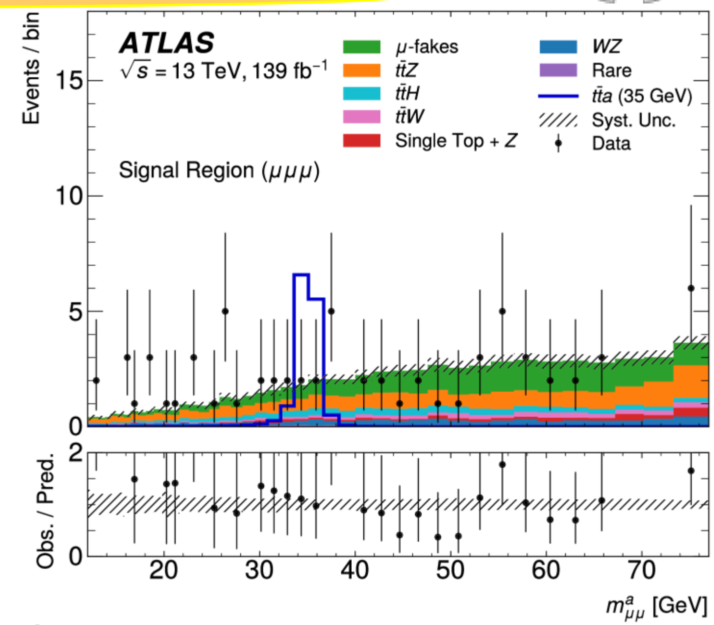
Searching for additional pseudo-scalars

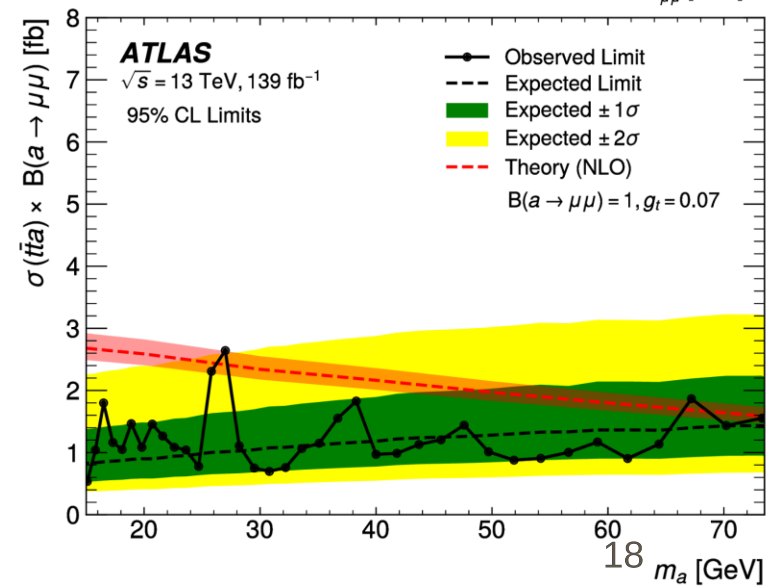
- Light pseudoscalar a→μμ is well-motivated
  - Galactic gamma-ray emissions, Coy dark matter
  - Enables strong first-order EW phase transition
  - Large top coupling, or via t→H⁺b, H⁺→Wa





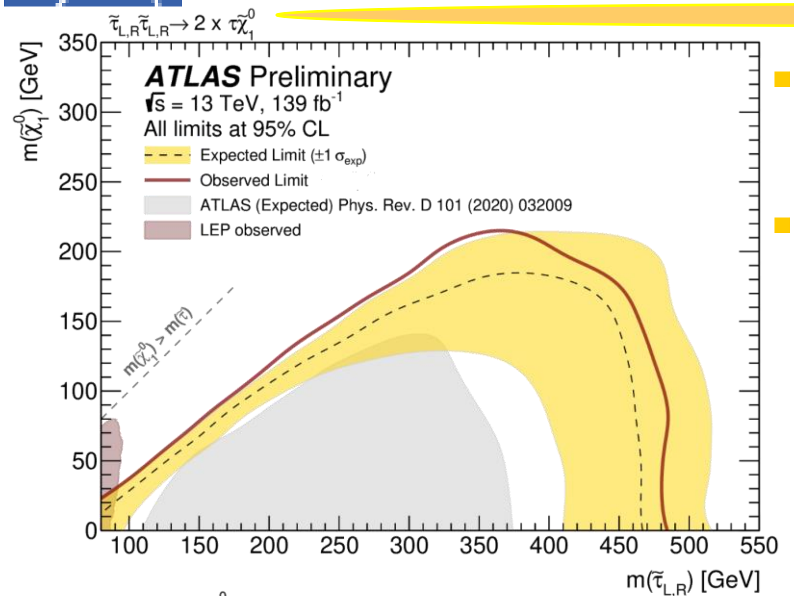
- Select eμμ or μμμ events with $12<m_{\mu\mu}<77$ GeV
  - Require ≥3 jets and ≥1 b-tag from top decay(s)
  - Backgrounds from tt+X or non-prompt leptons
- Limits set on σ(pp→tta) × Br(a→μμ)
  - 0.5-3 fb, local 2.4σ excess at 27 GeV, eμμ/μμμ
  - Also set limits on H⁺→Wa scenario
    - For $120<m_{H+}<160$ GeV
  - Statistically limited search ⟹ Run3 data

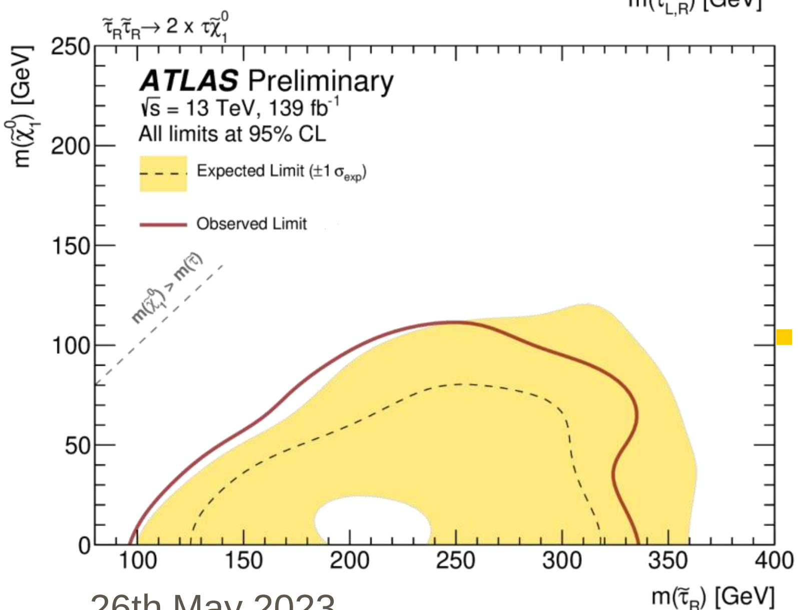




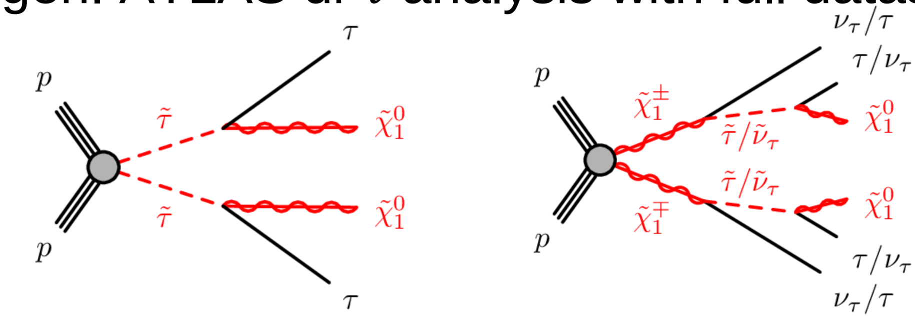
X. Lou, M. Kwok

Electroweak SUSY





- Final states with τ are challenging but interesting
  - Co-annihilation of neutralinos, dark matter, …
- 2nd gen. ATLAS di-τ analysis with full dataset

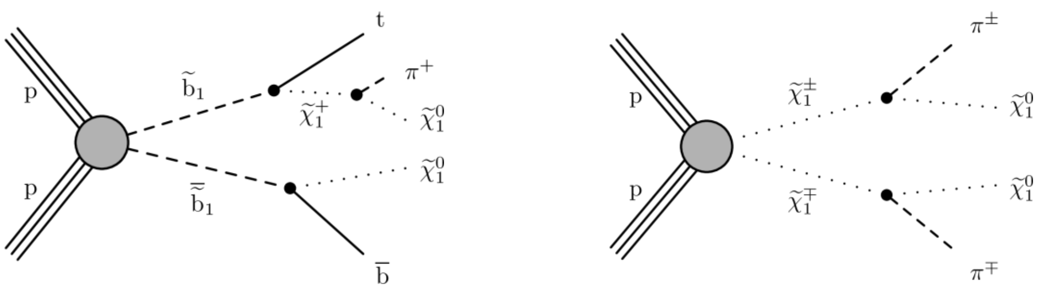


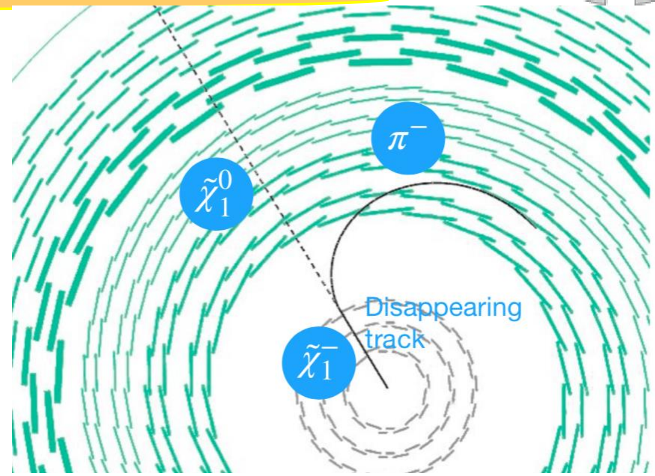
  - Improved τ-ID based on recurrent neural network
  - BDT based on kinematic variables (e.g. stransverse mass) to select signal candidates
    - Backgrounds from mutijets constrained from data, top and W/Z+jets from dedicated control regions
- Limits improve significantly on 1st gen analysis
  - Mass-degenerate s$\tau_{L,R}$ up to 480 GeV
  - Right-handed sτ_R up to 330 GeV (1st at LHC)
  - Also limits for χ^0 / χ^1 decaying to sτ or via Wh

S. Sekmen, L. Shchutska

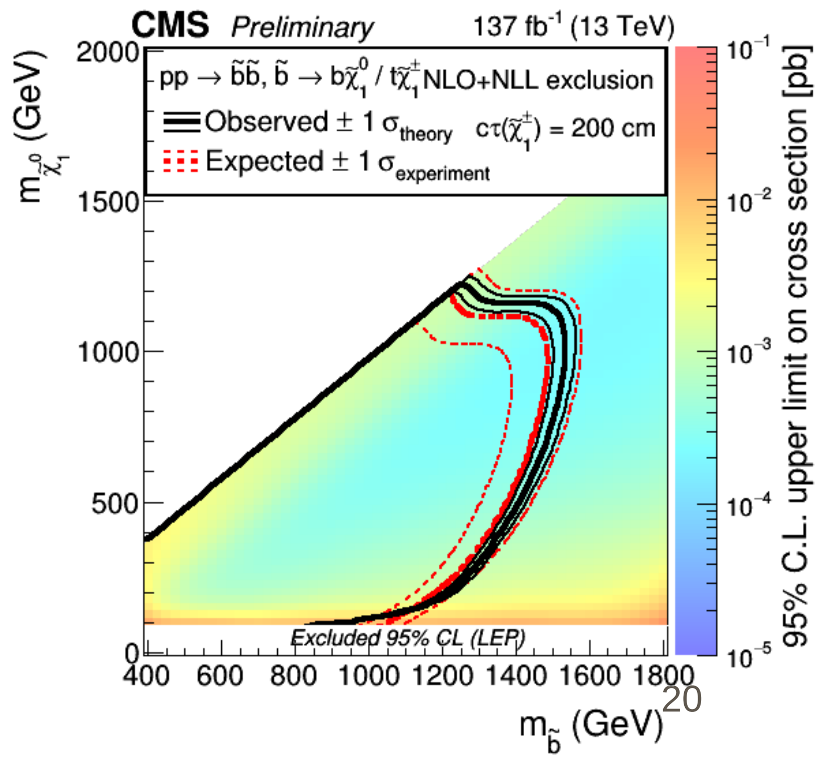
SUSY with disappearing tracks

- Compressed scenario, $\Delta m(\chi^+_1,\chi^0_1)$~100 MeV
  - Long-lived χ^+_1 decaying in tracker to $\pi^+ \chi^0_1$
  - Disappearing track(s) + p_T^{miss}
- Target a variety of scenarios: gluino, stop/sbottom





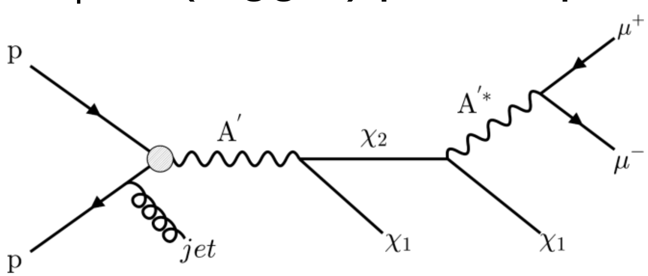
- Analysis uses pixel-only, pixel+strips tracks
  - With BDTs and use of pixel dE/dx
  - 49 search regions using p_T^{miss}, N_{jet}, leptons
  - O(10) candidates selected/region, data-driven estimation of fake-track background
- Limits set in a variety of models
  - Up to 1.1-1.5 TeV for χ^+_1,χ^0_1; $c\tau$=200cm
  - 500 GeV improvement c.f. prompt searches



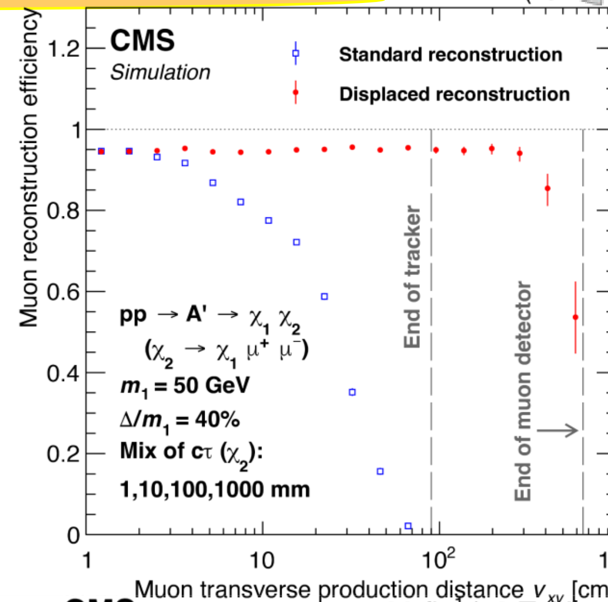
A. Li

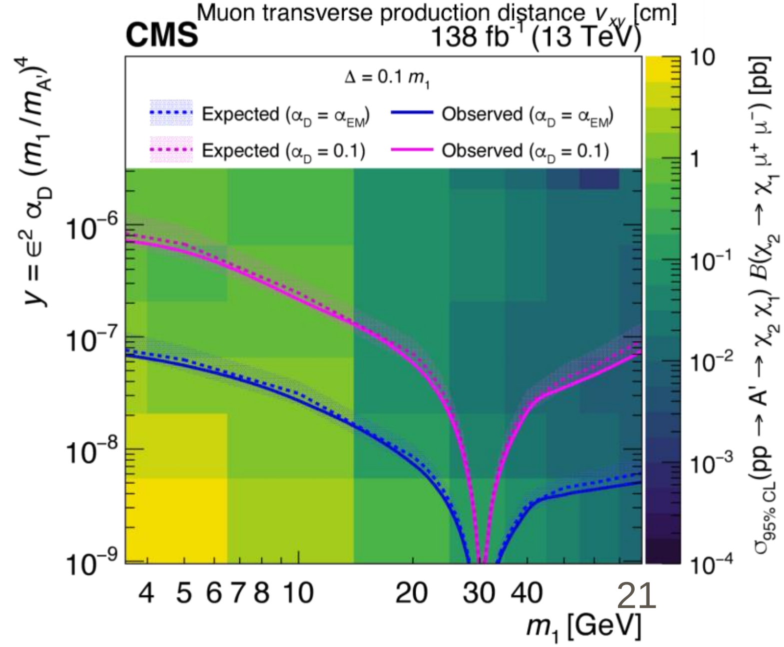
Dark matter and long-lived particles

- CMS search for ‘inelastic’ dark matter
  - Two DM states χ_1 and χ_2 with small Δm splitting
  - No elastic scattering with nuclear matter
  - Dark photon A’ coupling to SM hypercharge
    - Can account for thermal relic abundance whilst evading other constraints
- ISR jet, E_T^{miss} (trigger) plus displaced $\mu^+\mu^-$



  - Sensitive to χ_2 decay lengths from 1cm to few m
    - Dedicated muon reco. using muon system hits only, matched to standard muons where possible
- Limits set in (m_1, $\sigma\times$BR) plane
  - Shown here for $\Delta m=0.1m_1$, $m_{A'}=3m_1$

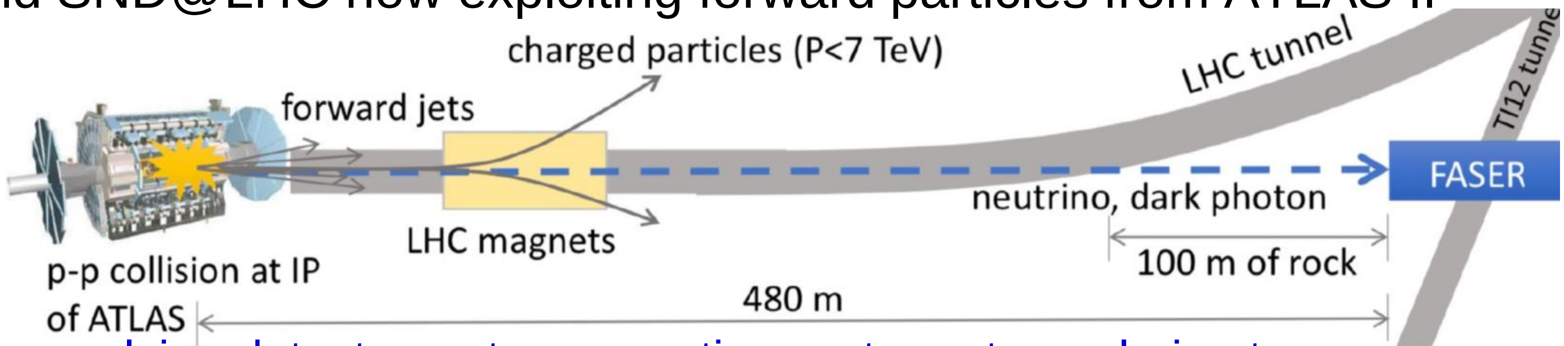




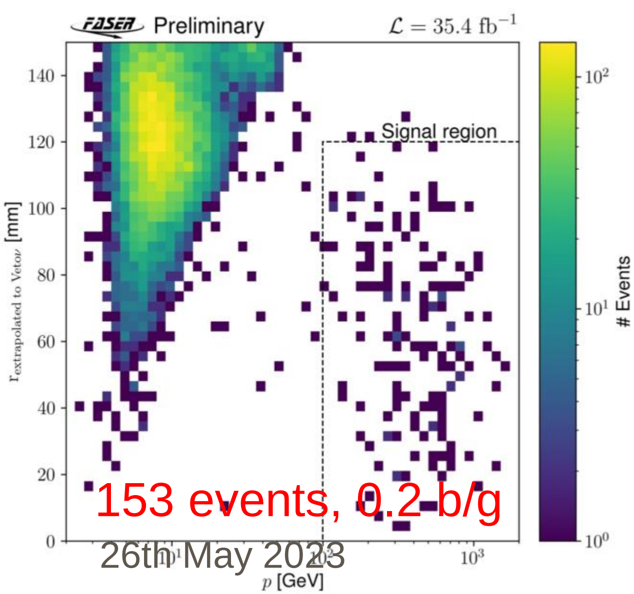
T. Bockh, S. Ilieva

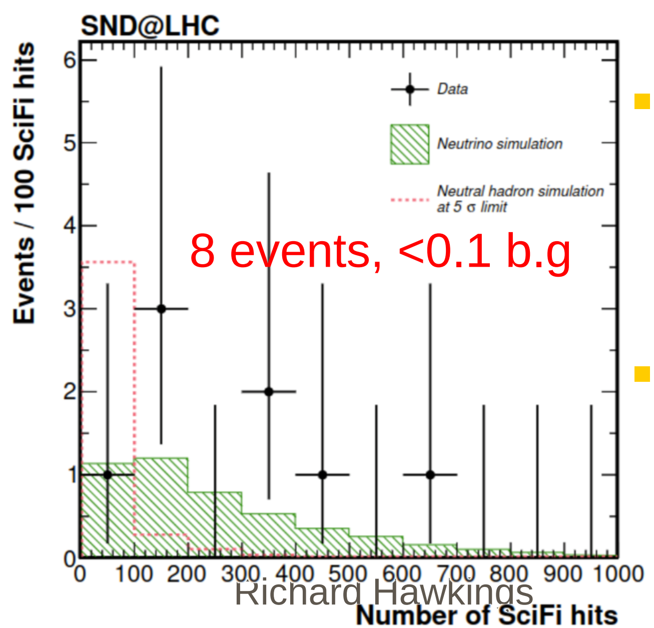
First collider neutrinos

- FASER and SND@LHC now exploiting forward particles from ATLAS IP



  - FASER: emulsion detector, veto, magnetic spectrometer, calorimeter
  - SND@LHC: emulsion detector, veto, interleaved calorimeter and muon tracking
- Both experiments see neutrinos undergoing CC→μ interactions in target



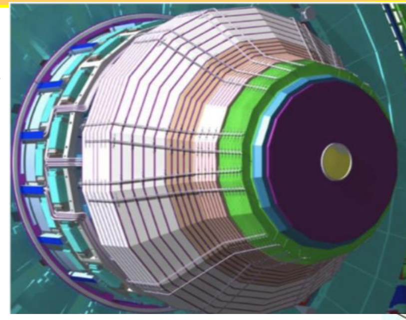


- Emulsion analysis to come
  - FASER has also set a dark photon limit ~ 10-100 MeV
  - See N. Tarannum
- Start of a new physics program at LHC

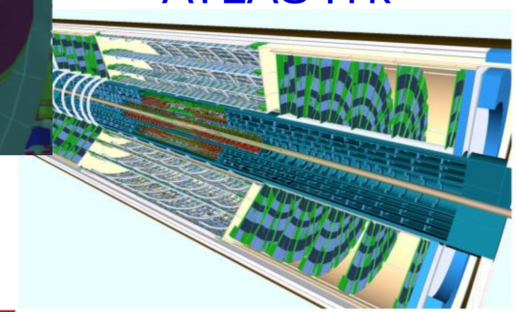
M Kocian, J Alimena, F Ferrari, R Munzer

Detector upgrades for HL-LHC phase

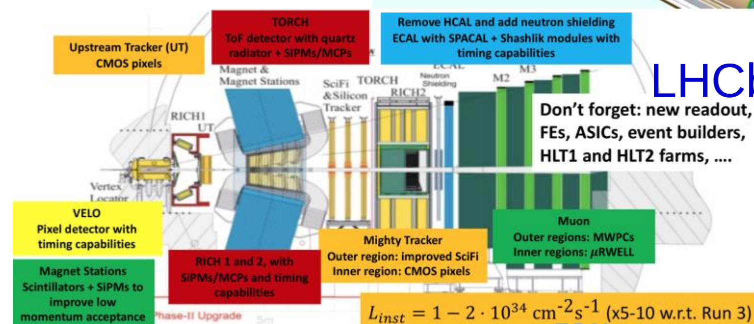
- Upgrades for Run-3 now being commissioned
  - Trigger/rate capability, pre-Run4 upgrades
  - Challenging to commission/exploit for physics
- ATLAS+CMS phase 2 upgrades for Run4
  - New tracking detectors, timing layers, muons
    - CMS HGCal endcap 'digital' calorimeter
  - New state-of the art TDAQ/trigger systems
- LHCb and ALICE intermediate upgrades
  - E.g. RICH electronics; ITS3/FoCal
- Phase2b upgrades for Run5-6
  - LHCb sub-ps precision timing everywhere, SciFi tracker, SiPM-based RICH
  - ALICE3 with superconducting solenoid and all-silicon tracker
- Effort/cost like building new experiments ...
  - Ambitious programme for next decade(s)



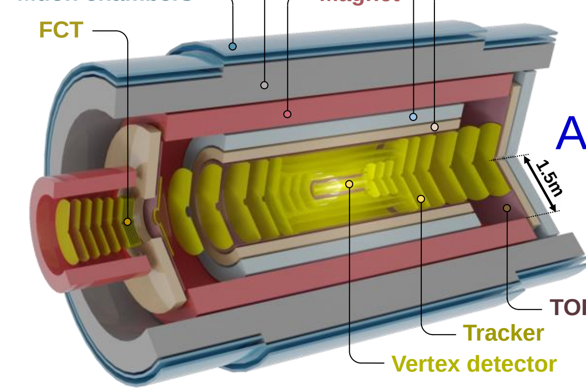
CMS HGCal



ATLAS ITk



LHCb 2b



ALICE3

G. Pietrzyk, O. Sunneborn

LHCPeople

- LHC physics done by a community
  - Should be inclusive and representative of society as a whole (gender, regions)
  - All collaborations now monitor this
  - Fraction of women ~20%, slowly increasing
    - But skewed towards young people
  - Lots of efforts to support early career scientists – majority of the collaborations!
    - Skills, mentoring, well-being, job-hunting
    - How can senior people support this better?

- Outreach activities
  - Sustaining/increasing interest in LHC physics, and science in general
  - Attracting talented young people to the field
  - Onsite and virtual visits to LHC experiments
  - First-data events, masterclasses, open data for educational use

Conclusions

- Impressive and rich array of results shown at this 11th LHCP conference
  - LHC physics is thriving …
  - Could only scratch the surface of all the activities that have been shown
- The Standard Model still reigns supreme
  - The Higgs is there, and behaves like the SM Higgs
  - Rare processes showing up as they should
  - No compelling evidence for new physics
    - Hints of lepton flavour violation are becoming less significant
    - Impressive ingenuity in finding new ways to exploit the LHC data
- An exciting and intense few years ahead
  - Gathering and analysing the Run-3 data sample – ‘the physics of this decade’
  - Building the HL-LHC upgrades, exploiting the Run-3 ‘pre-upgrades’
  - Renewing the collaborations – retaining ‘old’ collaborators and attracting new ones
- Don’t relax, and stay engaged ...