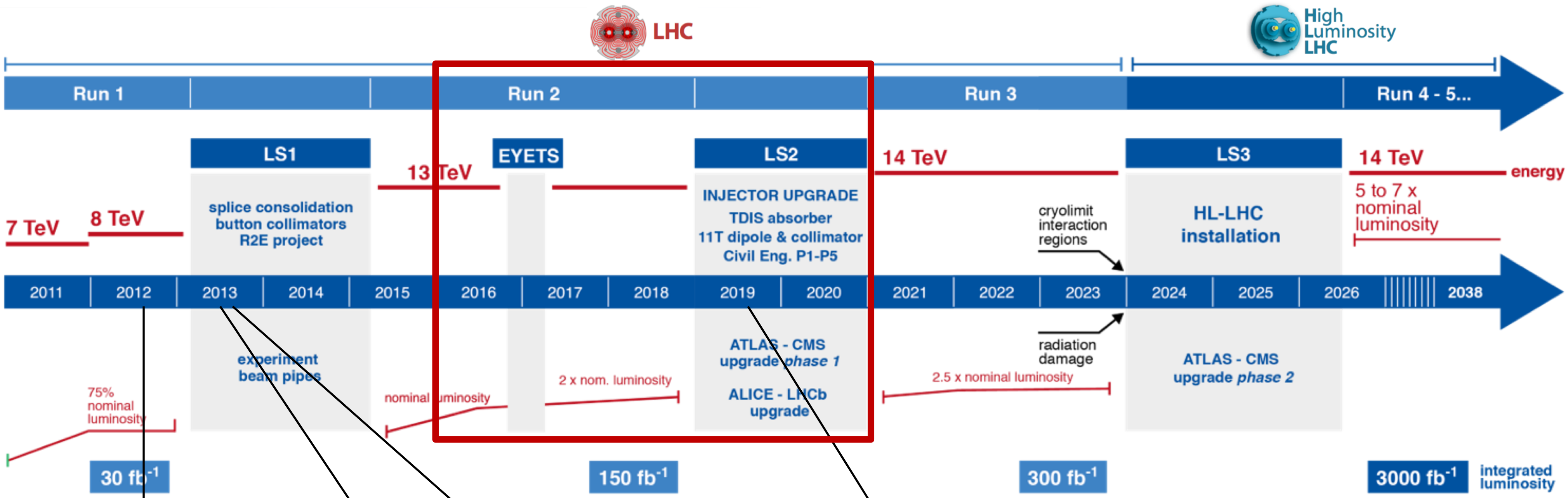
Highlights from CMS

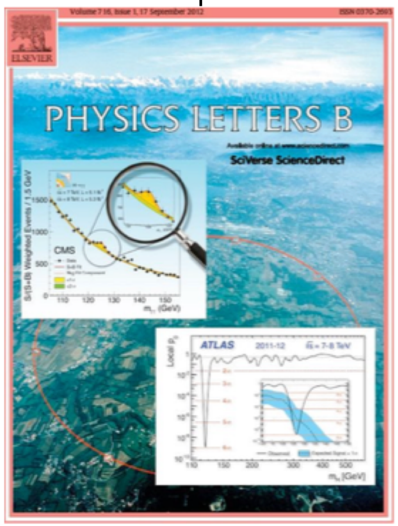
mia tosi
for the CMS collaboration

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

-- ICNFP 2019 --

introduction





the CMS detector evolution in Run 2

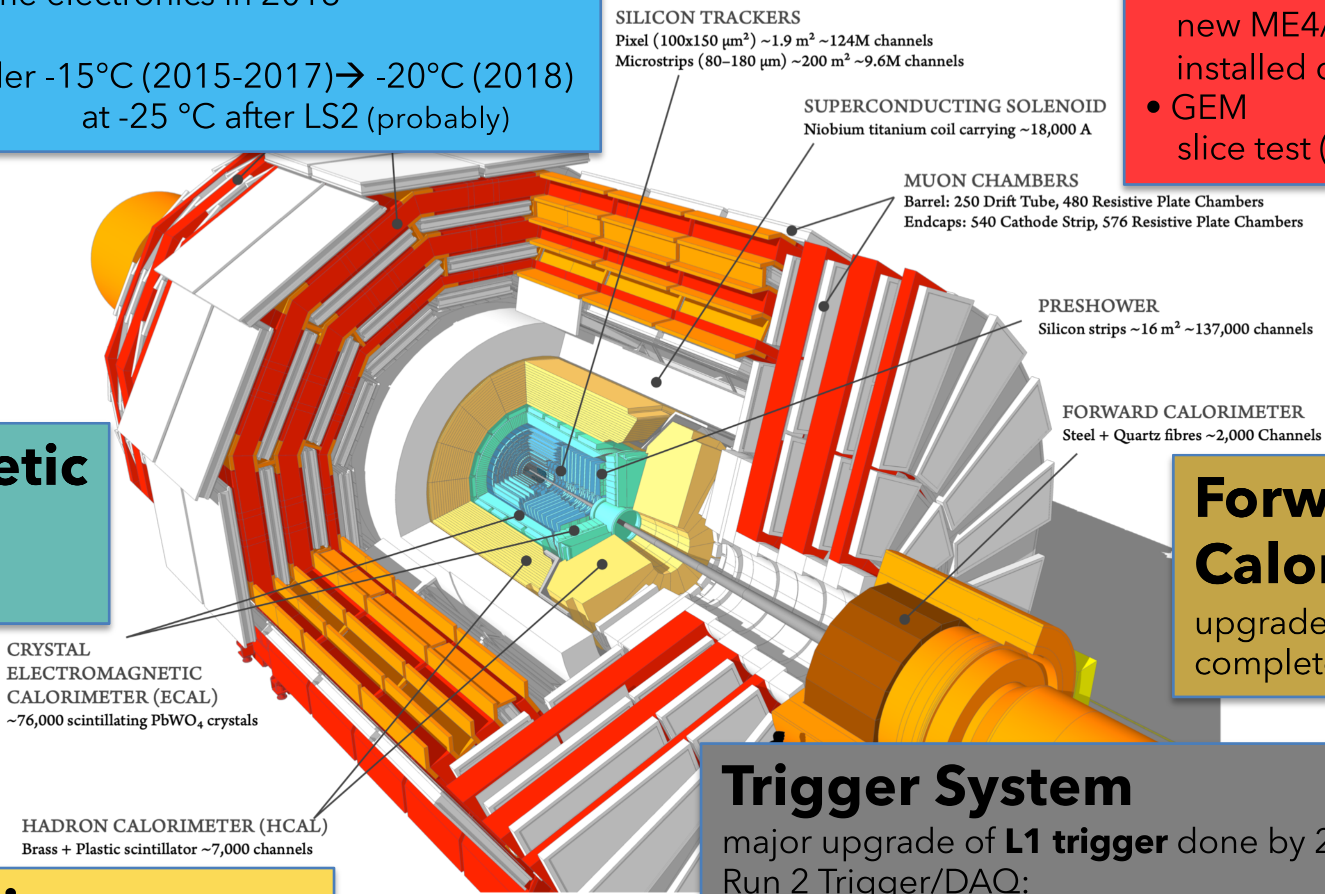
Run 2 data taken w/ an *evolving detector* configuration, in particular
the CMS detector Phase-1 upgrades started during the first Long Shutdown (2014)
and concluded during the Run 2 end of the year technical stops (2019)

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

Hadron Calorimeter

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

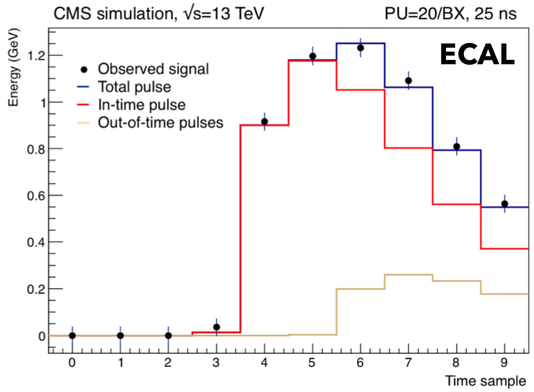
Trigger System

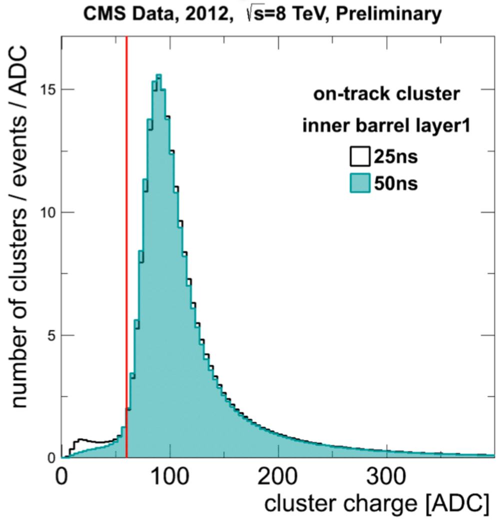
major upgrade of **L1 trigger** done by 2016
Run 2 Trigger/DAQ:
- L1 hardware ~100kHz
- HLT software ~1kHz

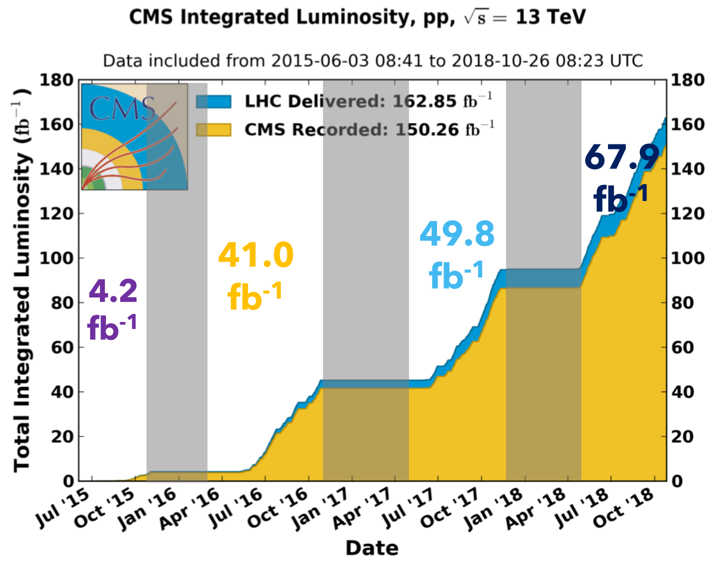
Run 2 Summary

few challenges :

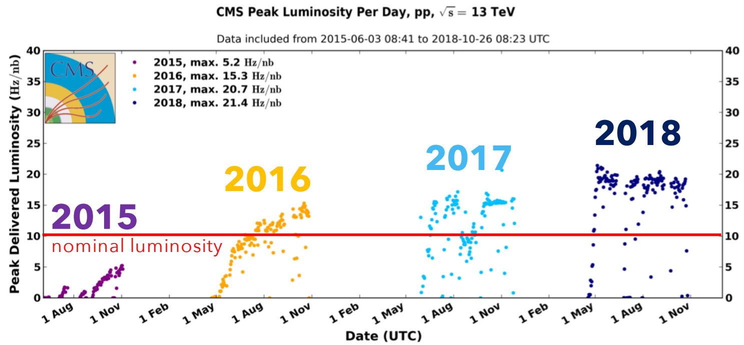
- 50ns → 25ns



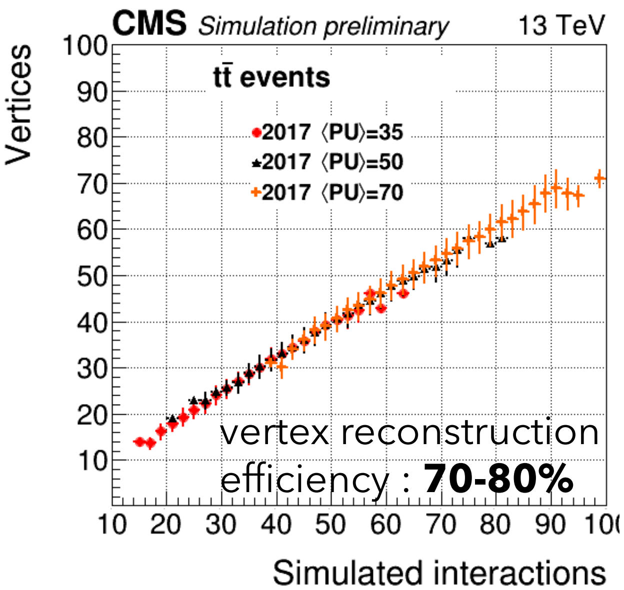




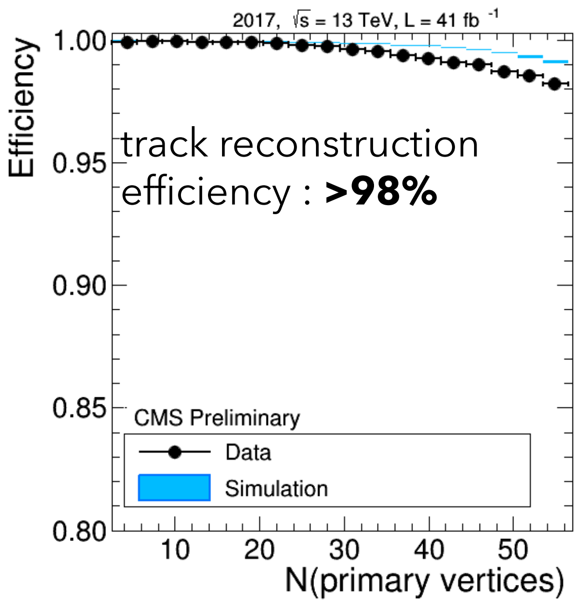
- much **higher PU** and **luminosity** (w.r.t. Run 1 and nominal)



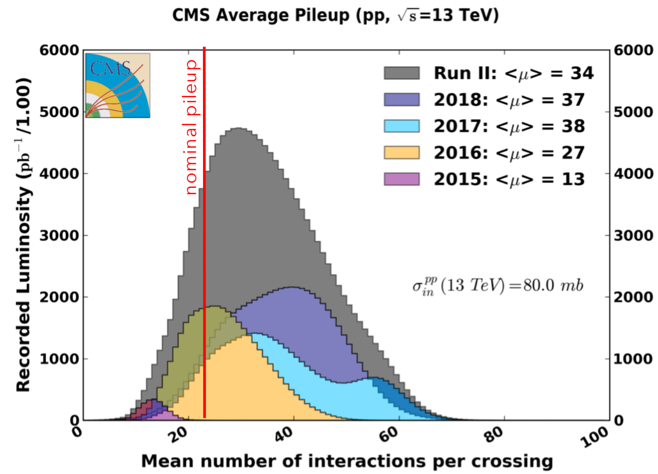
Run 2 pp **data taking efficiency 92.3%**
(94% in 2018)



vertex reconstruction efficiency : **70-80%**

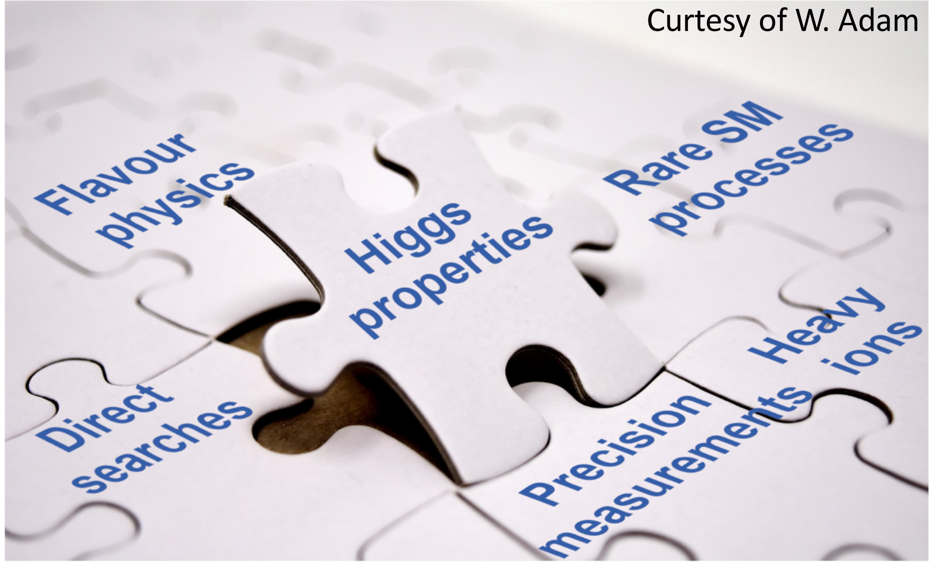


track reconstruction efficiency : **>98%**



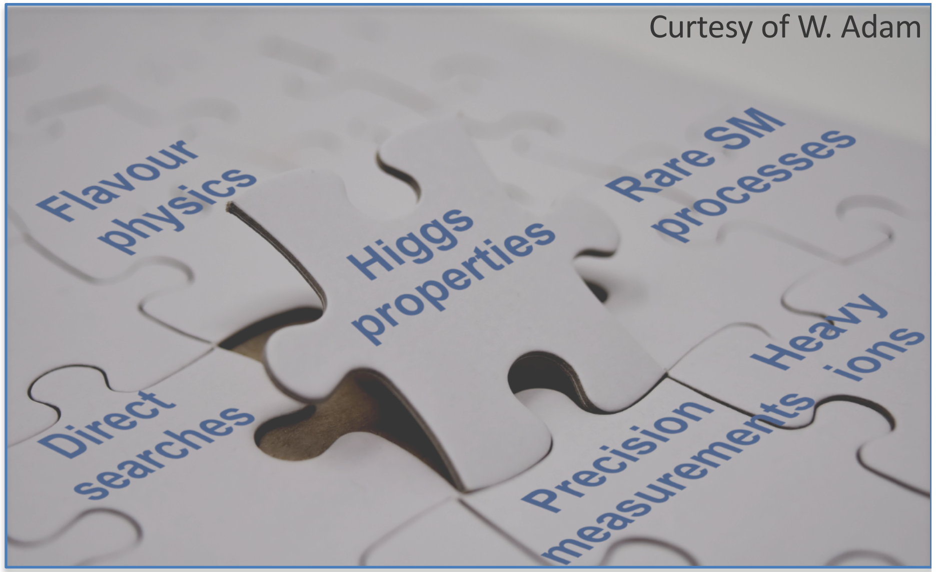
Run 2 Physics goals

simple !
completing our picture



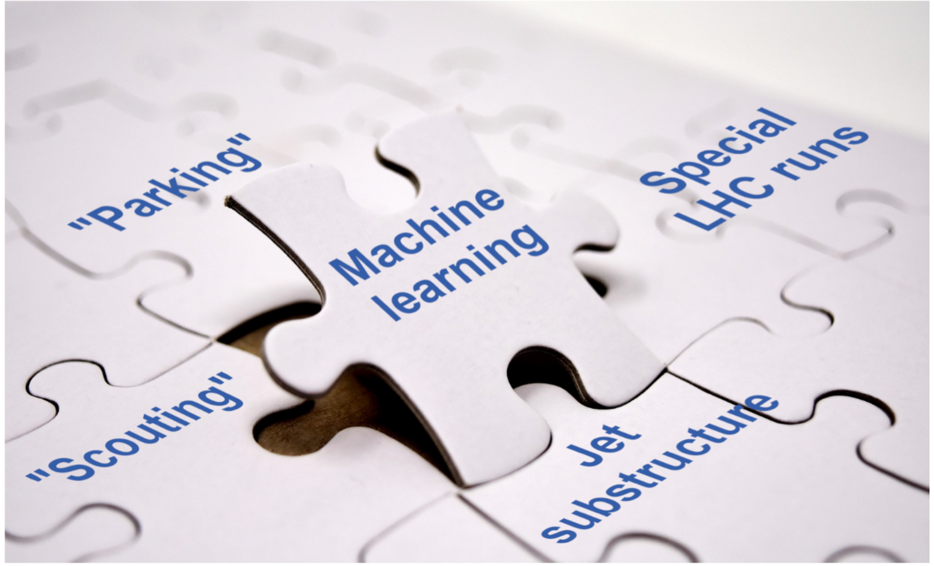
Run 2 Physics goals & methods

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

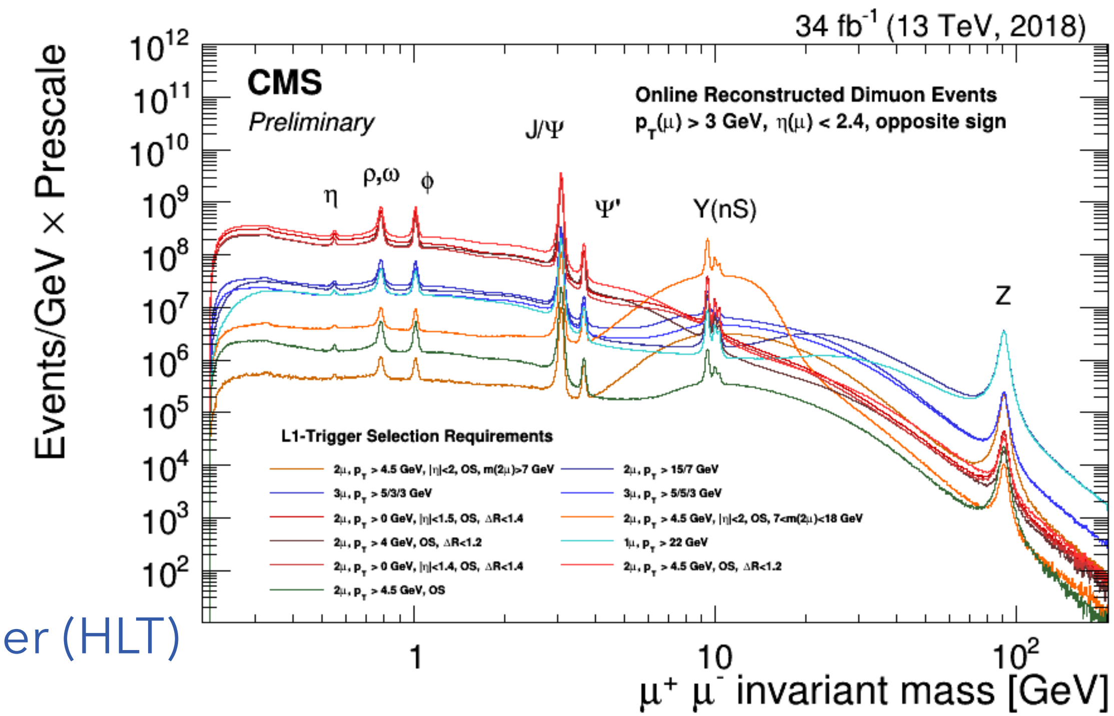
0.5% of the full size

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

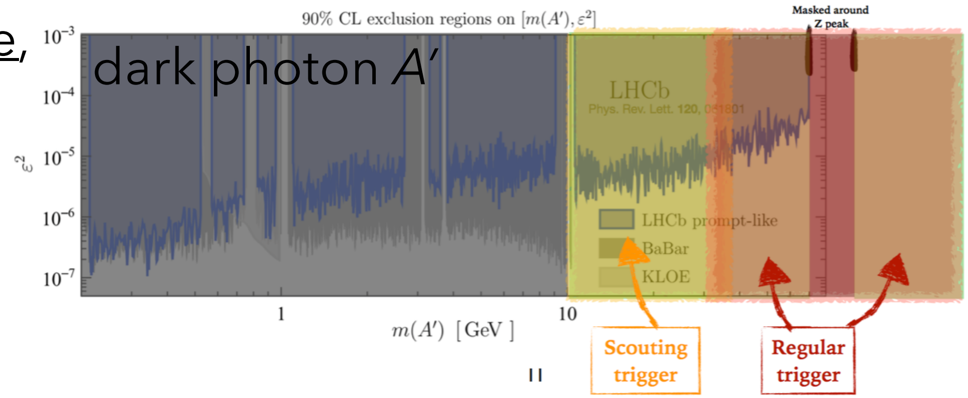
- analysis based on physics objects reconstructed at the High Level Trigger (HLT) (dropping RAW data)

- 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

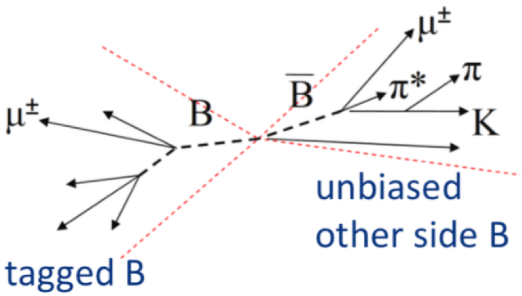


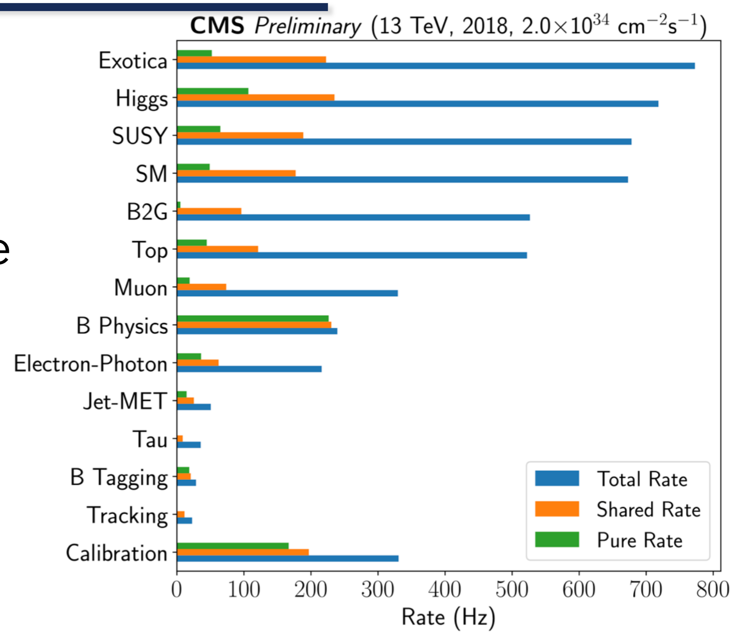
Run2 Physics goals & methods

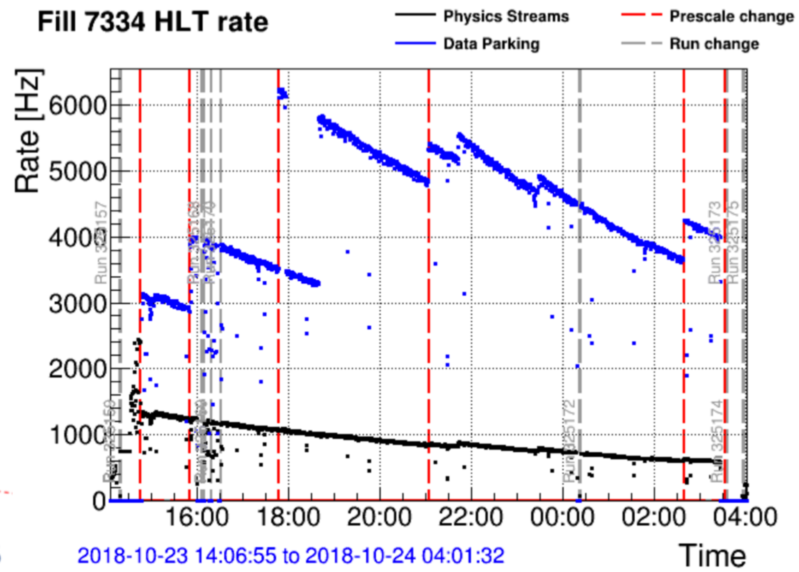
Data "Parking"

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 <u>planning taking into account data taking schedule and MC production</u>
- examples:
  - sample of *12B* events (!) enriched in **unbiased B-decays** collected w/ displaced muon triggers







Run2 Physics goals & methods

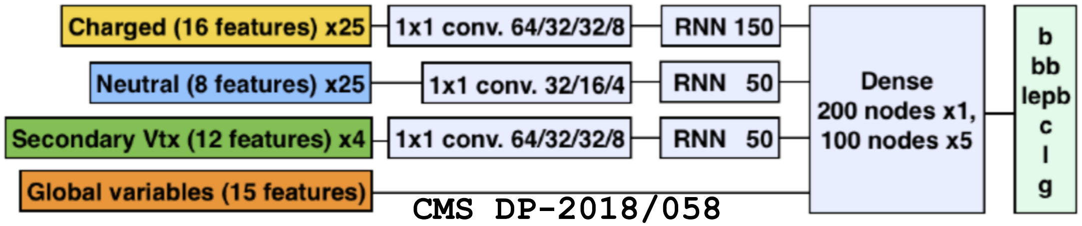
"Machine Learning"

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**

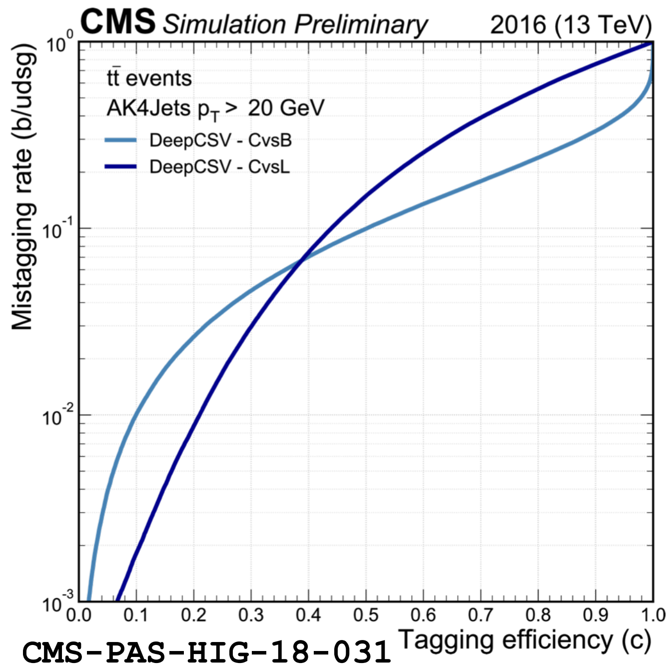
- needs adequate control regions for performance measurements and (typically) large MC samples O(100M)

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



CMS DP-2018/058

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

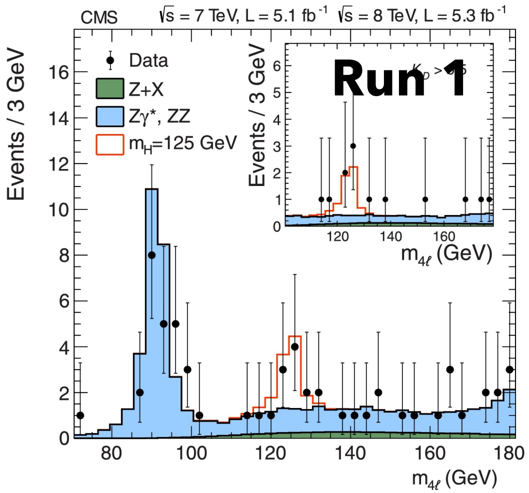


CMS-PAS-HIG-18-031

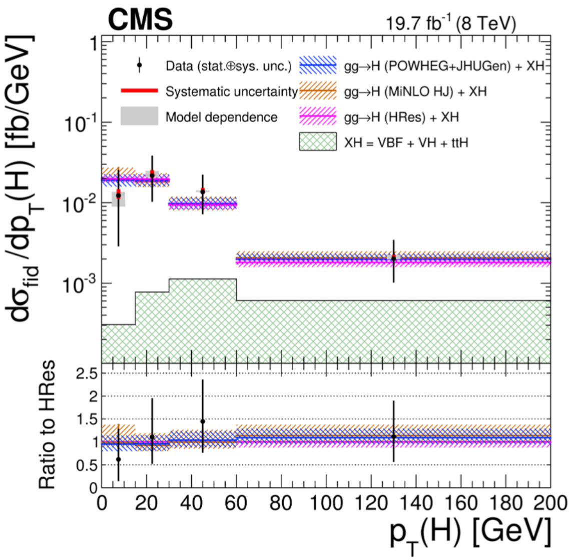
Higgs boson

- LHC Run 1 led to
  - **discovery** using decays to bosons
  - **exclusion** of **many BSM models** and specific **parameters phase-space**

PLB 716 (2012) 30



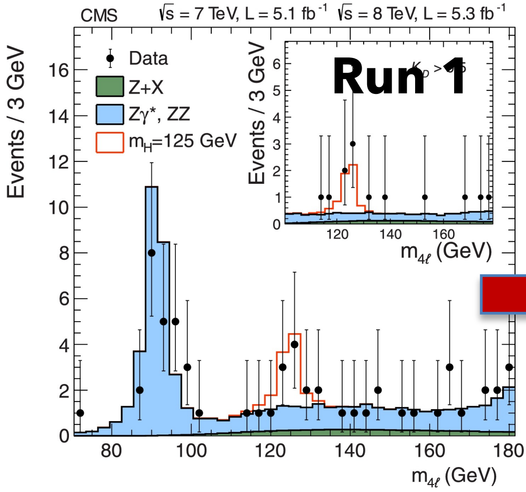
JHEP 04 (2016) 5

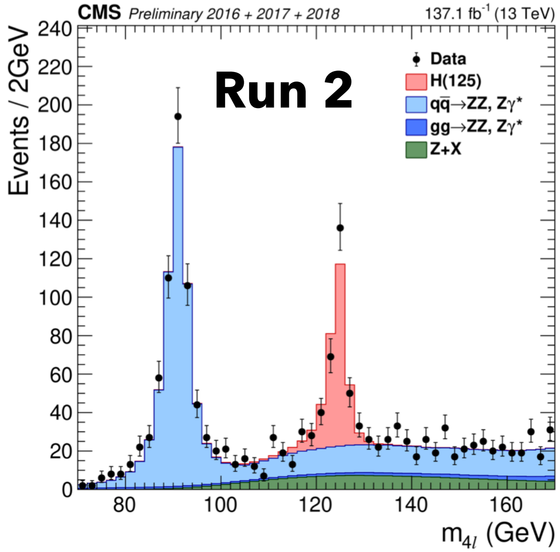


Higgs boson

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

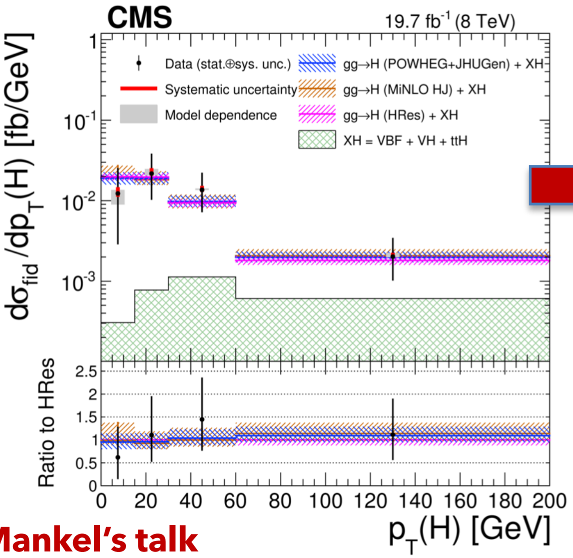
PLB 716 (2012) 30

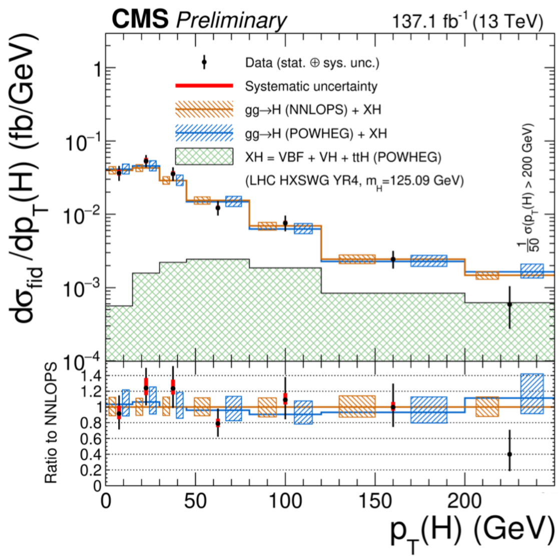




HIG-19-001

JHEP 04 (2016) 5





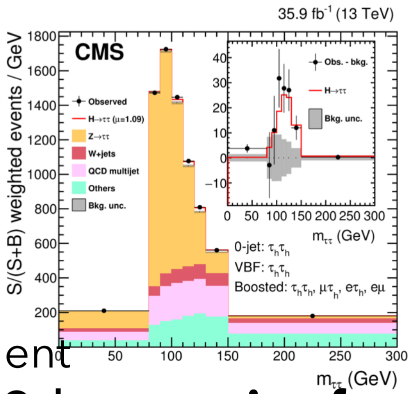
HIG-19-001

see Rainer Mankel's talk

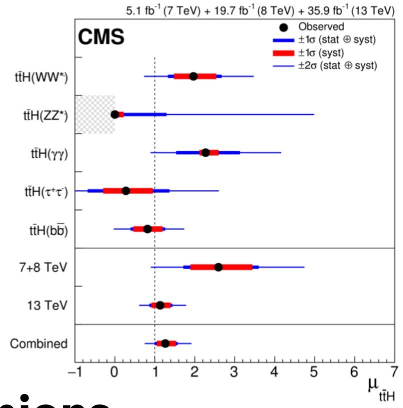
Higgs boson

- 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**

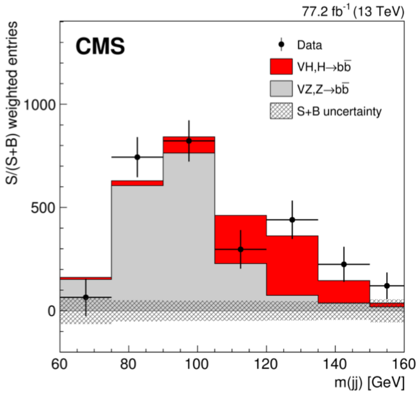
PLB 779 (2018) 283



PRL 120 (2018) 231801



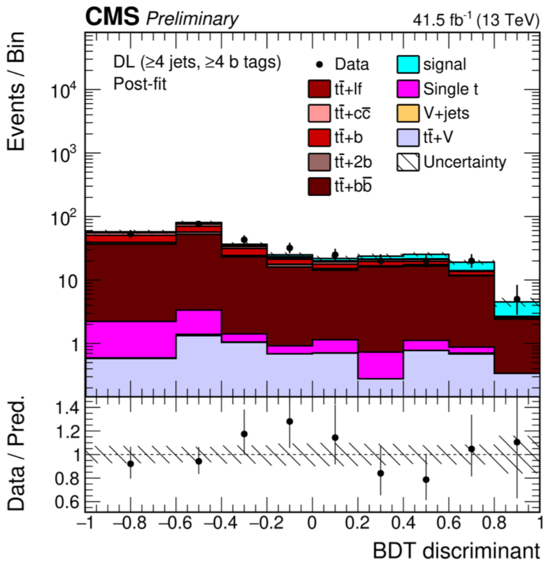
PRL 121 (2018) 121801

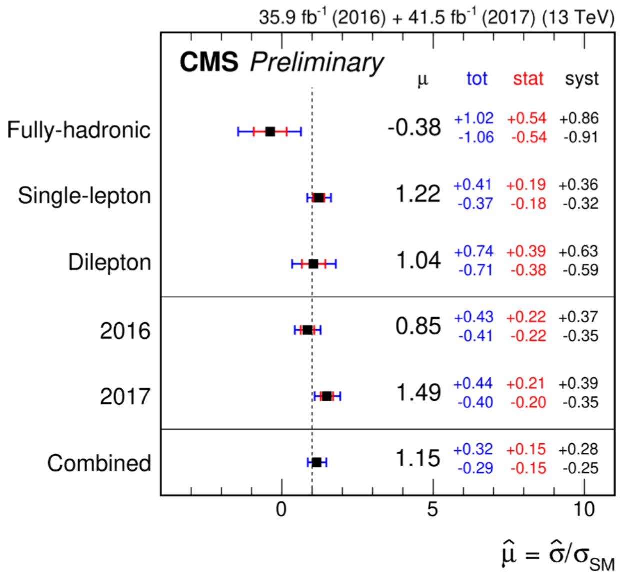


ttH (H→bb)

- 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

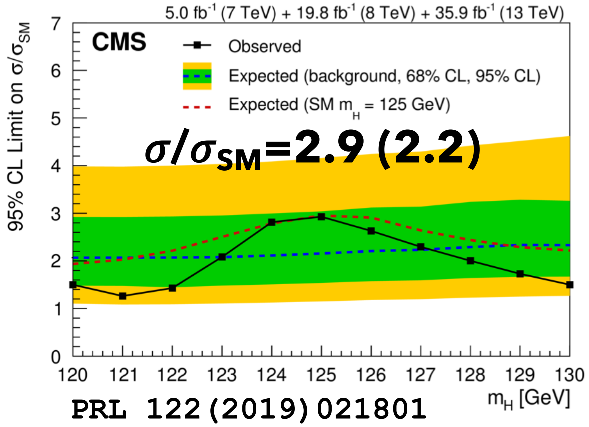
Higgs boson

- LHC Run 1 led to
  - discovery using decays to bosons
  - exclusion of many BSM models
- LHC Run 2 : unprecedent statistics
  - 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 :

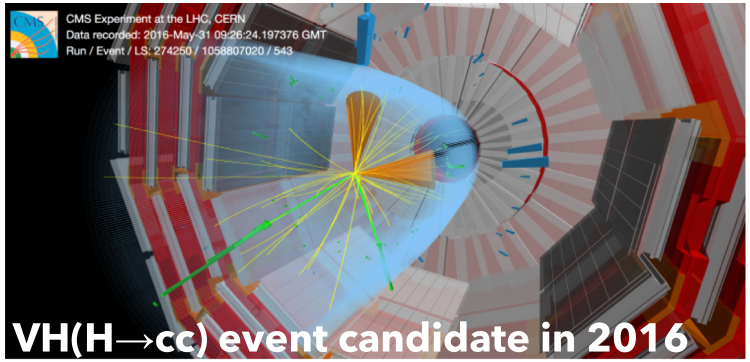
- small BR(H→μμ)=2×10^{-4} → $\mathcal{O}$(5-6) evt/fb^{-1}
- large backgrounds: Z/γ^*, diboson, top
- small S/(S+B) regime ~0.2%



PRL 122(2019)021801

see Rainer Mankel's talk

Higgs boson



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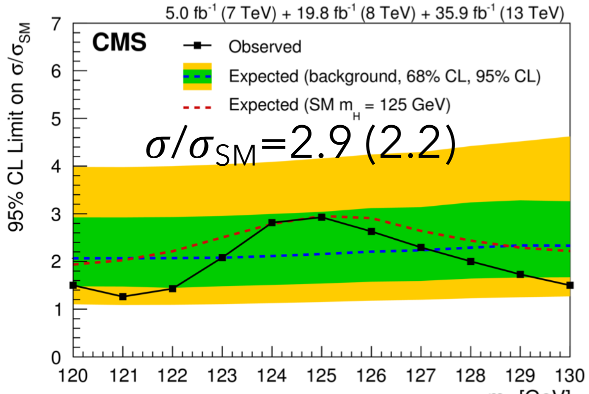


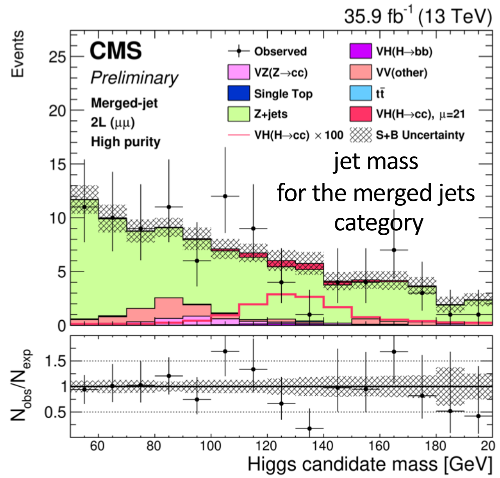
PRL 122 (2019) 021801

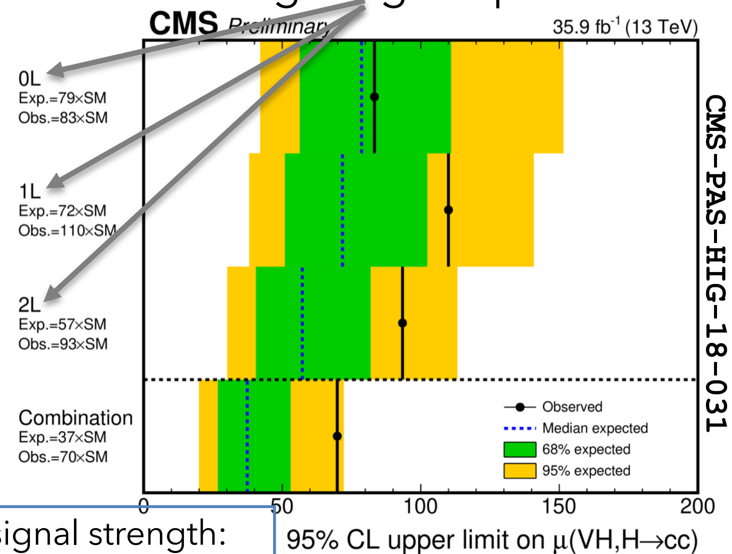
H→cc

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

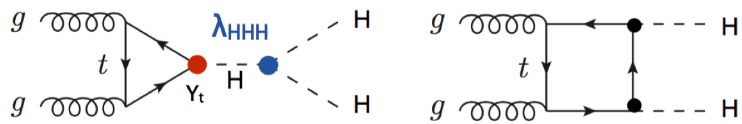
$$\mu(\mathrm{VH, H} \rightarrow c\bar{c}) = 36^{+20}_{-19}$$

see Rainer Mankel's talk

see Amina Zghiche's talk

Higgs boson

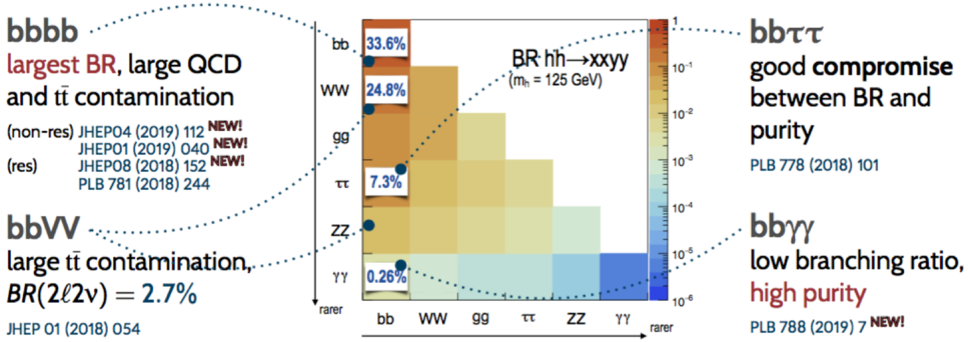
- LHC Run 1 led to discovery using decays to bosons
- LHC Run 2 directly established couplings to 3rd generation fermions
- LHC Run 3 will **extend sensitivity to physics beyond the SM**
- HL-LHC will **allow to probe** the **Higgs self-coupling**



non-resonant HH production

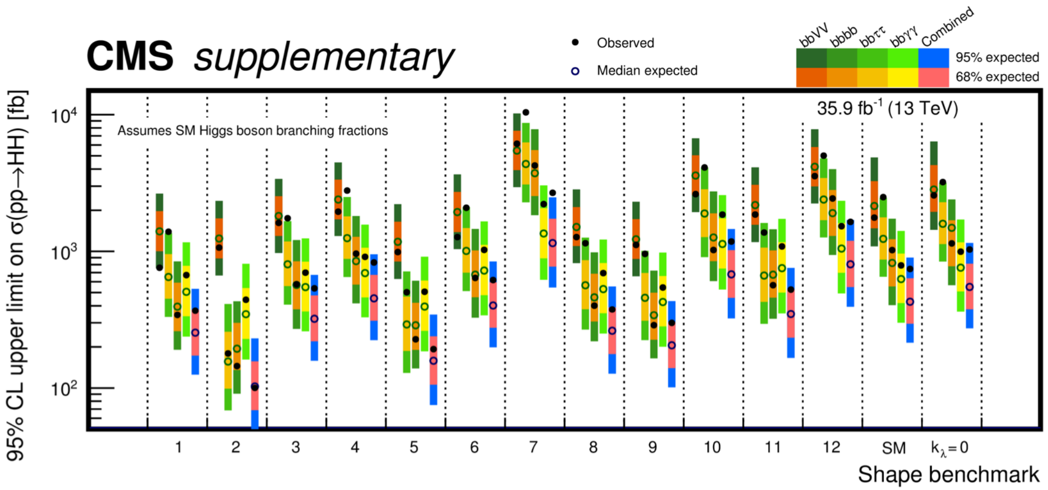
$\sigma(gg \rightarrow HH) = 33.5$ fb

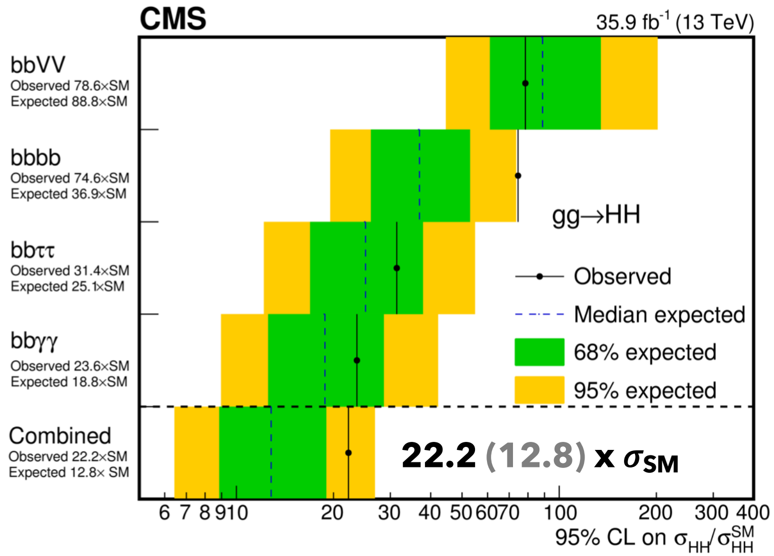
[@13 TeV NNLO+NNLO w/ top mass effects]



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

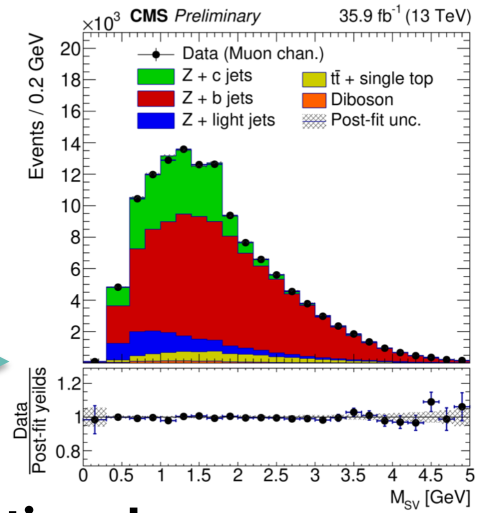
see Vitaliano Ciulli's talk

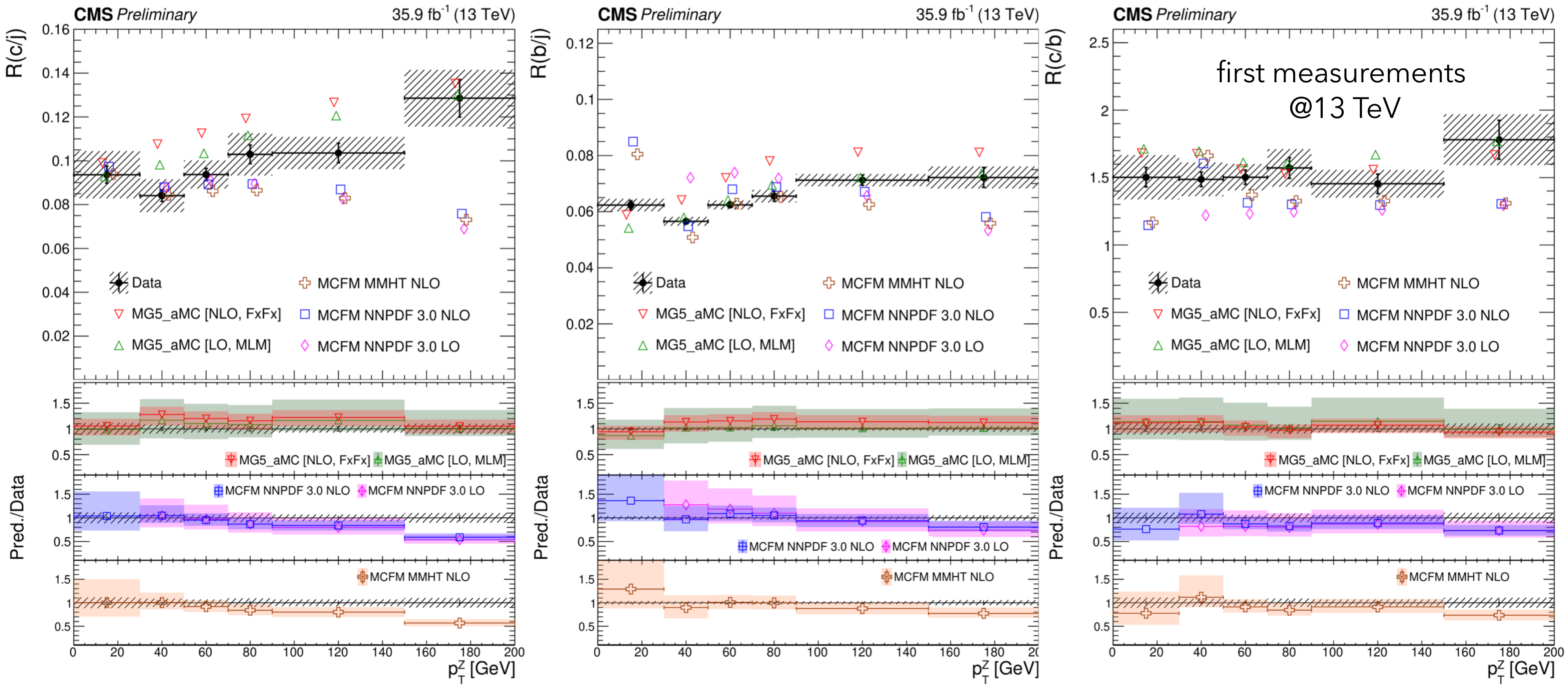
Z boson with charm and bottom

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 !**





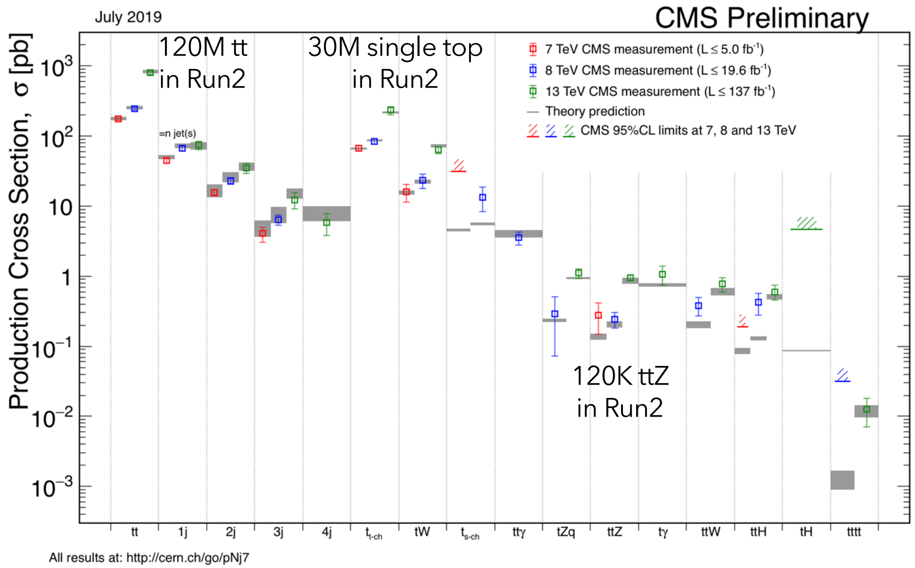
CMS-PAS-SMP-19-004

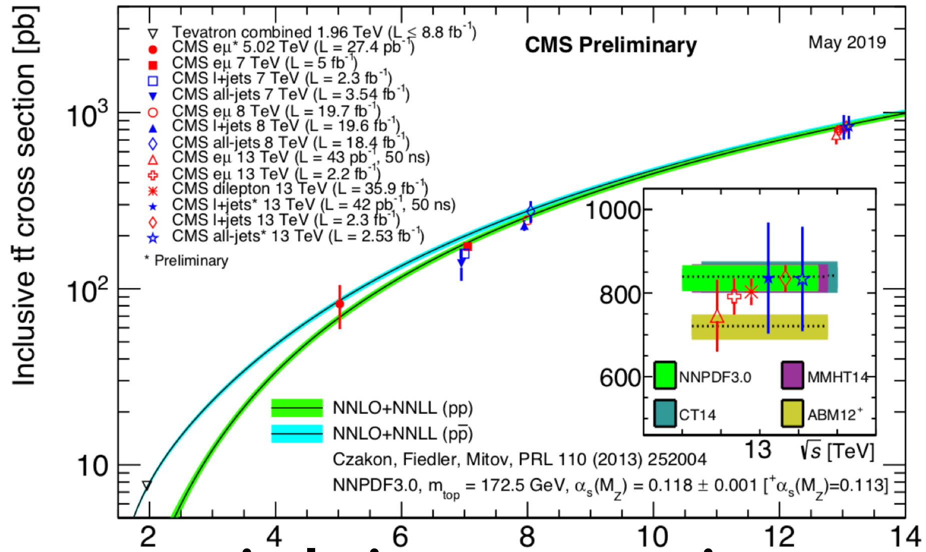
top-quark

- **high precision** top cross sections and properties

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

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





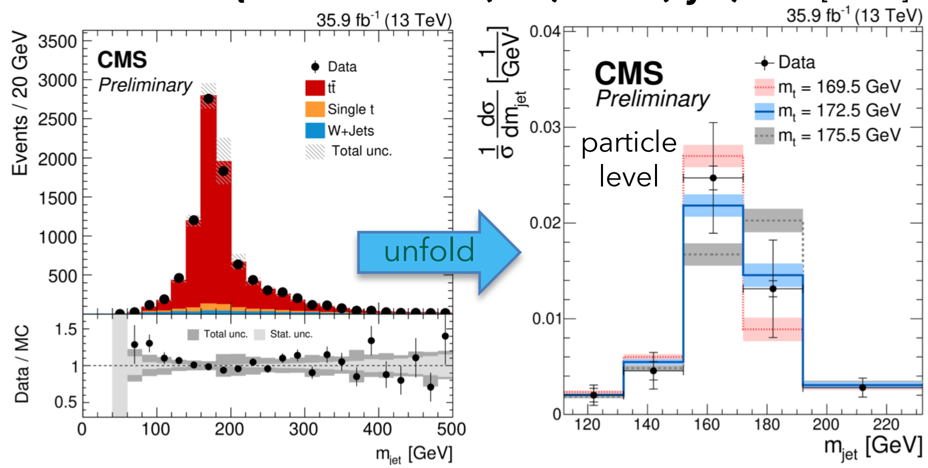
inclusive tt cross section

- 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 :

$$\mathbf{m_t = 172.56 \pm 0.41(stat) \pm 2.44(syst)\ GeV}\ [1.4\%]$$



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top-quark

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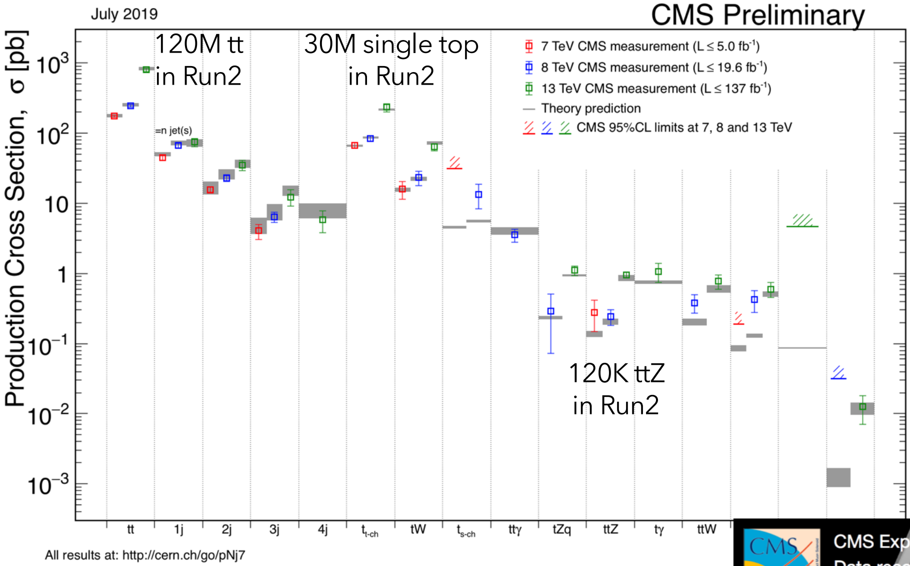

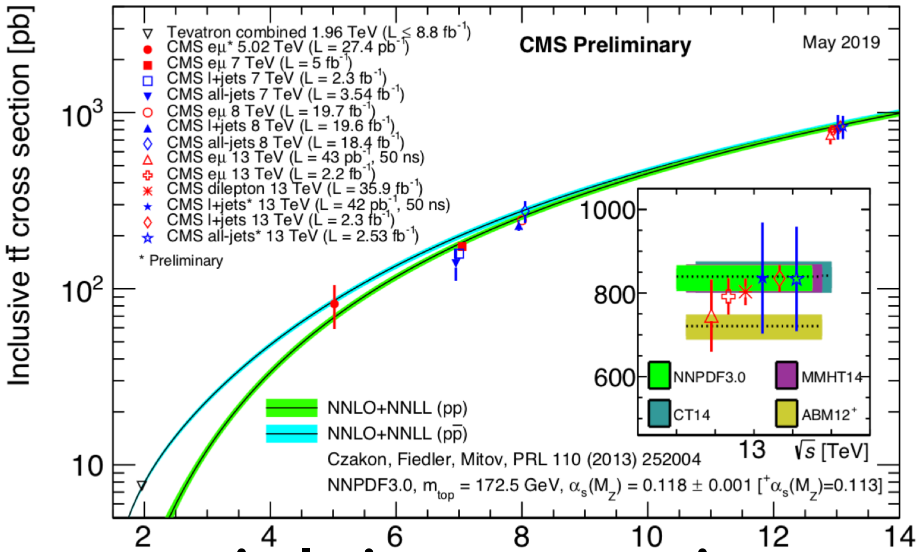

inclusive tt cross section $\sqrt{s}$ [TeV]

- measure all channels to look for the unexpected
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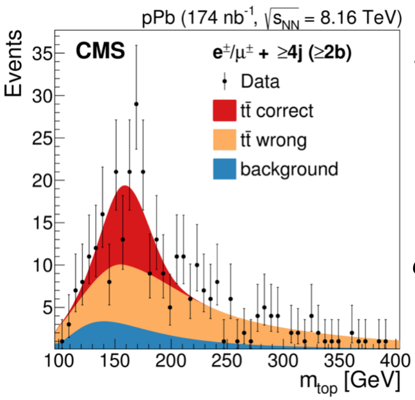
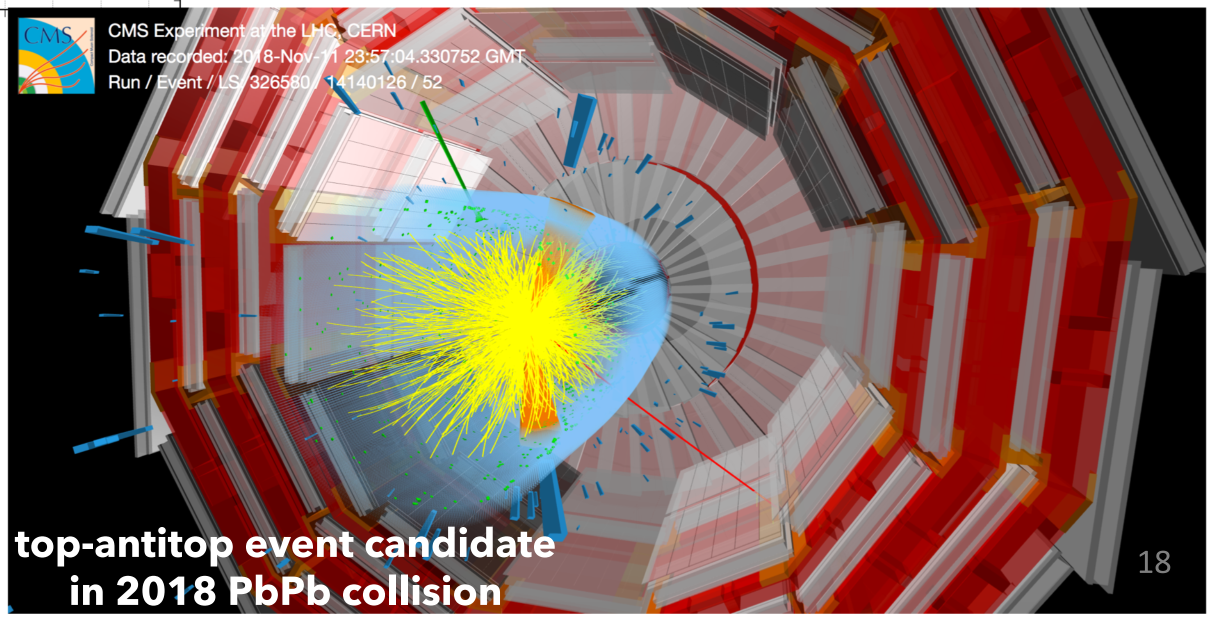


top quark also observed in proton-nucleus (Pb) collisions

σ(tt) = 45±8 nb



Phys.Rev.Lett.119(2017)242001

top-quark

top quark physics
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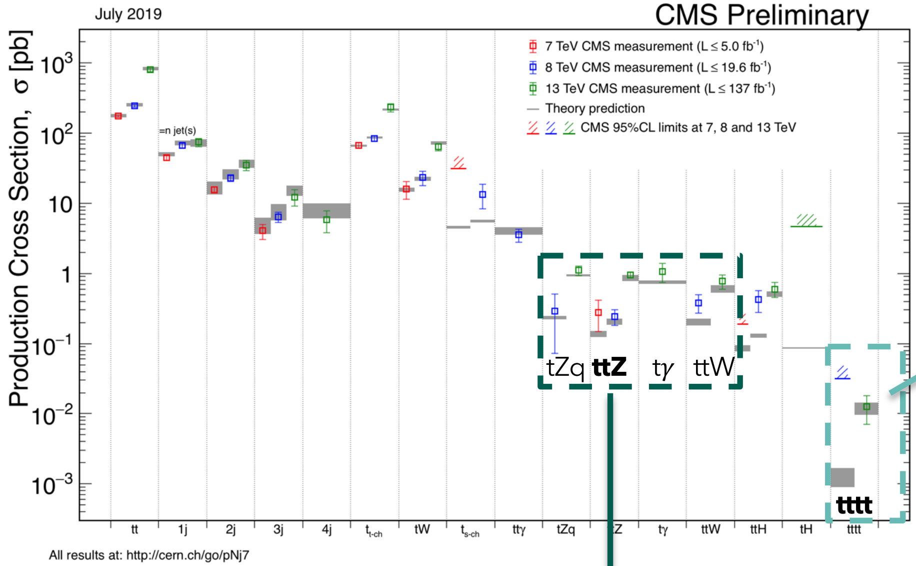
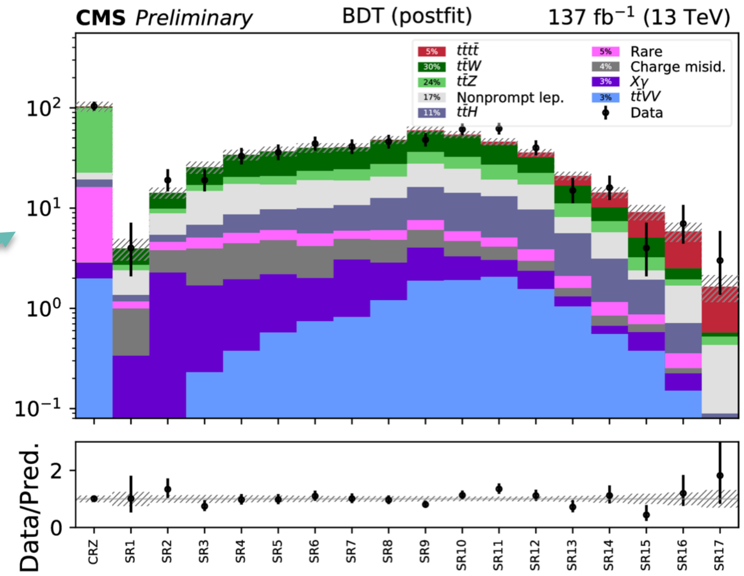


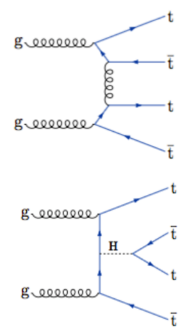
- **high precision** top cross sections and properties
- **rare processes** becoming less rare (some even systematically limited !)

→ started to challenge theory predictions in many respects

significance 2.6 (2.7) σ

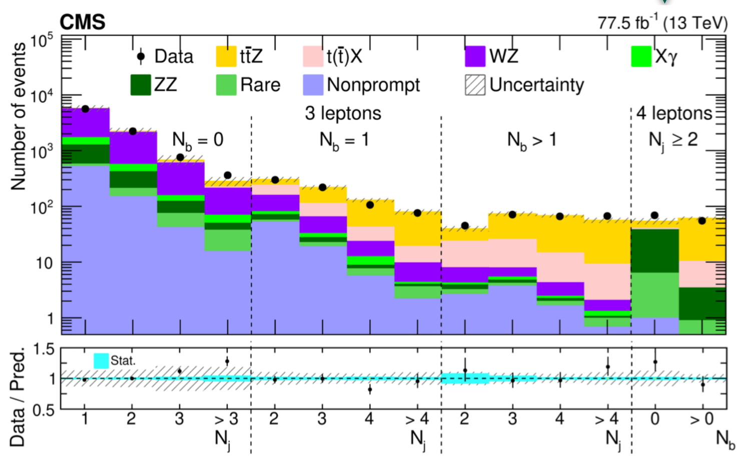
same-sign dilepton & trilepton final state



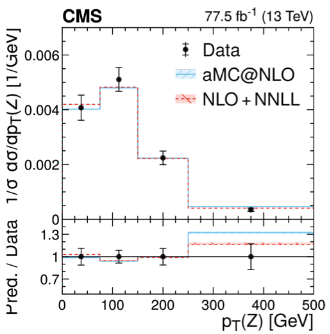


CMS-PAS-TOP-18-003

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



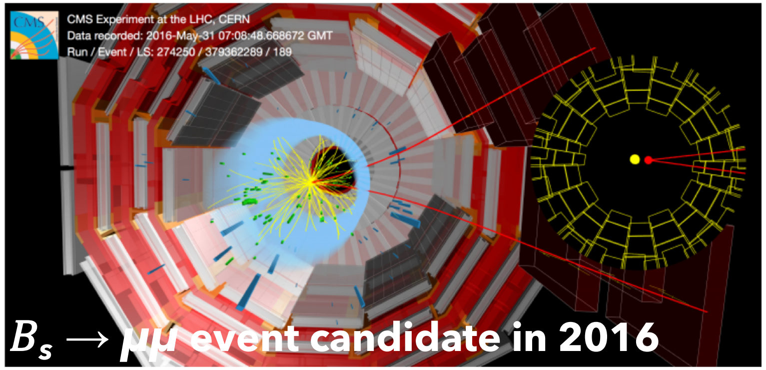
CERN-EP-2019-124



- 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 !

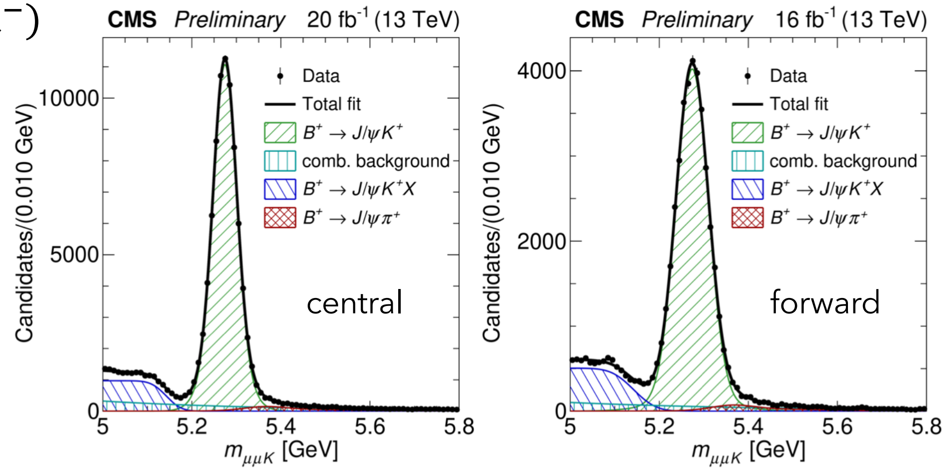
$B \rightarrow \mu\mu$



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

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

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



BPH-16-004

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

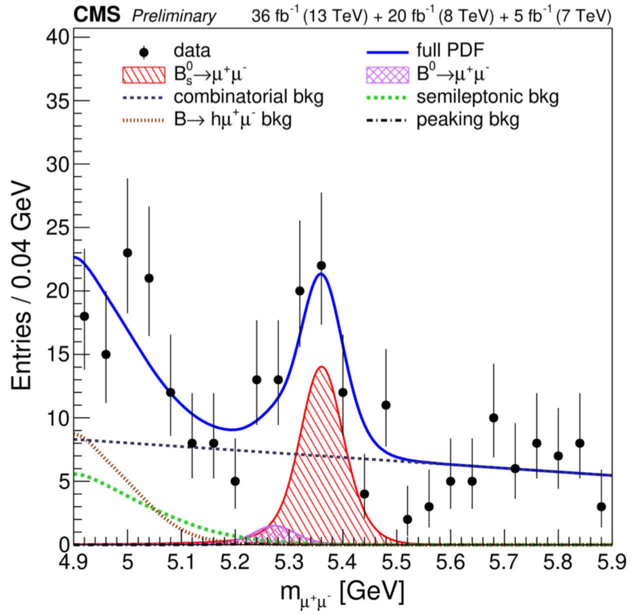
- the decay $B_s \rightarrow \mu\mu$ is observed w/

  - a significance : **5.6 (6.5)** $\boldsymbol{\sigma}$
  - a branching fraction :

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

  - 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 :

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

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

see Valentina Mariani's talk

$B \rightarrow \mu\mu$

- $B_s \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu$ **branching ratios**
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  - an effective lifetime :

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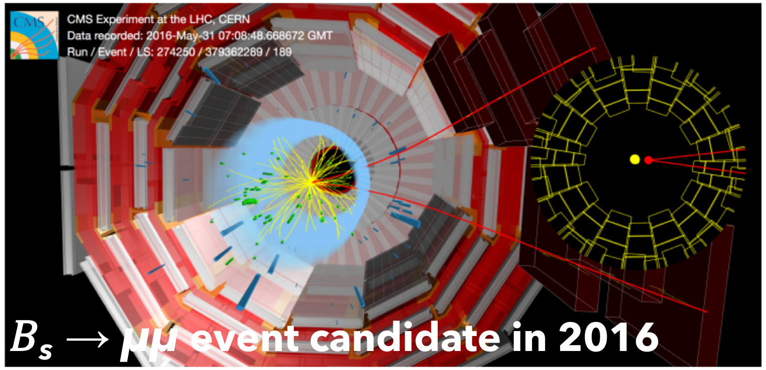
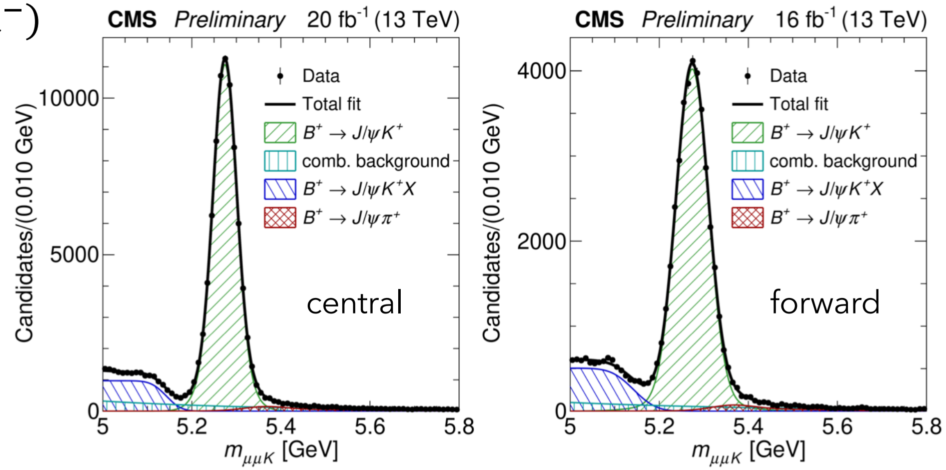
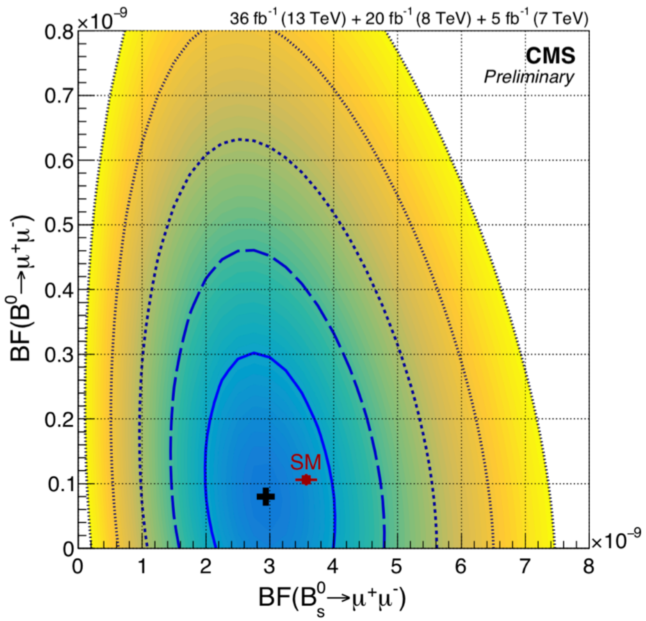
  previous CMS result : $BR(B_d \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @95% CL

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





BPH-16-004



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 $\boldsymbol{\sigma}$**

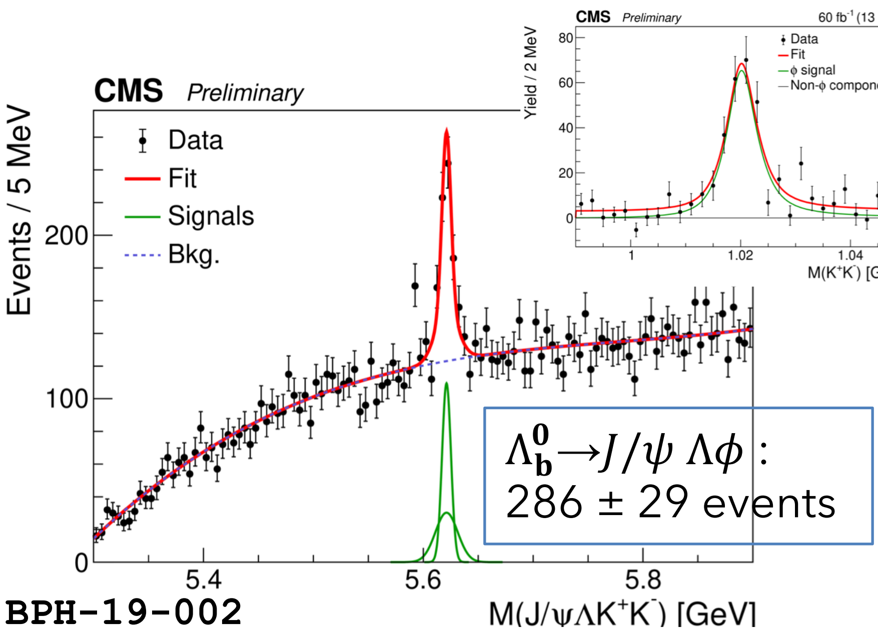
  decay expected to proceed via the **b → $\boldsymbol{c\bar{c}s}$** process [similar to $\Lambda_b^0 \to J/\psi\ \Lambda$ but requires an additional $s\bar{s}$ pair]

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

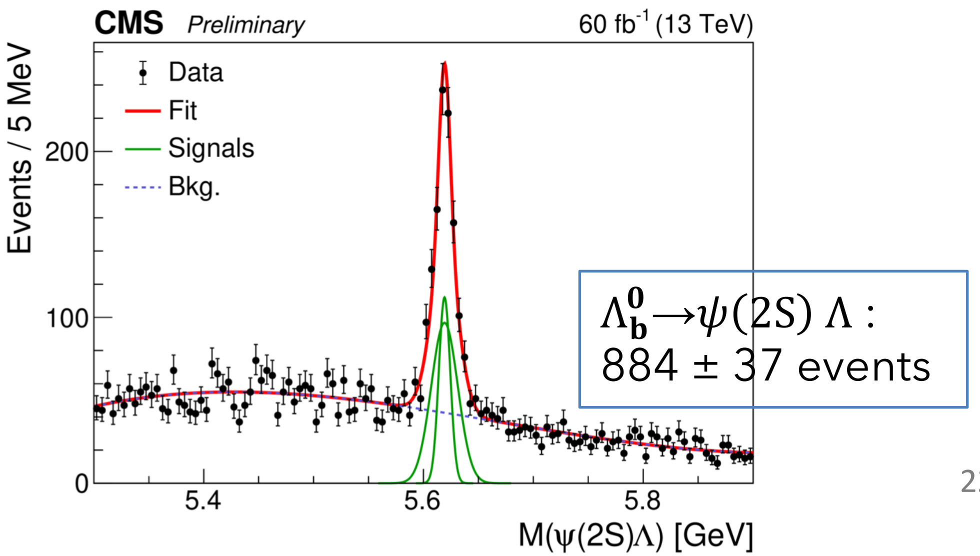
  [which has a similar topology]

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

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



BPH-19-002

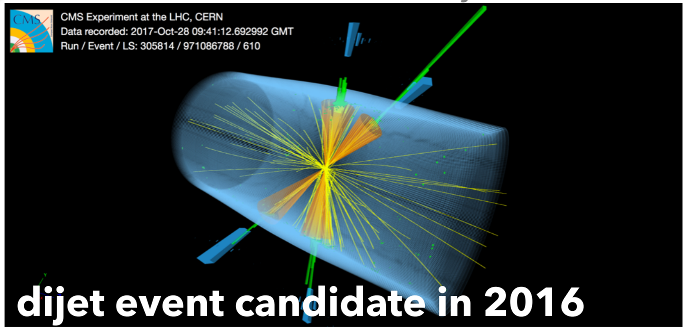


EXO-19-012

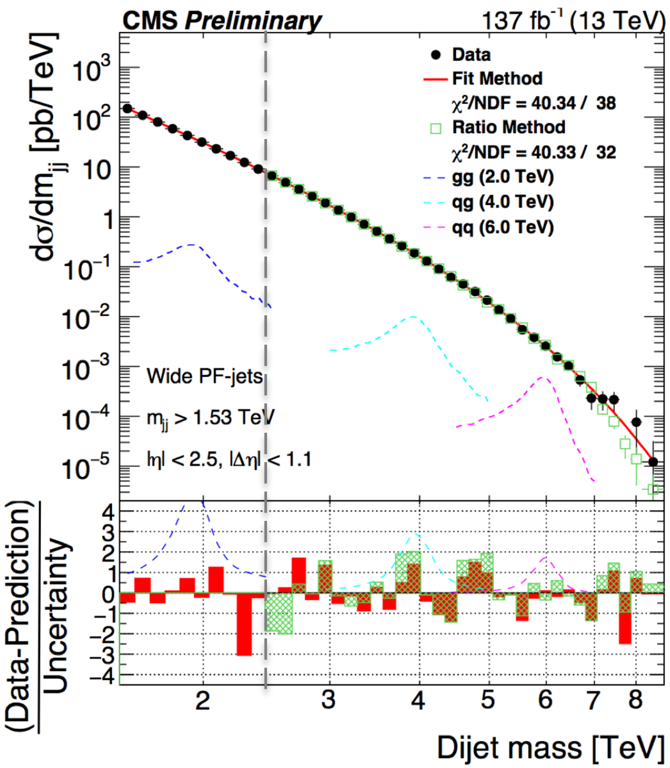
resonant decays into 2 jets

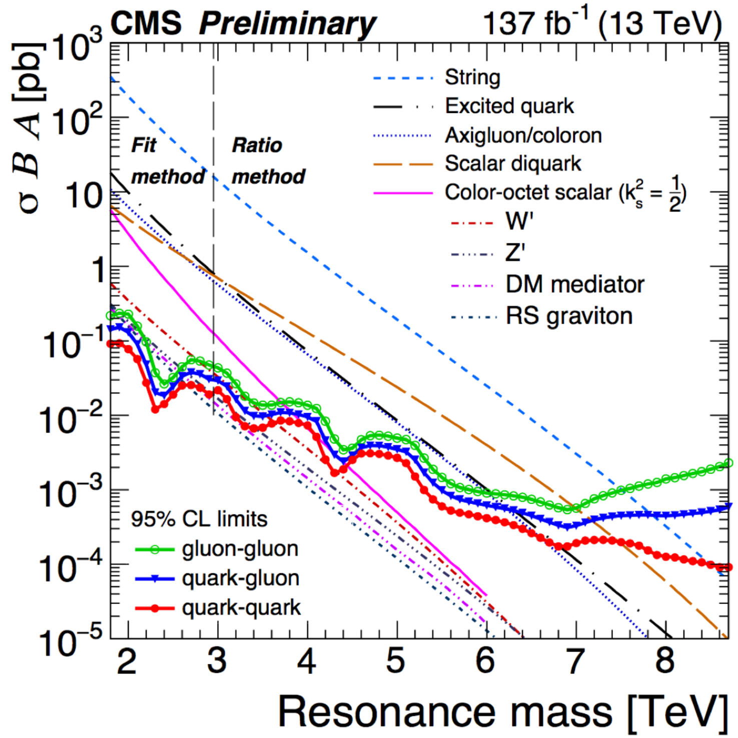
- ***classical* high-mass resonance search**
  can be interpreted in a wide range of BSM models predicting particles decaying to ***gg***, ***gq***, or ***qq***

wide jet



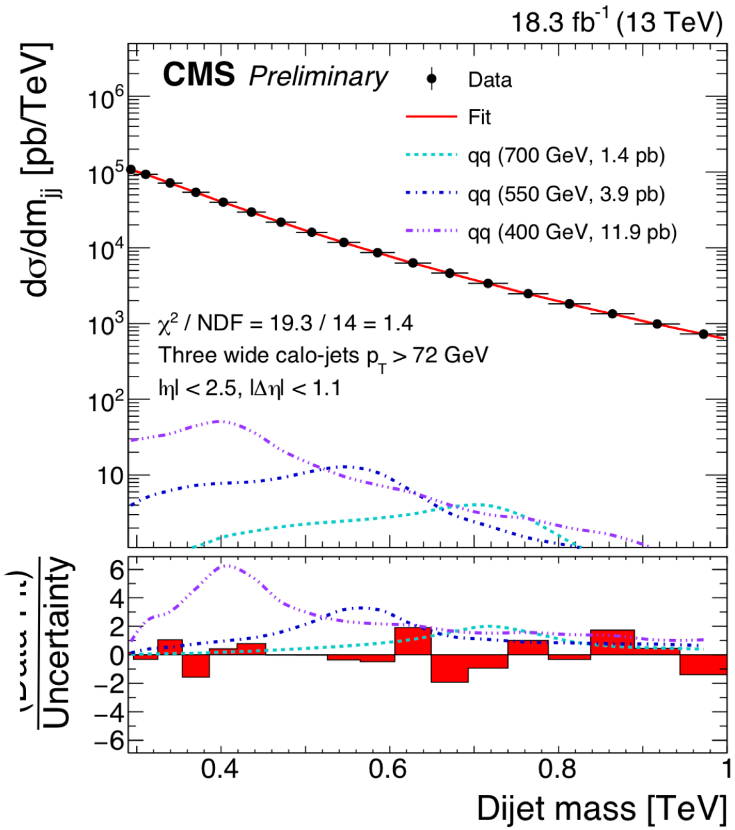
- continue to improve analysis w/ **new techniques**:
  → replace parametric background shape
  by data driven measurement in sideband region [$\Delta\eta_{jj}$]
  - ✓ robust method
  - ✓ smaller systematics uncertainties
  - ✓ more sensitive for broad resonance searches
- results consistent w/ background

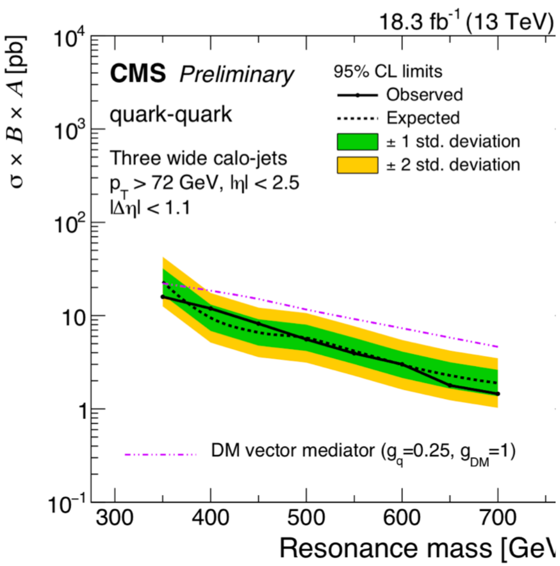


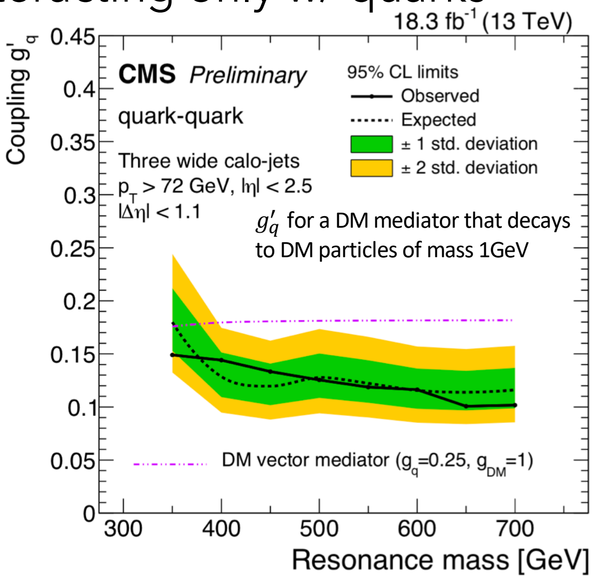


resonant decays into 2 jets in events w/ 3 jets

- 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



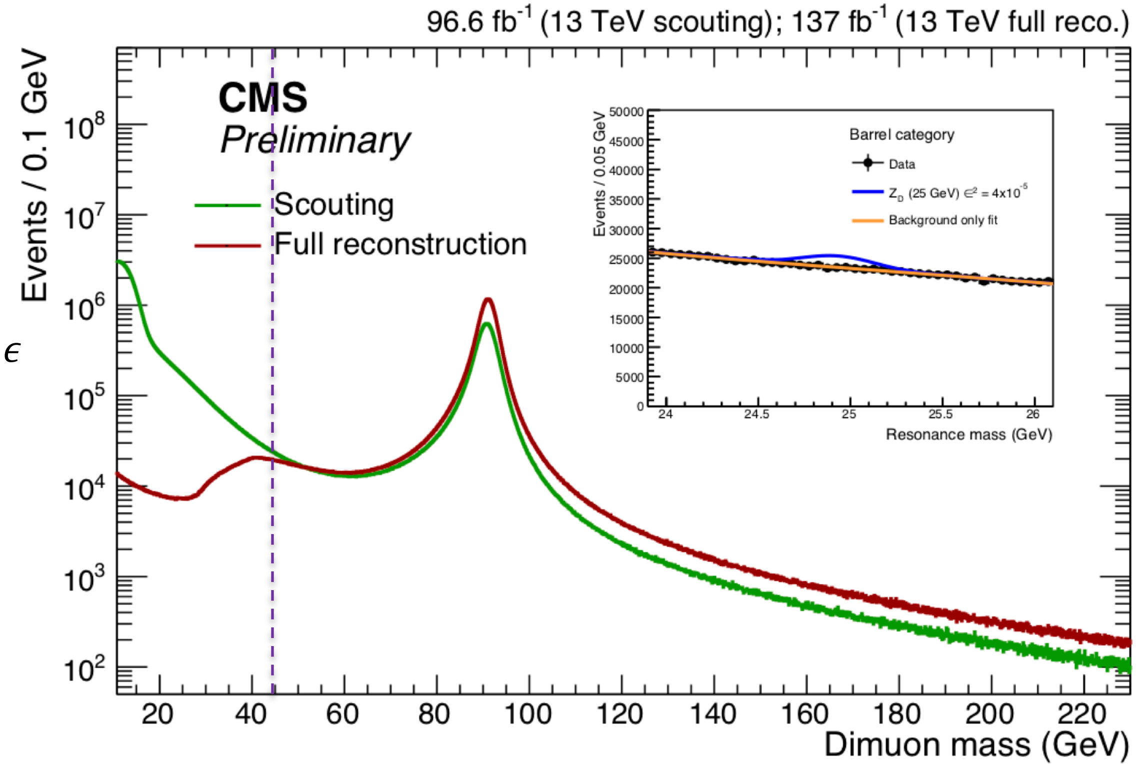




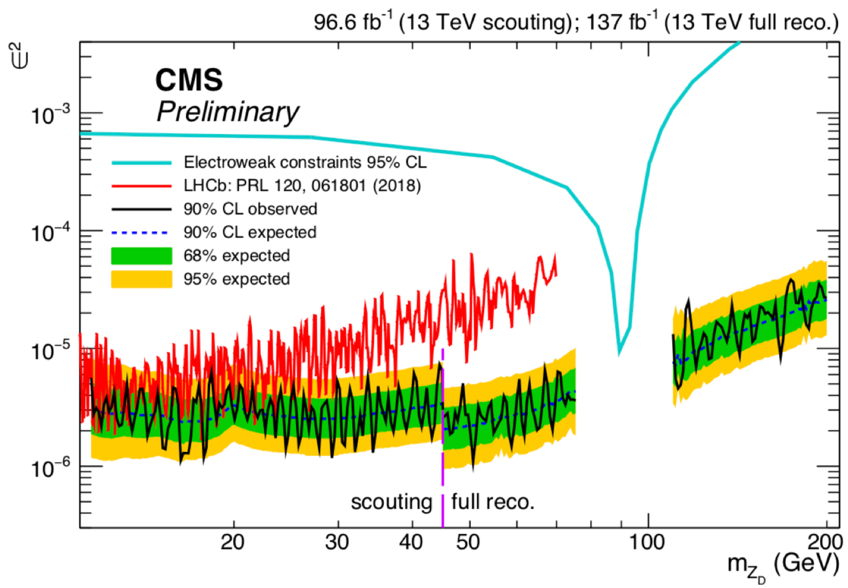
EXO-19-018
first CMS analysis
using
non-hadronic scouting

search for dimuon resonances (I)

- 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



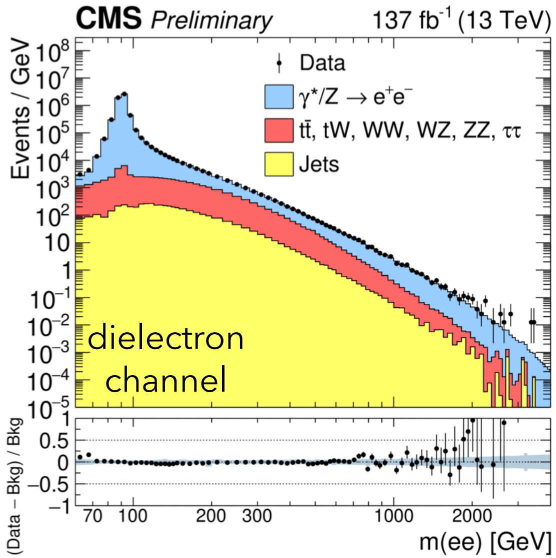
- the results can be interpreted as a **dark photon (Z_D)**
  that could couple the SM particles to a hidden, dark sector of particles
- the strength of the coupling w/ SM fermions is determined by the kinetic mixing coefficient ϵ
- data are found to be consistent w/ background expectations

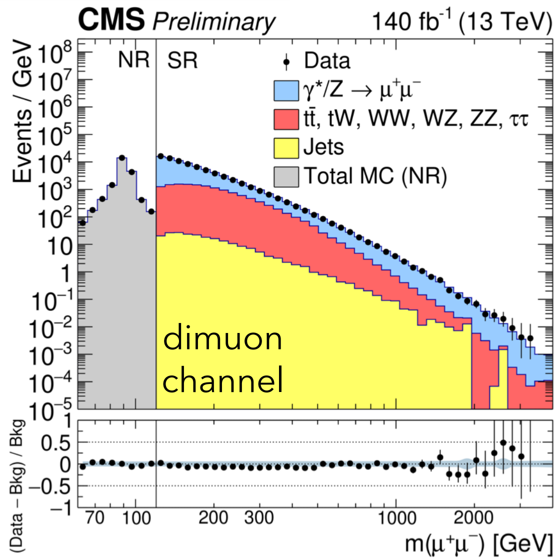


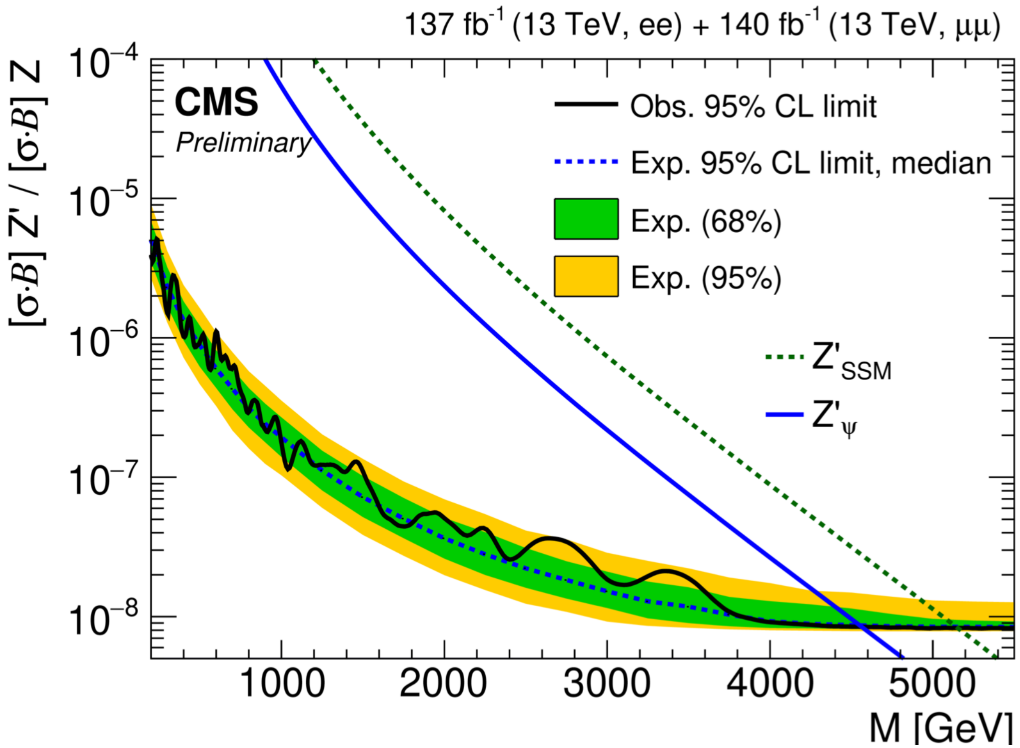
strongest constraints on
a hypothetical **dark photon**
w/ $m_{Z_D} > 11.5$ **GeV**

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

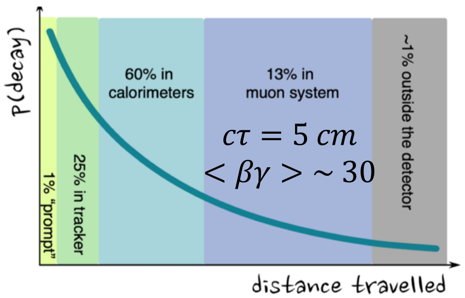
superstring-inspired sequential standard model

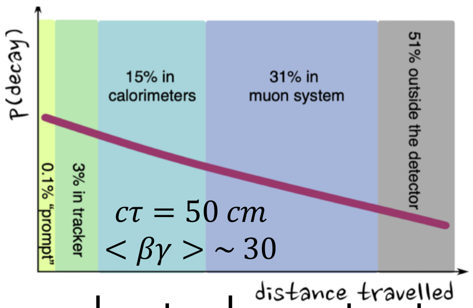
$\Rightarrow Z'_{SSM}$ (Z'_{ψ}) particle is excluded @ 95% CL below a mass of **5.15 (4.55) TeV**

long-lived particles

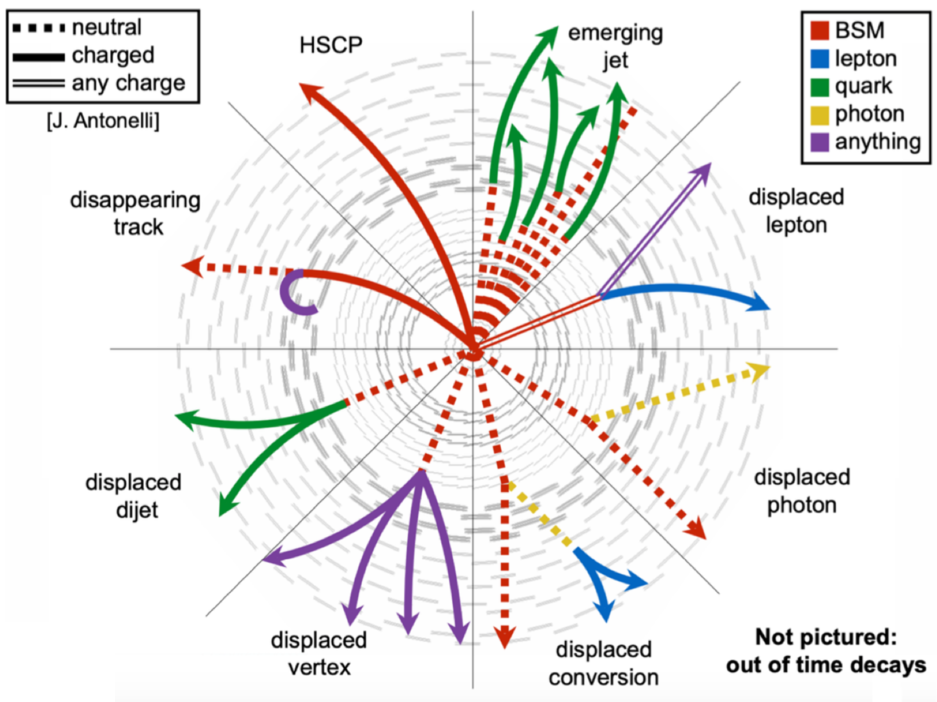
Long-lived particles (LLPs) appear in many BSM scenarios
– nearly mass-degenerate states (compressed SUSY, AMSB, etc.)
– heavy virtual mediators (split-SUSY, heavy neutral leptons, etc.)
– small couplings (dark photons, freeze-in DM, RPV SUSY, etc.)

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**

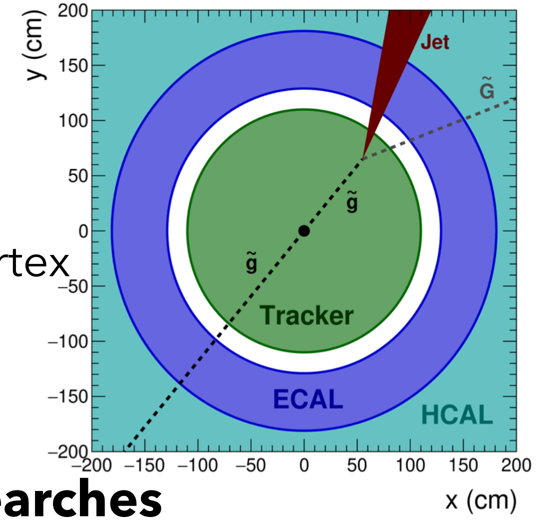


CMS has a **broad LL program**
based on *signature-driven* searches

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

long-lived particles

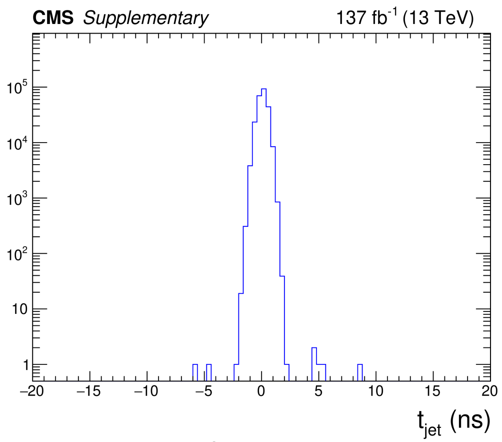
w/in ECAL
radial acceptance



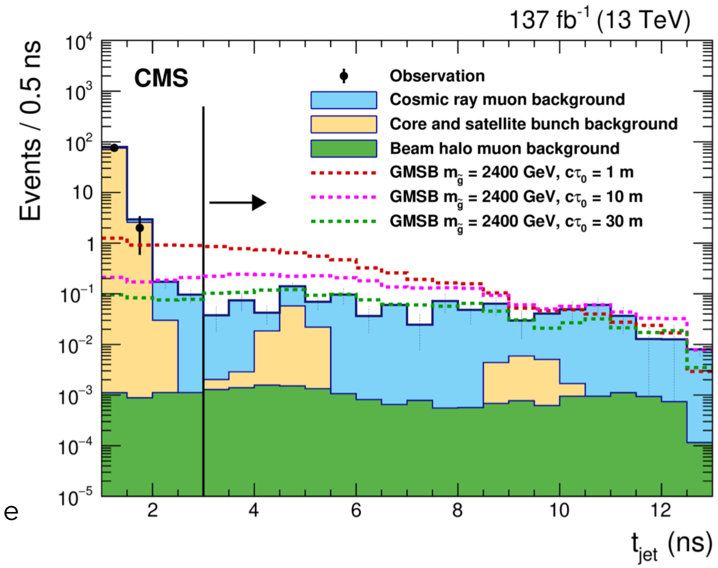
- **delayed jets** [heavy neutral LLPs decaying to at least 1 delayed jet + MET]
  benchmark : **long-lived gluinos** give rise to jets from displaced vertex
  → delay due to differences in velocity and in path length
  - **median time of all ECAL cells** in the jet cone, allows to
    → reduce the background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

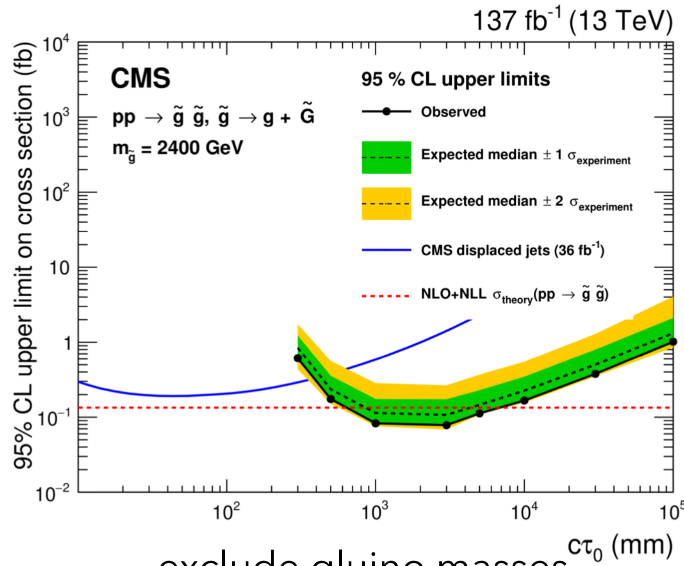
arXiv:1906.06441

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]

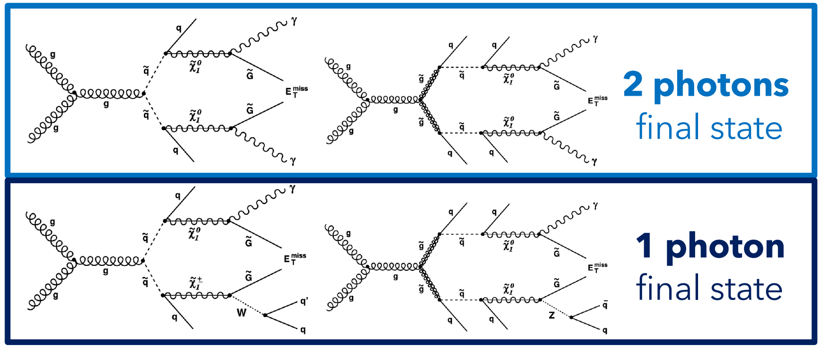




exclude gluino masses
up to **2.5 TeV** for **cτ = 1 m**

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**

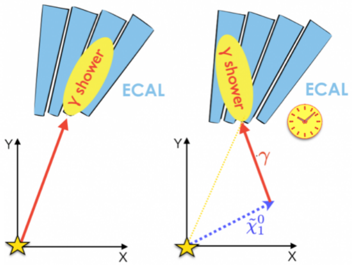
    → requires precise calibration of ECAL timing and resolution

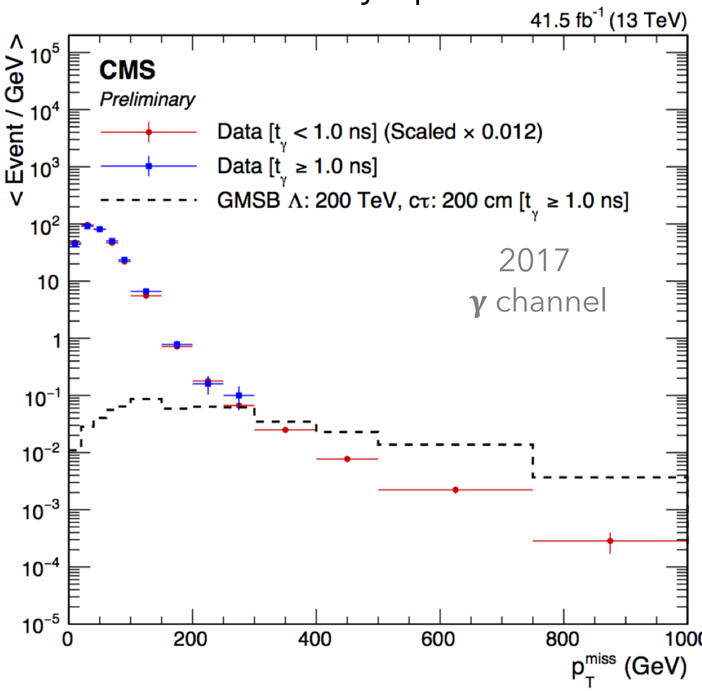
  - **dedicated trigger in 2017** for selecting events w/ **1 photon** consistent w/ production **at a displaced secondary vertex**
  - **dedicated out-of-time photon reconstruction**
  - **extend the previous best limits**

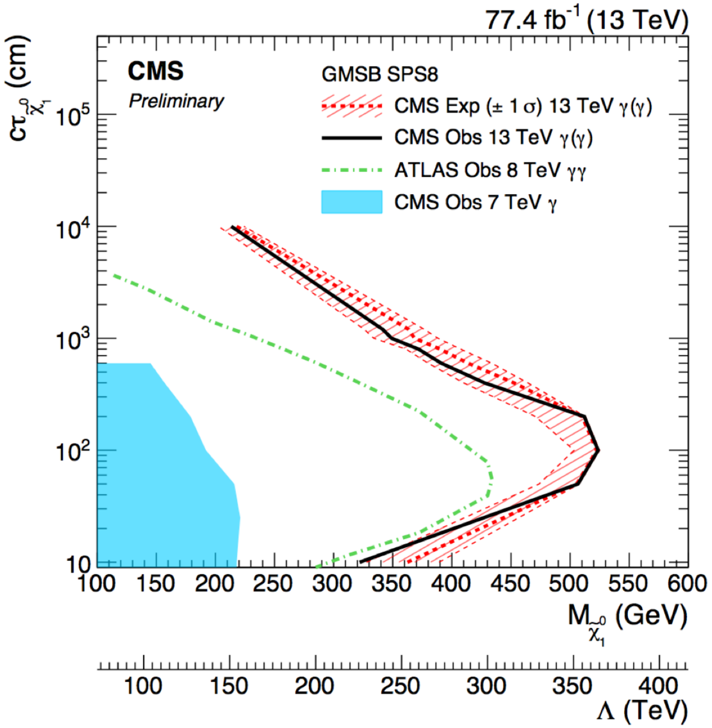
    in the neutralino proper decay length by up to about one order of magnitude

    in the neutralino mass by up to about 100 GeV

EM shower shape in η-ϕ plane more elliptical



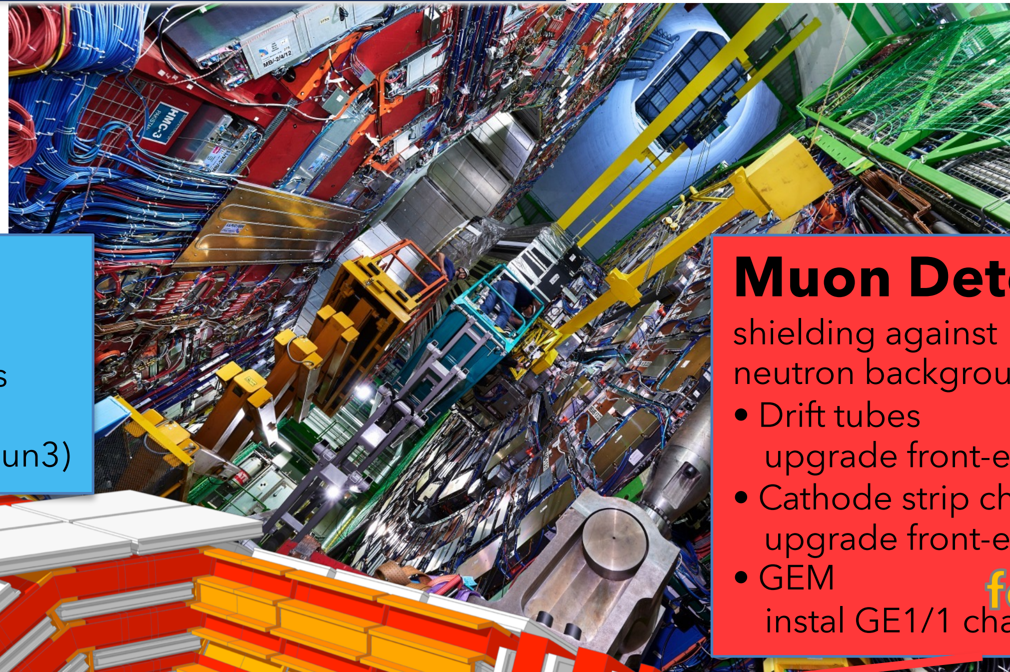




see Nancy Marinelli's talk

preparing for LHC Run3

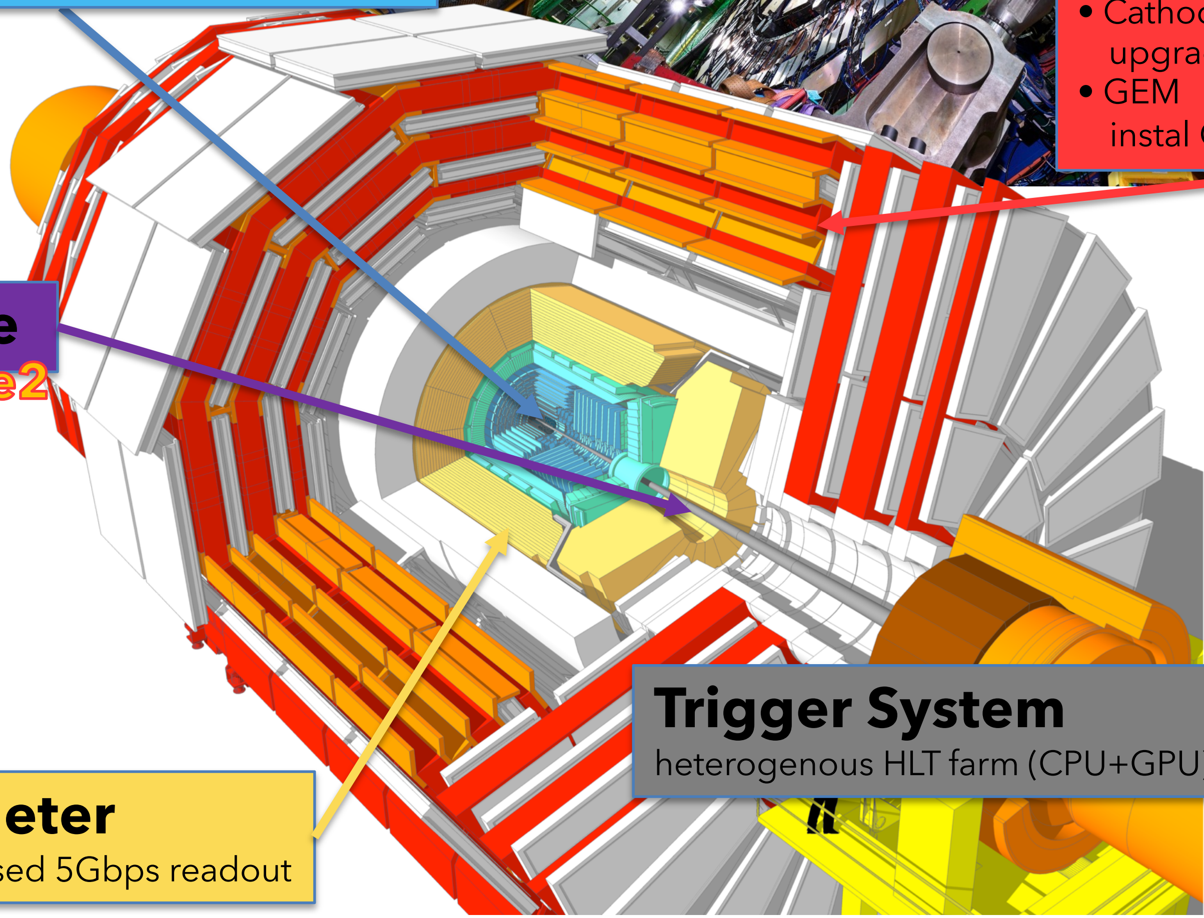
"Phase-1" upgrades of CMS
majority of the upgrades
have been done in the past years



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

for phase2



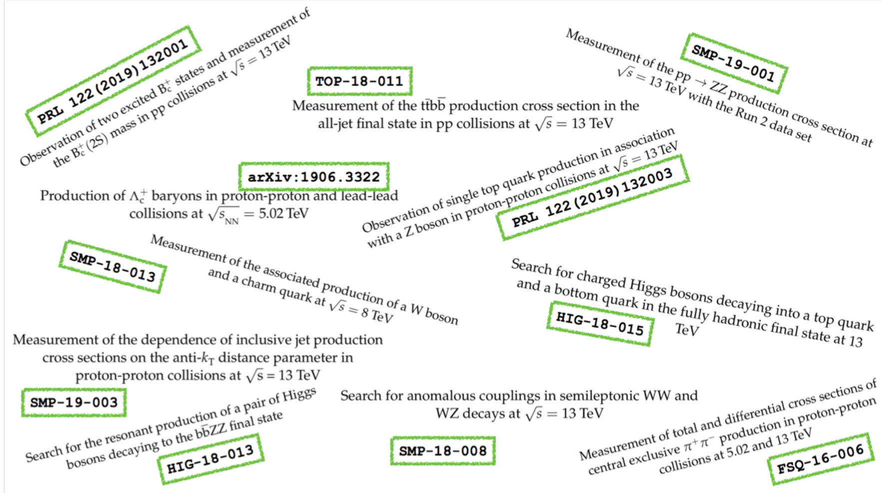
new beampipe
for phase2

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!

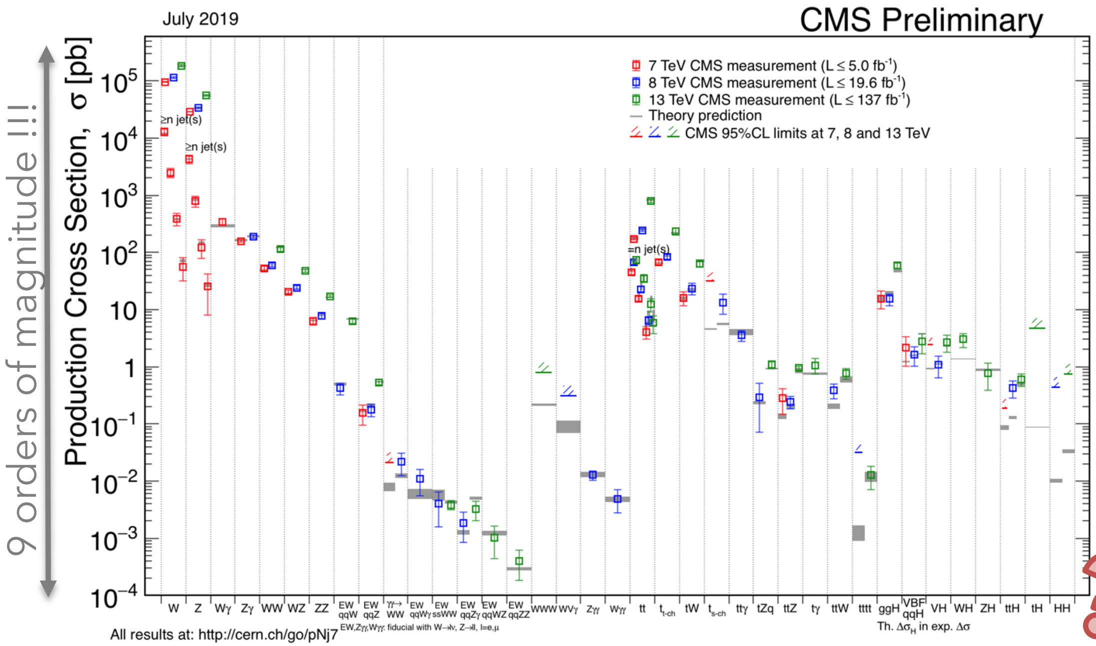


- **efficient technical program for the future**
  - completing Phase-1 upgrades
  - preparing for Run 3 (and in view of HL-LHC)

- 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



- 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

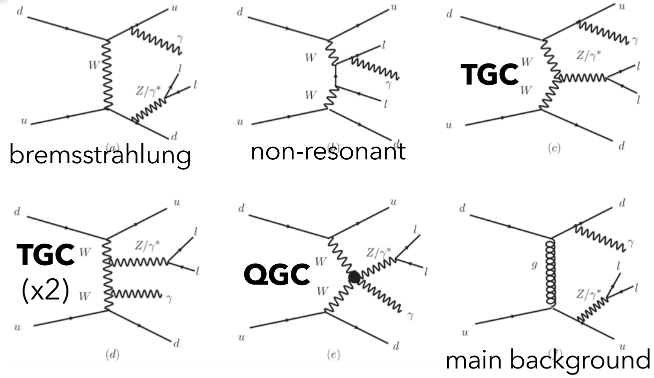
    the precision era in the gauge sector is starting

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

BACKUP

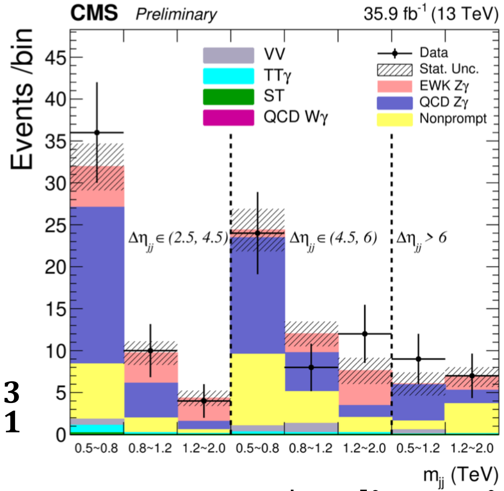
Vector Boson Scattering (VBS)

Vector Boson Scattering directly probes EWK SM gauge structure

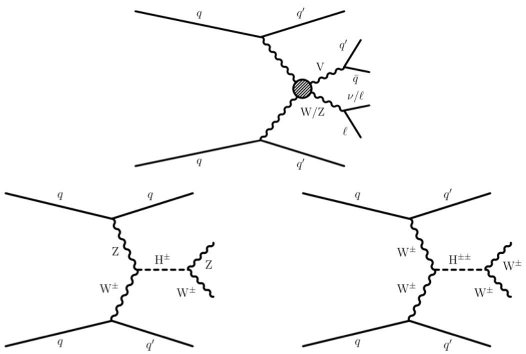


- **$Z\gamma$** production **w/ 2 jets**
  - signal extracted from 2D fit in different regions to properties of the djiet system: m_{jj} and $\Delta\eta_{jj}$
  - significance : **3.9 (5.2) σ**
    [4.7 (5.5) σ combining w/ 8 TeV analysis]
  - fiducial signal strengh $\boldsymbol{\mu_{EW} = 0.64^{+0.23}_{-0.21}}$
  - using the $m_{Z\gamma}$ distribution,
    most stringent limits to date on 2 aQGC parameters in the **dimension-8 (8D) EFT** : $F_{T,8}/\Lambda^4$ and $F_{T,9}/\Lambda^4$

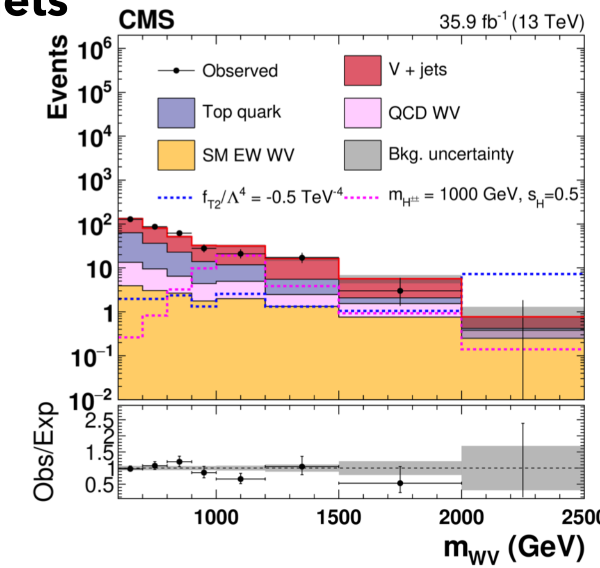
SMP-18-007

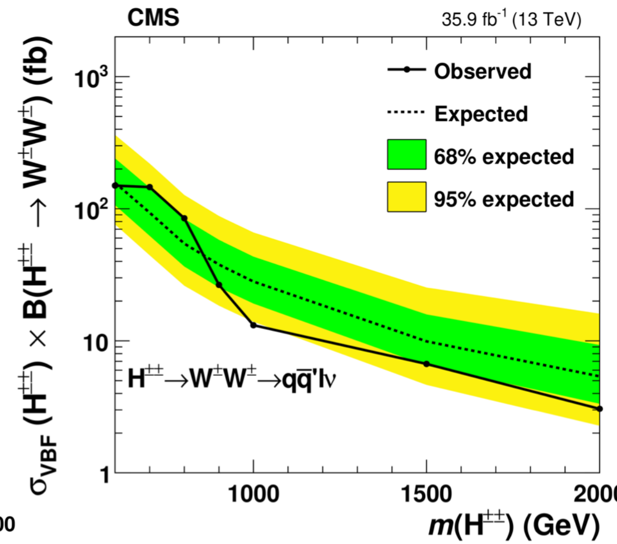


- **anomalous EW VV** production **w/ 2 jets**
  - using the WW, WZ, and ZZ channels
  - interpretation in the 8D EFT or as limits on $H^{\pm(\pm)}$ production



arXiv:1905.07445



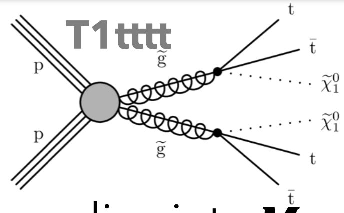


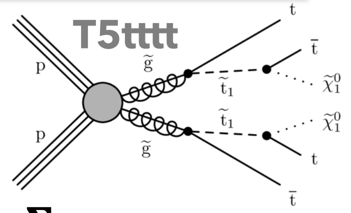
see Vitaliano Ciulli's talk

search for SUSY 1 lepton final state

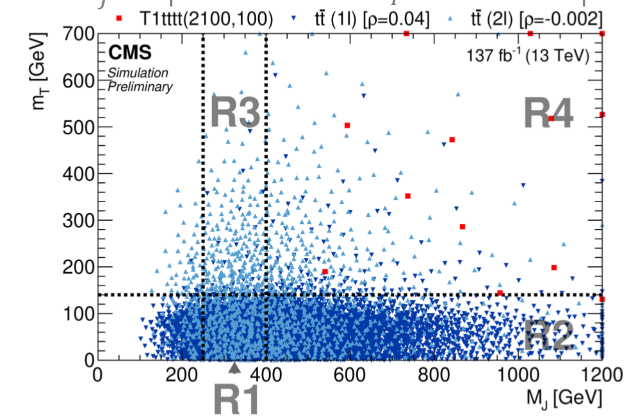
- **inclusive** search for strong SUSY production in final states w/ **MET**, **b-jets**, and **a lepton**
  - signal region divided in bins characterized by # jets, the # b-jets, p_T^{miss}, and the sum of the masses of large-radius jets $M_J \coloneqq \Sigma_{J_i} m_{J_i}$
- background yields from control regions
- no significant excess compared to SM

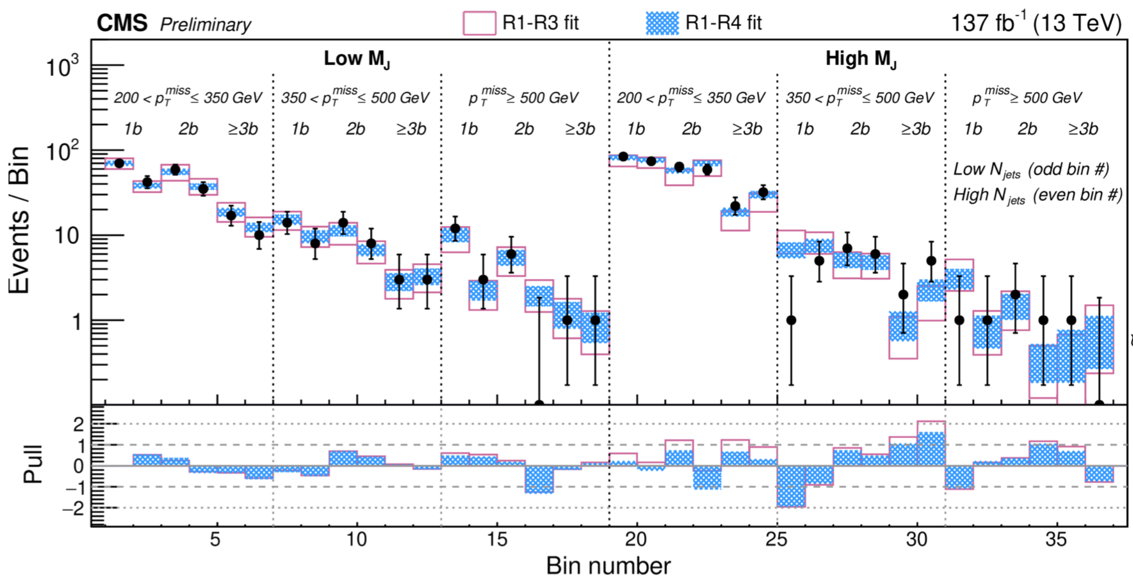
$\Longrightarrow$ gluino masses up to about 2150 GeV are excluded @ 95% CL for neutralino masses up to 700 GeV
highest excluded neutralino mass is about 1250 GeV

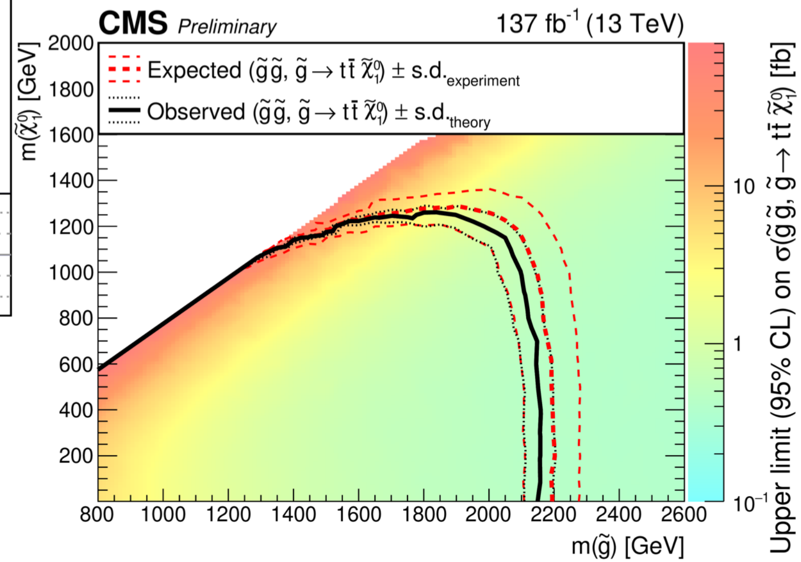




M_J is nearly uncorrelated to m_T
$\Rightarrow$ M_J background shape at high-m_T measured from M_J shape in the low-m_T control sample

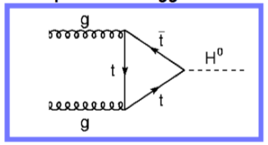




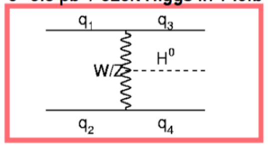


Higgs boson production and decay

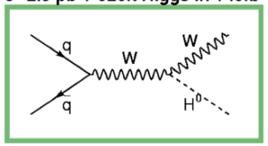
σ=49 pb / 6.9M Higgs in 140fb^{-1}



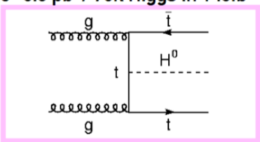
σ=3.8 pb / 520k Higgs in 140fb^{-1}

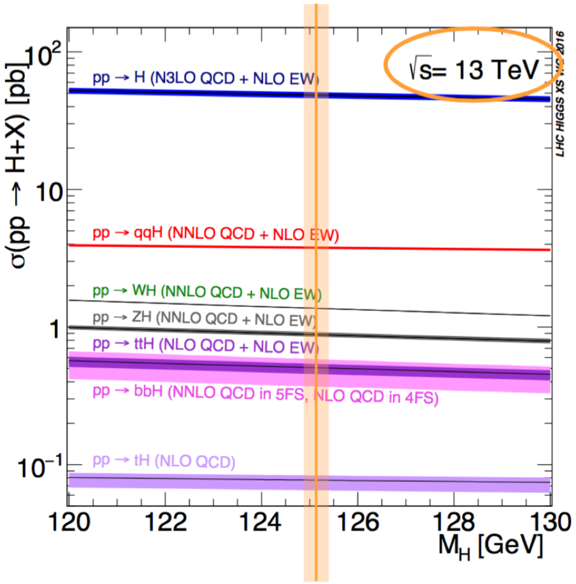


σ=2.3 pb / 320k Higgs in 140fb^{-1}

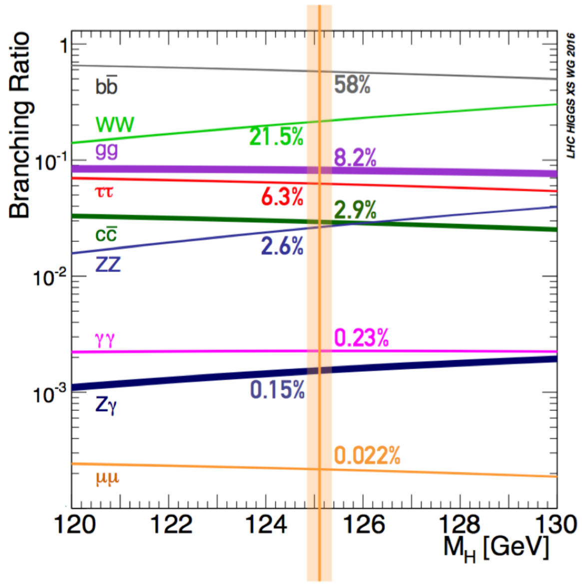


σ=0.5 pb / 70k Higgs in 140fb^{-1}





125.09 ± 0.24 GeV
LHC Run1 measurement



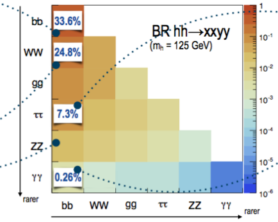
125.09 ± 0.24 GeV
LHC Run1 measurement

	ggH	VBF	VH	ttH
H→ZZ	HIG-19-001 (Run2)			
H→$\gamma\gamma$	HIG-18-029 ('16+'17)		HIG-16-040 ('16)	HIG-18-018 ('16+'17)
H→WW	HIG-16-042 ('16)			HIG-18-019 ('16+'17)
H→$\tau\tau$	HIG-18-032 ('16+'17)		HIG-18-007 ('16)	
H→bb	HIG-16-044 ('16)		HIG-18-016 ('16+'17)	HIG-18-030 ('16+'17)
H→$\mu\mu$	HIG-17-019 ('16)			
H→cc			HIG-18-031 ('16)	
H→inv	HIG-17-023 ('16)			

non-resonant HH

bbbb
largest BR, large QCD and $t\bar{t}$ contamination
(non-res) JHEP04 (2019) 112 NEW! JHEP01 (2019) 040 NEW!
(res) JHEP08 (2018) 152 NEW! PLB 781 (2018) 244

bbVV
large $t\bar{t}$ contamination, $BR(2\ell 2\nu) = 2.7\%$
JHEP 01 (2018) 054



$bb\tau\tau$
good compromise between BR and purity
PLB 778 (2018) 101

$bb\gamma\gamma$
low branching ratio, high purity
PLB 788 (2019) 7 NEW!

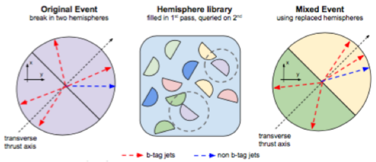
HH→bbbb (non-resonant)

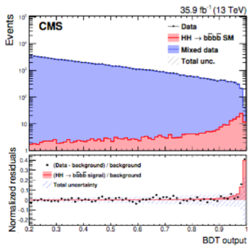
NEW! JHEP04 (2019) 112
NEW! JHEP01 (2019) 040

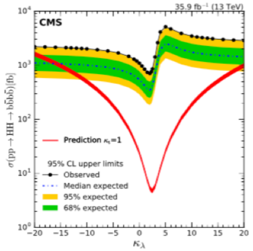
Two searches performed:
- 4 resolved b-tagged jets (best sensitivity to SM), results shown here
- one bb pair highly boosted (sensitive to specific BSM topologies)

Main challenge: QCD background contamination

- BDT technique optimised for SM HH signal
- Dedicated data-driven method: hemisphere mixing
  - Provide input for the BDT training
  - Predict the background BDT shape
- b-tag is crucial, used from trigger level (3 bjets)
- Signal extraction from BDT output







Limits

SM obs (exp): 75 (37)$\times\sigma_{SM}$

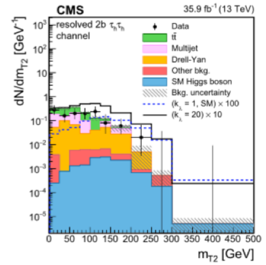
$k_\lambda = \lambda/\lambda_{SM}$ ($k_t = 1$) scan: no exclusion

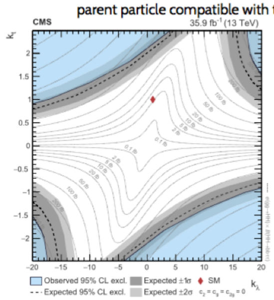
HH→bbττ

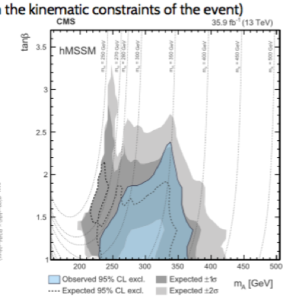
PLB 778 (2018) 101

Comprehensive set of results on resonant and non-resonant searches

- Final states: ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) + 2 jets
- Categorisation on number (1/2) of b-tagged jets
  - Boosted category: only 1 b-tagged large-area jet + substructure requirements
- BDT technique to reject tt background in $e\tau_h$, $\mu\tau_h$ channels
- Signal extraction from kinematic variables:
  - Resonant search: kinematic fit of HH decay (fit based on 4-momenta of the τ and b candidates and on $\vec{p}_T^{miss}$)
  - Non-resonant search: "stransverse mass" MT2 (largest mass of the parent particle compatible with the kinematic constraints of the event)







Limits

SM obs (exp): 31 (25)$\times\sigma_{SM}$

k_λ-k_t scan performed

Additional hMSSM interpretation

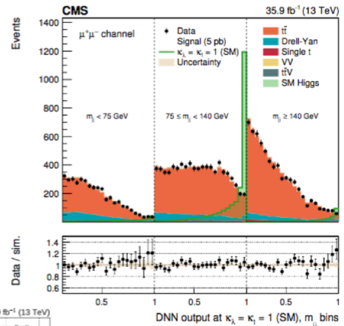
No exclusion on Radion nor Graviton mass

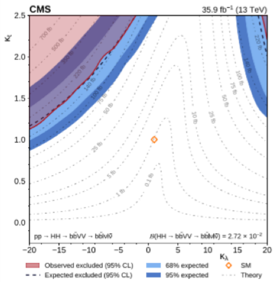
HH→bbVV

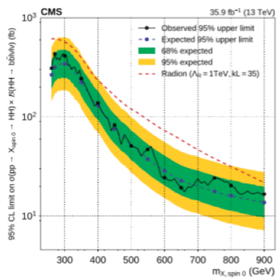
JHEP 01 (2018) 054

Resonant and non-resonant searches performed

- Event categories: bbee, bbμμ, bbeμ
- Dominant backgrounds: tt (irreducible), DY
  - Data-driven DY estimation
- DNN to improve signal-background separation
  - Output used as final discriminant







Limits

SM obs (exp): 79 (89)$\times\sigma_{SM}$

k_λ-k_t scan performed

No exclusion on Radion nor Graviton mass

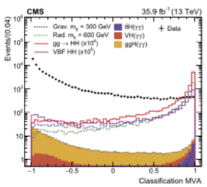
HH→bbγγ

NEW! PLB 788 (2019) 7

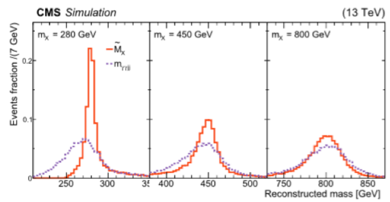
Resonant and non-resonant searches performed: most sensitive channel to SM HH

- Main backgrounds: nγ+jets, single-H
- Categorisation in MVA and reduced mass:

$M_X = m_{\gamma\gamma bb} - (m_{bb} - m_H) - (m_{\gamma\gamma} - m_H)$

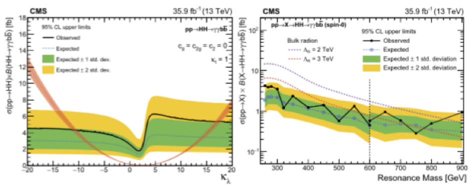


- MVA to efficiently discriminate against nγ+jets
- Striking improvement at low mass using M_X



Signal extraction through 2D likelihood $m_{\gamma\gamma} \times m_{bb}$

- 10% improvement w.r.t. 1D fit on $m_{\gamma\gamma}$: better discrimination against single-H



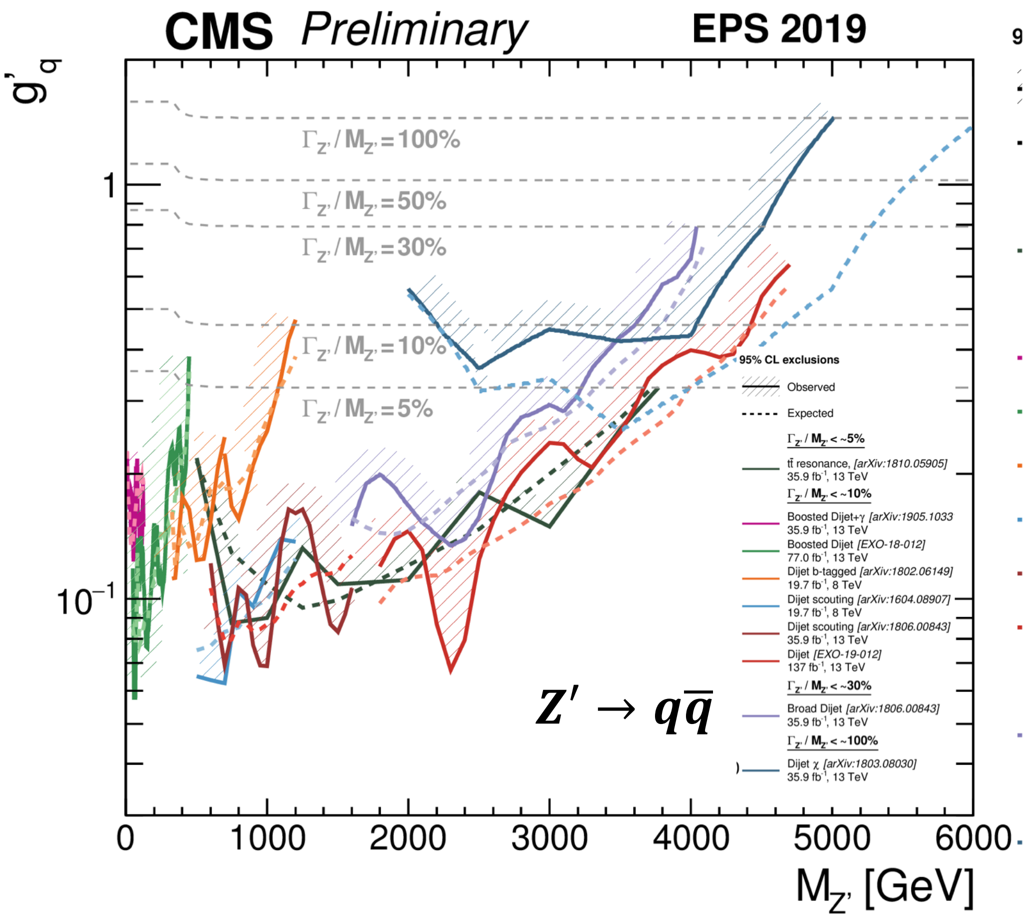
Limits

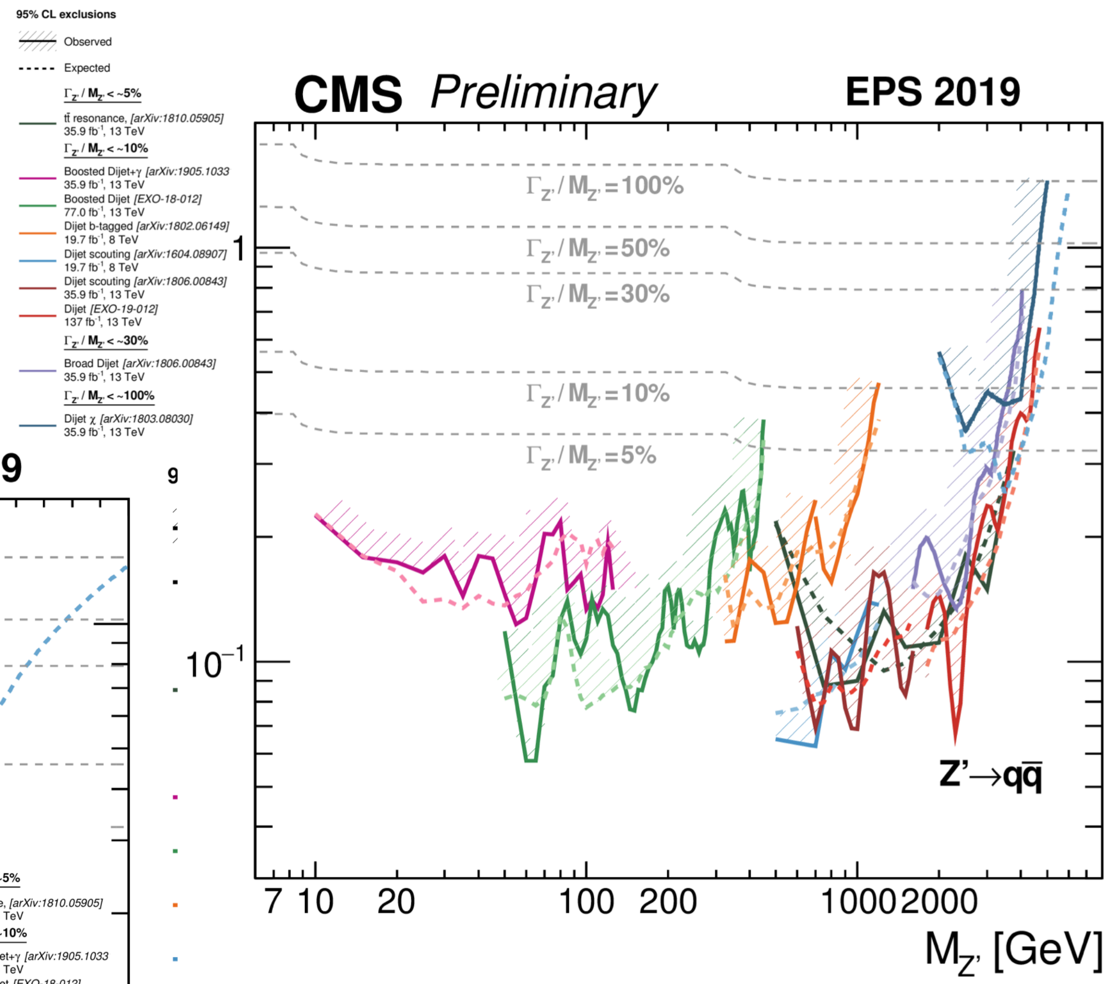
SM obs (exp): 24 (19)$\times\sigma_{SM}$
(VBF HH signal inclusion improves sensitivity by 1.3%)

Constrained λ to $-11 < k_\lambda < 17$

Radion (Λ_R = 3 TeV): excluded $m_X < 540$ GeV
Graviton: excluded $290 < m_X < 810$ GeV (backup)

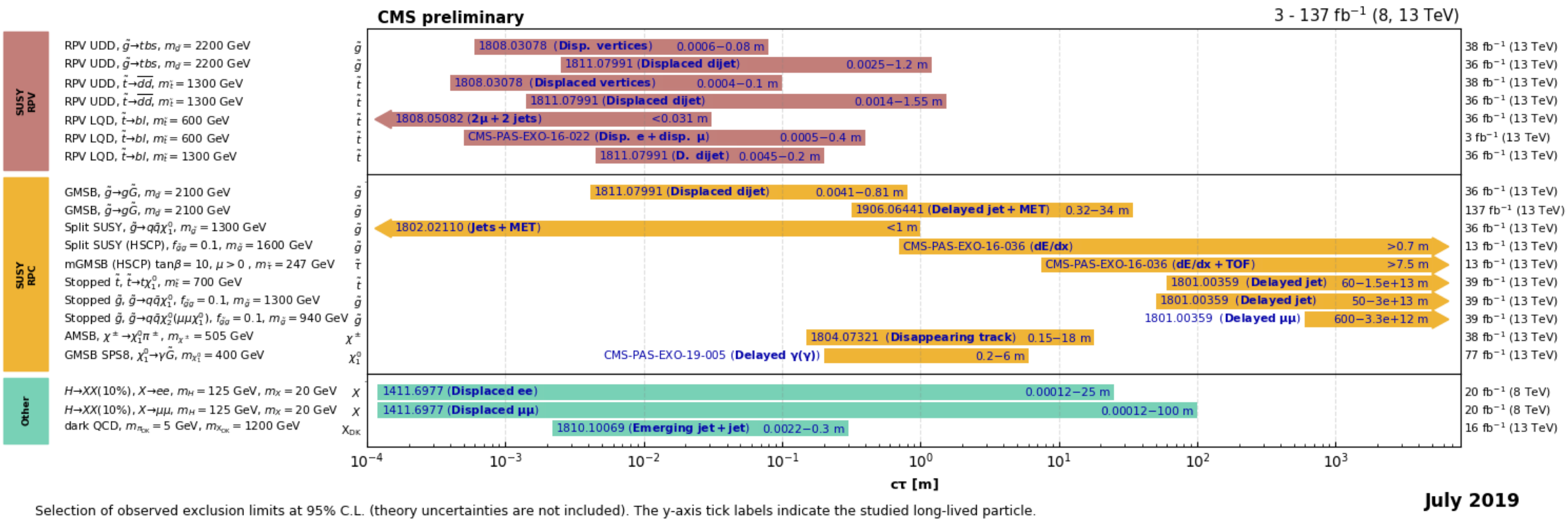
dijet summary plots





long lived particles

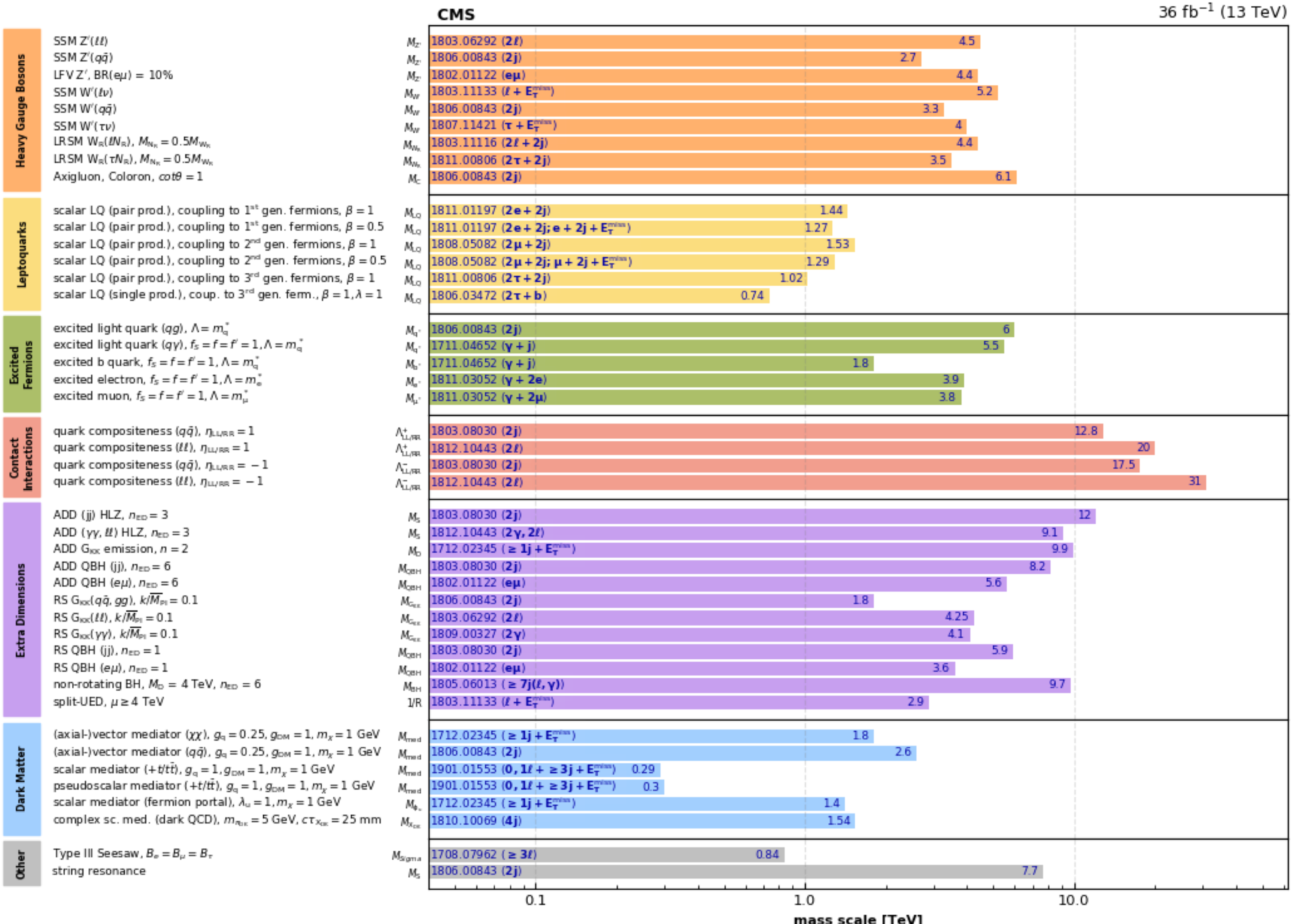
Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

CMS EXO results

Overview of CMS EXO results



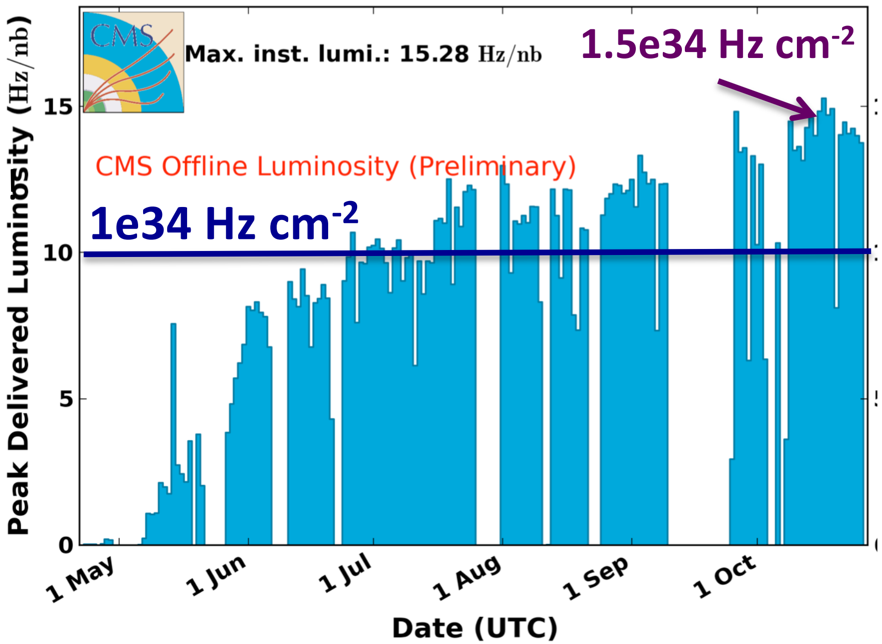
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

trigger in run2

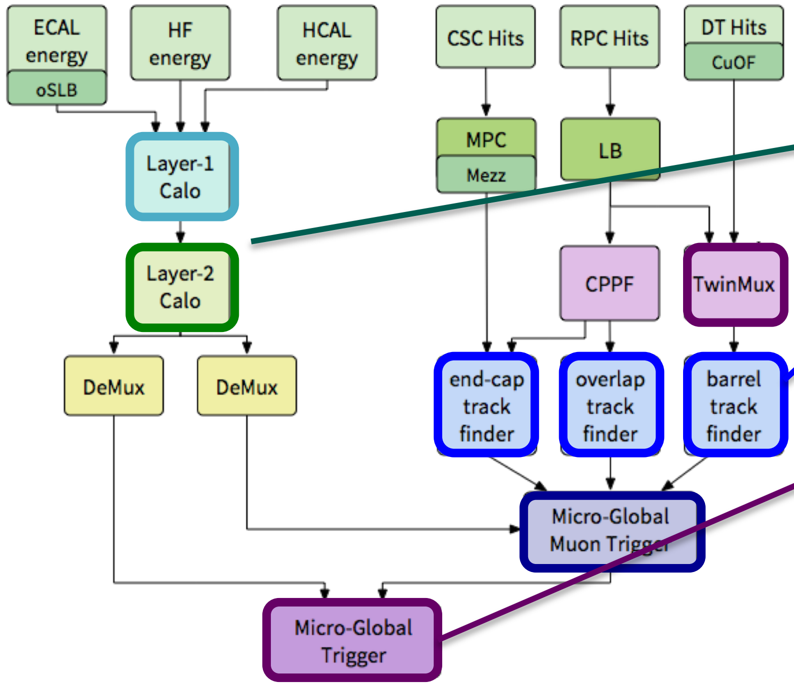
very, very busy years !

- after LS1, LHC achieved very high luminosity
  peak lumi (in both 2016 and 2017!): **1.5e34 Hz cm^{-2} → PU~50**
  exp. peak lumi in 2017: **2e34 Hz cm^{-2} → PU~60** !
- very high LHC duty cycle

➡ in order to **maintain** and **improve performance** while **keeping** the **rate under control**
[avoiding a significant increase in trigger thresholds]



- 2016 → **Phase I L1 Trigger Upgrade**

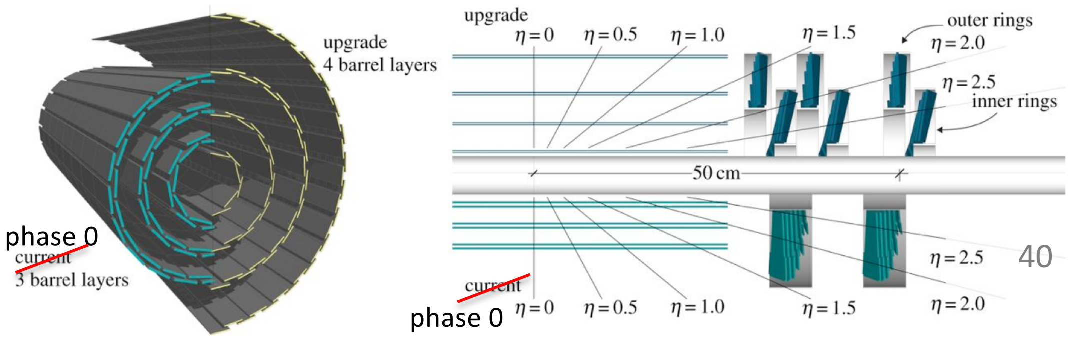


tower-level precision and pileup subtraction

integrated track-finding
with more sophisticated p_T measurement

allows to define
- 512 bits ;)
- more advanced operations
  (deltaR, di-object mass, deltaBX, …)

- 2017 → **Phase I detectors Upgrade**
  - ✓ new PIXEL detector → **Rachel Bartek's talk**
  - ✓ new HCAL readout
  - ✓ x1.2 HLT farm

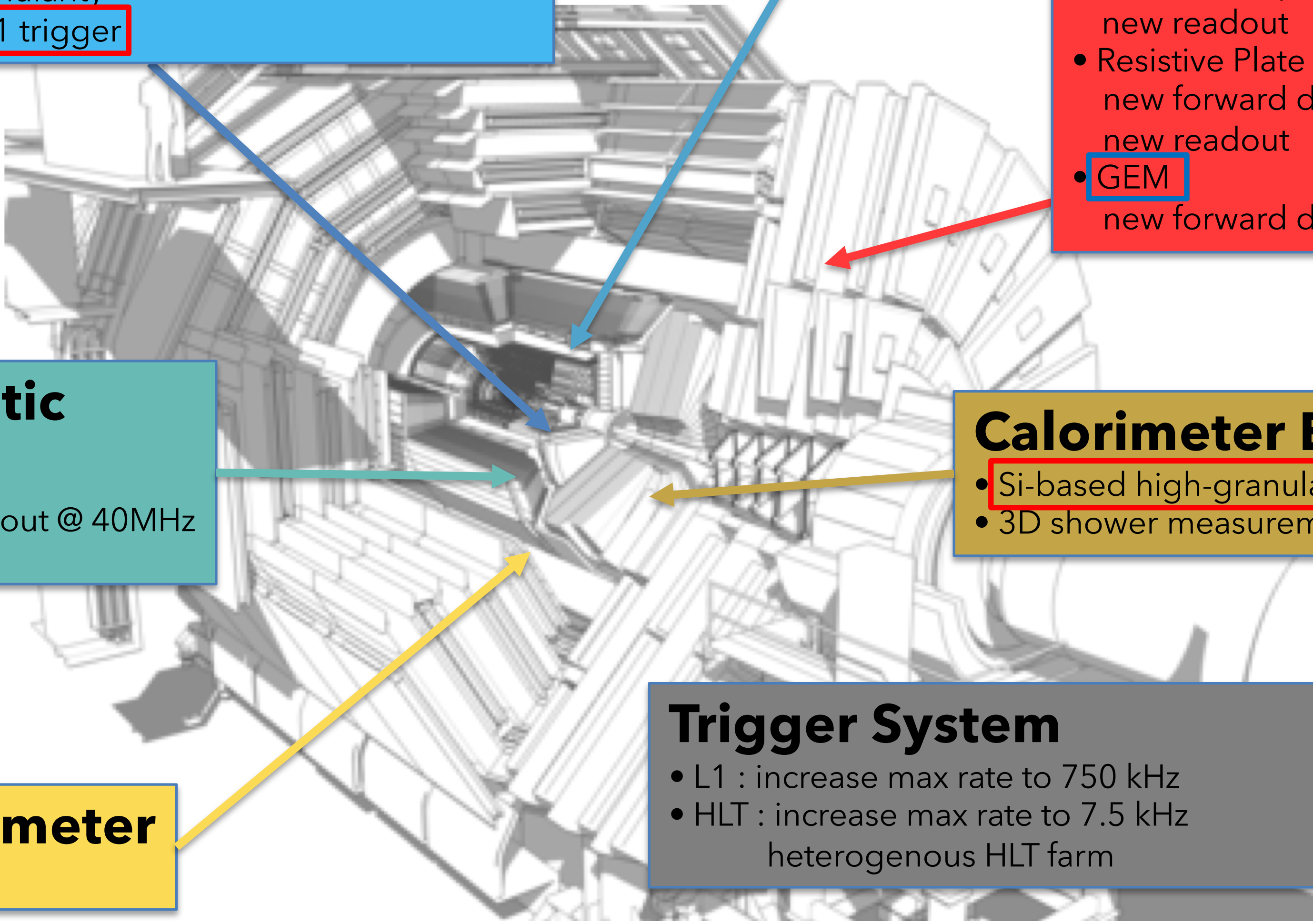


upgrade for HL-LHC

MIP timing detector
- precision timing (30 ps) for barrel & endcap

Silicon Tracker
- InnerTracker (Pixel-only)
  extension to $|\eta| = 4.0$
- OuterTracker (mixture of pixels and strips)
  - increase granularity
  - tracking @ L1 trigger

Muon Detectors
extended coverage to $|\eta| = 3.0$
- Drift tubes
  new readout
- Cathode strip chambers
  new readout
- Resistive Plate Chamber
  new forward detectors
  new readout
- GEM
  new forward detector



Electromagnetic Calorimeter
- crystal-granularity readout @ 40MHz
- new backend boards

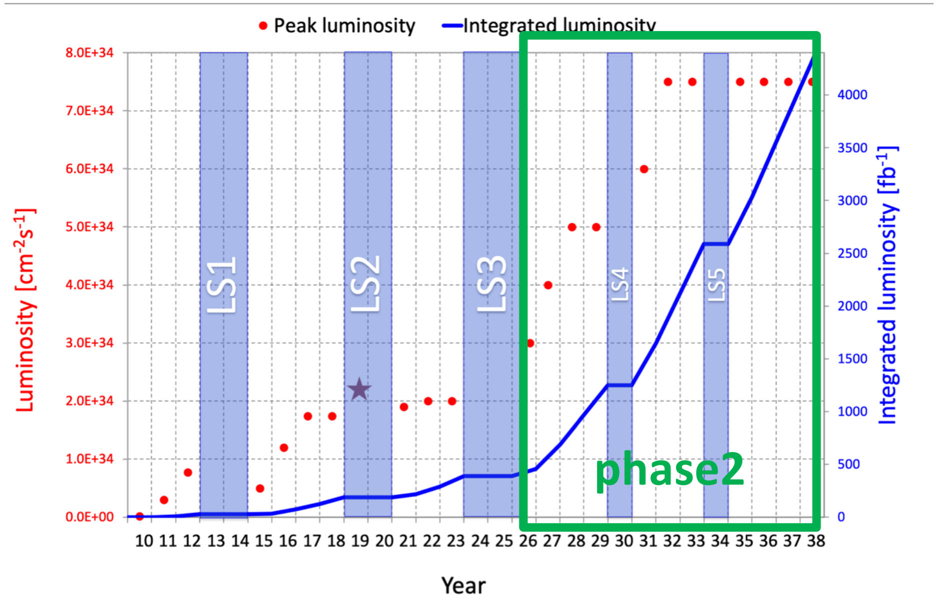
Calorimeter Endcaps
- Si-based high-granularity calorimeter
- 3D shower measurement + timing

Trigger System
- L1 : increase max rate to 750 kHz
- HLT : increase max rate to 7.5 kHz
  heterogenous HLT farm

Hadron Calorimeter
new backend boards

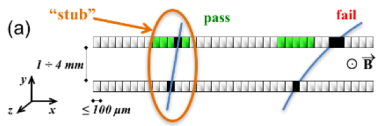
plans : phase2

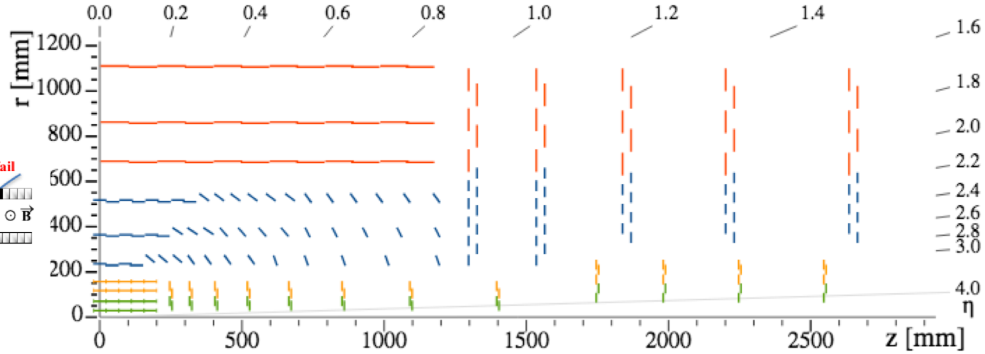
- present tracker designed for
  an integrated lumi of 500/fb and <PU> ~ 30-50

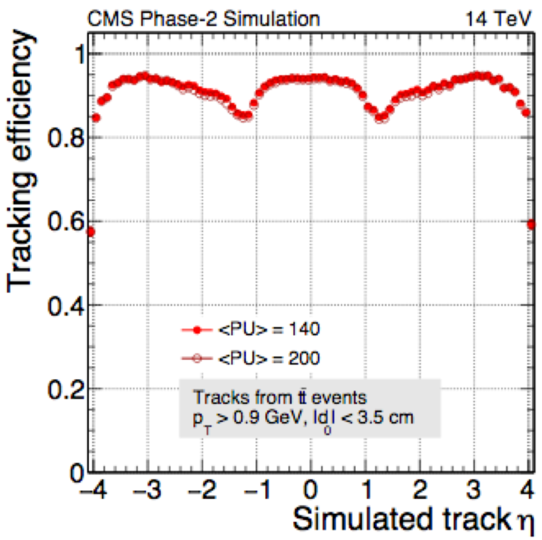


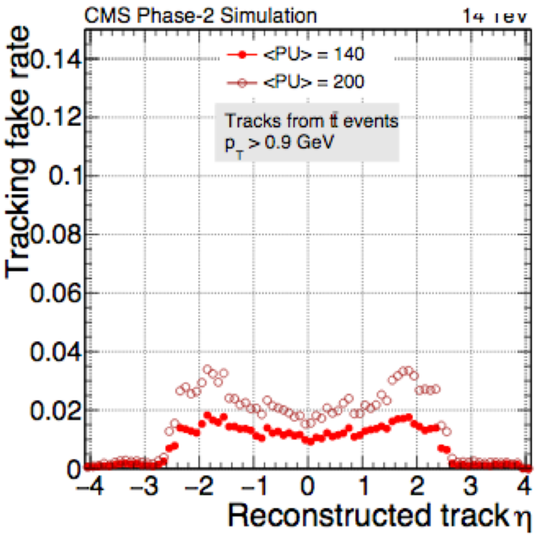
Requirements for Phase2

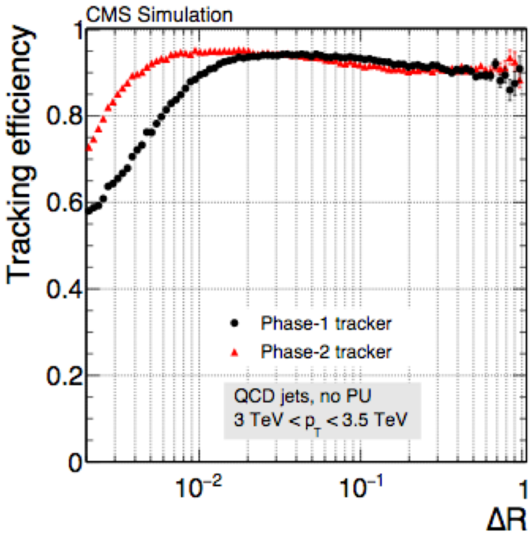
- High radiation tolerance to operate efficiently
  up to 3000/fb
- increased granularity to maintain channel occupancy around or below the % level
- reduced material in the tracking volume
- contribution to the Level-1 trigger
- extended tracking acceptance
- robust pattern recognition





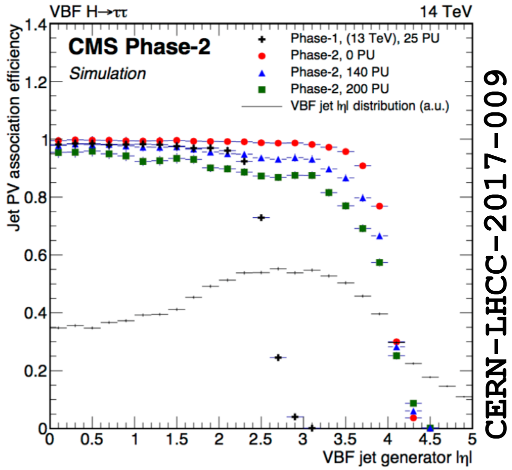




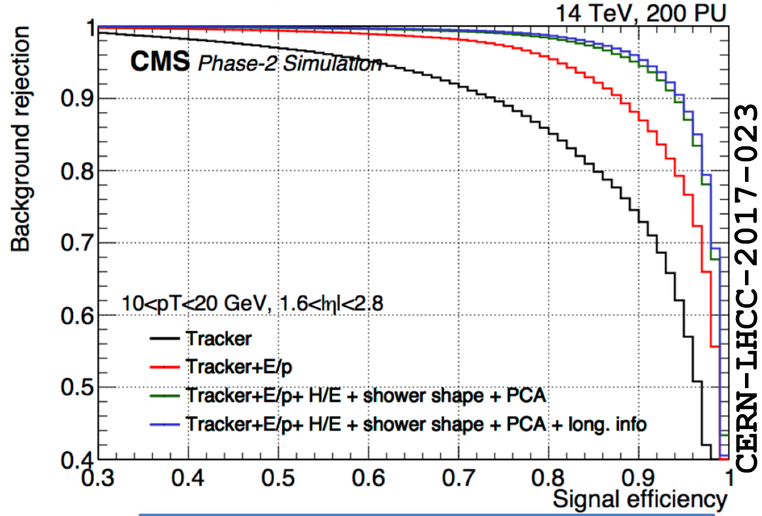


Step Name	Seeding	Target Tracks
HighPtQuad	pixel quadruplets	prompt, high p_T
HighPtTriplet	pixel triplets	prompt, high p_T, recovery
LowPtQuad	pixel quadruplets	prompt, low p_T
LowPtTriplet	pixel triplets	prompt, low p_T, recovery
DetachedQuad	pixel quadruplets	displaced
PixelPair	pixel pairs	high p_T, recovery
Muon Inside-Out	muon-tagged tracks	muon
Muon Outside-In	muon-tagged tracks	muon

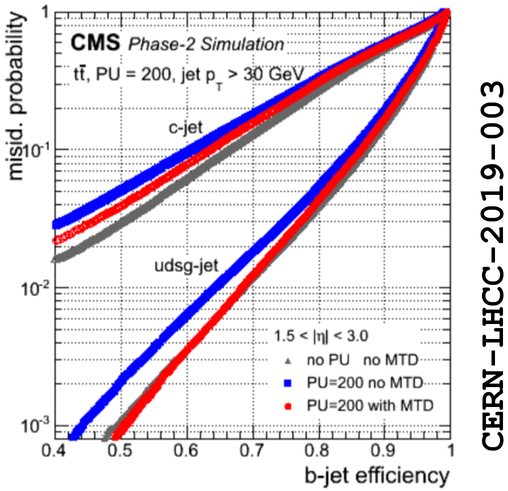
benefits: some examples



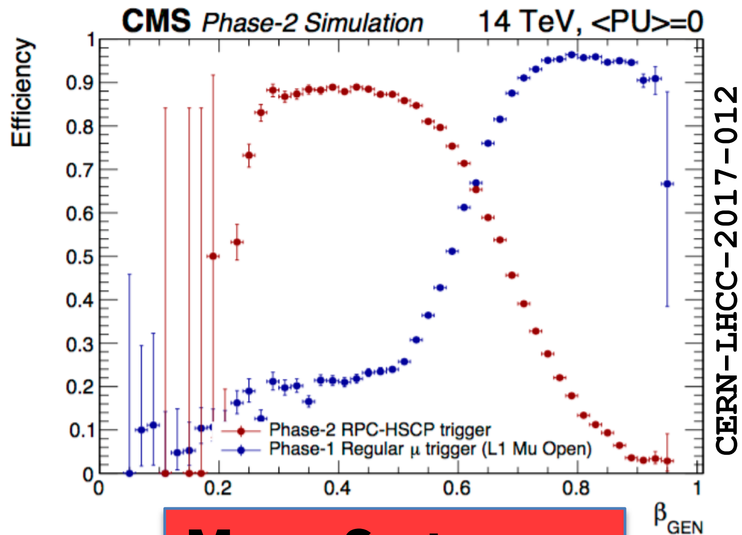
Silicon Tracker
increased granularity and extension improves the signal acceptance



Calorimeter Endcaps
fine segmentation provides powerful discriminating variables for e-ID



MIP timing detector
improved efficiency of the isolation selection for leptons

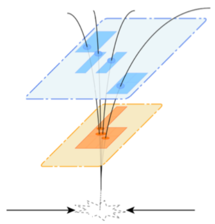


Muon System
L1 trigger on delayed signals with upgraded RPC readout

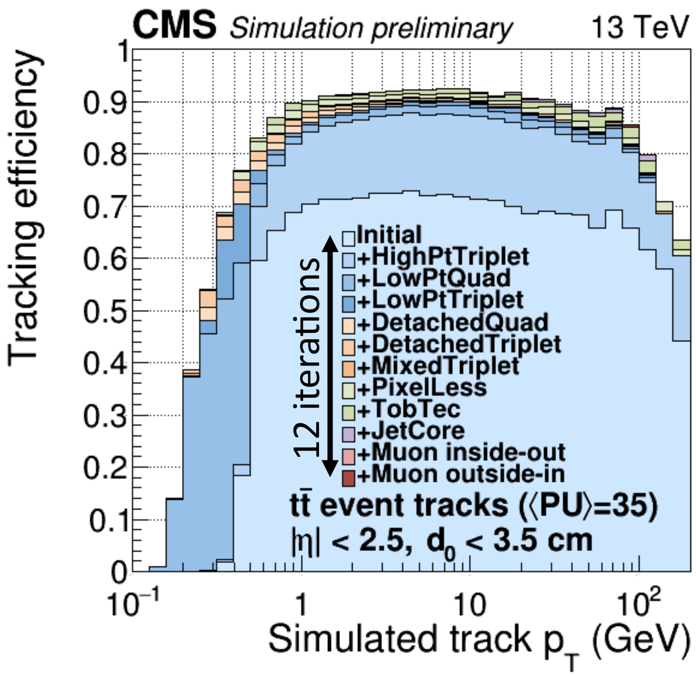
Iterative Tracking in CMS

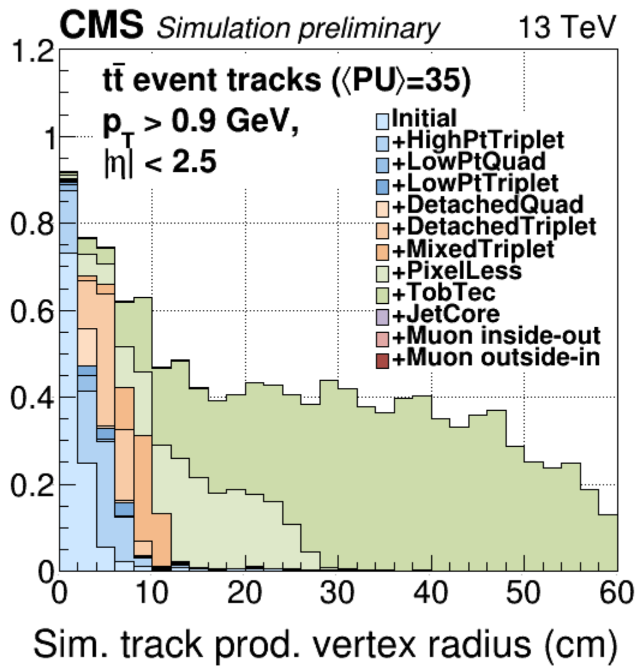
tracks reconstruction is an **iterative procedure**:

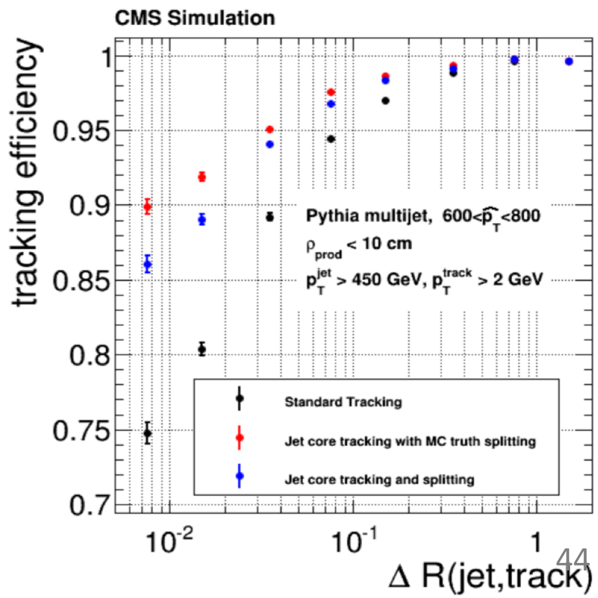
- the *InitialStep* makes use of high-p_T quadruplets coming from the beam spot region
- subsequent steps use triplets, or improve the acceptance either in p_T or in displacement
- the later steps use seeds w/ hits from the strip detector to find detached tracks,
- final steps are dedicated to special phase-space
  - highly dense environment (i.e. w/in jets)
  - clean environment (i.e. muons)



Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- recovery
MixedTriplet	pixel+strip triplets	displaced-
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high-p_T jets
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon







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