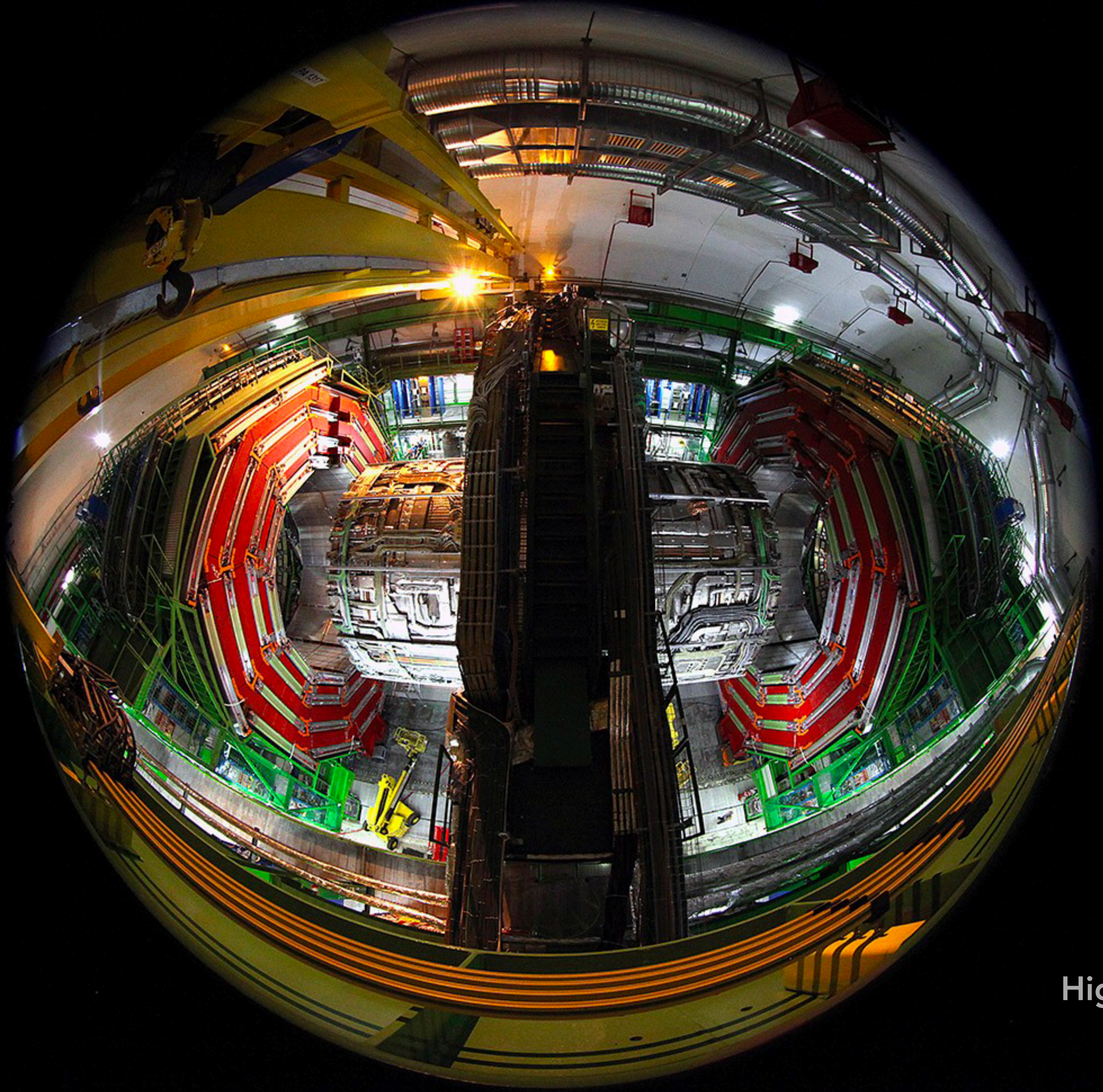


Status and highlights from the CMS experiment

Gautier Hamel de Monchenault
on behalf of the Collaboration

HEP 2022 — Conference on Recent Developments in **High Energy Physics and Cosmology**
Thessaloniki, Greece
June 2022

CEA - Saclay

The CMS Collaboration

2280 Authors

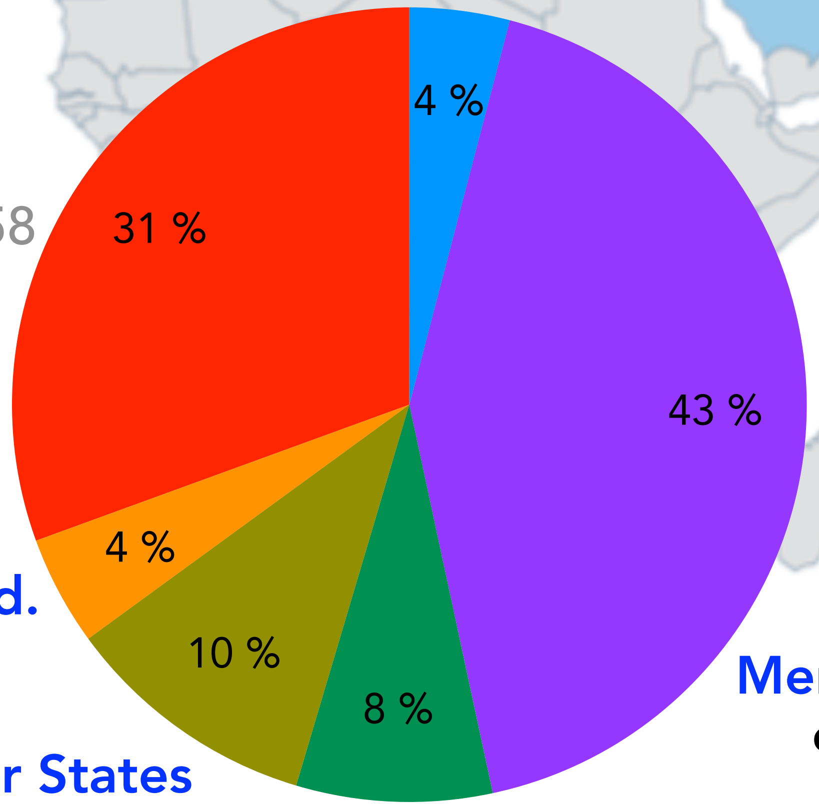
>5500 Members

210 Member Institutes

+ 8 Cooperating
and 23 Associated Institutes

from

55 countries or regions



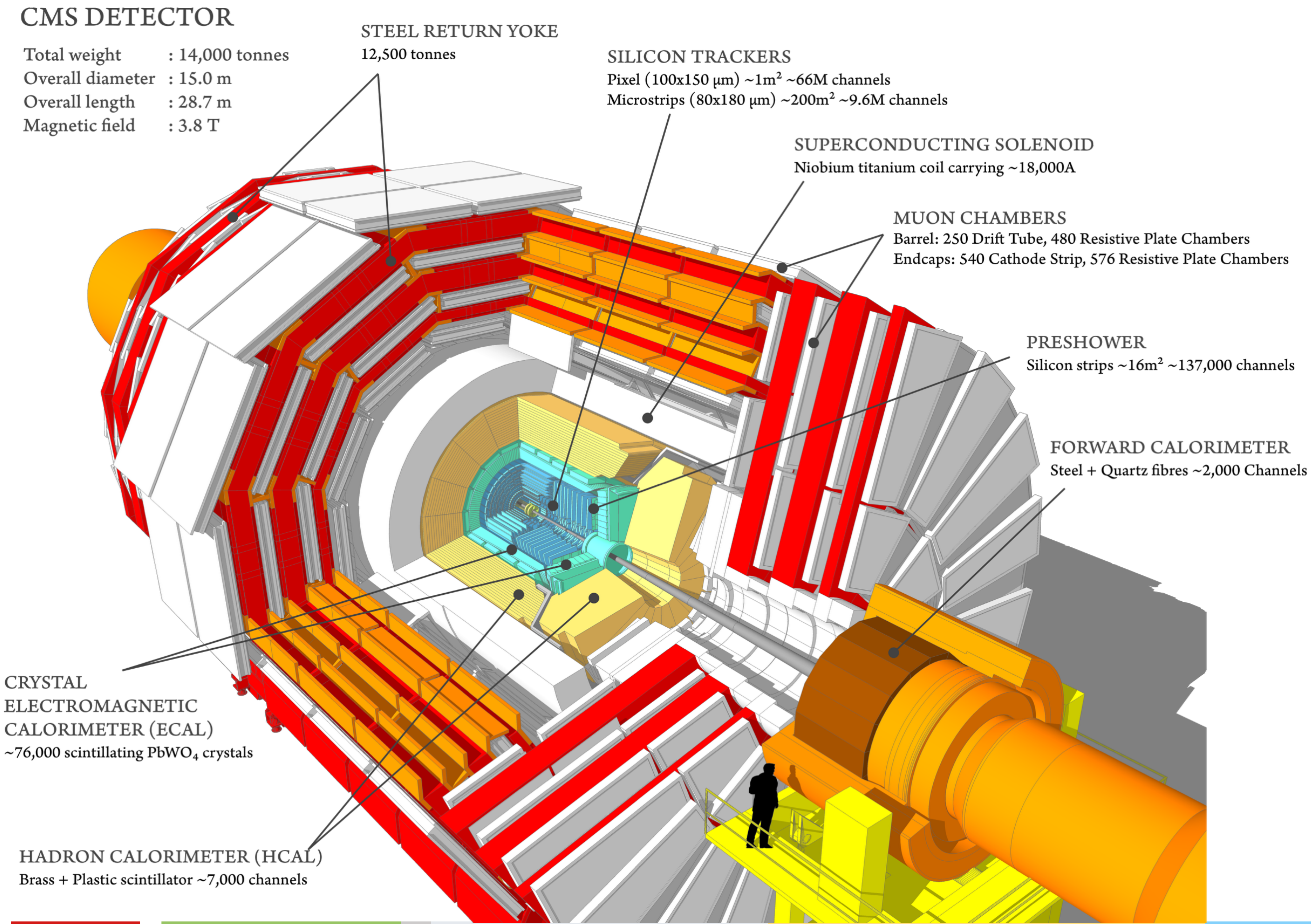
Greece: 32 authors, 62 members
- **Athens** (8/29) L1-trigger, PPD, …
- **Athens/NTUA** (6/9) DAQ, HGCAL, …
- **Demokritos** (6/10) Tracker, …
- **Ioànnina** (12/14) L1-trigger, …

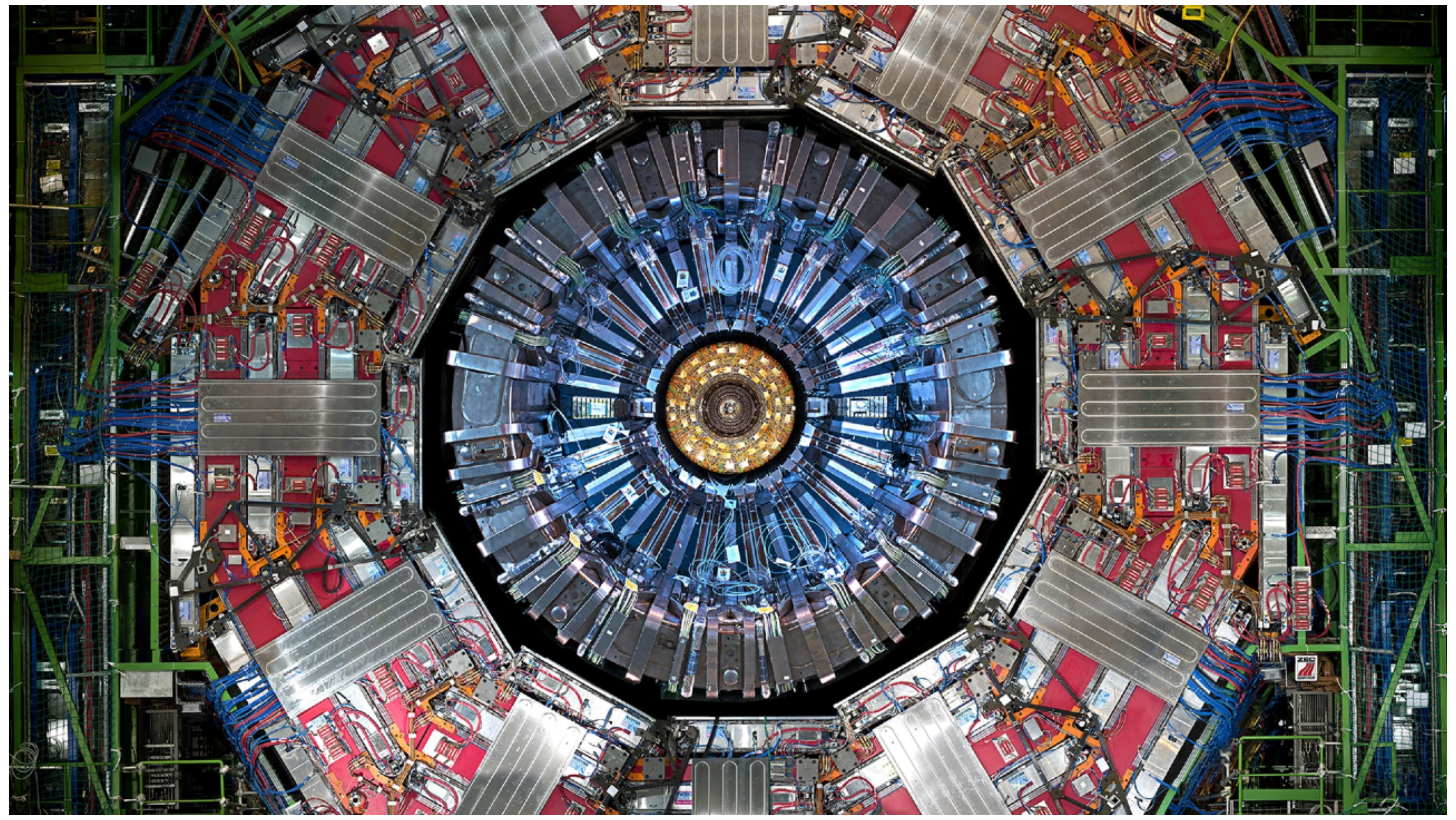
MS: **Italy** (12%), **Germany** (8%), UK (3%), France (3%), Switzerland (3%), Spain (3%), Belgium (3%) … **Greece (1.5%)** …
AS: India (3%), Turkey (2%) …
OS: **Russia** (4%), Korea (3%), China (2%), Brazil (1.5%) …

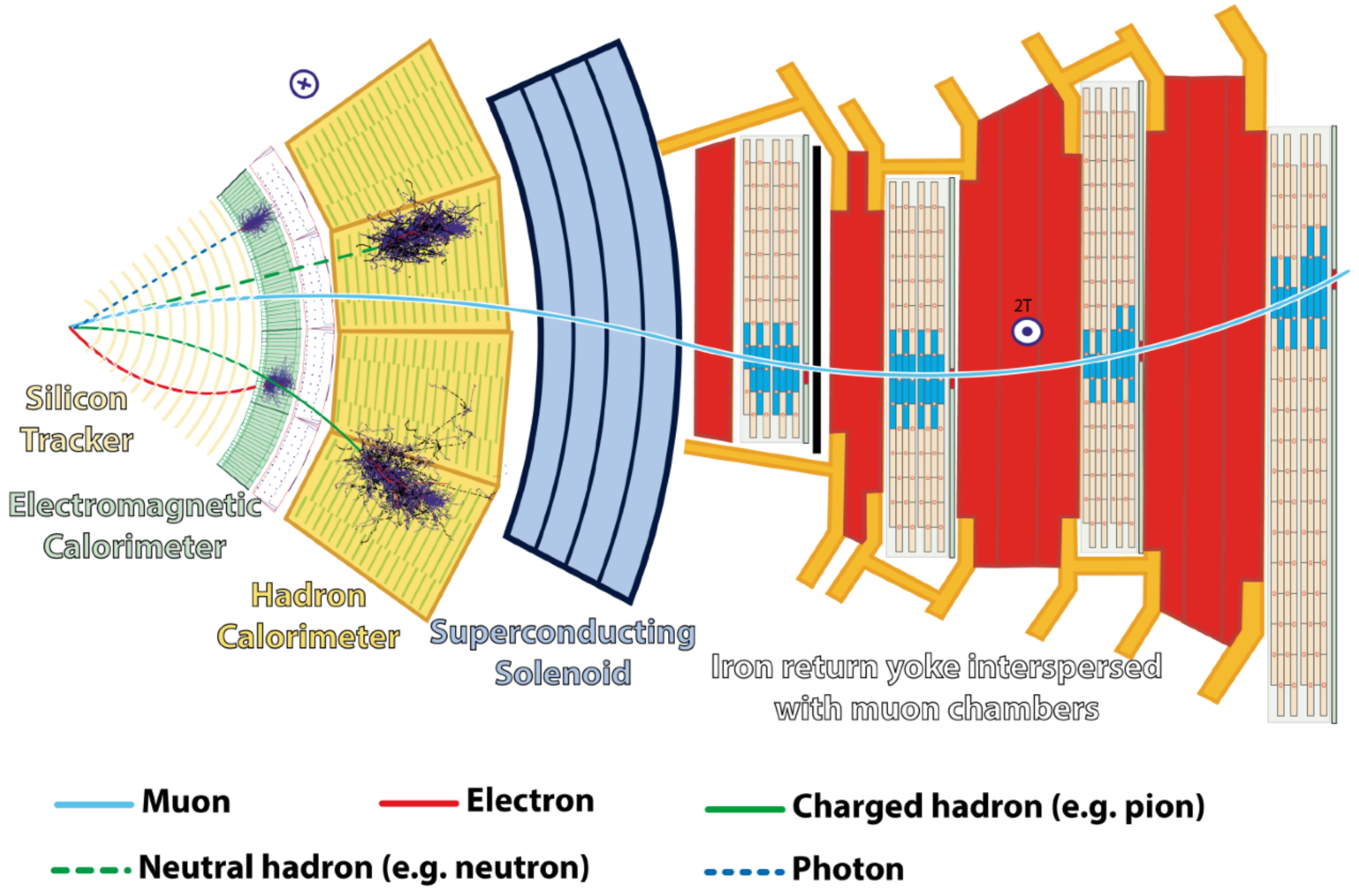
(04/2022)

The CMS Detector

General-purpose LHC detector

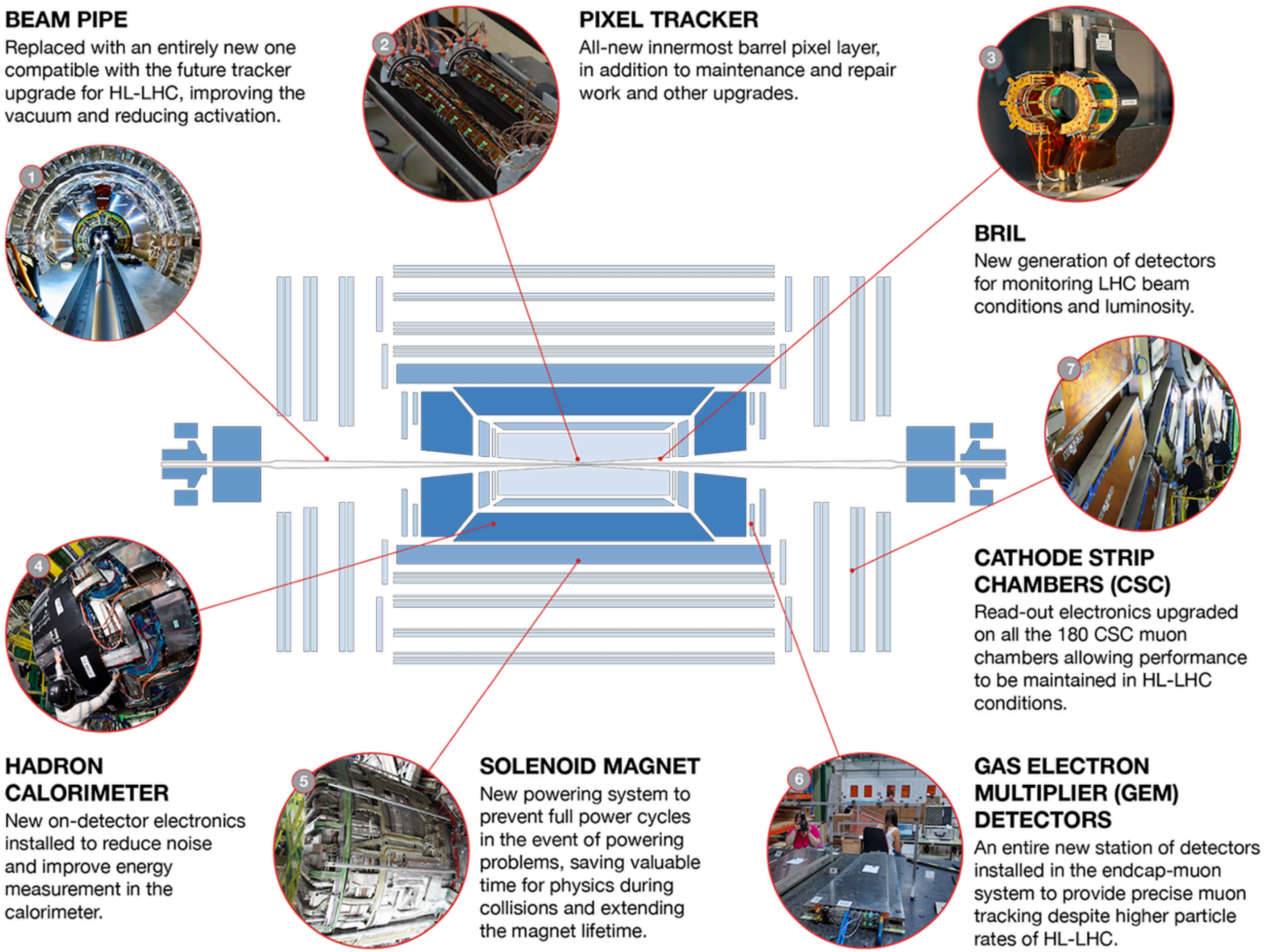


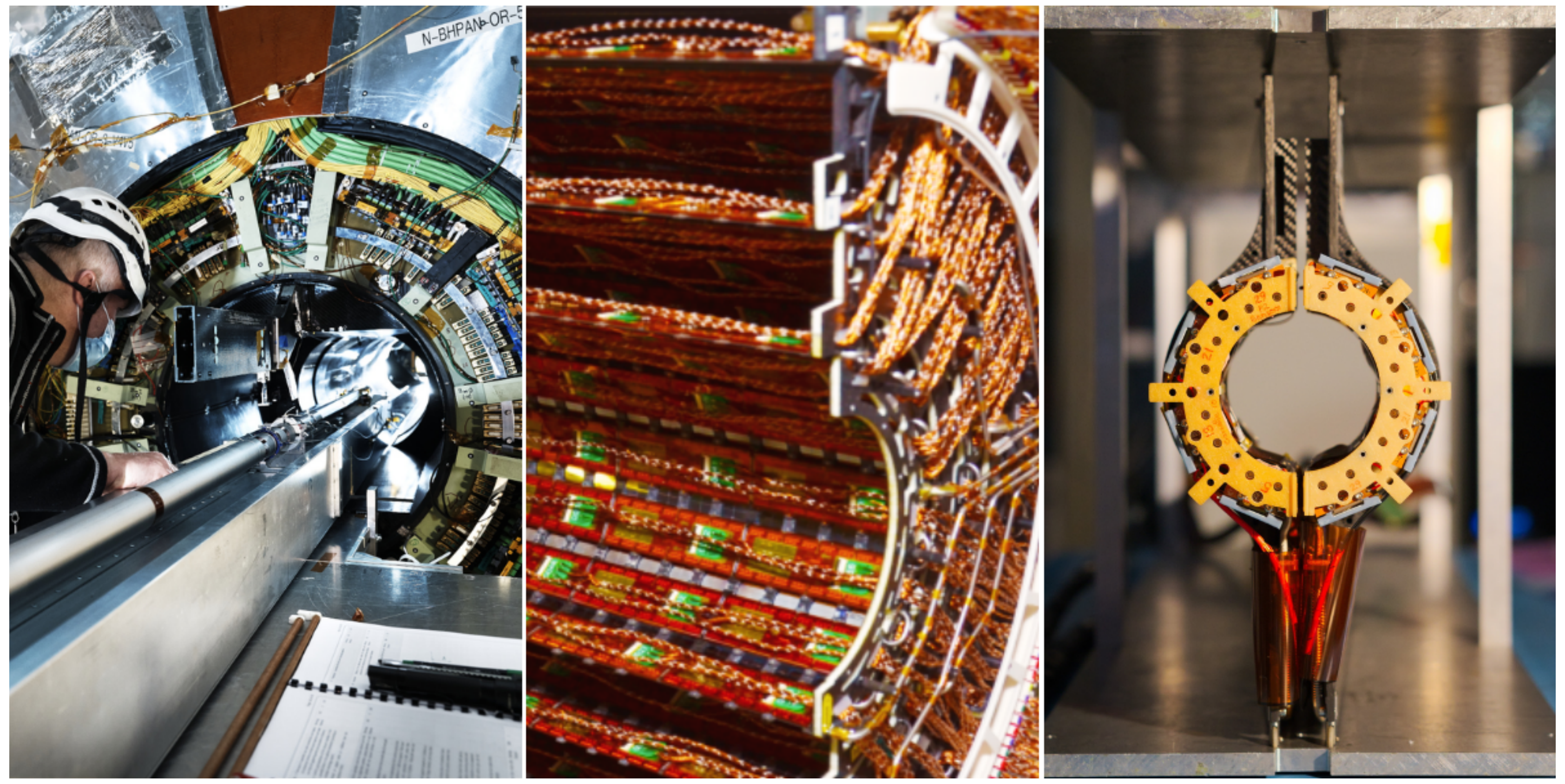




Successful Completion of LS2

LS2 = Long Shutdown 2 (2019-2021) = 1187 days





Main achievements

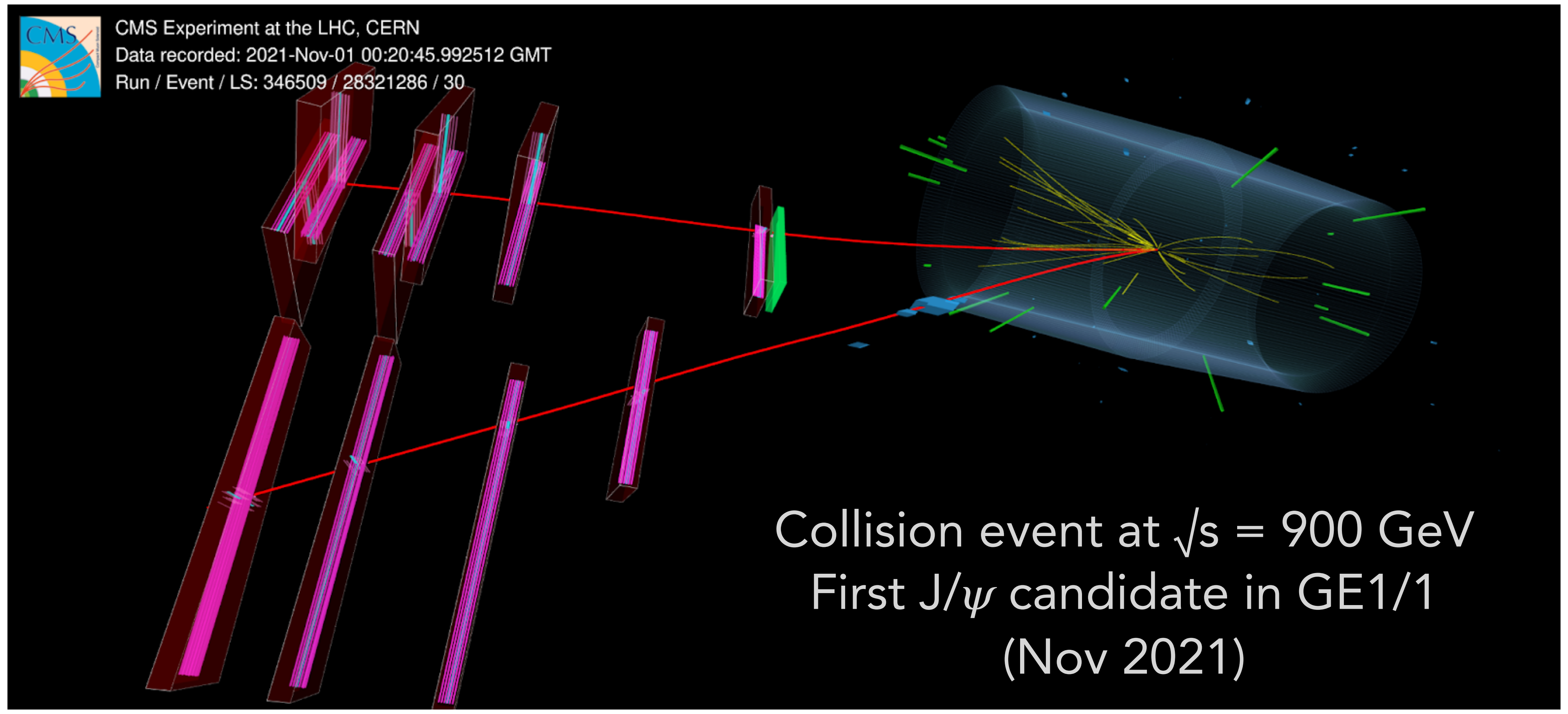
- CSC (forward muon detectors) readout
- HCAL SiPM readout and electronics
- refurbished pixel tracker with new Layer 1
- magnet fully re-commissioned at 3.8 T
- improved beam monitors and luminometers

Preparation to High Luminosity LHC

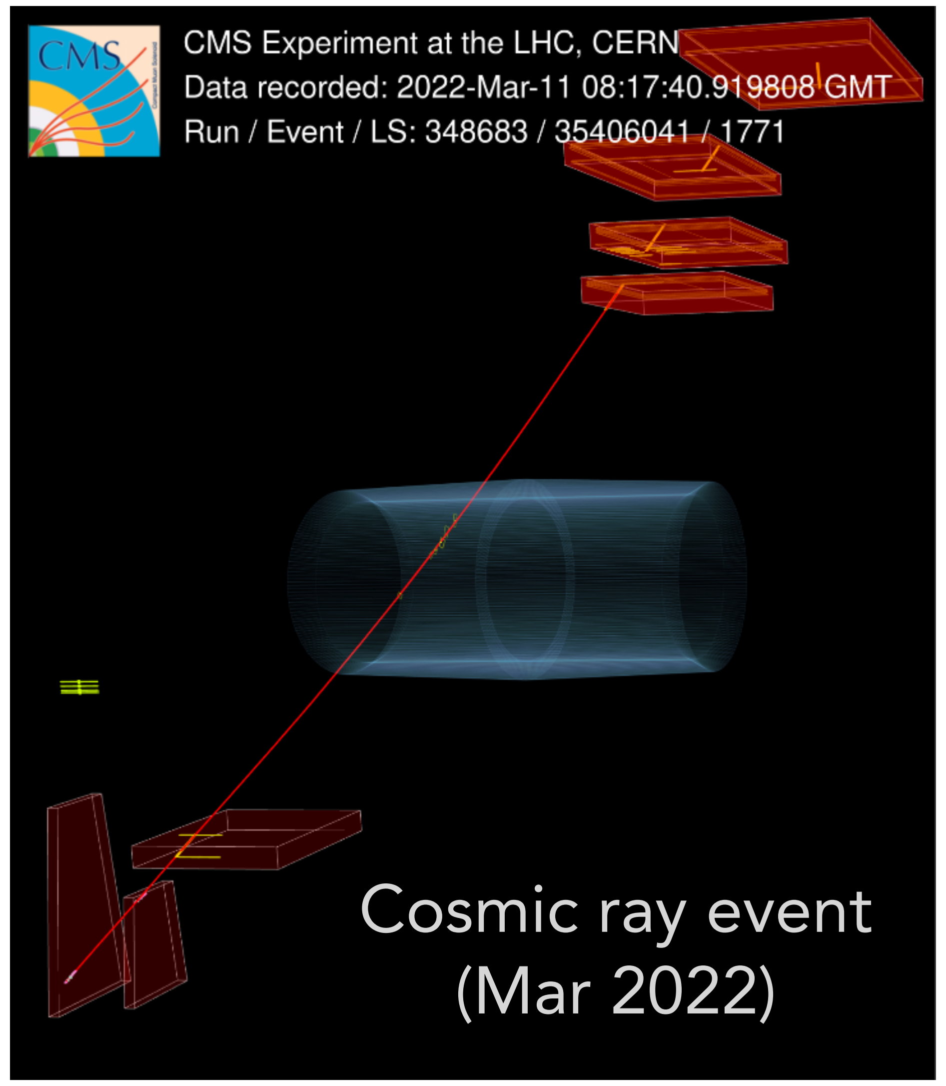
- new beam pipe
- first GEM muon layer (GE1/1)
- Phase-2 muon demonstrators
- HLT: hybrid CPU/GPU transition completed

CMS is Back and Running!

Successful **Pilot Beam Test** (Nov 2021)



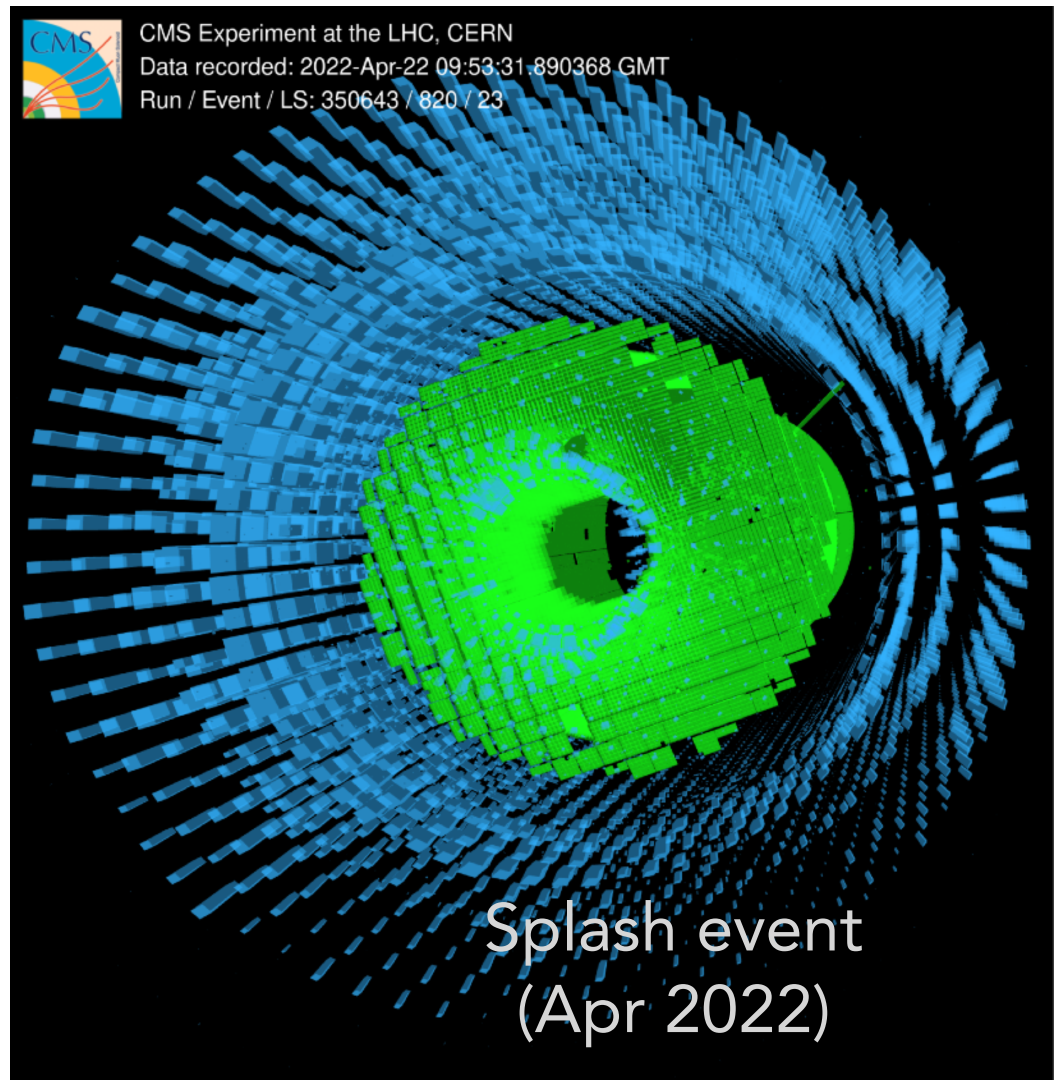
More than **6.6M cosmic ray events** collected for alignment and calibration purposes

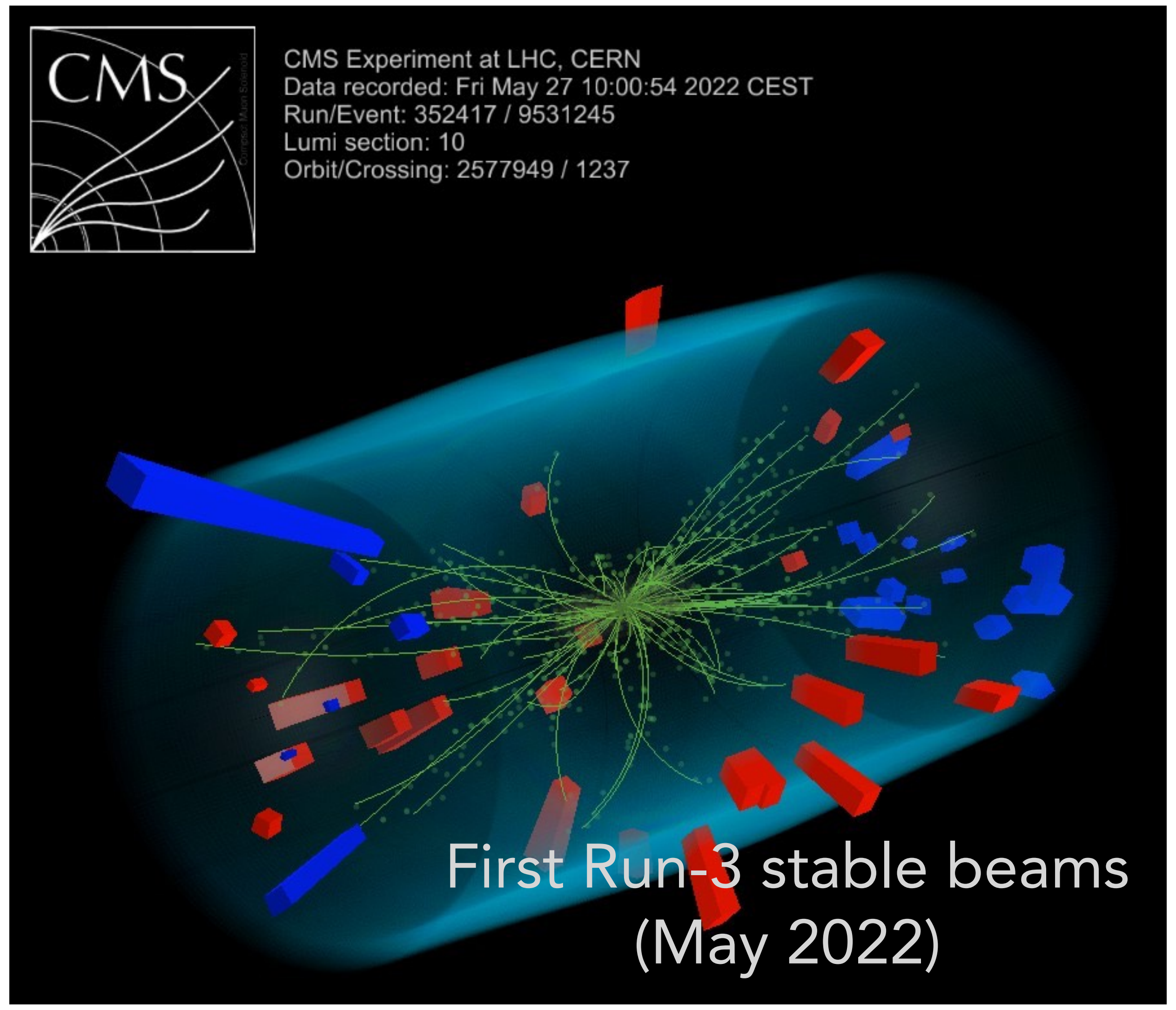


CMS closed on March 4

Commissioning with p-beams (since Apr 2022)

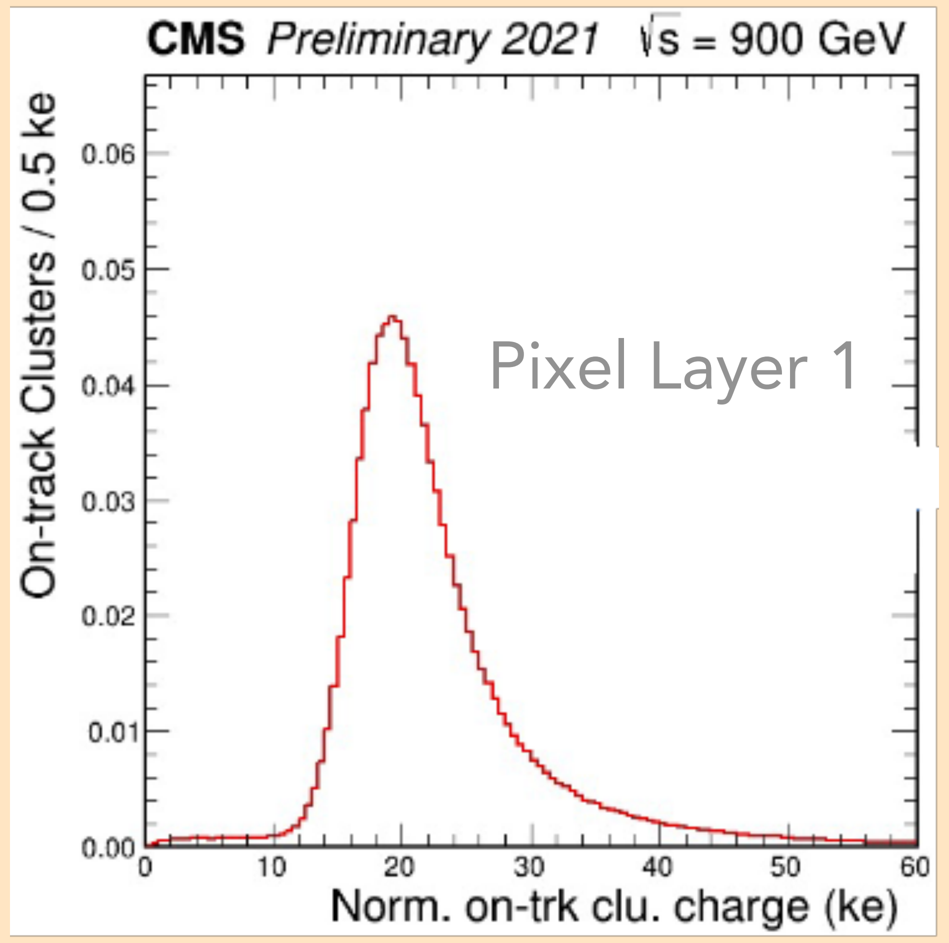
- "splash" events
- collisions in stable beams at injection energy (900 GeV)
- test collisions at Run-3 energy (13.6 TeV)

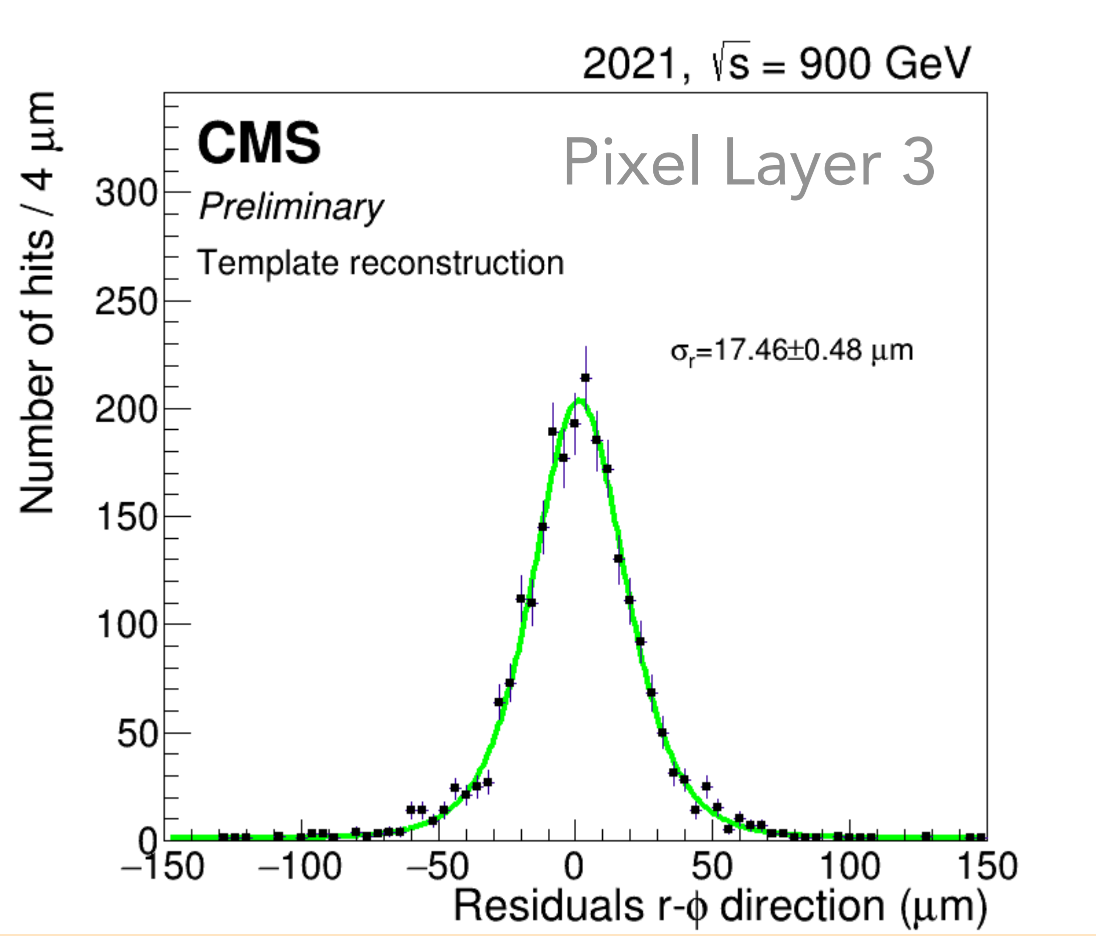


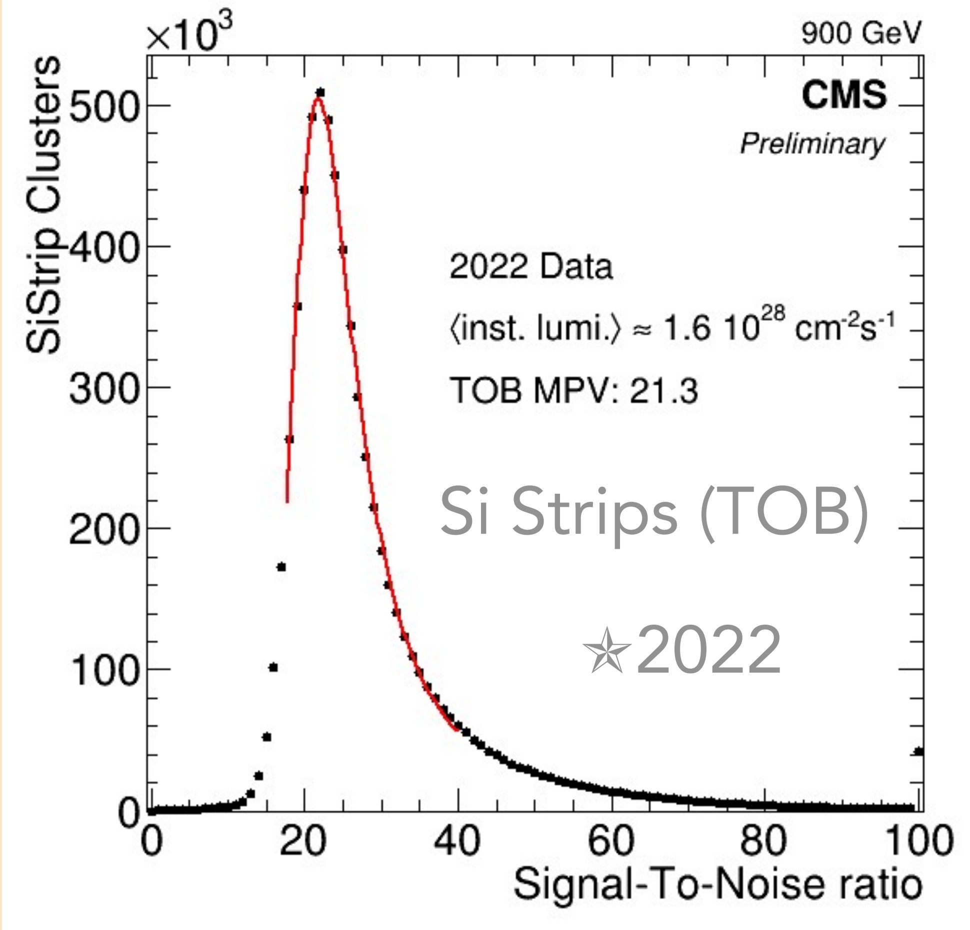


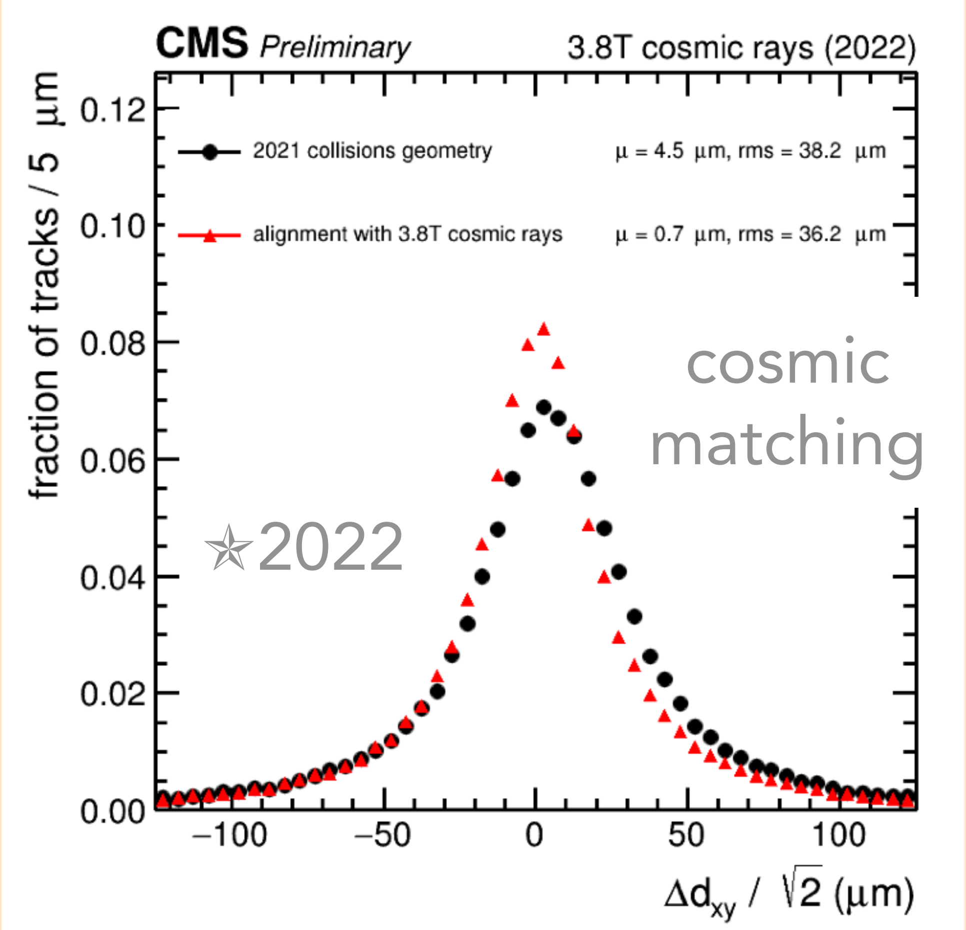
Commissioning and Preparation for Run-3

Examples of detector distributions (tracker)

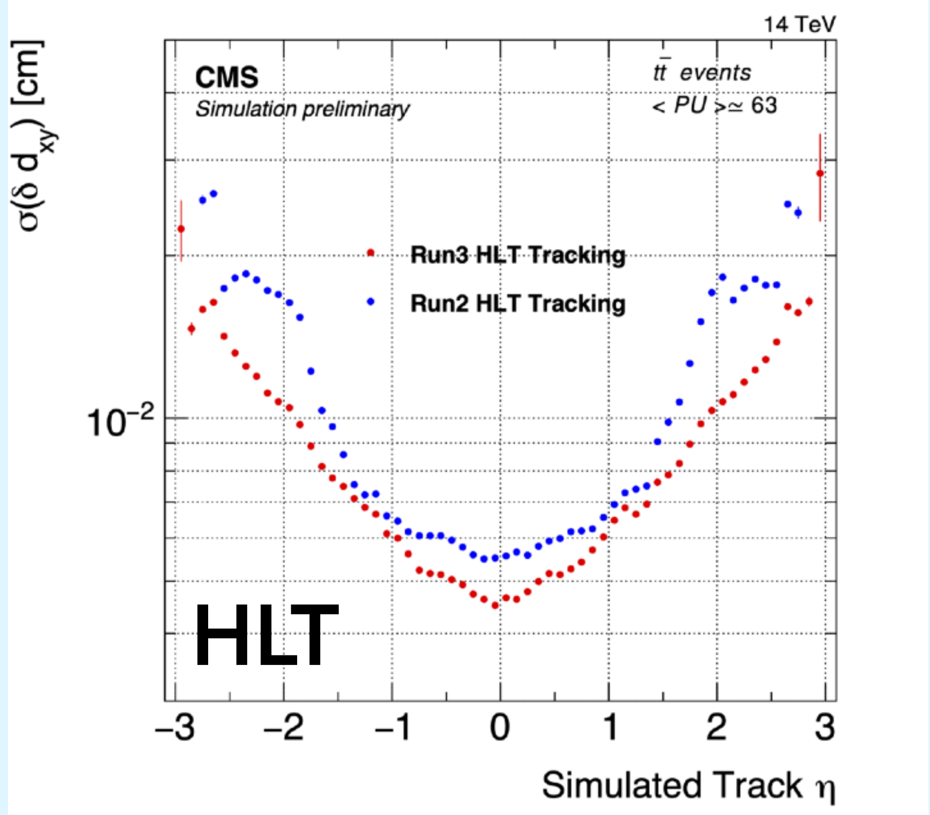


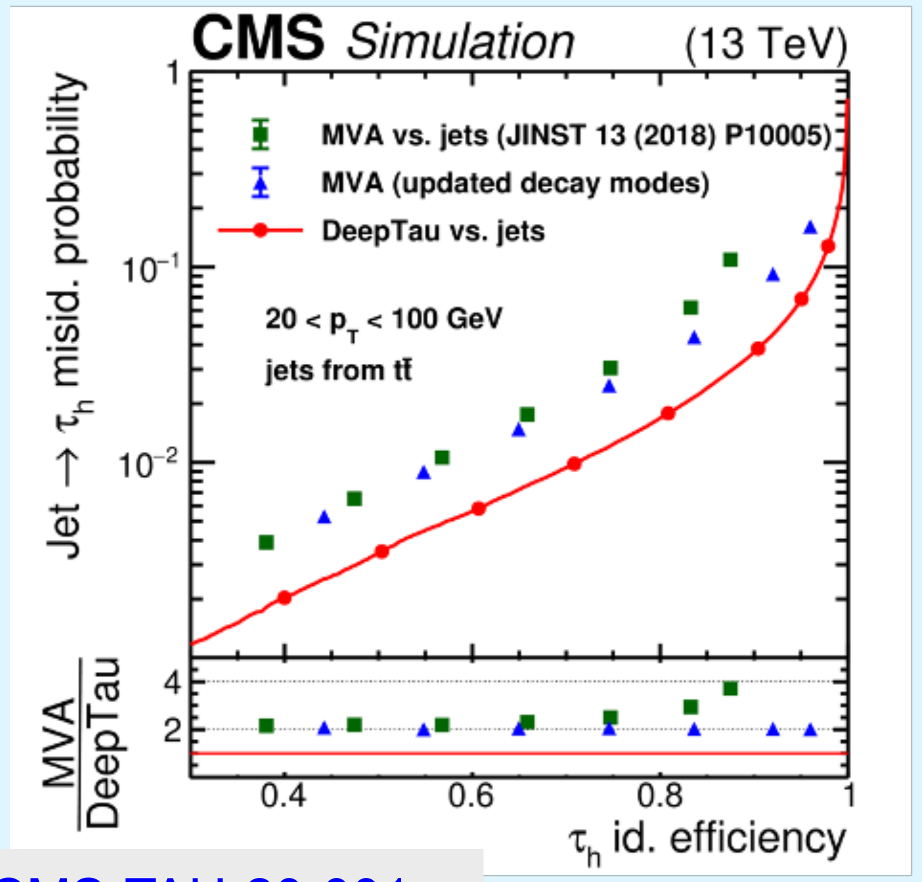






Examples of software improvements

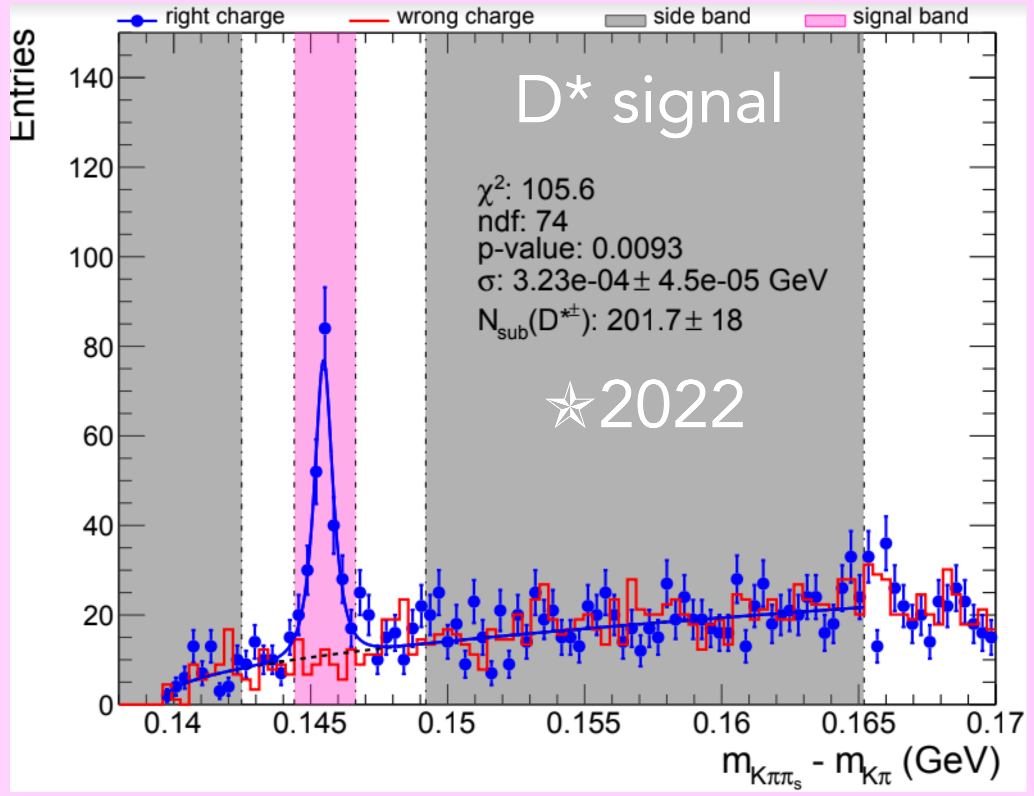




[CMS-TAU-20-001](CMS-TAU-20-001)
Submitted to JINST

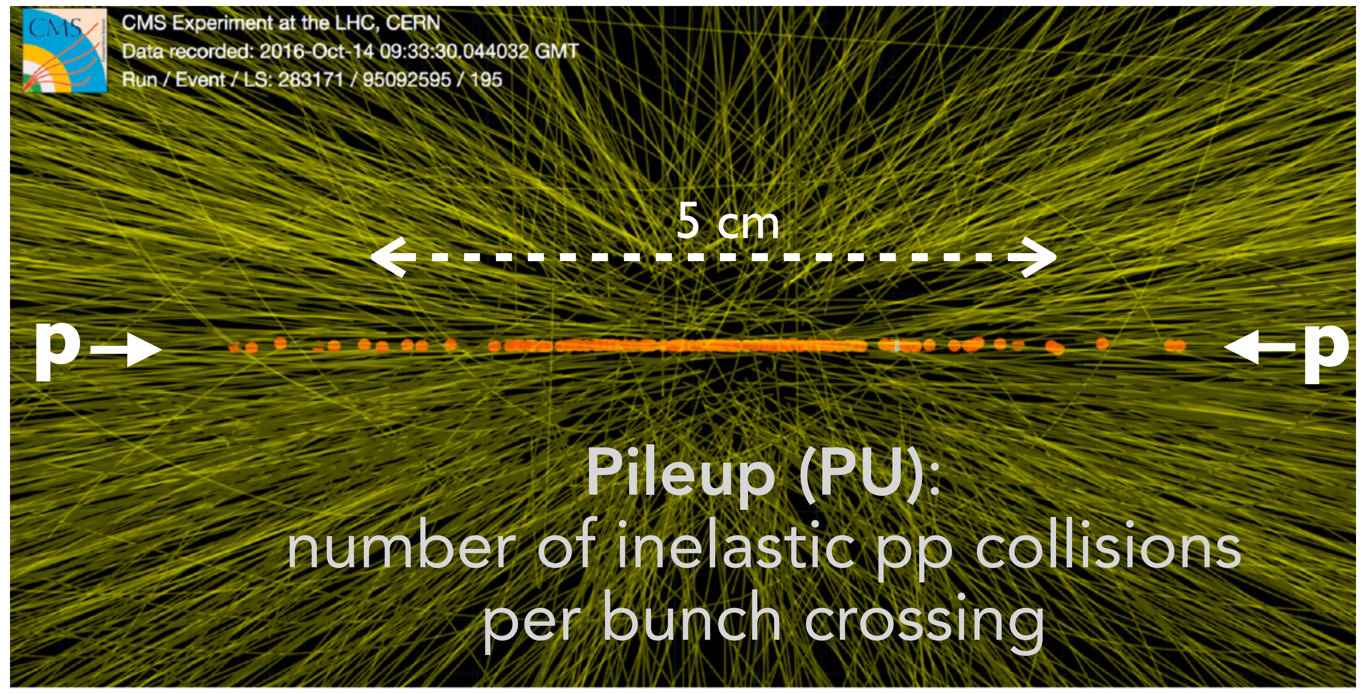
CMS Commissioning

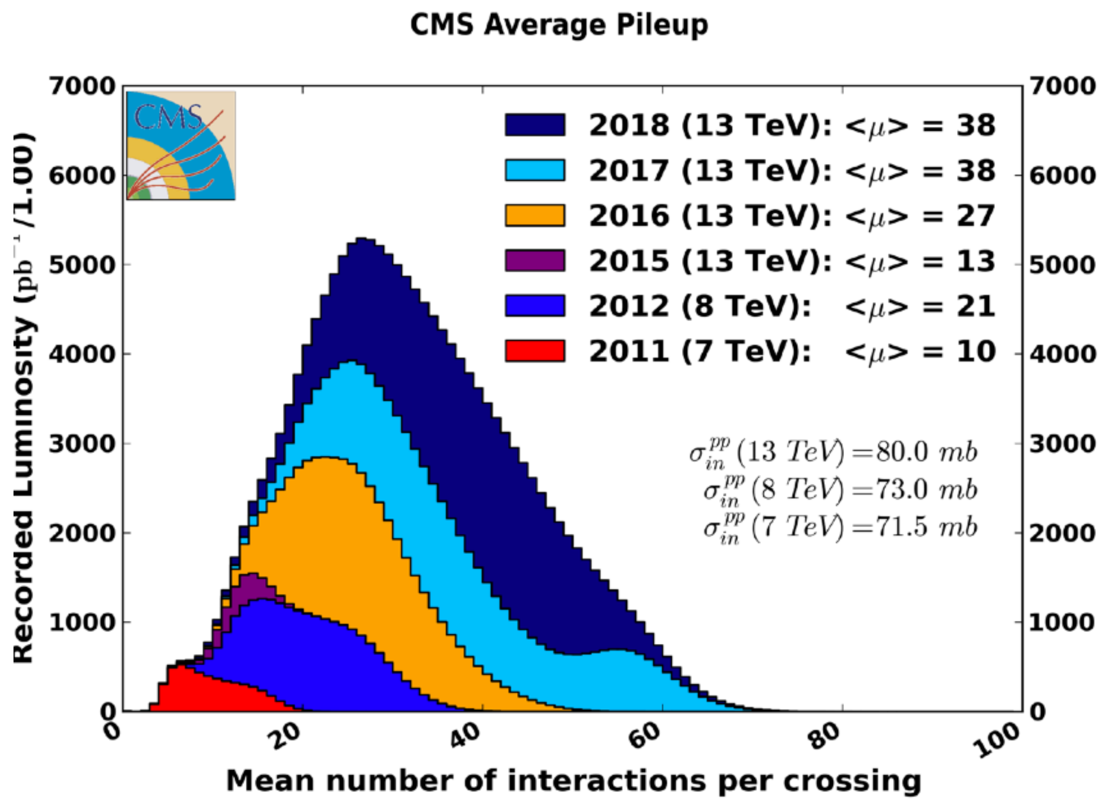
- DAQ and overall stability data taking confirmed
- full calibration and reconstruction chain exercised
- GEM efficiency and trigger integration with CSC completed
- trigger menus (L1/HLT) validated, with enhanced capabilities
- smooth computing operation
- first physics distributions



Towards Run-3

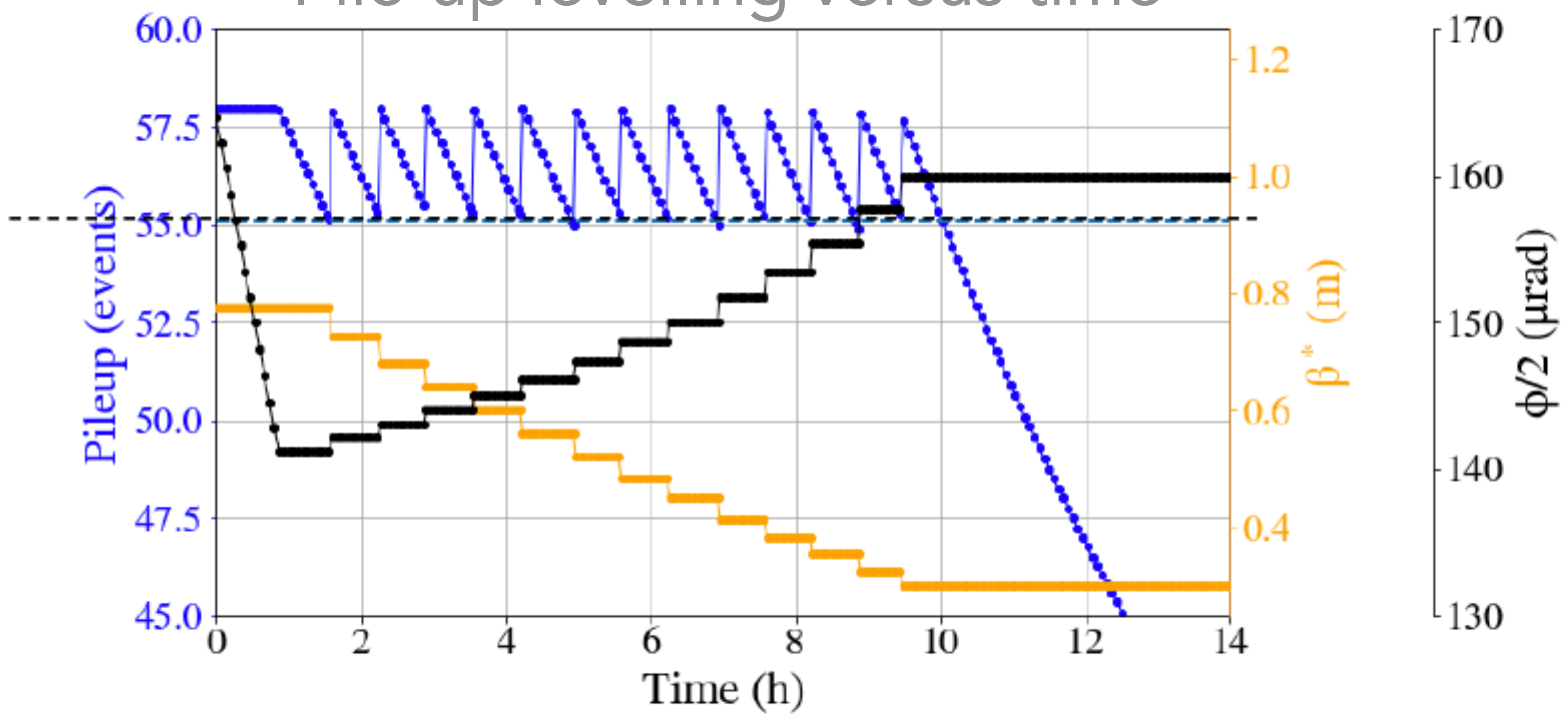
Run-3
- proton-proton collisions at $\sqrt{s}$ = 13.6 TeV
- high instantaneous luminosity with *levelling* $\mathscr{L} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- pileup μ = 55-58 (±2.5%)





2022
- **July 5**
  First 13.6 TeV collisions
  and start of intensity ramp-up
- **Aug. 4-Sept. 5**
  First pp running period (> 1,200 bunches)
- **Oct. 1-Nov. 2** (after TS1)
  Second pp running period
- **Nov. 14-Dec. 11** (after TS2)
  PbPb ion running ($\sqrt{s_{NN}}$ = 6.8 TeV, TBC)

Pile-up levelling versus time



crossing angle levelling only from 2023 onwards

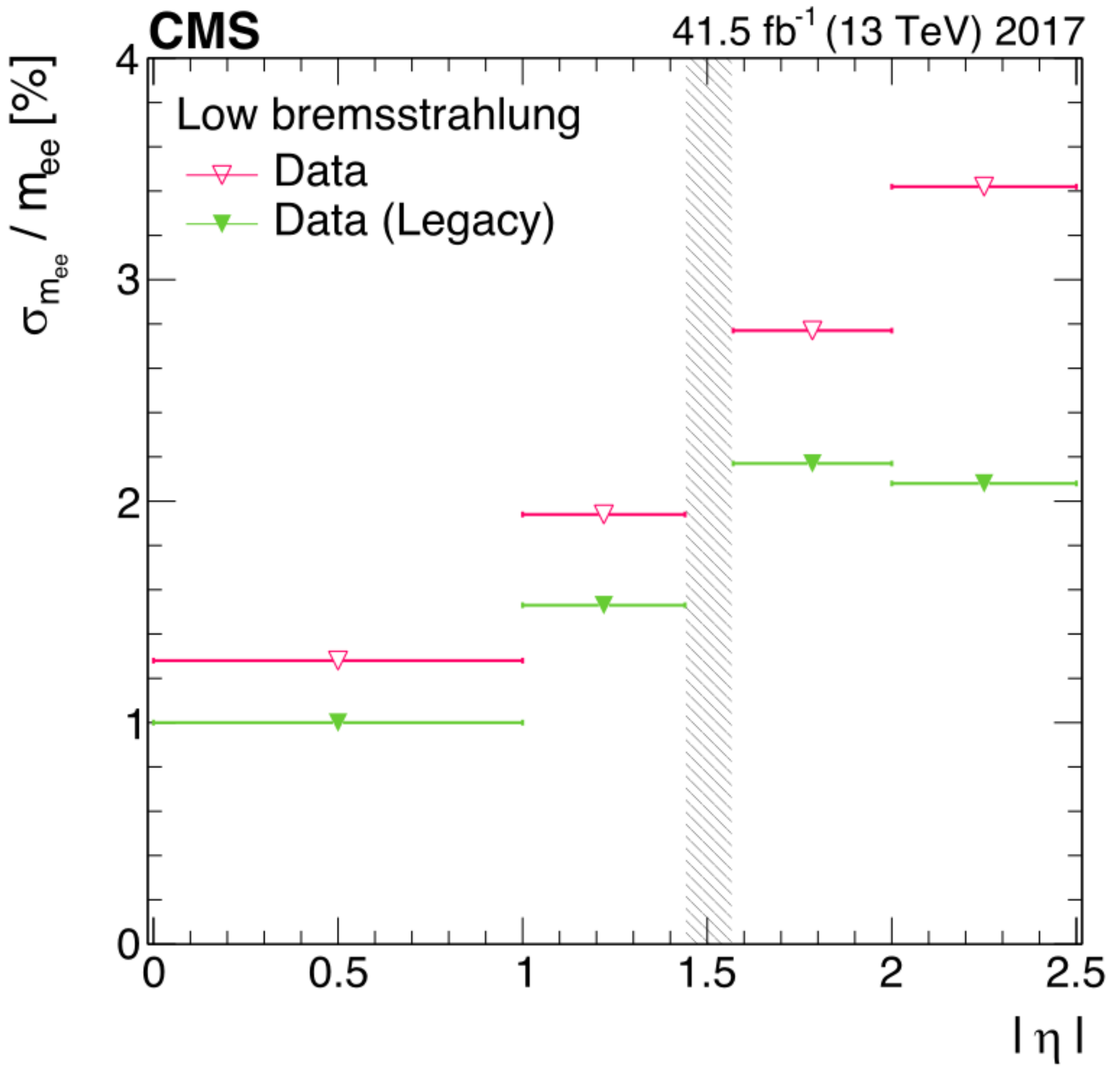
Robust-to-PU physics object reconstruction
- photons
- electrons, muons
- τ-leptons
- jets/MET, b- and c-jets
- boosted W/Z/H/top

CMS is fully operational
for the start of
Run-3 physics!

Run-2 Performance

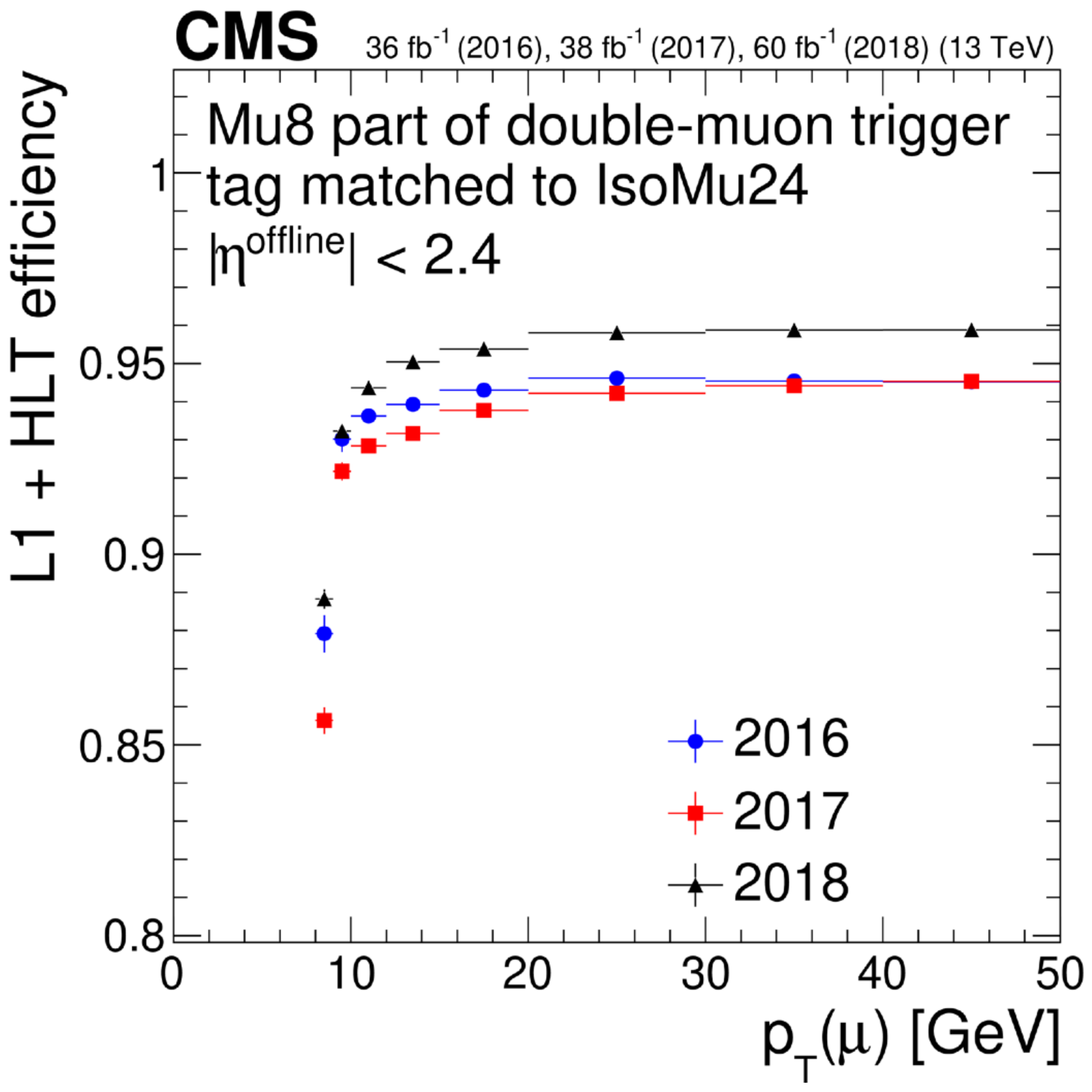
Thanks to a huge effort of improvement in calibration procedures and software tools, CMS Run-2 analyses are now performed on an optimally calibrated data sample (Legacy Run-2 data)

Comparison of Z mass resolution before and after final calibration included in Legacy Run 2 data



CMS-EGM-17-001
JINST 16 (2021) P05014

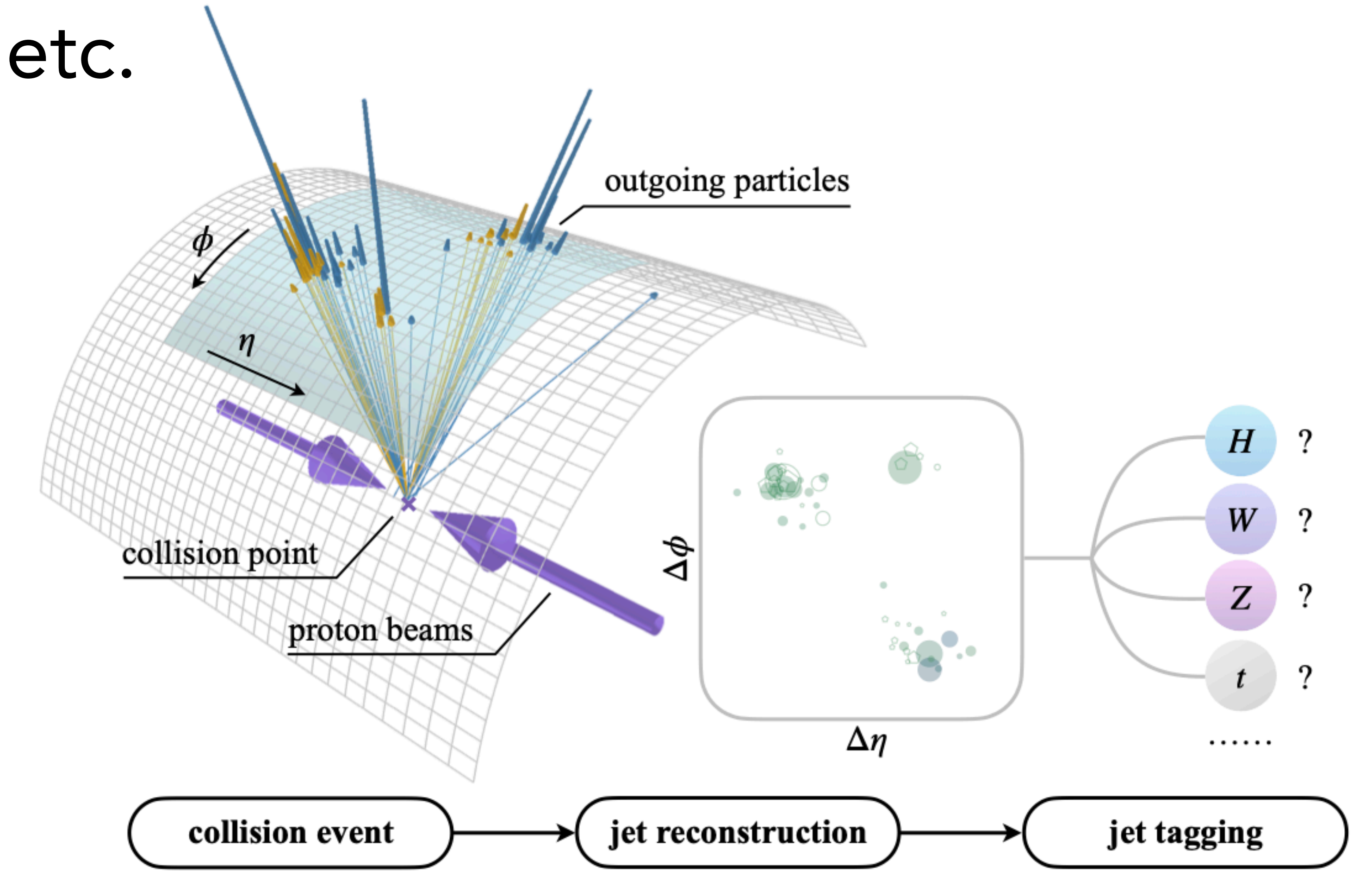
Extensive measurements of Run-2 L1 and HLT trigger performance



CMS-MUO-19-001
JINST 16 (2021) P07001

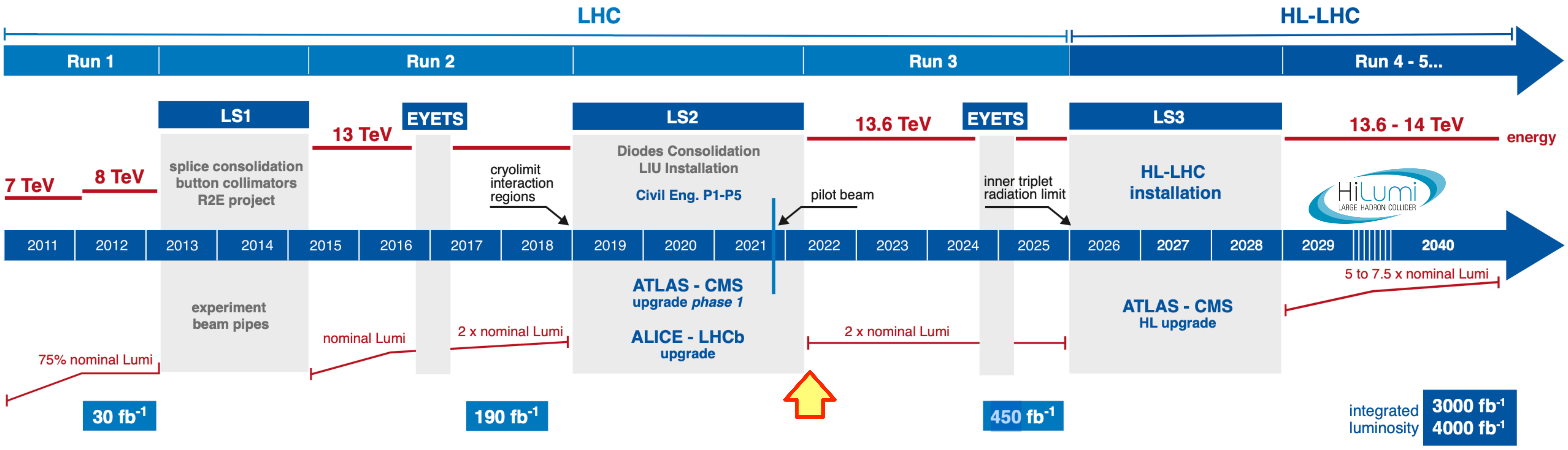
Impressive improvement in analysis techniques with intensive use of state-of-the-art ML techniques, deep-learning neural nets, etc.

- PU mitigation
- b- and c-jet tagging
- τ-lepton reconstruction
- Lorentz-boosted jet tagging and mass
- etc.



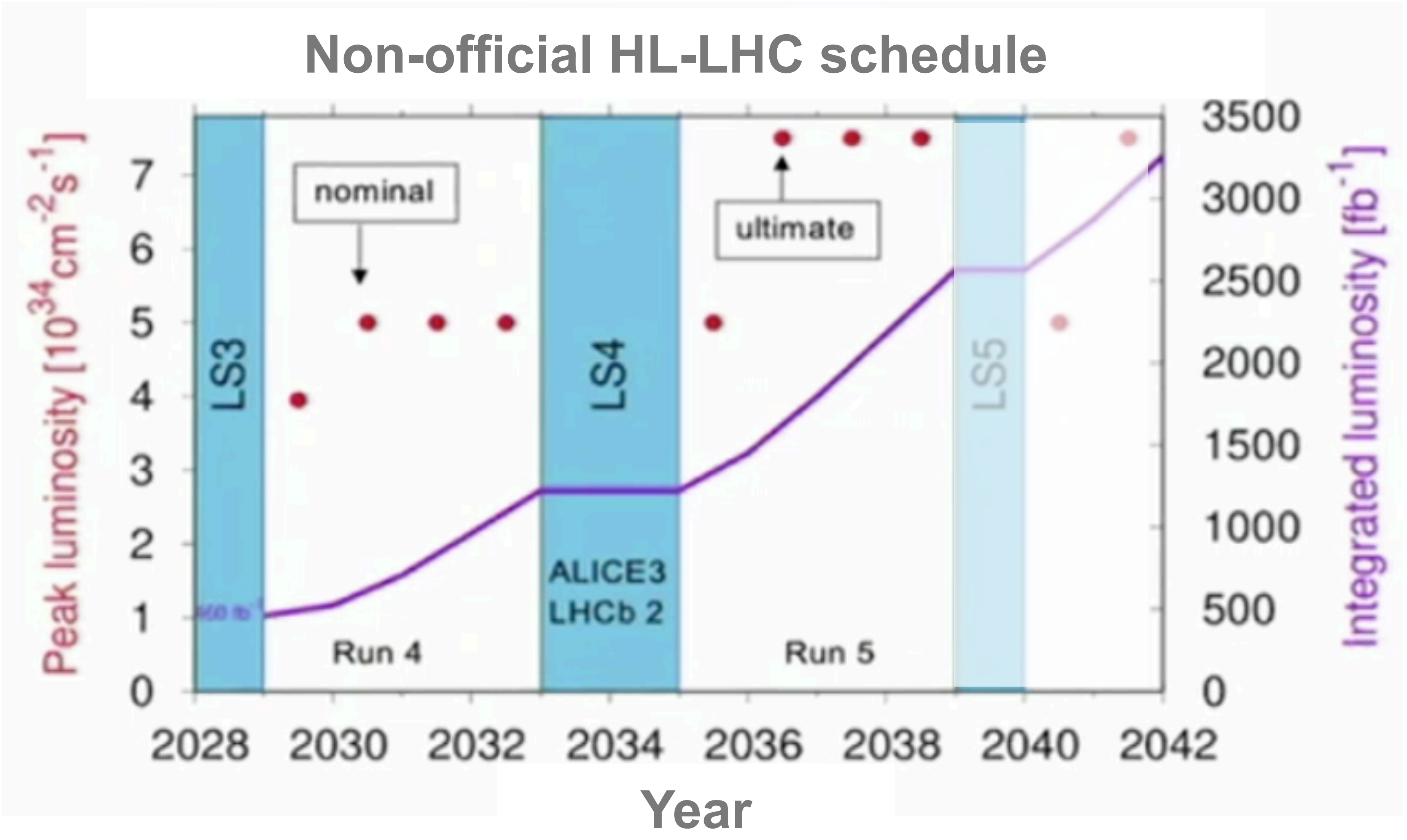
arXiv:2202.03772 Particle Transformer for jet tagging

Towards High-Luminosity LHC



New LS3 schedule

- Run-3 extended by 1 year
  → 2022-2025
  270 fb⁻¹ (PU50)
- LS3 extended to 3 years
  → 2026-2028
- start of Run-4: 2029



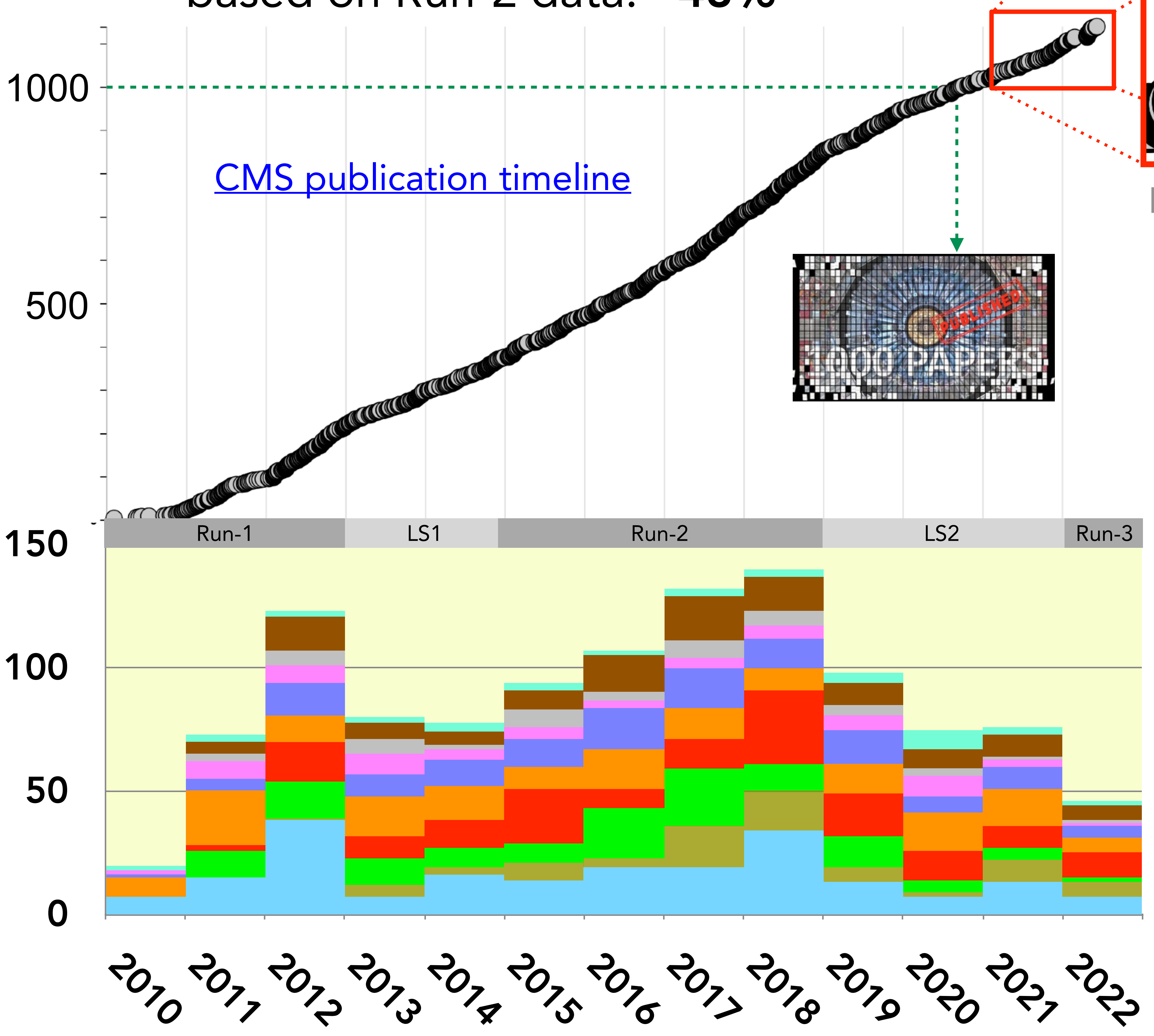
Possible scenario (CERN DG, Jan. 2022)

- Run 4 (2029-2032) = 740 fb⁻¹ (PU140)
- Run 5 (2035-2038) = 1300 fb⁻¹ (PU200)
- Run 6? (2040-2042) = 750 fb⁻¹ (PU200)

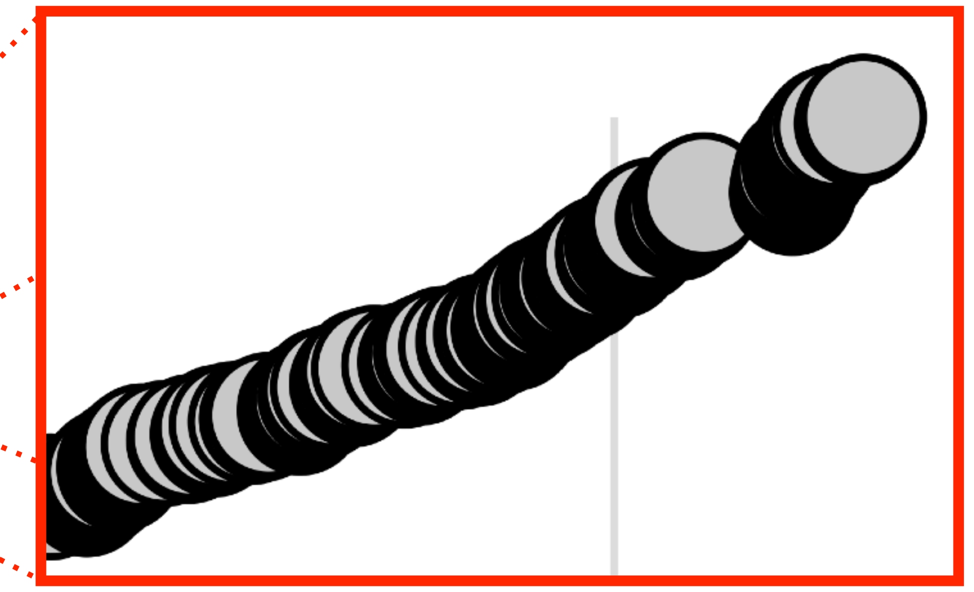
Expect **2500 fb⁻¹** by the end of **2038**
3250 fb⁻¹ by the end of **2042**

CMS Publications

CMS papers (**submitted**/published)
- total: **1164**/1113
- based on collision data: **1139**/1088
- based on Run-2 data: **48%**



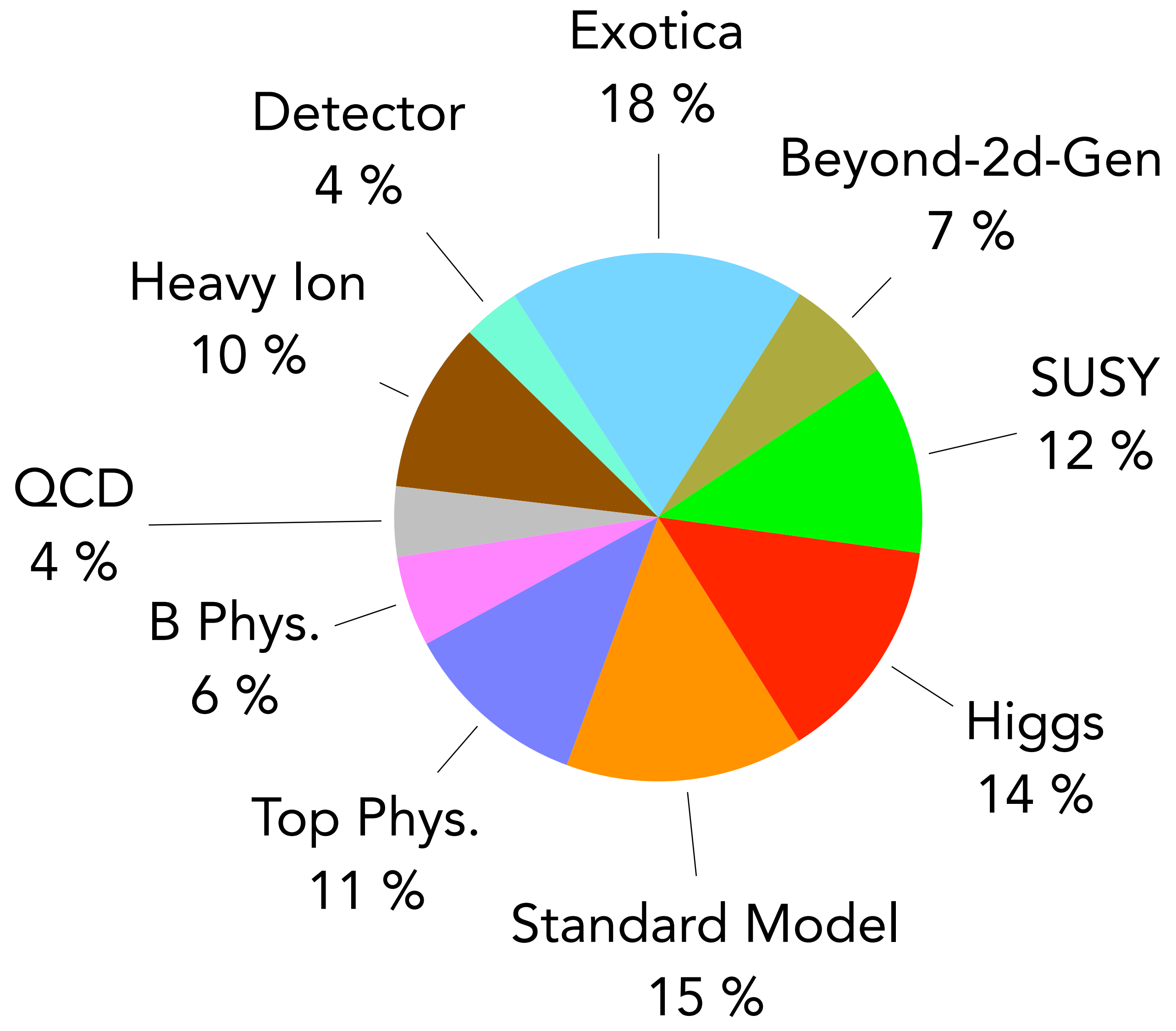
CMS publication timeline

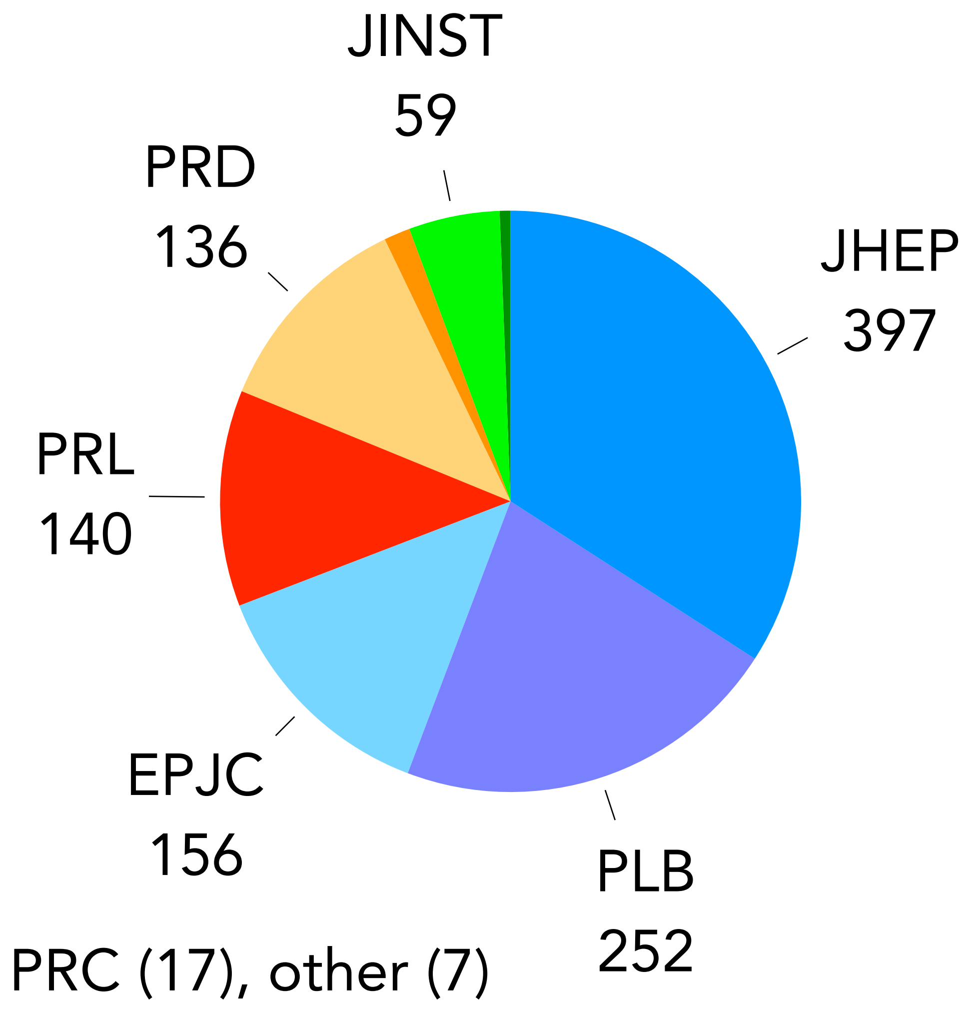


paper submission interrupted
Mar 1-Apr 26

CMS paper titles
- 573 "Search"
- 363 "Measurement" or "study"
- 47 "Observation"
- 20 "Evidence"

CMS with friends
- **ATLAS**: 6 (5 JHEP, 1 PRL)
- **LHCb**: 1 (Nature)
- **Totem**: 4 (1 JHEP, 2 EPJC, 1 PRL)





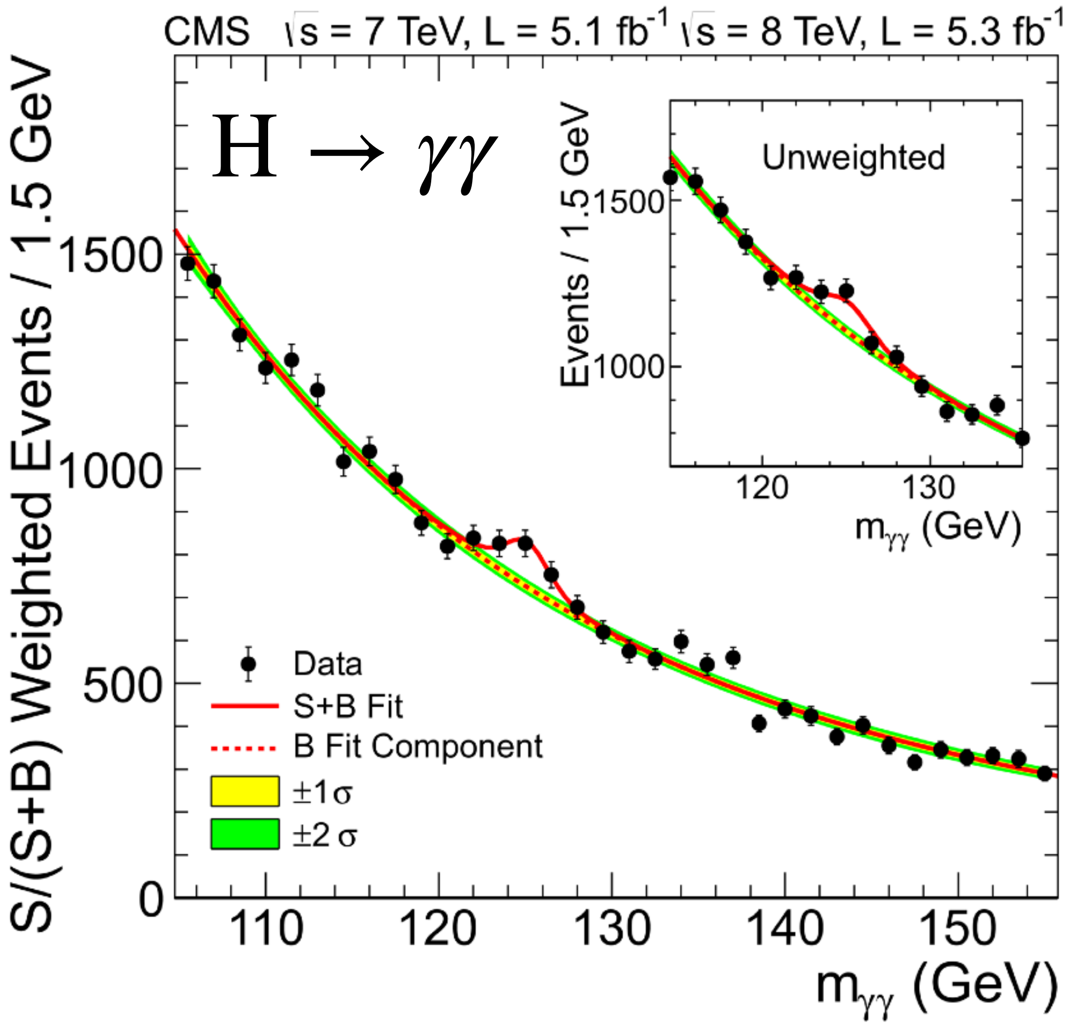
PRC (17), other (7)

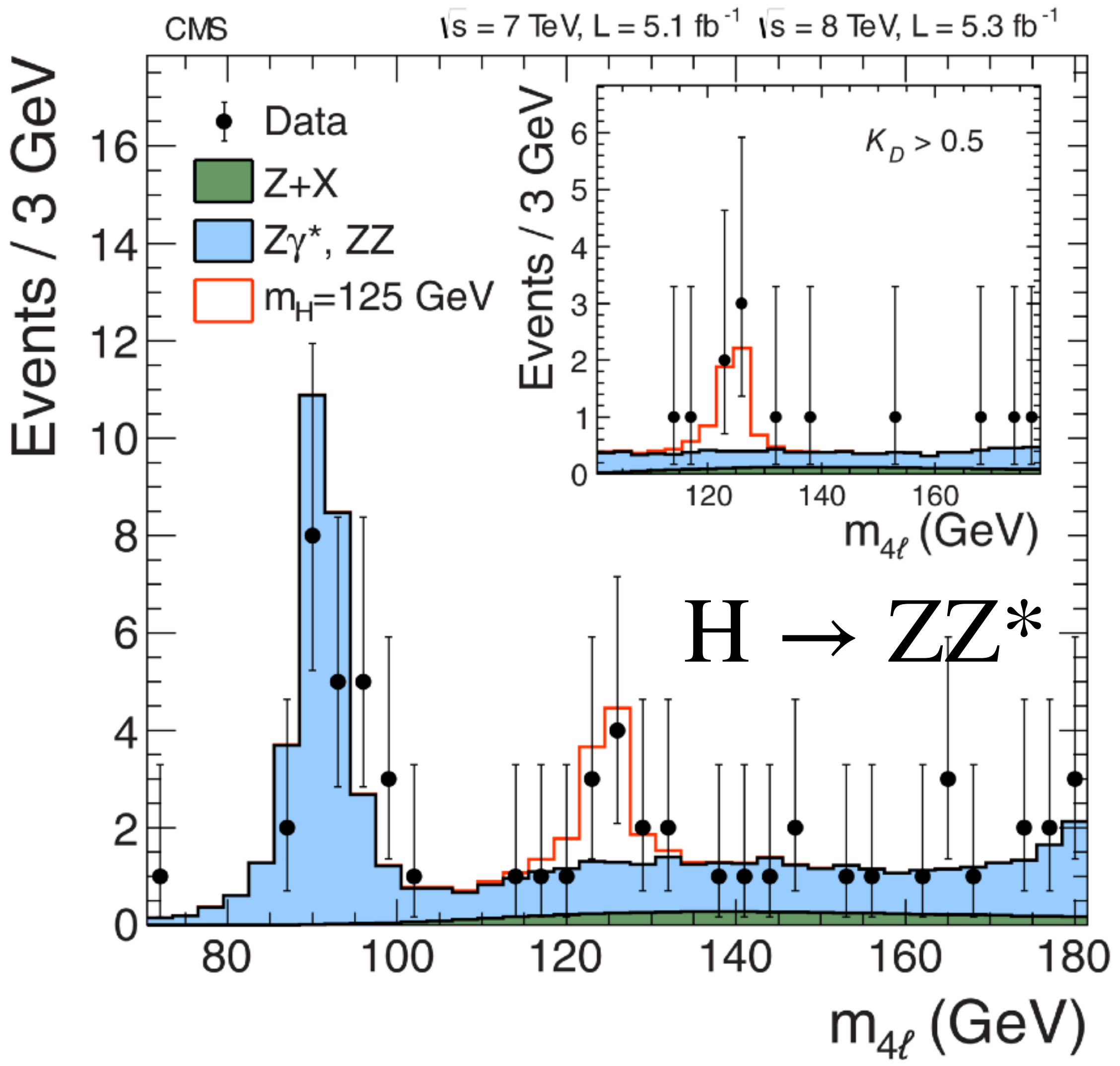
CMS public results

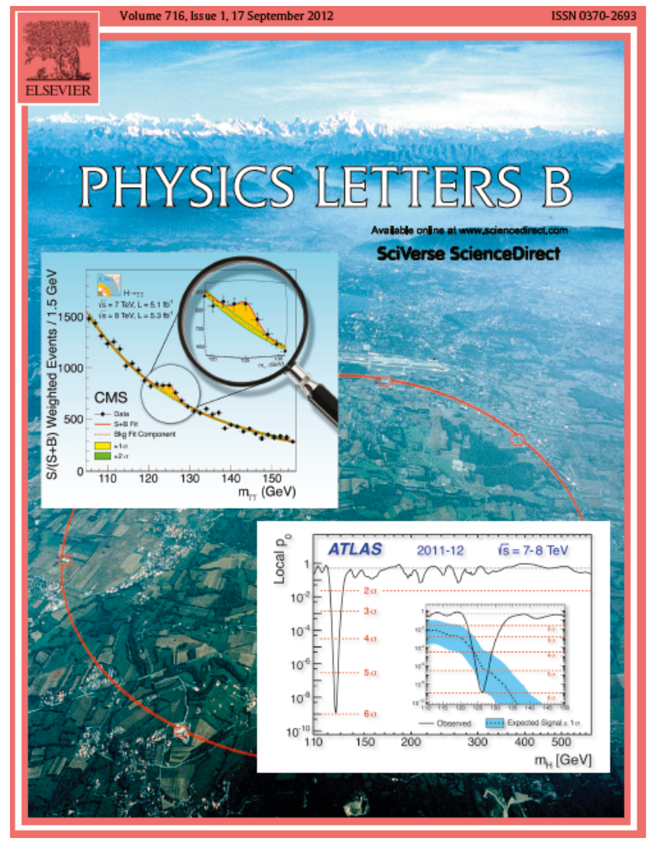
The Higgs Boson Turns 10!

years HIGGS boson discovery
[July 4 2022](#)

9 years and eleven months ago

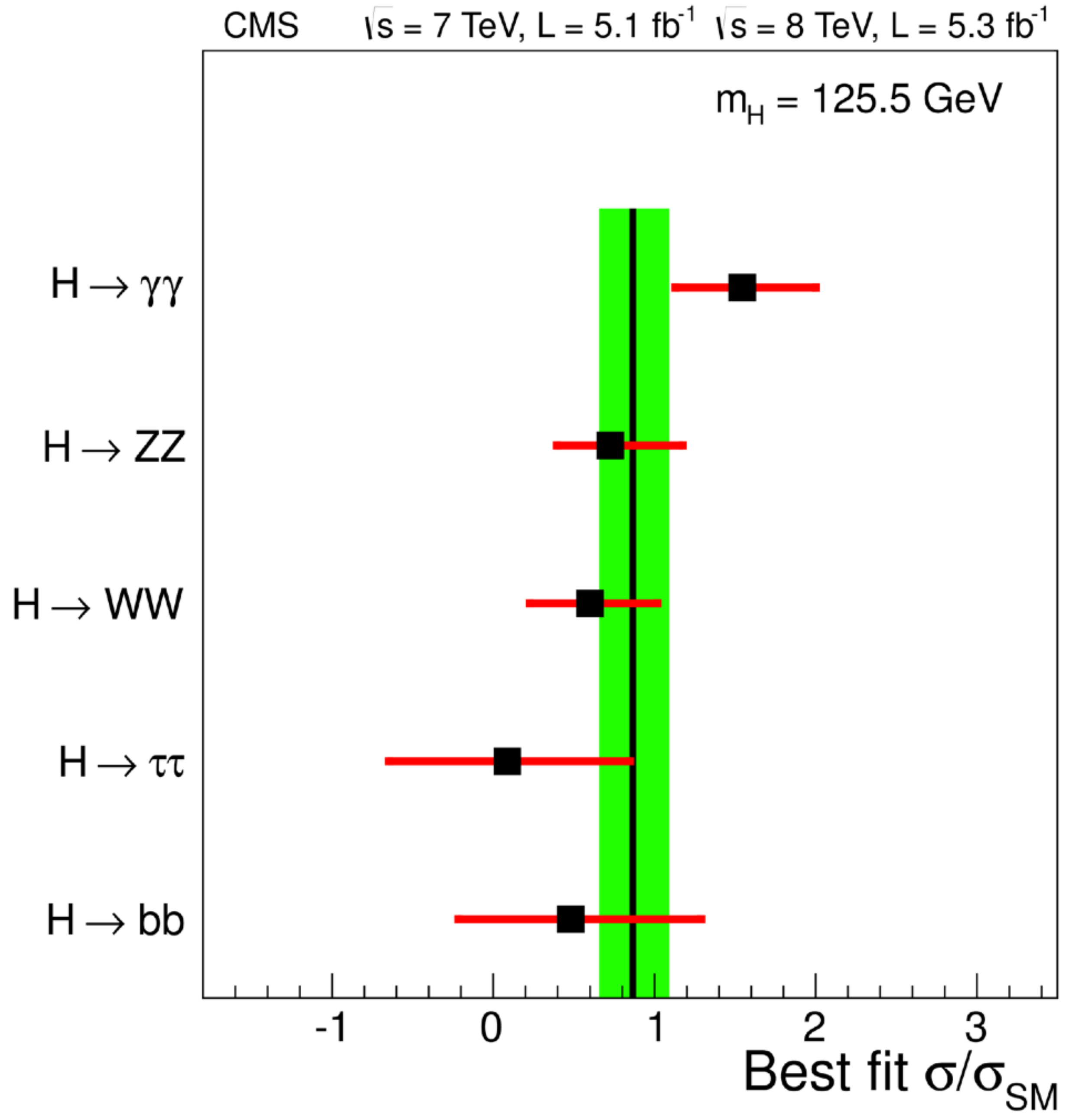


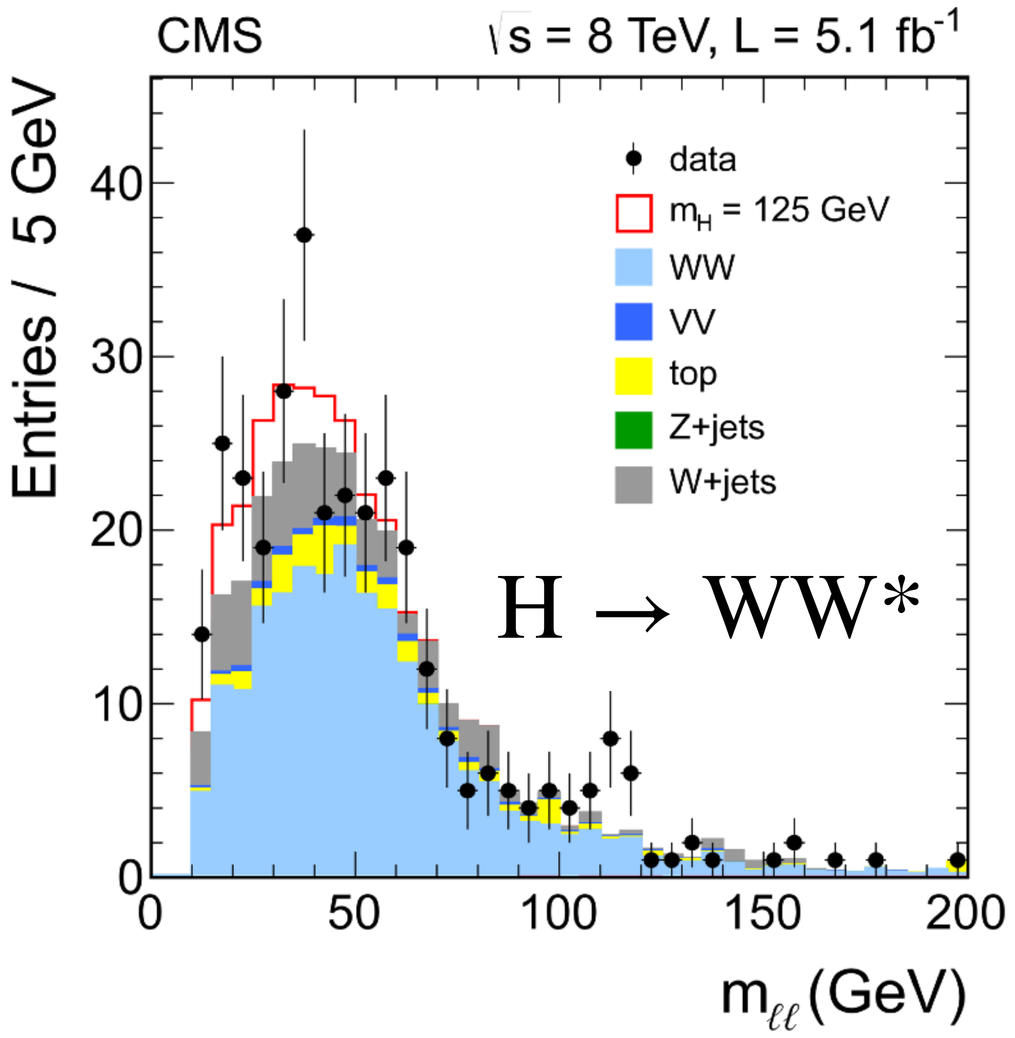


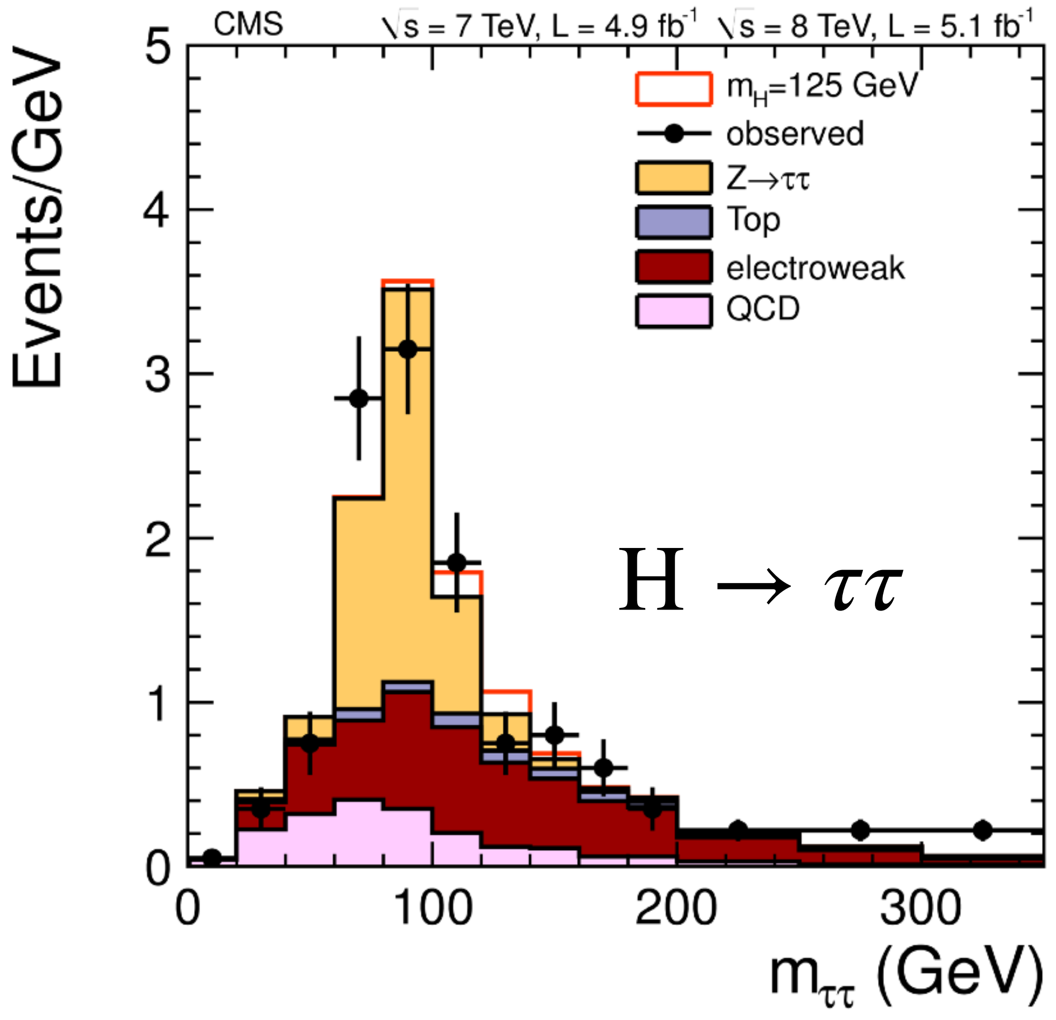


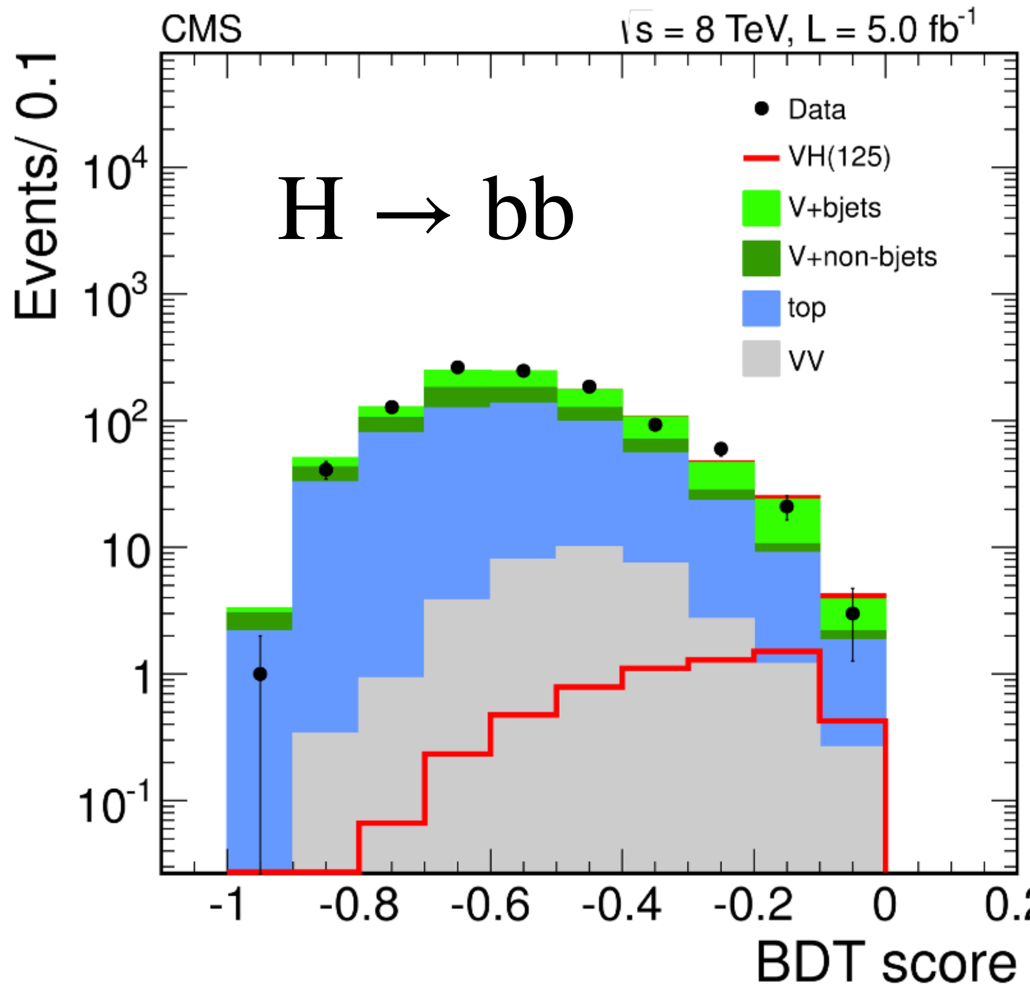
CMS-HIG-12-028
PLB 716 (2012) 30

Observation (5.0σ significance) combining the 5 modes









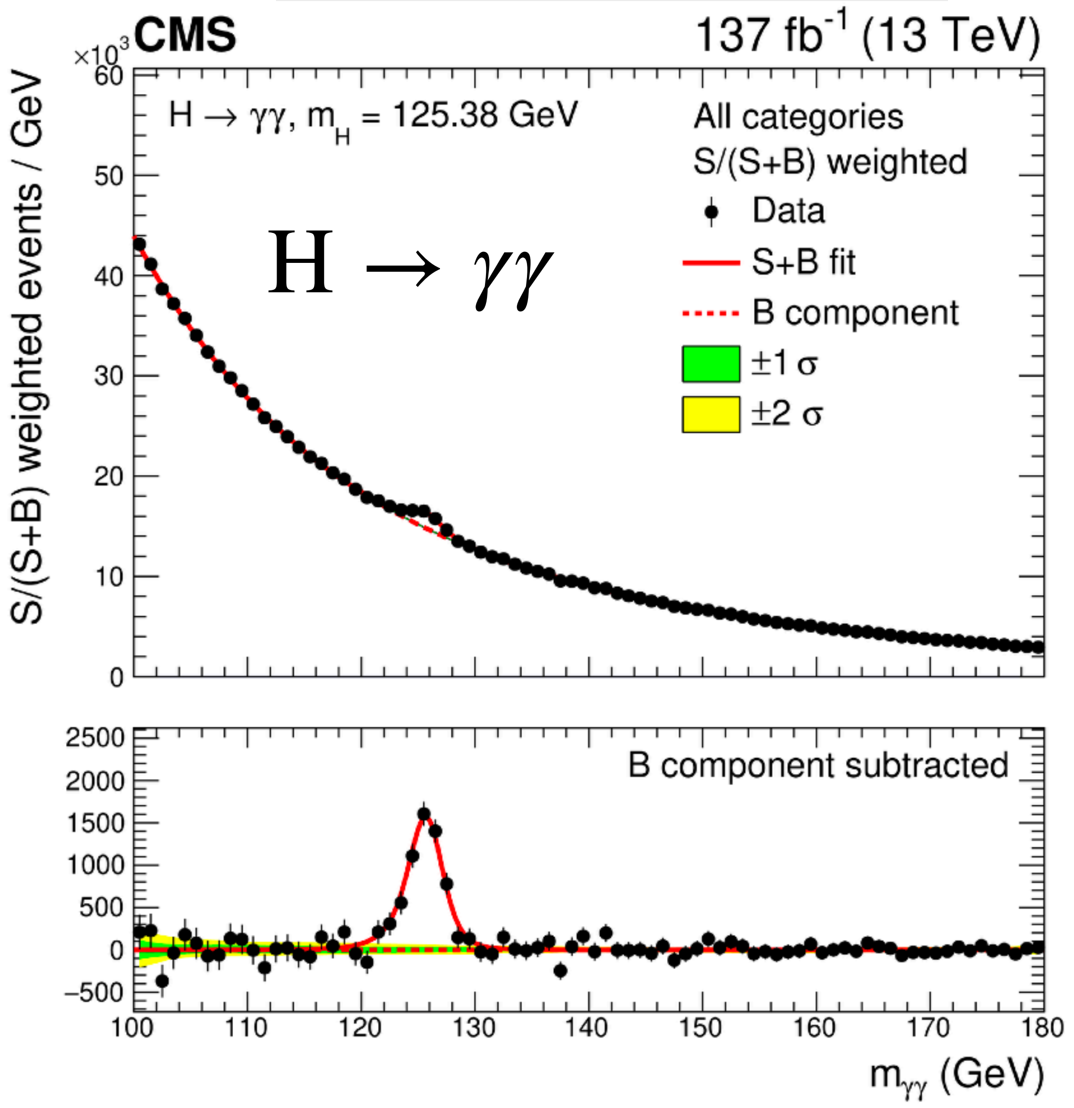
The Higgs Boson Turns 10!

years HIGGS boson discovery

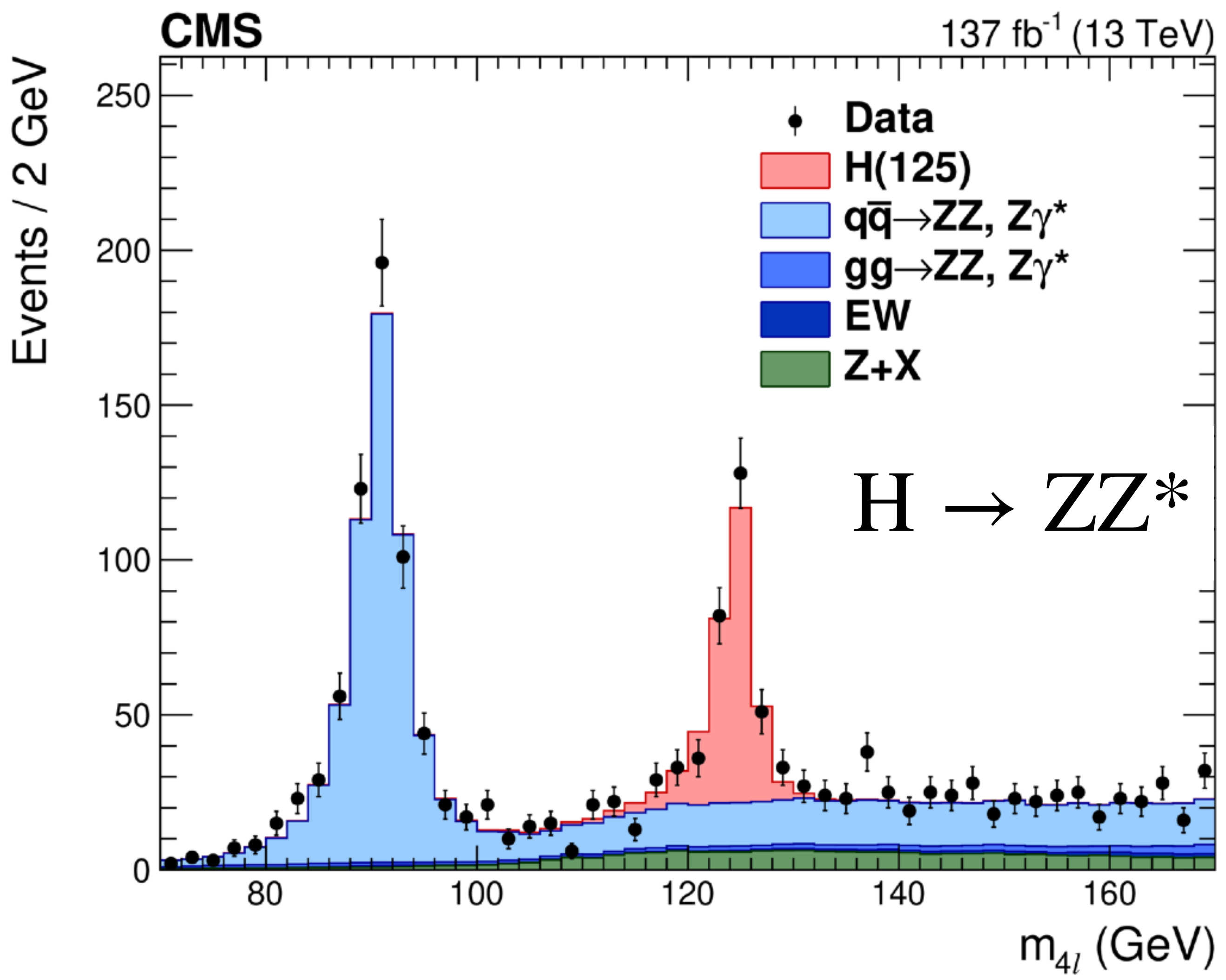
July 4 2022

$$m_{\mathrm{H}} = 125.38 \pm 0.14\,(\text{total})\ \text{GeV}$$

CMS-HIG-19-015
JHEP 07 (2021) 027

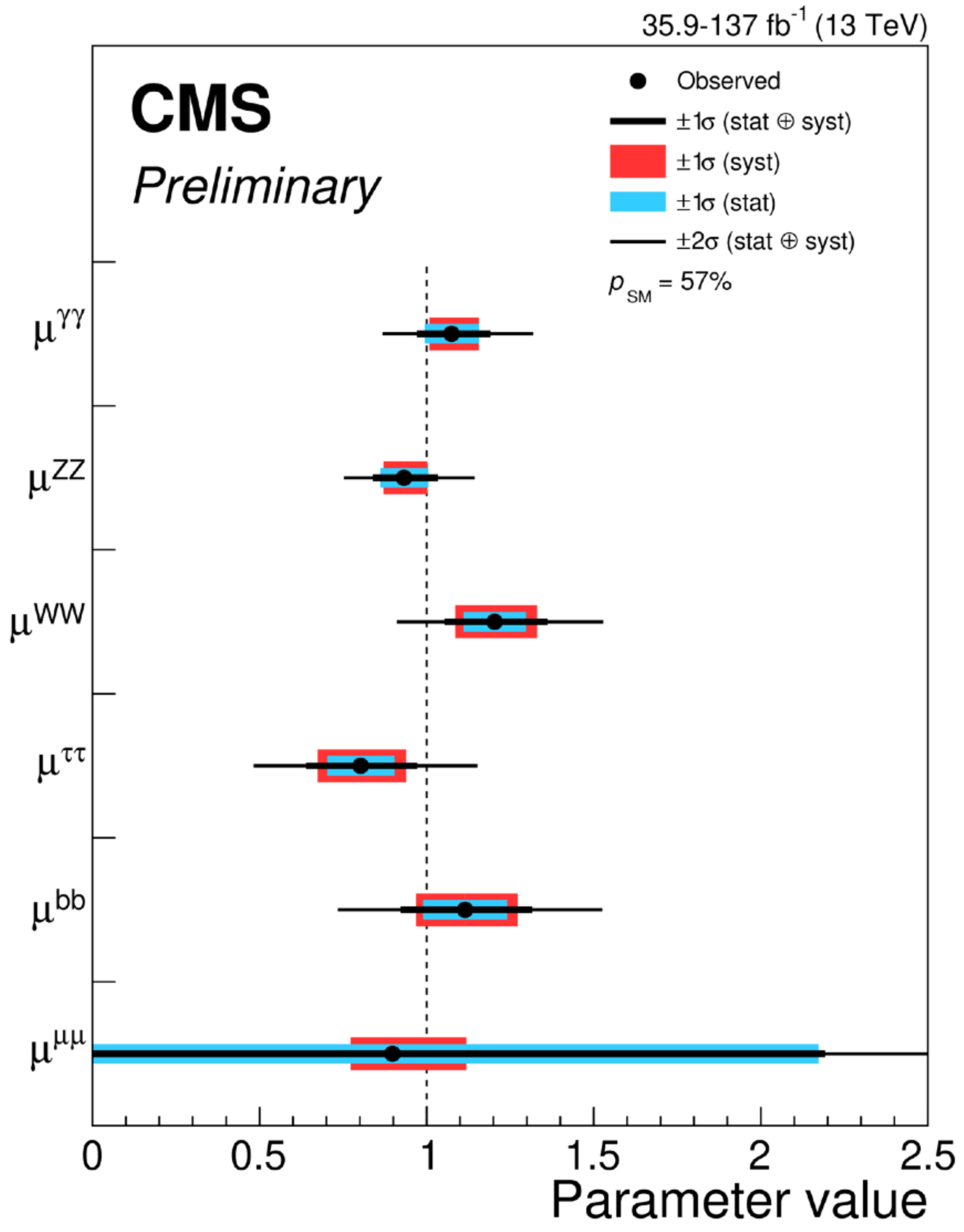


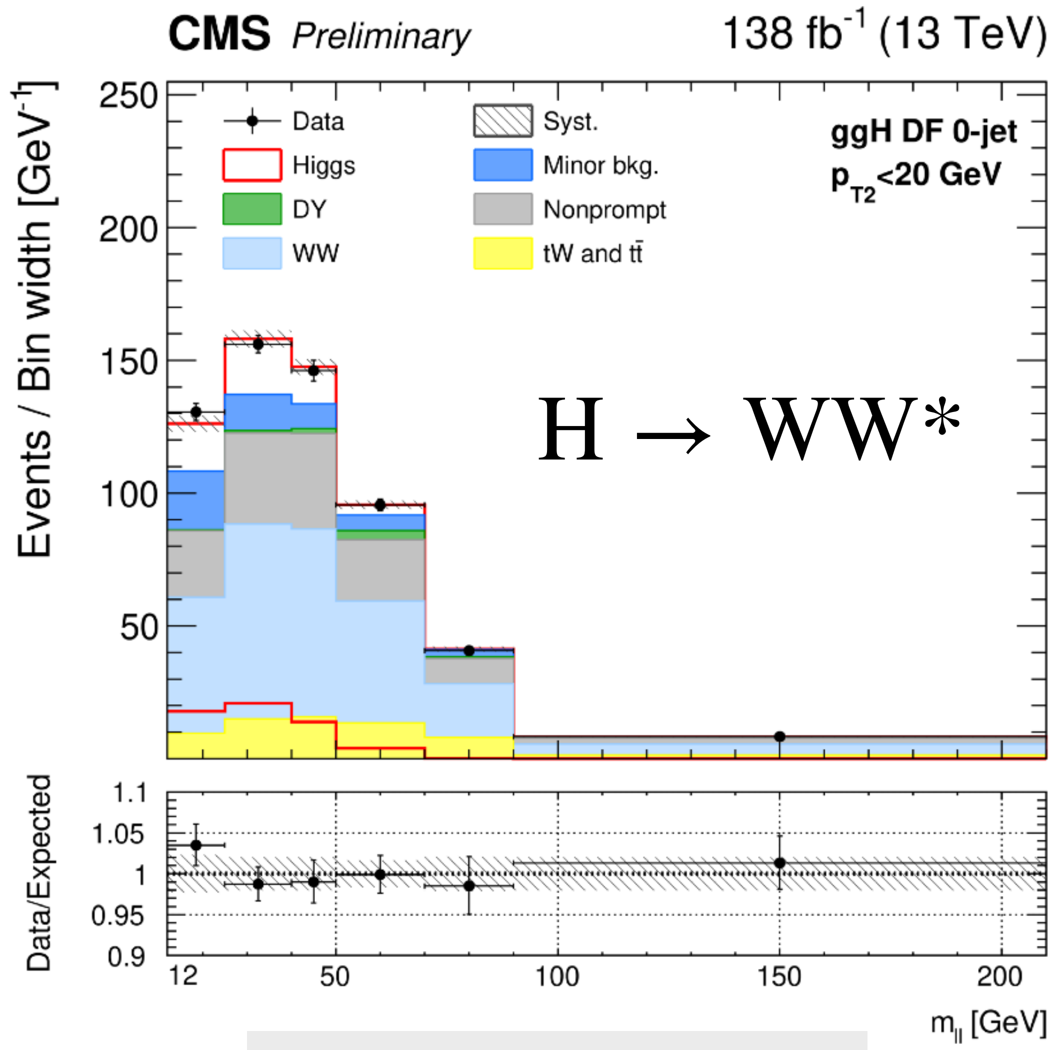
CMS-HIG-19-001
EPJC 81 (2021) 488



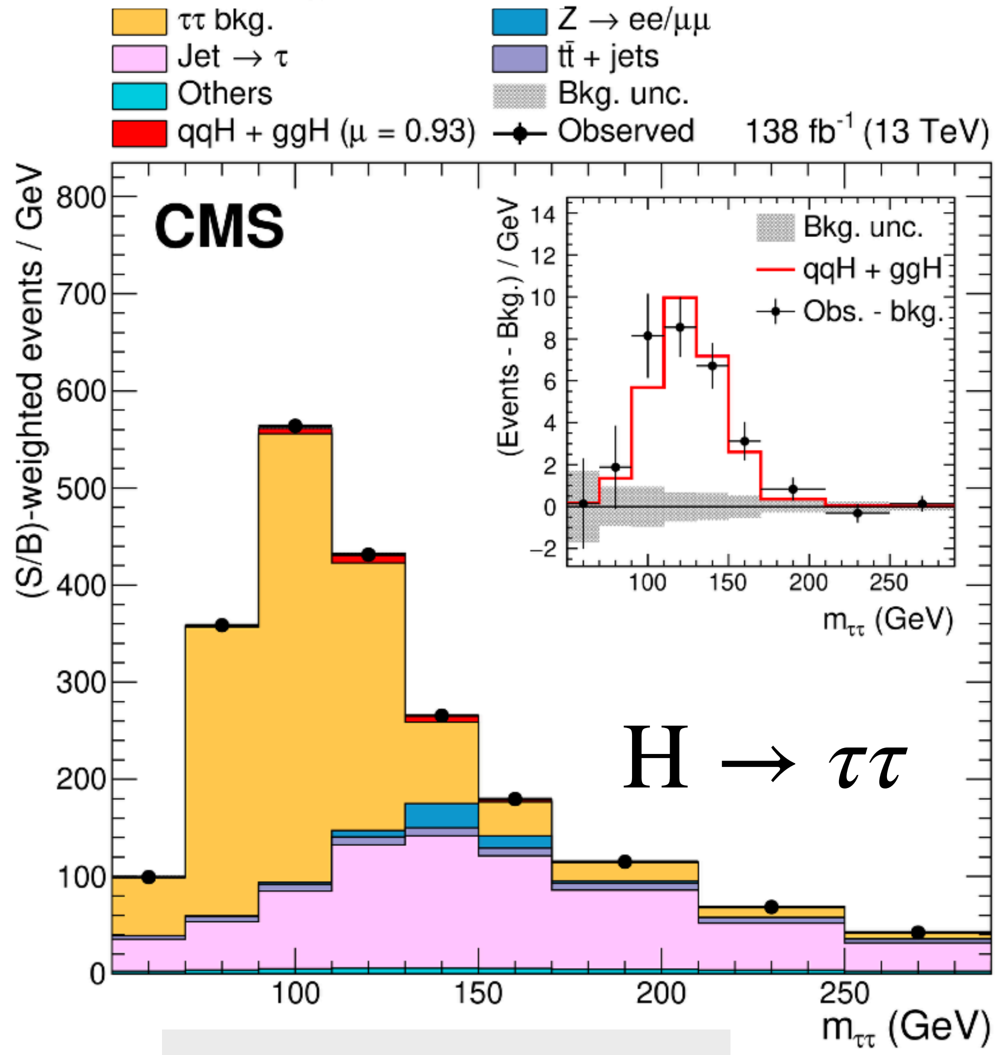
CMS-PAS-HIG-19-005

Observation independently in all 5 decay modes

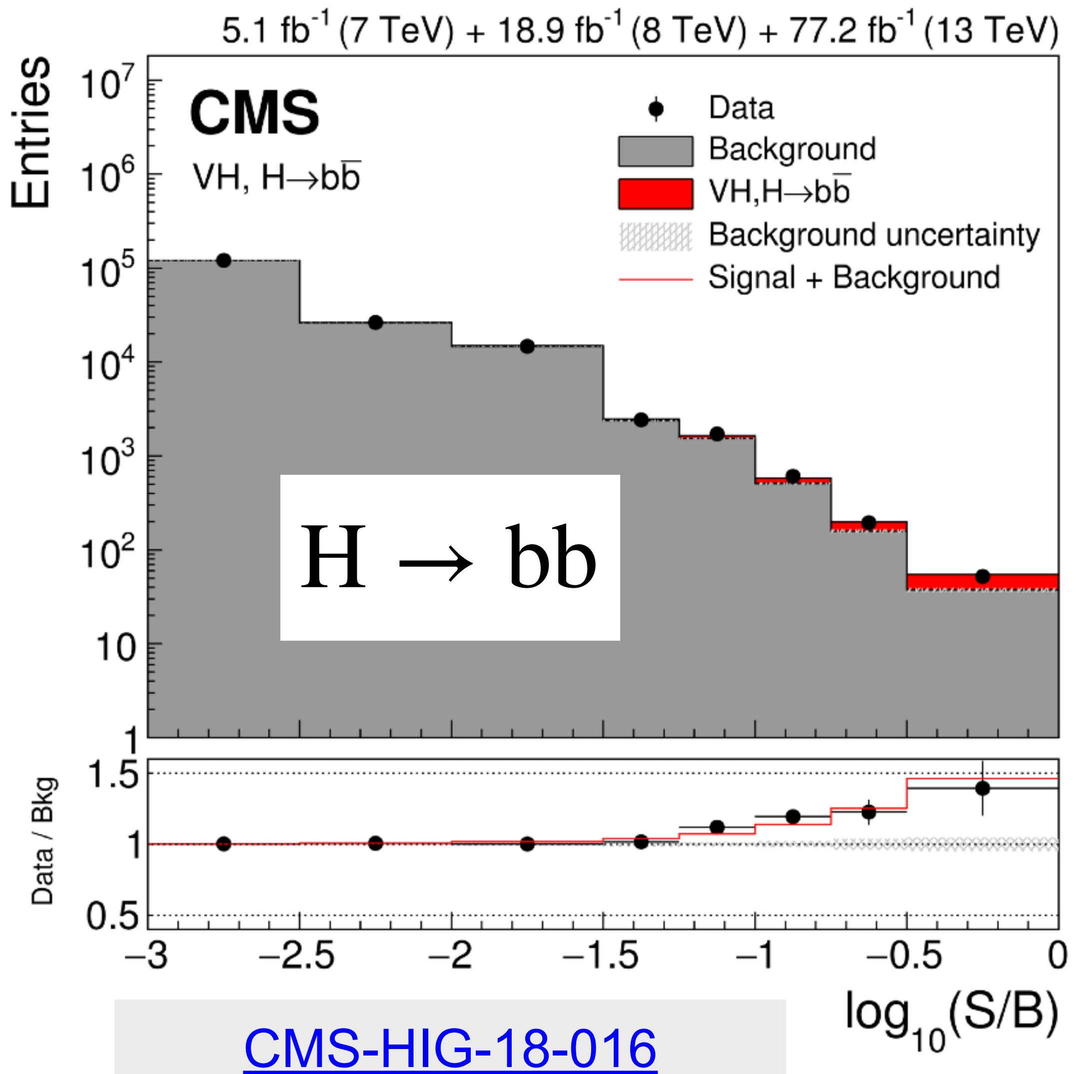




CMS-PAS-HIG-20-013



CMS-HIG-19-010
Submitted to EPJC



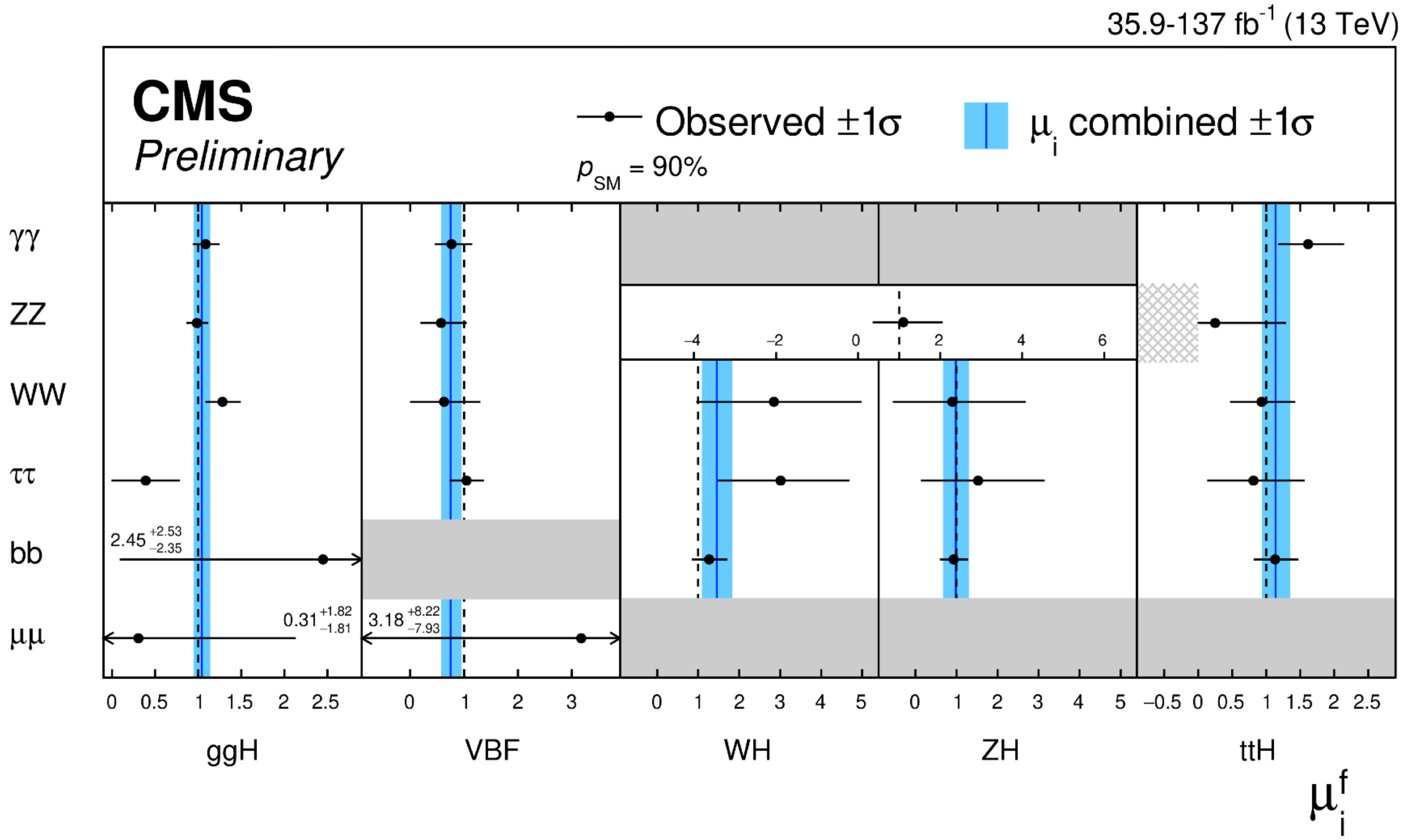
CMS-HIG-18-016
PRL 121 (2018) 121801

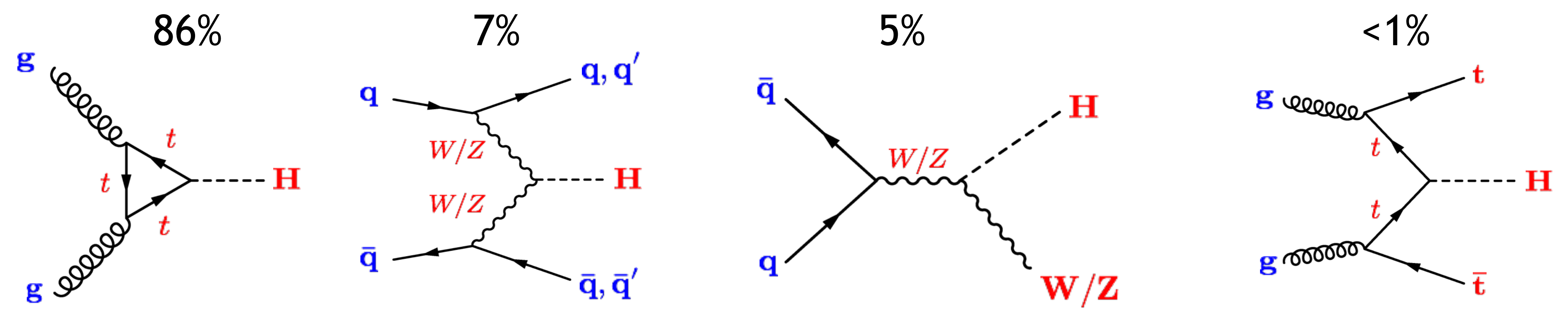
Higgs Production and Decay

July 4 2022

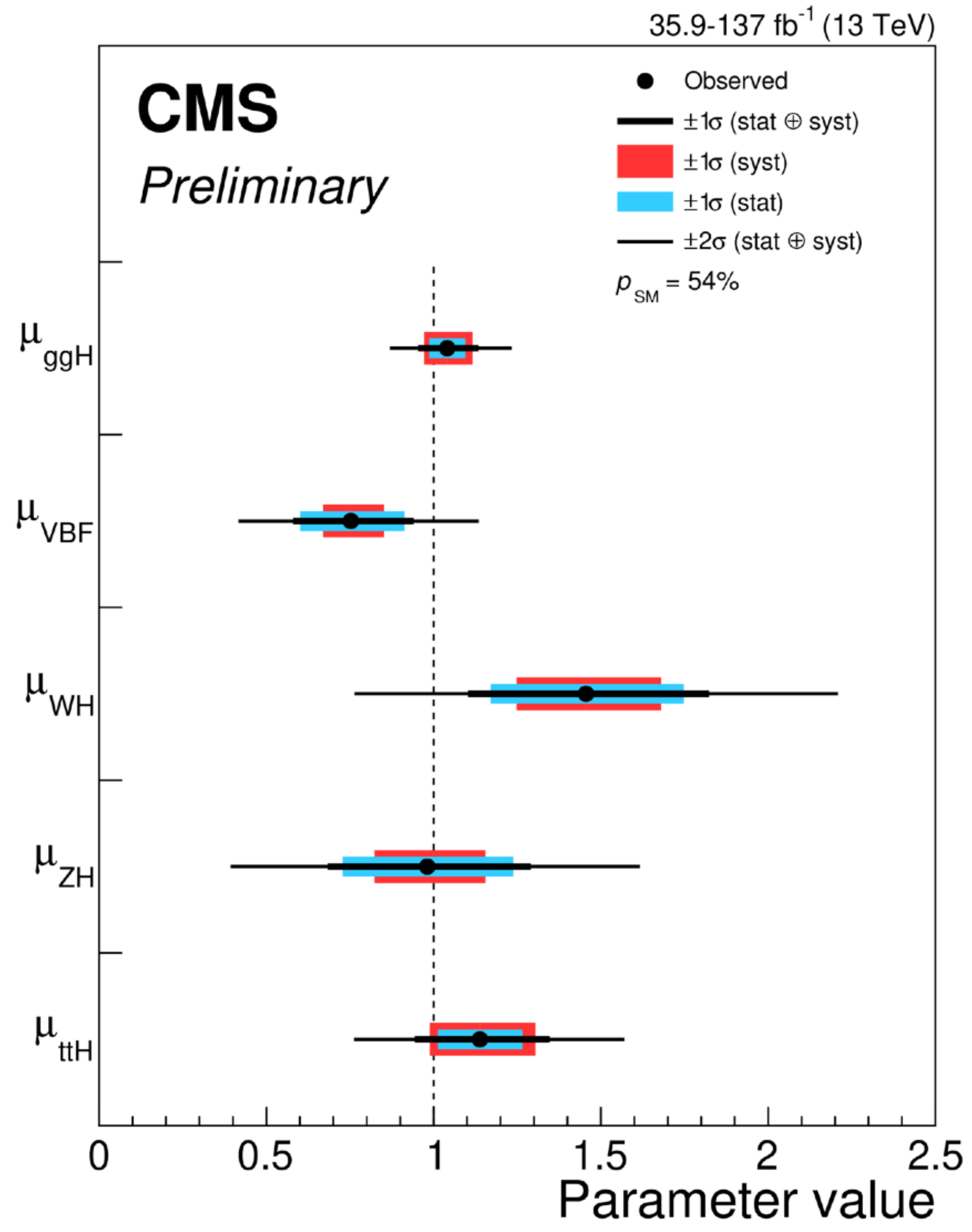
Signal strength modifiers for the production × decay mode

CMS-PAS-HIG-19-005

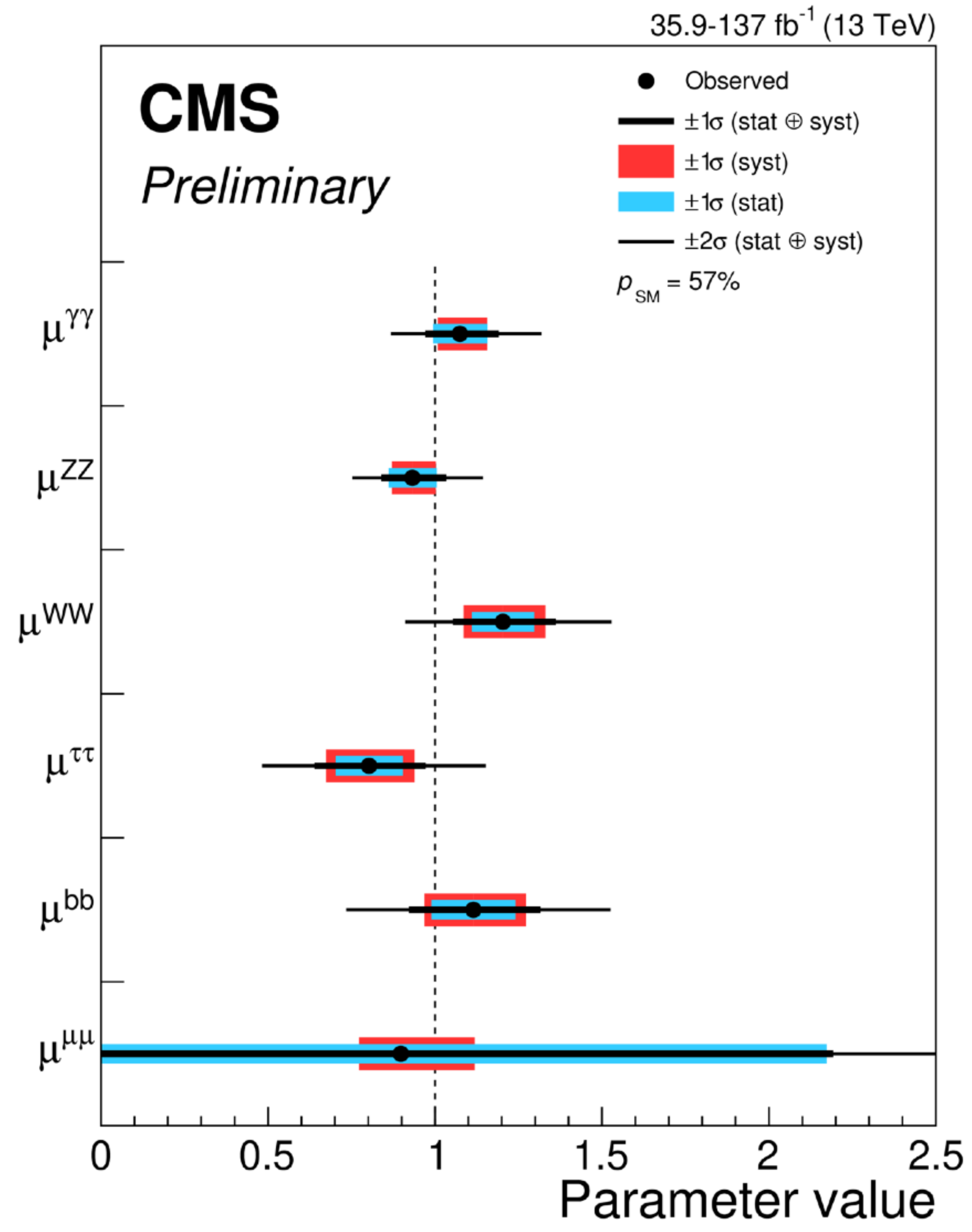




Observation independently
in all 5 decay and 5 production modes



Production



Decay

will be updated (very) soon
with full Run-2 data

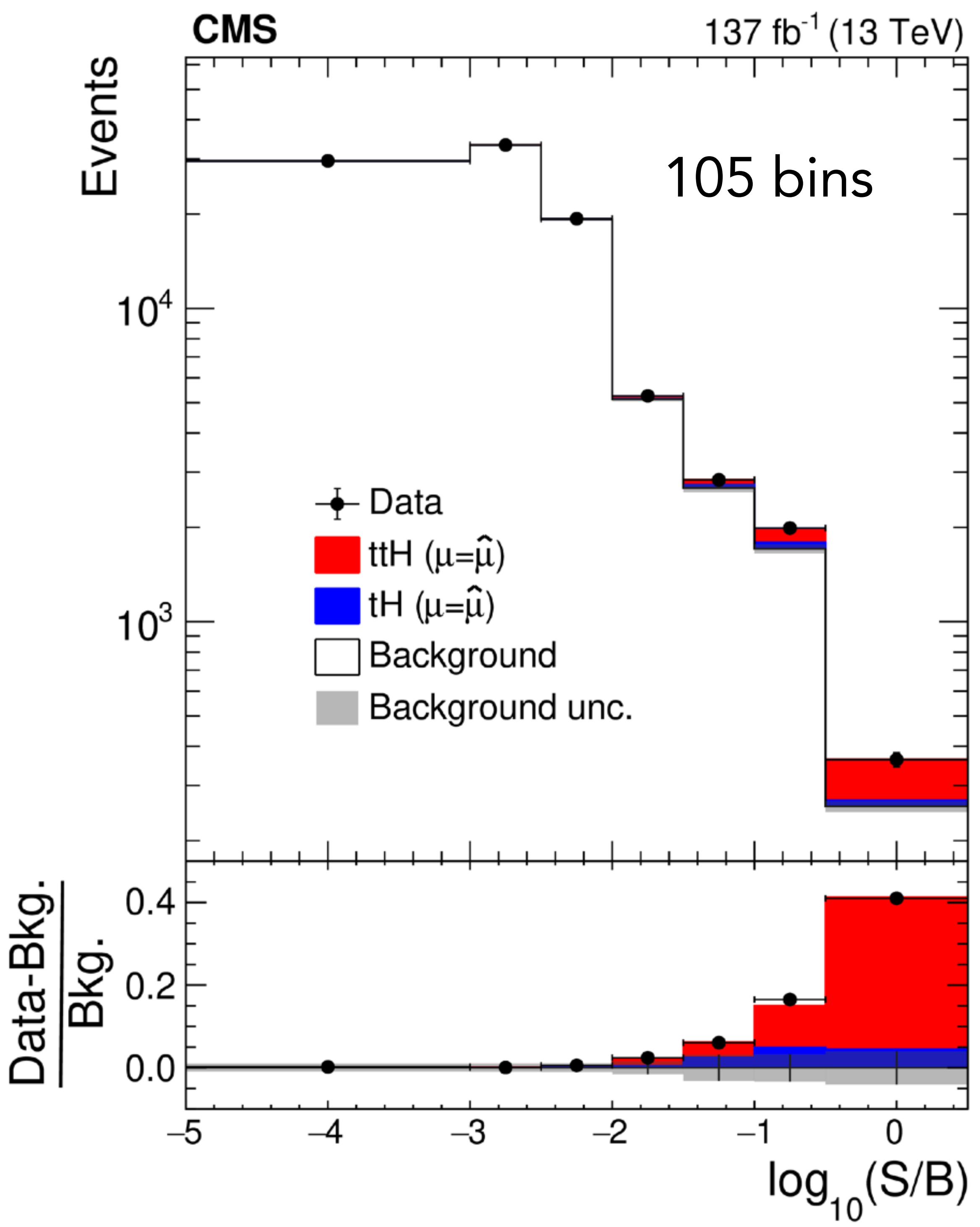
Higgs ttH and tH Production

2018: First observation at 5.2 (4.2) σ obtained by combing independent searches in the main decay modes with Run-1+Run-2 (2016) data

CMS-HIG-17-035
PRL 120 (2018) 231801

Since then, with full Run-2 data:

- strong evidence 4.7 (5.2) σ in the multi lepton final state
- observation in the $\mathrm{H} \rightarrow \gamma\gamma$ decay mode
- comprehensive study of CP structure and constraints on anomalous couplings combining $\mathrm{H} \rightarrow 4\ell$ and $\mathrm{H} \rightarrow \gamma\gamma$



Multi-lepton final states (e, μ, τ_h)
mostly $\mathrm{H} \rightarrow WW, ZZ, \tau\tau$

CMS-HIG-19-008
EPJC 81 (2021) 378

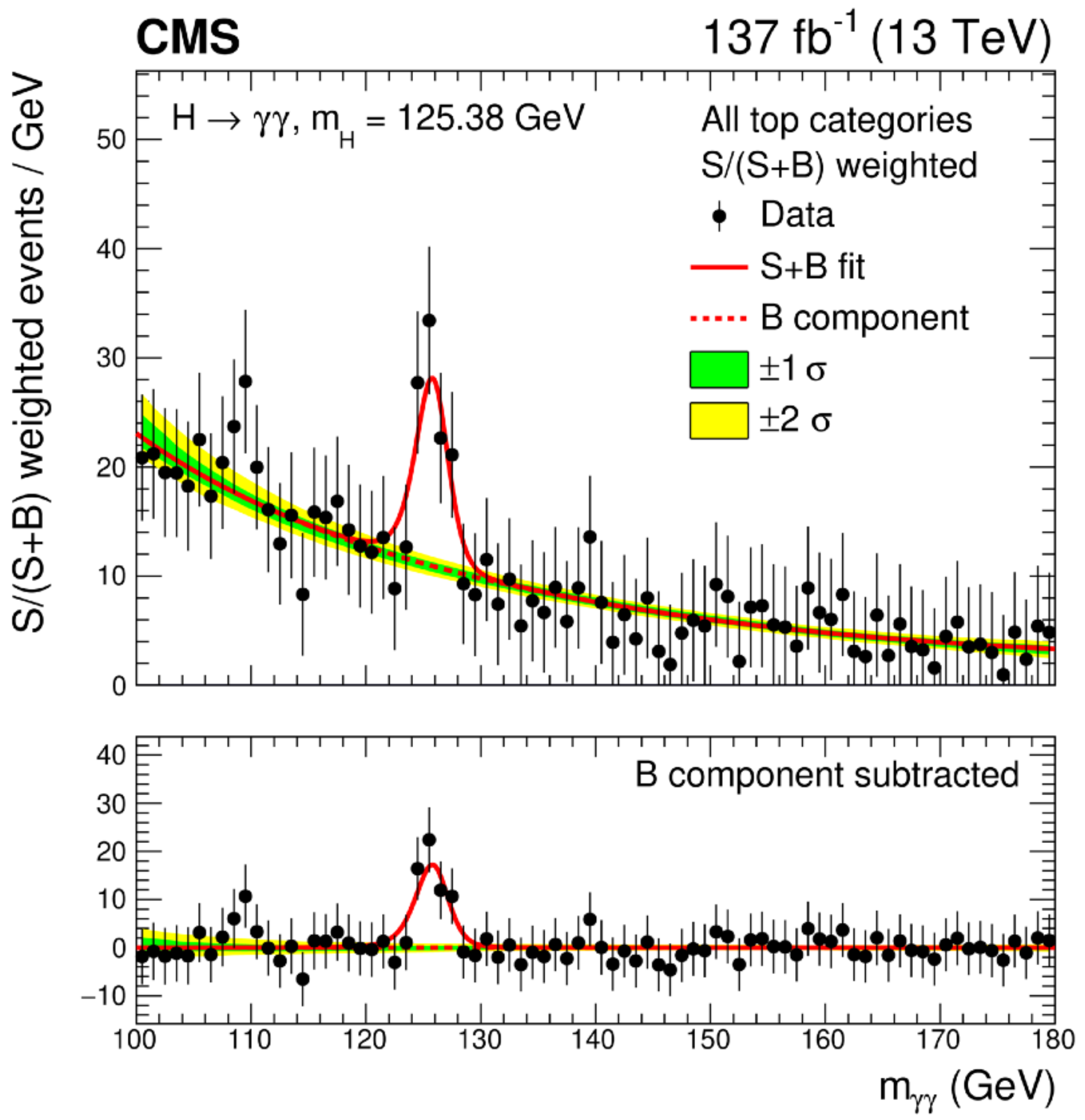
Phys. Briefing

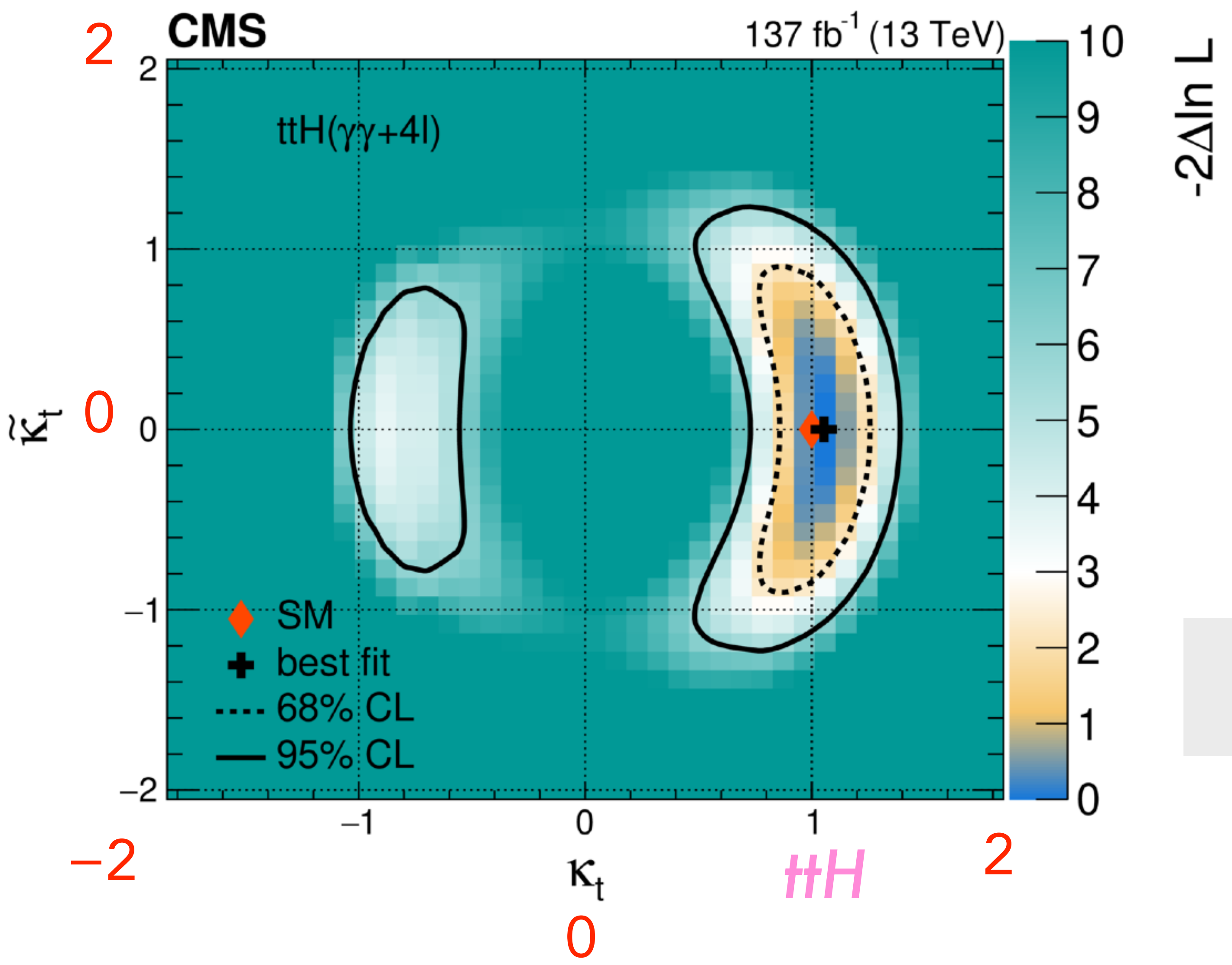
CMS-HIG-19-009
Submitted to PRD

Phys. Briefing

$\mathrm{H} \rightarrow \gamma\gamma$

Full Run-2, 137 fb^{-1}





$\mathrm{H} \rightarrow 4\ell$ and $\mathrm{H} \rightarrow \gamma\gamma$

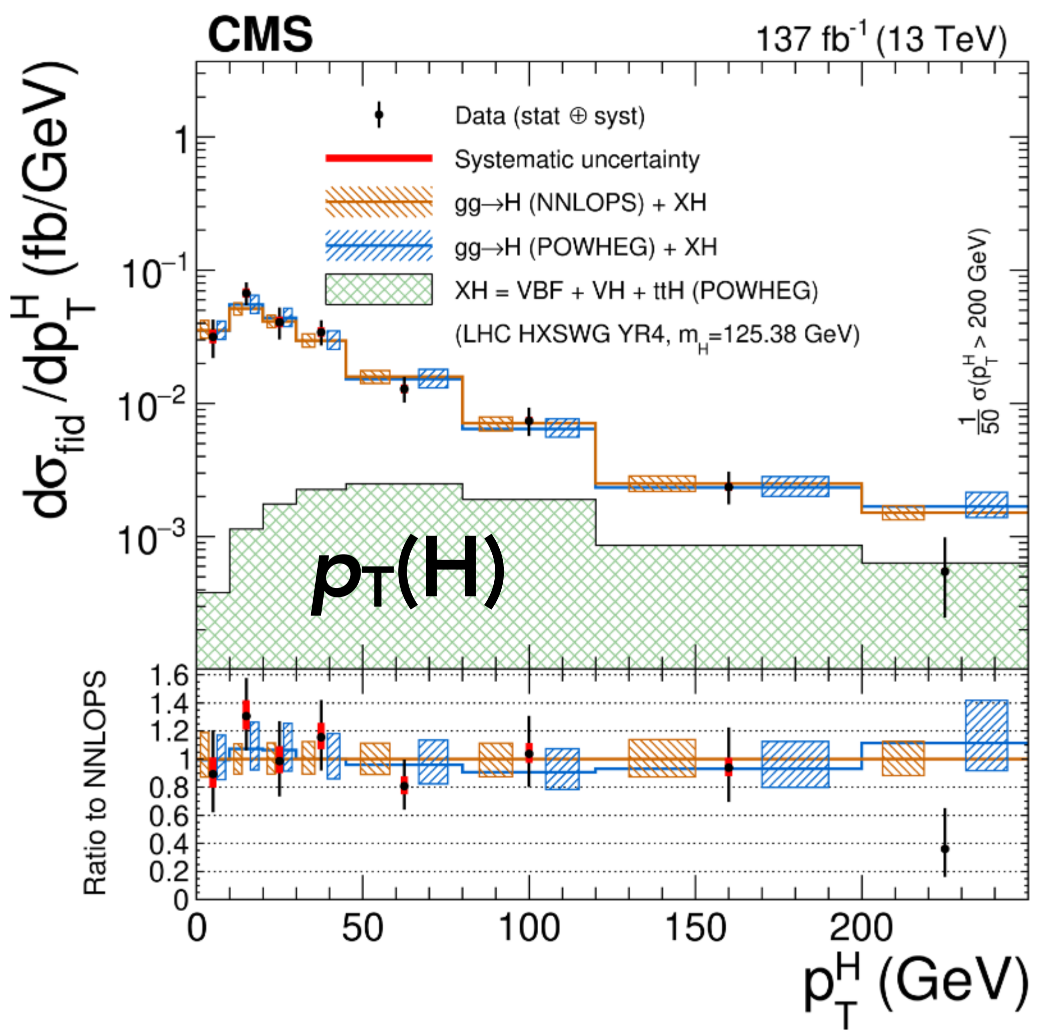
CMS-HIG-19-015
JHEP 07 (2021) 027

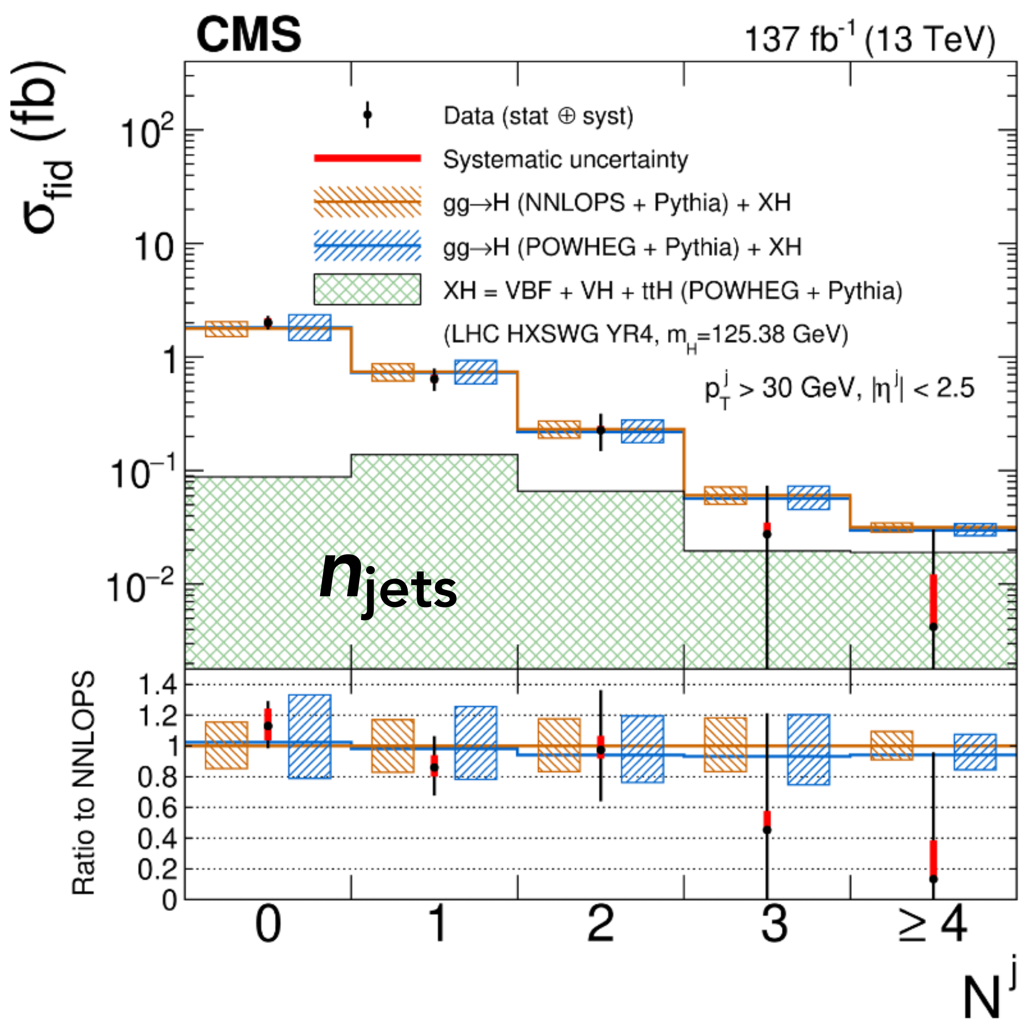
Phys. Briefing

Higgs Differential Cross Sections

- $H \to ZZ^* \to 4\ell$

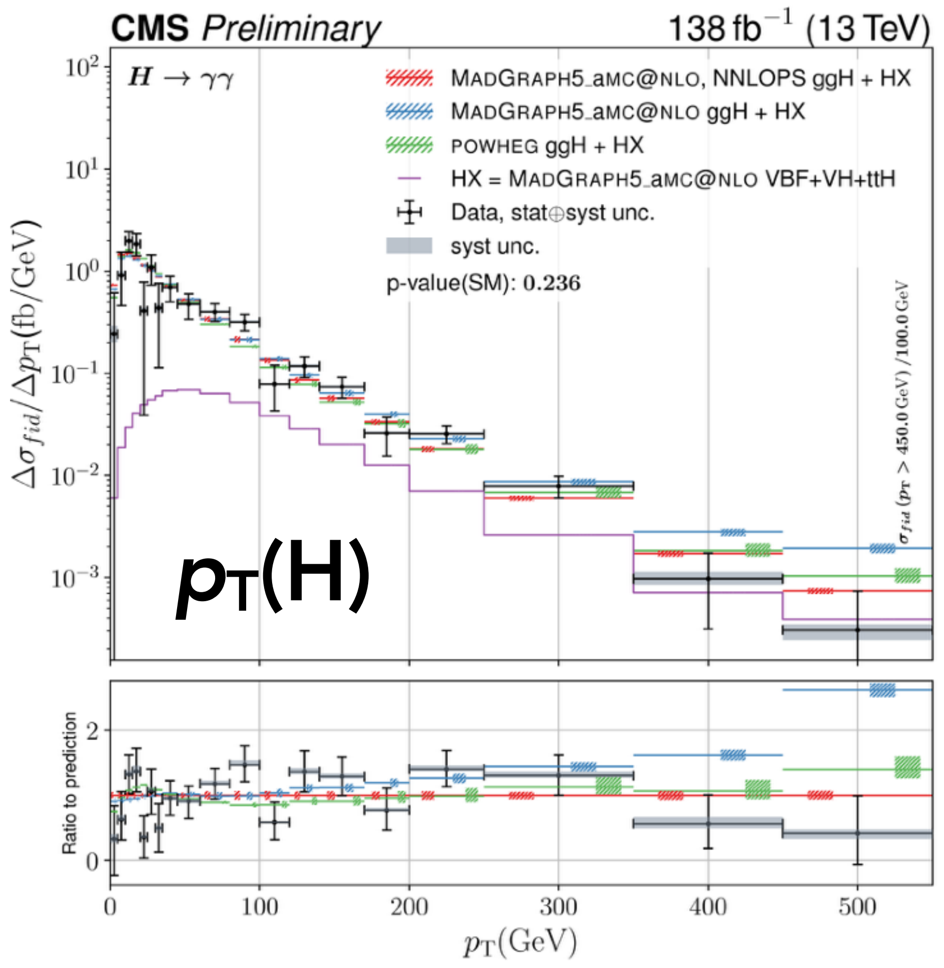
CMS-HIG-19-001
EPJC 81 (2021) 488

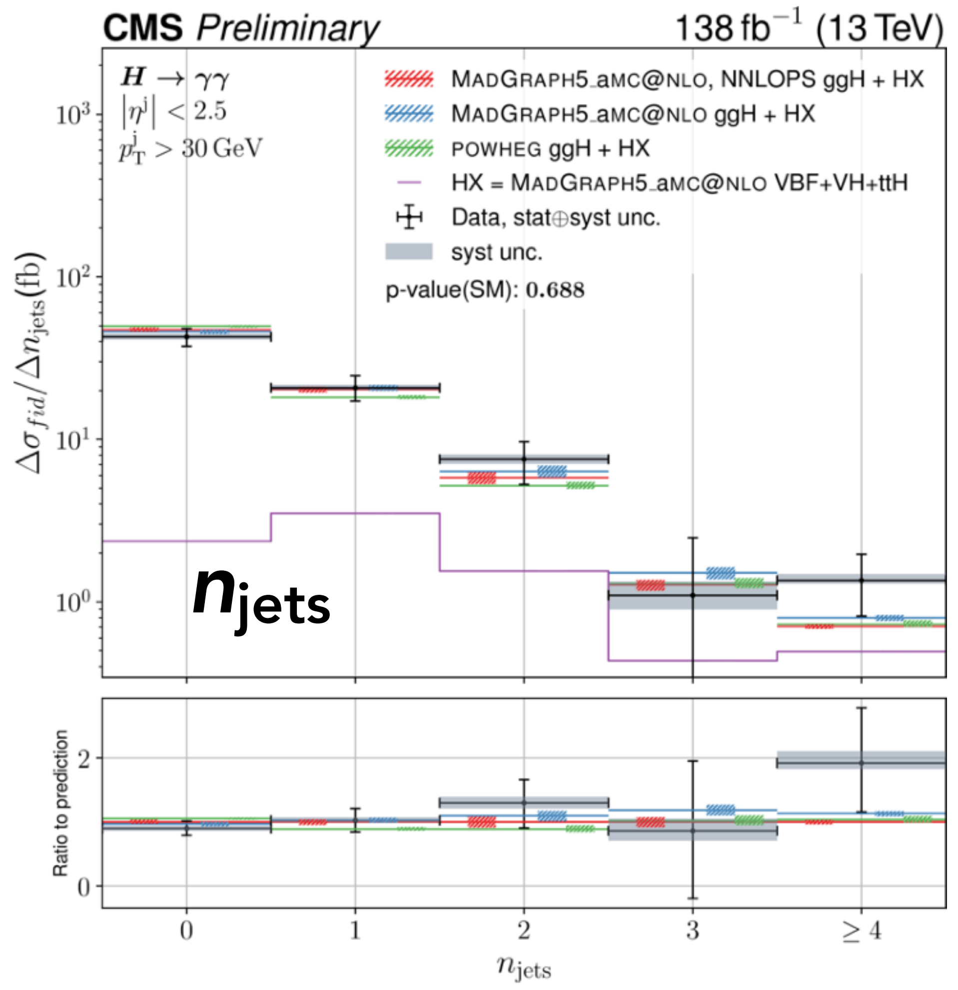




- $H \to \gamma\gamma$

CMS-PAS-HIG-19-016





Full Run-2, 137 fb^{-1}

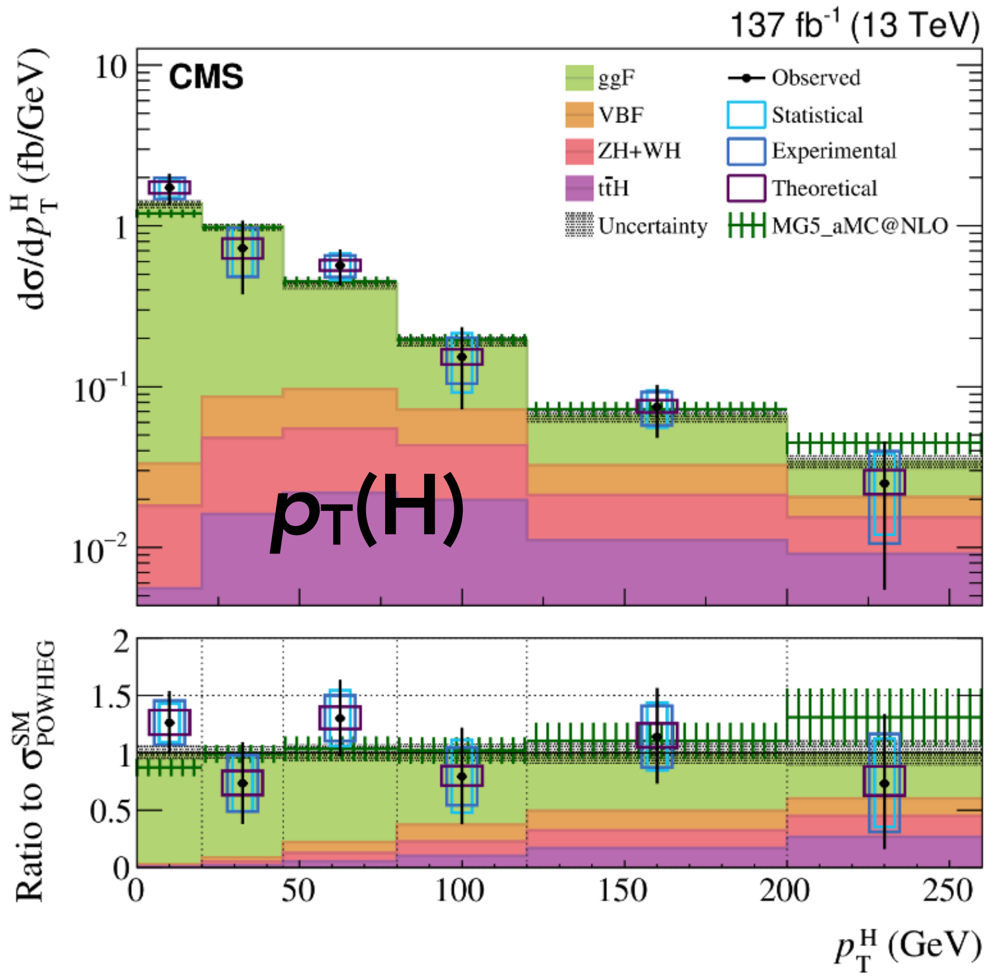
- $H \to WW^* \to e^{\pm}\mu^{\mp}\nu\bar{\nu}$

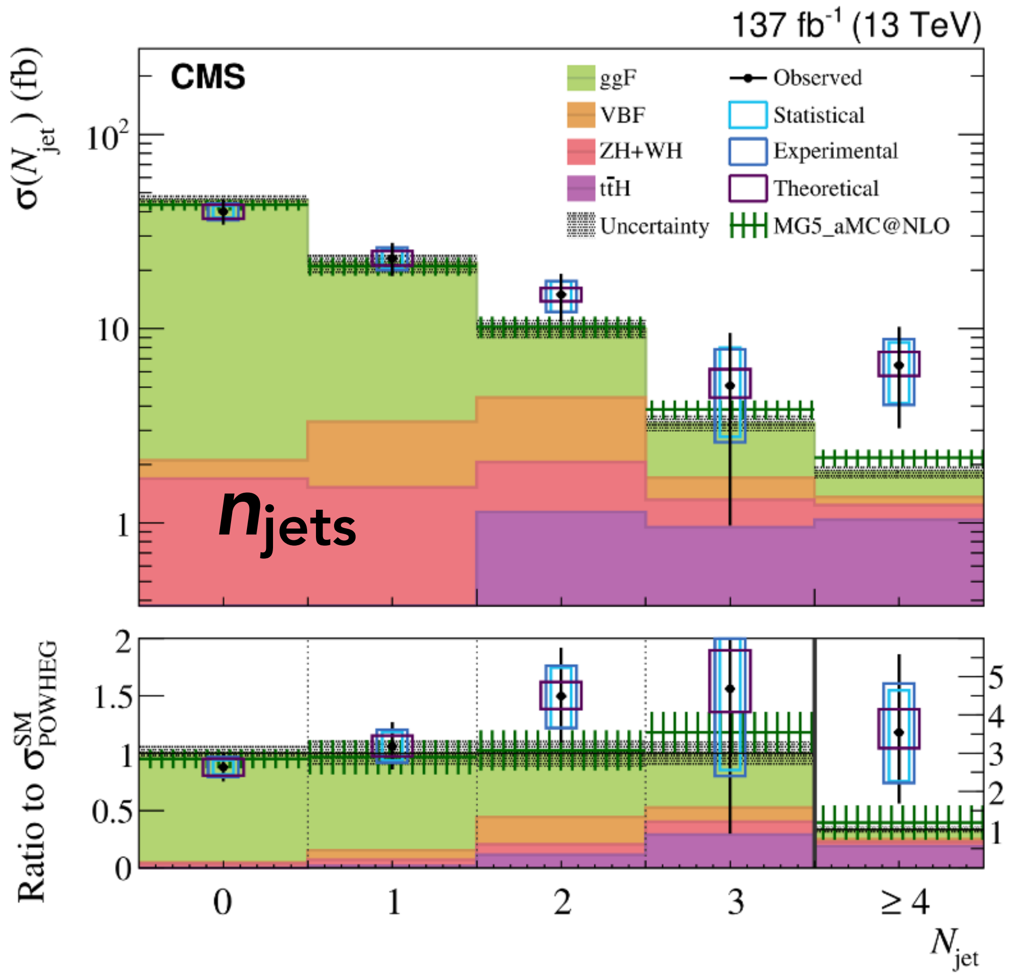
Differential fiducial production cross sections, unfolded for selection efficiency and resolution effects and compared to theoretical calculations

no significant deviation from SM predictions

CMS-HIG-19-002
JHEP 03 (2021) 003

Phys. Briefing





Also in $H \to \tau\tau$:

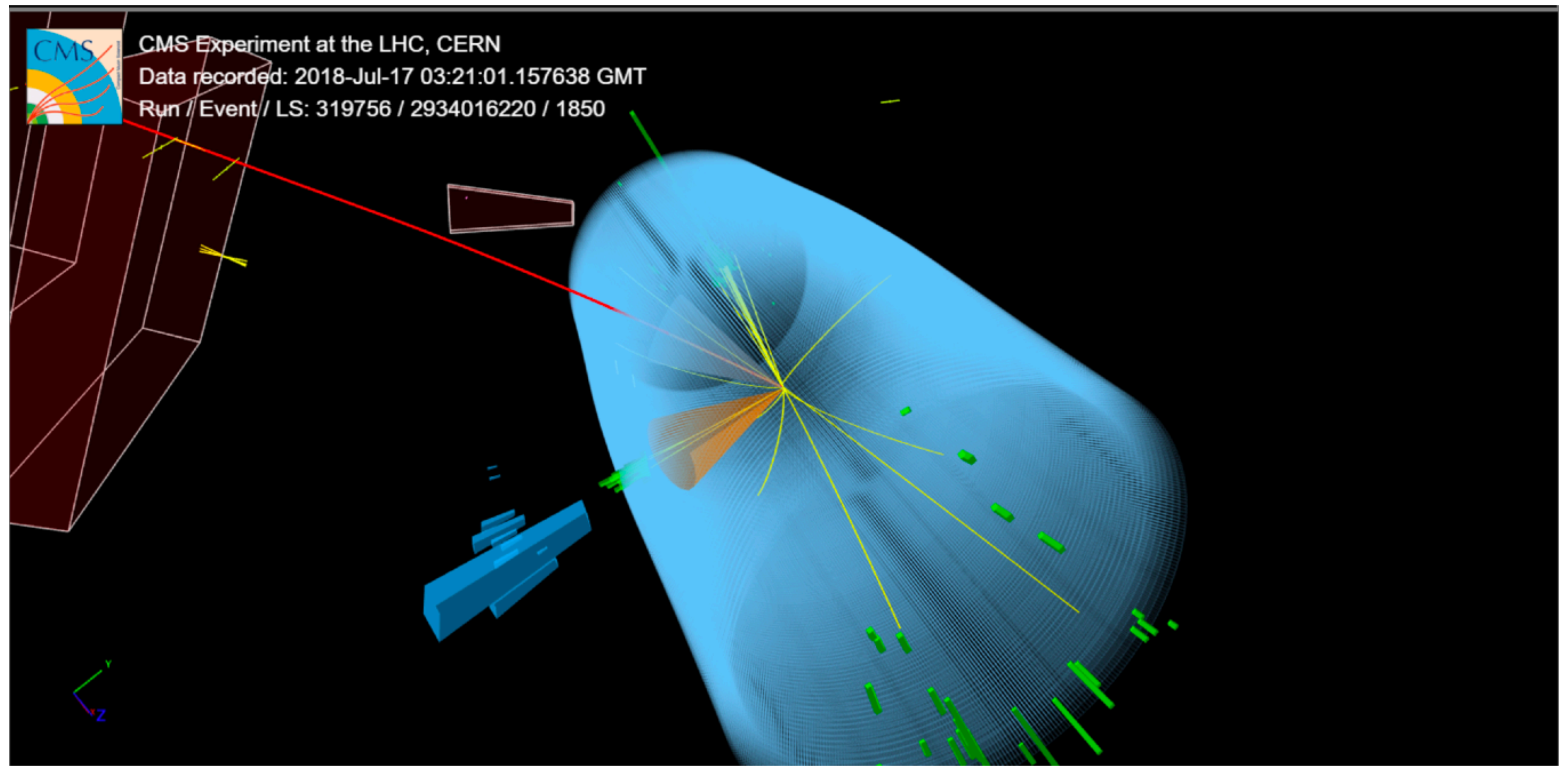
CMS-HIG-20-015
PRL 128 (2022) 081805

Higgs CP Properties of the $H \to \tau\tau$ Decay

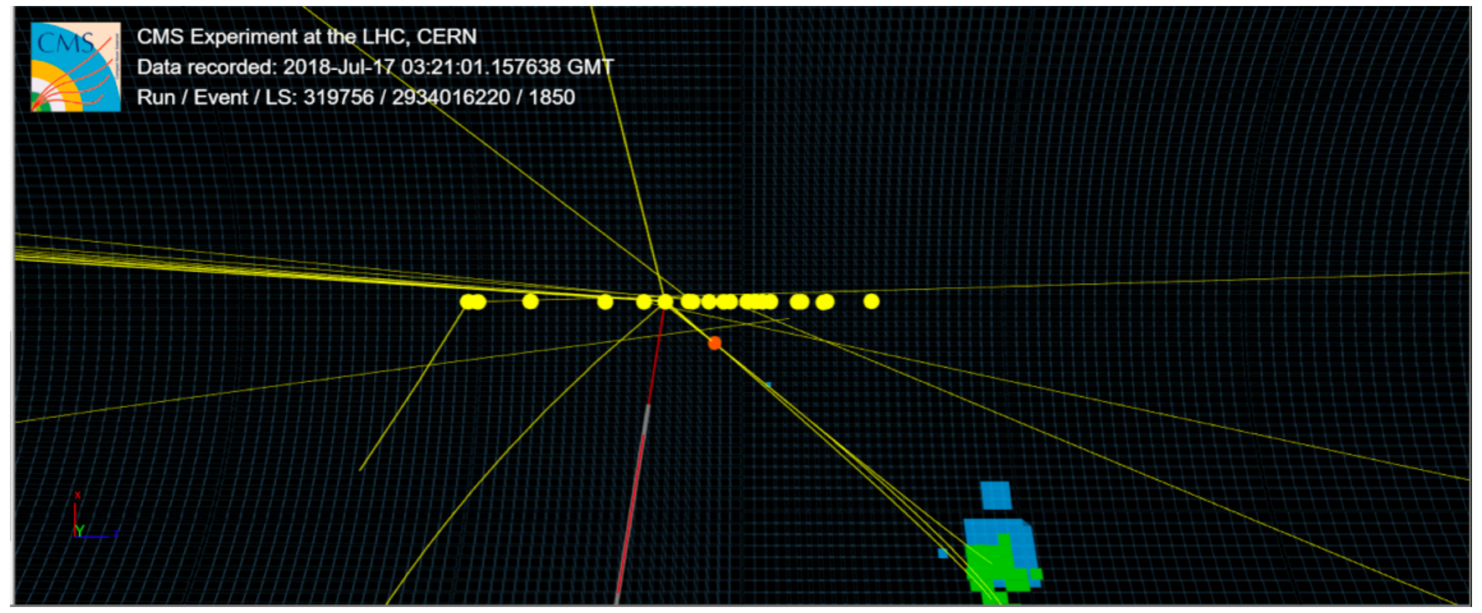
ϕ_{CP} : a variable sensitive to the **polarisation of the τ leptons**

- angle between the τ decay planes in the H rest frame
- 0° in the CP-even case (SM) vs ±90° in the CP-odd case
- measured using either the 1-prong momentum and impact parameter vector, the $\pi^0(\to\gamma\gamma)$ momentum or $\rho^0(\to\pi^+\pi^-)$ momentum (3-prong)

An example $\tau^+(\to \mu^+\nu\nu)\ \tau^-(\to \pi^+\pi^-\pi^-\nu)$ candidate



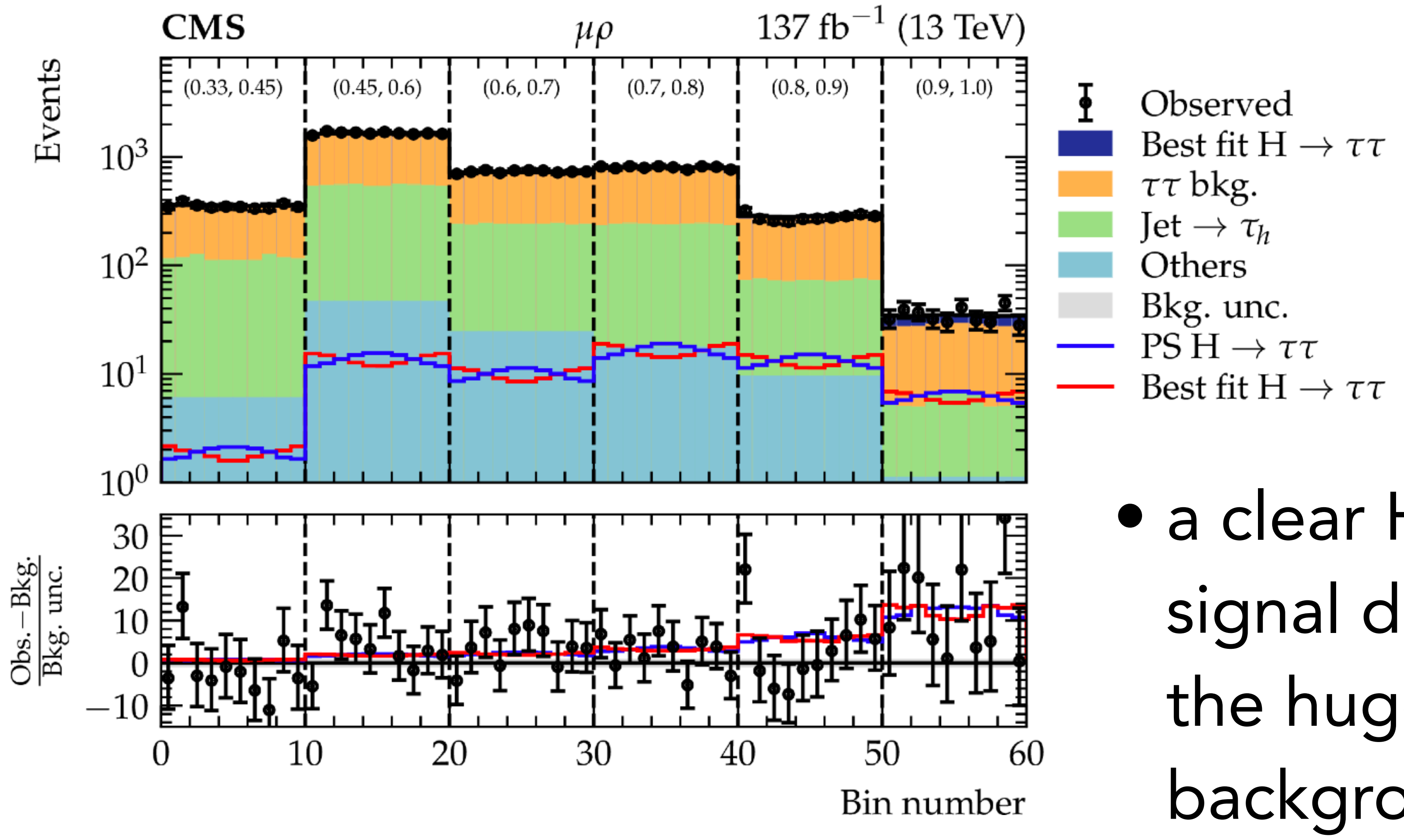
Zoom on the interaction region: impact parameter and secondary vertex



CMS-HIG-20-006
JHEP 06 (2022) 012

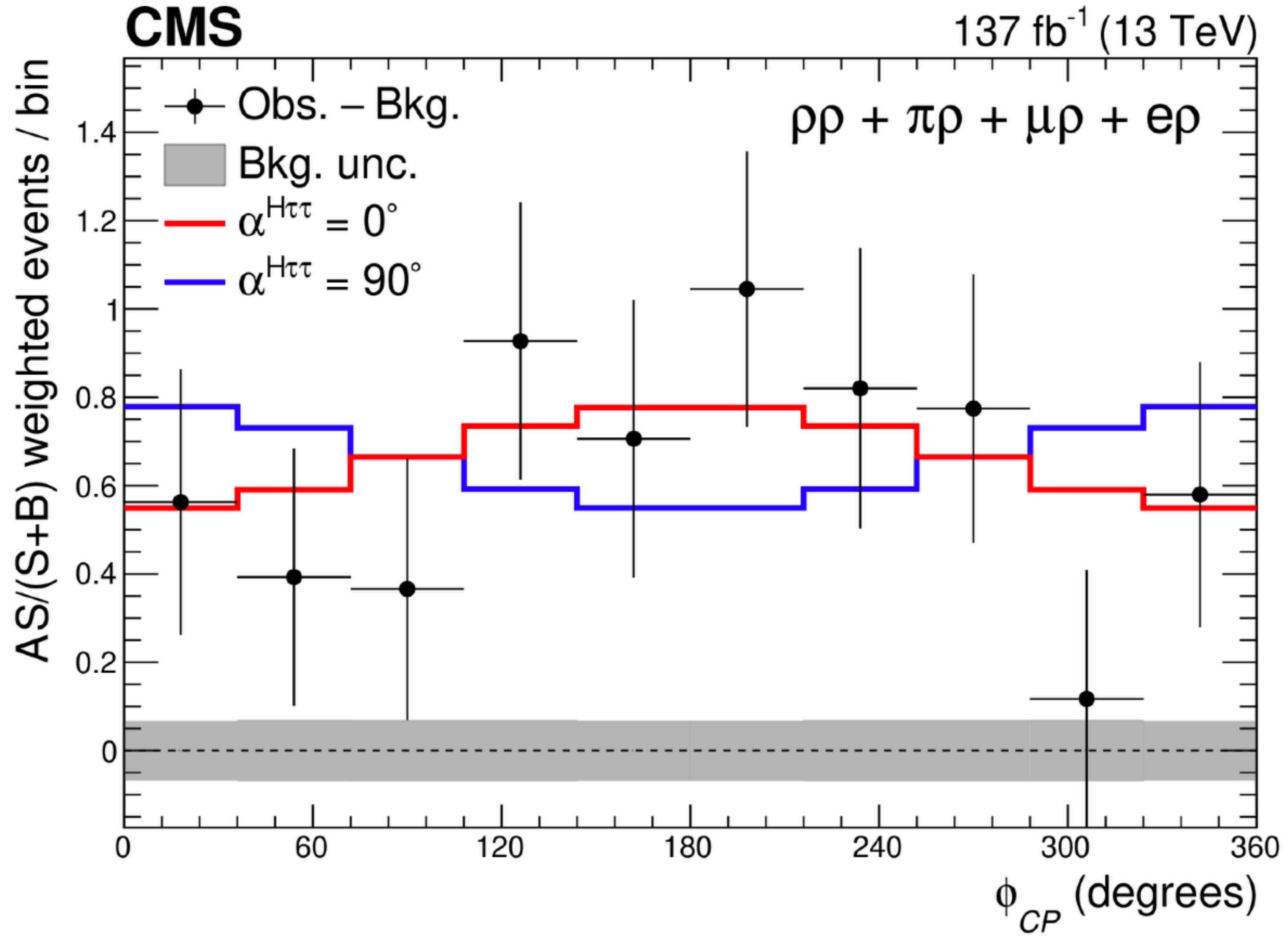
Full Run-2, 137 fb^{-1}

ϕ_{CP} distribution considered in different bins of a BDT score



- a clear H→ττ signal despite the huge Z→ττ background

Overall weighted distribution



$\phi_{CP} = 4^\circ \pm 17^\circ$

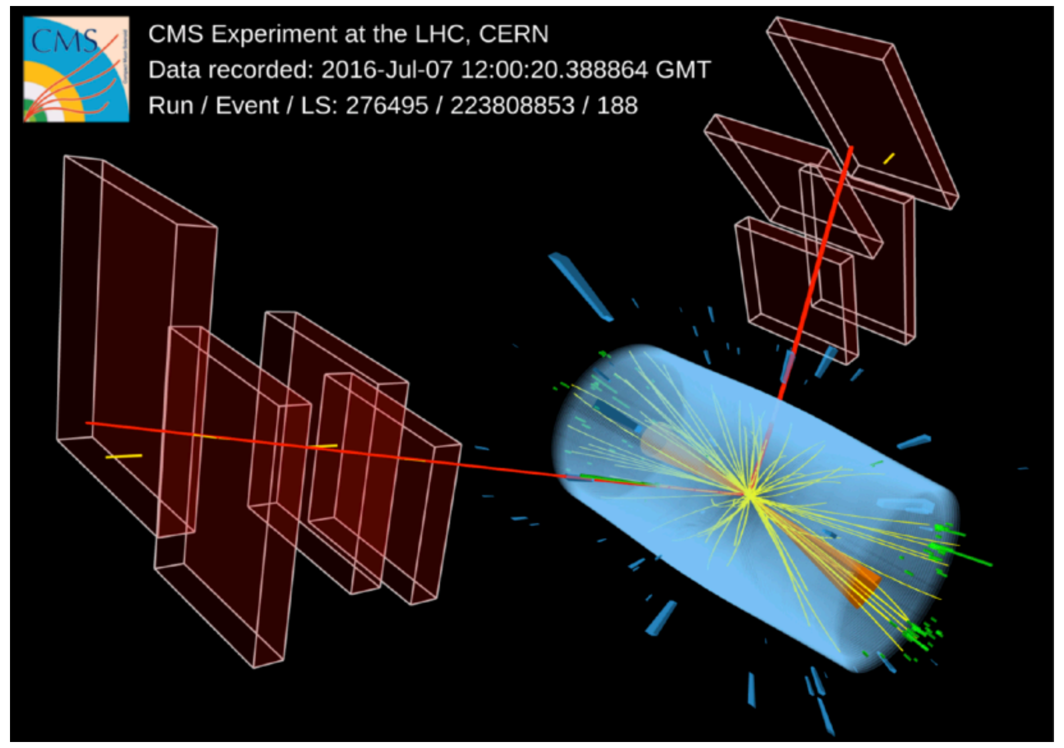
- **CP-even** preferred to CP-odd at the ~3σ level!

Rare Higgs Decays: H → μμ and H → Zγ

$H \to \mu^+\mu^-$

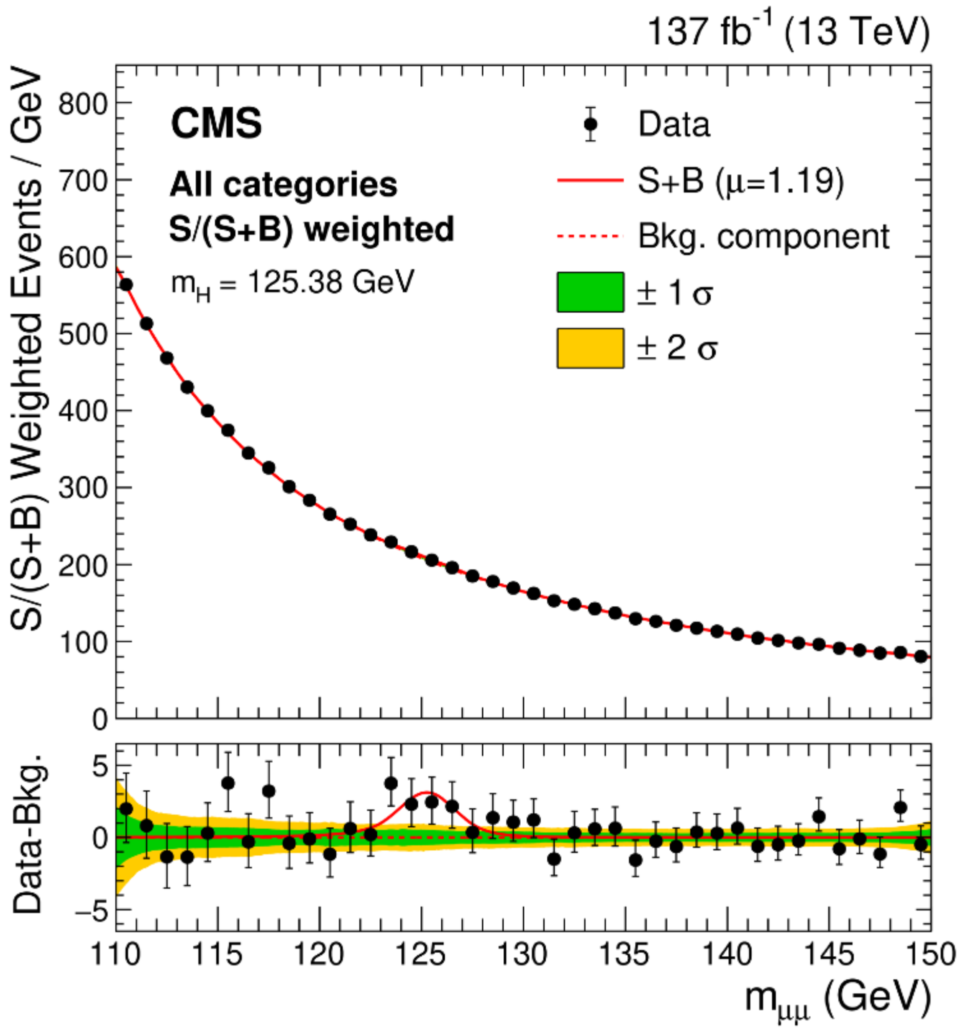
CMS-HIG-19-006
JHEP 01 (2021) 148

Phys. Briefing



improved sensitivity thanks to the use of advanced ML techniques in the VBF analysis

$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$$



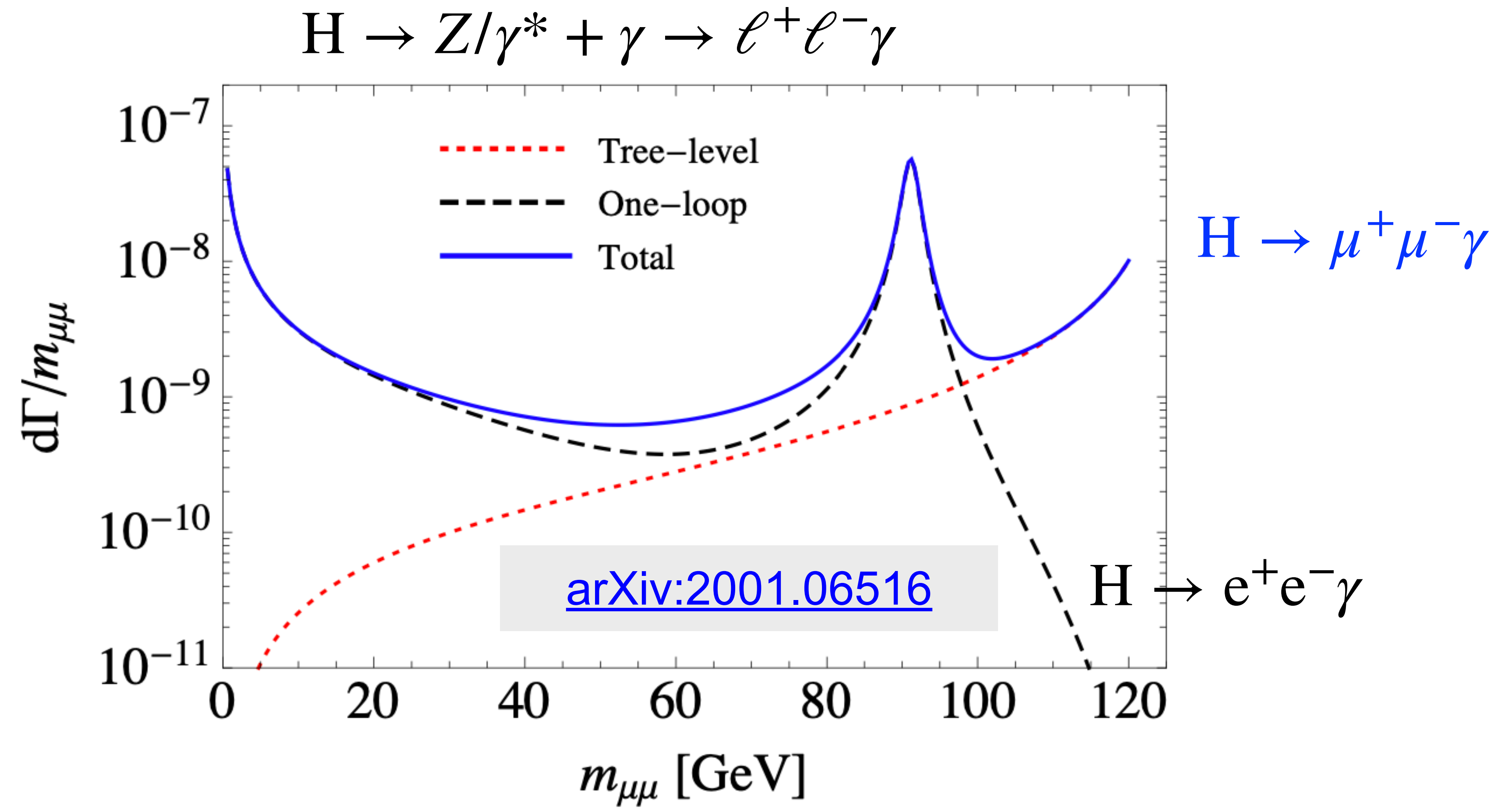
Obs. (exp.) significance: 3.0 (2.5) σ

First evidence of Higgs coupling to the second generation

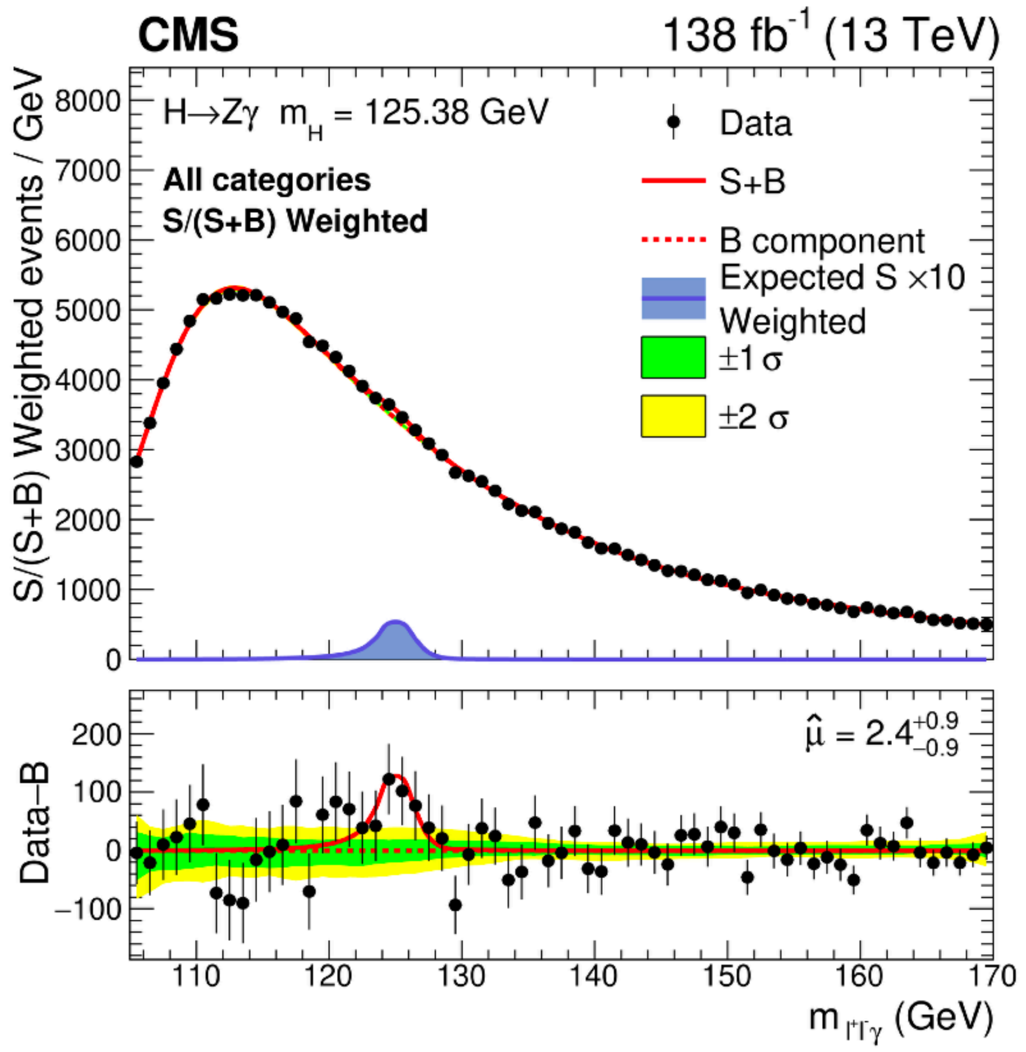
$$\kappa_\mu = 1.07 \pm 0.22\,(\text{at } 68\%\text{CL})$$

$H \to Z\gamma$

CMS-HIG-19-014
Submitted to JHEP



$m(\ell^+\ell^-) > 50$ GeV



Obs. (exp.) significance: 2.7 (1.2) σ

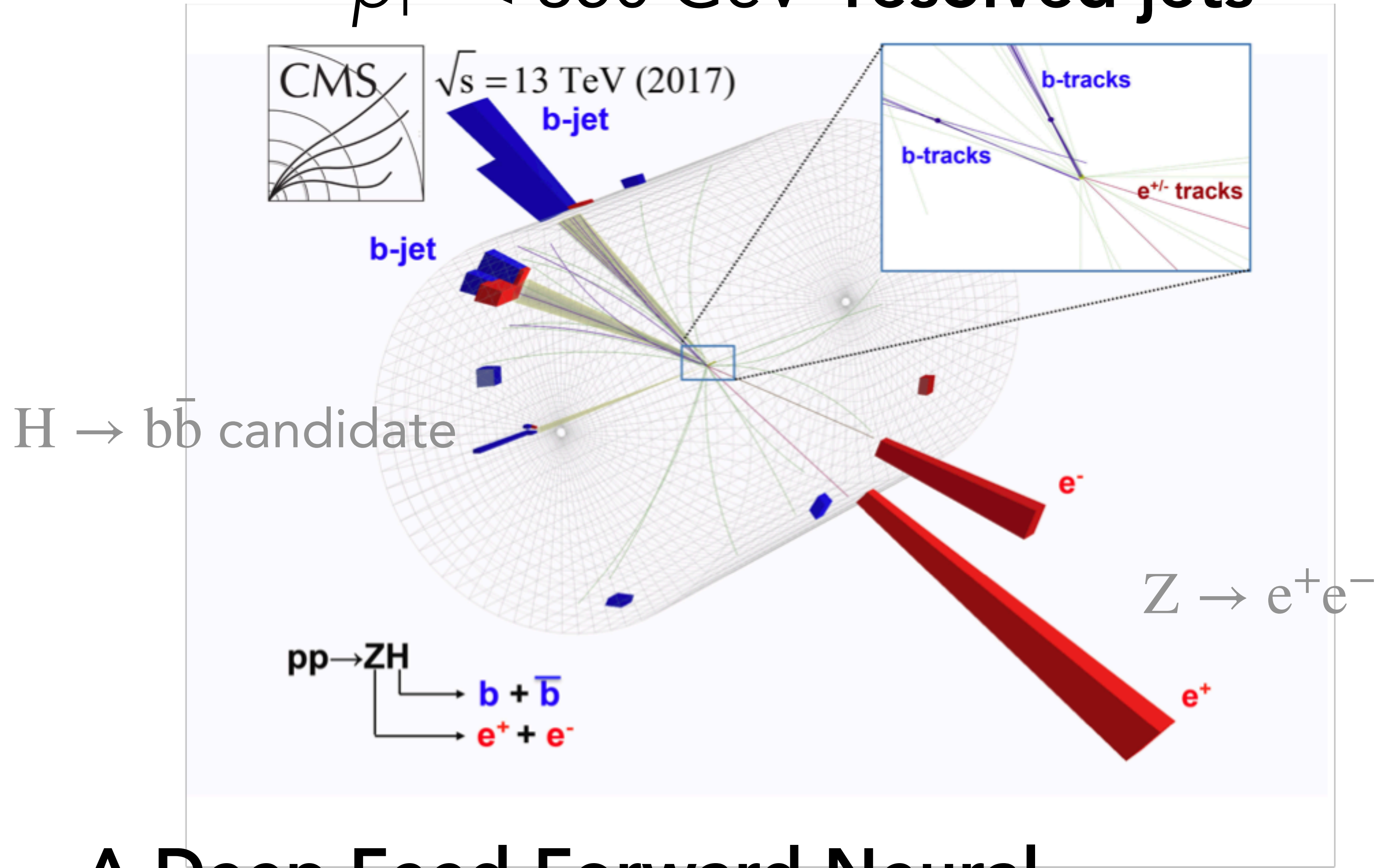
most of the excess in one of the VBF categories

$B(H \to Z\gamma)/B(H \to \gamma\gamma) = 1.5^{+0.7}_{-0.6}$ consistent with the SM expectation 0.69 ± 0.04 at the 1.5σ level

Boosted Higgs Boson

Full Run-2, 137 fb^{-1}

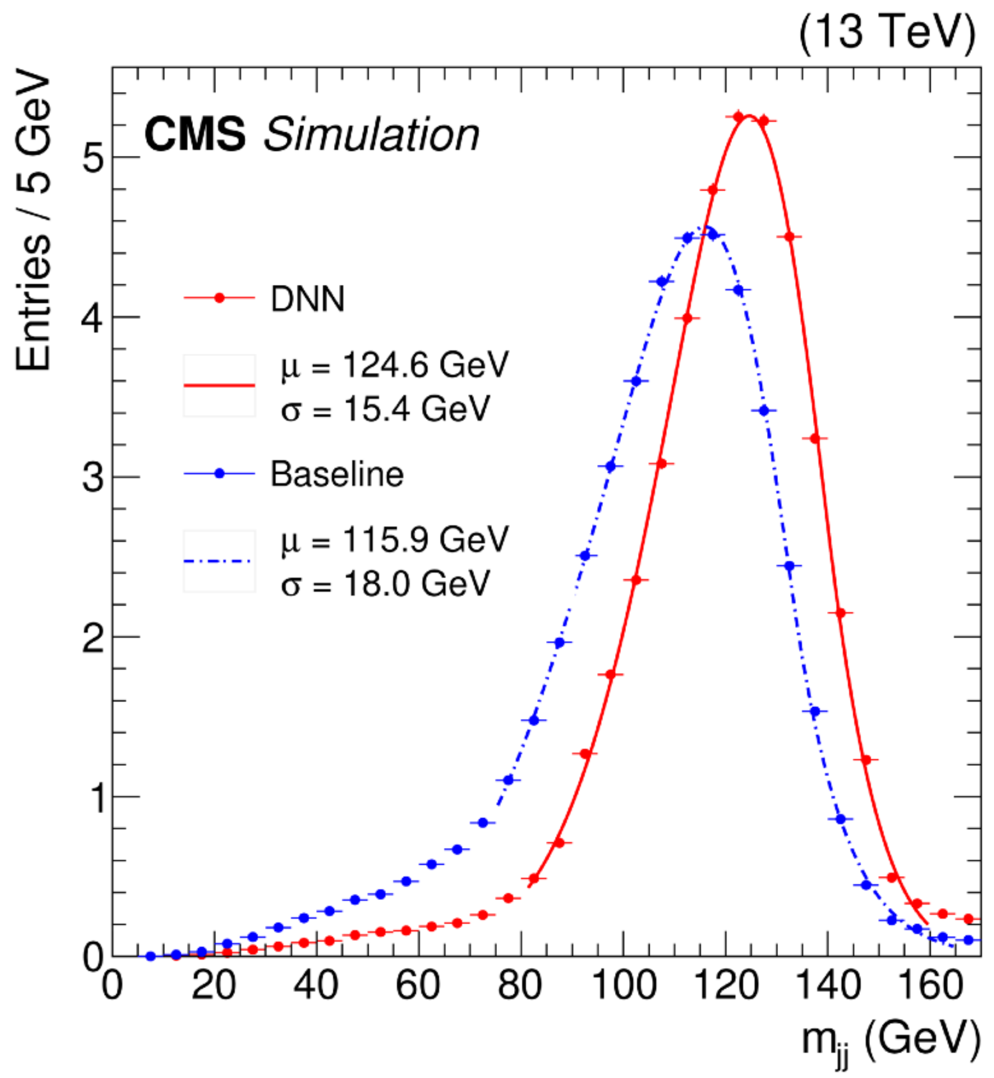
$p_T^H < 350$ GeV **resolved jets**



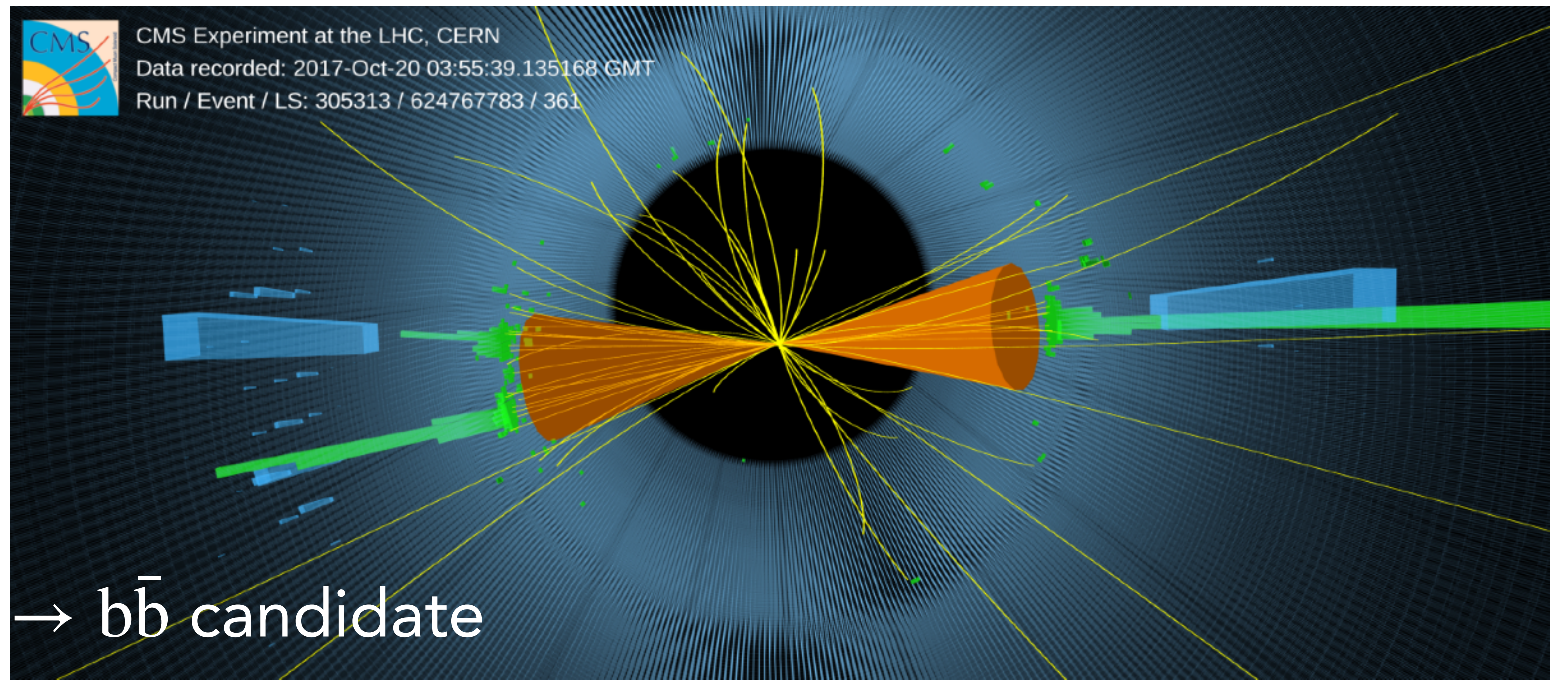
A Deep Feed-Forward Neural Network using jet properties information and secondary vertices associated to the jets (43 input variables)

- 13% improvement in jet resolution
- 20% improvement in di-jet mass resolution (as measured in data)

CMS-HIG-18-027
CSBS 4 (2020) 10



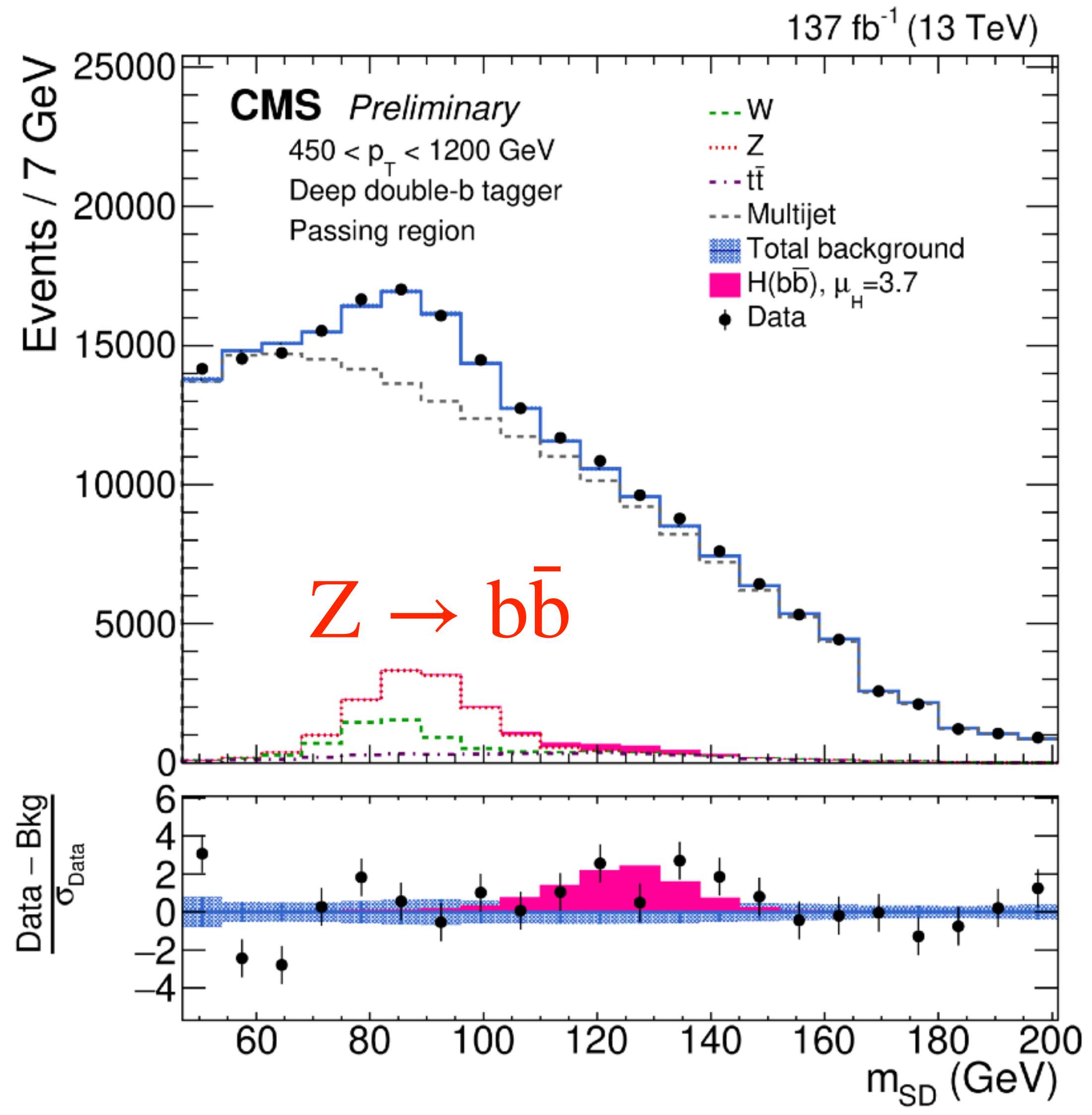
$p_T^H > 450$ GeV **merged jets**



huge improvement thanks to dedicated "deep double b tagger" (DDBT)

a technique validated with $Z \to b\bar{b}$

An Inclusive search for highly boosted $H \to b\bar{b}$



- a small (1.9σ) excess is observed

$\mu_H = 3.7^{+1.6}_{-1.5}$ 2.5σ (0.7σ exp)

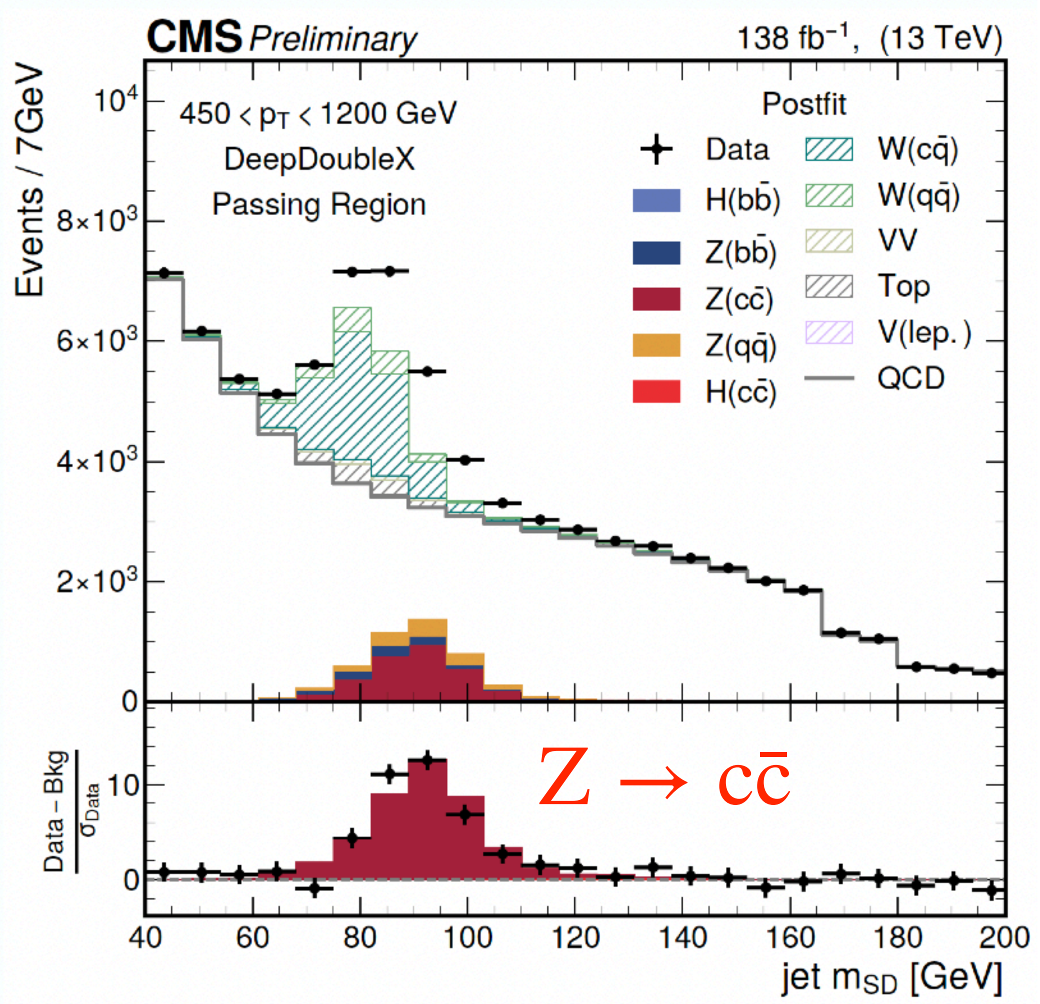
CMS-HIG-19-003
JHEP 12 (2020) 085

Phys. Briefing

Boosted Higgs Boson and Charm Decay

CMS-HIG-21-008
Submitted to PRL

An Inclusive search for highly-boosted $\mathrm{H} \rightarrow c\bar{c}$



Validation:

$$\mu_{Z\rightarrow c\bar{c}} = 1.06^{+0.18}_{-0.15} \quad (>10\sigma)$$

H(cc̄) signal strength (fixing Z(cc̄) to SM)

- $\mu_{\mathrm{H}} = 8\,^{+20}_{-19}$
- obs (exp) upper limit @95% CL: 45 (38) × SM

CMS-PAS-HIG-21-012

An search for boosted $\mathrm{VH(H} \rightarrow c\bar{c})$

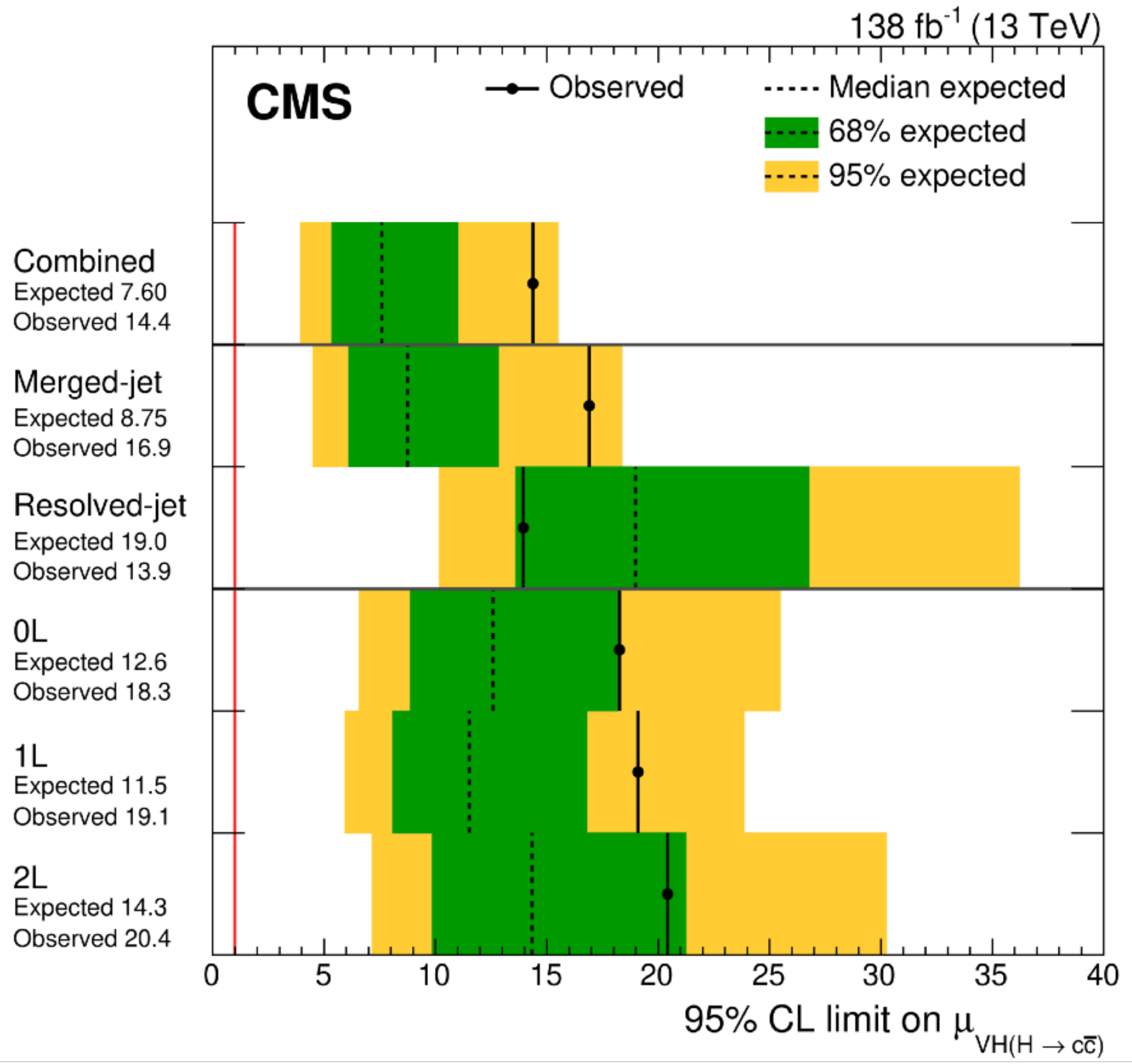
BDTs against background

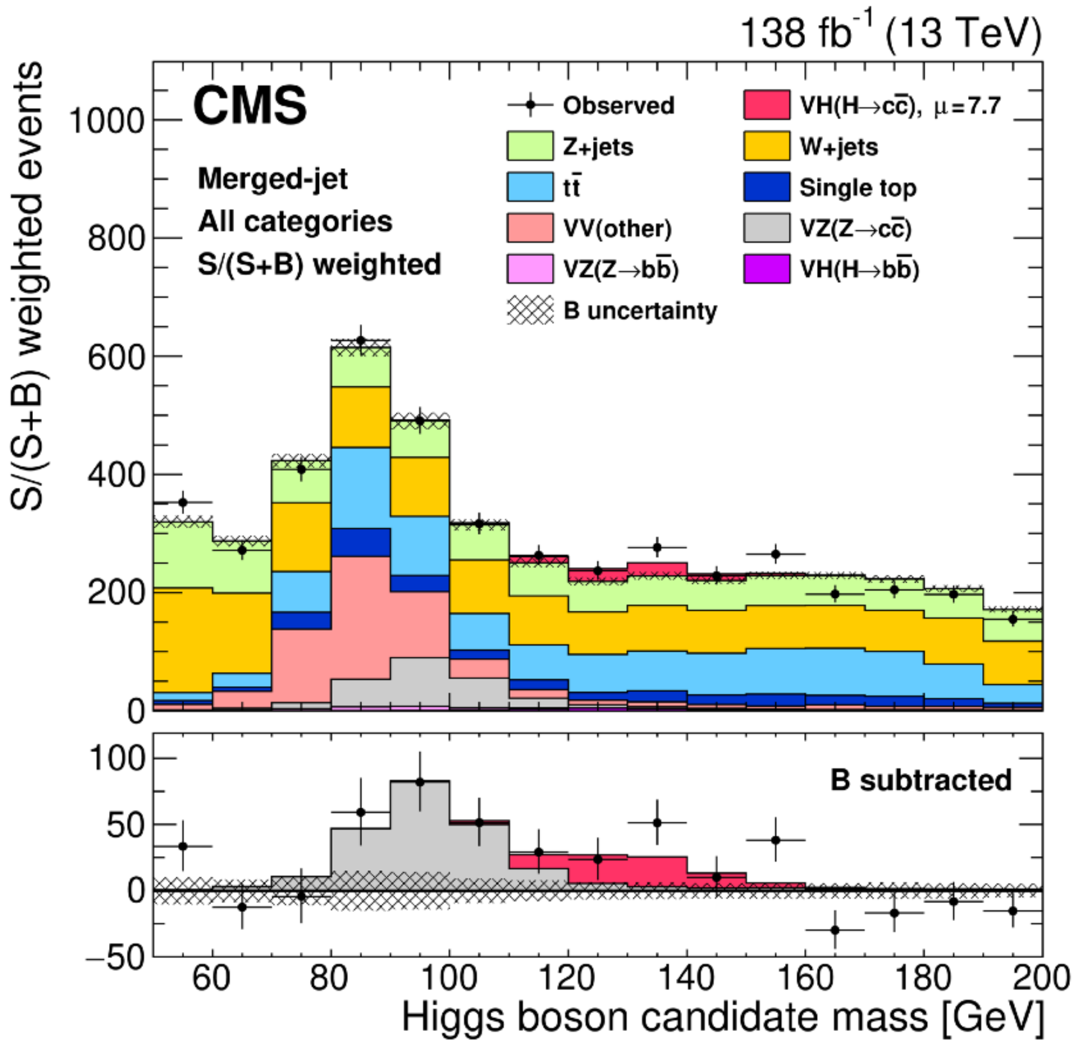
resolved

- c-jet charm tagging with **DeepJet**
- c-jet energy regression using **DNN**
- kinematic fit in 2-lepton channels

merged

- mass regression using **ParticleNet**





Validation:

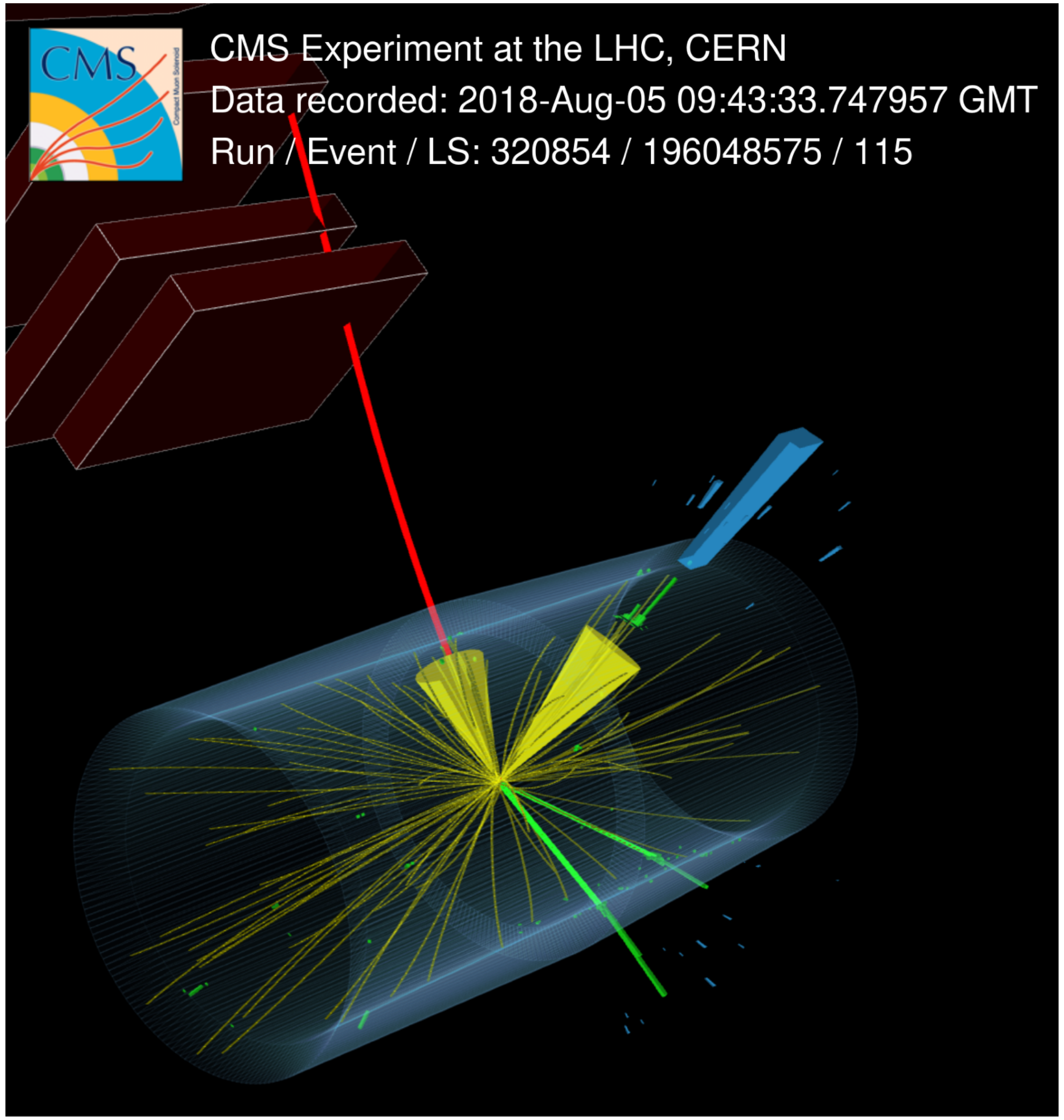
$$\mu_{\mathrm{VZ(Z\rightarrow c\bar{c})}} = 1.01^{+0.23}_{-0.21} \quad 5.7\sigma\ (5.9\sigma\ \text{exp})$$

VH(cc̄) signal strength

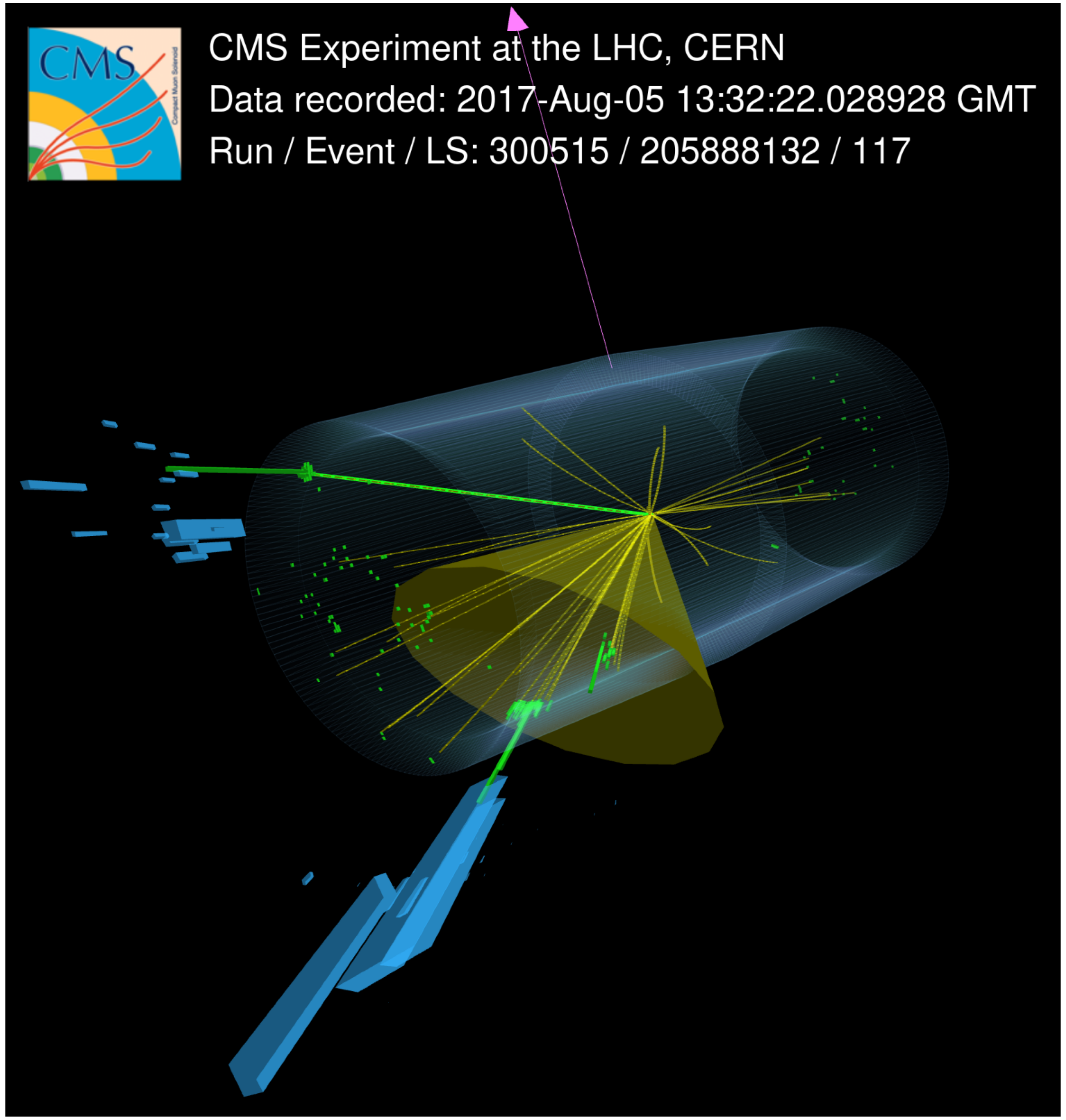
- $\mu_{\mathrm{VH(c\bar{c})}} = 7.1\,^{+3.8}_{-3.5}$
- obs (exp) upper limit @95% CL: 14 (7.6) × SM
- Constraint of the charm Yukawa $1.1 < |\kappa_c| < 5.5$ @ 95%CL

Boosted Higgs Boson and Charm Decay

Z(ee)H(cc) resolved candidate



W(eν)H(cc) boosted candidate



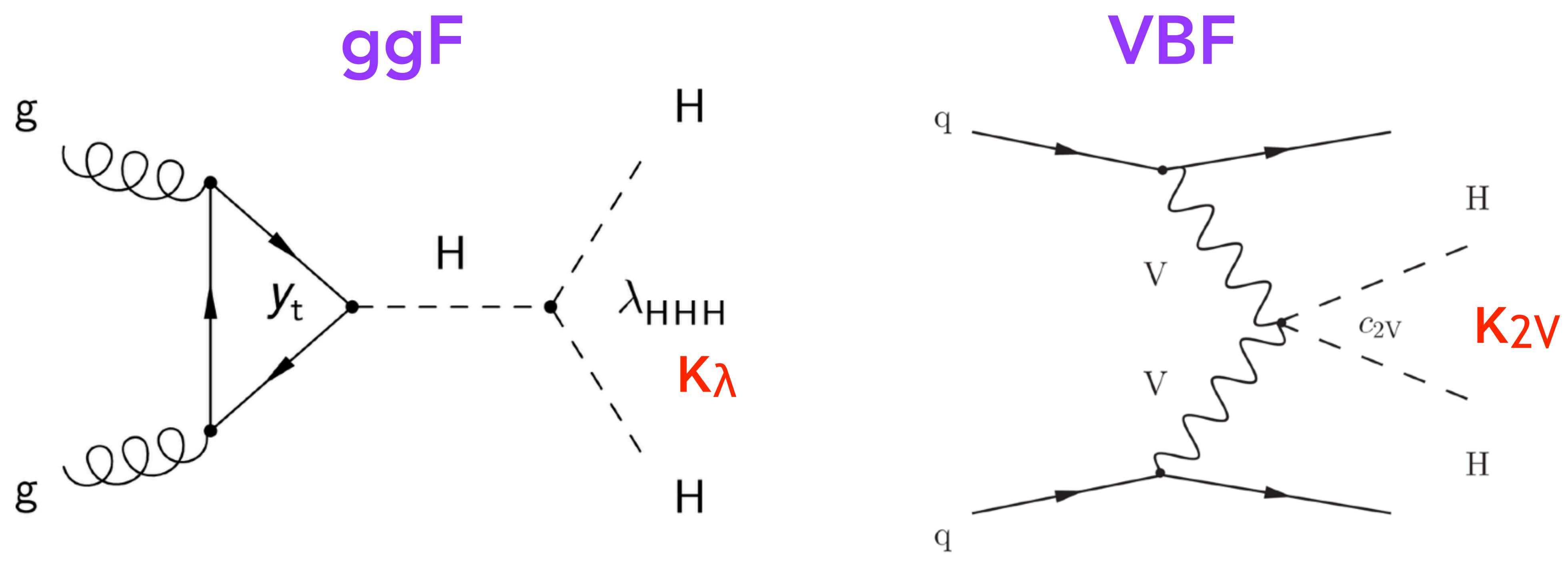
Search for Double Higgs Production

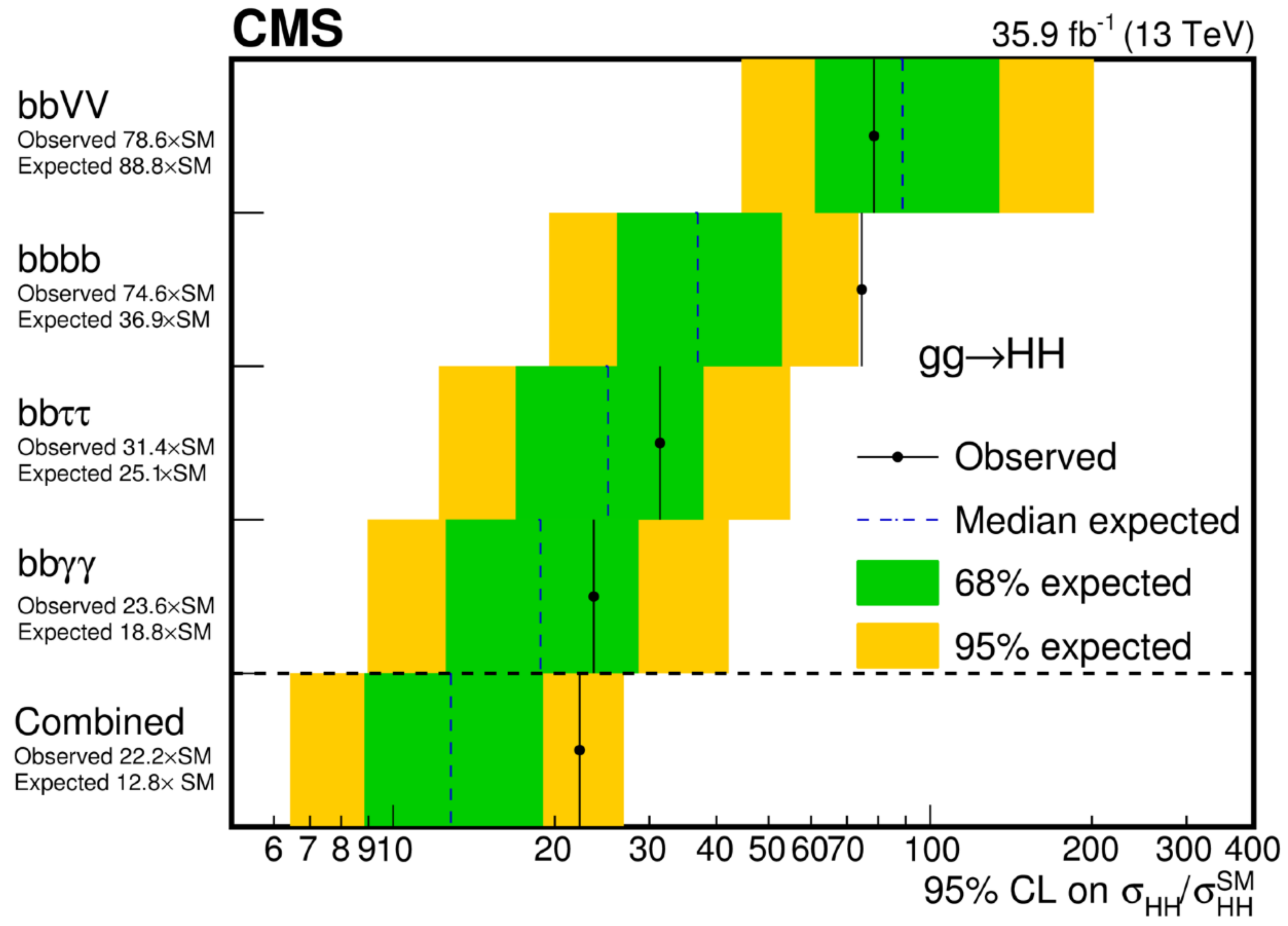
The observation of double Higgs production is one of the motivations for HL-LHC

Run-2 2016, 35.9 fb^{-1}

Double Higgs production involves these amplitudes:

CMS-HIG-17-030
PRL 122 (2019) 121803





Constraints on anomalous HHH (κ_λ) and VVHH (κ_{2V}) couplings

Combination of HH searches
$\sigma/\sigma_{SM} < 22$ (13) at 95% CL

The goal in Run-3 is either to find an anomalous production (resonant or non-resonant) or to set cross-section limits closer to the SM expectation

In the SM: $\lambda_{\mathrm{HHH}} = \lambda = m_{\mathrm{H}}^2/2v^2$

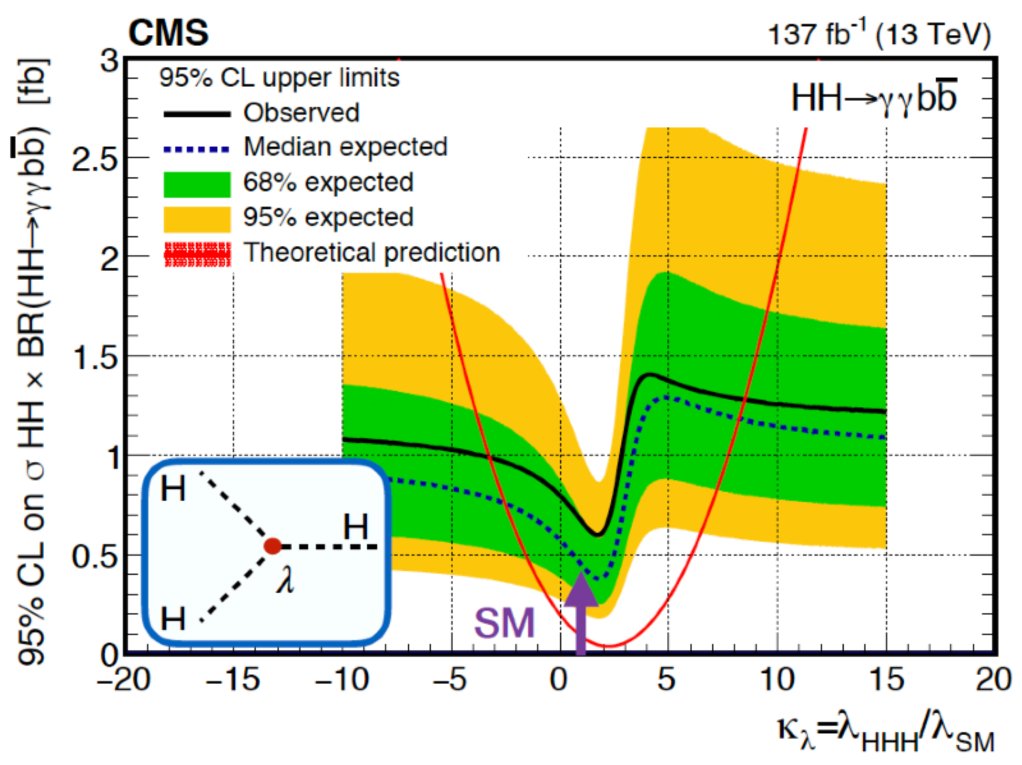
Search for Double Higgs Production

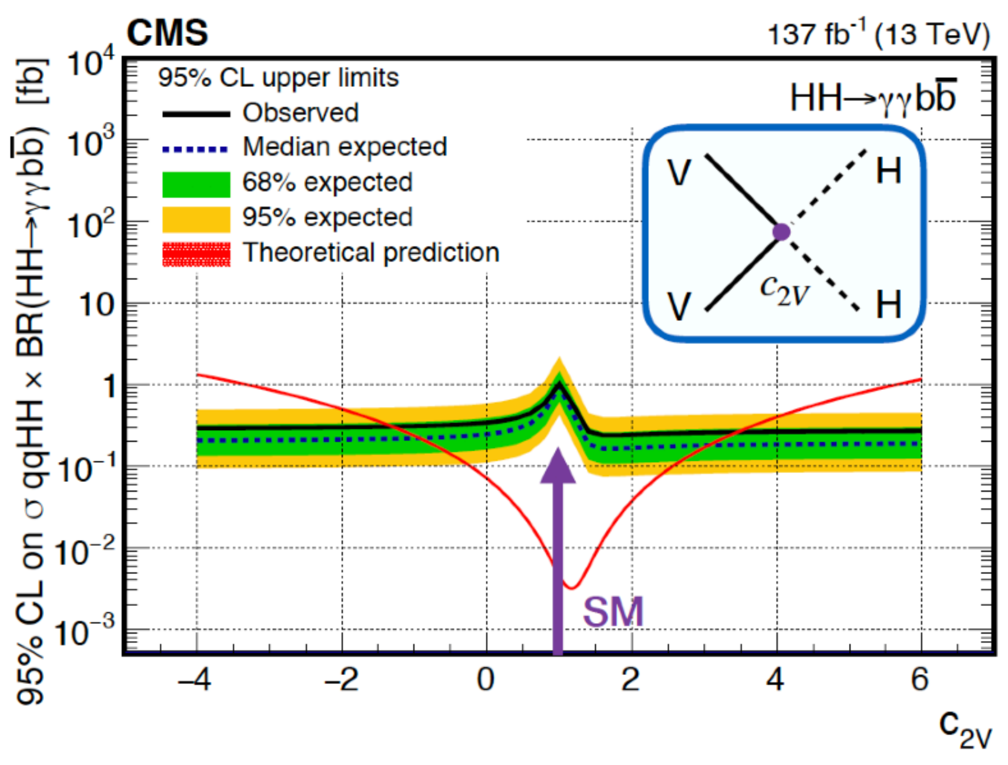
Full Run-2, 137 fb^{-1}

$\gamma\gamma b\bar{b}$

CMS-HIG-19-018
JHEP 03 (2021) 257

Phys. Briefing





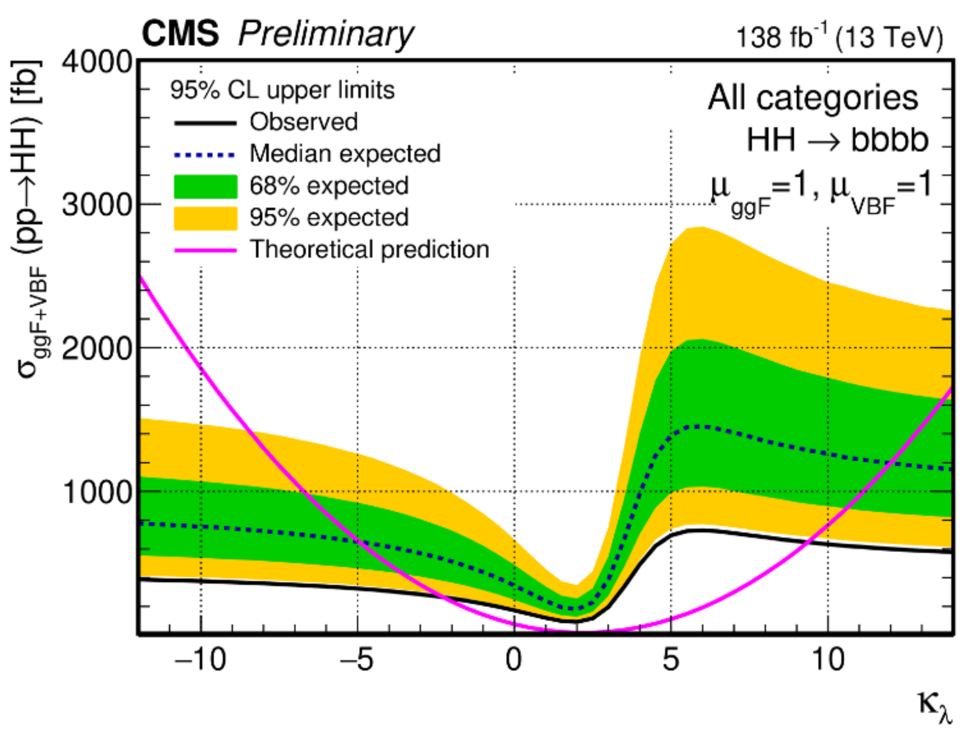
Driven by ggF categories *Driven by VBF categories*

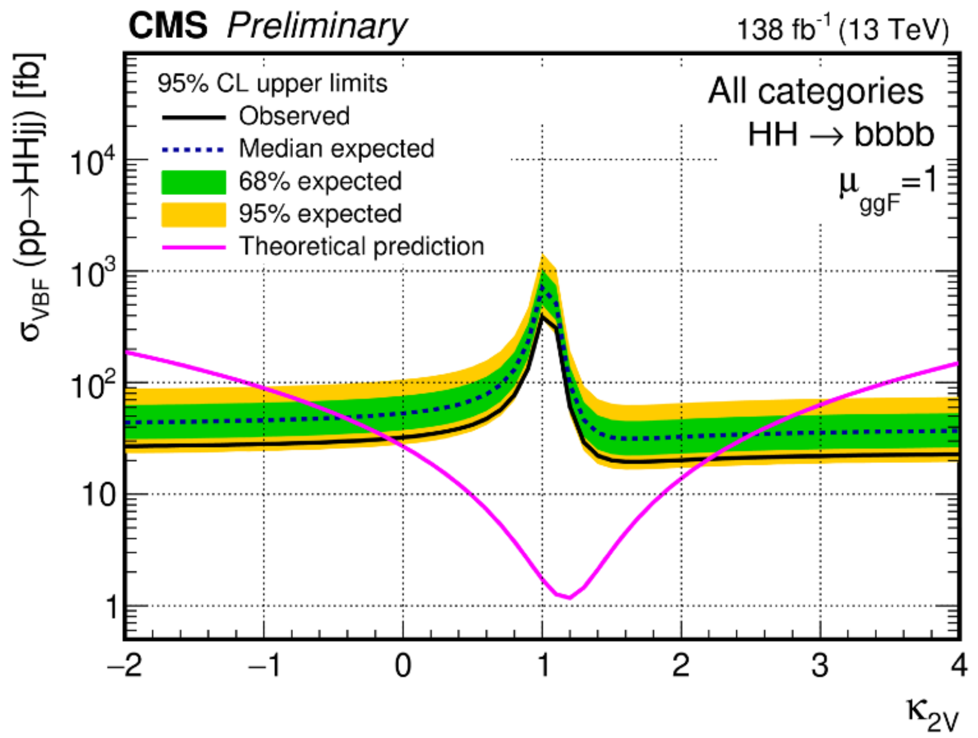
Inclusive $HH \to \gamma\gamma b\bar{b}$
σ/σ_{SM} < **7.7** (5.2) at 95% CL

Run-2 analyses already reaching **much higher sensitivity** than anticipated

$b\bar{b}b\bar{b}$

CMS-HIG-20-005
submitted to PRL





Inclusive $HH \to b\bar{b}b\bar{b}$
σ/σ_{SM} < **3.6** (7.3) at 95% CL

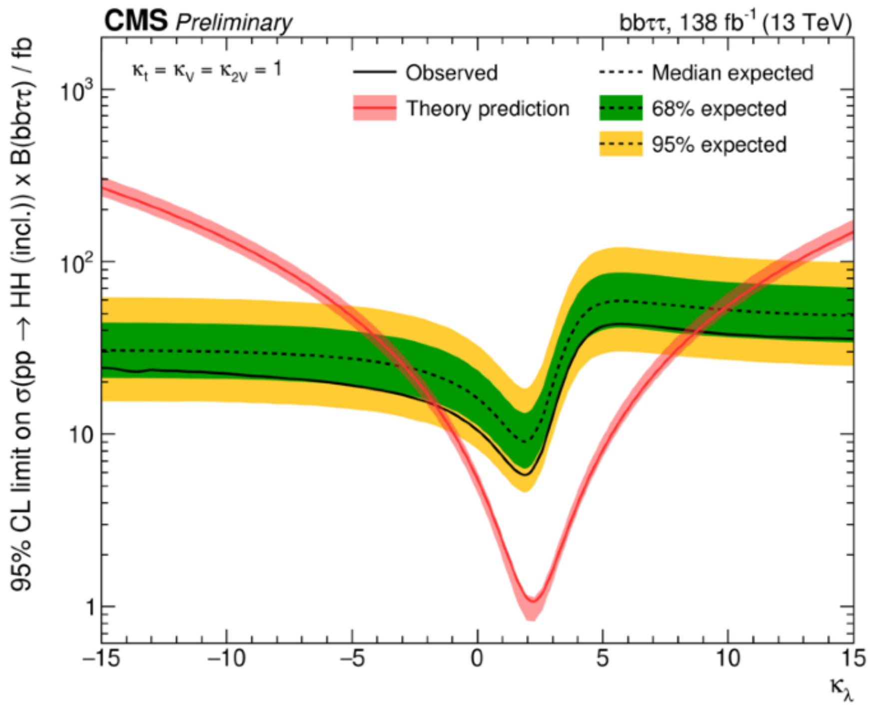
boosted $b\bar{b}b\bar{b}$

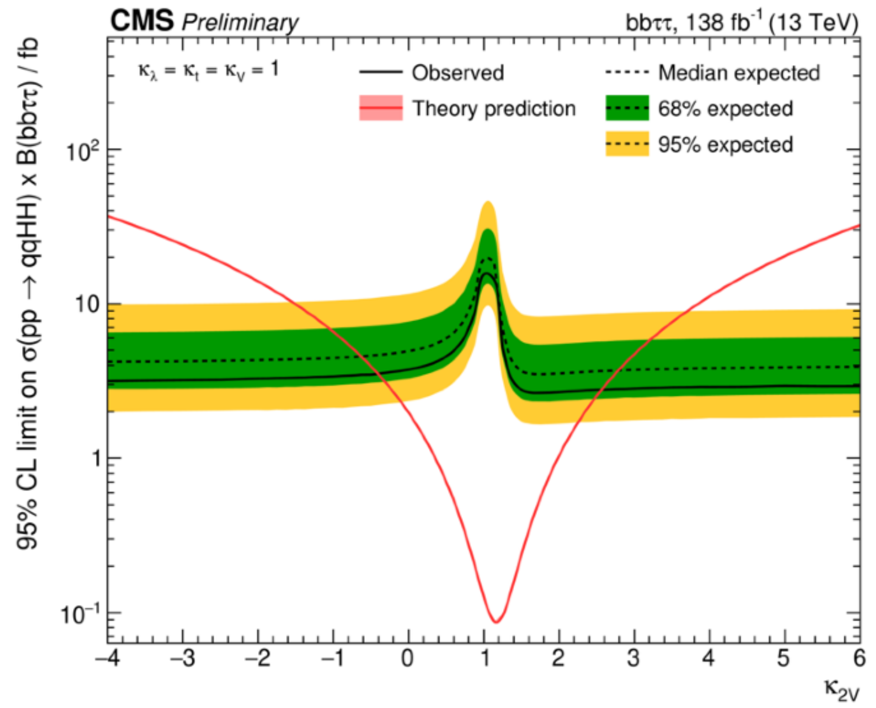
CMS-B2G-22-003
submitted to PRL

κ_{2V}=0 excluded with 6.3 sd!

$\tau\tau b\bar{b}$

CMS-PAS-HIG-20-010





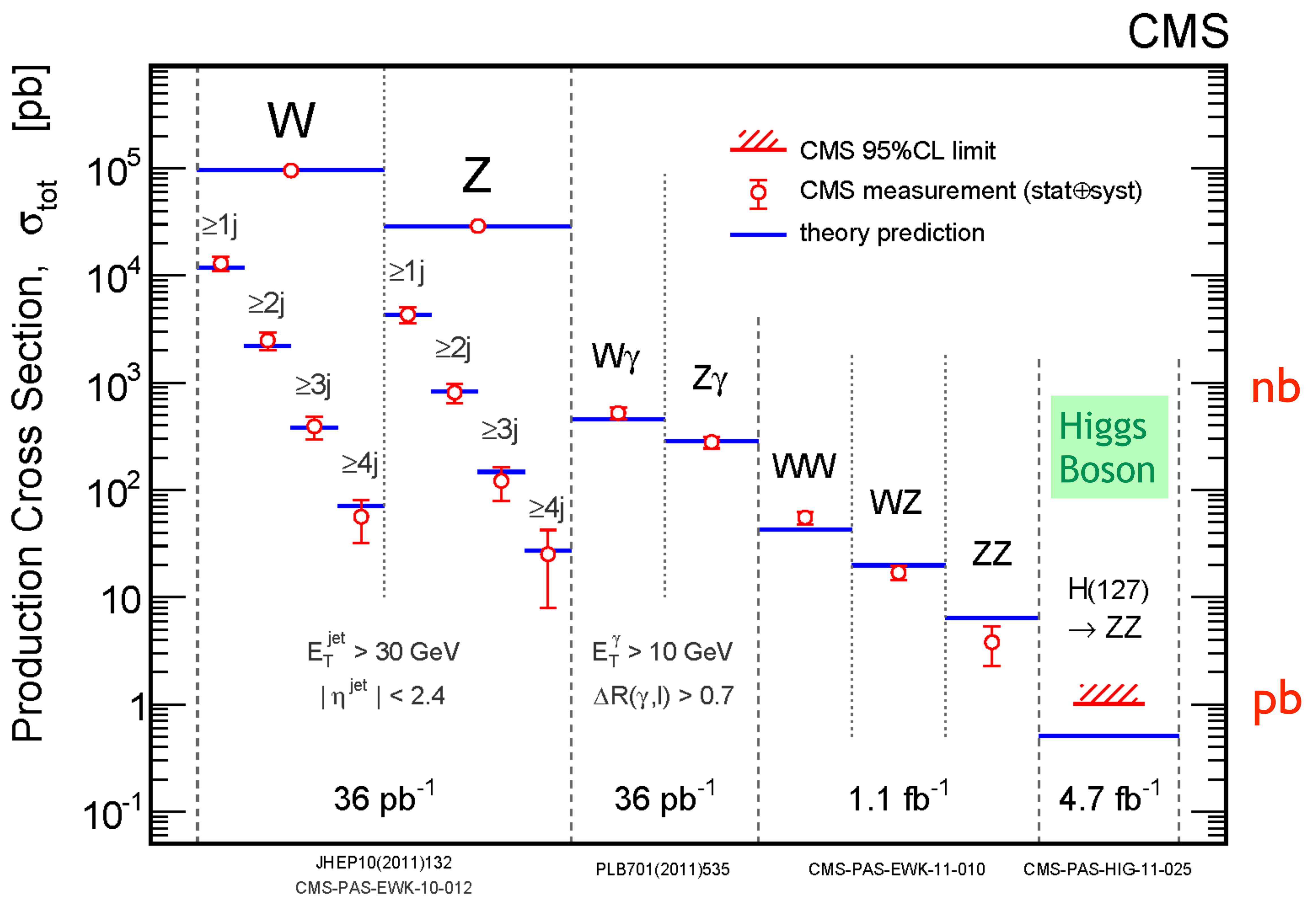
Inclusive $HH \to \tau\tau b\bar{b}$
σ/σ_{SM} < **3.3** (5.2) at 95% CL

Full Run-2 combination of all channels coming soon

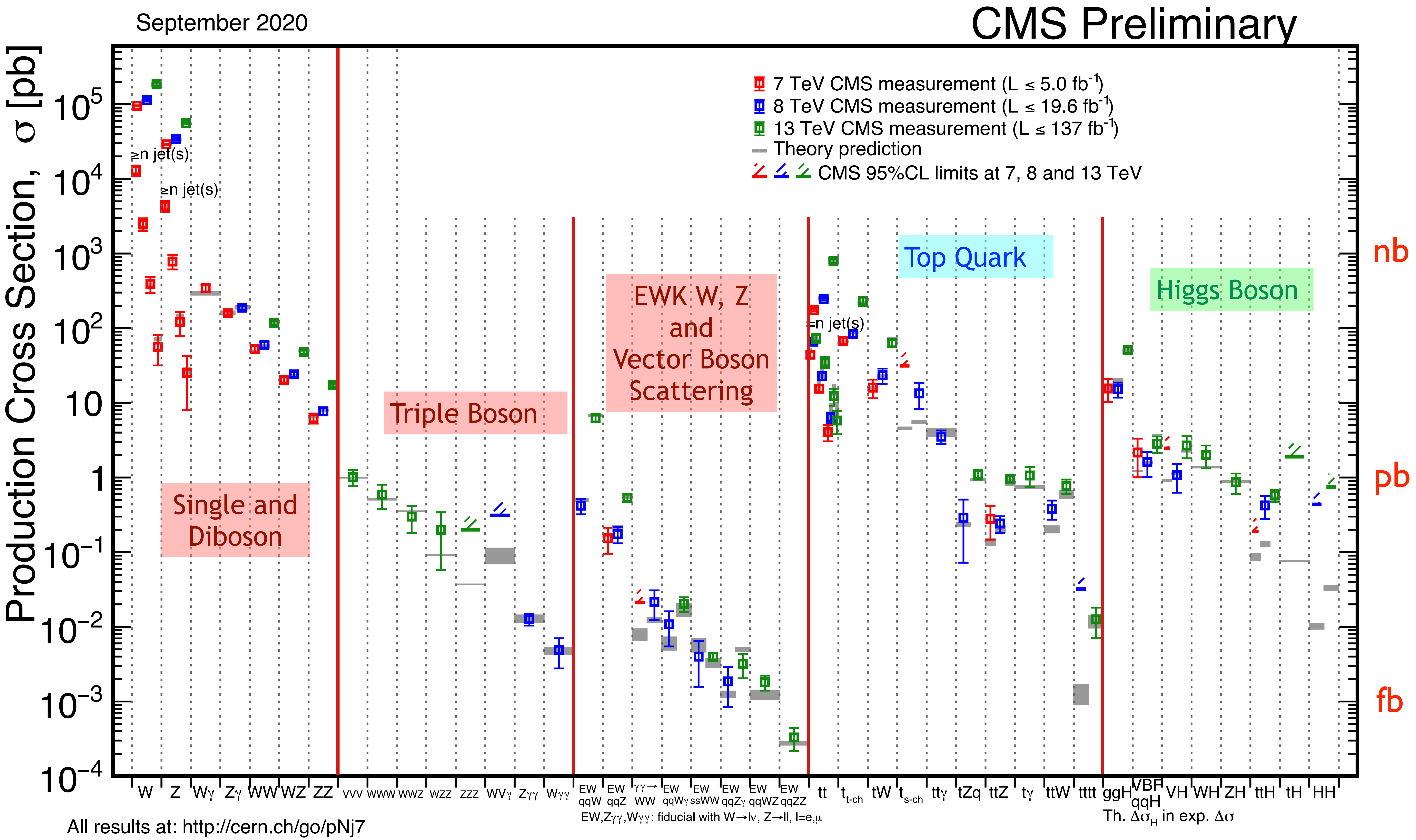
SM Production Cross Sections

10 years ago

Single and Diboson



SM Production Cross Sections



[Summaries of physics results]

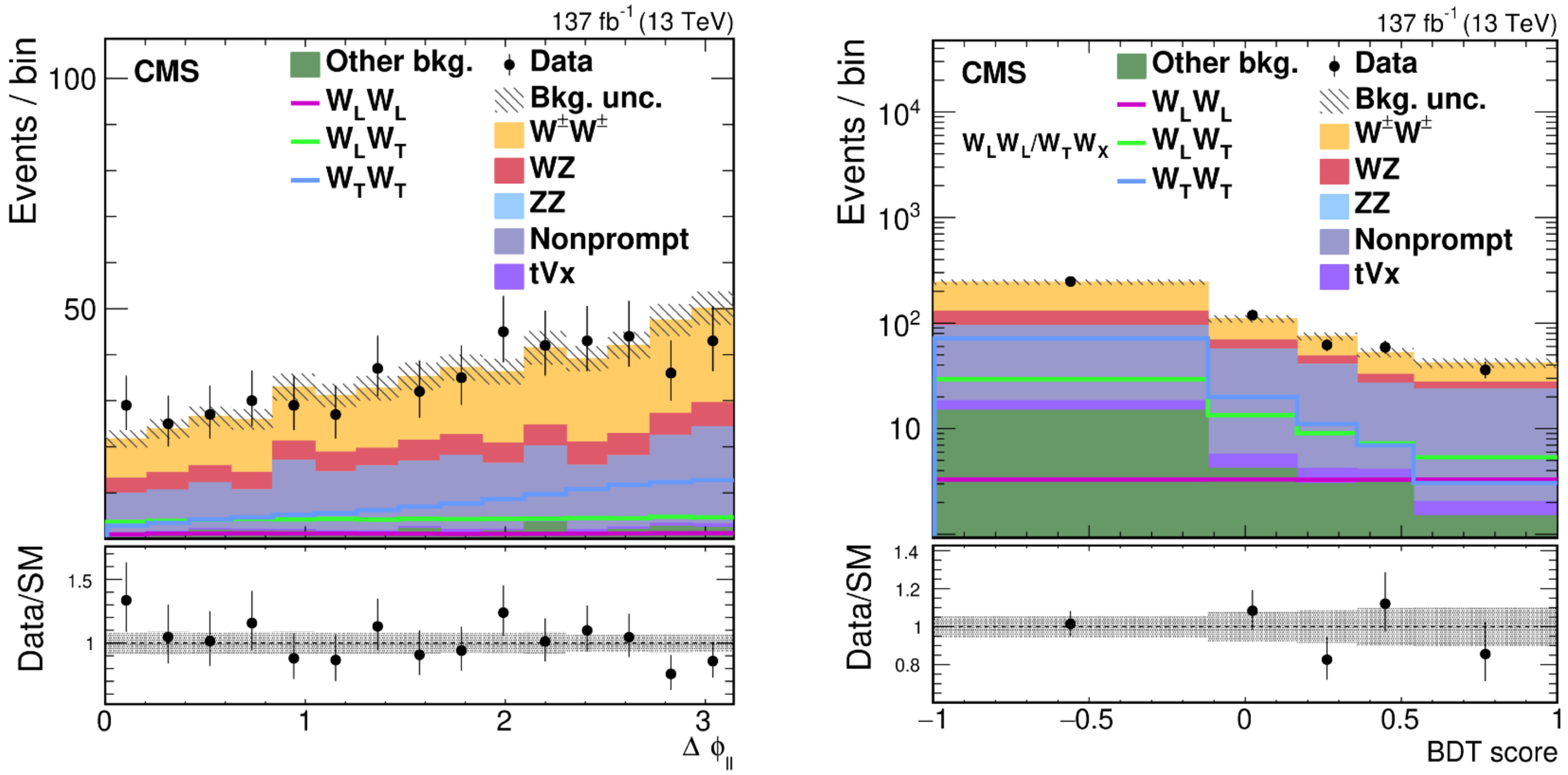
Vector Boson Scattering

Full Run-2, 137 fb^{-1}

VBS signature: two jets with large rapidity separation and dijet mass

Same-sign W pairs

with measurement of the polarisation



Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Exploiting event kinetics, extract polarisation components

CMS-SMP-20-006
PLB 812 (2020) 136018

first hint the scattering of at least one W_L at the 2.3σ (3.1σ exp) level

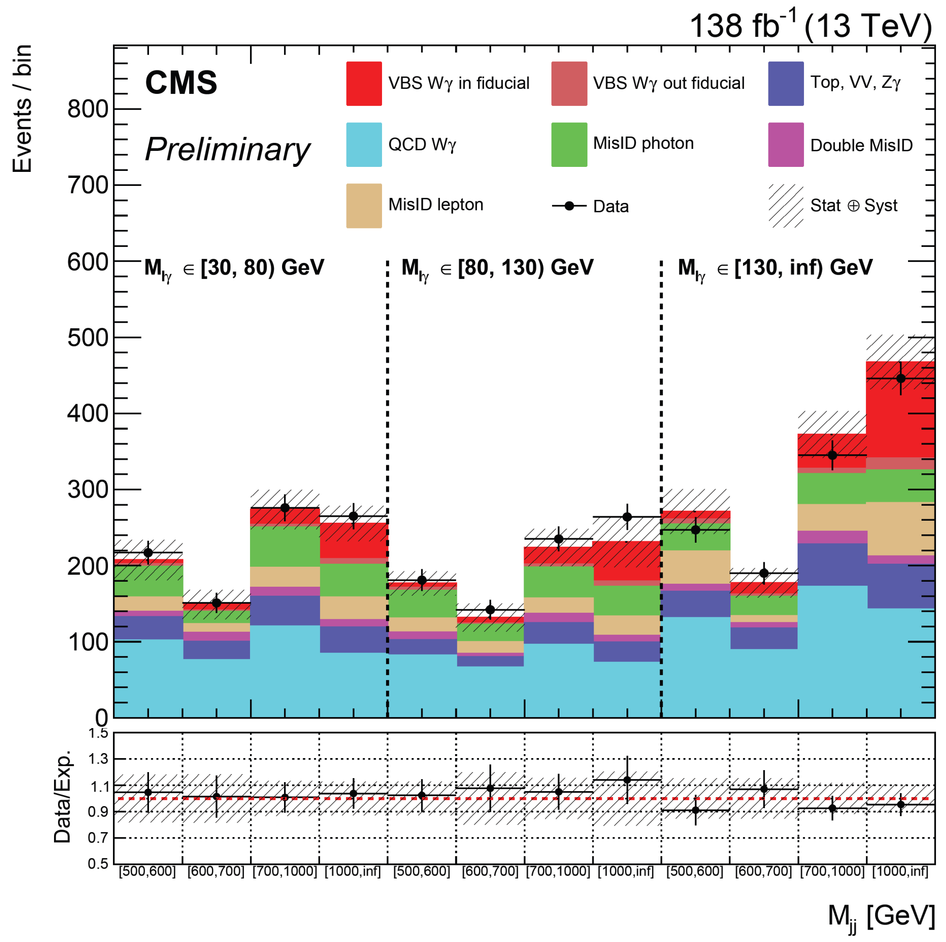
pp → Wγ jj

CMS-PAS-SMP-21-011

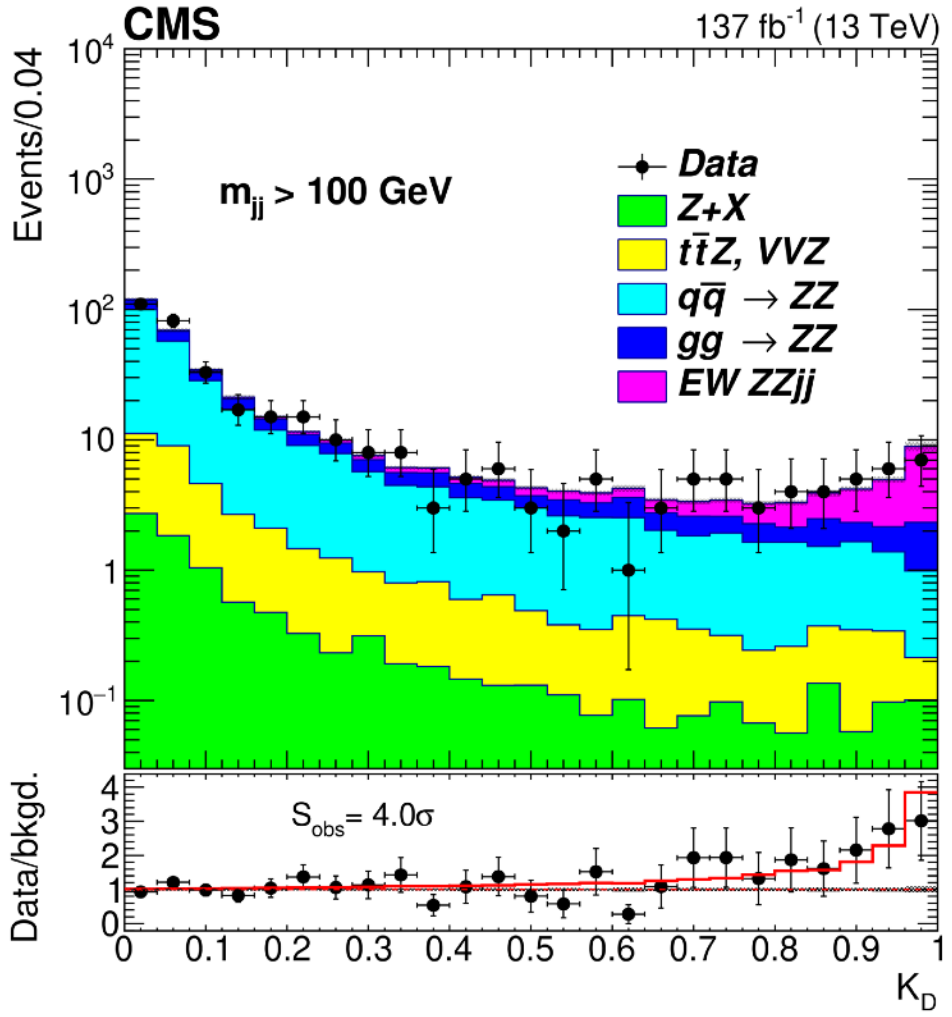
signal significance: 6.0σ (6.8σ exp)

Fiducial cross section:
(19.2 ± 4.0) fb

Differential and limits on aQGC



pp → ZZ jj



signal significance: 4.0σ (3.5σ exp)

CMS-SMP-20-001
PLB 812 (2020) 135992

limits on **anomalous quartic gauge couplings** in terms of dim-8 EFT operators

Fiducial cross section:

$$\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{ZZjj} \to \ell\,\ell\,\ell'\ell'\,\mathrm{jj}) = 0.33^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.04}_{-0.03}\,(\mathrm{syst})\,\mathrm{fb}$$

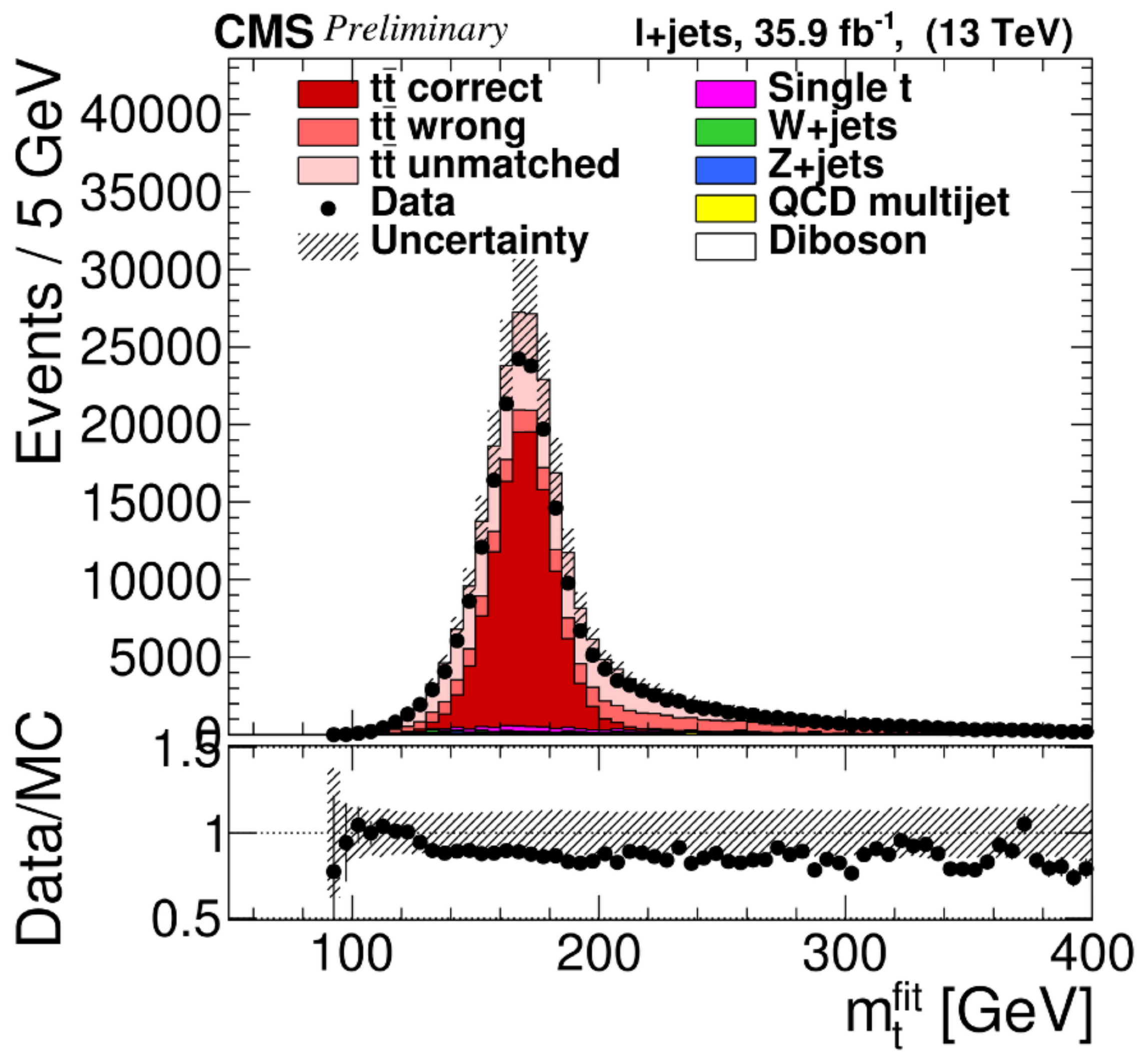
SM: $0.28 \pm 0.02\,\mathrm{fb}$

Recent Precision Top Mass Measurements

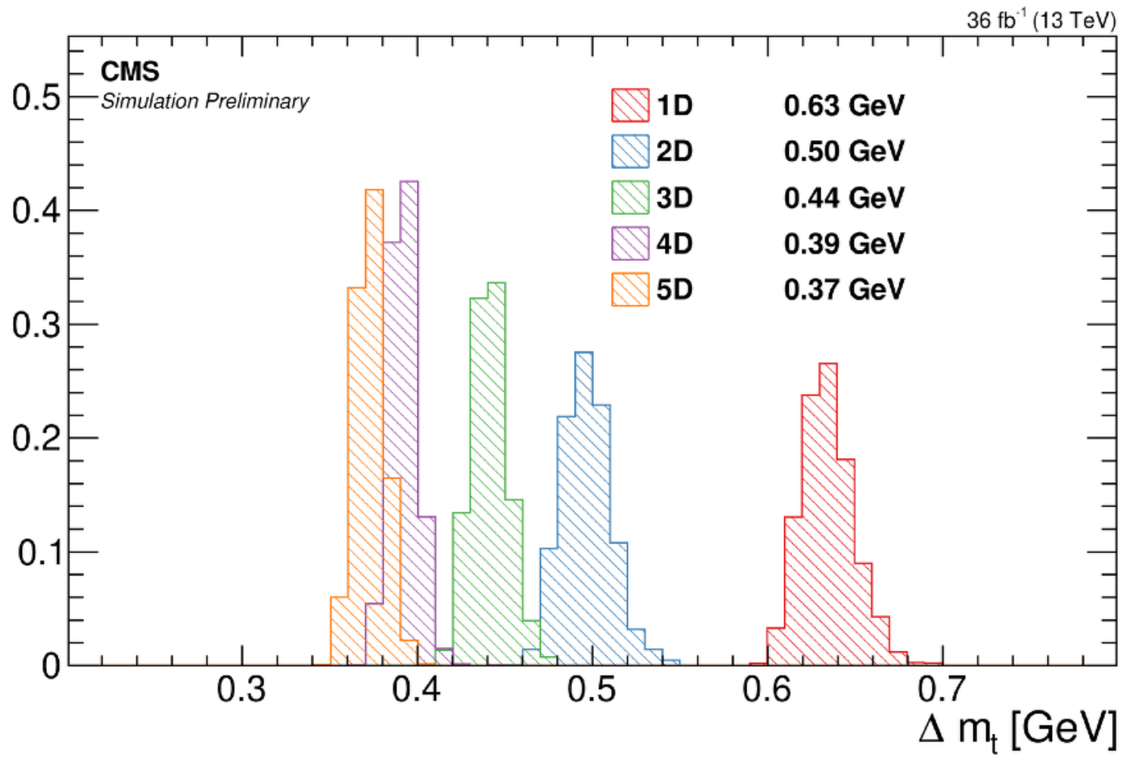
CMS-PAS-TOP-20-008

New top quark mass measurement in the lepton+jets mode

- profile likelihood method for the treatment of nuisances
- 5 variables m_t^{fit}, m_W^{reco}, $m_{\ell b}^{\mathrm{reco}}$, $m_{\ell b}^{\mathrm{reco}}/m_t^{\mathrm{fit}}$ and R_{bq}^{reco} (all with $P_{\mathrm{gof}} \geq 2$ except $m_{\ell b}^{\mathrm{reco}}$)
- most precise to date



$$m(t) = 171.77 \pm 0.38\,\mathrm{GeV}$$



also, pole mass measurement from differential cross-section of tt̄ plus at least one jet as a function of the inverse of the tt̄+j system mass

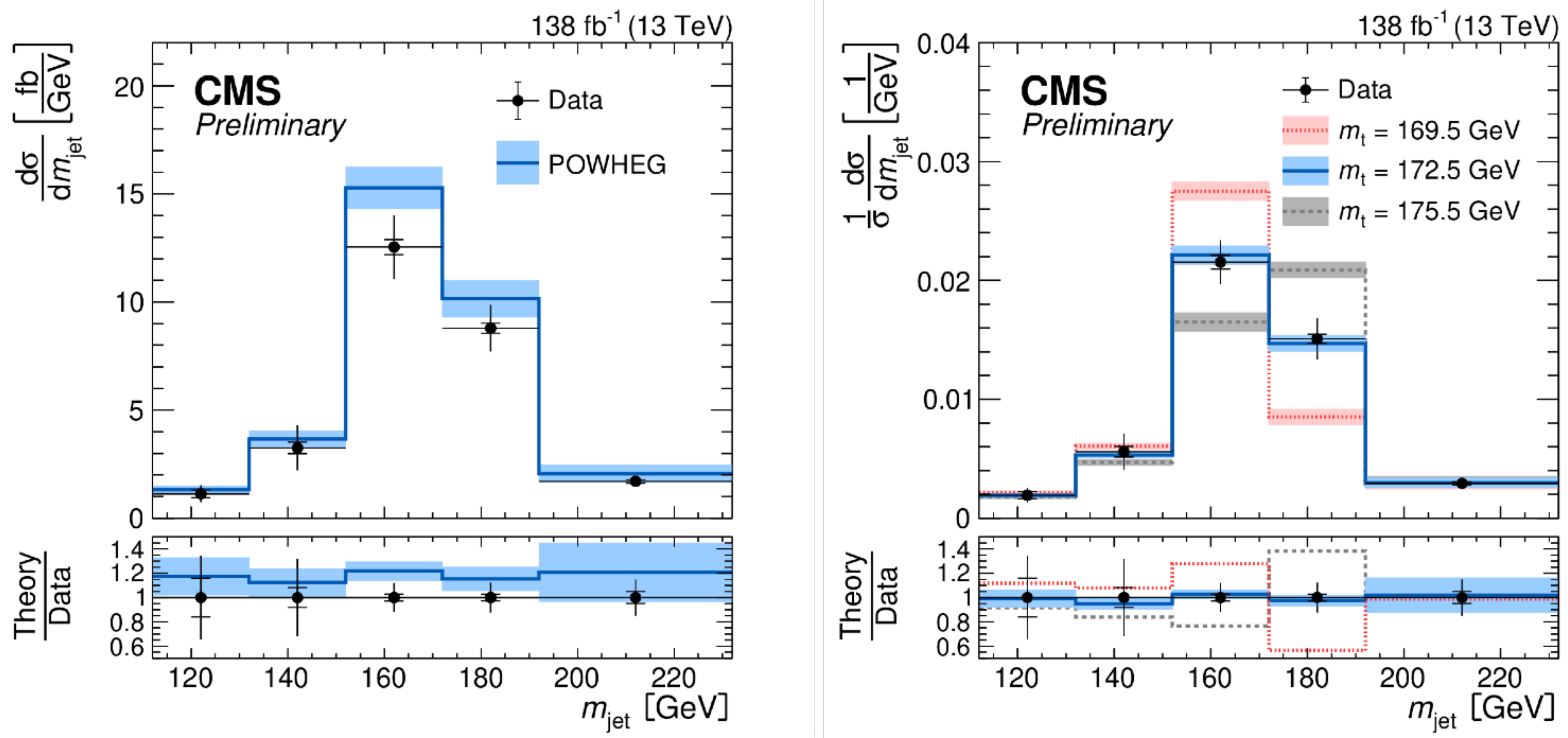
CMS-PAS-TOP-21-008

CMS-PAS-TOP-21-008

Measurement of the jet mass distribution in hadronic decays of boosted top quarks

- lepton+jets channels, fat jets with $p_T > 400$ GeV
- calibration with hadronic W decays
- modelling of FSR by study of jet substructure
- differential tt̄ x-section vs jet mass unfolded at particle level

$$m(t) = 172.76 \pm 0.81\ \mathrm{GeV}$$



also, charge asymmetry with boosted tops CMS-PAS-TOP-21-014

Recent BSM Searches at CMS

Since Moriond 20022

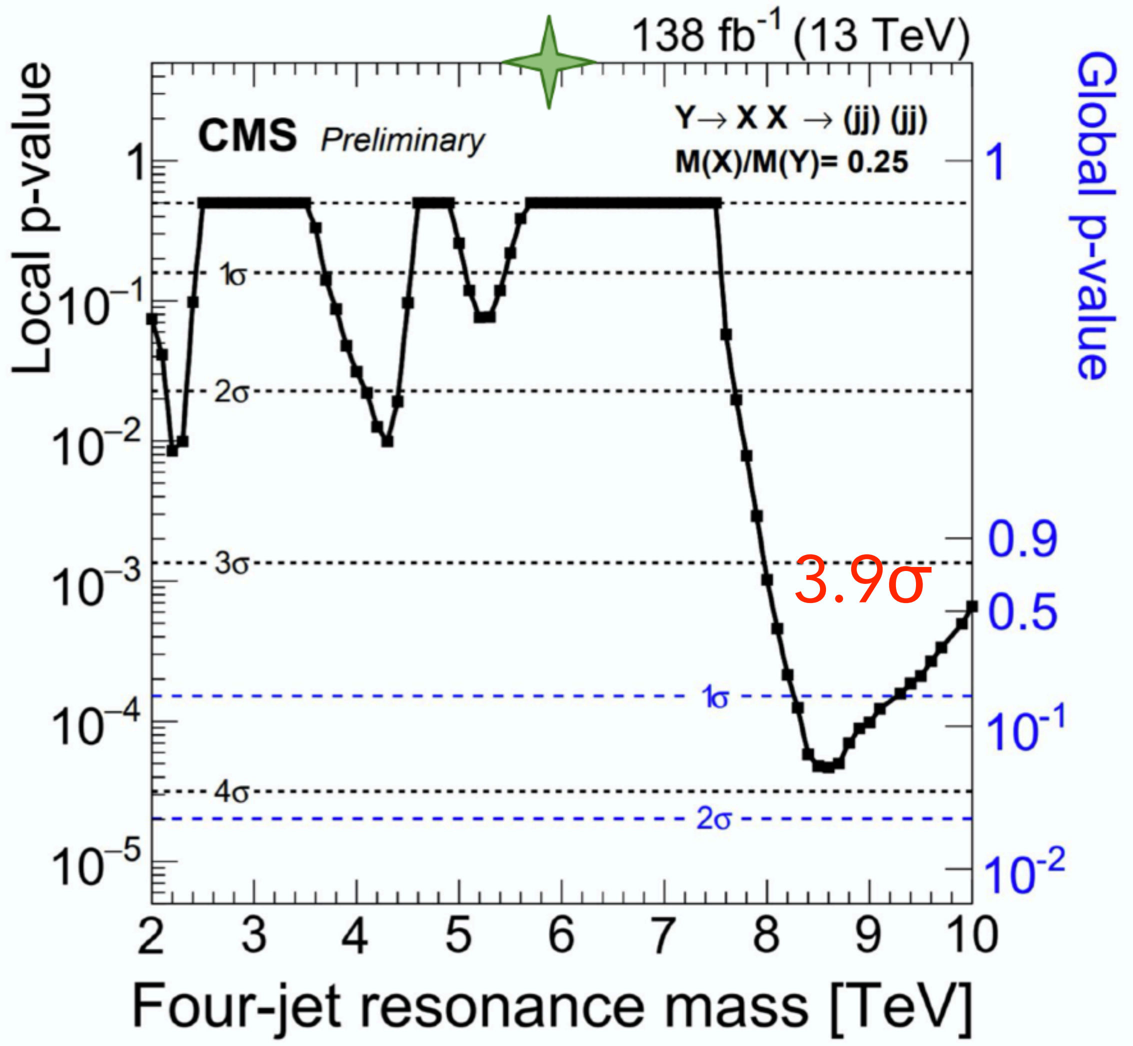
CMS-PAS-SUS-21-007	Search for supersymmetry in final states with a single electron or muon using angular correlations and heavy object tagging
CMS-PAS-EXO-21-003	Probing Majorana neutrinos and the Weinberg operator in the same-charge dimuon channel through vector boson fusion processes
CMS-PAS-EXO-20-006	Search for Z' bosons decaying to pairs of heavy Majorana neutrinos
CMS-PAS-EXO-21-010	Search for resonant and non-resonant production of pairs of identical dijet resonances
CMS-PAS-EXO-20-011	Search for a heavy composite Majorana neutrino
CMS-PAS-B2G-21-001	Search for Higgs boson pair production via vector boson fusion with highly Lorentz-boosted Higgs bosons in the four b quark final state
CMS-PAS-B2G-21-004	Search for pair-produced vector-like leptons in ≥ 3b + Nτ final states
CMS-PAS-B2G-20-009	Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state
CMS-B2G-22-003	Search for nonresonant pair production of highly energetic Higgs bosons decaying to bottom quarks
CMS-PAS-HIG-21-001	Searches for additional Higgs bosons and vector-like leptoquarks in ττ final states
CMS-PAS-HIG-21-010	Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson
CMS-PAS-HIG-21-001	Searches for additional Higgs bosons and vector-like leptoquarks in ττ final states
CMS-PAS-HIG-21-016	Search for exotic Higgs boson decays H → AA → 4γ with events containing two merged photons

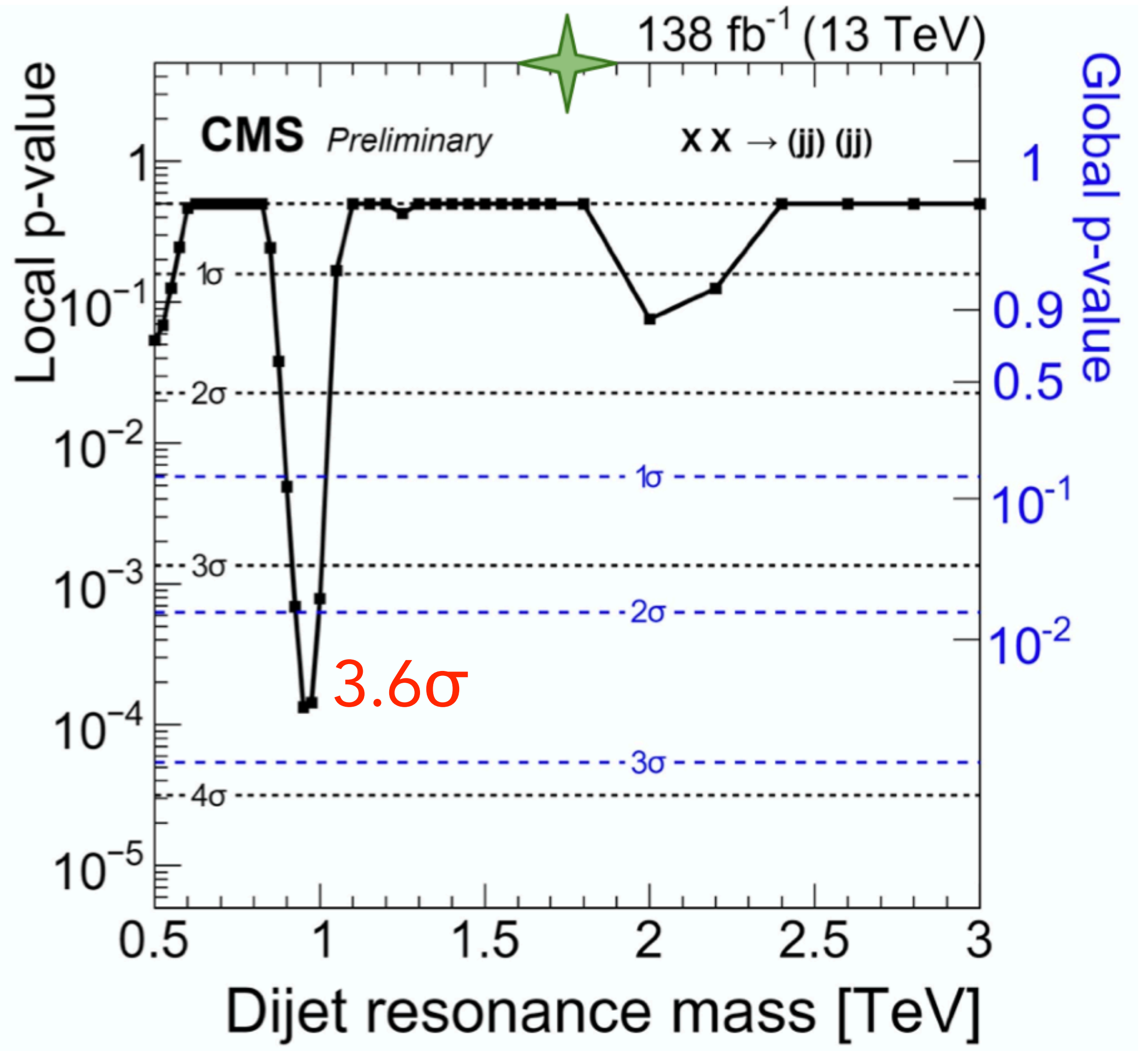
Search for paired dijet resonances

CMS-PAS-EXO-21-010

Search for both resonant and non-resonant production of pairs of diet resonances

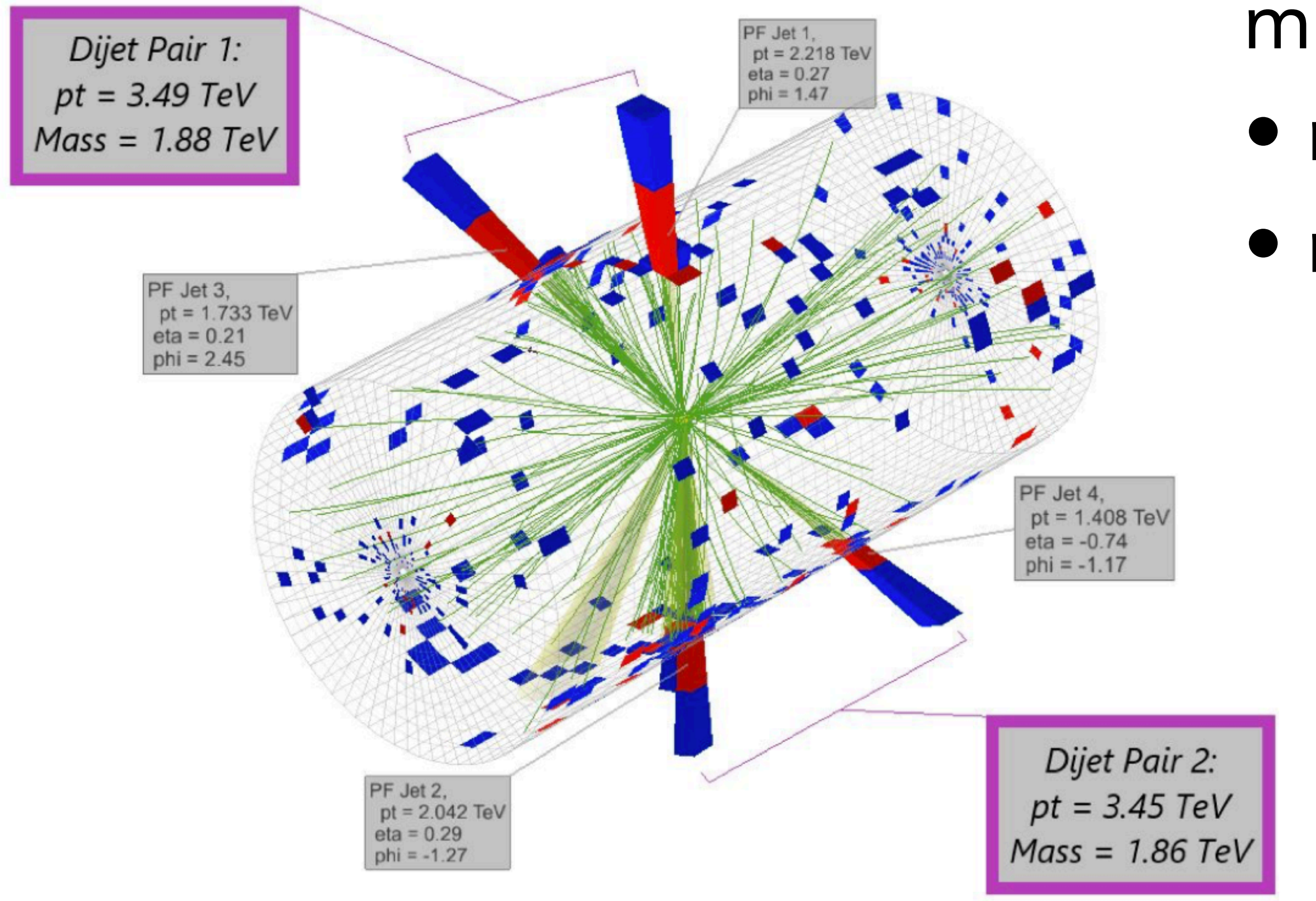
- full Run-2 dataset
- data driven background estimate

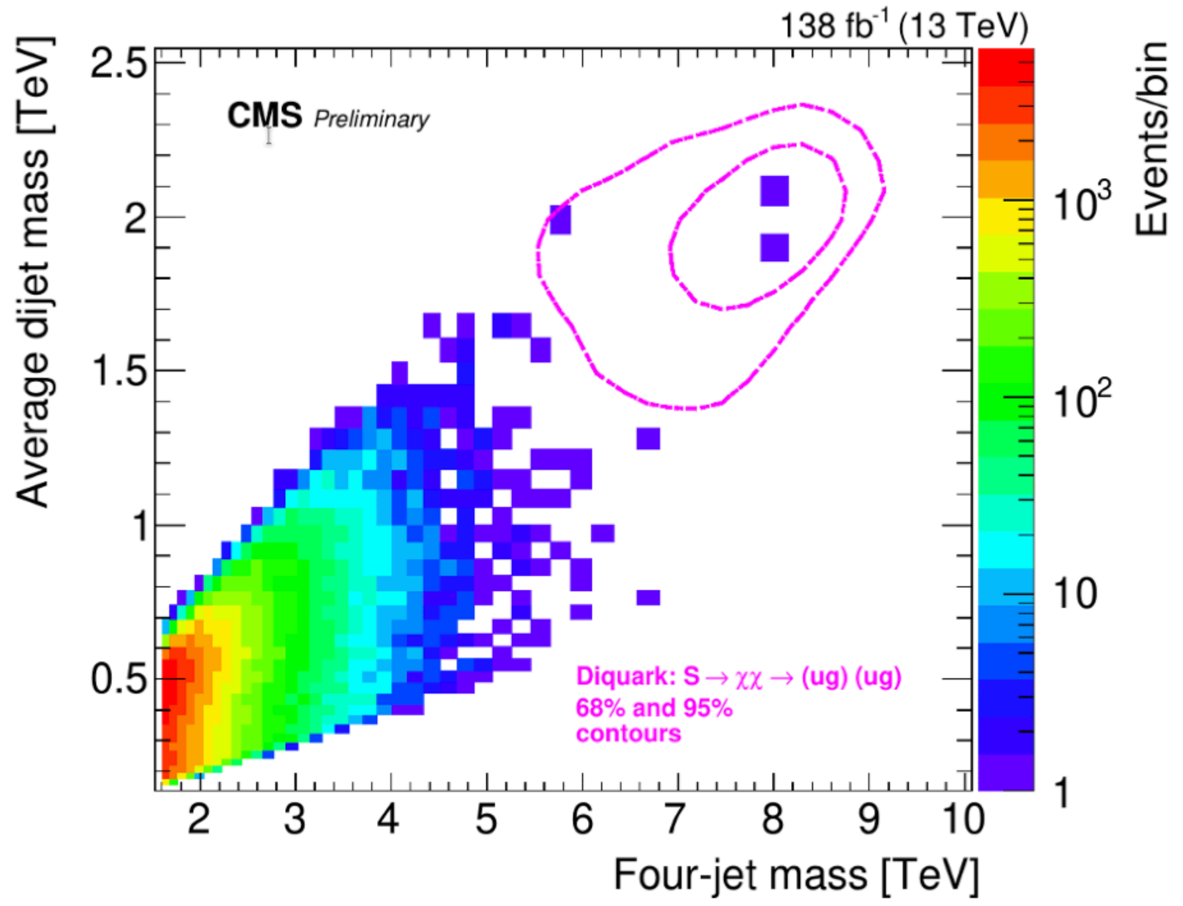


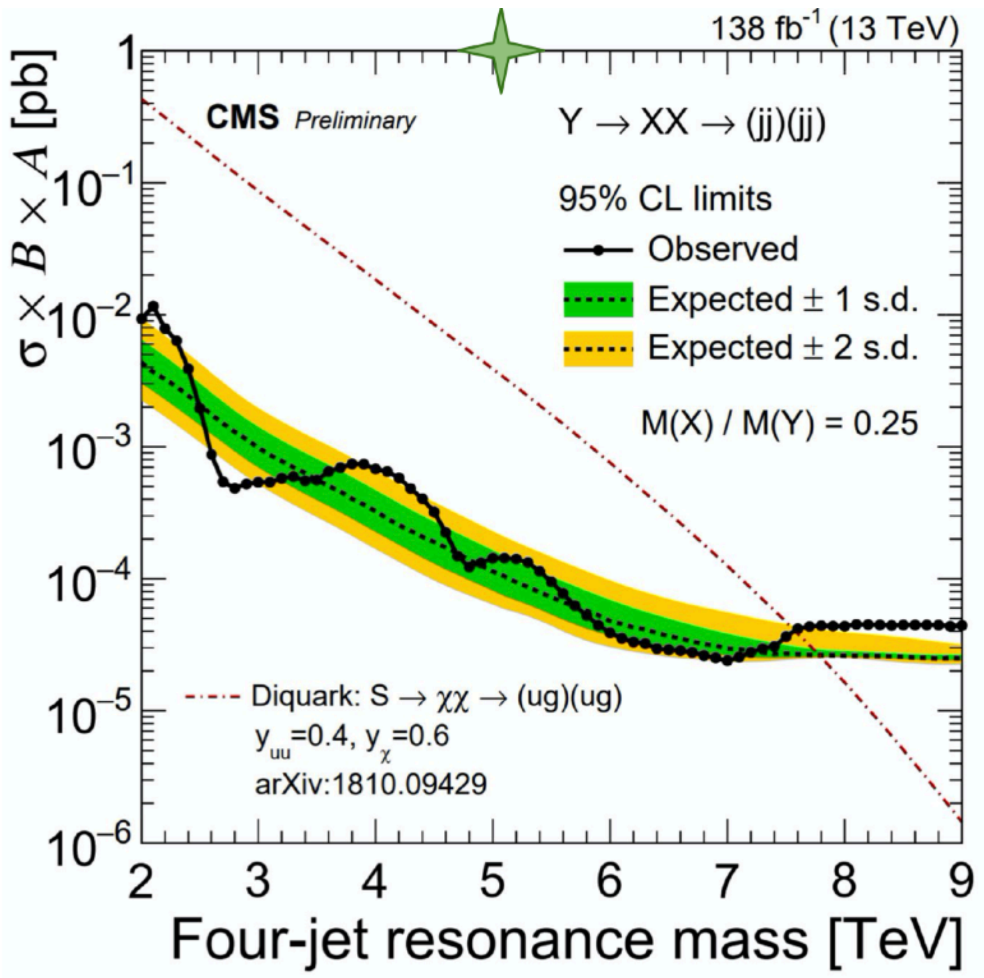


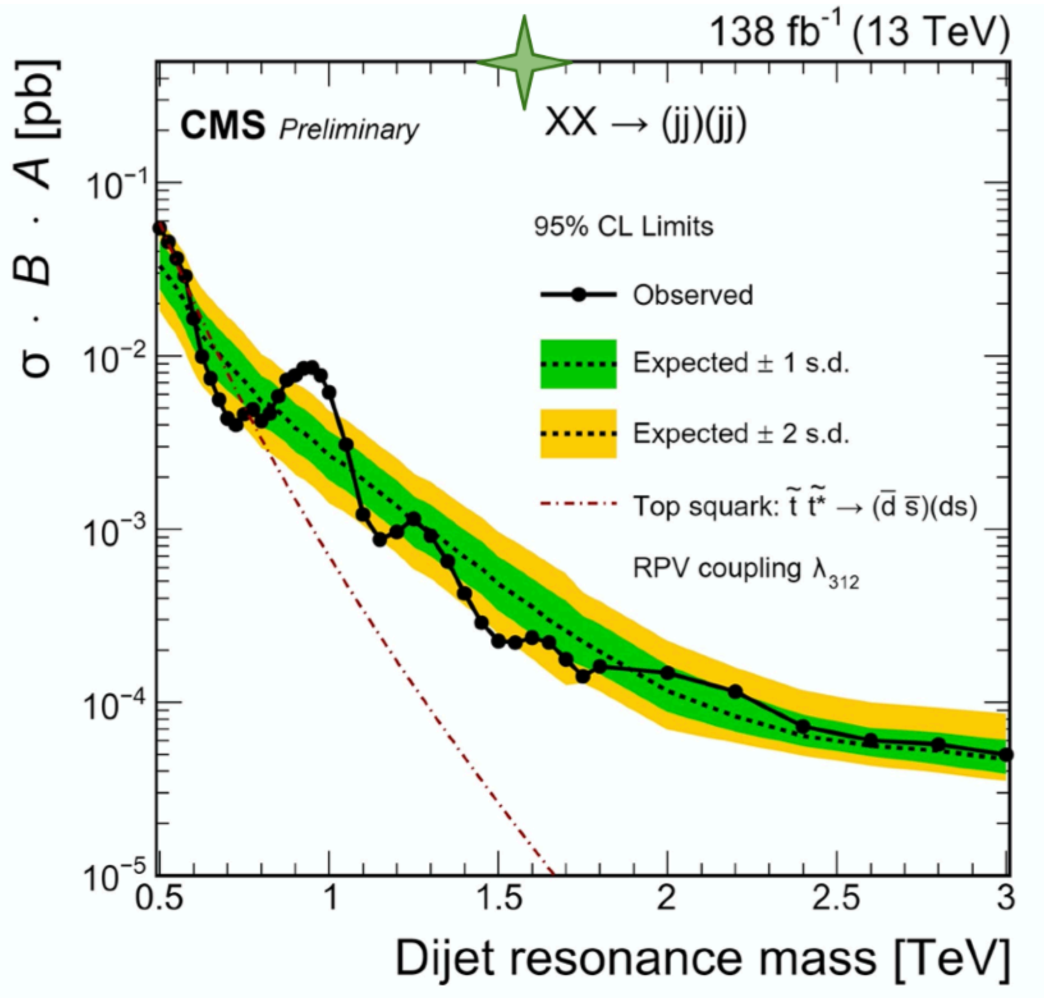
Limits with benchmark models:

- non-resonant: RPV stops
- resonant: diquarks







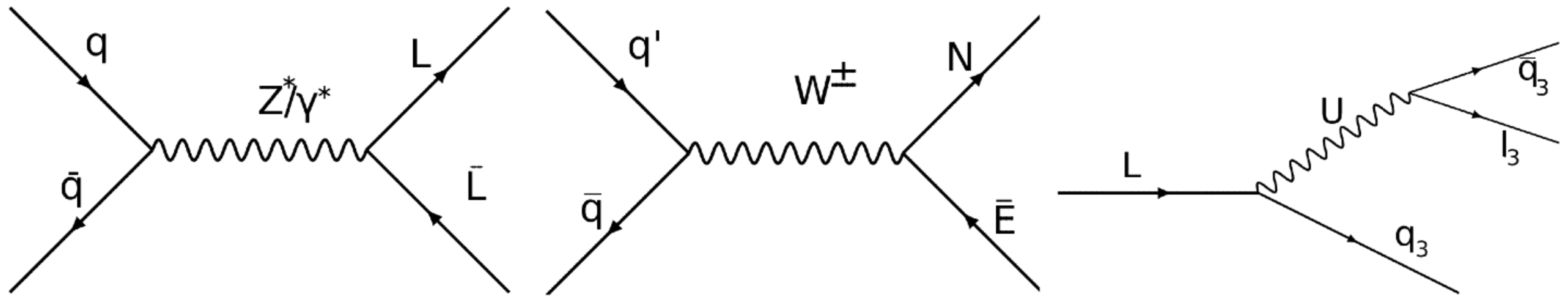


Two intriguing events
m_{2j}~2 TeV, m_{4j}~8 TeV

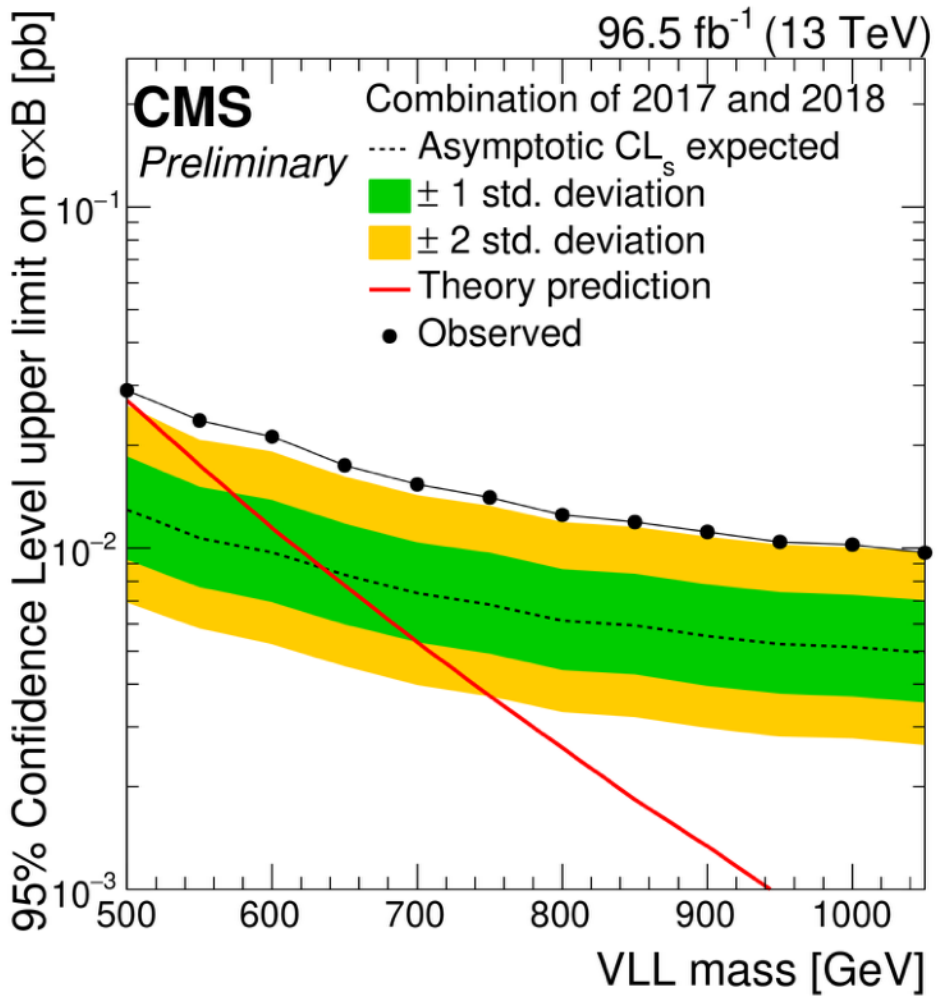
More Intriguing Excesses

CMS-PAS-B2G-21-004

Search for vector-like leptons (VLLs)

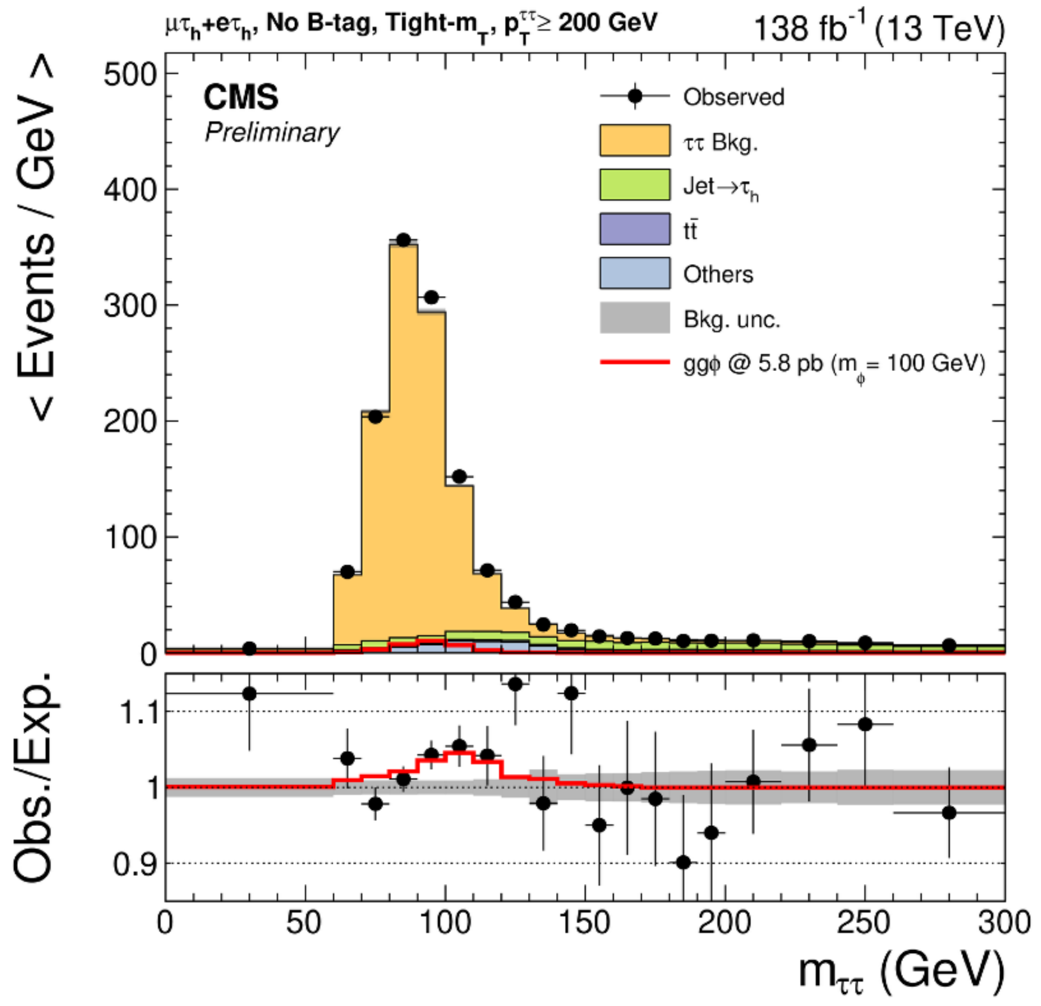


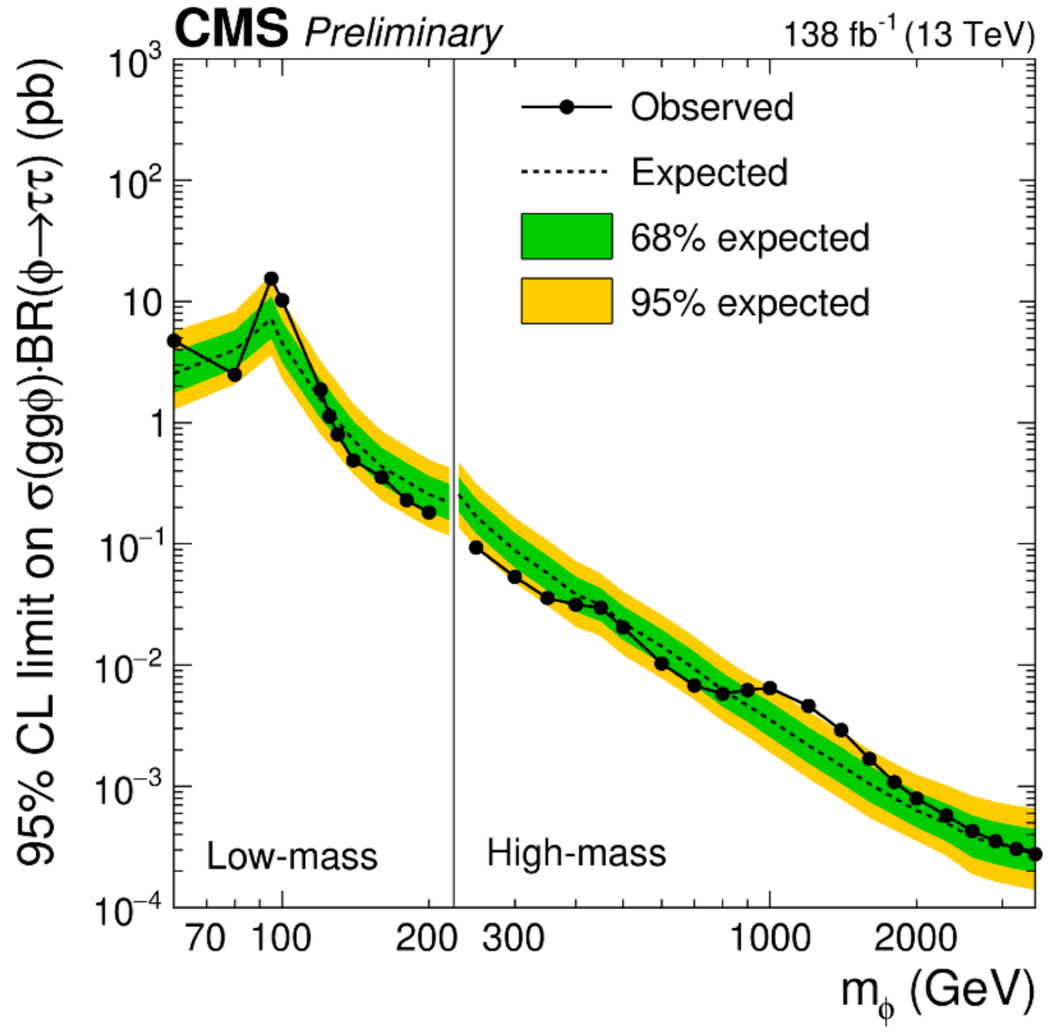
- pair-produced VLLs in final states with ≥ 3 b jets and up to 2 τ-leptons
- in the context of 4321 model, UV-complete and relevant to describe flavor anomalies
- mild excess is seen in 1τ and 2τ: 2.8σ



CMS-PAS-HIG-21-001

Search for additional Higgs bosons in ττ final states





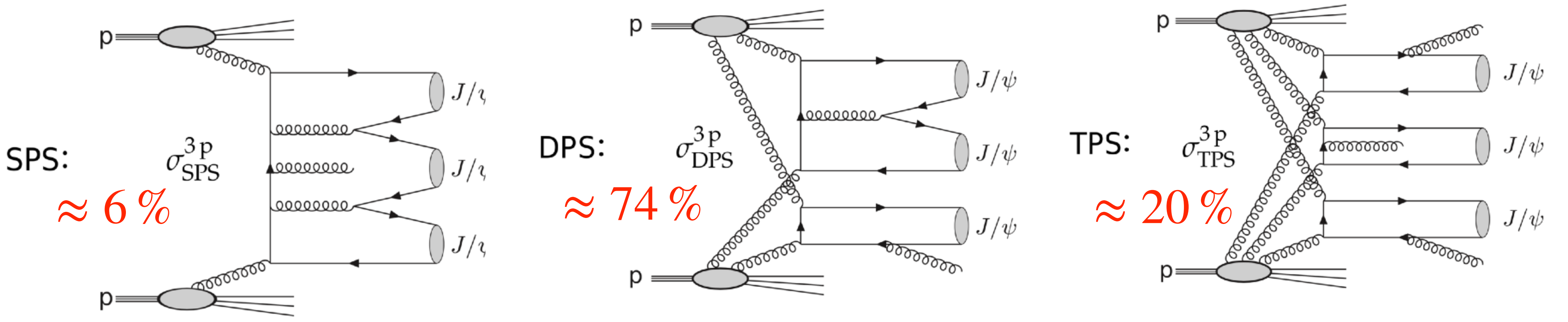
- two excesses for ϕ production via gluon fusion with local p-values equivalent to 3 s.d. at 100 GeV and 1.2 TeV, consistent across ττ final states and data-taking years

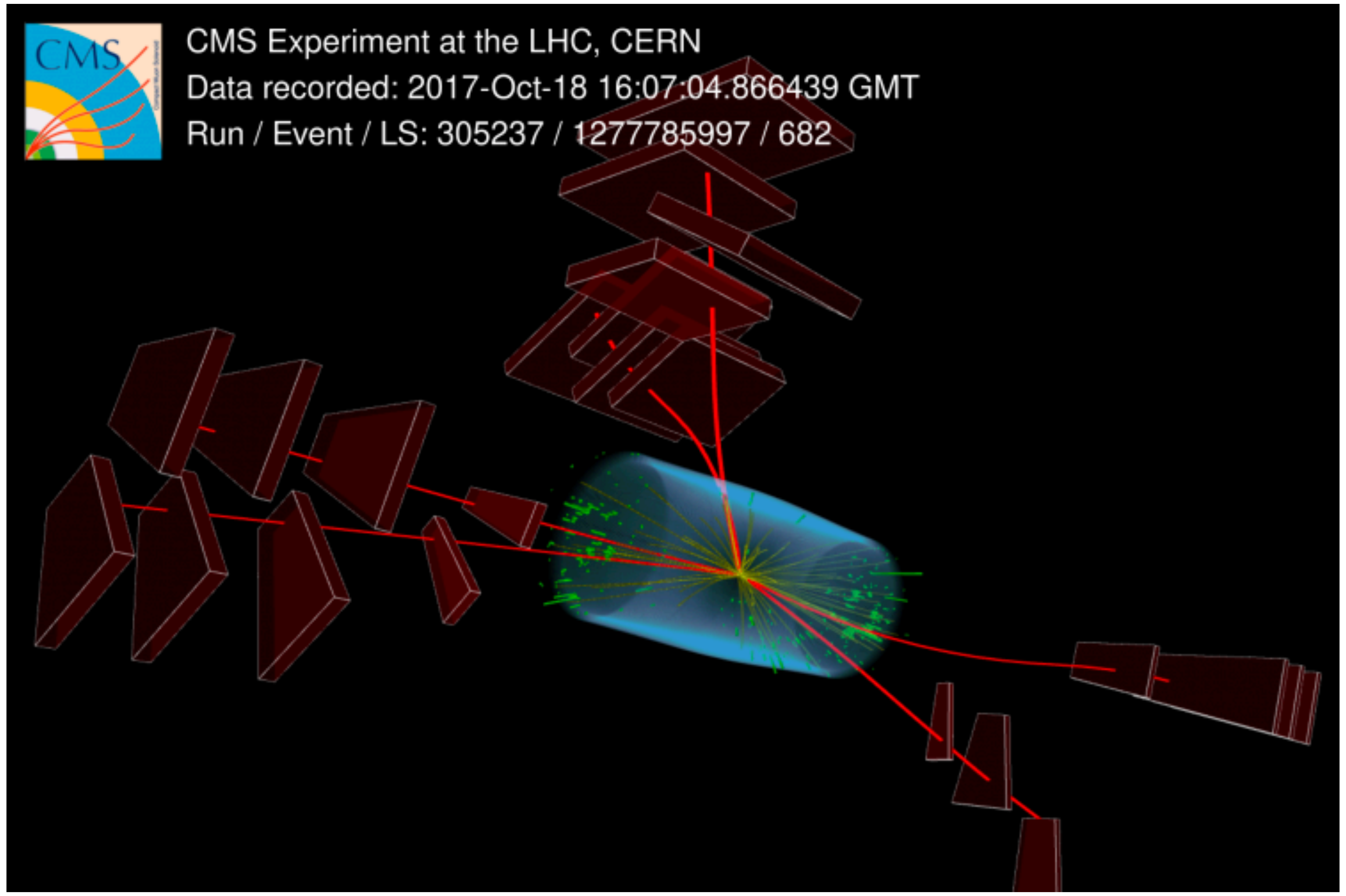
Simultaneous Production of 3 J/ψ Mesons

Observation of the $pp \to 3\,J/\psi + X$ process

- involves double (DPS) and triple (TPS) parton scattering

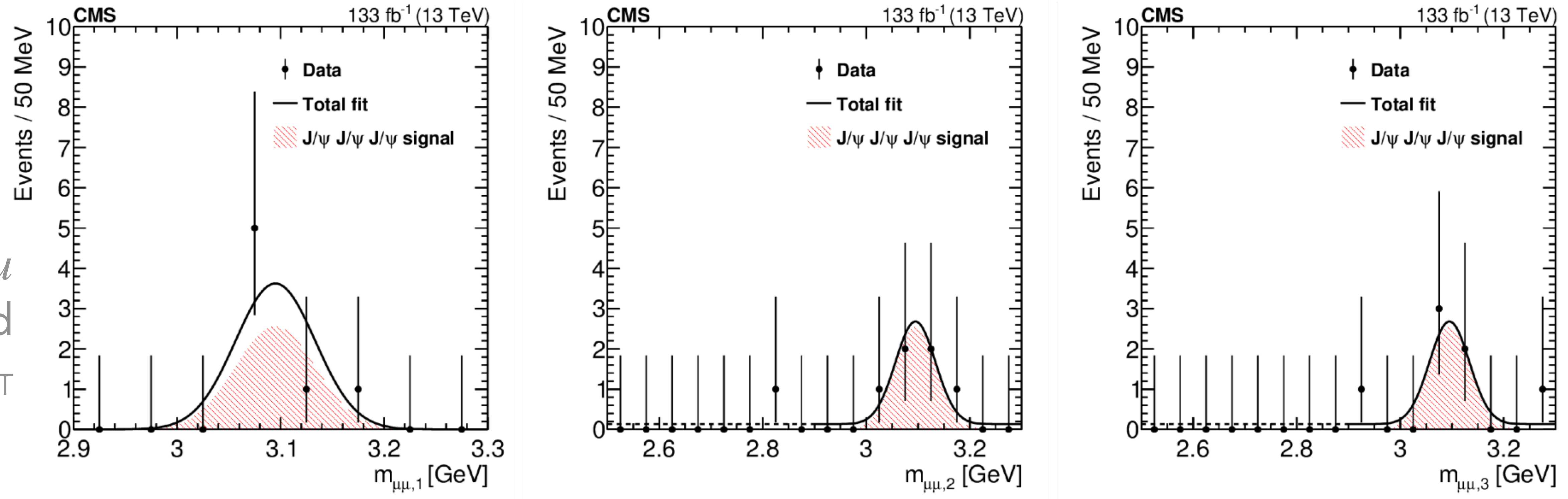
Run-2, 13 TeV, 133 fb^{-1}





6 events seen in data : $N(3\,J/\psi) = 5.0\,^{+2.6}_{-1.9}$ (significance >5σ)

3 $J/\psi \to \mu\mu$ ordered by p_T



- $\sigma^{\rm fid}(pp \to 3\,J/\psi + X) = 272^{+141}_{-104}$ (stat) $\pm$ 27 (syst) fb
- $\sigma_{\rm eff}({\rm DPS}) = 2.7^{+1.4}_{-1.0}$ (exp)$^{+1.5}_{-1.0}$ (theo) mb

$\sigma_{\rm eff}$(DPS) : consistent with double-quarkonium, smaller than other double-particles

CMS-BPH-21-004
Submitted to NP

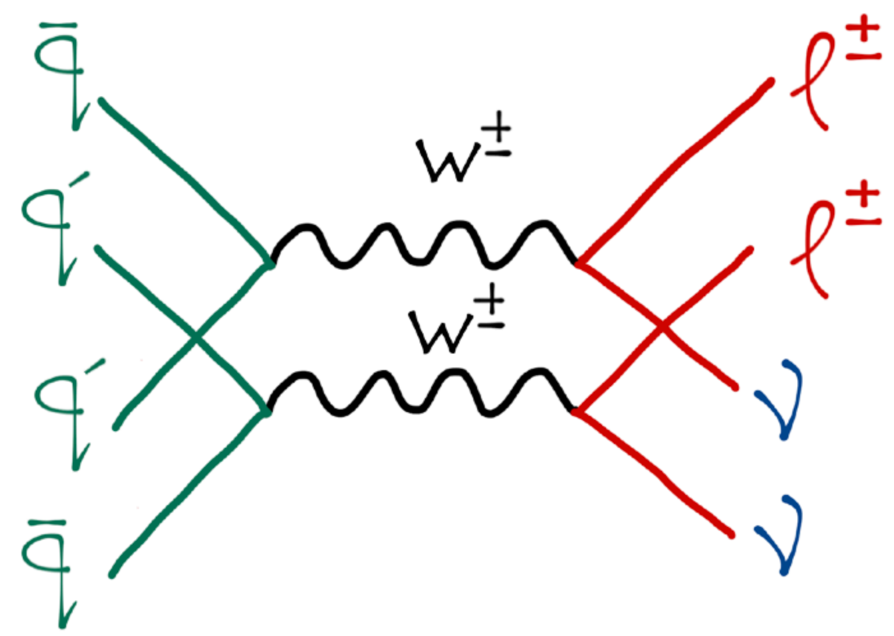
Phys. Briefing

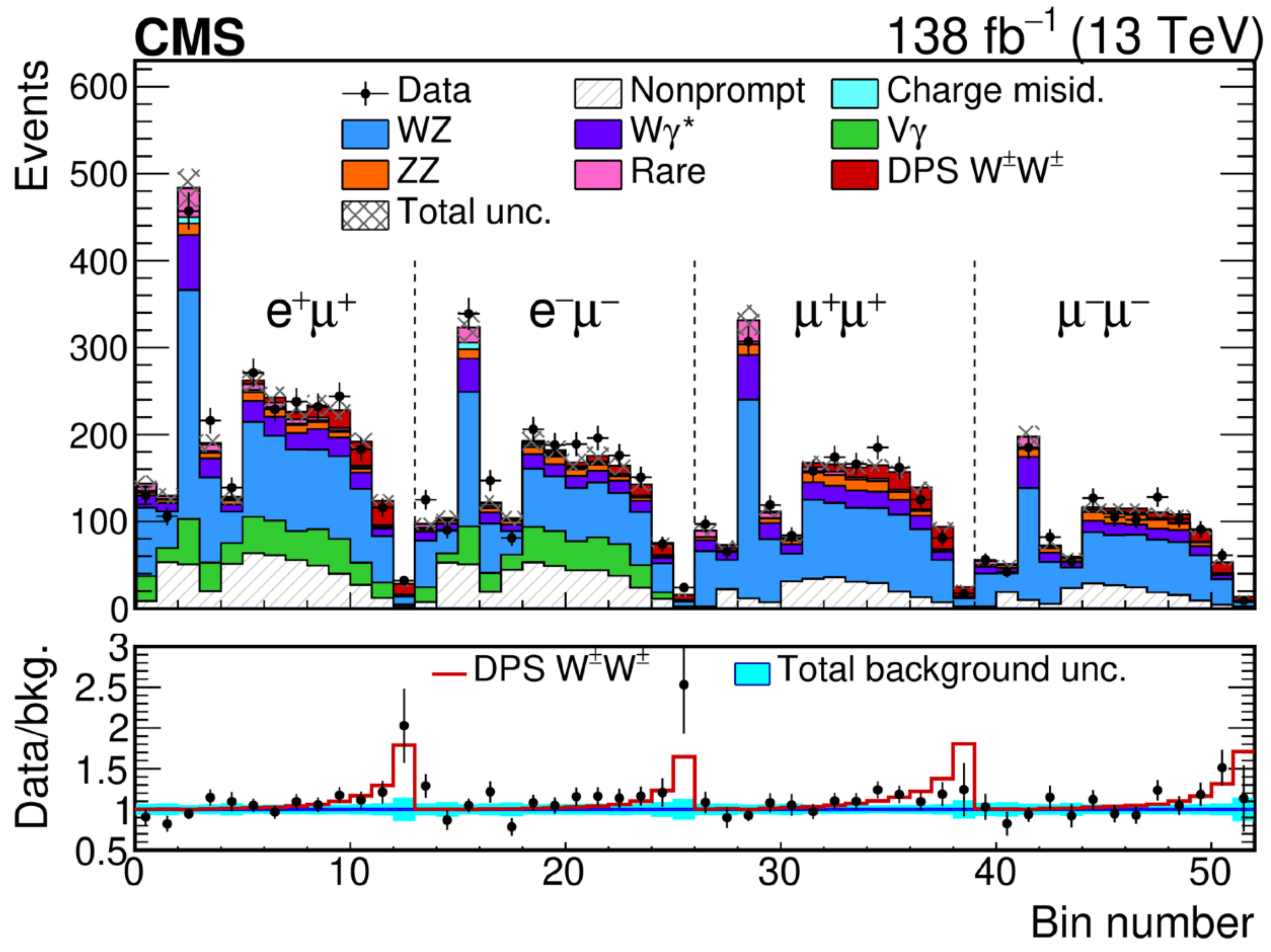
Simultaneous Production of Same-Sign W Bosons

Run-2, 13 TeV, 138 fb^{-1}

Observation of same-sign WW production, $pp \to W^{\pm}W^{\pm} + X$

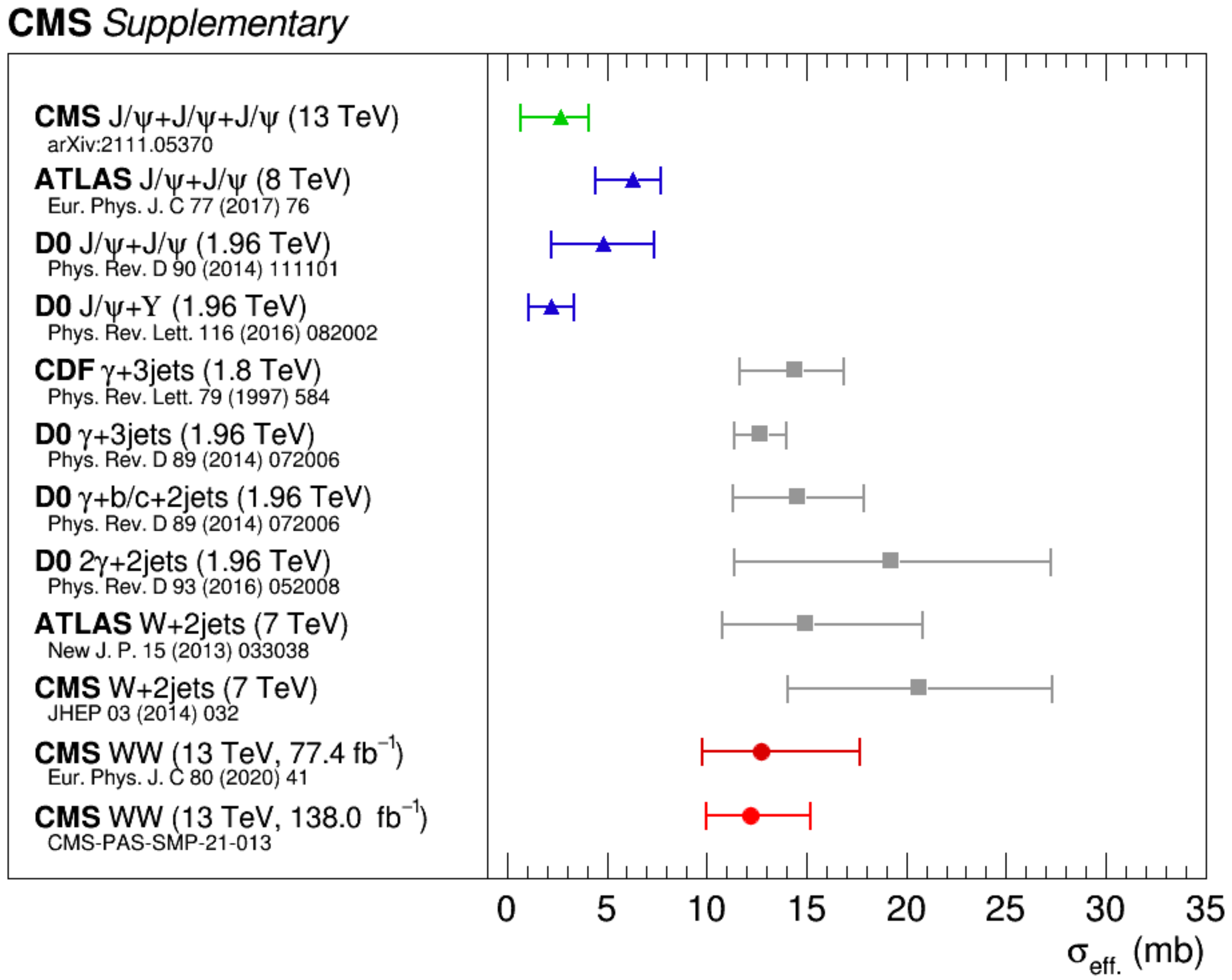
- involves double parton scattering (DPS)
- same-sign lepton pair (eμ or μμ), moderate MET and low jet multiplicity





Observation:
6.2σ (6.7σ exp.)

$$\sigma_{W^{\pm}W^{\pm}}(\text{DPS}) = \sigma_{W^{\pm}}(\text{SPS})^2/\sigma_{\text{eff}}(\text{DPS})$$



- $\sigma^{\text{fid}}(pp \to W^{\pm}W^{\pm} + X) =$
  $6.28 \pm 0.81\,(\text{stat}) \pm 0.69\,(\text{syst}) \pm 0.37\,(\text{model})$ fb
- $\sigma_{\text{eff}}(\text{DPS}) = 12.2^{+2.9}_{-2.2}$ mb

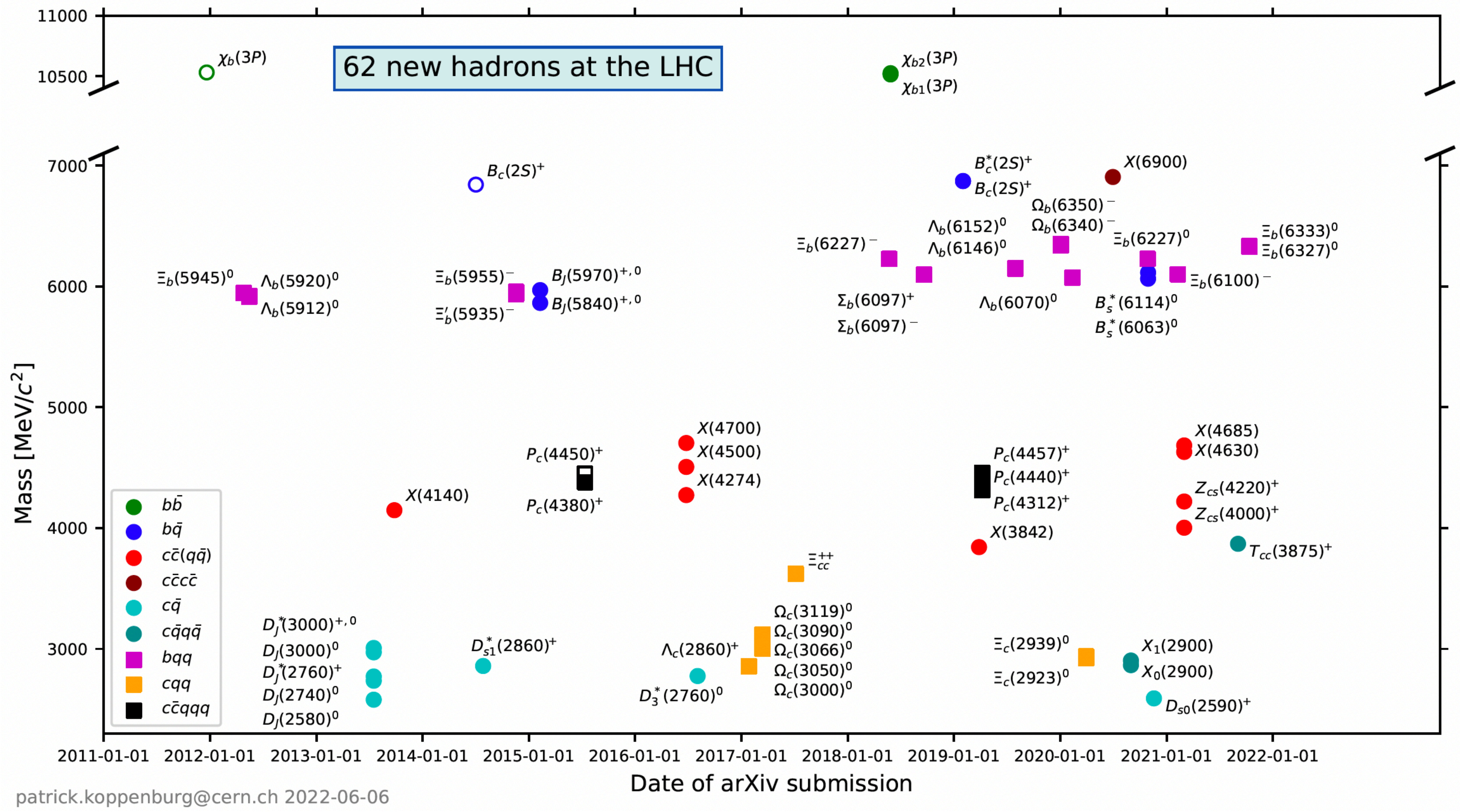
CMS-SMP-21-013
Submitted to PRL

Phys. Briefing

Hadron Spectroscopy

[62 new hadrons](#) discovered (so far) at the LHC

- mostly by LHCb (55)



Hadron Spectroscopy

62 new hadrons discovered (so far) at the LHC

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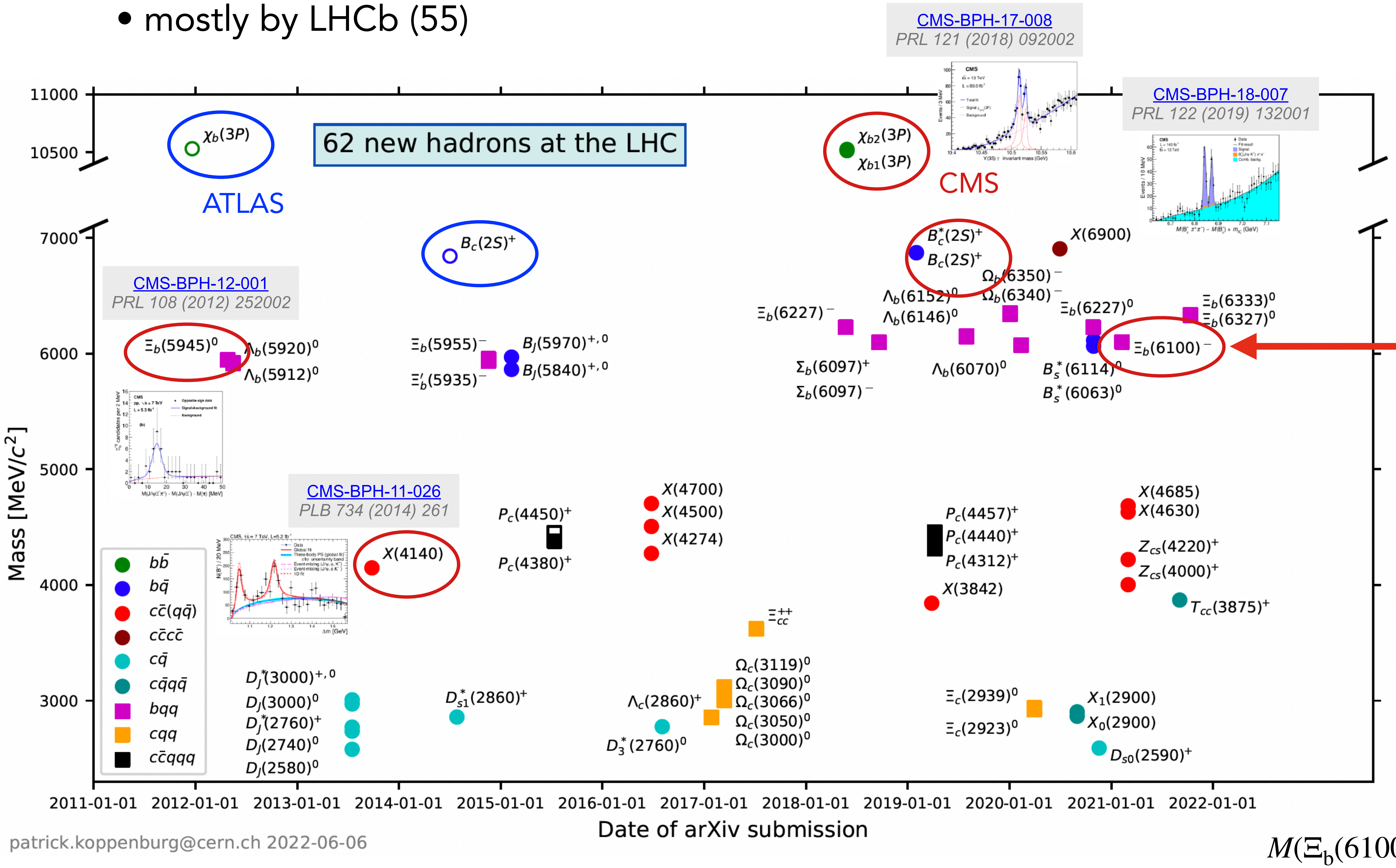
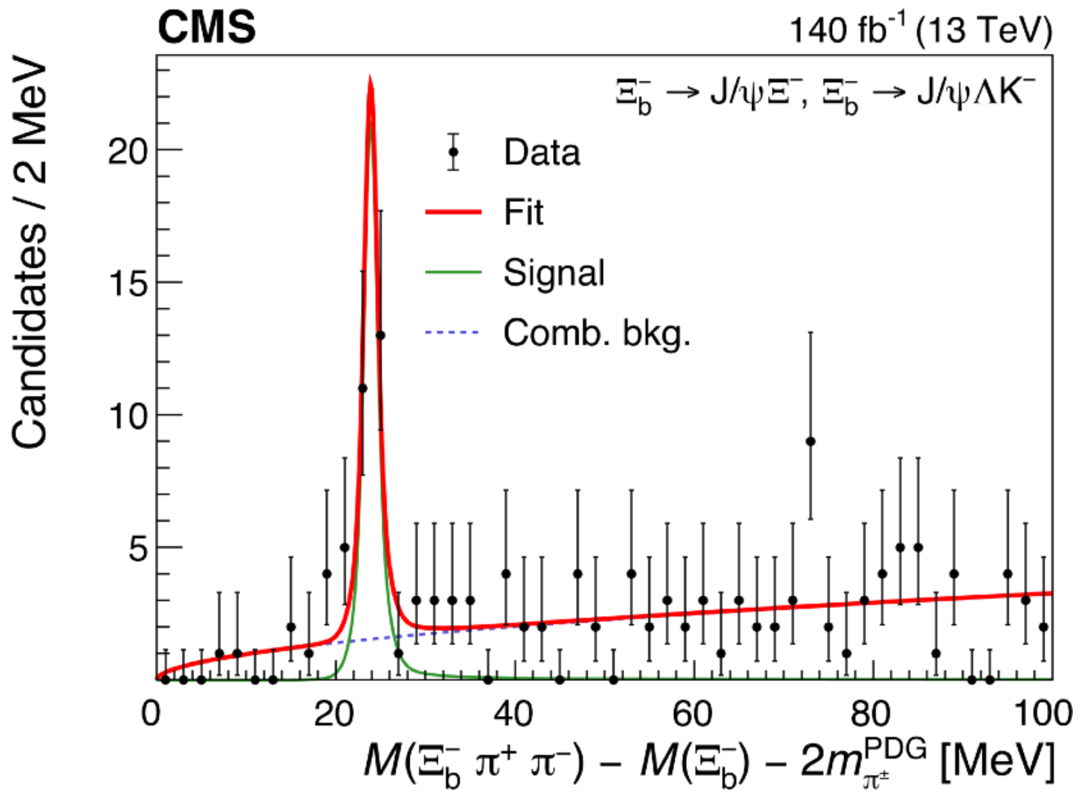


CMS-BPH-20-004
PRL 126 (2021) 252003



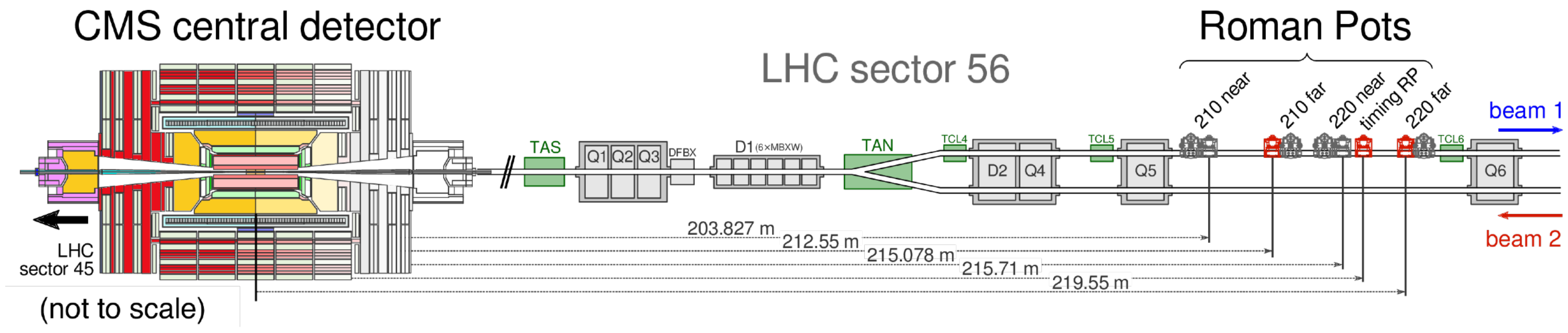
$\Xi_b(6100)^-$, an excited beautiful strange baryon decaying to $\Xi_b^-\pi^+\pi^-$

(possibly beauty analogue of the $\Xi_c(2815)$ baryon)

signal significance > 6.2σ

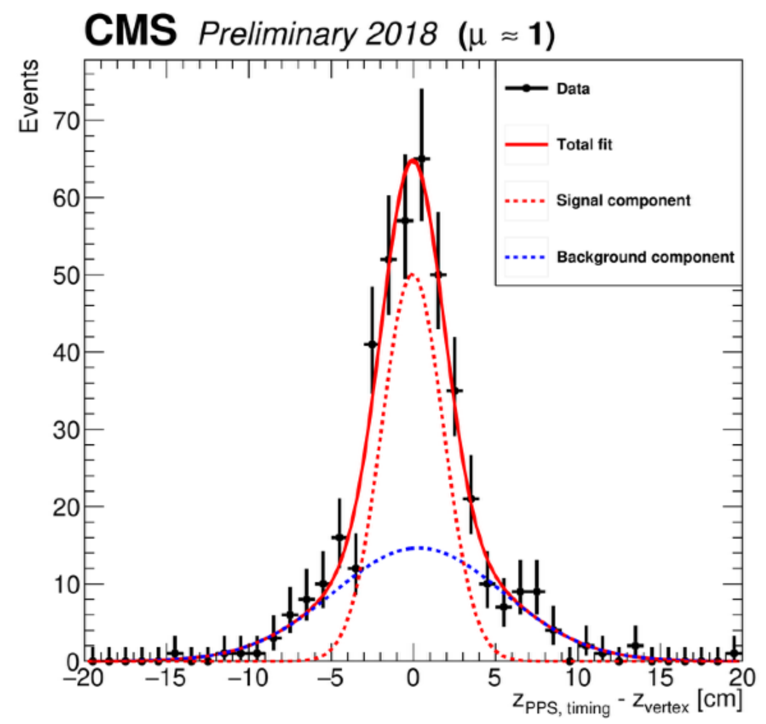
$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.6\,(\Xi_b^-)\ \text{MeV}$$

CT-PPS: Exclusive γγ Physics with Forward Protons



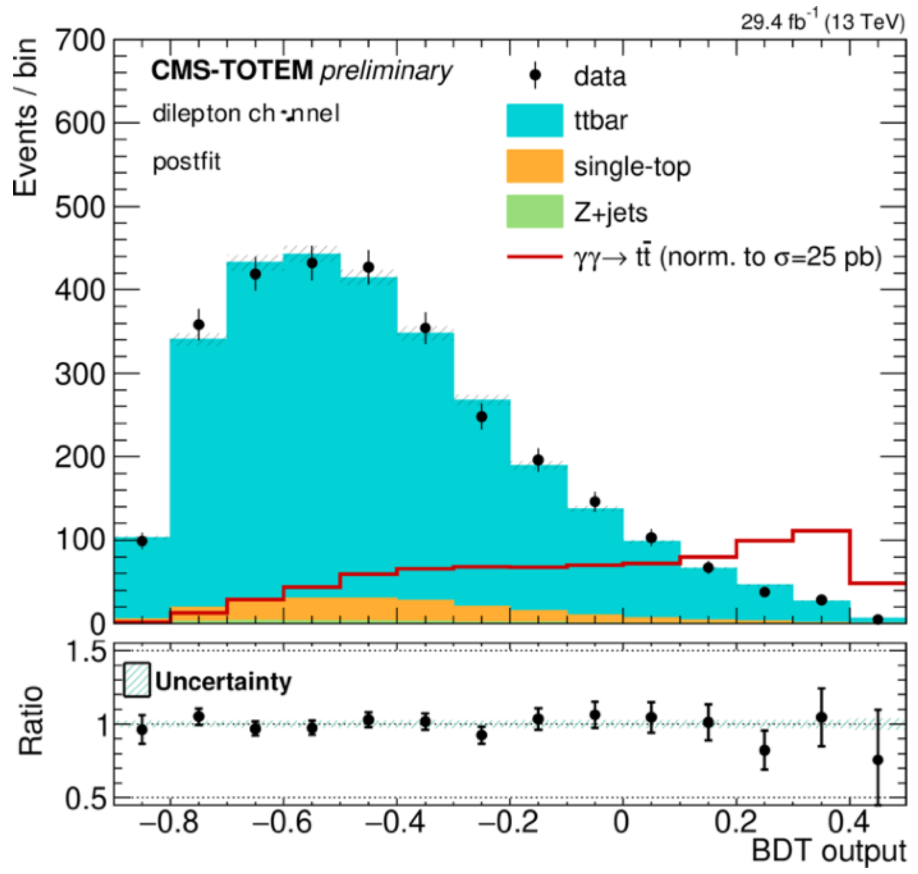
CMS-PAS-PRO-21-001

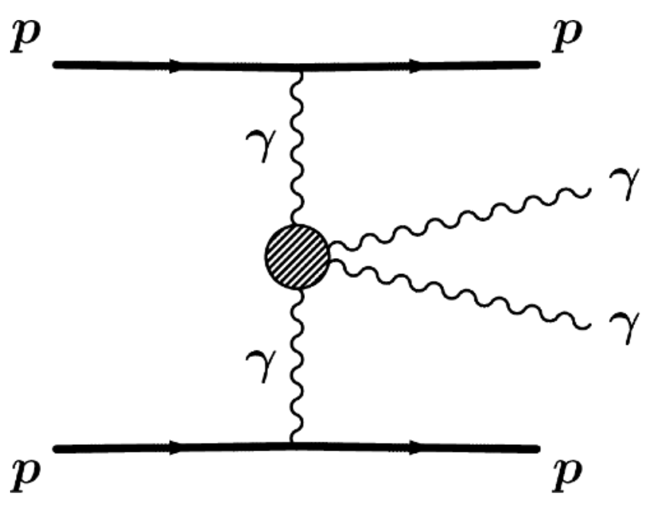
CMS/Totem-PPS collected 110 fb^{-1} of Run-2 data

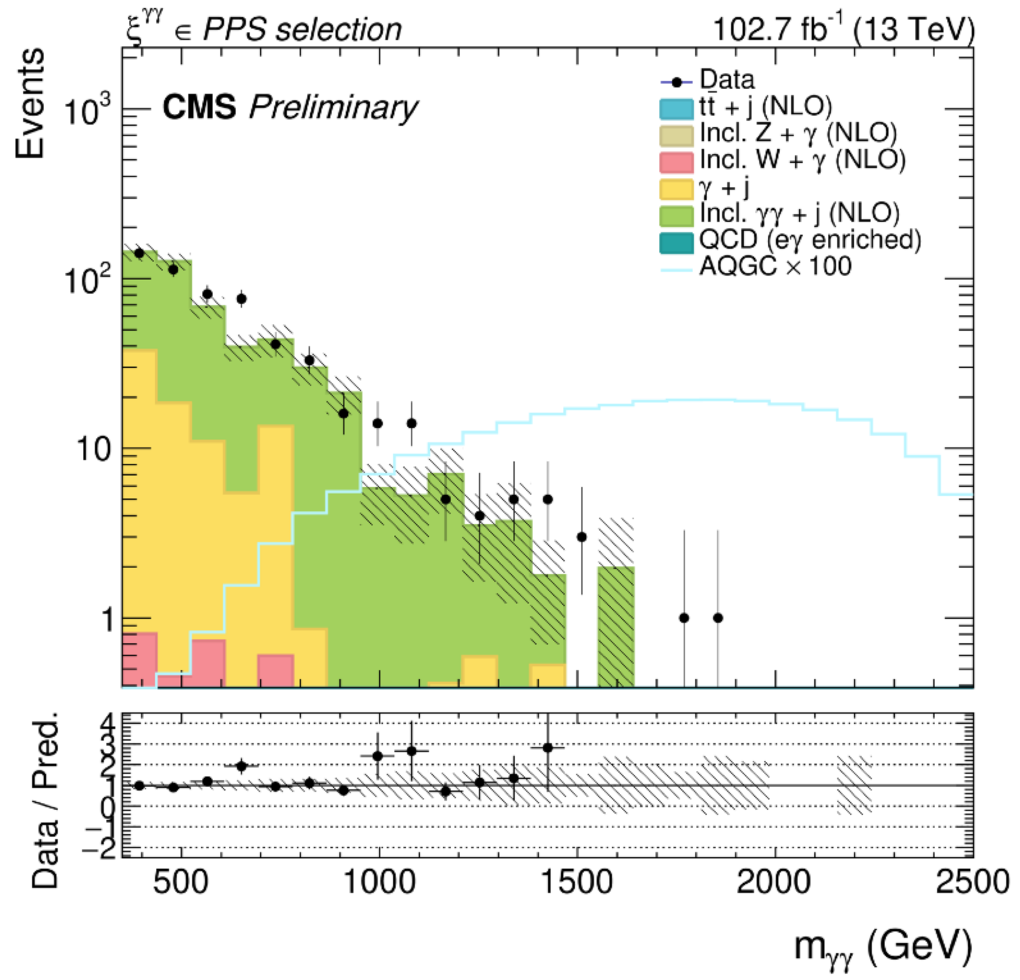


CMS-PAS-TOP-21-007

Search for exclusive production of γγ → tt

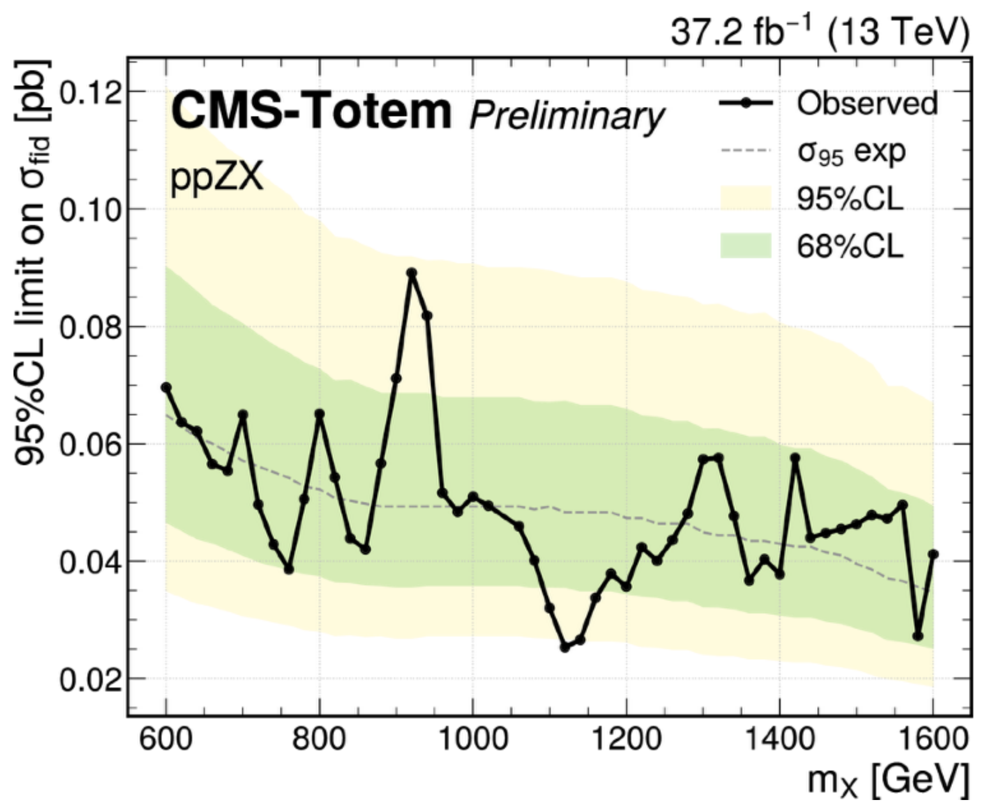






CMS-PAS-EXO-21-007

Search for high-mass exclusive diphoton events, limits on 4γ anomalous couplings and on ALP production

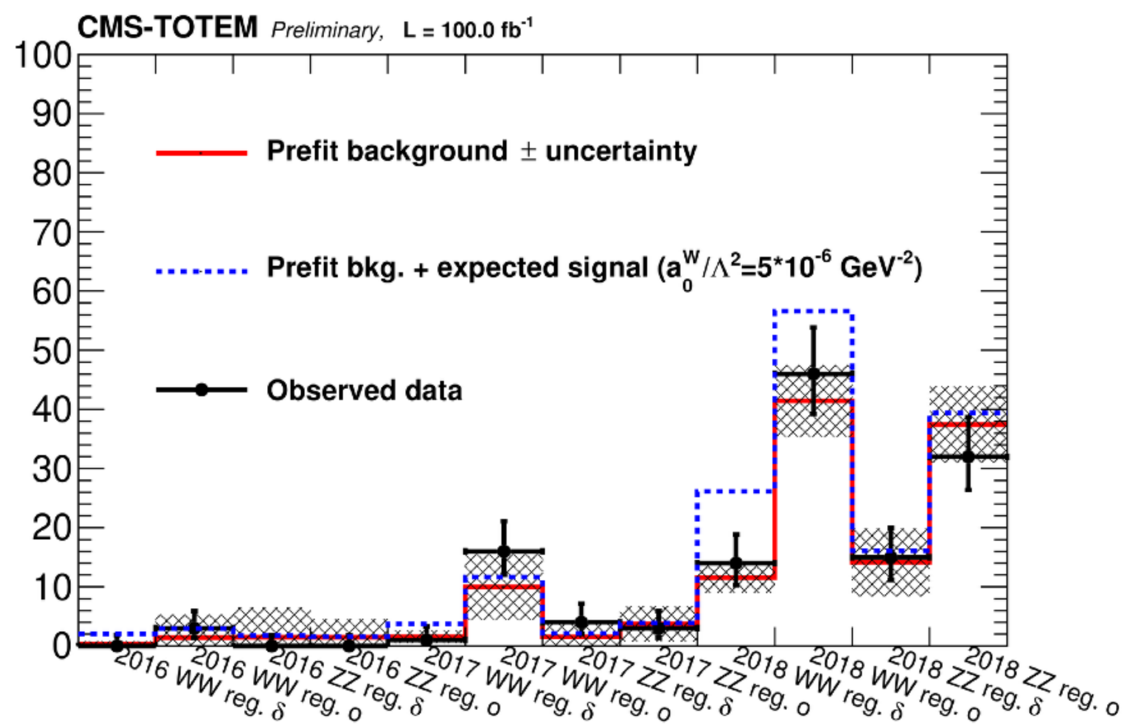


CMS-PAS-EXO-19-009

Search for anomalous Z/γ* central production

CMS-PAS-SMP-21-014

Search for anomalous high-mass γγ → WW and ZZ



A Rich Program in Heavy Ion Physics

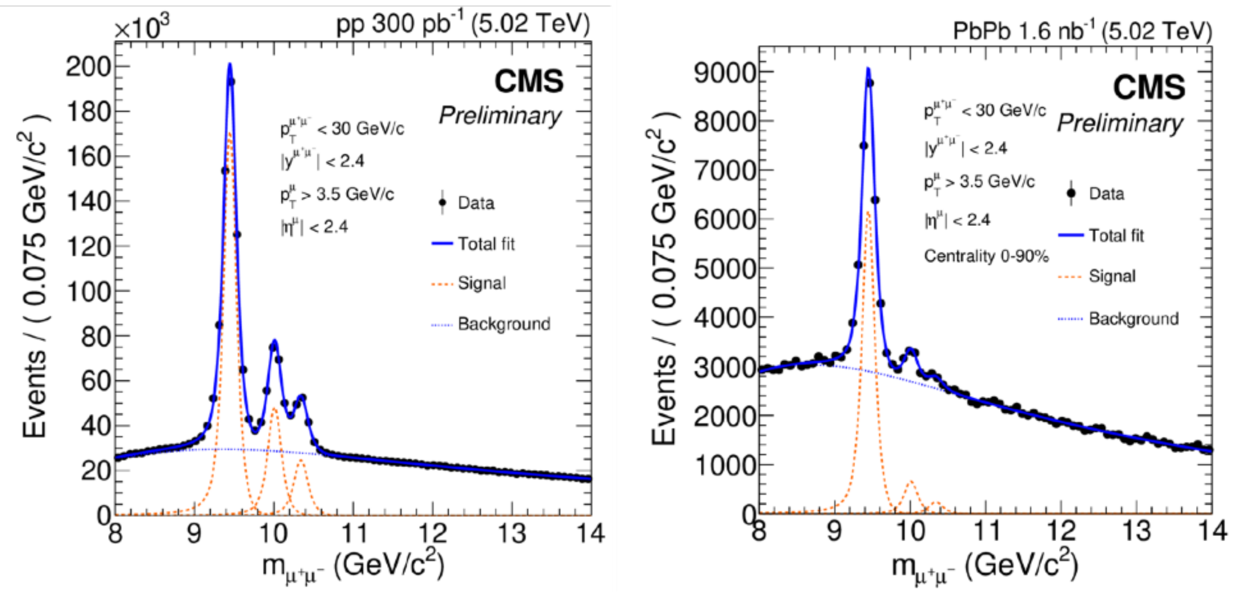
CMS contributions at Quark Matter 2022

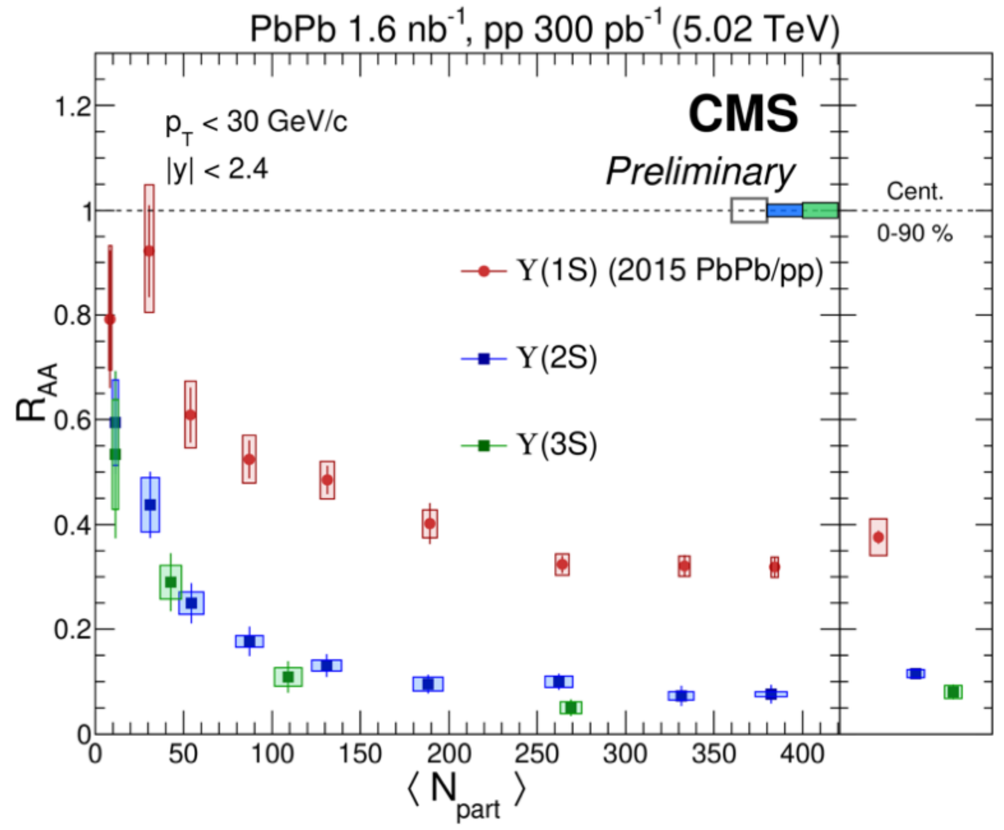
CMS-PAS-HIN-21-010	Probing hydrodynamics and the moments of the elliptic flow distribution in $\sqrt{s_{NN}}$ = 5.02 TeV lead-lead collisions using higher-order cumulants
CMS-PAS-HIN-21-003	Azimuthal anisotropy of nonprompt D^0 mesons in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS-PAS-HIN-21-001	Azimuthal anisotropy of Υ(1S) mesons in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV
CMS-PAS-HIN-21-011	Measurement of two-particle Bose-Einstein momentum correlations and their Lévy parameters at $\sqrt{s_{NN}}$ = 5.02 TeV PbPb collisions
CMS-PAS-HIN-21-012	Correlations between multiparticle cumulants and mean transverse momentum in small collision systems with the CMS detector
CMS-PAS-HIN-21-007	Observation of the Υ(3S) meson and sequential suppression of Υ states in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS-PAS-HIN-21-008	Measurements of the azimuthal anisotropy of charmonia in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS-PAS-HIN-21-002	Azimuthal anisotropy of jet quenching in dijet events in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS-PAS-HIN-20-003	Measurements of b jet shapes in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

CMS-PAS-HIN-21-007

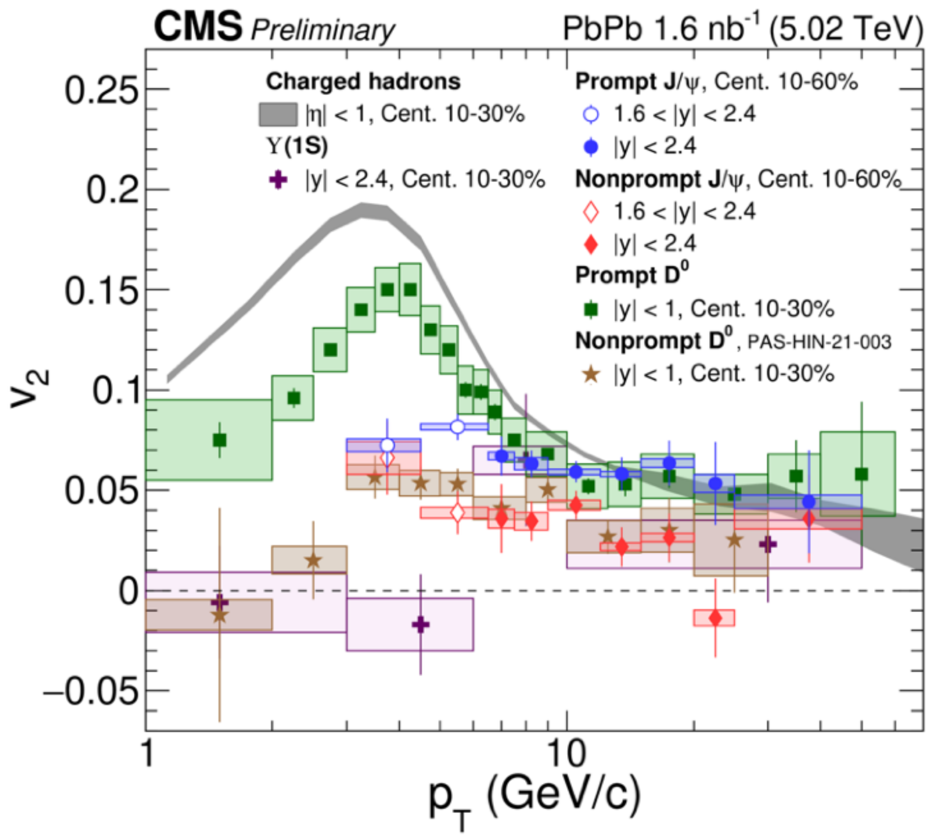
Suppression of Υ states in PbPb

- Υ(3S) observed for the 1st time in PbPb
- stronger Υ(3S) suppression than Υ(2S)





PbPb Run-2 (2018)
$\sqrt{s_{NN}}$ = 5.02 TeV
1.7 nb^{-1}

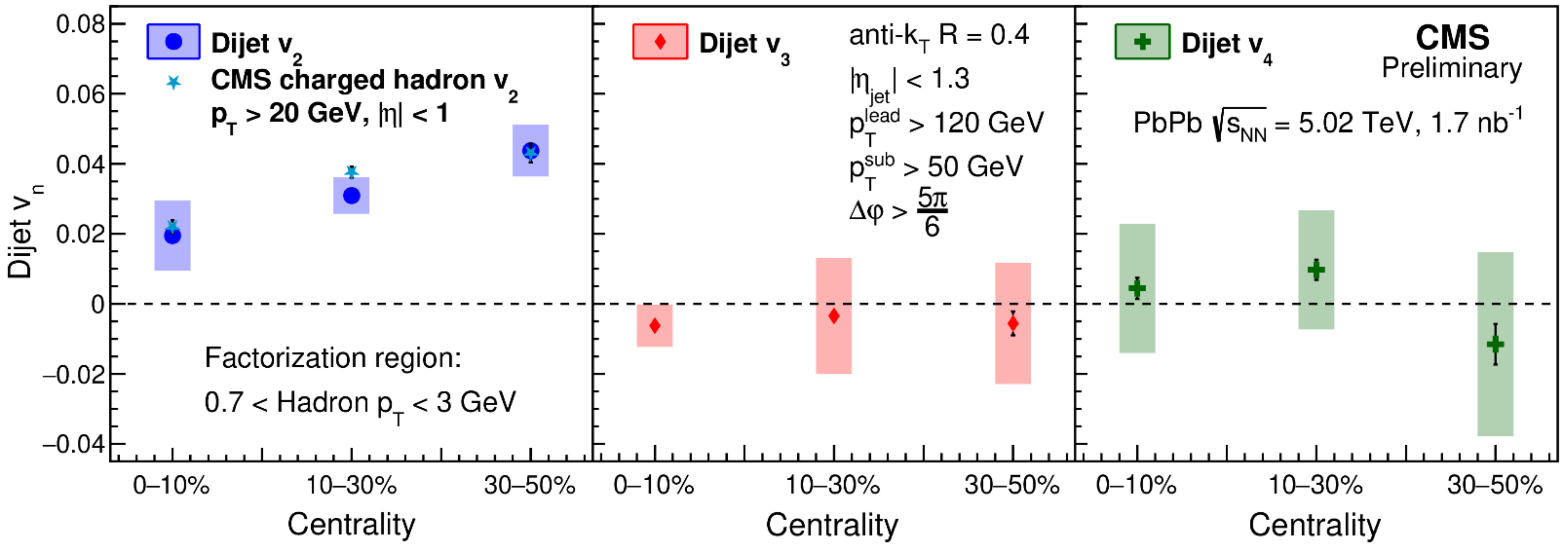


CMS-PAS-HIN-21-008

Charmonium: prompt and non-prompt J/ψ and prompt ψ(2S)

CMS-PAS-HIN-21-002

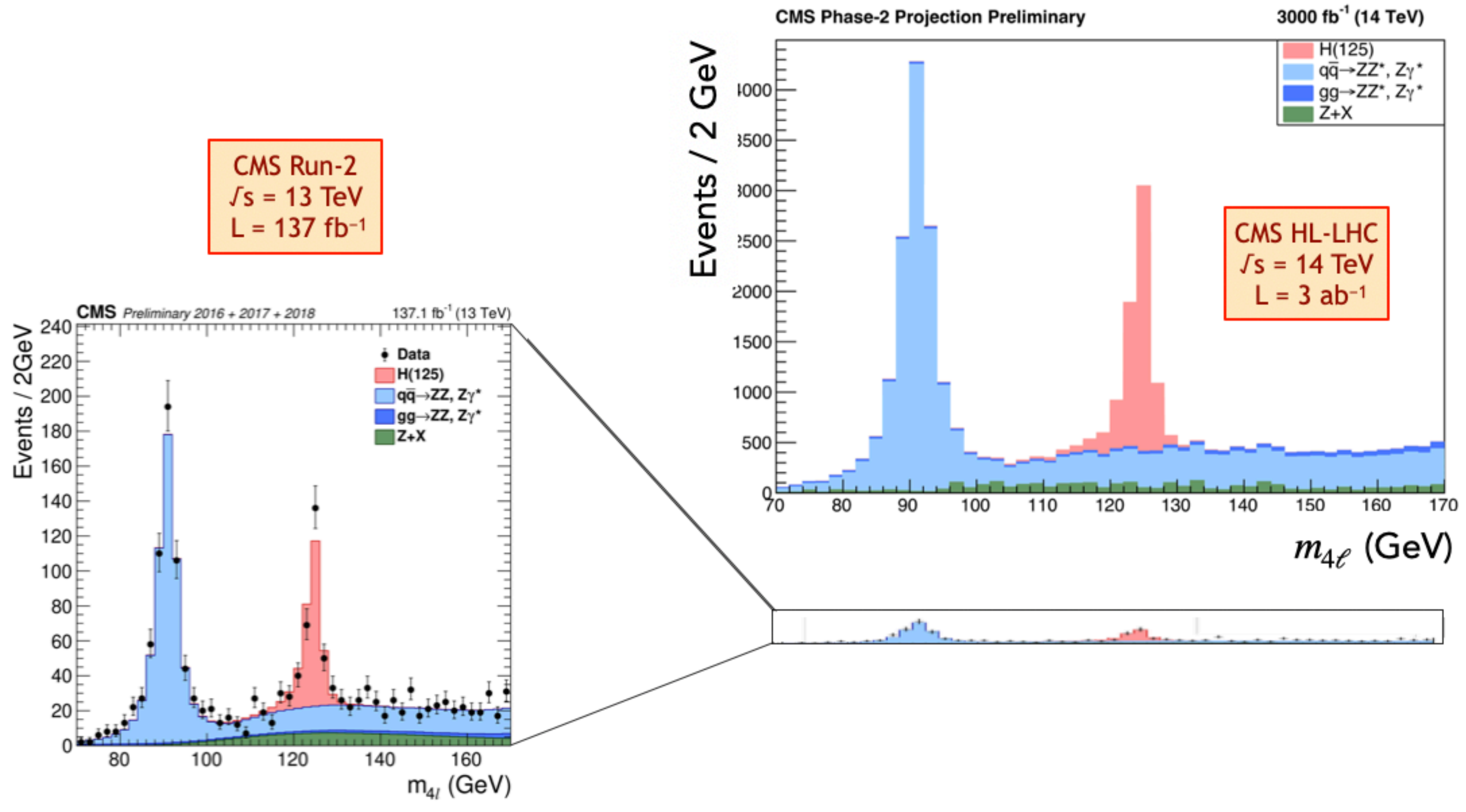
Azimuthal anisotropy of jet quenching in di-jet events



Future Performance at HL-LHC

It's only the beginning!

ATLAS and CMS released a joint White Paper for Snowmass with updated projections for physics performance at HL-LHC



With HL-LHC (3000 fb^{-1})

- $m_{\mathrm{H}}^{\gamma\gamma} = 125.38 \pm 0.07\,(\mathrm{tot})\ [\pm 0.02\,(\mathrm{stat})]$ GeV
- $m_{\mathrm{H}}^{4\ell} = 125.38 \pm 0.03\,(\mathrm{tot})\ [\pm 0.02\,(\mathrm{stat})]$ GeV
- $\Gamma_{\mathrm{H}}^{4\ell} < 0.18$ GeV @ 95 % CL

Prospects in pp collisions at √s = 14 TeV with the CMS detector at the HL-LHC

EWK	CMS-PAS-FTR-21-001	Prospects for the measurement of vector boson scattering production in leptonic same-sign WW and WZ diboson events
H	CMS-PAS-FTR-21-007	Projection of the Higgs boson mass and on-shell width measurements in H → ZZ* → 4ℓ decay channel
	CMS-PAS-FTR-21-008	A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel
	CMS-PAS-FTR-21-006	Prospects for the precise measurement of the Higgs boson properties in the H → μμ decay channel
	CMS-PAS-FTR-21-009	Search for rare Higgs boson decays with mesons
	CMS-PAS-FTR-21-002	Prospects for the measurement of ttH production in the opposite-sign dilepton channel
HH	CMS-PAS-FTR-21-003	Prospects for HH measurements in the WWγγ and ττγγ final states
	CMS-PAS-FTR-21-004	Prospects for non-resonant Higgs boson pair production measurement in bbγγ final states
	CMS-PAS-FTR-21-010	Search for the nonresonant ttHH production in the semileptonic decay of the top pair and the Higgs pair decay into b quarks
BSM-H	CMS-PAS-FTR-22-005	Search for dark matter in final states with a Higgs boson decaying to a pair of b-jets and missing transverse momentum
	CMS-PAS-FTR-22-006	Prospects for a search for doubly charged Higgs bosons
BSM	CMS-PAS-FTR-21-005	Sensitivity projections for a search for new phenomena at high dilepton mass
	CMS-PAS-FTR-21-011	Search for leptophobic Z' resonances decaying to charginos in the dilepton plus missing transverse momentum final state
	CMS-PAS-FTR-22-003	Seesaw model searches using multilepton final states

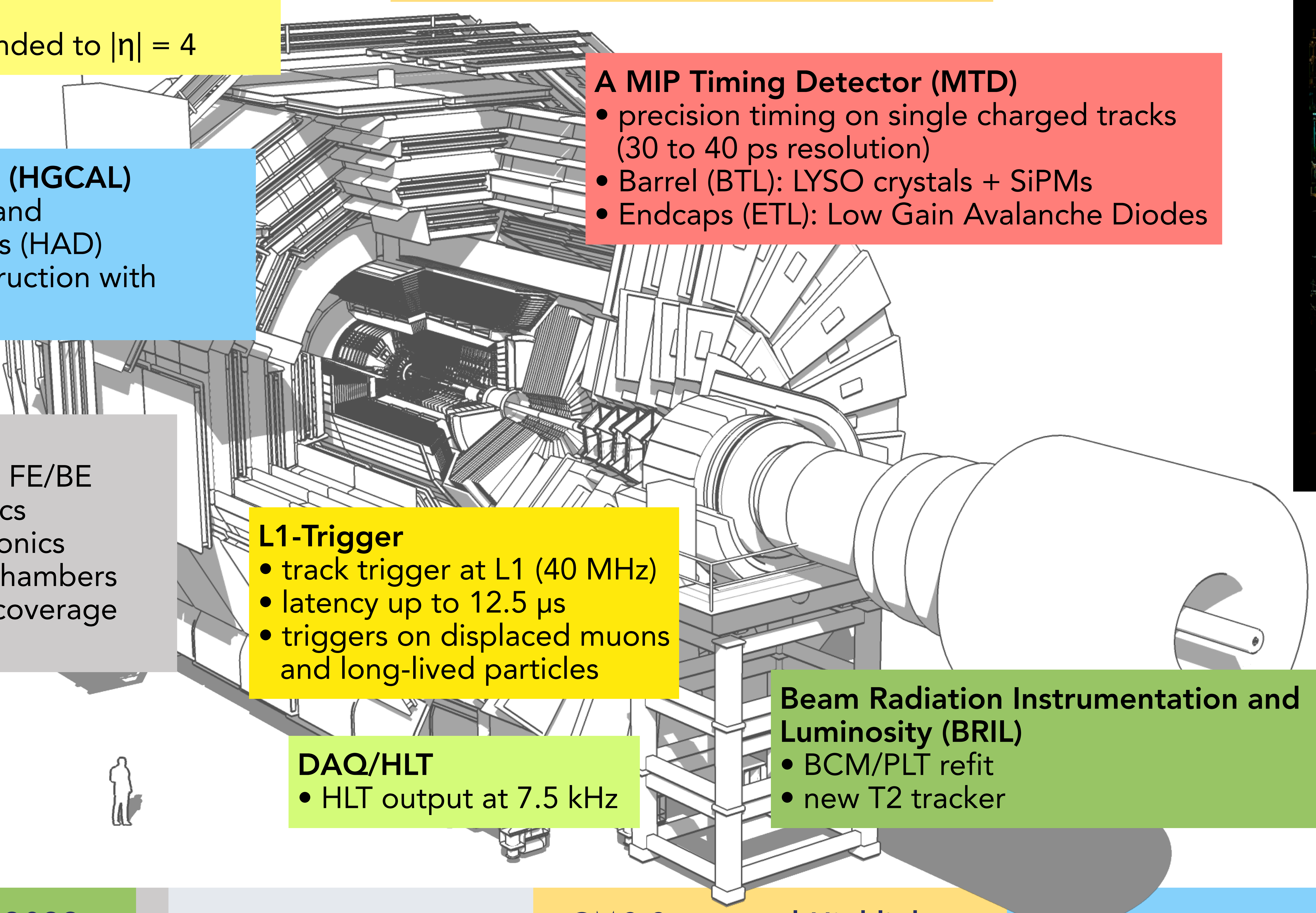
CMS Phase-II Upgrades

Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to $|\eta| = 4$

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for e/γ > 30 GeV
- ECAL operation at low temperature (10°)
- upgraded laser monitoring system

A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes

Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing



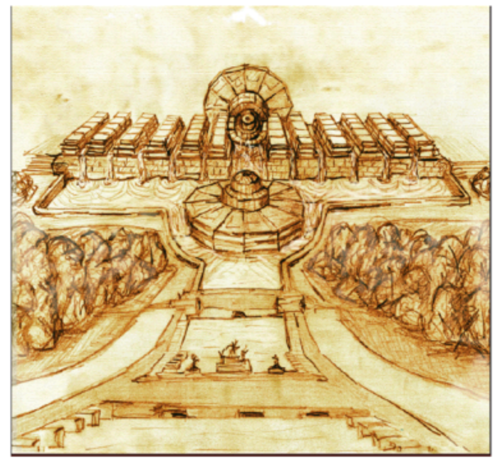
Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to $|\eta| = 3$

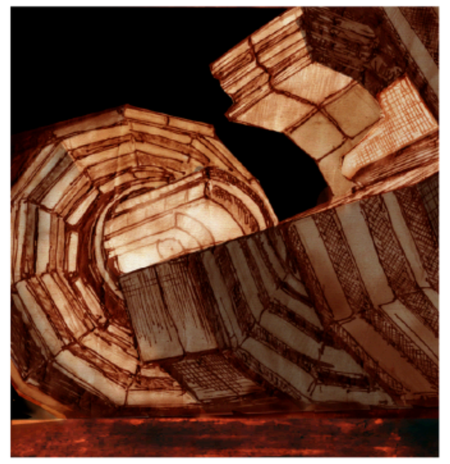
L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 μs
- triggers on displaced muons and long-lived particles

DAQ/HLT
- HLT output at 7.5 kHz

Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker

published last year:

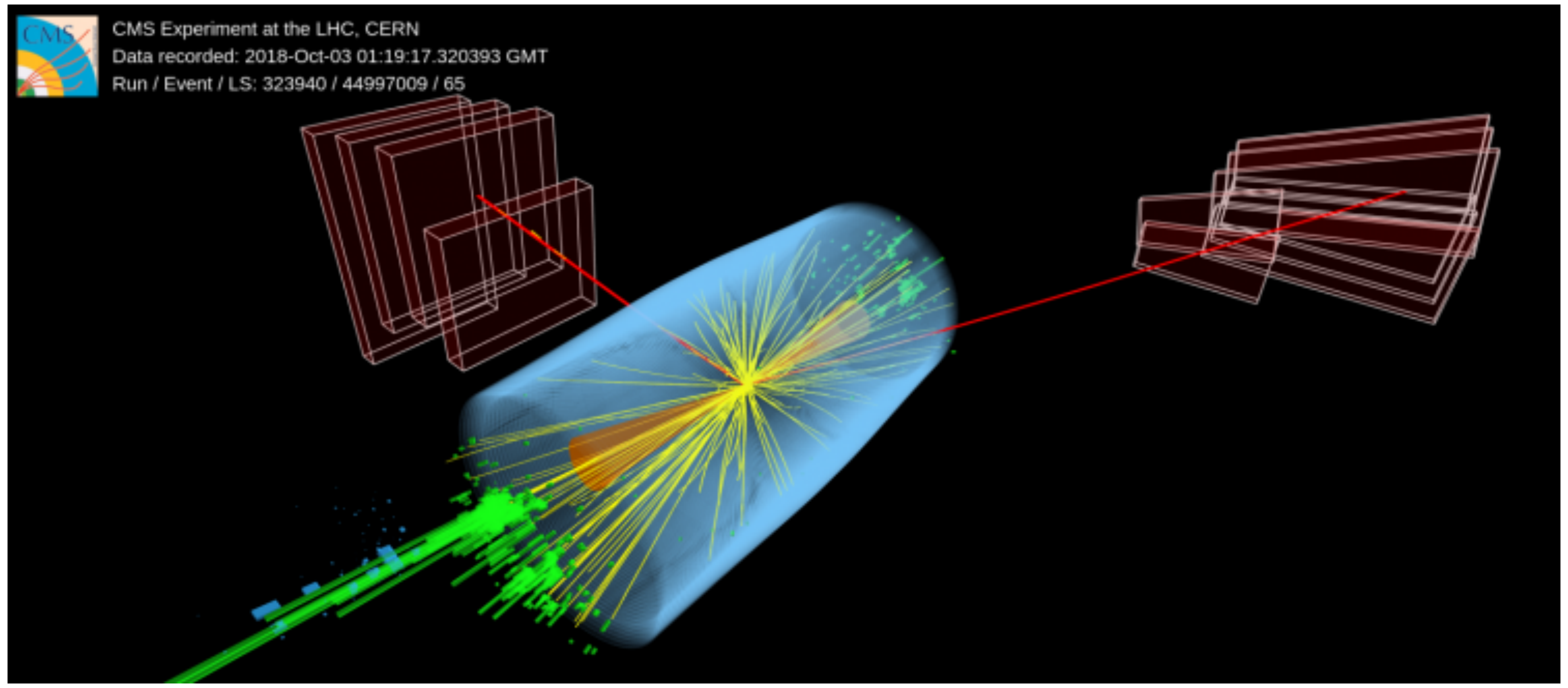

DAQ/HLT


BRIL

Summary and Prospects

LS2 is over: CMS has successfully completed all its upgrade activities

- upgrade of the Hadron Calorimeter readout
- first Phase-II muon detector (GE1/1)
- new beam-pipe for Phase-II
- fully-refurbished pixel detector



Phase-II Upgrades

- a new schedule: LS3 shifted by 1 year and extended by 6 months (2026-2028)
- excellent progress in all projects, despite difficult times due to the global situation

CMS commissioning for Run-3

- a very successful pilot beam test in Nov 2021
- intensive cosmic ray campaign with full field
- CMS back online with improved detector, DAQ, trigger, computing, software capability

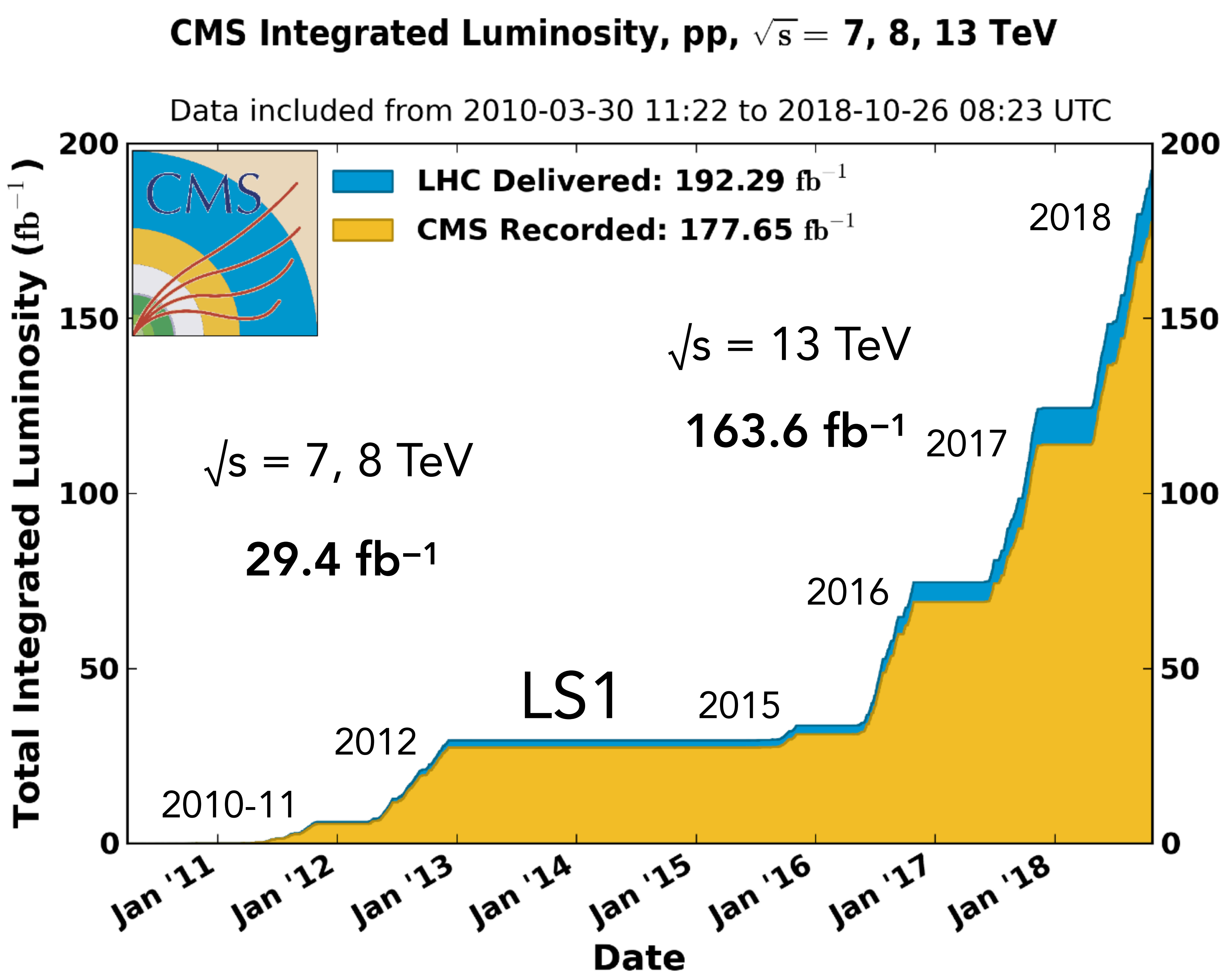
Physics

- an impressive physics harvest with the full Run-2 dataset
- many results way better than anticipated
- improved physics capabilities thanks to the deployment of advanced analysis techniques

CMS is fully ready for Run-3
and awaits the imminent return of
colliding beams with great eagerness


ME&RE-1/3/05
ME&RE-1/3/04
ME&RE-1/2/04
ME&RE-1/2/03
ME&RE-1/2/02
ME&RE-1/2/36
ME&RE-1/3/34

CMS pp Data at LHC Run-2



Excellent performance of the LHC in Run-2

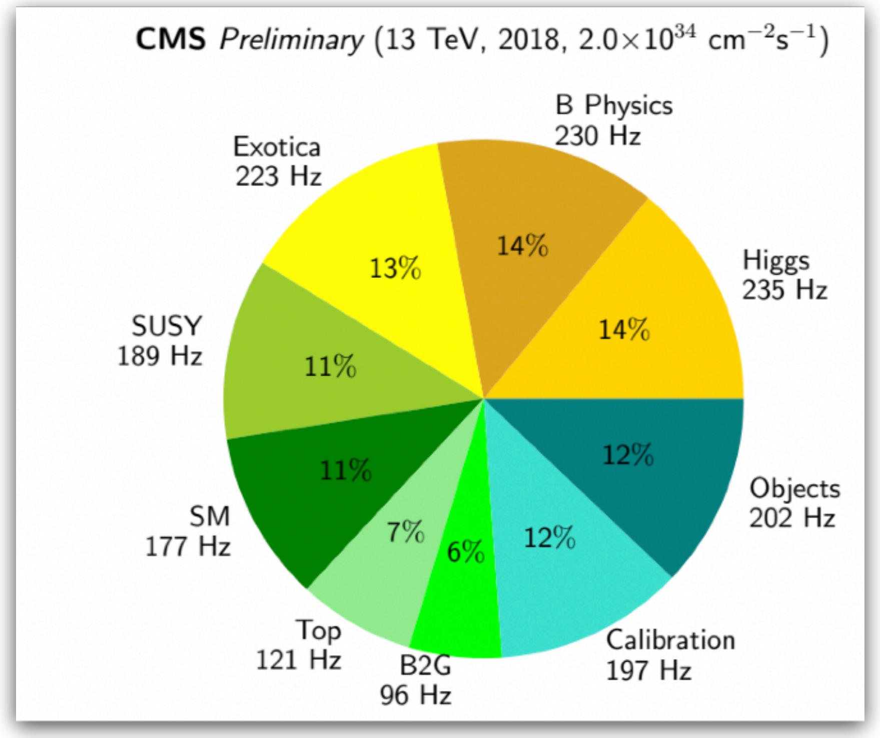
- max LHC luminosity (2018):
  $\mathscr{L}_{max} = 2.14 \times 10^{34}$ cm^{-2}s^{-1}
  (factor of 2 higher than designed 10^{34} cm^{-2}s^{-1})

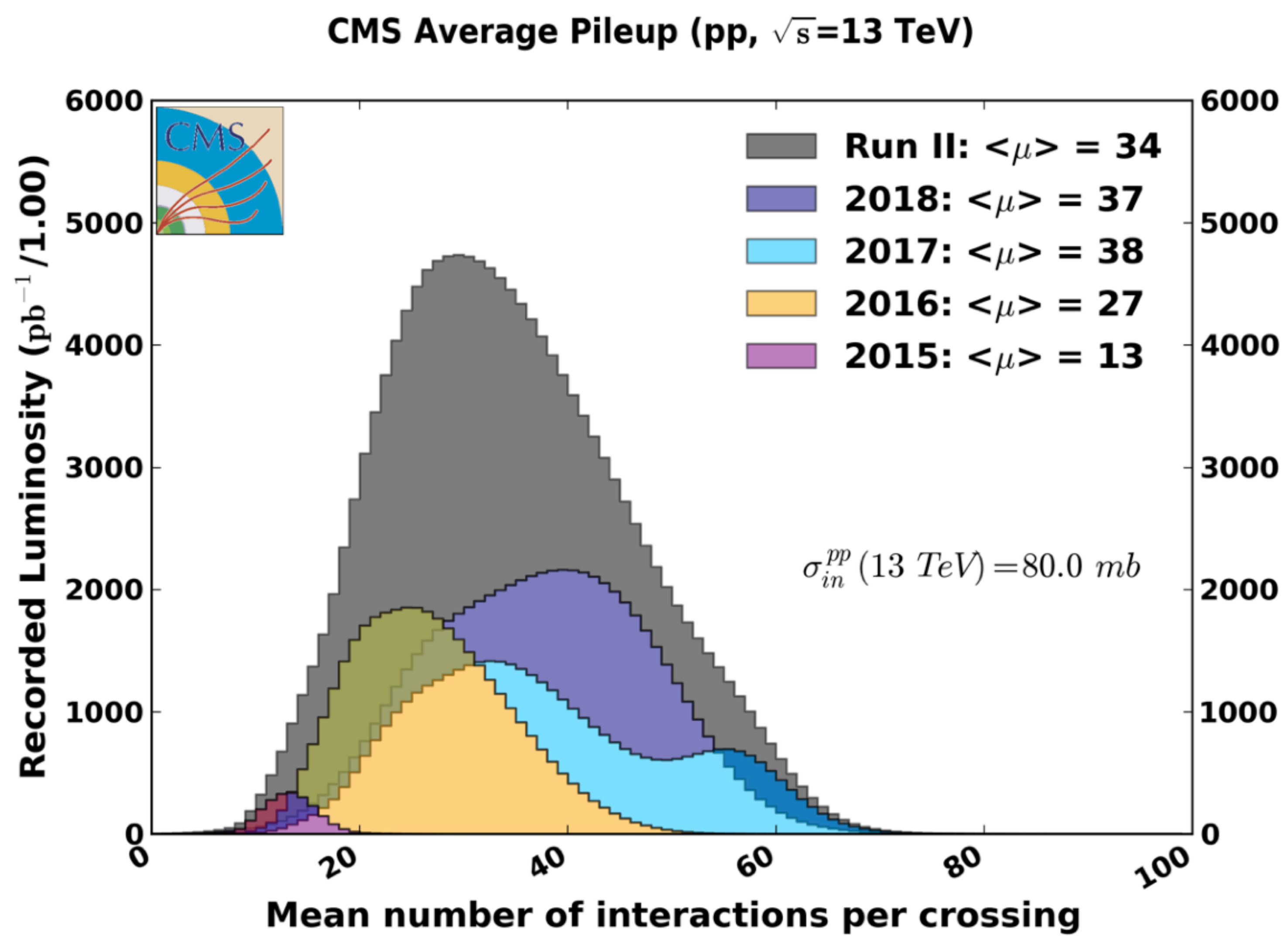
CMS Dataset Run-2

- 2016-2018: **137 fb^{-1}** of pp data "good for physics"
- data-taking efficiency > 92% (2018: 94%)
- number of pp interactions per beam crossing (PU): <μ> = 34

CMS Triggers for Run-2 (1.6 kHz)

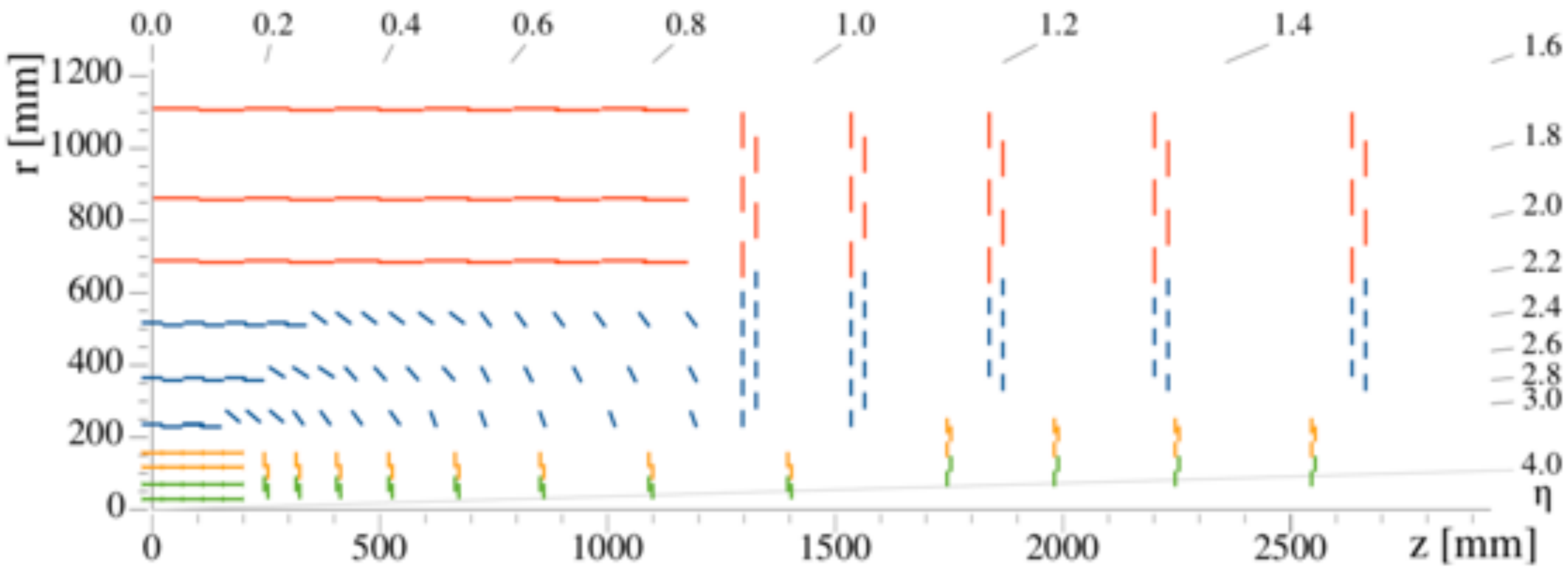
- Standard triggers (leptons, jets, MET)
- **B-parking triggers** (up to 5 kHz)
  10B events enriched in un-biased B decays
- Scouting triggers
  reduced events with physics objects

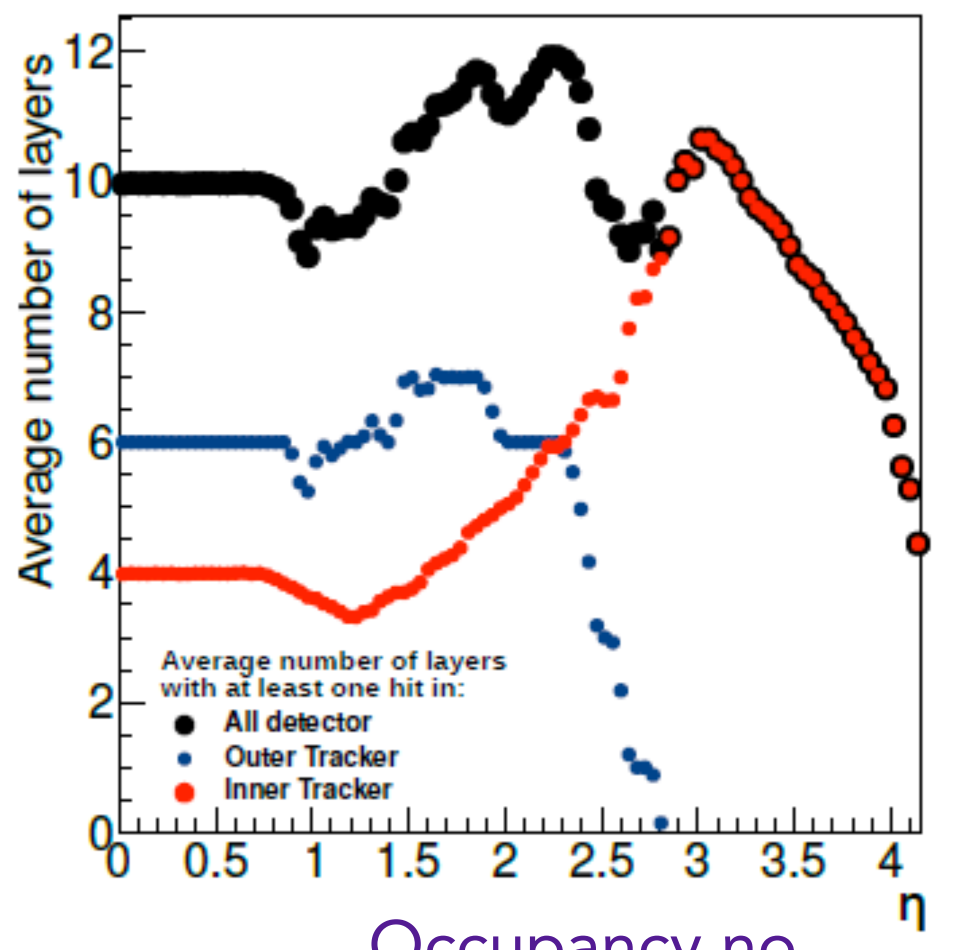




Phase-II Tracker Upgrade

Key features
- more granularity
- lower material budget
- extended coverage
- tracking included at L1-trigger level

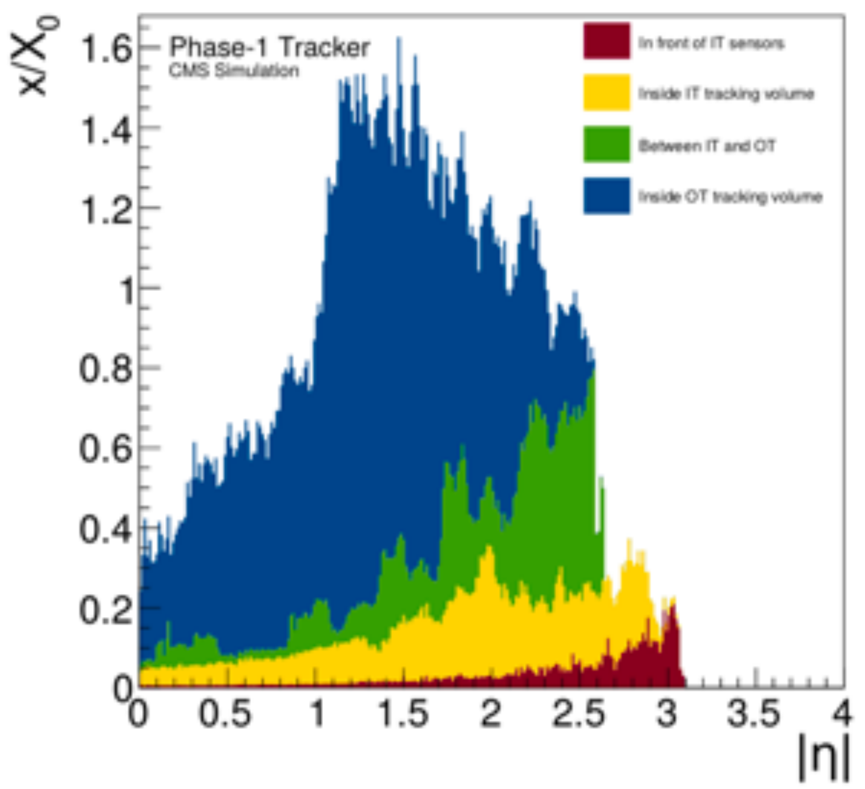




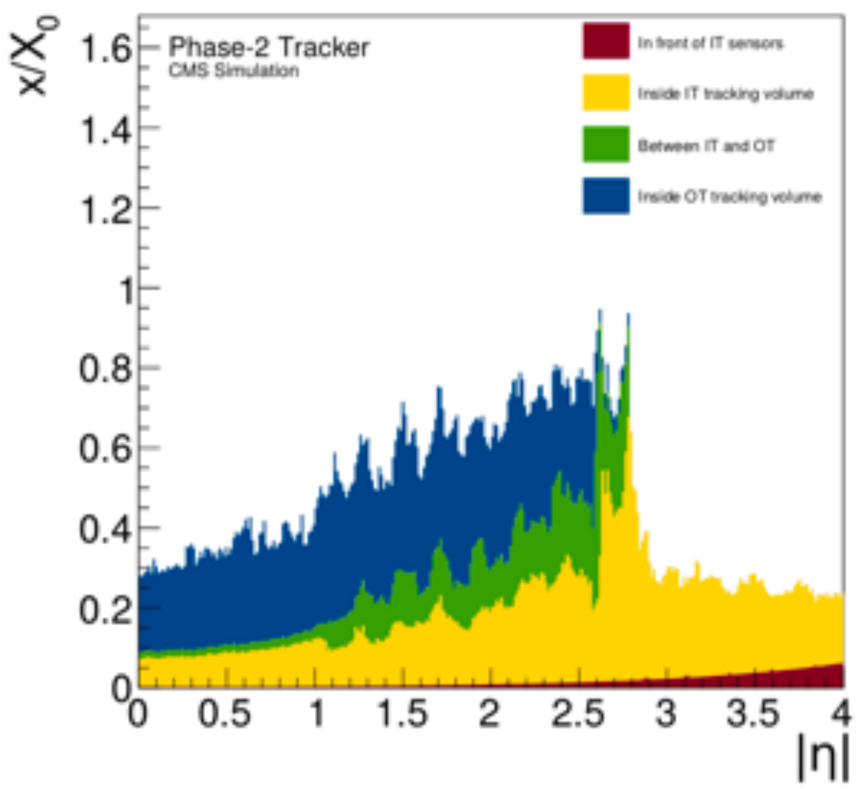
Occupancy no larger than 3%

Material budget

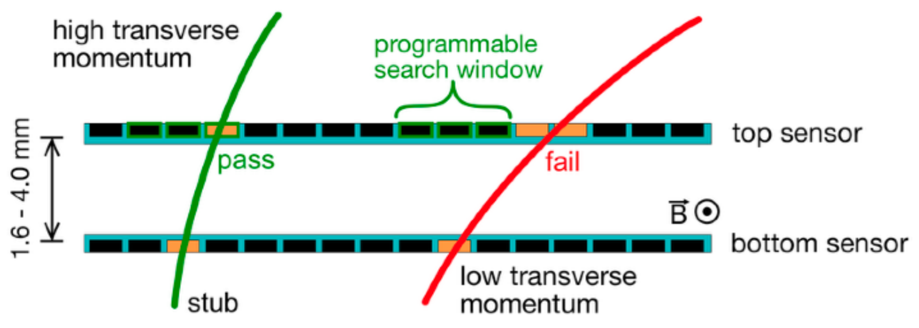
present tracker



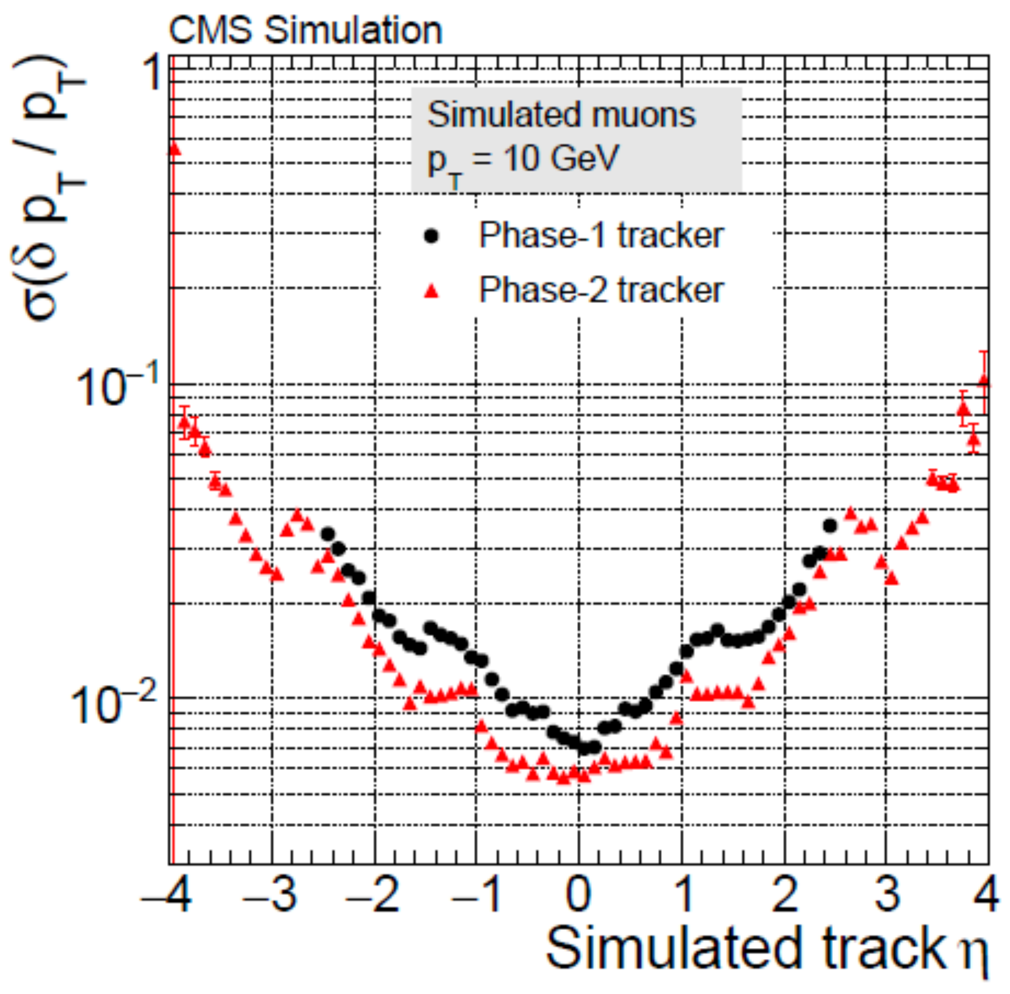
upgraded tracker



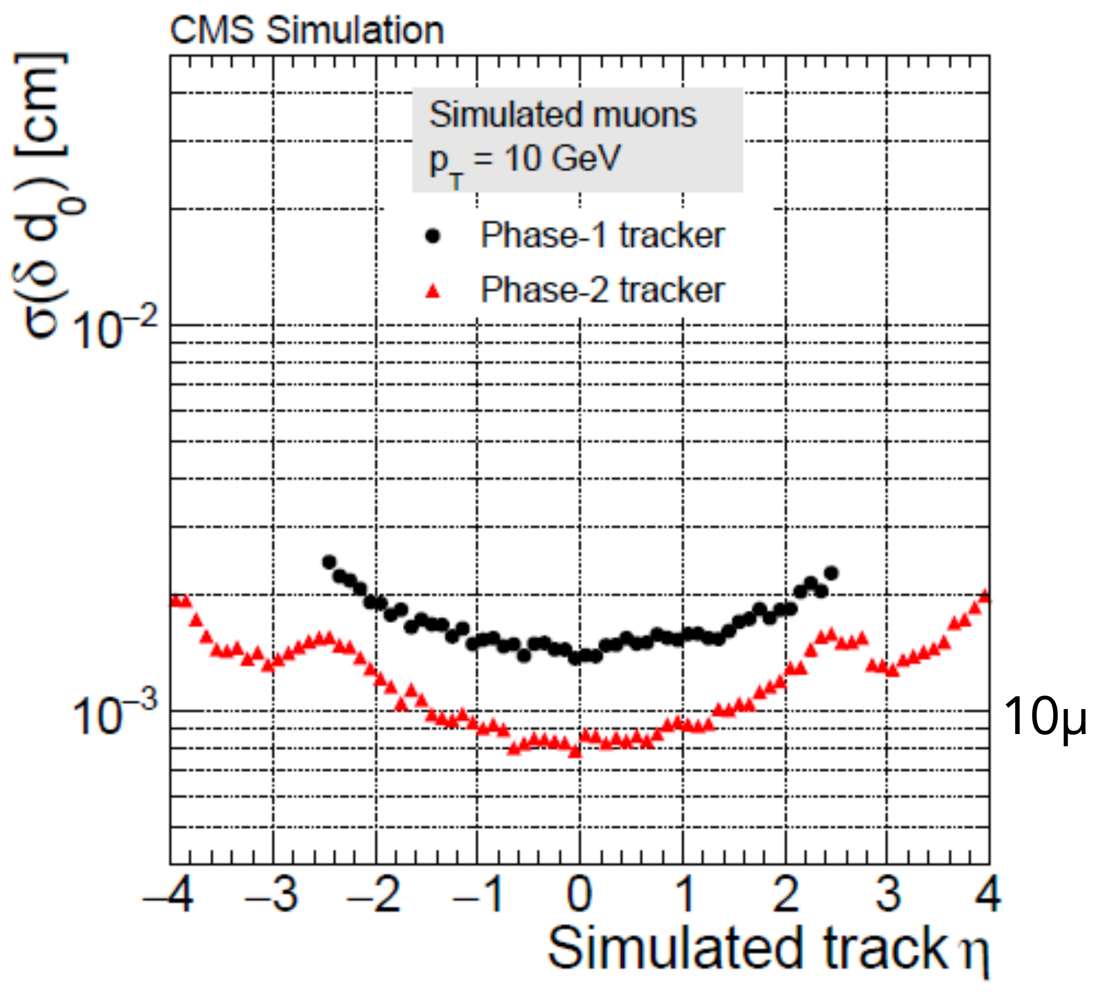
Local rejection of low p_T tracks



Expected performance
compared to present tracker

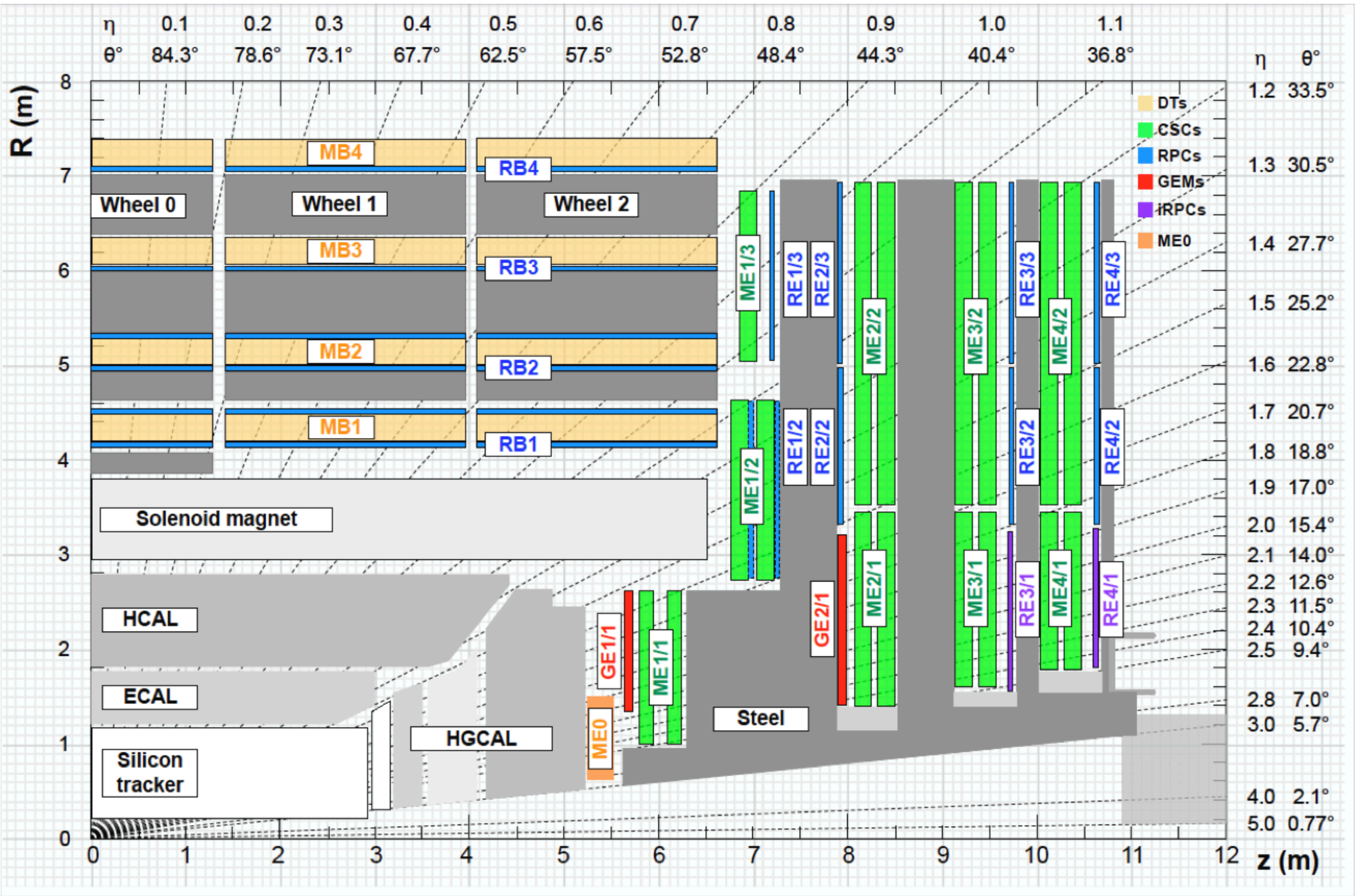


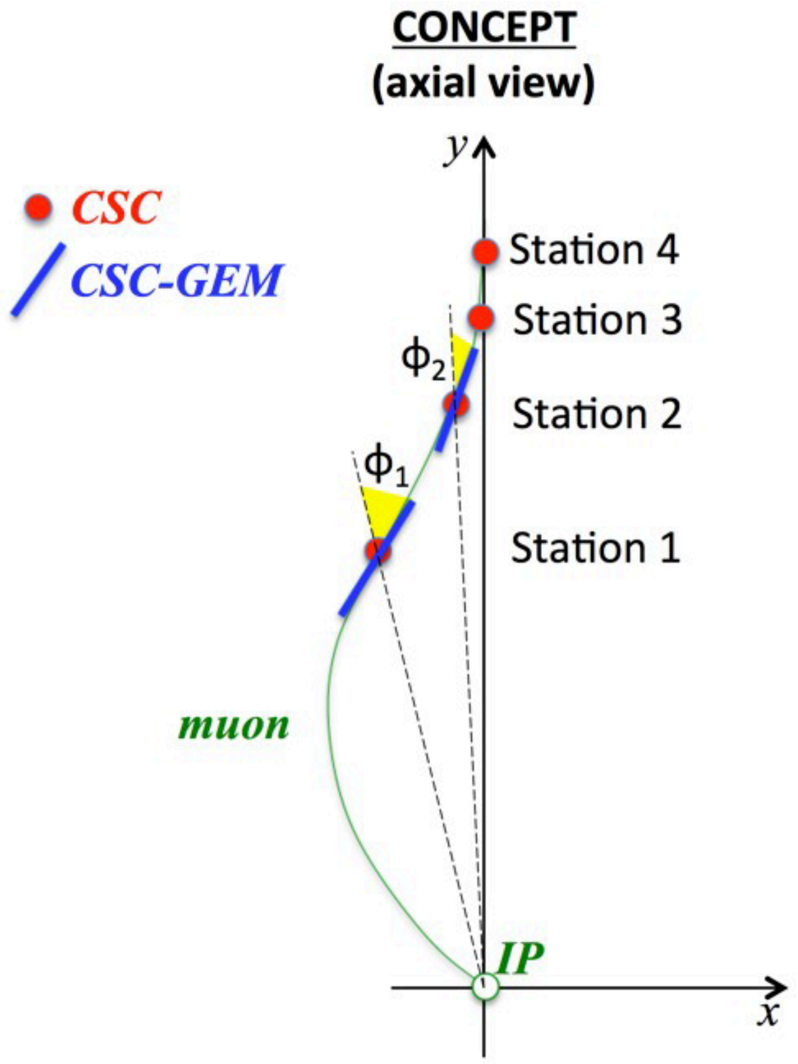
transverse momentum

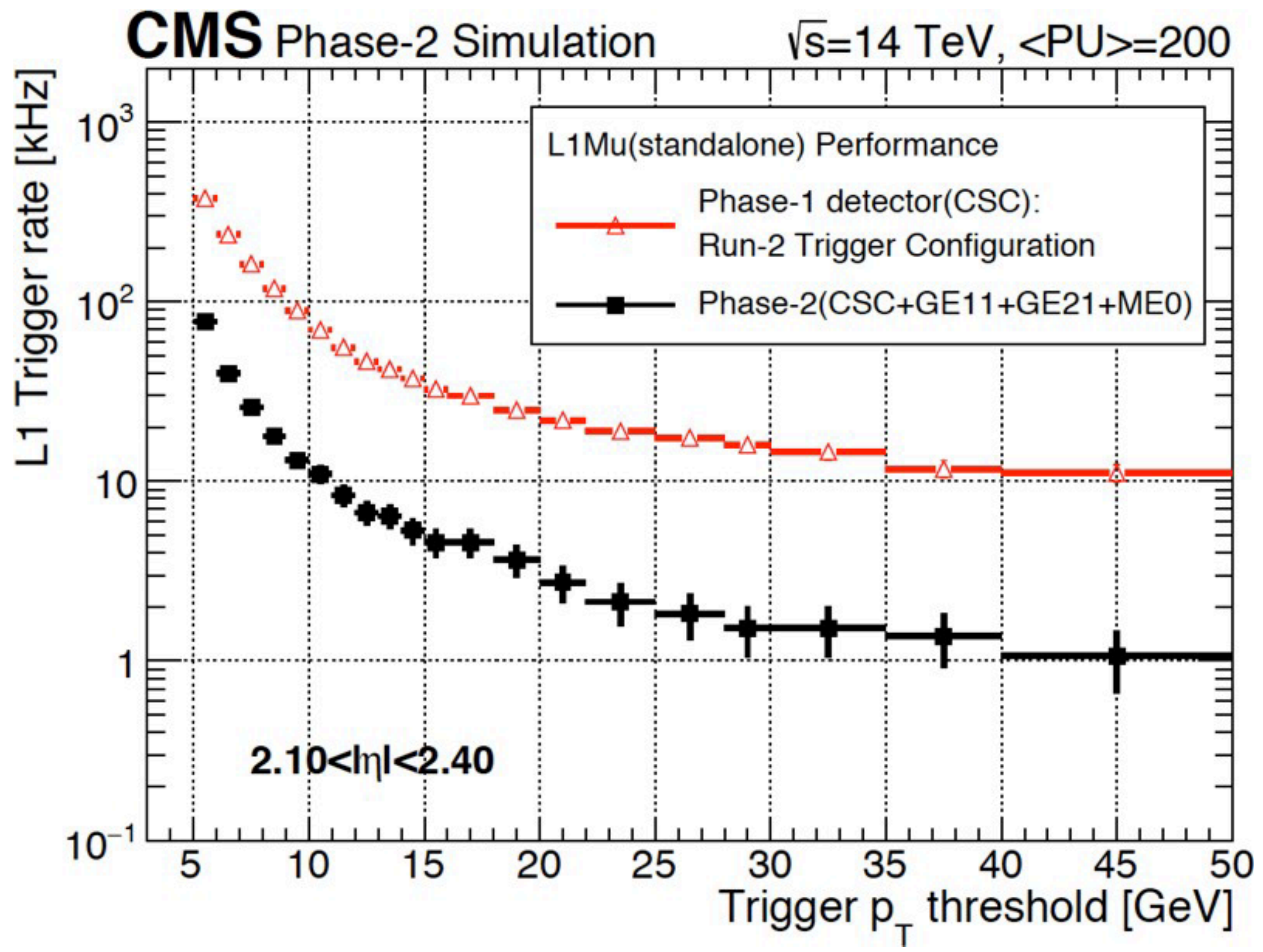


transverse impact parameter

Muon Detectors







Barrel and Endcaps

- Replacement of readout electronics for the new L1 trigger conditions

Athens/Ioànnina responsible for BMT Layer-1 HW and FW

Endcaps

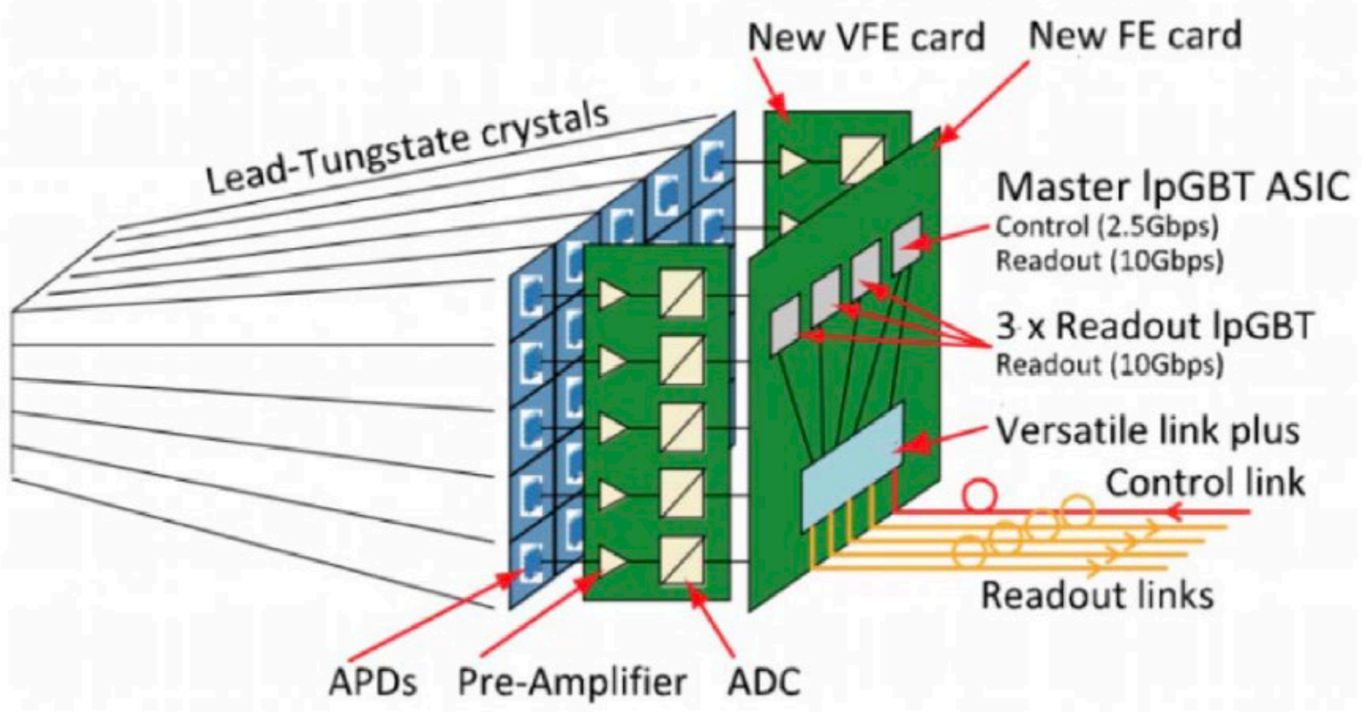
- Robust trigger up to |η| = 2.4 thanks to **RPC stations** RE3/1 and RE4/1 and 2-layer **GEM stations** GE1/1 and GE2/1
- Trigger extension up to |η| = 2.8 6-layer **GEM station** ME0

2 GEM/CSC "tandems"

- measurement of "local" μ direction (sensitive to p_T)
- standalone L1-trigger rate drops by factor up to 10
- important for off-pointing muon triggers (search for LLPs)

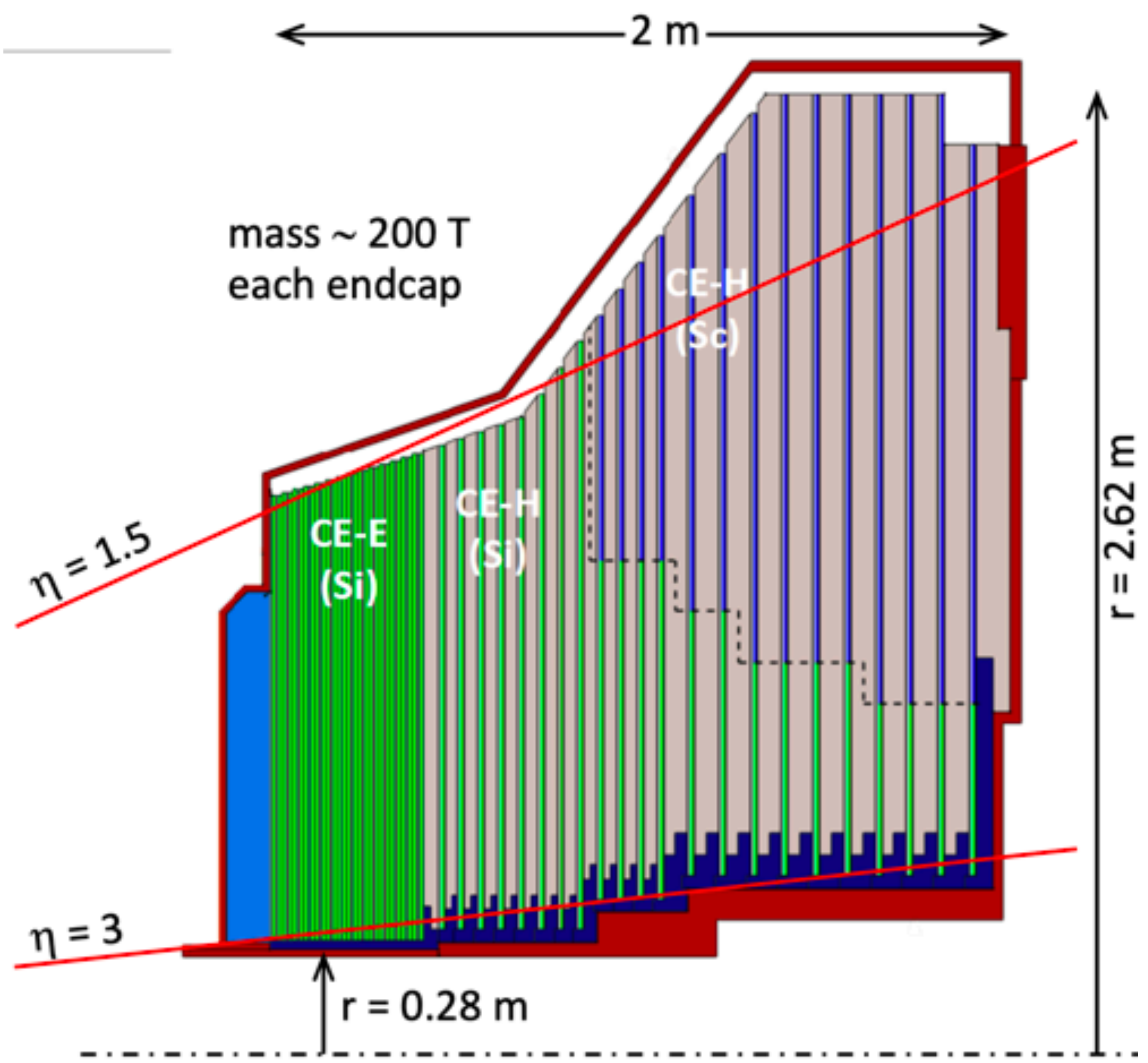
Calorimeters

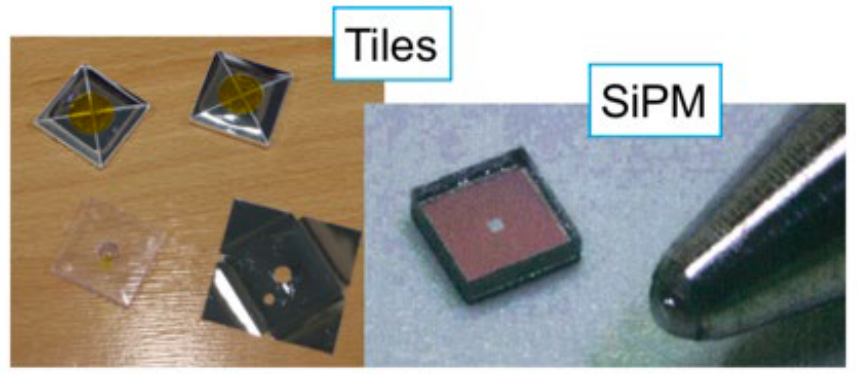
Barrel



New ECAL on-detector electronics
- digitisation at 160 MHz
- online pulse shape discrimination against spikes
- trigger granularity = single crystal
- 30 ps time resolution (E_γ > 50 GeV)
- cooled at 9°C to mitigate APD ageing

Endcaps: High-Granularity Calorimeter (HGCAL)

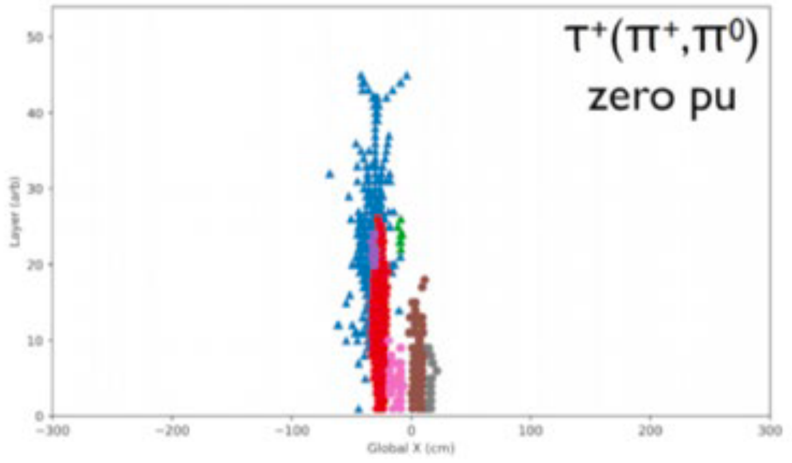




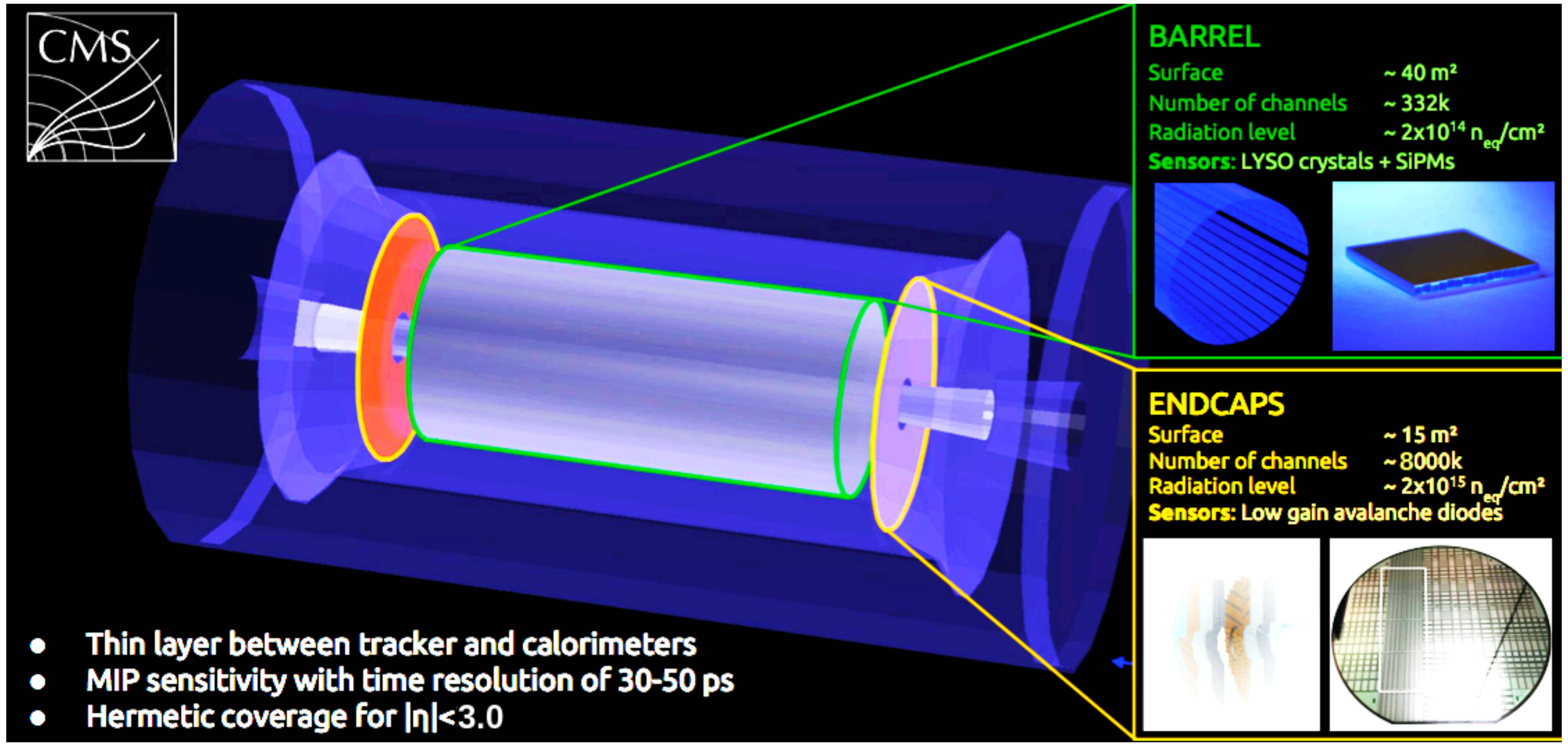
Electromagnetic (CE-E)
- Cu/CuW/Pb absorbers
- Si sensors, hexagonal modules
- 28 layers
- 25.5Xo and 1.7λ

Hadronic (CE-H)
- steel absorbers
- High-radiation regions: Si sensors
- Low-radiation regions: scintillation tiles with SiPM readout
- 22 layers
- 9.5λ (including CE-E)

6M Si channels
240k scint. channels

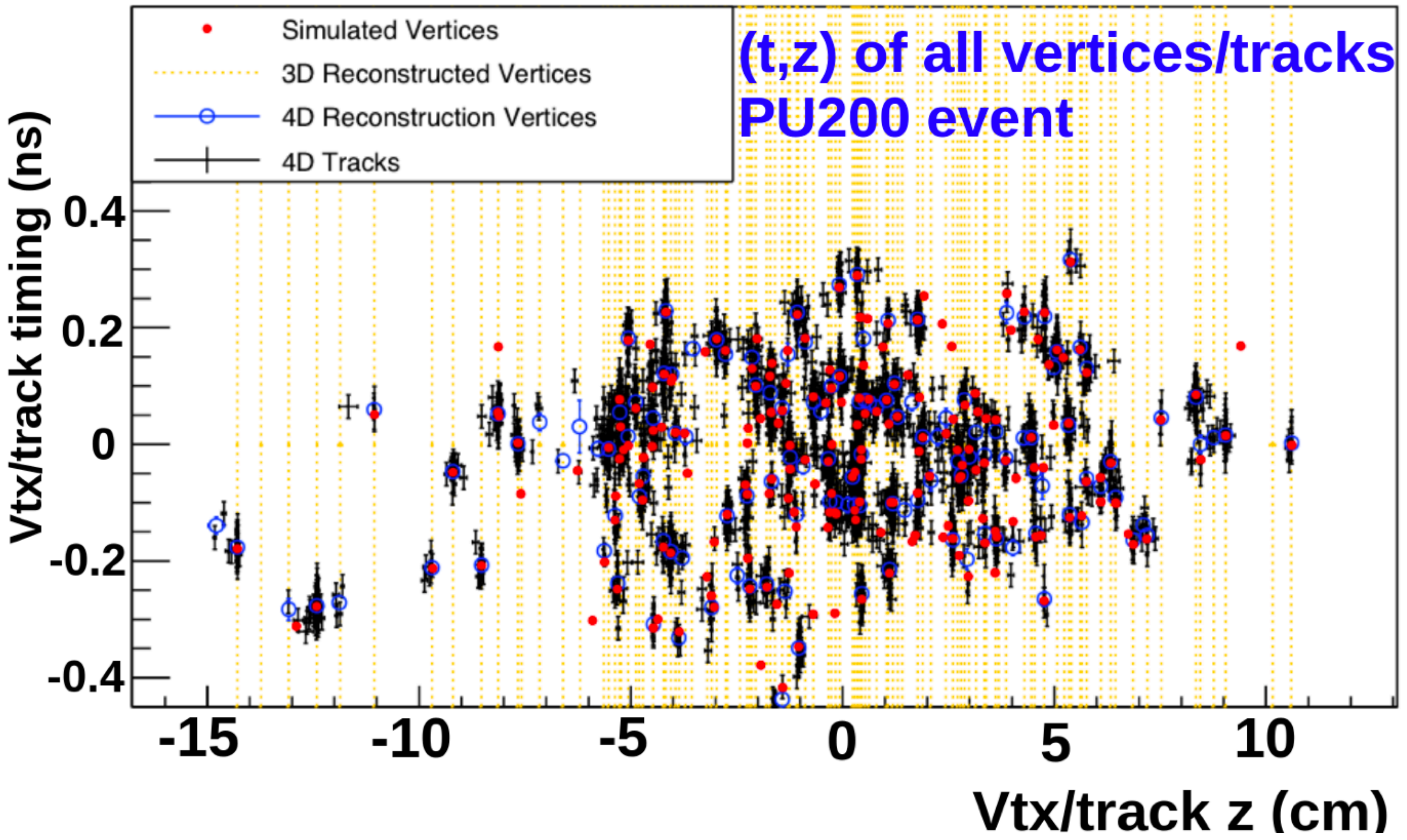


MIP Timing Detector



The MTD features

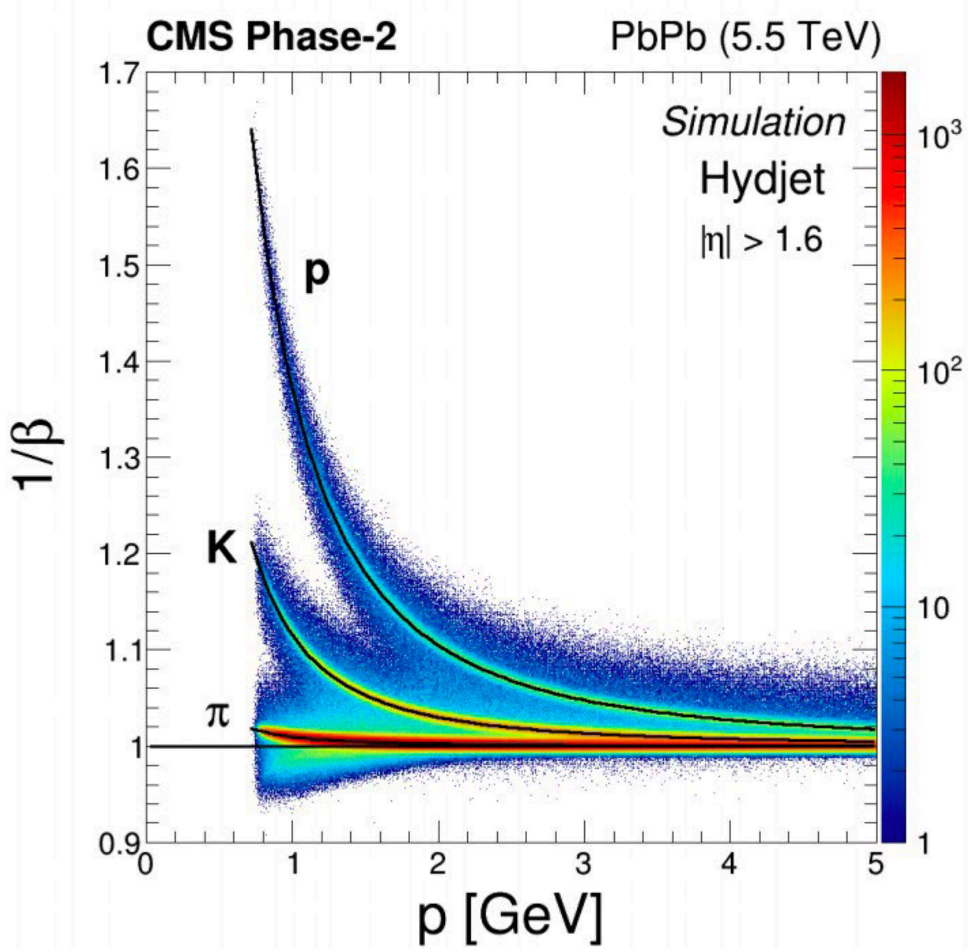
- a time resolution of 30-50 ps for MIPs
- a 4th dimension for PU rejection



Precise timing allows for the removal of spurious tracks from PU, this improving on

- lepton isolation and identification
- jet reconstruction and flavour tagging
- missing p_T reconstruction

Precise timing also offers time-and-flight identification at low momenta (relevant in HI)



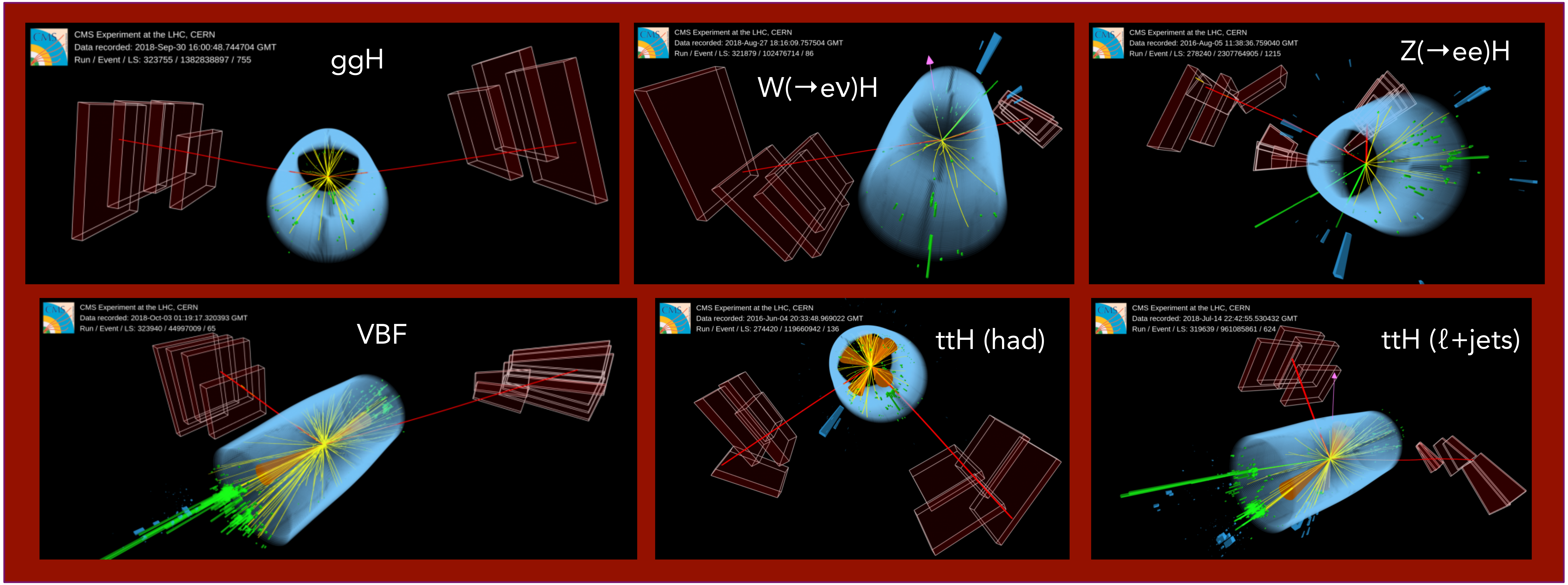
The MTD uses well-established technologies

- Barrel:
  LYSO crystals with dual end SiPM readout
- Endcaps:
  Low Gain Avalanche Detectors (LGAD)

Evidence for H → μμ

Exclusive categories: ggH, VBF, VH and ttH

Full Run-2, 137 fb^{-1}



CMS-HIG-19-006
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Phys. Briefing

$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\mathrm{stat})^{+0.17}_{-0.16}\,(\mathrm{syst})$$

Obs. (exp.) significance: 3.0 (2.5) σ

evidence made possible thanks to the use of advanced ML techniques in the VBF analysis

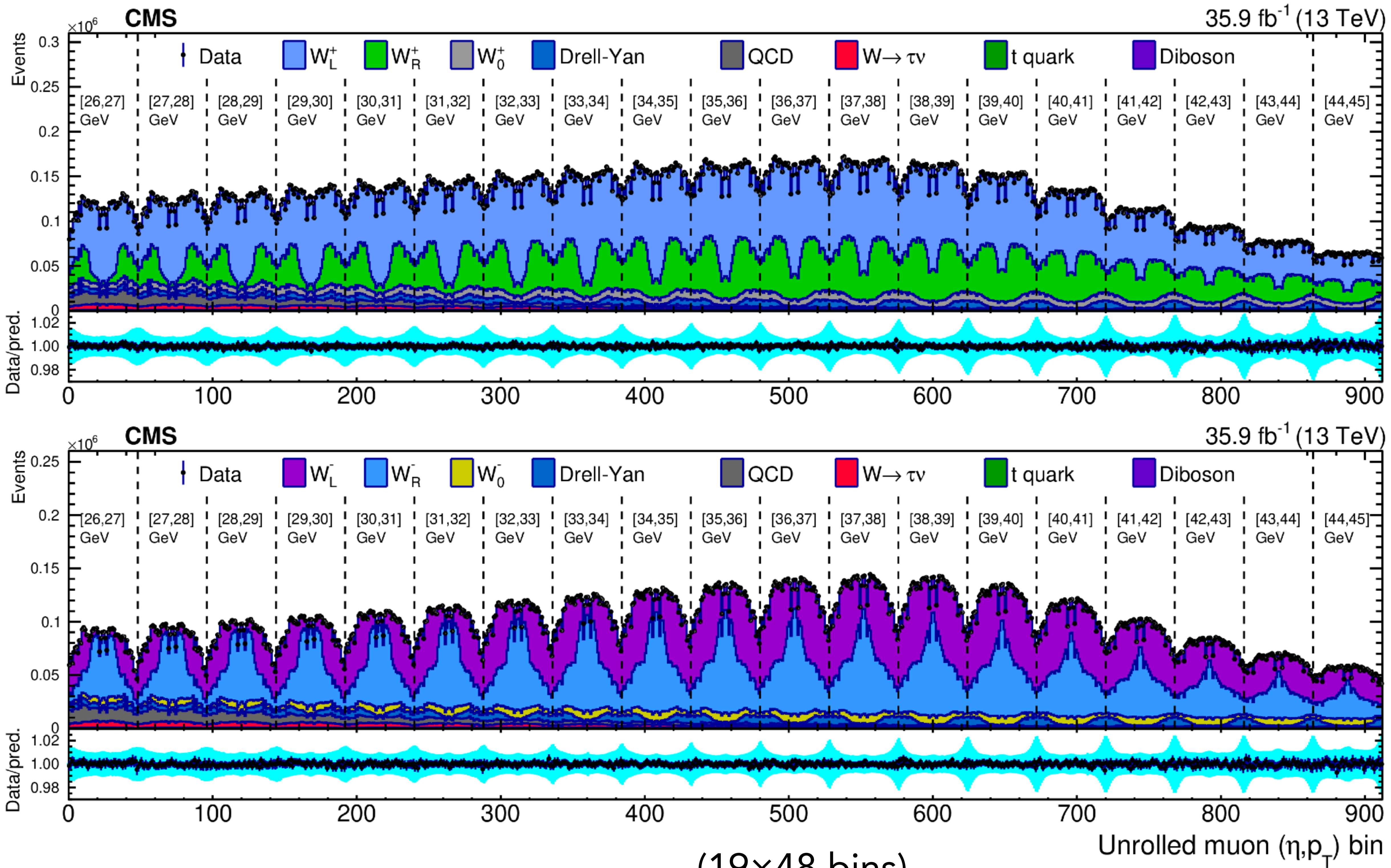
W Helicity Measurements

Run-2 2016, 35.9 fb^{-1}

Double-differential cross-sections in p_T^ℓ and η^ℓ (ℓ = e, μ) for W$^+$ and W$^-$

W$^+$

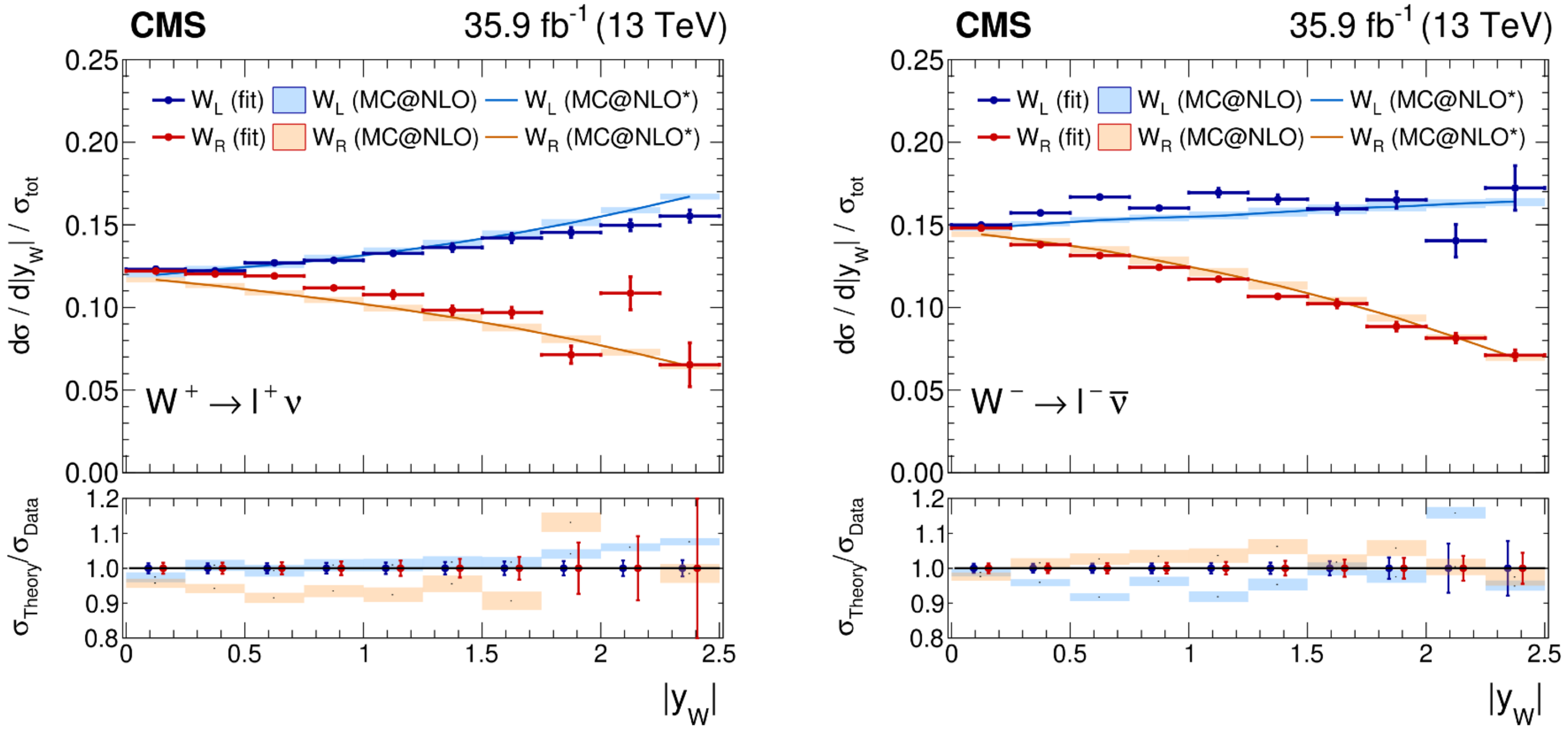
W$^-$

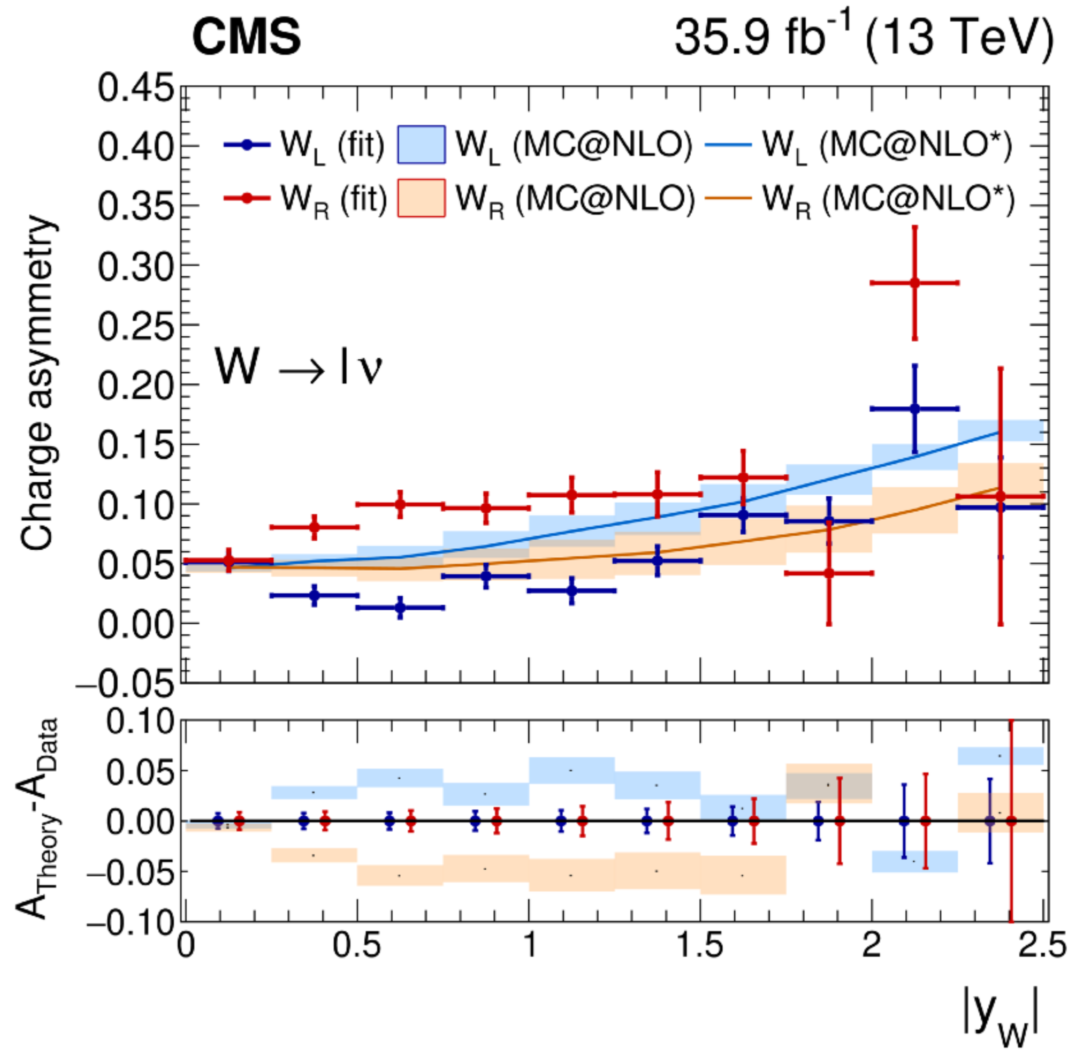


(19×48 bins)

p_T^μ = 26 GeV → 45 GeV

$\eta \in [-2.4, 2.4]$





- constraints on PDFs
- milestone towards the W mass measurement

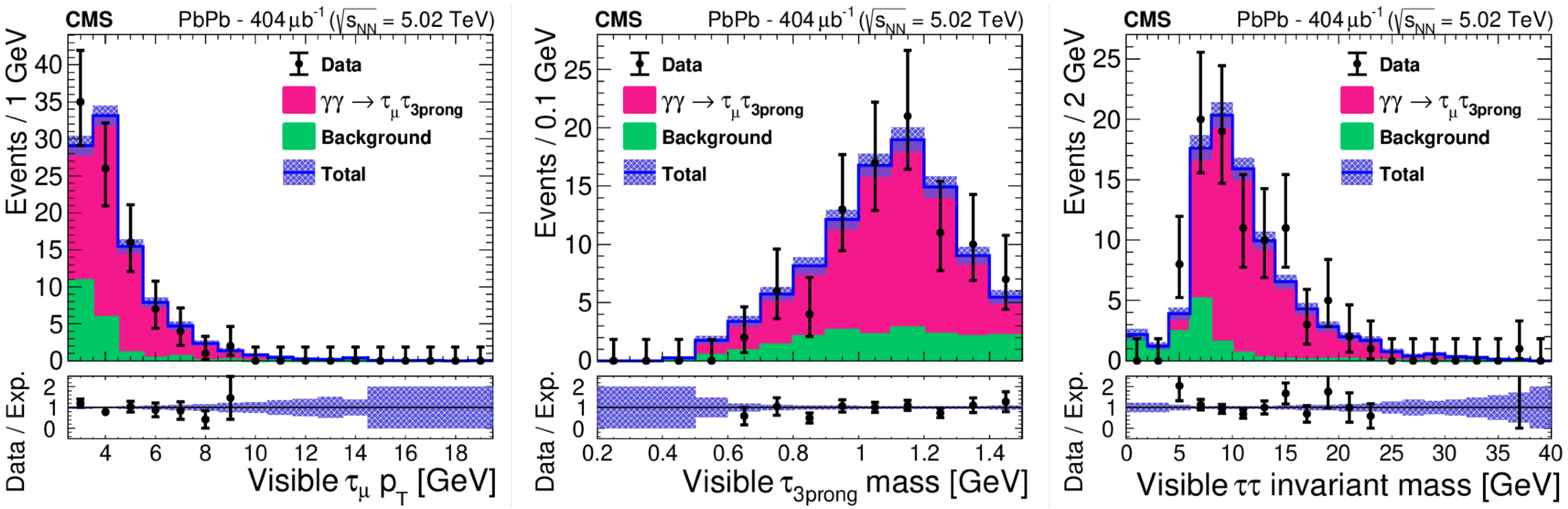
CMS-SMP-18-012
PRD 102 (2020) 092012

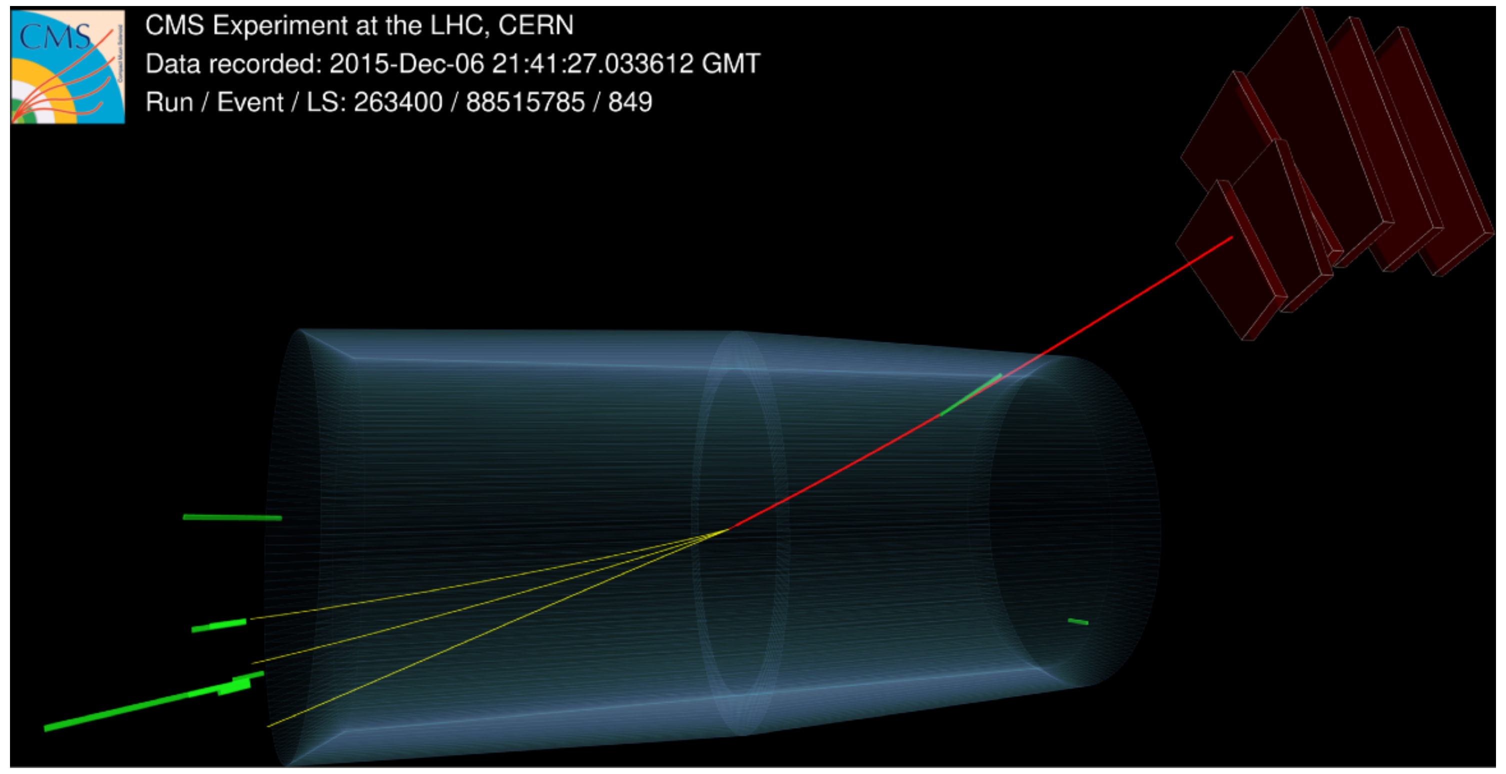
Template fit to extract **differential cross-sections** and **charge asymmetries** for the two **helicity states**

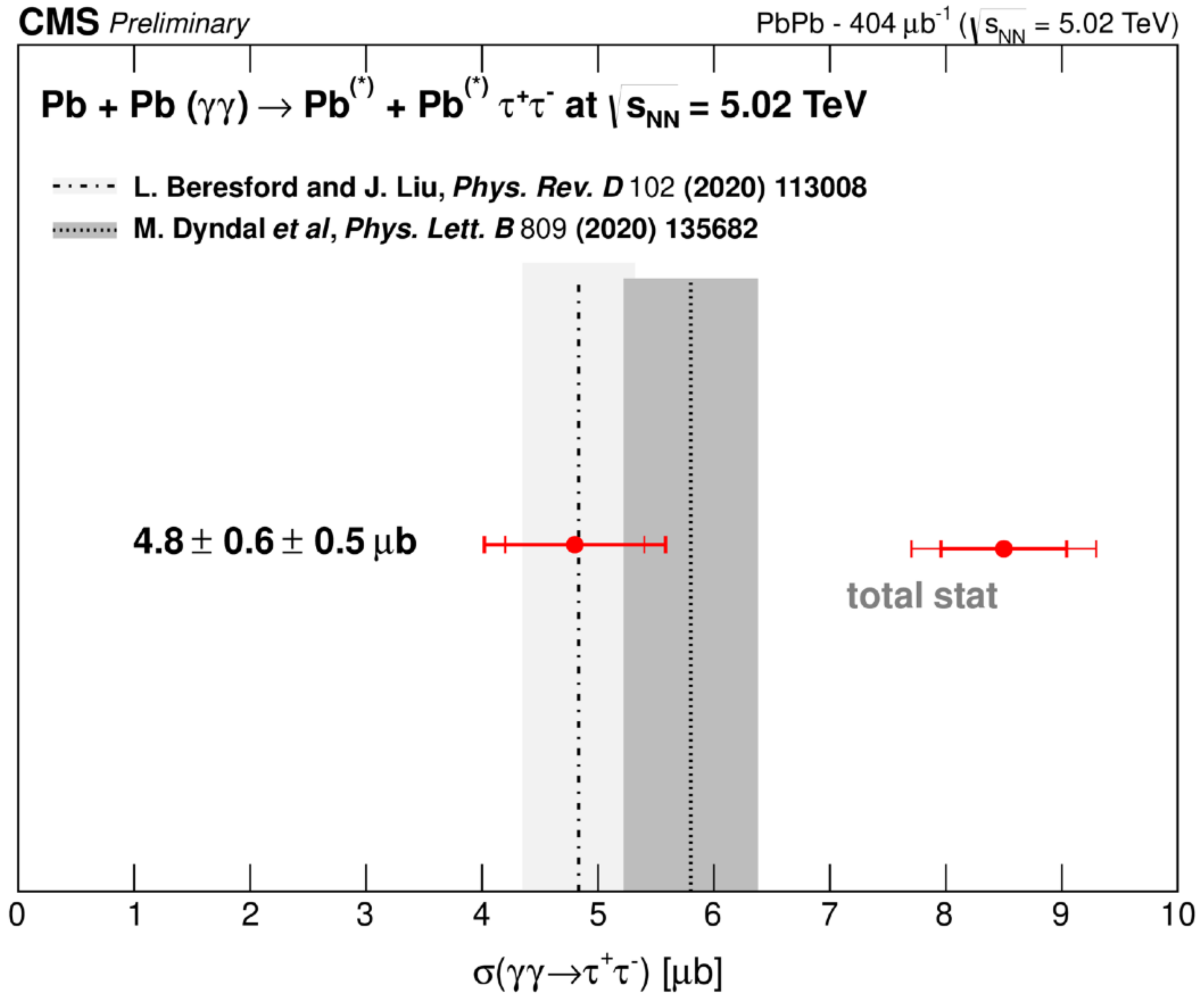
Photon-Induced τ-Pair Production

CMS-HIN-21-009
Submitted to PRL

Observation (>5σ) of photon-induced τ-lepton pair production $\gamma\gamma \to \tau^+\tau^-$ in ultra-peripheral lead-lead interactions PbPb, $\sqrt{s_{NN}}$ = 5.02 TeV, 404 μb^{-1} (2015) in agreement with QED predictions







Paves the way to the determination of the τ-lepton anomalous magnetic moment