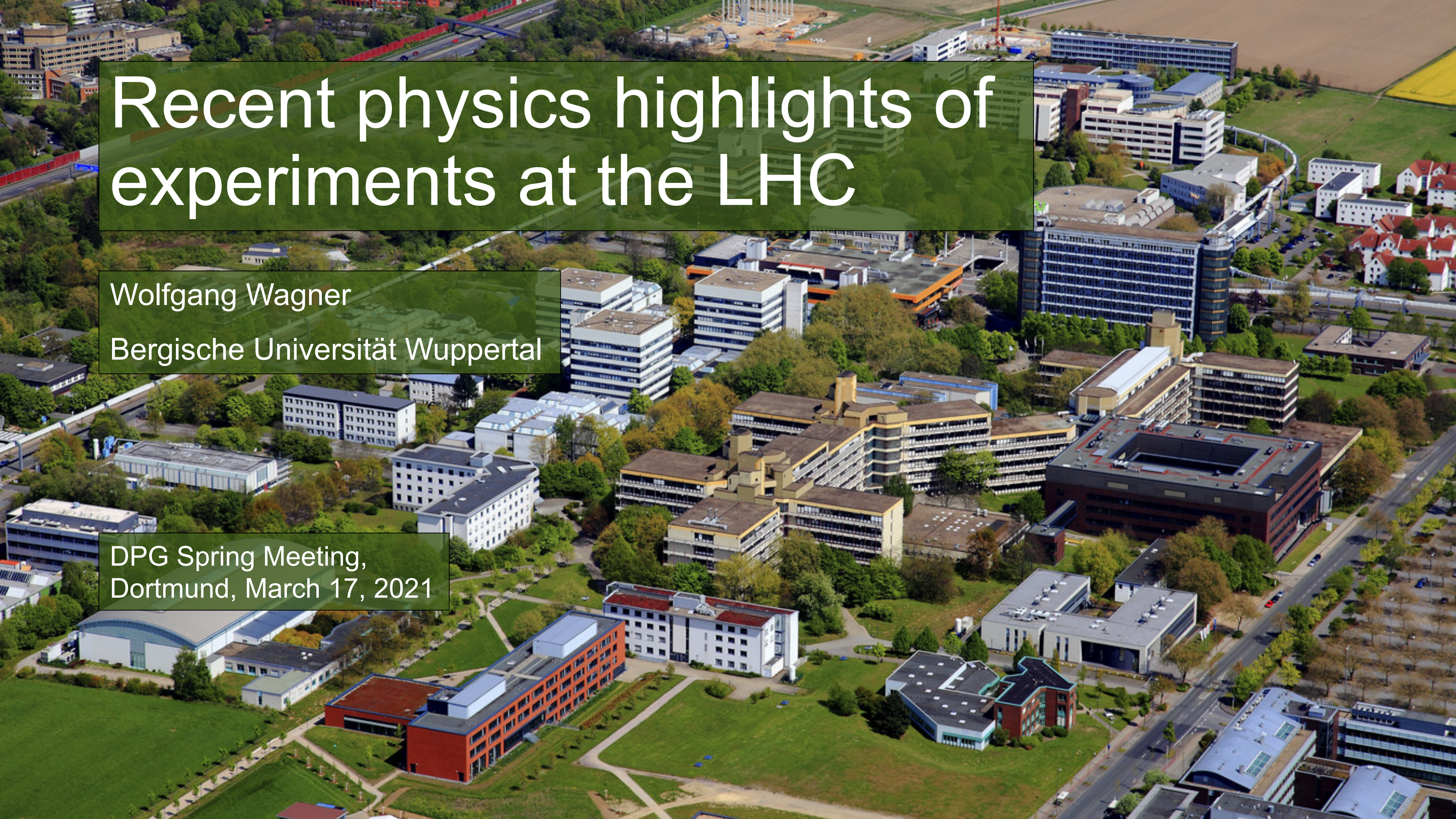
Recent physics highlights of experiments at the LHC

Wolfgang Wagner

Bergische Universität Wuppertal

DPG Spring Meeting,
Dortmund, March 17, 2021



Outline

1) Introduction: The LHC and its particle detectors

2) Measurements on the Higgs boson, the top-quark, electroweak and QCD processes

3) Flavour physics

4) Searches for physics beyond the Standard Model

5) Heavy-ion collisions

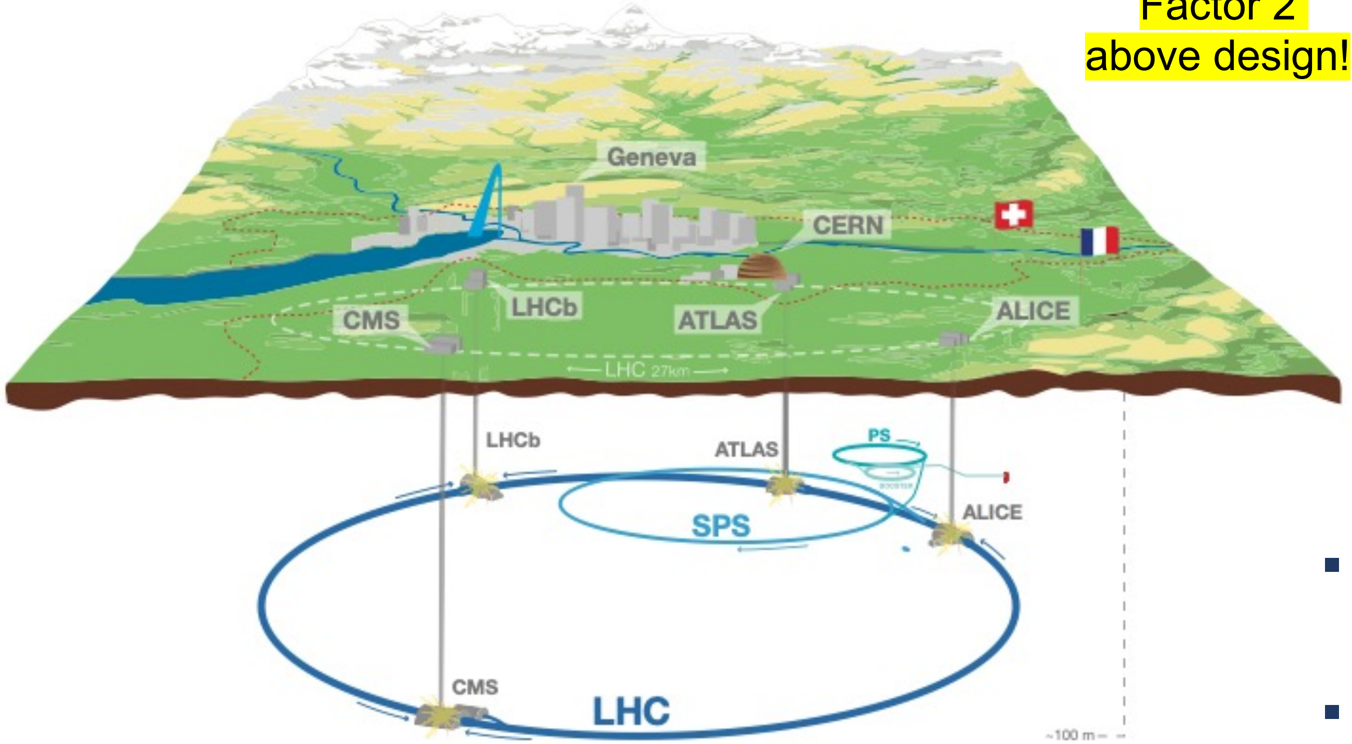
Disclaimer:

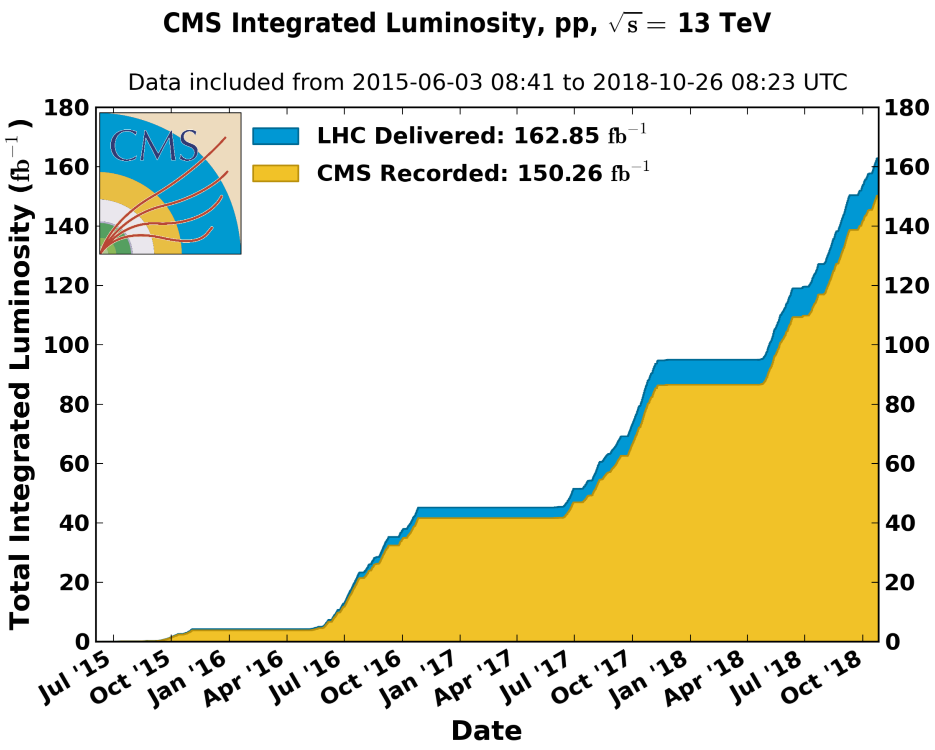
Cannot possibly discuss all beautiful and impressing results deserving coverage.

The Large Hadron Collider (LHC)

- The most powerful accelerator ever built.
- Outstanding performance in Run 2 at $\sqrt{s} = 13$ TeV:
  Record instantaneous luminosity: $\mathcal{L} = 2.1\times10^{34}$ cm^{-2}s^{-1}

Factor 2 above design!





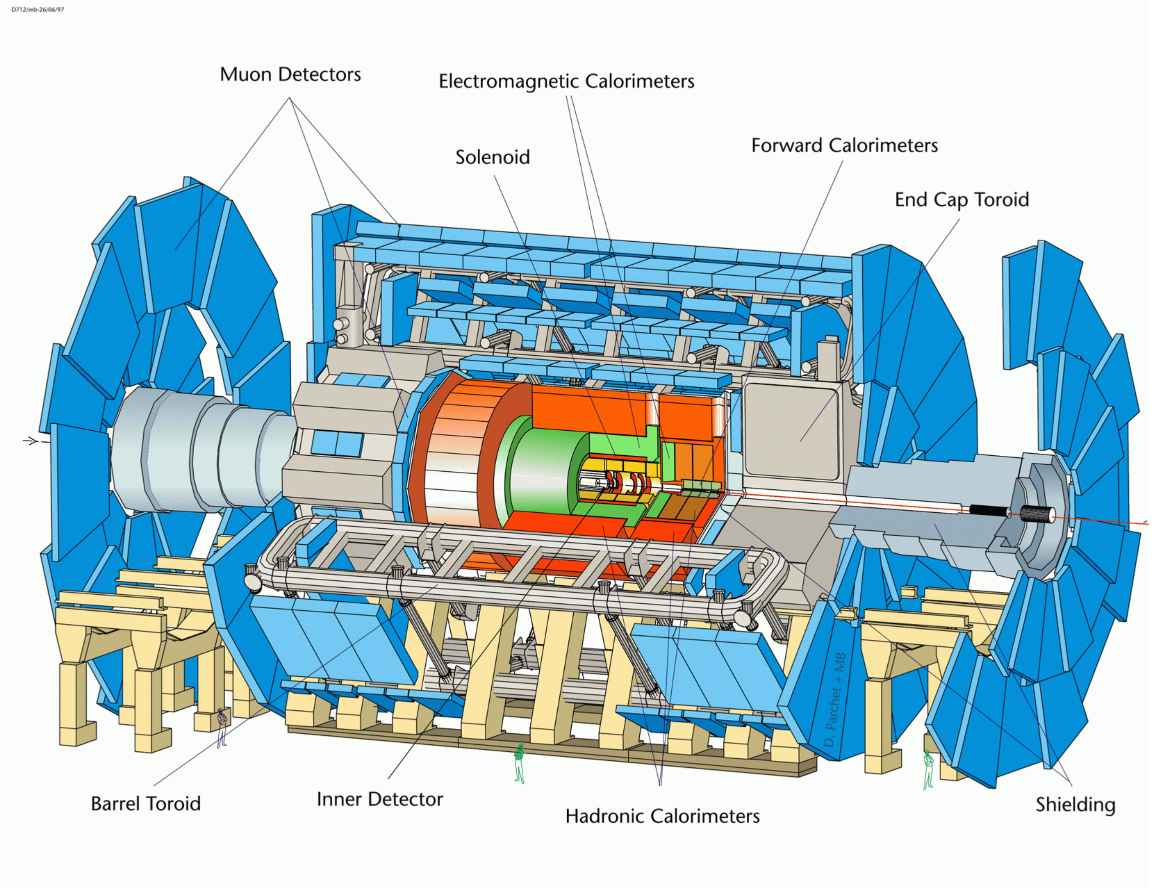
- Integrated luminosity (pp) delivered to ATLAS and CMS: $\cong 160$ fb^{-1}
- Luminosity levelling at ALICE and LHCb
- Other data sets Pb-Pb, proton-Pb, Xe-Xe

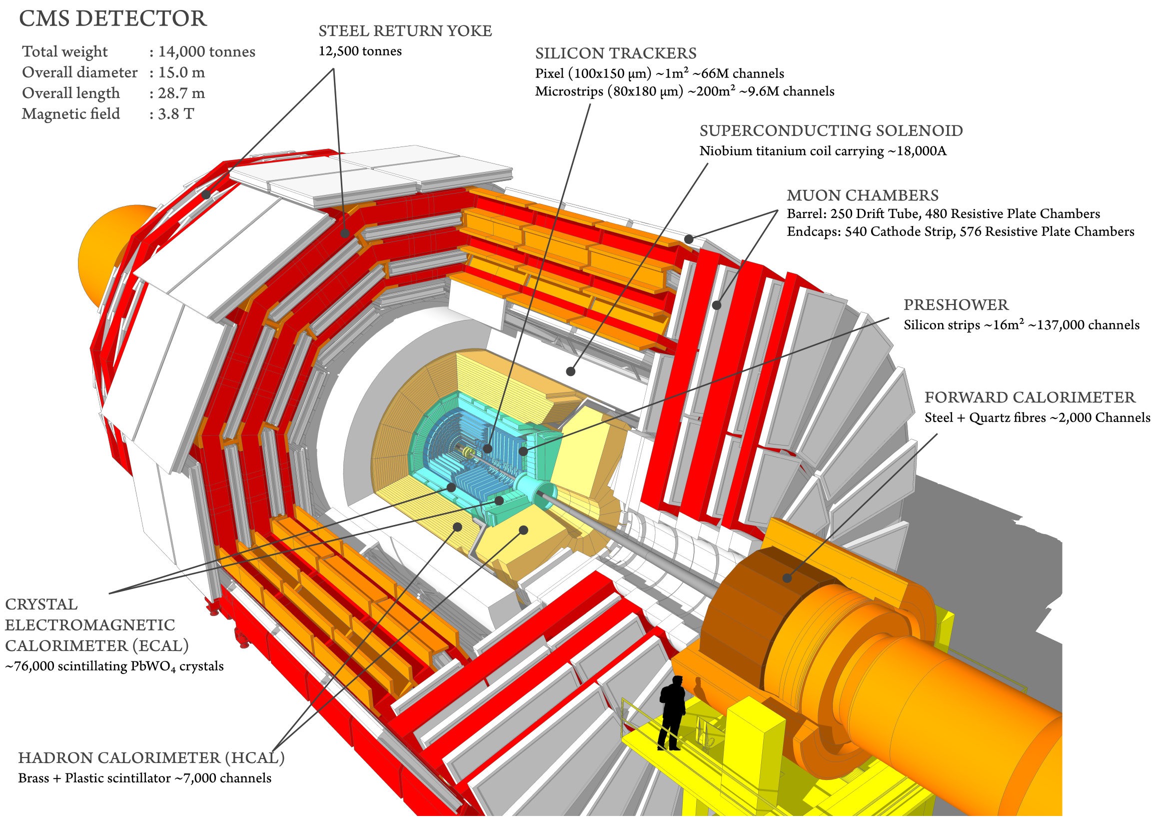
- Circumference: 27 km
- 2556 proton bunches
- Stable beams efficiency: 49%

More information: J. Wenninger, CERN-ACC-NOTE-2019-0007

ATLAS and CMS

- Two general-purpose detectors, covering nearly the entire solid angle around the collisions points.
- Inner tracking systems – solenoid – electromagnetic and hadronic calorimeters – muon system



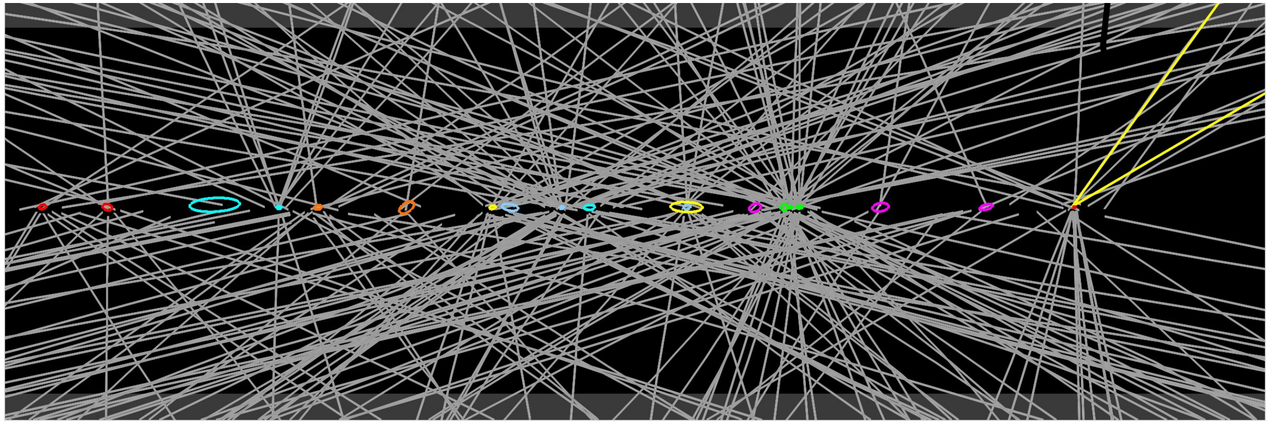


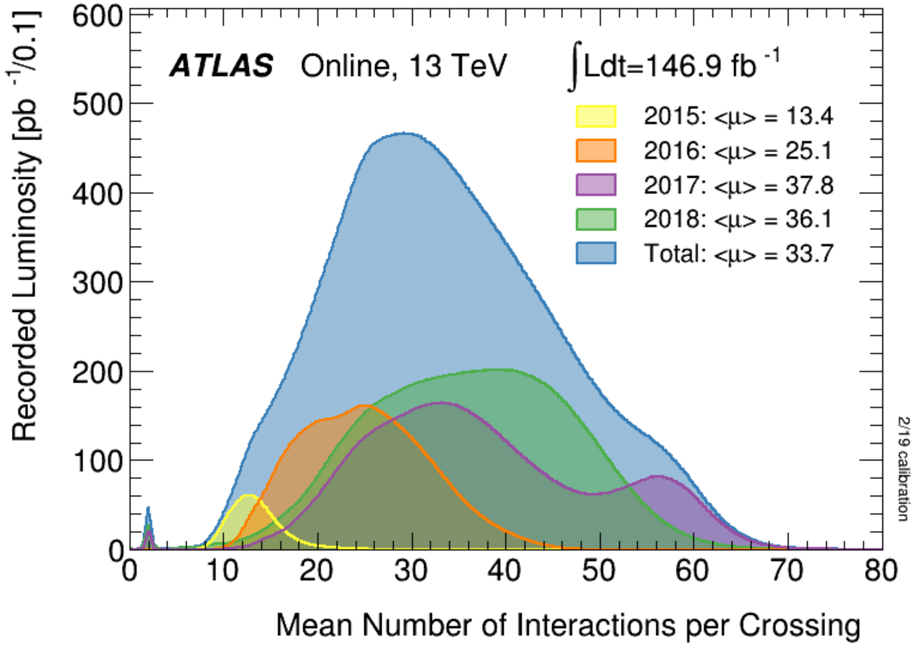
- Various upgrades ongoing during Long Shutdown 2 (2019 – 2022).

An experimental challenge: pile-up

- High luminosity comes at a prize: pile-up collisions

  On average 34 simultaneous *pp* collisions at the same bunch crossing.



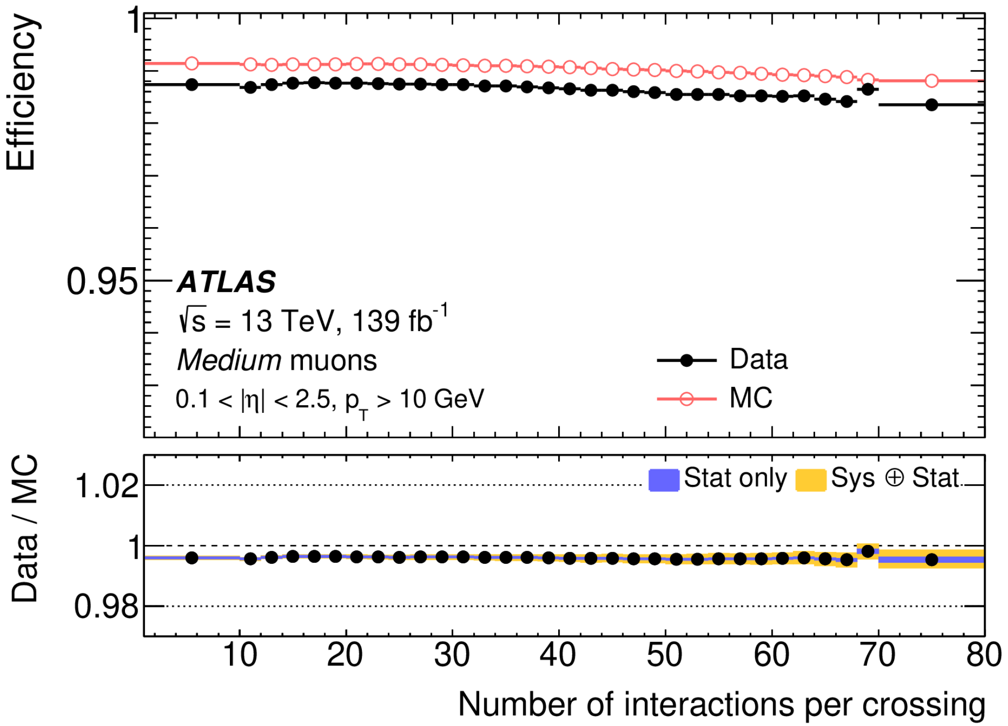


- Need good reconstruction and separation of primary (hard scattering) vertex and pile-up vertices.
- Reconstruction algorithms are designed to keep performance independent from pile-up.

Object reconstruction: charged leptons

Muons

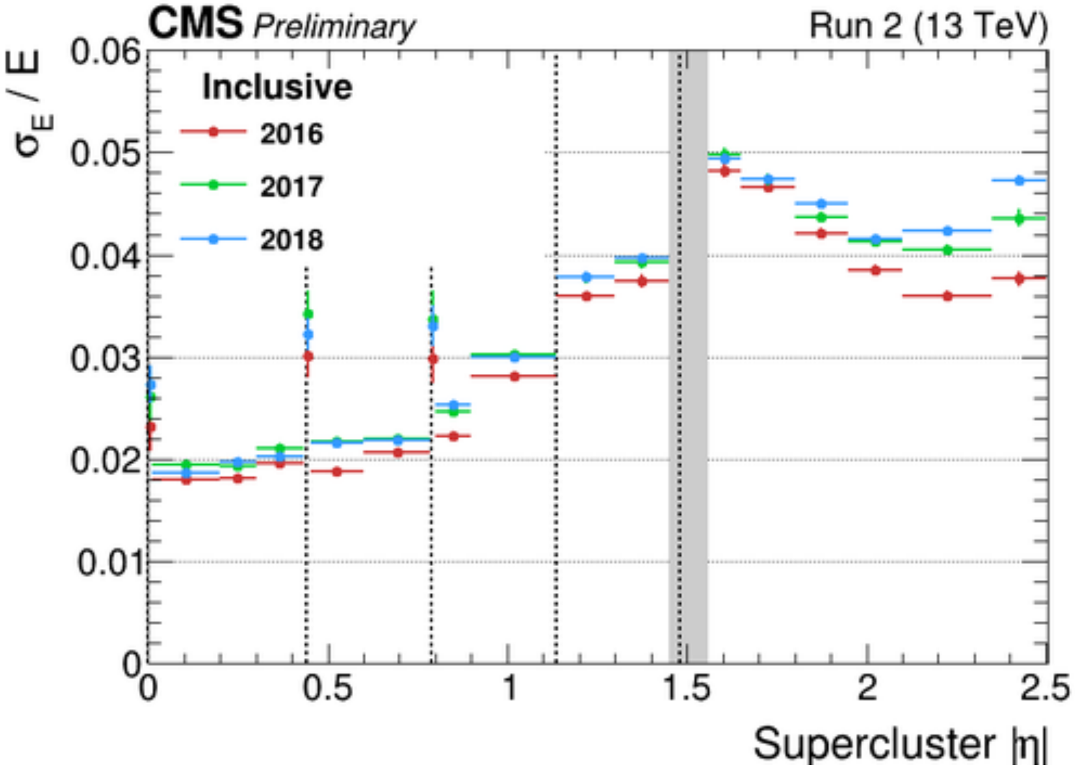
Efficiencies of muon reconstruction, identification, isolation and vertex association understood at per-mille level due to large samples of $Z \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow \mu^+\mu^-$.



arXiv: 2012.00578

Electrons

Excellent energy resolution for electrons is reached as determined with $Z \rightarrow e^+e^-$ events.



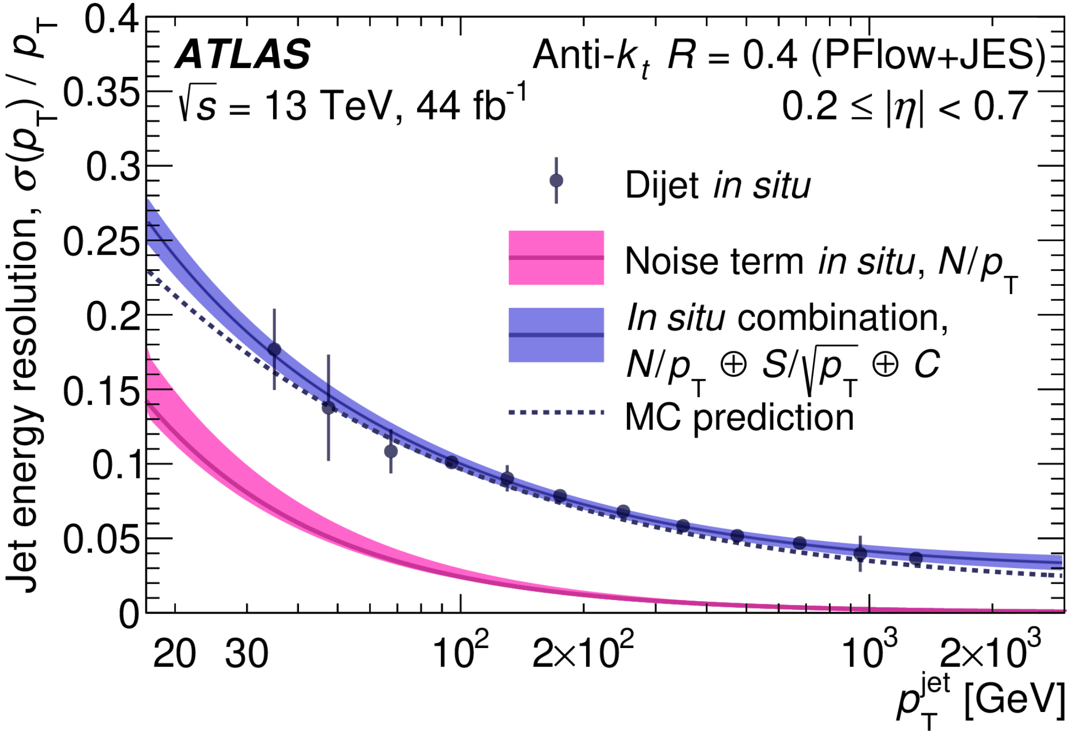
CMS-DP-2020-021

Object reconstruction: jets

BERGISCHE UNIVERSITÄT WUPPERTAL

Jet energy resolution

ranges from 24 ± 1.5 % at 20 GeV to 6 ± 0.5 % at 300 GeV for particle-flow jets.

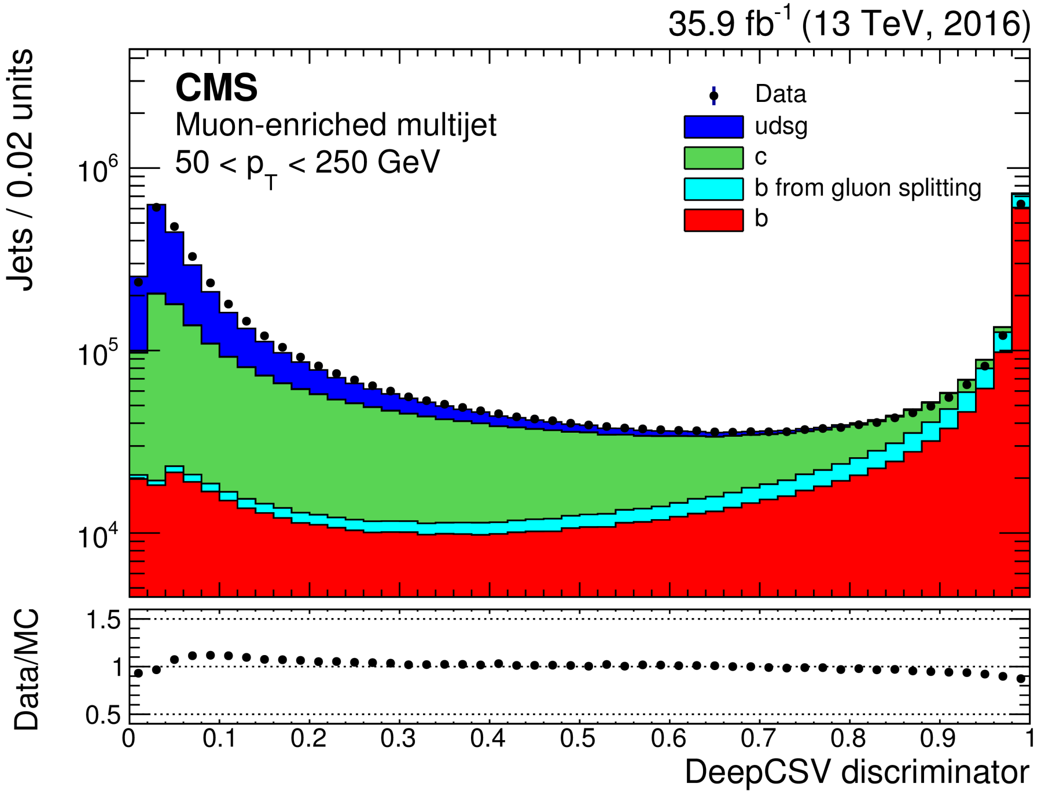


Measured with dijet events using the dijet-balance method.

arXiv: 2007.02645

Flavour tagging

Separation of *b*-, *c*- and light-flavour jets with machine-learning techniques*



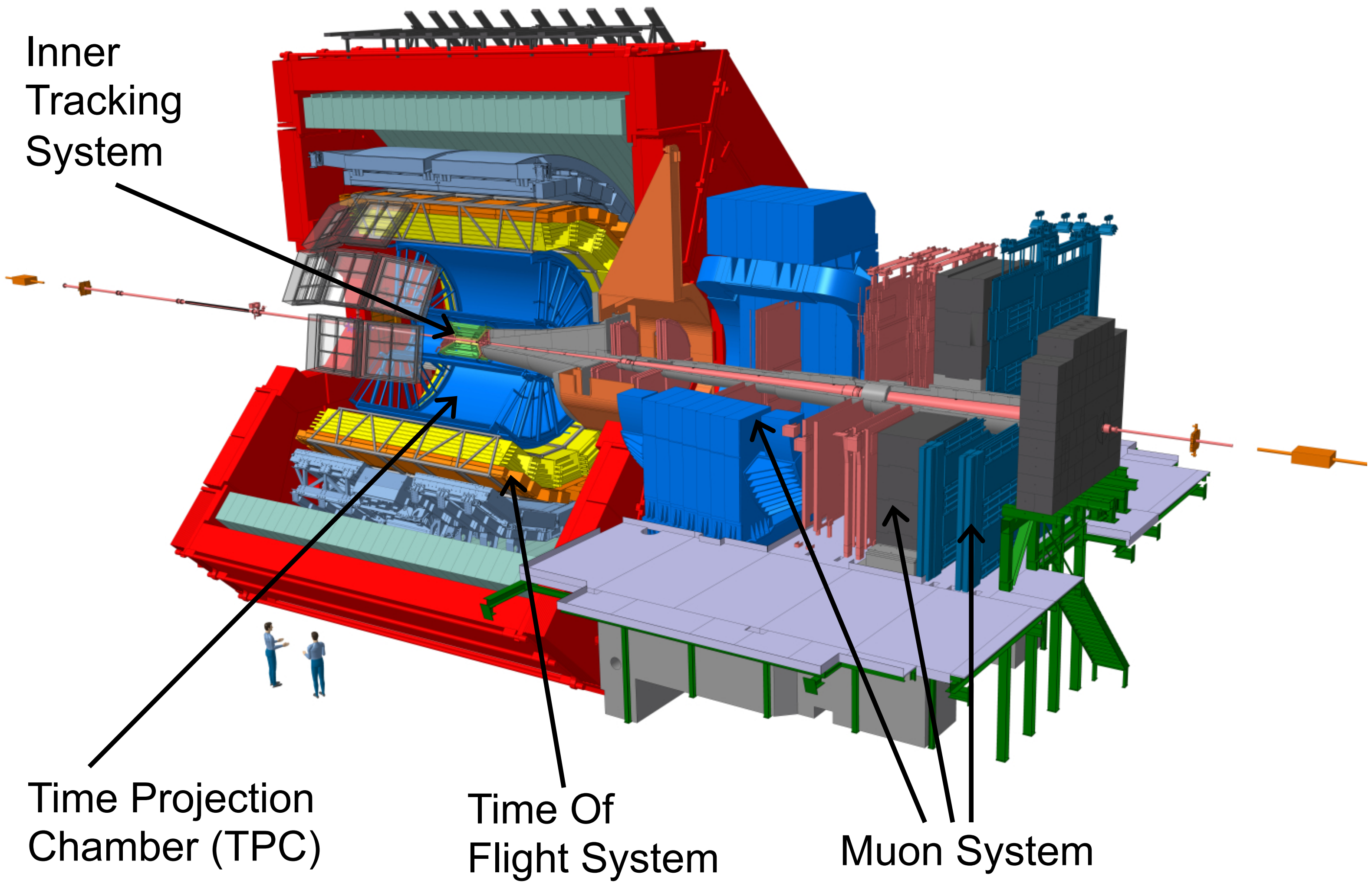
* Deep neural network implemented with Keras interfaced to TensorFlow.

JINST 13 (2018) P05011

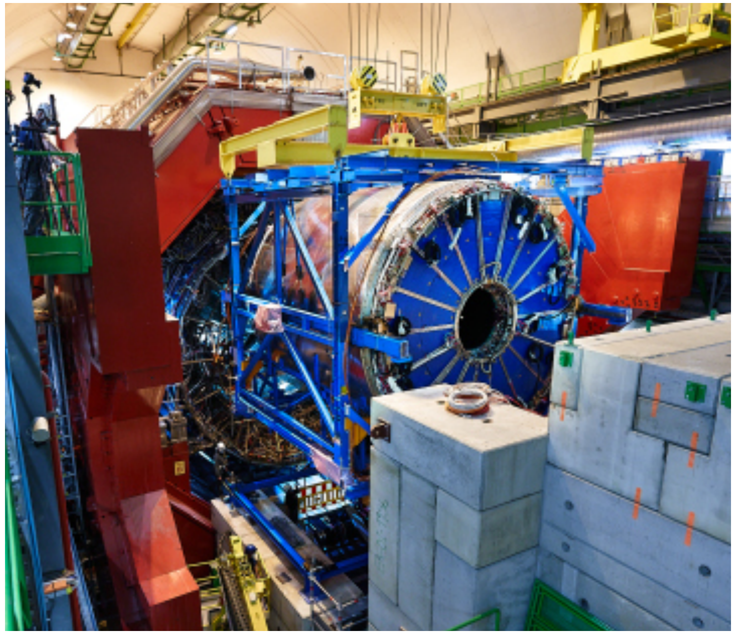
The ALICE detector – the heavy-ion specialist

BERGISCHE UNIVERSITÄT WUPPERTAL

- Understanding the quark-gluon plasma (QGP) – search for new bound states – understanding confinement

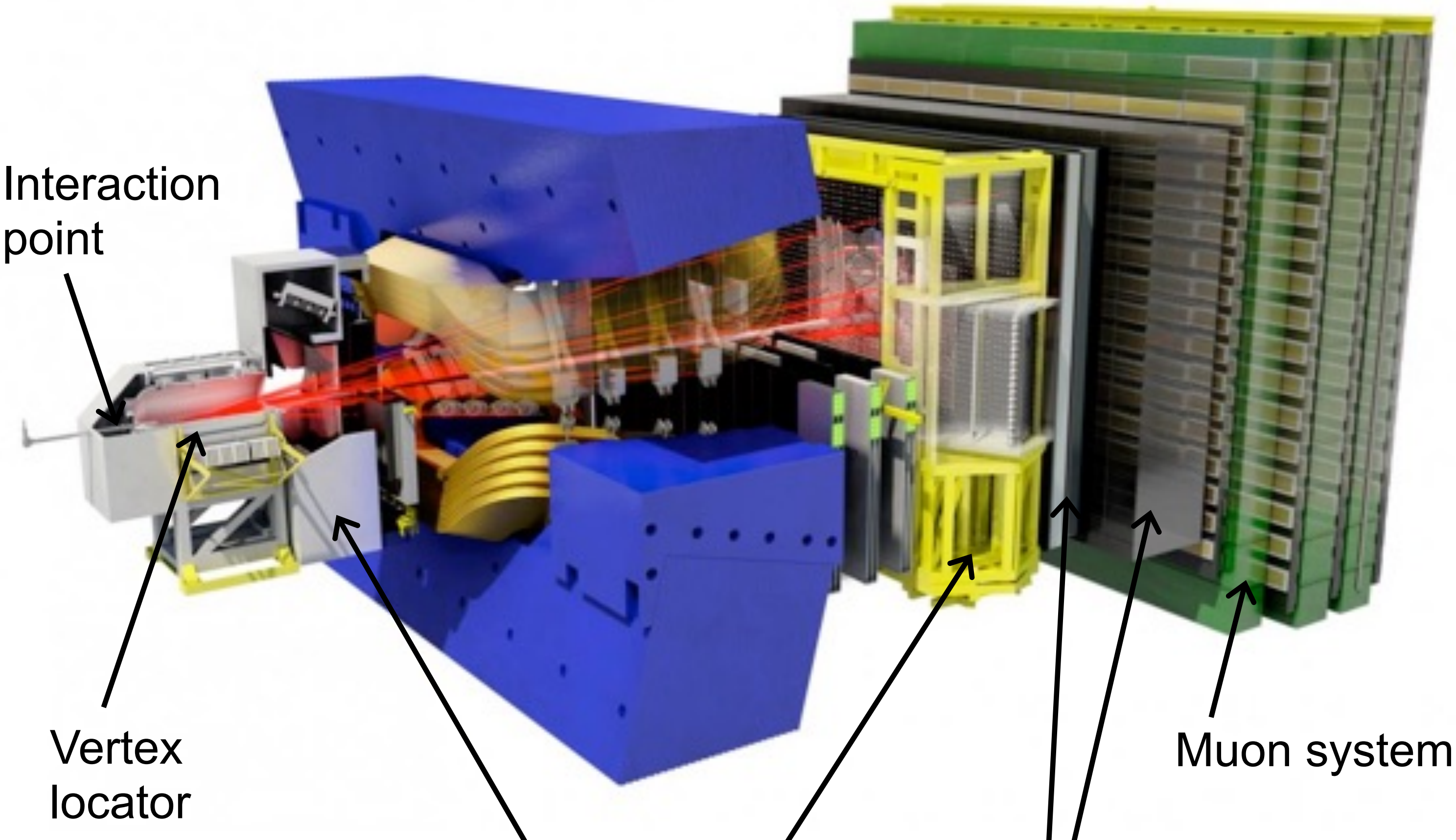


- Major upgrade program during Long Shutdown 2
- Among others: Upgrade of the TPC completed in 2020, featuring Gas Electron Multipliers (GEM):

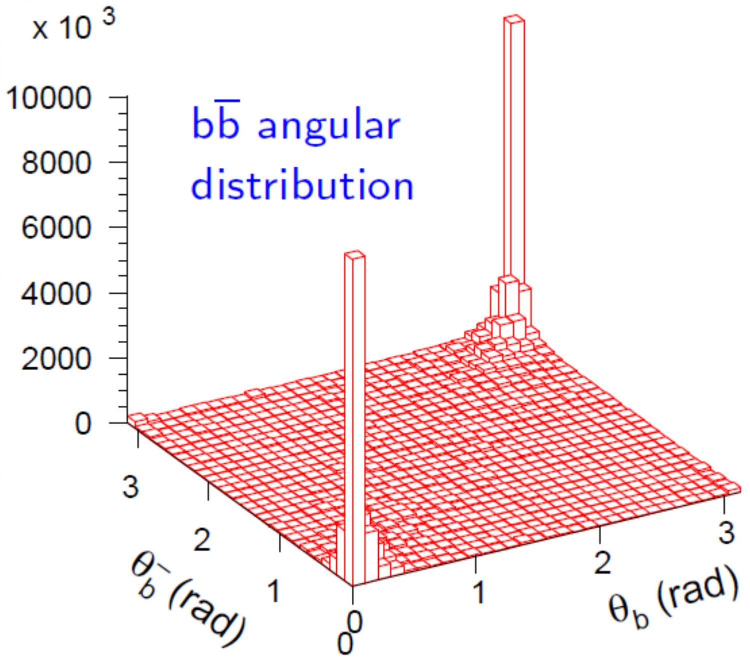


LHCb – the bottom- and charm-hadron specialist

- Scrutinizing CP violation in the SM – Search for exotic hadrons – Rare B-Meson decays
- Detector optimized for excellent vertex reconstruction and particle identification, e.g. K and π separation



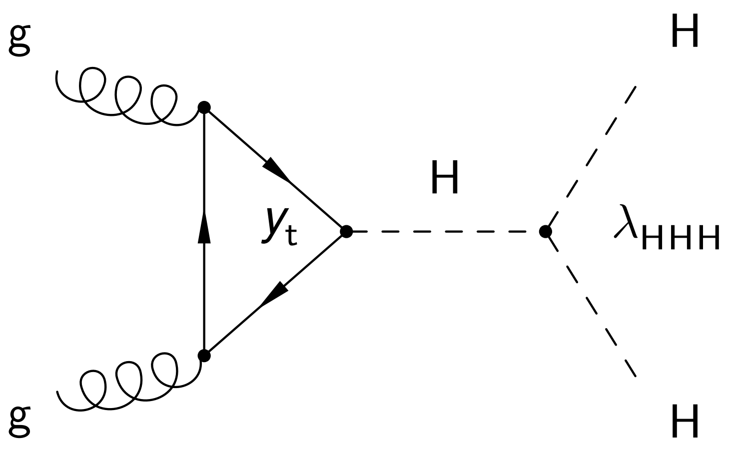
Forward spectrometer motivated by:

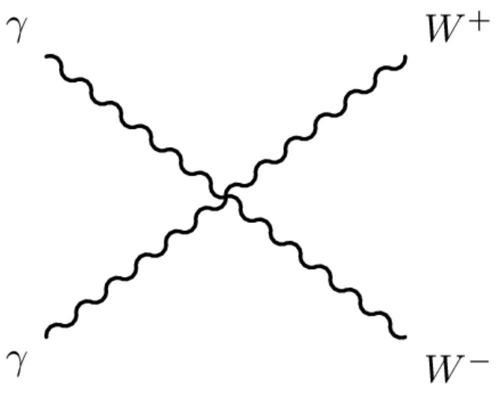


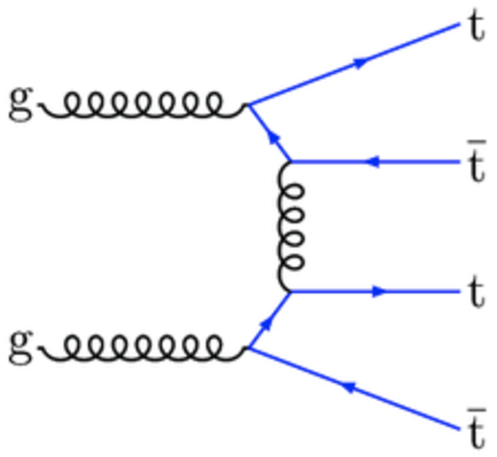
- Vertex detector, tracking systems and trigger are currently being replaced.
- Strong contribution of German institutes.

Part 2

Measurements on the Higgs boson, the top quark, electroweak and QCD processes







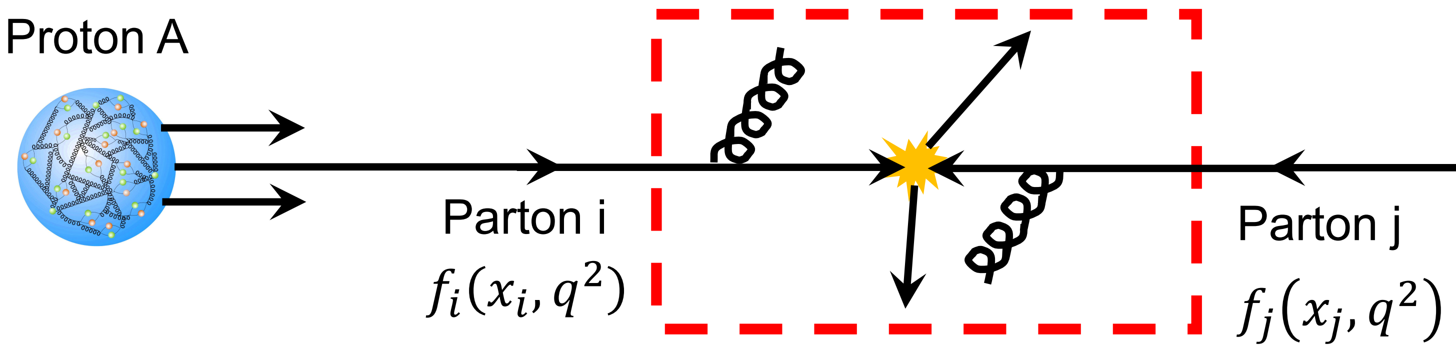
More on „Standard Model physics“ at this meeting:

- Hale Sert: A walk through $H \to \tau^+\tau^-$ in the CMS experiment, T 49.1, today 14:00
- Matthias Schröder: The Higgs boson at the LHC: a glimpse, T 73.1, Thursday 9:45
- Reinhild Yvonne Peters: No Time to die? Scrutinizing the SM and other Top Stories, T 73.2, Thursday 11:00
- Mathieu Pellen: Stress testing the Standard Model via vector-boson scattering at the LHC, T.74.3, Thursday 15:00
- Jonas Lindert: The quest for precise LHC predictions, T 99.2, Friday 11:00

High-p_T interactions in proton-proton collisions …

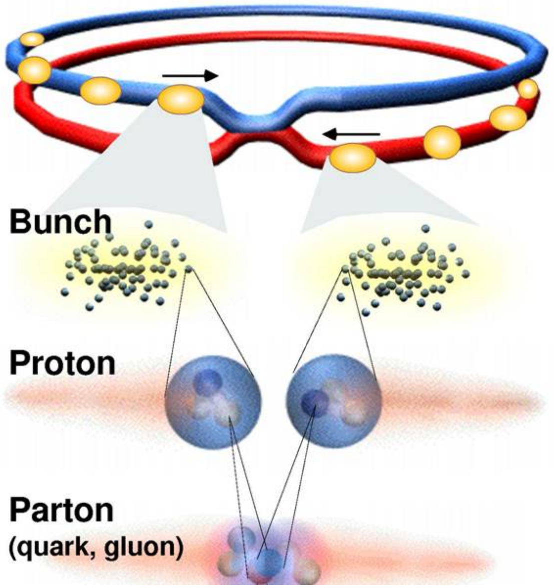
… described in the parton model

Partonic interaction
(hard process)



Parton distribution functions

Perturbative regime
(asymptotic freedom)



Factorisation theorem

Partonic cross-section

$$\sigma(pp \to XY) = \sum_{i,j} \int d\hat{s}\, \mathcal{L}_{ij}(\hat{s}; s, \mu_f) \cdot \hat{\sigma}_{ij}(ij \to XY;\ \hat{s};\ \mu_f)$$

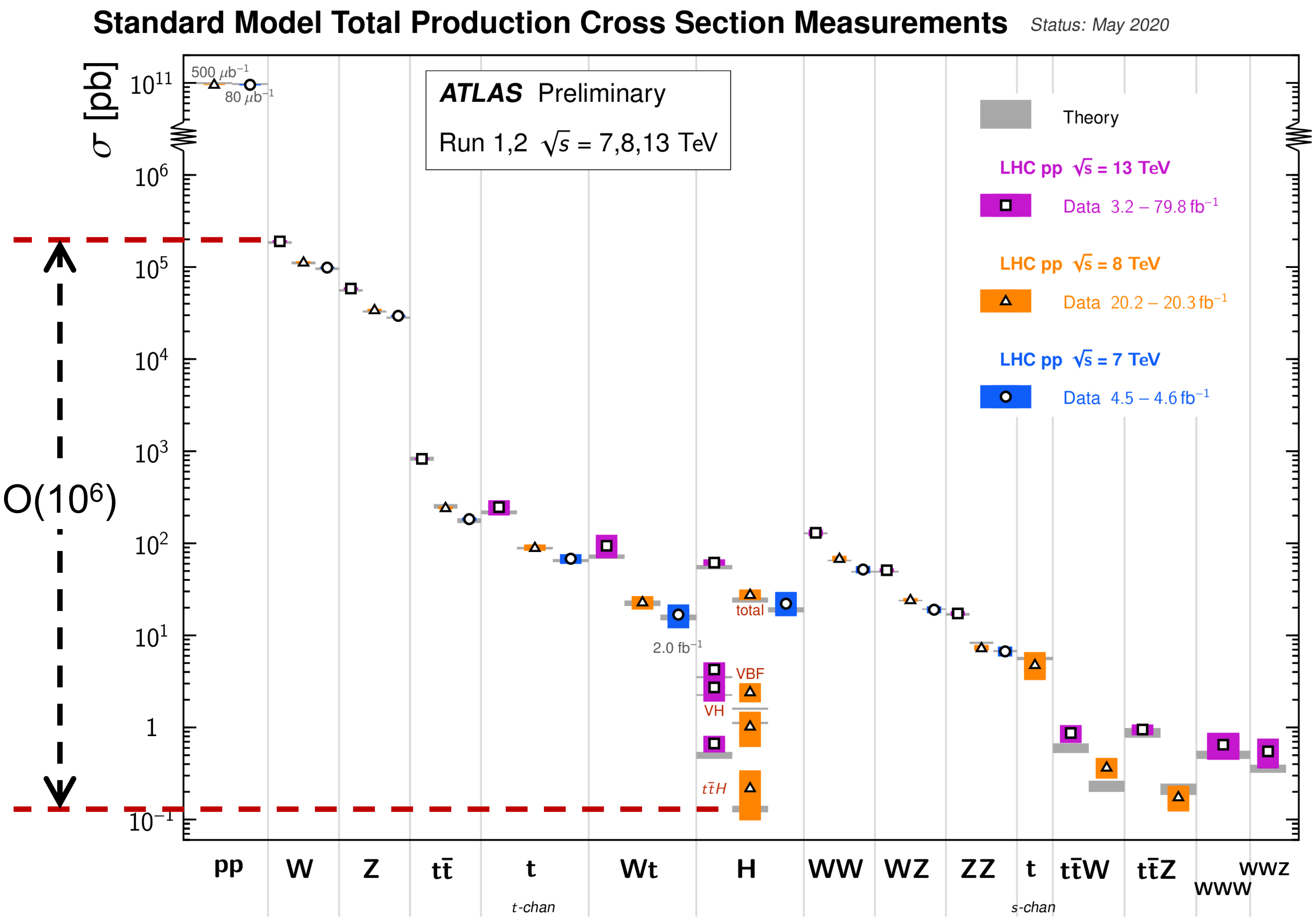
With $\mathcal{L}_{ij}(\hat{s}; s, \mu_f) = \frac{1}{s} \int_{\hat{s}}^{s} f_{i/A}\left(\frac{\tilde{s}}{s}\right) f_{j/B}\left(\frac{\hat{s}}{\tilde{s}}\right) \frac{1}{\tilde{s}}\, d\tilde{s}$ Parton luminosity

Cross-sections of standard model processes

BERGISCHE UNIVERSITÄT WUPPERTAL

- Cross-sections of high-p_T SM processes span 6 orders of magnitude!
- In 139 fb^{-1} (Run 2 data set):
  - O(26 billion) W events
  - O(28k) $t\bar{t}H$ events

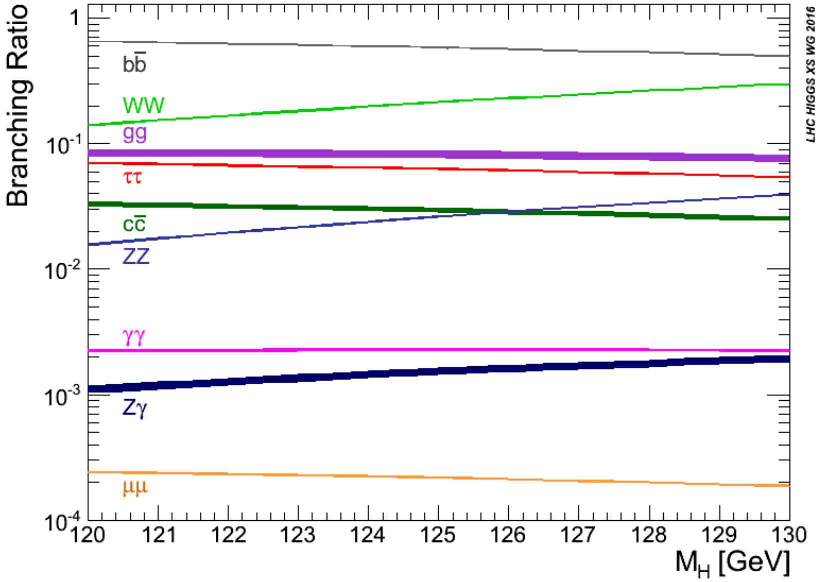
  produced.



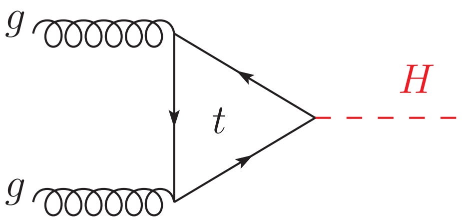
The Higgs boson agenda at the LHC

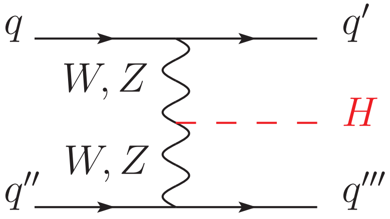
- Precise determination of Higgs boson properties
  - Mass → Use $H \to ZZ^*$ and $H \to \gamma\gamma$
  - *CP* structure → Use angular distributions
  - Coupling strengths → Measure all accessible production and decay modes
- Search for
  - multiple Higgs bosons as part of BSM physics
  - enhancements of “forbidden” decays

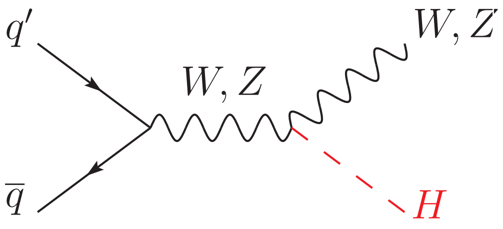
Higgs boson branching ratios

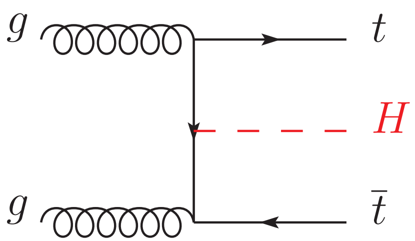


Gluon fusion	Vector boson fusion	VH associated production	$t\bar{t}H$ production







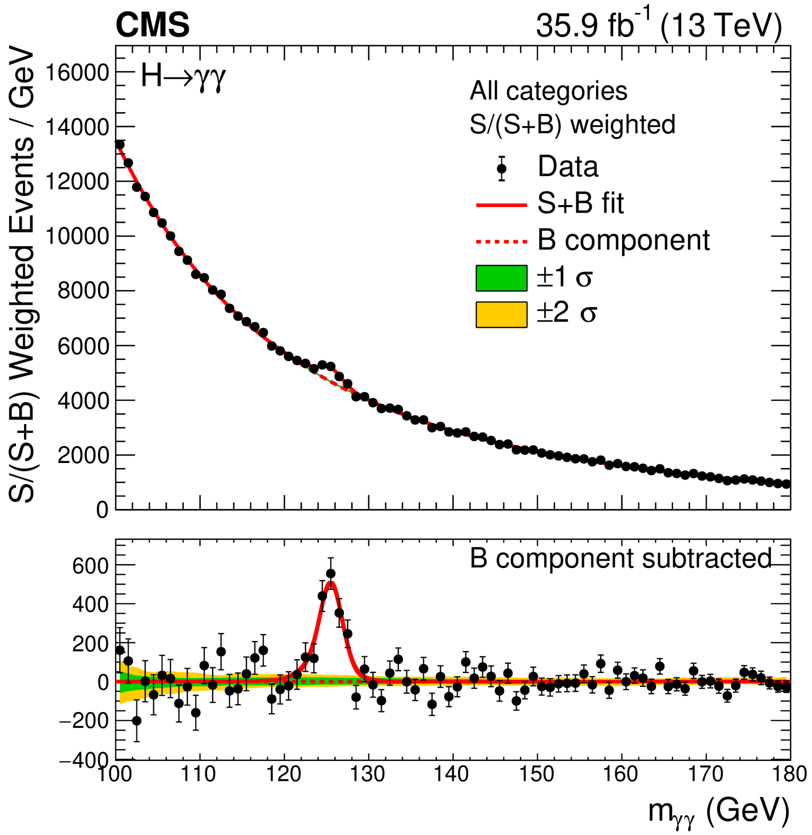


$\sigma =$	48.6 pb	3.78 pb	1.37 pb + 0.88 pb	0.5 pb

for $m_H = 125$ GeV/c²

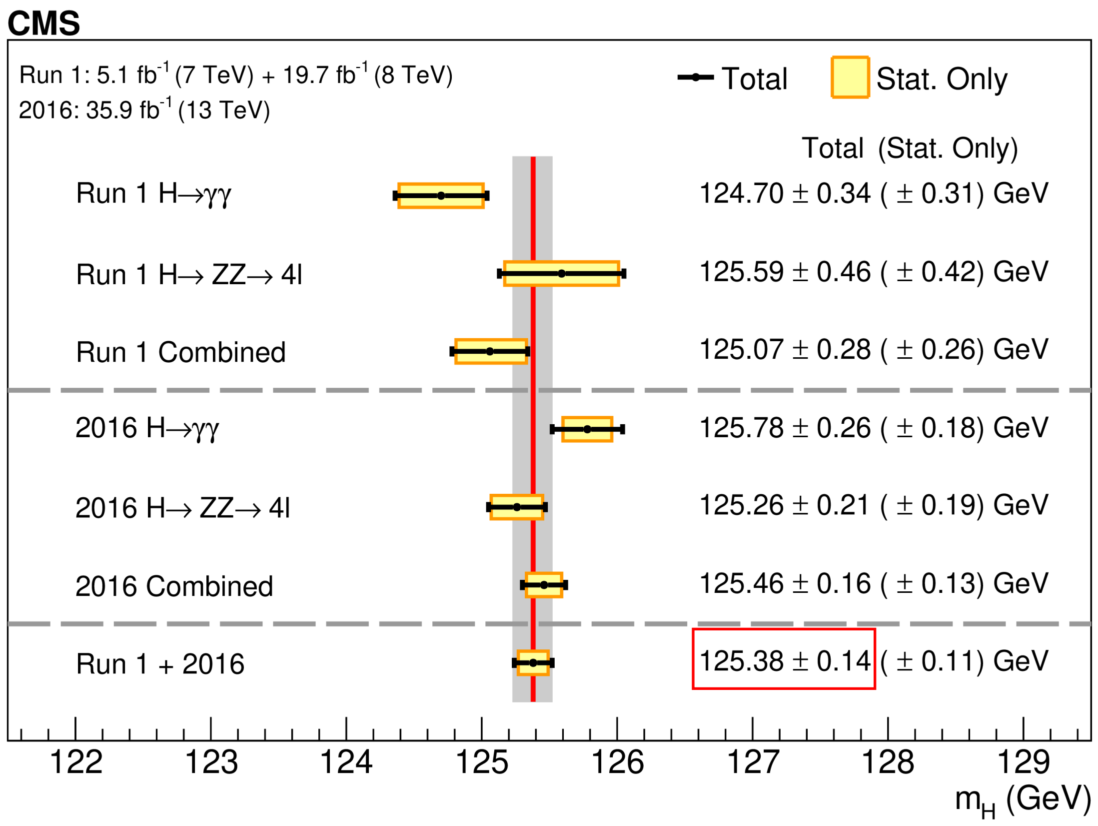
Higgs-boson mass

- Measurement in the $H \rightarrow \gamma\gamma$ channel.
- $m_H = 125.78 \pm 0.26$ GeV



- Statistical and systematic uncertainties are at an equal level: ± 0.18 GeV each.

Combination with previous measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$



Currently, the most precise measurement of m_H!

Measuring WH and ZH production with $H \to b\bar{b}$

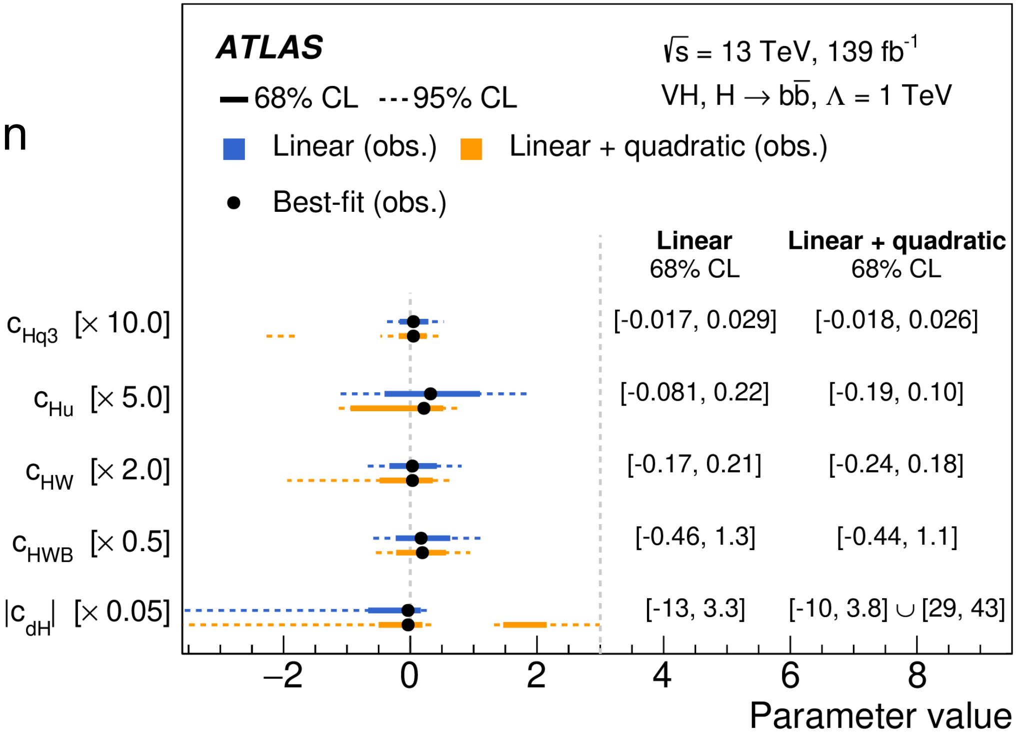
- Targeted signatures:

  $ZH \to \nu\nu b\bar{b}$, $WH \to \ell\nu b\bar{b}$ and $ZH \to \ell^+\ell^- b\bar{b}$
  $\Rightarrow$ three main channels: 0ℓ, 1ℓ and 2ℓ

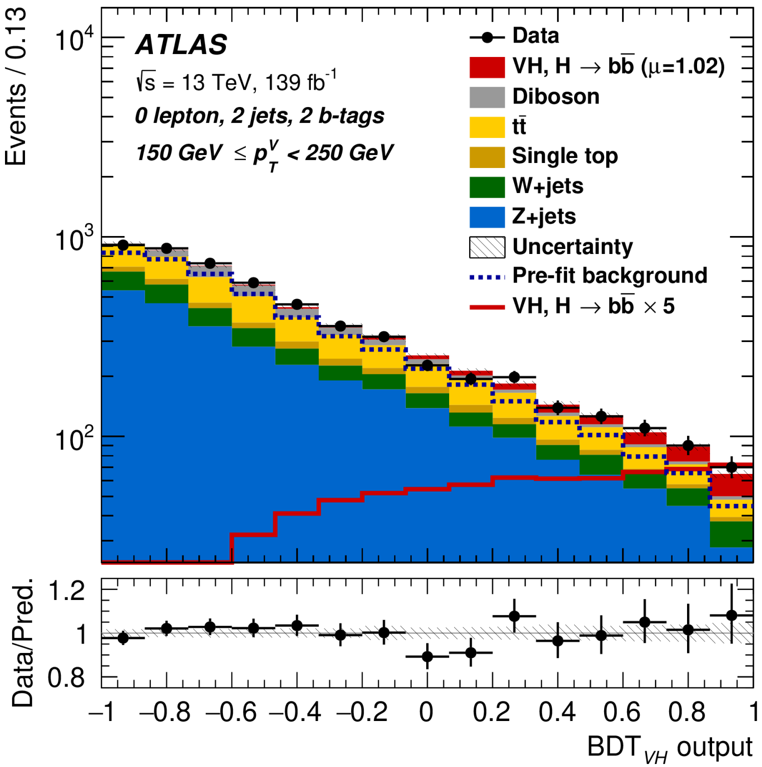
- Signal strength $\mu = \frac{(\sigma\times\mathcal{B})_{\text{obs}}}{(\sigma\times\mathcal{B})_{\text{pred}}} = 1.02\ ^{+0.18}_{-0.17}$.

- Limits to non-SM contributions are set in the context of an effective field theory (EFT) approach.

arXiv: 2007.02873

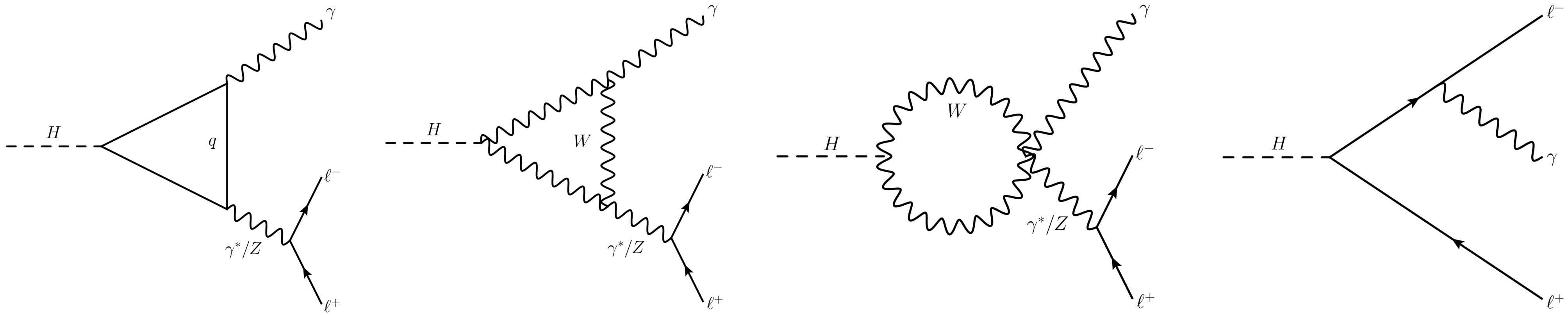


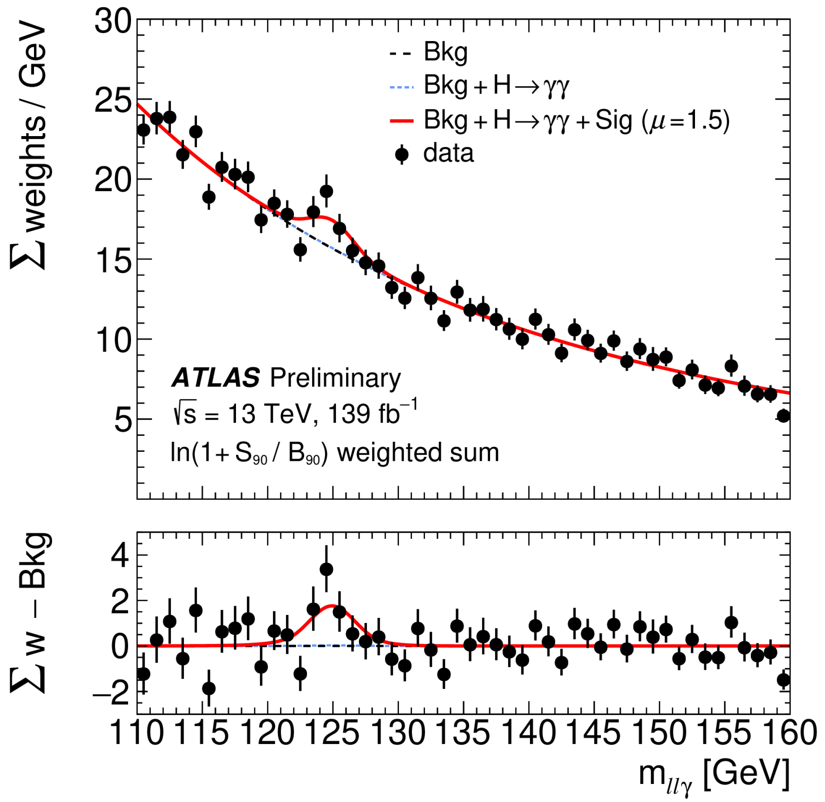
Boosted Decision Trees (BDTs) separate signal and background events



Evidence for the three-body decay $H \to \ell^+\ell^-\gamma$

Multiple amplitudes contribute:





- Require $m(\ell^+\ell^-) < 30$ GeV and $\frac{p_T(\gamma)}{m(\ell^+\ell^-\gamma)} > 0.3$
- Fit to $m(\ell^+\ell^-\gamma)$ distributions in 9 different event categories:

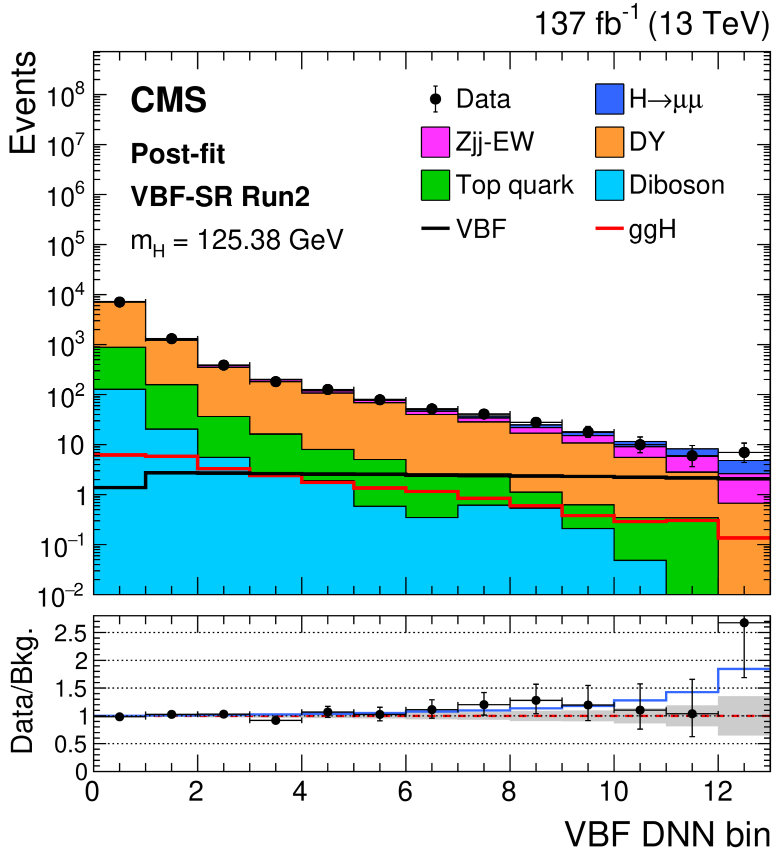
  Signal strength: $\mu = \frac{(\sigma\times\mathcal{B})_{\text{obs}}}{(\sigma\times\mathcal{B})_{\text{pred}}} = 1.5 \pm 0.5$

- Observed significance: 3.2 s.d. (2.1 s.d. expected)

ATLAS-CONF-2021-002

Evidence for the $H \rightarrow \mu^+\mu^-$ decay mode

- Prediction: $\mathcal{B}(H \rightarrow \mu^+\mu^-) = 2.18 \times 10^{-4}$
- Analysis considers the four major production mechanisms.
  ⇒ event categories: ggH, VBF, WH, ZH and $t\bar{t}H$
- Deep neural networks (DNN) and boosted decisions trees (BDT) for separating signal and background events.

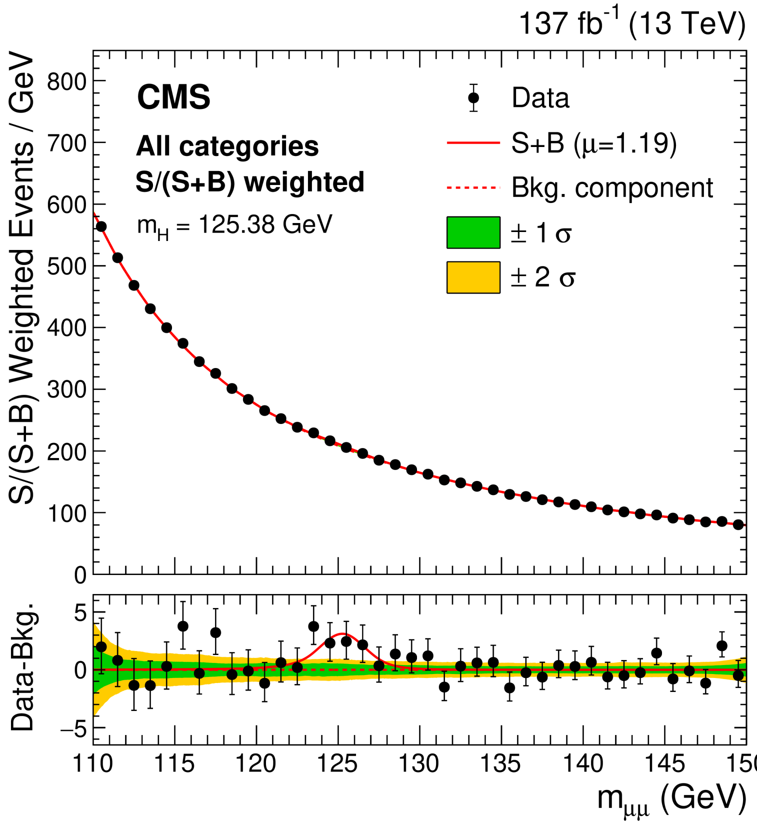


- Simultaneous fit to DNN and $m(\mu^+\mu^-)$ distributions of all categories and combination with Run 1:

  Signal strength:
  $\mu = \frac{(\sigma\times\mathcal{B})_{\text{obs}}}{(\sigma\times\mathcal{B})_{\text{pred}}} =$
  $1.19^{+0.40}_{-0.39}(\text{stat.})^{+0.15}_{-0.14}(\text{syst.})$

- Observed significance:
  3.0 s.d. (2.5 s.d. expected)

Distribution of $m(\mu^+\mu^-)$ with events weighted by $S/(S+B)$

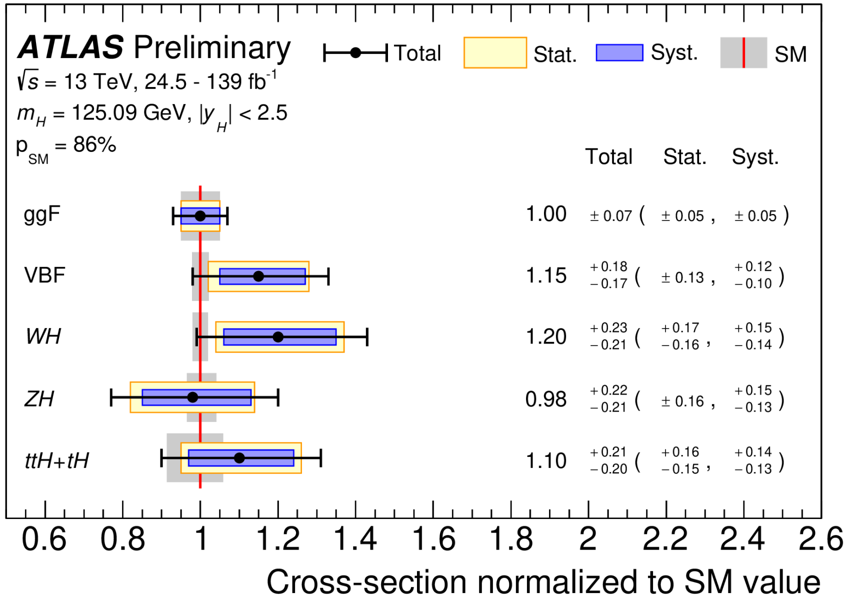


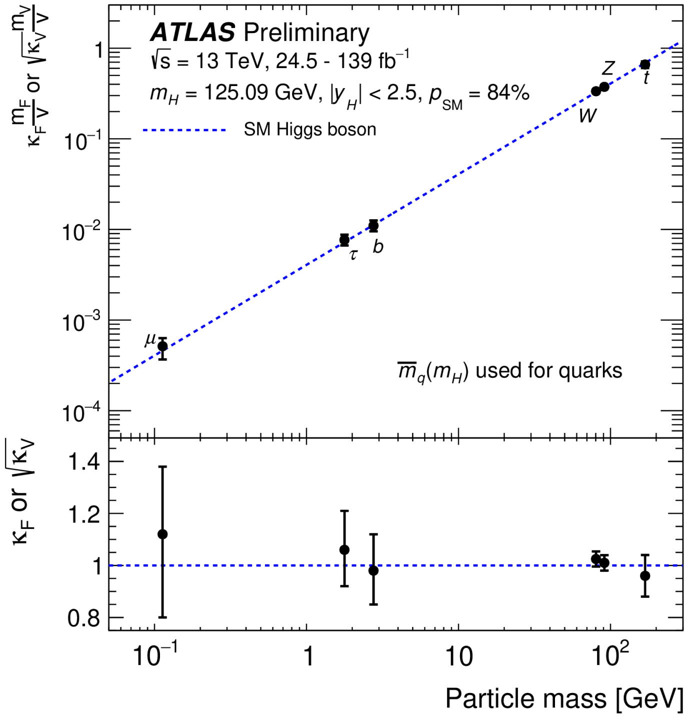
JHEP 01 (2021) 148
arXiv: 2009.04363

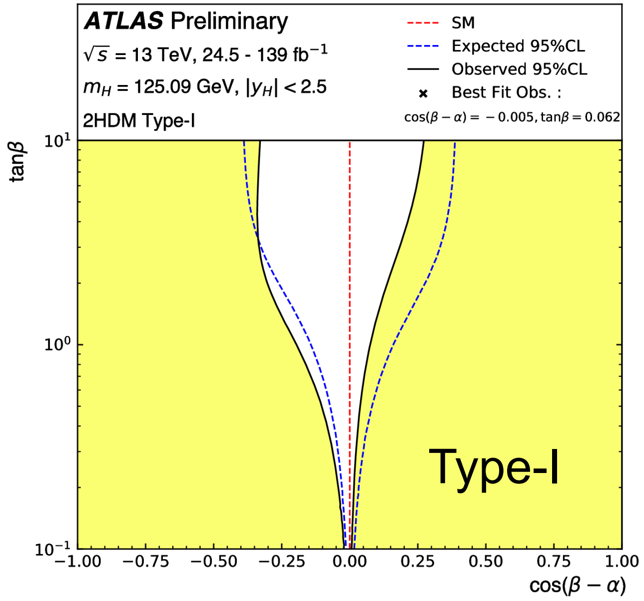
Combined measurement of production and decay rates

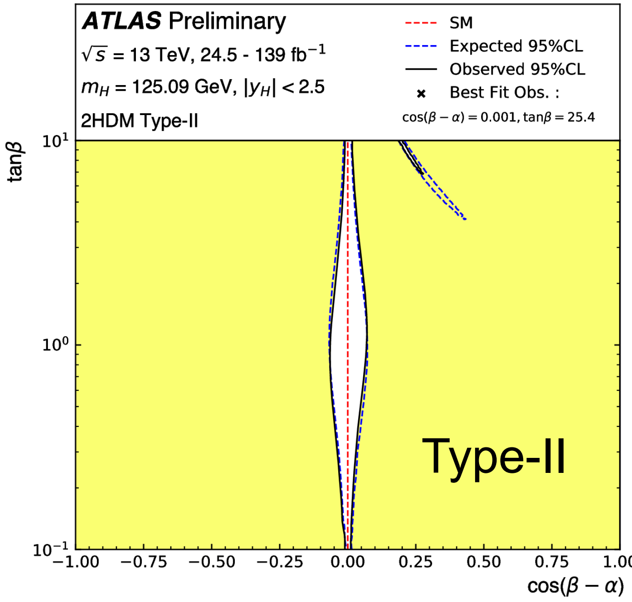
- Combine 11 analyses using their likelihood functions.
- Good agreement with SM predictions!
- Global signal strength:

$$\mu = \frac{(\sigma\times\mathcal{B})_{\text{obs}}}{(\sigma\times\mathcal{B})_{\text{pred}}} = 1.06 \pm 0.07$$





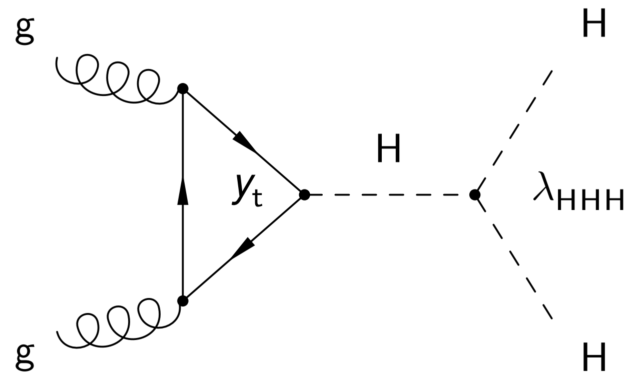




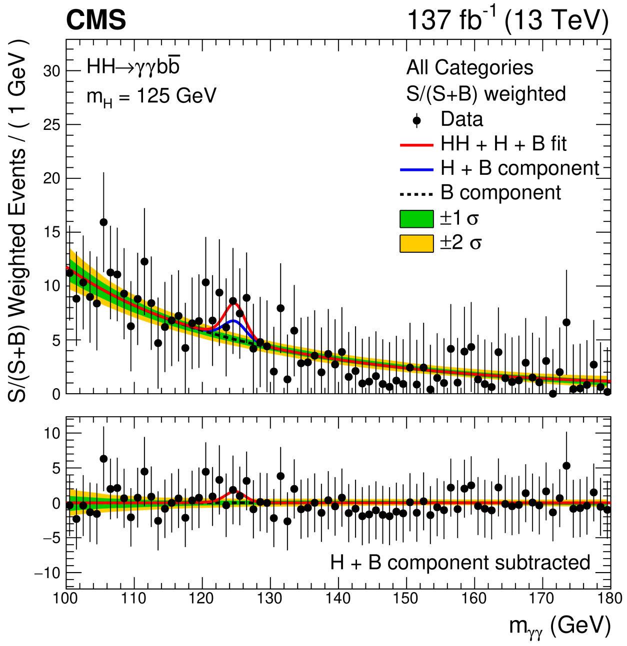
- Interpretation in Two-Higgs-doublet models (2HDMs).
- Assumption: observed Higgs boson is the light CP-even scalar h of the model.

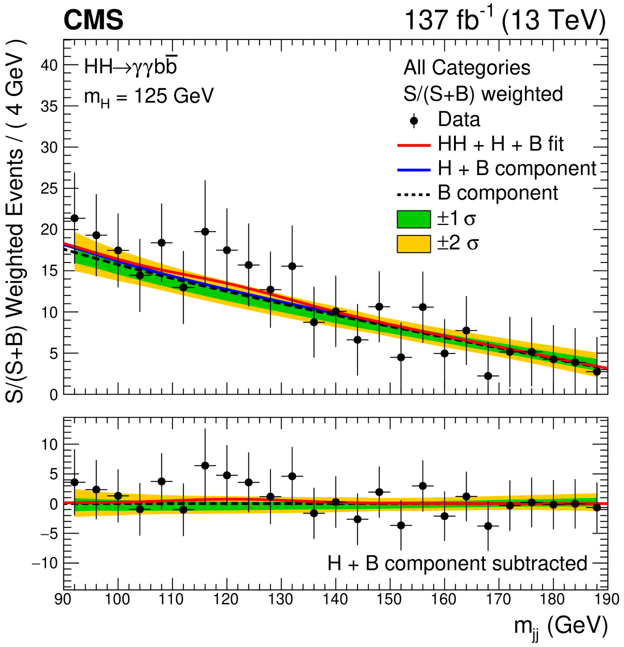
ATLAS-CONF-2020-027

Search for Higgs-pair production



- Pair production of Higgs bosons provides access to the trilinear self-coupling of the Higgs boson
- Search in the $HH \to \gamma\gamma b\bar{b}$ channel with $\mathcal{B} = 0.2633\ \%$.
- Use Boosted Decisions Trees and
  $$\widetilde{M}_X = m(\gamma\gamma b\bar{b}) - (m(\gamma\gamma) - m_H) - (m(b\bar{b}) - m_H)$$
  to define 14 event categories of different $S/\sqrt{B}$.





arXiv: 2011.12373

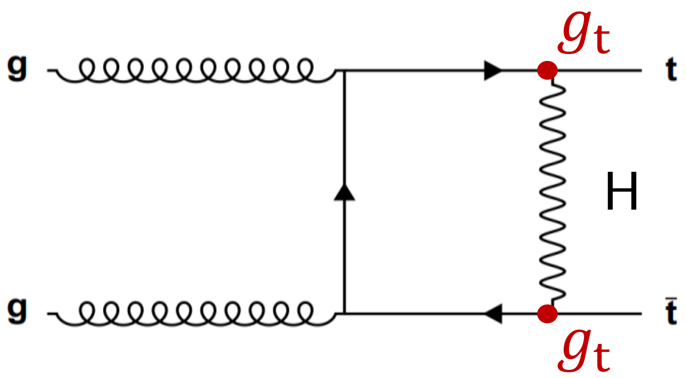
- Unbinned maximum-likelihood fit to the $m(\gamma\gamma)$ and $m(b\bar{b})$ distributions for extracting the signal yield and set an upper limit:

$$\sigma(HH \to \gamma\gamma b\bar{b}) < 0.67 \text{ fb @ 95\% C.L.}$$
$$= 7.7 \times \sigma_{\text{SM}}(HH \to \gamma\gamma b\bar{b})$$
expected: $5.2 \times \sigma_{\text{SM}}(HH \to \gamma\gamma b\bar{b})$

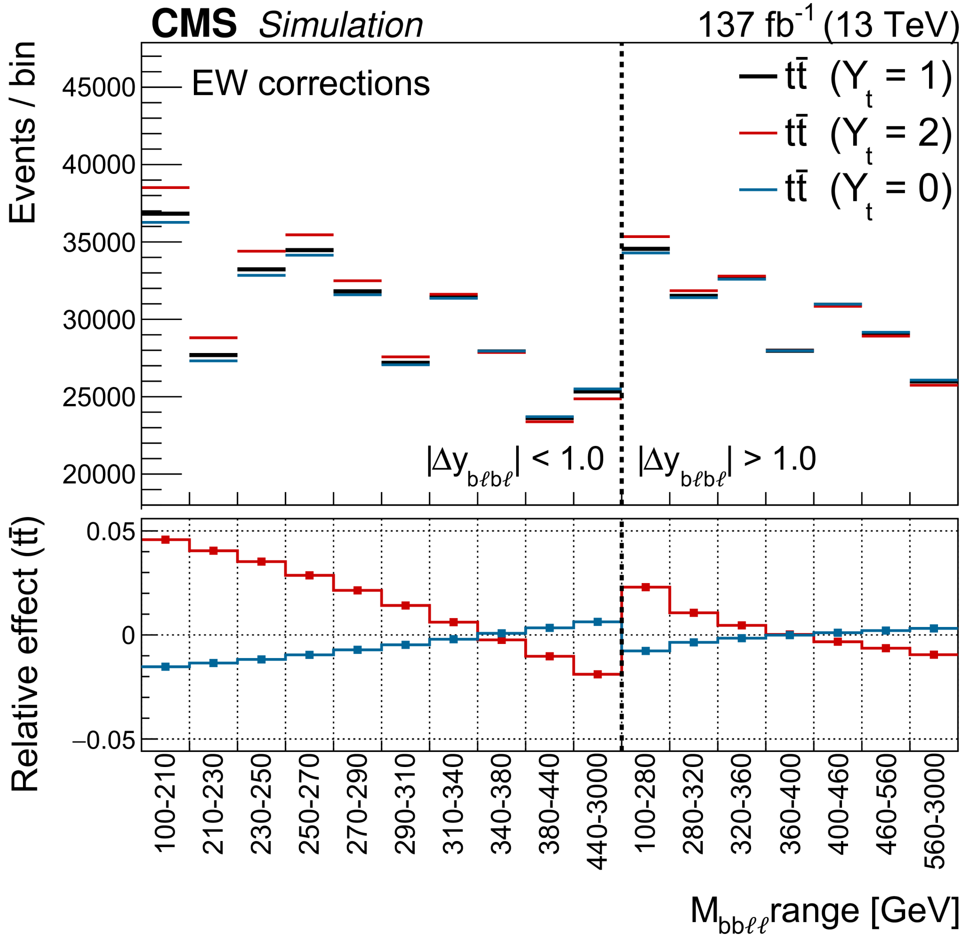
- Constraints on the Higgs self-coupling:

$$-3.3 < \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} < 8.5$$

Determination of the top-quark Yukawa coupling Y_t



- Use $t\bar{t}$ production for measuring Y_t, selecting events in the $e\mu$-dilepton channel.
- Sensitive variables: $m(bb\ell\ell) \sim m(t\bar{t})$ and $y(b\ell^+) - y(\bar{b}\ell^-) \sim \Delta y(t\bar{t})$.



- Use dependence of $\frac{d\sigma}{dm(bb\ell\ell)}$ and $\frac{d\sigma}{dy(bb\ell\ell)}$ on Y_t via a virtual Higgs exchange in a detector-level profile-likelihood fit
- Result: $Y_t = 1.16^{+0.24}_{-0.35}$
- Complementary to the result from the κ-framework (Higgs cross-sections): $Y_t = 0.98 \pm 0.14$

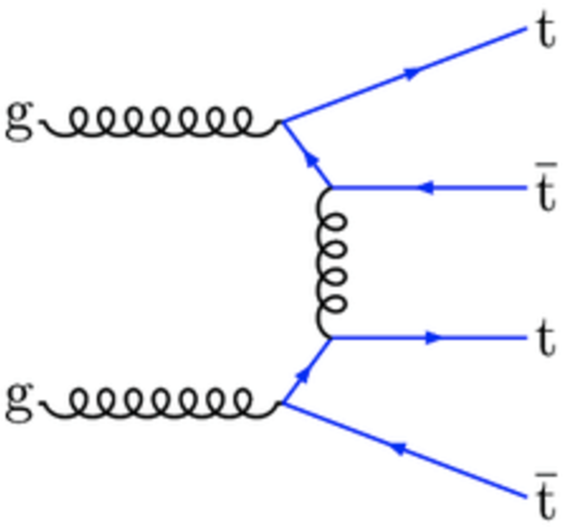
Phys. Rev. D. 102 (2020) 092013

arXiv: 2009.07123

Evidence for four-top-quarks production

- Very rare high-p_{T} scattering process!
- In the SM at NLO (QCD and EWK corr.):

$$\sigma(t\bar{t}t\bar{t}) = 12.0 \ \pm 2.4 \text{ (scale) fb}$$

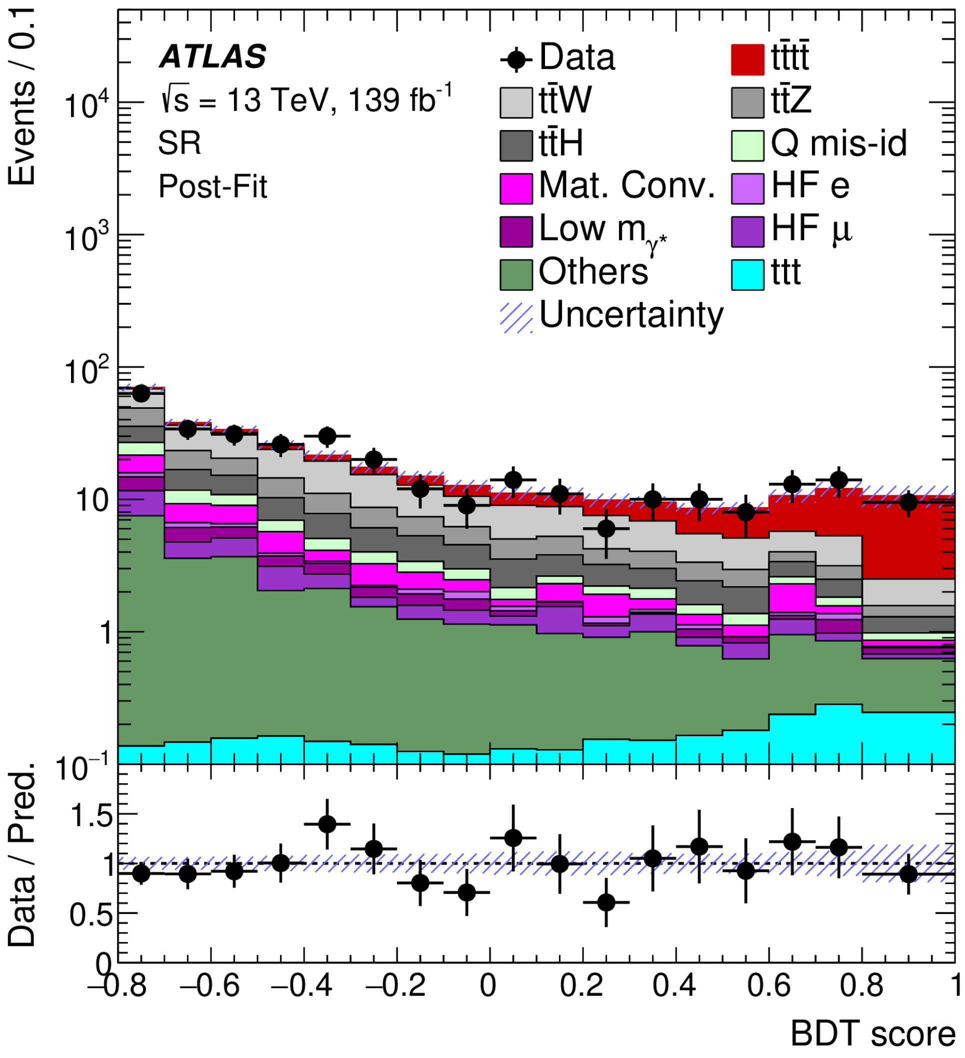


- Use channels with best signal-to-background ratio:
  - ➢ 2 leptons with same-charge
  - ➢ ≥ 3 leptons
- Measured signal strength:

$$\mu(t\bar{t}t\bar{t}) = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} = 2.0^{+0.9}_{-0.6}$$

Strong evidence of 4.3 s.d. (2.4 s.d. expected) for this very rare process!

Consistent to 1.7 s.d. with the SM prediction.



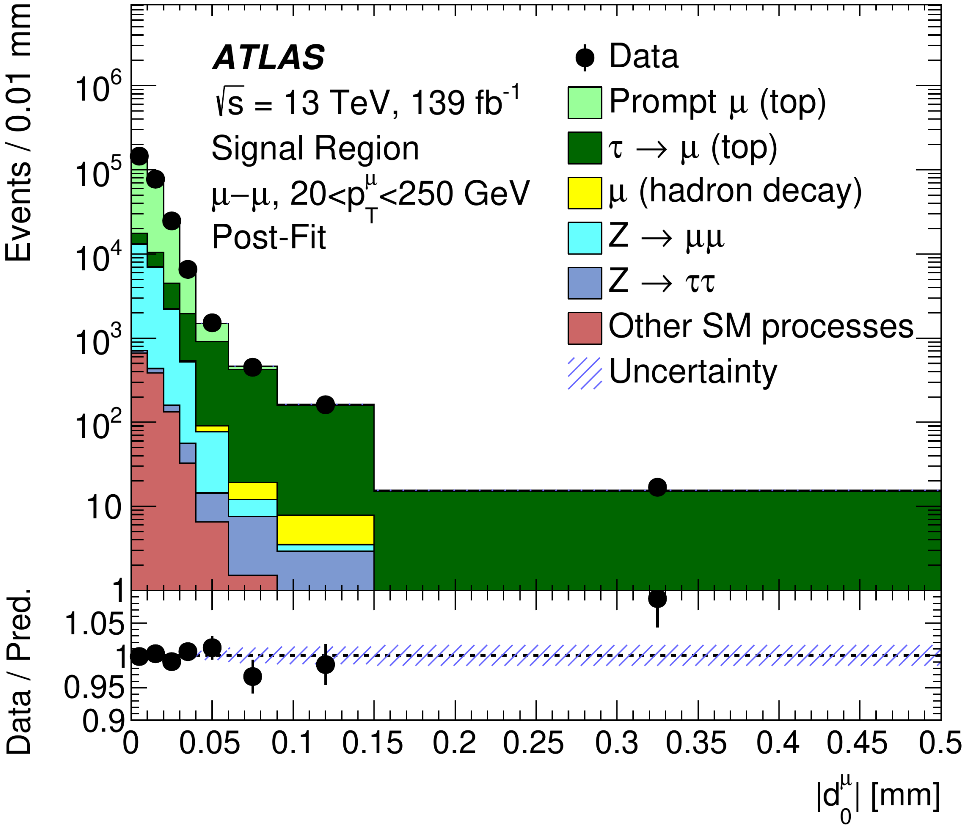
Eur. Phys. J. C 80 (2020) 1085

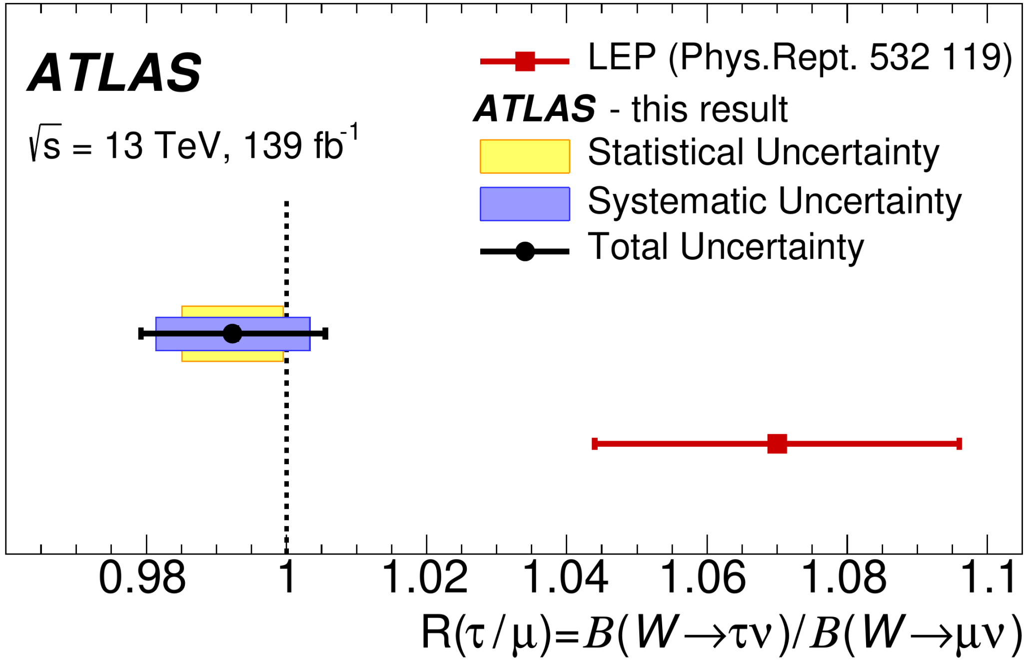
arXiv: 2007.14858

Testing the universality of the weak coupling to τ and μ

BERGISCHE UNIVERSITÄT WUPPERTAL

- Measure $R(\tau/\mu) = \frac{\mathcal{B}(W\to\tau\nu)}{\mathcal{B}(W\to\mu\nu)}$ in $t\bar{t}$ events.
- Transverse impact parameter $d_0(\mu)$ and $p_T(\mu)$ distributions are used to separate prompt muons and muons from the $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ decay chain.





- Measured value: $R(\tau/\mu) = 0.992 \pm 0.013$

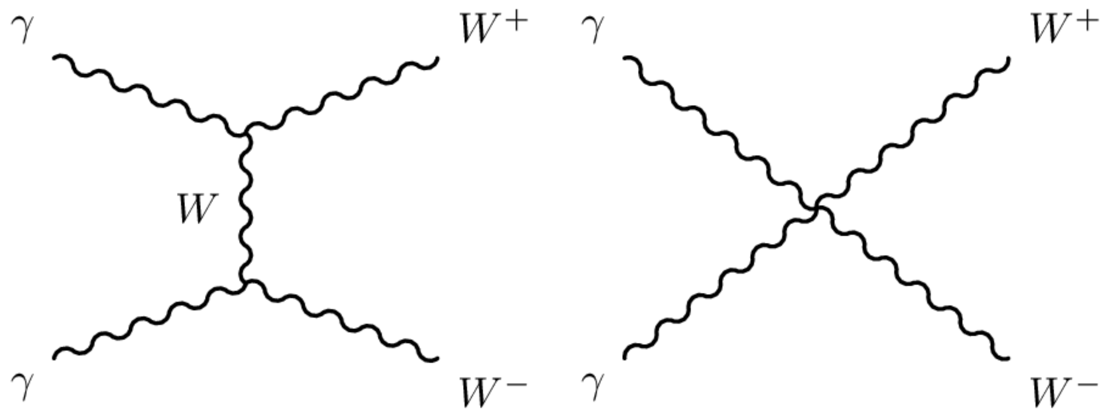
  $[\pm 0.007\ (\mathrm{stat}) \pm 0.011\ (\mathrm{syst})]$

- Most precise measurement of $R(\tau/\mu)$ to date.

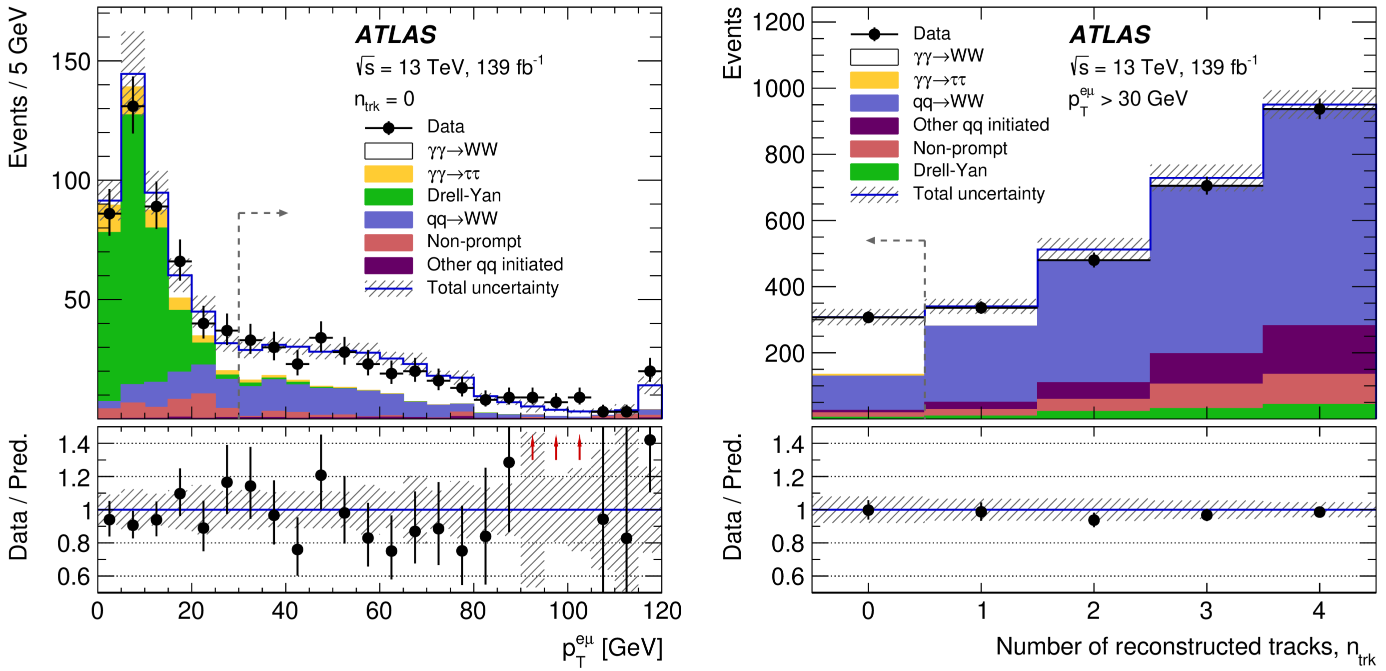
An excellent example for the LHC as a precision experiment!

arXiv: 2007.14040 Accepted by Nature Physics

Observation of photo-production of W^+W^- pairs



- Photon-induced production W^+W^- pairs proceeds via trilinear and quartic gauge-boson interactions.
- Select $e^\pm\mu^\mp$ events targeting $W^+W^- \to e^\pm\nu\mu^\mp\nu$ final states and suppressing $Z \to e^+e^-$ / $\mu^+\mu^-$.
- Suppress $Z \to \tau^+\tau^- \to e^\pm\nu_\tau\nu_e\mu^\mp\nu_\tau\ \nu_e$ events by requiring $p_T^{e\mu} > 30$ GeV.



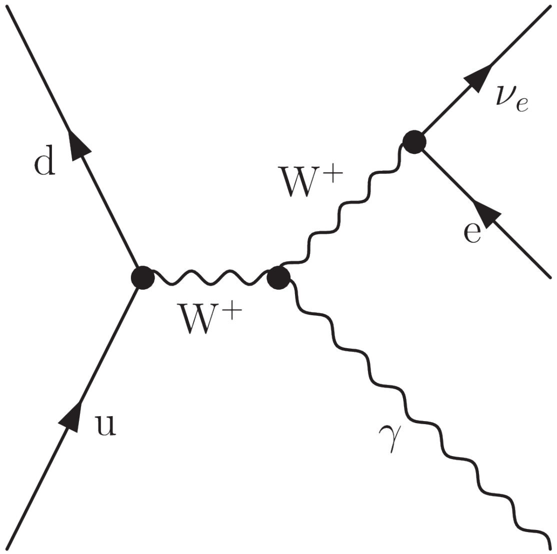
- $\gamma\gamma \to W^+W^-$ events have low track multiplicity (elastic, single- or double-dissociative production)
- Require $n_{\text{trk}} = 0$!
- Fiducial cross-section:

  $\sigma(\gamma\gamma \to W^+W^-) = 3.13\ \pm 0.31(\text{stat.}) \pm 0.28\ (\text{syst.})$ fb

  corresponding to 8.4 s.d. (6.7 s.d. are expected)

  arXiv: 2010.04019

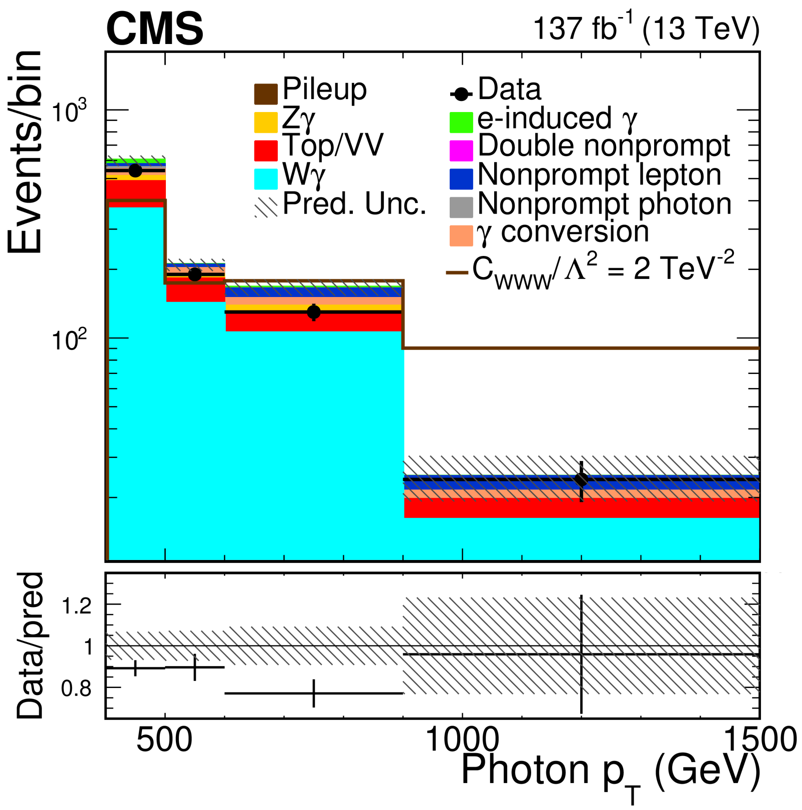
Measurement of $W\gamma$ production



[arXiv: 2102.02283](https://arxiv.org/abs/2102.02283)

- Probe the $WW\gamma$ triple-gauge coupling.
- Fit to the $m(\ell^{\pm}\gamma)$ distribution for estimating the signal yield.
- Fiducial cross-section:

  $\sigma_{\mathrm{fid}} = 15.58 \pm 0.75$ pb (4.8 % prec.)
- Use the $p_{\mathrm{T}}(\gamma)$ distribution for setting limits to anomalous gauge couplings in the context of effective field theory.



Limits of EFT coefficients

Coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper
c_{WWW}/Λ^2	−0.85	0.87	−0.90	0.91
c_B/Λ^2	−46	45	−40	41
$c_{\overline{W}WW}/\Lambda^2$	−0.43	0.43	−0.45	0.45
$c_{\overline{W}}/\Lambda^2$	−23	22	−20	20

Measurement of α_s

- Measure transverse energy-energy correlations (TEEC) in multi-jet events:

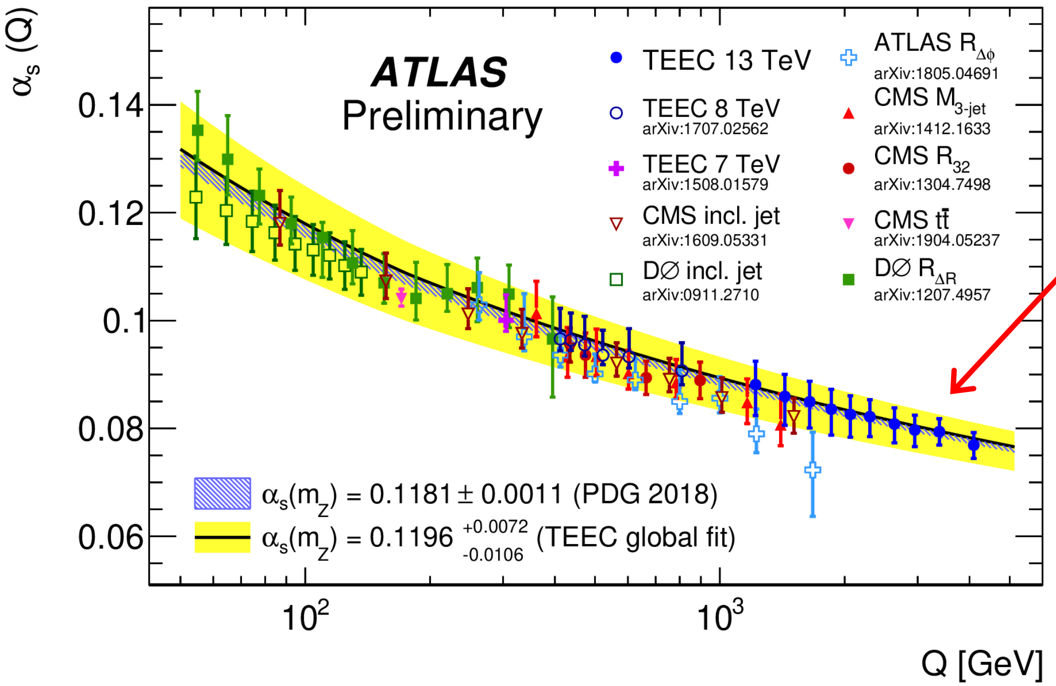
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

Index A runs over the selected events.

Distribution of the azimuthal differences $\cos\phi_{ij}$ of jet pairs weighted by the transverse energies of the jets.

- Use measurements to determine $\alpha_s(m_Z)$ and $\alpha_s(Q)$

ATLAS-CONF-2020-025



- Measurements of the α_s running are extended to a scale of several TeV

- Global fit to all scales:

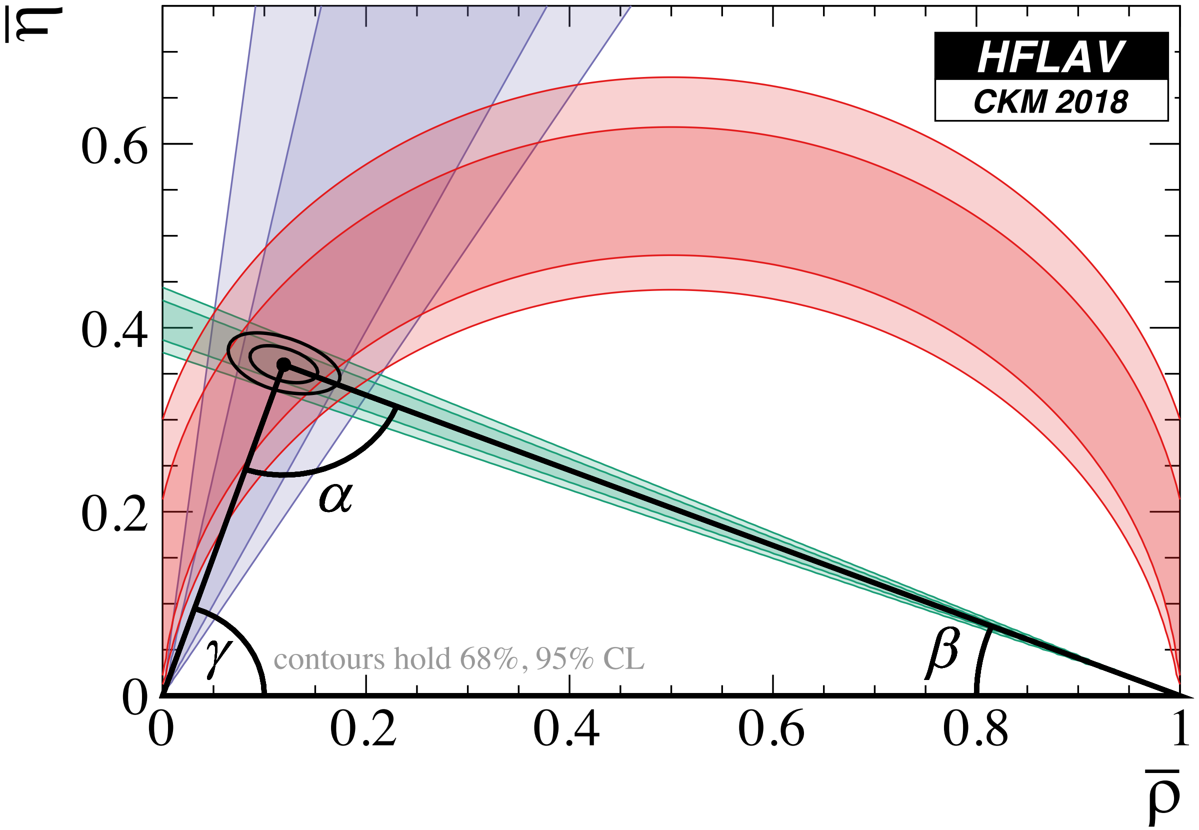
$$\alpha_s(m_Z) = 0.1196 \pm 0.0001\,(\mathrm{stat.}) \pm 0.0004\,(\mathrm{syst.})\,^{+0.0071}_{-0.0104}(\mathrm{scale}) \pm 0.0011(\mathrm{PDF}) \pm 0.0002(\mathrm{NP\ corr.})$$

- Scale uncertainties dominate by far.

Part 3

Flavour physics

“The” Unitarity Triangle Δ_{db}



$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

More on Flavour Physics at this meeting:

- Gudrun Hiller: Moving ahead with flavor, T 48.1, today at 9:45
- Michel De Can: Highlights from the LHCb experiment, T 48.2, today at 11:00

Measurement of B_s^0-$\bar{B}_s^0$ mixing and the CKM angle γ

- Measure frequency of B_s^0-$\bar{B}_s^0$ mixing in $B_s^0 \to D_s^- \pi^+\pi^+\pi^-$

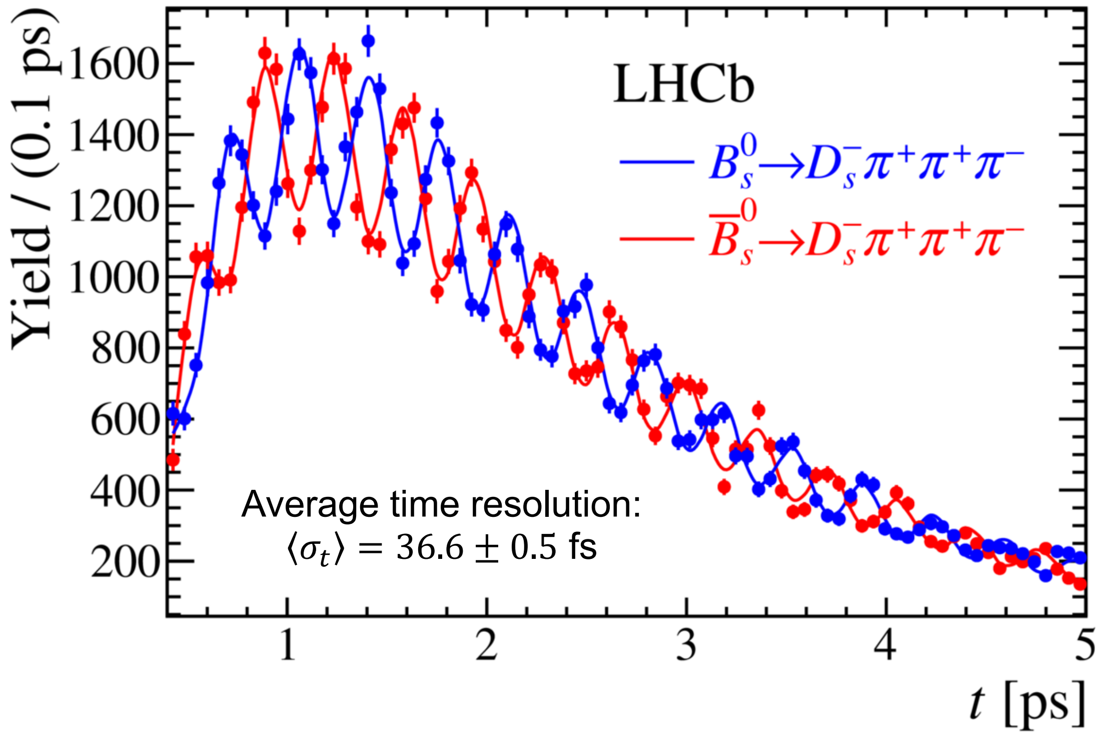
  $\Delta m_s = 17.757 \pm 0.007(\text{stat.}) \pm 0.008(\text{syst.})$ ps^{-1}

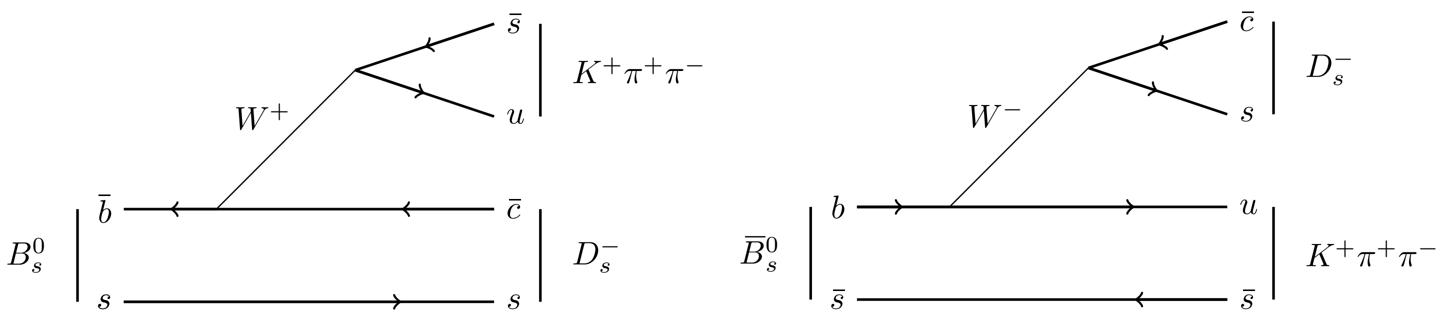
- Relative precision: 6×10^{-4}.
  More precise than the world average!

- Simultaneous calibration of production-flavour tagging algorithms in the fit.

- Use decay channels $B_s^0 \to D_s^{\mp} K^{\pm}\pi^{\pm}\pi^{\mp}$ to determine

  $\gamma = (44 \pm 12)°$ modulo 180°





- Evidence for mixing-induced CP violation at the level of 4.4 s.d.
- Agreement with world average: 2.2 s.d.

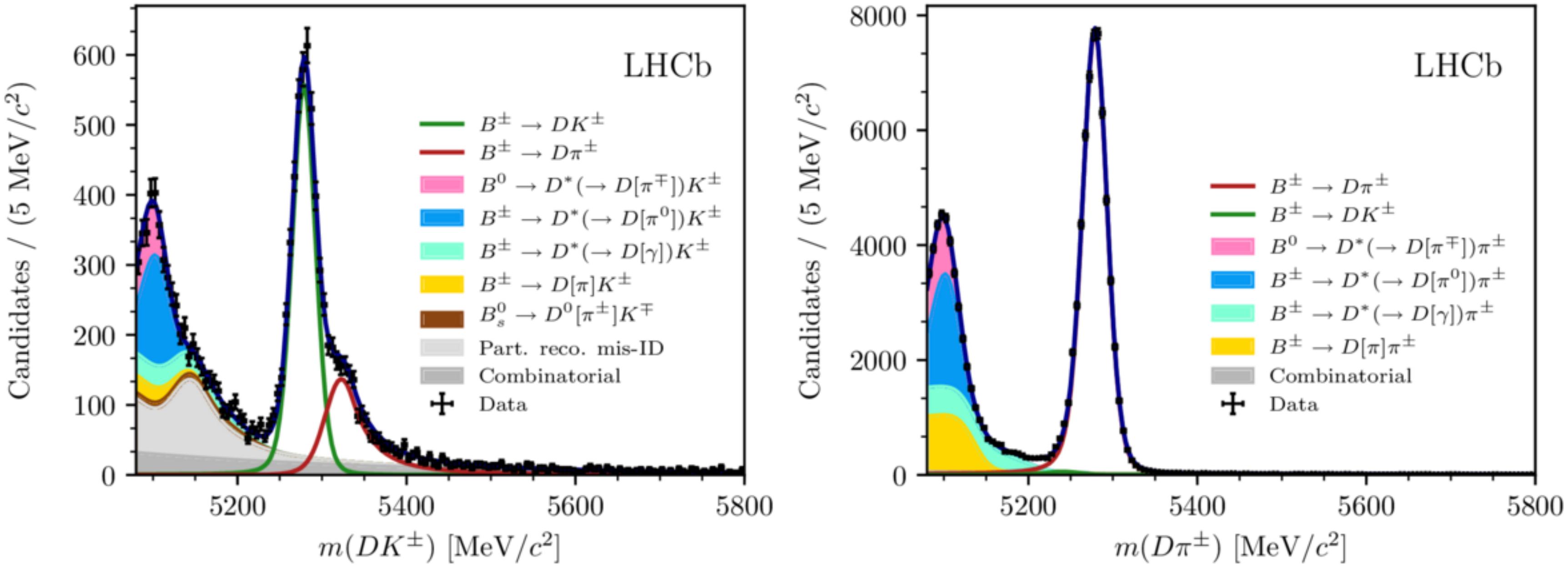
arXiv: 2011.12041

Measurement of the CKM angle γ in $B^{\pm} \to DK^{\pm}$ / $D\pi^{\pm}$

- D mesons reconstructed in the self-conjugate decay modes:

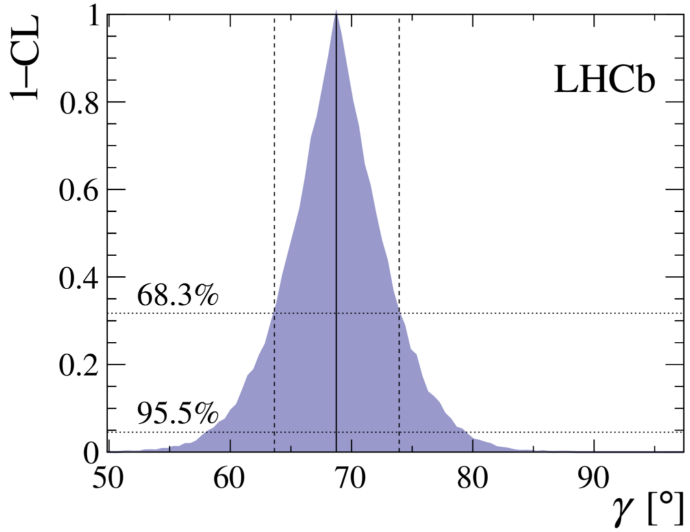
  $D \to K_S^0 \pi^+ \pi^-$ and
  $D \to K_S^0 K^+ K^-$

  common to D^0 and $\overline{D}^0$



- Analysis done in bins of D-decay phase space (Dalitz plot):
  → avoids assumptions on variation of the strong-phase across phase space.
- Result: $\gamma = \left(68.7^{+5.2}_{-5.1}\right)^{\circ}$
- Most precise single measurement!

  arXiv: 2010.08483



CP violation in two-body B_d^0 and B_s^0 decays

- Measurement of time-dependent CP asymmetries in the decays:

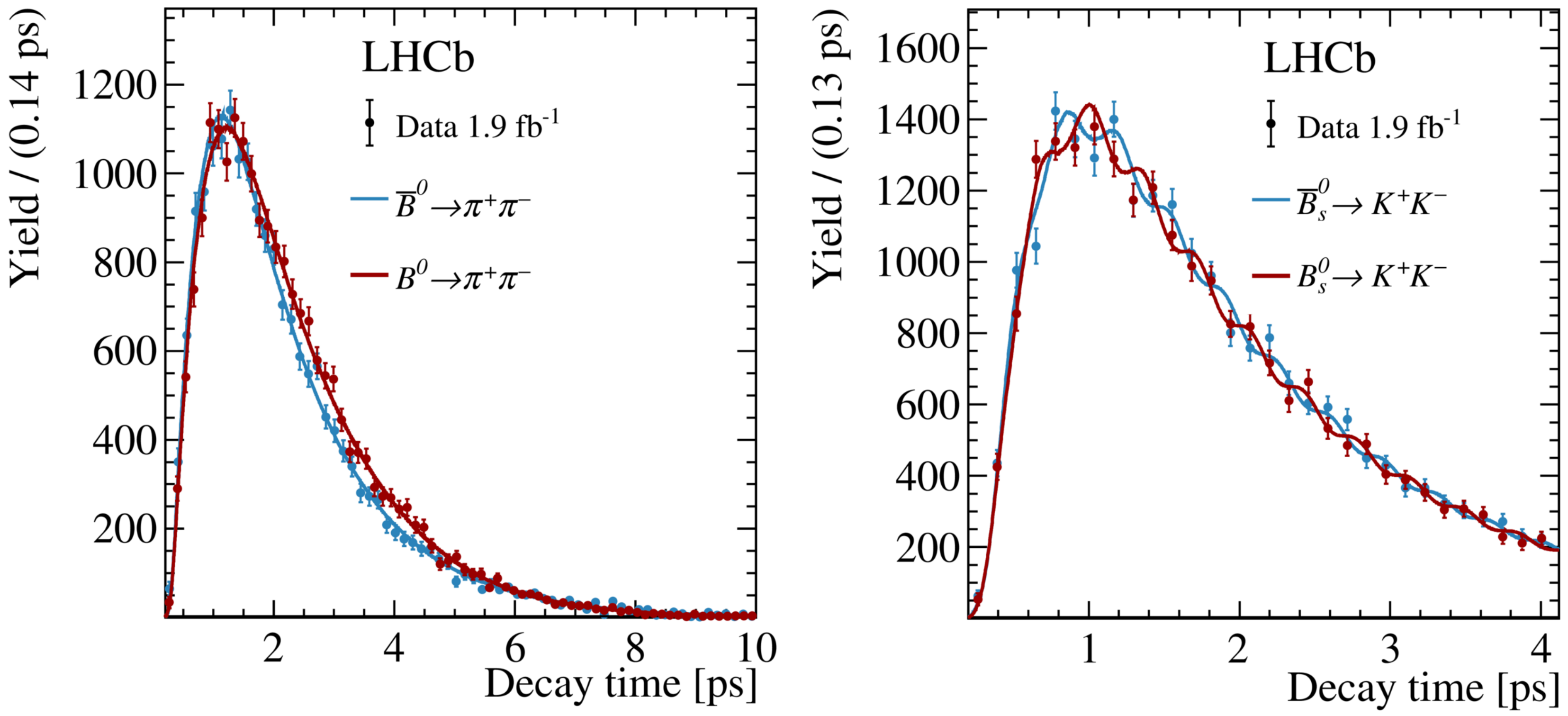
  $B_d^0 \to \pi^+\pi^-$ and

  $B_s^0 \to K^+K^-$

- Measurement of integrated CP asymmetries in the decays:

  $B_d^0 \to K^+\pi^-$ and

  $B_s^0 \to K^-\pi^+$



JHEP 03 (2021) 075

$$A_{CP}(B_d^0) = -0.0824 \pm 0.0033 \pm 0.0033$$

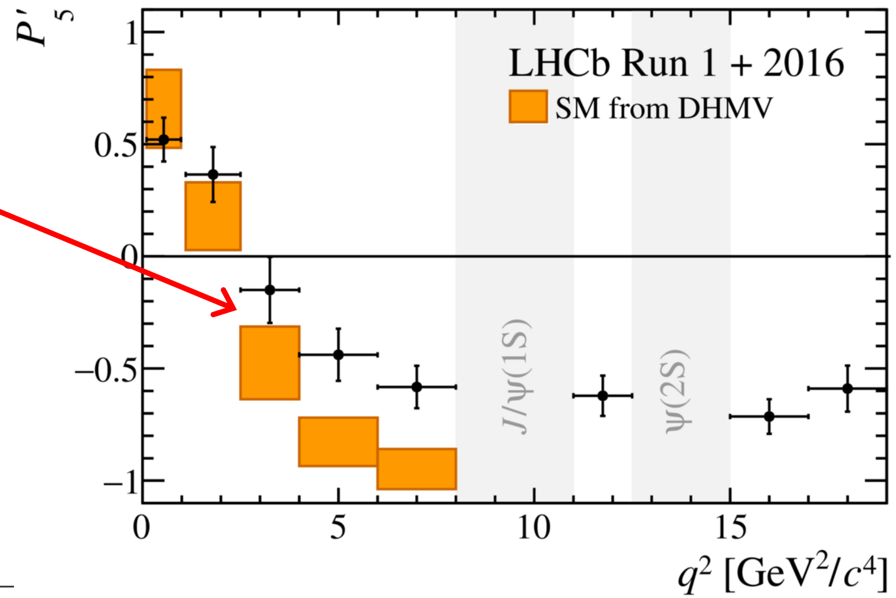
$$A_{CP}(B_s^0) = 0.236 \pm 0.013 \pm 0.011$$

Most precise single measurements!

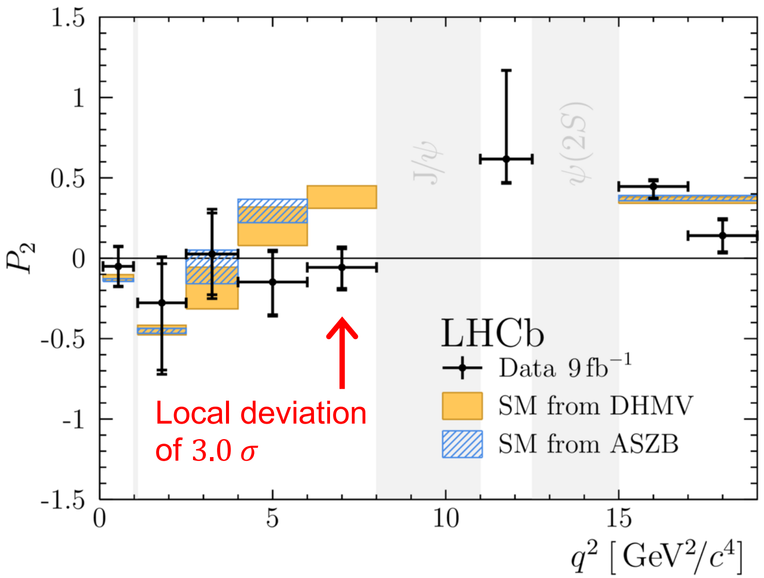
Angular analysis of the decay $B^+ \rightarrow K^{*+}\mu^+\mu^-$

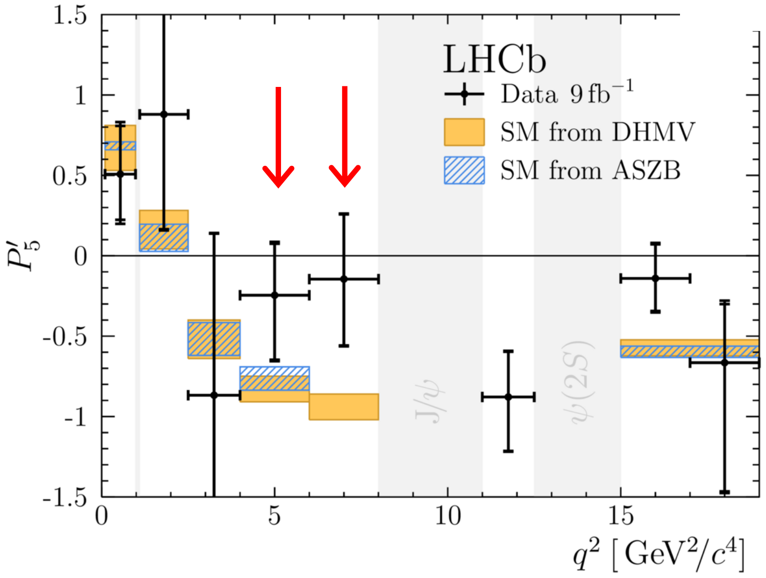
BERGISCHE UNIVERSITÄT WUPPERTAL

- Tensions observed in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays.
- Potential hint to BSM physics: e.g. leptoquarks.
- Investigate iso-spin partner decay: $B^+ \rightarrow K^{*+}\mu^+\mu^-$
- Veto events with $m(\mu^+\mu^-) = q^2$ close $\phi(1020)$, J/ψ or $\psi(2S)$
- Write the normalised differential decay rate as function of q^2 and three angles.



Phys. Rev. Lett. 125 (2020) 011802



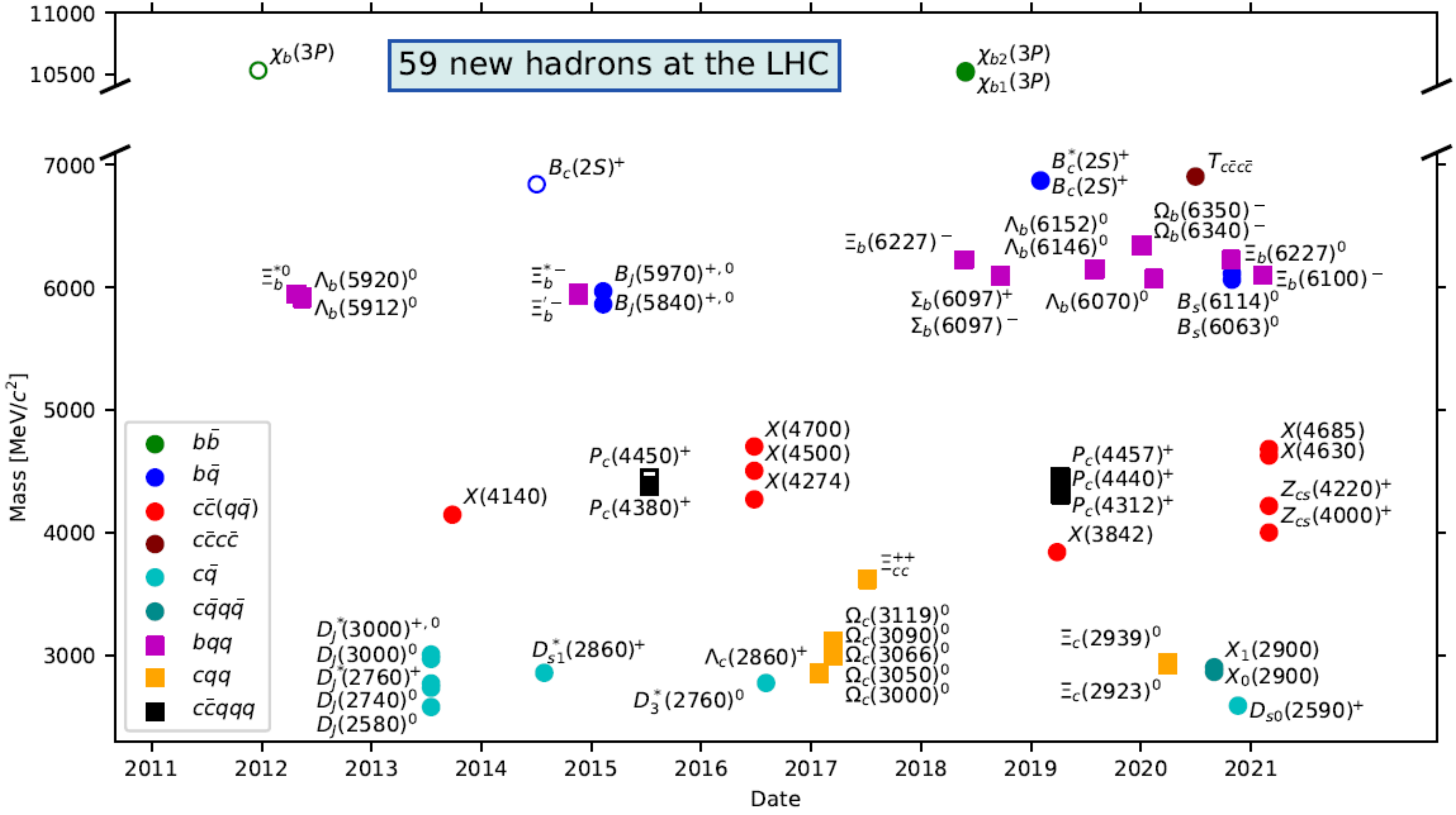


- Determine coefficients of the decay rate formula as a function of q^2.
- Pattern of deviations at intermediate q^2 are confirmed.

arXiv: 2012.13241

Hadron spectroscopy: 59 new particles discovered

BERGISCHE UNIVERSITÄT WUPPERTAL



[59 new hadrons and counting](https://cds.cern.ch/record/2749030)

https://cds.cern.ch/record/2749030

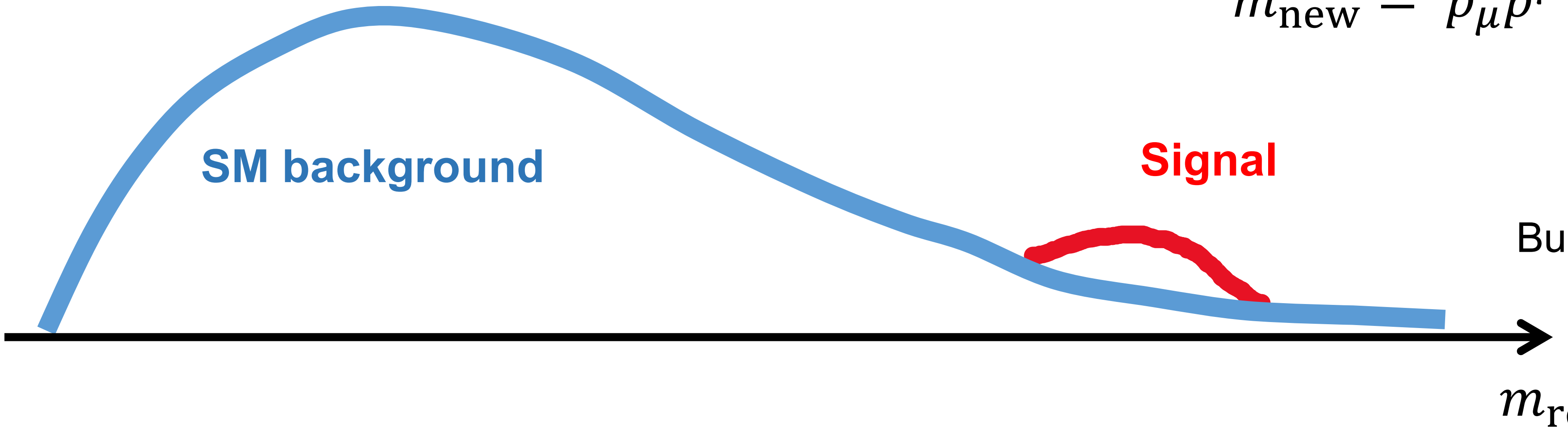
Part 4

Searches for physics beyond the standard model

More on "Searches" at this meeting:

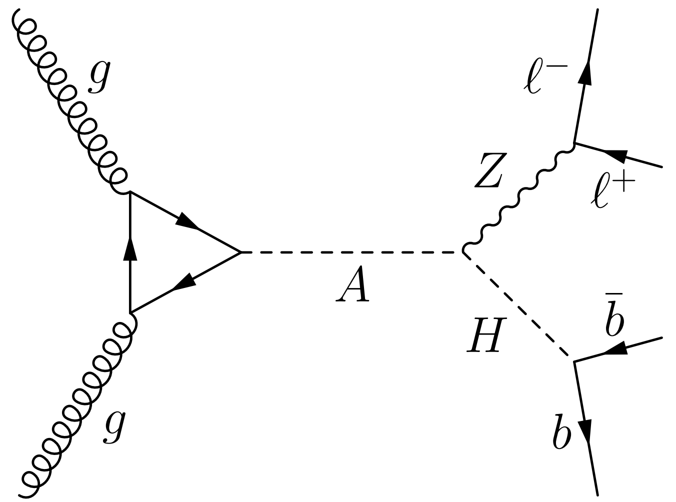
- Chris Malena Delitzsch: Looking inside jets – jet substructure techniques and their application in ATLAS, T 49.2, today 14:30
- Jeanette Miriam Lorenz: Searches for electroweak supersymmetry: highlights, coverage and limitations, T 74.1, Thursday 14:00
- Katharina Behr: To the top and beyond: top quarks as a probe of new interactions at the LHC, T 74.2, Thursday 14:30

$$m_{\text{new}}^2 = p_\mu p^\mu = E^2 - \vec{p} \cdot \vec{p}$$



Bump search

Search for a heavy CP-odd Higgs boson A

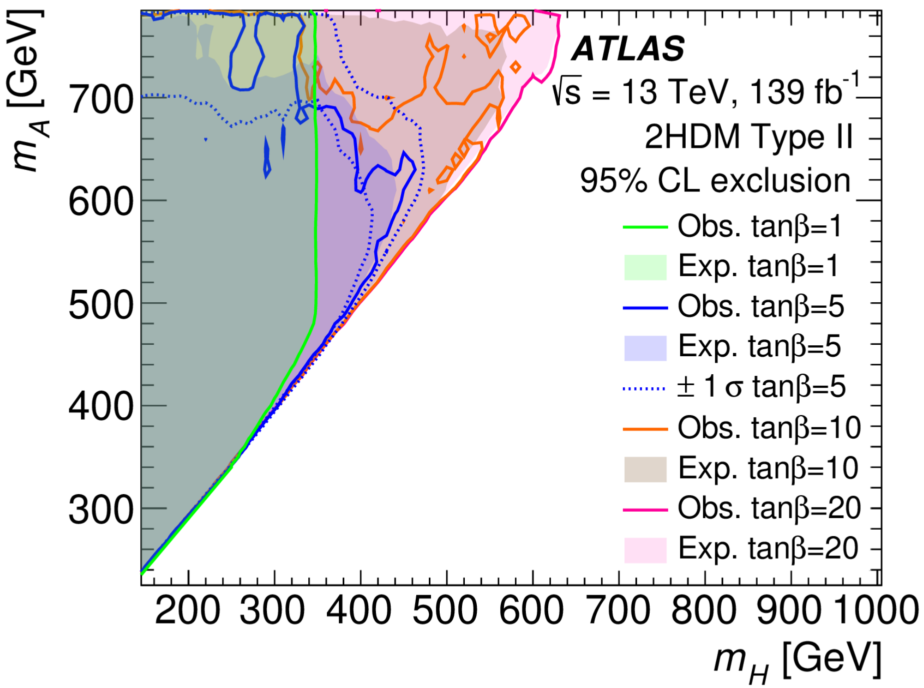


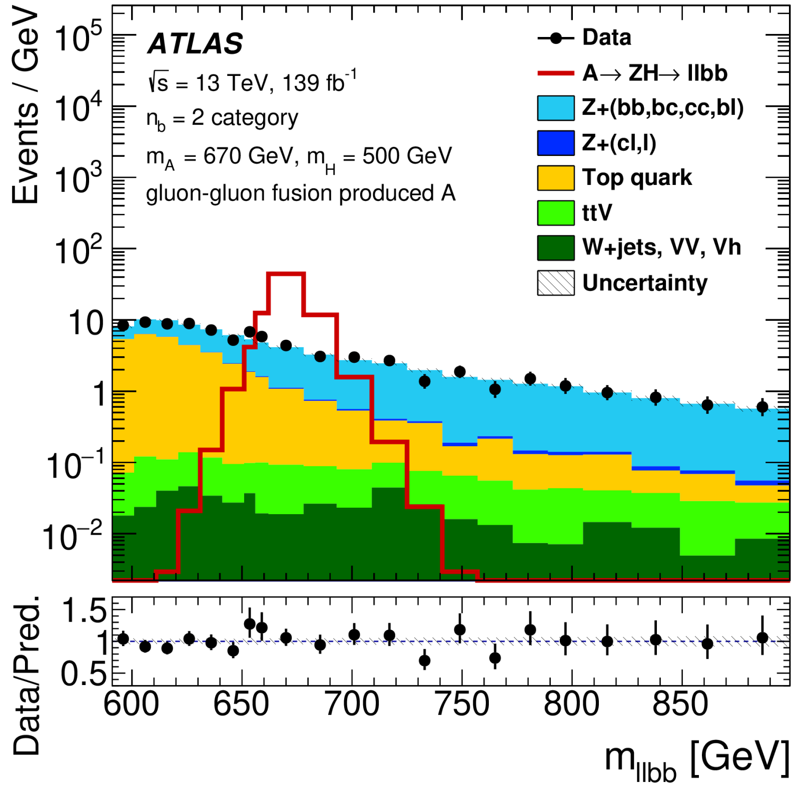
- Search for $A \to ZH$ events with $Z \to e^+e^-$ / $\mu^+\mu^-$ and $H \to b\bar{b}$ / W^+W^-
- Consider only hadronic W-boson decays.
- Search for resonant structures in $m(\ell^+\ell^- b\bar{b})$ and $m(\ell^+\ell^- q\bar{q}q\bar{q})$ spectra.

Interpretation in Two-Higgs-doublet benchmark models:

Limits as a function of $m(A)$, $m(H)$ and parameters α and β

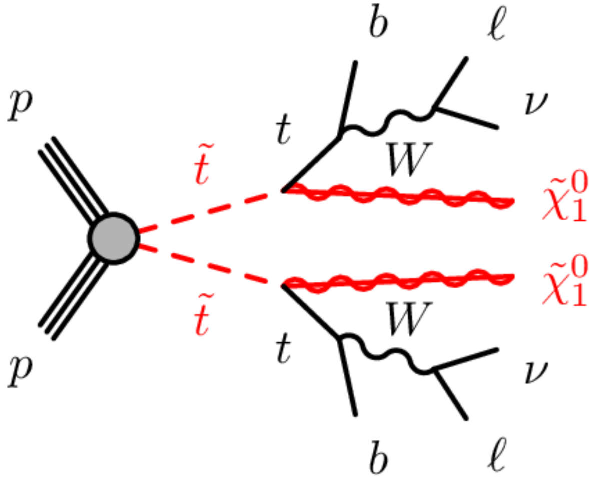
arXiv: 2011.05639



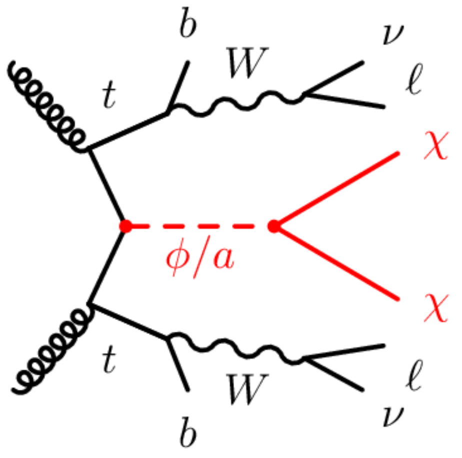


Search for top squarks and dark matter

Top squark pair production

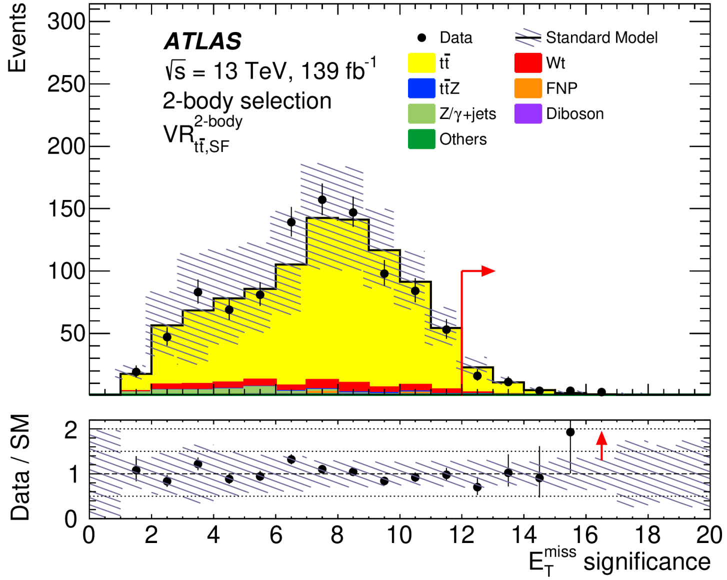


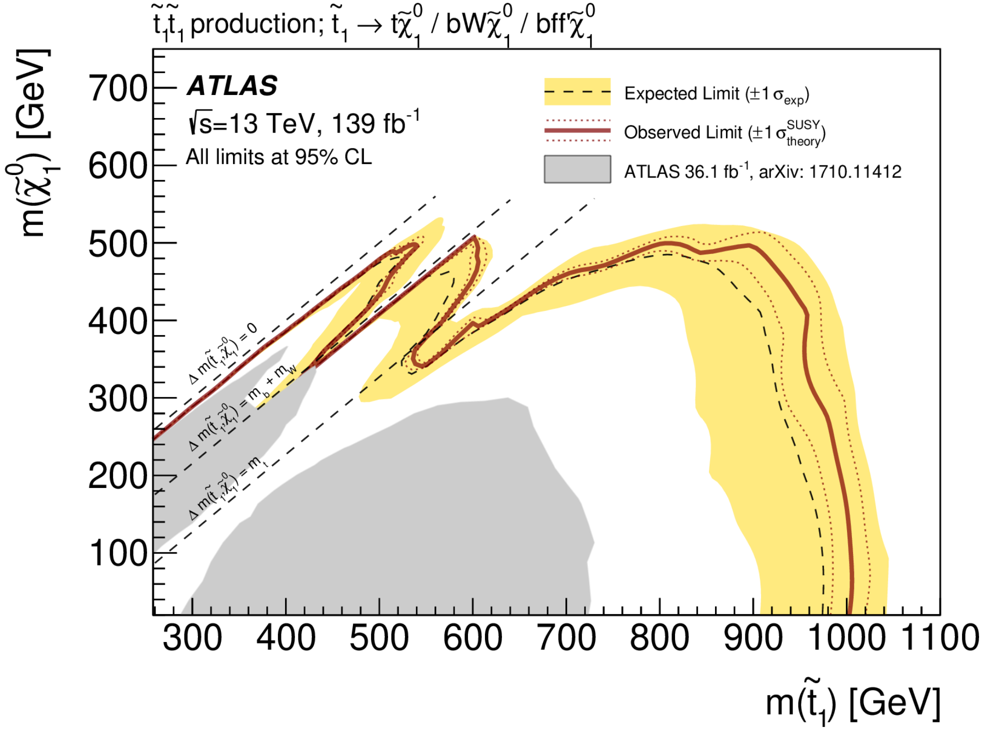
Dark matter production via mediator exchange



- Exploit common signature: $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$
- Select events with $e^{\pm}\mu^{\mp}$ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$
- Limit on mediator masses:
  $m(\phi) < 250$ GeV (scalar)
  $m(a) < 300$ GeV (pseudoscalar)
- Top squark and neutralino mass limits:

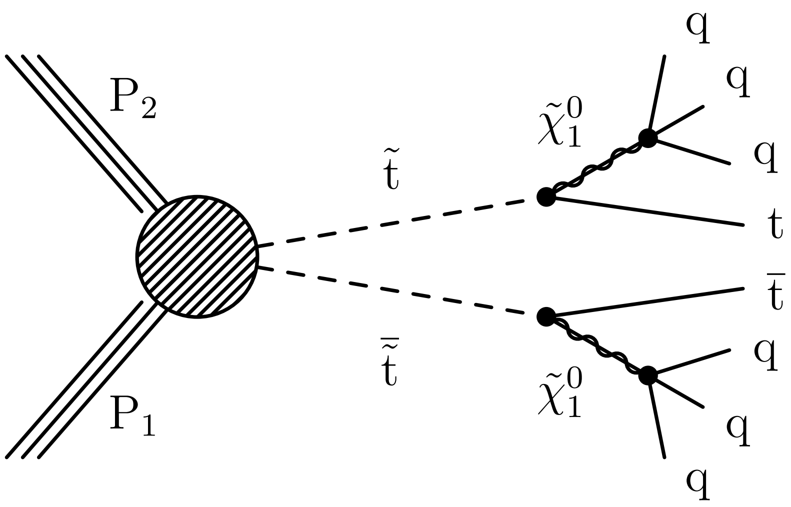
Requirement on the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance:



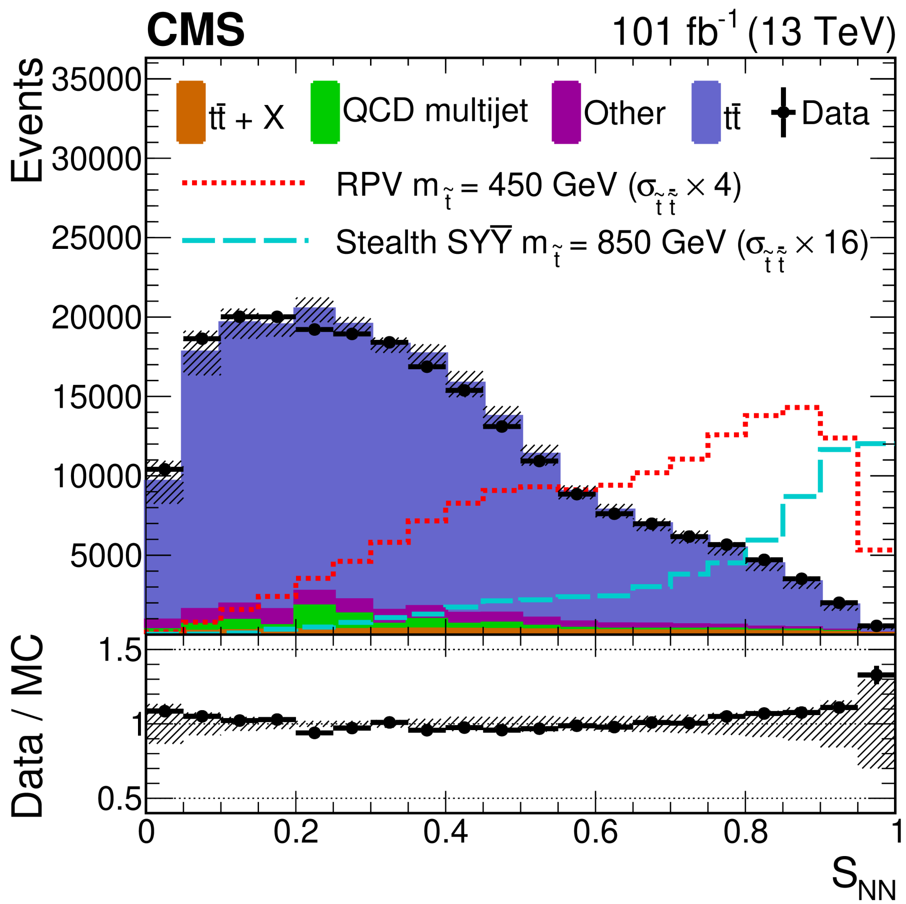


[arXiv: 2102.01444](https://arxiv.org/abs/2102.01444)

Search for top squarks in $t\bar{t}$ + jets final states



- Consider *R*-parity violation: the neutralino is unstable.
- Assume decay to light quarks.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ is relatively small.



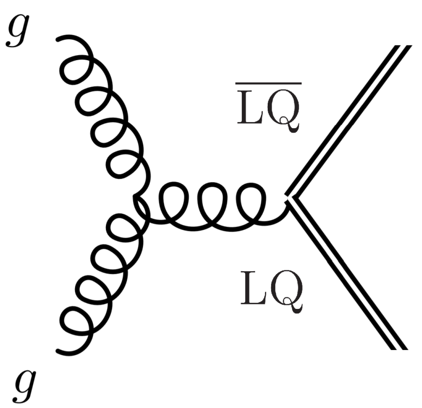
- Investigate benchmark model with $m(\tilde{\chi}_1^0) = 100$ GeV.
- Train neural network for separating signal and background.
- Top squarks excluded, if

  $300 < m(\tilde{t}) < 670$ GeV

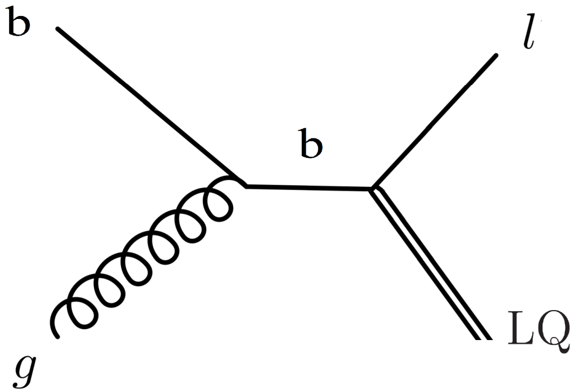
arXiv: 2102.06976

Search for leptoquarks

Pair production



Single production

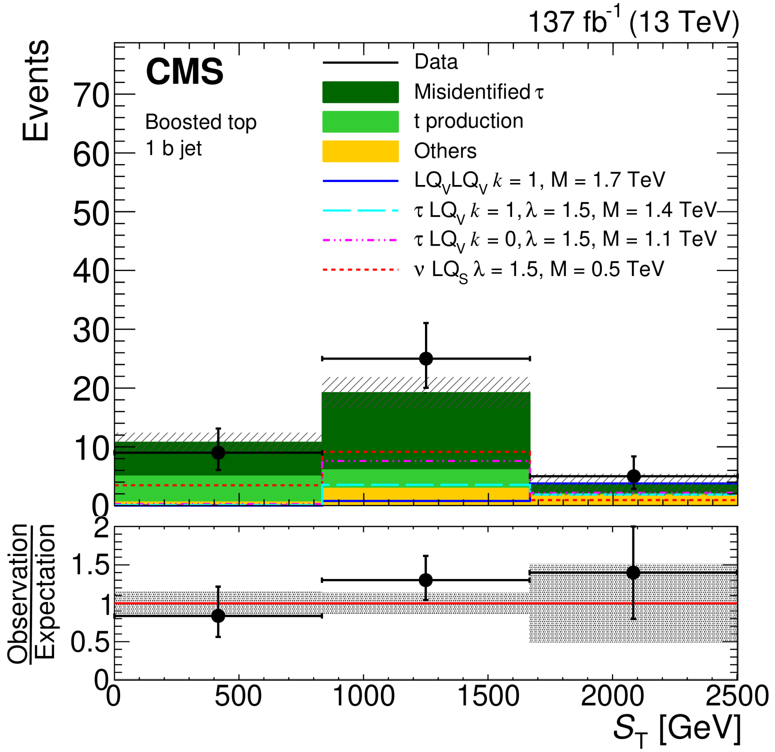


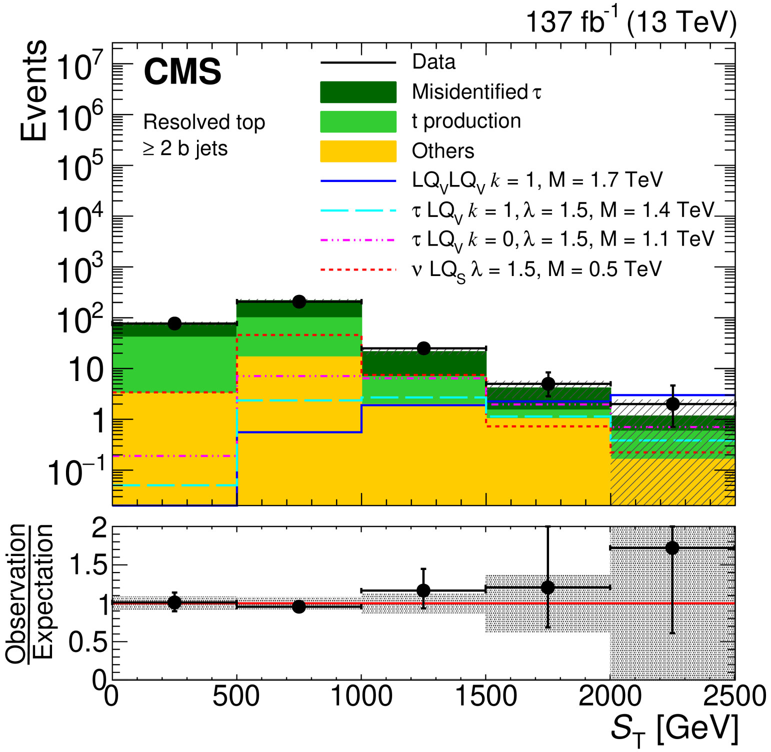
- Leptoquarks carry both lepton number and baryon number.
- Consider pair and single production simultaneously.
- Target $t\tau b\nu$ and $t\tau\nu$ signatures.

Upper limits on the LQ mass:

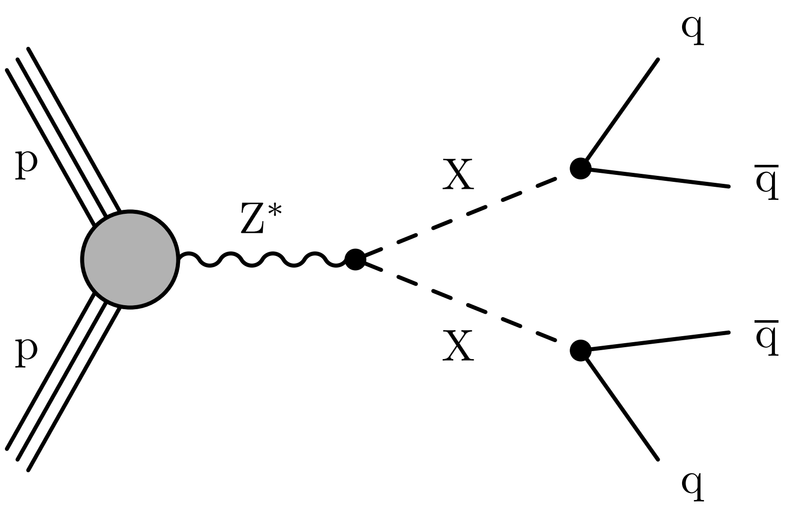
- $m(\mathrm{LQ}) > 0.98$ to 1.02 TeV (scalar)
- $m(\mathrm{LQ}) > 1.34$ to 1.73 TeV (vector)
- Depend on coupling assumptions.

arXiv: 2012.04178

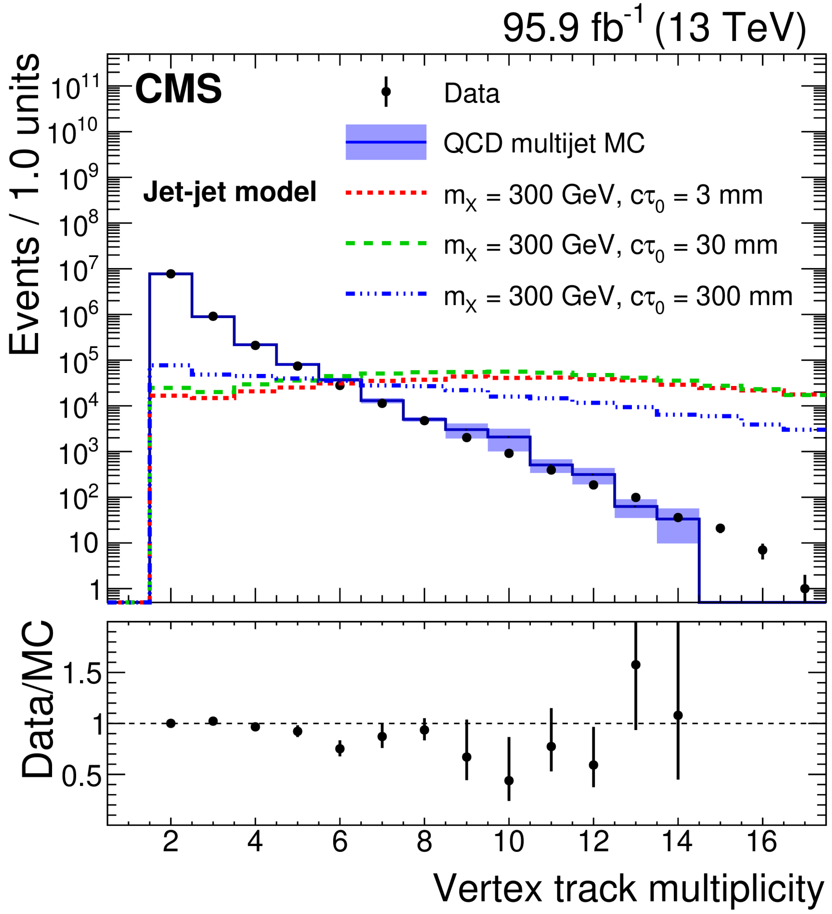




Search for long-lived particles producing displaced jets



- Benchmark model: Pair production of long-lived neutral scalar particle X decaying to a $q\bar{q}$ pair.
- Search for events with displaced tracks and displaced vertices associated with a dijet system.

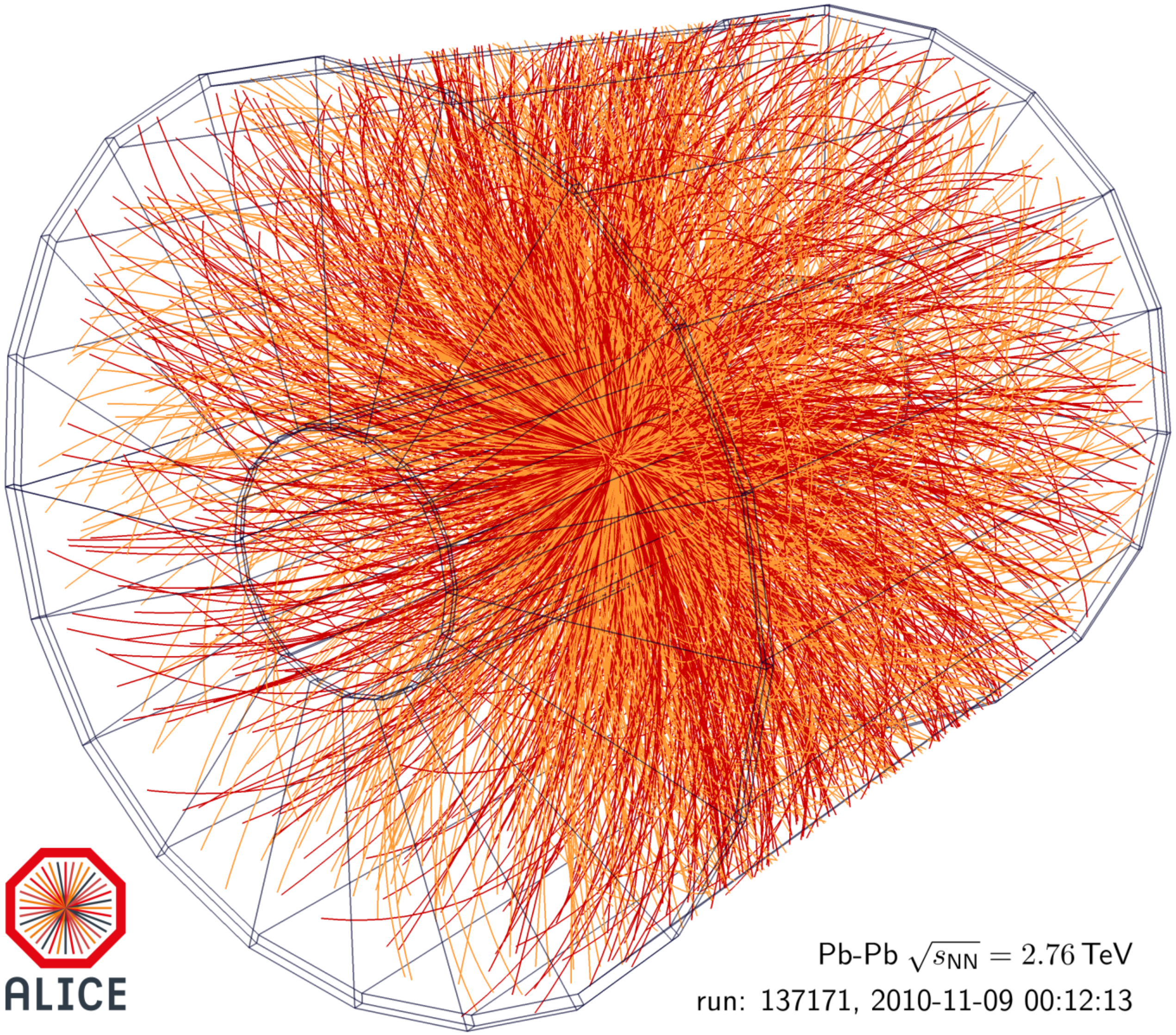


- Use a multivariate discriminant to separate signal and background events.
- Cross-section limits are set as a function of $c\tau$ and m_X.
- In addition interpretation in various SUSY models.

arXiv: 2012.01581

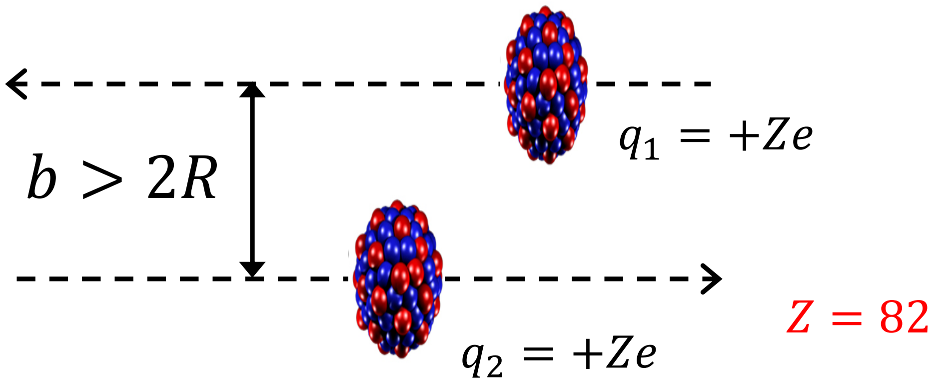
Part 5

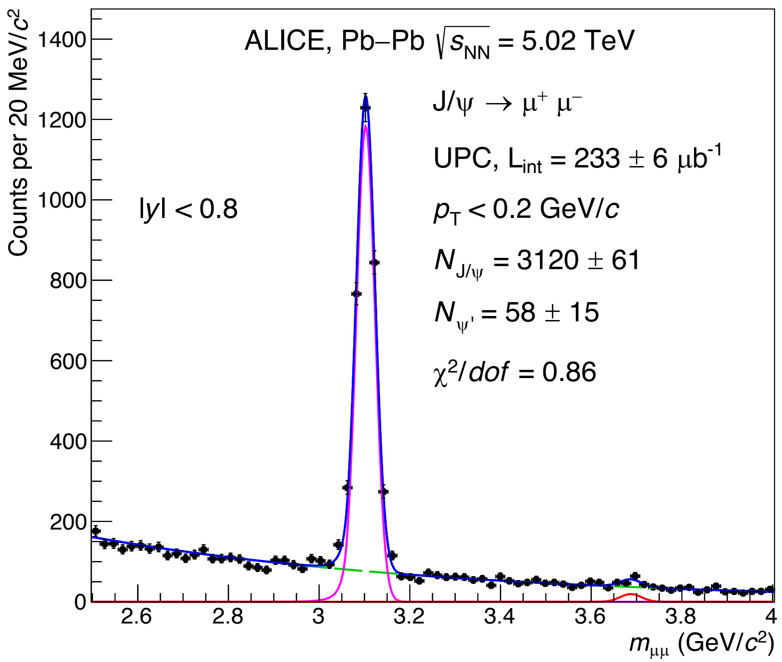
Heavy-ion collisions

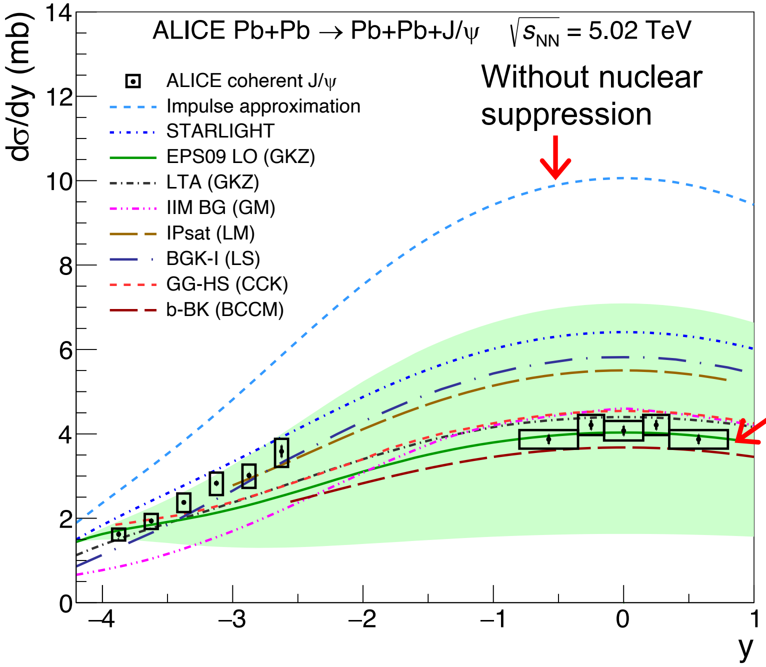


Coherent photoproduction of J/ψ and ψ'

- Look at ultra-peripheral Pb-Pb collisions.
- Hadronic interactions are suppressed (→ event veto).
- Large charges → large cross-sections
- Coherent production of mesons:
  photon interacts with the nucleus as a whole.







- Reconstruct:
  $J/\psi \to e^+e^- \;/\; \mu^+\mu^- \;/\; p\bar{p}$ and
  $\psi' \to e^+e^-\pi^+\pi^- \;/\; \mu^+\mu^-\pi^+\pi^-$
- Measure differential cross-sections in the midrapidity range:
  $-0.8 < y(\psi) < 0.8$
- Nuclear suppression factor due to gluon shadowing:

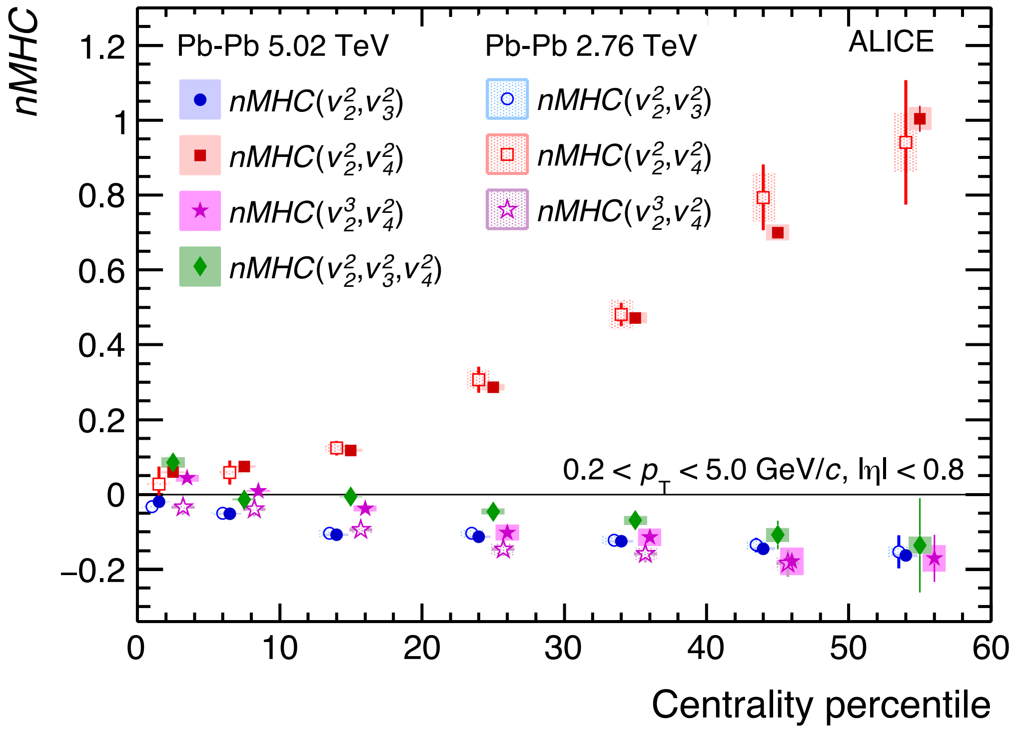
$$R_g(x, Q^2) = \frac{g_{\text{nuc}}(x, Q^2)}{g_{\text{prot}}(x, Q^2)} = 0.65 \pm 0.03$$

arXiv: 2101.04577

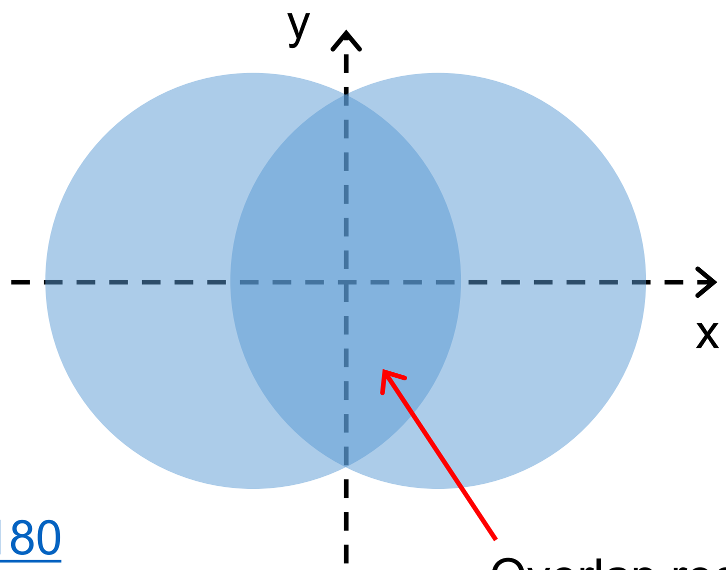
Measurement of mixed harmonic cumulants

- Almond shape of overlap region creates an anisotropy of the pressure gradient in the transverse plane.
  → anisotropy of azimuthal particle distribution
- Express the single-particle distribution as a Fourier series:

$$P(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \psi_n)\right]$$



arXiv: 2102.12180



- Fourier coefficient $v_n \equiv$ nth-order flow coefficient
- Measure mixed moments of different flow coefficients for investigating correlations as a function of centrality.
- Important input for testing hydrodynamic and transport models describing the evolution of a quark-gluon plasma.

Conclusions

- Experiments at the LHC are measuring a impressingly broad range of particle physics phenomena.
- Test the standard model in various ways:
  precision measurements – indirect searches – direct searches
- Recent highlights include:
  - Super-precise Higgs-mass measurements at 1 pre-mille level.
  - Evidence for $H \to \ell^+\ell^-\gamma$ and $H \to \mu^+\mu^-$ decays.
  - Evidence for 4-top-quarks production.
  - Precise measurement of the CKM angle γ at 5° precision.