Search for rare processes and phenomena with CMS

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Workshop on high energy physics and related topics
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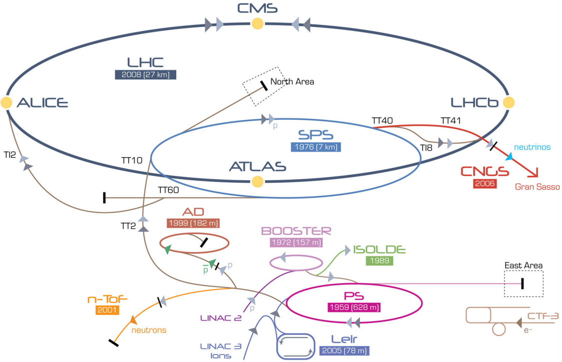
Overview

Acceleration complex at CERN

- The Large Hadron Collider (LHC) extends to both sides of the Franco-Swiss border
- Proton bunches are produced, split and accelerated sequentially through different accelerators before injection into the LHC
- Done with Run 2 at 13 TeV (2015-2018) $\rightarrow$ several analyses ongoing
- Preparation for Run 3 (2022 to 2024) and HL-LHC
(at least 160 fb^{-1} for ATLAS and CMS at $\sqrt{s}$ = 13-14 TeV)



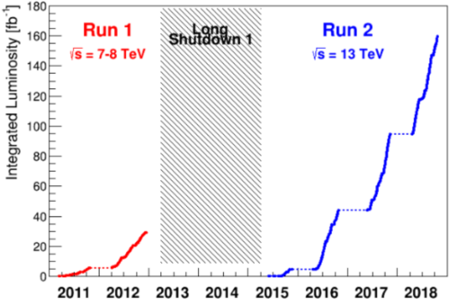
LHC / HL-LHC Plan with extended LS2

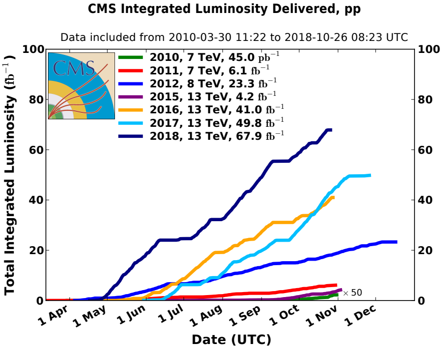
- Start of Run 3 beam commissioning is scheduled for March 7th 2022

Acceleration complex at CERN

- During Run 2 the LHC delivered to CMS a total of 163 fb^{-1} of integrated luminosity for proton-proton collisions at $\sqrt{s} = 13$ TeV

  - CMS recorded a total of 150.5 fb^{-1} with an overall efficiency of 92.5%

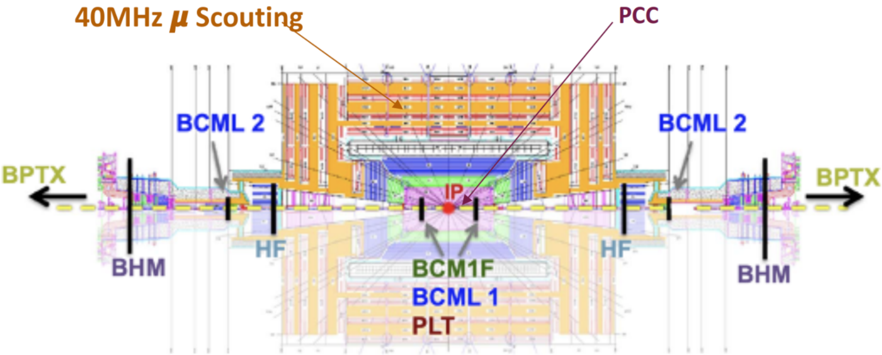




* Left plot from LHC Status and Future-EPS-HEP Conference 2021, J. Wenninger 27th July 2021

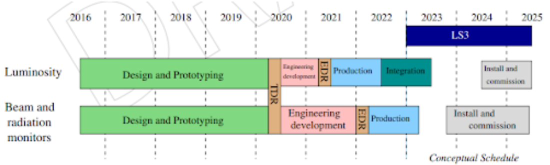
CMS BRIL system

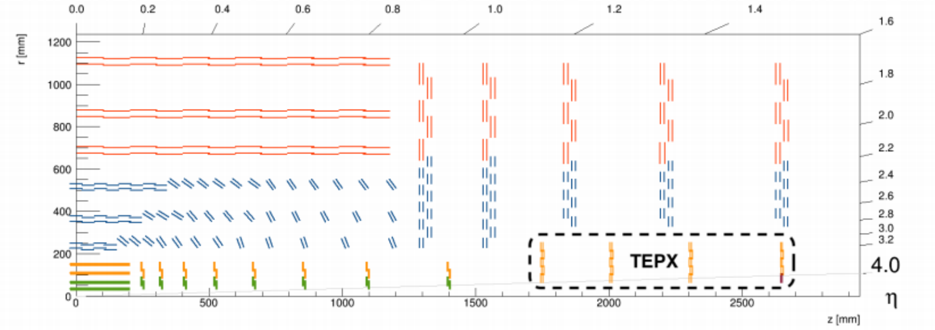
- Sonora and IBERO contributing with PLT, 40 MHz scouting, TEPX and PCC systems



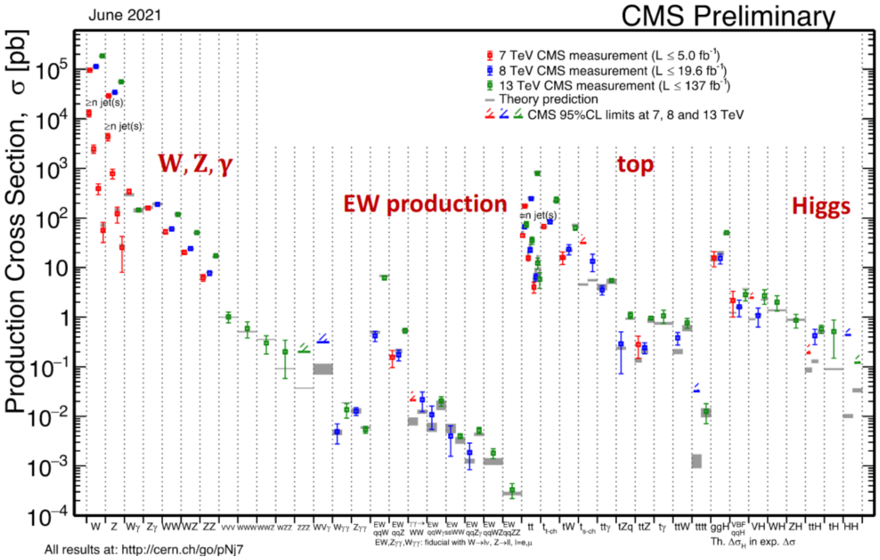
Mexican participation in CMS upgrade

- Luminosity and radiation measurement: BRIL System





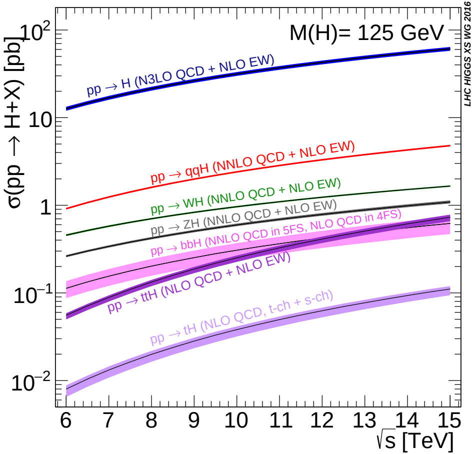
SM measurements at CMS

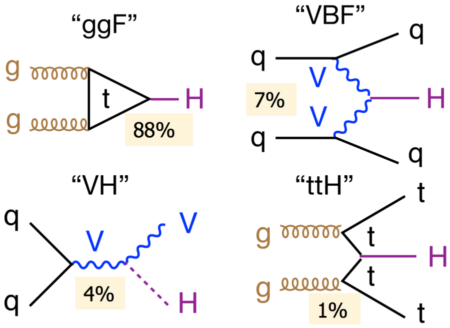


* Plot from Highlights from the CMS Experiment-EPS-HEP Conference 2021, Marco Pieri 27th July 2021

Higgs production at the LHC

- Observation of Higgs production in the ttH and VH channels was reported by CMS during 2018





ttH production at the LHC

ATLAS EXPERIMENT

Collaboration Site | Physics Results

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Updates > Briefing > New ATLAS result establishes production of Higgs boson in association with top quarks

Physics Briefing

Tags: physics results, Higgs boson, top quark, LHCP, LHCP 2018

New ATLAS result establishes production of Higgs boson in association with top quarks

This rare process is one of the most sensitive tests of the Higgs mechanism

4th June 2018 | By ATLAS Collaboration

According to the Standard Model, quarks, charged leptons, and W and Z bosons obtain their mass through interactions with the Higgs field, a quantum fluctuation of which gives rise to the Higgs boson. To test this theory, ATLAS takes high-precision measurements of the interactions between the Higgs boson and these particles. While the ATLAS and CMS experiments at CERN's Large Hadron Collider (LHC) had observed and measured the Higgs boson decaying to pairs of W or Z bosons, photons or tau leptons, the Higgs coupling to quarks had not – despite evidence – been observed.

In results presented today at the LHCP2018 conference, the ATLAS Collaboration has observed the production of the Higgs boson together with a top-quark pair (known as "ttH" production). Only about 1% of all Higgs bosons are produced through this rare process. This result establishes a direct measurement of the interaction between the top quark and the Higgs boson (known as the "top quark Yukawa coupling"). As the top quark is the heaviest particle in the Standard Model, this measurement is one of the most sensitive tests of the Higgs mechanism.

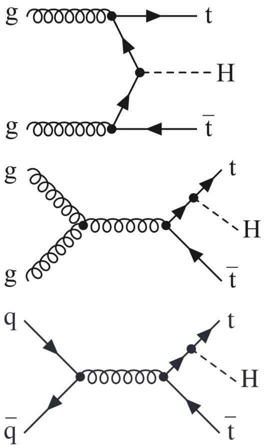
By CMS

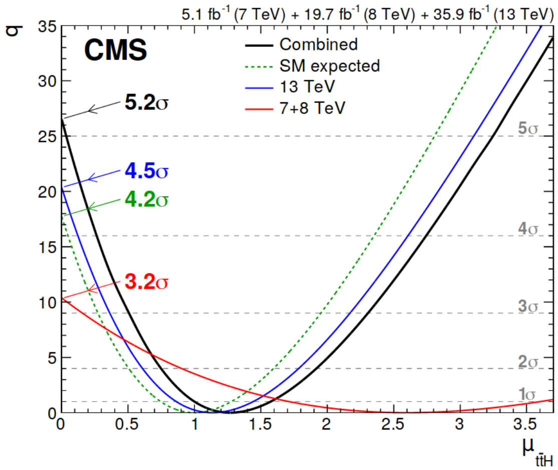
Observation of ttH production

The observation of a Higgs boson in 2012 at the Large Hadron Collider marked the starting point of a broad experimental program to determine the properties of the newly discovered particle. In the standard model, the Higgs boson couples to fermions in a Yukawa-type interaction, with a coupling strength proportional to the fermion mass. While decays into γγ, ZZ, WW, and ττ final states have been observed and there is evidence for the direct decay of the particle to the bb (down-type quarks) final state, the decay to the tt (up-type quarks) final state is not kinematically possible. Therefore, it is of paramount importance to probe the coupling of the Higgs boson to the top quark, the heaviest known fermion, by producing the Higgs in the fusion of a top quark-antiquark pair (left diagram) or through radiation from a top quark (right diagram).

2018 - Observation of Higgs production in the ttH channel

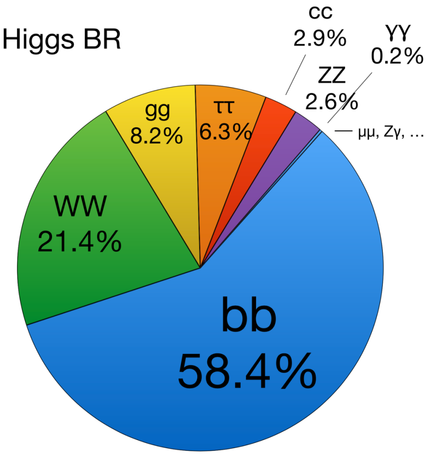
- The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-026}$
- Combination of 7 TeV ($5fb^{-1}$), 8 TeV ($20fb^{-1}$) and 13 TeV ($36fb^{-1}$) data



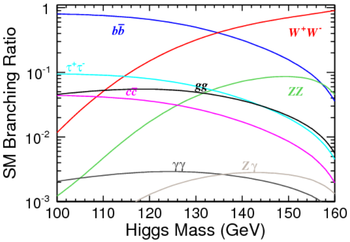


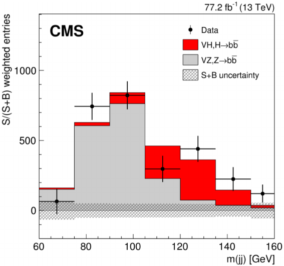
Higgs decays at the LHC

- Observation of Higgs decays via H$\rightarrow$ $b\bar{b}$ and H$\rightarrow$ $\tau^+\tau^-$ channels was reported by CMS during 2017 and 2018 respectively



arXiv:1310.0763

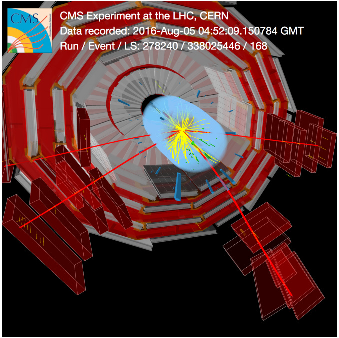




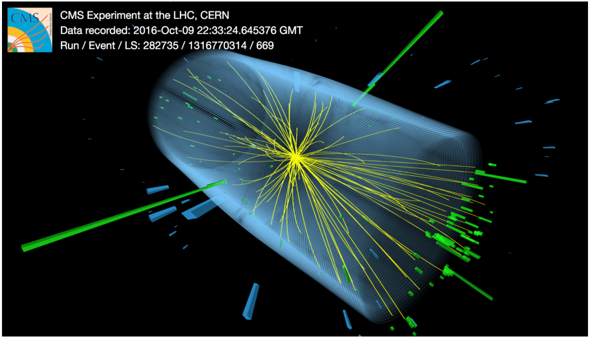
Higgs mass / Golden channels

- CMS collaboration has announced the most precise measurement so far of this property: 125.35 GeV with a precision of 0.15 GeV, or 0.12%
- Using mostly ggF and VBF production modes

H$\rightarrow 4\ell$



H$\rightarrow \gamma\gamma$

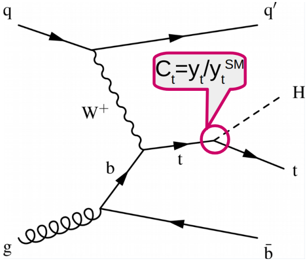


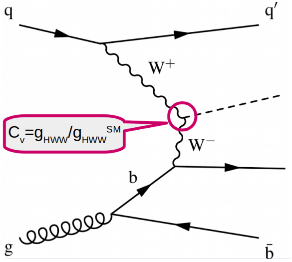
CMS-PHO-EVENTS-2019-008-2
CMS-PHO-EVENTS-2019-008-4

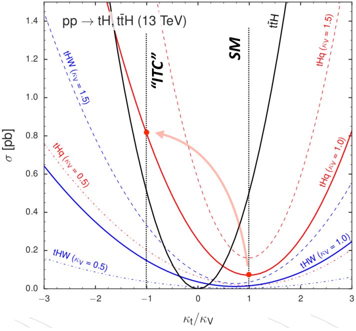
Evidence of Higgs decay to two muons

tHq production mode

- Interfering diagrams lead to large cross-section for inverted coupling scenario "ITC"
- Process is very sensitive to the magnitude and sign of a non-SM top-Higgs coupling







arXiv:1211.3736 [hep-ph]

2018 - Limits over C_t

- HIG-18-009 (arXiv:1811.09696)

  - 2016 combination: $b\bar{b}$, $\gamma\gamma$, multi-lep

  - Used only two Hgg categories:

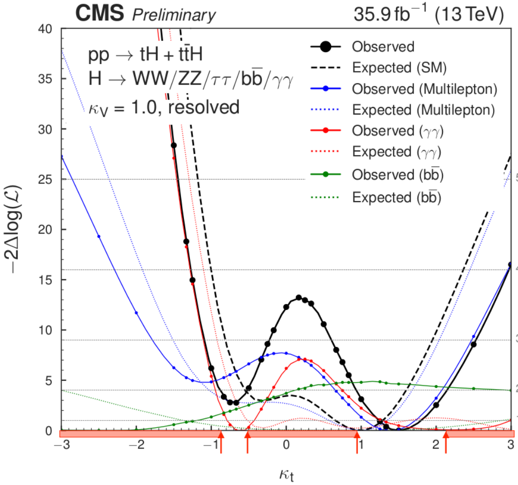
    tthLeptonic
    ttHHadronic

  - No dedicated tH category

  - $|k_t| = 0$ excluded at 3.5 sigma

  - ITC scenario only $\sim$ 1.5 sigma

  - Large improvements possible by adding new data and new categories



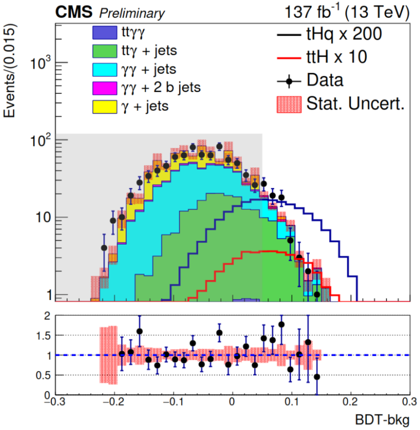
Phys. Rev. D 99 (2019) 092005

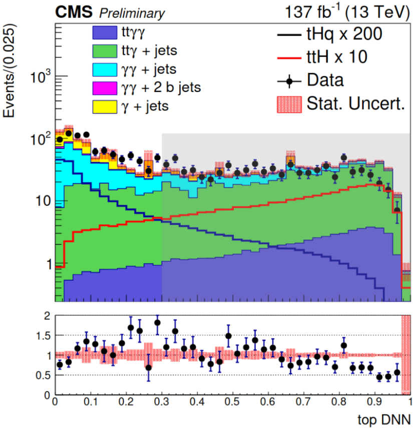
- DOI:10.1007/JHEP07(2021)027

J. A. Murillo Quijada, C. Oropeza Barrera, Edward Scott et al. "Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV"

- Published in the Journal of High Energy Physics (JHEP)

- Measurements of Higgs boson production cross-sections and couplings in events where Higgs boson decays to a pair of photons $H \to \gamma\gamma$





- $H \to \gamma\gamma$ diphoton channel

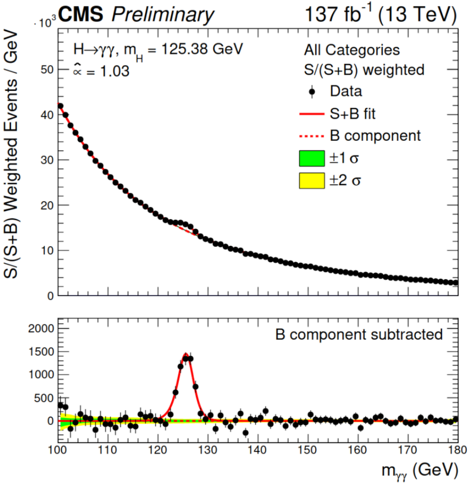
  - In the SM this channel has a small branching ration approximately 0.23% for a Higgs boson mass ($m_{\rm H}$) around 125 GeV

  - $\gamma_1(p_T) > 35$ GeV, $\gamma_2(p_T) > 25$ GeV after vertex assignment

  - $|\eta| < 2.5$, not in $1.44 < |\eta| < 1.57$ (barrel-endcap transition)

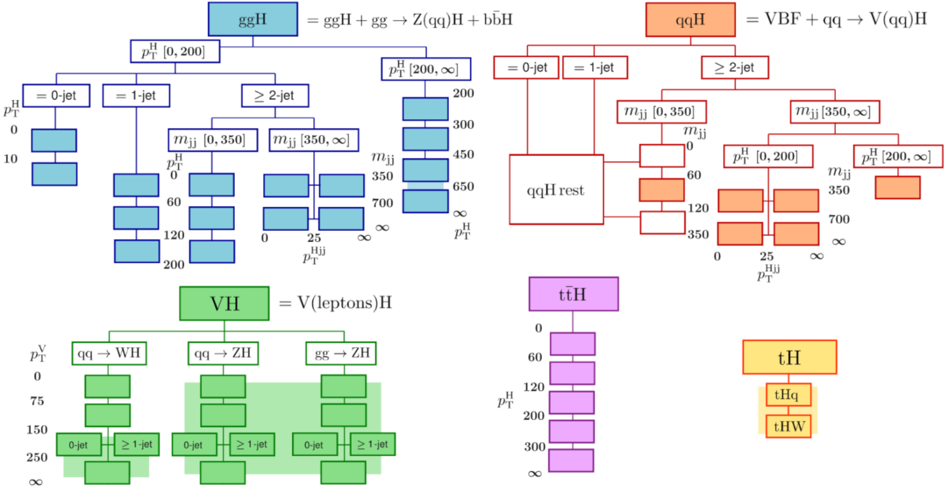
  - Aiming to exploit narrow H peak to measure ggH, VBF, VH, ttH and tH production modes

  - Use stage 1.2 STXS bins

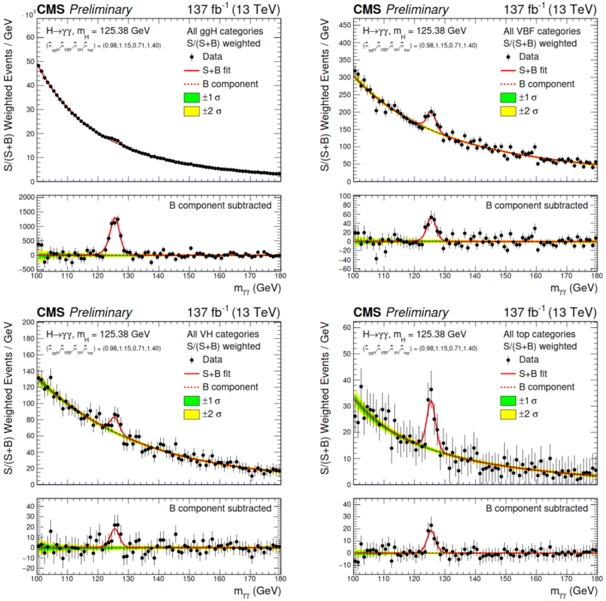


- STXS stage-1.2 bins for events with $|y_H| < 2.5$

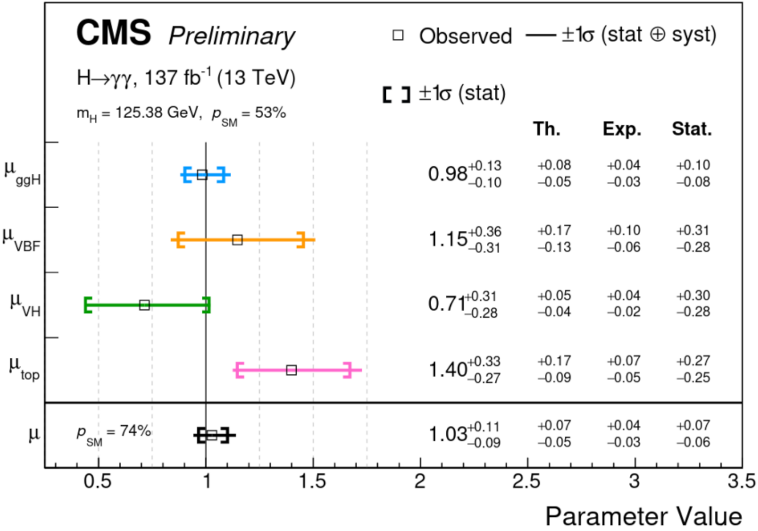
  - kinematic regions based upon Higgs boson production modes are defined



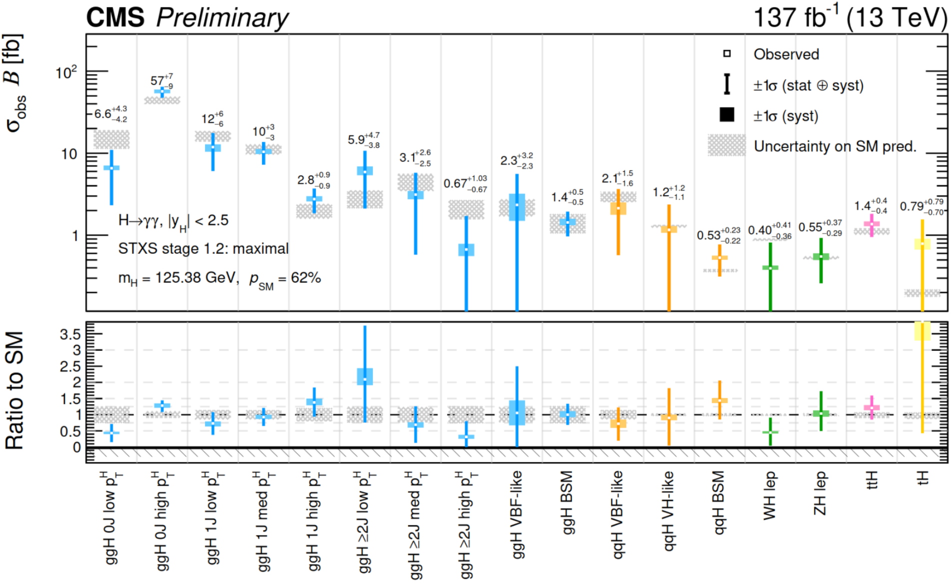
- Signal + background models fits for ggH, VBF, VH and tH/ttH categories



- Signal strength modifiers per production mode
  - ggF becoming syst-limited

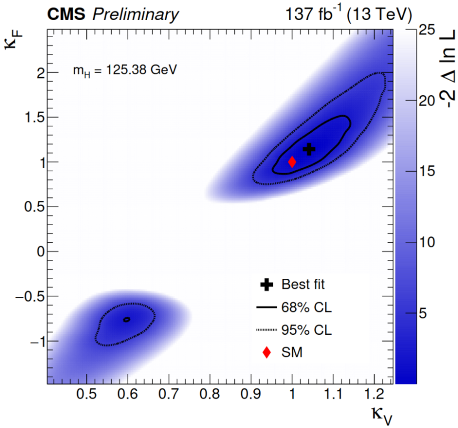


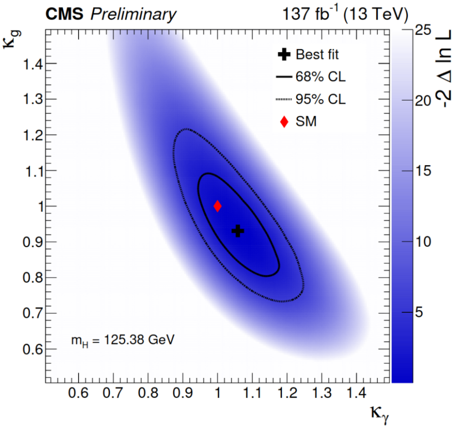
- Simultaneous measurement of ttH and tH
  - Best tH measurement to date, observed (expected) 95% C.L. is 12 (9)× SM value



Coupling modifiers

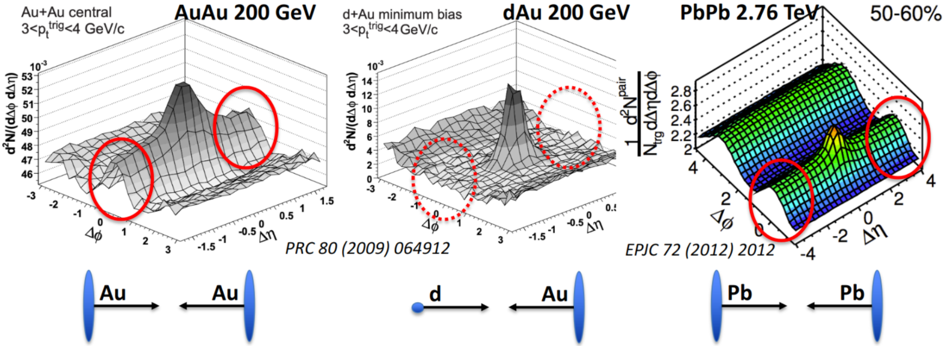
- Parametrise deviations from SM in Higgs couplings to other particles





Long-range, near-side ridge structure

- Emerges in the two-particle correlation functions
  - High energy nuclear collisions
  - Observed in large collision systems (AA)
  - Absent in MB small collision systems (dAu)
- Evidence of collectivity and one of the features of QGP



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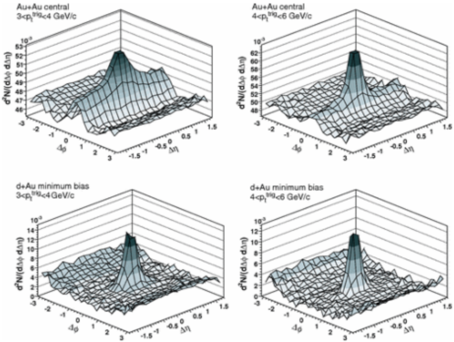
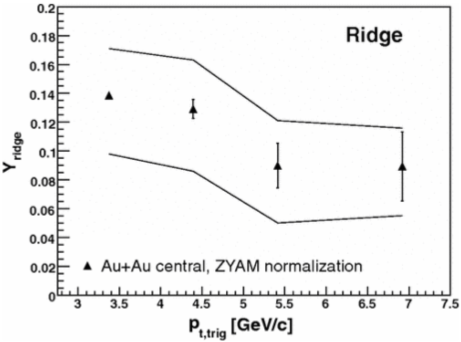
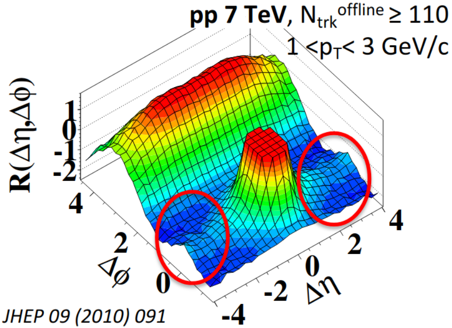


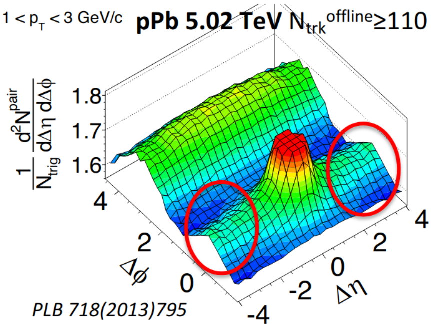


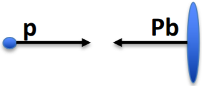
PRC 80 (2009) 064912

Discovery; strong collectivity found in small systems

- Ridge: near-side long-range 2-particle correlations
  - Observed also in small collision systems (pp, pPb) with high event multiplicity
  - Predicted by Color Glass Condesate (CGC) effective models



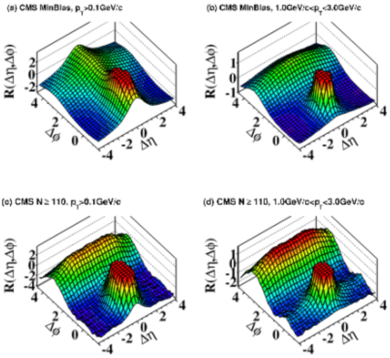


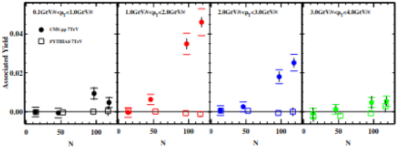


DOI: 10.1016/j.physletb.2011.01.024

Discovery; strong collectivity found in small systems

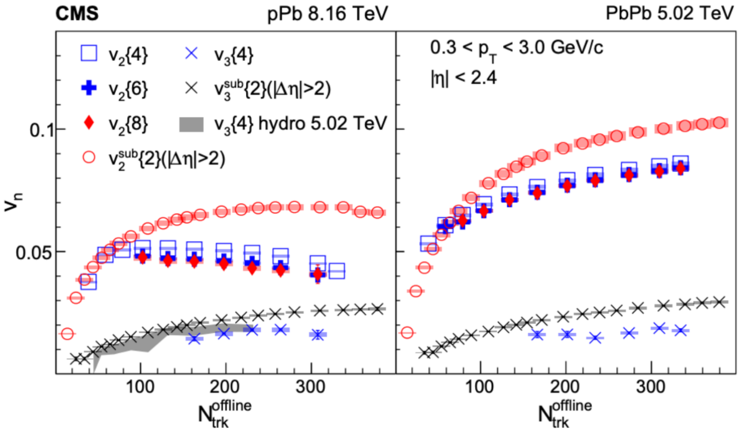
- Ridge: only seen in intermediate p_T categories





Small vs large collision systems

- Origin of the ridge in small systems?
  - Natural question is whether such signatures persist in even smaller collision systems
  - Final state effect?, Pure fluctuations? CGC?

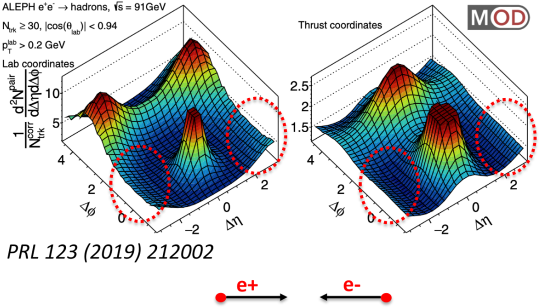


PRC 101 (2020) 014912

Recent explorations with small systems

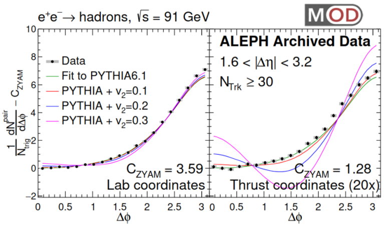
First measurement with e^+e^- system at $\sqrt{s} = 91$ GeV

- ALEPH e^+e^-
  - Sharp near-side peaks arise from jet-like (non-flow) correlations
  - No significant long-range correlations; better consistency with Pythia and Sherpa than Herwig
  - Confidence limits on associated yield as a function of N_{trk} have been set



PRL 123 (2019) 212002

N_{trk} range	Fraction of data (%)	$\langle N_{trk} \rangle$	$\langle N_{trk}^{corr} \rangle$
[5, 10)	3.1	8.2	8.9
[10, 20)	59.2	15.2	15.8
[20, 30)	34.6	23.1	23.4
[30, ∞)	3.1	32.4	32.6
[35, ∞)	0.5	36.9	37.2



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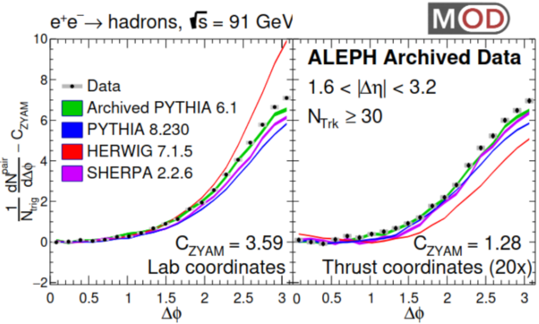
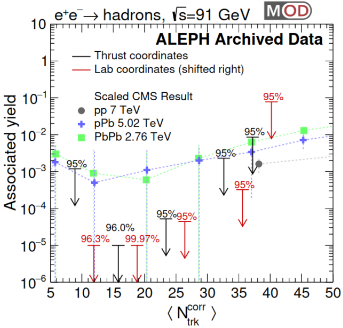
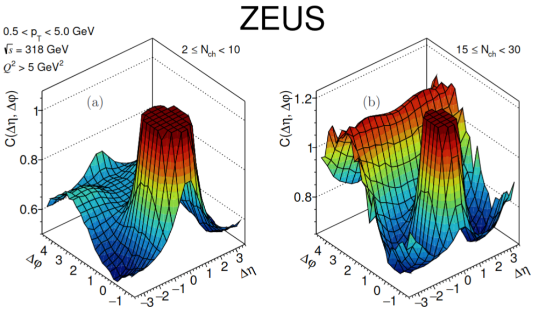
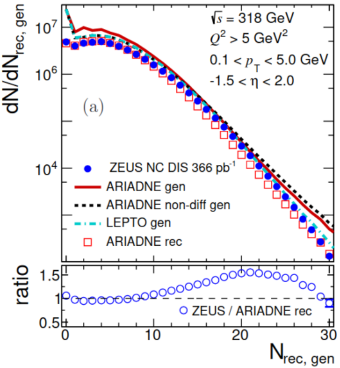




Deep inelastic ep scattering with ZEUS at HERA ($\sqrt{s} = 318$ GeV)

- Dominated by contributions from multijet production
  - $\langle N_{trk} \rangle \approx 5$
  - No indication of same collective behaviour observed in high-multiplicity hadronic collisions





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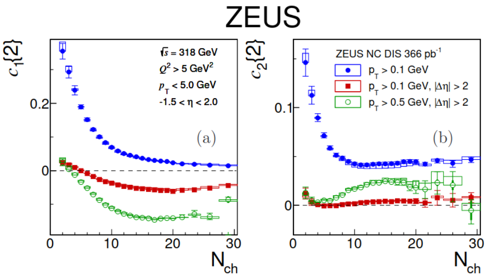

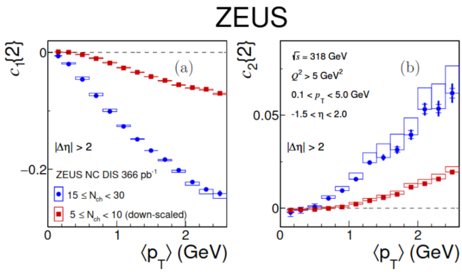

Deep inelastic ep scattering with H1 at HERA ($\sqrt{s} = 318$ GeV)

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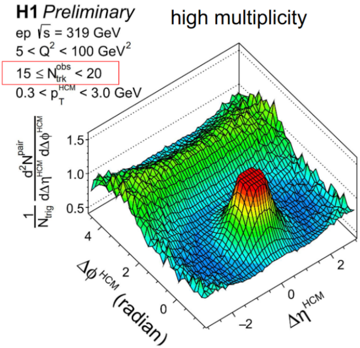
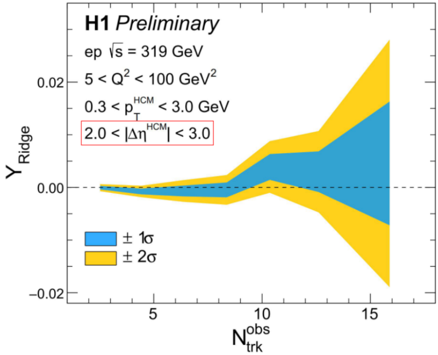
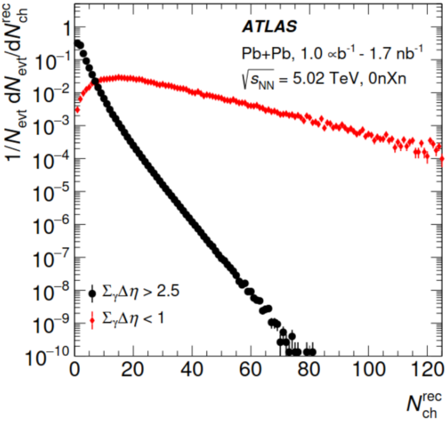
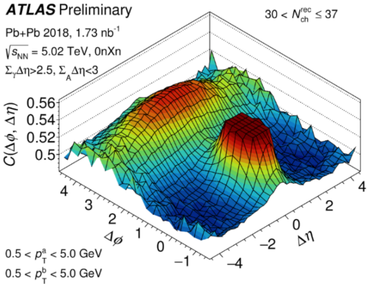




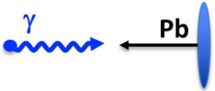
photonuclear ultraperipheral PbPb at 5.02 TeV with ATLAS

- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method





ATLAS-CONF-2019-022



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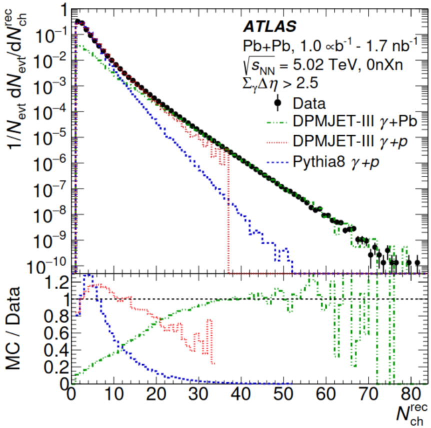
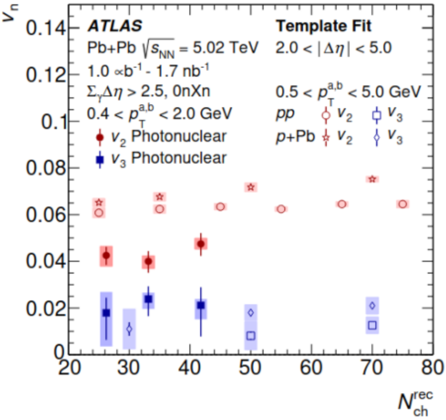
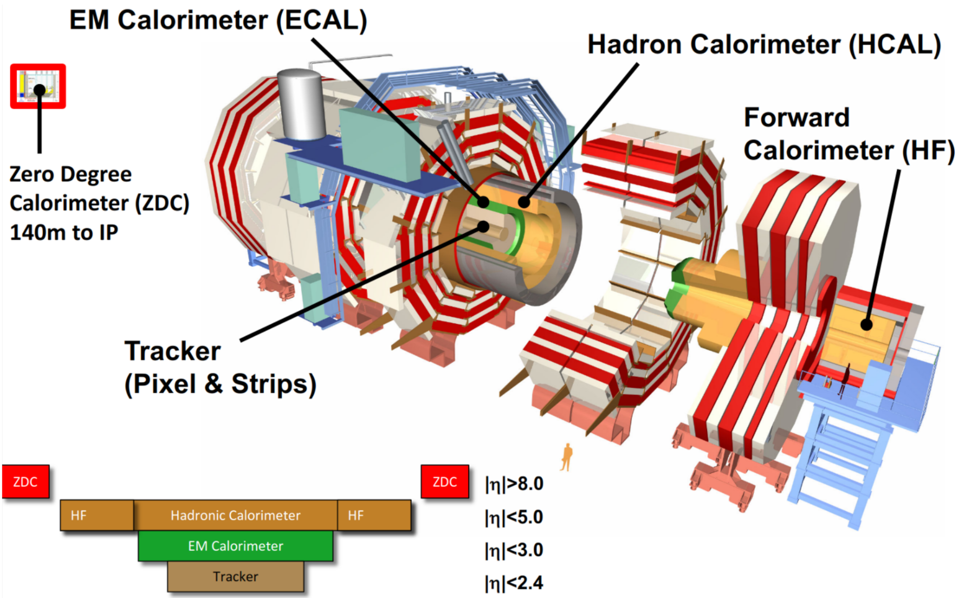
- Significant non-zero v_2
  - Substracting non-flow contribution using template fitting method





Crucial CMS detector subsystems



γp interactions within ultra-peripheral pPb collisions

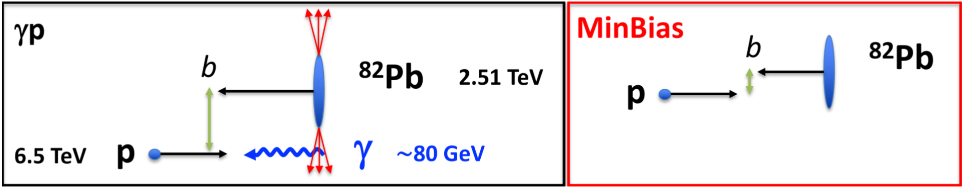
- CMS-PAS-HIN-18-008

  J. A. Murillo Quijada, Quan Wang, Michael Murray et al. "Search for elliptic azimuthal anisotropies in γp interactions within ultra-peripheral pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV"

  - Being submitted to Physics Letters B (PLB)

- γ-proton interactions (b>R_{Pb})

  - Minimum-bias (b<R_{Pb}))



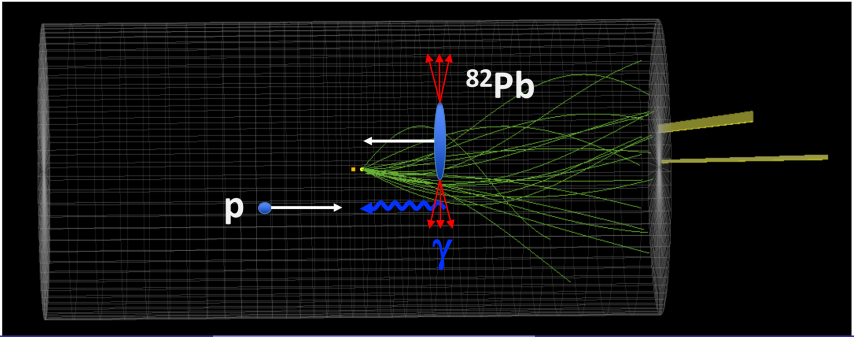
https://cds.cern.ch/record/2725477/

Selection requirements; 95% γp purity

- Pb-going side quiet;
  - $\rightarrow$ No neutrons detected by Zero Degree Calorimer (Pb nucleus is not broken)
  - $\rightarrow$ Rapidity Gap; No activity in Pb-going side using Particle Flow and tracks
- Activity in proton-going side; HF+ calorimeter with at least one tower with energy $>$ 10 GeV

Tracks satisfying following requirements:

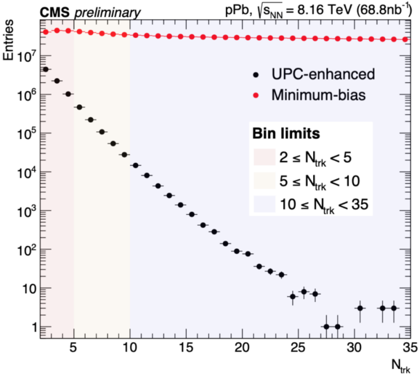
- Kinematic range: $\eta < 2.4$, $p_T > 0.4$ GeV
- Significance of z separation between track and best vertex: $d_z/\sigma(d_z) < 3.0$
- Impact parameter significance: $d_0/\sigma(d_0) < 3.0$, Momentum uncertainty: $\sigma(p_T)/p_T < 0.1$



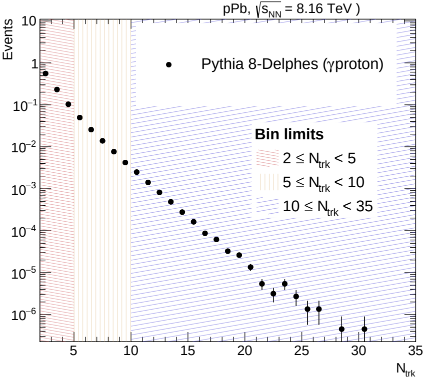
Available MC for signal γ-proton in pPb

- Recent addition to Pythia8 simulation: Standard Equivalent Photon Approximation (EPA) flux model with low-virtuality γp in pPb collisions[1]
- Comparison with montecarlo is being added to final paper
  - It reproduces N_{trk} distribution with limit up to $\sim$ 35 as data sample

CMS Data



Pythia8 + detector fast simulation



[1] Ilkka Helenius, Christine O. Rasmussen, "Hard diffraction in photoproduction with Pythia 8", Eur.Phys.J.C 79 (2019)

Signal pair distribution:

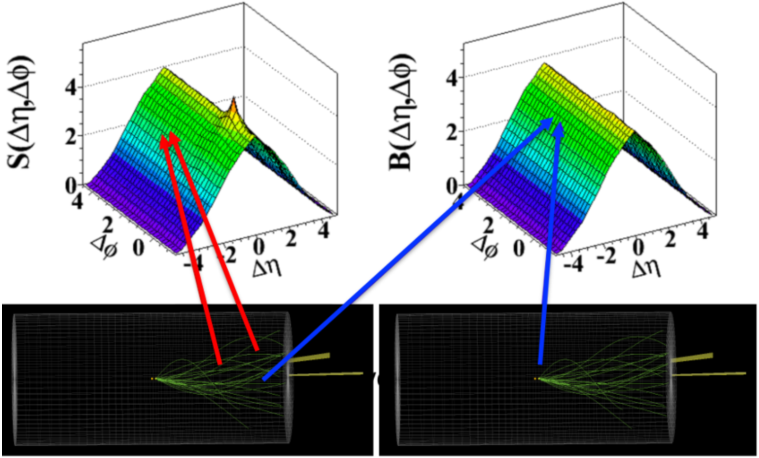
$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background pair distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

same event pairs

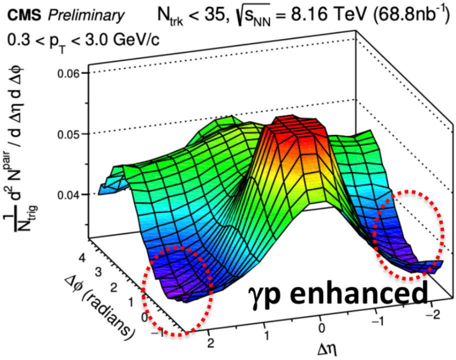
mixed event pairs

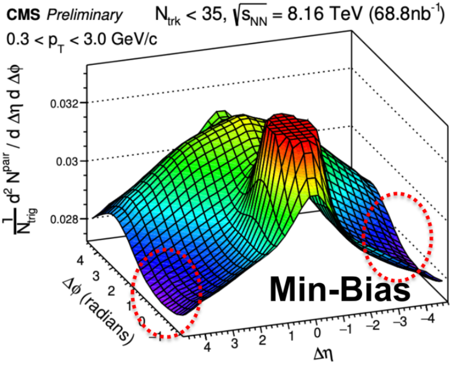


2D ratio distribution

- 2D correlations for γp enhanced and Minimum-bias
  - N_{trk} limited up to ~35 for γp → divided in different bins for two p_T categories
  - No evidence of ridge-like correlations

$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

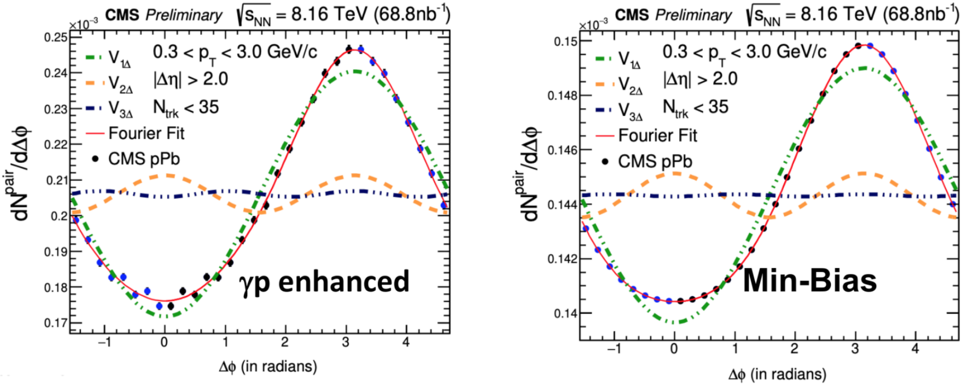




1D Long-range projection

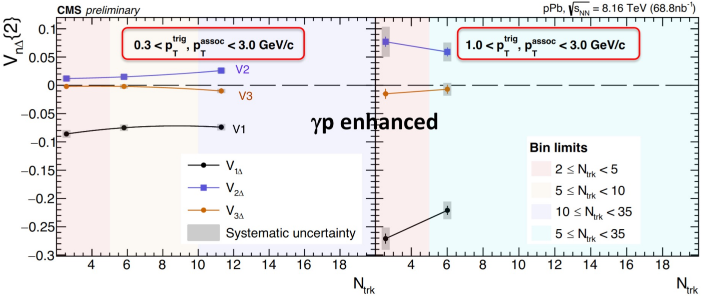
- Azimuthal distributions for $|\Delta\eta| > 2.0$
- $V_n\Delta$ Fourier coefficients obtained from the decomposition fit:

$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}[1+\sum_n 2V_{n\Delta}cos(n\Delta\phi)]; \qquad n = 1,2,3$$

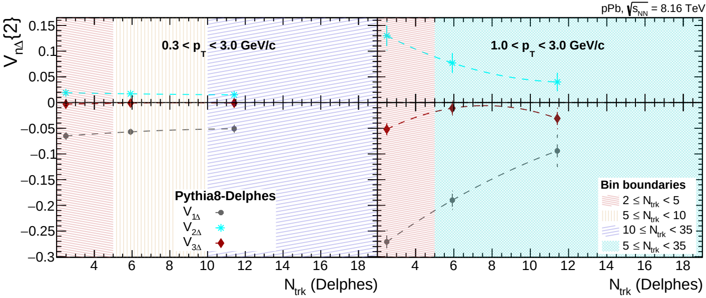


- Results on two-particle Fourier coefficient; $V_{n\Delta}$
  - $V_{1\Delta}$ negative, $V_{2\Delta}$ positive and $V_{3\Delta}$ consistent with zero

- Measurements with γp-enhanced dataset



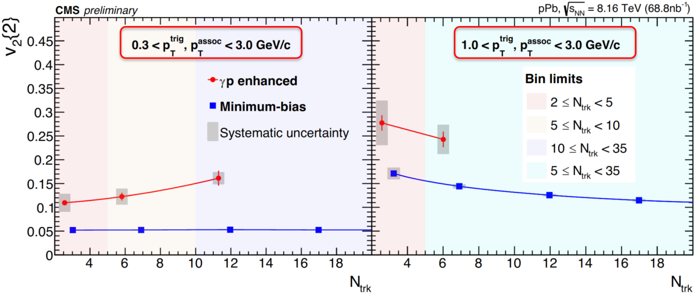
- Predictions from Pythia8 + Delphes fast simulation



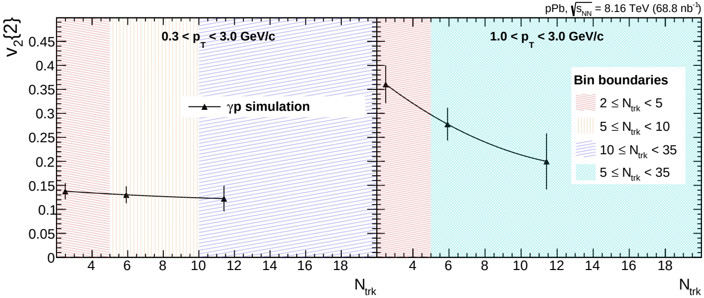
- Single-particle v_2 coefficient, $v_2 = \sqrt{V_{n\Delta}}$; consistent with non-flow effects

- Measurements with γp-enhanced dataset

  Comparison with simulation and Minimum-bias to appear in final paper



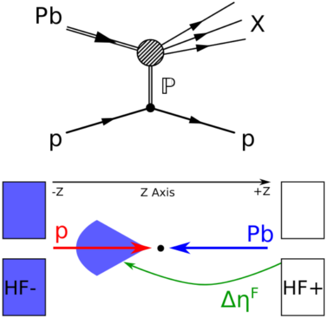
- Predictions from Pythia8 + Delphes fast simulation

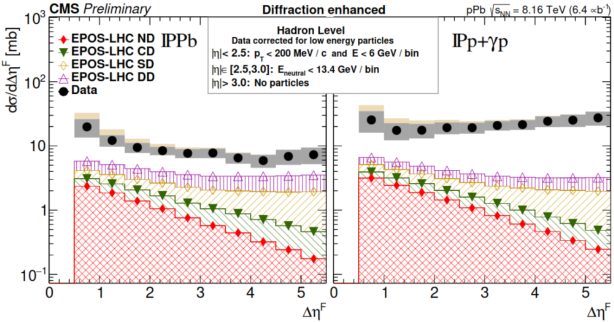


Other systems

Pomeron-Pb system within pPb 8.16 TeV collisions

- Large rapidity gaps
  - Generator predictions: Non (ND), Central (CD), Single (SD) and Double Diffractive (DD)

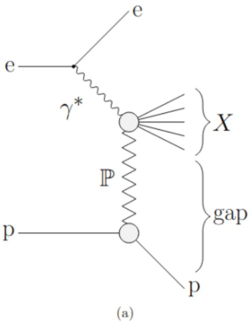


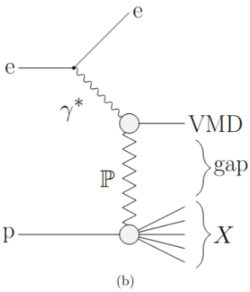


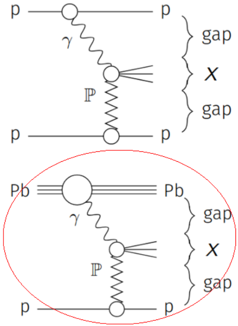
CMS-PAS-HIN-18-019

Pomeron-photon system within pPb 8.16 TeV collisions

- Hard diffraction with photons
  - Large rapidity gaps







[1] Ilkka Helenius, Christine O. Rasmussen, "Hard diffraction in photoproduction with Pythia 8", Eur.Phys.J.C 79 (2019) 5, 413

Summary

- The preparation for Run 3 is ongoing, with several upgrade work and performance studies under progress

- Observation of tH and search for its anomalous couplings will confirm standard model expectations for signal and Yukawa coupling strengths

  - Nothing beyond the SM prediction found so far

  - Experimental challenges faced such as the large overlap between the tH and ttH processes

- Study of two-particle correlations ($V_{1\Delta}$, $V_{2\Delta}$,$V_{3\Delta}$) and azimuthal anisotropies (v_2) in small systems has been expanded to e^+e^-, ep, γ-proton

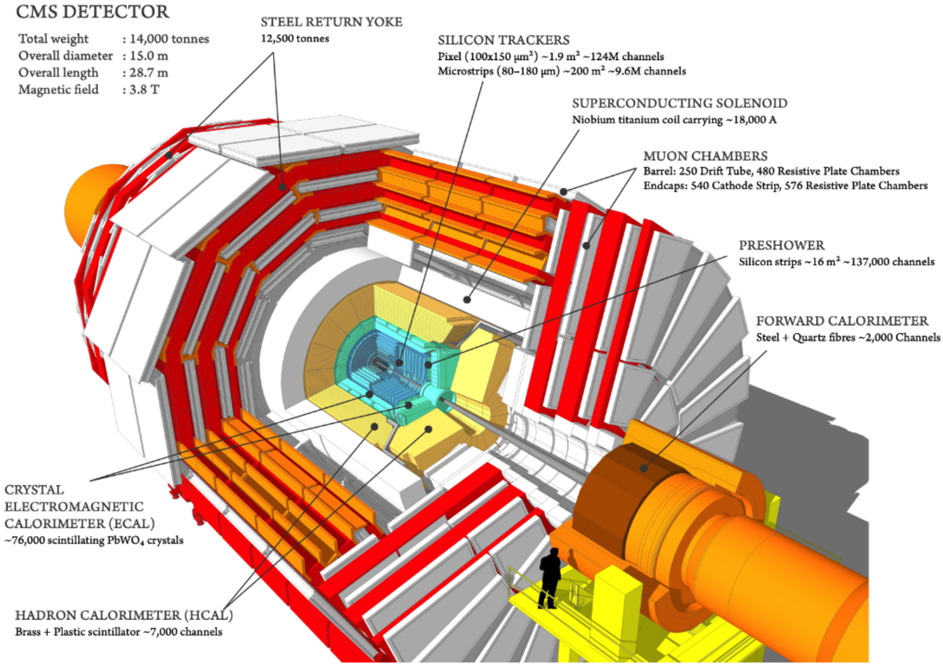
  - Limited N_{trk} range; confirmed by signal Monte Carlo

  - $V_{1\Delta}$ negative, $V_{2\Delta}$ positive and $V_{3\Delta}$ consistent with zero

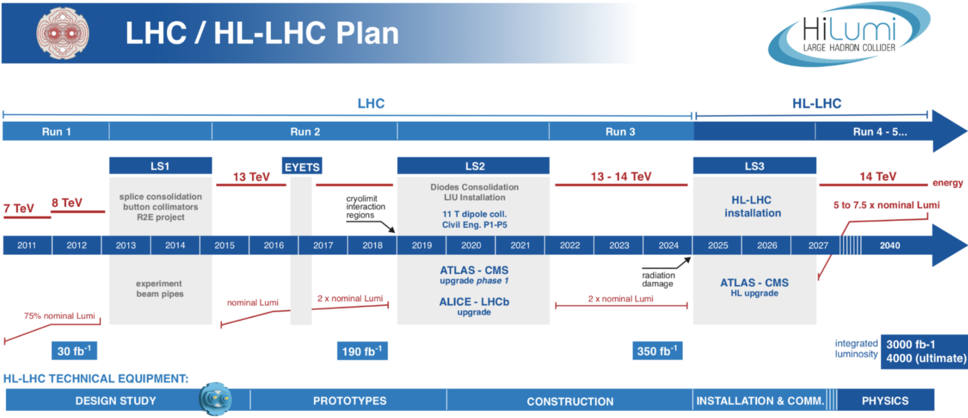
  - No evidence of ridge-like correlations observed

  - More systems such as pomeron-Lead or Pomeron-photon can be studied

Backup

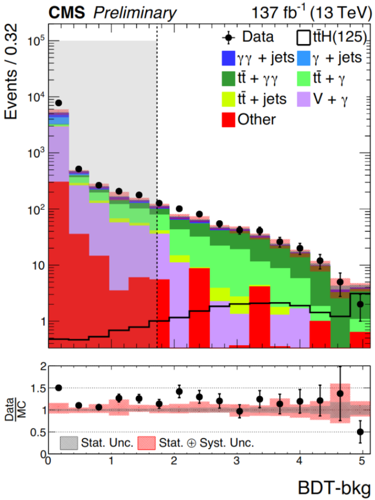

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

LHC / HL-LHC Plan with extended LS2

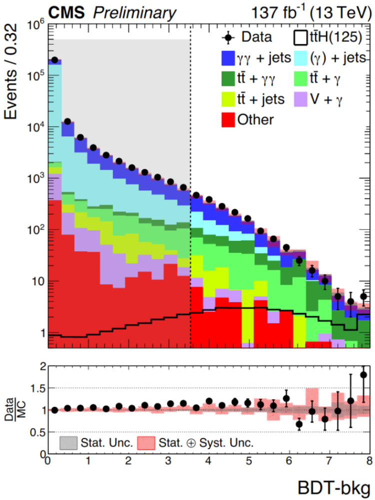


- Categories defined by cuts on BDT scores to maximise sensitivity
  - ttH hadronic and leptonic both split into 4 bins by p_T^H

ttH leptonic BDT



ttH hadronic BDT



Hydrodynamic flow in A-A collisions

- Azimuthal anisotropy Fourier coefficients v_n well understood in A-A collisions in the context of hydrodynamical model
  - Mass ordering dependence at low p_T
  - Quark content grouping at high p_T