Standard Model (including Top) at LHC

Reinhild Yvonne Peters

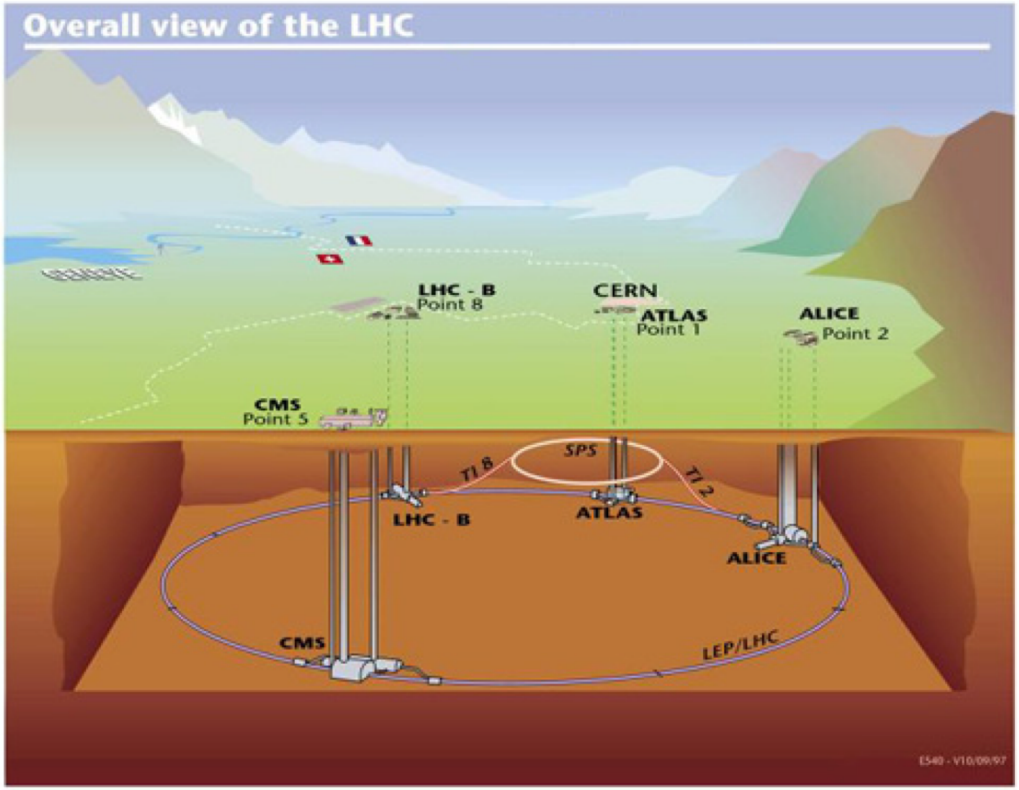
The University of Manchester

European Research Council

Established by the European Commission

The Large Hadron Collider

- Proton-proton and heavy ion (Pb+Pb) collisions
- pp collision Run I: 2011: 7 TeV; 2012: 8 TeV
- pp collision Run II: until end of 2018 with 13 TeV
- Special runs: 900 GeV, 2.76 TeV and 5.02 TeV



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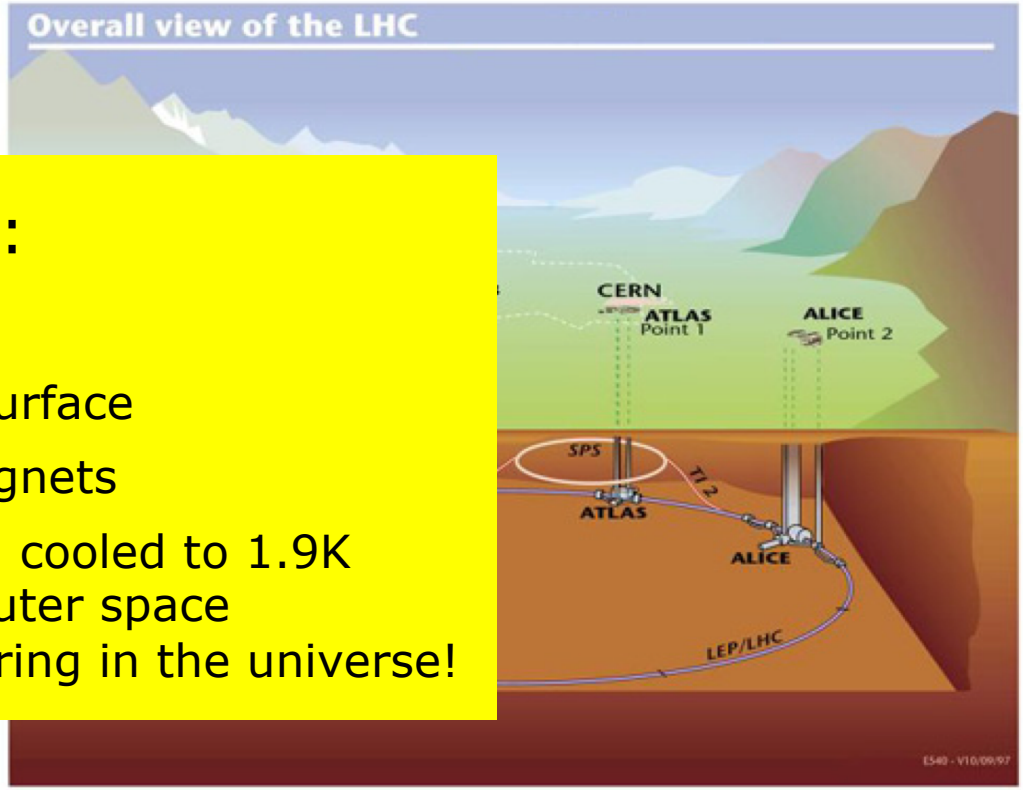
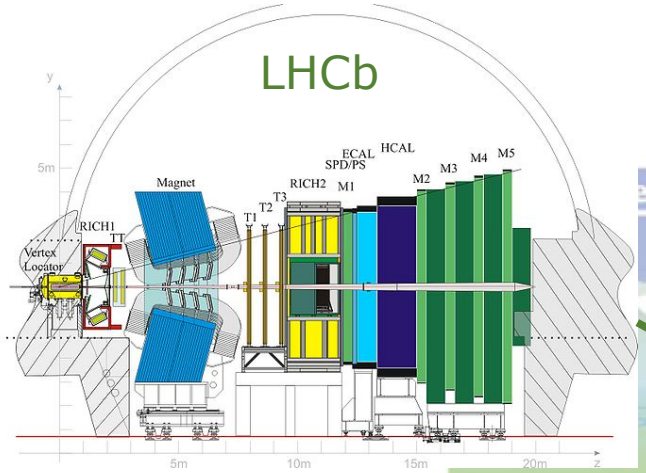


LHC Fun Facts:

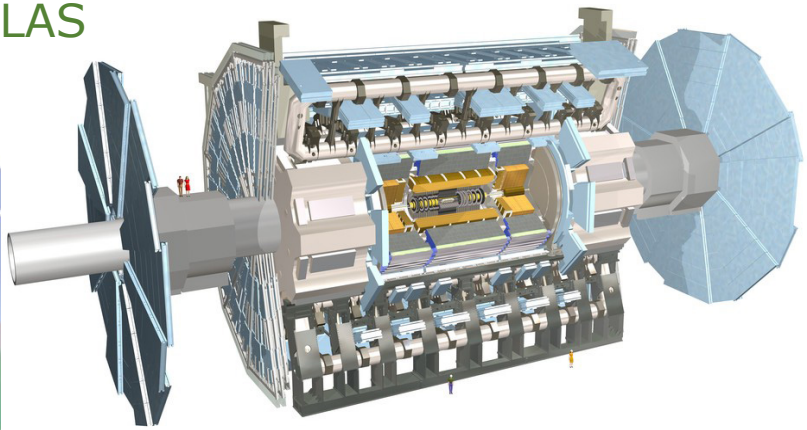
- 27 km ring
- ~100m under surface
- 1232 dipole magnets
- Magnets getting cooled to 1.9K
  → colder than outer space
  → LHC: coolest ring in the universe!

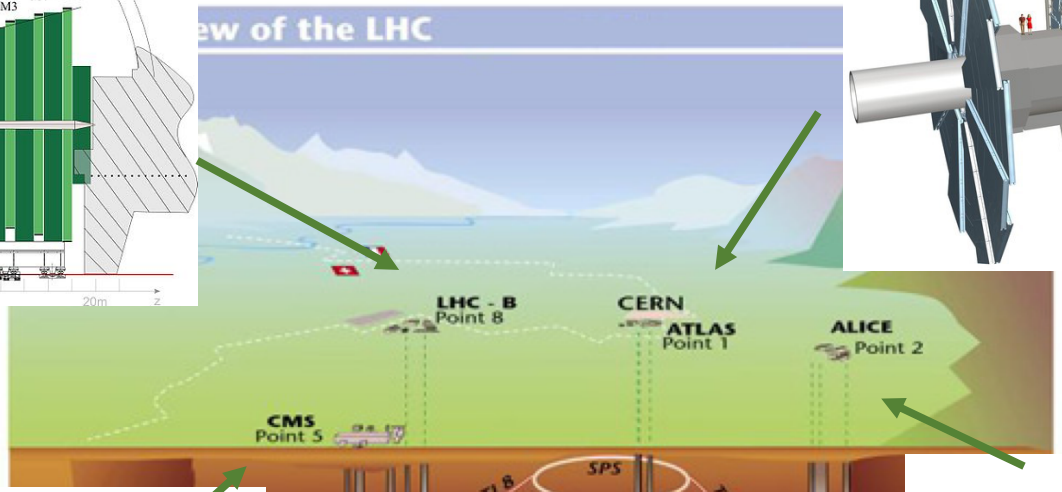
The LHC Experiments

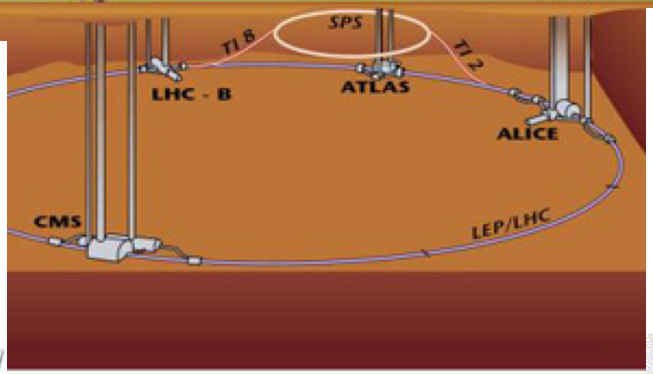
LHCb



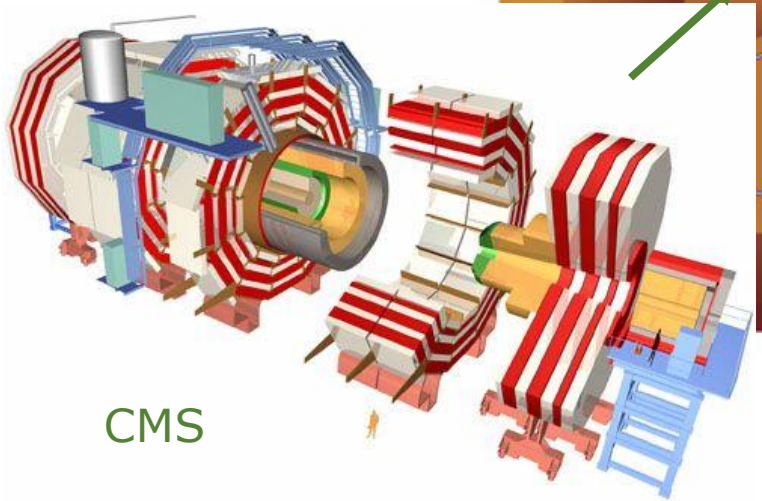
ATLAS



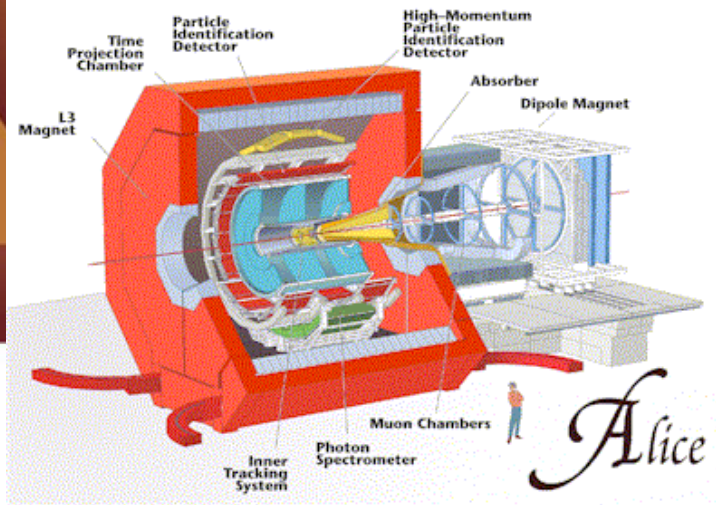




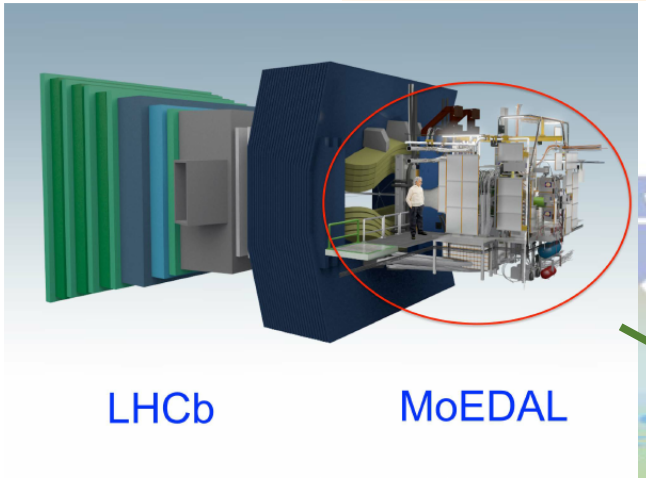
CMS



ALICE



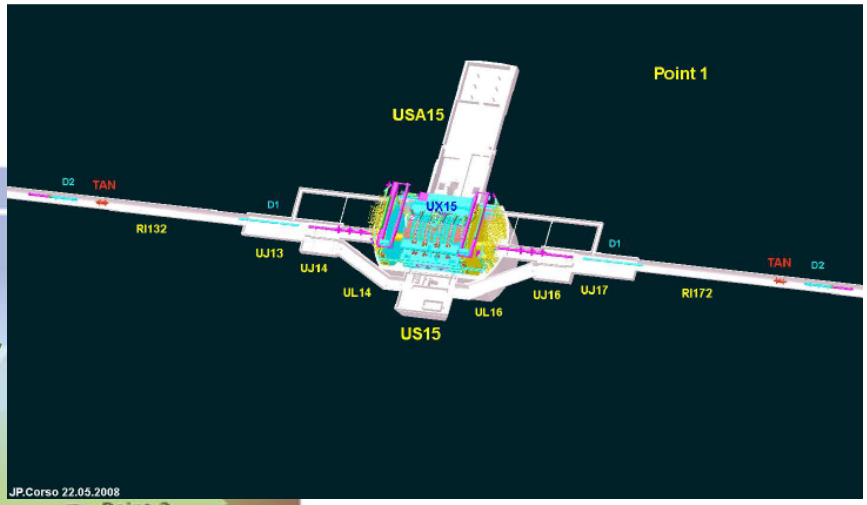
More LHC Experiments

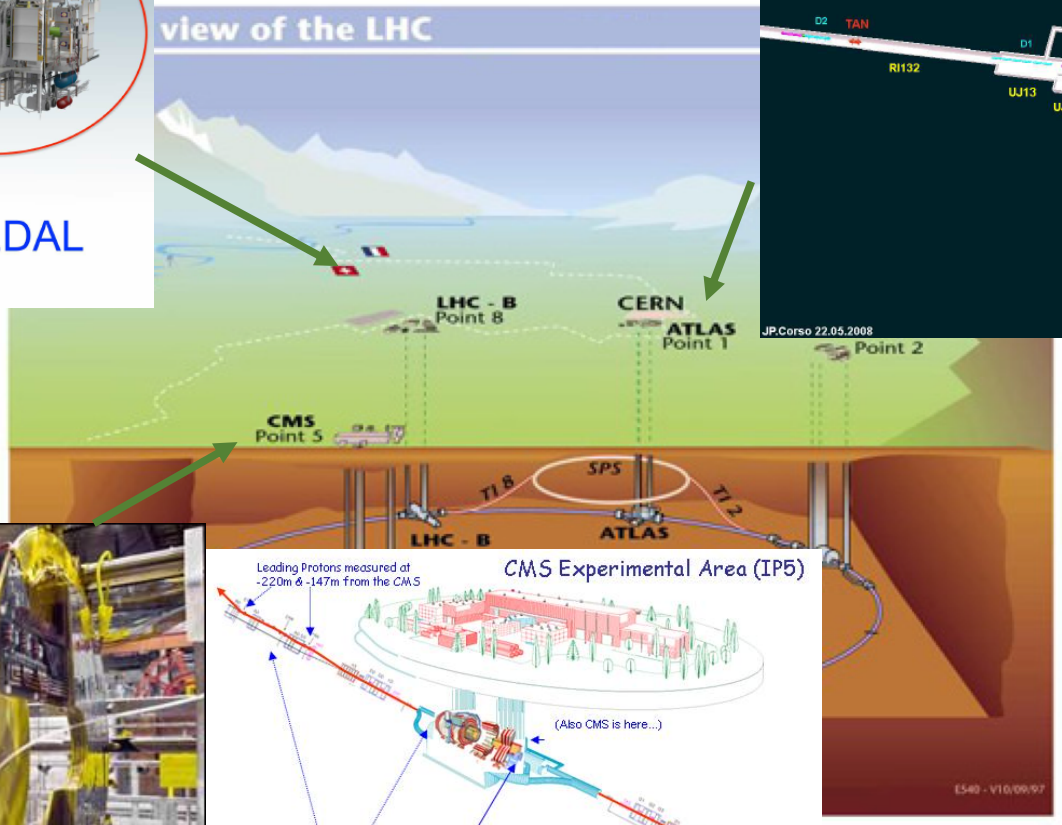


LHCb MoEDAL

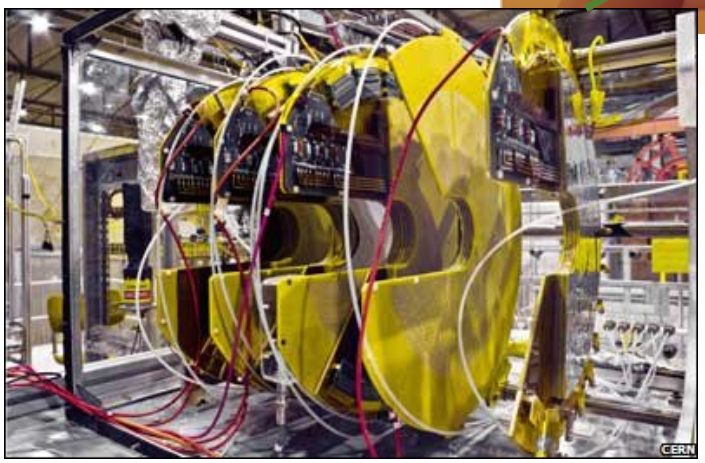
MoEDAL

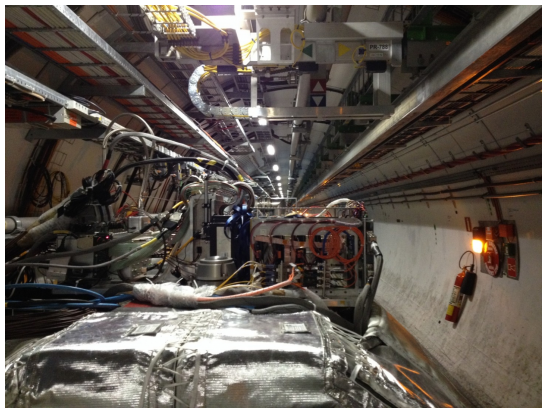
LHCf





TOTEM





All Experiments

- ATLAS & CMS: general purpose detectors
- LHCb: forward spectrometer
  → focused on b & c physics
- ALICE: study heavy ion interactions
  → quark-gluon plasma

- Smaller experiments:
  - Totem: forward detectors (around CMS)
  - LHCf: forward detector (around ATLAS)
    → both for forward physics
  - MoEDAL: near LHCb
    - Search for magnetic monopoles

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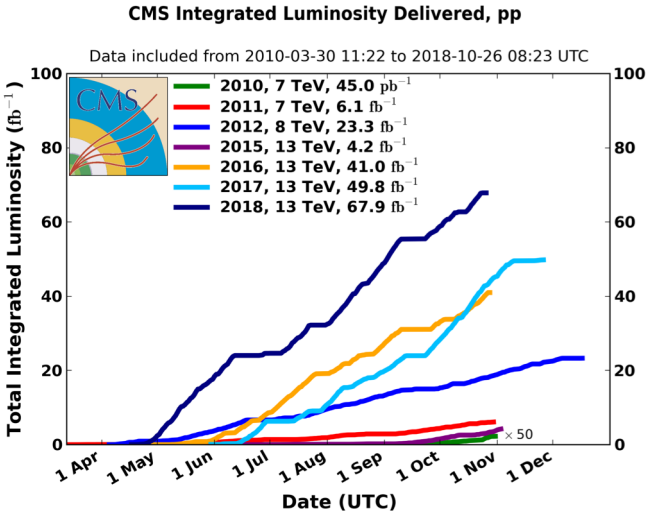
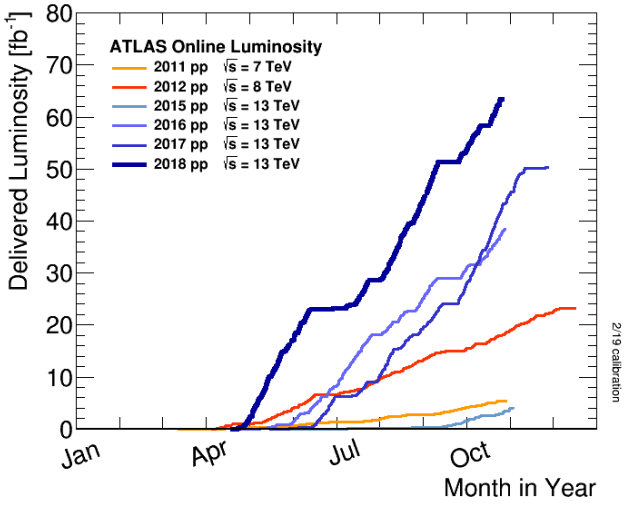
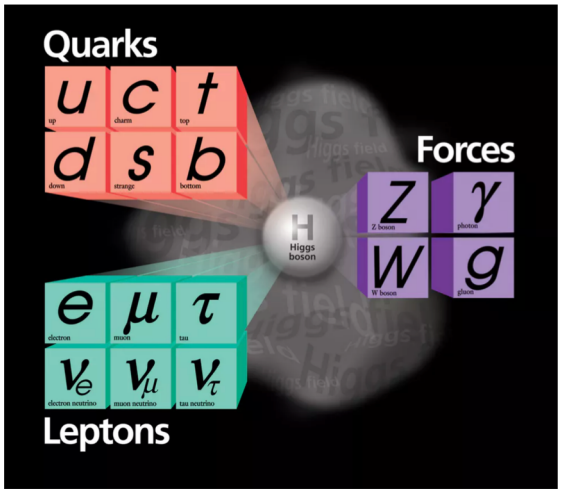
- All quite interesting
  - This talk: focused on ATLAS & CMS





The Standard Model

- Standard Model of Particle Physics:
  our best current description of matter and its interactions
  - Since 2012: technically completed with the Higgs sector
- What are "standard model" measurements?
  - Measurements of free parameters of the SM
  - Measurements of standard model processes
    - Scrutinizing the SM to find hint for new physics



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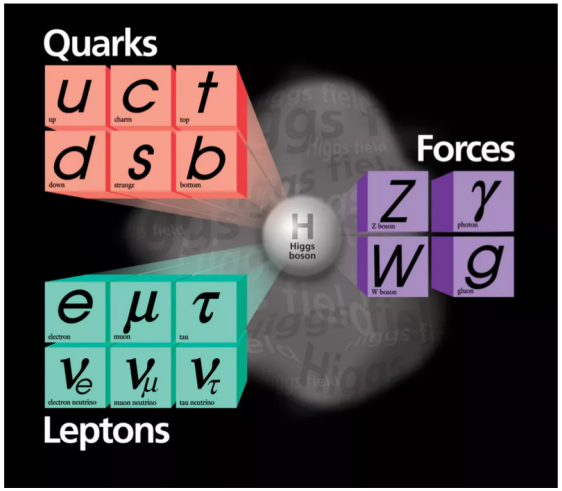
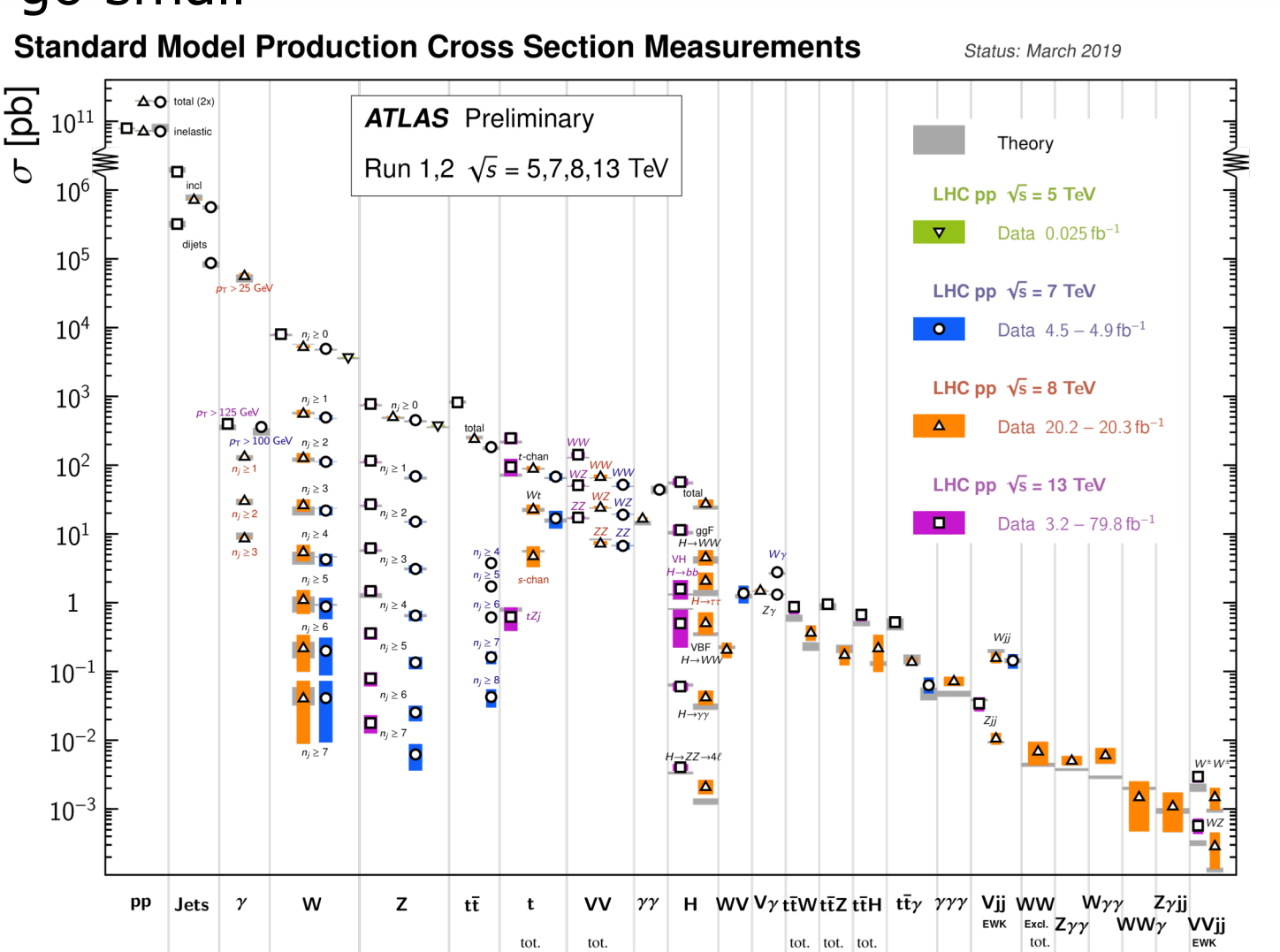


- What are "standard model" measurements?
  - Measurements of free parameters of the SM
  - Measurements of standard model processes
    - Scrutinizing the SM to find hint for new physics

- What are "standard model" measurements in this talk?
  - Everything above
    - Minus Higgs sector (see Trevor's talk)
    - Minus "flavour" sector (see Sneha's talk)
    - Minus everything not done at LHC (e.g. neutrino sector, g-2,…)
  - Given it is one talk and not whole conference: selected topics only

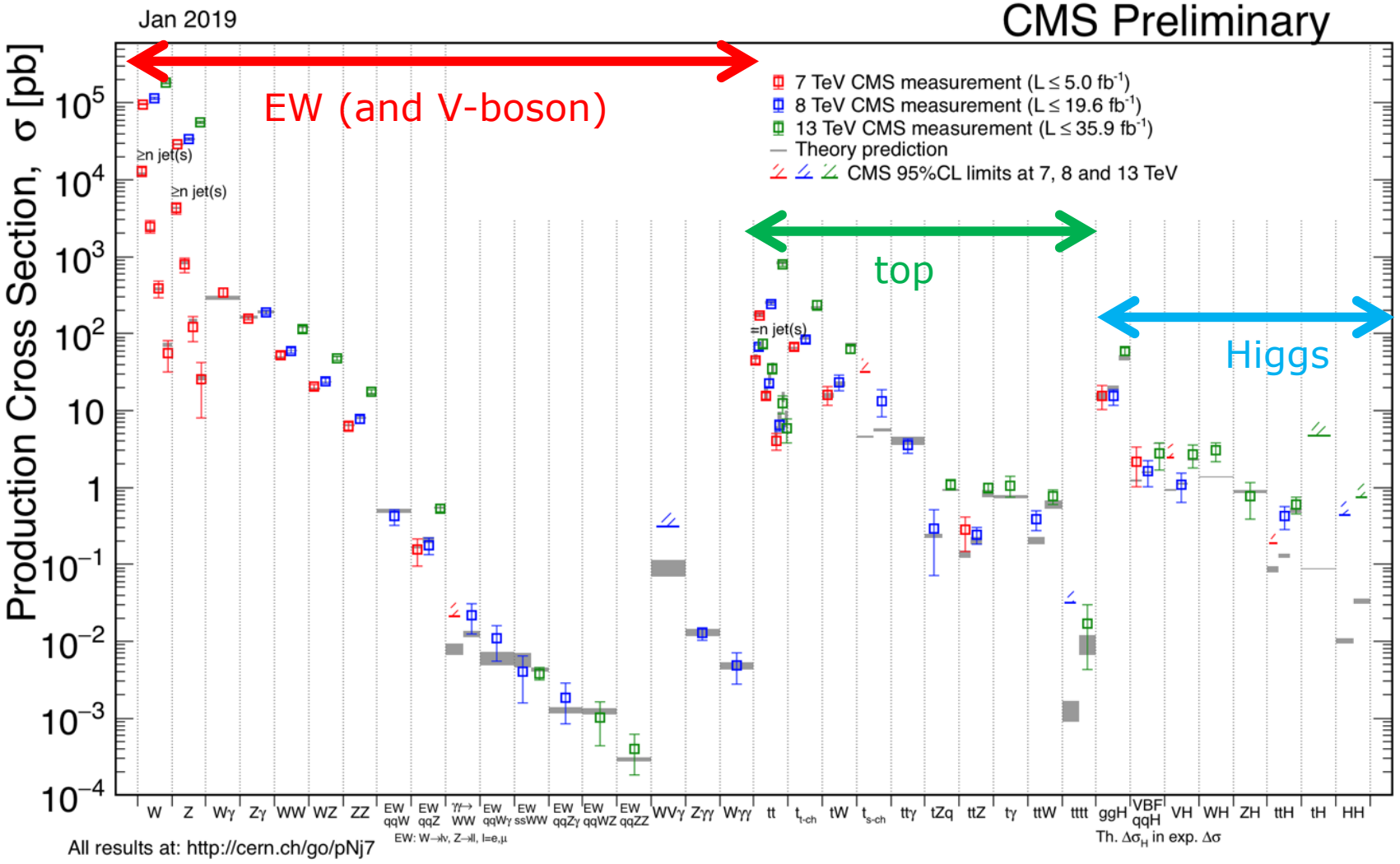
SM Measurements

- Start big, go small



SM Measurements

- Grouping



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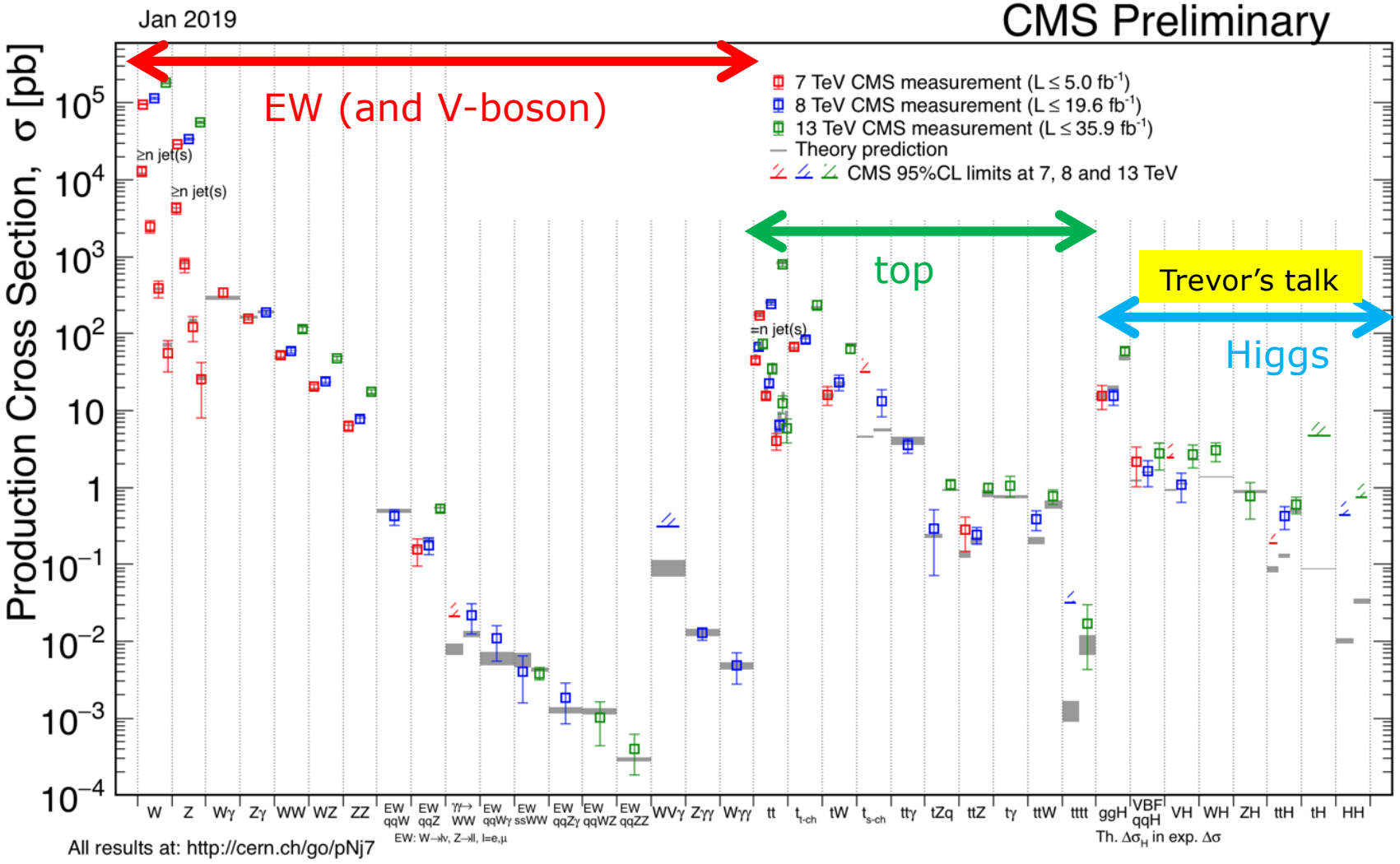
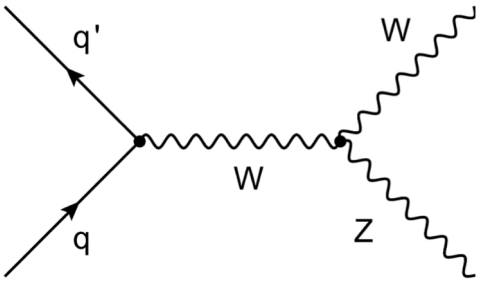
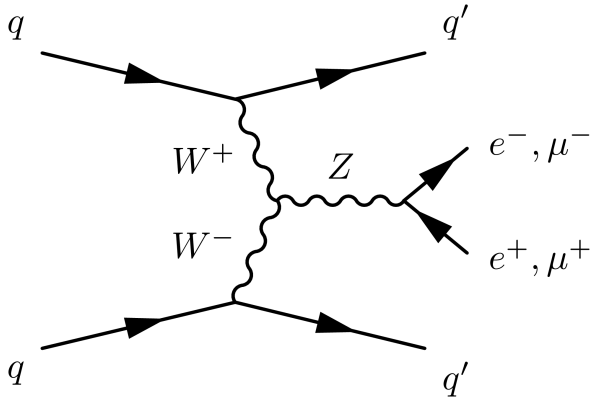
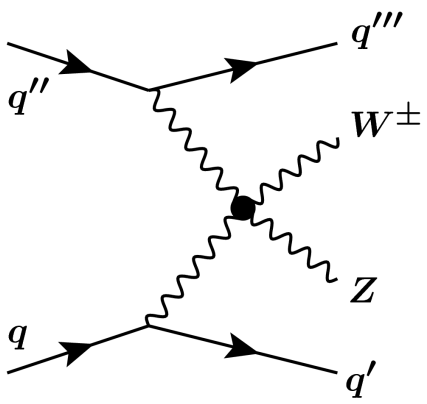


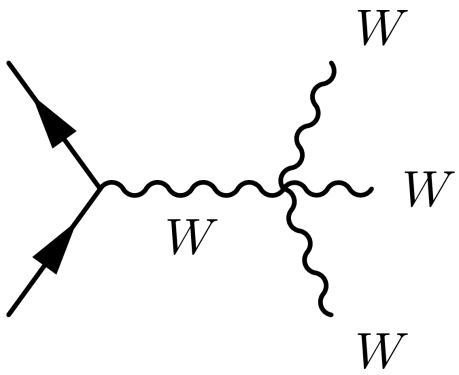
Electroweak and Vector Bosons

- Precision electroweak measurements: test of the SM
- Several new studies of vector bosons
  - Test of gauge symmetry and search for anomalous couplings
- VV production: WZ (cross section and polarization)
- VBF: EW W production
- VBS: Same sign WW, WZ
- VVV production:
  - WWW, WWZ, WZZ



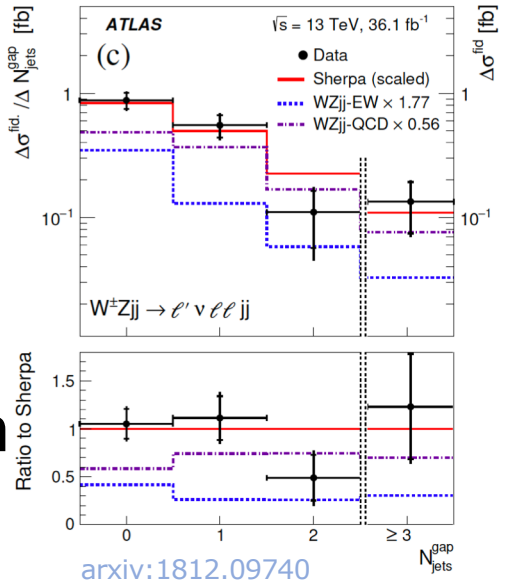






New Vector Boson Measurements

- Measurement of WZ production
  - Measurement of gauge boson polarization
- Observation of electroweak VBS WZ production
- Observation of VBS same sign WW production
- Measurement of electroweak VBF W production
- Measurement of 4-lepton invariant mass spectrum
- Search for anomalous electroweak production of WW/WZ/ZZ



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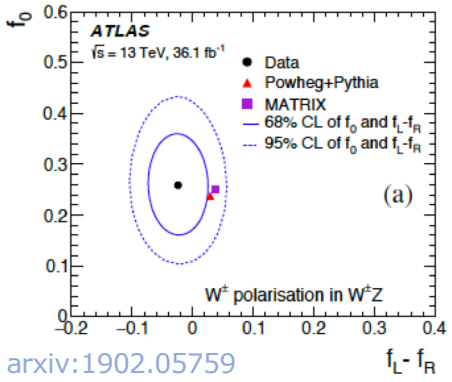

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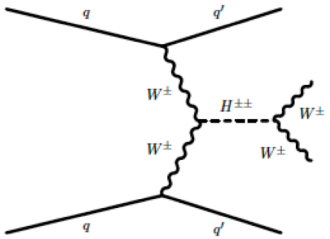

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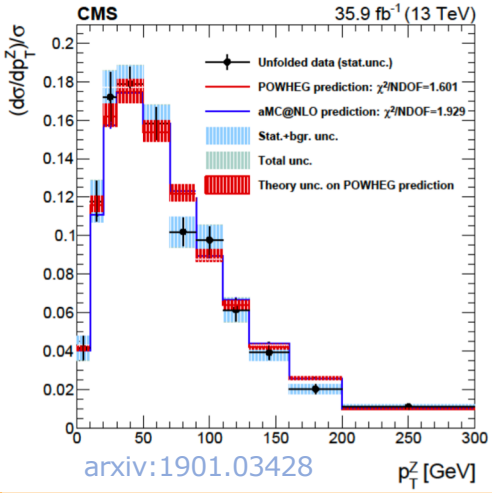

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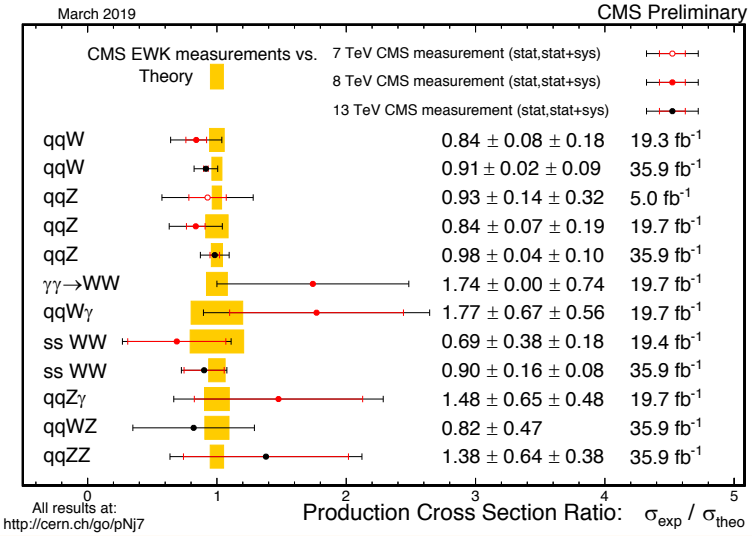
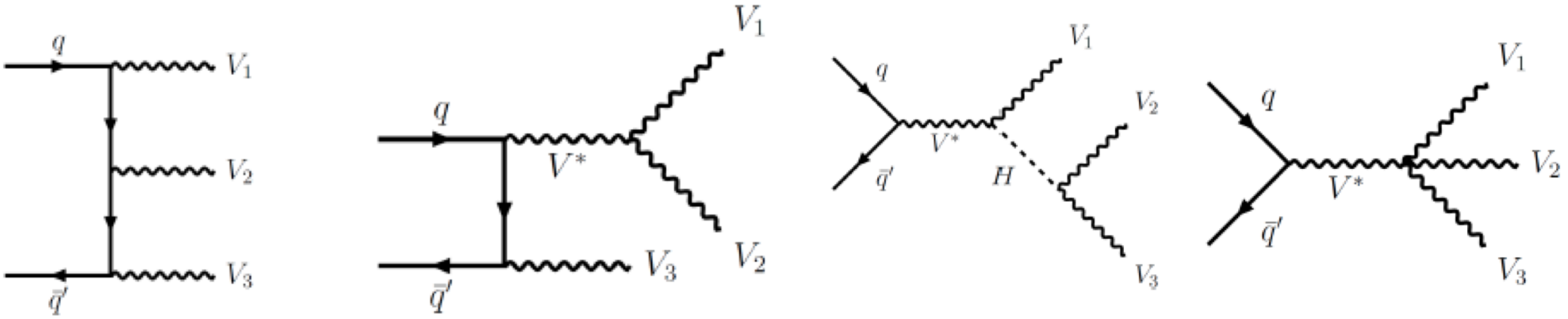


VVV Results

- VVV production sensitive to triple and quartic gauge couplings



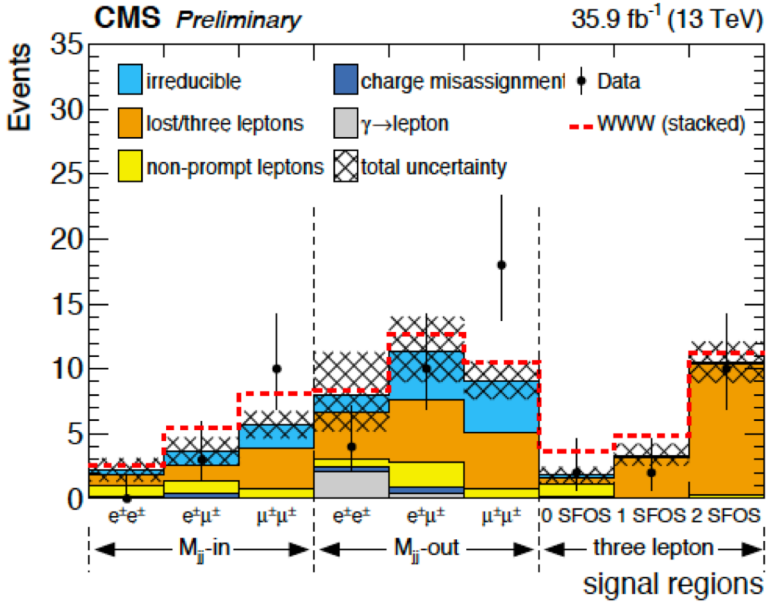
- Deviations from SM: can provide hints of NP at higher scales
- Complex analyses
  - Consider different signatures
  - Good estimation of backgrounds crucial
- New analyses by ATLAS and CMS

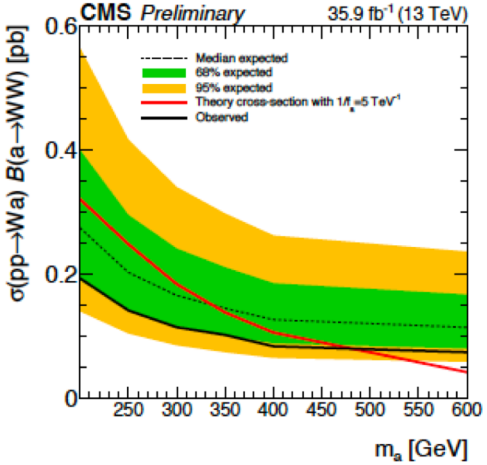
VVV Results

- New CMS measurement of WWW production
- Result: 34% of SM prediction

$$\sigma_{\mathrm{WWW}} = 173^{+326}_{-173}\ \mathrm{fb}$$

  - Prediction: $\sigma_{\mathrm{WWW}} = 509 \pm 13\ \mathrm{fb}$
- Interpretations
  - 1. Limits on anomalous quartic gauge couplings
  - 2. Limits on axion-like particles



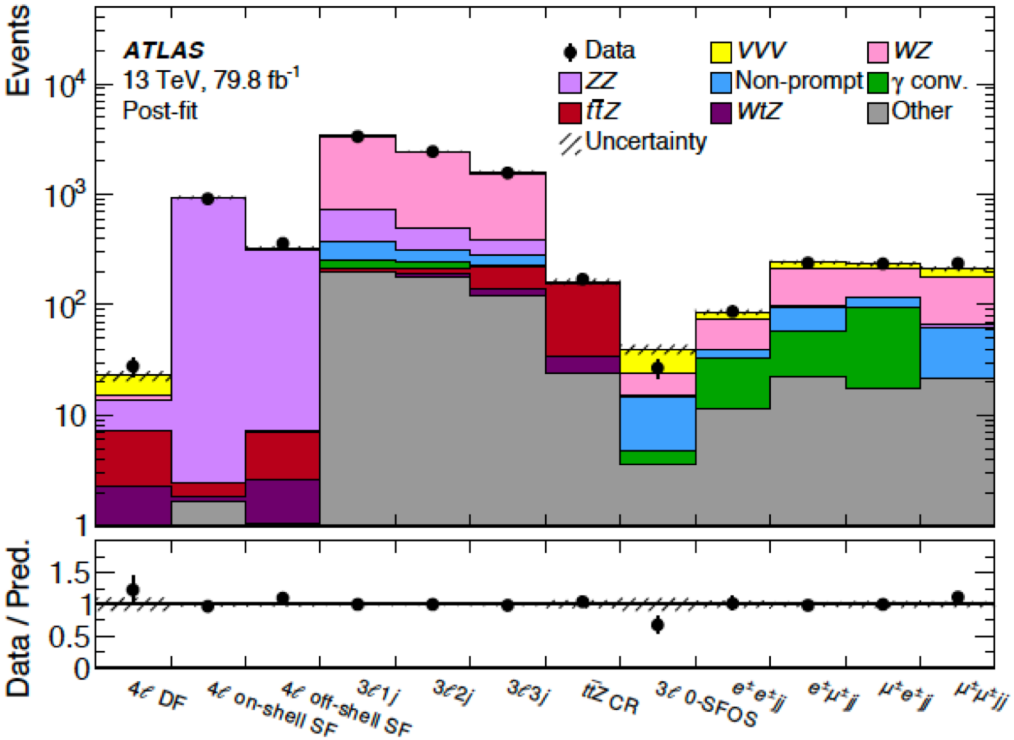


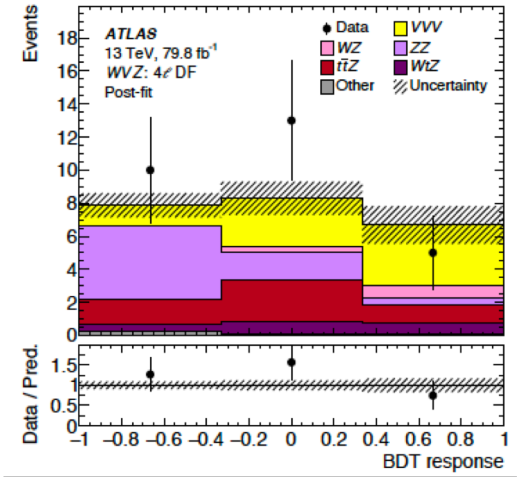
Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{T,0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{T,1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{T,2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

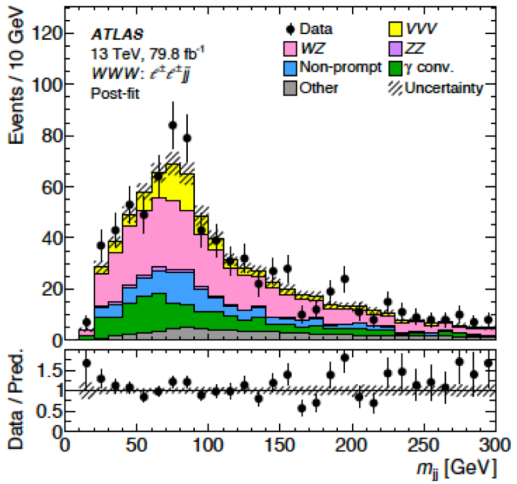
CMS-PAS-SMP-17-013

VVV Results

- First evidence for production of 3 massive vector bosons by ATLAS
  - WWW and WVZ
  - Usage of BDT in WVZ extraction
- Split into 11 signal regions





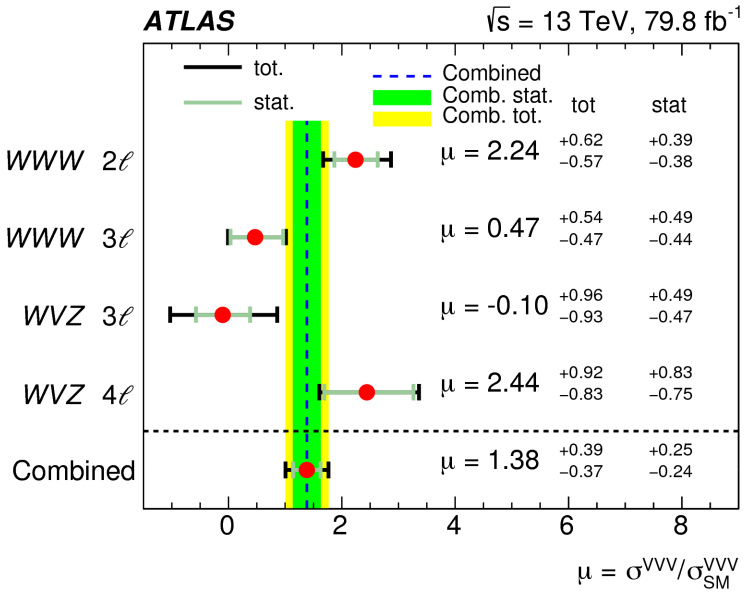


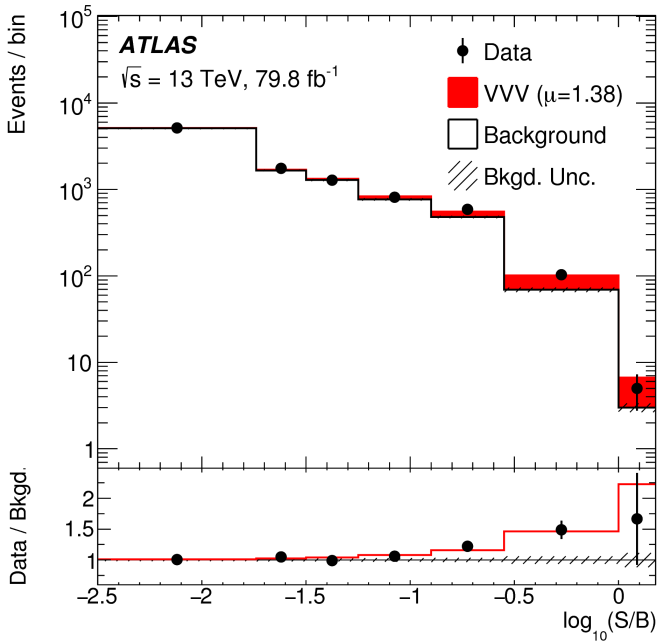
arXiv:1903.10415

VVV Results

- 4σ evidence for VVV
- Measured cross sections in agreement with SM prediction

$\sigma_{WWW} = 0.68^{+0.23}_{-0.21}$ pb $\sigma_{WWZ} = 0.49^{+0.20}_{-0.18}$ pb

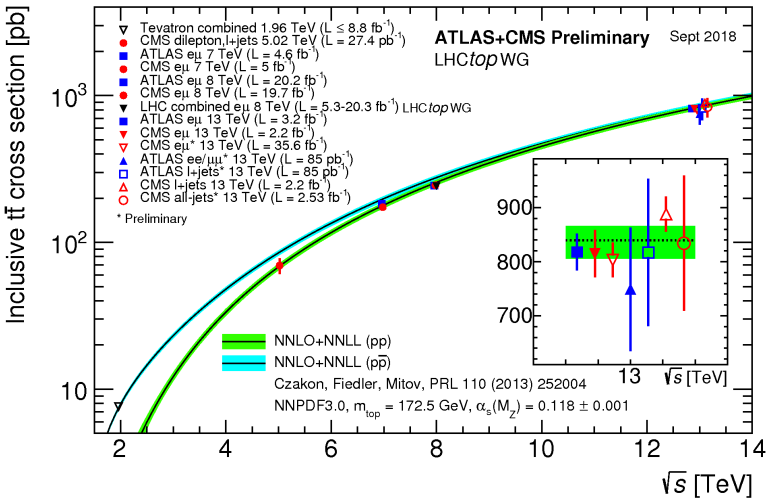


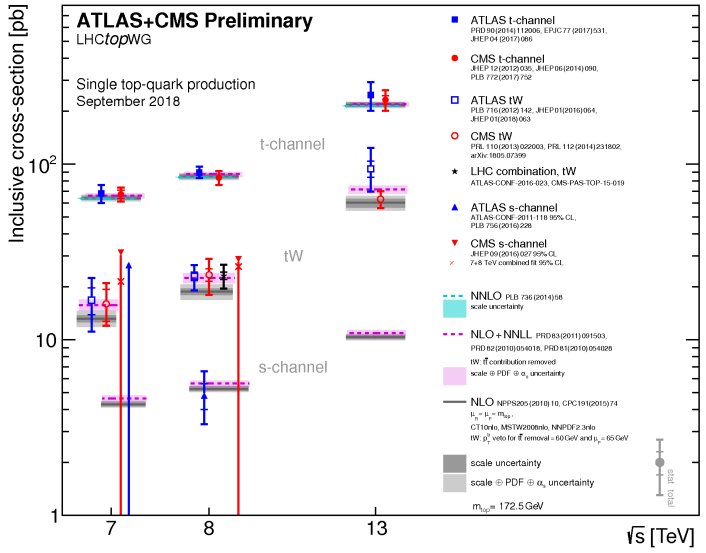


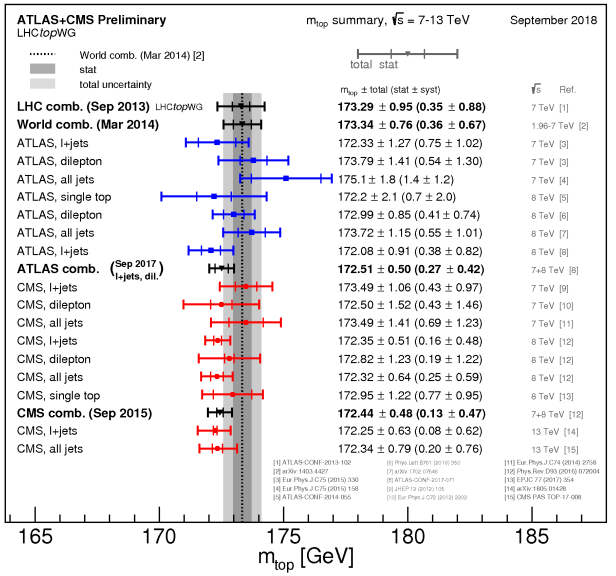
arXiv:1903.10415

Top Results

- Top quark: heaviest known elementary particle
  - Decays before hadronization - effective study of "bare" quark
  - Study of strong and electroweak interactions
- Many measurements of cross sections and properties ongoing
  - And searches for new physics (FCNC, resonances, MHDM)
- So far mostly compatible with SM predictions

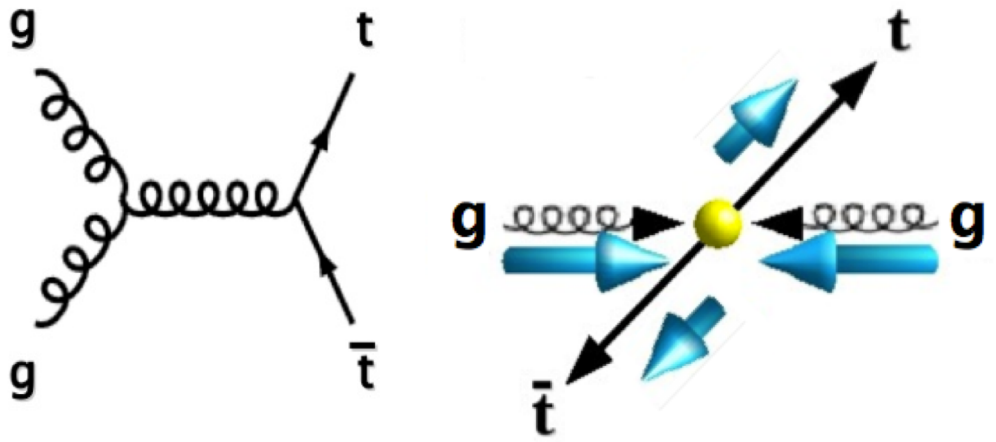






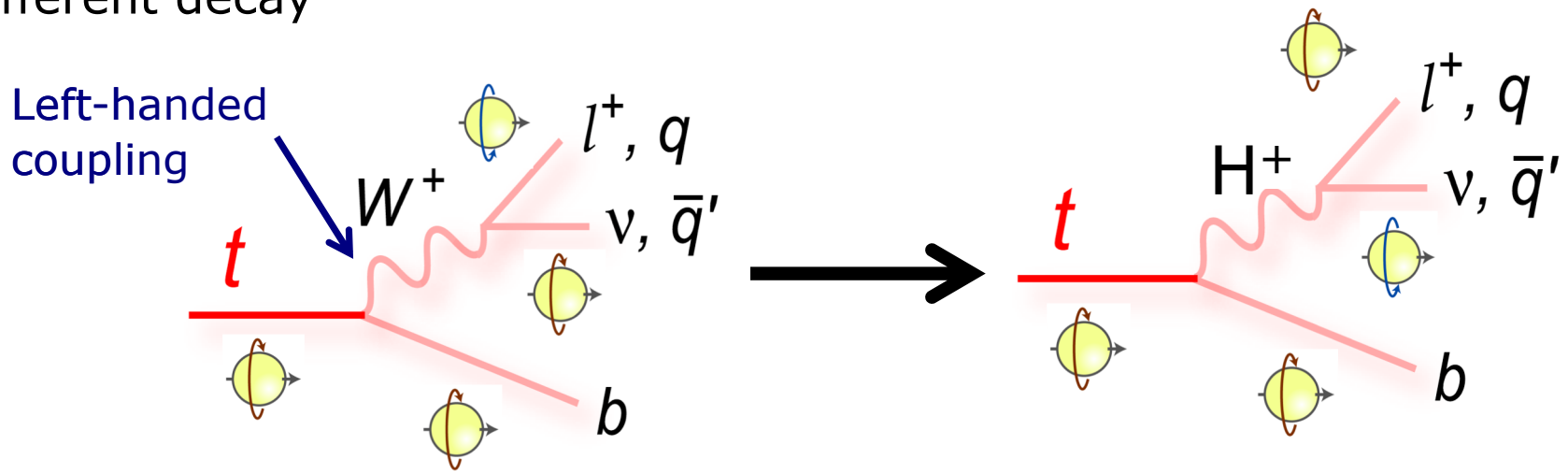
Spin Correlations

- Top quarks: decay before fragmentation
  - Spin information preserved in decay products
- Hadron colliders: top quarks produced unpolarized, but
  - New physics could induce polarization
    - For example: new physics can cause forward-backward asymmetry → more left-handed top quarks
  - Correlation between top and antitop quark can be measured

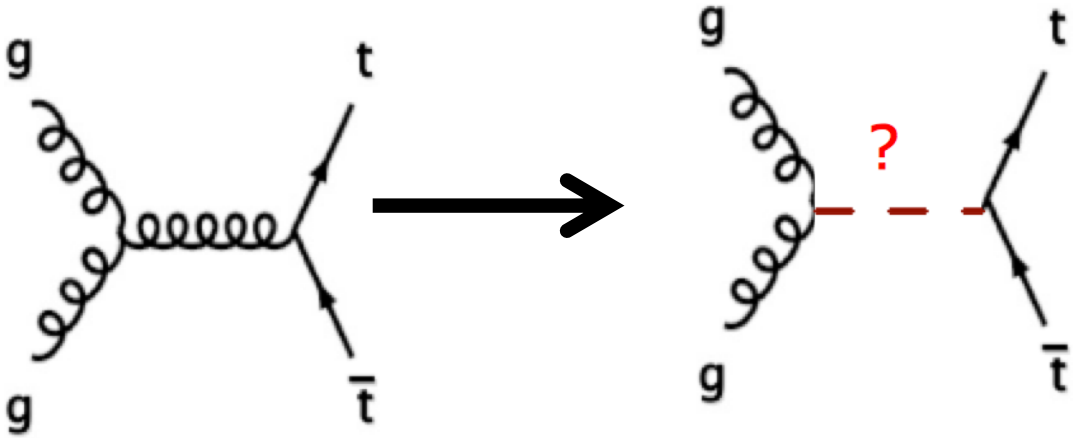


Spin Correlations

- Measured spin correlation can change
  - Due to different decay



  - Due to different production

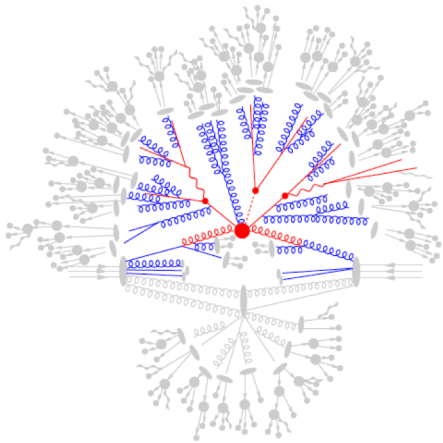


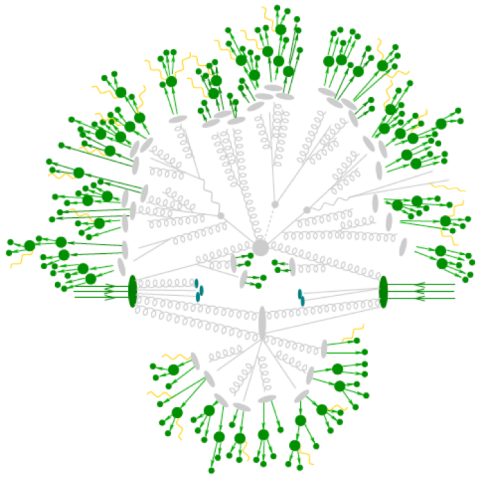
- Spin correlation: test full chain from production to decay

Analysis Strategy

- Highest spin analyzing power: leptons form top decay
  - Use dileptonic $t\bar{t}$ events
    - Very clean samples
- Use $\Delta\varphi$ between both leptons
  - No kinematic event reconstruction required
- Full $t\bar{t}$ event reconstruction for $m_{t\bar{t}}$
  - For example neutrino weighting in ATLAS

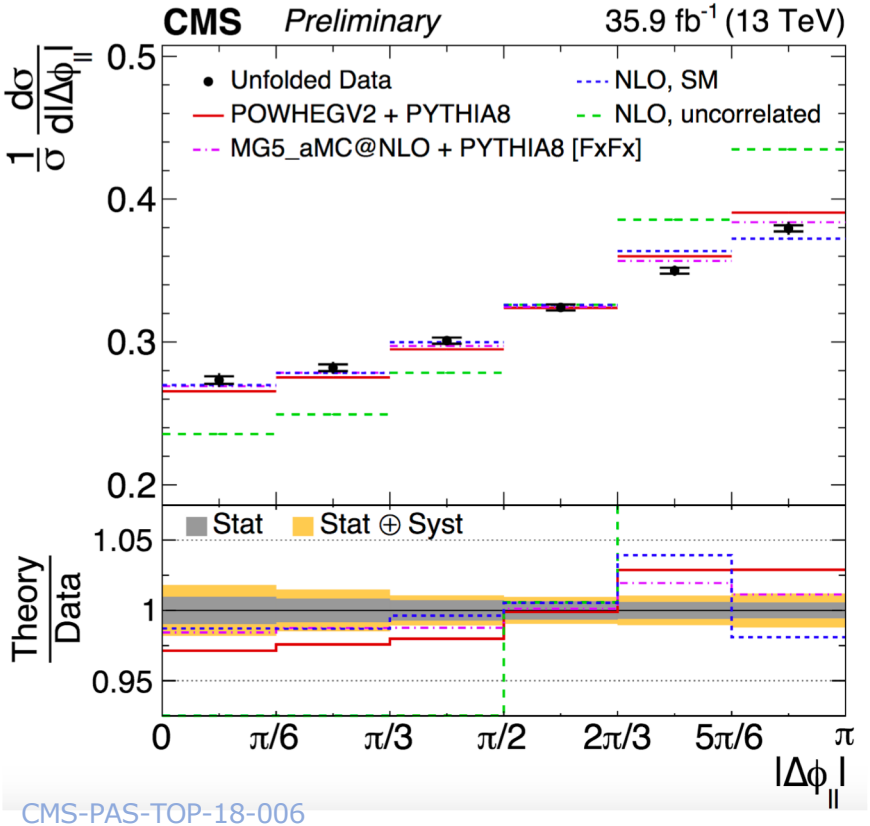
- Correct for detector effects
  - Parton and particle level distributions



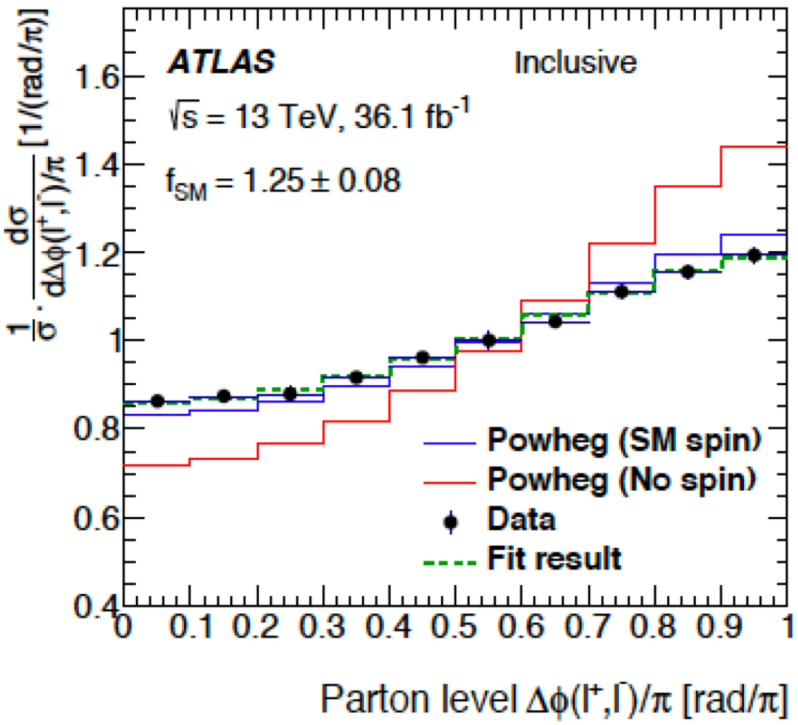


Measured Distributions

- Both ATLAS & CMS: fitted spin correlation higher than expected
  - ATLAS: 3.2 sigma from SM prediction of Powheg MC



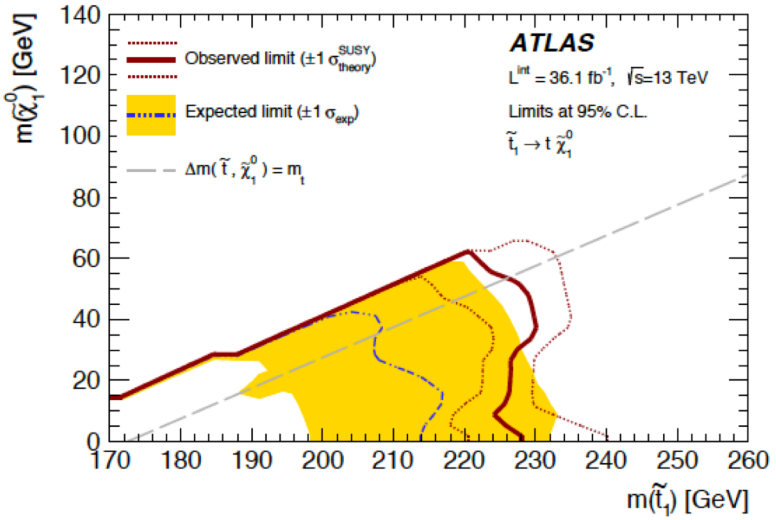
CMS-PAS-TOP-18-006

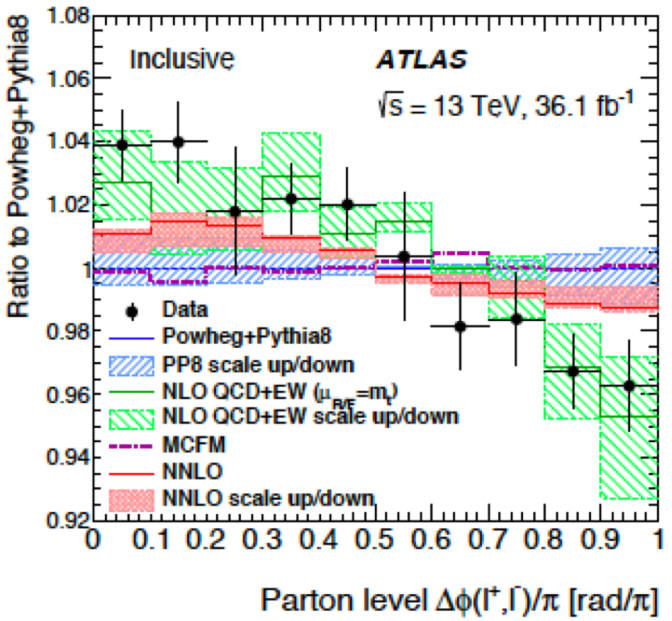


arxiv:1903.07570

More measured distributions

- Result caused interest in field → new theory predictions
- NLO+EW agrees better with measurement, NNLO (but no EW corrections) worse again
  - NLO+EW: large scale uncertainties
  - Still open riddle what's exactly going on!
  - Need more calculations/measurements?
- Interpretations done in terms of EFT and SuSy models





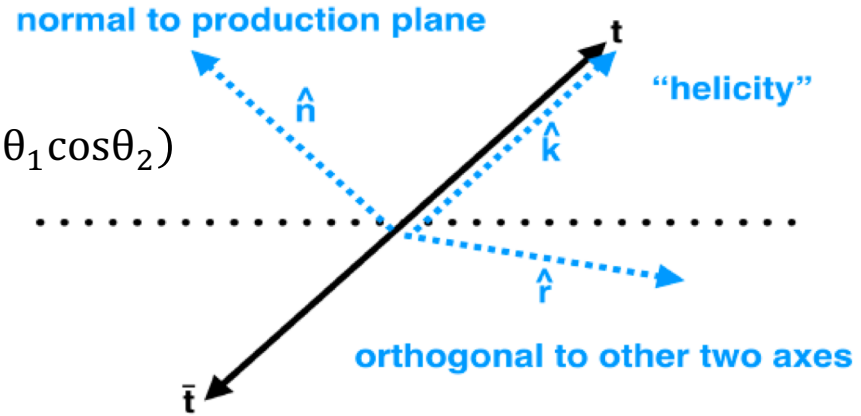
arxiv:1903.07570

Other Measurements

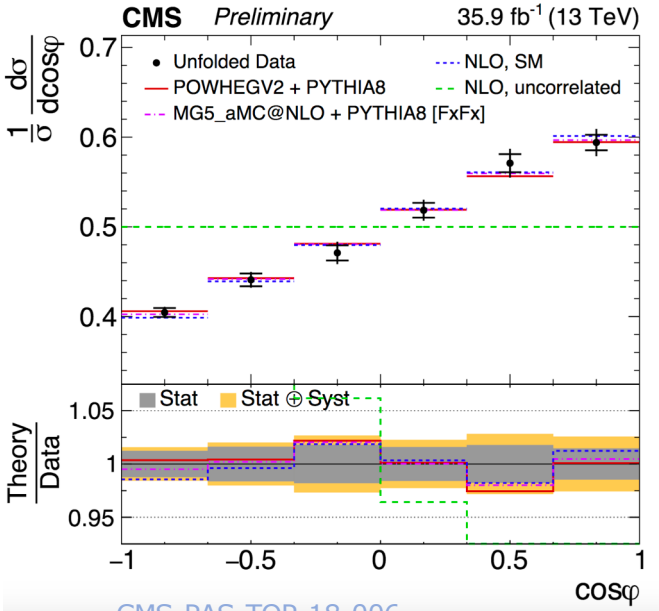
- Double differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 \pm (\alpha P)_1 \cos\theta_1 \pm (\alpha P)_2 \cos\theta_2 - C\cos\theta_1\cos\theta_2\right)$$

  - α: spin analyzing power of decay product
  - θ: direction of daughter particle wrt. chosen quantization axis
  - P: polarization and C: spin correlations



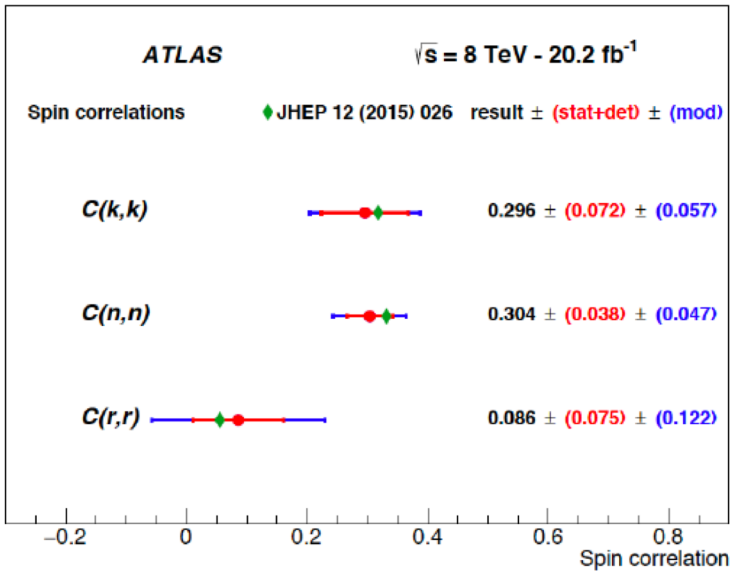
- More "direct" spin correlation measurement: Spin density matrix elements
  - Challenge: requires full event reconstruction
- ATLAS &CMS: Unfolded distributions extracted



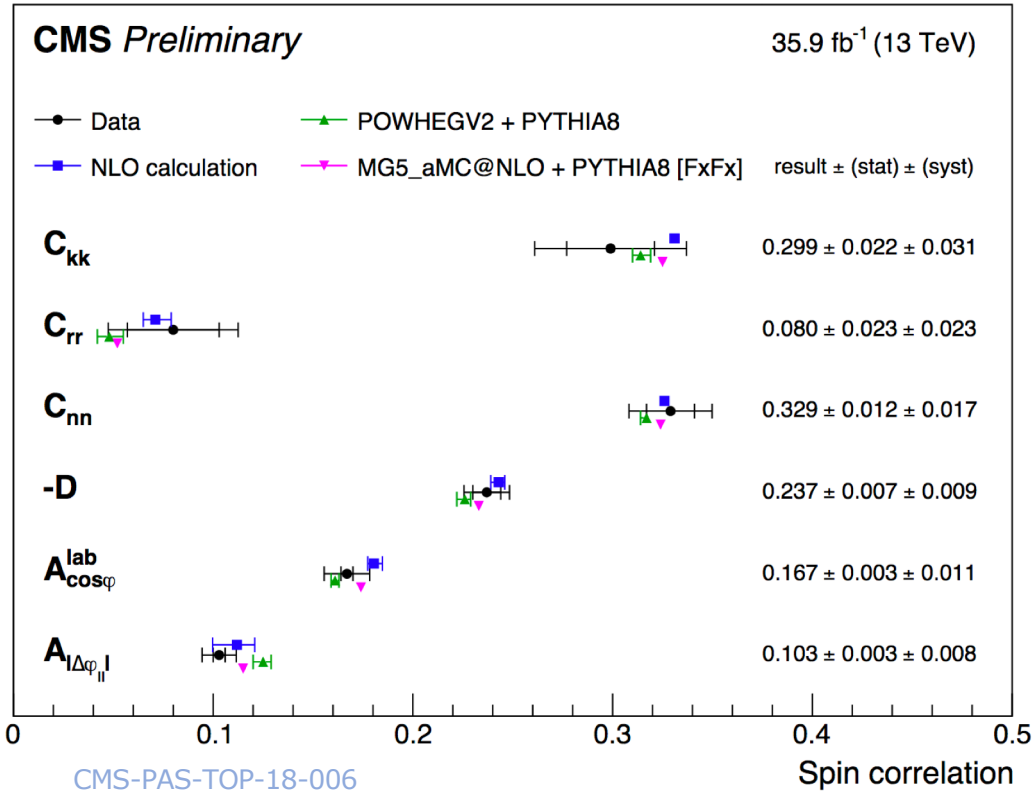
CMS-PAS-TOP-18-006

Other Spin Measurements

- All spin-density matrix elements measured
  - More to do to improve sensitivity



JHEP 03, 113 (2017)



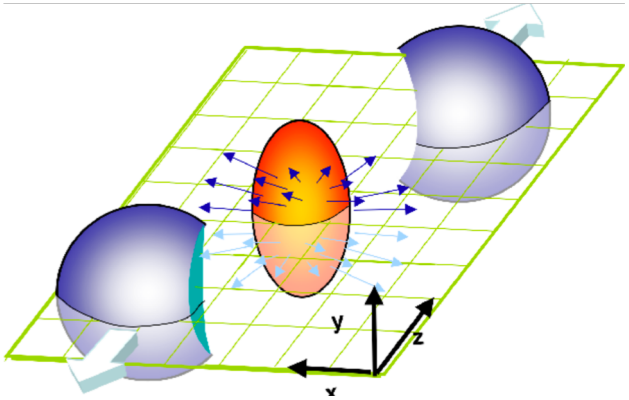
CMS-PAS-TOP-18-006

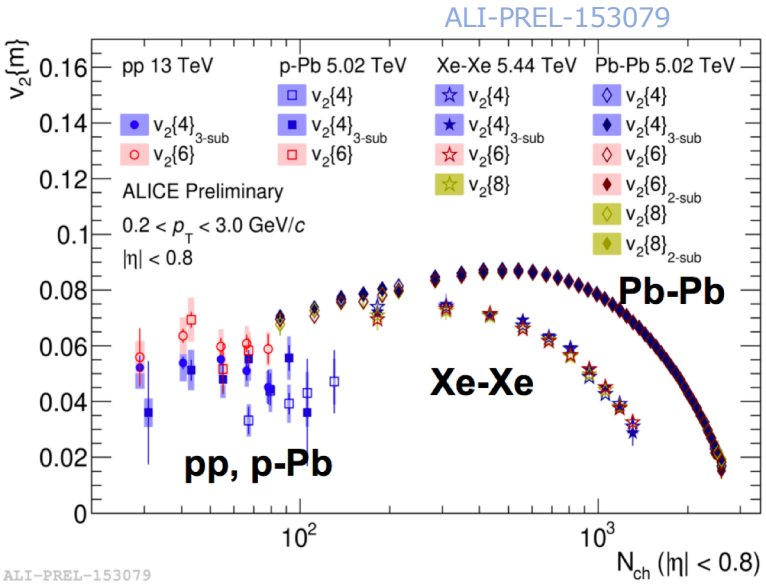
- Still more to do to understand the riddle of $t\bar{t}$ spin correlations!

Heavy Ions

- LHC collisions: p+Pb, Pb+Pb, Xe+Xe + high-multiplicity pp
  - Heavy Ion programme, mainly with Pb-Pb
  - 2017: few hours of Xe-Xe collisions

- Main goal of heavy ion collision programme: understand quark gluon plasma

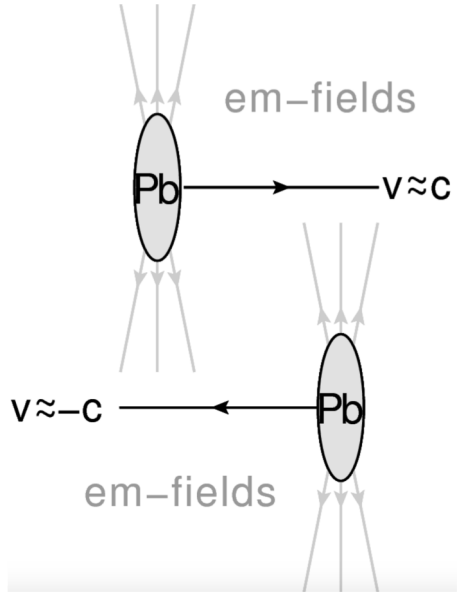




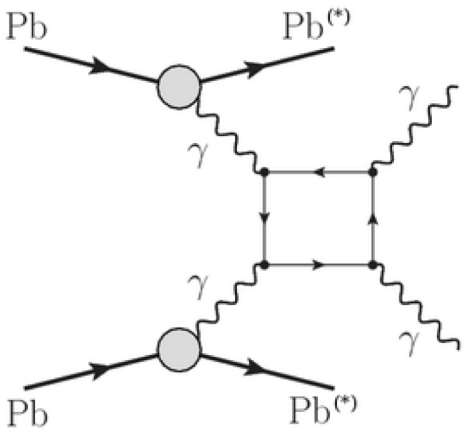
- Also possible to use heavy ions as generators for "photon beams"

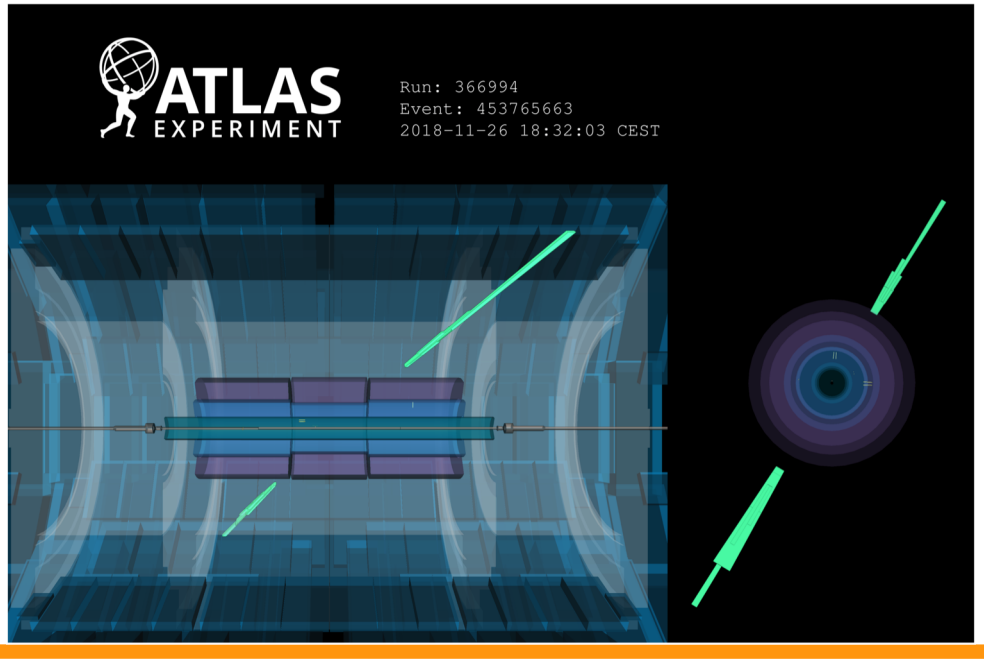
Light-by-Light

- Process $\gamma\gamma \rightarrow \gamma\gamma$: forbidden in classical theory of electrodynamics
  - Boosted protons/heavy ions: source of quasi-free photons
    - Flux scales with Z^2 per beam -> Z^4 total
      → cross section strongly enhanced in heavy ion collisions



- Studied by CMS and ATLAS in Pb+Pb collisions

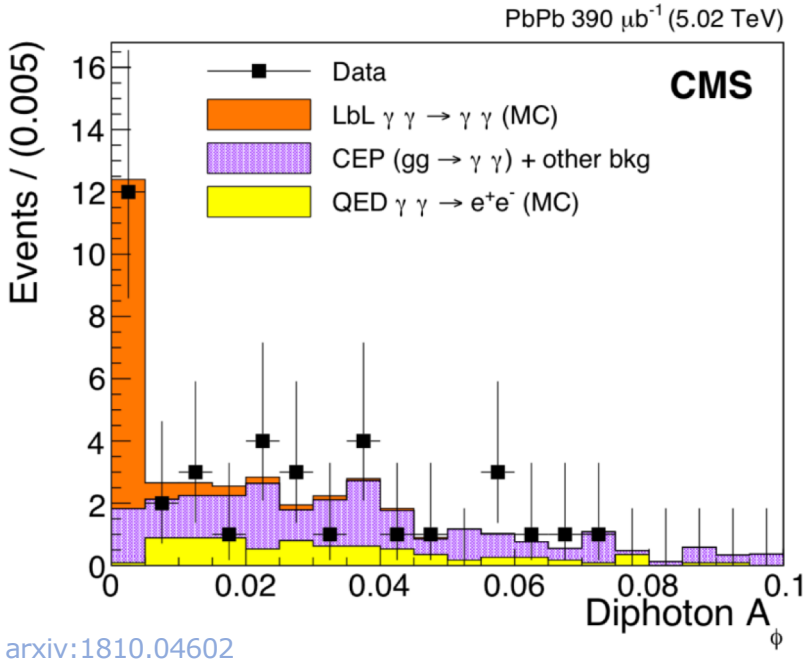




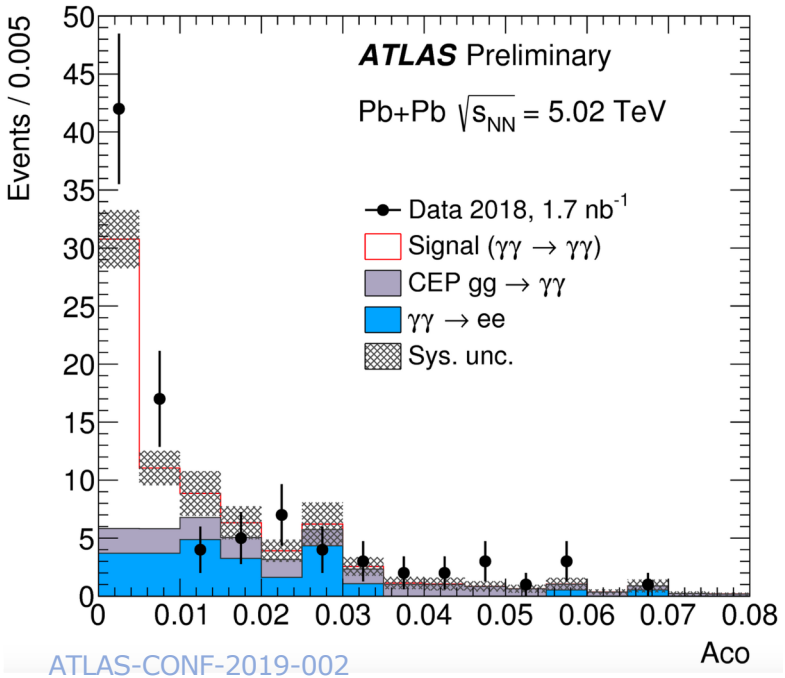
Light-by-Light

- Extraction of cross section in small region of photon acoplanarity
  - $Aco = (1 - |\Delta\varphi/\pi|)$
- Latest measurement by ATLAS (1.73 nb^{-1} data): Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions

$$\sigma = 78 \pm 13\,(\text{stat}) \pm 8\,(\text{syst})\ \text{np}$$ (Prediction: $\sigma = 49 \pm 5$ np)



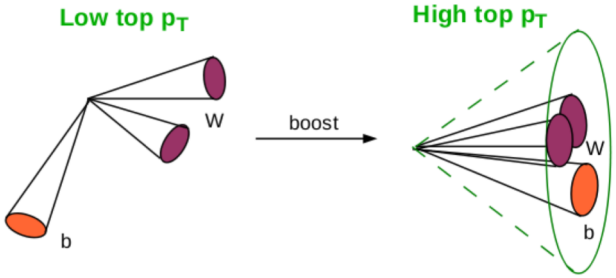
arxiv:1810.04602

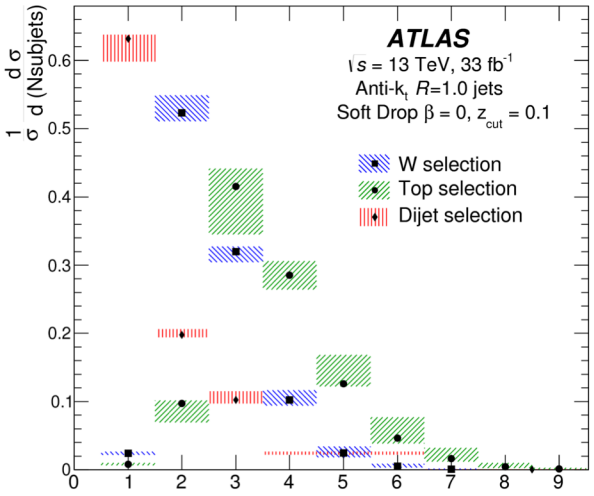


ATLAS-CONF-2019-002

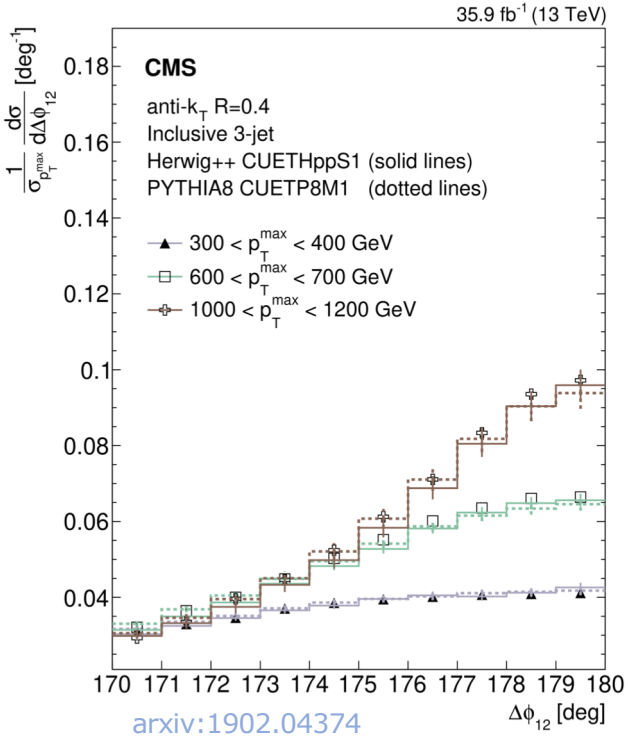
QCD Measurements

- Various analyses of jet substructures and jet topologies!
- All interesting to
  - Understand QCD
  - Constrain PDFs better
  - Understand boosted topologies
- Steady progress towards more detailed understanding of QCD and improved boosted tagging





arxiv:1903.02942



arxiv:1902.04374

Summary

- SM measurements: active, diverse field of research
- Precision measurements: way to go to search for new physics
  - Model independent
  - Usable for theorists (unfolded distributions)
  - EFT interpretations possible
- Many new sensitive results
  – too many to squeeze into 25 minutes!

- Examples shown:
  - First evidence for production of 3 massive vector bosons
    - Sensitive to non-Abelian gauge structure of the SM
  - Spin correlations in $t\bar{t}$ → trying to solve the ”riddle of $\Delta\varphi$”
  - Observation of light-by-light scattering → LHC as photon-collider

- Expect more “**let’s break the SM**” fun with Run III soon!

Backup

Boosting algorithms

Boosting algorithms important

- Higher collision energy → more events can be boosted
- Production of heavy particles → decay products can be boosted → results in boosted regimes