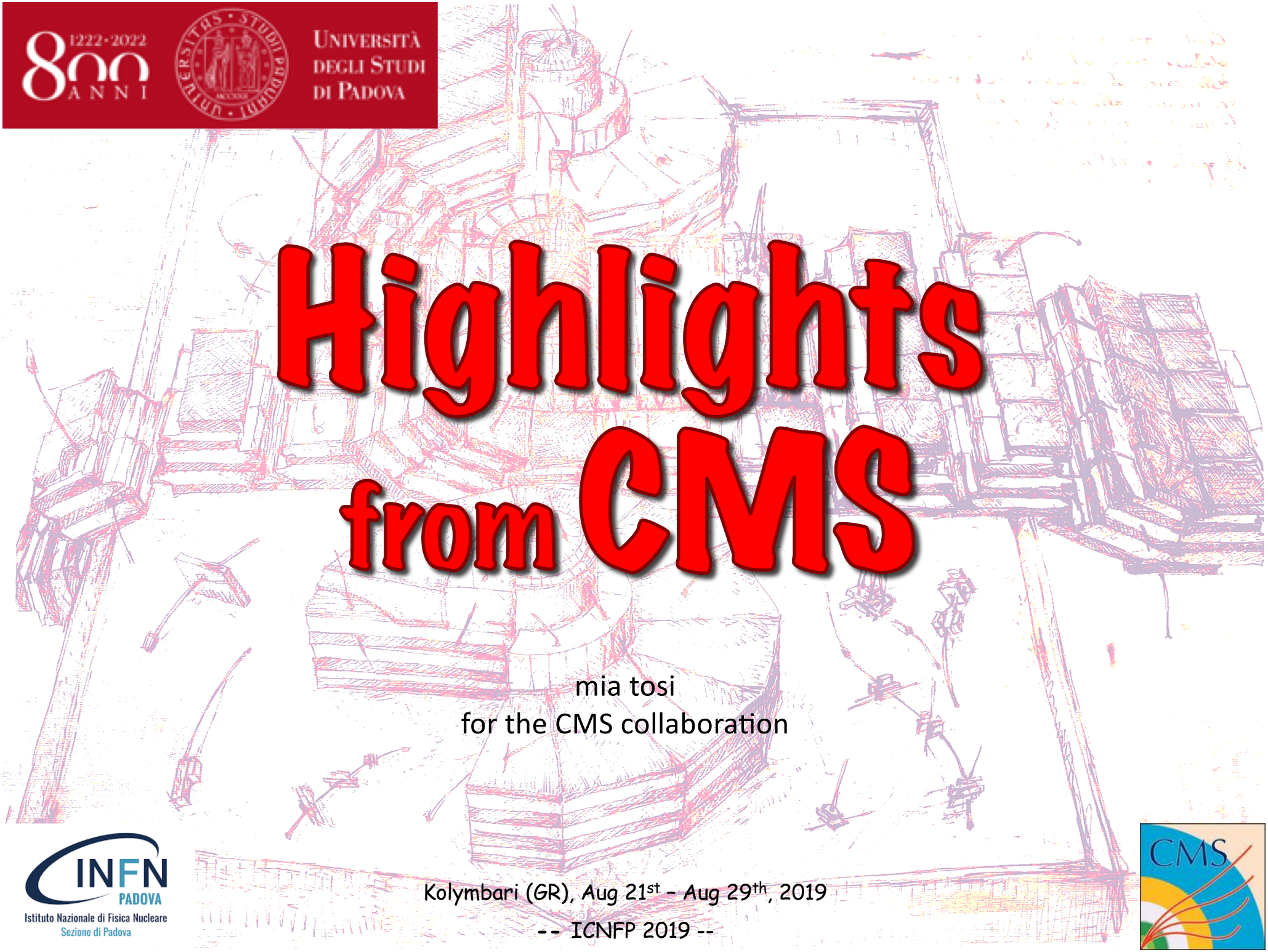
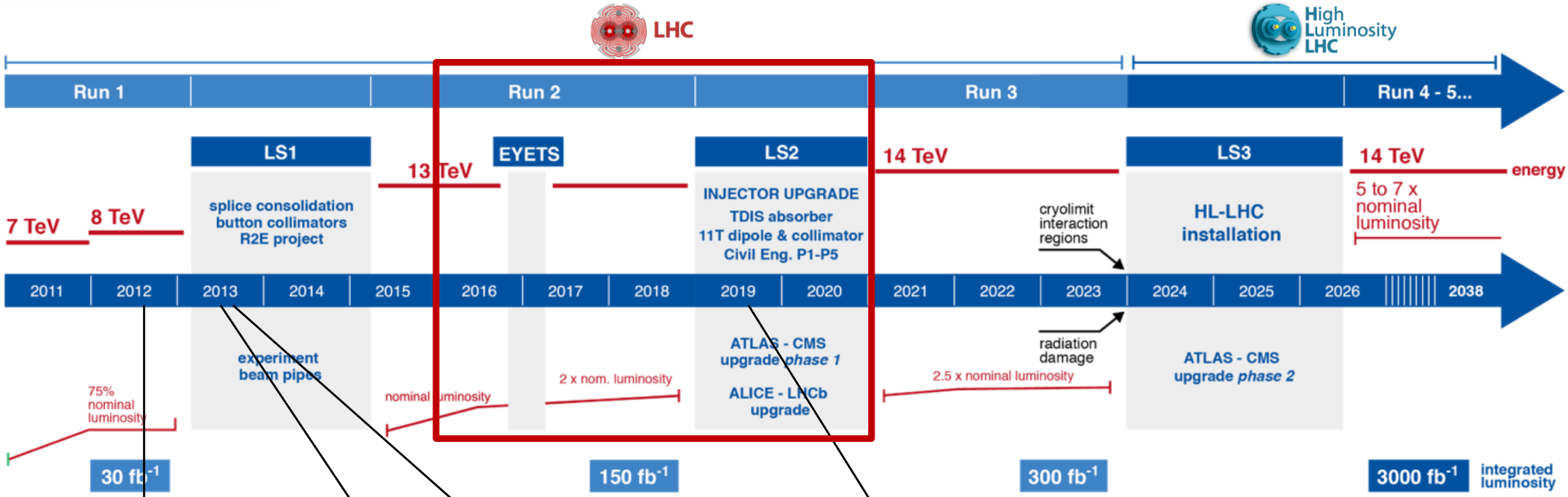


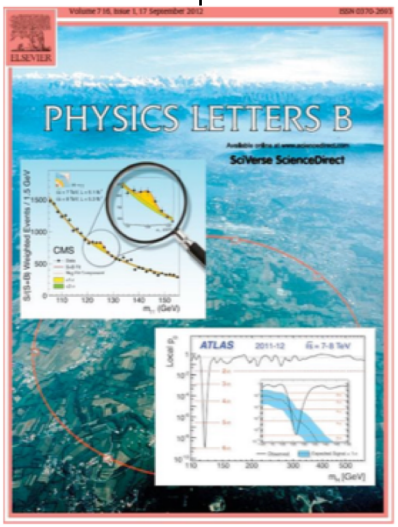
Highlights from CMS

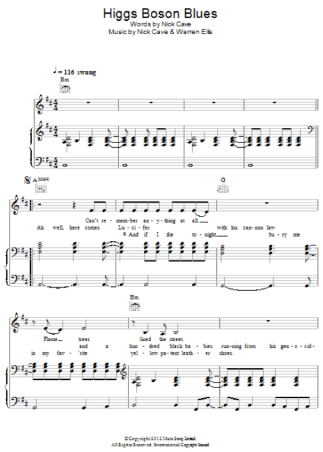
mia tosi
for the CMS collaboration

Kolymbari (GR), Aug 21st – Aug 29th, 2019
-- ICNFP 2019 --

introduction







the CMS detector evolution in Run 2

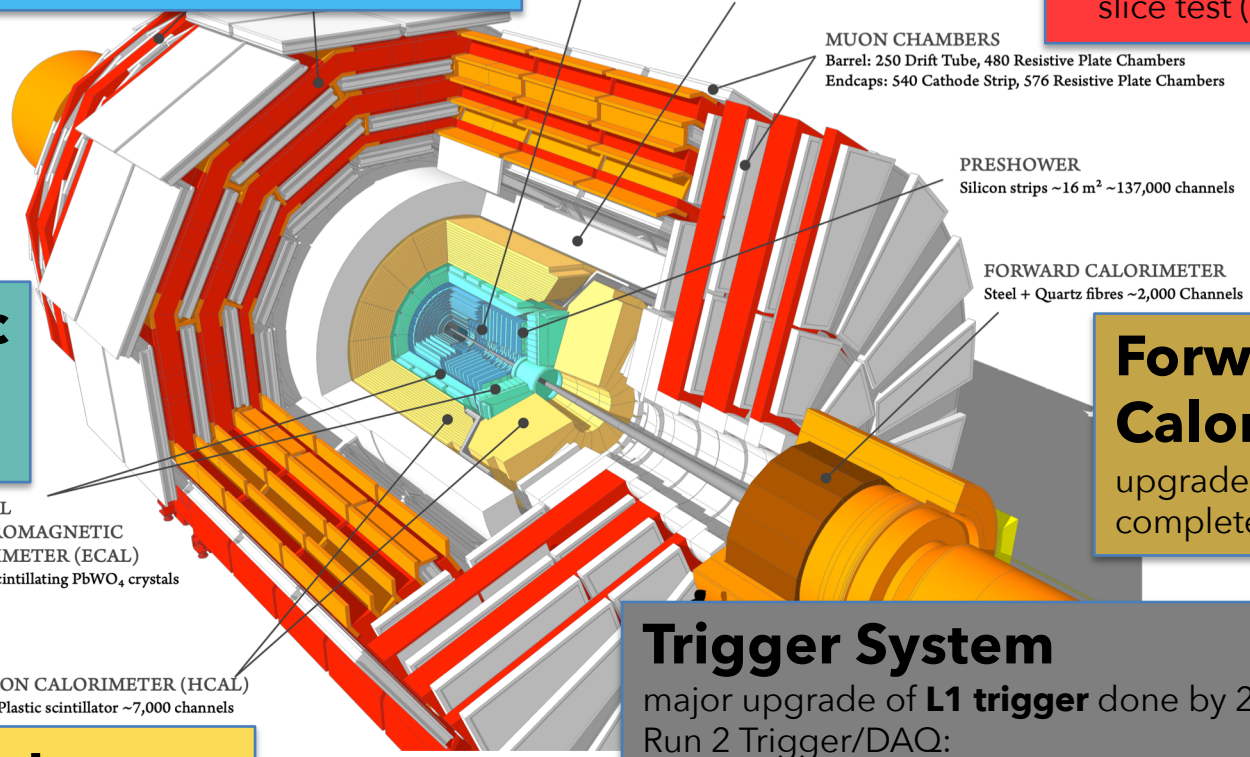
Run 2 data taken w/ an *evolving detector* configuration, in particular the CMS detector Phase-1 upgrades started during the first Long Shutdown (2014) and concluded during the Run 2 end of the year technical stops (2019)

Silicon Tracker

- **Pixel**
  upgraded in 2017 (4th layer)
  replaced some electronics in 2018
- Microstrips
  running colder -15°C (2015-2017)→ -20°C (2018)
  at -25 °C after LS2 (probably)

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



Electromagnetic Calorimeter

new DAQ links 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

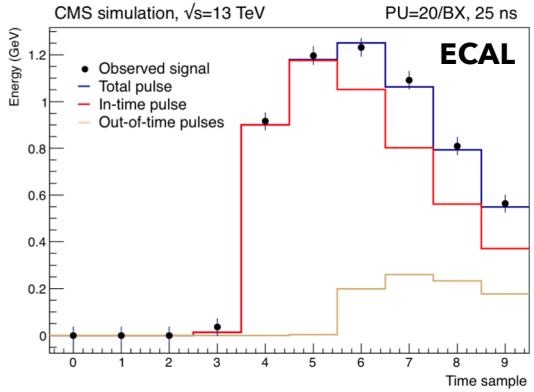
Hadron Calorimeter

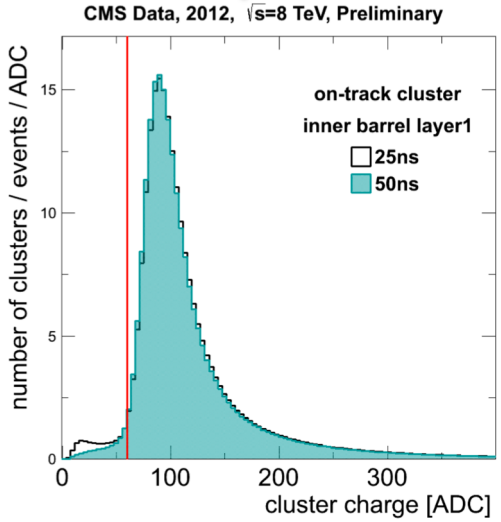
replaced HPDs→**SiPMs** in Endcaps in 2018

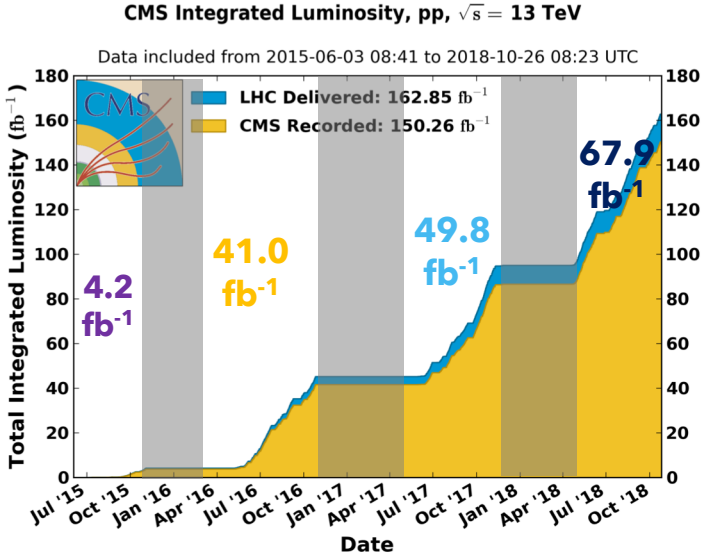
Run 2 Summary

few challenges :

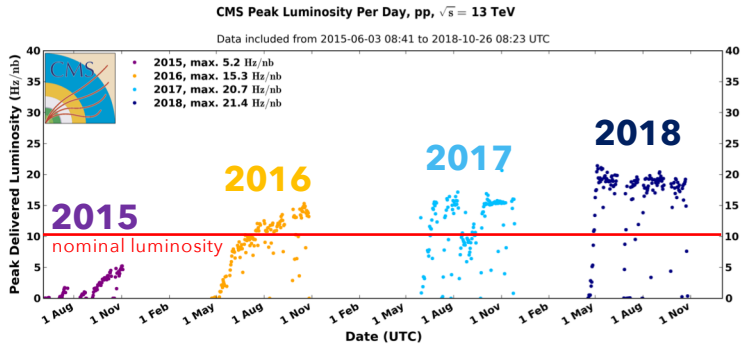
- 50ns → 25ns



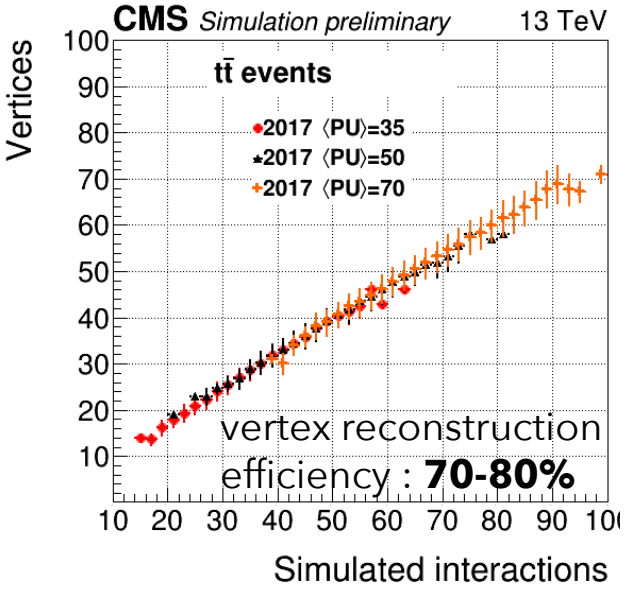


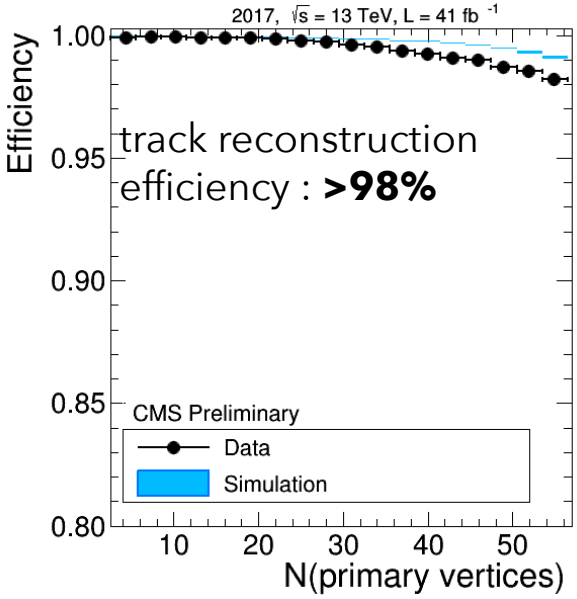


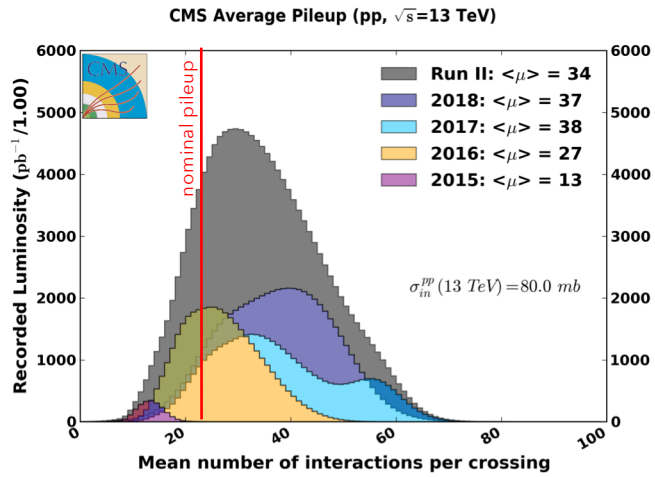
- much **higher PU** and **luminosity** (w.r.t. Run 1 and nominal)



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

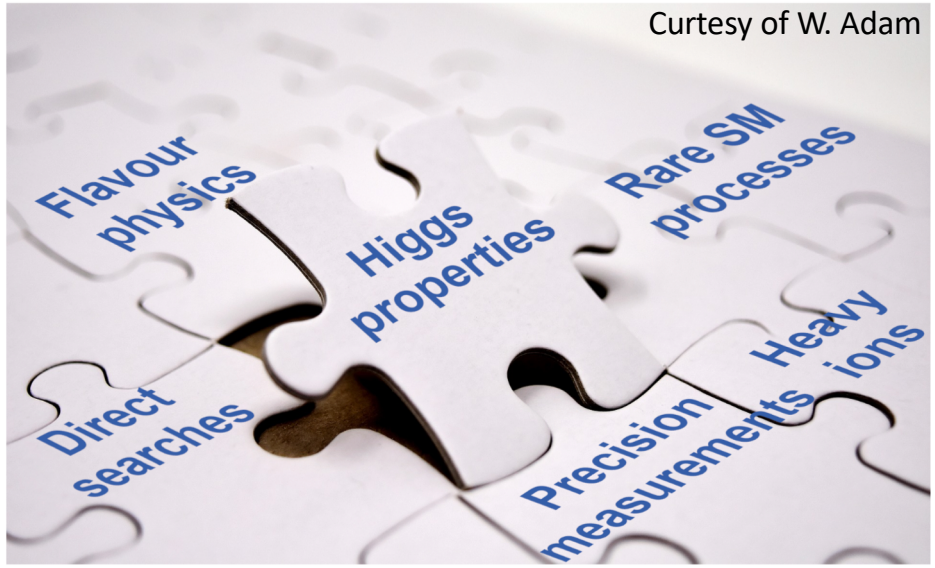






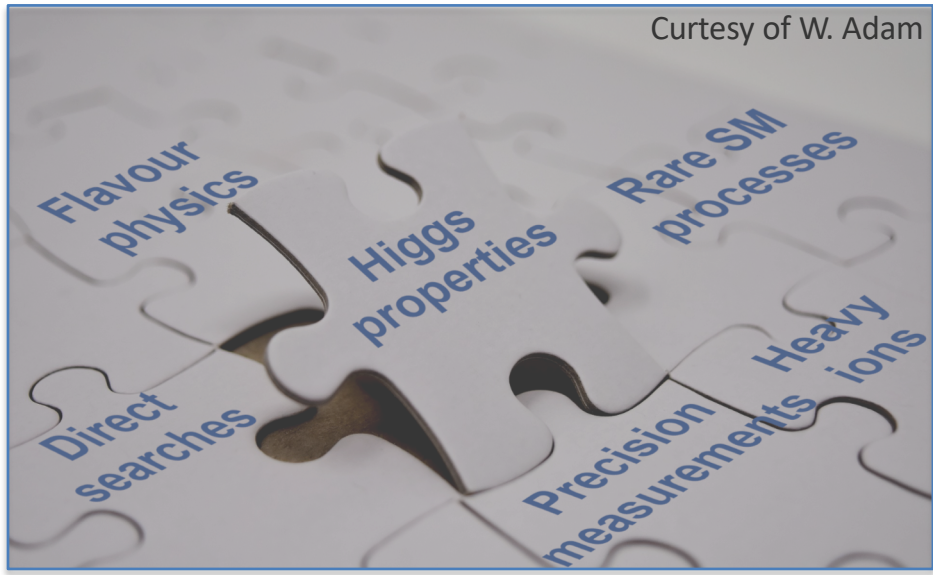
Run 2 Physics goals

simple !
completing our picture



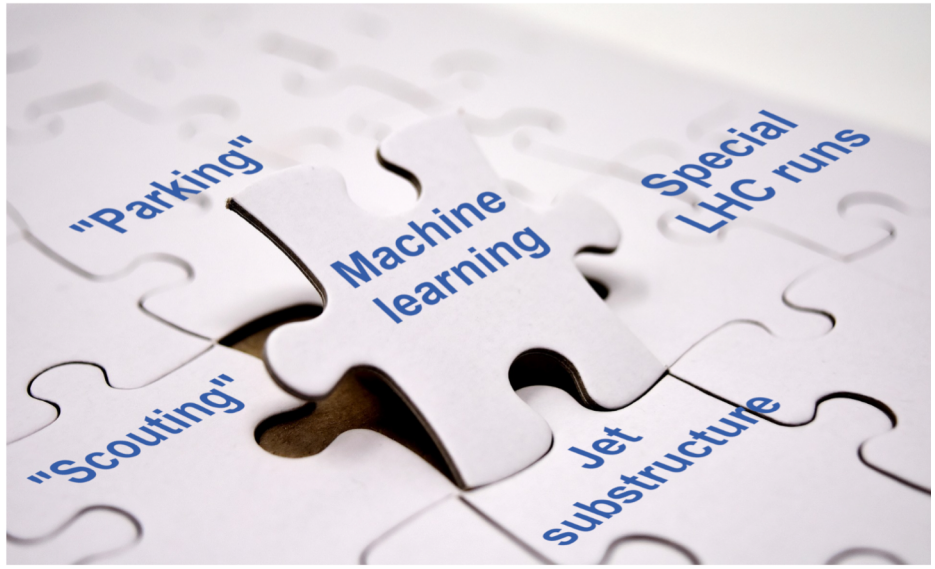
Run 2 Physics goals & methods

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

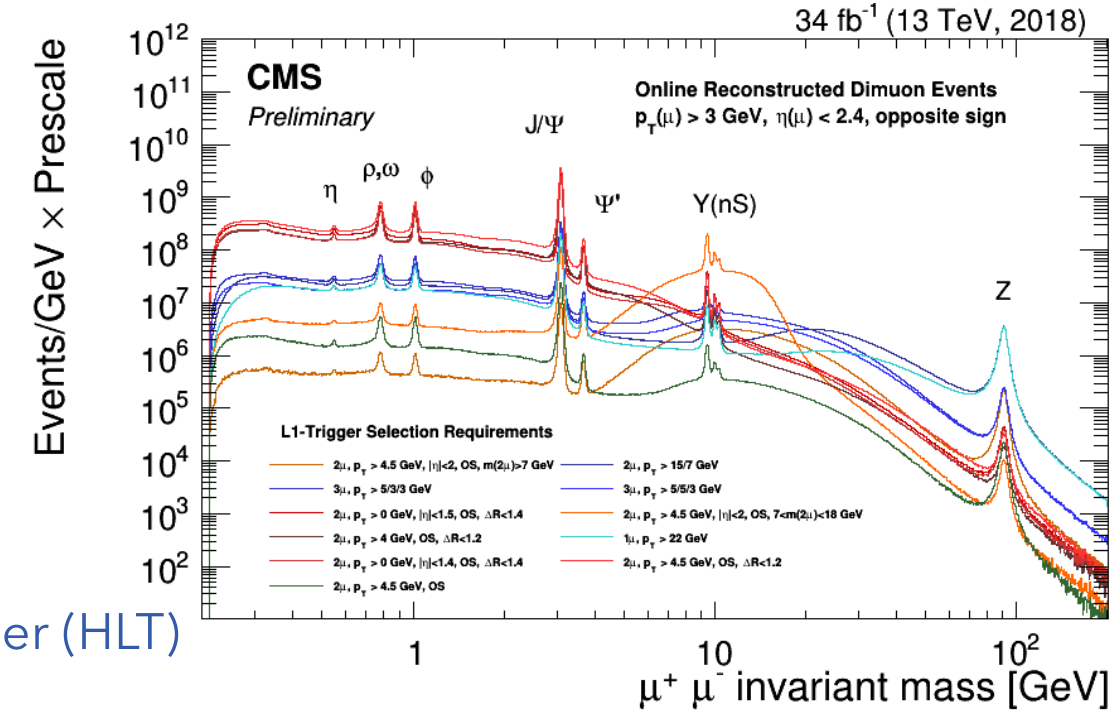
0.5% of the full size

- **reduction** of **event size to O(10kB)** allows trigger rates of several kHz

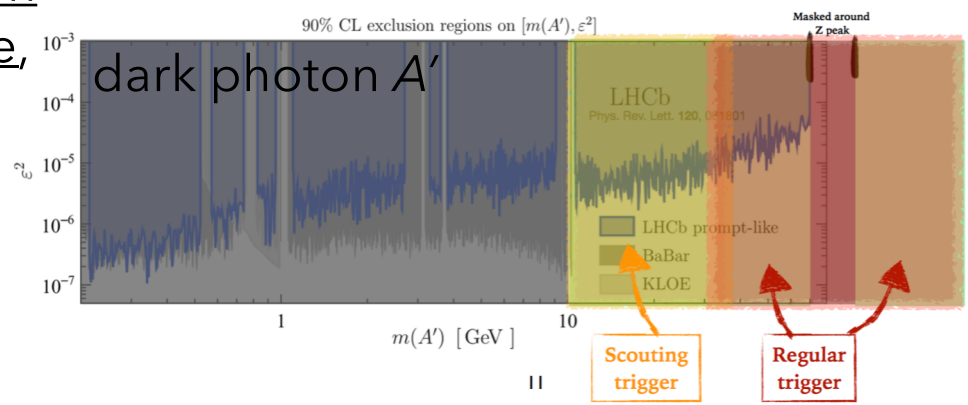
- analysis based on physics objects reconstructed at the High Level Trigger (HLT) (dropping RAW data)

- 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



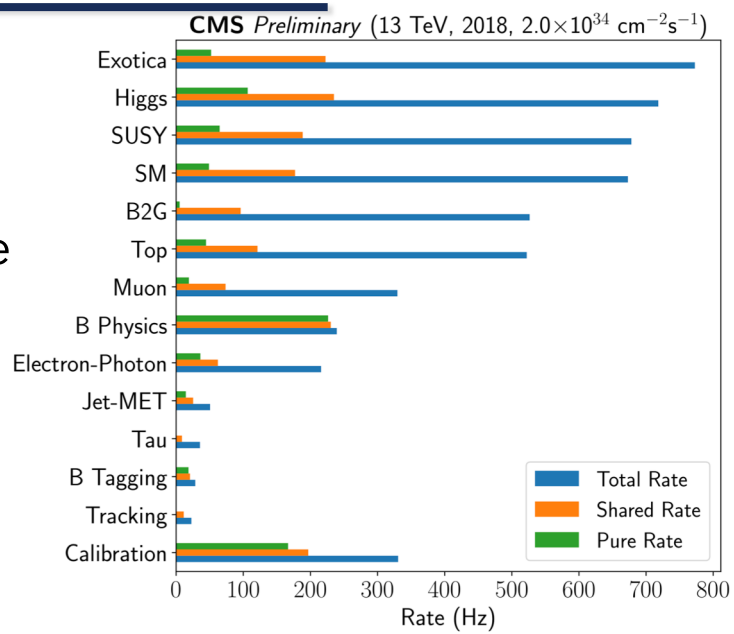
DP-2018/055



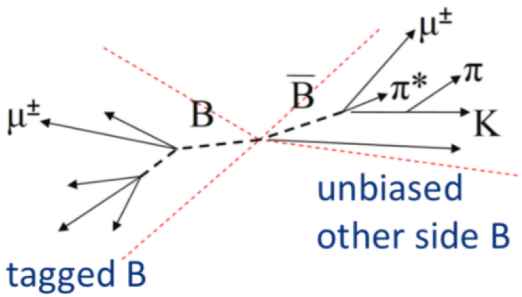
Run2 Physics goals & methods

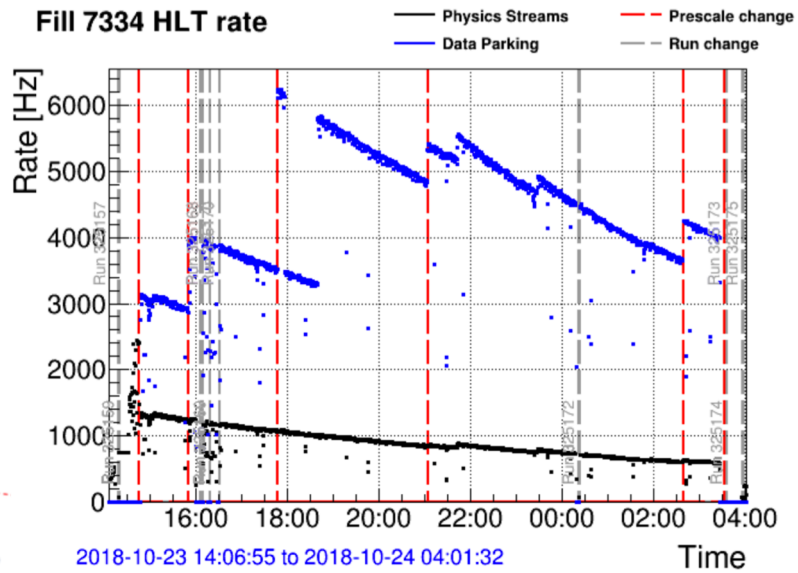
Data "Parking"

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





Run2 Physics goals & methods

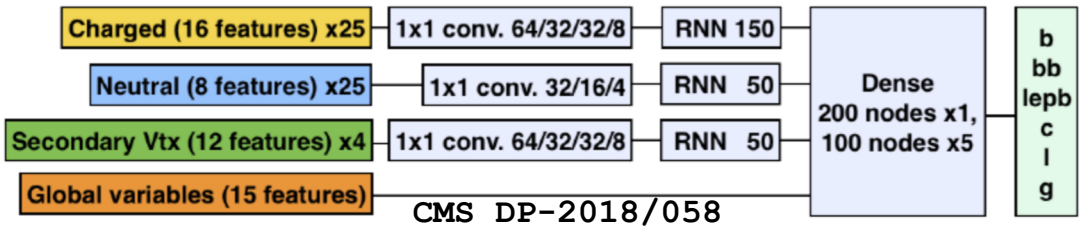
"Machine Learning"

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

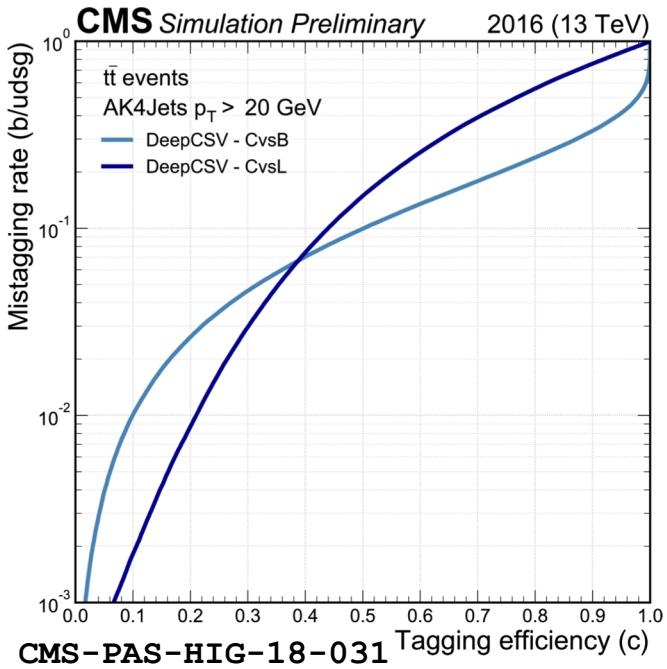
wide range of state-of-the-art algorithms used
for solving **combinatoric problems**, **regression**, and **classification**

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

- examples:
  - "DeepJet" **b-tagging**,
    neural networks for the ttH(H→bb) analysis



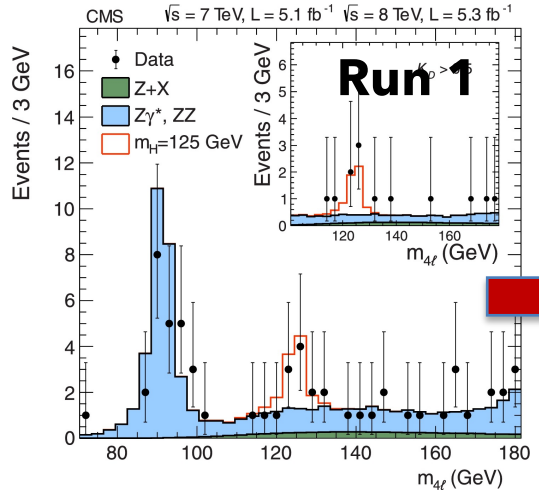
  - "DeepCSV" **c-tagging**,
    for the VH(H→cc) analysis

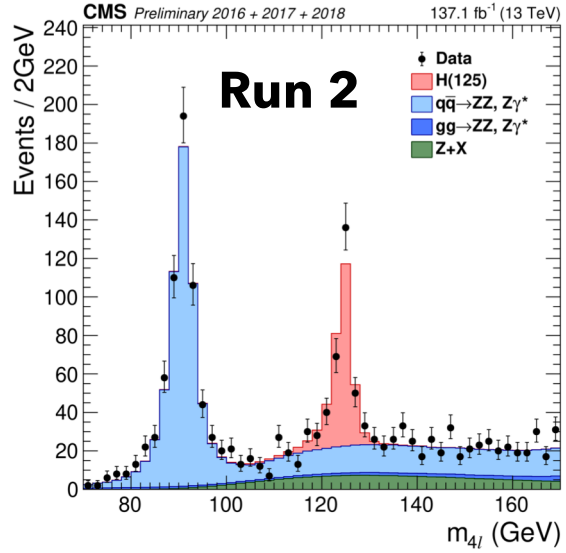


Higgs boson

- LHC Run 1 led to
  - **discovery** using decays to bosons
  - **exclusion** of **many BSM models** and specific **parameters phase-space**
- LHC Run 2 : <u>unprecedent statistics</u>
  - **differential cross section measurement**

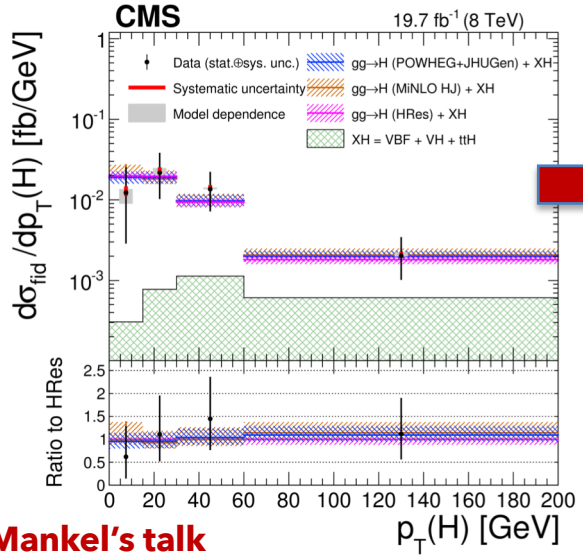
PLB 716(2012)30

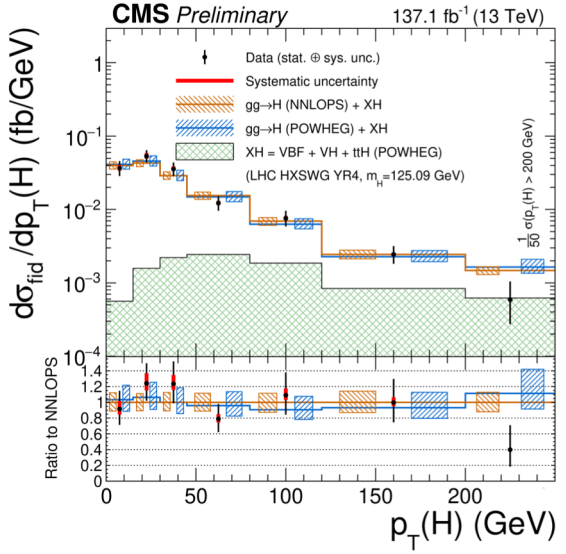




HIG-19-001

JHEP 04(2016)5





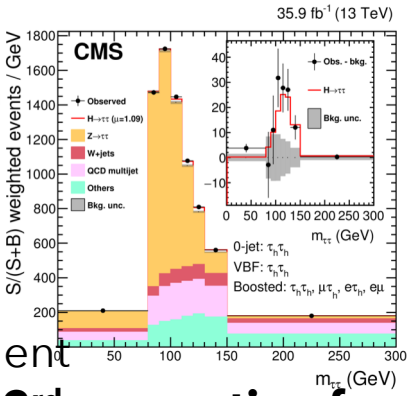
HIG-19-001

see Rainer Mankel's talk

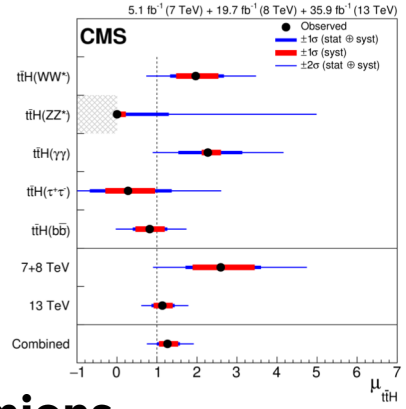
Higgs boson

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

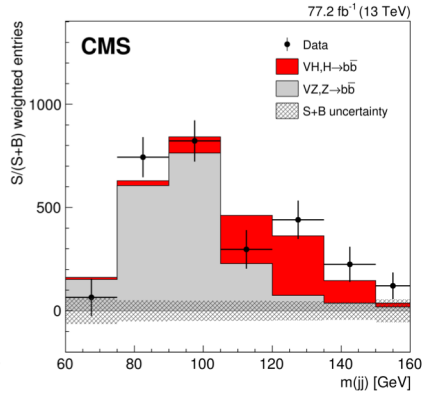
PLB 779(2018)283



PRL 120(2018)231801



PRL 121(2018)121801

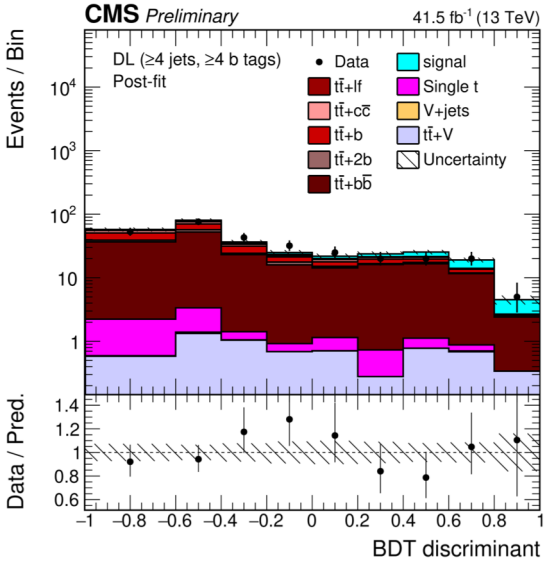


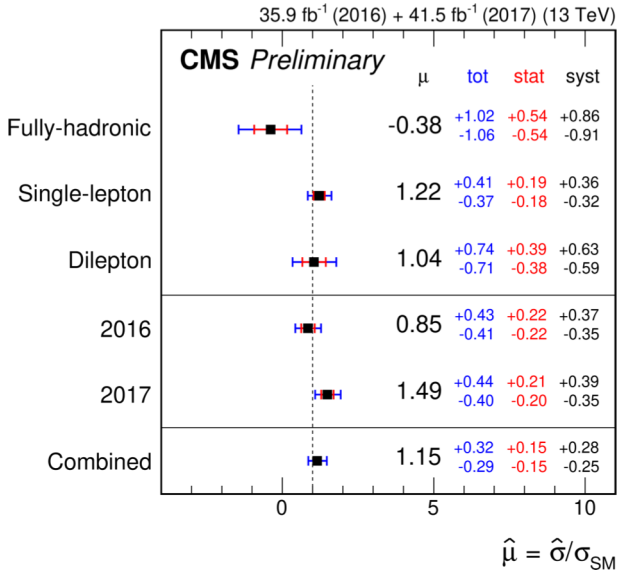
ttH (H→bb)

- 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) σ**
  signal-strength : $\boldsymbol{\mu_{comb} = 1.15^{+0.32}_{-0.29}}$

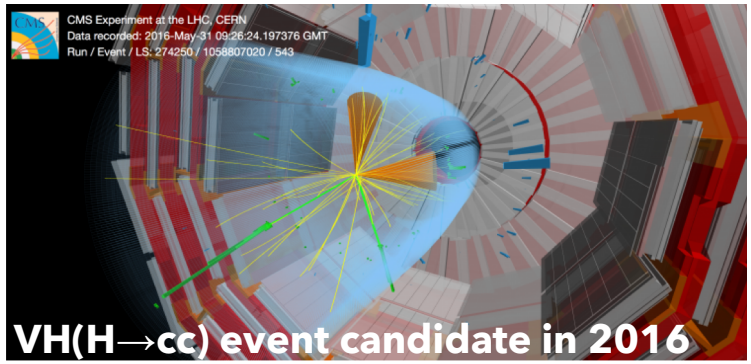




CMS-PAS-HIG-18-030

see Pietro Vischia's talk
see Rainer Mankel's talk

Higgs boson

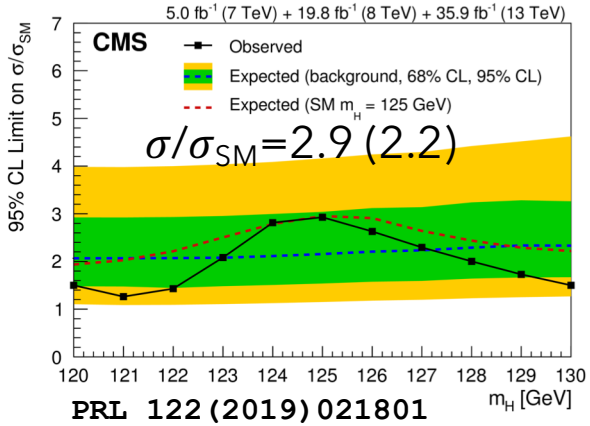


- LHC Run 1 led to
  - discovery using decays to bosons
  - exclusion of many BSM models
- LHC Run 2 : <u>unprecedent statistics</u>
  - differential cross section measurement
  - directly established couplings to 3rd generation fermions
  - provides an interesting challenge : **couplings to 2nd generation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

H→μμ

μ are the easiest object to identify and measure, but :

- small BR(H→μμ)=2×10^{-4} → ***O***(5-6) evt/fb^{-1}
- large backgrounds: Z/***γ****, diboson, top
- small S/(S+B) regime ~0.2%



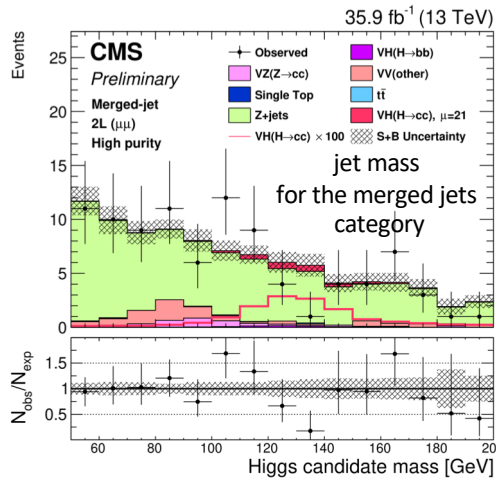
PRL 122(2019)021801

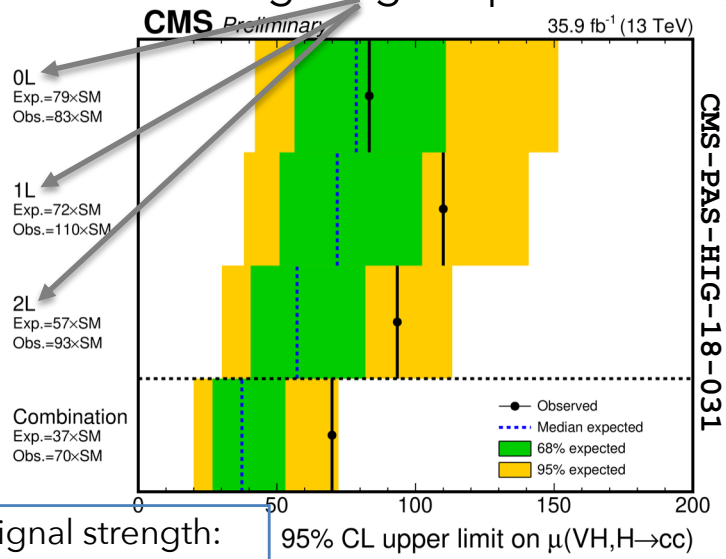
H→cc

coupling $\lambda_c \sim \lambda_\tau$, but way harder to probe :

- BR(H→cc)~0.05×BR(H→bb)
- large (hadronic) background [H→bb is background !]
- **charm jet ID** is highly challenging

first direct **H→cc** search in CMS targeting VH production





combined results for the signal strength:
upper limit: σ/σ_{SM} = 70 (37) @ 95% CL

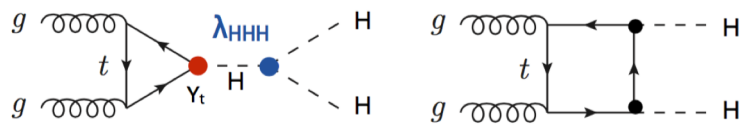
$$\mu(\mathrm{VH}, \mathrm{H} \to c\bar{c}) = 36^{+20}_{-19}$$

see Rainer Mankel's talk

Higgs boson

see Amina Zghiche's talk

- 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**

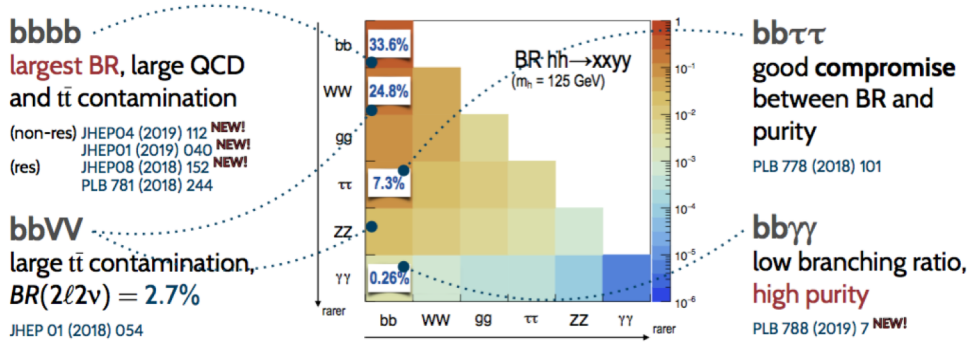


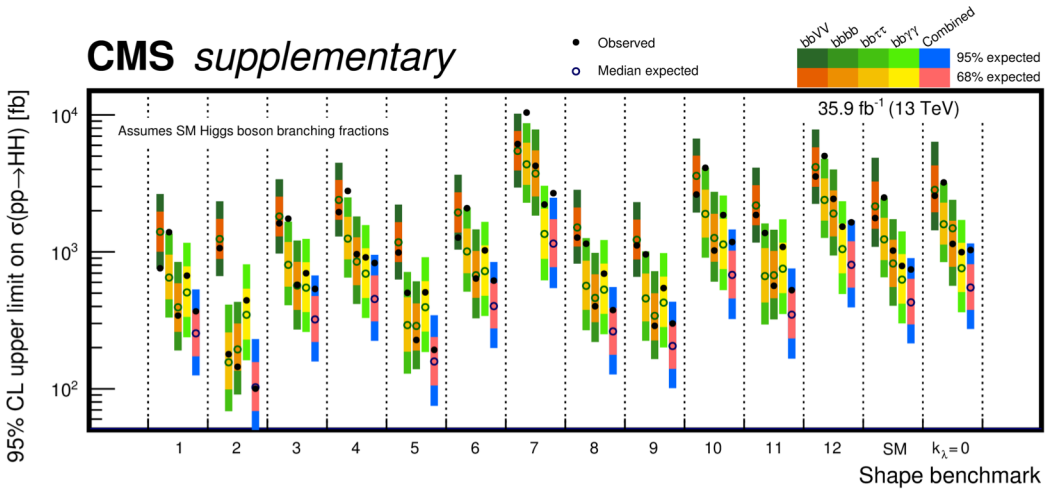
non-resonant HH production

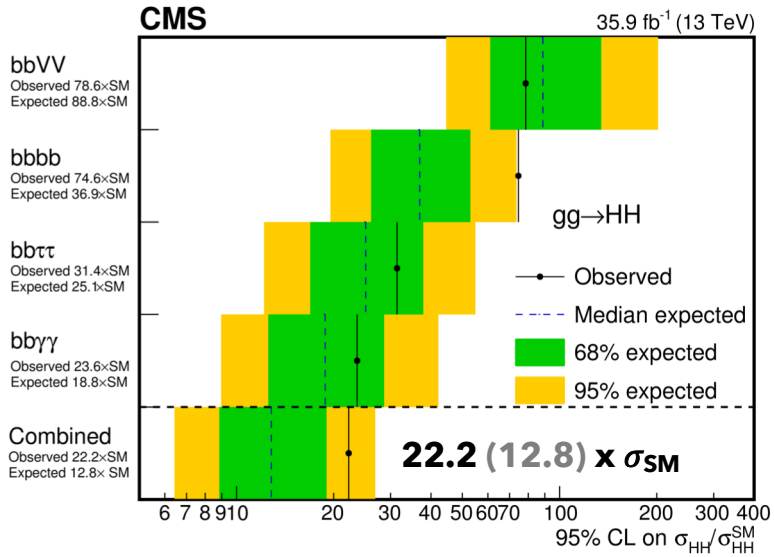
$\sigma(gg \rightarrow HH) = 33.5$ fb

[@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 λ
- brings information on the shape of the Higgs potential
- sensitive to BSM effects in both the yields and kinematic distributions







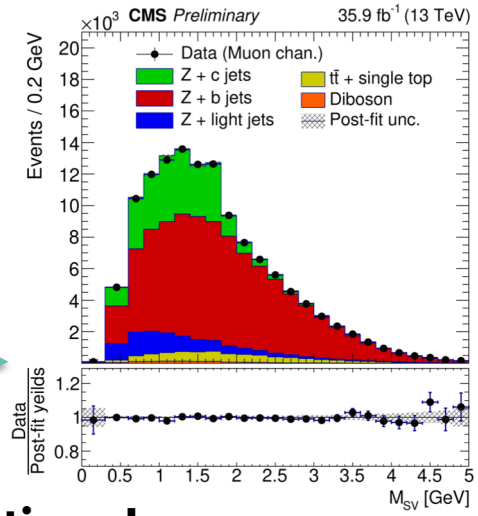
Phys.Rev.Lett.122(2019)121803

see Vitaliano Ciulli's talk

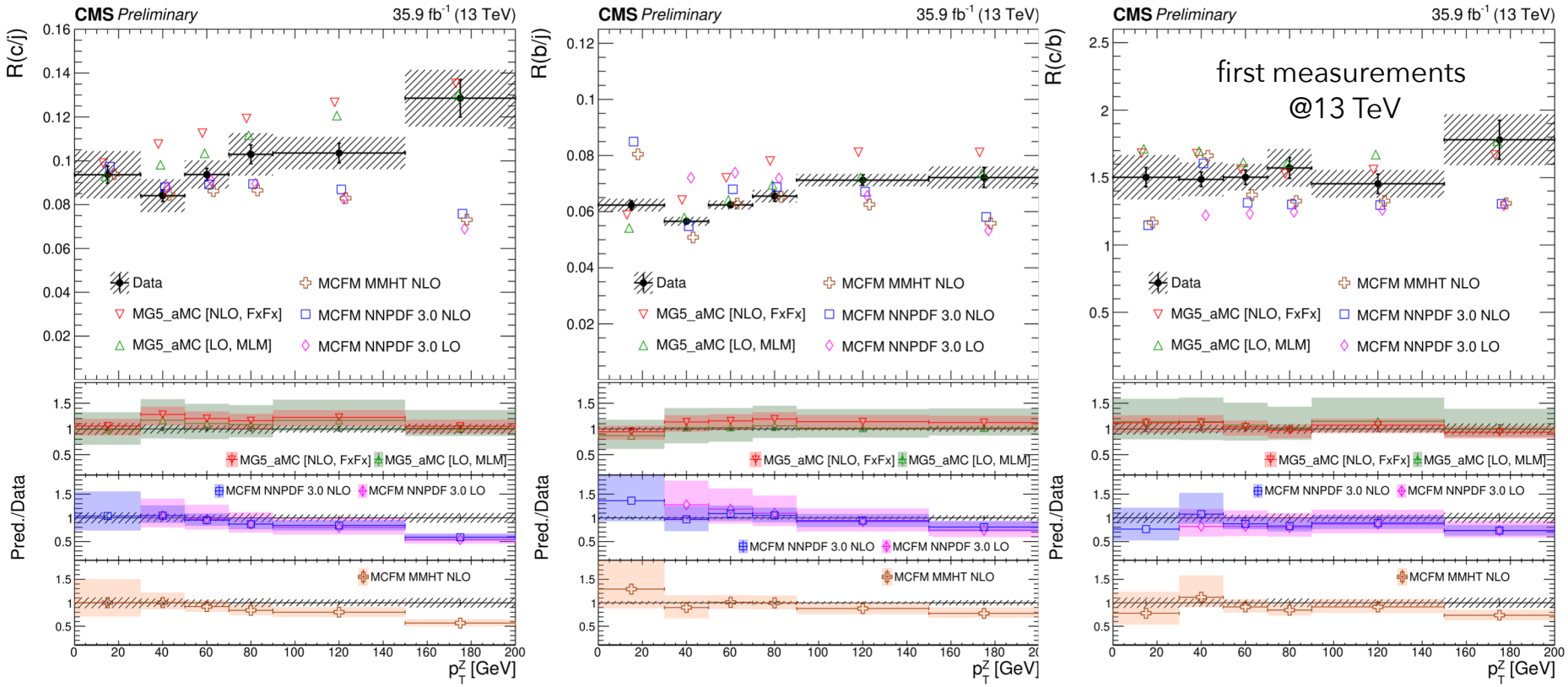
Z boson with charm and bottom

measure ratios of cross sections of the associated production of ***Z* + charm or bottom jet @ 13 TeV** as function of the *Z* and jet p_T

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



- b, c and light jets are distinguished using the **SV invariant mass**
- results are compared w/ predictions from LO and NLO perturbative QCD calculations
- **the measurement precision exceeds the current theoretical predictions !**

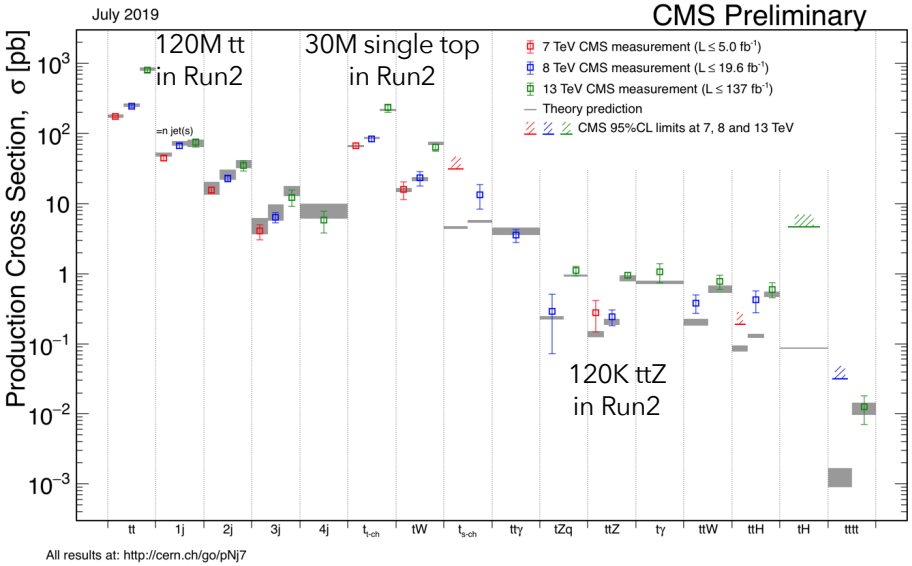


CMS-PAS-SMP-19-004

top-quark

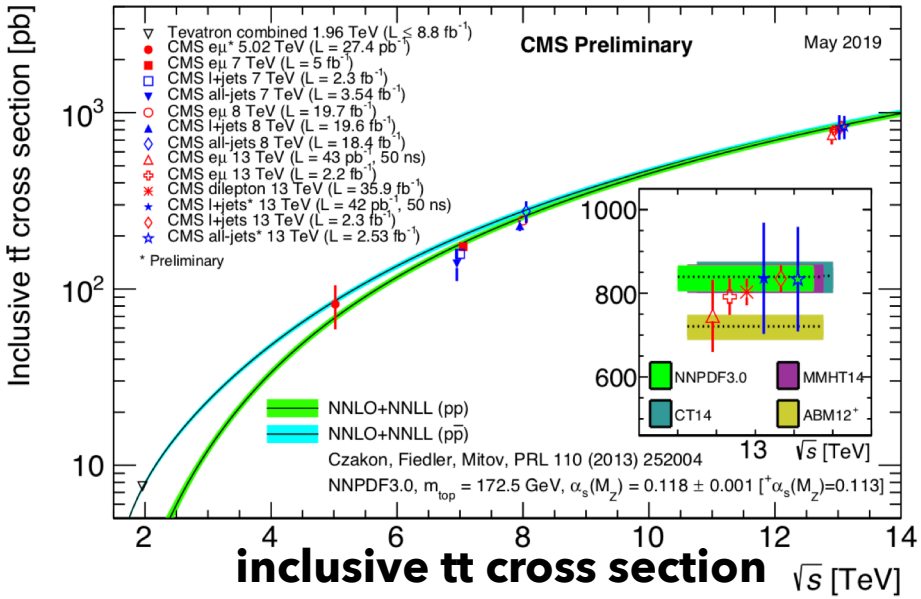
top quark physics

- 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

full Run2: **150 fb^{-1}**



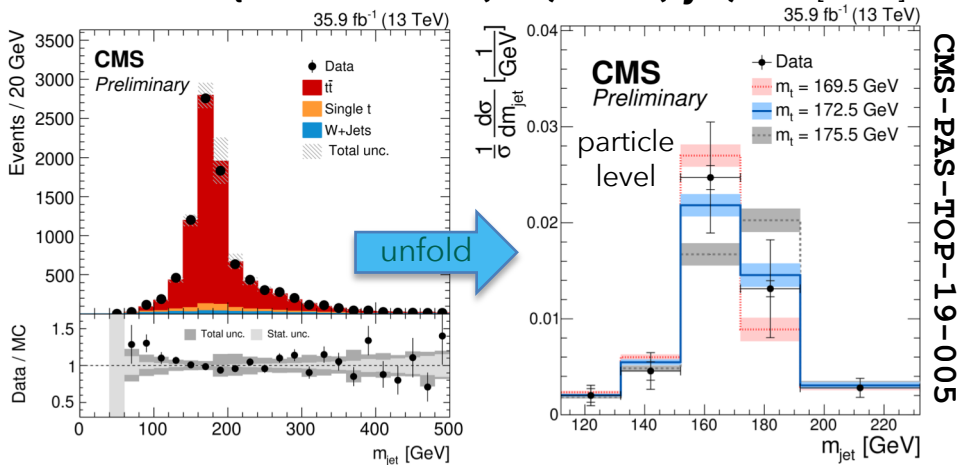
inclusive tt cross section

- 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 [XCone algorithm]
- mass from m_{jet} differential cross section :

m_t = 172.56±0.41(stat) ±2.44(syst) GeV [1.4%]



top-quark

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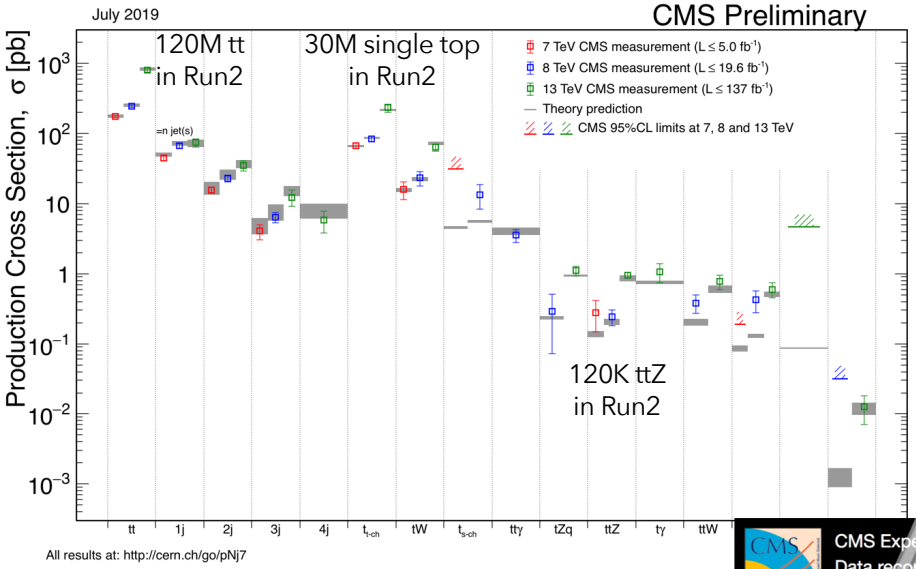
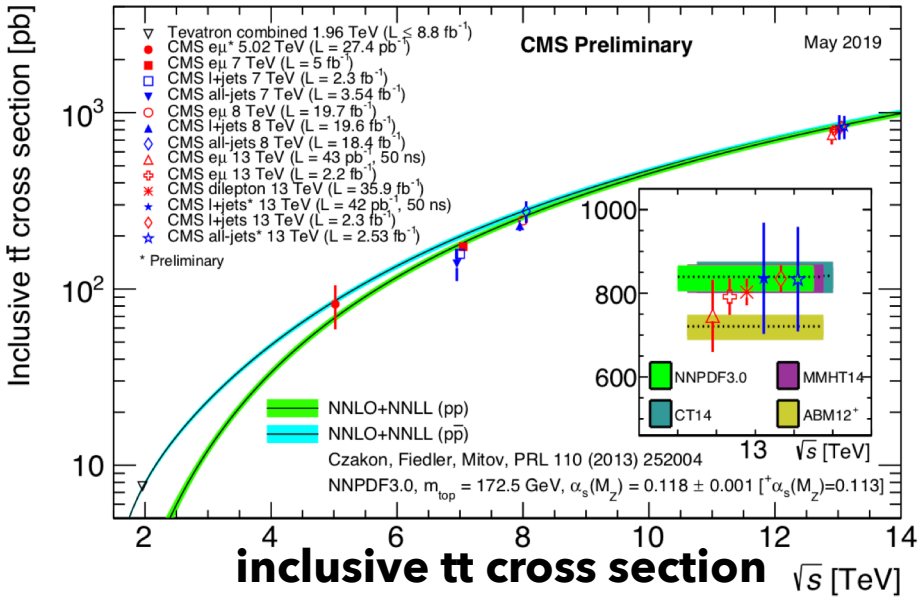
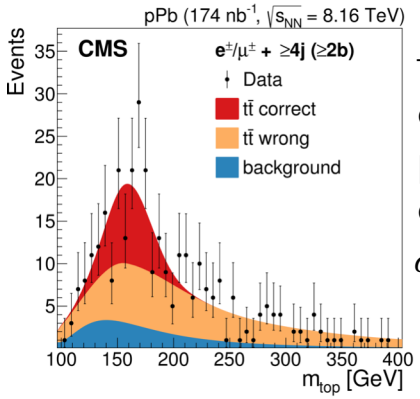




inclusive tt cross section

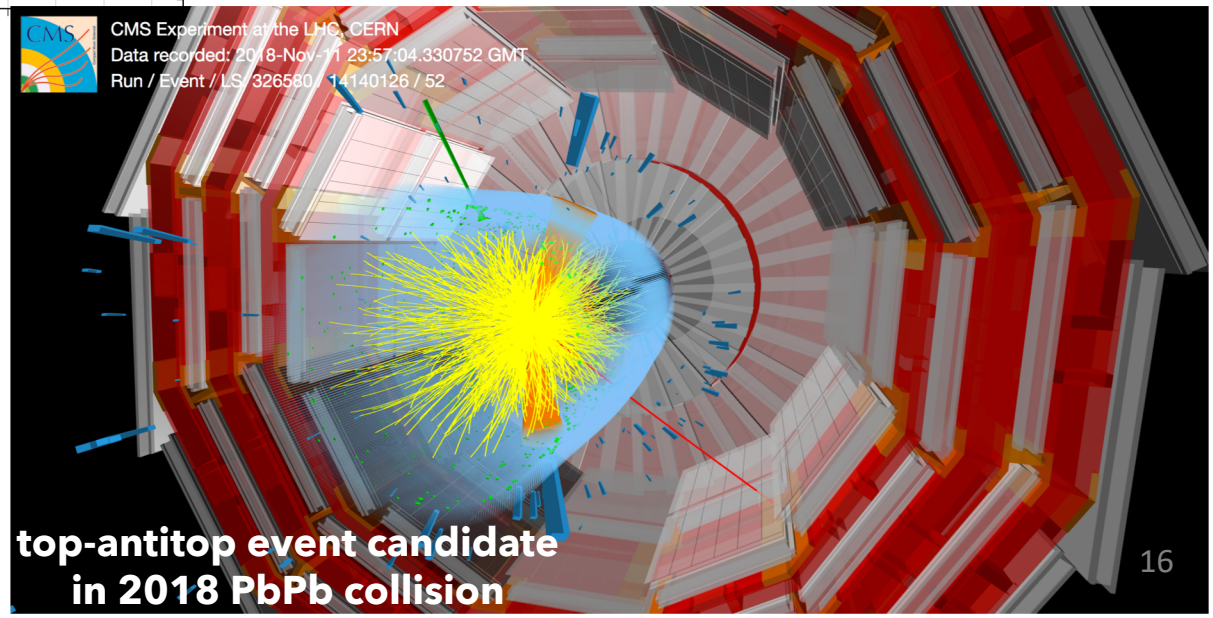
- measure all channels to look for the unexpected
- good agreement w/ NNLO+NNLL calculations
- highest precision: **dilepton and l+jets channels ~4%** (similar to theory prediction)



top quark also observed in proton-nucleus (Pb) collisions

$\sigma(tt) = 45 \pm 8$ nb

Phys.Rev.Lett.119(2017)242001



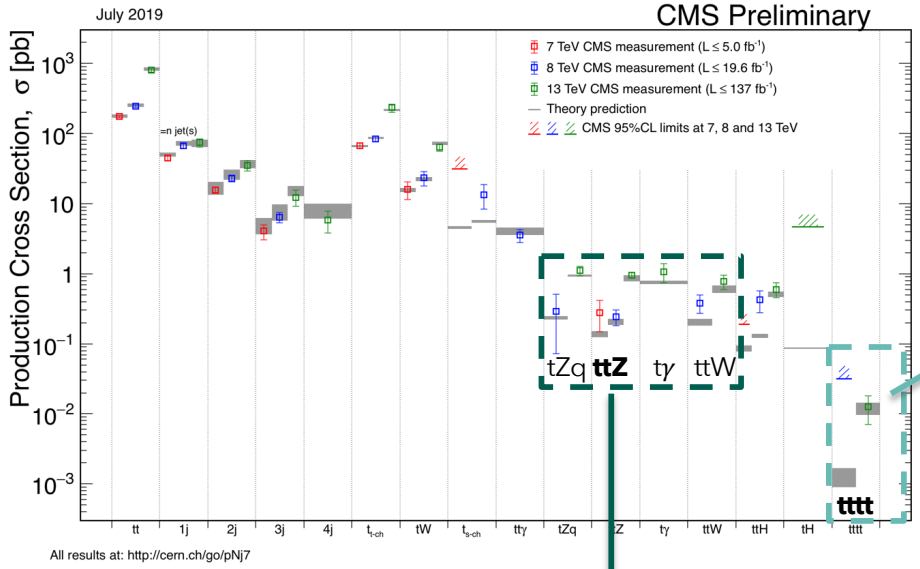
top-antitop event candidate in 2018 PbPb collision

top-quark

top quark physics
- is a key ingredient to probe QCD, electroweak, and BSM physics
- has a very rich experimental programme @LHC

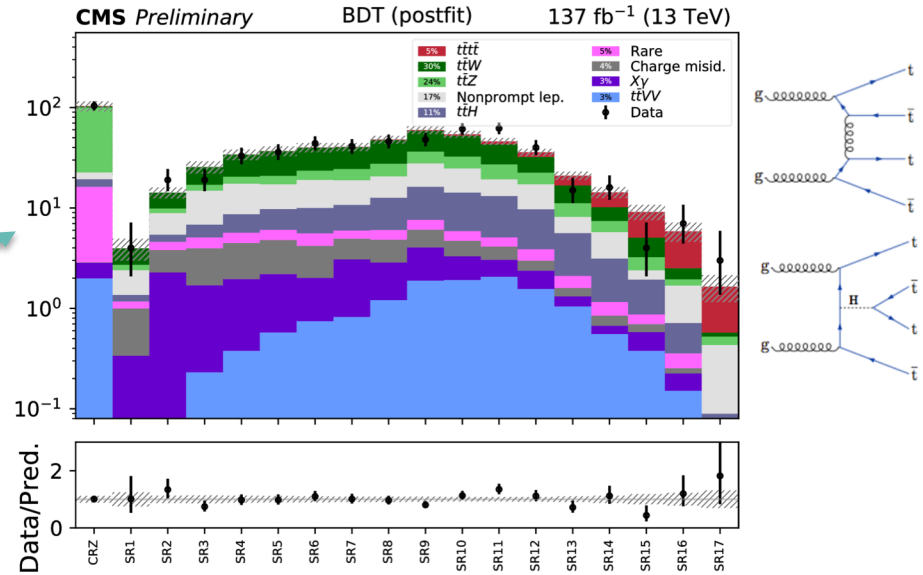
- **high precision** top cross sections and properties
- **rare processes** becoming less rare (some even systematically limited !)

→ started to challenge theory predictions in many respects



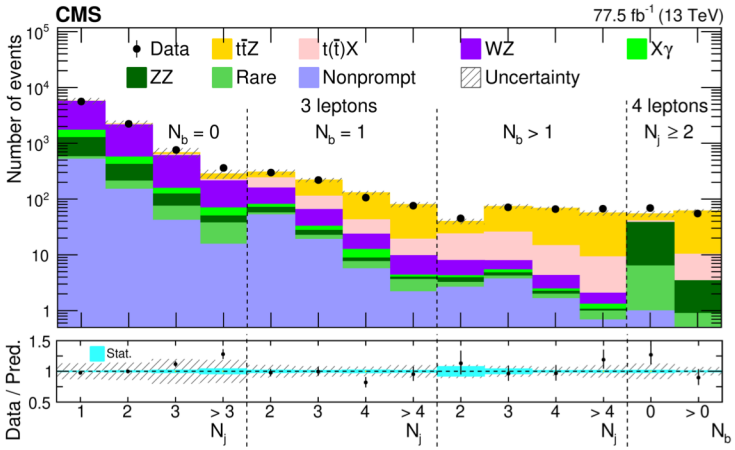
significance 2.6 (2.7) σ

same-sign dilepton & trilepton final state

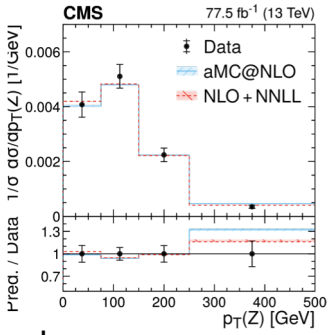


CMS-PAS-TOP-18-003

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



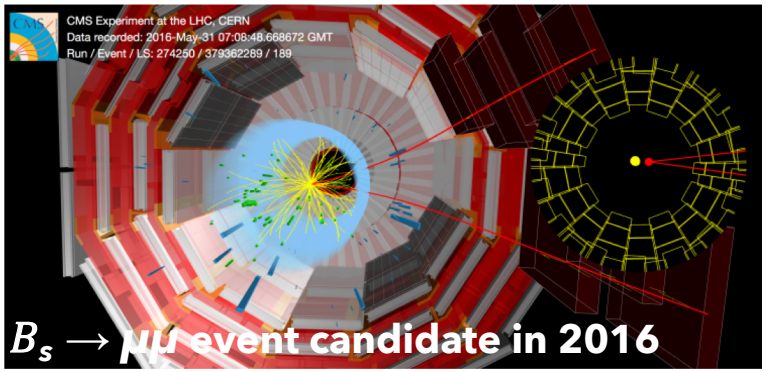
CERN-EP-2019-124



- 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 !

$B \to \mu\mu$



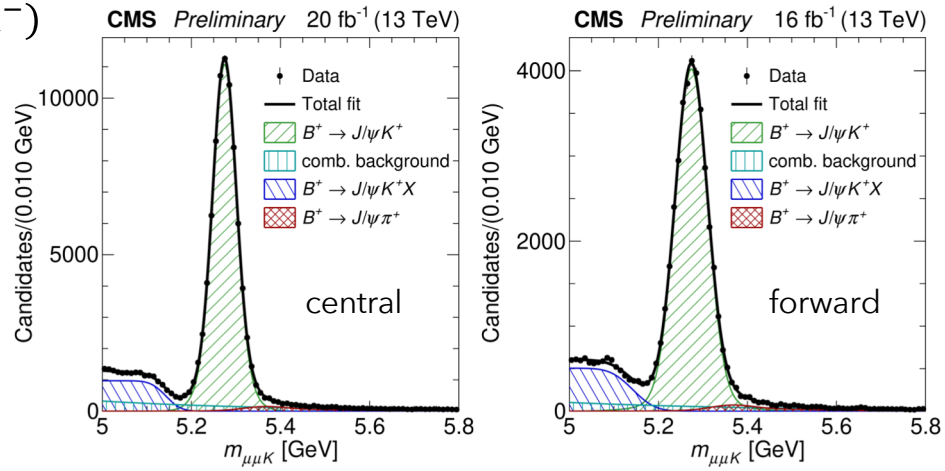
$B_s \to \mu\mu$ event candidate in 2016

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

$$BR(B_s \to \mu^+\mu^-) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\epsilon_{tot}^{B^+}}{\epsilon_{tot}} B(B^+ \to J/\psi K^+) B(J/\psi \to \mu^+\mu^-)$$

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)



BPH-16-004

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

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

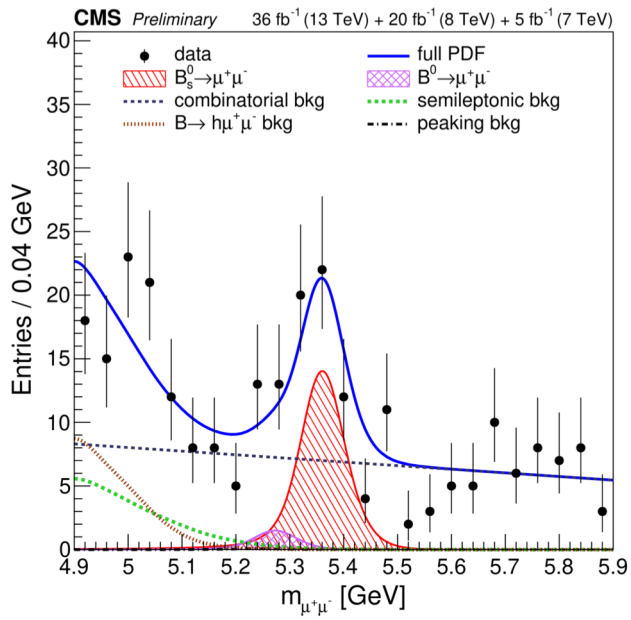
  - an effective lifetime :

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

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

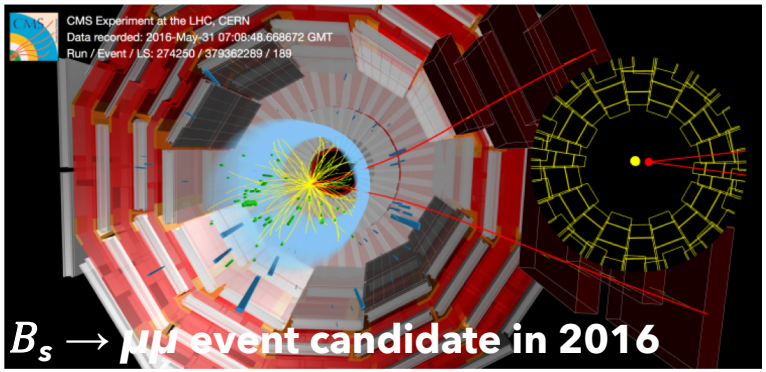
$$\boldsymbol{BR(B_d \to \mu^+\mu^-) < 3.6 \times 10^{-10}} \text{ @95\% } \textbf{CL}$$

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



see Valentina Mariani's talk

$B \to \mu\mu$



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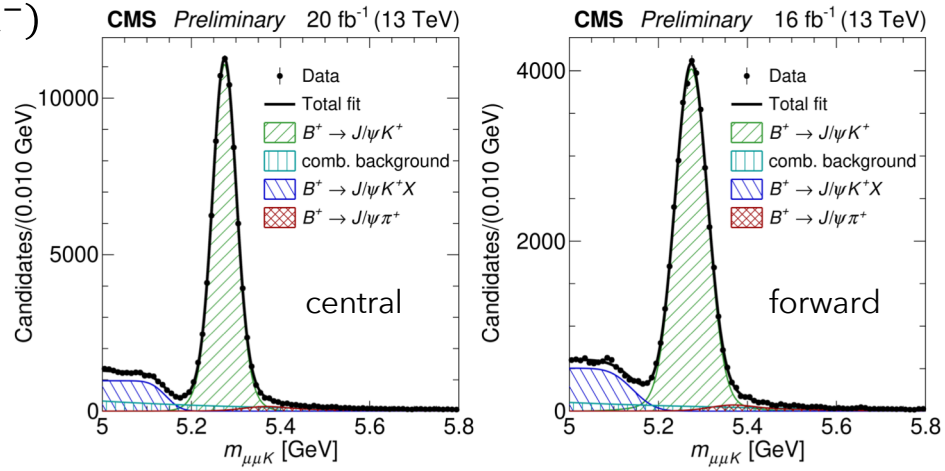

BPH-16-004

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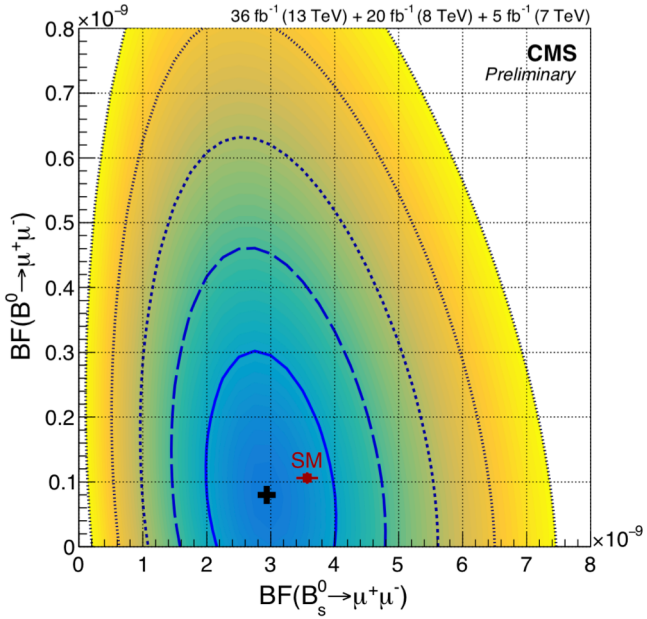


- these results are consistent w/ SM predictions and an earlier measurement of LHCb

see Valentina Mariani's talk

see Valentina Mariani's talk

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

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 $B^+ \to J/\psi\ \phi\ K^+$]

- 1st **observation** of the decay $\boldsymbol{\Lambda_b^0 \to J/\psi\ \Lambda\ \phi}$ w/ significance **9.7 σ**

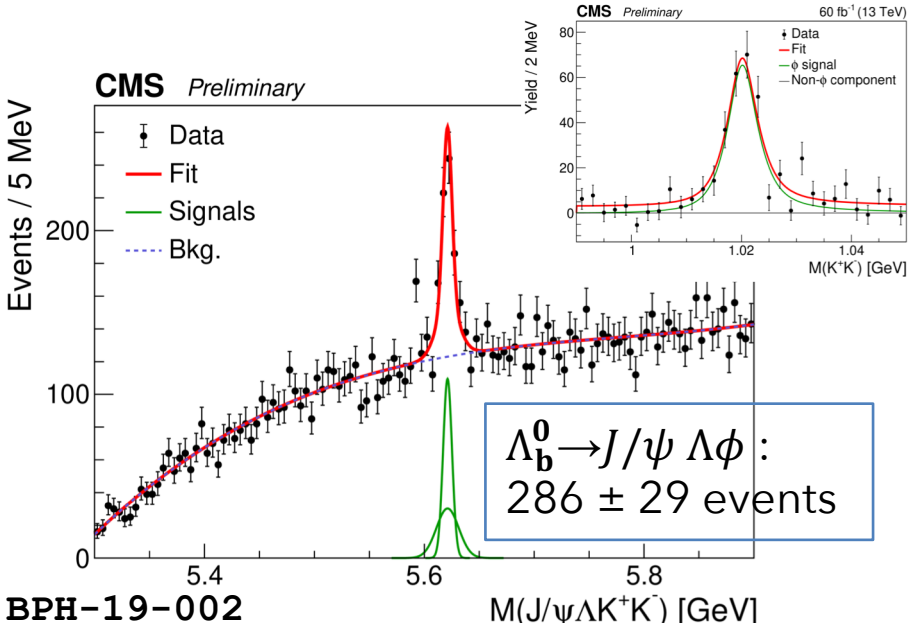
  decay expected to proceed via the **b → $c\bar{c}s$** process [similar to $\Lambda_b^0 \to J/\psi\ \Lambda$ but requires an additional $s\bar{s}$ pair]

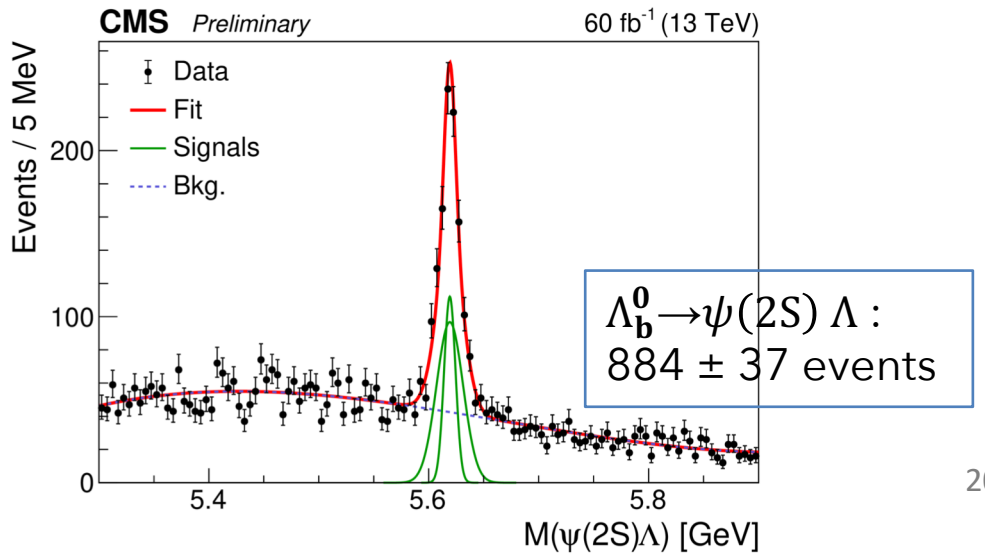
- measure the branching fraction relative to the decay mode $\Lambda_b^0 \to \psi(2S)\Lambda$

  [which has a similar topology]

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\ \Lambda\phi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi\ \Lambda\phi)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon(\Lambda_b^0 \to \psi(2S)\Lambda)}{\epsilon(\Lambda_b^0 \to J/\psi\ \Lambda\phi)} \frac{\mathcal{BR}(\psi(2S) \to J/\psi\pi^-\pi^+)}{\mathcal{BR}(\phi \to K^+K^-)}$$

$$= [\ 8.26 \pm 0.90\ (\text{stat}) \pm 0.68\ (\text{syst}) \pm 0.11(\mathcal{BR})\ ] \times 10^{-2}$$

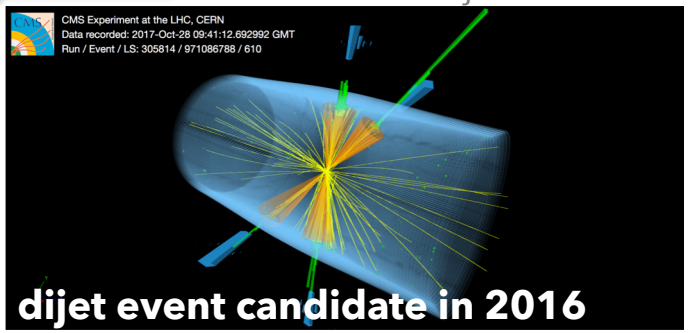




BPH-19-002

resonant decays into 2 jets

wide jet

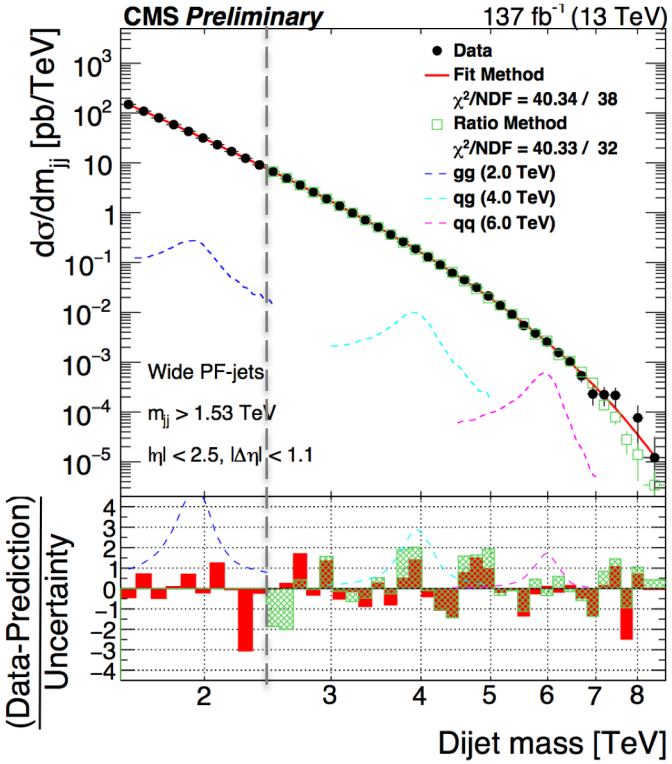


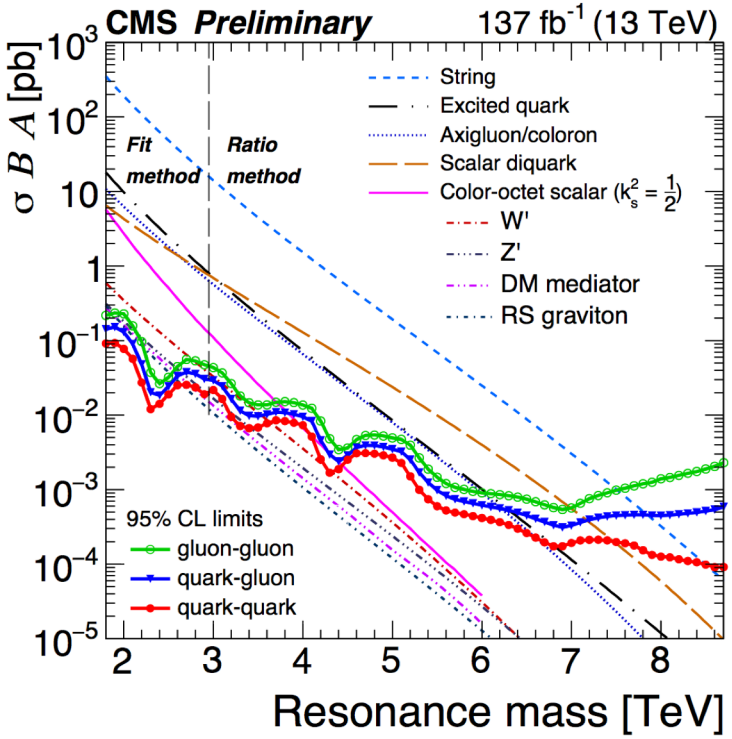
dijet event candidate in 2016

- ***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 $[\Delta\eta_{jj}]$
  - ✓ robust method
  - ✓ smaller systematics uncertainties
  - ✓ more sensitive for broad resonance searches

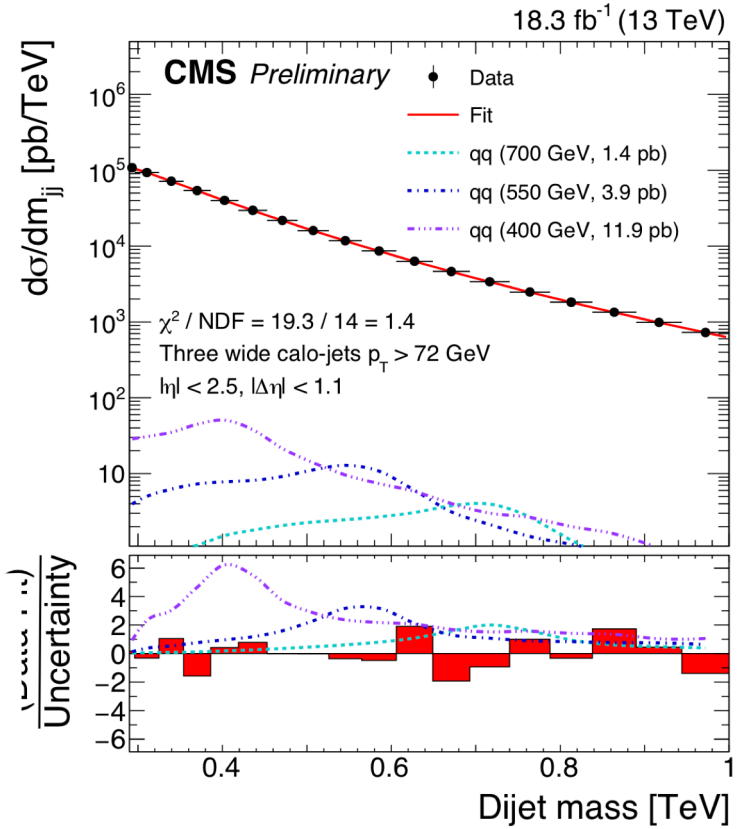
- results consistent w/ background

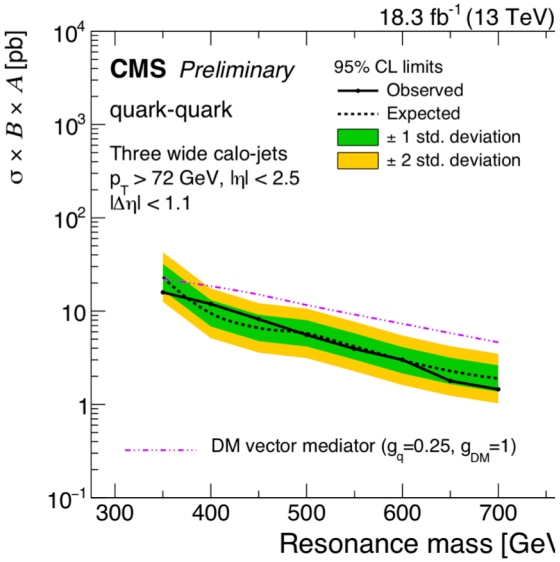


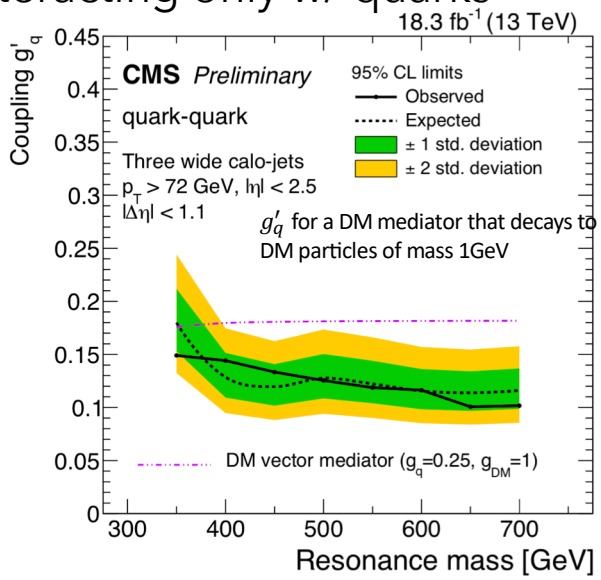


resonant decays into 2 jets in events w/ 3 jets

- 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







search for dimuon resonances (I)

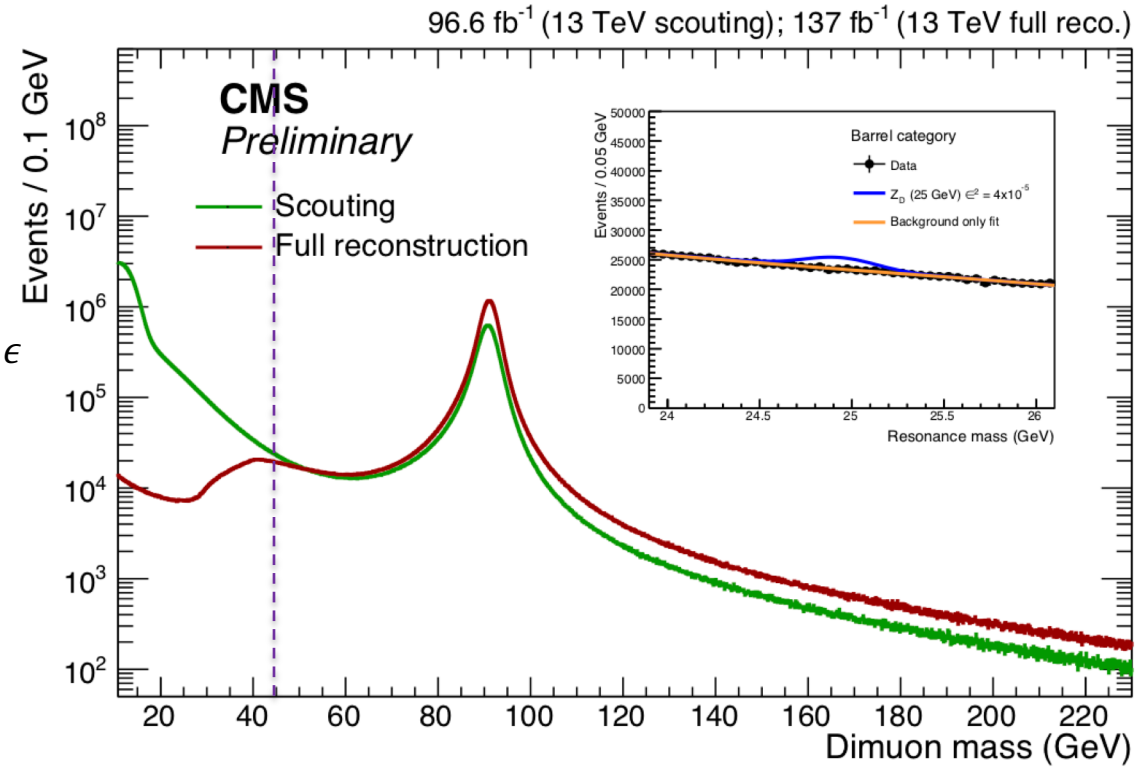
EXO-19-018
first CMS analysis using non-hadronic scouting

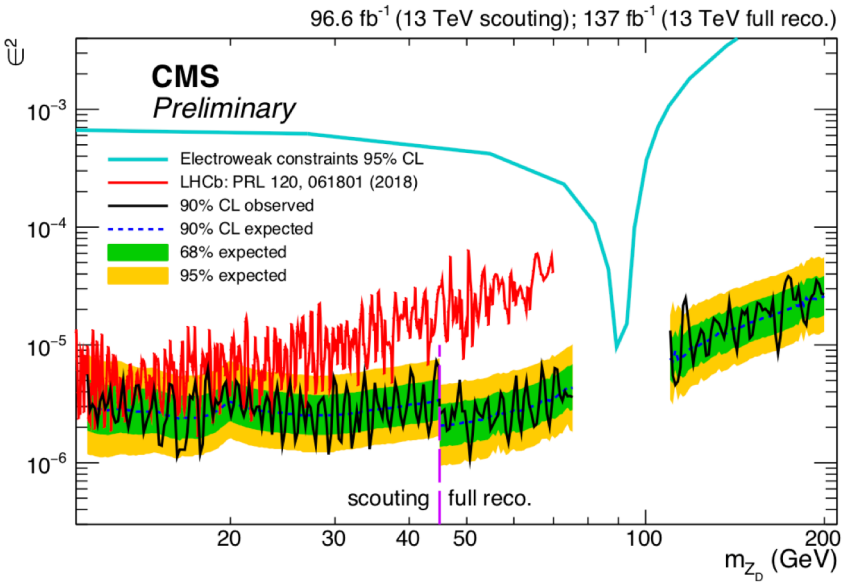
- search for **low-mass** dimuon resonances in the range **11.5- 200 GeV** [excluding the Z resonance range]
  - for masses < 45 GeV
    the high rate dimuon **data scouting** triggers [muon p_T > 4.5 GeV] is used
  - for mass range > 45 GeV, muon p_T > 20 and 10 GeV

- 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 ϵ

- data are found to be consistent w/ background expectations

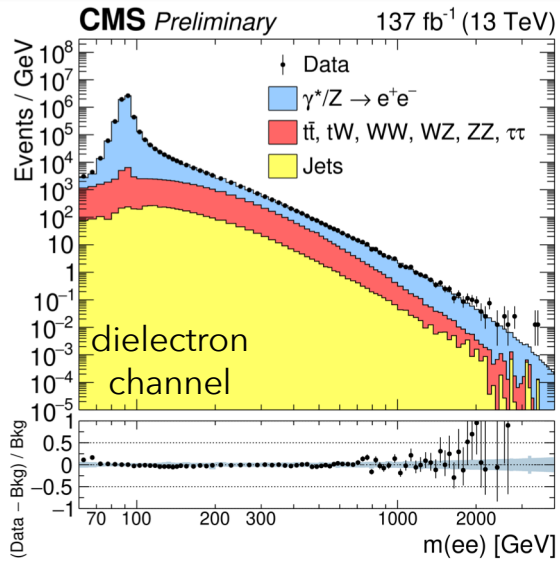


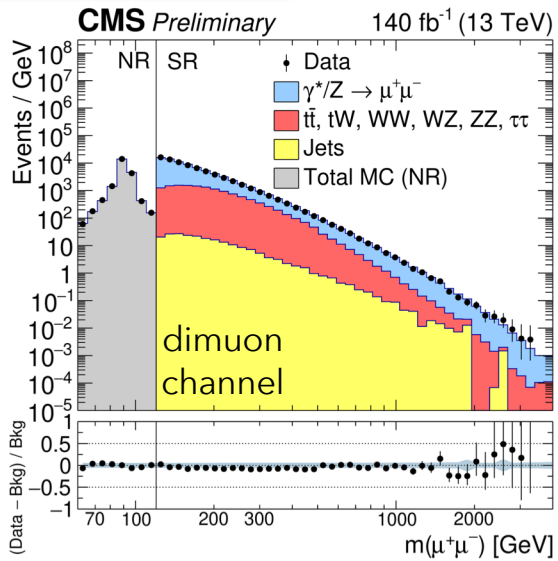


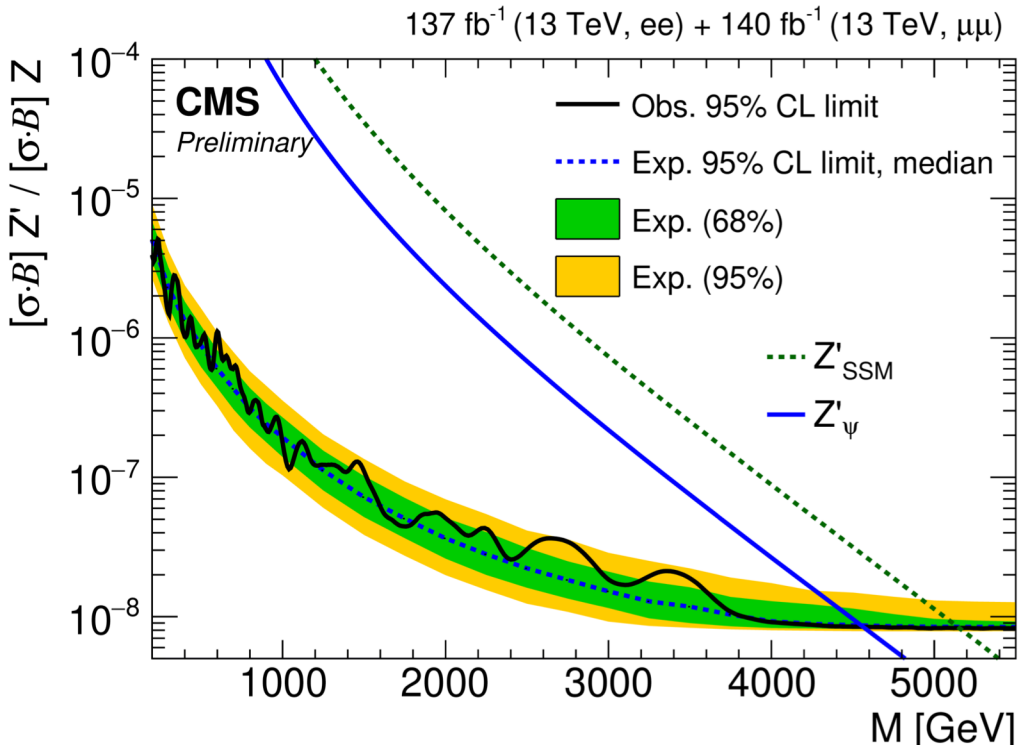
strongest constraints on a hypothetical **dark photon** w/ $m_{Z_D} > 11.5$ **GeV**

search for dimuon resonances (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 γ induced processes







no significant deviation from SM expectation is observed

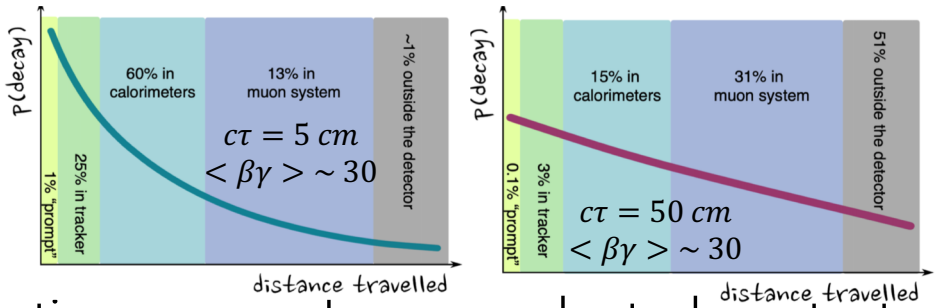
superstring-inspired sequential standard model

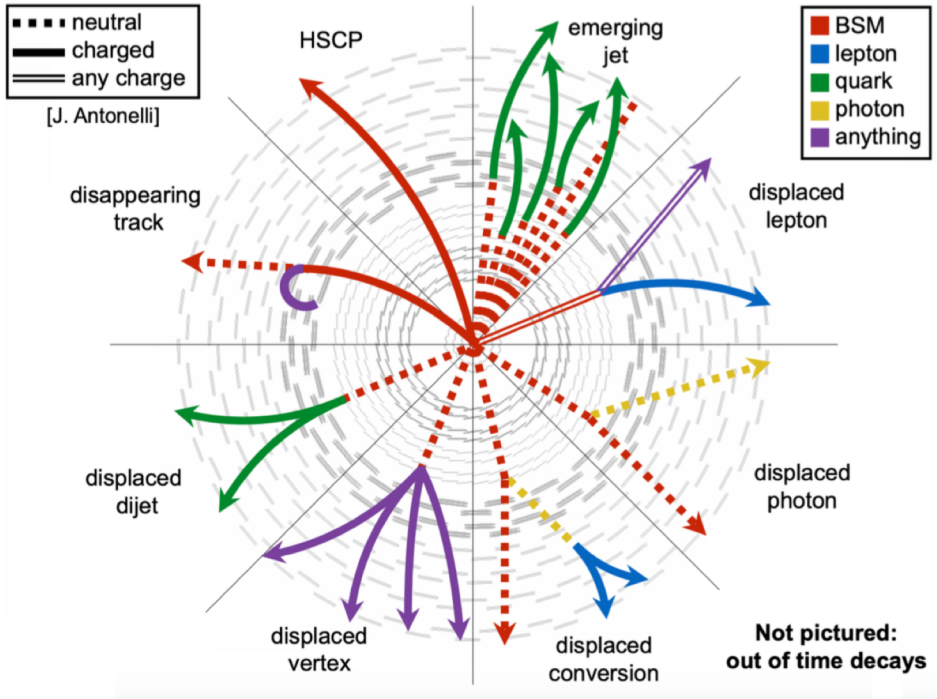
$\Rightarrow Z'_{SSM}$ (Z'_{ψ}) particle is excluded @ 95% CL below a mass of **5.15 (4.55) TeV**

long-lived particles

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





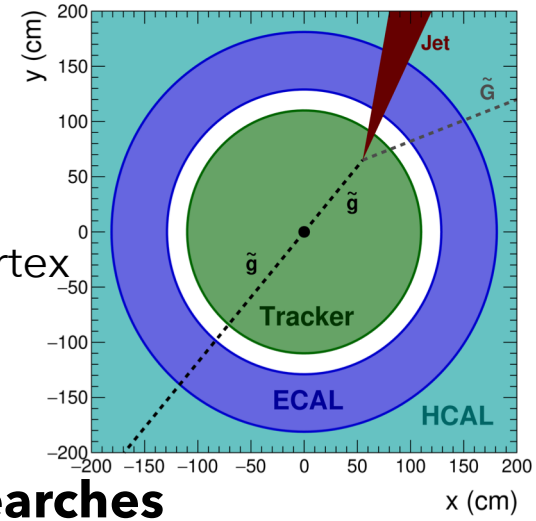
lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and **we need to use all subdetectors**

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

LLP varieties	challenges
- charges	- dedicated trigger
- final states	- unique object reconstruction
- decay locations	- atypical background
- lifetimes	- unusual discriminating variables

long-lived particles

w/in ECAL
radial acceptance

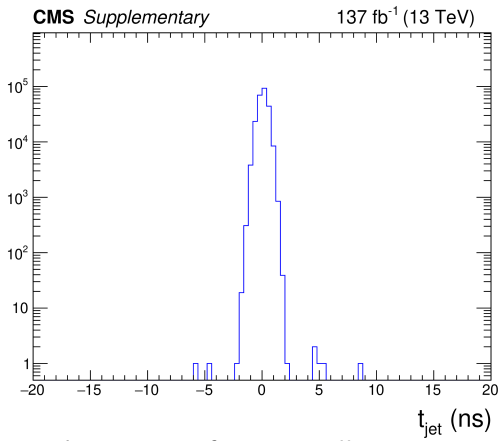


- **delayed jets** [heavy neutral LLPs decaying to at least 1 delayed jet + MET]
  benchmark : **long-lived gluinos** give rise to jets from displaced vertex
  → delay due to differences in velocity and in path length

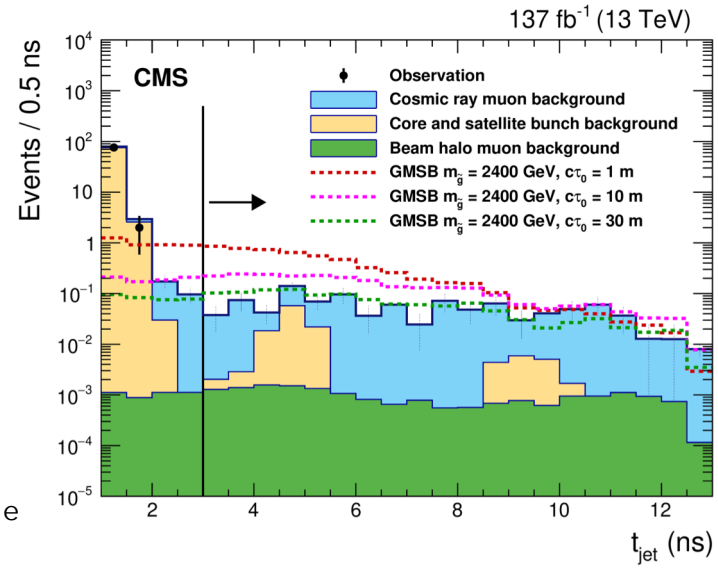
  - **median time of all ECAL cells** in the jet cone, allows to
    → reduce the background to few event level
    → **extend significantly the sensitivity w.r.t. tracker-based searches**

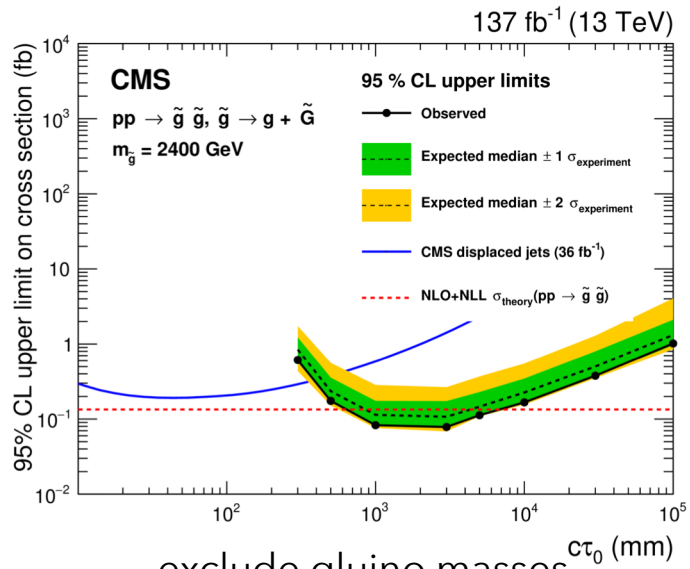
arXiv:1906.06441

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)



median time of ECAL cells in jet cone
after background subtraction
[T_{jet} >(<) 20 ns from next (previous) BX]

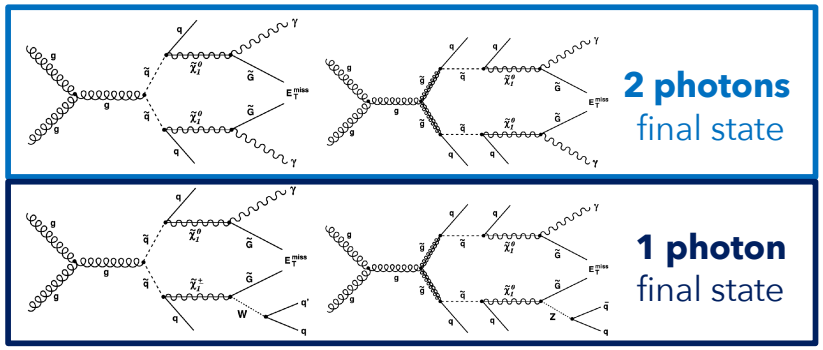




exclude gluino masses
up to **2.5 TeV** for **cτ = 1 m**

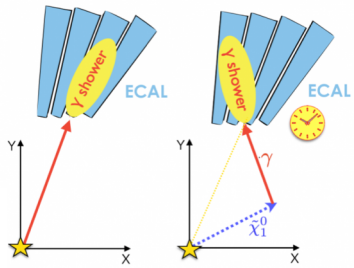
PF jets are not used in the offline analysis, because nonprompt jets do not produce reliable information in the tracker and out-of-time energy deposits are not included in the PF jet reconstruction

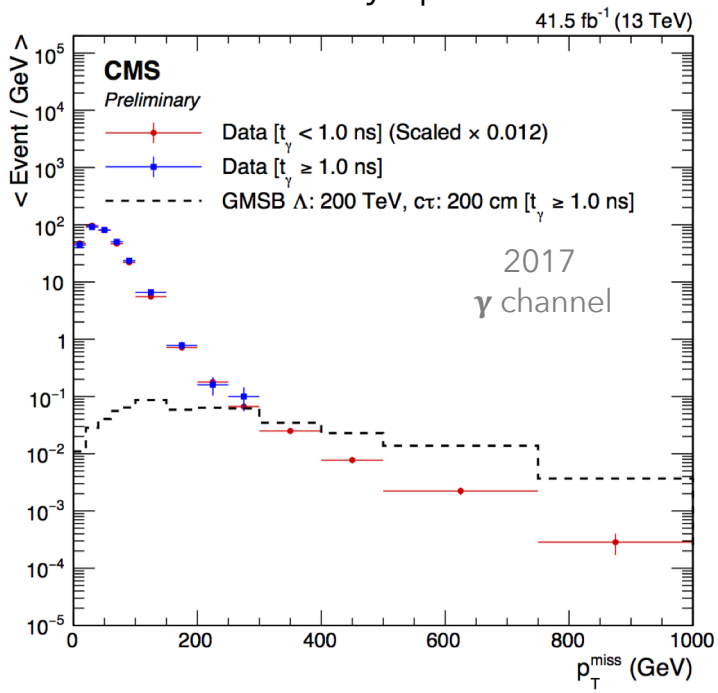
long-lived particles

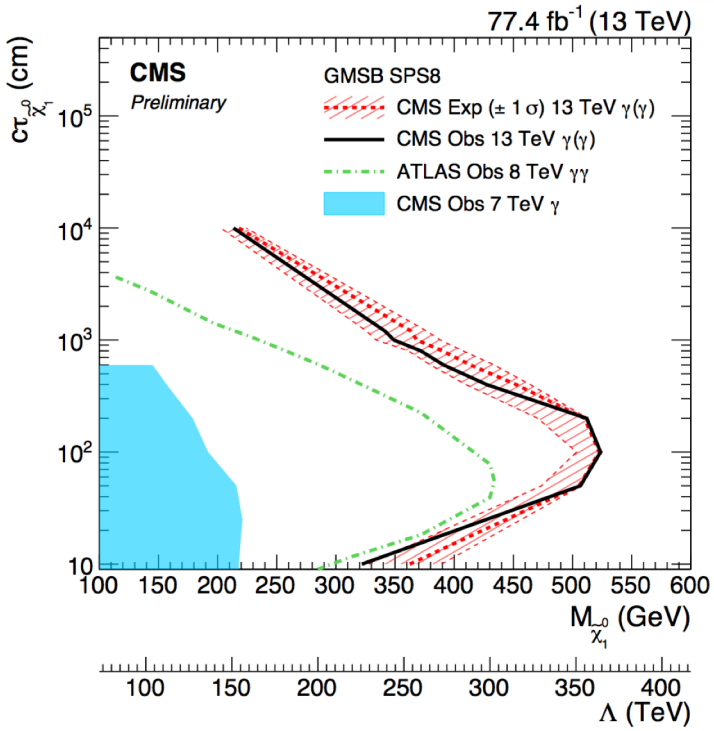


- **delayed photons** (at least) 1 delayed photon + MET
  benchmark : **long-lived neutralinos** decay to (at least) 1 photon and a gravitino
  - **photon timing using ECAL**
    → requires precise calibration of ECAL timing and resolution
  - **dedicated trigger in 2017** for selecting events w/ **1 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

EM shower shape in η-ϕ plane more elliptical



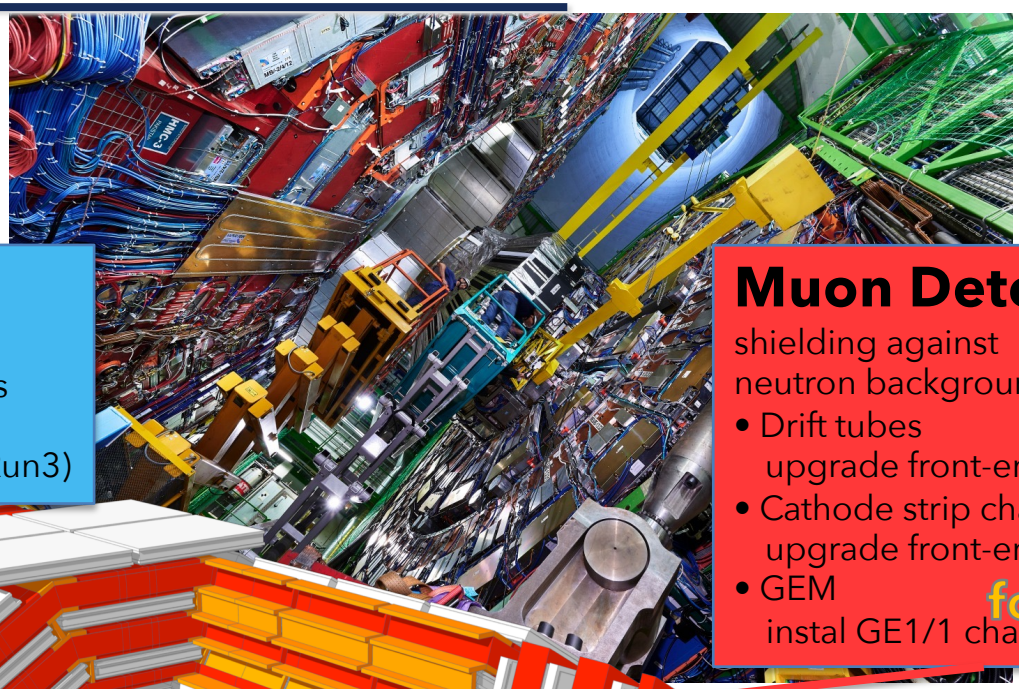




preparing for LHC Run3

see Nancy Marinelli's talk

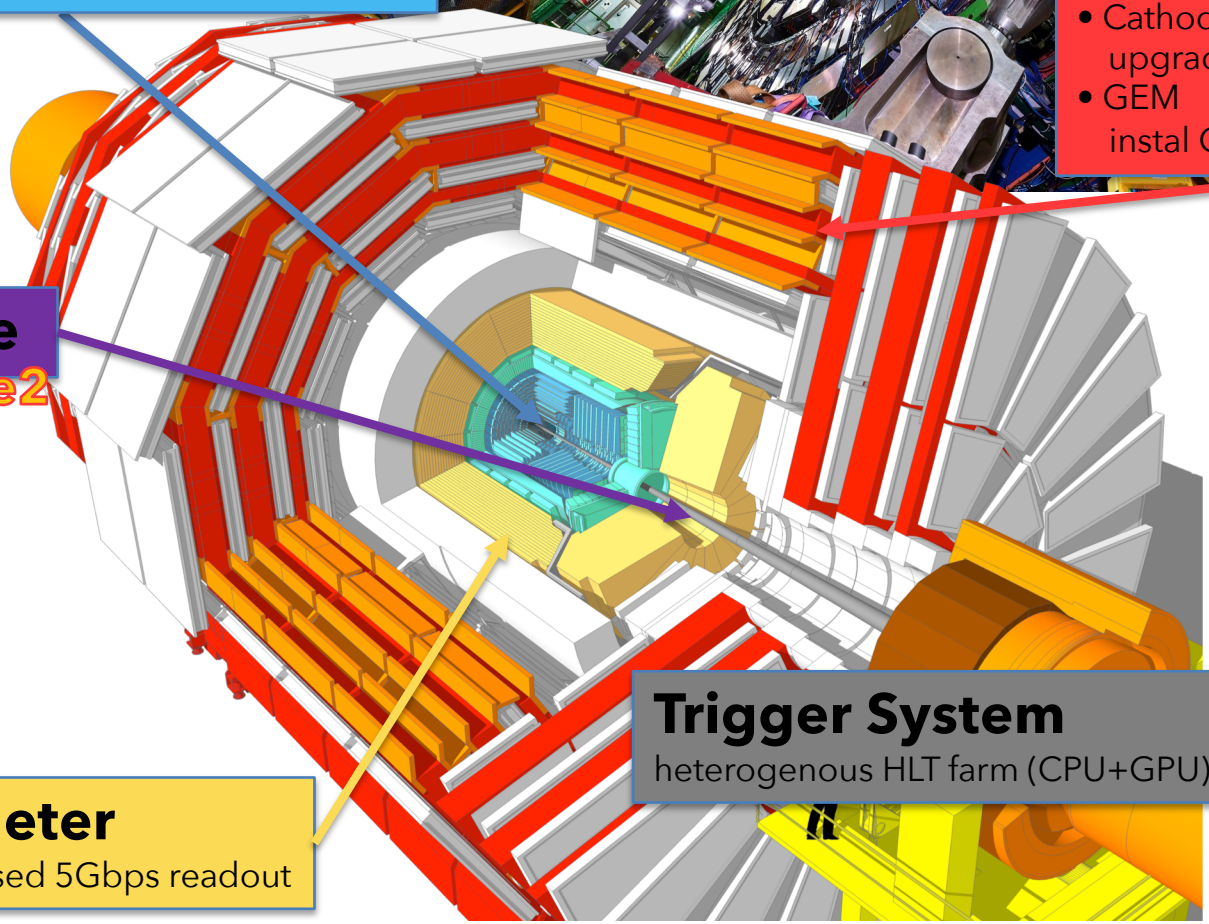
"Phase-1" upgrades of CMS
majority of the upgrades
have been done in the past years



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

for phase2



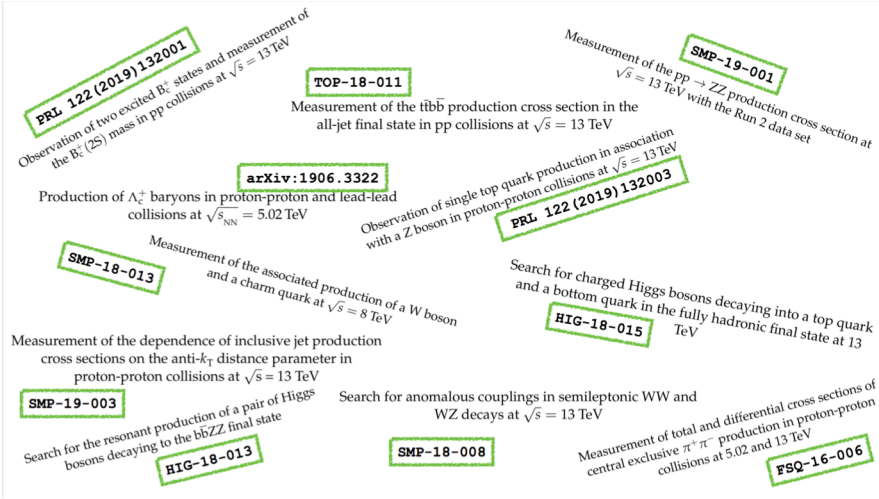
new beampipe
for phase2

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

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

summary

CMS is very busy during Long Shutdown 2!

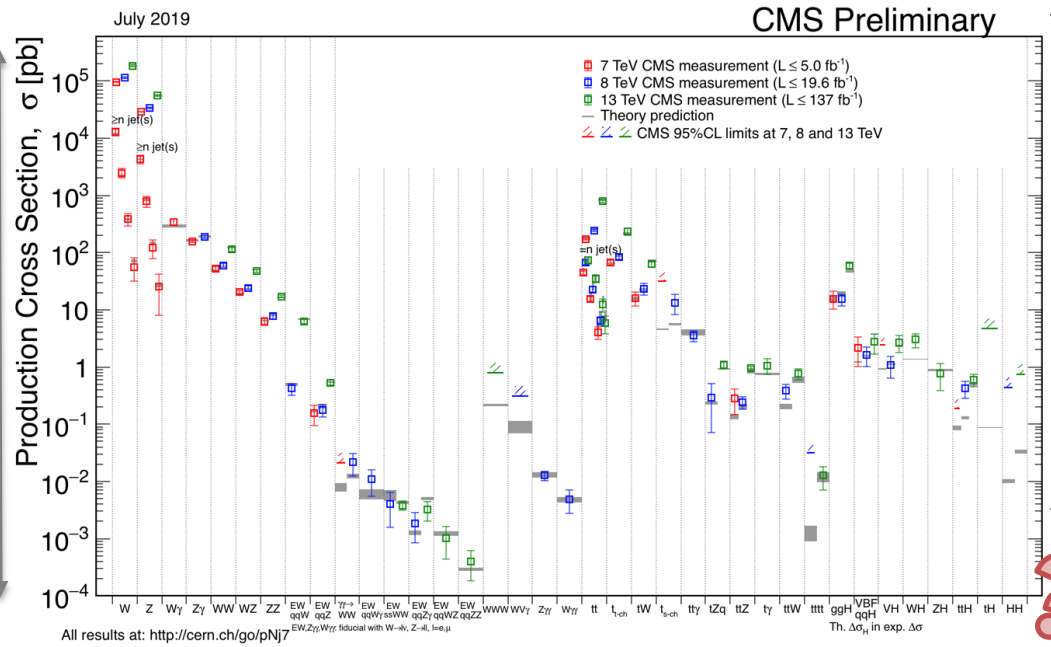


- **efficient technical program for the future**
  - completing Phase-1 upgrades
  - preparing for Run 3 (and in view of HL-LHC)

- 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

9 orders of magnitude !!!



- many results using the full dataset of 137 fb^{-1}
  - ✓ **searches**
    look for the *unknown*
  - ✓ **rare** processes
    scrutiny 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