Highlights from CMS

mia tosi
for the CMS collaboration

Kolymbari (GR), Aug 21st - Aug 29th, 2019
-- ICNFP 2019 --
introduction
the CMS detector evolution in Run 2

Run 2 data taken with an evolving detector configuration, in particular the CMS detector Phase-1 upgrades started during the first Long Shutdown (2014) and concluded during the Run 2 end of the year technical stops (2019).

Silicon Tracker
- Pixel upgraded in 2017 (4th layer) replaced some electronics in 2018

Electromagnetic Calorimeter
new DAQ links in 2018

Hadron Calorimeter
replaced HPDs → SiPMs in Endcaps in 2018

Muon Detectors
- Drift tubes VME → μTCA readout in 2018
- Cathode strip chambers new ME4/2 and RE4/1 installed during LS1
- GEM slice test (GE1/1) in 2018

Forward Hadron Calorimeter
upgraded started in LS1 and completed in 2017

Trigger System
major upgrade of L1 trigger done by 2016
Run 2 Trigger/DAQ:
- L1 hardware ~100kHz
- HLT software ~1kHz
Run 2 Summary

few challenges:
- 50ns → 25ns
- much higher PU and luminosity (w.r.t. Run 1 and nominal)

Run 2 pp data taking efficiency 92.3%
(94% in 2018)
Run 2 Physics goals

simple!

completing our picture
Run 2 Physics goals & methods

simple! completing our picture

How?

simple! new ideas for trigger, data processing, reconstruction and analysis

continue improving analyses in terms of precision and sensitivity, independently of increases in luminosity and collision energy
Run2 Physics goals & methods

“Scouting”

avoid bandwidth limitations in order to access lower $p_T$ and mass regions where trigger rates are (too) high

- reduction of event size to $O(10\text{kB})$ allows trigger rates of several kHz
- analysis based on physics objects reconstructed at the High Level Trigger (HLT) (dropping RAW data)
- needs efficient physics objects reconstruction and adequate calibration @ the HLT stage, and validation against full reconstruction
- examples:
  - searches for low-mass resonances in both the $n$-jet and dimuon channels

DP-2018/055
Run2 Physics goals & methods

Data “Parking”

avoid CPU limitations in prompt reconstruction in order to collect more statistics in specific phase-space

- store additional datasets [rate of up to 6kHz] using lower trigger thresholds at end of fill

- delay their processing to times of lower load on the computing system

- needs careful planning taking into account data taking schedule and MC production

- examples:
  - sample of $12B$ events (!) enriched in unbiased B-decays collected w/ displaced muon triggers
    - tagged B
    - unbiased other side B
"Machine Learning"

use full power of multiple variables and reduce need for manual tuning

wide range of state-of-the-art algorithms used for solving *combinatoric problems, regression, and classification*

- needs adequate control regions for performance measurements and (typically) large MC samples \(O(100M)\)

- examples:
  - “DeepJet” **b-tagging**, neural networks for the \(ttH(H \rightarrow bb)\) analysis
  - “DeepCSV” **c-tagging**, for the \(VH(H \rightarrow cc)\) analysis
Higgs boson

- LHC Run 1 led to
  - discovery using decays to bosons
  - exclusion of many BSM models and specific parameters phase-space
- LHC Run 2: unprecedented statistics
  - differential cross section measurement

see Rainer Mankel's talk
Higgs boson

- LHC Run 1 led to
discovery using decays to bosons
exclusion of many BSM models
- LHC Run 2: unprecedent statistics
differential cross section measurement
directly established couplings to 3rd generation fermions

**ttH (H→bb)**
- 2016 + 2017 datasets
- covers 0, 1, and 2l decay modes
- improvements in particular from
  - MVA techniques
  - b-jet identification
- achieved evidence for H→bb based on ttH only
  significance: \(3.9\ (3.5) \sigma\)
signal-strength: \(\mu_{\text{comb}} = 1.15^{+0.32}_{-0.29}\)

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see Pietro Vischia’s talk
see Rainer Mankel’s talk
**Higgs boson**

- LHC Run 1 led to
definitions using decays to bosons
- exclusion of many BSM models
- LHC Run 2: unprecedented statistics
differential cross section measurement
directly established couplings to 3rd generation fermions
- provides an interesting challenge: **couplings to 2nd generation fermions**

\( H \rightarrow \mu\mu \)

\( \mu \) are the easiest objects to identify and measure, **but**:
- small \( \text{BR}(H \rightarrow \mu\mu)=2 \times 10^{-4} \rightarrow \mathcal{O}(5-6) \text{ evt/fb}^{-1} \)
- large backgrounds: \( Z/\gamma* \), diboson, top
- small \( S/(S+B) \) regime \( \sim 0.2\% \)

\( H \rightarrow cc \)

coupling \( \lambda_c \sim \lambda_\tau \), but way harder to probe:
- \( \text{BR}(H \rightarrow cc) \sim 0.05 \times \text{BR}(H \rightarrow bb) \)
- large (hadronic) background [\( H \rightarrow bb \) is background!]
- **charm jet ID** is highly challenging

first direct \( H \rightarrow cc \) search in CMS targeting VH production

see Rainer Mankel’s talk

combined results for the signal strength:
upper limit: \( \sigma/\sigma_{\text{SM}} = 70 (37) @ 95\% \text{ CL} \)

\[ \mu(VH, H \rightarrow c\bar{c}) = 36^{+20}_{-14} \]
Higgs boson

- LHC Run 1 led to discovery using decays to bosons
- LHC Run 2 directly established couplings to 3rd generation fermions
- LHC Run 3 will **extend sensitivity to physics beyond the SM**
- HL-LHC will **allow to probe** the Higgs self-coupling

**non-resonant HH production**

$$\sigma(gg\to HH) = 33.5 \text{ fb}$$

[@13 TeV NNLO+NNLO w/ top mass effects]

is the unique probe of the BEH mechanism
- provides access to measurement of the Higgs self-coupling $\lambda$
- brings information on the shape of the Higgs potential
- sensitive to BSM effects in both the yields and kinematic distributions
Z boson with charm and bottom

measure ratios of cross sections of the associated production of

\[ Z + \text{charm or bottom jet} @ 13 \text{ TeV} \]

as function of the Z and jet \( p_T \)

- \( b, c \) and light jets are distinguished using the \textbf{SV invariant mass}

- results are compared w/ predictions from LO and NLO perturbative QCD calculations

- \textbf{the measurement precision exceeds the current theoretical predictions}!

- \( R(c/j) = \frac{\sigma(Z+c \text{ jets})}{\sigma(Z+ \text{ jets})} \)
- \( R(b/j) = \frac{\sigma(Z+b \text{ jets})}{\sigma(Z+ \text{ jets})} \)
- \( R(c/b) = \frac{\sigma(Z+c \text{ jets})}{\sigma(Z+b \text{ jets})} \)

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see Vitaliano Ciulli’s talk
top quark physics
• is a key ingredient to probe QCD, electroweak, and BSM physics
• has a very rich experimental programme @LHC

- high precision top cross sections and properties

- measure all channels to look for the unexpected
- good agreement w/ NNLO+NNLL calculations
- highest precision: dilepton and l+jets channels ~4%
  (similar to theory prediction)

top mass from boosted jets
• single jet (p_T>400 GeV) includes all top decay products [X Cone algorithm]
• mass from m_{jet} differential cross section:
  \( m_\text{t} = 172.56 \pm 0.41 \text{(stat)} \pm 2.44 \text{(syst)} \text{ GeV} \) [1.4%]
top-quark

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- high precision top cross sections and properties
- rare processes becoming less rare (some even systematically limited !)
→ started to challenge theory predictions in many respects

significance 2.6 (2.7) σ
same-sign dilepton & trilepton final state

- very rare, not yet observed [σ(tttt) ~ 12 fb⁻¹]
- sensitive to BSM
- direct access to top-Higgs Yukawa coupling

- best process to probe top-Z coupling and its structure
- most precise σ(ttZ) = 0.95±0.05 (stat) ±0.06 (syst) pb
- first differential measurements
→ sensitive to new physics effects !
\[B \rightarrow \mu \mu\]

- \(B_s \rightarrow \mu \mu\) and \(B_d \rightarrow \mu \mu\) branching ratios

measure relative to \(B^+ \rightarrow J/\psi K^+\) decays

[cancellation of many systematic uncertainties]

\[
\frac{N_s}{N_{obs}} \frac{f_s}{f_B^+} \varepsilon_{tot} B(B^+ \rightarrow J/\psi K^+) B(J/\psi \rightarrow \mu^+ \mu^-)
\]

ratio of fragmentation fractions: \(\frac{f_s}{f_B} = 0.252 \pm 0.012\) (exp) \(\pm 0.015\) (CMS)

- dataset: Run 1 (7 + 8 TeV) + Run 2 (2016 13 TeV)

- the decay \(B_s \rightarrow \mu \mu\) is observed w/
  - a significance: \(5.6\) (6.5) \(\sigma\)
  - a branching fraction:

\[
BR(B_s \rightarrow \mu^+ \mu^-) = [2.9 \pm 0.7\) (exp) \(\pm 0.2 (f_s/f_B)] \times 10^{-9}
\]

- an effective lifetime:

\[
\tau_{\mu^+ \mu^-} = 1.70^{+0.61}_{-0.44} \text{ ps}
\]

- no significant excess is observed for the decay \(B_d \rightarrow \mu \mu\)

\[
BR(B_d \rightarrow \mu^+ \mu^-) < 3.6 \times 10^{-10} @95\% \text{ CL}
\]

previous CMS result: \(BR(B_d \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-9} @95\% \text{ CL}\)

see Valentina Mariani’s talk
$B \rightarrow \mu \mu$

- $B_s \rightarrow \mu \mu$ and $B_d \rightarrow \mu \mu$ branching ratios measure relative to $B^+ \rightarrow J/\psi K^+$ decays 
  [cancellation of many systematic uncertainties]

$$BR(B_s \rightarrow \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \frac{f_s}{f_u} B(B^+ \rightarrow J/\psi K^+) B(J/\psi \rightarrow \mu^+\mu^-)$$

ratio of fragmentation fractions : $\frac{f_s}{f_u} = 0.252 \pm 0.012\ $(exp) $\pm 0.015\ $(CMS)

- dataset : Run 1 (7 + 8 TeV) + Run 2 (2016 13 TeV)

- the decay $B_s \rightarrow \mu \mu$ is observed w/ 
  - a significance : $5.6\ (6.5)\ \sigma$
  - a branching fraction :

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- an effective lifetime :

$$\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44}\ ps$$

- no significant excess is observed for the decay $B_d \rightarrow \mu \mu$
  - upper limit on the branching fraction :

$$BR(B_d \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10} \ @ 95\%\ CL$$

previous CMS result : $BR(B_d \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9} \ @ 95\%\ CL$

- these results are consistent w/ SM predictions and an earlier measurement of LHCb

see Valentina Mariani’s talk
**Observation of $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$**

*b baryon decays* are important to probe the dynamics of heavy-flavor decays and test the heavy-quark effective theory - potential channels for access to exotic resonances [like the $B^+ \rightarrow J/\psi \phi K^+$]

- **1st observation** of the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ w/ significance 9.7 $\sigma$
  
  decay expected to proceed via the $b \rightarrow c\bar{c}s$ process [similar to $\Lambda_b^0 \rightarrow J/\psi \Lambda$ but requires an additional $s\bar{s}$ pair]

- measure the branching fraction relative to the decay mode $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$
  
  $$\frac{B(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)}{B(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) \varepsilon(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)}{N(\Lambda_b^0 \rightarrow \psi(2S)\Lambda) \varepsilon(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)} \frac{BR(\psi(2S) \rightarrow J/\psi \pi^- \pi^+)}{BR(\phi \rightarrow K^+ K^-)}$$
  
  $$= [8.26 \pm 0.90 \text{ (stat)} \pm 0.68 \text{ (syst)} \pm 0.11(BR)] \times 10^{-2}$$

### Observation of $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$

- **286 ± 29 events**

### Observation of $\Lambda_b^0 \rightarrow \psi(2S) \Lambda$

- **884 ± 37 events**

**BPH-19-002**

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*see Valentina Mariani’s talk*
**resonant decays into 2 jets**

- **classical high-mass resonance search**
  can be interpreted in a wide range of BSM models predicting particles decaying to $gg$, $gq$, or $qq$

- continue to improve analysis w/ **new techniques**:
  - replace parametric background shape by data driven measurement in sideband region $[\Delta \eta_{jj}]$

- results consistent w/ background
  - robust method
  - smaller systematics uncertainties
  - more sensitive for broad resonance searches
resonant decays into 2 jets in events w/ 3 jets

• search for vector resonances decaying into 2 jets in the mass range 350 - 700 GeV
  → look for resonances recoiling against a 3rd jet
• 2016 data scouting w/ low H_T trigger thresholds
  event selection: require 3 wide jets p_T > 72 GeV
• no significant excess is found
  → most stringent limits on resonances decaying to light jets in the 350-450 GeV mass range
  → set upper limits @95% CL on the coupling to quarks g'_q in the range 0.10 - 0.15 for a vector resonance interacting only w/ quarks

EXO-19-004
search for dimuon resonances

- search for **low-mass** dimuon resonances in the range **11.5-200 GeV** [excluding the Z resonance range]
  - for masses < 45 GeV
    the high rate dimuon **data scouting** triggers \([\text{muon } p_T > 4.5 \text{ GeV}]\) is used
  - for mass range > 45 GeV, \(\text{muon } p_T > 20 \text{ and } 10 \text{ GeV}\)

- the results can be interpreted as a **dark photon (Z}_D\)**
  that could couple the SM particles to a hidden, dark sector of particles

- the strength of the coupling w/ SM fermions is determined by the kinetic mixing coefficient \(\epsilon\)

- data are found to be consistent w/ background expectations

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**strongest constraints on a hypothetical dark photon**
\(w/ m_{Z_D} > 11.5 \text{ GeV}\)
search for dimuon resonances \( ^\text{(II)} \)

- **high-mass** dielectron and dimuon search

- event selection and reconstruction are optimized for high-\( p_T \) leptons

- backgrounds estimated from simulation [w/ corrections to the DY] and includes the contribution from \( \gamma \) induced processes

no significant deviation from SM expectation is observed

\( \Rightarrow Z'_{\text{SSM}} (Z'_{\psi}) \) particle is excluded @ 95% CL below a mass of 5.15 (4.55) TeV
Long-lived particles (LLPs) appear in many BSM scenarios:
- nearly mass-degenerate states (compressed SUSY, AMSB, etc.)
- heavy virtual mediators (split-SUSY, heavy neutral leptons, etc.)
- small couplings (dark photons, freeze-in DM, RPV SUSY, etc.)

BSM searches need to be performed also considering the lifetime of the new particle. Lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and we need to use all subdetectors.

CMS has a broad LL program based on signature-driven searches.

- **LLP varieties**
  - charges
  - final states
  - decay locations
  - lifetimes

- **challenges**
  - dedicated trigger
  - unique object reconstruction
  - atypical background
  - unusual discriminating variables
long-lived particles

- **delayed jets** [heavy neutral LLPs decaying to at least 1 delayed jet + MET]
  - benchmark: long-lived gluinos give rise to jets from displaced vertex
    - delay due to differences in velocity and in path length
  - median time of all ECAL cells in the jet cone, allows to
    - reduce the background to few event level
    - extend significantly the sensitivity w.r.t. tracker-based searches

main backgrounds:
- **cosmic ray muon deposits** in ECAL
- **core and satellite bunches** (collisions of very low luminosity bunches at ~2.5 ns steps from main bunches)
- **beam halo muons** (muons from beam interacting with collimators)

PF jets are not used in the offline analysis, because nonprompt jets do not produce reliable information in the tracker and out-of-time energy deposits are not included in the PF jet reconstruction

arXiv:1906.06441
long-lived particles

- **delayed photons** (at least) 1 delayed photon + MET
  - benchmark: long-lived neutralinos decay to (at least) 1 photon and a gravitino

- **photon timing using ECAL**
  - requires precise calibration of ECAL timing and resolution
  - **dedicated trigger in 2017** for selecting events w/ 1 photon consistent w/ production at a displaced secondary vertex
  - **dedicated out-of-time photon reconstruction**
  - **extend the previous best limits**
    - in the neutralino proper decay length by up to about one order of magnitude
    - in the neutralino mass by up to about 100 GeV

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**EM shower shape in \( \eta-\phi \) plane more elliptical**

**2 photons final state**

**1 photon final state**

**\( \gamma \) channel**

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**CMS Preliminary**

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<th><strong>Event / GeV</strong></th>
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<tr>
<td>2017 ( \gamma ) channel</td>
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<tr>
<th><strong>( p_T ) (GeV)</strong></th>
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<td>0 200 400 600 800 1000</td>
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<tr>
<th><strong>GMSB SPS8</strong></th>
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<td>CMS Exp (s 1 o) 13 TeV ( \gamma(\gamma) )</td>
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<td>CMS Obs 13 TeV ( \gamma(\gamma) )</td>
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<td>ATLAS Obs 8 TeV ( \gamma )</td>
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<td>CMS Obs 7 TeV ( \gamma )</td>
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**EXO-19-005**
preparing for LHC Run3

“Phase-1” upgrades of CMS
majority of the upgrades have been done in the past years

Silicon Tracker
• Pixel replace layer1 and all DCDC converters
• Microstrips running colder -20°C (2018) → -25°C (Run3)

Muon Detectors
shielding against neutron background
• Drift tubes upgrade front-end electronics
• Cathode strip chambers upgrade front-end electronics
• GEM instal GE1/1 chambers

Hadron Calorimeter
install new SiPM+QIE11-based 5Gbps readout

new beampipe

Trigger System
heterogenous HLT farm (CPU+GPU) -decision in 2020

see Nancy Marinelli’s talk
CMS is very busy during Long Shutdown 2!

- **efficient technical program for the future**
  - completing Phase-1 upgrades
  - preparing for Run 3 (and in view of HL-LHC)

- **exciting, cutting edge slate of upgrades** for HL-LHC
  HL-LHC projections show the large gains w/ the upgraded detector and an integrated luminosity of 3ab$^{-1}$

- **vibrant physics research** program
  - CMS recently submitted its 905th scientific publication on results using LHC collision data

  - many results using the full dataset of 137 fb$^{-1}$

  - **searches** look for the unknown
  - **rare** processes scrutinize the SM predictions
  - **precision** measurements
    - tt+V measurements challenge the theoretical precision
  - a broad **Higgs** physics program
    - the precision era in the gauge sector is starting

  - upcoming full Run 2 results will use ultimate calibrations w/ a legacy reconstruction of Run 2 datasets